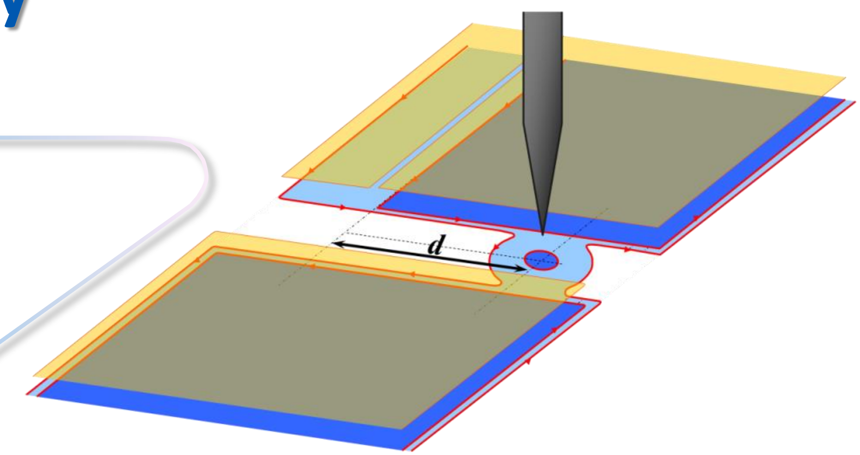
Tomography and manipulation of quantum Hall edge channels by Scanning Gate Microscopy



N. Paradiso

Scuola Normale Superiore di Pisa

Discussione della Tesi di Perfezionamento

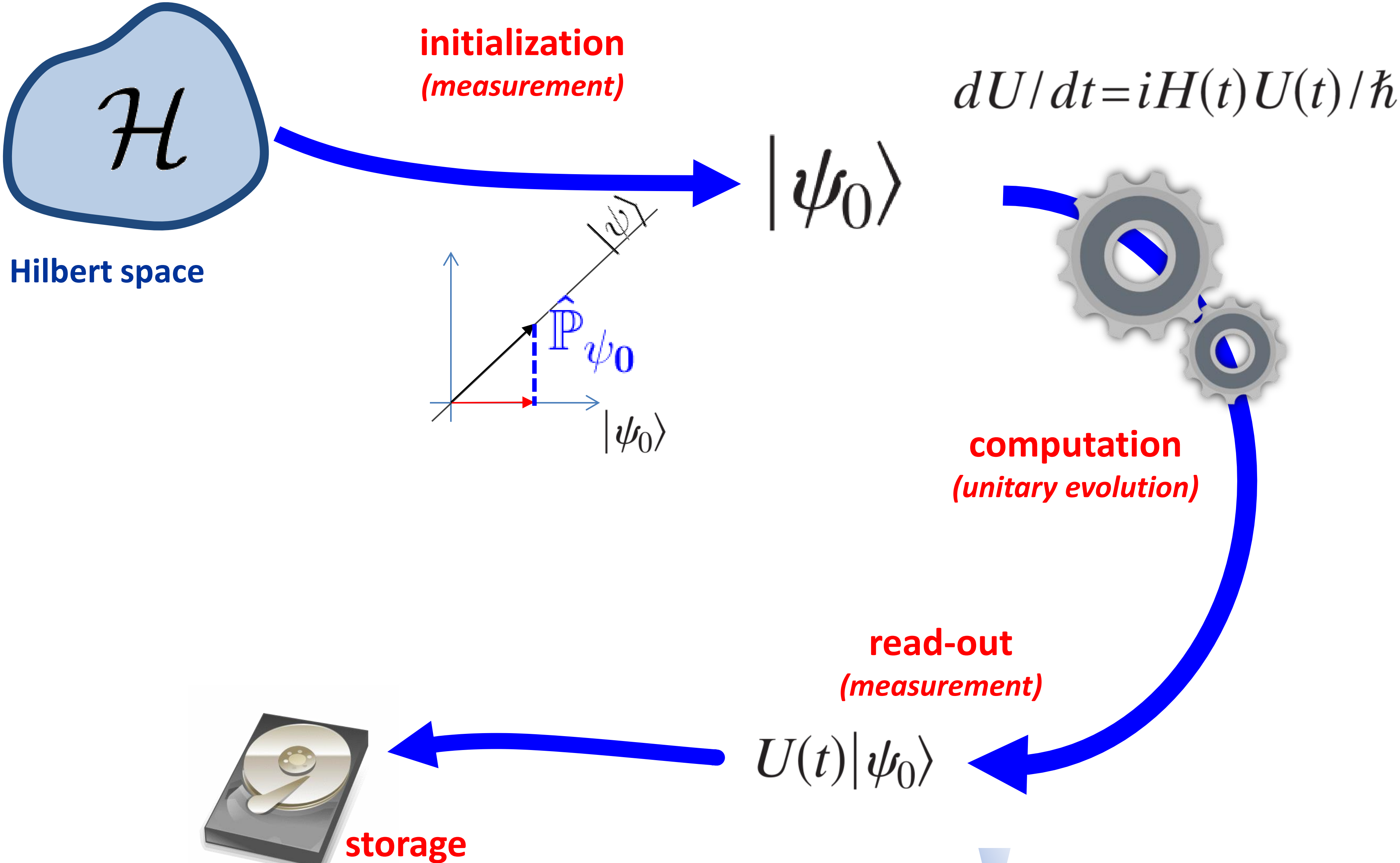
Advisors

Prof. F. Beltram, dr. S. Heun

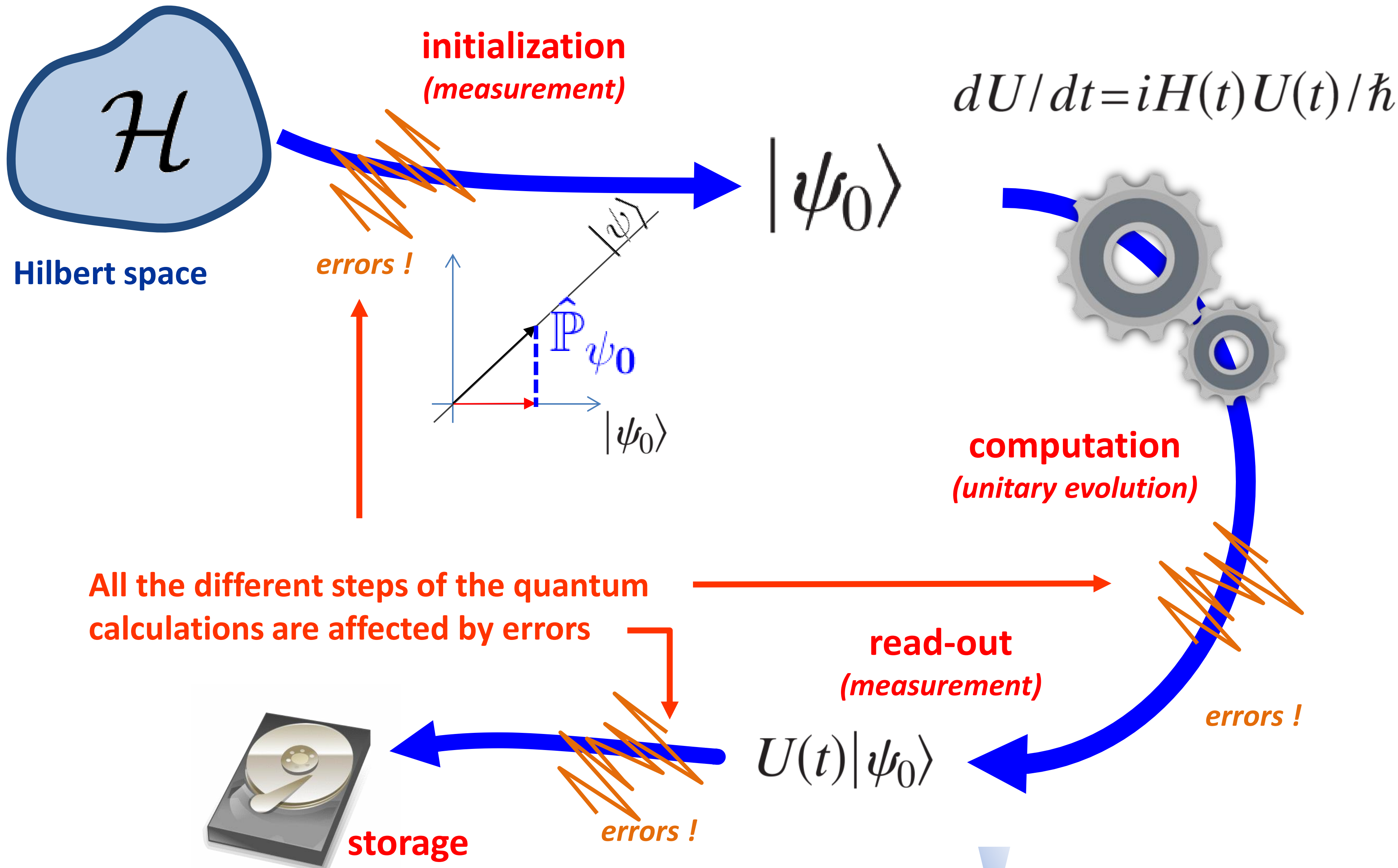
Co-workers

- NEST, Pisa, Italy: S. Roddaro, L. Sorba
- TASC, Trieste, Italy: G. Biasiol

The road to quantum computing



The road to quantum computing

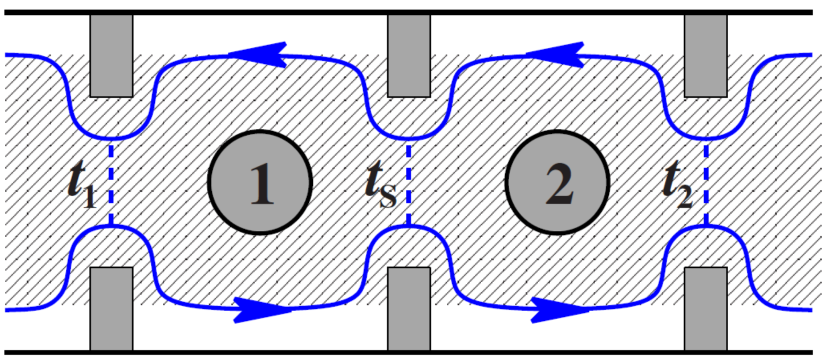


Why a quantum Hall quantum Computer?

Fundamental reasons: QH liquids at peculiar filling factors (5/2, 12/5) are expected to **exhibit non-Abelian excitations**. Since quantum operations on such objects are expected to only depend on the **topology**, they could implement **fault tolerant calculations.**
[Nayak *et al.*, Rev. Mod. Phys. **80**, 1083.]

REVIEWS OF MODERN PHYSICS, VOLUME 80, JULY–SEPTEMBER 2008

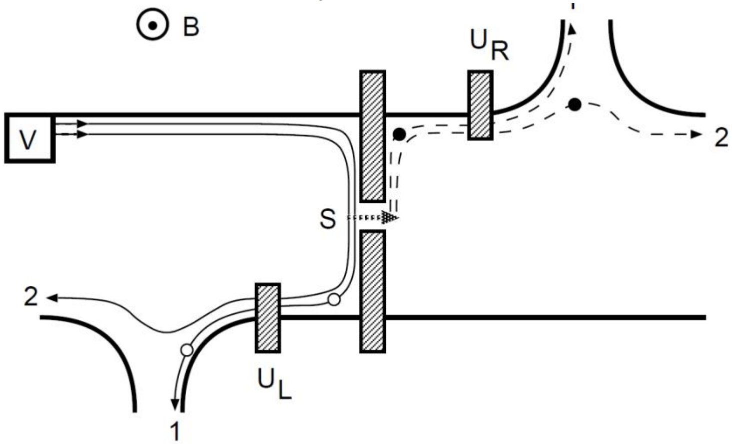
Non-Abelian anyons and topological quantum computation



a gate "NOT" operating with non-Abelian quasiparticles
[Nayak *et al.*, Rev. Mod. Phys. **80**, 1083 (2003)]

Proposal for Production and Detection of Entangled Electron-Hole Pairs in a Degenerate Electron Gas

C.W.J. Beenakker, C. Emary, M. Kindermann, and J. L. van Velsen



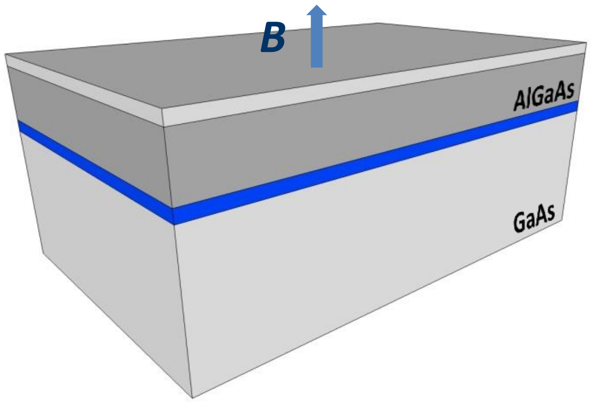
An electron-hole entangler
[Beenakker *et al.* PRL **91**, 147901 (2003)]

Why a quantum Hall quantum Computer?

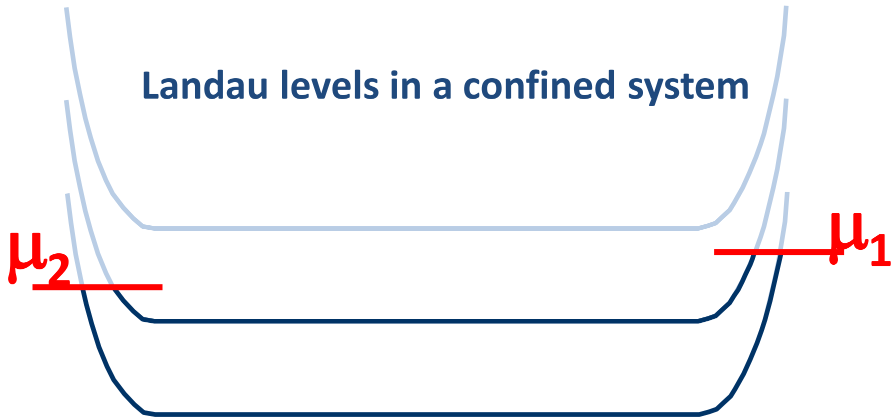
Practical reasons: highly **coherent, dissipationless transport** by means of chiral **1D channels**

- **Solid state devices.**
- **Chiral channels insensitive to backscattering.**
- **Single-fermion source**
- **Perfect transmission**
- **Accurate control of the chemical potential, tunnel probability, and occupation distribution of individual channels**
- **High design flexibility**

The non-interacting picture of the QH effect

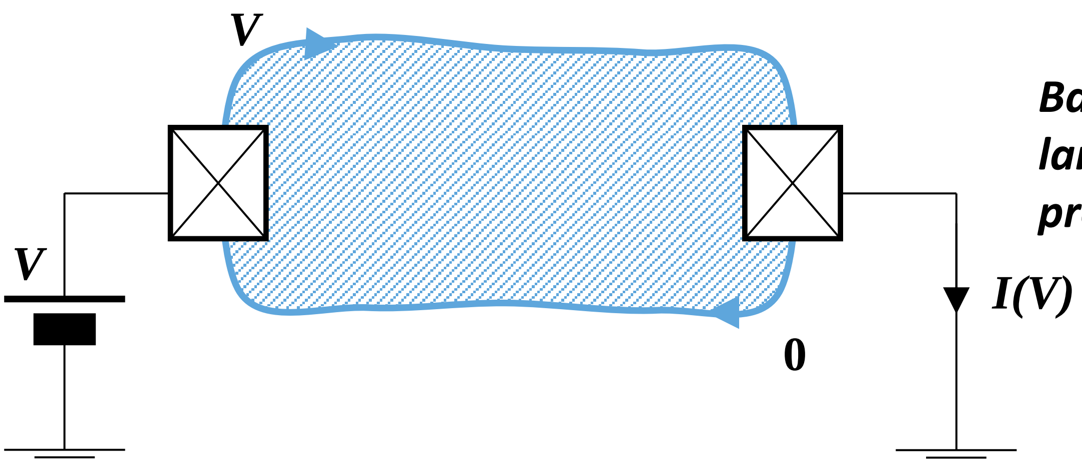


2DES
in high field



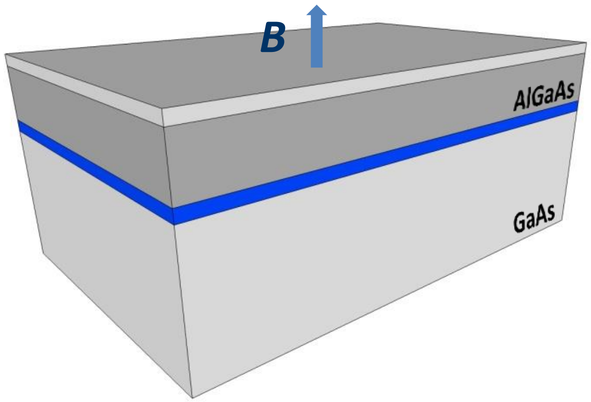
- Edge state picture:
  current is carried by chiral 1D channels

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

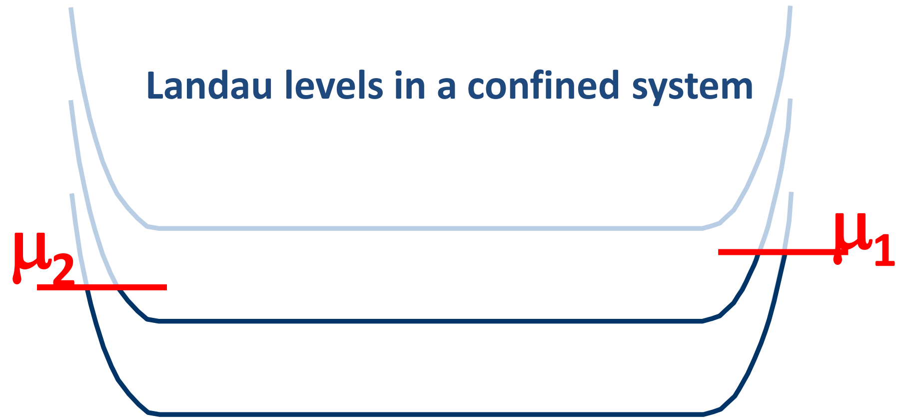


Backscattering is suppressed due to the large spatial separation between counter-propagating channels

