

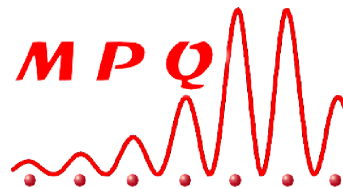
Soutenance de thèse

Alexandre Delga



**Du phénomène quantique au dispositif macroscopique,
transport électronique dans les détecteurs inter-sousbandes**

Sous l'encadrement de

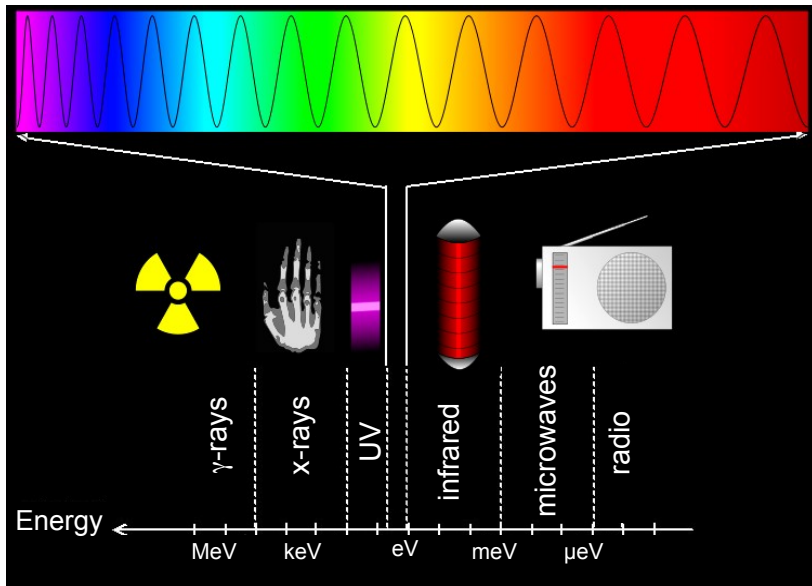


*Vincent Berger
Laetitia Doyennette*

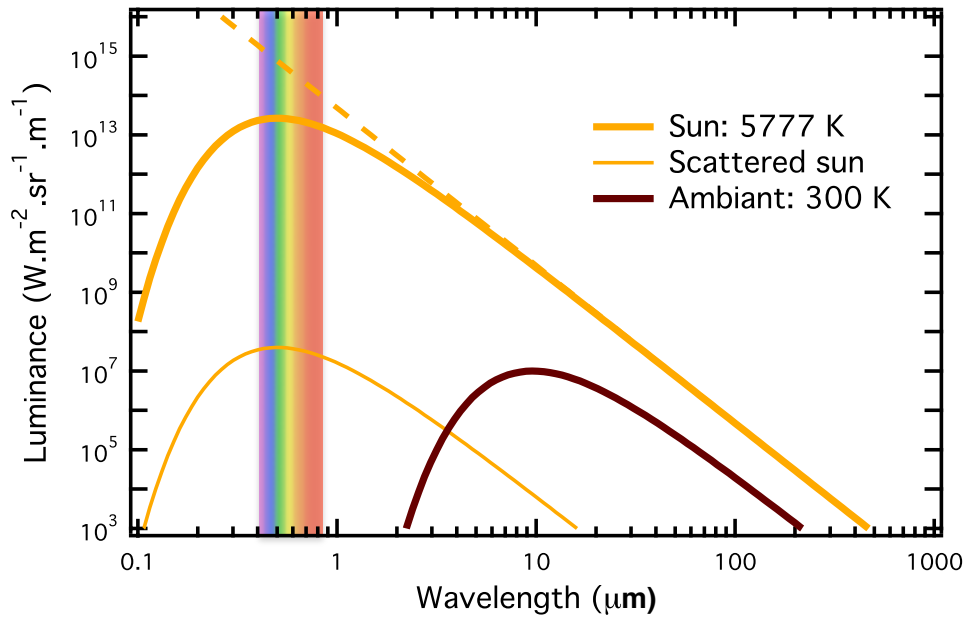
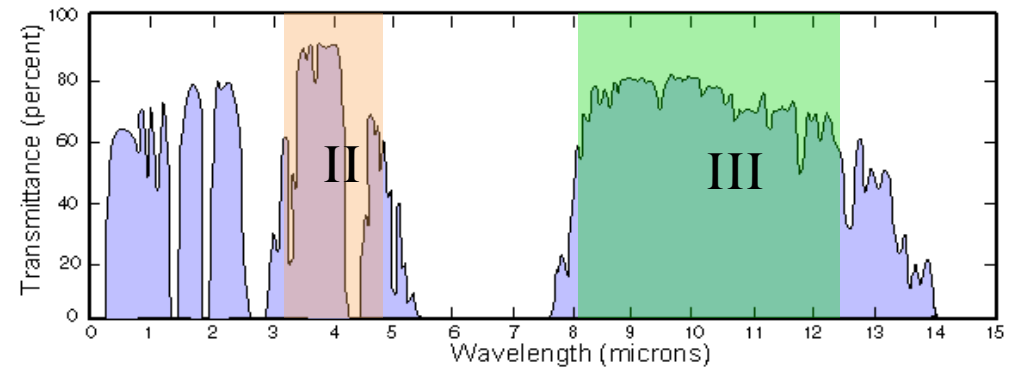


*Mathieu Carras
Virginie Trinité*

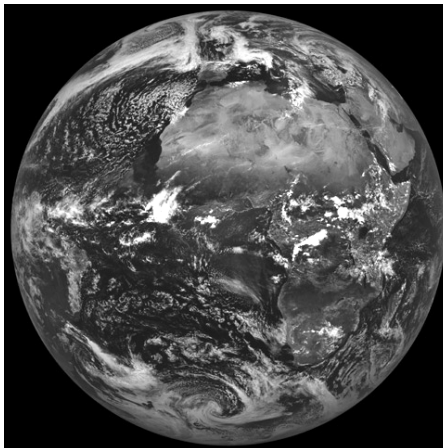
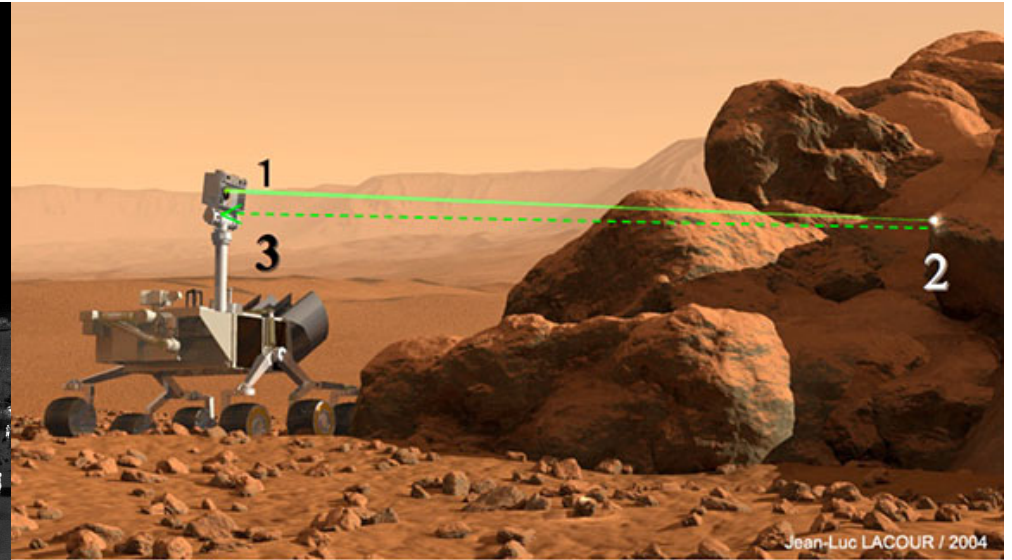
Infrared detection



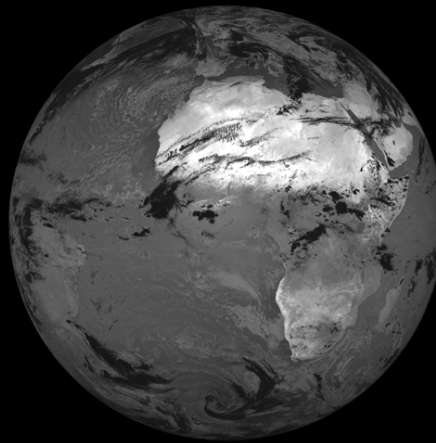
Atmospheric transparency



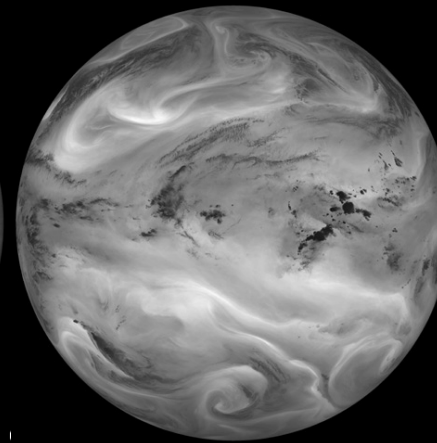
Technological motivations



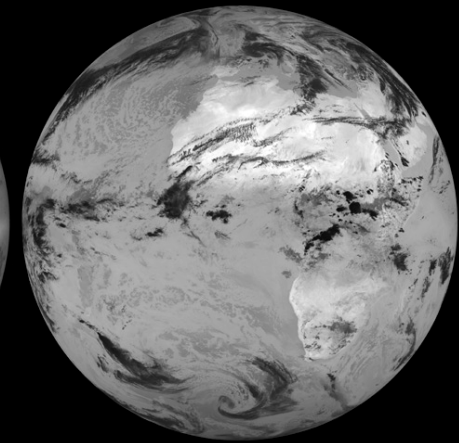
Visible
 $0.6 \mu\text{m}$



Band II
 $3.9 \mu\text{m}$



H₂O
 $6.2 \mu\text{m}$



Band III
 $10.8 \mu\text{m}$

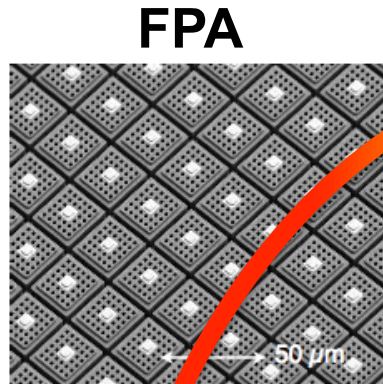
Detection System

Photonics

Electronics

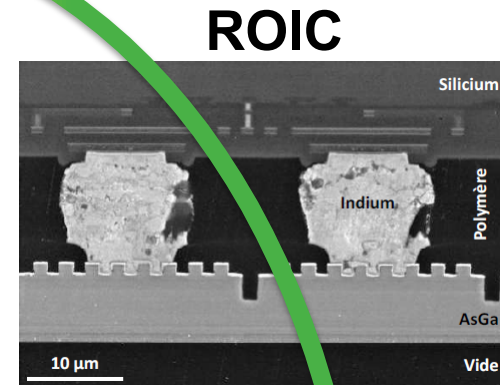
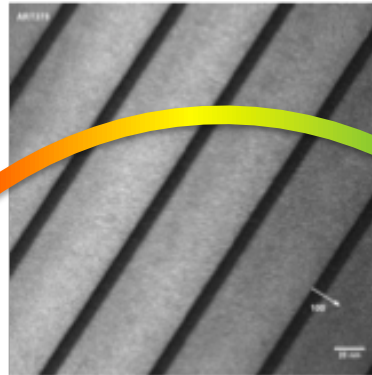


Catherine XP Thales



FPA

Active Layers



ROIC

Optics



Cryogenics

Analogic
→ Digital

Physics

Engineering

Scene



Introduction



Current



Noise



Prospects



Technologies

Thermal detectors

Quantum Detectors

$$\lambda_{Broglie} \overset{?}{\leftrightarrow} L$$

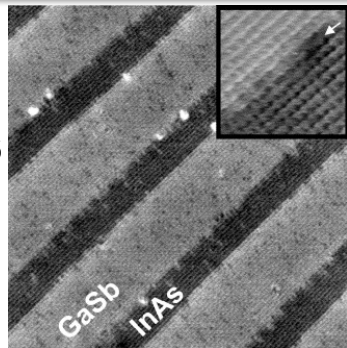
3D

2D

1D

0D

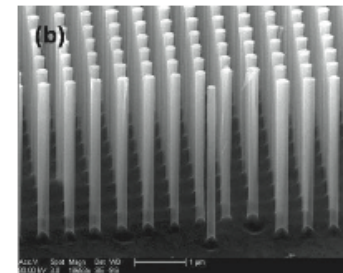
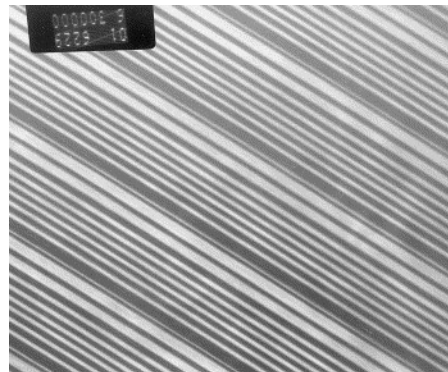
Type II superlattices



InGaAs
InSb
HgCdTe

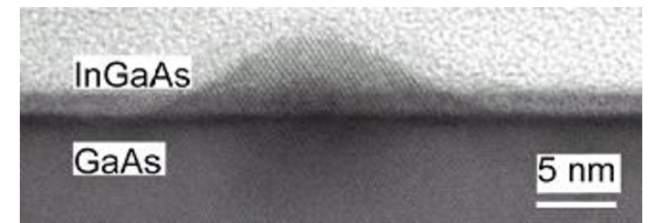


QWIP
QCD



Nanowire
Nanotubes

QDIP
DWELL



Introduction



Current



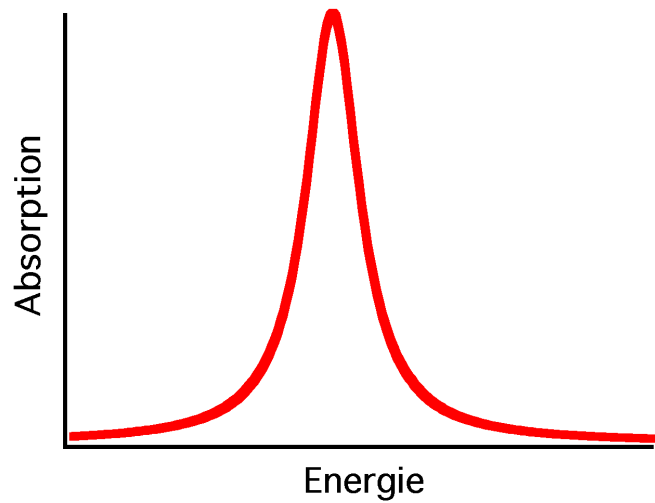
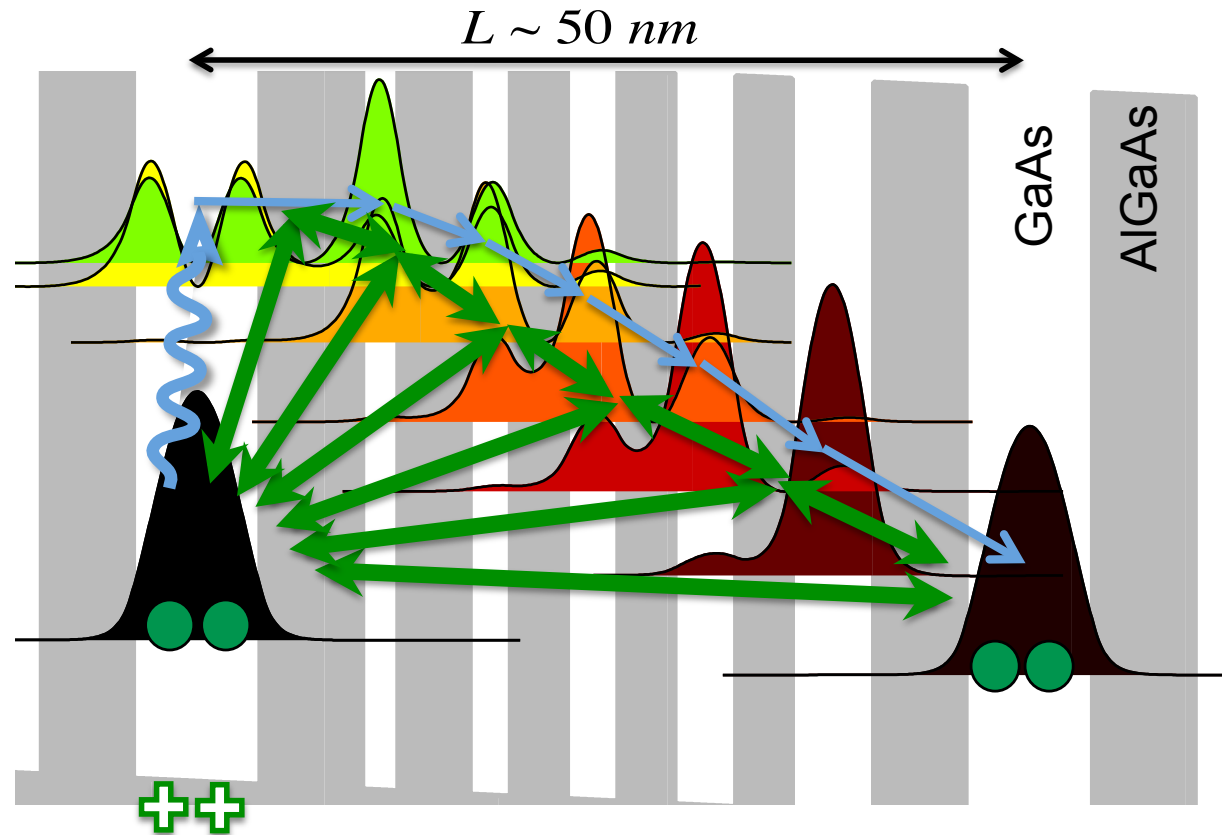
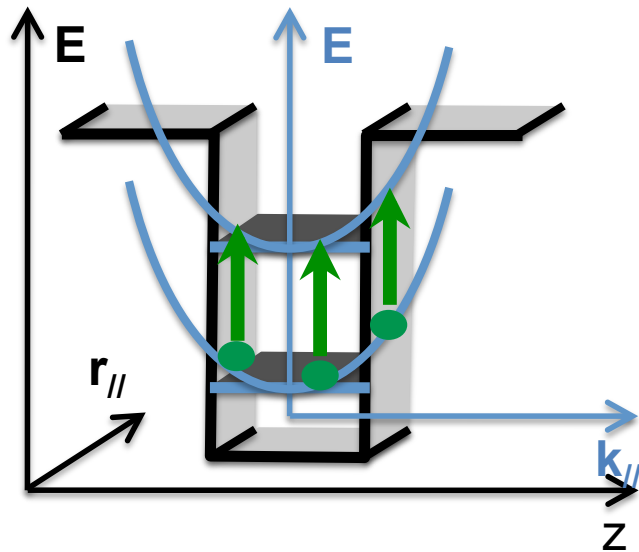
Noise



