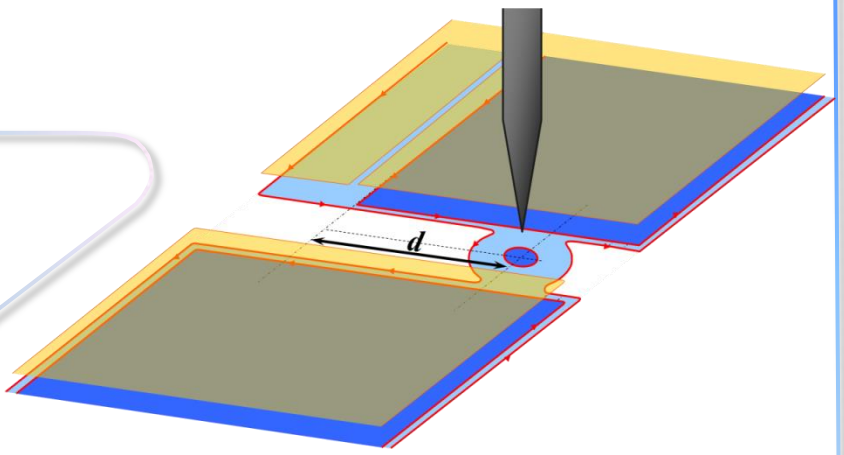
Tomography and manipulation of quantum Hall edge channels by Scanning Gate Microscopy



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Co-workers:

Stefan Heun, Stefano Roddaro, Lucia Sorba, and Fabio Beltram

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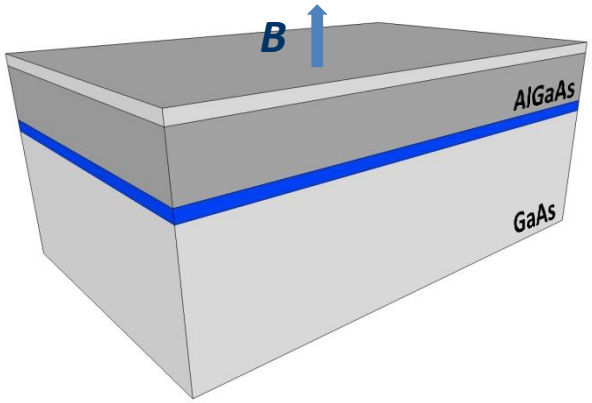
Giorgio Biasiol

Istituto Officina dei Materiali CNR, Laboratorio TASC, Trieste, Italy

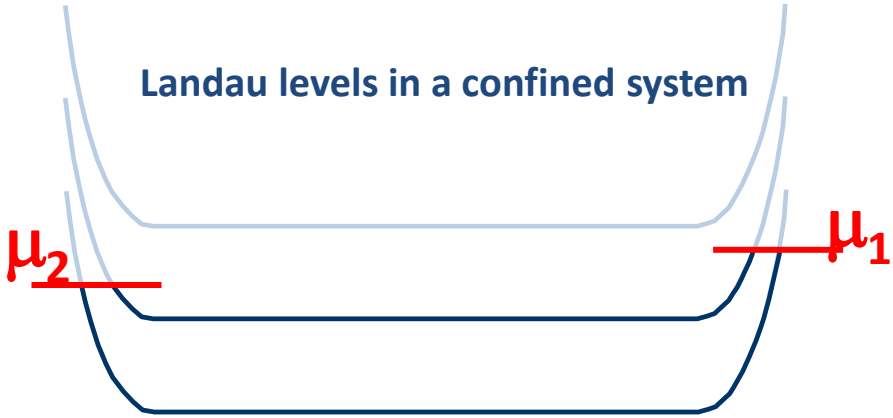
Loren N. Pfeiffer and Ken W. West

Department of Electrical Engineering, Princeton University, Princeton, USA

The non-interacting picture of the QH effect

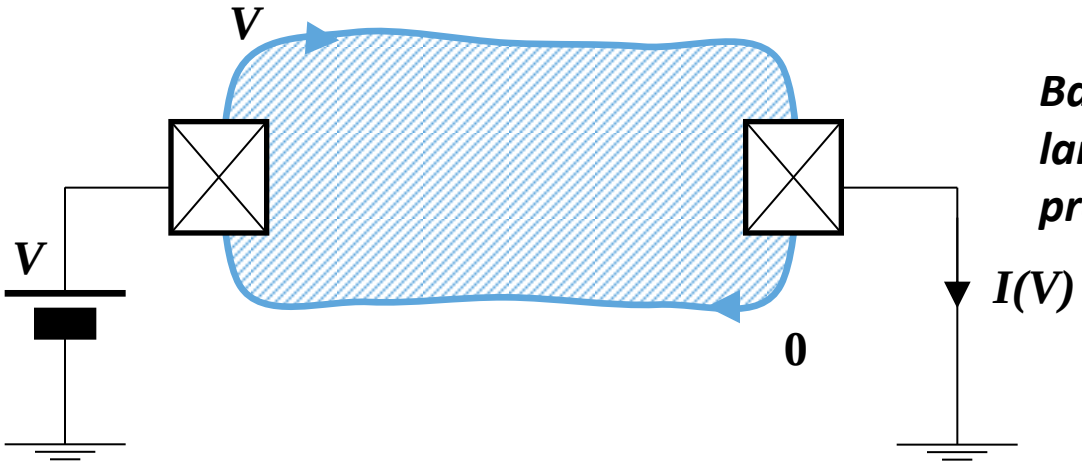


2DES
in high field



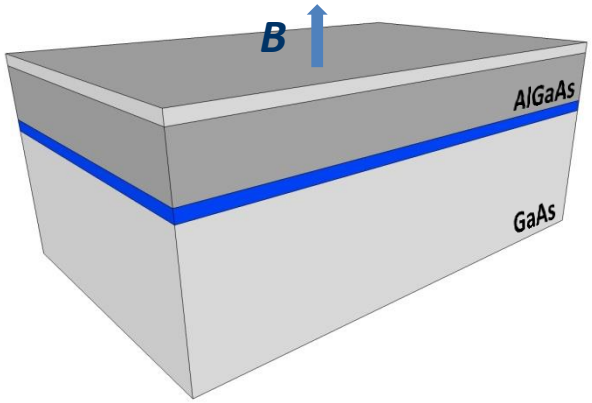
- Edge state picture:
  current is carried by chiral 1D channels

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



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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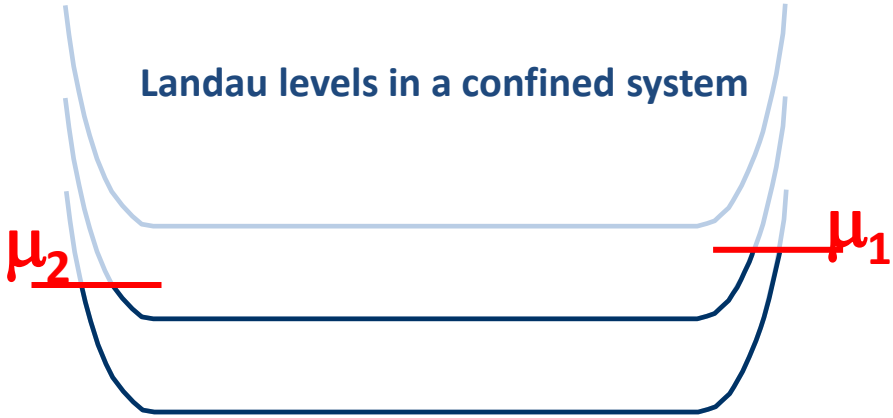
in high field



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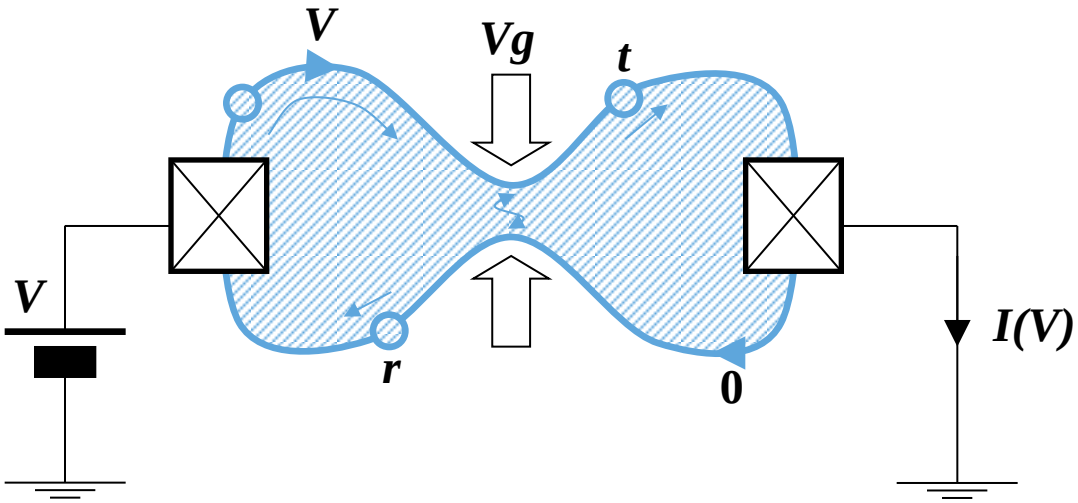


With a QPC we can intentionally induce backscattering, which provides us information about the edge properties

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

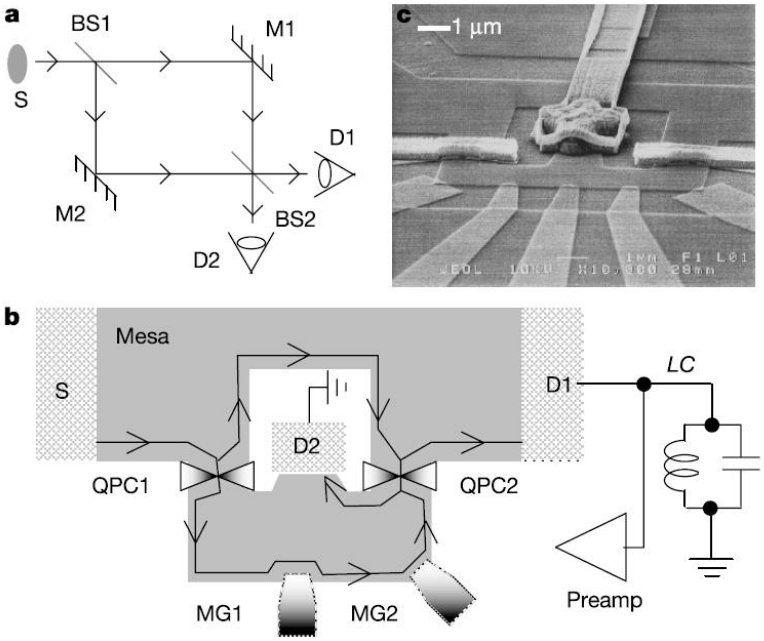
Edge channel-based interferometers

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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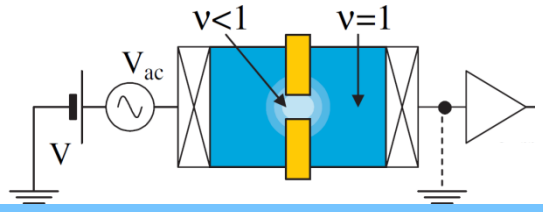
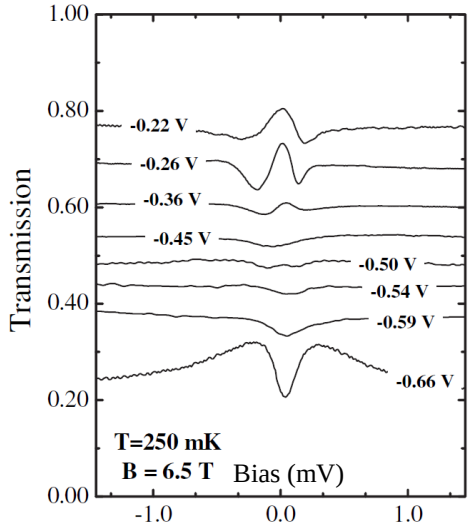
Role of the inner edge structure?

