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École doctorale
**Mathématiques
et informatique** / **université
de BORDEAUX**

THÈSE

présentée à

L'UNIVERSITÉ DE BORDEAUX

ÉCOLE DOCTORALE DE MATHÉMATIQUES ET INFORMATIQUE

par Jialun LI

sous la direction de Jean-François Quint

POUR OBTENIR LE GRADE DE

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Analyse harmonique des mesures stationnaires

Soutenue le 4 décembre 2018 à l'Institut de Mathématiques de Bordeaux

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Harmonic analysis of stationary measures

Thesis prepared under the supervision of
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Introduction en français

*Cette thèse est constituée de quatre articles de recherche. La première partie va être publiée dans *Mathematische Annalen* et la dernière a été soumise.*

Soit V une représentation irréductible de dimension finie du groupe de Lie $G = \mathrm{SL}_{m+1}(\mathbb{R})$. Soit $X = \mathbb{P}V$ l'espace projectif réel de V , qui est l'ensemble des droites vectorielles de V . Alors, nous avons une action du groupe G sur X . Soit μ une mesure de probabilité borélienne sur G et soit Γ_μ le sous-groupe engendré par le support de μ . Nous dirons que μ est Zariski dense si Γ_μ est un sous-groupe Zariski dense de G . Cela signifie que la mesure μ n'est pas concentrée sur un sous-groupe algébrique de G . Nous pouvons définir sur X une marche aléatoire associée à μ . Fixons un point x de X . Lors de chaque étape, nous nous déplaçons vers un point aléatoire gx , où g est un élément aléatoire de G , de loi μ . D'après un théorème de Furstenberg, cette marche aléatoire admet une unique mesure stationnaire ν sur X , appelée la mesure de Furstenberg ou la mesure μ -stationnaire. Cela signifie que la mesure ν vérifie $\nu = \mu * \nu := \int_G g_* \nu d\mu(g)$, où $g_* \nu$ est l'image de ν par l'action de g sur X . Cette mesure a été introduite par Furstenberg pour établir la loi des grands nombres pour les produits de matrices aléatoires. Les propriétés de la mesure μ -stationnaire sont importantes dans d'autres théorèmes limites pour les produits de matrices aléatoires.

Il y a beaucoup d'exemples intéressants de mesures μ -stationnaires. Nous nous restreignons à la basse dimension, c'est-à-dire au cas où $G = \mathrm{SL}_2(\mathbb{R})$ et $X = \mathbb{P}(\mathbb{R}^2)$, la droite projective réelle. Soit Γ un réseau de $\mathrm{SL}_2(\mathbb{R})$ (par exemple $\mathrm{SL}_2(\mathbb{Z})$). Furstenberg a construit des exemples où μ est une mesure portée par Γ et la mesure stationnaire ν est exactement la mesure de Lebesgue de X . Cette construction a été utilisée dans le travail de Furstenberg sur le bord de Poisson, qui a donné des propriétés de rigidité des réseaux. Récemment, les gens se sont intéressés aux propriétés de dimension et d'absolue continuité de la mesure μ -stationnaire ν quand μ a un support fini. Voir [BPS12] et [Bou12] pour des exemples de mesures stationnaires absolument continues et [HS17] pour des exemples de mesure stationnaires de dimension totale.

Mentionnons aussi une autre classe de mesures, les convolutions de Bernoulli. Soient X_0, X_1, \dots des variables aléatoires i.i.d telles que $\mathbb{P}(X_0 = 1) = \mathbb{P}(X_0 = -1) = 1/2$. Soit ν_λ la convolution de Bernoulli de paramètre $\lambda \in (0, 1)$, qui est définie comme la distribution de la variable aléatoire $\sum_{j \geq 0} X_j \lambda^j$. Elle peut être vue comme une mesure stationnaire sur \mathbb{R} pour l'action d'un groupe résoluble. Voir l'exemple 1.1.6. Des auteurs se sont intéressés à la dimension et la régularité des convolutions de Bernoulli. Il y a

beaucoup de travaux récents dans ce cadre. Voir par exemple [SS16], [Hoc14] et [Var16].

Avant d'énoncer notre question principale, nous introduisons une autre propriété de la mesure stationnaire. Nous aurons besoin d'une hypothèse de moment exponentiel fini, c'est-à-dire qu'il existe ϵ strictement positif tel que

$$\int_G \|g\|^\epsilon d\mu(g) < +\infty.$$

Dorénavant, nous supposons toujours que notre mesure μ est Zariski dense avec un moment exponentiel fini. Rappelons que $X = \mathbb{P}V$. Guivarc'h a établi la régularité höldérienne des mesures stationnaires. Cela signifie qu'il existe des nombres $C, c > 0$ tels que, pour tout $r > 0$, le r -voisinage de tout hyperplan de X a une ν -mesure inférieure à Cr^c . Cela implique que la mesure stationnaire ν a une dimension positive. Cela implique aussi que ν n'est pas concentrée sur un hyperplan, ce qui est raisonnable vue l'hypothèse de Zariski densité de μ .

Décroissance de Fourier

Notre problème principal ici est la décroissance de Fourier de la mesure stationnaire. Considérons d'abord l'exemple $G = \mathrm{SL}_2(\mathbb{R})$ et $X = \mathbb{P}(\mathbb{R}^2)$. Fixons l'identification de $\mathbb{P}(\mathbb{R}^2)$ avec le cercle $\mathbb{T} \simeq \mathbb{R}/\pi\mathbb{Z}$, donnée par l'action transitive du groupe PSO_2 . Nous pouvons alors définir les coefficients de Fourier de la mesure stationnaire ν par

$$\hat{\nu}(k) = \int_{\mathbb{T}} e^{2ikx} d\nu(x), \quad \text{pour } k \in \mathbb{Z}.$$

Théorème (Theorem 1.1.1, Theorem 2.1.2). *Soit μ une mesure de probabilité borélienne Zariski dense sur $\mathrm{SL}_2(\mathbb{R})$ avec un moment exponentiel fini. Soit ν la mesure μ -stationnaire sur \mathbb{T} . Alors il existe $\epsilon > 0$ tel que*

$$|\hat{\nu}(k)| = O(|k|^{-\epsilon}). \tag{0.0.1}$$

En d'autres termes, les coefficients de Fourier de la mesure stationnaire ont une décroissance polynomiale. Par un argument général, la décroissance polynomiale des coefficients de Fourier implique la régularité de Guivarc'h. En réalité, la régularité est un ingrédient essentiel de la démonstration. La décroissance de Fourier pour des mesures reliées à l'algorithme des fractions continues a été étudiée par Kaufman [Kau80], Queffelec-Ramaré [QR03] et Jordan-Sahlsten [JS16]. Récemment, la décroissance de Fourier des mesures de Patterson-Sullivan a été démontrée par Bourgain-Dyatlov [BD17]. Notre deuxième approche est inspirée par leurs méthodes.

Nous avons deux approches pour ce problème. La première (Chapitre 1) est plus élémentaire, nous utilisons le théorème de renouvellement pour les processus stochastiques. Mais le résultat est plus faible, nous pouvons seulement établir une version qualitative, à savoir $|\hat{\nu}(k)| \rightarrow 0$ quand $|k| \rightarrow +\infty$. Car la décroissance exponentielle dans le théorème de renouvellement n'est pas encore connue. Par la suite, nous établissons l'existence de ce terme d'erreur grâce à notre seconde approche.

La seconde approche (Chapitre 2) est inspirée par la méthode de Bourgain et Dyatlov. L'ingrédient principal, l'estimées sommes-produits, vient de la combinatoire additive. Nous expliquerons cette approche plus loin.

Un exemple intéressant est la mesure de Patterson-Sullivan sur l'ensemble limite d'un groupe fuchsien convexe co-compact. En combinant les méthodes de Connell-Muchnik [CM07] et de Lalley [Lal86], pour un groupe fuchsien convexe co-compact, nous pouvons trouver une mesure μ telle que la mesure de Patterson-Sullivan soit μ -stationnaire. Grâce à cette observation, nous pouvons retrouver le résultat de Bourgain-Dyatlov sur la décroissance de Fourier des mesures de Patterson-Sullivan. Mais notre vitesse de décroissance est plus faible.

En dimension plus grande, nous considérons la décroissance de la transformée de Fourier dans une carte affine. Soit v_0 un vecteur unitaire de V . Soit v_0^\perp le sous-espace vectoriel orthogonal de v_0 dans V . Soit U le sous-ensemble ouvert de $\mathbb{P}V$ qui est le complémentaire de l'hyperplan $\mathbb{P}v_0^\perp$. Nous prenons la carte locale affine (ψ, U) of $\mathbb{P}V$, donnée par

$$\psi : \mathbb{P}V \supset U \rightarrow v_0^\perp, \mathbb{R}v \mapsto \frac{v - \langle v_0, v \rangle v_0}{\langle v_0, v \rangle},$$

qui est bien définie sur U . L'inverse de ψ est donnée simplement par $\psi^{-1} : v_0^\perp \rightarrow U \subset \mathbb{P}V$, $u \mapsto \mathbb{R}(u + v_0)$.

Théorème (Theorem 2.1.1). *Soit μ une mesure de probabilité borélienne Zariski dense sur $\mathrm{SL}_{m+1}(\mathbb{R})$ avec un moment exponentiel fini. Soit V une représentation irréductible de dimension fini de $\mathrm{SL}_{m+1}(\mathbb{R})$. Soit ν la mesure μ -stationnaire sur $\mathbb{P}V$. Soit r une fonction C^1 dont le support est contenu dans U et qui vérifie $\|r\|_\infty \leq 1$. Alors, il existe $\epsilon > 0$ tel que, pour tout $\varsigma \in v_0^\perp$ de norme $\|\varsigma\|$ suffisamment grande, on ait*

$$\left| \int_{v_0^\perp} e^{i\langle \varsigma, u \rangle} r(u) d\nu(u) \right| \leq \|\varsigma\|^{-\epsilon}.$$

Notre méthode ne permet pas de traiter le cas des groupes de Lie non déployés comme par exemple $\mathrm{SL}_2(\mathbb{C})$. Il serait intéressant d'établir une décroissance de Fourier analogue pour $\mathrm{SL}_2(\mathbb{C})$. Nous pouvons considérer le groupe $\mathrm{SL}_2(\mathbb{Q}_p)$ et les mesures stationnaires sur \mathbb{Q}_p . Il serait aussi intéressant d'établir une décroissance de Fourier semblable pour ce groupe.

Théorème de renouvellement

Rappelons que $X = \mathbb{P}V$. Nous définissons la fonction cocycle $\sigma : G \times X \rightarrow \mathbb{R}$ par, pour $x = \mathbb{R}v$ dans X et g dans G , $\sigma(g, x) = \log \frac{\|gv\|}{\|v\|}$. Soit f une fonction lisse à support compact sur \mathbb{R} . L'opérateur de renouvellement R est défini par

$$Rf(x, t) = \sum_{n=0}^{+\infty} \int_G f(\sigma(g, x) - t) d\mu^{*n}(g), \text{ pour } x \in X \text{ et } t \in \mathbb{R}.$$

Le théorème de renouvellement a été introduit pour la première fois par Blackwell et dans notre situation par Kesten [Kes74]. Le résultat principal (dû à Guivarc'h et Le Page [GLP16]) est que, quand le temps t tend vers l'infini, la somme de renouvellement $Rf(x, t)$ tend vers $\frac{1}{\sigma_\mu} \int f$, où σ_μ est la constante de Lyapunov définie par $\sigma_\mu := \int_{G \times X} \sigma(g, x) d\mu(g) d\nu(x)$. Par définition, la constante de Lyapunov σ_μ est une moyenne de la fonction cocycle $\sigma(g, x)$ pour la mesure $\mu \otimes \nu$. Le théorème de renouvellement nous donne un phénomène d'équidistribution quand le temps t est assez grand. Dans notre première approche, le théorème de renouvellement est utilisé pour borner la somme de renouvellement Rf pour une fonction f fortement oscillante. Dans notre seconde approche, nous sommes en mesure de donner un terme d'erreur exponentiel.

Théorème (Theorem 2.1.4). *Soit μ une mesure de probabilité borélienne Zariski dense sur $\mathrm{SL}_{m+1}(\mathbb{R})$ avec un moment exponentiel fini. Soit V une représentation irréductible de $\mathrm{SL}_{m+1}(\mathbb{R})$. Il existe $\epsilon > 0$ tel que, pour $f \in C_c^\infty(\mathbb{R})$ et $t \in \mathbb{R}$, on ait*

$$Rf(x, t) = \frac{1}{\sigma_\mu} \int_{-t}^{\infty} f(u) d\mathrm{Leb}(u) + O_f(e^{-\epsilon|t|}),$$

où O_f dépend du support de f et de sa norme de Sobolev.

Ce théorème est à comparer avec le théorème de renouvellement dans \mathbb{R} (le cas commutatif). Si μ est une mesure sur \mathbb{R} dont le support est fini, le terme d'erreur dans le théorème de renouvellement n'est jamais exponentiel.

Nous espérons que ce type de résultat peut permettre d'obtenir un terme d'erreur exponentiel dans le comptage orbital en rang supérieur. Étant donné un sous-groupe discret Γ de G , nous cherchons une asymptotique pour la croissance de $\#\{\gamma \in \Gamma \mid d(\gamma o, o) \leq R\}$, où o est le point base de $\mathrm{SL}_{m+1}(\mathbb{R})/\mathrm{SO}(m+1)$. Voir par exemple Lalley [Lal89], Quint [Qui05] et Sambarino [Sam15]. Ce type de terme d'erreur est toujours relié à une propriété de trou spectral.

Trou spectral

Munissons $\mathbb{P}V$ d'une distance riemannienne. Pour $\gamma > 0$, soit $C^\gamma(\mathbb{P}V)$ l'espace des fonctions γ -höldériennes. Nous introduisons l'opérateur de transfert qui est un analogue de la fonction caractéristique dans notre cas.

Définition. *Pour z dans \mathbb{C} avec une partie réelle $|\Re z|$ suffisamment petite, soit P_z l'opérateur sur l'espace des fonctions continues donné par*

$$P_z f(x) = \int_G e^{z\sigma(g, x)} f(gx) d\mu(g), \text{ pour } x \in \mathbb{P}V.$$

Nous conservons l'hypothèse que μ est une mesure de probabilité borélienne Zariski dense sur $\mathrm{SL}_{m+1}(\mathbb{R})$ avec un moment exponentiel fini. L'utilisation de cet opérateur de transfert pour l'étude des produits de matrices aléatoires a été introduite par Guivarc'h et Le Page. En raison de la propriété de moment exponentiel, l'opérateur P_z préserve

l'espace de Banach $C^\gamma(\mathbb{P}V)$ pour $\gamma > 0$ suffisamment petit. En raison des propriétés de contraction de l'action de G dans X , pour z dans une petite boule centrée en 0, le rayon spectral de P_z dans $C^\gamma(\mathbb{P}V)$ est < 1 sauf pour $z = 0$. En raison de la non-arithméticité de Γ_μ , sur l'axe imaginaire, l'opérateur P_z a aussi un rayon spectral < 1 , sauf en 0. Ces faits ont été utilisés par Le Page et Guivarc'h pour donner des théorèmes limites pour des produits de matrices aléatoires (voir [LP82b] et [BQ16]).

Théorème (Theorem 2.1.5). *Soit μ une mesure de probabilité borélienne Zariski dense sur $\mathrm{SL}_{m+1}(\mathbb{R})$ avec un moment exponentiel fini. Soit V une représentation irréductible de $\mathrm{SL}_{m+1}(\mathbb{R})$. Pour tout $\gamma > 0$ suffisamment petit, il existe $\delta > 0$ tel que, pour tous $|b| > 1$ et $|a|$ suffisamment petit, le rayon spectral de P_{a+ib} agissant dans $C^\gamma(\mathbb{P}V)$ vérifie*

$$\rho(P_{a+ib}) < 1 - \delta.$$

Même dans le cas de $\mathrm{SL}_2(\mathbb{R})$, ce résultat est nouveau et connu seulement dans des cas particuliers. Quand μ est portée par un nombre fini d'éléments de $\mathrm{SL}_2(\mathbb{R})$ et que ces éléments engendrent un sous-semi-groupe de Schottky, ce résultat est dû à Naud [Nau05]. Quand μ est absolument continue par rapport à la mesure de Haar de $\mathrm{SL}_2(\mathbb{R})$, ce résultat peut être obtenu directement en utilisant des propriétés d'oscillation forte.

Il est intéressant de constater que ces trois propriétés, la décroissance de Fourier, le théorème de renouvellement et le trou spectral sont essentiellement équivalentes. Dans la première approche, nous utilisons le théorème de renouvellement pour prouver la décroissance de Fourier. Dans la seconde approche, nous utilisons la décroissance de Fourier pour démontrer le trou spectral, puis utilisons le trou spectral pour établir le théorème de renouvellement. Ces propriétés sont analogues à des phénomènes de la théorie des surfaces convexes co-compactes. Dans ce contexte plus géométrique, la décroissance de Fourier a été étudiée récemment par Bourgain-Dyatlov ; le trou spectral peut être interprété comme l'existence d'une zone sans zéro pour la fonction zêta de Selberg ou le trou dans les valeurs propres de l'opérateur de Laplace de la surface ; le théorème de renouvellement est remplacé par le problème de comptage des orbites du groupe fondamental ou celui des géodésiques fermées primitives. Voir [Bor07] et les références qui y sont données.

Estimées sommes-produits

Nous expliquons à présent notre deuxième approche, qui est inspirée par le travail de Bourgain et Dyatlov. L'ingrédient essentiel est une propriété de décroissance de Fourier des convolutions multiplicatives de mesures sur \mathbb{R} , qui découle de l'estimées sommes-produits discrétisée de Bourgain.

Grossièrement, l'estimées sommes-produits nous dit que la taille d'un sous-ensemble de \mathbb{Z} doit grandir rapidement par des sommes ou des produits. Cette propriété vient de la combinatoire additive. La propriété discrétisée a été introduite par Katz et Tao. Bourgain a démontré l'estimées sommes-produits discrétisée dans [Bou03]. Une de ses nombreuses applications est un résultat de trou spectral dans $\mathrm{SU}(2)$ [BG08], qui a été

ensuite généralisé dans [BdS16] et [BISG17]. Notre seconde approche peut être vue comme un analogue dans $\mathrm{SL}_{m+1}(\mathbb{R})$.

Pour des groupes de Lie de rang supérieur, nous avons besoin de généraliser la décroissance de Fourier des convolutions multiplicatives à \mathbb{R}^n . He-de Saxcé ont démontré une version de l'estimées sommes-produits discrétisée dans \mathbb{R}^n . En utilisant leur résultat, nous pouvons démontrer le

Théorème (Theorem 3.1.1). *Étant donné $\kappa_0 > 0$, il existe $\epsilon, \epsilon_1 > 0$ et $k \in \mathbb{N}$ tels que la propriété suivante est vérifiée pour $\delta > 0$ suffisamment petit. Soit μ une mesure de probabilité sur $[1/2, 1]^n \subset \mathbb{R}^n$ qui vérifie la condition de $(\delta, \kappa_0, \epsilon)$ non concentration projective, à savoir*

$$\forall \rho \geq \delta, \quad \sup_{a \in \mathbb{R}, v \in \mathbb{S}^{n-1}} (\pi_v)_* \mu(B_{\mathbb{R}}(a, \rho)) = \sup_{a, v} \mu\{x | \langle v, x \rangle \in B_{\mathbb{R}}(a, \rho)\} \leq \delta^{-\epsilon} \rho^{\kappa_0}. \quad (0.0.2)$$

Alors, pour tout $\xi \in \mathbb{R}^n$ avec $\|\xi\| \in [\delta^{-1}/2, \delta^{-1}]$,

$$\left| \int \exp(2i\pi \langle \xi, x^1 \cdots x^k \rangle) d\mu(x^1) \cdots d\mu(x^k) \right| \leq \delta^{\epsilon_1}. \quad (0.0.3)$$

Ce théorème est utilisé dans la démonstration de la décroissance de Fourier pour $\mathrm{SL}_{m+1}(\mathbb{R})$. Comme nous l'avons déjà dit, le cas de \mathbb{R} est dû à Bourgain [Bou10].

Finitude des petites valeurs propres

Notre dernier résultat concerne une classe de variétés qui contient les surfaces hyperboliques convexes cocompactes. Soit \mathbb{H}^3 la variété hyperbolique de dimension 3 simplement connexe. La notion de finitude géométrique a été introduite par Ahlfors lors de l'étude du problème suivant: soit Γ un sous-groupe discret de type fini du groupe des isométries directes de \mathbb{H}^3 (isomorphe à $\mathrm{PSL}_2(\mathbb{C})$). Le problème consiste à savoir si l'ensemble limite de Γ est constitué de la sphère entière ou s'il a mesure de Lebesgue nulle. On l'appelle la conjecture mesurée d'Ahlfors et c'est maintenant un théorème grâce à des progrès en géométrie hyperbolique. La définition originale de la finitude géométrique est qu'il existe un domaine fondamental pour l'action de Γ sur \mathbb{H}^3 qui est un polyèdre possédant un nombre fini de côtés. Mais cette définition en termes de polyèdres est difficile à généraliser. Nous utiliserons la définition de Bowditch [Bow95], qui demande que la partie épaisse de l'enveloppe convexe de l'ensemble limite soit compacte modulo Γ .

Nous nous donnons une variété géométriquement finie localement symétrique de rang un, ce qui signifie que son revêtement universel est $X = \mathbb{H}_{\mathbb{F}}^n$ pour $\mathbb{F} = \mathbb{R}, \mathbb{C}, \mathbb{H}$ ou $\mathbb{H}_{\mathbb{F}}^n = \mathbb{H}_{\mathbb{C}}^2$. Soit $\delta(X)$ l'exposant de croissance, qui vaut $(n+1) \dim_{\mathbb{R}} \mathbb{F} - 2$. Le spectre de l'opérateur de Laplace est relié à de nombreuses quantités, comme le taux de croissance des orbites du groupe fondamental et la dimension de Hausdorff de l'ensemble limite. Nous généralisons un résultat de Lax et Phillips pour $X = \mathbb{H}_{\mathbb{R}}^n$ [LP82a] et un résultat de Hamenstädt dans le cas général [Ham04].

Théorème (Theorem 4.1.1). *Soit $M = \Gamma \backslash X$ une variété géométriquement finie localement symétrique de rang 1. Alors, l'intersection du spectre de l'opérateur de Laplace et de l'intervalle critique $(-\delta(X)^2/4, 0]$ est constituée d'un nombre fini de valeurs propres de multiplicité finie.*

Ce résultat peut être utilisé pour donner un trou spectral pour l'opérateur de Laplace. Alors le trou spectral donne un terme d'erreur pour le problème de comptage orbital.

Introduction

*This thesis consists of four research papers. The first part will appear in *Mathematische Annalen* and the last part has been submitted.*

Let V be a finite dimensional irreducible representation of the Lie group $G = \mathrm{SL}_{m+1}(\mathbb{R})$. Let $X = \mathbb{P}V$ be the real projective space of V , which is the set of lines of V . Then we have a group action of G on X . Let μ be a Borel probability measure on G and let Γ_μ be the subgroup generated by the support of μ . We call μ Zariski dense if Γ_μ is a Zariski dense subgroup of G . This means that the measure μ does not concentrate on any algebraic subgroup of G . We can give a random walk on X induced by μ . Fix a point x in X . At each step, we go to a random point gx , where g is a random element in G with the law of μ . By a theorem of Furstenberg, this random walk has a unique stationary measure ν on X , called the Furstenberg measure or the μ -stationary measure. That is to say, the measure ν satisfies $\nu = \mu * \nu := \int_G g_* \nu d\mu(g)$, where $g_* \nu$ is the push-forward of ν by the action of g on X . This measure was introduced by Furstenberg when he established the law of large numbers for products of random matrices. The properties of the μ -stationary measure is important in other limit theorems for products of random matrices.

There are many interesting examples of μ -stationary measures. We restrict our attention to low dimension, that is $G = \mathrm{SL}_2(\mathbb{R})$ and $X = \mathbb{P}(\mathbb{R}^2)$, the real projective line. Let Γ be a lattice in $\mathrm{SL}_2(\mathbb{R})$ (for example $\mathrm{SL}_2(\mathbb{Z})$). Furstenberg constructed examples where μ is a measure supported on Γ and the μ -stationary measure ν is exactly the Lebesgue measure on X . This construction was used in Furstenberg's work on the Poisson boundary, which gave some rigidity properties of lattices. Recently, people have been interested in the dimension and the absolute continuity of the μ -stationary measure ν when μ has finite support. Please see [BPS12] and [Bou12] for examples of absolutely continuous stationary measures, and [HS17] for examples of stationary measures with full dimension.

We also mention another class of measures, the Bernoulli convolutions. Let X_0, X_1, \dots be i.i.d. random variables such that $\mathbb{P}(X_0 = 1) = \mathbb{P}(X_0 = -1) = 1/2$. Let ν_λ be the Bernoulli convolution with parameter $\lambda \in (0, 1)$, defined to be the distribution of the random variable $\sum_{j \geq 0} X_j \lambda^j$. This can be seen as a stationary measure on \mathbb{R} for the action of a solvable group. Please see Example 1.1.6. People are interested in the dimension and the regularity of the Bernoulli convolutions. There are many recent works on this setting. See for instance [SS16], [Hoc14] and [Var16].

Before stating our main question, we introduce another property of the stationary measure. We need the hypothesis of finite exponential moment, that is there exists ϵ positive such that

$$\int_G \|g\|^\epsilon d\mu(g) < +\infty.$$

From now on, we always suppose that our measure μ is Zariski dense with a finite exponential moment. Recall that $X = \mathbb{P}V$. Guivarc'h proved Hölder regularity of stationary measures. This means that there exist C, c positive such that for every r positive, the r neighbourhood of any hyperplane in X has ν measure less than Cr^c . This implies that the stationary measure ν has positive dimension. This also says that ν does not concentrate on some hyperplane, which is reasonable due to the hypothesis of Zariski density of μ .

Fourier decay

Our main problem here is the Fourier decay of the stationary measure. Let us first see the example $G = \mathrm{SL}_2(\mathbb{R})$ and $X = \mathbb{P}(\mathbb{R}^2)$. Fix the identification of $\mathbb{P}(\mathbb{R}^2)$ with the circle $\mathbb{T} \simeq \mathbb{R}/\pi\mathbb{Z}$, given by the transitive action of the group PSO_2 . We can define the Fourier coefficients of the stationary measure ν by

$$\hat{\nu}(k) = \int_{\mathbb{T}} e^{2ikx} d\nu(x), \quad \text{for } k \in \mathbb{Z}.$$

Theorem (Theorem 1.1.1, Theorem 2.1.2). *Let μ be a Zariski dense Borel probability measure on $\mathrm{SL}_2(\mathbb{R})$ with a finite exponential moment. Let ν be the μ -stationary measure on \mathbb{T} . Then there exists ϵ positive such that*

$$|\hat{\nu}(k)| = O(|k|^{-\epsilon}). \tag{0.0.4}$$

In other words, the Fourier coefficients of the stationary measure have polynomial decay. By a general argument, the polynomial decay of Fourier coefficients implies Guivarc'h's regularity. In fact, the regularity is a crucial ingredient in the proof. The Fourier decay of similar measures related to continued fractions have been studied by Kaufman [Kau80], Queffélec-Ramaré [QR03] and Jordan-Sahlsten [JS16]. Recently, the Fourier decay of Patterson-Sullivan measures was proved by Bourgain-Dyatlov [BD17]. Our second approach is inspired by their methods.

We have two different approaches for this problem. The first approach (Chapter 1) is more elementary, we use the renewal theorem from the theory of stochastic processes. But the result is weaker, we can only prove a qualitative version, that is $|\hat{\nu}(k)| \rightarrow 0$ as $|k| \rightarrow +\infty$. Because the exponential error term in the renewal theorem was not yet known. Later, the exponential error term is proved by our second approach through the Fourier decay.

The second approach (Chapter 2) is inspired by the method of Bourgain and Dyatlov. The main ingredient comes from additive combinatorics, the sum-product estimate. We will explain this approach later.

An interesting example is the Patterson-Sullivan measure on the limit set of convex cocompact Fuchsian groups. Combining the method of Connell-Muchnik [CM07] and Lalley [Lal86], we can find a measure μ for convex cocompact Fuchsian groups, such that the Patterson-Sullivan measure is μ -stationary. With this observation, we can recover the result of Bourgain-Dyatlov on the Fourier decay of Patterson-Sullivan measures. But the decay rate is weaker.

In higher dimension, we consider the decay of the Fourier transform on an affine chart. Let v_0 be a unit vector in V . Let v_0^\perp be the linear subspace of V , which is orthogonal to v_0 . Let U be the open subset of $\mathbb{P}V$, which is the complement of the hyperplane $\mathbb{P}v_0^\perp$. We take the affine local chart (ψ, U) of $\mathbb{P}V$, given by

$$\psi : \mathbb{P}V \supset U \rightarrow v_0^\perp, \mathbb{R}v \mapsto \frac{v - \langle v_0, v \rangle v_0}{\langle v_0, v \rangle},$$

which is well defined on U . The inverse of ψ is simply given by $\psi^{-1} : v_0^\perp \rightarrow U \subset \mathbb{P}V$, $u \mapsto \mathbb{R}(u + v_0)$.

Theorem (Theorem 2.1.1). *Let μ be a Zariski dense Borel probability measure on $\mathrm{SL}_{m+1}(\mathbb{R})$ with a finite exponential moment. Let V be an irreducible representation of $\mathrm{SL}_{m+1}(\mathbb{R})$ and let ν be the μ -stationary measure on $\mathbb{P}V$. Let r be a C^1 function whose support is in U and $\|r\|_\infty \leq 1$. Then there exists $\epsilon > 0$ such that for every $\varsigma \in v_0^\perp$ with the norm $\|\varsigma\|$ sufficiently large, we have*

$$\left| \int_{v_0^\perp} e^{i\langle \varsigma, u \rangle} r(u) d\nu(u) \right| \leq \|\varsigma\|^{-\epsilon}.$$

Our method cannot treat the Lie groups which are not split, for example $\mathrm{SL}_2(\mathbb{C})$. It would be interesting to establish a similar Fourier decay for $\mathrm{SL}_2(\mathbb{C})$. We can consider the group $\mathrm{SL}_2(\mathbb{Q}_p)$ and the stationary measure on \mathbb{Q}_p . It would also be interesting to establish a similar Fourier decay for this group.

Renewal theorem

Recall that $X = \mathbb{P}V$. We define the cocycle function $\sigma : G \times X \rightarrow \mathbb{R}$ by, for $x = \mathbb{R}v$ in X and g in G , $\sigma(g, x) = \log \frac{\|gv\|}{\|v\|}$. Let f be a smooth compactly supported function on \mathbb{R} . The renewal operator R is defined by

$$Rf(x, t) = \sum_{n=0}^{+\infty} \int_G f(\sigma(g, x) - t) d\mu^{*n}(g), \text{ for } x \in X \text{ and } t \in \mathbb{R}.$$

The renewal theorem was first introduced by Blackwell and in our situation by Kesten [Kes74]. The main result (due to Guivarc'h and Le Page [GLP16]) is that when time t tends to infinite, the renewal sum $Rf(x, t)$ tends to $\frac{1}{\sigma_\mu} \int f$, where σ_μ is the Lyapunov constant defined by $\sigma_\mu := \int_{G \times X} \sigma(g, x) d\mu(g) d\nu(x)$. From the definition, we see that the

Lyapunov constant σ_μ is an average of the cocycle function $\sigma(g, x)$ with respect to the measure $\mu \otimes \nu$. The renewal theorem gives us a phenomenon of equidistribution when the time t is large enough. In our first approach, the renewal theorem is used to bound the renewal sum Rf when f is a function with high oscillation. With our second approach, we are able to give an exponential error term.

Theorem (Theorem 2.1.4). *Let μ be a Zariski dense Borel probability measure on $\mathrm{SL}_{m+1}(\mathbb{R})$ with finite exponential moment. Let V be an irreducible representation of $\mathrm{SL}_{m+1}(\mathbb{R})$. There exists $\epsilon > 0$ such that for $f \in C_c^\infty(\mathbb{R})$ and $t \in \mathbb{R}$, we have*

$$Rf(x, t) = \frac{1}{\sigma_\mu} \int_{-t}^{\infty} f(u) d\mathrm{Leb}(u) + O_f(e^{-\epsilon|t|}),$$

where O_f depends on the support and some Sobolev norm of f .

We should compare this result with the renewal theorem on \mathbb{R} (the commutative case). If μ is a measure on \mathbb{R} whose support is finite, then the error term in the renewal theorem is never exponential.

Our result improves a result of Boyer, where the error term is polynomial on t . We hope this type of result can give some exponential error terms in the orbital counting problem of higher rank. Given a discrete subgroup Γ of $\mathrm{SL}_{m+1}(\mathbb{R})$, we are interested in the asymptotic for the growth of $\#\{\gamma \in \Gamma \mid d(\gamma o, o) \leq R\}$, where o is the base point in $\mathrm{SL}_{m+1}(\mathbb{R})/\mathrm{SO}(m+1)$. See for instance Lalley [Lal89], Quint [Qui05] and Sambarino [Sam15]. This type of error term is always connected with some spectral gap property.

Spectral gap

Equip $\mathbb{P}V$ with a Riemannian distance. For γ positive, let $C^\gamma(\mathbb{P}V)$ be the space of γ -Hölder functions. We introduce the transfer operator, which is an analogue of the characteristic function in our case.

Definition. *For z in \mathbb{C} with the real part $|\Re z|$ small enough, let P_z be the operator on the space of continuous functions, which is given by*

$$P_z f(x) = \int_G e^{z\sigma(g, x)} f(gx) d\mu(g), \text{ for } x \in \mathbb{P}V.$$

We keep the assumption that μ is a Zariski dense Borel probability measure on $\mathrm{SL}_{m+1}(\mathbb{R})$ with a finite exponential moment. The use of this transfer operator on the products of random matrices has been introduced by Guivarc'h and Le Page. Due to the property of exponential moment, when $|\Re z|$ is small enough, the operator P_z preserves the Banach space $C^\gamma(\mathbb{P}V)$ for $\gamma > 0$ small enough. Due to the contracting action of G on X , for z in a small ball centred at 0, the spectral radius of P_z on $C^\gamma(\mathbb{P}V)$ is less than 1 except at 0. Due to the non-arithmeticity of Γ_μ , on the imaginary line, the operator P_z also has spectral radius less than 1 except at 0. These were used to give limit theorems for products of random matrices by Le Page and Guivarc'h (Please see [LP82b] and [BQ16]).

Theorem (Theorem 2.1.5). *Let μ be a Zariski dense Borel probability measure on $\mathrm{SL}_{m+1}(\mathbb{R})$ with finite exponential moment. Let V be an irreducible representation of $\mathrm{SL}_{m+1}(\mathbb{R})$. For every $\gamma > 0$ small enough, there exists $\delta > 0$ such that for all $|b| > 1$ and $|a|$ small enough the spectral radius of P_{a+ib} acting on $C^\gamma(\mathbb{P}V)$ satisfies*

$$\rho(P_{a+ib}) < 1 - \delta.$$

Even in the case of $\mathrm{SL}_2(\mathbb{R})$, the result is new and only known in some special case. When μ is supported on a finite number of elements of $\mathrm{SL}_2(\mathbb{R})$ and these elements generate a Schottky semi group, this result is due to Naud [Nau05]. When μ is absolutely continuous with respect to the Haar measure on $\mathrm{SL}_2(\mathbb{R})$, this result can be obtained directly using high oscillations.

It is interesting that the three objects, the Fourier decay, the Renewal theorem and the spectral gap are roughly equivalent. In the first approach, we use the Renewal theorem to prove the Fourier decay. In the second approach, we use the Fourier decay to prove the spectral gap, and then use the spectral gap to prove the Renewal theorem. They are analogue with similar objects for convex cocompact surfaces. In this more geometric setting, the Fourier decay was recently studied by Bourgain-Dyatlov; the spectral gap can be interpreted as the zero free region of the Selberg zeta function or the gap of the eigenvalues of the Laplace operator on the surface; the renewal theorem is replaced by the counting problem of the lattice points or the primitive closed geodesics. Please see Borthwick [Bor07] and the references there.

Sum-product estimates

Now we explain our second approach, which is inspired by the work of Bourgain and Dyatlov. The key ingredient is a Fourier decay of multiplicative convolution of measures on \mathbb{R} , which is a consequence of the discretized sum-product estimate of Bourgain.

The sum-product estimate roughly says that a subset of \mathbb{Z} must grow rapidly under sum or product. This comes from additive combinatorics. The discretized setting was introduced by Katz and Tao. Bourgain proved the discretized sum-product estimate in [Bou03]. One of its many applications is a spectral gap result in $\mathrm{SU}(2)$ [BG08], which was further generalized in [BdS16] and [BISG17]. Our second approach can be seen as an analogue in $\mathrm{SL}_{m+1}(\mathbb{R})$.

For Lie groups of higher rank, we need to generalize the Fourier decay of multiplicative convolutions to \mathbb{R}^n . He-de Saxcé have proved a version of discretized sum-product estimate in \mathbb{R}^n [HdS18]. Using their result, we are able to prove the following:

Theorem (Theorem 3.1.1). *Given $\kappa_0 > 0$, there exist $\epsilon, \epsilon_1 > 0$ and $k \in \mathbb{N}$ such that the following holds for $\delta > 0$ small enough. Let μ be a probability measure on $[1/2, 1]^n \subset \mathbb{R}^n$ which satisfies $(\delta, \kappa_0, \epsilon)$ projective non concentration assumption, that is*

$$\forall \rho \geq \delta, \quad \sup_{a \in \mathbb{R}, v \in \mathbb{S}^{n-1}} (\pi_v)_* \mu(B_{\mathbb{R}}(a, \rho)) = \sup_{a, v} \mu\{x | \langle v, x \rangle \in B_{\mathbb{R}}(a, \rho)\} \leq \delta^{-\epsilon} \rho^{\kappa_0}. \quad (0.0.5)$$

Then for all $\xi \in \mathbb{R}^n$ with $\|\xi\| \in [\delta^{-1}/2, \delta^{-1}]$,

$$\left| \int \exp(2i\pi \langle \xi, x^1 \cdots x^k \rangle) d\mu(x^1) \cdots d\mu(x^k) \right| \leq \delta^{\epsilon_1}. \quad (0.0.6)$$

This theorem is used in the proof of Fourier decay for $\mathrm{SL}_{m+1}(\mathbb{R})$. As we have already mentioned, the case of \mathbb{R} is due to Bourgain [Bou10].

Finiteness of small eigenvalues

Our last result concerns a class of manifolds which contains convex cocompact hyperbolic surfaces. Let \mathbb{H}^3 be the simply connected hyperbolic three manifold. The definition of geometric finiteness was first introduced by Ahlfors in studying the following problem: Let Γ be a discrete finitely generated subgroup of the oriented isometry group of \mathbb{H}^3 (isomorphic to $\mathrm{PSL}_2(\mathbb{C})$). The problem is whether the limit set of Γ is a full sphere or has Lebesgue measure zero. This is called Ahlfors' measure conjecture, which is a theorem now due to progresses of hyperbolic geometry. The original definition of geometric finiteness is that there exists a fundamental domain of Γ acting on \mathbb{H}^3 , which is a finitely sided polyhedra. But this definition of fundamental polyhedra is hard to generalize. We will use the definition of Bowditch [Bow95], that the thick part of the convex hull is cocompact.

We are given a geometrically finite rank one locally symmetric manifold, which means the universal cover is $X = \mathbb{H}_{\mathbb{F}}^n$ for $\mathbb{F} = \mathbb{R}, \mathbb{C}, \mathbb{H}$ or $\mathbb{H}_{\mathbb{F}}^n = \mathbb{H}_{\mathbb{O}}^2$. Let $\delta(X)$ be the exponent of growth, which equals $(n+1)\dim_{\mathbb{R}} \mathbb{F} - 2$. The spectrum of the Laplace operator is related to many quantities, such as the growth rate of the number of lattice points and the Hausdorff dimension of the limit set. We generalize a result of Lax and Phillips on $X = \mathbb{H}_{\mathbb{R}}^n$ [LP82a] and a result of Hamenstädt in the general case [Ham04].

Theorem (Theorem 4.1.1). *Let $M = \Gamma \backslash X$ be a geometrically finite rank one locally symmetric manifold. Then the intersection of the spectrum of the Laplace operator and the critical interval $(-\delta(X)^2/4, 0]$ consists of finitely many eigenvalues of finite multiplicities.*

This result can be used to give a spectral gap for the spectrum of the Laplace operator. Then the spectral gap gives an exponential error in the orbital counting problem.

Chapter 1

Decrease of Fourier coefficients of stationary measures

Let μ be a Borel probability measure on $\mathrm{SL}_2(\mathbb{R})$ with a finite exponential moment, and assume that the subgroup Γ_μ generated by the support of μ is Zariski dense. Let ν be the unique μ -stationary measure on \mathbb{P}^1 . We prove that the Fourier coefficients $\hat{\nu}(k)$ of ν converge to 0 as $|k|$ tends to infinity. Our proof relies on a generalized renewal theorem for the Cartan projection.

1.1 Introduction

Let μ be a Borel probability measure on $\mathrm{SL}_2(\mathbb{R})$. The linear action of $\mathrm{SL}_2(\mathbb{R})$ on \mathbb{R}^2 induces an action on $\mathbb{P}^1 = \mathbb{P}(\mathbb{R}^2)$. For a Borel probability measure ν on \mathbb{P}^1 , we define its convolution with μ by

$$\mu * \nu = \int_{\mathrm{SL}_2(\mathbb{R})} g_* \nu d\mu(g),$$

where $g_* \nu$ is the pushforward of ν by g . The measure ν is called μ -stationary if $\mu * \nu = \nu$. We add the condition that the subgroup Γ_μ generated by the support of μ is Zariski dense in $\mathrm{SL}_2(\mathbb{R})$. In the case of $\mathrm{SL}_2(\mathbb{R})$, Zariski density is equivalent to unsolvability. When Γ_μ is Zariski dense in $\mathrm{SL}_2(\mathbb{R})$, there is a unique μ -stationary measure (see [Fur63],[GR85]).

This stationary measure is also called the Furstenberg measure. It was first considered by Furstenberg in the study of the noncommutative law of large numbers. The stationary measure takes part in the subtle properties of random products of matrices. Please see [Fur63],[GR85] and [BL85].

In this paper, we are interested in the decay of the Fourier coefficients of stationary measures. The action of $\mathrm{PSO}_2 = \mathrm{SO}_2 / \{\pm Id\}$ on \mathbb{P}^1 is transitive and free. We fix the point $x_o = [1 : 0]$ in \mathbb{P}^1 , then identify \mathbb{P}^1 as the orbit space $\mathrm{PSO}_2 x_o$. As a group, PSO_2 is isomorphic to the circle $\mathbb{T} \simeq \mathbb{R} / \pi\mathbb{Z}$. This is given by the map from \mathbb{T} to PSO_2 ,

$$\theta \mapsto \begin{pmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{pmatrix} / \{\pm Id\}.$$

So we have a homeomorphism from \mathbb{T} to \mathbb{P}^1 , that is $\theta \mapsto [\cos \theta : \sin \theta]$. We can define the Fourier coefficients of the stationary measure ν by the following formula

$$\widehat{\nu}(k) = \int_{\mathbb{T}} e^{2ik\theta} d\nu(\theta).$$

We also demand that μ has a finite exponential moment, which means that there exists a constant $\epsilon_1 > 0$ such that $\int \|g\|^{\epsilon_1} d\mu(g) < \infty$. We will prove

Theorem 1.1.1. *Let μ be a Borel probability measure on $\mathrm{SL}_2(\mathbb{R})$ with a finite exponential moment, and assume that the subgroup Γ_μ is Zariski dense. Then the μ -stationary measure ν is a Rajchman measure, in other words*

$$\widehat{\nu}(k) \rightarrow 0 \text{ as } |k| \rightarrow +\infty. \quad (1.1.1)$$

Remark 1.1.2. *Fourier decay of measures on fractal sets and its applications have been studied in [Kau80],[QR03],[JS16] and [BD17]. Our situation is much general and we introduce a quite different method.*

Being a Rajchman measure is a local property (see [KL87]): Indeed, let ν_1 be a Rajchman measure. If ν_2 is absolutely continuous with respect to ν_1 , then ν_2 is also a Rajchman measure. Conversely, the sum of two Rajchman measures is a Rajchman measure.

In this spirit, we have the following theorem:

Theorem 1.1.3. *Let μ be a Borel probability measure on $\mathrm{SL}_2(\mathbb{R})$ with a finite exponential moment, and assume that the subgroup Γ_μ is Zariski dense. Let ν be the unique μ -stationary measure. Assume that r is a C^1 function on \mathbb{P}^1 and ϕ is a C^2 function on \mathbb{P}^1 such that $|\phi'| \geq 1/C_1 > 0$ on the support of r and*

$$\|r\|_{C^1}, \|\phi\|_{C^2} \leq C_1 \text{ for some constant } C_1 > 0.$$

Then we have

$$\int e^{i\xi\phi(x)} r(x) d\nu(x) \rightarrow 0 \text{ as } |\xi| \rightarrow \infty, \quad (1.1.2)$$

uniformly with respect to C_1 .

This is the main theorem of this paper. It will be proved in Section 1.3.

Corollary 1.1.4. *Let μ be a Borel probability measure on $\mathrm{SL}_2(\mathbb{R})$ with a finite exponential moment, and assume that the subgroup Γ_μ is Zariski dense. Let ν be the unique μ -stationary measure. Then for a C^2 -diffeomorphism ϕ on \mathbb{P}^1 , the pushforward of the stationary measure $\phi_*\nu$ is a Rajchman measure. In other words*

$$\widehat{\phi_*\nu}(k) \rightarrow 0 \text{ as } |k| \rightarrow +\infty. \quad (1.1.3)$$

Theorem 1.1.1 is a special case of this corollary, where ϕ is the identity function.

Proof of Corollary 1.1.4 from Theorem 1.1.3. By the identification $\mathbb{P}^1 \simeq \mathbb{T}$, we may consider all the objects as living on \mathbb{T} . Take a partition of unity of \mathbb{T} : let r_1, r_2 be non negative Lipschitz functions on \mathbb{T} such that $r_1 + r_2 = 1$, and the supports of r_1, r_2 are connected subintervals of \mathbb{T} . For $j = 1, 2$, we can lift the function $\phi|_{\text{suppr}_j}$ to a function ϕ_j from suppr_j to \mathbb{R} . Then

$$\int_{\mathbb{T}} e^{2ik\phi(\theta)} d\nu(\theta) = \int_{\mathbb{T}} (r_1(\theta) + r_2(\theta)) e^{2ik\phi(\theta)} d\nu(\theta) = \int_{\mathbb{T}} \left(e^{2ik\phi_1(\theta)} r_1(\theta) + e^{2ik\phi_2(\theta)} r_2(\theta) \right) d\nu(\theta).$$

Since ϕ is a diffeomorphism, the functions ϕ_j, r_j satisfy the conditions in Theorem 1.1.3. We use this theorem twice to conclude. \square

Let us use another coordinate system on \mathbb{P}^1 . We identify \mathbb{P}^1 with $\mathbb{R} \cup \{\infty\}$ through the map $\varphi(x) = v_1/v_2$, where $x = \mathbb{R}v$ is a point in \mathbb{P}^1 . Then the action of $\text{SL}_2(\mathbb{R})$ on \mathbb{P}^1 reads as the Möbius action, that is for $r \in \mathbb{R} \cup \{\infty\}$ and $g = \begin{pmatrix} a & b \\ c & d \end{pmatrix}$ in $\text{SL}_2(\mathbb{R})$, we have $gr = \frac{ar+b}{cr+d}$.

If the support of a μ -stationary measure ν does not contain $[1 : 0]$, then $\varphi_*\nu$ is a stationary measure on \mathbb{R} . From Theorem 1.1.3, we get

Corollary 1.1.5. *Let μ be a Borel probability measure on $\text{SL}_2(\mathbb{R})$ with a finite exponential moment, and assume that the subgroup Γ_μ is Zariski dense. Let ν be the unique μ -stationary measure. If the support of ν does not contain $[1 : 0]$, then the μ -stationary measure $\varphi_*\nu$ is a Rajchman measure on \mathbb{R} . In other words*

$$\widehat{\varphi_*\nu}(\xi) = \int_{\mathbb{P}^1} e^{i\varphi(x)\xi} d\nu(x) \rightarrow 0 \text{ as } |\xi| \rightarrow +\infty. \quad (1.1.4)$$

Example 1.1.6 (Solvable case). *For stationary measures on \mathbb{R} , consider the following*

$$\mu = \frac{1}{2}(\delta_{g_1} + \delta_{g_2}) = \frac{1}{2}\delta \begin{pmatrix} \sqrt{\lambda} & -1/\sqrt{\lambda} \\ 0 & 1/\sqrt{\lambda} \end{pmatrix} + \frac{1}{2}\delta \begin{pmatrix} \sqrt{\lambda} & 1/\sqrt{\lambda} \\ 0 & 1/\sqrt{\lambda} \end{pmatrix},$$

where $\lambda \in (0, 1)$. Then the actions of g_1, g_2 are given by $g_1r = \lambda r - 1$, $g_2r = \lambda r + 1$ for $r \in \mathbb{R}$. By definition, a μ -stationary measure ν on \mathbb{R} must satisfy the equation

$$\nu = \mu * \nu = \frac{1}{2}((g_1)_*\nu + (g_2)_*\nu). \quad (1.1.5)$$

Let X_0, X_1, \dots be i.i.d. random variables such that $\mathbb{P}(X_0 = 1) = \mathbb{P}(X_0 = -1) = 1/2$. Let ν_λ be the Bernoulli convolution with parameter λ , defined to be the distribution of $\sum_{j \geq 0} X_j \lambda^j$. The measure ν_λ satisfies (1.1.5), thus it is a μ -stationary measure on \mathbb{R} . In [Erd39], Erdős proved that when λ^{-1} is a Pisot number, the Fourier transform of ν_λ does not converge to zero. In this example Γ_μ is solvable, so the Zariski density condition is necessary in the theorem.

Remark 1.1.7. 1. A similar result for Bernoulli convolutions was obtained in [Kau76]. Kaufman proved that for Bernoulli convolutions ν_λ , if λ^{-1} is not a Pisot number, then it satisfies the same conclusion as in Corollary 1.1.3. That is, the pushforward measure $\phi_*\nu_\lambda$ is a Rajchman measure, where ϕ is a C^1 function on \mathbb{R} with $\phi' > 0$ everywhere.

2. Our result for the measure ν is stronger than being a Rajchman measure. Indeed, for a probability measure on \mathbb{T} , being a Rajchman measure is not invariant by diffeomorphisms. We can find examples in [Kau84]. A typical example is the standard $\frac{1}{3}$ -Cantor measure ν , which is not a Rajchman measure. Let ϕ be the quadratic map $r \mapsto r^2$. Then the pushforward measure $\phi_*\nu$ becomes a Rajchman measure with polynomial decay.

One of our motivations for establishing Theorem 1.1.1 comes from the theory of Bernoulli convolutions. One of the main questions of this theory is to determine for which parameter λ , the measure ν_λ is absolutely continuous with respect to the Lebesgue measure. We have already mentioned that when λ^{-1} is a Pisot number, Erdős proved that ν_λ is not a Rajchman measure. Thus, in particular, ν_λ is not absolutely continuous with respect to the Lebesgue measure. Recently, people have been interested in the same problem for stationary measures for random walks on $\mathrm{SL}_2(\mathbb{R})$, see [Bou12],[KLP11]. Our result shows that we cannot generalize the method of Erdős to the Zariski dense case.

Our other motivation is the same question for the Patterson-Sullivan measure on the limit set of Fuchsian groups. With Theorem 1.1.1, it suffices to prove that there exists a probability measure μ on $\mathrm{SL}_2(\mathbb{R})$ such that the Patterson-Sullivan measure is μ -stationary, and μ has a finite exponential moment.

In [Lal89] and [Lal86], Lalley announced the existence of such a μ for Schottky groups. But Lalley's proof only works for Schottky semigroups. In [CM07], the authors proved the existence of such a μ without the moment condition in geometrically finite cases. Combining the methods of Connell, Muchnik and Lalley, we can prove the existence of such a measure μ for convex cocompact Fuchsian groups, see [Li]. Therefore, we have

Corollary 1.1.8. *Let Γ be a convex cocompact Fuchsian group. Then the Patterson-Sullivan measure associated to Γ is a Rajchman measure.*

Remark 1.1.9. *Corollary 1.1.8 also holds if we replace the Patterson-Sullivan measure by any Gibbs measure. In [Li], we have a similar realization for any Gibbs measure associated to a convex cocompact Fuchsian group, as it is done by Lalley for any Gibbs measure on the limit set of a Schottky semigroup in [Lal86].*

Remark 1.1.10. *Using the uniform spectral gap proved in [Nau05], we can prove a polynomial decay in the convergence to zero of the Fourier coefficients of the μ -stationary measure, when the support of μ is the set of generators of a Schottky semigroup. In this case, the uniform spectral gap implies an exponential error term in the renewal theorem, which is the only obstacle for polynomial decay. Please see Remark 1.3.10 for more details. We believe it is true for the general case, but the question is still open.*

Remark 1.1.11. *Very recently, Bourgain and Dyatlov [BD17] have proved a polynomial decay of the Fourier coefficients of the Patterson-Sullivan measure associated to a convex*

cocompact Fuchsian group. Their method, which comes from additive combinatorics, is totally different from ours. They use the Fourier decay bound and the fractal uncertainty principle to obtain an essential spectral gap for a convex cocompact hyperbolic surface. We can not recover their result directly as in Remark 1.1.10. It is possible if we modify some steps and use the uniform spectral gap in [Nau05], but we do not pursue in this direction in this work.

On the other hand, in the geometrically finite case, this approach can not work. The finite exponential moment condition is impossible for noncompact lattice Γ in $\mathrm{SL}_2(\mathbb{R})$ (see [GLJ93], [DKN09], [BHM11]). That is, if μ is a measure on Γ with a finite first moment, then the μ -stationary measure ν is singular with respect to the Lebesgue measure. Maybe the generalization of the method of [JS16] works in this case, where they proved the Gibbs measures for the Gauss map which has dimension greater than $1/2$ are Rajchman measures.

In this paper, our main idea is to obtain the convergence to zero of Fourier coefficients from a renewal type result.

The strategy of proof: To simplify, identify \mathbb{P}^1 with $\mathbb{T} = \mathbb{R}/\pi\mathbb{Z}$ as before. The starting point is the relation $\nu = \mu * \nu$. Consider a random walk on $\mathrm{SL}_2(\mathbb{R})$, $X_n = b_1 b_2 \cdots b_n$, where b_j are independent random variables with the same law μ . Let \mathcal{B}_n be the Borel σ -algebra generated by X_1, \dots, X_n . Let $Y_n = (X_n)_* \nu$. They are random variables which take values in the space of Borel measures on \mathbb{T} . By definition, we have

$$\mathbb{E}(Y_{n+1} | \mathcal{B}_n) = \mathbb{E}((X_n)_*(b_{n+1})_* \nu | \mathcal{B}_n) = (X_n)_* \mathbb{E}((b_{n+1})_* \nu) = Y_n.$$

Therefore $\{Y_n\}$ is a martingale. For $t > 0$, we define the stopping time by $\tau = \inf\{n \in \mathbb{N} | \log \|X_n\| \geq t\}$. Then the martingale property implies that

$$\mathbb{E}((X_\tau)_* \nu) = \mathbb{E}(Y_\tau) = \mathbb{E}(Y_0) = \nu.$$

(See Proposition 1.3.5). Thus for the Fourier coefficients, we have for $k \in 2\mathbb{Z}$ (since $\hat{\nu}(k) = \hat{\nu}(-k)$, we only consider $k \geq 0$.)

$$\hat{\nu}(k) = \int e^{ikx} d\nu(x) = \int e^{ikx} d\mathbb{E}((X_\tau)_* \nu)(x) = \int \mathbb{E}(e^{ikX_\tau x}) d\nu(x).$$

Recall our circle \mathbb{T} is $\mathbb{R}/\pi\mathbb{Z}$. The idea is to find some cancellations in the “trigonometric series” $\mathbb{E}(e^{ikX_\tau x})$. By the Cauchy-Schwarz inequality, it suffices to prove $\mathbb{E}(e^{ik(X_\tau x - X_\tau y)}) \rightarrow 0$ as $k \rightarrow \infty$.

By analogy with the case of classical random walks on \mathbb{R} , we expect that there exists a measurable density function p on \mathbb{R}^+ such that for a continuous compactly supported function f on \mathbb{R} and $t \in \mathbb{R}$,

$$\mathbb{E}(f(\log \|X_\tau\| - t)) \longrightarrow \int_{\mathbb{R}^+} f(u)p(u)du \text{ as } t \rightarrow +\infty.$$

Then absolute continuity of the limit distribution would imply the convergence to zero of $\hat{\nu}(k)$.

In the actual proof, we do not use this stopping time, but a residue process. Indeed, the latter is easier to treat with transfer operators and Fourier analysis. We will establish a limit theorem for the residue process, a generalization of the renewal theorem, in Section 1.4.

Notation: When f and g are functions on a set X , we write $f(x) \lesssim g(x)$, if there exists $C > 0$ independent of $x \in X$ such that $f(x) \leq Cg(x)$, and $f(x) = O(g(x))$ means $|f(x)| \lesssim g(x)$. We also write $f(x, y) = O_y(g(x, y))$, which means $|f(x, y)| \leq C_y g(x, y)$, where C_y is a constant only depending on y .

We introduce a notation $O_{\exp, \epsilon}(s)$. We write $f(\epsilon, s) = O_{\exp, \epsilon}(s)$ if for $\epsilon > 0$ and $s \in \mathbb{R}$, there exists a constant $\epsilon' > 0$ such that $f(\epsilon, s) = O(e^{-\epsilon' s})$, where all the constants only depend on ϵ . We write $f(s) = O_{\exp}(s)$, if there exists a uniform constant ϵ' such that $f(s) = O(e^{-\epsilon' s})$.

1.2 Preliminaries on random walks on \mathbb{P}^1

Fix the norm induced by the standard inner product on \mathbb{R}^2 , $\|v\| = \sqrt{v_1^2 + v_2^2}$, which is $\mathrm{SO}_2(\mathbb{R})$ invariant. Then define a metric on \mathbb{P}^1 . For two points $x = \mathbb{R}v$, $x' = \mathbb{R}w$, we set

$$d(x, x') = \frac{|\det(v, w)|}{\|v\|\|w\|}.$$

This is a sine distance. If we write $x = \mathbb{R} \begin{pmatrix} \cos \theta \\ \sin \theta \end{pmatrix}$ and $x' = \mathbb{R} \begin{pmatrix} \cos \theta' \\ \sin \theta' \end{pmatrix}$, then $d(x, x') = |\sin(\theta - \theta')|$. From now on, we write $G = \mathrm{SL}_2(\mathbb{R})$ and $X = \mathbb{P}^1$.

Definition 1.2.1. For g in G and $x = \mathbb{R}v$ in X , define the function $\sigma : G \times X \rightarrow \mathbb{R}$ by $\sigma(g, x) = \log \frac{\|gv\|}{\|v\|}$.

This function σ is a cocycle, because for g, h in G we have

$$\sigma(gh, x) = \log \frac{\|ghv\|}{\|v\|} = \log \frac{\|ghv\|}{\|hv\|} + \log \frac{\|hv\|}{\|v\|} = \sigma(g, hx) + \sigma(h, x),$$

where we use the fact that the action is linear, $hx = \mathbb{R}hv$.

Lemma 1.2.2. For g in G and x, x' in X with $x \neq x'$, we have

$$\frac{d(gx, gx')}{d(x, x')} = \exp(-\sigma(g, x) - \sigma(g, x')). \quad (1.2.1)$$

Proof. As in the definition of the distance $d(\cdot, \cdot)$, we take two non zero vectors v and w in x and x' respectively. By definition,

$$\frac{d(gx, gx')}{d(x, x')} = \left| \frac{\det(gv, gw)}{\det(v, w)} \right| \frac{\|v\|\|w\|}{\|gv\|\|gw\|} = |\det g| \frac{\|v\|\|w\|}{\|gv\|\|gw\|} = \exp(-\sigma(g, x) - \sigma(g, x')).$$

The proof is complete. \square

If the point x is near x' , we know from the above equation that the cocycle σ is essentially the logarithm of the contracting or expanding ratio. Let μ be a Borel probability measure on G , and let b_1, b_2, \dots be independent random variables with the same law μ . Then the behavior of the mean value of the cocycle,

$$\frac{1}{n} \sigma(b_n b_{n-1} \cdots b_1, x) = \frac{1}{n} \left(\sum_{j=1}^n \sigma(b_j, b_{j-1} \cdots b_1 x) \right),$$

follows an asymptotic law similar to the law of large numbers. In particular,

Theorem 1.2.3. [*Fur63*][*GR85*] *Let μ be a Borel probability measure on G having an exponential moment. Assume that the subgroup Γ_μ is Zariski dense. Then for all x in X , random variables b_j defined as above, we have*

$$\lim_{n \rightarrow \infty} \frac{\sigma(b_n b_{n-1} \cdots b_1, x)}{n} = \int_G \int_X \sigma(g, y) d\mu(g) d\nu(y) = \sigma_\mu > 0 \quad \text{a.s } \mu^{\otimes \mathbb{N}^*}. \quad (1.2.2)$$

The constant σ_μ is called the Lyapunov exponent of μ .

Theorem 1.2.4 (Hölder regularity). [*Gui90*][*BL85*, Chapter 6, Proposition 4.1] *Under the assumptions of Theorem 1.1.1, there exist constants $C > 0$, $\alpha > 0$ such that for every x in X and $r > 0$ we have*

$$\nu(B(x, r)) \leq Cr^\alpha. \quad (1.2.3)$$

We need the Cartan decomposition of the Lie group G , i.e. $G = \text{SO}_2 A^+ \text{SO}_2$, where $A^+ = \left\{ \begin{pmatrix} e^t & 0 \\ 0 & e^{-t} \end{pmatrix}, t \geq 0 \right\}$. For g in G , we can write $g = k_g a_g l_g$, where k_g, l_g are in SO_2 , and $a_g = \text{diag}\{e^{\kappa(g)}, e^{-\kappa(g)}\}$ is the diagonal matrix whose diagonal elements are $e^{\kappa(g)}$ and $e^{-\kappa(g)}$ with $\kappa(g) \geq 0$. The positive number $\kappa(g)$ is called the Cartan projection. Identify the two spaces X and $\mathbb{T} \simeq \mathbb{R}/\pi\mathbb{Z}$. For an element x in X , associate it to the unique element $\theta(x)$ in $\mathbb{R}/\pi\mathbb{Z}$ satisfying $x = \mathbb{R} \begin{pmatrix} \cos \theta(x) \\ \sin \theta(x) \end{pmatrix}$. When there is no ambiguity, we will abbreviate $\theta(x)$ to x .

Let $e_1 = \mathbb{R} \begin{pmatrix} 1 \\ 0 \end{pmatrix}$, $e_2 = \mathbb{R} \begin{pmatrix} 0 \\ 1 \end{pmatrix}$, which mean elements in X . Let $r_\theta = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix}$ be a rotation matrix in G . For g in G , choosing a decomposition $g = k_g a_g l_g$, we define $x_g^m = l_g^{-1} e_2$, $x_g^M = k_g e_1$. If $\kappa(g) > 0$, then x_g^M, x_g^m are uniquely defined.

Proposition 1.2.5. *For g in G with $\kappa(g) > 0$, we have*

$$x_g^m = x_{g^{-1}}^M. \quad (1.2.4)$$

Proof. For a real number $a \neq 0$, we have

$$\begin{pmatrix} a & 0 \\ 0 & a^{-1} \end{pmatrix} = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \begin{pmatrix} a^{-1} & 0 \\ 0 & a \end{pmatrix} \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix} = r_{\pi/2} \begin{pmatrix} a^{-1} & 0 \\ 0 & a \end{pmatrix} r_{3\pi/2}.$$

This implies that

$$g^{-1} = (k_g a_g l_g)^{-1} = l_g^{-1} a_g^{-1} k_g^{-1} = l_g^{-1} r_{\pi/2} a_g r_{3\pi/2} k_g^{-1}.$$

Therefore $x_{g^{-1}}^M = l_g^{-1} r_{\pi/2} e_1 = l_g^{-1} e_2 = x_g^m$. \square

Lemma 1.2.6. *For g in G and $x = \mathbb{R}v$ in X , we have*

$$d(x_g^m, x) \leq \frac{\|gv\|}{\|g\|\|v\|} \leq d(x_g^m, x) + e^{-2\kappa(g)}. \quad (1.2.5)$$

Another form that will be used frequently is

$$\sigma(g, x) \geq \kappa(g) + \log d(x_g^m, x).$$

Proof. Suppose that the vector v has norm 1, then

$$\frac{\|gv\|}{\|v\|} = \frac{\|k_g a_g l_g v\|}{\|v\|} = \frac{\|a_g l_g v\|}{\|l_g v\|}.$$

Since $d(x_g^m, x) = d(l_g^{-1} e_2, x) = d(e_2, l_g x)$, it suffices to prove this inequality for diagonal elements, in other words $g = \mathrm{diag}\{e^{\kappa(g)}, e^{-\kappa(g)}\}$. Hence

$$\frac{\|gv\|}{\|v\|} = \left| \begin{pmatrix} e^{\kappa(g)} & 0 \\ 0 & e^{-\kappa(g)} \end{pmatrix} \begin{pmatrix} v_1 \\ v_2 \end{pmatrix} \right| = |e^{2\kappa(g)} v_1^2 + e^{-2\kappa(g)} v_2^2|^{1/2}. \quad (1.2.6)$$

The equality $d(x_g^m, x) = d(e_2, x) = |v_1|$ implies that

$$\begin{aligned} \frac{\|gv\|}{\|g\|\|v\|} &\geq |v_1| = d(x_g^m, x), \\ \frac{\|gv\|}{\|g\|\|v\|} &\leq |v_1| + e^{-2\kappa(g)} = d(x_g^m, x) + e^{-2\kappa(g)}. \end{aligned}$$

The proof is complete. \square

The following lemma is an important tool, which gives a precise approximation of the cocycle by the Cartan projection and distance.

Lemma 1.2.7. *Let x, x' be two points in X and let g be in G . Assume that*

$$e^{-2\kappa(g)} + d(x_g^m, g^{-1}x) \leq \frac{1}{2}d(g^{-1}x', x),$$

then

$$|\sigma(g, x) - \kappa(g) - \log d(g^{-1}x', x)| \leq 2 \frac{e^{-2\kappa(g)} + d(x_g^m, g^{-1}x')}{d(g^{-1}x', x)}. \quad (1.2.7)$$

Proof. Inequality (1.2.5) implies that

$$\begin{aligned} |e^{\sigma(g,x)-\kappa(g)} - d(g^{-1}x',x)| &\leq \max\{|d(x_g^m,x) - d(g^{-1}x',x)|, |e^{-2\kappa(g)} + d(x_g^m,x) - d(g^{-1}x',x)|\} \\ &\leq e^{-2\kappa(g)} + d(x_g^m, g^{-1}x'). \end{aligned}$$

Thus by hypothesis, we have

$$|\exp(\sigma(g,x) - \kappa(g)) - d(g^{-1}x',x)| \leq 1/2d(g^{-1}x',x).$$

Since $|\log(1+t)| \leq 2|t|$ for $t > -1/2$, we obtain

$$\begin{aligned} |\sigma(g,x) - \kappa(g) - \log d(g^{-1}x',x)| &= \log \left| 1 + \frac{\exp(\sigma(g,x) - \kappa(g)) - d(g^{-1}x',x)}{d(g^{-1}x',x)} \right| \\ &\leq 2 \frac{|\exp(\sigma(g,x) - \kappa(g)) - d(g^{-1}x',x)|}{d(g^{-1}x',x)} \leq 2 \frac{e^{-2\kappa(g)} + d(x_g^m, g^{-1}x')}{d(g^{-1}x',x)}. \end{aligned}$$

The proof is complete. \square

In the next proposition we summarize the large deviations principle for the cocycle and for the Cartan projection,

Proposition 1.2.8. [*BQ16, Thm13.11, Thm 13.17*] *Under the assumptions of Theorem 1.1.1, for every $\epsilon > 0$ we have*

$$\mu^{*n}\{g \in G \mid |\sigma(g,x) - n\sigma_\mu| \geq n\epsilon\} = O_{\exp,\epsilon}(n), \quad (1.2.8)$$

$$\mu^{*n}\{g \in G \mid |\kappa(g) - n\sigma_\mu| \geq n\epsilon\} = O_{\exp,\epsilon}(n), \quad (1.2.9)$$

uniformly for all x in X and $n \geq 1$.

Let t be a real number. Write $[t]$ for the integer part of t .

Corollary 1.2.9. *Under the assumptions of Theorem 1.1.1, for every $\epsilon > 0$ we have*

$$\begin{aligned} \sum_{m \geq n} \mu^{*m}\{g \in G \mid \sigma(g,x) \leq t\} &= O_{\exp,\epsilon}(n), \\ \sum_{m \geq n} \mu^{*m}\{g \in G \mid \kappa(g) \leq t\} &= O_{\exp,\epsilon}(n), \end{aligned}$$

uniformly for all x in X , $t > 0$ and $n \geq \lceil \frac{t}{\sigma_\mu - \epsilon} \rceil$.

By the hypothesis of finite exponential moment and the Chebyshev inequality, we have

Lemma 1.2.10. *Under the assumptions of Theorem 1.1.1, let M_μ be the finite exponential moment of μ defined by $M_\mu = \int \|g\|^{\epsilon_1} d\mu(g)$. For $s > 0$, we have*

$$\mu\{g \in G \mid \kappa(g) \geq s\} \leq M_\mu e^{-\epsilon_1 s}. \quad (1.2.10)$$

Corollary 1.2.11. *Under the assumptions of Theorem 1.1.1, for every $\epsilon > 0$ we have*

$$\begin{aligned} \sum_{m \leq n} \mu^{*m} \{g \in G \mid \sigma(g, x) \geq t\} &= O_{\exp, \epsilon}(t), \\ \sum_{m \leq n} \mu^{*m} \{g \in G \mid \kappa(g) \geq t\} &= O_{\exp, \epsilon}(t), \end{aligned}$$

uniformly for all x in X , $t > 0$ and $n = \lfloor \frac{t}{\sigma_\mu + \epsilon} \rfloor$.

Proof. The inequality about the cocycle follows from the one about the Cartan projection, because $\kappa(g) \geq \sigma(g, x)$. It suffices to prove the second inequality:

- When $m \leq \epsilon_2 t$, where $\epsilon_2 > 0$ is a small constant such that $\epsilon_2 \leq \epsilon_1 / (2 \log M_\mu)$, from Chebyshev's inequality and the subadditivity of the Cartan projection, we have

$$\begin{aligned} \sum_{m=1}^{\lfloor \epsilon_2 t \rfloor} \mu^{\otimes m} \{\kappa(g) \geq t\} &\leq \sum_{m=1}^{\lfloor \epsilon_2 t \rfloor} e^{-\epsilon_1 t} \int e^{\epsilon_1 \kappa(g)} d\mu^{\otimes m}(g) \leq \sum_{m=1}^{\lfloor \epsilon_2 t \rfloor} e^{-\epsilon_1 t} \left| \int \|g\|^{\epsilon_1} d\mu(g) \right|^m \\ &\leq e^{-\epsilon_1 t} M_\mu^{\lfloor \epsilon_2 t \rfloor} / (M_\mu - 1). \end{aligned}$$

This implies that $\sum_{m=1}^{\lfloor \epsilon_2 t \rfloor} \mu^{\otimes m} \{\kappa(g) \geq t\} \lesssim e^{-t\epsilon_1/2}$.

- When $m \in [\epsilon_2 t, t/(\sigma_\mu + \epsilon)]$, we have $\kappa(g) > t \geq m(\sigma_\mu + \epsilon)$. Then use (1.2.9) to deduce that the measure of this part is less than $\sum_{m \in [\epsilon_2 t, t/(\sigma_\mu + \epsilon)]} O_{\exp, \epsilon}(m) = O_{\exp, \epsilon}(t)$.

The proof is complete. \square

The following proposition describes regularity properties of μ^{*n} , which is a corollary of the large deviations principle.

Proposition 1.2.12. *[BQ16, Prop14.3] Under the assumptions of Theorem 1.1.1, for every $\epsilon > 0$ we have*

$$\mu^{*n} \{g \in G \mid d(gx, x') \leq e^{-n\epsilon}\} = O_{\exp, \epsilon}(n), \quad (1.2.11)$$

$$\mu^{*n} \{g \in G \mid d(x_g^M, x) \leq e^{-n\epsilon}\} = O_{\exp, \epsilon}(n), \quad (1.2.12)$$

$$\mu^{*n} \{g \in G \mid d(x_g^m, g^{-1}x) \geq e^{-(2\sigma_\mu - \epsilon)n}\} = O_{\exp, \epsilon}(n), \quad (1.2.13)$$

$$\mu^{*n} \{g \in G \mid d(x_g^M, gx) \geq e^{-(2\sigma_\mu - \epsilon)n}\} = O_{\exp, \epsilon}(n), \quad (1.2.14)$$

uniformly for all x, x' in X and $n \geq 1$.

Corollary 1.2.13. *Under the assumptions of Theorem 1.1.1, for every $\epsilon > 0$ we have*

$$\mu^{*n} \{g \in G \mid d(gx, x') \leq e^{-t}\} = O_{\exp, \epsilon}(t), \quad (1.2.15)$$

uniformly for all x, x' in X , $t > 0$ and $n \geq t/\epsilon$.

For every $\epsilon > 0$ we have

$$\mu^{*n} \{g \in G \mid d(x_g^M, gx) \geq e^{-t}\} = O_{\exp, \epsilon}(t), \quad (1.2.16)$$

uniformly for all x in X , $t > 0$ and $n \geq t/(2\sigma_\mu - \epsilon)$.

Proof. There exists an integer $n_t \leq n$ such that $\epsilon n_t < t \leq \epsilon(n_t + 1)$. By inequality (1.2.11), we have $\mu^{*n_t}\{d(gx, x') \leq e^{-\epsilon n_t}\} \lesssim e^{-\epsilon' n_t}$. This implies that

$$\begin{aligned} \mu^{*n}\{g \in G \mid d(gx, x') \leq e^{-t}\} &= \int_G \mu^{*n_t}\{l \in G \mid d(l(hx), x') \leq e^{-t}\} d\mu^{*(n-n_t)}(h) \\ &\leq \int_G \mu^{*n_t}\{l \in G \mid d(l(hx), x') \leq e^{-\epsilon n_t}\} d\mu^{*(n-n_t)}(h) \\ &\lesssim e^{-\epsilon' n_t} \lesssim e^{-\epsilon'(t/\epsilon-1)} \lesssim e^{-\epsilon' t/\epsilon}. \end{aligned}$$

The second inequality follows from the same argument. \square

The following lemma describes the difference between the cocycle and the Cartan projection.

Lemma 1.2.14. [BQ16, Lemma 17.8] *Under the assumptions of Theorem 1.1.1, for every $\epsilon > 0$, there exist $C > 0, \epsilon' > 0$ such that for all $n \geq l > 0$ and x in X , there exists a subset $S_{n,l,x} \subset G \times G$, which satisfies*

$$\mu^{*(n-l)} \otimes \mu^{*l}(S_{n,l,x}^c) \leq C e^{-\epsilon' l} = O_{\text{exp}, \epsilon}(l),$$

and for all $(g_1, g_2) \in S_{n,l,x}$, we have

$$|\kappa(g_1 g_2) - \sigma(g_1, g_2 x) - \kappa(g_2)| \leq e^{-\epsilon l}.$$

By the identification $X \simeq \mathbb{T}$, we can work on \mathbb{T} . Since the circle \mathbb{T} is a quotient space of \mathbb{R} , it has the induced orientation. For two different points x, y in \mathbb{T} , which are not the two endpoints of a diameter, they divide the circle into two arcs. Call the arc with longer length the large arc, and the other arc the small arc $x \frown y$. For a function ϕ on \mathbb{T} , it can be seen as a function Φ on \mathbb{R} with period π . Define $\phi'(\theta)$ as the derivative of Φ .

We introduce a sign for two different points x, y in X , where x, y are not the two endpoints of a diameter. If in the small arc $x \frown y$, the point x is the start point in the orientation sense, then we define $\text{sign}(x, y) = 1$; otherwise, we define $\text{sign}(x, y) = -1$. We have a Newton-Leibniz formula on the circle

$$\phi(y) - \phi(x) = \text{sign}(x, y) \int_{x \frown y} \phi'(\theta) d\theta, \quad (1.2.17)$$

where $d\theta$ is the Lebesgue measure on \mathbb{T} induced by the Lebesgue measure on \mathbb{R} with total mass π .

Definition 1.2.15 (Orientation). *Let x, y, z be three points in X . Define*

$$\text{sign}(x, y, z) = \begin{cases} 0 & \text{if any two points coincide,} \\ 1 & \text{if } \{x, y, z\} \text{ is counterclockwise,} \\ -1 & \text{otherwise.} \end{cases}$$

Proposition 1.2.16. *Let x, y be two different points in X , and let g be in G such that $\kappa(g) > 2$ and $d(x_g^m, x), d(x_g^m, y) > e^{-\kappa(g)}$. Then*

$$\mathrm{sign}(gx, gy) = \mathrm{sign}(x, y, x_g^m). \quad (1.2.18)$$

Proof. With the same argument as in the proof of Lemma 1.2.6, it suffices to prove the statement in case $g = a_g$, that is $\mathrm{sign}(a_g x, a_g y) = \mathrm{sign}(x, y, e_2)$.

If x' is a point in X such that $d(e_2, x') > e^{-\kappa(g)}$, then

$$d(a_g x', e_1) = d(a_g x', a_g e_1) = d(x', e_1) \exp(-\sigma(a_g, x') - \sigma(a_g, e_1)).$$

By (1.2.5), we obtain $\sigma(a_g, x') \geq \kappa(g) + \log d(e_2, x') > 0$, so

$$d(a_g x', e_1) \leq \exp(-\kappa(g)) \leq e^{-2}.$$

Thus the action of a_g on the interval $B(e_2, e^{-\kappa(g)})^c$ is contracting with fixed point e_1 , and the image is in the interval $B(e_1, e^{-\kappa(g)})$. Especially, e_2 is not in $B(e_1, e^{-\kappa(g)})$ and the small arc $a_g x \frown a_g y$ is contained in $B(e_1, e^{-\kappa(g)})$. By definition we have

$$\mathrm{sign}(a_g x, a_g y) = \mathrm{sign}(a_g x, a_g y, e_2).$$

Since the action of a_g on \mathbb{T} preserves the orientation, we have $\mathrm{sign}(a_g x, a_g y, e_2) = \mathrm{sign}(x, y, e_2)$. The proof is complete. \square

1.3 Decrease of the Fourier transform

Here we give a proof of Theorem 1.1.3, by admitting the technical results that will be proved in the following two sections. Recall the notations $G = \mathrm{SL}_2(\mathbb{R})$ and $X = \mathbb{P}^1$.

Definition 1.3.1. *Let $\Sigma = \bigcup_{n \in \mathbb{N}} G^{\times n}$ be the symbol space of all finite sequences with elements in G . Let μ be a Borel probability measure on G , and let $\mu^{\otimes n}$ be the product measure on $G^{\times n}$. Then $\mu^{\otimes n}$ can be seen as a measure on Σ which is nonzero only on $G^{\times n}$. Let $\bar{\mu}$ be the measure on Σ defined by $\bar{\mu} = \delta_0 + \mu + \mu^{\otimes 2} + \dots$.*

Let the integer $\omega(g)$ be the length of an element g in Σ . Then an element g can be written as $(g_1, g_2, \dots, g_\omega)$, where ω is the abbreviation of $\omega(g)$.

Let T be the shift map on Σ , defined by $Tg = T(g_1, g_2, \dots, g_\omega) = (g_1, g_2, \dots, g_{\omega-1})$, when $\omega(g) \geq 2$, and $Tg = \emptyset$, when $\omega(g) = 1, 0$.

Let L be the left shift map on Σ , defined by $Lg = L(g_1, g_2, \dots, g_\omega) = (g_2, \dots, g_{\omega-1}, g_\omega)$, when $\omega(g) \geq 2$, and $Lg = \emptyset$, when $\omega(g) = 1, 0$.

When considering the action of g on X , we write $gx = g_1 \cdots g_\omega x$, $\sigma(g, x) = \sigma(g_1 \cdots g_\omega, x)$, $x_g^m = l_{g_1 \cdots g_\omega}^{-1} e_2$, as well as the Cartan projection $\kappa(g) = \kappa(g_1 \cdots g_\omega)$.

Remark 1.3.2. *When using this definition, we may meet the convolution measure μ^{*n} on G or the product measure $\mu^{\otimes n}$ on $G^{\times n}$. Denote $F : G^{\times n} \rightarrow G$ by $F(g_1, g_2, \dots, g_n) = g_1 \cdots g_n$, then $F_*(\mu^{\otimes n}) = \mu^{*n}$.*

Definition 1.3.3. For $t > 0$, define two sets that contain all the sequences which make the value of the Cartan projection pass t ,

$$M_t^+ = \{g \in \Sigma \mid \kappa(Tg) < t \leq \kappa(g)\}, \quad M_t^- = \{g \in \Sigma \mid \kappa(Tg) \geq t > \kappa(g)\}.$$

Remark 1.3.4. In some special cases, for b_j in $\text{supp}\mu$, the Cartan projection $\kappa(b_1 b_2 \cdots b_n)$ is increasing with respect to n . Then M_t^- has $\bar{\mu}$ measure zero. Let $X_n = b_1 b_2 \cdots b_n$ be a random walk on G , where b_j are i.i.d. random variables taking values in G with the same law μ . Let τ be the stopping time defined by $\tau = \inf\{n \in \mathbb{N} \mid \kappa(X_n) \geq t\}$. In such special case

$$\bar{\mu}(M_t^+ \cap G^{\times n}) = \mathbb{P}(\tau = n).$$

So in the measure sense, M_t^+ is a set of the steps. That is for $\bar{\mu}$ -almost every g in M_t^+ , it is of the form $g = (b_1, b_2, \dots, b_\tau) = (X_1, X_1^{-1}X_2, \dots, X_{\tau-1}^{-1}X_\tau)$ which corresponds to the set of steps of the trajectory $(X_1, X_2, \dots, X_\tau)$. But this is not always true for general cases.

By Corollary 1.2.9, these two sets M_t^+ , M_t^- have finite $\bar{\mu}$ measure. We have a property of M_t^+ , M_t^- due to the definition of stationary measures. Our proof is a generalization of the property of the stopping time for martingales.

Proposition 1.3.5. Under the assumptions of Theorem 1.1.1, for a real number $t > 0$ and a continuous function f on X , we have

$$\int_X f(x) d\nu(x) = \int_X \left(\int_{g \in M_t^+} f(gx) d\bar{\mu}(g) - \int_{g \in M_t^-} f(gx) d\bar{\mu}(g) \right) d\nu(x).$$

Proof. For a natural number N , let

$$\begin{aligned} F_N = & \int_X \left(\int_{g \in M_t^+, \omega(g) \leq N} f(gx) d\bar{\mu}(g) - \int_{g \in M_t^-, \omega(g) \leq N} f(gx) d\bar{\mu}(g) \right. \\ & \left. + \int_{\omega(g)=N, \kappa(g) < t} f(gx) d\bar{\mu}(g) \right) d\nu(x). \end{aligned}$$

Then $F_0 = \int_X f(x) d\nu(x)$. Since all the terms are finite, we have

$$\begin{aligned} F_{N+1} - F_N = & \int_X \left(\int_{g \in M_t^+, \omega(g)=N+1} f(gx) d\bar{\mu}(g) - \int_{g \in M_t^-, \omega(g)=N+1} f(gx) d\bar{\mu}(g) \right. \\ & \left. + \int_{\omega(g)=N+1, \kappa(g) < t} f(gx) d\bar{\mu}(g) - \int_{\omega(g)=N, \kappa(g) < t} f(gx) d\bar{\mu}(g) \right) d\nu(x). \end{aligned}$$

By the relation $\nu = \mu * \nu$, the set of integration of the last term becomes $\{\omega(g) = N + 1, \kappa(Tg) < t\}$. Compare these sets of integration

$$\begin{aligned} & \{g \in M_t^+, \omega(g) = N + 1\} \cup \{\omega(g) = N + 1, \kappa(g) < t\} \\ &= \{\omega(g) = N + 1, \kappa(Tg) < t, \kappa(g) \geq t\} \cup \{\omega(g) = N + 1, \kappa(g) < t\} \\ &= \{\omega(g) = N + 1, \kappa(Tg) \geq t, \kappa(g) < t\} \cup \{\omega(g) = N + 1, \kappa(Tg) < t\} \\ &= \{g \in M_t^-, \omega(g) = N + 1\} \cup \{\omega(g) = N + 1, \kappa(Tg) < t\}. \end{aligned}$$

Therefore, $F_{N+1} = F_N = \dots = F_0$. Corollary 1.2.9 and Inequality (1.2.9) imply that $\bar{\mu}\{g \in M_t^\pm, \omega(g) > N\}, \bar{\mu}\{\omega(g) = N, \kappa(g) < t\} \rightarrow 0$, as $N \rightarrow \infty$. Thus

$$F_N \rightarrow \int_X \left(\int_{g \in M_t^+} f(gx) d\bar{\mu}(g) - \int_{g \in M_t^-} f(gx) d\bar{\mu}(g) \right) d\nu(x) \text{ as } N \rightarrow \infty,$$

which completes the proof. \square

With these preparations, we start to prove Theorem 1.1.3, by admitting Lemma 1.5.2, Corollary 1.5.5 and Proposition 1.4.28.

