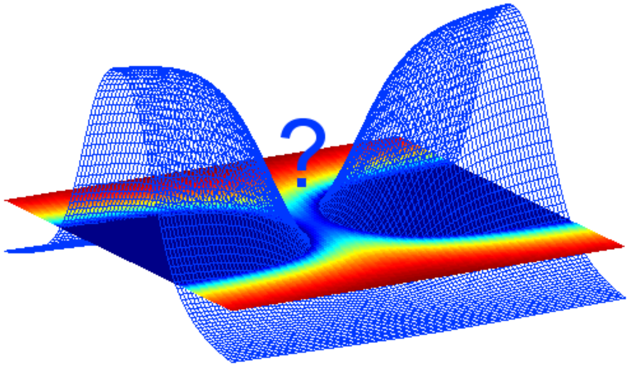
Electron interactions in quantum point contacts

Investigation of the 0.7 and zero-bias anomalies by scanning gate microscopy



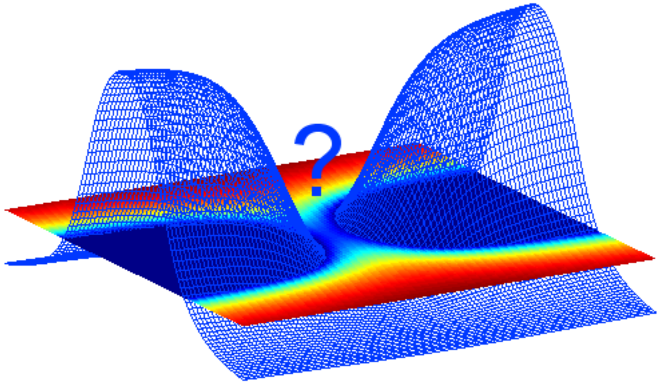
Boris Brun [1], F. Martins [2], S. Faniel [2], B. Hackens [2], V. Bayot [2],
D. Mailly [4], U. Gennser [4], S. Huant [1], M. Sanquer [3], **Hermann Sellier** [1]

[1]Institut Néel (CNRS/UJF), Grenoble (France)
[2]IMCN/NAPS (UCL), Louvain-la-Neuve (Belgium)
[3]Institut Nanosciences et Cryogénie (CEA), Grenoble (France)
[4]Laboratoire de Photonique et de Nanostructures (CNRS), Marcoussis (France)

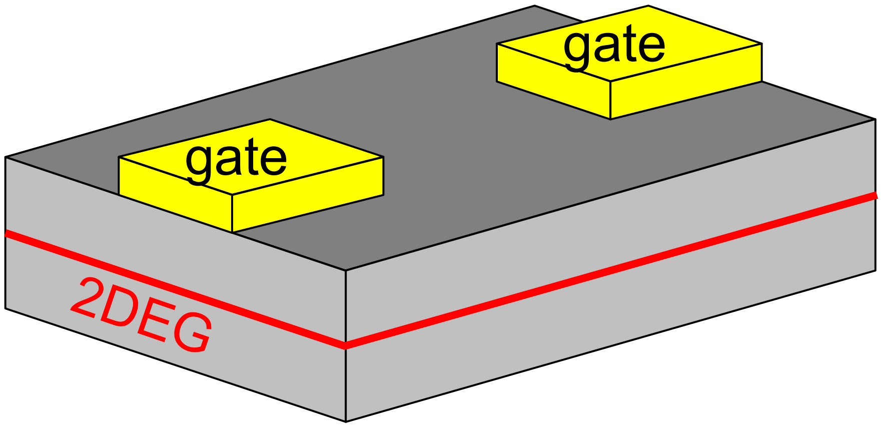
See arXiv:1307.8328

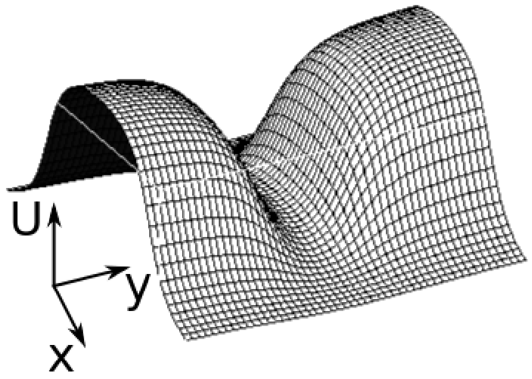
Outline

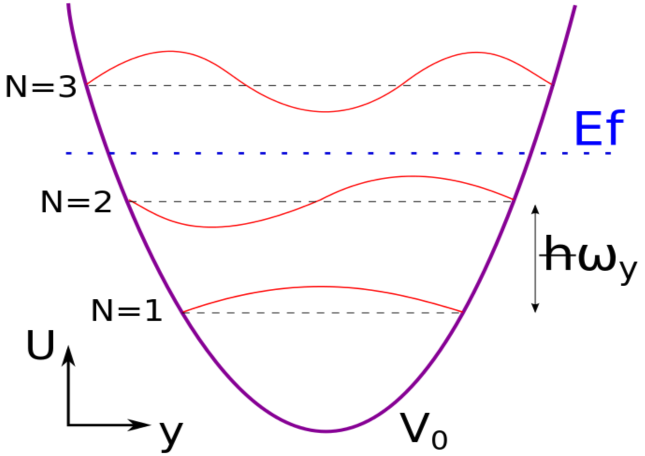
- Conductance anomalies
- Theoretical models
- Tunable-in-length experiment
- **Scanning gate experiment**
- **Interferometers**
- Conclusion

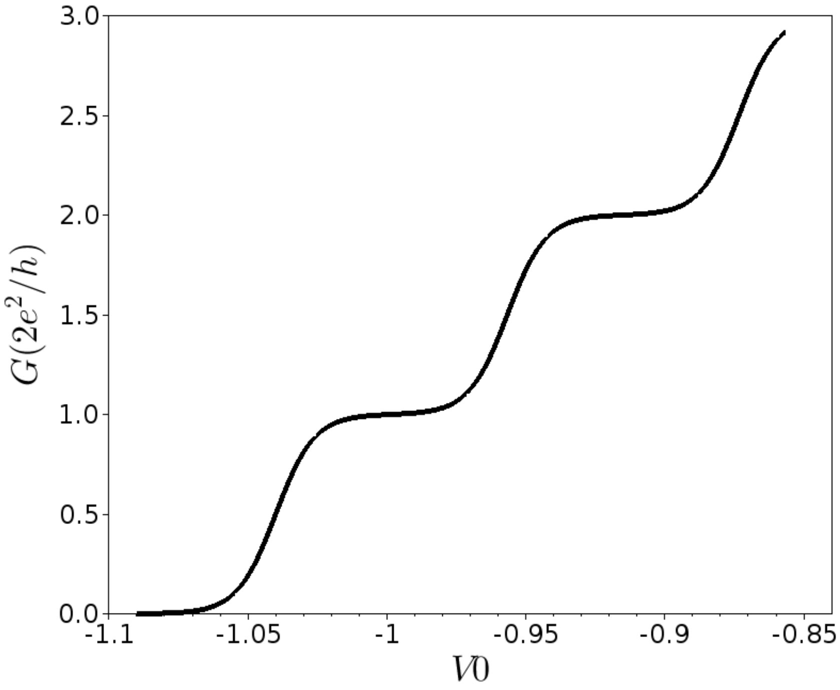


1 – Conductance anomalies : introduction



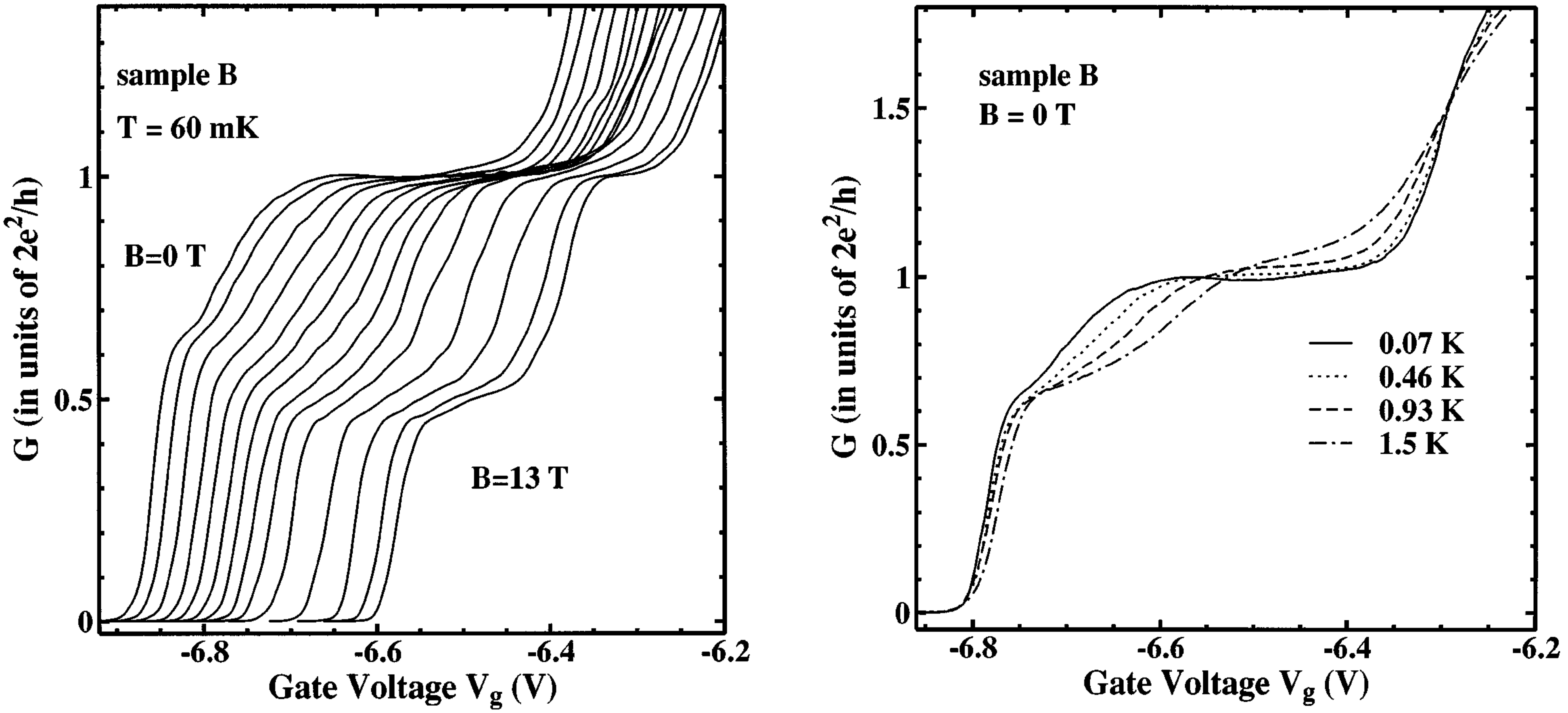






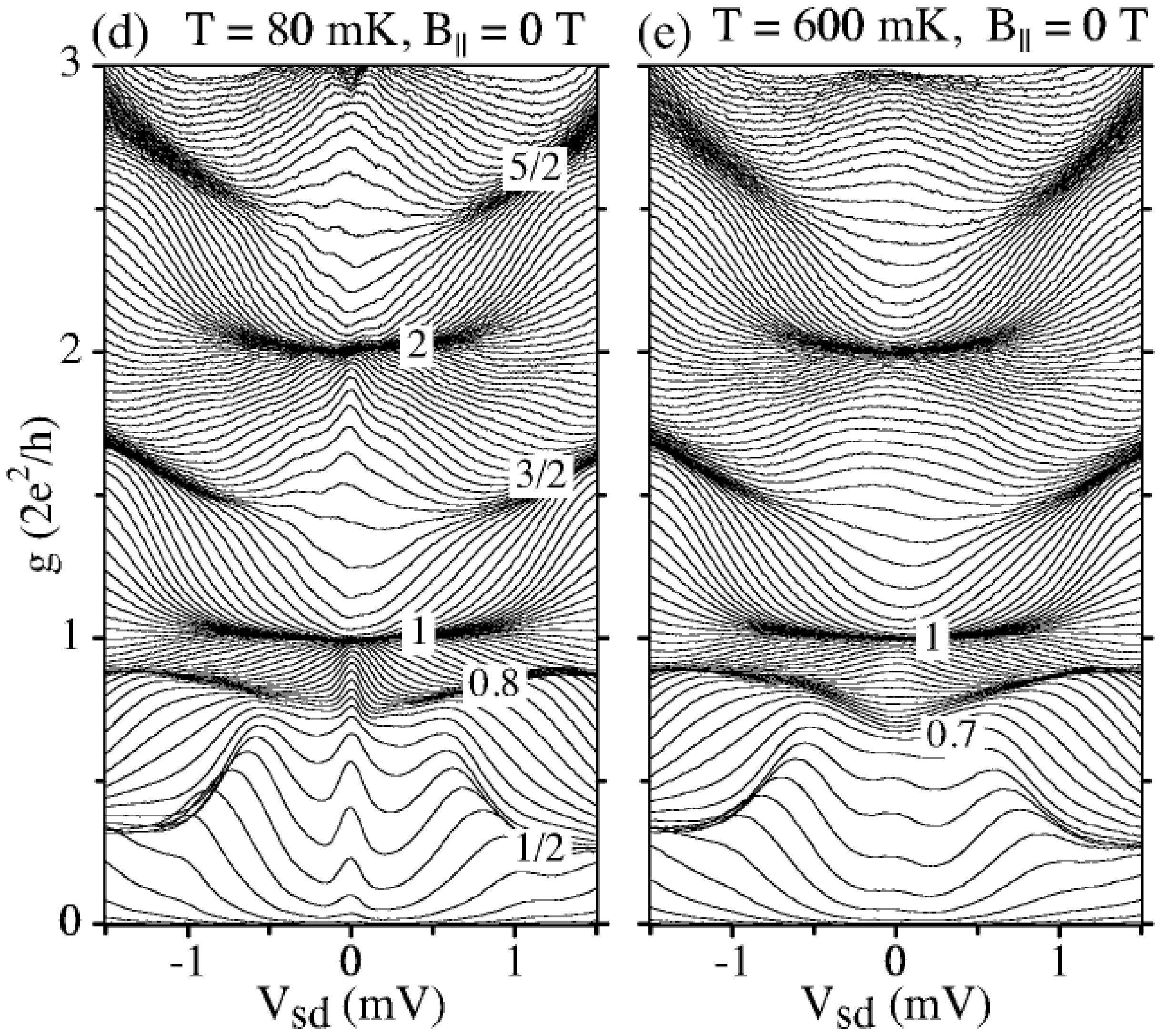
A split-gate defines a quasi-one-dimensional channel in a 2DEG.
Quantization of transverse motion => Quantization of conductance.

1 – Conductance anomalies : the 0.7 feature



Thomas, *et al.*, Phys. Rev. Lett. **77**, 135 (1996)

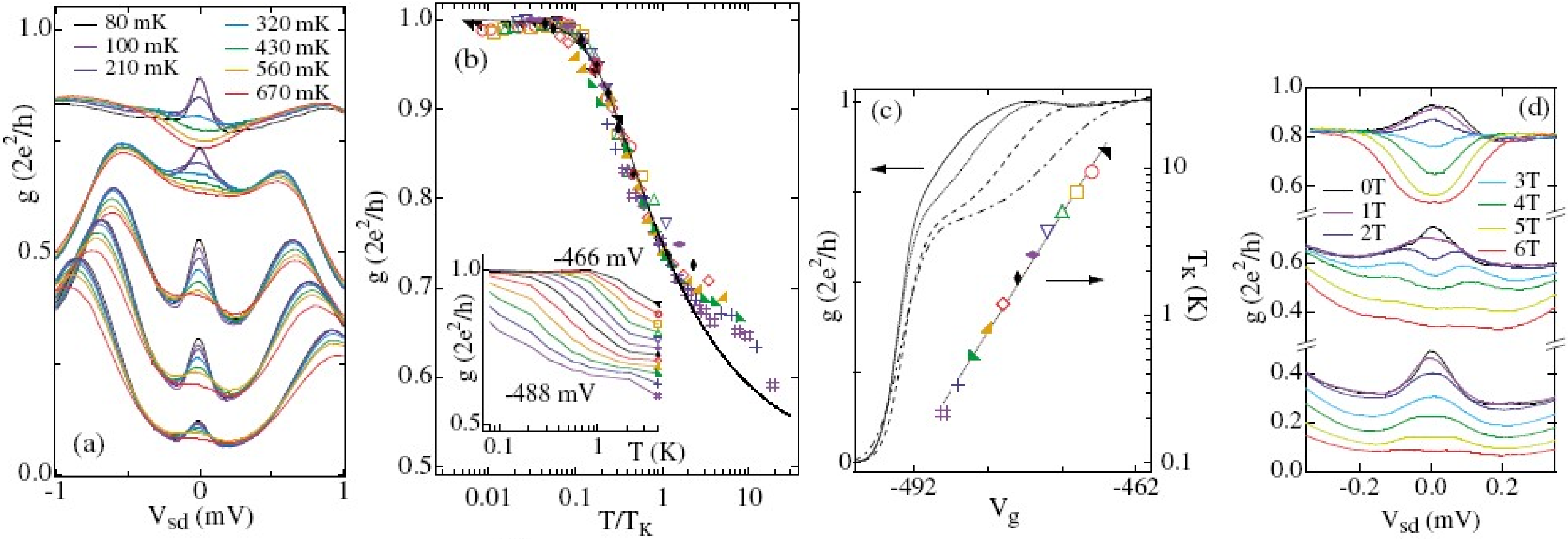
1 – Conductance anomalies : the zero-bias peak



Cronenwett, *et al.*, Phys. Rev. Lett. **88**, 226805 (2002)

1 – Conductance anomalies : the zero-bias peak

Kondo scaling



Cronenwett, *et al.*, Phys. Rev. Lett. **88**, 226805 (2002)

