Topologically protected edge states in the quantum Hall regime

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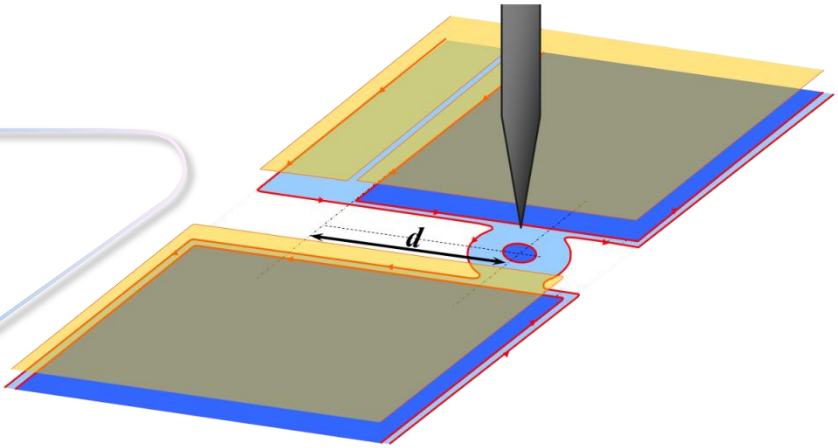
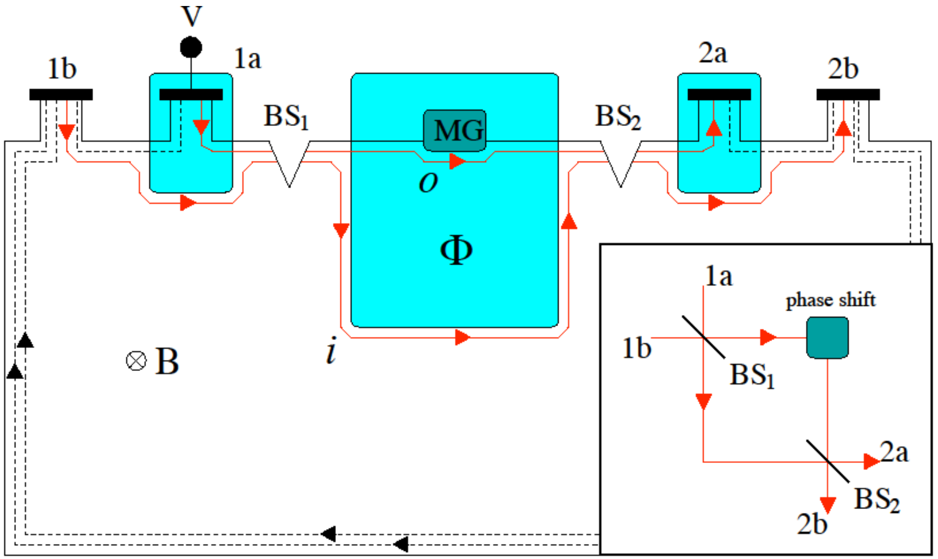


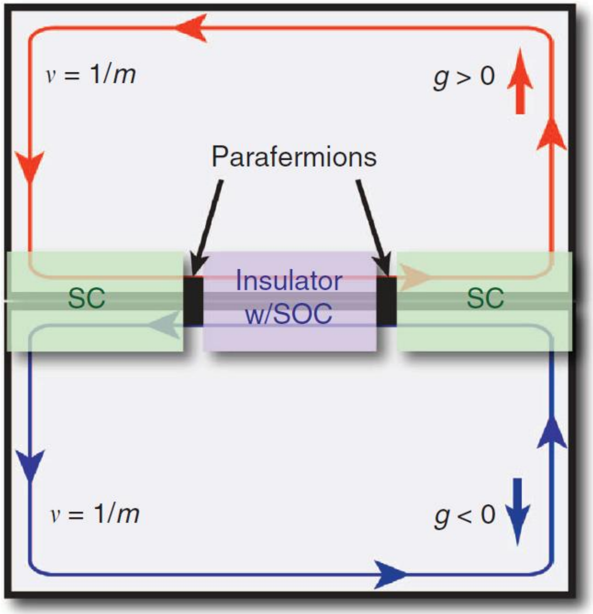
Contributions from: Andrea Bertoni, Alessandro Braggio, Matteo Carrega, Francesco Giazotto, Vittorio Giovannetti, Stefan Heun, Stefano Roddaro, Fabio Taddei

Outline

- Quantum Hall Edge Channel Interferometry



- Hybrid SNS Josephson Junctions in the QH Regime



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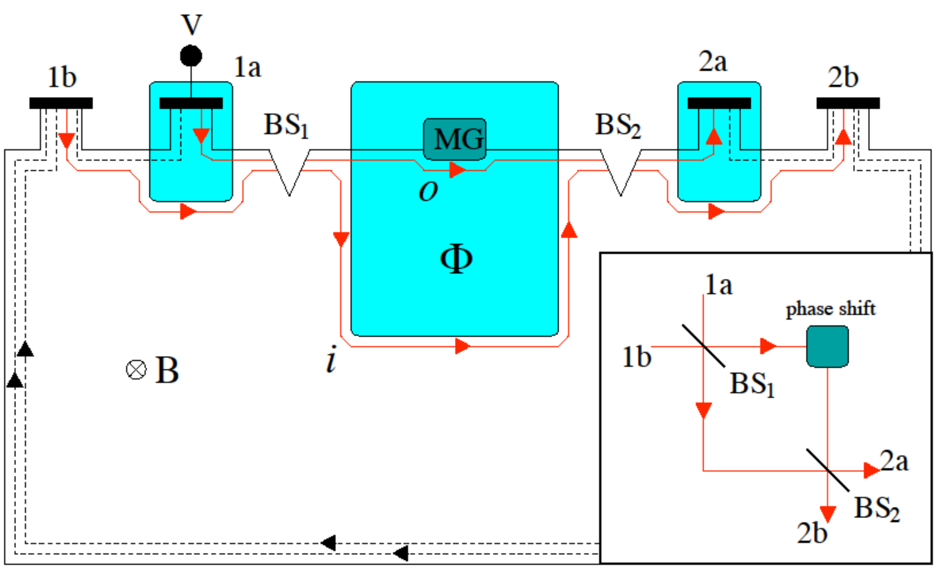
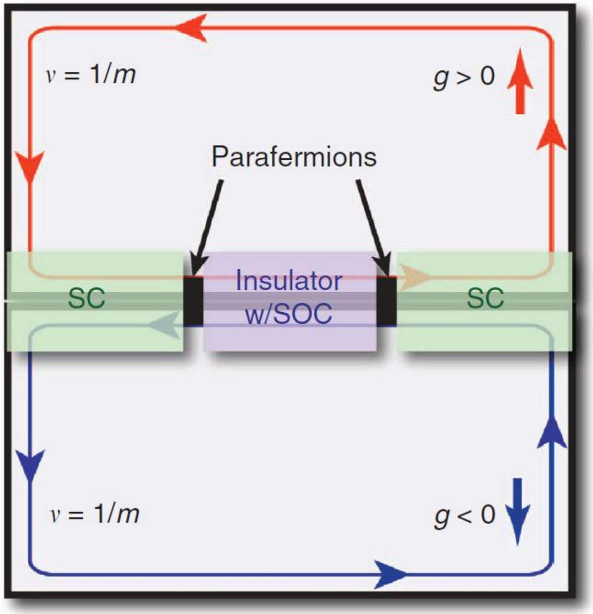


- Hybrid SNS Josephson Junctions in the QH Regime

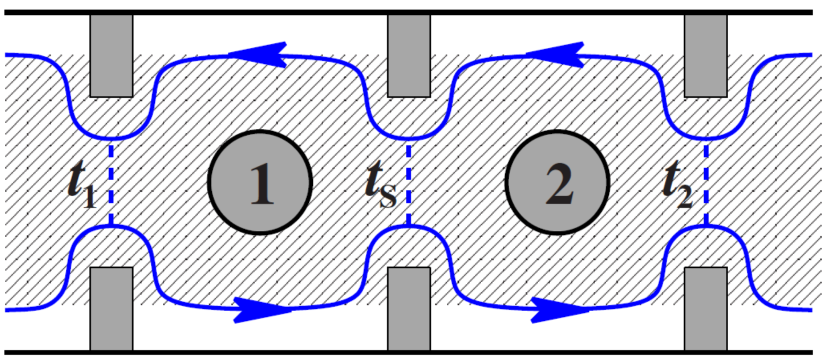


Why a quantum Hall quantum Computer?

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

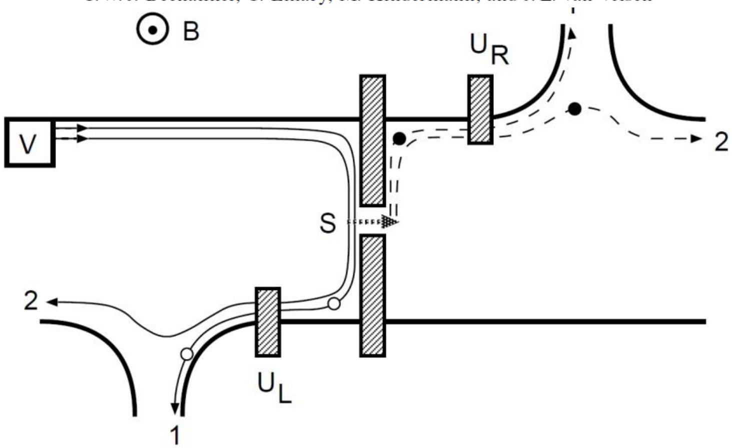
Non-Abelian anyons and topological quantum computation



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

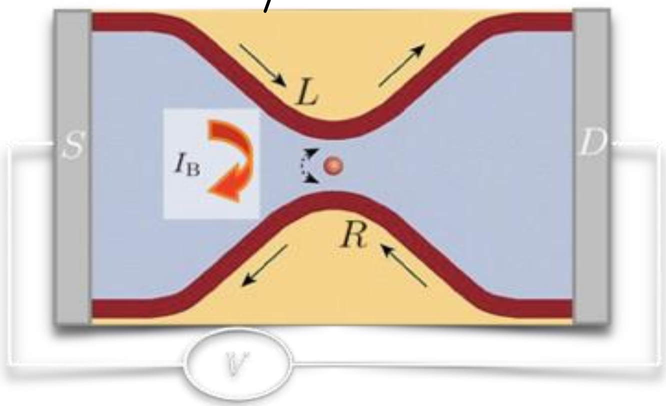


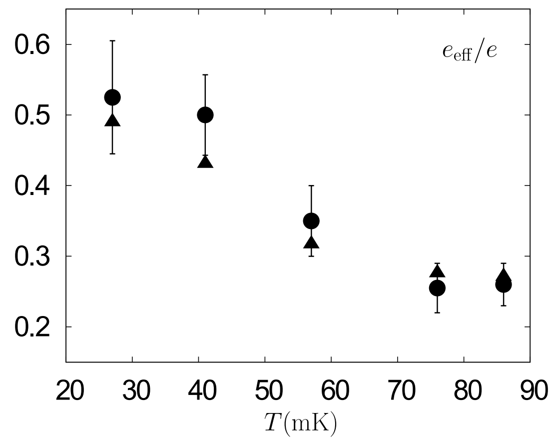
An electron-hole entangler
[Beenakker *et al.* PRL **91**, 147901 (2003)]

