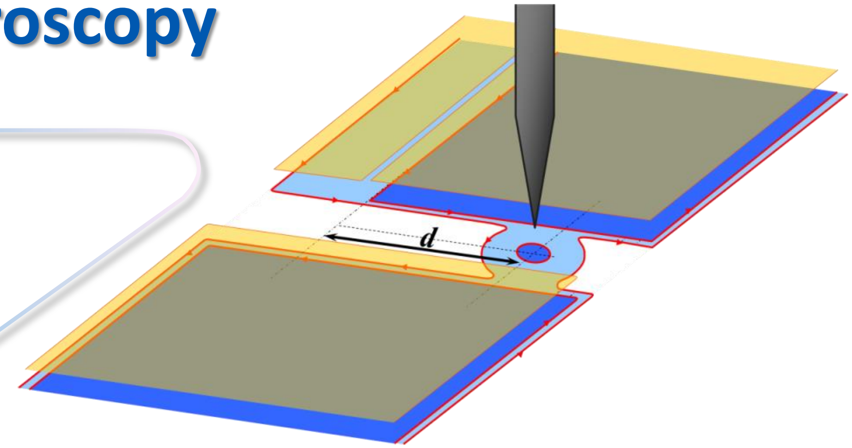
Nanomaterials characterization by low-temperature scanning gate microscopy



Stefan Heun

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

Outline

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

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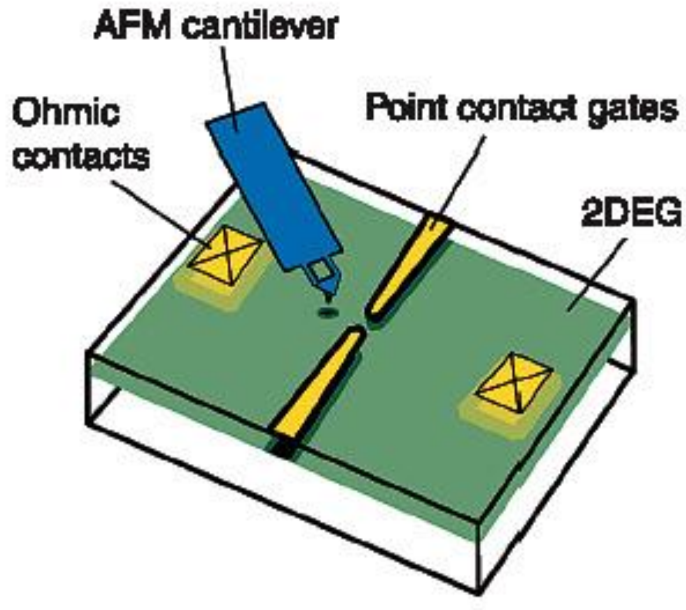
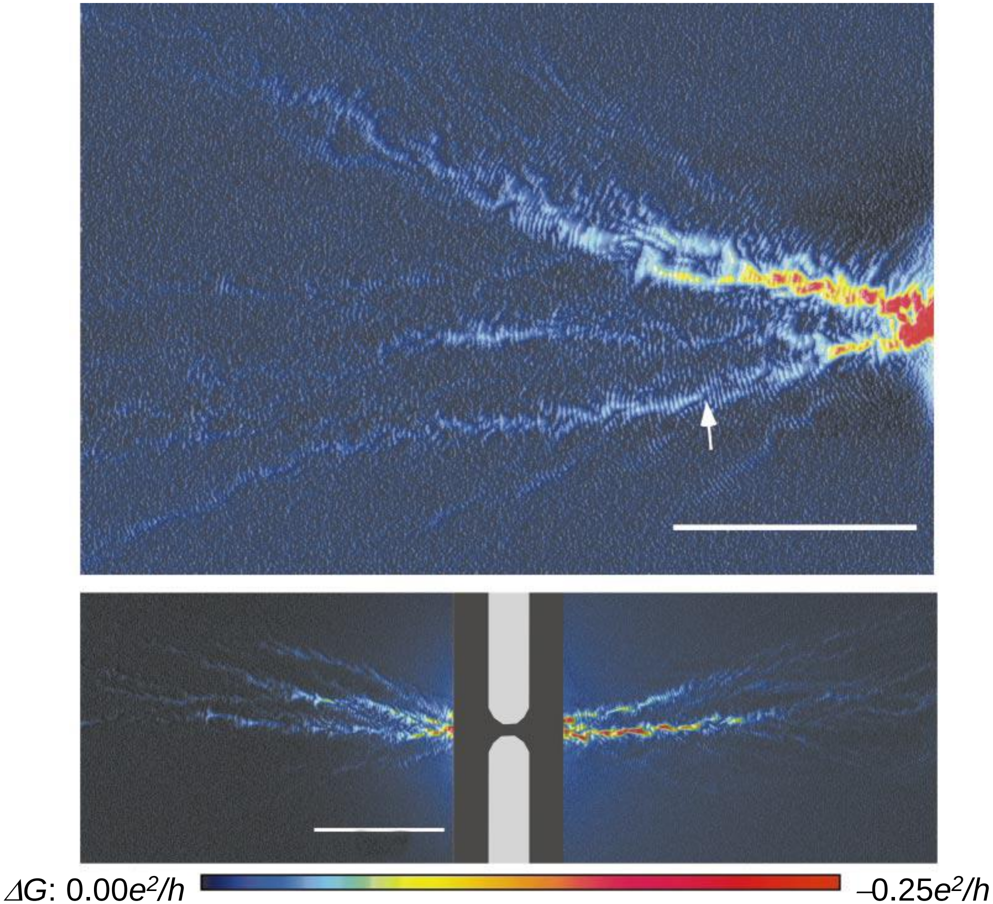
Scanning Gate Microscopy

- 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



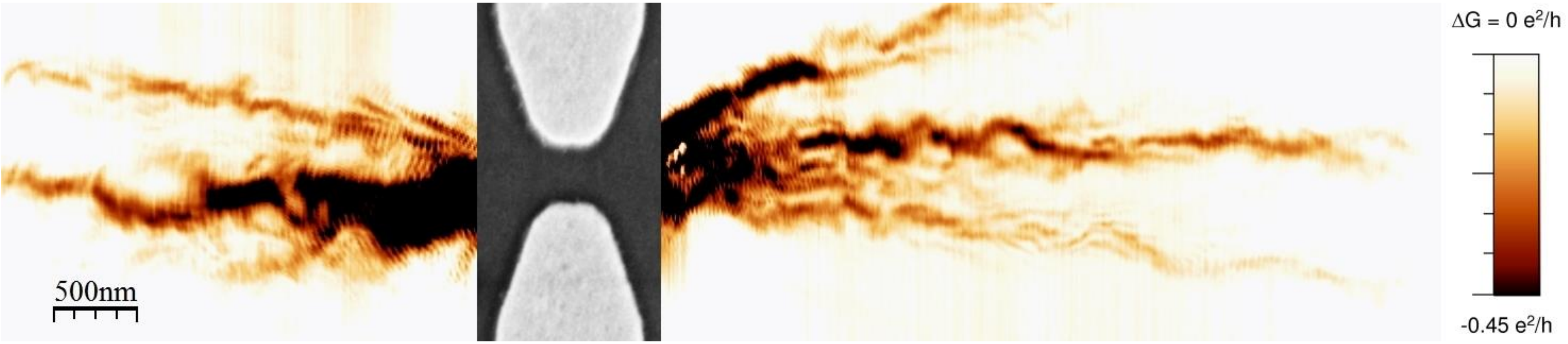
M. A. Topinka et al.: Science **289** (2000) 2323.

Coherent branched flow of electrons



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

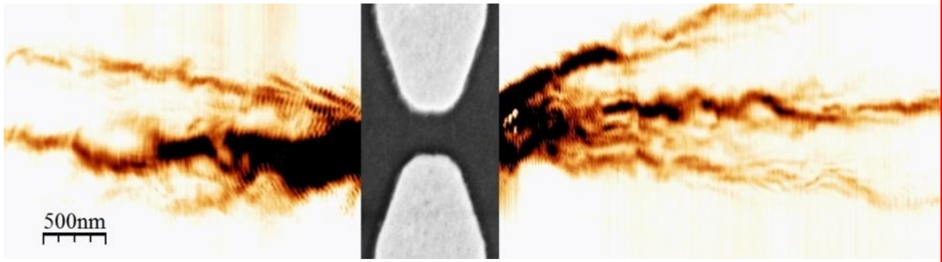
Branched flow of electrons

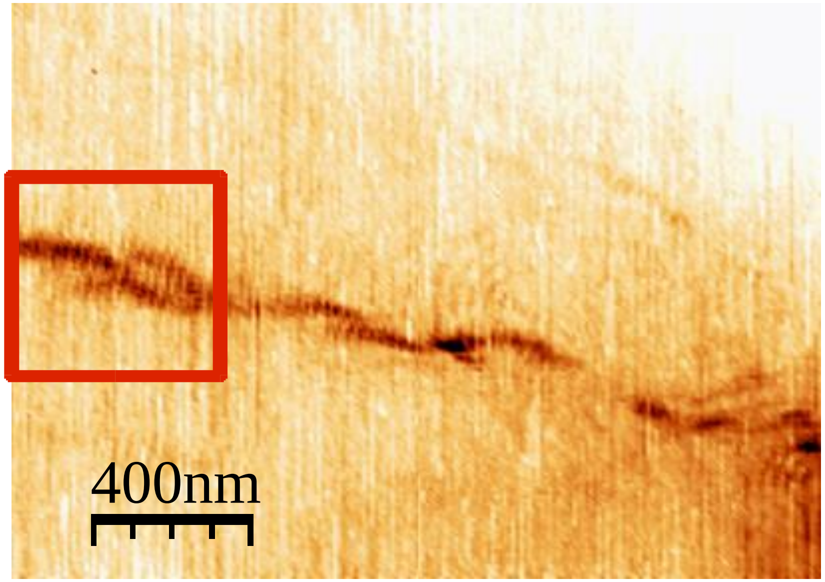


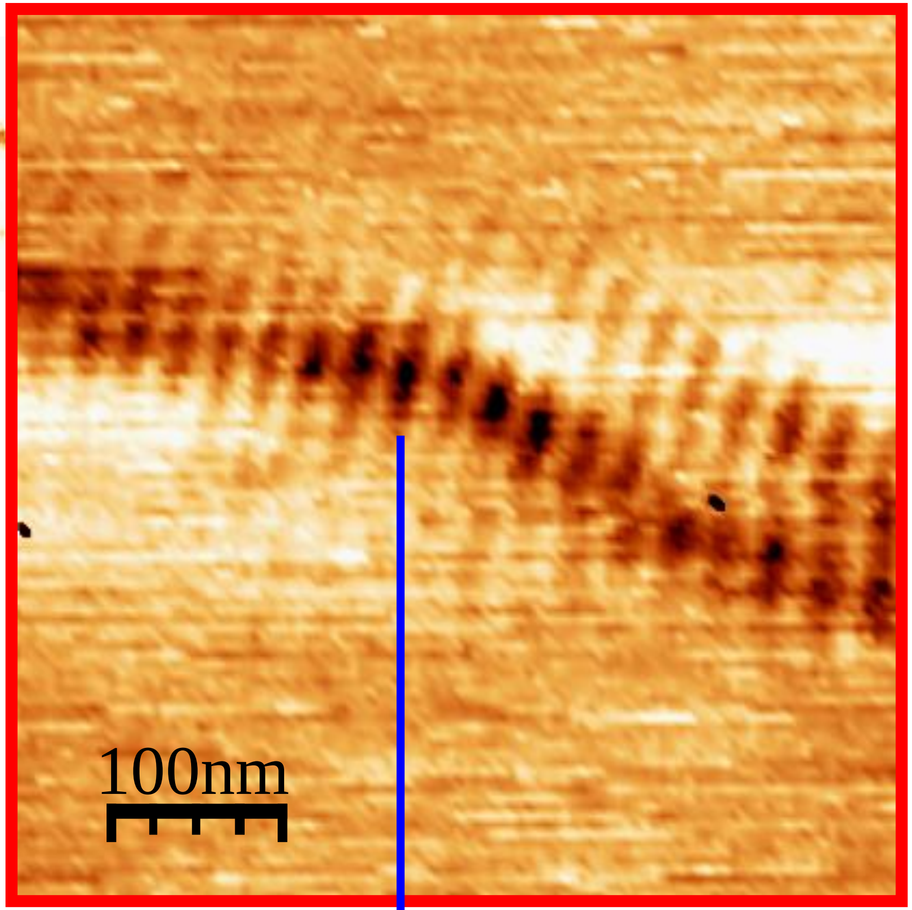
- No magnetic field (B = 0)
- QPC conductance G = 6 e^2/h (3rd plateau)
- Tip voltage V_{tip} = -5 V, height h_{tip} = 10 nm

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

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

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

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

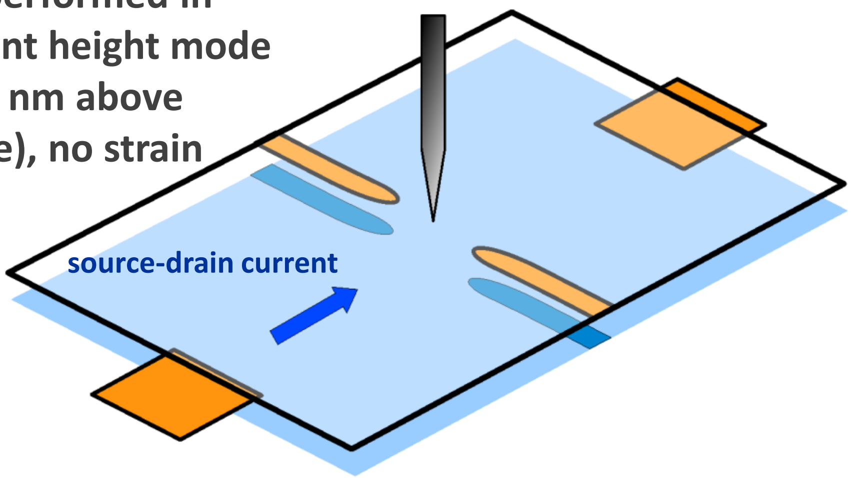
The SGM @NEST lab in Pisa

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**

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

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



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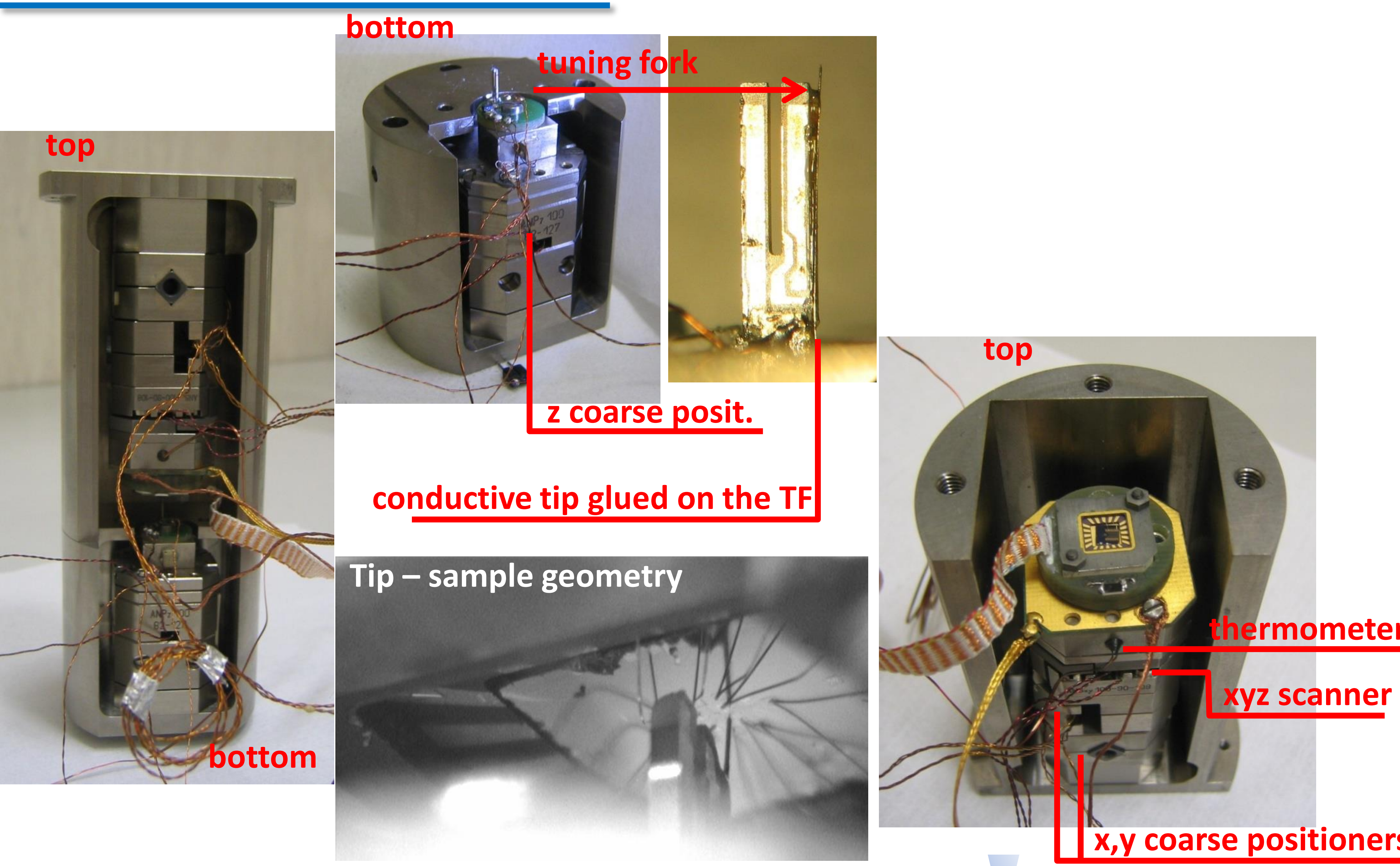
Tuning fork and sample holder