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



PRL **95**, 156804 (2005)



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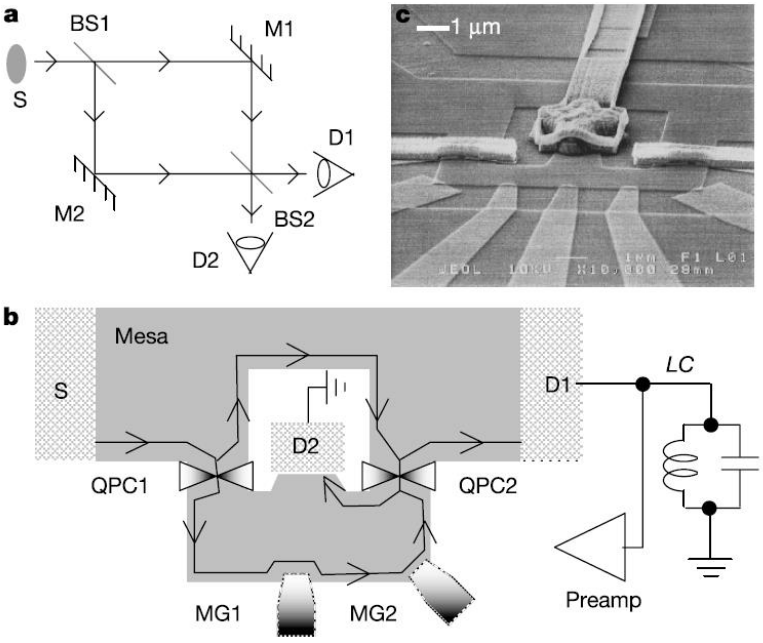
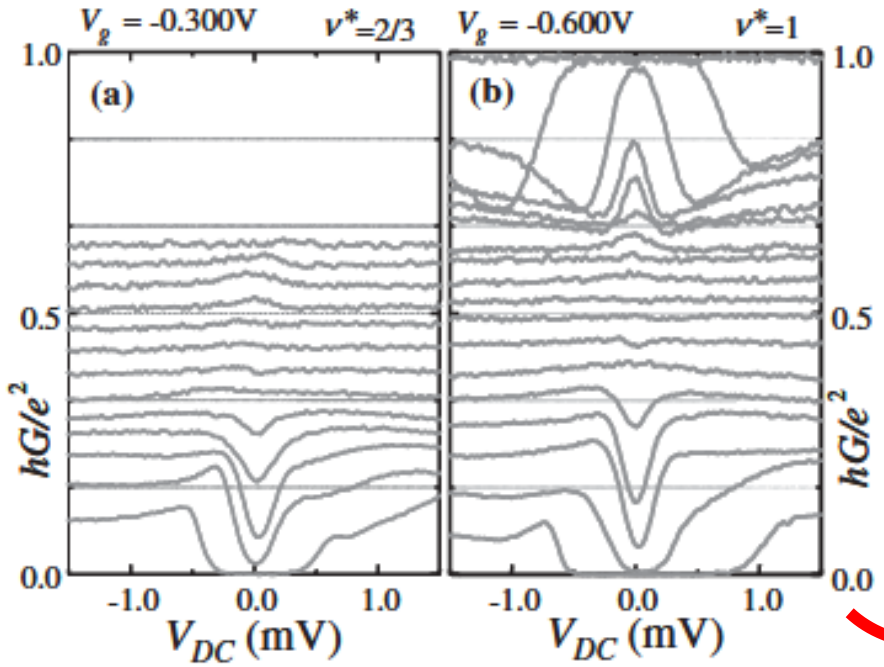


Ji *et al.*: Nature **422**, 415 (2003)

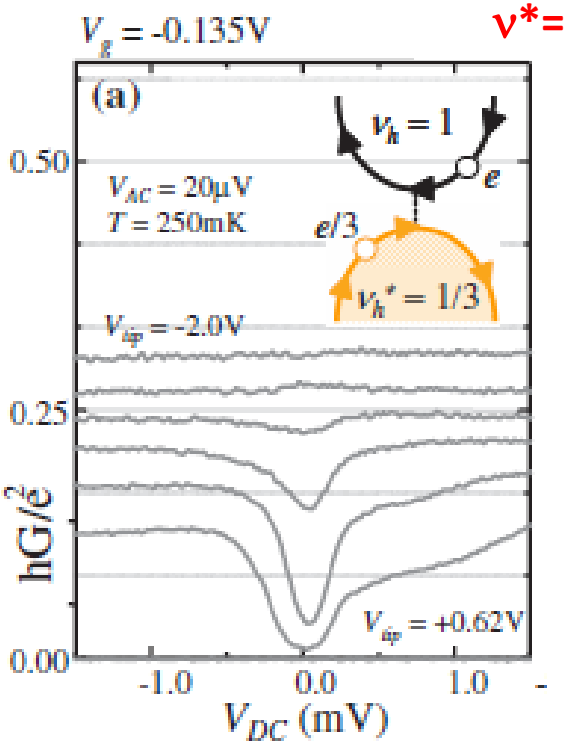
Fractional structures in integer edges

Our first transport measurements found evidences of fractional structures (Luttinger liquid-like) in a single edge (Fermi liquid).

ν*=2/3 ν*=1



ν*=1/3



-S. Roddaro, N. Paradiso, et al: "Tuning Nonlinear Charge Transport between Integer and Fractional Quantum Hall States"; Phys. Rev. Lett. **103**, (2009) 016802.

Need for spatially resolved measurements

Non-interacting VS interacting picture

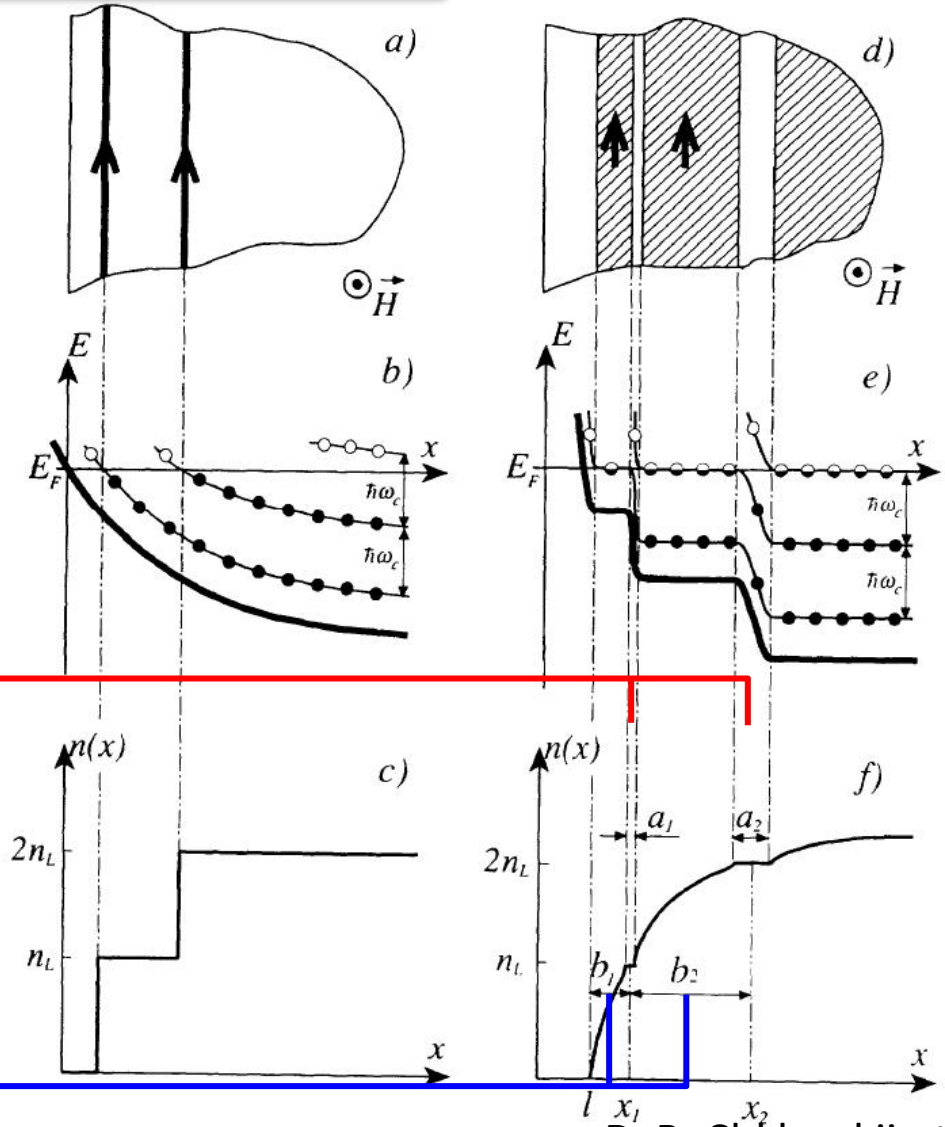
- The self consistent potential due to e-e interactions modifies the edge structure

- 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.

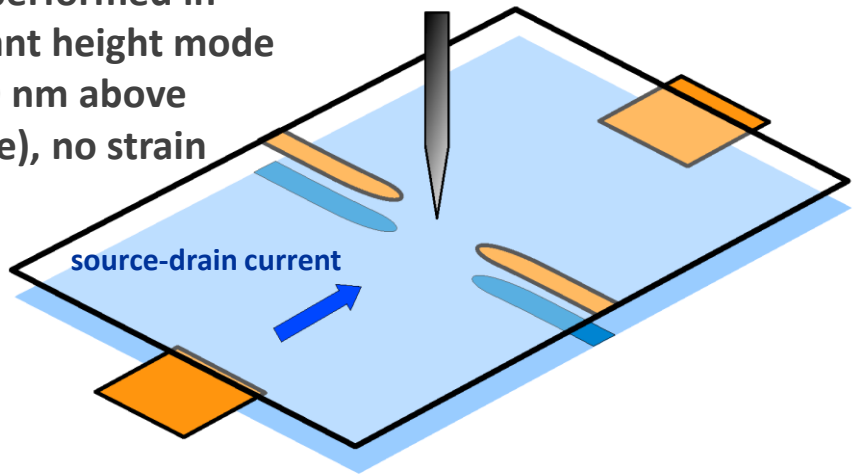
The SGM setup

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)