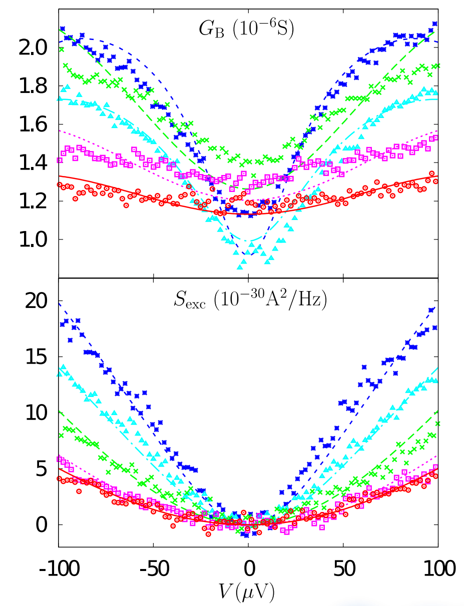
Transport and noise properties in quantum Hall edge states

Effective charges in Abelian and non-Abelian states

$\nu = 5/2$



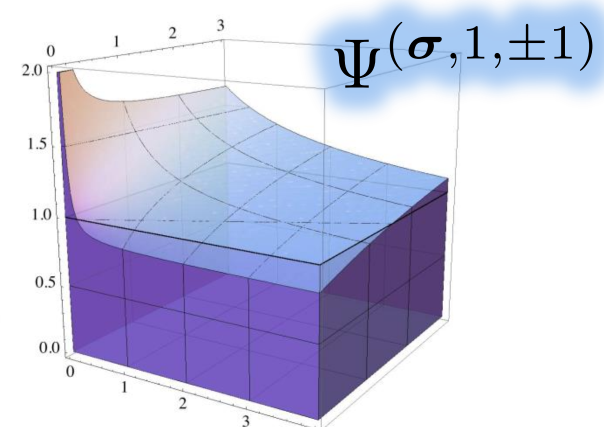




$\frac{v_n}{v_c}$

Moty Heiblum's measurements

M. Carrega, D. Ferraro, A. Braggio, N. Magnoli, and M. Sassetti, PRL 107, 146404 (2011)
M. Carrega, D. Ferraro, A. Braggio, N. Magnoli, and M. Sassetti NJP 14, 023017 (2012)
A. Braggio, D. Ferraro, M. Carrega, N. Magnoli, and M. Sassetti, NJP 14, 093032 (2012)
D. Ferraro, M. Carrega, A. Braggio, and M. Sassetti, NJP 16, 043018 (2014)

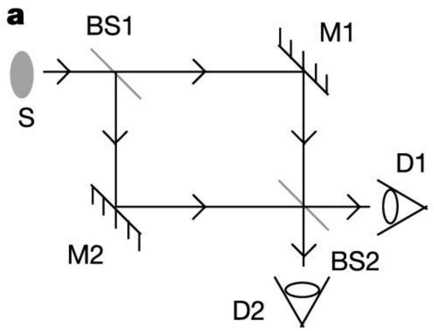


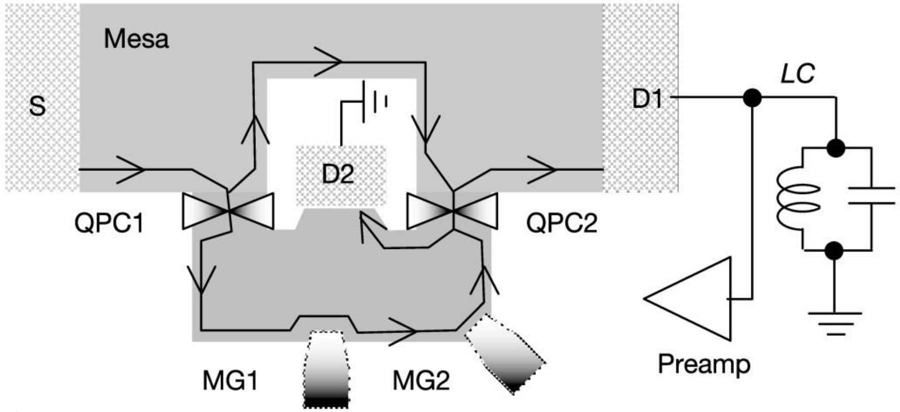
Abelian qp. $\Psi^{(\mathbf{I},2,0)}$

Non-Abelian qp. $\Psi^{(\boldsymbol{\sigma},1,\pm1)}$

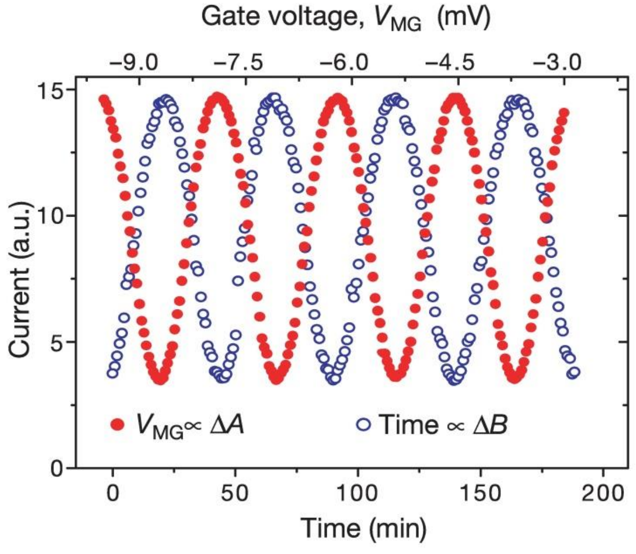
Mach-Zehnder interferometer

Solid state: electron on edge channels of IQHE

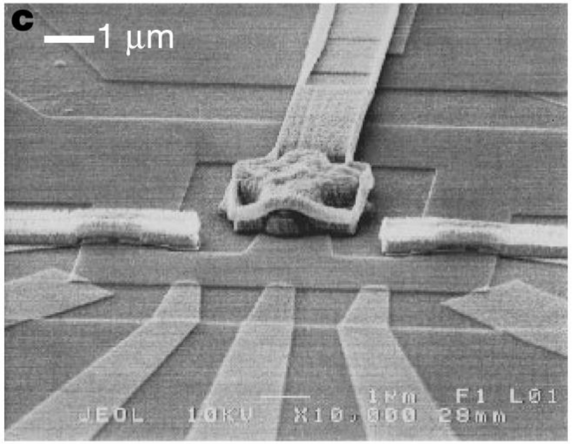




$$I_{D1} \propto |t_1 t_2|^2 + |r_1 r_2|^2 + 2|t_1 t_2 r_1 r_2| \cos\varphi$$



60% visibility



Ji, Chung, Sprinzak, Heiblum, Mahalu, Shtrikman, Nature **422**, 415 (2003)

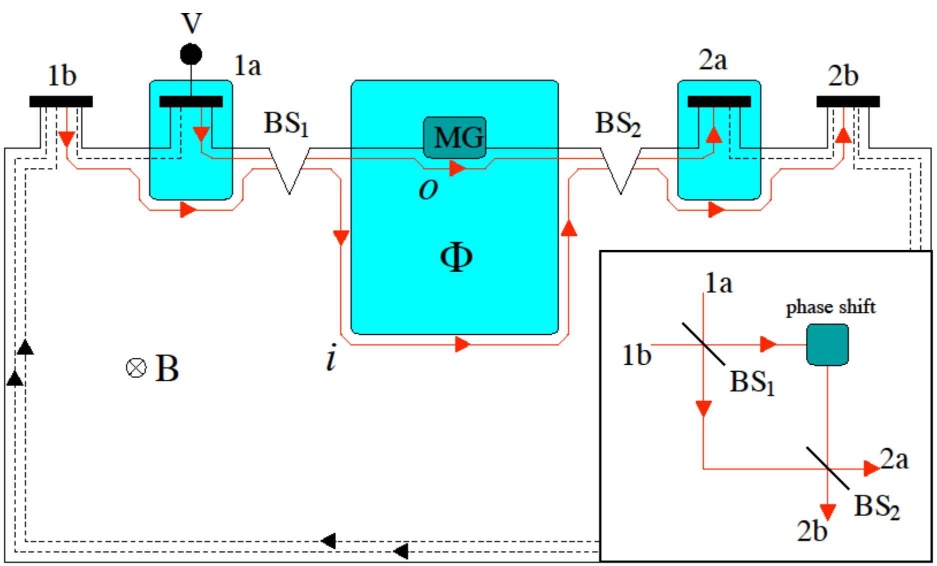
A new architecture for QH interferometry

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]

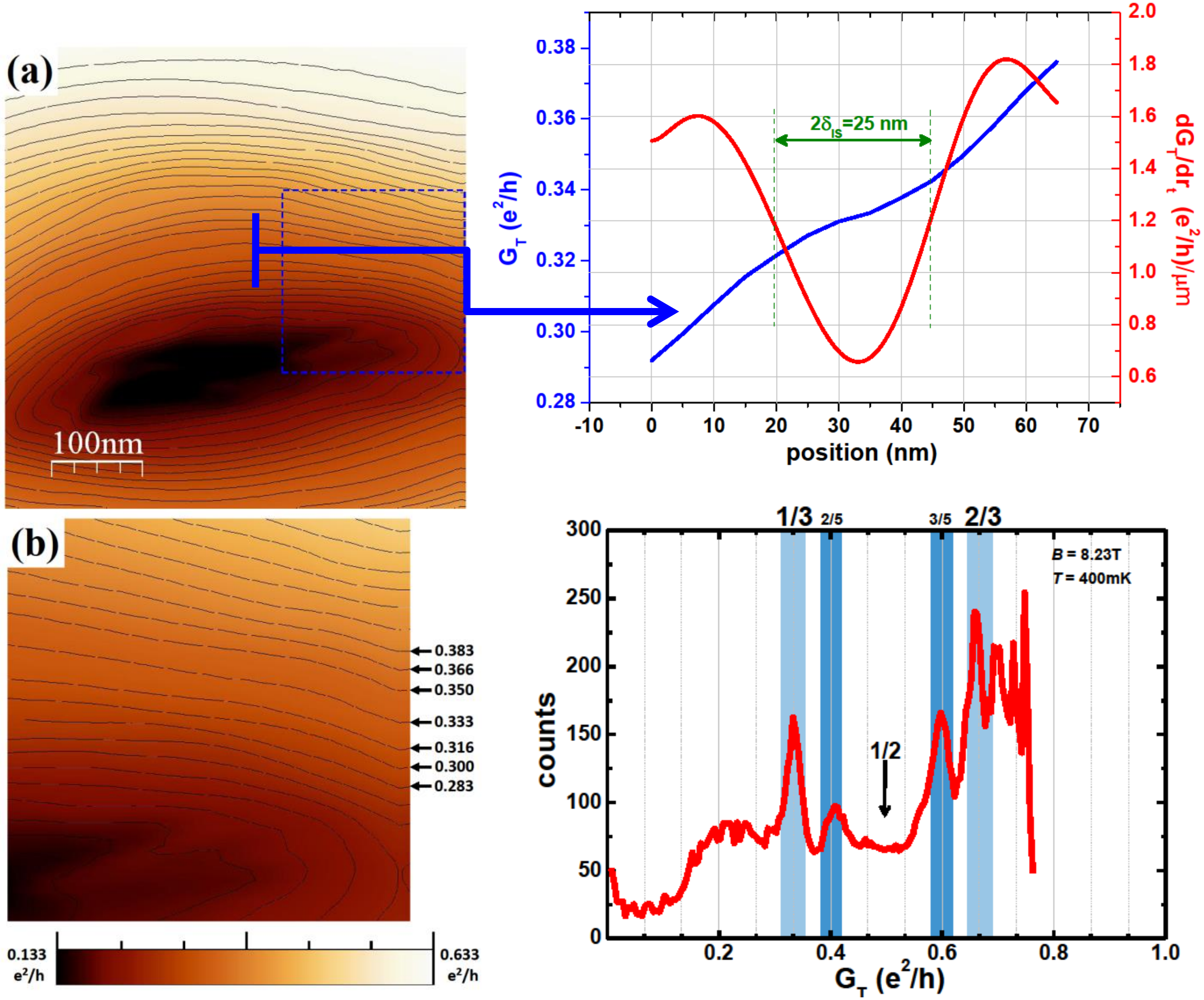


New architecture: beam splitters induce mixing between co-propagating edge channels

