Ballistic edge states in Bismuth nanowires revealed by SQUID interferometry

Anil Murani, Alik Kasumov, Shamashis Sengupta, François Brisset, Raphaelle Delagrange, Alexei Chepelianski, Richard Deblock, Sophie Guéron, Hélène Bouchiat

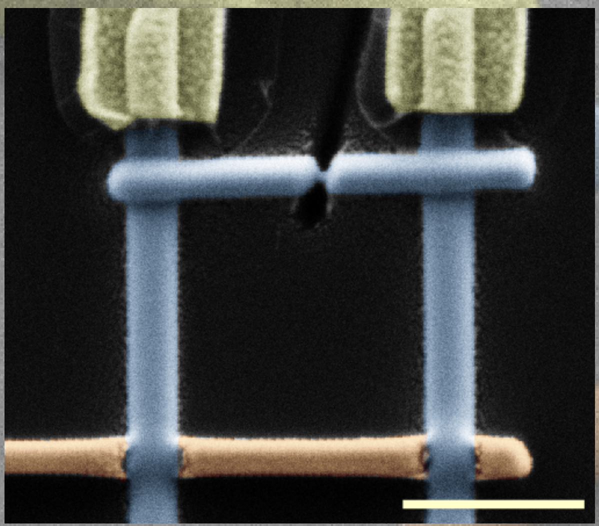
UNIVERSITÉ PARIS SUD

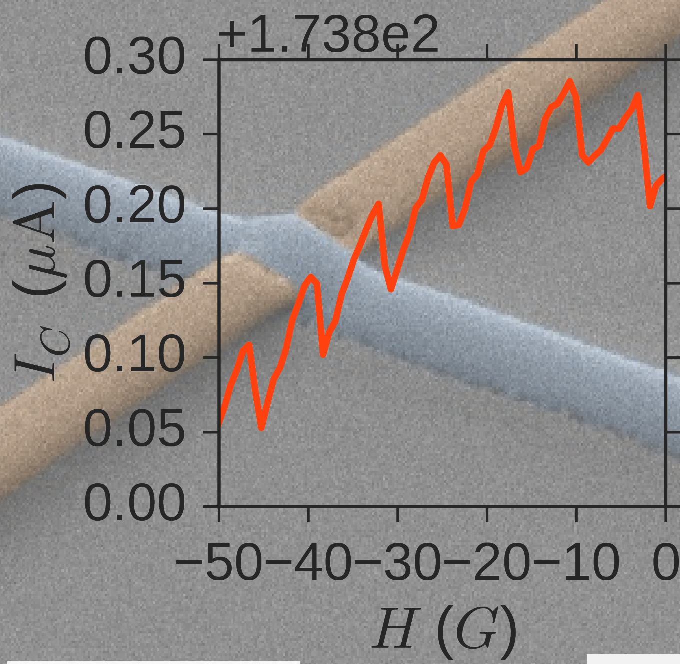
université PARIS-SACLAY

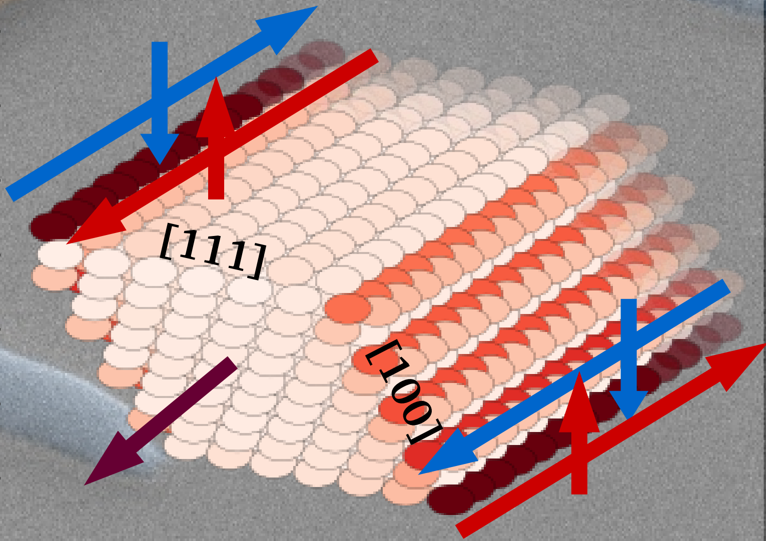
Laboratoire de Physique des Solides, Paris-Saclay University, France

cnrs dépasser les frontières

Arxiv 1609.04848







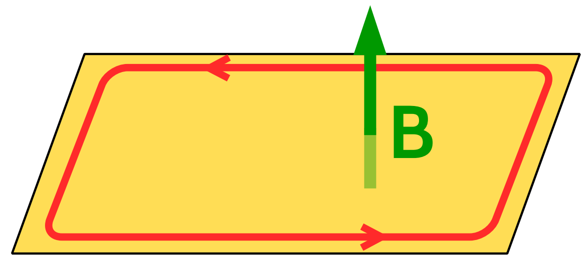
LPS ORSAY

CSNSM

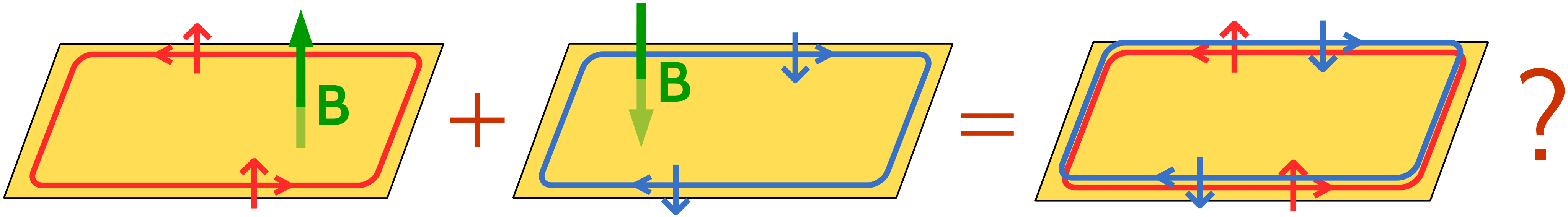
ICMMO

Topological edge states

(Integer) Quantum Hall Effect



Without breaking time reversal symmetry ?



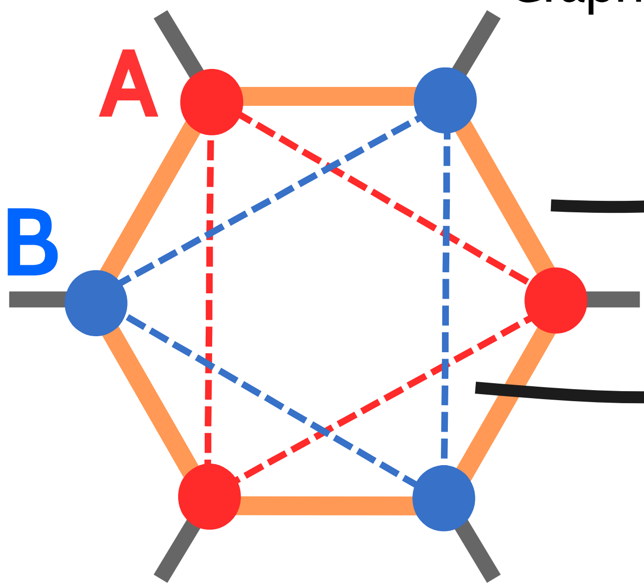
$\mathscr{H} \propto \mathbf{k}\cdot\boldsymbol{\sigma},\ \ \mathbf{k}\times\boldsymbol{\sigma}$ Spin-orbit coupling term

Quantum Spin Hall Effect

How to realize it in practice ?

Practical implementation

Graphene + intrinsic spin-orbit coupling

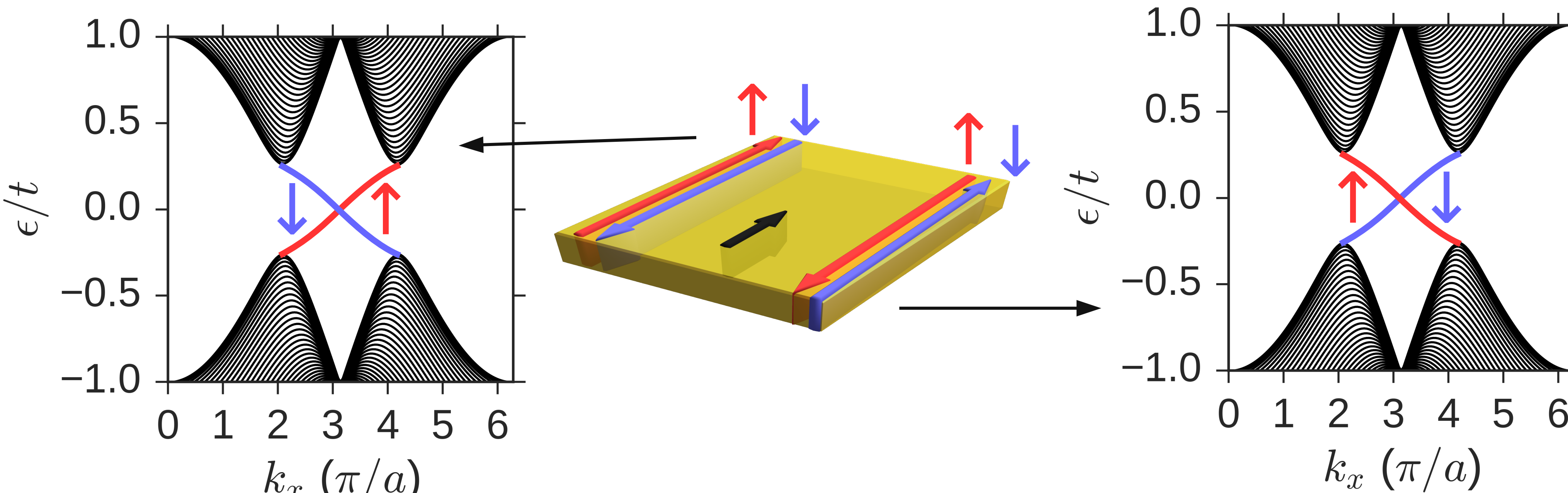


$$\mathscr{H} = t \sum_{\langle i,j \rangle \alpha} c^{\dagger}_{i,\alpha} c_{j,\alpha}$$ Hopping term