The non-interacting picture of the QH effect



2DES
in high field



- Edge state picture:
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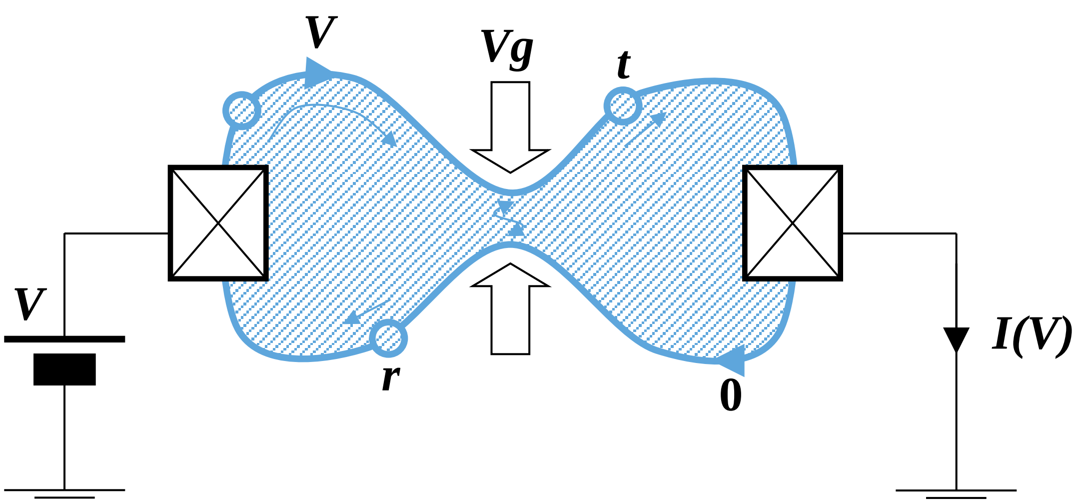


With a QPC we can intentionally induce backscattering, which provides us information about the edge properties

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

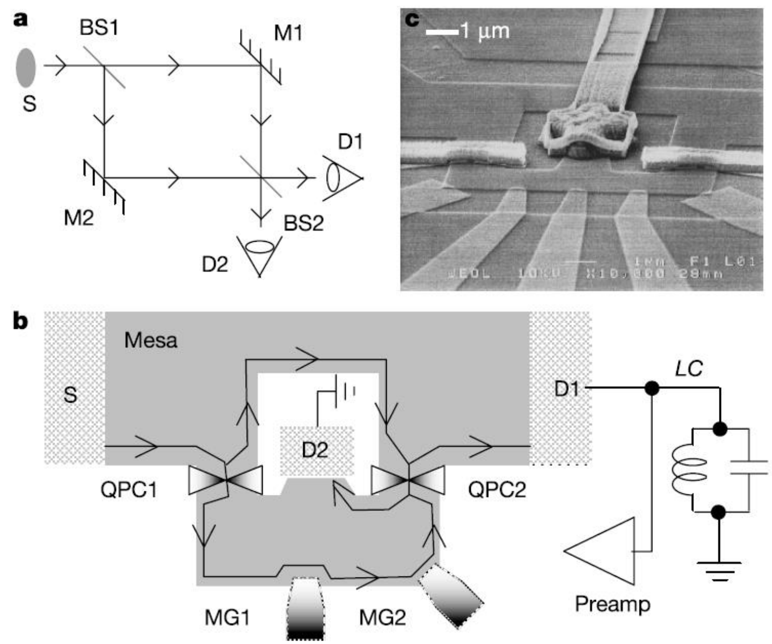
Edge channel-based interferometers

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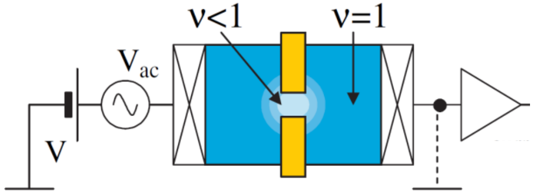
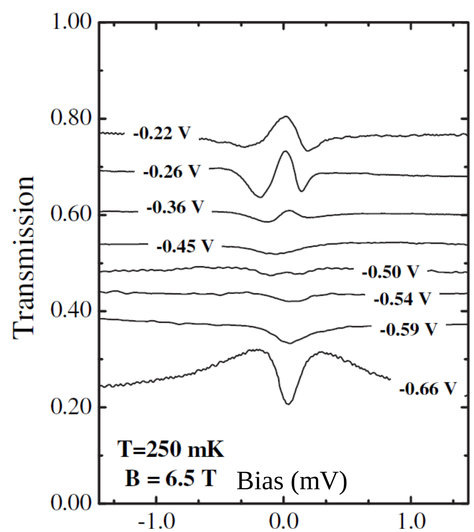
Puzzle: so far, MZI only work with electron-like excitations. **The interference of fractional quasi-particles is inexplicably still elusive**

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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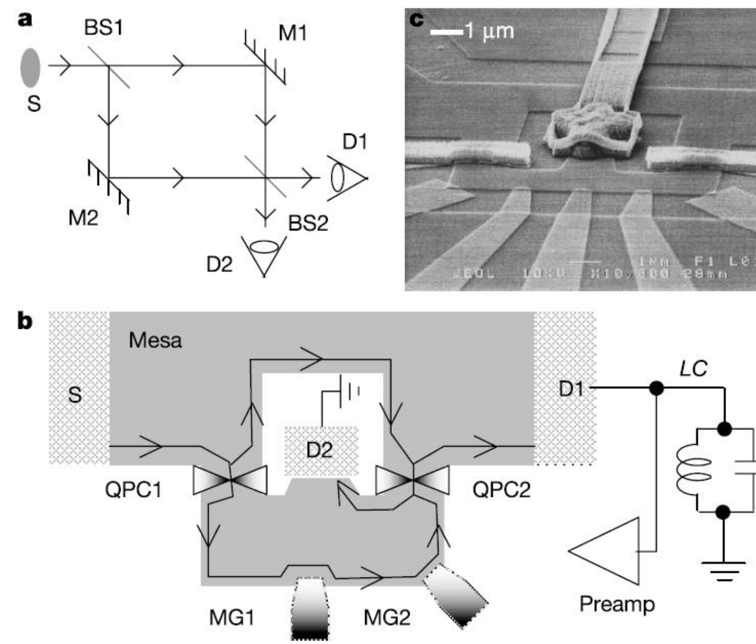
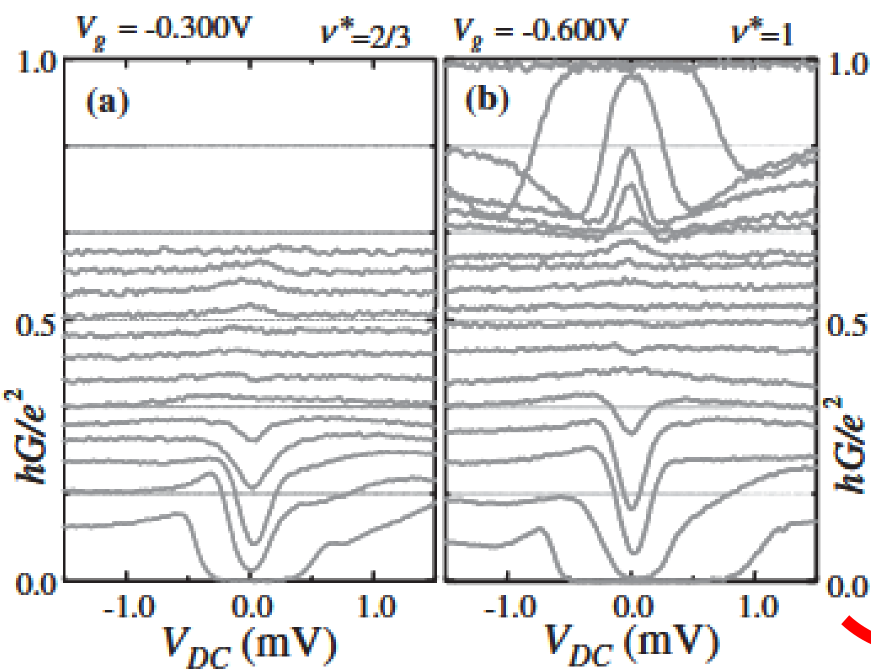


Ji *et al.*: Nature **422**, 415 (2003)

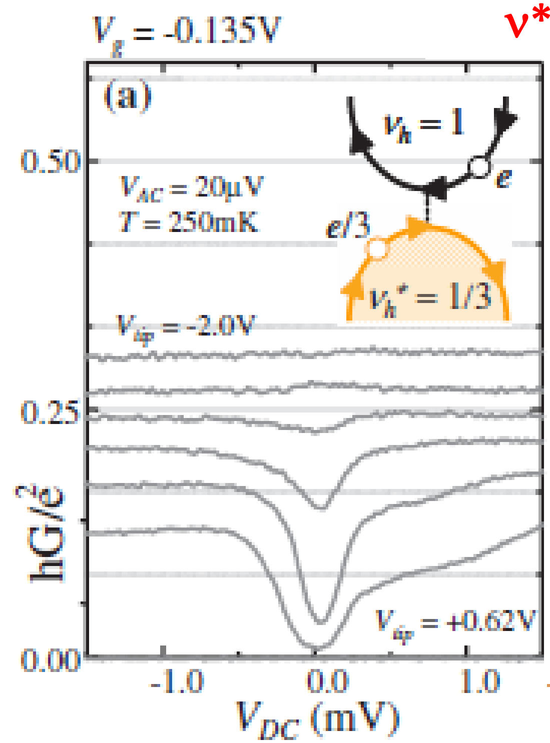
Fractional structures in integer edges

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

<u>Incompressible</u> stripes:

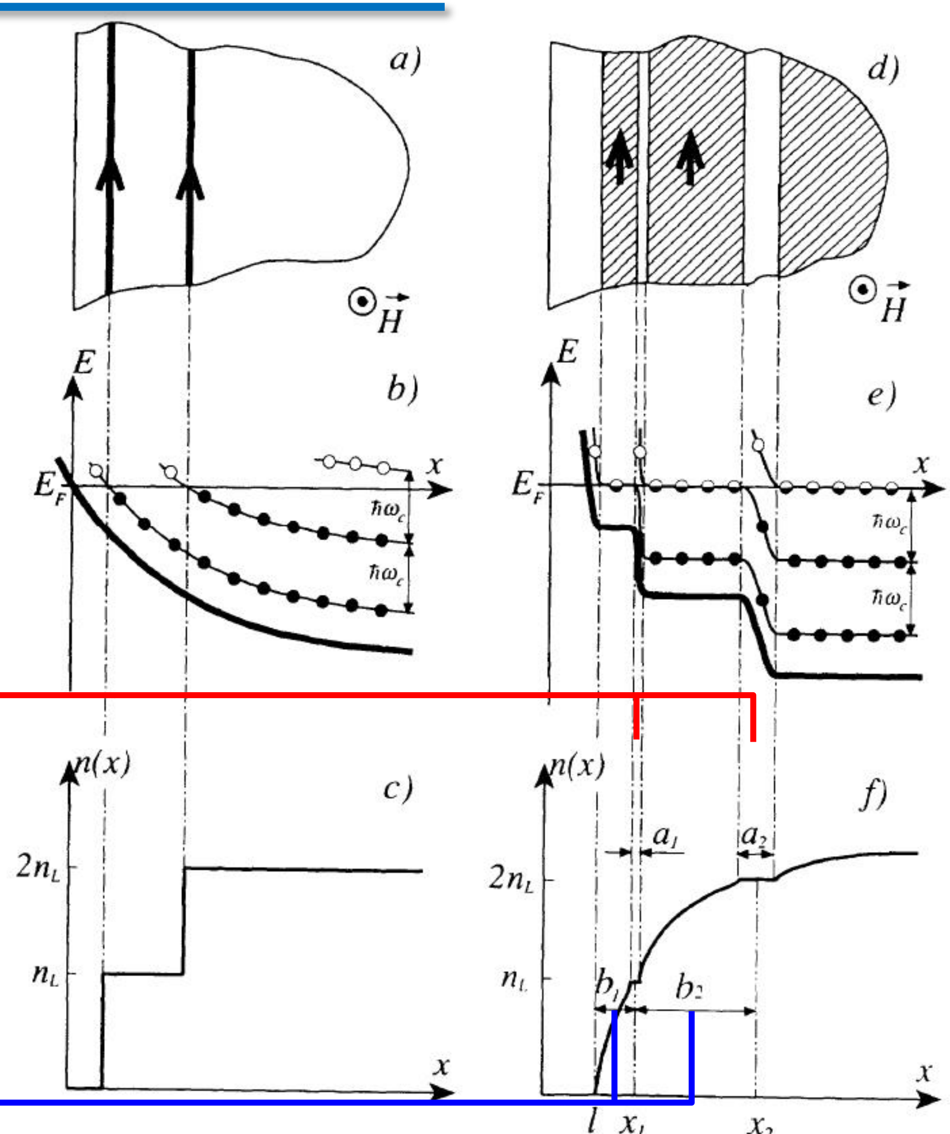
•The electron density is constant

•The potential has a jump

<u>Compressible</u> stripes:

•The electron density has a jump

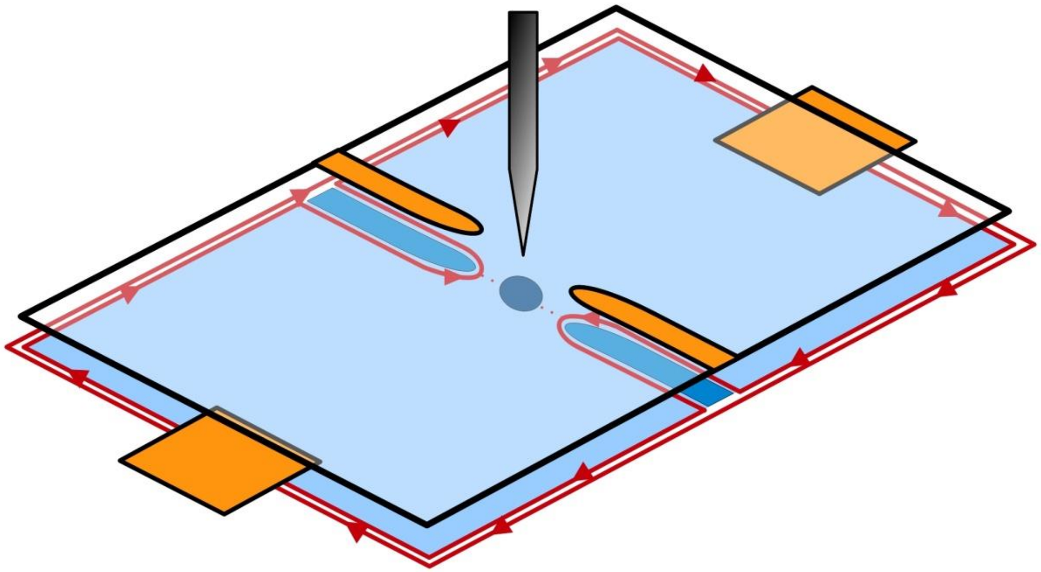
•The potential is constant

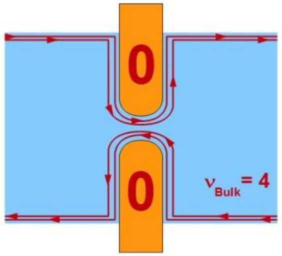


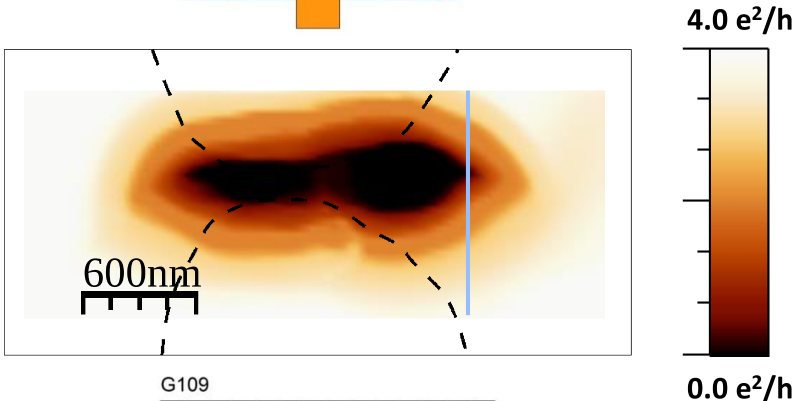
D. B. Chklovskii *et al*.: PRB **46** (1992) 4026.