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**

Imaging fractional structures in integer channels



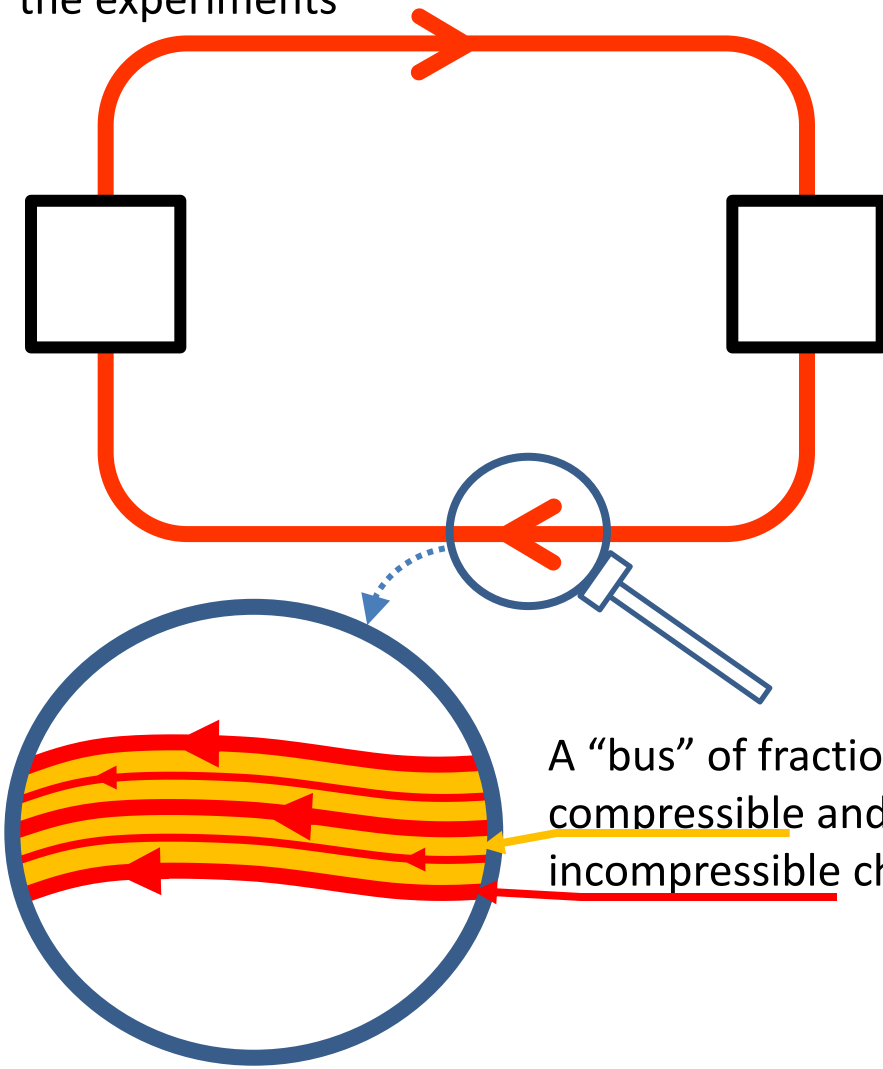
The Reconstruction Picture suggests that at the edge of a smooth **integer** edge a series of compressible/ **incompressible fractional stripes** can occur.

We used the SGM technique to image them.

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

Can we exploit the non-trivial edge structure?

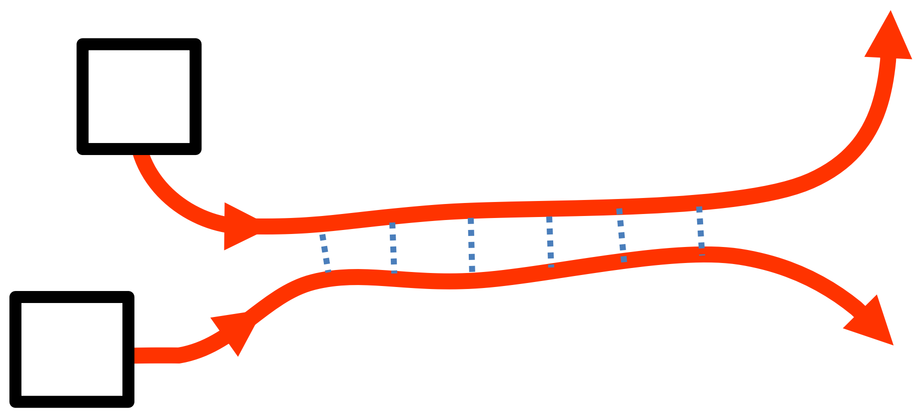
The picture of a QH device emerging from the experiments



A "bus" of fractional compressible and incompressible channels:

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

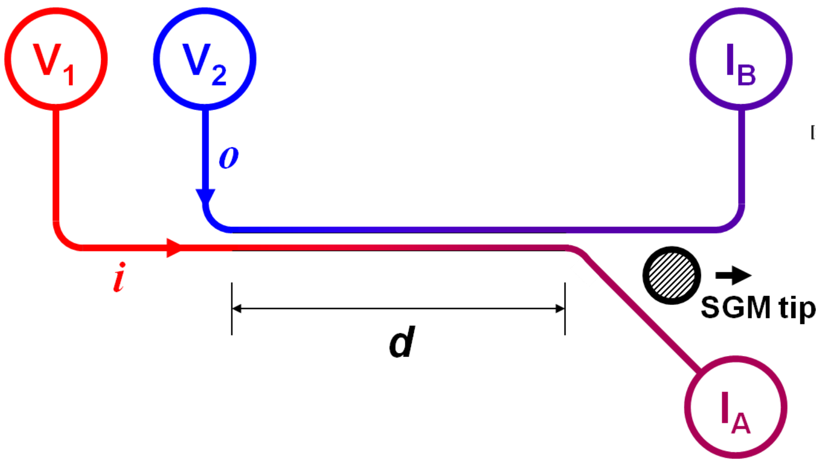
Komiyama et al. PRB **45**, 11085 (1992).
Karmakar et al., PRL **107**, 236804 (2011)



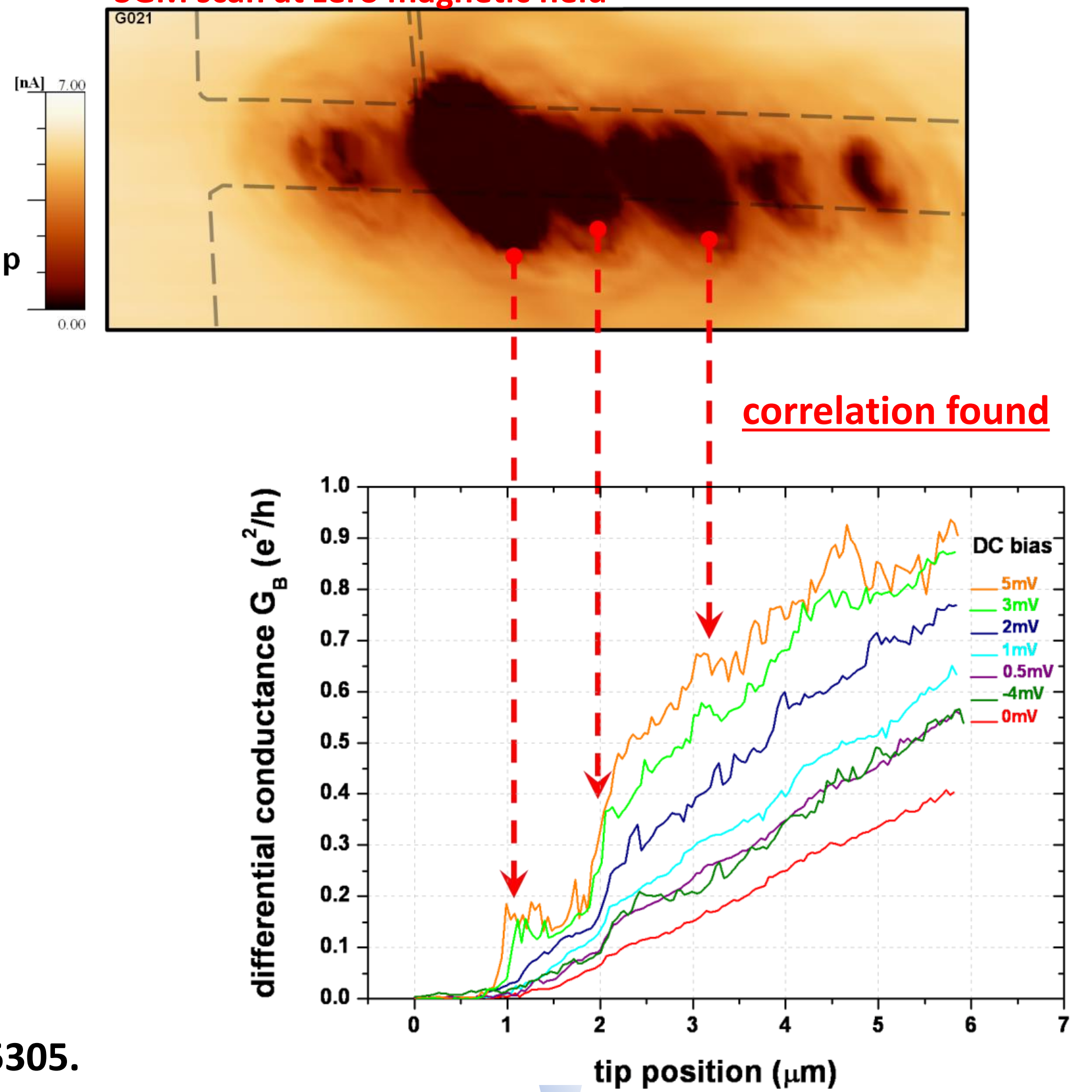
How do these channels interact?:

