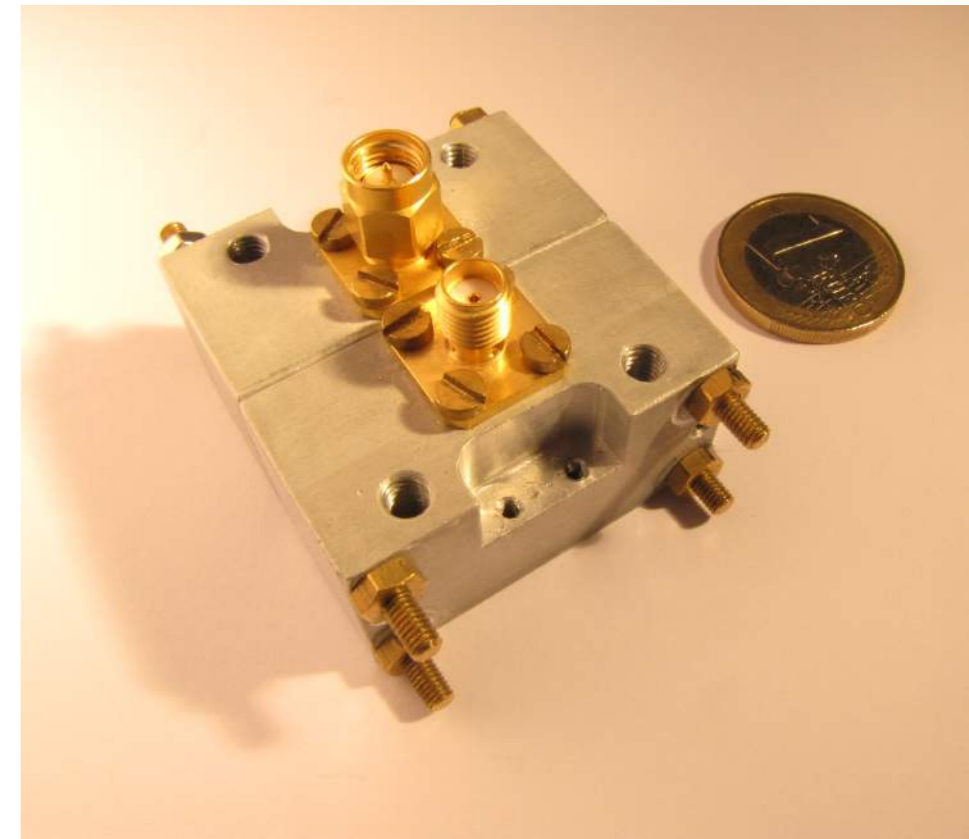
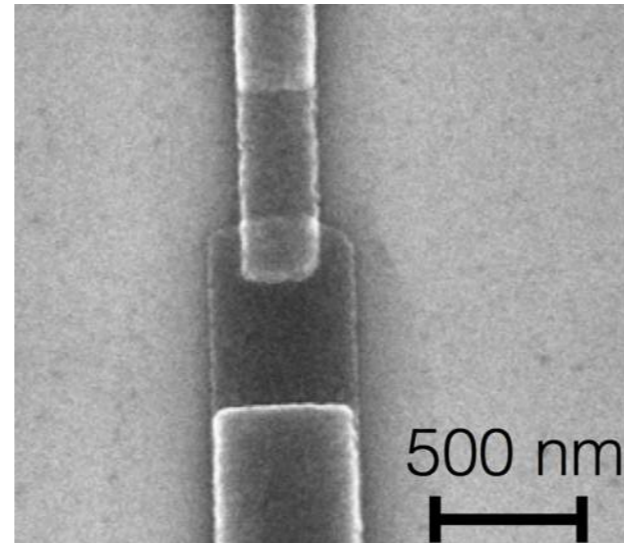
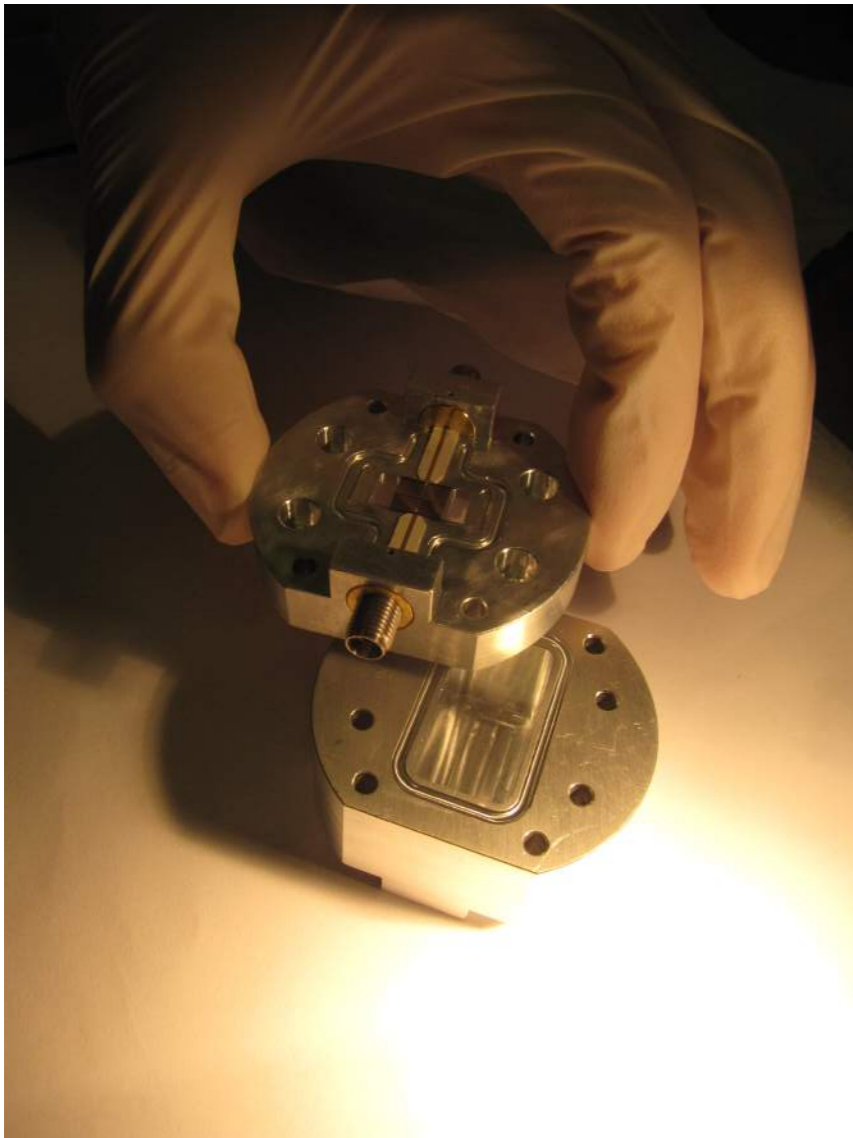


Quantum information with superconducting circuits

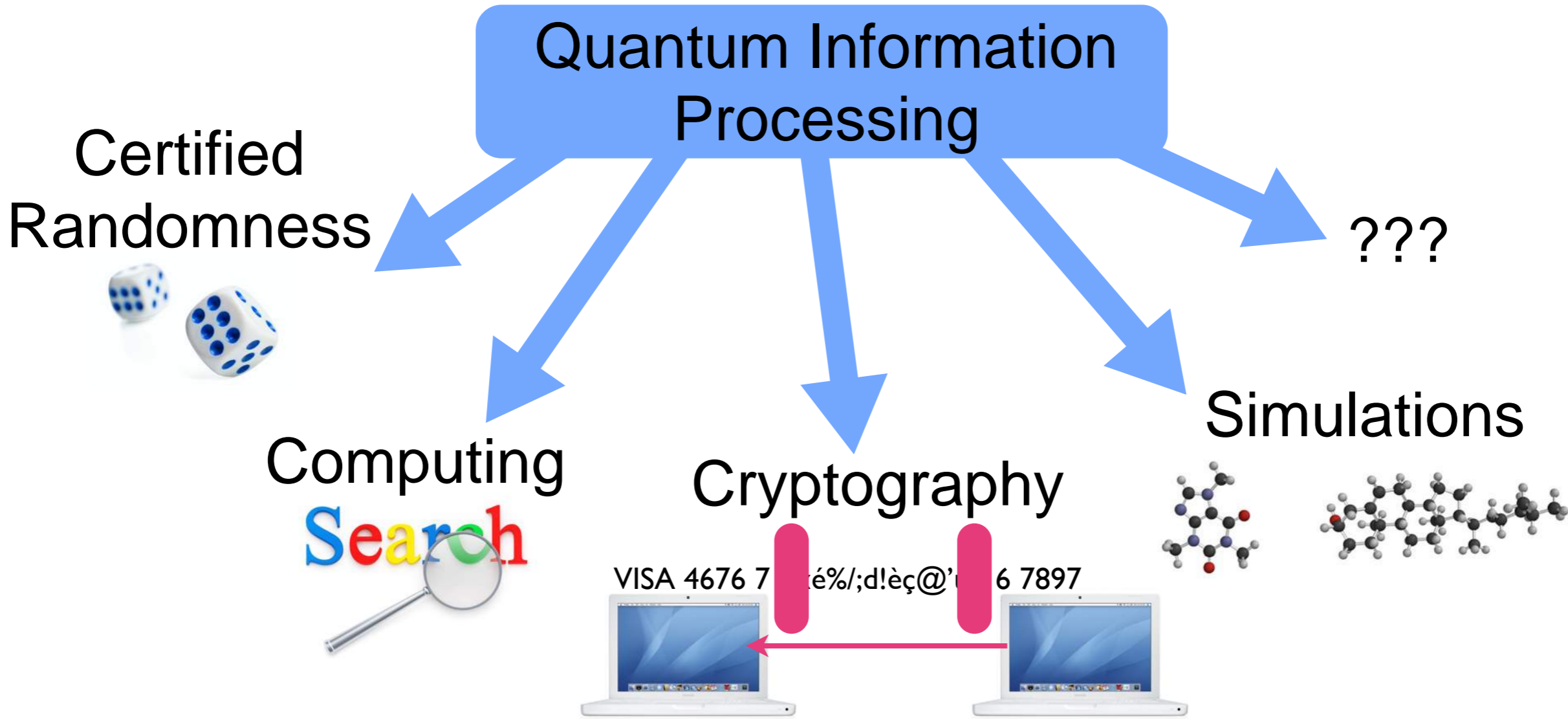
Benjamin Huard

Quantum Electronics group

LPA - Ecole Normale Supérieure de Paris, France



Quantum information



Quantum systems

logical gate



decoherence

Quantum systems

logical gate



decoherence



measurement

Quantum systems

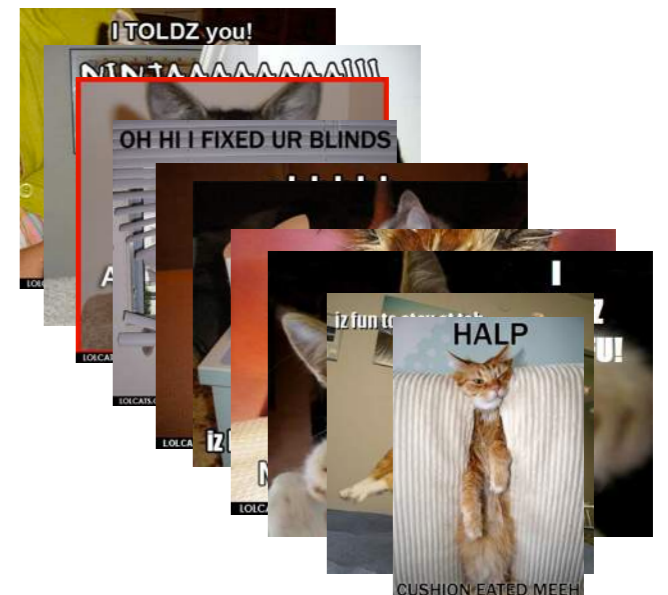
logical gate



decoherence



measurement

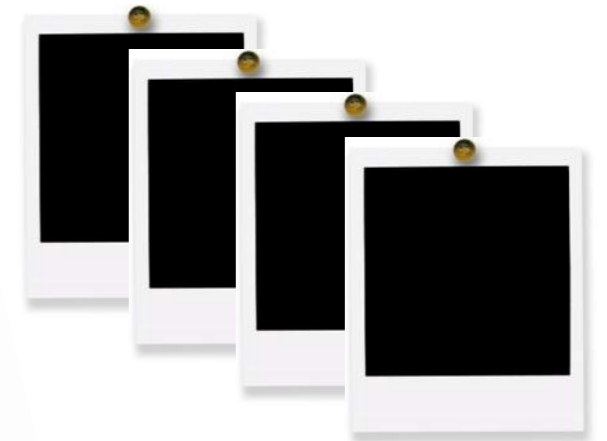


Quantum systems

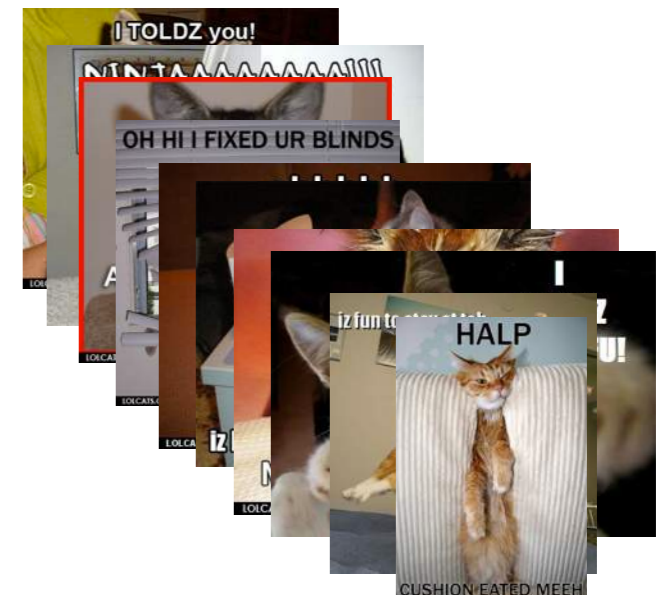
logical gate



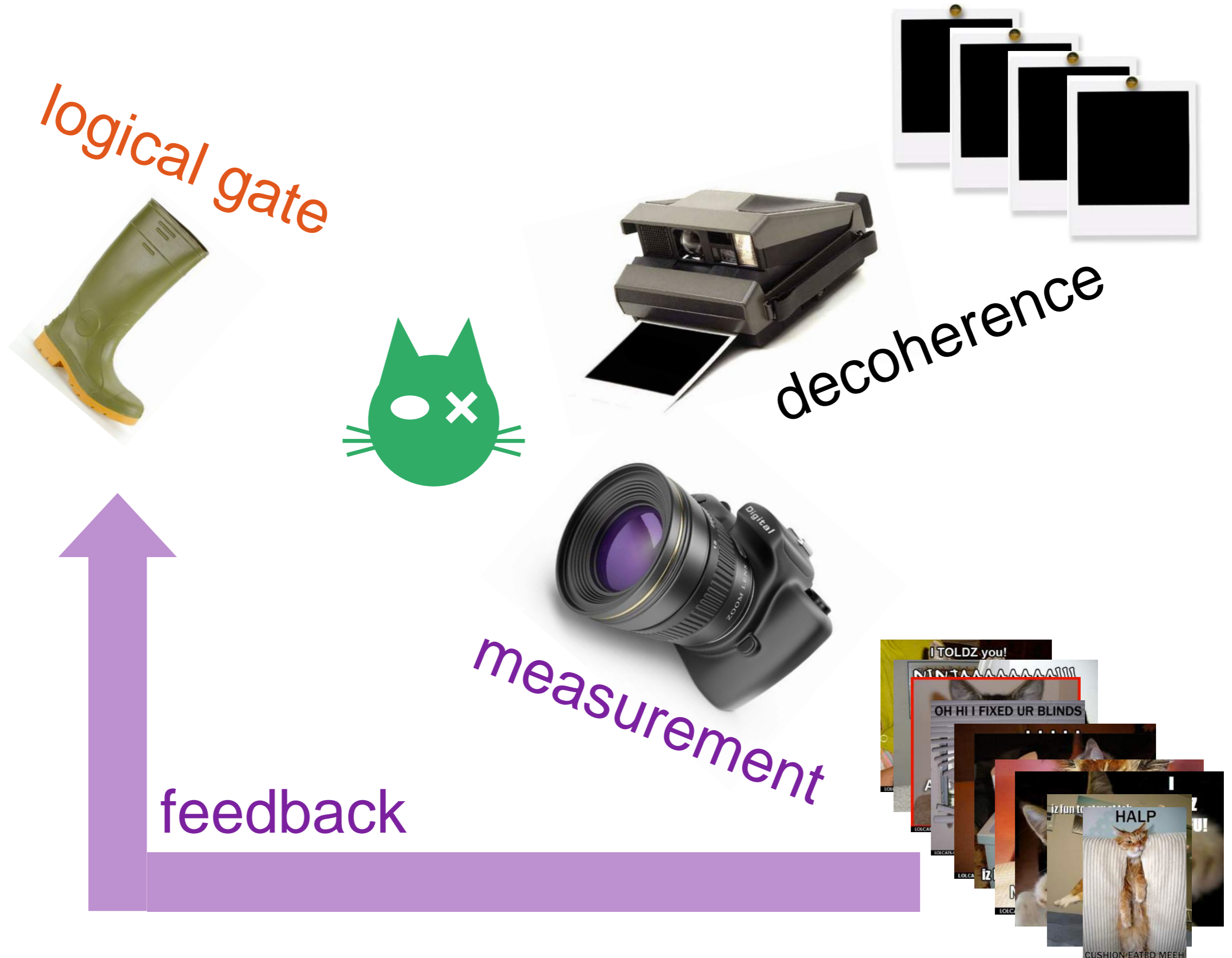
decoherence



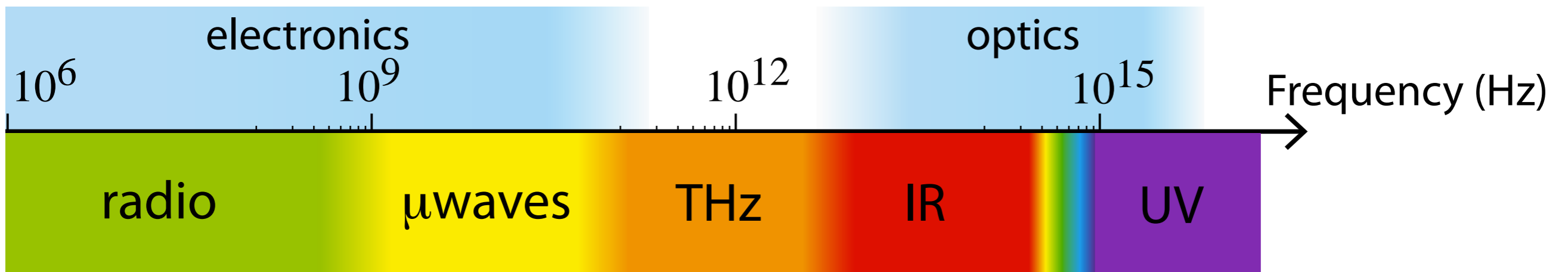
measurement



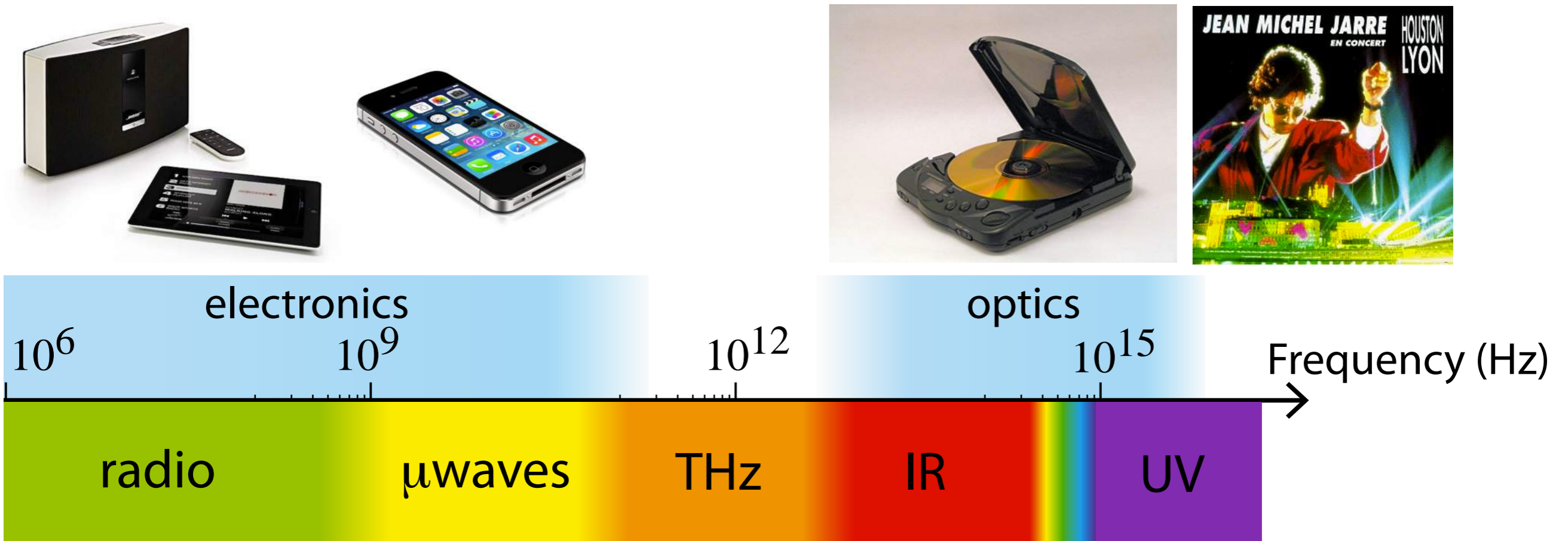
Quantum systems



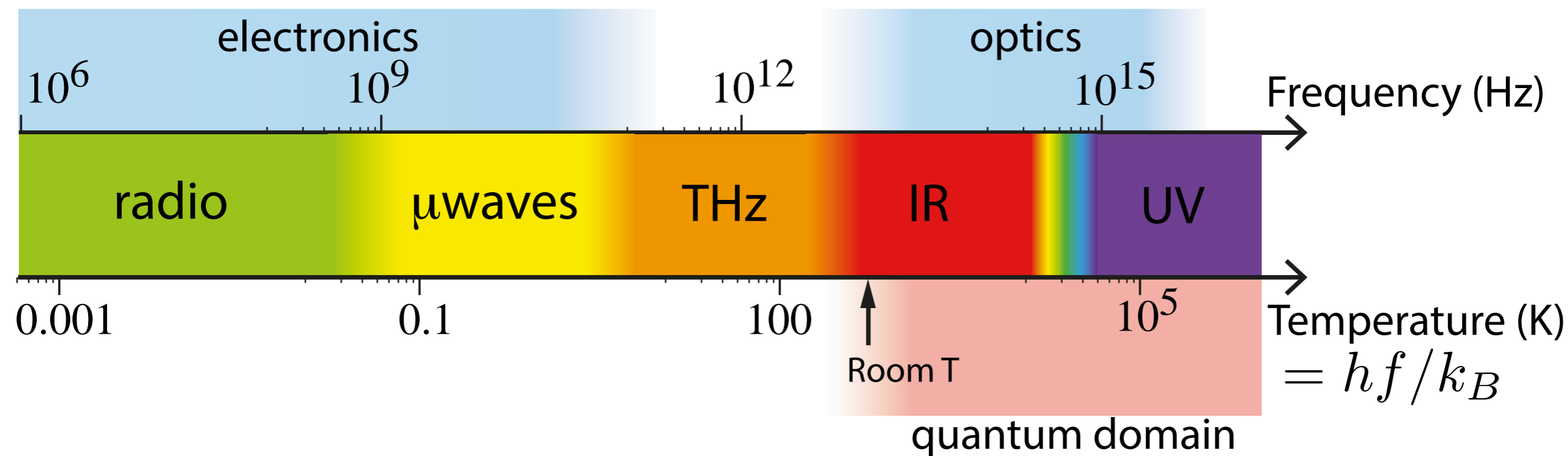
Microwave quantum optics



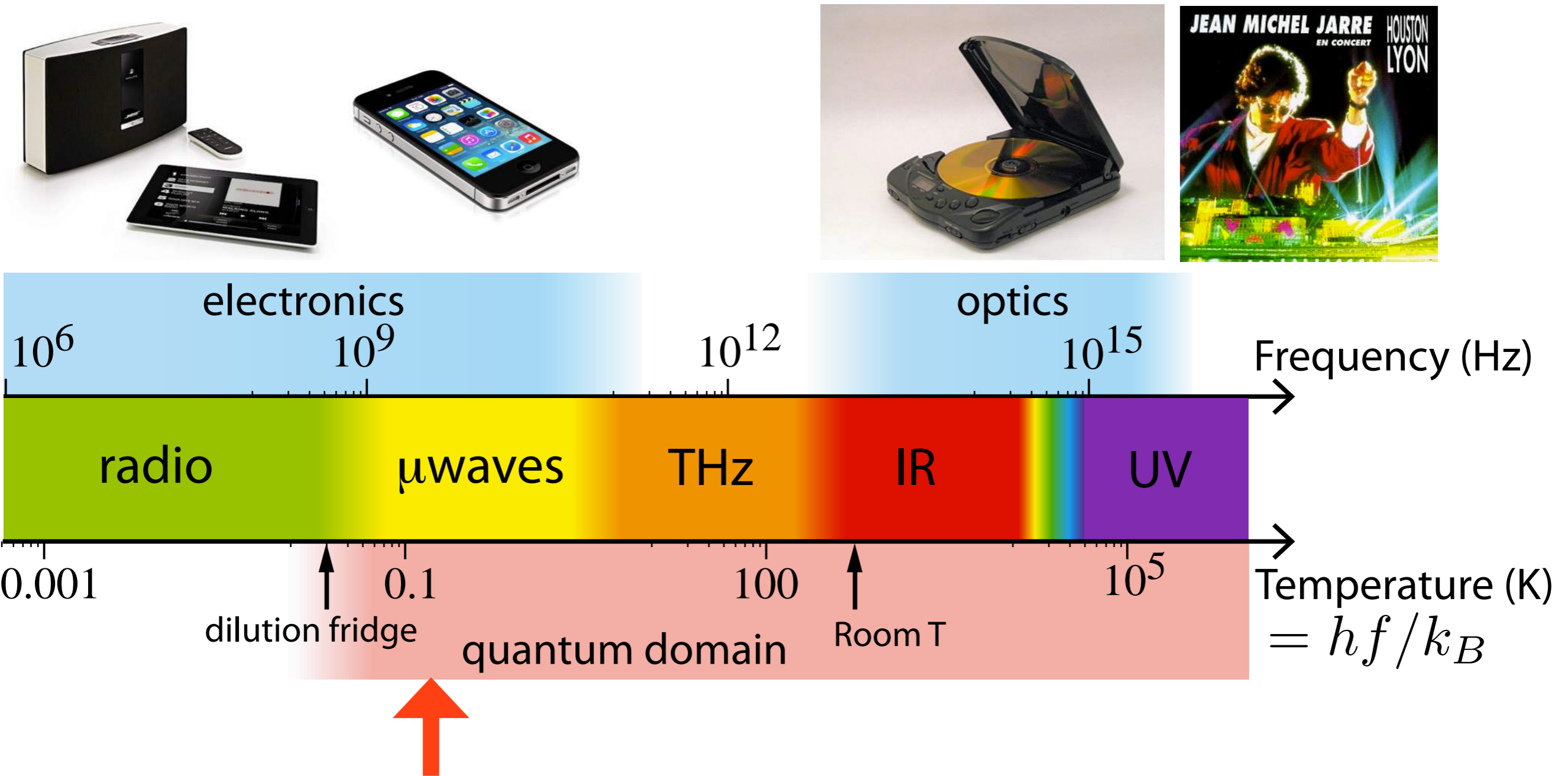
Microwave quantum optics



Microwave quantum optics



Microwave quantum optics



Ce que même l'AMÉRIQUE ne connaît pas encore !

le Radiofrigo

Dernière nouveauté
PHILIPS



160 litres
169.000 Frs +T.L.



Quand vous aurez le "Radiofrigo" PHILIPS, vous serez encore plus fière de votre cuisine!... et vous étonnerez vos amis.
Tellement commode! Tellement agréable!

PHILIPS c'est plus sûr!

RÉFRIGÉRATEUR
Le Réfrigérateur 160 litres à compression muni de l'aménagement intérieur le plus complet, est minutieusement étudié pour le service familial maximum.
Grand freezer avec 2 tiroirs à glace et emplacement pour rafraîchissement rapide de 3 bouteilles.
2 clayettes amovibles permettant de modifier l'agencement intérieur et de placer 4 bouteilles d'un litre.
Dans le bas, grand tiroir à légumes.
Dans la contre-porte 1 galerie et emplacement pour 4 bouteilles.
Présentation luxueuse et lignes très élégantes.

RADIO
2 gammes d'ondes, 4 lampes, cadre incorporé.
Tous courants : 110-127 volts.
Trois coloris :
sur porte plastique - | blanche | verte | bleue
 | ivoire | vert | gris

Dimensions du Radiofrigo
haut : 1 m. 19, larg. : 0 m. 55, profond. : 0 m. 60

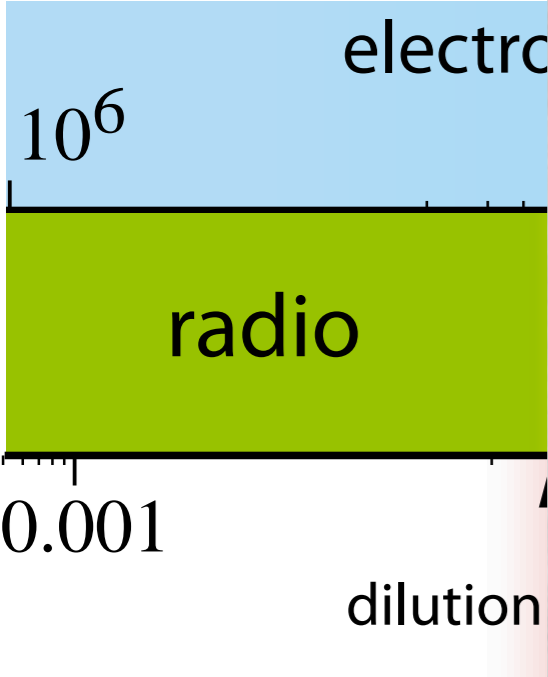


Démonstration chez tous les revendeurs et au magasin d'exposition PHILIPS, 48, Avenue Montaigne - PARIS-8^e

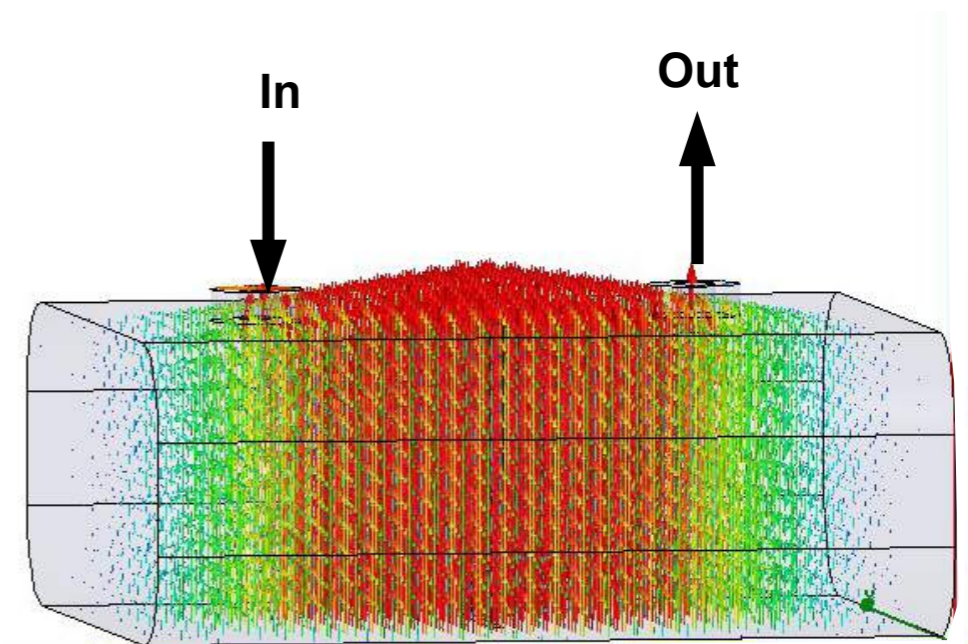
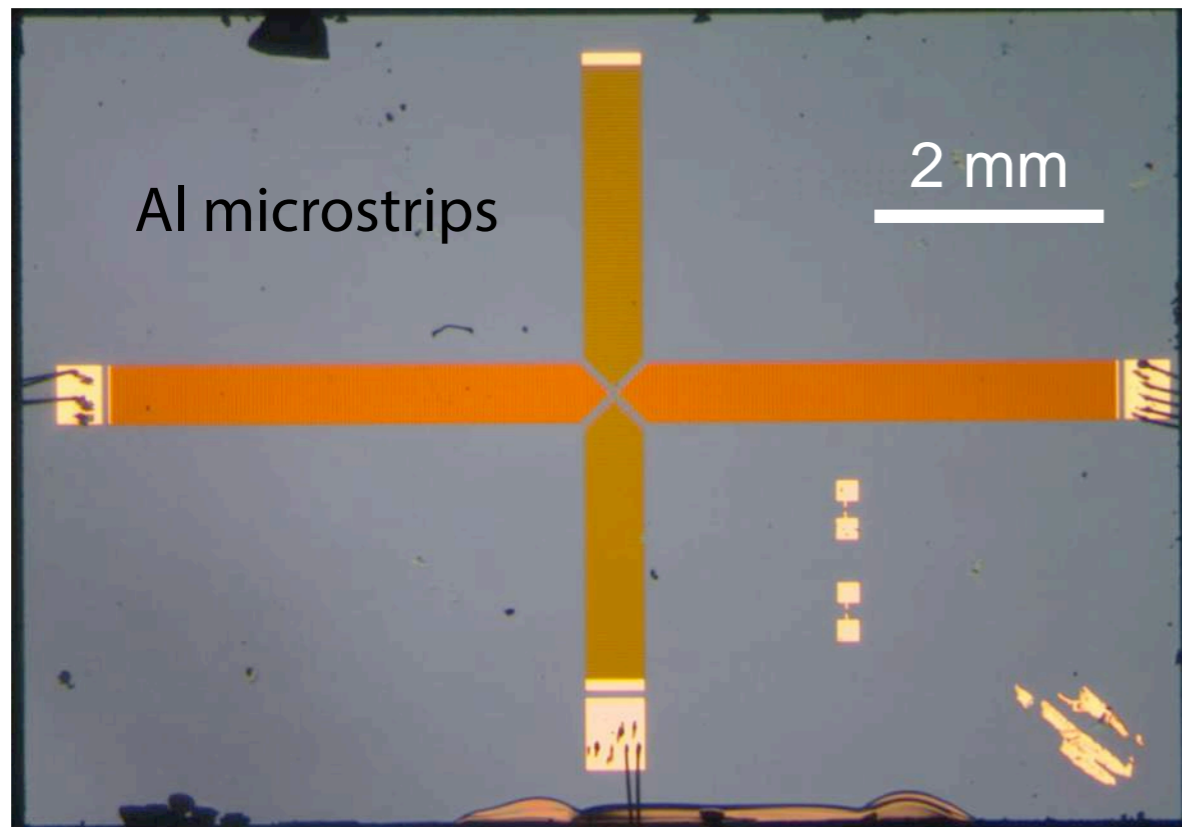
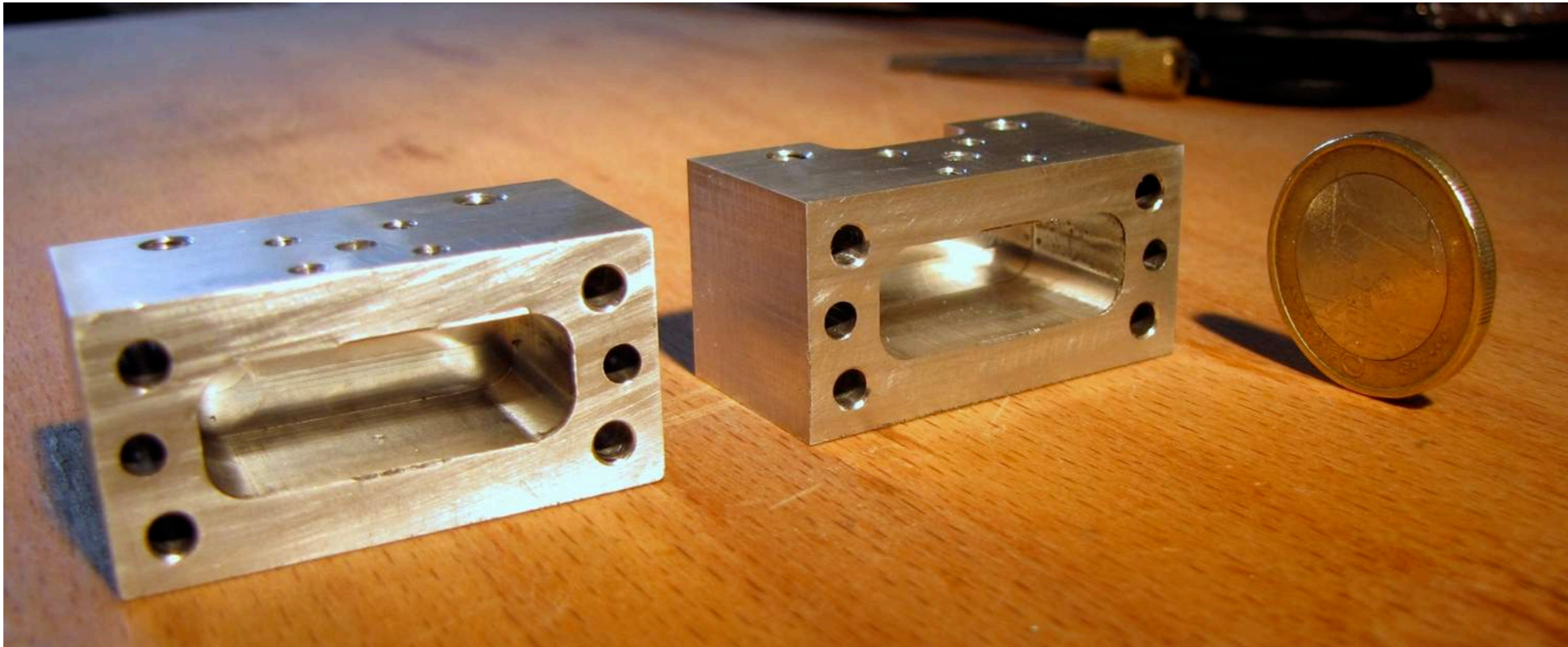


