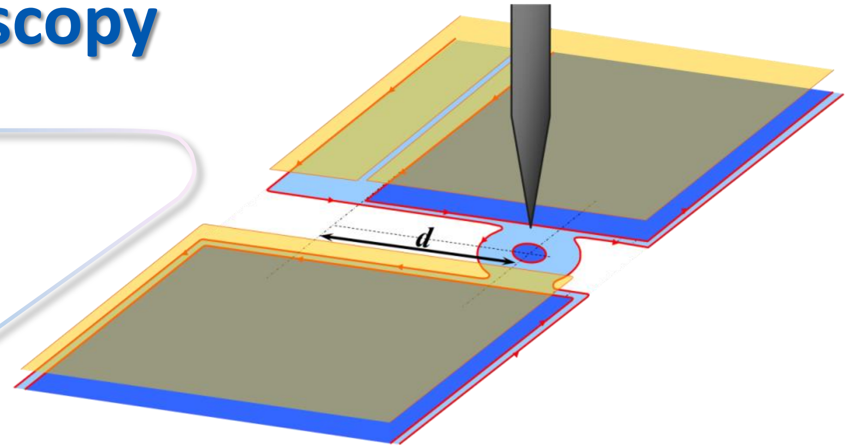
Exploring the physics of one-dimensional systems by scanning gate microscopy



Stefan Heun

NEST, Istituto Nanoscienze-CNR and Scuola Normale Superiore, Pisa, Italy

Coworkers

NEST, Pisa, Italy:

Experiment:
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Lucia Sorba
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Fabio Taddei
Vittorio Giovannetti
Rosario Fazio

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Giorgio Biasiol

Princeton University, USA:
Loren N. Pfeiffer
Ken W. West

ETH Zurich, Switzerland:
Christian Reichl
Werner Wegscheider

Outline

- Basics of Scanning Gate Microscopy (SGM)
- Quantum Point Contact w/o magnetic field
- QPC in the quantum Hall regime
- Edge channel equilibration

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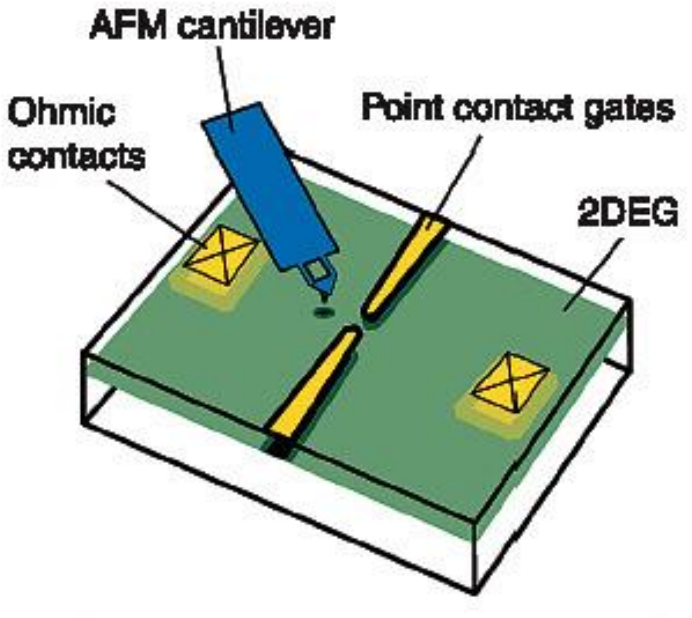
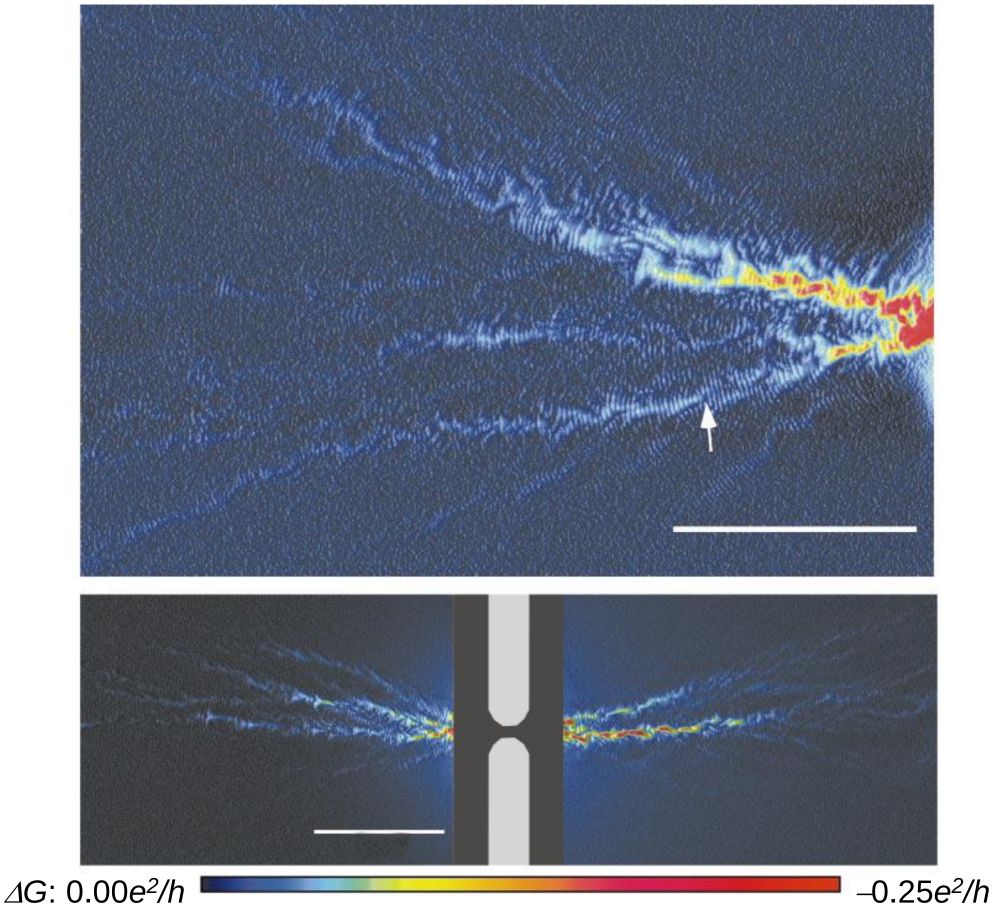
Scanning Gate Microscopy

- AFM with conductive tip
- Tip at negatively bias (local gate - locally depletes the 2DEG), no current flows
- SGM performed in constant height mode (10-50 nm above surface), no strain



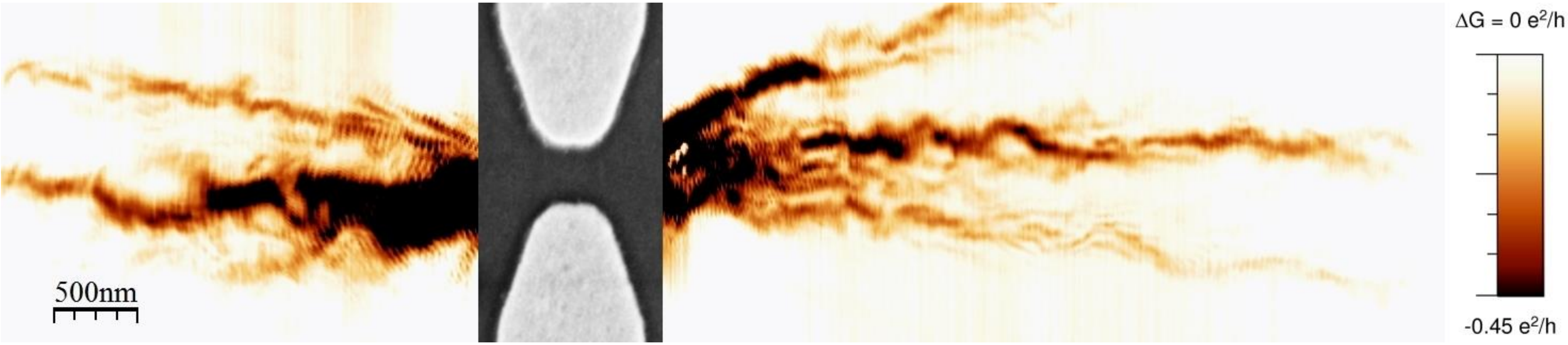
M. A. Topinka et al.: Science **289** (2000) 2323.

Coherent branched flow of electrons



M. A. Topinka et al., Nature 410 (2001) 183.

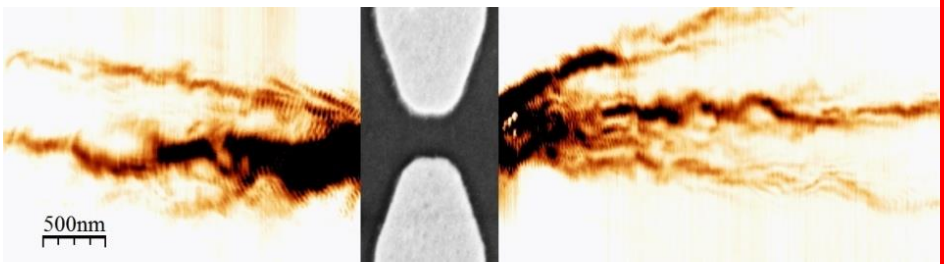
Branched flow of electrons

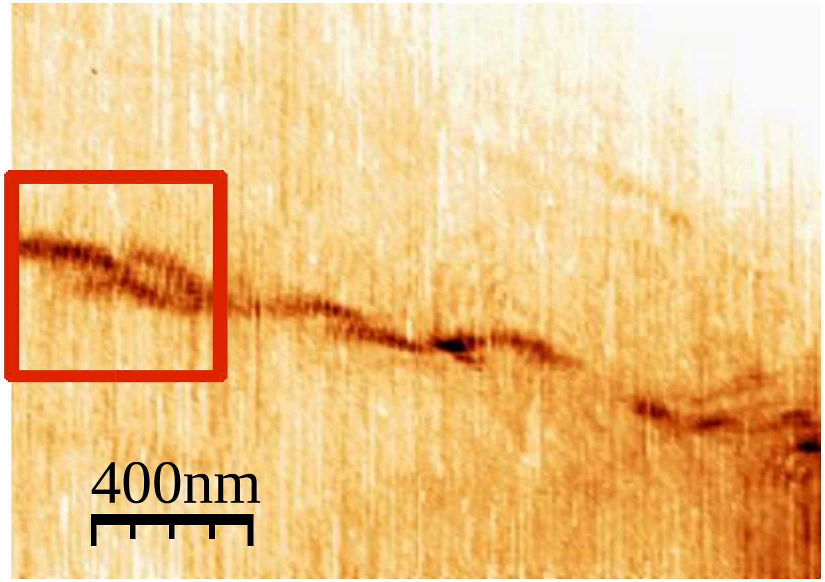


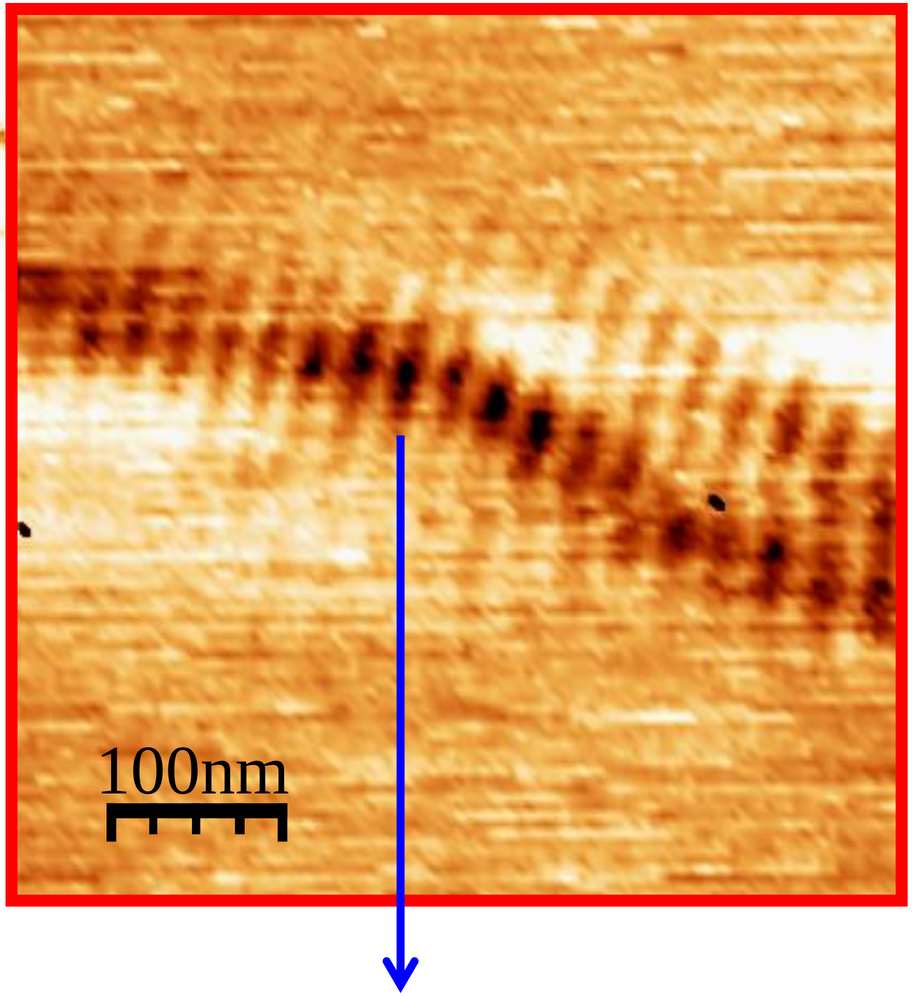
- No magnetic field (B = 0)
- QPC conductance G = 6 e^2/h (3rd plateau)
- Tip voltage V_{tip} = -5 V, height h_{tip} = 10 nm
- see also M. A. Topinka et al., Nature **410** (2001) 183.

N. Paradiso et al., Physica E **42** (2010) 1038.

Appendix: branched flow and interference fringes







- QPC conductance G = 6 e^2/h (3^{rd} plateau)
- Tip voltage V_{tip} = -5 V, height h_{tip} = 10 nm
- *see also M. A. Topinka et al., Nature* ***410*** *(2001) 183.*

Fringe periodicity: $\lambda_F/2$=20 nm

N. Paradiso *et al., Physica E 42 (2010) 1038.*

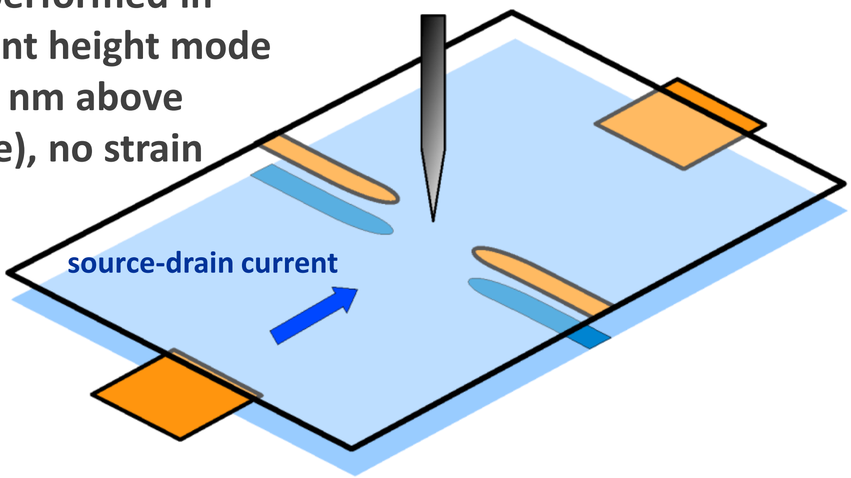
The SGM @NEST lab in Pisa

Setup:

- **AFM non-optical detection scheme (tuning fork)**
- **With vibration and noise isolation system**
- **^{3}He insert (cold finger base temp. :300 mK)**
- **9 T cryomagnet**

Tip at negative bias (moveable gate locally depletes the 2DEG)

SGM performed in constant height mode (10-50 nm above surface), no strain

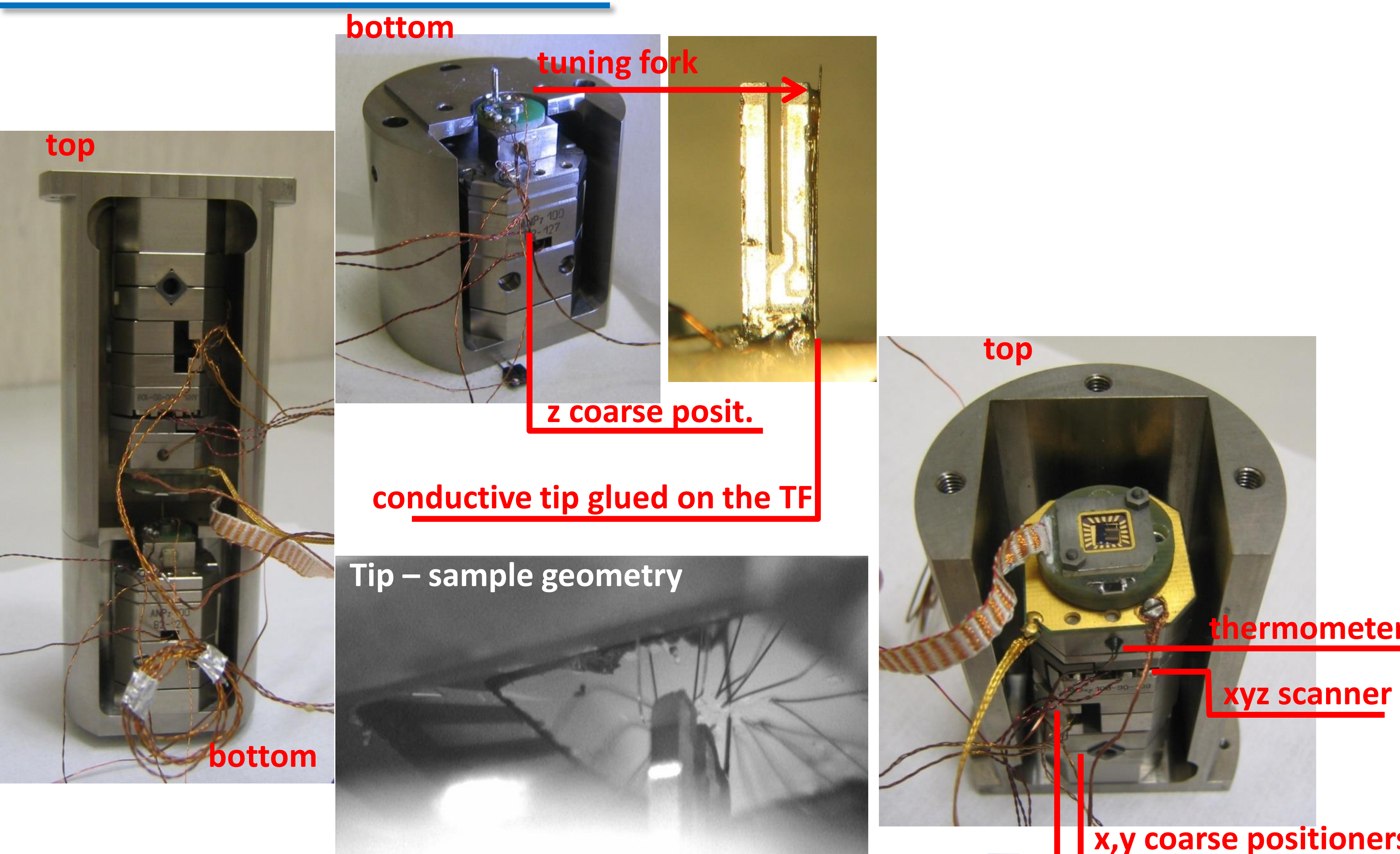


attocube systems
explore your nanoworld

Pioneering work by:

