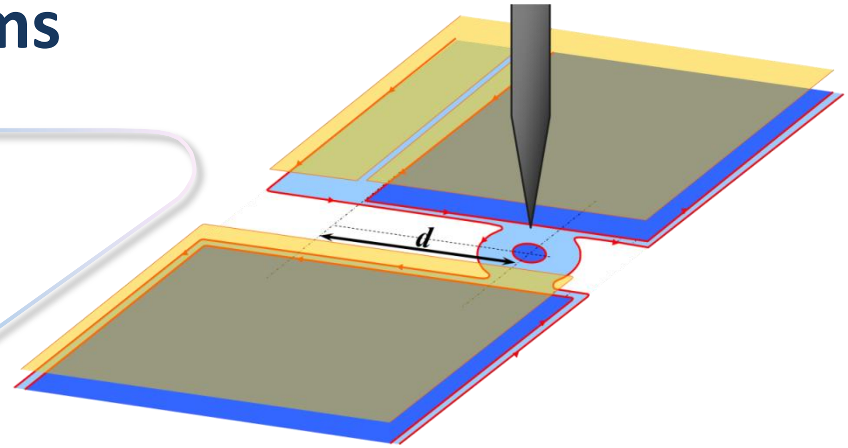
Imaging Fractional Incompressible Stripes in Integer Quantum Hall Systems



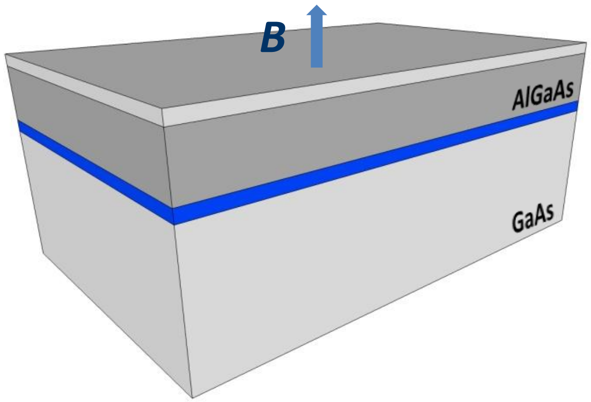
Nicola Paradiso,[1] Stefan Heun,[1] Stefano Roddaro,[1] Giorgio Biasiol,[2] Lucia Sorba,[1] Loren N. Pfeiffer,[3] Ken W. West,[3] and Fabio Beltram[1]

1. *NEST, Istituto Nanoscienze-CNR and Scuola Normale Superiore, Pisa, Italy*
2. *Istituto Officina dei Materiali CNR, Laboratorio TASC, Basovizza (TS), Italy*
3. *Dept. of Electrical Engineering, Princeton University, New Jersey 08544, USA*

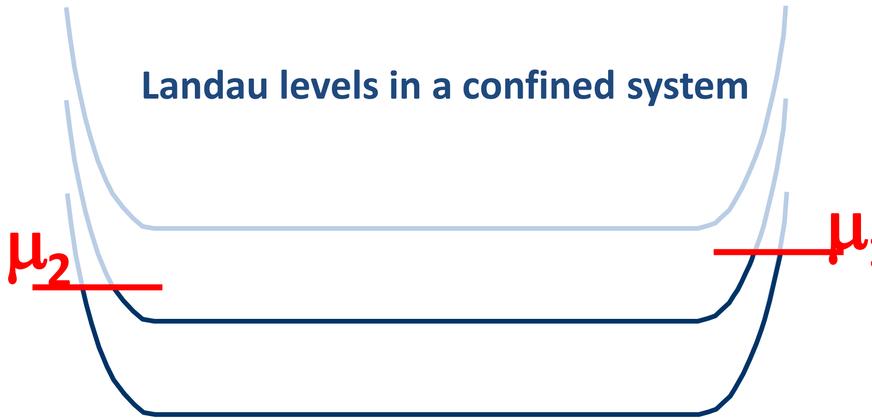
SGM Group

National Enterprise for nanoScience and nanoTechnology

The non-interacting picture of the QH effect

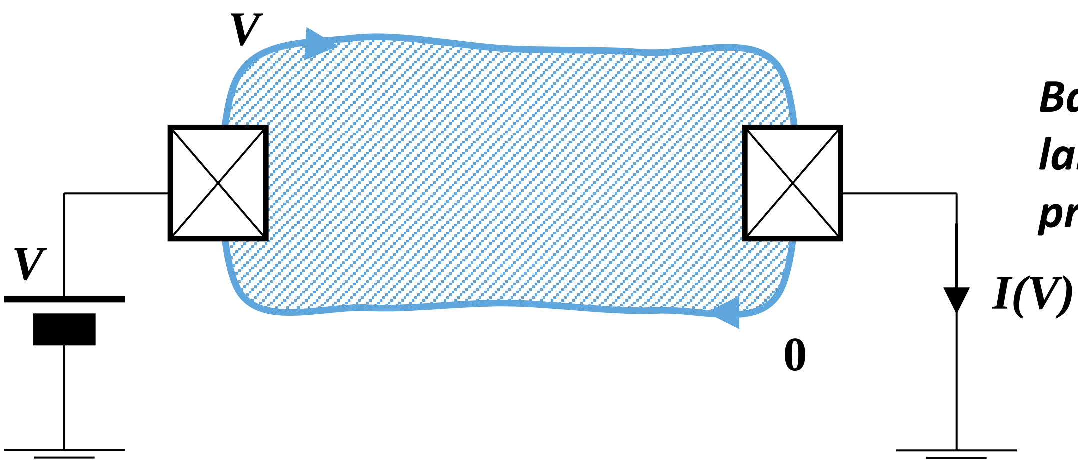


2DES
in high field



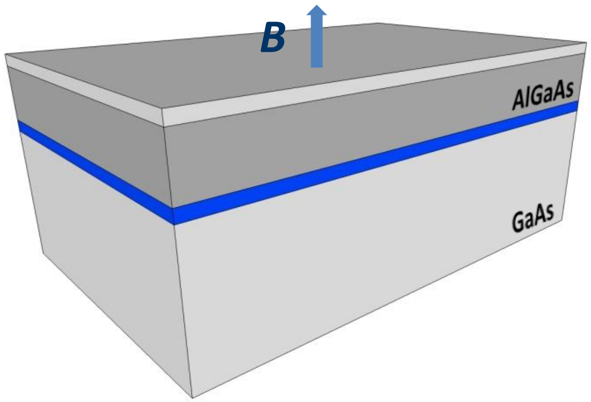
- Edge state picture:
  current is carried by chiral 1D channels

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

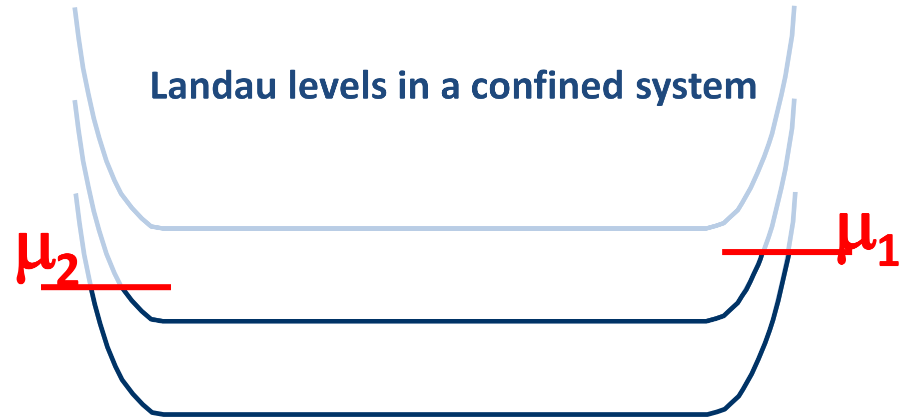


Backscattering is suppressed due to the large spatial separation between counter-propagating channels

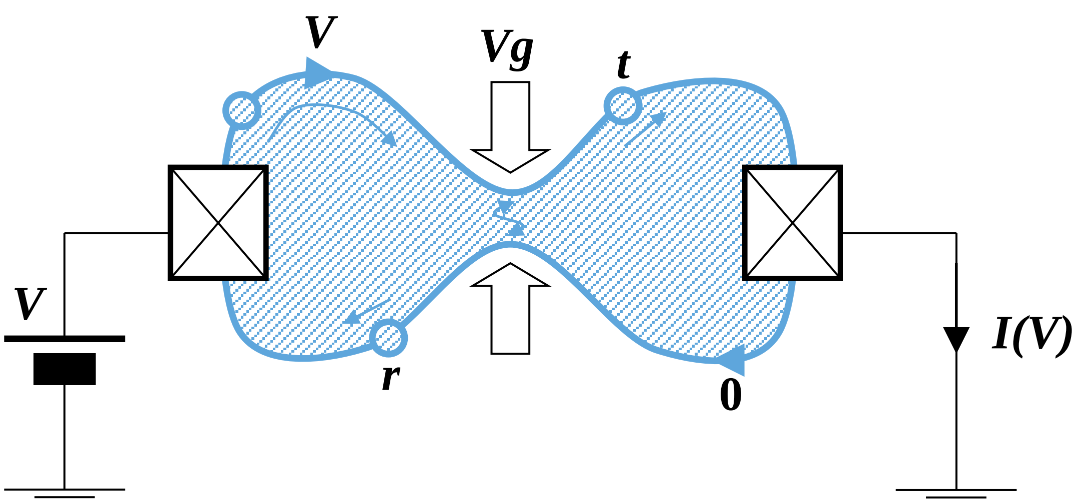
The non-interacting picture of the QH effect



2DES
in high field



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



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

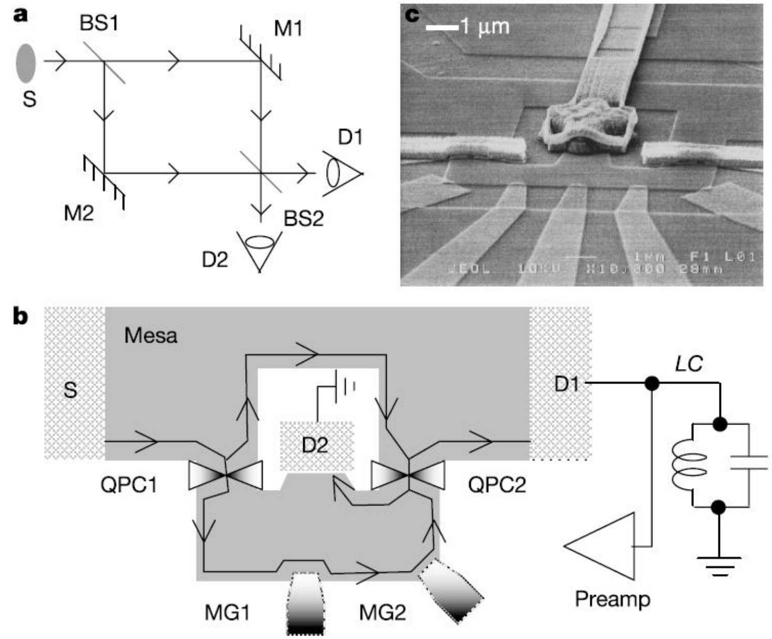
Roddaro et al.: PRL **90** (2003) 046805
Roddaro et al.: PRL **93** (2004) 046801
Roddaro et al.: PRL **95** (2005) 156804
Roddaro, Paradiso et al.: PRL **103** (2009) 016802

Edge channel-based interferometers

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

An electronic Mach–Zehnder interferometer

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



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

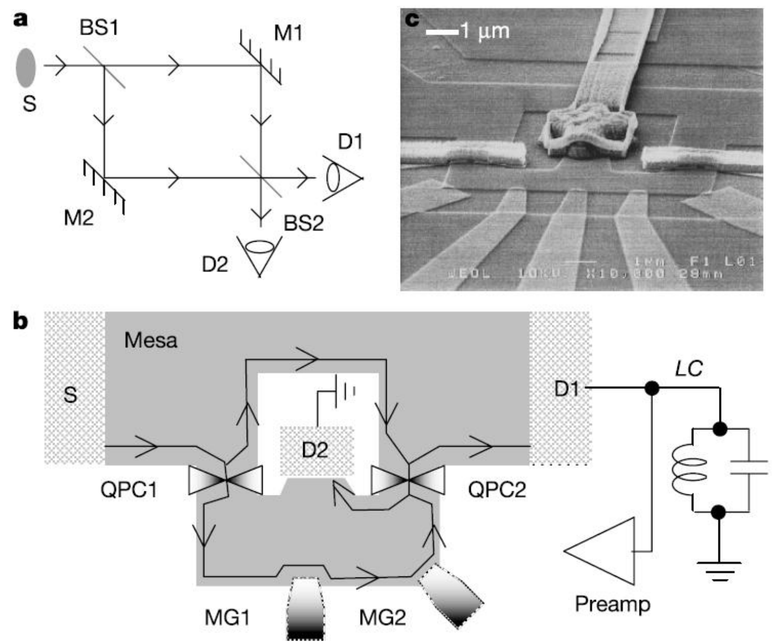
Edge channel-based interferometers

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

Puzzle: internal structure of edge seems to play no role here

An electronic Mach–Zehnder interferometer

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



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

Edge channel-based interferometers

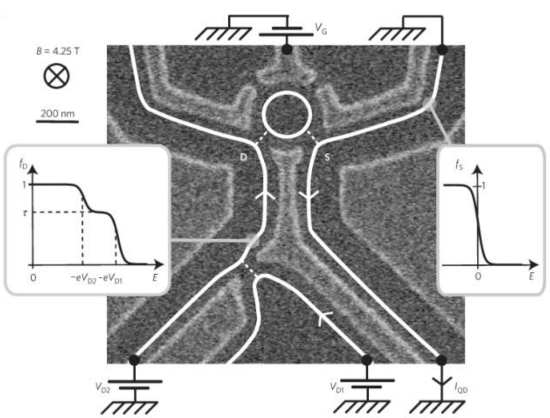
The very large coherence length has been exploited to implement complex interferometers as the electronic Mach-Zehnder.

