CNR-NANO (PISA)
NEST Laboratory
Scuola Normale Superiore

# *INVESTIGATION OF InAs-BASED DEVICES FOR TOPOLOGICAL APPLICATIONS*

Dr. Matteo Carrega

# Outline

- Topological states of matter
- Anyons in condensed matter
- Suspended InAs nanowire
- Coexistence of Quantum Hall and superconductivity
- New tunable JJ geometry

# Topological states

NEWS IN FOCUS

PHYSICS

**Nobel for 2D exotic matter**

*Physics award goes to theorists who used topology to explain strange phenomena.*

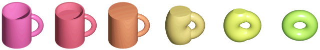
BY ELIZABETH GIBNEY AND DAVIDE CASTELVECCHI

David Thouless, Duncan Haldane and Michael Kosterlitz have won the 2016 Nobel Prize in Physics for their theoretical explanations of strange states of matter in 2D materials, known as topological phases.

The British-born trio's work in the 1970s and 1980s laid the foundations for predicting and explaining bizarre behaviours that experimentalists discovered at the surfaces of materials, and inside extremely thin layers. These include superconductivity — the ability to conduct without resistance — and magnetism in very thin materials. At the time, these mathematical theories were quite abstract, said Haldane in an

Physics prizewinners Michael Kosterlitz (left), David Thouless (centre) and Duncan Haldane (right).

Topology in condensed matter **NOBEL 2016**

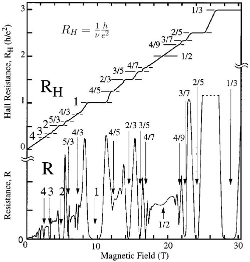


**Intrinsic robustness $\leftrightarrow$ Topological protection**

# Quantum Hall effect

Von Klitzing'80, Laughlin'83, Tsui'99

$$R_H = \frac{V_H}{I} = \frac{h}{\nu e^2}$$




Fractional charge and statistics

Büttiker'88, Stern'08

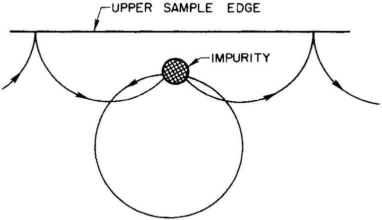
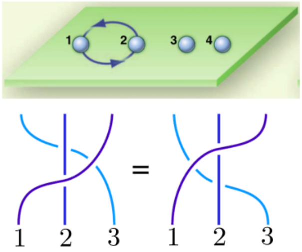


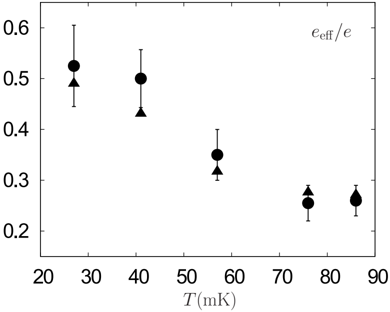

FIG. 4. Quasiclassical skipping orbits along the upper edge of the sample in presence of a localized impurity. In a high magnetic field backscattering over distances large compared to the cyclotron radius is suppressed.

- **first topological state of matter**
- chiral edge states

# Anyons in FQHE

Exotic filling factors $\nu = \frac{5}{2}$




Non abelian anyons with effective charge $e/4$

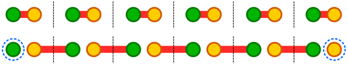
chiral Majorana modes on the edge

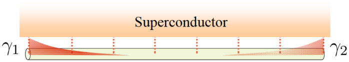
Stern'08, Dolev'10, Carrega et al., PRL'11

# Kitaev chain

Majorana modes in condensed matter

$$H = \sum_x \left[ -\mu c_x^\dagger c_x - \frac{1}{2} \left( T c_x^\dagger c_{x+1} + \Delta c_x c_{x+1} + \mathrm{H.c.} \right) \right],$$