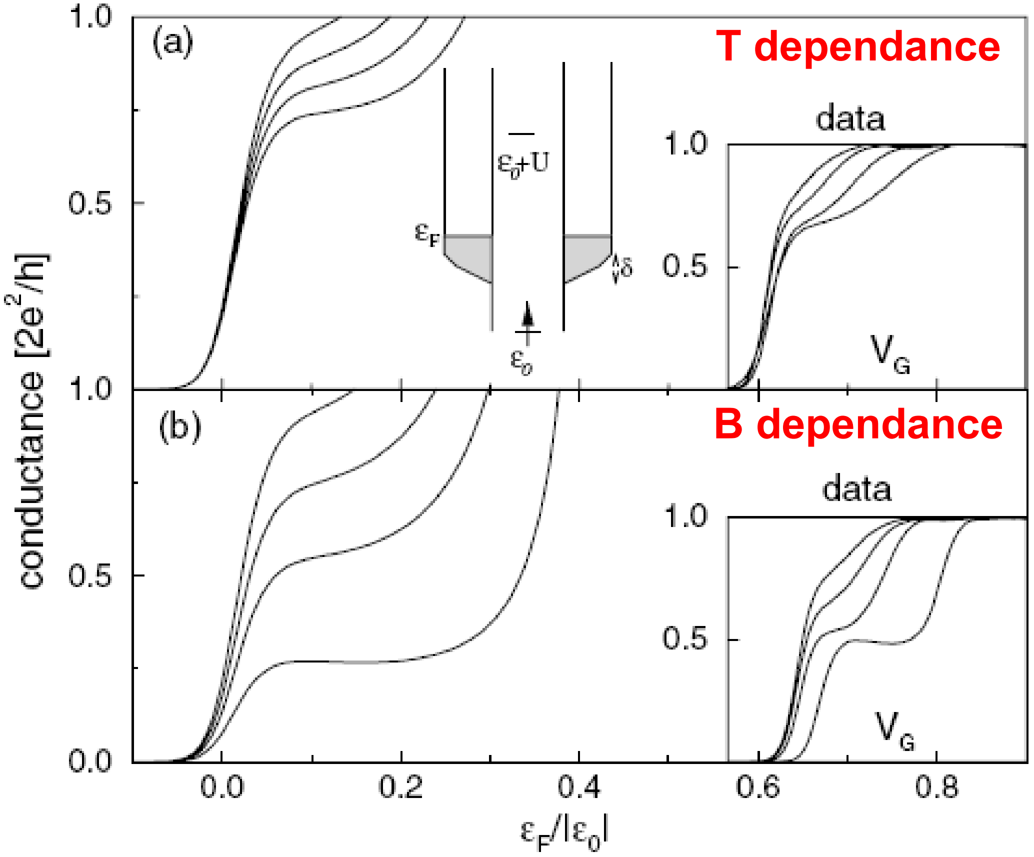
2 – Theoretical models : a long debate

List of models describing the anomalies :

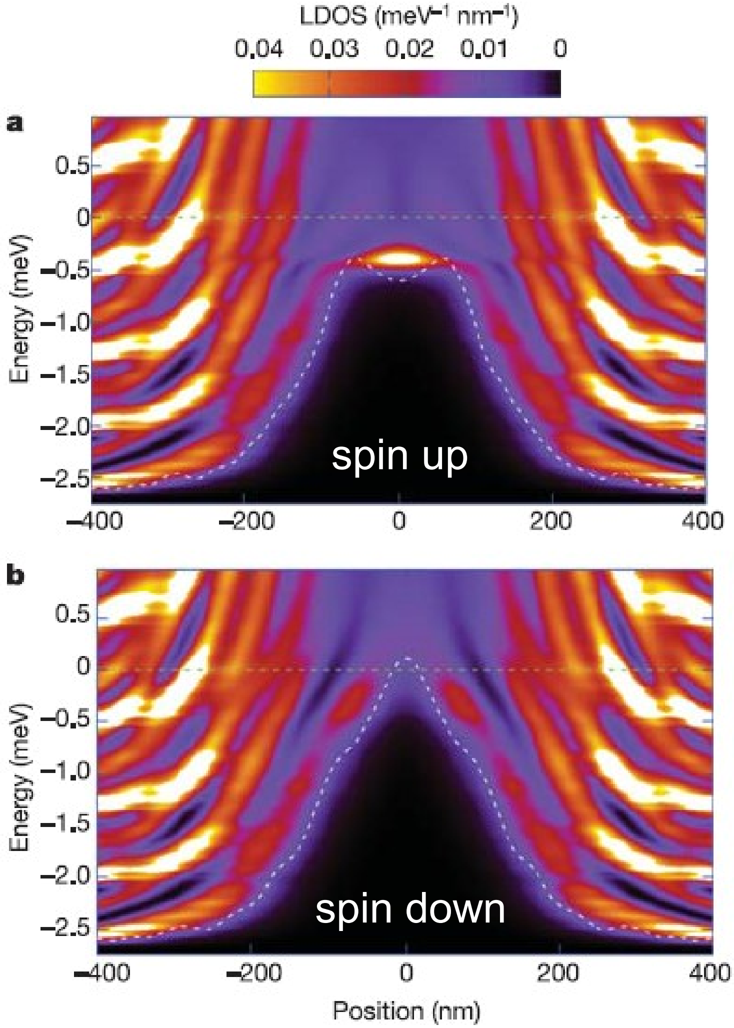
- spontaneous spin polarization: Wang *et al.*, PRB (1998)
- charge density wave: Sushkov, PRB (2001)
- **Kondo effect on a localized state:** Meir *et al.*, PRL (2002)
- electron-phonon scattering: Seelig *et al.*, PRL (2003)
- **one-dimensional Wigner crystal:** Matveev, PRL (2004)
- ...
- van Hove singularity: Bauer *et al.*, Nature (2013)

A nice review can be found in :
Micolich, *J. Phys.: Condens. Matter* **23**, 443201 (2011)

2 – Theoretical models : Kondo

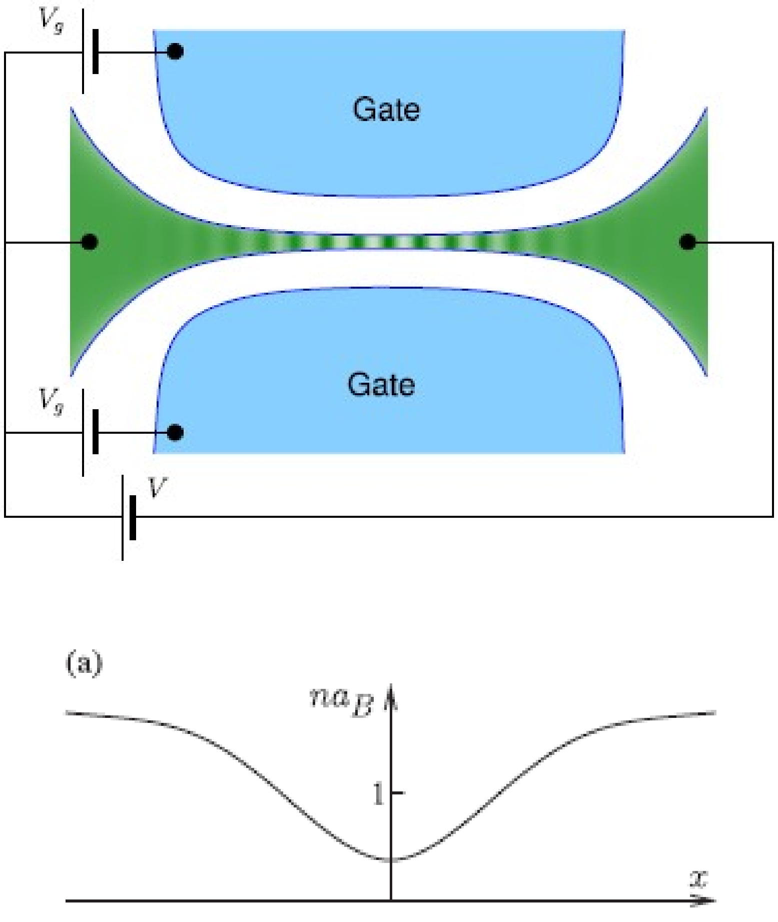


Meir, Hirose, and Wingreen,
Phys. Rev. Lett. **89**, 196802 (2002)

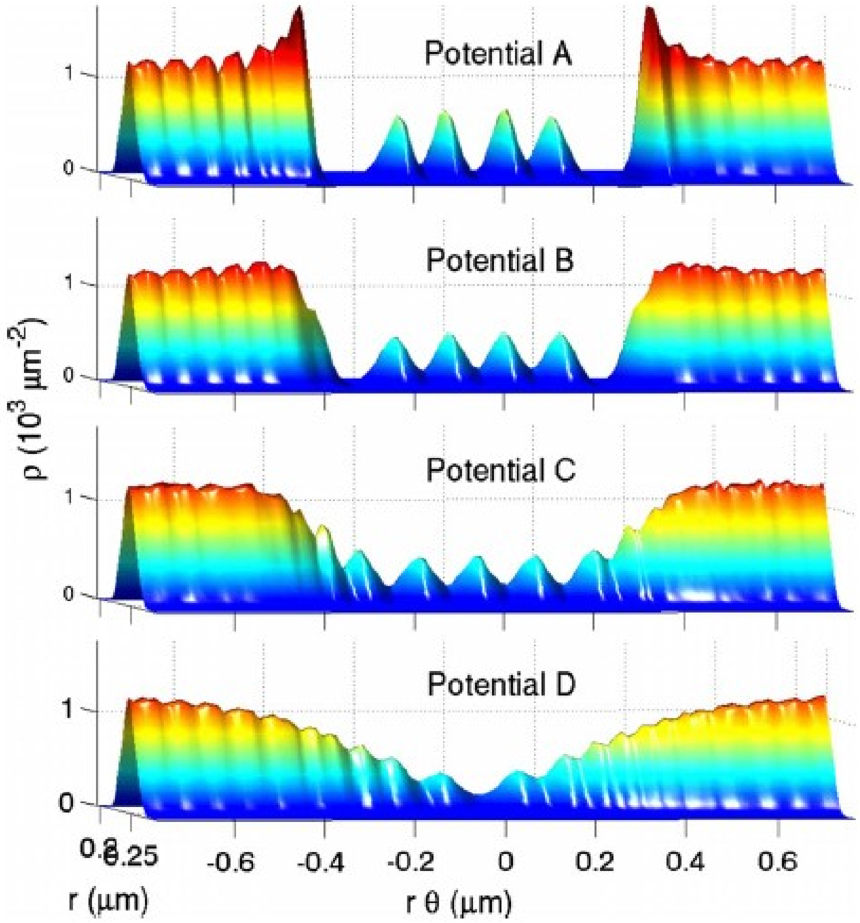


Meir and Rejec,
Nature **442**, 900 (2006)

2 – Theoretical models : Wigner



Matveev,
Phys. Rev. Lett. **92**, 106801 (2004)



Güçlü, *et al.*,
Phys. Rev. B **80**, 201302R (2009)

3 – Tunable length experiment

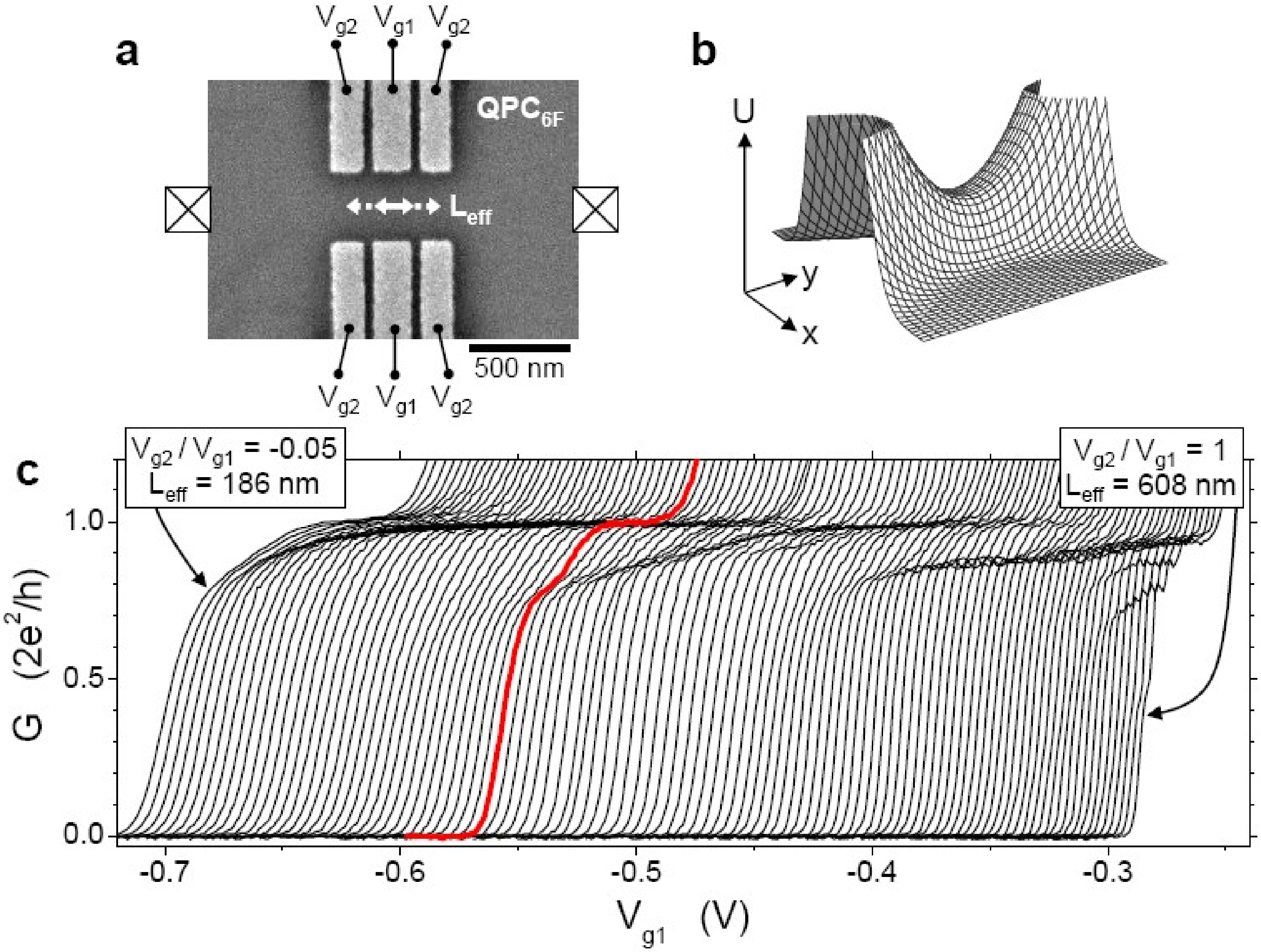
University of Gröningen (NL) : group of **Caspar van der Wal**

Odd and even Kondo effects from emergent localization in quantum point contacts

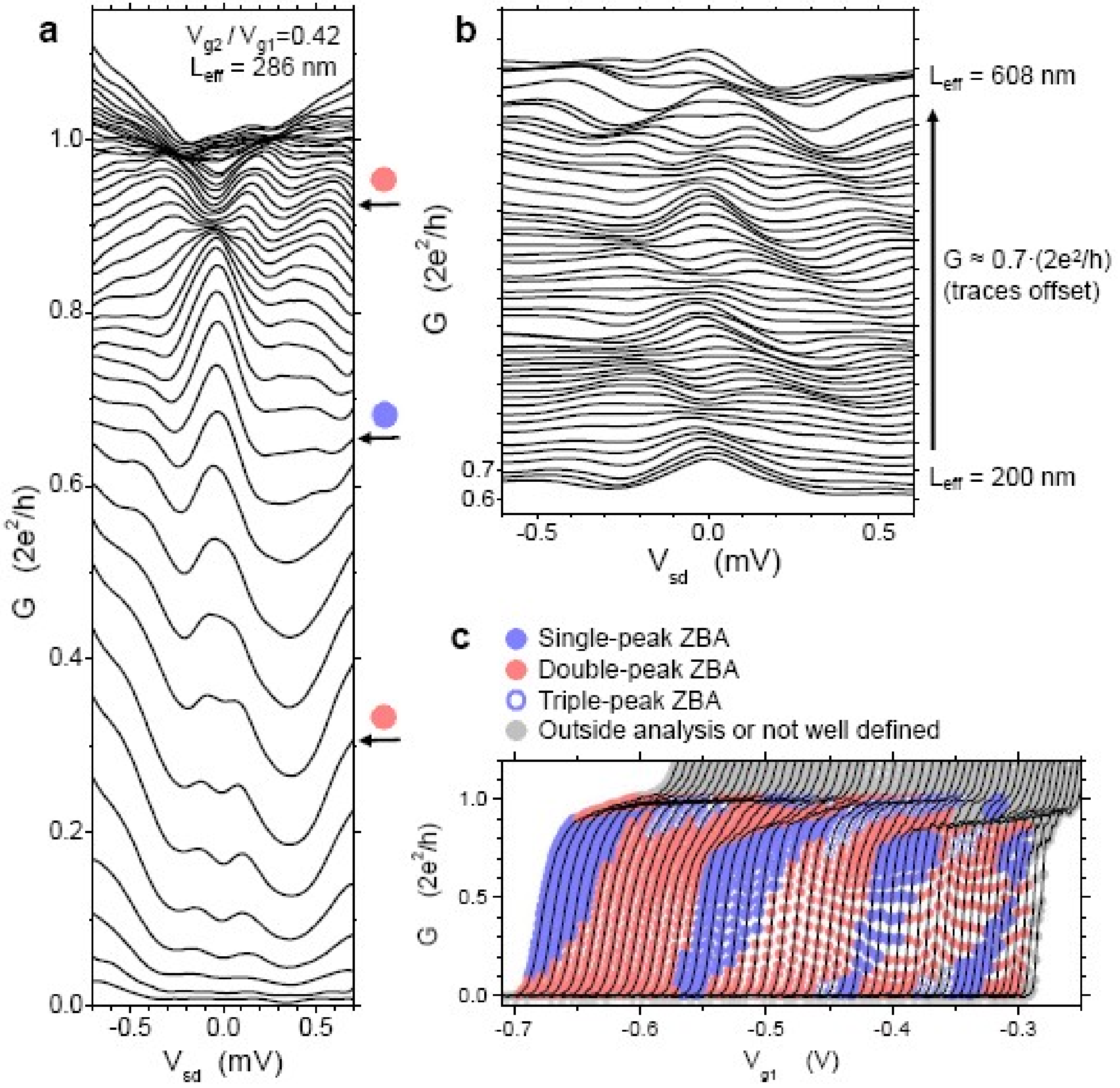
Iqbal, *et al.*, Nature **501**, 79 (28 August 2013)

QPC channel length continuously tunable from 200 to 600 nm

Successive appearances of the 0.7 anomaly versus channel length

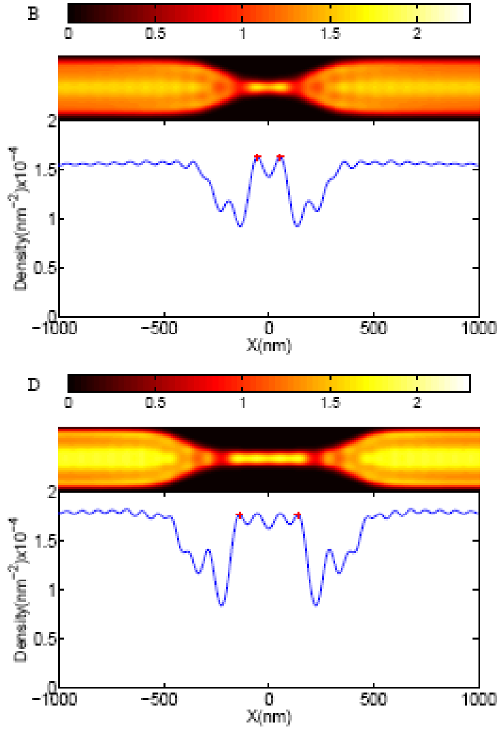


3 – Tunable length experiment



Successive ZBA splittings :