M. A. Topinka et al.: Science ***289*** *(2000) 2323.*

Tuning fork and sample holder



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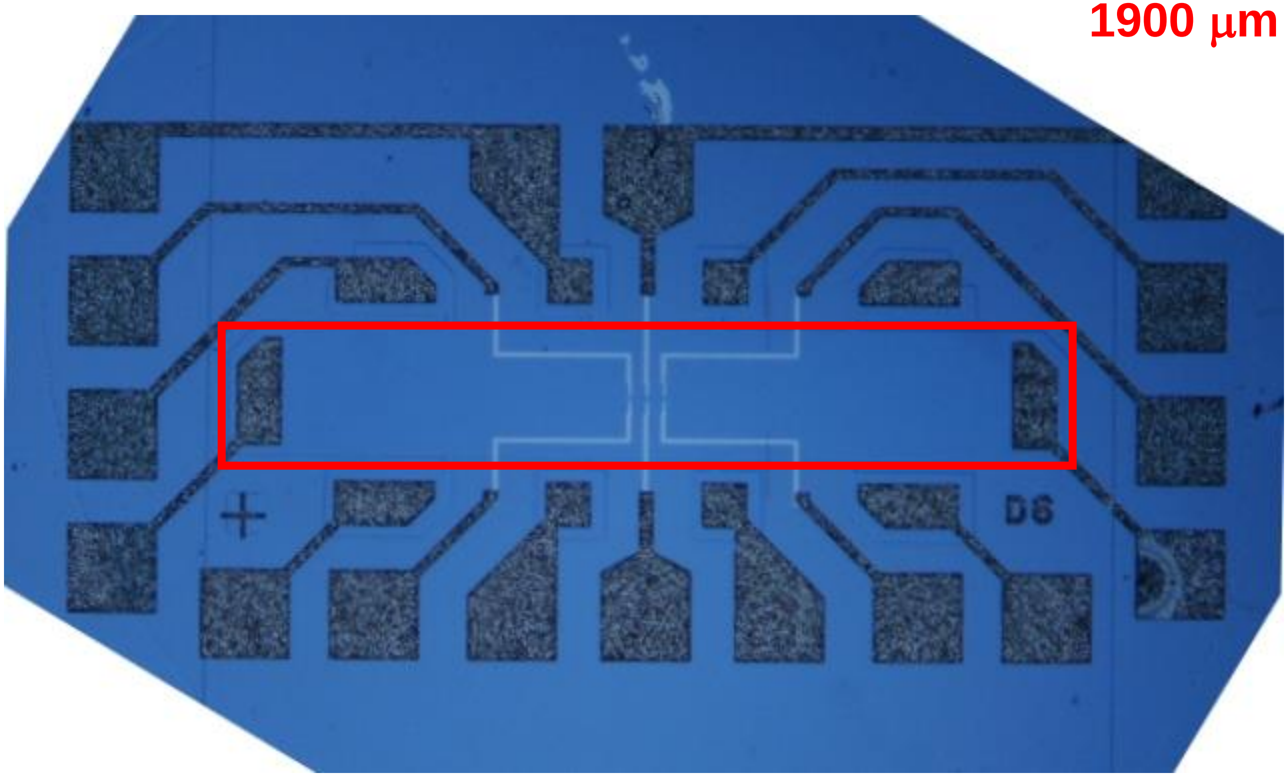
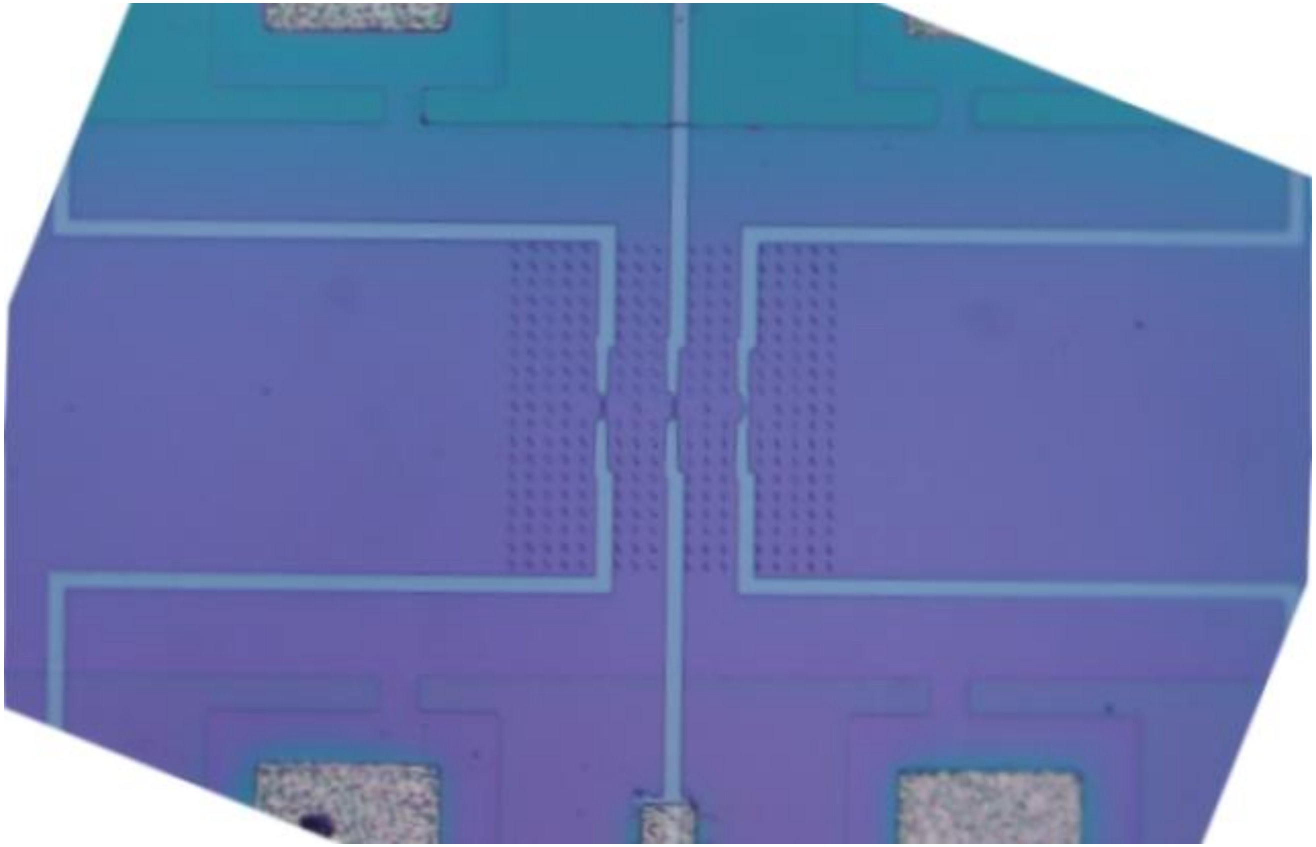
Hall-bar samples



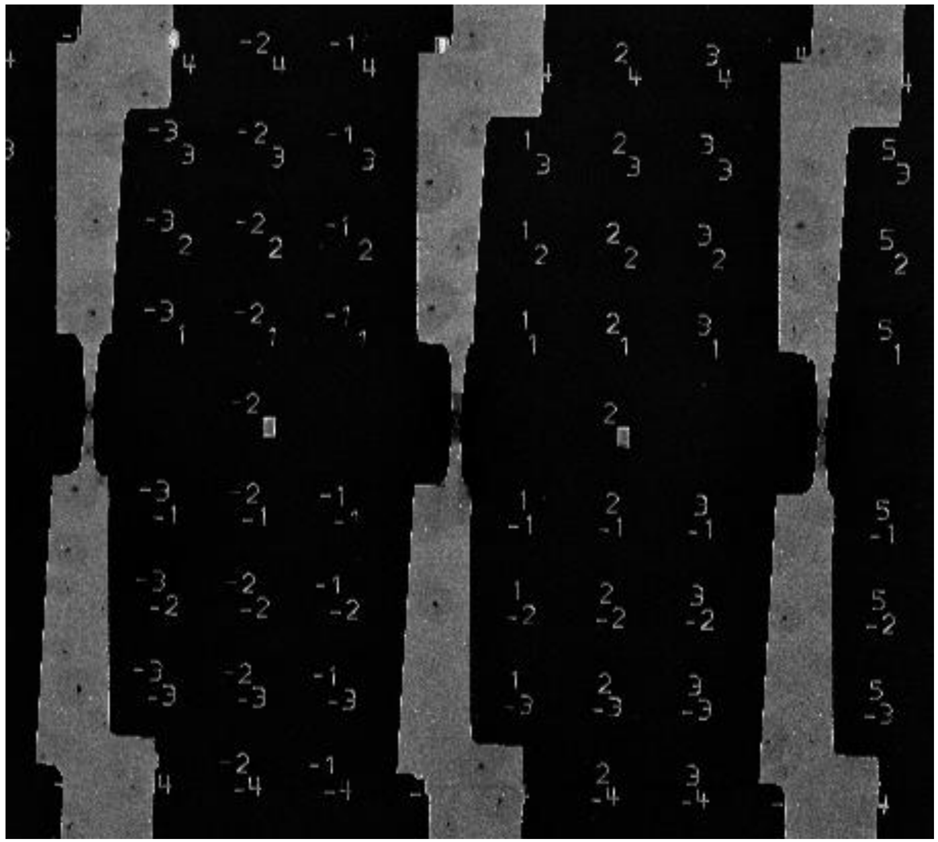
N. Paradiso et al., Physica E **42** (2010) 1038.

Hall-bar samples



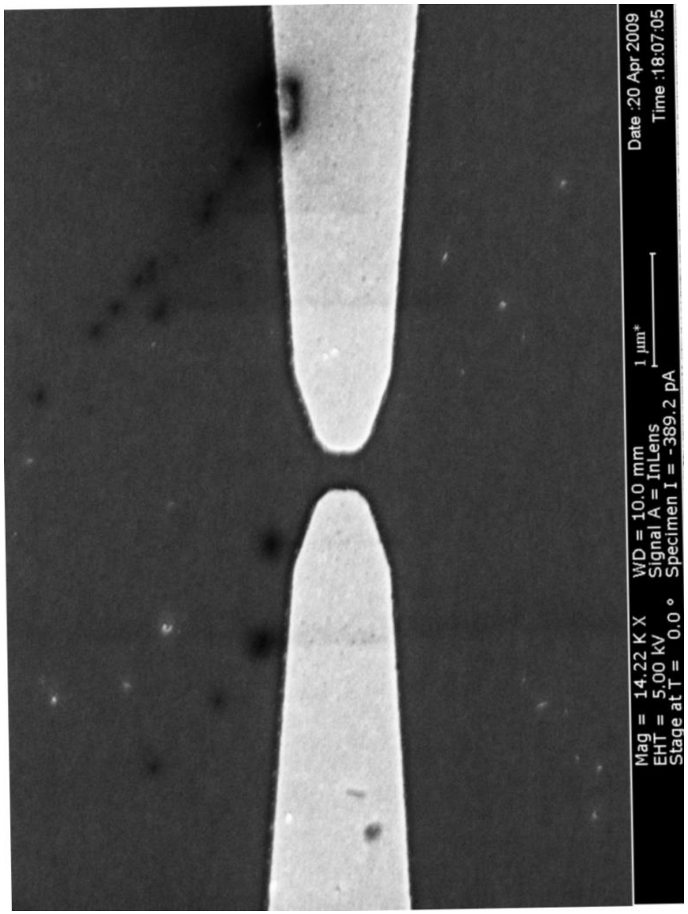
N. Paradiso et al., Physica E **42** (2010) 1038.

Hall-bar samples



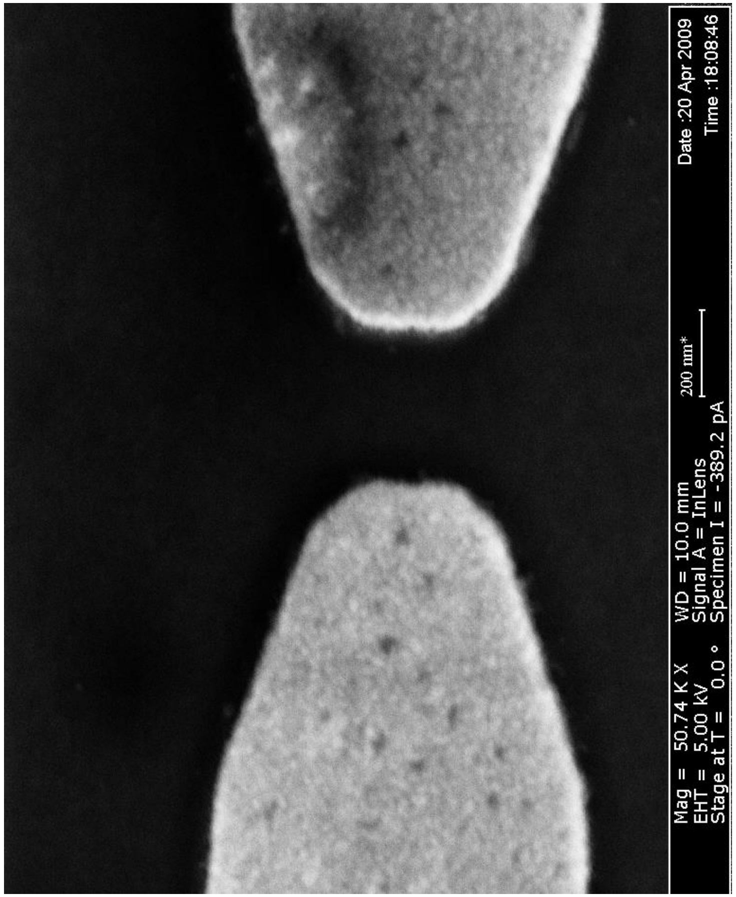
N. Paradiso et al., Physica E **42** (2010) 1038.

Hall-bar samples



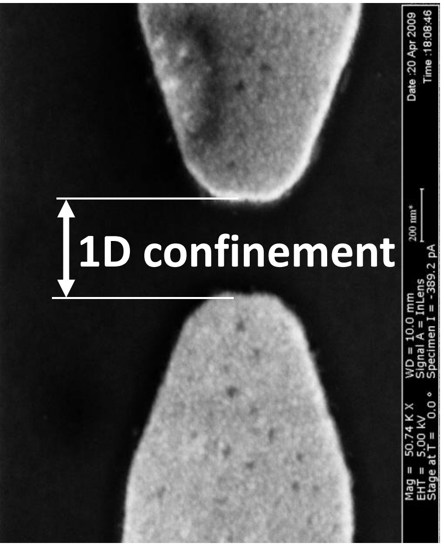
N. Paradiso et al., Physica E **42** (2010) 1038.

Hall-bar samples

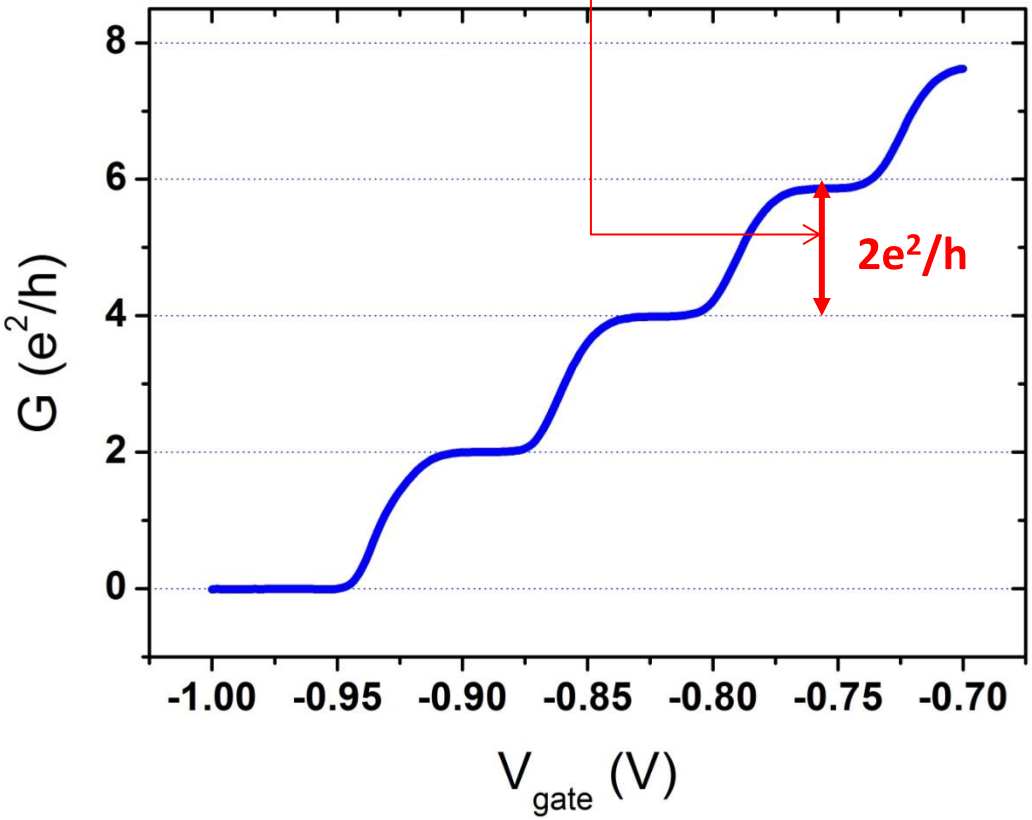


N. Paradiso et al., Physica E **42** (2010) 1038.

Conductance quantization in QPCs

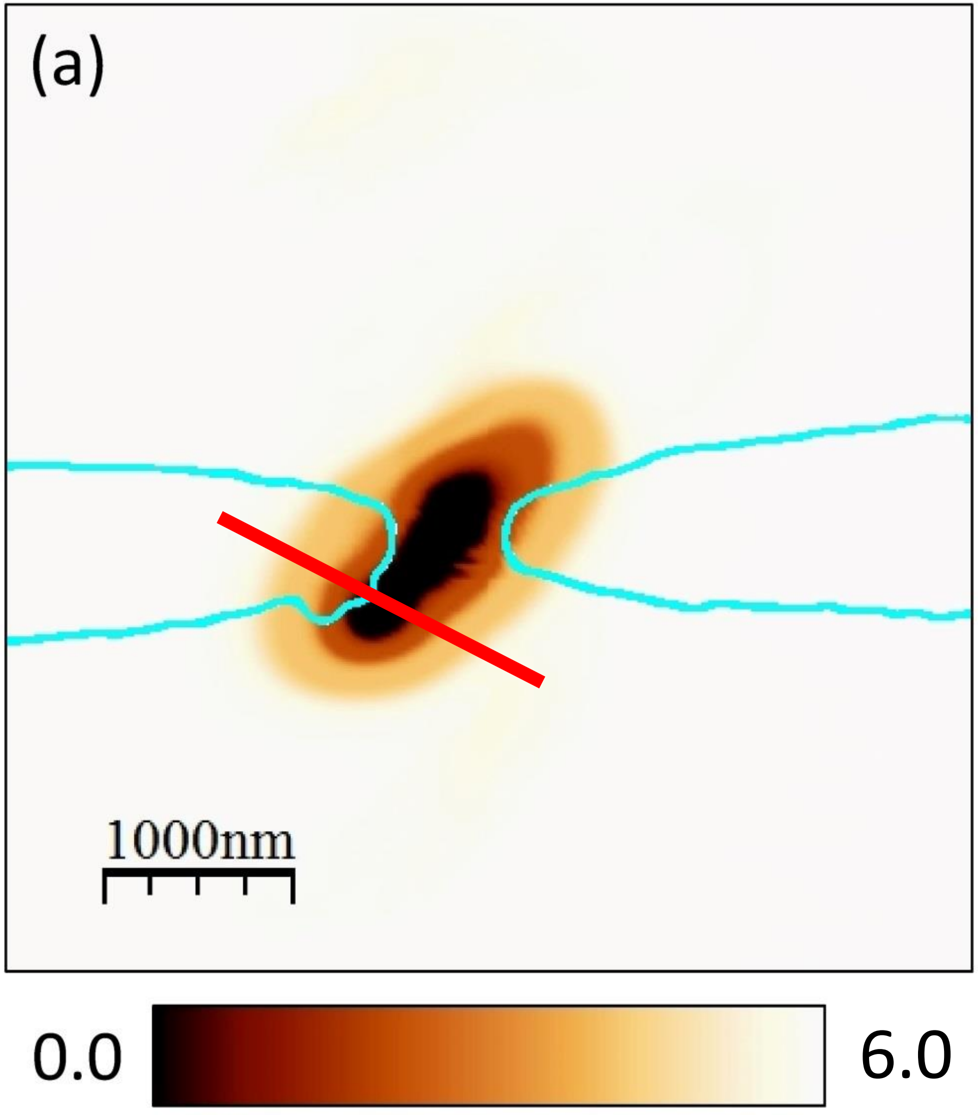


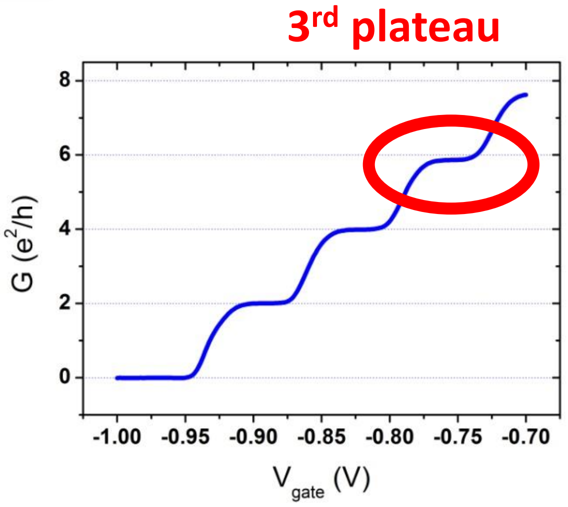
In 1D systems the current is carried by a finite number of modes (arising from confined subbands) . Each mode contributes two quantum of conductance.

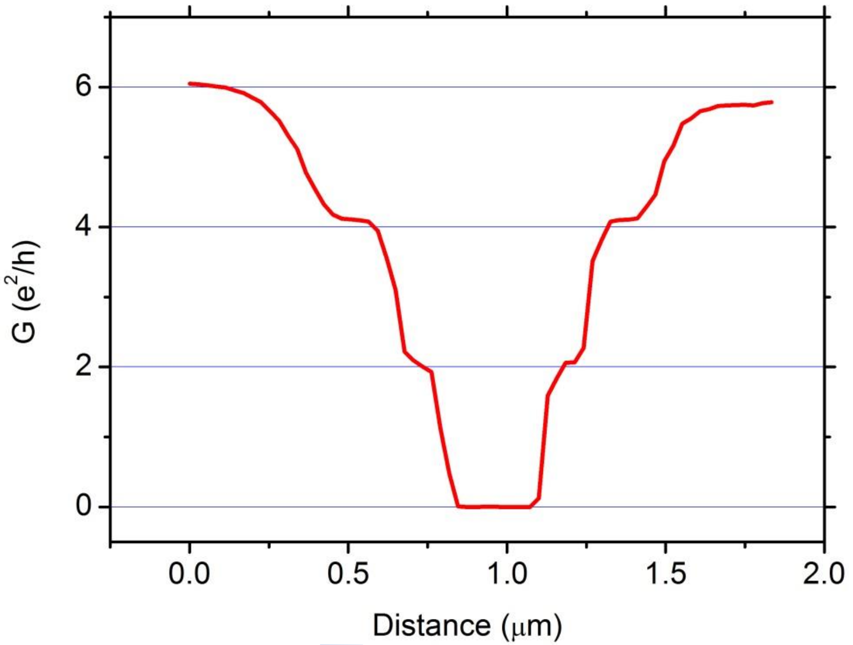


First we fix the mode number (QPC setpoint), then we start scanning the biased tip at a fixed height.