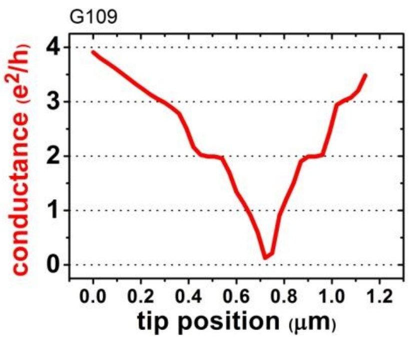
Edge channel tomography by SGM

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.**





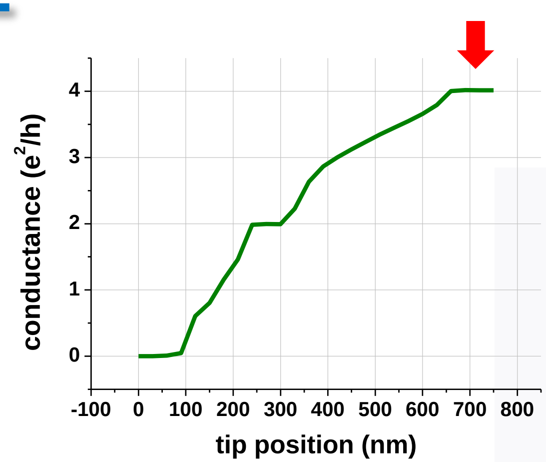


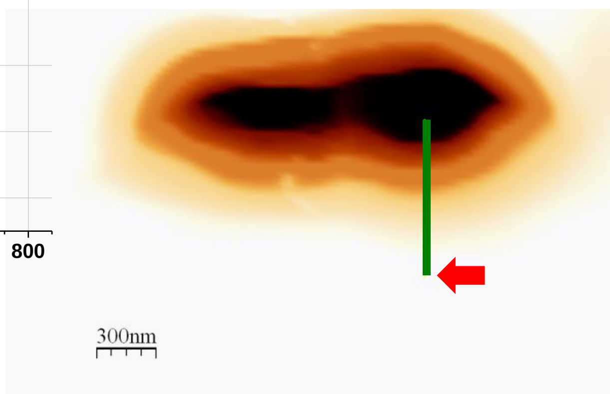


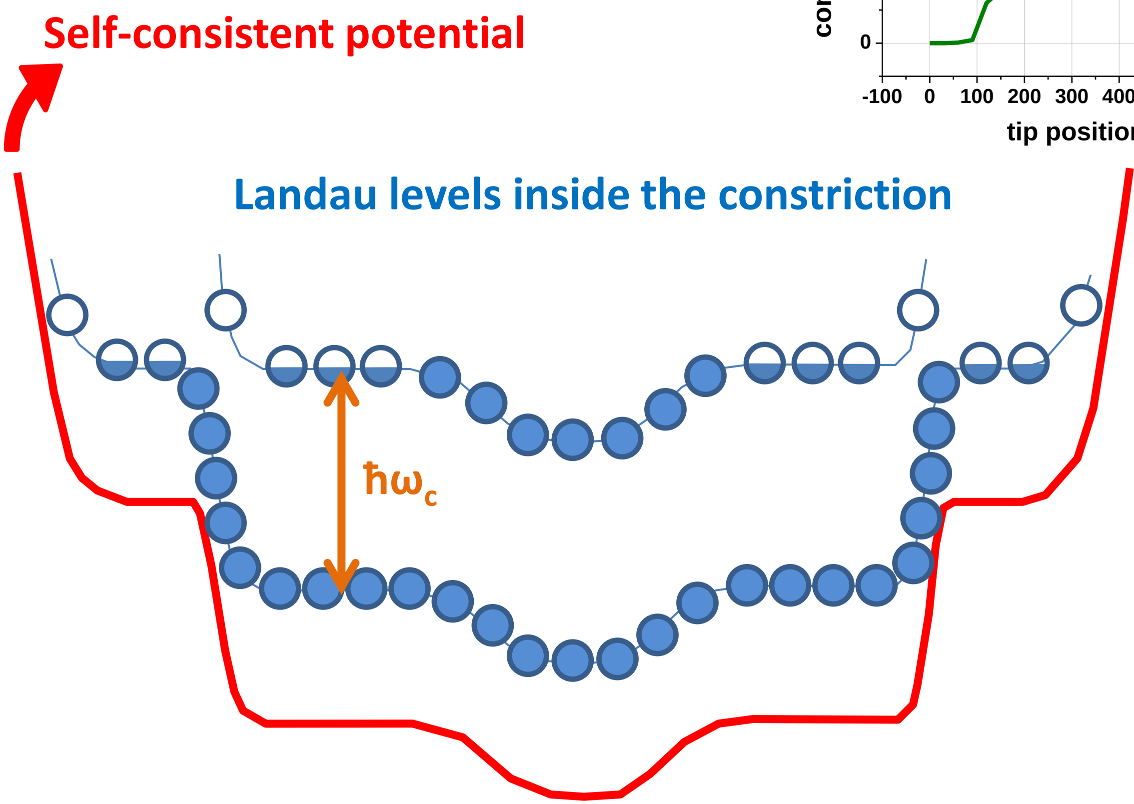
- Bulk filling factor ν=4
- B = 3.04 T
- 2 spin-degenerate edge channels
- gate-region filling factors $g_1 = g_2 = 0$

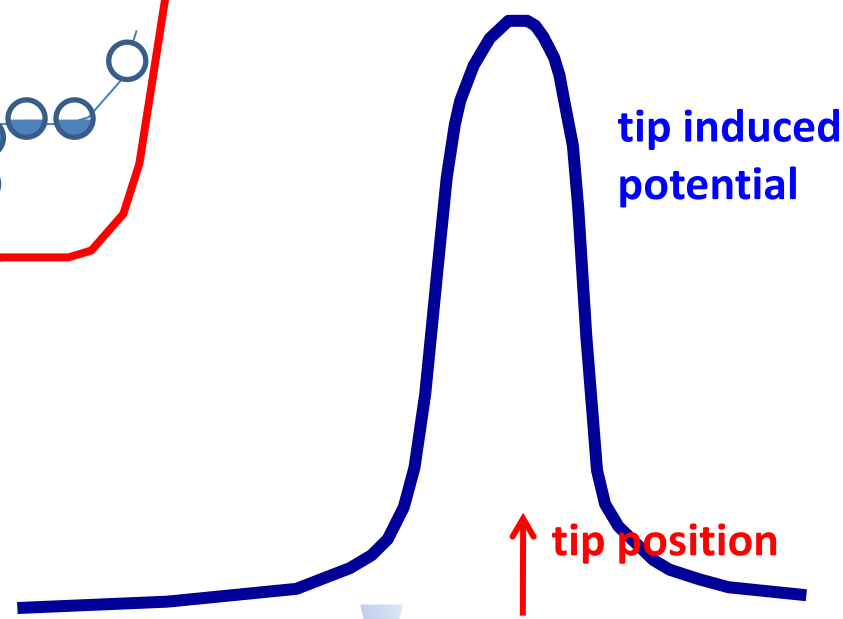
N. Paradiso *et al., Physica E 42 (2010) 1038.*