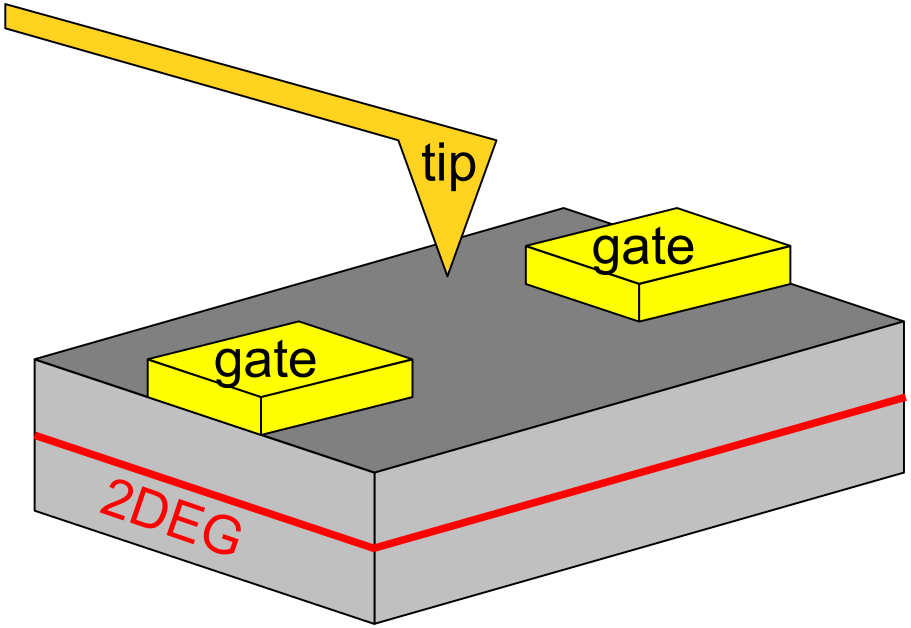
- versus gate voltage
- versus channel length

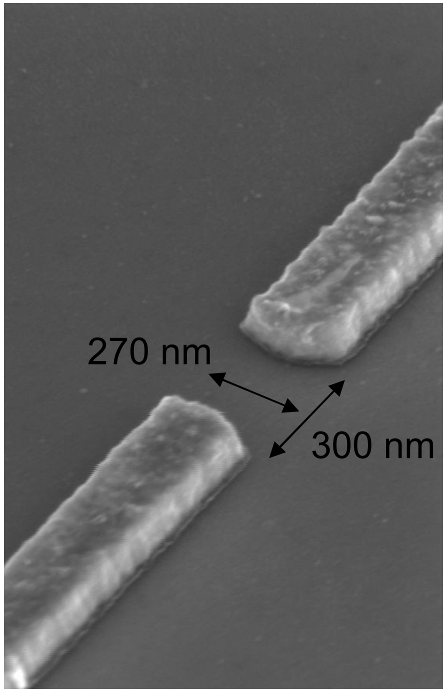


Theoretical model :
Ygal Meir

4 – Scanning gate experiment

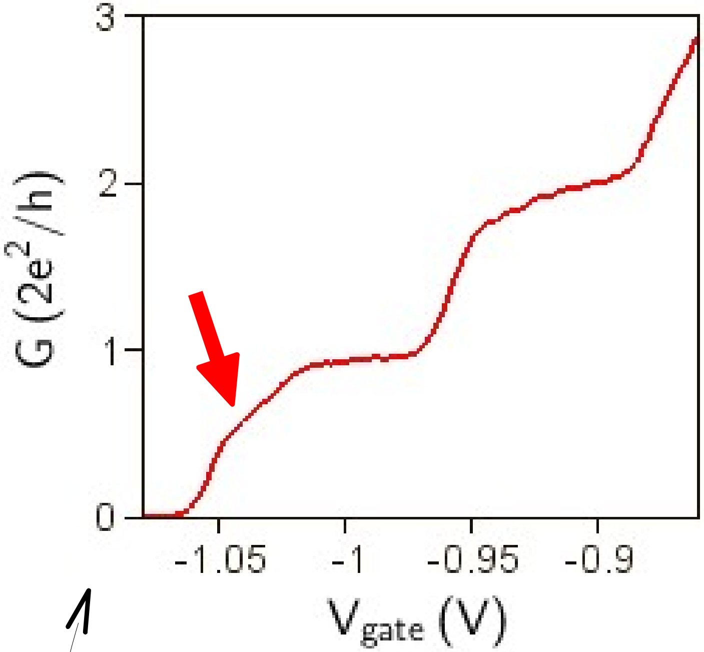
NEEL, *Grenoble (France)* : **B. Brun**, **H. Sellier**
INAC, *Grenoble (France)* : M. Sanquer : 100 mK transport experiments
UCL, *Louvain-la-Neuve (Belgium)* : B. Hackens, V. Bayot : 20 mK SGM experiments
LPN, *Marcoussis (France)* : U. Gennser, D. Mailly : 2DEG and QPC fabrication





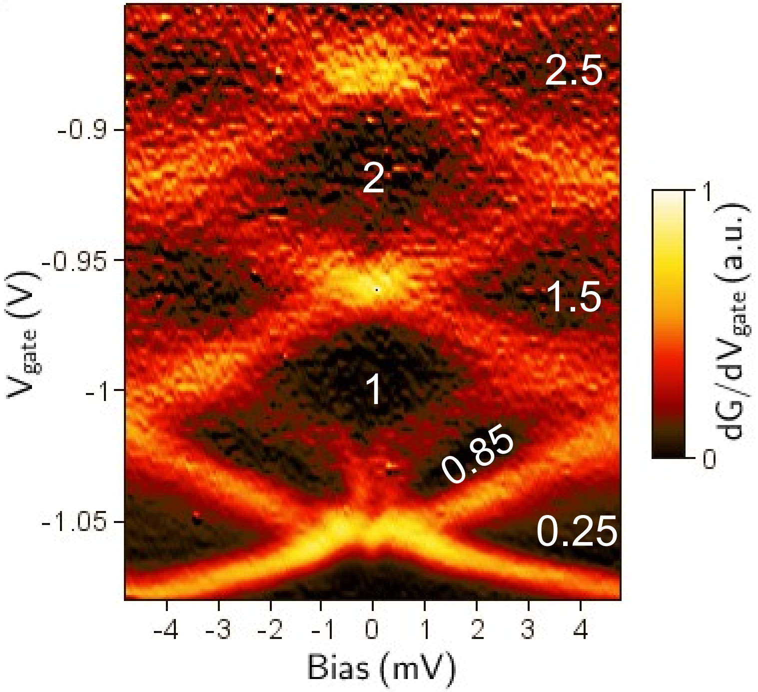
Preprint available on arXiv:1307.8328

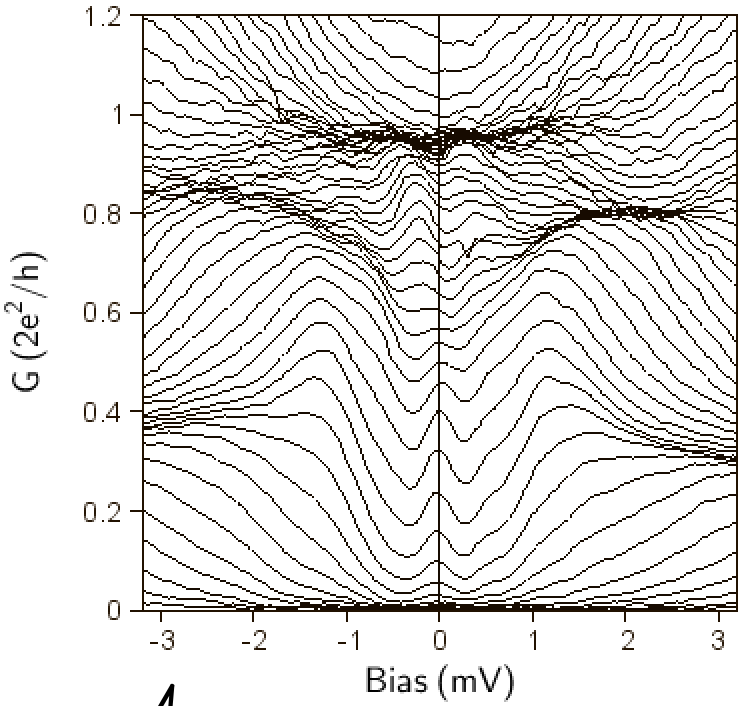
4 – Scanning gate experiment : transport



Linear conductance :
0.7 anomaly

T = 20 mK
for all the data
(transport and SGM)

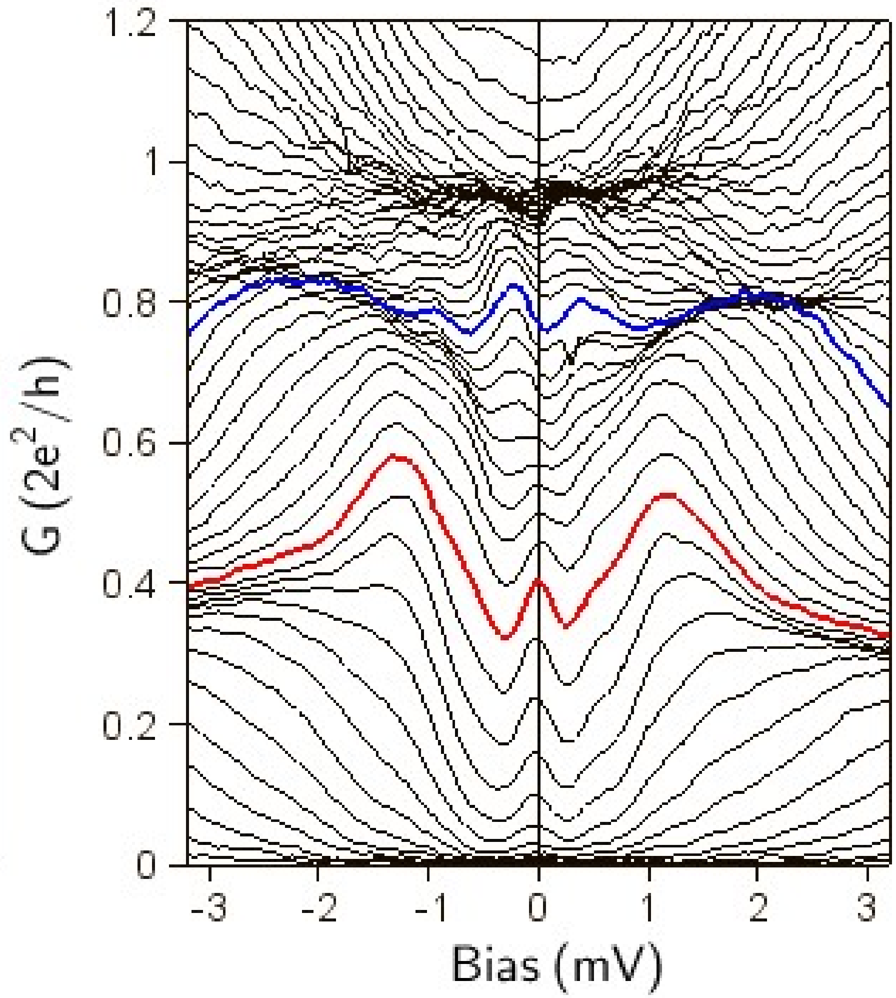


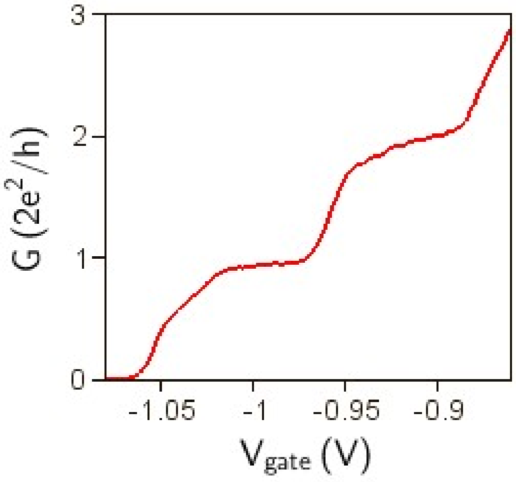


Non-linear conductance :
zero-bias anomaly

4 – Scanning gate experiment : transport

The **zero-bias peak** splits into **finite-bias peaks** versus gate voltage.

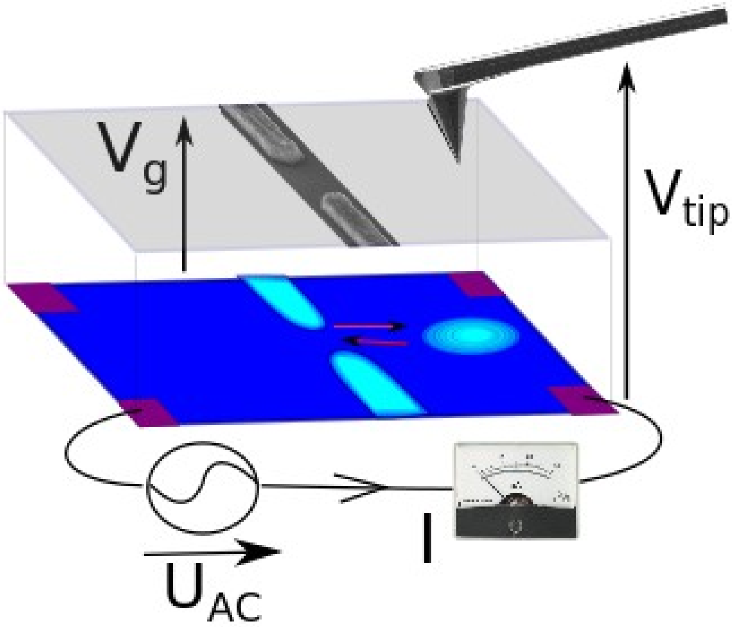


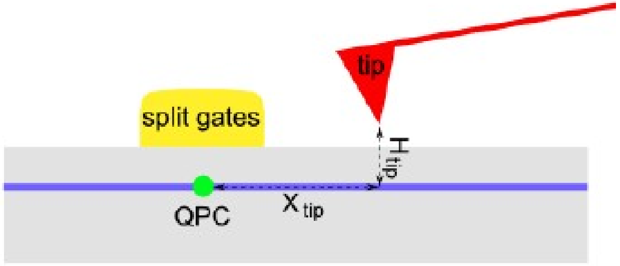


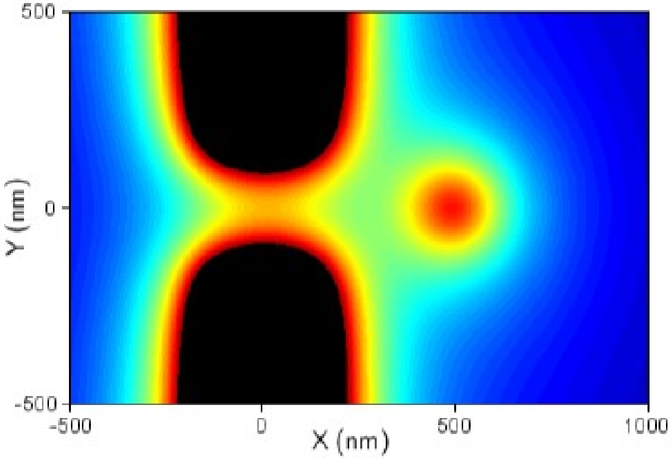
see also Komijani *et al.*, PRB (2013)

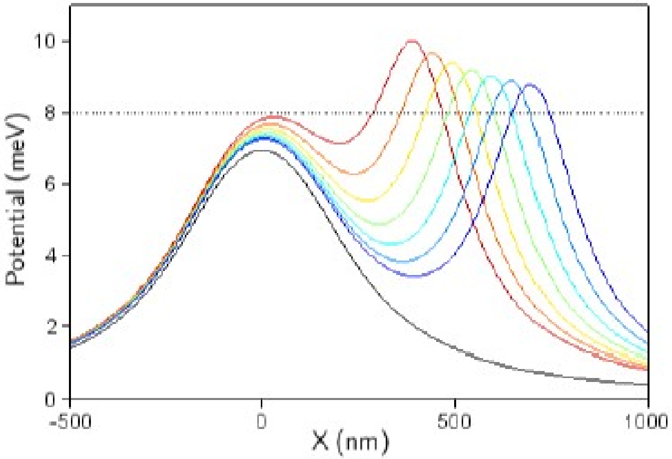
4 – Scanning gate experiment : principle

- gate voltage V_g
- tip voltage V_{tip}
- tip position X_{tip} Y_{tip} Z_{tip}
- device bias V_{ds}
- device conductance $G = I_{AC} / U_{AC}$





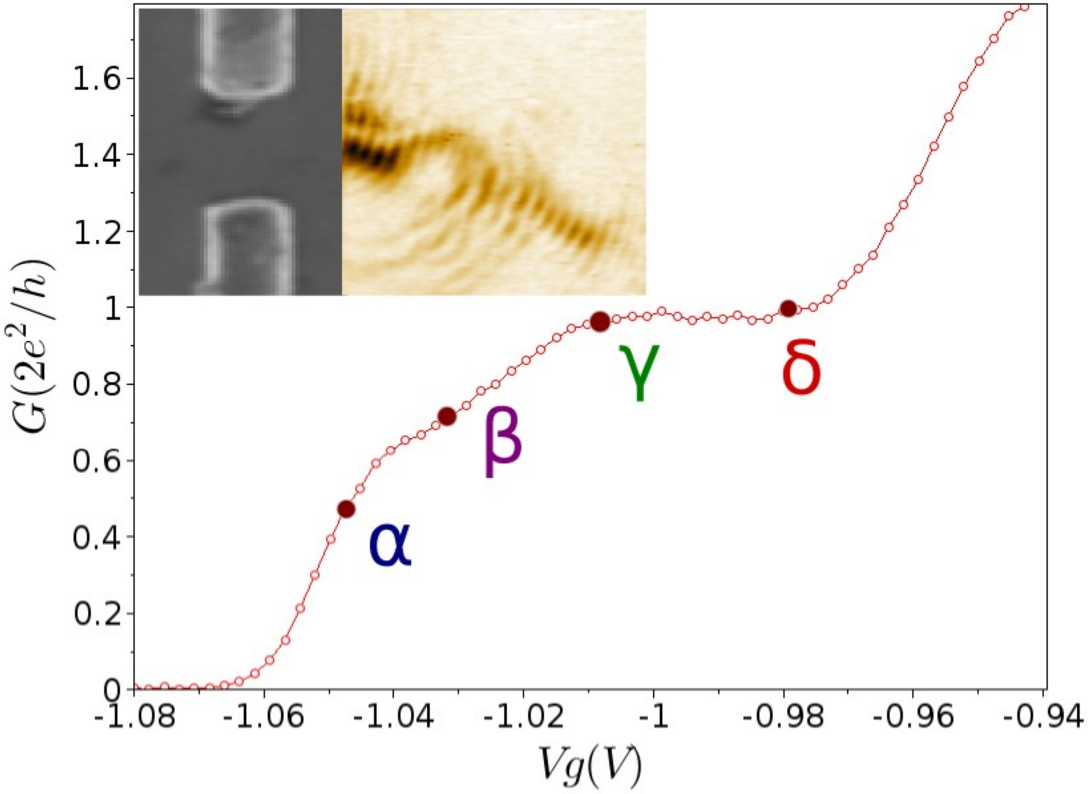




see also Topinka *et al*., Nature (2001)
see also Crook *et al*., Science (2006)