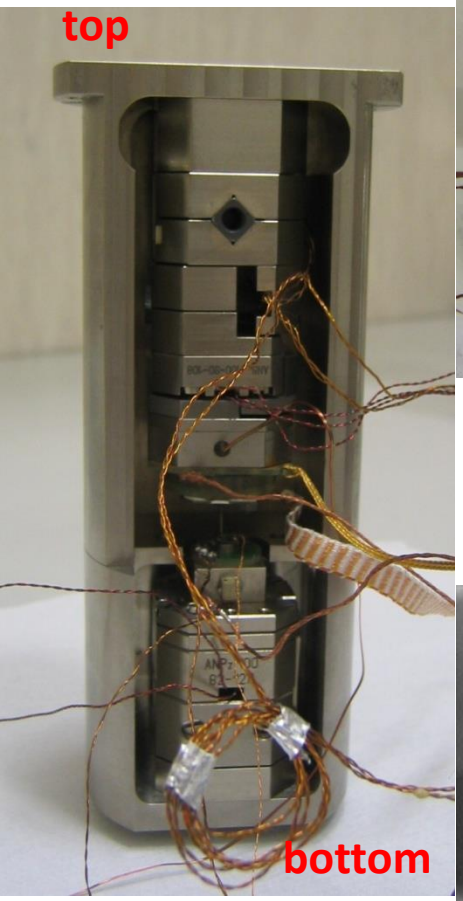


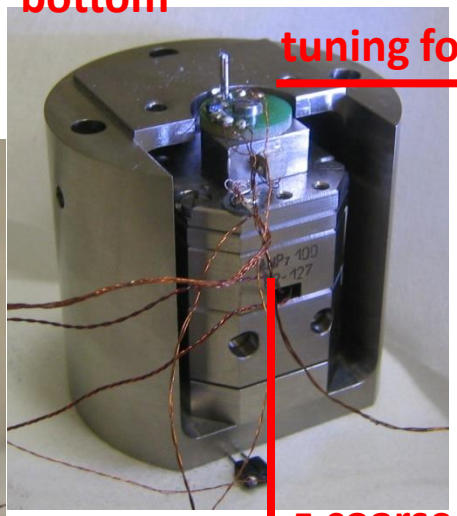
Pioneering work by:

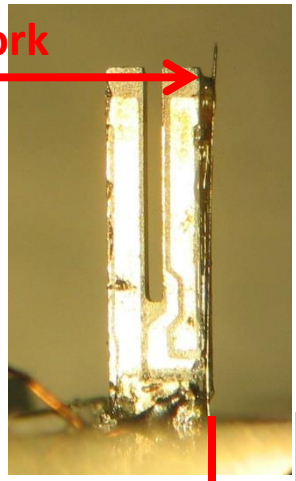
*M. A. Topinka et al.: Science **289** (2000) 2323.*

attocube systems
explore your nanoworld

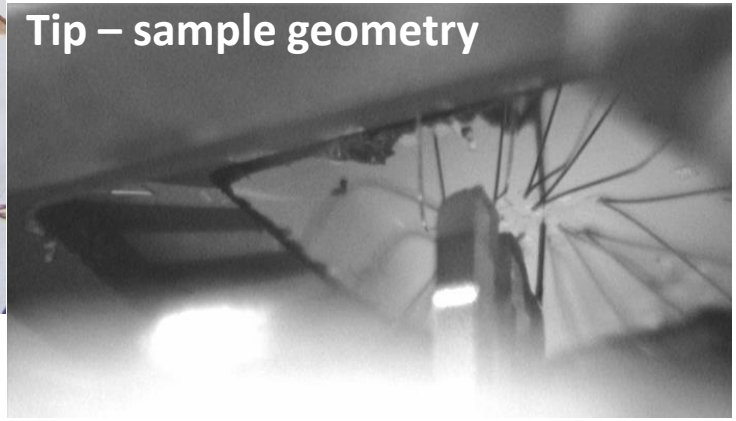
Tuning fork and sample holder

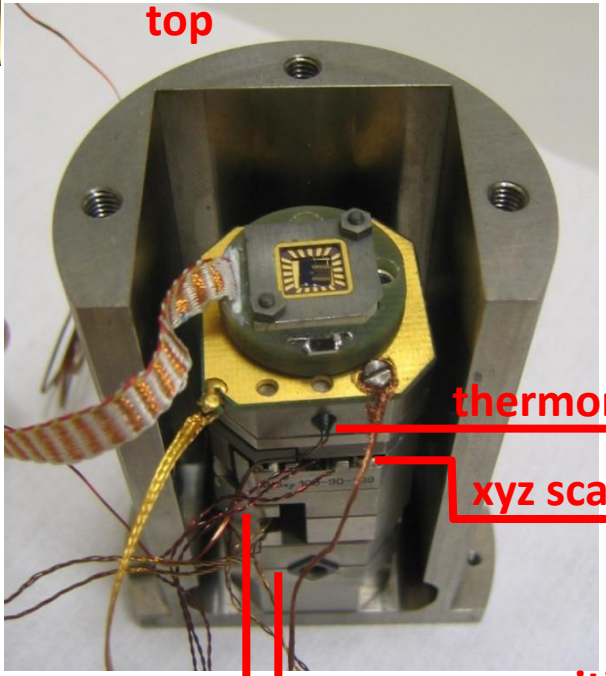




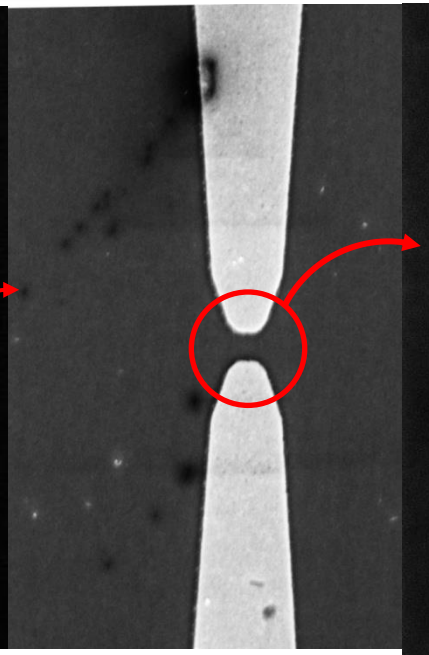


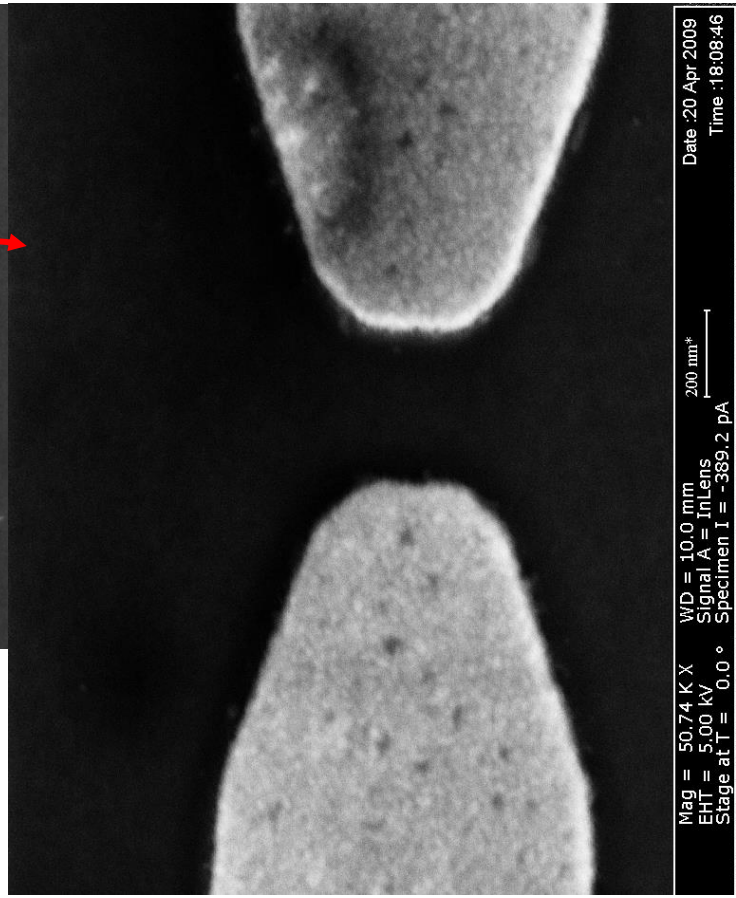
conductive tip glued on the TF



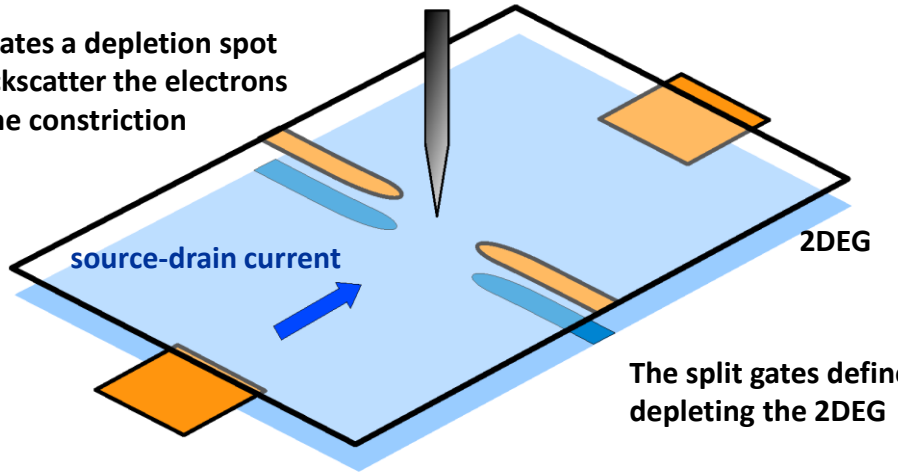


SGM test measurements on QPCs



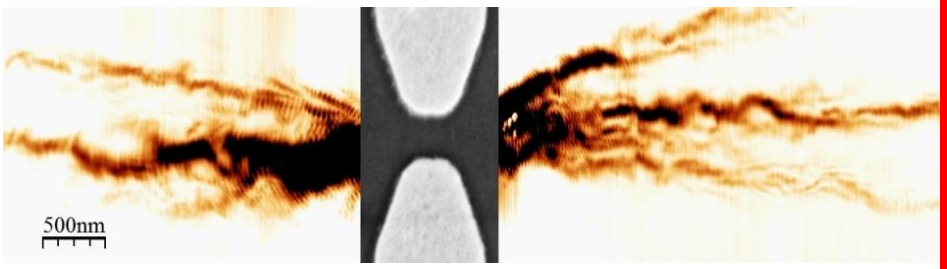


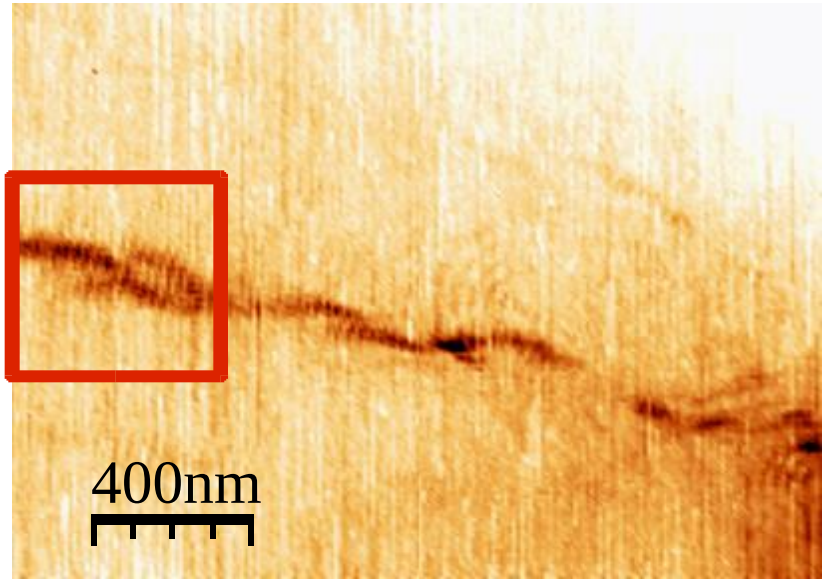
The biased tip creates a depletion spot that we use to backscatter the electrons passing through the constriction