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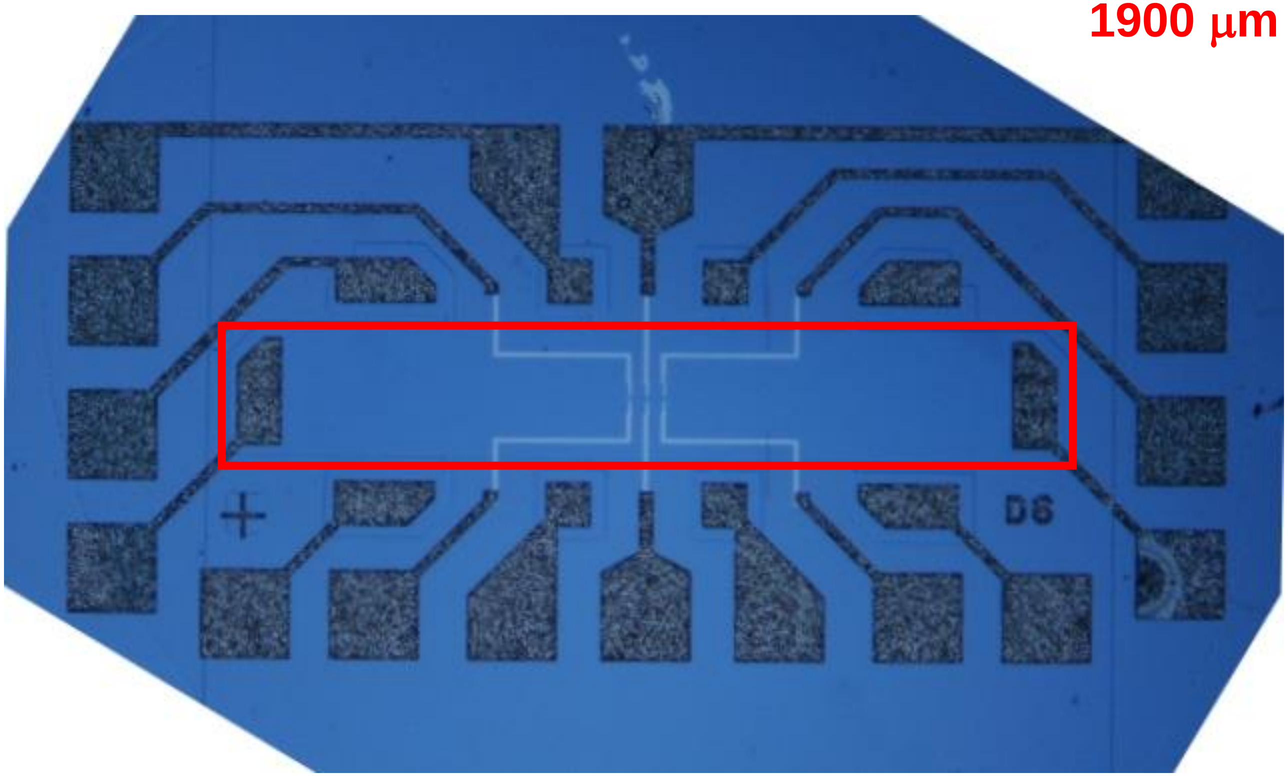
Hall-bar samples

1900 μm x 300 μm



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

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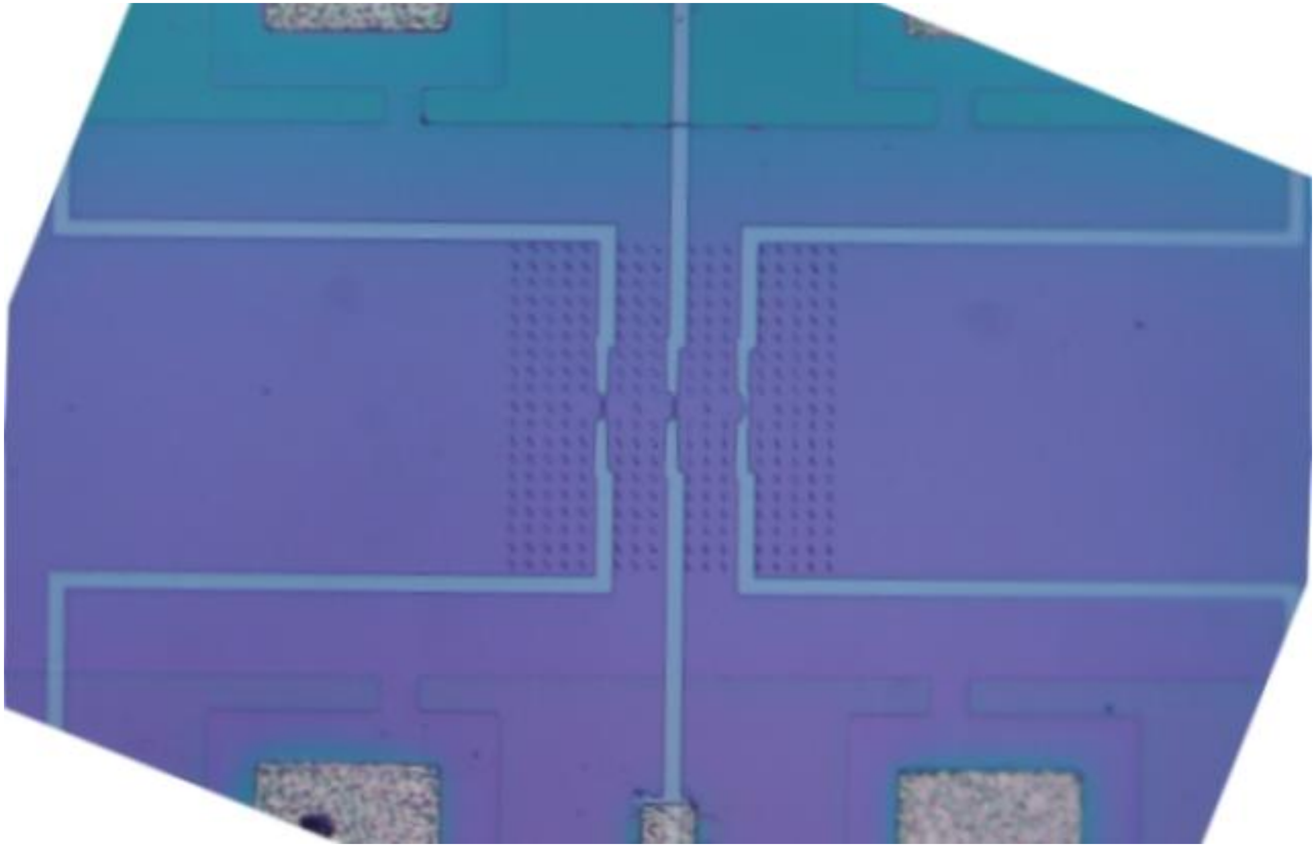

N. Paradiso et al., Physica E **42** (2010) 1038.

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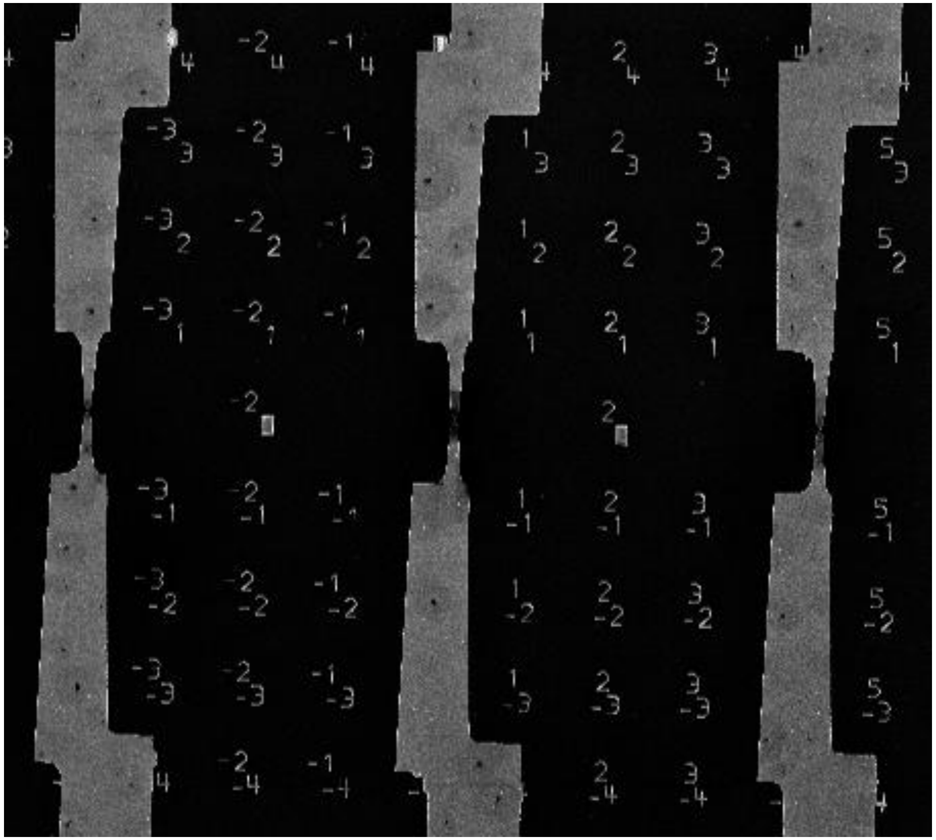

N. Paradiso et al., Physica E **42** (2010) 1038.

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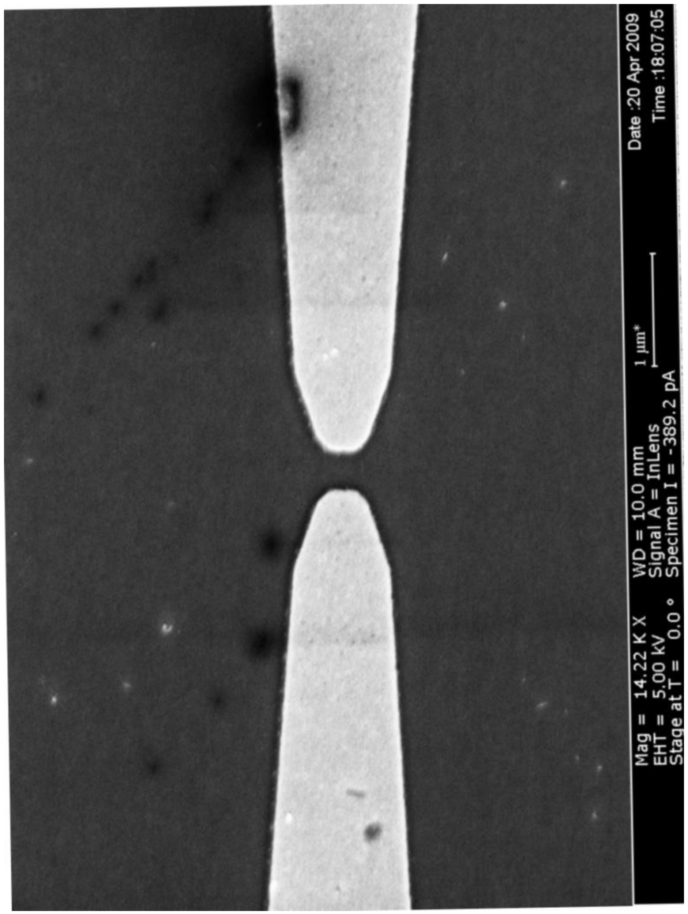

N. Paradiso et al., Physica E **42** (2010) 1038.

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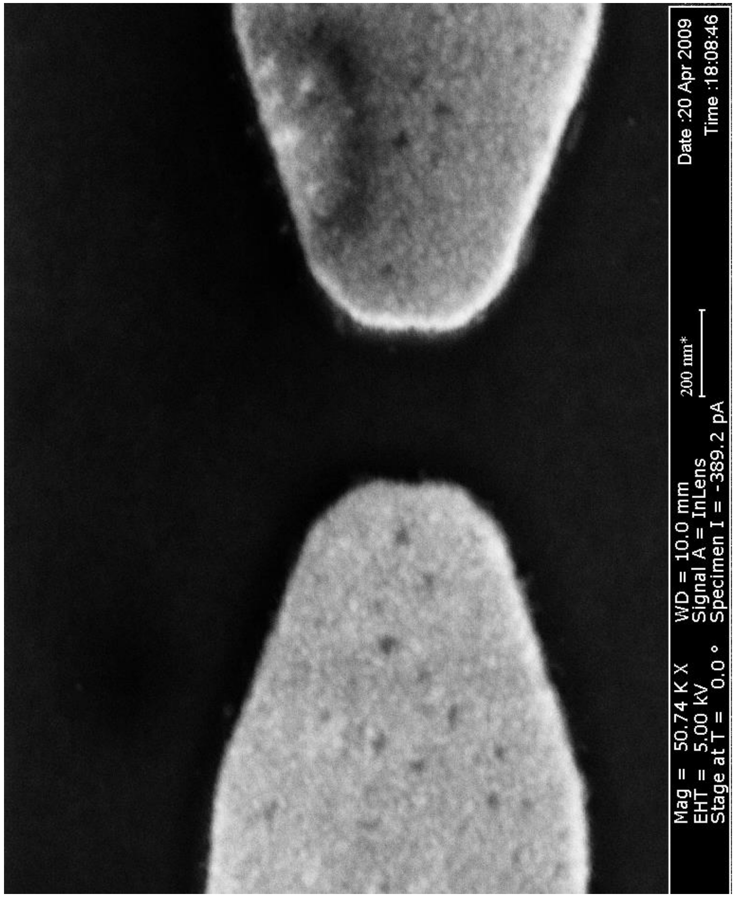
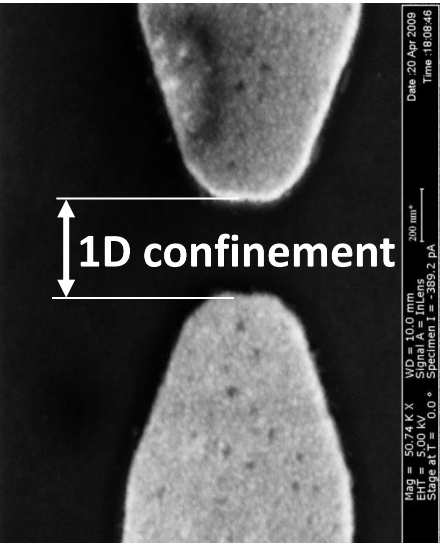
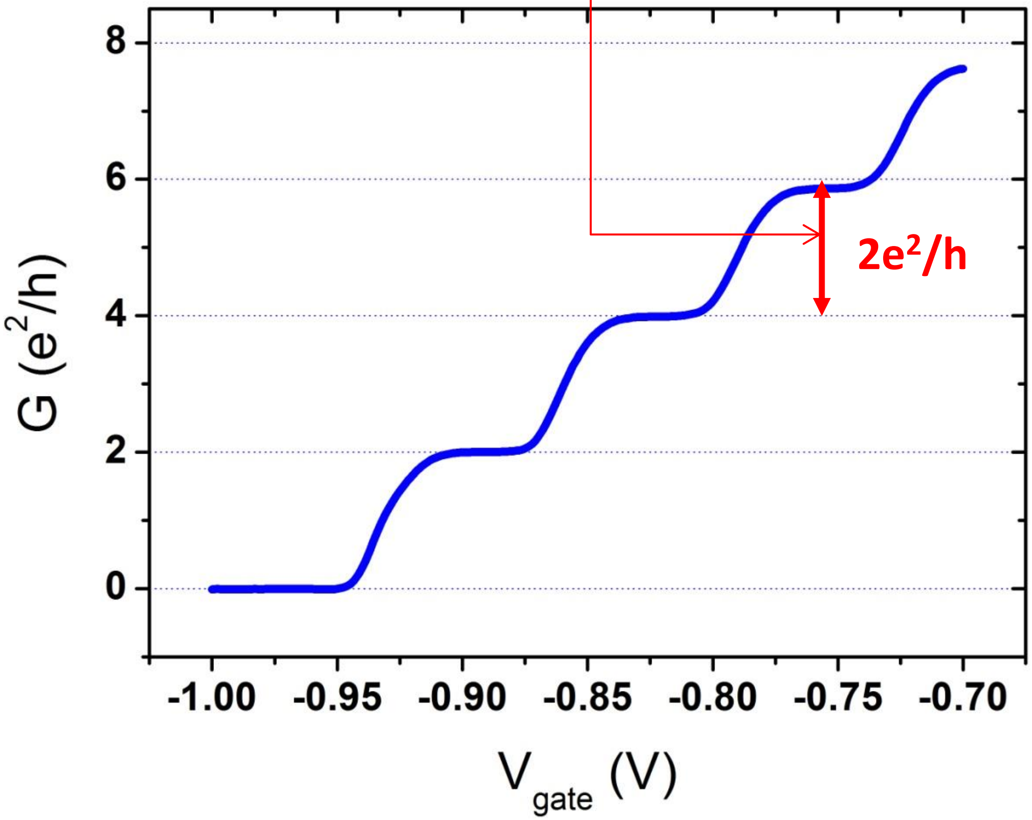


N. Paradiso et al., Physica E **42** (2010) 1038.

Conductance quantization in QPCs

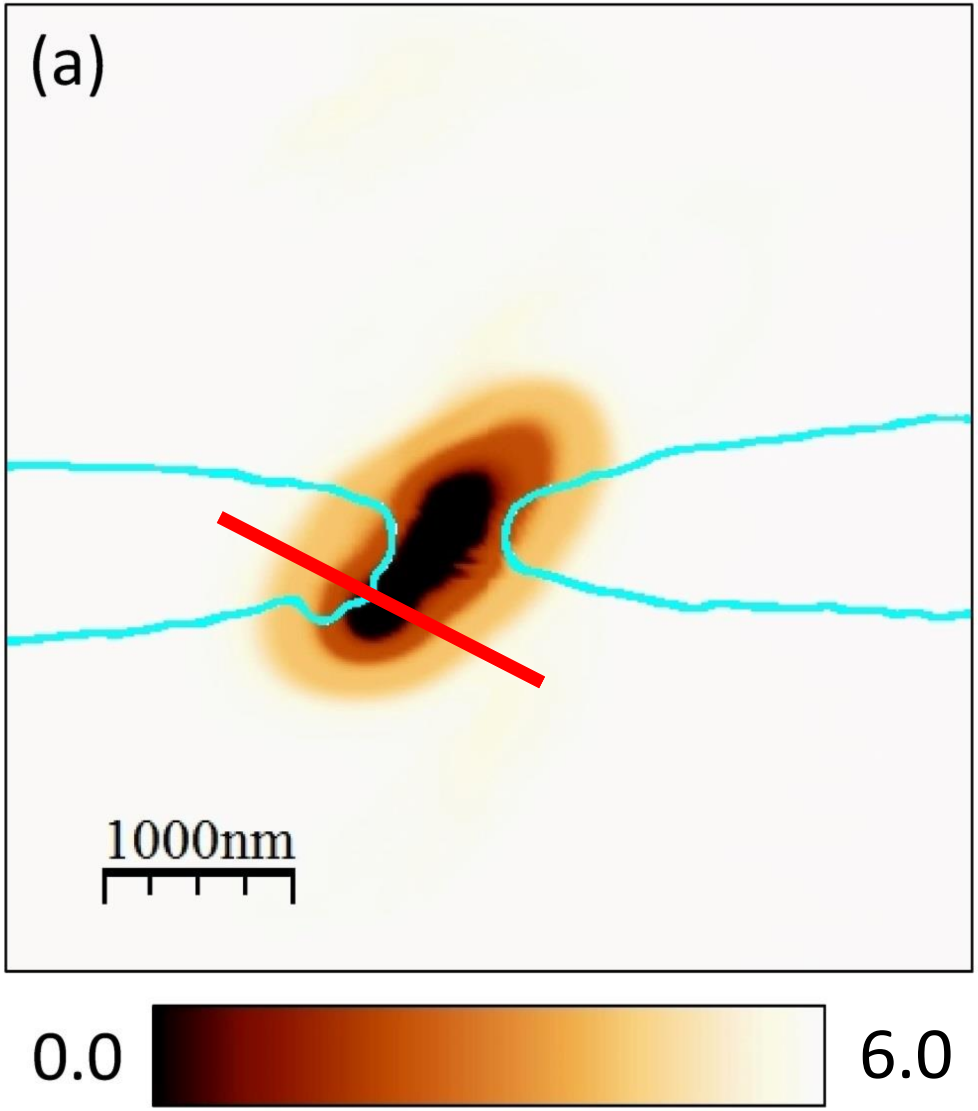


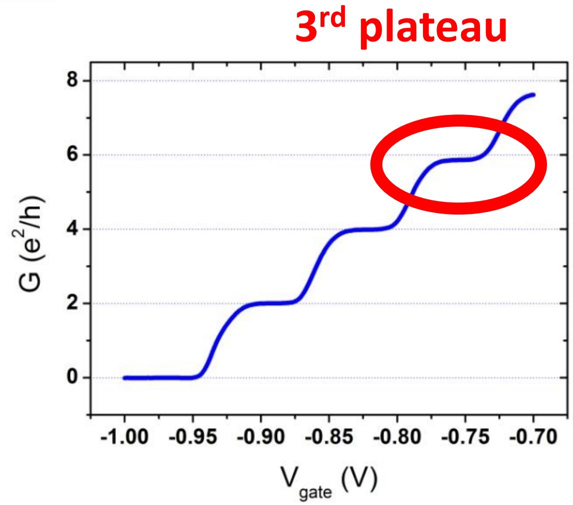
In 1D systems the current is carried by a finite number of modes (arising from confined subbands) . Each mode contributes two quantum of conductance.