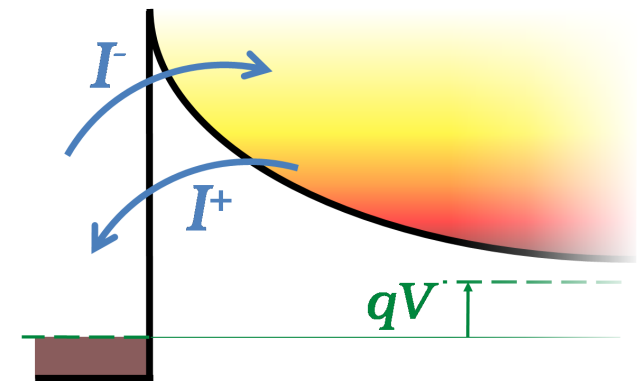
Prospects



Quantum Cascade Detectors

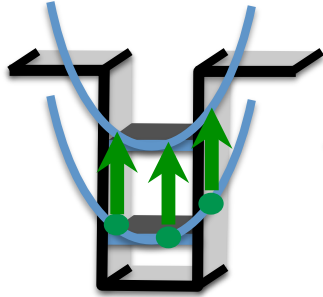


- Unipolar
- Selection rule
- Photovoltaic

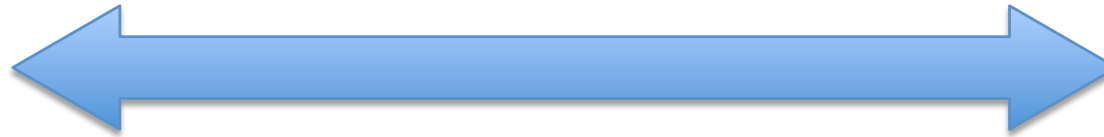


Du phénomène quantique au dispositif macroscopique, transport électronique dans les détecteurs inter-sousbandes

Quantum
phenomenon



Macroscopic
device



■ Current

- Historical model
- Theoretical Framework
- Hybrid model

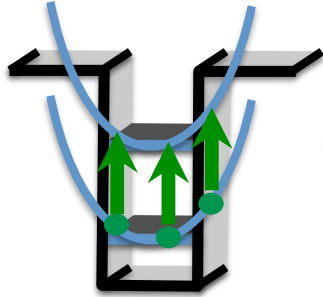
■ Noise

- Shot and Johnson noise
- New approach

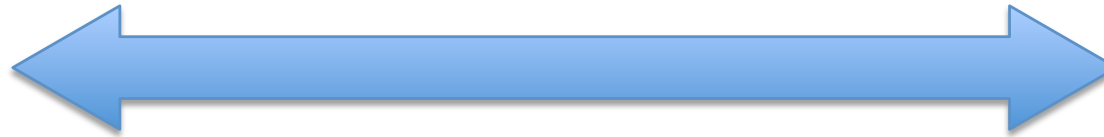
■ Prospects

Du phénomène quantique au dispositif macroscopique, transport électronique dans les détecteurs inter-sousbandes

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■ Current

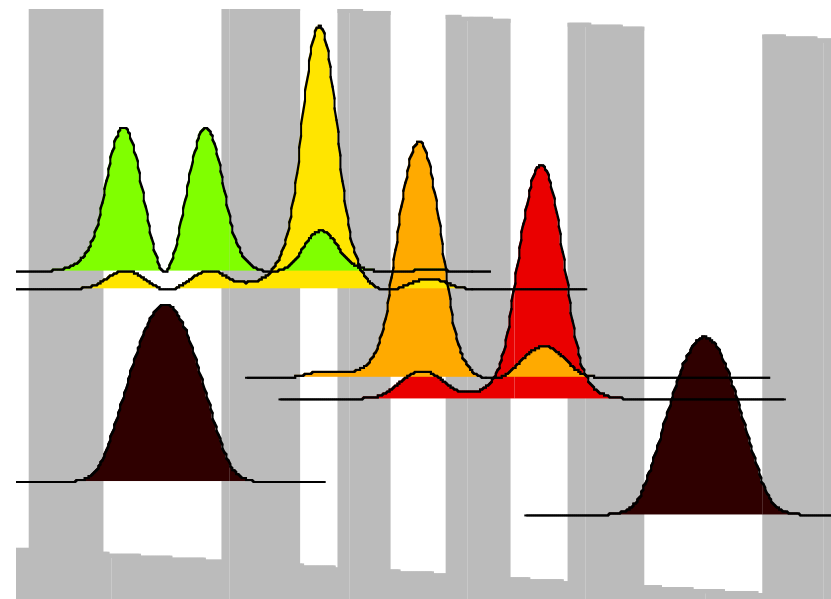
- Historical model
- Theoretical Framework
- Hybrid model

■ Noise

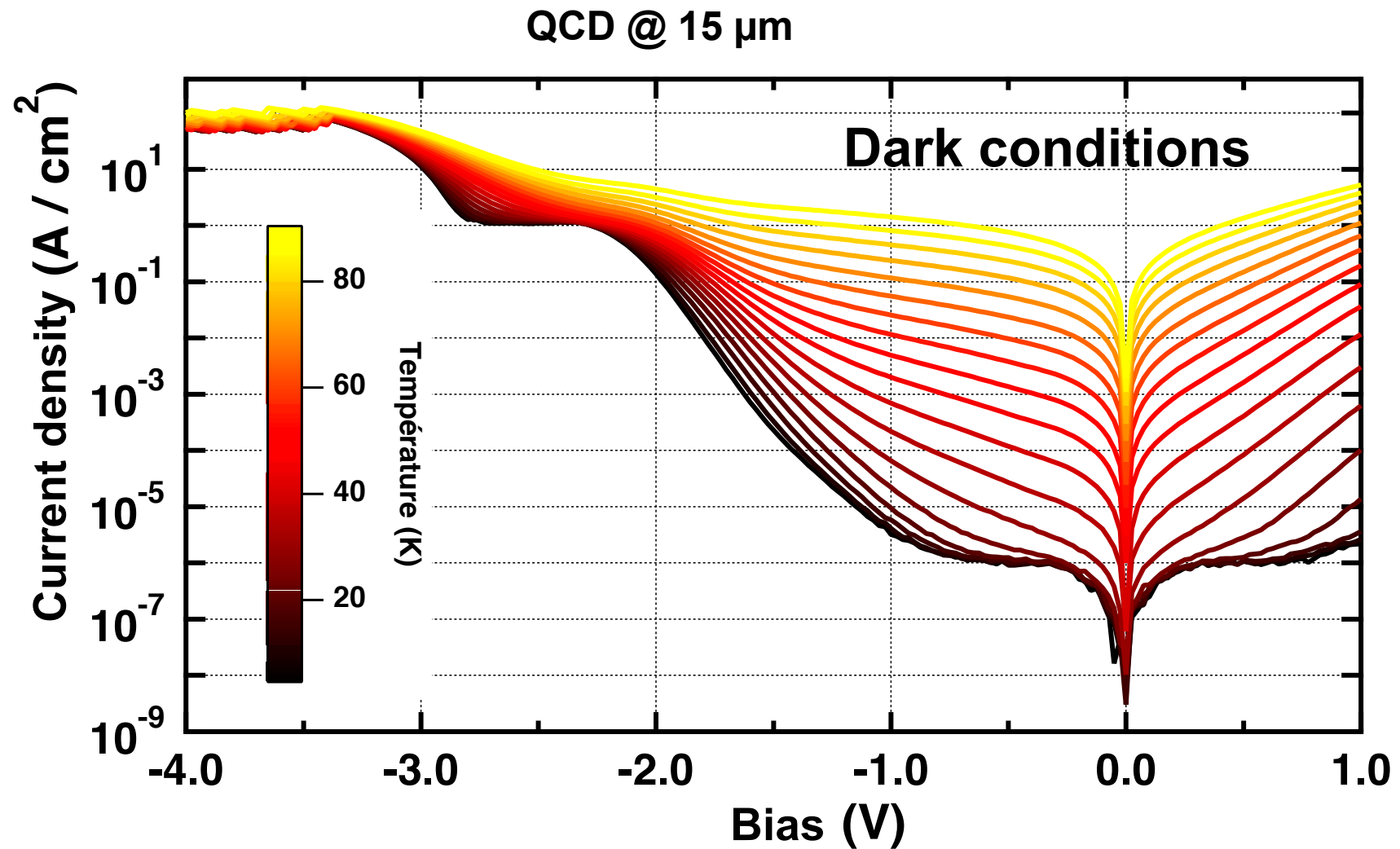
- Shot and Johnson noise
- New approach

■ Prospects

QCD @ 15 μm

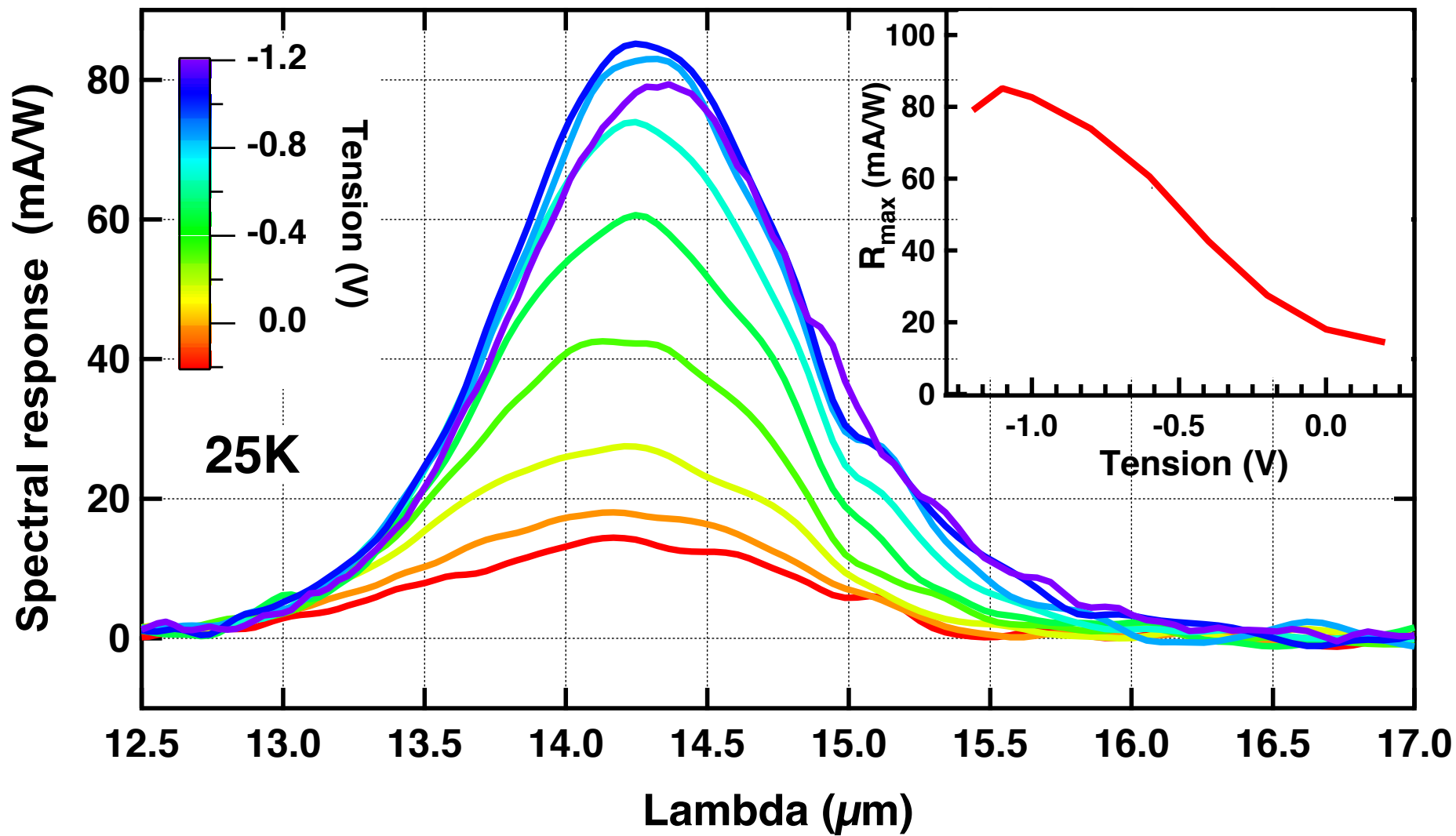


Signal related quantities




Signal related quantities

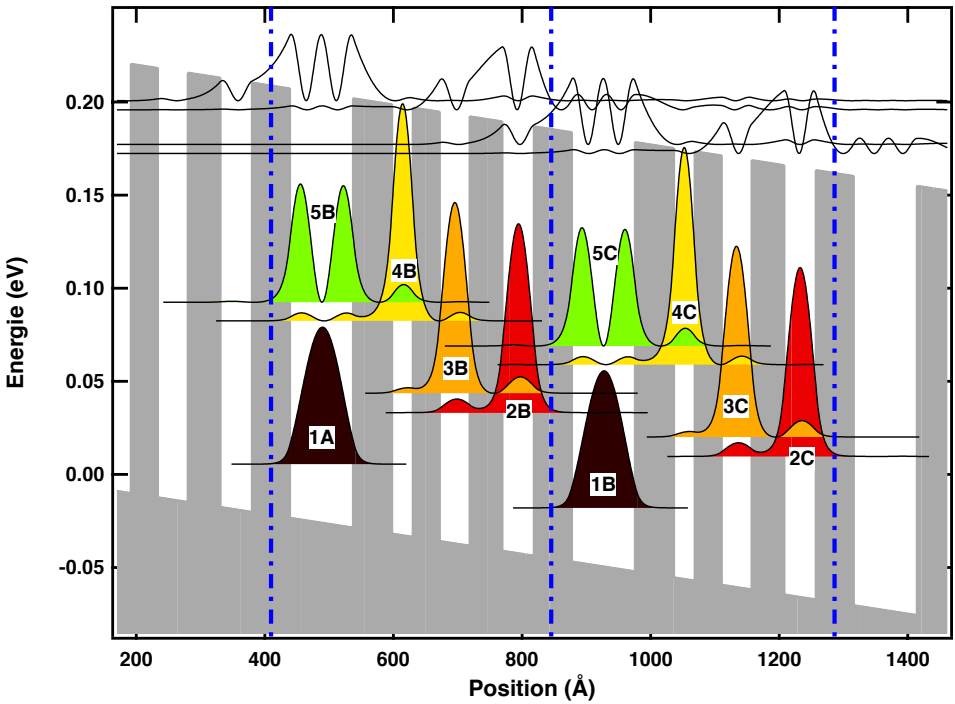
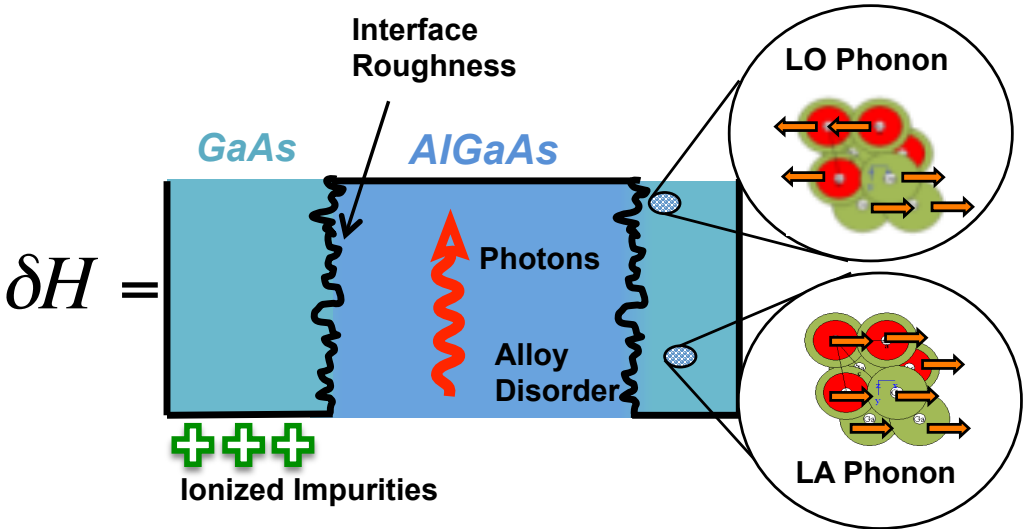
QCD @ 15 μm



Wannier-Stark hopping: Hamiltonian



$$H_z = \underbrace{\frac{p_z^2}{2m^*}}_{\text{Kinetic Energy}} + \underbrace{H_{het}}_{\text{Heterostructure Potential}} + \underbrace{eFz}_{\text{Electric Field}}$$