Frequency (Hz)
→

→
Temperature (K)
 $= hf/k_B$



Superconducting circuits

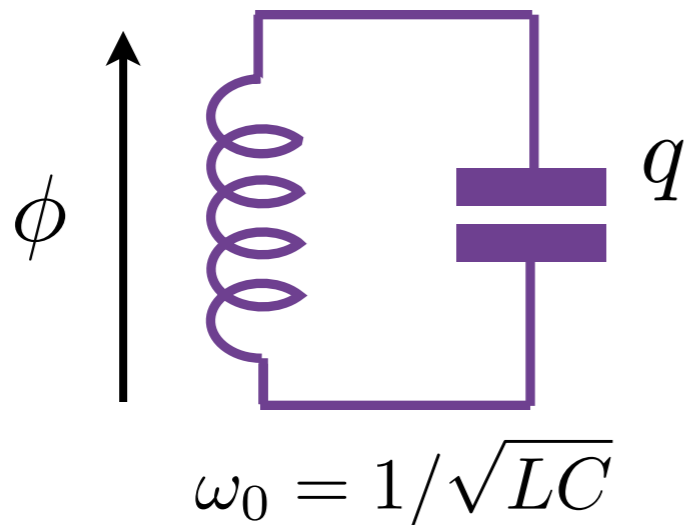


1st mode : 7.63 GHz

$$Q \approx 10^6$$

Superconducting circuits

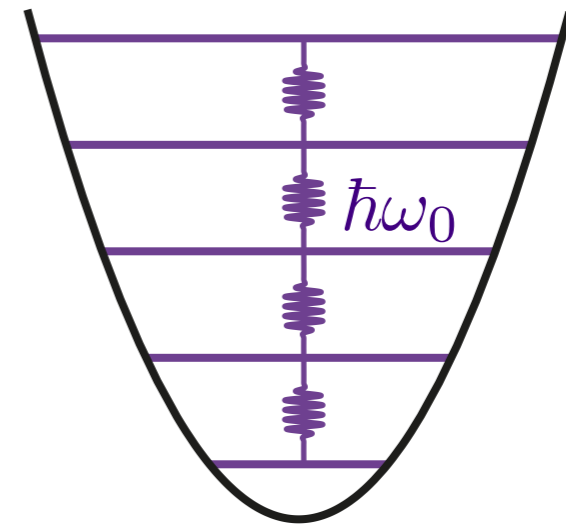
dissipationless LC circuit...



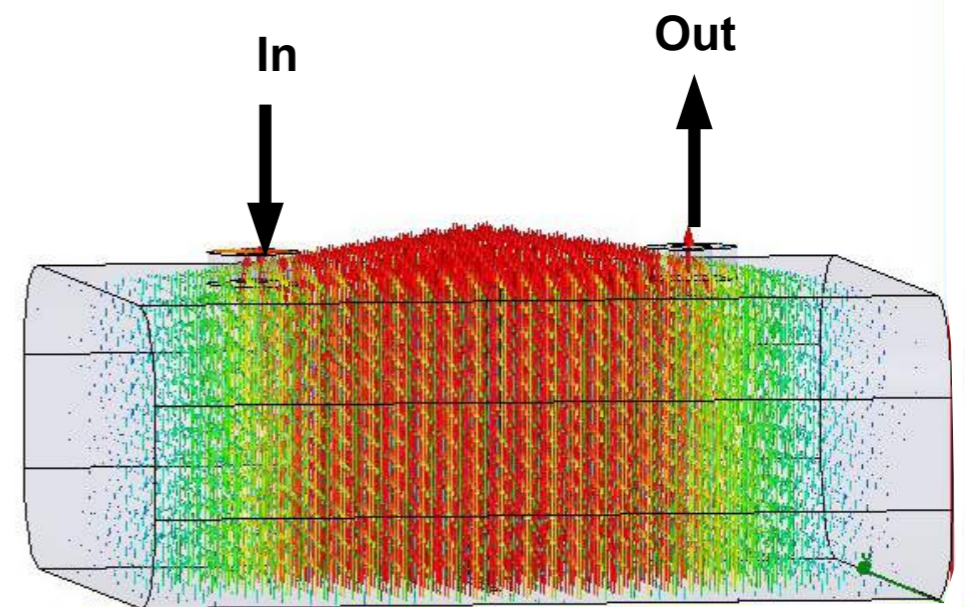
$$\hat{H} = \frac{\hat{q}^2}{2C} + \frac{\hat{\phi}^2}{2L} \quad [\hat{\phi}, \hat{q}] = i\hbar$$

→

....canonically quantized



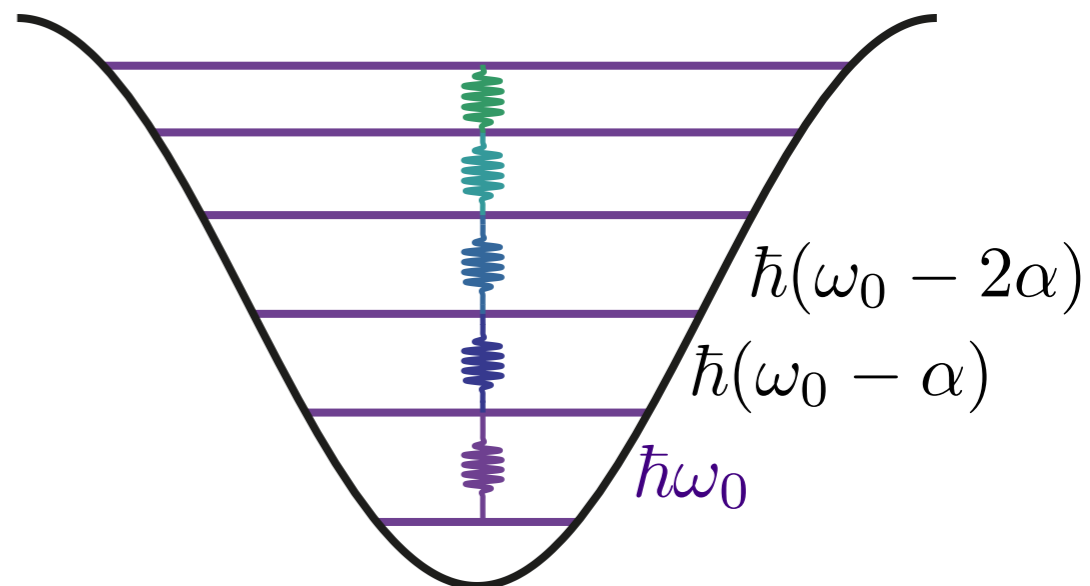
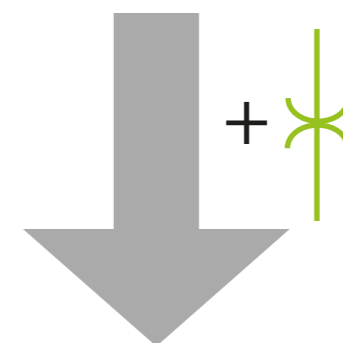
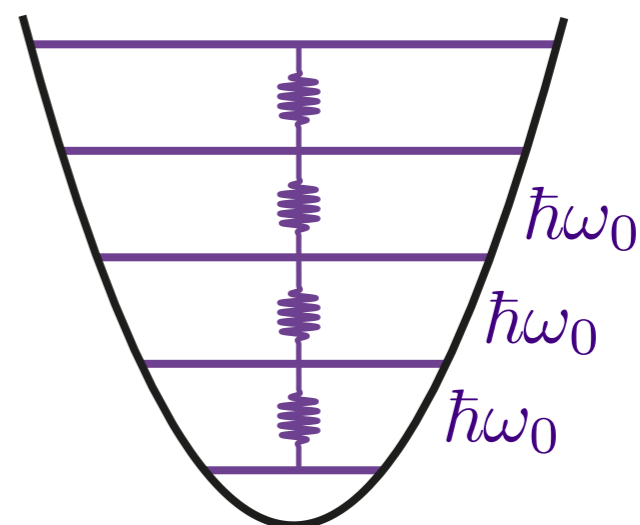
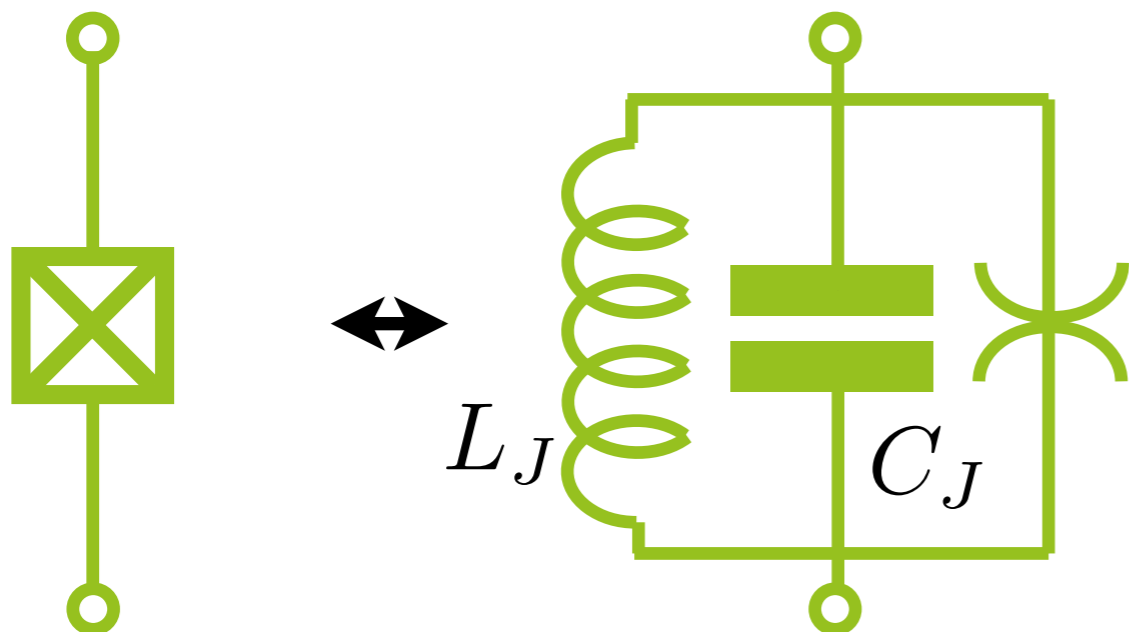
$$\hat{H} = \hbar\omega_0 \left(\frac{1}{2} + \hat{a}^\dagger \hat{a} \right)$$



1st mode : 7.63 GHz
 $Q \approx 10^6$

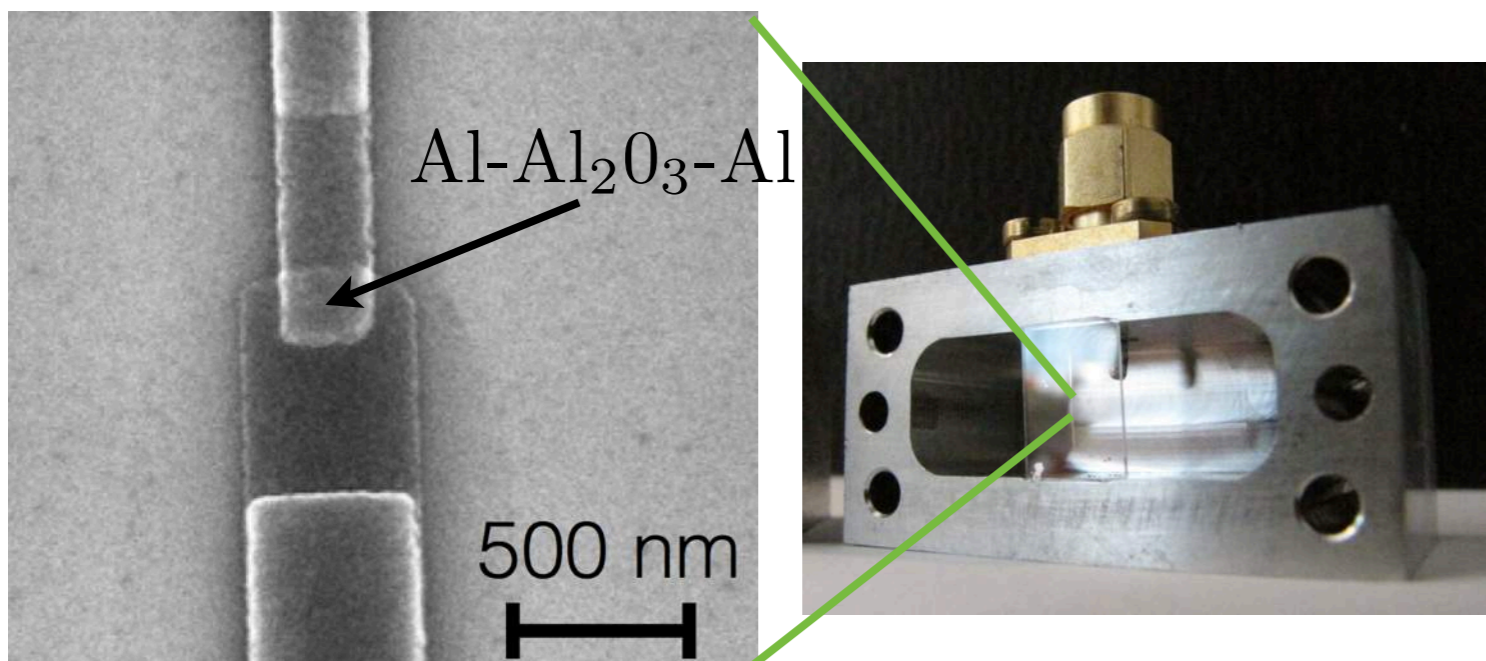
Superconducting circuits with Josephson junctions

dissipation-less **non linear** LC circuit



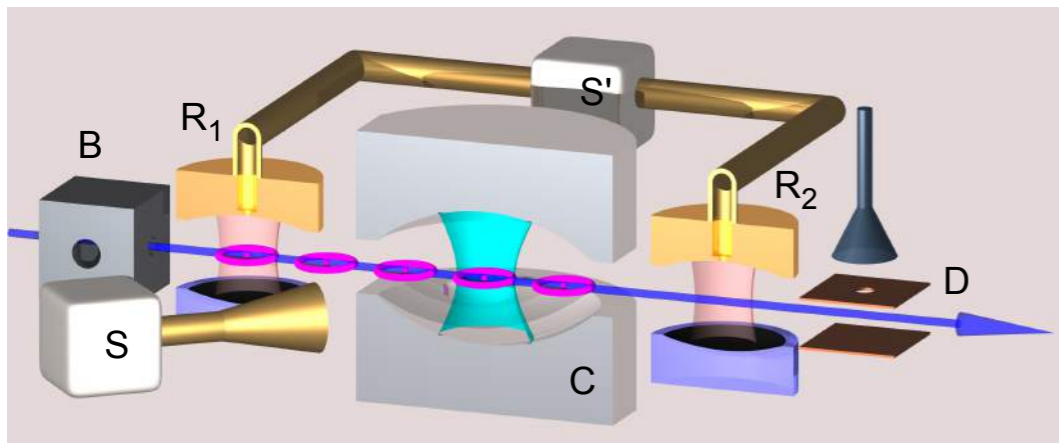
transitions observed in 1980's [Berkeley & Saclay]
strong coupling regime of CQED in 2004 [Yale]

$$\hat{H} = \frac{\hat{q}^2}{2C_J} - E_J \cos \frac{\hat{\phi}}{\hbar/2e} = \frac{\hat{q}^2}{2C_J} + \frac{\hat{\phi}^2}{2L_J} + H_{\text{non-lin}}(\hat{\phi})$$

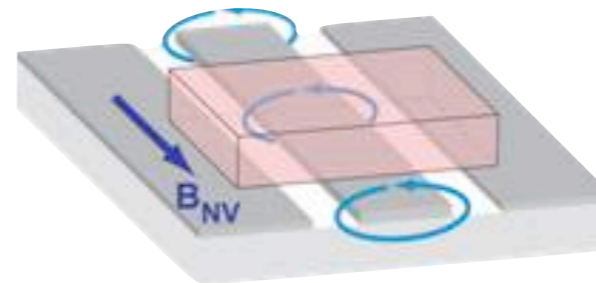


Superconducting circuits with non linear systems

Rydberg atoms

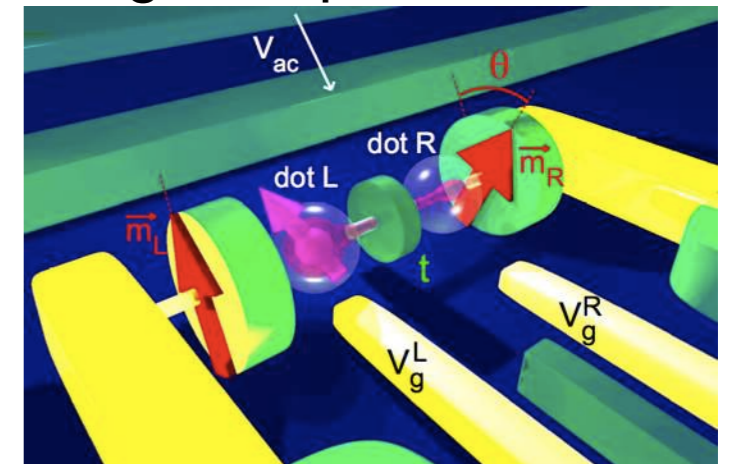


[pic from CQED group at ENS]



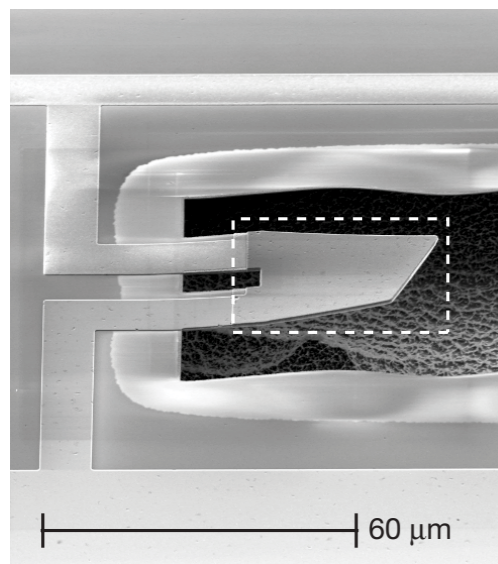
NV centers

Organic quantum dots

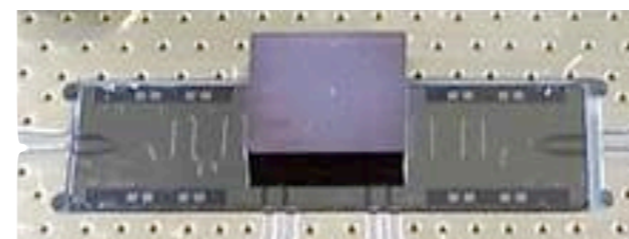


[pic from HQC group at ENS]

Piezoelectric oscillator

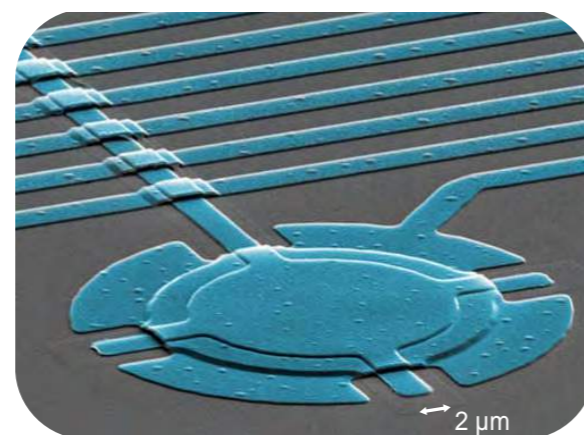


[pic from UCSB group]



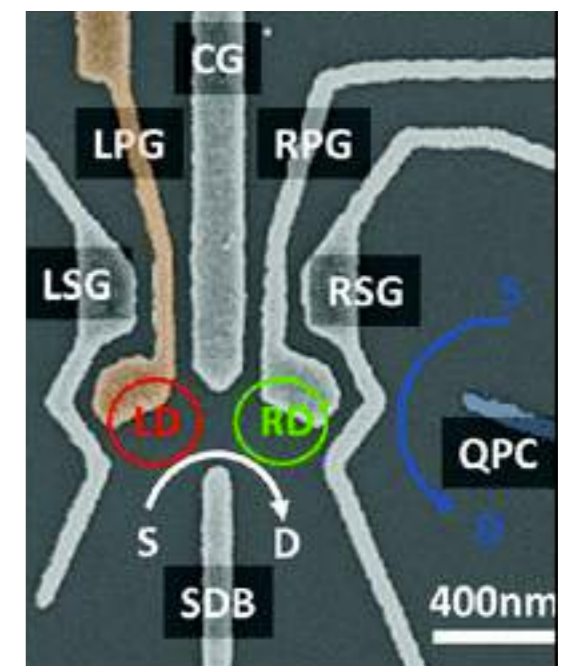
[pic from Quantronics group at Saclay]

Metallic membrane



[pic from Boulder group]

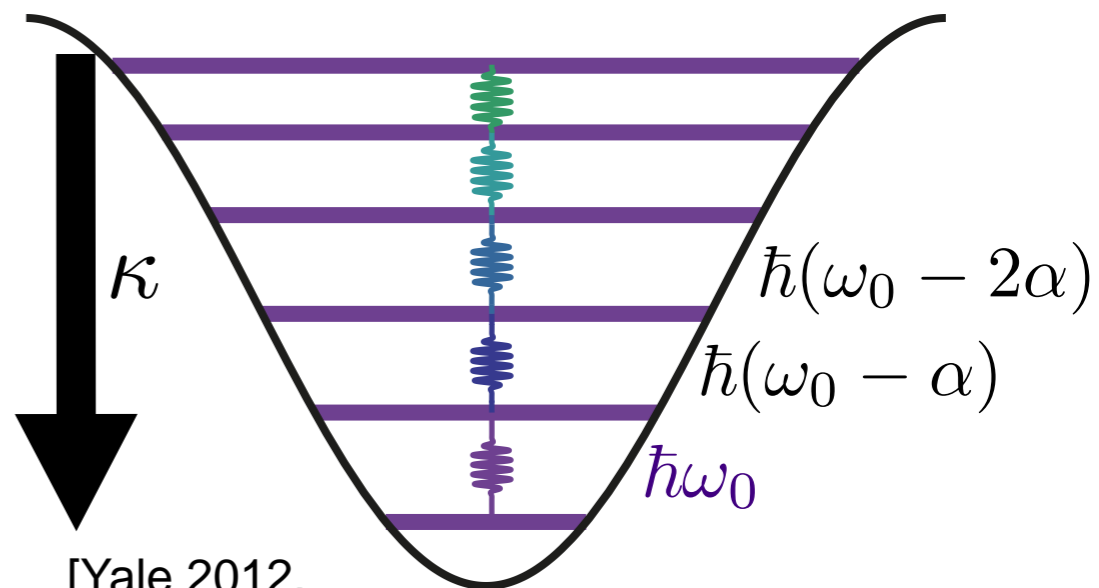
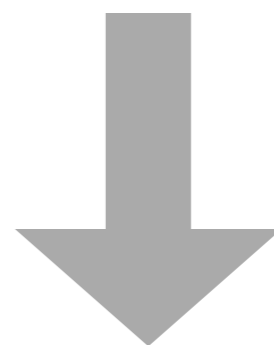
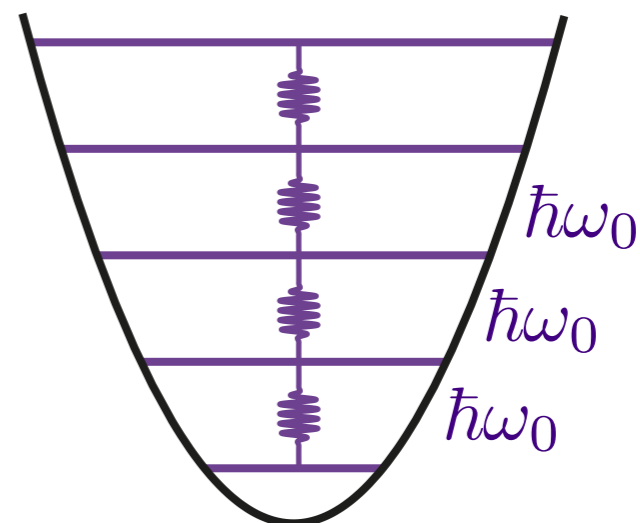
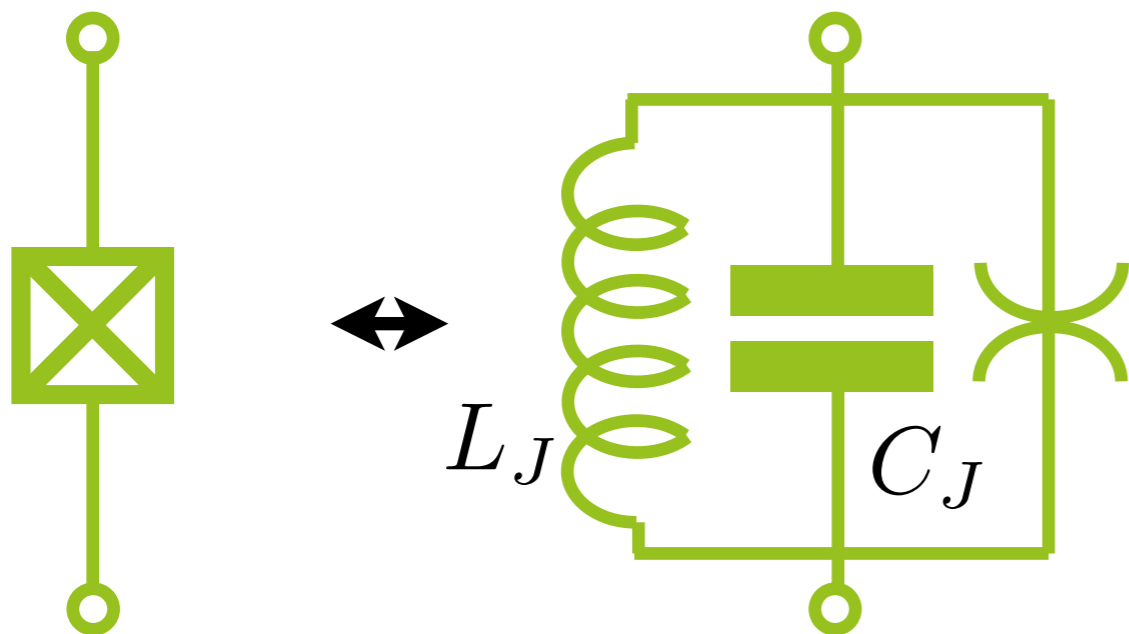
Semiconductor quantum dots



[pic from ETH group]

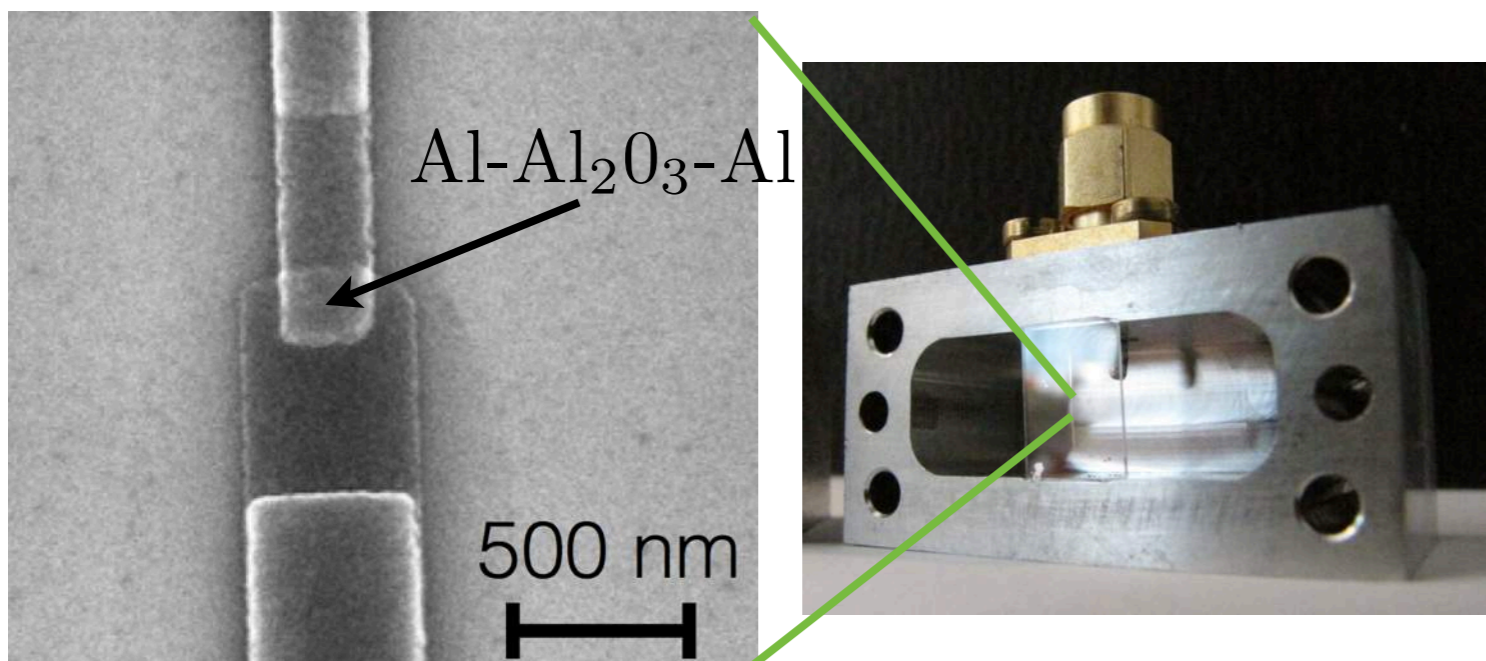
Superconducting circuits with Josephson junctions

dissipation-less **non linear** LC circuit

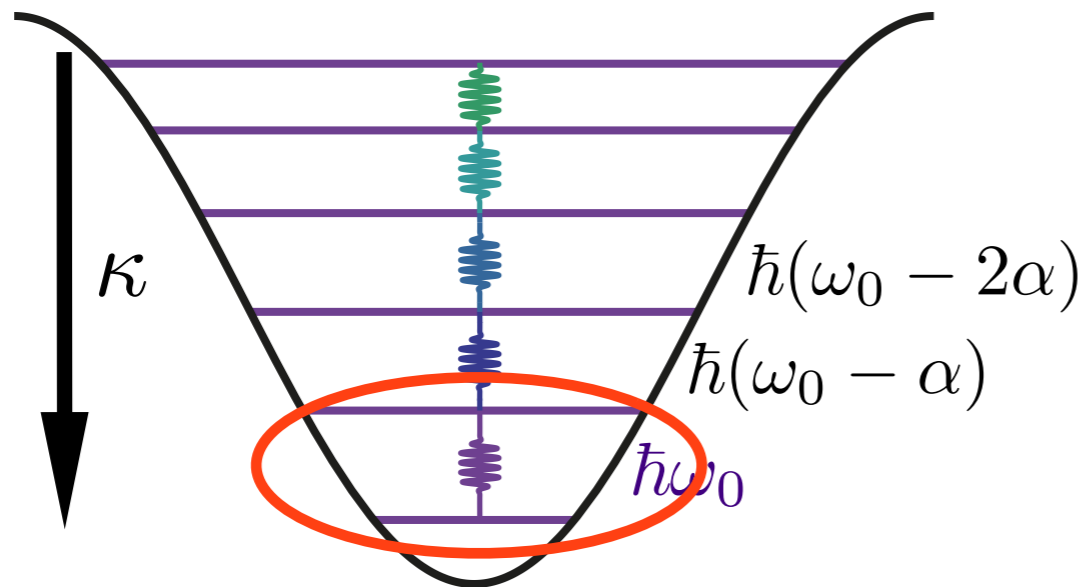


[Yale 2012,
Sherbrooke & IBM 2012,
Aachen & IBM 2014]

$$\hat{H} = \frac{\hat{q}^2}{2C_J} - E_J \cos \frac{\hat{\phi}}{\hbar/2e} = \frac{\hat{q}^2}{2C_J} + \frac{\hat{\phi}^2}{2L_J} + H_{\text{non-lin}}(\hat{\phi})$$



Non-linear superconducting circuits

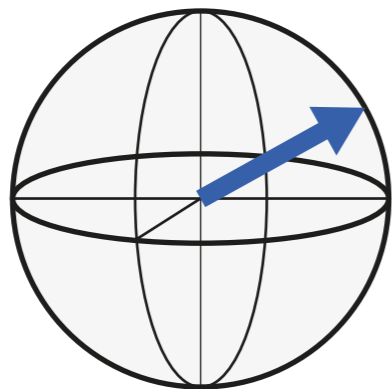


Strongly anharmonic

$$\alpha \gg \kappa$$



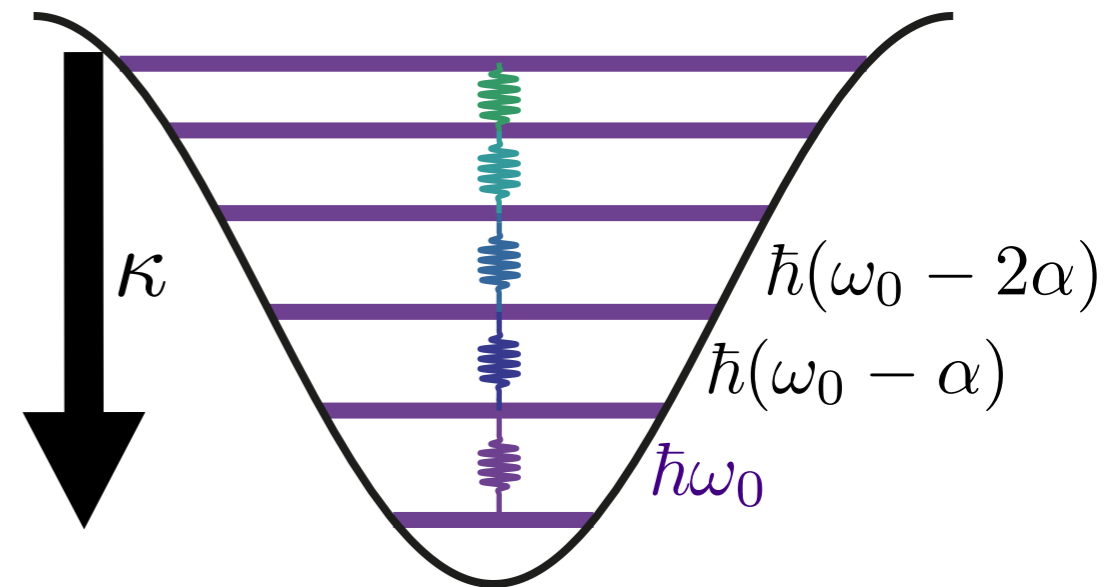
qubit $\hbar\omega\hat{\sigma}_z/2$



First Rabi oscillations in 1999 [NEC group]

Quantonium in 2002 [Saclay group]

Charge qubit, phase qubit [Grenoble & others], flux qubit, transmon [Yale, ETH & others], fluxonium, Xmon...