Puzzle: internal structure of edge seems to play no role here

LETTERS
PUBLISHED ONLINE: 25 OCTOBER 2009 | DOI: 10.1038/NPHYS1429
nature physics

Non-equilibrium edge-channel spectroscopy in the integer quantum Hall regime

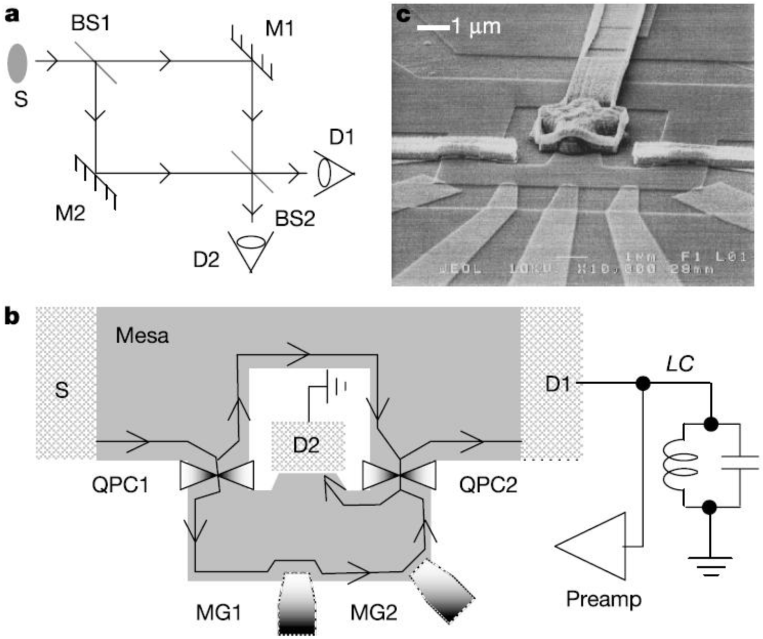
C. Altimiras, H. le Sueur, U. Gennser, A. Cavanna, D. Mailly and F. Pierre*



Nat. Phys. **6**, 34 (2010)

An electronic Mach–Zehnder interferometer

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



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

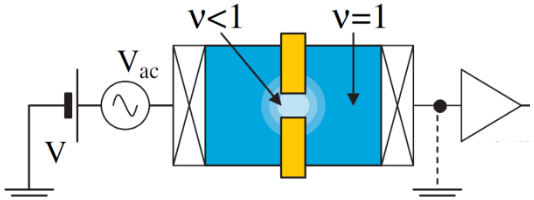
Edge channel-based interferometers

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

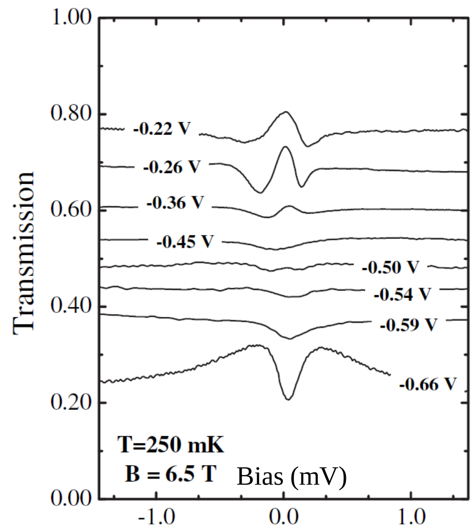
Puzzle: internal structure of edge seems to play no role here

Role of the inner edge structure?

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

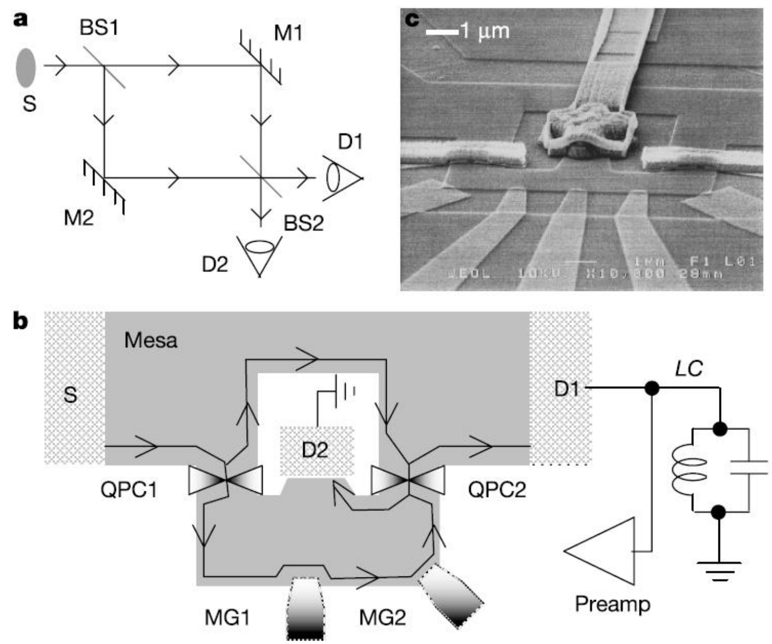


PRL **95**, 156804 (2005)



An electronic Mach–Zehnder interferometer

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



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

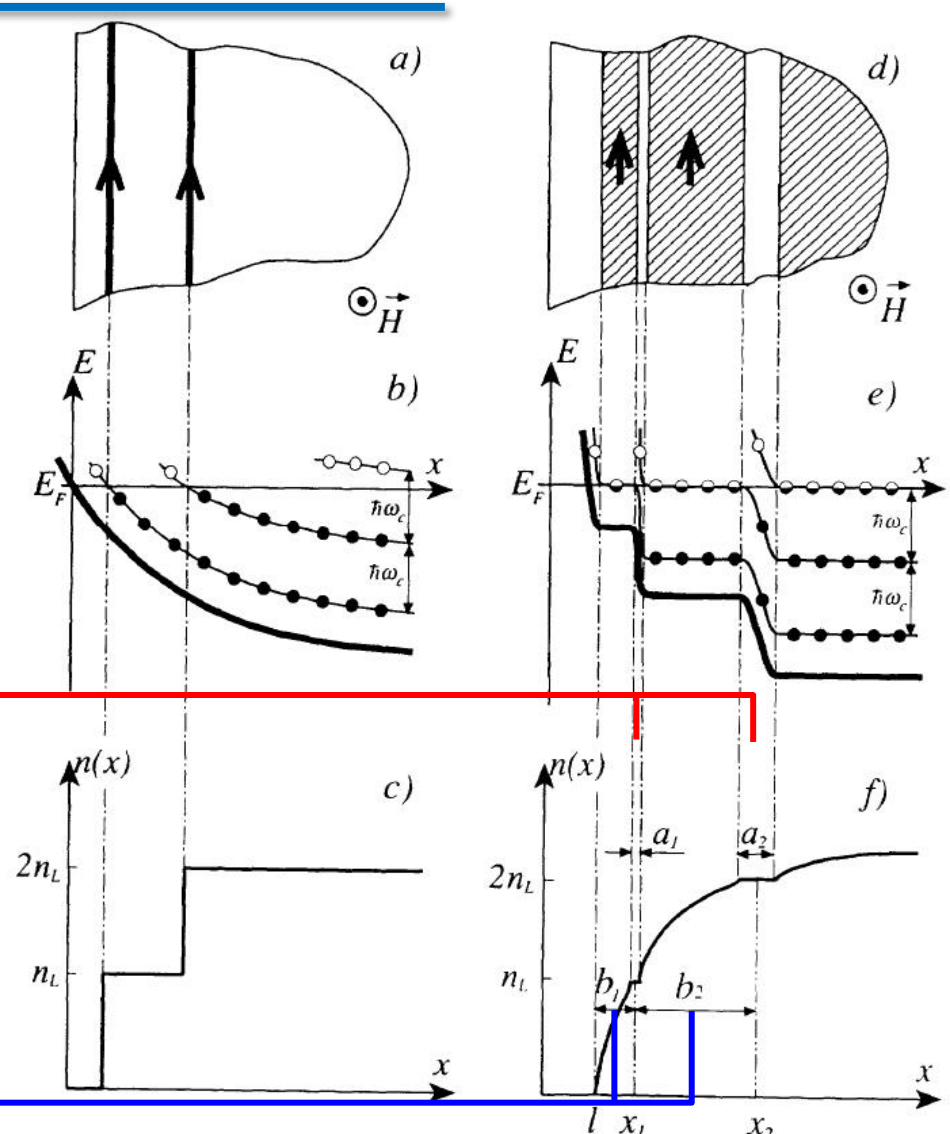
Need for spatially resolved measurements

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



<u>Incompressible</u> stripes:

- The electron density is constant
- The potential has a jump

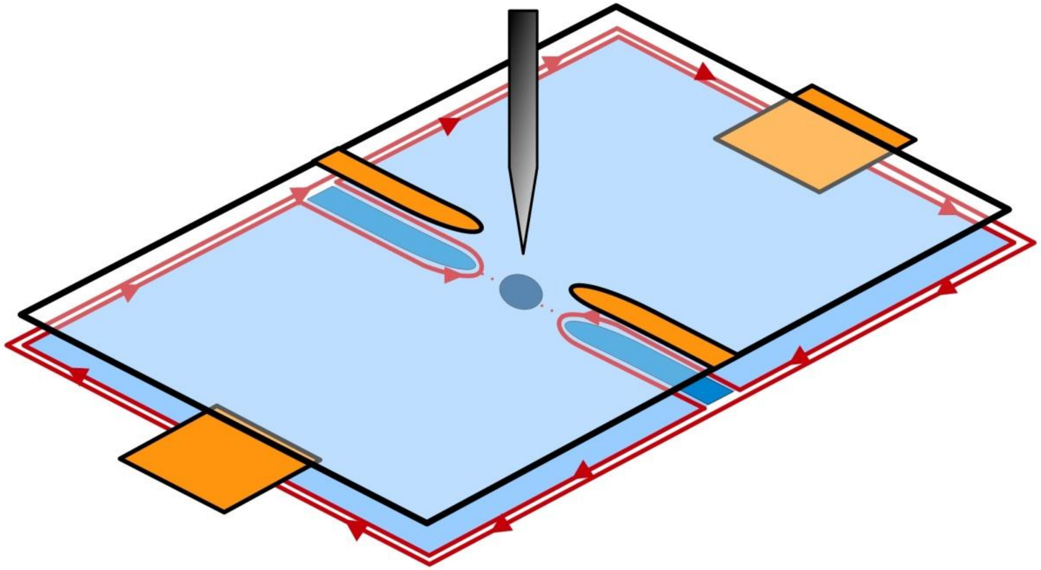
<u>Compressible</u> stripes:

- The electron density has a jump
- The potential is constant

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

Edge channel tomography by SGM

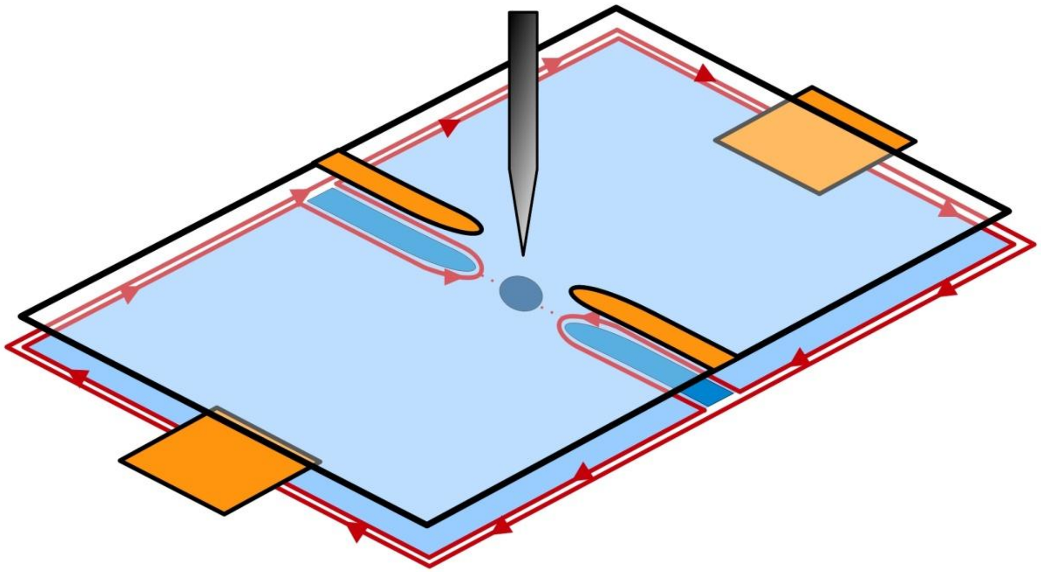
SGM technique: we select individual channels from the edge of a quantized 2DEG, we send them to the constriction and make them backscatter with the biased SGM tip.

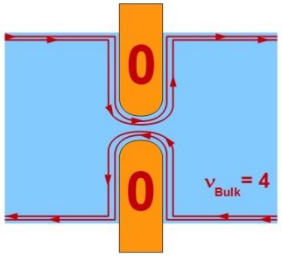


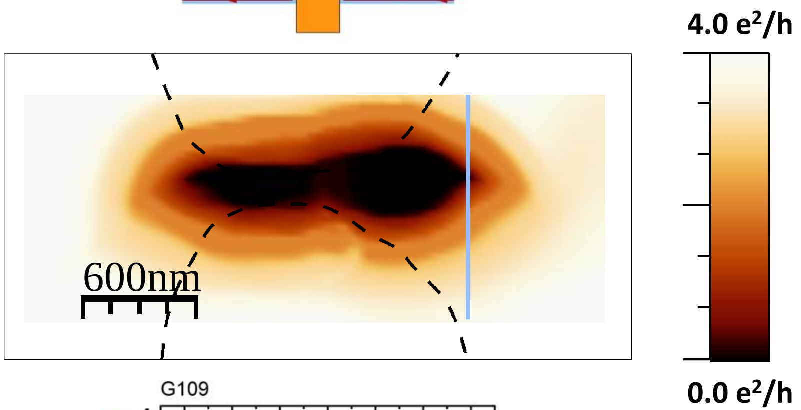
- Bulk filling factor ν=4
- B = 3.04 T
- 2 spin-degenerate edge channels
- gate-region filling factors $g_1 = g_2 = 0$

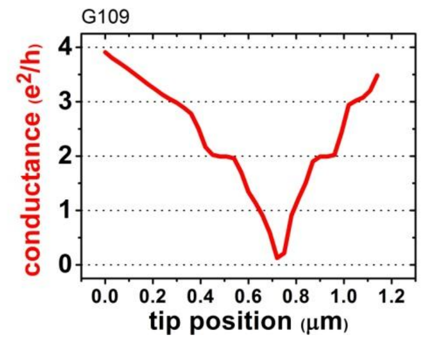
Edge channel tomography by SGM

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.