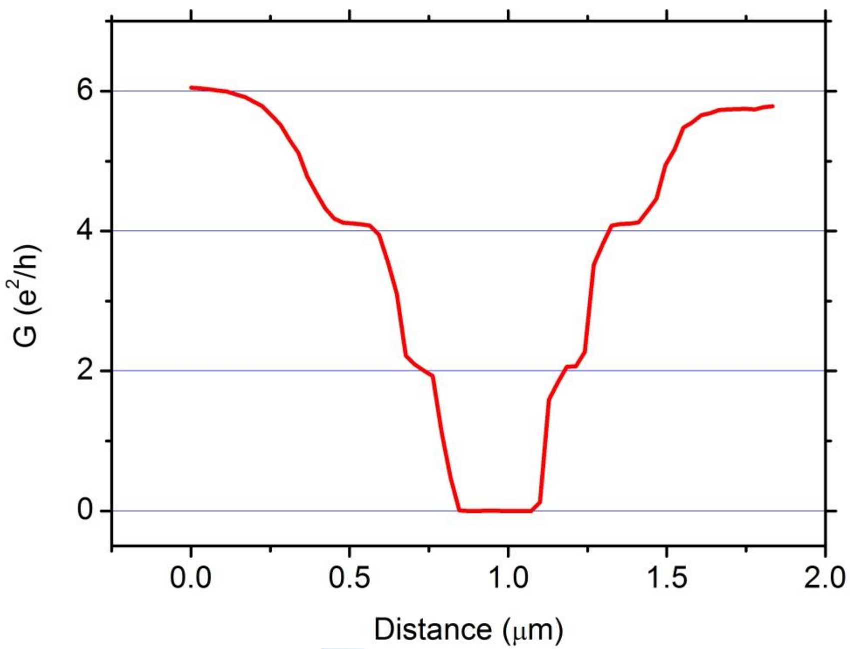


First we fix the mode number (QPC setpoint), then we start scanning the biased tip at a fixed height.

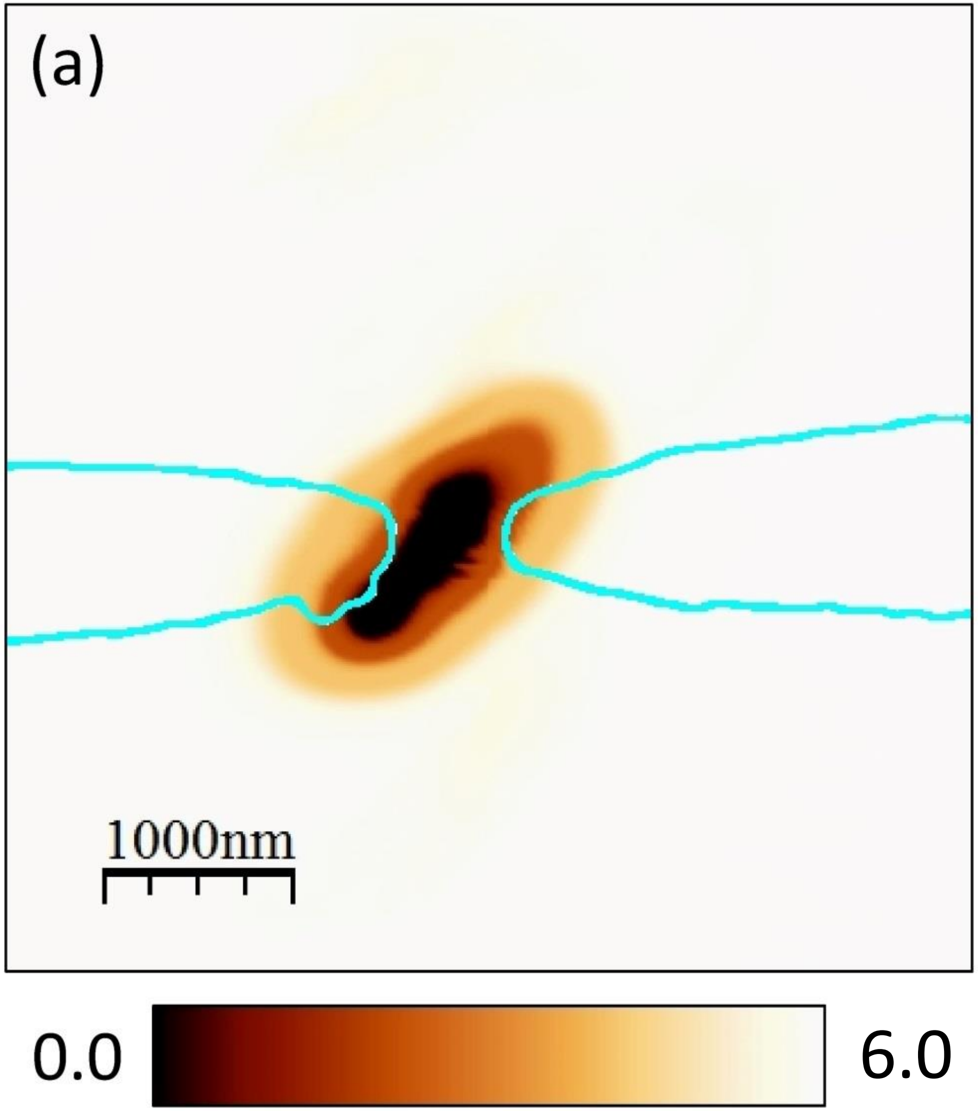
QPC at 3rd plateau



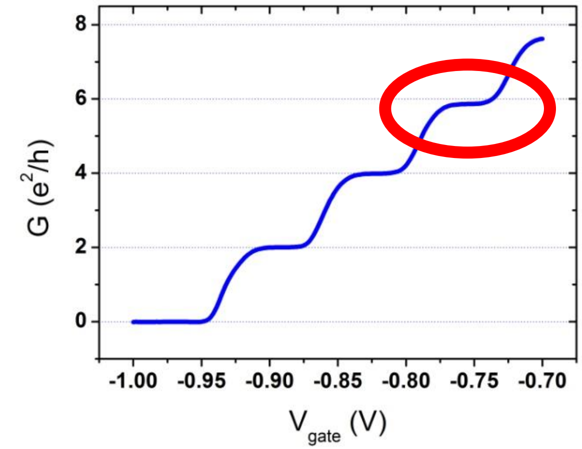


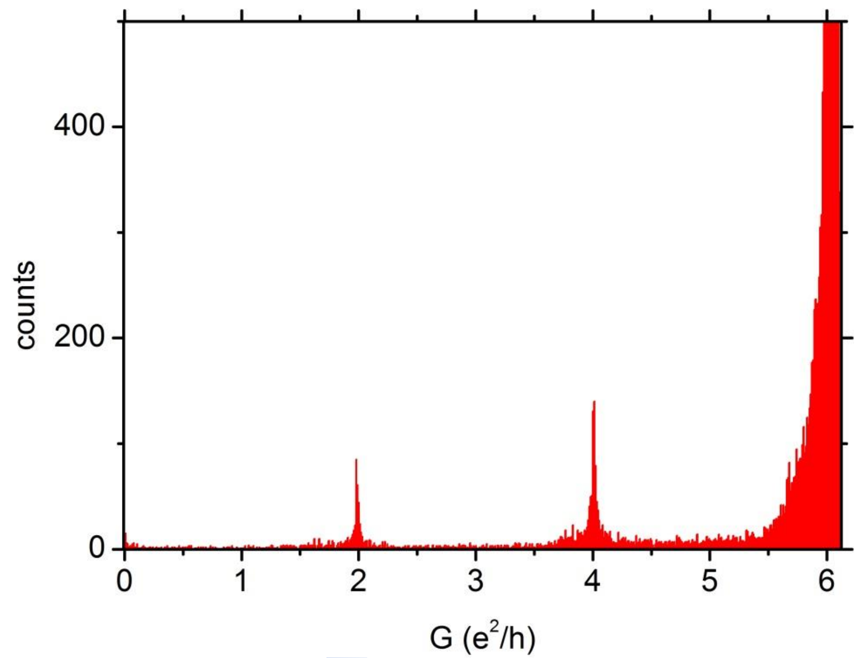


Histogram analysis

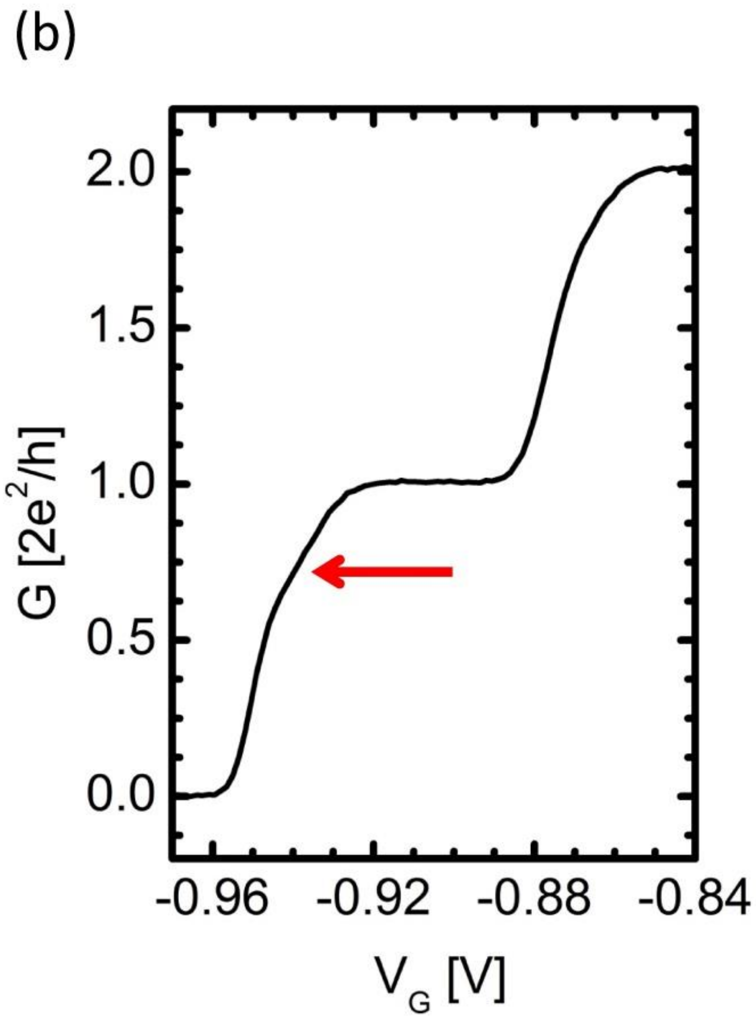


3rd plateau





0.7 Anomaly



Origin still debated

Intrinsic or extrinsic?

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

A. Iagallo *et al.,* Nano Research, doi: 10.1007/s12274-014-0576-y

0.7 Anomaly

LETTER

doi:10.1038/nature12421

Microscopic origin of the ‘0.7-anomaly’ in quantum point

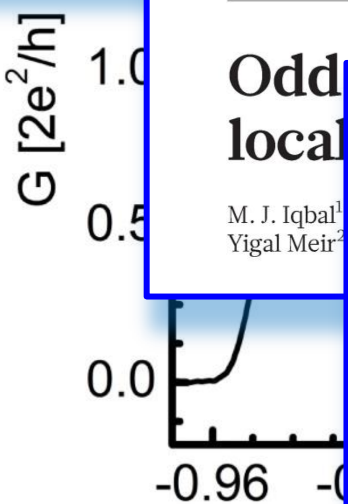
Florian Bauer[1]
Werner Wegsc

LETTER

doi:10.1038/nature12491

Odd
local

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



nature COMMUNICATIONS

ARTICLE

Received 27 Nov 2013 | Accepted 4 Jun 2014 | Published 30 Jun 2014

DOI: 10.1038/ncomms5290

Wigner and Kondo physics in quantum point contacts revealed by scanning gate microscopy

B. Brun[1,2], F. Martins[3], S. Faniel[3], B. Hackens[3], G. Bachelier[1,2], A. Cavanna[4], C. Ulysse[4], A. Ouerghi[4], U. Gennser[4], D. Mailly[4], S. Huant[1,2], V. Bayot[1,3], M. Sanquer[1,5] & H. Sellier[1,2]

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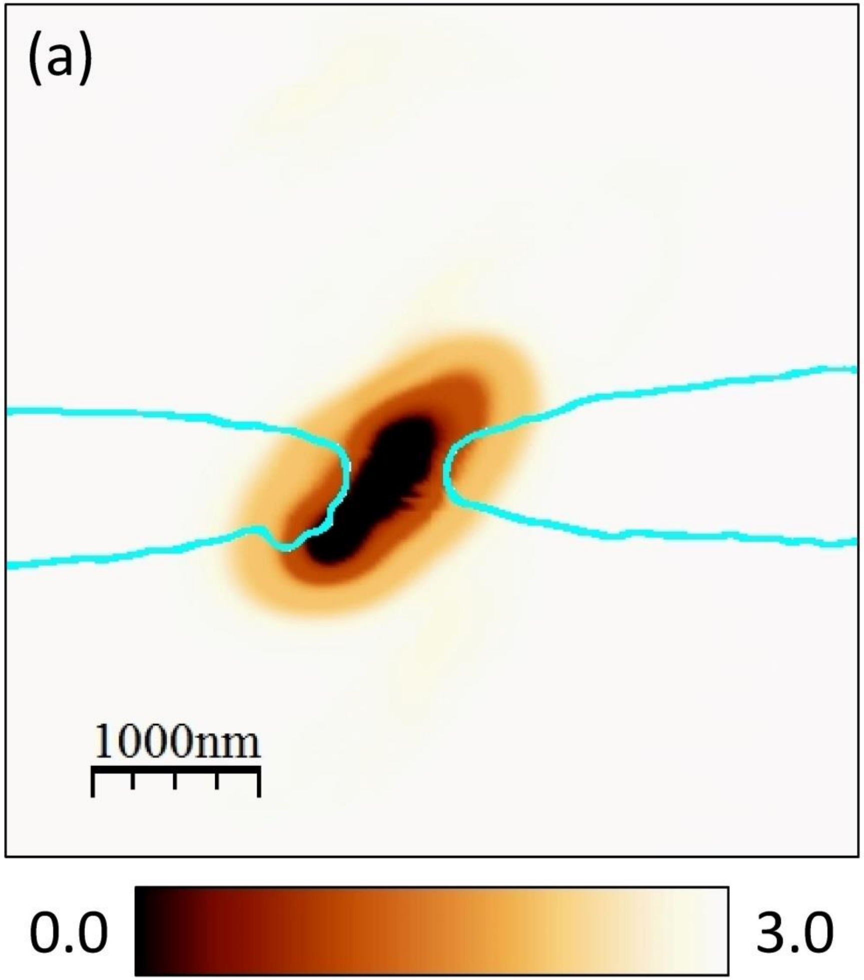
sic?