Proof of Theorem 1.1.3. We will prove that there exist constants $\epsilon_0 > 0, C_0 > 0$ such that for every $s > 0$, the Fourier transform $\int e^{i\xi\phi(\theta)} r(\theta) d\nu(\theta)$ is less than $C_0 e^{-\epsilon_0 s}$ for all $|\xi|$ large enough depending on s .

Fix a constant $\epsilon_3 \leq 1/10$. Write $t = (\log |\xi| - s)/2$, and take $|\xi|$ large enough such that $t > 10s$.

Step 1: Let $e_\xi(x)$ be the function $e^{i\xi\phi(x)} r(x)$. Using Proposition 1.3.5 and the Cauchy-Schwarz inequality, we have

$$\begin{aligned} \left| \int_X e_\xi(x) d\nu(x) \right| &= \left| \int_{g \in M_t^+} \int_X e_\xi(gx) d\nu(x) d\bar{\mu}(g) - \int_{g \in M_t^-} \int_X e_\xi(gx) d\nu(x) d\bar{\mu}(g) \right| \\ &\leq \bar{\mu}(M_t^+)^{1/2} \left(\int_{M_t^+} \left| \int_X e_\xi(gx) d\nu(x) \right|^2 d\bar{\mu}(g) \right)^{1/2} \\ &\quad + \bar{\mu}(M_t^-)^{1/2} \left(\int_{M_t^-} \left| \int_X e_\xi(gx) d\nu(x) \right|^2 d\bar{\mu}(g) \right)^{1/2}. \end{aligned}$$

By Lemma 1.5.2 and Proposition 1.3.5, $\bar{\mu}(M_t^+), \bar{\mu}(M_t^-)$ are uniformly bounded with t . Change the order of integration, then

$$\begin{aligned} \left| \widehat{\phi_* (r d\nu)}(\xi) \right| &\lesssim \left(\int_{X^2} \int_{M_t^+} e^{i\xi(\phi(gx) - \phi(gy))} r(gx) r(gy) d\bar{\mu}(g) d\nu(x) d\nu(y) \right)^{1/2} \\ &\quad + \left(\int_{X^2} \int_{M_t^-} e^{i\xi(\phi(gx) - \phi(gy))} r(gx) r(gy) d\bar{\mu}(g) d\nu(x) d\nu(y) \right)^{1/2}. \end{aligned} \quad (1.3.1)$$

From now on, we only consider M_t^+ . The set M_t^- has similar properties, and the needed changes will be discussed in remarks, which appear at the end of each section.

Step 2: The main approximation, which will be proved in Section 1.5, replaces the distance $\phi(gx) - \phi(gy)$ with $\phi'e^{-2\kappa(g)}d(x, y)$. The intuition here is that in a large set, whose complement has exponentially small measure, the behavior is nice.

To apply replacement, some regularity conditions on x, y and g are needed. Define a subset of M_t^+ for x, y in X by

$$M_t^+(x, y) = \{g \in M_t^+ \mid |\kappa(g) - \kappa(Tg)| < \epsilon_3 s, d(x_g^m, g^{-1}x) < e^{-t}, d(g^{-1}x, x), d(g^{-1}x, y) > 2e^{-\epsilon_3 s}\}. \quad (1.3.2)$$

For fixed x, y , set

$$\begin{aligned} A_0(g) &= e^{i\xi(\phi(gx) - \phi(gy))} r(gx)r(gy), \\ A_1(g) &= e^{i\xi \text{sign}(g^{-1}x, x, y) \phi'(gx)d(x, y) \exp(-2\kappa(g)) / (d(g^{-1}x, x)d(g^{-1}x, y))} r(gx)^2. \end{aligned}$$

We give a control of the error, which appears in the replacement.

Proposition 1.3.6. *Assume that $t > 2s$. We have an exponential decay for all g in $M_t^+(x, y)$. That is*

$$|A_0(g) - A_1(g)| = O_{\text{exp}}(s). \quad (1.3.3)$$

This property will be proved in Section 1.5. We want to use some smooth cutoffs to regularize the function $A_1(g, x, y)$. Let ρ be a smooth function on \mathbb{R} such that $\rho|_{[-1, 1]} = 1$, ρ takes values in $[0, 1]$, $\text{supp}\rho \subset [-2, 2]$ and $|\rho'| \leq 2$. Let

$$A_2(g) = A_1(g)(1 - \rho(d(g^{-1}x, x)e^{\epsilon_3 s}))(1 - \rho(d(g^{-1}x, y)e^{\epsilon_3 s}))\rho\left(\frac{\kappa(g) - \kappa(Tg)}{\epsilon_3 s}\right)\rho\left(\frac{\kappa(Tg) - t}{2\epsilon_3 s}\right). \quad (1.3.4)$$

When $d(g^{-1}x, x) < e^{-\epsilon_3 s}$ or $d(g^{-1}x, y) < e^{-\epsilon_3 s}$, the function A_2 will be 0. With fixed x, y , $\text{sign}(g^{-1}x, x, y)$ is a function of $g^{-1}x$, and the discontinuity is at x and y . Hence the discontinuity of $\text{sign}(g^{-1}x, x, y)$ is removed in A_2 .

If $g \in M_t^+(x, y)$, it follows from definition that $|\kappa(Tg) - t| \leq |\kappa(g) - \kappa(Tg)| \leq \epsilon_3 s$. Then $A_2 = A_1$. Since $t > 10s$, using Corollary 1.5.5, Lemma 1.5.2 and (1.3.3), we get

$$\begin{aligned} \left| \int_{M_t^+} (A_0 - A_2) d\bar{\mu}(g) \right| &\leq \bar{\mu}(M_t^+ - M_t^+(x, y)) + \left| \int_{M_t^+(x, y)} (A_0 - A_2) d\bar{\mu}(g) \right| \\ &= \bar{\mu}(M_t^+ - M_t^+(x, y)) + \left| \int_{M_t^+(x, y)} (A_0 - A_1) d\bar{\mu}(g) \right| = O_{\text{exp}}(s). \end{aligned} \quad (1.3.5)$$

Step 3: Introduce the residue process for the Cartan projection. This is inspired by the stopping time. For the stopping time, the existence of the limit distribution of the residual waiting time was proved in [Kes74], but in that paper we do not have a rate

of convergence, which is necessary in our method. Here we use the transfer operator to get a uniform rate of convergence. It is difficult to treat the stopping time with transfer operators, because the operator will no longer be continuous. However, the residue process, which will be introduced here, can be routinely analyzed by the transfer operator. What's more, we will get the limit distribution of gx and $g^{-1}y$ simultaneously, which is important to us.

We generalize the inverse action on Σ , letting $g^{-1} = (g_1, \dots, g_\omega)^{-1} = (g_\omega^{-1}, \dots, g_1^{-1})$ for g in Σ . For a subset M of Σ , set $\iota(M) = \{g^{-1} | g \in M\}$. Let $\check{\mu}$ be the pushforward of μ by the inverse action. Let t be a positive number. Consider the limit of the following quantity as $t \rightarrow \infty$

$$\sum_{n \geq 0} \int_{\kappa(g) < t \leq \kappa(hg)} f((hg)^{-1}x', hgx, \kappa(hg) - \kappa(g), \kappa(g) - t) d\mu(h) d\mu^{*n}(g),$$

where x, x' are points in X and f is a smooth, compactly supported function on $X^2 \times \mathbb{R}^2$. Our result is similar to renewal theory. By Proposition 1.4.28, when t tends to infinity, the limit is

$$\int_{X^2} \int_G \int_{-\sigma(h,y)}^0 f(y', hy, \sigma(h,y), u) du d\mu(g) d\nu(y) d\check{\nu}(y'),$$

where $\check{\nu}$ is the stationary measure of $\check{\mu}$ and the integral $\int_{-\sigma(h,y_1)}^0 = 0$ if $\sigma(h, y_1) < 0$.

Since $(Tg)^{-1} = L(g^{-1})$ and $\kappa(g^{-1}) = \kappa(g)$, we can define

$$N_t^+ = \iota(M_t^+) = \{g \in \Sigma | \kappa(Lg) < t \leq \kappa(g)\}. \quad (1.3.6)$$

Therefore

$$\int_{M_t^+} \Lambda_2(g) d\bar{\mu}(g) = \int_{N_t^+} \Lambda_2(g^{-1}) d\check{\mu}(g).$$

Recall that x, y, ρ are fixed. For x_1, x_2 in X and v, u in \mathbb{R} , define

$$\begin{aligned} \lambda(x_1, x_2) &= d(x, y) e^s \operatorname{sign}(\xi) \operatorname{sign}(x, y, x_2) \phi'(x_1) / (d(x_2, x) d(x_2, y)), \\ \varphi(x_1, x_2, v, u) &= r(x_1)^2 \times (1 - \rho(d(x_2, x) e^{\epsilon_3 s})) (1 - \rho(d(x_2, y) e^{\epsilon_3 s})) \rho\left(\frac{v}{\epsilon_3 s}\right) \rho\left(\frac{u}{2\epsilon_3 s}\right). \end{aligned}$$

By the relation $\xi = \operatorname{sign}(\xi) e^{2t+s}$, regroup the terms and rewrite the function

$$\Lambda_2(g^{-1}) = e^{i\lambda(g^{-1}x, gx) \exp(-2(\kappa(g)-t))} \varphi(g^{-1}x, gx, \kappa(g) - \kappa(Lg), \kappa(Lg) - t). \quad (1.3.7)$$

Note that the function λ is not continuous, but the function φ will remove the discontinuity as we have discussed in Step 2. In the language of the residue process, let f be the function on $X^2 \times \mathbb{R}^2$ defined by

$$f(x_1, x_2, v, u) = e^{i\lambda(x_1, x_2) \exp(-2(u+v))} \varphi(x_1, x_2, v, u). \quad (1.3.8)$$

Thus the function $\Lambda_2(g^{-1})$ can be written as

$$\Lambda_2(g^{-1}) = f(g^{-1}x, gx, \kappa(g) - \kappa(Lg), \kappa(Lg) - t).$$

By Proposition 1.4.28, for $\delta > 0$, $t > 2(|K| + \delta)$ (where K is the projection of $\text{supp} f$ onto \mathbb{R}_v), we have

$$\begin{aligned} \int_{M_t^+} \Lambda_2 d\bar{\mu}(g) &= \int_{N_t^+} f d\bar{\mu}(g) \\ &= \int_{X^2} \int_G \int_{-\sigma(h, x_2)}^0 f(x_1, hx_2, \sigma(h, x_2), u) dud\mu(g) d\nu(x_2) d\check{\nu}(x_1) + O_K(\delta + O_\delta/t) |f|_{Lip}. \end{aligned} \quad (1.3.9)$$

Here $|f|_{Lip}$ is the Lipschitz norm defined by

$$|f|_{Lip} = |f|_\infty + \sup_{(x_1, x_2, v, u) \neq (x'_1, x'_2, v', u')} \frac{|f(x_1, x_2, v, u) - f(x'_1, x'_2, v', u')|}{d(x_1, x'_1) + d(x_2, x'_2) + |v - v'| + |u - u'|}.$$

Lemma 1.3.7. *There exist constants $\delta_0(s)$ and $t(\delta, s)$ such that if $\delta < \delta_0(s)$ and $t > t(\delta, s)$, then*

$$O_K(\delta + O_\delta/t) |f|_{Lip} \leq e^{-s}. \quad (1.3.10)$$

Proof. By the definition of ρ and f , the support of f is in the compact set $X^2 \times [-4\epsilon_3 s, 4\epsilon_3 s]^2$. The size of K , the projection of $\text{supp} f$ onto \mathbb{R}_v , is bounded by $8\epsilon_3 s$. The definition of ρ implies that f is locally Lipschitz. Together with the fact that f is compactly supported, we conclude that $|f|_{Lip}$ is controlled by e^{2s} independently of x, y . Take δ small enough according to s , then take t large enough according to δ and s . We get the inequality. \square

Step 4: For the major term in (1.3.9), use the following lemma.

Lemma 1.3.8. *For $b_1 < b_2$ and λ nonzero, we have*

$$\left| \int_{b_1}^{b_2} e^{i\lambda \exp(-u)} du \right| \leq \frac{2(e^{b_1} + e^{b_2})}{|\lambda|}. \quad (1.3.11)$$

Proof. Integration by parts gives

$$\int_{b_1}^{b_2} e^{i\lambda \exp(-u)} du = \int_{b_1}^{b_2} \frac{\partial_u(e^{i\lambda \exp(-u)})}{-i\lambda e^{-u}} du = \frac{e^{i\lambda \exp(-u)}}{-i\lambda e^{-u}} \Big|_{b_1}^{b_2} + \int_{b_1}^{b_2} e^{i\lambda \exp(-u)} \partial_u \left(\frac{1}{-i\lambda e^{-u}} \right) du.$$

This implies that

$$\left| \int_{b_1}^{b_2} e^{i\lambda \exp(-u)} du \right| \leq \left| \frac{e^{i\lambda \exp(-u)}}{\lambda e^{-u}} \Big|_{b_1}^{b_2} \right| + \int_{b_1}^{b_2} \partial_u \left(\frac{e^u}{|\lambda|} \right) du \leq \frac{2(e^{b_1} + e^{b_2})}{|\lambda|}.$$

The proof is complete. \square

When $d(x, y) > e^{-\epsilon_3 s}$, due to the definition of $\rho(\frac{v}{\epsilon_3 s})$, the major term only integrates on h, x_2 such that $|\sigma(h, x_2)| \leq 2\epsilon_3 s$. The inequality $|u| \leq |\sigma(h, x_2)| \leq 2\epsilon_3 s$ implies that $\rho(\frac{u}{2\epsilon_3 s}) = 1$. By the hypotheses on ϕ , when $r(x_1) \neq 0$, we have $|\phi'(x_1)| \geq 1/C_1 > 0$. Therefore

$$|\lambda(x_1, hx_2)| = |d(x, y)e^s \mathrm{sign}(\xi) \mathrm{sign}(x, y, hx_2) \phi'(x_1) / (d(hx_2, x)d(hx_2, y))| \geq e^{(1-\epsilon_3 s)}/C_1.$$

We use Lemma 1.3.8 to obtain

$$\left| \int_{-\sigma(h, x_2)}^0 f du \right| \leq |r|_\infty^2 \left| \int_0^{\sigma(h, x_2)} e^{i\lambda \exp(-2u)} du \right| \leq C_1 |r|_\infty^2 \frac{1 + e^{2\epsilon_3 s}}{e^{1-\epsilon_3 s}} \leq |r|_\infty^2 2e^{(3\epsilon_3 - 1)s} C_1.$$

Combined with (1.3.9), they imply that $\int_{M_t^+} \Lambda_2 d\bar{\mu}(g) = O_{\mathrm{exp}}(s)$. When $d(x, y) \leq e^{-\epsilon_3 s}$, the Hölder regularity of stationary measure (1.2.3) implies that

$$\int_{X \times X} \mathbb{1}_{d(x, y) \leq e^{-\epsilon_3 s}} d\nu(x) d\nu(y) \leq \int_X \nu(B(x, e^{-\epsilon_3 s})) d\nu(x) = O_{\mathrm{exp}}(s).$$

Finally we obtain

$$\begin{aligned} & \int_{X^2} \int_{M_t^+} \Lambda_2(x, y) d\bar{\mu}(g) d\nu(x) d\nu(y) \\ & \leq \int_{X^2} \mathbb{1}_{d(x, y) > e^{-\epsilon_3 s}} \int_{M_t^+} \Lambda_2(x, y) d\bar{\mu}(g) d\nu(x) d\nu(y) \\ & \quad + \int_{X^2} \mathbb{1}_{d(x, y) \leq e^{-\epsilon_3 s}} \int_{M_t^+} \Lambda_2(x, y) d\bar{\mu}(g) d\nu(x) d\nu(y) \leq O_{\mathrm{exp}}(s)(1 + \bar{\mu}(M_t^+)). \end{aligned}$$

By Lemma 1.5.2, the measure $\bar{\mu}(M_t^+)$ is uniformly bounded. By using (1.3.1) and (1.3.5), the proof is complete. \square

Remark 1.3.9 (Minus case). For M_t^- , we have another version of Lemma 1.5.2, Corollary 1.5.5 and Proposition 1.4.28. The integral $|\int_{-\sigma(h, y_1)}^0 f du|$ is replaced by $|\int_0^{-\sigma(h, y_1)} f du|$.

Remark 1.3.10. When s is large and ξ is of size e^{Cs} , all the error terms have polynomial decay except the one from Proposition 1.4.28. As we have mentioned in Remark 1.1.10, a uniform spectral gap makes Proposition 1.4.28 effective. Then we will have a polynomial decay.

The uniformity with respect to $\|r\|_{C^1}$, $\|\phi\|_{C^2}$ and $1/\inf_{\mathrm{suppr}} |\phi'|$ is due to the fact that all the terms depend only on these norms and the measure μ .

1.4 Renewal theory

We define a renewal operator R as follows. For a positive bounded Borel function f on $X \times \mathbb{R}$, a point x in X and a real number t , we set

$$Rf(x, t) = \sum_{n=0}^{+\infty} \int_G f(gx, \sigma(g, x) - t) d\mu^{*n}(g).$$

Because of the positivity of f , this sum is well defined. In [Kes74], Kesten proved a renewal theorem for Markov chains, which is valid in our case [GLP16]. But a uniform speed of convergence is needed. We will give a proof using the complex transfer operator, which fulfills our demands. The treatment of the transfer operator will be along the path in [Boy16]. The renewal theorem will give us an equidistribution phenomenon, where the key input is non-arithmeticity.

First we give a proof of renewal theorem for good functions. Then we prove some regularity properties and independence properties for the renewal process. These will imply a version of residue process. Finally, we prove a theorem for the Cartan projection from a similar theorem for the cocycle.

Fix the constant $\epsilon = \sigma_\mu/4$ in this section. Keep in mind that the assumptions of Theorem 1.1.1 are always satisfied.

1.4.1 Complex transfer operators

We introduce the complex transfer operator $P(z)$. Let $\mathcal{H}^\gamma(X)$ be the space of γ -Hölder functions on X , a Banach space with the norm $|f|_\gamma = |f|_\infty + m_\gamma(f) = |f|_\infty + \sup_{x \neq y} \frac{|f(x) - f(y)|}{d(x,y)^\gamma}$. For f in $\mathcal{H}^\gamma(X)$ and a complex number z , define

$$P(z)f(x) = \int_G e^{-z\sigma(g,x)} f(gx) d\mu(g).$$

The main properties of $P(z)$ are summarized as follows

Proposition 1.4.1. [Boy16, Theorem 4.1, Lemma 4.7] *For any $\gamma > 0$ small enough, there exists $\eta > 0$ such that when $|\Re z| < \eta$, the transfer operator $P(z)$ is a bounded operator on $\mathcal{H}^\gamma(X)$ and depends analytically on z . Moreover there exists an analytic operator $U(z)$ on a neighborhood of $0 \leq \Re z < \eta$ such that the following equality holds for $0 \leq \Re z < \eta$*

$$(I - P(z))^{-1} = \frac{1}{\sigma_\mu z} N_0 + U(z), \quad (1.4.1)$$

where N_0 is the operator defined by $N_0 f = \int f d\nu$

Remark 1.4.2. *In Proposition 1.4.1, the non-arithmeticity is crucial to prove that $(I - P(z))^{-1}$ has only one pole in the imaginary axis, which is 0. The non-arithmeticity follows from Zariski density. See for instance [Ben00] and [Dal00].*

The assumption of Theorem 4.1 in [Boy16] are complicated. It is verified, in the proof of theorem 1.4, page 8 [Boy16], that our condition on μ is enough to apply Theorem 4.1. The idea is due to Guivarch and Le Page.

Proposition 1.4.3. [Boy16, Lemma 4.4] *For any $\gamma > 0$ small enough, there exist $\eta > 0$, $0 < \rho < 1$, $C > 0$ such that when $0 \leq \Re z < \eta$, for a natural number n and a γ -Hölder function f , we have*

$$|P(z)^n f|_\infty \leq (C\rho^n)^{\Re z} |f|_\infty \quad (1.4.2)$$

Remark 1.4.4. For further usage, we need a bound on γ . Let $\epsilon, \epsilon'(\epsilon)$ be the two constants in (1.2.11), that is $\mu^{*n}\{d(gx, x') \leq e^{-\epsilon s}\} \leq Ce^{-\epsilon' s}$, and ϵ_1 the constant in exponential moment. Choose a small γ such that $\gamma \leq \frac{1}{4} \max\{\frac{\sigma_\mu/4}{\epsilon'(\sigma_\mu/4)}, \epsilon_1\}$.

1.4.2 Renewal theory for regular functions

We start to compute the renewal operator. A result for the renewal operator for “good” functions will be proved. Let f be a function on $X \times \mathbb{R}$. Define a norm by $|f|_{L^\infty \mathcal{H}^\gamma} = \sup_{\xi \in \mathbb{R}} |f(x, \xi)|_{\mathcal{H}^\gamma}$, which is the supremum of the Hölder norm of $f(\cdot, \xi)$. Define another norm $|f|_{W^{1, \infty} \mathcal{H}^\gamma} = |f|_{L^\infty \mathcal{H}^\gamma} + |\partial_\xi f|_{L^\infty \mathcal{H}^\gamma}$. Write the Fourier transform $\hat{f}(x, \xi) = \int e^{i\xi u} f(x, u) du$.

Proposition 1.4.5. Let f be a positive bounded continuous function in $L^1(X \times \mathbb{R}, \nu \otimes \mathrm{Leb})$ such that its Fourier transform satisfies $\hat{f} \in L^\infty \mathcal{H}^\gamma$ and $\partial_\xi \hat{f} \in L^\infty \mathcal{H}^\gamma$. Assume that the projection of $\mathrm{supp} \hat{f}$ onto \mathbb{R} is in a compact set K . Then for all $t > 0$ and x in X , we have

$$Rf(x, t) = \frac{1}{\sigma_\mu} \int_{-t}^{\infty} f(y, u) du d\nu(y) + \frac{1}{t} O_K(|\hat{f}|_{W^{1, \infty} \mathcal{H}^\gamma}).$$

Proof. Combine the following two lemmas. □

Lemma 1.4.6. Under the same assumption as in Proposition 1.4.5, we have

$$Rf(x, t) = \frac{1}{\sigma_\mu} \int_t^{\infty} f(y, u) du d\nu(y) + \frac{1}{2\pi} \int e^{it\xi} U(i\xi) \hat{f}(x, \xi) d\xi.$$

Proof. Introduce a local notation: for (x, t) in $X \times \mathbb{R}$ and $s \geq 0$, write

$$B_s f(x, t) = \int_G e^{-s\sigma(g, x)} f(gx, \sigma(g, x) + t) d\mu(g).$$

When $s = 0$, we abbreviate the notation B_0 to B . We want to prove the following equality,

$$\sum_{n \geq 0} B^n(f)(x, t) = \lim_{s \rightarrow 0^+} \sum_{n \geq 0} B_s^n(f)(x, t). \quad (1.4.3)$$

By definition, one has

$$\begin{aligned} B_s^n(f)(x, t) &= \int_G e^{-s\sigma(g, x)} f(gx, \sigma(g, x) + t) d\mu^{*n}(g) \\ &= \int_G e^{-s\sigma(g, x)} (\mathbb{1}_{\sigma(g, x) > 0} + \mathbb{1}_{\sigma(g, x) \leq 0}) f(gx, \sigma(g, x) + t) d\mu^{*n}(g). \end{aligned}$$

- The part $\mathbb{1}_{\sigma(g, x) > 0}$, since $f \geq 0$, use the monotone convergence theorem. When $s \rightarrow 0^+$ then

$$\sum_{n \geq 0} \int_G e^{-s\sigma(g, x)} \mathbb{1}_{\sigma(g, x) > 0} f(gx, \sigma(g, x) + t) d\mu^{*n}(g) \rightarrow \sum_{n \geq 0} \int_G \mathbb{1}_{\sigma(g, x) > 0} f(gx, \sigma(g, x) + t) d\mu^{*n}(g).$$

- For the part $\mathbb{1}_{\sigma(g,x)\leq 0}$, take s in $[0, \eta/2]$. Proposition 1.4.3 implies that

$$\int_G e^{-s\sigma(g,x)} \mathbb{1}_{\sigma(g,x)\leq 0} f(gx, \sigma(g,x)+t) d\mu^{*n}(g) \leq \int_G e^{-\eta\sigma(g,x)/2} |f|_\infty d\mu^{*n}(g) \leq (C\rho^n)^{\eta/2} |f|_\infty.$$

Since $\sum_{n\geq 0} \rho^{n\eta/2}$ is finite, take $e^{-\eta\sigma(g,x)/2} |f|_\infty$ as the dominant function. Then use the dominated convergence theorem to conclude.

This proves equation (1.4.3).

Using the inverse Fourier transform, we have

$$\begin{aligned} \sum_{n\geq 0} B_s^n(f)(x, t) &= \sum_{n\geq 0} \int_G e^{-s\sigma(g,x)} f(gx, \sigma(g,x) + t) d\mu^{*n}(g) \\ &= \sum_{n\geq 0} \int_G e^{-s\sigma(g,x)} \frac{1}{2\pi} \int_{\mathbb{R}} e^{i\xi(\sigma(g,x)+t)} \hat{f}(gx, \xi) d\xi d\mu^{*n}(g). \end{aligned} \quad (1.4.4)$$

Since $\hat{f}(x, \xi)$ has compact support, $|\hat{f}(x, \xi)| \leq |\hat{f}(x, \xi)|_{L^\infty_{\xi} \mathcal{H}^\gamma}$ and $|P(s)^n \mathbb{1}| \leq C\rho^{sn}$ for s in $[0, \eta/2]$ (Proposition 1.4.3), we have

$$\sum_{n\geq 0} \int_G e^{-s\sigma(g,x)} \int_{\mathbb{R}} |\hat{f}(gx, \xi)| d\xi d\mu^{*n}(g) \leq C_f \sum_{n\geq 0} \int_G e^{-s\sigma(g,x)} d\mu^{*n}(g) = C_f \sum_{n\geq 0} P(s)^n(\mathbb{1}) < \infty,$$

which implies that the right hand side of (1.4.4) is absolutely convergent. Consequently, we can use the Fubini theorem to change the order of the integration. By the hypothesis $\hat{f}(x, \xi) \in \mathcal{H}^\gamma(X)$, Proposition 1.4.1 implies that

$$\begin{aligned} \sum_{n\geq 0} B_s^n(f)(x, t) &= \frac{1}{2\pi} \int_{\mathbb{R}} \sum_{n\geq 0} \int_G e^{(-s+i\xi)\sigma(g,x)} \hat{f}(gx, \xi) d\mu^{*n}(g) e^{it\xi} d\xi \\ &= \frac{1}{2\pi} \int_{\mathbb{R}} \sum_{n\geq 0} P^n(s - i\xi) \hat{f}(x, \xi) e^{it\xi} d\xi \\ &= \frac{1}{2\pi} \int_{\mathbb{R}} (1 - P(s - i\xi))^{-1} \hat{f}(x, \xi) e^{it\xi} d\xi \\ &= \frac{1}{2\pi} \int_{\mathbb{R}} \left(\frac{N_0}{\sigma_\mu(s - i\xi)} + U(s - i\xi) \right) \hat{f}(x, \xi) e^{it\xi} d\xi. \end{aligned}$$

Since $\frac{1}{s-i\xi} = \int_0^{+\infty} e^{-(s-i\xi)u} du$ for $s > 0$, together with the property $\hat{f} \in L^1(\mathbb{R})$, we have

$$\begin{aligned} \frac{1}{2\pi} \int_{\mathbb{R}} \frac{N_0}{\sigma_\mu(s - i\xi)} \hat{f}(x, \xi) e^{it\xi} d\xi &= \frac{1}{2\pi} \frac{1}{\sigma_\mu} \int_X \int_{\mathbb{R}} \frac{\hat{f}(y, \xi)}{s - i\xi} e^{it\xi} d\xi d\nu(y) \\ &= \frac{1}{\sigma_\mu} \int_X \int_0^{+\infty} f(y, u+t) e^{-su} du d\nu(y). \end{aligned}$$

When $s \rightarrow 0^+$, since f is integrable with respect to the product measure $\nu \otimes \mathrm{Leb}$, by monotone convergence theorem, the limit is $\frac{1}{\sigma_\mu} \int_X \int_t^\infty f(y, u) du d\nu(y)$. Since $\hat{f}(x, \xi)$ is compactly supported, we have

$$\lim_{s \rightarrow 0^+} \int_{\mathbb{R}} U(-s + i\xi) \hat{f}(x, \xi) e^{it\xi} d\xi = \int_{\mathbb{R}} U(i\xi) \hat{f}(x, \xi) e^{it\xi} d\xi.$$

The proof is complete. \square

Lemma 1.4.7. *Under the same assumption as in Proposition 1.4.5, we have*

$$\left| \int e^{-it\xi} U(i\xi) \hat{f}(x, \xi) d\xi \right| \leq \frac{1}{t} O_K \left(|\hat{f}|_{L^\infty \mathcal{H}^\gamma} + |\partial_\xi \hat{f}|_{L^\infty \mathcal{H}^\gamma} \right).$$

Proof. Use the fact that $\hat{f}(x, \xi)$ is compactly supported and $|\hat{f}(x, \xi)|_{\mathcal{H}^\gamma}, |\partial_\xi \hat{f}(x, \xi)|_{\mathcal{H}^\gamma} < \infty$. Then applying integration by parts, we have

$$\begin{aligned} \int e^{-it\xi} U(i\xi) \hat{f}(x, \xi) d\xi &= \frac{1}{it} \int e^{-it\xi} \partial_\xi (U(i\xi) \hat{f}(x, \xi)) d\xi \\ &= \frac{1}{it} \int e^{-it\xi} \left(\partial_\xi (U(i\xi)) \hat{f}(x, \xi) + U(i\xi) \partial_\xi \hat{f}(x, \xi) \right) d\xi. \end{aligned}$$

Since the operator norms of $U(i\xi)$ and $\partial_\xi U(i\xi)$ are uniformly bounded on compact regions, the result follows. \square

1.4.3 Regularity properties of renewal measures

We have two principles in this subsection. **Principle 1:** Let f be a bounded Borel function supported in $X \times [0, a]$. When we take the renewal sum outside of the interval $I_t = [\frac{t}{\sigma_\mu + \epsilon}, \frac{t+a}{\sigma_\mu - \epsilon}]$,

$$\sum_{n \in \mathbb{N} - I_t} \int_G f(gx, \sigma(g, x) - t) d\mu^{*n}(g) = \sum_{n \in \mathbb{N} - I_t} \int_G f(gx, \sigma(g, x) - t) \mathbb{1}_{[0, a]}(\sigma(g, x) - t) d\mu^{*n}(g),$$

this sum decays exponentially with t . This is given by the large deviations principle (Corollary 1.2.9, 1.2.11). For n in the interval I_t , if some property is valid for each n with an exponential error of n , we sum up. Since the length of this interval is comparable with t , this property is also valid for the renewal sum with an exponential error of t .

Principle 2: The other is independence. By Proposition 1.4.5, the limit distribution of $(\sigma(g, x) - t, gx)$ is $\frac{1}{\sigma_\mu} \nu \otimes \mathrm{Leb}$, which is a product measure. That roughly means the following: As in Remark 1.3.4, let $X_n = b_n \cdots b_1$ be a random walk on G . Let $F = F_1 \times F_2$ where F_1, F_2 are Borel subsets of X, \mathbb{R} respectively. Then

$$\sum_{n \geq 0} \mathbb{P}\{(X_n x, \sigma(X_n, x) - t) \in F_1 \times F_2\} \rightarrow \frac{1}{\sigma_\mu} \nu(F_1) \otimes \mathrm{Leb}(F_2) \text{ as } t \rightarrow +\infty.$$

More concretely, we could expect that $R(\mathbb{1}_{F_1 \times F_2})(x, t)$ is almost $\frac{1}{\sigma_\mu} \nu(F_1) \otimes \mathrm{Leb}(F_2)$ when t is large.

We want to use convolution to smooth out the target function. There exists an even function ψ such that it is a probability density, and the Fourier transform $\hat{\psi}$ is compactly supported. Let $\psi_\delta(t) = \frac{1}{\delta^2}\psi(\frac{t}{\delta^2})$. Then $\int_{-\delta}^{\delta} \psi_\delta(t)dt = \int_{-1/\delta}^{1/\delta} \psi(t)dt > 1 - C\delta$.

Proposition 1.4.8. *Let $\delta \leq 1/3$ and $b_2 \geq b_1$. If $b_2 - b_1 \geq 2\delta$, then for x in X and $t > 0$, we have*

$$R(\mathbb{1}_{[b_1, b_2]})(x, t) \lesssim (b_2 - b_1)(1/\sigma_\mu + C_\delta(1 + |b_2| + |b_1|)/t). \quad (1.4.5)$$

If $0 \leq b_2 - b_1 < 2\delta$, then for x in X and $t > 0$, we have

$$R(\mathbb{1}_{[b_1, b_2]})(x, t) \lesssim \delta(1/\sigma_\mu + C_\delta(1 + |b_1|)/t). \quad (1.4.6)$$

Proof. When $b_2 - b_1 \geq 2\delta$, if u is in $[b_1, b_2]$, then $[u - b_2, u - b_1]$ contains at least one of $[0, \delta]$ or $[-\delta, 0]$. Therefore

$$\psi_\delta * \mathbb{1}_{[b_1, b_2]}(u) = \int_{b_1}^{b_2} \psi_\delta(u - v)dv \geq \int_0^\delta \psi(v)dv \geq (1 - \delta)/2.$$

Then

$$\mathbb{1}_{[b_1, b_2]} \leq 3\psi_\delta * \mathbb{1}_{[b_1, b_2]}. \quad (1.4.7)$$

It is sufficient to bound $R(\psi_\delta * \mathbb{1}_{[b_1, b_2]})$. Proposition 1.4.5 implies that

$$R(\psi_\delta * \mathbb{1}_{[b_1, b_2]}) = \frac{1}{\sigma_\mu} \int_{-t}^{\infty} \psi_\delta * \mathbb{1}_{[b_1, b_2]} + \frac{O_\delta}{t} |\hat{\psi}_\delta \hat{\mathbb{1}}_{[b_1, b_2]}|_{W^{1, \infty} \mathcal{H}^\gamma}.$$

The first term is less than $\int \psi_\delta * \mathbb{1}_{[b_1, b_2]} = (b_2 - b_1)$. For the second term, we have

$$\begin{aligned} |\hat{\psi}_\delta \hat{\mathbb{1}}_{[b_1, b_2]}|_{W^{1, \infty} \mathcal{H}^\gamma} &= |\hat{\psi}_\delta \hat{\mathbb{1}}_{[b_1, b_2]}|_{L^\infty \mathcal{H}^\gamma} + |\partial_\xi \hat{\psi}_\delta \hat{\mathbb{1}}_{[b_1, b_2]}|_{L^\infty \mathcal{H}^\gamma} \\ &= |\hat{\psi}_\delta \hat{\mathbb{1}}_{[b_1, b_2]}|_{L^\infty} + |\partial_\xi \hat{\psi}_\delta \hat{\mathbb{1}}_{[b_1, b_2]}|_{L^\infty} \\ &\leq C'_\delta (|\mathbb{1}_{[b_1, b_2]}(u)|_{L^1} + |u \mathbb{1}_{[b_1, b_2]}(u)|_{L^1}) \leq C'_\delta (b_2 - b_1)(1 + |b_1| + |b_2|). \end{aligned}$$

When $b_2 - b_1 \in [0, 2\delta]$, the renewal sum $R(\mathbb{1}_{[b_1, b_2]})$ is bounded by $R(\mathbb{1}_{[b_1, b_1 + 2\delta]})$. Then use the previous case. \square

In Proposition 1.4.5, since we do not have a good control of the spectral radius of the operator $U(i\xi)$ for large $|\xi|$, the estimates are effective only for large t , which means that when t is small the error term will be out of control. The following lemma combines the transfer operator and the large deviations principle to give a uniform estimate.

Lemma 1.4.9. *For real numbers s, t and a point x in X , we have*

$$R(\mathbb{1}_{[0, s]})(x, t) \lesssim \max\{1, s\}. \quad (1.4.8)$$

Proof. We can suppose that $s > 1$. If not, then $R(\mathbb{1}_{[0,s]})(x, t) \leq R(\mathbb{1}_{[0,1]})(x, t)$. When $t \geq s$, this is a direct corollary of Proposition 1.4.8. Fixing $\delta = 1/3$, we get

$$\frac{1 + |b_1| + |b_2|}{t} \leq \frac{1 + s}{t} \leq 2.$$

Then $R(\mathbb{1}_{[0,s]})(x, t) \lesssim s(1/\sigma_\mu + 2C_\delta)$.

When $t < s$, let $m = \lceil \max\{0, (t + s)/(\sigma_\mu - \epsilon)\} \rceil + 1$. By Corollary 1.2.9, we have

$$\begin{aligned} R(\mathbb{1}_{[0,s]})(x, t) &\leq R(\mathbb{1}_{[0,2s]})(x, 0) \leq \sum_{n \leq m} \mu^{\otimes n} \{\sigma(g, x) \leq 2s\} + \sum_{n > m} \mu^{\otimes n} \{\sigma(g, x) \leq 2s\} \\ &\lesssim m + e^{-\epsilon' m} \lesssim s. \end{aligned}$$

The proof is complete. \square

In the renewal theorem, the limits of the scalar part $\sigma(g, x)$ and the angle part gx are independent. Using this spirit, we give the following lemma, which quantifies this independence. In the proof, when t is large enough, using Proposition 1.4.5, the remainder term will be small. When t is small, we have another estimate from the regularity of the convolution measure $\mu^{\otimes n}$.

Proposition 1.4.10. *For $s > 0$, $a > 0$, $t > 5s$, and x, x' in X , we have*

$$R(\mathbb{1}_{B(x', e^{-s}) \times [0, a]})(x, t) = (1 + a)^2 O_{\exp}(s). \quad (1.4.9)$$

Proof. Decompose the region of t into two parts:

- When $5s < t \leq e^{2\gamma s}$, by Corollaries 1.2.9, 1.2.11, it suffices to consider $n \in [t/(\sigma_\mu + \epsilon), (t + a)/(\sigma_\mu - \epsilon)]$. Due to the hypothesis in this situation $s \leq t/5 = \epsilon t/(\sigma_\mu + \epsilon) \leq \epsilon n$, we can use Corollary 1.2.13 to obtain

$$\mu^{*n} \{d(gx, x') \leq e^{-s}\} \lesssim e^{-\epsilon' s/\epsilon}.$$

Then the measure of this part, summing up the above inequality over all $n \in [t/(\sigma_\mu + \epsilon), (t + a)/(\sigma_\mu - \epsilon)]$, is less than $C(t + a)e^{-\epsilon' s/\epsilon} \lesssim (1 + a)e^{-\gamma s}$ (here we use the Remark 1.4.4, $4\gamma \leq \epsilon/\epsilon'$).

- When $t \geq e^{2\gamma s}$, we take $f = \mathbb{1}_{[0, a]} \varpi(x)$ where $\varpi(x)$ is a function on X such that $\varpi_{B(x', e^{-s})} = 1$, $\mathrm{supp} \varpi \subset B(x', 2e^{-s})$ and $|\varpi|_\gamma \leq e^{\gamma s}$. As in the proof of Proposition 1.4.8, we use ψ_δ to regularize this function. By (1.4.7), we have

$$3R(\psi_\delta * f)(x, t) \geq R(\mathbb{1}_{B(x', e^{-s}) \times [0, a]})(x, t).$$

Proposition 1.4.5 implies

$$R(\psi_\delta * f) = \frac{1}{\sigma_\mu} \int_X \int_{-t}^{\infty} \psi_\delta * f(x, u) du d\nu(x) + \frac{C_\delta}{t} (\widehat{|\psi_\delta * f|}_{W^{1, \infty} \mathcal{H}_\gamma}).$$

Since $\widehat{\psi_\delta * f}(x, \xi) = \widehat{\psi_\delta}(\xi) \widehat{\mathbb{1}}_{[0,a]}(\xi) \varpi(x)$, the two functions are independent. We can use the same estimate as in the proof of Proposition 1.4.8. So the rest term is less than $C'_\delta(1+a)^2 e^{\gamma s}/t$. The major term, due to the regularity of the stationary measure (1.2.3), is controlled by $ae^{-\alpha s}/\sigma_\mu$. The result follows from the hypothesis $t > e^{2\gamma s}$.

The proof is complete. \square

We also need the independence of $\sigma(g, x)$ and $g^{-1}x_o$, where x, x_o are two points in X . For proving this property, we pass through the Cartan projection, because the order of products in the Cartan projection can be reversed. The following proof uses Lemma 1.2.14, which is a central tool to prove a renewal type theorem for the Cartan projection from a renewal type theorem for the cocycle.

Let f be a positive bounded Borel function on $X \times \mathbb{R}$. For $(x, t) \in X \times \mathbb{R}$, we define

$$R_P(f)(x, t) = \sum_{n \geq 0} \int_G f(gx, \kappa(g) - t) d\mu^{*n}(g).$$

Lemma 1.4.11. *For $s > 0$, $a > 0$, $t > 10s$, and x, x' in X , we have*

$$R_P(\mathbb{1}_{B(x', e^{-s}) \times [0,a]})(x, t) = (1+a)^2 O_{\text{exp}}(s). \quad (1.4.10)$$

Proof. Due to Corollary 1.2.9 and Corollary 1.2.11, the sum of the integral of $n \leq t/(\sigma_\mu + \epsilon)$ and $n \geq (t+a)/(\sigma_\mu - \epsilon)$ is exponentially small.

It suffices to consider n in the interval $I_t = [t/(\sigma_\mu + \epsilon), (t+a)/(\sigma_\mu - \epsilon)]$. Fix $l = [\epsilon_4 t / \sigma_\mu]$ with $\epsilon_4 = 1/10$. By Lemma 1.2.14, there exists $S_{n,l,x} \subset G^{\times n}$ such that $\mu^{\otimes n} S_{n,l,x}^c = O_{\text{exp}}(l)$, and for (g_n, \dots, g_1) in $S_{n,l,x}$, letting $g = (g_n, \dots, g_{l+1})$ and $j = (g_l, \dots, g_1)$, we have

$$|\kappa(gj) - \sigma(g, jx) - \kappa(j)| \leq e^{-\epsilon l} \leq 1.$$

Thus

$$\begin{aligned} & \mu^{\otimes n} \{ \kappa(gj) \in [t, t+a], d(gjx, x') \leq e^{-s} \} \\ & \leq \mu^{\otimes n} \{ S_{n,l,x}^c \} + \mu^{\otimes n} \{ gj \in S_{n,l,x} \mid \kappa(gj) \in [t, t+a], d(gjx, x') \leq e^{-s} \} \\ & \leq O_{\text{exp}}(l) + \mu^{\otimes n} \{ \sigma(g, jx) + \kappa(j) \in [t-1, t+a+1], d(gjx, x') \leq e^{-s} \}. \end{aligned}$$

Therefore summing over n and integrating first with respect to g , we get

$$\begin{aligned} & \sum_{n \in I_t} \mu^{\otimes n} \{ \kappa(gj) \in [t, t+a], d(gjx, x') \leq e^{-s} \} \\ & \leq \sum_{n \in I_t} \mu^{\otimes n} \{ \sigma(g, jx) + \kappa(j) \in [t-1, t+a+1], d(gjx, x') \leq e^{-s} \} + t O_{\text{exp}}(l) \quad (1.4.11) \\ & \leq t O_{\text{exp}}(l) + \int R(\mathbb{1}_{B(x', e^{-s}) \times [-1, a+1]})(jx, t - \kappa(j)) d\mu^{*l}(j). \end{aligned}$$

Hence, it is sufficient to bound $\int R(\mathbb{1}_{B(x', e^{-s}) \times [-1, a+1]})(jx, t - \kappa(j)) d\mu^{*l}(j)$. Let $G_{l, \epsilon} = \{j \in G^{\times l} \mid \kappa(j) \leq l(\sigma_\mu + \epsilon)\}$. By the large deviations principle (Corollary 1.2.11), we have $\mu^{*l} G_{l, \epsilon}^c = O_{\exp}(l)$.

- For $j \in G_{l, \epsilon}$, we have $t - \kappa(j) \geq t - l(\sigma_\mu + \epsilon) = t - \epsilon_4(\sigma_\mu + \epsilon)t/\sigma_\mu > t/2 \geq 5s$. Hence, Proposition 1.4.10 implies that

$$R(\mathbb{1}_{B(x', e^{-s}) \times [-1, a+1]})(jx, t - \kappa(j)) \lesssim (1+a)^2 O_{\exp}(s).$$

- For $j \in G_{l, \epsilon}^c$, Lemma 1.4.9 implies that

$$R(\mathbb{1}_{B(x', e^{-s}) \times [-1, a+1]})(jx, t - \kappa(j)) \lesssim (1+a).$$

Combining the above two inequalities, we have

$$\int R(\mathbb{1}_{B(x', e^{-s}) \times [-1, a+1]})(jx, t - \kappa(j)) d\mu^{*l}(j) \lesssim (1+a)^2 O_{\exp}(s) + O_{\exp}(l)(1+a).$$

(1.4.12)

The proof is complete. \square

There is a byproduct of the above lemma. When the function f does not depend on X , abbreviate $R_P(f)(x, t)$ by $R_P(f)(t)$.

Lemma 1.4.12. *For real numbers s, t , we have*

$$R_P(\mathbb{1}_{[0, s]})(t) \lesssim \max\{1, s^2\}. \quad (1.4.13)$$

Remark 1.4.13. *Here the term s^2 is not optimal. With some extra work, it can be improved to s .*

Proof. Suppose that $s \geq 1$. If not, then $R_P(\mathbb{1}_{[0, s]})(x, t) \leq R_P(\mathbb{1}_{[0, 1]})(x, t)$. When $t \geq 10$, apply Lemma 1.4.11 with $a = s$, $e^{-s} = e^{-1}$, $x' = x_j$, $j \in J$, where J is a finite set such that $\cup_{j \in J} B(x_j, e^{-1})$ covers X . So we get $R_P(\mathbb{1}_{[0, s]})(t) \lesssim s^2$.

When $t < 10 \leq 10s$, let $m = \lceil \max\{0, (t+s)/(\sigma_\mu - \epsilon)\} \rceil + 1$. By Corollary 1.2.11, we have

$$\begin{aligned} R_P(\mathbb{1}_{[0, s]})(t) &\leq R_P(\mathbb{1}_{[0, 2s]})(0) \leq \sum_{n \leq m} \mu^{*n} \{\kappa(g) \leq t+s\} + \sum_{n > m} \mu^{*n} \{\kappa(g) \leq t+s\} \\ &\lesssim m + e^{-\epsilon' m} \lesssim s. \end{aligned}$$

The proof is complete. \square

Now we are going to prove the independence of $\sigma(g, x)$ and $g^{-1}x$. Recall that $\check{\mu}$ is the pushforward of μ by the inverse action. Let f be a positive bounded Borel function on $X \times \mathbb{R}$. For $(x_o, x, t) \in X^2 \times \mathbb{R}$, we define

$$R_I(f)(x_o, x, t) = \sum_{n \geq 0} \int_G f(g^{-1}x_o, \sigma(g, x) - t) d\mu^{*n}(g).$$

Proposition 1.4.14. *For $s > 0$, $a > 0$, $t > \max\{10s, 10\}$, and x, x', x_o in X , we have*

$$R_I(\mathbb{1}_{B(x', e^{-s}) \times [0, a]})(x_o, x, t) = (1 + a)^2 O_{\exp}(s). \quad (1.4.14)$$

Proof. Due to Corollary 1.2.9 and Corollary 1.2.11, the sums of the integral of $n \leq t/(\sigma_\mu + \epsilon)$ and $n \geq (t + a)/(\sigma_\mu - \epsilon)$ is exponentially small.

It suffices to consider n in the interval $I_t = [t/(\sigma_\mu + \epsilon), (t + a)/(\sigma_\mu - \epsilon)]$. Let

$$G_{\epsilon, n} = \{g \in G^{\times n} \mid \kappa(g) \geq n(\sigma_\mu - \epsilon/2), d(g^{-1}x_o, x) > e^{-\epsilon n}, d(g^{-1}x_o, x_g^m) \leq e^{-(2\sigma_\mu - \epsilon)n}\}.$$

By inequalities (1.2.9), (1.2.11) and (1.2.13), we have $\mu^{\otimes n} G_{\epsilon, n} \geq 1 - O_{\exp}(n)$. Since $t > 10$, for n in I_t , we have $n \geq t/(\sigma_\mu + \epsilon) \geq 10/(\sigma_\mu + \epsilon)$. For $g \in G_{\epsilon, n}$, we have

$$\frac{e^{-2\kappa(g)} + d(x_g^m, g^{-1}x_o)}{d(g^{-1}x_o, x)} \leq \frac{2e^{-(2\sigma_\mu - \epsilon)n}}{e^{-\epsilon n}} = 2e^{-(2\sigma_\mu - 2\epsilon)n} \leq 2e^{-20(\sigma_\mu - \epsilon)/(\sigma_\mu + \epsilon)} \leq 1/2.$$

Using Lemma 1.2.7 with $g \in G_{\epsilon, n}$, we have

$$|\sigma(g, x) - \kappa(g) - \log d(g^{-1}x_o, x)| \leq 2 \frac{e^{-2\kappa(g)} + d(x_g^m, g^{-1}x_o)}{d(g^{-1}x_o, x)} \leq 4e^{-(2\sigma_\mu - 2\epsilon)n} \leq 1.$$

Therefore,

$$\begin{aligned} & \mu^{\otimes n} \{\sigma(g, x) \in [t, t + a], d(g^{-1}x_o, x') \leq e^{-s}\} \leq O_{\exp}(n) + \\ & \mu^{\otimes n} \{\kappa(g) \in [t - 1, t + a + 1] - \log d(g^{-1}x_o, x), d(g^{-1}x_o, x') \leq e^{-s}\}. \end{aligned}$$

Summing up over I_t and using the definition of $\check{\mu}$, we have

$$\begin{aligned} & \sum_{n \in I_t} \mu^{\otimes n} \{\sigma(g, x) \in [t, t + a], d(g^{-1}x_o, x') \leq e^{-s}\} \\ & \leq O_{\exp}(t) + \sum_{n \geq 0} \mu^{\otimes n} \{\kappa(g) \in [t - 1, t + a + 1] - \log d(g^{-1}x_o, x), d(g^{-1}x_o, x') \leq e^{-s}\} \\ & = O_{\exp}(t) + \sum_{n \geq 0} \check{\mu}^{\otimes n} \{\kappa(g) \in [t - 1, t + a + 1] - \log d(gx_o, x), d(gx_o, x') \leq e^{-s}\}. \end{aligned} \quad (1.4.15)$$

Hence, it is sufficient to bound $R_P(\mathbb{1}_{u + \log d(y, x) \in [-1, a+1], d(y, x') \leq e^{-s}})(x_o, t)$, where we use (y, u) to denote the variables, and the measure μ is replaced by $\check{\mu}$. For simplicity, we use the same notation R_P . Cutting the region along $\{y \in X \mid \log d(y, x) \leq -t_1\}$ and the subsets $\{y \in X \mid \log d(y, x) \in [-(k + 1)s, -ks]\}$ for $0 \leq k < t_1/s$, where $t_1 = (t - 1)/9$.

- When $k = 0$, since $t - 1 > 10s$, we can use Lemma 1.4.11 to obtain

$$\begin{aligned} & R_P(\mathbb{1}_{u+\log d(y,x) \in [-1, a+1], d(y,x') \leq e^{-s}, d(y,x) \geq e^{-s}})(x_o, t) \\ & \leq R_P(\mathbb{1}_{d(y,x') \leq e^{-s}, u \in [-1, s+a+1]})(x_o, t) \lesssim (1+s+a)^2 e^{-\epsilon' s}. \end{aligned}$$

- When $0 < k < t_1/s$, since $t + ks - 1 > 10ks$, again we use Lemma 1.4.11

$$\begin{aligned} & R_P(\mathbb{1}_{u+\log d(y,x) \in [-1, a+1], d(y,x') \leq e^{-s}, d(y,x) \in [e^{-(k+1)s}, e^{-ks}]})(x_o, t) \\ & \leq R_P(\mathbb{1}_{d(y,x) \leq e^{-ks}, u \in [-1+ks, a+1+(k+1)s]})(x_o, t) \lesssim (1+s+a)^2 e^{-\epsilon' ks}. \end{aligned}$$

- In the last case, $\log d(y, x) \leq -t_1$, we have

$$\begin{aligned} & R_P(\mathbb{1}_{u+\log d(y,x) \in [-1, a+1], d(y,x') \leq e^{-s}, d(y,x) \leq e^{-t_1}})(x_o, t) \\ & \leq R_P(\mathbb{1}_{u+\log d(y,x) \in [-1, a+1], d(y,x) \leq e^{-t_1}})(x_o, t). \end{aligned}$$

This is similar to the original quantity $R_P(\mathbb{1}_{u+\log d(y,x) \in [-1, a+1], d(y,x') \leq e^{-s}})(x_o, t)$. The difference is that here t_1 is comparable with t , which is crucial in the following argument. Return to the definition of R_P , and discuss on the length $n = \omega(g)$.

- When $n > (t + a + 1)/(\sigma_\mu - 2\epsilon)$, by inequality (1.2.9) and (1.2.11), we have $\check{\mu}^{\otimes n} \{g \in G^{\times n} | \kappa(g) - n\sigma_\mu \leq n\epsilon, d(gx_o, x) \geq e^{-\epsilon n}\} > 1 - Ce^{-\epsilon' n}$. By hypothesis $n > (t + a + 1)/(\sigma_\mu - 2\epsilon)$, the element in this set satisfies

$$\kappa(g) \geq (\sigma_\mu - \epsilon)n > t + a + 1 + n\epsilon \geq t + a + 1 - \log d(gx_o, x).$$

Thus $\check{\mu}^{\otimes n} \{g \in G^{\times n} | \kappa(g) \in [t-1, t+a+1] - \log d(gx_o, x)\} = O_{\exp}(n)$. Summing over n , we see that the measure of this part is $O_{\exp}(t)$.

- When $n \in [(t-1)/(\sigma_\mu + \epsilon), (t+a+1)/(\sigma_\mu - 2\epsilon)]$, since $\epsilon n \geq \epsilon(t-1)/(\sigma_\mu + \epsilon) > (t-1)/9 = t_1$, Corollary 1.2.13 implies that

$$\check{\mu}^{\otimes n} \{g \in G^{\times n} | d(gx_o, x) \leq e^{-t_1}\} = O_{\exp}(t_1) = O_{\exp}(t).$$

- When $n \leq (t-1)/(\sigma_\mu + \epsilon)$, Corollary 1.2.11 implies the measure of this part is $O_{\exp}(t)$.

Therefore we have

$$R_P(\mathbb{1}_{u+\log d(y,x) \in [-1, a+1], d(y,x) \leq e^{-t_1}})(x_o, t) = O_{\exp}(t_1).$$

Combining the three cases, we have finished the proof. \square

1.4.4 Residue process

We introduce the residue process, which not only deals with $\sigma(g_n g_{n-1} \cdots g_1, x)$ but also takes into account the next step $\sigma(g_{n+1}, g_n g_{n-1} \cdots g_1 x)$. Let f be a positive bounded Borel function on $X \times \mathbb{R}^2$. For $(x, t) \in X \times \mathbb{R}$, we define the residue operator by

$$Ef(x, t) = \sum_{n \geq 0} \int f(hgx, \sigma(h, gx), \sigma(g, x) - t) d\mu^{*n}(g) d\mu(h). \quad (1.4.16)$$

Let $\mathcal{F}_u f(x, v, \xi) = \int f(x, v, u) e^{iu\xi} du$ be the Fourier transform on \mathbb{R}_u . Let F be a function on $X \times \mathbb{R}_v \times \mathbb{R}_\xi$. Define a partial Lipschitz norm by

$$|F|_{L^\infty Lip} = \sup_{\xi \in \mathbb{R}} |F(\xi)|_{Lip} = \sup_{\xi \in \mathbb{R}} \left(|F(\xi)|_\infty + \sup_{(x,v), (x',v') \in X \times \mathbb{R}} \frac{|F(x, v, \xi) - F(x', v', \xi)|}{d(x, x') + |v - v'|} \right).$$

Proposition 1.4.15 (Residue process). *If f is a positive bounded continuous function on $X \times \mathbb{R}^2$. Assume that the projection of $\text{supp} \mathcal{F}_u(f)$ onto \mathbb{R}_ξ is contained in a compact set K , and $|\mathcal{F}_u(f)|_{L^\infty Lip}, |\partial_\xi \mathcal{F}_u(f)|_{L^\infty Lip}$ are finite. Then for $t > 0$ and $x \in X$, we have*

$$Ef(x, t) = \frac{1}{\sigma_\mu} \int_{-t}^{\infty} \int_G \int_X f(hy, \sigma(h, y), u) d\nu(y) d\mu(h) du + \frac{1}{t} O_K (|\mathcal{F}_u(f)|_{L^\infty Lip} + |\partial_\xi \mathcal{F}_u(f)|_{L^\infty Lip}). \quad (1.4.17)$$

Proof. For a bounded continuous function f on $X \times \mathbb{R}^2$ and $(x, u) \in X \times \mathbb{R}$, we define an operator Q by

$$Qf(x, u) = \int_G f(hx, \sigma(h, x), u) d\mu(h).$$

Then

$$Ef(x, t) = \sum_{n \geq 0} \int Qf(gx, \sigma(g, x) - t) d\mu^{*n}(g) = R(Qf)(x, t).$$

We want to use Proposition 1.4.5, so we need to verify the hypotheses. The function Qf is bounded and integrable by the hypotheses on f . Then

$$\begin{aligned} \widehat{Qf}(x, \xi) &= \int Qf(x, u) e^{iu\xi} du = \int f(hx, \sigma(h, x), u) e^{iu\xi} du d\mu(h) \\ &= \int_G \mathcal{F}_u f(hx, \sigma(h, x), \xi) d\mu(h). \end{aligned}$$

Thus \widehat{Qf} is also compactly supported on ξ . It remains to estimate the Hölder norm of \widehat{Qf} . Since $\mathcal{F}_u f(x, v, \xi)$ is Lipschitz on $(x, v) \in X \times \mathbb{R}$, this implies that

$$\begin{aligned} |\widehat{Qf}(x, \xi) - \widehat{Qf}(y, \xi)| &\leq \int_G |\mathcal{F}_u f(hx, \sigma(h, x), \xi) - \mathcal{F}_u f(hy, \sigma(h, y), \xi)| d\mu(h) \\ &\leq \int_G |\mathcal{F}_u f|_{L^\infty Lip} (d(hx, hy) + |\sigma(h, x) - \sigma(h, y)|) d\mu(h). \end{aligned}$$

Using Lipschitz property of the distance and the cocycle, and finite exponential moment, we have

$$|\widehat{Q}f(x, \xi) - \widehat{Q}f(y, \xi)| \leq |\mathcal{F}_u f|_{L^\infty Lip} d(x, y)^\gamma \int_G (1 + \kappa(h)) \|h\|^{2\gamma} d\mu(h) \lesssim |\mathcal{F}_u f|_{L^\infty Lip} d(x, y)^\gamma,$$

where we use the Remark 1.4.4 that $4\gamma \leq \epsilon_1$. Therefore

Lemma 1.4.16 (Change of norm). *Under the assumptions of Proposition 1.4.15, we have*

$$|\widehat{Q}f|_{L^\infty \mathcal{H}^\gamma} \lesssim |\mathcal{F}_u(f)|_{L^\infty Lip}, \quad |\partial_\xi \widehat{Q}f|_{L^\infty \mathcal{H}^\gamma} \lesssim |\partial_\xi \mathcal{F}_u f|_{L^\infty Lip}.$$

Proof. The second inequality follows by the same computation. \square

By Proposition 1.4.5, we have

$$\begin{aligned} R(Qf)(x, t) &= \frac{1}{\sigma_\mu} \int_X \int_{-t}^\infty Qf(y, u) du d\nu(y) + \frac{1}{t} O_K \left(|\widehat{Q}f|_{L^\infty \mathcal{H}^\gamma} + |\partial_\xi \widehat{Q}f|_{L^\infty \mathcal{H}^\gamma} \right) \\ &= \frac{1}{\sigma_\mu} \int_X \int_{-t}^\infty Qf(y, u) du d\nu(y) + \frac{1}{t} O_K (|\mathcal{F}_u(f)|_{L^\infty Lip} + |\partial_\xi \mathcal{F}_u(f)|_{L^\infty Lip}). \end{aligned}$$

The proof is complete. \square

1.4.5 Residue process with cutoff

In this section, we restrict the residue process to the sequences $(g_{n+1}, g_n, \dots, g_1)$ such that $\sigma(g_n \cdots g_1, x) < t \leq \sigma(g_{n+1} \cdots g_1, x)$. Let f be a function on $X \times \mathbb{R}^2$. Define a Lipschitz norm by

$$|f|_{Lip} = |f|_\infty + \sup_{(x,v,u) \neq (x',v',u')} \frac{|f(x, v, u) - f(x', v', u')|}{d(x, x') + |v - v'| + |u - u'|}. \quad (1.4.18)$$

Define an operator from bounded Borel functions on $X \times \mathbb{R}^2$ to functions on $X \times \mathbb{R}$ by

$$E_C f(x, t) = \sum_{n \geq 0} \int_{\sigma(g, x) < t \leq \sigma(hg, x)} f(hgx, \sigma(h, gx), \sigma(g, x) - t) d\mu(h) d\mu^{*n}(g).$$

By Lemma 1.4.21, which will be proved later, this operator is well defined. Let K be a compact set in \mathbb{R} . We denote $|K|$ by the supremum of the distance between a point in K and 0.

Proposition 1.4.17. *Let f be a continuous function on $X \times \mathbb{R}^2$ with $|f|_{Lip}$ finite. Assume that the projection of $\text{supp } f$ on \mathbb{R}_v is contained in a compact set K . For all $\delta > 0$, $t > |K| + \delta$ and $x \in X$, we have*

$$E_C f(x, t) = \int_X \int_G \int_{-\sigma(h, y)}^0 f(hy, \sigma(h, y), u) du d\mu(h) d\nu(y) + O_K(\delta + O_\delta/t) |f|_{Lip}, \quad (1.4.19)$$

where O_K does not depend on δ, f, t, x , and the integral $\int_{-\sigma(h, y)}^0 = 0$ if $\sigma(h, y) < 0$.

Remark 1.4.18. We decompose f into real and imaginary parts, then decompose these two parts into positive and negative parts. Each part satisfies the hypotheses of Proposition 1.4.17, with the support and the Lipschitz norm bounded by the original one. Thus, it is sufficient to prove this proposition for f positive.

The following lemma connects the operator E_C with E .

Lemma 1.4.19. Under the assumptions of Proposition 1.4.17, let $f_o(x, v, u) = \mathbb{1}_{-v \leq u < 0} f(x, v, u)$. Then

$$E_C f(x, t) = E f_o(x, t).$$

Before proving this proposition, we describe some regularity and independence properties. They are corollaries of analogous properties for the renewal process. The idea is to decompose the integral according to the last letter. The following lemma means that the residue process with cutoff has exponential decay with respect to the last jump.

Lemma 1.4.20. For t, s in \mathbb{R} and x in X , we have

$$E_C(\mathbb{1}_{v \geq s})(x, t) = E(\mathbb{1}_{-v \leq u < 0, v \geq s})(x, t) = O_{\exp}(s). \quad (1.4.20)$$

Proof. By Lemma 1.4.9 and finiteness of the exponential moment, we have

$$\begin{aligned} & \sum_{n \geq 0} \mu \otimes \mu^{*n} \{(h, g) \in G^2 \mid \sigma(g, x) - t \in [-\sigma(h, gx), 0], \sigma(h, gx) \geq s\} \\ & \leq \sum_{n \geq 0} \mu \otimes \mu^{*n} \{(h, g) \in G^2 \mid \sigma(g, x) - t \in [-\kappa(h), 0], \kappa(h) \geq s\} \\ & = \int_{\kappa(h) > s} R(\mathbb{1}_{[-\kappa(h), 0]})(x, t) d\mu(h) \lesssim \int_{\kappa(h) > s} \max\{1, \kappa(h)\} d\mu(h) = O_{\exp}(s). \end{aligned}$$

The proof is complete. \square

Lemma 1.4.21. There exists $C > 0$ such that for all $t \in \mathbb{R}$ and $x \in X$, we have

$$E_C(\mathbb{1})(x, t) = E(\mathbb{1}_{-v \leq u < 0})(x, t) \leq C. \quad (1.4.21)$$

This is a special case of Lemma 1.4.20. The following lemma quantifies the independence of the scalar part and the angle part. Abbreviate $\mathbb{1}_{d(y, x') \leq e^{-s}, -v \leq u < 0}(y, v, u)$ to $\mathbb{1}_{d(y, x') \leq e^{-s}, -v \leq u < 0}$, and others are similar.

Lemma 1.4.22. For $t > 5s > 0$ and x, x' in X , we have

$$E_C(\mathbb{1}_{d(y, x') \leq e^{-s}})(x, t) = E(\mathbb{1}_{d(y, x') \leq e^{-s}, -v \leq u < 0})(x, t) = O_{\exp}(s). \quad (1.4.22)$$

Proof. Since

$$\mathbb{1}_{-v \leq u < 0} \leq \mathbb{1}_{d(y, x') \leq e^{-s}, -v \leq u < 0, v \geq s} + \mathbb{1}_{d(y, x') \leq e^{-s}, 0 \leq u + v < s},$$

we have

$$E(\mathbb{1}_{d(y,x') \leq e^{-s}, -v \leq u < 0})(x, t) \leq E(\mathbb{1}_{-v \leq u < 0, v \geq s})(x, t) + E(\mathbb{1}_{d(y,x') \leq e^{-s}, 0 \leq u+v < s})(x, t).$$

By definition, we have

$$\begin{aligned} E(\mathbb{1}_{d(y,x') \leq e^{-s}, 0 \leq u+v < s})(x, t) &= \sum_{n \geq 0} \int \mathbb{1}_{d(hgx, x') \leq e^{-s}, \sigma(h, gx) + \sigma(g, x) - t \in [0, s]} d\mu^{*n}(g) d\mu(h) \\ &= \sum_{n \geq 1} \int \mathbb{1}_{d(gx, x') \leq e^{-s}, \sigma(g, x) - t \in [0, s]} d\mu^{*n}(g) = R(\mathbb{1}_{B(x', e^{-s}), [0, s]})(x, t). \end{aligned}$$

By Lemma 1.4.20 and Proposition 1.4.10, the result follows. \square

Lemma 1.4.23. *For $s > 0$, $t > \max\{10s, 10\}$ and $x, x_o, x' \in X$, we have*

$$\sum_{n \geq 0} \mu \otimes \mu^{*n} \{(h, g) \in G \times G \mid \sigma(hg, x) \geq t, \sigma(g, x) < t, d((hg)^{-1}x_o, x') \leq e^{-s}\} = O_{\exp}(s).$$

By the same argument as in the proof of Lemma 1.4.22, we only need to replace Proposition 1.4.10 by Proposition 1.4.14. The difference between this lemma and Lemma 1.4.22 is the angle part $(hg)^{-1}x$.

Using ψ_δ to regularize these functions, we write $f_\delta(x, v, u) = \int f_o(x, v, u - u_1) \psi_\delta(u_1) du_1 = \psi_\delta * f_o(x, v, u)$.

Lemma 1.4.24. *Under the same hypotheses as in Proposition 1.4.17, we have*

$$E(f_\delta)(x, t) = \int_X \int_G \int_{-\sigma(h, y)}^0 f(hy, \sigma(h, y), u) du d\mu(g) d\nu(y) + O_K(\delta + \frac{O_\delta}{t}) \|f\|_{Lip}.$$

Proof. We want to verify the conditions in Proposition 1.4.15 and then use this proposition. The integrable condition is valid because $|\int_{\mathbb{R}^u} f_\delta| = |\int_{\mathbb{R}^u} f_o(x, v, u) du| = |\int_{-v}^0 f(x, v, u) du| \leq |K| \|f\|_\infty$. For the Fourier transform, we have

$$\mathcal{F}_u f_\delta = \mathcal{F}_u(\psi_\delta * f_o) = \hat{\psi}_\delta \mathcal{F}_u f_o.$$

We need to estimate the Lipschitz norm of $\mathcal{F}_u f_o$. This function equals

$$\int f_o(x, v, u) e^{i\xi u} du = \int_{-v}^0 f(x, v, u) e^{i\xi u} du.$$

Taking $(x, v) \neq (x', v')$, we have

$$\begin{aligned} & \left| \int_{-v}^0 f(x, v, u) e^{i\xi u} du - \int_{-v'}^0 f(x', v', u) e^{i\xi u} du \right| \\ & \leq \left| \int_{-v}^0 (f(x, v, u) - f(x', v', u)) e^{i\xi u} du \right| + |v' - v| \|f\|_\infty \lesssim |K| \|f\|_{Lip} (d(x, x') + |v - v'|). \end{aligned}$$

Then we have

Lemma 1.4.25 (Change of norm). *Under the same hypotheses as in Proposition 1.4.17, we have*

$$|\mathcal{F}_u f_\delta|_{L^\infty Lip} \leq |K| |f|_{Lip}, \quad |\partial_\xi \mathcal{F} f_\delta|_{L^\infty Lip} \leq |K|^2 |f|_{Lip}.$$

Proof. Noting that in the integration $|u| \leq |v|$, we get the second inequality by the same computation. \square

Therefore by Proposition 1.4.15, we have

$$E(f_\delta)(x, t) = \frac{1}{\sigma_\mu} \int_{-t}^{\infty} \int_G \int_X f_\delta(hy, \sigma(h, y), u) d\nu(y) d\mu(h) du + \frac{O_\delta}{t} (|f|_{Lip}(|K| + |K|^2)).$$

Then

$$\begin{aligned} \int_{-t}^{\infty} f_\delta(x, v, u) du &= \int_{-t}^{\infty} \int_{-v}^0 f(x, v, u_1) \psi_\delta(u - u_1) du_1 du = \int_{-v}^0 f(x, v, u_1) \int_{-t}^{\infty} \psi_\delta(u - u_1) du du_1 \\ &= \int_{-v}^0 f(x, v, u_1) du_1 - \int_{-v}^0 f(x, v, u_1) \int_{-\infty}^{-t-u_1} \psi_\delta(u) du du_1. \end{aligned}$$

Since $t - \delta \geq |K|$, we have $-t - u_1 \leq -t + v \leq -\delta$. By $\int_{-\infty}^{-\delta} \psi_\delta \leq C_\psi \delta$, this implies that $\int_{-t}^{\infty} f_\delta(x, v, u) du = \int_{-v}^0 f_\delta(x, v, u) du (1 + O(\delta))$. Using Lemma 1.4.21, we have

$$\left| \int_X \int_G \int_{-\sigma(h, y)}^0 f(hy, \sigma(h, y), u) du d\mu(g) d\nu(y) \right| \leq |f|_\infty E_C(\mathbb{1}) = O(|f|_\infty).$$

Therefore

$$\begin{aligned} \int_{-t}^{\infty} \int_G \int_X f_\delta(hy, \sigma(h, y), u) d\nu(y) d\mu(h) du \\ = \int_X \int_G \int_{-\sigma(h, y)}^0 f(hy, \sigma(h, y), u) du d\mu(g) d\nu(y) + O(\delta |f|_\infty). \end{aligned}$$

The proof is complete. \square

Next lemma gives the difference between a function and its regularization.

Lemma 1.4.26. *Let $\varphi_0(u) = \mathbb{1}_{[b_1, b_2]}(u) \varphi(u)$, where $b_2 > b_1$ and $|\varphi'|_{L^\infty} < \infty$, $|\varphi|_{L^\infty} \leq 1$. Then we have*

$$|\psi_\delta * \varphi_0(u) - \varphi_0(u)| \leq \begin{cases} (|\varphi'|_\infty + 2)\delta & u \in [b_1 + \delta, b_2 - \delta], \\ 2 & u \in [b_1 - \delta, b_1 + \delta] \cup [b_2 - \delta, b_2 + \delta], \\ \psi_\delta * \mathbb{1}_{[b_1, b_2]}(u) & u \in [b_1 - \delta, b_2 + \delta]^c. \end{cases} \quad (1.4.23)$$

Proof. We will prove this inequality in each interval.

- When u is in $[b_1 + \delta, b_2 - \delta]$, we have

$$|(\psi_\delta * \varphi_0 - \varphi_0)(u)| = \left| \int \psi_\delta(t)(\varphi_0(u-t) - \varphi_0(u))dt \right| \leq \int_{-\delta}^{\delta} \psi_\delta(t)|\varphi_0(u-t) - \varphi_0(u)|dt + 2\delta.$$

When $|t| \leq \delta$, we have $u-t \in [b_1, b_2]$. Since $|\varphi'_0(u)| \leq |\varphi'|_\infty$ for $u \in [b_1, b_2]$, this implies that

$$\int_{-\delta}^{\delta} \psi_\delta(t)|\varphi_0(u-t) - \varphi_0(u)|dt \leq \int_{-\delta}^{\delta} \psi_\delta(t)|t||\varphi'|_\infty dt \leq \delta|\varphi|_\infty.$$

- When $u \in [b_1 - \delta, b_1 + \delta] \cup [b_2 - \delta, b_2 + \delta]$, we use the trivial bound $|\psi_\delta * \varphi_0(u) - \varphi_0(u)| \leq 2$.
- When $u \in (-\infty, b_1 - \delta] \cup [b_2 + \delta, \infty)$, we have $\varphi_0(u) = 0$, then $|\psi_\delta * \varphi_0| \leq |\psi_\delta * \mathbb{1}_{[b_1, b_2]}|$.

Thus collecting all together, we get the inequality. \square

Proof of Proposition 1.4.17. To simplify the notation, we normalize f in such a way that $|f|_\infty = 1$. By Lemma 1.4.24, we only need to give an estimate of $E(|f_\delta - f_o|)(x, t)$.

Since $f_o(x, v, u) = \mathbb{1}_{-v \leq u < 0}(u)f(x, v, u)$ with (x, v) fixed, Lemma 1.4.26 implies that

$$|f_\delta - f_o|(u) \leq \begin{cases} (|\partial_u f|_\infty + 2)\delta & u \in [-v + \delta, -\delta], \\ 2 & u \in [-v - \delta, -v + \delta] \cup [-\delta, \delta], \\ \psi_\delta * \mathbb{1}_{[-v, 0]}(u) & u \in [-v - \delta, \delta]^c. \end{cases}$$

By definition of $|K|$, the first term is less than $(|\partial_u f|_\infty + 2)\delta \mathbb{1}_{[-|K| + \delta, -\delta]}$. The third term equals

$$\begin{aligned} \mathbb{1}_{[-\infty, -v - \delta] \cup [\delta, \infty]} \psi_\delta * \mathbb{1}_{[-v, 0]}(u) &= \mathbb{1}_{[-\infty, -v - \delta] \cup [\delta, \infty]}(u) \int_{-v}^0 \psi_\delta(u - u_1) du_1 \\ &= \mathbb{1}_{[-\infty, -v - \delta] \cup [\delta, \infty]}(u) \int_u^{u+v} \psi_\delta(u_1) du_1. \end{aligned}$$

By definition and the above arguments, we have

$$\begin{aligned} E(|f_\delta - f_o|)(x, t) &= \sum_{n \geq 0} \int |f_\delta - f_o|(hgx, \sigma(h, gx), \sigma(g, x) - t) d\mu^{*n}(g) d\mu(h) \\ &\leq \sum_{n \geq 0} \int \left((|\partial_u f|_\infty + 2)\delta \mathbb{1}_{[-|K|, -\delta]}(\sigma(g, x) - t) + \right. \\ &\quad \left. + 2\mathbb{1}_{[-\sigma(h, gx) - \delta, -\sigma(h, gx) + \delta] \cup [-\delta, \delta]}(\sigma(g, x) - t) \right. \\ &\quad \left. + \mathbb{1}_{[-\infty, -\sigma(h, gx) - \delta] \cup [\delta, \infty]}(\sigma(g, x) - t) \int_{\sigma(g, x) - t}^{\sigma(hg, x) - t} \psi_\delta(u_1) du_1 \right) d\mu^{*n}(g) d\mu(h). \end{aligned}$$

By Lemma 1.4.9, the first term is controlled by $(|\partial_u f|_\infty + 2)\delta|K|$. The second term is less than $R(\mathbb{1}_{[-\delta, \delta]})(x, t)$. Due to Proposition 1.4.8, it is controlled by $6\delta(1/\sigma_\mu + C_\delta(1 + 2\delta)/t)$.

For the third term, we need to change the order of integration. Since $\sigma(g, x) - t > \delta$ or $\sigma(g, x) - t < -\sigma(h, gx) - \delta$, we have $u_1 \geq \sigma(g, x) - t > \delta$ or $u_1 \leq \sigma(hg, x) - t = \sigma(h, gx) + \sigma(g, x) - t \leq -\delta$. We integrate first with respect to u_1 , then the third term is less than

$$\int_{[-\infty, -\delta] \cup [\delta, \infty]} \psi_\delta(u_1) \sum_{n \geq 0} \mu \otimes \mu^{*n} \{ (h, g) | \sigma(hg, x) \geq u_1 + t, \sigma(g, x) \leq u_1 + t \} du_1.$$

By Lemma 1.4.21, the above quantity is less than $C \int_{[-\infty, -\delta] \cup [\delta, \infty]} \psi_\delta(u_1) du_1 \lesssim \delta$.

Therefore, we have

$$E(|f_\delta - f|)(x, t) = O_K(\delta + C_\delta/t) |f|_{Lip}.$$

The proof is complete. \square

Remark 1.4.27 (Minus case). *The lemmas in this part concern plus and minus. The another version we need is for $E_C^-(f)(x, t) = E(\mathbb{1}_{0 < u \leq -v} f)(x, t)$, the proofs are exactly the same.*

Proposition* 1.4.17. *Under the assumptions of Proposition 1.4.17, we have*

$$E_C^-(f)(x, t) = \int_X \int_G \int_0^{-\sigma(h, y)} f(hy, \sigma(h, y), u) du d\mu(h) d\nu(y) + O_K(\delta + O_\delta/t) |f|_{Lip}.$$

1.4.6 Residue process for the Cartan Projection

We consider the residue process for the cutoff of a function f on $X^2 \times \mathbb{R}^2$, where the cocycle is replaced by the Cartan projection. We will give a limit not only with gx , but also with $g^{-1}x'$.

As in the previous subsection, we can define a similar Lipschitz norm on the space of Lipschitz functions on $X^2 \times \mathbb{R}^2$, using the same name $|f|_{Lip}$. Define the operator from bounded Borel functions on $X^2 \times \mathbb{R}^2$ to functions on $X^2 \times \mathbb{R}$ by

$$E_P f(x', x, t) = \sum_{n \geq 0} \int_{\kappa(g) < t \leq \kappa(hg)} f((hg)^{-1}x', hgx, \kappa(hg) - \kappa(g), \kappa(g) - t) d\mu(h) d\mu^{*n}(g).$$

Proposition 1.4.28. *Let f be a continuous function on $X^2 \times \mathbb{R}^2$ with $|f|_{Lip}$ finite. Assume that the projection of $\text{supp} f$ on \mathbb{R}_v is contained in a compact set K . For all $\delta > 0$, $t > \max\{2(|K| + \delta), 20\}$ and x', x in X , we have*

$$E_P f(x', x, t) = \int_{X^2} \int_G \int_{-\sigma(h, y)}^0 f(y', hy, \sigma(h, y), u) du d\mu(h) d\nu(y) d\check{\nu}(y') + O_K(\delta + O_\delta/t) |f|_{Lip}, \quad (1.4.24)$$

where O_K does not depend on δ, f, t, x, x' , the integral $\int_{-\sigma(h, y)}^0 = 0$ if $\sigma(h, y) < 0$.

Proof. We introduce local notations here: for an element g in G and a continuous function f on $X^2 \times \mathbb{R}^2$, define $gf(x', x, v, u) = f(g^{-1}x', x, v, u)$. Let $f_{x'}(x, v, u) = f(x', x, v, u)$, which emphasizes that the first coordinate is fixed. Let $l = \lceil \epsilon_5 t / \sigma_\mu \rceil$, where $\epsilon_5 < 1/10$. We use the decomposition

$$h = g_{n+1}, g = (g_n, \dots, g_{l+1}), j = (g_l, \dots, g_1).$$

Recall that $N_t^+ = \bigcup_{n \geq 0} \{(g_{n+1}, g_n, \dots, g_1) \mid \kappa(g_{n+1} \cdots g_1) \geq t > \kappa(g_n \cdots g_1)\}$. Let $N_t^+(n) = N_t^+ \cap G^{\times(n+1)} = \{(g_{n+1}, \dots, g_1) \mid \kappa(gj) \leq t, \kappa(hgj) > t\}$. Let

$$T_n(x, t) = \{(g_{n+1}, \dots, g_1) \in G^{\times(n+1)} \mid \sigma(hg, jx) > t - \kappa(j), \sigma(g, jx) \leq t - \kappa(j)\},$$

and let $G_{\epsilon, l} = \{(g_l, \dots, g_1) \mid |\kappa(j) - l\sigma_\mu| \leq l\epsilon, d(x_{g_l \dots g_1}^M, x') \geq e^{-\epsilon l}\}$, as well as

$$T_{n, \epsilon} = \{(g_{n+1}, \dots, g_1) \in T_n \mid (g_l, \dots, g_1) \in G_{\epsilon, l}\}.$$

Step 1: Due to Corollary 1.2.9 and Corollary 1.2.11, the sum of the integrals $\int_{N_t^+(n)}$ for n ranging from $t/(\sigma_\mu + \epsilon) - 1$ to $t/(\sigma_\mu - \epsilon)$ is exponentially small in t . In other words, we have

$$\begin{aligned} & \left| \sum_{n=\lceil t/(\sigma_\mu + \epsilon) \rceil}^{\lfloor t/(\sigma_\mu - \epsilon) \rfloor} \int_{N_t^+(n)} f((hgj)^{-1}x', hgjx, \kappa(hgj) - \kappa(gj), \kappa(gj) - t) d\mu^{\otimes(n+1)} \right. \\ & \qquad \qquad \qquad \left. - E_P f(x', x, t) \right| = O_{\exp}(t) |f|_\infty \end{aligned} \quad (1.4.25)$$

The following lemma replaces the Cartan projection with the cocycle.