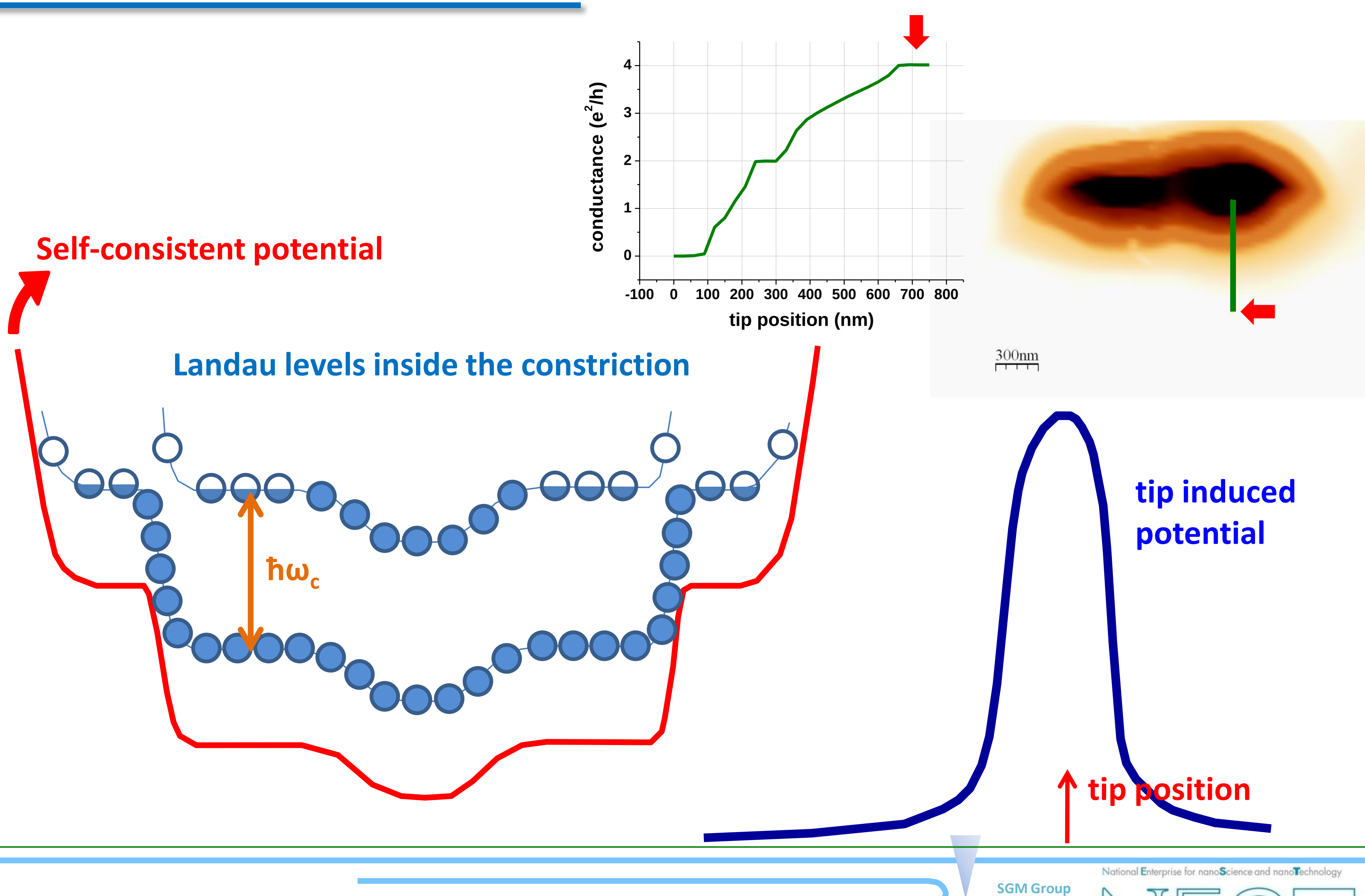




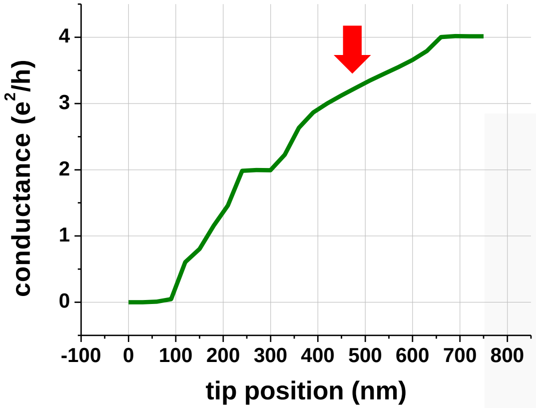
- **Bulk filling factor ν=4**
- **B = 3.04 T**
- **2 spin-degenerate edge channels**
- **gate-region filling factors $g_1 = g_2 = 0$**

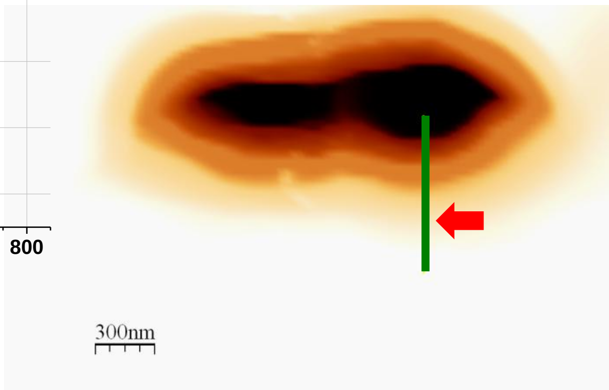
N. Paradiso *et al., Physica E 42 (2010) 1038.*