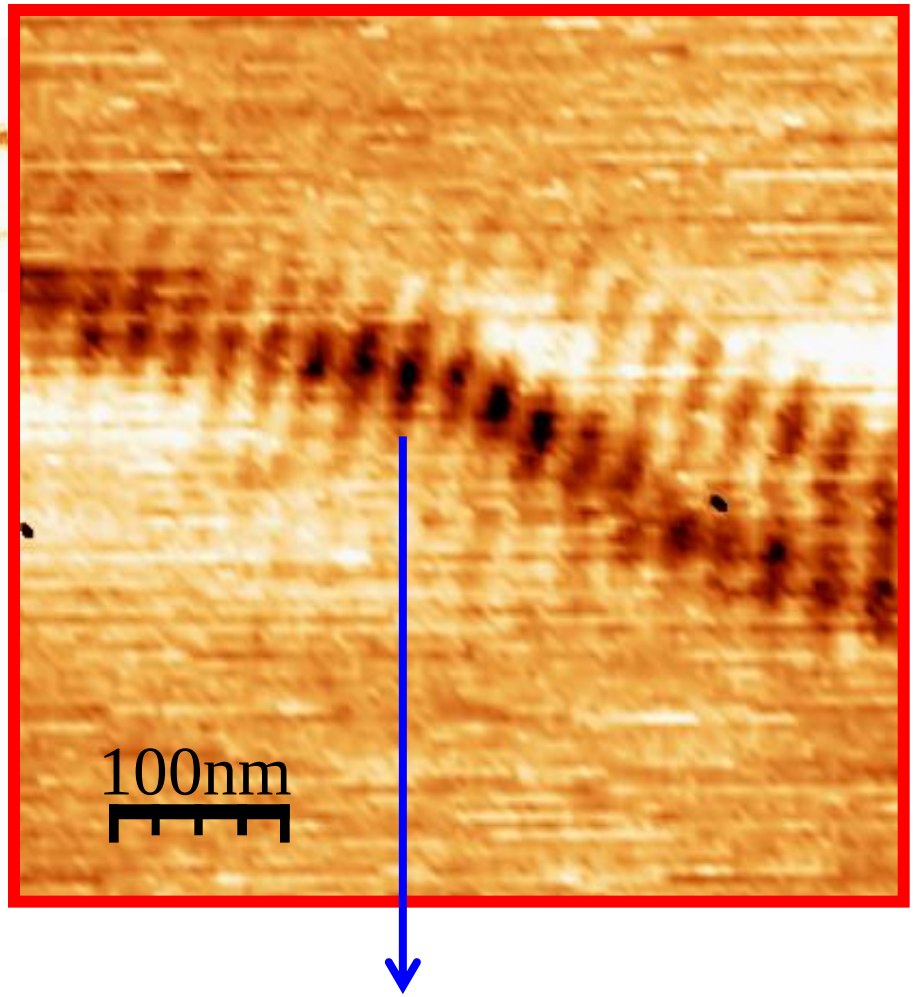


The split gates define a constriction by depleting the 2DEG underneath

Branched flow and interference fringes





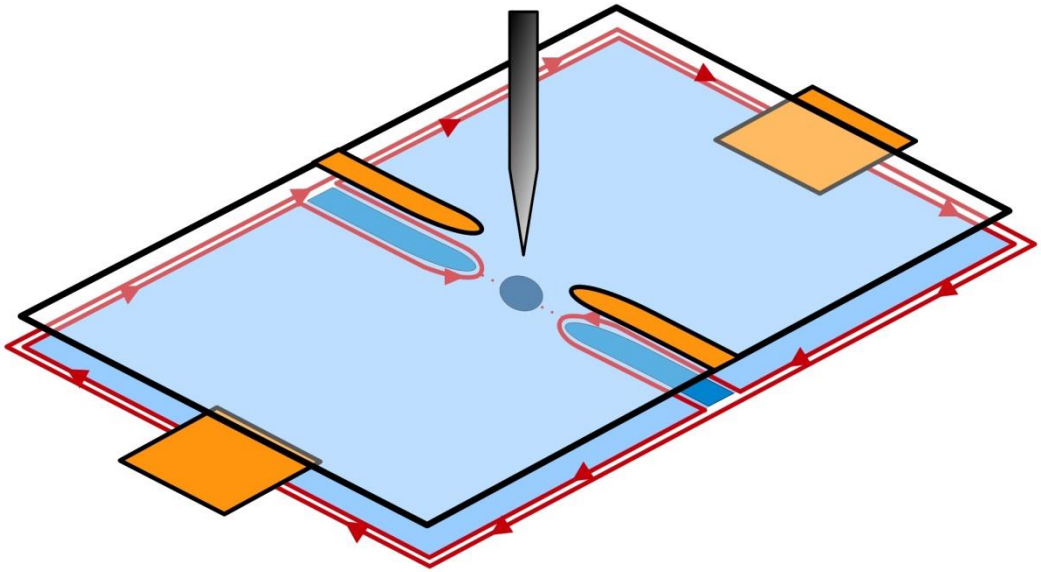


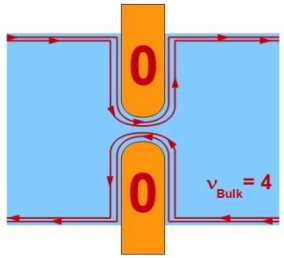
- QPC conductance G = 6 e^2/h (3rd plateau)
- Tip voltage V_{tip} = -5 V, height h_{tip} = 10 nm
- *see also M. A. Topinka et al., Nature **410** (2001) 183.*

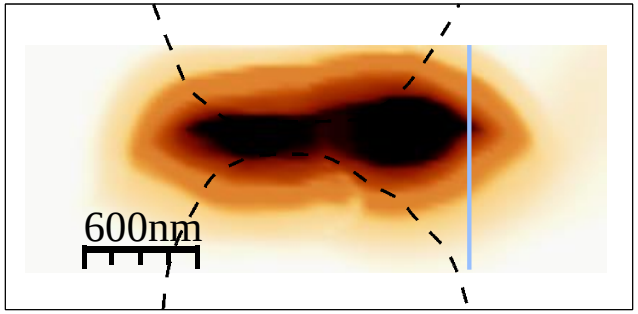
Fringe periodicity: $\lambda_F/2$=20 nm

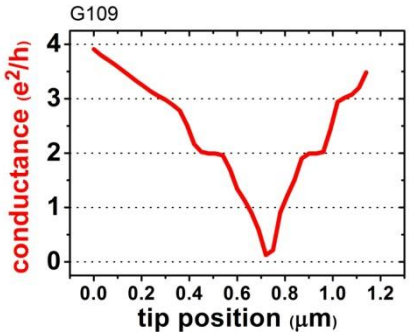
In the QH regime: edge tomography by SGM

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.**





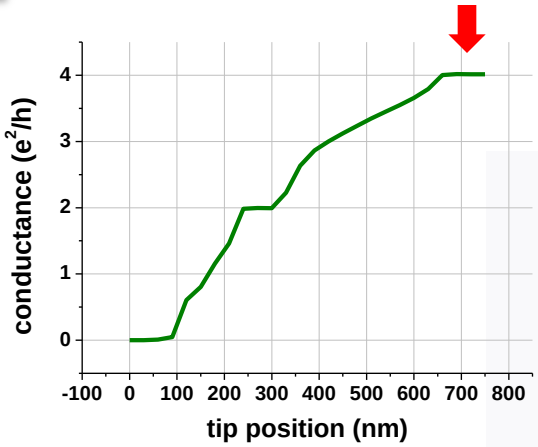


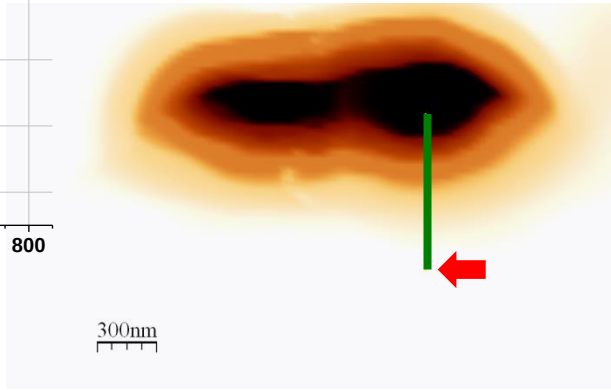


- Bulk filling factor ν=4
- B = 3.04 T
- 2 spin-degenerate edge channels
- gate-region filling factors $g_1 = g_2 = 0$