$$+ \; i t_2 \sum_{\langle\langle i,j \rangle\rangle \alpha\beta} c^{\dagger}_{i,\alpha} \nu_{ij} s^{z}_{\alpha\beta} c_{j,\alpha}$$ Intrinsic spin-orbit coupling

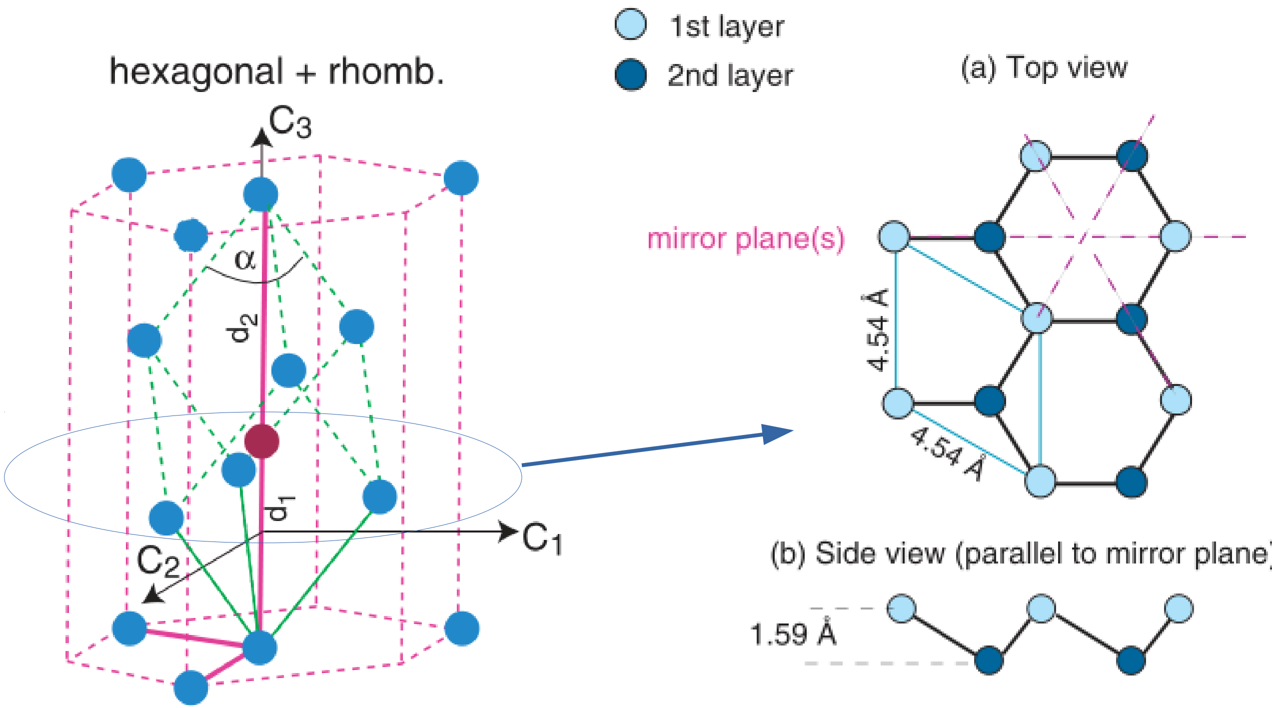
Kane & Mele, **PRL**, 2004

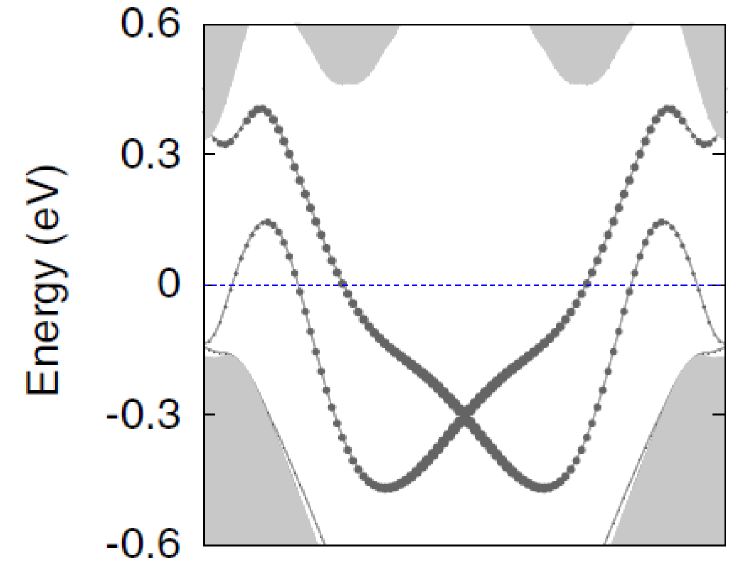
$t_2 > 0$



Look for strong intrinsic SOC : __**heavy materials**__

Bismuth (111)