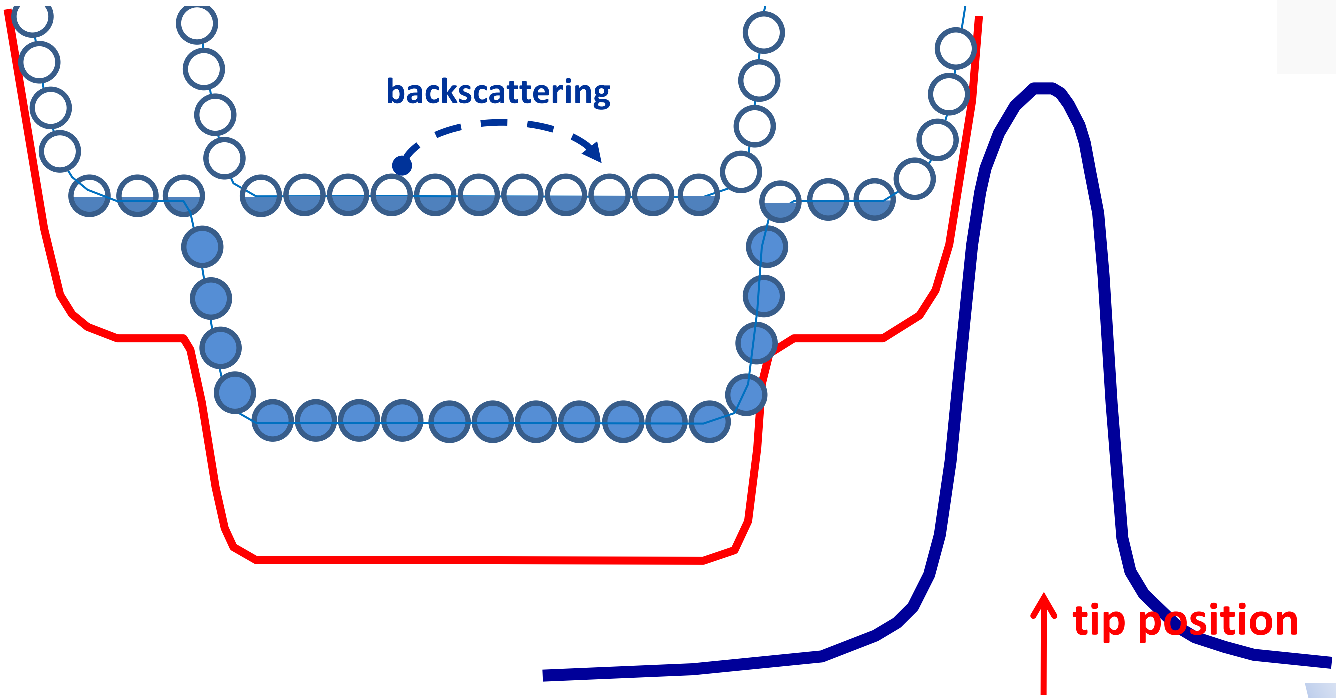
How we probe incompressible stripes



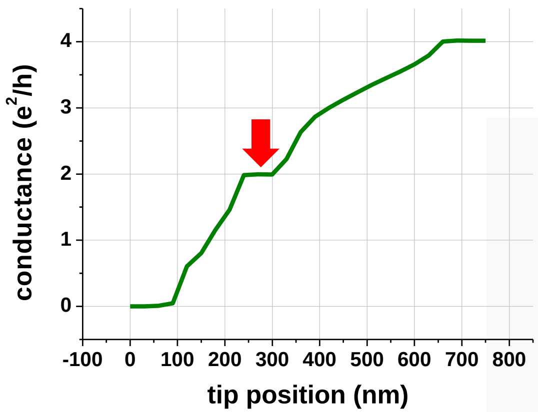
How we probe incompressible stripes

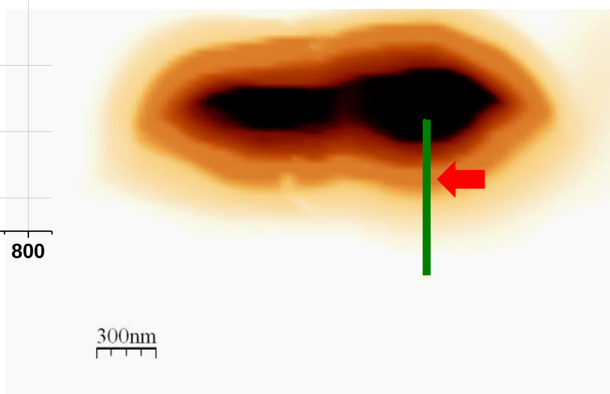


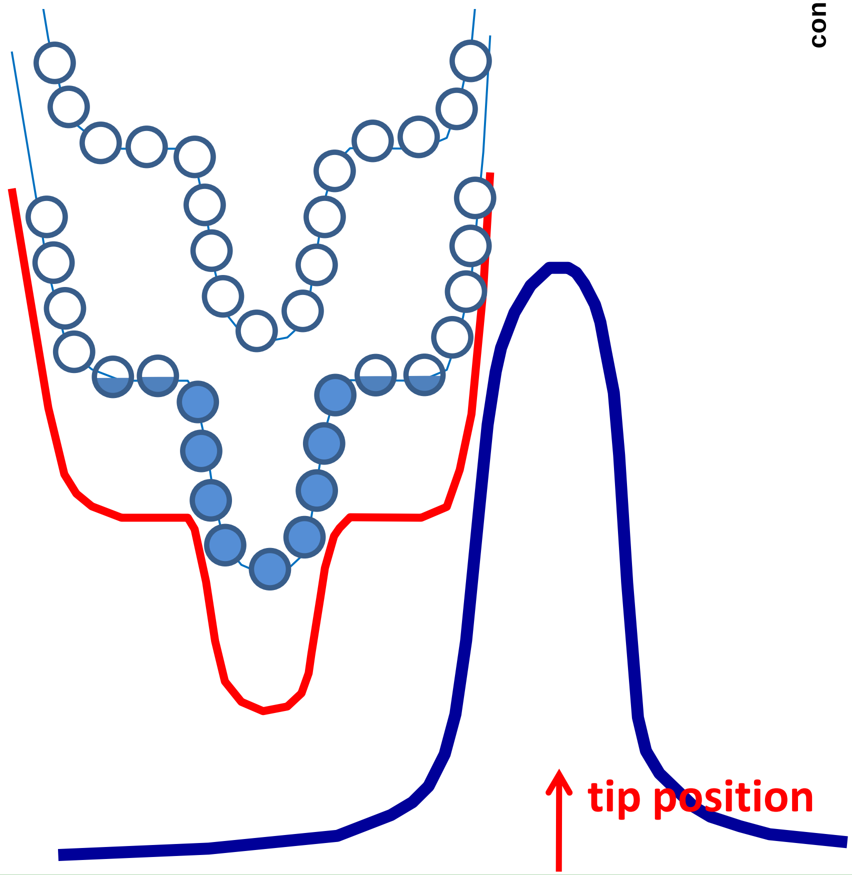




How we probe incompressible stripes

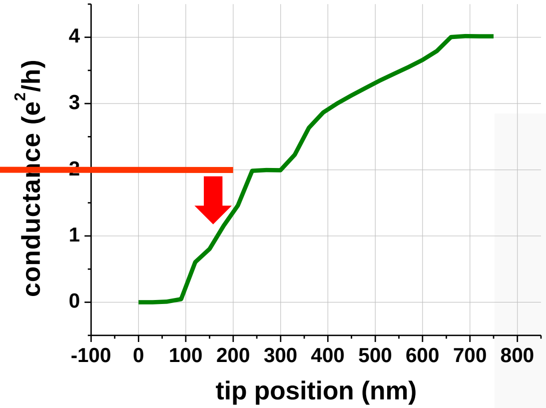


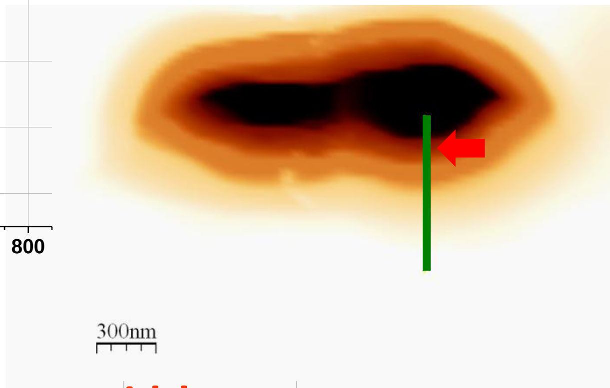


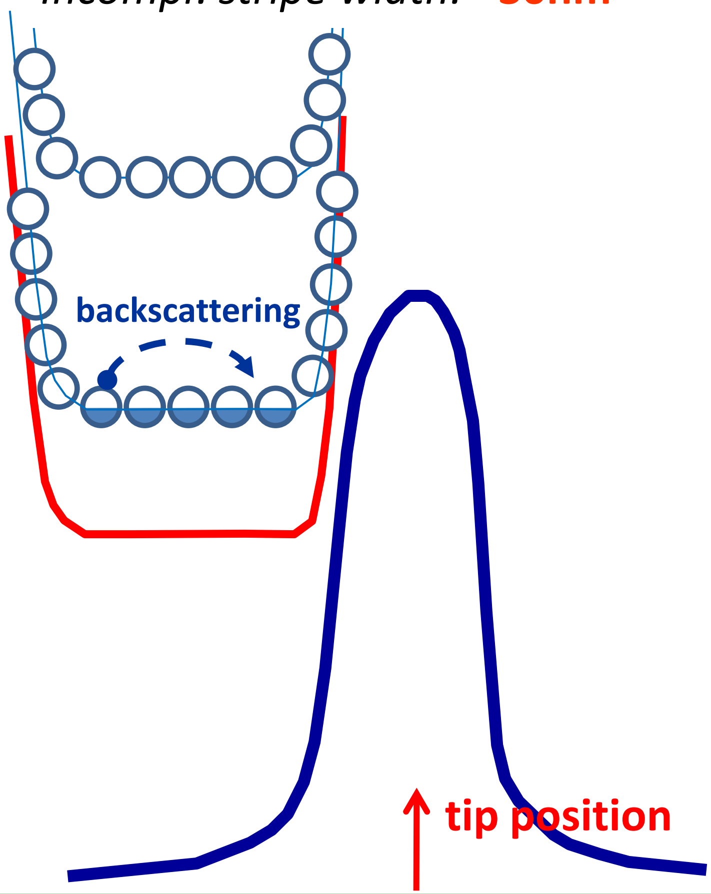


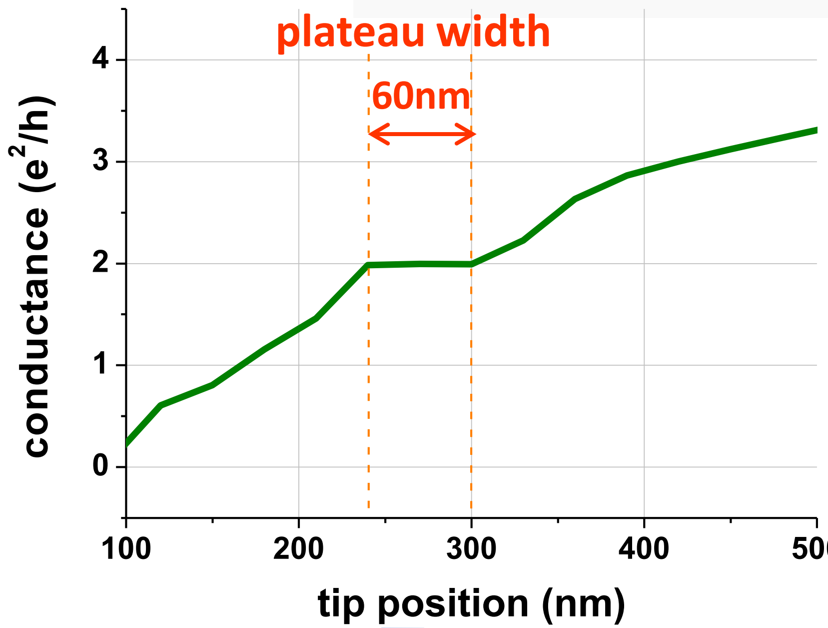
How we probe incompressible stripes

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

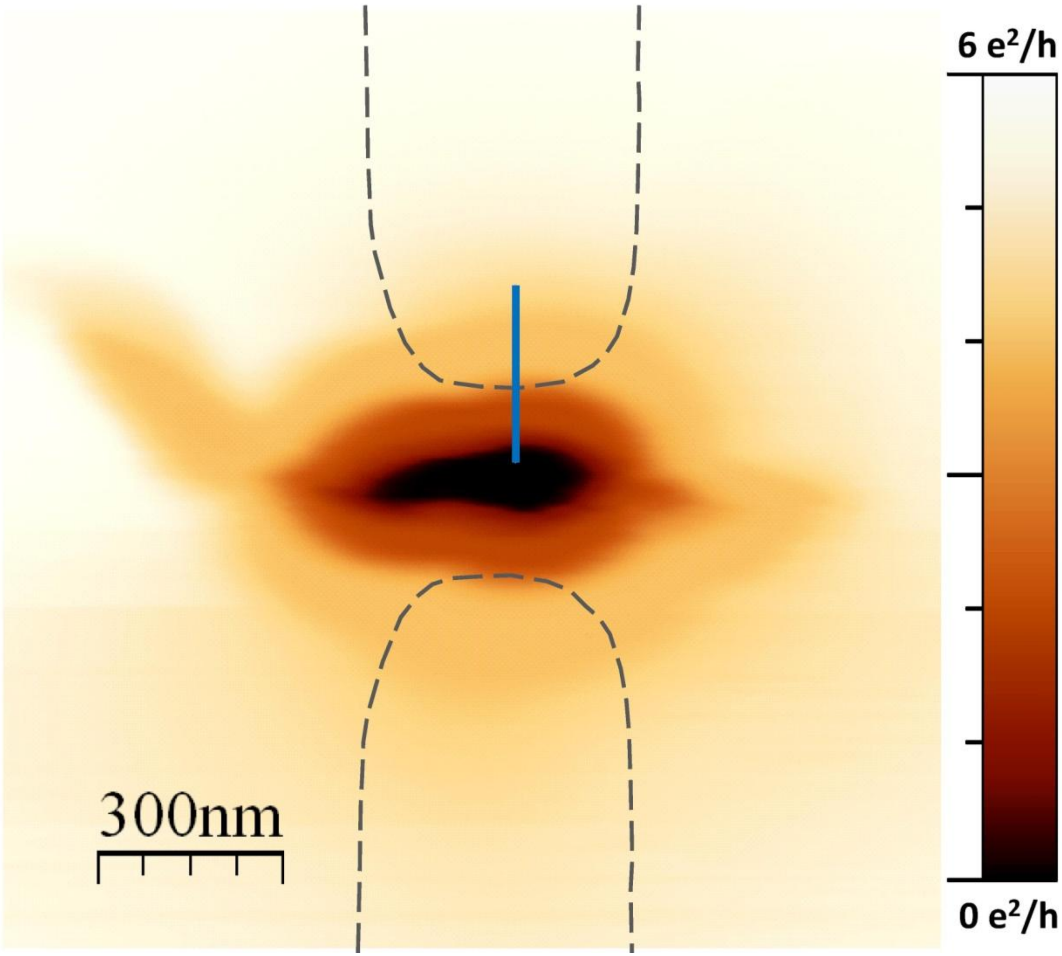


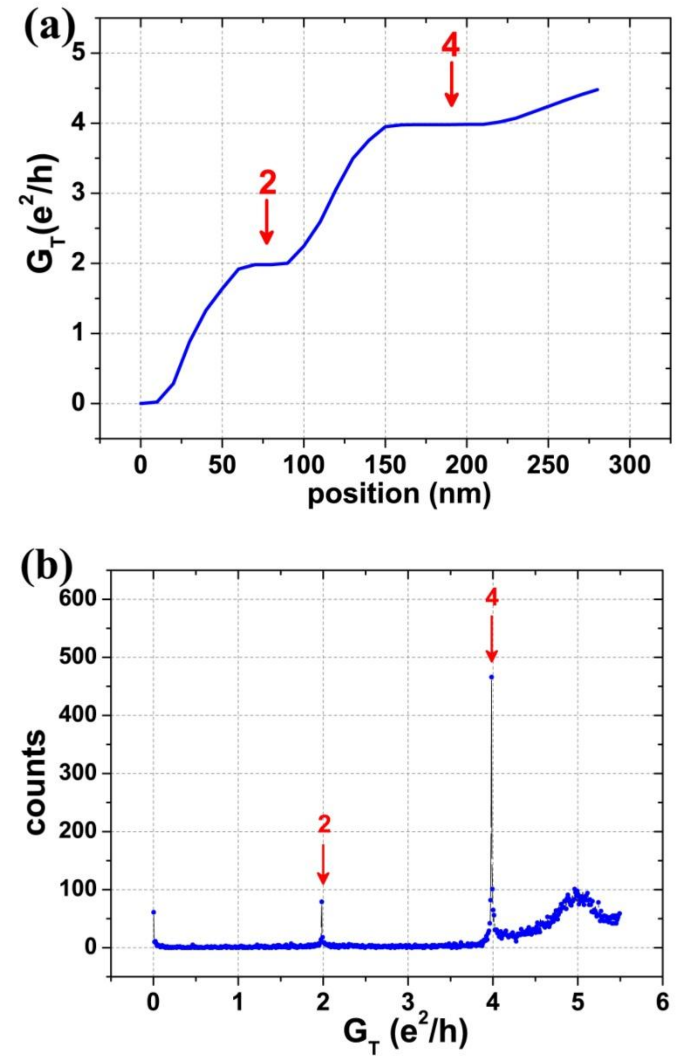






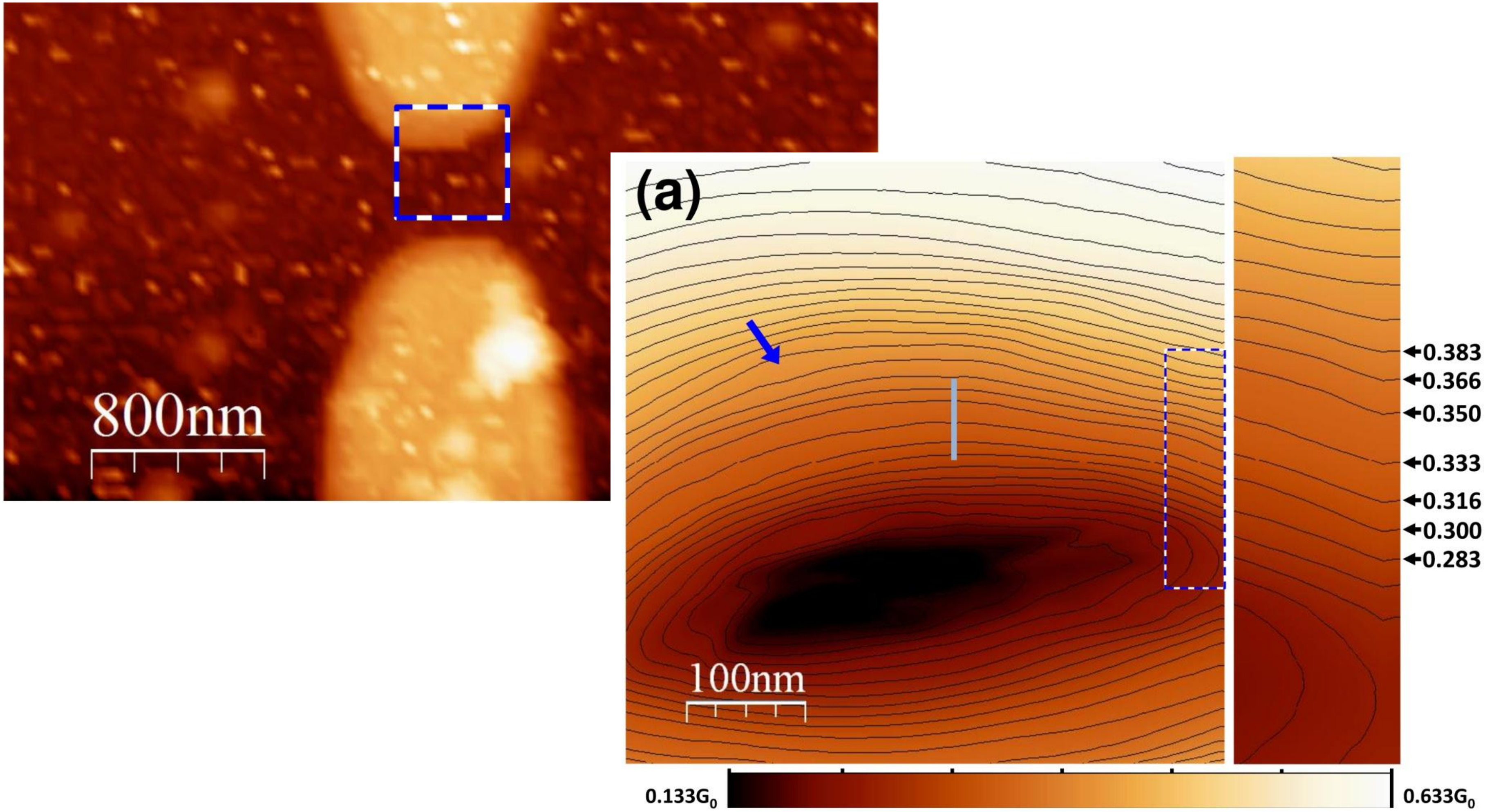
Histogram analysis





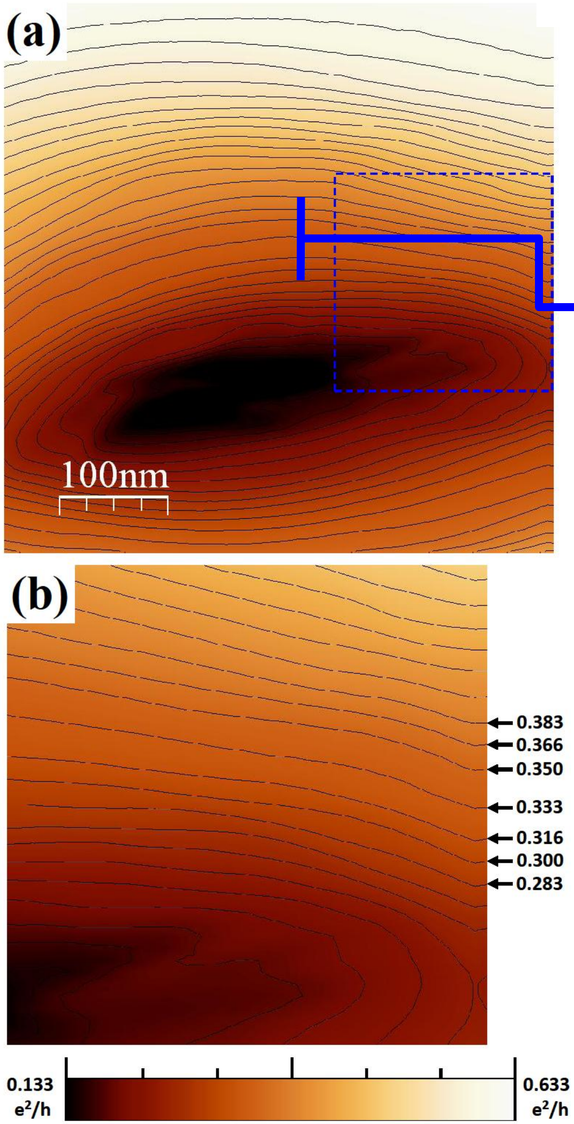
$\nu=6$

Imaging fractional structures in integer channels (ν=1)

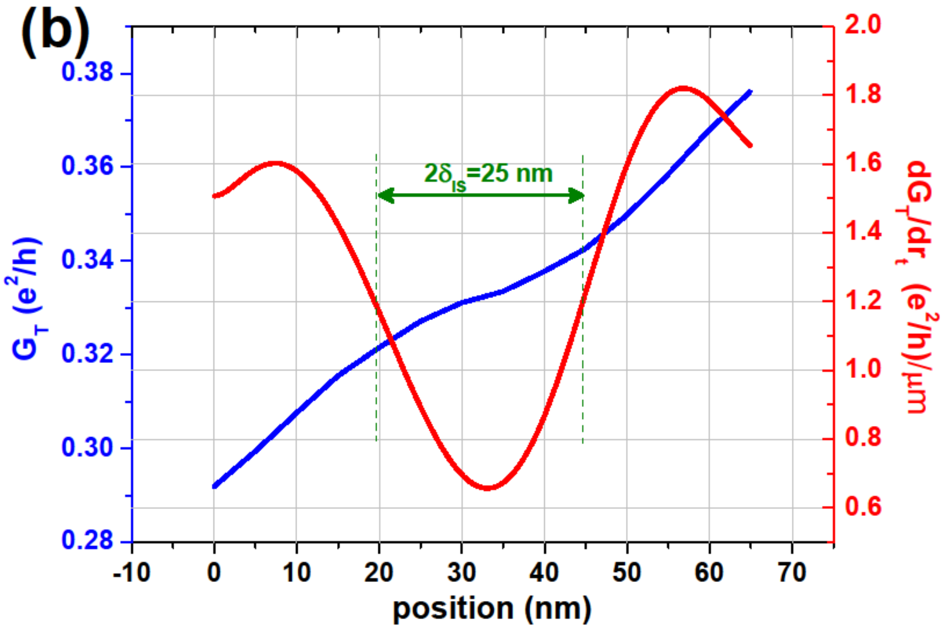


N. Paradiso *et al.* Phys. Rev. Lett. **108**, 246801 (2012)

Imaging fractional structures in integer channels (ν=1)