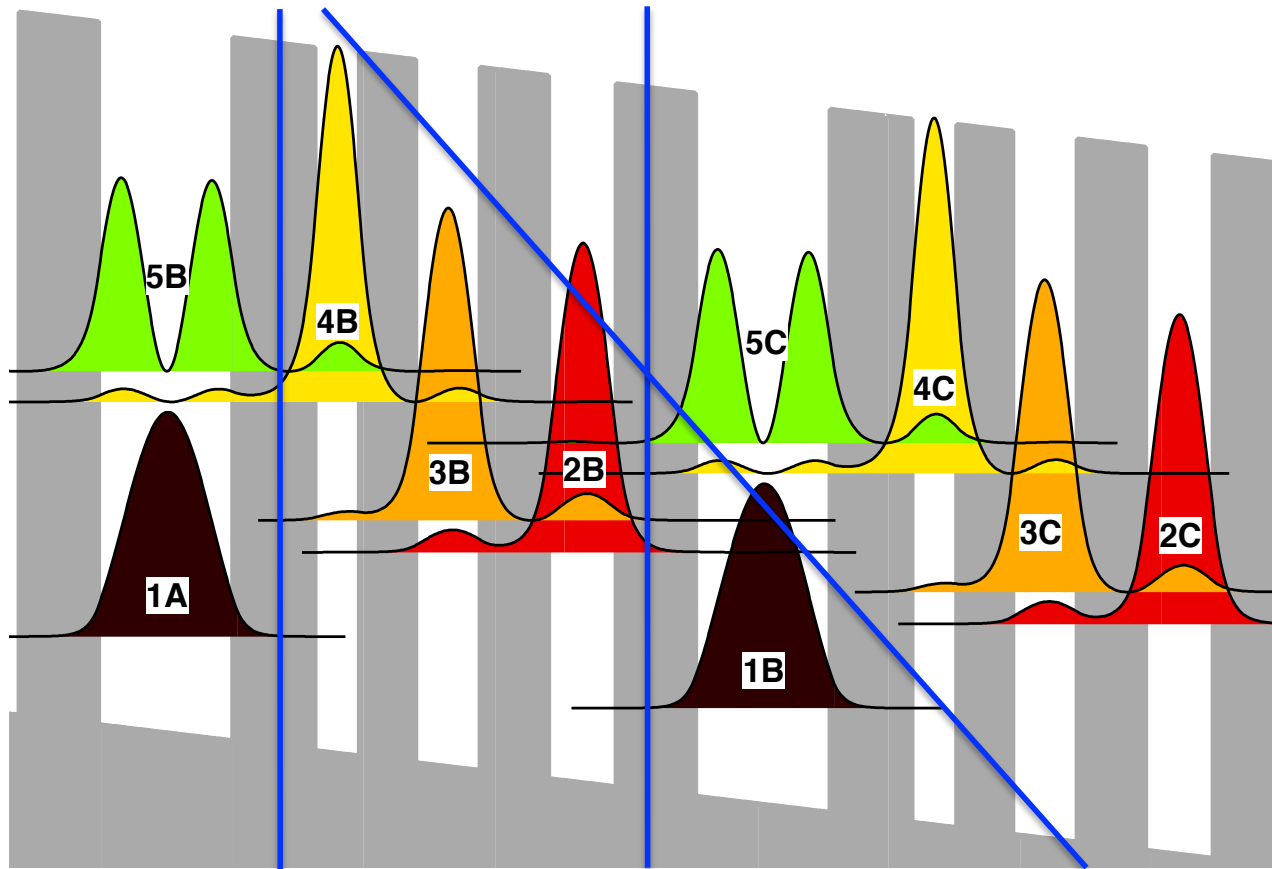
Fermi Golden Rule
 τ_{ij}

Inter-subband scattering

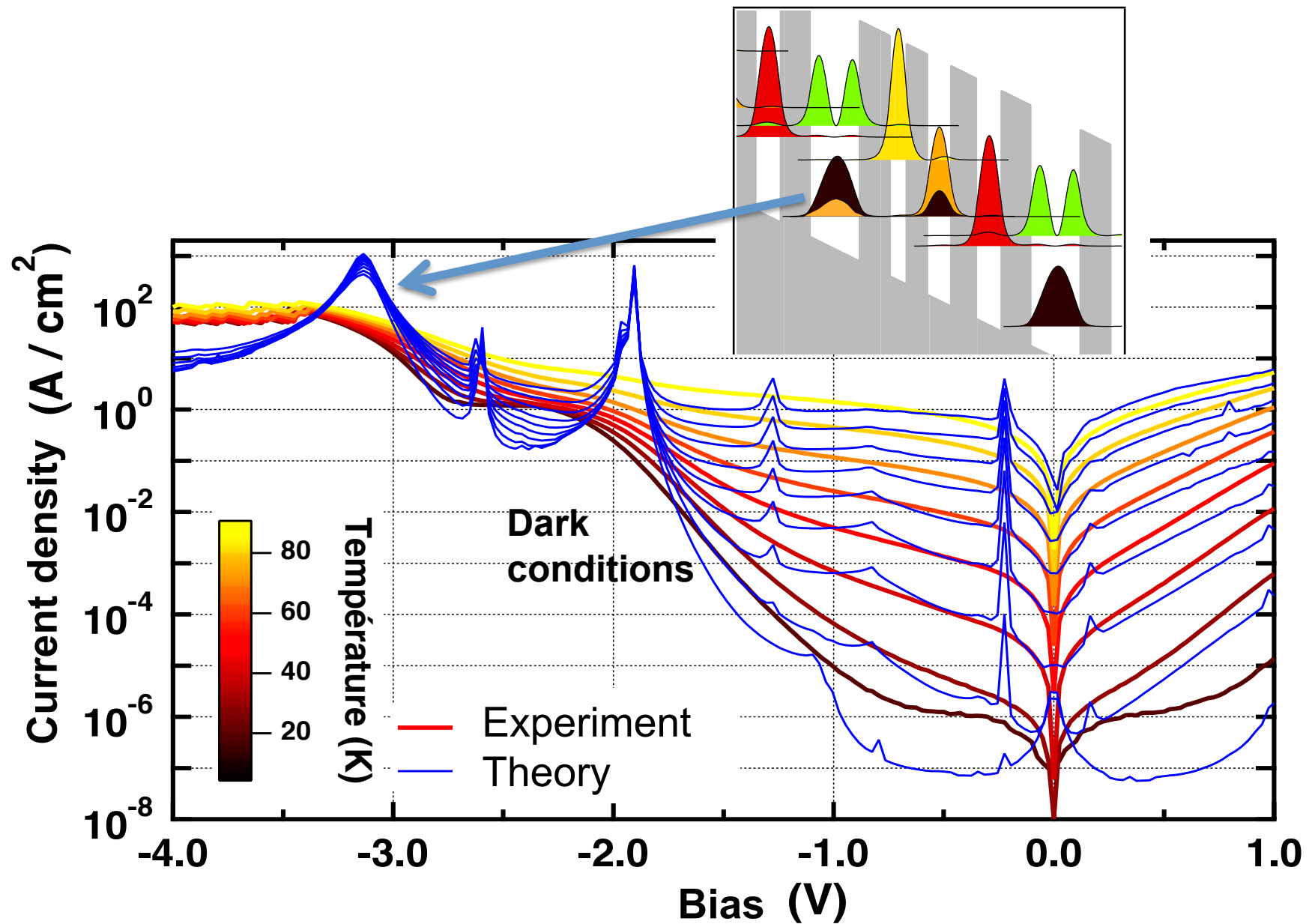
$$\frac{dn_i}{dt} = -\frac{n_i}{\tau_i} + \sum_{j \neq i} \frac{n_j}{\tau_{ji}}$$

Wannier-Stark hopping: rate equation

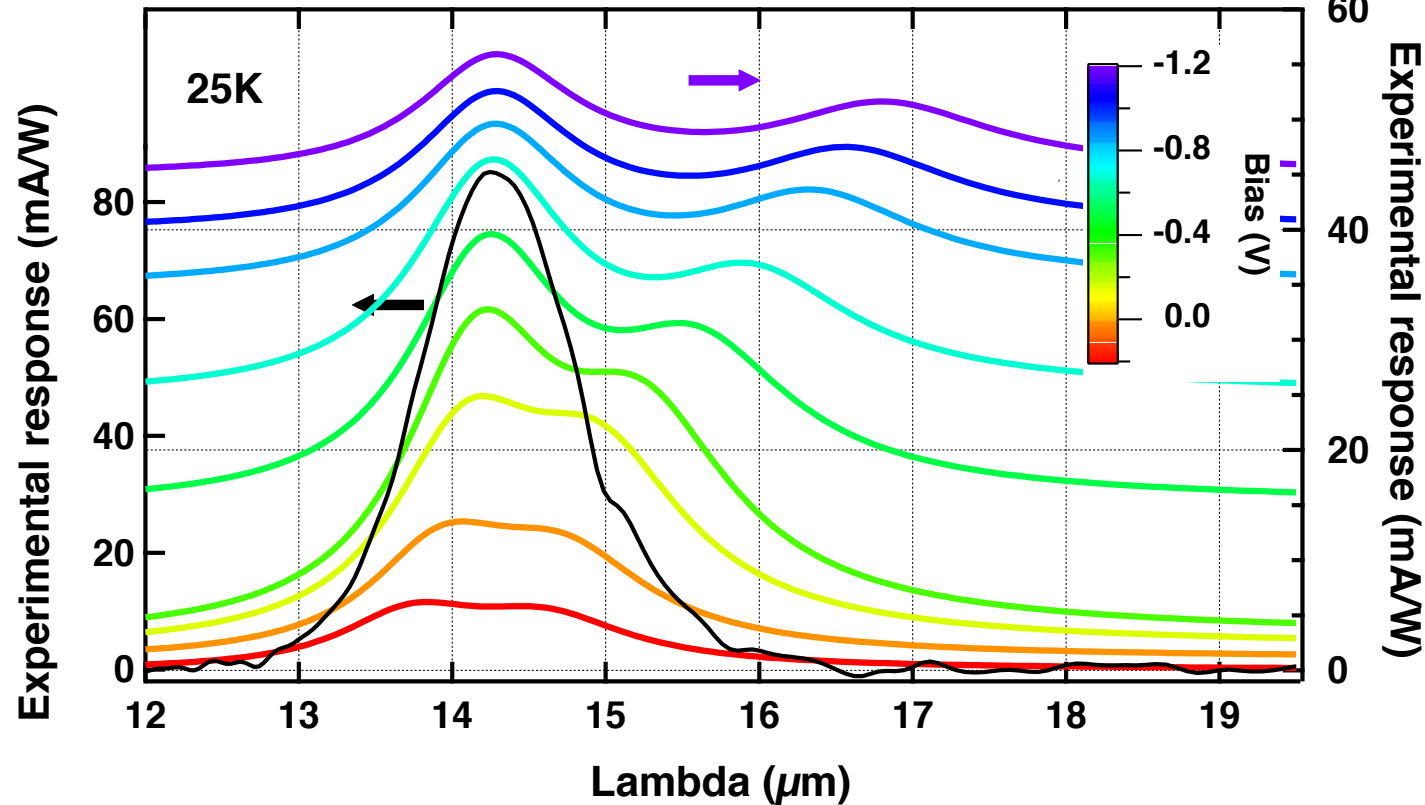
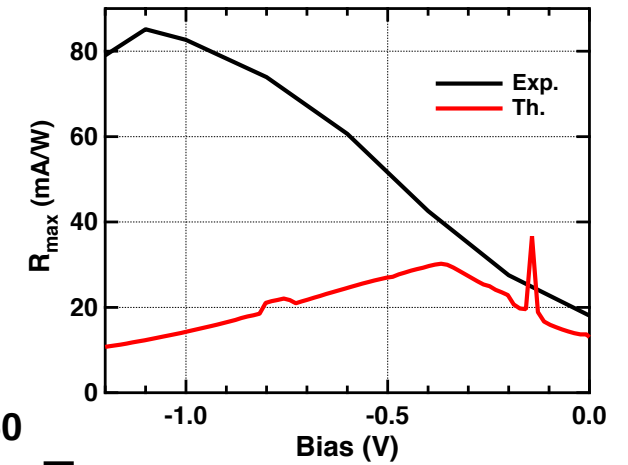
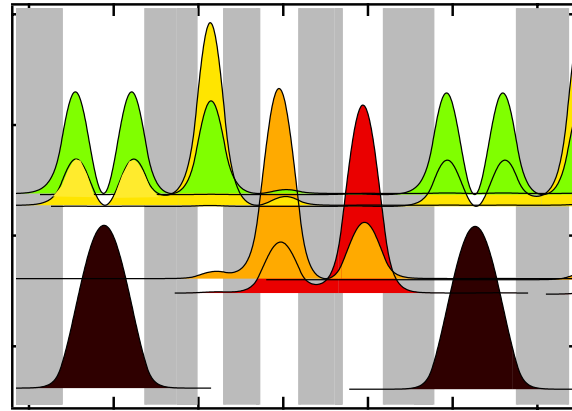
$$0 = -\frac{n_i}{\tau_i} + \sum_{j \neq i} \frac{n_j}{\tau_{ji}}$$



Wannier-Stark hopping: current



Wannier-Stark hopping: responsivity

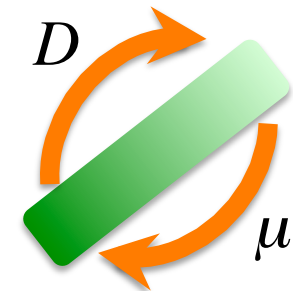
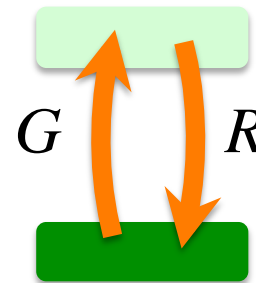
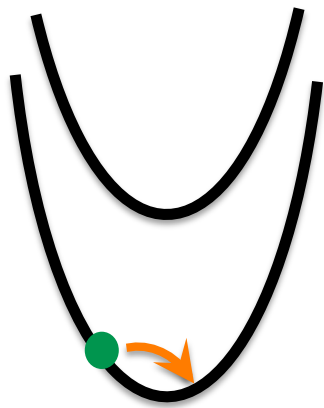


Transport models

$$\rho_{ij} \Rightarrow \tau_{ij}$$

$$\vec{k} \Rightarrow n, p, w, T_e$$

$$p, w \Rightarrow \mu, D$$



Density matrix
Coherences

Boltzmann equation
Diffusions

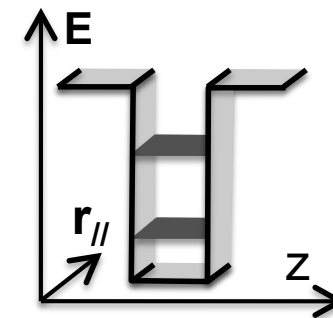
Hydrodynamics
Local equilibrium

Drift-diffusion
Global equilibrium



Intra-subband thermalisation

$$\tau_z \gg \tau_{//}$$



E. Schöll, *Theory of transport properties in semiconductor nanostructures* (1997)

Introduction

Current

Noise

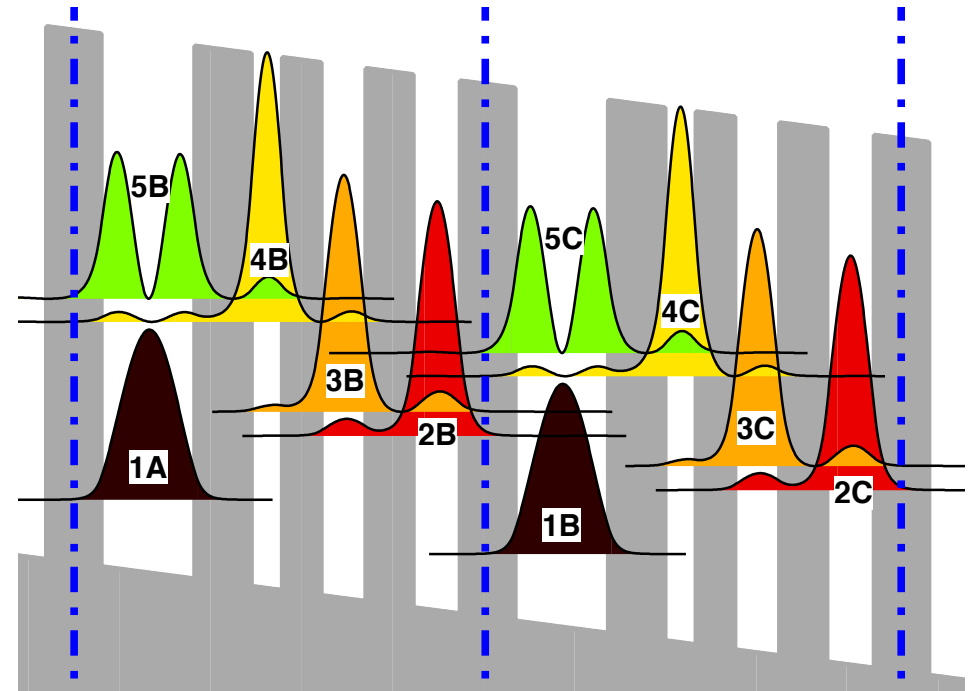
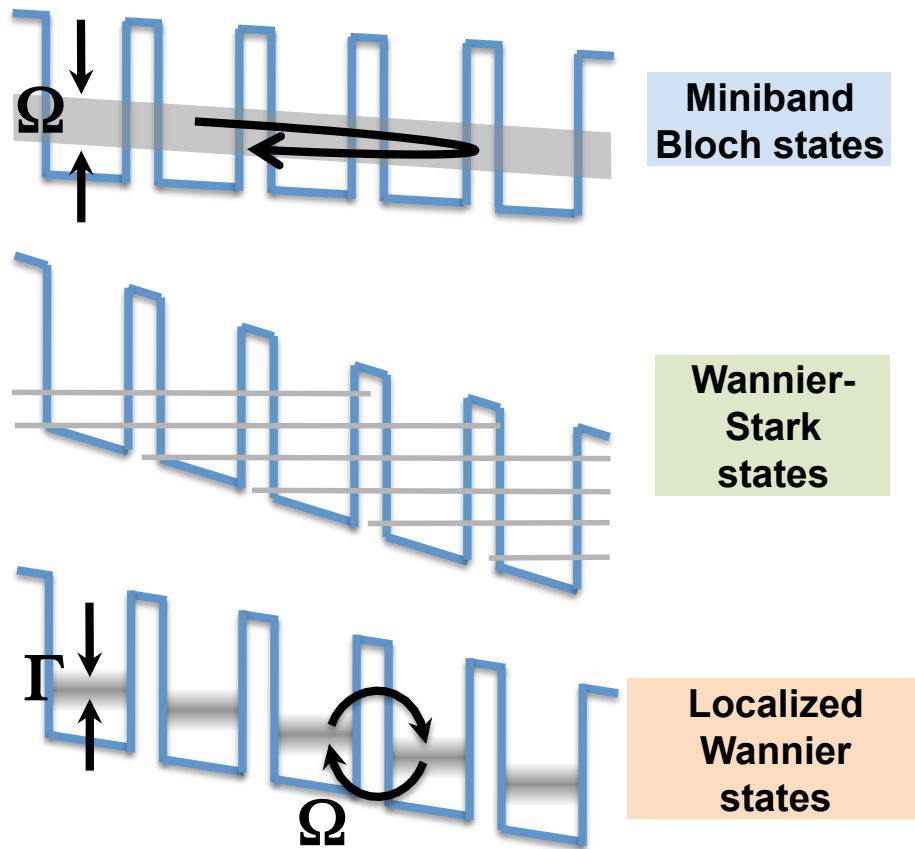
Prospects



Hamiltonian

$$H_z = \frac{p_z^2}{2m^*} + H_{het} + eFz + \delta H$$

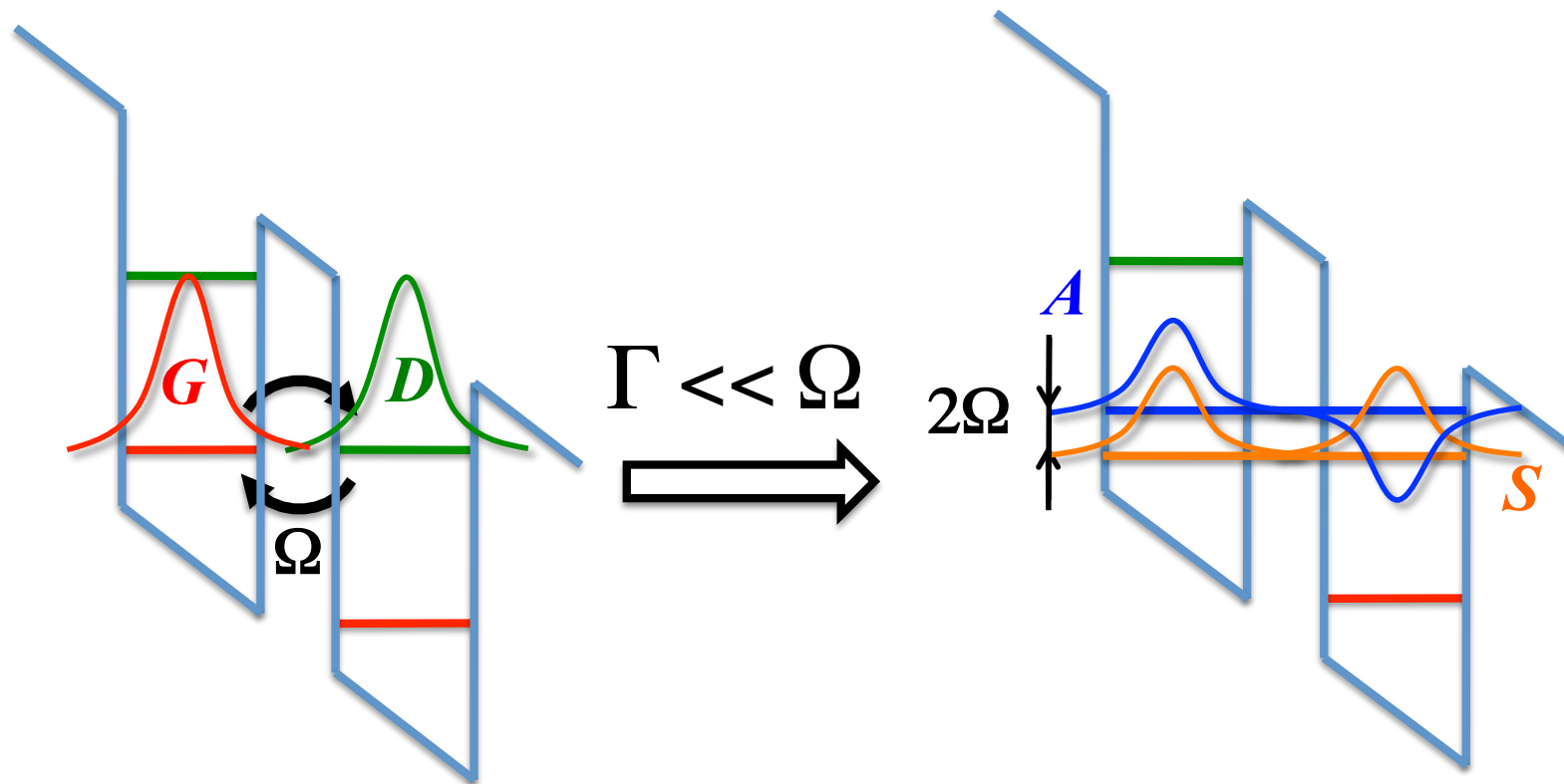
- Ω Coupling ≤ 5 meV
- Γ Scattering ~ 10 meV
- Δ Detuning any