How we probe incompressible stripes

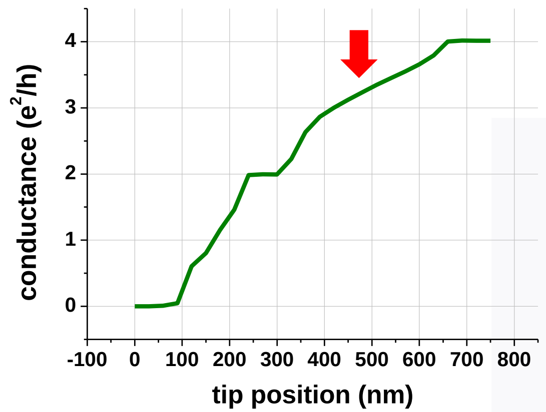


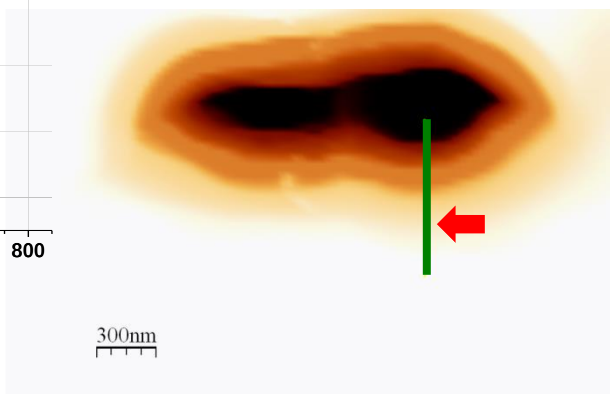


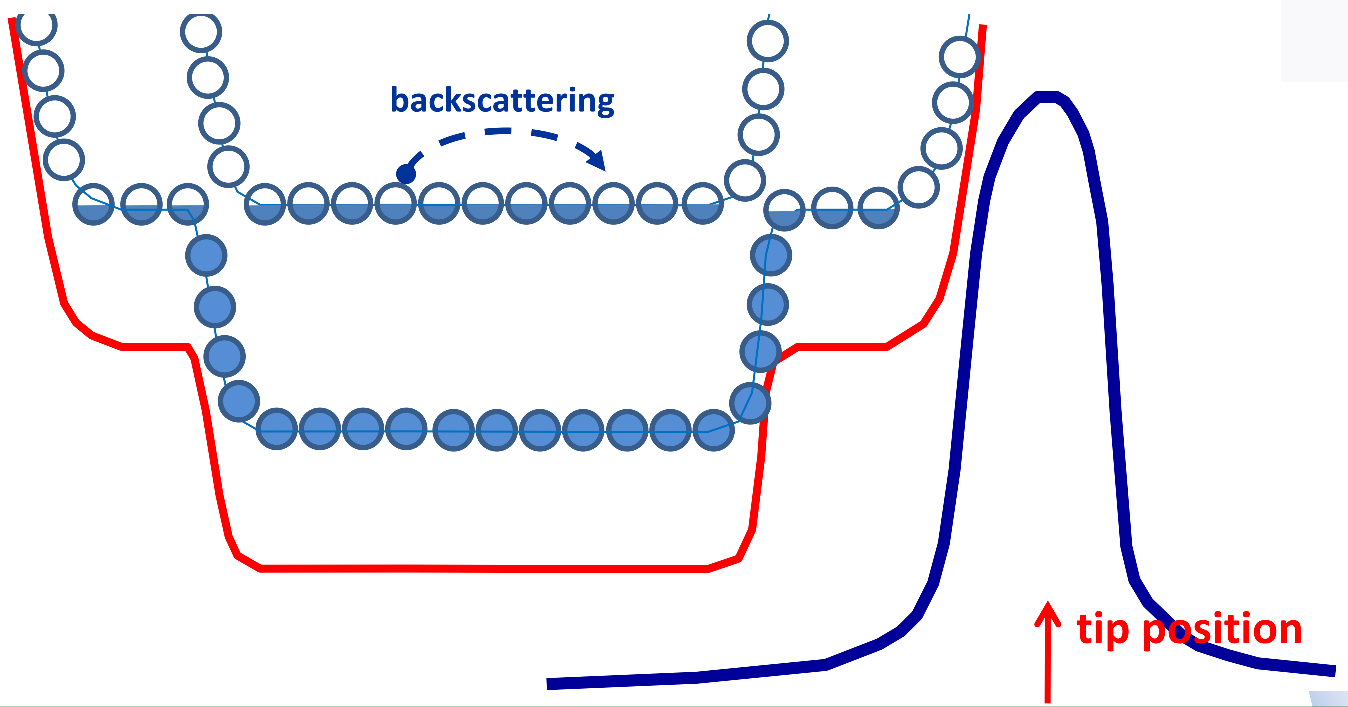




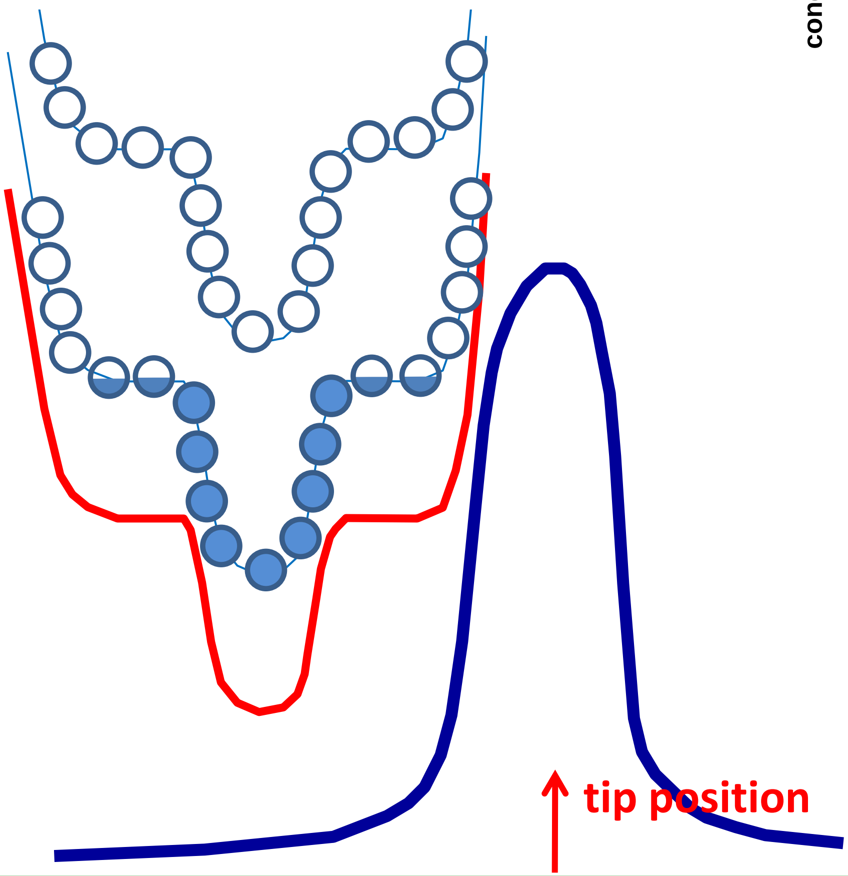
How we probe incompressible stripes

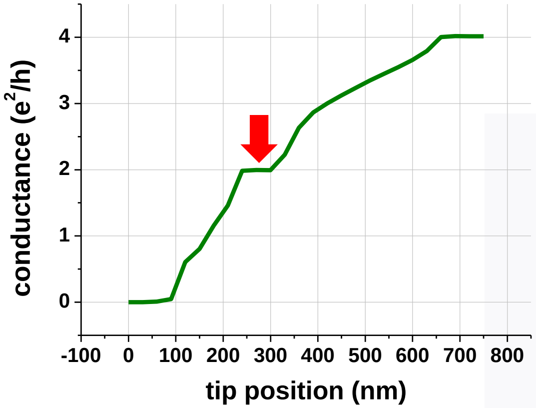


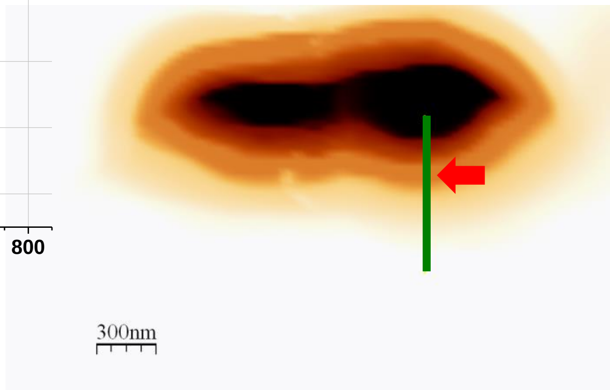




How we probe incompressible stripes

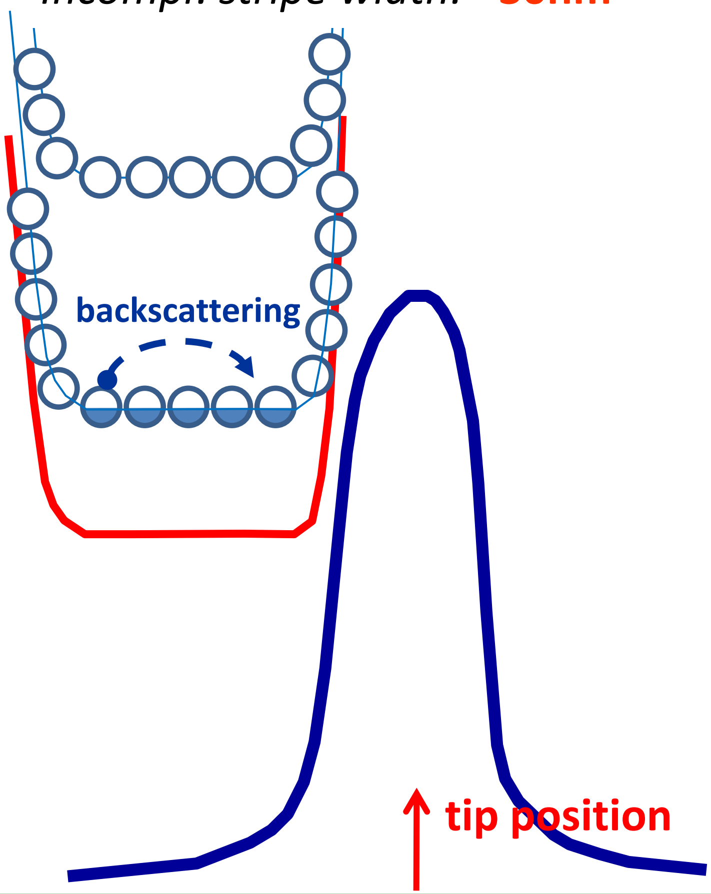


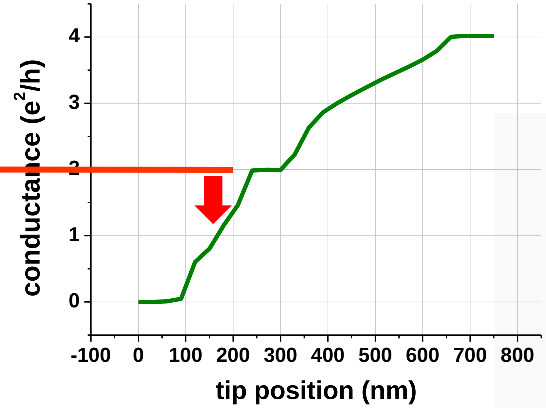


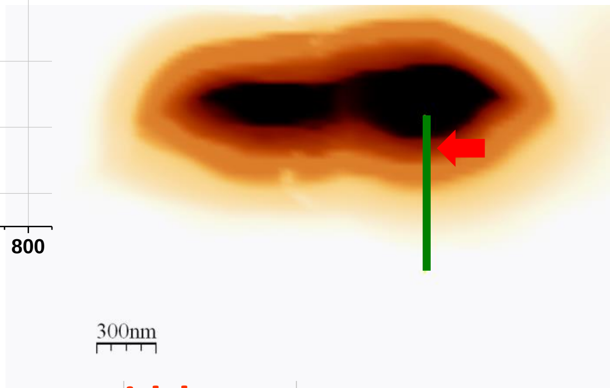


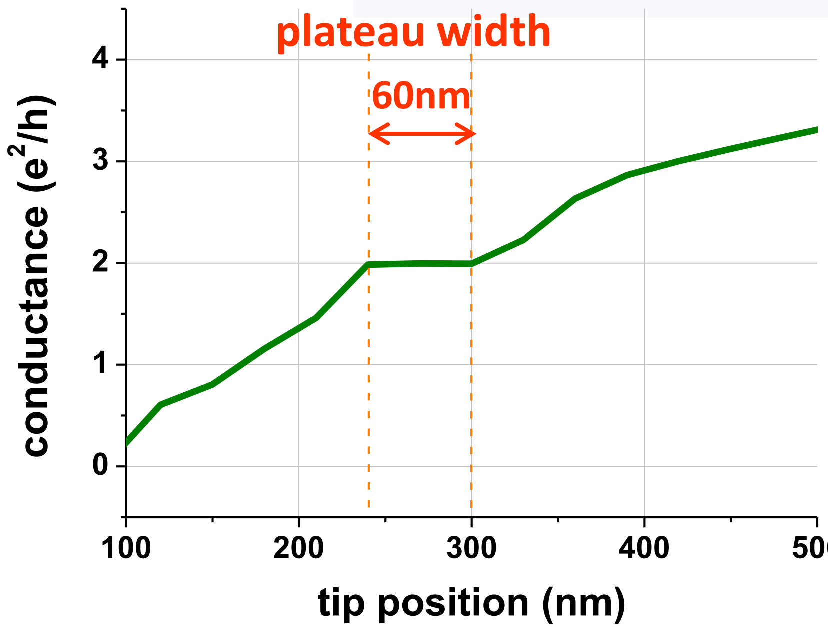
How we probe incompressible stripes

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

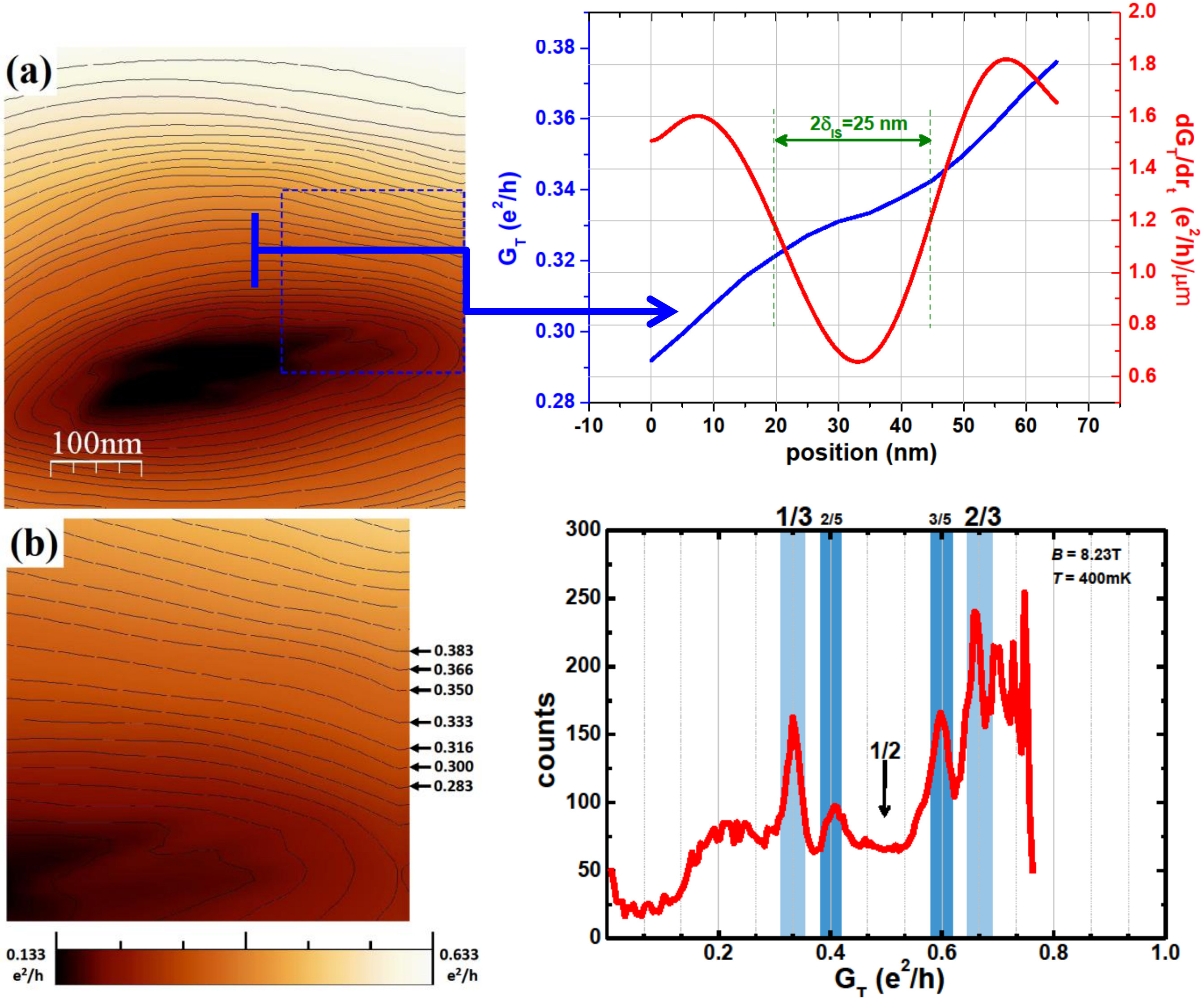








Imaging fractional structures in integer channels

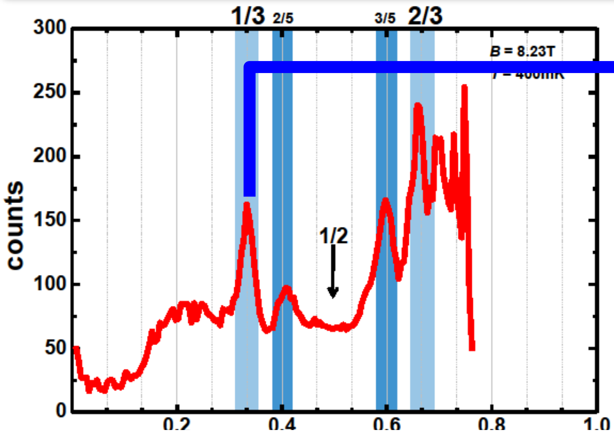


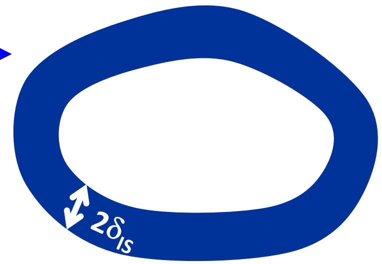
The Reconstruction Picture suggests that at the edge of a smooth **integer** edge a series of compressible/ **incompressible fractional stripes** can occur.

We used the SGM technique to image them.

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

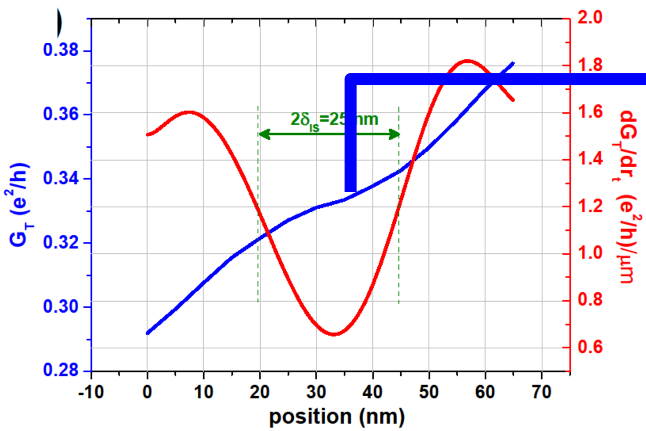
Fractional edge reconstruction





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

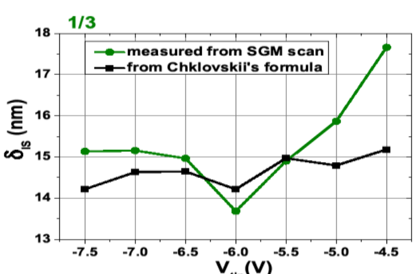
δ_{IS} determined from SGM measurements

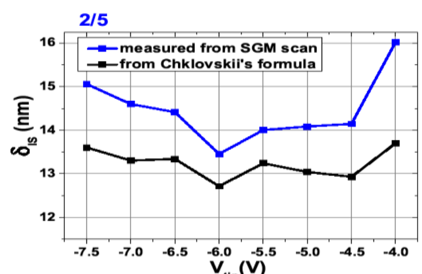


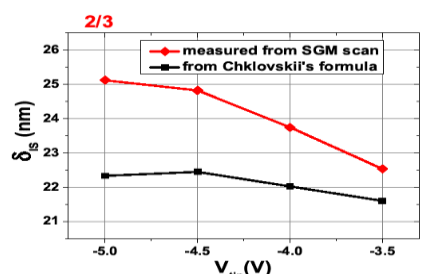
$$\frac{dn}{dr}$$

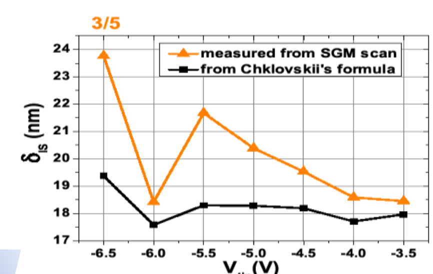
δ_{IS} determined from Chklovskii's formula

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



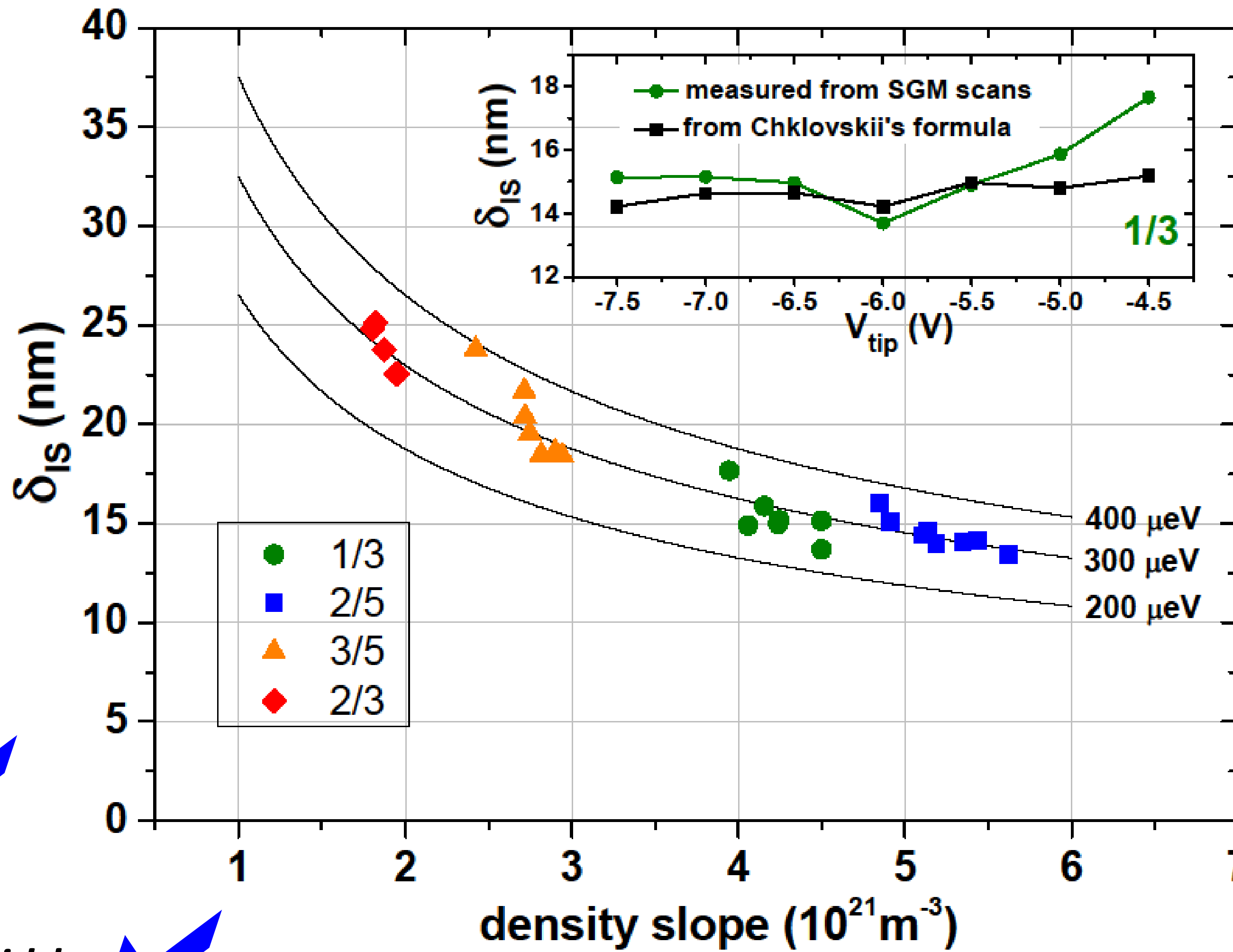






Fractional edge reconstruction

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

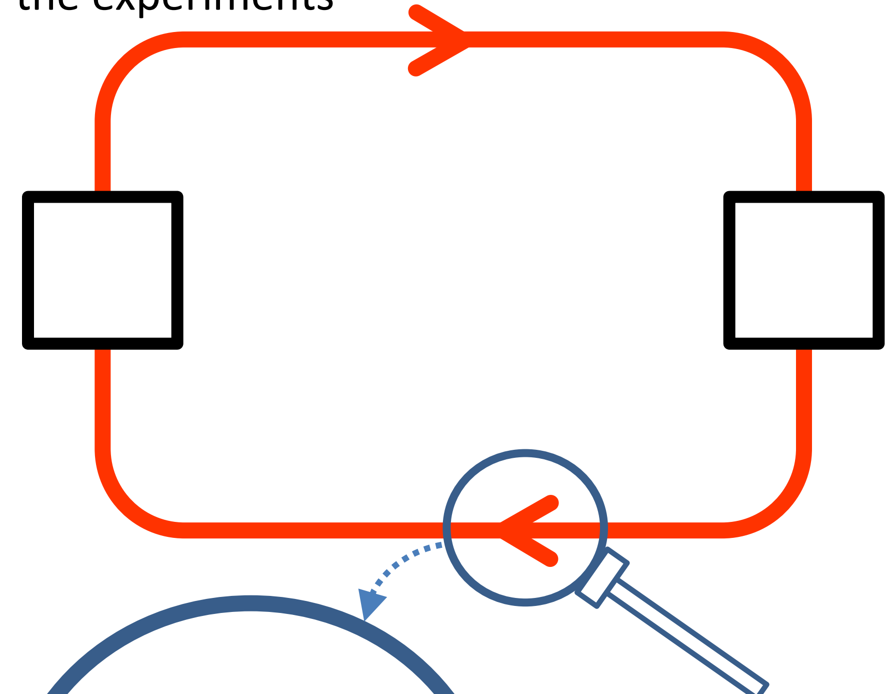


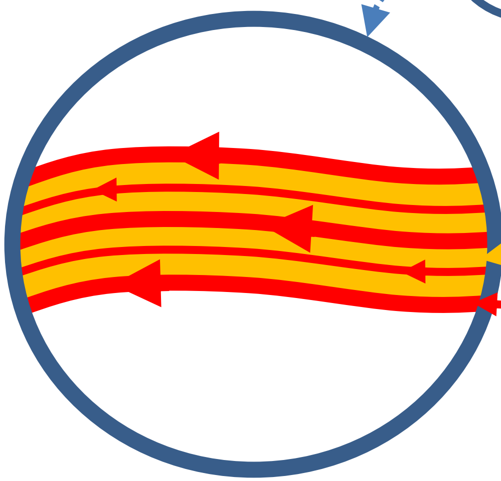
Inner edge structure** **demonstrated** **and** **imaged

Quantitative test of the IS width dependence on the density slope

Can we exploit the non-trivial edge structure?