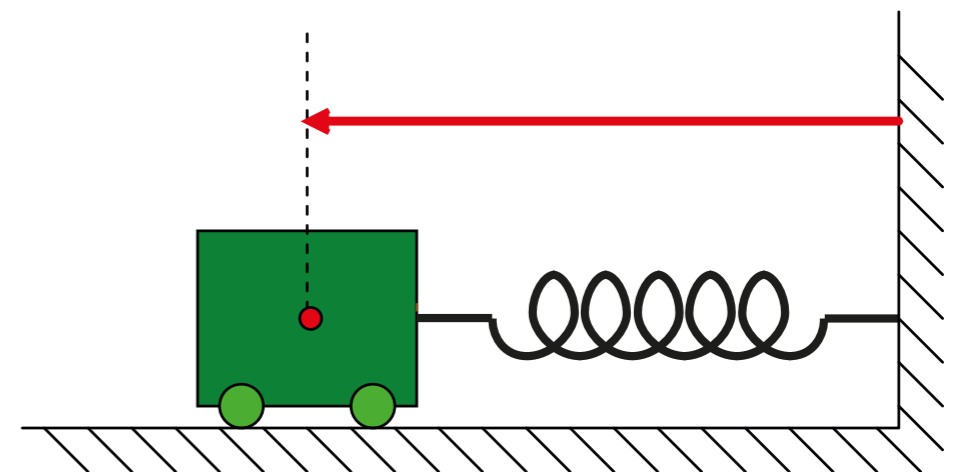


Weakly anharmonic

$$\alpha \ll \kappa$$

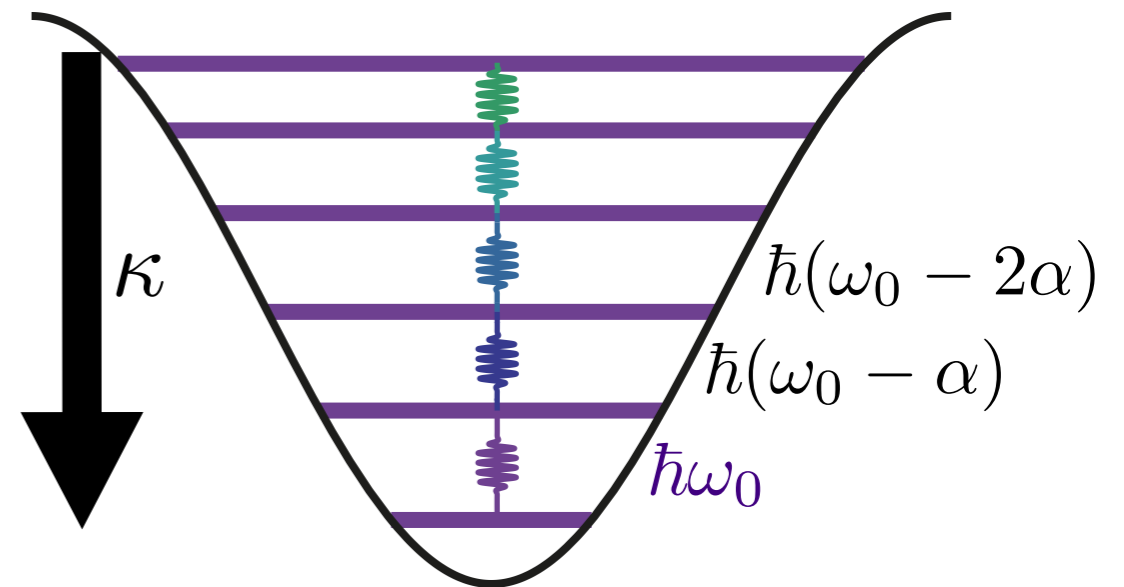


oscillator $\hbar\omega\hat{a}^\dagger\hat{a}$



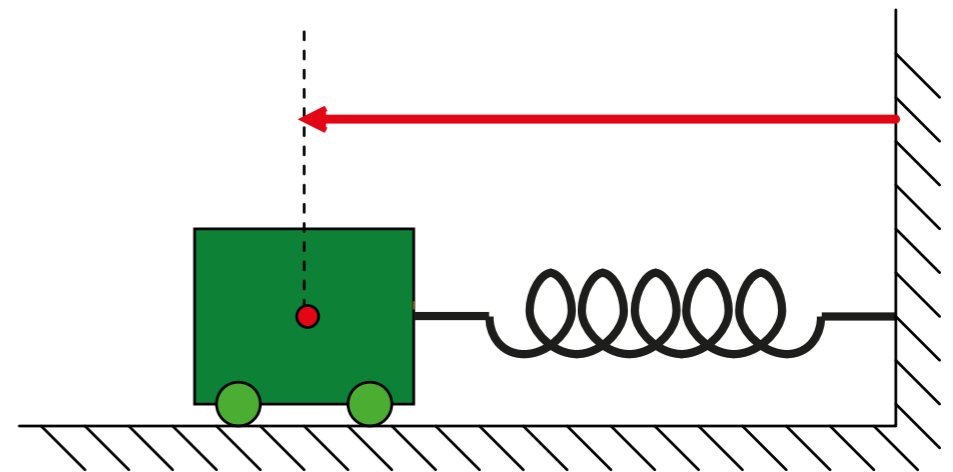
Parametric amplifiers & squeezing
in 1980's [Bell Labs]

Non-linear superconducting circuits

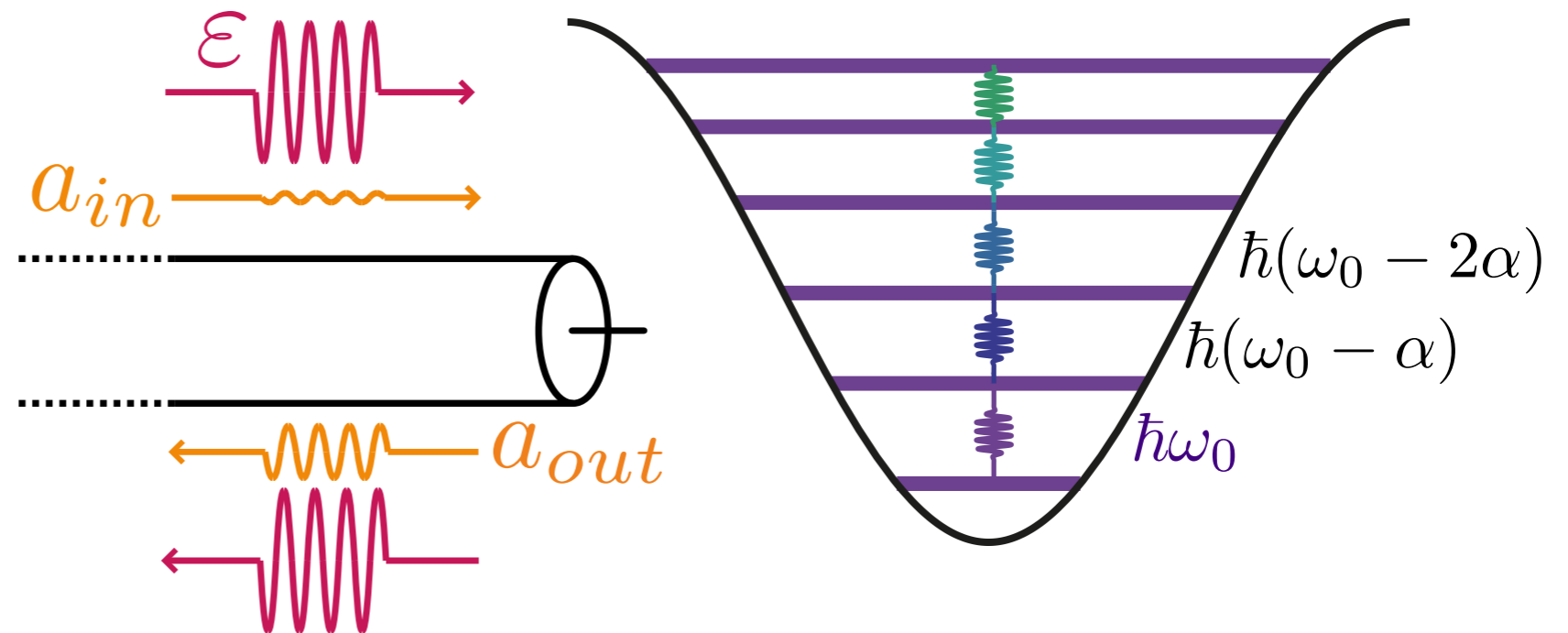


Weakly anharmonic
 $\alpha \ll \kappa$

oscillator $\hbar\omega\hat{a}^\dagger\hat{a}$



Degenerate parametric amplification



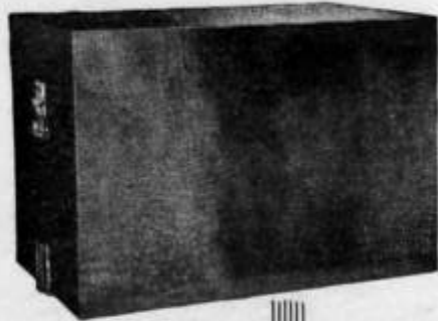
$$H = \hbar\omega_0 p^\dagger p - \hbar\alpha p^\dagger p^\dagger p p / 2$$

$$\hat{a}_{out} = \sqrt{G'} \text{Re}(\hat{a}_{in}) + \frac{i}{\sqrt{G'}} \text{Im}(\hat{a}_{in})$$

[Bell Labs, 1989]
 [Boulder, 2007]
 [Chalmers, 2010]
 [ETH Zurich, 2011]
 [Berkeley, 2011]

...

Ne partez pas en vacances sans un
SUPERHÉTÉRODYNE
MODÈLE PORTATIF



Coffret contenant
 le Superhétérodyne avec tous
 ses accessoires.

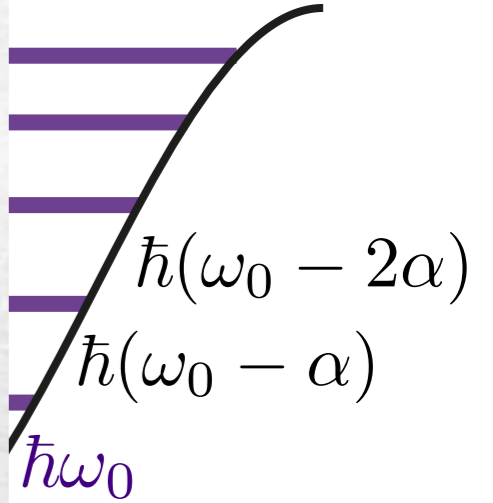
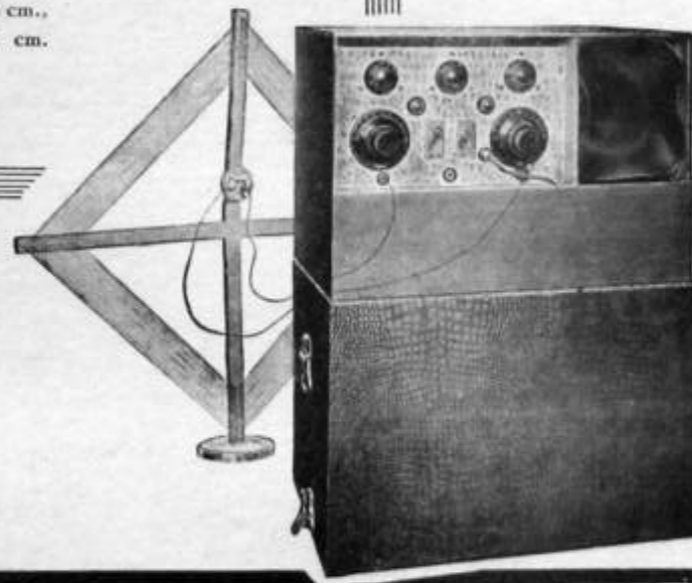
Partout où vous serez : chez vous, à l'hôtel,
 au camping, vous installerez en moins de
 5 minutes votre *Superhétérodyne* et recevrez,
 avec une étonnante pureté, tous les Radio-
 Concerts en haut-parleur.

Rien de plus enfantin à installer qu'un *Superhétérodyne* :
 le *Superhétérodyne* étant dans son coffret, vous enlevez le
 capot et posez l'appareil dessus, comme le montre la gravure
 au bas de la page ; vous déployez le cadre et le connectez aux
 bornes de l'appareil. C'est tout.

**Le réglage du Superhétérodyne
 est presque automatique et,
 en tout cas, d'une simplicité
 extraordinaire.**

Dans son coffret, l'appareil, avec tous ses accessoires, est à l'abri
 de l'humidité et de la poussière. Ce coffret s'arrime sur une
 voiture, exactement comme une malle-auto. Le poids total de
 l'installation est d'environ 12 kilos. Les
 dimensions du coffret sont : long. 58 cm.,
 hauteur 40 cm., profondeur 35 cm.

NOTICE FRANCO



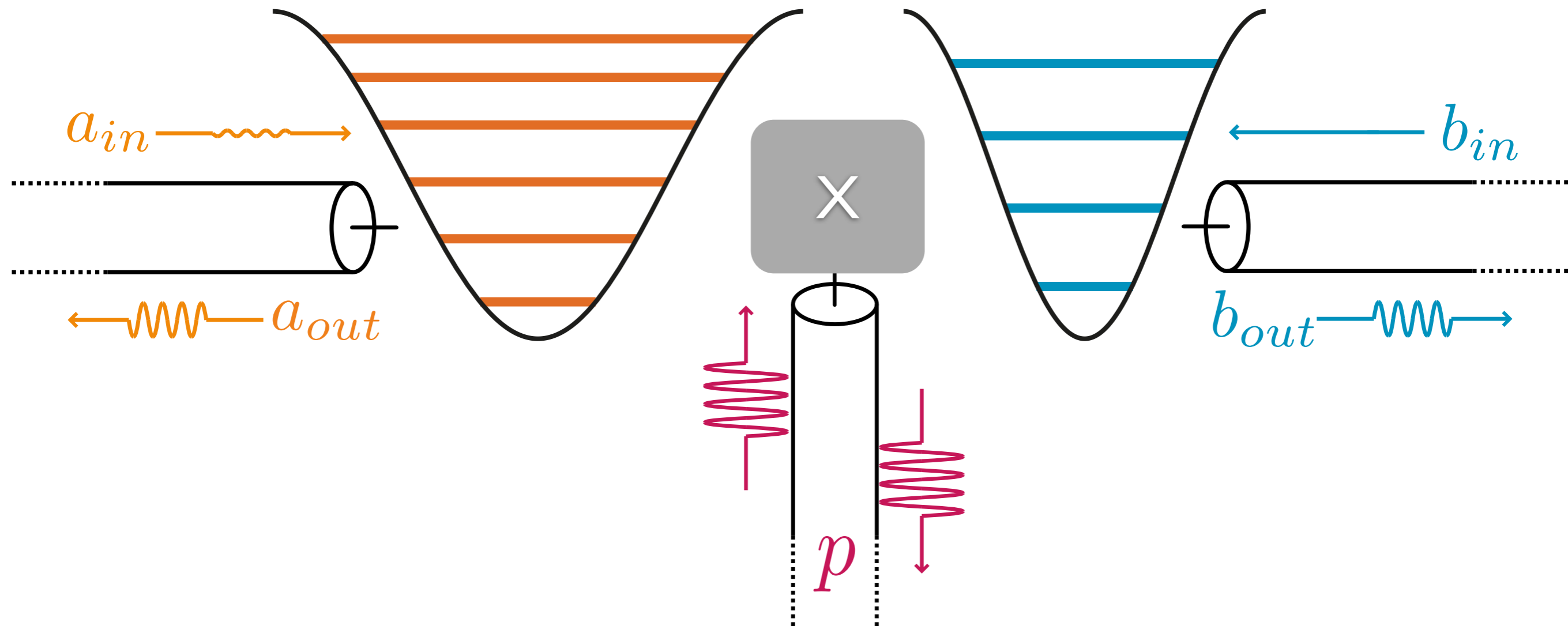
$$H = \hbar\omega_0 p^\dagger p -$$

\hat{a}

Ets Radio-L.-L. Inventeurs-Constructeurs du **SUPERHÉTÉRODYNE**
 66, Rue de l'Université -- PARIS

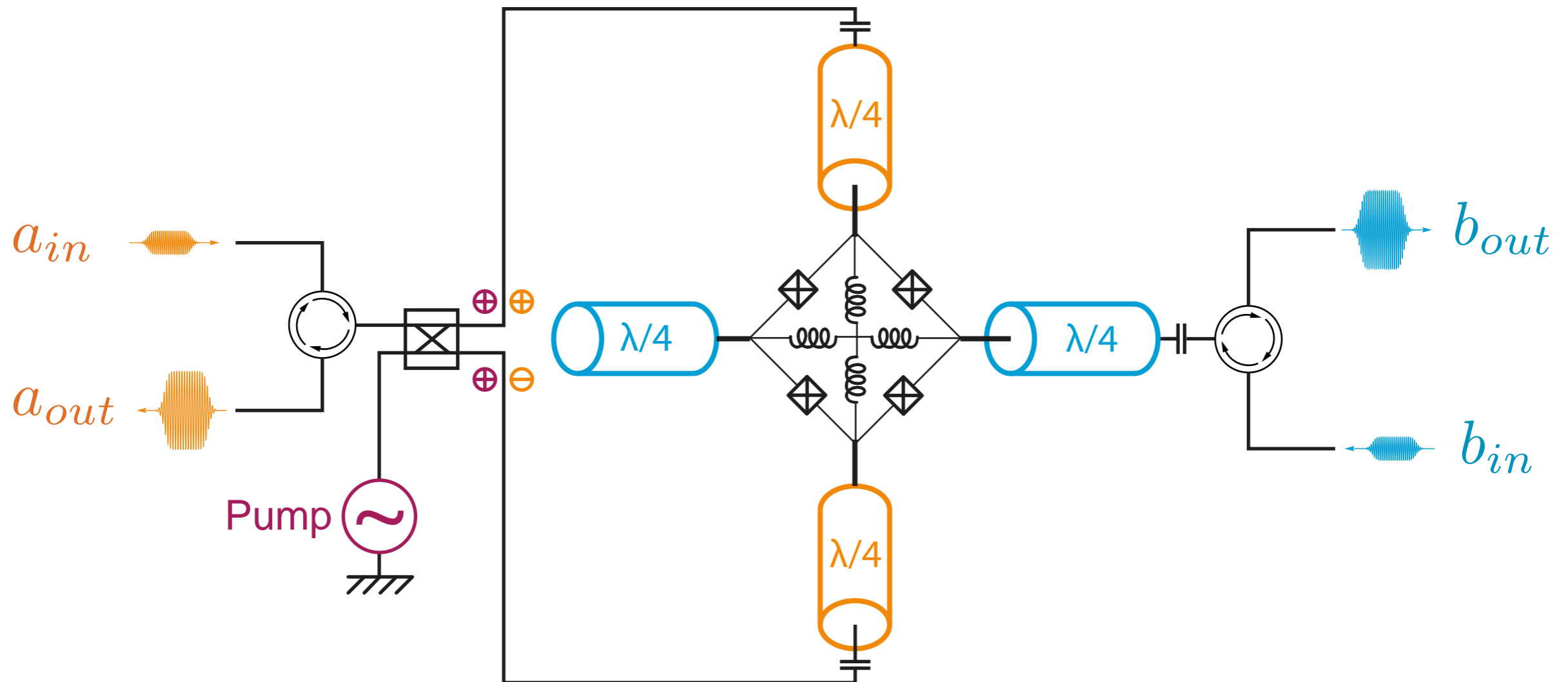
Three wave mixing at micro-wave frequencies

$$\hat{H}_{\text{mix}} = \hbar\chi(\hat{p} + \hat{p}^\dagger)(\hat{a} + \hat{a}^\dagger)(\hat{b} + \hat{b}^\dagger)$$



Three wave mixing at micro-wave frequencies

$$\hat{H}_{\text{mix}} = \hbar\chi(\hat{p} + \hat{p}^\dagger)(\hat{a} + \hat{a}^\dagger)(\hat{b} + \hat{b}^\dagger)$$



Central inductor enables to operate the device on a larger flux range
 → frequency tunability

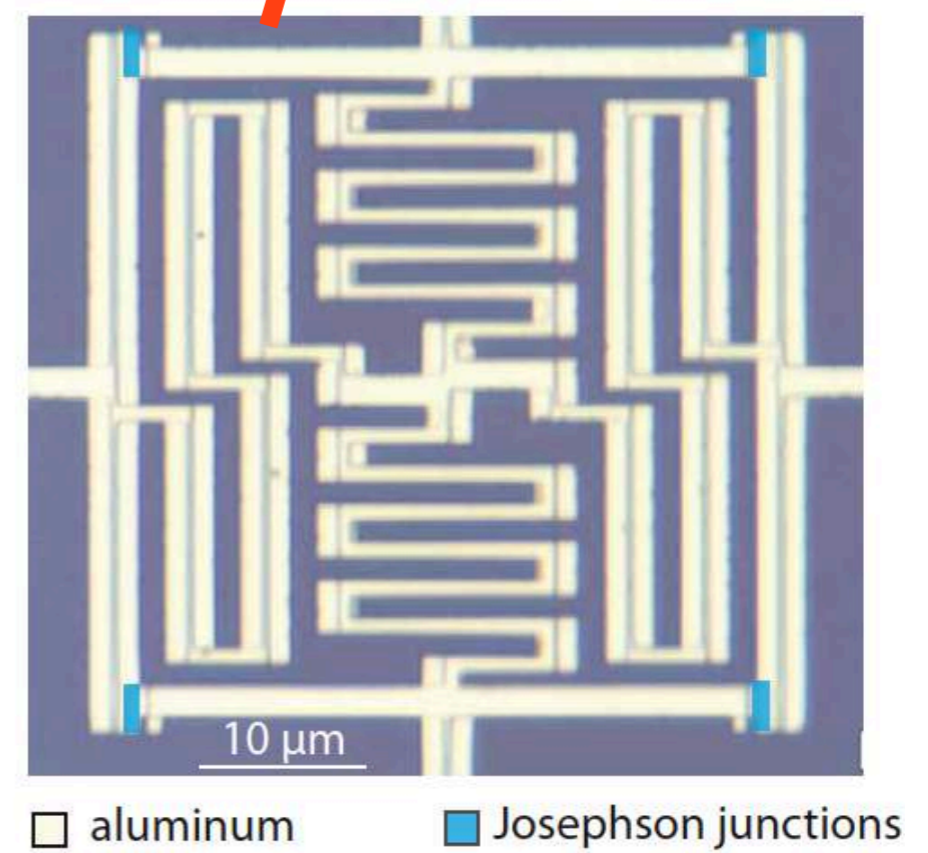
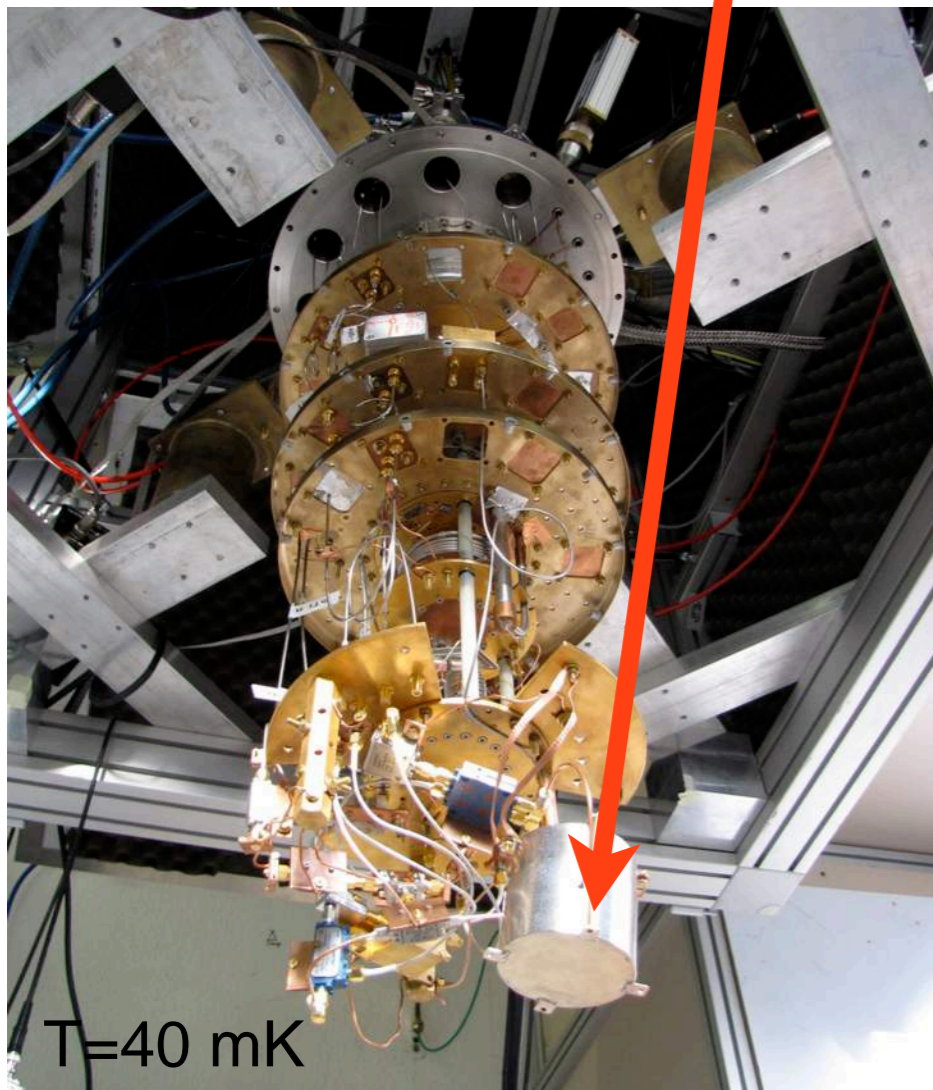
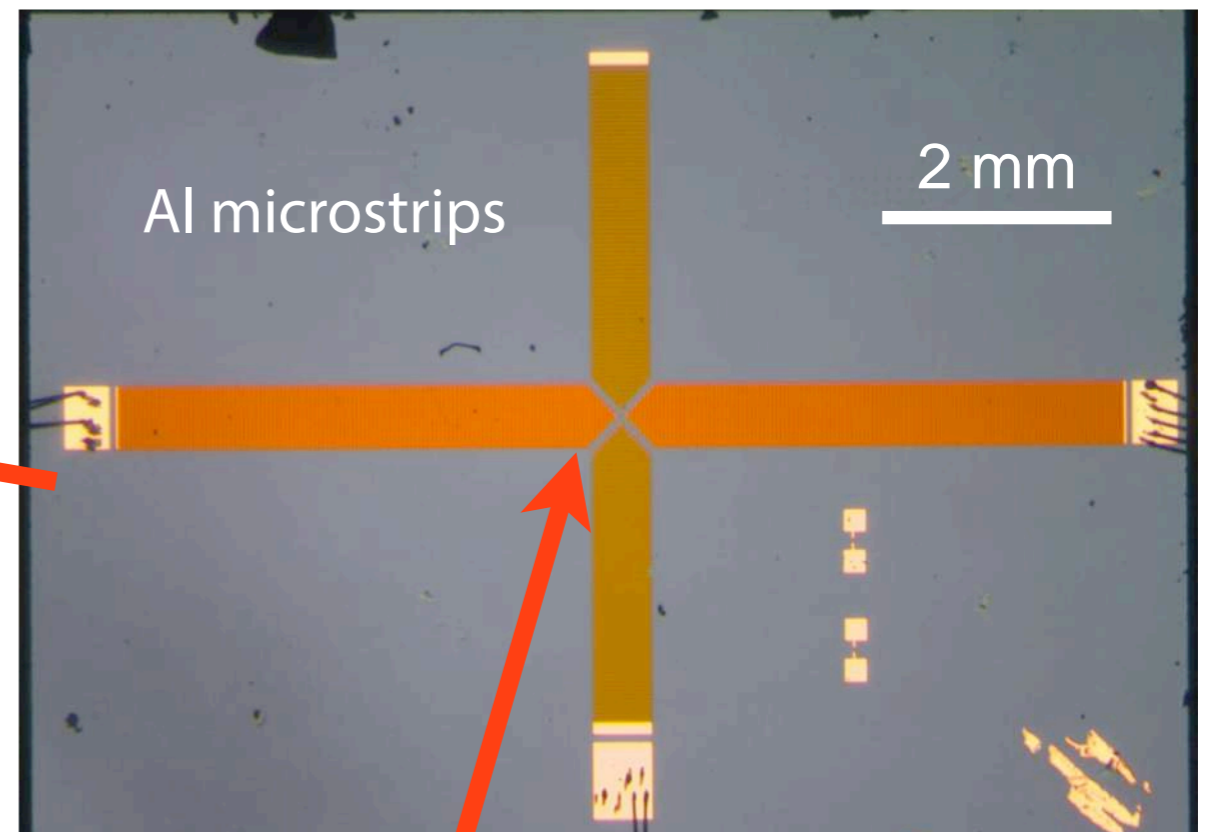
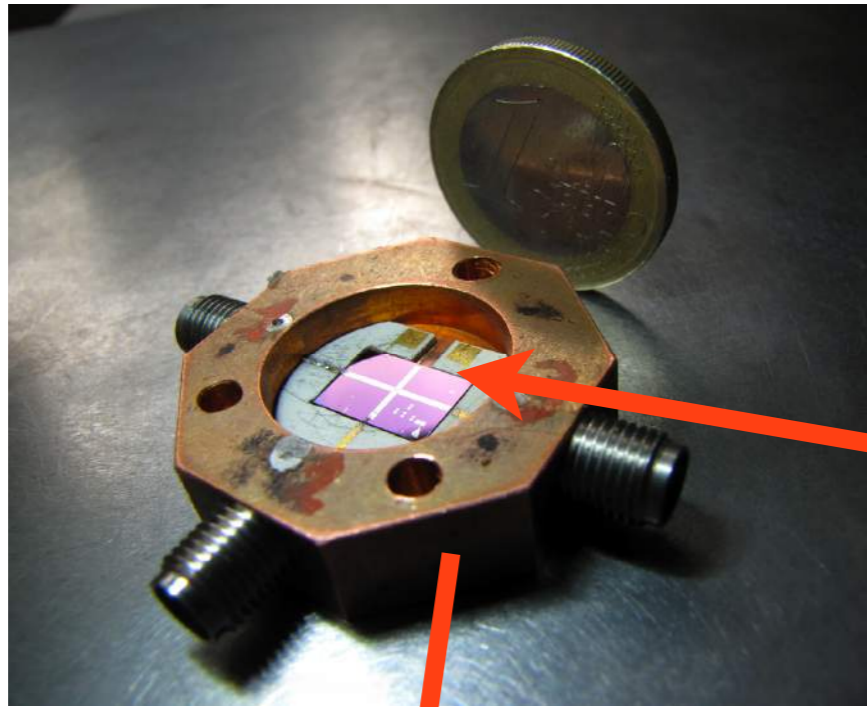
[Roch, Flurin *et al.*, PRL (2012)]

improvement on

[Bergeal *et al.*, Nature (2010)]

[Bergeal *et al.*, Nature Physics (2010)]

Realization

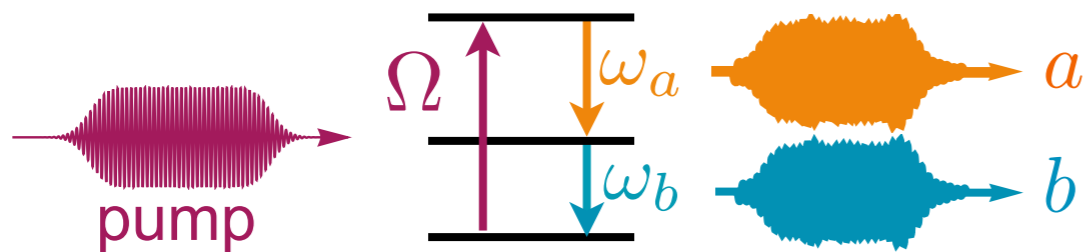


Parametric down-conversion mode

$$\hat{H}_{\text{mix}} = \hbar\chi(\hat{p} + \hat{p}^\dagger)(\hat{a} + \hat{a}^\dagger)(\hat{b} + \hat{b}^\dagger)$$