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

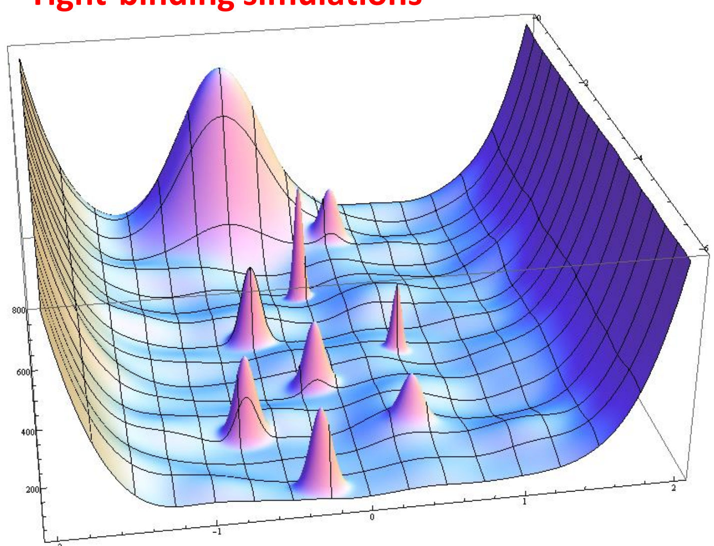
Imaging the inter-channel equilibration



SGM scan at zero magnetic field



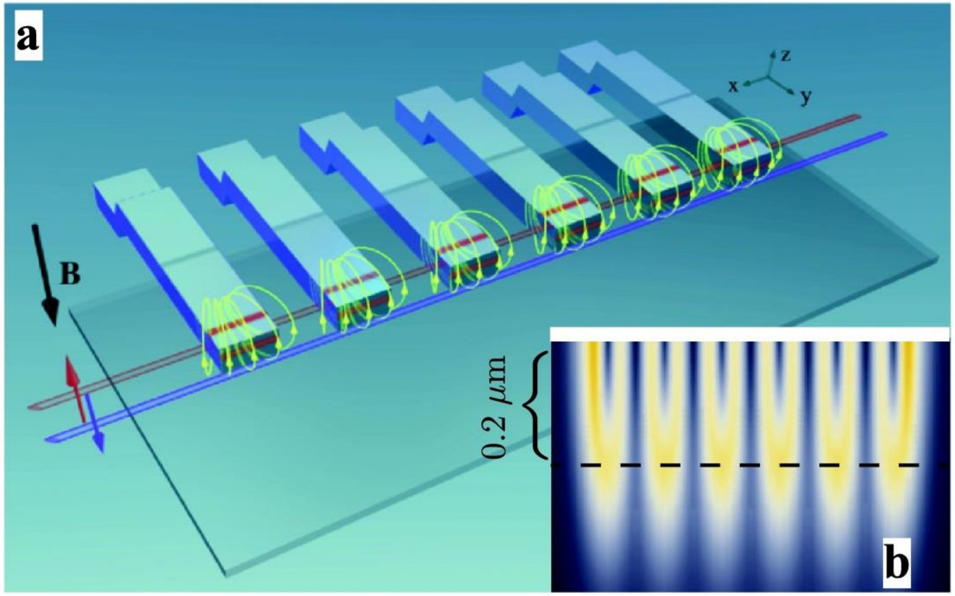
Tight-binding simulations



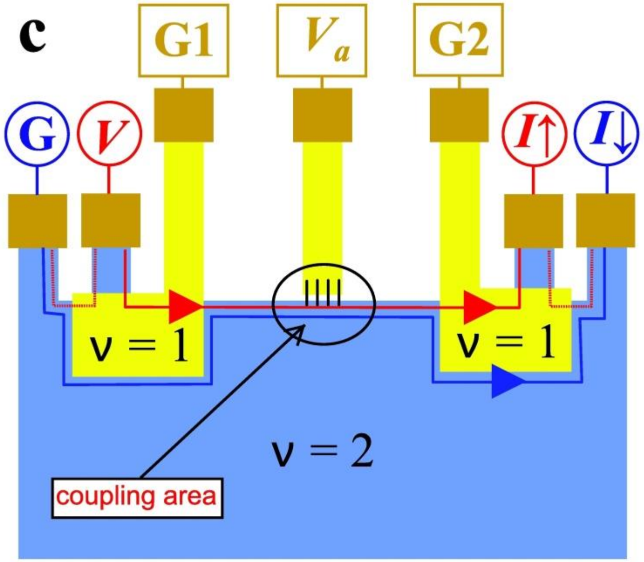
N. Paradiso *et al.* Phys. Rev. B 83 (2011) 155305.

Channel mixing

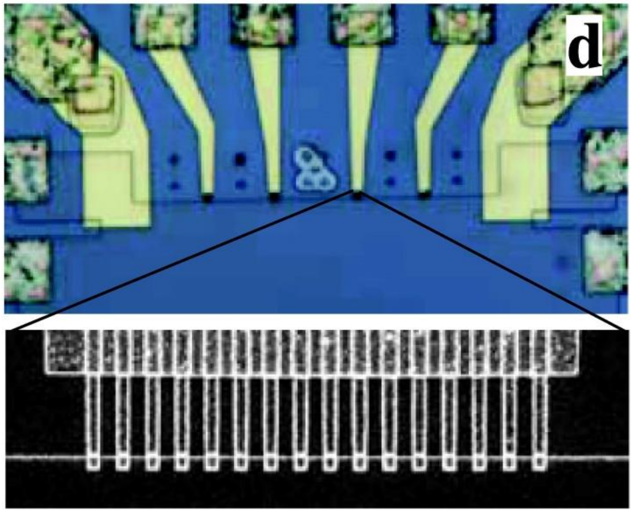
Periodic potential



Controlled coupling with an array of magnetic nanofingers



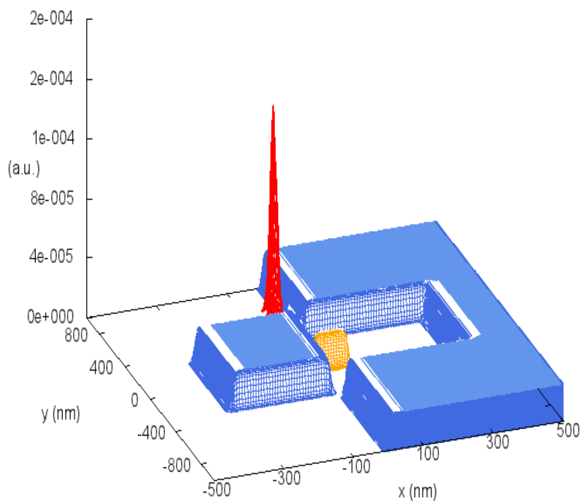
λ = 286 333 400 500 nm



Karmakar, Venturelli, Chirolli, Taddei, Giovannetti, Fazio, Roddaro, Biasiol, Sorba, Pellegrini, Beltram, PRL **107**, 236804 (2011)

Modena: Andrea Bertoni, A. Beggi, P. Bordone

Time-resolved electron dynamics in complex Hall geometries



DONE

- Quantum Hall edge states interferometry with arbitrary integer ff
- Efficient numerical solution with Fourier split-step parallel algorithm
- Effect of split-gate confinement on visibility
- Energy selectivity of QPCs (J. Phys; Cond. Mat. 27, 475301 2015)
- Delocalized scattering states calculation

IN PROGRESS

- Two-particle (two-qubit) simulations with e-e interaction
- Effect of noise on entanglement
- Simulation of quantum teleportation of an electron

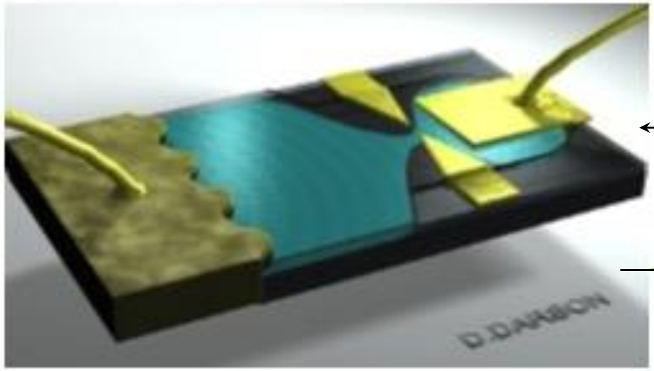
Theoretical validation of universal set of quantum gates

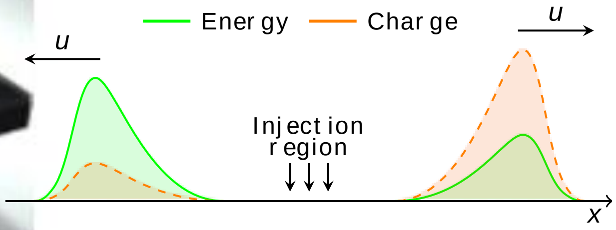
QUBIT (in order of preference):

- Optical path
- Landau level edge number
- Spin

Non equilibrium properties in topological edge states

- Electron quantum optics (mesoscopic capacitors)



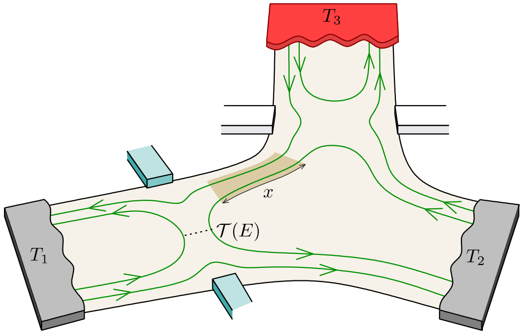


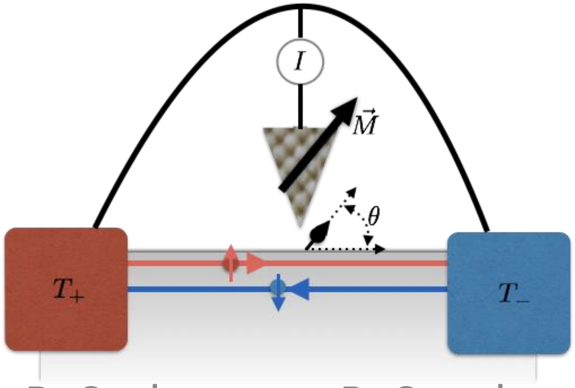
Charge fractionalization and energy partitioning After single electron injection

Collaborations: M.Sassetti, D. Ferraro

Glattli's group

- Interaction induced thermo-electrical effects

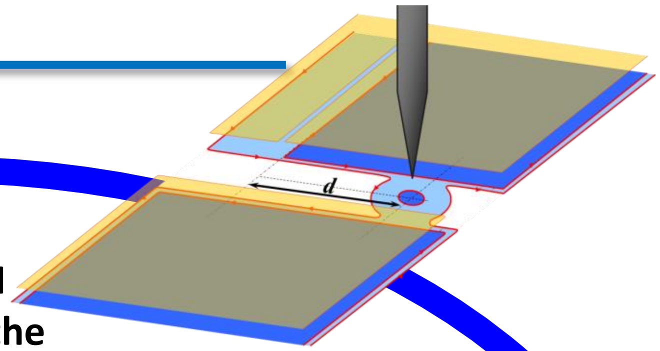




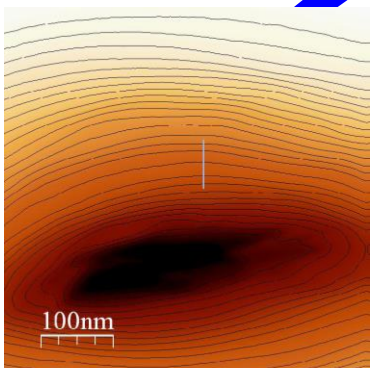
Collaborations: N. Magnoli, I. Levkinsky, B. Sothmann , R. Sanchez