The picture of a QH device emerging from the experiments

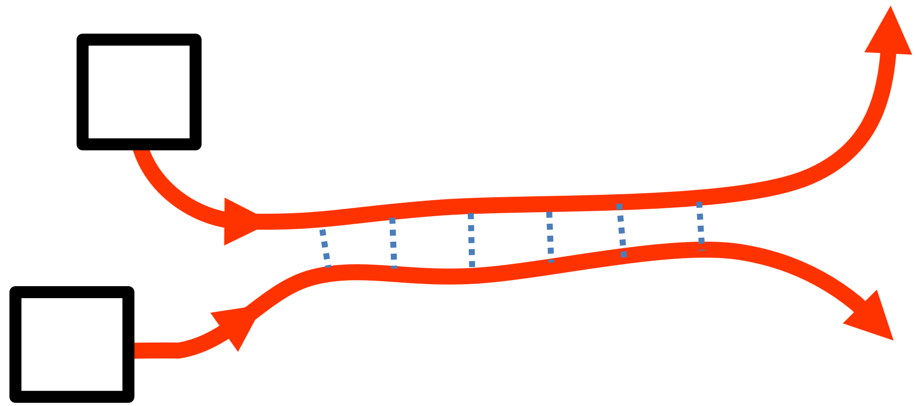




A “bus” of fractional compressible and incompressible channels:

Charge transfer between **parallel** (i.e.***co-propagating***) edge channels

Komiyama et al. PRB **45**, 11085 (1992).
Karmakar et al., PRL **107**, 236804 (2011)

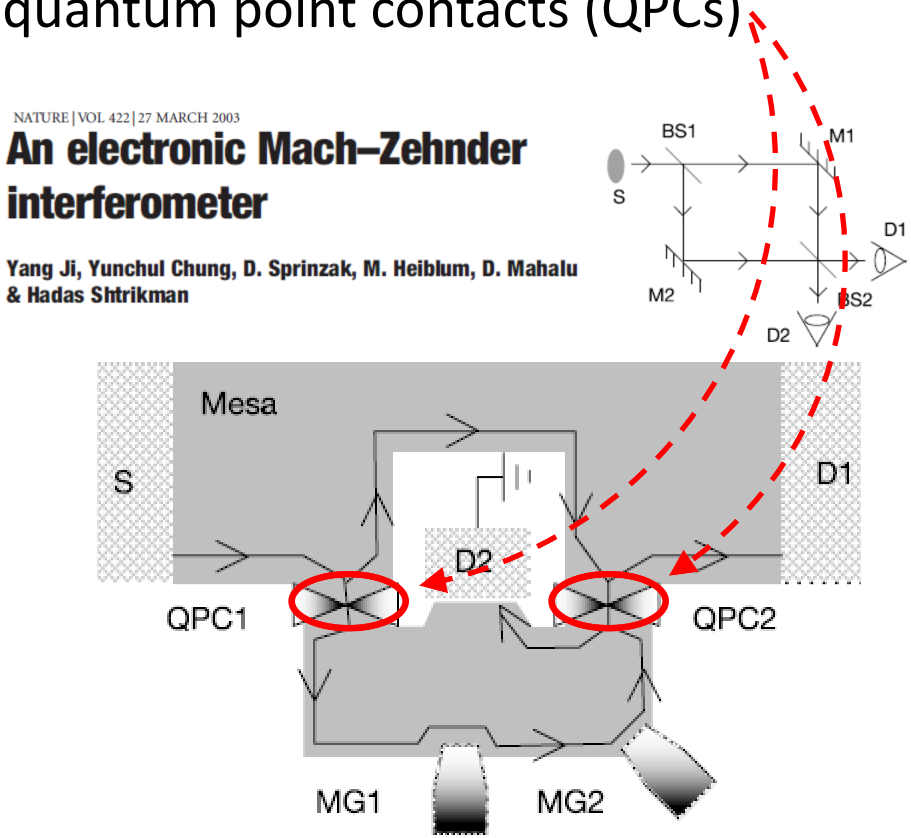


➡ **How do these channels interact?:**

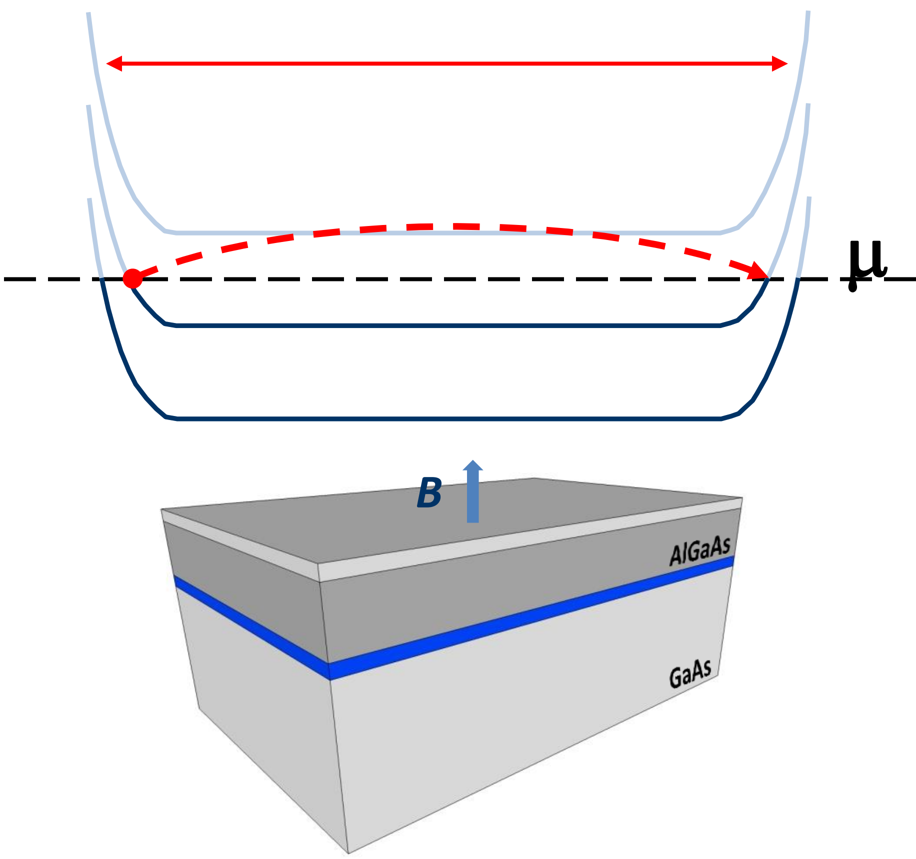
*We will exploit the SGM technique to implement a variable-geometry device to **image** the scattering processes*

The state of the art of electronic quantum interferometry

At the **beam splitters** the electrons are backscattered into the **counter-propagating edge** through two quantum point contacts (QPCs)



we induce backscattering by reducing this distance



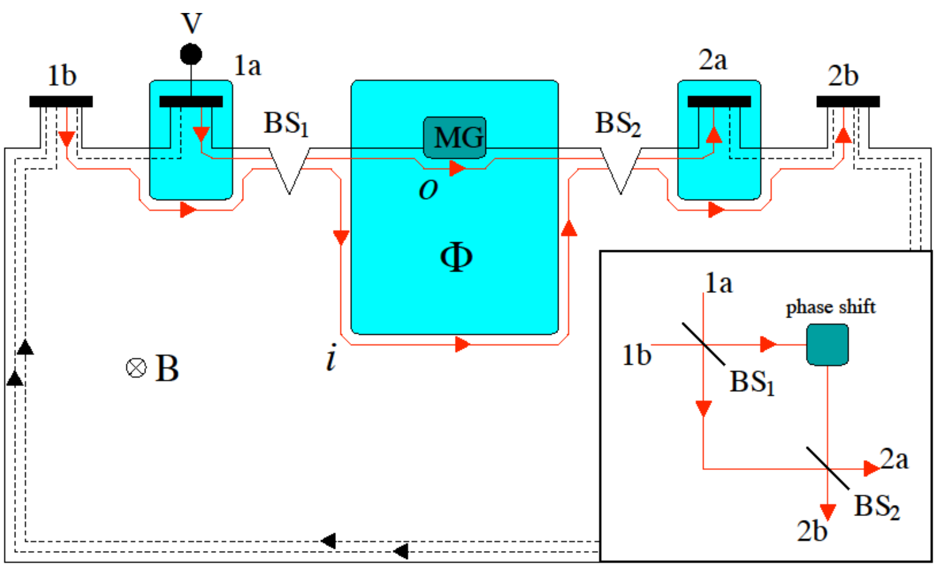
A new architecture for QH interferometry

a simply connected QH interferometer: the proposal of *Giovannetti et al.*

PHYSICAL REVIEW B 77, 155320 (2008)

Multichannel architecture for electronic quantum Hall interferometry

Vittorio Giovannetti,[1] Fabio Taddei,[1] Diego Frustaglia,[2] and Rosario Fazio[1,3]



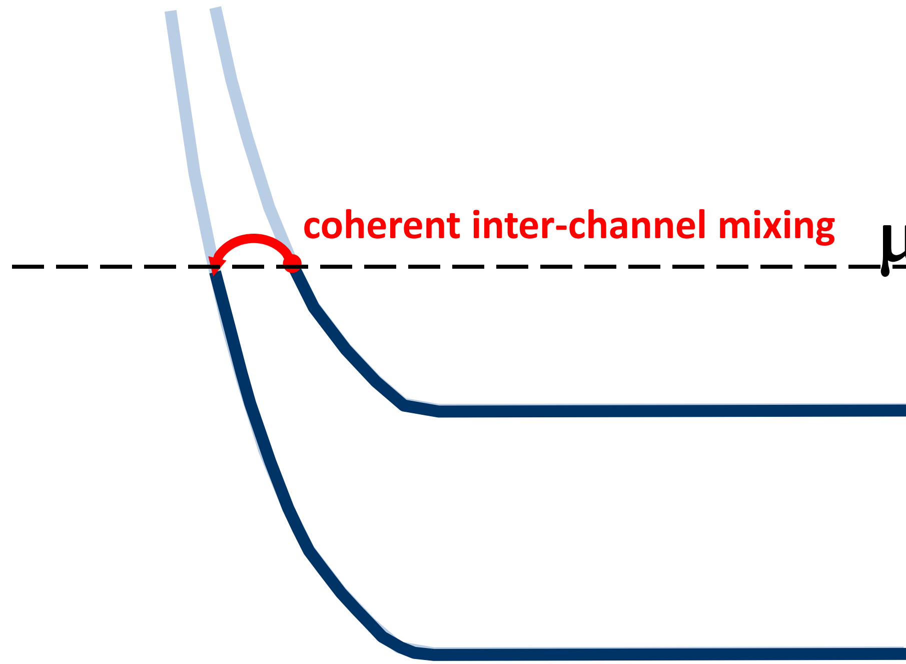
New architecture: beam splitters induce mixing between co-propagating edge channels

Advantages:

- **simply connected topology (no air bridges)**
- **very small Φ area, only a few flux quanta are involved**
- **the device is scalable: it is possible to put many devices in series**

A new architecture for QH interferometry

a simply connected QH interferometer: the proposal of *Giovannetti et al.*



PHYSICAL REVIEW B 77, 155320 (2008)

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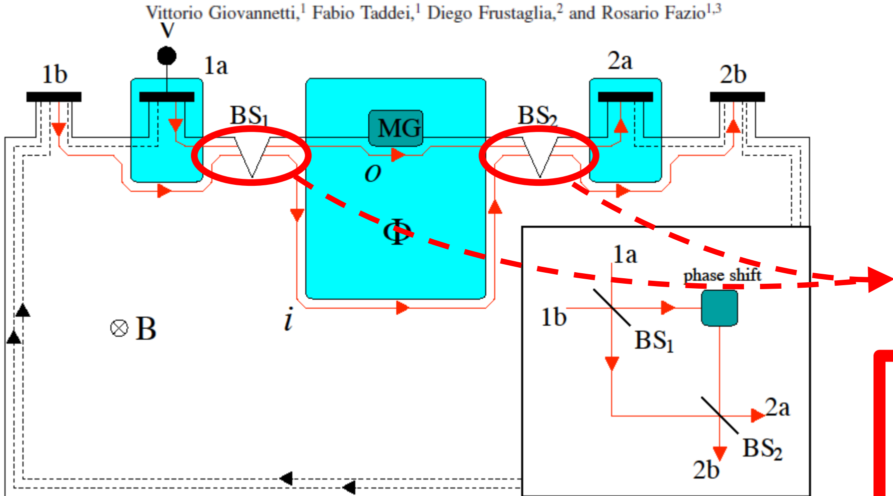


the only elusive parts are the **beam mixers** between **co-propagating channels**

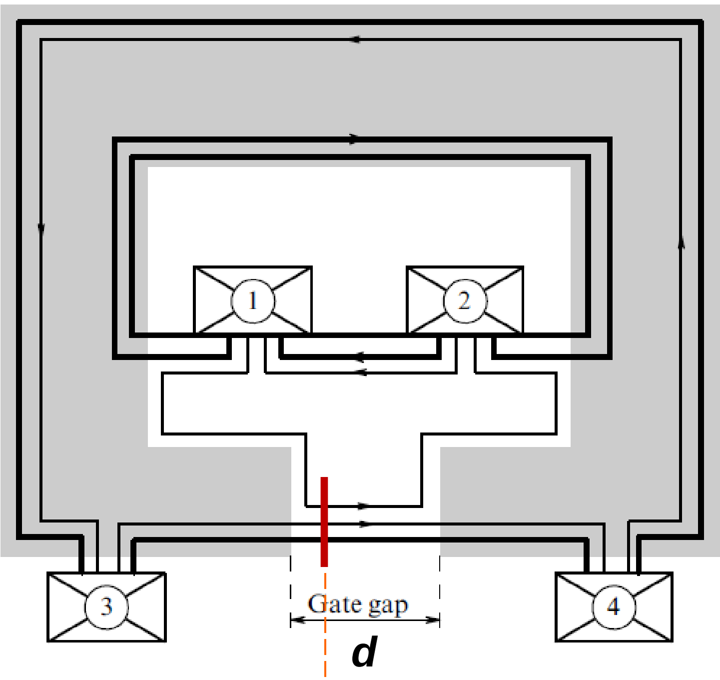
Is it possible to study and image the microscopic details of the inter-channel scattering?

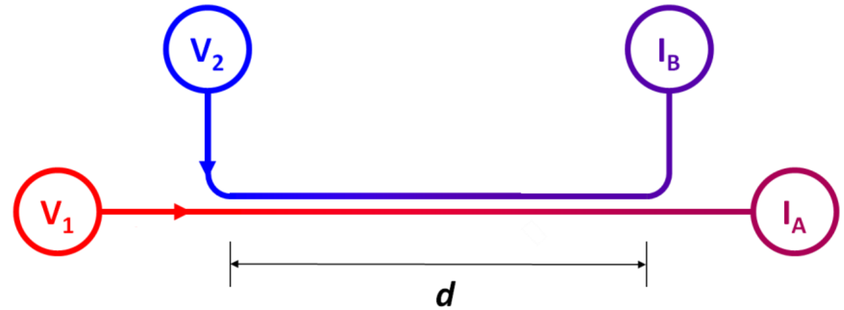
Studying the inter-channel equilibration

Edge states in the regimes of integer and fractional quantum Hall effects

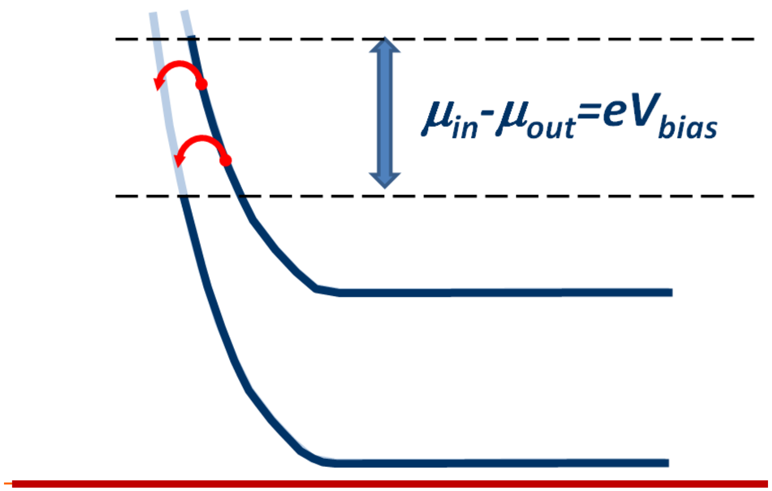
E V Deviatov

Physics – Uspekhi **50** (2) 197 – 218 (2007)





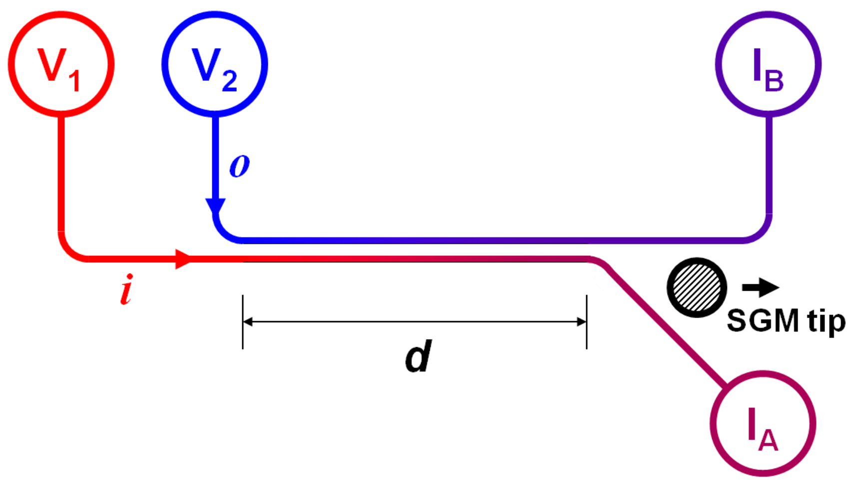
devices with fixed interaction length *d*:
elusive determination of the microscopic details of the equilibration mechanisms