Wacker et al, PRL 80, 369 (1998)

Wannier-Stark hopping: current

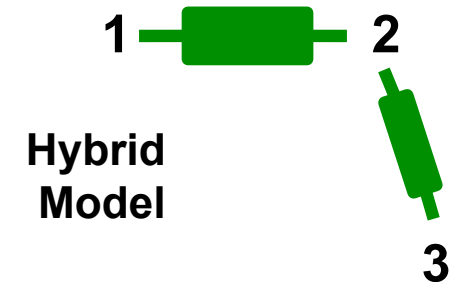
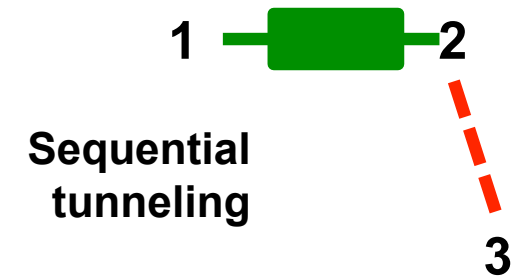
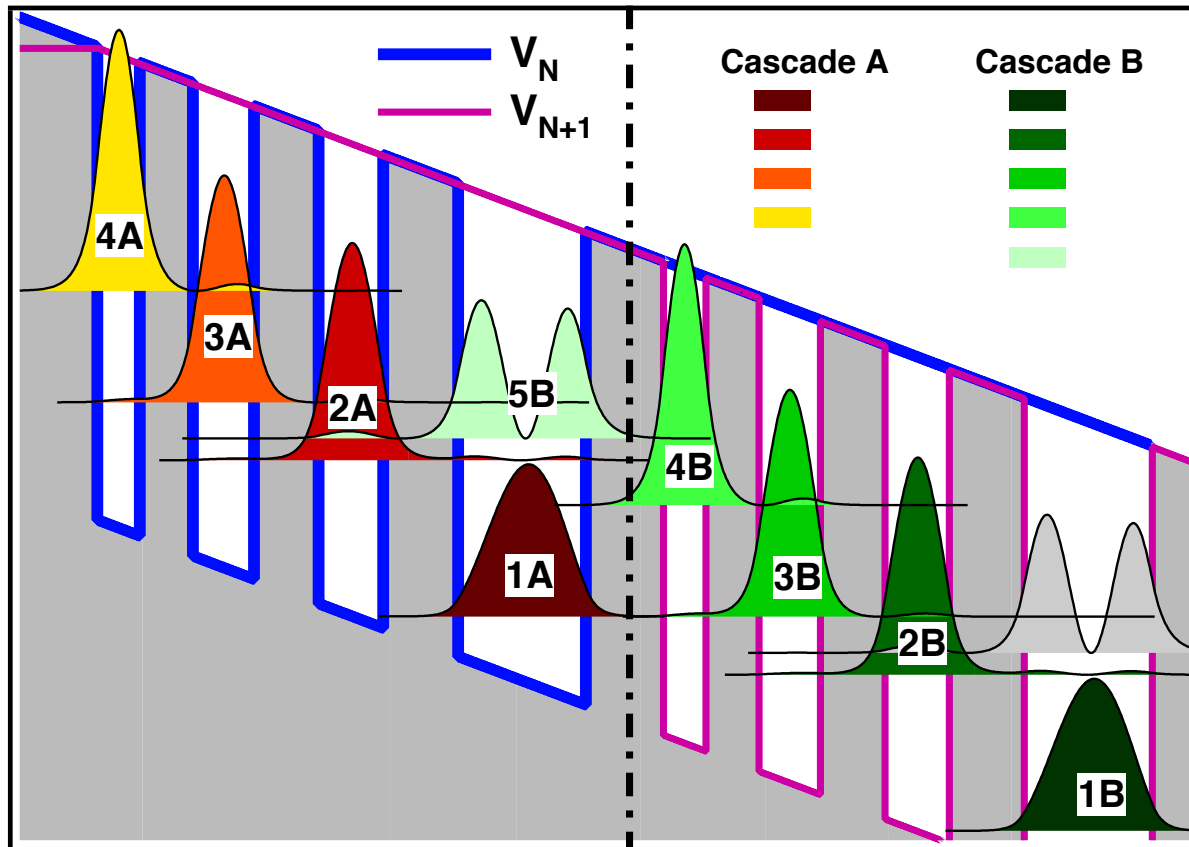
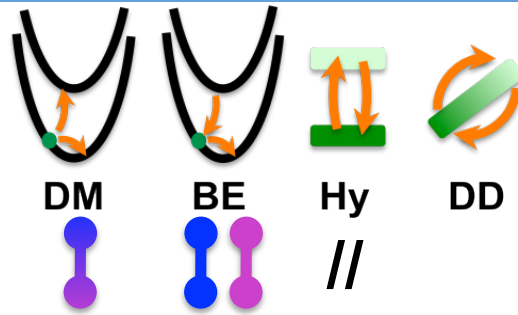
- WS basis: infinite coherence
- In reality $\Omega < \Gamma$
- Works when $2\Gamma < \Delta$
- Ω Coupling ≤ 5 meV
- Γ Scattering ~ 10 meV
- Δ Detuning any



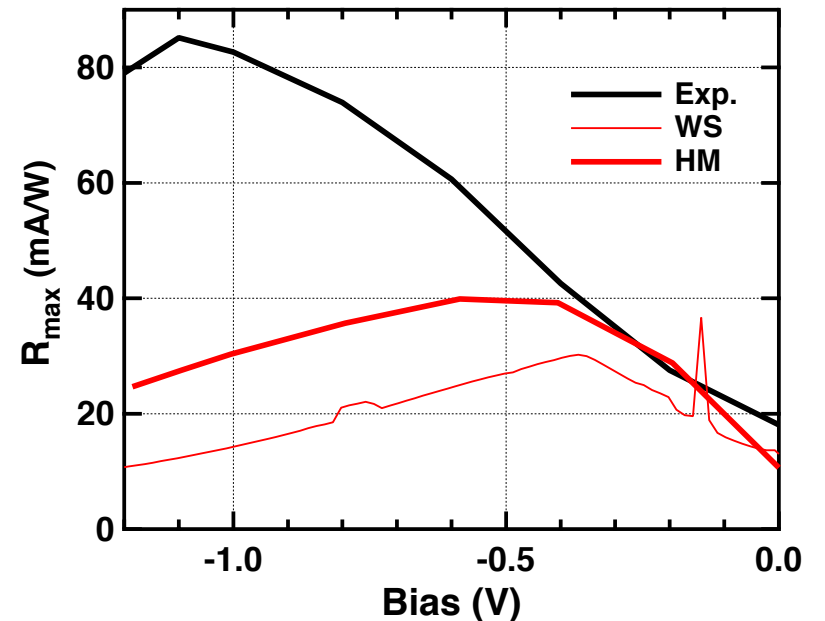
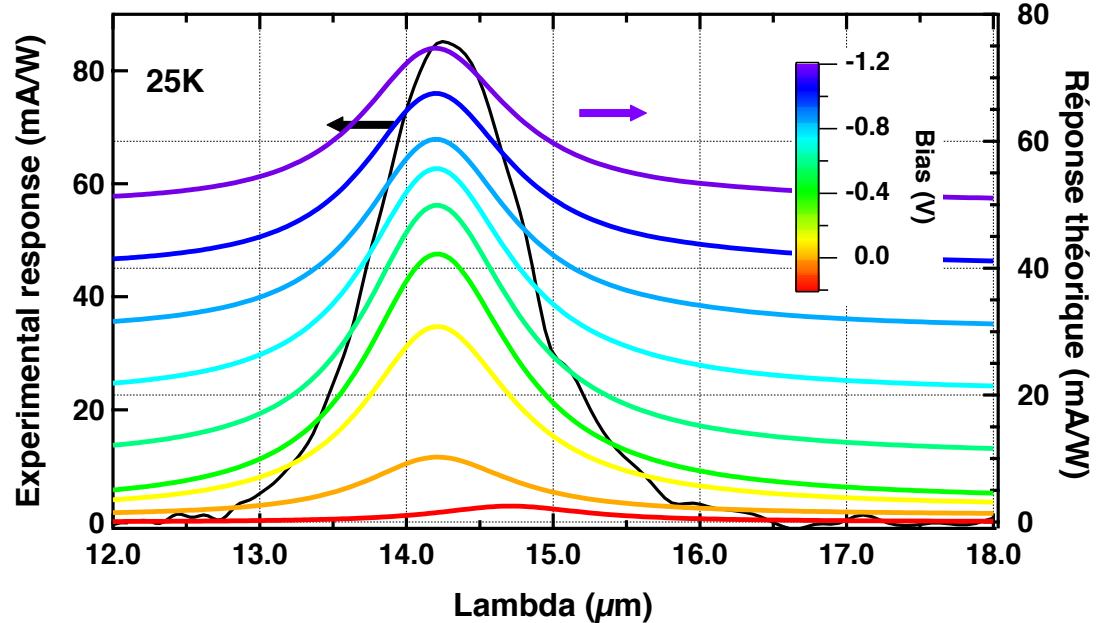
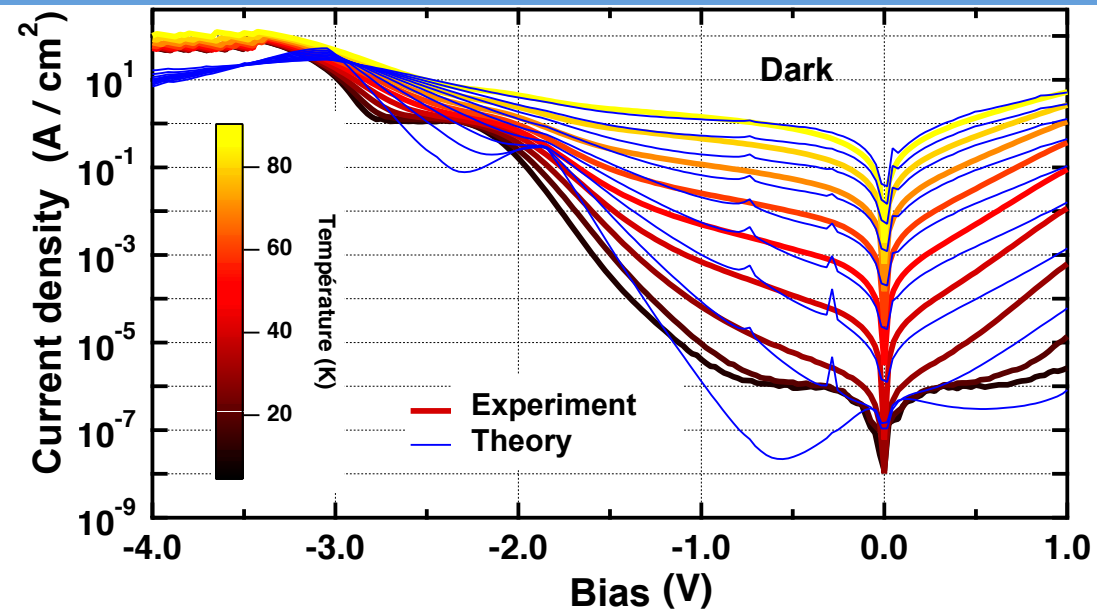
Callebaut et al, JAP 98, 104505 (2005)

Hybrid model: principle

- Pairs of localized states
- Rabi coupling
- 2nd order tunneling

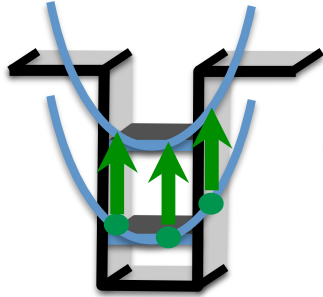


Hybrid model: results



Du phénomène quantique au dispositif macroscopique, transport électronique dans les détecteurs inter-sousbandes

Quantum
phenomenon



Macroscopic
device



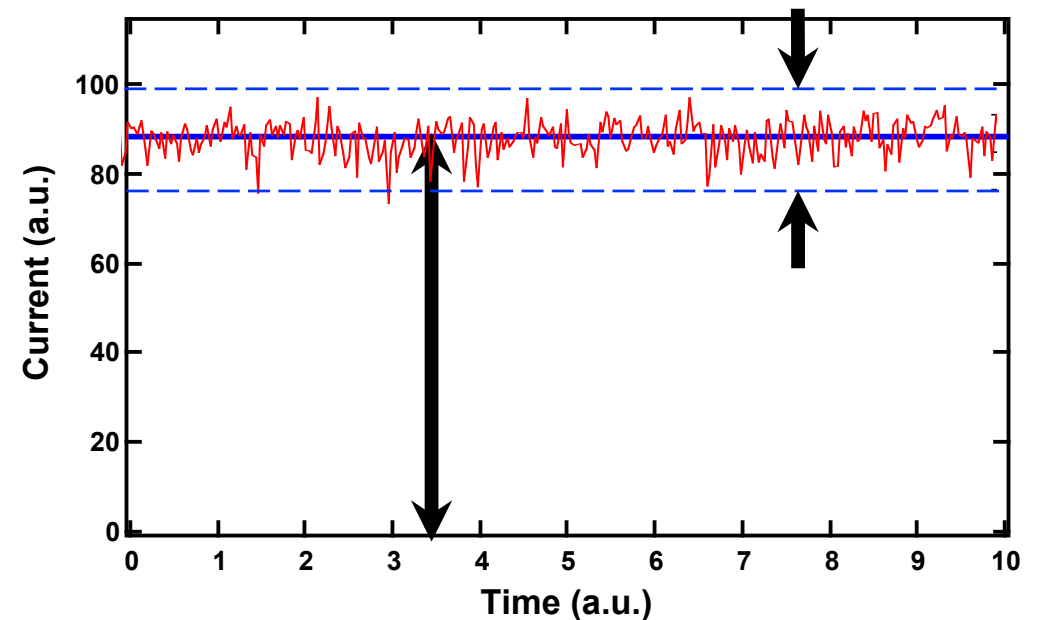
■ Current

- Historical model
- Theoretical Framework
- Hybrid model

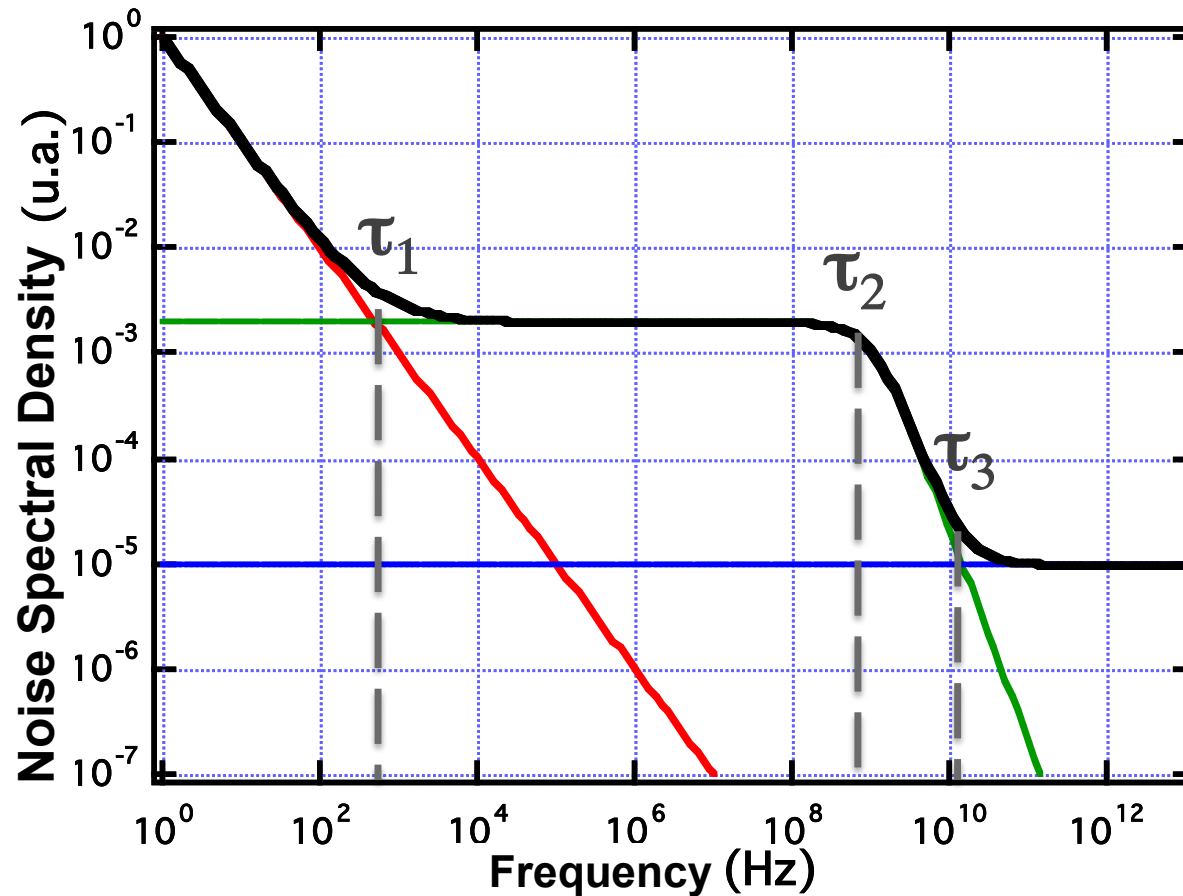
■ Noise

- Shot and Johnson noise
- New approach

■ Prospects



General ideas



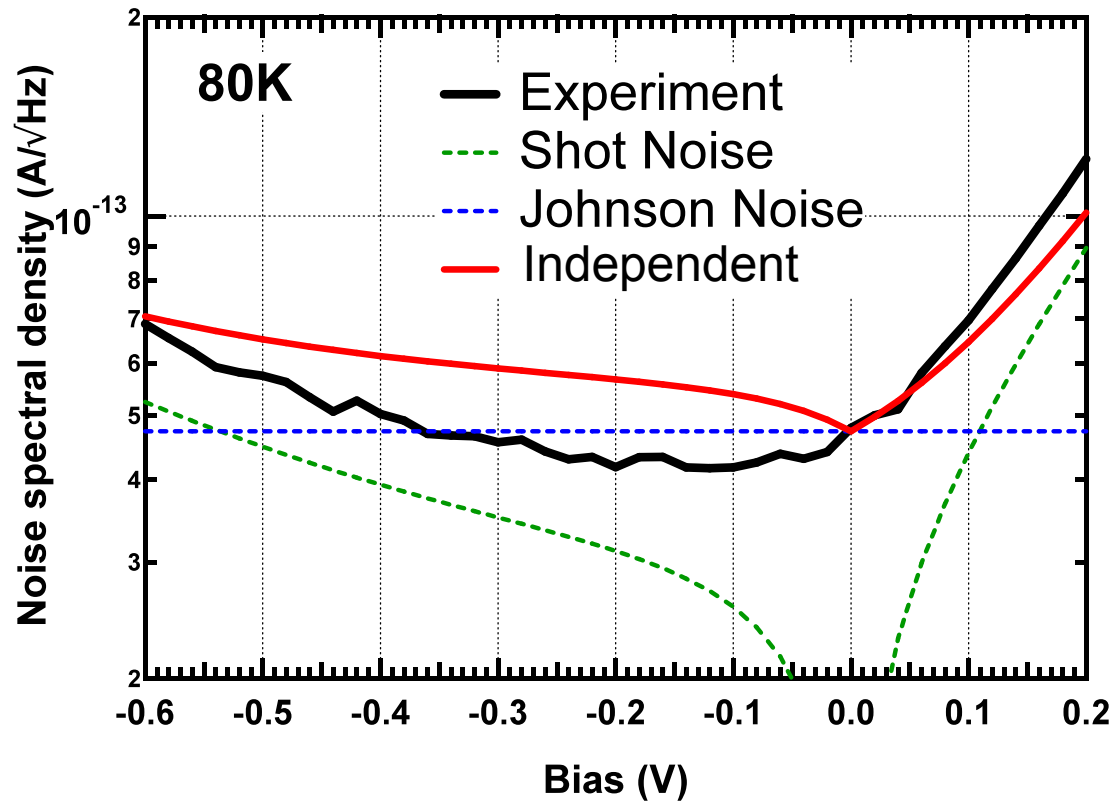
- **1/f (technological)**
none in ISB detectors