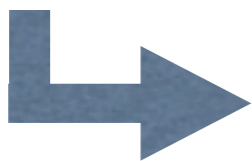
$$\Omega = \omega_a + \omega_b$$

$$\hat{H}_{\text{mix}} = \hbar\chi(p \hat{a}^\dagger \hat{b}^\dagger + p^* \hat{a} \hat{b})$$



Quantum limited amplifier
Entanglement source

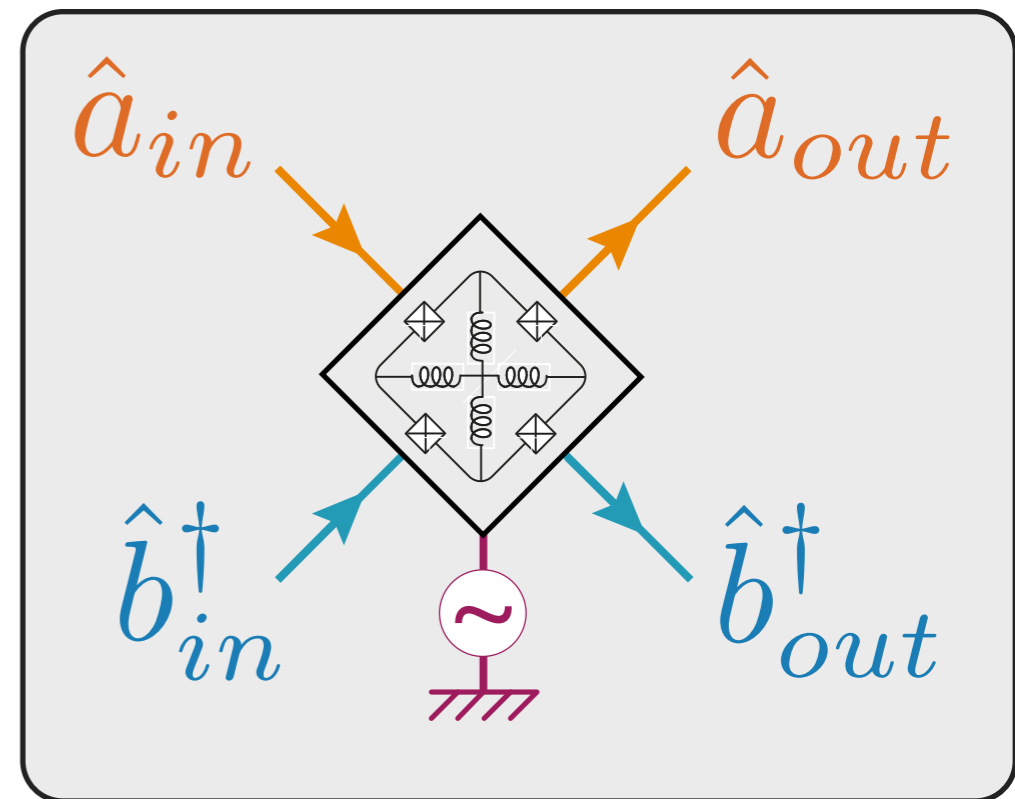
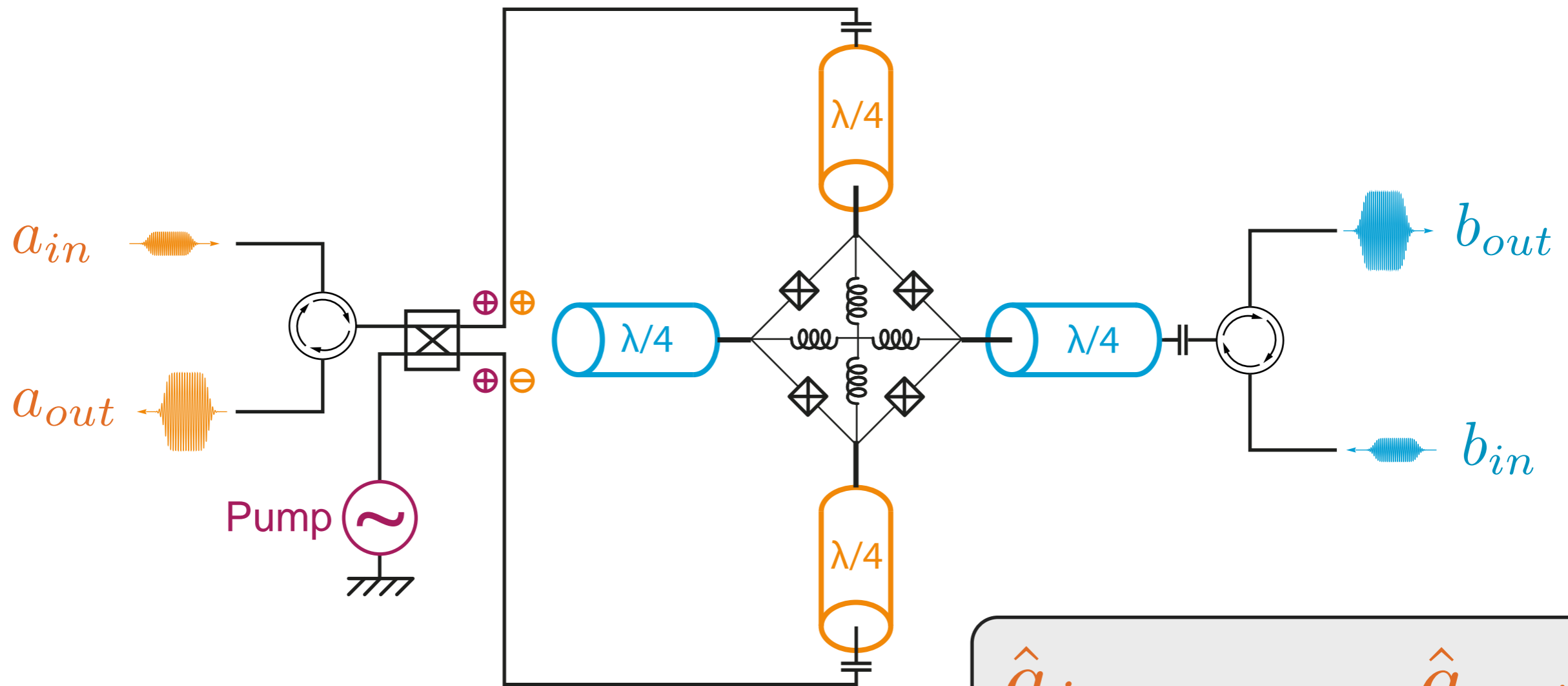
Unitary evolution



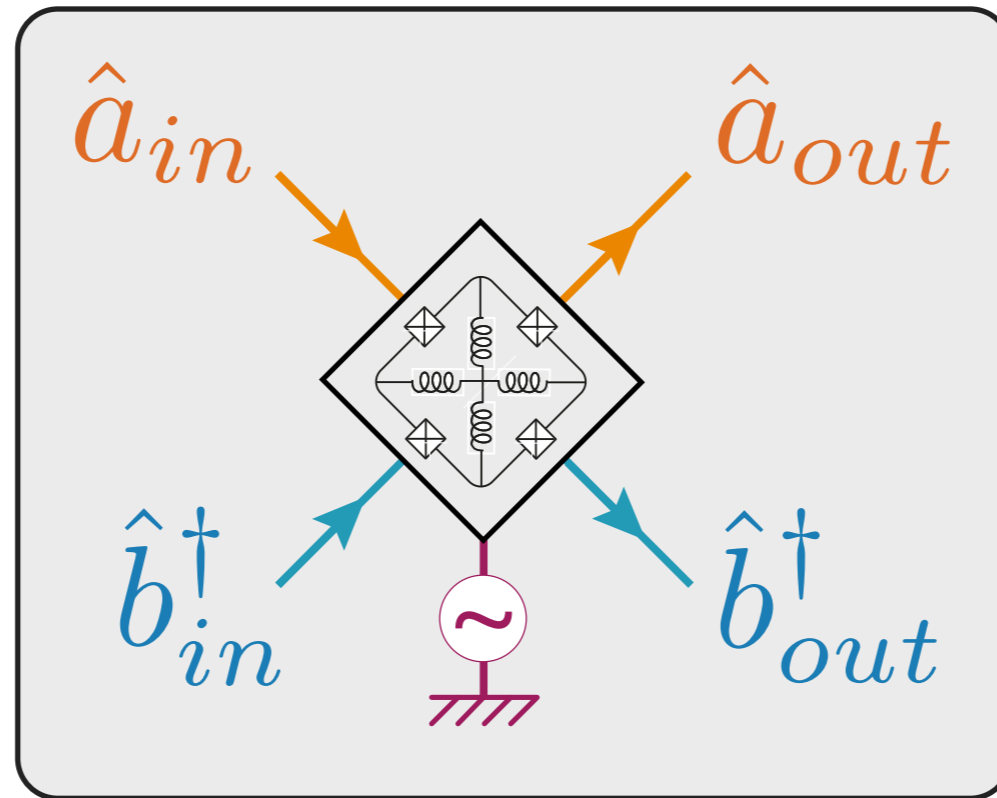
2-mode squeezing operator

$$\hat{S} = e^{r\hat{a}^\dagger \hat{b}^\dagger - r^* \hat{a} \hat{b}}$$

Josephson mixer



Josephson mixer



$$\hat{a}_{out} = \hat{S}^\dagger \hat{a}_{in} \hat{S} = \cosh(r) \hat{a}_{in} + e^{i\theta_p} \sinh(r) \hat{b}_{in}^\dagger$$

$$\hat{b}_{out}^\dagger = \hat{S}^\dagger \hat{b}_{in}^\dagger \hat{S} = \cosh(r) \hat{b}_{in}^\dagger + e^{-i\theta_p} \sinh(r) \hat{a}_{in}$$

$$\text{with } \hat{S} = e^{r \hat{a}^\dagger \hat{b}^\dagger - r^* \hat{a} \hat{b}}$$

Josephson mixer as an amplifier

Quantum limited phase preserving amplifier

$$\langle \hat{a}_{out} \rangle = \cosh(r) \langle \hat{a}_{in} \rangle \quad \text{for} \quad \langle \hat{b}_{in}^\dagger \rangle = 0$$

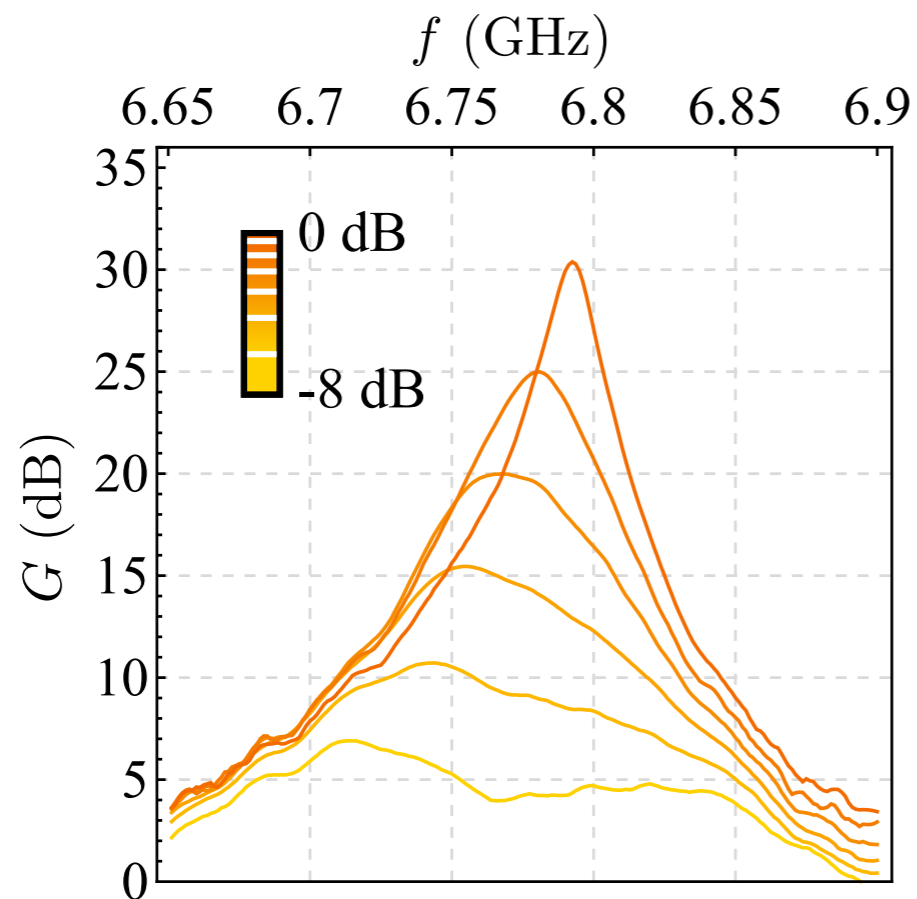
$$\hat{a}_{out} = \hat{S}^\dagger \hat{a}_{in} \hat{S} = \cosh(r) \hat{a}_{in} + e^{i\theta_p} \sinh(r) \hat{b}_{in}^\dagger$$

$$\hat{b}_{out}^\dagger = \hat{S}^\dagger \hat{b}_{in}^\dagger \hat{S} = \cosh(r) \hat{b}_{in}^\dagger + e^{-i\theta_p} \sinh(r) \hat{a}_{in}$$

Josephson mixer as an amplifier

Quantum limited phase preserving amplifier

$$\langle \hat{a}_{out} \rangle = \cosh(r) \langle \hat{a}_{in} \rangle \quad \text{for} \quad \langle \hat{b}_{in}^\dagger \rangle = 0$$



Gain = 20dB

Bandwidth = 10 MHz

Tunability > 400 MHz

[Roch et al., PRL (2012)]

System efficiency > 80%

[Campagne et al., PRX (2013)]

Lumped version

Gain = 20 dB

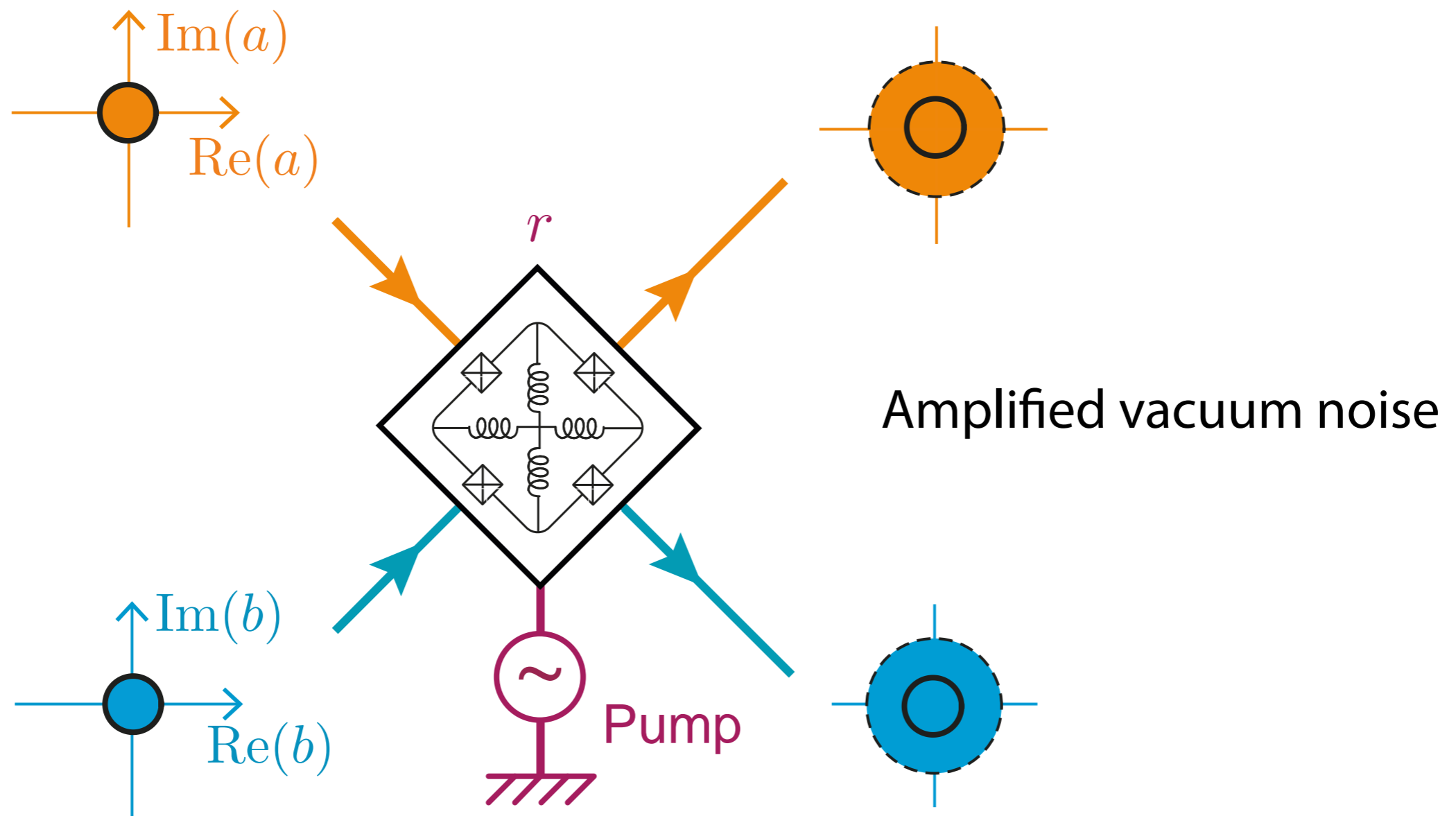
Bandwidth > 50 MHz

P1dB = -104 dBm

Tunability = 1 GHz

[Pillet et al., in prep. (2014)]

EPR state generation

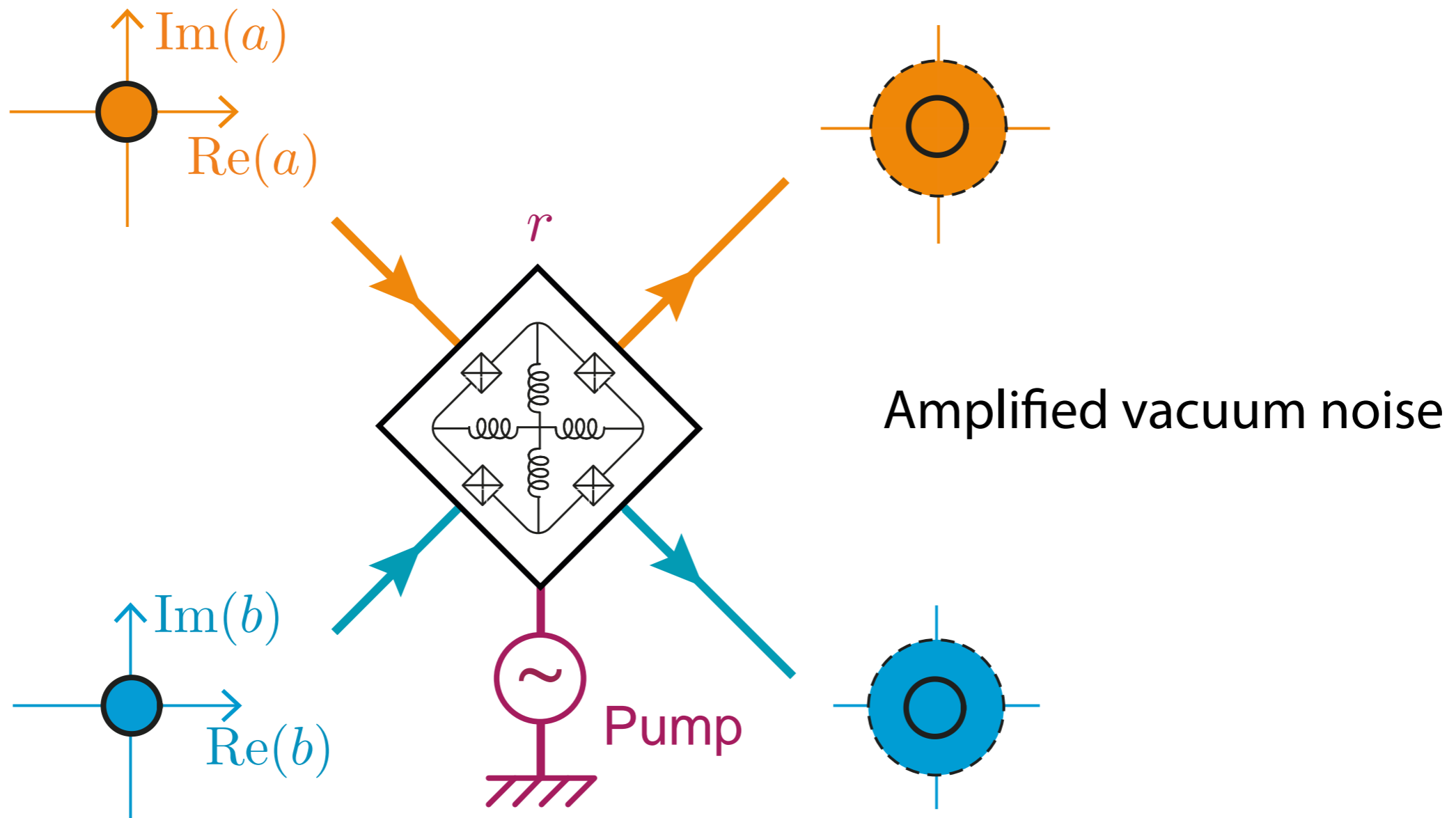


EPR state generation

$$|0\rangle_a |0\rangle_b$$

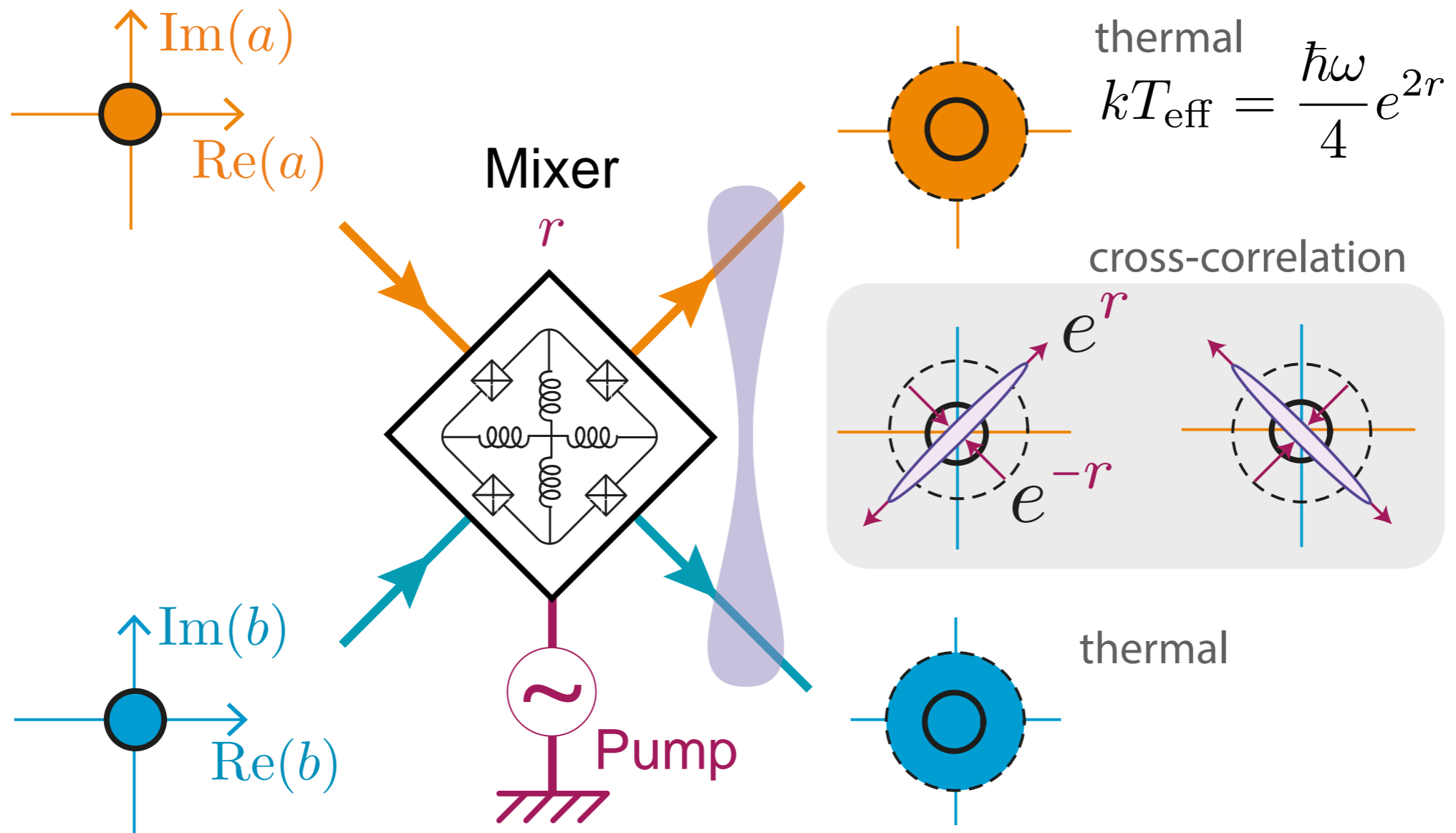


$$|\text{EPR}\rangle = \hat{S}|0\rangle_a |0\rangle_b$$



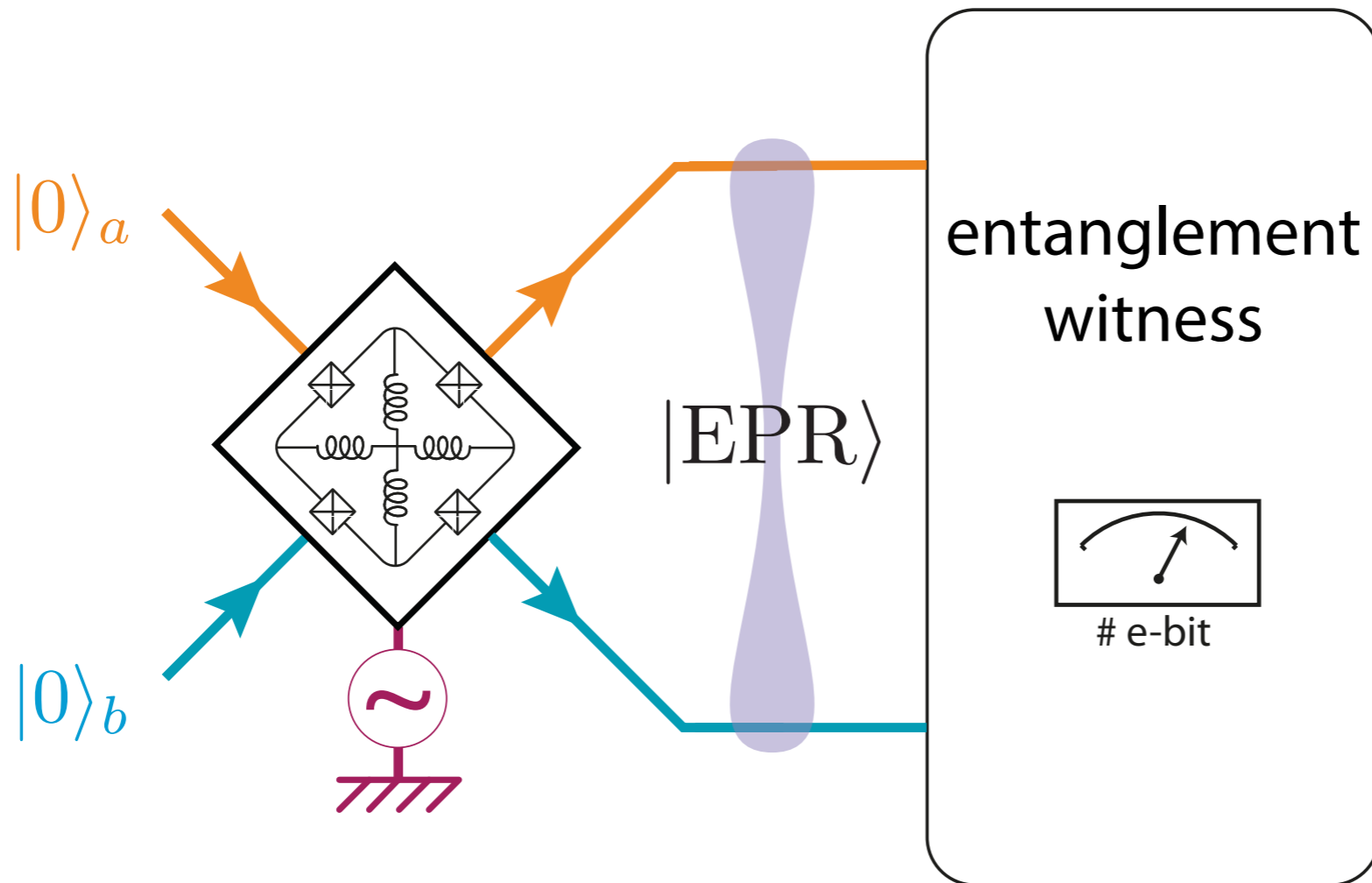
EPR state generation

$$|0\rangle_a |0\rangle_b \longrightarrow \frac{1}{\cosh r} \sum_n (\tanh r)^n |n\rangle_a |n\rangle_b$$

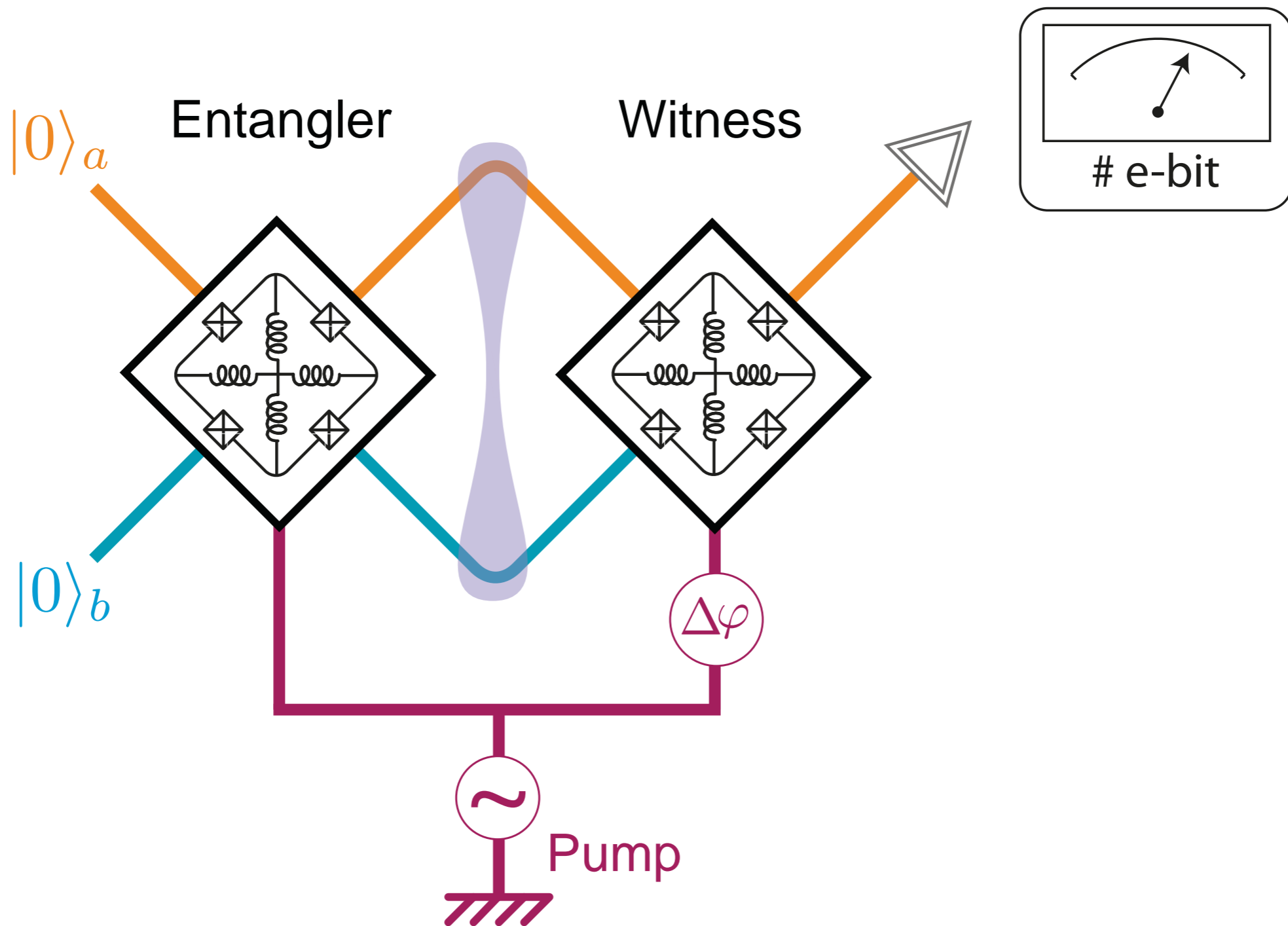


Entanglement measurement

$$|\text{EPR}\rangle = \hat{S}|0\rangle_a|0\rangle_b \longrightarrow \text{Entanglement witness}$$



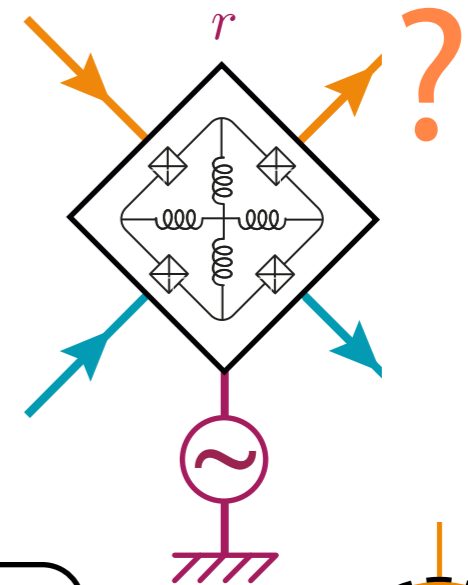
Generation and measurement of entangled beams



Josephson Mixer as Entanglement witness

Entanglement witness

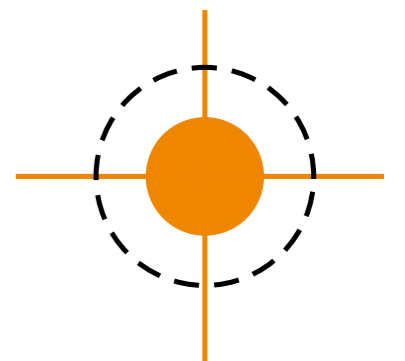
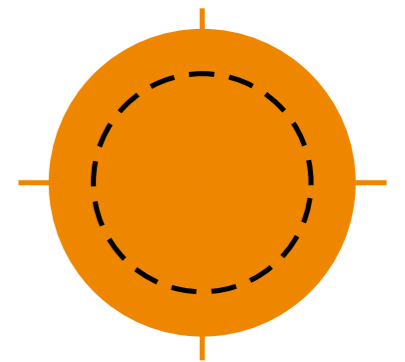
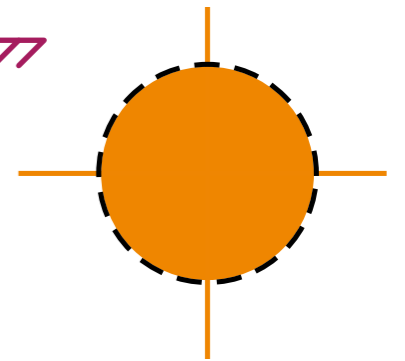
sufficient criterion for input entanglement