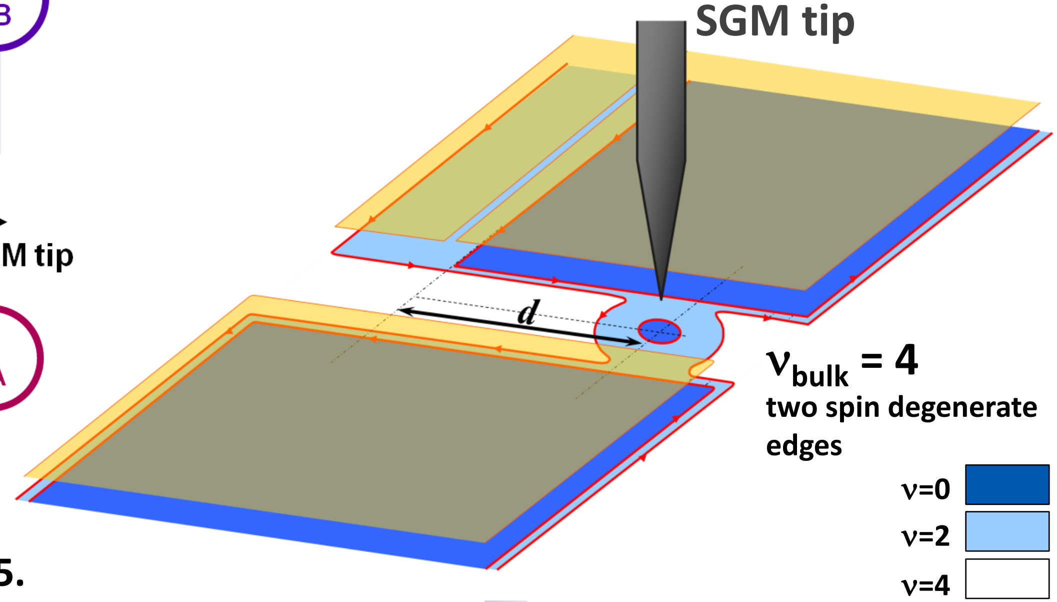


The oppurtunity of the Scanning Gate Microscopy

Our technique allows to selectively control the channel trajectory

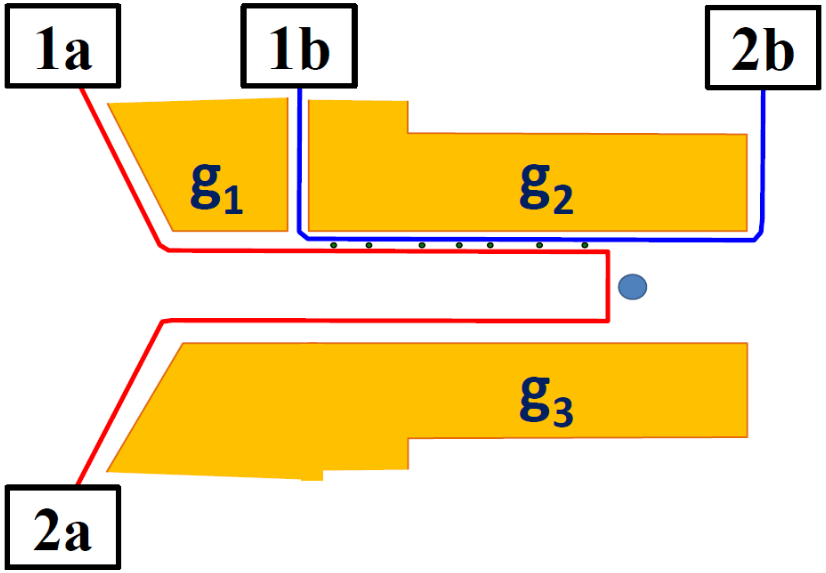
Our idea: exploit the mobile depletion spot induced by the SGM to continuously tune ***d***

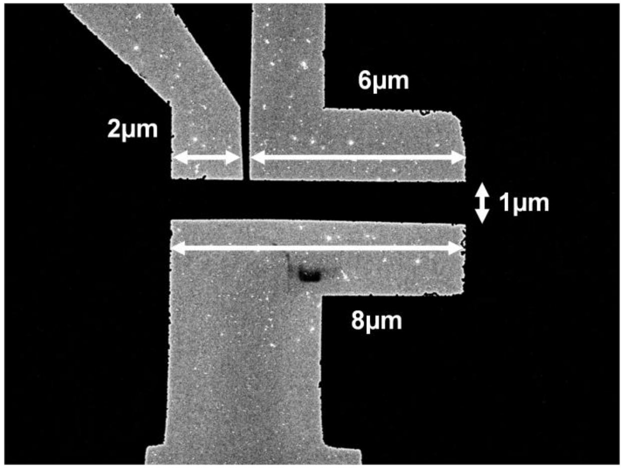




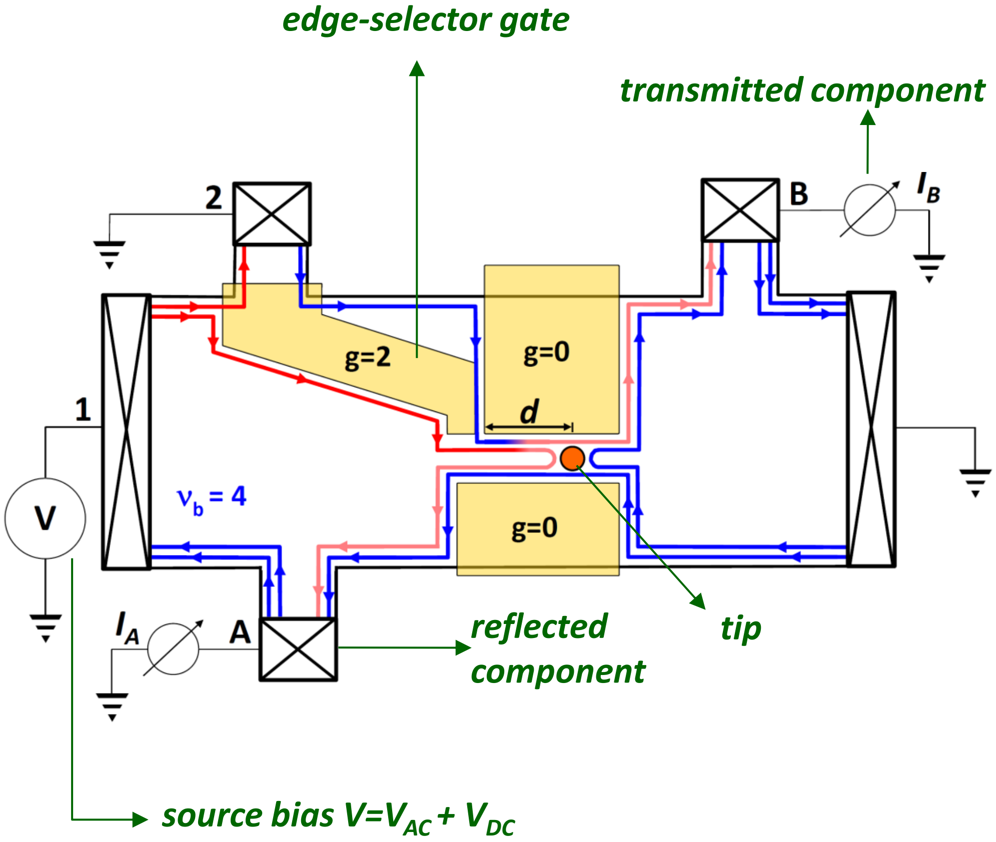
N. Paradiso *et al.* Phys. Rev. B 83 (2011) 155305.

Experimental setup





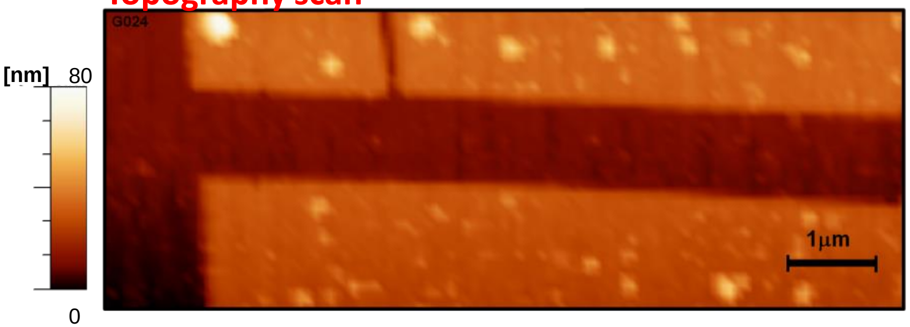
SEM micrograph of the device



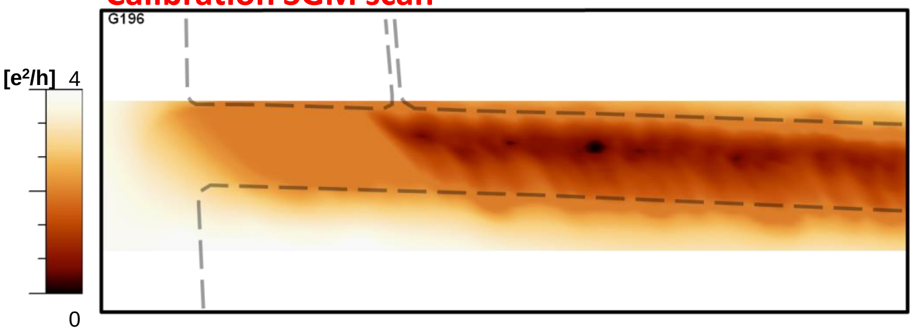
Scheme of the electronic setup

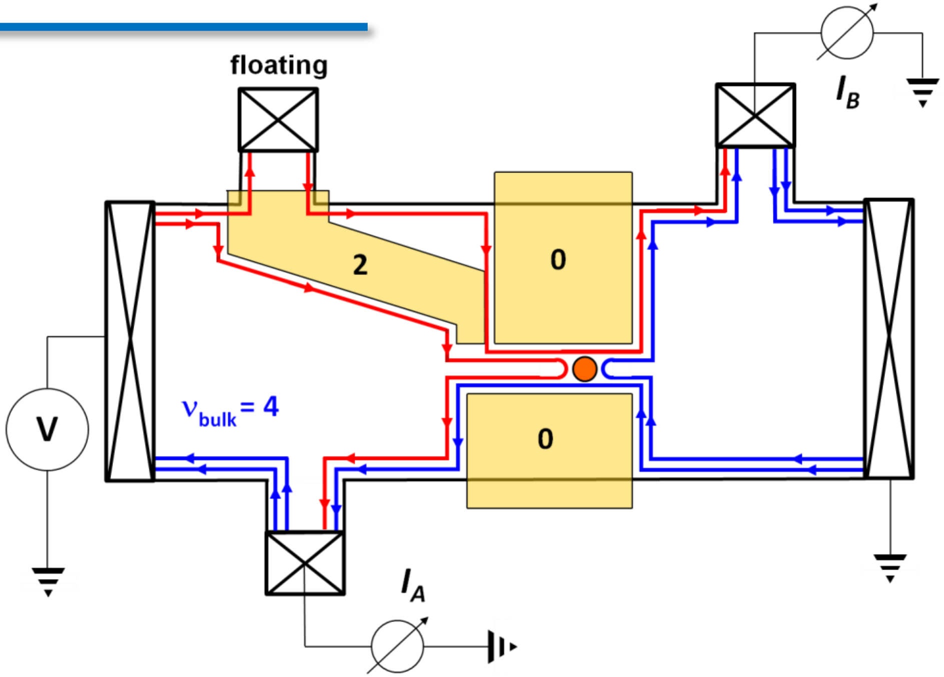
Calibration step

Topography scan

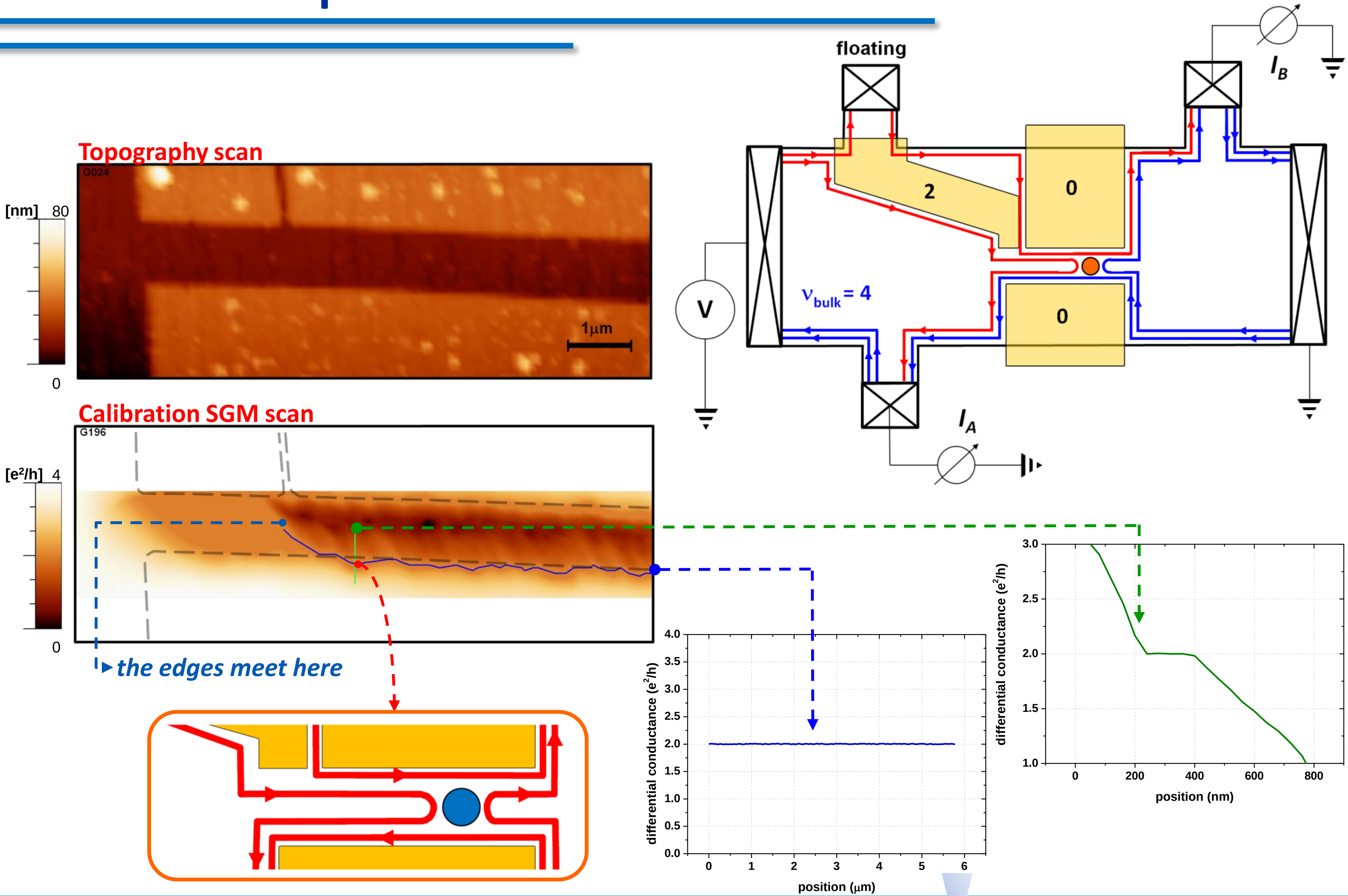


Calibration SGM scan



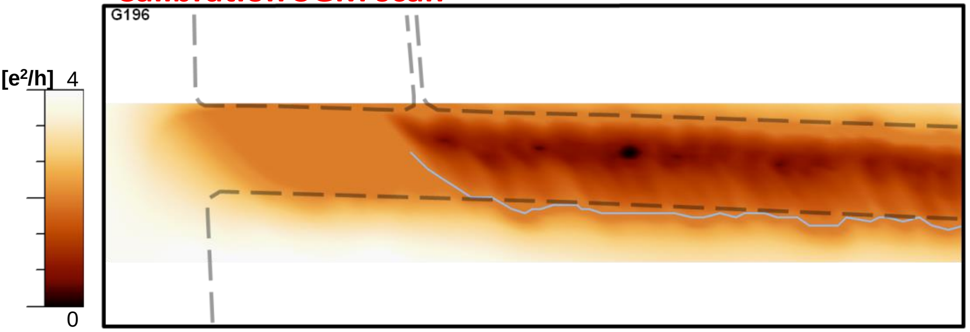


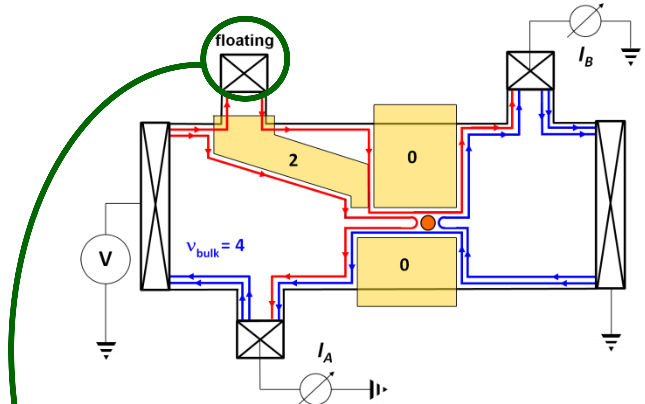
Calibration step



Imaging the inter-channel equilibration

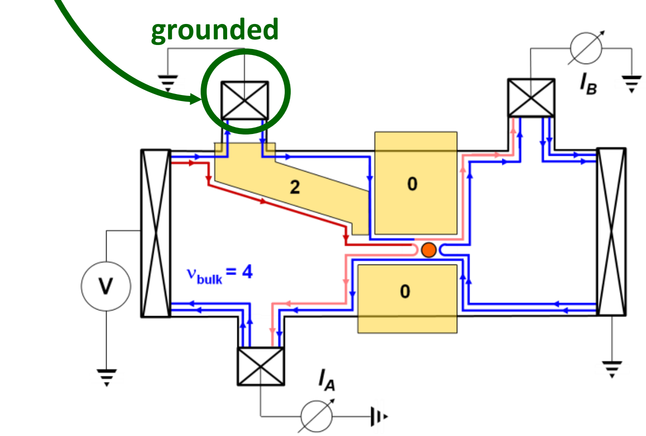
Calibration SGM scan



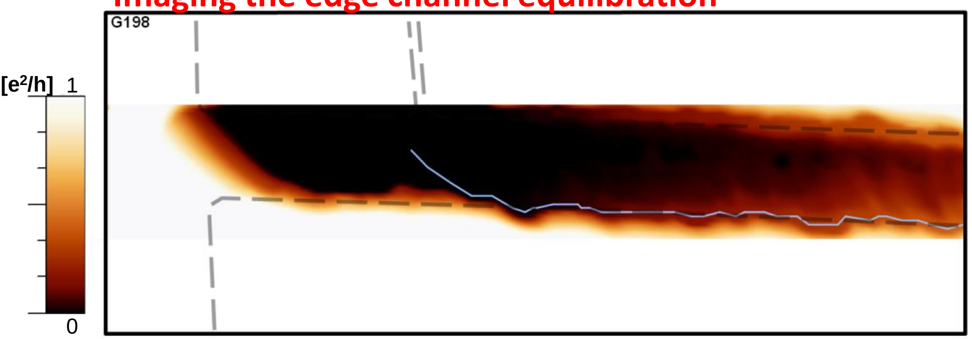


SGM map of the I_B signal: direct imaging of the equilibration process.