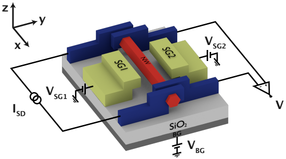


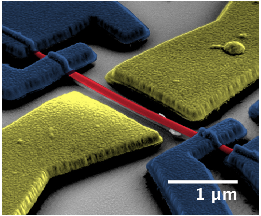

Smoking gun evidence still lacking

Kitaev'01, Lutchin'10, Alicea'14, Stanescu'18, Woods'19

# InAs nanowire

## Quantum transport in suspended *InAs* nanowire




### Geometry

- $L = 2\mu$ m
- $L_{SG} = 1\mu$ m
- $w = 90$ nm
- $h = 100$ nm

### Transport parameters

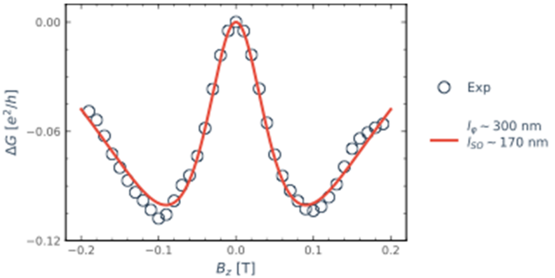
- mobility $\sim 1200$ cm$^2$/(Vs)
- $n \sim 2 \cdot 10^{18}$ cm$^{-3}$
- $v_{\mathrm{F}} \sim 2 \cdot 10^6$ m/s
- $l_{\mathrm{mfp}} \sim 30$ nm

A. Iorio et al., nanoletters 19, 2 652 2018

# Transport measurements

Low temperature $\sim$ 10 mK transport measurements

- Weak Anti-localization $\rightarrow$ spin-orbit length

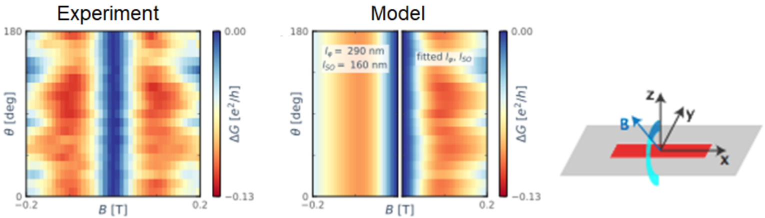



$$\Delta G(B) \propto -\frac{2e^2}{hL}\Big[\frac{3}{2}\Big(\frac{1}{l_\phi^2}+\frac{4}{3l_{SO}^2}+\frac{1}{l_B^2}\Big)^{-1/2}-\frac{1}{2}\Big(\frac{1}{l_\phi^2}+\frac{1}{l_B^2}\Big)^{-1/2}\Big]$$

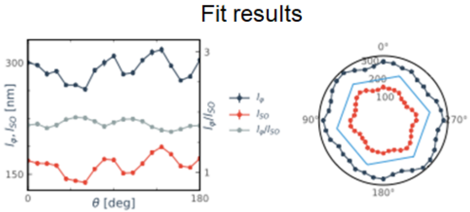
$$l_B = \frac{\hbar}{eBw}$$ Bergman'84

A. Iorio et al., nanoletters 19, 2 652 2018

# Spin-orbit interactions



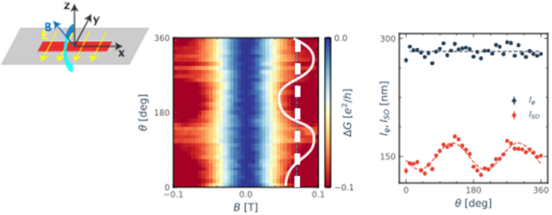

Polar map in a vectorial $B$-field



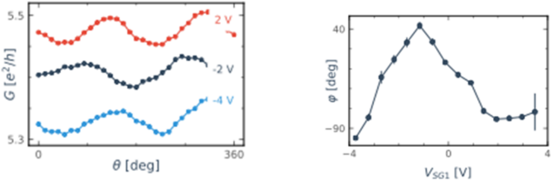

Strong correlations between $l_\phi$ and $l_{SO}$

A. Iorio et al., nanoletters 19, 2 652 2018

# Tuning Rashba coupling




Vector evolution of the spin-orbit coupling




Manipulating Rashba coupling with asymmetric gating

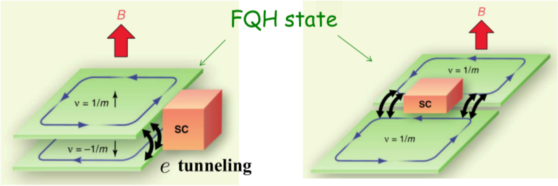
A. Iorio et al., nanoletters 19, 2 652 2018