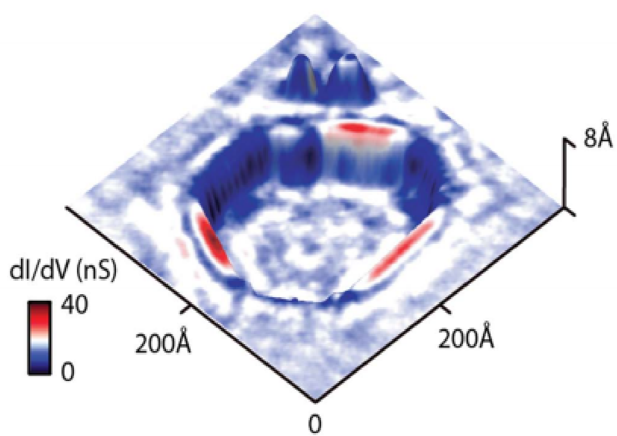


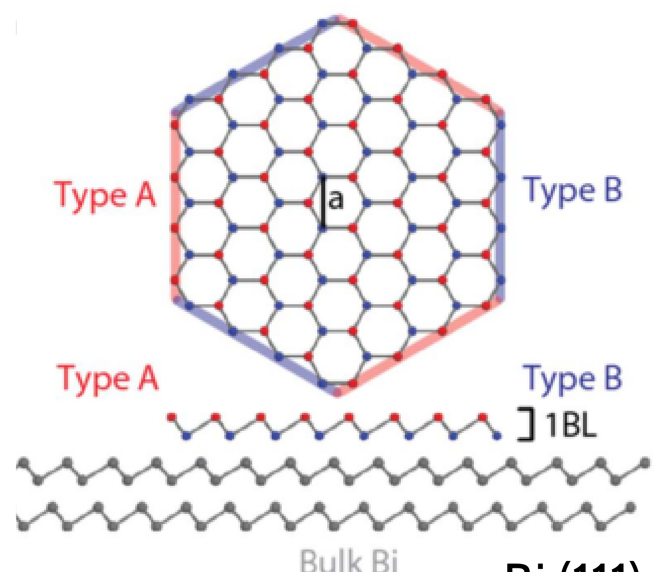


Murakami, **PRL**, 2006
Liu & Allen, 1991

Experiments

STM



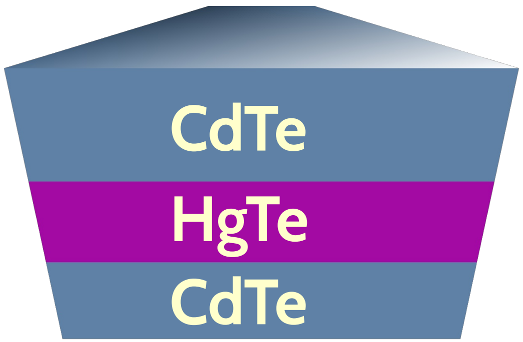


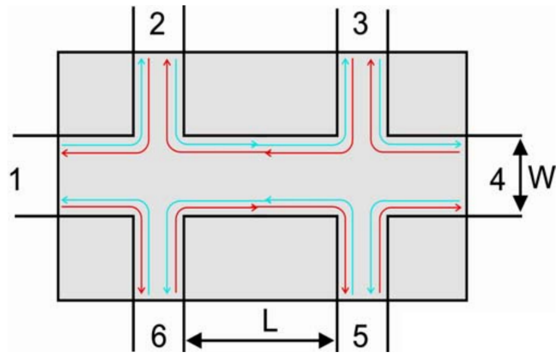
Drozdov *et al*, **Nat.Phys.**, 2012

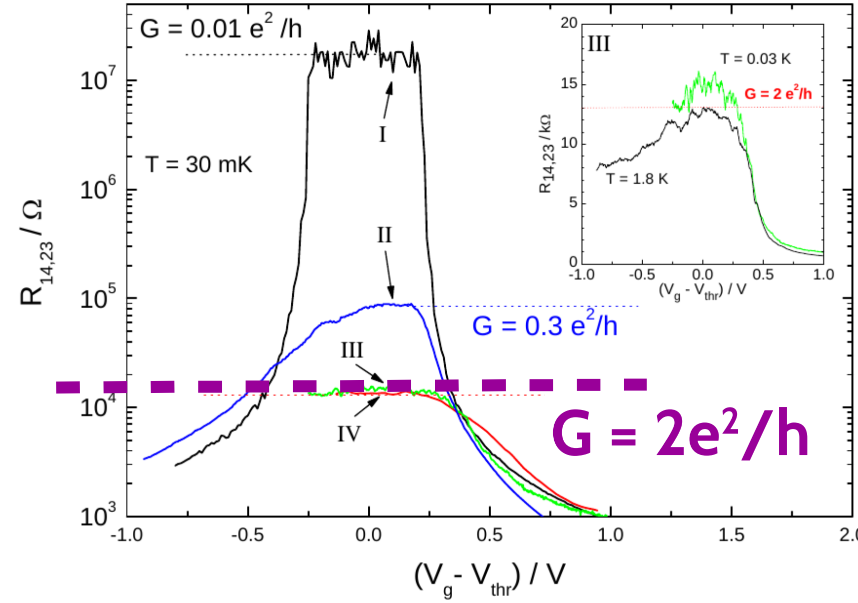
Bi (111) has 1D edge states !

Consequence for transport

1°) Quantized conductance

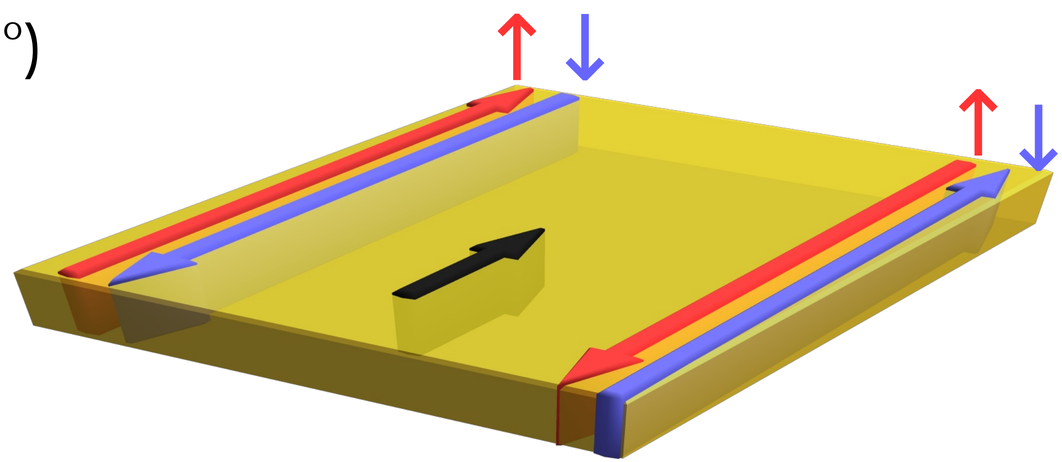






Konig et al, **Science**, 2007

2°)



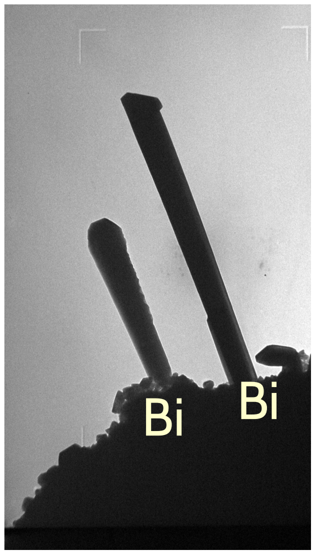
Flip velocity ⇒ Flip spin

Absence of retrodiffusion

Goal : prove that these 1D channels are ballistic !

Bismuth nanowires

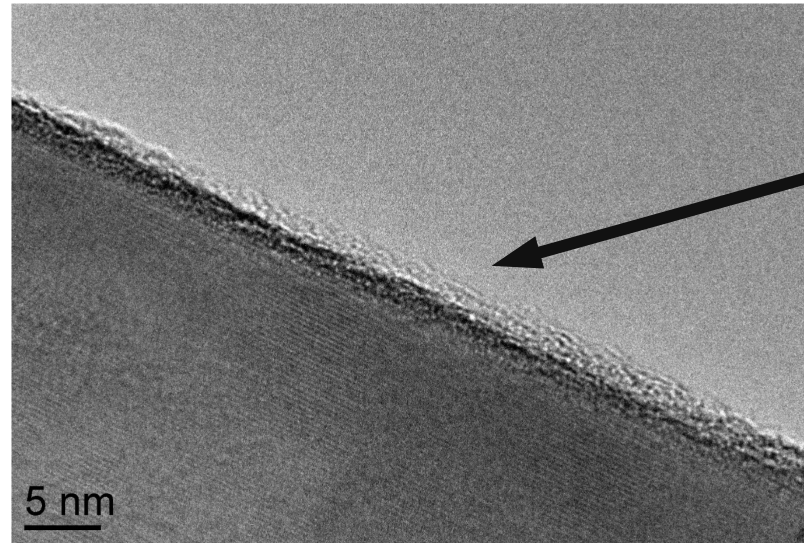
Growth : Sputtering on a hot surface



Alik Kasumov

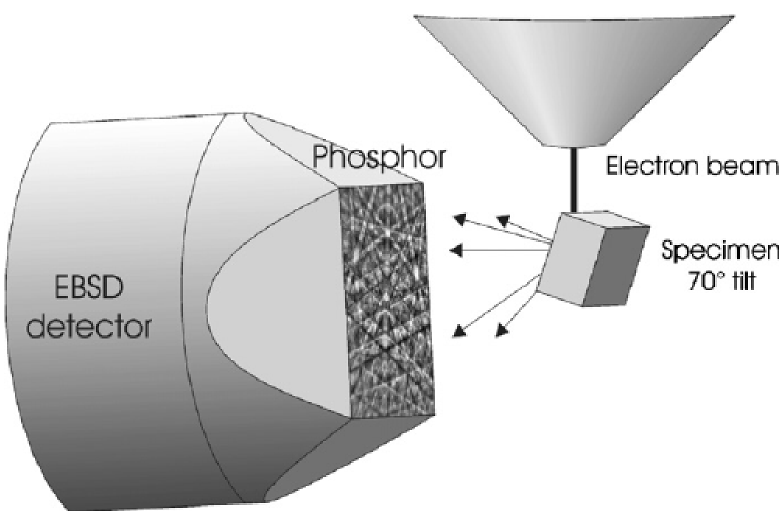
High quality
single crystals
$\varnothing \sim 100\,\mathrm{nm}$