A. Iagallo *et al.*, Nano R

Device A: QPC with localized impurities



A. Iagallo *et al.,* Nano Research, doi: 10.1007/s12274-014-0576-y

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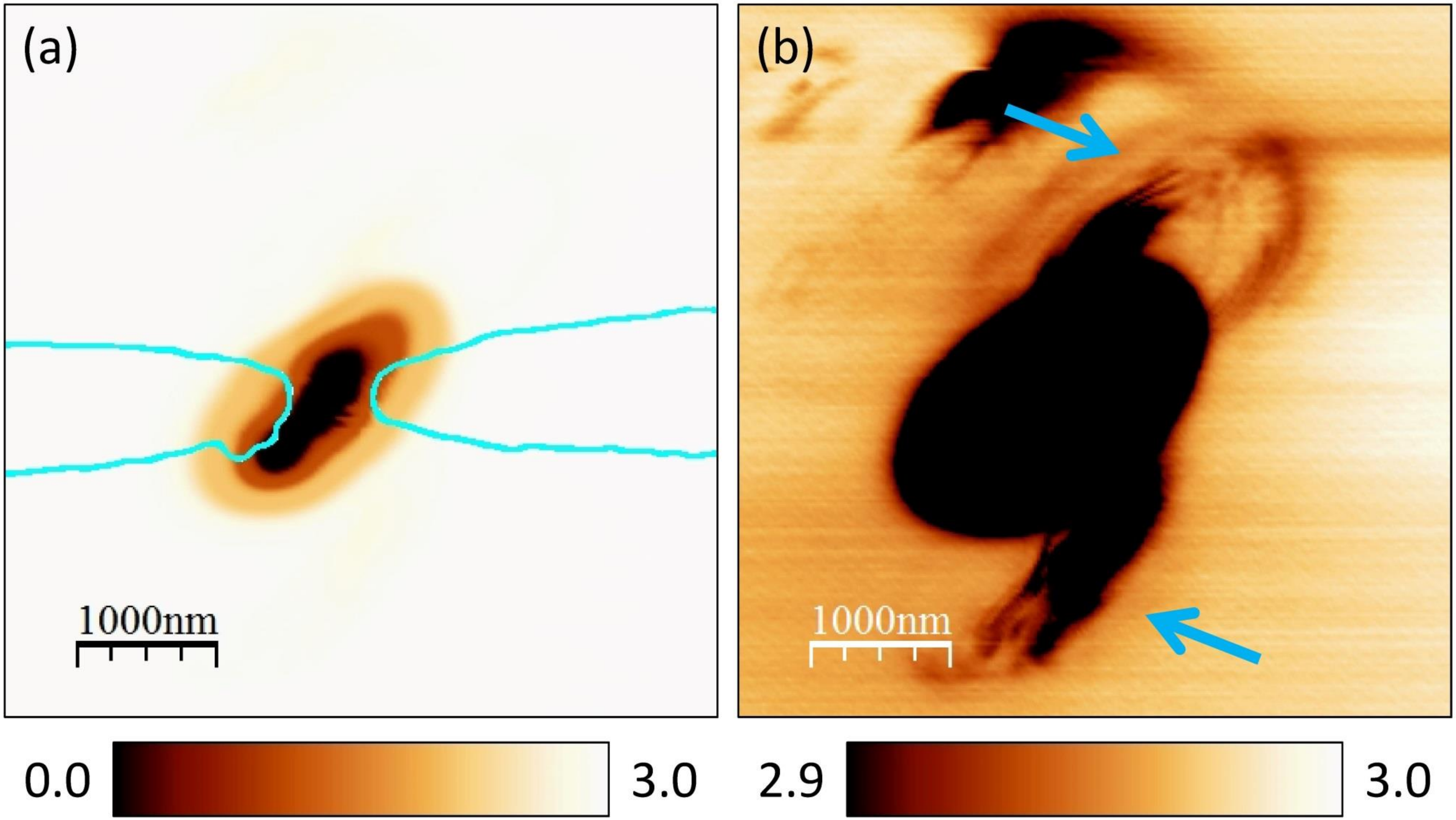
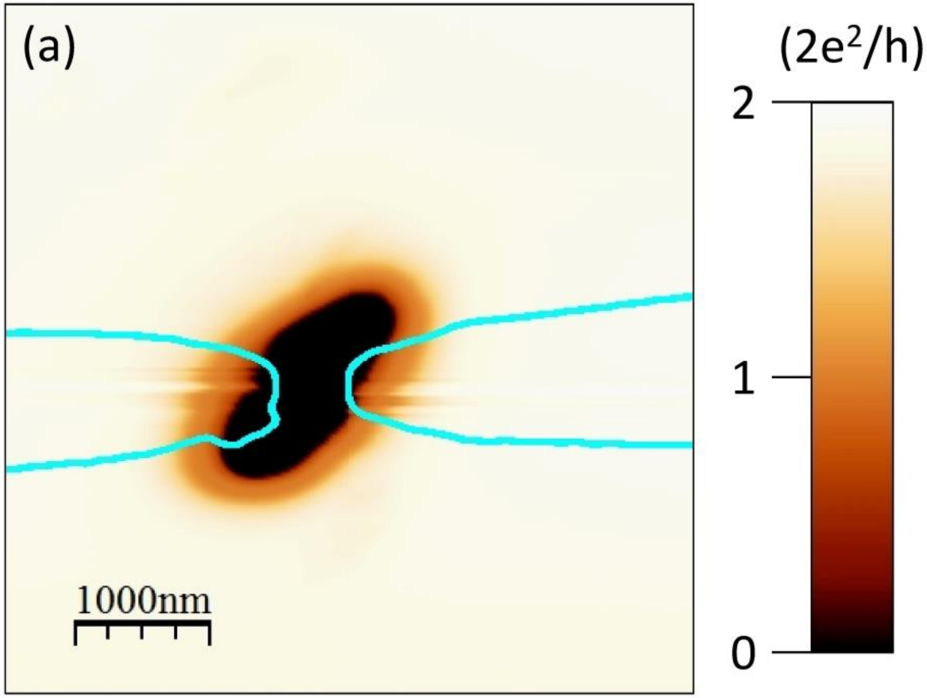
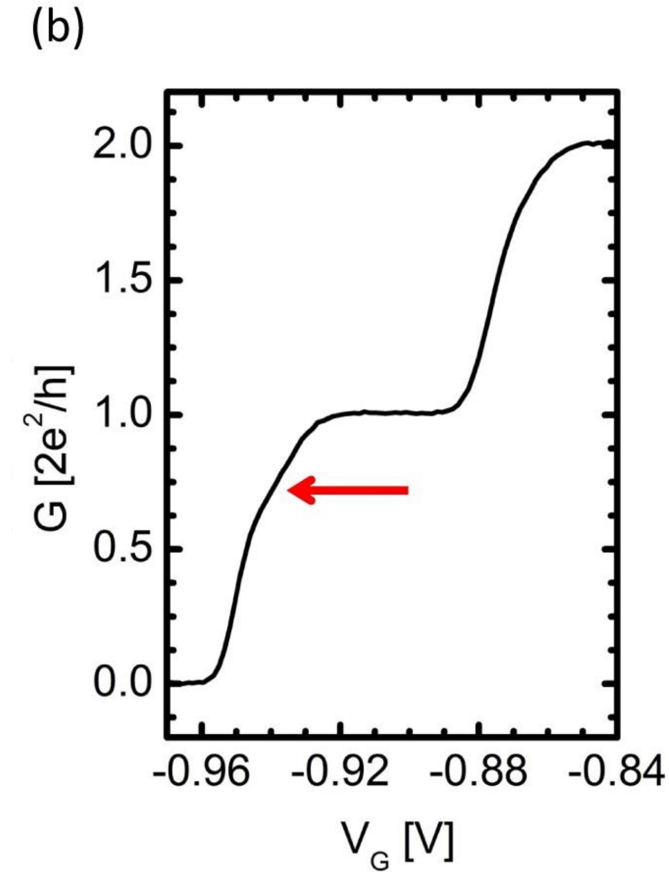


A. Iagallo *et al.,* Nano Research, doi: 10.1007/s12274-014-0576-y

0.7 Anomaly in Device A





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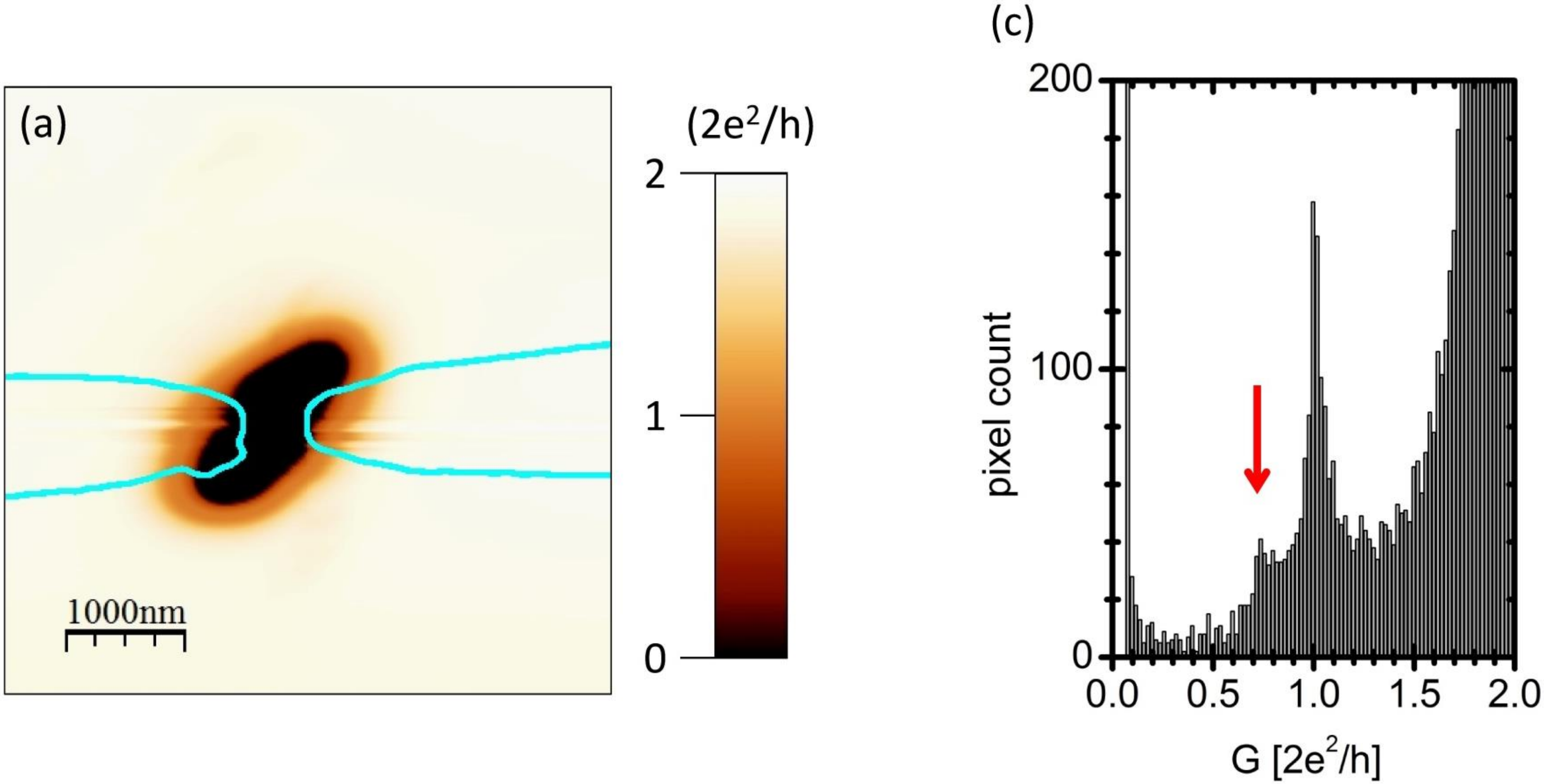
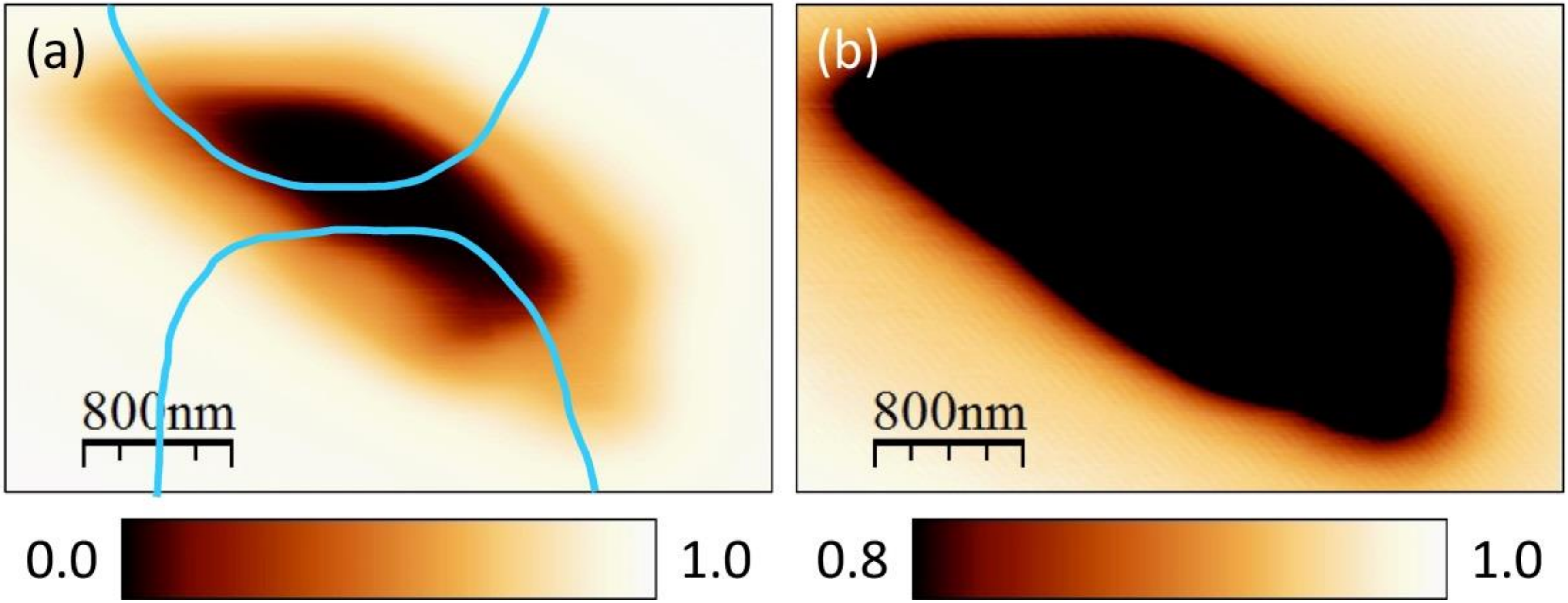


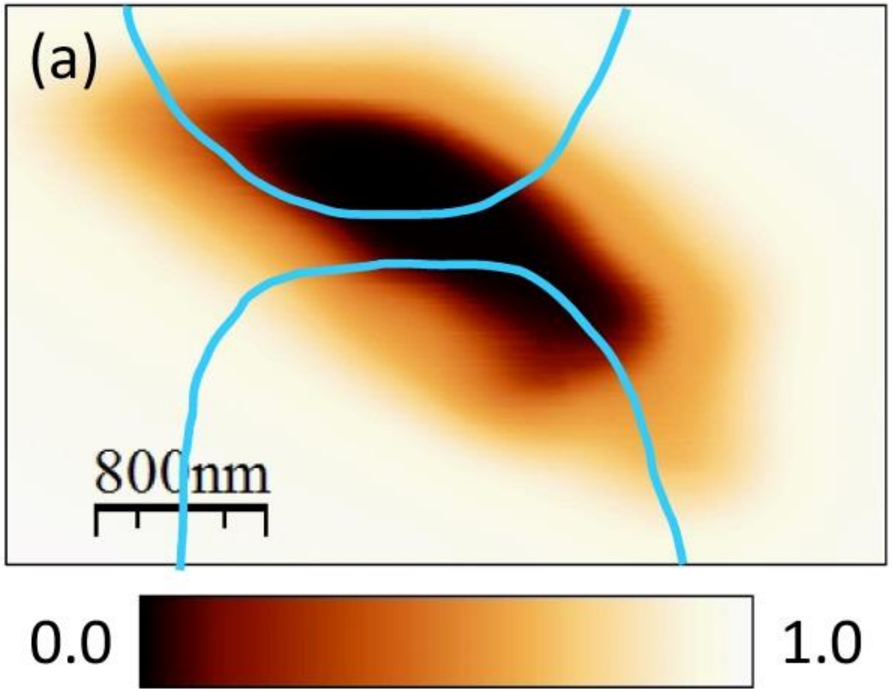
A. Iagallo *et al.,* Nano Research, doi: 10.1007/s12274-014-0576-y

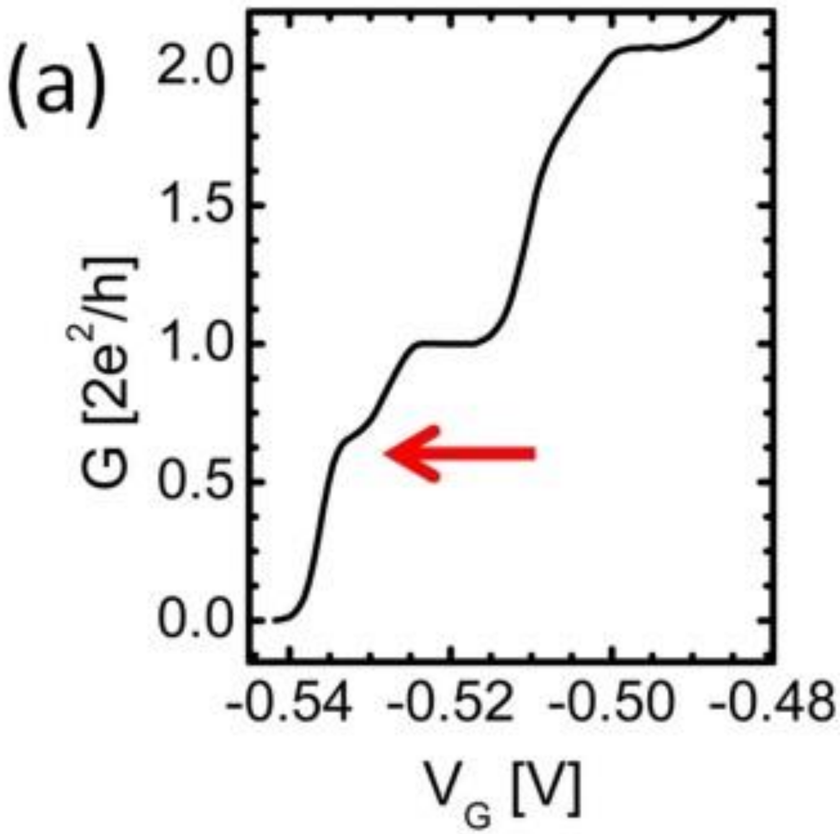
Device B: QPC without localized impurities