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

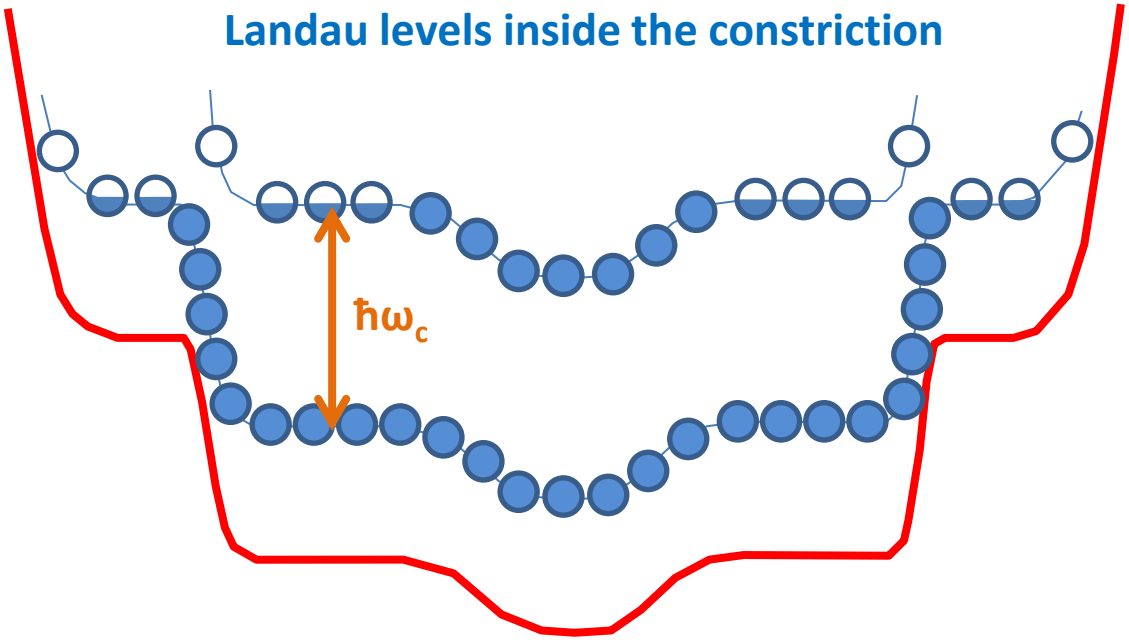
How we probe incompressible stripes

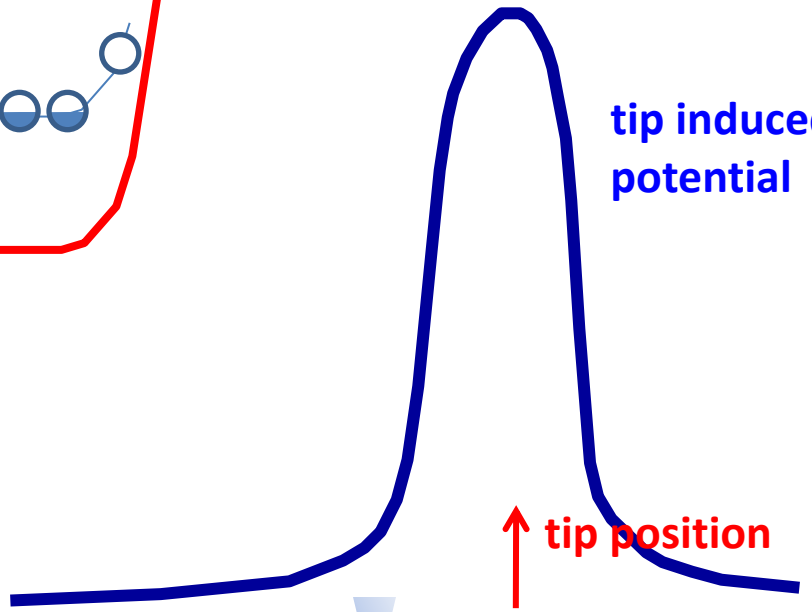




Self-consistent potential

Landau levels inside the constriction





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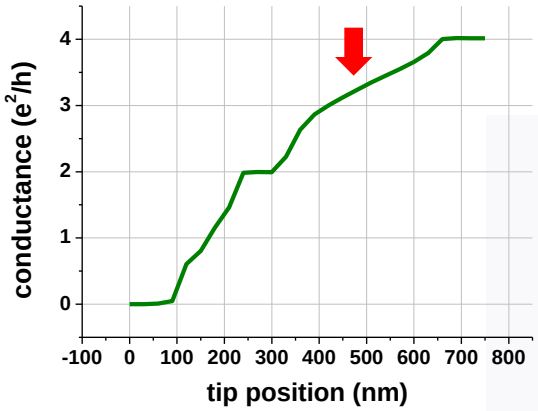
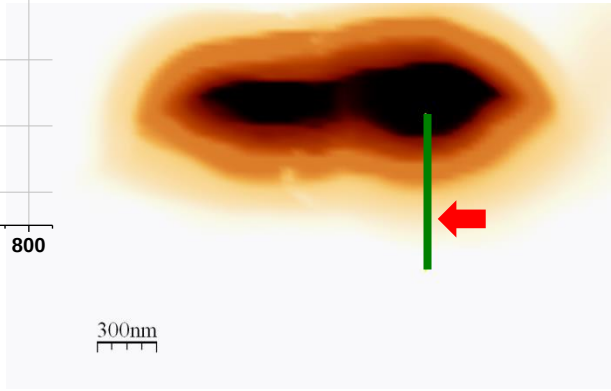
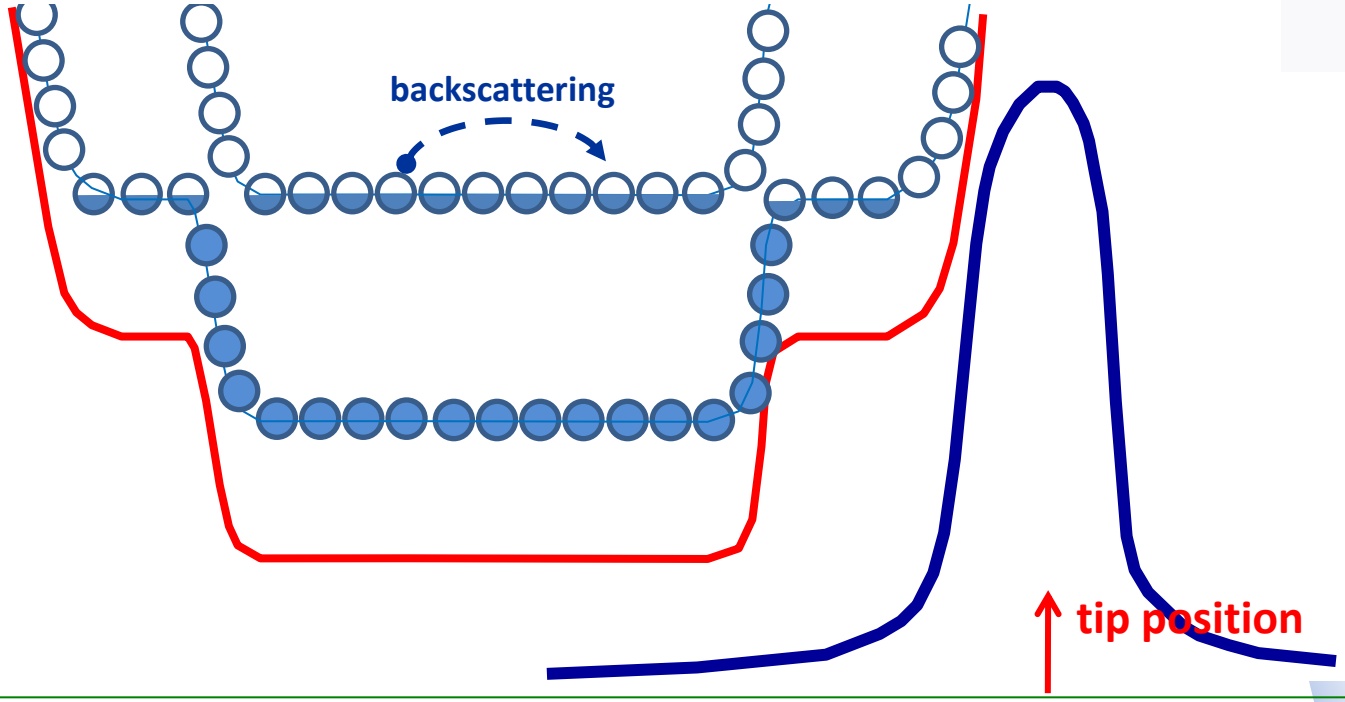
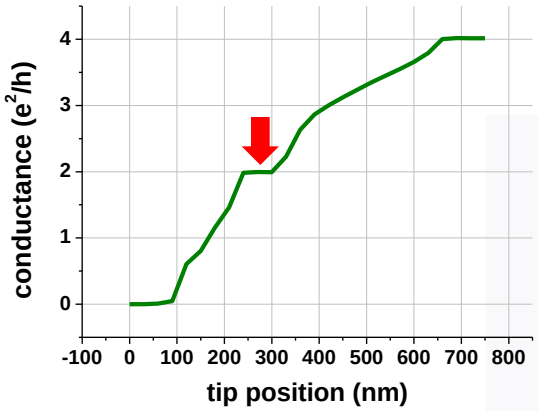
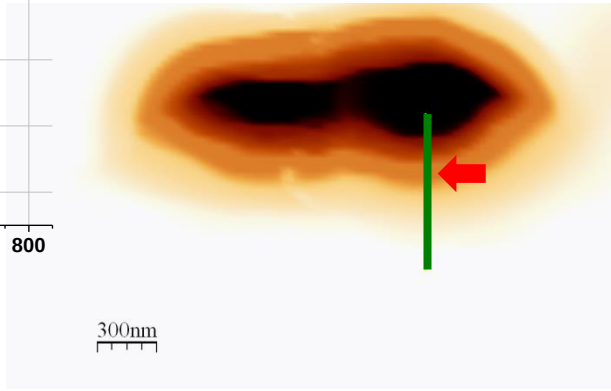