By grounding the upper contact an imbalance is established between the edges.



Imaging the edge channel equilibration

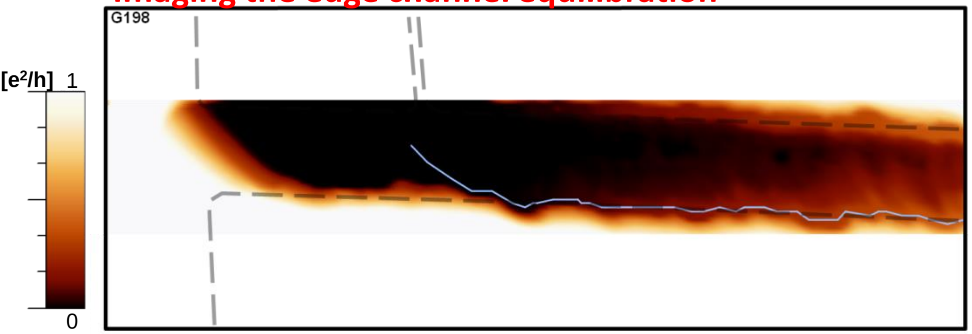


Source bias: V_{AC}=50µV, V_{DC}=0mV

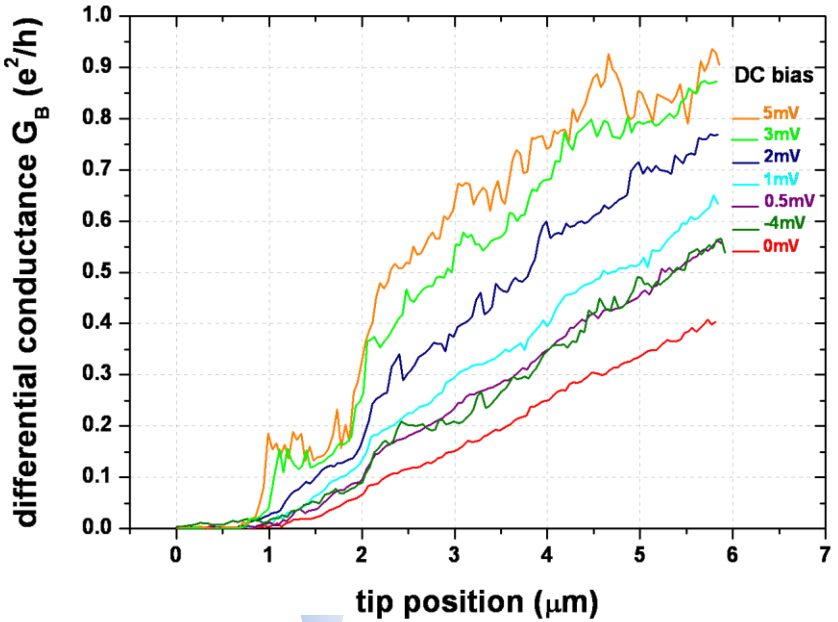
Imaging the inter-channel equilibration

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

Imaging the edge channel equilibration



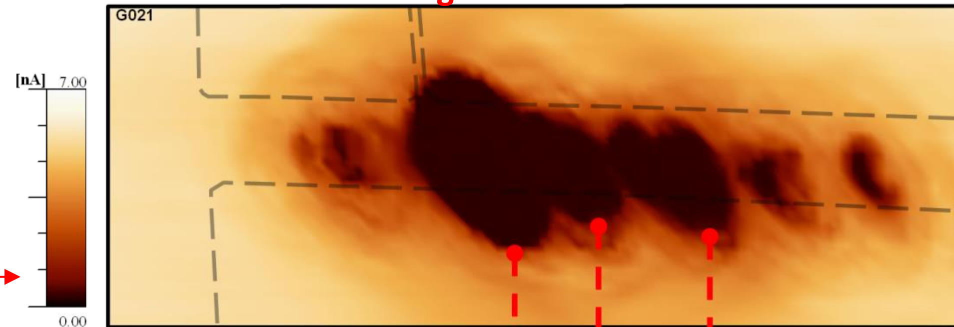
Source bias: V_{AC}=50μV, V_{DC}=0mV



Imaging the inter-channel equilibration

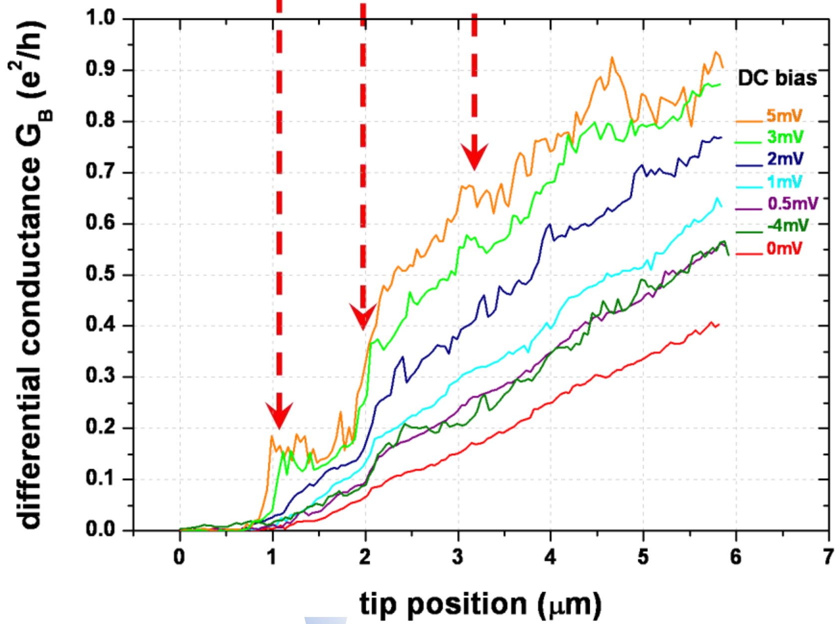
We can directly image the potential induced by the most important defects by means of a scan at zero magnetic field

SGM scan at zero magnetic field

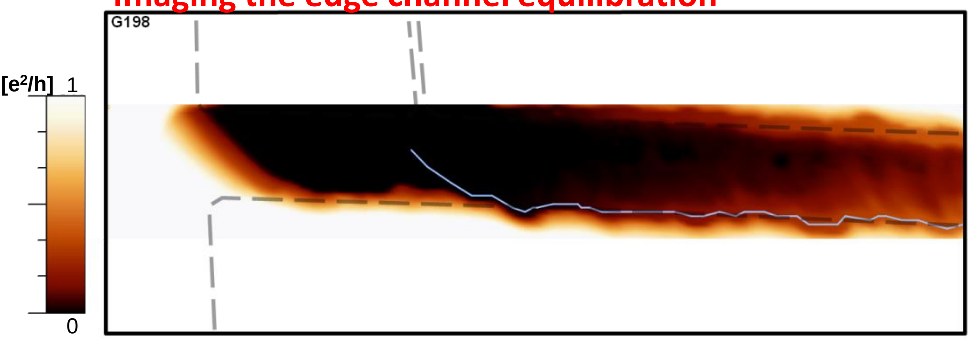


The profiles of $G_B(d)$ along the trajectory show a strict dependance on the local details

correlation found

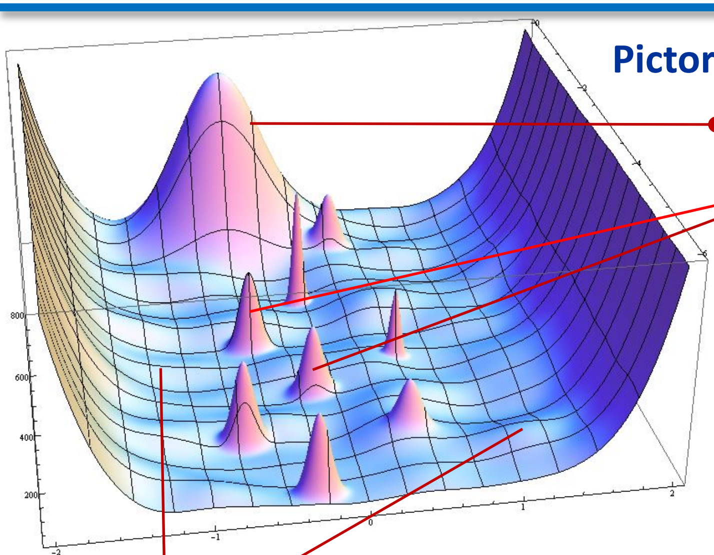


Imaging the edge channel equilibration



Source bias: V_{AC}=50μV, V_{DC}=0mV

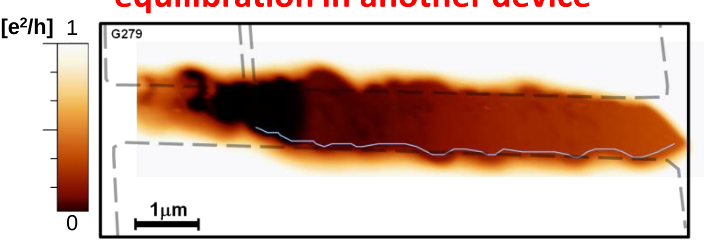
Tight binding simulations



Pictorial model for the disorder potential

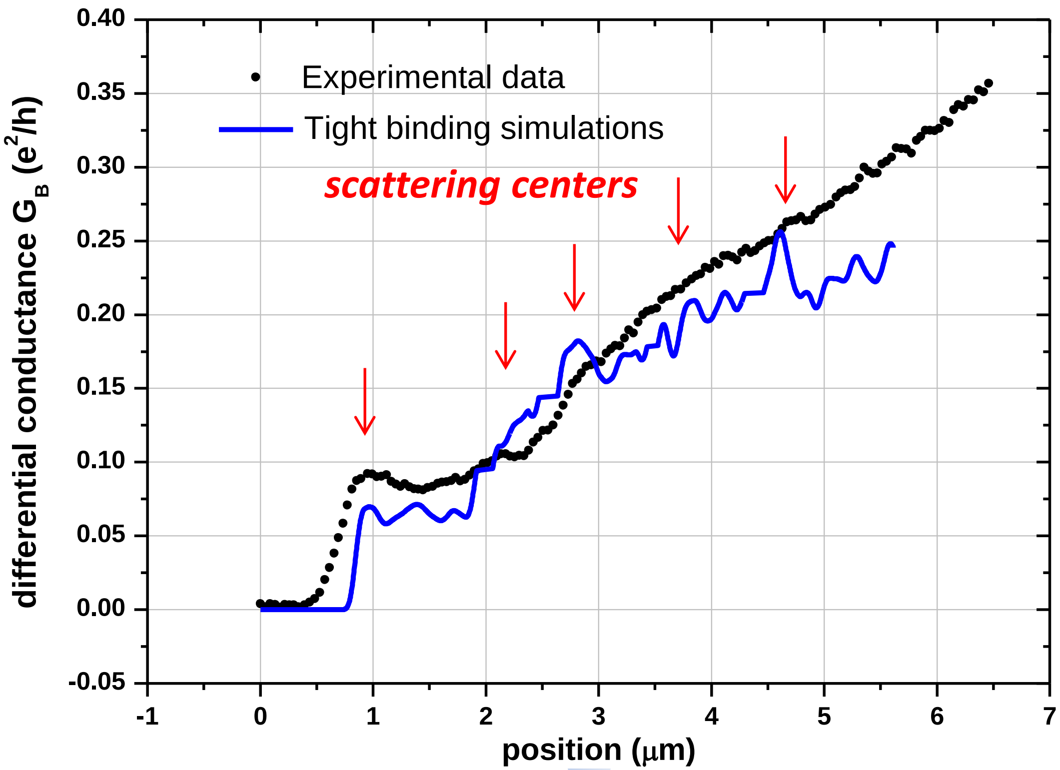
- tip potential
- “big impurities” potential
- background potential

SGM map of the inter-channel equilibration in another device

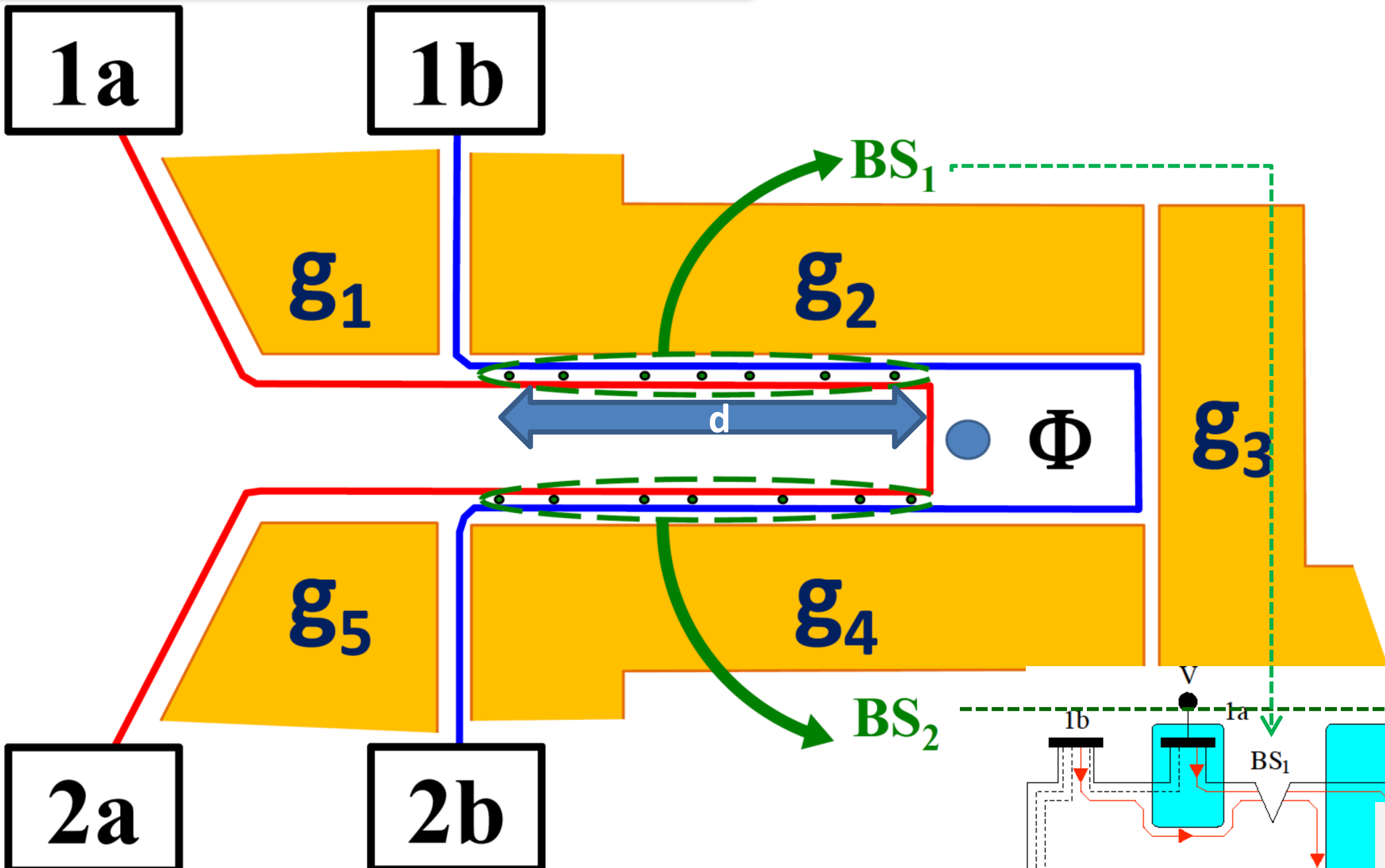


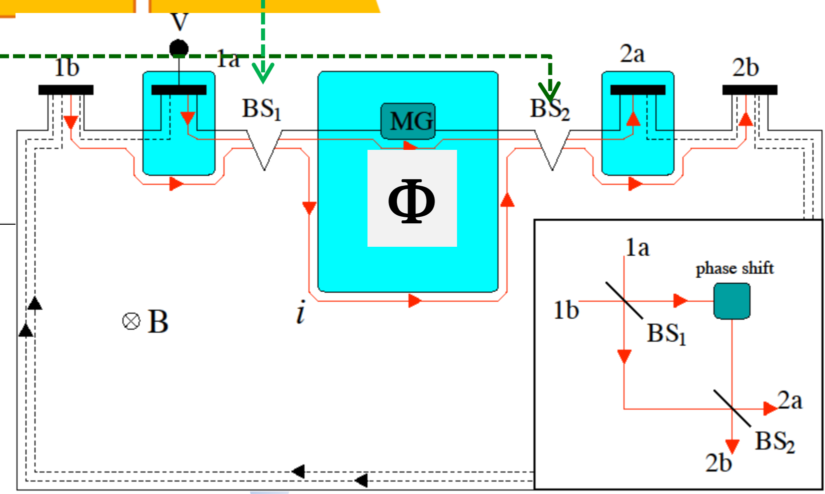
Simulations made by the theoretical group of Scuola Normale Superiore (Pisa, Italy)

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



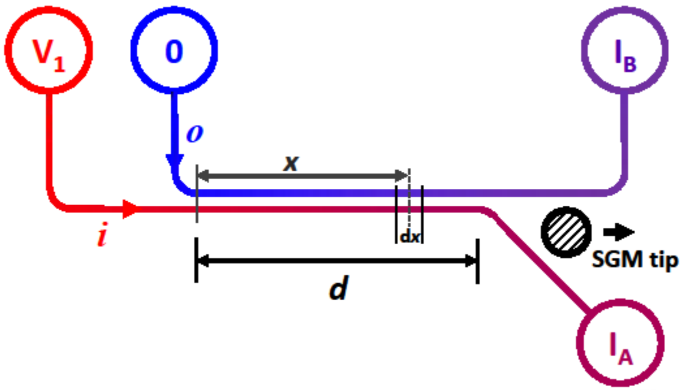
Next step: a simply connected MZI





Our idea to implement the Mach-Zehnder interferometer proposed by Giovannetti *at al.*