Summary and outlook

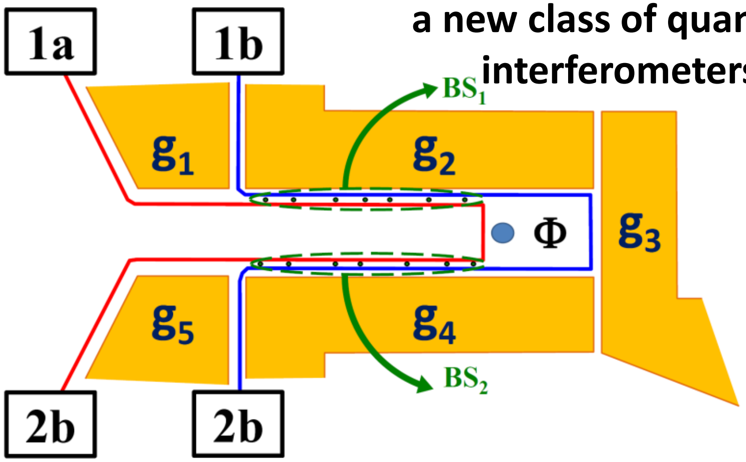
SGM technique in the QH regime



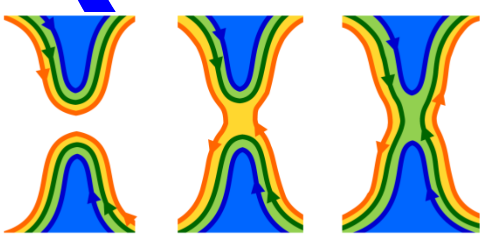
size-tunable QH circuits: study of the channel mixing



Edge channel tomography: imaging of fractional stripes



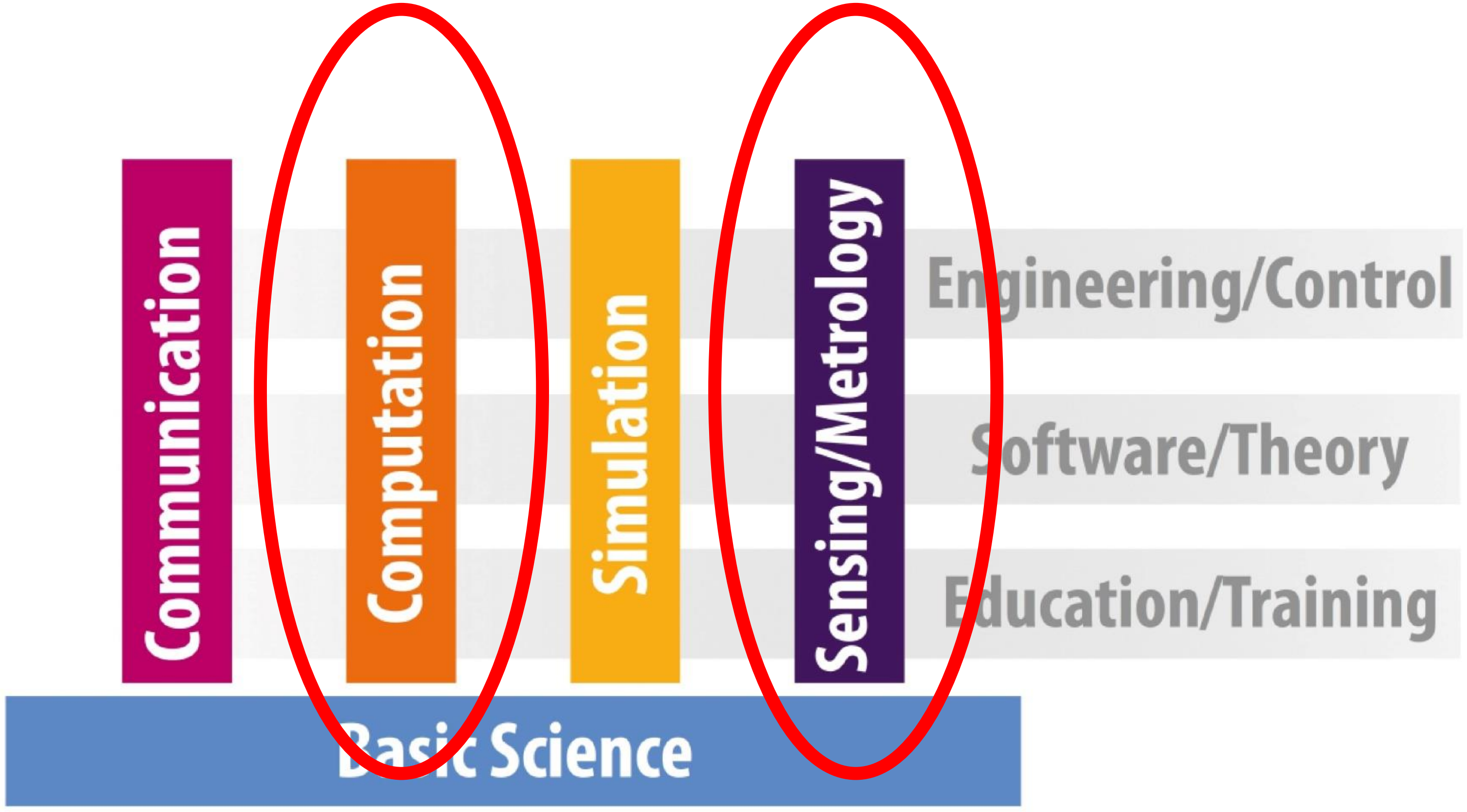
a new class of quantum interferometers



Future directions: Interference of fractional quasi-particles ?

Topological qubits in solid state
Topological quantum states

Quantum Hall effect for Metrology
Resistance standards



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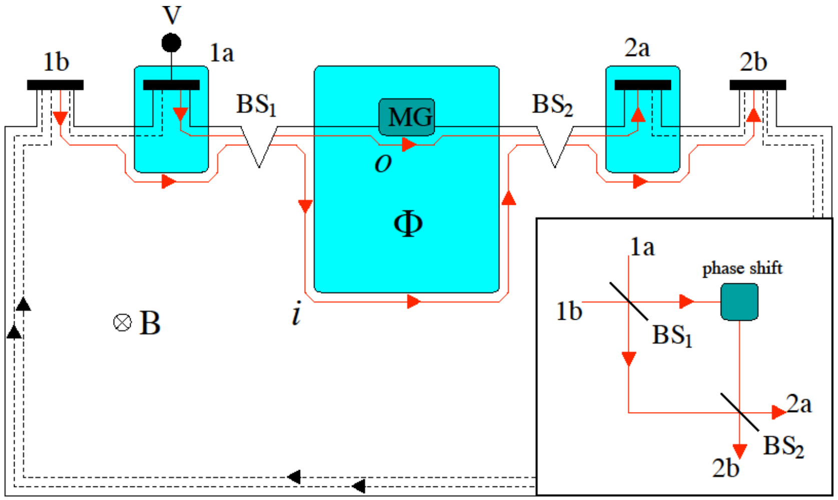
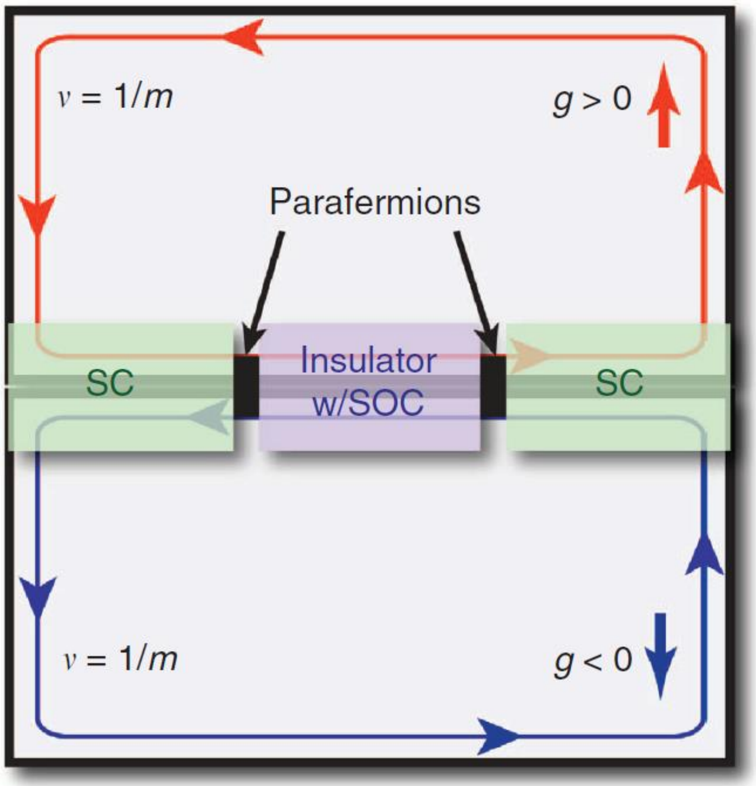
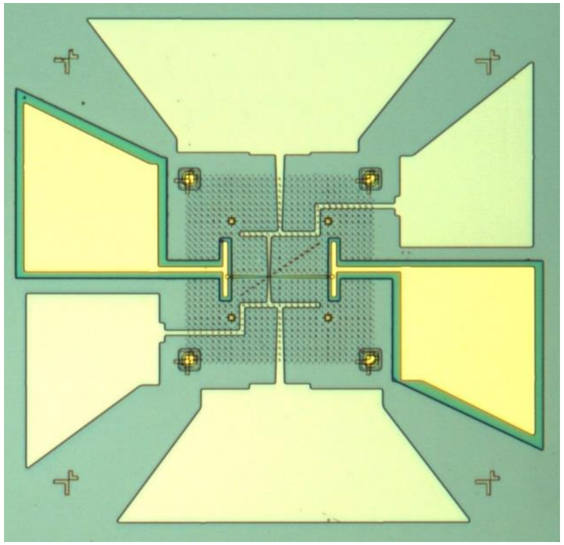
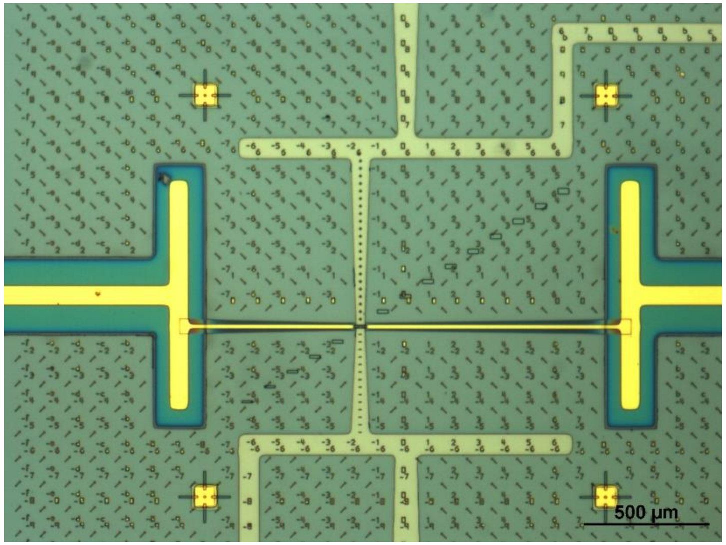