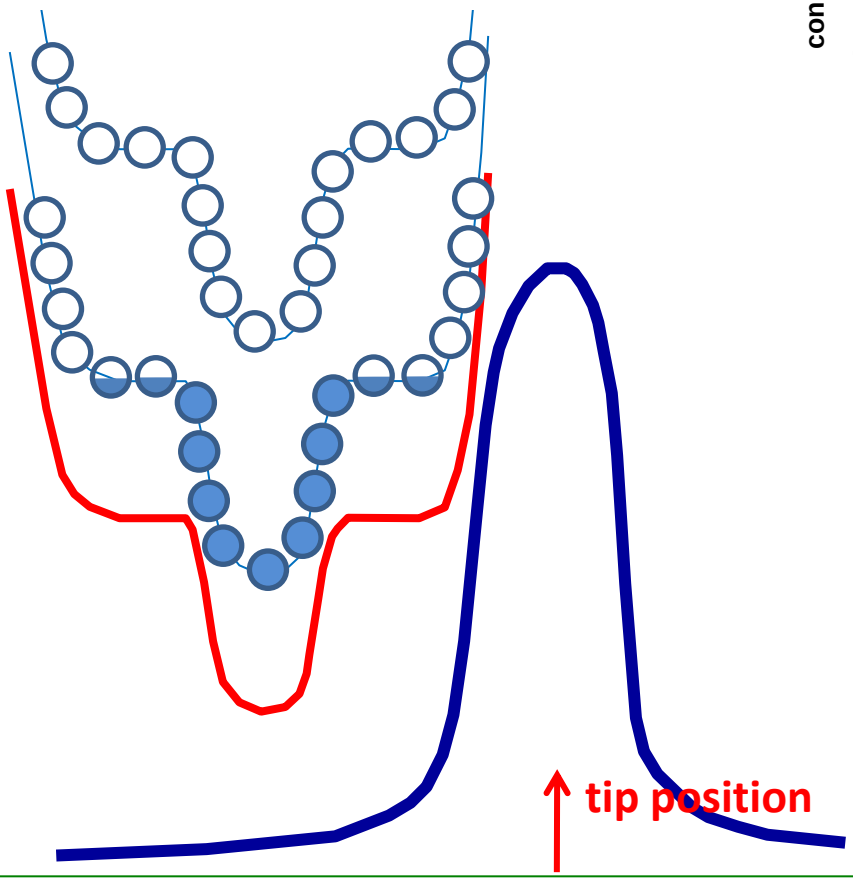




How we probe incompressible stripes

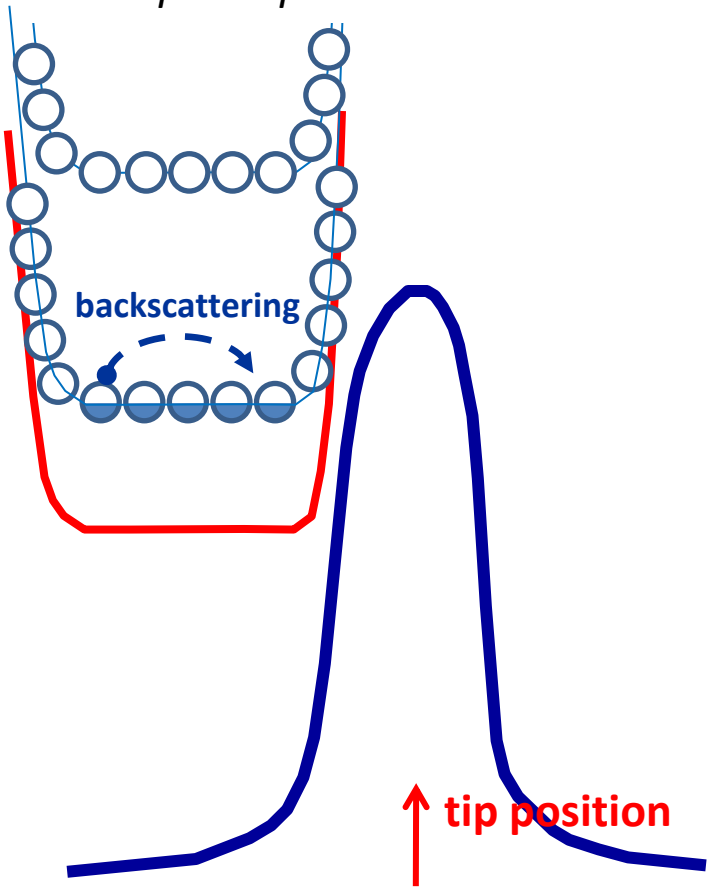


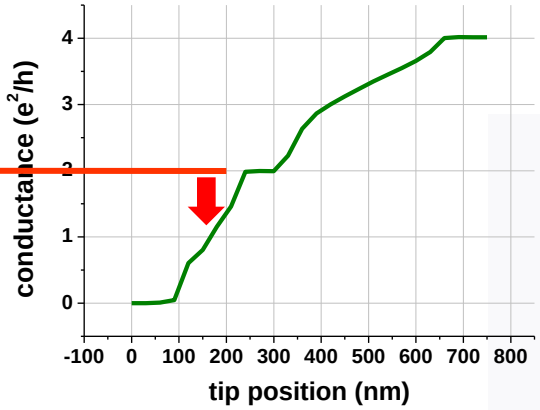


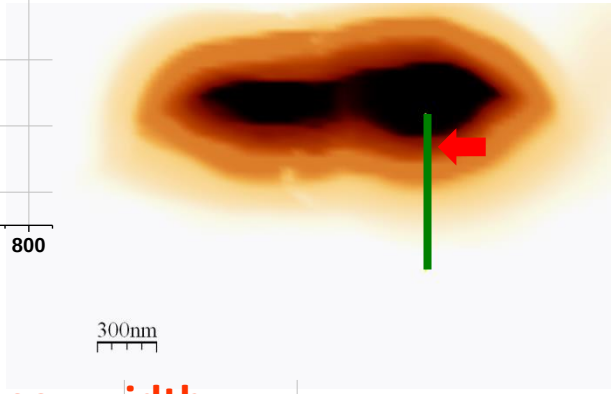


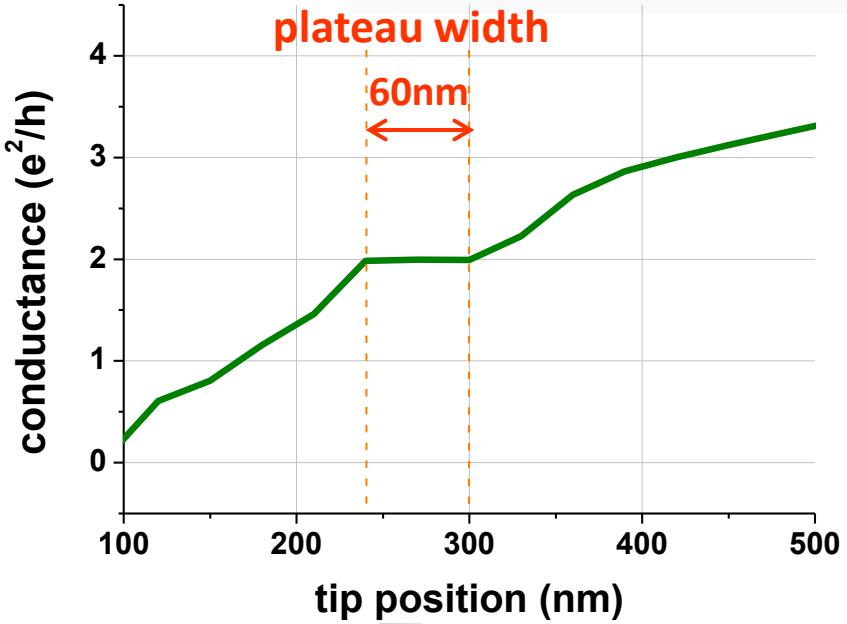
How we probe incompressible stripes

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

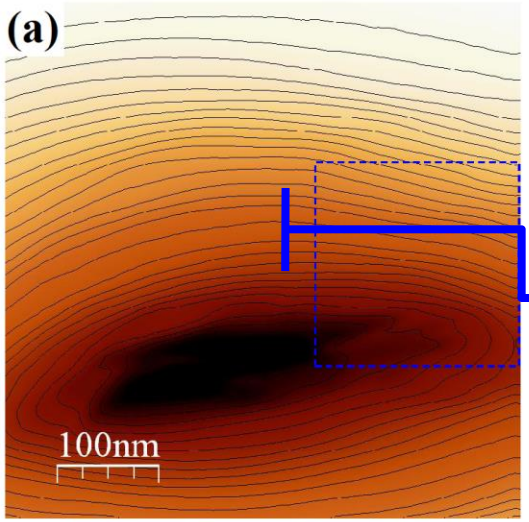


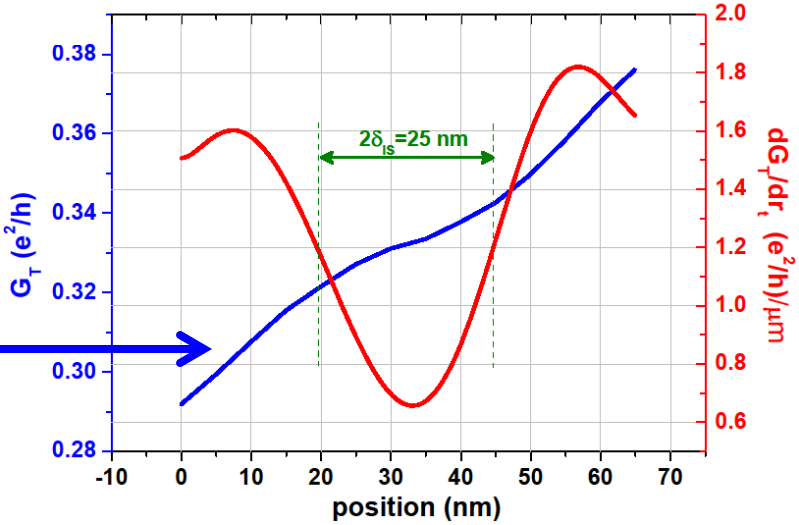




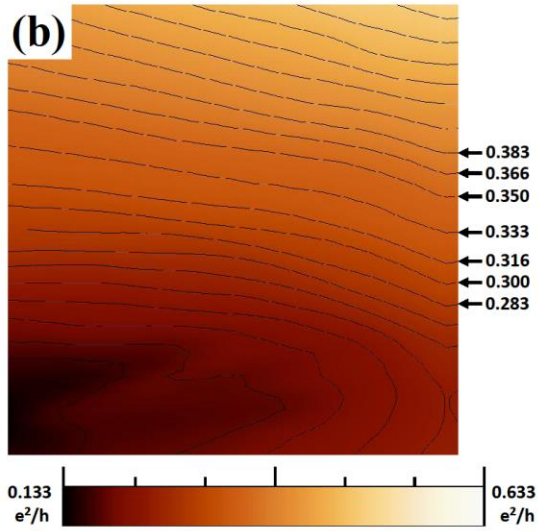


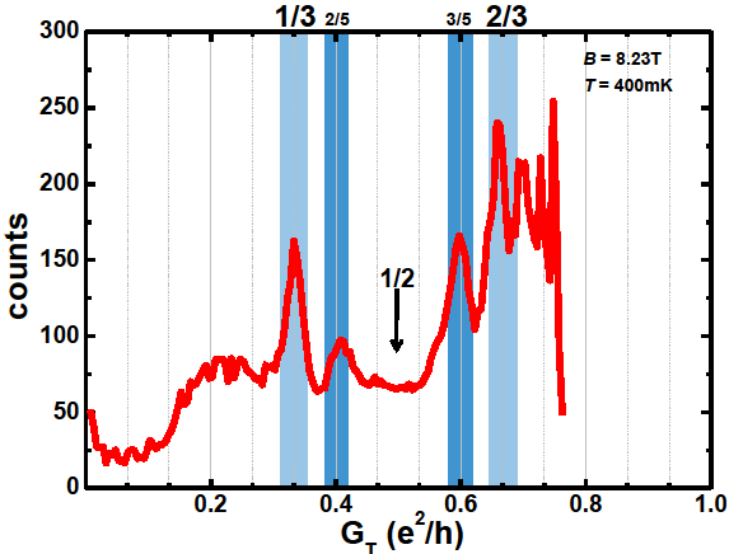
Imaging fractional structures in integer channels





The Reconstruction Picture suggests that at the edge of a smooth **integer** edge a series of compressible/ **incompressible fractional stripes** can occur.
We used the SGM technique to image them.





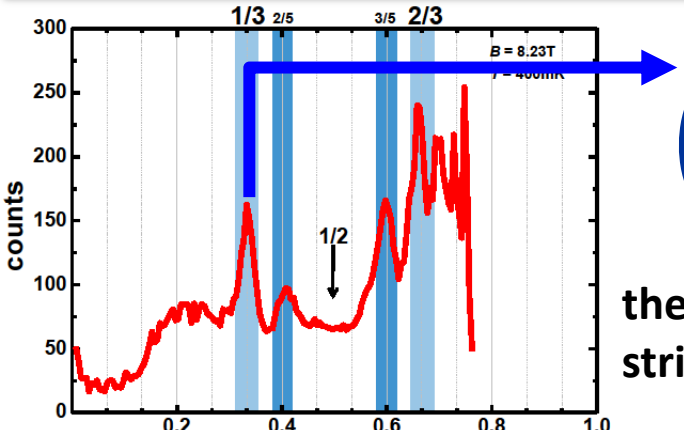
Data published in:

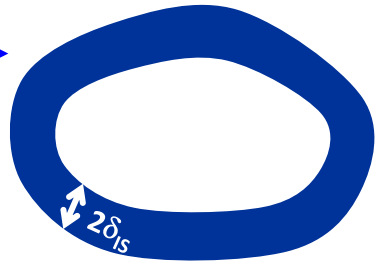
N. Paradiso *et al.*

PHYSICAL REVIEW LETTERS

PRL **108,** 246801 (2012)