A. Iagallo *et al.,* Nano Research, doi: 10.1007/s12274-014-0576-y

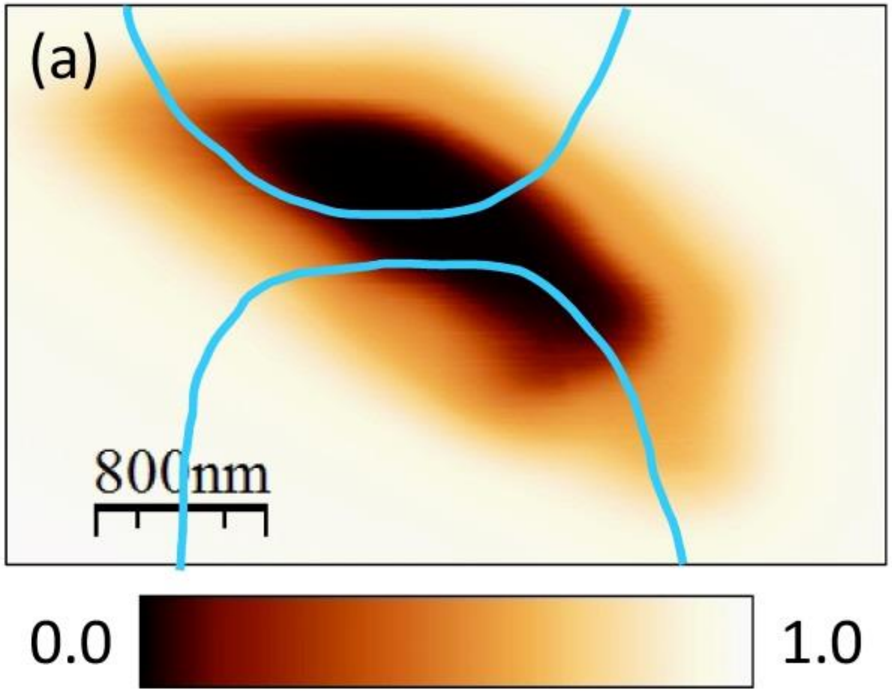
0.7 Anomaly in Device B

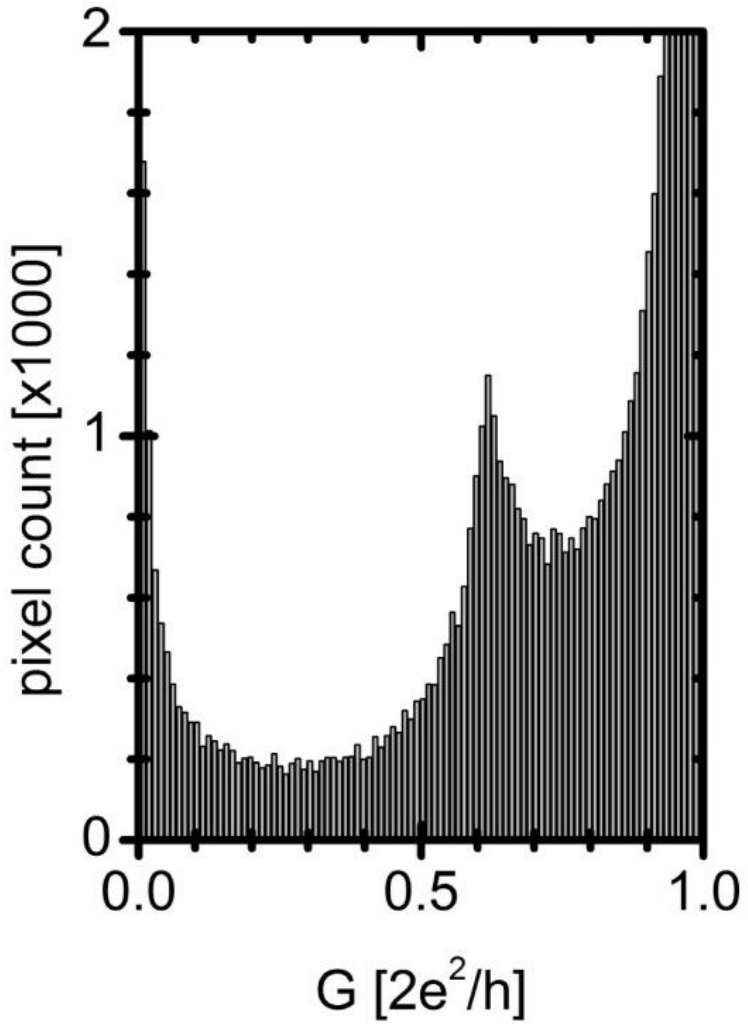




A. Iagallo *et al.,* Nano Research, doi: 10.1007/s12274-014-0576-y

0.7 Anomaly in Device B





A. Iagallo *et al.,* Nano Research, doi: 10.1007/s12274-014-0576-y

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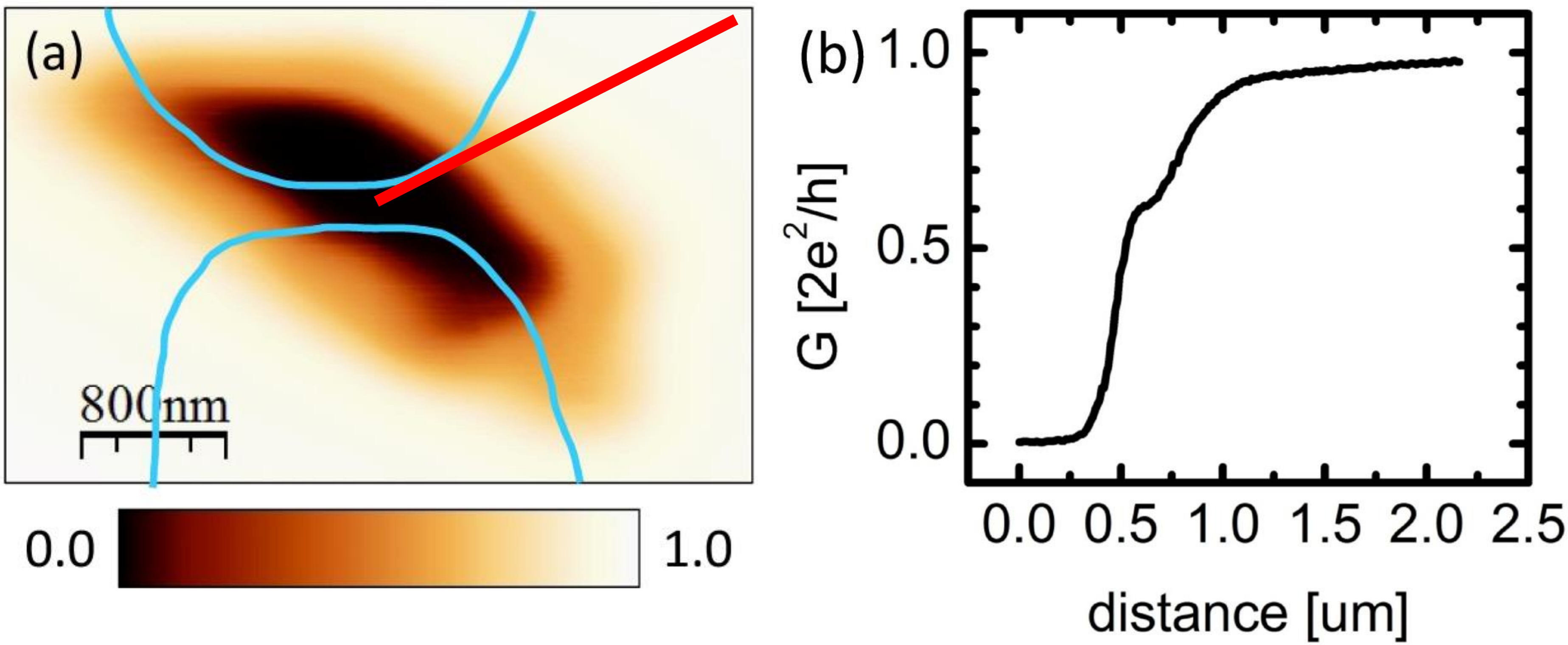

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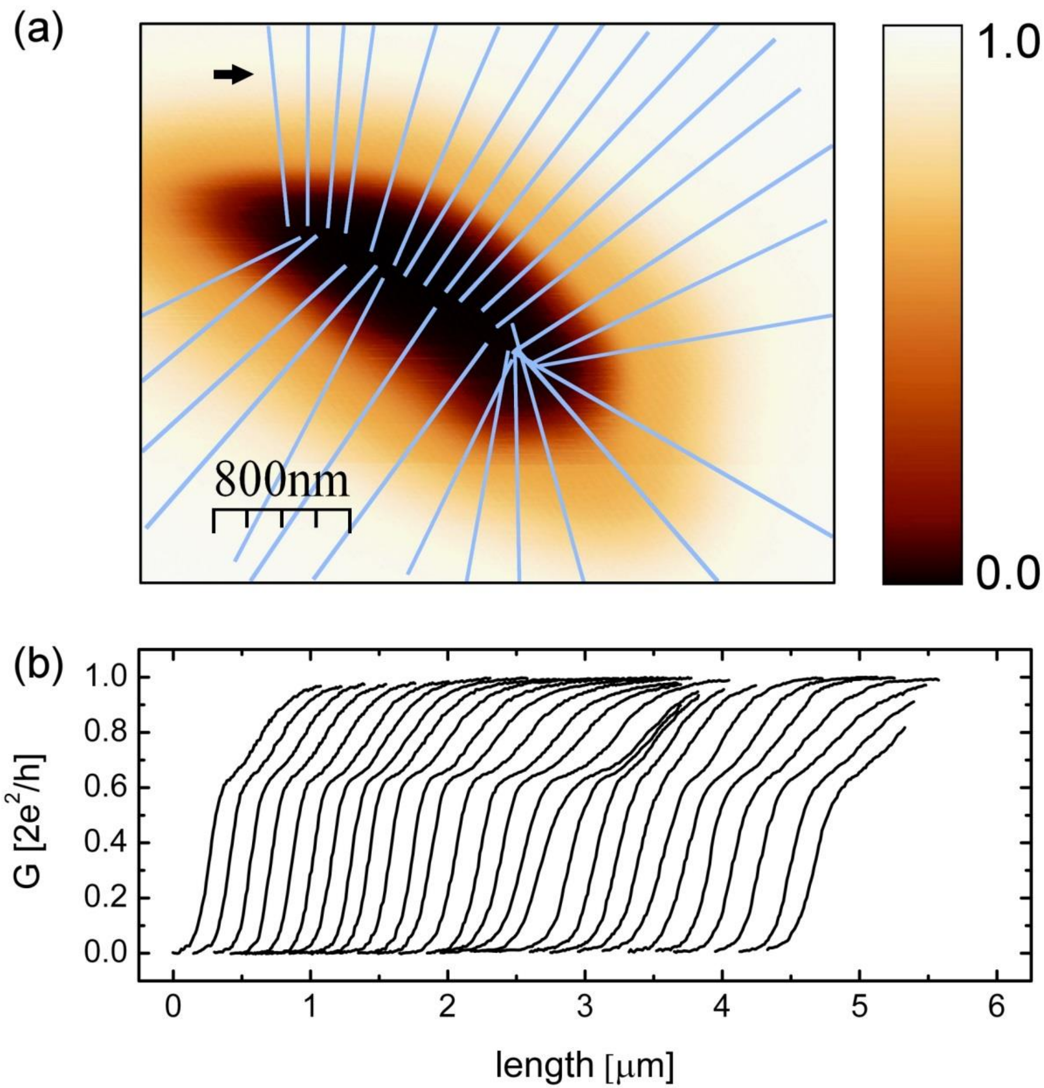

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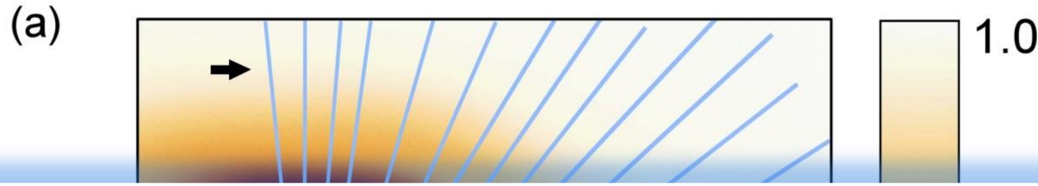
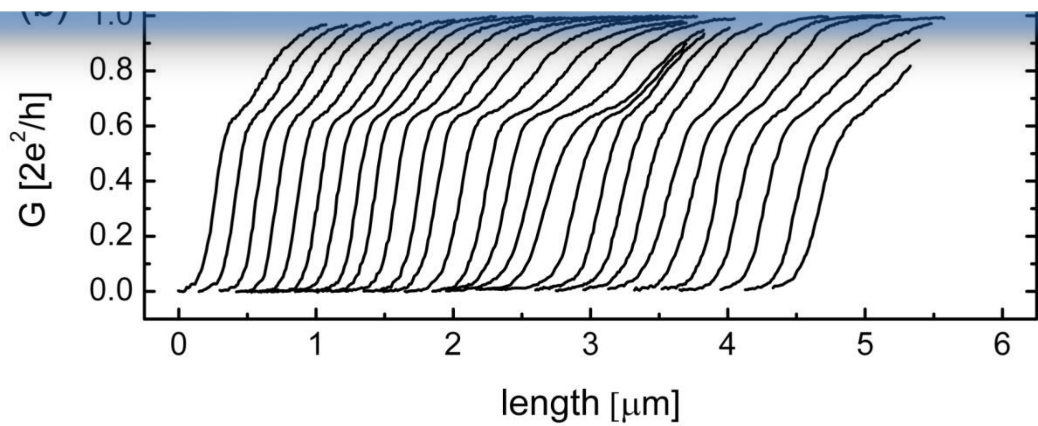


The 0.7 anomaly is observed irrespective of the presence of localized defects and is therefore a fundamental property.



A. Iagallo *et al.,* Nano Research,
doi: 10.1007/s12274-014-0576-y

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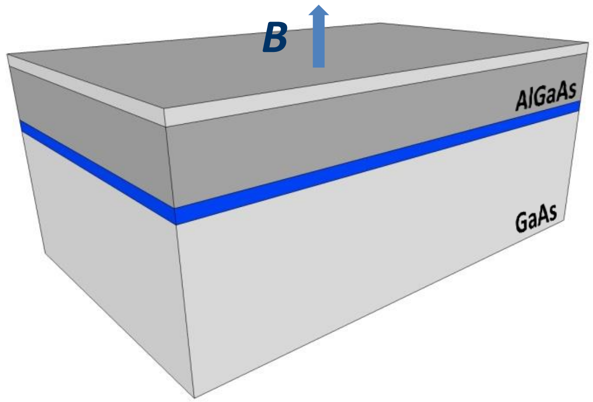
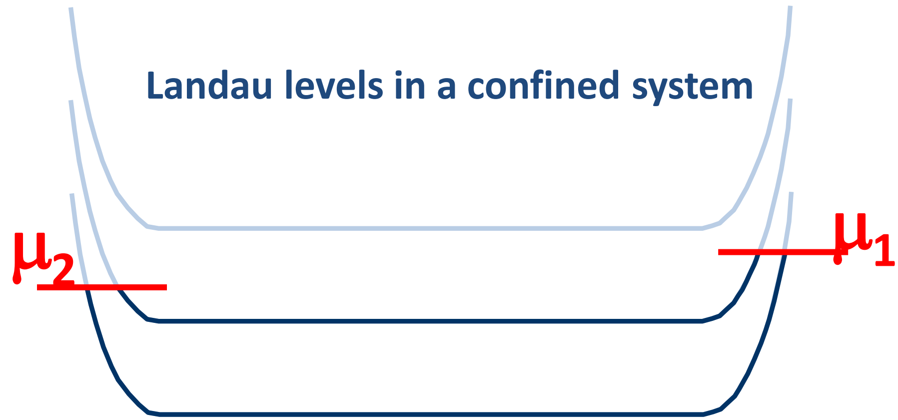
The non-interacting picture of the QH effect

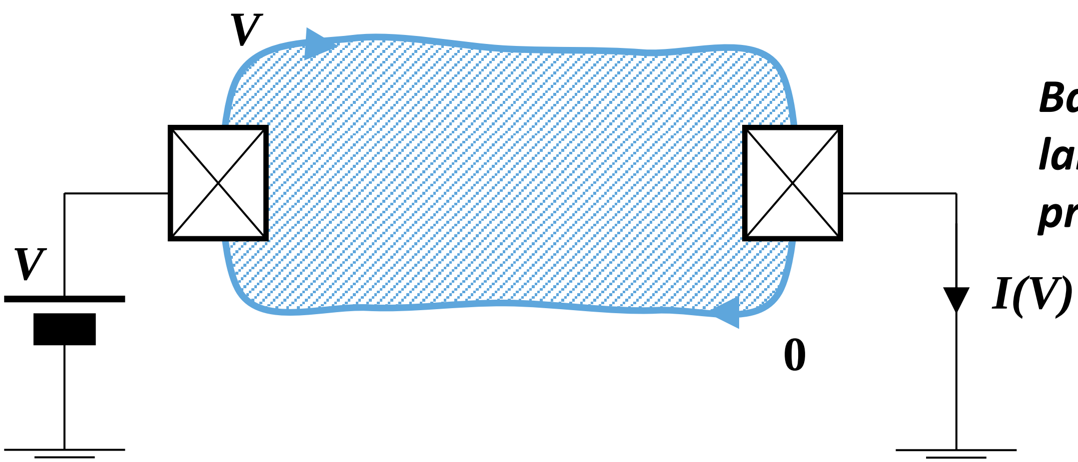


2DES
in high field



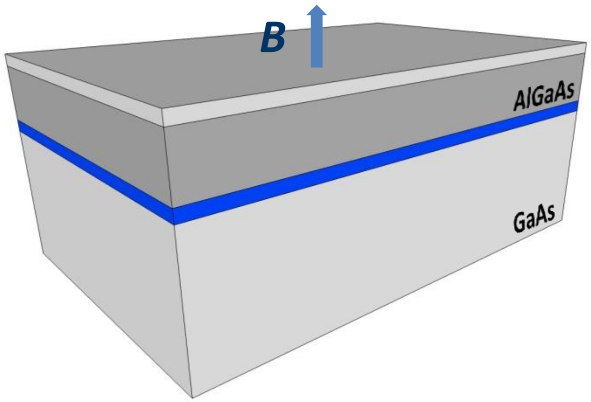
- Edge state picture:
  current is carried by chiral 1D channels

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



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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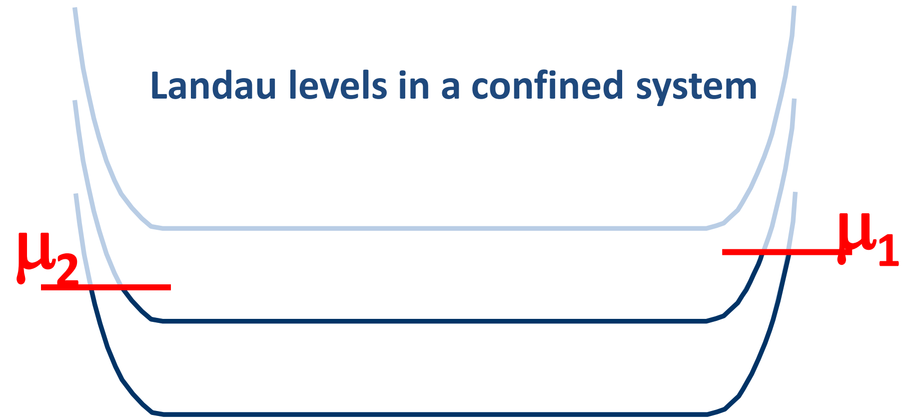

- Edge state picture:
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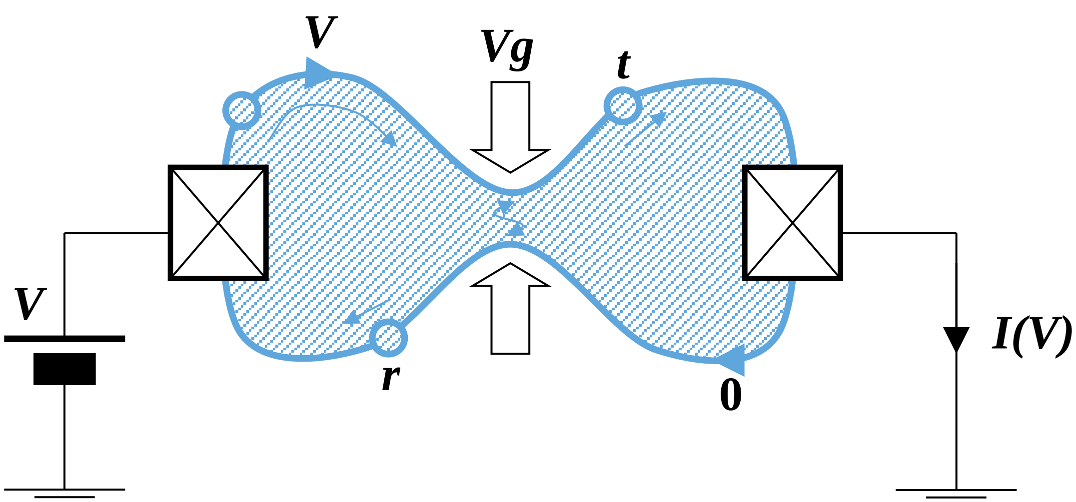