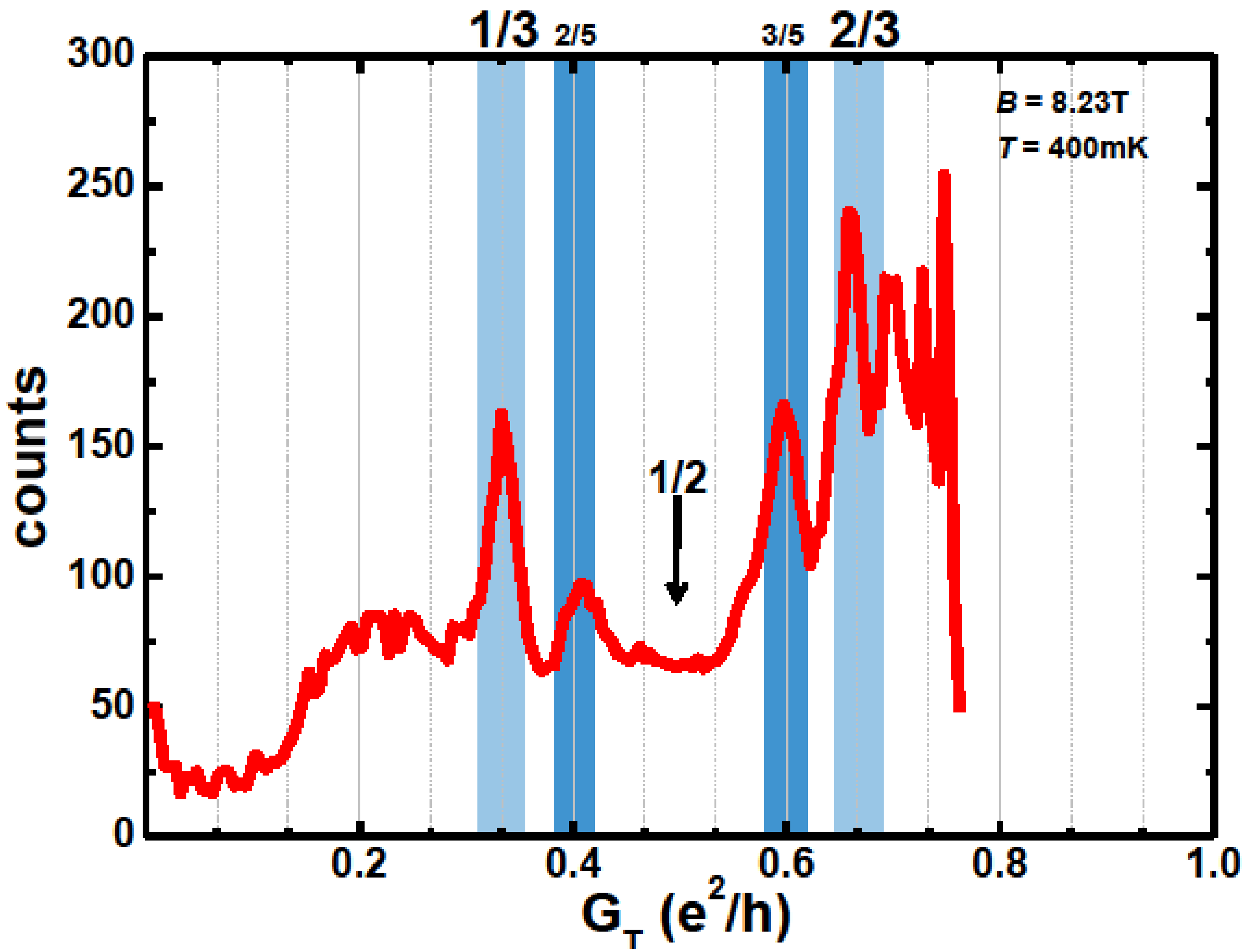


δ_{IS} ~ 12 nm



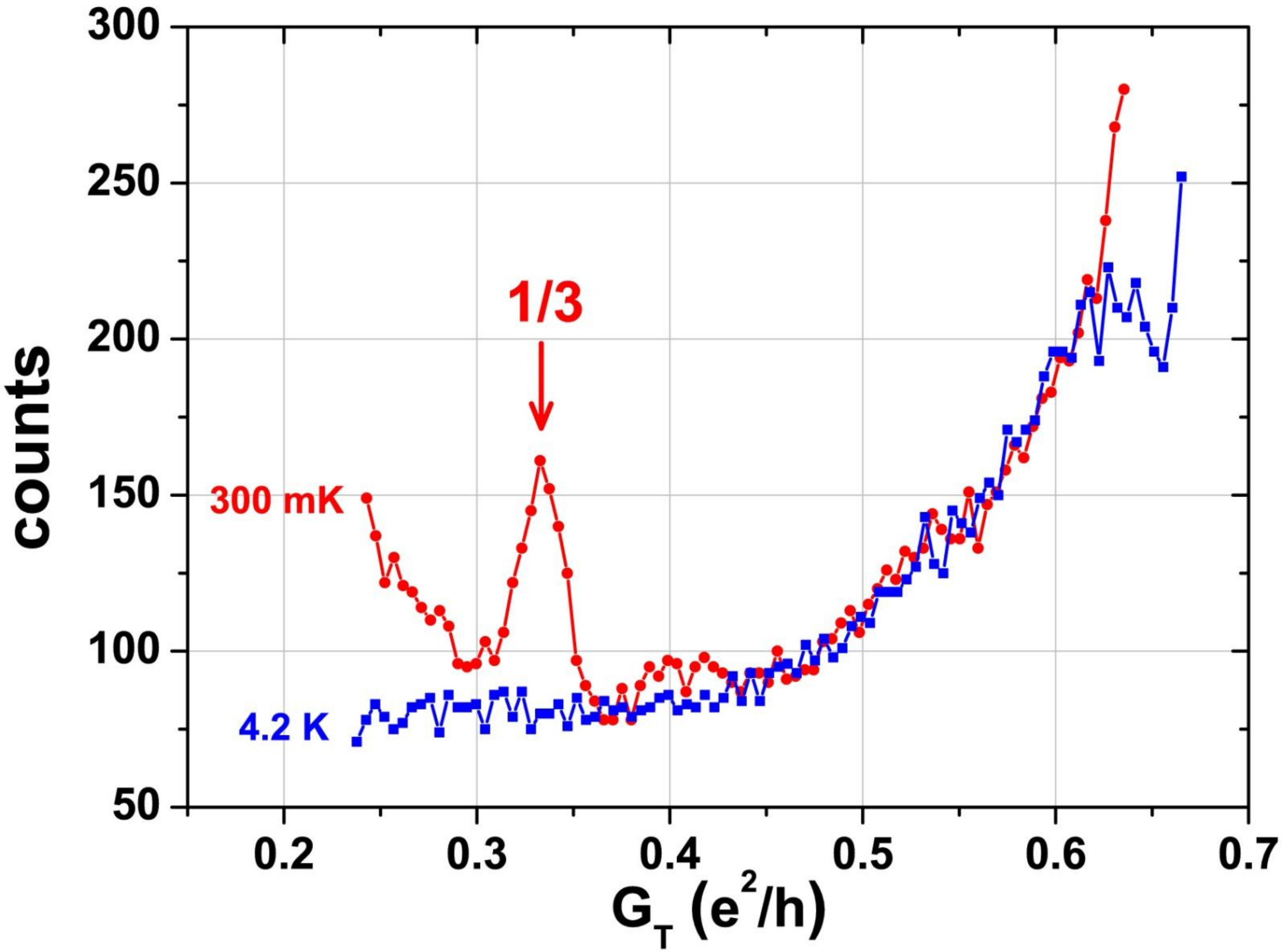
N. Paradiso *et al.* Phys. Rev. Lett. **108**, 246801 (2012)

Imaging fractional structures in integer channels (ν=1)



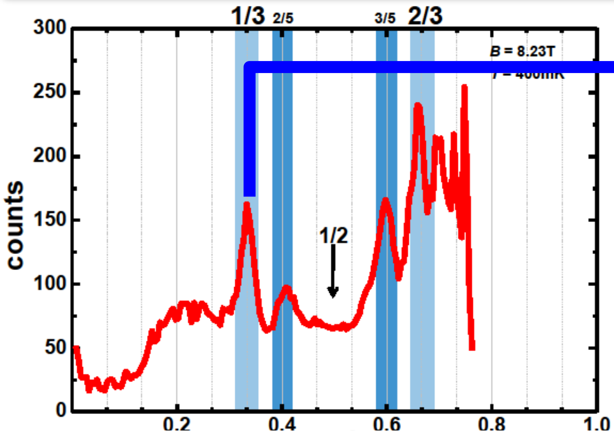
N. Paradiso *et al.* Phys. Rev. Lett. **108**, 246801 (2012)

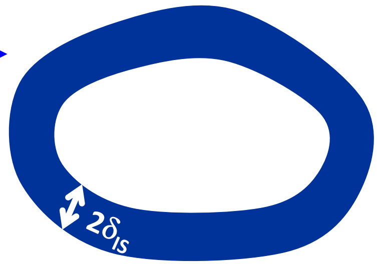
Temperature dependence of 1/3 peak in histogram



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

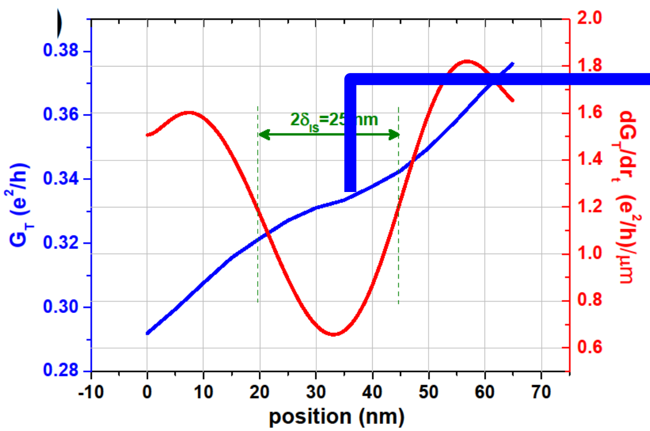
Fractional edge reconstruction





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

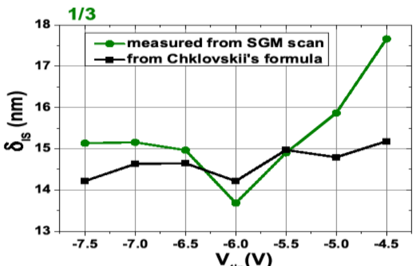
δ_{IS} determined from SGM measurements

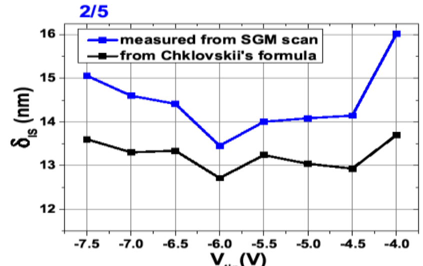


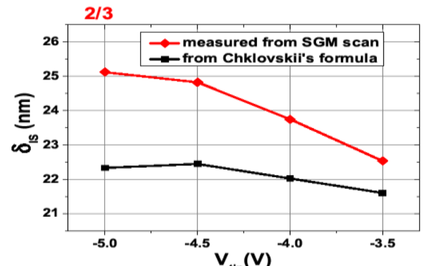
$$\frac{dn}{dr}$$

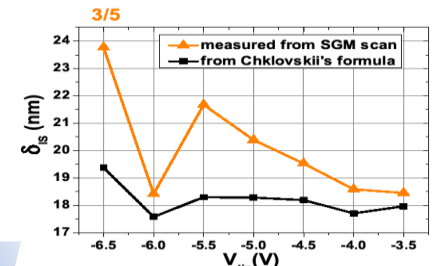
δ_{IS} determined from Chklovskii's formula