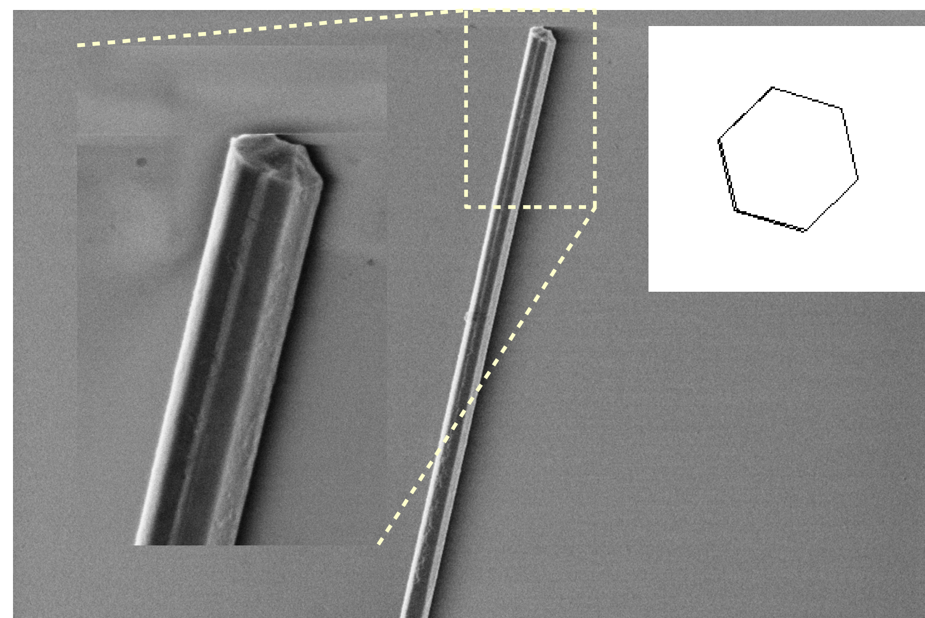
High resolution TEM



Thin layer
of oxyde

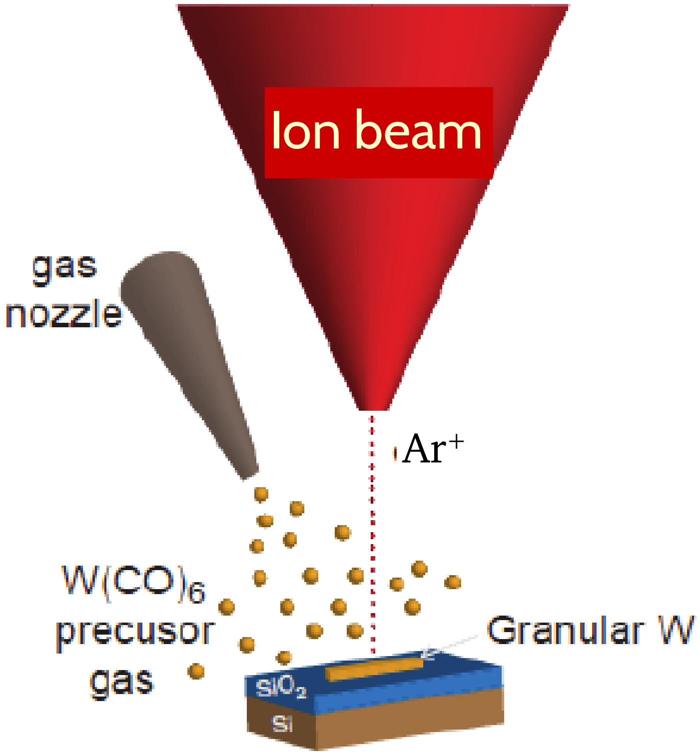
EBSD (François Brisset, ICCMO)





Selection of nanowires with 111 top surface

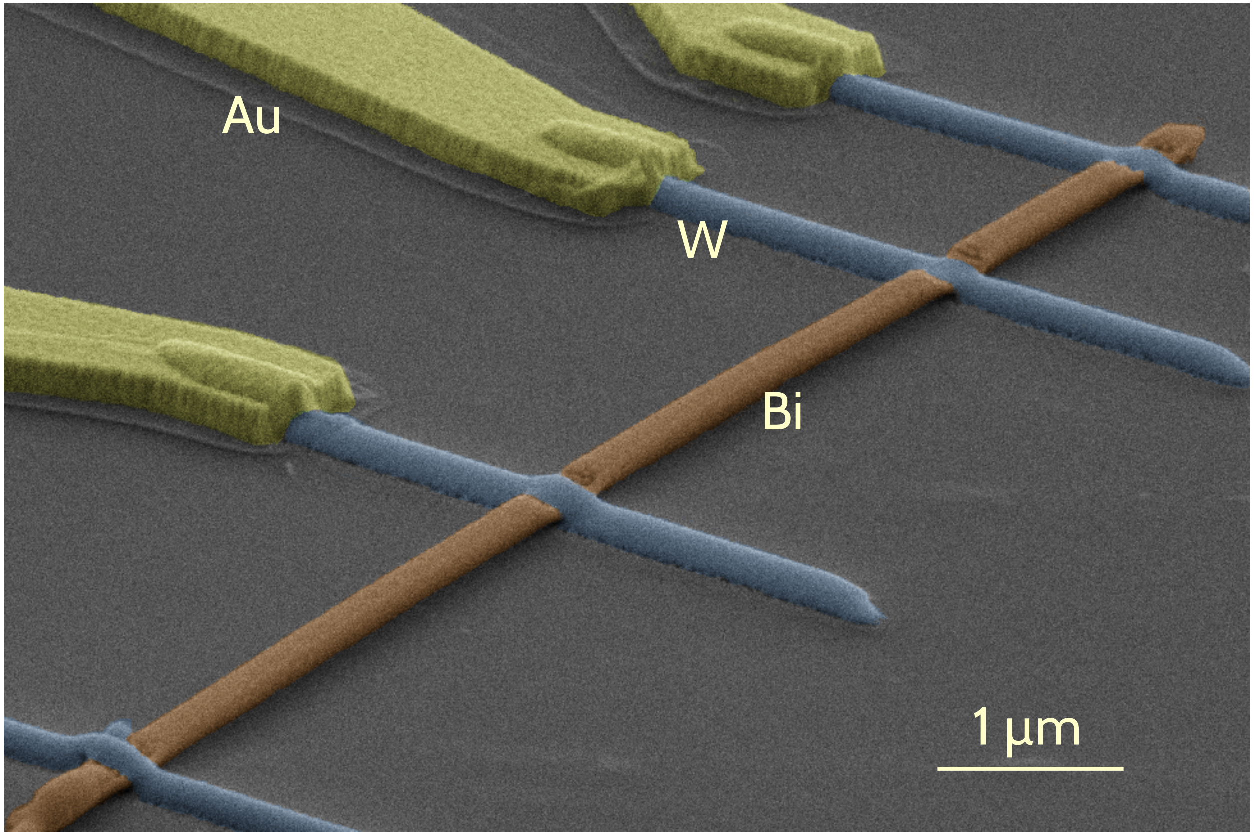
Connection to superconducting electrodes



Kasumov et al., **PRB**, 2005

Tungsten
using Focused Ion Beam (FIB)