With a QPC we can intentionally induce backscattering, which provides us information about the edge properties

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

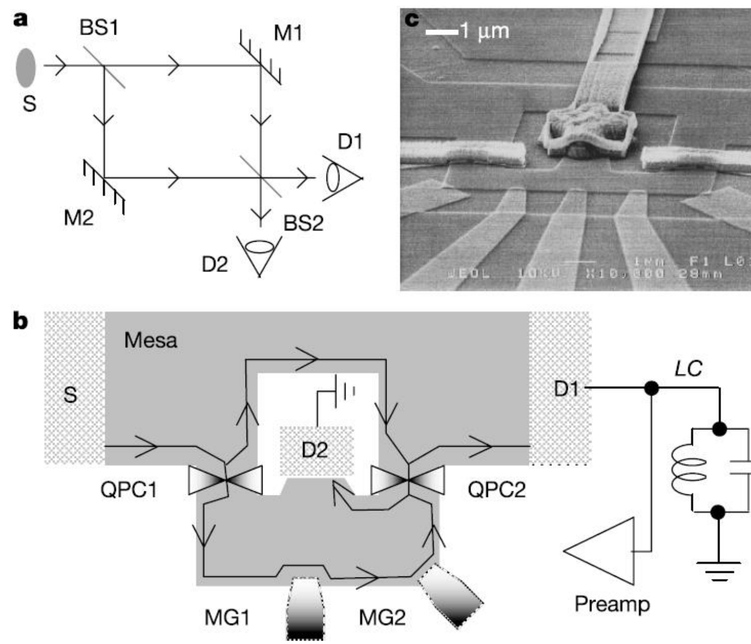
Edge channel-based interferometers

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**

An electronic Mach–Zehnder interferometer

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



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

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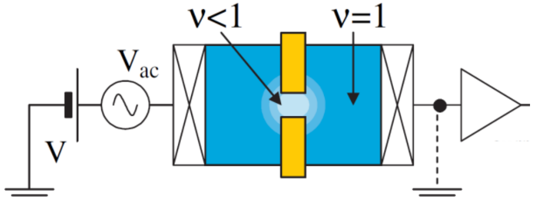
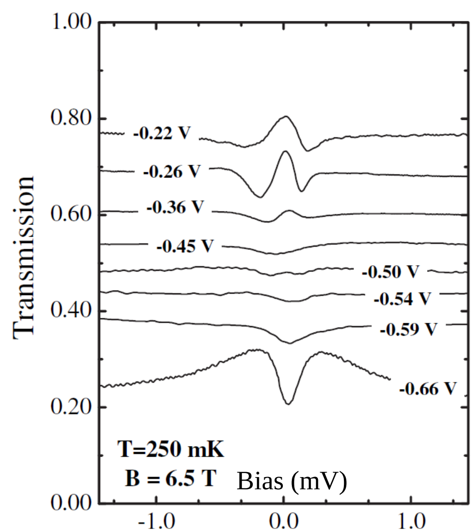
Role of the inner edge structure?

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



PRL **95**, 156804 (2005)



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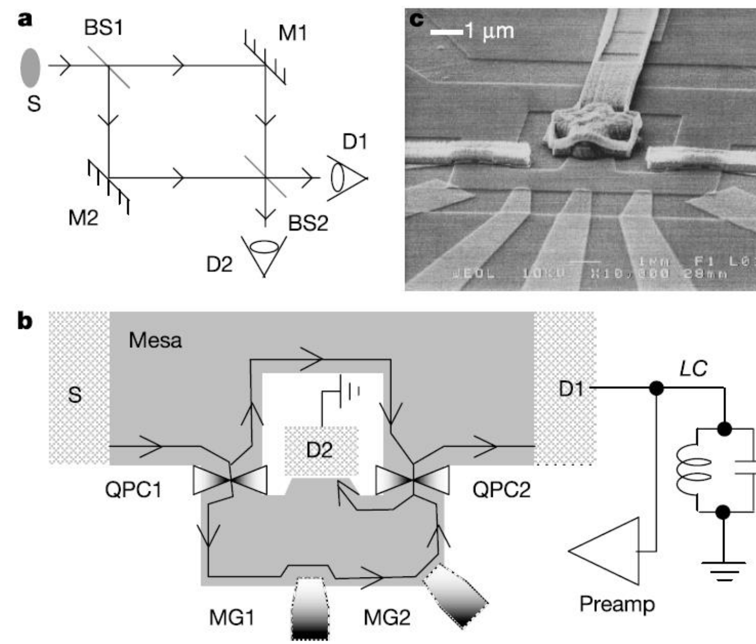


Ji *et al.*: Nature **422**, 415 (2003)

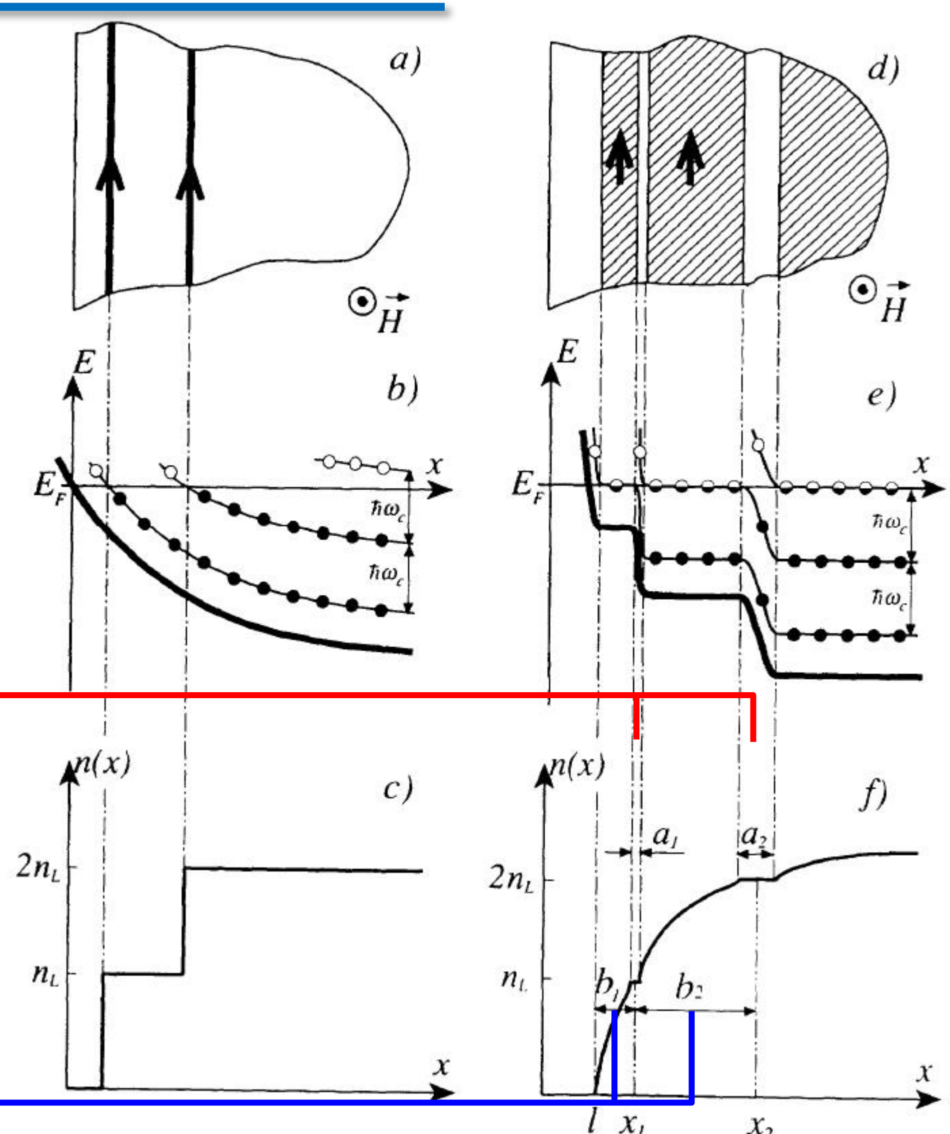
Need for spatially resolved measurements

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



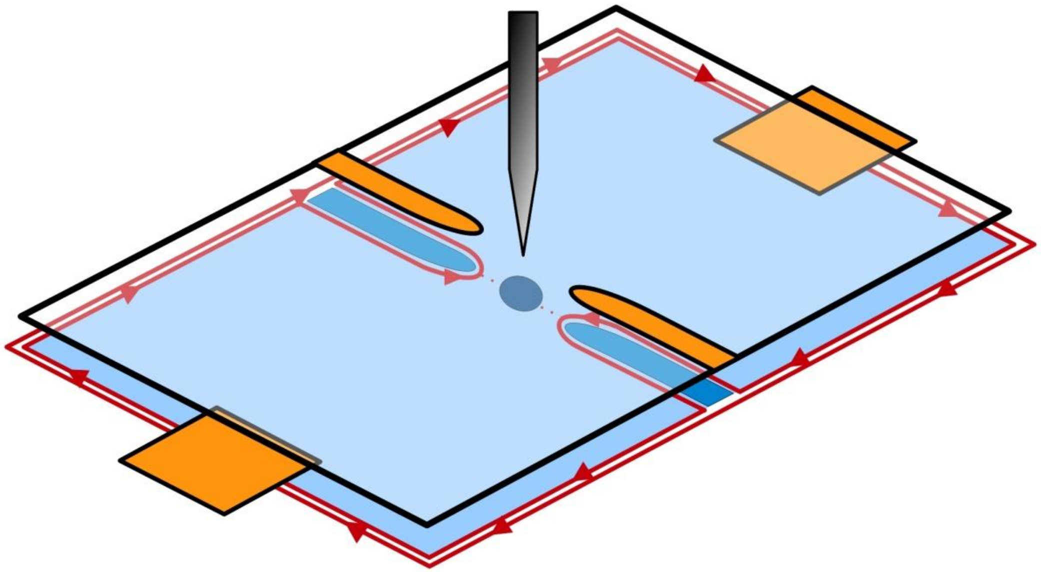
<u>Incompressible</u> stripes:
- The electron density is constant
- The potential has a jump

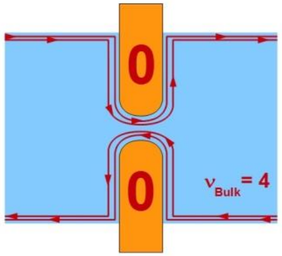
<u>Compressible</u> stripes:
- The electron density has a jump
- The potential is constant

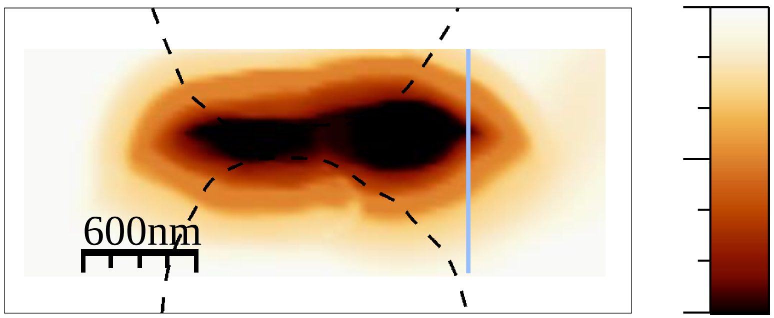
D. B. Chklovskii *et al*.: PRB **46** (1992) 4026.

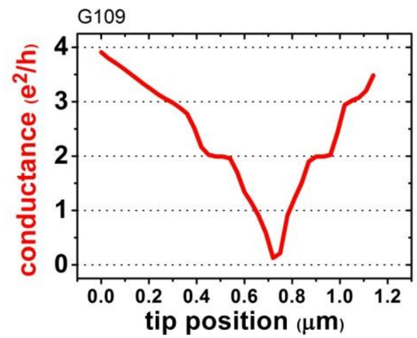
Edge channel tomography by SGM

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.





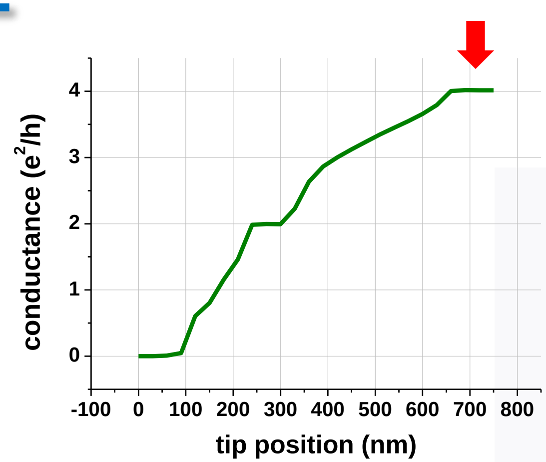


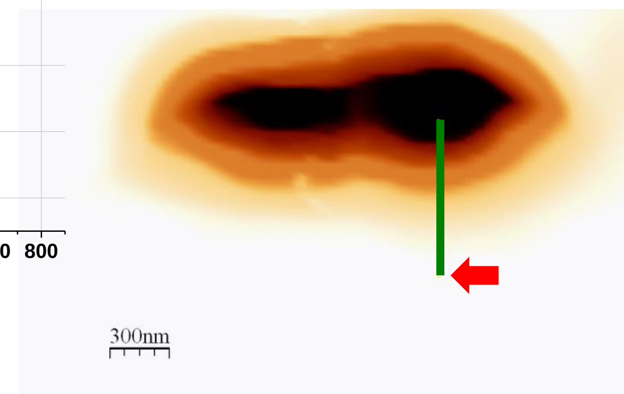


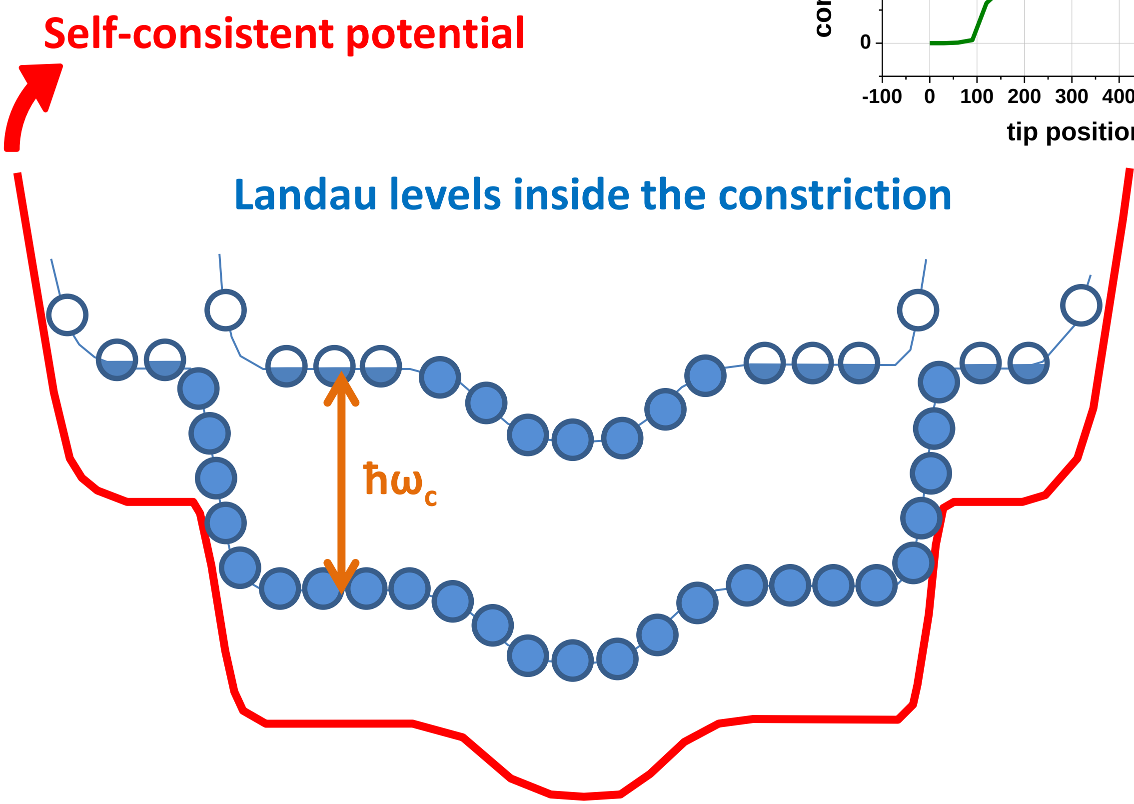
- **Bulk filling factor ν=4**
- **B = 3.04 T**
- **2 spin-degenerate edge channels**
- **gate-region filling factors $g_1 = g_2 = 0$**

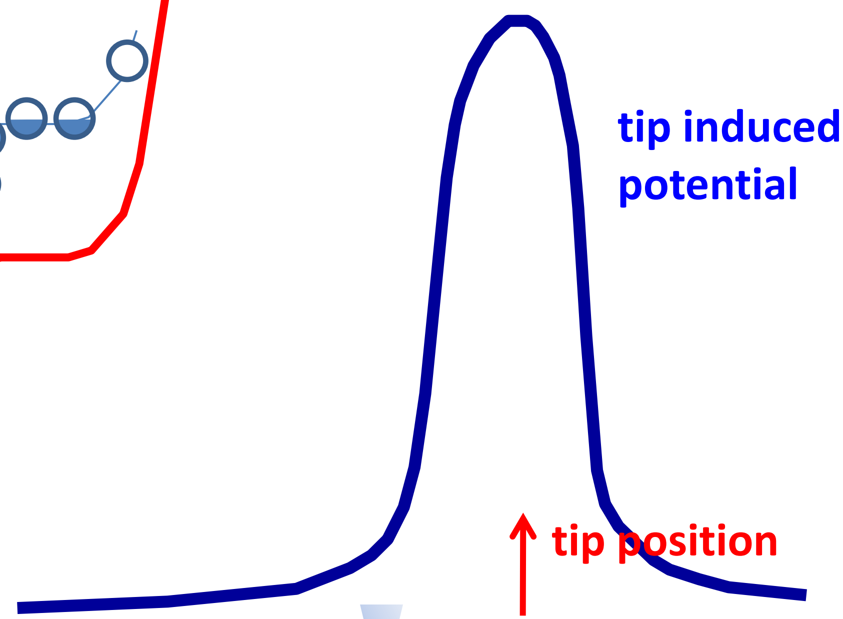
N. Paradiso *et al., Physica E 42 (2010) 1038.*