- **Shot noise**
 $S_I = 2eI$

- **Thermal noise**
Nyquist theorem

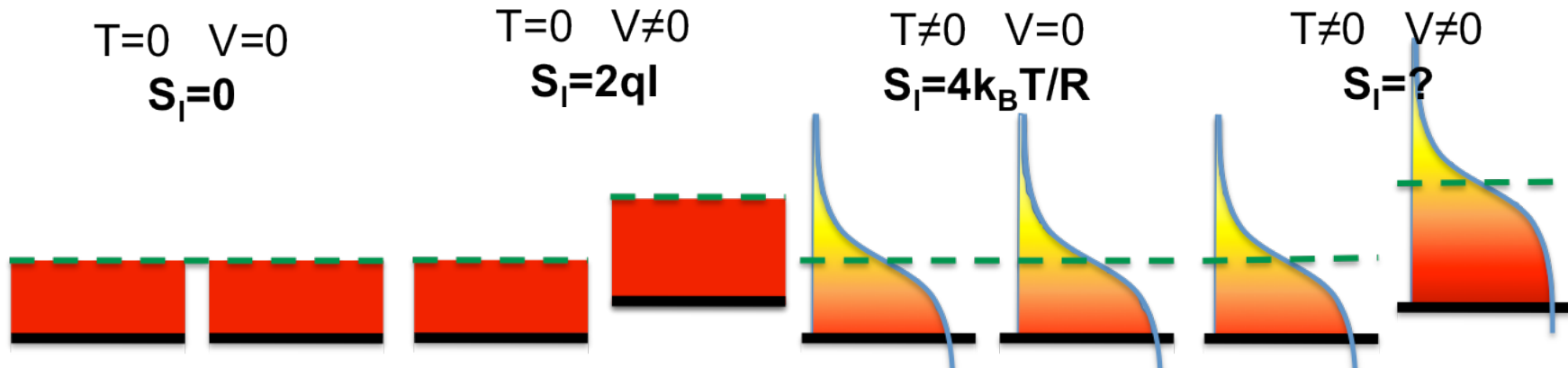
$$S_I = \frac{4k_B T}{R}$$

Shot and Johnson noises



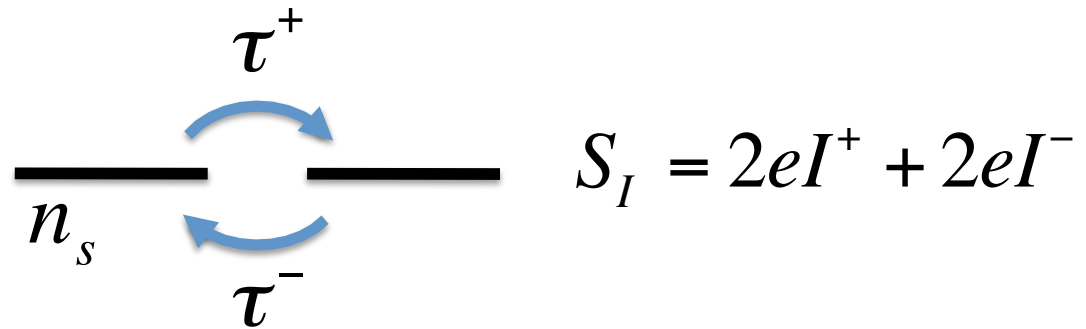
$$S_I = \frac{4k_B T}{R} \oplus 4e g I$$

R. Landauer PRB 47, 16427 (1993)

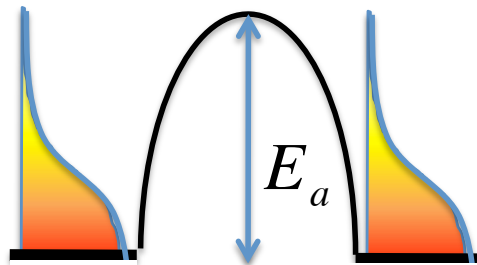


Two facets of a single phenomenon

Microscopic



Carriers, long time



Sites, long distance (Drude)



Macroscopic

$$\frac{1}{\tau} = \exp\left(-\frac{E_a - eV}{k_B T}\right)$$

$$S_I = \frac{4e^2 n}{\tau_0} \coth\left(\frac{eV}{k_B T}\right)$$

$$v = a/\tau$$

$$k_B T = \frac{1}{2} m v^2$$

$$S_I = 4k_B T G$$

Reintroduce fluctuation: master equation

Intersubband scattering

$$\frac{dn_i}{dt} = -\frac{n_i}{\tau_i} + \sum_{j \neq i} \frac{n_j}{\tau_{ji}}$$

Stochastic process

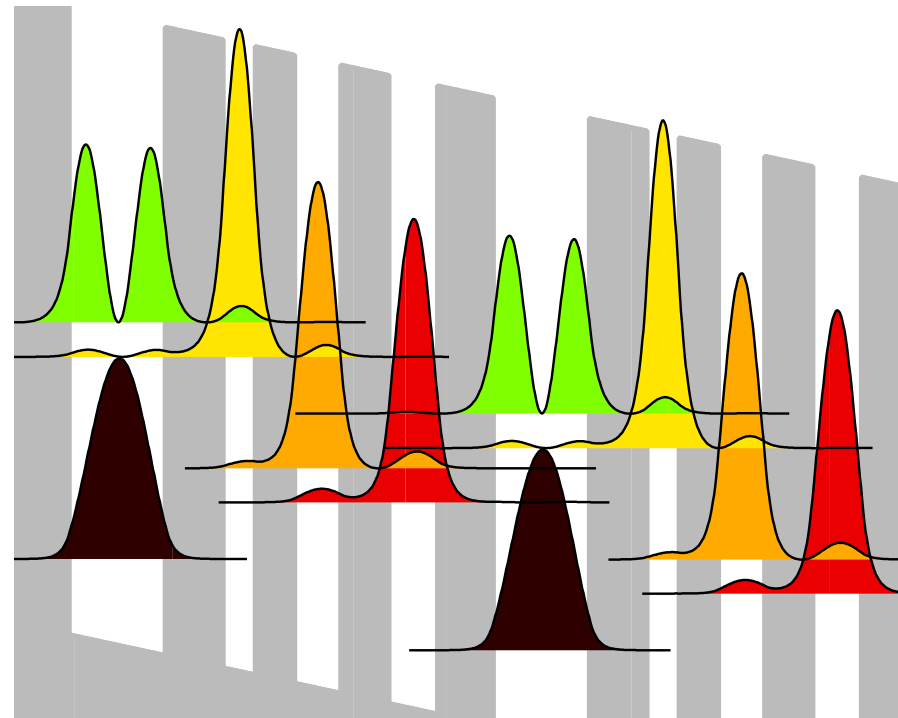
$$p(\underline{n}, t)$$

$$\underline{n} = (n_1, n_2, n_3, n_4, n_5)$$

Intrasubband relaxation

→ Markov process

$$\frac{dp(\underline{n}, t)}{dt} = -\Gamma_{\underline{n}} p(\underline{n}, t) + \int d\underline{n}' w_{\underline{n}', \underline{n}} p(\underline{n}', t)$$



1st moment : mean values
signal

2nd moment : correlations
noise

Delga et al, PRB 85, 245414 (2012)

Introduction



Current



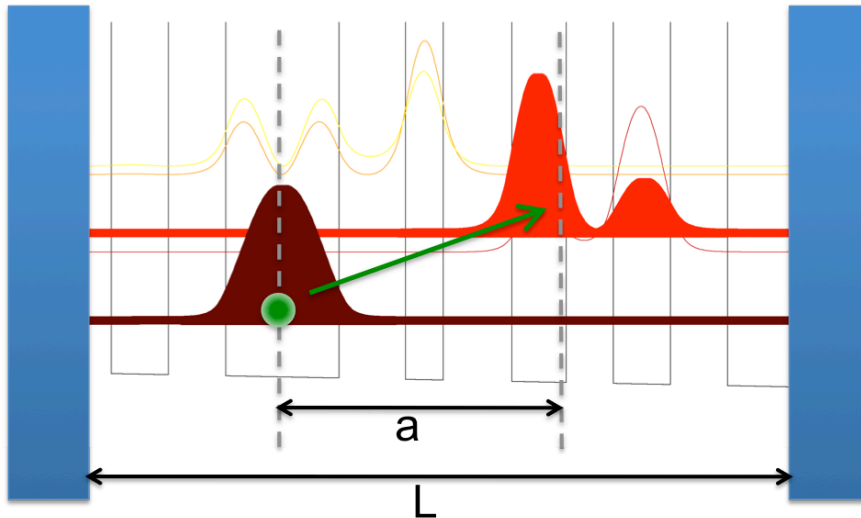
Noise



Prospects



Micro-macro link: Ramo-Shockley theorem



$$\alpha_{ij} = \frac{a}{L}$$

- Current = sum of hops
- Noise = hop correlations
Population correlations

$$S_I(\omega) = 2e^2 \sum_{i,j,k,l} \langle w_{kl} \rangle_0 \alpha_{ij} \alpha_{kl} \left[\delta_{ij,kl} - \Gamma_{ij} \sum_s M_{is}(\omega) \left(\frac{\langle n_s \rangle_0}{N} - \delta_{ls} \right) \right]$$

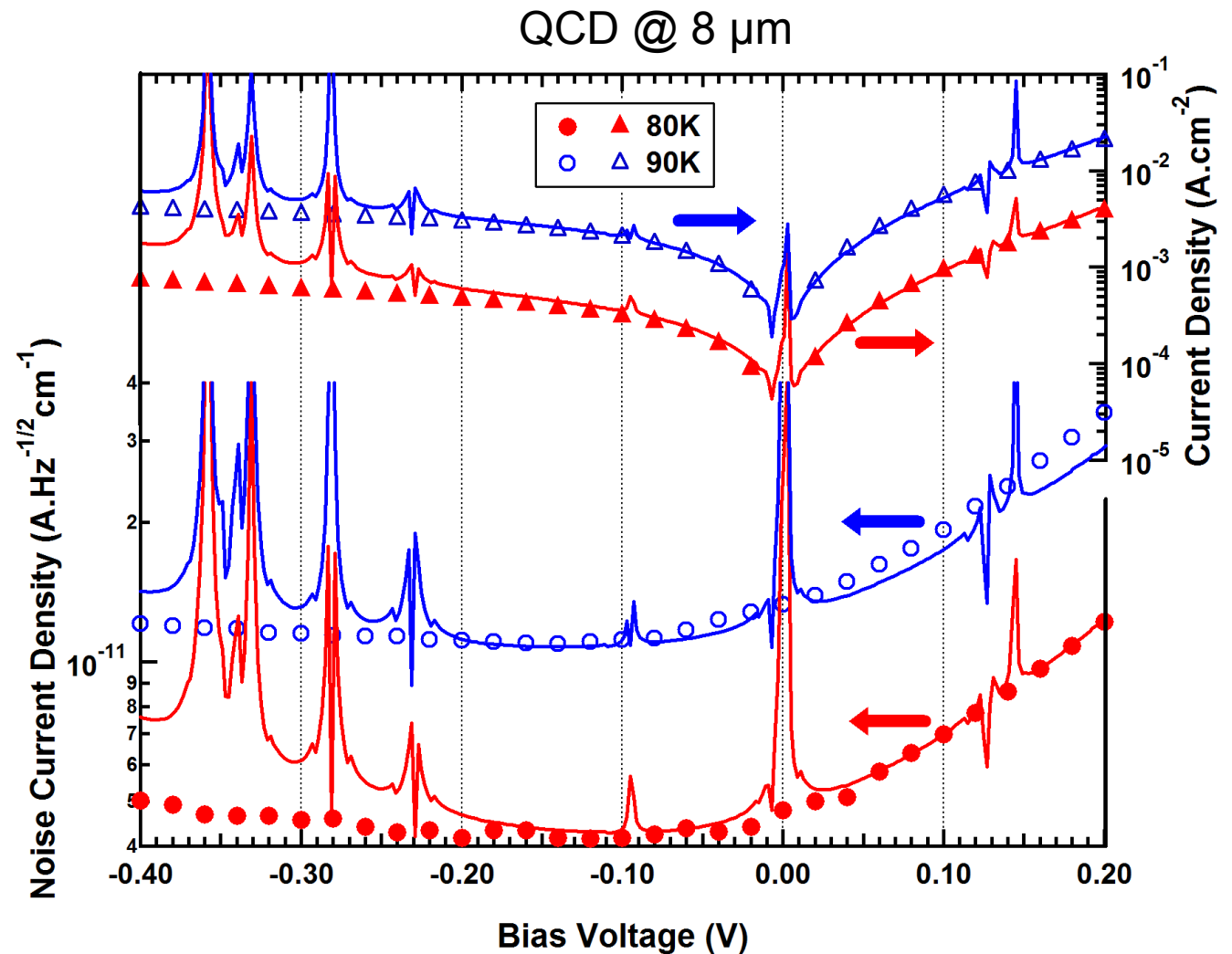
poissonian
source

scaling
factor

Conservation of carriers

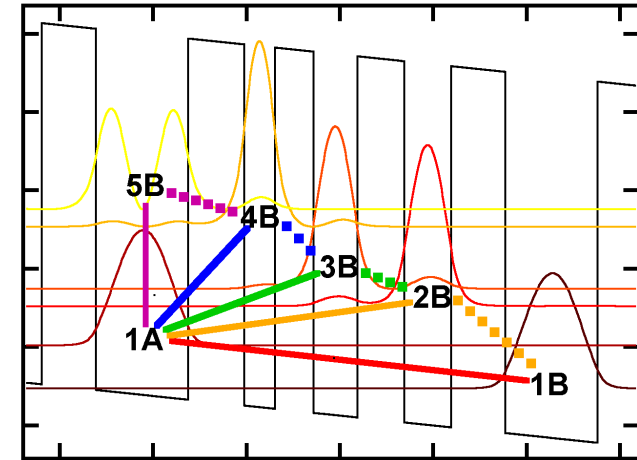
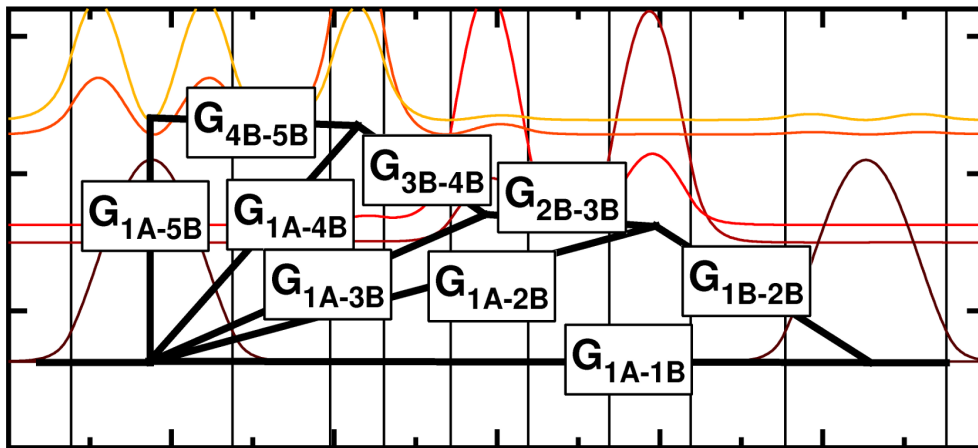
Results

- Johnson and shot limits
- Same theory for signal & noise
- Quantitative agreement
- Works for other unipolar detectors

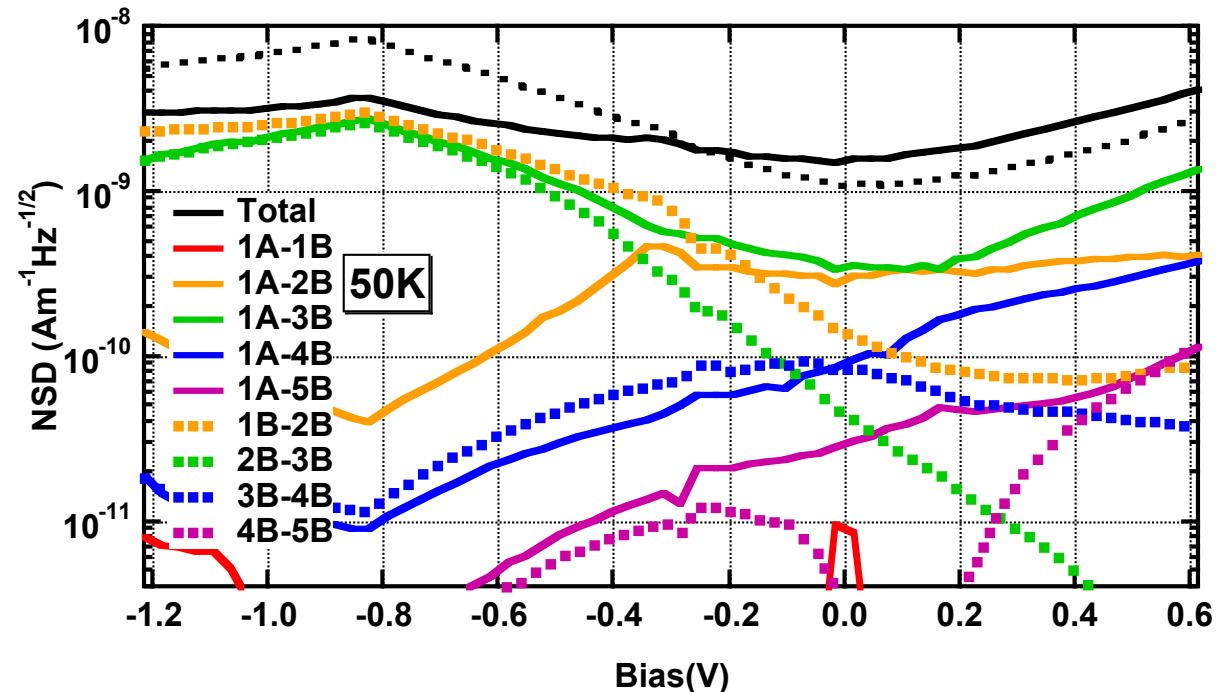


Delga et al, PRB 85, 245414 (2012)