4 – Scanning gate experiment : parameters

QPC parameters :



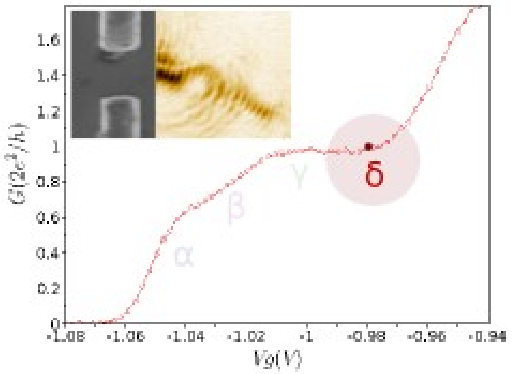
Tip parameters :

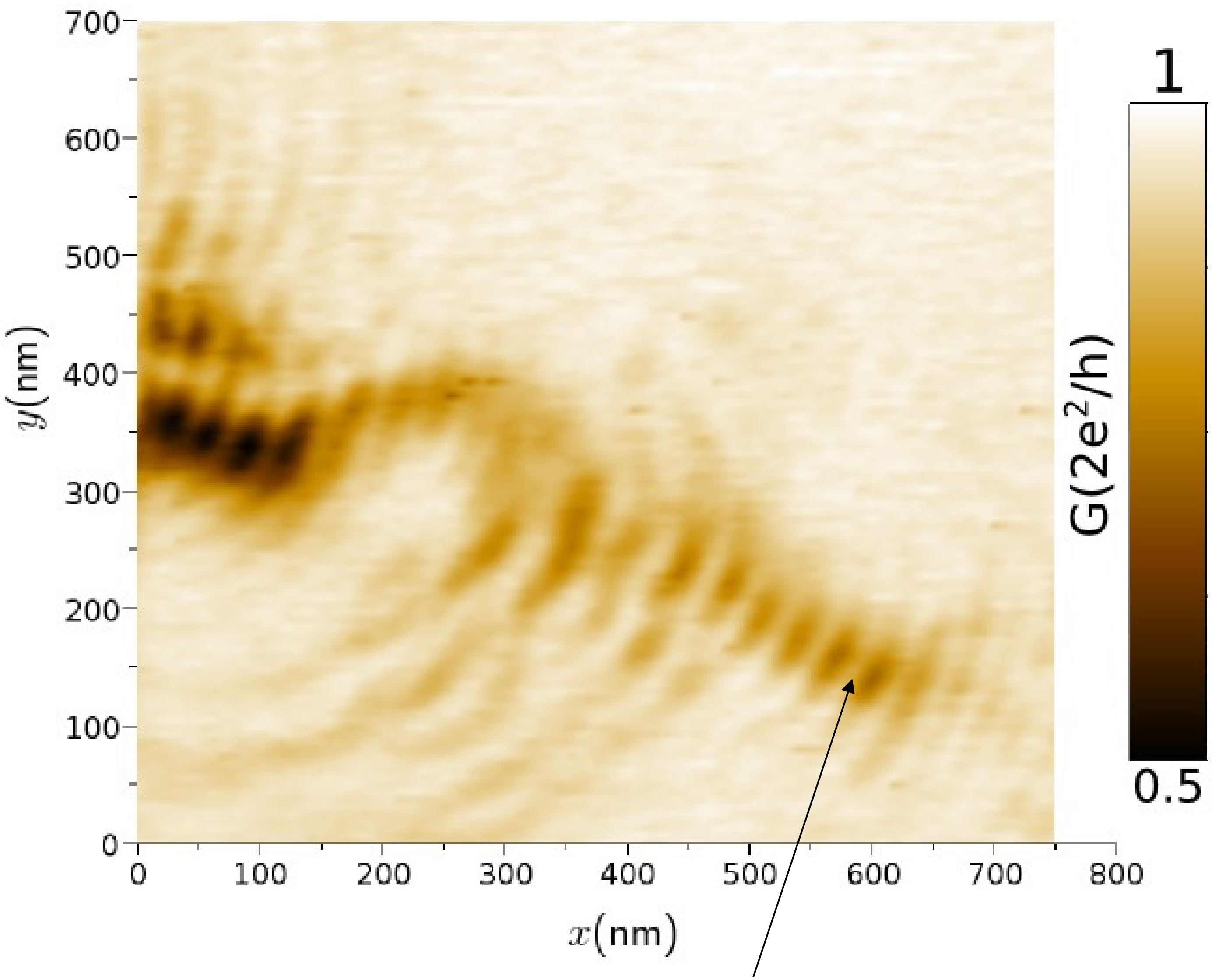
V_{tip} = -6 V

Z_{tip} = 40 nm above the surface

H_{tip} = 140 nm including 2DEG depth

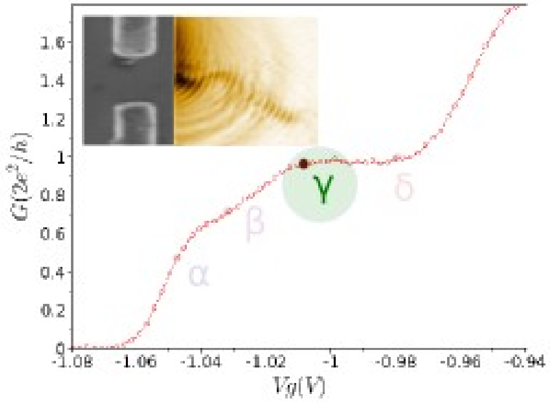
4 – Scanning gate experiment : horizontal maps

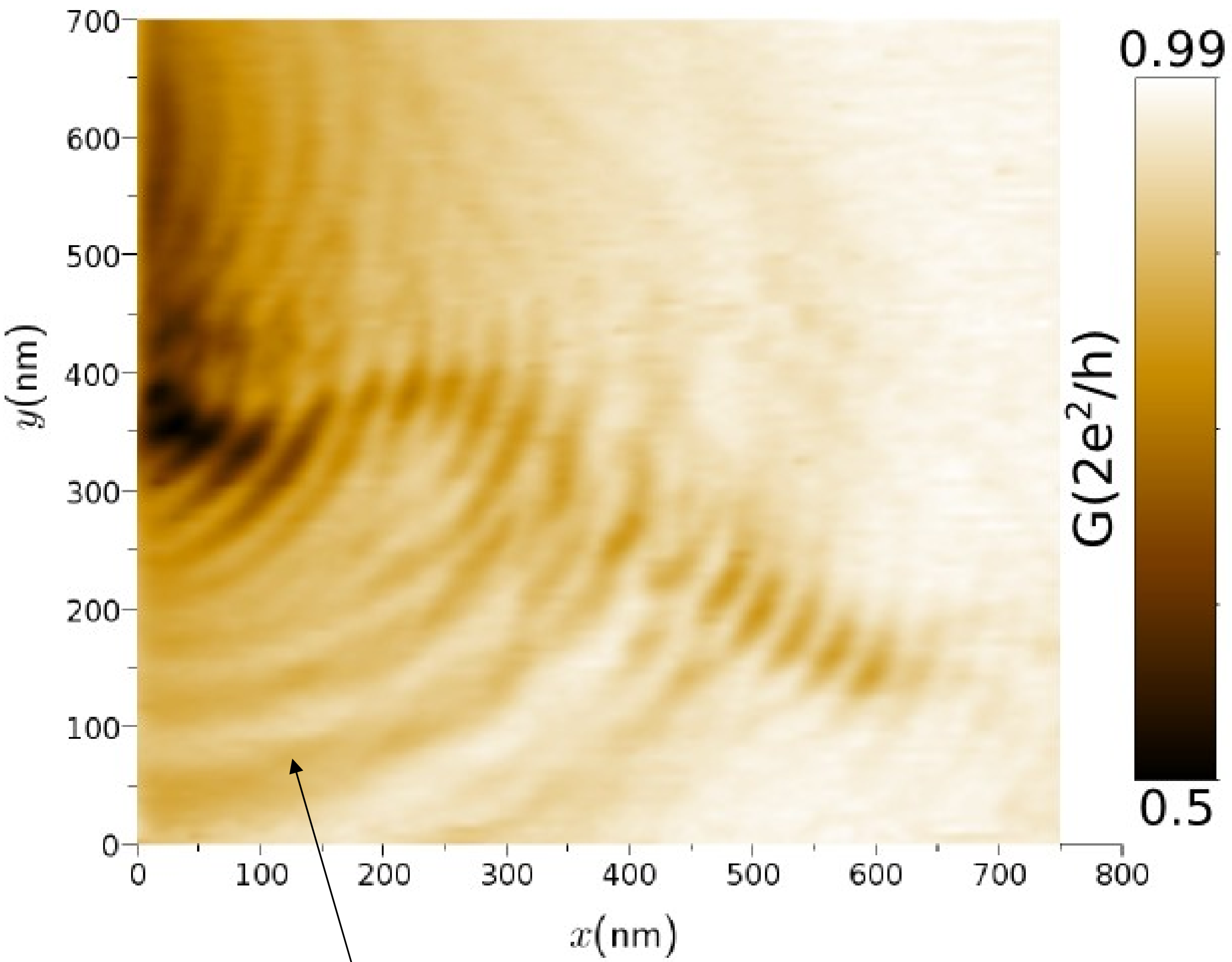




SGM maps reveal electron flow and interference fringes

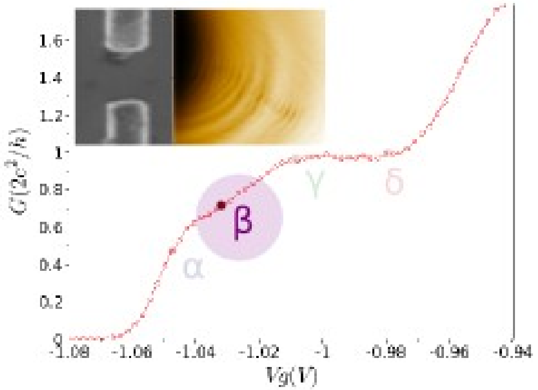
4 – Scanning gate experiment : horizontal maps

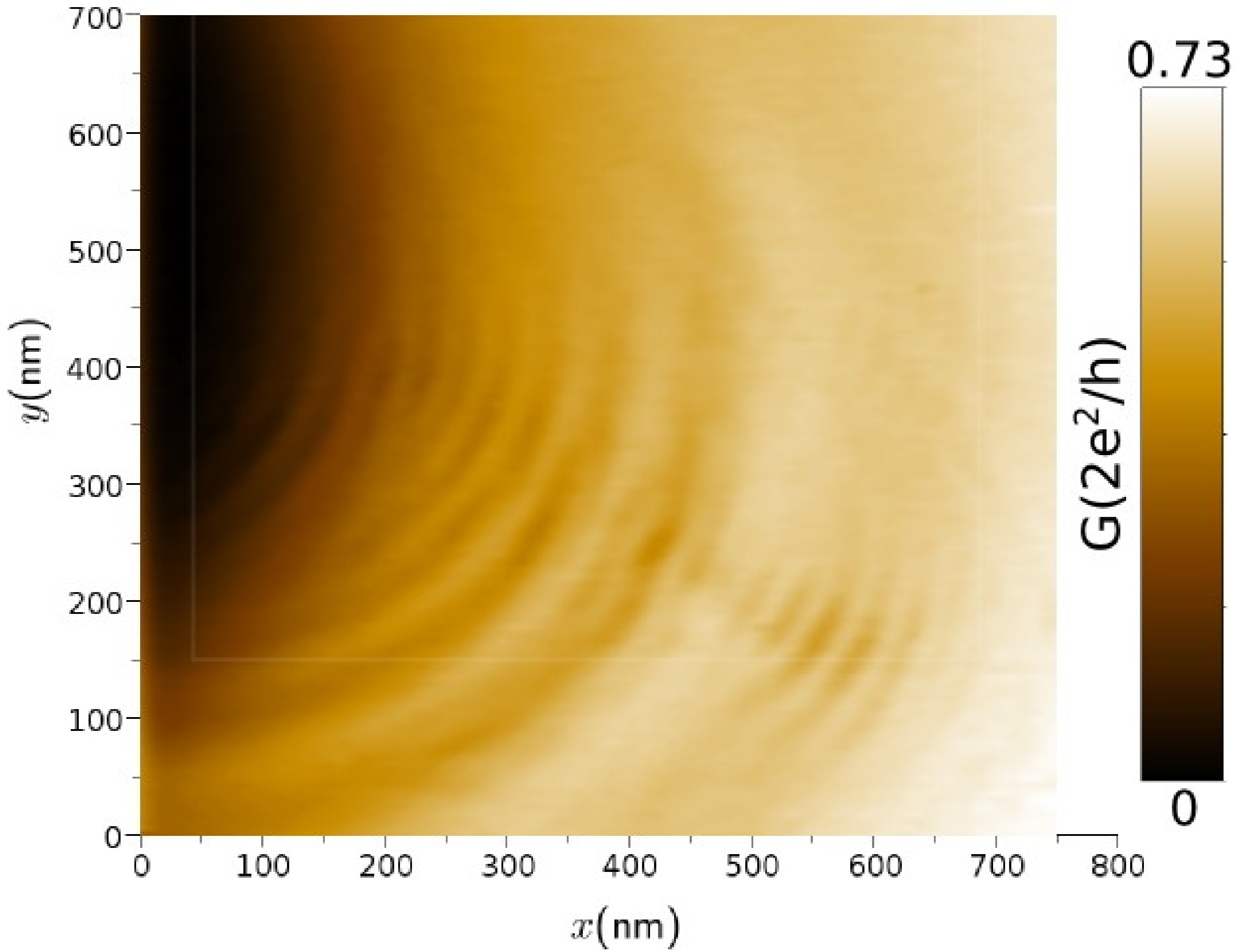




Another kind of conductance oscillations appears below $G=2e^2/h$

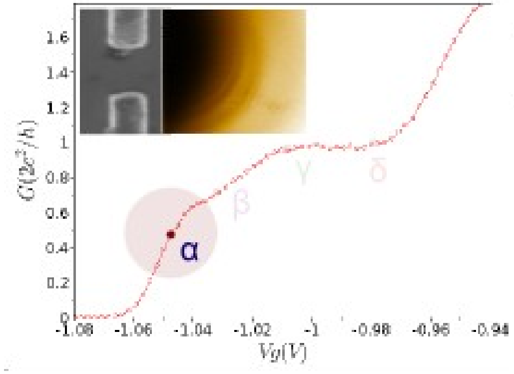
4 – Scanning gate experiment : horizontal maps