- Hybrid SNS Josephson Junctions in the QH



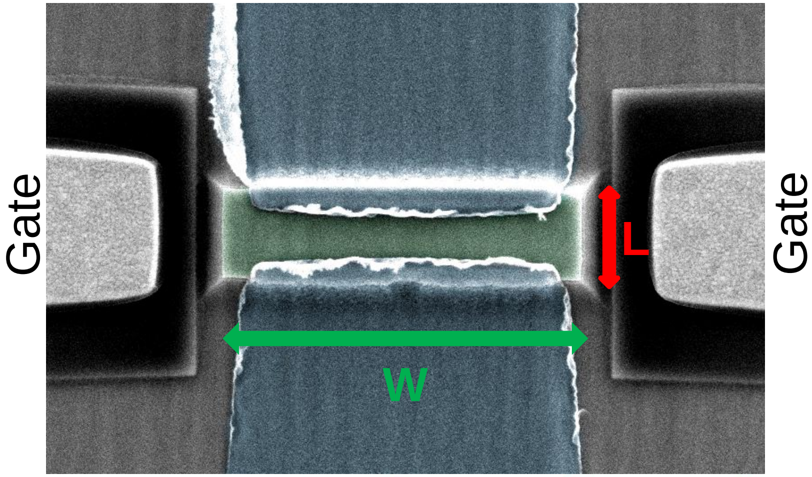
SNS Josephson junctions





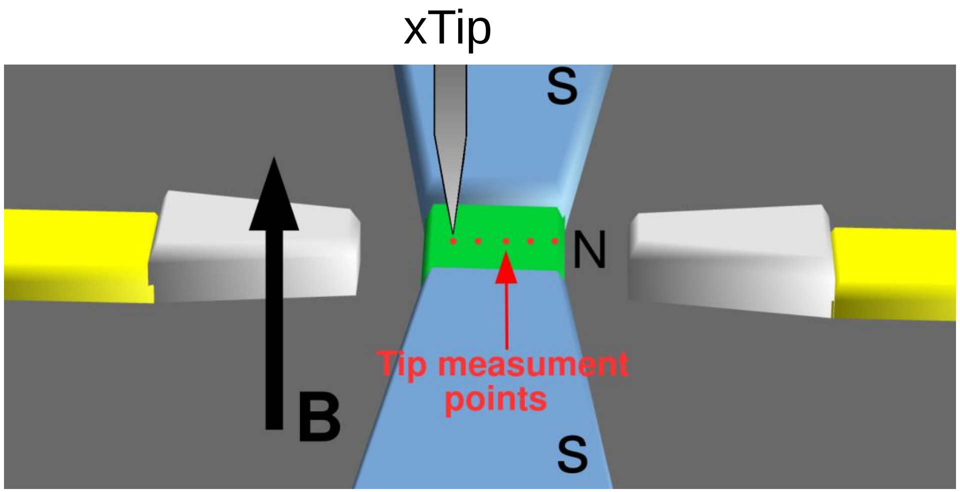
S. Guiducci, Master Thesis, NEST Pisa

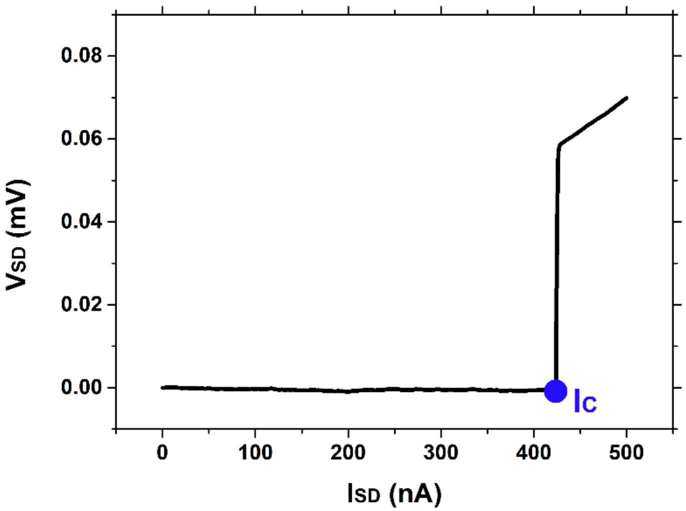
Vedi anche M. Amado et al.,
Phys. Rev. B 87, 134506 (2013).

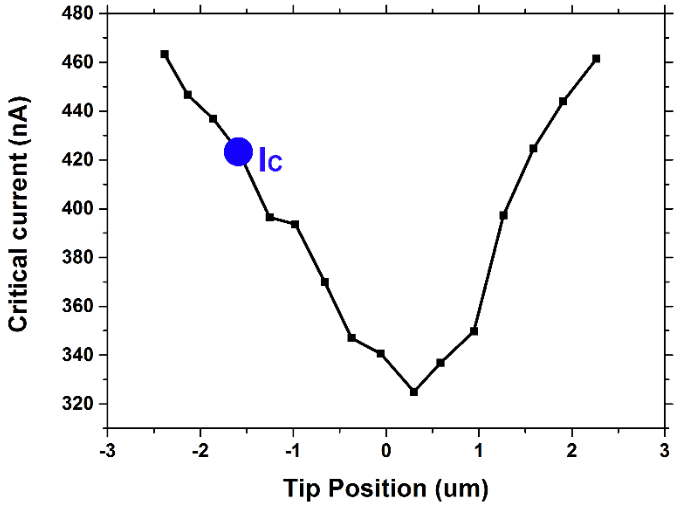


National Enterprise for nanoScience and nanoTechnology
NEST

Local Spectroscopy (B = 0)







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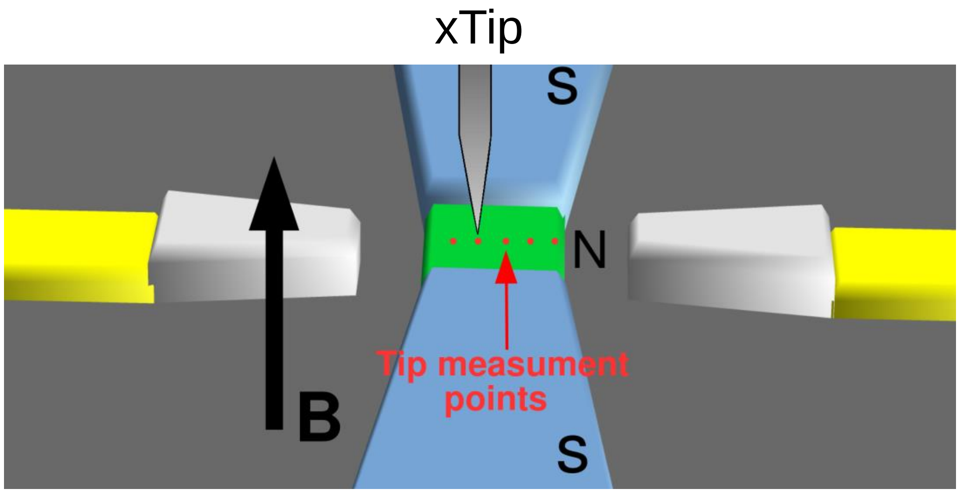

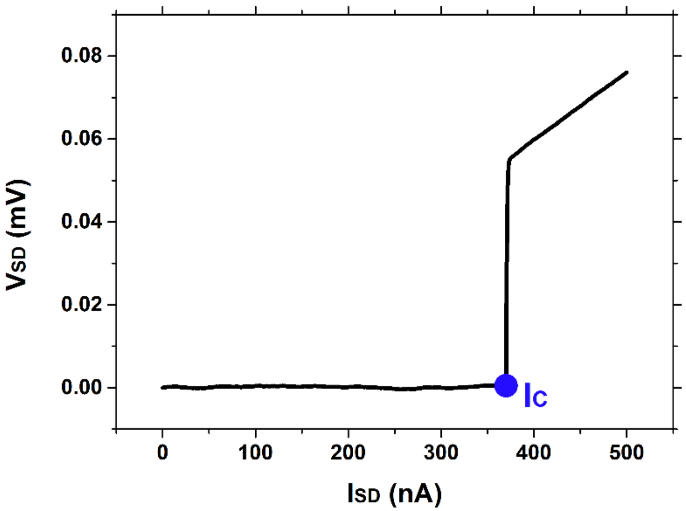

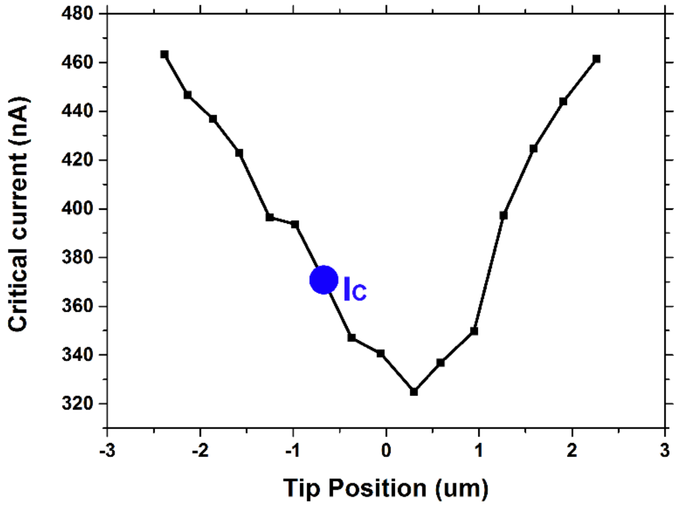

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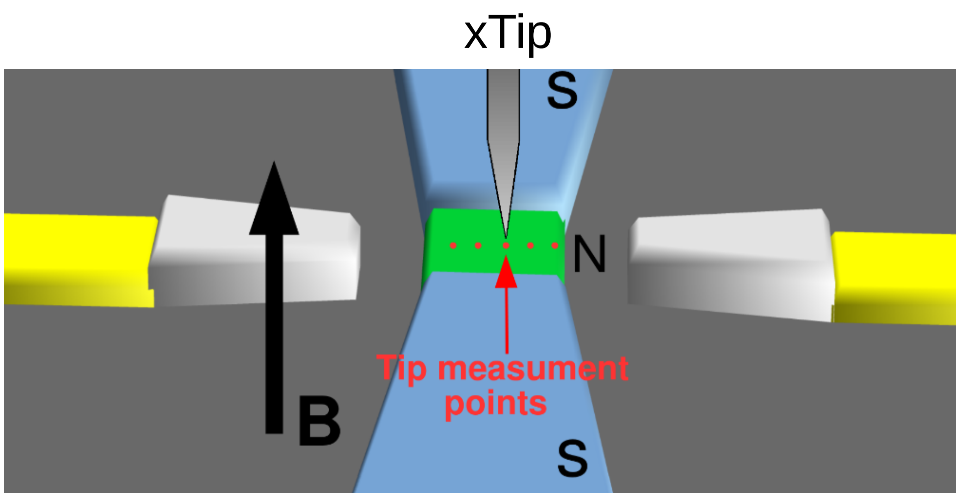