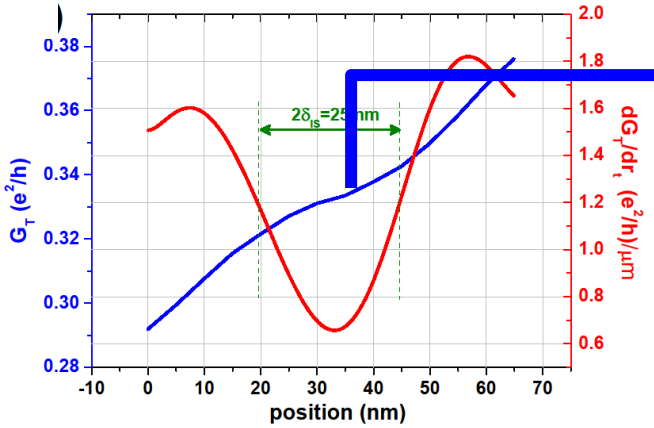
Fractional edge reconstruction





the finite range in GT defines a stripe in the SGM map

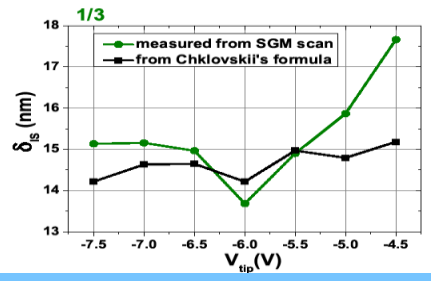
δ_{IS} determined from SGM measurements

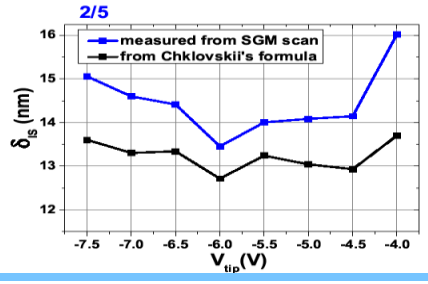


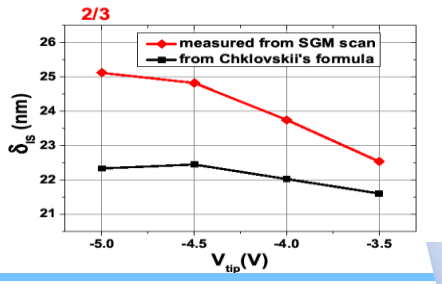
$$\frac{dn}{dr}$$

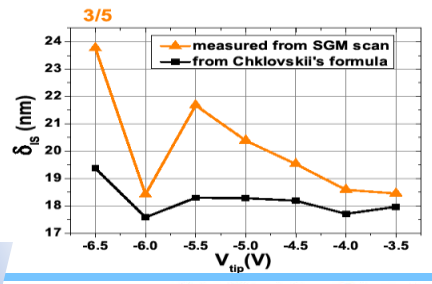
δ_{IS} determined from Chklovskii's formula

$$\delta_{IS}^2 = \frac{4\Delta\mu_f\varepsilon}{\pi^2 e^2 dn/dr|_{r=r_f}}$$



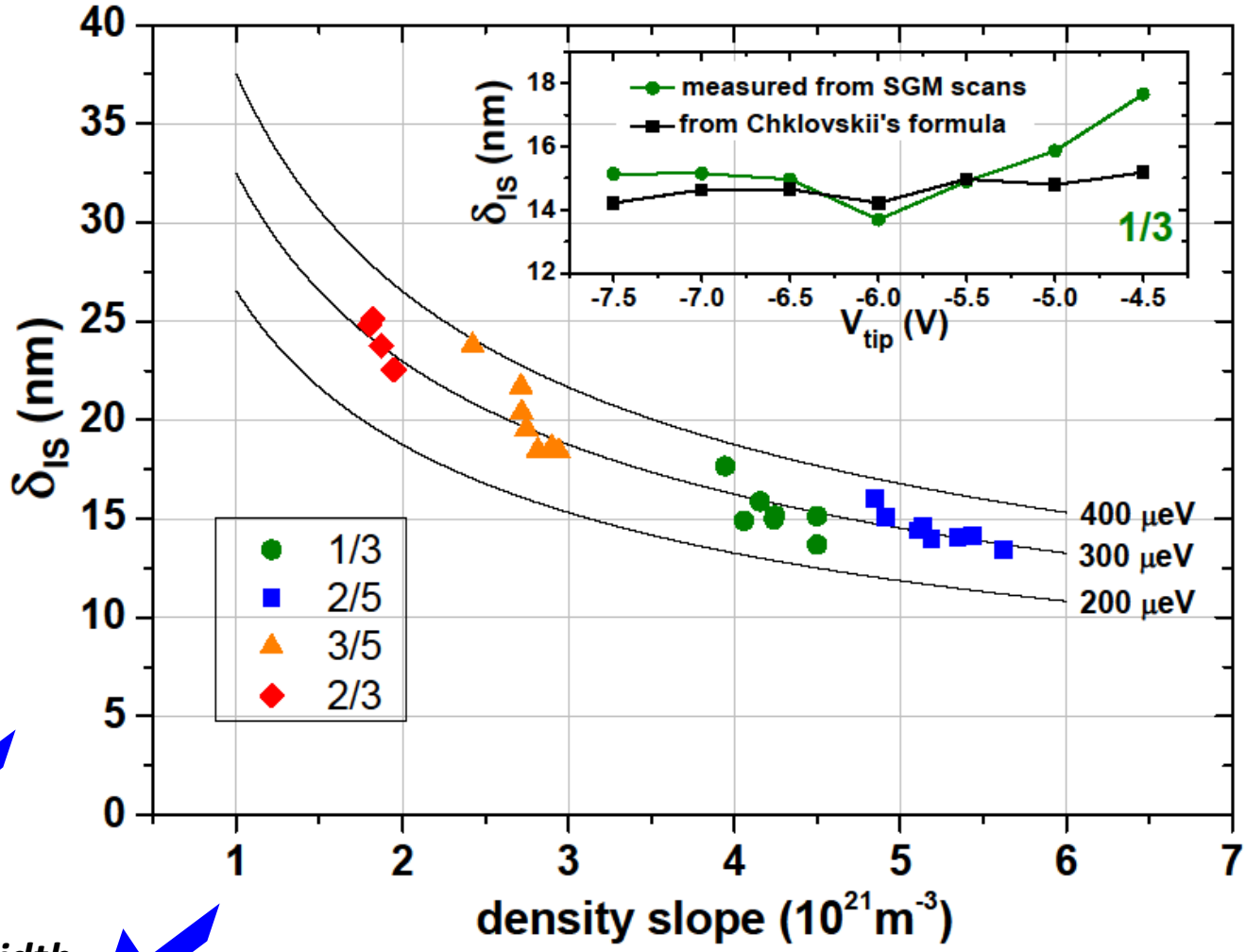






Fractional edge reconstruction

The IS width values (colored dots àæòî) 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

Subsequent developments

nature nanotechnology

LETTERS

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Real-space imaging of fractional quantum Hall liquids

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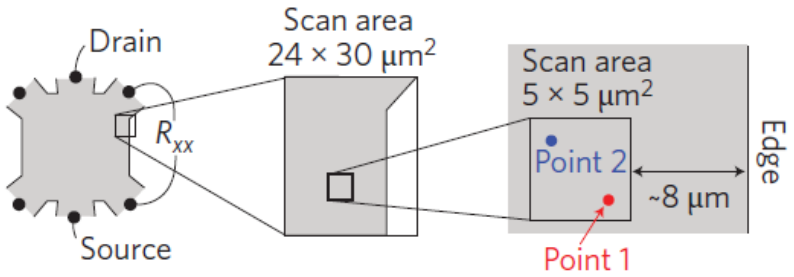
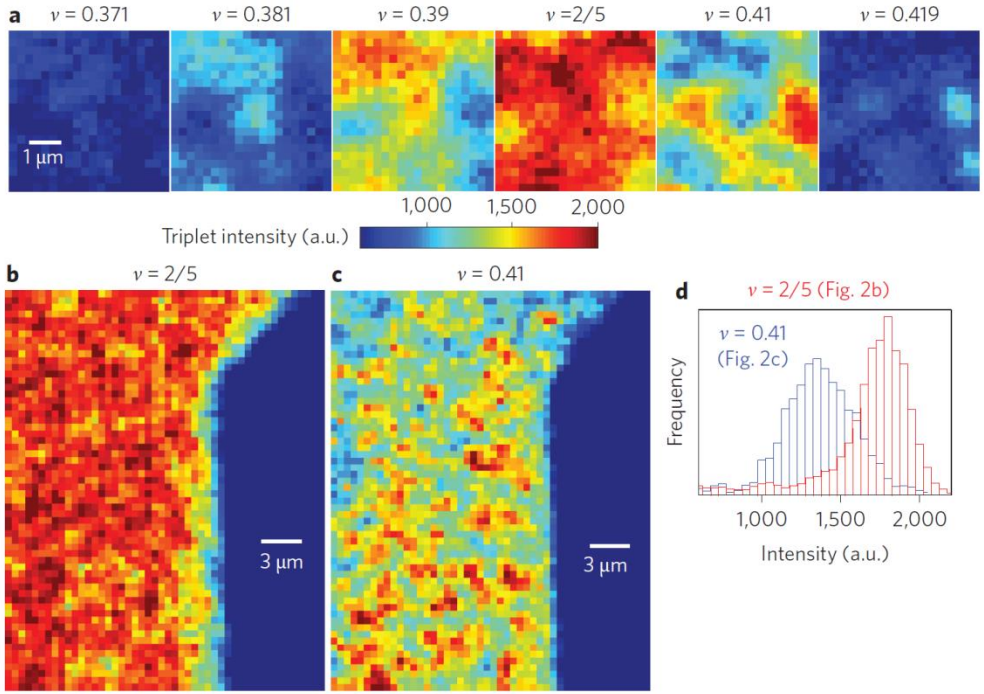
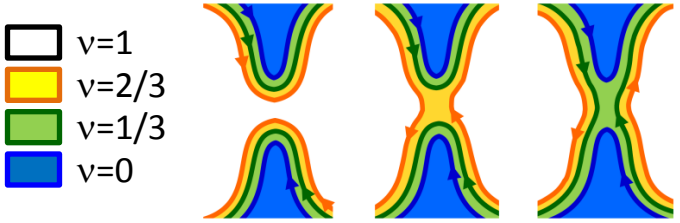


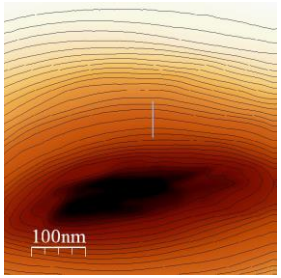


Six months after the publication in PRL of our results, another group (Hayakawa *et al.* Tohoku University, Japan) published in Nature Nanotechnology real space images of fractional liquids using a Scanning Confocal Microscopy technique

Conclusions and outline

- ***The inner structure of the edge channels has been directly demonstrated and imaged. Integer edges display fractional substructures.***

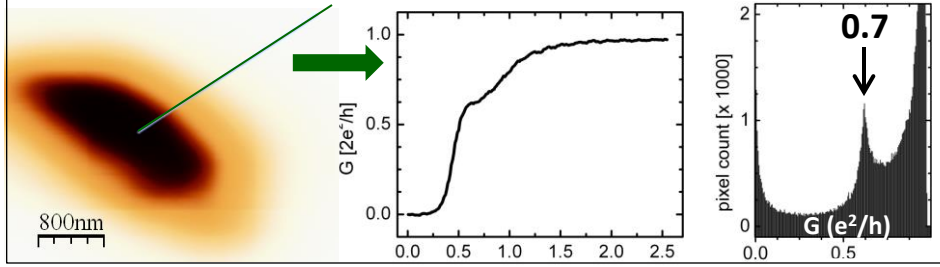




- ***The SGM maps allowed us to quantitatively test how the IS width depends on the details of the density slope***
- ***The SGM is a promising technique for real space investigation and manipulation of the electrons in transport experiments***

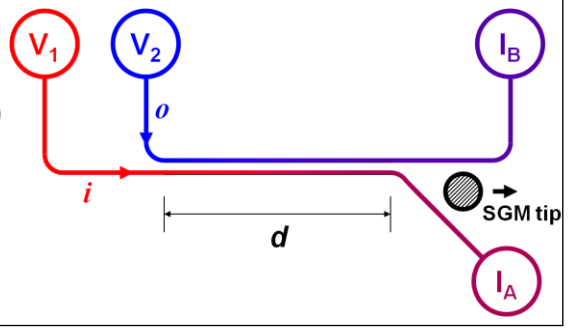
Real space investigation of the 0.7 anomaly

Iagallo *et al.* (2013, manuscript in preparation)



Spatially resolved analysis of edge equilibration

Paradiso *et al.* (2012)
PRB, **83** 155305



Thank you for your attention!