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



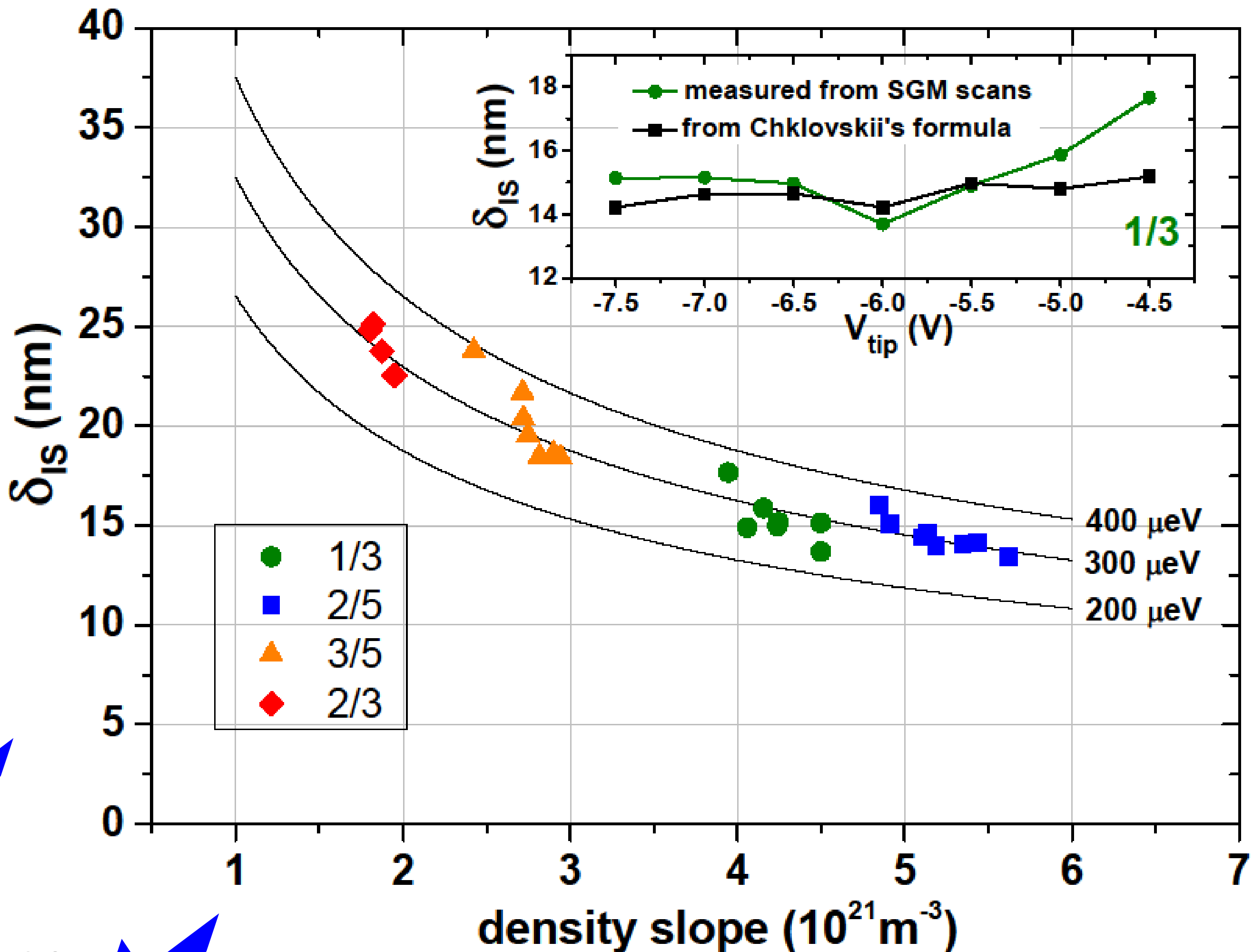






Fractional edge reconstruction

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

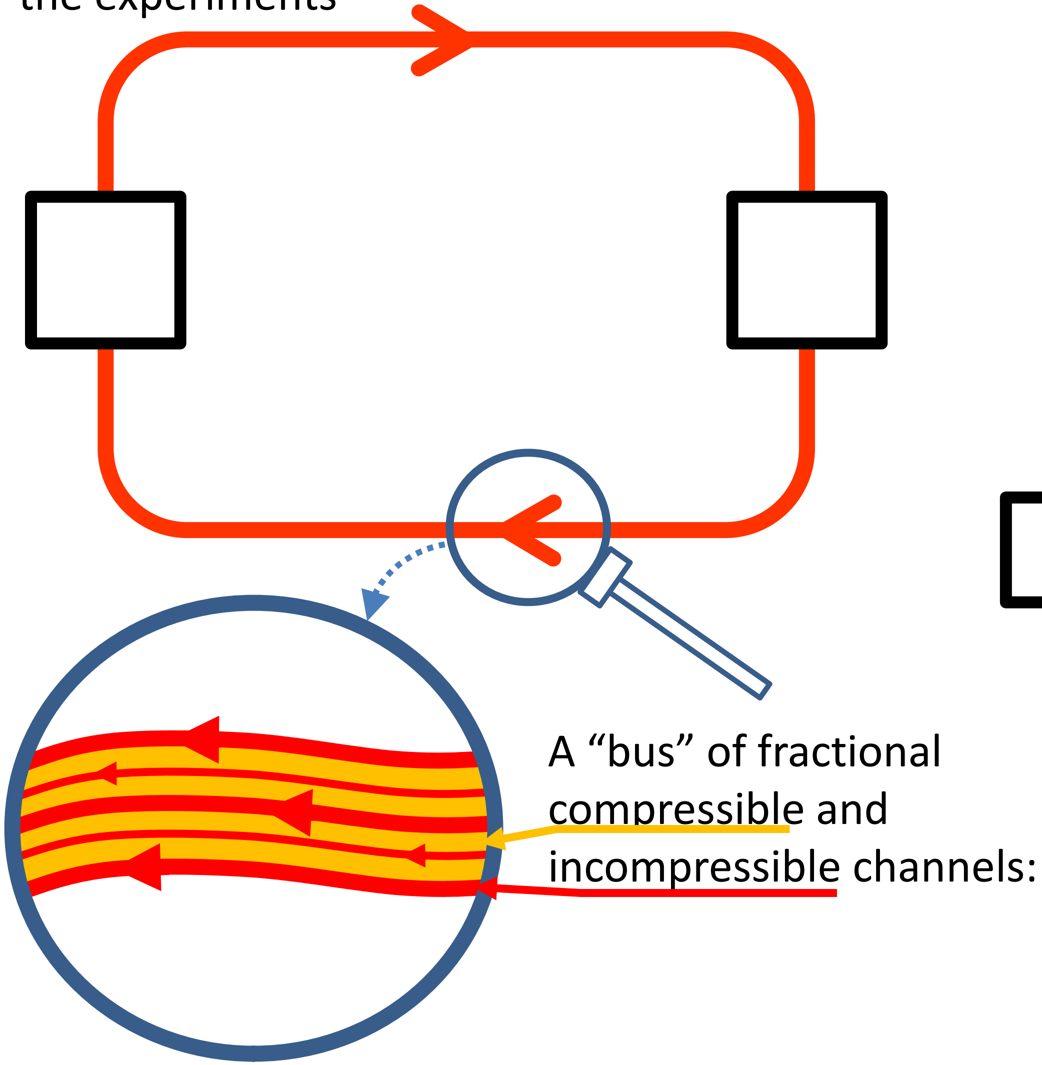


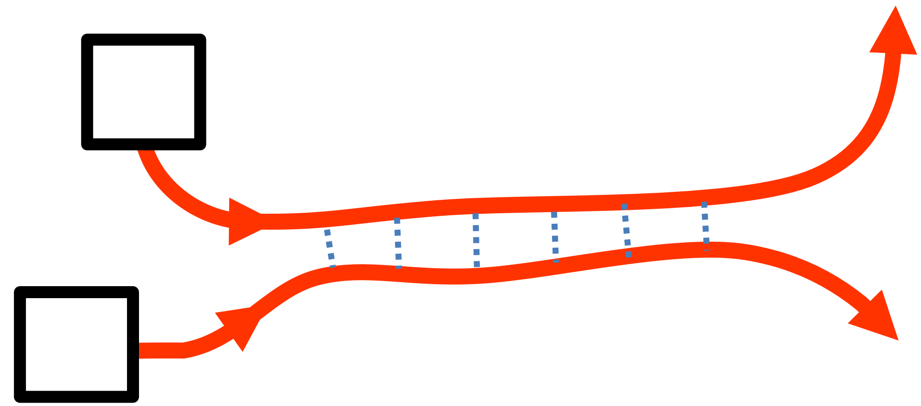
Inner edge structure ***demonstrated*** *and* ***imaged***

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

Can we exploit the non-trivial edge structure?

The picture of a QH device emerging from the experiments





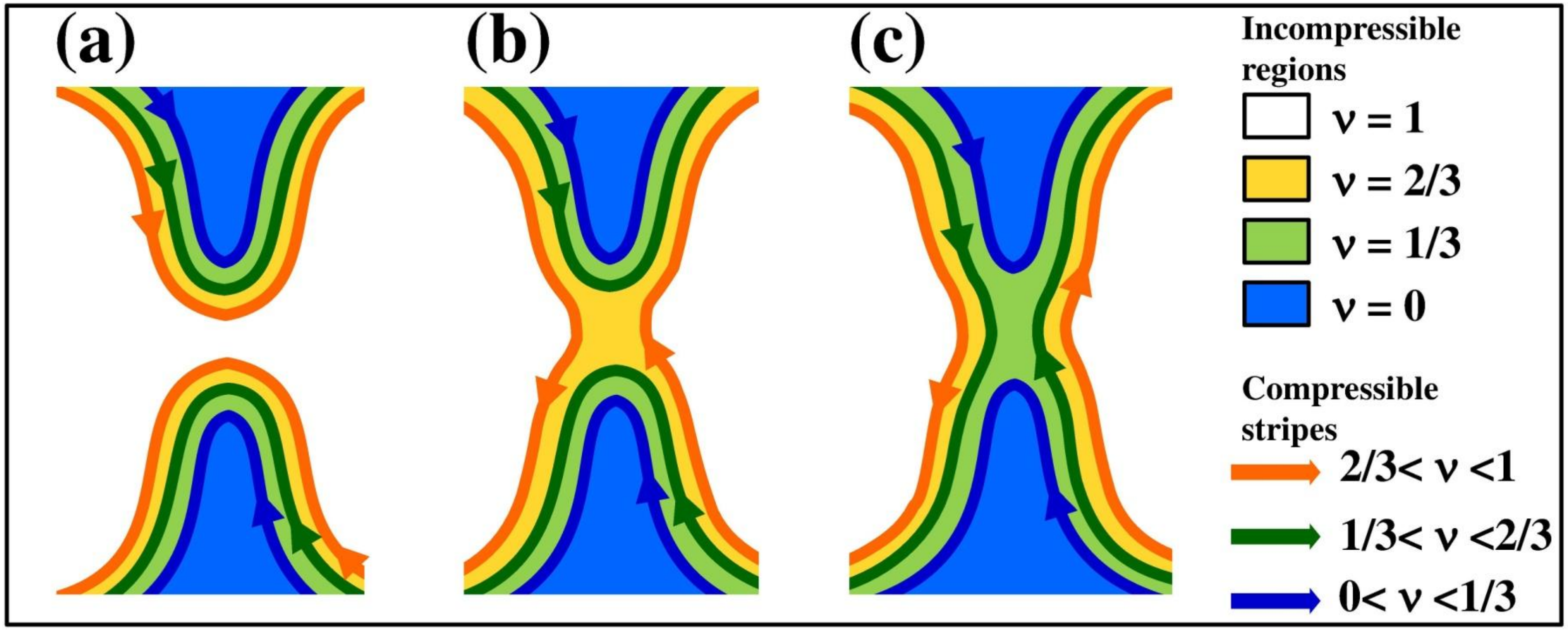
How do these channels interact?

N. Paradiso *et al.*

Phys. Rev. B 83, 155305 (2011)

Phys. Rev. B 84, 235318 (2011)

Summary



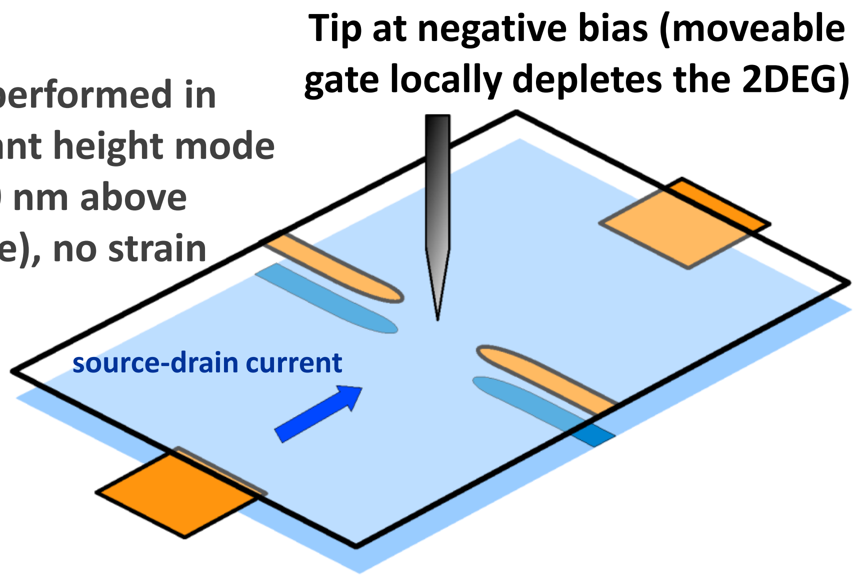
- Fractional incompressible stripes observed in integer edge channels
- Estimate width of these stripes
- Comparison with edge reconstruction theory

Appendix: 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**

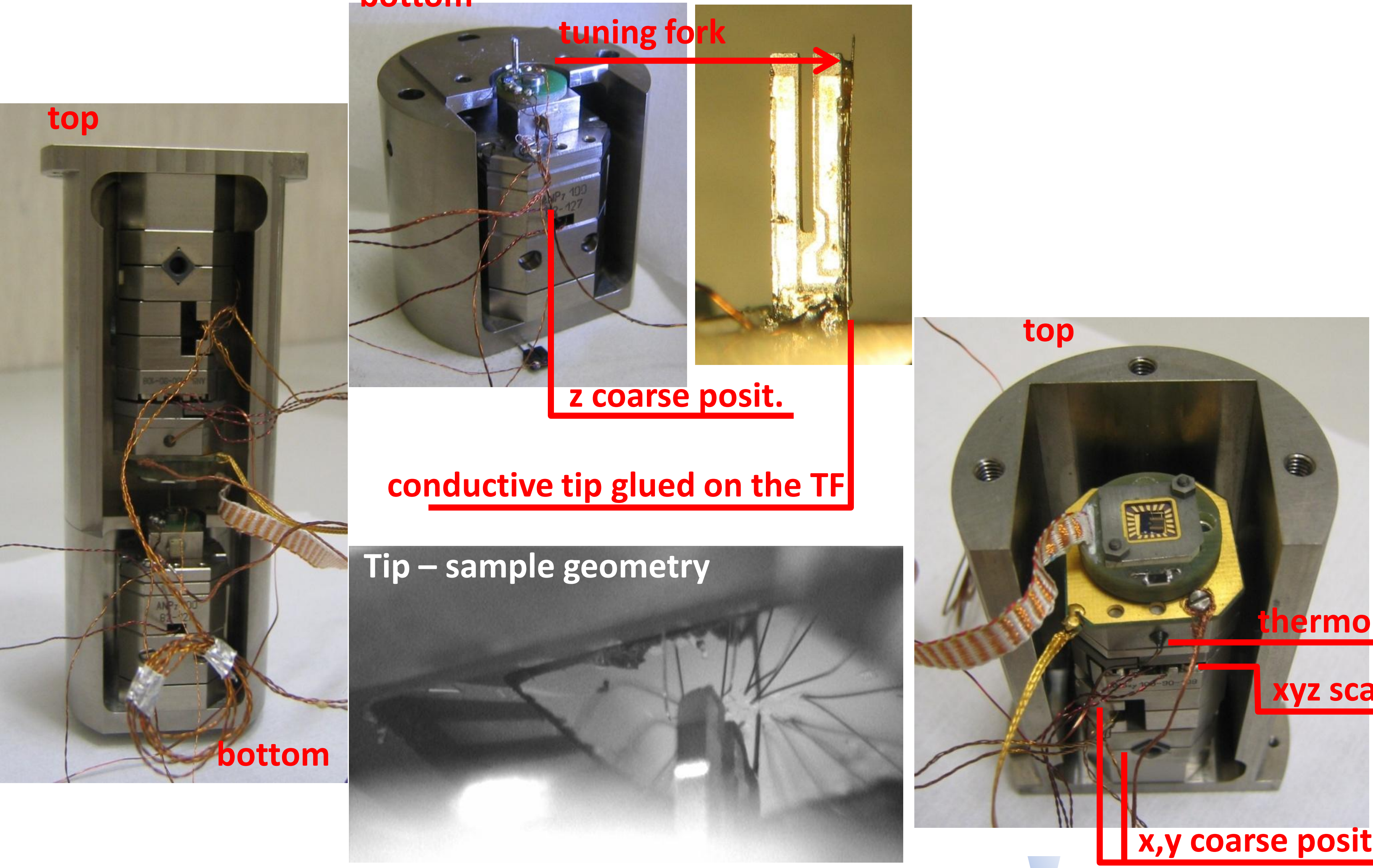
SGM performed in constant height mode (10-50 nm above surface), no strain



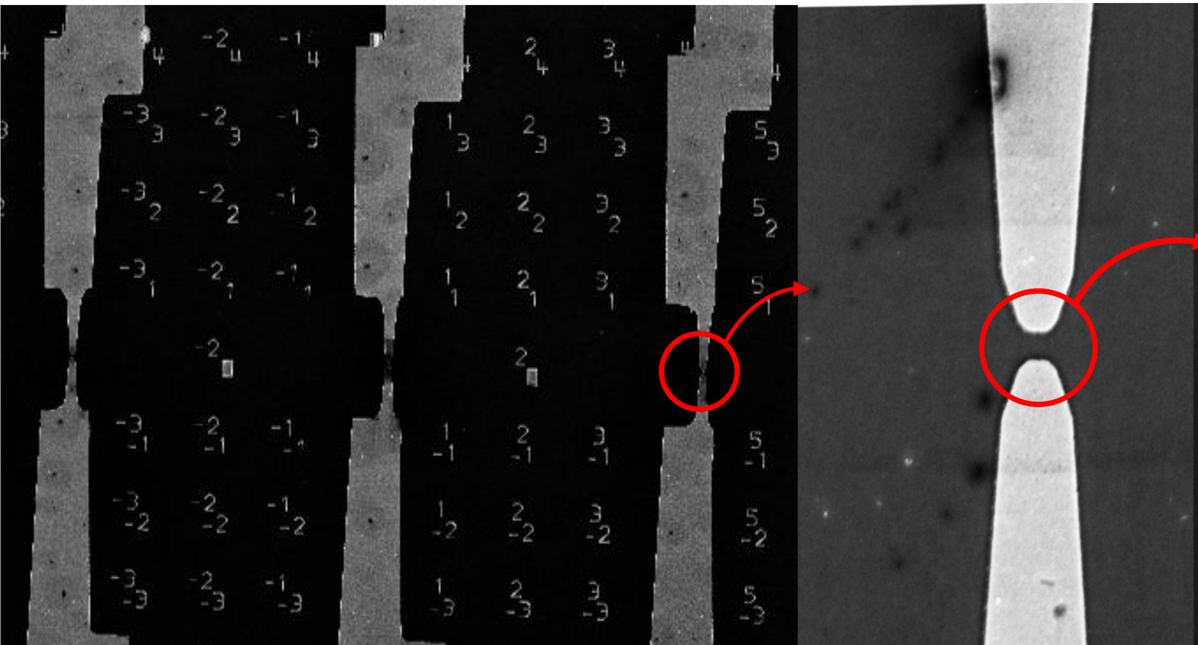
attocube systems
explore your nanoworld

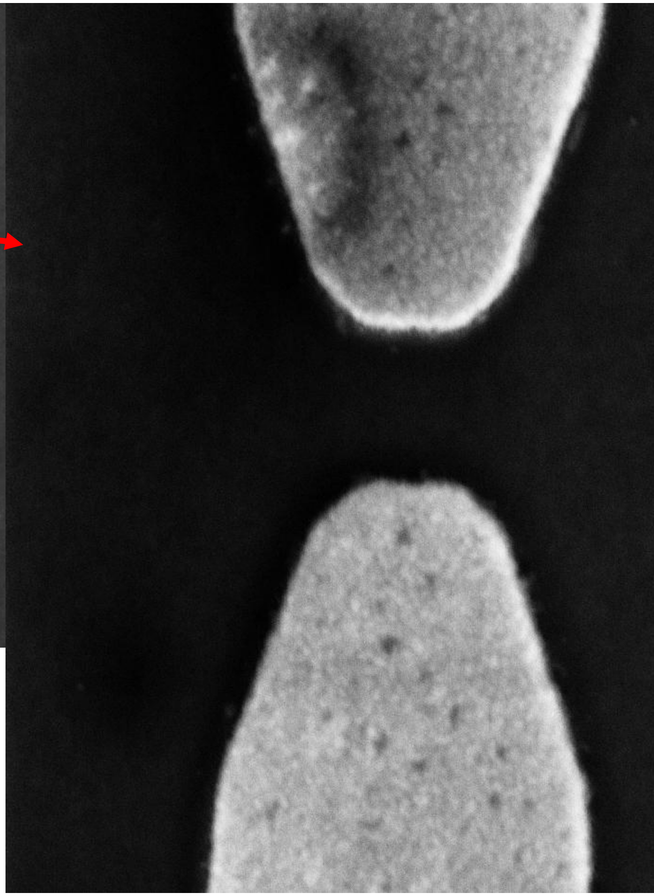
Pioneering work by:
M. A. Topinka et al.: Science ***289*** *(2000) 2323.*