How we probe incompressible stripes

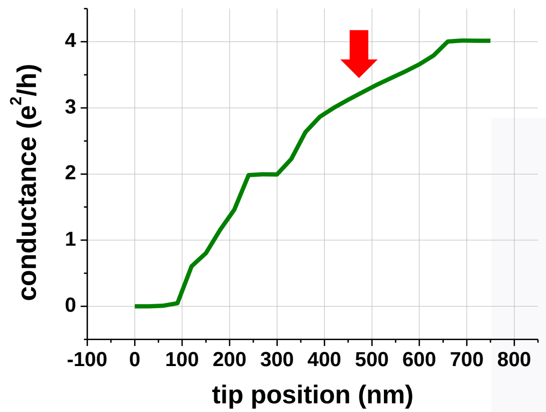


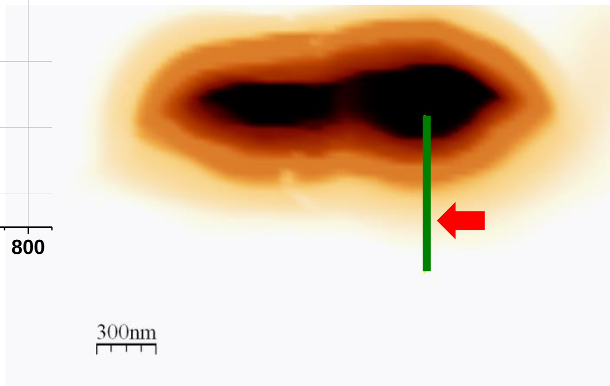


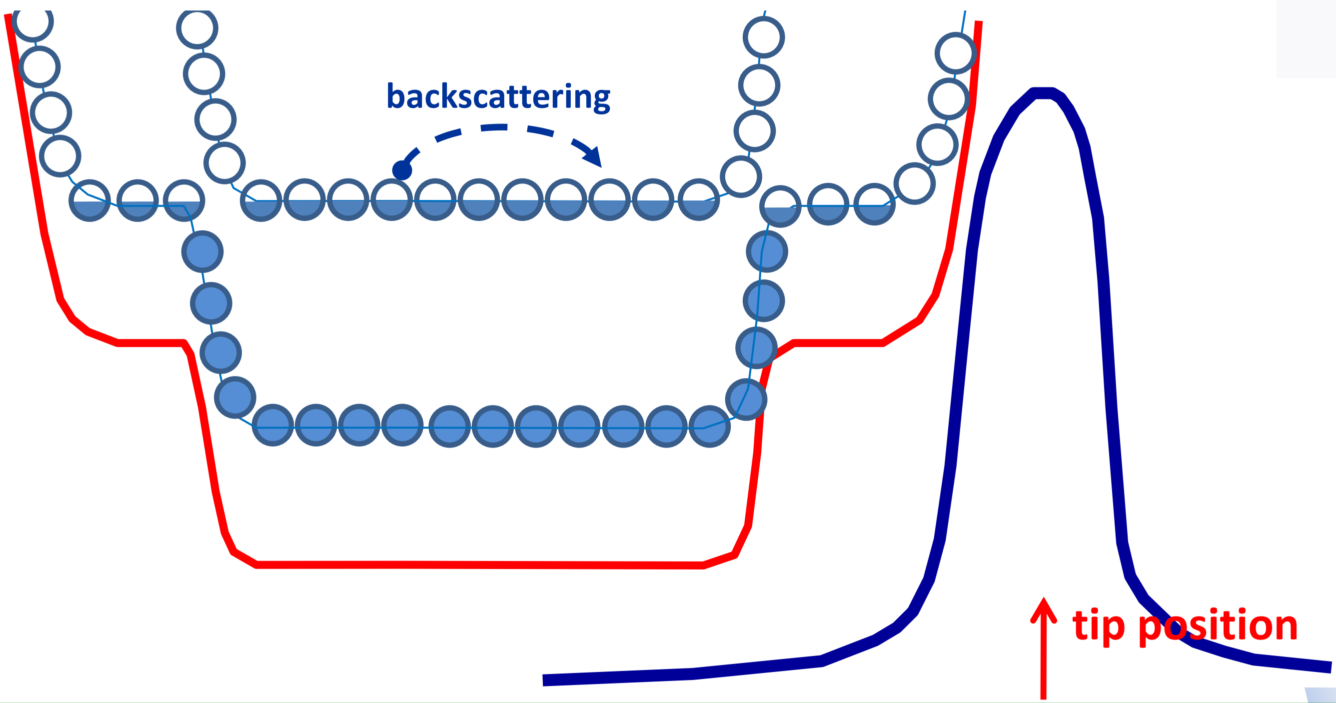




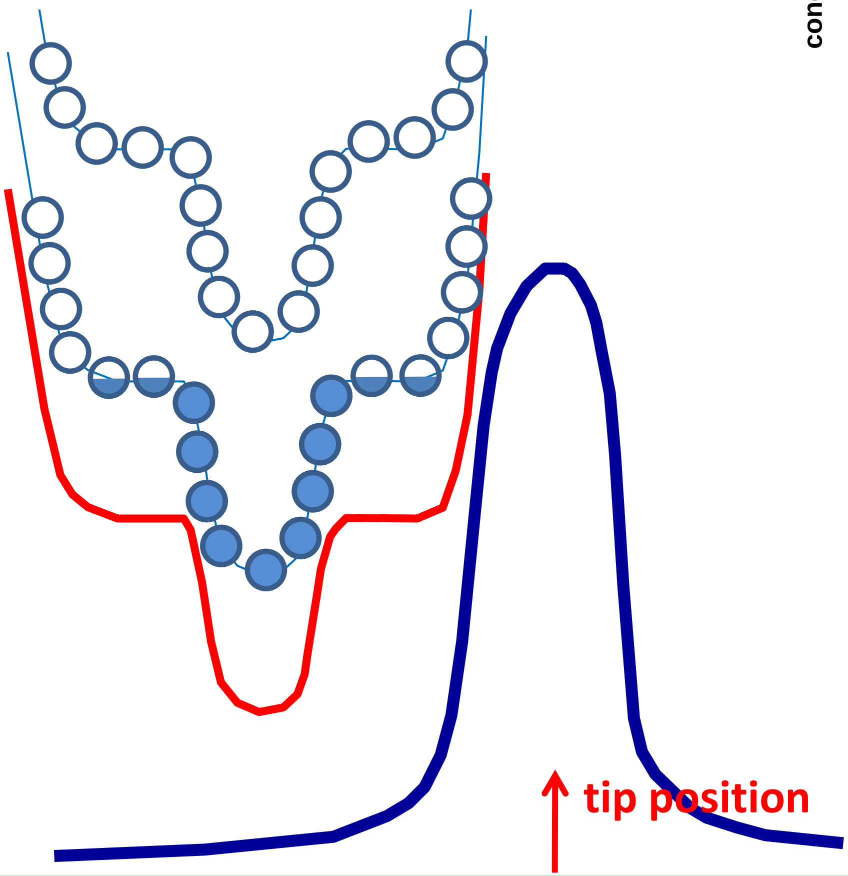
How we probe incompressible stripes

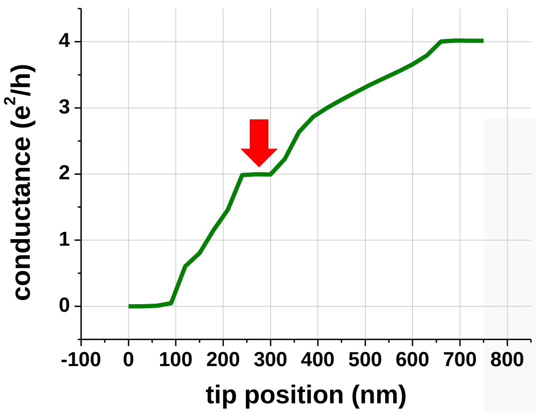


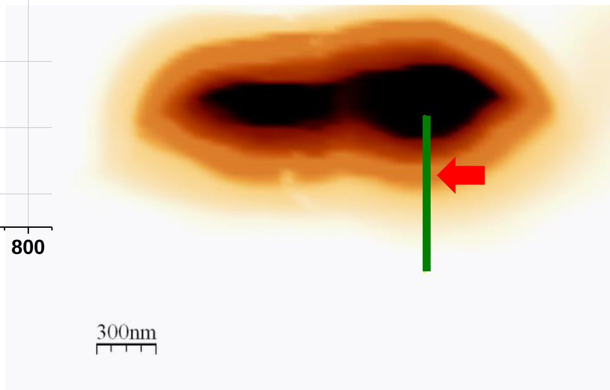




How we probe incompressible stripes

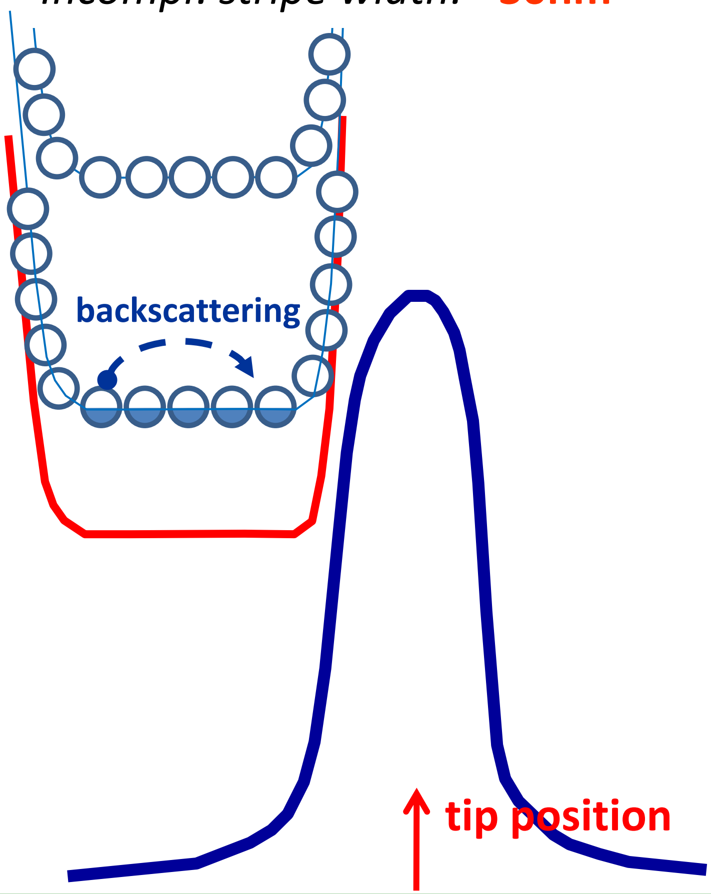


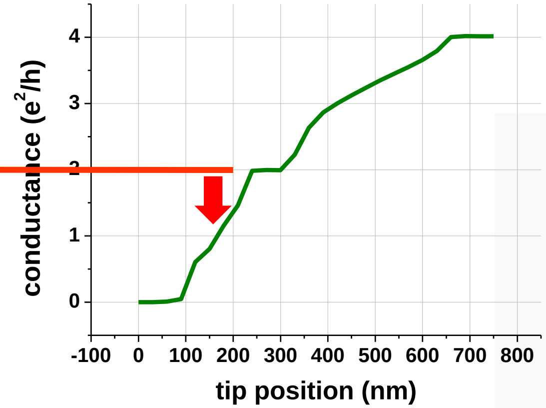


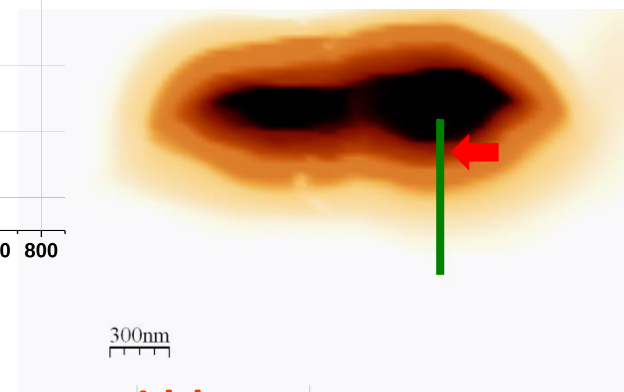


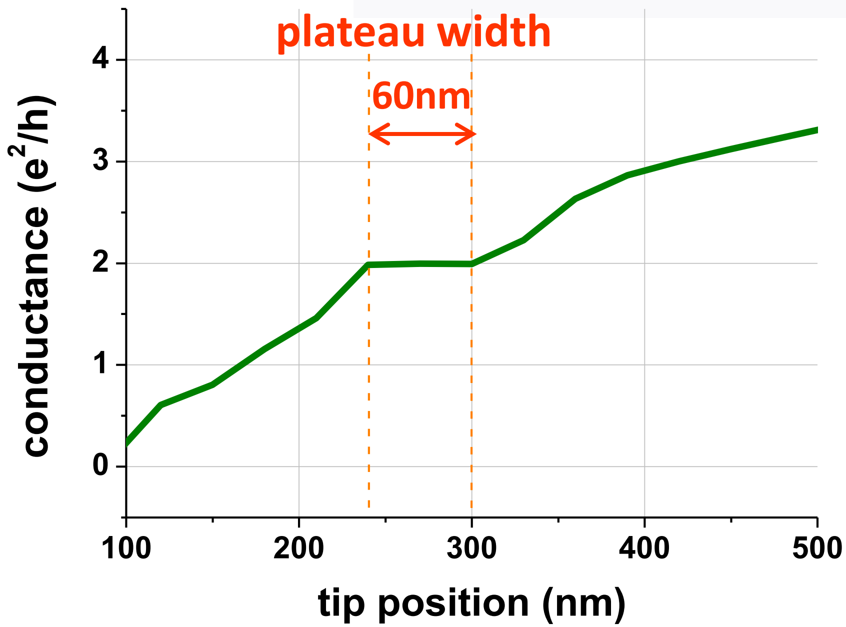
How we probe incompressible stripes

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

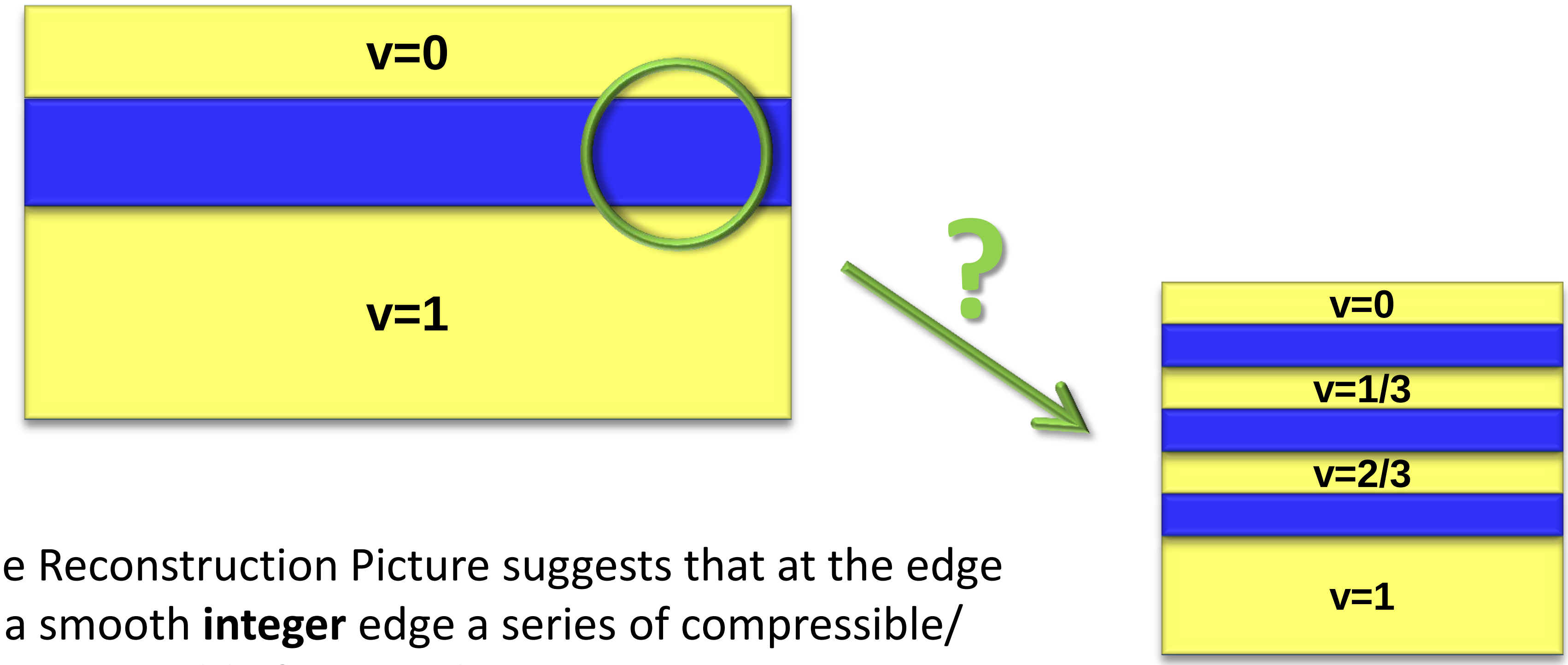






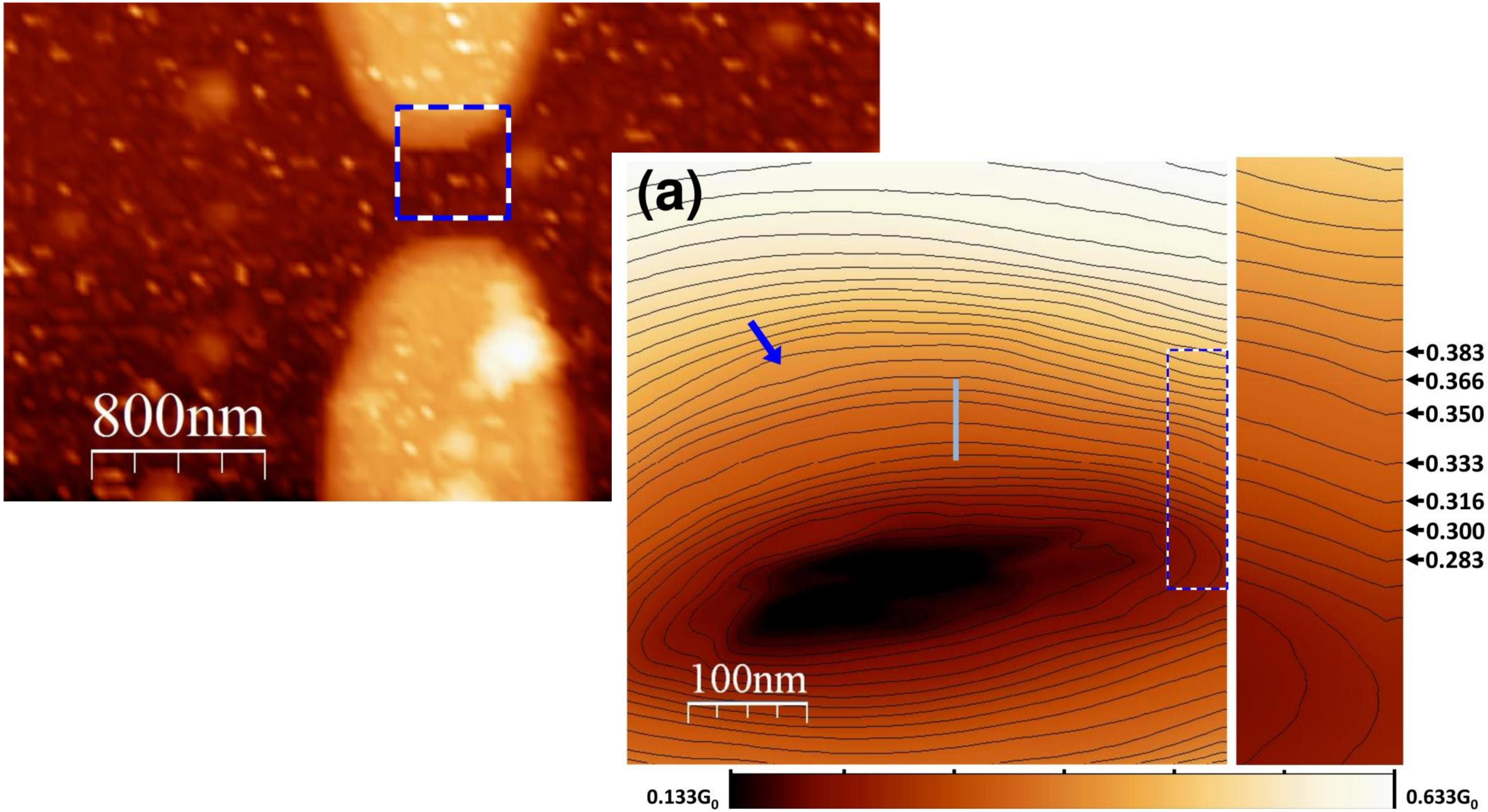


Imaging fractional structures in integer channels (ν=1)