Hc = 9.5 T
Tc = 5.5 K

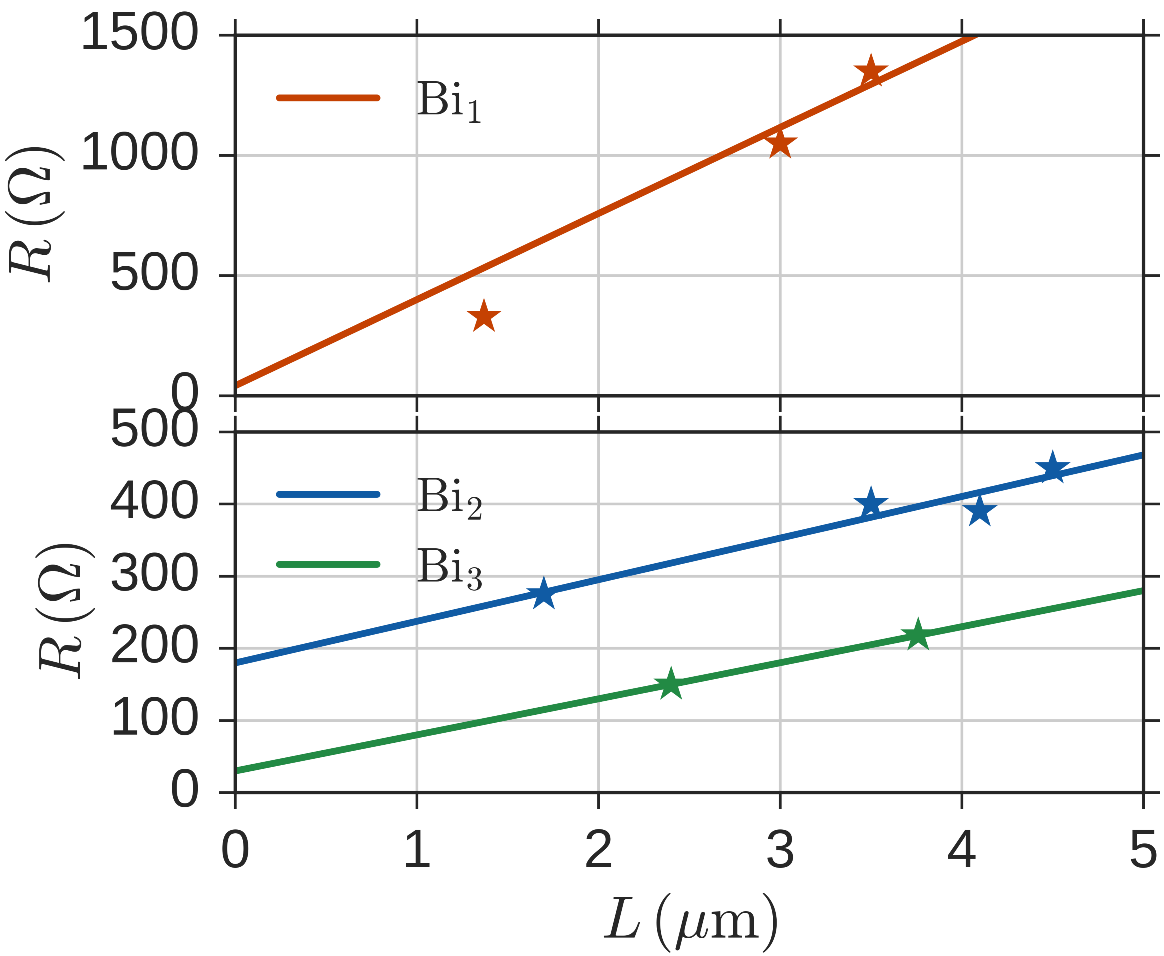


Surface states dominated transport

Bulk $\lambda_F \simeq 50\,\mathrm{nm}$

Surface $\lambda_F \simeq 5\,\mathrm{nm}$

$10-100\times$ more surface states than bulk states



$$R(L) = R_c + \frac{R_Q}{M}\frac{L}{l_e}$$

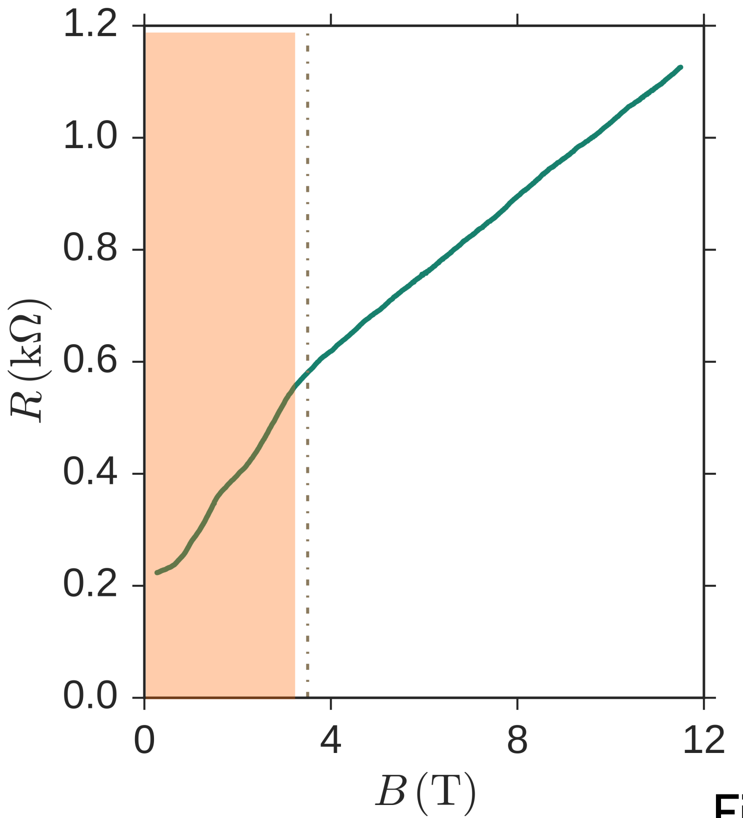
Thus $l_e \lesssim 200\,\mathrm{nm}$

Diffusive surface states

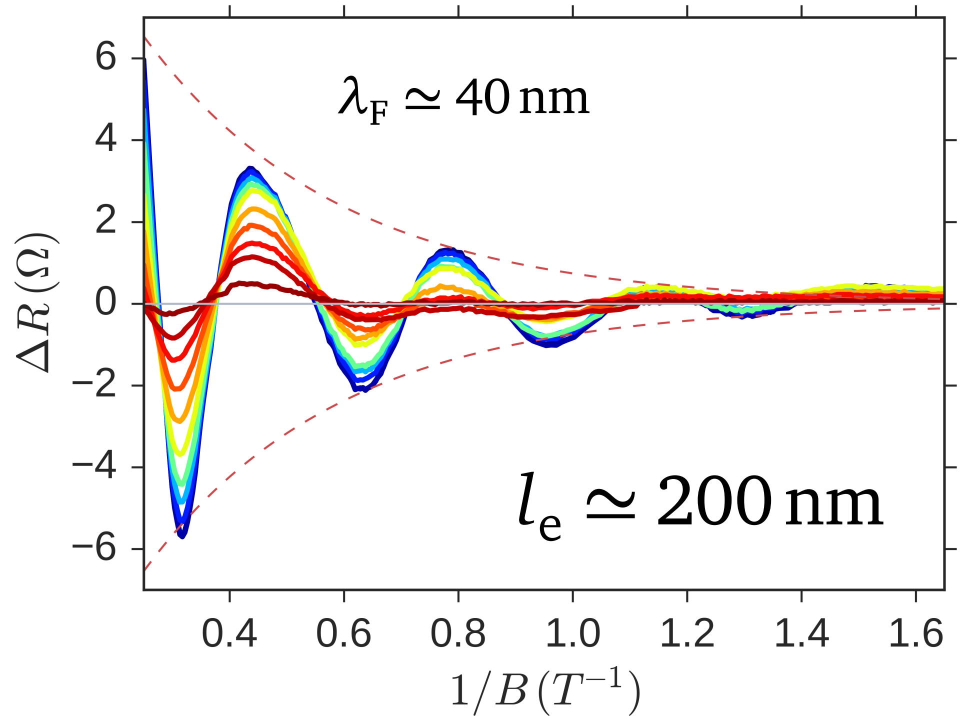
Normal state : magnetotransport

There can be few bulk states $\lambda_F \simeq 50\,\mathrm{nm}$ → For nanowire <200 nm wide $M \simeq 0-10$ modes

Magnetoresistance at 4.2 K



Shubnikov de Haas oscillations



Finite size limited diffusion

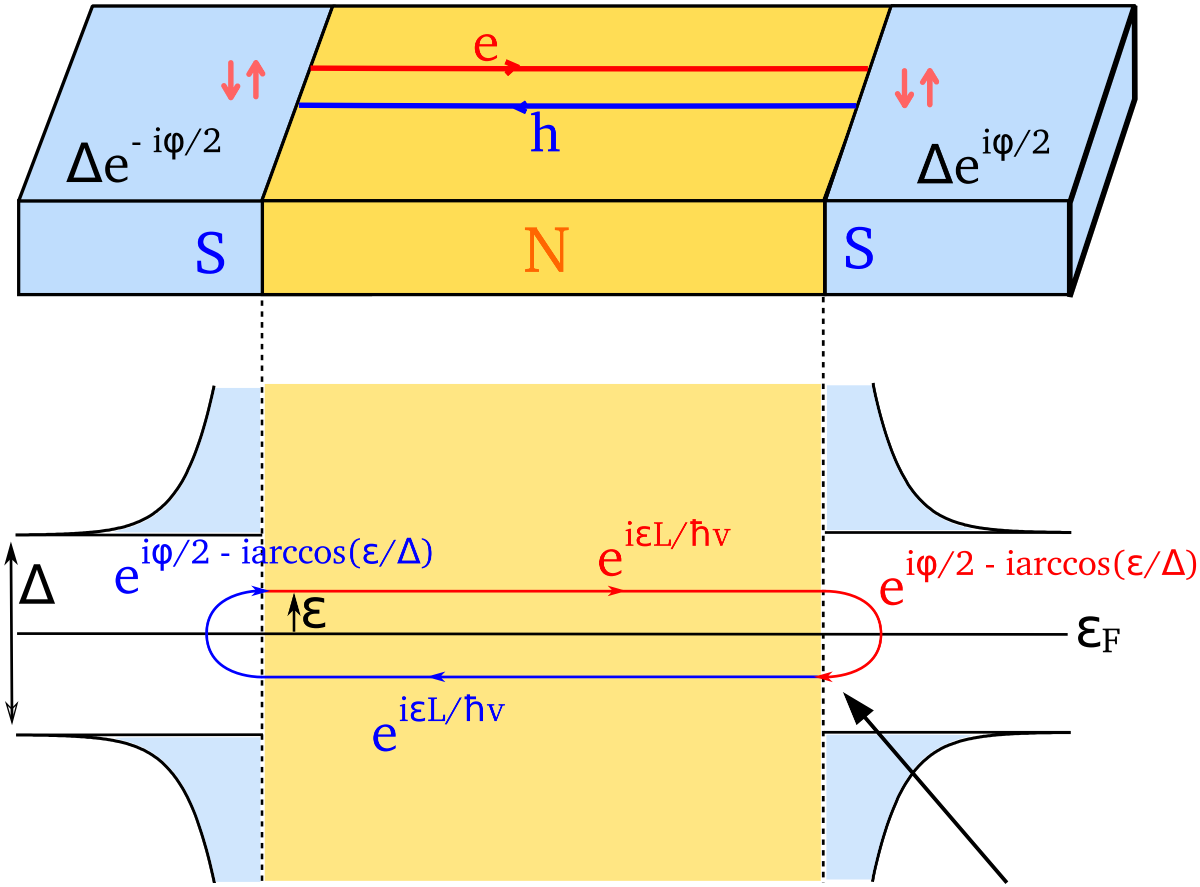
Diffusive bulk states

Superconducting state

How to transport a Cooper pair across a normal metal ?