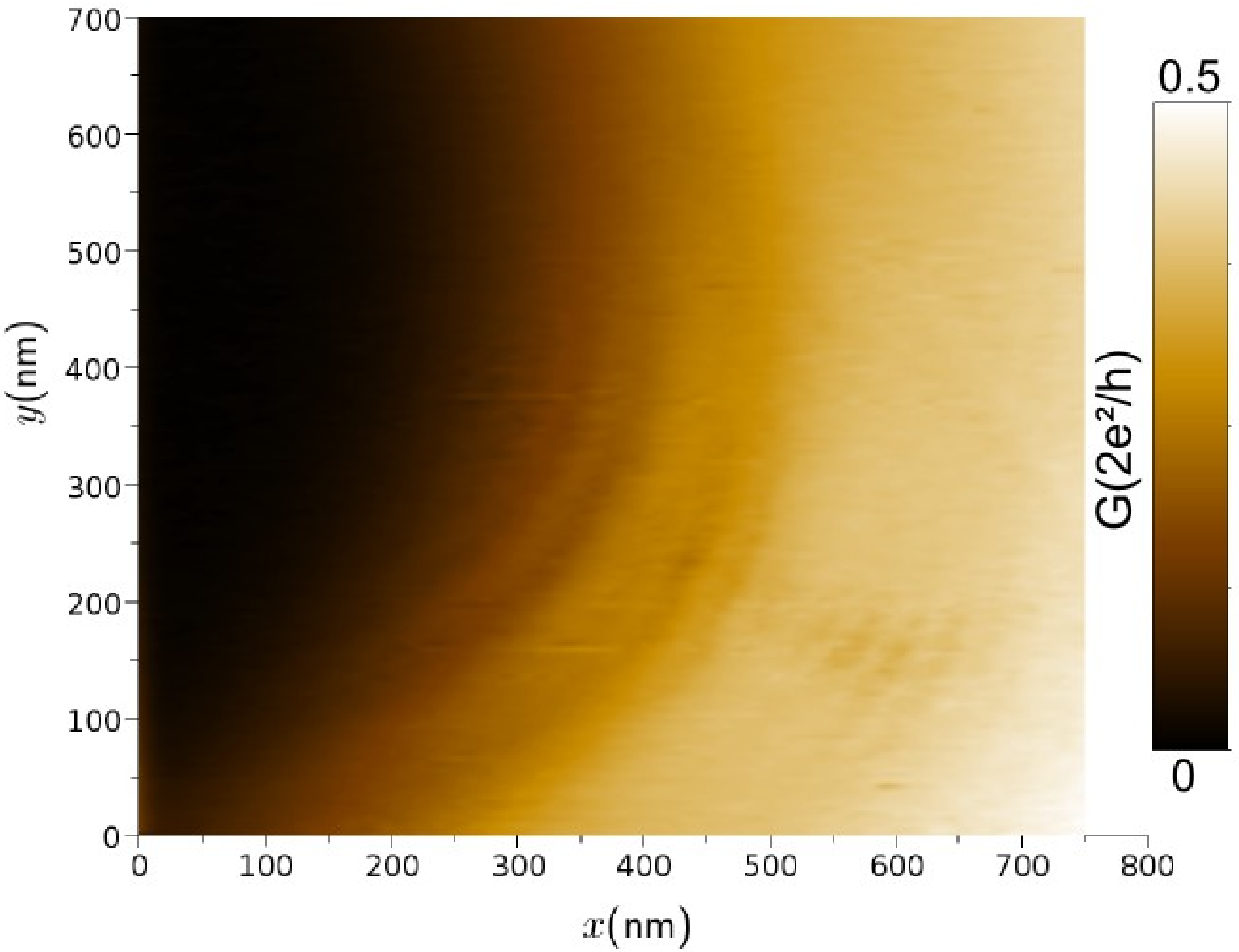




Conductance oscillations below G=2e²/h have increasing spacing with tip distance

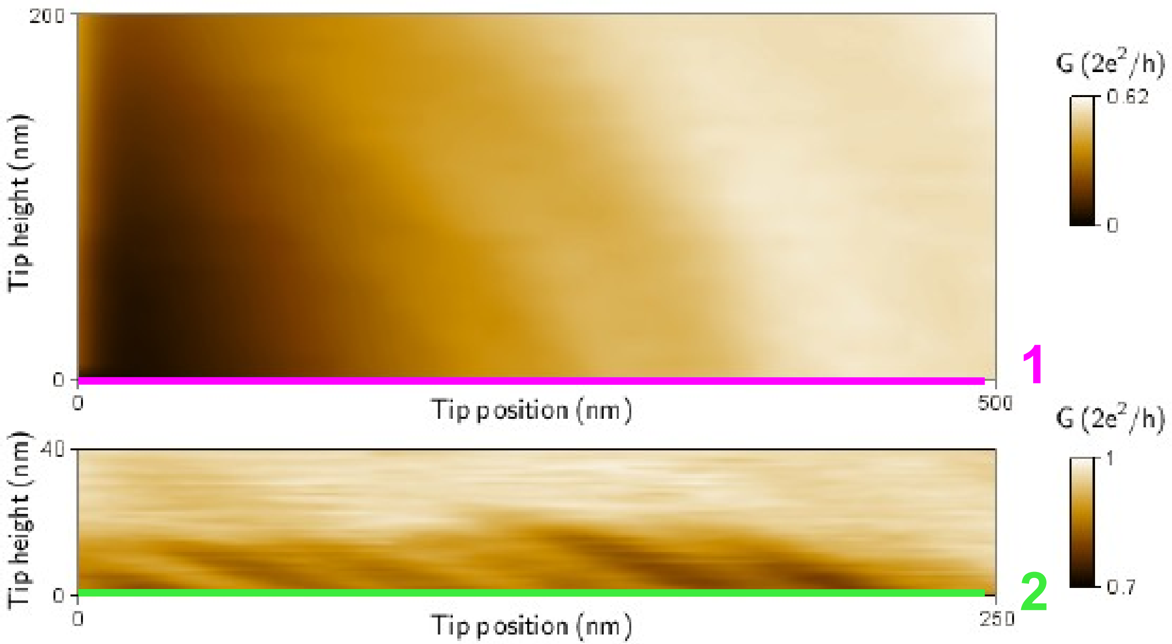
4 – Scanning gate experiment : horizontal maps

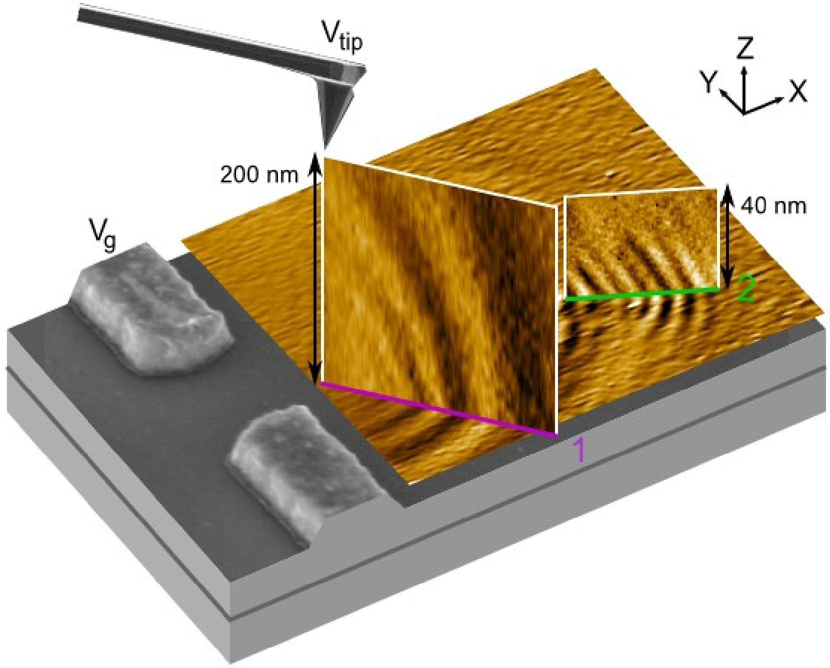


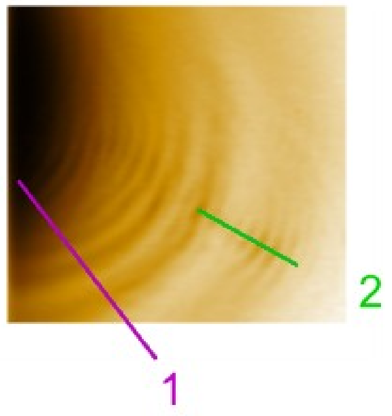


Oscillations are still visible below $0.5 \times 2e^2/h$ before the QPC channel is closed

4 – Scanning gate experiment : vertical maps







Line 1 :

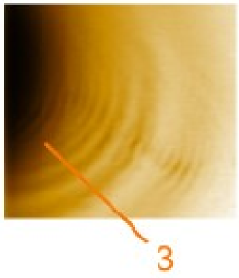
- circular rings extend isotropically around the QPC
- they do not depend on 2DEG potential below the tip
- they induce a direct tuning of the QPC potential

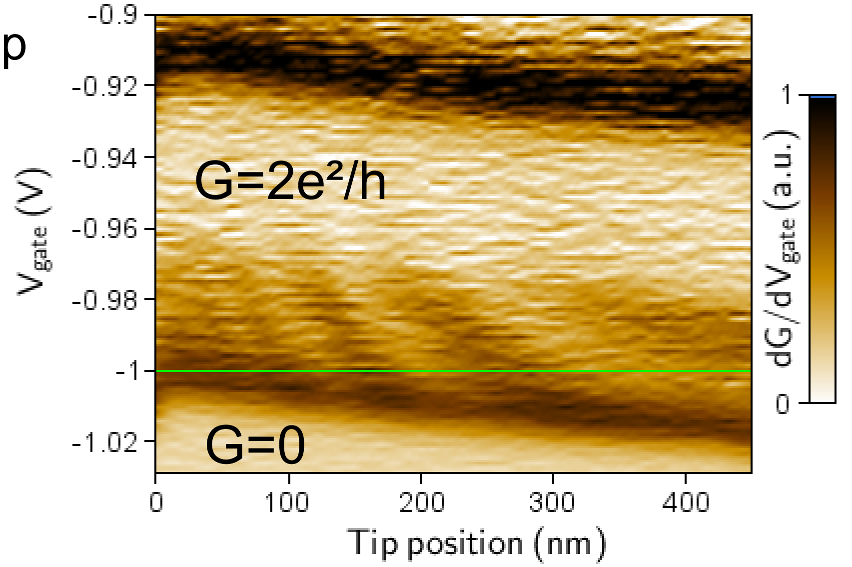
Line 2 :

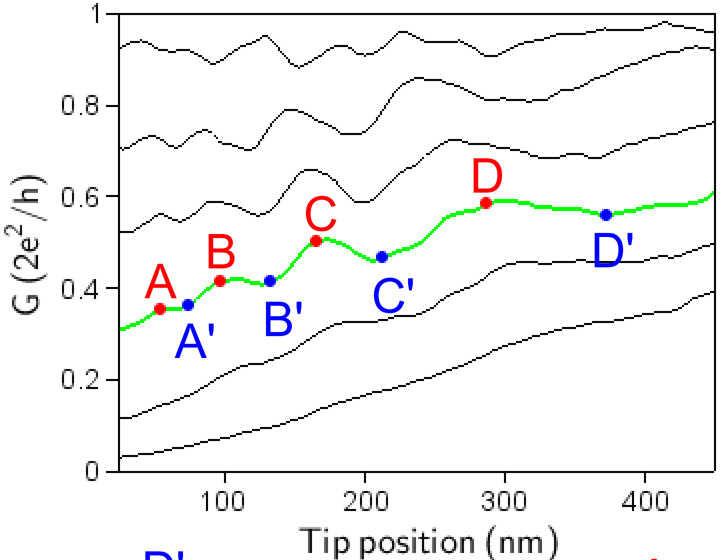
- interferences and back-scattering disappear simultaneously
- the 2DEG should be depleted below the tip

4 – Scanning gate experiment : the 0.7 anomaly

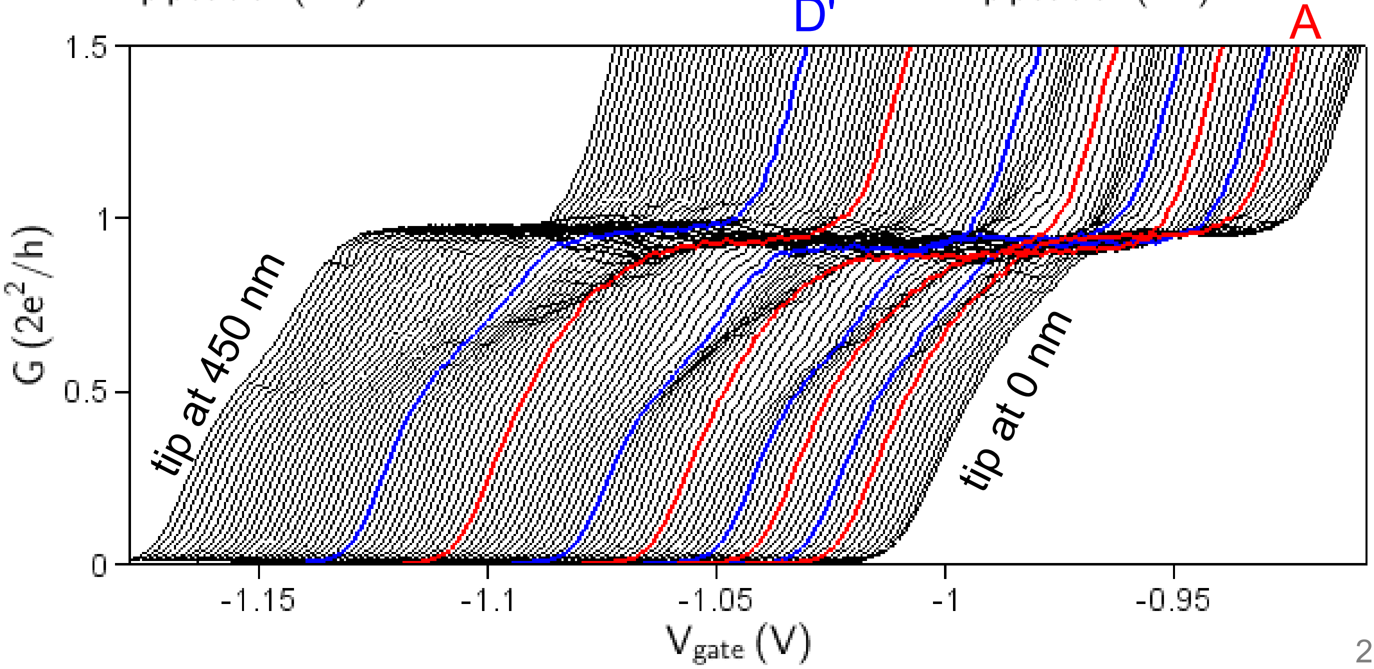
Gate voltage sweep on single scan line



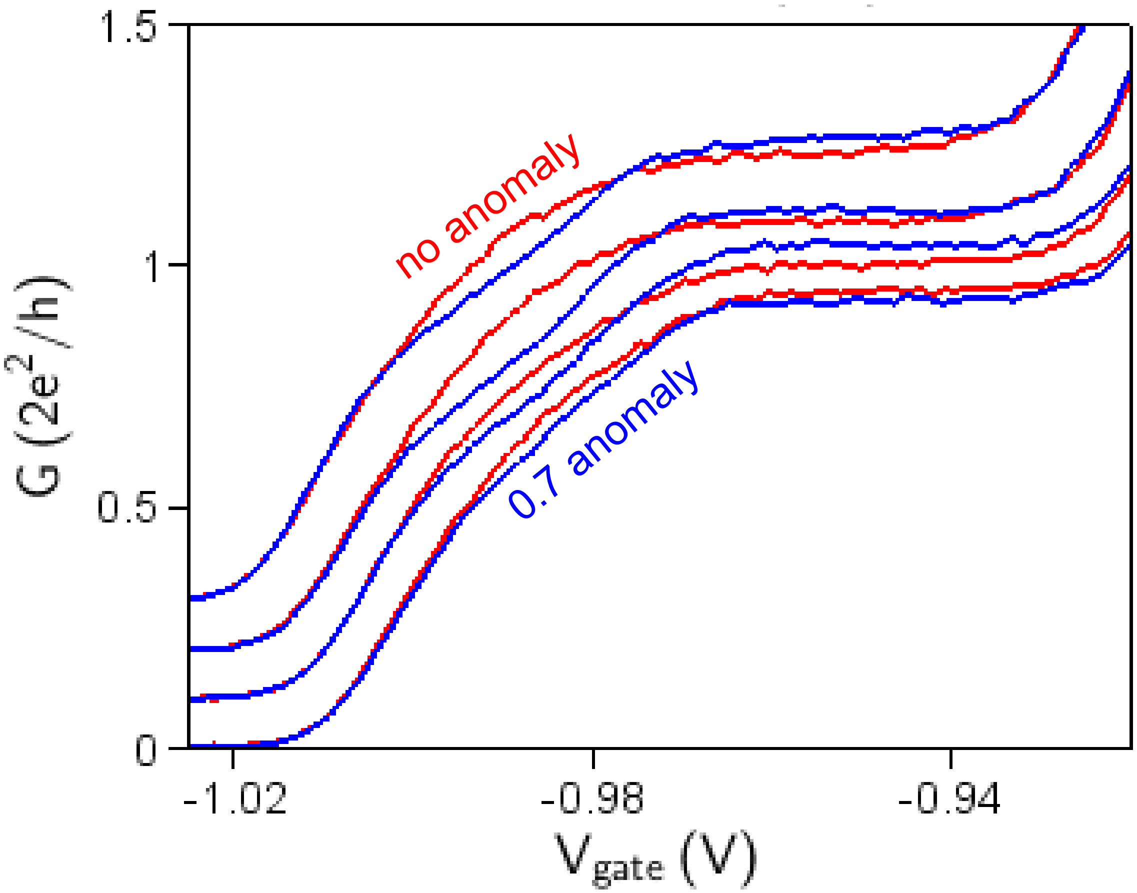




Conductance oscillations correspond to a modulation of the 0.7 anomaly



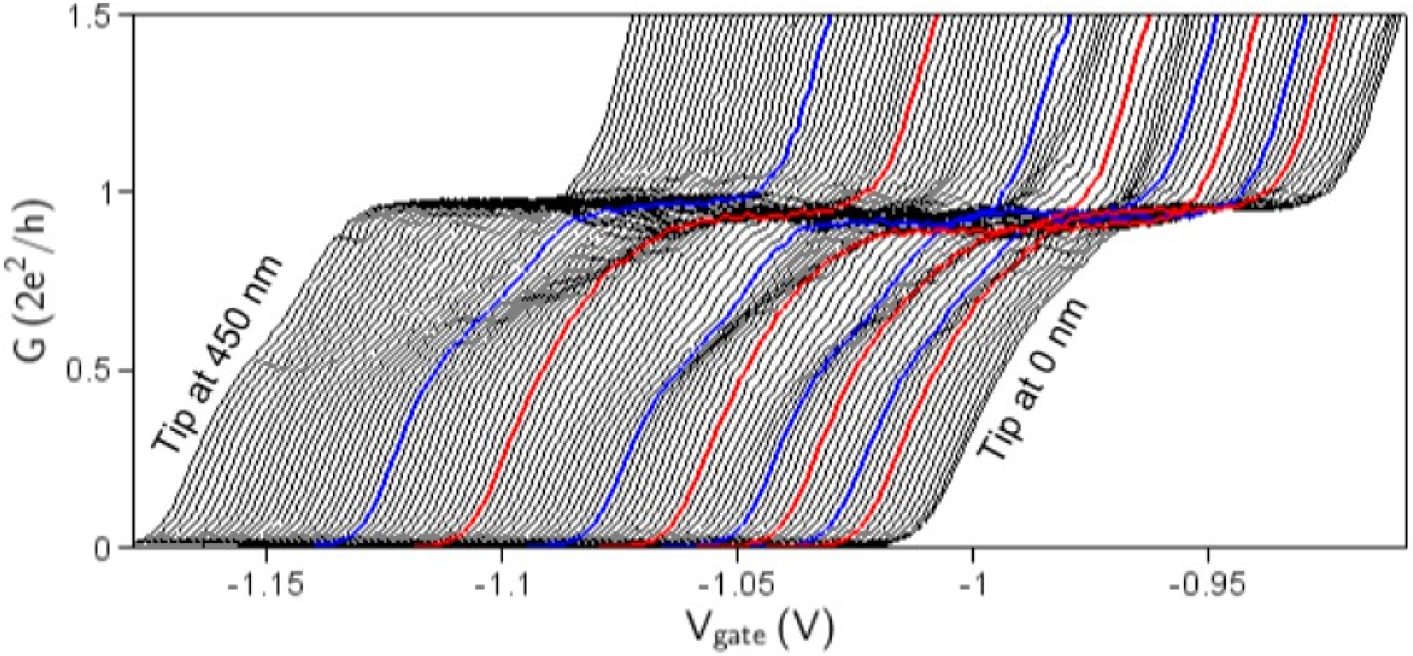
4 – Scanning gate experiment : the 0.7 anomaly