Circuit theory



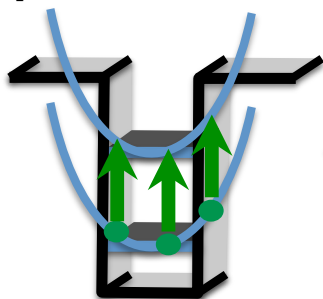
- Microscopic source: vacuum diodes
- Scaling factor: noise equivalent circuit
- Insightful for design



Delga et al, APL 99, 252106 (2011)

Du phénomène quantique au dispositif macroscopique, transport électronique dans les détecteurs inter-sousbandes

Quantum
phenomenon



Macroscopic
device



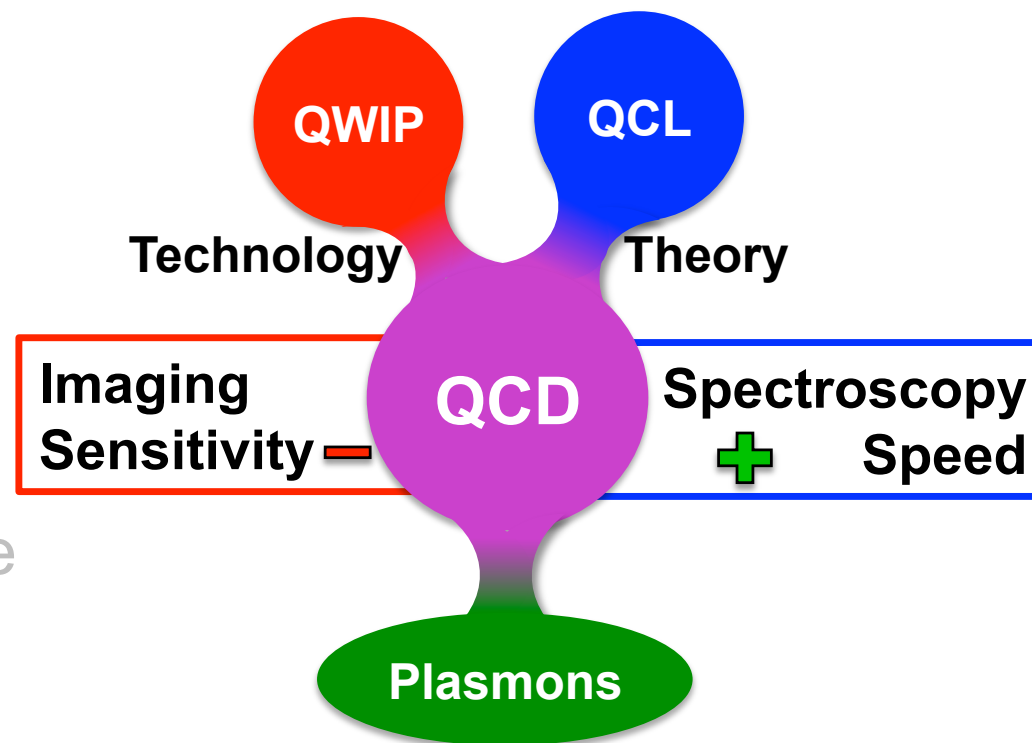
■ Current

- Historical model
- Theoretical Framework
- Hybrid model

■ Noise

- Shot and Johnson noise
- New approach

■ Prospects



Imaging prospects

Thermal Imaging



Catherine XP $\tau_{int}=7ms$

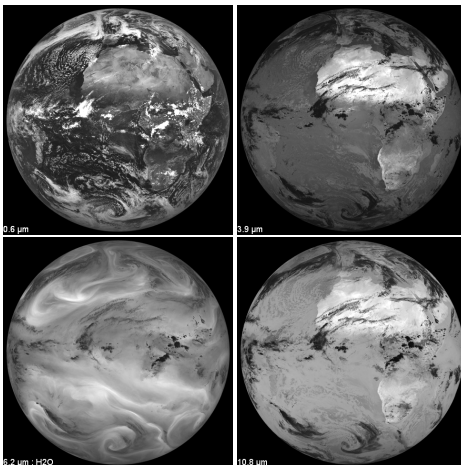
NETD=40mK

QWIP@75K

Ideal QCD@85K (80K)



Hyperspectral imaging



Meteosat $\tau_{int}=42ms$



Landsat $\tau_{int}=16ms$

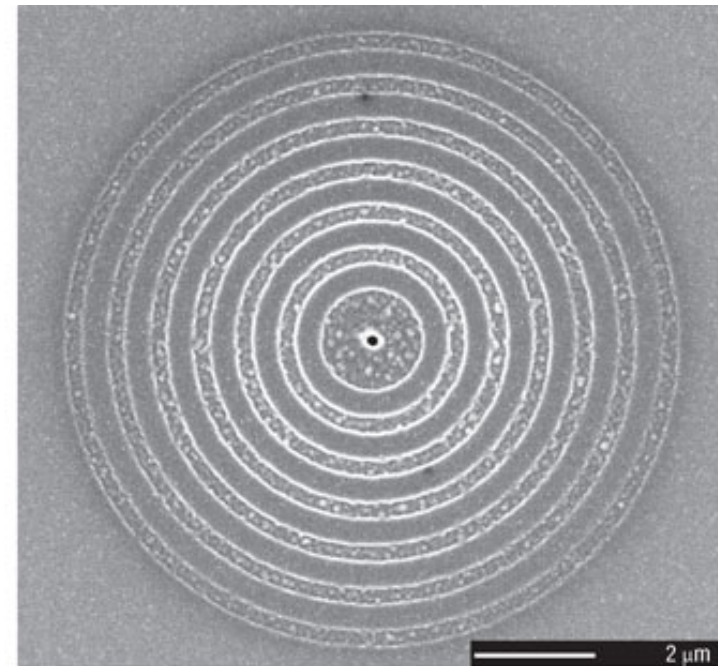


■ Plasmonics for QCDs

- Enhance responsivity
- Reduce detector volume
- Multispectral
- Polarization sensing

■ QCDs for Plasmonics

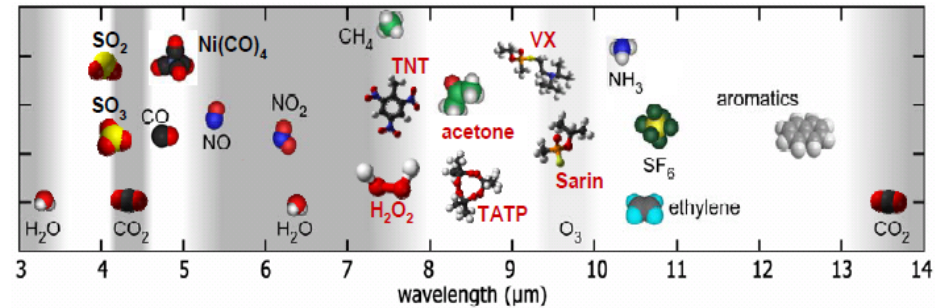
- III-V AlGaAs/GaAs technology
- Lorentzian shaped absorption
- Model system
- Tunable thickness



Laux et al, Nature Photonics 2, 161 (2008)

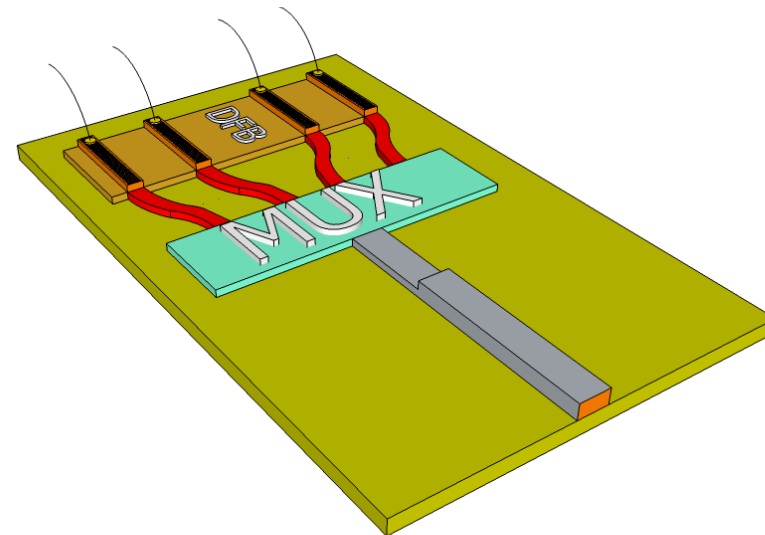
On chip spectroscopy

$$SNR \propto \frac{\Delta\Phi}{\sqrt{\Phi}} \propto \sqrt{\Phi}$$



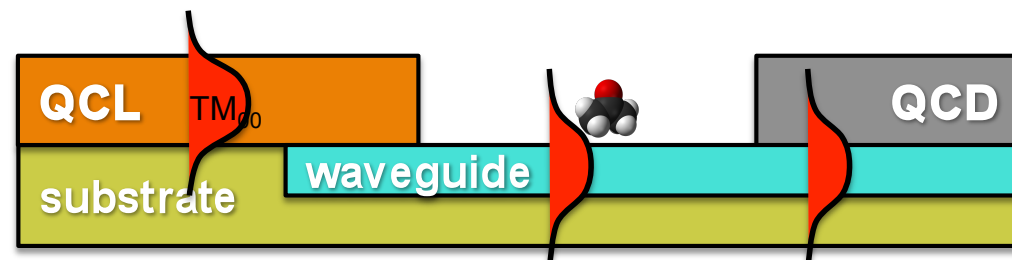
■ Rise of QCLs

- Room T
- Watt power
- Tunability

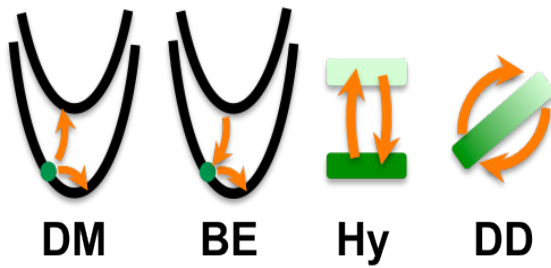
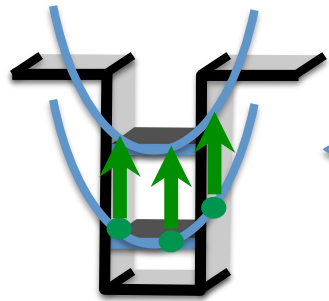


■ Need for QCDs

- Unsaturable
- Good sensitivity
- Broadband capability
- Integrated QCD/QCL



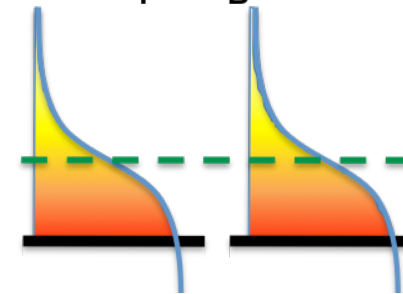
Conclusion



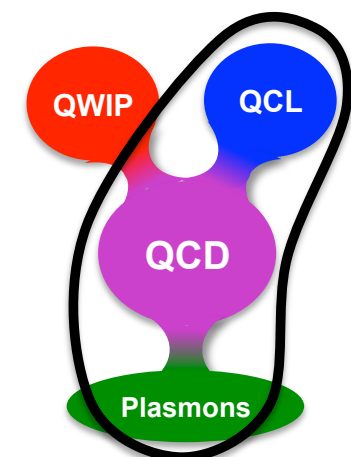
$$S_I = 2qI$$



$$S_I = 4k_B T/R$$



- **QCD signal & noise understood quantitatively**
 - Coherence is not infinite
 - Shot and Johnson noises:
limit visions of same phenomenon
- **future of QCDs : spectroscopy, plasmonics**



Acknowledgements and thanks



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M. Carras, V. Trinité
A. Nedelcu, P. Bois
E. Costard, B. Vinter
V. Guériaux, A. Bérurier
M. Naurois, G. Maisons



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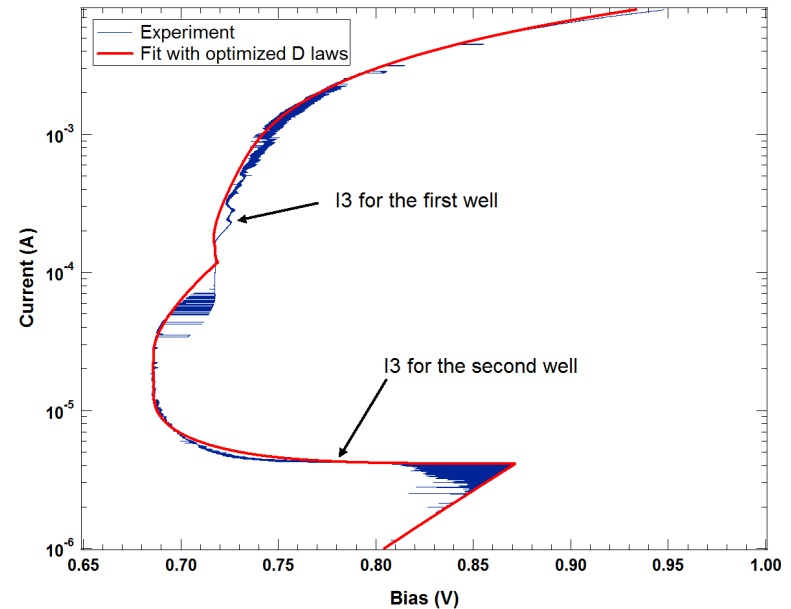
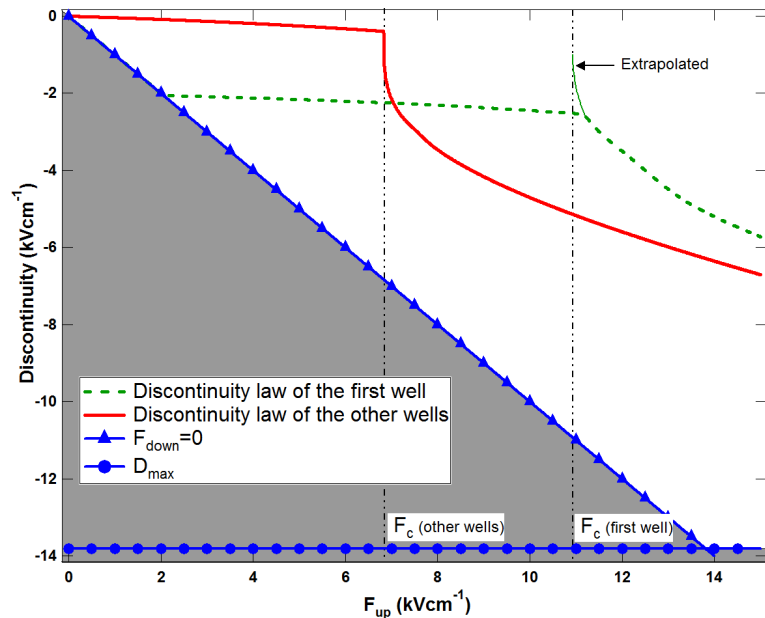
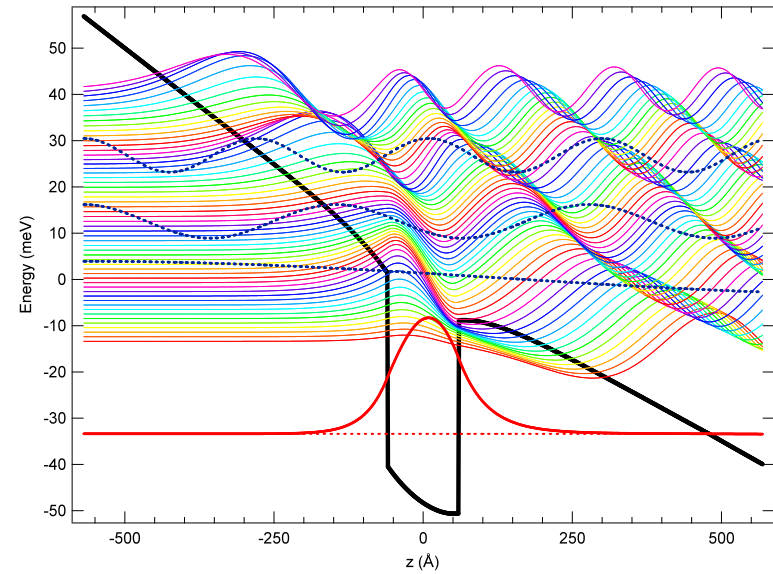
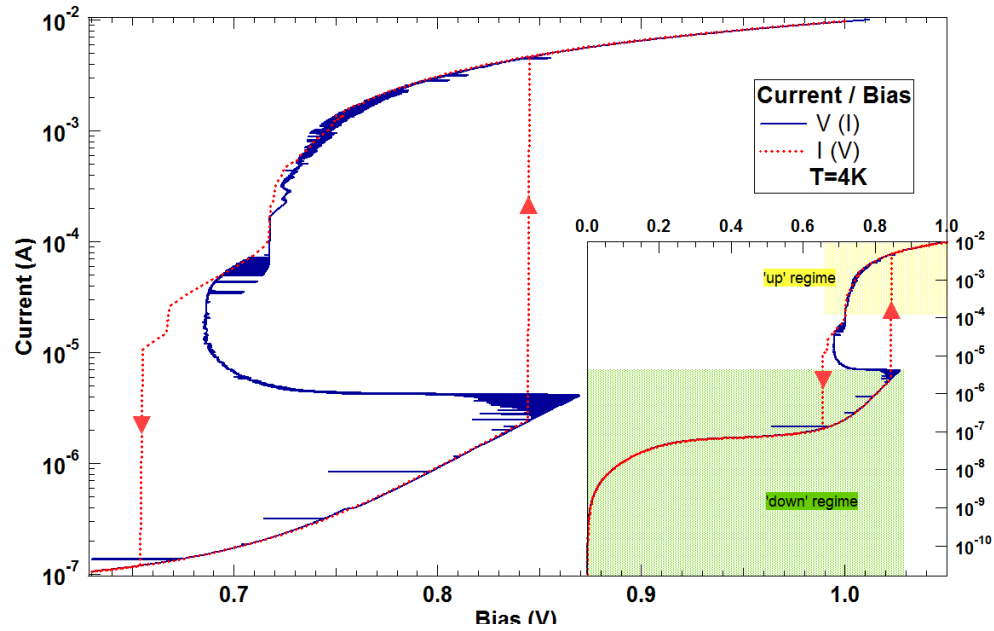
S. Rousset, C. Sirtori,
A. Vasanelli, A. Servouze,
J. Mercier