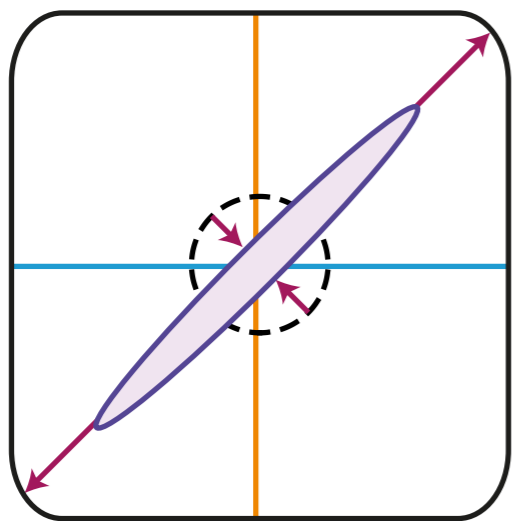
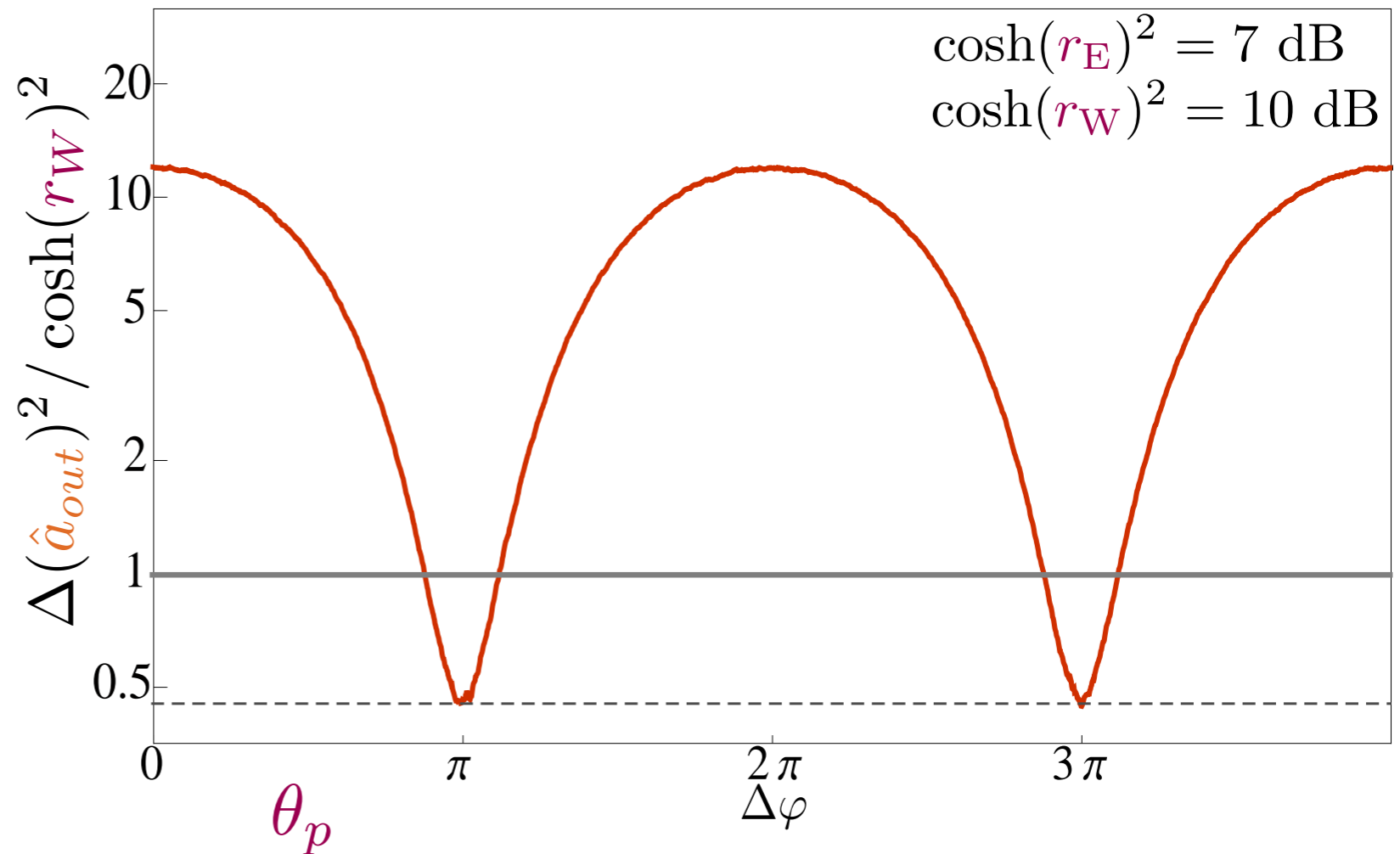
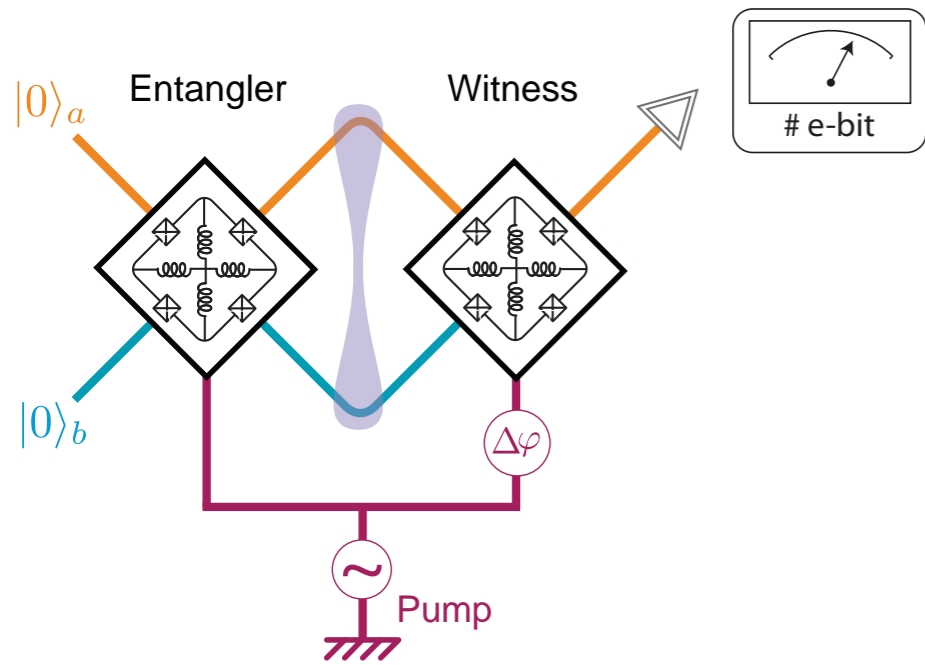
$$|0\rangle_{a_{in}} |0\rangle_{b_{in}} \implies \forall \theta_p \frac{\Delta(\hat{a}_{out})^2}{\cosh(r)^2} = 1$$

$$(\hat{a}_{in}, \hat{b}_{in}^\dagger) \text{ non-entangled} \implies \forall \theta_p \frac{\Delta(\hat{a}_{out})^2}{\cosh(r)^2} \geq 1$$

$$\exists \theta_p \frac{\Delta(\hat{a}_{out})^2}{\cosh(r)^2} < 1 \implies (\hat{a}_{in}, \hat{b}_{in}^\dagger) \text{ entangled}$$



EPR: Entanglement measurement



$+11 \text{ dB}$ anti-squeezing
 -3.5 dB squeezing

Logarithmic negativity

$$E_N = -\log_2(\min) = 1.15 \text{ ebits}$$

Entanglement rate

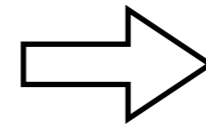
$$E_N \cdot \Delta f = 10 \text{ Mebits} \cdot \text{s}^{-1}$$

Can we do something useful of CV-entanglement?

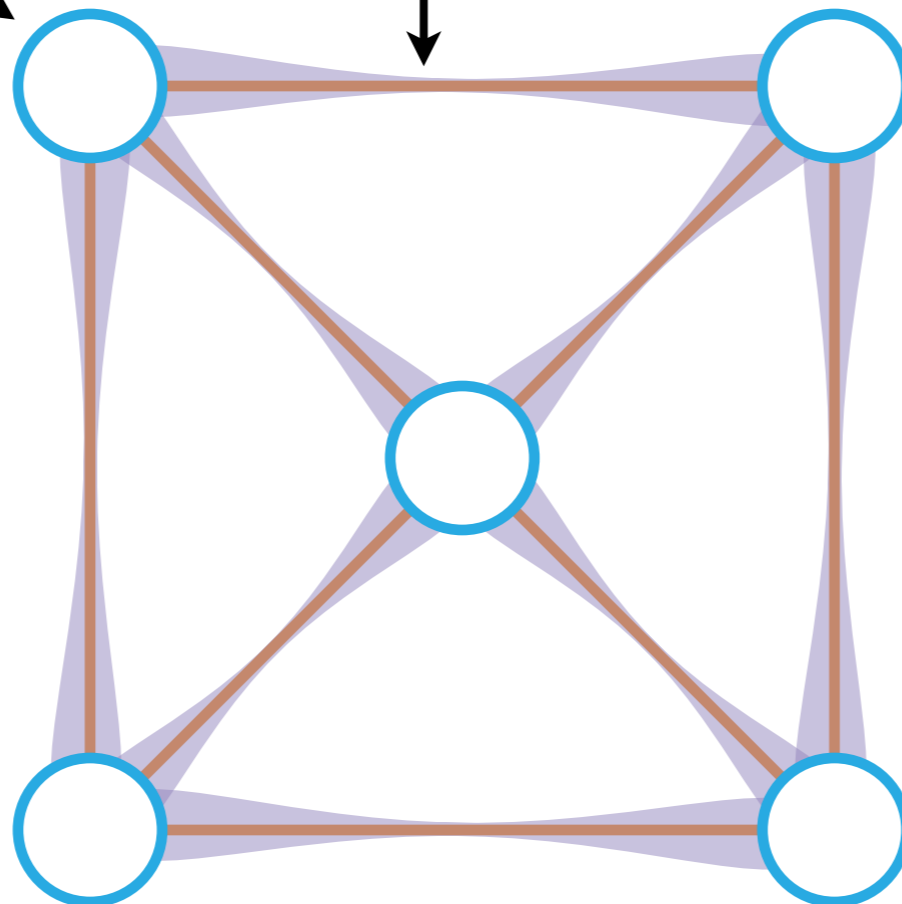
quantum network

quantum node
entanglement generation
+
quantum memory

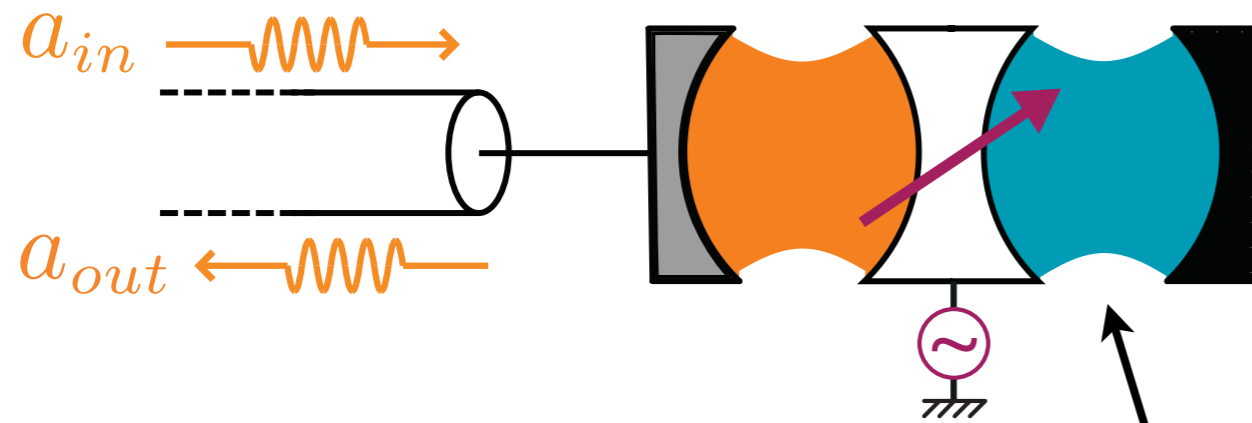
photonic channel



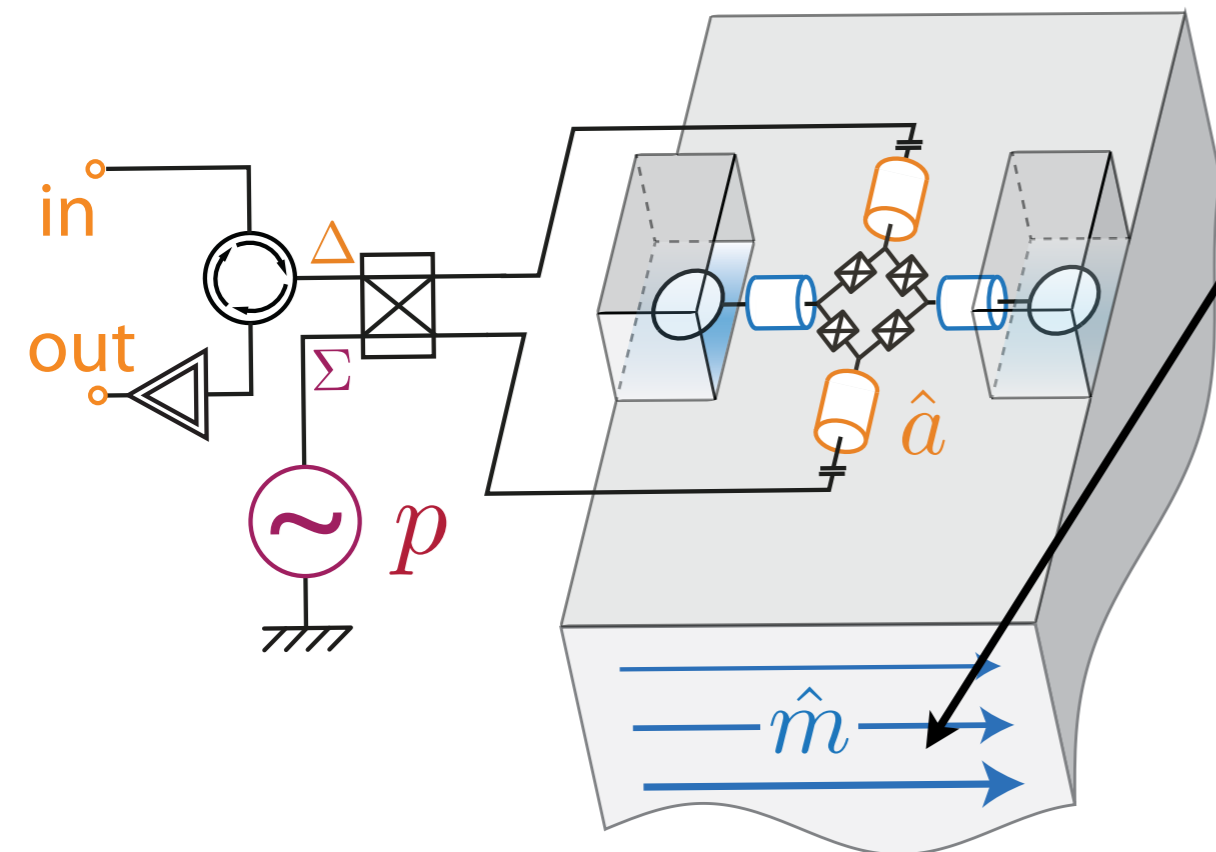
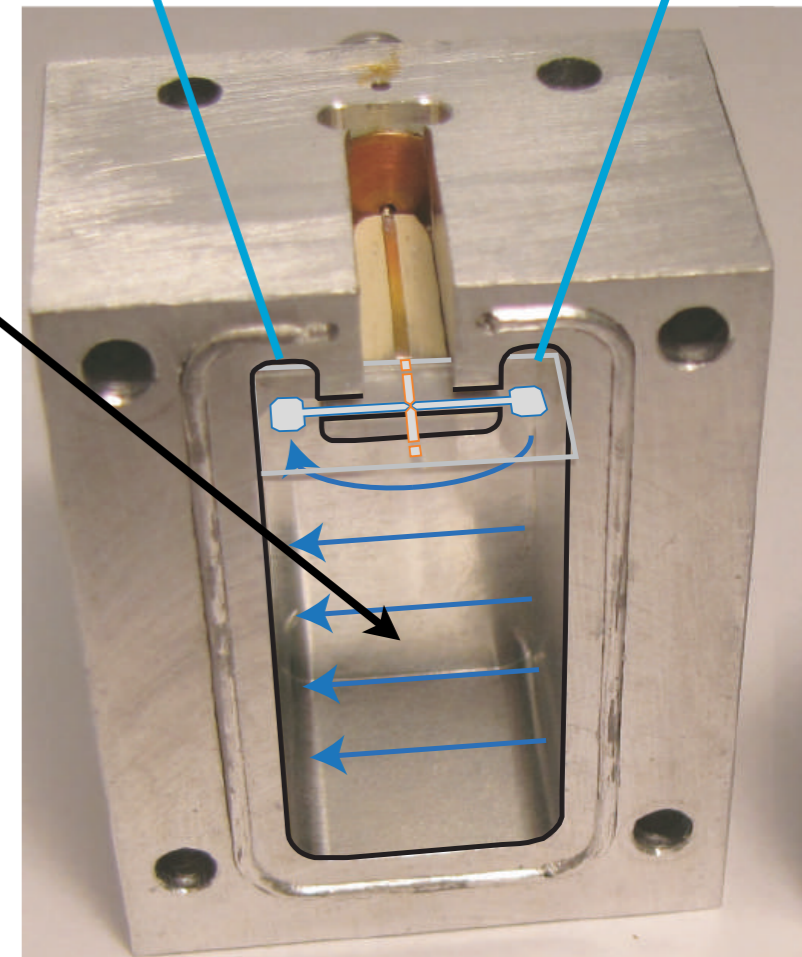
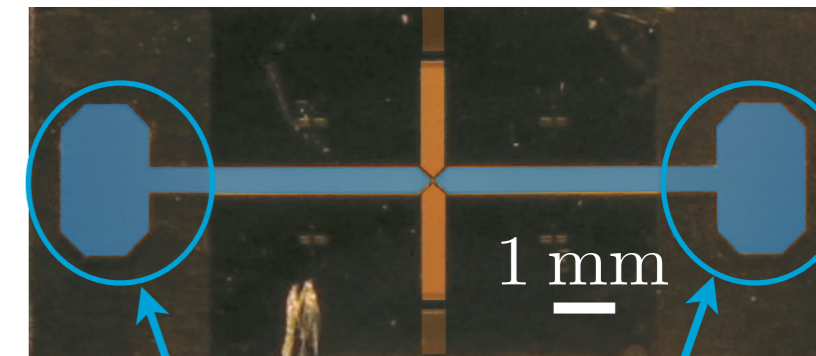
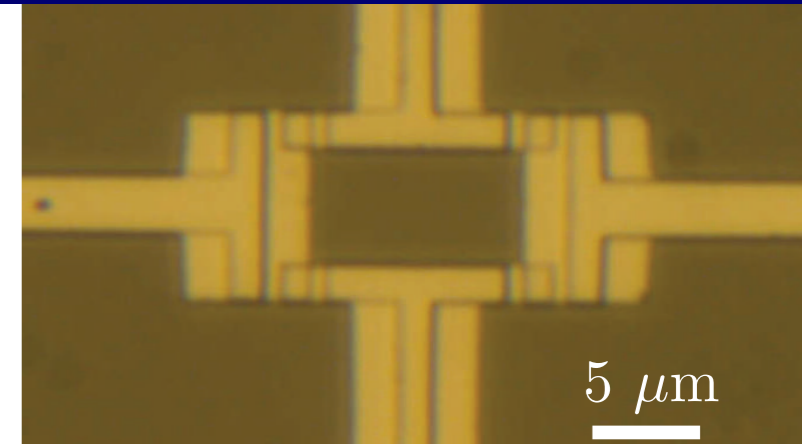
Distribution of
entanglement
over a network



Quantum memory for microwaves

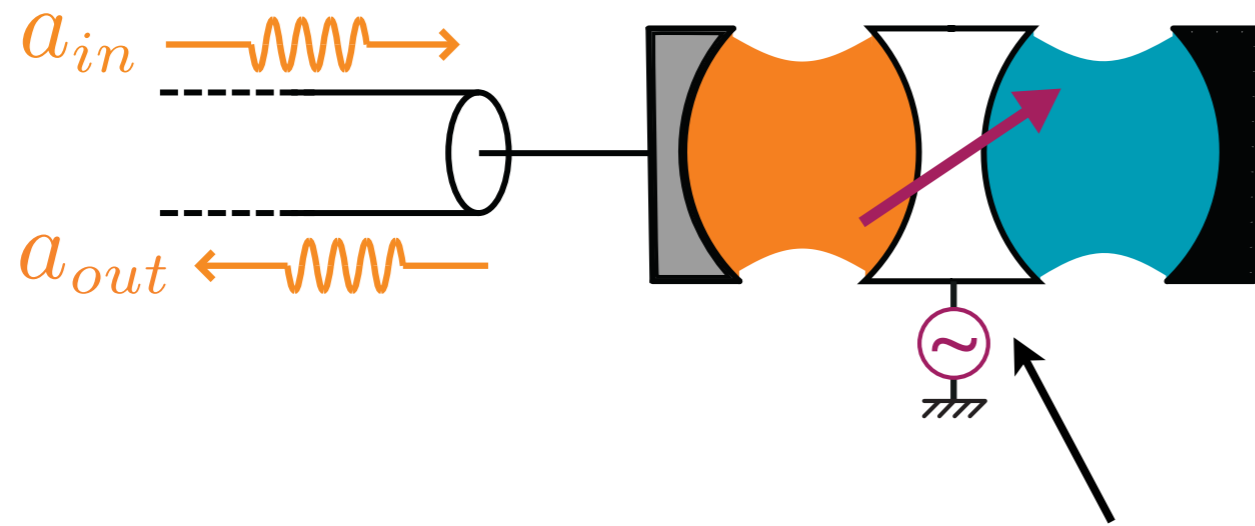


memory cavity \hat{b}
3D superconducting
cavity for
enhanced storage
time

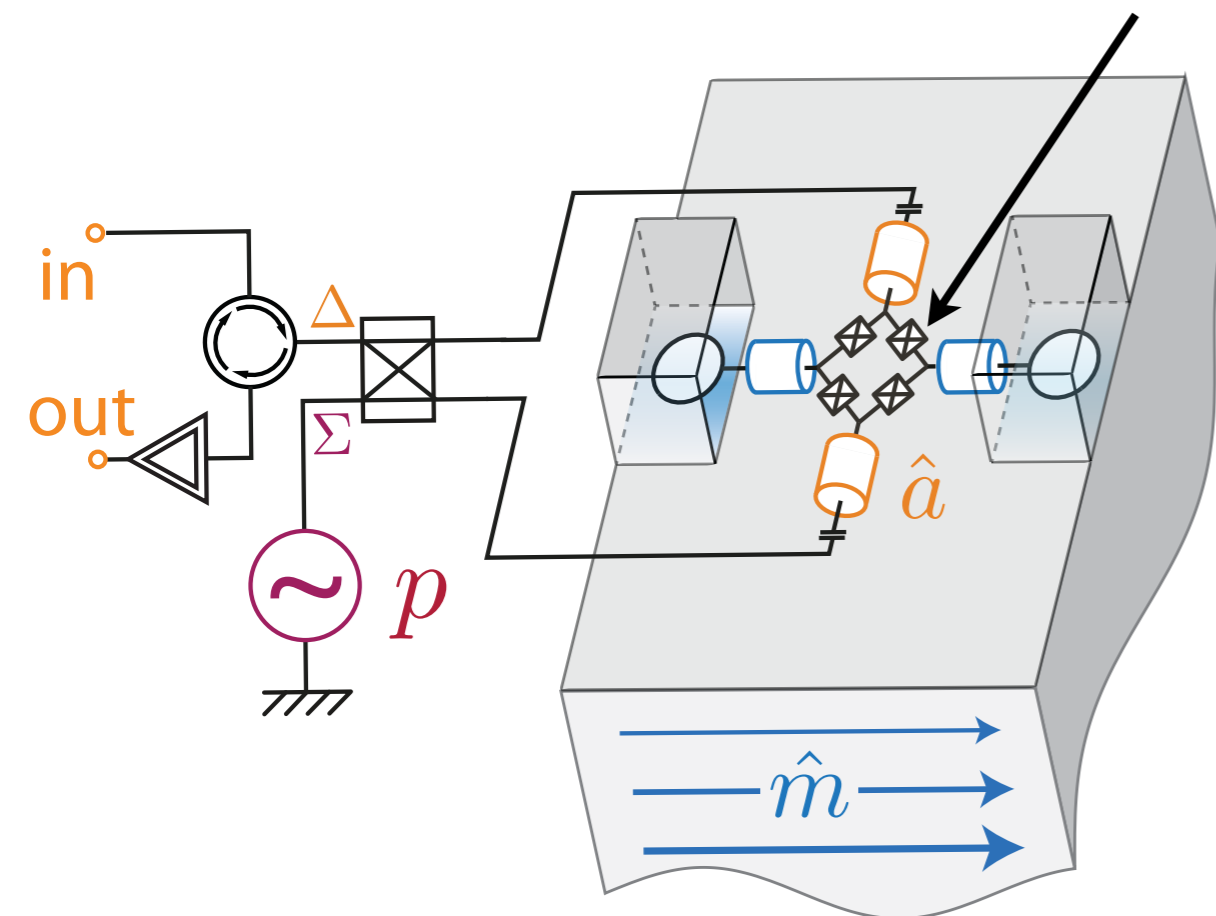
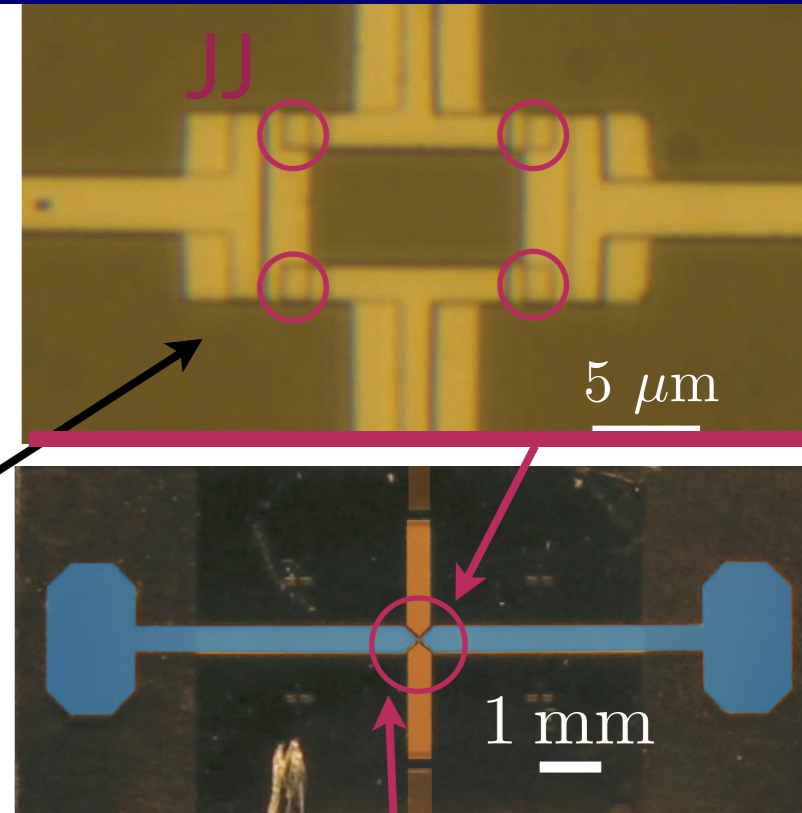


$$f_b = 7.5 \text{ GHz}$$

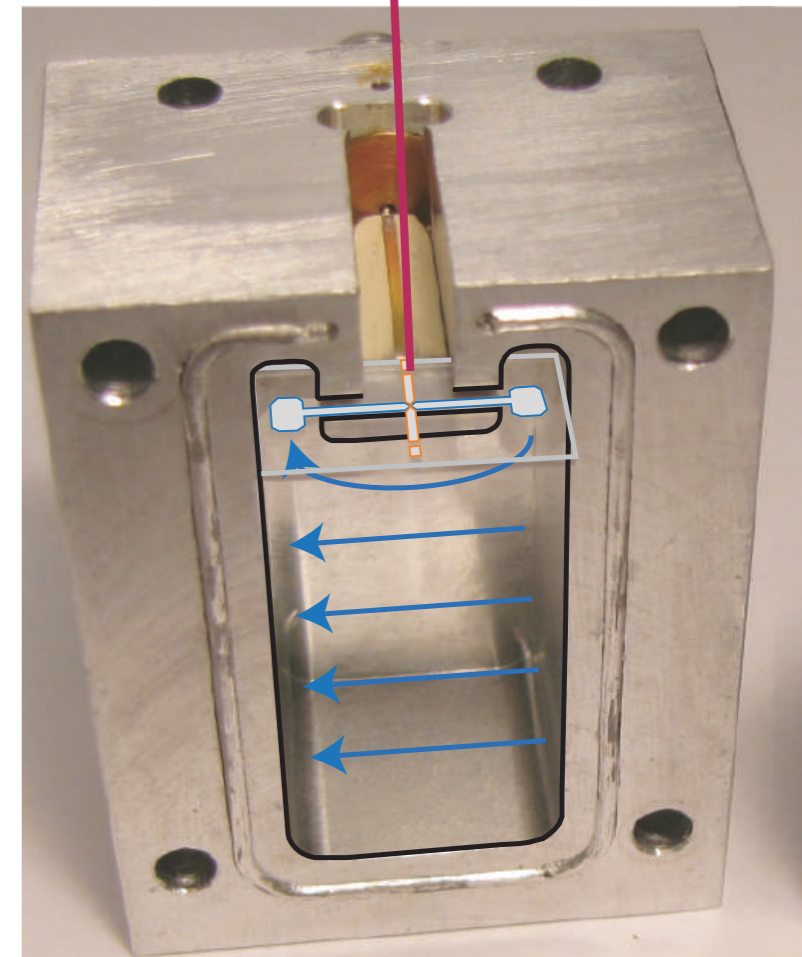
Quantum memory for microwaves



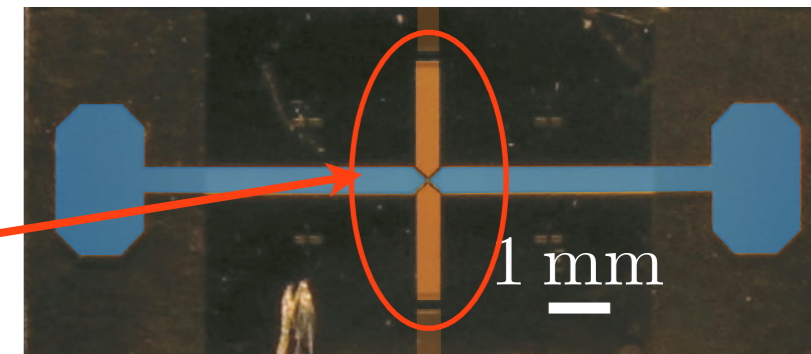
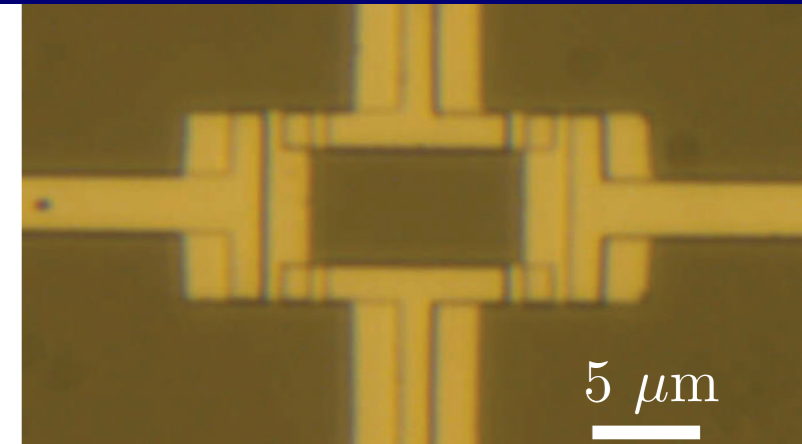
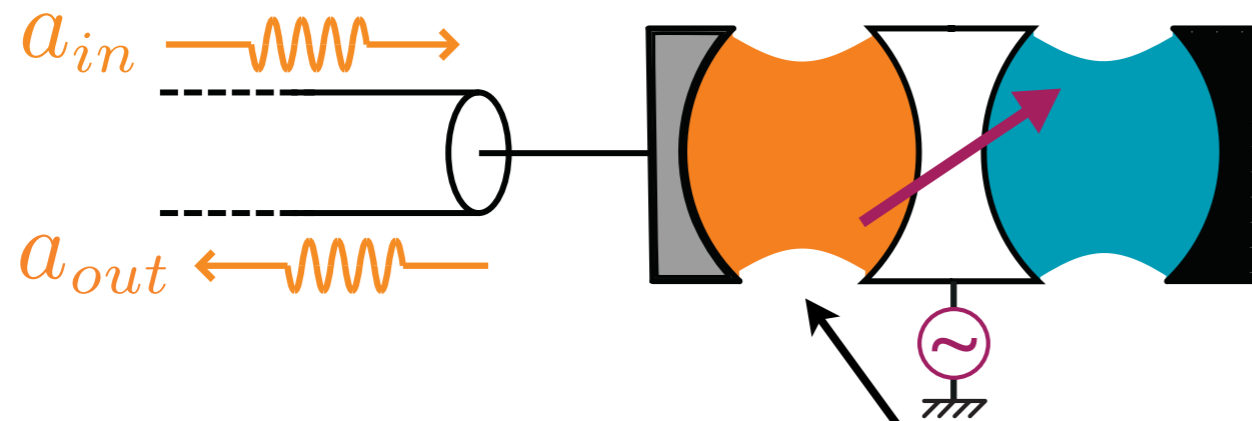
Fast tunable coupling
Josephson Ring