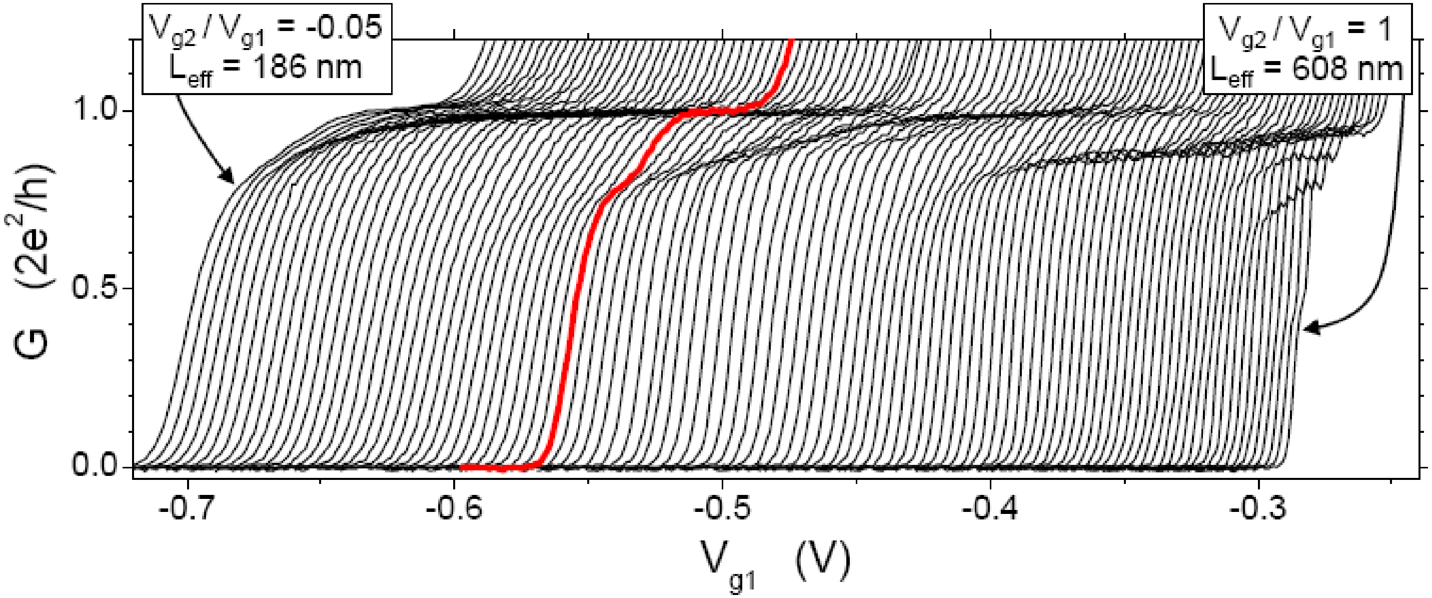
- conductance maxima correspond to red curves without anomaly
- conductance minima correspond to blue curves with 0.7 anomaly

=> The tip position controls the appearance of the 0.7 anomaly

4 – Scanning gate experiment : the 0.7 anomaly

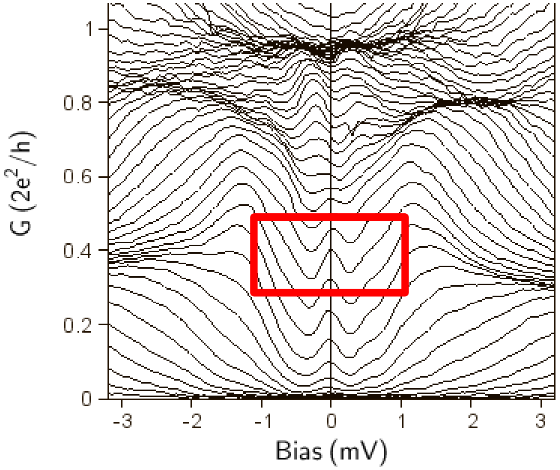


Scanning gate experiment

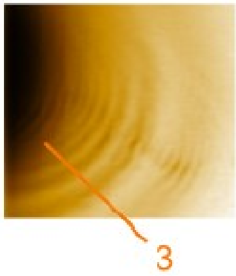


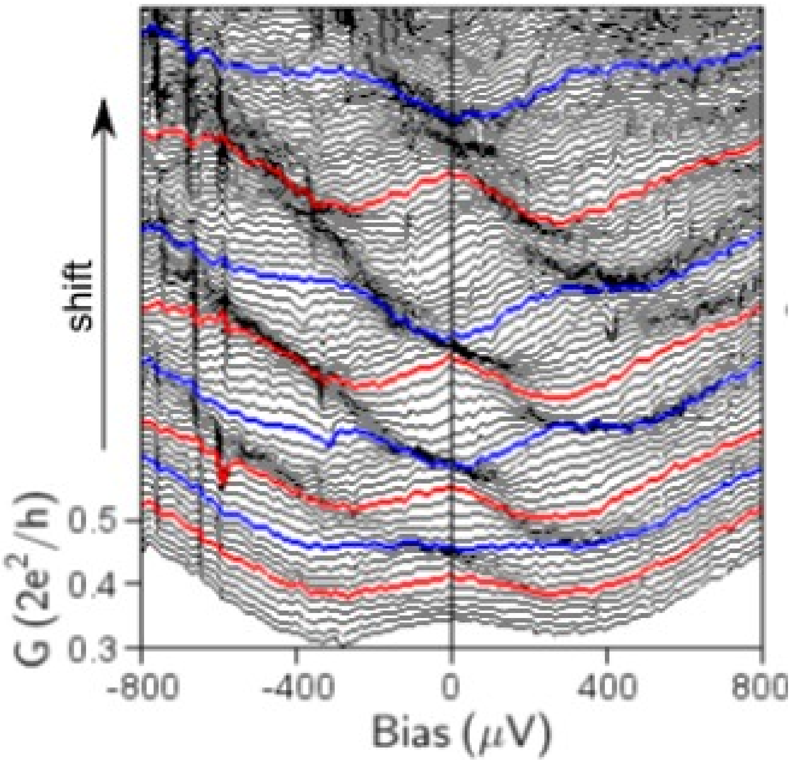
Tunable length experiment

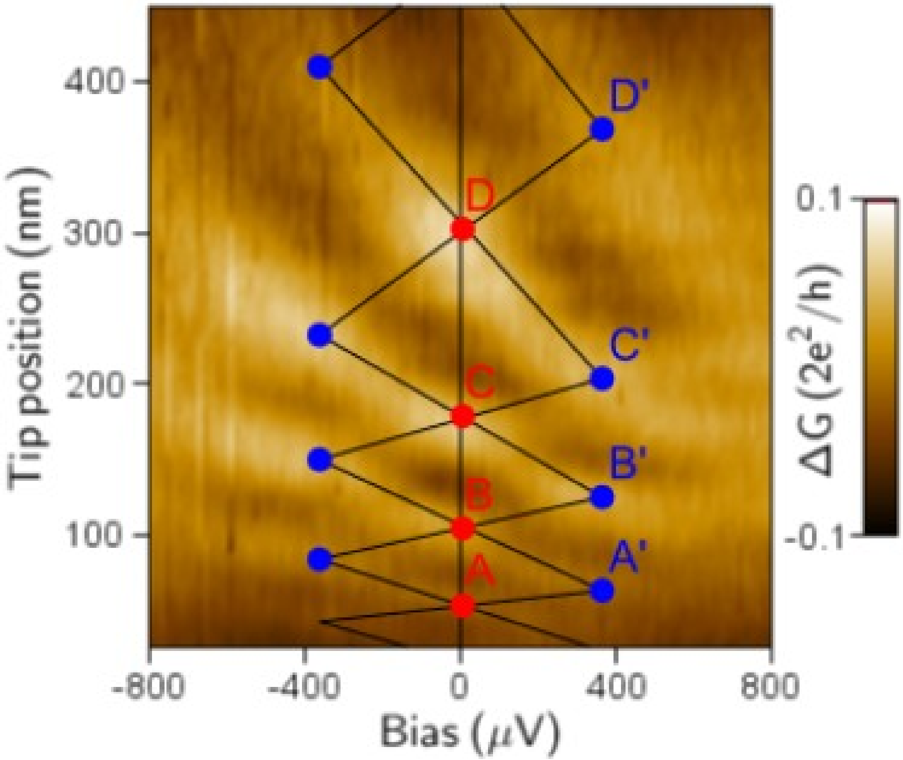
4 – Scanning gate experiment : the zero-bias anomaly



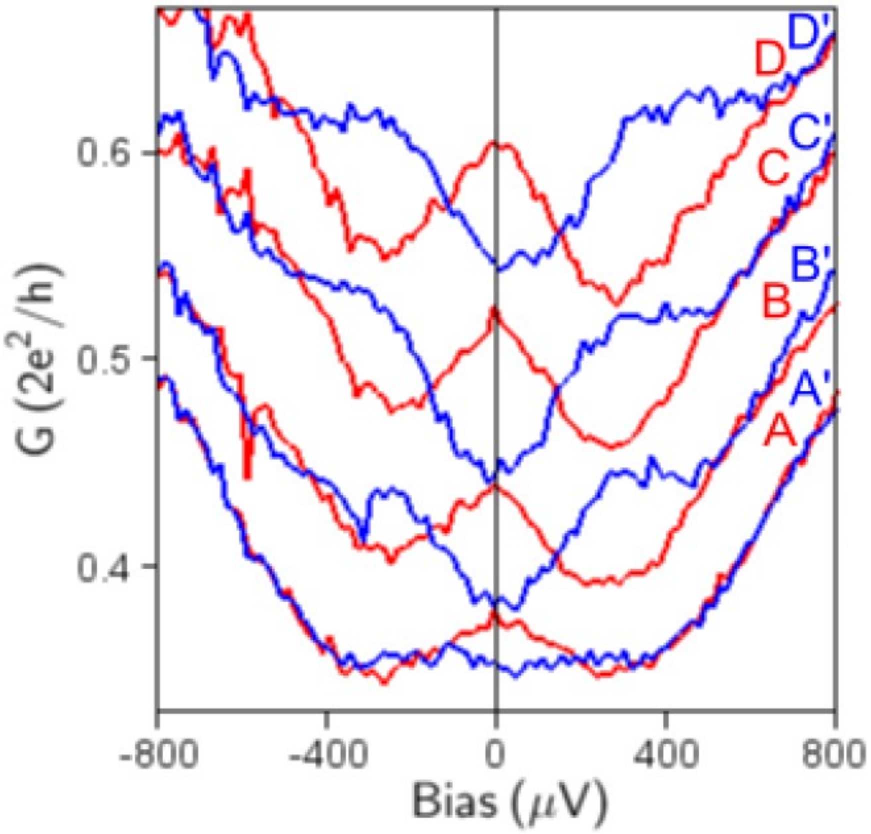
Source-drain bias sweep
at fixed gate voltage
on a single scan line







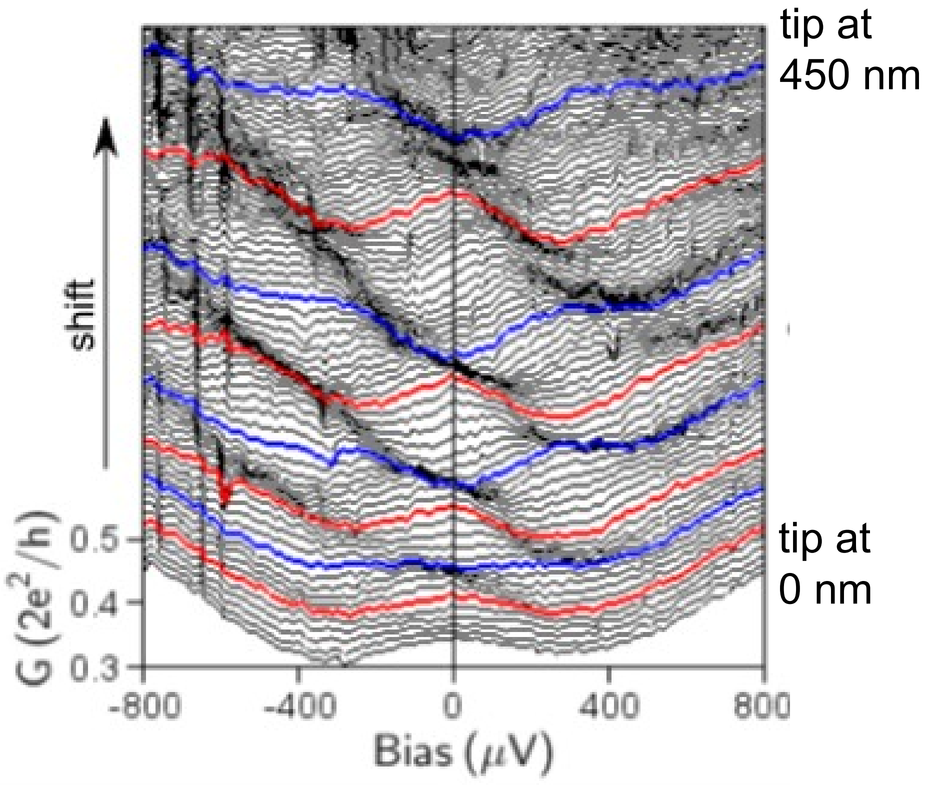
4 – Scanning gate experiment : the zero-bias anomaly

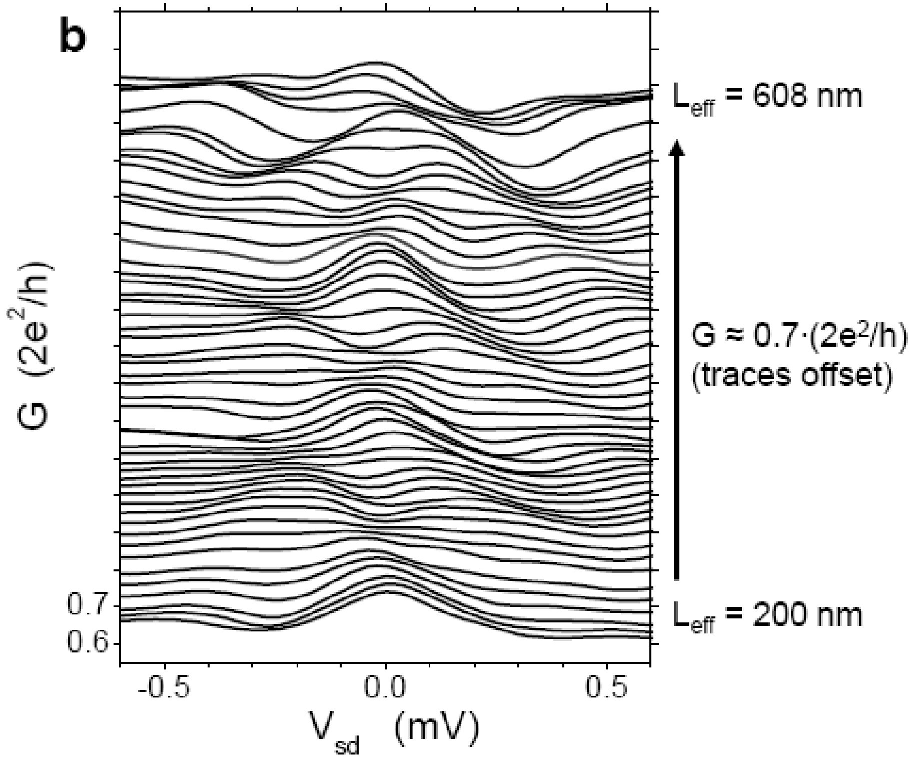


- conductance maxima correspond to red curves with a zero-bias peak
- conductance minima correspond to blue curves with finite-bias peaks