Appendix: tuning fork and sample holder

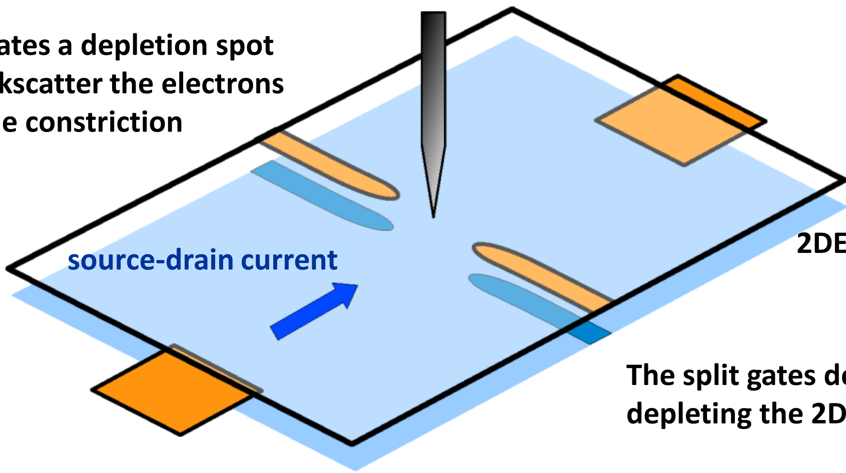


Appendix: SGM measurements on QPCs



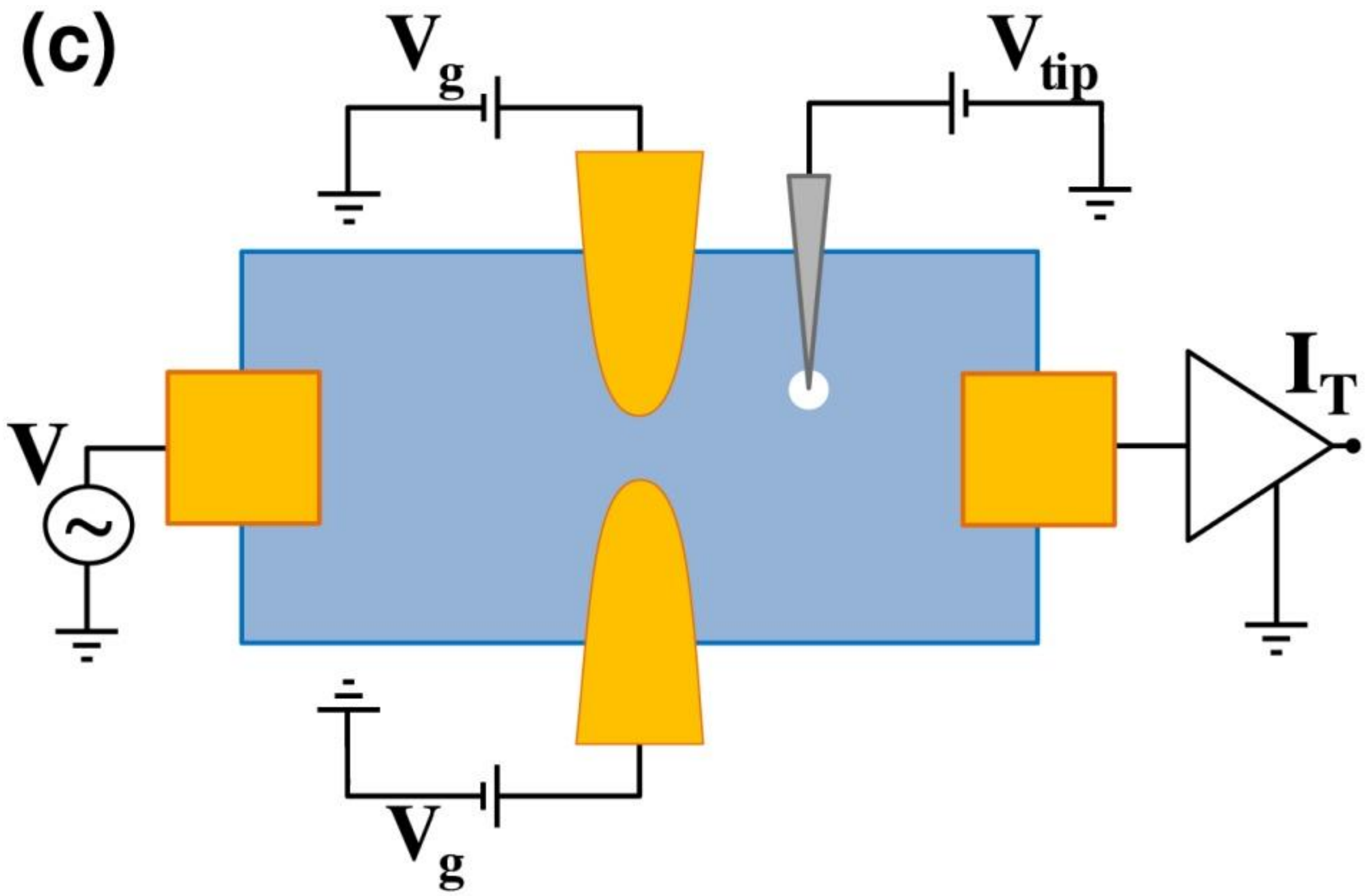


The biased tip creates a depletion spot that we use to backscatter the electrons passing through the constriction

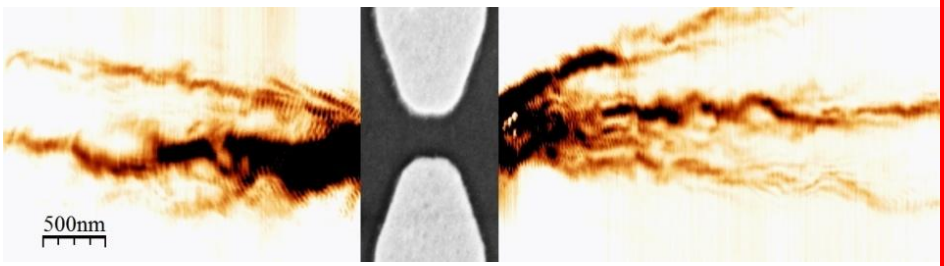


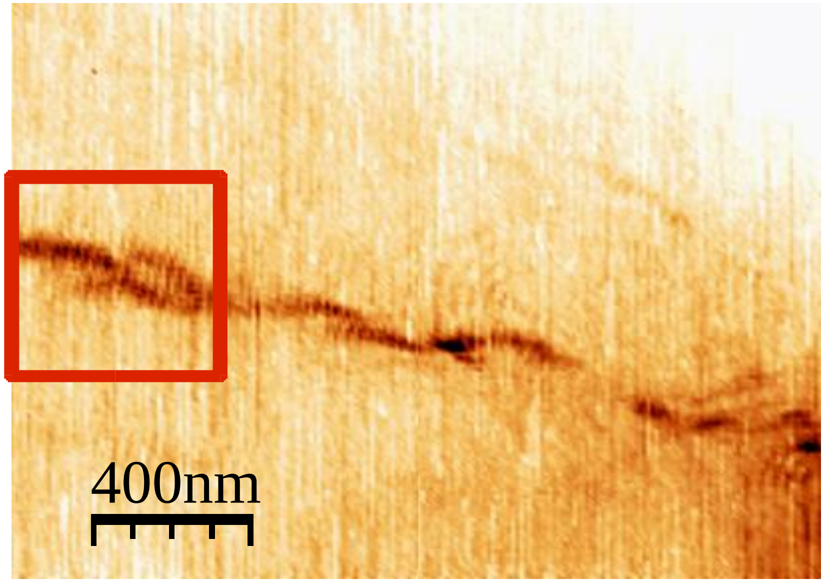
The split gates define a constriction by depleting the 2DEG underneath

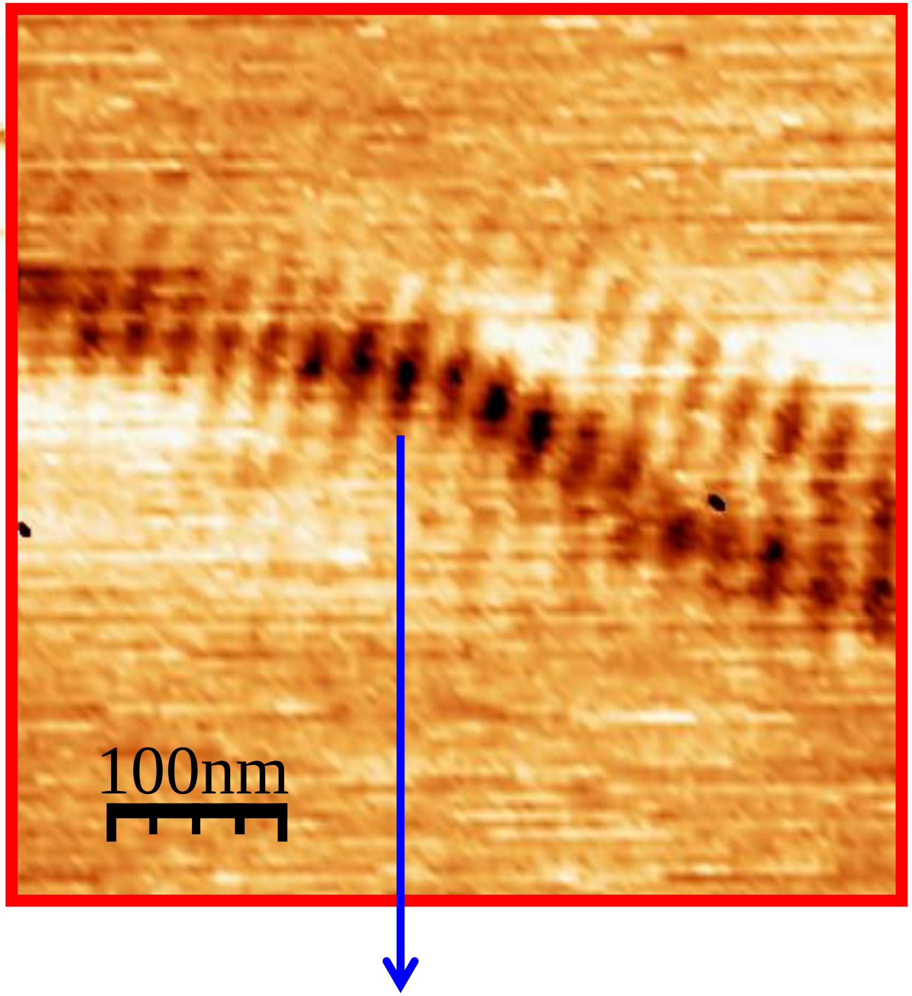
Appendix: SGM measurements on QPCs



Appendix: branched flow and interference fringes



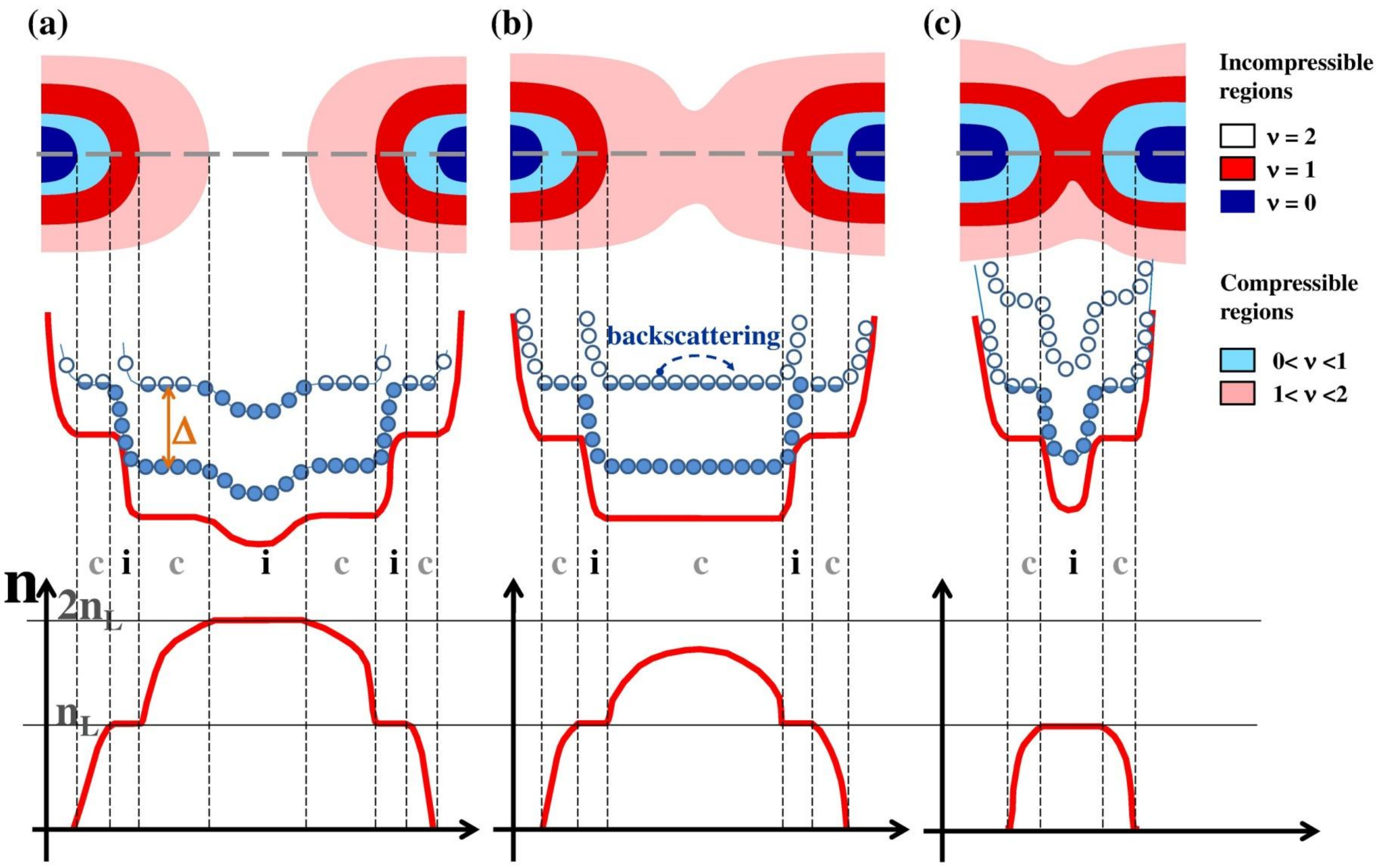




- QPC conductance G = 6 e^2/h (3^{rd} plateau)
- Tip voltage V_{tip} = -5 V, height h_{tip} = 10 nm
- *see also M. A. Topinka et al., Nature **410** (2001) 183.*