Lemma 1.4.29. *Under the same assumption as in Proposition 1.4.28, we have*

$$\begin{aligned} & \left| \sum_{n=\lceil t/(\sigma_\mu + \epsilon) \rceil}^{\lfloor t/(\sigma_\mu - \epsilon) \rfloor} \int_{N_t^+(n)} f((hgj)^{-1}x', hgjx, \kappa(hgj) - \kappa(gj), \kappa(gj) - t) d\mu^{\otimes(n+1)}(hgj) \right. \\ & \quad - \sum_{n=\lceil t/(\sigma_\mu + \epsilon) \rceil}^{\lfloor t/(\sigma_\mu - \epsilon) \rfloor} \int_{T_{n, \epsilon}} j f((hg)^{-1}x', hgjx, \sigma(h, gjx), \sigma(g, jx) - (t - \kappa(j))) d\mu^{\otimes(n+1)}(hgj) \left. \right| \\ & = O(\delta + O_\delta/t) |f|_{Lip}. \end{aligned} \quad (1.4.26)$$

This lemma will be proved later. We will decompose $T_{n, \epsilon}(x, t)$ to apply the residue process for the cocycle. The space $T_{n, \epsilon}(x, t)$ can be seen as a fibered space over $G_{\epsilon, l}$. When the first l elements are fixed, the elements (h, g) such that $hgj = (g_{n+1}, \dots, g_1) \in T_{n, \epsilon}(x, t)$, are the admitted elements in the residue process with cutoff, whose start point is jx and time is $t - \kappa(j)$. Since $(n - l)(\sigma_\mu + \epsilon) \leq t - \kappa(j)$ and $(n - l)(\sigma_\mu - \epsilon) \geq t - \kappa(j)$,

we can apply Principle 1 to this residue process. Integrating over $G_{\epsilon,l}$ implies that

$$\begin{aligned} & \left| \sum_{n=\lceil t/(\sigma_\mu+\epsilon) \rceil}^{\lfloor t/(\sigma_\mu-\epsilon) \rfloor} \int_{T_{n,\epsilon}} jf((hg)^{-1}x', hgjx, \sigma(h, gjx), \sigma(g, jx) - (t - \kappa(j))) d\mu^{\otimes(n+1)}(hgj) \right. \\ & \quad \left. - \int_{G_{\epsilon,l}} E_I jf(x', jx, t - \kappa(j)) d\mu^{\otimes l}(j) \right| = O_{\exp}(t) |f|_\infty. \end{aligned} \quad (1.4.27)$$

where

$$E_I f(x', x, t) = \sum_{n \geq 0} \int_{\sigma(g,x) < t \leq \sigma(hg,x)} f((hg)^{-1}x', hgx, \sigma(h, gx), \sigma(g, x) - t) d\mu(h) d\mu^{*n}(g).$$

The following inequality, whose proof relies on Lemma 1.4.23, will give a major term.

Lemma 1.4.30. *Under the same assumption as in Proposition 1.4.28, for all $j \in G_{\epsilon,l}$, we have*

$$|E_C f_{j^{-1}x'}(jx, t - \kappa(j)) - E_I jf(x', jx, t - \kappa(j))| \leq |f|_{Lip} O_{\exp}(l), \quad (1.4.28)$$

This lemma will be proved later. Integrating (1.4.28) over $G_{\epsilon,l}$, we obtain

$$\left| \int_{G_{\epsilon,l}} E_C f_{j^{-1}x'}(jx, t - \kappa(j)) - E_I jf(x', jx, t - \kappa(j)) d\mu^{\otimes l}(j) \right| \leq |f|_{Lip} O_{\exp}(t). \quad (1.4.29)$$

By (1.4.25)(1.4.26)(1.4.27), it suffices to compute the major term

$$\int_{G_{\epsilon,l}} E_C f_{j^{-1}x'}(jx, t - \kappa(j)) d\mu^{\otimes l}(j).$$

Step 2: Recall that $N_0, P(0)$ are the two operators defined by $N_0\varphi = \int \varphi d\nu$, $P(0)\varphi(x) = \int \varphi(gx) d\nu(g)$, where φ is a function in $\mathcal{H}^\gamma(X)$. We have another property of transfer operators [BQ16, Lemma 11.18]: The spectral radius of $P = P(0)$ restricted to $\ker N_0$ is less than 1, which means that there exist $\rho < 1, C > 0$ such that for every function φ in $\mathcal{H}^\gamma(X)$, we have

$$|P^n \varphi - \int \varphi d\nu|_\infty \leq C \rho^n |\varphi|_\gamma.$$

Thus by $\mu^{\otimes l} G_{\epsilon,l} = O_{\exp}(l)$, we have

$$\left| \int_{G_{\epsilon,l}} \varphi(j^{-1}x) d\mu^{\otimes l} - \int \varphi d\check{\nu} \right| = \left| \int_{G^{\times l}} \varphi(j^{-1}x) d\mu^{\otimes l}(j) - \int \varphi d\check{\nu} \right| + O_{\exp}(l) |\varphi|_\infty = O_{\exp}(l) |\varphi|_{Lip}. \quad (1.4.30)$$

By the definition of $|\cdot|_{Lip}$ on $X \times \mathbb{R}^2$, the function $f_{j^{-1}x'}(x, v, u)$ has a finite $|\cdot|_{Lip}$ value. Together with $t - \kappa(j) \geq t/2 \geq |K| + \delta$, Proposition 1.4.17 implies that

$$\begin{aligned} & \int_{G_{\epsilon,l}} E_C f_{j^{-1}x'}(jx, t - \kappa(j)) d\mu^{\otimes}(j) \\ &= \int_{G_{\epsilon,l}} \left(\int_X \int_G \int_{-\sigma(h,y)}^0 f_{j^{-1}x'}(y, \sigma(h, y), u) du d\mu(h) d\nu(y) d\mu^{\otimes l}(j) + O_K(\delta + O_\delta/t) |f_{j^{-1}x'}|_{Lip} \right) \\ &= \int_X \int_G \int_{-\sigma(h,y)}^0 \int_{G_{\epsilon,l}} f(j^{-1}x', y, \sigma(h, y), u) d\mu^{\otimes l}(j) du d\mu(h) d\nu(y) + O_K(\delta + O_\delta/t) |f|_{Lip}. \end{aligned} \quad (1.4.31)$$

With (x, v, u) fixed, $f(x', x, v, u)$ is a Lipschitz function on x' , so it is a Hölder function. Together with Lemma 1.4.21 and inequality (1.4.30), we have

$$\begin{aligned} & \int_{G_{\epsilon,l}} E_C f_{j^{-1}x'}(jx, t - \kappa(j)) d\mu^{\otimes}(j) \\ &= \int_X \int_G \int_{-\sigma(h,y)}^0 \int_X f(u, \sigma(h, y), y, y') d\check{\nu}(y') du d\mu(h) d\nu(y) + (O_{\exp}(l) + O_K(\delta + O_\delta/t)) |f|_{Lip}. \end{aligned} \quad (1.4.32)$$

The result follows. \square

It remains to prove Lemma 1.4.29 and Lemma 1.4.30.

Proof of Lemma 1.4.29. There exist $S_{n+1,l,x} \subset G^{\times(n+1)}$ and $S_{n,l,x} \subset G^{\times n}$ which satisfy the conditions in Lemma 1.2.14. Let $S_n(x) = S_{n+1,l,x} \cap (G \times S_{n,l,x})$. Then

$$\mu^{\otimes(n+1)} S_n(x)^c = O_{\exp}(l), \quad (1.4.33)$$

and for (g_{n+1}, \dots, g_1) in $S_n(x)$, we have

$$\begin{aligned} |\kappa(hgj) - \sigma(hg, jx) - \kappa(j)| &\leq e^{-\epsilon l} \\ |\kappa(gj) - \sigma(g, jx) - \kappa(j)| &\leq e^{-\epsilon l}. \end{aligned}$$

In $N_t^+(n) \cap S_n(x) \cap T_n(x, t)$, we can replace the Cartan projection by the cocycle with exponentially small error. Fortunately, the difference of this set with $N_t^+(n)$ and $T_n(x, t)$ has exponentially small measure. By definition, we have

$$N_t^+(n) \cap S_n(x) \subset \{\sigma(hg, jx) > t - e^{-l\epsilon} - \kappa(j), \sigma(g, jx) \leq t + e^{-l\epsilon} - \kappa(j)\},$$

and

$$N_t^+(n) \supset \{\sigma(hg, jx) > t + e^{-l\epsilon} - \kappa(j), \sigma(g, jx) \leq t - e^{-l\epsilon} - \kappa(j)\} \cap S_n(x).$$

Therefore

$$(N_t^+(n) \cap S_n(x) - T_n(x, t)) \subset \{\sigma(hg, jx) \in [-e^{-\epsilon l}, 0] + t - \kappa(j)\} \\ \cup \{\sigma(g, jx) \in [0, e^{-\epsilon l}] + t - \kappa(j)\},$$

and

$$(T_n(x, t) \cap S_n(x) - N_t^+(n)) \subset \{\sigma(hg, jx) \in [0, e^{-\epsilon l}] + t - \kappa(j)\} \\ \cup \{\sigma(g, jx) \in [-e^{-\epsilon l}, 0] + t - \kappa(j)\}.$$

Hence, these imply that

$$\mu^{\otimes(n+1)}(N_t^+(n) - N_t^+(n) \cap S_n(x) \cap T_n(x, t)) \leq \mu^{\otimes(n+1)} S_n(x)^c \\ + \mu^{\otimes(n+1)}(N_t^+(n) \cap S_n(x) - T_n(x, t)) \\ \leq O_{\text{exp}}(l) + \mu^{\otimes(n+1)}\{\sigma(hg, jx) \in [-e^{-\epsilon l}, 0] + t - \kappa(j)\} \cup \{\sigma(g, jx) \in [0, e^{-\epsilon l}] + t - \kappa(j)\}.$$

and

$$\mu^{\otimes(n+1)}(T_n(x, t) - N_t^+(n) \cap S_n(x) \cap T_n(x, t)) \leq \mu^{\otimes(n+1)} S_n(x)^c \\ + \mu^{\otimes(n+1)}(T_n(x, t) \cap S_n(x) - N_t^+(n)) \\ \leq O_{\text{exp}}(l) + \mu^{\otimes(n+1)}\{\sigma(hg, jx) \in [0, e^{-\epsilon l}] + t - \kappa(j)\} \cup \{\sigma(g, jx) \in [-e^{-\epsilon l}, 0] + t - \kappa(j)\}.$$

Moreover, for (g_{n+1}, \dots, g_1) in the set $N_t^+(n) \cap S_n(x) \cap T_n(x, t)$, the definition of $S_n(x)$ implies that

$$|f((hgj)^{-1}x', hgjx, \kappa(hgj) - \kappa(gj), \kappa(gj) - t) \\ - jf((hg)^{-1}x', hgjx, \sigma(h, gjx), \sigma(g, jx) - (t - \kappa(j)))| \leq e^{-\gamma t \epsilon} |f|_{Lip}. \quad (1.4.34)$$

Thus, for $n \in [t/(\sigma_\mu + \epsilon) - 1, t/(\sigma_\mu - \epsilon)]$, we have

$$|\int_{N_t^+(n)} f((hgj)^{-1}x', hgjx, \kappa(hgj) - \kappa(gj), \kappa(gj) - t) d\mu^{\otimes(n+1)} \\ - \int_{T_n(x, t)} jf((hg)^{-1}x', hgjx, \sigma(h, gjx), \sigma(g, jx) - (t - \kappa(j))) d\mu^{\otimes(n+1)}| \\ \leq \mu^{\otimes}(N_t^+(n) - N_t^+(n) \cap S_n(x) \cap T_n(x, t)) \cup (T_n(x, t) - N_t^+(n) \cap S_n(x) \cap T_n(x, t)) \\ + \mu^{\times(n+1)} N_t^+(n) \cap S_n(x) \cap T_n(x, t) O_{\text{exp}}(l) |f|_{Lip} \\ \leq (O_{\text{exp}}(l) + \mu^{\otimes(n+1)}\{|\sigma(hg, jx) - t + \kappa(j)|, |\sigma(g, jx) - t + \kappa(j)| \leq e^{-l\epsilon}\}) |f|_\infty + O_{\text{exp}}(l) |f|_{Lip}.$$

Sum up over all $n \in [t/(\sigma_\mu + \epsilon) - 1, t/(\sigma_\mu - \epsilon)]$. Then the above inequality becomes

$$\begin{aligned} & \left| \sum_{n=[t/(\sigma_\mu+\epsilon)]}^{[t/(\sigma_\mu-\epsilon)]} \int_{N_t^+(n)} f((hgj)^{-1}x', hgjx, \kappa(hgj) - \kappa(gj), \kappa(gj) - t) d\mu^{\otimes(n+1)}(hgj) \right| \\ & - \sum_{n=[t/(\sigma_\mu+\epsilon)]}^{[t/(\sigma_\mu-\epsilon)]} \int_{T_n} jf((hg)^{-1}x', hgjx, \sigma(h, gjx), \sigma(g, jx) - (t - \kappa(j))) d\mu^{\otimes(n+1)}(hgj) \\ & \leq tO_{\exp}(l) |f|_{Lip} + |f|_\infty \int_{G^{\times l}} 2R(\mathbb{1}_{[-e^{-\epsilon l}, e^{-\epsilon l}]})(jx, t - \kappa(j)) d\mu^{\otimes l}(j). \end{aligned} \quad (1.4.35)$$

By (1.2.9), (1.2.12), we have $\mu^{\otimes l} G_{\epsilon, l} \geq 1 - O_{\exp}(l)$. Thus combined with Lemma 1.4.21, we get

$$\sum_{n \geq l} \mu^{\otimes(n+1)}(T_n(x, t) - T_{n, \epsilon}(x, t)) = \int_{G_{\epsilon, l}^c} E\mathbb{1}(jx, t - \kappa(j)) d\mu^{\otimes l}(j) = O_{\exp}(l).$$

This enables us to replace the integration domain T_n by $T_{n, \epsilon}$ with exponentially small error. It is sufficient to control the right hand side of (1.4.35).

The last term can be bounded by the similar argument as in (1.4.12), with Proposition 1.4.10 replaced by inequality (1.4.6). It follows that

$$\int_{G^{\times l}} 2R(\mathbb{1}_{[-e^{-\epsilon l}, e^{-\epsilon l}]})(jx, t - \kappa(j)) d\mu^{\otimes l}(j) = O_{\exp}(l) + \delta O(1 + O_\delta/t). \quad (1.4.36)$$

The proof is complete. \square

Proof of Lemma 1.4.30. We want to replace $(hgj)^{-1}x'$ with $(j)^{-1}x'$ in the first coordinate in order to find the residue process with cutoff. The idea is always similar. We have a good approximation in a large set, whose complement has exponentially small measure. Let

$$\Sigma_l = \bigcup_{n \geq 0} \{(h, g) \in G \times G^{\times n} \mid \sigma(g, jx) < t - \kappa(j) \leq \sigma(hg, jx), d((hg)^{-1}x', x_j^M) \leq e^{-\epsilon l}\}.$$

Since $t - \kappa(j) \geq t - (\sigma_\mu + \epsilon)l \geq 10\epsilon l$ and $t - \kappa(j) \geq t/2 > 10$, we can use Lemma 1.4.23 with $s = \epsilon l$ and jx, x', x_j^M to obtain

$$\mu \otimes \bar{\mu} \Sigma_l = O_{\exp}(l). \quad (1.4.37)$$

The definition of $G_{\epsilon, l}$ implies that $d(x_j^M, x') \geq e^{-\epsilon l}$ and $\kappa(j) \geq (\sigma_\mu - \epsilon)l$. It follows from (1.2.4) that $x_j^M = x_{j-1}^m$. Together with (1.2.1), (1.2.5), for (h, g) outside of the set Σ_l , we have

$$\begin{aligned} & d((hgj)^{-1}x', j^{-1}x') = d(j^{-1}(hg)^{-1}x', j^{-1}x') \\ & \leq \exp(-2\kappa(j^{-1}) - \log d(x_{j-1}^m, x') - \log d(x_{j-1}^m, (hg)^{-1}x')) \leq \exp(-2(\sigma_\mu - \epsilon)l + 2\epsilon l). \end{aligned}$$

Therefore

$$|f(j^{-1}x', x, v, u) - f((hgj)^{-1}x', x, v, u)| \leq |f|_{Lip} d(j^{-1}x', (hgj)^{-1}x') = |f|_{Lip} O_{\exp}(l). \quad (1.4.38)$$

In the bad part Σ_l , we use inequality (1.4.37) to control. Outside of Σ_l , we apply inequality (1.4.38). Thus we have

$$\begin{aligned} & \left| \sum_{n \geq 0} \int_{\sigma(hg, jx) > t - \kappa(j) \geq \sigma(g, jx)} f(j^{-1}x', hg, jx, \sigma(h, gx), \sigma(g, jx) + \kappa(j) - t) \right. \\ & \quad \left. - f((hgj)^{-1}x', hg, jx, \sigma(h, gx), \sigma(g, jx) + \kappa(j) - t) d\mu(h) d\mu^{*n}(g) \right| \\ & \leq |f|_{Lip} (O_{\exp}(l) + O_{\exp}(l) E_C \mathbb{1}(jx, t - \kappa(j))). \end{aligned}$$

Then by Lemma 1.4.21, the proof is complete. \square

Remark 1.4.31 (Minus case). *Let*

$$E_{\bar{P}}^- f(x', x, t) = \sum_{n \geq 0} \int_{\kappa(g) \geq t > \kappa(hg)} f((hg)^{-1}x', hg, x, \kappa(hg) - \kappa(g), \kappa(g) - t) d\mu(h) d\mu^{*n}(g).$$

Then by the same proof, we have

Proposition* 1.4.28. *Under the assumptions of Proposition 1.4.28, we have*

$$E_{\bar{P}}^- f(x', x, t) = \int_{X^2} \int_G \int_0^{-\sigma(h, y)} f(y', hy, \sigma(h, y), u) du d\mu(h) d\nu(y) d\bar{\nu}(y') + O_K(\delta + O_\delta/t) |f|_{Lip}.$$

1.5 Main Approximation

In this section, we want to complete the proof in Section 1.3. It remains to prove Proposition 1.3.6 and the following Lemma 1.5.2 and Corollary 1.5.5.

Recall the definitions in Section 1.3: Let μ be a Borel probability measure on $\mathrm{SL}_2(\mathbb{R})$ with a finite exponential moment, and assume that the subgroup Γ_μ is Zariski dense. Let $\Sigma = \bigcup_{n \in \mathbb{N}} G^{\times n}$ be the symbol space of all finite sequences with elements in G . Let $\bar{\mu}$ be the measure on Σ defined by

$$\bar{\mu} = \sum_{n=0}^{+\infty} \mu^{\otimes n}, \quad \text{where } \mu^{\otimes 0} = \delta_\emptyset.$$

Let the integer $\omega(g)$ be the length of an element g in Σ . Let T be the shift map on Σ , defined by $Tg = T(g_1, g_2, \dots, g_\omega) = (g_1, g_2, \dots, g_{\omega-1})$, when $\omega(g) \geq 2$, and $Tg = \emptyset$, when $\omega(g) = 1, 0$. Let L be the left shift map on Σ , defined by $Lg = L(g_1, g_2, \dots, g_\omega) = (g_2, \dots, g_{\omega-1}, g_\omega)$, when $\omega(g) \geq 2$, and $Lg = \emptyset$, when $\omega(g) = 1, 0$.

The sets M_t^+, N_t^+ are defined by

$$\begin{aligned} M_t^+ &= \{g \in \Sigma \mid \kappa(Tg) < t \leq \kappa(g)\}, \\ N_t^+ &= \iota(M_t^+) = \{g \in \Sigma \mid \kappa(Lg) < t \leq \kappa(g)\}, \end{aligned}$$

where $\iota(M)$ equals $\{g^{-1}|g \in M\}$ for any subset M of Σ .

Let $\check{\mu}$ be the pushforward of μ by the inverse action. It also satisfies the assumptions of Theorem 1.1.1. By definition $\bar{\mu}(M_t^+) = \check{\mu}(N_t^+)$.

For x, y in X , write $s_1 = \epsilon_3 s$ and

$$M_t^+(x, y) = \{g \in M_t^+ \mid |\kappa(g) - \kappa(Tg)| < s_1, d(x_g^m, g^{-1}x) < e^{-t}, d(g^{-1}x, x), d(g^{-1}x, y) > 2e^{-s_1}\}.$$

We need some regularity properties of N_t^+ . These lemmas are of the same type as the ones with the cocycle, using the Cartan projection instead. The correspondences are: Lemma 1.5.1 with Lemma 1.4.20, Lemma 1.5.2 with Lemma 1.4.21, Lemma 1.5.3 with Lemma 1.4.22. In fact, for all the regularity properties, there are similar versions for the Cartan projection. The subadditivity is sufficient. We follow the same procedure as in the proof for the cocycle.

Lemma 1.5.1. *For s in \mathbb{R} , we have*

$$\bar{\mu}\{g \in N_t^+ \mid |\kappa(g) - \kappa(Lg)| > s\} = O_{\exp}(s). \quad (1.5.1)$$

Proof. Subadditivity of Cartan projection implies $\kappa(g_\omega) \geq |\kappa(g_\omega \cdots g_1) - \kappa(g_{\omega-1} \cdots g_1)| = |\kappa(g) - \kappa(Lg)| > s$ and $\kappa(Lg) \geq \kappa(g) - \kappa(g_\omega)$. Then

$$\begin{aligned} & \bar{\mu}\{g \in N_t^+ \mid |\kappa(g) - \kappa(Lg)| > s\} \\ &= \sum_{n \geq 0} \mu \otimes \mu^{*n} \{(h, g) \in G \times G \mid \kappa(g) < t \leq \kappa(hg), |\kappa(hg) - \kappa(g)| > s\} \\ &\leq \sum_{n \geq 0} \mu \otimes \mu^{*n} \{(h, g) \in G \times G \mid t - \kappa(h) \leq \kappa(g) < t, \kappa(h) > s\} \\ &= \int_{\kappa(h) > s} R_p(\mathbb{1}_{[-\kappa(h), 0]})(t) d\mu(h). \end{aligned}$$

By Lemma 1.4.12 and finite exponential moment, we have

$$\bar{\mu}\{g \in N_t^+ \mid |\kappa(g) - \kappa(Lg)| > s\} \lesssim \int_{\kappa(h) > s} \max\{1, \kappa(h)^2\} d\mu(h) = O_{\exp}(s).$$

The proof is complete. □

A special case is when $s = 0$. Applying the above lemma with $\check{\mu}$, we have

Lemma 1.5.2. *The measure $\bar{\mu}(M_t^+) = \check{\mu}(N_t^+)$ is uniformly bounded with t .*

The following lemma quantifies the independence of the scalar part and the angle part of residue process for the Cartan projection.

Lemma 1.5.3. *For $s > 0$, $t > 10s$ and $x, x_o \in X$, we have*

$$\bar{\mu}\{g \in N_t^+ \mid d(x_g^M, gx) \geq e^{-t}\} = O_{\exp}(t), \quad (1.5.2)$$

$$\bar{\mu}\{g \in N_t^+ \mid d(gx_o, x) \leq e^{-s}\} = O_{\exp}(s). \quad (1.5.3)$$

The proof of the second inequality follows the same procedure as in the proof of Lemma 1.4.22, replacing Lemma 1.4.20 and Proposition 1.4.10 with Lemma 1.5.1 and Lemma 1.4.11. The first inequality is standard, using Principle 1 and Principle 2. When $n \in [\frac{t}{\sigma_\mu + \epsilon} - 1, \frac{t}{\sigma_\mu - \epsilon}]$, use Corollary 1.2.13, and when n is outside of this interval, use Corollary 1.2.9 and Corollary 1.2.11.

Joining Lemma 1.5.1 and Lemma 1.5.3, we have the following corollary

Corollary 1.5.4. *Let $s > 0$, $t > 10s$ and let x, y be in X . Let*

$$N_t^+(x, y) = \{g \in N_t^+ \mid |\kappa(g) - \kappa(Lg)| < s, d(x_g^M, gx) < e^{-t}, d(gx, x), d(gx, y) > 2e^{-s}\}. \quad (1.5.4)$$

Then we have

$$\bar{\mu}(N_t^+) - \bar{\mu}(N_t^+(x, y)) = O_{\exp}(s). \quad (1.5.5)$$

Corollary 1.5.5. *For $s > 0$, $t > 10s$ and x, y in X , we have*

$$\bar{\mu}(M_t^+) - \bar{\mu}(M_t^+(x, y)) = O_{\exp}(s).$$

Proof. By definition, we have

$$\bar{\mu}(M_t^+) - \bar{\mu}(M_t^+(x, y)) = \bar{\check{\mu}}(N_t^+) - \bar{\check{\mu}}(N_t^+(x, y)).$$

Applying the above corollary with $\bar{\check{\mu}}$, we have completed the proof. \square

We start to proof Proposition 1.3.6. The central tool here is Lemma 1.2.7, which enables us to replace the cocycle with the sum of the scalar part and the angle part.

Proof of Proposition 1.3.6. We first replace the distance with the cocycle. By hypothesis, we have

$$d(x_g^m, x) \geq d(g^{-1}x, x) - d(x_g^m, g^{-1}x) \geq 2e^{-s_1} - e^{-t} \geq e^{-s_1}.$$

Using the same argument, we have $d(x_g^m, y), d(x_g^m, x) \geq e^{-s_1}$. Then (1.2.1) and (1.2.5) imply

$$d(gx, gy) = d(x, y) \exp(-\sigma(g, x) - \sigma(g, y)) \leq \frac{\exp(-2\kappa(g))}{d(x_g^m, x)d(x_g^m, y)} \leq e^{-2(t-s_1)}.$$

Applying the Newton-Leibniz formula (1.2.17) to ϕ at gx, gy , we have

$$\phi(gx) - \phi(gy) = \text{sign}(gx, gy) \int_{gx \frown gy} \phi'(\theta) d\theta.$$

Since $\kappa(g) > t > s_1$, we have $d(x_g^m, x) \geq e^{-s_1} \geq e^{-\kappa(g)}$. Then (1.2.18) implies that

$$\phi(gx) - \phi(gy) = \text{sign}(x, y, x_g^m) \int_{gx \frown gy} \phi'(\theta) d\theta.$$

We need the arc length distance $d_a(\cdot, \cdot)$ on $\mathbb{R}/\pi\mathbb{Z}$. Since $d(gx, gy) \leq e^{-2(t-s_1)}$, for θ in the small arc $gx \frown gy$, we have $d_a(\theta, gx) \leq e^{-2(t-s_1)}$. Therefore

$$|\phi(gx) - \phi(gy) - \mathrm{sign}(x, y, x_g^m)\phi'(gx)d_a(gx, gy)| \leq |\phi''|_\infty e^{-4(t-s_1)}. \quad (1.5.6)$$

By equality $\sin d_a(gx, gy) = d(gx, gy)$, we have

$$|d_a(gx, gy) - d(gx, gy)| = O(d(gx, gy)^3).$$

So we can replace the arc length distance with the sine distance. Again by hypothesis, we have $d(x_g^m, g^{-1}x) \leq e^{-t} < d(g^{-1}x, x), d(g^{-1}x, y)$. When changing x_g^m to $g^{-1}x$, the relative place with respect to x, y does not change, therefore we get

$$\mathrm{sign}(x, y, x_g^m) = \mathrm{sign}(x, y, g^{-1}x).$$

Inequality (1.2.1), together with the above two inequalities, implies

$$|\phi(gx) - \phi(gy) - \mathrm{sign}(x, y, g^{-1}x)\phi'(gx)d(x, y) \exp(-\sigma(g, x) - \sigma(g, y))| \leq |\phi''|_\infty 2e^{-4(t-s_1)}. \quad (1.5.7)$$

We may now replace the cocycle with the Cartan projection and the angle part. Since

$$\frac{e^{-2\kappa(g)} + d(x_g^m, g^{-1}x)}{d(g^{-1}x, x)} \leq 2e^{-t+s_1} < 1/2,$$

Lemma 1.2.7 implies that

$$\begin{aligned} |\sigma(g, x) - \kappa(g) - \log d(g^{-1}x, x)| &\leq 2 \frac{e^{-2\kappa(g)} + d(x_g^m, g^{-1}x)}{d(g^{-1}x, x)} \leq 4e^{-t+s_1}, \\ |\sigma(g, y) - \kappa(g) - \log d(g^{-1}x, y)| &\leq 2 \frac{e^{-2\kappa(g)} + d(x_g^m, g^{-1}x)}{d(g^{-1}x, y)} \leq 4e^{-t+s_1}. \end{aligned}$$

We have an inequality for z_1, z_2 in \mathbb{C} ,

$$|e^{z_1} - e^{z_2}| \leq \max\{e^{\Re z_1}, e^{\Re z_2}\}|z_1 - z_2|.$$

Since $\sigma(g, x) \geq \kappa(g) + \log d(x_g^m, x) \geq t - s_1$ and $\kappa(g) + \log d(g^{-1}x, x) \geq t - s_1$, we have

$$|\exp(-\sigma(g, x)) - \exp(-\kappa(g))/d(g^{-1}x, x)| \leq e^{-t+s_1} 4e^{-t+s_1}.$$

Therefore by inequality $|a_1a_2 - b_1b_2| \leq |(a_1 - b_1)a_2| + |(a_2 - b_2)b_1|$, we have

$$|e^{-\sigma(g, x) - \sigma(g, y)} - e^{-2\kappa(g)}/(d(g^{-1}x, x)d(g^{-1}x, y))| \leq 8e^{-3(t-s_1)}.$$

Then by the hypothesis $|\xi| = e^{2t+s}$ and (1.5.7), we have

$$\begin{aligned} &\left| e^{i\xi(\phi(gx) - \phi(gy))} - e^{i\xi\phi'(gx)\mathrm{sign}(x, y, g^{-1}x)d(x, y) \exp(-2\kappa(g))/(d(g^{-1}x, x)d(g^{-1}x, y))} \right| \\ &\leq |\xi| |\phi(gx) - \phi(gy) - \phi'(gx)\mathrm{sign}(x, y, g^{-1}x)d(x, y) \exp(-2\kappa(g))/(d(g^{-1}x, x)d(g^{-1}x, y))| \\ &\leq |\xi| (|\phi''|_\infty 2e^{-4(t-s_1)} + |\xi| |\phi' d(x, y)| |e^{-\sigma(g, x) - \sigma(g, y)} - e^{-2\kappa(g)}/(d(g^{-1}x, x)d(g^{-1}x, y))|) \\ &\leq |\xi| (|\phi''|_\infty 2e^{-4(t-s_1)} + 8|\phi'|_\infty e^{-3(t-s_1)}) \leq 8(|\phi''|_\infty + |\phi'|_\infty) e^{-t+s+3s_1}. \end{aligned}$$

Finally, for $|\Lambda_0 - \Lambda|$, it suffices to add the difference

$$|r(gx)r(gy) - r(gx)^2| \leq |r|_\infty |r'|_\infty e^{-2(t-s_1)}.$$

Then

$$|\Lambda_0 - \Lambda| \leq |r|_\infty |r'|_\infty e^{-2(t-s_1)} + |r|_\infty^2 (|\phi''|_\infty + |\phi'|_\infty) e^{-t+s+3s_1} = O_{\text{exp}}(s),$$

where $O_{\text{exp}}(s)$ does not depend on t , but depends on r, ϕ . The proof is complete. \square

Remark 1.5.6 (Minus case). *The proof works the same for M_t^- .*

Chapter 2

Fourier dimension and spectral gaps for random walks on $SL_{m+1}(\mathbb{R})$

List of Abbreviations and Symbols in Chapter 2

χ^\sharp	78
$\delta(\eta, \zeta)$	82
$\delta(x, y)$	79
$\delta_\alpha(\eta, \zeta)$	132
η_g^M	76
$\gamma_{1,2}(g)$	79
$\gamma(g)$	83
ν_V	69
\mathcal{P}_0	84
$\partial_\alpha \varphi$	90
$m(g, g')$	87
$\sigma_{V,\mu}$	70
ζ_g^m	76
$B_g^m(r)$	82
$b_g^M(r)$	82
$B_{V,g}^m(r)$	79
$b_{V,g}^M(r)$	79
$C^\gamma(X)$	69
c_γ	69
$d(\eta, \eta')$	82
$d(x, x')$	79
$d_0(k, k')$	139
$d_\alpha(\eta, \eta')$	82
$d_A(z_1, z_2)$	90
P_z	71
q_λ	99

Rf	.....	70
$V_{\alpha,\eta}$	.....	82
$V_{\chi,\eta}$	.....	76
x_g^M	.....	79
y_g^m	.....	79

2.1 Introduction

The purpose of this manuscript is to study the Fourier decay of stationary measures on projective spaces and some spectral properties of random walks on $G = \mathrm{SL}_{m+1}(\mathbb{R})$, the special linear group of degree $m+1$. Let μ be a Borel probability measure on G . Let Γ_μ be the subsemigroup of G generated by the support of μ . If Γ_μ is Zariski dense in G , then we call μ a Zariski dense measure. We say that μ has a finite exponential moment if there exists $\epsilon > 0$ such that

$$\int_G \|g\|^\epsilon d\mu(g) < \infty.$$

If we have a group action of G on a compact manifold X , then a Borel probability measure ν on X is called μ -stationary if $\nu = \mu * \nu$, which means

$$\nu = \int_G g_* \nu d\mu(g)$$

and where $g_* \nu$ is the pushforward measure, that is $g_* \nu(E) = \nu(g^{-1}E)$ for any Borel subset E of X . For a metric space X , let $C^\gamma(X)$ be the space of γ -Hölder functions on X . For f in $C^\gamma(X)$ let $c_\gamma(f) = \sup_{x \neq x'} \frac{|f(x) - f(x')|}{d(x, x')^\gamma}$ and $|f|_\gamma = |f|_\infty + c_\gamma(f)$.

Let (ρ, V) be a finite dimensional irreducible linear representation of G with a norm. (For example $V = \mathbb{R}^{m+1}$) Let $\mathbb{P}V$ be the real projective space defined by $(V \setminus \{0\})/\mathbb{R}^*$, the set of all the directions in V . Then we have the group action of G on $\mathbb{P}V$, given by $g\mathbb{R}v = \mathbb{R}\rho(g)v$ for g in G and $\mathbb{R}v$ in $\mathbb{P}V$. A result of Furstenberg says that when μ is Zariski dense, there exists a unique μ -stationary measure ν_V on $\mathbb{P}V$.

Let v_0 be a unit vector in V . Let v_0^\perp be the linear subspace of V , which is orthogonal to v_0 . Let U be the open subset of $\mathbb{P}V$, which is the complement of the hyperplane $\mathbb{P}v_0^\perp$. We take an affine local chart (ψ, U) of $\mathbb{P}V$, given by

$$\psi: \mathbb{P}V \supset U \rightarrow v_0^\perp, \mathbb{R}v \mapsto \frac{v - \langle v_0, v \rangle v_0}{\langle v_0, v \rangle},$$

which is well defined on U . The inverse of ψ is simply given by $\psi^{-1}: v_0^\perp \rightarrow U \subset \mathbb{P}V$, $u \mapsto \mathbb{R}(u + v_0)$.

Theorem 2.1.1. *Let μ be a Zariski dense Borel probability measure on $\mathrm{SL}_{m+1}(\mathbb{R})$ with a finite exponential moment. Let V be an irreducible representation of $\mathrm{SL}_{m+1}(\mathbb{R})$. Let ν_V be the μ -stationary measure on $\mathbb{P}V$. Let r be a C^1 continuous function whose support is in U and $\|r\|_\infty \leq 1$. Then there exists $\epsilon > 0$ such that for every $\varsigma \in v_0^\perp$ with the norm $\|\varsigma\|$ sufficiently large, we have*

$$\left| \int_{v_0^\perp} e^{i\langle \varsigma, u \rangle} r(u) d\nu_V(u) \right| \leq \|\varsigma\|^{-\epsilon}.$$

Remark. *For simplicity, we use the same notation ν_V for the measure on $\mathbb{P}V$ and the measure on v_0^\perp . More precisely, the integral actually means $\int_{\mathbb{P}V} e^{i\langle \varsigma, \psi(x) \rangle} r(\psi(x)) d\nu_V(x)$.*

The constant ϵ only depends on μ and V , and inequality holds for $\|\varsigma\|$ sufficiently large only depending on μ , V , the support of r and $c_\gamma(r)$.

We state a stronger version for $m = 1$, $\mathrm{SL}_2(\mathbb{R})$, which is a quantitative version of the main result in Chapter 1

Theorem 2.1.2. *Let μ be a Zariski dense Borel probability measure on $\mathrm{SL}_2(\mathbb{R})$ with a finite exponential moment. Let $X = \mathbb{P}(\mathbb{R}^2)$ and let ν be the μ -stationary measure on X .*

For every $\gamma > 0$, there exist $\epsilon_0 > 0, \epsilon_1 > 0$ depending on μ such that the following holds. For any $f \in C^2(X)$, $r \in C^\gamma(X)$ such that $|\varphi'| \geq |\xi|^{-\epsilon_0}$ on the support of r , $\|r\|_\infty \leq 1$ and

$$\|\varphi\|_{C^2} + c_\gamma(r) \leq |\xi|^{\epsilon_0},$$

then

$$\left| \int e^{i\xi\varphi(x)} r(x) d\nu(x) \right| \leq |\xi|^{-\epsilon_1} \quad \text{for all } |\xi| \text{ large enough.}$$

Remark 2.1.3. *As a consequence of the case of $\mathrm{SL}_2(\mathbb{R})$, the Fourier coefficients of the stationary measure ν on the circle converge to zero with a power decay. This is also a generalization of the same theorem for the Patterson-Sullivan measures as in [BD17].*

This stronger version is not valid if we replace \mathbb{R}^2 by higher dimensional representation V of $\mathrm{SL}_2(\mathbb{R})$. Because the support of the stationary measure ν_V is in a one dimensional subvariety of $\mathbb{P}V$. We can always find a φ which is constant on the subvariety and satisfies similar assumptions in Theorem 2.1.2. Then we have no Fourier decay for this function φ .

Another result is an exponential remainder term in the renewal theorem. Define the renewal operator R as follows. For a positive bounded Borel function f on $\mathbb{P}V \times \mathbb{R}$, a point $x = \mathbb{R}v$ in $\mathbb{P}V$ and a real number t , we set

$$Rf(x, t) = \sum_{n=0}^{+\infty} \int_G f(gx, \log \frac{\|gv\|}{\|v\|} - t) d\mu^{*n}(g).$$

Here $\log \frac{\|gv\|}{\|v\|}$ is an analogue of the sum of i.i.d. real random variables. Because of the positivity of f , this sum is well defined. In [Kes74], Kesten proved a renewal theorem for Markov chains, which is valid in our case. The assumptions of [Kes74] were verified in [GLP16]. Using spectral gap, more precisely by Proposition 2.4.22, we can give a version with exponential remainder term. Let $\sigma_{V,\mu}$ be the Lyapunov constant defined by

$$\sigma_{V,\mu} = \int_G \int_{\mathbb{P}V} \log \frac{\|gv\|}{\|v\|} d\nu(x) d\mu(g), \quad \text{where } x = \mathbb{P}v.$$

Theorem 2.1.4 (Renewal theorem). *Let μ be a Zariski dense Borel probability measure on $\mathrm{SL}_{m+1}(\mathbb{R})$ with finite exponential moment. Let V be an irreducible representation of $\mathrm{SL}_{m+1}(\mathbb{R})$. There exists $\epsilon > 0$ such that for $f \in C_c^\infty(\mathbb{R})$ and $t \in \mathbb{R}$, we have*

$$Rf(x, t) = \frac{1}{\sigma_{V,\mu}} \int_{-t}^{\infty} f(u) d\mathrm{Leb}(u) + O_f(e^{-\epsilon|t|}),$$

where O_f depends on the support and some Sobolev norm of f .

It is a standard Fourier analysis argument which follows from the spectral gap. We give a proof in Section 2.4.5 for completeness.

Now, we will introduce our results on spectral gaps. On $\mathbb{P}V$, we fix a Riemannian distance and we define the transfer operator.

Definition. For $z \in \mathbb{C}$ with $|\Re z|$ small enough, let P_z be the operator on the space of continuous functions, which is given by

$$P_z f(x) = \int_G e^{z \log \frac{\|gv\|}{\|v\|}} f(gx) d\mu(g), \text{ where } x = \mathbb{R}v \in \mathbb{P}V.$$

We keep the assumption that μ is a Zariski dense Borel probability measure on $\mathrm{SL}_{m+1}(\mathbb{R})$ with a finite exponential moment. The use of this transfer operator on the products of random matrices has been introduced by Guivarc'h. Due to the contracting action of G on X , when $|\Re z|$ is small enough, the operator P_z preserves the Banach space $C^\gamma(\mathbb{P}V)$ for $\gamma > 0$ small enough. For z in a small ball centred at 0, the spectral radius of P_z on $C^\gamma(\mathbb{P}V)$ is less than 1 except at 0. Due to the non-arithmeticity of Γ_μ , on the imaginary line, the operator P_z also has spectral radius less than 1 except at 0. These were used to give limit theorems for products of random matrices by Le Page and Guivarc'h (Please see [LP82b] and [BQ16]).

Theorem 2.1.5 (Spectral gap). *Let μ be a Zariski dense Borel probability measure on $\mathrm{SL}_{m+1}(\mathbb{R})$ with finite exponential moment. Let V be an irreducible representation of $\mathrm{SL}_{m+1}(\mathbb{R})$. For every $\gamma > 0$ small enough, there exists $\delta > 0$ such that for all $|b| > 1$ and $|a|$ small enough the spectral radius of P_{a+ib} acting on $C^\gamma(\mathbb{P}V)$ satisfies*

$$\rho(P_{a+ib}) < 1 - \delta.$$

Even in the case of $\mathrm{SL}_2(\mathbb{R})$, the result is new and only known in some special case. When μ is supported on a finite number of elements in $\mathrm{SL}_2(\mathbb{R})$ and these elements generate a Schottky semigroup, this result is due to Naud [Nau05]. When μ is absolutely continuous with respect to the Haar measure on $\mathrm{SL}_2(\mathbb{R})$, this result can be obtained directly using oscillation integral.

This result should be compared with similar results for random walks on \mathbb{R} . Let μ be a Borel probability measure on \mathbb{R} with finite support. Then

$$\liminf_{|b| \rightarrow \infty} |1 - \hat{\mu}(ib)| = 0,$$

which is totally different from our case and where $\hat{\mu}(z)$ is the Laplace transform of the measure μ , given by

$$\hat{\mu}(z) = \int_{\mathbb{R}} e^{zx} d\mu(x).$$

The proof is direct. Let $\{x_1, \dots, x_l\}$ be the support of μ . Then $\hat{\mu}(ib) = \sum_{1 \leq j \leq l} \mu(x_j) e^{ibx_j}$, and we only need to find b such that all the terms are uniformly near 1. Using the fact that $\liminf_{b \rightarrow \infty} d_{\mathbb{R}^l}(b(x_1, \dots, x_l), 2\pi\mathbb{Z}^l) = 0$, we have the claim.

We can also compare with the counting problem in the setting of hyperbolic surfaces. The spectral gap is used to obtain an exponential remainder term in the counting problem as in [LP82a], [Nau05].

An analogous result is valid if we replace the projective space $\mathbb{P}V$ by the flag variety \mathcal{P} . Let \mathcal{P} be the full flag variety of $\mathrm{SL}_{m+1}(\mathbb{R})$ and let \mathfrak{a} be a Cartan subspace of Lie algebra $\mathfrak{sl}_{m+1}\mathbb{R}$. For $g \in G$ and $\eta \in \mathcal{P}$, let $\sigma(g, \eta)$ be the Iwasawa cocycle, which takes values in \mathfrak{a} . We fix a Riemannian distance on \mathcal{P} . We can similarly define the space of γ -Hölder functions $C^\gamma(\mathcal{P})$. Let ϖ, θ be in \mathfrak{a}^* . For a continuous function f on \mathcal{P} and $|\varpi|$ small enough, the transfer operator $P_{\varpi+i\theta}$ on the flag variety is defined by

$$P_{\varpi+i\theta}f(\eta) = \int_G e^{(\varpi+i\theta)\sigma(g,\eta)} f(g\eta) d\mu(g).$$

Theorem 2.1.6 (Spectral gap). *Let μ be a Zariski dense Borel probability measure on $\mathrm{SL}_{m+1}(\mathbb{R})$ with finite exponential moment. For every $\gamma > 0$ small enough, there exists $\delta > 0$ such that for all θ, ϖ in \mathfrak{a}^* with $|\theta| > 1$ and $|\varpi|$ small enough the spectral radius of $P_{\varpi+i\theta}$ acting on $C^\gamma(\mathcal{P})$ satisfies*

$$\rho(P_{\varpi+i\theta}) < 1 - \delta.$$

Fourier decay

The key ingredient of the proof of the above results is the following Fourier decay property of the μ -stationary measure on the flag variety \mathcal{P} . In order to state the Fourier decay on the flag variety, we need to introduce a special condition. Let r be a continuous function on \mathcal{P} and let $C > 0$. For a C^2 function φ on \mathcal{P} , we say φ is (C, r) good if it satisfies some assumptions on the Lipschitz norm and derivative, which will be defined later (Definition 2.4.1). When $G = \mathrm{SL}_2(\mathbb{R})$, the (C, r) goodness is exactly the assumption of φ in Theorem 2.1.2, which is natural for having a Fourier decay. Recall that for a γ -Hölder function f , we have defined $c_\gamma(f) = \sup_{x \neq x'} \frac{|f(x) - f(x')|}{d(x, x')^\gamma}$.

Theorem 2.1.7 (Fourier decay). *Let μ be Zariski dense Borel probability measure on $\mathrm{SL}_{m+1}(\mathbb{R})$ with finite exponential moment. Let ν be the μ -stationary measure on the flag variety \mathcal{P} .*

For every $\gamma > 0$, there exist $\epsilon_0 > 0, \epsilon_1 > 0$ depending on μ such that the following holds. For any real function $\varphi \in C^2(\mathcal{P})$, $r \in C^\gamma(\mathcal{P})$ and $\xi > 0$ such that φ is (ξ^{ϵ_0}, r) good, $\|r\|_\infty \leq 1$ and $c_\gamma(r) \leq \xi^{\epsilon_0}$, then

$$\left| \int e^{i\xi\varphi(\eta)} r(\eta) d\nu(\eta) \right| \leq \xi^{-\epsilon_1} \quad \text{for all } \xi \text{ large enough.} \quad (2.1.1)$$

Remark 2.1.8. *The decay rate only depends on the constants in the large deviation principles and the regularity of stationary measures. This should be compared with [BD17], where the spectral gap and the decay rate only depend on the dimension of the Patterson-Sullivan measure.*

Now we explain the (C, r) good condition. In higher dimension, we observe that under the action of G there are some directions contracting slower than other directions. Roughly speaking, we will only consider these principal directions in the flag variety \mathcal{P} and generalize the condition of $\mathrm{SL}_2(\mathbb{R})$ to higher dimension. The exact definition is a little technique and all the notation will be explained in Section 2.4.1.

A key ingredient in the proof of Theorem 2.1.7 comes from the discretized sum-product estimate, Proposition 2.3.17, which is a generalized version of a result of Bourgain in [Bou10]. The key input to use the machine of the discretized sum-product estimate is a non concentration hypothesis. A analogue hypothesis for measures on \mathbb{R} is as follows.

Definition (non concentration). *Let μ be a Borel probability measure on \mathbb{R} . We say that μ satisfies non concentration hypothesis if there exist $\epsilon, \kappa, C > 0$ such that for every $n \in \mathbb{N}$ and $\rho = e^{-\epsilon n}$,*

$$\sup_{a \in \mathbb{R}} \mu^{*n} \{x \in \mathbb{R} \mid |x - a| \leq \rho\} \leq C \rho^\kappa.$$

But this hypothesis is never satisfied when the measure μ supports on a finite set, for example $\{x_1, \dots, x_l\} \subset \mathbb{R}$. Because the convolution μ^{*n} is supported on at most n^l points, there exists a point y such that $\mu^{*n}\{y\} \gg n^{-l}$. The decay rate of $\sup_{a \in \mathbb{R}} \mu^{*n}(B(a, \rho))$ is at most polynomial in n , which does not satisfy the definition of non concentration.

In Section 2.3, we will introduce a similar non concentration hypothesis and we will verify the hypothesis for our measure μ . The main ingredients are the large deviation principle, a Hölder regularity for stationary measures and highest weight representations. The strategy can be roughly summarized by saying that once the non concentration of the Iwasawa cocycle is verified, by the discretized sum-product estimate, we will have a Fourier decay and a speed in the equidistribution of the Iwasawa cocycle (the renewal theorem). This is in the similar spirit of the work of Bourgain and Gamburd on the spectral gap for compact Lie groups [BG08].

The action of the group G on the flag variety \mathcal{P} is not conformal if the rank m is greater than 1, which is quite different from the theory of Kleinian groups. In Section 2.2, we will study the action of G on the tangent bundle of \mathcal{P} and we will find directions of slowest contraction speed.

We will make use of some classical notation: for two real functions A and B , we write $A = O(B)$, $A \ll B$ or $B \gg A$ if there exists a constant $C > 0$ such that $|A| \leq CB$, where C only depends on the ambient group G and the measure μ . We write $A \asymp B$ if $A \ll B$ and $B \ll A$. We write $A = O_\epsilon(B)$, $A \ll_\epsilon B$ or $B \gg_\epsilon A$ if the constant C depends on an extra parameter $\epsilon > 0$.

We always use $0 < \delta < 1$ to denote an error term and $0 < \beta < 1$ to denote the magnitude. The quantity β^{-1} is supposed to be greater than $\delta^{-O(1)}$. If $\delta^{O(1)}A \leq B \leq \delta^{-O(1)}A$, then we say that A and B are of the same size.

2.2 Random walks on Lie groups

In this manuscript, we only consider $G = \mathrm{SL}_{m+1}(\mathbb{R})$.

2.2.1 Semisimple Lie groups and representations

We will introduce the vocabulary of semisimple algebraic connected real Lie groups. Please see [Hel79], [Bor90] and [BQ16] for more details.

Semisimple Lie groups

Let G be a semisimple algebraic connected real Lie group. Let \mathfrak{g} be its Lie algebra. Since all the maximal compact subgroups are conjugate, we fix a maximal compact subgroup K of G . Let \mathfrak{k} be its Lie algebra. For X, Y in \mathfrak{g} , the Killing form is defined as

$$K(X, Y) = \mathrm{tr}(\mathrm{ad}X\mathrm{ad}Y).$$

The Killing form is non degenerate on \mathfrak{g} and negative definite on \mathfrak{k} . Let \mathfrak{s} be the orthogonal complement of \mathfrak{k} in \mathfrak{g} . Then the Killing form is positive definite on \mathfrak{s} . Let τ be the Cartan involution which fixes \mathfrak{k} and equals $-id$ on \mathfrak{s} .

We say an element X in \mathfrak{g} is hyperbolic, if $\mathrm{ad}X$ is diagonalizable over \mathbb{R} . Let \mathfrak{a} be a maximal abelian subalgebra of \mathfrak{s} whose elements are hyperbolic. Such subalgebras are called Cartan subspaces, and they are conjugate under K . The dimension of \mathfrak{a} is called the **real rank** of G . The real rank of the group G will always be denoted by m . Endowed with the Killing form, the Cartan subalgebra \mathfrak{a} and its dual \mathfrak{a}^* become Euclidean spaces. Let A be the algebraic subgroup of G with the Lie algebra \mathfrak{a} . We write \exp for the exponential map from \mathfrak{a} to A .

Root systems and the Weyl group

Let R be the root system of \mathfrak{g} with respect to \mathfrak{a} , which is a finite subset of \mathfrak{a}^* . Fix a choice of positive roots R^+ . Let Π be the collection of primitive simple roots of R^+ . Let \mathfrak{a}^+ be the Weyl chamber defined by $\{X \in \mathfrak{a} \mid \alpha(X) \geq 0, \forall \alpha \in \Pi\}$. Let \mathfrak{a}^{++} be the interior of Weyl chamber defined by $\{X \in \mathfrak{a} \mid \alpha(X) > 0, \forall \alpha \in \Pi\}$. Using the root system, we have a decomposition of \mathfrak{g} into eigenspaces of \mathfrak{a} ,

$$\mathfrak{g} = \mathfrak{z} \oplus \bigoplus_{\alpha \in R} \mathfrak{g}^\alpha,$$

where \mathfrak{z} is the centralizer of \mathfrak{a} and \mathfrak{g}^α is the eigenspace given by

$$\mathfrak{g}^\alpha = \{X \in \mathfrak{g} \mid [Y, X] = \alpha(Y)X \text{ for all } Y \in \mathfrak{a}\}.$$

The real Lie group is called **split** if $\mathfrak{a} = \mathfrak{z}$, which is equivalent to saying that \mathfrak{g}^α are of dimension 1. The groups $\mathrm{SL}_{m+1}(\mathbb{R})$ are split groups.

Recall that for every root α in R , there is an orthogonal symmetry s_α which preserves R and $s_\alpha(\alpha) = -\alpha$. For $\alpha \in R$, let H_α be the unique element in \mathfrak{a} such that $s_\alpha(\alpha') =$

$\alpha' - \alpha'(H_\alpha)\alpha$ for $\alpha' \in \mathfrak{a}^*$. The set $\{H_\alpha \mid \alpha \in R\}$ is called the set of dual roots in \mathfrak{a} . Since the Cartan involution τ equals $-id$ on \mathfrak{a} , this implies $\tau\mathfrak{g}^\alpha = \mathfrak{g}^{-\alpha}$ for $\alpha \in R$. Using the Killing form, we can prove that $[\mathfrak{g}^\alpha, \mathfrak{g}^{-\alpha}] = \mathbb{R}H_\alpha$. (See [Ser66, Cha. 4, Theorem 2] for more details) Hence, there is a unique choose (up to sign) $X_\alpha \in \mathfrak{g}^\alpha$, $Y_\alpha \in \mathfrak{g}^{-\alpha}$ such that

$$[X_\alpha, Y_\alpha] = H_\alpha \text{ and } \tau(X_\alpha) = -Y_\alpha.$$

Let $K_\alpha = X_\alpha - Y_\alpha$. Due to $\tau K_\alpha = K_\alpha$, the element K_α is in \mathfrak{k} .

Let W be the Weyl group of R . Then the group W acts simply transitively on the set of Weyl chambers. Let w_0 be the unique element in W which sends the Weyl chamber \mathfrak{a}^+ to the Weyl chamber $-\mathfrak{a}^+$. Let $\iota = -w_0$ be the opposition involution. The Weyl group also acts on \mathfrak{a}^* by the dual action. Let $N_G(A)$ be the normalizer of A in G . An element in $N_G(A)/A$ induces an automorphism on the tangent space \mathfrak{a} . This gives an isomorphism from $N_G(A)/A$ to the Weyl group W . Hence w_0 can be realized as an element in G/A and its action on \mathfrak{a} is given by conjugation.

The Iwasawa cocycle

Let $\mathfrak{n} = \bigoplus_{\alpha \in R^+} \mathfrak{g}^\alpha$ and $\mathfrak{n}^- = \bigoplus_{\alpha \in R^+} \mathfrak{g}^{-\alpha}$. They are nilpotent Lie algebras. Let N be the connected algebraic subgroup of G with Lie algebra \mathfrak{n} . The group N is normalized by A . Let $P = AN$ be a minimal parabolic subgroup. The flag variety \mathcal{P} is defined to be the set of conjugations of P under the action of G . Since the normalizer of P in G is itself, we have an isomorphism

$$G/P \rightarrow \mathcal{P}.$$

We write η_o for the subgroup P seen as a point in \mathcal{P} . The action of K on \mathcal{P} is transitive. Hence \mathcal{P} is a compact manifold. Let $M = P \cap K$. The fact that the group G is split implies that M is discrete.

Recall that N is the nilpotent subgroup with Lie algebra \mathfrak{n} . We have an Iwasawa decomposition of G given by

$$G = KA_eN,$$

where $A_e = \exp(\mathfrak{a})$ is the analytical connected component of A . This is a bijection between G and $K \times A_e \times N$. Then we can define the Iwasawa cocycle σ from $G \times \mathcal{P}$ to \mathfrak{a} . Let η be in \mathcal{P} and g be in G . By the transitivity of K , there exists $k \in K$ such that $\eta = k\eta_o$. By the Iwasawa decomposition, there exists a unique element $\sigma(g, \eta)$ in \mathfrak{a} such that

$$gk \in K \exp(\sigma(g, \eta))N.$$

We can verify that this is well defined and σ is an additive cocycle, that is for g, h in G and η in \mathcal{P}

$$\sigma(gh, \eta) = \sigma(g, h\eta) + \sigma(h, \eta).$$

The Cartan decomposition

The Cartan decomposition says that $G = KA^+K$, where A^+ is the image of the Weyl chamber \mathfrak{a}^+ under the exponential map. For g in G , by Cartan decomposition, we can write $g = k_g a_g \ell_g$ with k_g, ℓ_g in K and a_g in A^+ . The element a_g is unique and there is a unique element $\kappa(g)$ in \mathfrak{a}^+ such that $a_g = \exp(\kappa(g))$. We call $\kappa(g)$ the Cartan projection of g . Then $\kappa(g^{-1}) = \iota\kappa(g)$, where ι is the opposition involution. Since A is contained in P , we can define $\zeta_o = w_0\eta_o$, where the element w_0 in the Weyl group is seen as an element in G/A . (As an element in \mathcal{P} , ζ_o is the opposite parabolic group with respect to P and A) Let $\eta_g^M = k_g\eta_o$ and $\zeta_g^m = \ell_g^{-1}\zeta_o$. When $\kappa(g)$ is in \mathfrak{a}^{++} , they are uniquely defined, independently of the choice of k_g and ℓ_g .

Representations and highest weight

Let (ρ, V) be a linear finite dimensional algebraic representation of G . In this manuscript, we only consider finite dimensional representations. The set of restricted weights $\Sigma(\rho)$ of the representation is the set of elements ω in \mathfrak{a}^* such that the eigenspace

$$V^\omega = \{v \in V \mid \forall X \in \mathfrak{a}, d\rho(X)v = \omega(X)v\}$$

is nonzero, where $d\rho$ is the tangent map of ρ from \mathfrak{g} to $\mathrm{End}(V)$. We define a partial order on the restricted weights: For ω_1, ω_2 in $\Sigma(\rho)$,

$$\omega_1 \geq \omega_2 \Leftrightarrow \omega_1 - \omega_2 \text{ is a sum of positive roots.}$$

If ω is in $\Sigma(\rho)$, then we say that ω is a weight of V and a vector v in V^ω is said to have weight ω . We call ρ proximal if there exists χ in $\Sigma(\rho)$ which is greater than the other restricted weights and such that V^χ is of dimension 1. We should pay attention that a proximal representation is not supposed to be irreducible. The advantage of the splitness of G is that all the irreducible representations are proximal, which will be extensively used later on.

Let $\{\chi_\alpha\}_{\alpha \in \Pi}$ be the set of fundamental weights, which is the dual basis of the dual roots $(H_\alpha)_{\alpha \in \Pi}$, a basis of \mathfrak{a}^* . For an element χ in \mathfrak{a} , there exists a finite dimensional representation with highest weight χ if and only if it is a dominant weight, which means that χ is a sum of multiple of fundamental weights.

Suppose that (ρ, V) is an irreducible representation. Let $\chi \in \mathfrak{a}^*$ be the highest weight of (ρ, V) . We write $V_{\chi, \eta} = \rho(g)V^\chi$ for $\eta = g\eta_o$, which is well defined because the parabolic subgroup P fixes the subspace V^χ . This gives a map from \mathcal{P} to $\mathbb{P}V$ by

$$\mathcal{P} \rightarrow \mathbb{P}V, \eta \mapsto V_{\chi, \eta}. \quad (2.2.1)$$

Lemma 2.2.1. *Let G be $\mathrm{SL}_{m+1}(\mathbb{R})$. There exists a family of representations $(\rho_\alpha, V_\alpha)_{\alpha \in \Pi}$ such that the highest weight of ρ_α is χ_α . Furthermore, the other weights of ρ_α are of the form*

$$\chi_\alpha - \alpha - \sum_{\beta \in \Pi} n_\beta \beta, \text{ where } n_\beta \in \mathbb{N}_{\geq 0}.$$

The product of the maps given by (2.2.1)

$$\mathcal{P} \longrightarrow \prod_{\alpha \in \Pi} \mathbb{P}V_{\alpha}, \quad \eta \mapsto (V_{\chi_{\alpha}, \eta})_{\alpha \in \Pi},$$

is an embedding of \mathcal{P} to the product of projective spaces.

Please see [Tit71]. The set of restrict weight is invariant under the Weyl group. Due to $\chi_{\alpha}(H_{\beta}) = 0$ when $\beta \neq \alpha$, we have $s_{\beta}(\chi_{\alpha} - \beta) = \chi_{\alpha} + \beta$. Hence $\chi_{\alpha} - \beta$ is not a weight of V_{α} except $\beta = \alpha$. This explains the structure of weights of ρ_{α} .

Definition 2.2.2 (Super proximal representation). *Let (V, χ) be an irreducible representation of G . We call V super proximal if the exterior square $\wedge^2 V$ is also proximal. This is equivalent to say that there is only one simple root α such that $\chi - \alpha$ is a weight of V , and $V^{\chi - \alpha}$ is of dimension 1.*

Lemma 2.2.3. *Fundamental representations are super proximal.*

Proof. Let α be a simple root. By Lemma 2.2.1, we only need to prove that $V^{\chi_{\alpha} - \alpha}$ is of dimension 1. Let v be a nonzero vector with highest weight χ_{α} . By [Ser66, Chapter 7, Proposition 2], the representation V is generated by vectors $Y_{\beta_1} \cdots Y_{\beta_k} v$, where β_1, \dots, β_k are positive roots. Hence a vector of weight $\chi_{\alpha} - \alpha$ can only be obtained by $Y_{\alpha} v$. The dimension of $V^{\chi_{\alpha} - \alpha}$ is no greater than 1. Due to $\chi_{\alpha} - \alpha = s_{\alpha}(\chi_{\alpha})$, the element $\chi_{\alpha} - \alpha$ is a weight of V_{α} . The proof is complete. \square

Remark 2.2.4. *We can prove that an irreducible representation is super proximal if and only if its highest weight is a multiple of fundamental weight, by using Freudenthal's multiplicity formula.*

Representations and good norms

Let $\|\cdot\|$ be an euclidean norm on V . For g in $GL(V)$, let $\|g\|$ be its application norm. We call $\|\cdot\|$ a good norm if $\rho(A)$ is symmetric and $\rho(K)$ preserves the norm. By [Hel79], [BQ16, Lemma 6.33], good norms exist on every representation of G . The application (2.2.1) enables us to get information on \mathcal{P} by the representations.

Lemma 2.2.5. *Let G be a connected algebraic semisimple real Lie group. Let (ρ, V) be an irreducible linear representation of G with good norm. Let χ be the highest weight of V . For η in \mathcal{P} and a non zero vector $v \in V_{\chi, \eta}$, we have*

$$\frac{\|\rho(g)v\|}{\|v\|} = \exp(\chi\sigma(g, \eta)), \quad (2.2.2)$$

$$\|\rho(g)\| = \exp(\chi\kappa(g)). \quad (2.2.3)$$

Please see [BQ16, Lemma 6.33] for the proof.

Algebraic characters

Let $X(A)$ be the set of algebraic characters of A . For any character χ of A , there exists a unique weight χ^ω in \mathfrak{a}^* such that for any X in \mathfrak{a} ,

$$\chi(\exp(X)) = e^{\chi^\omega(X)}.$$

When $G = \mathrm{SL}_{m+1}(\mathbb{R})$, for every weight ϖ , which is in $\Gamma(G) := \bigoplus_{\alpha \in \Pi} \mathbb{Z}\chi_\alpha$ (the lattice generated by $\{\chi_\alpha\}_{\alpha \in \Pi}$), we can find an algebraic character χ in $X(A)$ such that $\chi^\omega = \varpi$. In fact, this is an isomorphism between $X(A)$ and $\Gamma(G)$. By the definition of eigenspace V^ω , we have

Lemma 2.2.6. *Let (ρ, V) be an irreducible representation of G . Let χ be an algebraic character of A . For a in A and $v \in V^{\chi^\omega}$, we have*

$$\rho(a)v = \chi(a)v.$$

Algebraic characters will be used to determine the sign in Section 2.2.5. We will use the same symbol χ to denote a weight in $\Gamma(G)$ and χ^\sharp to denote its corresponding algebraic character in $X(A)$, that is $(\chi^\sharp)^\omega = \chi$.

Examples

For the group $\mathrm{SL}_{m+1}(\mathbb{R})$, the maximal torus A can be taken as the diagonal subgroup and the Lie algebra \mathfrak{a} is the set of diagonal matrices with trace 0. For X in \mathfrak{a} , we write $X = \mathrm{diag}(x_1, \dots, x_{m+1})$ with $x_i \in \mathbb{R}$ and $\sum_{1 \leq i \leq m+1} x_i = 0$. The restriction of Killing form on \mathfrak{a} is a multiple of the standard euclidean norm on \mathbb{R}^{m+1} . Let λ_i in \mathfrak{a}^* be the linear map given by $\lambda_i(X) = x_i$. The root system R is given by

$$R = \{\lambda_i - \lambda_j \mid i \neq j, \text{ and } i, j \in \{1, \dots, m+1\}\}.$$

A choice of positive roots is $\lambda_i - \lambda_j$ with $i < j$. The set of simple roots is $\Pi = \{\lambda_i - \lambda_{i+1} \mid i = 1, \dots, m\}$. Let $\alpha_i = \lambda_i - \lambda_{i+1}$. The Weyl chamber is

$$\mathfrak{a}^+ = \{X \in \mathfrak{a} \mid x_1 \geq x_2 \geq \dots \geq x_{m+1}\}.$$

The fundamental weights are $\chi_{\alpha_i} = \lambda_1 + \dots + \lambda_i$ for $i = 1, \dots, m$. The fundamental representations are $V_{\alpha_i} = \wedge^i \mathbb{R}^{m+1}$ for $i = 1, \dots, m$. The maximal compact subgroup K is $\mathrm{SO}(m+1)$ and the parabolic group P is the upper triangular subgroup and N is the subgroup of P with all the diagonal entries equal to 1. The flag variety \mathcal{P} is the set of all flags

$$W_1 \subset W_2 \subset \dots \subset W_m,$$

where W_i is a subspace of \mathbb{R}^{m+1} of dimension i .

Let $\epsilon_{i,j}$ be the square matrix of dimension $m+1$ with the only nonzero entry at the i -th row and j -th column, which equals 1. The element H_{α_i} is $\epsilon_{i,i} - \epsilon_{i+1,i+1}$. The element $X_{\alpha_i}, Y_{\alpha_i}$ are given by $\epsilon_{i,i+1}, \epsilon_{i+1,i}$. The Cartan involution τ is the additive inverse of the transpose, that is $\tau(X) = -{}^t X$ for X in \mathfrak{a} .

The Weyl group W is isomorphic to the symmetric group \mathcal{S}_{m+1} . The action on \mathfrak{a} is simply given by the permutation of coordinates and the element w_0 sends $X = \mathrm{diag}(x_1, \dots, x_{m+1})$ to $w_0 X = \mathrm{diag}(x_{m+1}, \dots, x_1)$.

2.2.2 Linear actions on vector spaces

Let V be a vector space with euclidean norm. Then we have an induced norm on its dual space V^* , exterior powers $\wedge^j V$ and tensor products $\otimes^j V$.

For $x = \mathbb{R}v, x' = \mathbb{R}v'$ in $\mathbb{P}V$, we define the distance between x, x' by

$$d(x, x') = \frac{\|v \wedge v'\|}{\|v\| \|v'\|}. \quad (2.2.4)$$

This distance has the advantage that it behaves well under the action of $GL(V)$. See for example Lemma 2.2.8. For $y = \mathbb{R}f$ in $\mathbb{P}V^*$, let $y^\perp = \mathbb{P}(\ker f) \subset \mathbb{P}V$ be a hyperplane in $\mathbb{P}V$. For $x = \mathbb{R}v$ in $\mathbb{P}V$, we define the distance of x to y^\perp by

$$\delta(x, y) = \frac{|f(v)|}{\|f\| \|v\|},$$

which is explained by $\delta(x, y) = d(x, y^\perp) = \min_{x' \in y^\perp} d(x, x')$. Let K_V be the compact group which preserves the norm. Let A_V^+ be the set of diagonal elements such that $\{a = \text{diag}(a_1, \dots, a_d) | a_1 \geq a_2 \geq \dots \geq a_d\}$, under the basis $\{e_1, \dots, e_d\}$. Let A_V^{++} be the interior of A_V^+ . For g in $GL(V)$, by the Cartan decomposition we can choose

$$g = k_g a_g \ell_g, \text{ where } a_g \in A_V^+ \text{ and } k_g, \ell_g \in K_V. \quad (2.2.5)$$

Let $x_g^M = \mathbb{R}k_g e_1$ and $y_g^m = \mathbb{R}{}^t g e_1^*$ be the density points of g on $\mathbb{P}V$ and ${}^t g$ on $\mathbb{P}V^*$, which is unique and independent of the choice of basis when a_g is in A_V^{++} . For $r > 0$ and g in $GL(V)$, let

$$\begin{aligned} b_{V,g}^M(r) &= \{x \in \mathbb{P}V | d(x, x_g^M) \leq r\}, \\ B_{V,g}^m(r) &= \{x \in \mathbb{P}V | \delta(x, y_g^m) \geq r\}. \end{aligned}$$

These two sets play important role when we want to get some ping-pong property. The elements in set $B_{V,g}^m$ have distance at least r to the hyperplane determined by y_g^m . For g in $GL(V)$, let $\gamma_{1,2}(g) := \frac{\|\wedge^2 g\|}{\|g\|^2}$ be the gap of g .

Distance and norm

We start with general g in $GL(V)$, where V is a finite dimensional vector space with euclidean norm. We need some technical control of distance. These are quantitative versions of the same controls in [Qui02, Lemma 2.5, 4.3, 6.5].

For g in $GL(V)$ and $x = \mathbb{R}v \in \mathbb{P}V$, we define an additive cocycle $\sigma_V : GL(V) \times \mathbb{P}V \rightarrow \mathbb{R}$ by

$$\sigma_V(g, x) = \log \frac{\|gv\|}{\|v\|}. \quad (2.2.6)$$

This is called cocycle, because for g, h in G , we have

$$\sigma_V(gh, x) = \sigma_V(g, hx) + \sigma_V(h, x).$$

We fix the operator norm $\|\cdot\|$ on $GL(V)$.

Lemma 2.2.7. For any g in $GL(V)$ and x in $\mathbb{P}V$, we have

$$\delta(x, y_g^m) \leq \frac{\|gv\|}{\|g\|\|v\|} \leq 1. \quad (2.2.7)$$

Please see [BQ16, Lem 14.2] for the proof.

Lemma 2.2.8. Let $\delta > 0$. For g in $GL(V)$, if $\beta = \gamma_{1,2}(g) \leq \delta^2$, then

- the action of g on $B_{V,g}^m(\delta)$ is $\beta\delta^{-2}$ -Lipschitz and

$$gB_{V,g}^m(\delta) \subset b_{V,g}^M(\beta\delta^{-1}) \subset b_{V,g}^M(\delta),$$

- the restriction of the real valued function $\sigma_V(g, \cdot)$ on $B_{V,g}^m(\delta)$ is $2\delta^{-1}$ -Lipschitz.

Proof. Due to [BQ16, Lem 14.2],

$$d(gx, x_g^M)\delta(x, y_g^m) \leq \gamma_{1,2}(g) = \beta.$$

Hence

$$d(gx, x_g^M) \leq \beta\delta(x, y_g^m)^{-1} \leq \beta\delta^{-1},$$

which implies the inclusion.

For $x = \mathbb{R}v$ and $x' = \mathbb{R}v'$ in $B_{V,g}^m(\delta)$, by (2.2.7), we have

$$d(gx, gx') = \frac{\|gv \wedge gv'\|}{\|v \wedge v'\|} \frac{\|v \wedge v'\|}{\|v\|\|v'\|} \frac{\|v\|\|v'\|}{\|gv\|\|gv'\|} \leq \gamma_{1,2}(g)d(x, x')\delta^{-2},$$

which implies the Lipschitz property of g .

For the Lipschitz property of $\sigma_V(g, \cdot)$, please see [BQ16, Lemma 17.11]. \square

For two different points $x = \mathbb{R}v$ and $x' = \mathbb{R}v'$ in $\mathbb{P}V$, we write $x \wedge x' = \mathbb{R}(v \wedge v') \in \mathbb{P}(\wedge^2 V)$.

Lemma 2.2.9. For any g in $GL(V)$ and two different points $x = \mathbb{R}v, x' = \mathbb{R}v'$ in $\mathbb{P}V$, we have

$$\gamma_{1,2}(g)\delta(x \wedge x', y_{\wedge^2 g}^m) \leq \frac{d(gx, gx')}{d(x, x')}. \quad (2.2.8)$$

Proof. By definition and (2.2.7), we have

$$d(gx, gx') = \frac{\|gv \wedge gv'\|}{\|v \wedge v'\|} \frac{\|v \wedge v'\|}{\|v\|\|v'\|} \frac{\|v\|\|v'\|}{\|gv\|\|gv'\|} \geq \gamma_{1,2}(g)\delta(x \wedge x', y_{\wedge^2 g}^m)d(x, x').$$

The proof is complete. \square

2.2.3 Actions on Flag varieties

Representations and Density points

Now, suppose that V is a representation of G with a good norm. Recall that V^χ is the eigenspace of the highest weight. Let V^* be the dual space of V . The representation of G on V^* is the dual representation given by: for $g \in G$ and $f \in V^*$, let $\rho^*(g)f = {}^t\rho(g^{-1})f$. This definition gives

$$\langle \rho^*(g)f, \rho(g)v \rangle = \langle {}^t\rho(g^{-1})f, \rho(g)v \rangle = \langle f, v \rangle,$$

for f in V^* and v in V . Then the highest weight of V^* is $\iota\chi$. The following results explain the relation between different definitions by using combinatoric information on root systems and representations.

Lemma 2.2.10. *We claim that for every irreducible representation V and weight χ ,*

$$V_{\chi, \zeta_0} = V^{w_0\chi}. \quad (2.2.9)$$

Proof. This can be verified as follows: For X in \mathfrak{a} and v in V^χ ,

$$d\rho(X)\rho(w_0)v = w_0 d\rho(w_0X)v = \chi(w_0X)w_0v = (w_0\chi)(X)w_0v.$$

The proof is complete. \square

Lemma 2.2.11. *Let V be a proximal representation of G . Then we have*

$$x_{\rho(g)}^M = \rho(k_g)V^\chi \text{ and } y_{\rho(g)}^m = {}^t\rho(\ell_g)(V^*)^{-\chi}. \quad (2.2.10)$$

If V is irreducible, then we have

$$x_{\rho(g)}^M = V_{\chi, \eta_g^M} \text{ and } y_{\rho(g)}^m = V_{\iota\chi, \zeta_g^m}^*.$$

Proof. Let $\{e_1, \dots, e_d\}$ be an orthonormal basis of V composed of eigenvectors of $\rho(A)$ such that $e_1 \in V^\chi$. Then $\rho(A)$ is diagonal. For $g = \exp(X) \in A^+$, since χ is the highest weight, we have

$$a_1 = \exp(\chi(X)) \geq a_2, \dots, a_d.$$

By the definition of a good norm, $\rho(K)$ preserves the norm. Hence for g in G , the formula $\rho(g) = \rho(k_g)\rho(a_g)\rho(\ell_g)$ is a decomposition which satisfies (2.2.5) in the previous paragraph with some permutation of $\{e_2, \dots, e_d\}$. But these permutations do not change the density points. Hence we have $x_{\rho(g)}^M = \mathbb{R}\rho(k_g)e_1 = \rho(k_g)V^\chi$. If V is irreducible we have $x_{\rho(g)}^M = V_{\chi, \eta_g^M}$.

In the dual space, we can verify that e_1^* has weight $-\chi$, which is the lowest weight in weights of V^* . By the same argument as in $\mathbb{P}V$, we have

$$y_{\rho(g)}^m = \mathbb{R} {}^t\rho(\ell_g)e_1^* = {}^t\rho(\ell_g)(V^*)^{-\chi}.$$

We also have a map from \mathcal{P} to $\mathbb{P}V^*$. Hence by (2.2.9) with representation V^* and weight $\iota\chi$, we know $V_{\iota\chi, \zeta_o}^* = (V^*)^{w_0\iota\chi} = (V^*)^{-\chi}$. For $\zeta = g\zeta_o$ in \mathcal{P} , by definition,

$$V_{\iota\chi, \zeta}^* = gV_{\iota\chi, \zeta_o}^* = g(V^*)^{-\chi}. \quad (2.2.11)$$

Since V is irreducible, by (2.2.11) we have $y_{\rho(g)}^m = {}^t\rho(\ell_g)(V^*)^{-\chi} = \rho^*(\ell_g^{-1})(V^*)^{-\chi} = V_{\iota\chi, \zeta_g^m}^*$. \square

Distance on Flag varieties

For α in Π , we abbreviate $V_{\chi_\alpha, \eta}, V_{\iota\chi_\alpha, \zeta}^*$ to $V_{\alpha, \eta}, V_{\alpha, \zeta}^*$. For g in G , by Lemma 2.2.11, we find $x_{\rho_\alpha(g)}^M = V_{\alpha, \eta_g^M}$ and $y_{\rho_\alpha(g)}^m = V_{\alpha, \zeta_g^m}^*$. For η, η' in \mathcal{P} , let

$$d_\alpha(\eta, \eta') = d(V_{\alpha, \eta}, V_{\alpha, \eta'})$$

be its distance between their images in $\mathbb{P}V_\alpha$. We define a distance on the flag variety. It is the maximal distance induced by projections,

$$d(\eta, \eta') = \max_{\alpha \in \Pi} d_\alpha(V_{\alpha, \eta}, V_{\alpha, \eta'}). \quad (2.2.12)$$

We have another embedding of the flag variety

$$\mathcal{P} \rightarrow \prod_{\alpha \in \Pi} \mathbb{P}(V_\alpha^*).$$

For $\zeta = k\zeta_o \in \mathcal{P}$, by definition, we have $V_{\alpha, \zeta}^* = kV_{\alpha, \zeta_o}^*$. For $\eta \in \mathcal{P}$ and $\zeta \in \mathcal{P}$, we set

$$\delta(\eta, \zeta) = \min_{\alpha \in \Pi} \delta(V_{\alpha, \eta}, V_{\alpha, \zeta}^*).$$

In particular, because the images of η_o, ζ_o in $\mathbb{P}V_\alpha, \mathbb{P}V_\alpha^*$ are $V^{\chi_\alpha}, (V^*)^{-\chi_\alpha}$, we know $\delta(V_{\alpha, \eta_o}, V_{\alpha, \zeta_o}^*) = \delta(V^{\chi_\alpha}, (V^*)^{-\chi_\alpha}) = 1$, and then

$$\delta(\eta_o, \zeta_o) = 1. \quad (2.2.13)$$

We write

$$b_{V_\alpha, g}^M(r) = \{x \in \mathbb{P}V_\alpha \mid d(x, x_{\rho_\alpha(g)}^M) \leq r\},$$

$$B_{V_\alpha, g}^m(r) = \{x \in \mathbb{P}V_\alpha \mid \delta(x, y_{\rho_\alpha(g)}^m) \geq r\}.$$

They are subsets of $\mathbb{P}V_\alpha$. Write

$$b_g^M(r) = \{\eta \in \mathcal{P} \mid \forall \alpha \in \Pi, V_{\alpha, \eta} \in b_{V_\alpha, g}^M(r)\} = \{\eta \in \mathcal{P} \mid d(\eta, \eta_g^M) \leq r\},$$

$$B_g^m(r) = \{\eta \in \mathcal{P} \mid \forall \alpha \in \Pi, V_{\alpha, \eta} \in B_{V_\alpha, g}^m(r)\} = \{\eta \in \mathcal{P} \mid \delta(\eta, \zeta_g^m) \geq r\}.$$

They are subsets of \mathcal{P} .

Distance and norms

We need a multidimensional version of the lemmas in Section 2.2.2. Recall that $G = \mathrm{SL}_{m+1}(\mathbb{R})$. They are about the similar quantities on flag varieties. The idea is to use all the fundamental representations ρ_α . For an element X in \mathfrak{a} , we have

$$\sup_{\alpha \in \Pi} |\chi_\alpha(X)| \leq \|X\| \ll \sup_{\alpha \in \Pi} |\chi_\alpha(X)|. \quad (2.2.14)$$

Using Lemma 2.2.5 and (2.2.14), we deduce the following two lemmas from Lemma 2.2.7 and Lemma 2.2.8

Lemma 2.2.12. *For g in G and η in \mathcal{P} ,*

$$\|\sigma(g, \eta) - \kappa(g)\| \ll |\log \delta(\eta, \zeta_g^m)|.$$

For g in G and $\alpha \in \Pi$, by Lemma 2.2.5,

$$\gamma_{1,2}(\rho_\alpha(g)) = \frac{\|\wedge^2 \rho_\alpha(g)\|}{\|\rho_\alpha(g)\|^2} = e^{(2\chi_\alpha - \alpha - 2\chi_\alpha)\kappa(g)} = e^{-\alpha\kappa(g)}.$$

Let

$$\gamma(g) = \sup_{\alpha \in \Pi} e^{-\alpha\kappa(g)}. \quad (2.2.15)$$

We call it the gap of g .

Lemma 2.2.13. *Let $\delta > 0$. For g in G , if $\beta = \gamma(g) = \sup_{\alpha \in \Pi} \exp(-\alpha\kappa(g)) \leq \delta^2$, then*

- *the action of g on $B_g^m(\delta)$ is $\beta\delta^{-2}$ -Lipschitz and*

$$gB_g^m(\delta) \subset b_g^M(\beta\delta^{-1}) \subset b_g^M(\delta),$$

- *the restriction of the \mathfrak{a} -valued function $\sigma(g, \cdot)$ on $B_g^m(\delta)$ is $O(\delta^{-1})$ -Lipschitz.*

These properties tell us that the action of an element g on a large set of the flag variety \mathcal{P} behaves like uniformly contracting map.

We also need to compare the distance on the projective space and the flag variety. Recall the map from \mathcal{P} to $\mathbb{P}V$ defined in (2.2.1).

Lemma 2.2.14. *Let (ρ, V) be an irreducible representation of G with highest weight χ . There exists a constant $C > 0$ depending on the chosen norm such that for η, η' in \mathcal{P} ,*

$$d(V_{\chi, \eta}, V_{\chi, \eta'}) \leq Cd(\eta, \eta'). \quad (2.2.16)$$

The intuition is that a differentiable map between two compact Riemannian manifolds is Lipschitz. For more details, please see Corollary 2.5.6 in Appendix 2.5.2.

2.2.4 Actions on the tangent bundle of the Flag variety

In this section, we will study the action of G on the tangent bundle of \mathcal{P} . Recall that $\mathcal{P} \simeq G/P$ is the flag variety and $P = AN$ is a parabolic subgroup.

We first study the tangent bundle of the homogeneous space

$$\mathcal{P}_0 = G/A_eN.$$

Recall that A_e is the analytical connected component of A , given by $\exp(\mathfrak{a})$. Note that the left action of K on \mathcal{P}_0 is simply transitive (due to the Iwasawa decomposition). Let z_o be the base point A_eN in \mathcal{P}_0 . We can identify the left K -invariant vector fields as

$$T_{z_o}\mathcal{P}_0 = T_{z_o}(G/A_eN) \simeq \mathfrak{g}/\mathfrak{p}.$$

Hence the tangent bundle of \mathcal{P}_0 has an isomorphism

$$T\mathcal{P}_0 \simeq \mathcal{P}_0 \times \mathfrak{g}/\mathfrak{p},$$

that is because we can identify the tangent space at z_o and $z = kz_o$ by the left action of k . We denote by (z, Y) a point of $T\mathcal{P}_0$ where z is in \mathcal{P}_0 and Y is in $\mathfrak{g}/\mathfrak{p}$. We use elements in $\mathfrak{n}^- = \bigoplus_{\alpha \in R^+} \mathfrak{g}^{-\alpha}$ as representative elements in $\mathfrak{g}/\mathfrak{p}$.

Then we describe the left action of G on $T\mathcal{P}_0$. Take Y in $\mathfrak{g}^{-\alpha}$ and $z = kz_o$ in \mathcal{P}_0 . For g in G , by the Iwasawa decomposition we have a unique k' in K and a unique $\sigma(g, k)$ in \mathfrak{a} such that $gk = k'p \in k' \exp(\sigma(g, k))N$, where $p \in A_eN$. Here $\sigma(g, k)$ is understood as $\sigma(g, k\eta_o)$. Due to

$$gk \exp(tY)z_o = k'p \exp(tY)z_o = k' \exp(t\mathrm{Ad}_p Y)z_o,$$

by taking derivative at $t = 0$, the left action of g on the tangent vector (z, Y) satisfies

$$L_g(z, Y) = (z', \mathrm{Ad}_p Y),$$

where $z' = k'\langle_o$ and Ad is the adjoint action of P on $\mathfrak{g}/\mathfrak{p}$.