A. Gomez, E. Lhuillier
T. Antoni, A. Buffaz

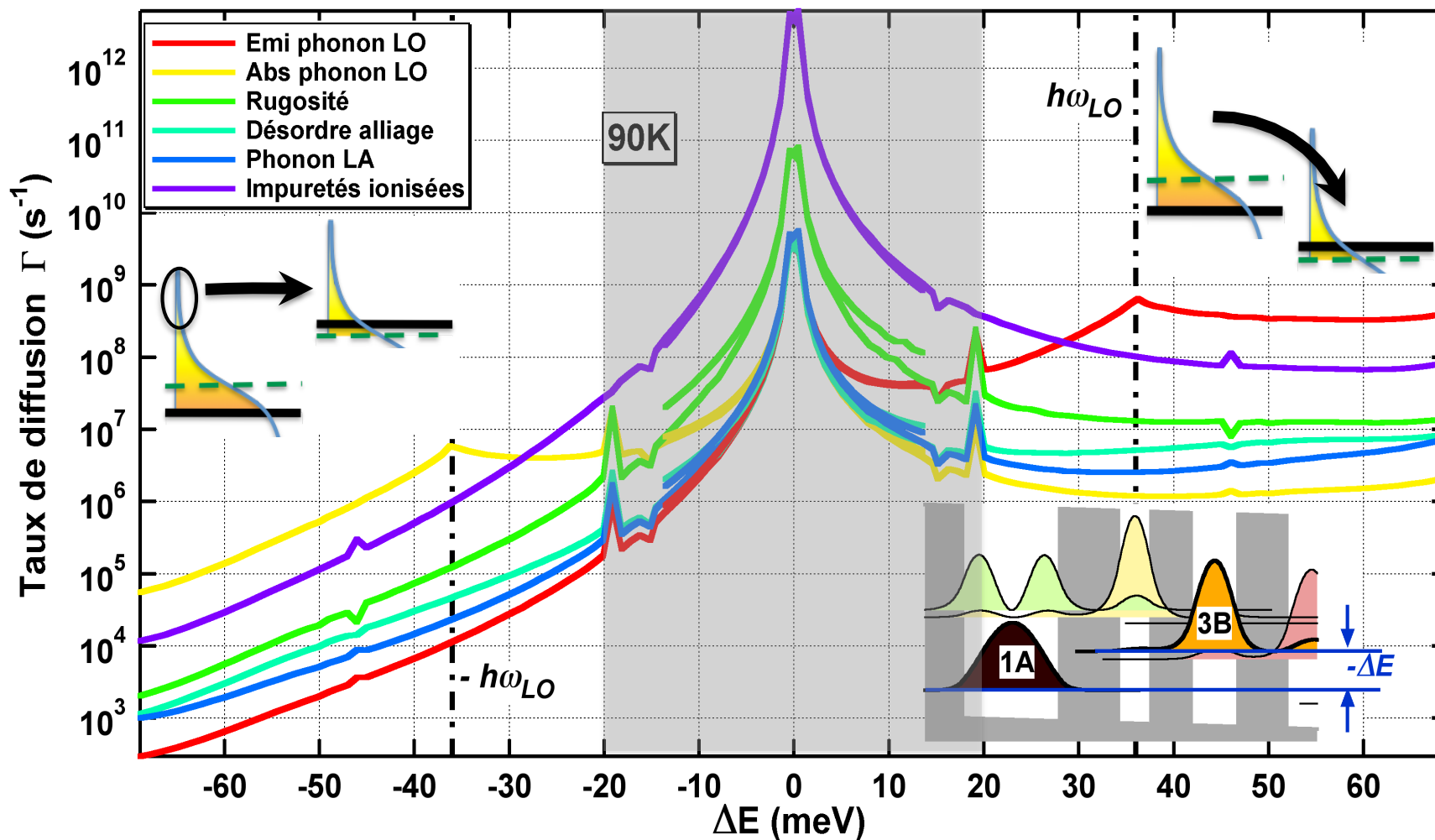
A. Ghrib, M. Andia
G. Altamura, S. Fall



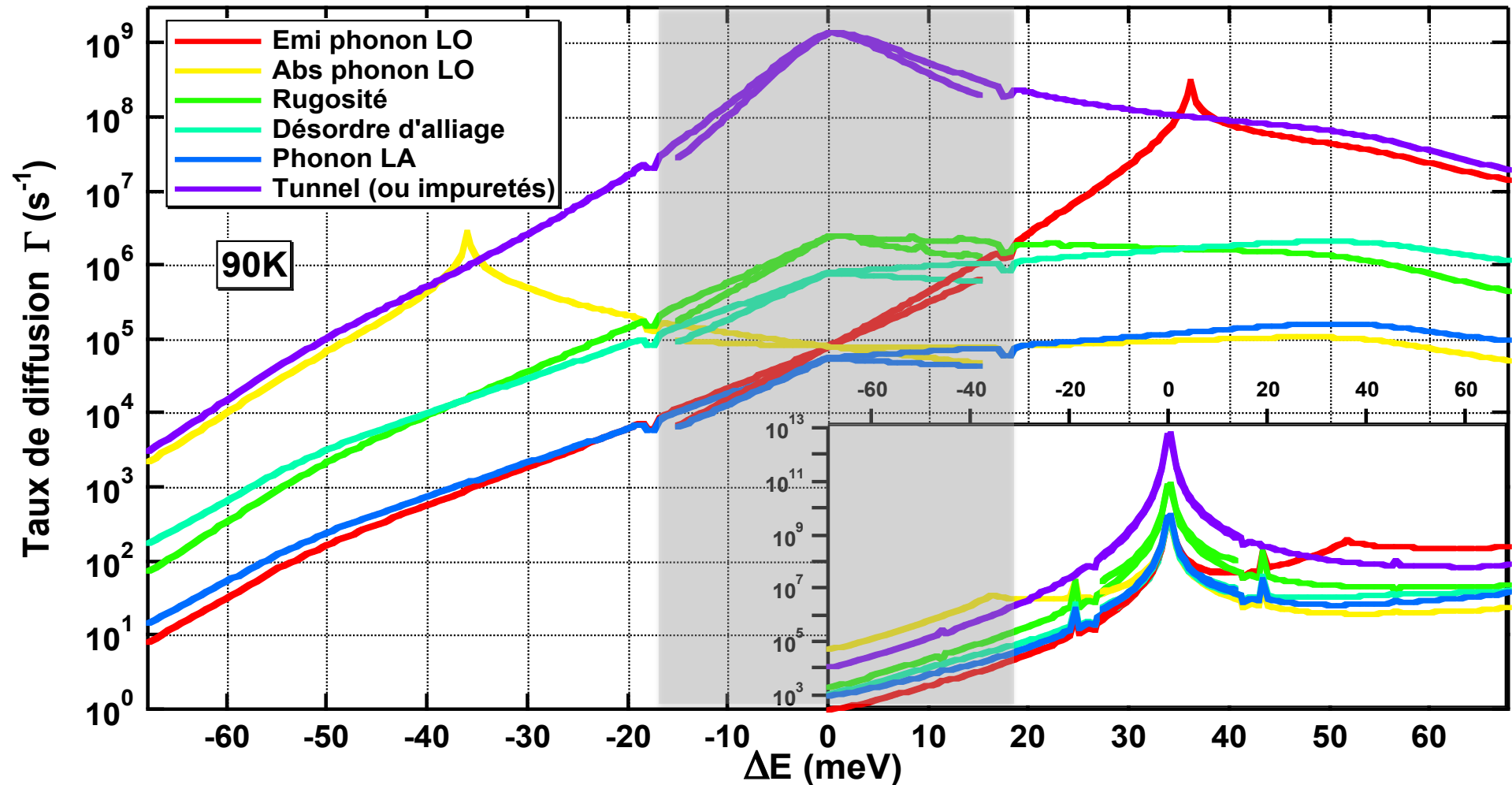
THz QWIP



Wannier-Stark hopping: scattering



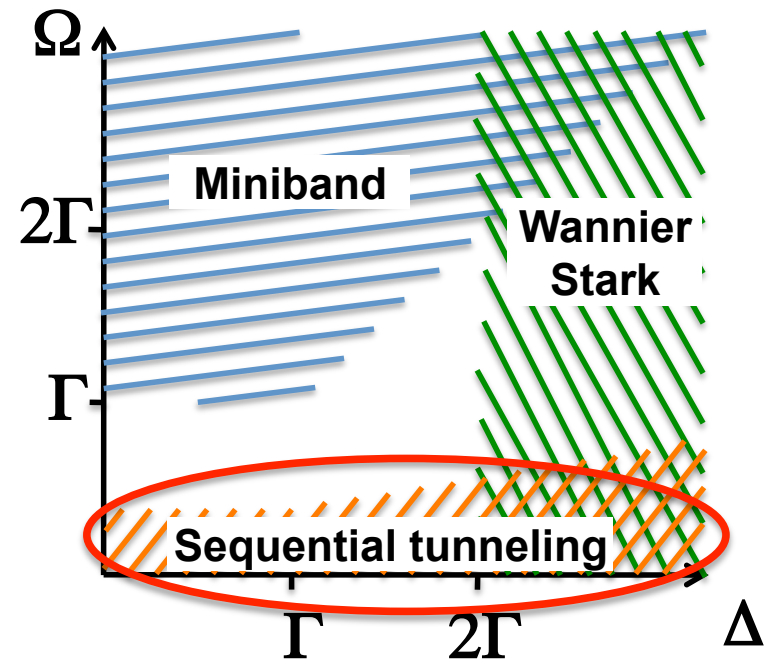
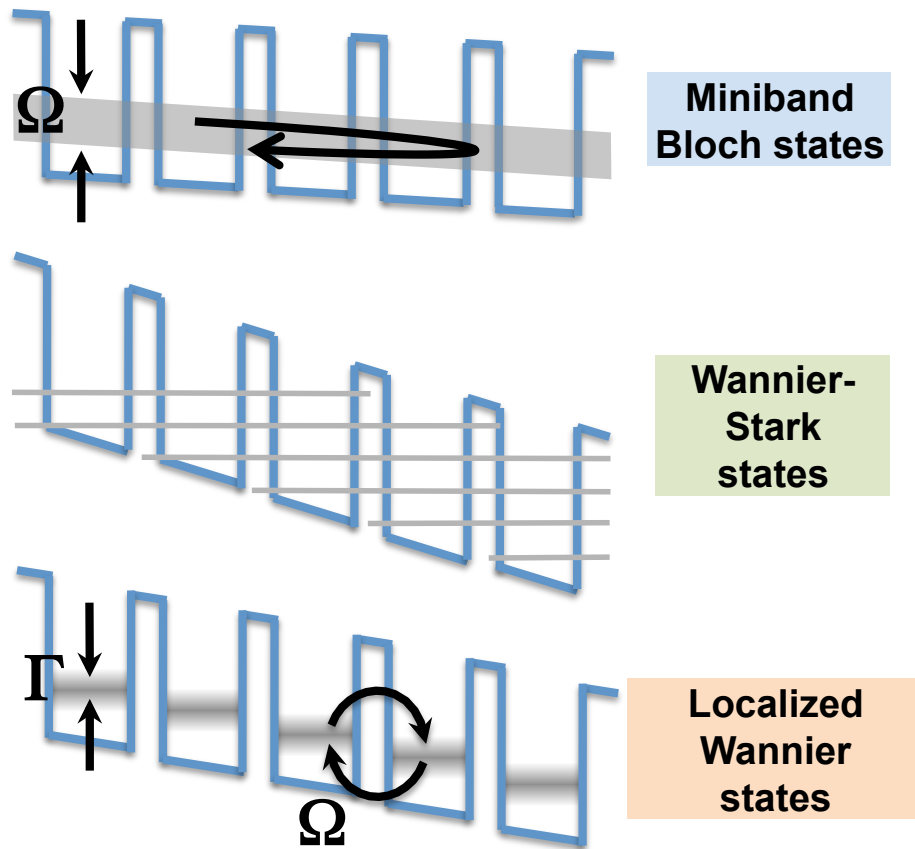
Wannier-Stark hopping: scattering



Hamiltonian

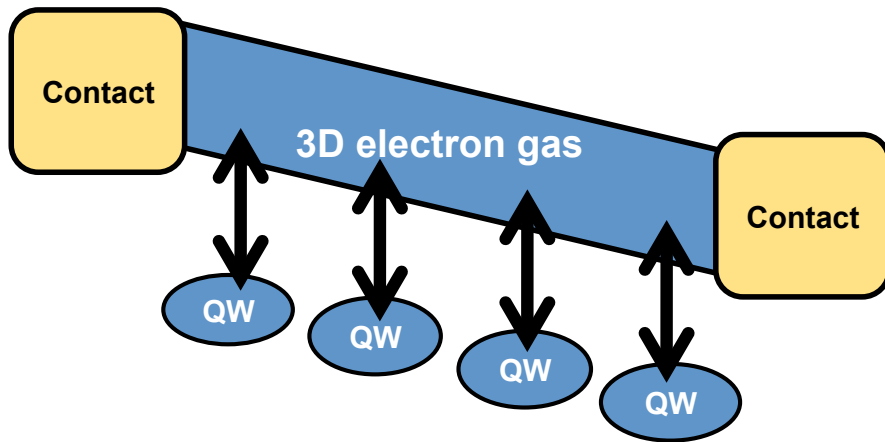
$$H_z = \frac{p_z^2}{2m^*} + H_{het} + eFz + \delta H$$

- Ω Coupling ≤ 5 meV
- Γ Scattering ~ 10 meV
- Δ Detuning any



Wacker et al, PRL 80, 369 (1998)

Noise in QWIPs: issues

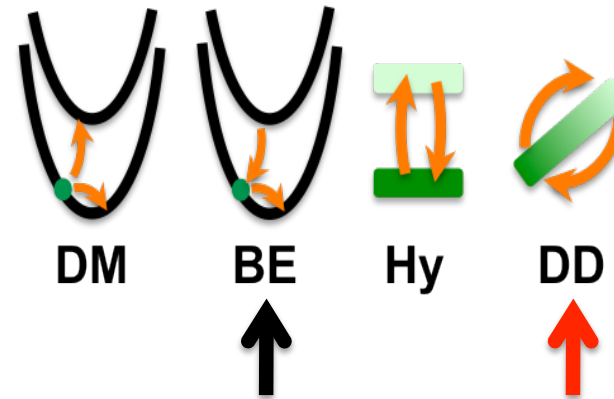


- Gain and capture probability derivation
- Static or dynamic resistance?
- Macro independence without micro
- Adequate transport model & scale?