Superconducting electrodes

Density of states :



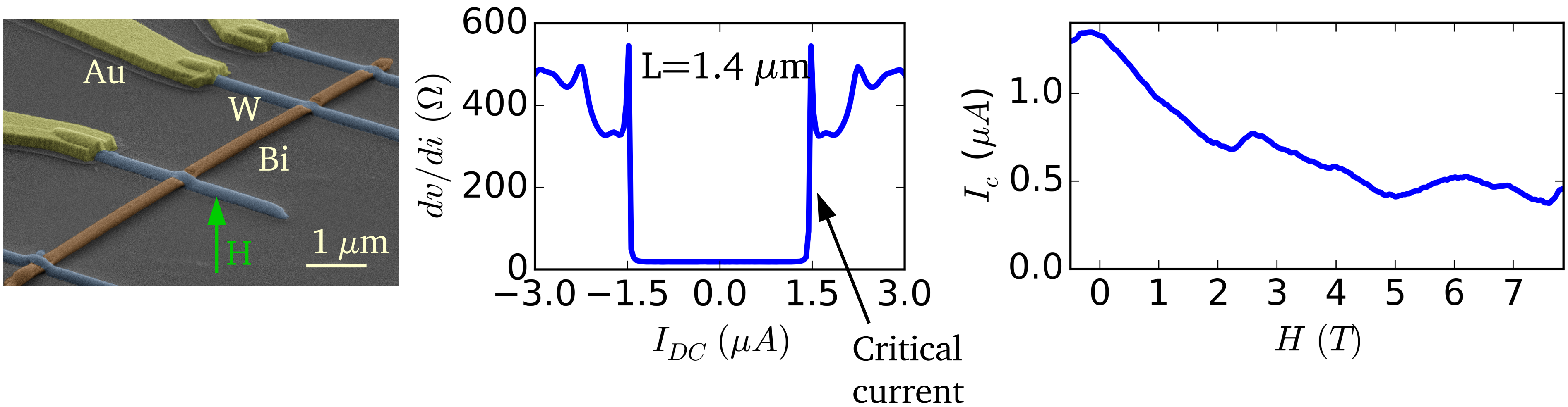
Andreev reflection

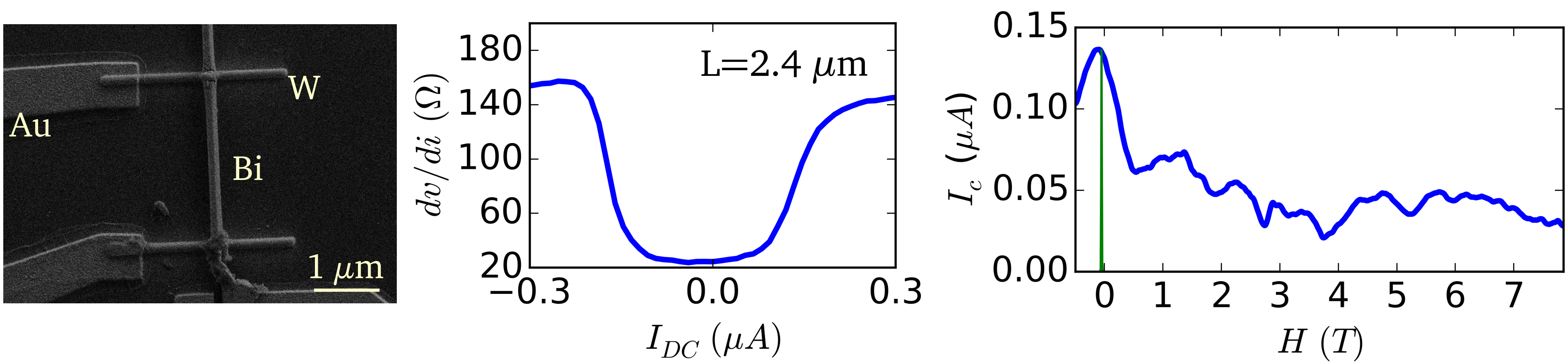
Bound state condition : $$\frac{\hbar \epsilon L}{v_F} \pm \frac{\varphi}{2} + \arccos\left(\frac{\epsilon}{\Delta}\right) = n\pi$$ Kulik, **JETP**, 1970

Discrete energy levels within the gap : Andreev bound states

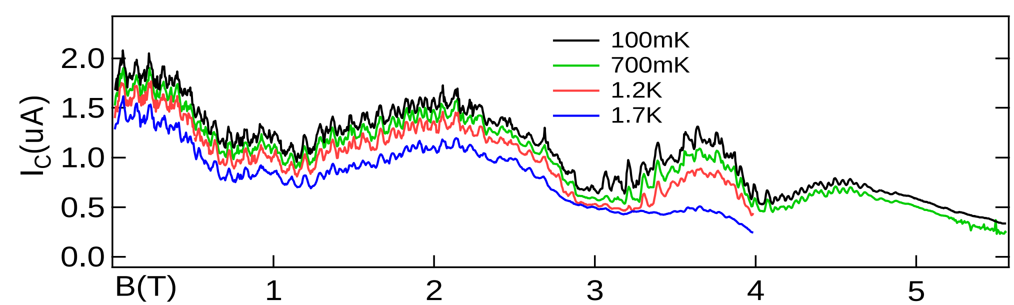
Supercurrent persists up to huge magnetic field

Superconducting proximity effect in Bi nanowires





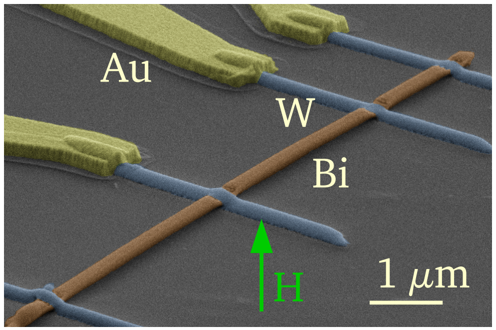
Confirms our previous results

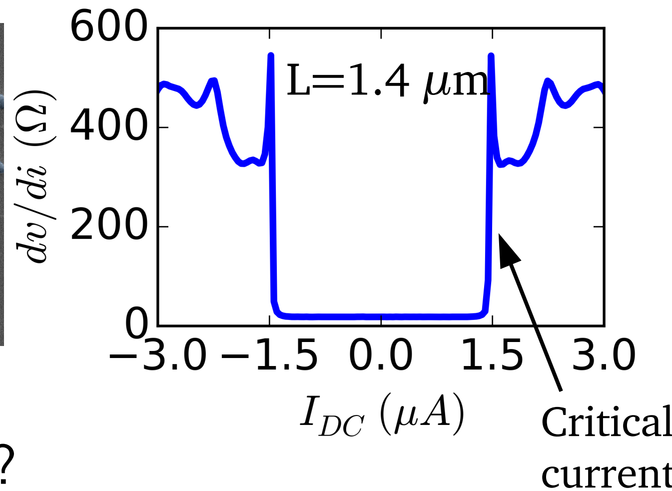


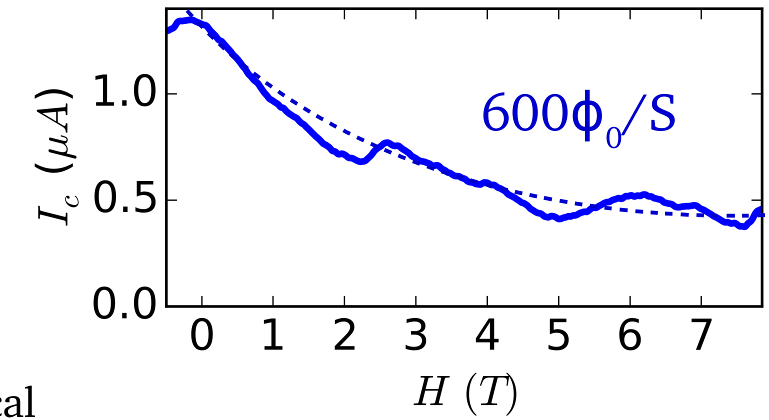
C. Li, A. Kasumov, AM, **PRB**, 2014

Supercurrent persists up to huge magnetic field

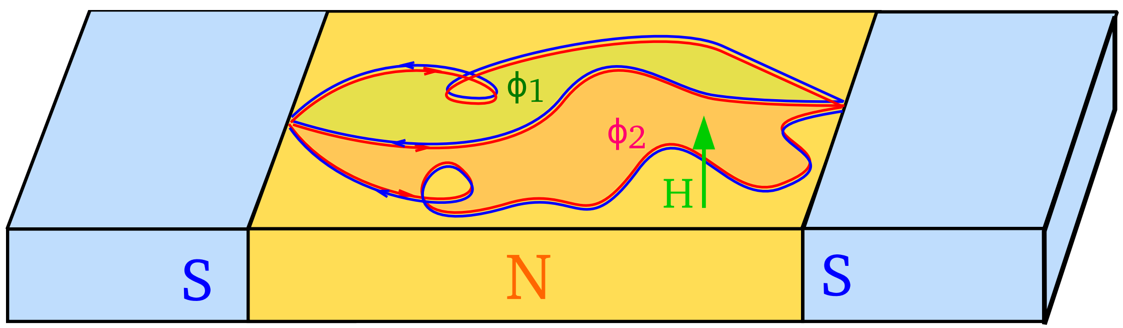
Superconducting proximity effect in Bi nanowires







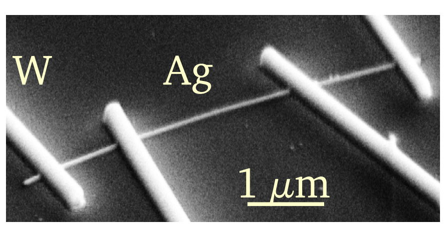
Why is this unusual ?