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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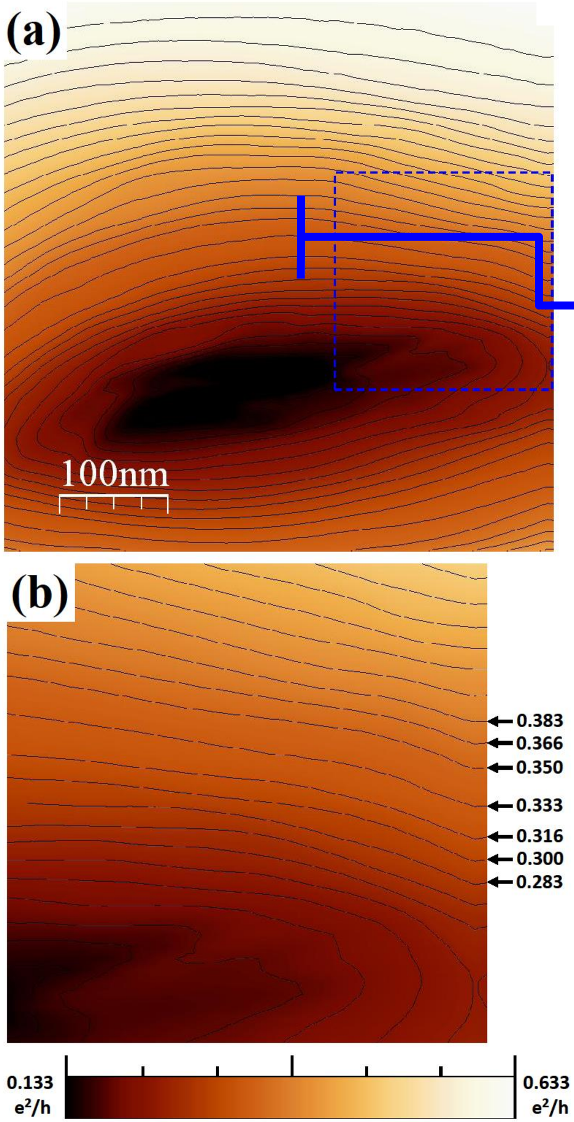
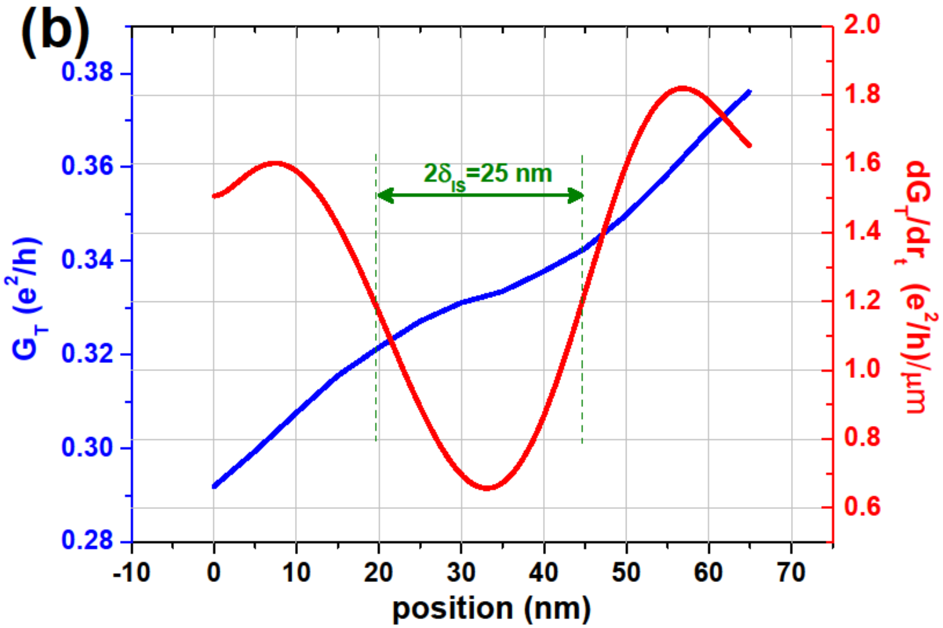
Imaging fractional structures in integer channels (ν=1)



δ_{IS} ~ 12 nm



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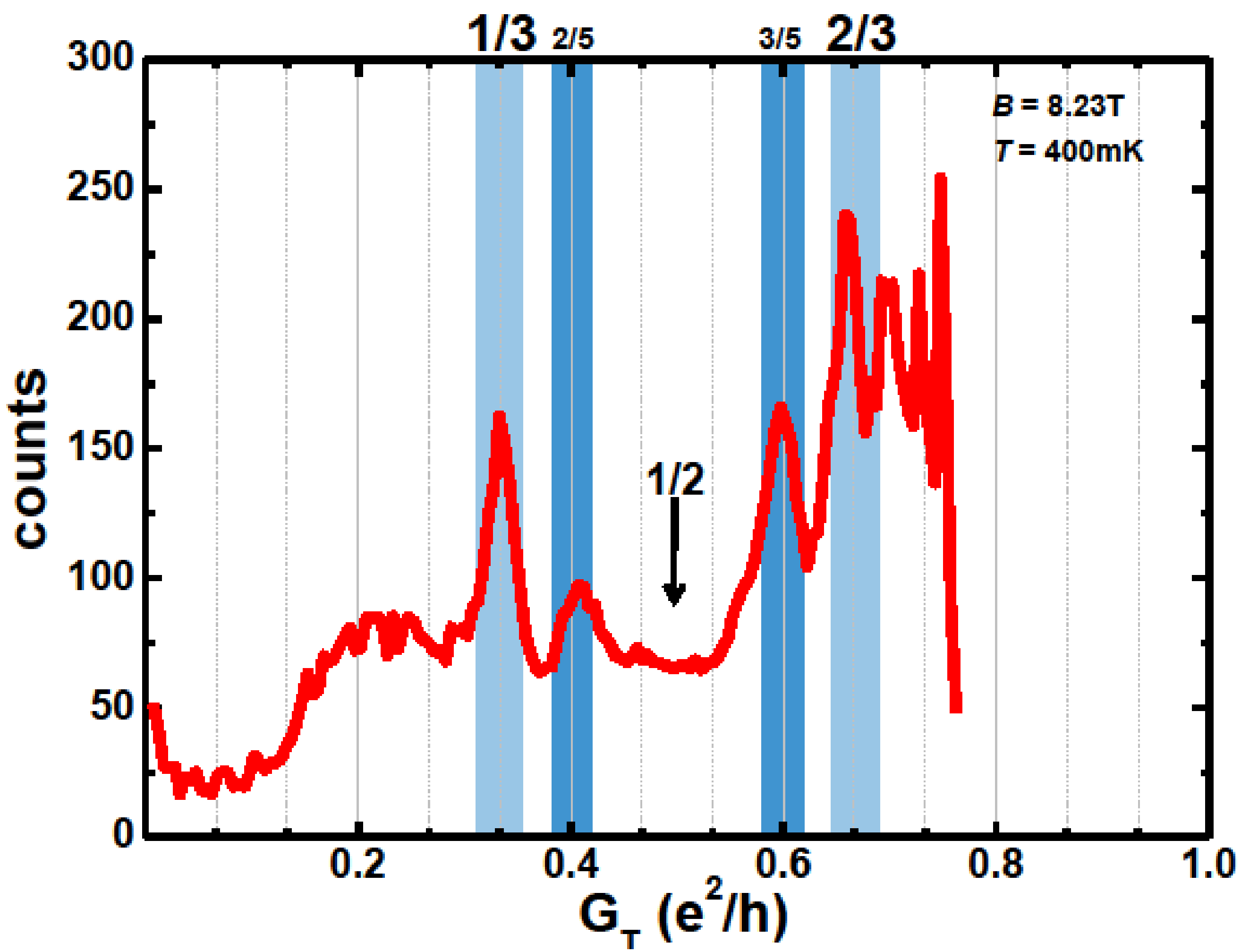
Imaging fractional structures in integer channels (ν=1)



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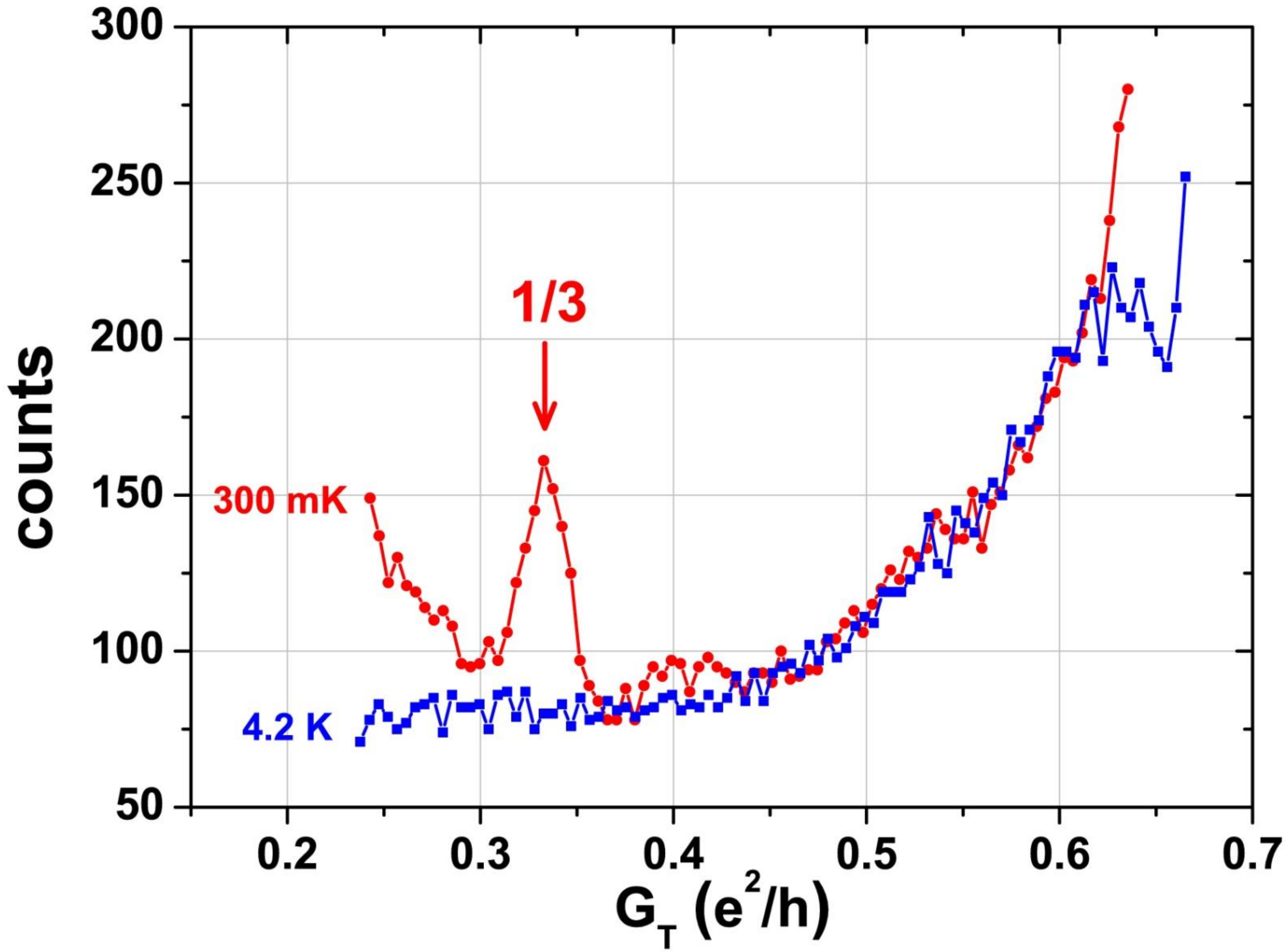
Temperature dependence of 1/3 peak in histogram



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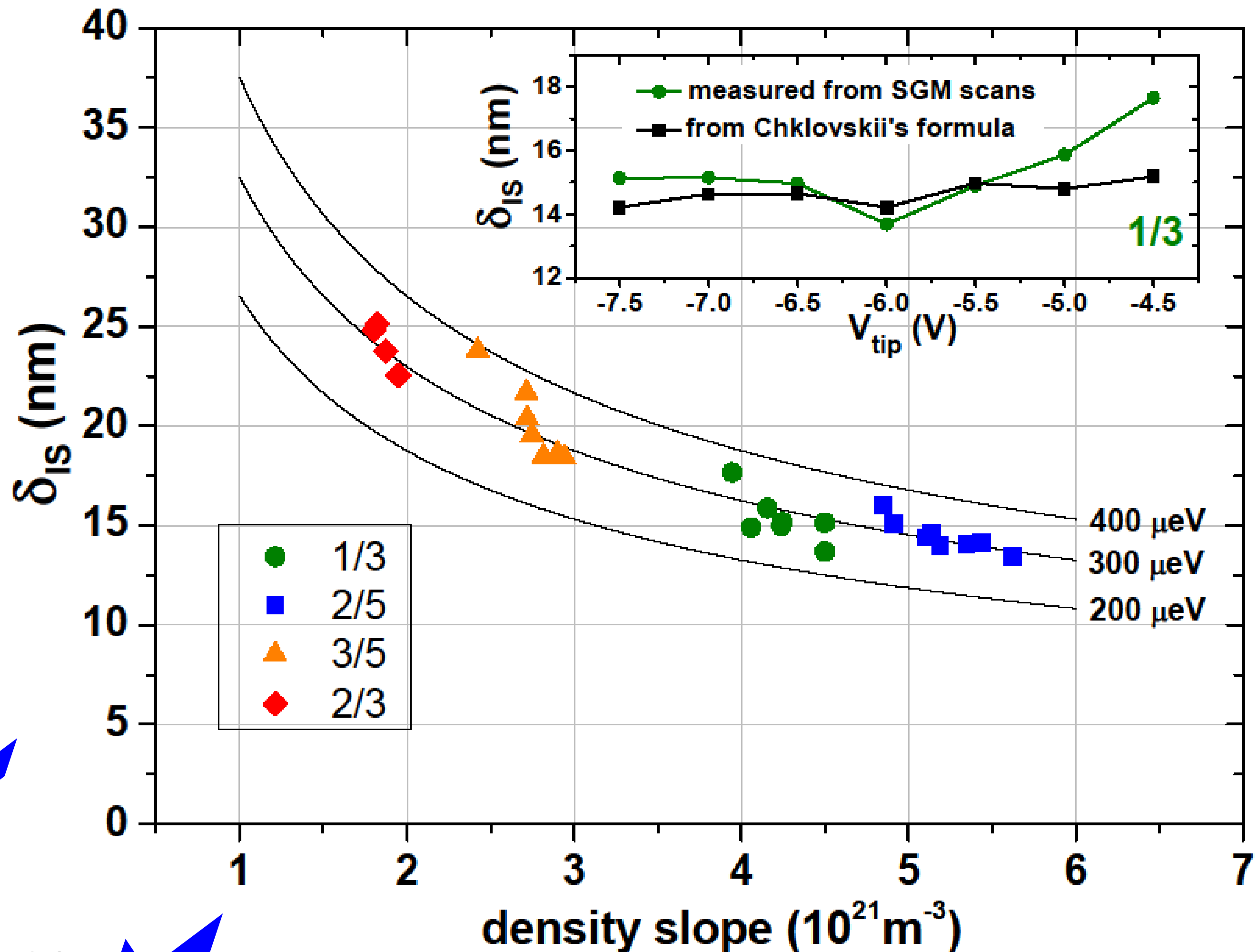
Fractional edge reconstruction

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

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Conclusions

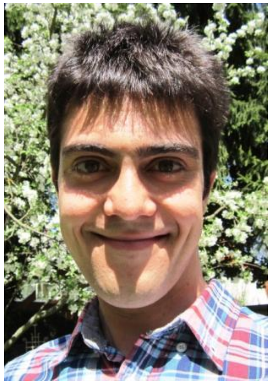
- We explore the use of Scanning Gate Microscopy to study one-dimensional systems

- 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

Coworkers



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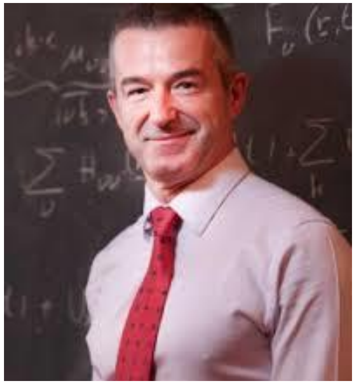

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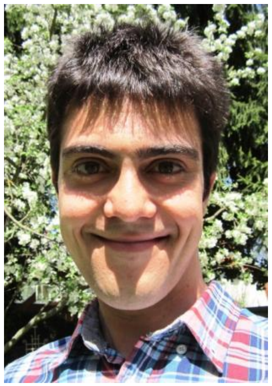
D. Venturelli

F. Taddei

V. Giovannetti

R. Fazio

Coworkers



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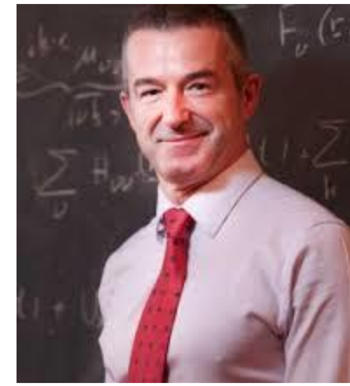

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National Enterprise for nanoScience and nanoTechnology

NEST

CNRNANO PISA NEST

Funding

Consiglio Nazionale delle Ricerche

Japan Society for the Promotion of Science
日本学術振興会

Repubblica Italiana
Ministero degli Affari Esteri e della Cooperazione Internazionale

GRAPHENE FLAGSHIP