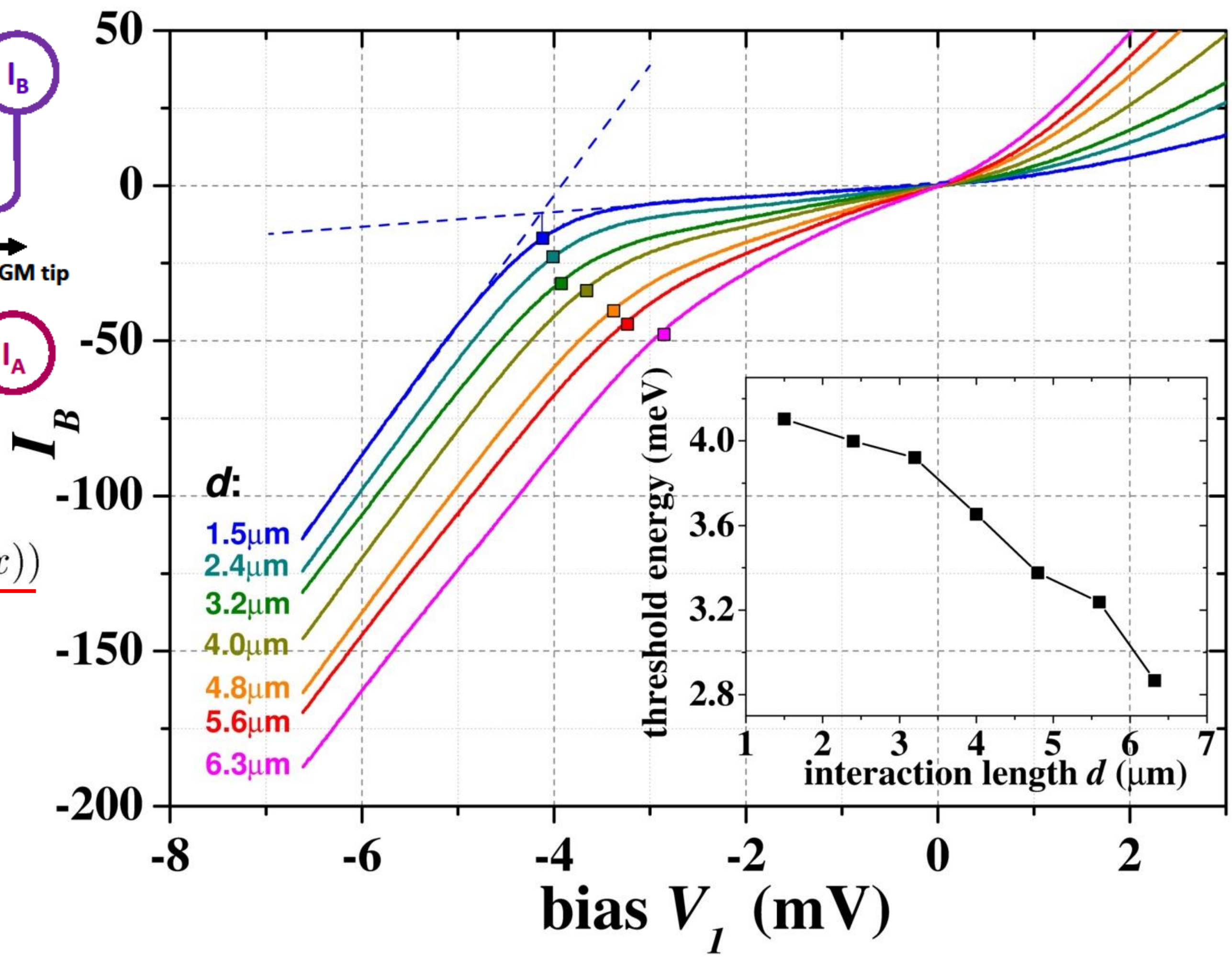
Nonlinear regime



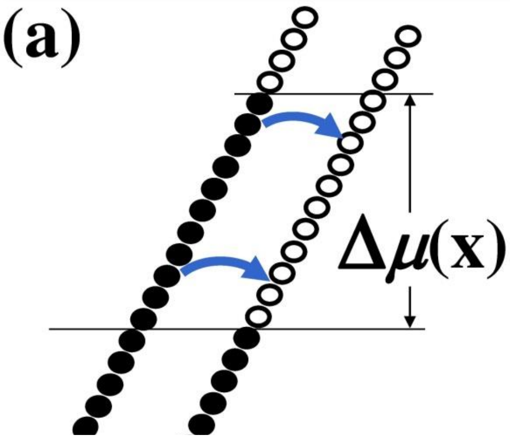
$$\frac{dI}{dx} = -\frac{e^2}{h}\frac{d}{dx}\Delta V(x) = \underline{\Phi(\Delta V(x))}$$

The backscattered current is a function of the local imbalance Δ*V(x)* that depends on the specific scattering process.

N. Paradiso *et al.*: Phys. Rev. B 84, 235318 (2011)

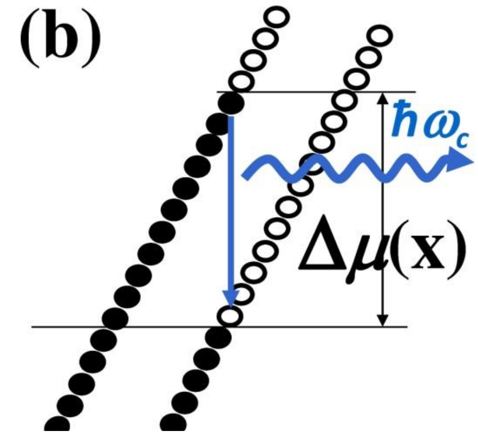


Two mechanisms for the inter-channel scattering



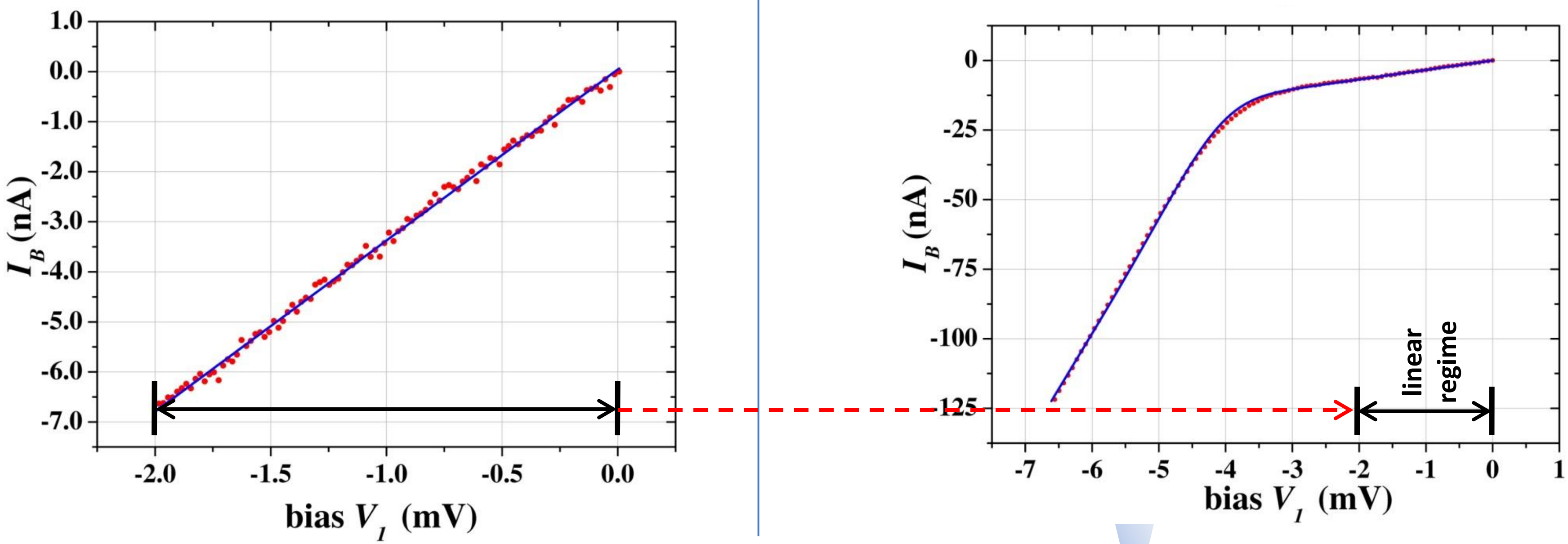
For low bias the only relevant mechanism is the elastic scattering induced by impurities, which determines an ohmic behavior (linear I-V)

At high bias ($\Delta\mu \approx \hbar\omega_c$) vertical transition with photon emission are enabled (threshold and saturation)



$$dI = dx\frac{2e\mathcal{T}_0}{hv_d}\int_{-\infty}^{\infty}(f_{\mu_i,T}(\epsilon)-f_{\mu_o,T}(\epsilon))d\epsilon = dx\frac{2e^2\mathcal{T}_0}{hv_d}\Delta V(x)$$

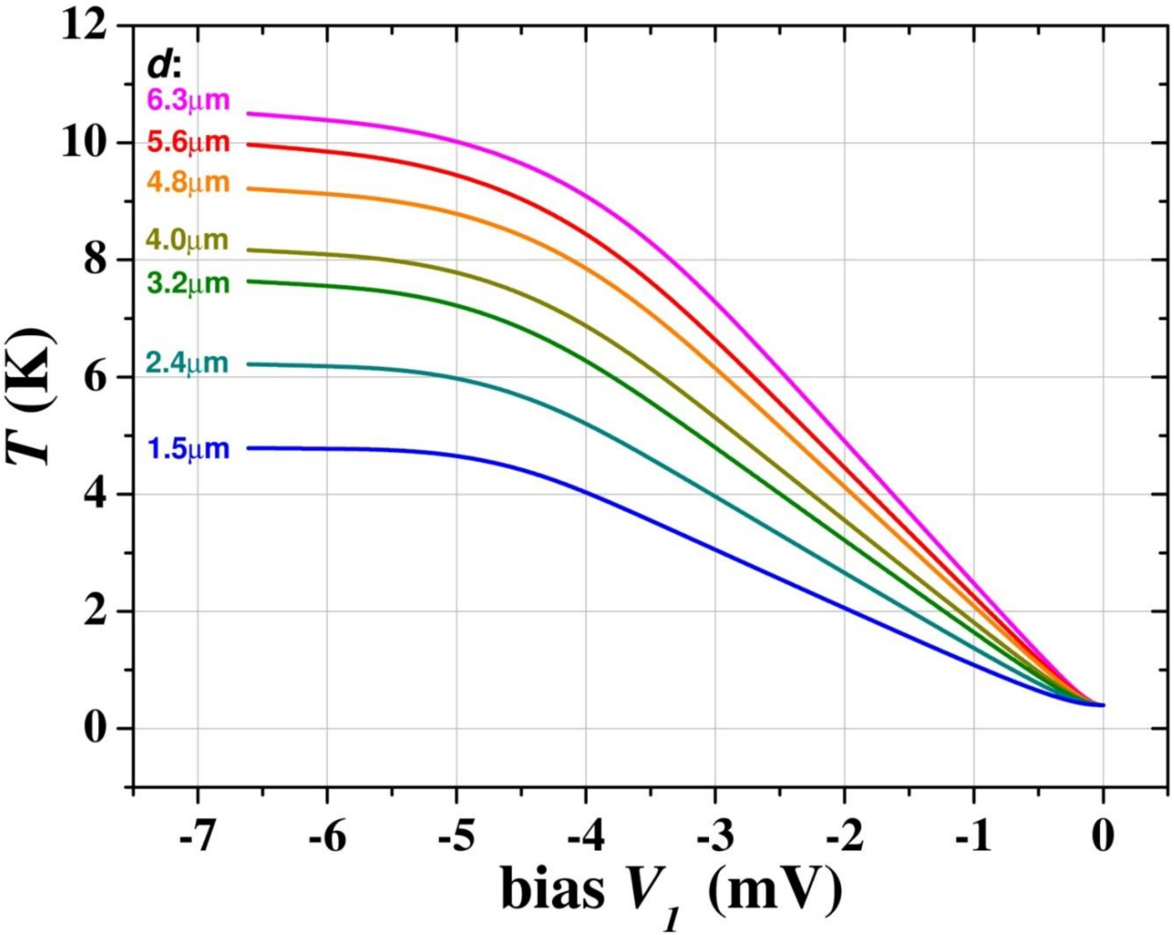
$$dI = dx\frac{2e\mathcal{T}_1}{hv_d}\int_{-\infty}^{\infty}[f_{\mu_i,T}(\epsilon)(1-f_{\mu_o,T}(\epsilon-\hbar\omega_c))]d\epsilon = dx\frac{2e\mathcal{T}_1}{hv_d}\left(\frac{e\Delta V(x)-\hbar\omega_c}{1-e^{\frac{\hbar\omega_c-e\Delta V(x)}{k_BT}}}\right)$$

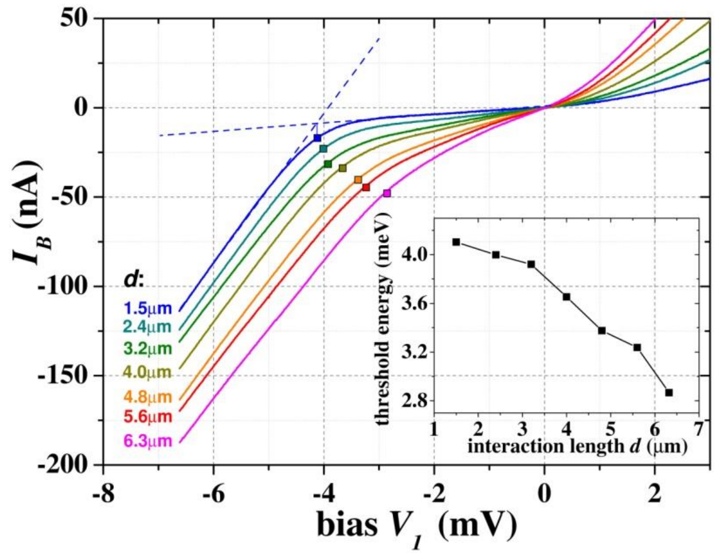


Impact of the electron heating

Electron heating due to injection of hot carriers:

$$\frac{d}{dx}T(x) = \frac{3e^2}{4\pi^2 k_B^2 \ell_{eq}} \frac{\Delta V^2(x)}{T(x)}$$

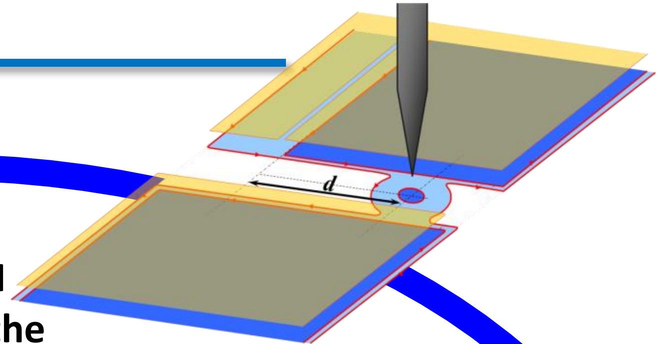




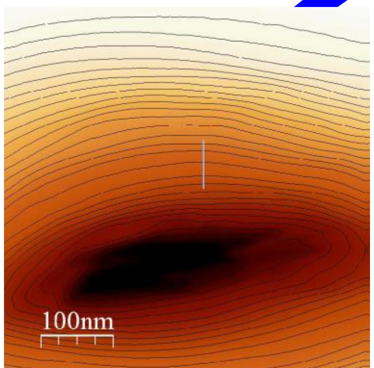
The relaxation of hot carriers induces a dramatic temperature increase. This is why the transition is smoothened and the threshold voltage reduced for high *d*

Summary and outlook

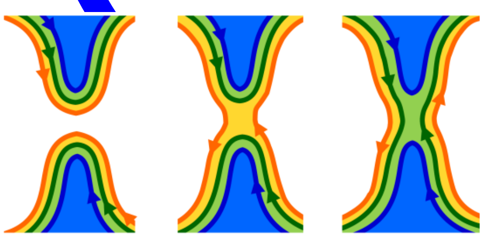
SGM technique in the QH regime



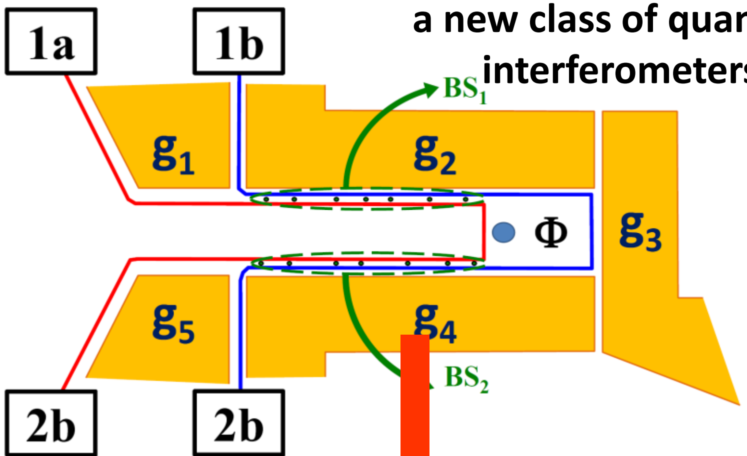
size-tunable QH circuits: study of the channel mixing



Edge channel tomography: imaging of fractional stripes



a new class of quantum interferometers



Future directions: Interference of fractional quasi-particles ?

National Enterprise for nanoScience and nanoTechnology

Thank you for your attention!

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SCUOLA NORMALE SUPERIORE

How everything began...
[LT-AFM installation, Pisa, October 2007]