$$f_b = 7.5 \text{ GHz}$$



Quantum memory for microwaves

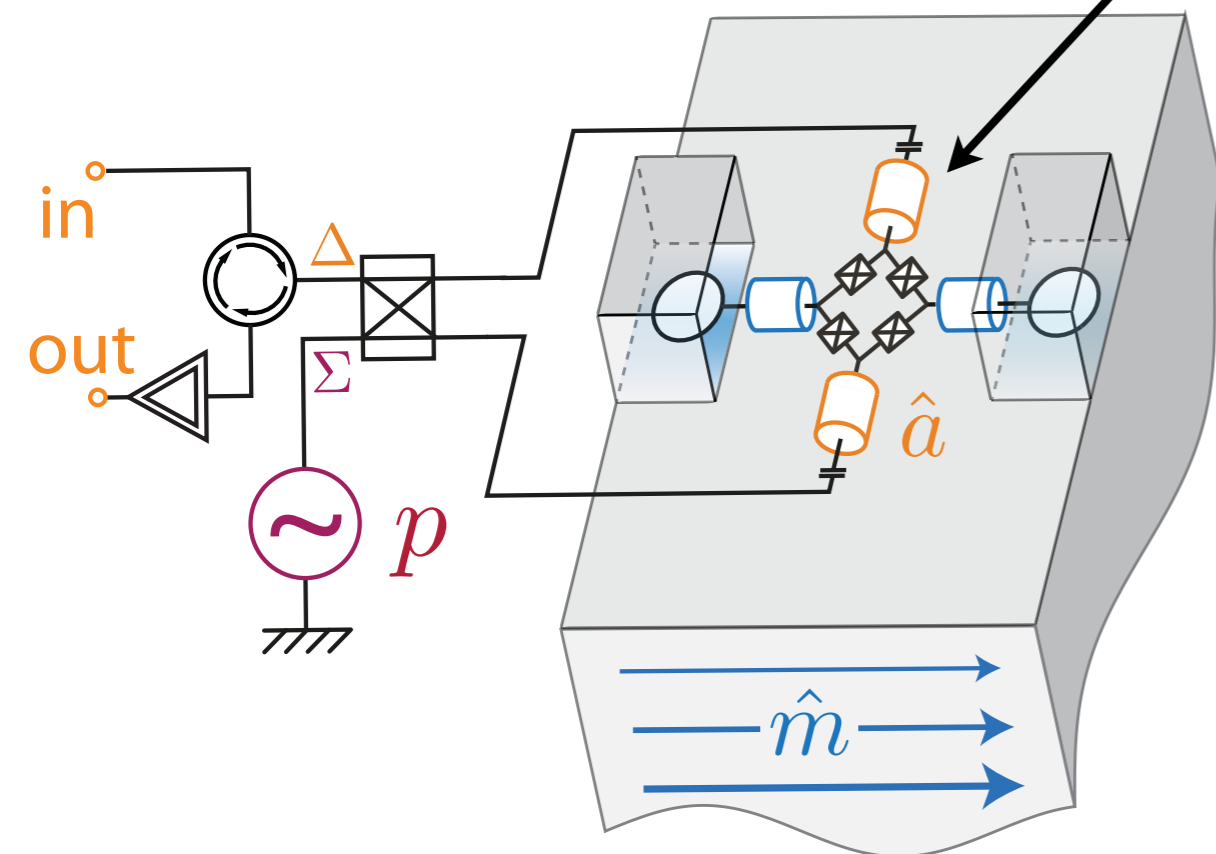


buffer cavity \hat{a}

bandwidth \searrow

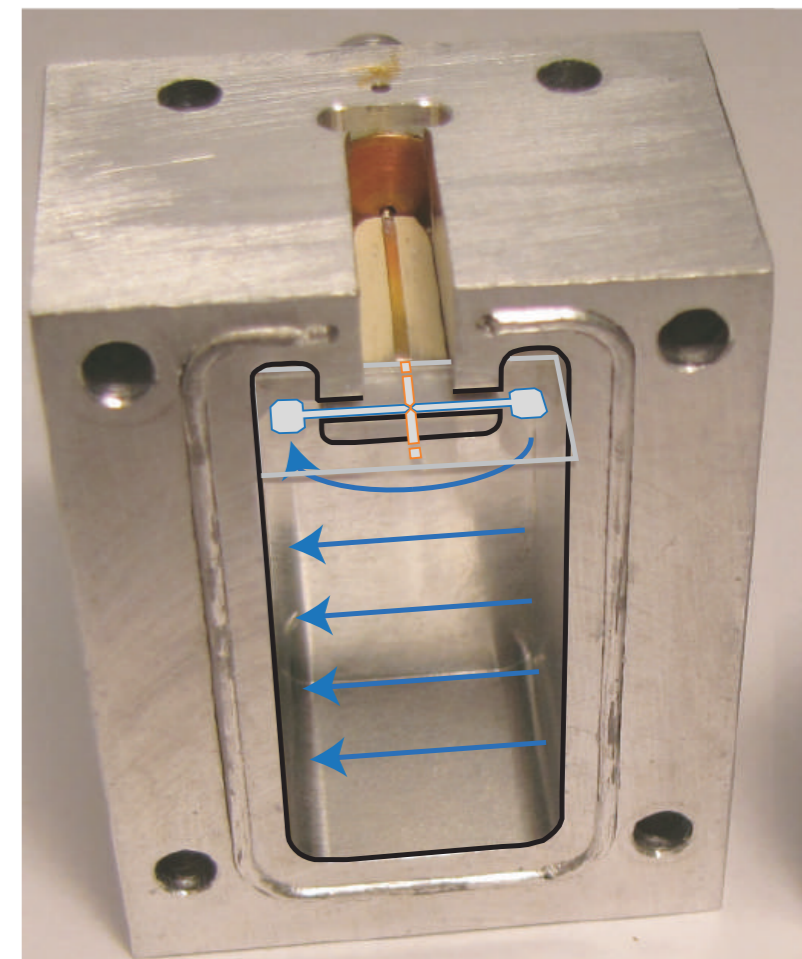
vs

efficiency \nearrow

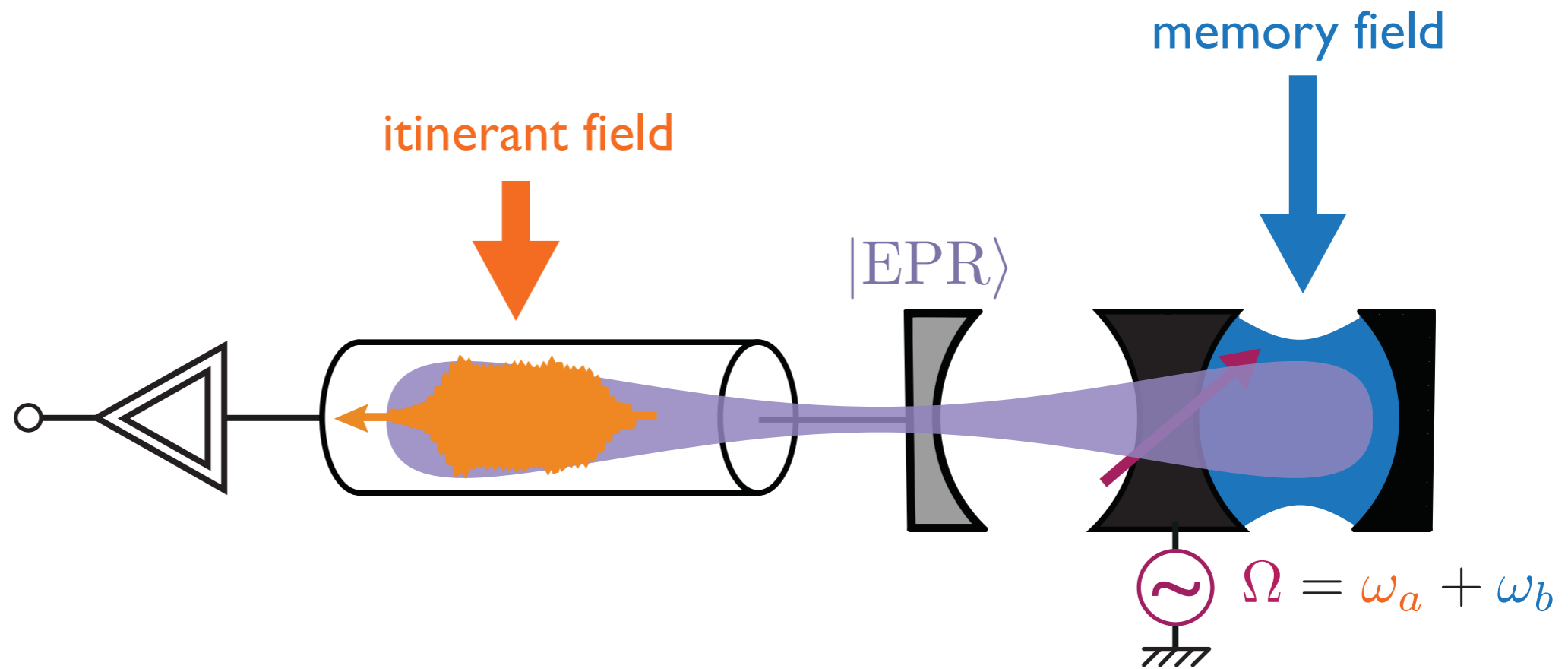
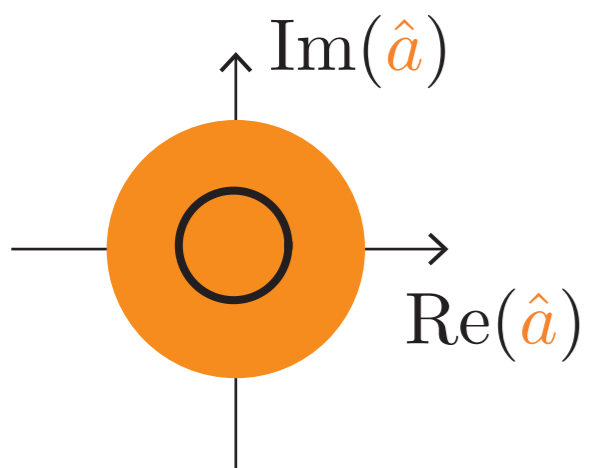


$$f_a = 9.5 \text{ GHz}$$

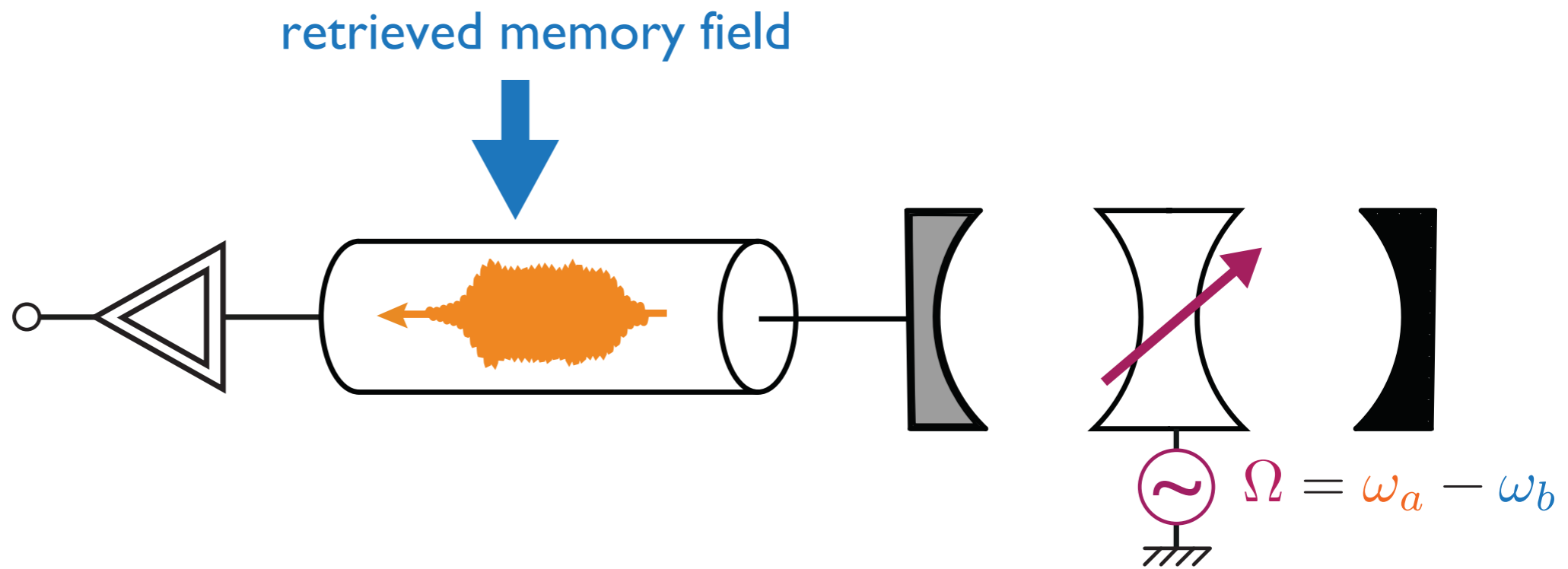
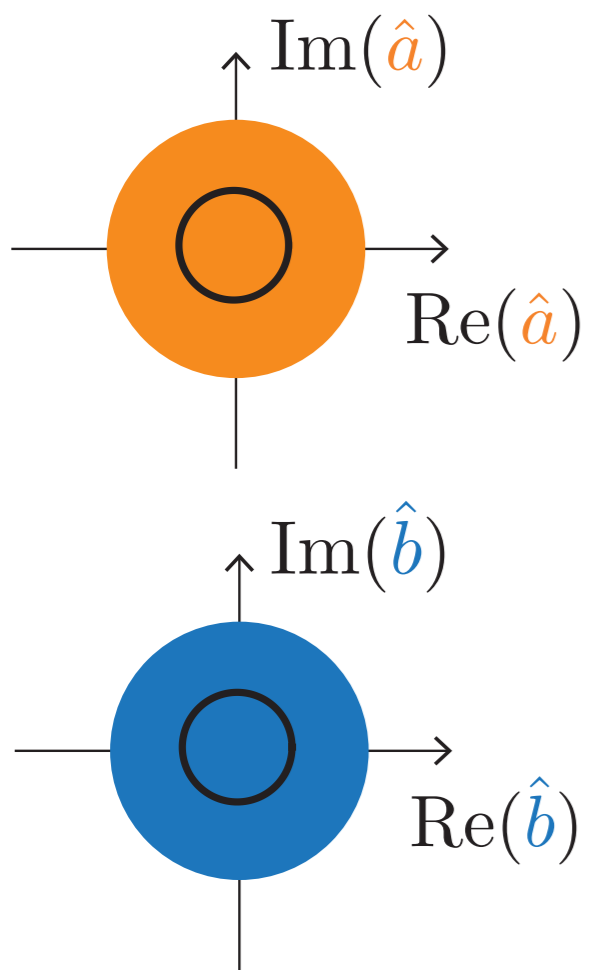
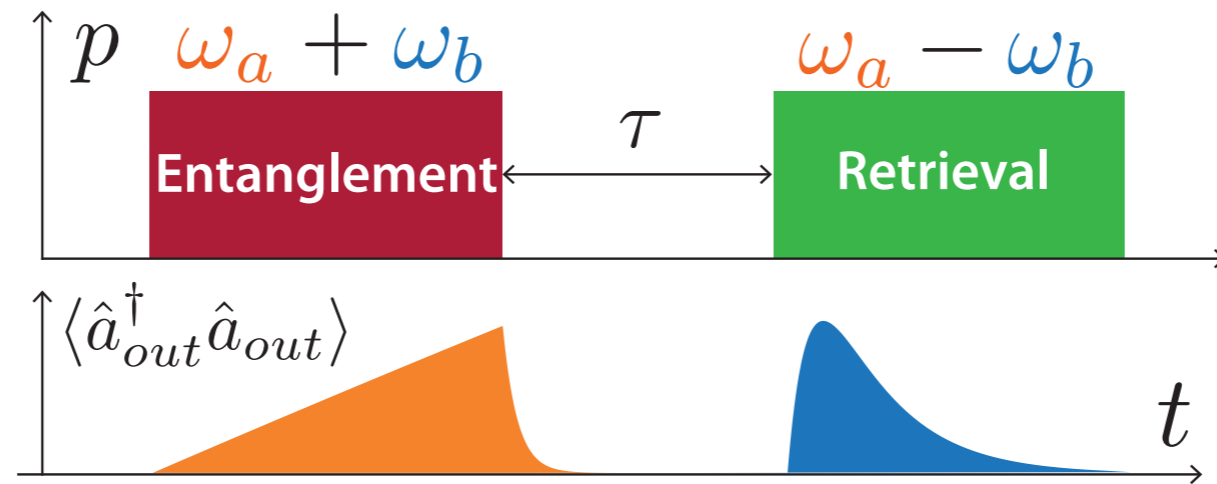
$$f_b = 7.5 \text{ GHz}$$



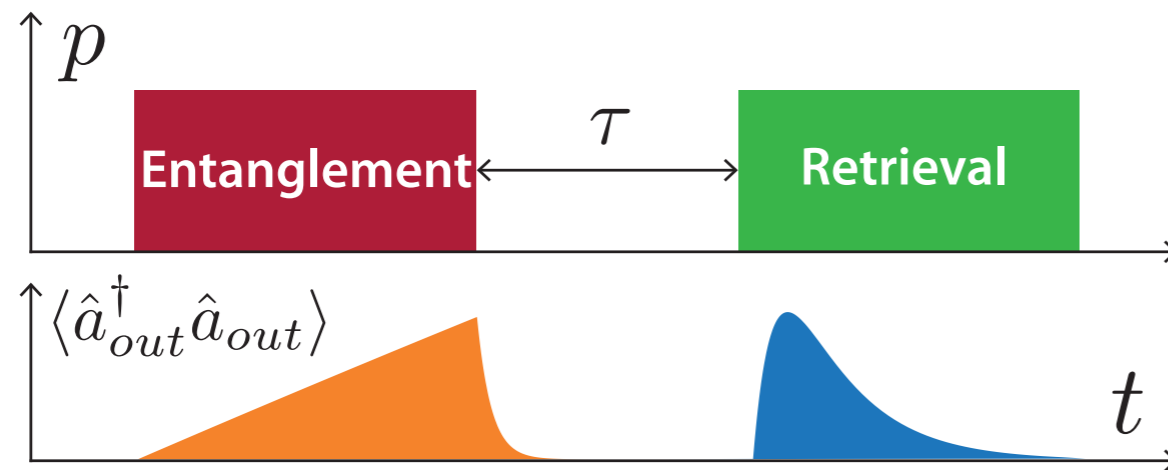
Entanglement generation



Retrieval



Covariance matrix and entanglement

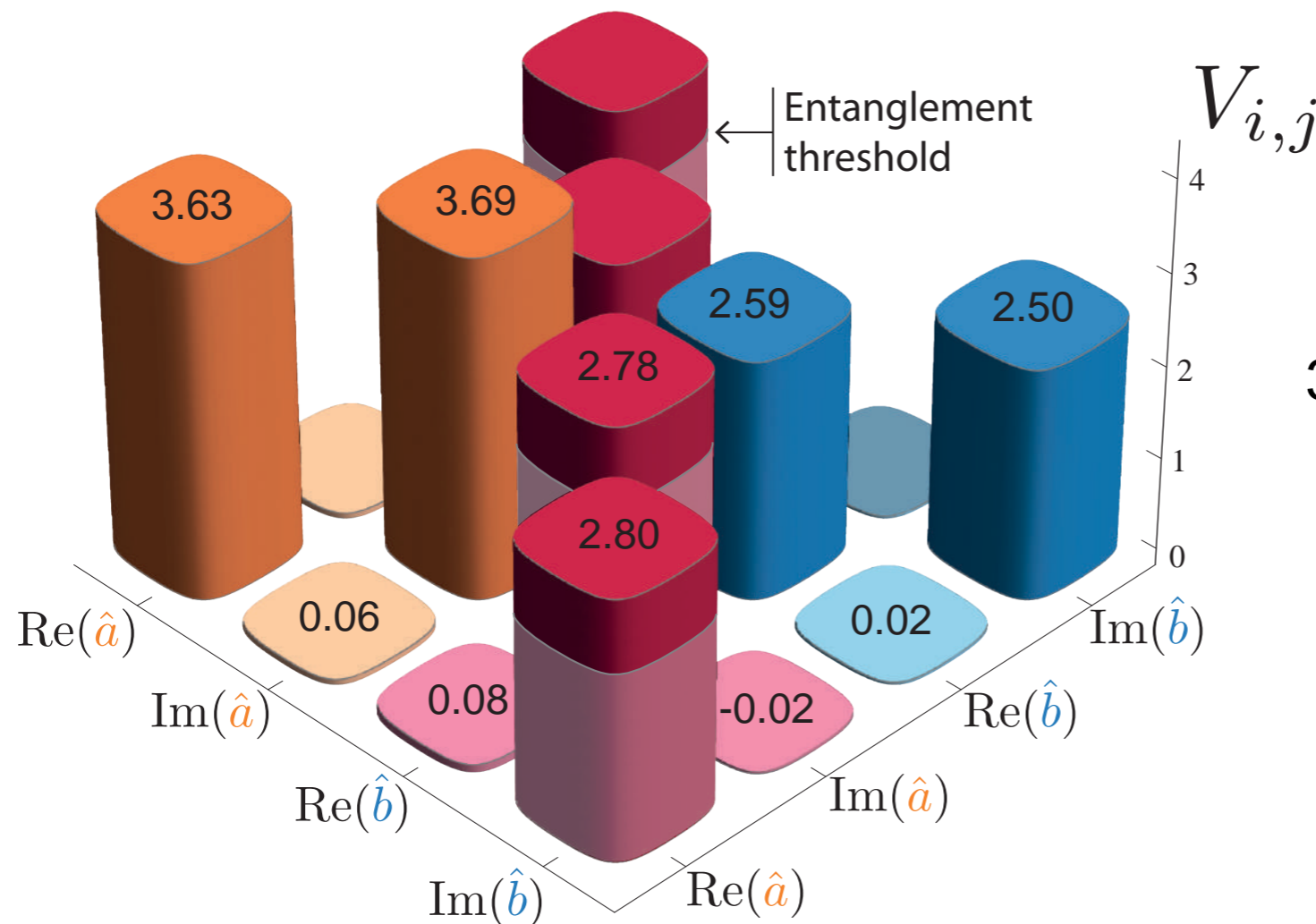


Logarithmic negativity

$$E_N = 1.36 \text{ e-bits}$$

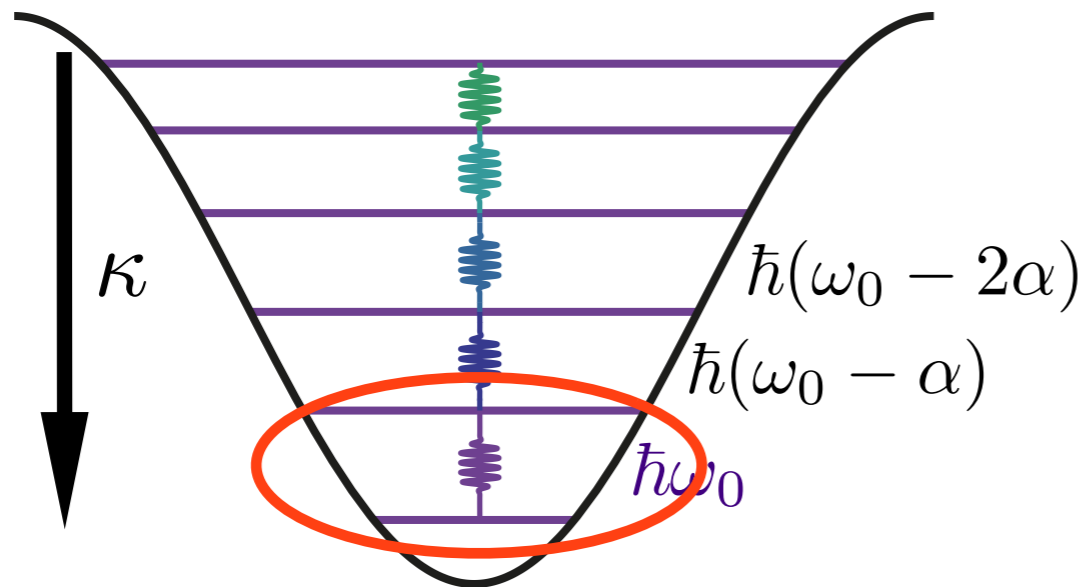
[Flurin *et al.*, ArXiv (2014)]

$$V_{i,j} = 2\langle x_i x_j + x_j x_i \rangle - 4\langle x_i \rangle \langle x_j \rangle$$



FPGA board
30 millions measurements in 5 min
[as in Eichler *et al.*, PRL 2011]

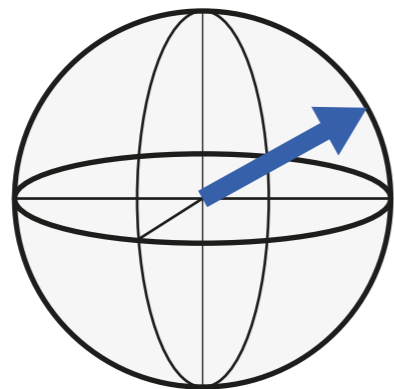
Non-linear superconducting circuits



Strongly anharmonic

$$\alpha \gg \kappa$$

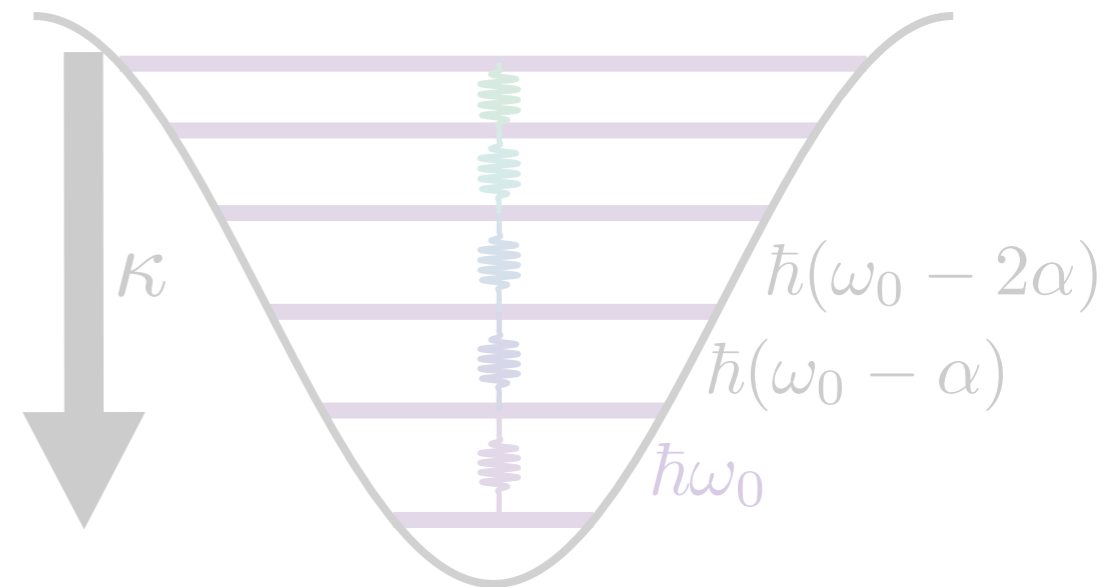
qubit $\hbar\omega\hat{\sigma}_z/2$



First Rabi oscillations in 1999 [NEC group]

Quantonium in 2002 [Saclay group]

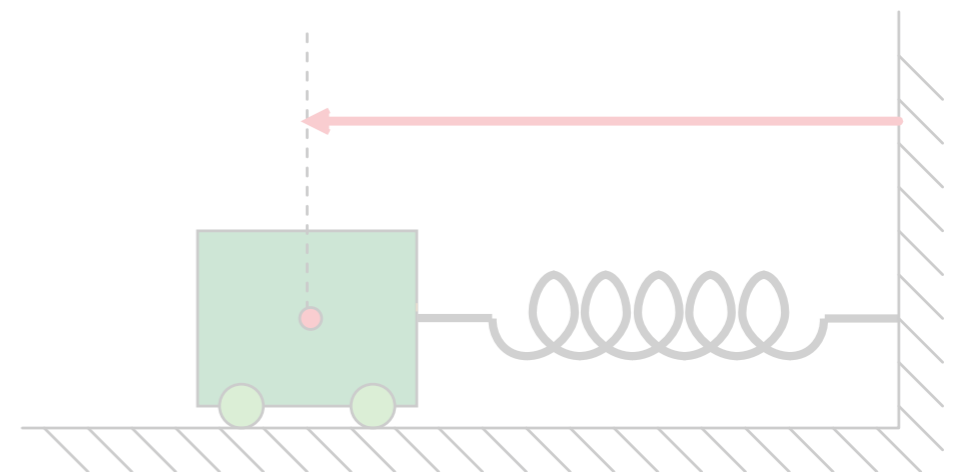
Charge qubit, phase qubit [Grenoble & others], flux qubit, transmon [Yale, ETH & others], fluxonium, Xmon...



Weakly anharmonic

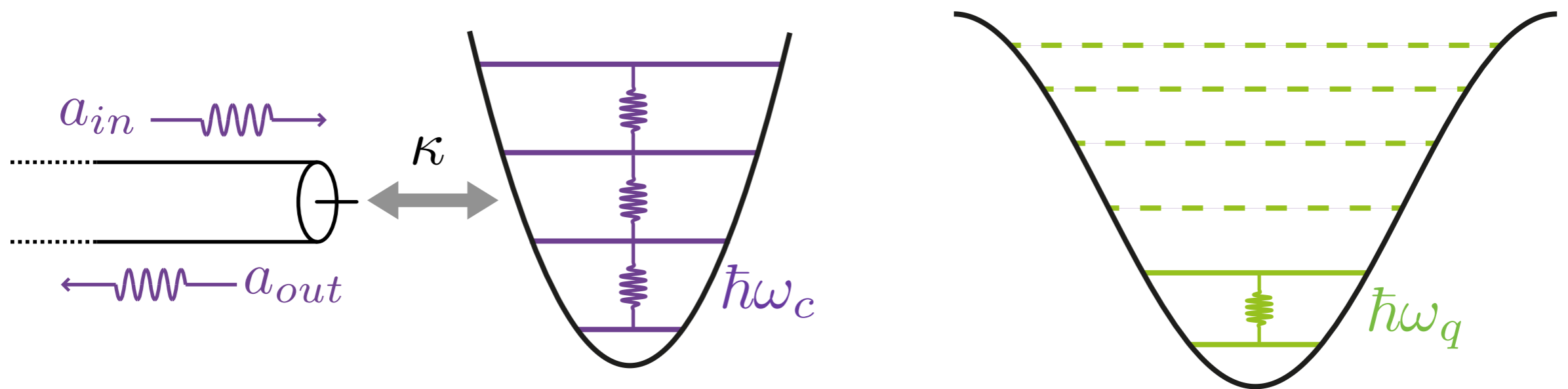
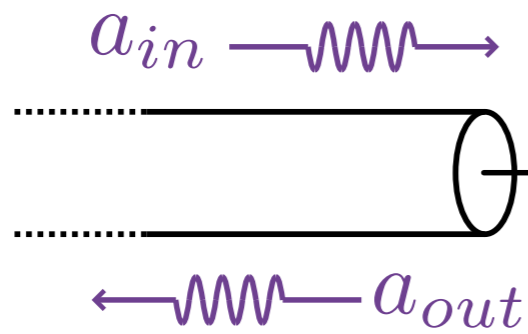
$$\alpha \ll \kappa$$

oscillator $\hbar\omega\hat{a}^\dagger\hat{a}$



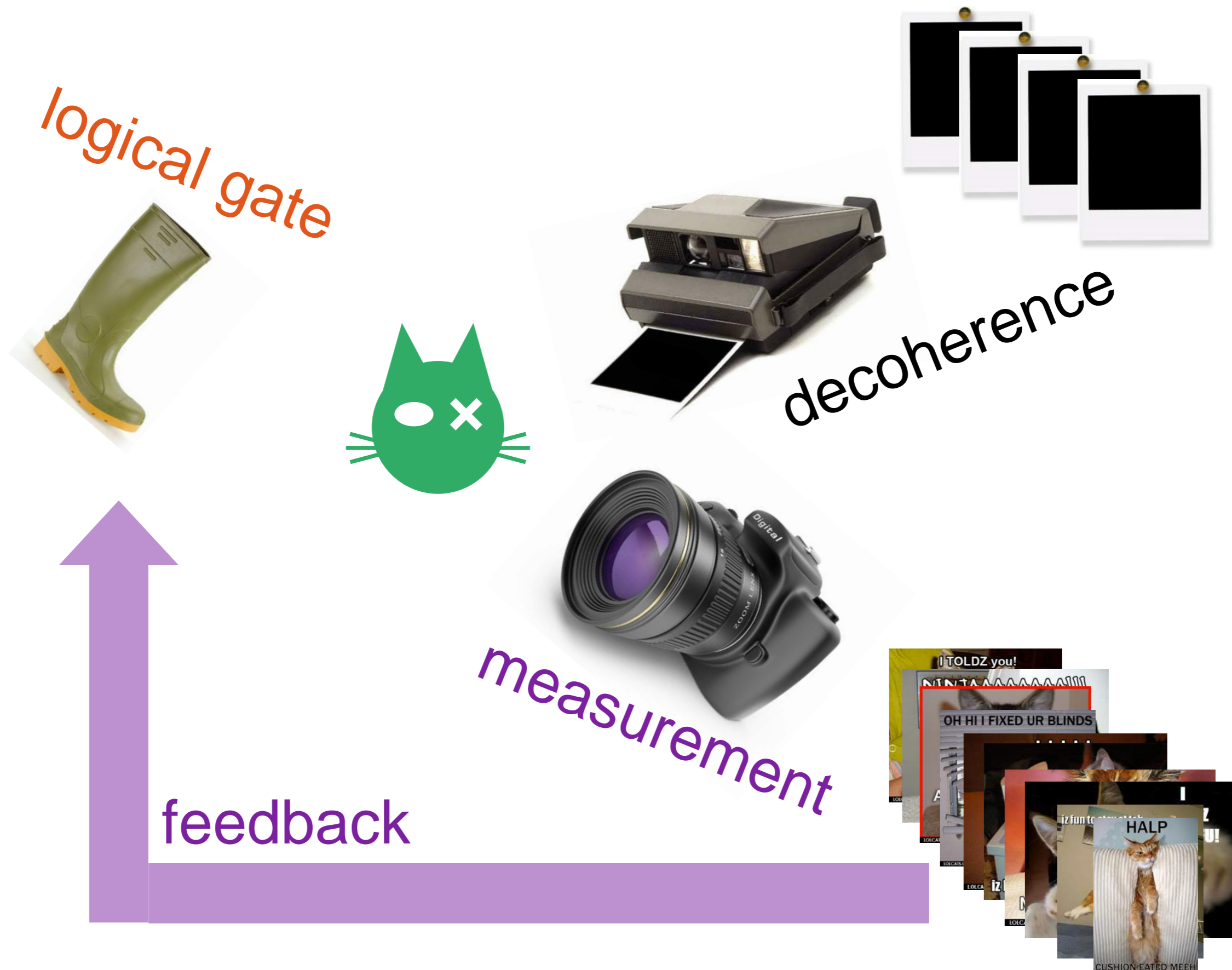
Parametric amplifiers & squeezing
in 1980's [Bell Labs]

Circuit-QED



$$H_{\text{coupl}} = \hbar\chi a^\dagger a \frac{\sigma_z}{2}$$

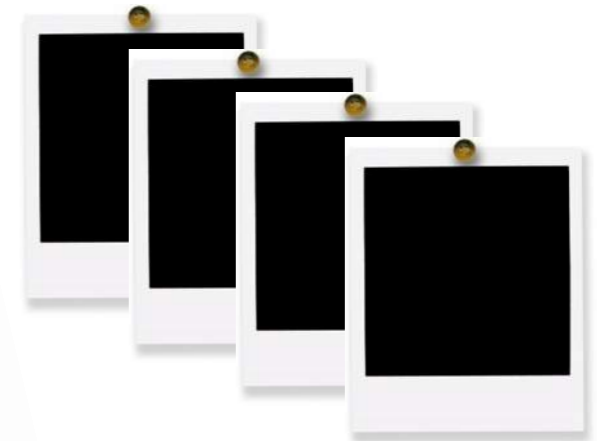
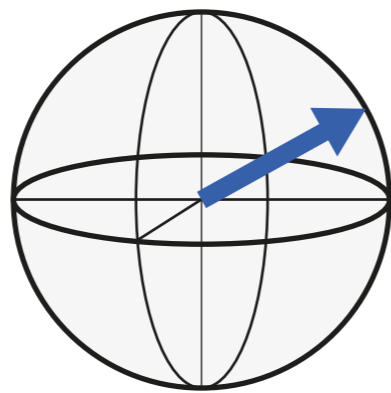
Measurement based feedback