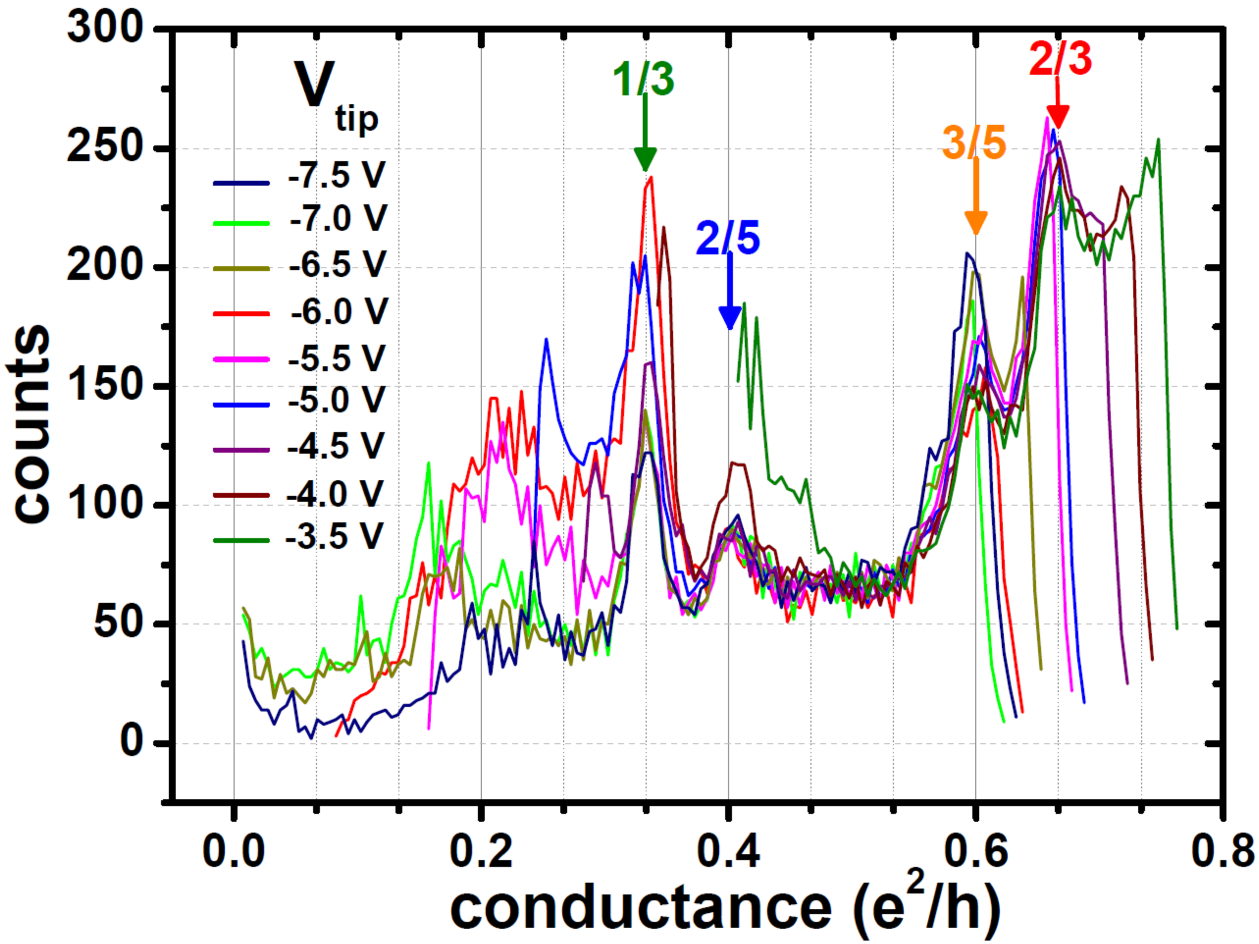
Fringe periodicity: $\lambda_F/2$=20 nm

Appendix



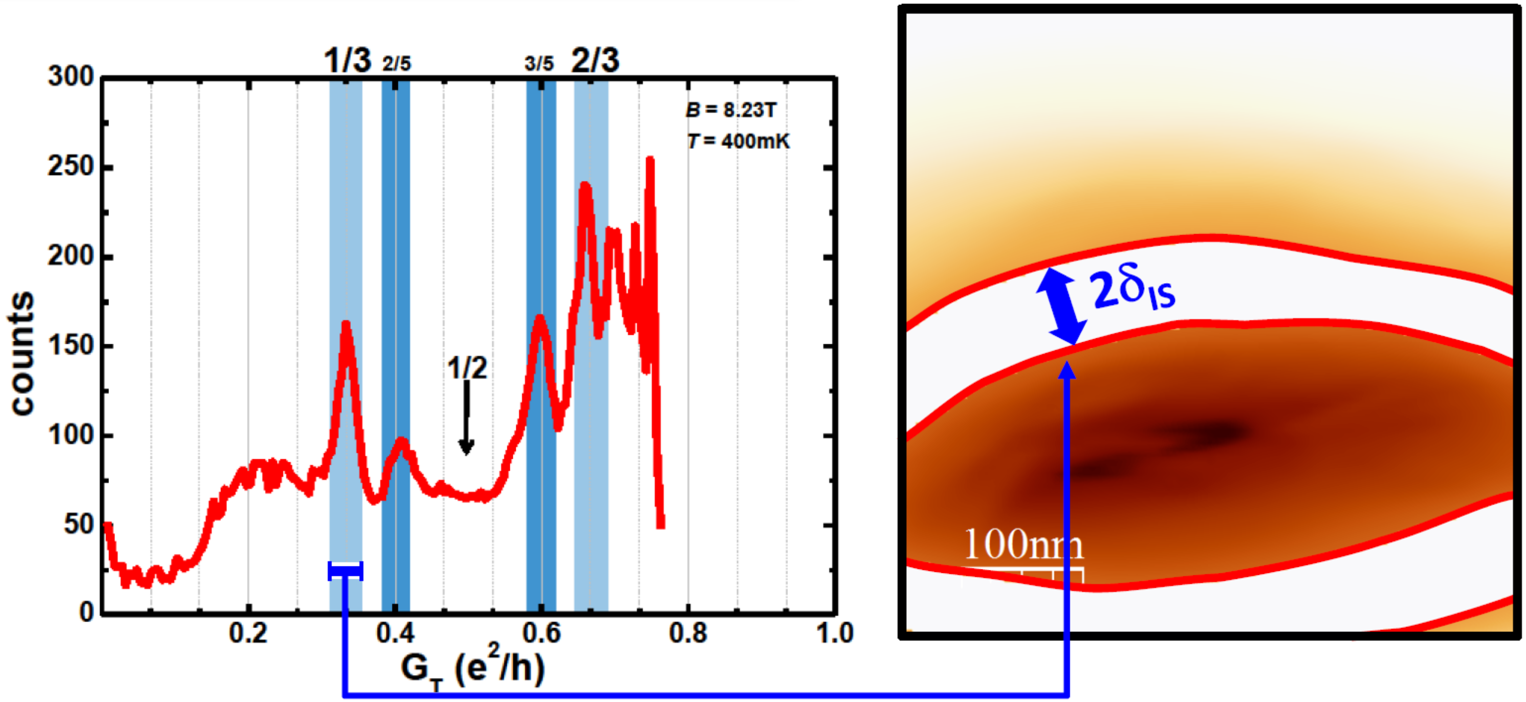
(a)
(b)
(c)
Incompressible regions
ν = 2
ν = 1
ν = 0
Compressible regions
0< ν <1
1< ν <2
Δ
backscattering
c i c i c i c
c i c i c
c i c
n
2n_L
n_L

Appendix: Individual histograms



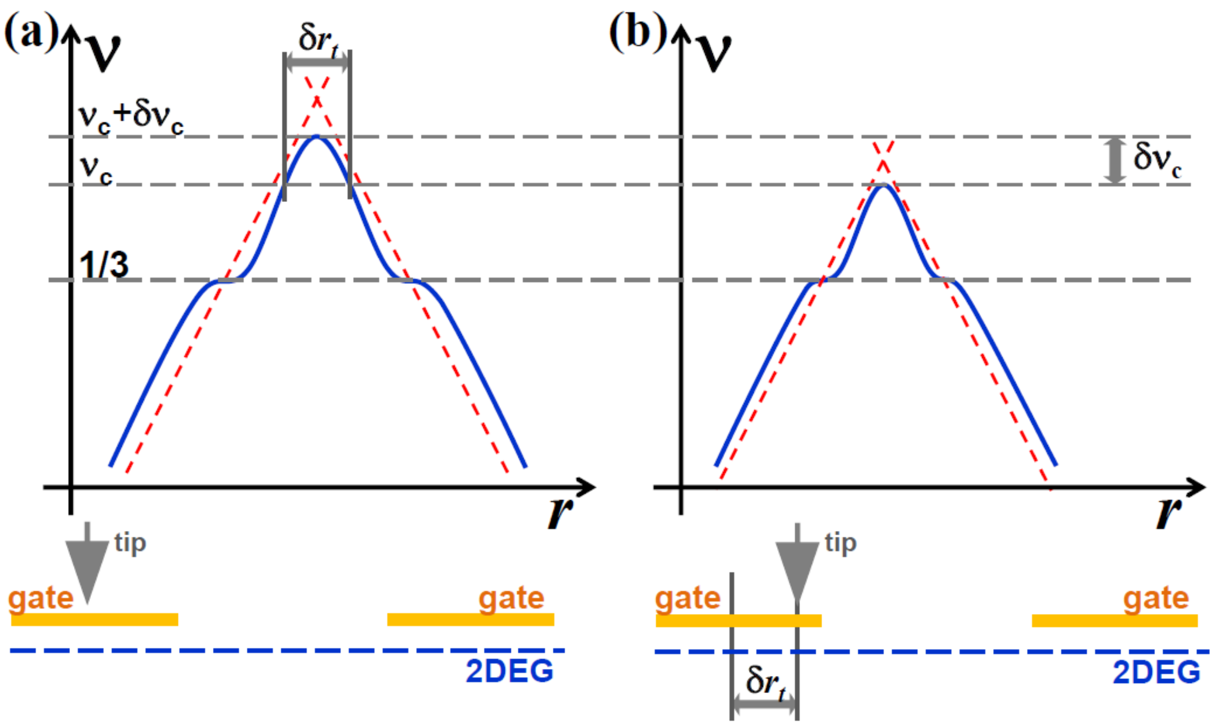
Histograms of the occurrence of each G_T value for all the 9 different SGM scans performed at different V_{tip} values. Fractional peaks are visible in each individual histogram.

Appendix: Determination of the IS width



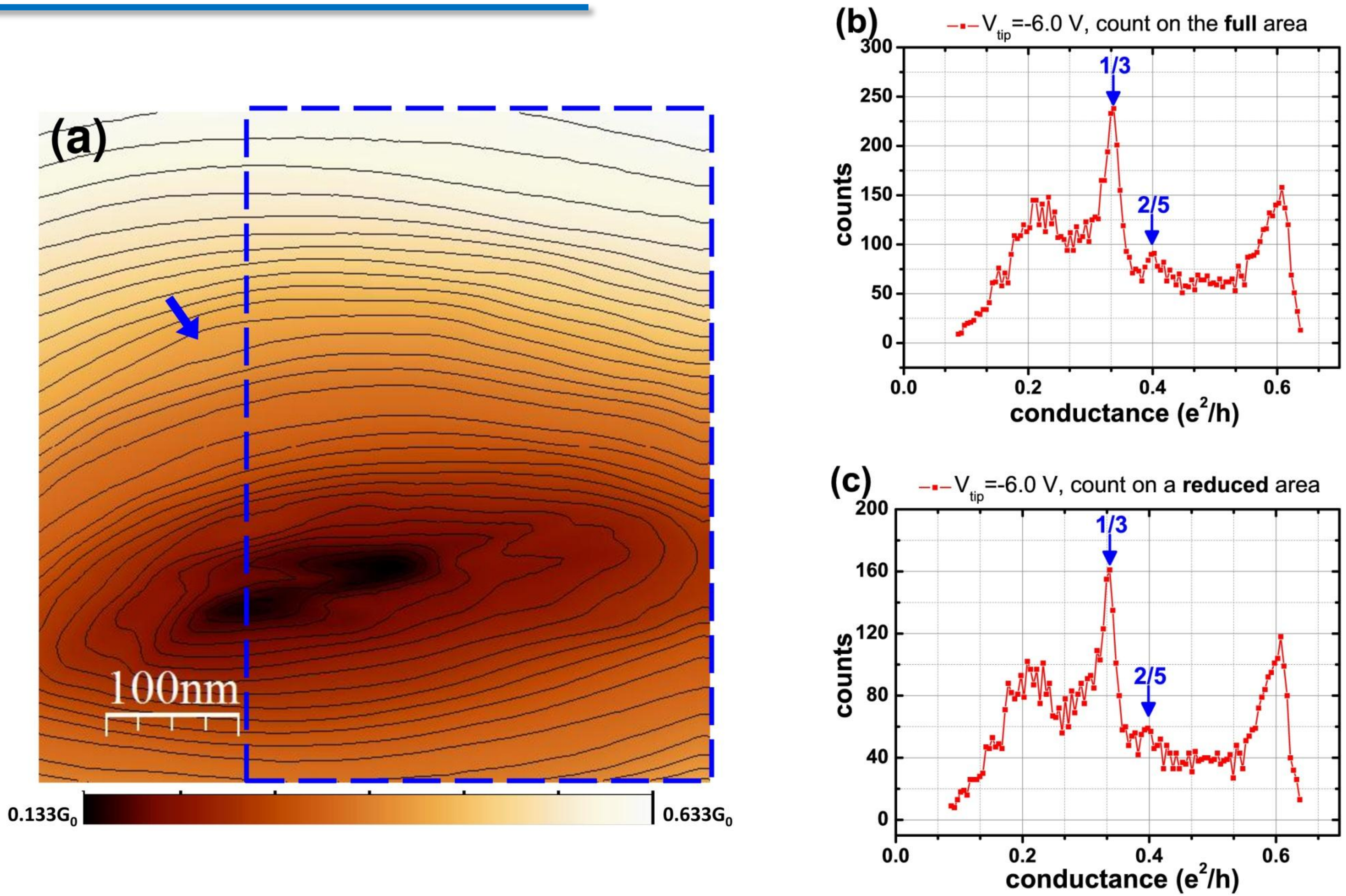
The incompressible stripe width δ_{IS} is obtained starting from the FWHM of the corresponding peak in the histogram (left panel). This range of G_T values defines a circular stripe in the SGM map (right panel). δ_{IS} is given by the average width of such a stripe.

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.

Appendix



(a)
100nm
0.133G0
0.633G0
(b)
Vtip=-6.0 V, count on the full area
counts
conductance (e2/h)
1/3
2/5
(c)
Vtip=-6.0 V, count on a reduced area
counts
conductance (e2/h)
1/3
2/5