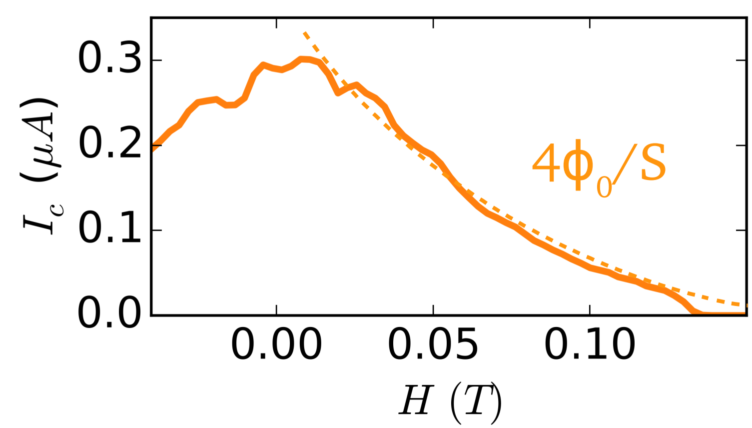


Scrambling interferences between trajectories

Characteristic field scale ϕ_0/S

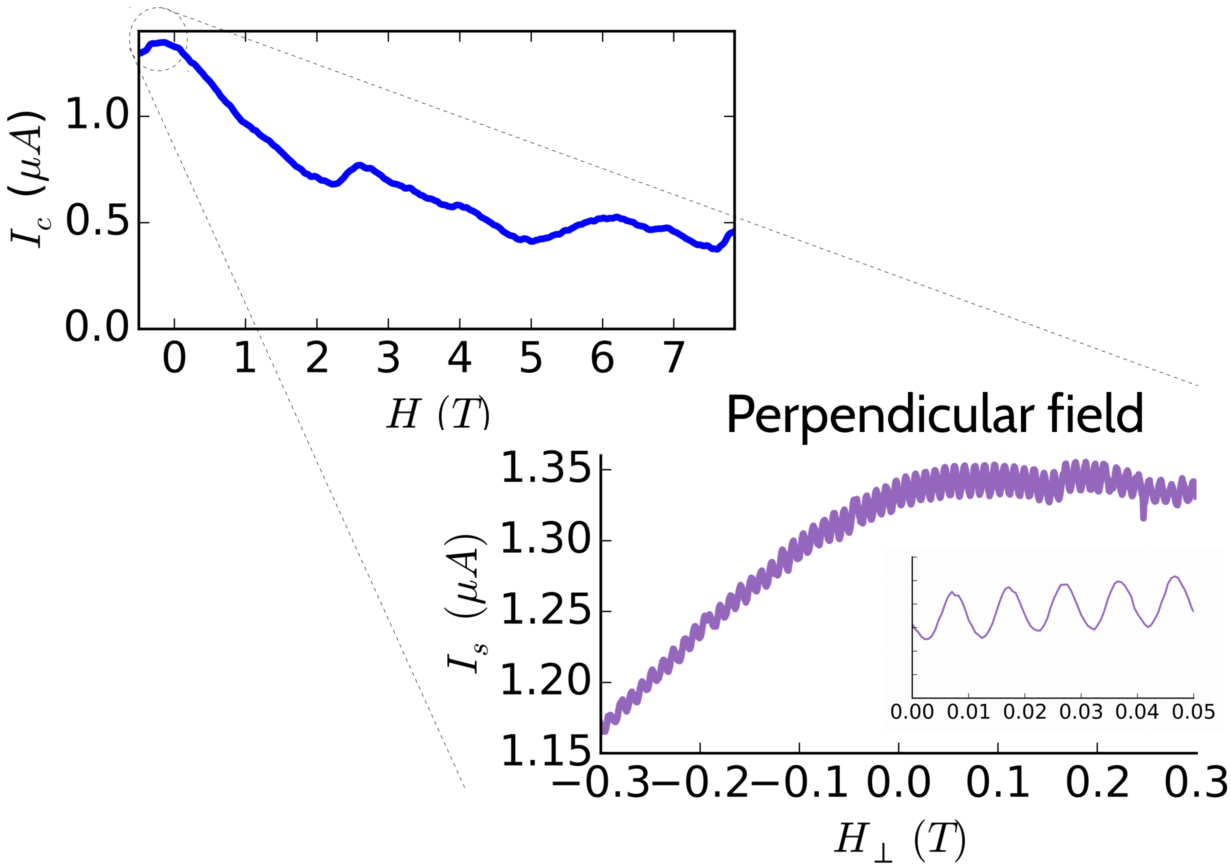
Same measurement with Ag nanowires :

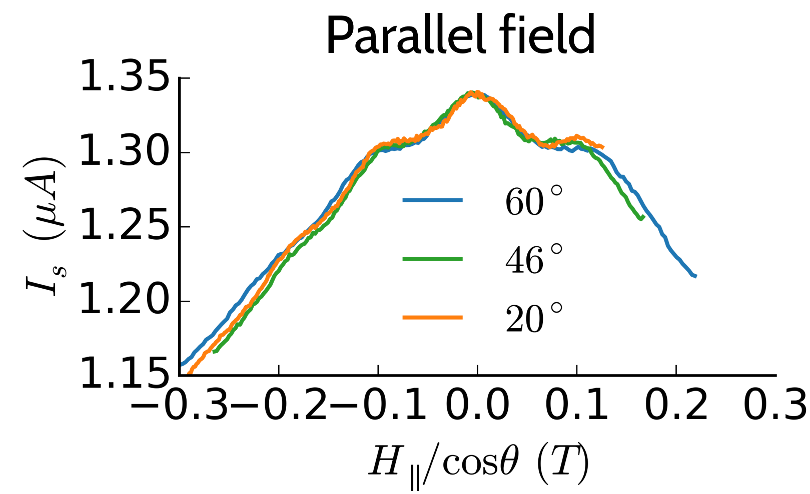


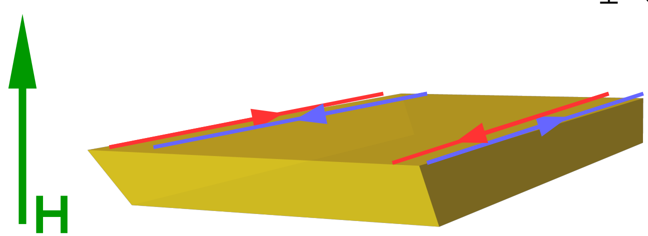


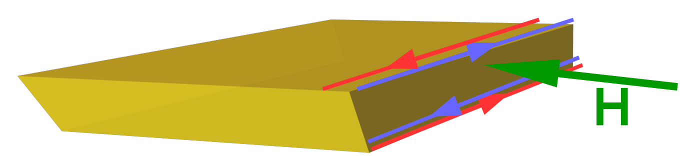
In Bismuth nanowires : only few narrow channels