Measurement based feedback

Cavity state: CQED group at ENS (2011)

Qubit state: Berkeley (2011) & Delft (2012)



decoherence



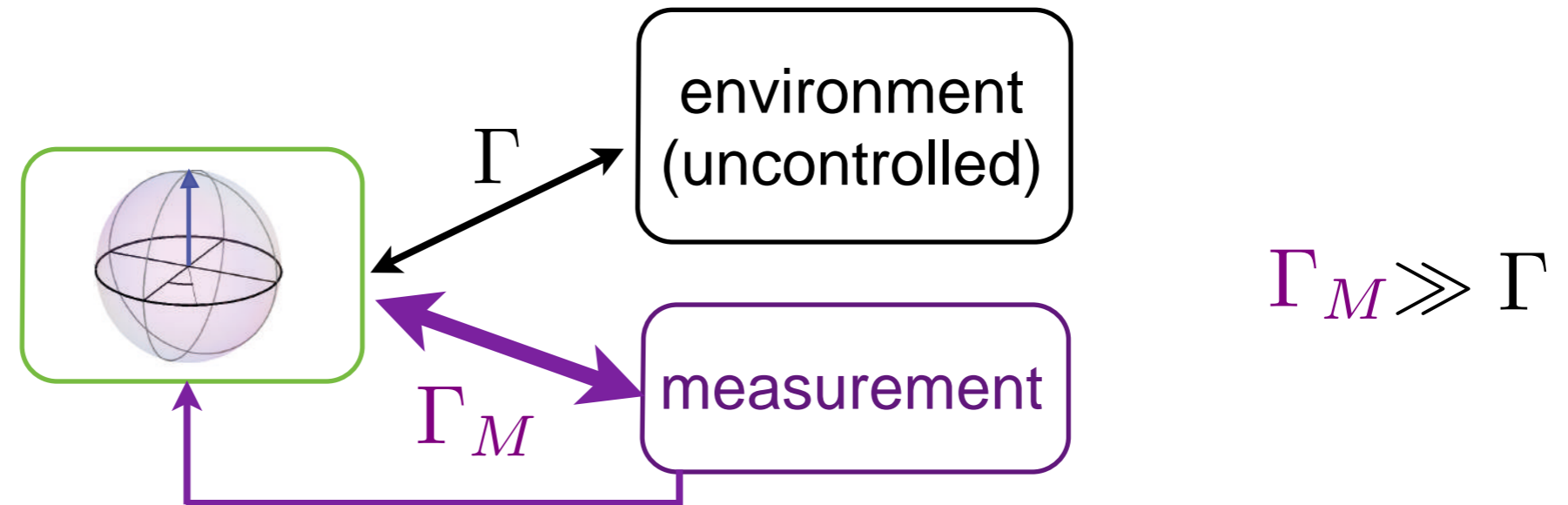
measurement



feedback



What is needed for measurement based feedback?



$$\Gamma_M \gg \Gamma$$

Isolate the system

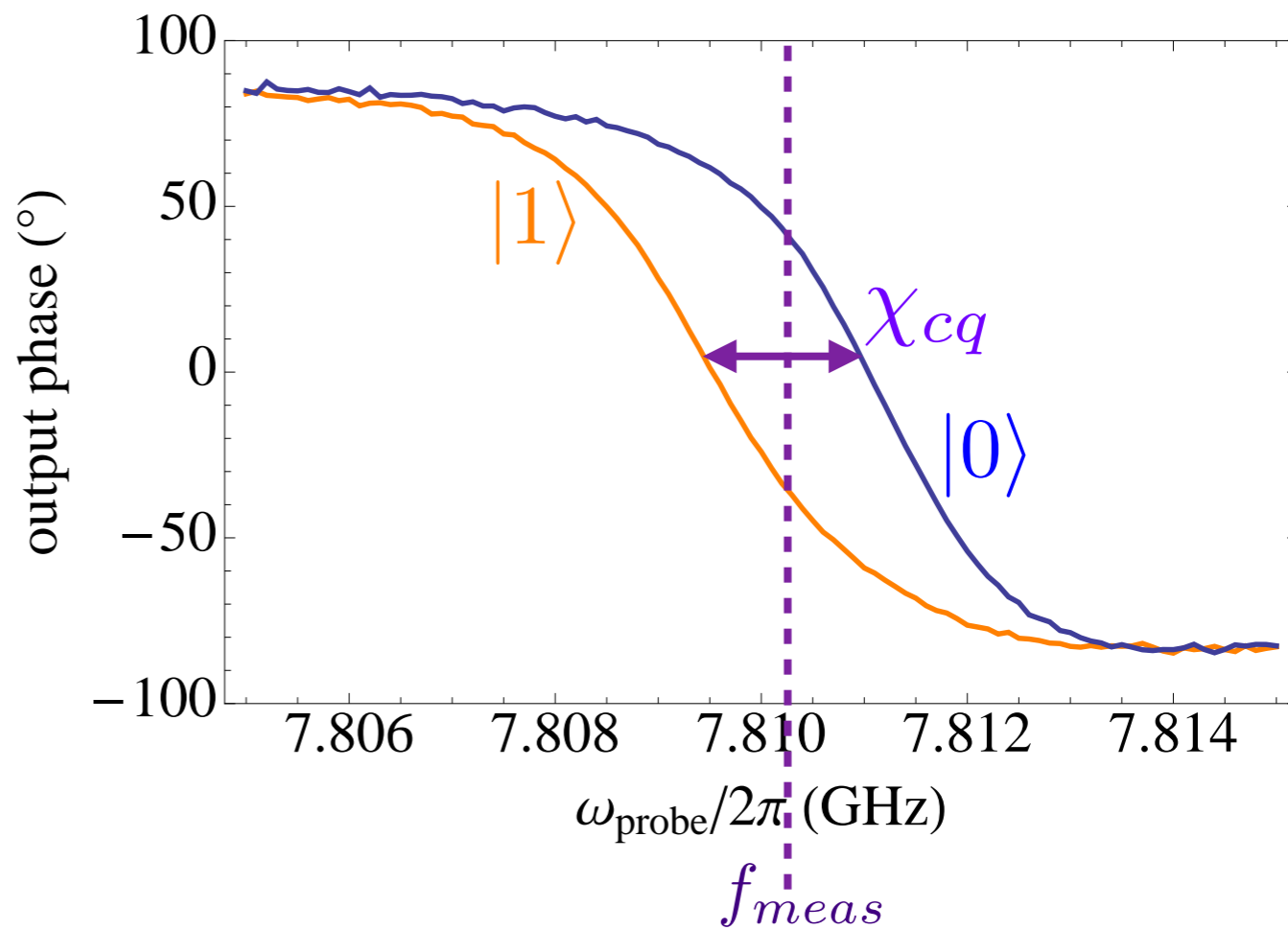
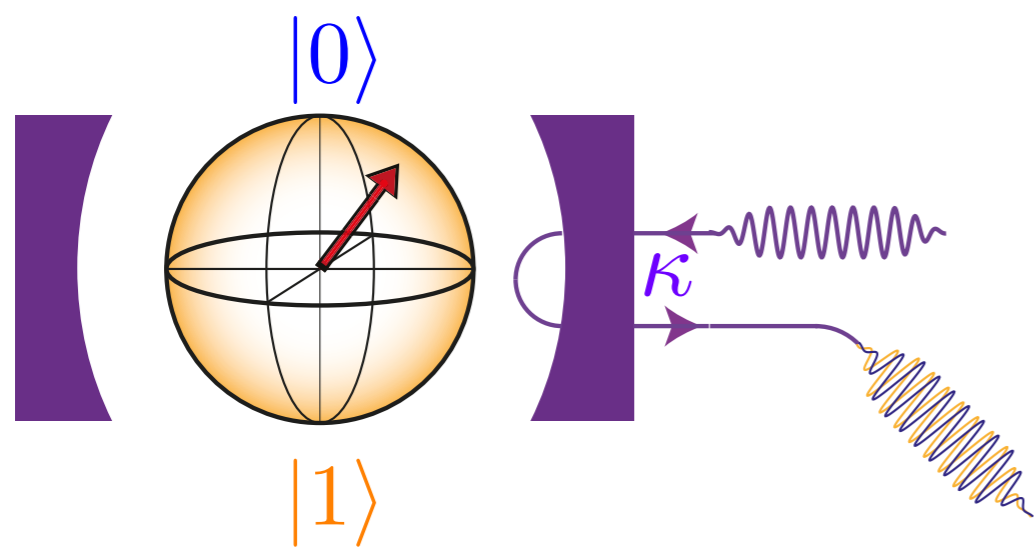
$\Gamma \searrow$

Improve measurement rate

$\Gamma_M \nearrow$

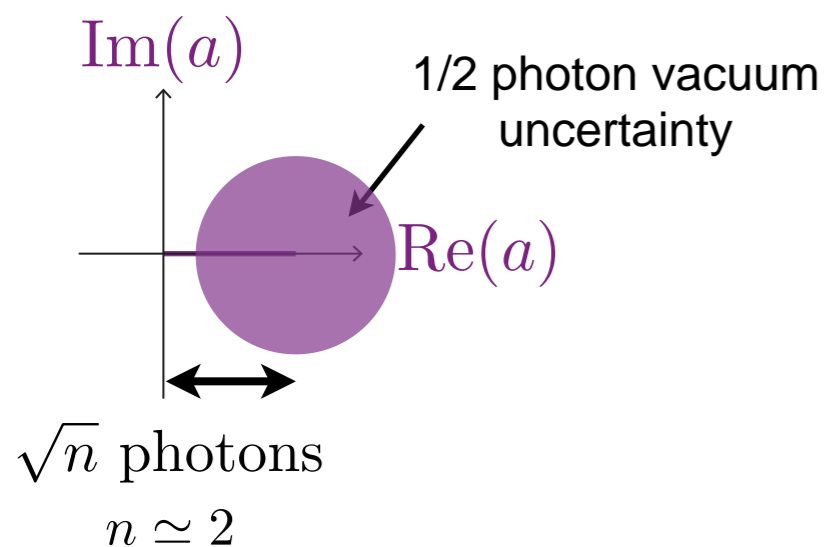
Decrease actuation delay

Dispersive readout

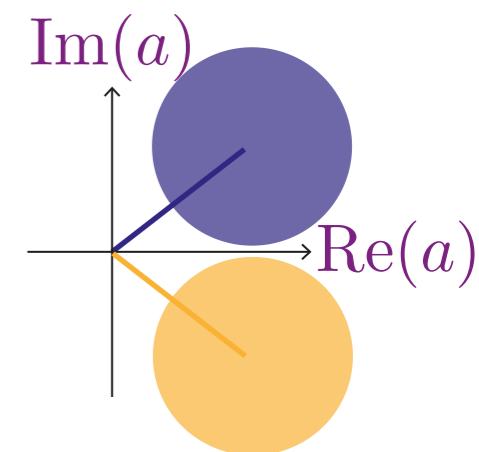


field going in...

... field coming out



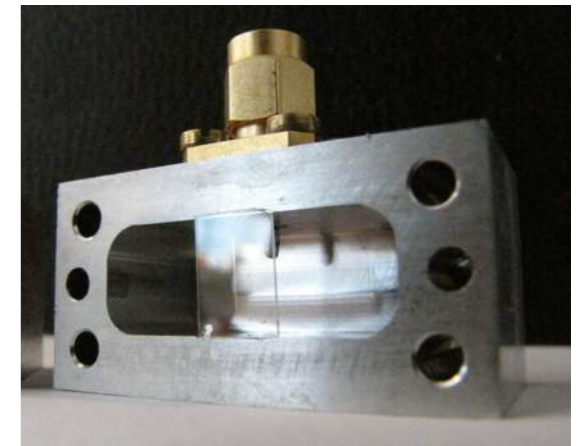
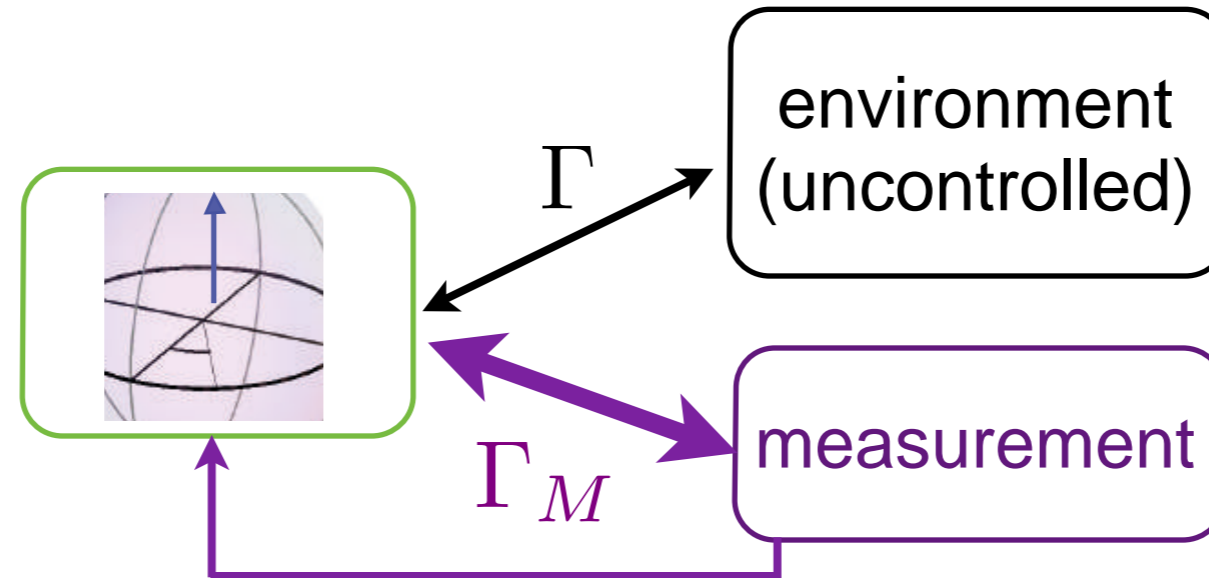
$$H_{\text{coupl}} = \hbar \chi a^\dagger a \frac{\sigma_z}{2}$$



Strong QND measurement

What is needed for quantum feedback?

control
slower than χ_{qq}
<100 MHz



Isolate the system

$\Gamma \searrow$

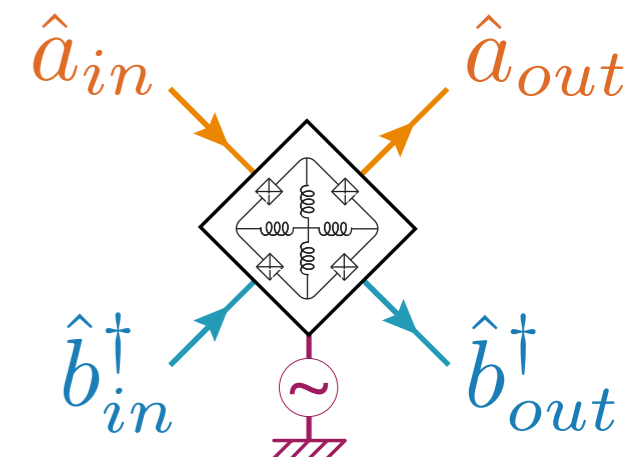
best < 10 kbit/s

Improve measurement rate

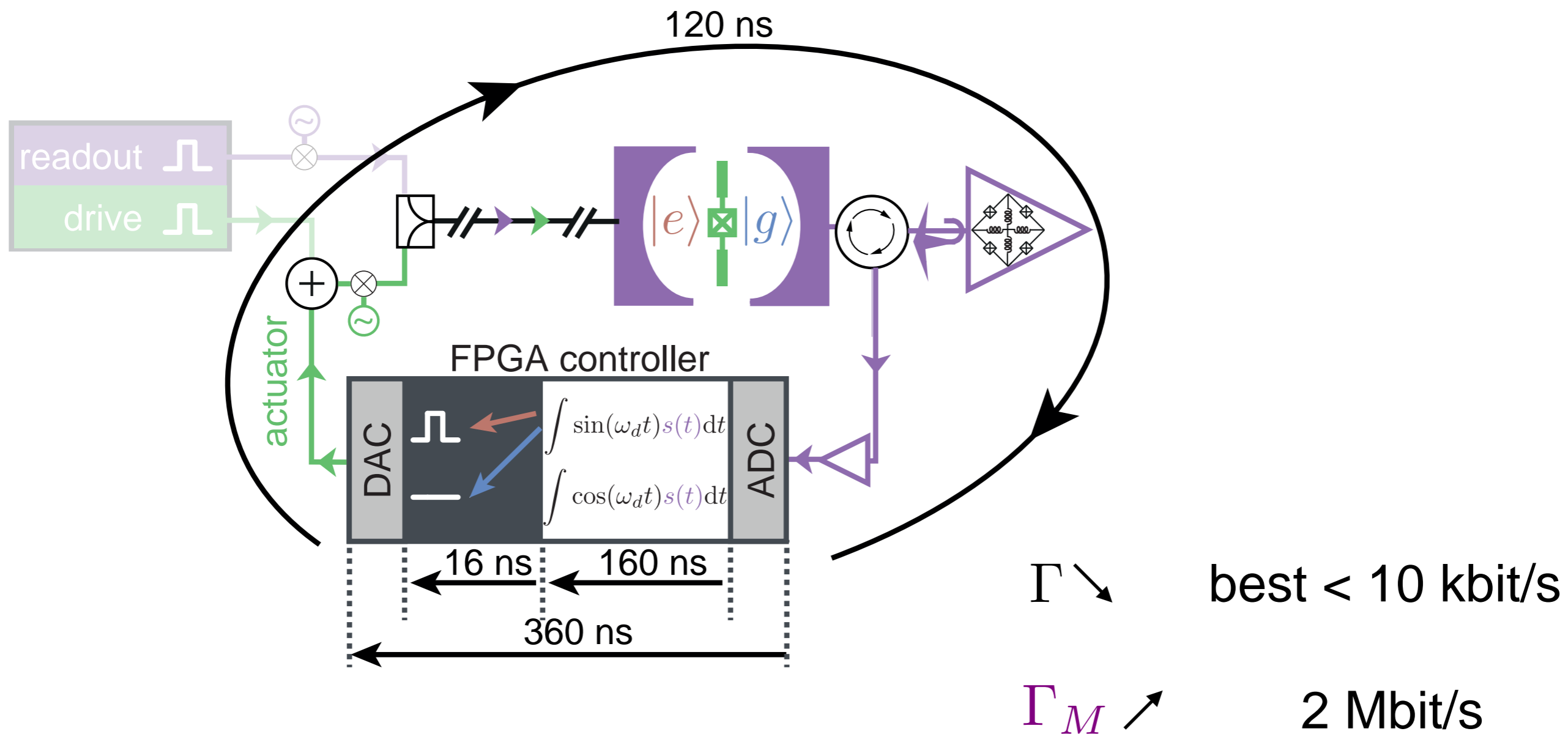
$\Gamma_M \nearrow$

2 Mbit/s

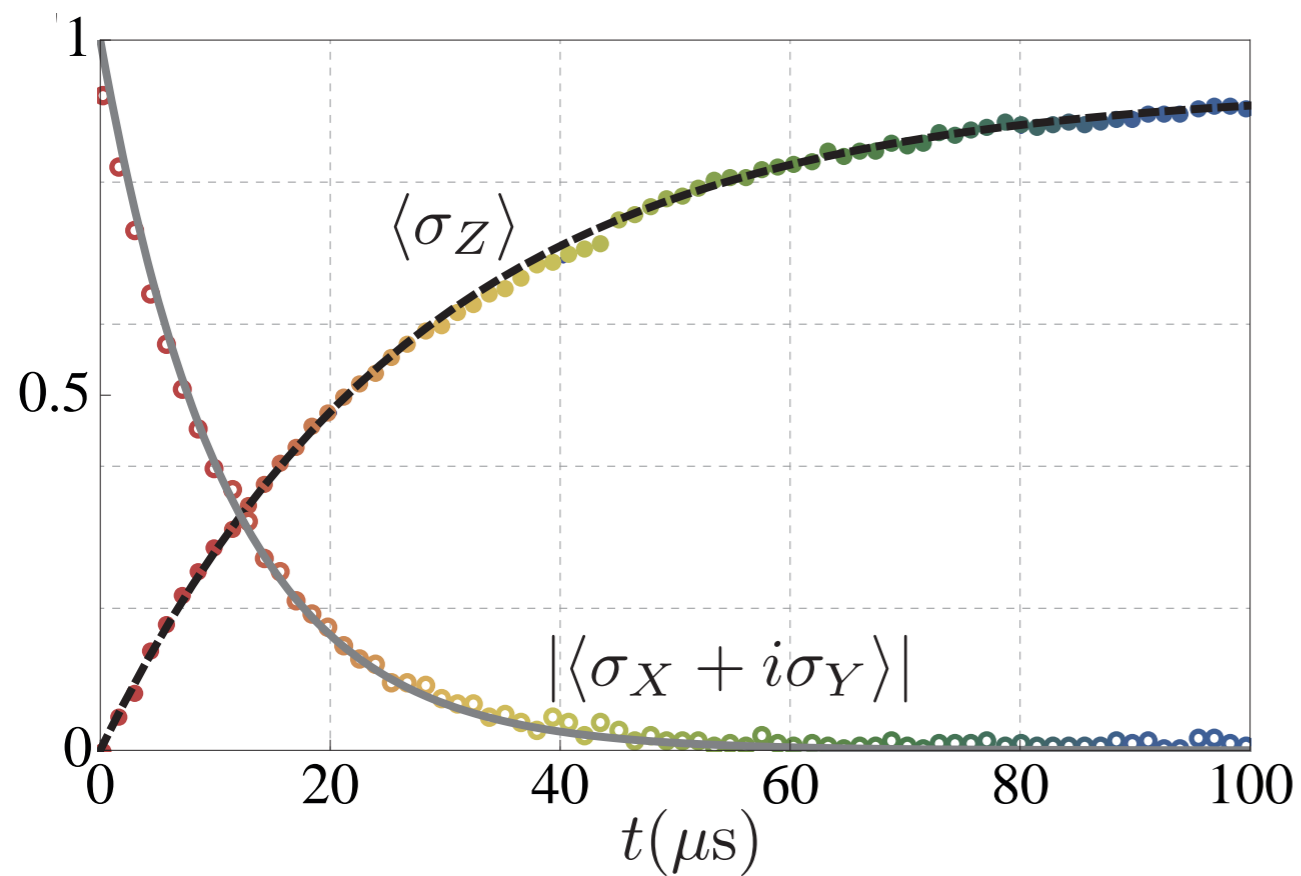
Decrease actuation delay



closing the feedback loop: FPGA board

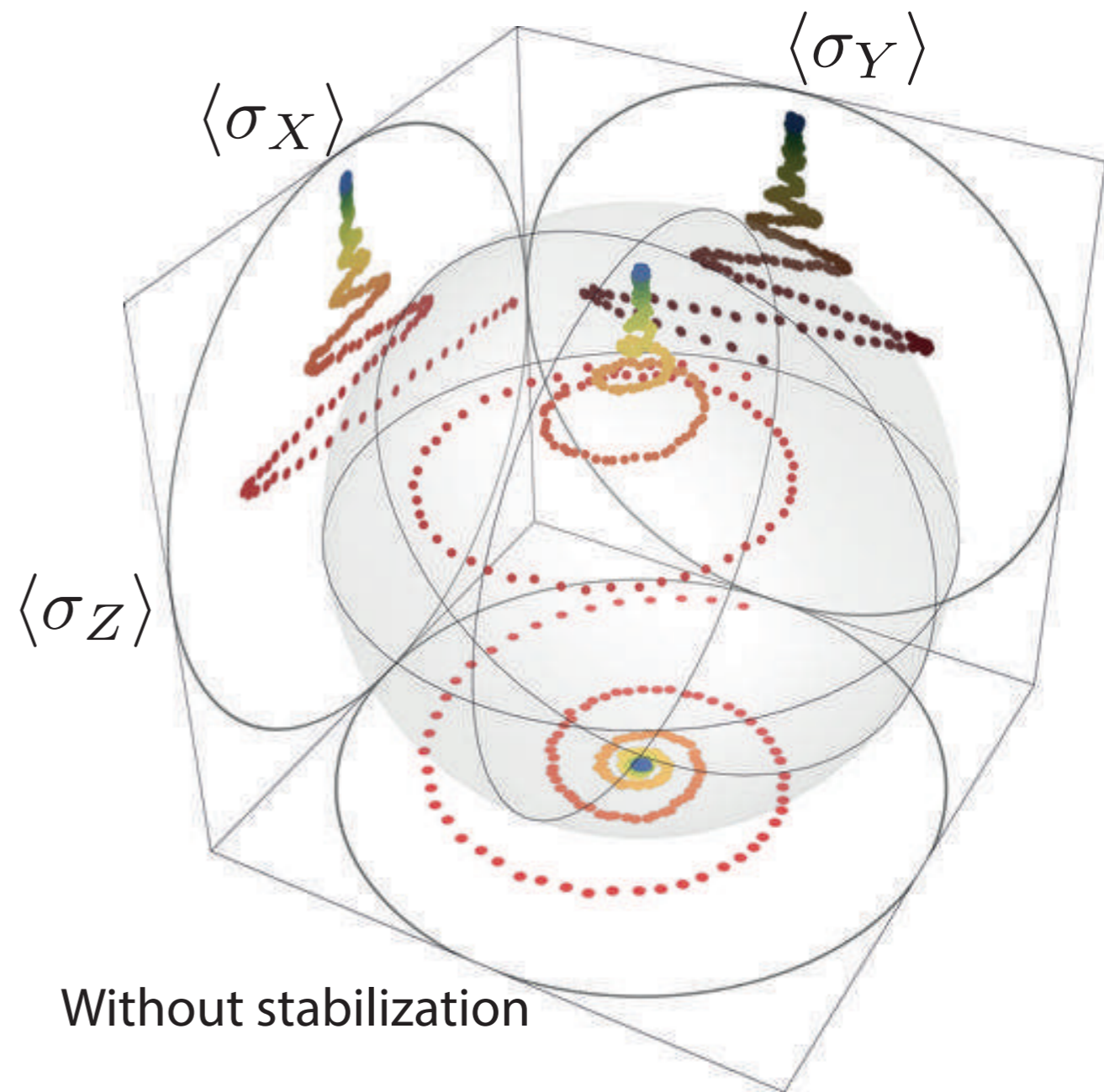


Stabilizing $\frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$



$$T_1 = 26 \mu\text{s}$$

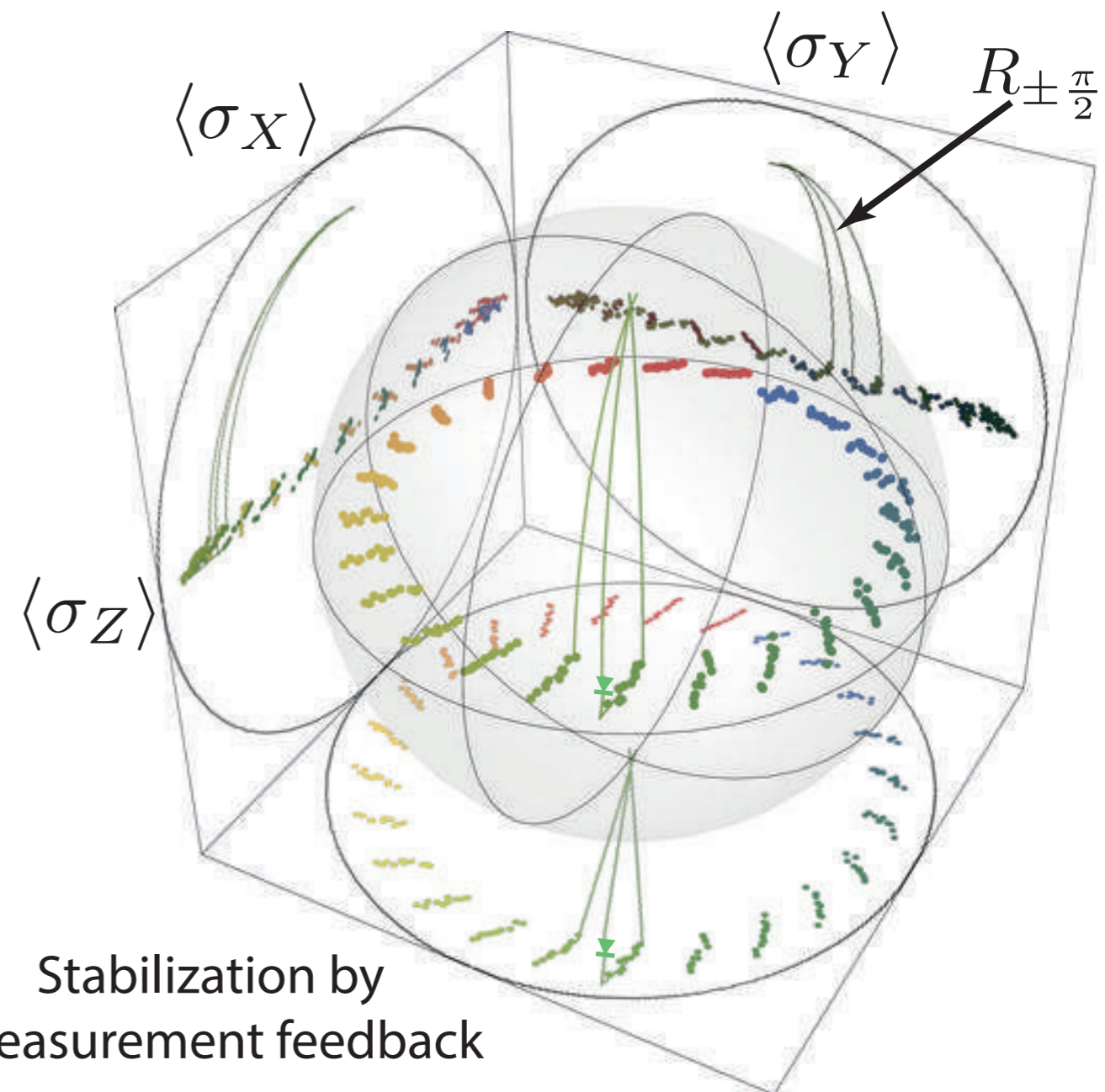
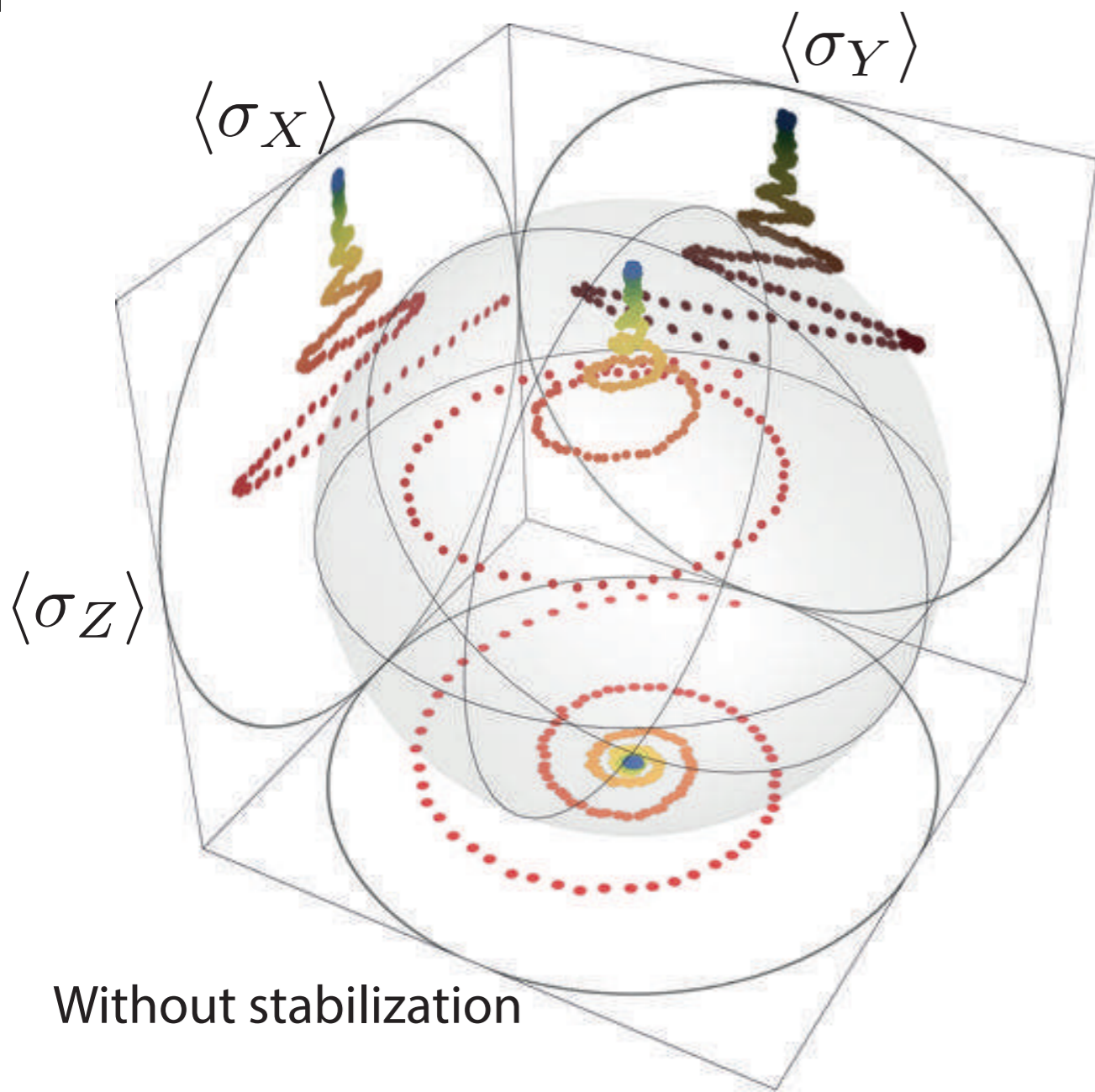
$$T_2 = 11 \mu\text{s}$$



Without stabilization

[Campagne-Ibarcq et al.,
PRX 2013 (Paris)]