# Quantum Hall/Superconductor

other platforms hosting anyons with non-trivial braiding

$$\gamma_x \gamma_{x'} = \gamma_{x'} \gamma_x e^{i \frac{2\pi}{N} \mathrm{sgn}(x'-x)}$$

$N = 2$ Majorana modes $\qquad$ $N > 2$ Parafermions



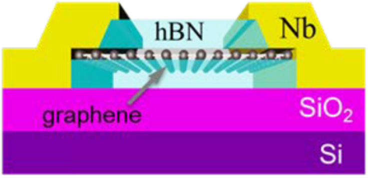

integer/fractional quantum Hall with superconducting proximity effect!

Alicea'12, Lindner'12, Alicea'15, Schmidt'19

# QH/SC experiment

Coexistence of superconductivity and quantum Hall regime

- Superconductors with high critical field $B_C$
- quantum Hall plateau at relatively low $B$ field

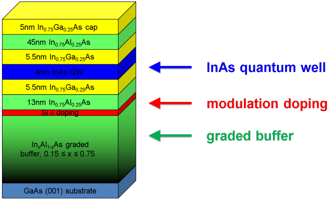


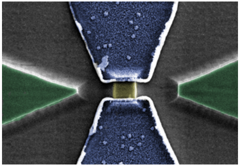

JJ supercurrent mediated by QH edge states

Ben Shalom'16, Lee'16, Amet'17, Wu'18

# Hybrid 2DEG/SC

## Josephson junction with *InAs* quantum well and *Nb* contacts



$n_{2D} = 6.2 \cdot 10^{11}$ cm$^{-2}$ $\qquad \mu = 1.6 \cdot 10^{5}$ cm$^{2}$/(V s)

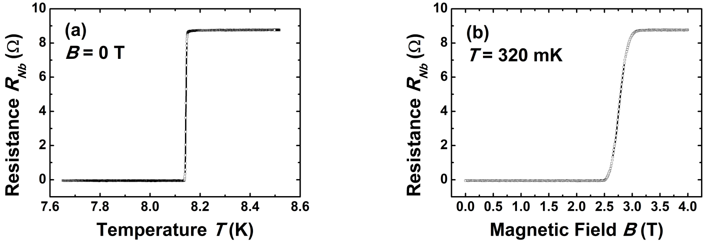
$l_{MFP} = 2.16$ $\mu$m

Hybrid 2DEG JJ with patterned side gates

Guiducci et al., PSS (RRL) 1800222 2018

# Superconductivity

critical temperature $T_C = 8.1$ K $\rightarrow$ $\Delta_{Nb} = 1.235$ meV
critical field $B_C = 2.77$ T at $T = 320$ mK




coherence length $\xi_0 = \frac{\hbar v_F}{\pi \Delta_{Nb}} = 230$ nm $< l \sim 1\mu$m

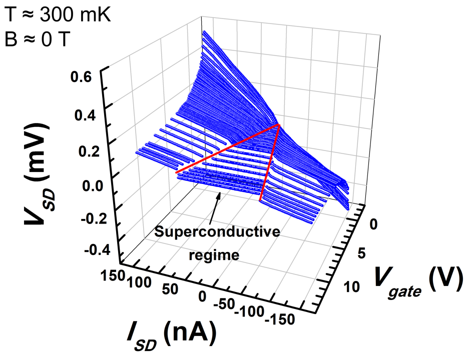
clean and ballistic regime $\xi_0 < l < l_{MFP}$