Now we restrict our attention to simple roots. Let α be a simple root. Due to $Y \in \mathfrak{g}^{-\alpha}$, we have $\mathrm{Ad}_N Y \subset Y + \mathfrak{a} + \mathfrak{n}$, which implies that the unipotent part N acts trivially on $(\mathfrak{g}^{-\alpha} + \mathfrak{p})/\mathfrak{p}$. By $p \in \exp(\sigma(g, k))N$, we have

$$\mathrm{Ad}_p Y = \exp(-\alpha\sigma(g, k))Y \text{ on } (\mathfrak{g}^{-\alpha} + \mathfrak{p})/\mathfrak{p}. \quad (2.2.17)$$

This means that the line bundle $\mathcal{P}_0 \times \mathfrak{g}^{-\alpha}$ is stable under the left action of G , and we call it the α -bundle.

The flag variety \mathcal{P} is a quotient of \mathcal{P}_0 by the right action of group M , due to $A = MA_e$. We use π to denote the quotient map. The right action of M also induces an action on the tangent bundle. For (z, Y) in $T\mathcal{P}_0$ and m in M , by $k \exp(tY)mz_o = km \exp(t\mathrm{Ad}_{m^{-1}} Y)z_o$, we have

$$R_m(kz_o, Y) = (kmz_o, \mathrm{Ad}_{m^{-1}} Y). \quad (2.2.18)$$

Descending to the quotient implies the tangent bundle of \mathcal{P} satisfies

$$T\mathcal{P} \simeq \mathcal{P}_0 \times_M \mathfrak{g}/\mathfrak{p},$$

which is the quotient space of $\mathcal{P}_0 \times \mathfrak{g}/\mathfrak{p}$ by the equivalence relation generated by the action of M , (2.2.18). Due to $M < A$, its adjoint action preserves the line $\mathfrak{g}^{-\alpha}$ in $\mathfrak{g}/\mathfrak{p}$. Hence the α -bundle on \mathcal{P}_0 descends to a line bundle on \mathcal{P} , and we call it \mathcal{P}_α , a subbundle of the tangent bundle. The integral curves of α -bundle on \mathcal{P}_0 are closed, and we call them α -circles on \mathcal{P}_0 . At a point $z = kz_o$ in \mathcal{P}_0 , it is given by

$$\gamma_\alpha : \mathbb{R} \rightarrow \mathcal{P}_0, t \mapsto k \exp(tK_\alpha)z_o. \quad (2.2.19)$$

This can be verified directly, because the tangent vector of the curve at time t is $(\gamma_\alpha(t), K_\alpha) = (\gamma_\alpha(t), Y_\alpha)$, due to the definition of $\mathfrak{g}/\mathfrak{p}$, which belongs to the α -bundle. The one parameter subgroup $\{\exp(tK_\alpha) : t \in \mathbb{R}\}$ is a compact subgroup of G , which is isomorphic to $SO(2)$. We call it O_α .

Under the right action of M , the α -circles on \mathcal{P}_0 descends to the α -circles on \mathcal{P} .

Lemma 2.2.15. *Under the map (2.2.1), the image of the α -circle containing $\eta = k\eta_0$ in $\mathbb{P}V_\alpha$ is the projective line generated by $\rho_\alpha(k)V^{\chi_\alpha}$ and $\rho_\alpha(k)V^{\chi_\alpha - \alpha}$.*

Let α' be another simple root. The image of an α -circle in $\mathbb{P}V_{\alpha'}$ is a point.

Proof. Since α -bundle is left K -invariant, the set of α -circles are also left K -invariant. It is sufficient to consider the α -circle containing η_0 . Let (ρ, V) be an irreducible representation of highest weight χ . By (2.2.19) and (2.2.1), the image of α -circle is given by $\rho(O_\alpha)V^\chi$.

Consider the Lie algebra \mathfrak{s}_α generated by $H_\alpha, X_\alpha, Y_\alpha$, which is isomorphic to \mathfrak{sl}_2 . For v in V^χ , we have $d\rho(H_\alpha)v = \chi(H_\alpha)v$. Due to the classification of the irreducible representation of \mathfrak{sl}_2 , the irreducible representation V_1 of \mathfrak{s}_α generating by V^χ is of dimension $\chi(H_\alpha) + 1$.

When $\chi = \chi_{\alpha'}$, we have $\chi_{\alpha'}(H_\alpha) = 0$, which implies V_1 is a trivial representation and $\rho(O_\alpha)$ acts trivially on V_1 . Hence the image of the α -circle is a point.

When $\chi = \chi_\alpha$, the same argument implies V_1 is of dimension 2. Another eigenspace of V_1 is $V^{\chi_\alpha - \alpha}$. The group $\rho(O_\alpha)$ acts as $SO(2)$ on V_1 , which implies the result. \square

Remark 2.2.16. *If we introduce the partial flag variety $\mathcal{P}_{\Pi - \{\alpha\}}$, then α -circle is simply the fiber of the quotient map $\mathcal{P} \rightarrow \mathcal{P}_{\Pi - \{\alpha\}}$. This point of view also implies Lemma 2.2.15.*

Generally, the α -bundle on \mathcal{P} is non trivial in the sense of line bundle.

Example 2.2.17. *Let G be $SL_3(\mathbb{R})$. Recall that*

$$\mathfrak{a} = \{X = \text{diag}(x_1, x_2, x_3) \mid x_1 + x_2 + x_3 = 0, x_1, x_2, x_3 \in \mathbb{R}\},$$

and α_1, α_2 are two simple roots given by $\alpha_1 = \lambda_1 - \lambda_2$ and $\alpha_2 = \lambda_2 - \lambda_3$. The group M is $\{e, \mathrm{diag}(1, -1, -1), \mathrm{diag}(-1, 1, -1), \mathrm{diag}(-1, -1, 1)\} \simeq (\mathbb{Z}/2\mathbb{Z})^2$. We have

$$\mathrm{Ad}_{\mathrm{diag}(1, -1, -1)} Y_{\alpha_1} = \mathrm{Ad}_{\mathrm{diag}(1, -1, -1)} \begin{pmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} = -Y_{\alpha_1}.$$

In this case the action of M is nontrivial and it is not a normal subgroup of $K = \mathrm{SO}(3)$. The α -bundle on \mathcal{P} restricted to an α -circle is roughly a Möbius band.

In this case, α_1 -circles are given by $\{W_1 \subset W_2\}$, where W_2 is a fixed two dimensional subspace of \mathbb{R}^3 and W_1 varies in one dimensional subspaces of W_2 . On the contrary, α_2 -circles are given by $\{W_1 \subset W_2\}$ with W_1 fixed and W_2 varying in two planes which contain W_1 . From this description, we can easily see the G invariance of the set of α circles.

It is better to work on \mathcal{P}_0 , where the α -bundle is trivial. One difficulty is that in the covering space \mathcal{P}_0 , we need to capture the missing information of group M . More precisely, for h in G and z, z' in \mathcal{P}_0 if $h\pi(z), h\pi(z')$ are close, we do not know whether hz, hz' are close or not. This will be answered at the end of Section 2.2.5.

Remark 2.2.18. In an abstract language as in [BQ14, Lemma 4.8], we have a principal bundle $M \rightarrow \mathcal{P}_0 \rightarrow \mathcal{P}$, where the action of M on \mathcal{P}_0 is a right action. We also have a left action of a semigroup Γ in G on \mathcal{P}_0 and \mathcal{P} (Γ will be taken as Γ_μ in our case). Suppose that we have a Γ -minimal set Λ_Γ in \mathcal{P} . The lifting of Λ_Γ to \mathcal{P}_0 has different possibilities. Let η be a point in Λ_Γ and $z = kz_o$ be a lifting in \mathcal{P}_0 . Let $M_z = \{m \in M \mid \Gamma km = \Gamma k\}$. Then we have a nice equivalence

$$\{\Gamma - \text{minimal orbit in } \mathcal{P}_0\} \longleftrightarrow M_z \backslash M.$$

In particular, if Γ is a semigroup of matrices of positive entries, then $M_z = \{e\}$ and Γ has the maximal number of minimal orbits in \mathcal{P}_0 .

2.2.5 The sign group

Recall the notation for Lie groups and Lie algebras. Let N^- be the subgroup with Lie algebra \mathfrak{n}^- . We have a Bruhat decomposition of the Lie group G , where the main part is given by

$$N^- \times M \times A_e \times N \rightarrow G.$$

The image U is a Zariski open subset of G and the map is injective. For elements in U , we can define a map m to the group M , mapping an element g to the part of M in the Bruhat decomposition.

In order to study the M part, we will use fundamental representations defined in Lemma 2.2.1. This is in the same spirit as the treatment of the sign group M in [Ben05]. Let v_α be a non zero eigenvector with highest weight χ_α in V_α . Let sg be the sign function on \mathbb{R} .

Lemma 2.2.19. *For g in U , we have*

$$\text{sg}\langle v_\alpha, \rho_\alpha(g)v_\alpha \rangle = \chi_\alpha^\sharp(\mathfrak{m}(g)),$$

where χ_α^\sharp is the corresponding algebraic character on A of the fundamental weight χ_α .

Proof. Since v_α is N -invariant and the transpose of N^- is N ,

$$\langle v_\alpha, \rho_\alpha(N^-MA_eN)v_\alpha \rangle = \langle \rho_\alpha({}^t(N^-))v_\alpha, \rho_\alpha(MA_eN)v_\alpha \rangle = \langle v_\alpha, \rho_\alpha(MA_e)v_\alpha \rangle.$$

The action of A_e does not change the sign, hence by Lemma 2.2.6 we have

$$\text{sg}\langle v_\alpha, \rho_\alpha(g)v_\alpha \rangle = \text{sg}\langle v_\alpha, \rho_\alpha(\mathfrak{m}(g))v_\alpha \rangle = \chi_\alpha^\sharp(\mathfrak{m}(g)).$$

The proof is complete. \square

In the case $G = \text{SL}_{m+1}(\mathbb{R})$, the algebraic character $\chi_{\alpha_i}^\epsilon$ is given by $\chi_{\alpha_i}^\sharp(a) = a_1 \cdots a_i$ for $a = \text{diag}(a_1, \dots, a_{m+1}) \in A$. Hence we have

Lemma 2.2.20. *The function $\Pi_{\alpha \in \Pi} \chi_\alpha^\sharp : M \rightarrow \mathbb{R}^m$ given by*

$$\Pi_{\alpha \in \Pi} \chi_\alpha^\sharp(m) = (\chi_\alpha^\sharp(m))_{\alpha \in \Pi} \quad \text{for } m \in M,$$

is injective.

Definition 2.2.21. *We define the sign function from $G \times G$ to $M \cup \{0\}$ by*

$$\mathfrak{m}(g, g') = \begin{cases} \mathfrak{m}({}^tgg') & \text{if } {}^tgg' \in U, \\ 0 & \text{if not,} \end{cases}$$

where g, g' in G .

This definition exploits the relation between g and g' . More precisely, for u, v in V_α we have $\langle v, \rho_\alpha({}^tgg')u \rangle = \langle \rho_\alpha gv, \rho_\alpha g'u \rangle$, which explains the definition. Due to ${}^tN = N^-$, the sign function \mathfrak{m} factors through $G/A_eN \times G/A_eN = \mathcal{P}_0 \times \mathcal{P}_0$.

We now explain the sign function for the case $m = 1$, that is $\text{SL}_2(\mathbb{R})$. We only need to consider the representation of $\text{SL}_2(\mathbb{R})$ on \mathbb{R}^2 . Let $v_0 = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$ be a vector with highest weight in \mathbb{R}^2 . Then

$$\langle v_0, {}^tgg'v_0 \rangle = \langle gv_0, g'v_0 \rangle,$$

which is the inner product of the first column of g and g' . The sign function is used to determine whether these two vectors $gv_0, g'v_0$ have an acute angle or not.

By the Bruhat decomposition, we have the following two lemmas.

Lemma 2.2.22. *For g, g' in G and m in M , we have*

$$\mathfrak{m}(g, g'm) = \mathfrak{m}(gm, g') = \mathfrak{m}(g, g')m.$$

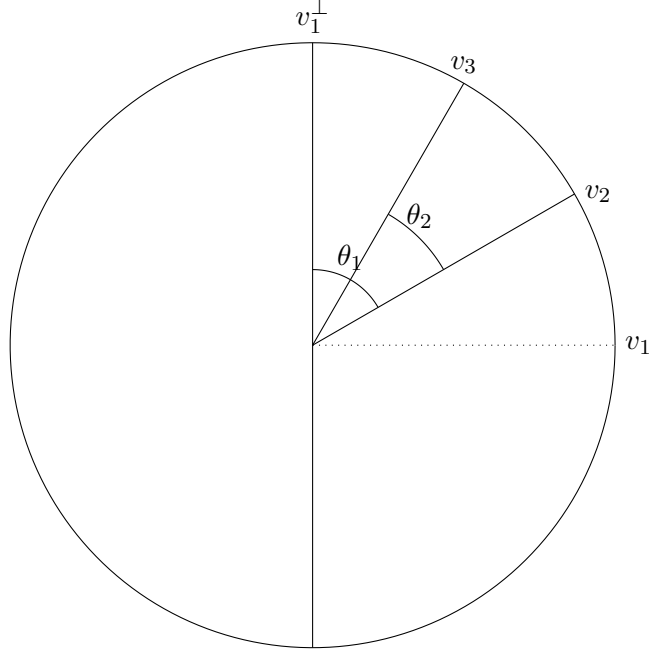


Figure 2.1: Angle

Lemma 2.2.23. *Take a Cartan decomposition of g , that is $g = k_g a_g \ell_g \in KA^+K$. Then for h in G ,*

$$m(k_g, gh) = m(\ell_g^{-1}, h)$$

The key observation here is that the sign function is locally constant. Recall that ζ_o is point in \mathcal{P} and its image in $\mathbb{P}V_\alpha^*$ is the linear functional on V_α which vanishes on the hyperplane perpendicular to V^{χ_α} . Recall that $\delta(\eta, \zeta) = \min_{\alpha \in \Pi} \delta(V_{\alpha, \eta}, V_{\alpha, \zeta}^*)$ and $d(\eta, \eta') = \max_{\alpha \in \Pi} d(V_{\alpha, \eta}, V_{\alpha, \eta'})$.

Lemma 2.2.24. *For k_1, k_2, k_3 in K , if $\delta(k_2 \eta_o, k_1 \zeta_o) > d(k_2 \eta_o, k_3 \eta_o)$, then*

$$m(k_1, k_2) = m(k_1, k_3)m(k_2, k_3).$$

Proof. By definition, we have $\delta(k_2 \eta_o, k_1 \zeta_o) = \delta({}^t k_1 k_2 \eta_o, \zeta_o)$ and $m(k_1, k_2) = m(id, {}^t k_1 k_2)$. Hence, we can suppose that $k_1 = e$, the identity element in K . Lemma 2.2.19 and Lemma 2.2.20 imply that it is sufficient to prove that if $\delta(k_2 \eta_o, \zeta_o) > d(k_2 \eta_o, k_3 \eta_o)$ and $m(k_2, k_3) = e$, then for every simple root α , we have

$$\mathrm{sg}\langle v_\alpha, \rho_\alpha(k_2)v_\alpha \rangle = \mathrm{sg}\langle v_\alpha, \rho_\alpha(k_3)v_\alpha \rangle.$$

Fix a simple root α in Π . Abbreviate $v_\alpha, \rho_\alpha(k_2)v_\alpha, \rho_\alpha(k_3)v_\alpha$ to v_1, v_2, v_3 . Let θ_1 be the angle between the vector v_2 and the hyperplane v_1^\perp and let θ_2 be the angle between

v_2 and v_3 . Due to $m(k_2, k_3) = e$, this implies

$$0 < \langle v_1, {}^t k_2 k_3 v_1 \rangle = \langle k_2 v_1, k_3 v_1 \rangle = \langle v_2, v_3 \rangle,$$

the angle θ_2 is acute. The image of ζ_0 in $\mathbb{P}V_\alpha^*$ is given by $\mathbb{R}\langle v_1, \cdot \rangle$. The hypothesis $\delta(k_2 \eta_o, \zeta_o) > d(k_2 \eta_o, k_3 \eta_o)$ implies that

$$\sin \theta_1 = \langle v_1, v_2 \rangle > \|v_2 \wedge v_3\| = \sin \theta_2.$$

Hence $\theta_2 < \theta_1$ and v_2, v_3 are in the same side of the hyperplane v_1^\perp , which implies $\text{sg}\langle v_1, v_2 \rangle = \text{sg}\langle v_1, v_3 \rangle$. Please see figure 2.1. \square

We state a consequence of Lemma 2.2.24 which will be used in Section 2.4.2 to get independence of certain measures λ_j .

Lemma 2.2.25. *Let $\delta < 1/2$, let g, h be in G and k, k' in K . If h, k, k' satisfy*

$$d(k\eta_o, k'\eta_o) < \delta, k\eta_o, k'\eta_o \in B_h^m(\delta), \eta_h^M \in B_g^m(3\delta) \text{ and } \gamma(h) < \delta^2,$$

then

$$m(k_g, ghk) = m(\ell_g^{-1}, hk')m(k, k').$$

Proof. By Lemma 2.2.22, it is sufficient to prove the case that $m(k, k') = e$. By Lemma 2.2.23,

$$m(k_g, ghk) = m(\ell_g^{-1}, hk). \quad (2.2.20)$$

Denote $k\eta_o, k'\eta_o$ by η, η' . Then by Lemma 2.2.13, we have $h\eta, h\eta' \in b_h^M(\delta) \subset B_g^m(2\delta)$. Hence by $d(h\eta, h\eta') < 2\delta \leq \delta(h\eta, \zeta_g^m) = \delta(h\eta, \ell_g^{-1}\zeta_o)$ and Lemma 2.2.24, we have

$$m(\ell_g^{-1}, hk) = m(\ell_g^{-1}, hk')m(hk, hk'). \quad (2.2.21)$$

The main point here is to prove the following lemma.

Lemma 2.2.26. *Under the same assumption as in Lemma 2.2.25, we have*

$$m(hk, hk') = m(k, k').$$

Combined with (2.2.20) and (2.2.21), the proof is complete. \square

Proof of Lemma 2.2.26. Without loss of generality, suppose that $m(k, k') = e$. Due to $k\eta_o \in B_h^m(\delta)$, we can chose a ℓ_h in the Cartan decomposition $h = k_h a_h \ell_h$ such that $m(\ell_h^{-1}, k) = e$. By Lemma 2.2.24, the hypothesis that $\delta(k\eta_o, \ell_h^{-1}\zeta_o) > \delta > d(k\eta_o, k'\eta_o)$ implies $m(\ell_h^{-1}, k') = m(\ell_h^{-1}, k) = e$. By Lemma 2.2.23, we conclude that $e = m(k_h, hk) = m(\ell_h^{-1}, k) = m(\ell_h^{-1}, k') = m(k_h, hk')$. Here we need a distance d_0 on \mathcal{P}_0 , which is defined in Appendix 2.5.2. Let $z = kz_o$ and $z' = k'z_o$. By Lemma 2.5.5,

$$d_0(hz, hz') \leq d_0(hz, z_h) + d_0(z_h, hz') \leq d(hk\eta_o, \eta_h^M) + d(\eta_h^M, hk'\eta_o). \quad (2.2.22)$$

Hence by (2.2.22), we have $d_0(hz, hz') \leq 2\delta < 1$, which implies $m(hk, hk') = e$ due to Lemma 2.5.5. \square

The proof of Lemma 2.2.26 also says that if z, z' are close and away from the subvariety defined by h , the gap of h is large, then hz, hz' are also close.

2.2.6 Derivative

Let φ be a C^1 function on \mathcal{P}_0 . We will give some property of the directional derivative of φ . We write $\partial_\alpha\varphi$ for the directional derivative $\partial_{Y_\alpha}\varphi$, where α is a simple root. It turns out later that these directions are the major directions when we consider the action of G on \mathcal{P}_0 .

Definition 2.2.27 (Arc length). *Let z_1, z_2 be two points in the same α -circle in \mathcal{P}_0 . If $\mathfrak{m}(z_1, z_2) = e$, we define the arc length distance between z_1, z_2 by*

$$d_A(z_1, z_2) := \arcsin d(\pi z_1, \pi z_2).$$

Remark 2.2.28. *This is a restriction of left K -invariant distance, which can be induced by the K -invariant Riemann metric d_2 in the appendix.*

Lemma 2.2.29 (The Newton-Leibniz formula). *Let z_1, z_2 be two points in the same α -circle on \mathcal{P}_0 such that $\mathfrak{m}(z_1, z_2) = e$. Let $u = d_A(z_1, z_2)$ and let $\gamma : [0, u] \rightarrow \mathcal{P}_0$ be the curve in the α -circle connecting z_1, z_2 with unit speed (in the sense of arc length). Then for g in G*

$$\varphi(gz_1) - \varphi(gz_2) = \pm \int_0^u \partial_\alpha \varphi_{g\gamma(s)} e^{-\alpha\sigma(g, \gamma(s))} ds, \quad (2.2.23)$$

where the sign depends on the direction of γ .

Remark 2.2.30. *The α -circle already has an orientation given by Y_α . The sign is negative if the curve γ is negatively oriented.*

Proof. Without loss of generality, suppose that γ is positively oriented. Recall that $K_\alpha = Y_\alpha - X_\alpha$ for $\alpha \in \Pi$. The images of K_α and Y_α coincide in $\mathfrak{g}/\mathfrak{p}$. Then $k_2 = k_1 \exp(uK_\alpha)$ and $\gamma(s) = k_1 \exp(sK_\alpha)z_o$ for $s \in [0, u]$. By the Newton-Leibniz formula and (2.2.17) we have

$$\begin{aligned} \varphi(gz_2) - \varphi(gz_1) &= \int_0^u d\varphi_{g\gamma(s)} dg_{\gamma(s)} K_\alpha ds = \int_0^u d\varphi_{g\gamma(s)} dg_{\gamma(s)} Y_\alpha ds \\ &= \int_0^u d\varphi_{g\gamma(s)} \exp(-\alpha\sigma(g, \gamma(s))) Y_\alpha ds = \int_0^u \partial_\alpha \varphi_{g\gamma(s)} e^{-\alpha\sigma(g, \gamma(s))} ds. \end{aligned}$$

The proof is complete. □

Since a root α lies in $\Gamma(G)$, the lattice generated by fundamental weights, there is a corresponding algebraic character α^\sharp of A . For m in M and α in Π , by Lemma 2.2.6 with the adjoint representation of G on \mathfrak{g} , due to $Y_\alpha \in \mathfrak{g}^{-\alpha}$, we have $\mathrm{Ad}_m Y_\alpha = (-\alpha)^\sharp(m) Y_\alpha = \alpha^\sharp(m)^{-1} Y_\alpha = \alpha^\sharp(m) Y_\alpha$. The last equality is due to $\alpha^\sharp(m) \in \{\pm 1\}$. Thanks to (2.2.18), we have

Lemma 2.2.31. *Let m be in M and let φ be a C^1 function on \mathcal{P}_0 which is right M -invariant. We have for $z = kz_o$ in \mathcal{P}_0*

$$\partial_\alpha \varphi_{kmz_o} = \alpha^\sharp(m) \partial_\alpha \varphi_z.$$

We say a function φ on \mathcal{P}_0 is the lift of a function on $\mathbb{P}V_\alpha$, if there exists a function φ_1 on $\mathbb{P}V_\alpha$ such that for $z = kz_o \in \mathcal{P}_0$

$$\varphi(z) = \varphi_1(V_{\alpha, k\eta_0}).$$

By Lemma 2.2.15, we have

Lemma 2.2.32. *If φ is a C^1 function on \mathcal{P}_0 , which is the lift of a C^1 function on $\mathbb{P}V_\alpha$, then*

$$\partial_{\alpha'}\varphi = 0 \text{ for } \alpha' \neq \alpha, \alpha' \in \Pi.$$

2.2.7 Changing Flags

This part is trivial for $\mathrm{SL}_2(\mathbb{R})$, where the flag variety $\mathbb{P}(\mathbb{R}^2)$ is a single α -orbit. In this section, we suppose that the rank m is no less than two.

On the flag variety, we have many directions in the tangent space. Roughly speaking, the action of g is contracting and the contraction speed on Y_α is given by $e^{-\alpha\kappa(g)}$, $\alpha \in R^+$. Due to $\kappa(g)$ being in the Weyl chamber \mathfrak{a}^+ , the slowest directions are given by simple roots. Other directions are negligible. The main result Lemma 2.2.40 is a quantitative version of this intuition.

We have already seen that if two points η, η' are in the same α -circle, then we have a nice formula for the difference of the value of a real function φ at $g\eta$ and $g\eta'$, where $g \in G$. We want to do this for η, η' in general position. For this purpose, we need to change the point according to g . This is a key new observation in higher rank.

If we are on the euclidean space \mathbf{E}^n and we are only allowed to move along the directions of coordinate vectors. For any two points x, x' , we can walk from x to x' with at most n moves. But this is not true for the flag variety \mathcal{P} . Suppose that we are only allowed to move along α circles with $\alpha \in \Pi$. Then for two general points η, η' in \mathcal{P} , it takes more than $m = \#\Pi$ moves to walk from one point to the other point. We try to move in each α circle at most one time and to make the resulting points as close as possible.

Recall that V is a finite dimensional vector space with euclidean norm. Let $l = \mathbb{R}(v_1 \wedge v_2)$ be a point in $\mathbb{P}(\wedge^2 V)$, which is also a line in $\mathbb{P}V$.

Lemma 2.2.33. *Let $x = \mathbb{R}w_1$ be a point in $\mathbb{P}V$ and $l = \mathbb{R}(v_1 \wedge v_2)$ be a line in $\mathbb{P}V$. Then we have*

$$d(l, x) := \min_{x' \in l} d(x', x) = \frac{\|v_1 \wedge v_2 \wedge w_1\|}{\|v_1 \wedge v_2\| \|w_1\|}.$$

Proof. The geometric meaning of $\|v_1 \wedge v_2 \wedge w_1\|$ is the volume of the parallelepiped generated by three vectors v_1, v_2, w_1 . This volume can also be calculated as the product of the area of the parallelogram generated by v_1 and v_2 , that is $\|v_1 \wedge v_2\|$, and the distance of w_1 to the plane generated by v_1 and v_2 , that is $d(w_1, \mathrm{Span}(v_1, v_2))$. Hence, we have the formula

$$\|v_1 \wedge v_2 \wedge w_1\| = \|v_1 \wedge v_2\| d(w_1, \mathrm{Span}(v_1, v_2)). \quad (2.2.24)$$

The distance $d(w_1, \mathrm{Span}(v_1, v_2))$ equals $\|w_1\|d(l, x)$, because the geometric sense of $d(l, x)$ is the sine of the angle between the vector w_1 and the plane $\mathrm{Span}(v_1, v_2)$. Together with (2.2.24), we have the result. \square

Lemma 2.2.34. *Let x be a point in $\mathbb{P}V$ and l be a line in $\mathbb{P}V$. If $g \in \mathrm{GL}(V)$ satisfies that $\delta(x, y_g^m), \delta(l, y_{\wedge^2 g}^m) > \delta$, then*

$$d(gl, gx) \leq \delta^{-2} \gamma_{1,3}(g) d(l, x),$$

where $\gamma_{1,3}(g) = \frac{\|\wedge^3 g\|}{\|\wedge^2 g\| \|g\|}$.

Compared with Lemma 2.2.9, with more degree of freedom the contracting speed is significantly greater.

Proof. By definition and $l = \mathbb{R}(v_1 \wedge v_2), x = \mathbb{R}w_1$, we have

$$d(gl, gx) = \frac{\|\wedge^2 g(v_1 \wedge v_2) \wedge gw_1\|}{\|\wedge^2 g(v_1 \wedge v_2)\| \|gw_1\|} \leq \frac{\|\wedge^3 g\| \|v_1 \wedge v_2 \wedge w_1\|}{\|\wedge^2 g(v_1 \wedge v_2)\| \|gw_1\|}$$

Then by Lemma 2.2.7, we have

$$d(gl, gx) \leq \frac{\|\wedge^3 g\| \|v_1 \wedge v_2 \wedge w_1\|}{\delta^2 \|\wedge^2 g\| \|v_1 \wedge v_2\| \|g\| \|w_1\|} = \frac{\|\wedge^3 g\|}{\delta^2 \|\wedge^2 g\| \|g\|} d(l, x).$$

The proof is complete. \square

Lemma 2.2.34 can also be understood that there exists a point $x' = \mathbb{R}v' \in l$ such that $v' \wedge w_1$ is orthogonal to the vector of highest weight in $\wedge^2 V$. Then the distance between gx' and gx will be roughly $\gamma_{1,3}(g)$.

We will start to change the flags. Recall that for $\alpha \in \Pi$ and η, η' in \mathcal{P} , the function $d_\alpha(\eta, \eta')$ is the distance between the images of η and η' in $\mathbb{P}V_\alpha$. If one wants to change a flag in the α -circle in \mathcal{P} , there are some constraints from the structure of flags. We introduce the following definition which explains the constraint.

Definition 2.2.35. *Let*

$$\eta = \{W_1 \subset W_2 \subset \cdots \subset W_{m+1} = \mathbb{R}^{m+1}\}$$

be a flag in \mathcal{P} . Recall that W_r are r -dimensional subspaces of \mathbb{R}^{m+1} . Let i_r be the natural embedding of the Grassmannian to projective spaces, that is $\mathbb{G}_r(\mathbb{R}^{m+1}) \rightarrow \mathbb{P}(\wedge^r \mathbb{R}^{m+1})$. We write

$$l_{r,\eta} = l_{\alpha_r,\eta} := i_r(W_{r+1} \supset W'_r \supset W_{r-1})$$

for a line in $\mathbb{P}(\wedge^r \mathbb{R}^{m+1})$, which is the image of all the r dimensional subspace W'_r of \mathbb{R}^{m+1} such that $W_{r-1} \subset W'_r \subset W_{r+1}$. Take $W_0 = \{0\}$. We also write $l_{r,\eta}$ when the line $l_{r,\eta}$ is seen as a point in $\mathbb{P}(\wedge^2(\wedge^r \mathbb{R}^{m+1}))$.

Recall that $V_{\alpha_r} = \wedge^r V_{\alpha_1} = \wedge^r \mathbb{R}^{m+1}$ and e_1, \dots, e_{m+1} is the standard basis of \mathbb{R}^{m+1} .

Lemma 2.2.36. *The line $l_{r,\eta}$ is the image of the α_r -circle of η in $\mathbb{P}V_{\alpha_r}$.*

Proof. Due to $l_{r,k\eta_0} = kl_{r,\eta_0}$ and the left K invariance of the set of α circles, it is sufficient to consider η_0 . The line l_{r,η_0} is generated by two points $V^{\chi_{\alpha_r}} = \mathbb{R}e_1 \wedge \cdots \wedge e_{r-1} \wedge e_r$ and $V^{\chi_{\alpha_r} - \alpha_r} = \mathbb{R}e_1 \wedge \cdots \wedge e_{r-1} \wedge e_{r+1}$ in $\mathbb{P}V_{\alpha_r}$. By Lemma 2.2.15, this is exactly the image of α_r circle containing η_0 in $\mathbb{P}V_{\alpha_r}$. \square

Definition 2.2.37. *Let $(\eta_0, \eta_1, \dots, \eta_k)$ be a sequence of points in \mathcal{P} . We call it a chain if any consecutive elements η_i, η_{i+1} are in the same α -circle for some $\alpha \in \Pi$, and we write $\alpha(\eta_i, \eta_{i+1})$ for this simple root.*

By the structure of the root system of G , we have

Lemma 2.2.38. *We can separate Π into a disjoint union Π_1 and Π_2 such that for α, α' in the same atom Π_j ,*

$$\alpha + \alpha' \text{ is not a root.}$$

Let $l_1 = \#\Pi_1$ and $l_2 = \#\Pi_2$.

By Lemma 2.2.15

Lemma 2.2.39. *Let (η_0, \dots, η_l) be a chain and let α be a simple root. If the set of simple roots appearing in the chain does not contain α , then the image of the chain in $\mathbb{P}V_{\alpha}$ is a single point, that is*

$$V_{\alpha, \eta_j} = V_{\alpha, \eta_0}, \quad \forall j = 1, \dots, l.$$

Now, we state our main result of this part, which will be used in the main approximation (Proposition 2.4.11).

Lemma 2.2.40. *Let η, η' be two points in \mathcal{P} and let g be in G . If for $\alpha \in \Pi_1$,*

$$\delta(V_{\alpha, \eta'}, y_{\rho_{\alpha}(g)}^m), \delta(l_{\alpha, \eta}, y_{\wedge^2 \rho_{\alpha}(g)}^m) > \delta,$$

for $\alpha \in \Pi_2$,

$$\delta(V_{\alpha, \eta}, y_{\rho_{\alpha}(g)}^m), \delta(l_{\alpha, \eta'}, y_{\wedge^2 \rho_{\alpha}(g)}^m) > \delta.$$

Then we can find two chains $(\eta = \eta_0, \eta_1, \dots, \eta_{l_1})$ and $(\eta' = \eta'_0, \eta'_1, \dots, \eta'_{l_2})$ such that

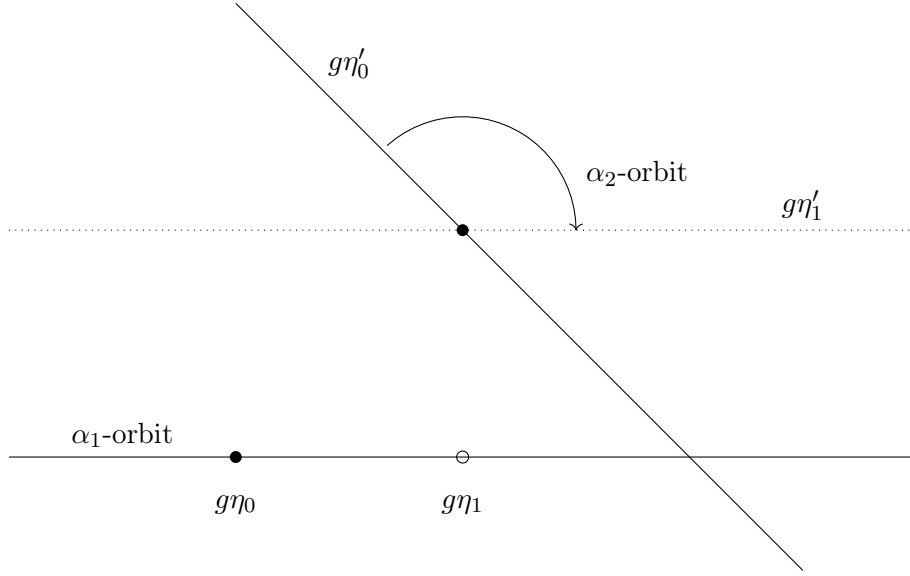
$$d(g\eta_j, g\eta_{j+1}) = d_{\alpha}(g\eta_j, g\eta_{j+1}) = d_{\alpha}(g\eta, g\eta') + O(\delta^{-2}\beta e^{-\alpha\kappa(g)}), \quad (2.2.25)$$

where $\alpha = \alpha(\eta_j, \eta_{j+1}) \in \Pi_1$ and different j correspond to different roots; similarly for η' .

We also have that for all $\alpha \in \Pi$

$$d_{\alpha}(g\eta_{l_1}, g\eta'_{l_2}) \leq \beta e^{-\alpha\kappa(g)} \delta^{-2}, \quad (2.2.26)$$

where β is the gap of g , that is $\beta = \gamma(g) = \max_{\alpha \in \Pi} \{e^{-\alpha\kappa(g)}\}$.

Figure 2.2: Changing Flag for $\mathrm{SL}_3(\mathbb{R})$

The point is that the contraction speed β implies that the term $\delta^{-2}\beta e^{-\alpha\kappa(g)}$ is of smaller magnitude than $e^{-\alpha\kappa(g)}$. The objective is to walk from $g\eta$ to $g\eta'$ only through α circles and to preserve information of distance. Since we can neglect error term, it is simpler to walk from $g\eta$ to $g\eta_{l_1}$ through some α circles and to walk from $g\eta'$ to $g\eta'_{l_2}$ through the other α circles, which means the corresponding simple roots are different from the first walk. After this operation, the distance between $g\eta_{l_1}$ and $g\eta'_{l_2}$ is negligible, due to (2.2.26). The distance of the move in the α circle is approximately the distance between the images of $g\eta$ and $g\eta'$ in $\mathbb{P}V_\alpha$, due to (2.2.25).

Proof of Lemma 2.2.40. If we have already found (η_0, \dots, η_j) and $j < l_1$, we want to find η_{j+1} . Let $\alpha = \alpha_r \in \Pi_1$ be a root that does not appear in the chain. Hence by Lemma 2.2.39,

$$V_{\alpha_r, \eta_j} = V_{\alpha_r, \eta_0} = V_{\alpha_r, \eta}. \quad (2.2.27)$$

Due to Lemma 2.2.38, the neighbour simple roots α_{r-1} and α_{r+1} are not in Π_1 , since $\alpha_{r-1} + \alpha_r$ and $\alpha_{r+1} + \alpha_r$ are roots. By Lemma 2.2.39,

$$V_{\alpha_{r-1}, \eta_j} = V_{\alpha_{r-1}, \eta} \text{ and } V_{\alpha_{r+1}, \eta_j} = V_{\alpha_{r+1}, \eta}.$$

We are in the situation of Lemma 2.2.34 with $V = V_{\alpha_r} = \wedge^r \mathbb{R}^{m+1}$, $x = V_{\alpha_r, \eta'}$ and $l = l_{r, \eta}$. Due to the hypothesis, Lemma 2.2.34 and Lemma 2.2.36, we can find η_{j+1} in the same α_r -circle of η_j such that

$$d_{\alpha_r}(g\eta_{j+1}, g\eta') = d(\rho_{\alpha_r} g V_{\alpha_r, \eta_{j+1}}, \rho_{\alpha_r} g V_{\alpha_r, \eta'}) \leq \delta^{-2} \gamma_{1,3}(\rho_{\alpha_r} g) \leq \delta^{-2} \beta e^{-\alpha_r \kappa(g)}. \quad (2.2.28)$$

Hence by (2.2.27) and (2.2.28),

$$d_{\alpha_r}(g\eta_{j+1}, g\eta_j) = d_{\alpha_r}(g\eta_{j+1}, g\eta) = d_{\alpha_r}(g\eta, g\eta') + O(\delta^{-2}\beta e^{-\alpha_r\kappa(g)}),$$

which is (2.2.25). Please see Figure 2.2, where an element in the flag variety is represented by a projective line with a point.

We need to verify the distance between $g\eta_{l_1}$ and $g\eta'_{l_2}$. Without loss of generality, suppose that $\alpha \in \Pi_1$. Then by Lemma 2.2.39, the construction and (2.2.28),

$$d_\alpha(g\eta_{l_1}, g\eta'_{l_2}) = d_\alpha(g\eta_{l_1}, g\eta') = d_\alpha(g\eta_{j+1}, g\eta') \leq \delta^{-2}\beta e^{-\alpha\kappa(g)},$$

where j is the unique number such that $\alpha(\eta_j, \eta_{j+1}) = \alpha$. \square

Remark 2.2.41. *In the case of $\mathrm{SL}_3(\mathbb{R})$, we know that $\wedge^2 V_{\alpha_1}$ and $\wedge^2 V_{\alpha_2}$ are isomorphic to V_{α_2} and V_{α_1} , respectively. The condition in Lemma 2.2.40 is equivalent to η, η' in $B_g^m(\delta)$.*

In the case of $\mathrm{SL}_{m+1}(\mathbb{R})$, the representations $V_r = \wedge^r \mathbb{R}^{m+1}$ are fundamental representation. Since $\mathrm{SL}_{m+1}(\mathbb{R})$ is split, $\wedge^2 V_r$ is again proximal, but may not be irreducible. In Lemma 2.2.58, we will proceed to give a control on $y_{\wedge^2(\wedge^r g)}^m$.

The condition of Lemma 2.2.40 is not really important, what we need is that the condition is true with a loss of exponentially small measure when we consider the random walks on $\mathrm{SL}_{m+1}(\mathbb{R})$.

Lemma 2.2.42. *With the same assumption and construction in Lemma 2.2.40, if we also have $\eta, \eta' \in B_g^m(\delta)$, then $g\eta_j, g\eta'_l$ are in $b_g^M(\beta\delta^{-O(1)})$ for $1 \leq j \leq l_1$ and $1 \leq l \leq l_2$.*

Proof. By hypothesis, Lemma 2.2.13 implies that $g\eta, g\eta' \in b_g^M(\beta\delta^{-1})$. By (2.2.25),

$$d(g\eta_j, g\eta_{j+1}) \leq 2\beta\delta^{-1} + O(\delta^{-2}\beta e^{-\alpha\kappa(g)}) \leq \beta\delta^{-O(1)}.$$

Hence by induction, we have $g\eta_j \in b_g^M(\beta\delta^{-O(1)})$ for all j . Similarly the results hold for $g\eta'_l$. \square

2.2.8 Random walks and Large deviation principles

The study of random walks on projective spaces and flag varieties are connected by representation theory.

Let X be \mathcal{P} or $\mathbb{P}V$, where V is an irreducible representation of G . There is a natural group action of G on X . Let μ be a Borel probability measure on G . Then a Borel probability measure ν on X is called μ -stationary if

$$\nu = \mu * \nu := \int_G g_* \nu d\mu(g),$$

where $g_* \nu$ is the pushforward measure of ν under the action of g on X .

Lemma 2.2.43 (Furstenberg). *Let μ be a Zariski dense Borel probability measure on G . There exists a unique μ -stationary probability measure ν on the flag variety and its images in the projective spaces $\mathbb{P}V$ are the unique μ -stationary probability measures when V is an irreducible representation of G .*

See [Fur73], [BQ16, Proposition 10.1] for more details. In order to distinguish stationary measures on different spaces, we use ν_V to denote a μ -stationary measure on $\mathbb{P}V$.

Definition 2.2.44. *Let μ be a Zariski dense Borel probability measure with exponential moment on G . The Lyapunov constant σ_μ is defined as the average of the Iwasawa cocycle*

$$\sigma_\mu := \int_{G \times \mathcal{P}} \sigma(g, \eta) d\mu(g) d\nu(\eta).$$

Lemma 2.2.45. *Let μ be a Zariski dense Borel probability measure with exponential moment on G . Then the Lyapunov constant σ_μ is in \mathfrak{a}^{++} , the interior of the Weyl chamber. Equivalently, for any simple root α , we have $\alpha(\sigma_\mu) > 0$.*

The maximal positivity of Lyapunov constant in Lemma 2.2.45 is due to Guivarc'h-Raugi [GR85] and Goldsheid-Margulis [GM89]. See [BQ16, Corollary 10.15] for more details. Lemma 2.2.45 will be used to show that the action of G on \mathcal{P} is contracting in Section 2.4.2, where the contraction speed is given by $\beta = \sup_{\alpha \in \Pi} \{e^{-\alpha\sigma_\mu}\}$.

In following proposition, we give the large deviation principle for the Cartan projection. We keep the assumption that μ is a **Zariski dense Borel probability measure on G with a finite exponential moment**.

Proposition 2.2.46. *For every $\epsilon > 0$ there exist $C, c > 0$ such that for all $n \in \mathbb{N}$ and $\eta \in \mathcal{P}$ we have*

$$\mu^{*n} \{g \in G \mid \|\kappa(g) - n\sigma_\mu\| \geq n\epsilon\} \leq Ce^{-c\epsilon n}, \quad (2.2.29)$$

See [BQ16, Thm 13.17] for more details.

Proposition 2.2.47. *If (ρ, V) is an irreducible representation of G , then for every $\epsilon > 0$ there exist C, c such that for all x in $\mathbb{P}V$ and y in $\mathbb{P}V^*$ and $n \geq 1$ we have*

$$\begin{aligned} \mu^{*n} \{g \in G \mid \delta(x, y_g^m) \leq e^{-n\epsilon}\} &\leq Ce^{-c\epsilon n}, \\ \mu^{*n} \{g \in G \mid \delta(x_g^M, y) \leq e^{-n\epsilon}\} &\leq Ce^{-c\epsilon n}. \end{aligned} \quad (2.2.30)$$

See [BQ16, Prop 14.3] for more details. Attention, we need ρ to be proximal in Proposition 2.2.47. Here the representation is automatically proximal due to the splittness of G .

Proposition 2.2.48. *For every $\epsilon > 0$ there exist C, c such that for all η, η' in \mathcal{P} and $n \geq 1$ we have*

$$\mu^{*n} \{g \in G \mid \delta(\eta_g^M, \zeta) \leq e^{-n\epsilon}\} \leq Ce^{-c\epsilon n}, \quad (2.2.31)$$

$$\mu^{*n} \{g \in G \mid \delta(\eta, \zeta_g^m) \leq e^{-n\epsilon}\} \leq Ce^{-c\epsilon n}, \quad (2.2.32)$$

Proposition 2.2.48 is a multidimensional version of Proposition 2.2.47.

Proposition 2.2.49 (Hölder regularity). *If (ρ, V) is an irreducible representation of G , then there exist constants $C > 0, c > 0$ such that for every y in $\mathbb{P}V^*$ and $r > 0$ we have*

$$\nu_V(\{x \in \mathbb{P}V \mid \delta(x, y) \leq r\}) \leq Cr^c. \quad (2.2.33)$$

The proximality of the representation is also needed in Proposition 2.2.49. This result is due to Guivarc'h [Gui90]. See [BQ16, Thm 14.1] for more details. As a corollary of Proposition 2.2.49, we have the following.

Corollary 2.2.50. *If (ρ, V) is an irreducible representation of G with highest weight χ , then there exist constants $C > 0, c > 0$ such that for every y in $\mathbb{P}V^*$ and $r > 0$ we have*

$$\nu(\{\eta \in \mathcal{P} \mid \delta(V_{\chi, \eta}, y) \leq r\}) \leq Cr^c. \quad (2.2.34)$$

Proof. By Lemma 2.2.43, we have

$$\nu(\{\eta \in \mathcal{P} \mid \delta(V_{\chi, \eta}, y) \leq r\}) = \nu_V(\{x \in \mathbb{P}V \mid \delta(x, y) \leq r\}).$$

Hence Corollary 2.2.50 follows from Proposition 2.2.49. \square

All the results in this section mean that the quantities considered here are really flexible. We can always imagine that things happen as wished in a large probability, a very positive expectation. Bad things are near some algebraic subvariety and have exponential small measures. For later convenience, we introduce the following definition.

Definition 2.2.51 (Good element). *For $n \in \mathbb{N}, \epsilon > 0$ and $\eta, \zeta \in \mathcal{P}$, we say that an element h is $(n, \epsilon, \eta, \zeta)$ good if*

$$\|\kappa(h) - n\sigma_\mu\| \leq \epsilon n / C_A \text{ and } \delta(\eta, \zeta_h^m), \delta(\eta_h^M, \zeta) > 2e^{-\epsilon n / C_A}, \quad (2.2.35)$$

where C_A is a constant greater than 2, which is only depend on the whole group and will be determined in Lemma 2.2.53.

Lemma 2.2.52. *We have that h is $(n, \epsilon, \eta, \zeta)$ good outside an exponentially small set, that is to say there exist $C > 0, c > 0$ such that*

$$\mu^{*n}\{h \text{ is not } (n, \epsilon, \eta, \zeta) \text{ good.}\} \leq Ce^{-c\epsilon n}.$$

Proof. This is due to the large deviation principle (2.2.29), (2.2.31) and (2.2.32). \square

Lemma 2.2.53. *Let $\delta = e^{-\epsilon n}$ and $\beta = \max_{\alpha \in \Pi} e^{-\alpha \sigma_\mu n}$. Suppose that ϵ is small enough such that $\beta < \delta^3$. If h is $(n, \epsilon, \eta, \zeta_g^m)$ good, then*

$$\gamma(h) \leq \beta \delta^{-1} \leq \delta^2 \text{ and } \|\sigma(gh, \eta) - \kappa(g) - n\sigma_\mu\| \leq \epsilon n.$$

Proof. By hypothesis,

$$\gamma(h) = \max_{\alpha \in \Pi} e^{-\alpha \kappa(h)} = \sup_{\alpha \in \Pi} e^{-\alpha n \sigma_\mu} e^{\alpha(n\sigma_\mu - \kappa(h))} \leq \beta \delta^{-1},$$

if we take C_A large enough such that for all simple roots α and X in \mathfrak{a} , we have $|\alpha(X)| \leq C_A \|X\|$.

By Lemma 2.2.13, we have $h\eta \in b_h^M(\gamma(h)/\delta) \subset b_h^M(\delta) \subset B_g^m(\delta)$. Hence by Lemma 2.2.12

$$\begin{aligned} \|\sigma(gh, \eta) - \kappa(g) - n\sigma_\mu\| &= \|\sigma(g, h\eta) - \kappa(g) + \sigma(h, \eta) - n\sigma_\mu\| \\ &\ll |\log \delta(h\eta, \zeta_g^m)| + |\log \delta(\eta, \zeta_h^m)| + \|\kappa(h) - n\sigma_\mu\| \ll \epsilon n / C_A. \end{aligned}$$

Hence if C_A is large enough depending on the whole group, the inequality holds. \square

For later usage in Section 2.3, we will define another notation of goodness.

Definition 2.2.54. For $n \in \mathbb{N}, \epsilon > 0$ and $\zeta \in \mathcal{P}$, we say that an element h is (n, ϵ, ζ) good if

$$\|\kappa(h) - n\sigma_\mu\| \leq \epsilon n / C_A \text{ and } \delta(\eta_h^M, \zeta) > 2e^{-\epsilon n / C_A}. \quad (2.2.36)$$

Lemma 2.2.55. Let $\delta = e^{-\epsilon n}$ and $\beta = \max_{\alpha \in \Pi} e^{-\alpha \sigma_\mu^n}$. Let η_d be a flag which is different from η_o only in d -dimensional subspace, that is

$$\eta_d = \{\mathbb{R}e_1 \subset \cdots \subset \mathbb{R}e_1 \oplus \cdots \oplus \mathbb{R}e_{d-1} \subset \mathbb{R}e_1 \oplus \cdots \oplus \mathbb{R}e_{d-1} \oplus \mathbb{R}e_{d+1} \subset \cdots\}. \quad (2.2.37)$$

If h is (n, ϵ, ζ_g^m) good, then for $\eta = l_h^{-1} \eta_d$, we have

$$e^{\chi_j(\sigma(gh, \eta) - \kappa(g) - n\sigma_\mu)} \in [\delta, \delta^{-1}] \text{ for } j \neq d \text{ and } e^{\chi_d(\sigma(gh, \eta) - \kappa(g) - n\sigma_\mu)} \leq \beta \delta^{-1}. \quad (2.2.38)$$

Proof. Without loss of generality, we can suppose that $l_h = e$. The image of η_d in $\mathbb{P}V_j$ is the same as η_o if $j \neq d$. Hence by (2.2.2), we have $\chi_j \sigma(gh, \eta_d) = \chi_j \sigma(gh, \eta_o)$ for $j \neq d$. By (2.2.13), that is $\delta(\eta_o, \zeta_o) = 1$, the element h is $(n, \epsilon, \eta_o, \zeta_g^m)$ good. By Lemma 2.2.53, we obtain the first part of (2.2.38).

The image of η_d in $\mathbb{P}V_d$ is $\mathbb{R}v = \mathbb{R}(e_1 \wedge \cdots \wedge e_{d-1} \wedge e_{d+1})$, whose weight is $\chi_d - \alpha_d$. Hence by (2.2.2),

$$\chi_d \sigma(h, \eta_d) = \log \frac{\|hv\|}{\|v\|} = \log \frac{\|\exp(\kappa(h))v\|}{\|v\|} = (\chi_d - \alpha_d) \kappa(h). \quad (2.2.39)$$

By (2.2.2) and (2.2.3), we have $\chi_d(\sigma(g, h\eta) - \kappa(g)) \leq 0$. Together with (2.2.39),

$$e^{\chi_d(\sigma(gh, \eta) - \kappa(g) - n\sigma_\mu)} = e^{\chi_d(\sigma(g, h\eta) - \kappa(g))} e^{\chi_d(\sigma(h, \eta) - n\sigma_\mu)} \leq e^{(\chi_d - \alpha_d) \kappa(h) - n\chi_d \sigma_\mu} = e^{-\alpha_d \kappa(h)}.$$

By (2.2.36), the proof is complete. \square

This Lemma tells us that by changing the image of η in one projective space, the value of Iwasawa cocycle only changes in that space. There is some independence of the value of Iwasawa cocycle with respect to η .

Let V be a representation of G . Let $\mathbb{G}_2(V) := \{2\text{-planes in } V\}$ be the Grassmannian variety of V . Let $q_\lambda : \wedge^2 V \rightarrow \wedge^2 V$ be the G -equivalent projection on the sum of all the irreducible subrepresentations of $\wedge^2 V$ with highest weight equal to λ .

Lemma 2.2.56. *Let V be an irreducible representation of G with highest weight χ . For a simple root α , let $q_{2\chi-\alpha}$ be the G -equivalent projection from $\wedge^2 V$ to $\wedge^2 V$. There exists $c > 0$ such that for all v, v' in V*

$$\sum_{\alpha \in \Pi} \|q_{2\chi-\alpha}(v \wedge v')\| \geq c \|v \wedge v'\|.$$

Proof. By Lemma 2.2.57, we know that $\frac{\sum_{\alpha \in \Pi} \|q_{2\chi-\alpha}(v \wedge v')\|}{\|v \wedge v'\|} : \mathbb{G}_2(V) \rightarrow \mathbb{R}_{\geq 0}$ is a positive continuous function. Since $\mathbb{G}_2(V)$ is a compact space, on which positive continuous function has a lower bound, the result follows. \square

The following lemma is similar to [BQ12, Lemma 3.3].

Lemma 2.2.57. *With the same assumption as in Lemma 2.2.56, then $\bigcap_{\alpha \in \Pi} q_{2\chi-\alpha}$ does not contain any pure wedge.*

Proof. Let W' be the intersection of all the kernels, that is $W' = \bigcap_{\alpha \in \Pi} \ker q_{2\chi-\alpha}$. The two sets $\mathbb{G}_2(V)$ and $\mathbb{P}W'$ are closed subset of $\mathbb{P}(\wedge^2 V)$ and G invariant. Therefore their intersection is again a G invariant closed subvariety which is complete. Let B be the Borel subgroup of G , which is solvable. By [Bor90, Thm.10.4], the action of a solvable algebraic connected group on a complete variety has fixed points. We claim that the fixed points of B on $\mathbb{G}_2(V)$ are the lines with the highest weight. Then the result follows by the fact that these lines do not belong to W' .

Suppose that there exist v, u in V such that $v \wedge u$ is B invariant. We can decompose v, u as a sum $v = \sum_{\lambda} v_{\lambda}$ and $u = \sum_{\lambda} u_{\lambda}$. Since we can replace v, u by bv, bu for b in B , we can suppose that the component of highest weight v_{χ} is non zero. Since the dimension of V^{χ} is 1, we can suppose that $u_{\chi} = 0$. Let $\rho \neq \chi$ be a highest weight such that u_{ρ} is nonzero. The B invariance of $\mathbb{R}(v \wedge u)$ also implies that the action of X_{α} , for α simple roots, fixes the line. Hence $X_{\alpha}(v \wedge u) = X_{\alpha}v \wedge u + v \wedge X_{\alpha}u \in \mathbb{R}v \wedge u$. The weight $\chi + \rho + \alpha$ is higher than all the weights appear in $v \wedge u$, hence $v_{\chi} \wedge X_{\alpha}u_{\rho} = 0$ for all simple roots α . This implies that $\rho = \chi - \alpha$ for some simple root α . Therefore $v \wedge u$ contains $v_{\chi} \wedge u_{\chi-\alpha}$. Since $v \wedge u$ is also A invariant, all the components in the weight decomposition have the same weight. Hence $v \wedge u = v_{\chi} \wedge u_{\chi-\alpha}$ which is a vector of highest weight in $\wedge^2 V$. \square

We want to prove a large deviation principle for a special reducible representation. This lemma will be used in Lemma 2.4.10 to control $y_{\wedge^2 g}^m$ in Lemma 2.2.9 and Lemma 2.2.40.

Lemma 2.2.58. *Let V be a super proximal representation of G (Definition 2.2.2). For $\epsilon > 0$ there exist $C, c > 0$ such that the following holds. For $x = \mathbb{R}v, x' = \mathbb{R}v' \in \mathbb{P}V$ with $x \neq x'$, we have*

$$\mu^{*n}\{g \in G \mid \delta(x \wedge x', y_{\wedge^2 \rho(g)}^m) < e^{-cn}\} \leq Ce^{-c\epsilon n}.$$

Due to Definition 2.2.2, there is only one simple root α such that $q_{2\chi-\alpha}(\wedge^2 V)$ is non zero. Write $\wedge^2 V = W \oplus W'$, where W is the irreducible representation generated by the vector corresponding to the highest weight in $\wedge^2 V$, and W' is the G -invariant complementary subspace. Then $q_{2\chi-\alpha}(\wedge^2 V) = W$, and we write $Pr_W = q_{2\chi-\alpha}$.

Proof of Lemma 2.2.58. By (2.2.10), we see that a non zero vector in $y_{\wedge^2 g}^m$ vanishes on W' and $y_{\wedge^2 g}^m$ can be seen as an element in $\mathbb{P}W^*$. We only need to consider the projection of $v \wedge v'$ onto W and use large deviation principle (2.2.30). By Lemma 2.2.56,

$$\delta(x \wedge x', y_{\wedge^2 g}^m) = \frac{|f(v \wedge v')|}{\|v \wedge v'\|} = \frac{|f(Pr_W(v \wedge v'))|}{\|Pr_W(v \wedge v')\|} \frac{\|Pr_W(v \wedge v')\|}{\|v \wedge v'\|} \geq c\delta(Pr_W(x \wedge x'), y_{\wedge^2 g}^m),$$

where f is a unit vector in $y_{\wedge^2 g}^m$. The proof is complete. \square

2.3 Non concentration condition

We want to verify the main input for the sum-product estimate, the non concentration condition. If we want to get the non concentration directly, then this becomes an effective local limit estimate, which is difficult due to the lack of spectral gap. Hence, we transfer it to the Hölder regularity of stationary measure.

For the first time read, the reader can neglect g in the left of h . The main idea of the proof is already there. Adding g is a technical step, which is needed in its application. (We only need an additional condition on η_h^M to control $\kappa(gh)$.)

2.3.1 Projective, Weak and Strong non concentration

Recall that m is the real rank of G and χ_1, \dots, χ_m are the fundamental weights, where we change the subscript from $\alpha \in \Pi$ to $i \in \{1, \dots, m\}$. Recall that $\alpha_1, \dots, \alpha_m$ are the simple roots of \mathfrak{a}^* , which are linear combinations of fundamental weights χ_i with integral coefficients.

In order to distinguish different objects, we will use capital letter X to denote functions or random variables and use small letter x to denote vectors or indeterminates.

Let L be the $d \times d$ square matrix which changes the basis (χ_1, \dots, χ_m) of \mathfrak{a}^* to the basis $(-\alpha_1, \dots, -\alpha_m)$, that is $L_{ij} = -\alpha_i(H_j)$. Then L is an integer matrix. Hence, we can define E_d , a rational map from $(\mathbb{R}^*)^m$ to $(\mathbb{R}^*)^d$, which is given by $y = E_d(x)$ for $x \in (\mathbb{R}^*)^m$ where

$$y_i = \prod_{1 \leq j \leq m} x_j^{L_{ij}}.$$

Fix an element g in G . Let

$$\begin{aligned} X_g(n, h, \eta) &= (e^{\chi_1(\sigma(gh, \eta) - \kappa(g) - n\sigma_\mu)}, \dots, e^{\chi_m(\sigma(gh, \eta) - \kappa(g) - n\sigma_\mu)}), \\ Y_g^n(h, \eta) &= (e^{-\alpha_1(\sigma(gh, \eta) - \kappa(g) - n\sigma_\mu)}, \dots, e^{-\alpha_m(\sigma(gh, \eta) - \kappa(g) - n\sigma_\mu)}) \end{aligned}$$

for η in \mathcal{P} and h in G . By definition, $E_d X_g(n, h, \eta)$ is the vector which is composed of the first d components of $Y_g^n(h, \eta)$, that is

$$p_d Y_g^n(h, \eta) = E_d X_g(n, h, \eta), \quad (2.3.1)$$

where $p_d : \mathbb{R}^m \rightarrow \mathbb{R}^d$ is the map which takes a vector x of \mathbb{R}^m to the vector of \mathbb{R}^d composed of the first d components of x . In the following argument g is fixed or g equals identity. Hence we will abbreviate X_g, Y_g^n, Y_e^n to X, Y^n, Y_0^n .

We define an affine determinant A_d on $(\mathbb{R}^d)^{d+1}$. For $d+1$ vectors y^1, \dots, y^{d+1} in \mathbb{R}^d , let A_d be the determinant of the $(d+1) \times (d+1)$ matrix $\begin{pmatrix} y^1 & \dots & y^{d+1} \\ 1 & \dots & 1 \end{pmatrix}$, which is the volume of the $d+1$ -dimensional parallelogram generated by vectors $(y^i, 1)$ for $i = 1, \dots, d+1$. Let e_i be the vector in \mathbb{R}^d with only i -th coordinate nonzero and equal to 1. By identifying $e_1 \wedge \dots \wedge e_d$ with number 1, we can also define A_d by

$$A_d(y^1, \dots, y^{d+1}) = \sum_{1 \leq i \leq d+1} (-1)^{i+d+1} y^1 \wedge \dots \wedge \widehat{y^i} \wedge \dots \wedge y^{d+1}.$$

For $d+1$ vectors x^1, \dots, x^{d+1} in \mathbb{R}^m , let B_d be a rational function defined by

$$B_d(x^1, \dots, x^{d+1}) = A_d(E_d x^1, \dots, E_d x^{d+1}).$$

We introduce the notation

$$\mathbf{h}_{d+1} = (h_1, \dots, h_{d+1}),$$

which is an element in $G^{\times(d+1)}$. Let

$$A_d^n(\mathbf{h}_{d+1}, \eta) := B_d(X(n, h_1, \eta), \dots, X(n, h_{d+1}, \eta)).$$

Definition 2.3.1. We say that μ satisfies the projective non concentration (PNC) on dimension d , if for every $\epsilon > 0$ there exist $c, C > 0$ such that for all n in \mathbb{N} , η in \mathcal{P} and g in G

$$\sup_{a \in \mathbb{R}, v \in \mathbb{S}^{d-1}} \mu^{*n} \{h \in G \mid |\langle v, Y^n(h, \eta) \rangle - a| \leq e^{-\epsilon n}\} \leq C e^{-c\epsilon n},$$

where v is regarded as a vector in $\mathbb{R}^d \times \{0\}^{m-d} \subset \mathbb{R}^m$.

More geometrically, this is equivalent to say that the measure of $Y^n(h, \eta)$ close to an affine hyperplane is exponentially small.

Definition 2.3.2. We say that μ satisfies the weak non concentration (WNC) on dimension d , if for every $\epsilon > 0$ there exist $c, C > 0$ such that for all n in \mathbb{N} , η in \mathcal{P} and g in G

$$(\mu^{*n})^{\otimes(d+2)}\{(\mathbf{h}_{d+1}, \ell) \in G^{\times(d+2)} \mid |A_d^n(\mathbf{h}_{d+1}, \ell\eta)| \leq e^{-\epsilon n}\} \leq Ce^{-c\epsilon n}.$$

Definition 2.3.3. We say that μ satisfies the strong non concentration (SNC) on dimension d , if for every $\epsilon > 0$ there exist $c, C > 0$ such that for all n in \mathbb{N} , η in \mathcal{P} and g in G

$$(\mu^{*n})^{\otimes(d+1)}\{\mathbf{h}_{d+1} \in G^{\times(d+1)} \mid |A_d^n(\mathbf{h}_{d+1}, \eta)| \leq e^{-\epsilon n}\} \leq Ce^{-c\epsilon n}.$$

We will proceed by induction. When $d = 0$, we make the convention that $A_0^d = 1$ and it is trivial that SNC holds. Then

- SNC on dimension $d \Rightarrow$ WNC on dimension d (By definition)
- PNC on dimension $d \Leftrightarrow$ SNC on dimension d (Lemma 2.3.7)
- WNC on dimension $d \Rightarrow$ PNC on dimension d (Lemma 2.3.9)
- SNC on dimension $d - 1 \Rightarrow$ WNC on dimension d (Lemma 2.3.10).

In the above implications, the constants C, c will change. We can conclude

Proposition 2.3.4. Let μ be a Zariski dense Borel probability measure on G with exponential moment. Then μ satisfies PNC on dimension m .

2.3.2 Away from affine hyperplanes

We need a lemma of linear algebra, which relates different non concentrations. This lemma is already known from [EMO05, Lemma 7.5]. Recall that for two subsets A, B of a metric space (X, d) , the distance between A and B is defined as

$$d(A, B) = \inf_{x \in A, y \in B} d(x, y)$$

Lemma 2.3.5. Let $C > 0, c > 0$. Let u_1, \dots, u_{d+1} be vectors in \mathbb{R}^d with length less than C . Consider the following conditions:

- i. There exists an affine hyperplane l such that for $i = 1, \dots, d + 1$,

$$d(u_i, l) \leq c.$$

- ii. We have

$$\left\| \sum_{1 \leq i \leq d+1} (-1)^i u_1 \wedge \dots \wedge \widehat{u}_i \wedge \dots \wedge u_{d+1} \right\| < c,$$

where \widehat{u}_i means this term is not in the wedge product.

iii. There exists i in $\{1, \dots, d\}$ such that

$$d(u_i, \text{Span}_{\text{aff}}(u_{d+1}, u_1, \dots, u_{i-1})) < c,$$

where Span_{aff} is the affine subspace generated by the elements in the bracket.

Then $i(c) \Rightarrow ii(2^{d+1}C^{d-1}c)$, $ii(c) \Rightarrow iii(c^{1/d})$ and $iii(c) \Rightarrow i(c)$.

Proof. We first transfer the affine problem to a linear problem. Let $v_i = u_i - u_{d+1}$ for $i = 1, \dots, d$. Then v_i are vectors with length less than $2C$. The above three conditions are equivalent to (with change of constants in i)

i'. There exists a linear subspace l of codimension 1 such that for $i = 1, \dots, d$

$$d(v_i, l) \leq c.$$

ii'. We have

$$\|v_1 \wedge \dots \wedge v_d\| < c.$$

iii'. There exists i such that

$$d(v_i, \text{Span}(v_1, \dots, v_{i-1})) < c,$$

where Span is the linear subspace generated by the elements in the bracket.

$iii'(c) \Rightarrow i'(c)$: Let the hyperplane l be $\text{Span}(v_1, \dots, \hat{v}_i, \dots, v_d)$. Then $i'(c)$ follows from $iii'(c)$.

$i'(c) \Rightarrow ii'(2^d C^{d-1} c)$: Due to i' , the volume of the parallelogram generated by $\{v_i\}_{1 \leq i \leq d}$ is less than $(2C)^{d-1} 2c$, which is ii' .

$ii'(c) \Rightarrow iii'(c^{1/d})$: Due to the same argument as in Lemma 2.2.33, we have a formula of volume,

$$\|v_1 \wedge \dots \wedge v_d\| = \prod_{1 \leq i \leq d} d(v_i, \text{Span}(v_1, \dots, v_{i-1})),$$

from which the result follows. \square

As a corollary, we have the following lemma, which is general and deals with random variables.

Corollary 2.3.6. *Let X_1, \dots, X_{d+1} be i.i.d. random vectors in \mathbb{R}^d bounded by $C > 0$. Let l be an affine hyperplane in \mathbb{R}^d . Then for any $c > 0$, we have*

$$\mathbb{P}\{d(X_1, l) < c\}^{d+1} \leq \mathbb{P}\{\|\sum (-1)^i X_1 \wedge \dots \wedge \hat{X}_i \wedge \dots \wedge X_{d+1}\| < 2^{d+1} C^{d-1} c\}, \quad (2.3.2)$$

and

$$\begin{aligned} & \mathbb{P}\{\|\sum (-1)^i X_1 \wedge \dots \wedge \hat{X}_i \wedge \dots \wedge X_{d+1}\| < c\} \\ & \leq \sum_{1 \leq i \leq d} \mathbb{P}\{d(X_i, \text{Span}_{\text{aff}}(X_{d+1}, X_1, \dots, X_{i-1})) < c^{1/d}\}. \end{aligned} \quad (2.3.3)$$

Lemma 2.3.7. *PNC on dimension d is equivalent to SNC on dimension d .*

Proof. Let $X_i = E_d X(n, h_i, \eta)$ for $i = 1, \dots, d+1$, where h_i has distribution μ^{*n} . Due to Lemma 2.2.53, with a loss of exponentially small measure, we can suppose that X_i are bounded by $C = e^{\epsilon_2 n}$, where $\epsilon_2 = \epsilon/(2d)$.

Due to (2.3.1), we have $\langle v, Y^n(h, \eta) \rangle = \langle p_d v, E_d X(n, h, \eta) \rangle$. PNC asks exactly that the probability that $E_d X$ is close to a hyperplane is small. By (2.3.2), PNC on dimension d follows from SNC on dimension d .

By (2.3.3), SNC on dimension d follows from PNC on dimension d . \square

Remark 2.3.8. *We explain that SNC implies the stronger form of SNC, which will be used later. Let $\mathrm{O}(d)$ be the orthogonal group in dimension d . The stronger form of SNC says that for any $(\rho_1, \dots, \rho_{d+1}) \in \mathrm{O}(d)^{\times(d+1)}$, we have*

$$(\mu^{*n})^{\otimes(d+1)} \{ \mathbf{h}_{d+1} \in G^{\times(d+1)} \mid |A_d(\rho_1 E_d X(n, h_1, \eta), \dots, \rho_{d+1} E_d X(n, h_{d+1}, \eta))| \leq e^{-\epsilon n} \} \leq C e^{-c\epsilon n}.$$

By Lemma 2.3.7, SNC implies PNC. We adopt the notation in the proof of Lemma 2.3.7. By (2.3.3) and the fact that $\mathrm{O}(d)$ preserves the distance,

$$\begin{aligned} & \mathbb{P} \{ \left\| \sum_{i=1}^d (-1)^i \rho_1 X_1 \wedge \dots \wedge \widehat{\rho_i X_i} \wedge \dots \wedge \rho_{d+1} X_{d+1} \right\| < c \} \\ & \leq \sum_{1 \leq i \leq d} \mathbb{P} \{ d(\rho_i X_i, l_i) < c^{1/d} \} = \sum_{1 \leq i \leq d} \mathbb{P} \{ d(X_i, \rho_i^{-1} l_i) < c^{1/d} \}, \end{aligned}$$

where $l_i = \mathrm{Span}_{\mathrm{aff}}(\rho_{d+1} X_{d+1}, \rho_1 X_1, \dots, \rho_{i-1} X_{i-1})$. Therefore SNC implies the stronger form of SNC.

Lemma 2.3.9. *WNC on dimension d implies PNC on dimension d .*

WNC is weaker than SNC, because WNC is not uniform on position η . Let $f(\eta)$ be $(\mu^{*n})^{\otimes(d_2)} \{ \dots \eta \}$ in SNC (Definition 2.3.3). Then WNC only asks that $\int f(\eta) d\mu^{*n}(\eta)$ is small, whereas SNC asks that $f(\eta)$ is small for every η . The cocycle property is the key point to obtain an estimate uniform on position from an estimate not uniform on position.

Proof of Lemma 2.3.9. Let $\delta = e^{-\epsilon n}$. We first prove the result for $2n$. Recall that h is a random variable which takes values in G with the distribution μ^{*2n} . Let $h = \ell_1 \ell$ such that ℓ_1 and ℓ have distribution μ^{*n} . Then the cocycle property implies $Y^n(h, \eta) = Y^n(\ell_1 \ell, \eta) = Y^n(\ell_1, \ell \eta) Y_0^n(\ell, \eta)$. Fubini's theorem implies

$$\begin{aligned} E & := \sup_{a, v} \mu^{*2n} \{ h \mid \langle v, Y^{2n}(h, \eta) \rangle \in B(a, \delta) \} \\ & \leq \int_G \sup_{a, v} \mu^{*n} \{ \ell_1 \mid \langle v, Y^n(\ell_1, \ell \eta) Y_0^n(\ell, \eta) \rangle \in B(a, \delta) \} d\mu^{*n}(\ell). \end{aligned}$$

The cocycle property is crucial here. Fix ℓ and fix a, v . We can write

$$\langle v, Y^n(\ell_1, \ell \eta) Y_0^n(\ell, \eta) \rangle = R \langle v', Y^n(\ell_1, \ell \eta) \rangle,$$

where $R = \|v \cdot Y_0^n(\ell, \eta)\| \geq \min_{1 \leq j \leq d} |Y_0^n(\ell, \eta)_j|$. Here v' is a vector of norm 1, defined by $v' = v \cdot Y_0^n(\ell, \eta)/R$, depending on v, l and η . By Lemma 2.2.52 and Lemma 2.2.53, for ℓ outside an exponentially small set independent of a, v , we have $R \geq \delta^{1/2}$. Therefore

$$E \leq \int_G \sup_{a,v} \mu^{*n} \{ \ell_1 | \langle v, Y^n(\ell_1, \ell\eta) \rangle \in B(a, \delta^{1/2}) \} d\mu^{*n}(\ell) + O_\epsilon(\delta^c), \quad (2.3.4)$$

where $c > 0$ comes from the large deviation principle (Lemma 2.2.52). By Hölder's inequality,

$$\begin{aligned} & \int_G \sup_{a,v} \mu^{*n} \{ \ell_1 | \langle v, Y^n(\ell_1, \ell\eta) \rangle \in B(a, \delta^{1/2}) \} d\mu^{*n}(\ell) \\ & \leq \left(\int_G (\sup_{a,v} \mu^{*n} \{ \ell_1 | \langle v, Y^n(\ell_1, \ell\eta) \rangle \in B(a, \delta^{1/2}) \})^{d+1} d\mu^{*n}(\ell) \right)^{1/(d+1)}. \end{aligned} \quad (2.3.5)$$

By the same argument as in Lemma 2.3.7

$$\sup_{a,v} \mu^{*n} \{ \ell_1 | \langle v, Y^n(\ell_1, \ell\eta) \rangle \in B(a, \delta^{1/2}) \}^{d+1} \leq \mu^{*(d+1)n} \{ (\mathbf{h}_{d+1}) | |A_d^n(\mathbf{h}_{d+1}, \ell\eta)| \leq 2\delta^{1/4} \} + O_\epsilon(\delta^c).$$

Therefore, by (2.3.4) and (2.3.5), we have

$$E^{d+1} \leq \mu^{*(d+2)n} \{ (\mathbf{h}_{d+1}, \ell) | |A_d^n(\mathbf{h}_{d+1}, \ell\eta)| \leq 2\delta^{1/4} \} + O_\epsilon(\delta^c).$$

The proof for $2n$ ends by Definition 2.3.2.

It remains to prove the same result for $2n+1$. Let $h = \ell\ell$ such that ℓ has distribution $\mu^{*(n+1)}$ and ℓ_1 has distribution μ^{*n} . Following the same argument, we have

$$E^{d+1} \leq \mu^{*(d+1)n+(n+1)} \{ (\mathbf{h}_{d+1}, \ell) | |A_d^n(\mathbf{h}_{d+1}, \ell\eta)| \leq 2\delta^{1/4} \} + O_\epsilon(\delta^c).$$

Since ℓ only changes the position η , the uniformity of WNC implies that

$$\begin{aligned} & \mu^{*(d+1)n+(n+1)} \{ (\mathbf{h}_{d+1}, \ell) | |A_d^n(\mathbf{h}_{d+1}, \ell\eta)| \leq 2\delta^{1/4} \} \\ & = \int_{l_3 \in G} \mu^{*(d+2)n} \{ (\mathbf{h}_{d+1}, l_2) | |A_d^n(\mathbf{h}_{d+1}, l_2(l_3\eta))| \leq 2\delta^{1/4} \} d\mu(l_3) \ll_\epsilon \delta^c. \end{aligned}$$

The proof is complete. \square

2.3.3 Hölder regularity

In this section, we will prove

Lemma 2.3.10. *SNC on dimension $d-1$ implies WNC on dimension d .*

Using other representations, we can get more information on the Iwasawa cocycle. This idea has already been used in [Aou13] for problem concerning transience of algebraic subvariety of split real Lie groups. It is also used in the work of Bourgain-Gamburd on the spectral gap of dense subgroups in $SU(n)$, for establishing transience of subgroups.

The key tool is the following estimate. See [BQ16, Proposition 14.3] or [Gui90] for example.

Lemma 2.3.11. *Let V be an irreducible representation of G . Let μ be a Zariski dense Borel probability measure on G with exponential moment. For every $\epsilon > 0$ there exist $c, C > 0$ such that for v in V and f in V^* we have*

$$\mu^{*n}\{\ell \in G \mid |f(\ell v)| \leq \|f\| \|\ell\| e^{-cn}\} \leq C e^{-c\epsilon n}.$$

The intuition is that if a function f is not small at some point, then it is robustly large for almost all points.

In this part, we write $V_j = V_{\chi_j}$ for the fundamental representation and we write $V_{j,\eta}$ for the image of $\eta \in \mathcal{P}$ in $\mathbb{P}V_j$ for $j = 1, \dots, m$. Let v^j be a nonzero vector in $V_{j,\eta}$. For ℓ in G , we abbreviate $\rho_j(\ell)v^j$ to ℓv^j . Since v^j lives in V_j , we use the same symbol $\|\cdot\|$ for norms on different V_j , which makes no confusion. For a vector x in \mathbb{R}^m , we denote by x_i the i -th coordinate. We use upper script to denote different vectors.

Before proving Lemma 2.3.10, we introduce some linear algebras. We want to construct a linear form. Recall that E_d is a rational map, A_d is the affine determinant, B_d is the composition of A_d and E_d and

$$A_d^n(\mathbf{h}_{d+1}, \eta) := B_d(X(n, h_1, \eta), \dots, X(n, h_{d+1}, \eta)),$$

where

$$X(n, h, \eta) = (e^{\chi_j(\sigma(gh, \eta) - \kappa(g) - n\sigma_\mu)})_{1 \leq j \leq m} = \left(\frac{\|ghv^j\|}{e^{\chi_j(\kappa(g) + n\sigma_\mu)} \|v^j\|} \right)_{1 \leq j \leq m}, \quad (2.3.6)$$

and the second equality is due to (2.2.3) and (2.2.2). Let

$$X^i(n, \eta) := X(n, h_i, \eta). \quad (2.3.7)$$

In order to use Lemma 2.3.11, we need to linearise some function related to $A_d^n(\mathbf{h}_{d+1}, \eta)$ with \mathbf{h}_{d+1} fixed. We will multiply B_d by its denominator, and all the Galois conjugate to get a polynomial on $\|X_j^i\|^2$, which can be realized as a linear functional.

The function B_d can be seen as a rational function on

$$(x) := (x^1, \dots, x^{d+1}) = (x_j^i)_{1 \leq i \leq d+1, 1 \leq j \leq m}.$$

By definition, B_d has a special form. Each term in B_d can be expressed as a quotient of two monomials. Let D_d be the lowest common denominator of B_d such that $D_d B_d$ is a polynomial on (x) . In other words, suppose that

$$B_d = \sum_{\mathbf{n} \in \mathbb{Z}^{m(d+1)}} b_{\mathbf{n}} \prod_{1 \leq j \leq m, 1 \leq i \leq d+1} (x_j^i)^{n_{ij}},$$

where \mathbf{n} is a multi index and $b_{\mathbf{n}}$ is the coefficient. Let $q_{ij} = \sup_{\mathbf{n} \in \mathbb{Z}^{m(d+1)}} \{-n_{ij}, 0\}$ for $1 \leq j \leq m, 1 \leq i \leq d+1$. Then $D_d = \prod_{1 \leq j \leq m, 1 \leq i \leq d+1} (x_j^i)^{q_{ij}}$.

Definition 2.3.12. Let F be a polynomial on (x^1, \dots, x^k) where x^1, \dots, x^k are vectors in \mathbb{R}^n . Then we call F a multi homogeneous polynomial of degree $\mathbf{q} = (q_1, \dots, q_n) \in \mathbb{N}^n$ if for ξ in $(\mathbb{R}^*)^n$ we have

$$F(\xi x^1, \dots, \xi x^k) = \xi^{\mathbf{q}} F(x^1, \dots, x^k),$$

where $\xi^{\mathbf{q}} = \prod_{1 \leq j \leq n} \xi_j^{q_j}$.

Let Γ be the finite group $(\mathbb{Z}/2\mathbb{Z})^{d(d+1)}$ which acts on $\mathbb{R}^{d(d+1)}$. Let $(\underline{y}) := (y^1, \dots, y^{d+1}) = (y_j^i)_{1 \leq i \leq d+1, 1 \leq j \leq d} \in (\mathbb{R}^d)^{d+1}$. For $\rho \in \Gamma$, we write $\rho(\underline{y})$ for the action on the coefficient y_j^i , which is of dimension $d(d+1)$. Due to the definition of Γ , the product $\prod_{\rho \in \Gamma} A_d \rho(y^1, \dots, y^{d+1})$ is invariant under the action Γ , hence it is a polynomial on $(y_j^i)^2$. Let

$$F_d(x^1, \dots, x^{d+1}) = \prod_{\rho \in \Gamma} D_d A_d \rho(E_d x^1, \dots, E_d x^{d+1}), \quad (2.3.8)$$

then

Lemma 2.3.13. F_d is a multi homogeneous polynomial on $((x^1)^2, \dots, (x^{d+1})^2)$ with degree $\mathbf{q} = (q_1, \dots, q_m) \in \mathbb{N}^m$.

Proof. We only need to verify that F_d is a multi homogeneous polynomial. The fact that the determinant is a multilinear function implies that for λ and y^i in \mathbb{R}^d

$$A_d(\lambda y^1, \dots, \lambda y^{d+1}) = \det(\lambda) A_d(y^1, \dots, y^{d+1}), \quad (2.3.9)$$

where $\det(\lambda) = \lambda_1 \cdots \lambda_d$. The functions E_d and D_d are group morphisms due to definition. Hence we have

$$E_d(\xi x) = E_d(\xi) E_d(x) \text{ and } D_d(\xi x^1, \dots, \xi x^{d+1}) = D_d(\xi, \dots, \xi) D_d(x^1, \dots, x^{d+1}). \quad (2.3.10)$$

Therefore by (2.3.8), (2.3.9) and (2.3.10), for ξ and x^i in \mathbb{R}^m ,

$$\begin{aligned} F_d(\xi x^1, \dots, \xi x^{d+1}) &= \prod_{\rho \in \Gamma} D_d A_d \rho(E_d(\xi x^1), \dots, E_d(\xi x^{d+1})) \\ &= \prod_{\rho \in \Gamma} D_d A_d \rho(E_d(\xi) E_d(x^1), \dots, E_d(\xi) E_d(x^{d+1})) \\ &= \prod_{\rho \in \Gamma} D_d A_d \rho(E_d(x^1), \dots, E_d(x^{d+1})) \det(E_d(\xi)) D_d(\xi, \dots, \xi) \\ &= \xi^{\mathbf{q}} F_d(x^1, \dots, x^{d+1}), \end{aligned}$$

where \mathbf{q} is a vector in \mathbb{N}^m such that $\xi^{\mathbf{q}} = (\det(E_d(\xi)) D_d(\xi, \dots, \xi))^{|\Gamma|}$. \square

For $\mathbf{h}_{d+1} \in G^{\times(d+1)}$ and η in \mathcal{P} , we write

$$F(\mathbf{h}_{d+1}, \eta) = F_d(X(n, h_1, \eta), \dots, X(n, h_{d+1}, \eta)).$$

Fix \mathbf{h}_{d+1} . By (2.3.6), F is a function on v^j for $1 \leq j \leq m$. Recall that v^j are vectors in $V_{j,\eta}$. Let

$$F_0(v^1, \dots, v^m) = F(\mathbf{h}_{d+1}, \eta) \prod_{1 \leq j \leq m} \|v^j\|^{2q_j}.$$

Now, we want to explain how to realize F_0 as a linear functional.