$$I = env$$

$$S_I = 4egI + \frac{4k_B T}{R}$$

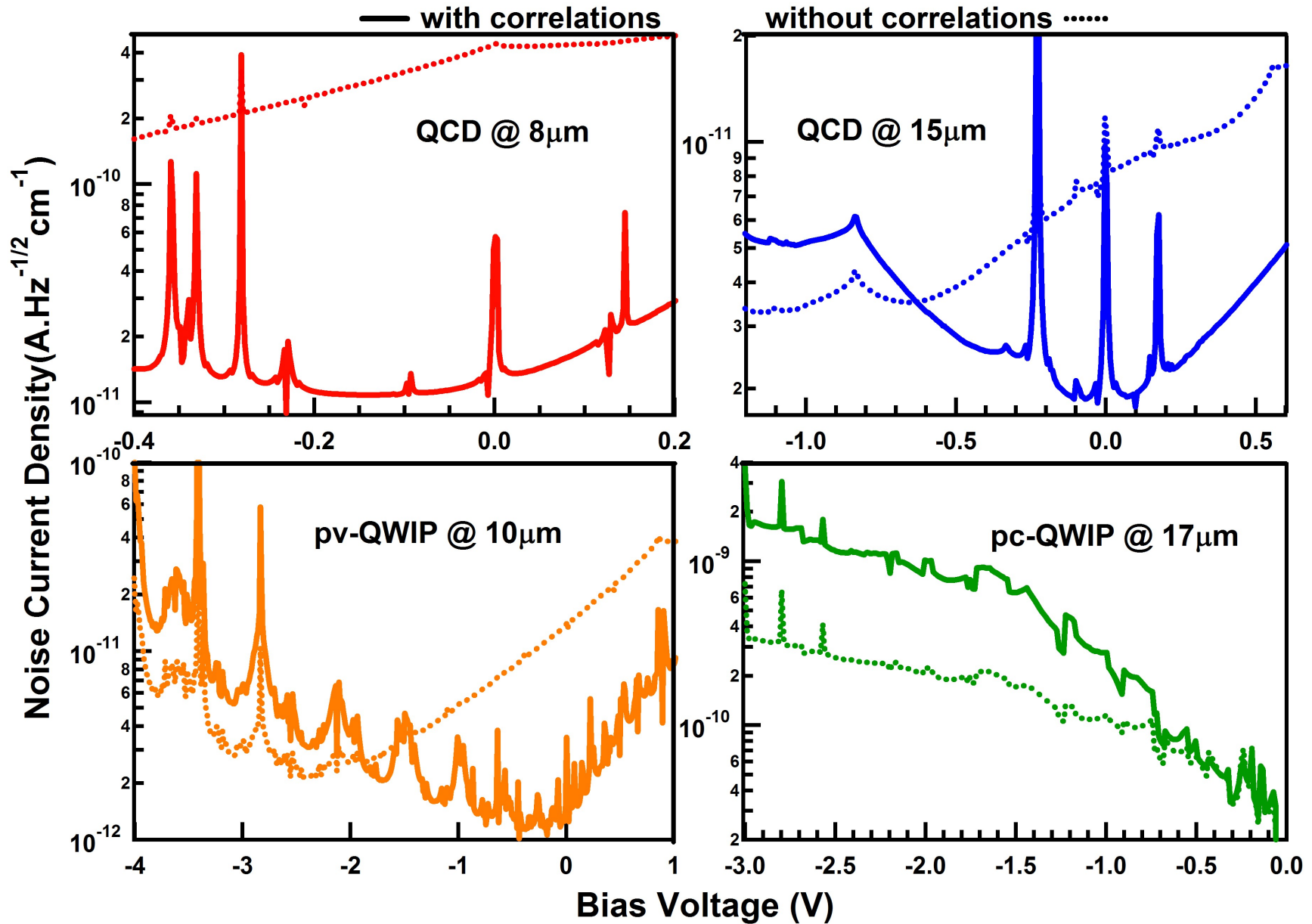
“Excess” shot noise Johnson noise



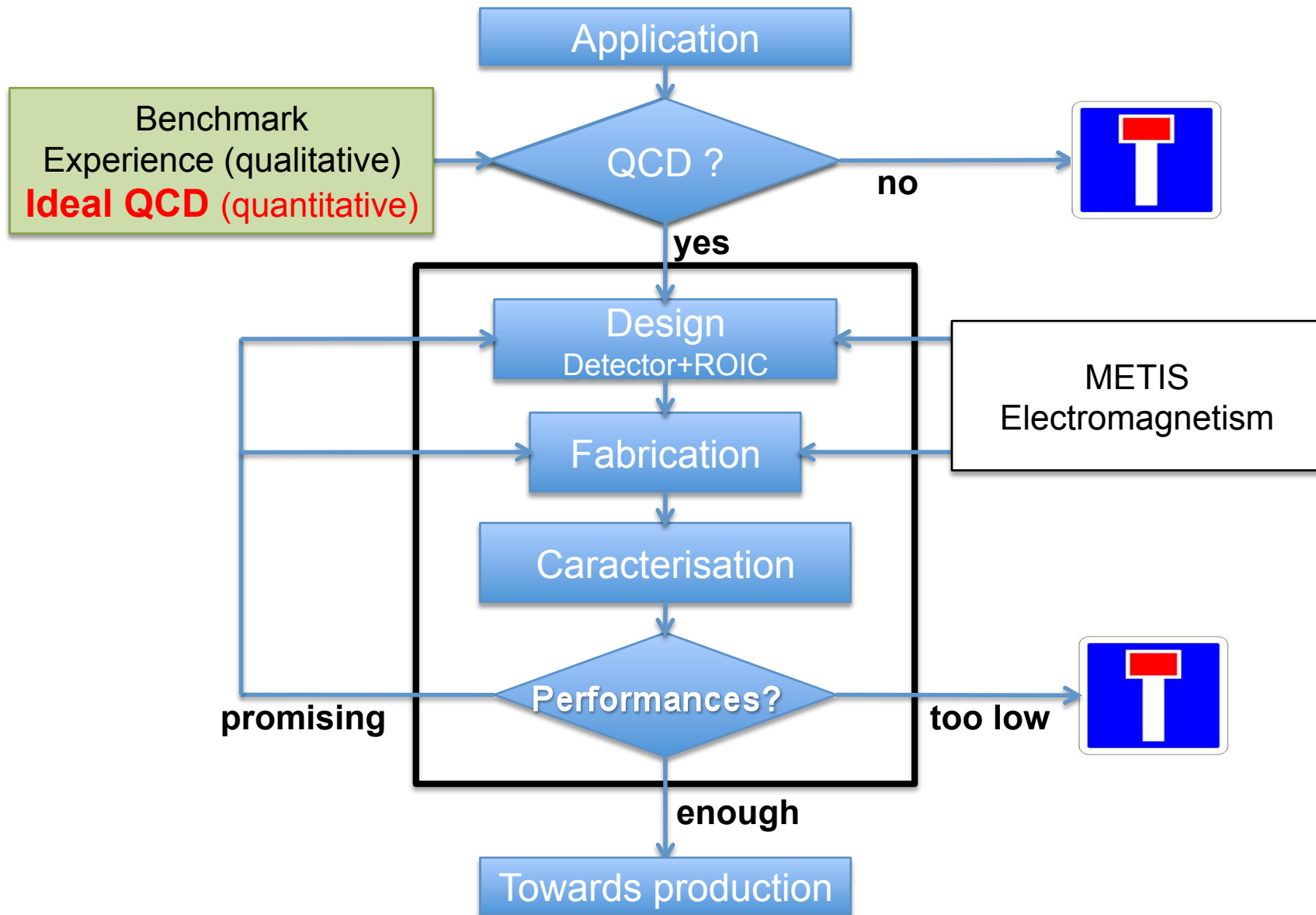
Johnson << Shot & gain adjustable

Noise: measured quantity

Correlations



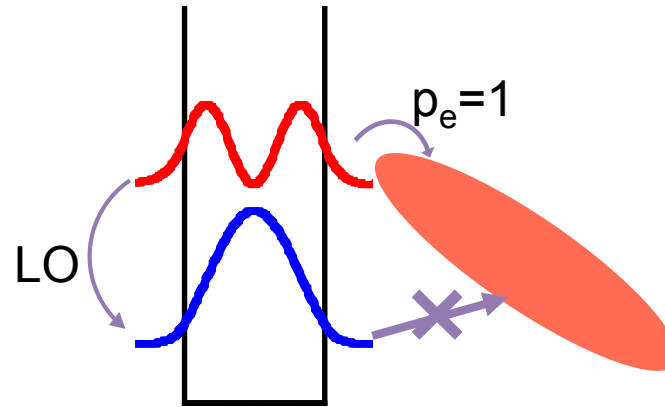
Ideal QCD for imaging



Ideal QCD: Physics

- **Electronics: ideal**

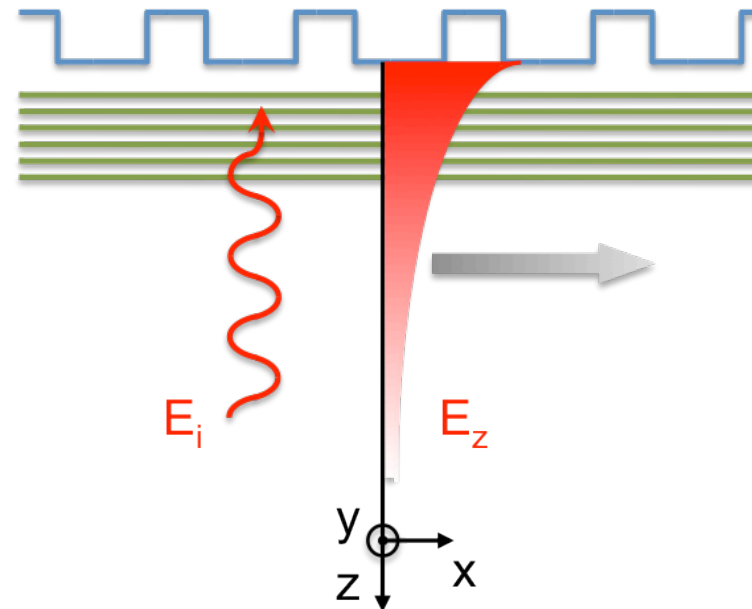
- Optical Well
- Perfect Cascade



- **Optics: real**

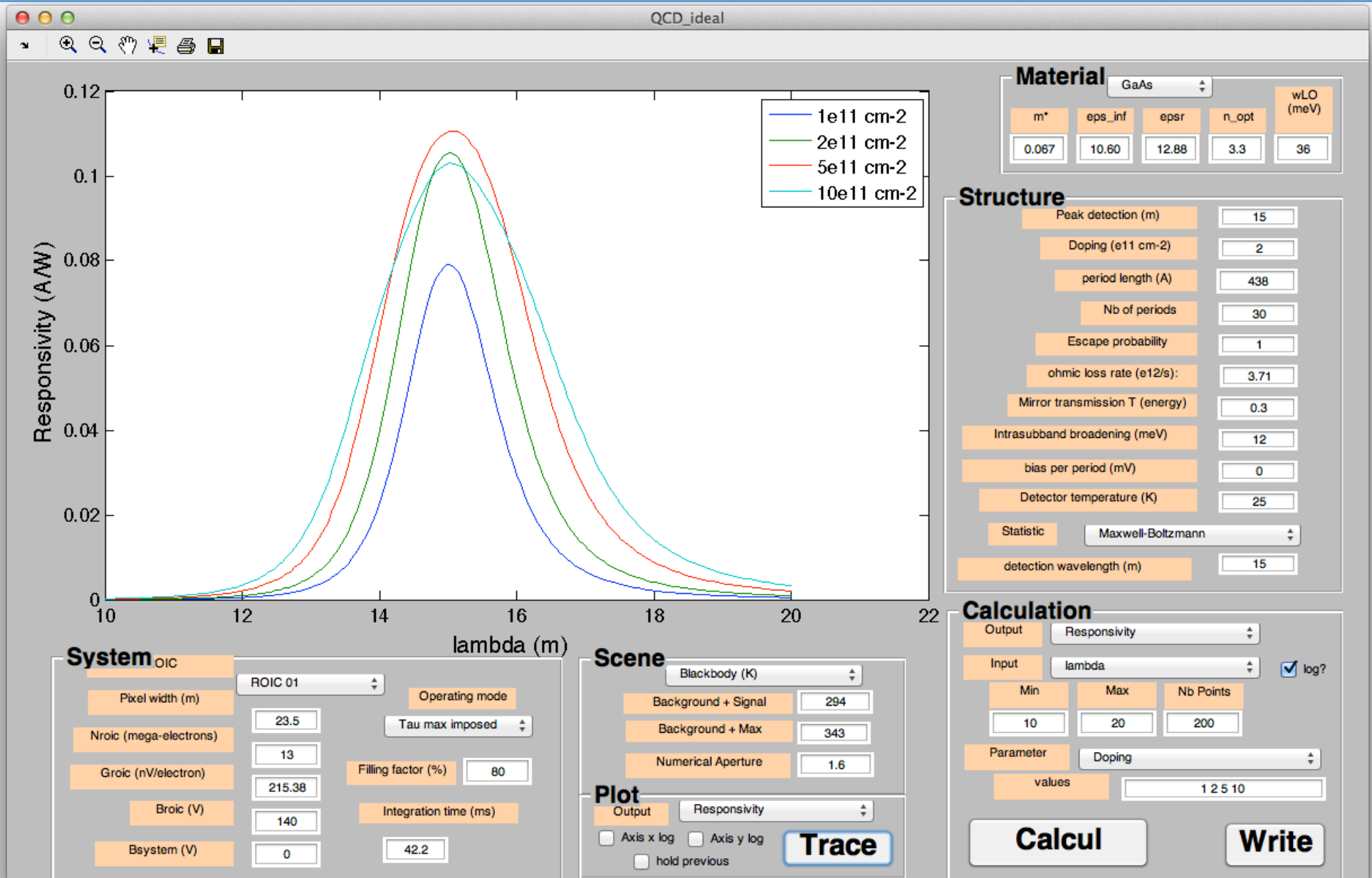
- Grating = Fabry-Perot

$$E_z = \frac{tE_i}{1 - re^{-(\alpha + \beta)\lambda_0} e^{i\Delta\phi}}$$

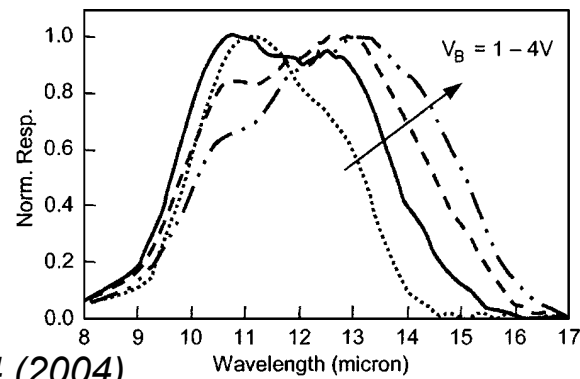
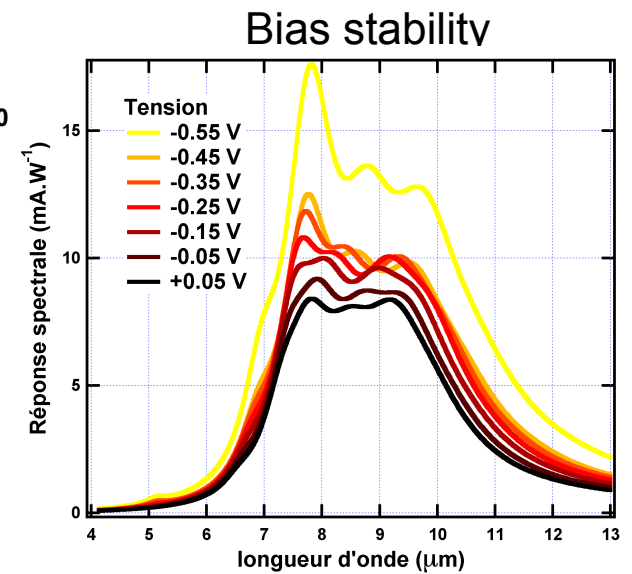
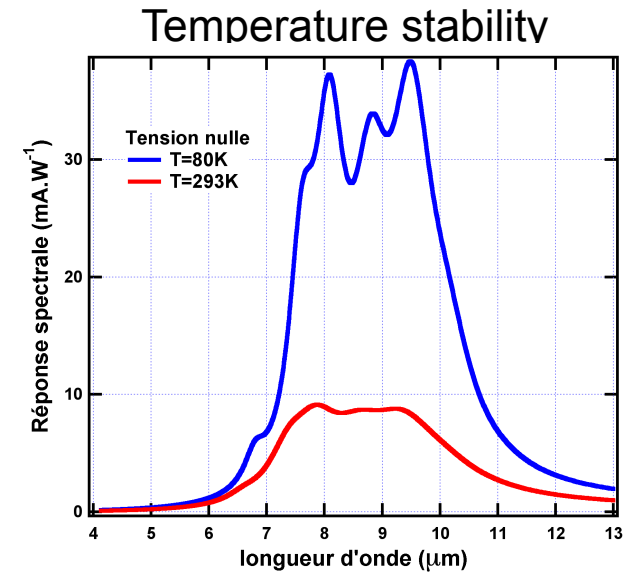
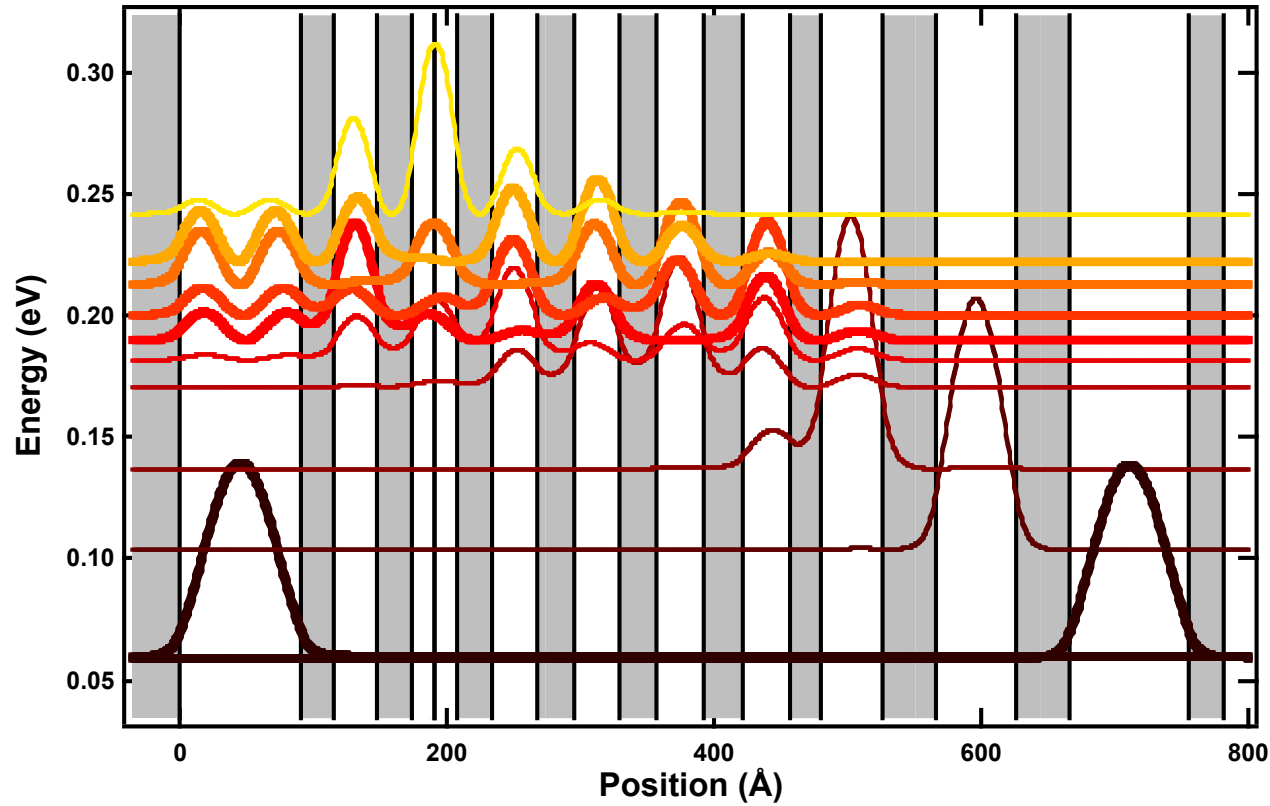


- **Keep things simple**

Ideal QCD: implementation

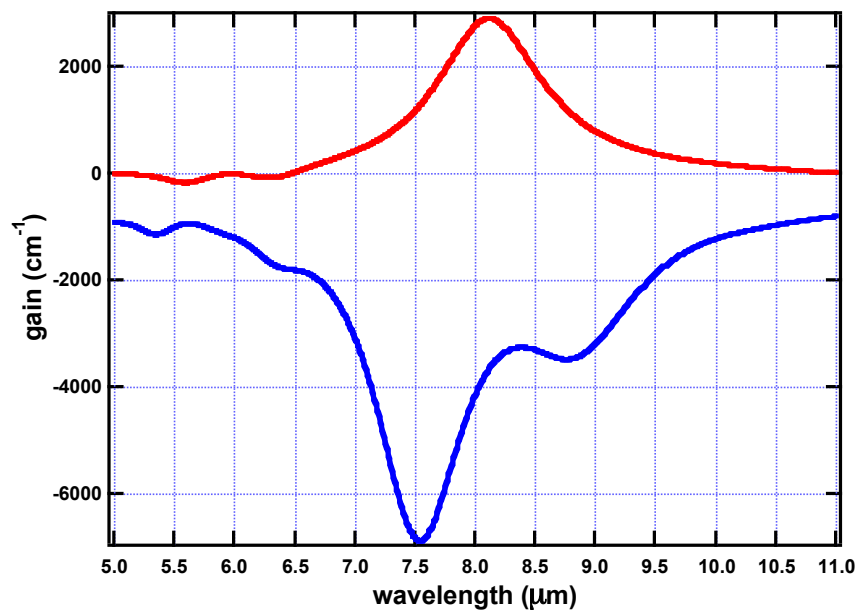
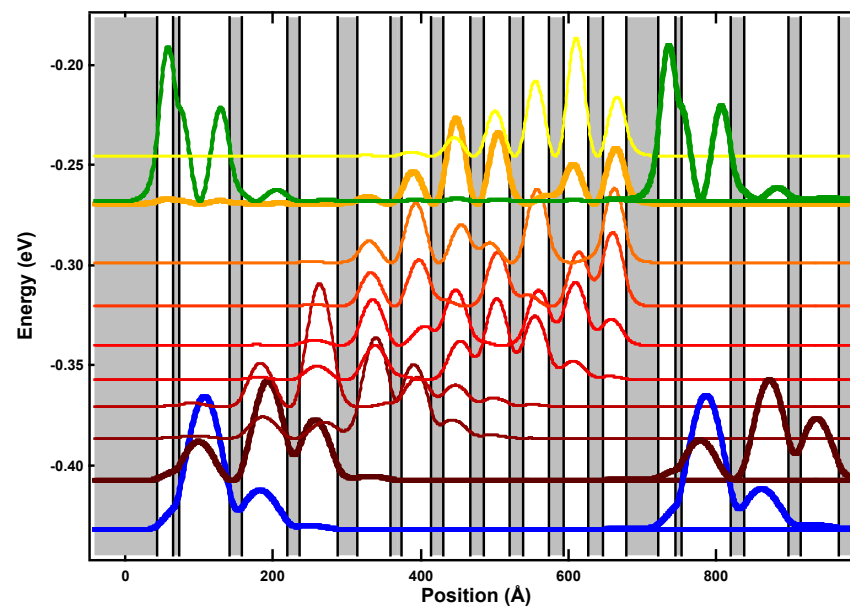
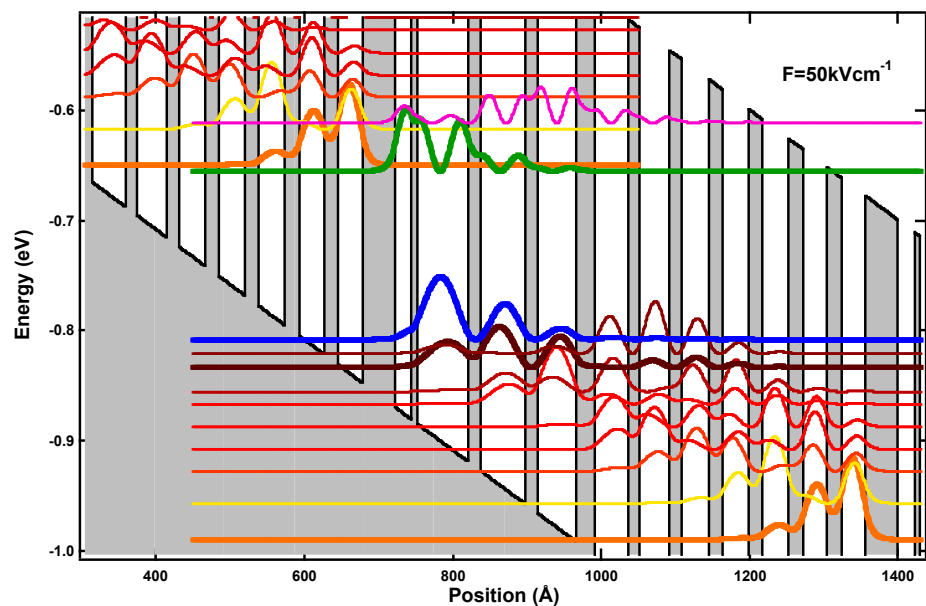


Broadband detector



Bandara et al. APL 86,151104 (2004)

Integrated QCD/QCL



Schwarz et al,
 APL **101**,191109 (2012)