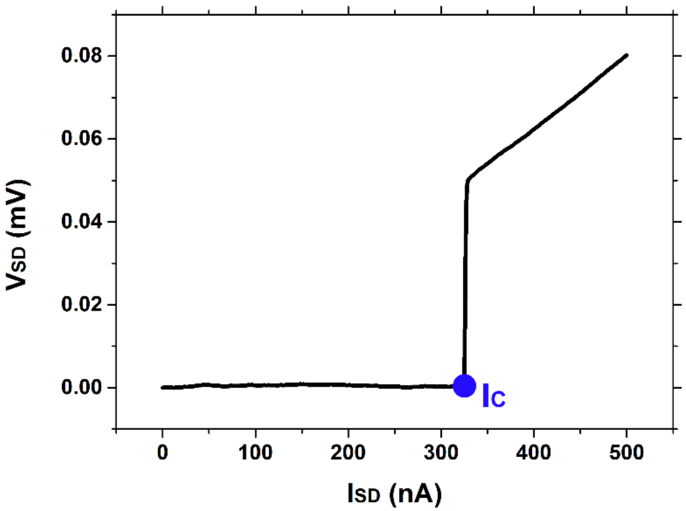

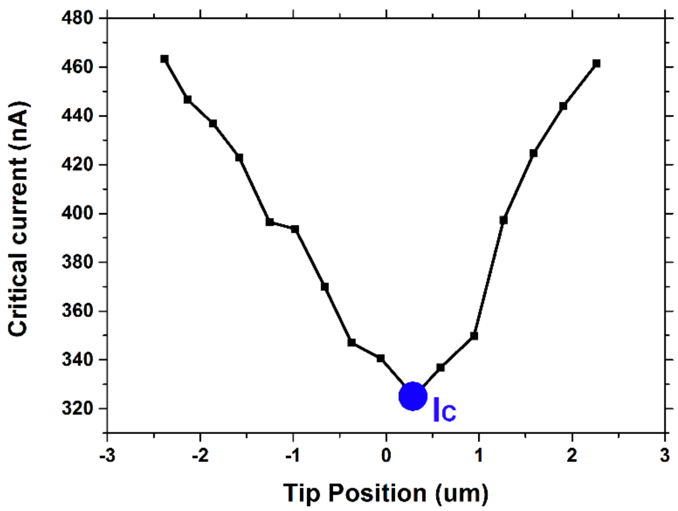

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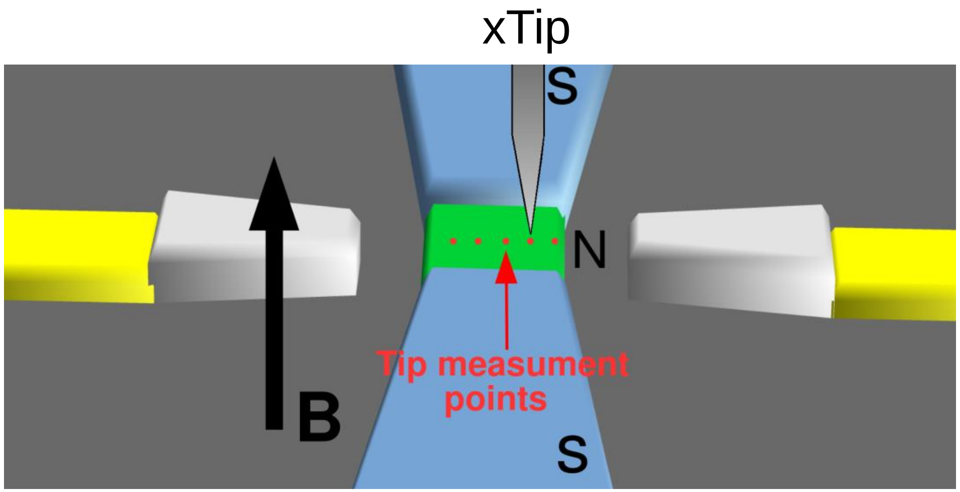

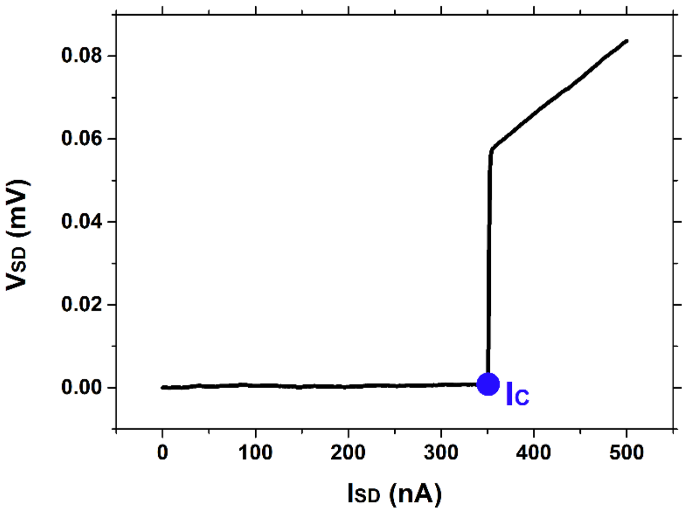

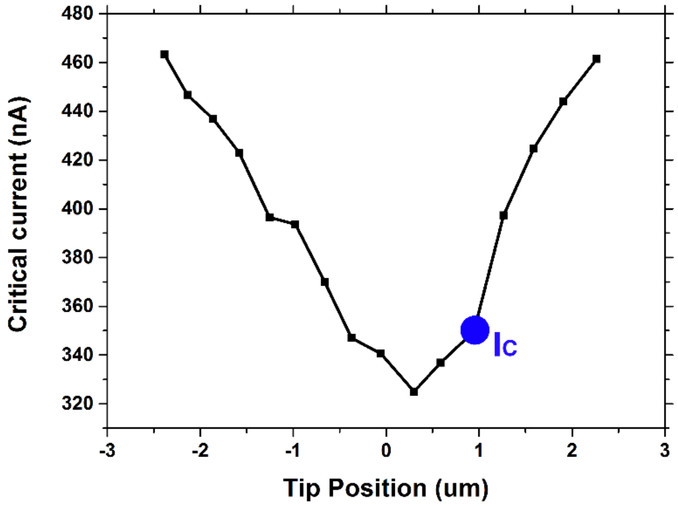

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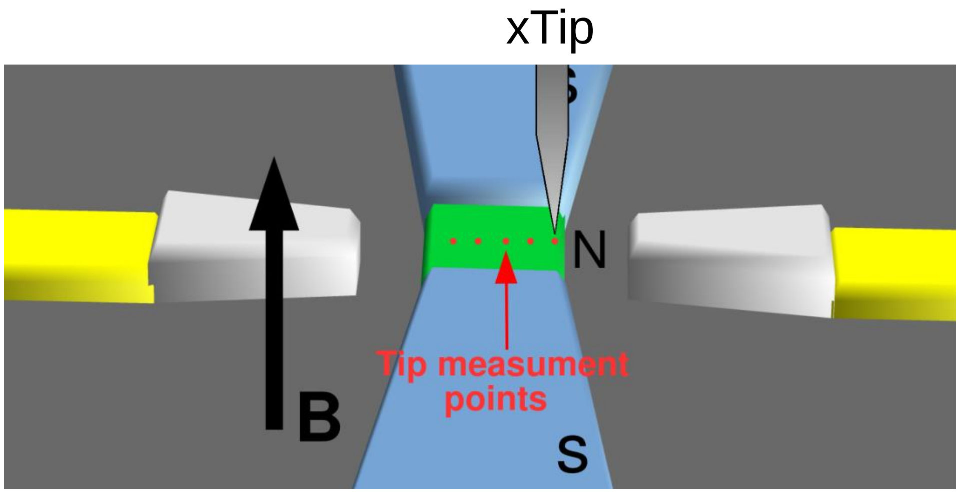

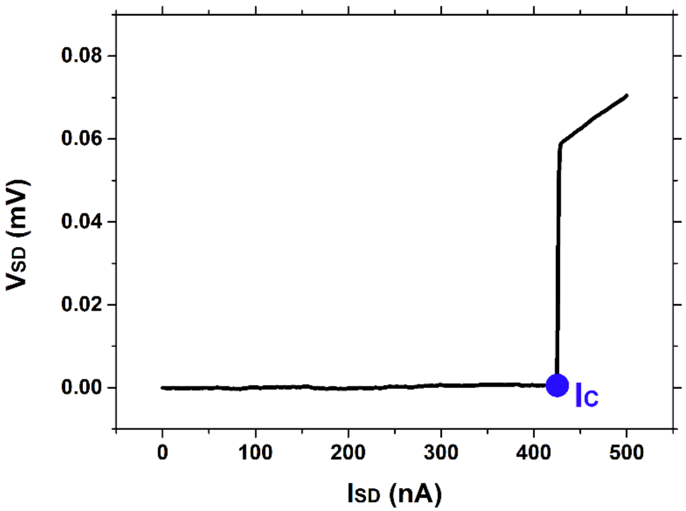

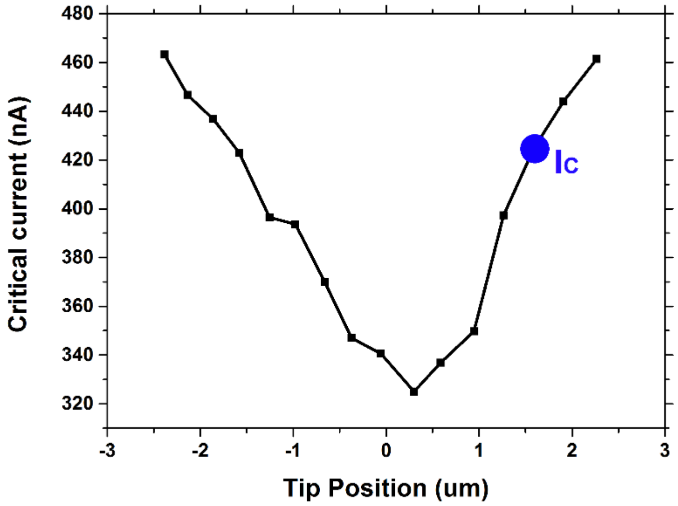

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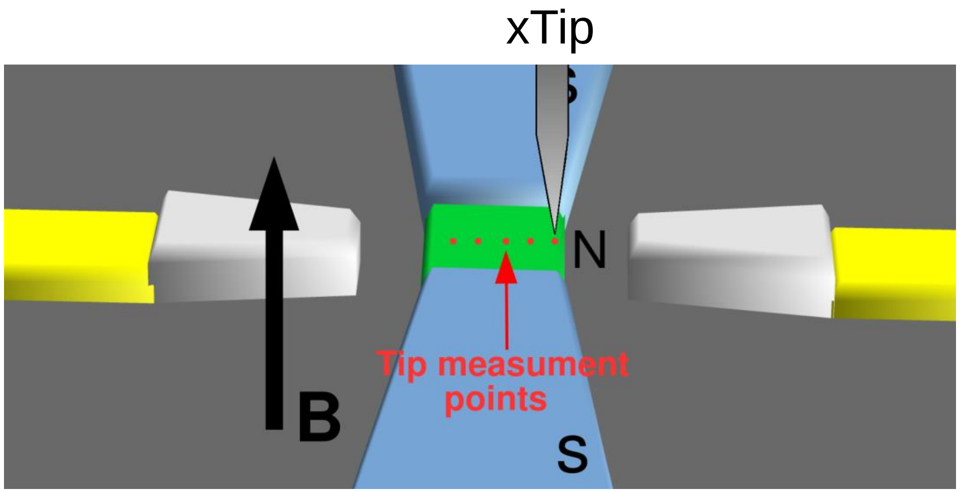
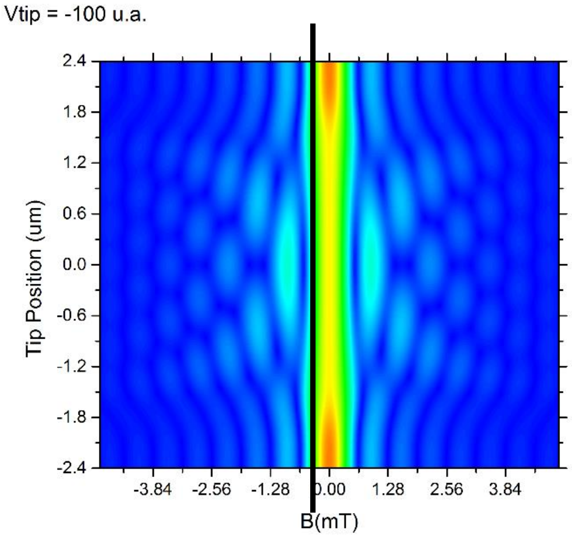
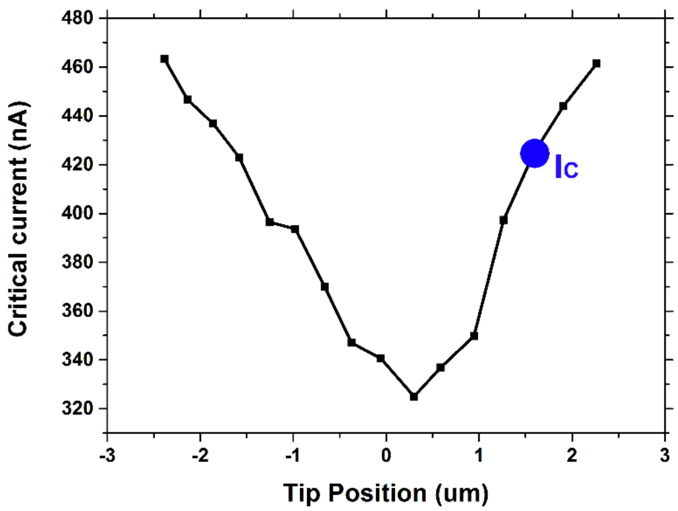
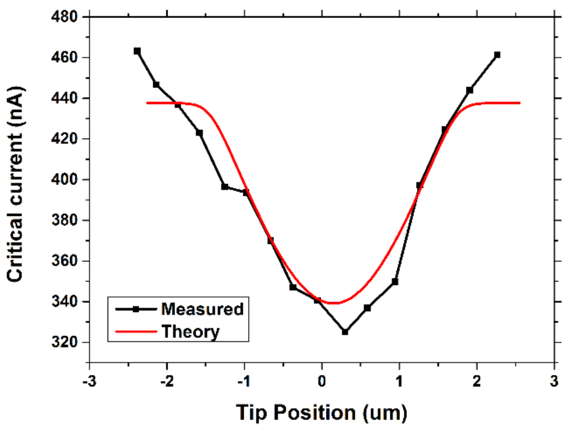