Lemma 2.3.14. *Let F be a multi homogeneous polynomial of degree $\mathbf{q} = (q_1, \dots, q_{d+1}) \in (\mathbb{N})^{d+1}$. Then $F_0(v^1, \dots, v^m) := F((X^1)^2, \dots, (X^{d+1})^2) \|v^j\|^{2q_j}$ is a linear functional F_1 on the space $V_0 = \bigotimes_{1 \leq j \leq m} (\mathrm{Sym}^2 V_j)^{\otimes q_j}$, where X^j is defined in (2.3.7).*

Proof. Since F is a multi homogeneous polynomial, it is sufficient to prove that every monomial in F has the same property. By Definition 2.3.12, a monomial of F is of the form

$$\prod_{1 \leq j \leq m} \prod_{1 \leq i \leq d+1} (x_j^i)^{2n_{ij}},$$

with $n_{ij} \in \mathbb{N}$ and $\sum_{1 \leq i \leq d+1} n_{ij} = q_j$. The term $\prod \|v^j\|^{2q_j}$ is used to compensate $\|v^j\|$ in the denominator of X_j^i in (2.3.6). Now, by multiplying $\|v^j\|$, we can view X_j^i as $\|gh_i v^j\|$ with some coefficient. By (2.3.6) and $\|ghv^j\|^2 = \langle ghv^j, ghv^j \rangle$, the function $(X_j^i)^2$ is a linear functional on $\mathrm{Sym}^2 V_j$. Hence $\prod_{1 \leq i \leq d+1} (X_j^i)^{2n_{ij}}$ is a linear functional on $(\mathrm{Sym}^2 V_j)^{\otimes q_j}$. This is because if we have two linear functionals f_1 and f_2 on W_1 and W_2 , then $f_1 f_2$ is the linear functional on $W_1 \otimes W_2$ given by $f_1 f_2(w_1 \otimes w_2) = f_1(w_1) f_2(w_2)$. Then by the same reason, the monomial $\prod_{i,j} (X_j^i)^{2n_{ij}}$ is a linear functional on V_0 . In order to express the linearity of F_0 , we rewrite

$$F_1(\bigotimes_j ((v^j)^2)^{\otimes q_j}) := F_0(v^1, \dots, v^m),$$

where v^j is in $V_{j,\eta}$ and F_1 is understood as a linear functional on V_0 . \square

Proof of Lemma 2.3.10. Recall $\beta = \max_{\alpha \in \Pi} e^{-\alpha \sigma_\mu^n}$. Let $\delta = e^{-\epsilon_2 n}$, where the constant ϵ_2 will be determined later depending on ϵ . We suppose that n is large enough such that $\delta \leq 1/2$. Because for small n , WNC can be obtained by enlarging the constant C .

Step 1: We take into account of measures. We want to reduce the condition of WNC on A_d^n to F , which is essentially a linear functional.

For this purpose, we will bound the measure of small A_d^n by the measure of small F .

Lemma 2.3.15. *Let f_1, f_2 be two Borel measurable functions on a locally compact Hausdorff space X and m be a Borel probability measure on X . Then for $c > 0$*

$$m\{h \in X \mid |f_1(h)| \leq c\} \leq m\{h \in X \mid |f_1(h)f_2(h)| \leq c \sup_X |f_2|\}.$$

In order to control $F/A_d^n(\mathbf{h}_{d+1}, \eta)$, we take \mathbf{h}_{d+1} which is η good, that means for every i in $\{1, \dots, d+1\}$, the group element h_i is $(n, \epsilon_2, \eta, \zeta_g^m)$ good (Definition 2.2.51). By Lemma 2.2.53 and (2.3.6), for $1 \leq i \leq d+1, 1 \leq j \leq m$

$$|X_j^i| \leq \delta^{-1}.$$

Since F/A_d^n is a polynomial on X_j^i , for \mathbf{h}_{d+1} which is η good, we have

$$F/A_d^n = D_d \Pi_{\rho \in \Gamma, \rho \neq e} D_d A_d^n \rho \leq \delta^{-O(1)}. \quad (2.3.11)$$

Using Lemma 2.3.15 with $f_1 = A_d^n$ and $f_2 = F/A_d^n$, hence by (2.3.11) and Lemma 2.2.52, we have

$$\begin{aligned} M &:= \mu^{*(d+2)n} \{(\mathbf{h}_{d+1}, \ell) \mid |A_d^n(\mathbf{h}_{d+1}, \ell \eta)| \leq e^{-\epsilon n}\} \\ &\leq \mu^{*(d+2)n} \{\mathbf{h}_{d+1} \text{ is } \ell \eta \text{ good, } \ell \in G \mid |A_d^n(\mathbf{h}_{d+1}, \ell \eta)| \leq e^{-\epsilon n}\} + O_{\epsilon_2}(\delta^c) \\ &\leq \mu^{*(d+2)n} \{\mathbf{h}_{d+1} \text{ is } \ell \eta \text{ good, } \ell \in G \mid |F(\mathbf{h}_{d+1}, \ell \eta)| \leq e^{-\epsilon n} \delta^{-O(1)}\} + O_{\epsilon_2}(\delta^c) \\ &\leq \mu^{*(d+2)n} \{(\mathbf{h}_{d+1}, \ell) \mid |F(\mathbf{h}_{d+1}, \ell \eta)| \leq e^{-\epsilon n} \delta^{-O(1)}\} + O_{\epsilon_2}(\delta^c) \end{aligned} \quad (2.3.12)$$

Step 2: Lemma 2.3.13 implies that F is a multi homogeneous polynomial on $(x_j^i)^2$ of degree $\mathbf{q} = (q_1, \dots, q_{d+1})$. Lemma 2.3.14 implies that

$$F(\mathbf{h}_{d+1}, \eta) = F_1(\otimes_j ((v^j)^2)^{\otimes q_j}) / \Pi \|v_j\|^{2q_j},$$

where F_1 is a linear functional on $V_0 = \otimes_j (\text{Sym}^2 V_j)^{\otimes q_j}$. To be more precise, F_1 will be restricted to a linear form on W , the unique irreducible representation of V_0 with maximal weight. (This is specific for real split Lie groups)

It remains to show that for most \mathbf{h}_{d+1} in $G^{\times(d+1)}$, the norm of F_1 is robustly large. It is sufficient to find one η such that $|F(\mathbf{h}_{d+1}, \eta)|$ is large. We will prove that $|D_d A_d \rho|$ is large for each ρ in Γ , which implies that $|F(\mathbf{h}_{d+1}, \eta)|$ is large.

Using the $d+1$ -th column expansion of the matrix $\begin{pmatrix} y^1 & \cdots & y^{d+1} \\ 1 & \cdots & 1 \end{pmatrix}$, we have

$$\begin{aligned} A_d(y^1, \dots, y^{d+1}) &= -A_{d-1}(r_d y^1, \dots, r_d y^d) y_d^{d+1} + \text{other terms,} \\ &= \sum_{1 \leq j \leq d} (-1)^{j+d+1} A_{d-1}(r_j y^1, \dots, r_j y^d) y_j^{d+1} + \det(y^1, \dots, y^d), \end{aligned} \quad (2.3.13)$$

where $r_j : \mathbb{R}^d \rightarrow \mathbb{R}^{d-1}$ is the map forgetting the j -th coordinate. Replacing y^i by $E_d x^i$, due to $r_d E_d x^i = E_{d-1} x^i$, we obtain

$$A_d(E_d x^1, \dots, E_d x^{d+1}) = -A_{d-1}(E_{d-1} x^1, \dots, E_{d-1} x^d) (E_d x^{d+1})_d + \text{other terms.} \quad (2.3.14)$$

Using SNC on dimension $d-1$, we are able to give a lower bound of $A_{d-1}(E_{d-1} X^1, \dots, E_{d-1} X^d)$ with a loss of exponentially small probability of \mathbf{h}_{d+1} . But the problem is in other similar terms. Due to $y_j^{d+1} = \prod_{1 \leq i \leq m} (x_i^{d+1})^{-\alpha_j(H_i)}$ and the structure of root system, the degree of x_d^{d+1} in $y_j^{d+1} = (E_d x^{d+1})_j$ is

$$-\alpha_d(H_d) = -2 \text{ and } -\alpha_j(H_d) \geq 0 \text{ for } j < d. \quad (2.3.15)$$

Hence, we will make $X_d^{d+1} \leq \beta$, which makes the first term in (2.3.13) greater than $\delta^{O(1)} \beta^{-2}$, and the other terms are less than $\delta^{-O(1)}$.

Now, here is the precise proof. Take h_{d+1} good, that means h_{d+1} is $(n, \epsilon_2, \zeta_g^m)$ good (Definition 2.2.54). We take

$$\eta = \ell_h^{-1} \eta_d \quad (2.3.16)$$

as in Lemma 2.2.55. By Lemma 2.2.55

$$X_j^{d+1} \in [\delta, \delta^{-1}] \text{ for } j \neq d \text{ and } X_d^{d+1} \leq \beta \delta^{-1}. \quad (2.3.17)$$

Let $\Gamma_{d-1} = (\mathbb{Z}/2\mathbb{Z})^{(d-1)d}$, seen as a subgroup of Γ , which acts on $\mathbb{R}^{(d-1)d}$. Then we demand that \mathbf{h}_d satisfies

$$|A_{d-1}^n \rho(\mathbf{h}_d, \eta)| \geq \delta \text{ for all } \rho \in \Gamma_{d-1} \text{ and } \mathbf{h}_d \text{ is } \eta \text{ good.} \quad (2.3.18)$$

Recall that \mathbf{h}_d is η good means that h_i is $(n, \epsilon_2, \eta, \zeta_g^m)$ good for $1 \leq i \leq d$. By Lemma 2.2.53 and (2.3.6),

$$X_j^i(\eta) \in [\delta, \delta^{-1}], \text{ for } 1 \leq i \leq d, 1 \leq j \leq m. \quad (2.3.19)$$

Recall that W is the unique irreducible subrepresentation of V_0 with the highest weight.

Lemma 2.3.16. *We claim that if h_{d+1} is good ($(n, \epsilon_2, \zeta_g^m)$ good), η is taken as in (2.3.16) and the assumption (2.3.18) is satisfied for \mathbf{h}_d , then the operator norm satisfies*

$$\|F_1|_W\| \geq \delta^{O(1)}.$$

Proof of Lemma 2.3.16. As we have already explained, it is sufficient to prove that for ρ in Γ , we have

$$|D_d A_d^n \rho(\mathbf{h}_d, \eta)| \geq \delta^{O(1)}.$$

The proof is similar for ρ in Γ , we will only prove the case $\rho = e$.

By (2.3.13) and (2.3.14)

$$\begin{aligned} D_d A_d(E_d x^1, \dots, E_d x^{d+1}) &= -A_{d-1}(E_{d-1} x^1, \dots, E_{d-1} x^d) D_d(E_d x^{d+1})_d \\ &+ \sum_{1 \leq j < d} (-1)^{j+d+1} A_{d-1}(r_j E_d x^1, \dots, r_j E_d x^d) D_d(E_d x^{d+1})_j + D_d \det(E_d x^1, \dots, E_d x^d) \end{aligned} \quad (2.3.20)$$

where $r_j : \mathbb{R}^d \rightarrow \mathbb{R}^{d-1}$ is the map forgetting the j -th coordinate. Since x_d^{d+1} only appears in $E_d x^{d+1}$, by (2.3.15), we know that the degree of x_d^{d+1} in D_d equals $\alpha_d(H_d) = 2$, which implies that

$$D_d \leq \delta^{-O(1)} \beta^2.$$

Hence by (2.3.17)-(2.3.19) and the property (2.3.15) that the degree of X_d^{d+1} in $(E_d X^{d+1})_d$ is -2 , the degree in $(E_d X^{d+1})_j$ is non negative for $j < d$, we have

$$\begin{aligned} D_d(E_d X^{d+1})_d &\geq \delta^{O(1)}, \quad |A_{d-1}(E_{d-1} X^1, \dots, E_{d-1} X^d)| \geq \delta^{O(1)}, \\ D_d(E_d X^{d+1})_j &\leq \delta^{-O(1)} \beta^2, \quad |A_{d-1}(r_j E_d X^1, \dots, r_j E_d X^d)| \leq \delta^{-O(1)} \text{ for } 1 \leq j < d \\ \text{and } D_d \det(E_d X^1, \dots, E_d X^d) &\leq \delta^{-O(1)} \beta^2. \end{aligned} \quad (2.3.21)$$

By (2.3.20) and (2.3.21), we have

$$|D_d A_d^n| \geq \delta^{O(1)} - \delta^{-O(1)} \beta^2 \geq \delta^{O(1)}.$$

The proof is complete. \square

Step 3. We return to the proof of Lemma 2.3.10. We write ℓv for the vector $\otimes_j (\ell(v^j)^2)^{\otimes q_j}$ in V_0 . Then $\mathbb{R}lv$ is exactly the image of $\ell\eta$ in $\mathbb{P}W$. Using the Fubini theorem and (2.3.12), we have

$$M \leq \int d\mu^{*n}(h_{d+1}) \int d\mu^{*(d-1)n}(\mathbf{h}_d) \mu^{*n} \left\{ \ell \left| \frac{|F_1(\ell v)|}{\|F_1|_W\| \|\ell\|} \leq e^{-\epsilon n} \delta^{-O(1)} \|F_1|_W\|^{-1} \right. \right\} + O_{\epsilon_2}(\delta^c).$$

Using SNC on dimension $d-1$, for all $\rho \in \Gamma_{d-1}$, we have $\mu^{*(d-1)n}\{(\mathbf{h}_d) | |A_{d-1}^n \rho(\mathbf{h}_d, \eta)| \leq \delta\} = O_{\epsilon_2}(\delta^c)$. (This is a stronger form of SNC on dimension $d-1$. Due to $\Gamma_{d-1} \in O(d-1)^{\times d}$, it follows from Remark 2.3.8 that SNC implies this stronger form.) By Lemma 2.2.52, the set that h_{d+1} is not $(n, \epsilon_2, \zeta_g^m)$ good and \mathbf{h}_d is not η good have exponentially small measure. Hence

$$M \leq \int_{good} d\mu^{*n}(h_{d+1}) \int_{\mathbf{h}_d \text{ satisfies (2.3.18)}} d\mu^{*(d-1)n}(\mathbf{h}_d) \mu^{*n} \left\{ \ell \left| \frac{|F_1(\ell v)|}{\|F_1|_W\| \|\ell\|} \leq e^{-\epsilon n} \delta^{-O(1)} \|F_1|_W\|^{-1} \right. \right\} + O_{\epsilon_2}(\delta^c). \quad (2.3.22)$$

Due to Lemma 2.3.16, when ϵ_2 is small enough with respect to ϵ , we have $(\delta = e^{-\epsilon_2 n}$ and $\|F_1|_W\| \ll \delta^{-O(1)})$

$$e^{-\epsilon n} \delta^{-O(1)} \|F_1|_W\|^{-1} \leq e^{-\epsilon n} \delta^{-O(1)} \leq e^{-\epsilon n/2}.$$

Using Lemma 2.3.11 with $V = W$, due to ℓv in W we conclude that under the condition of Lemma 2.3.16,

$$\mu^{*n} \left\{ \ell \left| \frac{|F_1(\ell v)|}{\|F_1|_W\| \|\ell\|} \leq e^{-\epsilon n} \delta^{-O(1)} \|F_1|_W\|^{-1} \right. \right\} \leq e^{-c\epsilon n}. \quad (2.3.23)$$

By (2.3.22) and (2.3.23), the proof is complete. \square

2.3.4 Combinatoric tool

Proposition 2.3.17. Fix $\kappa_1 > 0$. Let $C_0 > 0$. Then there exist ϵ_3 and $k \in \mathbb{N}, \epsilon > 0$ depending only on κ_1 such that the following holds for τ large enough depending on C_0 . Let $\lambda_1, \dots, \lambda_k$ be Borel measures on $([-\tau^{\epsilon_4}, -\tau^{-\epsilon_4}] \cup [\tau^{-\epsilon_4}, \tau^{\epsilon_4}])^m \subset \mathbb{R}^m$ where $\epsilon_4 = \min\{\epsilon_3, \epsilon_3 \kappa_0\}/10k$, with total mass less than 1. Assume that for all $\rho \in [\tau^{-2}, \tau^{-\epsilon_3}]$ and $j = 1, \dots, k$

$$\sup_{a \in \mathbb{R}, v \in \mathbb{S}^{m-1}} (\pi_v)_* \lambda_j(B_{\mathbb{R}}(a, \rho)) = \sup_{a, v} \lambda_j\{x | \langle v, x \rangle \in B_{\mathbb{R}}(a, \rho)\} \leq C_0 \rho^{\kappa_1}. \quad (2.3.24)$$

Then for all $\varsigma \in \mathbb{R}^m$, $\|\varsigma\| \in [\tau^{3/4}, \tau^{5/4}]$ we have

$$\left| \int \exp(i\langle \varsigma, x_1 \cdots x_k \rangle) d\lambda_1(x_1) \cdots d\lambda_k(x_k) \right| \leq \tau^{-\epsilon_3}.$$

This is Proposition 3.4.4 in Chapter 3, based on a discretized sum-product estimate by He-de Saxcé. When $n = 1$, this is due to Bourgain in [Bou10]. The assumption (2.3.24) is called the projective non concentration in the introduction (Definition 2.1).

2.3.5 Application to our measure

From Proposition 2.3.4, we fix $\epsilon_2 < \frac{1}{10} \min_{\alpha \in \Pi} \{\alpha \sigma_\mu\}$ and we can find c_1 such that PNC holds. Let $(\epsilon_2/2, c')$ be the constants in Lemma 2.2.53. Take

$$\kappa_0 = \frac{1}{10} \min\{c_1, c'\}.$$

Using Proposition 2.3.17 with $\kappa_1 = \kappa_0$, we get ϵ_3, ϵ_4 .

For g, h in G and η in \mathcal{P} , recall that $Y^n(h, \eta) = (e^{-\alpha(\sigma(gh, \eta) - \kappa(g) - n\sigma_\mu)})_{\alpha \in \Pi} \in \mathbb{R}^m$. Let $\lambda_{g, \eta}$ be a pushforward measure on \mathbb{R}^m of μ^{*n} restricted on a subset $G_{n, g, \eta}$ of G , which is defined by

$$\lambda_{g, \eta}(E) = \mu^{*n}\{h \in G_{n, g, \eta} | Y^n(h, \eta) \in E\},$$

for any Borel subset E of \mathbb{R}^m , where

$$G_{n, g, \eta} = \{h \in G | h \text{ is } (n, \epsilon, \eta, \zeta_g^m) \text{ good}\} \quad (2.3.25)$$

and where $\epsilon_\mu \geq \epsilon > 0$ will be determined later.

PNC is only at one scale, we need to verify all the scales needed in the sum-product estimate. The idea is to separate the random variable and try to use PNC in other scale, where we need the cocycle property to change scale.

Proposition 2.3.18 (Change scale). *With ϵ small enough depending on $\epsilon_4 \epsilon_2$, there exists C_0 independent of n such that the measure $\lambda_{g, \eta}$ satisfies the conditions in Proposition 2.3.17 with constant $\tau = e^{\epsilon_2 n}$ for all $n \in \mathbb{N}$.*

Proof. We abbreviate $\lambda_{g, \eta}$ to λ . By taking ϵ small depending on $\epsilon_4 \epsilon_2$, Lemma 2.2.53 implies that the support of λ is contained in the cube $[\tau^{-\epsilon_4}, \tau^{\epsilon_4}]^m$.

Then we verify (2.3.24). Let $\rho \in [\tau^{-2}, \tau^{-\epsilon_3}]$. Let $n_1 = \lceil \frac{\log \rho}{2\epsilon_2} \rceil$. and $n_2 = n - n_1$. Then n_1 lies in $[\epsilon_3 n/2, n]$. We separate $h = h_1 h_2$ such that h_1, h_2 have distributions $\mu^{*n_1}, \mu^{*(n-n_1)}$, respectively. We have

$$Y^n(h, \eta) = Y^{n_1}(h_1, h_2 \eta) Y_0^{n_2}(h_2, \eta), \quad (2.3.26)$$

We can not use the cocycle property directly to change the scale. The problem is in (2.3.26), where the term $Y_0^{n_2}$ behaves bad if $n_2 \gg n_1$, that is to say that the probability of h_2 such that $Y_0^{n_2}(h_2, \eta)$ is smaller than $\rho = e^{-2\epsilon_2 n_1}$ is large. In order to overcome this difficulty, we use the support of Y^n . We will prove that if $Y_0^{n_2}$ is too small, then

the support of Y^n will force Y^{n_1} to become large, which can be controlled by the large deviation principle.

Now we give the details of the proof. For (2.3.24), due to the fact that the support of λ is contained in $[\tau^{-\epsilon_4}, \tau^{\epsilon_4}]^m$, we have

$$(\pi_w)_*\lambda(B(a, \rho)) \leq \sup_{h_2, v} \mu^{*n_1} \{h_1 | \langle v, Y^{n_1}(h_1, h_2\eta) \rangle \in R^{-1}B(a, \rho), Y^n(h_1 h_2, \eta) \in [\tau^{-\epsilon_4}, \tau^{\epsilon_4}]^m\}, \quad (2.3.27)$$

where $R = \|wY_0^{n_2}(h_2, \eta)\|$ depends on h_2 .

- If $R \geq \rho^{1/2}$, then $\rho R^{-1} \leq \rho^{1/2} = e^{-\epsilon_2 n_1}$. It follows by PNC at scale n_1 that

$$\mu^{*n_1} \{h_1 | \langle v, Y^{n_1}(h_1, h_2\eta) \rangle \in B(a, e^{-\epsilon_2 n_1})\} \ll_{\epsilon_2} e^{-c_1 \epsilon_2 n_1} \leq \rho^{\kappa_0}. \quad (2.3.28)$$

- If $R \leq \rho^{1/2}$. There exists one coordinate α such that $|Y_0^{n_2}(h_2, \eta)_\alpha| \leq \rho^{1/2}$, which implies that $Y^{n_1}(h_1, h_2\eta)_\alpha = Y^n(h, \eta)_\alpha / Y_0^{n_2}(h_2, \eta)_\alpha \geq \tau^{-\epsilon_4} \rho^{-1/2}$. Due to $\epsilon_3 \geq 4\epsilon_4$ and $n_1 \geq \epsilon_3 n / 2$, we have $\epsilon_2 n_1 \geq 2\epsilon_4 \epsilon_2 n$. Therefore $\tau^{-\epsilon_4} \rho^{-1/2} = \tau^{-\epsilon_4} e^{\epsilon_2 n_1} \geq e^{\epsilon_2 n_1 / 2}$. For such h_2 , we have

$$\mu^{*n_1} \{h_1 | Y^{n_1}(h_1 h_2, \eta) \in [\tau^{-\epsilon_4}, \tau^{\epsilon_4}]^m\} \leq \sum_{\alpha \in \Pi} \mu^{*n_1} \{h_1 | Y^{n_1}(h_1, h_2\eta)_\alpha \geq e^{\epsilon_2 n_1 / 2}\}. \quad (2.3.29)$$

It follows from Lemma 2.2.53 that

$$\begin{aligned} \mu^{*n_1} \{h_1 | Y^{n_1}(h_1, h_2\eta)_\alpha \geq e^{\epsilon_2 n_1 / 2}\} &\leq \mu^{*n_1} \{h_1 | \|\sigma(gh_1, h_2\eta) - \kappa(g) - n_1 \sigma_\mu\| \geq \epsilon_2 n_1 / 2\} \\ &\ll_{\epsilon_2} e^{-c' \epsilon_2 n_1} \leq \rho^{\kappa_0}. \end{aligned} \quad (2.3.30)$$

By (2.3.27)-(2.3.30), for $\rho \in [\tau^{-2}, \tau^{-\epsilon_3}]$ we have

$$(\pi_w)_*\lambda(B(a, \rho)) \ll_{\epsilon_2} \rho^{\kappa_0}.$$

The proof is complete. \square

2.4 Proof of the main theorems

In this section, we will use the results of Section 2.2 and Section 2.3 to give the proofs of the main theorems. We will add many assumptions on the elements of G and \mathcal{P} . The assumptions seem complicate. In fact, they are not really important. They are taken to make the result work outside a set of exponentially small measure. These assumptions says that the elements are away from certain closed subvarieties of G or \mathcal{P} , which also explains that they are true almost everywhere.

2.4.1 (C, r) good function

For a C^1 function φ on the flag variety \mathcal{P} . We first lift it to $\mathcal{P}_0 = G/A_eN$. Let $\partial_\alpha\varphi = \partial_{Y_\alpha}\varphi$ be the directional derivative on \mathcal{P}_0 . By Lemma 2.2.31 the action of the group M only changes the sign of the directional derivative $\partial_\alpha\varphi$, hence $|\partial_\alpha\varphi|$ is actually a function on \mathcal{P} . Recall that for η, η' in \mathcal{P} and simple root α , we have defined $d_\alpha(\eta, \eta') = d(V_{\alpha, \eta}, V_{\alpha, \eta'})$.

Definition 2.4.1. *Let r be a continuous function on \mathcal{P} . Let J be the open set in \mathcal{P} , which is the $1/C$ -neighbourhood of the support of r . Let φ be a C^2 function on \mathcal{P} . For a simple root α , let $v_\alpha = \sup_{\eta \in \mathrm{supp} r} |\partial_\alpha\varphi(\eta)|$. We say that φ is (C, r) good if:*

(G1) For η, η' in J such that $d(\eta, \eta') \leq 1/C$,

$$|\varphi(\eta) - \varphi(\eta')| \leq C \sum_{\alpha \in \Pi} d_\alpha(\eta, \eta') v_\alpha, \quad (2.4.1)$$

(G2) For every simple root α and for every η in the support of r , we have

$$|\partial_\alpha\varphi(\eta)| \geq \frac{1}{C} v_\alpha, \quad (2.4.2)$$

(G3) For z, z' in $\pi^{-1}(J) \subset \mathcal{P}_0$,

$$|\partial_\alpha\varphi(z) - \partial_\alpha\varphi(z')| \leq C d_0(z, z') v_\alpha. \quad (2.4.3)$$

(G4)

$$\sup_{\alpha \in \Pi} v_\alpha \in [1/C, C]. \quad (2.4.4)$$

In the above definition, only G3 assumption (2.4.3) really need \mathcal{P}_0 , where the Lipschitz norm is defined with respect to the distance d_0 on \mathcal{P}_0 . G1 assumption is new in higher dimension which means that we can bound the difference by its difference in each fundamental representation, and in a fundamental representation the directional derivative $|\partial_\alpha\varphi|$ can bound the Lipschitz norm. G2 and G3 assumptions are natural generalizations of the case $m = 1$, $\mathrm{SL}_2(\mathbb{R})$. G4 assumption is used to normalize the function.

The role of J is to simplify the verification of (C, r) goodness. With this definition, we only need to verify assumptions on a neighbourhood of the support of r .

2.4.2 From sum-product estimates to Fourier decay

In this subsection we will prove Theorem 2.1.7, an estimate of Fourier decay, by using the results established in Section 2.2 and Section 2.3.

Recall that we have fixed (ϵ_2, c_1) for Proposition 2.3.4 in Section 2.3.5, the constant $(\epsilon_2/2, c')$ in Lemma 2.2.52 and

$$\kappa_0 = \frac{1}{10} \min\{c_1, c'\}.$$

Take $k, \epsilon_3, \epsilon_4$ from Proposition 2.3.17 with this κ_0 . Let ϵ be a positive number to be determined later (the only constant which is not fixed yet). The constant ϵ_0 in the hypothesis of Theorem 2.1.7 is defined as

$$\epsilon_0 = \frac{\epsilon}{\max_{\alpha \in \Pi} \{(2k+1)\alpha\sigma_\mu + \epsilon_2\} + \epsilon} \quad (2.4.5)$$

which will be fixed once ϵ is fixed.

Here, we define and give relations of different constants. Let v be the vector in \mathbb{R}^m whose components are $v_\alpha = \sup_{\eta \in \text{suppr}} |\partial_\alpha \varphi(\eta)|$, for $\alpha \in \Pi$. Then by G4 assumption (2.4.4), we have

$$\sup_{\alpha \in \Pi} v_\alpha \in [\xi^{-\epsilon_0}, \xi^{\epsilon_0}]. \quad (2.4.6)$$

Let n be the minimal integer such that

$$e^{\epsilon_2 n} \geq \xi \max_{\alpha \in \Pi} \{v_\alpha e^{-(2k+1)\alpha\sigma_\mu n}\}. \quad (2.4.7)$$

The existence is guaranteed by the positivity of Lyapunov constant, that is $\alpha\sigma_\mu > 0$ for $\alpha \in \Pi$ (Lemma 2.2.45). Let the regularity scale δ be given by

$$\delta = e^{-\epsilon n} < 1/2,$$

where we take ξ large enough such that n is large enough. Let the contraction scale β given by

$$\beta_\alpha = e^{-\alpha\sigma_\mu n}, \beta = \max_{\alpha \in \Pi} \{\beta_\alpha\}.$$

The point is that the contraction speed β decides the magnitude of a term and δ is only an error term, much larger than β .

Let the frequency τ be defined by $\tau = e^{\epsilon_2 n}$. By (2.4.7), we have

$$\tau \geq \xi \max_{\alpha \in \Pi} \{v_\alpha \beta_\alpha^{2k+1}\} \geq C_{\epsilon_2} \tau, \quad (2.4.8)$$

where $C_{\epsilon_2} = e^{-\epsilon_2} \min_{\alpha \in \Pi} \{e^{-(2k+1)\alpha\sigma_\mu}\}$. By (2.4.6), there exists α_o in Π such that $v_{\alpha_o} \geq \xi^{-\epsilon_0}$. Then (2.4.8) and (2.4.5) imply that

$$\xi \leq \tau v_{\alpha_o}^{-1} \beta_{\alpha_o}^{-2k-1} \leq \xi^{\epsilon_0} \tau \beta_{\alpha_o}^{-(2k+1)} \leq \xi^{\epsilon_0} e^{n\epsilon \frac{1-\epsilon_0}{\epsilon_0}}.$$

Hence the regularity scale satisfies

$$\xi^{\epsilon_0} \leq e^{\epsilon n} = \delta^{-1}. \quad (2.4.9)$$

Notation: We state some notation which will be used throughout Section 2.4.2.

- Let $\mathbf{g} = (g_0, \dots, g_k)$ be an element in $G^{\times(k+1)}$.
- Let $\mathbf{h} = (h_1, \dots, h_k)$ be an element in $G^{\times k}$.

- We write $\mathbf{g} \leftrightarrow \mathbf{h} = g_0 h_1 \cdots h_k g_k \in G$ for the product of \mathbf{g}, \mathbf{h} .
- We write $T\mathbf{g} \leftrightarrow \mathbf{h} = g_0 h_1 \cdots g_{k-1} h_k \in G$.
- For $l \in \mathbb{N}$, let $\mu_{l,n}$ be the product measure on $G^{\times l}$ given by $\mu_{l,n} = \underbrace{\mu^{*n} \otimes \cdots \otimes \mu^{*n}}_{l \text{ times}}$.
- Recall that for g, h in G and η in \mathcal{P} , we define $Y_g^n(h, \eta)_\alpha = \exp(-\alpha(\sigma(gh, \eta) - \kappa(g) - n\sigma_\mu))$ and $Y_g^n(h, \eta) = (Y_g^n(h, \eta)_\alpha)_{\alpha \in \Pi} \in \mathbb{R}^m$.
- For z in \mathcal{P}_0 , let $\tilde{Y}_g^n(h, z)_\alpha = \alpha^\sharp(\mathfrak{m}(\ell_g^{-1}, hz)) Y_g^n(h, \eta)_\alpha$, where α^\sharp is the corresponding algebraic character of the simple root α and we make a choice of ℓ_g and $\eta = \pi(z)$.
- For g in G , z in \mathcal{P}_0 and $\eta = \pi(z)$, let $\tilde{\lambda}_{g,z}$ be the pushforward measure on \mathbb{R}^m of μ^{*n} restricted to a subset $G_{n,g,\eta}$ under the map $\tilde{Y}_g^n(\cdot, z)$. In other words, for a Borel set E ,

$$\tilde{\lambda}_{g,z}(E) = \mu^{*n}\{h \in G_{n,g,\eta} | \tilde{Y}_g^n(h, z) \in E\}.$$

Recall that the set $G_{n,g,\eta}$ is defined by $G_{n,g,\eta} = \{h \in G | h \text{ is } (n, \epsilon, \eta, \zeta_g^m) \text{ good}\}$.

- After fixing \mathbf{g} , we will also fix a choice of k_{g_j}, ℓ_{g_j} for g_j and let $z_{g_j} = k_{g_j} z_0$, $m_j(h) = \mathfrak{m}(\ell_{g_j}^{-1}, h k_{g_j})$ and $\lambda_j = \tilde{\lambda}_{g_j^{-1}, z_{g_j}}$, for $j = 1, \dots, k$.

Lemma 2.4.2. *The measure $\tilde{\lambda}_{g,z}$ satisfies the same property (2.3.24) as $\lambda_{g,\eta}$ with C_0 replaced by $2^m C_0$, where $\eta = \pi(z)$.*

Proof. Since the difference is only in the sign, we have

$$(\pi_v)_* \tilde{\lambda}_{g,z}(B_{\mathbb{R}}(a, \rho)) \leq \sum_{f \in (\mathbb{Z}/2\mathbb{Z})^m} (\pi_{fv})_* \lambda_{g,\eta}(B_{\mathbb{R}}(a, \rho)),$$

where we identify $(\mathbb{Z}/2\mathbb{Z})^m$ with $\{-1, 1\}^m \subset \mathbb{R}^m$. The result follows from this inequality. \square

First step: For η, η' in \mathcal{P} , let

$$f(\eta, \eta') = \int_G e^{i\xi(\varphi(g\eta) - \varphi(g\eta'))} r(g\eta) r(g\eta') d\mu^{*(2k+1)n}(g). \quad (2.4.10)$$

Lemma 2.4.3. *We have*

$$\left| \int_{\mathcal{P}} e^{i\xi\varphi(\eta)} r(\eta) d\nu(\eta) \right|^2 \leq \int_{\mathcal{P}^2} f(\eta, \eta') d\nu(\eta) d\nu(\eta'). \quad (2.4.11)$$

Proof. By the definition of μ -stationary measure and the Cauchy-Schwarz inequality,

$$\begin{aligned} & \left| \int_{\mathcal{P}} e^{i\xi\varphi(\eta)} r(\eta) d\nu(\eta) \right|^2 \\ &= \left| \int_{\mathcal{P} \times G} e^{i\xi\varphi(g\eta)} r(g\eta) d\mu^{*(2k+1)n}(g) d\nu(\eta) \right|^2 \leq \int_G \left| \int_{\mathcal{P}} e^{i\xi\varphi(g\eta)} r(g\eta) d\nu(\eta) \right|^2 d\mu^{*(2k+1)n}(g) \\ &= \int_{\mathcal{P}^2} \int_G e^{i\xi(\varphi(g\eta) - \varphi(g\eta'))} r(g\eta) r(g\eta') d\mu^{*(2k+1)n}(g) d\nu(\eta) d\nu(\eta'). \end{aligned}$$

The proof is complete. \square

Recall that for η in \mathcal{P} , we write $V_{\alpha,\eta}$ for its image in $\mathbb{P}V_\alpha$ and $d_\alpha(\eta, \eta') = d(V_{\alpha,\eta}, V_{\alpha,\eta'})$.

Definition 2.4.4 (Good Position). *Let η, η' be in \mathcal{P} . We say that they are in good position if*

$$\forall \alpha \in \Pi, d_\alpha(\eta, \eta') \geq \delta.$$

We fix η, η' in good position, which means that η, η' are far in all $\mathbb{P}V_\alpha$. We rewrite the formula.

Lemma 2.4.5. *We have*

$$\left| \int_{\mathcal{P}} e^{i\xi\varphi(\eta)r(\eta)} d\nu(\eta) \right|^2 \leq \int_{\eta, \eta' \text{ good}} f(\eta, \eta') d\nu(\eta) d\nu(\eta') + O(\delta^c). \quad (2.4.12)$$

Proof. By the regularity of stationary measure (2.2.34), we have

$$\nu\{\eta' \in \mathcal{P} | d_\alpha(\eta, \eta') \leq \delta\} = \nu\{\eta' \in \mathcal{P} | d(V_{\alpha,\eta}, V_{\alpha,\eta'}) \leq \delta\} \leq C\delta^c. \quad (2.4.13)$$

Therefore by (2.4.13) and Fubini's theorem,

$$\nu \otimes \nu\{(\eta, \eta') \in \mathcal{P}^2 | d_\alpha(\eta', \eta) < \delta\} = \int_{\eta \in \mathcal{P}} \nu\{\eta' \in \mathcal{P} | d_\alpha(\eta, \eta') \leq \delta\} d\nu(\eta) \ll \delta^c.$$

Summing over simple roots α , we obtain the result by $\|r\|_\infty \leq 1$. \square

Second step: The purpose of this part is to give a Ping-Pong Lemma in measure sense. We will eliminate sets with negligible measure such that the Ping-Pong condition is almost preserved by iteration on the complement.

We fix g_j for $j = 0, \dots, k-1$ which satisfies

$$\|\kappa(g_j) - n\sigma_\mu\| \leq \epsilon n / C_A. \quad (2.4.14)$$

Recall that C_A is a constant in Definition 2.2.51. We also demand that

$$h_{j+1} \text{ is } (n, \epsilon, \eta_{g_{j+1}}^M, \zeta_{g_j}^m) \text{ good.} \quad (2.4.15)$$

Recall that the Cartan subspace \mathfrak{a} is equipped with the norm induced by the Killing form, and with this norm \mathfrak{a} is isomorphic to the euclidean space \mathbb{R}^m .

Lemma 2.4.6. *Suppose that $\mathfrak{g}, \mathfrak{h}$ satisfy the above conditions (2.4.14) and (2.4.15). Then the action of $T\mathfrak{g} \leftrightarrow \mathfrak{h}$ on $b_{V_\alpha, g_k}^M(\delta)$ is $\beta_\alpha^{2k} \delta^{-O(1)}$ Lipschitz and*

$$e^{-\alpha\sigma(g_0 h_1, x_{g_1}^M)} \dots e^{-\alpha\sigma(g_{k-1} h_k, x_{g_k}^M)} \leq \beta_\alpha^{2k} \delta^{-O(1)}, \quad (2.4.16)$$

for every α in Π . For $t \in b_{g_k}^M(\delta)$, let $t_j = g_j h_{j+1} \dots h_k t$ for $j = 0, \dots, k$, where we let $t_k = t$. Then

$$t_j \in b_{g_j}^M(\beta\delta^{-2}) \subset b_{g_j}^M(\delta), \quad (2.4.17)$$

$$\|\sigma(g_j h_{j+1}, t_{j+1}) - \sigma(g_j h_{j+1}, \eta_{g_{j+1}}^M)\| \ll \beta\delta^{-O(1)}. \quad (2.4.18)$$

Remark 2.4.7. The contraction constant β here is a little different from the gap $\gamma(g_j)$, but $\gamma(g_j)/\beta$ is in the interval $[\delta^{O(1)}, \delta^{-O(1)}]$ by Lemma 2.2.53. Hence they are of the same largeness and we will not distinguish them.

The intuition here is that by controlling $\kappa(g), \eta_g^M, \zeta_g^m$, all the other position or length will also be controlled, which is similar to hyperbolic dynamics.

Proof. For every α in Π , using Lemma 2.2.8 $2k$ times, we obtain the Lipschitz property. By Lemma 2.2.53, we have (2.4.16) from (2.4.15) for all α in Π at the same time.

We use induction to prove the inclusion. For $j = k$, it is due to the hypothesis of Lemma 2.4.6.

Suppose that the property holds for $j + 1$. By definition, $t_j = g_j h_{j+1} t_{j+1}$. We abbreviate $g_j, h_{j+1}, t_{j+1}, \eta_{g_{j+1}}^M$ to g, h, η, η' . The condition becomes

$$d(\eta, \eta') \leq \delta, \|\kappa(g) - n\sigma_\mu\| \leq \epsilon n / C_A \text{ and } h \text{ is } (n, \epsilon, \eta', \zeta_g^m) \text{ good.}$$

By Lemma 2.2.53, we have $\gamma(h) \leq \beta\delta^{-1}$. By Lemma 2.2.13, due to $\eta \in B(\eta', \delta) \subset B_h^m(\delta)$, we have $h\eta \in b_h^M(\beta/\delta^2) \subset B_g^m(\delta)$. Therefore $gh\eta \in b_g^M(\beta/\delta^2)$, which is the inclusion condition.

Then we will prove (2.4.18) and we keep the notation g, h, η, η' .

$$\|\sigma(gh, \eta) - \sigma(gh, \eta')\| \ll \|\sigma(g, h\eta) - \sigma(g, h\eta')\| + \|\sigma(h, \eta) - \sigma(h, \eta')\|.$$

By the same argument, due to Lemma 2.2.13 and $\eta, \eta' \in B(\eta', \beta/\delta^2) \subset B_h^m(\delta)$, we have $h\eta, h\eta' \in b_h^M(\beta/\delta^2) \subset B_g^m(\delta)$. Therefore by the Lipschitz property of Lemma 2.2.13

$$\|\sigma(gh, \eta) - \sigma(gh, \eta')\| \ll (d(\eta, \eta') + d(h\eta, h\eta'))\delta \ll \beta/\delta^3.$$

The proof is complete. \square

Lemma 2.4.8. Suppose that \mathbf{g}, \mathbf{h} satisfy the conditions (2.4.14) and (2.4.15). Let s be in $\{z \in \mathcal{P}_0 \mid d_0(z, z_{g_k}) \leq \delta\}$. Let $s_j = g_j h_{j+1} \cdots h_k s$ for $j = 0, \dots, k$, where we let $s_k = s$. We have

$$m(s_0, k_{g_0}) = \prod_{1 \leq j \leq k} m(\ell_{g_{j-1}}^{-1}, h_j k_{g_j}) = \prod_{1 \leq j \leq k} m_j(h_j). \quad (2.4.19)$$

Proof. We let $\eta = \pi(s)$, then η is in $b_{g_k}^M(\delta)$. By (2.4.17) with $j = 1$ and (2.4.15) with $j = 0$, Lemma 2.2.25 implies

$$m(s_0, k_{g_0}) = m(k_{g_0}, g_0 h_1 s_1) = m(\ell_{g_0}^{-1}, h_1 k_{g_1}) m(s_1, k_{g_1}).$$

Iterating this formula, we obtain the result. \square

Third step: Here we mimic the proof of [BD17], where they heavily use the properties of Schottky groups and symbolic dynamics. But in our case, the group is much more complicate from the point of view of dynamics. We use the large deviation principle to get a similar formula.

By very careful control of g_l , with a loss of an exponentially small measure, we are able to rewrite the formula in a form to use the sum-product estimates. The key point

is that by controlling the Cartan projection and the position of η_g^M and ζ_g^m of each g_l , we are able to get good control of their product $\mathbf{g} \leftrightarrow \mathbf{h}$.

We should notice that the element g_j will be fixed, and we will integrate first with respect to h_j . This gives the independence of the cocycle $\sigma(g_{j-1}h_j, \eta_{g_j}^M)$, that is for different j they are independent, which is an important point to apply sum-product estimates.

We return to (2.4.12). We call \mathbf{g} “good” with respect to η, η' if

$$\begin{aligned} \mathbf{g} \text{ satisfies (2.4.14), } g_k \text{ satisfies conditions in Lemma 2.2.40, } \eta_{g_0}^M \in \text{suppr} \\ \text{and } \delta(\eta, \zeta_{g_k}^m), \delta(\eta', \zeta_{g_k}^m), \delta(V_{\alpha, \eta} \wedge V_{\alpha, \eta'}, y_{\wedge^2 \rho_{\alpha} g_k}^m) \geq 4\delta. \end{aligned} \quad (2.4.20)$$

Lemma 2.4.9. *If η and η' are in good position and \mathbf{g} is “good”, then $g_k \eta, g_k \eta'$ are in $b_{g_k}^M(\delta)$, and for $\alpha \in \Pi$ the d_α distance between $g_k \eta$ and $g_k \eta'$ is almost β_α , that is*

$$d_\alpha(g_k \eta, g_k \eta') \in \beta_\alpha[\delta^{O(1)}, \delta^{-O(1)}].$$

Proof. The inclusion is due to Lemma 2.2.13. Since g is good (2.4.20), by (2.2.8) we have the lower bound and by the Lipschitz property in Lemma 2.2.8 we have the upper bound. \square

For η, η' in \mathcal{P} , we can rewrite the formula of $f(\eta, \eta')$ as

$$f(\eta, \eta') = \int e^{i\xi(\varphi(\mathbf{g} \leftrightarrow \mathbf{h}\eta) - \varphi(\mathbf{g} \leftrightarrow \mathbf{h}\eta'))} r(\mathbf{g} \leftrightarrow \mathbf{h}\eta) r(\mathbf{g} \leftrightarrow \mathbf{h}\eta') d\mu_{k,n}(\mathbf{h}) d\mu_{k+1,n}(\mathbf{g}). \quad (2.4.21)$$

We call \mathbf{h} is \mathbf{g} -regular if \mathbf{h} satisfies (2.4.15). Let

$$f_{\mathbf{g}}(\eta, \eta') = \int_{\mathbf{g}\text{-regular}} e^{i\xi(\varphi(\mathbf{g} \leftrightarrow \mathbf{h}\eta) - \varphi(\mathbf{g} \leftrightarrow \mathbf{h}\eta'))} d\mu_{k,n}(\mathbf{h}).$$

Lemma 2.4.10. *For η, η' in \mathcal{P}*

$$|f(\eta, \eta')| \leq \int_{\mathbf{g}\text{“good”}} |f_{\mathbf{g}}(\eta, \eta')| d\mu_{k+1,n}(\mathbf{g}) + O_\epsilon(\delta^c), \quad (2.4.22)$$

if ϵ is small enough with respect to γ , that is $\epsilon \leq \min_{\alpha \in \Pi} \{\alpha \sigma_\mu \gamma / (2 + 2\gamma)\}$.

Proof. Let

$$\tilde{f}_{\mathbf{g}}(\eta, \eta') = \int_{\mathbf{g}\text{-regular}} e^{i\xi(\varphi(\mathbf{g} \leftrightarrow \mathbf{h}\eta) - \varphi(\mathbf{g} \leftrightarrow \mathbf{h}\eta'))} r(\mathbf{g} \leftrightarrow \mathbf{h}\eta) r(\mathbf{g} \leftrightarrow \mathbf{h}\eta') d\mu_{k,n}(\mathbf{h}).$$

We call \mathbf{g} “semi-good” if \mathbf{g} satisfies (2.4.20) except the assumption of $\eta_{g_0}^M \in \text{suppr}$ in (2.4.20). By large deviation principle (Proposition 2.2.46, Proposition 2.2.48, Lemma 2.2.58), we conclude that

$$\mu_{k+1,n}\{g \text{ not “semi-good”}\} \leq O_\epsilon(\delta^c). \quad (2.4.23)$$

Then by (2.4.21), Lemma 2.2.52 and (2.4.23),

$$|f(\eta, \eta')| \leq \int_{\mathbf{g}} |\tilde{f}_{\mathbf{g}}(\eta, \eta')| d\mu_{k+1, n}(\mathbf{g}) + O_{\epsilon}(\delta^c) \leq \int_{\mathbf{g}^{\text{"semi-good"}}} |\tilde{f}_{\mathbf{g}}(\eta, \eta')| d\mu_{k+1, n}(\mathbf{g}) + O_{\epsilon}(\delta^c). \quad (2.4.24)$$

By Lemma 2.4.9, (2.4.17) with $j = 0$ and $c_{\gamma}(r) \leq \xi^{\epsilon_0} \leq \delta^{-1}$,

$$|r(\eta_{g_0}^M)^2 - r(\mathbf{g} \leftrightarrow \mathbf{h}\eta)r(\mathbf{g} \leftrightarrow \mathbf{h}\eta')| \leq 2\|r\|_{\infty} c_{\gamma}(r) (\beta\delta^{-2})^{\gamma} \leq 2\beta^{\gamma} \delta^{-1-2\gamma} \leq 2\delta,$$

if ϵ is small enough with respect to γ . Hence

$$\begin{aligned} |\tilde{f}_{\mathbf{g}}(\eta, \eta')| &\leq \left| \int_{\mathbf{g}\text{-regular}} e^{i\xi(\varphi(\mathbf{g} \leftrightarrow \mathbf{h}\eta) - \varphi(\mathbf{g} \leftrightarrow \mathbf{h}\eta'))} r(\eta_{g_0}^M)^2 d\mu_{k, n}(\mathbf{h}) \right| + O(\delta^c) \\ &\leq r(\eta_{g_0}^M)^2 |f_{\mathbf{g}}(\eta, \eta')| + O(\delta^c). \end{aligned} \quad (2.4.25)$$

If $r(\eta_{g_0}^M) \neq 0$, then that \mathbf{g} is “semi-good” implies \mathbf{g} is “good”. Combined with (2.4.24) and (2.4.25), by $\|r\|_{\infty} \leq 1$, we have

$$\begin{aligned} |f(\eta, \eta')| &\leq \int_{\mathbf{g}^{\text{"semi-good"}}} (r(\eta_{g_0}^M)^2 |f_{\mathbf{g}}(\eta, \eta')| + O(\delta^c)) d\mu_{k+1, n}(\mathbf{g}) + O_{\epsilon}(\delta^c) \\ &\leq \int_{\mathbf{g}^{\text{"good"}}} |f_{\mathbf{g}}(\eta, \eta')| d\mu_{k+1, n}(\mathbf{g}) + O_{\epsilon}(\delta^c). \end{aligned}$$

The proof is complete. \square

Recall that β is the magnitude which is really small, δ is only an error term and τ is the frequency for applying the sum-product estimate, which lies between δ^{-1} and β^{-1} .

Proposition 2.4.11. *Let $I_{\tau} = [\tau^{3/4}, \tau^{5/4}]$. The following formula is true for η, η' in good position and \mathbf{g} “good”,*

$$|f_{\mathbf{g}}(\eta, \eta')| \leq \sup_{\|\varsigma\| \in I_{\tau}} \left| \int e^{i\langle \varsigma, x_1 \cdots x_k \rangle} d\lambda_1(x_1) \cdots d\lambda_k(x_k) \right| + O(\beta\delta^{-O(1)}\tau), \quad (2.4.26)$$

when ϵ is small enough with respect to ϵ_2 .

Remark 2.4.12. *This is the most complicate step, where the difficulty comes from higher rank. We need to use the technique of changing flags to find the direction of slowest contraction speed, where we can use Newton-Leibniz’s formula. Since the action of the sign group M is non trivial on the slowest directions, we also carefully treat the sign.*

Proof. The element η, η' and \mathbf{g} are already fixed. Since g_k satisfies the conditions in Lemma 2.2.40, we obtain two chains $(\eta = \eta_o, \eta_1, \dots, \eta_{l_1})$ and $(\eta' = \eta'_o, \eta'_1, \dots, \eta'_{l_2})$ as in Lemma 2.2.40. Then we write

$$\begin{aligned} \varphi(\mathbf{g} \leftrightarrow \mathbf{h}\eta) - \varphi(\mathbf{g} \leftrightarrow \mathbf{h}\eta') &= \sum_{0 \leq j \leq l_1 - 1} (\varphi(\mathbf{g} \leftrightarrow \mathbf{h}\eta_j) - \varphi(\mathbf{g} \leftrightarrow \mathbf{h}\eta_{j+1})) \\ &- \sum_{0 \leq j \leq l_2 - 1} (\varphi(\mathbf{g} \leftrightarrow \mathbf{h}\eta'_j) - \varphi(\mathbf{g} \leftrightarrow \mathbf{h}\eta'_{j+1})) + (\varphi(\mathbf{g} \leftrightarrow \mathbf{h}\eta_{l_1}) - \varphi(\mathbf{g} \leftrightarrow \mathbf{h}\eta'_{l_2})), \end{aligned} \quad (2.4.27)$$

The terms for different j and for η, η' are similar. We fix j and we simplify $\alpha(\eta_j, \eta_{j+1})$ to α .

We compute the term $\varphi(\mathbf{g} \leftrightarrow \mathbf{h}\eta_j) - \varphi(\mathbf{g} \leftrightarrow \mathbf{h}\eta_{j+1})$. In order to treat the sign, we will work on $\mathcal{P}_0 = G/A_e N$. Recall that $\pi : \mathcal{P}_0 \rightarrow \mathcal{P}$ is the projection and we use $z = kz_o$ to denote the element $kA_e N$ in \mathcal{P}_0 .

By Lemma 2.2.42 and (2.4.20), we know that $g_k\eta_j, g_k\eta_{j+1}$ are in $b_{g_k}^M(\delta)$, which satisfy the condition of Lemma 2.4.6. Let z_0, z_1 be preimages of $g_k\eta_j$ and $g_k\eta_{j+1}$ in \mathcal{P}_0 such that $\mathfrak{m}(z_0, z_1) = e$. Notice that z_0, z_1 are in the same α -circle. By Lemma 2.2.40 (2.2.25) and Lemma 2.4.9

$$d(g_k\eta_j, g_k\eta_{j+1}) = d_\alpha(g_k\eta, g_k\eta') + O(\beta e^{-\alpha\kappa(g_k)} \delta^{O(1)}) \in \beta_\alpha[\delta^{O(1)}, \delta^{-O(1)}].$$

Due to $\mathfrak{m}(z_0, z_1) = e$, the arc length distance also satisfies

$$d_A(z_0, z_1) = \arcsin d(g_k\eta_j, g_k\eta_{j+1}) \in \beta_\alpha[\delta^{O(1)}, \delta^{-O(1)}]. \quad (2.4.28)$$

Now, we lift φ to \mathcal{P}_0 , becoming a right M -invariant function. By abuse of notation, we also use φ to denote the lifted function. Let γ be an arc connecting z_0, z_1 with unit speed in the α -circle with length less than $\pi/2$. Without loss of generality, we suppose that γ is in the positive direction (If not, we add minus in the right hand side of (2.4.29)). By Newton-Leibniz's formula (2.2.23), we have

$$\varphi(T\mathbf{g} \leftrightarrow \mathbf{h}z_0) - \varphi(T\mathbf{g} \leftrightarrow \mathbf{h}z_1) = \int_0^u \partial_\alpha \varphi(T\mathbf{g} \leftrightarrow \mathbf{h}\gamma(t)) e^{-\alpha\sigma(T\mathbf{g} \leftrightarrow \mathbf{h}, \gamma(t))} dt, \quad (2.4.29)$$

where $u = d_A(z_0, z_1)$. Fix a time t in $[0, u]$, let $s_j = g_j h_{j+1} \cdots h_k \gamma(t)$. Then $\pi(\gamma(t))$ is in $b_{g_k}^M(\delta)$, because $g_k\eta_j$ and $g_k\eta_{j+1}$ are in $b_{g_k}^M(\delta)$ and by (2.4.28). By (2.4.17), the element $\pi(s_0)$, the image of $s_0 = T\mathbf{g} \leftrightarrow \mathbf{h}\gamma(t)$ in \mathcal{P} , is in $b_{g_0}^M(\beta\delta^{-O(1)})$.

Recall that we have made a choice of the Cartan decomposition of every g_j for $0 \leq j \leq k$. In particular, k_{g_0} is given in the decomposition of $g_0 = k_{g_0} a_{g_0} \ell_{g_0} \in KA^+K$. Let $m_0 = \mathfrak{m}(s_0, k_{g_0})$ and $\underline{s}_0 = s_0 m_0$, then $\mathfrak{m}(\underline{s}_0, k_{g_0}) = e$. By Lemma 2.2.31,

$$\partial_\alpha \varphi_{s_0} = \partial_\alpha \varphi_{\underline{s}_0 m_0} = \alpha^\sharp(m_0) \partial_\alpha \varphi_{\underline{s}_0}. \quad (2.4.30)$$

By Lemma 2.5.5 and $\pi s_0, \pi z_{g_0} = \eta_{g_0}^M$ in $b_{g_0}^M(\beta\delta^{-O(1)})$, we have

$$d_0(\underline{s}_0, z_{g_0}) \leq d(\pi s_0, \pi z_{g_0}) < \beta\delta^{-O(1)}. \quad (2.4.31)$$

Due to \mathbf{g} good (2.4.20), we have $\eta_{g_0}^M \in \text{suppr}$. By G2 assumption (2.4.2), we have $|\partial_\alpha \varphi(z_{g_0})| \geq \delta v_\alpha$. By (2.4.31), the point πs_0 is in J , the δ neighbourhood of suppr . By G3 assumption (2.4.3), $|\partial_\alpha \varphi(\underline{s}_0) - \partial_\alpha \varphi(z_{g_0})| \leq \delta^{-1} v_\alpha d_0(\underline{s}_0, z_{g_0})$, which implies

$$\partial_\alpha \varphi(\underline{s}_0) / \partial_\alpha \varphi(z_{g_0}) \in [1 - \beta\delta^{-O(1)}, 1 + \beta\delta^{-O(1)}].$$

By Lemma 2.4.6 (2.4.18), we have

$$(1 - \beta\delta^{-O(1)}) e^{-O(\beta/\delta)} \leq \frac{\partial_\alpha \varphi(\underline{s}_0) e^{-\alpha\sigma(g_0 h_1, s_1)} \cdots e^{-\alpha\sigma(g_{k-1} h_k, s_k)}}{\partial_\alpha \varphi(z_{g_0}) e^{-\alpha\sigma(g_0 h_1, x_{g_1}^M)} \cdots e^{-\alpha\sigma(g_{k-1} h_k, x_{g_k}^M)}} \leq (1 + \beta\delta^{-O(1)}) e^{O(\beta/\delta)}. \quad (2.4.32)$$

By (2.4.16),

$$B_\alpha := e^{-\alpha\sigma(g_0 h_1, x_{g_1}^M)} \dots e^{-\alpha\sigma(g_{k-1} h_k, x_{g_k}^M)} \leq \beta_\alpha^{2k} \delta^{-O(1)}.$$

Together with (2.4.28)-(2.4.32)

$$|\varphi(\mathbf{g} \leftrightarrow \mathbf{h}\eta_j) - \varphi(\mathbf{g} \leftrightarrow \mathbf{h}\eta_{j+1}) - d_A(z_0, z_1) \alpha^\sharp(m_0) \partial_\alpha \varphi(z_{g_0}) B_\alpha| \leq \beta \beta_\alpha^{2k+1} \delta^{-O(1)} v_\alpha. \quad (2.4.33)$$

We deal with the error term which comes from the process of changing flags. The Lipschitz property in Lemma 2.4.6 and Lemma 2.2.40 (2.2.26) imply that

$$d_\alpha(\mathbf{g} \leftrightarrow \mathbf{h}\eta_{l_1}, \mathbf{g} \leftrightarrow \mathbf{h}\eta'_{l_2}) \leq \beta_\alpha^{2k} \delta^{-O(1)} d_\alpha(g_k \eta_{l_1}, g_k \eta'_{l_2}) \leq \beta_\alpha^{2k+1} \beta \delta^{-O(1)},$$

Due to (2.4.17) in Lemma 2.4.6 and Lemma 2.2.42, the two points $\mathbf{g} \leftrightarrow \mathbf{h}\eta_{l_1}, \mathbf{g} \leftrightarrow \mathbf{h}\eta'_{l_2}$ are in J , the δ neighbourhood of suppr . Due to G1 assumption (2.4.1)

$$|\varphi(\mathbf{g} \leftrightarrow \mathbf{h}\eta_{l_1}) - \varphi(\mathbf{g} \leftrightarrow \mathbf{h}\eta'_{l_2})| \leq \delta^{-1} \sum_\alpha v_\alpha d_\alpha(\mathbf{g} \leftrightarrow \mathbf{h}\eta_{l_1}, \mathbf{g} \leftrightarrow \mathbf{h}\eta'_{l_2}).$$

Therefore

$$|\varphi(\mathbf{g} \leftrightarrow \mathbf{h}\eta_{l_1}) - \varphi(\mathbf{g} \leftrightarrow \mathbf{h}\eta'_{l_2})| \leq \delta^{-O(1)} \beta \sum_\alpha v_\alpha \beta_\alpha^{2k+1}. \quad (2.4.34)$$

We collect information for different simple roots. Recall that for a fixed g in G and for $h \in G, z \in \mathcal{P}_0$, we have defined $\tilde{Y}_g^n(h, z)_\alpha = e^{-\alpha(\sigma(gh, z) - \kappa(g) - n\sigma_\mu)} \alpha(m(\ell_g, hk))$. Let

$$\varsigma_\alpha := \frac{\xi d_A(z_0, z_1) \alpha^\sharp(m_0) \partial_\alpha \varphi(z_{g_0}) B_\alpha}{\prod_{l=1}^k \tilde{Y}_{g_{l-1}}^n(h_l, z_{g_l})_\alpha}.$$

Let $\varsigma = (\varsigma_\alpha)_{\alpha \in \Pi} \in \mathbb{R}^m$. Hence by (2.4.27), (2.4.33), (2.4.34) and (2.4.8)

$$|\xi(\varphi(\mathbf{g} \leftrightarrow \mathbf{h}x) - \varphi(\mathbf{g} \leftrightarrow \mathbf{h}x')) - \langle \varsigma, \prod_{l=1}^k \tilde{Y}_{g_{l-1}}^n(h_l, z_{g_l}) \rangle| \leq \beta \delta^{-O(1)} \sum_\alpha \beta_\alpha^{2k+1} v_\alpha \xi \ll \beta \delta^{-O(1)} \tau. \quad (2.4.35)$$

We want to verify that $\|\varsigma\| \in I_\tau$. By (2.4.19), we have

$$\varsigma_\alpha = \xi d_A(z_0, z_1) \partial_\alpha \varphi(z_{g_0}) \beta_\alpha^k e^{-\alpha\kappa(g_0) - \dots - \alpha\kappa(g_{k-1})}.$$

By (2.4.14), (2.4.28), (2.4.20) and (2.4.2) we have $|\varsigma_\alpha| \in \xi v_\alpha \beta_\alpha^{2k+1} [\delta^{O(1)}, \delta^{-O(1)}]$. Therefore by (2.4.8),

$$\|\varsigma\| \in \sup_\alpha \xi v_\alpha \beta_\alpha^{2k+1} [\delta^{O(1)}, \delta^{-O(1)}] \in \tau [\delta^{O(1)}, \delta^{-O(1)}] \subset [\tau^{3/4}, \tau^{5/4}] = I_\tau.$$

By definition, the distribution of $\tilde{Y}_{g_{l-1}}^n(h_l, z_{g_l})$, where h_l satisfies (2.4.15) with distribution μ^{*n} , is the measure λ_l . Finally, due to $|e^{ix} - e^{iy}| \leq |x - y|$ for $x, y \in \mathbb{R}$, the inequality (2.4.35) implies (2.4.26). \square

Fourth step: We are able to apply sum-product estimates.

Proof of Theorem 2.1.7. For $l = 1, 2, \dots, k$, Proposition 2.3.18 and Lemma 2.4.2 tell us that with ϵ small enough depending on $\epsilon_4\epsilon$, there exists C_0 such that the measures λ_l satisfy the assumptions in Proposition 2.3.17 with τ .

Proposition 2.3.17 implies that for τ large enough,

$$\left| \int \exp(i\langle \varsigma, x_1 \cdots x_k \rangle) d\lambda_1(x_1) \cdots d\lambda_k(x_k) \right| \leq \tau^{-\epsilon_3}.$$

Then by (2.4.12), (2.4.22) and (2.4.26), we have

$$\left| \int e^{i\xi\varphi(\eta)} r(\eta) d\nu(\eta) \right|^2 \leq O_\epsilon(\delta^c) + O(\beta\delta^{-O(1)}\tau) + \tau^{-\epsilon_3}.$$

Due to $\beta\delta^{-O(1)}\tau = \max_{\alpha \in \Pi} e^{(-\alpha\sigma_\mu + O(1)\epsilon + \epsilon_2)n}$, take ϵ small enough. The proof is complete. \square

Remark 2.4.13. *Another difference with [BD17] is that we avoid using the renewal idea, which simplifies the proof of this part. The renewal idea is that instead of using μ^{*n} , we use a renewal measure μ_t , which is defined to be the distribution of $g_1 \cdots g_n$ for the first time that its Cartan projection exceeds t , where g_1, g_2, \dots are i.i.d. random variables with distribution μ . This is because we generalize the sum-product estimate to a form that the measure can have a support which depends on the frequency, and we use the large deviation principle to prove that our measure has a support not too large with respect to the frequency.*

2.4.3 Examples of Fourier decay

In this section, we give a nice application of Theorem 2.1.7, that is Theorem 2.1.1. This application also serves as a “baby case” for Section 2.4.4.

Recall that v_0 is a unit vector in V and ς is a vector in v_0^\perp . We fix the direction, that is $u_0 := \varsigma/\|\varsigma\|$, and we let $\xi = \|\varsigma\|$. Then for $x = \mathbb{R}v$, we have $\langle \varsigma, \psi(v) \rangle = \xi \langle u_0, \psi(v) \rangle = \xi \langle u_0, v \rangle / \langle v_0, v \rangle$, and we take

$$\varphi(x) = \frac{\langle u_0, v \rangle}{\langle v_0, v \rangle}.$$

Since we are only interested in the value on the support of ν_V , which is contained in the image of \mathcal{P} in $\mathbb{P}V$. The functions φ, r can be lifted to functions on \mathcal{P} . We use the same notation φ to denote the lifted functions. We first calculate the directional derivative of φ . Recall that the inner product on the exterior square $\wedge^2 V$ is given by

$$\langle v_1 \wedge v_2, w_1 \wedge w_2 \rangle = \langle v_1, w_1 \rangle \langle v_2, w_2 \rangle - \langle v_1, w_2 \rangle \langle v_2, w_1 \rangle, \quad (2.4.36)$$

for v_1, v_2, w_1, w_2 in V . Recall that $q_{2\chi-\alpha}$ is the projection of $\wedge^2 V$ on the subrepresentations of highest weight $2\chi - \alpha$. By the same proof as in Lemma 2.2.3, we see that the multiplicity of an irreducible representation of highest weight $2\chi - \alpha$ is at most 1 in $\wedge^2 V$. Hence the image of the projection $q_{2\chi-\alpha}$ is an irreducible subrepresentation or zero. Let e_1 be a unit vector of highest weight in V .

Lemma 2.4.14. *Let v_0, u_0 be two unit vectors in V . Let φ be defined as above. Then for a simple root α and $z = kz_0 \in \mathcal{P}_0$,*

$$\partial_\alpha \varphi(z) = \frac{\langle v_0 \wedge u_0, v \wedge u \rangle}{\langle v_0, v \rangle^2} = \frac{\langle q_{2\chi-\alpha}(v_0 \wedge u_0), v \wedge u \rangle}{\langle v_0, v \rangle^2}, \quad (2.4.37)$$

where $v = ke_1$ and $u = kY_\alpha e_1$.

Proof. By definition,

$$\partial_\alpha \varphi(z) = \partial_t \left. \frac{\langle u_0, k \exp(tY_\alpha) e_1 \rangle}{\langle v_0, k \exp(tY_\alpha) e_1 \rangle} \right|_{t=0} = \frac{\langle u_0, kY_\alpha e_1 \rangle \langle v_0, ke_1 \rangle - \langle u_0, ke_1 \rangle \langle v_0, kY_\alpha e_1 \rangle}{\langle v_0, ke_1 \rangle^2}.$$

By (2.4.36), we have the first equality. The vector $e_1 \wedge Y_\alpha e_1$ is a vector of weight $2\chi - \alpha$, which is in the irreducible subrepresentation of $\wedge^2 V$ with highest weight $2\chi - \alpha$. The vector $v \wedge u = k(e_1 \wedge Y_\alpha e_1)$ is also in this subrepresentation, hence

$$\langle v_0 \wedge u_0, v \wedge u \rangle = \langle q_{2\chi-\alpha}(v_0 \wedge u_0), v \wedge u \rangle.$$

The proof is complete. \square

For a vector v in an euclidean space W , let v^* be the linear functional on W given by

$$v^*(w) = \langle v, w \rangle \quad \text{for } w \in W.$$

Proof of Theorem 2.1.1 from Theorem 2.1.7. Let $\delta > 0$ be a constant to be fixed later. Recall that φ, r have been lifted to functions on \mathcal{P} . In order to use Theorem 2.1.7, we need to verify the (ξ^{ϵ_0}, r) goodness assumption for φ . Let $C_0 > 0$ be a constant such that

$$c_\gamma(r) \leq C_0, \quad |\langle v_0, v \rangle| \geq \|v\|/C_0 \quad \text{for } \mathbb{R}v \in V_{\chi, \eta} \text{ and } \eta \in \text{supp} r, \quad (2.4.38)$$

$$\max_{\alpha \in \Pi} \frac{\|q_{2\chi-\alpha}(v \wedge u)\|}{\|v \wedge u\|} \geq 1/C_0 \quad \text{for every couple } v, u \text{ in } V \text{ with } v \wedge u \neq 0. \quad (2.4.39)$$

The existence of C_0 for (2.4.39) is due to Lemma 2.2.56.

We want to verify that φ is (ξ^{ϵ_0}, r) good. Let $l_\alpha = q_{2\chi-\alpha}(v_0 \wedge u_0)$ and $\theta_\alpha = \|l_\alpha\|$. The main problem is to verify G2, because $\partial_\alpha \varphi$ may vanish. We need a cutoff. Let τ be a smooth function on \mathbb{R} such that $\tau|_{[0, \infty)} = 1$, τ takes values in $[0, 1]$, $\text{supp} \tau \subset [-1, \infty)$ and $|\tau'| \leq 2$. Set $\tau_\delta(x) = \tau(x/\delta)$ for $x \in \mathbb{R}$. Let $r_1 = r \cdot \prod_{\alpha \in \Pi} \tau_\alpha$, where

$$\tau_\alpha = \tau_\delta(\delta(V_{2\chi-\alpha, \eta}, \mathbb{R}l_\alpha^*) - 2\delta).$$

If $l_\alpha = 0$, then we let $\tau_\alpha = 1$. Let J be the $\xi^{-\epsilon_0}$ neighbourhood of the support of r_1 , an open set of \mathcal{P} . When ξ is large enough, we can suppose that for $\eta \in J$ and $v \in V_{\chi, \eta}$ we have $|\langle v_0, v \rangle| > \|v\|/(2C_0)$.

We claim that if $\delta = \xi^{-\epsilon_0/2}$ and ξ is large enough such that $\delta^{-1} \geq CC_0^{m+4}$, where C is a constant only depending on the group G and the norm on V , which is defined in Lemma 2.5.7. Then φ, r_1 satisfy the assumptions of Theorem 2.1.7.

For η in the support of r_1 , due to (2.4.37) and $\delta(V_{2\chi-\alpha,\eta}, \mathbb{R}l_\alpha^*) > \delta$, we have

$$|\partial_\alpha \varphi(\eta)| = \frac{|\langle l_\alpha, v \wedge u \rangle|}{\langle v_0, v \rangle^2} = \theta_\alpha \delta(V_{2\chi-\alpha,\eta}, \mathbb{R}l_\alpha^*) \langle v_0, v \rangle^{-2} \geq \delta \theta_\alpha. \quad (2.4.40)$$

Due to $|\langle v_0, v \rangle| \geq \|v\|/C_0$ for $\eta \in \text{suppr}$ and $v \in V_{\chi,\eta}$,

$$v_\alpha = \sup_{\eta \in \text{suppr}_1} |\partial_\alpha \varphi(\eta)| = \sup_{\eta \in \text{suppr}_1} \frac{|\langle l_\alpha, v \wedge u \rangle|}{\langle v_0, v \rangle^2} \leq C_0^2 \theta_\alpha. \quad (2.4.41)$$

Then for η in suppr_1 , by (2.4.40) and (2.4.41) we have

$$|\partial_\alpha \varphi(\eta)| \geq C_0^{-2} \delta v_\alpha$$

which implies G2 assumption (2.4.2). The inequality (2.4.40) also implies that

$$v_\alpha \geq \delta \theta_\alpha, \quad (2.4.42)$$

that is v_α and θ_α are of the same magnitude. Hence by (2.4.39), we have

$$\sup_{\alpha \in \Pi} v_\alpha \in [\delta, C_0^2] \sup_{\alpha \in \Pi} \theta_\alpha \in [\delta C_0^{-1}, C_0^2],$$

which is G4 assumption (2.4.4).

Now, we verify G1 assumption (2.4.1). If χ is a fundamental weight χ_α , then (2.4.39) implies $\theta_\alpha = \|q_{2\chi-\alpha}(v_0 \wedge u_0)\| \geq 1/C_0$. Hence, for η, η' in J and unit vectors $v \in V_{\chi,\eta}$, $v' \in V_{\chi,\eta'}$, we have

$$\begin{aligned} |\varphi(\eta) - \varphi(\eta')| &= \left| \frac{\langle u_0 \wedge v_0, v \wedge v' \rangle}{\langle v_0, v \rangle \langle v_0, v' \rangle} \right| \leq 4C_0^2 \|u_0 \wedge v_0\| \|v \wedge v'\| \leq 4C_0^3 \theta_\alpha d(V_{\alpha,\eta}, V_{\alpha,\eta'}) \\ &\leq 4\delta^{-1} C_0^3 v_\alpha d(V_{\alpha,\eta}, V_{\alpha,\eta'}). \end{aligned} \quad (2.4.43)$$

For general case, this step is more complicate. Please see Lemma 2.5.7.

For G3 assumption (2.4.3), for $z = kz_0, z' = k'z_0$ in $\pi^{-1}(J) \subset \mathcal{P}_0$ and $v' = k'e_1, u' = k'Y_\alpha e_1$

$$\begin{aligned} |\partial_\alpha \varphi(z) - \partial_\alpha \varphi(z')| &\leq C_0^4 (|\langle l_\alpha, v \wedge u - v' \wedge u' \rangle| + |\langle l_\alpha, v \wedge u \rangle \langle v_0, v - v' \rangle|) \\ &\ll C_0^4 \theta_\alpha d_0(z, z') \end{aligned}$$

where the last inequality is due to Lemma 2.5.3.

We also need to calculate $c_\gamma(r_1)$. Lemma 2.2.14 implies $c_\gamma(\tau_\alpha) \ll \delta^{-\gamma}$. Hence $c_\gamma(r_1) \ll \delta^{-\gamma} + c_\gamma(r) \leq \delta^{-\gamma} + C_0$. The claim is true and Theorem 2.1.7 implies that

$$\left| \int e^{i\xi\varphi(\eta)} r_1(\eta) d\nu(\eta) \right| \leq \xi^{-\epsilon_1}.$$

Finally, by regularity of stationary measure, Corollary 2.2.50, the set where $r_1 \neq r$ has measure bounded by $O(\delta^c) = O(\xi^{-\epsilon_0 c/2})$, that is there exist $C, c > 0$ such that for all $\delta > 0$

$$\nu\{\eta \in \mathcal{P} \mid \delta(V_{2\chi-\alpha,\eta}, \mathbb{R}l_\alpha^*) \leq 2\delta\} \leq C\delta^c.$$

The proof is complete. \square

Remark 2.4.15. *In higher dimension, the differential $d\varphi$ at a point always vanishes in some direction of the tangent space. The cutoff in the proof can be understood as removing a neighbourhood of the zero locus of $d\varphi$ in the unit tangent bundle of $\mathbb{P}V$. The language of flag variety makes the proof obscure, but this language is really powerful.*

2.4.4 From Fourier decay to spectral gap

Derivative of the cocycle

This part is devoted to the derivative of the cocycle. The results of this part imply that for most g, h in G , the difference of the Iwasawa cocycle $\sigma(g, \cdot) - \sigma(h, \cdot)$ satisfies the (C, r) good condition in Definition 2.4.1 (See Lemma 2.4.25). Since the α -bundle is trivial on \mathcal{P}_0 , we will work on \mathcal{P}_0 . We need to lift the Iwasawa cocycle σ to \mathcal{P}_0 and we use the same notation σ .

Let V be an irreducible representation of G with a good norm. Recall that $\sigma_V(g, x) = \frac{\|\rho(g)v\|}{\|v\|}$ for g in G and v in V . We will abbreviate ρg to g in the proof, because (ρ, V) is the only representation to be studied in this part. Let α be a simple root. Let e_1 be a unit vector of highest weight in V and let $e_2 = Y_\alpha e_1$.

Lemma 2.4.16. *Let V be an irreducible representation of G with a good norm. For $z = kz_o$ in \mathcal{P}_0 , we have*

$$\partial_\alpha \sigma_V(g, z) = \frac{\langle \rho g v, \rho g u \rangle}{\|\rho g v\|^2},$$

where $v = ke_1$ and $u = ke_2$.

Proof. Without loss of generality, we suppose that $z = z_o$. Since Y_α is a left K invariant vector field on \mathcal{P}_0 , we have

$$\begin{aligned} \partial_{Y_\alpha} \sigma_V(g, e) &= \partial_t \sigma_V(g, \exp(tY_\alpha)z_o)|_{t=0} = \partial_t \left(\log \frac{\|g \exp(tY_\alpha)e_1\|}{\|\exp(tY_\alpha)e_1\|} \right) \Big|_{t=0} \\ &= \frac{\langle ge_1, gY_\alpha e_1 \rangle}{\|ge_1\|^2} - \frac{\langle e_1, Y_\alpha e_1 \rangle}{\|e_1\|^2}. \end{aligned}$$

Since the norm is good, eigenvectors of different weights are orthogonal, we have $\langle e_1, Y_\alpha e_1 \rangle = 0$. The result follows. \square

Form this lemma, we know that the derivative of the cocycle σ_V in the direction Y_α is nonzero only if $\chi - \alpha$ is a weight of V . Lemma 2.2.32 only implies that $\partial_\alpha \sigma_{\alpha'} = 0$ for $\alpha \neq \alpha'$, which works for fundamental representations $\sigma_{V_{\alpha'}} = \sigma_{\alpha'}$. We fix the distance d_0 on \mathcal{P}_0 , which is defined in Appendix 2.5.2.

Lemma 2.4.17. *Let $\delta < 1/2$. Let $\widetilde{B_{V,g}^m}(\delta)$ be the preimage of $B_{V,g}^m(\delta) \subset \mathbb{P}V$ in \mathcal{P}_0 . For $z = kz_o \in \widetilde{B_{V,g}^m}(\delta)$,*

$$|\partial_\alpha \sigma_V(g, z)| \leq \delta^{-O(1)}. \quad (2.4.44)$$

We also have

$$\mathrm{Lip}_{\mathcal{P}_0}(\partial_\alpha \sigma_V(g, \cdot)|_{\widetilde{B_{V,g}^m}(\delta)}) \leq \delta^{-O(1)}. \quad (2.4.45)$$

Proof. By Lemma 2.4.16, the hypothesis that $\mathbb{R}ke_1 \in B_{V,g}^m(\delta)$ and (2.2.7)

$$|\partial_\alpha \sigma_V(g, z)| = \left| \frac{\langle gke_1, gke_2 \rangle}{\|gke_1\|^2} \right| \leq \frac{\|Y_\alpha\| \|g\|^2 \|e_1\|^2}{\|g\|^2 \delta^2 \|e_1\|^2}.$$

Since the operator norm of Y_α is bounded, we have

$$|\partial_\alpha \sigma_V(g, z)| \leq \delta^{-O(1)}.$$

The estimate of Lipschitz norm is more complicate. Let $v = ke_1, v' = k'e_1, u = ke_2, u' = k'e_2$. We have

$$|\partial_\alpha \sigma_V(g, z) - \partial_\alpha \sigma_V(g, z')| = \frac{|\langle gv, gu \rangle \|gv'\|^2 - \langle gv', gu' \rangle \|gv\|^2|}{\|gv\|^2 \|gv'\|^2}.$$

By the same argument, due to $v = ke_1 \in B_{V,g}^m(\delta)$, we use (2.2.7) to give a lower bound of the denominator, that is

$$\|gv\|^2 \|gv'\|^2 \geq \delta^4 \|g\|^4 \|v\|^2 \|v'\|^2 = \delta^4 \|g\|^4 \|e_1\|^4.$$

Use the difference to give an upper bound of the numerator, that is

$$\begin{aligned} & |\langle gv, gu \rangle \|gv'\|^2 - \langle gv', gu' \rangle \|gv\|^2| \\ & \ll \|g\|^3 \|e_1\|^3 (\|gv - gv'\| + \|gu - gu'\|) \ll \|g\|^4 \|v\|^3 (\|v - v'\| + \|u - u'\|). \end{aligned}$$

Therefore we have

$$|\partial_\alpha \sigma_V(g, z) - \partial_\alpha \sigma_V(g, z')| \ll \delta^{-O(1)} (\|ke_1 - k'e_1\| + \|ke_2 - k'e_2\|).$$

Then by Lemma 2.5.3, the proof is complete. \square

Let V be a finite dimensional vector space with euclidean norm. Recall that $\wedge^2 \text{Sym}^2 V$ is the exterior square of the symmetric square of V . It is a linear space generated by vectors of the form $v_1 v_2 \wedge v_3 v_4$ where v_i are in V , for $i = 1, 2, 3, 4$. For g, h in $GL(V)$, let $F_{g,h}$ be the linear functional on $\wedge^2 \text{Sym}^2 V$, whose action on the vector $v_1 v_2 \wedge w_1 w_2$ is defined by

$$F_{g,h}(v_1 v_2 \wedge w_1 w_2) = \langle hv_1, hv_2 \rangle \langle gw_1, gw_2 \rangle - \langle gv_1, gv_2 \rangle \langle hw_1, hw_2 \rangle.$$

This formula is well defined because v_1, v_2 and w_1, w_2 are symmetric, respectively. We also have $F_{g,h}(v_1 v_2 \wedge w_1 w_2) = -F_{g,h}(w_1 w_2 \wedge v_1 v_2)$. Since the vectors of form $v_1 v_2 \wedge w_1 w_2$ generate the space $\wedge^2 \text{Sym}^2 V$, the linear form $F_{g,h}$ is uniquely defined.

Suppose that V is a super proximal representation of G with highest weight χ (Definition 2.2.2). Let α be the unique simple root such that $\chi - \alpha$ is a weight of V . The space $\wedge^2 \text{Sym}^2 V$ may be reducible. The two highest weights of $\text{Sym}^2 V$ are $2\chi, 2\chi - \alpha$, whose eigenspaces have dimension 1. Hence, the highest weight of $\wedge^2 \text{Sym}^2 V$ is $4\chi - \alpha$, and the eigenspace has dimension 1. Let W be the irreducible subrepresentation of $\wedge^2 \text{Sym}^2 V$ with the highest weight $\chi_1 := 4\chi - \alpha$. In the following lemma, we abbreviate $\rho(g), \rho(h)$ to g, h .

Lemma 2.4.18. *Let $\delta < 1/2$. Let V be a super proximal representation of G and let α be the unique simple root such that $\chi - \alpha$ is a weight of V . Recall that $V_{\chi_1, \eta}$ is the image of $\eta \in \mathcal{P}$ in $\mathbb{P}W$. If g, h in G and $z = kz_o \in \mathcal{P}_0, \eta = \pi(z)$ satisfy*

- (1) $\ell_h^{-1}V^\chi, \ell_h^{-1}V^{\chi-\alpha} \in B_{V,g}^m(\delta), \gamma_{1,2}(g) \leq \delta^3,$
- (2) $\delta(V_{\chi_1, \eta}, F_{g,h}|_W) > \delta$ and $V_{\chi, \eta} \in B_{V,g}^m(\delta) \cap B_{V,h}^m(\delta),$

then

$$|\partial_\alpha(\sigma_V(g, z) - \sigma_V(h, z))| \geq \delta^{O(1)}.$$

Remark 2.4.19. *This is similar to the non local integrability property as defined in [Dol98] [Nau05] and [Sto11]. Although the above two conditions are complicate, we will see later that in the measure sense, most pairs g, h satisfy these conditions.*

The key idea here is to use other representation to linearise polynomial functions on V . As long as the function is linear, we will have a good control of it. Another point is that the image of \mathcal{P} stays in the same irreducible subrepresentation.

Proof of Lemma 2.4.18. By Lemma 2.4.16, let

$$L := \partial_\alpha(\sigma_V(g, z) - \sigma_V(h, z)) = \frac{F_{g,h}(v^2 \wedge vu)}{\|gv\|^2 \|hv\|^2}, \quad (2.4.46)$$

where $v = ke_1$ and $u = kY_\alpha e_1$ as in Lemma 2.4.16.