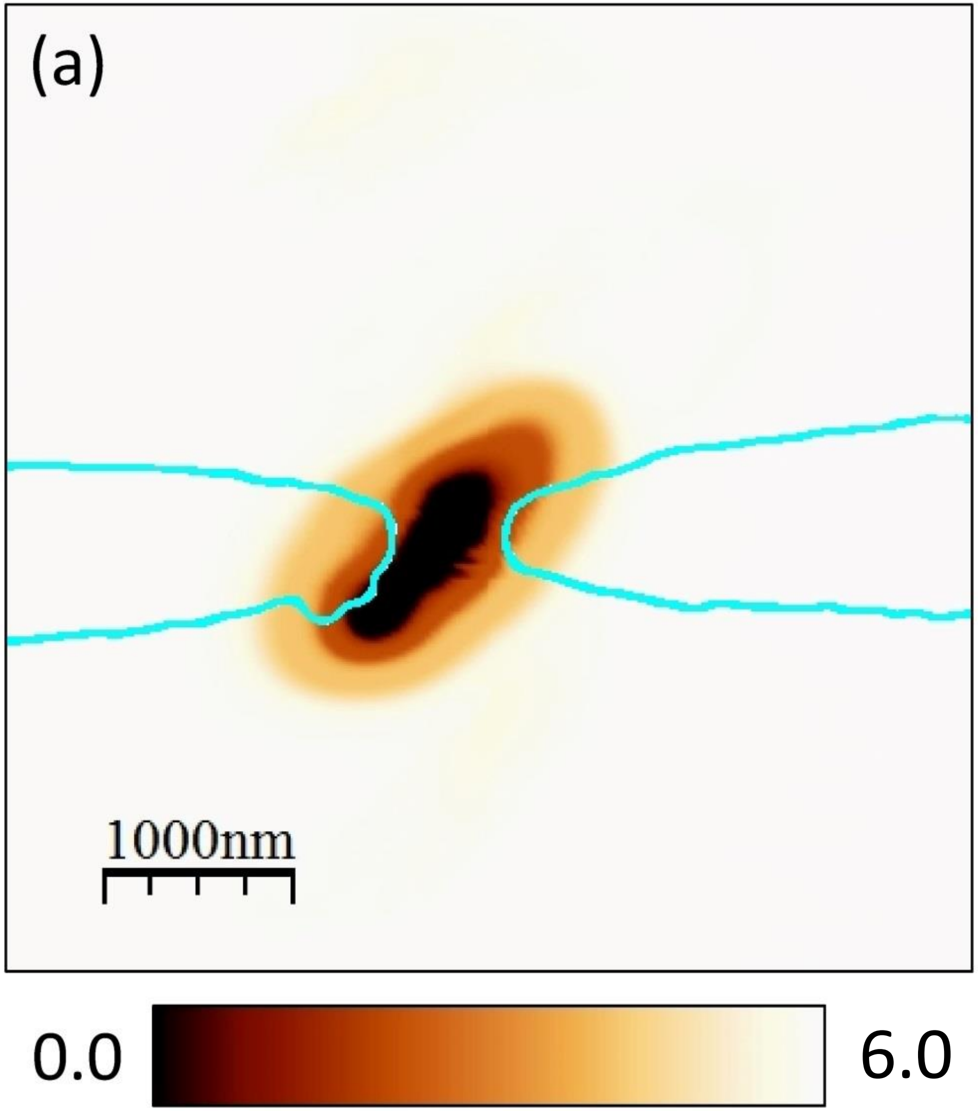
QPC at 3rd plateau

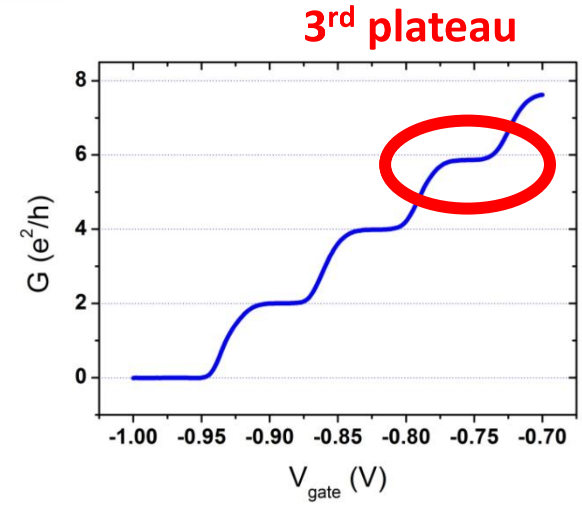


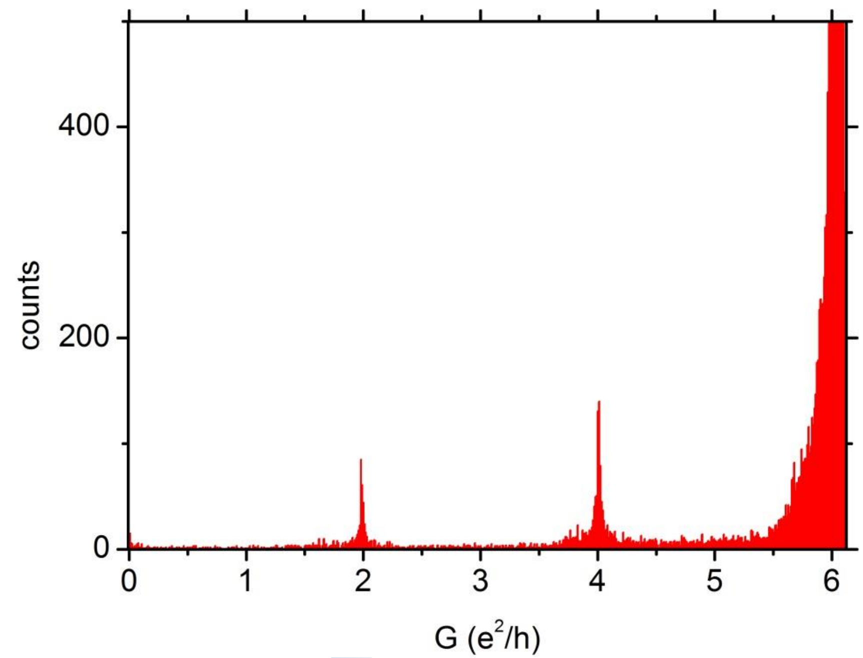




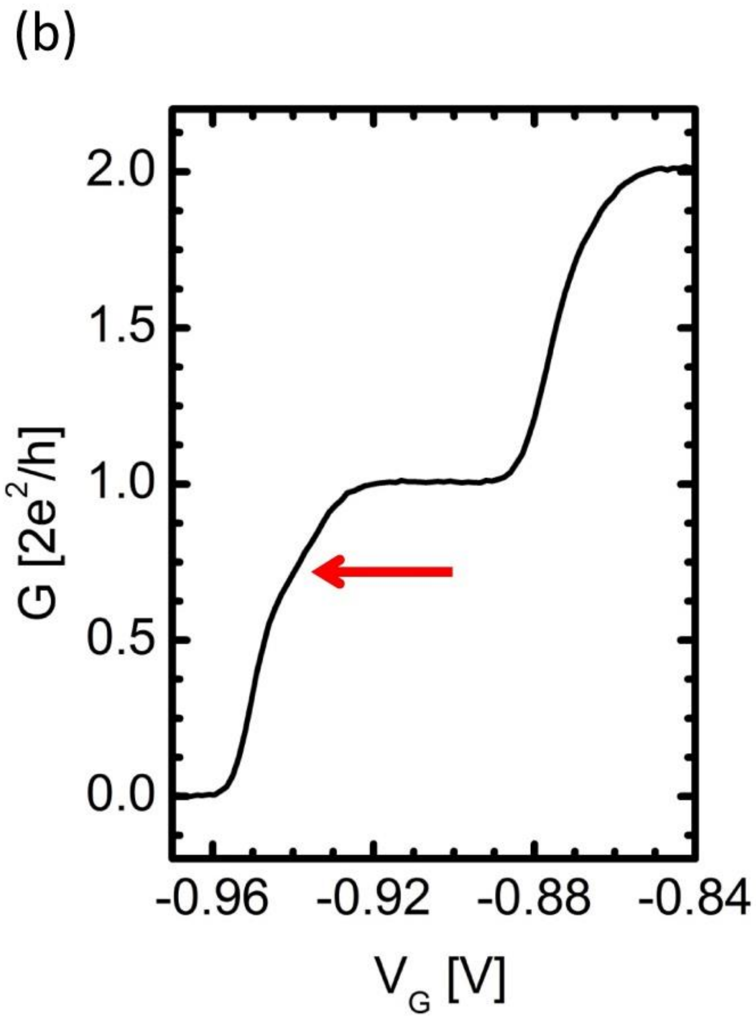
Histogram analysis







0.7 Anomaly



Origin still debated

Intrinsic or extrinsic?

- Quantum interference
- Spin polarization
- Kondo effect
- Wigner crystallization

A. Iagallo *et al.*, arXiv:1311.6303

0.7 Anomaly

d

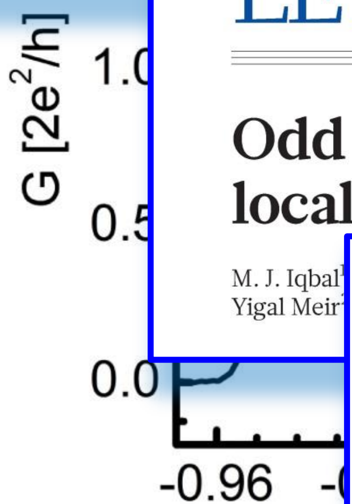
sic?

LETTER

doi:10.1038/nature12421

Microscopic origin of the '0.7-anomaly' in quantum point contacts

Florian Bauer[1]
Werner Wegsc



LETTER

doi:10.1038/nature12491

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

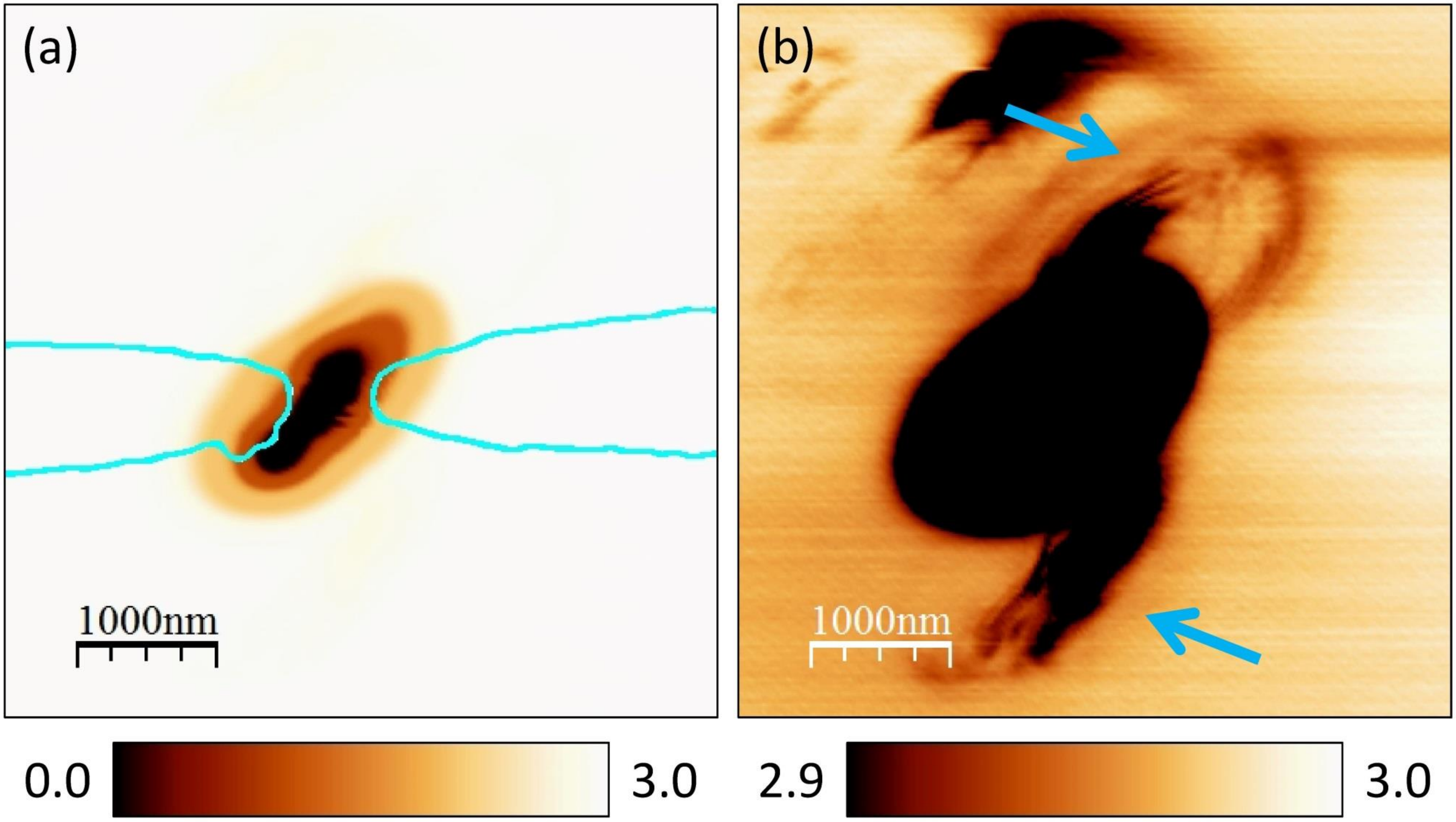
M. J. Iqbal[1]
Yigal Meir[2]

Scanning gate control over conductance anomalies in a quantum point contact

B. Brun[1], F. Martins[2], S. Faniel[2], B. Hackens[2], A. Cavanna[4], C. Ulysse[4], A. Ouerghi[4], U. Gennser[4], D. Mailly[4], S. Huant[1], V. Bayot[1,2], M. Sanquer[3] and H. Sellier[1*]
[1] *Institut Néel, CNRS et Université Joseph Fourier, 25 rue des Martyrs, F-38042 Grenoble, France*
[2] *IMCN/NAPS, Université catholique de Louvain, B-1348 Louvain-la-Neuve, Belgium*
[3] *SPSMS, UMR-E CEA / UJF-Grenoble 1, INAC, 17 rue des Martyrs, F-38054 Grenoble, France*
[4] *Laboratoire de Photonique et de Nanostructures CNRS, Route de Nozay, F-91460 Marcoussis, France*
* *Electronic address: hermann.sellier@grenoble.cnrs.fr*
(Dated: August 1, 2013)