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SCUOLA NORMALE SUPERIORE

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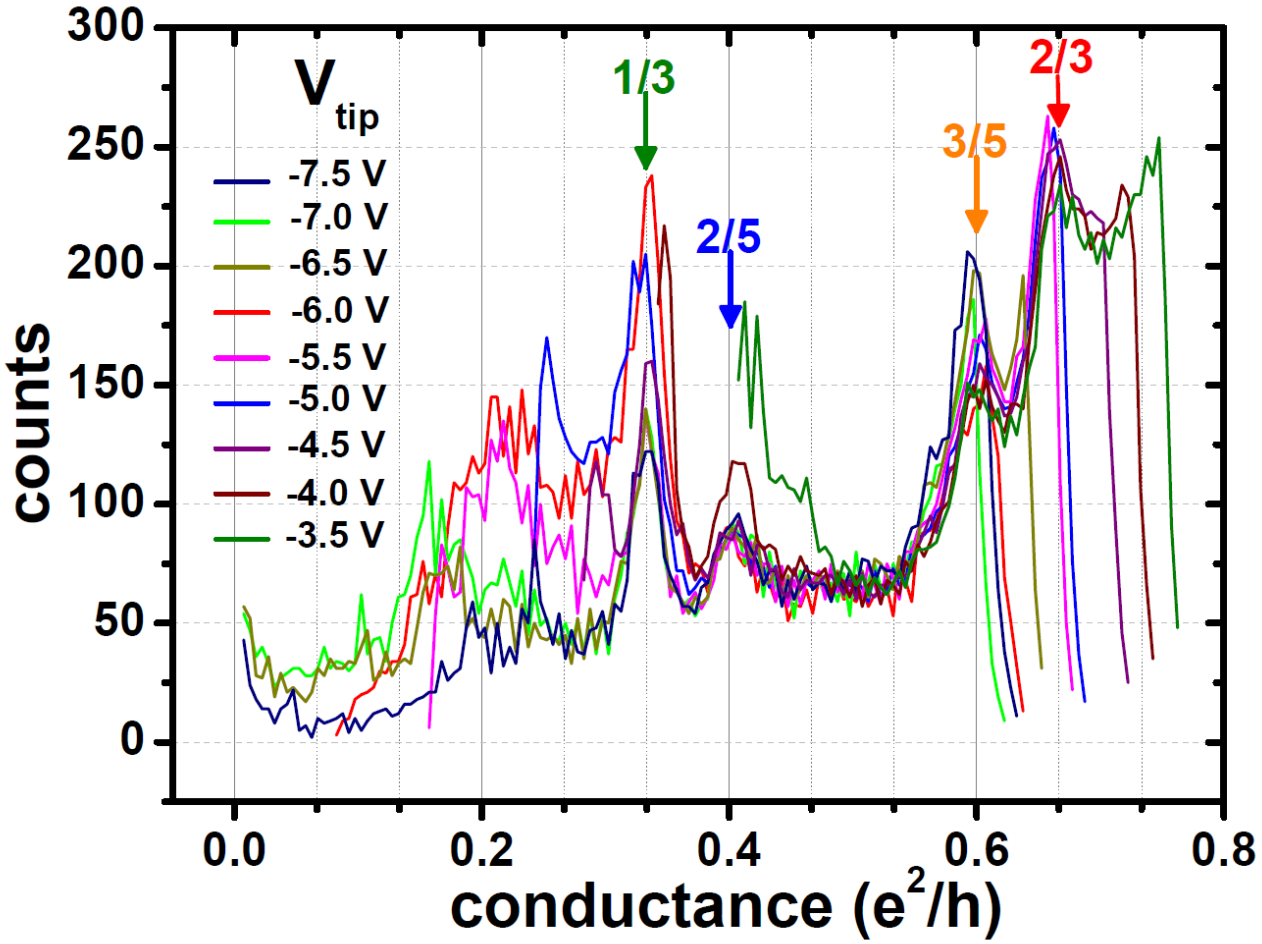
NEST SCUOLA NORMALE SUPERIORE PISA National Enterprise for nanoScience and nanoTechnology

For further information see also the Supplementary Material in:

PRL **108,** 246801 (2012) PHYSICAL REVIEW LETTERS week ending 15 JUNE 2012

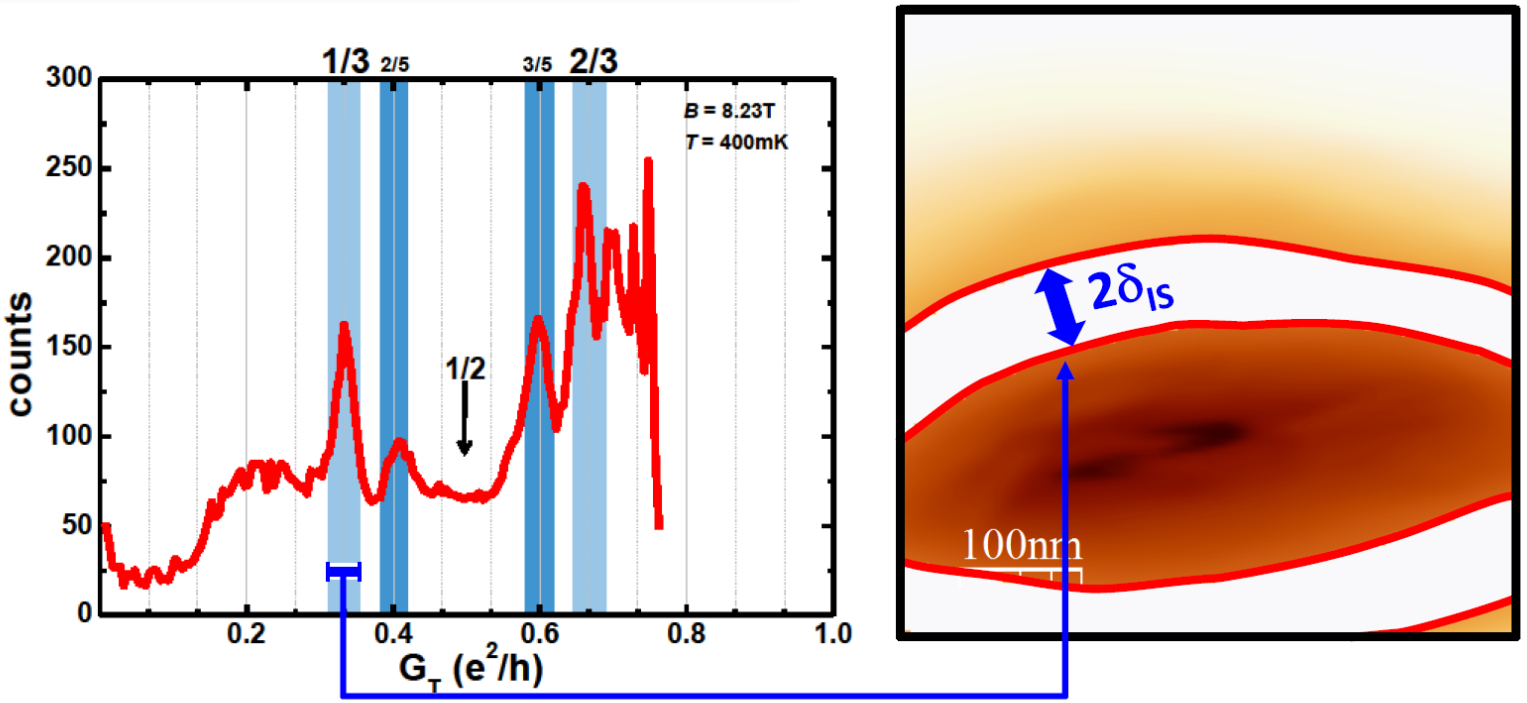
Imaging Fractional Incompressible Stripes in Integer Quantum Hall Systems

Appendix: Individual histograms



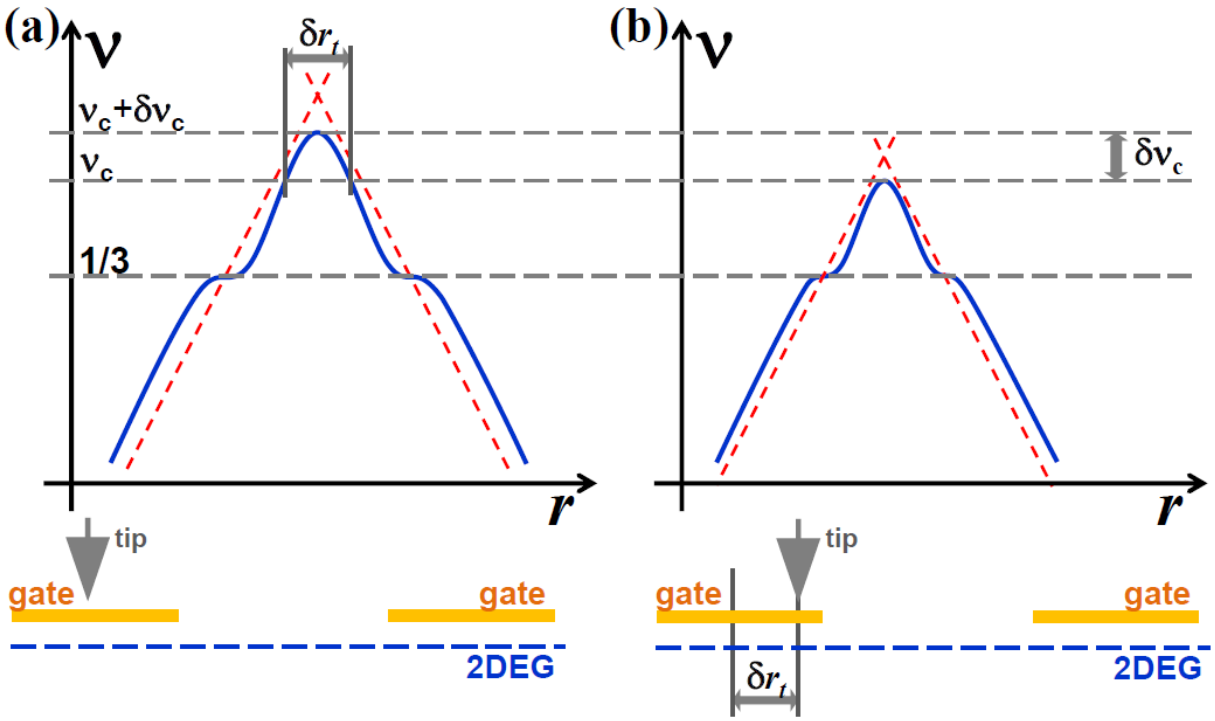
Histograms of the occurrence of each G_T value for all the 9 different SGM scans performed at different V_{tip} values. Fractional peaks are visible in each individual histogram.

Appendix: Determination of the IS width



The incompressible stripe width δ_{IS} is obtained starting from the FWHM of the corresponding peak in the histogram (left panel). This range of G_T values defines a circular stripe in the SGM map (right panel). δ_{IS} is given by the average width of such a stripe.

Appendix: Determination of the electron density slope



A displacement δr_t of the SGM tip toward the QPC center reduces the QPC width of the same amount. The corresponding reduction of the filling factor at the QPC center (which is measured as a reduction of $G_T = \nu G_0$) is approximately given by $\delta r_t/2$ times the filling factor slope.