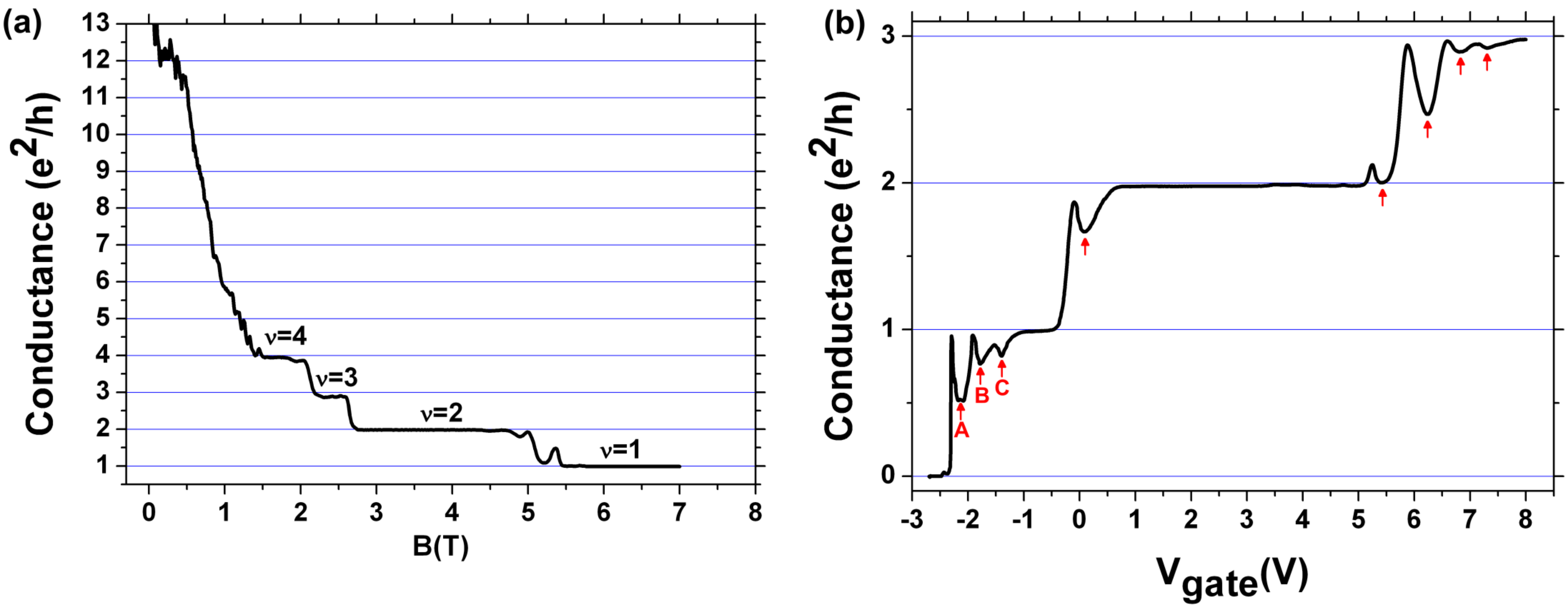






The next step

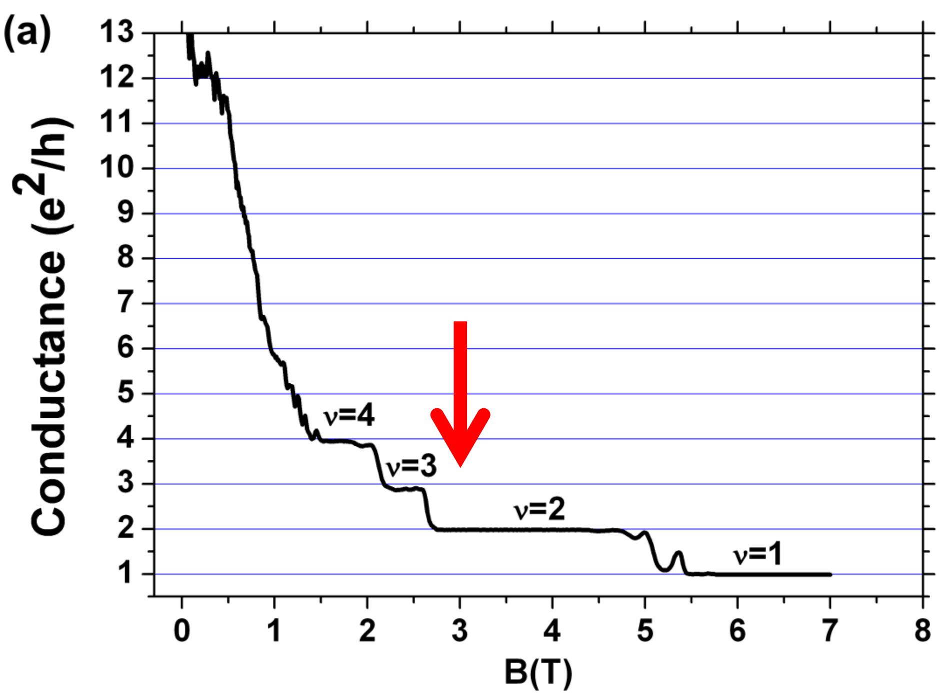
- Investigations of JJs in the QH regime

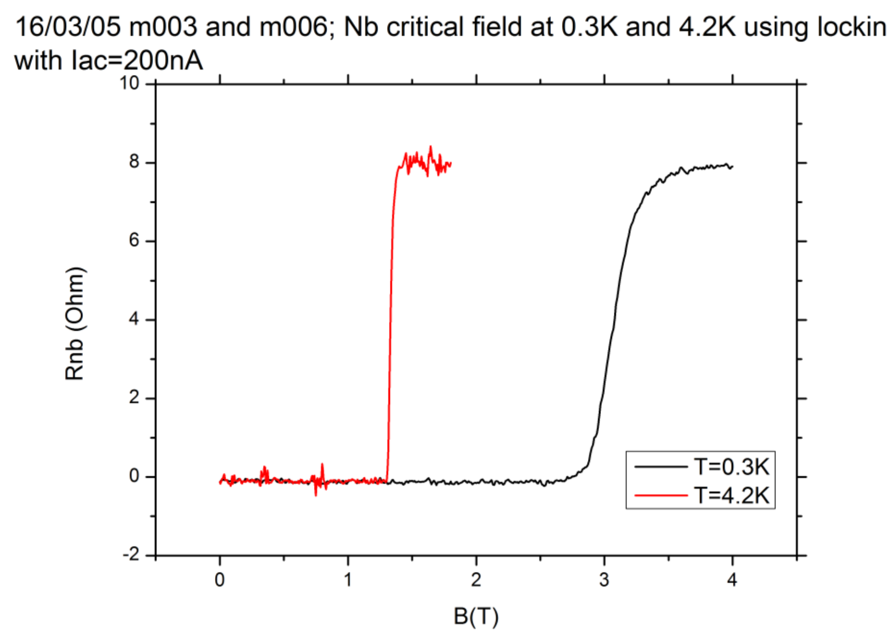


S. Guiducci, Master thesis

The next step

- Investigations of JJs in the QH regime





S. Guiducci, Master thesis

The next step

- Investigations of JJs in the QH regime
- QuantERA proposal

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Exotic non-Abelian anyons from conventional fractional quantum Hall states

David J. Clarke[1,2], Jason Alicea[1,2] & Kirill Shtengel[3,4,5]

Non-Abelian anyons—particles whose exchange noncommutatively transforms a system's quantum state—are widely sought for the exotic fundamental physics they harbour and for quantum computing applications. Numerous blueprints now exist for stabilizing the simplest type of non-Abelian anyon, defects binding Majorana modes, by interfacing widely available materials. Here we introduce a device fabricated from conventional fractional quantum Hall states and *s*-wave superconductors that supports exotic non-Abelian defects binding parafermionic zero modes, which generalize Majorana bound states. We show that these new modes can be experimentally identified (and distinguished from Majoranas) using Josephson measurements. We also provide a practical recipe for braiding parafermionic zero modes and show that they give rise to non-Abelian statistics. Interestingly, braiding in our setup produces a richer set of topologically protected operations when compared with the Majorana case. As a byproduct, we establish a new, experimentally realistic Majorana platform in weakly spin-orbit-coupled materials such as gallium arsenide.

The next step

- Investigations of JJs in the QH regime
- QuantERA proposal: *Parafermions in hybrid superconductor-quantum Hall systems for topological quantum computation*

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Target Outcomes

Funded projects are expected to address one or more of the following areas:

1. Quantum communication

Methods/tools/strategies to deal with the issues of distance, reliability, efficiency, robustness and security in quantum communication; novel protocols for multipartite quantum communication; quantum memory and quantum repeater concepts.

Novel photonic sources for quantum information and quantum communication, coherent transduction of quantum states between different physical systems; integrated quantum photonics; quantum communication embedded in optical telecommunications systems; other communication protocols with functionality enhanced by quantum effects.

2. Quantum simulation

4. Quantum information sciences

Novel sources of non-classical states and methods to engineer such states. Development of device-independent quantum information processing. Methods for the reconstruction and estimation of complex quantum states or channels and certification of their properties. Development of resource theory for quantum information. Study of topological systems for quantum information purposes. Understanding and control of open quantum systems, development of methods to confine dynamics in controllable decoherence-free subspaces. Study of thermodynamics processes at the quantum scale.

5. Quantum metrology sensing and imaging

Use of quantum properties for time and frequency standards, light-based calibration and measurement, gravimetry, magnetometry, accelerometry, and other applications. Development of detection schemes that are optimised with respect to extracting relevant information from physical systems; novel solutions for quantum imaging and ranging. Implementation of micro- and nano-quantum sensors, for instance for quantum limited sensitivity in the measurement of magnetic fields at the nanoscale. Extension of the reach of quantum sensing and metrology to other fields of science including e.g. the prospects of offering new medical diagnostic tools.

6. Novel ideas and applications in quantum science and technologies

Quantum phenomena, such as superposition and entanglement, as means to achieve new or radically enhanced functionalities.