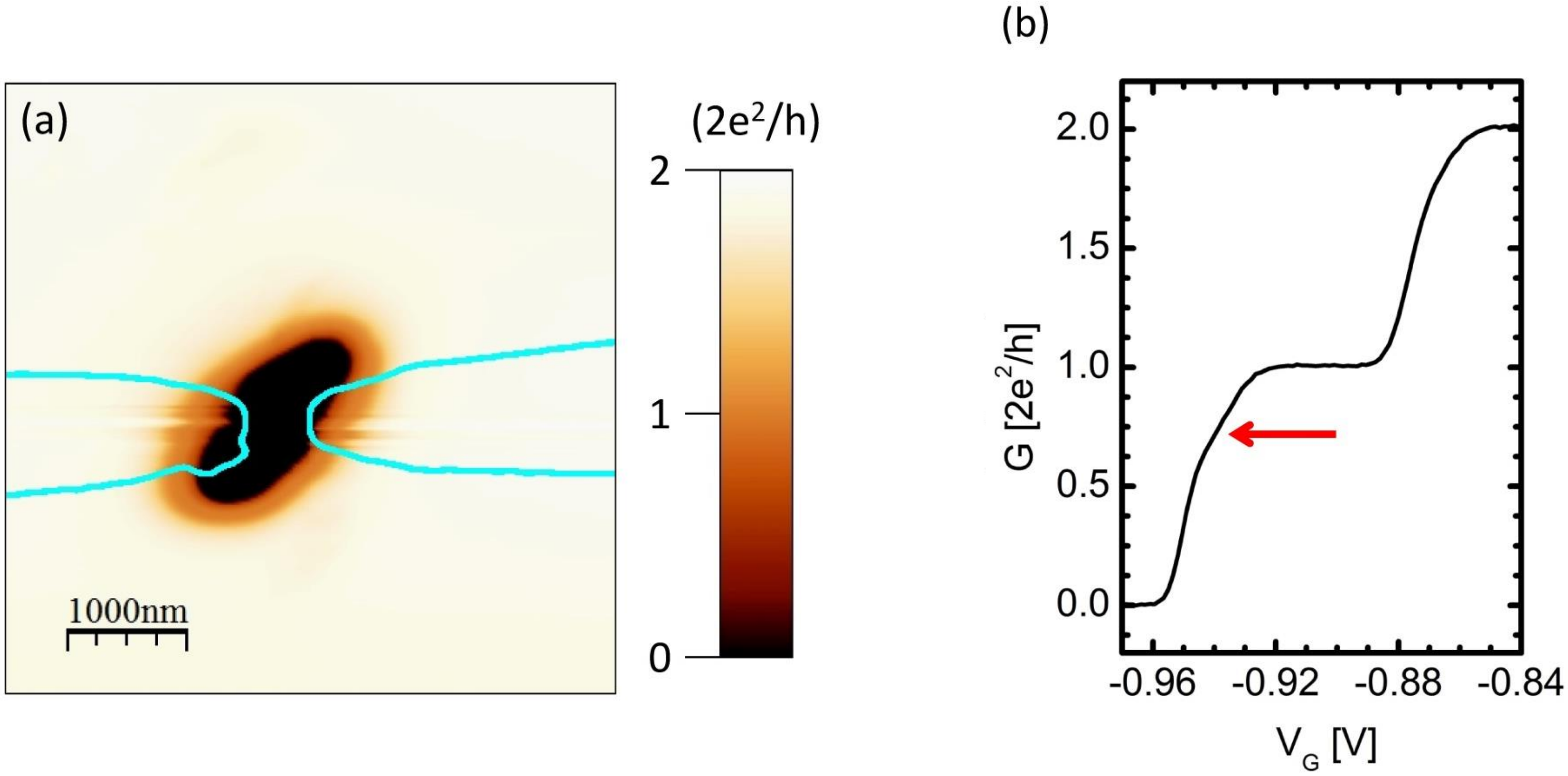
A. Iagallo *et al.*, arXiv:1311.6303

Device A: QPC with localized impurities



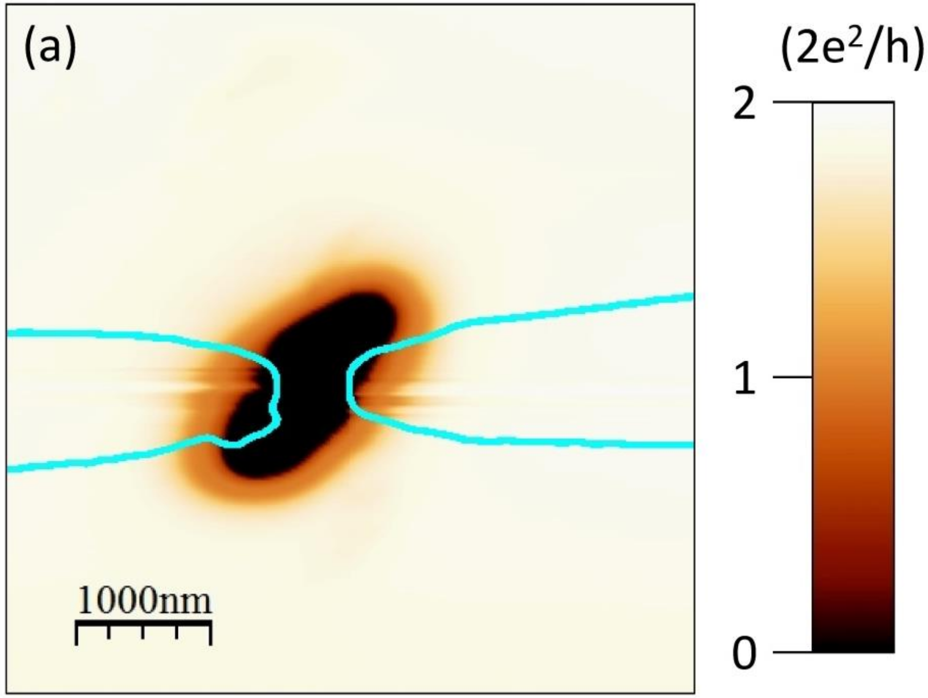
A. Iagallo *et al.,* arXiv:1311.6303

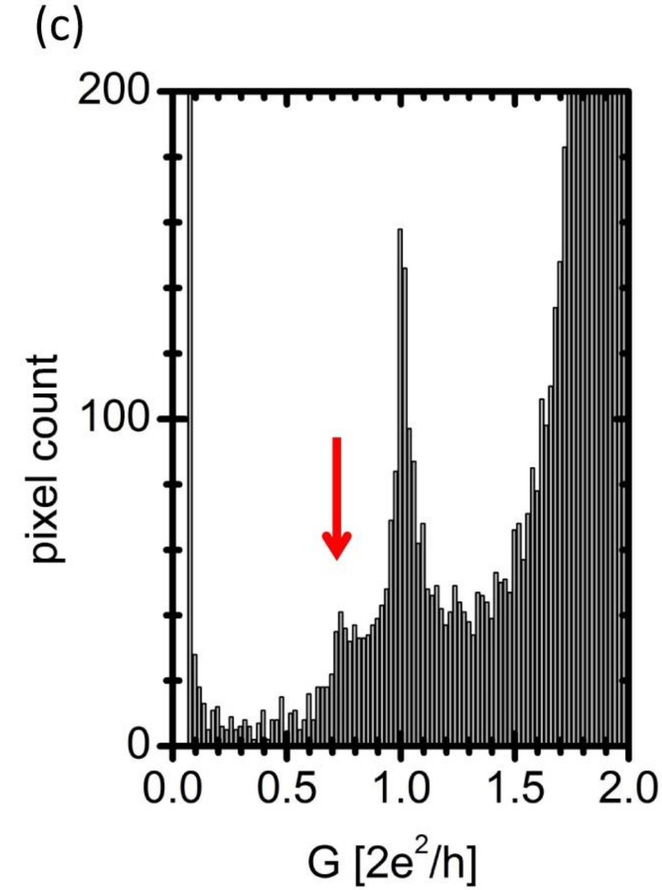
0.7 Anomaly in Device A



A. Iagallo *et al.*, arXiv:1311.6303

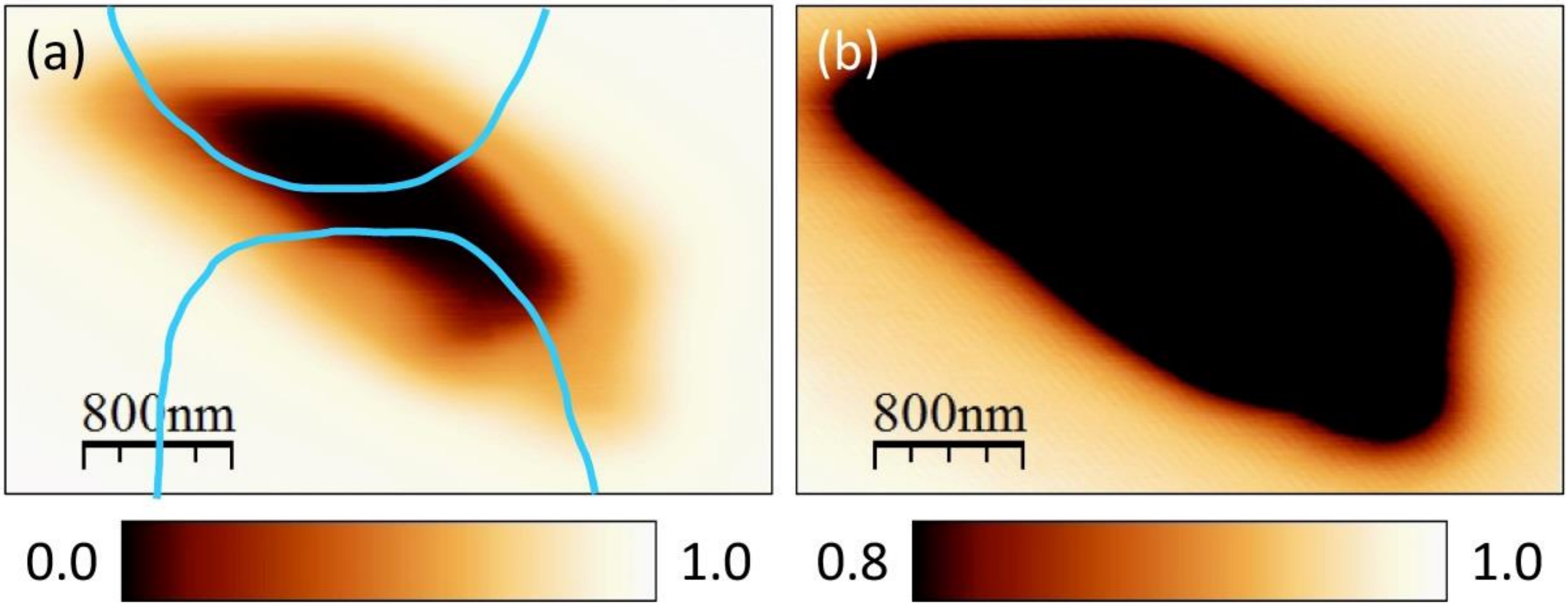
0.7 Anomaly in Device A





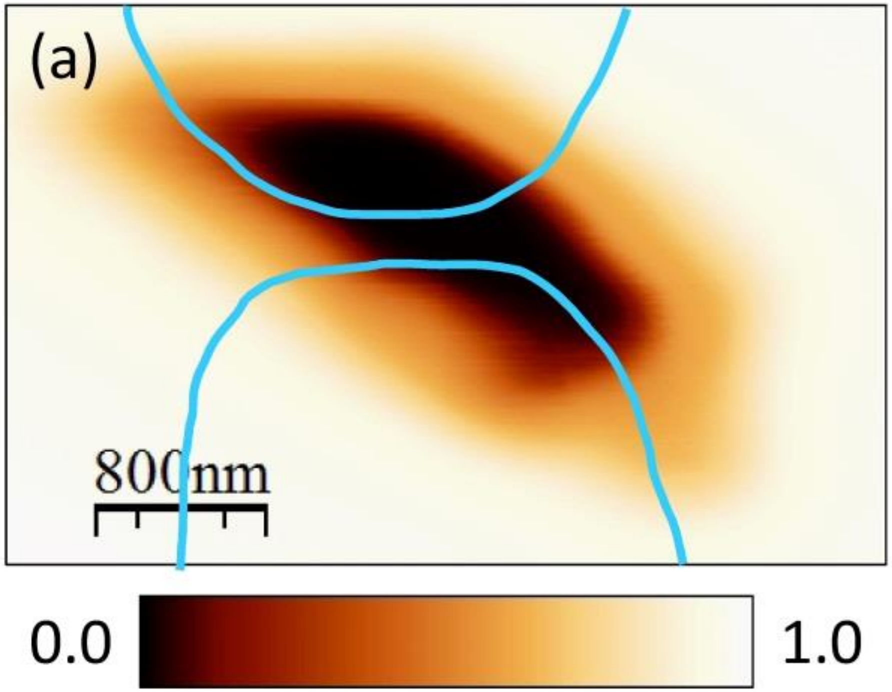
A. Iagallo *et al.,* arXiv:1311.6303

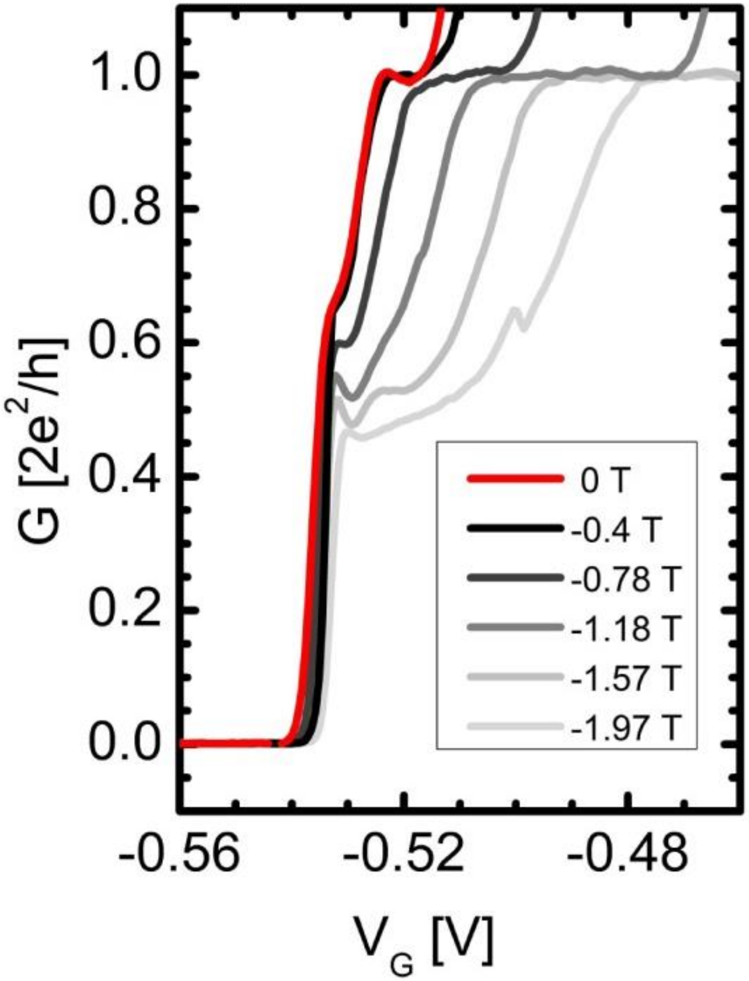
Device B: QPC without localized impurities



A. Iagallo *et al.*, arXiv:1311.6303

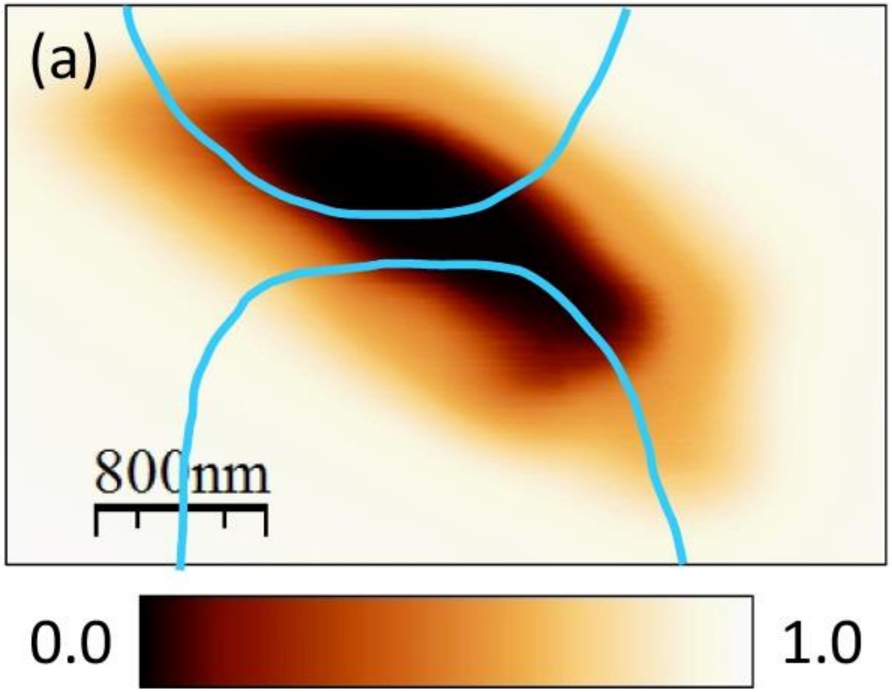
0.7 Anomaly in Device B

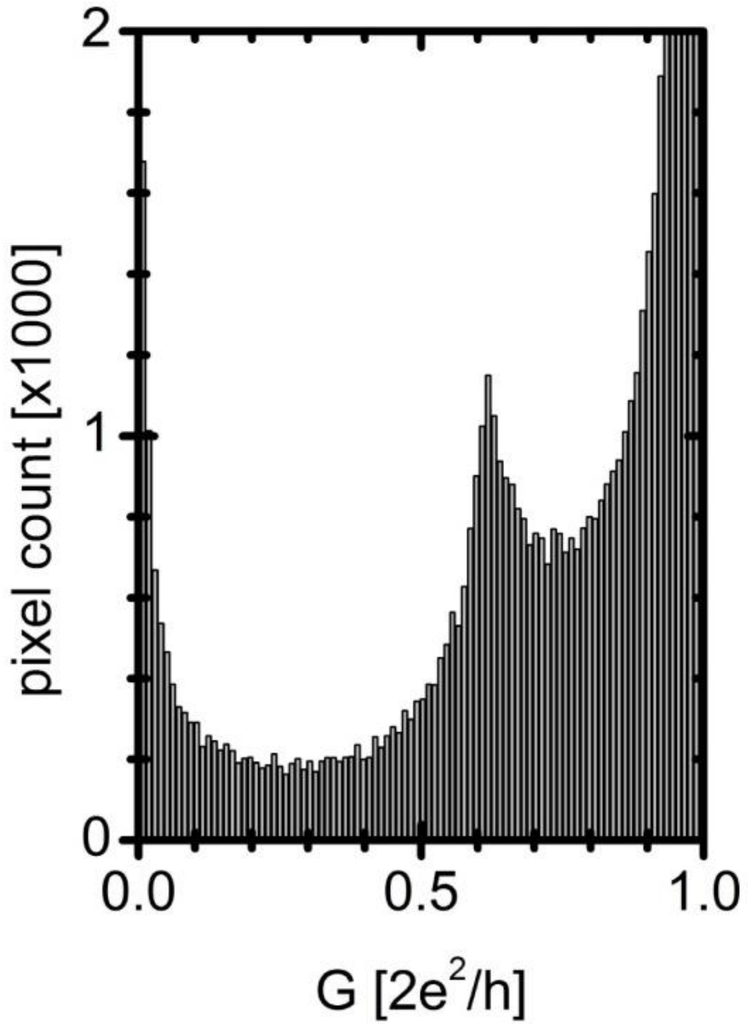




A. Iagallo *et al.*, arXiv:1311.6303

0.7 Anomaly in Device B





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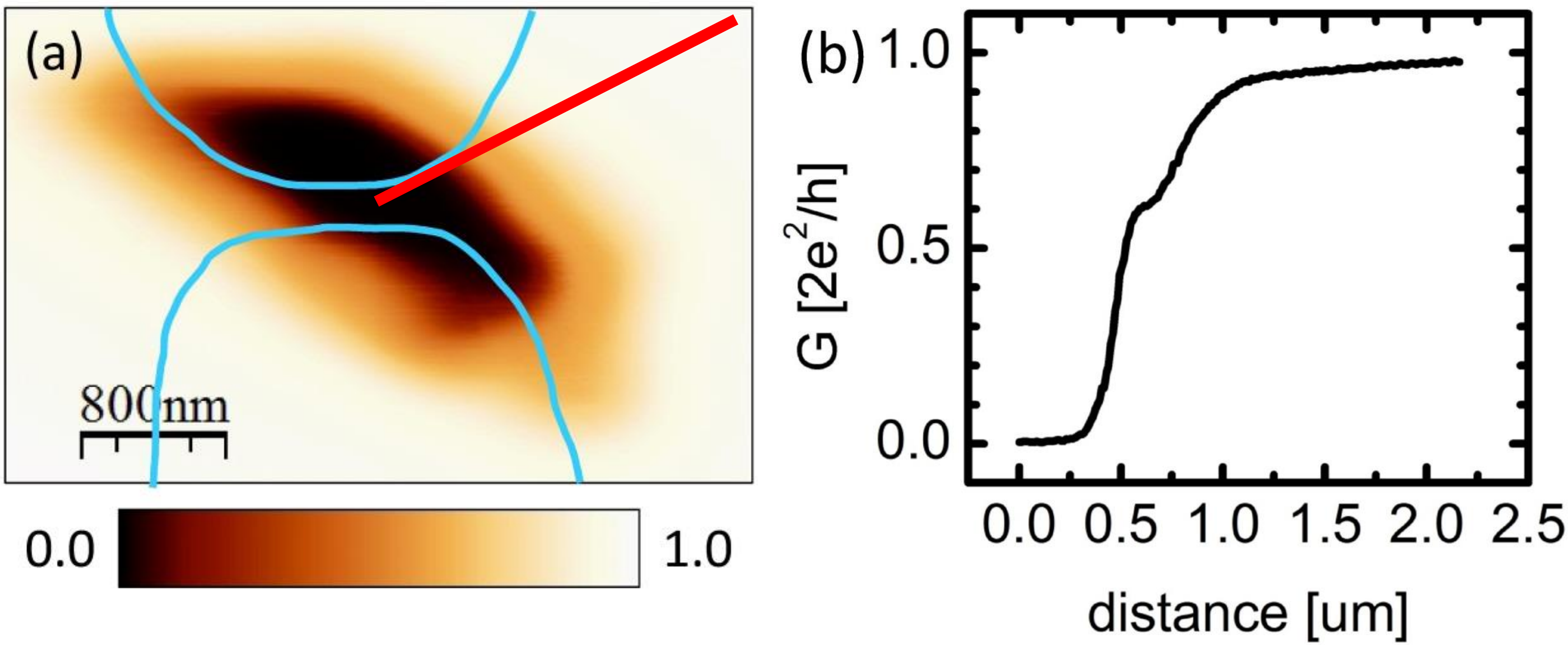

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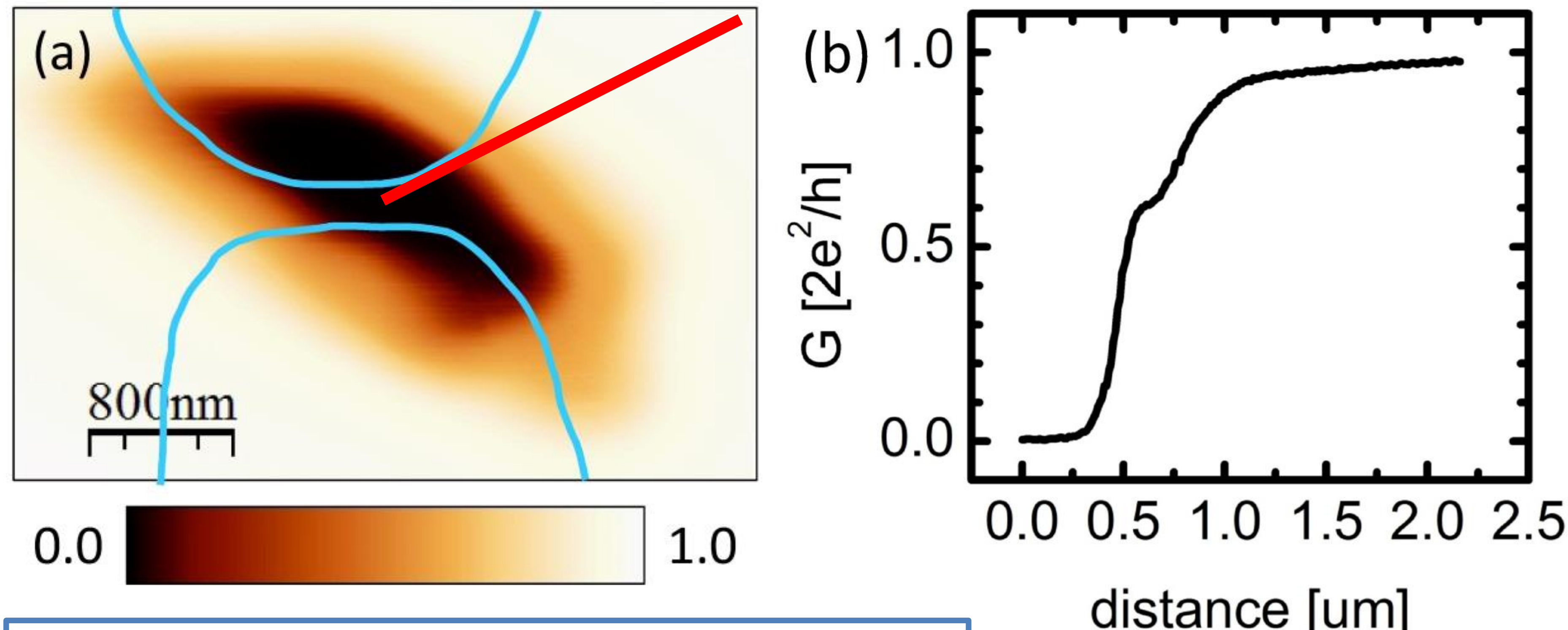
0.7 Anomaly in Device B



The 0.7 anomaly is observed irrespective of the presence of localized defects and is therefore a fundamental property

A. Iagallo *et al.*, arXiv:1311.6303

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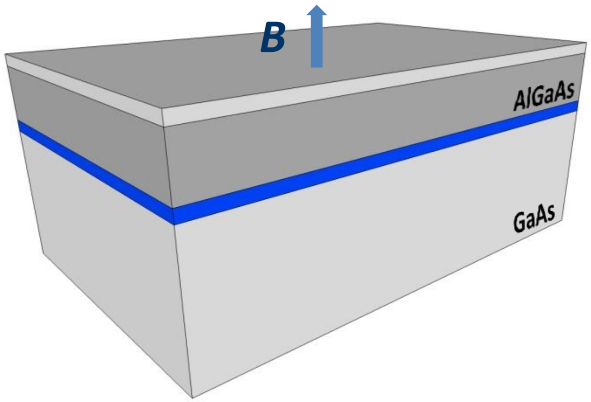
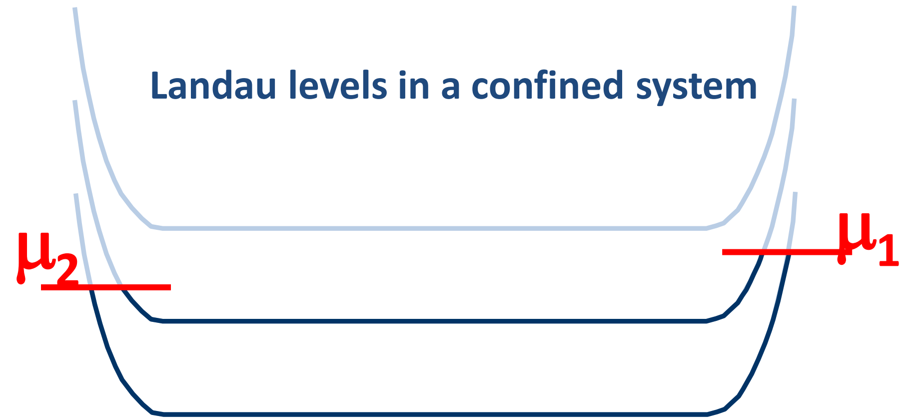
The non-interacting picture of the QH effect

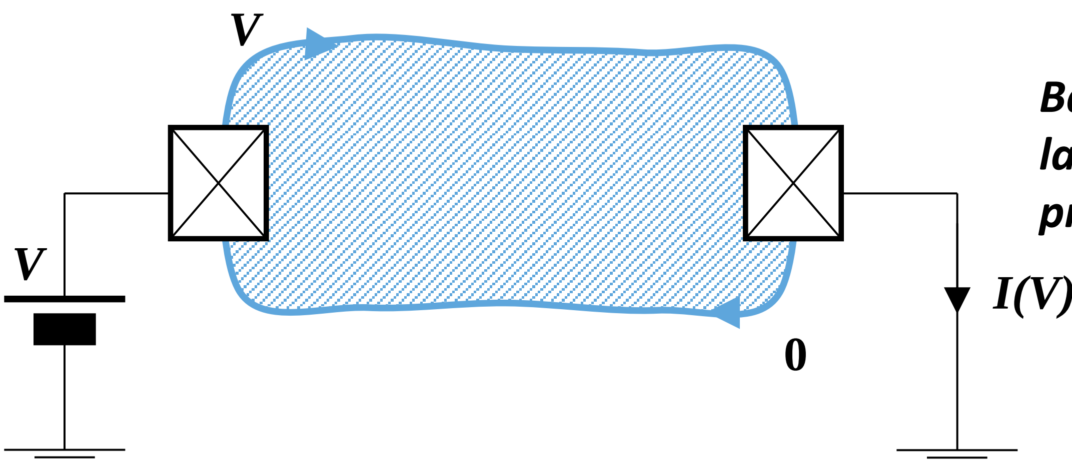


2DES
in high field



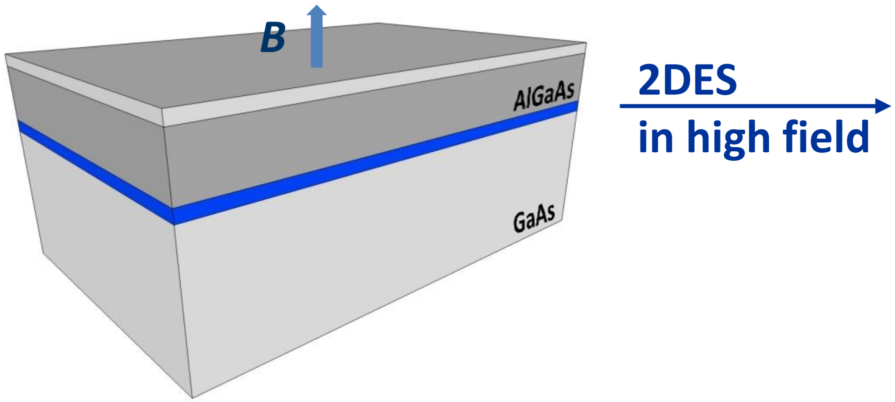
- Edge state picture:
  current is carried by chiral 1D channels

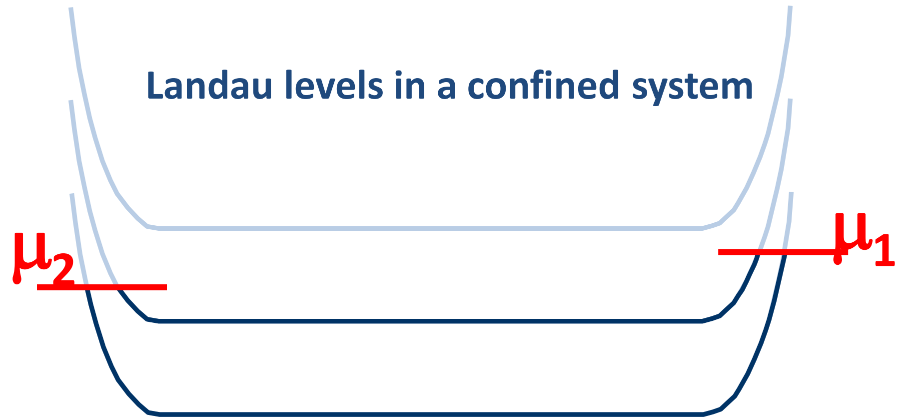
$$G \equiv \frac{dI}{dV} = \nu \frac{e^2}{h}$$



Backscattering is suppressed due to the large spatial separation between counter-propagating channels