=> The tip position controls the appearance of the zero-bias anomaly

4 – Scanning gate experiment : the zero-bias anomaly

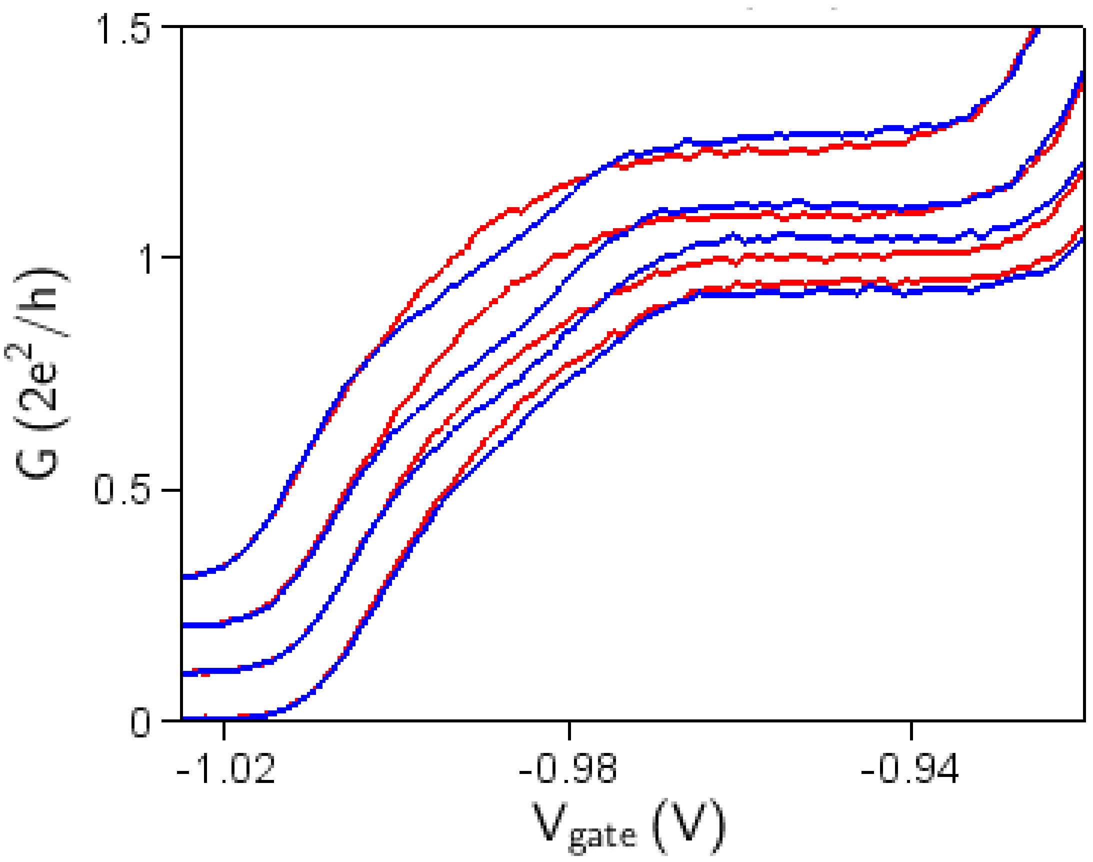


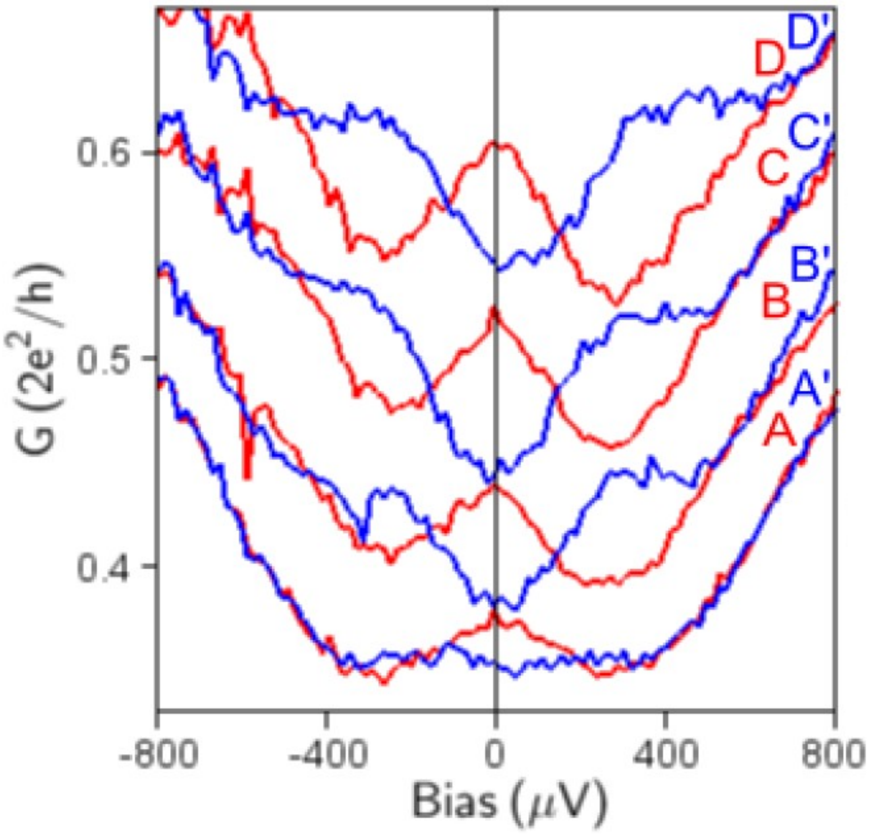


Scanning gate experiment

Tunable length experiment

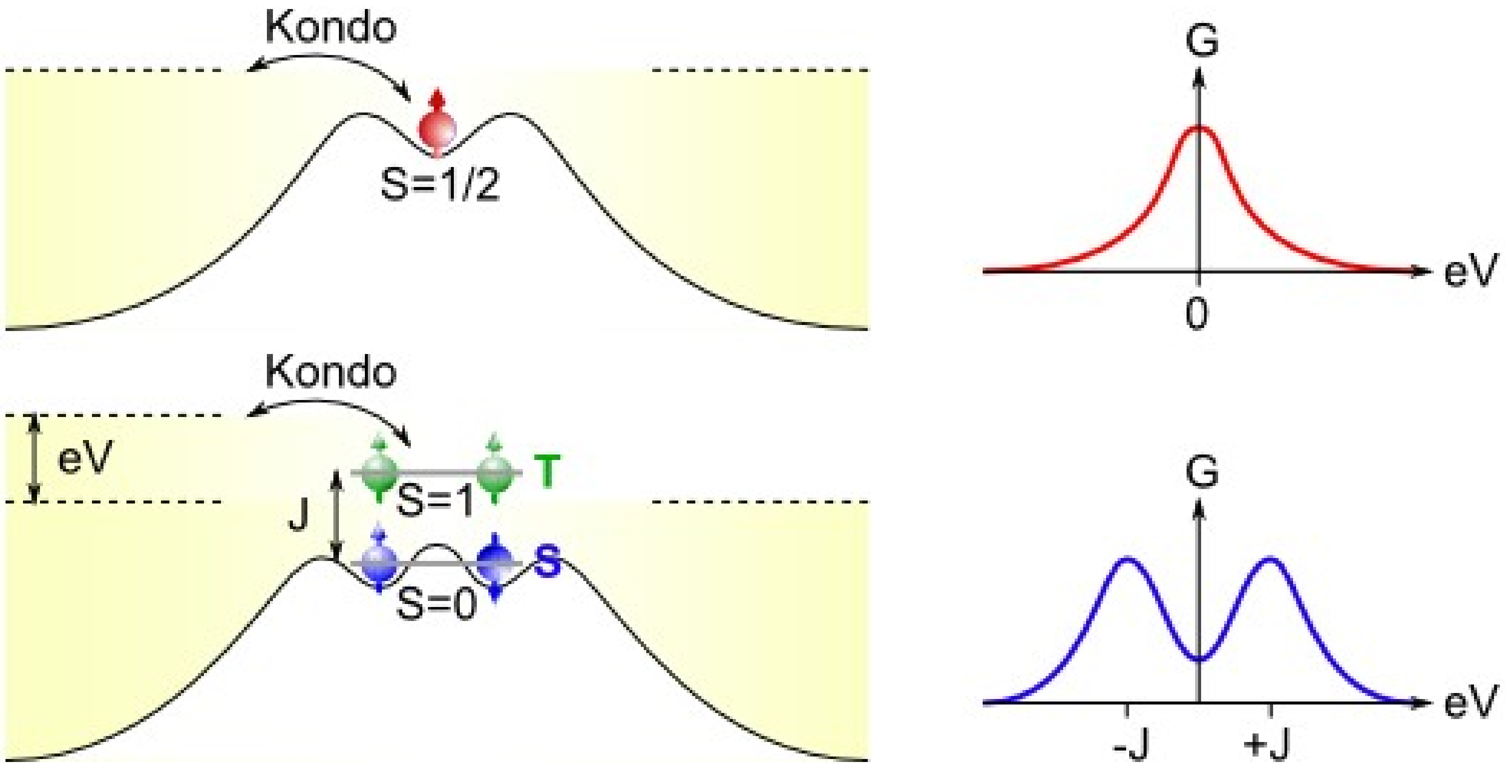
4 – Scanning gate experiment : tunes both anomalies





Conclusion : the 0.7 anomaly corresponds to a splitting of the zero-bias anomaly

4 – Scanning gate experiment : interpretation

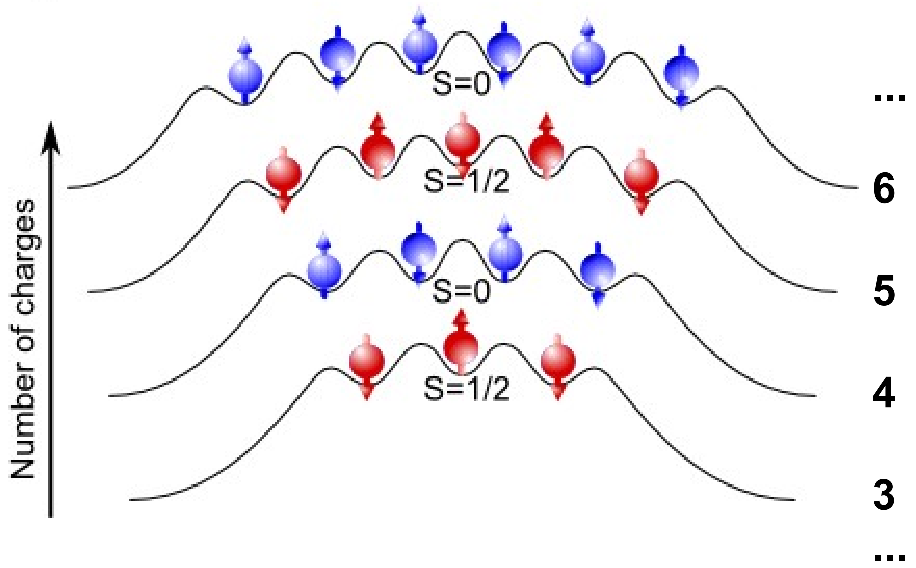


The zero-bias anomaly is usually attributed to Kondo screening of a single localized state.
A splitting of the zero bias peak can be explained by a two-impurity Kondo model:

- the ground state is a singlet that does not show Kondo effect
- but the excited state is a triplet that shows out-of-equilibrium Kondo effect

cf. coupled quantum dots and molecular junctions

4 – Scanning gate experiment : interpretation



<u>Since :</u>
4 successive zero-bias splittings correspond to 8 localized charges, we need a varying channel length.

<u>But :</u>

- in tunable length experiment, $L_{effective}$ varies from 200 to 600 nm
- in scanning gate experiment, $L_{effective}$ is constant at 250 nm

<u>So :</u>
Explanation is not as straightforward as for tunable length QPC.
We need another explanation for increasing localized charges...

4 – Scanning gate experiment : interpretation

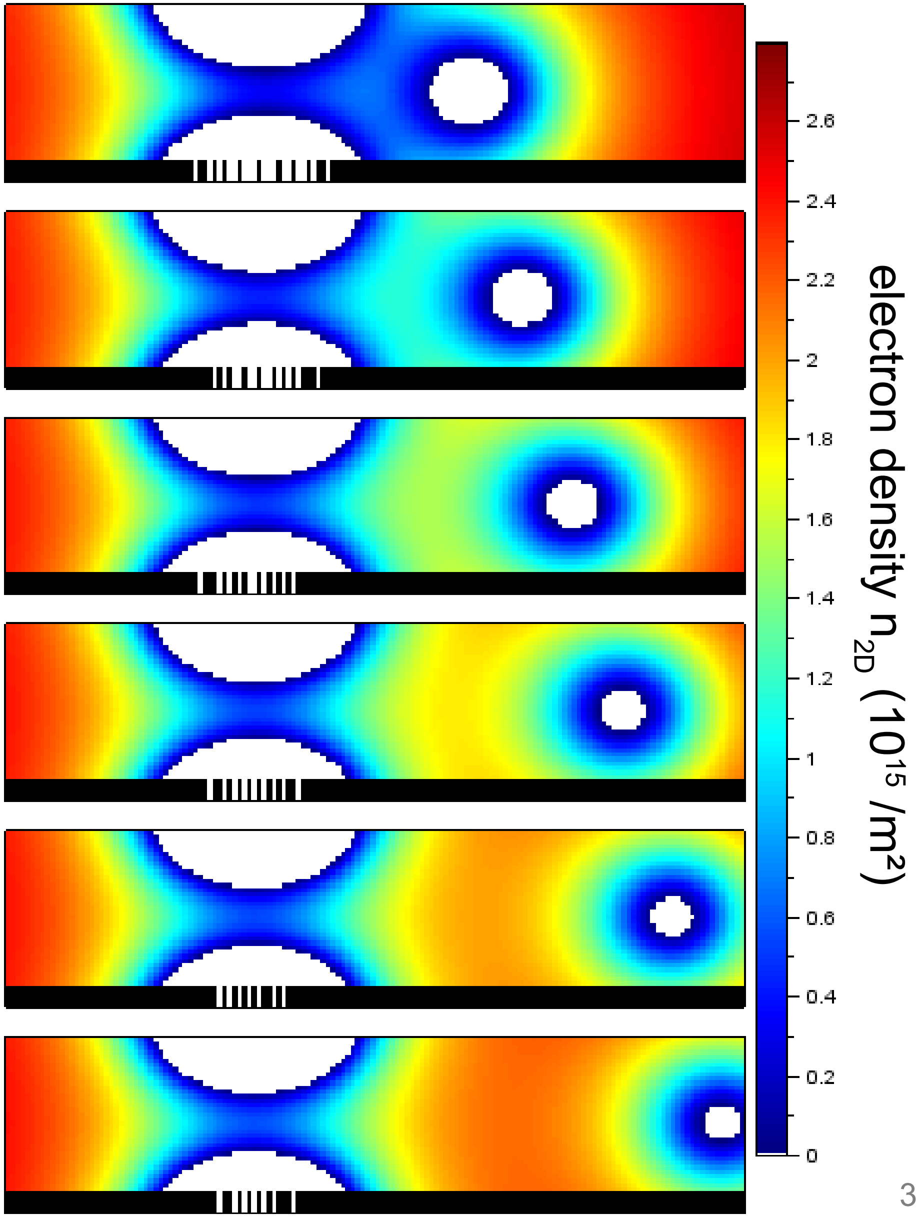
1D Wigner crystal predicted when $E_{kinetic} < E_{Coulomb}$

i.e. $r_s = (2\, n_{1D}\, a_B)^{-1} > 1$

where :

n_{1D} is the 1D electron density

a_B is the effective Bohr radius (10 nm for GaAs)

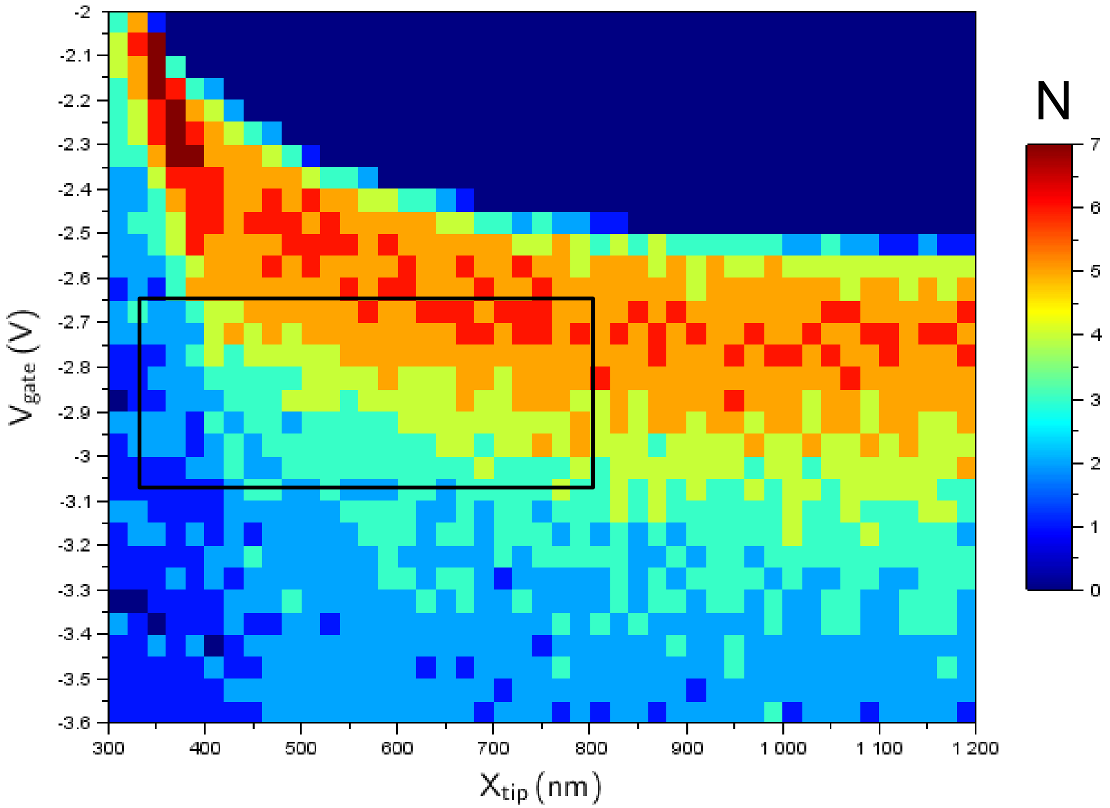


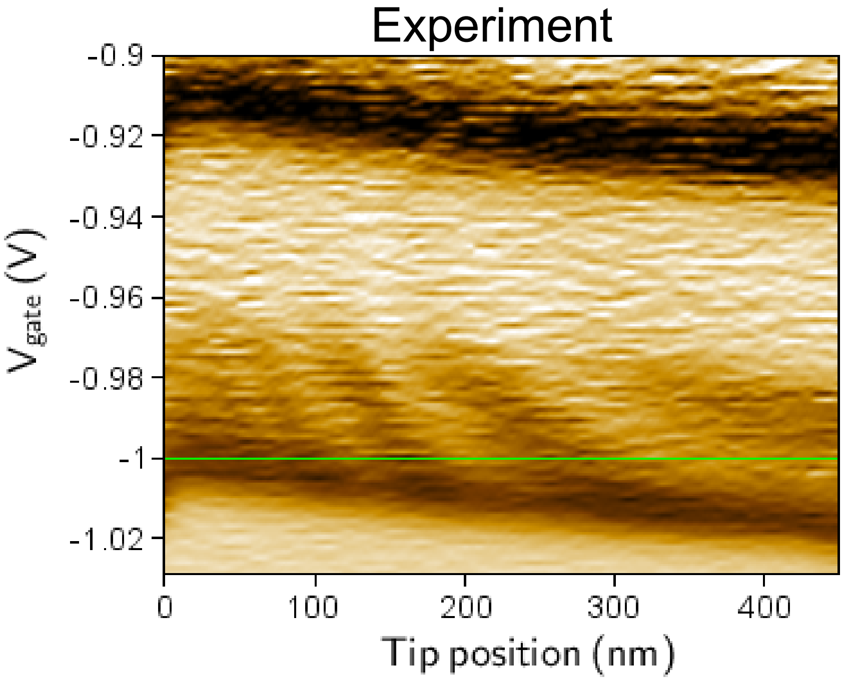
Simulation :

- gate and tip potentials
- local 2D electron density
- transverse integration
- local 1D electron density
- count electrons separated by more than $2\, a_B$

4 – Scanning gate experiment : interpretation

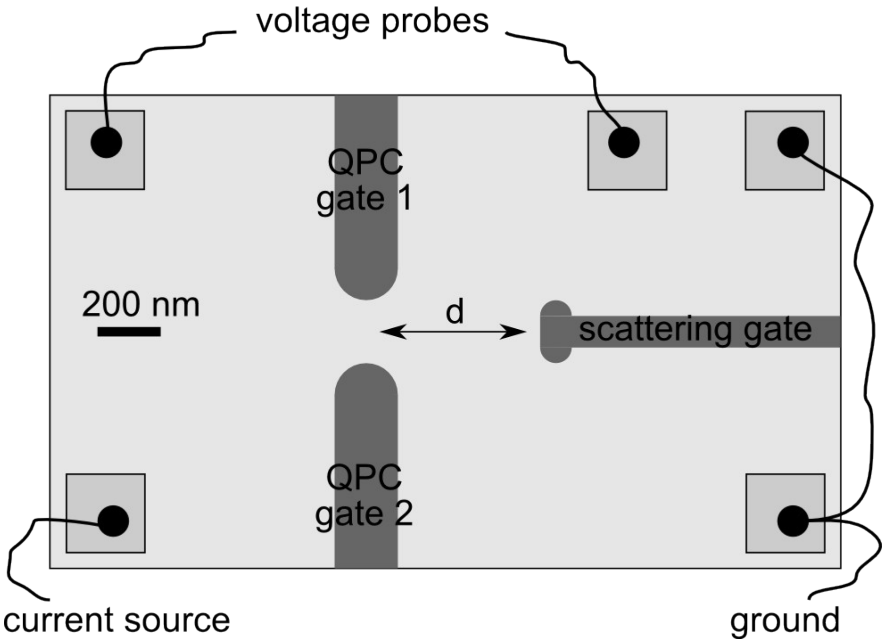
Number of electrons separated by more than 2 a_B = 20 nm (i.e. crystallized if $r_s^{critical}$ = 1)





The number of crystallized electrons can changed by a few units when scanning the tip or sweeping the gate voltage.