Lemma 2.4.20. *If g, h satisfy assumption (1), then the operator norm satisfy*

$$\|F_{g,h}|_W\| \geq \delta^{O(1)} \|g\|^2 \|h\|^2.$$

Proof. Using the Cartan decomposition and good norm, we can suppose that h is diagonal and $h = \mathrm{diag}(a_1, a_2, \dots, a_n)$ with $a_1 \geq a_2 \geq \dots \geq a_n$. By Definition 2.2.2, we know that $he_1 = a_1 e_1$ and $he_2 = a_2 e_2$. The assumption (1) becomes

$$\delta(\mathbb{R}e_1, y_g^m), \delta(\mathbb{R}e_2, y_g^m) > \delta, \gamma_{1,2}(g) \leq \delta^3. \quad (2.4.47)$$

In (2.4.46), let $z = z_o$, then $v = e_1, u = e_2$, which make

$$\langle hv, hu \rangle = \langle a_1 e_1, a_2 e_2 \rangle = 0.$$

Therefore, due to

$$\langle v_1, v_2 \rangle \geq \|v_1\| \|v_2\| - \|v_1 \wedge v_2\|,$$

for v_1, v_2 in V , we have

$$F_{g,h}(e_1^2 \wedge e_1 e_2) = a_1^2 \langle ge_1, ge_2 \rangle \geq a_1^2 (\|ge_1\| \|ge_2\| - \|ge_1 \wedge ge_2\|).$$

Then (2.2.7) and (2.4.47) imply

$$F_{g,h}(e_1^2 \wedge e_1 e_2) \geq \|h\|^2 \|g\|^2 (\delta^2 - \gamma_{1,2}(g)).$$

The proof is complete. □

By Definition 2.2.2, the representation $\wedge^2 \text{Sym}^2 V$ is a proximal representation. Due to $\mathbb{R}(v^2 \wedge vu) = \mathbb{R}k(e_1^2 \wedge e_1 e_2) = kV^{\chi_1}$, the line $\mathbb{R}(v^2 \wedge vu)$ is contained in the K -orbit of the subspace of highest weight V^{χ_1} . Since V^{χ_1} is in W , we see that $v^2 \wedge vu$ is also in W . By (2.4.46),

$$L = \frac{F_{g,h}(v^2 \wedge vu)}{\|F_{g,h}|_W\|} \frac{\|g\|^2 \|h\|^2}{\|gv\|^2 \|hv\|^2} \frac{\|F_{g,h}|_W\|}{\|g\|^2 \|h\|^2}.$$

When η satisfies assumption (2), the result follows by applying (2.2.7) to $\|gv\|^2, \|hv\|^2$ and by Lemma 2.4.20. \square

Proof of the spectral gap

Here we will prove the theorem of uniform spectral gap. The first part is classic, where we use some ideas of Dolgopyat [Dol98] to transform the problem to an effective estimate Proposition 2.4.24, see also [Nau05] and [Sto11]. The key observation is that this effective estimate (Proposition 2.4.24) can be obtained by the Fourier decay, regarding the difference of cocycle as a function on \mathcal{P} . The intuition here is from Lemma 2.4.18. When g, h are in general position and η not too close to ζ_g^m, ζ_h^m , the difference $\varphi(\eta) = \sigma(g, \eta) - \sigma(h, \eta)$ will be (C, r) good (Definition 2.4.1). But in order to accomplish this, we need some sophisticate cutoff, which makes the proof complicate.

Recall that the Iwasawa cocycle takes values in the Cartan subspace \mathfrak{a} . We can write θ in \mathfrak{a}^* as a linear combination of fundamental weights, $\{\chi_\alpha | \alpha \in \Pi\}$, that is

$$\theta = \sum_{\alpha \in \Pi} \theta_\alpha \chi_\alpha.$$

Set $|\theta| = \max_{\alpha \in \Pi} |\theta_\alpha|$.

We want to treat the spectral gap on the flag variety \mathcal{P} and the projective space $\mathbb{P}V$ at the same time, where V is an irreducible representation of G with good norm. Let X be \mathcal{P} or $\mathbb{P}V$. Let $\sigma : G \times X \rightarrow E$ be the cocycle, which is given by the Iwasawa cocycle and $E = \mathfrak{a}$ when $X = \mathcal{P}$, and given by σ_V (defined in (2.2.6)) and $E = \mathbb{R}$ when $X = \mathbb{P}V$. Let $E_{\mathbb{C}} = E \otimes_{\mathbb{R}} \mathbb{C}$ and $E_{\mathbb{C}}^*$ be the dual space of $E_{\mathbb{C}}$. For $z \in E_{\mathbb{C}}^*$, write $z = \varpi + i\theta$, where θ, ϖ are elements in E^* . Recall that the transfer operator P_z is defined as: For $|\varpi|$ small enough and for f in $C^0(X)$, x in X

$$P_z f(x) = \int_G e^{z\sigma(g,x)} f(gx) d\mu(g).$$

Recall that for f in $C^\gamma(X)$ let $c_\gamma(f) = \sup_{x \neq x'} \frac{|f(x) - f(x')|}{d(x, x')^\gamma}$ and $|f|_\gamma = |f|_\infty + c_\gamma(f)$.

Remark 2.4.21. Here we should be careful that the distances on $\mathbb{P}V$ and \mathcal{P} are defined in (2.2.4) and (2.2.12). They are not the Riemannian distances defined in the introduction. But on a compact Riemannian manifold, different Riemannian distances are equivalent. In particular, every Riemannian distance on \mathcal{P} is equivalent to the K -invariant Riemannian distance on \mathcal{P} . By Corollary 2.5.6, we know it is equivalent to the distances defined (2.2.12). The case of the projective space $\mathbb{P}V$ is similar. Hence, the norm $|\cdot|_\gamma$ induced by different distances are equivalent.

We state our main result of this section

Proposition 2.4.22. *Let μ be a Zariski dense Borel probability measure on G with a finite exponential moment. For $\gamma > 0$ small enough, there exist $\rho < 1, C > 0$ such that for all θ and ϖ in E^* with $|\theta|$ large enough, $|\varpi|$ small enough and f in $C^\gamma(X)$, n in \mathbb{N} we have*

$$|P_{\varpi+i\theta}^n f|_\gamma \leq C|\theta|^{2\gamma} \rho^n |f|_\gamma.$$

Theorem 2.1.5 and Theorem 2.1.6 follow directly from Proposition 2.4.22. The assumption on μ will be needed throughout this section.

We start with standard *a priori* estimates. When $z = 0$, we will write P for P_0 .

Proposition 2.4.23. *For every $\gamma > 0$ small enough, there exist $C > 0$ and $0 < \rho < 1$ such that for all f in $C^\gamma(X)$, $|\varpi|$ small enough and $n \in \mathbb{N}$*

$$|P_z^n f|_\infty \leq C^{|\varpi|^n} |f|_\infty, \quad (2.4.48)$$

$$|P^n f|_\infty \leq \left| \int_X f d\nu \right| + C\rho^n |f|_\gamma, \quad (2.4.49)$$

$$c_\gamma(P_z^n f) \leq C(C^{|\varpi|^n} |\theta|^\gamma |f|_\infty + \rho^n c_\gamma(f)). \quad (2.4.50)$$

The inequality (2.4.48) is a consequence of exponential moment and the Hölder inequality. For (2.4.49), please see [BL85, V, Thm.2.5] and [BQ16, Prop 11.10, Lem.13.5] for more details. This inequality (2.4.49) is a consequence of the fact that the action of G on X is contracting. The third inequality (2.4.50) is called the Lasota-Yorke inequality. The proof is classic and we include a proof in the appendix for completeness.

We reduce Proposition 2.4.22 to Proposition 2.4.24. The reduction is standard, using Proposition 2.4.23. Please see [Dol98] and [Nau18] for more details. We also include a proof in the appendix for completeness. For f in $C^\gamma(X)$, we define another norm $|f|_{\gamma,\theta} = |f|_\infty + c_\gamma(f)/|\theta|^\gamma$ for $\theta \neq 0$.

Proposition 2.4.24. *For every $\gamma > 0$ small enough, for $|\theta|$ large enough and $|\varpi|$ small enough, there exist $\epsilon_2, C_2 > 0$ such that for f in $C^\gamma(X)$ and $|f|_{\gamma,\theta} \leq 1$, we have*

$$\int \left| P_{\varpi+i\theta}^{[C_2 \ln |\theta|]} f \right|^2 d\nu \leq e^{-\epsilon_2 \ln |\theta|}. \quad (2.4.51)$$

Now we will distinguish two cases. **We claim that the case of $\mathbb{P}V$ is a corollary of the case of \mathcal{P} up to a constant.** Recall that the stationary measure on $\mathbb{P}V$ is written as ν_V . Let f be a function in $C^\gamma(\mathbb{P}V)$ and $|f|_{\gamma,\theta} \leq 1$. The estimate only depends on the value of f on the support of the stationary measure ν_V . By Lemma 2.2.43, the stationary measure on $\mathbb{P}V$ is the pushforward measure of the stationary measure ν on \mathcal{P} . Hence we can define the function \tilde{f} on \mathcal{P} by

$$\tilde{f}(\eta) = f(V_{\chi,\eta}),$$

where χ is the highest weight of V . Then by $\sigma_V(g, V_{\chi,\eta}) = \chi\sigma(g, \eta)$ (see (2.2.2)),

$$\int \left| P_{\varpi+i\theta}^{[C_2 \ln |\theta|]} f \right|^2 d\nu_V = \int \left| P_{(\varpi+i\theta)\chi}^{[C_2 \ln |\theta|]} \tilde{f} \right|^2 d\nu.$$

We will verify that \tilde{f} satisfies $|\tilde{f}|_{\gamma, \theta} \ll 1$. By (2.2.16), for two distinct points η, η' in \mathcal{P} we have

$$\frac{|\tilde{f}(\eta) - \tilde{f}(\eta')|}{d(\eta, \eta')^\gamma} = \frac{|\tilde{f}(\eta) - \tilde{f}(\eta')|}{d(V_{\chi, \eta}, V_{\chi, \eta'})^\gamma} \frac{d(V_{\chi, \eta}, V_{\chi, \eta'})^\gamma}{d(\eta, \eta')^\gamma} \ll \frac{|f(V_{\chi, \eta}) - f(V_{\chi, \eta'})|}{d(V_{\chi, \eta}, V_{\chi, \eta'})^\gamma} = |f|_\gamma.$$

Hence with some change of constant, we can deduce the case of $\mathbb{P}V$ from the case of \mathcal{P} .

We only need to prove Proposition 2.4.24 for the case of \mathcal{P} .

From Fourier decay to Proposition 2.4.24. We need to reduce (2.4.51) to Fourier decay (Theorem 2.1.7). Let

$$n = [C_2 \log |\theta|] \text{ and } \delta = e^{-\epsilon n} \quad (2.4.52)$$

(with $C_2 \geq \max_{\alpha \in \Pi} \{1/\alpha \sigma_\mu\} + 1$ and $\epsilon > 0$ to be determined later), and let $G_{n, \epsilon, \alpha}$ be the subset of $G \times G$, defined as the set of couples which satisfy Lemma 2.4.18 (1) with $V = V_\alpha$. Let

$$G_{n, \epsilon} = \{g \in G \mid \|\kappa(g) - n\sigma_\mu\| \leq n\epsilon\}^2 \bigcap_{\alpha \in \Pi} G_{n, \epsilon, \alpha} \subset G \times G.$$

For $|f|_{\gamma, \theta} \leq 1$, let

$$A_{g, h} := \int_X e^{z\sigma(g, \eta) + \bar{z}\sigma(h, \eta)} f(g\eta) \bar{f}(h\eta) d\nu(\eta).$$

Then

$$\begin{aligned} \int |P_z^n f|^2 d\nu &= \int e^{z\sigma(g, \eta) + \bar{z}\sigma(h, \eta)} f(g\eta) \bar{f}(h\eta) d\nu(\eta) d\mu^{*n}(g) d\mu^{*n}(h) \\ &= \int_{G_{n, \epsilon}} A_{g, h} d\mu^{*n}(g) d\mu^{*n}(h) + \int_{G_{n, \epsilon}^c} A_{g, h} d\mu^{*n}(g) d\mu^{*n}(h). \end{aligned} \quad (2.4.53)$$

We first compute the term with (g, h) outside of $G_{n, \epsilon}$, where the behaviour is singular. By the Cauchy-Schwarz inequality,

$$\left| \int_{G_{n, \epsilon}^c} A_{g, h} d\mu^{*n}(g) d\mu^{*n}(h) \right|^2 \leq \mu(G_{n, \epsilon}^c) \int |A_{g, h}|^2 d\mu^{*n}(g) d\mu^{*n}(h). \quad (2.4.54)$$

By large deviation principle (Proposition 2.2.46, Proposition 2.2.47), the set $G_{n, \epsilon}^c$ has exponentially small μ^{*2n} measure, that is

$$\mu(G_{n, \epsilon}^c) \ll_\epsilon \delta^\epsilon. \quad (2.4.55)$$

By $\|f\|_\infty \leq 1$ and (2.4.48), we have

$$\int |A_{g, h}|^2 d\mu^{*n}(g) d\mu^{*n}(h) \leq |P_{2\varpi}^n \mathbb{1}|_\infty^2 \leq C^{4n\varpi}. \quad (2.4.56)$$

When $|\varpi|$ is small enough depending on ϵ , by (2.4.54), (2.4.55) and (2.4.56)

$$\int_{G_{n,\epsilon}^c} A_{g,h} d\mu^{*n}(g) d\mu^{*n}(h) \ll_{\epsilon} \delta^{c/2} \leq |\theta|^{-c\epsilon/(2C_2)}. \quad (2.4.57)$$

We compute the major term, that is (g, h) in $G_{n,\epsilon}$. We want to use Theorem 2.1.7 to control this part with $\varphi = \theta(\sigma(g, \eta) - \sigma(h, \eta))$ and a suitable r . For applying Theorem 2.1.7, we need that φ is (C, r) good, which will be accomplished by multiplying smooth cutoffs. The most important is G2 assumption (2.4.2), which will be verified with the help of Lemma 2.4.18. Hence we want that r vanishes when η does not satisfy Lemma 2.4.18 (2).

Let $X_{g,h,\alpha}$ be the subset of \mathcal{P} , defined as the set of elements which satisfy Lemma 2.4.18 (2) with $V = V_{\alpha}$. Let $X_{g,h} = \bigcap_{\alpha \in \Pi} X_{g,h,\alpha}$. Recall that τ be a smooth function on \mathbb{R} such that $\tau|_{[0,\infty)} = 1$, τ takes values in $[0, 1]$, $\mathrm{supp}\tau \subset [-1, \infty)$ and $|\tau'| \leq 2$. For $\delta > 0$, set $\tau_{\delta}(x) = \tau(x/\delta)$ for $x \in \mathbb{R}$. Let

$$\varphi(\eta) = |\theta|^{-1} \theta(\sigma(g, \eta) - \sigma(h, \eta)) = |\theta|^{-1} \sum_{\alpha \in \Pi} \theta_{\alpha}(\sigma_{\alpha}(g, \eta) - \sigma_{\alpha}(h, \eta)) \quad (2.4.58)$$

and

$$r(\eta) = f(g\eta) \bar{f}(h\eta) e^{\varpi(\sigma(g,\eta) + \sigma(h,\eta))} \prod_{\alpha \in \Pi} \tau_{\alpha}, \quad (2.4.59)$$

where

$$\tau_{\alpha}(\eta) = \tau_{\delta}(4\delta_{\alpha}(\eta, \zeta_g^m) - 4\delta) \tau_{\delta}(4\delta_{\alpha}(\eta, \zeta_h^m) - 4\delta) \tau_{\delta}(4\delta(V_{4\chi_{\alpha} - \alpha, \eta}, F_{\rho_{\alpha}g, \rho_{\alpha}h}) - 4\delta),$$

where δ_{α} is defined to be

$$\delta_{\alpha}(\eta, \zeta_g^m) = \delta(V_{\alpha, \eta}, y_{\rho_{\alpha}(g)}^m).$$

The choice of τ_{α} is sophisticate. We only need to keep in mind that they come from Lemma 2.4.18. Then $e^{i|\theta|\varphi} r(\eta)$ equals $e^{z\sigma(g,\eta) + \bar{z}\sigma(h,\eta)} f(g\eta) \bar{f}(h\eta)$ on $X_{g,h}$.

Lemma 2.4.25. *Let ϵ_0, ϵ_1 be given by Theorem 2.1.7. Let (g, h) be in $G_{n,\epsilon}$. With ϵ small enough depending on ϵ_0 and $|\varpi|$ small enough depending on ϵ and ϵ_1 , for φ, r defined in (2.4.58) and (2.4.59) we have that φ is $(|\theta|^{\epsilon_0}, r)$ good and $c_{\gamma}(r) \leq |\theta|^{\epsilon_0}$, $|r|_{\infty} \leq |\theta|^{\epsilon_1/2}$.*

By Lemma 2.4.25, we can fix a value of ϵ and the functions φ and $r|\theta|^{-\epsilon_1/2}$ satisfy the condition in Theorem 2.1.7. (Theorem 2.1.7 still holds when r is a complex function) Hence Theorem 2.1.7 implies

$$\left| \int e^{i|\theta|\varphi(\eta)} r(\eta) d\nu(\eta) \right| \leq |\theta|^{-\epsilon_1/2}. \quad (2.4.60)$$

The difference between $A_{g,h}$ and $\int e^{i|\theta|\varphi(\eta)} r(\eta) d\nu(\eta)$ is bounded by

$$\nu(X_{g,h}^c) \leq \sum_{\alpha \in \Pi} \nu(X_{g,h,\alpha}^c). \quad (2.4.61)$$

Using the regularity of stationary measure (2.2.34) with $V = W_\alpha$, the irreducible subrepresentation of $\wedge^2 \text{Sym}^2 V_\alpha$ with the highest weight, we have

$$\nu\{\eta \in \mathcal{P} | \delta(V_{4\chi_\alpha - \alpha, \eta}, F_{\rho_\alpha g, \rho_\alpha h}) < \delta\} \ll_\epsilon e^{-c\epsilon n}. \quad (2.4.62)$$

Using the regularity of stationary measure (2.2.34) with $V = V_\alpha$, we obtain

$$\nu\{\eta \in \mathcal{P} | V_{\alpha, \eta} \in B_h^m(\delta) \cup B_g^m(\delta)\} \ll_\epsilon e^{-c\epsilon n}. \quad (2.4.63)$$

Hence by (2.4.61)-(2.4.63), we have

$$\nu(X_{g,h}^c) \ll_\epsilon e^{-c\epsilon n} = |\theta|^{-c\epsilon/C_2}. \quad (2.4.64)$$

For (g, h) in $G_{n,\epsilon}$, by (2.4.60) and (2.4.64)

$$A_{g,h} \ll |\theta|^{-\epsilon_1/2} + |\theta|^{-c\epsilon/C_2}.$$

Combined with (2.4.53) and (2.4.57), the proof is complete by setting $\epsilon_2 = \min\{\frac{\epsilon_1}{2}, \frac{c\epsilon}{4C_2}\}$. \square

It remains to prove Lemma 2.4.25.

Proof of Lemma 2.4.25. We first verify that φ is $(|\theta|^{\epsilon_0}, r)$ good. Since ϵ will be taken small enough, we can suppose $|\theta|^{-\epsilon_0} \leq \delta/4$. Let J be the $|\theta|^{-\epsilon_0}$ neighbourhood of suppr . Then for $\eta \in J$, we have $\delta_\alpha(\eta, \zeta_g^m) \geq \delta/2$ for α in Π .

The function φ is a sum of functions. Each function is the lift of a function on $\mathbb{P}V_\alpha$ for some simple root α . We write $\varphi = \sum_{\alpha \in \Pi} \varphi_\alpha$ where $\varphi_\alpha(\eta) = |\theta|^{-1} \theta_\alpha(\sigma_\alpha(g, \eta) - \sigma_\alpha(h, \eta))$. By Lemma 2.2.32, that is $\partial_{\alpha'} \varphi_\alpha = 0$ for $\alpha' \neq \alpha$, in order to verify $(|\theta|^{\epsilon_0}, r)$ good condition, it is enough to verify G1-G3 assumptions (2.4.1)-(2.4.3) for φ_α and the G4 assumption (2.4.4) for φ . Since G1-G3 are linear, we can forget the coefficients $|\theta|^{-1} \theta_\alpha$ in φ_α .

Now, we verify G1-G3 assumptions and we fix a simple root α and consider $\varphi = \varphi_\alpha = \sigma_\alpha(g, \cdot) - \sigma_\alpha(h, \cdot)$. Recall that $v_\alpha = \sup_{\eta \in \text{suppr}} |\partial_\alpha \varphi(\eta)|$. Since J satisfies the hypothesis of Lemma 2.4.17 with $V = V_\alpha$, we have

$$v_\alpha, \text{Lip}_{\mathcal{P}_0}(\partial_\alpha \varphi|_{\pi^{-1}J}) < \delta^{-O(1)}. \quad (2.4.65)$$

Since $(g, h) \in G_{n,\epsilon}$ satisfies Lemma 2.4.18(1) and the support of r satisfies Lemma 2.4.18(2), for η in the support of r , by Lemma 2.4.18,

$$|\partial_\alpha \varphi(\eta)| > \delta^{O(1)} \geq \delta^{O(1)} v_\alpha$$

which is G2 assumption (2.4.2). This also implies

$$v_\alpha > \delta^{O(1)}, \quad (2.4.66)$$

G4 assumption (2.4.4). By (2.4.65), we have G3 assumption (2.4.3). Let φ_1 be a function on $\mathbb{P}V_\alpha$ such that $\varphi_1(V_{\alpha,\eta}) = \varphi(\eta)$. Since J satisfies hypothesis of Lemma 2.2.8, this Lemma implies

$$\frac{|\varphi(\eta) - \varphi(\eta')|}{d_\alpha(\eta, \eta')} = \frac{|\varphi_1(V_{\alpha,\eta}) - \varphi_1(V_{\alpha,\eta'})|}{d(V_{\alpha,\eta}, V_{\alpha,\eta'})} \leq |\text{Lip}_{\mathbb{P}V_\alpha} \varphi_1| < \delta^{-O(1)} \leq \delta^{-O(1)} v_\alpha,$$

which is G1 assumption (2.4.1).

For general φ , it remains to verify G4 assumption (2.4.4). There exists a simple root α such that $|\theta_\alpha| = |\theta|$. Since φ_α satisfies G4 assumption and $|\partial_\alpha \varphi| = |\partial_\alpha \varphi_\alpha|$ by Lemma 2.2.32, the function φ also satisfies G4 assumption.

Finally, we verify the term $c_\gamma(r)$ and $|r|_\infty$.

Lemma 2.4.26. *For $0 < \gamma \leq 1$, let f, τ be two γ -Hölder functions on a compact metric space X . Then*

$$c_\gamma(\tau f) \leq c_\gamma(\tau) \|f\|_{\mathrm{supp}\tau} + |\tau|_\infty c_\gamma(f|_{\mathrm{supp}\tau}).$$

The proof of Lemma 2.4.26 is elementary. Recall that

$$r(\eta) = f(g\eta) \bar{f}(h\eta) e^{\varpi(\sigma(g,\eta) + \sigma(h,\eta))} \prod_{\alpha \in \Pi} \tau_\alpha.$$

For the infinity norm, due to $(g, h) \in G_{n,\epsilon}$, we have

$$|r| \leq e^{|\varpi|(\|\kappa(g)\| + \|\kappa(h)\|)} \leq e^{|\varpi|(2\|\sigma_\mu\| + \epsilon)n} \leq |\theta|^{|\varpi|C_2(2\|\sigma_\mu\| + \epsilon)}.$$

Take $|\varpi|$ small enough, then $|r|_\infty \leq |\theta|^{\epsilon_1/2}$.

For the term $c_\gamma(r)$, we only need to verify that each term in the formula of r has a bounded c_γ value. Due to Lemma 2.4.26, we only need to verify the c_γ value on $X_{g,h}$.

- Since the action of g on $X_{g,h}$ is contracting, by Lemma 2.2.13, we have

$$c_\gamma(f(g\cdot)|_{X_{g,h}}) \leq c_\gamma(f)(\mathrm{Lip} g|_{X_{g,h}})^\gamma \leq (|\theta|\beta\delta^{-2})^\gamma.$$

Due to (2.4.52), we have $\log \beta = -n \min_{\alpha \in \Pi} \alpha \sigma_\mu < -n/C_2 \leq -\log |\theta|$. Therefore $c_\gamma(f(g\cdot)|_{X_{g,h}}) \leq \delta^{-O(1)}$.

- Due to

$$|e^a - e^b| \leq \max\{e^a, e^b\} |a - b|^\gamma$$

for all a, b in \mathbb{R} and $0 \leq \gamma \leq 1$, by Lemma 2.2.13,

$$c_\gamma(e^{\varpi\sigma(g,\cdot)}|_{X_{g,h}}) \leq e^{|\varpi|\|\kappa(g)\|} (\mathrm{Lip} \varpi\sigma(g, \cdot)|_{X_{g,h}})^\gamma \leq e^{|\varpi|(\|\sigma_\mu\| + \epsilon)n + \epsilon\gamma n} |\varpi|^\gamma.$$

Hence when $|\varpi|$ is small enough depending on σ_μ , we obtain $c_\gamma(e^{\varpi\sigma(g,\cdot)}|_{X_{g,h}}) \leq \delta^{-O(1)}$.

- In $c_\gamma(\tau_\alpha)$, the only term we need to be careful about is $\tau_\delta(4\delta(V_{4\chi_\alpha - \alpha, \eta}, F_{\rho_\alpha g, \rho_\alpha h}) - 4\delta)$. By Lemma 2.2.14, we have $d(V_{4\chi_\alpha - \alpha, \eta}, V_{4\chi_\alpha - \alpha, \eta'}) \ll d(\eta, \eta')$. Hence the c_γ value of this term is also bounded by $\delta^{-O(1)}$.

The proof is complete. □

2.4.5 Exponential error term

In this section, we will prove that the speed of convergence in the renewal theorem is exponential using our result on the spectral gap. (Proposition 2.4.22) Recall $X = \mathbb{P}V$ and we have defined a renewal operator R as follows: For a positive bounded Borel function f on $X \times \mathbb{R}$, a point x in X and a real number t , we set

$$Rf(x, t) = \sum_{n=0}^{+\infty} \int_G f(gx, \sigma(g, x) - t) d\mu^{*n}(g).$$

Recall P_z is the transfer operator defined by $P_z f(x) = \int_G e^{z\sigma_V(g, x)} f(gx) d\mu(g)$. Using the analytical Fredholm theorem, we summarize the property of P_z .

Proposition 2.4.27. *With the same assumption as in Theorem 2.1.4, for any $\gamma > 0$ small enough, there exists $\eta > 0$ such that when $|\Re z| < \eta$, the transfer operator P_z is a bounded operator on $C^\gamma(X)$ and depends analytically on z . Moreover there exists an analytic operator $U(z)$ on a neighbourhood of $|\Re z| < \eta$ such that the following holds for $|\Re z| < \eta$*

$$(I - P_z)^{-1} = \frac{1}{\sigma_{V, \mu} z} N_0 + U(z),$$

where N_0 is the operator defined by $N_0 f = \int_X f d\nu_V$. There exists $C > 0$ such that for $|\Re z| \leq \eta$

$$\|U(z)\|_{C^\gamma \rightarrow C^\gamma} \leq C(1 + |\Im z|)^{2\gamma}. \quad (2.4.67)$$

This is generalization of Proposition 1.4.1 in Chapter 1 and [Boy16, Theorem 4.1], and the proof is exactly the same. The main difference is that the spectral radius of P_z is bounded below 1 in a strip of imaginary line (except at 0), due to Proposition 2.4.22. From this we have the analytic continuation of $U(z)$ to the strip and the bound of the operator norm of $U(z)$.

Now, we give the precise statement and the proof of Theorem 2.1.4.

Proposition 2.4.28. *With the same assumption as in Theorem 2.1.4, there exists $\epsilon > 0$ such that for $f \in C_c^\infty(\mathbb{R})$, we have*

$$Rf(x, t) = \frac{1}{\sigma_{V, \mu}} \int_{-t}^{\infty} f(u) du + e^{-\epsilon|t|} O(e^{\epsilon|\text{supp} f|} (|f''|_{L^1} + |f|_{L^1})).$$

Proof. By the same computation as in Proposition 1.4.5 in Chapter 1 and [Boy16, Prop. 4.14], we have

$$Rf(x, t) = \frac{1}{\sigma_{V, \mu}} \int_{-t}^{\infty} f(u) du + \lim_{s \rightarrow 0^+} \frac{1}{2\pi} \int e^{-it\xi} \hat{f}(\xi) U(s + i\xi) \mathbb{1}(x) d\xi,$$

where \hat{f} is the Fourier transform of f given by $\hat{\xi} = \int e^{i\xi u} f(u) du$. Hence, we only need to control the error term.

By Proposition 2.4.27, we know that $U(z)$ is analytical on $\{z \in \mathbb{C} \mid |\Re z| \leq \eta\}$ and uniformly bounded by $(1 + |\Im z|)^{2\gamma}$. Since f is a compactly supported smooth function, the Fourier transform \hat{f} is an analytic function on \mathbb{C} . By $|\hat{f}(i\epsilon + \xi)| \leq e^{\epsilon|\mathrm{supp}f|} \frac{1}{|\xi|^2} |f''|_{L^1}$, and $|\hat{f}(i\epsilon + \xi)| \leq e^{\epsilon|\mathrm{supp}f|} |f|_{L^1}$ for ϵ, ξ in \mathbb{R} , we have

$$|\hat{f}(i\epsilon + \xi)| \leq e^{\epsilon|\mathrm{supp}f|} \frac{2}{1 + |\xi|^2} (|f''|_{L^1} + |f|_{L^1}). \quad (2.4.68)$$

By (2.4.67), (2.4.68) and the dominant convergence theorem, we have

$$\lim_{s \rightarrow 0^+} \frac{1}{2\pi} \int e^{-it\xi} \hat{f}(\xi) U(s + i\xi) \mathbb{1}(x) d\xi = \frac{1}{2\pi} \int e^{-it\xi} \hat{f}(\xi) U(i\xi) \mathbb{1}(x) d\xi. \quad (2.4.69)$$

Lemma 2.4.29. [RS75, Thm.IX14] *If T is in $\mathcal{S}'(\mathbb{R})$, tempered distributions, the distribution T has analytic continuation to $|\Im \xi| < a$ and $\sup_{|b| < a} \int |T(ib + y)| dy < \infty$, then \check{T} is a continuous function. For all $b < a$, let $C_b = \max \int |T(\pm ib + y)| dy$. We have*

$$|\check{T}(t)| \leq C_b e^{-b|t|}.$$

Using Lemma 2.4.29 with $T(\xi) = \hat{f}(\xi) U(i\xi) \mathbb{1}(x)$, we have

$$\left| \int \hat{f}(\xi) U(i\xi) \mathbb{1}(x) e^{-it\xi} d\xi \right| = |\check{T}(t)| \leq e^{-\epsilon|t|} \max |T(\pm i\epsilon + \xi)|_{L^1(\xi)} \quad (2.4.70)$$

By (2.4.68), we have

$$\begin{aligned} \max |T(\pm i\epsilon + \xi)|_{L^1(\xi)} &\leq e^{\epsilon|\mathrm{supp}f|} \int \frac{2}{1 + |\xi|^2} (|f''|_{L^1} + |f|_{L^1}) |U(\mp\epsilon + i\xi) \mathbb{1}(x)| d\xi \\ &\ll_{\gamma} e^{\epsilon|\mathrm{supp}f|} (|f''|_{L^1} + |f|_{L^1}). \end{aligned} \quad (2.4.71)$$

Combining (2.4.69), (2.4.70) and (2.4.71), we have the result. \square

2.5 Appendix

2.5.1 Two classic proofs in Section 2.4.4

In order to simplify the notation, we abbreviate ϖ, θ to a, b .

Proof of (2.4.50). We need an idea of Guivarc'h

Definition 2.5.1. *We call the action of G on X is (μ, γ) contracting, if there exist $C > 0, \rho < 1$ such that for all $x \neq x'$ in X*

$$\int \left(\frac{d(gx, gx')}{d(x, x')} \right)^{\gamma} d\mu^{*n}(g) \leq C\rho^n. \quad (2.5.1)$$

This was defined in [BQ16, Definition 11.1] and was verified for the action on the flag variety in [BQ16, Lemma 13.5]. For the projective space $\mathbb{P}V$, the same proof also works.

For the γ norm, let x, y in X and g in G

$$e^{z\sigma(g,x)} f(gx) - e^{z\sigma(g,y)} f(gy) = (e^{z\sigma(g,x)} - e^{z\sigma(g,y)})f(gx) + e^{z\sigma(g,y)}(f(gx) - f(gy))$$

Let $A_n = |\int_G \frac{e^{z\sigma(g,y)}(f(gx)-f(gy))}{d(x,y)^\gamma} d\mu^{*n}(g)|$ and $B_n = |\int_G \frac{(e^{z\sigma(g,x)}-e^{z\sigma(g,y)})f(gx)}{d(x,y)^\gamma} d\mu^{*n}(g)|$. By Cauchy-Schwarz's inequality

$$\begin{aligned} A_n &\leq c_\gamma(f) \int_G e^{a\sigma(g,y)} \frac{d(gx,gy)^\gamma}{d(x,y)^\gamma} d\mu^{*n}(g) \\ &\leq c_\gamma(f) \left(\int_G e^{2a\sigma(g,y)} d\mu^{*n}(g) \right)^{1/2} \left(\int_G \left(\frac{d(gx,gy)}{d(x,y)} \right)^{2\gamma} d\mu^{*n}(g) \right)^{1/2} \end{aligned}$$

One term is controlled by (2.4.48), the other term is due to (μ, γ) contraction (2.5.1). Therefore when a small enough, there exists $\rho_1 < 1$ such that $A_n \leq C_1 \rho_1^n c_\gamma(f)$, where $C_1 > 0$.

Since

$$|e^c - e^d| \leq (2 \max(e^{\Re c}, e^{\Re d}))^{1-\gamma} (\max(e^{\Re c}, e^{\Re d}) |c - d|)^\gamma$$

for c, d in \mathbb{C} , we have

$$\frac{|e^{z\sigma(g,x)} - e^{z\sigma(g,y)}|}{d(x,y)^\gamma} \leq (2e^{|a|\kappa(g)})^{1-\gamma} (e^{|a|\kappa(g)} |z| \text{Lip}(\sigma(g, \cdot)))^\gamma \leq 2e^{|a|\kappa(g) + \gamma\kappa_0(g)} |b|^\gamma,$$

where $\kappa_0(g)$ is the Lipschitz norm of $\sigma(g, \cdot)$ and $\kappa_0(g) \leq C\|\kappa(g)\|$ by [BQ16, Lemma 13.1]. Then by the hypothesis of finite exponential moment and Hölder's inequality, we have

$$B_n \leq |b|^\gamma |f|_\infty C_1^{(|a|+\gamma)n}$$

(we take the same constant C_1). Therefore

$$c_\gamma(P_z^n f) \leq C_1 \rho_1^n c_\gamma(f) + |b|^\gamma C_1^{1+(|a|+\gamma)n} |f|_\infty \quad (2.5.2)$$

We want the term $C_1^{(|a|+\gamma)n}$ does not depend on γ . Fix n large enough such that $C_1 \rho_1^n = \rho_2 < 1$. For natural number N , iterate (2.5.2) N times and use (2.4.48). We have

$$\begin{aligned} c_\gamma(P_z^{nN} f) &\leq \rho_2 c_\gamma(P_z^{n(N-1)} f) + |b|^\gamma C_1^{1+(|a|+\gamma)n} |P_z^{n(N-1)} f|_\infty \\ &\leq \rho_2 c_\gamma(P_z^{n(N-1)} f) + |b|^\gamma C_1^{1+(|a|+\gamma)n} |f|_\infty C_1^{|a|n(N-1)} \\ &\leq c_\gamma(f) \rho_2^N + |b|^\gamma C_1^{1+(|a|+\gamma)n} |f|_\infty \frac{C_1^{|a|nN}}{1 - \rho_2 C_1^{-|a|n}} \leq c_\gamma(f) \rho_2^N + O_n(|b|^\gamma C_1^{|a|nN}) |f|_\infty \end{aligned} \quad (2.5.3)$$

Given $m \in \mathbb{N}$, we can write $m = nN + r$ with $r \in [0, n - 1]$. Therefore by (2.5.3) (2.5.2)

$$\begin{aligned} c_\gamma(P_z^m f) &= c_\gamma(P^{nN+r} f) \leq \rho_2^N c_\gamma(P_z^r f) + O_n(|b|^\gamma C^{|a|nN}) |P_z^r f|_\infty \\ &\leq \rho_2^N (C_1 \rho_1^r c_\gamma(f) + |b|^\gamma C_1^{1+(a+\gamma)r}) |f|_\infty + O_n(|b|^\gamma C_1^{|a|m}) |f|_\infty. \end{aligned}$$

By setting $\rho = \rho_2^{1/n}$ and choosing C large enough, we have (2.4.50). \square

From Proposition 2.4.24 to Proposition 2.4.22. We set $N = [C_1 \ln |b|]$, by the Cauchy-Schwarz's inequality and (2.4.48), using (2.4.49) for P^{mN} , (2.4.51) for $P_z^N f$ and (2.4.50) for P_z^N

$$\begin{aligned} |P_z^{(m+1)N} f|_\infty^2 &\leq C^{|a|mN} |P^{mN} |P_z^N f|^2|_\infty \leq C^{|a|mN} \left(\int |P_z^N f|^2 d\nu + \rho^{mN} |P_z^N f|_{C^\gamma}^2 \right) \\ &\leq C^{|a|mN} \left(e^{-\epsilon_2 N/C_1} + \rho^{mN} (C^{1+|a|N} (1 + |b|^\gamma) + C \rho^N |b|^\gamma)^2 \right) \end{aligned} \quad (2.5.4)$$

So we can choose m large such that $\rho^{mN} |b|^{2\gamma} = \rho^{mC \ln |b|} |b|^{2\gamma} < 1$. This m is only depend on γ, C and ρ . By continuity of a we obtain the equality for infinity norm. That is when m is large enough and a is small enough depending on m we have $|P_z^{(m+1)N} f|_\infty^2 \ll |b|^{-\epsilon_3}$, where $\epsilon_3 > 0$

For γ norm, we use (2.4.50) for $(P_z^N, P_z^{(m+1)N} f)$ and $(P_z^{(m+1)N}, f)$

$$\begin{aligned} c_\gamma(P_z^{(m+2)N} f) / |b|^\gamma &\leq C^{|a|N} |P_z^{(m+1)N} f|_\infty + \rho^N c_\gamma(P_z^{(m+1)N} f) / |b|^\gamma \\ &\leq C^{|a|N} |P_z^{(m+1)N} f|_\infty + \rho^N (C^{1+|a|mN} |b|^\gamma + \rho^{mN} |b|^\gamma) / |b|^\gamma \end{aligned}$$

Then, when $|b|$ is large enough and a is small enough, we have

$$|P_z^{(m+2)N} f|_{\gamma,b} \leq |b|^{-\epsilon_4} \quad (2.5.5)$$

(where we should use (2.5.4) with m replaced by $m + 1$).

Let $N_1 = (m + 2)N = (m + 2)C_1 \ln |b|$. Given n , we can write $n = dN_1 + r$ with $0 \leq r < N_1$. By (2.5.5), (2.4.48), (2.4.50)

$$|P_z^n f|_{\gamma,b} \leq |b|^{-\epsilon_4 d} |P_z^r f|_{\gamma,b} \leq |b|^{-\epsilon_4 d} C^{1+|a|r} \leq C |b|^{\epsilon_4} \rho^n,$$

where $\rho = |b|^{-\epsilon_4/N_1} C^{|a|} = e^{-\frac{\epsilon_4}{(m+2)C_1}} C^{|a|}$. The result follows by taking $|a|$ small enough. \square

2.5.2 Equivalence of distances

Definition 2.5.2. Let (X, d) be a metric space. Let d' be another metric on X . We say that d, d' are equivalent metrics if there exist $c, C > 0$ such that for all x_1, x_2 in X

$$cd(x_1, x_2) \leq d'(x_1, x_2) \leq Cd(x_1, x_2).$$

Recall that \mathcal{P}_0 is the homogeneous space G/A_eN , on which the compact group K acts simply transitively. We will define three distances on \mathcal{P}_0 . Due to the fact that \mathcal{P}_0 is homeomorphic to K , a distance on \mathcal{P}_0 is also a distance on K and we will continue our argument on K . Let k, k' be two points in K .

- $d_0(k, k') = \sup_{\alpha \in \Pi} \|kv_\alpha - k'v_\alpha\|/\sqrt{2}$, where v_α is a unit vector in V_α with highest weight. This is also the distance induced by the embedding of \mathcal{P}_0 to $\prod_{\alpha \in \Pi} \mathbb{S}V_\alpha$.
- $d_1(k, k') = \|k - k'\|$, where $\|\cdot\|$ is a K invariant norm on the space of $(m+1) \times (m+1)$ square matrices $M_{m+1}(\mathbb{R}) \supset K$.
- $d_2(k, k')$ is the distance induced by the bi-invariant Riemannian metric on K .

We can easily verify that they are distances.

Lemma 2.5.3. *The three distances d_0, d_1 and d_2 on \mathcal{P}_0 are equivalent.*

Proof. First we observe that the three distances are left K invariant. It is sufficient to prove the equivalence for k' equal to the identity e .

Fix ϵ small depending on K . Let B_ϵ be the neighbourhood of e given by $\{k \in K \mid d_1(k, e) < \epsilon\}$. Then B_ϵ is a compact subset of K . Consider the function $f_{i,j}(k) = \frac{d_i(k, e)}{d_j(k, e)}$ for $k \in B_\epsilon$ and $i, j \in \{0, 1, 2\}$. Then $f_{i,j}$ is a positive continuous function B_ϵ^c . The compactness of B_ϵ^c implies that it has positive minimum on B_ϵ^c . Hence there exists $c_{i,j} > 0$ such that for k outside of B_ϵ

$$d_i(k, e) \geq c_{i,j} d_j(k, e).$$

Finally, we only need to consider a small neighbourhood of the identity. We take ϵ small such that the exponential map at e is bi-Lipschitz. Suppose that $k = \exp(tZ)$ with Z a unit vector in \mathfrak{k} and $t > 0$. Then

$$d_1(k, e) = \|e - \exp(tZ)\| \asymp t = d_2(k, e).$$

Due to $d_0(k, e) = \max_{\alpha \in \Pi} \|kv_\alpha - v_\alpha\|/\sqrt{2} \ll \|k - e\| = d_1(k, e)$, it remains to prove that d_0 is not small. We can decompose Z as

$$Z = \sum_{\alpha \in R^+} c_\alpha K_\alpha.$$

There exists $\alpha_o \in R^+$ such that $c_{\alpha_o} \gg 1$. Since v_α is a vector of highest weight, for a positive root β let

$$A_{\alpha,\beta} := d\rho_\alpha(K_\beta)v_\alpha = d\rho_\alpha(Y_\beta)v_\alpha.$$

Consider the representation of $\mathfrak{s}_\beta = \{Y_\beta, X_\beta, H_\beta\} \simeq \mathfrak{sl}_2$. Due to the classification of the representations of \mathfrak{sl}_2 ,

Lemma 2.5.4. *The vector $A_{\alpha,\beta}$ is non zero if and only if $\chi_\alpha(H_\beta) > 0$.*

Now take $\beta = \alpha_o$. Since $\{\chi_\alpha, \alpha \in \Pi\}$ is a basis of \mathfrak{a}^* , there exists a simple root α such that $\chi_\alpha(H_{\alpha_o}) \neq 0$. Hence by the fact that vectors of different weights are orthogonal, we have

$$\|kv_\alpha - v_\alpha\| = \|\exp(tZ)v_\alpha - v_\alpha\| \asymp t\|d\rho_\alpha(Z)v_\alpha\| \geq tc_{\alpha_o}\|d\rho_\alpha Y_{\alpha_o}v_\alpha\| \gg t.$$

Then we have $d_0(k, e) \gg d_2(k, e)$. The proof is finished. \square

Recall the definition of the sign function m of Section 2.2.5.

Lemma 2.5.5. *Let $z = kz_o, z' = k'z_o$ be two points in \mathcal{P}_0 , then*

$$\sqrt{2}d_0(z, z') \geq d(\pi(z), \pi(z')).$$

We have

$$m(z, z') = e \iff d_0(z, z') < 1$$

If $m(z, z') = e$, then

$$d(\pi(z), \pi(z')) \geq d_0(z, z').$$

Proof. Suppose that the angle between kv_α and $k'v_\alpha$ is $\theta \in [0, \pi)$, then $\|kv_\alpha - k'v_\alpha\| = 2\sin\frac{\theta}{2}$ and $d(V_{\alpha, k\eta_o}, V_{\alpha, k'\eta_o}) = \|kv_\alpha \wedge k'v_\alpha\| = \sin\theta = 2\sin\frac{\theta}{2}\cos\frac{\theta}{2} \leq 2\sin\frac{\theta}{2}$, which implies the first inequality.

The assumption $d_0(z, z') \leq 1$ is equivalent to that for every simple root α , the angle θ is less than $\pi/2$, which is equivalent to $m(z, z') = e$ due to Lemma 2.2.19.

If $m(z, z') = e$, then for every simple root α , the angle θ is less than $\pi/2$. Hence $\sin\theta = 2\sin\frac{\theta}{2}\cos\frac{\theta}{2} \geq \sqrt{2}\sin\frac{\theta}{2}$, which implies the result. \square

Corollary 2.5.6. *The K -invariant Riemannian distance on \mathcal{P} is equivalent to the distance defined in (2.2.12).*

Proof. By $\mathcal{P} = \mathcal{P}_0/M$ and since the group M is a subgroup of K which preserves the distance, let d_2 also be the quotient Riemannian distance on \mathcal{P} . By the same argument of the proof as in Lemma 2.5.3, it is sufficient to prove on a small neighbourhood of η_0 . For any two points η, η' in this small neighbourhood, we can find z, z' in \mathcal{P}_0 such that $\pi(z) = \eta, \pi(z') = \eta'$ and $d_2(z, z') = d_2(\eta, \eta')$. Due to $d_2(z, z')$ small, we see that $d_0(z, z')$ is less than 1. Hence by Lemma 2.5.5, we have $m(z, z') = e$ and then

$$d(\eta, \eta') \asymp d_0(z, z').$$

By Lemma 2.5.3, we have $d_0(z, z') \asymp d_2(z, z') = d_2(\eta, \eta')$. The proof is complete. \square

Here we give a proof of G1 assumption (2.4.1) in the proof of Theorem 2.1.1 (Section 2.4.3).

Recall that V is an irreducible representation of G with a norm and with highest weight χ , and v_0, u_0 are two unit vectors in V and $\theta_\alpha = \|q_{2\chi-\alpha}(v_0 \wedge u_0)\|$ for simple root α . Recall that $\varphi(\eta) = \frac{\langle u_0, v \rangle}{\langle v_0, v \rangle}$ for a nonzero vector v in $V_{\chi, \eta}$ and $\eta \in \mathcal{P}$. By (2.4.42), we

only need to verify that if $d(\eta, \eta') \leq \xi^{-\epsilon_0}$ and η, η' satisfies that $|\langle v_0, v \rangle| \geq \|v\|/C_0$ for v in $V_{\chi, \eta}$ and $V_{\chi, \eta'}$, then

$$|\varphi(\eta) - \varphi(\eta')| \leq \xi^{\epsilon_0/2} \sum_{\alpha \in \Pi} \theta_\alpha d(V_{\alpha, \eta}, V_{\alpha, \eta'}),$$

for ξ large enough. Replacing (2.4.43) by the following lemma, we conclude that G1 assumption is always verified if ξ is large enough.

Lemma 2.5.7. *Let $C_0, C_1 > 0$ and let η, η' be two points in \mathcal{P} such that $d(\eta, \eta') \leq 1/(C_1 C_0)$ and $|\langle v_0, v \rangle| \geq \|v\|/C_0$ for v in $V_{\chi, \eta}$ and $V_{\chi, \eta'}$. Then with C_1 large enough depending on the norm, we have*

$$|\varphi(\eta) - \varphi(\eta')| \leq C C_0^m \sum_{\alpha \in \Pi} \theta_\alpha d(V_{\alpha, \eta}, V_{\alpha, \eta'}),$$

where C only depends on the group G and the norm on V .

Proof. The main idea is to take derivative on \mathcal{P} , and prove that in every direction the result is true. We will first prove the directions given by positive roots.

The structure of $Sym^2(\wedge^2 V)$ gives us a formula, that is for v_1, v_2, w_1, w_2, w_3 in V

$$\langle v_1 \wedge v_2, w_1 \wedge w_2 \rangle = \langle v_1 \wedge v_2, w_3 \wedge \frac{\langle v_1, w_2 \rangle w_1 - \langle v_1, w_1 \rangle w_2}{\langle v_1, w_3 \rangle} \rangle. \quad (2.5.6)$$

In order to simplify the notation, we write Y_1, \dots, Y_m for $Y_{\alpha_1}, \dots, Y_{\alpha_m}$. The structure of Lie algebra gives us that for a vector v in V

$$v \wedge Y_1 \cdots Y_k v = Y_1 \cdots Y_{k-1} (v \wedge Y_k v) - \sum_I Y_I v \wedge Y_{I^c} v, \quad (2.5.7)$$

where $I = \{j_1, \dots, j_l\}$ is a nonempty subset of $\{1, \dots, k-1\}$, I^c is the complement of I in $\{1, \dots, k\}$ and $Y_I = Y_{j_1} \cdots Y_{j_l}$ with $j_1 < \dots < j_l$.

Let e_1 be the unit vector in V with highest weight. We claim that if $|\langle v_0, e_1 \rangle| \geq 1/C_0$, then for $J \subset \{1, \dots, m\}$, we have

$$|\langle v_0 \wedge u_0, e_1 \wedge Y_J e_1 \rangle| \leq C C_0^{|J|} \sum_{i \in J} \theta_{\alpha_i}. \quad (2.5.8)$$

We make an induction on $k = |J|$. By symmetry, it is sufficient to prove the claim for $Y_J = Y_1 \cdots Y_k$. For $k = 1$, due to $e_1 \wedge Y_1 e_1 \in q_{2\chi - \alpha_1}(\wedge^2 V)$, we have

$$|\langle v_0 \wedge u_0, e_1 \wedge Y_1 e_1 \rangle| \leq \|q_{2\chi - \alpha_1}(v_0 \wedge u_0)\| = \theta_{\alpha_1}.$$

Suppose that (2.5.8) holds for all the integer less than $k-1$. Then by (2.5.7),

$$\begin{aligned} \langle v_0 \wedge u_0, e_1 \wedge Y_1 \cdots Y_k e_1 \rangle &= \langle v_0 \wedge u_0, Y_1 \cdots Y_{k-1} (e_1 \wedge Y_k e_1) \rangle \\ &\quad - \sum_I \langle v_0 \wedge u_0, Y_I e_1 \wedge Y_{I^c} e_1 \rangle \end{aligned}$$

Due to $Y_1 \cdots Y_{k-1}(e_1 \wedge Y_k e_1) \in \mathfrak{q}_{2\chi - \alpha_k}(\wedge^2 V)$, the first term is controlled by θ_{α_k} . The other term, due to $I \neq \emptyset$, using (2.5.6) with $w_3 = e_1$, we have

$$\begin{aligned} |\langle v_0 \wedge u_0, Y_I e_1 \wedge Y_{I^c} e_1 \rangle| &= |\langle v_0 \wedge u_0, e_1 \wedge \frac{\langle v_0, Y_{I^c} e_1 \rangle Y_I e_1 - \langle e_1, Y_I e_1 \rangle Y_{I^c} e_1}{\langle v_0, e_1 \rangle} \rangle| \\ &\leq C_0 (|\langle v_0 \wedge u_0, e_1 \wedge Y_I e_1 \rangle| + |\langle v_0 \wedge u_0, e_1 \wedge Y_{I^c} e_1 \rangle|) \end{aligned}$$

Since the length of I and I^c are less than k , by the hypothesis of induction, we have the claim for k .

The choice of Y_β for a positive root β is fixed in Section 2.2 and we have $Y_{\alpha_1 + \cdots + \alpha_k} = C_{\alpha_1, \dots, \alpha_k} [Y_{\alpha_1}, [Y_{\alpha_2}, \dots, [Y_{\alpha_{k-1}}, Y_{\alpha_k}] \cdots]]$ with a constant $C_{\alpha_1, \dots, \alpha_k}$. By the claim,

Lemma 2.5.8. *Let β be a positive root. If $|\langle v_0, e_1 \rangle| \geq 1/C_0$, then*

$$|\langle v_0 \wedge u_0, e_1 \wedge Y_\beta e_1 \rangle| \leq CC_0^m \sum_{\alpha \in \Pi, \alpha \leq \beta} \theta_\alpha,$$

where C only depends on G and the norm on V . In particular, for $Z = \sum_{\beta \in R^+} c_\beta K_\beta$

$$|\langle v_0 \wedge u_0, e_1 \wedge Z e_1 \rangle| \leq CC_0^m \sum_{\alpha \in \Pi} \theta_\alpha \sum_{\beta \geq \alpha, \beta \in R^+} |c_\beta|.$$

This is almost the directional derivative of $G1$. For $\eta = k\eta_0, \eta' = k'\eta_0$ in \mathcal{P} , we can find a unit vector Z in the Lie algebra \mathfrak{k} such that $k' = k \exp(tZ)$ with $t \ll d(\eta, \eta')$. Let $\gamma(s) = k \exp(sZ)\eta_0$ for $0 \leq s \leq t$. Then by the Newton-Leibniz formula,

$$|\varphi(\eta) - \varphi(\eta')| \leq \int_0^t |\partial_s \varphi(\gamma(s))| ds.$$

Let $k_s = k \exp(sZ)$. By the same computation of Lemma 2.4.14, we have

$$\partial_s \varphi(\gamma(s)) = \partial_Z \varphi(\gamma(s)) = \frac{\langle v_0 \wedge u_0, k_s e_1 \wedge k_s Z e_1 \rangle}{\langle v_0, k_s e_1 \rangle} = \frac{\langle k_s^{-1} v_0 \wedge k_s^{-1} u_0, e_1 \wedge Z e_1 \rangle}{\langle k_s^{-1} v_0, e_1 \rangle}.$$

Due to $\|k_s e_1 - e_1\| \ll d(\gamma(s), \gamma(0)) \leq d(\eta, \eta') \leq 1/(C_0 C_1)$, with C_1 large enough, we have

$$|\langle k_s^{-1} v_0, e_1 \rangle| = |\langle v_0, k_s e_1 \rangle| \geq |\langle v_0, e_1 \rangle| - \|k_s e_1 - e_1\| \geq 1/(2C_0)$$

Due to $\|\mathfrak{q}_{2\chi - \alpha}(k_s^{-1}(v_0 \wedge u_0))\| = \|\mathfrak{q}_{2\chi - \alpha}(v_0 \wedge u_0)\| = \theta_\alpha$, by Lemma 2.5.8, we have

$$|\partial_s \varphi(\gamma(s))| \leq CC_0^m \sum_{\alpha \in \Pi} \theta_\alpha \sum_{\beta \geq \alpha, \beta \in R^+} |c_\beta|.$$

Hence

$$|\varphi(\eta) - \varphi(\eta')| \leq CC_0^m t \sum_{\alpha \in \Pi} \theta_\alpha \sum_{\beta \geq \alpha, \beta \in R^+} |c_\beta|. \quad (2.5.9)$$

For Z in \mathfrak{k} , let $Z_\alpha = \sum_{\beta \geq \alpha, \beta \in R^+} c_\beta K_\beta$. Due to t small, we only need to consider distance in a small neighbourhood. Hence by the fact that vectors of different weights are orthogonal, we have $(Y_\beta v_\alpha)$ is nonzero for every positive root $\beta \geq \alpha$ due to Lemma 2.5.4)

$$d(V_{\alpha,\eta}, V_{\alpha,\eta'}) = d(v_\alpha, \exp(tZ)v_\alpha) \asymp \|\exp(tZ)v_\alpha - v_\alpha\| \asymp t\|Zv_\alpha\| = t\|Z_\alpha v_\alpha\| \asymp t\|Z_\alpha\|.$$

Therefore, combined with (2.5.9)

$$\sum_{\alpha \in \Pi} \theta_\alpha d(V_{\alpha,\eta}, V_{\alpha,\eta'}) \geq \sum_{\alpha \in \Pi} t\theta_\alpha \|Z_\alpha\| \geq t \sum_{\alpha \in \Pi} \theta_\alpha \sum_{\beta \geq \alpha, \beta \in R^+} |c_\beta| \geq \frac{1}{CC_0^m} |\varphi(\eta) - \varphi(\eta')|.$$

The proof is complete. □

Chapter 3

Discretized Sum-product and Fourier decay in \mathbb{R}^n

3.1 Introduction

The purpose of this manuscript is to generalize a result of Bourgain to \mathbb{R}^n . This result deals with the Fourier decay of the multiplicative convolution of Borel probability measures on \mathbb{R} .

If E is a metric space, we write $B_E(x, r)$ for a close ball centered at x of radius r . Vectors in \mathbb{R}^n are seen as column vectors. The product structure on \mathbb{R}^n is given by coordinate, that is for $x = (x_1, \dots, x_n)$ and $y = (y_1, \dots, y_n)$ in \mathbb{R}^n , the product is defined to be $xy = (x_1y_1, \dots, x_ny_n)$. For a Borel probability measure on \mathbb{R}^n , let μ_k be the k -times multiplicative convolution of μ .

Theorem 3.1.1. *Given $\kappa_0 > 0$, there exist $\epsilon, \epsilon_1 > 0$ and $k \in \mathbb{N}$ such that the following holds for $\delta > 0$ small enough. Let μ be a probability measure on $[1/2, 1]^n \subset \mathbb{R}^n$ which satisfies $(\delta, \kappa_0, \epsilon)$ projective non concentration assumption, that is*

$$\forall \rho \geq \delta, \quad \sup_{a \in \mathbb{R}, v \in \mathbb{S}^{n-1}} (\pi_v)_* \mu(B_{\mathbb{R}}(a, \rho)) = \sup_{a, v} \mu\{x | \langle v, x \rangle \in B_{\mathbb{R}}(a, \rho)\} \leq \delta^{-\epsilon} \rho^{\kappa_0}. \quad (3.1.1)$$

Then for all $\xi \in \mathbb{R}^n$ with $\|\xi\| \in [\delta^{-1}/2, \delta^{-1}]$,

$$|\hat{\mu}_k(\xi)| = \left| \int \exp(2i\pi \langle \xi, x^1 \dots x^k \rangle) d\mu(x^1) \dots d\mu(x^k) \right| \leq \delta^{\epsilon_1}. \quad (3.1.2)$$

Remark 3.1.2. *We cannot have a sharper result like $\epsilon_1 \geq n/2$, because here we only use the product structure. In \mathbb{R}^* , there exist Borel subgroups which have fractional dimension. (See [EV66] for example) For a measure supported on a fractional Borel subgroup, the decay rate of Fourier transform is controlled by the Hausdorff dimension of the Borel subgroup. Hence, fractional Borel subgroups are obstacles for large decay rate of Fourier transform.*

If we continue to exploit the additive structure, that is to say replacing μ_k by $\nu = (\mu_k)^{*r}$, the r -times additive convolution of μ_k , then the Fourier transform of ν can have arbitrary large decay rate.

The Fourier transform detects the additive structure. But our measure μ_k has the multiplicative structure. The decay of Fourier transform means that the additive and multiplicative structures are hard to coexist, the sum-product philosophy.

The projective non concentration means the projection of the measure μ on every one dimensional linear subspace $\mathbb{R}v$ satisfies a non concentration assumption (the case of \mathbb{R}).

The case $n = 1$ is due to Bourgain [Bou10, Lemma 8.43]. The main ingredient of the proof of Fourier decay is the discretized sum-product estimates in \mathbb{R}^n . The sum-product estimate roughly says that if the set does not concentrate in small balls, then under addition or multiplication the size of the set will become robustly larger than the initial set.

For $\delta > 0$ and a bounded set A in a metric space E , let $\mathcal{N}_\delta(A)$ be the minimal number of closed balls of radius δ needed to cover A . In a metric space, we say that a set A is ρ **away from** a set B if A is not contained in the ρ neighborhood of B , that is there exists x in A such that $d(x, B) \geq \rho$. In $(\mathbb{R}^*)^n$, we note id the identity element $(1, \dots, 1) \in (\mathbb{R}^*)^n$. In \mathbb{R}^n , we will consider maximal proper unitary subalgebras, such subalgebras are given by $\{x \in \mathbb{R}^n | x_i = x_j\}$ for $1 \leq i < j \leq n$. We say that A is ρ away from proper unitary subalgebras of \mathbb{R}^n if A is ρ away from any maximal proper unitary subalgebra of \mathbb{R}^n .

Now we state the discretized sum-product estimates on \mathbb{R}^n , which is the main ingredient of the proof of Theorem 3.1.1.

Theorem 3.1.3. *We will consider the action of $(\mathbb{R}^*)^n$ on $V = \mathbb{R}^n$. The action is given by $gv = (g_1v_1, \dots, g_nv_n)$ for g in $(\mathbb{R}^*)^n$ and v in V . There exists a neighborhood U of the identity in $(\mathbb{R}^*)^n$ such that the following holds. Given $\kappa > 0, \sigma \in (0, n)$, there exists $\epsilon > 0$ such that for all $\delta > 0$ sufficiently small, if $A \subset U$ and $X \subset B_V(0, \delta^{-\epsilon})$ satisfy the following $(\delta, \kappa, \sigma, \epsilon)$ assumption:*

(i) For $j = 1, \dots, n$

$$\forall \rho \geq \delta, \mathcal{N}_\rho(\pi_j(A)) \geq \delta^\epsilon \rho^{-\kappa},$$

where π_j denotes the projection into j -th coordinate,

(ii) A is δ^ϵ away from proper unitary subalgebras of \mathbb{R}^n ,

(iii) For $j = 1, \dots, n$

$$\forall \rho \geq \delta, \mathcal{N}_\rho(\pi_j(X)) \geq \delta^\epsilon \rho^{-\kappa},$$

(iv) $\mathcal{N}_\delta(X) \leq \delta^{-(n-\sigma)-\epsilon}$.

Then

$$\mathcal{N}_\delta(X + X) + \sup_{a \in A} \mathcal{N}_\delta(X + aX) \geq \delta^{-\epsilon} \mathcal{N}_\delta(X).$$

Remark 3.1.4. *The case $n = 1$ is due to Bourgain. Compared with [BG12, Prop.1], our situation does have invariant subspace under the action. Hence we put more regularity on the projection into coordinate subspaces.*

Remark 3.1.5. *Roughly speaking, (i) and (iii) mean that the projections of A, X into coordinate subspaces are non concentrate. Assumption (ii) is reasonable since it prevents A from being trapped in a subalgebra.*

Compared with the projective non concentration in Theorem 3.1.1, the assumption here is weaker. In multiplicative convolution, we need additionally that μ is not trapped in any affine subspace.

From the discretized sum-product theorem to the Fourier decay of multiplicative convolution can be found in [Bou10]. The analogue result for finite fields is established in [BGK06]. See also [Gre09], where he gave a really clear treatment of the sum-product phenomenon in \mathbb{F}_p . The proof of Theorem 3.1.1 from Theorem 3.1.3 will be given in Section 3.3.

Notation

We will make use of some classic notation: For two real valued functions A and B , we write $A = O(B)$, $A \ll B$ or $B \gg A$ if there exists constant $C > 0$ such that $|A| \leq CB$, where C only depends on the ambient space. We also write $A \sim B$ if $B \ll A \ll B$.

We write $A = O_r(B)$, $A \ll_r B$, $B \gg_r A$ and $A \sim_r B$ if the constant C depends on an extra parameter $r > 0$.

3.2 Discretized sum-product estimates in \mathbb{R}^n

The non concentration assumption in Theorem 3.1.1 is a little different from that in [Bou10], but the two assumptions are equivalent up to constants.

Lemma 3.2.1. *Let $1 > \delta > 0$. Let ν be a Borel probability measure on \mathbb{R} . We have two non concentration assumptions.*

(1) $(\delta, \kappa_1, \epsilon_1)$ For $\forall \rho \geq \delta$, we have $\nu(B(a, \rho)) \leq \delta^{-\epsilon_1} \rho^{\kappa_1}$.

(2) $(\delta, \kappa, \epsilon)$ For $\rho \in [\delta, \delta^\epsilon]$, we have $\nu(B(a, \rho)) \leq \rho^\kappa$.

Then (2) $(\delta, \kappa, \epsilon)$ implies (1) $(\delta, \min \kappa, 1, \epsilon)$ and if $\kappa_1 > 2\epsilon_1$, we have that (1) $(\delta, \kappa_1, \epsilon_1)$ implies (2) $(\delta, \kappa_1/2, 2\epsilon_1/\kappa_1)$.

Proof. (2) \Rightarrow (1) For $\rho < \delta^\epsilon$, it is obvious. For $\rho > \delta^\epsilon$, we use the trivial bound

$$\nu(B(a, \rho)) \leq 1 \leq \delta^{-\epsilon + \epsilon \min\{\kappa, 1\}}.$$

Hence (2) implies that (1) holds for $(\epsilon_1, \kappa_1) = (\epsilon, \min\{\kappa, 1\})$.

(1) \Rightarrow (2) We want to find (ϵ, κ) such that (2) holds. Let $\rho = \delta^t$. That means

$$\epsilon_1 - t\kappa_1 \leq -t\kappa \text{ for } t \in [\epsilon, 1].$$

Due to $\kappa_1 > 2\epsilon_1$, we can take $(\epsilon, \kappa) = (2\epsilon_1/\kappa_1, \kappa_1/2)$. □

The assumption (2) in Lemma 3.2.1 is the original definition of Bourgain. This assumption roughly says that the measure ν has dimension κ at scale δ to scale δ^ϵ . The assumption (1) is more convenient to be proved. The smaller the parameter ϵ_1 is, the more regularity the measure ν has.

Let A be a bounded subset of \mathbb{R}^n . Let $\langle A \rangle_s$ be the set of elements which are obtained by taking sum or multiplication of elements in A at most s times.

Lemma 3.2.2. *Let A be a subset of $B_{\mathbb{R}^n}(0, K)$. If*

$$\mathcal{N}_\delta(A + A) + \mathcal{N}_\delta(A + A \cdot A) \leq K\mathcal{N}_\delta(A),$$

then for any integer s

$$\mathcal{N}_\delta(\langle A \rangle_s) \leq K^{O_s(1)}\mathcal{N}_\delta(A).$$

(See [He, Lemma 11] and [Bre11, Lemma 4.5] for more details) This lemma tells us that instead of proving that $A + A$ or $A + A \cdot A$ is large, it is sufficient to prove that $\langle A \rangle_s$ is substantially large.

Our result on the discretized sum-product estimates relies on a result of He and de Saxcé. They study sum-product phenomenon in finite dimensional linear representations of Lie groups. We will state the version we need, their theorem is much more general.

Definition 3.2.3. *Recall that we consider the action of $(\mathbb{R}^*)^n$ on $V = \mathbb{R}^n$ given by multiplication in each coordinate. Let W be a linear subspace of V such that W is not a submodule, that is there exists g in $(\mathbb{R}^*)^n$ such that $gW \not\subseteq W$. Then we call $\text{Stab}_{(\mathbb{R}^*)^n}(W)$ a **proper stabilizer**.*

Let A be a subset of $(\mathbb{R}^*)^n$ and let X be a subset of \mathbb{R}^n . For $s \geq 1$, we define $\langle A, X \rangle_s$ to be the set of elements which can be obtained as sums, differences and products of at most s elements of A and X . For example, we have $\langle A, X \rangle_s = \{\pm g_{1,1} \cdots g_{1,i_1} v_1 \pm \cdots \pm g_{l,1} \cdots g_{l,i_l} v_l \mid i_1, \dots, i_l, l \in \mathbb{N}, i_1 + \cdots + i_l \leq s\}$

Proposition 3.2.4. [HdS18, Thm.2.3] *Recall that we consider the action of $(\mathbb{R}^*)^n$ on $V = \mathbb{R}^n$ given by multiplication in each coordinate. There exists a neighborhood U of the identity in $(\mathbb{R}^*)^n$ such that the following holds. Given $\epsilon_0, \kappa > 0$, there exist $s \geq 1$ and $\epsilon > 0$ such that for all $\delta > 0$ sufficiently small, if $A \subset U$ and $X \subset B_V(0, 1)$ satisfy the following $(\delta, \kappa, \epsilon)$ assumption:*

(i) For $j = 1, \dots, n$

$$\forall \rho \geq \delta, \mathcal{N}_\rho(\pi_j(A)) \geq \delta^\epsilon \rho^{-\kappa},$$

where π_j denotes the projection into j -th coordinate,

(ii) A is δ^ϵ away from proper stabilizers,

(iii) X is δ^ϵ away from coordinate subspaces.

Then,

$$B_V(0, \delta^{\epsilon_0}) \subset \langle A, X \rangle_s + B_V(0, \delta).$$

We will use the ring structure of \mathbb{R}^n . Recall that for a subset A of $(\mathbb{R}^*)^n$, which is also a subset of \mathbb{R}^n , we define $\langle A \rangle_s$ as $\langle A, X \rangle_s$ with $X = A$. As a corollary of Proposition 3.2.4, we have

Proposition 3.2.5. *There exists a neighborhood U of the identity in $(\mathbb{R}^*)^n$ such that the following holds. Given $\kappa > 0, \epsilon_0 > 0$, there exist $\epsilon > 0$ and $s > 0$ such that, for δ sufficiently small, if A is a subset of U satisfies the following $(\delta, \kappa, \epsilon)$ assumption:*

(i) For $j = 1, \dots, n$

$$\forall \rho \geq \delta, \mathcal{N}_\rho(\pi_j(A)) \geq \delta^\epsilon \rho^{-\kappa},$$

where π_j denotes the projection into j -th coordinate,

(ii) A is δ^ϵ away from maximal proper unitary subalgebras.

Then we have

$$B_{\mathbb{R}^n}(0, \delta^{\epsilon_0}) \subset \langle A \rangle_s + B_{\mathbb{R}^n}(0, \delta).$$

Proof. Take $X = A - A$. We can shrink U to ensure that $X \subset U - U \subset B_{\mathbb{R}^n}(0, 1)$. Then we claim that A, X satisfies $(\delta, \kappa, 2\epsilon/\kappa)$ assumption of Proposition 3.2.4.

Assumption (i) of Proposition 3.2.4 is the same as Assumption (i) of this proposition. For assumption (iii) of Proposition 3.2.4, take $\rho = \delta^{2\epsilon/\kappa}$. Then

$$\mathcal{N}_\rho(\pi_j(X)) \geq \mathcal{N}_\rho(\pi_j(A)) \geq \delta^\epsilon \rho^{-\kappa} = \delta^{-\epsilon} > 1.$$

Hence, X is $\delta^{2\epsilon/\kappa}$ away from coordinate subspaces. The assumption(iii) in Proposition 3.2.4 is satisfied.

It remains to verify Assumption (ii) of Proposition 3.2.4. We need to change the point of view. The set $G = (\mathbb{R}^*)^n \subset \mathbb{R}^n$ is seen as subsets of $Aut(V) \subset End(V)$, the automorphism group and the endomorphism ring of V . The main point is that in the case of \mathbb{R}^n , proper stabilizers are contained in the subalgebras. In other words, let W be a subspace of V which is not a G -submodule. Then the proper stabilizer satisfies

$$Stab_G(W) = G \cap Stab_{\mathbb{R}^n}(W) = G \cap \{a \in \mathbb{R}^n \mid a \cdot W \subset W\}.$$

By definition, $Stab_G W$ is a proper subgroup of G . The fact that $Stab_{\mathbb{R}^n}(W)$ is a unitary subalgebra of \mathbb{R}^n implies that $Stab_{\mathbb{R}^n}(W)$ must be a proper unitary subalgebra of \mathbb{R}^n . Hence, the assumption (ii) of Proposition 3.2.4 is automatically satisfied.

Applying Proposition 3.2.4 with κ, ϵ_0 implies that there exists s_1 such that

$$B_{\mathbb{R}^n}(0, \delta^{\epsilon_0}) \subset \langle A, X \rangle_{s_1} + B_{\mathbb{R}^n}(0, \delta),$$

when ϵ is small enough. The observation that

$$\langle A, X \rangle_{s_1} = \langle A, A - A \rangle_{s_1} \subset \langle A \rangle_{2s_1}$$

implies the result. □

As a byproduct, using Lemma 3.2.2, we have the following version of discretized sum-product estimates in \mathbb{R}^n .

Proposition 3.2.6. *There exists a neighborhood U of the identity in $(\mathbb{R}^*)^n$ such that the following holds. Given $\kappa > 0, \sigma \in (0, n)$, there exists $\epsilon > 0$ such that for all $\delta > 0$ sufficiently small, if $A \subset U$ satisfies the following:*

(i) For $j = 1, \dots, n$

$$\forall \rho \geq \delta, \mathcal{N}_\rho(\pi_j(A)) \geq \delta^\epsilon \rho^{-\kappa},$$

where π_j denotes the projection into j -th coordinate,

(ii) A is δ^ϵ away from proper unitary subalgebras of \mathbb{R}^n ,

(iii) $\mathcal{N}_\delta(A) \leq \delta^{-\sigma-\epsilon}$.

Then

$$\mathcal{N}_\delta(A + A) + \mathcal{N}_\delta(A + A \cdot A) \geq \delta^{-\epsilon} \mathcal{N}_\delta(A).$$

We deduce Proposition 3.2.6 from Lemma 3.2.2 and Proposition 3.2.5. The proof is exactly the same as the proof of [He, Theorem 2]. We include its proof for completeness.

Proof of Proposition 3.2.6. Suppose that the result fails. For every $\epsilon > 0$ there exists A satisfying the hypothesis of Proposition 3.2.6 but

$$\mathcal{N}_\delta(A + A) + \mathcal{N}_\delta(A + A \cdot A) < \delta^{-\epsilon} \mathcal{N}_\delta(A).$$

We will reach a contradiction when ϵ is small enough depending only on κ, σ and \mathbb{R}^n .

Then by Lemma 3.2.2 and assumption (ii) of Proposition 3.2.6, for every integer s , we have

$$\mathcal{N}_\delta(\langle A \rangle_s) \leq \delta^{-O_s(\epsilon)} \mathcal{N}_\delta(A) \leq \delta^{-O_s(\epsilon)-\sigma}. \quad (3.2.1)$$

On the other hand, A also satisfies the assumptions of Proposition 3.2.5. Given $\epsilon_0 > 0$, there exist $\epsilon_1 > 0$ and integer s such that if $\epsilon \leq \epsilon_1$, then

$$B_{\mathbb{R}^n}(0, \delta^{\epsilon_0}) \subset \langle A \rangle_s + B_{\mathbb{R}^n}(0, \delta).$$

Therefore

$$\mathcal{N}_\delta(\langle A \rangle_s) \geq \mathcal{N}_\delta(B_{\mathbb{R}^n}(0, \delta^{\epsilon_0})) = \delta^{n(-1+\epsilon_0)} \quad (3.2.2)$$

If we take ϵ_0 sufficiently small such that $n(1 - \epsilon_0) > \sigma$, and take ϵ sufficiently small such that

$$n(1 - \epsilon_0) > O_s(\epsilon) + \sigma,$$

then (3.2.1) contradicts (3.2.2). \square

This version is not sufficient to imply the decrease of Fourier transform of multiplicative convolution of measures. We will introduce more tools of additive combinatorics to obtain a stronger form of discretized sum-product estimates.

3.2.1 Basics of discretized sets

Before proving our results, we recall some elementary and known results in the discretized setting. Let $\delta > 0$ be the scale. Let $K \geq 2$ be a roughness constant. Two quantities bounded by a polynomial of K is considered as equivalent.

Lemma 3.2.7. *Let f be a K -Lipschitz function from \mathbb{R}^n to \mathbb{R}^n . Let A be a bounded subset of \mathbb{R}^n . We have*

$$\mathcal{N}_\delta(fA) \ll K^n \mathcal{N}_\delta(A). \quad (3.2.3)$$

Definition 3.2.8. *For a bounded subset A of \mathbb{R}^n , we denote by $A^{(\delta)}$ the δ -neighborhood of A , given by*

$$A^{(\delta)} = \{x \in \mathbb{R}^n \mid d(x, A) \leq \delta\}.$$

Lemma 3.2.9. *Let A be a bounded subset of \mathbb{R}^n . Let \tilde{A} be a maximal δ -separated subset of A , that is different elements of \tilde{A} have distance at least δ and \tilde{A} is maximal for inclusion. Then*

$$\mathcal{N}_\delta(A) \sim |A^{(\delta)}| \delta^{-n} \sim \#\tilde{A}, \quad (3.2.4)$$

where $|A|$ denotes the volume of A and $\#\tilde{A}$ denotes the number of elements of \tilde{A} .

Definition 3.2.10 (Ruzsa distance). *Let A, B be two bounded subsets of \mathbb{R}^n . We define the Ruzsa distance of A, B at scale δ by*

$$d_\delta(A, B) = \frac{1}{2} \log \frac{\mathcal{N}_\delta(A - B)^2}{\mathcal{N}_\delta(A)\mathcal{N}_\delta(B)}.$$

This is not a real distance. It measures the additive structure of A and B .

Lemma 3.2.11 (Ruzsa triangular inequality). *Let A, B, C be three bounded subsets of \mathbb{R}^n . Then*

$$\mathcal{N}_\delta(B)\mathcal{N}_\delta(A - C) \ll \mathcal{N}_\delta(A - B)\mathcal{N}_\delta(B - C). \quad (3.2.5)$$

The above inequality (3.2.5) is roughly a triangular inequality for the Ruzsa distance d_δ .

Lemma 3.2.12 (Plünnecke-Ruzsa inequality). *Let A, B be two bounded subsets of \mathbb{R}^n . If $\mathcal{N}_\delta(A + B) \leq K\mathcal{N}_\delta(B)$, then for k, l in \mathbb{N} we have*

$$\mathcal{N}_\delta(kA - lA) \leq O(K)^{k+l} \mathcal{N}_\delta(B).$$

In [He17], He explains how to deduce the discretized version from the discrete version of the above two lemmas. For the discrete version, please see [TV06]. The main ingredient of proof is the Ruzsa covering lemma.

Definition 3.2.13. *Let A, B be two bounded subsets of \mathbb{R}^n . We define the doubling constant of A at scale δ by*

$$\sigma_\delta[A] := \frac{\mathcal{N}_\delta(A + A)}{\mathcal{N}_\delta(A)} = \exp(d_\delta(A, -A)).$$

We write $A \approx_K B$ if $\mathcal{N}_\delta(A + B) \leq K\mathcal{N}_\delta(A)^{1/2}\mathcal{N}_\delta(B)^{1/2}$, which is equivalent to that the Ruzsa distance is small, that is $d_\delta(A, -B) \leq \log K$.

Lemma 3.2.14 (Ruzsa calculus). *Let A, B, C be three bounded subsets of \mathbb{R}^n . Then*

- (1) *If $A \approx_K B$, then $A \approx_{K^{O(1)}} -B$, $K^{-O(1)}\mathcal{N}_\delta(B) \leq \mathcal{N}_\delta(A) \leq K^{O(1)}\mathcal{N}_\delta(B)$ and $\sigma_\delta[A], \sigma_\delta[B] \leq K^{O(1)}$.*
- (2) *If $A \approx_K B$ and $B \approx_K C$, then $A \approx_{K^{O(1)}} C$.*
- (3) *If $\sigma_\delta[A], \sigma_\delta[B] \leq K$ and $\mathcal{N}_\delta(A^{(\delta)} \cap B^{(\delta)}) \geq K^{-1}\mathcal{N}_\delta(A)^{1/2}\mathcal{N}_\delta(B)^{1/2}$, then $A \approx_{K^{O(1)}} B$.*

The proofs are direct applications of the Ruzsa triangular inequality and the Plünnecke-Ruzsa inequality. For the discrete version, please see [TV06] and the second note of Green in [Gre]. The first and second statements says that the Ruzsa distance is symmetric and transitive. The Ruzsa calculus will be used to prove Proposition 3.3.9 (Additive-Multiplicative Balog-Szemerédi-Gowers theorem).

The additive energy: the discrete case

We first introduce the additive energy in the discrete case. Let A, B be two finite sets in an abelian group G . We define the additive energy $\omega(+, A \times B)$ as the number of the quadruplet (a, b, a', b') in $A \times B \times A \times B$ such that $a + b = a' + b'$, that is

$$\omega(+, A \times B) = \#\{(a, b, a', b') \in A \times B \times A \times B \mid a + b = a' + b'\}.$$

We also have a formulation with ℓ^2 norm

$$\omega(+, A \times B) = \|\mathbb{1}_A * \mathbb{1}_B\|_2^2, \quad (3.2.6)$$

where the measure in defining ℓ^2 norm is the counting measure. From the definition, by Young's inequality, we have

$$\omega(+, A \times B) \leq |A|^{3/2}|B|^{3/2}, \quad (3.2.7)$$

where $|A|$ denotes the number of elements in A . The additive energy is important because it reflects the additive structure of A and B . If $|A + B| \leq K|A|^{1/2}|B|^{1/2}$, then by the Cauchy-Schwarz inequality,

$$\omega(+, A \times B) \geq \frac{|A|^2|B|^2}{|A + B|} \geq K^{-1}|A|^{3/2}|B|^{3/2}, \quad (3.2.8)$$

which is robustly large with respect to the optimal value of $\omega(+, A \times B)$ (3.2.7). (See [TV06] and [Gre09] for more details).

The additive energy: the continuous case

We now define the discretized version of the additive energy. On a Cartesian product $X \times Y$ of metric spaces, we use the distance defined by

$$d((x, y), (x', y')) = \sqrt{d_X^2(x, x') + d_Y^2(y, y')},$$

where x, x' are in X and y, y' are in Y .

Definition 3.2.15 (Energy of a map). *Let X, Y be two metric spaces, and let φ be a Lipschitz map from X to Y . For a subset C of X , the energy of φ at scale δ is defined by*

$$\omega_\delta(\varphi, C) = \mathcal{N}_\delta(\{(a, a') \in C \times C \mid d(\varphi(a), \varphi(a')) \leq \delta\}). \quad (3.2.9)$$

Lemma 3.2.16. *Let φ be a K -Lipschitz map from \mathbb{R}^m to \mathbb{R}^n , and let C be a bounded subset of \mathbb{R}^m . Then*

(i) *We have*

$$\mathcal{N}_\delta(C)^2 \gg \omega_\delta(\varphi, C) \gg_{n,m} \frac{\mathcal{N}_\delta(C)^2}{\mathcal{N}_\delta(\varphi(C))}. \quad (3.2.10)$$

(ii) *Let \tilde{C} be a maximal δ -separated subset of C . Then*

$$\omega_\delta(\varphi, C) \ll \#\{(a, a') \in \tilde{C}^2 \mid d(\varphi(a), \varphi(a')) \leq (1 + 2K)\delta\}. \quad (3.2.11)$$

(See [He, Lemma 12] for more details) When $m = 2n$, $C = A \times B \subset \mathbb{R}^{2n}$ with A, B in \mathbb{R}^n and $\varphi(a, b) = a + b$, we call $\omega_\delta(+, A \times B)$ the additive energy of A, B at scale δ . We have a formulation with L^2 norm (see [BISG17, Appendix A.1] for example. This is also the discretized version of (3.2.6).) We have an inequality

$$\omega_\delta(+, A \times B) \gg \delta^{-3n} \|\mathbb{1}_A * \mathbb{1}_B\|_2^2. \quad (3.2.12)$$

Lemma 3.2.16 (i) implies that

$$\omega_\delta(+, A \times B) \gg \frac{\mathcal{N}_\delta(A \times B)^2}{\mathcal{N}_\delta(A + B)} \geq \frac{\mathcal{N}_\delta(A)^2 \mathcal{N}_\delta(B)^2}{\mathcal{N}_\delta(A + B)}. \quad (3.2.13)$$

If $A \approx_K B$, that is $\mathcal{N}_\delta(A + B) \leq K \mathcal{N}_\delta(A)^{1/2} \mathcal{N}_\delta(B)^{1/2}$, then (3.2.13) implies

$$\omega_\delta(+, A \times B) \gg K^{-1} \mathcal{N}_\delta(A)^{3/2} \mathcal{N}_\delta(B)^{3/2}. \quad (3.2.14)$$

This means that when two sets A, B have additive structure then the additive energy is relatively large.

The additive energy is powerful when combined with the following proposition, a partial converse to (3.2.14), which says that if two sets have relatively large additive energy, then there exist large subsets which have additive structure.

Proposition 3.2.17 (Balog-Szemerédi-Gowers). [Tao08, Theorem 6.10] *Let A, B be two bounded subsets of \mathbb{R}^n such that*

$$\omega_\delta(+, A \times B) \geq K^{-1} \mathcal{N}_\delta(A)^{3/2} \mathcal{N}_\delta(B)^{3/2}.$$

Then there exist subsets A', B' of A, B such that

$$\mathcal{N}_\delta(A') \gg_n K^{-O(1)} \mathcal{N}_\delta(A), \quad \mathcal{N}_\delta(B') \gg_n K^{-O(1)} \mathcal{N}_\delta(B)$$

and

$$\mathcal{N}_\delta(A' + B') \ll_n K^{O(1)} \mathcal{N}_\delta(A')^{1/2} \mathcal{N}_\delta(B')^{1/2}.$$

3.2.2 Sum-product estimates in \mathbb{R}^n

We first state the discrete version of the growth under a ball.