The non-interacting picture of the QH effect





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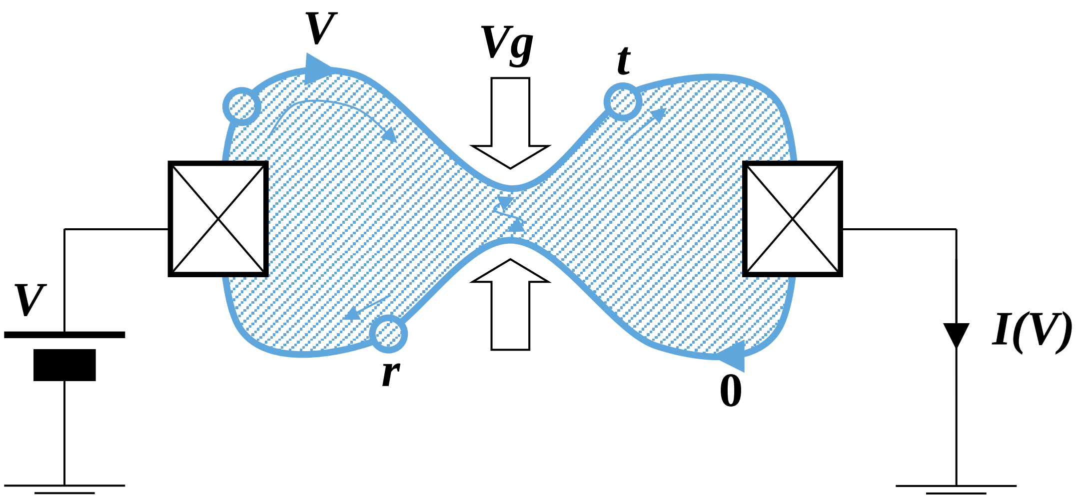


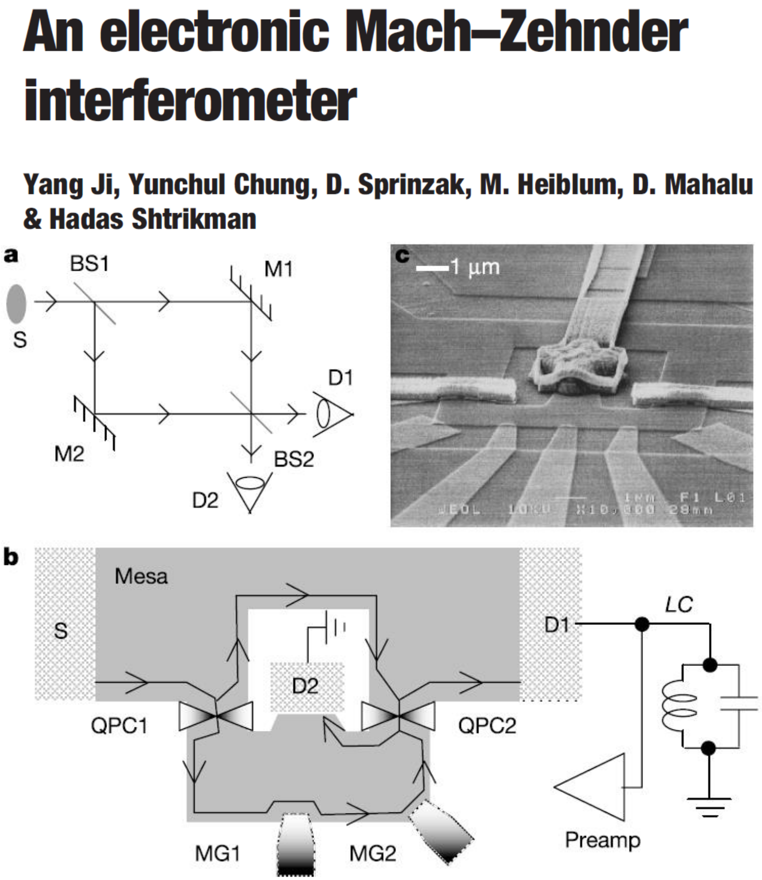
With a QPC we can intentionally induce backscattering, which provides us information about the edge properties

Roddaro et al.: PRL **90** (2003) 046805
Roddaro et al.: PRL **93** (2004) 046801
Roddaro et al.: PRL **95** (2005) 156804
Roddaro, Paradiso et al.: PRL **103** (2009) 016802

Edge channel-based interferometers

The very large coherence length has been exploited to implement complex interferometers as the electronic Mach-Zehnder.

Puzzle: so far, MZI only work with electron-like excitations. **The interference of fractional quasi-particles is inexplicably still elusive**



Ji *et al.*: Nature **422**, 415 (2003)

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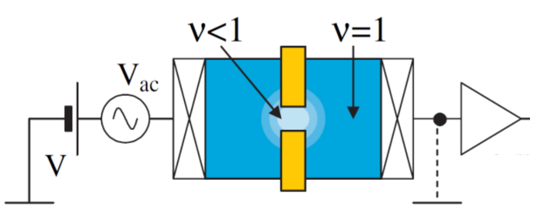
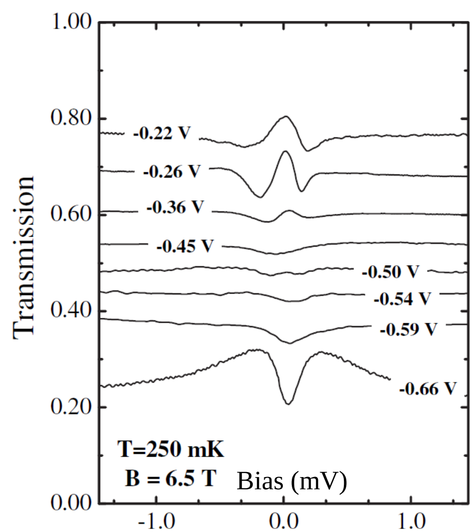
Role of the inner edge structure?

Roddaro *et al.*: experiments on QPCs revealed signatures of **fractional components** in “simple” **integer channels**

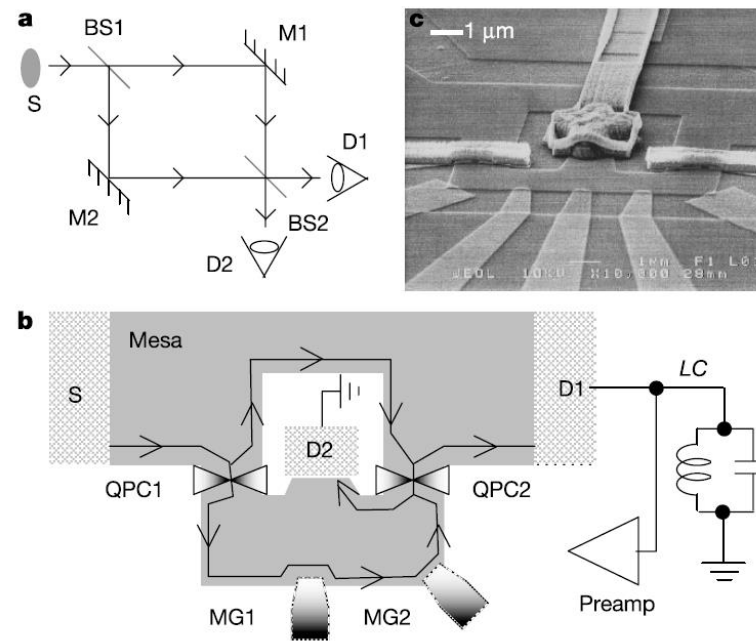


PRL **95**, 156804 (2005)



An electronic Mach–Zehnder interferometer

Yang Ji, Yunchul Chung, D. Sprinzak, M. Heiblum, D. Mahalu & Hadas Shtrikman



Ji *et al.*: Nature **422**, 415 (2003)

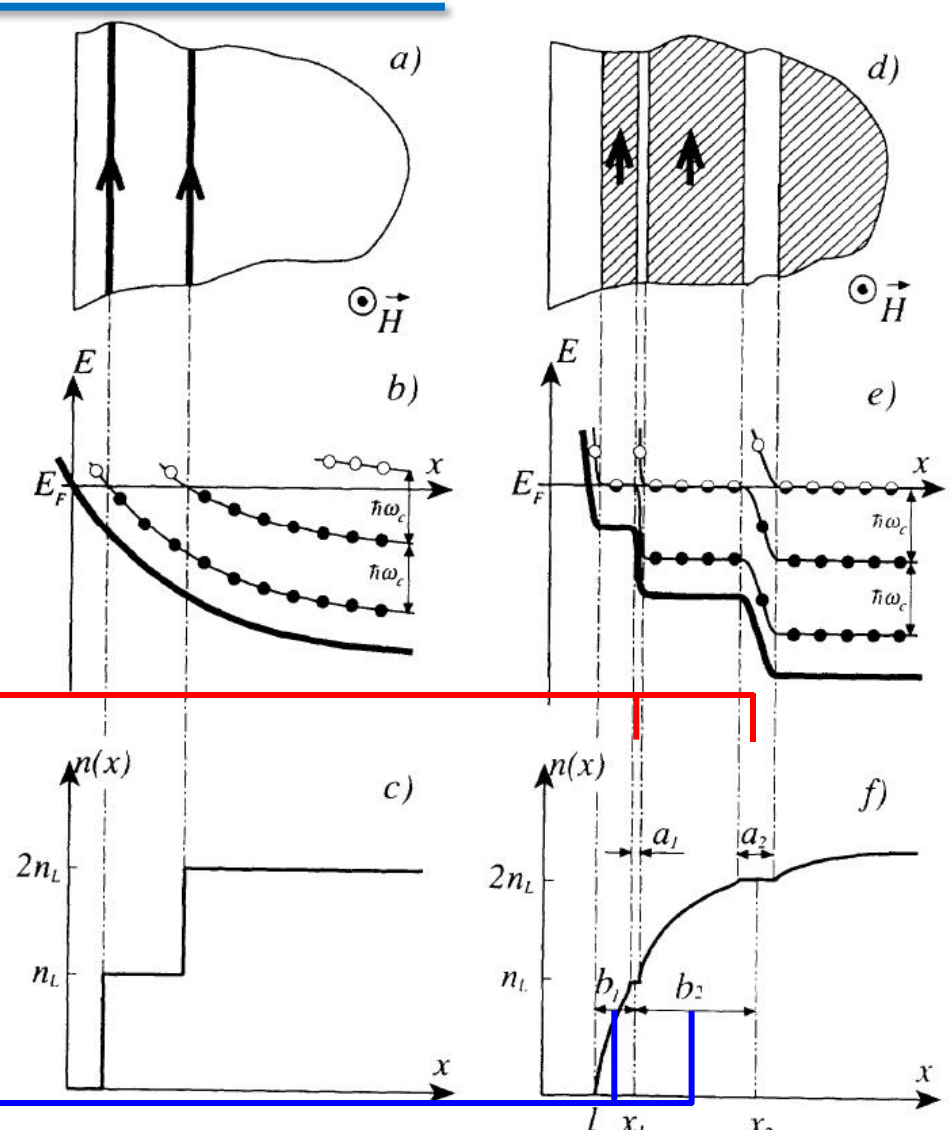
Need for spatially resolved measurements

Non-interacting VS interacting picture

• The self consistent potential due to e-e interactions modifies the edge structure

•For any realistic potential the density goes smoothly to zero.

•Alternating compressible and incompressible stripes arise at the sample edge



Incompressible stripes:

•The electron density is constant

•The potential has a jump

Compressible stripes:

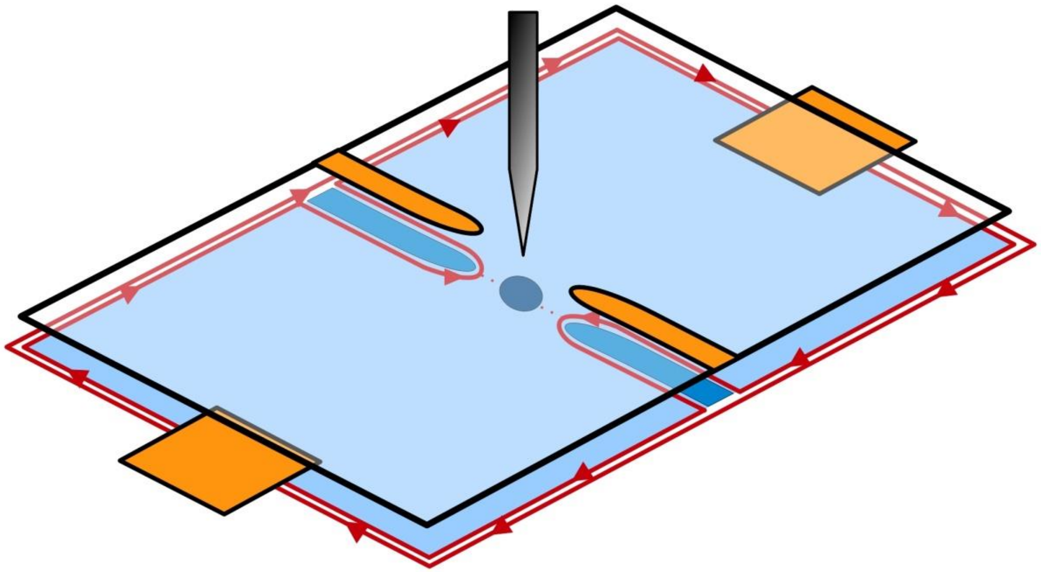
•The electron density has a jump

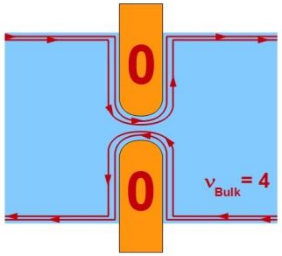
•The potential is constant

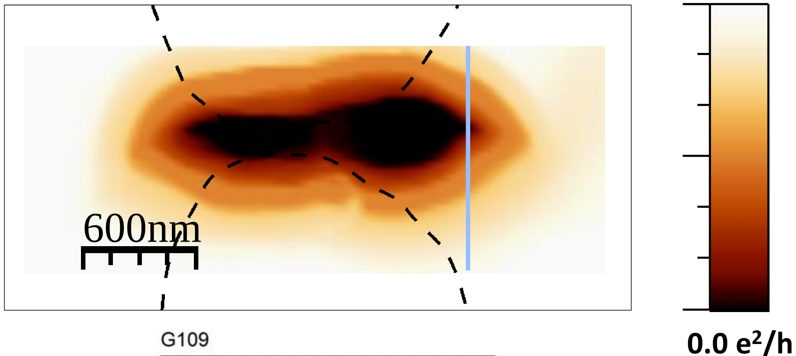
D. B. Chklovskii *et al.*: PRB **46** (1992) 4026.

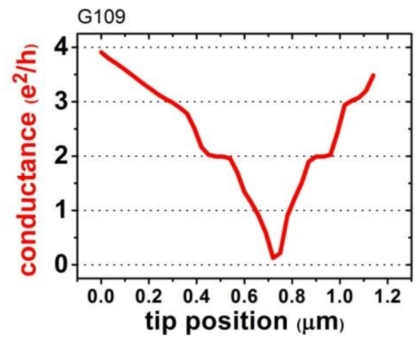
Edge channel tomography by SGM

SGM technique: we **select** individual channels from the edge of a quantized 2DEG, we **send** them to the constriction and make them **backscatter** with the biased **SGM tip.**





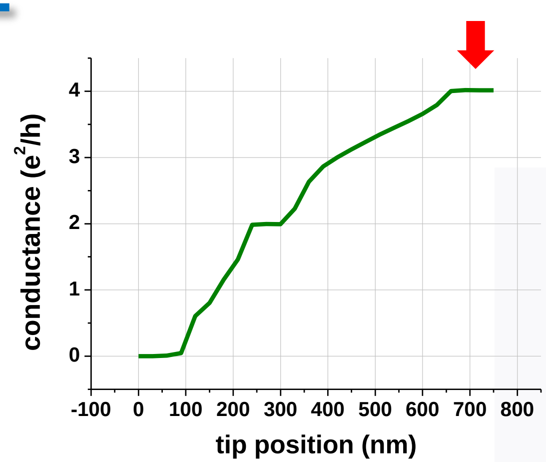


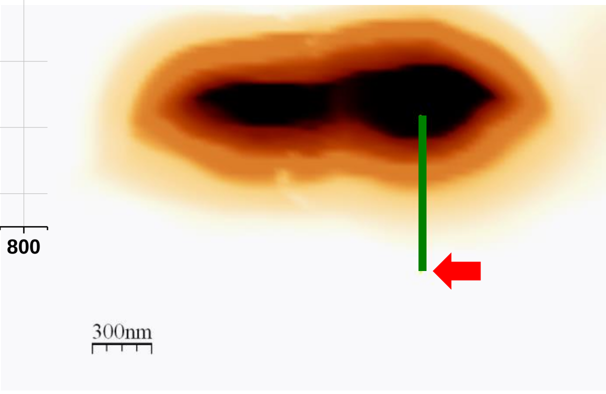


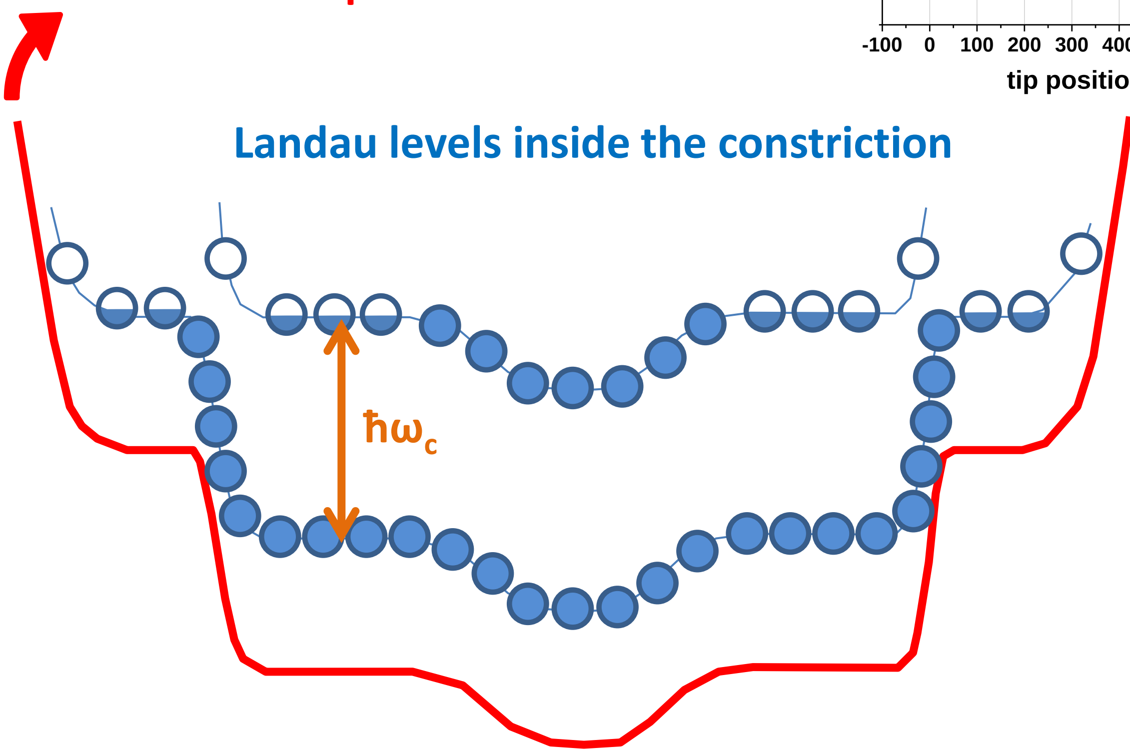
- Bulk filling factor $\nu=4$
- B = 3.04 T
- 2 spin-degenerate edge channels
- gate-region filling factors $g_1 = g_2 = 0$

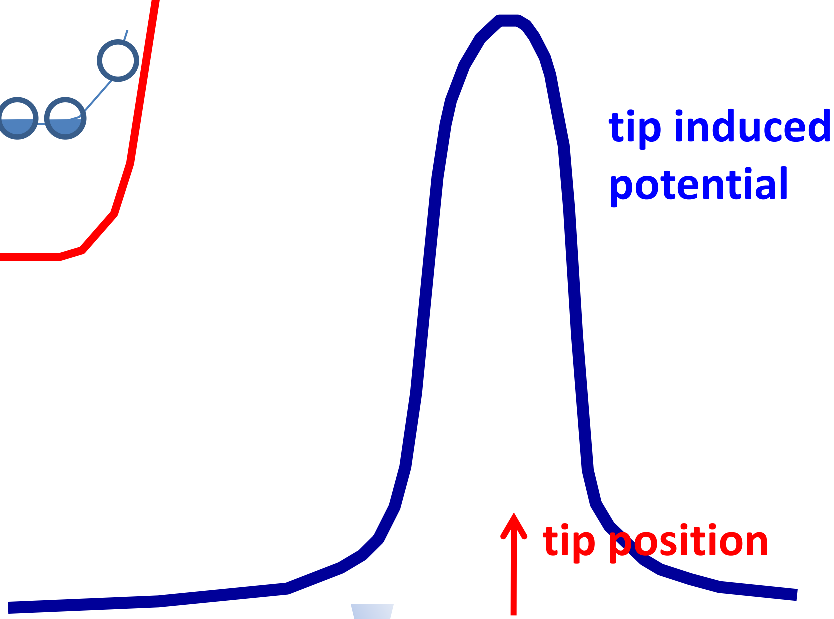
N. Paradiso *et al., Physica E 42 (2010) 1038.*