4 – Interferometers : principle

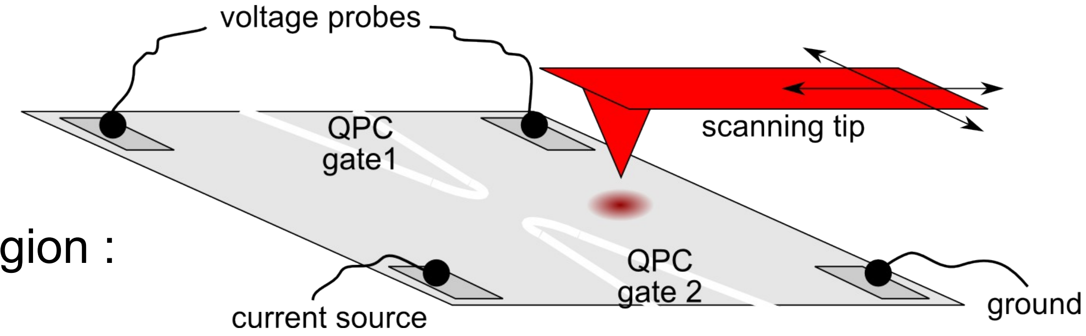


Interferometer = cavity between two barriers : QPC at ½ transmission + local potential barrier (depleted region below the "scattering gate")

Part of the electron flow is back-scattered towards the QPC and then partially reflected again to the right, such that interferences build-up in the cavity.

The total transmission oscillates with the cavity length d with period $\lambda_F/2$.

Alternatively, one can use a scanning gate to have more flexibility on the scattering region :



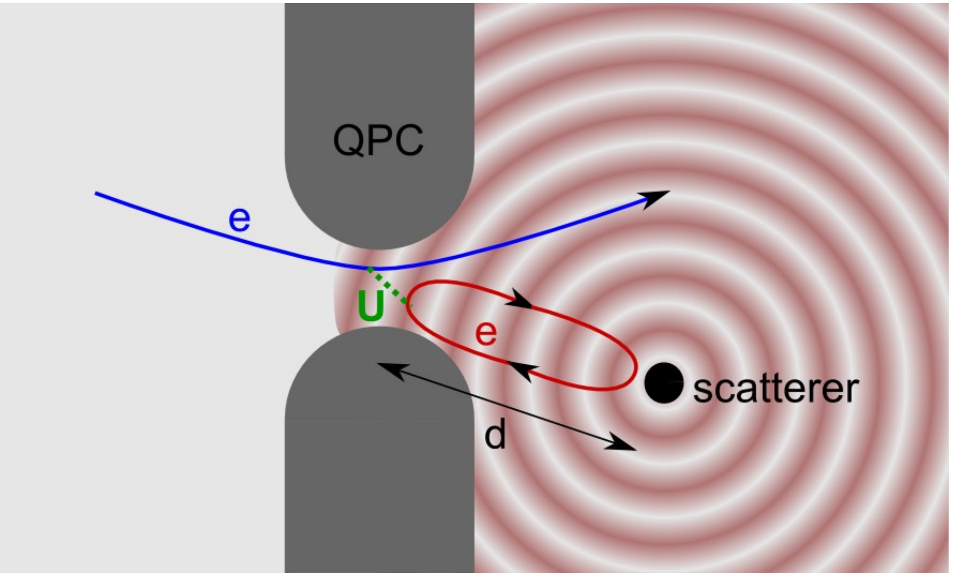
4 – Interferometers : motivation

How to use interferometers to probe electron interactions in the QPC ?

Proposal by J.L. Pichard, D. Weinmann, R. Jalabert

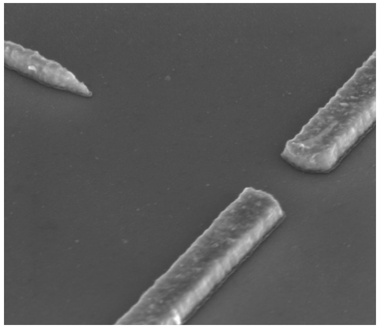
Freyn *et al.*, Phys. Rev. Lett. **100**, 226802 (2008)
Weinmann *et al.*, Eur. Phys. J. B **66**, 239 (2008)

In addition to single-particle interferences, Friedel oscillations modulates the density in the QPC, and thus modulates electron transmission by Coulomb interactions. Both effects have the same periodicity, but different spatial dependence.

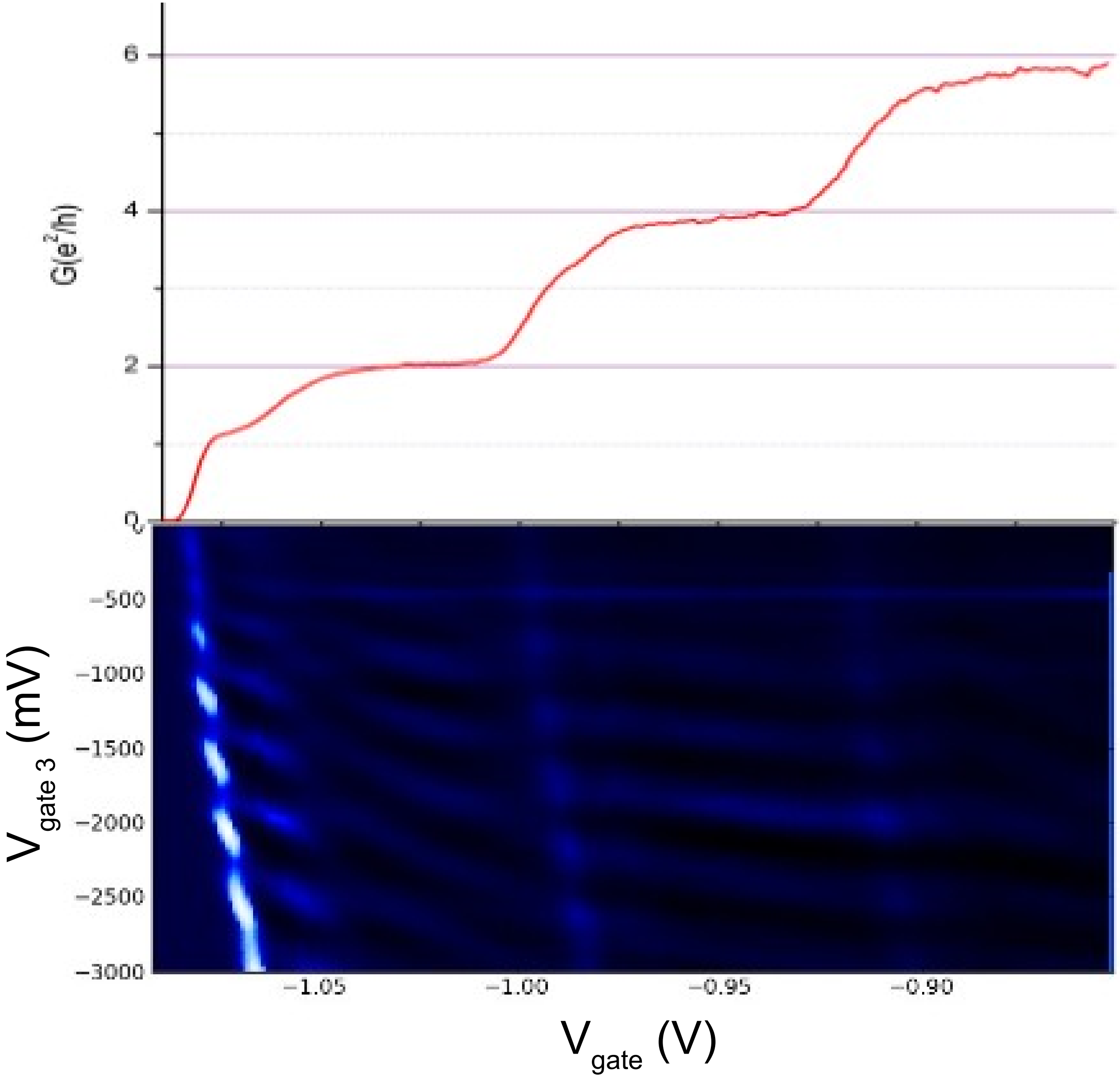


4 – Interferometers : results

1) Surface gate :

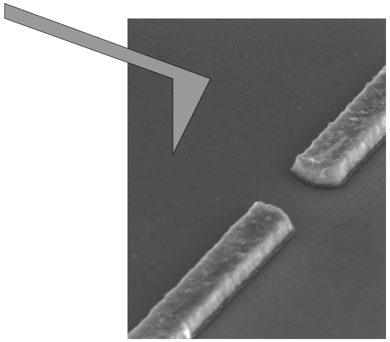


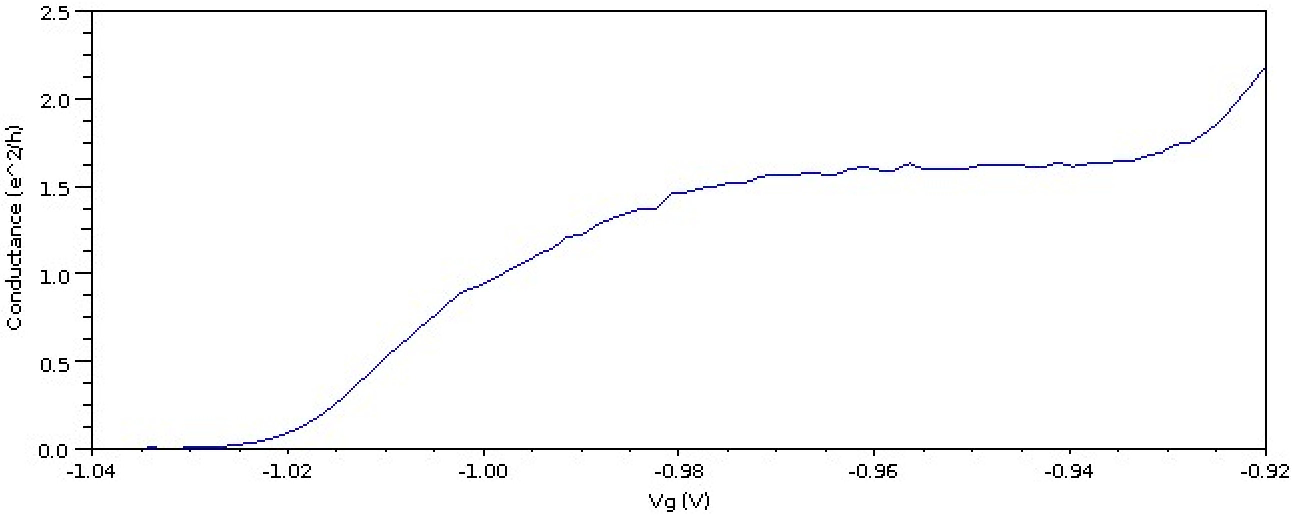
signal = dG/dV_{gate3}
(trans-conductance)



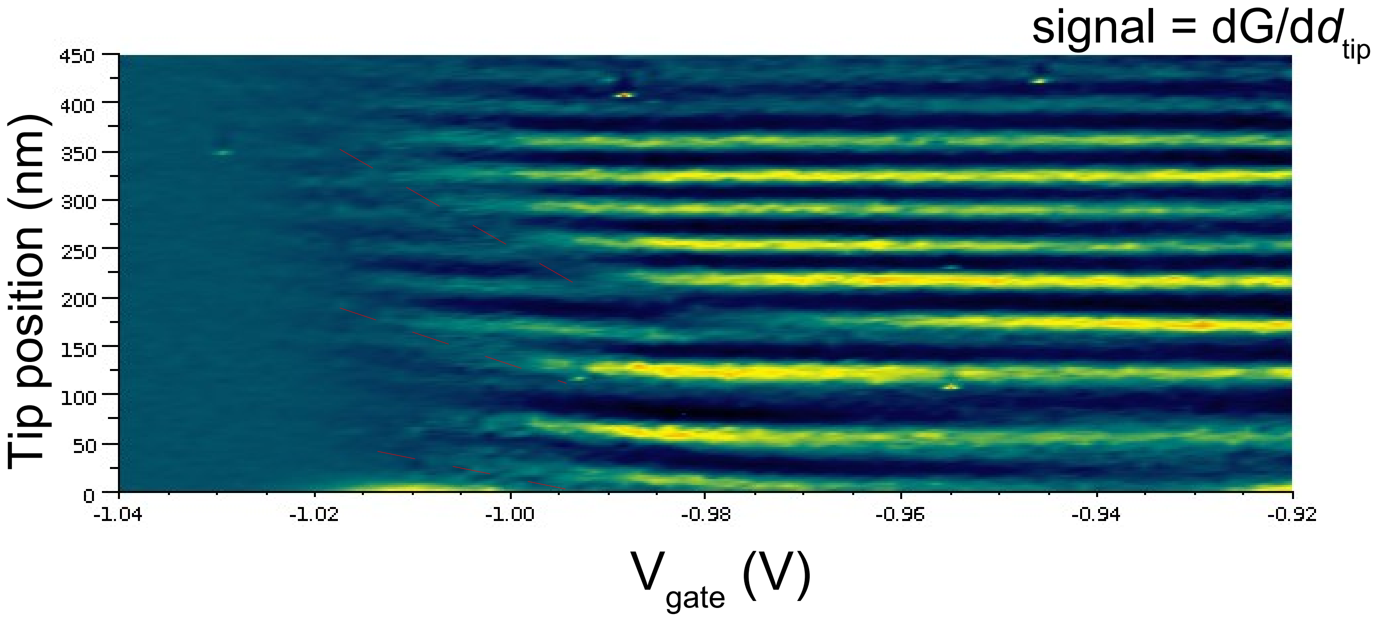
4 – Interferometers : results

2) Scanning gate :





Fringes below the plateau have a strange behavior : work still in progress...

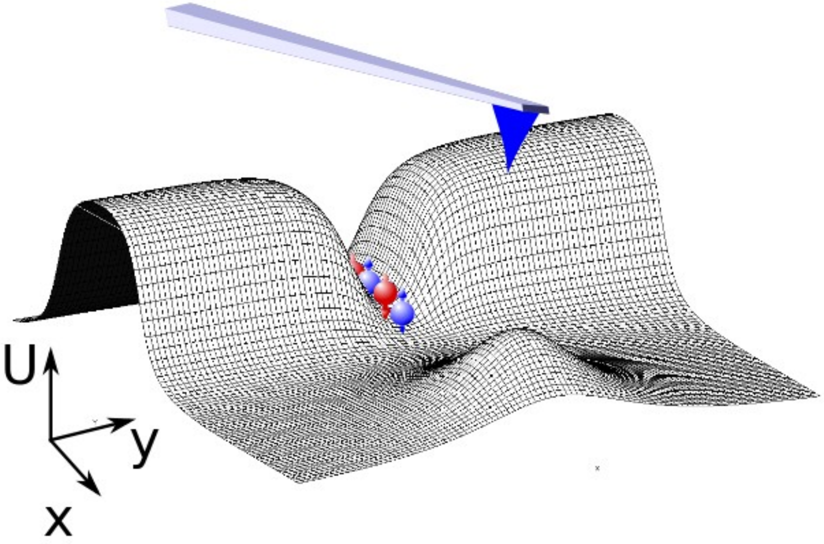


Conclusion

Scanning Gate Microscopy is a versatile tool to probe electrons in 2DEG nanostructures.

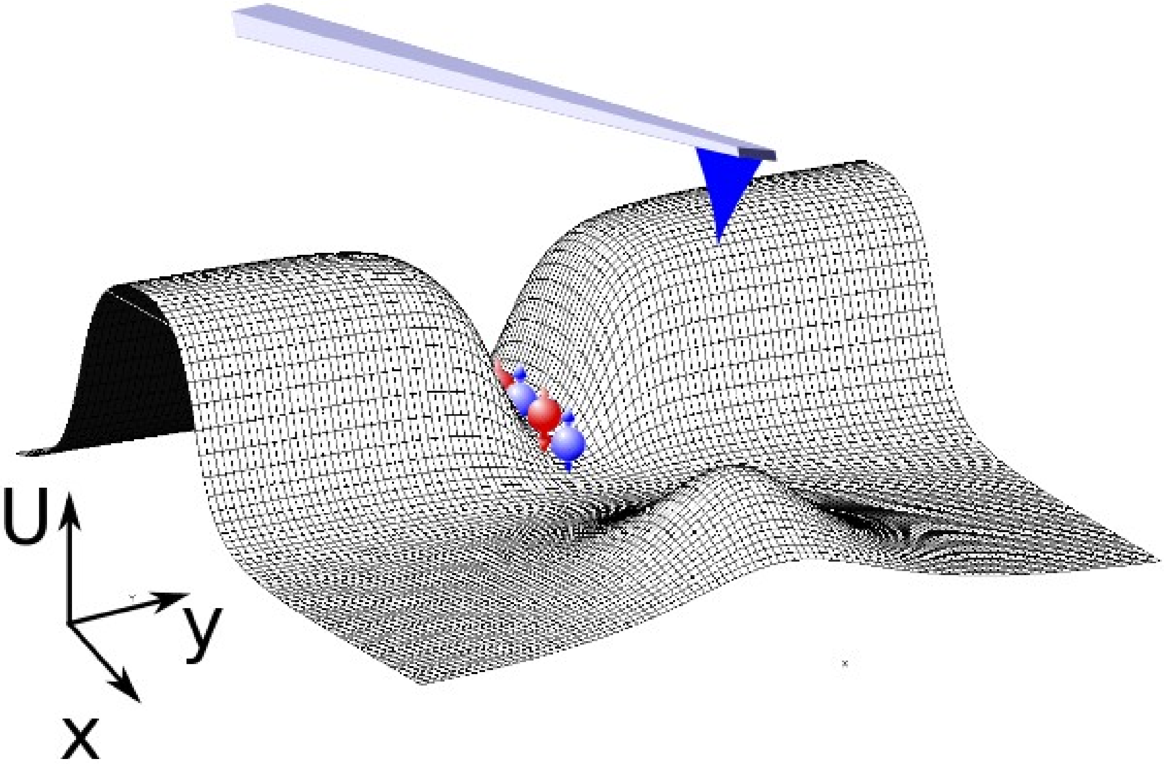
Although one of the most basic device, the quantum point contact
is a very nice platform to study many-body physics.

The 0.7 and zero-bias anomalies may result from an interplay
between Wigner crystallization and Kondo screening.



Preprint available on arXiv:1307.8328

Thank you for your attention !



Preprint available on arXiv:1307.8328