Guiducci et al., PSS(RRL) 1800222 2018

## Josephson supercurrent

supercurrent flow monitored by $V_{SD}(I_{SD})$

Typical hysteretic behaviour of Josephson device $\rightarrow$ $I_C = 170$ nA




Manipulation of $I_C$ and $R_n$ by changing $2D$ electron density

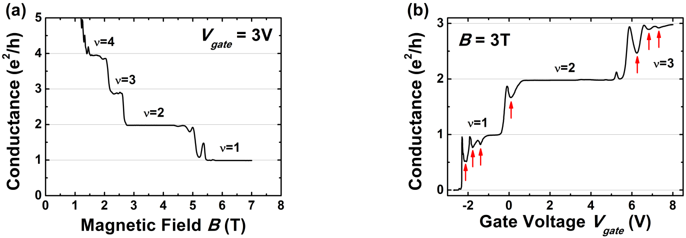
Side gates make it a **Jo-FET**

Guiducci et al., PSS(RRL) 1800222 2018

# Quantum Hall regime

Quantum Hall plateau develop at $B \geq 1.5$ T

Filling factor $\nu = 2$ at $B = 3$ T and $V_{gate} = 3$ V

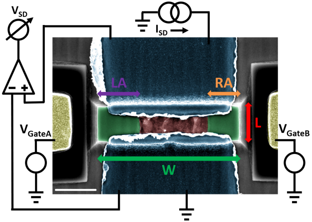


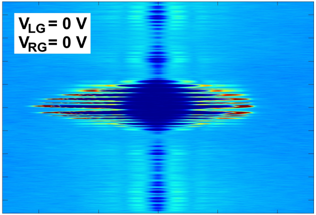

Side gates control channel width and carrier density

Guiducci et al., PSS(RRL) 1800222 2018

# New hybrid device

Hybrid Josephson junction with removed central region



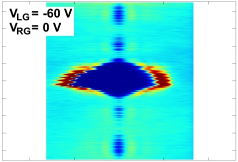

Supercurrent with fast and slow oscillations

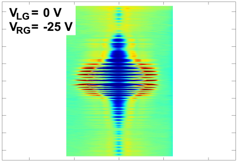
Fast oscillations caused by the hole (with no gate dependence)

Guiducci et al., PRB 99, 235419 2019

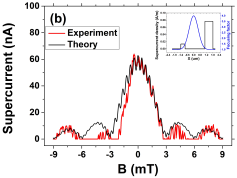
# Tuning quantum interference

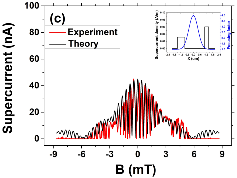
asymmetric gating → independent tuning of $I_c$ in each arm




From Fraunhofer pattern to SQuID behaviour



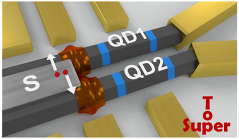

Extended JJ $\Delta B_{fast} = 0.34$ mT $\Delta B_{slow} = 2.9$ mT

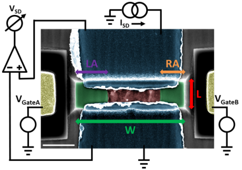
→ effective width of the arms and supercurrent densities

Guiducci et al., PRB 99, 235419 2019

# Conclusions and outlook

- New topological states of matter
- Investigation of InAs nanowires
- Coexistence of quantum Hall and superconducting correlations
- New hybrid superconductor/semiconductor geometry




S. Guiducci et al., **Towards quantum Hall effect in a Josephson junction** (2018);
A. Iorio et al., **Vectorial control of the spin-orbit interaction in suspended InAs nanowires** (2018);
S. Guiducci et al., **Full electrostatic control of quantum interference in an extended trenched JJ** (2019).

# Collaborations

- **Quant-ERA Project EU (SUPERTOP):** S. Csonka, C. Schonenberger, A. Baumgartner, J. Nygard, A. Geresdi, M. Wimmer, T. Contos;
- **CNR-NANO:** S. Guiducci, A. Iorio, E. Strambini, A. Braggio, F. Giazotto, L. Sorba, F. Beltram, S. Heun;
- **UniGE:** A. Calzona, F. Ronetti, D.Ferraro, M. Sassetti;
- **UniPI:** S. Roddaro, D. Rossini;
- **CNR-IOM:** G. Biasiol;
- **Univ. Grenoble, CNRS:** H. Courtois.

QUANTERA
ERA-NET Cofund in Quantum Technologies