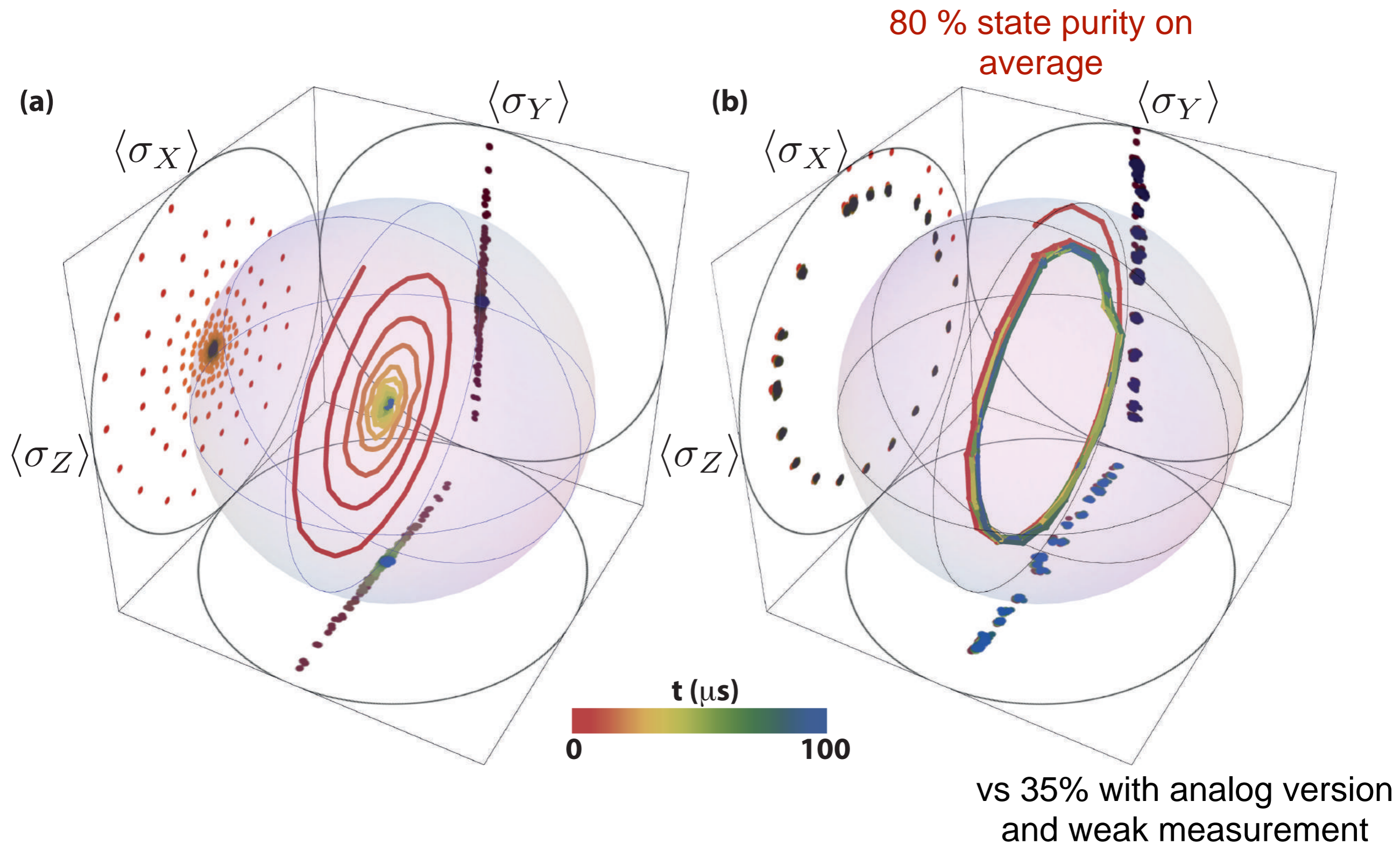
Stabilizing $\frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$



76% purity on average
92% purity right after feedback

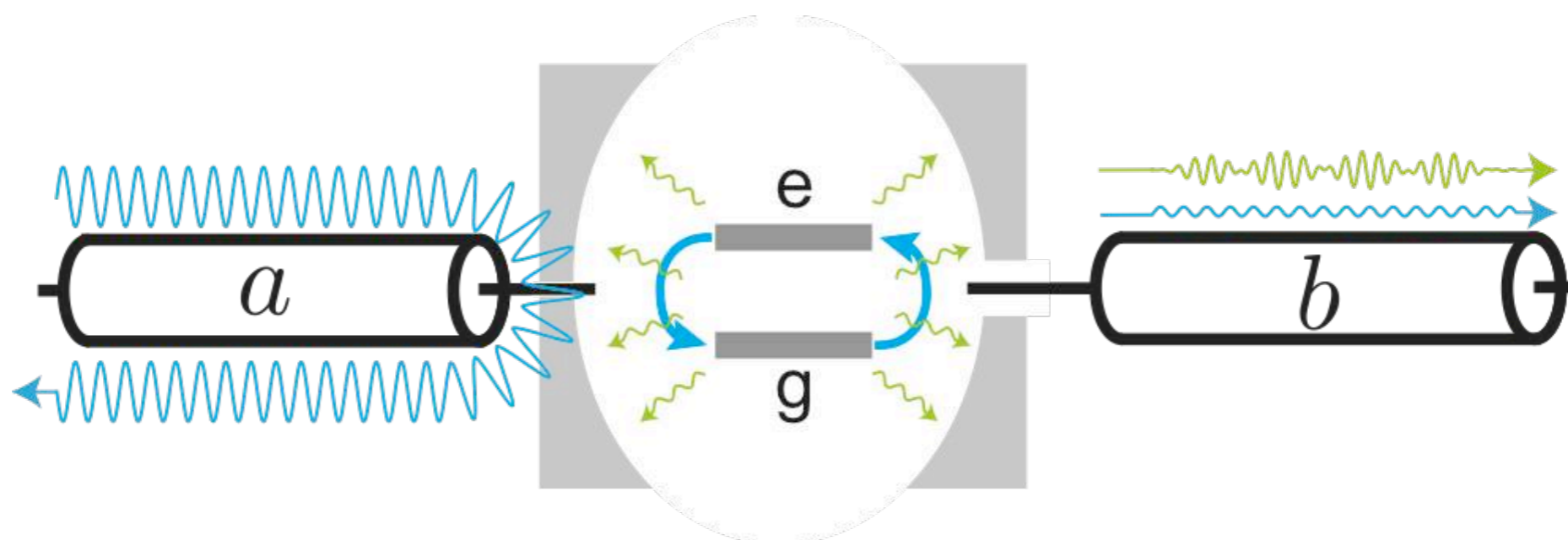
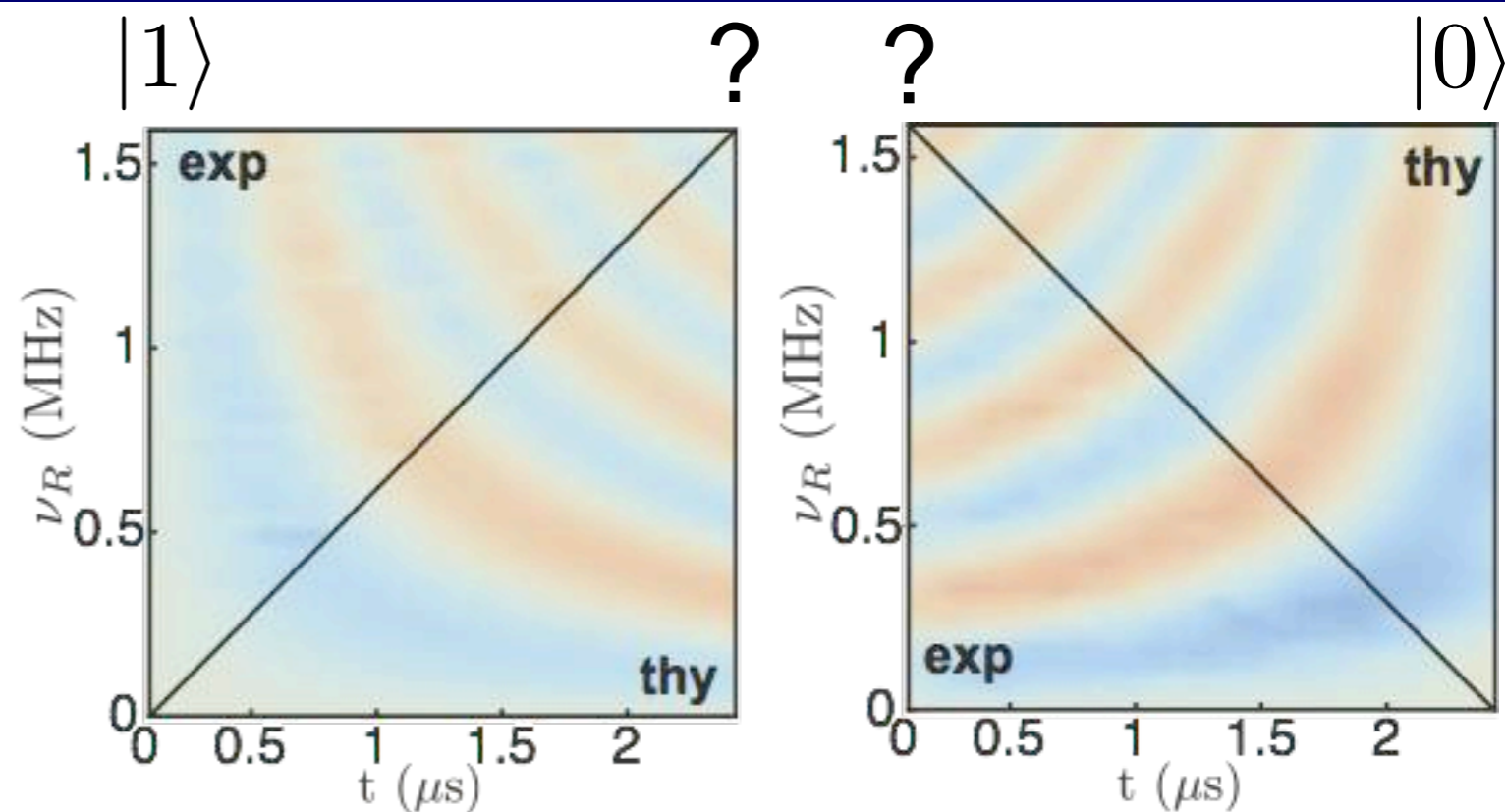
[Campagne-Ibarcq et al.,
PRX 2013 (Paris)]

Stabilizing Rabi oscillations



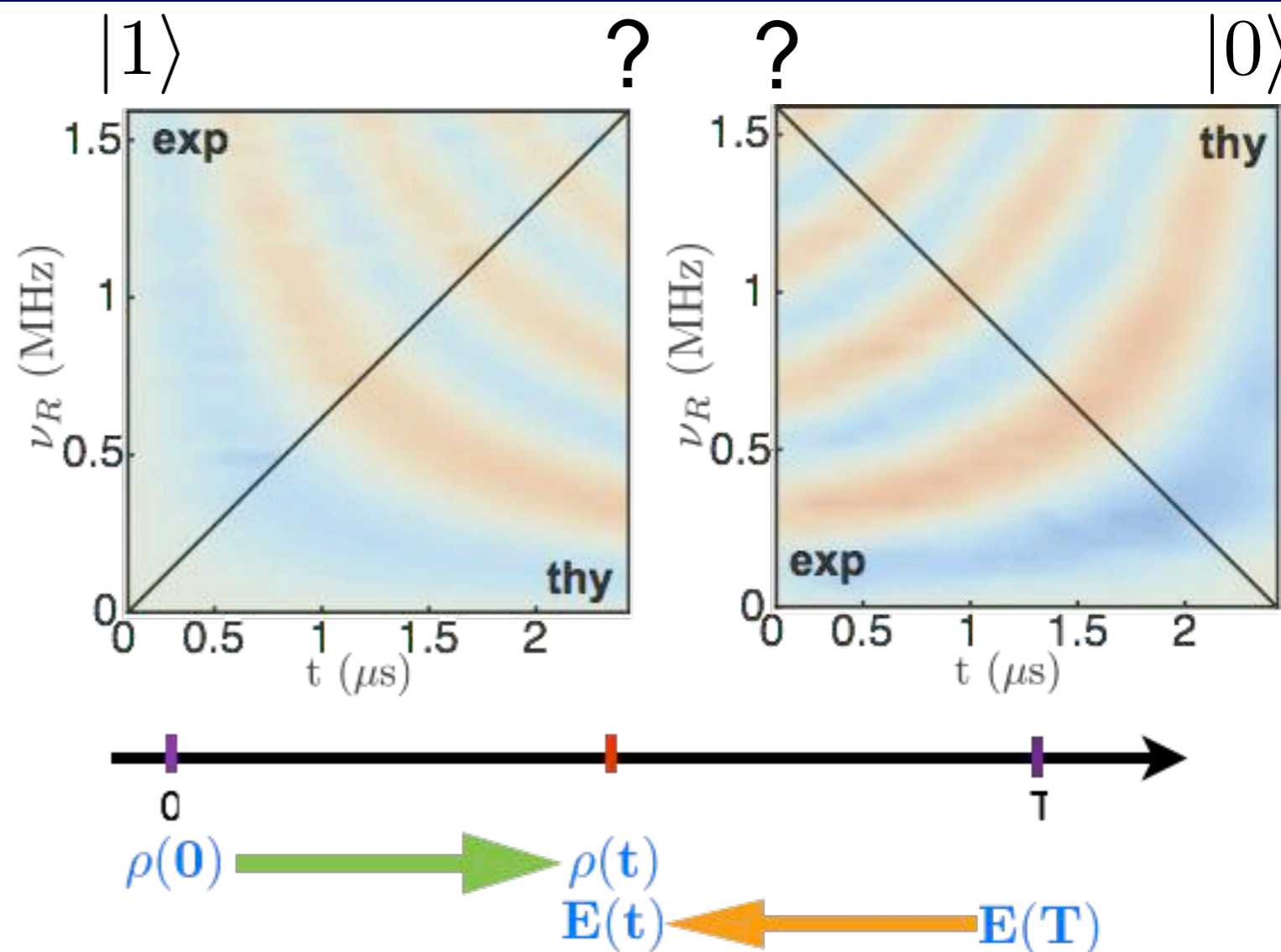
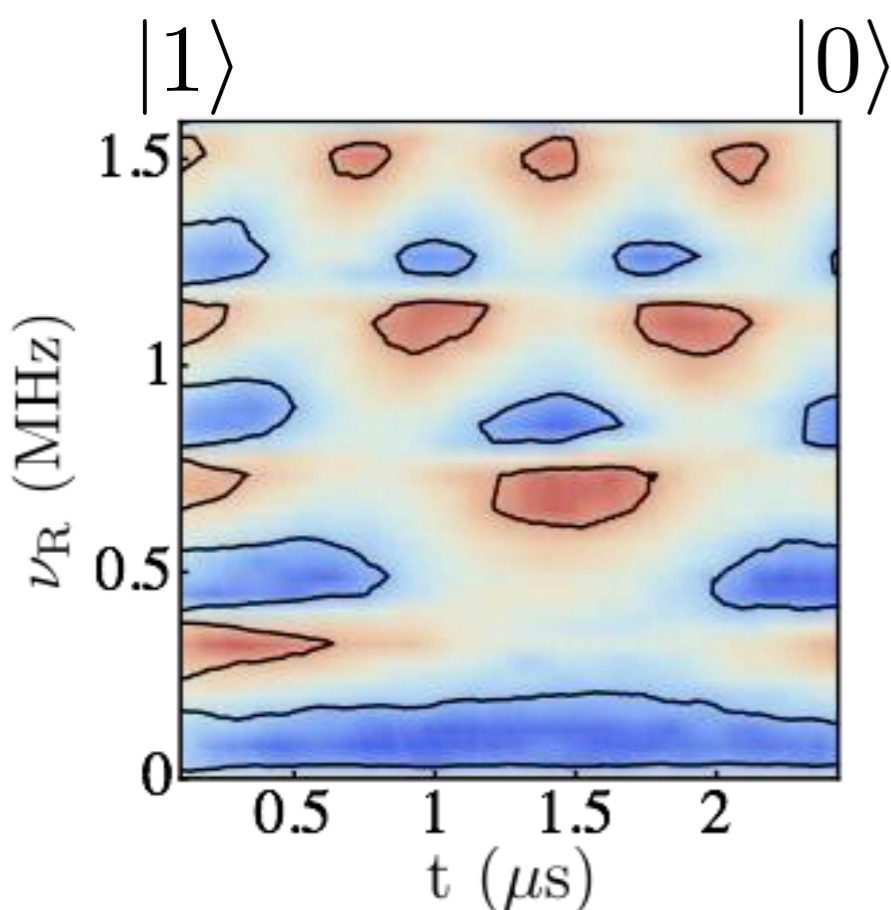
Fluorescence with past and future information

- Monitoring fluorescence in time
- Time-reversal symmetry between preparation and post-selection even with decoherence



Fluorescence with past and future information

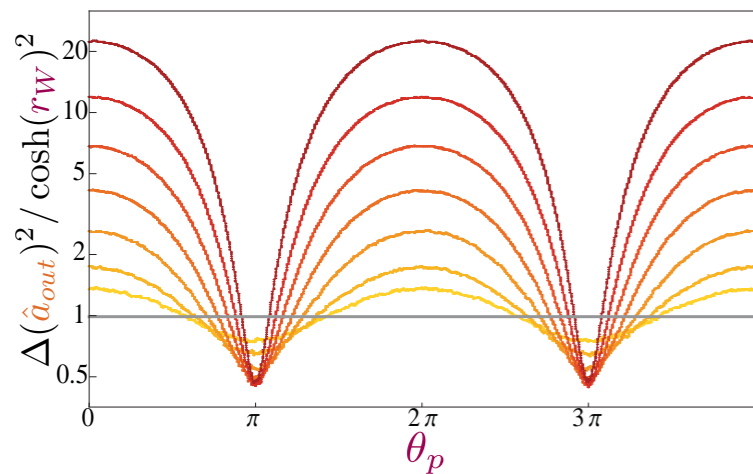
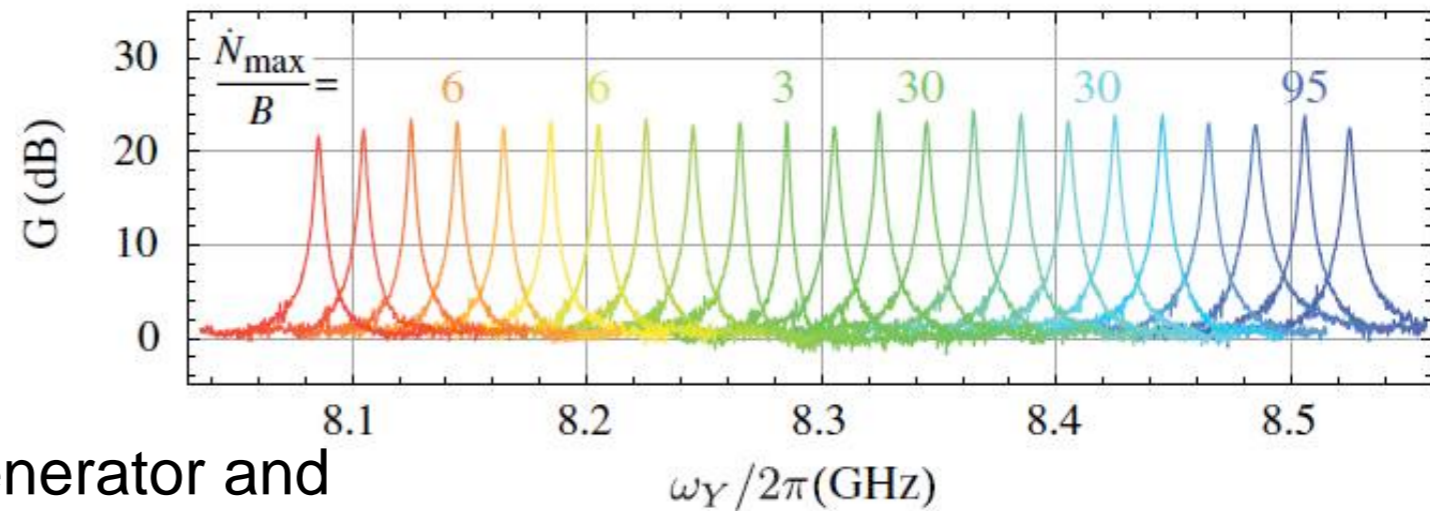
- Monitoring fluorescence in time
- Time-reversal symmetry between preparation and post-selection even with decoherence



- Interference between past and future quantum states
 - Non-classical weak values
 - Direct probing of a non-Hermitian operator

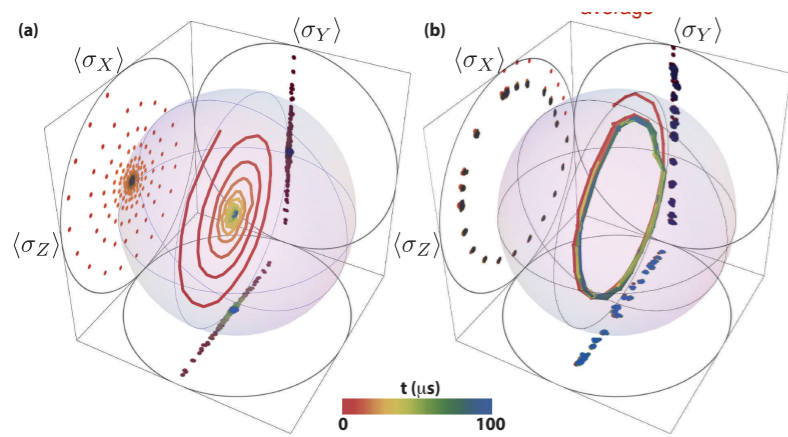
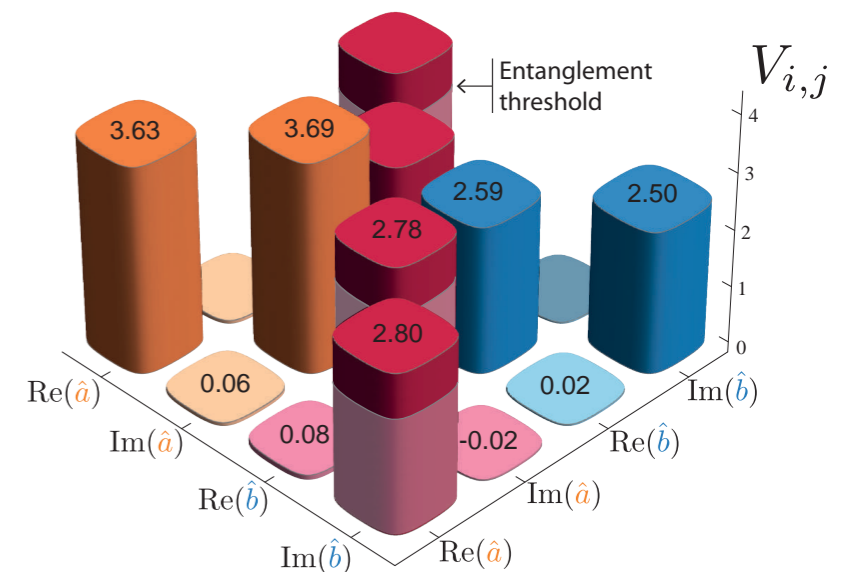
Summary

>80% microwave amplifier



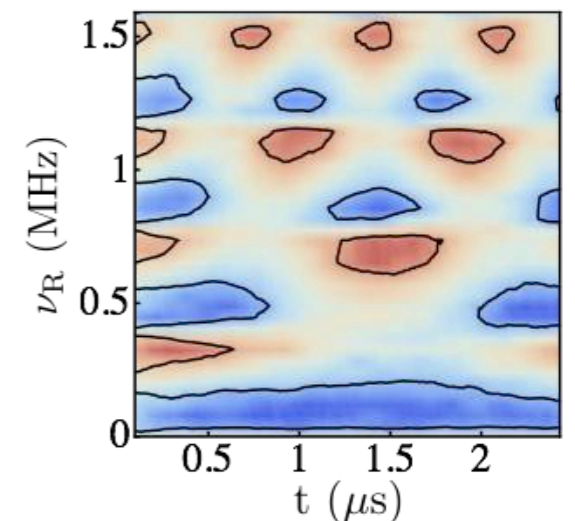
Entanglement generator and witness

Quantum node for microwave network catch/release/entangle



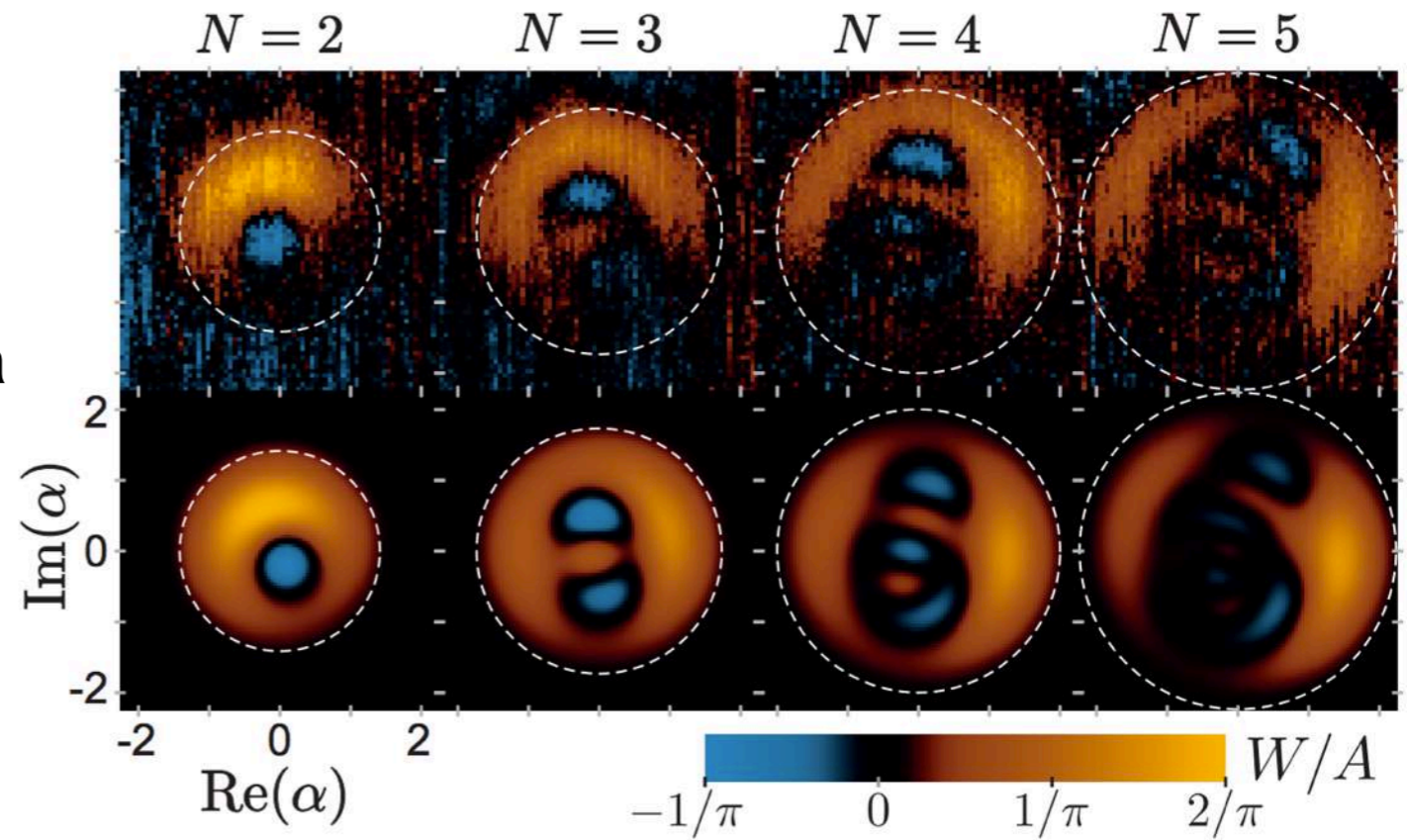
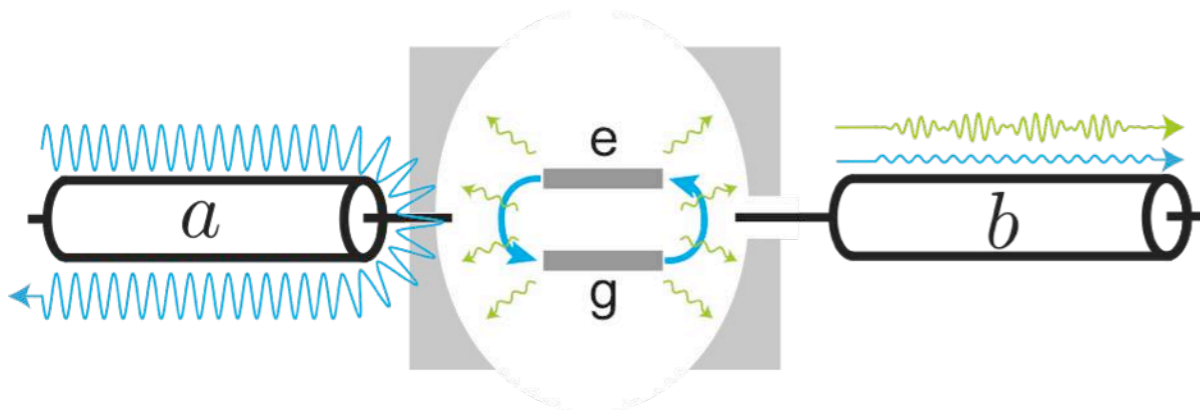
Measurement based feedback for stabilizing trajectories

Fluorescence seen in the time domain with post selection



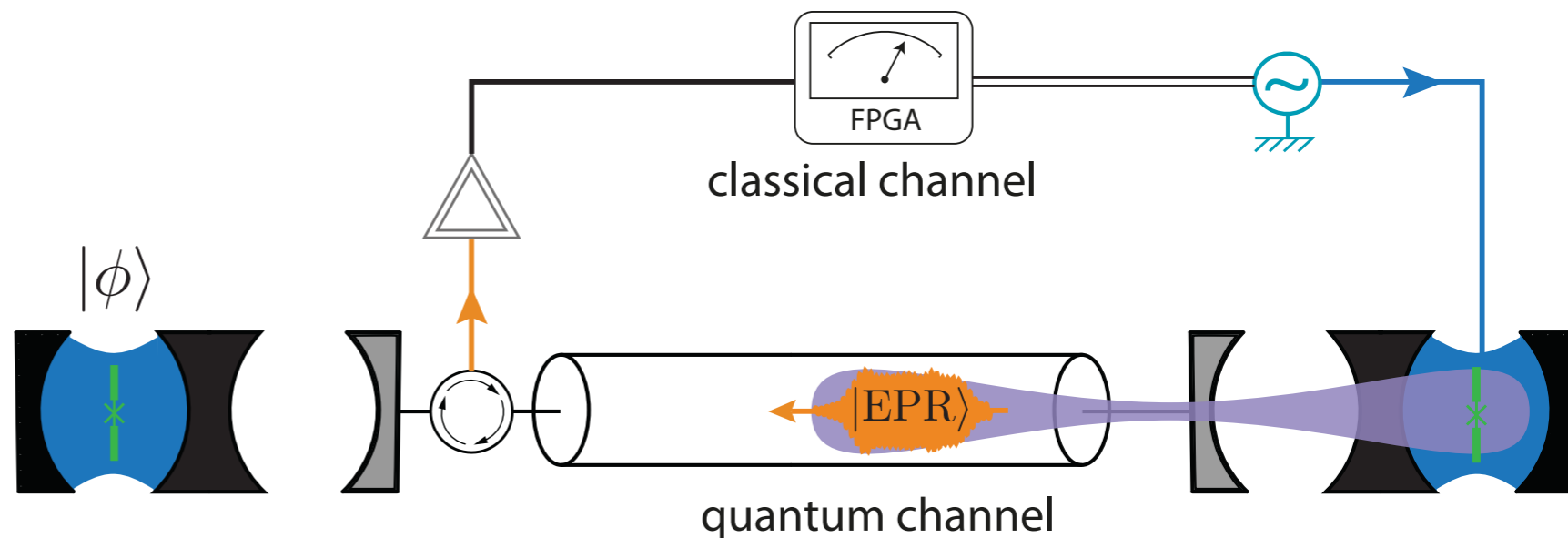
Ongoing projects

Quantum Zeno Dynamics of a microwave mode

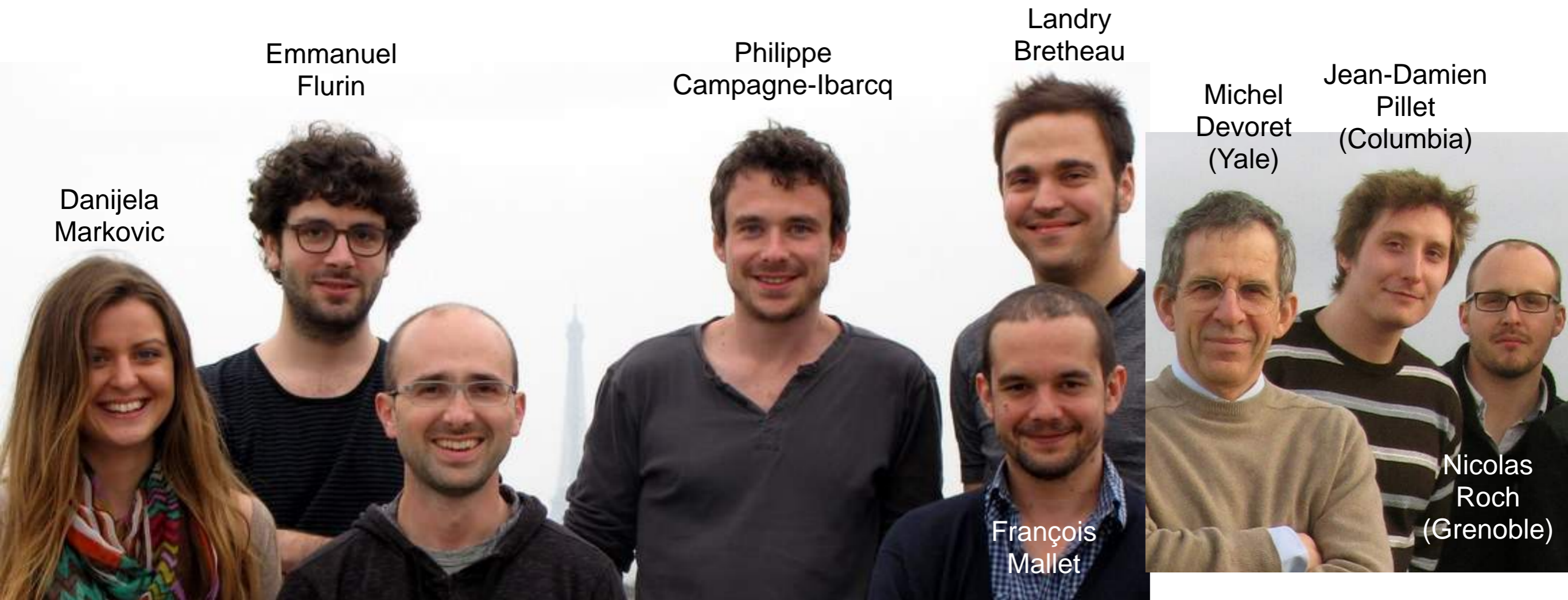


Unravelling a quantum jump by measuring fluorescence only

Quantum teleportation and remote state preparation



Thanks



Danijela Markovic

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Philippe Campagne-Ibarcq

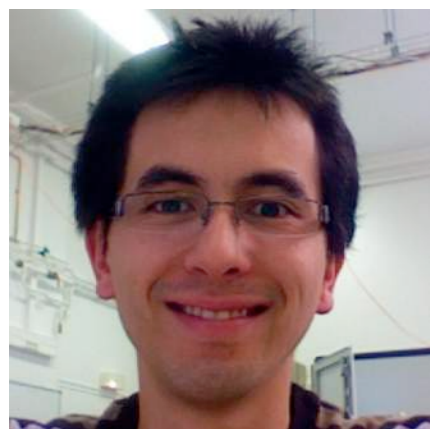
Landry Bretheau

Michel Devoret (Yale)

Jean-Damien Pillet (Columbia)

François Mallet

Nicolas Roch (Grenoble)



François Nguyen



Vlad Manucharyan (JQI Maryland)



Mazyar Mirrahimi (INRIA)



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Karin and Bethsabée