How we probe incompressible stripes

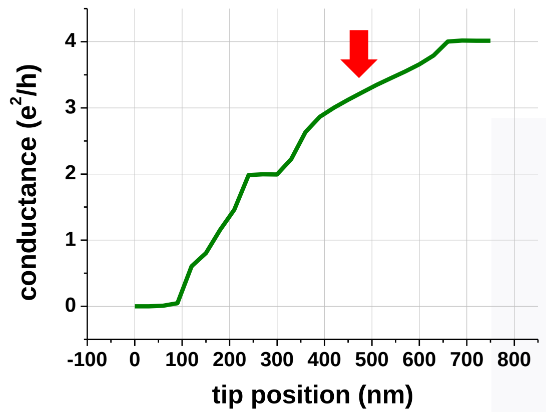


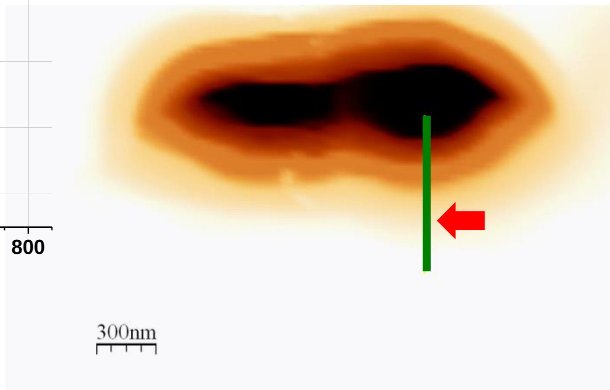


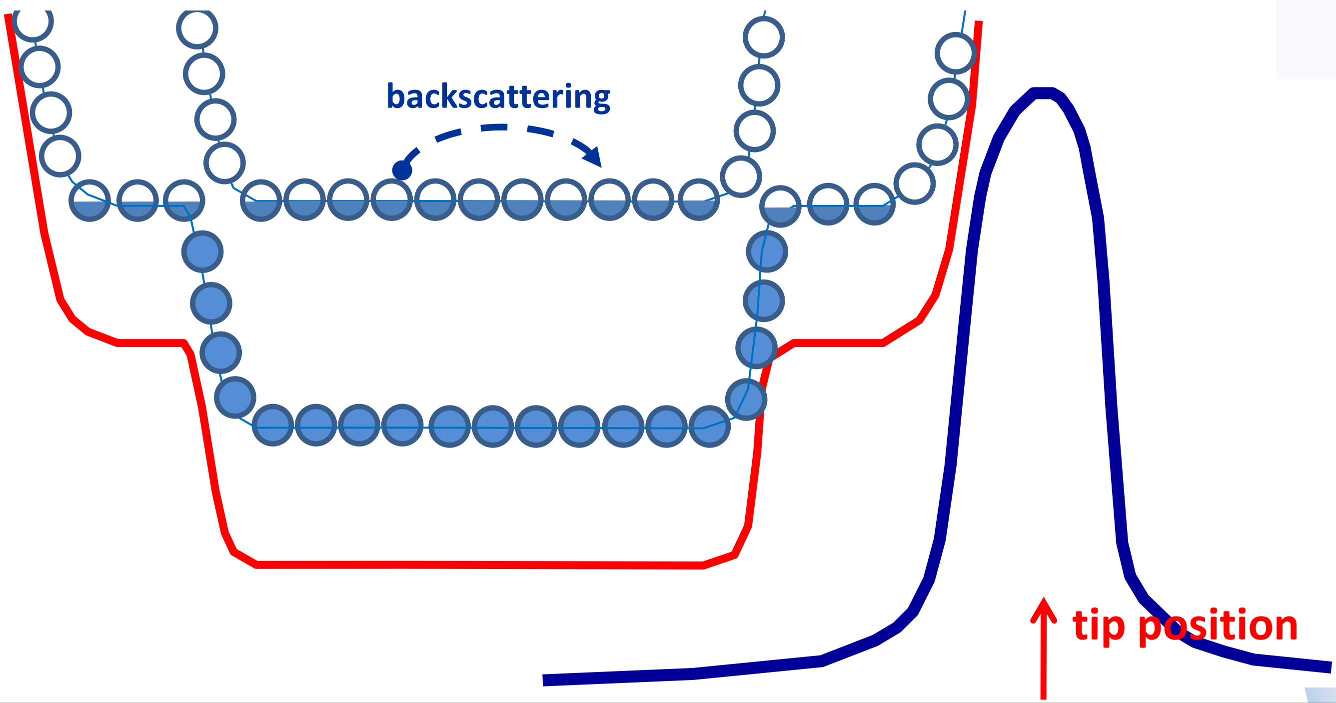




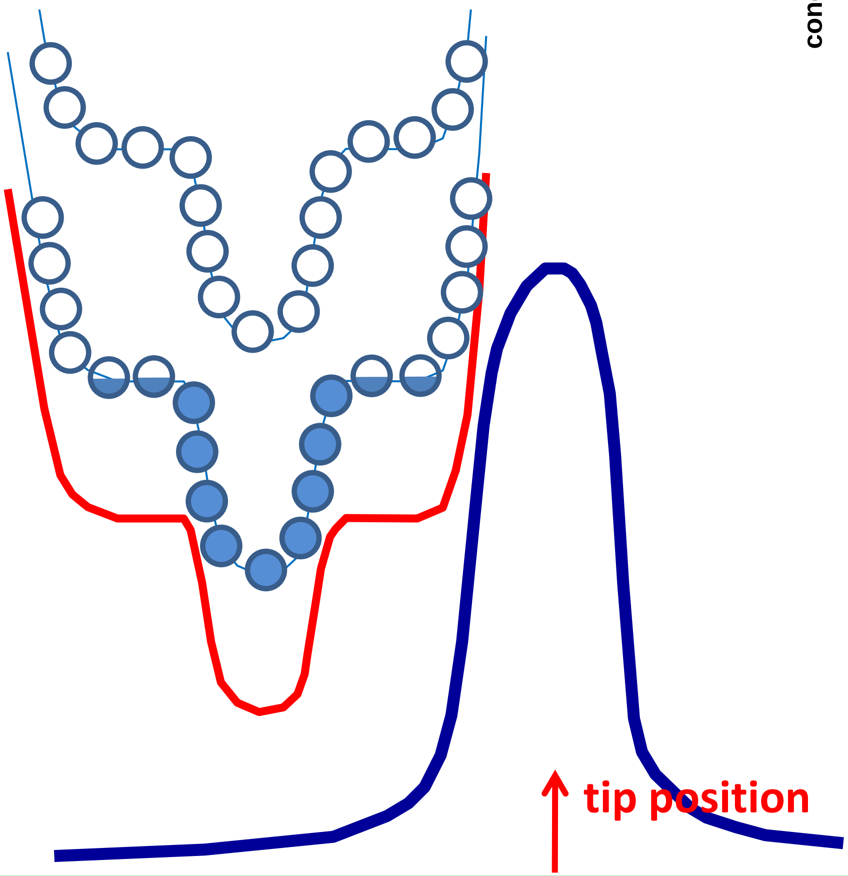
How we probe incompressible stripes

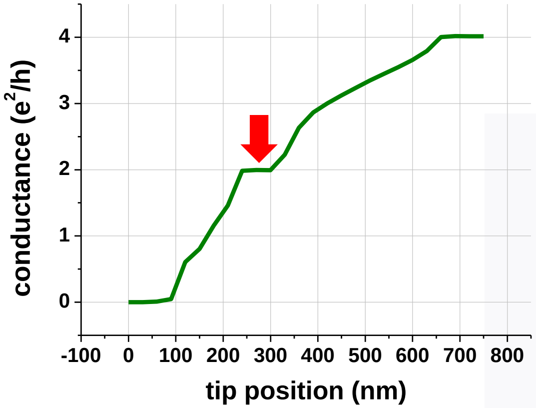


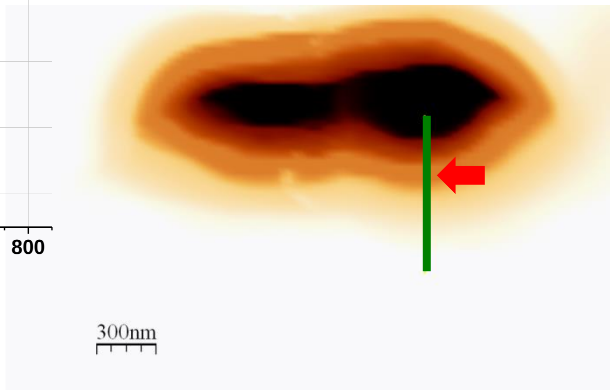




How we probe incompressible stripes

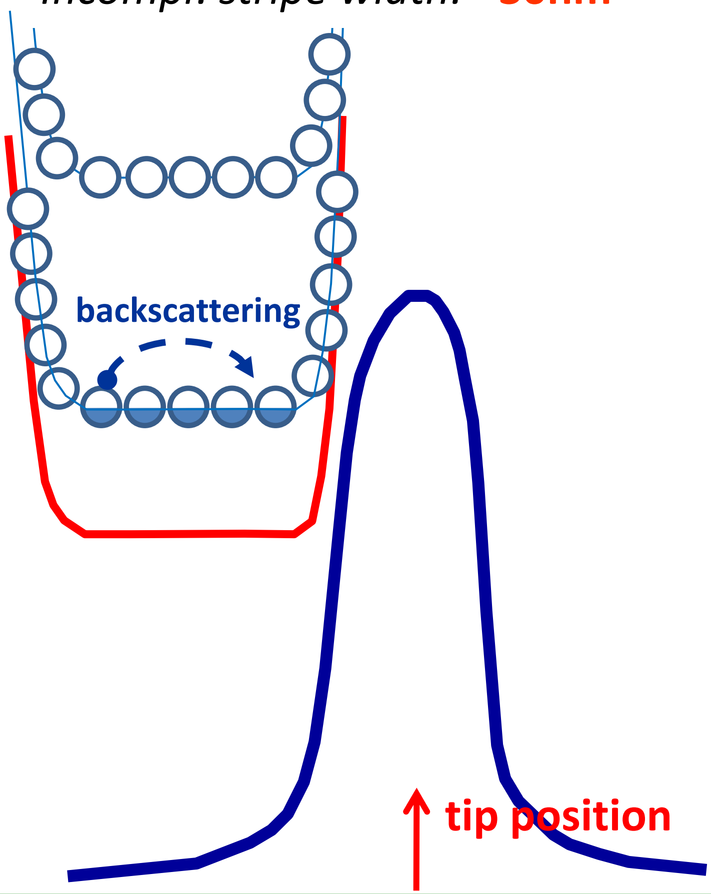


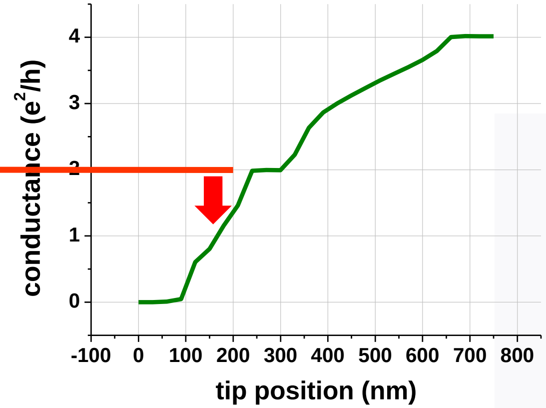


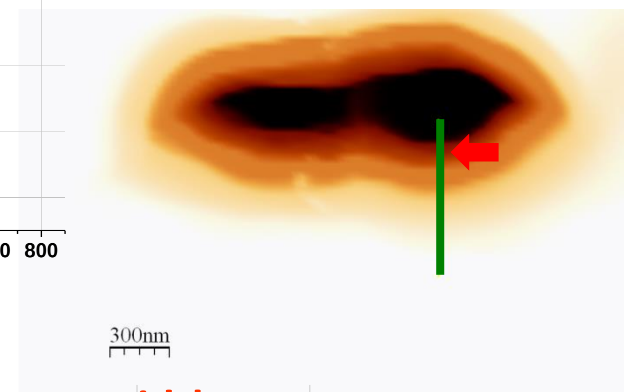


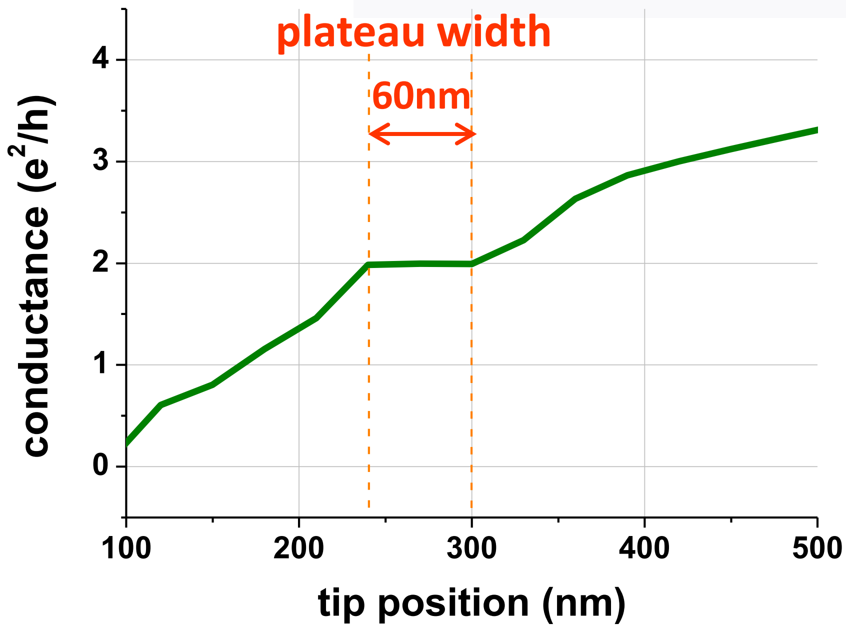
How we probe incompressible stripes

Energy gap: **ħω=5.7 meV**
Plateau width: **60 nm**
Incompr. stripe width: **≈30nm**

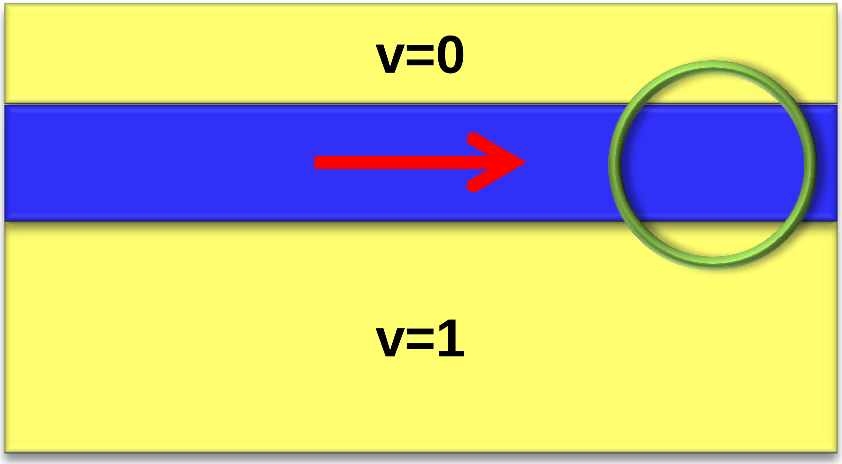


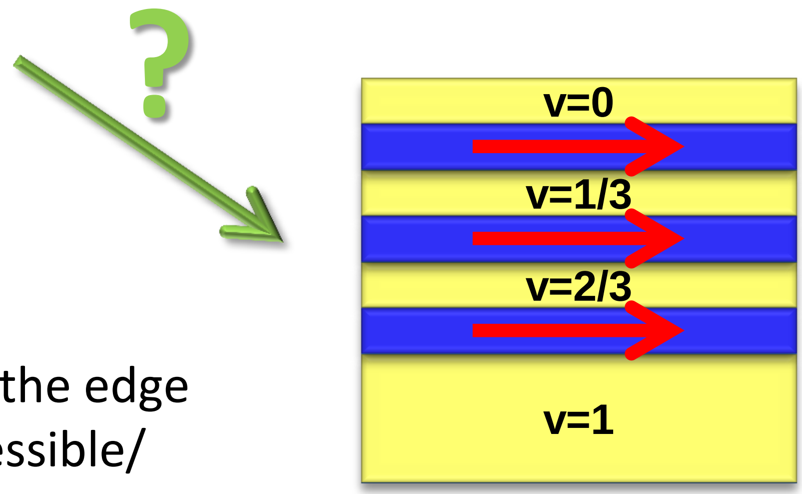






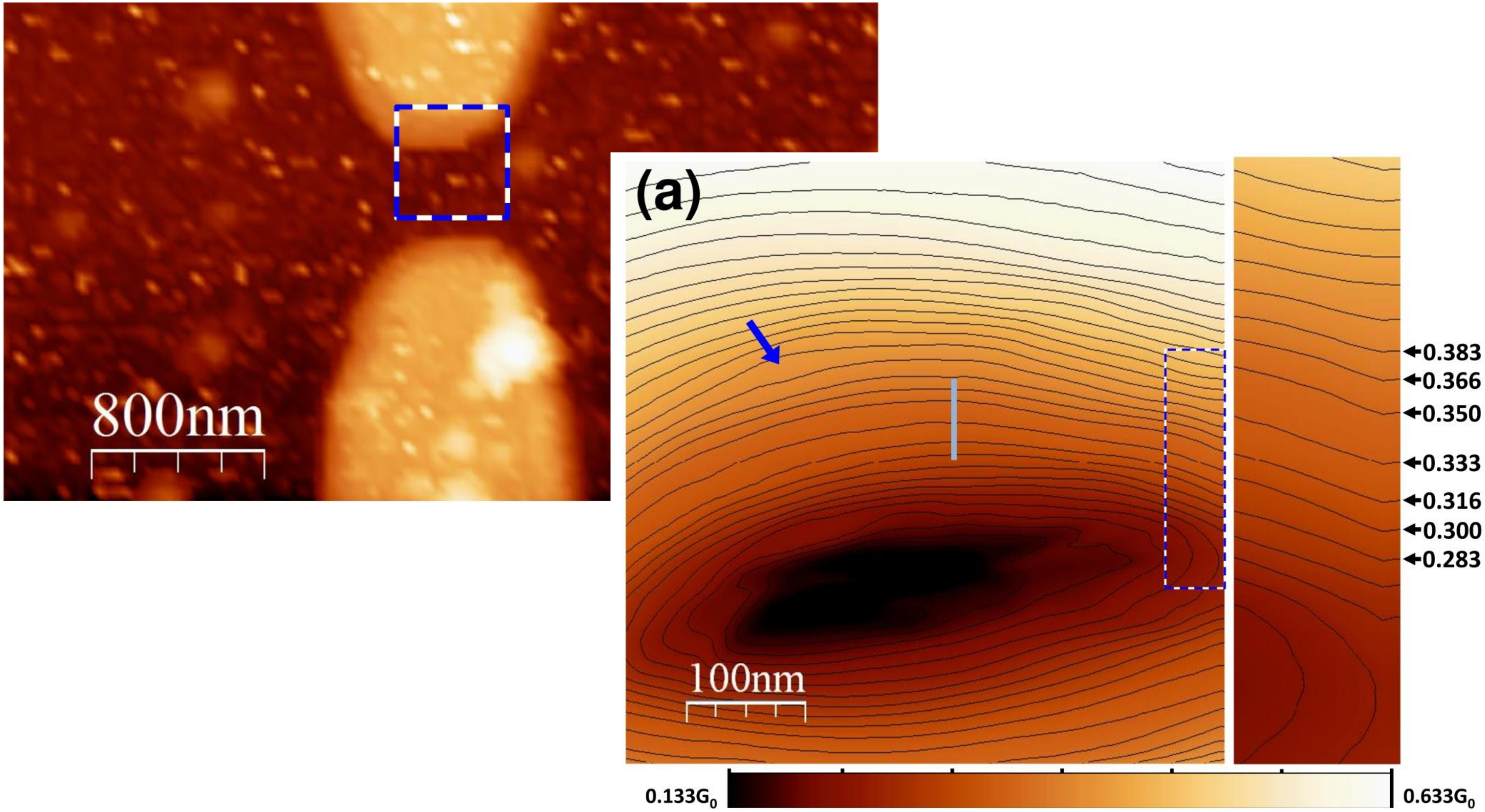
Imaging fractional structures in integer channels (ν=1)





The Reconstruction Picture suggests that at the edge of a smooth **integer** edge a series of compressible/ **incompressible fractional stripes** can occur.

Imaging fractional structures in integer channels (ν=1)



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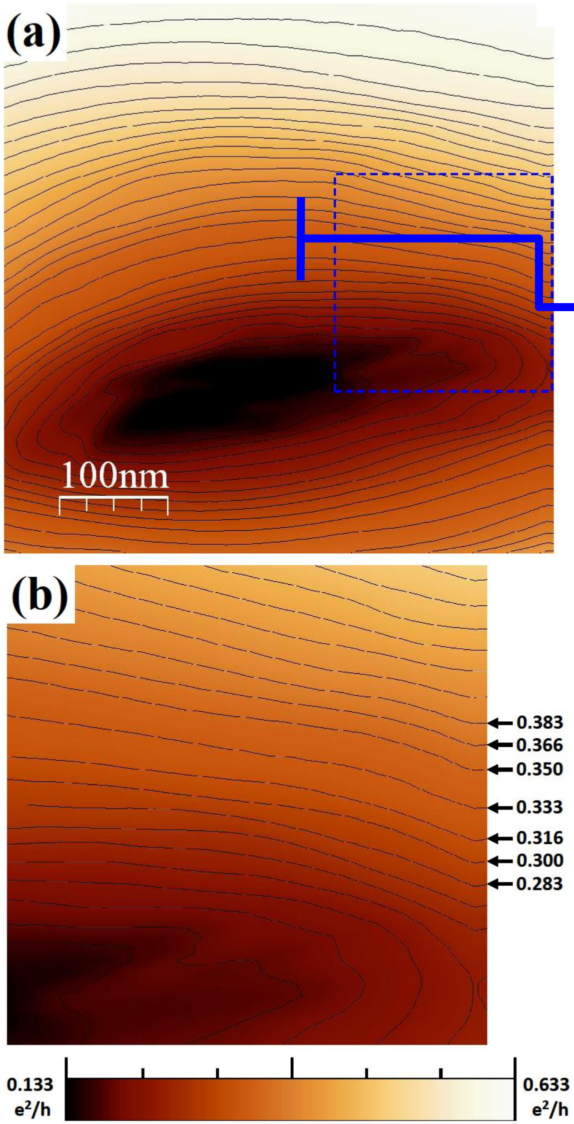
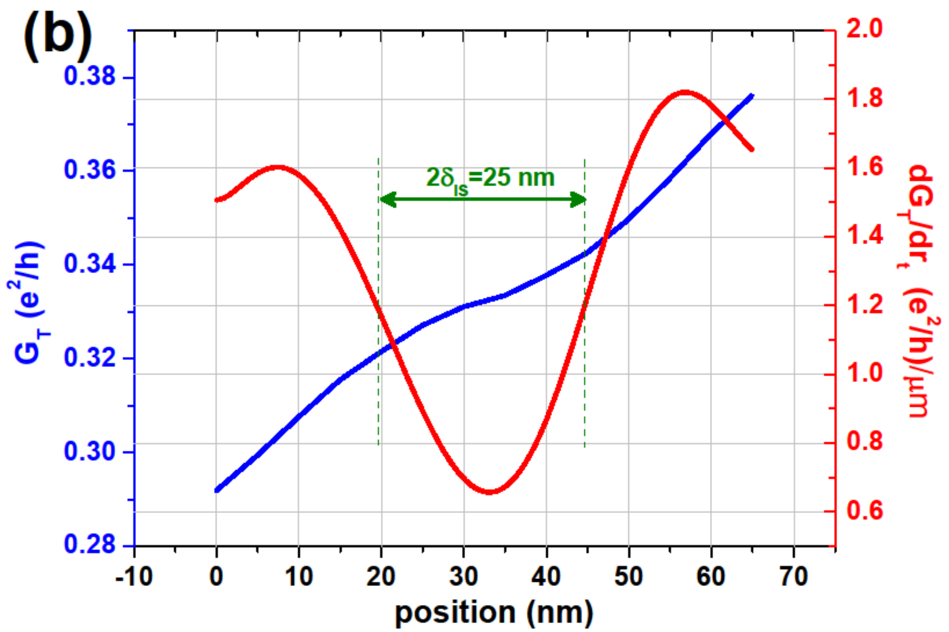
Imaging fractional structures in integer channels (ν=1)