Lemma 3.2.18. [*Gre09, Lemma 3.1*] *Let p be a prime number. If X is a subset of \mathbb{F}_p , then*

$$\sup_{a \in \mathbb{F}_p} |X + aX| \geq \frac{1}{2} \min\{|X|^2, p\}.$$

The proof is by calculating the additive energy in two ways. Suppose that the result does not hold, then the additive energy $\omega(+, X \times aX)$ is large for every a in \mathbb{F}_p . But the sum of the additive energy $\omega(+, X \times aX)$ with respect to a in \mathbb{F}_p is small, which gives the contradiction.

The continuous version uses a Fubini type argument to study the growth under a ball in $(\mathbb{R}^*)^n$. Recall that $\text{id} = (1, \dots, 1)$ is the identity in $(\mathbb{R}^*)^n$.

Lemma 3.2.19. *Given $\kappa > 0, \sigma \in (0, n)$, there exists $\epsilon > 0$ such that for δ sufficiently small the following holds. Let X be a bounded subset of \mathbb{R}^n such that for $j = 1, \dots, n$*

$$\forall \rho > \delta, \mathcal{N}_\rho(\pi_j(X)) \geq \delta^\epsilon \rho^{-\kappa}$$

and $\mathcal{N}_\delta(X) \leq \delta^{-\sigma-\epsilon}$. Then

$$\sup_{a \in B_{\mathbb{R}^n}(\text{id}, 1/2)} \mathcal{N}_\delta(X + aX) \geq \delta^{-\epsilon} \mathcal{N}_\delta(X).$$

Remark 3.2.20. *We follow closely the proof of [He, Theorem 3]. To prove the stronger version, we need another lemma, which is a reducible version of [He, Prop.29]. The proof is essentially the same as the irreducible version, with the estimate of small balls replaced by thin cylinders.*

Proof of Lemma 3.2.19. Assume that $\mathcal{N}_\delta(X + X) < \delta^{-\epsilon} \mathcal{N}_\delta(X)$, if not the proof is finished. For $\rho > \delta$ and $j = 1, \dots, n$, we have

$$\mathcal{N}_\delta(X + X) \geq \mathcal{N}_\rho(\pi_j(X)) \max_{b \in \mathbb{R}} \mathcal{N}_\delta(X \cap \pi_j^{-1} B_{\mathbb{R}}(b, \rho)). \quad (3.2.15)$$

This can be proved by the following standard argument. Choose a maximal subset $\{c_i\}$ of X such that $\pi_j(c_i)$ is 2ρ -separated. Fix b in \mathbb{R} . Choose a maximal δ -separated subset $\{d_k\}$ of $X \cap \pi_j^{-1} B_{\mathbb{R}}(b, \rho)$. If $(i, k) \neq (i', k')$, then

$$d(c_i + d_k, c_{i'} + d_{k'}) \geq \delta.$$

Hence $\{c_i + d_k\}_{i,k}$ is a δ -separated subset of $X + X$ and (3.2.15) follows.

For all b in \mathbb{R} , by (3.2.15) and hypothesis

$$\mathcal{N}_\delta(X \cap \pi_j^{-1} B_{\mathbb{R}}(b, \rho)) \leq \frac{\mathcal{N}_\delta(X + X)}{\mathcal{N}_\rho(\pi_j(X))} \leq \frac{\delta^{-\epsilon} \mathcal{N}_\delta(X)}{\delta^\epsilon \rho^{-\kappa}} = \delta^{-2\epsilon} \rho^\kappa \mathcal{N}_\delta(X). \quad (3.2.16)$$

Let μ be the normalized Lebesgue measure on $B_{\mathbb{R}^n}(\text{id}, 1/2)$ with total mass 1, and let a be a random variable following the law of μ . Define $\varphi_a : \mathbb{R}^n \times \mathbb{R}^n \rightarrow \mathbb{R}^n$ by

$$\varphi_a(x, y) = x + ay.$$

By Lemma 3.2.16 (i),

$$\mathcal{N}_\delta(\varphi_a(X \times X)) \gg \frac{\mathcal{N}_\delta(X \times X)^2}{\omega_\delta(\varphi_a, X \times X)},$$

which is also

$$\mathcal{N}_\delta(X + aX) \gg \frac{\mathcal{N}_\delta(X)^4}{\omega_\delta(\varphi_a, X \times X)}.$$

By the Jensen inequality on the function $t \mapsto \frac{1}{t}$ from \mathbb{R}^+ to \mathbb{R}^+ ,

$$\mathbb{E}(\mathcal{N}_\delta(X + aX)) \gg \frac{\mathcal{N}_\delta(X)^4}{\mathbb{E}(\omega_\delta(\varphi_a, X \times X))}. \quad (3.2.17)$$

Therefore it is sufficient to give a bound that $\mathbb{E}(\omega_\delta(\varphi_a, X \times X)) \ll \delta^\epsilon \mathcal{N}_\delta(X)^3$.

By Lemma 3.2.16 (ii), letting \tilde{X} be a maximal δ -separated subset of X , we have

$$\begin{aligned} \mathbb{E}(\omega_\delta(\varphi_a, X \times X)) &\ll \mathbb{E}(\#\{(x, x', y, y') \in \tilde{X}^4 \mid \|(x - x') + a(y - y')\| \leq 5\delta\}) \\ &= \sum_{x, x', y, y' \in \tilde{X}} \mathbb{P}\{\|a(y - y') + (x - x')\| \leq 5\delta\}, \end{aligned} \quad (3.2.18)$$

where a is contained in $B_{\mathbb{R}^n}(\text{id}, 1/2)$ and $K = 2$. Let ρ be a parameter to be fixed later. We distinguish two cases

- If $\min_j |y_j - y'_j| \geq \rho$, then

$$\mathbb{P}\{\|a(y - y') + (x - x')\| \leq 5\delta\} \ll \delta^n \rho^{-n}. \quad (3.2.19)$$

- Otherwise, the number of pairs (y, y') such that $\min_j |y_j - y'_j| < \rho$ can be bounded using (3.2.16) and (3.2.4)

$$\#\{(y, y') \in \tilde{X}^2 \mid \min_j |y_j - y'_j| < \rho\} \leq \#\tilde{X} \left(\sum_j \max_{b \in \mathbb{R}} \#\{\tilde{X} \cap \pi_j^{-1} B_{\mathbb{R}}(b, \rho)\} \right) \ll \delta^{-2\epsilon} \rho^\kappa \mathcal{N}_\delta(X)^2. \quad (3.2.20)$$

Moreover, we have for all $x, y, y' \in \tilde{X}$,

$$\sum_{x' \in \tilde{X}} \mathbb{P}\{\|a(y - y') + (x - x')\| \leq 5\delta\} \ll 1, \quad (3.2.21)$$

since for every event, there exists a finite number of x' which satisfies the assumption.

Therefore combining (4.4.3) (3.2.19) (3.2.20) and (3.2.21), and taking $\rho = \delta^{\frac{n-\sigma}{n+\kappa}}$,

$$\begin{aligned} \mathbb{E}(\omega_\delta(\varphi_a, X \times X)) &\ll \mathcal{N}_\delta(X)^4 \delta^n \rho^{-n} + \mathcal{N}_\delta(X)^3 \delta^{-2\epsilon} \rho^\kappa \\ &\ll \mathcal{N}_\delta(X)^3 (\delta^{n-\sigma-\epsilon} \rho^{-n} + \delta^{-2\epsilon} \rho^\kappa) \\ &\ll \mathcal{N}_\delta(X)^3 \delta^{-2\epsilon + \frac{\kappa(n-\sigma)}{n+\kappa}}. \end{aligned}$$

When ϵ is sufficiently small, we have $\mathbb{E}(\omega_\delta(\varphi_a, X \times X)) \ll \mathcal{N}_\delta(X)^3 \delta^\epsilon$, which finishes the proof. \square

Before proving Theorem 3.1.3, we need to introduce S_δ , the set of “good elements”. Let A be a bounded subset of \mathbb{R}^n . Let

$$S_\delta(A, K) = \{a \in B_{\text{End}(\mathbb{R}^n)}(0, K) \mid \mathcal{N}_\delta(A + aA) \leq K \mathcal{N}_\delta(A)\}.$$

The following lemma says that $S_\delta(A, K)$ has a “ring structure”.

Lemma 3.2.21. *Let $A \subset B(0, K)$ be a subset of \mathbb{R}^n .*

- (i) *If a is in $S_\delta(A, K)$ and $\|a - b\| \leq K\delta$, then b belongs to $S_\delta(A, K^{O(1)})$.*
- (ii) *If id, a, b are in $S_\delta(A, K)$, then $a - b, a + b, ab$ belong to $S_\delta(A, K^{O(1)})$.*
- (iii) *Suppose that a is invertible. If a^{-1} is in $B(0, K)$ and a is in $S_\delta(A, K)$, then a^{-1} belongs to $S_\delta(A, K^{O(1)})$.*

(See [He, Lemma 30] and [BKT04, Proposition 3.3] for more details)

Proof of Theorem 3.1.3. The idea is to use Proposition 3.2.5 to force A to grow to a fat ball. Then Lemma 3.2.19 implies the growth of regularity under the action of a fat ball.

Assume that the result fails. That is for every $\epsilon > 0$, there exist A, X satisfying the assumptions of Theorem 3.1.3 such that

$$A \subset S_\delta(X, \delta^{-\epsilon}). \tag{3.2.22}$$

We will reach a contradiction when ϵ is small enough depending on κ, σ .

By Proposition 3.2.5, for every $\epsilon_0 > 0$, there exist $s \in \mathbb{N}$ and $\epsilon_1 > 0$ depending only on ϵ_0 and κ , such that if $\epsilon < \epsilon_1$ then

$$B_{\mathbb{R}^n}(0, \delta^{\epsilon_0}) \subset \langle A \rangle_s + B_{\mathbb{R}^n}(0, \delta). \tag{3.2.23}$$

By Lemma 3.2.21 (ii) with $K = \delta^{-\epsilon}$ and (3.2.22), we have

$$\langle A \rangle_s \subset S_\delta(X, \delta^{-O(s)\epsilon}). \tag{3.2.24}$$

By Lemma 3.2.21 (i) with $K = \delta^{-O(s)\epsilon}$ and (3.2.24), (3.2.23)

$$B_{\mathbb{R}^n}(0, \delta^{\epsilon_0}) \subset S_\delta(X, \delta^{-O(s)\epsilon}). \tag{3.2.25}$$

By Lemma 3.2.21 (iii) with $K = \delta^{-O(s)\epsilon - \epsilon_0}$, $a = \frac{\delta^{\epsilon_0}}{2}\text{id}$ and (3.2.25), we have

$$2\delta^{-\epsilon_0}\text{id} = a^{-1} \in S_\delta(X, \delta^{-O(s)\epsilon - O(\epsilon_0)}). \quad (3.2.26)$$

Again by Lemma 3.2.21 (ii), using product and (3.2.25), (3.2.26), we obtain

$$B_{\mathbb{R}^n}(\text{id}, 1/2) \subset B_{\mathbb{R}^n}(0, 2) = 2\delta^{-\epsilon_0}\text{id} \cdot B_{\mathbb{R}^n}(0, \delta^{\epsilon_0}) \subset S_\delta(X, \delta^{-O(s)\epsilon - O(\epsilon_0)}). \quad (3.2.27)$$

By Lemma 3.2.19, there exists $\epsilon_2 > 0$ depending only on σ and κ , such that when $\epsilon < \epsilon_2$

$$\sup_{a \in B_{\mathbb{R}^n}(\text{id}, 1/2)} \mathcal{N}_\delta(X + aX) \geq \delta^{-\epsilon_2} \mathcal{N}_\delta(X). \quad (3.2.28)$$

Taking ϵ_0 sufficiently small, and then taking ϵ sufficiently small such that $O(s)\epsilon + O(\epsilon_0) < \epsilon_2$, we get a contradiction from (3.2.27) (3.2.28)

$$\delta^{-O(s)\epsilon - O(\epsilon_0)} \mathcal{N}_\delta(X) \geq \sup_{a \in B_{\mathbb{R}^n}(\text{id}, 1/2)} \mathcal{N}_\delta(X + aX) \geq \delta^{-\epsilon_2} \mathcal{N}_\delta(X).$$

The proof is complete. \square

3.3 Application to multiplicative convolution of measures

Notation: For a measure μ on \mathbb{R}^n , let μ^- be the symmetry of μ , that is $\mu^-(E) = \mu(-E)$ for any Borel set E of \mathbb{R}^n . Let $\mu^{(r)}$ be the r -times additive convolution of μ . Recall that μ_k is the k -times multiplicative convolution of μ . For an element x in \mathbb{R}^n , we write x_j for its j -th coordinate, $j = 1, 2, \dots, n$. We use the norm induced by the standard scalar product on \mathbb{R}^n , that is to say for $x \in \mathbb{R}^n$, $\|x\| = \sqrt{x_1^2 + \dots + x_n^2}$. All vectors x, ξ in \mathbb{R}^n are column vectors, and $\langle \cdot, \cdot \rangle$ is the inner product. For y in \mathbb{R}^n and measure ν on \mathbb{R}^n , let $(m_y)_*\nu$ be the pushforward measure of ν by the multiplication action of y , that is $(m_y)_*\nu(E) = \nu(y^{-1}E)$. In order to simplify the notation, we abbreviate $B_{\mathbb{R}^n}(0, R)$ to $B(0, R)$. For a function f on \mathbb{R}^n , we write $\|f\|_p$, $p = 1, 2, \infty$, for its L^p norm on \mathbb{R}^n .

Let $P_\delta = \frac{1_{B(0, \delta)}}{|B(0, \delta)|}$, where $|\cdot|$ is the Lebesgue measure of a Borel set in \mathbb{R}^n . Let $\nu_\delta = \nu * P_\delta$, which is an approximation of ν at scale δ .

3.3.1 L^2 -flattening

Lemma 3.3.1 (L^2 -flattening). *Given $\sigma_1, \kappa > 0$, there exists $\epsilon = \epsilon(\sigma_1, \kappa) > 0$ such that the following holds for δ small enough. Let ν be a symmetric Borel probability measure on $[-\delta^{-\epsilon}, \delta^{-\epsilon}]^n \subset \mathbb{R}^n$. Assume that*

$$\|\nu_\delta\|_2^2 \geq \delta^{-\sigma_1}$$

and ν satisfies $(\delta, \kappa, \epsilon)$ projective non concentration assumption, that is

$$\forall \rho \geq \delta, \quad \sup_{a \in \mathbb{R}, v \in \mathbb{S}^{n-1}} (\pi_v)_*\nu(B_{\mathbb{R}}(a, \rho)) = \sup_{a, v} \nu\{x \mid \langle v, x \rangle \in B_{\mathbb{R}}(a, \rho)\} \leq \delta^{-\epsilon} \rho^\kappa. \quad (3.3.1)$$

Then

$$\int \|\nu_\delta * (m_y)_*\nu_\delta\|_2^2 d\nu(y) \leq \delta^\epsilon \|\nu_\delta\|_2^2. \quad (3.3.2)$$

Remark 3.3.2. *The first assumption that the L^2 norm is not small means that the measure is not too smooth. Because if the measure is already smooth, then the convolution can not make the measure more smooth. This assumption should be compared with the assumption (iv) in Theorem 3.1.3, where we need that the covering number of the set is not too large.*

By definition and (3.3.1), $\|\nu_\delta\|_2^2 \leq \|\nu_\delta\|_\infty \|\nu_\delta\|_1 \leq \delta^{\kappa-\epsilon-n}$. Hence $\kappa + \sigma_1 \leq \epsilon + n$, that is the non concentration assumption gives a upper bound of L^2 norm. Another explication of the L^2 norm is in Lemma 3.3.14.

Remark 3.3.3. *The non concentration assumption here is stronger than the non concentration in Theorem 3.1.3. This is because we need to make multiplication in the proof. The projective non concentration assumption is stable under multiplication and addition. But the non concentration assumption in Theorem 3.1.3 is not.*

The hypothesis of projective non concentration can be weakened to (i) non concentration on coordinate subspaces and (ii) away from linear subspaces. Please see Remark 3.3.11. But the assumption needed in Theorem 3.1.1 is projective non concentration. Hence we write the same assumption here for simplicity. The step where we really need a projective non concentration is explained in Remark 3.3.18.

Remark 3.3.4. *When n equals 1, this is due to Bourgain [Bou03] [Bou10]. It roughly says that under multiplicative and additive convolution the Hölder regularity of a measure will increase, that is given $\kappa > 0$ there exists $\epsilon > 0$ such that if for all x in \mathbb{R} and $r > 0$, we have $\nu(B(x, r)) \leq r^\kappa$, then $\nu * \nu_2(B(x, r)) \leq r^{\kappa+\epsilon}$. With this observation, Bourgain gave a quantitative proof of the Erdős-Volkmann ring conjecture [Bou03, Section 4].*

Instead of using the original approach in [Bou03] [Bou10], we will follow the approach used for proving L^2 -flattening in the case of simple Lie groups, using dyadic decomposition to simplify the argument, developed by Bourgain and Gamburd (see [BG08], [BdS16], [BISG17] for example). We introduce an approximation by dyadic level sets.

Definition 3.3.5. *Let $\{D_i\}_{i \in I}$ be a family of subsets of \mathbb{R}^n . We call $\{D_i\}_{i \in I}$ an essentially disjoint union, if each point x in \mathbb{R}^n is covered by at most C different D_i , where C is a fixed constant only depending on \mathbb{R}^n .*

Lemma 3.3.6. [LS15][BISG17, Lemma A.4] *Let ν be a Borel probability measure on \mathbb{R}^n . Let \mathcal{C} be a maximal δ -separated set of \mathbb{R}^n . Let $\mathcal{C}_0 = \{x \in \mathcal{C} | 0 < \nu_{2\delta}(x) \leq 1\}$ and $\mathcal{C}_i = \{x \in \mathcal{C} | 2^{i-1} < \nu_{2\delta}(x) \leq 2^i\}$ for $i \geq 1$. For $i \geq 0$, let $X_i = \cup_{x \in \mathcal{C}_i} B(x, \delta)$. Then X_i is empty if $i \geq O(\log \frac{1}{\delta})$, and we have*

$$(1) \nu_\delta \ll \sum_{i \geq 0} 2^i \mathbb{1}_{X_i} \text{ and } \sum_{i > 0} 2^i \mathbb{1}_{X_i} \ll \nu_{3\delta}.$$

$$(2) X_i \text{ is an essentially disjoint union of balls of radius } \delta, \text{ for each } i \geq 0.$$

Lemma 3.3.7. [BISG17, Lemma A.5] *Let $a > 0$ and ν be a Borel probability measure on \mathbb{R}^n . Then*

$$\|\nu_{a\delta}\|_2 \ll_a \|\nu_\delta\|_2.$$

We also need the following inequality, which is an inverse Chebyshev's inequality. Its proof is elementary.

Lemma 3.3.8. *Let $K > 0$. Let ν be a probability measure on a measure space X . Let f be a nonnegative function on X . If $|f(x)| \leq K \int_X f d\nu$ on the support of ν , then*

$$\nu \left\{ x \in X \mid f(x) \geq \frac{1}{2} \int_X f d\nu \right\} \geq \frac{1}{2K}.$$

Here is the main idea of the proof of L^2 -flattening: Suppose that (3.3.2) fails. By (3.2.12), we can obtain two sets with large additive energy from the convolution of its character function. Hence we can find some sets in the support of ν_δ with large additive energy. Together with Balog-Szemerédi-Gowers theorem (Proposition 3.2.17), this produces two sets which violate sum-product estimates (Theorem 3.1.3).

Proof of L^2 -flattening (Lemma 3.3.1). We follow closely the proof of [BdS16, Lemma 2.5]. Proof by contradiction: Assume that the result fails. Then for every $\epsilon > 0$, there exist δ small and a measure ν satisfying

$$\int \|\nu_\delta * (m_y)_* \nu_\delta\|_2^2 d\nu(y) > \delta^\epsilon \|\nu_\delta\|_2^2. \quad (3.3.3)$$

We will reach a contradiction for ϵ sufficiently small.

Lemma 3.3.6, (3.3.3) and Cauchy-Schwarz's inequality imply

$$\delta^\epsilon \|\nu_\delta\|_2^2 \ll \int \left\| \sum_{i,j} 2^i \mathbb{1}_{X_i} * 2^j \mathbb{1}_{yX_j} \right\|_2^2 d\nu(y) \ll (\log \delta)^2 \sum_{i,j} \int \|2^i \mathbb{1}_{X_i} * 2^j \mathbb{1}_{yX_j}\|_2^2 d\nu(y).$$

There must exist i, j such that

$$Q := \int \|2^i \mathbb{1}_{X_i} * 2^j \mathbb{1}_{yX_j}\|_2^2 d\nu(y) \gg \frac{\delta^\epsilon}{(\log \delta)^4} \|\nu_\delta\|_2^2 \gg \delta^{O(\epsilon)} \|\nu_\delta\|_2^2 \geq \delta^{O(\epsilon) - \sigma}. \quad (3.3.4)$$

With the same argument as in [BISG17, Appendix A.2], we can conclude that $i, j > 0$. If $i = 0$, since $\text{supp } \nu \subset [-\delta^{-\epsilon}, \delta^{-\epsilon}]^n$, we have a bound on volume, that is $|X_0| \leq \delta^{-O(\epsilon)}$. If $j > 0$, by Lemma 3.3.6, then $\|2^j \mathbb{1}_{X_j}\|_1 \ll \|\nu_{3\delta}\|_1 = 1$. Therefore, for $j \geq 0$ and $\|y\| \leq \delta^{-\epsilon}$, by Young's inequality

$$\|\mathbb{1}_{X_0} * 2^j \mathbb{1}_{yX_j}\|_2 \leq \|\mathbb{1}_{X_0}\|_2 \|2^j \mathbb{1}_{yX_j}\|_1 \leq \delta^{-O(\epsilon)},$$

which contradicts to (3.3.4) if ϵ is sufficiently small with respect to σ . Similarly, we obtain $j > 0$.

Therefore, Lemma 3.3.6 implies

$$\begin{aligned} 2^i |X_i| &= \|2^i \mathbb{1}_{X_i}\|_1 \ll \|\nu_{3\delta}\|_1 = 1, \\ 2^{2i} |X_i| &= \|2^i \mathbb{1}_{X_i}\|_2^2 \ll \|\nu_{3\delta}\|_2^2 \ll \|\nu_\delta\|_2^2, \text{ and similarly for } j, \end{aligned} \quad (3.3.5)$$

where the last inequality is due to Lemma 3.3.7. Hence by Young's inequality, for every y in the support of ν

$$\|2^i \mathbb{1}_{X_i} * 2^j \mathbb{1}_{yX_j}\|_2 \leq \|2^i \mathbb{1}_{X_i}\|_1 \|2^j \mathbb{1}_{yX_j}\|_2 = 2^i |X_i| \|2^j \mathbb{1}_{X_j}\|_2 |\det y|^{1/2} \ll \delta^{-O(\epsilon)} \|\nu_\delta\|_2, \quad (3.3.6)$$

where $\det y$ is the determinant of y seen as an endomorphism of \mathbb{R}^n , that is $\det y = y_1 \cdots y_n$.

Then we take a set B such that for every y in B we have that $\|2^i \mathbb{1}_{X_i} * 2^j \mathbb{1}_{yX_j}\|_2^2$ is relatively large. Let

$$B = \{y \in \mathbb{R}^n \mid \|2^i \mathbb{1}_{X_i} * 2^j \mathbb{1}_{yX_j}\|_2^2 \geq Q/2\}. \quad (3.3.7)$$

Using Lemma 3.3.8 with $f(y) = \|2^i \mathbb{1}_{X_i} * 2^j \mathbb{1}_{yX_j}\|_2^2$ and (3.3.4), (3.3.6) we have

$$\nu(B) \geq \frac{Q}{2 \sup_{y \in \text{supp } \nu} f(y)} \gg \delta^{O(\epsilon)}. \quad (3.3.8)$$

We verify that X_i, X_j and B satisfy some natural assumptions. Take y in B . By (3.3.4) and Young's inequality, we have

$$\delta^{O(\epsilon)} \|\nu_\delta\|_2 \ll \|2^i \mathbb{1}_{X_i} * 2^j \mathbb{1}_{yX_j}\|_2 \leq \|2^i \mathbb{1}_{X_i}\|_2 \|2^j \mathbb{1}_{yX_j}\|_1 = 2^j |X_j| \|2^i \mathbb{1}_{X_i}\|_2 |\det y|. \quad (3.3.9)$$

By (3.3.5), the inequality (3.3.9) gives

$$|\det y| \gg \delta^{O(\epsilon)}, \text{ for } y \in B. \quad (3.3.10)$$

By $\|2^j \mathbb{1}_{X_j}\|_2 \ll \|\nu_\delta\|_2$, $|\det y| \leq \delta^{-O(\epsilon)}$ and (3.3.5), the inequality (3.3.9) implies

$$2^j |X_j| = \delta^{O(\epsilon)}, \text{ and similarly } 2^i |X_i| = \delta^{O(\epsilon)}. \quad (3.3.11)$$

Next, (3.3.5) and (3.3.9) also imply

$$\delta^{O(\epsilon)} \|\nu_\delta\|_2 \ll 2^j |X_j| \|2^i \mathbb{1}_{X_i}\|_2 |\det y| \ll \delta^{-O(\epsilon)} 2^i |X_i|^{1/2} \leq \delta^{-O(\epsilon)} 2^{i/2}.$$

We have

$$2^i \gg \delta^{O(\epsilon)} \|\nu_\delta\|_2^2 \geq \delta^{-\sigma_1 + O(\epsilon)}. \quad (3.3.12)$$

Since X_i is an essentially disjoint union of δ balls, we have $\mathcal{N}_\delta(X_i) \sim \frac{|X_i|}{\delta^n}$ and $\mathcal{N}_\delta(X_i \cap \pi_l^{-1} B_{\mathbb{R}}(a, \rho)) \ll \delta^{-n} |X_i \cap \pi_l^{-1} B_{\mathbb{R}}(a, 2\rho)|$ for every $\rho \geq \delta$ and $l = 1, \dots, n$. By (3.3.11) and (3.3.12) we have

$$\mathcal{N}_\delta(X_i) \sim \frac{|X_i|}{\delta^n} = \delta^{O(\epsilon)} 2^{-i} \delta^{-n} \ll \delta^{-n + \sigma_1 - O(\epsilon)}. \quad (3.3.13)$$

By Lemma 3.3.6(1), the projective non concentration and (3.3.13) for $\rho \geq \delta$, $a \in \mathbb{R}$ and $l = 1, \dots, n$,

$$\begin{aligned} \mathcal{N}_\delta(X_i \cap \pi_l^{-1} B_{\mathbb{R}}(a, \rho)) &\ll \delta^{-n} |X_i \cap \pi_l^{-1} B_{\mathbb{R}}(a, 2\rho)| \leq \delta^{-n} 2^{-i} \nu_{3\delta}(\pi_l^{-1} B_{\mathbb{R}}(a, 2\rho)) \\ &\ll \mathcal{N}_\delta(X_i) \delta^{-O(\epsilon)} \rho^\kappa. \end{aligned} \quad (3.3.14)$$

This means that X_i inherits non concentration from ν .

We calculate additive energy. By (3.2.12) we have

$$\omega_\delta(+, X_i \times yX_j) \gg \delta^{-3n} \|\mathbb{1}_{X_i} * \mathbb{1}_{yX_j}\|_2^2.$$

Then for every y in B , by (3.3.7), (3.3.5), (3.3.11) and (3.3.13)

$$\begin{aligned} \omega_\delta(+, X_i \times yX_j) &\gg \delta^{-3n+O(\epsilon)} \|\nu_\delta\|_2^2 2^{-2i-2j} \\ &\gg \delta^{-3n+O(\epsilon)} 2^{-i-j} |X_i|^{1/2} |X_j|^{1/2} \gg \delta^{-3n+O(\epsilon)} |X_i|^{3/2} |X_j|^{3/2} \\ &\gg \delta^{O(\epsilon)} \mathcal{N}_\delta(X_i)^{3/2} \mathcal{N}_\delta(X_j)^{3/2}. \end{aligned}$$

We can use the following proposition, which is a uniform version of the Balog-Szemerédi-Gowers theorem, inspired by the version on finite field \mathbb{F}_p due to Bourgain.

Proposition 3.3.9 (Additive-Multiplicative Balog-Szemerédi-Gowers theorem). *Let $K > 2$ be the roughness constant, let X, X', B be bounded subsets of \mathbb{R}^n in $B(0, K)$, with B^{-1} bounded by K (if $b \in B$ then $|b_j| \geq 1/K$ for $j = 1, \dots, n$), and let μ be a Borel probability measure on B . If for every $b \in B$ we have*

$$\omega_\delta(+, X \times bX') \geq \frac{1}{K} \mathcal{N}_\delta(X)^{3/2} \mathcal{N}_\delta(X')^{3/2}.$$

Then there exist $X_o \subset X$, $b_o \in B$ and $B_1 \subset B \cap B(b_o, 1/K^2)$ such that $\mathcal{N}_\delta(X_o) \geq K^{-O(1)} \mathcal{N}_\delta(X)$, $\mu(B_1) \geq K^{-O(1)}$ and for every $b \in b_o^{-1}B_1$

$$\mathcal{N}_\delta(X_o + bX_o) \leq K^{O(1)} \mathcal{N}_\delta(X_o).$$

Take $K = \delta^{O(\epsilon)}$, $\mu = \frac{1}{\nu(B)} \nu|_B$, $X = X_i$ and $X' = X_j$. By (3.3.10), the set B satisfies the assumption in Proposition 3.3.9. Take $B(1, 2r) \subset U$ as in Theorem 3.1.3 with the group $G = (\mathbb{R}^*)^n$, $V = \mathbb{R}^n$. Proposition 3.3.9 implies that for δ small enough that $\delta^\epsilon \leq r$ there exist $C_1 > 0$,

$$X_o \subset X_i \text{ and } B_1 \subset B \cap B(b_o, \delta^\epsilon r)$$

such that

$$\mathcal{N}_\delta(X_o) \geq \delta^{C_1 \epsilon} \mathcal{N}_\delta(X_i), \quad (3.3.15)$$

$$\mu(B_1) \geq \delta^{C_1 \epsilon}, \quad (3.3.16)$$

and for $b \in b_o^{-1}B_1$

$$\mathcal{N}_\delta(X_o + bX_o) \leq \delta^{-C_1 \epsilon} \mathcal{N}_\delta(X_o). \quad (3.3.17)$$

Lemma 3.3.10. *There exists $C_2 > 0$. These sets $b_o^{-1}B_1, X_o$ satisfy the $(\delta, \kappa, \sigma_1, C_2 \epsilon)$ assumption of Theorem 3.1.3 when δ is small enough.*

Proof. By Proposition 3.3.9, the set X_o satisfies $X_o \subset X_i \subset \text{supp} \nu^{(4\delta)} \subset B(0, \delta^{-O(\epsilon)})$, and B_1 satisfies $b_o^{-1}B_1 \subset b_o^{-1}B(b_o, \delta^\epsilon r) \subset U$.

Let

$$\nu_1 = \frac{1}{\nu(B_1)} (\nu|_{B_1}).$$

By (3.3.8) and (3.3.16)

$$\nu(B_1) = \nu(B)\mu(B_1) \gg \delta^{O(\epsilon)}.$$

Hence for any Borel measurable set E , we have

$$\nu_1(E) \leq \delta^{-O(\epsilon)}\nu(E). \quad (3.3.18)$$

Assumption (i) (non concentration): By (3.3.18) and projective non concentration

$$\forall \rho > \delta, \sup_{a \in \mathbb{R}} \nu_1(\pi_j^{-1}B_{\mathbb{R}}(a, \rho)) \ll \delta^{-O(\epsilon)} \sup_{a \in \mathbb{R}} \nu(\pi_j^{-1}B_{\mathbb{R}}(a, \rho)) \leq \delta^{-O(\epsilon)}\rho^\kappa,$$

Therefore by $\|b_o^{-1}\| \leq \delta^{-O(\epsilon)}$ and Lemma 3.2.7,

$$\mathcal{N}_\rho(\pi_j(b_o^{-1}B_1)) \geq \delta^{O(\epsilon)}\mathcal{N}_\rho(\pi_j(B_1)) \geq \frac{\nu_1(B_1)}{\sup_{a \in \mathbb{R}} \nu_1(\pi_j^{-1}B_{\mathbb{R}}(a, \rho))} \geq \delta^{O(\epsilon)}\rho^{-\kappa}. \quad (3.3.19)$$

Assumption (ii) (away from proper unitary subalgebras): All the maximal unitary subalgebras of \mathbb{R}^n have a form $\{x \in \mathbb{R}^n | x_i = x_j\}$ with $i \neq j$. Let $f_{ij}(x) = x_i - x_j$ for $x \in \mathbb{R}^n$. By (3.3.10) we know that $|(b_o)_i|, |(b_o)_j| \geq \delta^{O(\epsilon)}$. By (3.3.18),

$$\nu_1\{x | f_{ij}(b_o^{-1}x) \in B_{\mathbb{R}}(0, \rho)\} \leq \delta^{-O(\epsilon)}\nu\{x | f_{ij}(b_o^{-1}x) \in B_{\mathbb{R}}(0, \rho)\}.$$

This is an estimate of being away from linear subspace. If we take the vector w with its i -th, j -th coordinate equal to $(b_o)_i^{-1}$, $-(b_o)_j^{-1}$, and other coordinates equal to zero, and let $v = w/\|w\|$, then

$$f_{ij}(b_o^{-1}x) = \langle w, x \rangle.$$

Hence projective non concentration (3.3.1) for v implies that

$$\nu\{x | f_{ij}(b_o^{-1}x) \in B_{\mathbb{R}}(0, \rho)\} \leq \nu(\pi_v^{-1}B_{\mathbb{R}}(0, \delta^{-O(\epsilon)}\rho)) \leq \delta^{-O(\epsilon)}\rho^\kappa.$$

Hence $b_o^{-1}B_1$ is $\delta^{O(\epsilon)}$ away from proper subalgebra.

Assumption (iii) (non concentration of X_o): By (3.3.15) and (3.3.14) we have for $\rho \geq \delta$ and $j = 1, \dots, n$,

$$\mathcal{N}_\rho(\pi_j(X_o)) \geq \frac{\mathcal{N}_\delta(X_o)}{\sup_{a \in \mathbb{R}} \mathcal{N}_\delta(X_o \cap \pi_j^{-1}B_{\mathbb{R}}(a, \rho))} \gg \delta^{O(\epsilon)} \frac{\mathcal{N}_\delta(X_i)}{\sup_{a \in \mathbb{R}} \mathcal{N}_\delta(X_i \cap \pi_j^{-1}B_{\mathbb{R}}(a, \rho))} \gg \delta^{O(\epsilon)}\rho^{-\kappa}.$$

Assumption (iv): By (3.3.13),

$$\mathcal{N}_\delta(X_o) \ll \mathcal{N}_\delta(X_i) \ll \delta^{-n+\sigma_1-O(\epsilon)}.$$

When δ is small enough such that $\delta^\epsilon \leq 1/2$, the inequalities with Landau notation can be replaced by \geq or \leq with augmenting $O(\epsilon)$. \square

The end of the proof of the L^2 -flattening lemma: Let $C_1\epsilon$ and $C_2\epsilon$ be given in (3.3.17) and Lemma 3.3.10, respectively. Suppose that $C_2 \geq C_1$ (we can always augment C_2 in Lemma 3.3.10. The larger C_2 is, the easier the assumption is). Applying Theorem 3.1.3 with $A = b_o^{-1}B_1$ and $X = X_o$, when ϵ is sufficiently, we have

$$\mathcal{N}_\delta(X_o + X_o) + \sup_{b \in b_o^{-1}B_1} \mathcal{N}_\delta(X_o + bX_o) \geq \delta^{-C_2\epsilon} \mathcal{N}_\delta(X_o).$$

Due to $C_2 \geq C_1$, we have $\delta^{-C_2\epsilon} \mathcal{N}_\delta(X_o) \geq \delta^{-C_1\epsilon} \mathcal{N}_\delta(X_o)$, which contradicts (3.3.17). The proof is complete. \square

Remark 3.3.11. *The only place where we need a stronger non concentration than non concentration on coordinate subspaces is in the proof of Lemma 3.3.10, when we check assumption (ii) of Theorem 3.1.3. In this step, we need a property of being away from a linear subspace.*

It remains to prove Proposition 3.3.9. We first state a similar version on \mathbb{F}_p

Proposition 3.3.12. *[Bou09, Thm.C] [Gre09, Prop. 4.1] Let $K > 1$. Let $A \subset \mathbb{F}_p$ and $B \subset \mathbb{F}_p^*$ be two sets. If for all b in B , we have $\omega(+, A \times bA) \geq K^{-1}|A|^{3/2}|B|^{3/2}$. Then there exist x in B and $A' \subset A$, $B' \subset x^{-1}B$ with $|A'| \geq K^{-O(1)}|A|$ and $|B'| \geq K^{-O(1)}|B|$ such that for all $b' \in B'$,*

$$|A' + b'A'| \leq K^{O(1)}|A'|.$$

The main point is to find A' which is uniform for b . This is accomplished by using the pigeonhole principle. For more details, please see [Gre09, Prop. 4.1] or the following proof.

Proof of Proposition 3.3.9. We follow closely the proof of [Gre09, Proposition 4.1]. Since B and B^{-1} are bounded by K , if we multiply a set by an element in B , then Lemma 3.2.7 implies that we only lose some power on K , which does not change the result. That means for b in B and a subset X of \mathbb{R}^n , we have

$$K^{-O(1)}\mathcal{N}_\delta(bX) \leq \mathcal{N}_\delta(X) \leq K^{O(1)}\mathcal{N}_\delta(bX)$$

Hence, we will not write the comparison of $\mathcal{N}_\delta(A)$ with $\mathcal{N}_\delta(bA)$ for bounded set A . They have the same size.

For every $b \in B$, using additive Balog-Szemerédi-Gowers theorem (Proposition 3.2.17), we have $X_b \times X'_b \subset X \times X'$ such that

$$\mathcal{N}_\delta(X_b + bX'_b) \leq K^{O(1)}\mathcal{N}_\delta(X)^{1/2}\mathcal{N}_\delta(X')^{1/2} \quad (3.3.20)$$

and

$$\mathcal{N}_\delta(X_b) \geq K^{-O(1)}\mathcal{N}_\delta(X), \quad \mathcal{N}_\delta(X'_b) \geq K^{-O(1)}\mathcal{N}_\delta(X'). \quad (3.3.21)$$

The result we need is a uniform version, independent of b . For this purpose, we want to find an element b_o in B and a portion of B such that the intersection of X_{b_o} , X_b is large for b in this portion.

Lemma 3.3.13. *Let μ be a probability measure on a set $B \subset B_{\mathbb{R}^n}(K)$. Let S be a compact set of \mathbb{R}^n . Assume that for every b in B , there exists $S_b \subset S$ such that*

$$|S_b| \geq K^{-1}|S|.$$

Then there exists b_o in B and $B_1 \subset B \cap B(b_o, 1/K^2)$ such that $\mu(B_1) \geq K^{-O(1)}$, and for every b in B_1

$$|S_b \cap S_{b_o}| \geq K^{-O(1)}|S|. \quad (3.3.22)$$

Proof. We cover B with $O(K^{2n})$ balls of radius $1/K^2$, written as C_1, \dots, C_j . We claim that: There exists i such that

$$\int_{C_i^2} |S_b \cap S_{b'}| d\mu(b) d\mu(b') \gg K^{-O(1)}|S|. \quad (3.3.23)$$

By hypothesis, we have

$$\int_B \int_S \mathbb{1}_{S_b}(x) dx d\mu(b) = \int_B |S_b| d\mu(b) \geq K^{-1}|S|. \quad (3.3.24)$$

By Cauchy-Schwarz's inequality

$$K^{2n} \sum_i \left(\int_{C_i} \mathbb{1}_{S_b}(x) d\mu(b) \right)^2 \gg \left(\int_B \mathbb{1}_{S_b}(x) d\mu(b) \right)^2. \quad (3.3.25)$$

By Cauchy-Schwarz's inequality and (3.3.24)

$$\int_S \left(\int_B \mathbb{1}_{S_b}(x) d\mu(b) \right)^2 dx \geq \left(\int_S \int_B \mathbb{1}_{S_b}(x) d\mu(b) dx \right)^2 / |S| \geq K^{-O(1)}|S|. \quad (3.3.26)$$

Rewrite the left hand side of (3.3.25) and integrate it with respect to the Lebesgue measure on S . Combined with (3.3.26) we have

$$\sum_i \int_{C_i^2} |S_b \cap S_{b'}| d\mu(b) d\mu(b') \gg K^{-O(1)}|S|.$$

The claim (3.3.23) follows.

By Lemma 3.3.8, we can find C' , a subset of C_i^2 , such that $\mu \otimes \mu(C') \gg K^{-O(1)}$ and for all $(b, b') \in C'$

$$|S_b \cap S_{b'}| \gg K^{-O(1)}|S|. \quad (3.3.27)$$

By Fubini's theorem, we can find a b_o such that $\mu\{b \in C_i | (b_o, b) \in C'\} \gg K^{-O(1)}$. We let $B_1 = \{b \in C_i | (b_o, b) \in C'\}$, then this set satisfies the measure assumption. \square

The δ neighborhood of a set behaves well under intersection. In order to simplify the notation, abbreviate $X^{(\delta)}, X'^{(\delta)}, X_b^{(\delta)}, X_b'^{(\delta)}$ to Y, Y', Y_b, Y_b' . By (3.2.4) we have

$$\mathcal{N}_\delta(X) \sim |Y|\delta^{-n}. \quad (3.3.28)$$

Due to (3.3.20) and (3.3.21), we have $\mathcal{N}_\delta(X)^{1/2}\mathcal{N}_\delta(X')^{1/2} \geq K^{-O(1)}\mathcal{N}_\delta(X_b + bX'_b) \geq K^{-O(1)}\mathcal{N}_\delta(X_b) \geq K^{-O(1)}\mathcal{N}_\delta(X)$, which implies

$$\mathcal{N}_\delta(X) \sim_{K^{O(1)}} \mathcal{N}_\delta(X').$$

Hence

$$|Y| \sim \delta^n \mathcal{N}_\delta(X) \sim_{K^{O(1)}} \delta^n \mathcal{N}_\delta(X') \sim |Y'|. \quad (3.3.29)$$

Let

$$S = Y \times Y' \text{ and } S_b = Y_b \times Y'_b \text{ for } b \in B. \quad (3.3.30)$$

By (3.3.21), we have $|Y_b| \geq \delta^{O(\epsilon)}|Y|$ and $|Y'_b| \geq \delta^{O(\epsilon)}|Y'|$. Hence, we can use Lemma 3.3.13 with $K = \delta^{-O(\epsilon)}$ to obtain μ, B_1 with desired property. Next, we want to find X_o . Due to

$$\delta^{O(\epsilon)}|Y||Y'| = \delta^{O(\epsilon)}|S| \leq |S_b \cap S_{b_o}| = |Y_b \cap Y_{b_o}||Y'_b \cap Y'_{b_o}|,$$

together with (3.3.29), we obtain

$$|Y_b \cap Y_{b_o}|, |Y'_b \cap Y'_{b_o}| \geq \delta^{O(\epsilon)}|Y|. \quad (3.3.31)$$

The proof concludes by Ruzsa calculus. By Lemma 3.2.14(1) and (3.3.20), we have

$$\sigma_\delta[X_{b_o}], \sigma_\delta[X_b], \sigma_\delta[X'_{b_o}], \sigma_\delta[X'_b] \leq K^{O(1)}.$$

By (3.3.31) and (3.3.28), we have

$$|X_{b_o}^{(\delta)} \cap X_b^{(\delta)}|, |X'_{b_o}^{(\delta)} \cap X'_b{}^{(\delta)}| \geq K^{-O(1)}|X^{(\delta)}| \geq K^{-O(1)}\delta^n \mathcal{N}_\delta(X).$$

By Lemma 3.2.14(3), we have $X_{b_o} \approx_{K^{O(1)}} X_b$ and $X'_{b_o} \approx_{K^{O(1)}} X'_b$, the latter implies $bX'_{b_o} \approx_{K^{O(1)}} bX'_b$. Therefore by Lemma 3.2.14(2)

$$X_{b_o} \approx_{K^{O(1)}} X_b \approx_{K^{O(1)}} bX'_b \approx_{K^{O(1)}} bX'_{b_o} = \frac{b}{b_o} b_o X'_{b_o} \approx_{K^{O(1)}} \frac{b}{b_o} X_{b_o}.$$

We get $X_{b_o} \approx_{K^{O(1)}} \frac{b}{b_o} X_{b_o}$. Let $X_o = X_{b_o} \subset X$. The proof is complete. \square

3.3.2 Proof of the Fourier decay of multiplicative convolutions

Using L^2 -flattening (Lemma 3.3.1), we give a proof of Theorem 3.1.1. The strategy is to apply L^2 -flattening to

$$\nu = \frac{1}{2} \left((\mu_{2k} * \mu_{2k}^-)^{(r)} + (\mu_k * \mu_k^-)^{(r)} \right).$$

We need a lemma which explains the connection of $\|\nu_\delta\|_2$ and the Fourier transform of ν

Lemma 3.3.14. *Let $\delta > 0$, $C > 1$ and let $\delta_1 = 2\delta/C$. Let ν be a Borel probability measure on \mathbb{R}^n with support in $B(0, C)$. We have*

$$\|\nu_{\delta_1}\|_2^2 \sim_C \int_{B(0, 2\delta^{-1})} |\hat{\nu}(\xi)|^2 d\xi, \quad (3.3.32)$$

$$\int \|\nu_{\delta_1} * (m_y)_* \nu_{\delta_1}\|_2^2 d\nu(y) \gg \int_{B(0, 2\delta^{-1})} \int |\hat{\nu}(\xi)|^2 |\hat{\nu}(y\xi)|^2 d\nu(y) d\xi. \quad (3.3.33)$$

The proof of Lemma 3.3.14 will be given at the end of this section.

Recall that μ_k is the k -times multiplicative convolution of μ . We have

$$\left| \int \exp(2i\pi\langle \xi, x^1 \cdots x^k \rangle) d\mu(x^1) \cdots d\mu(x^k) \right| = |\hat{\mu}_k(\xi)|.$$

For $k, r \in \mathbb{N}$, let $\sigma_{k,r}$ be the real number defined by

$$\sigma_{k,r} = \frac{\log \int_{\xi \in B(0, 2\delta^{-1})} |\hat{\mu}_k(\xi)|^{2r} d\xi}{|\log \delta|} \sim \frac{\|(\mu_{k,r})_\delta\|_2^2}{|\log \delta|}, \quad (3.3.34)$$

where $\mu_{k,r} = (\mu_k * \mu_k^-)^{*r}$.

The remainder of the proof is to control $\sigma_{k,r}$, divided into two steps. We first prove that if $\sigma_{k,r}$ is not sufficiently small, then L^2 -flattening (Lemma 3.3.1) reduces the value of $\sigma_{k,r}$. When $\sigma_{k,r}$ is sufficiently small, the Hölder regularity of μ enables us to finish the proof. This can be understood that if a measure μ satisfies non concentration assumption, then after sufficient multiplicative and additive convolutions, the sum-product phenomenon implies that $\mu_{k,r}$ is much more smooth.

Proof of Theorem 3.1.1. Let

$$\kappa_1 = \kappa_0/4, \quad \epsilon = \min\{\epsilon(\kappa_1/2, \kappa_0), \kappa_0\}/2, \quad (3.3.35)$$

where $\epsilon(\kappa_1/2, \kappa_0)$ is given in L^2 -flattening (Lemma 3.3.1).

Reducing the value: We have a consequence of L^2 -flattening (Lemma 3.3.1), whose proof will be given later.

Lemma 3.3.15. *Under the assumption of Theorem 3.1.1, if $\sigma_{k,r} \geq \kappa_1$, then for δ small enough depending on k, r , we have*

$$\sigma_{2k,r'} \leq \sigma_{k,r} - \epsilon,$$

where $r' = 8r^2 + 4r$.

Sufficient regularity: We have a higher dimensional version of [Bou10, Theorem 7], which says that if two measures have sufficient Hölder regularity, then the multiplicative convolution of these two measures has power decay in its Fourier transform.

Lemma 3.3.16. *Let $\alpha > \beta > 0$ and $\delta > 0$. Let μ be a measure on $B(0, 1)$ such that for $j = 1, \dots, n$*

$$\sup_a (\pi_j)_* \mu(B_{\mathbb{R}}(a, \delta)) \leq \delta^\alpha. \quad (3.3.36)$$

Let $K > 2$ be a parameter. Let ν be a compactly supported measure on $B(0, K)$ such that

$$\int_{B(0, 2\delta^{-1})} |\hat{\nu}(\xi)| d\xi \leq \delta^{-\beta}. \quad (3.3.37)$$

Then for $\|\xi\| \in [\delta^{-1}/2, \delta^{-1}]$

$$\int |\hat{\nu}(x\xi)| d\mu(x) \ll_{K,n} \delta^{\frac{\alpha-\beta}{n+2}}.$$

The proof of Lemma 3.3.16 is classic and will be given at the end of Section 3.3.2 for completeness.

If $\sigma_{1,1} \geq \kappa_1$, iterating Lemma 3.3.15 several times implies that $\sigma_{k,r} < \kappa_1$, where k, r only depend on κ_1 .

We will now apply Lemma 3.3.16 to a well-chosen measure. Take $(\mu_k * \mu_k^-)^{(r)}$ as ν , $\alpha = \kappa_0 - \epsilon$, $\beta = \kappa_1$ and $\tau = \frac{\alpha - \beta}{n+2}$. For $\|\xi\| \in [\delta^{-1}/2, \delta^{-1}]$, by Hölder's inequality and Lemma 3.3.16,

$$|\hat{\mu}_{k+1}(\xi)|^{2r} = \left| \int \hat{\mu}_k(x\xi) d\mu(x) \right|^{2r} \leq \int |\hat{\mu}_k(x\xi)|^{2r} d\mu(x) = \int |\hat{\nu}(x\xi)| d\mu(x) \leq_{k,n} \delta^\tau.$$

When δ is small enough, this yields (3.1.2) with

$$\epsilon_1 = \frac{\tau}{4r} = \frac{\kappa_0 - \epsilon - \kappa_1}{4(n+2)r} \geq \frac{\kappa_0/2 - \kappa_1}{4(n+2)r} \geq \frac{\kappa_1}{4(n+2)r},$$

where the last two inequalities are due to (3.3.35) and r only depends on κ_0 . \square

Now we will prove Lemma 3.3.15, where we use the L^2 -flattening (Lemma 3.3.1).

Proof of Lemma 3.3.15. Fix k, r and set

$$\nu = \frac{1}{2} \left((\mu_{2k} * \mu_{2k}^-)^{(r)} + (\mu_k * \mu_k^-)^{(r)} \right). \quad (3.3.38)$$

This is the key construction of this proof. The measure ν is the bridge to connect μ_{2k} and μ_k . We summarize the properties of ν in the following lemma.

Lemma 3.3.17. *The measure ν satisfies $(\delta/r, \kappa_0, 2\epsilon)$ projective non concentration assumption when δ is sufficient small depending on k, r .*

Proof. Projective non concentration property is invariant under addition. That is if a probability measure m satisfies projective non concentration, then $m * m'$ also satisfies projective non concentration for any probability measure m' . The reason is the following calculation. By Fubini's theorem, we have

$$(\pi_v)_*(m * m')(B_{\mathbb{R}}(a, \rho)) \leq \sup_{b \in \mathbb{R}} (\pi_v)_* m(B_{\mathbb{R}}(b, \rho)).$$

Hence we can drop the additive convolution, and for $\rho \geq \delta_1$, we have

$$\sup_{a \in \mathbb{R}, v \in \mathbb{S}^{n-1}} (\pi_v)_* \nu(B_{\mathbb{R}}(a, \rho)) \leq \frac{1}{2} \sup_{a,v} (\pi_v)_* \mu_k(B_{\mathbb{R}}(a, \rho)) + \frac{1}{2} \sup_{a,v} (\pi_v)_* \mu_{2k}(B_{\mathbb{R}}(a, \rho)). \quad (3.3.39)$$

The property that the support of μ is contained in $[1/2, 1]^n$ and the projective non concentration of μ imply the left hand side of (3.3.39) is less than

$$\sup_{a,v} (\pi_v)_* \mu(B_{\mathbb{R}}(a, 4^k \rho)) \leq \delta^{-\epsilon} (\max\{4^k \rho, r\rho\})^{\kappa_0} \leq \delta_1^{-2\epsilon} \rho^{\kappa_0}, \quad (3.3.40)$$

where we have used $r\rho \geq r\delta_1 = \delta$ for projective non concentration and the last inequality holds for δ small enough depending on k, r . Then (3.3.1) follows from (3.3.39) and (3.3.40). The measure ν satisfies non concentration with $(\kappa_0, 2\epsilon)$ at scale δ_1 . \square

Remark 3.3.18. *This is a step where we really need projective non concentration.*

Lemma 3.3.19. *Let $C > 0$ and $r \in \mathbb{N}$. Let μ be a probability measure on $[1/C, 1]^n \subset \mathbb{R}^n$. Let ν be defined by*

$$\nu = \frac{1}{2} \left((\mu_2 * \mu_2^-)^{(r)} + (\mu * \mu^-)^{(r)} \right).$$

We have

$$\int_{B(0, 2\delta^{-1})} |\hat{\nu}(\xi)|^2 d\xi \sim_C \int_{B(0, 2\delta^{-1})} |\hat{\mu}(\xi)|^{4r} d\xi, \quad (3.3.41)$$

and

$$\int_{B(0, 2\delta^{-1})} |\hat{\mu}_2(\xi)|^{r'} d\xi \ll \int_{B(0, 2\delta^{-1})} \int |\hat{\nu}(\xi)|^2 |\hat{\nu}(y\xi)|^2 d\nu(y) d\xi, \quad (3.3.42)$$

where $r' = 8r^2 + 4r$.

The proof is an elementary computation, using Fourier transform and the Hölder inequality.

Proof. The lower bound part of (3.3.41) is trivial, which is due to the definition of ν .

For a measure m on \mathbb{R} and $r \in \mathbb{N}$, we have a formula

$$|\hat{m}(\xi)|^{4r} = |(\widehat{m * m^-})^{(2r)}(\xi)|. \quad (3.3.43)$$

By the multiplicative structure of \mathbb{R}^n , we have

$$|\hat{\mu}_2(\xi)| = \left| \int e^{2i\pi\langle \xi, xy \rangle} d\mu(x) d\mu(y) \right| = \left| \int \hat{\mu}(y\xi) d\mu(y) \right|. \quad (3.3.44)$$

By the Hölder inequality,

$$|\hat{\mu}_2(\xi)|^{4r} \leq \int |\hat{\mu}(y\xi)|^{4r} d\mu(y).$$

Integrating ξ on $B(0, 2\delta^{-1})$, we have

$$\int_{B(0, 2\delta^{-1})} |\hat{\mu}_2(\xi)|^{4r} d\xi \leq \int_{y \in \mathbb{R}^n, \xi \in B(0, 2\delta^{-1})} |\hat{\mu}(y\xi)|^{4r} d\mu(y) d\xi.$$

Due to $\text{supp} \mu \subset [1/C, 1]^n$, we have

$$\begin{aligned} \int_{B(0, 2\delta^{-1})} \int |\hat{\mu}(y\xi)|^{4r} d\mu(y) d\xi &\leq C^n \int \int_{B(0, 2\delta^{-1})} |\hat{\mu}(y\xi)|^{4r} d(y\xi) d\mu(y) \\ &= C^n \int_{B(0, 2\delta^{-1})} |\hat{\mu}(\xi)|^{4r} d\xi, \end{aligned}$$

which implies that

$$\int_{B(0, 2\delta^{-1})} |\hat{\mu}_2(\xi)|^{4r} d\xi \leq C \int_{B(0, 2\delta^{-1})} |\hat{\mu}(\xi)|^{4r} d\xi.$$

Therefore (3.3.41) follows from

$$\int_{B(0,2\delta^{-1})} |\hat{\nu}(\xi)|^2 d\xi = \frac{1}{4} \int_{B(0,2\delta^{-1})} (|\hat{\mu}(\xi)|^{2r} + |\hat{\mu}_2(\xi)|^{2r})^2 d\xi \leq_C \int_{B(0,2\delta^{-1})} |\hat{\mu}(\xi)|^{4r} d\xi.$$

By (3.3.44), Hölder's inequality and (3.3.43)

$$\begin{aligned} |\hat{\mu}_2(\xi)|^{8r^2} &= \left| \int \hat{\mu}(x\xi) d\mu(x) \right|^{8r^2} \leq \left(\int |\hat{\mu}(x\xi)|^{2r} d\mu(x) \right)^{4r} \\ &= \left| \int (\widehat{\mu * \mu^-})^{(r)}(x\xi) d\mu(x) \right|^{4r}. \end{aligned}$$

By the Plancherel theorem and Hölder's inequality, the above inequality becomes

$$|\hat{\mu}_2(\xi)|^{8r^2} \leq \left| \int \hat{\mu}(y\xi) d(\mu * \mu^-)^{(r)}(y) \right|^{4r} \leq \int |\hat{\mu}(y\xi)|^{4r} d(\mu * \mu^-)^{(r)}(y). \quad (3.3.45)$$

Let

$$A_r = \int_{y \in \mathbb{R}^n, \xi \in B(0,2\delta^{-1})} |\hat{\mu}(\xi)|^{4r} |\hat{\mu}(y\xi)|^{4r} d(\mu * \mu^-)^{(r)}(y) d\xi.$$

Therefore, by (3.3.45) and (3.3.43)

$$\int_{B(0,2\delta^{-1})} |\hat{\mu}_2(\xi)|^{8r^2+4r} d\xi \leq \int_{B(0,2\delta^{-1})} |\hat{\mu}_2(\xi)|^{4r} \int |\hat{\mu}(y\xi)|^{4r} d(\mu * \mu^-)^{(r)}(y) d\xi = A_r. \quad (3.3.46)$$

By (3.3.38)

$$A_r \ll \int_{y \in \mathbb{R}^n, \xi \in B(0,2\delta^{-1})} |\hat{\nu}(\xi)|^2 |\hat{\nu}(y\xi)|^2 d\nu(y) d\xi.$$

Combined with (3.3.46), we obtain (3.3.42). \square

Lemma 3.3.17 and Lemma 3.3.19 enable us to decrease the parameter $\sigma_{k,r}$ by L^2 -flattening (Lemma 3.3.1).

We return to the proof of Lemma 3.3.15. By (3.3.41) and the hypothesis $\sigma_{k,2r} \geq \kappa_1$, we have

$$\int_{B(0,2\delta^{-1})} |\hat{\nu}(\xi)|^2 d\xi \gg_k \delta^{-\kappa_1}. \quad (3.3.47)$$

Due to $\text{supp } \nu \in [-r, r]^n$ and (3.3.47), taking $C = r$ in Lemma 3.3.14, we have

$$\|\nu_{\delta_1}\|_2^2 \gg_{r,k} \delta^{-\kappa_1} = r^{-\kappa_1} \delta_1^{-\kappa_1}.$$

When δ is small enough depending on k, r, κ_1 , we have

$$\|\nu_{\delta_1}\|_2^2 \geq \delta_1^{-\kappa_1/2} \text{ and } \text{supp } \nu \subset [-r, r]^n \subset [-\delta_1^{-2\epsilon}, \delta_1^{-2\epsilon}]^n. \quad (3.3.48)$$

Lemma 3.3.17 implies that ν satisfies assumption of L^2 -flattening lemma with $\sigma_1 = \kappa_1/2, \kappa = \kappa_0$ at scale δ_1 . Also notice that (3.3.35) implies $2\epsilon \leq \epsilon(\kappa_1/2, \kappa_0)$. Then L^2 -flattening (Lemma 3.3.1) implies

$$\int \|\nu_{\delta_1} * (m_y)_* \nu_{\delta_1}\|_2^2 d\nu(y) \leq \delta_1^{2\epsilon} \|\nu_{\delta_1}\|_2^2. \quad (3.3.49)$$

Using Lemma 3.3.17, we obtain

$$\int_{B(0, 2\delta^{-1})} \int |\hat{\nu}(\xi)|^2 |\hat{\nu}(y\xi)|^2 d\nu(y) d\xi \leq_r \delta_1^{2\epsilon} \int_{B(0, 2\delta^{-1})} |\hat{\nu}(\xi)|^2 d\xi. \quad (3.3.50)$$

Using Lemma 3.3.19 with $\mu = \mu_k$ and $C = 2^k$, by (3.3.50), we have

$$\int_{B(0, 2\delta^{-1})} |\hat{\mu}_{2k}(\xi)|^{r'} d\xi \ll_{r,k} \delta_1^{2\epsilon} \int_{B(0, 2\delta^{-1})} |\hat{\mu}_k(\xi)|^{4r} d\xi = \delta^{-\sigma_{k,2r}} \delta_1^{2\epsilon} \ll_r \delta^{2\epsilon - \sigma_{k,2r}}.$$

Therefore we have

$$\sigma_{2k,r'} \leq \sigma_{k,2r} - 2\epsilon + C_{k,r}/\log \delta^{-1},$$

with some constant $C_{k,r} > 0$. For δ small enough, it follows that $\delta_{2k,r'} \leq \sigma_{k,2r} - \epsilon$. \square

It remains to prove Lemma 3.3.14 and Lemma 3.3.16.

Proof of Lemma 3.3.14. Recall that $\delta = 2C\delta_1$. We observe that the Fourier transform of P_δ satisfies

$$\widehat{P}_\delta(\xi) = \int P_\delta(x) e^{i\langle \xi, x \rangle} dx = \int P_1(x/\delta) \delta^{-n} e^{i\langle \xi, x \rangle} dx = \widehat{P}_1(\delta\xi).$$

Due to $\widehat{P}_1(\xi) = \Re \int_{B(0,1)} e^{i\langle \xi, x \rangle} dx |B(0,1)|^{-1} = \int_{B(0,1)} \cos(\langle \xi, x \rangle) dx |B(0,1)|^{-1}$, we see that

$$\widehat{P}_1 \text{ is positive for } \xi \in B(0,1). \quad (3.3.51)$$

We are going to prove (3.3.32). By (3.3.51), we have $\widehat{P}_1(\delta_1\xi) \gg 1$ for ξ in $B(0, 1/\delta_1)$, which implies

$$\begin{aligned} \|\nu_{\delta_1}\|_2^2 &= \int |\hat{\nu}(\xi)|^2 |\widehat{P}_{\delta_1}(\xi)|^2 d\xi = \int |\hat{\nu}(\xi)|^2 |\widehat{P}_1(\delta_1\xi)|^2 d\xi \\ &\gg \int_{B(0, 1/\delta_1)} |\hat{\nu}(\xi)|^2 d\xi \geq \int_{B(0, 2\delta^{-1})} |\hat{\nu}(\xi)|^2 d\xi. \end{aligned} \quad (3.3.52)$$

For the other direction of (3.3.32), let $\delta_2 = 2\delta = 4C\delta_1$. Due to $1/\delta_2 + 1/\delta_2 = 1/\delta$, we have $P_{1/\delta} \gg P_{1/\delta_2} * P_{1/\delta_2}$, which implies

$$\begin{aligned} \int_{B(0, 2\delta^{-1})} |\hat{\nu}(\xi)|^2 d\xi &\gg \int |\hat{\nu}(\xi)|^2 |P_{1/\delta}(\xi)|^2 \delta^{-2n} d\xi \gg \int |\hat{\nu}(\xi)|^2 |P_{1/\delta_2} * P_{1/\delta_2}(\xi)|^2 \delta^{-2n} d\xi \\ &= \delta^{-2n} \int |\nu * \widehat{P}_{1/\delta_2}^2(x)|^2 dx. \end{aligned} \quad (3.3.53)$$

By (3.3.51), we have $\widehat{P}_{1/\delta_2}^2(x) = \widehat{P}_1^2(x/\delta_2) \gg \mathbb{1}_{B(0,\delta_2)}(x)$. Combined with $|B(0,\delta_1)| \gg_C \delta^{-n}$, this implies

$$\nu * \widehat{P}_{1/\delta_2}^2(x)\delta^{-n} \geq \nu * P_{\delta_1}(x) = \nu_{\delta_1}(x).$$

Together with (3.3.53), we have the other direction of (3.3.32).

The second inequality (3.3.33) follows from the same argument. By Parseval's formula

$$\begin{aligned} \int \|\nu_{\delta_1} * (m_y)_* \nu_{\delta_1}\|_2^2 d\nu(y) &= \int \int |\widehat{\nu}_{\delta_1}(\xi)|^2 |\widehat{(m_y)_* \nu_{\delta_1}}(\xi)|^2 d\xi d\nu(y) \\ &= \int \int |\widehat{\nu}(\xi)|^2 |\widehat{\nu}(y\xi)|^2 |\widehat{P}_{\delta_1}(y)|^2 |\widehat{P}_{\delta_1}(y\xi)|^2 d\nu(y) d\xi \\ &= \int \int |\widehat{\nu}(\xi)|^2 |\widehat{\nu}(y\xi)|^2 |\widehat{P}_1(\delta_1 y)|^2 |\widehat{P}_1(\delta_1 y\xi)|^2 d\nu(y) d\xi. \end{aligned} \quad (3.3.54)$$

For $y \in B(0,C)$ and $\xi \in B(0,2\delta^{-1})$, we have $\|\delta_1 y\xi\| \leq 1$. By (3.3.51), the inequality (3.3.54) implies (3.3.33). \square

Proof of Lemma 3.3.16. Let $R = \delta^{-1}$. Consider $H_{R,t} = \{\xi \in B(0,R) \mid |\widehat{\nu}(\xi)| \geq t\}$, where $0 < t < 1$ will be fixed later. Since ν is supported on $B(0,K)$, the function $|\widehat{\nu}|$ is K Lipschitz. We have

$$H_{R,t} + B\left(0, \frac{t}{2K}\right) \subset H_{R+1, \frac{t}{2}}.$$

Hence by (3.2.4)

$$\mathcal{N}_t(H_{R,t}) \ll_K |H_{R,t}^{(\frac{t}{2K})}| t^{-n} \leq |H_{R+1, \frac{t}{2}}| t^{-n}.$$

By the definition of $H_{R,t}$, Chebyshev's inequality and (3.3.37),

$$\mathcal{N}_t(H_{R,t}) \ll t^{-n-1} \int_{B(0,R+1)} |\widehat{\nu}(\xi)| d\xi \ll R^\beta t^{-n-1}. \quad (3.3.55)$$

From now on, suppose that $\|\xi\| \in [R/2, R]$. Let $H_{R,t}^\xi = \{x \in \mathbb{R}^n \mid x\xi \in H_{R,t}\}$. Then due to $\|\xi\| \leq R$, we have $\|x\xi\| \leq R$ for $x \in \text{supp}\mu \subset B(0,1)$, and

$$\int |\widehat{\nu}(x\xi)| d\mu(x) \leq t + \mu(H_{R,t}^\xi). \quad (3.3.56)$$

We cover $H_{R,t}$ with balls of radius t and we also get a cover of $H_{R,t}^\xi$ by $B^\xi(y,t) = \{x \in \mathbb{R}^n \mid x\xi \in B(y,t)\}$. Due to $\|\xi\| \geq R/2$, there is at least one $j \in \{1, \dots, n\}$ such that $|\xi_j| \geq R/(2n)$. Therefore, we can replace $B^\xi(y,t)$ by a cylinder $\pi_j^{-1} B_{\mathbb{R}}(y, 2n/R)$ and we obtain

$$\mu B^\xi(y,t) = \mu\{x \in \mathbb{R}^n \mid x\xi \in B(y,t)\} \ll \sup_{y \in \mathbb{R}, j=1, \dots, n} (\pi_j)_* \mu\{x \mid x \in B_{\mathbb{R}}(y, 2n/R)\}.$$

The above inequality combined with the hypothesis (3.3.36) implies

$$\mu B^\xi(y,t) \ll R^{-\alpha}. \quad (3.3.57)$$

Therefore by (3.3.55) and (3.3.57)

$$\mu(H_{R,t}^\xi) \leq \mathcal{N}_t(H_{R,t}) \max \mu B^\xi(y, t) \ll_K R^{\beta-\alpha} t^{-(n+1)}. \quad (3.3.58)$$

If we take $t = R^{-\frac{\alpha-\beta}{n+2}}$, then the result follows from (3.3.56) and (3.3.58). \square

3.4 Appendix

The main purpose of the Appendix is to give a version of Theorem 3.1.1 (Proposition 3.4.4) for its application to the random product of matrices.

In the application, we need to vary the measure. Using the same idea as in [BD17, Propostion 3.2], we have a version for several different measures (Proposition 3.4.2). The measures appearing in the random product of matrices are not compactly supported, hence we will relax the assumption on support in Proposition 3.4.4.

Proposition 3.4.1. *Fix $\kappa > 0$. Then there exist $k \in \mathbb{N}, \epsilon > 0$ depending only on κ_1 such that the following holds for τ large enough. Let λ be a Borel probability measure on $[\frac{1}{2}, 1]^n \subset \mathbb{R}^n$. Assume that for all $\rho \in [\tau^{-1}, \tau^{-\epsilon}]$ and*

$$\sup_{a \in \mathbb{R}, v \in \mathbb{S}^{n-1}} (\pi_v)_* \lambda(B_{\mathbb{R}}(a, \rho)) = \sup_{a, v} \lambda\{x | \langle v, x \rangle \in B_{\mathbb{R}}(a, \rho)\} \leq \rho^\kappa. \quad (3.4.1)$$

Then for ξ in \mathbb{R}^n with $\|\xi\| \in [\tau/2, \tau]$

$$\left| \int \exp(2i\pi \langle \xi, x_1 \cdots x_k \rangle) d\lambda(x_1) \cdots d\lambda(x_k) \right| \leq \tau^{-\epsilon}.$$

Proof. By Lemma 3.2.1, Theorem 3.1.1 implies the result. \square

We state a version with different measures.

Proposition 3.4.2. *Fix $\kappa > 0$. Then there exist $k \in \mathbb{N}, \epsilon > 0$ depending only on κ_1 such that the following holds for τ large enough. Let $\lambda_1, \dots, \lambda_k$ be Borel measures on $[\frac{1}{2}, 1]^n \subset \mathbb{R}^n$ with total mass less than 1. Assume that for all $\rho \in [\tau^{-1}, \tau^{-\epsilon}]$ and $j = 1, \dots, k$*

$$\sup_{a \in \mathbb{R}, v \in \mathbb{S}^{n-1}} (\pi_v)_* \lambda_j(B_{\mathbb{R}}(a, \rho)) = \sup_{a, v} \lambda_j\{x | \langle v, x \rangle \in B_{\mathbb{R}}(a, \rho)\} \leq \rho^\kappa. \quad (3.4.2)$$

Then for ξ in \mathbb{R}^n with $\|\xi\| \in [\tau/2, \tau]$

$$\left| \int \exp(2i\pi \langle \xi, x_1 \cdots x_k \rangle) d\lambda_1(x_1) \cdots d\lambda_k(x_k) \right| \leq \tau^{-\epsilon}.$$

Proof. The proof is the same as the argument in [BD17, Propostion 3.2]. For completeness, we give a ketch here.

We first verify that if the mass of the measure λ is less than 1, the result also holds. Let ϵ_2 be given by Proposition 3.4.1 when the regular exponent equals $\kappa/2$. We distinguish two cases

- If $\lambda(\mathbb{R}^d) \geq \tau^{-\epsilon_2\kappa/2}$, then replace λ by $\lambda' = \lambda/\lambda(\mathbb{R}^d)$. For $\rho \in [\tau^{-1}, \tau^{-\epsilon_2}]$, we have

$$\sup_{a \in \mathbb{R}, v \in \mathbb{S}^{n-1}} (\pi_v)_* \lambda'(B_{\mathbb{R}}(a, \rho)) \leq \tau^{\epsilon_2\kappa/2} \sup_{a \in \mathbb{R}, v \in \mathbb{S}^{n-1}} (\pi_v)_* \lambda(B_{\mathbb{R}}(a, \rho)) \leq \tau^{\epsilon_2\kappa/2} \rho^\kappa$$

Due to $\rho \leq \tau^{-\epsilon_2}$, we have $\tau^{\epsilon_2\kappa/2} \rho^\kappa \leq \rho^{\kappa/2}$. The measure λ' satisfies non concentration with $\kappa/2$. By Proposition 3.4.1, we have the result.

- If $\lambda(\mathbb{R}^d) < \tau^{-\epsilon_2\kappa/2}$, then we have

$$\left| \int \exp(2i\pi \langle \xi, x_1 \cdots x_k \rangle) d\lambda(x_1) \cdots d\lambda(x_k) \right| \leq \tau^{-k\epsilon_2\kappa/2}.$$

Hence we can take $\epsilon = \min\{\epsilon_2, k\epsilon_2\kappa/2\}$.

Then we want to prove that the result holds for different measures. For $z \in \mathbb{R}^k$, let $\lambda_z = \sum_{1 \leq j \leq k} z_j \lambda_j$. Let

$$G(\lambda_1, \dots, \lambda_k) = \int \exp(2i\pi \langle \xi, x_1 \cdots x_k \rangle) d\lambda_1(x_1) \cdots d\lambda_k(x_k)$$

and

$$F(z) = F(z_1, \dots, z_k) = G(\lambda_z, \dots, \lambda_z).$$

Then $F(z)$ is polynomial of k variables of degree k , and $k!G(\lambda_1, \dots, \lambda_k)$ is the coefficient of $z_1 \cdots z_k$ in $F(z)$. For $z \in \mathbb{R}_{\geq 0}^k$, we have

$$|F(z)| \leq |z|^k \tau^{-\epsilon}, \text{ where } |z| = \sum_{1 \leq j \leq k} |z_j|,$$

by using the result of the first part with $\lambda = \frac{1}{|z|} \lambda_z$.

Lemma 3.4.3. *Let F be a polynomial of k variables of degree less than n . Let $h(F)$ be the maximum of the absolutely value of the coefficients in F . Then*

$$h(F) \leq O_{k,n} \sup_{z \in \{0, \dots, n\}^k \subset \mathbb{R}^k} \{|F(z)|\}.$$

In this lemma, we define two norms on the space of polynomials of k variable of degree less than n . The inequality is due to the equivalence of norms on finite dimensional vector space. Hence

$$|G(\lambda_1, \dots, \lambda_k)| \ll_k h(F) \ll_k \tau^{-\epsilon}.$$

The proof is complete. □

Now we will give another version of Fourier decay of multiplicative convolution, which releases the assumption on the support of λ_j .

Proposition 3.4.4. *Fix $\kappa_0 > 0$. Let $C_0 > 0$. Then there exist ϵ_2 and $k \in \mathbb{N}$ depending only on κ_0 such that the following holds for τ large enough depending on C_0, κ_0 . Let $\lambda_1, \dots, \lambda_k$ be Borel measures on \mathbb{R}^n supported in $([-\tau^{\epsilon_3}, -\tau^{-\epsilon_3}] \cup [\tau^{-\epsilon_3}, \tau^{\epsilon_3}])^n$ with total mass less than 1, where $\epsilon_3 = \min\{\epsilon_2, \epsilon_2 \kappa_0, 1\}/10k$. Assume that for all $\rho \in [\tau^{-2}, \tau^{-\epsilon_2}]$ and $j = 1, \dots, k$*

$$\sup_{a \in \mathbb{R}, v \in \mathbb{S}^{n-1}} (\pi_v)_* \lambda_j(B_{\mathbb{R}}(a, \rho)) = \sup_{a, v} \lambda_j\{x | \langle v, x \rangle \in B_{\mathbb{R}}(a, \rho)\} \leq C_0 \rho^{\kappa_0}. \quad (3.4.3)$$

Then for all $\varsigma \in \mathbb{R}^n, \|\varsigma\| \in [\tau^{3/4}, \tau^{5/4}]$ we have

$$\left| \int \exp(2i\pi \langle \varsigma, x_1 \cdots x_k \rangle) d\lambda_1(x_1) \cdots d\lambda_k(x_k) \right| \leq \tau^{-\epsilon_2}. \quad (3.4.4)$$

Remark 3.4.5. *The proof is tedious, but the idea is clear. If the non concentration assumption is valid in some large range, then there is some place to rescale a little the measure and the result still holds. We only need to find some exponent ϵ_3 carefully.*

Proof. It is sufficient to prove the case that $\text{supp} \lambda_j \in [\tau^{-\epsilon_3}, \tau^{\epsilon_3}]^n$. Because we can divide each measure into $\lambda_j = \sum_{m \in (\mathbb{Z}/2\mathbb{Z})^n} \lambda_j^m$, where λ_j^m is the unique part of λ_j whose support is in the same orthant as m and we identify $(\mathbb{Z}/2\mathbb{Z})^n$ with $\{-1, 1\}^n \in \mathbb{R}^n$. Then

$$\begin{aligned} & \left| \int \exp(2i\pi \langle \varsigma, x_1 \cdots x_k \rangle) d\lambda_1^{m_1}(x_1) \cdots d\lambda_k^{m_k}(x_k) \right| \\ &= \left| \int \exp(2i\pi \langle \langle \varsigma m_1 \cdots m_k, x_1 \cdots x_k \rangle \rangle) d\lambda_1^{m_1}(m_1 x_1) \cdots d\lambda_k^{m_k}(m_k x_k) \right|. \end{aligned}$$

We know that the support of measure $(m_j)_* \lambda_j$ is in $[\tau^{-\epsilon_3}, \tau^{\epsilon_3}]^n$. Hence by the result of the case $\text{supp} \lambda_j$ positive, we have the result with a constant 2^{nk} .

Let ϵ as in Proposition 3.4.2 with $\kappa = \kappa_0/2$, and let $\epsilon_2 = \epsilon/4$.

Divide $[\tau^{\epsilon_3}, \tau^{-\epsilon_3}]^n$ into $[2^l, 2^{l+1}] = [2^{l_1}, 2^{l_1+1}] \times \cdots \times [2^{l_n}, 2^{l_n+1}]$ with $l \in \mathbb{Z}^n$. We rescale the measure in each interval to $[1/2, 1]^n$. Let $\lambda^l(A) = \lambda|_{[2^{l-1}, 2^l]}(2^l A)$. For $\rho \in [\tau^{3/2}, \tau^{\epsilon_2/2}]$ we have

$$(\pi_v)_* \lambda^l(B_{\mathbb{R}}(a, \rho)) \leq (\pi_{v'})_* \lambda(\|2^l v\| B_{\mathbb{R}}(a, \rho)), \quad (3.4.5)$$

where $v' = 2^l v / \|2^l v\|$. The inequality $\|2^l v\| \in [\tau^{-\epsilon_3}, \tau^{\epsilon_3}]$ implies that $\|2^l v\| \rho \in [\tau^{-3/2-\epsilon_3}, \tau^{-\epsilon_2/2+\epsilon_3}] \subset [\tau^{-2}, \tau^{-\epsilon_2/4}]$. Due to $\rho^{-1/2} \geq \tau^{\epsilon_2/4} \geq \tau^{\epsilon_3} \geq \|2^l v\|$ for $\rho \in [\tau^{-3/2}, \tau^{-\epsilon_2/2}]$, by (3.4.5) we have

$$(\pi_v)_* \lambda^l(B_{\mathbb{R}}(a, \rho)) \leq C_0 (\|2^l v\| \rho)^{\kappa_0} \leq \rho^{\kappa_0/2}, \quad (3.4.6)$$

for τ large enough depending on C_0 .

Summing up over $\|l\| \leq \epsilon_3 \log_2 \tau$, we have

$$\begin{aligned} & \left| \int \exp(2i\pi \langle \varsigma, x_1 \cdots x_k \rangle) d\lambda_1(x_1) \cdots d\lambda_k(x_k) \right| \\ & \leq \sum_{l^j \in \mathbb{Z}^n, \|l^j\| \leq \epsilon_3 \log_2 \tau} \left| \int \exp(2i\pi \langle \varsigma, x_1 \cdots x_k \rangle) d\lambda_1^{l^1}(2^{-l^1} x_1) \cdots d\lambda_k^{l^k}(2^{-l^k} x_k) \right| \\ & = \sum_{l^j \in \mathbb{Z}^n, \|l^j\| \leq \epsilon_3 \log_2 \tau} \left| \int \exp(2i\pi \langle \varsigma, 2^{l^1 + \cdots + l^k} y_1 \cdots y_k \rangle) d\lambda_1^{l^1}(y_1) \cdots d\lambda_k^{l^k}(y_k) \right|. \end{aligned}$$

Let $\tau_1 = \|\varsigma 2^{l^1 + \cdots + l^k}\|$, then $\tau_1 \in [\tau^{3/4 - k\epsilon_3}, \tau^{5/4 + k\epsilon_3}]$. Then we have $[\tau_1^{-1}, \tau_1^{-\epsilon_2}] \subset [\tau^{-3/2}, \tau^{-\epsilon_2/2}]$. The assumption of Proposition 3.4.2 is verified by (3.4.6) with τ replaced by τ_1 . Therefore

$$\begin{aligned} & \sum_{l^j} \left| \int \exp(2i\pi \langle \varsigma, 2^{l^1 + \cdots + l^k} y_1 \cdots y_k \rangle) d\lambda_1^{l^1}(y_1) \cdots d\lambda_k^{l^k}(y_k) \right| \leq \sum_{l^j \in \mathbb{Z}^n, \|l^j\| \leq \epsilon_3 \log_2 \tau} \|\varsigma 2^{l^1 + \cdots + l^k}\|^{-\epsilon_2} \\ & \leq (2\epsilon_3 \log_2 \tau)^{kn} (\tau^{3/4 - k\epsilon_3})^{-\epsilon} \leq \tau^{-\epsilon/4}, \end{aligned}$$

when τ is large enough depending on k, n, ϵ . The proof is complete. \square

Chapter 4

Finiteness of Small Eigenvalues of Geometrically Finite Rank one Locally Symmetric Manifolds

Let M be a geometrically finite rank one locally symmetric manifolds. We prove that the spectrum of the Laplace operator on M is finite in a small interval which is optimal.

4.1 Introduction

Let M be a complete Riemannian manifold. The Laplace operator Δ acts on the compactly supported smooth functions and admits an extension to an unbounded self-adjoint operator on $L^2(M)$. The study of the spectrum of the Laplace operator on geometrically finite hyperbolic manifolds was started by Lax and Phillips in [LP82a]. The motivation is to give an exponential error term in the asymptotic distribution of orbits for discrete subgroups of the group of isometries of \tilde{M} . They proved that on a geometrically finite real hyperbolic manifold of dimension n , the intersection of the interval $-(n-1)^2/4, 0]$ and the spectrum consists of at most finitely many eigenvalues. Geometrical finiteness means that the quotient manifold has a fundamental domain which is a finitely sided polyhedron.

For general cases (see [Ham04]), Hamenstädt proved that on geometrically finite rank one locally symmetric manifolds $\Gamma \backslash X$, where $X = \mathbb{H}_{\mathbb{F}}^n$ for $\mathbb{F} = \mathbb{R}, \mathbb{C}, \mathbb{H}$ or $\mathbb{H}_{\mathbb{F}}^n = \mathbb{H}_{\mathbb{O}}^2$, the intersection of the interval $[-\delta(X)^2/4 + \chi, 0]$ and the spectrum also consists of at most finitely many eigenvalues, where χ is any positive number and the exponent of growth $\delta(X)$ is $(n+1) \dim_{\mathbb{R}} \mathbb{F} - 2$. In this case, the applications to counting problems were given in [Kim15]. Inspired by the method in [LP82a], we generalize the result of Lax and Phillips to the case of rank one locally symmetric manifolds.

Theorem 4.1.1. *Let $M = \Gamma \backslash X$ be a geometrically finite rank one locally symmetric manifold. Then the intersection of the spectrum of the Laplace operator and the critical*

interval $(-\delta(X)^2/4, 0]$ consists of finitely many eigenvalues of finite multiplicities.

Remark 4.1.2. 1. If M has infinite volume, the result is optimal in the following sense. Under the same assumption as in Theorem 4.1.1, the interval $(-\infty, -\delta(X)^2/4]$ is contained in the essential spectrum of Δ . This may be proved as in [Bor07, Prop.7.2]. Together with our result, this implies that the essential spectrum of Δ is exactly $(-\infty, -\delta(X)^2/4]$ when the volume is infinite.