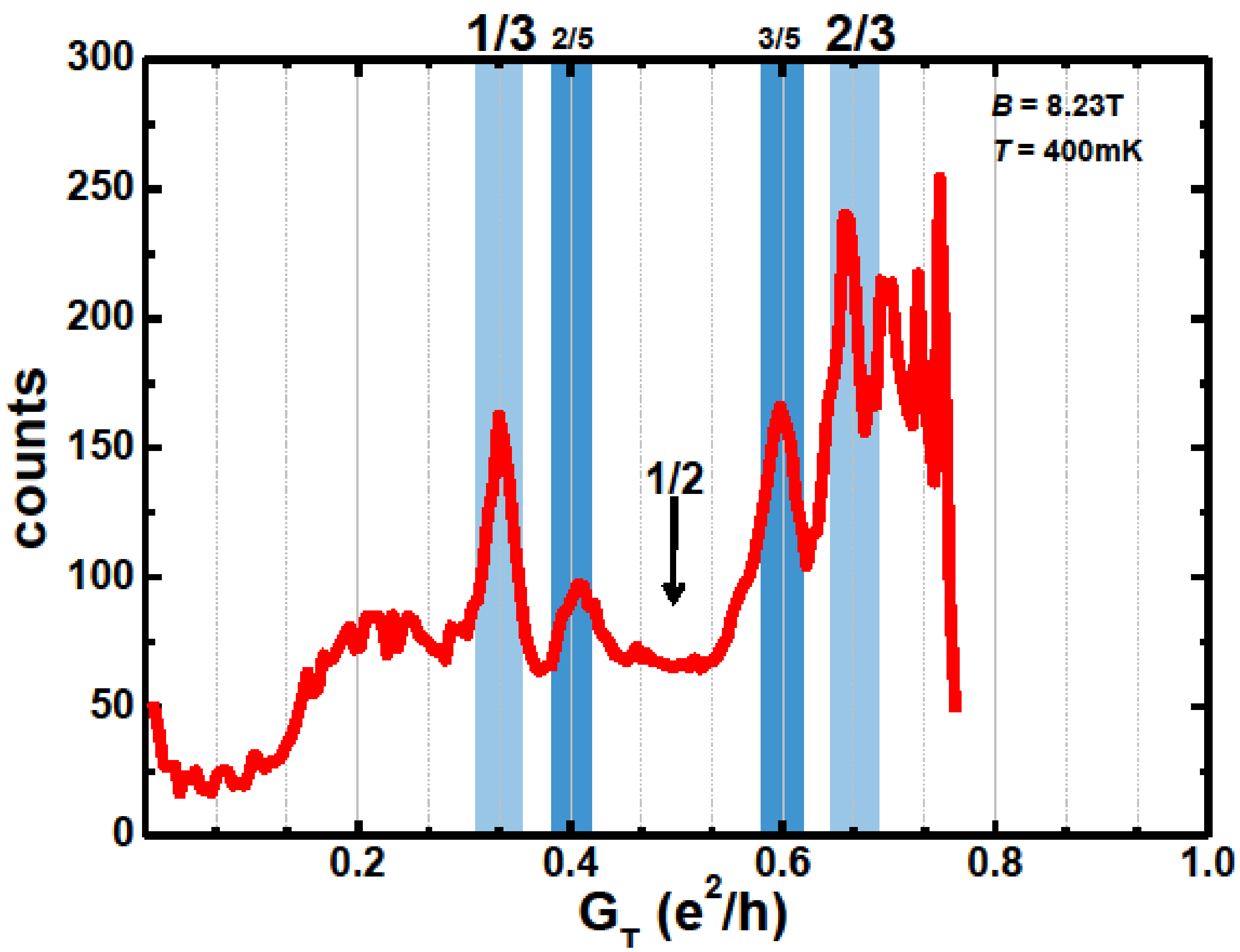


δ_{IS} ~ 12 nm



N. Paradiso *et al.* Phys. Rev. Lett. **108**, 246801 (2012)

Imaging fractional structures in integer channels (ν=1)



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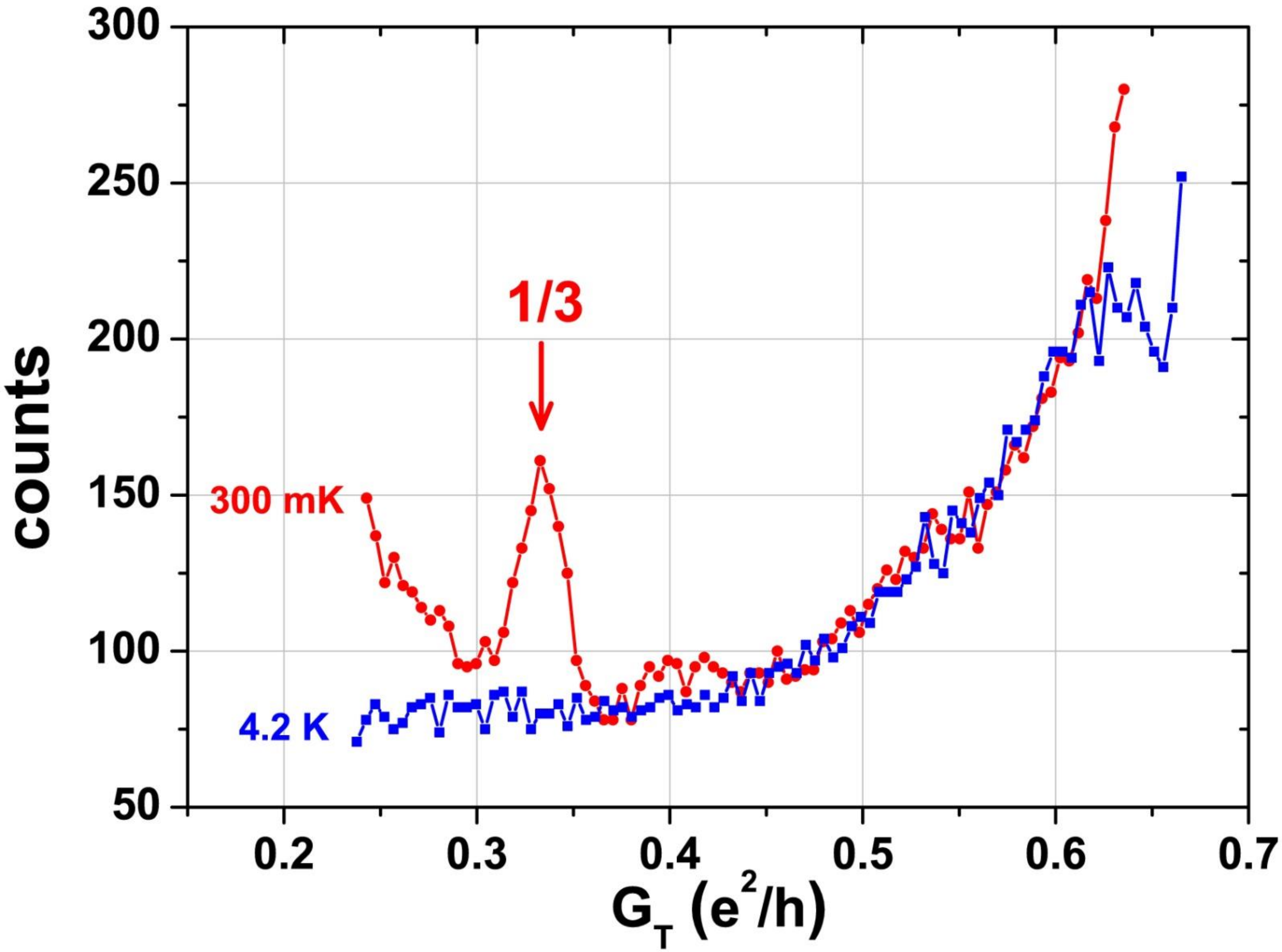
Temperature dependence of 1/3 peak in histogram



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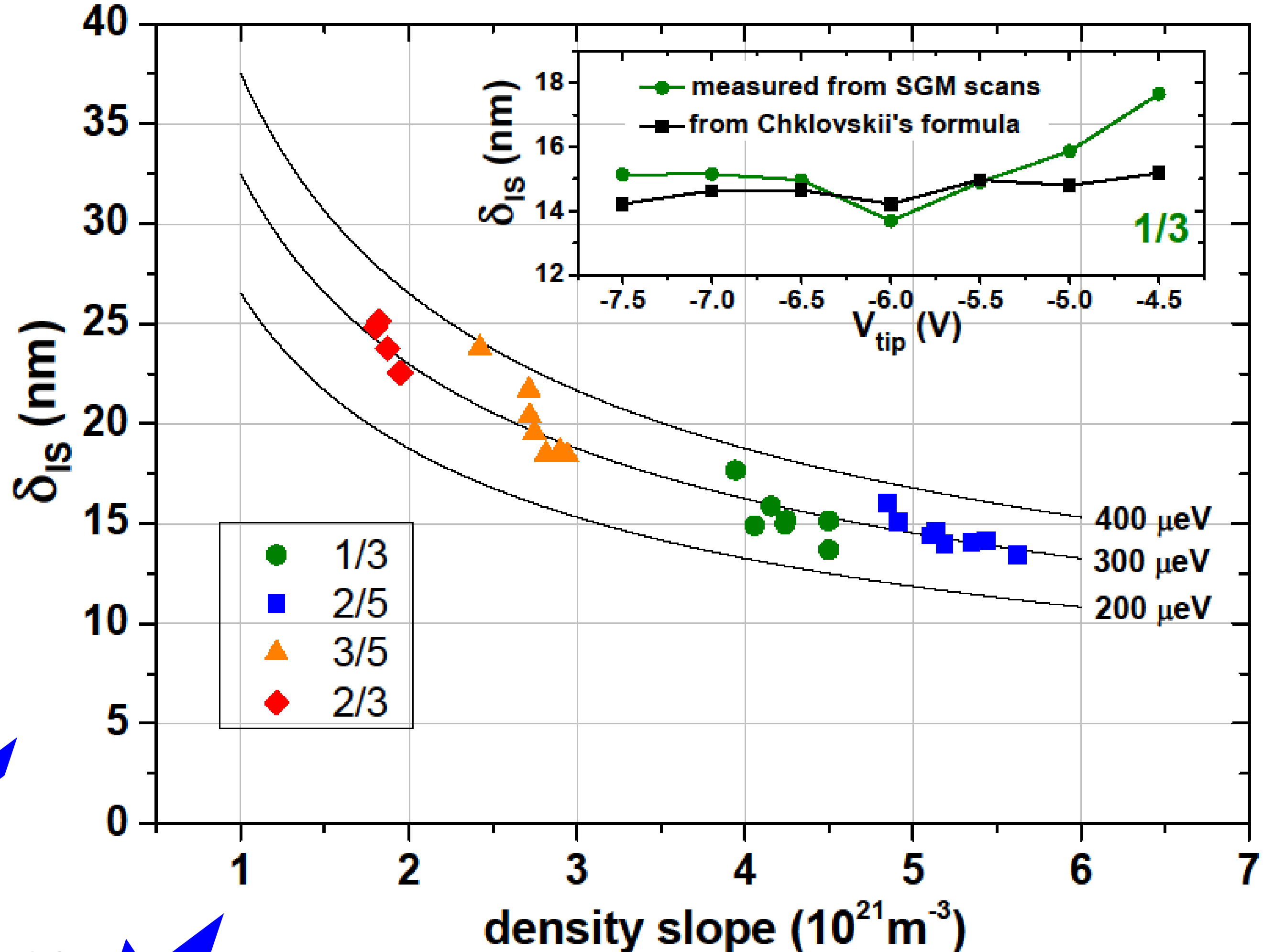
Fractional edge reconstruction

The IS width values (colored dots) obtained from SGM images compare well with the reconstruction picture predictions (black lines)



Inner edge structure ***demonstrated*** ***and*** ***imaged***

Quantitative test ***of the IS width dependence on the density slope***

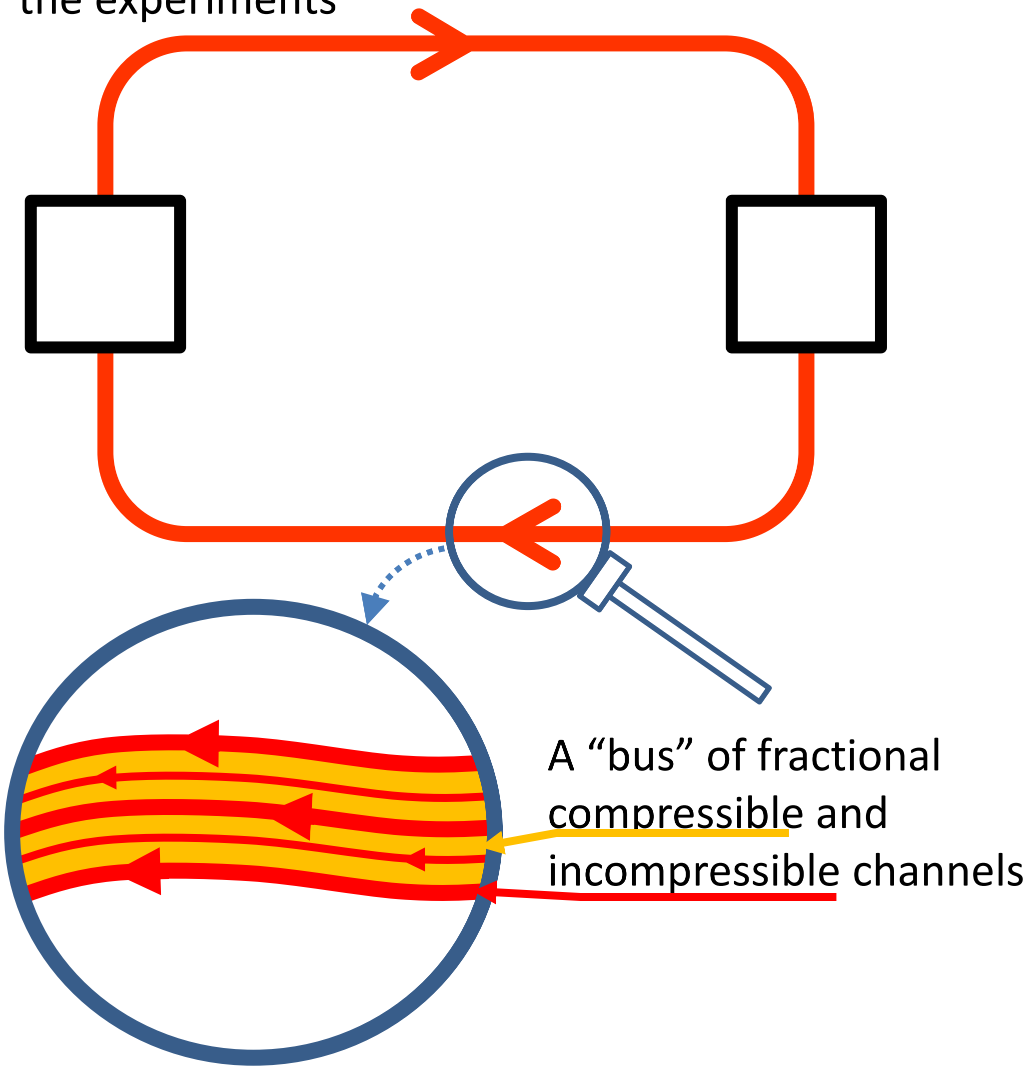
N. Paradiso *et al.* Phys. Rev. Lett. **108**, 246801 (2012)

Outline

- Basics of Scanning Gate Microscopy (SGM)
- Quantum Point Contact w/o magnetic field
- QPC in the quantum Hall regime
- Edge channel equilibration

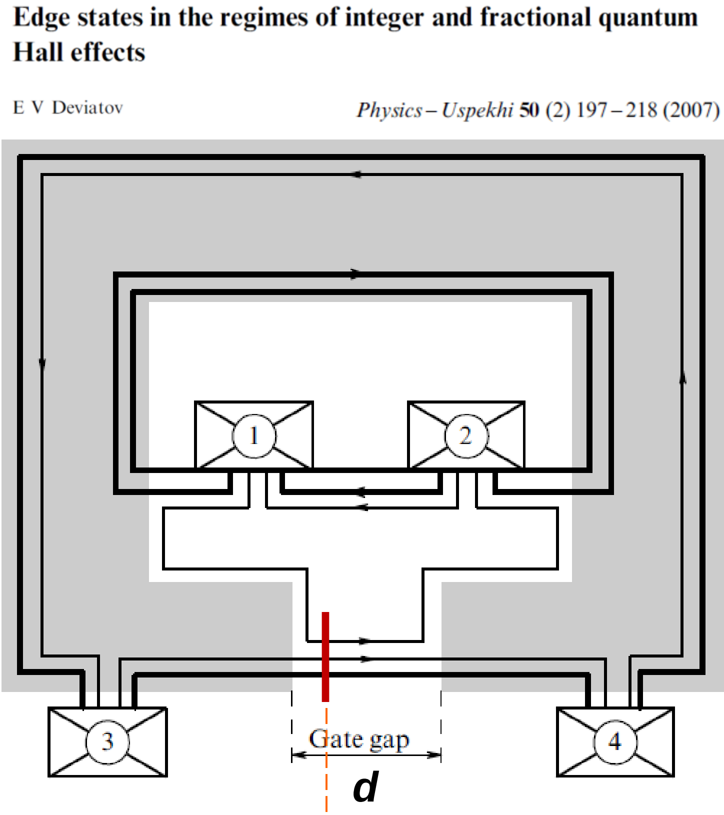
Can we exploit the non-trivial edge structure?

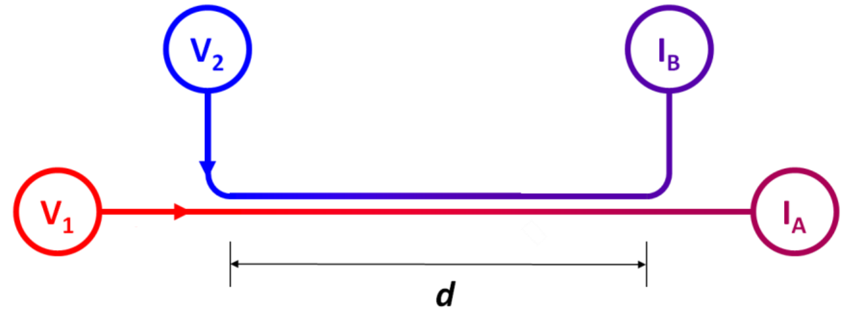
The picture of a QH device emerging from the experiments



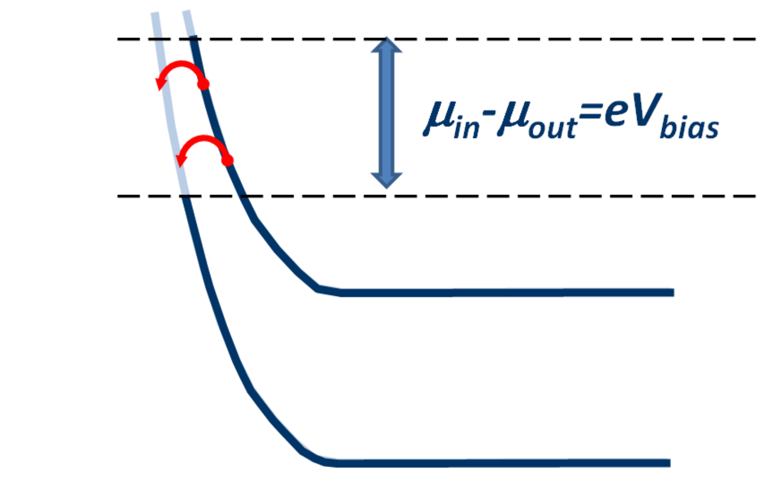
Is it possible to study and image the microscopic details of the inter-channel scattering?

Studying the inter-channel equilibration





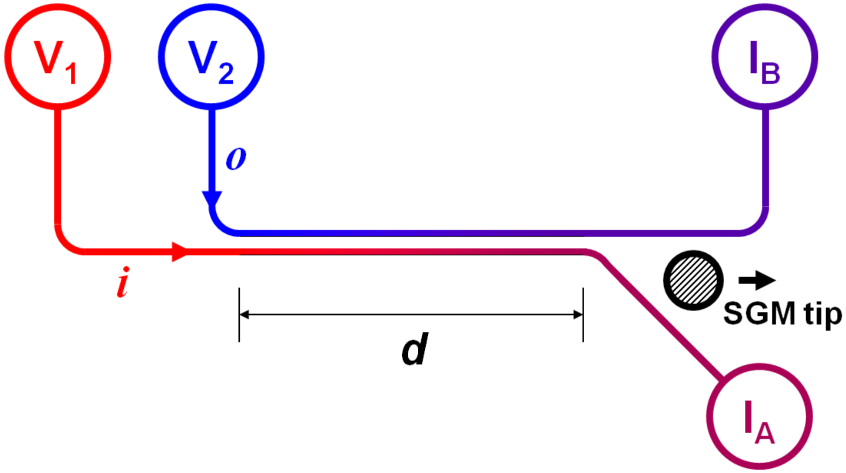
devices with fixed interaction length *d*:
elusive determination of **the microscopic details of the equilibration mechanisms**

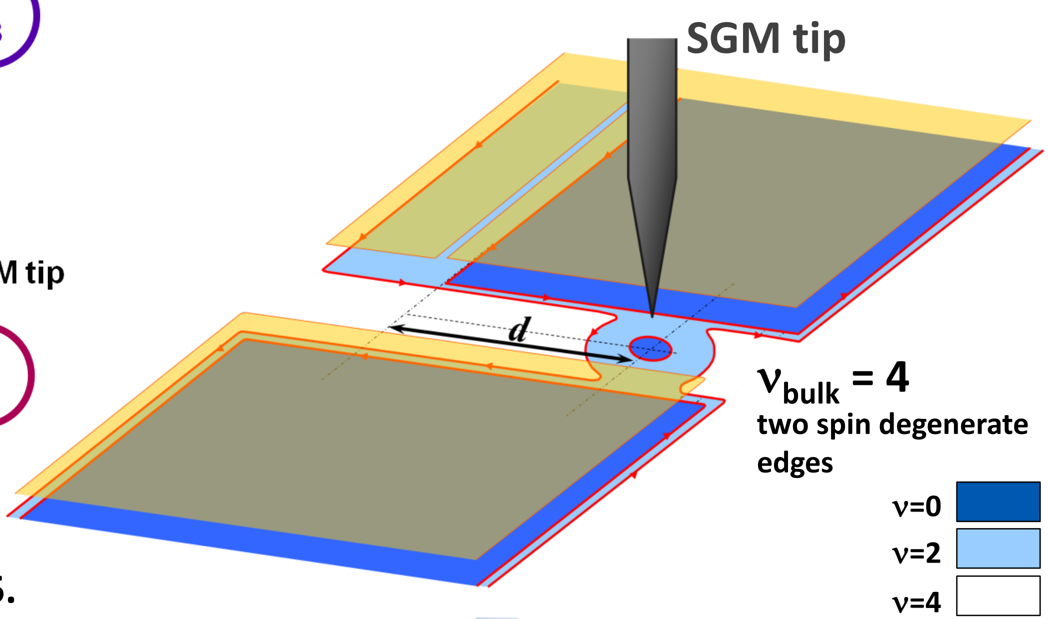


The oppurtunity of the Scanning Gate Microscopy

Our technique allows to selectively control the channel trajectory

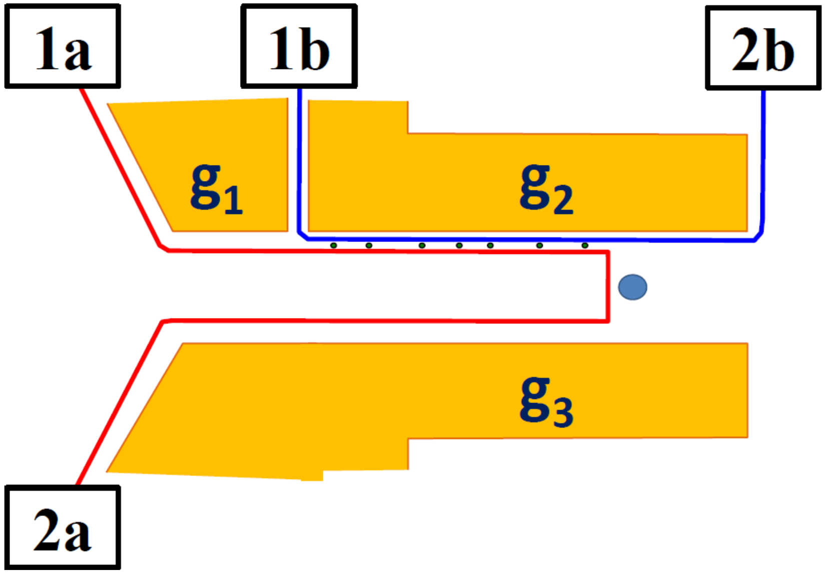
Our idea: exploit the mobile depletion spot induced by the SGM to continuously tune ***d***

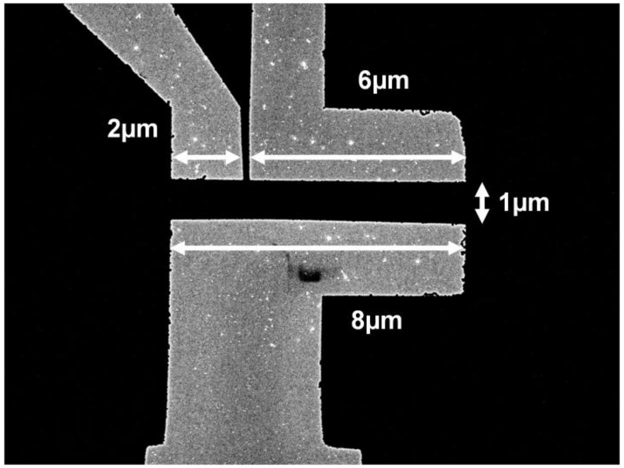




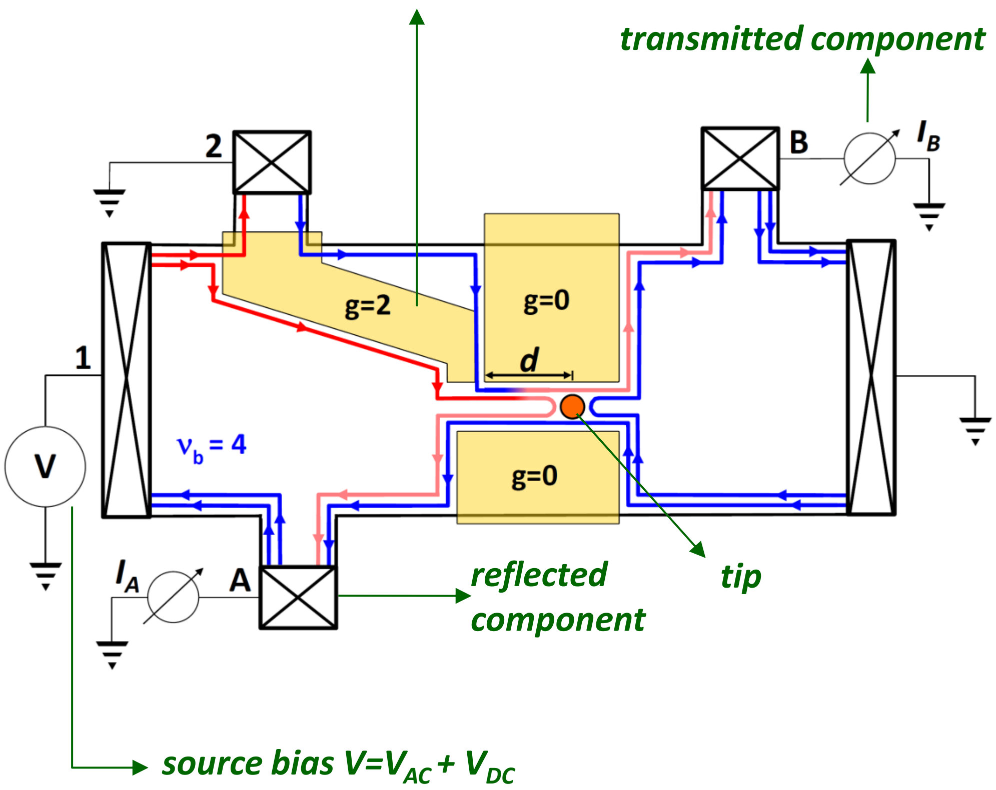
N. Paradiso *et al.* Phys. Rev. B 83 (2011) 155305.

Experimental setup





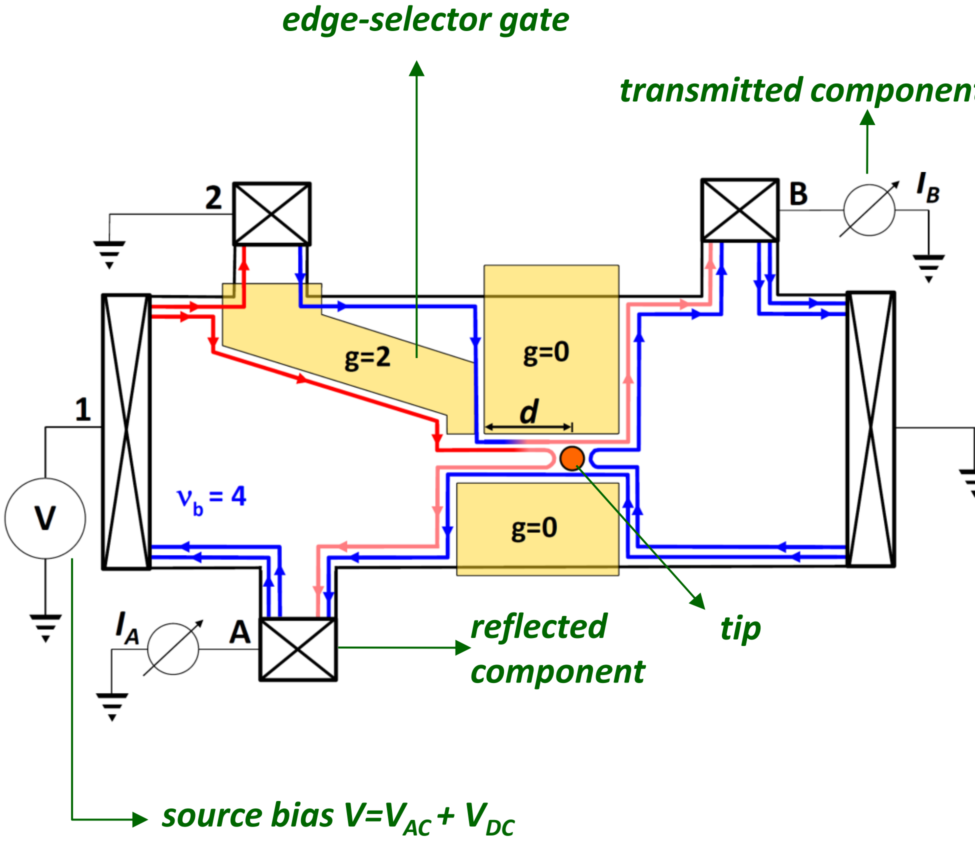
SEM micrograph of the device



Scheme of the electronic setup

Experimental setup

	No eq.	Full eq.
A	2 e²/h	1 e²/h
B	0 e²/h	1 e²/h

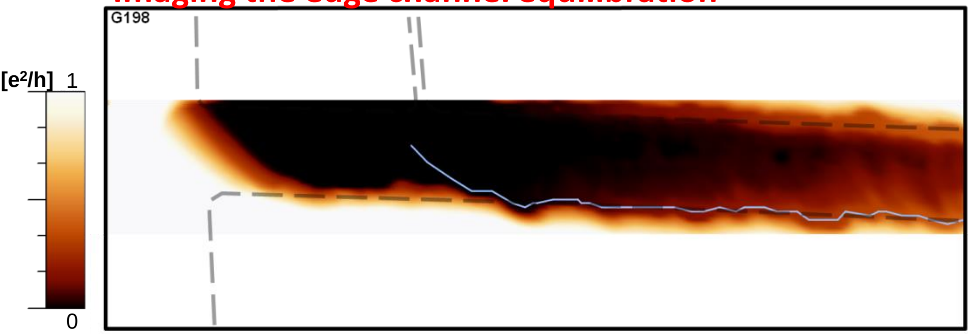


Scheme of the electronic setup

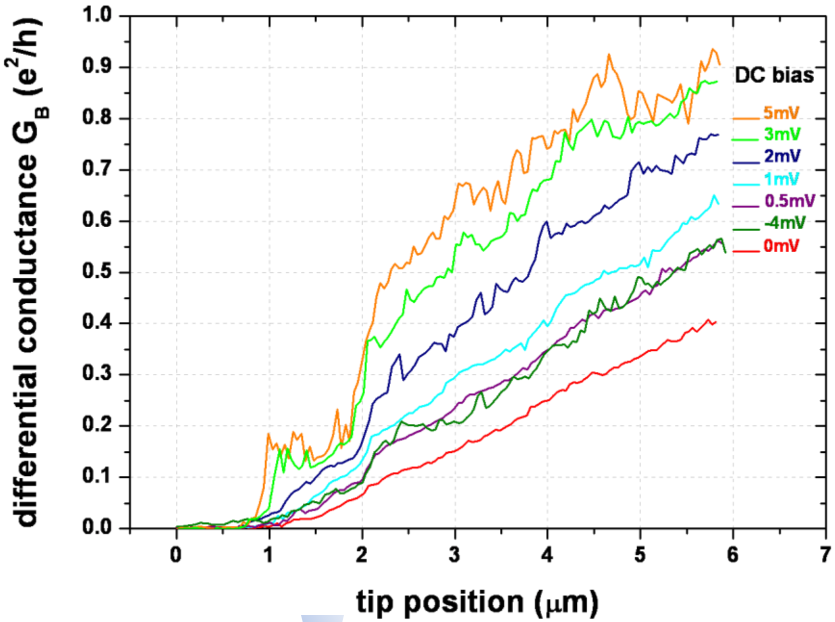
Imaging the inter-channel equilibration

The profiles of $G_B(d)$ along the trajectory show a strict dependance on the <u>local details</u>

Imaging the edge channel equilibration

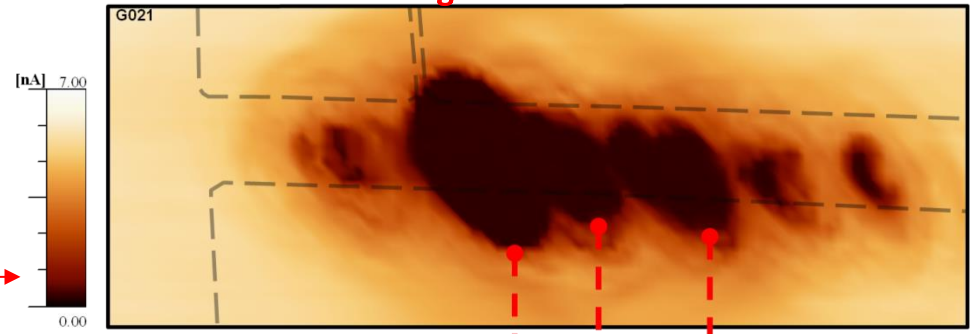


Source bias: V_{AC}=50μV, V_{DC}=0mV



Imaging the inter-channel equilibration

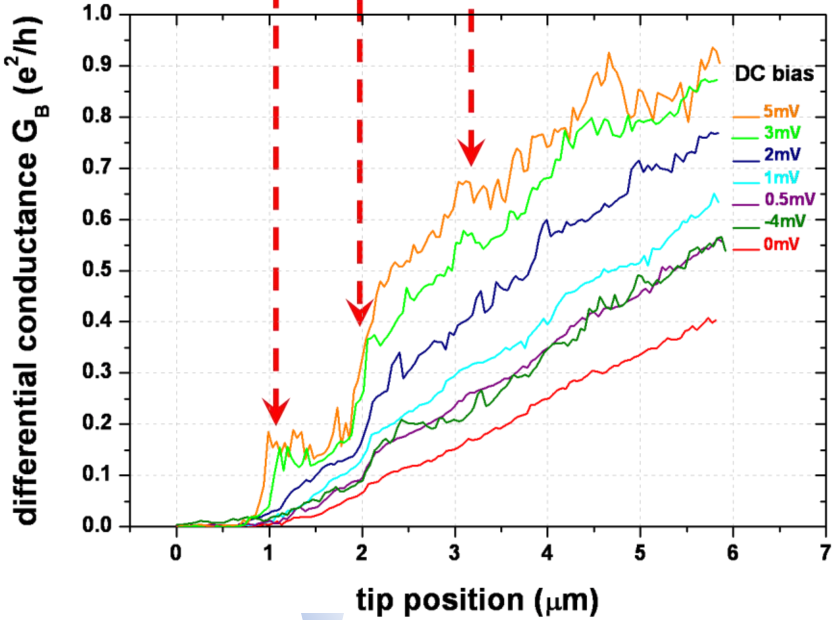
SGM scan at zero magnetic field



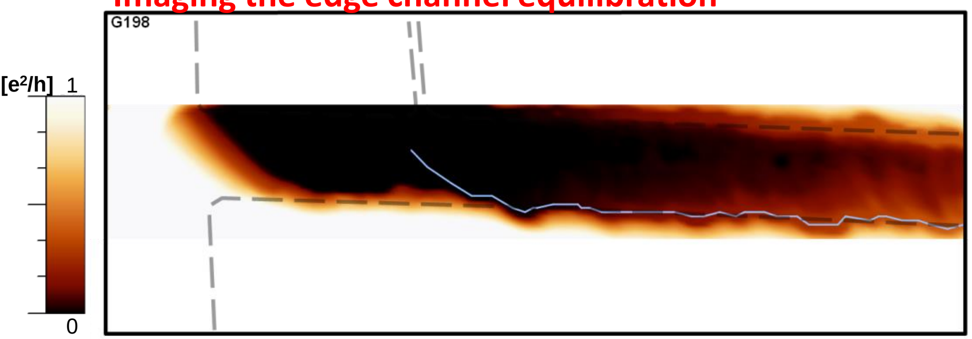
We can directly image the potential induced by the most important defects by means of a scan at zero magnetic field

correlation found

The profiles of $G_B(d)$ along the trajectory show a strict dependance on the local details

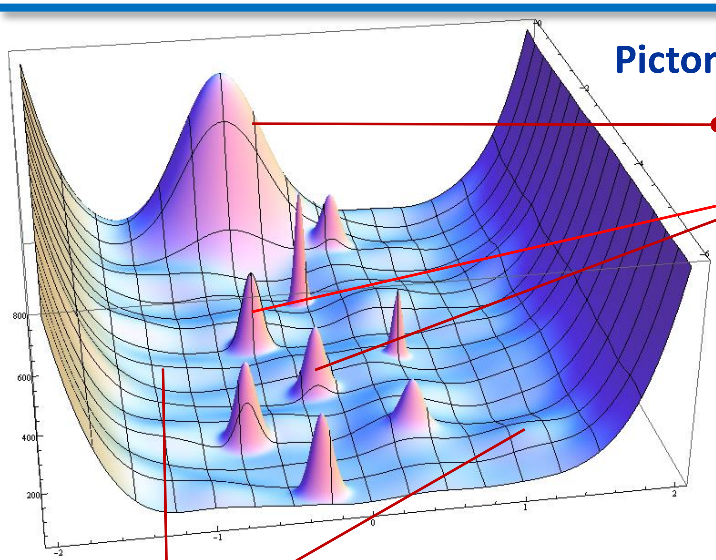


Imaging the edge channel equilibration



Source bias: V_{AC}=50μV, V_{DC}=0mV

Tight binding simulations



Pictorial model for the disorder potential

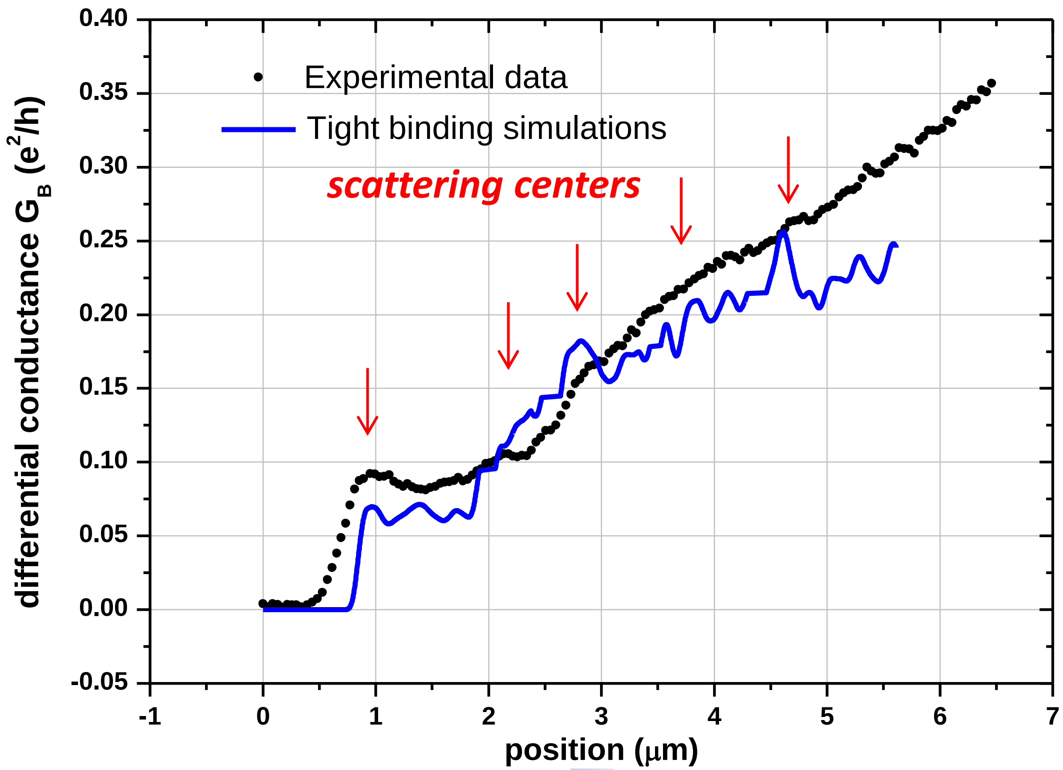
tip potential

"big impurities" potential

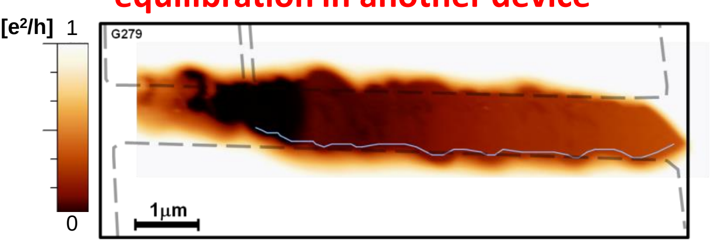
background potential

Simulations made by the theoretical group of Scuola Normale Superiore (Pisa, Italy)

D. Venturelli, F. Taddei, V. Giovannetti and R.Fazio

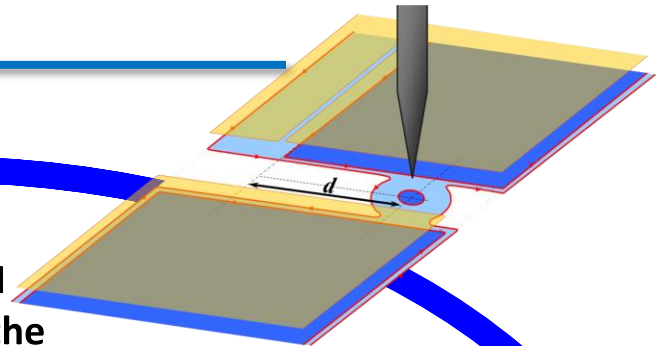


SGM map of the inter-channel equilibration in another device

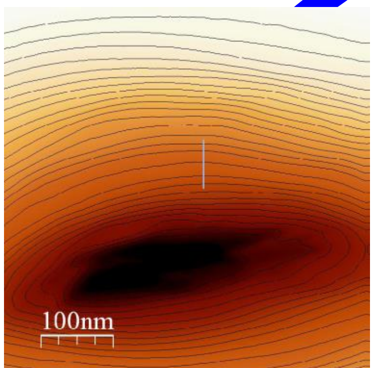


Summary

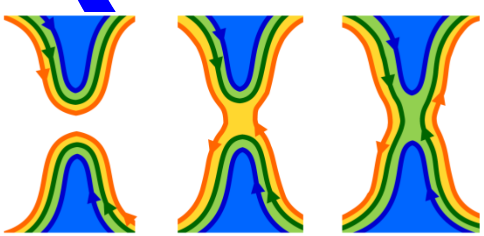
SGM technique in the QH regime



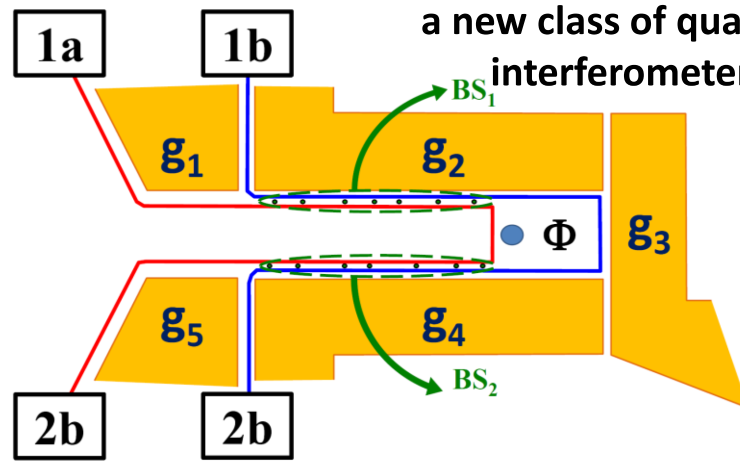
size-tunable QH circuits: study of the channel mixing



Edge channel tomography: imaging of fractional stripes



a new class of quantum interferometers



Future directions: Interference of fractional quasi-particles ?

Conclusions

- We explore the use of Scanning Gate Microscopy to study one-dimensional systems
- The 0.7 anomaly is observed irrespective of the presence of localized defects and is therefore a fundamental property
- Control of the edge channel trajectory by SGM allows us to study their structure
- We observe a fractional substructure in integer QH channels and measured the width of fractional incompressible stripes
- We built size-tunable QH circuits to directly image the equilibration between imbalanced co-propagating edges