2. In the convex cocompact complex hyperbolic case, the meromorphic extension of the resolvent is already known from [MM87]. The finiteness of the spectrum in the critical interval is a consequence of the meromorphic extension, as in [Bor07, Prop.7.3]. The main idea is that an eigenvalue of the Laplace operator in the critical interval corresponds to a pole of the resolvent in $[0, \delta(X)/2)$.

3. In the convex cocompact quaternion hyperbolic case, the finiteness of the discrete spectrum is due to [BO00]. Later, they published a paper [BO08] to treat the geometrically finite rank one case. But they made an additional assumption for quaternion case and they didn't treat the Cayley hyperbolic case. Our result is new in these two cases.

Unless otherwise stated we assume that the manifolds, the Riemannian metrics and the functions are C^∞ smooth.

4.2 Estimates for the spectrum on Riemannian manifolds

4.2.1 Barta's trick

Here we will use Barta's trick, a way to estimate the bottom of the spectrum of the Laplace operator by one good function (see [RT15, Lem.3.3]). Recall that for every complete Riemannian manifold M , the bottom of the spectrum of the Laplace operator $\lambda_0(M)$ equals the infimum of the Rayleigh quotients $\mathcal{R}(f) = \frac{\int \|\nabla f\|^2 d\text{vol}}{\int f^2 d\text{vol}}$, over all nonzero smooth functions on M with compact support. Hence it is natural to consider the quantity $\int (\|\nabla f\|^2 - \lambda f^2) d\text{vol}$.

Lemma 4.2.1. Let u, φ be two real smooth functions on a Riemannian manifold M , the support of u being compact. We have

$$\int \|\nabla(\varphi u)\|^2 d\text{vol} = \int \varphi^2 \|\nabla u\|^2 d\text{vol} - \int u^2 \varphi \Delta \varphi d\text{vol}. \quad (4.2.1)$$

Please see [RT15, Lemma 3.3]

Proposition 4.2.2. Let M be a Riemannian manifold. Let f be a real smooth function on M with compact support. Assume that for some $\lambda > 0$ there exists a smooth function φ such that $\varphi > 0$ and $-\Delta \varphi \geq \lambda \varphi$. Then

$$\int \|\nabla f\|^2 d\text{vol} - \lambda \int f^2 d\text{vol} \geq \int \varphi^2 \|\nabla(f/\varphi)\|^2 d\text{vol}.$$

Proof. Applying Lemma 4.2.1 with $u = f/\varphi$ implies

$$\begin{aligned} \int \|\nabla f\|^2 d\text{vol} &= \int \varphi^2 \|\nabla(f/\varphi)\|^2 d\text{vol} - \int (f/\varphi)^2 \varphi \Delta \varphi d\text{vol} \\ &\geq \int \varphi^2 \|\nabla(f/\varphi)\|^2 d\text{vol} + \lambda \int f^2 d\text{vol}. \end{aligned}$$

The proof is complete. □

Remark 4.2.3. Compared with [RT15, Proposition 3.2], we keep the last term $\int \varphi^2 \|\nabla(f/\varphi)\|^2$. This term is important and will be exploited in Section 4.2.2.

The following proposition says that for a Riemannian manifold with quasi-warped product structure, the derivative of the volume density along the vertical geodesic can give us a good control of the bottom of the spectrum.

Proposition 4.2.4. Let $M = L \times \mathbb{R}$ be a Riemannian manifold with the metric given by

$$g = dt^2 + g(x, t), \tag{4.2.2}$$

where $g(x, t)$ is a metric on $L \times \{t\}$. We call this a quasi-warped product metric.

The Riemannian volume element can be written as $\omega = dt \times h(x, t)dx$, where dx is the volume element on $L \times \{0\}$ and h is a density function from $L \times \mathbb{R}$ to $\mathbb{R}_{\geq 0}$. Assume that for some $\lambda > 0$ and a nonnegative function c on \mathbb{R} , we have

$$\partial_t h \geq 2\lambda(1 - c(t))h. \tag{4.2.3}$$

Then for $f \in C_c^\infty(M)$, we have

$$\int \|\nabla f\|^2 d\text{vol} - \lambda^2 \int (1 - 2c(t))f^2 d\text{vol} \geq \int e^{-2\lambda t} \|\nabla(fe^{\lambda t})\|^2 d\text{vol}. \tag{4.2.4}$$

Remark 4.2.5. The terminology quasi-warped product is a generalization of warped product in Riemannian geometry. Let $(M_1, g_1), (M_2, g_2)$ be two Riemannian manifolds. The warped product $M_1 \times_f M_2$ is the product manifold $M_1 \times M_2$ equipped with the warped product metric given by

$$g = g_1 + fg_2, \text{ where } f \text{ is a positive function on } M_1.$$

Proof. Let $\varphi(x, t) = e^{-\lambda t}$. We will prove that $-\Delta\varphi \geq \lambda^2(1 - 2c(t))\varphi$ on $L \times \mathbb{R}$. It is sufficient to prove this inequality locally.

Take a local chart on L by $\phi : \mathbb{R}^n \supset U \rightarrow L$. Then $\tilde{\phi} = (\phi, Id) : U \times \mathbb{R} \rightarrow L \times \mathbb{R}$ is a local chart on M . We write elements in $U \times \mathbb{R}$ by $(x_1, \dots, x_n, x_{n+1})$ with $x_{n+1} = t$. By the definition of Δ , we have

$$\Delta\varphi = \frac{1}{\sqrt{|\det(g)|}} \sum_{1 \leq i, j \leq n+1} \partial_i(\sqrt{|\det(g)|}g^{ij}\partial_j\varphi),$$

where g^{ij} is the inverse matrix of the matrix of metric. By definition, we have

$$h(x, t) = \sqrt{|\det(g_{x,t})|}.$$

Since φ is a function only depending on t and the formula of metric implies $g^{tj} = 0$ when $j \neq t$, we have

$$\Delta\varphi = \frac{1}{\sqrt{|\det(g)|}} \partial_t(\sqrt{|\det(g)|} \partial_t\varphi) = \frac{1}{h} \partial_t(h \partial_t\varphi) = \partial_{tt}\varphi + \frac{\partial_t h \partial_t\varphi}{h}. \quad (4.2.5)$$

Due to $\partial_t h \geq 2\lambda(1 - c(t))h$ and $\partial_t\varphi = -\lambda\varphi < 0$, we have

$$-\Delta\varphi \geq -\partial_{tt}\varphi - 2\lambda(1 - c(t))\partial_t\varphi = \lambda^2(1 - 2c(t))\varphi.$$

Applying Lemma 4.2.1 with this φ and $u = f/\varphi$, we obtain the result. \square

4.2.2 The Lax-Phillips inequality

Compared with [Ham04], where she fully used the information from the spectrum of the Laplace operator on each component and the negative curvature, the key new input in our article is the observation that the particular form of the Laplace operator gives us more information. A version on \mathbb{R} is as follows:

Proposition 4.2.6. *Let $\Delta = \partial_{tt}$ be the standard Laplace operator on \mathbb{R} . For every $C > 0$, the positive spectrum of $\Delta + Ce^{-|t|}$ on $L^2(\mathbb{R})$ is finite.*

This is a classical result in spectral theory (see [Dav96, Thm 8.5.1] for a similar version, which says that the positive spectrum is at most countable). In Davies' book, the result comes from a compact perturbation. Another way to prove this type of result is to use the following observation, because the exponential function $e^{-|t|}$ has a very rapid decay. We will give a proof of Proposition 4.2.6 in Section 4.3.

Lemma 4.2.7. *For every $C_0 > 0$, there exist a compact interval U and $C_1 > 0$ such that for every real smooth, compactly supported function f on \mathbb{R} we have*

$$\int \|\nabla f\|^2 + C_1 \int_U f^2 \geq C_0 \int e^{-|t|} f(t)^2 dt. \quad (4.2.6)$$

We call (4.2.6) the Lax-Phillips inequality (LPI). This is a consequence of the following elementary lemma.

Lemma 4.2.8. *If g is a real smooth bounded function on \mathbb{R} , then for all r in $\mathbb{R}_{\geq 0}$ we have*

$$\int_r^\infty g(t)^2 e^{-t} dt \leq 2 \left(g(r)^2 e^{-r} + \int_r^\infty g'(t)^2 (1 + t - r) e^{-t} dt \right). \quad (4.2.7)$$

Proof. By the Newton-Leibniz formula,

$$g(t) = g(r) + \int_r^t g'(s) ds. \quad (4.2.8)$$

By the Cauchy-Schwarz inequality,

$$g(t)^2 \leq 2g(r)^2 + 2 \left(\int_r^t g'(s) ds \right)^2 \leq 2g(r)^2 + 2(t-r) \int_r^t g'(s)^2 ds. \quad (4.2.9)$$

Combining (4.2.8) and (4.2.9), we have

$$\begin{aligned} \int_r^\infty g(t)^2 e^{-t} dt &\leq \int_r^\infty \left(2g(r)^2 + 2(t-r) \int_r^t g'(s)^2 ds \right) e^{-t} dt \\ &= 2 \left(g(r)^2 e^{-r} + \int_r^\infty g'(s)^2 (1+s-r) e^{-s} ds \right). \end{aligned}$$

The proof is complete. \square

Proof of LPI (Lemma 4.2.7). We divide \mathbb{R} into $\mathbb{R}_{\geq 0}$ and $\mathbb{R}_{< 0}$. By symmetry, we only need to prove the inequality on $\mathbb{R}_{\geq 0}$. Let T be a large number such that $e^T \geq C_0$. Then by monotonicity, we have $(1+t-T)e^{-t} \leq 1/C_0$ for all $t \geq T$. Integrating (4.2.7) on $[T, T+1]$ with $g = f$, we have

$$\int_{T+1}^\infty f(t)^2 e^{-t} dt \leq \int_T^{T+1} f(t)^2 e^{-t} dt + \frac{1}{C_0} \int_T^\infty f'(t)^2 dt.$$

The result follows by taking $U = [0, T+1]$ and $C_1 = 2C_0$. \square

This idea is already utilized in Theorem 3.3 of [LP82a]. The error term $\int e^{-|x|} f^2$ is not artificial, which will appear naturally when we estimate the spectrum on the complement of the convex core.

Corollary 4.2.9. *Under the same assumption as in Proposition 4.2.4, suppose that $c(t) = e^{-t}$. If there exists $C_0 > 0$ such that $e^{2\lambda t}/C_0 \leq h(t) \leq C_0 e^{2\lambda t}$ for $t \in \mathbb{R}$, then for every $C > 0$, there exist a compact interval I and a positive constant C_1 such that the following holds. For every smooth, compactly supported function f on $L \times \mathbb{R}$ and every compact subset K of L , we have*

$$\int (\|\nabla f\|^2 - \lambda^2 f^2) dvol + C_1 \int_{K \times I} f^2 dvol \geq C \int_{K \times \mathbb{R}} e^{-|t|} f^2 dvol.$$

Proof. Let $f_1 = f e^{\lambda t}$. Due to the quasi-warped product structure of the Riemannian metric,

$$\|\nabla f_1\|^2 = \|\nabla' f_1\|^2 + \partial_t f_1^2 \geq \partial_t f_1^2, \quad (4.2.10)$$

where ∇' is the gradient on $L \times \{t\}$. Substituting (4.2.10) into LPI (Lemma 4.2.7), with the constant $C_2 = C_0^2(C + 2\lambda^2)$, implies that there exist I compact, $C_1 > 0$ such that

$$\int_{\mathbb{R}} \|\nabla f_1(x, t)\|^2 dt + C_1 \int_I f_1(x, t)^2 dt \geq C_2 \int_{\mathbb{R}} e^{-|t|} f_1^2(x, t) dt, \text{ everywhere on } L. \quad (4.2.11)$$

Integrating (4.2.11) over K with respect to dx , we get

$$\int_{K \times \mathbb{R}} \|\nabla f_1\|^2 dx dt + C_1 \int_{K \times I} f_1^2 dx dt \geq (C + 2\lambda^2) \int_{K \times \mathbb{R}} e^{-|t|} f_1^2 dx dt.$$

Using $dvol = h(x, t) dt dx$ and $e^{2\lambda t}/C_0 \leq h(t) \leq C_0 e^{2\lambda t}$, we obtain

$$\int_{K \times \mathbb{R}} \|\nabla f_1\|^2 e^{-2\lambda t} dvol + C_1 \int_{K \times I} f^2 dvol \geq (C + 2\lambda^2) \int_{K \times \mathbb{R}} e^{-|t|} f^2 dvol.$$

This formula together with Proposition 4.2.4 implies the result. \square

4.3 Finiteness of the spectrum

Proposition 4.3.1. *Let M be a complete Riemannian manifold. If for some smooth bounded function $c(x) \geq 0$, there exists a compact subset U with smooth boundary and $\epsilon, C_U > 0$ such that the following holds. For any compact subset V there is $\epsilon_V > 0$ such that for all complex valued function $f \in C_c^\infty(M)$ we have*

$$\int (\|\nabla f\|^2 - c(x)|f|^2) dvol + C_U \int_U |f|^2 dvol \geq \epsilon \int_U \|\nabla f\|^2 dvol + \epsilon_V \int_V |f|^2 dvol. \quad (4.3.1)$$

Then the positive spectrum of the operator $T = \Delta + c(x)$ consists of at most finitely many eigenvalues of finite multiplicities.

Proof of Proposition 4.2.6 from Proposition 4.3.1. From Lemma 4.2.7, we have

$$\int \left(\|\nabla f\|^2 - \frac{C_0}{4} e^{-|t|} f^2 \right) dt + \frac{1}{2} C_1 \int_U f^2 \geq \frac{1}{2} \int \|\nabla f\|^2 + \frac{C_0}{4} \int e^{-|t|} f(t)^2 dt.$$

Take $C_0 = 4C$ and $c(x) = Ce^{-|x|}$. Then $c(x)$ satisfies (4.3.1). Therefore, Proposition 4.2.6 follows from Proposition 4.3.1. \square

This is a "baby case" of the main result of this manuscript, whose proof will also follow from Proposition 4.3.1. We will establish (4.3.1) for geometrically finite rank one locally symmetric manifolds in Section 4.5.

It remains to prove Proposition 4.3.1. Recall some results in spectral theory:

Definition 4.3.2. *Let H be a complex Hilbert space, T be a linear operator with the domain of definition D , which is dense in H . We call T self-adjoint if its adjoint T^* equals T on D and the domain of definition of T^* satisfies $D^* = D$, where D^* is defined as*

$$D^* = \{f \in H \mid \exists C_f > 0 \text{ such that } \forall g \in D, |(f, Tg)| \leq C_f |g|_H\}.$$

We call T positive if for every nonzero f in D , we have $(Tf, f) > 0$.

Proposition 4.3.3. *Let M be a complete Riemannian manifold. Define the space $H_0^1(M)$ as the completion of $C_c^\infty(M)$ under the norm*

$$\|f\|_{H^1} = \|f\|_{L^2} + \|\nabla f\|_{L^2}.$$

Let the domain of the Laplace operator be

$$D = \{f \in H_0^1(M) \mid \Delta f \in L^2(M)\}.$$

Then $\Delta : D \subset L^2 \rightarrow L^2$ is a self-adjoint operator.

(See [Tay10b, Sec.8.2] for more details.)

Proposition 4.3.4. *If T is a self-adjoint operator on a Hilbert space H , then there is a decomposition*

$$H = H_+ \oplus H_- \oplus \ker T$$

such that T preserves the decomposition, T is self-adjoint on H_+ , H_- and T is positive, negative on H_+ , H_- , respectively.

If there exists $\lambda > 0$ such that $\lambda Id - T$ is positive, then H_+ in the above decomposition is actually in D , the domain of definition.

(See [Lax02, 32 Thm1] for more details.) For $f \in C_c^\infty(M)$, define

$$K(f) = C_U \int_U |f|^2 dvol, \quad E(f) = \int (\|\nabla f\|^2 - c(x)|f|^2) dvol,$$

and $F(f) = E(f) + K(f)$. Inequality (4.3.1) implies that F is a positive definite quadratic form on $C_c^\infty(M)$. We define a Hilbert space \mathcal{H} as the completion of $C_c^\infty(M)$ with respect to the norm $|\cdot|_F$, written as $\mathcal{H} = \overline{C_c^\infty(M)}_F$.

For an open subset V of M , we define $H^1(V)$ as the completion of $C^\infty(V)$ with respect to the norm $\|f\|_{H^1(V)}^2 = \int_V |f|^2 + \int_V \|\nabla f\|^2$.

Proposition 4.3.5. *With the same assumption as in Proposition 4.3.1, there exists a subspace \mathcal{H}_1 of finite codimension in \mathcal{H} , on which E is positive definite.*

Proof. Because of inequality (4.3.1), we can define a bounded restriction map from \mathcal{H} to $H^1(U)$ and compose it with the injection ι from $H^1(U)$ to $L^2(U)$, that is

$$S : \mathcal{H} \rightarrow H^1(U) \xrightarrow{\iota} L^2(U).$$

Let S^* be the adjoint of S , then $S^*S : \mathcal{H} \rightarrow \mathcal{H}$ is a self-adjoint operator. For $f \in \mathcal{H}$, we have

$$F(S^*Sf, f) = \int_U |f|^2 dvol = \frac{1}{C_U} K(f).$$

By the Rellich theorem [Tay10a, Chapter 4, Proposition 4.4] and the smoothness of the boundary of U , the injection ι is compact. Therefore S^*S is a compact self-adjoint

operator. The set of eigenvalues has a unique accumulation point 0. In a subspace of finite codimension in \mathcal{H} , we have $|K(f)| = C_U |F(S^*Sf, f)| \leq \frac{1}{2}|F(f)|$. Therefore

$$E(f) = F(f) - K(f) \geq \frac{1}{2}F(f).$$

The proof is complete. \square

Proof of Proposition 4.3.1. By definition,

$$\|f\|_F \leq \|f\|_{L^2} + \|\nabla f\|_{L^2} = \|f\|_{H^1}.$$

Thus we can extend the injection $C_c^\infty(M) \rightarrow \mathcal{H}$ to an application $j : H_0^1(M) \rightarrow \mathcal{H}$. By (4.3.1), for any compact subset V of M , we have $F(f) \geq \epsilon_V \int_V |f|^2$ for f in $C_c^\infty(M)$. Therefore j is injective and can be seen as an inclusion.

Since Δ is self-adjoint and c is bounded, the operator $T = \Delta + c(x)$ is also self-adjoint. Since $(\|c\|_\infty + 1)Id - T$ is positive, by using Proposition 4.3.4 with T and $H = L^2(M)$, we have $H_+ \subset D \subset H_0^1(M) \subset \mathcal{H}$. For a nonzero element u in H_+ , we have

$$E(u) = \int_M (\|\nabla u\|^2 - c(x)|u|^2) dvol = \int_M -(Tu)\bar{u} dvol = -(Tu, u) < 0.$$

Proposition 4.3.5 implies $\mathcal{H}_1 \cap H_+ = \{0\}$, therefore H_+ is of finite dimension. Due to Proposition 4.3.4, the operator T is self-adjoint on H_+ , hence the positive spectrum of T is finite and each element is an eigenvalue of finite multiplicity. \square

4.4 Rank one locally symmetric manifolds

We study the spectrum on cusps and complement of convex sets in this section, which will be used in Section 4.5 to obtain global result.

4.4.1 Real rank one globally symmetric spaces

Real rank one globally symmetric spaces are usually classified into four families: $\mathbb{H}_{\mathbb{R}}^n = SO_o(1, n)/SO(n)$, $\mathbb{H}_{\mathbb{C}}^n = PU(1, n)/U(n)$, $\mathbb{H}_{\mathbb{H}}^n = PSp(1, n)/(Sp(1) \times Sp(n))$ and an exceptional one, the Cayley hyperbolic plane $\mathbb{H}_{\mathbb{O}}^2 = F_4/Spin(9)$. For the first three types, we have a uniform treatment by projective models, in which the metric and the curvature can be computed explicitly (see for example [Mos73], [Pan89], [Qui06]). But the Cayley hyperbolic plane needs different model.

The space $\mathbb{H}_{\mathbb{F}}^n$ is a Riemannian manifold with pinched curvature between -1 and -4 . The ideal boundary of the symmetric space $\mathbb{H}_{\mathbb{F}}^n$, denoted by $\partial\mathbb{H}_{\mathbb{F}}^n$, is the set of equivalent classes of geodesic rays. From now on, abbreviate $\mathbb{H}_{\mathbb{F}}^n$, $\partial\mathbb{H}_{\mathbb{F}}^n$, $\mathbb{H}_{\mathbb{F}}^n \cup \partial\mathbb{H}_{\mathbb{F}}^n$ to X , X_I , X_c . Equip X_c with the topology such that X_c becomes a compact manifold with boundary. The space X is homeomorphic to an open ball of dimension $n \dim_{\mathbb{R}} \mathbb{F}$, and X_c

is homeomorphic to a closed ball of the same dimension. Let ξ be a point in X_I , and let x, y be two points in X . We define the Busemann function by

$$b_\xi(x, y) = \lim_{t \rightarrow +\infty} (d(x, \gamma(t)) - d(y, \gamma(t))),$$

where d is the distance induced by the Riemannian metric, and $\gamma(t)$ is a geodesic ray asymptotic to ξ . Let o be a fixed reference point in X . The level sets of $b_\xi(\cdot, o)$ are called horospheres based at ξ . A horoball based at ξ is a set $b_\xi(\cdot, o)^{-1}(-\infty, r]$.

We introduce the horospherical model for X following [Pan89, Section 9]. Fix a point ∞ of X_I . Let $G = KAN$ be the Iwasawa decomposition with A and N fixing ∞ , and K , a maximal compact subgroup, fixing o . The group A is isomorphic to \mathbb{R} and N is a simply connected nilpotent Lie group. Let $M = K \cap \text{Stab}_\infty(G)$. Here M is also the maximal subgroup of K which commutes with A . Let \mathcal{N} be the Lie algebra of N . The group A normalizes N , and the conjugation action of A induces an automorphism on \mathcal{N} . We make a choice of a particular generator of A such that \mathcal{N} admits a decomposition

$$\mathcal{N} = V^1 \oplus V^2,$$

where V^j equals to $\text{Ker}(\text{Ad}(a_t) - e^{jt})$ for $t \neq 0$ and a_t is an element in A . Moreover, V^2 is the centre of \mathcal{N} and $[V^1, V^1] = V^2$. We can identify V^1, V^2 with $\mathbb{F}^{n-1}, \mathfrak{S}\mathbb{F}$, and the Lie algebra structure is given by

$$[(x_1, \dots, x_{n-1}), (y_1, \dots, y_{n-1})] = \mathfrak{S} \sum_{j=1}^{j=n-1} \bar{x}_j y_j.$$

Starting from $V^1 \oplus V^2$, we obtain two left invariant distributions W^1, W^2 on N . Let α be the endomorphism on \mathcal{N} , which is the differential of $\text{Ad}(a_t)$ at $t = 0$, mapping vector v in V^j to jv . Let e^α be the induced automorphism on N . Let $c(t)$ be the geodesic ray starting from o to ∞ , that is $c(t) = a_t o$. We have a diffeomorphism from $N \times A$ to X given by $(\nu, t) \rightarrow \nu \cdot c(t)$, and the action of A reads as $a_t(\nu, s) = (e^{t\alpha}\nu, t + s)$. Let $m = (n - 1) \dim_{\mathbb{R}} \mathbb{F}$ and $q = \dim_{\mathbb{R}} \mathbb{F} - 1$. The hyperbolic metric on X can be written as

$$g = g_t \oplus dt^2, \tag{4.4.1}$$

where these left invariant metrics g_t on N have, under the distribution W^1, W^2 , a matrix of the form

$$\begin{pmatrix} e^{2t} Id_m & 0 \\ 0 & e^{4t} Id_q \end{pmatrix}.$$

We also need to calculate the Riemann curvature tensor. Let \mathbf{n} be the unit tangent vector at o to the geodesic $c(t)$. If $v \in V^1$, then \mathbf{n}, v are tangent to a totally real 2-plane of curvature -1 . If $v \in V^2$, then \mathbf{n}, v are tangent to a \mathbb{F} -line of curvature -4 . Therefore

$$R(\mathbf{n}, v_j, \mathbf{n}) = -j^2 v_j \text{ for } v_j \in V^j \quad j = 1, 2. \tag{4.4.2}$$

We introduce a half space model. As in the horospherical model, with o in X and ∞ in X_I fixed, let $y = e^{-t}$. The coordinate map is replaced by a map from $N \times \mathbb{R}_{>0}$ to

X , that is $(\nu, y) \rightarrow \nu \cdot c(\log y)$. We also give a differential structure to X_c . Locally the compactification is obtained by adding the hyperplane $\{y = 0\}$. Locally, this also gives a differential structure to the manifold with boundary. If we fix another point in X_I , and give a differential structure by the same procedure, then by the compatibility of the differential structures, we have a differential structure on X_c .

4.4.2 Discrete subgroups

Let G be the group of isometries of the symmetric space X , and let Γ be a discrete subgroup of G . The group Γ may have torsion. In the geometrically finite case, the group Γ is always finitely generated [Bow95, Prop5.5.1]. We can use a result of Selberg [Sel60], passing to a normal subgroup Γ' which is of finite index in Γ and has no torsion. Since the spectrum of the Laplace operator on a finite covering space contains the spectrum of the original one, we suppose that Γ is without torsion.

Fix a point x in X , and let $\overline{\Gamma \cdot x}$ be the closure of the orbit $\Gamma \cdot x$ in X_c . The limit set of the group Γ is defined by

$$\Lambda(\Gamma) = X_I \cap \overline{\Gamma \cdot x}.$$

This definition of the limit set is independent of the choice of x . Let $\Omega = X_I - \Lambda(\Gamma)$. Since the actions of Γ on $X \cup \Omega$ and X are properly discontinuous [Bow95, Prop3.2.6], we set

$$M_c(\Gamma) = \Gamma \backslash (X \cup \Omega), \quad M(\Gamma) = \Gamma \backslash X.$$

These are a manifold with boundary and a rank one locally symmetric manifold, respectively.

In order to study the spectrum, we define an energy form, which will be used throughout the paper. Let

$$E(f) = \int_{M(\Gamma)} (\|\nabla f\|^2 - \ell^2 f^2) dvol \tag{4.4.3}$$

for $f \in C_c^\infty(M(\Gamma))$, where Γ is a discrete subgroup of G and $\ell = \delta(X)/2 = ((n+1) \dim_{\mathbb{R}} \mathbb{F} - 2)/2$ is half the exponent of growth.

4.4.3 Cusps

Definition 4.4.1 (Parabolic subgroup). *Let Π be a subgroup of G . We call Π parabolic if the set of fixed points of Π in X_c consists of a unique point ξ in X_I , and Π preserves setwise every horosphere based at ξ .*

Let Π be a discrete parabolic subgroup with fixed point ∞ , a point in X_I . We use the horospherical model $N \times A \rightarrow X$ introduced in Section 4.4.1. Then Π is a subgroup of $M \rtimes N$. Recall that M is the subgroup of K which preserves setwise every horosphere based at ∞ and the metric g_t on N . The part N of $M \rtimes N$ acts as translation on N and M acts as rotation. Let $\Pi \backslash N$ be the quotient space of N under the action of Π . The quotient manifold satisfies

$$M(\Pi) \simeq (\Pi \backslash N) \times \mathbb{R} \text{ as a topologic space.}$$

We will apply Proposition 4.2.4 to $M(\Pi)$. Since Π preserves the metric g_t , we have a quotient metric on $\Pi \backslash N$. The formula (4.4.1) implies that the metric on $(\Pi \backslash N) \times \mathbb{R}$ is a quasi-warped product metric, and the volume element is equal to $e^{2\ell t} dt d\eta$, where $d\eta$ is the volume element on $(\Pi \backslash N) \times \{0\}$. So the function h in Proposition 4.2.4 equals $e^{2\ell t}$, and h satisfies (4.2.3) with $\lambda = \ell$ and $c(t) = 0$. Applying Proposition 4.2.4 and Corollary 4.2.9, we have

Lemma 4.4.2. *Let E be as in (4.4.3). For a function $f \in C_c^\infty((\Pi \backslash N) \times \mathbb{R})$, we have*

$$E(f) = \int \|\nabla(e^{\ell t} f)\|^2 e^{-2\ell t} d\text{vol}. \quad (4.4.4)$$

Given $C > 0$, there exist a compact interval $I \subset \mathbb{R}$ and a constant $C_1 > 0$ such that for all compact set K in $\Pi \backslash N$ we have

$$E(f) + C_1 \int_{K \times I} f^2 d\text{vol} \geq C \int_{K \times \mathbb{R}_{\geq 0}} e^{-t} f^2 d\text{vol}. \quad (4.4.5)$$

4.4.4 Convex subsets and the normal exponential map

We need a lemma which says that in the normal exponential coordinate, the Riemannian manifold has a quasi-warped product metric. This lemma is similar to the Gauss lemma, where the hypersurface S degenerates to a point.

Lemma 4.4.3. *Let S be a smooth hypersurface of a Riemannian manifold M . Let $\exp^\perp : S \times \mathbb{R}_{\geq 0} \rightarrow M$ be the normal exponential map given by $\exp^\perp(x, t) = \exp_x(\mathbf{tn}(x))$. Assume \exp^\perp is an embedding. Then for every x in S and $s \geq 0$, the curve $\gamma_x : t \rightarrow \exp_x(\mathbf{tn}(x))$ is normal to the hypersurfaces $\exp^\perp(S \times \{s\})$.*

Definition 4.4.4. *Let M be a complete Riemannian manifold, and let D be a closed subset of M . We call D geodesically convex if the preimage \tilde{D} of D in the universal cover \tilde{M} is convex, that is for any two points x, y in \tilde{D} there exists a unique minimizing geodesic contained in \tilde{D} which connects x, y .*

Let M be a rank one locally symmetric manifold such that its universal cover has exponent of growth 2ℓ . Let D be a geodesically convex closed subset of M with non empty interior and with smooth boundary. Let $S = \partial D$, and let $\exp^\perp : S \times \mathbb{R}_{\geq 0}$ be the outer normal exponential map given by $\exp^\perp(x, t) = \exp_x(\mathbf{tn}(x))$. Assume that \exp^\perp is a diffeomorphism from $S \times \mathbb{R}_{\geq 0}$ to $M - \overset{\circ}{D}$. By Lemma 4.4.3, the metric can be written as in (4.2.2). Let h be the density function defined as in Proposition 4.2.4.

Lemma 4.4.5. *With the above assumption, if we have an upper bound on the second fundamental form on S , then there exists $C_1 > 0$ depending on the bound such that the density function h satisfies the following inequalities for every x in S , and every $t \geq 0$:*

$$\partial_t h(x, t) \geq 2\ell(\tanh t)h(x, t), \quad e^{2\ell t}/C_1 \leq h(x, t) \leq C_1 e^{2\ell t}. \quad (4.4.6)$$

Remark 4.4.6. *The first inequality in (4.4.6) has already been used in [Ham04, Lemma 2.3] without proof. For completeness, a proof is given here.*

Remark 4.4.7. *This lemma is a consequence of the negative curvature and the convexity. We do not have a better inequality $\partial_t h(t) \geq 2\ell h(t)$. For example, in \mathbb{H}^2 , let D be the r -neighbourhood of a geodesic, then we can compute explicitly that $h(x, t) = \cosh(t + r)/\cosh r$.*

The proofs of these two lemmas, which use the standard computations for Jacobi fields, will be given later. By Lemma 4.4.5, we have

$$\partial_t h \geq 2\ell(\tanh t)h \geq 2\ell(1 - 2e^{-t})h. \quad (4.4.7)$$

Using Proposition 4.2.4 and Corollary 4.2.9 with $S \times \mathbb{R}_{\geq 0}$, (Proposition 4.2.4 deals with manifolds $L \times \mathbb{R}$, but the proof of $L \times \mathbb{R}_{\geq 0}$ is exactly the same) we have

Lemma 4.4.8. *Let E be as in (4.4.3). With the same assumptions as in Lemma 4.4.5, for a function $f \in C_c^\infty(\exp^\perp(S \times \mathbb{R}_{\geq 0}))$, we have*

$$E(f) \geq \int (\|\nabla(e^{lt})f\|^2 e^{-2lt} - 4\ell^2 e^{-t} f^2) d\text{vol}. \quad (4.4.8)$$

Given $C > 0$, there exist a compact set $I \subset \mathbb{R}_{\geq 0}$ and a constant $C_1 > 0$ such that for all compact set K in S

$$E(f) + C_1 \int_{\exp^\perp(K \times I)} f^2 d\text{vol} \geq C \int_{\exp^\perp(K \times \mathbb{R}_{\geq 0})} e^{-t} f^2 d\text{vol}. \quad (4.4.9)$$

It remains to prove Lemma 4.4.3 and Lemma 4.4.5.

Proof of Lemma 4.4.5. The main idea is to compute the density function h by the second fundamental form. The second fundamental form of S at x is defined to be the symmetric form $\text{II}_S : T_x S \times T_x S \rightarrow \mathbb{R}$,

$$\text{II}_S(v, u) = g(D_v \mathbf{n}(x), u),$$

where v, u are two vectors in the tangent space $T_x S$. By the convexity of S , the second fundamental form II_S is positive definite at every x in S .

Fix a point x in S . By (4.4.2), starting from the outer unit normal vector $\mathbf{n}(x)$, we can find an orthonormal basis $\{\mathbf{n}(x), (Y_j)_{1 \leq j \leq m}, (Y_k)_{m+1 \leq k \leq m+q}\}$ of $T_x M$ such that

$$R(\mathbf{n}(x), Y_j, \mathbf{n}(x)) = -Y_j, \quad R(\mathbf{n}(x), Y_k, \mathbf{n}(x)) = -4Y_k, \quad \text{where } m = (n-1) \dim_{\mathbb{R}} \mathbb{F}, q = \dim_{\mathbb{R}} \mathbb{F} - 1.$$

Let B be the matrix representation of II_S with the basis $\{(Y_j)_{1 \leq j \leq m}, (Y_k)_{m+1 \leq k \leq m+q}\}$ of $T_x S$.

Lemma 4.4.9. *With the same assumption as in Lemma 4.4.5, we have*

$$h(x, t) = \det \left(\begin{pmatrix} \cosh t Id_m & 0 \\ 0 & \cosh 2t Id_q \end{pmatrix} + B \begin{pmatrix} \sinh t Id_m & 0 \\ 0 & \frac{1}{2} \sinh 2t Id_q \end{pmatrix} \right). \quad (4.4.10)$$

Proof. There exists a local chart on S defined by (ϕ, U) $\phi : \mathbb{R}^{m+q} \supset U \rightarrow S$ such that $\phi(0) = x$ and $\frac{\partial}{\partial u_i} \phi(0) = Y_i$. This particular choice of local chart implies that du is the volume element at x . Let

$$\tilde{\phi}(u, t) = \exp_{\phi(u)}(t\mathbf{n}(\phi(u)))$$

and $\tilde{U} = U \times \mathbb{R}_{\geq 0}$. Then $(\tilde{\phi}, \tilde{U})$ is a local chart of M . For every fixed u , the curve $t \rightarrow \tilde{\phi}(u, t)$ is a geodesic starting from $\phi(u)$ with tangent vector $\mathbf{n}(\phi(u))$.

Fix all u_w to 0 except $w = i$. Then the map $H : \mathbb{R}^2 \rightarrow M$ defined by $(u_i, t) \mapsto \tilde{\phi}(u_i, t)$, is a variation of geodesic. Let $J_i(t)$ be the Jacobi field defined by $J_i(t) = \frac{\partial}{\partial u_i} H(0, t)$. The volume element, in a local chart, can be written as $\sqrt{\det\left(g\left(\frac{\partial}{\partial x_i}, \frac{\partial}{\partial x_w}\right)\right)} dx$. In our case, the volume element at $\tilde{\phi}(0, t)$ is $\sqrt{\det(g(J_i(t), J_w(t)))} du dt$. Therefore by definition, we have $h(x, t) = \sqrt{\det(g(J_i(t), J_w(t)))}$.

Let $Y_i(t), \mathbf{n}(t)$ be the images of Y_i and $\mathbf{n}(x)$ under the parallel transport along the geodesic $t \mapsto \tilde{\phi}(0, t)$ with $t \geq 0$. They also form an orthonormal basis. By Lemma 4.4.3, the vectors $J_i(t)$ are orthogonal to $\mathbf{n}(t)$. We decompose $J_i(t)$ with respect to $Y_i(t)$, that is $J_i(t) = \sum_w a_{iw}(t) Y_w(t)$, and write $A(t) = (a_{iw}(t))_{1 \leq i, w \leq m+q}$. Then $A(0) = Id_{m+q}$ and the matrix $A'(0)$ equals B , the matrix representation of the second fundamental form. This is because by Schwarz's theorem, we have

$$a'_{iw}(0) = \partial_t g(J_i(t), Y_w(t))|_{t=0} = g\left(\frac{D}{dt} J_i(0), Y_w\right) = g\left(D_{\frac{\partial}{\partial u_i}} \frac{\partial}{\partial t}, Y_w\right) = g(D_{Y_i} \mathbf{n}(x), Y_w).$$

Because J_i are Jacobi fields, they satisfy the Jacobi equation:

$$\frac{D^2}{dt^2} J_i(t) + R(\mathbf{n}(t), J_i(t)) \mathbf{n}(t) = 0. \quad (4.4.11)$$

The map $R(\mathbf{n}(t), \cdot) \mathbf{n}(t)$ is a linear map on the orthogonal complement of $\mathbf{n}(t)$ in the tangent space $T_{\tilde{\phi}(0, t)} M$. By [Hel79, IV, Thm1.3], in locally symmetric spaces the curvature tensor R is invariant under parallel transport. Hence in our choice of the orthonormal basis $\{Y_i(t)\}_{1 \leq i \leq m+q}$, the linear map $R(\mathbf{n}(t), \cdot) \mathbf{n}(t)$ can be represented by the matrix $\text{diag}\{Id_m, 4Id_q\}$. From (4.4.11), we have

$$A''(t) = A(t) \begin{pmatrix} Id_m & 0 \\ 0 & 4Id_q \end{pmatrix}.$$

The solution is determined by the initial conditions. Due to $A(0) = Id$ and $A'(0) = B$, it is

$$A(t) = \begin{pmatrix} \cosh t Id_m & 0 \\ 0 & \cosh 2t Id_q \end{pmatrix} + B \begin{pmatrix} \sinh t Id_m & 0 \\ 0 & \frac{1}{2} \sinh 2t Id_q \end{pmatrix}.$$

Hence $h(x, t) = \det(g(J_i(t), J_w(t)))^{1/2} = \det(A(t))$, which implies the result. \square

For computing the determinant, we need a lemma.

Lemma 4.4.10. *Let D be a diagonal matrix with nonnegative entries, let B be a symmetric positive semidefinite matrix, and let $\begin{pmatrix} B_{11} & B_{12} \\ B_{21} & B_{22} \end{pmatrix}$ be a block partition of B such that B_{11}, B_{22} are square matrices. Then for all $\lambda_1, \lambda_2 > 0$ we have*

$$\det \left(D + \begin{pmatrix} \lambda_1 B_{11} & \lambda_2 B_{12} \\ \lambda_1 B_{21} & \lambda_2 B_{22} \end{pmatrix} \right) \geq \det(D).$$

Proof. It is elementary that the sum of two symmetric positive semidefinite matrices has determinant no less than the determinant of each one. We only need to transform our matrix to a symmetric matrix. We have

$$\det \left(D + \begin{pmatrix} \lambda_1 B_{11} & \lambda_2 B_{12} \\ \lambda_1 B_{21} & \lambda_2 B_{22} \end{pmatrix} \right) = \det \left(\left(D \begin{pmatrix} \lambda_1^{-1} Id_m & 0 \\ 0 & \lambda_2^{-1} Id_q \end{pmatrix} + \begin{pmatrix} B_{11} & B_{12} \\ B_{21} & B_{22} \end{pmatrix} \right) \begin{pmatrix} \lambda_1 Id_m & 0 \\ 0 & \lambda_2 Id_q \end{pmatrix} \right).$$

Since D is diagonal, the first matrix in the right-hand side is again symmetric. We have

$$\det \left(D + \begin{pmatrix} \lambda_1 B_{11} & \lambda_2 B_{12} \\ \lambda_1 B_{21} & \lambda_2 B_{22} \end{pmatrix} \right) \geq \det(D).$$

The proof is complete. \square

Return to the proof of Lemma 4.4.5. Let $\begin{pmatrix} B_{11} & B_{12} \\ B_{21} & B_{22} \end{pmatrix}$ be the block partition of B such that B_{11}, B_{22} are square matrices of order m, q . By (4.4.10)

$$h(x, t) = (\cosh t)^m (\cosh 2t)^q \det \left(Id_{m+q} + \begin{pmatrix} \tanh t B_{11} & \frac{\tanh 2t}{2} B_{12} \\ \tanh t B_{21} & \frac{\tanh 2t}{2} B_{22} \end{pmatrix} \right). \quad (4.4.12)$$

Since B is positive semidefinite, using Lemma 4.4.10, we have $h(t) \geq \cosh^m t \cosh^q 2t \geq e^{2\ell t}/C_1$. The upper bound of $h(t)$ is due to the upper bound on the second fundamental form, that is to say B is bounded.

The derivative in the scalar part of (4.4.12), $\cosh^m t \cosh^q 2t$, gives us

$$(m \tanh t + 2q \tanh 2t)h(t) \geq (m + 2q) \tanh t h(t) = 2\ell \tanh t h(t).$$

It remains to prove the positivity of the derivative of the determinant part of (4.4.12), which is the sum of derivatives in every column. Since all the terms are similar, we need only to show that the derivative in the first column is non negative. The derivative of $\tanh t$ is $1/\cosh^2 t$, and we multiply the first column with $\tanh t \cosh^2 t$ to recover the original column. The determinant of the derivative of the first column becomes

$$\frac{1}{\tanh t \cosh^2 t} \det \left(\begin{pmatrix} 0 & 0 \\ 0 & Id_{m+q-1} \end{pmatrix} + \begin{pmatrix} \tanh t B_{11} & \frac{\tanh 2t}{2} B_{12} \\ \tanh t B_{21} & \frac{\tanh 2t}{2} B_{22} \end{pmatrix} \right),$$

which is nonnegative by Lemma 4.4.10. \square

It remains to prove Lemma 4.4.3.

Proof of Lemma 4.4.3. Use the same notation as in the proof of Lemma 4.4.9. Let

$$J(t) = \frac{\partial}{\partial u_i} H(0, t) = \frac{\partial}{\partial u_i} \tilde{\phi}(u, t)|_{u=0}.$$

Then $J(t)$ is a variation of geodesic, and it is a Jacobi field, which is determined by its value and derivative at 0. We have $J(0) = \frac{\partial}{\partial u_i} \tilde{\phi}(u, 0)|_{u=0} = \frac{\partial}{\partial u_i} \phi(0)$, which is a tangent vector of S at x . Hence $J(0)$ is normal to $\mathbf{n}(x)$. For the derivative, by Schwarz's theorem we have

$$J'(0) = \frac{D}{dt} J(t)|_{t=0} = D \frac{\partial}{\partial t} \frac{\partial}{\partial u_i} = D \frac{\partial}{\partial u_i} \frac{\partial}{\partial t}. \quad (4.4.13)$$

Therefore

$$g(J'(0), \mathbf{n}(x)) = g\left(D \frac{\partial}{\partial u_i} \frac{\partial}{\partial t}, \frac{\partial}{\partial t}\right) = \frac{1}{2} \frac{\partial}{\partial u_i} \left\| \frac{\partial}{\partial t} \right\|^2 = 0.$$

Hence $J(t)$ is normal to the tangent vector of the geodesic. This is true for all i , and the result follows. \square

4.5 Geometrically finite manifolds

We return to the study of the spectrum of the whole manifold. We give a topological decomposition of geometrically finite manifolds. In order to describe it, we use standard cusp regions. For a subset S of M_c , we use \mathring{S} to denote its topological interior, that is $\mathring{S} = S - \bar{S}^c \cap S$. The reader who is only interested in convex cocompact manifolds (geometrically finite manifolds without cusps) can skip Section 4.5.1 and go directly to Section 4.5.2. Our goal in this section is to obtain the Lax-Phillips inequality, then Theorem 4.1.1 follows by Proposition 4.3.1.

4.5.1 Standard cusp regions

The manifold with boundary M_c may have some cusps. To analyse the structure of cusps, we introduce the concept of a topological end.

Definition 4.5.1. *Let T be a differential manifold. An end e is a function which assigns every compact subset K of T a non empty connected component of $T \setminus K$, such that if $K \subset K'$, then $e(K) \supset e(K')$.*

Let $K_1 \subset K_2 \subset \dots$ be an ascending sequence of compact subsets whose interiors cover T . We call $e(K_i)$ a system of neighbourhoods for the end e .

A neighbourhood for the end e is an open subset U such that $U \supset e(K_n)$ for some n .

Proposition 4.5.2. *[Bow95, Proposition 4.4] If Π is a discrete parabolic subgroup of G , then $M_c(\Pi)$ has precisely one topological end. Moreover, we can find a system of neighbourhoods for the end consisting of geodesically convex submanifolds of $M_c(\Pi)$.*

Following [Bow95], we define a *standard cusp region* (with boundary). This definition is not explicitly written, but it is implicitly defined in [Bow95, Sec.5.1]. For more details on the real hyperbolic case, we refer to [Bow93, Sec.3.1]

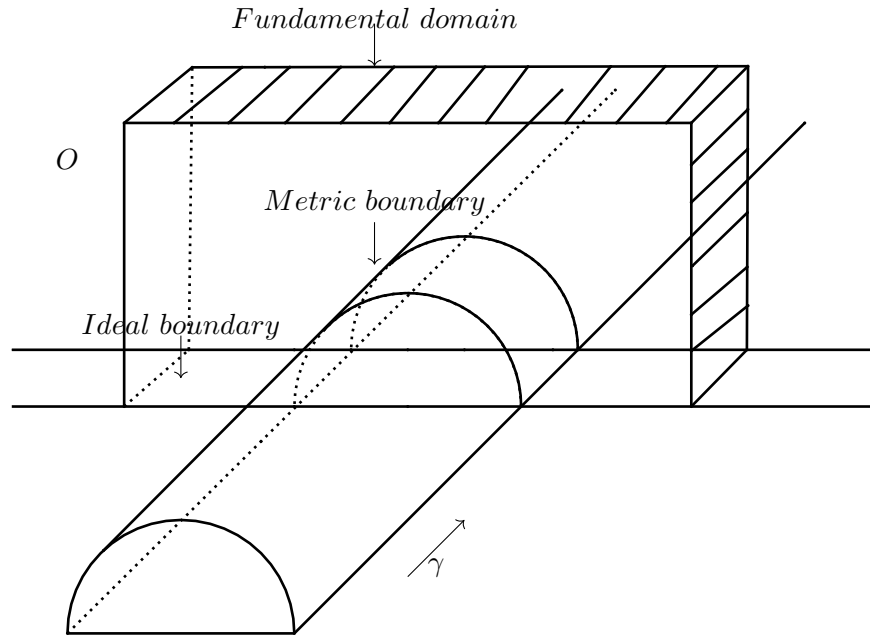


Figure 4.5.1: A standard cusp region

Definition 4.5.3. Let Γ be a discrete subgroup of G . An end of $M_c(\Gamma)$ is called a cusp. A standard cusp region of $M_c(\Gamma)$ is a closed subset O which is isometric to a closed subset E of $M_c(\Pi)$, where Π is a discrete parabolic subgroup of Γ and the interior of E is supposed to be a geodesically convex submanifold and a neighbourhood for the end of $M_c(\Pi)$.

We have a corollary of Proposition 4.5.2.

Proposition 4.5.4. Let Γ be a discrete subgroup of G , and let O be a standard cusp region of $M_c(\Gamma)$. There exists a smaller standard cusp region O' such that O' is contained in the interior of O .

Proof. By Definition 4.5.3, the cusp region O is isometric to E and the complement of the interior of E is a compact subset K of $M_c(\Pi)$. Denote by f the isometric map from O to E . By Proposition 4.5.2, $M_c(\Pi)$ has only one end and we have a larger compact subset K_1 , whose interior contains K and whose complement is geodesically convex. Let $E_1 = \overline{K_1^c}$ and let O' be the corresponding subset of O , that is $O' = f^{-1}(E_1)$. \square

For a symmetric space of real rank one, we use the half space model introduced at the end of Section 4.4.1, that is a diffeomorphism from $N \times \mathbb{R}_{>0}$ to X . Recall that Π

is a parabolic subgroup of G which fixes ∞ . It is a subgroup of $M \times N$, which acts isometrically on N equipped with the metric g_t . We have

$$M_c(\Pi) \simeq (\Pi \backslash N) \times \mathbb{R}_{\geq 0} \text{ as topological spaces}$$

Then our standard cusp region is isometric to the complement of an open relatively compact subset in $M_c(\Pi)$, with additional convex condition on the interior. (see figure 4.5.1.)

Definition 4.5.5 (Maximal rank). *Let Π be a discrete parabolic subgroup of G . We call Π a subgroup of maximal rank if the quotient $\Pi \backslash N$ is compact.*

A cusp region is said to be maximal rank, if the corresponding discrete parabolic subgroup is of maximal rank

Remark 4.5.6. *We explain our definition as follows. The rank of a nilpotent group is defined to be the sum of the rank of its central series.*

For real hyperbolic case, Π is a discrete subgroup of $Isom(\mathbb{R}^{n-1}) = O(n-1) \times \mathbb{R}^{n-1}$. By Bieberbach's theorem (see for example [Bow93, Theorem 2.2.5]), the group Π is virtually abelian. The rank of Π is defined to be the rank of its maximal normal abelian subgroup. Hence when Π attains maximal rank, the quotient space is compact.

For rank one symmetric spaces, by Margulis' Lemma, the discrete parabolic subgroup Π is virtually nilpotent. As in [CI99, Lemma 3.4], for a virtually nilpotent discrete subgroup $\Pi < M \times N$, we can find a subgroup $\Pi_1 < \Pi$ of finite index which is nilpotent, and there exists a subgroup $\Pi_2 < N$ which is isomorphic to Π_1 and satisfies $\Pi_1 \cdot x = \Pi_2 \cdot x$ for some x in N . This means that the Π_1, Π_2 -orbits of x are the same in N . Let N_2 be the Zariski closure of Π_2 . Then the rank of Π is the same as the rank of N_2 . When Π attains maximal rank, N_2 coincides with N . Then Π_2 is a cocompact subgroup of N because N is nilpotent. Due to $\Pi_2 \cdot x = \Pi_1 \cdot x$, every point in N has a bounded distance to the orbit $\Pi_1 \cdot x$. Hence $\Pi_1 \backslash N$ is compact, so is $\Pi \backslash N$.

Proposition 4.5.7 (Maximal rank). *Let Γ be a discrete subgroup of G . Let O be a standard cusp region of $M_c(\Gamma)$ with maximal rank. Then we can find a smaller cusp region O_1 , which is isomorphic to the quotient of a horoball by a discrete parabolic subgroup of Γ .*

Proof. By Definition 4.5.3, there is a discrete subgroup Π of Γ , such that O is isometric to a closed subset E of $M_c(\Pi)$, whose interior is a neighbourhood for the end of $M_c(\Pi)$. By Definition 4.5.2 and Proposition 4.5.2, the complement of E in $M_c(\Pi)$ is relatively compact. Under the half space model, we can suppose that $E^c \subset (\Pi \backslash N) \times [0, 1]$. Let B be the horoball, which is homeomorphic to $N \times \mathbb{R}_{\geq 1}$. Then the quotient $\Pi \backslash B$ is a subset of E . Due to maximal rank, the quotient $\Pi \backslash N$ is compact. Hence

$$M_c(\Pi) - \Pi \backslash \mathring{B} \simeq (\Pi \backslash N) \times [0, 1]$$

is compact. The quotient $\Pi \backslash B$ is geodesically convex. Let O_1 be the preimage of $\Pi \backslash B$ in O under the isometric map from O to E . The proof is complete. \square

In later proof, for cusps of maximal rank, we will always take the quotient of horoball as a standard cusp region.

4.5.2 A good partition of unity

Definition 4.5.8 (Geometrical finiteness). *A discrete subgroup Γ in G is called geometrically finite, if $M_c(\Gamma)$ is the union of a compact set and a finite number of standard cusp regions O_i for $1 \leq i \leq k$, that is to say $M_c(\Gamma) - \bigcup_{1 \leq i \leq k} \mathring{O}_i$ is compact.*

This definition is not explicitly written in [Bow95], but is given in the discussion after [Bow95, Def. F1]. (See also [Bow93, Def.(GF1)] for the real hyperbolic case. In [Bow93], Bowditch explained the equivalence of the definition in the introduction and Definition 4.5.8 for the real hyperbolic case.) By [Bow95, Lemma 6.2], if Γ is geometrically finite, then there exist standard cusp regions O_i for $1 \leq i \leq k$, such that O_i are pairwise disjoint. For the purpose of the exposition, we can limit our consideration to the case that there is at most one cusp; the results hold and the methods of proof work for general cases.

For a real number $r > 0$, we define the r -neighbourhood of a set Q in X by $N_r(Q) = \{x \in X | d(x, Q) \leq r\}$. Let $W_r = N_r(\text{hull}(\Lambda(\Gamma)) \cap X)$ be the r -neighbourhood of the convex hull of the limit set $\Lambda(\Gamma)$. Let $C(M)$ be the convex core defined by $C(M) = \Gamma \backslash (\text{hull}(\Lambda(\Gamma)) \cap X)$. Let $C_r(M) = \Gamma \backslash W_r$ be the r -neighbourhood of the convex core. One problem here is that the boundary of $C_r(M)$ may not be C^∞ -smooth, but is only $C^{1,1}$ -smooth (see for instance [Wal76] or [Fed59]). To overcome this difficulty, we use a result of [PP12, Prop.6]. (In the statement of Proposition 6 in [PP12], they do not have a Γ -invariant condition. But if we start from a Γ -invariant set, their method automatically gives us a Γ -invariant set.) We can find a closed convex subset W' with C^∞ smooth boundary such that $W_1 \subset W' \subset W_{3/2}$ and W' is also Γ -invariant. Let $D = \Gamma \backslash W'$. Then $D \subset C_2(M)$.

Let O be a standard cusp region of the unique cusp in M_c . We have a smaller standard cusp region O' such that $O' \subset \mathring{O}$.

We can cover the geometrically finite manifold with three open sets

$$M_c = \mathring{O} \cup (D^c - O') \cup (C_2(M) - O'), \quad (4.5.1)$$

where D^c is the complement in M_c . For the simplicity of the notation, we write

$$M_1 = \mathring{O}, M_2 = D^c - O' \text{ and } M_3 = C_2(M) - O'.$$

Since M_c inherits the differential structure from $X \cup \Omega$, the covering is about a differential manifold with boundary. We can find a smooth partition of unity subordinate to this cover, written as $\{\bar{\varphi}_1, \bar{\varphi}_2, \bar{\varphi}_3\}$, which is smooth on the boundary. Here M_1, M_2 may intersect the ideal boundary $M_I = M_c - M$.

Our covering has the advantage that M_3 is compact, and M_1, M_2 have quasi-warped product Riemannian structure.

Proposition 4.5.9. *The set M_3 is relatively compact in M .*

Proof. By Definition 4.5.8, we have that $M_c - \mathring{O}'$ is compact in M_c . Therefore $C_2(M) - \mathring{O}'$ is compact in M_c . It is also contained in M , hence it is a compact subset of M . \square

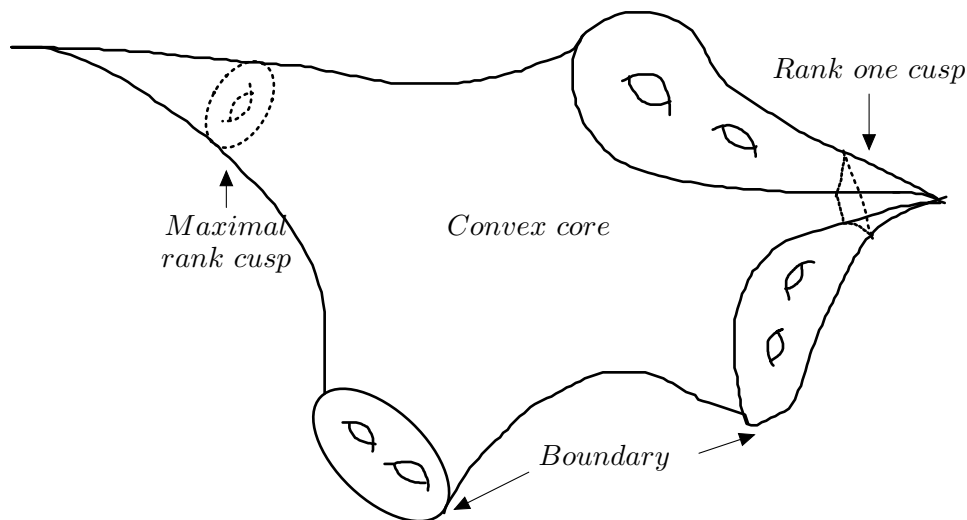


Figure 4.5.2: Convex core

4.5.3 The energy form

We keep the assumptions on M of Sec.4.5.2, that M is a geometrically finite locally symmetric manifold of real rank one with at most one cusp. Recall that E is the energy form defined in (4.4.3).

Lemma 4.5.10. *Let $f \in C_c^\infty(M)$, and let φ be a smooth function. We have*

$$E(\varphi f) = \int_M \varphi^2 (\|\nabla f\|^2 - \ell^2 f^2) dvol - \int_M f^2 \varphi \Delta \varphi dvol.$$

This is a direct consequence of Lemma 4.2.1. The following proposition says that in order to calculate the energy form on the entire manifold, it is sufficient to calculate the energy forms on M_1, M_2, M_3 and an error term. We want to separate the energy formula, but we need a partition of unity such that the square root of the partition function is also smooth. The exact choice of the partition function is not important and we take $\theta = \frac{\pi}{2}\bar{\varphi}_1, \vartheta = \frac{\pi}{2}\bar{\varphi}_2$ and $\varphi_1 = \sin \theta, \varphi_2 = \sin \vartheta$.

Proposition 4.5.11. *For $f \in C_c^\infty(M)$, we have*

$$\begin{aligned} E(f) &= \int_{M_3} ((1 - \varphi_1^2 - \varphi_2^2)(\|\nabla f\|^2 - \ell^2 f^2) + (\varphi_1 \Delta \varphi_1 + \varphi_2 \Delta \varphi_2) f^2) dvol \\ &+ E(\varphi_1 f) + E(\varphi_2 f) - \int_{M_3^c} \|\nabla \theta\|^2 f^2 dvol. \end{aligned} \tag{4.5.2}$$

Proof. By Lemma 4.5.10, we have

$$E(\varphi_2 f) + E(\varphi_1 f) = \int (\varphi_2^2 + \varphi_1^2)(\|\nabla f\|^2 - \ell^2 f^2) - \int (\varphi_2 \Delta \varphi_2 + \varphi_1 \Delta \varphi_1) f^2.$$

Since $\theta + \vartheta = \pi/2$ outside of M_3 , we have for $x \in M_3^c$

$$\begin{aligned} \varphi_2 \Delta \varphi_2 + \varphi_1 \Delta \varphi_1 &= \sin \theta \Delta \sin \theta + \sin \vartheta \Delta \sin \vartheta \\ &= \frac{1}{2}(\Delta(\sin^2 \theta + \cos^2 \theta) - \|\nabla \sin \theta\|^2 - \|\nabla \cos \theta\|^2) = -\|\nabla \theta\|^2. \end{aligned}$$

The proof is complete. \square

We want to prove that $E(\varphi_1 f)$ and $E(\varphi_2 f)$ are positive after adding an integral over a compact subset, and to give an estimate of the error term $\int_{M_3^c} \|\nabla \theta\|^2 f^2$.

4.5.4 Positivity of the energy form

In this part, we take into account the topology of the whole manifold, together with the results in standard cusp regions and the complement of convex subsets, to prove the positivity.

Proposition 4.5.12 (the Lax-Phillips inequality). *Let M be a geometrically finite locally symmetric manifold of real rank one. There exist a relatively compact open set U in M with smooth boundary and a constant $C_U > 0$ such that the following holds. For any compact set V in M there exists $\epsilon_V > 0$ such that for all complex valued function $f \in C_c^\infty(M)$ we have*

$$E(f) + C_U \int_U |f|^2 \text{dvol} \geq \frac{1}{4} \int_U \|\nabla f\|^2 \text{dvol} + \epsilon_V \int_V |f|^2 \text{dvol}. \quad (4.5.3)$$

Proof of Theorem 4.1.1. Our main theorem of this manuscript follows from Proposition 4.5.12 and 4.3.1 with $c(x) = \ell^2$. \square

It remains to prove Proposition 4.5.12.

Remark 4.5.13. *For the simplicity of the exposition, here we will only prove the case that M has only maximal rank cusps (M may have no cusp). For the general case, please see the appendix. The idea of the proof is the same, but the appearance of non-maximal cusps will add some technical difficulties.*

It is sufficient to prove this inequality for real valued functions. The complex version is immediate by separating $f = f_1 + if_2$ with f_1, f_2 real valued and using the real version for each component f_1, f_2 .

Let $\tilde{\rho}$ be the nearest point retraction from X to W' . We can extend this map continuously to $X \cup \Omega$, such that if ξ is in Ω , then $\tilde{\rho}(\xi)$ is the first point of contact of

W' with an expanding family of horoballs based at ξ . (See [Bow95, Lem.2.2.4] for more details.) This retraction descends to a map

$$\rho : M_c \rightarrow D,$$

which is also continuous by the openness of the covering map.

In the cusp region, recall that we will use the half space model $(\Pi \setminus N) \times \mathbb{R}_{\geq 0}$ for $M_c(\Pi)$. We write $M_c(\Pi) = (\Pi \setminus N) \times \mathbb{R}_{\geq 0}$, which means the equality holds under the coordinate map. Others equalities are similar. By definition, O' is isometric to a subset of $M_c(\Pi)$, where Π is a discrete parabolic subgroup. Hence we can identify the two sets. By Definition 4.5.1 and Proposition 4.5.2, the complement of the cusp region O' in $M_c(\Pi)$ is relatively compact. Hence we can suppose that $(O')^c$ is contained in $(\Pi \setminus N) \times [0, 1]$. (Otherwise, we can change the coordinate.) Let H be the quotient of a horoball based at ∞ , defined by $H = (\Pi \setminus N) \times [1, \infty) \subset O'$. We define $proj_H$ to be the nearest point retraction from $M_c(\Pi)$ to H . For a point $(\eta, y) \in M_c(\Pi)$ with $y < 1$, the map is given by $proj_H(\eta, y) = (\eta, 1)$.

Lemma 4.5.14. *Let $K = \rho(M_2)$ and let $L = proj_H(O - O')$. Then K, L are relatively compact in M .*

When O is of maximal rank, we can take $O = (\Pi \setminus N) \times \mathbb{R}_{\geq c_1}$ and $O' = (\Pi \setminus N) \times \mathbb{R}_{\geq c_2}$ for some $0 < c_1 < c_2 \leq 1$ and we have $L = (\Pi \setminus N) \times \{1\}$.

Proof. Since M_c has only one cusp, by Definition 4.5.8, the sets $M_2 = D^c - O'$ and $O - O'$ are relatively compact in M_c . The continuity of ρ and $proj_H$ implies that $\rho(M_2)$ and $proj_H(O - O')$ are relatively compact in D and H . The latter two sets are in M , hence we have the result.

The last assertion is due to Proposition 4.5.7. □

For x in M , let

$$t_1(x) = d(x, H), t_2(x) = d(x, D). \tag{4.5.4}$$

Later we will see that t_1, t_2 are the geometric descriptions of the coordinate t in cusps and the complement of convex set. Recall that M_1, M_2 are subsets of M_c , which may intersect the ideal boundary M_I .

Lemma 4.5.15. *In the standard cusp region, there exist a compact set U_1 in $M_1 \cap M$ and a constant $C_1 > 0$ such that the following holds. For any compact set V in $M_1 \cap M$ there exists $\epsilon_V > 0$ such that for all $f \in C_c^\infty(M_1 \cap M)$ we have*

$$E(f) + C_1 \int_{U_1} f^2 dvol \geq \frac{1}{2} \int \|\nabla(e^{t_1} f)\|^2 e^{-2t_1} dvol + \epsilon_V \int_V f^2 dvol. \tag{4.5.5}$$

Proof. Recall that we identify $M_1 = O'$ as a subset of $(\Pi \setminus N) \times \mathbb{R}_{\geq 0}$. Due to the choice of H , we have $O - O' \subset H^c$, and the coordinate y of a point x under the horospherical model satisfies $y = e^{-t_1(x)}$ for $x \in H^c$. We have that $t_1(x)$ equals the coordinate t in horospherical model when $x \in H^c$. Using Lemma 4.4.2 with compact set L and constant

$C = 2$, and adding (4.4.4) and (4.4.5), we obtain inequality (4.5.5) with the last term replaced by $\int_{L \times \mathbb{R}_{\geq 0}} e^{-t_1} f^2 dvol$. Since O is of maximal rank, by Lemma 4.5.14 we have $L \times \mathbb{R}_{\geq 0} \simeq M_c(\Pi) \supset M_1$. The proof is complete. \square

Lemma 4.5.16. *In the complement of the convex core, there exist a compact set U_2 in $M_2 \cap M$ and a constant $C_2 > 0$ such that the following holds. For any compact set V in $M_2 \cap M$ there exists $\epsilon_V > 0$ such that for all $f \in C_c^\infty(M_2 \cap M)$ we have*

$$E(f) + C_2 \int_{U_2} f^2 dvol \geq \frac{1}{2} \int \|\nabla(e^{\ell t_2} f)\|^2 e^{-2\ell t_2} dvol + \epsilon_V \int_V f^2 dvol. \quad (4.5.6)$$

Proof. We first verify that D satisfies the conditions in Lemma 4.4.5.

Recall that $D = \Gamma \backslash W'$, where W' is a convex subset of X with smooth boundary. By convexity, the normal exponential map, given by $\exp_x(t\mathbf{n}(x))$, is a diffeomorphism from $\partial W' \times \mathbb{R}_{\geq 0}$ onto $X - \overset{\circ}{W}'$, and satisfies $t = d(\exp_x(t\mathbf{n}(x)), W')$. With the help the nearest point retraction $\tilde{\rho}$, the inverse of the normal exponential map from $X - \overset{\circ}{W}'$ to $\partial W' \times \mathbb{R}_{\geq 0}$ is given by

$$x \mapsto (\tilde{\rho}(x), d(x, W')).$$

Descend to the quotient space. Let S be the boundary of D . Then the normal exponential map $\exp^\perp : (x, t) \mapsto \exp_x(t\mathbf{n}(x))$ from $S \times \mathbb{R}_{\geq 0}$ to $M - \overset{\circ}{D}$ is again a diffeomorphism, and

$$t = d(\exp^\perp(x, t), S) = t_2(\exp^\perp(x, t)).$$

The upper bound of the second fundamental form is due to [PP12, Thm.1, Prop.6], that is the obtained convex set W' has bounded second fundamental form on its boundary.

Applying Lemma 4.4.8 with the set $K = \rho(M_2)$, defined in Lemma 4.5.14, and the constant $C = 2(4\ell^2 + 1)$, there exists a bounded interval $I \in \mathbb{R}_{\geq 0}$ such that (4.4.9) holds for $U_2 = K \times I$. Adding (4.4.8) and (4.4.9) implies the result. \square

Proof of Proposition 4.5.12. In view of (4.5.2), the main problem is the term $\int_{M_3^\epsilon} \|\nabla\theta\|^2 f^2 dvol$. The support of $\|\nabla\theta\|$ is contained in $O - O'$, which may not be compact. But with the hypothesis that the manifold has only maximal rank cusps, the region $O - O'$ is already relatively compact in M due to Lemma 4.5.14. Because O does not intersect the ideal boundary and the complement of O' is relatively compact. Hence $\|\nabla\theta\|^2$ is a bounded function supported on $O - O'$.

The compact set V is replaced by $V \cap M_1$ and $V \cap M_2$ in Lemma 4.5.15 and Lemma 4.5.16. Using Lemma 4.5.15 and 4.5.16, we obtain U_1, U_2 . Since $O - O', M_3, U_1, U_2$ are relatively compact in M , we can find a relatively compact open set $U \subset M$ with smooth boundary, which contains the four sets. By (4.5.2), (4.5.5) and (4.5.6), there exists a constant C_4 large enough such that

$$\begin{aligned} E(f) + C_4 \int_U f^2 dvol &\geq \frac{1}{2} \int \left(\|\nabla(\varphi_1 f e^{\ell t_1})\|^2 e^{-2\ell t_1} + \|\nabla(\varphi_2 f e^{\ell t_2})\|^2 e^{-2\ell t_2} \right) dvol \\ &\quad + \int_{M_3} (1 - \varphi_1^2 - \varphi_2^2) \|\nabla f\|^2 dvol + \epsilon_V \int_V f^2 dvol. \end{aligned}$$

We restrict our computation on $U \cap \text{supp}\varphi_2 \subset M_2$

$$\|\nabla(\varphi_2 f e^{lt_2})\|^2 \geq \frac{1}{2}(\varphi_2 e^{lt_2})^2 \|\nabla f\|^2 - f^2 \|\nabla(\varphi_2 e^{lt_2})\|^2 \geq e^{2lt_2} \left(\frac{1}{2} \varphi_2^2 \|\nabla f\|^2 - C_{\varphi_2} f^2 \right),$$

where we use the estimate $\sup_{x \in U} \|\nabla \varphi_2(x)\| < \infty$, thanks to the relative compactness of U . In the standard cusp region we have the same estimate. Therefore taking C_U large enough, we have (4.5.3). \square

4.6 Appendix

As stated in Section 4.5.4, we will give a proof of Proposition 4.5.12 without the assumption that M has only maximal rank cusps.

4.6.1 Compactification and estimate at infinite

Let g be a Riemannian metric on a manifold M . We define the musical isomorphism as follows (see [GHL04] for more details). For a vector X in $T_x M$, let X^b be the unique 1-form such that $X^b(v) = g(X, v)$ for every $v \in T_x M$. This isomorphism gives a dual tensor field (the symmetric covariant 2-tensor fields) g^* of g , and $(\nabla f)^b = df$.

We will consider the compactification of a Riemannian manifold $M = L \times (0, 1]$ with metric given by $g = g_1(x, y)/y^2$, where $g_1(x, y)$ is a positive definite symmetric bilinear form on $T_{(x, y)} M$. Now we add $y = 0$ to obtain a differential manifold with boundary, called \bar{M} . By definition, we have (using local coordinate vectors $(\frac{\partial}{\partial x_i})_{1 \leq i \leq n}$ and $(dx_i)_{1 \leq i \leq n}$, g^* can be written as the inverse matrix of g)

$$g^* = (g_1/y^2)^* = y^2 g_1^*. \quad (4.6.1)$$

Suppose that g_1^* can be smoothly extended to $y = 0$, but $g_1^*(x, 0)$ may degenerate to a positive semidefinite form, that means $g_1(x, y)$ may blow up when $y \rightarrow 0$.

Lemma 4.6.1. *Assume that the Riemannian metric on $L \times (0, 1]$ satisfies the above condition. Let f be a smooth function on $L \times [0, 1]$. For every compact subset U of L , there exists a constant $C > 0$ such that for any $(x, y) \in U \times (0, 1]$ we have*

$$\|\nabla f(x, y)\|^2 \leq C y^2.$$

Proof. By definition and (4.6.1), we have

$$\|\nabla f\|^2 = g^*(df, df) = y^2 g_1^*(df, df).$$

By the smoothness of f and g_1^* on the boundary and the compactness, there exists a constant $C > 0$ such that $\|\nabla f\|^2 \leq C y^2$. \square

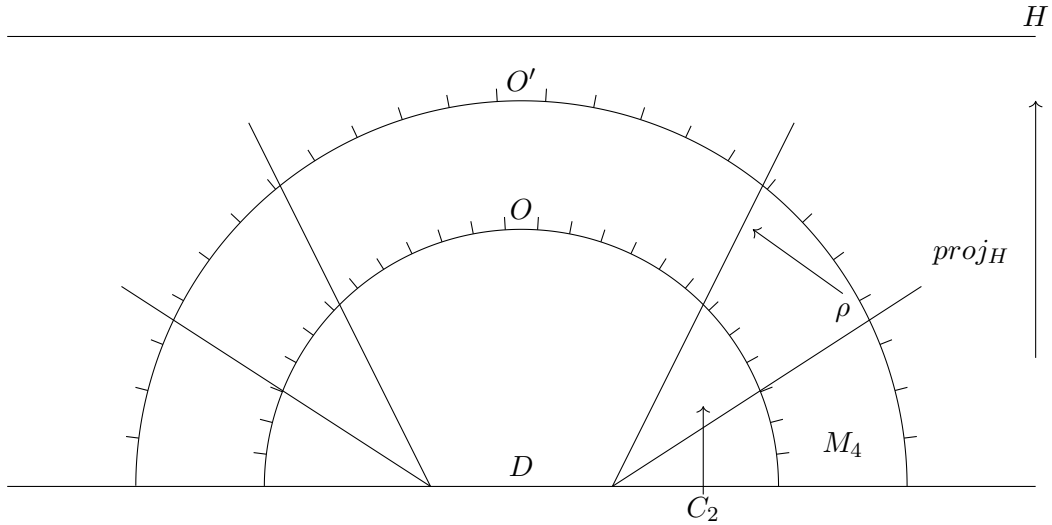


Figure 4.6.1: Projection in standard cusp region

4.6.2 Manifolds with non maximal rank cusp

We will give a proof of Proposition 4.5.12 with non-maximal rank cusps. In Section 4.5.4, the assumption that M has only maximal rank cusps is only used in Lemma 4.5.15 and in the proof of Proposition 4.5.12. The proof works similarly, and we will strengthen Lemma 4.5.15, 4.5.16 and give a control of $\int_{M_3^c} \|\nabla\theta\|^2 f^2 dvol$.

If O is a standard cusp region of non-maximal rank, then the region $(O - O') \cap M$ is not relatively compact in M . Because the cusp region O intersects the ideal boundary $M_I = M_c - M$. To overcome this difficulty, we use the compactness in M_c . The fact that the partition of unity is smooth not only on M but also on M_c is the key point to apply Lemma 4.6.1.

Recall that M is a geometrically finite rank one locally symmetric manifold. We have a covering $M_c = M_1 \cup M_2 \cup M_3$, where M_1 is the cusp region and M_2 is a subset of the complement of the convex core. Recall that $D = \Gamma \backslash W'$ is a neighbourhood of the convex core and H is a subset of M_1 , which is the quotient of a horoball. For x in M , in (4.5.4) we have defined

$$t_1(x) = d(x, H), t_2(x) = d(x, D).$$

Recall that φ_1, φ_2 are two smooth functions supported on M_1, M_2 , respectively, and $\varphi_1^2 + \varphi_2^2 = 1$ outside of M_3 . Let $M_4 = M_1 \cap M_2 - M_3$. The following lemma is the key additional ingredient for the general case.

Lemma 4.6.2. *For every smooth function f on M_4 , there exists $C_f > 0$, such that for all $x \in M_4 \cap M$*

$$\|\nabla f(x)\|^2 \leq C_f \left(e^{-t_1(x)} \varphi_1(x)^2 + e^{-t_2(x)} \varphi_2(x)^2 \right). \tag{4.6.2}$$

Proof. By (4.4.1), letting $y = e^{-t}$, the metric in the half space model is given by $g = g_y \oplus \frac{dy^2}{y^2}$ where $g_y = \begin{pmatrix} \frac{1}{y^2} Id_m & 0 \\ 0 & \frac{1}{y^4} Id_q \end{pmatrix}$ under some distributions W^1 and W^2 on N , which satisfies the condition in Lemma 4.6.1. Due to $M_4 \subset M_1 \subset M_c(\Pi) = (\Pi \backslash N) \times \mathbb{R}_{\geq 0}$, where Π is a discrete parabolic subgroup of Γ which preserves the metric g_y on N for every y in $\mathbb{R}_{\geq 0}$, the quotient metric on M_4 also satisfies the condition in Lemma 4.6.1. Moreover, by $M_4 \subset M_1 \cap M_2 \subset O - O'$, we have that M_4 is contained in $L \times [0, 1]$, where $L = \text{proj}_H(O - O')$ is relatively compact by Lemma 4.5.14. Therefore, using Lemma 4.6.1 with $U = L$ there exists $C'_f > 0$ such that

$$\|\nabla f(\cdot, y)\|^2 \leq C'_f y^2. \quad (4.6.3)$$

Due to $M_4 = M_1 \cap M_2 - M_3$ and the definition of φ_1, φ_2 , we have $1 = \varphi_1^2(x) + \varphi_2^2(x)$ for x in M_4 , and the right-hand side of the above inequality equals $C'_f y^2 (|\varphi_1|^2 + |\varphi_2|^2)$.

We restrict our attention to x in $M_4 \cap M$. By the argument of the proof of Lemma 4.5.15, we have

$$y = e^{-t_1(x)}. \quad (4.6.4)$$

By definition of K, L , the nearest points of x in H and D are contained in K and L . Therefore by compactness of K, L (Lemma 4.5.14), we have

$$|t_1(x) - t_2(x)| = |d(x, H) - d(x, D)| \leq \sup\{d(x_1, x_2) | x_1 \in K, x_2 \in L\} = C_{K,L}. \quad (4.6.5)$$

Hence $e^{-t_1(x)} \leq e^{C_{K,L}} e^{-t_2(x)}$ for x in $M_4 \cap M$. Therefore on $M_4 \cap M$, by (4.6.3), (4.6.4) and (4.6.5)

$$\|\nabla f(x)\|^2 \leq C'_f e^{-2t_1(x)} (\varphi_1^2(x) + \varphi_2^2(x)) \leq C'_f (e^{-2t_1(x)} \varphi_1^2(x) + e^{2C_{K,L}} e^{-2t_2(x)} \varphi_2^2(x)).$$

The proof is complete due $t_1, t_2 \geq 0$. \square

We state our strengthened version of Lemma 4.5.15 and 4.5.16.

Lemma* 4.5.15. *In the standard cusp region, for every $C > 0$ there exist a compact set U_1 in $M_1 \cap M$ and a constant $C_1 > 0$ such that the following holds. For any compact set V in $M_1 \cap M$ there exists $\epsilon_V > 0$ such that for all $f \in C_c^\infty(M_1 \cap M)$ we have*

$$E(f) + C_1 \int_{U_1} f^2 d\text{vol} \geq \frac{1}{2} \int \|\nabla(e^{\ell t_1} f)\|^2 e^{-2\ell t_1} d\text{vol} + \epsilon_V \int_V f^2 d\text{vol} + C \int_{M_4} e^{-t_1} f^2 d\text{vol}. \quad (4.6.6)$$

Proof. By Lemma 4.5.14, we have $M_4 \subset L \times \mathbb{R}_{\geq 0}$. By the same argument as in the proof of Lemma 4.5.15, using Proposition 4.4.2, we have the above inequality with $\int_V f^2$ replaced by $\int_{L \times \mathbb{R}_{\geq 0}} e^{-t_1} f^2$. The desired term is due to Poincaré's inequality.

Lemma 4.6.3. *For relatively compact sets V_1, V_2 in a Riemannian manifold M , where V_1 is connected open and V_2 is a subset of V_1 with nonempty interior, there exists a positive constant ϵ , such that for all $g \in C_c^\infty(M)$ we have*

$$\int_{V_1} \|\nabla g\|^2 d\text{vol} + \int_{V_2} g^2 d\text{vol} \geq \epsilon \int_{V_1} g^2 d\text{vol}. \quad (4.6.7)$$

Applying (4.6.7) with $g = e^{\ell t_1} f$, $V_2 = L \times [1, 2]$ and V_1 a connected open set containing $V_2 \cup V$ implies that

$$\begin{aligned} \int_{V_1} \|\nabla(e^{\ell t_1} f)\|^2 e^{-2\ell t_1} \, d\text{vol} + \int_{V_2} e^{-t_1} f^2 \, d\text{vol} &\geq \epsilon_1 \left(\int_{V_1} \|\nabla g\|^2 \, d\text{vol} + \int_{V_2} g^2 \, d\text{vol} \right) \\ &\geq \epsilon_2 \int_{V_1} g^2 \, d\text{vol} = \epsilon_2 \int_{V_1} f^2 e^{2\ell t_1} \, d\text{vol} \geq \epsilon_3 \int_V f^2 \, d\text{vol}. \end{aligned}$$

The proof is complete. \square

Lemma* 4.5.16. *In the complement of the convex core, for every $C > 0$ there exist a compact set U_2 in $M_2 \cap M$ and a constant $C_2 > 0$ such that the following holds. For any compact set V in $M_2 \cap M$ there exists $\epsilon_V > 0$ such that for all $f \in C_c^\infty(M_2 \cap M)$ we have*

$$E(f) + C_2 \int_{U_2} f^2 \, d\text{vol} \geq \frac{1}{2} \int \|\nabla(e^{\ell t_2} f)\|^2 e^{-2\ell t_2} \, d\text{vol} + \epsilon_V \int_V f^2 \, d\text{vol} + C \int_{M_4} e^{-t_2} f^2 \, d\text{vol}. \quad (4.6.8)$$

Proof. By Lemma 4.5.14, we have $M_4 \subset M_2 \subset \exp^\perp(K \times \mathbb{R}_{\geq 0})$. Then the proof is exactly the same as the proof of Lemma 4.5.16, using Lemma 4.4.8 with the constant $2(4\ell^2 + 1) + C$. \square

Proof of Proposition 4.5.12. Applying Lemma 4.6.2 with $\theta = \frac{\pi}{2}\bar{\varphi}_3$, we get a constant C_θ such that (4.6.2) holds for θ . Using Lemma* 4.5.15 and 4.5.16 with $C = C_\theta$, we obtain U_1, U_2 . Then follow the same argument as in the proof of the special case of Proposition 4.5.12. The proof is complete. \square

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Harmonic analysis of stationary measures

Abstract:

Let μ be a Borel probability measure on $SL_n(\mathbb{R})$, whose support generates a Zariski dense subgroup. Let V be a finite dimensional irreducible linear representation of $SL_n(\mathbb{R})$. A theorem of Furstenberg says that there exists a unique μ -stationary probability measure on $\mathbb{P}V$ and we are interested in the Fourier decay of the stationary measure. The main result of the thesis is that the Fourier transform of the stationary measure has a power decay. From this result, we obtain a spectral gap of the transfer operator, whose properties allow us to establish an exponential error term for the renewal theorem in the context of products of random matrices. A key technical ingredient for the proof is a Fourier decay of multiplicative convolutions of measures on \mathbb{R}^n , which is a generalisation of Bourgain's theorem on dimension 1. We establish this result by using a sum-product estimate due to He-de Saxcé.

In the last part, we generalize a result of Lax-Phillips and a result of Hamenstädt on the finiteness of small eigenvalues of the Laplace operator on geometrically finite hyperbolic manifolds.

Key words : *stationary measures, harmonic analysis, Lie groups, sum-product estimates, Fourier decay, renewal theorem.*

Analyse harmonique des mesures stationnaires

Résumé:

Soit μ une mesure de probabilité borélienne sur $SL_n(\mathbb{R})$ tel que le sous-groupe engendré par le support de μ est Zariski dense. Soit V une représentation irréductible de dimension finie de $SL_n(\mathbb{R})$. D'après un théorème de Furstenberg, il existe une unique mesure μ -stationnaire sur $\mathbb{P}V$ et nous sommes intéressés à la décroissance de Fourier de cette mesure. Le résultat principal de cette thèse est que la transformée de Fourier de la mesure stationnaire a une décroissance polynomiale. À partir de ce résultat, nous obtenons un trou spectral de l'opérateur de transfert, dont les propriétés nous permettent d'établir un terme d'erreur exponentiel pour le théorème de renouvellement dans le cadre des produits de matrices aléatoires. L'ingrédient essentiel est une propriété de décroissance de Fourier des convolutions multiplicatives de mesures sur \mathbb{R}^n , qui est une généralisation d'un théorème de Bourgain en dimension 1. Nous établissons cet ingrédient en utilisant une estimée somme-produit de He et de Saxcé.

Dans la dernière partie, nous généralisons un résultat de Lax et Phillips et un résultat de Hamenstädt sur la finitude des petites valeurs propres de l'opérateur de Laplace sur les variétés hyperboliques géométriquement finies.

Mots clefs : *mesures stationnaires, analyse harmonique, groupes de Lie, estimées sommes-produits, décroissance de Fourier, théorème de renouvellement.*