Interferences at low magnetic field







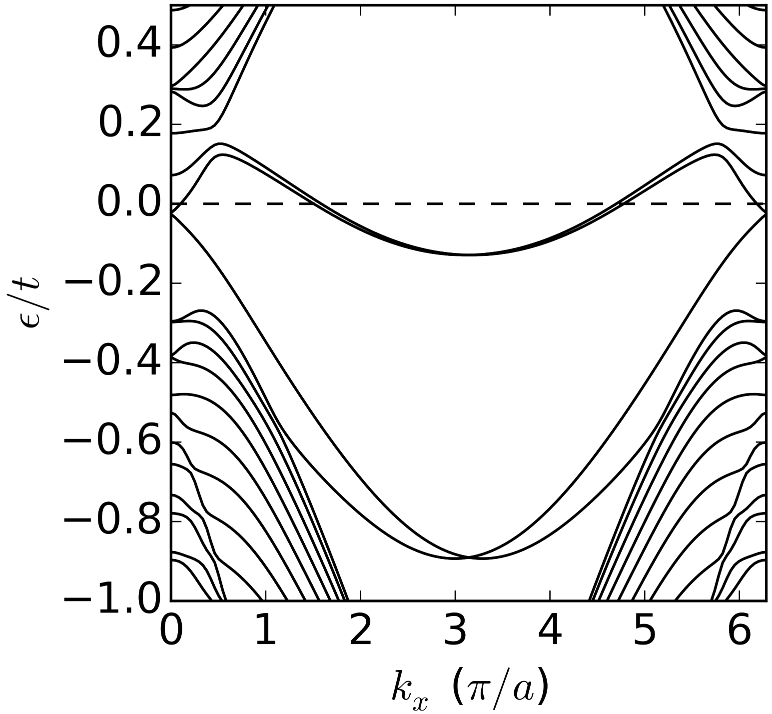


Period = 80 G
$= \phi_0/S_{top}$

Period = 800 G

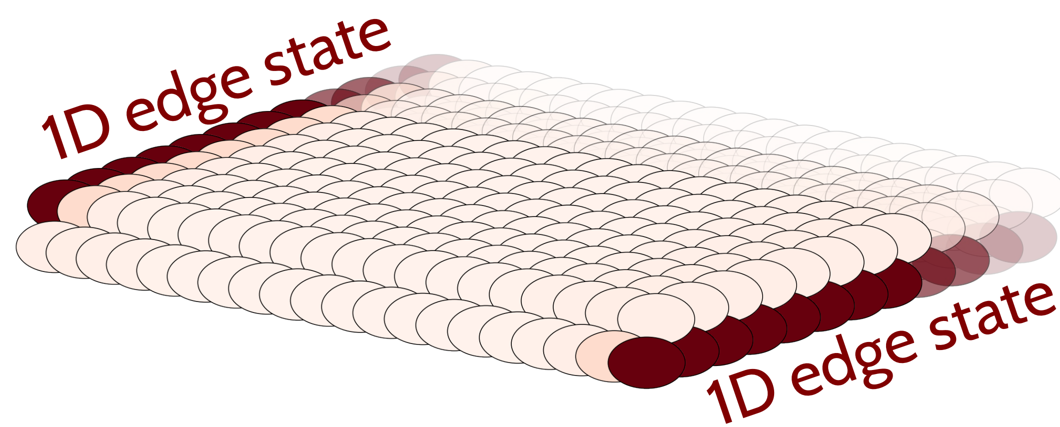
Interferences between channels

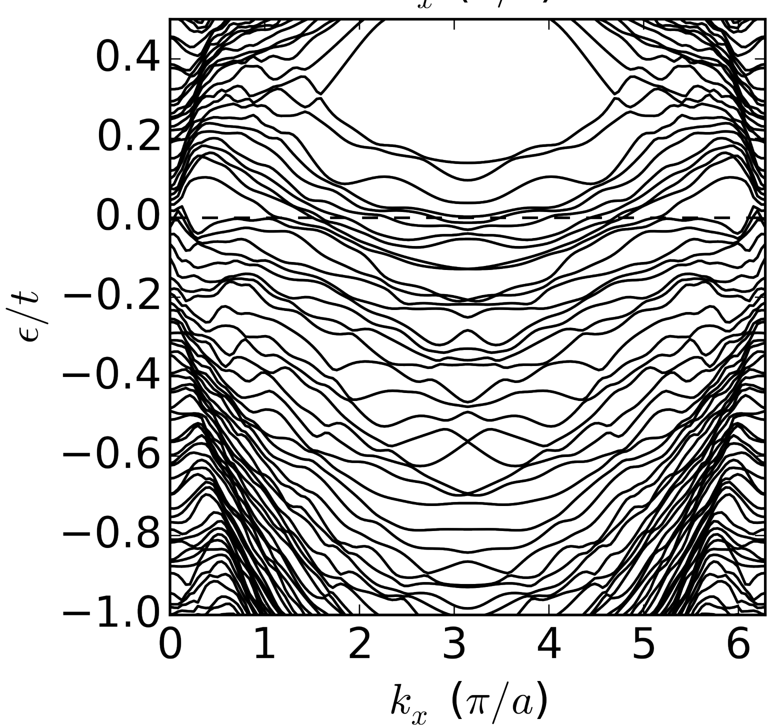
Exact diagonalization : spectrum and LDOS



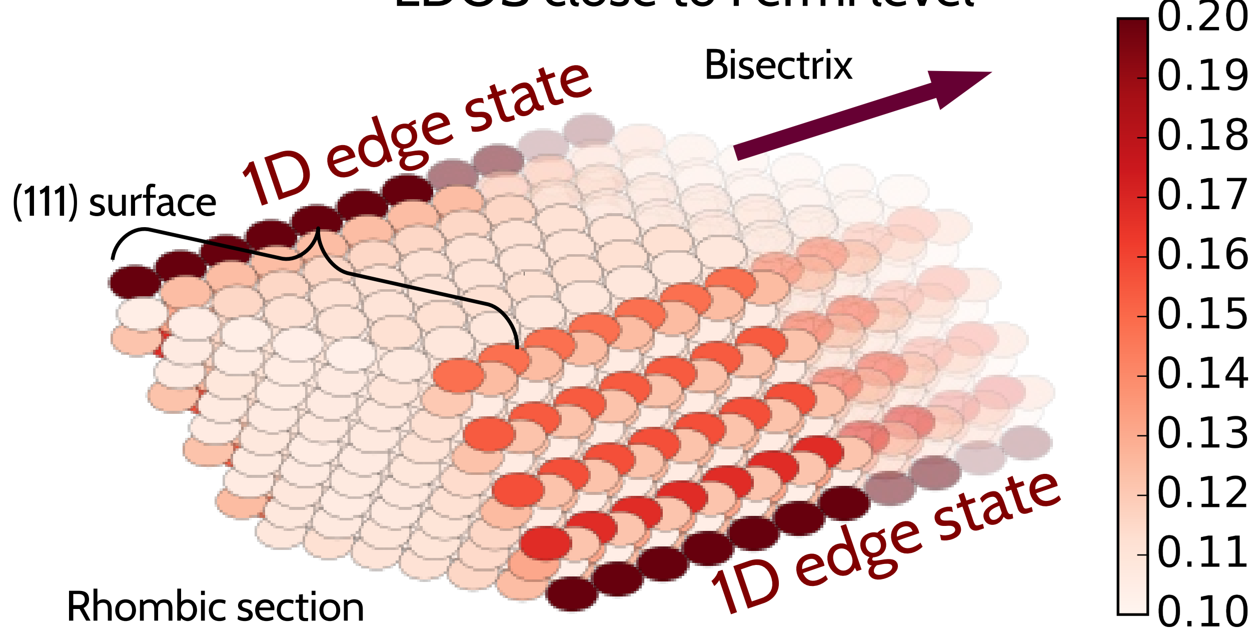
Bi bilayer (Murakami 2006)

Using kwant





LDOS close to Fermi level

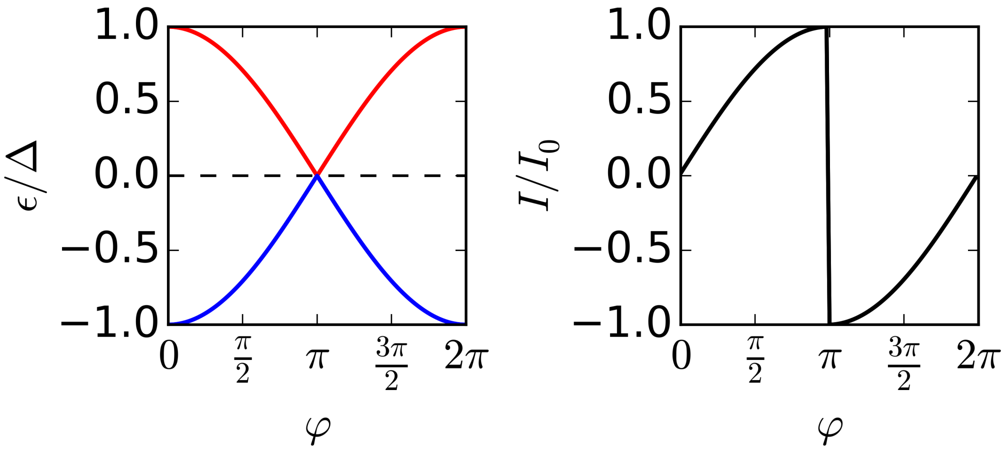


Reminiscence of topological edge states

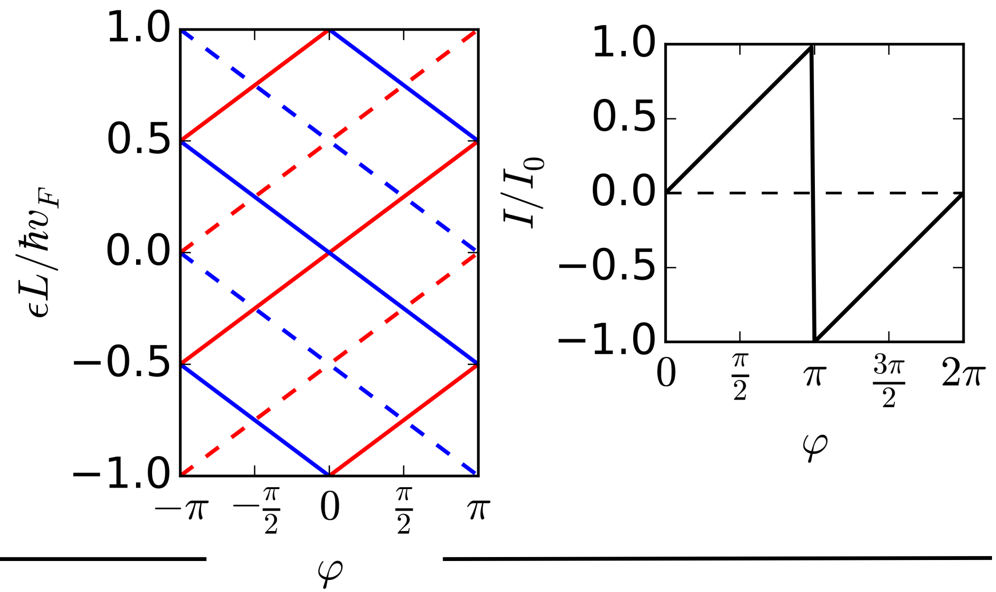
Different regimes of proximity induced superconductivity

$$\hbar \epsilon L / v_F \pm \varphi/2 + \arccos(\epsilon/\Delta) = n\pi$$

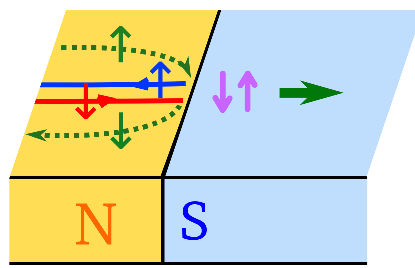
Short junction $L \ll \xi_N \equiv \hbar v_F / \Delta$

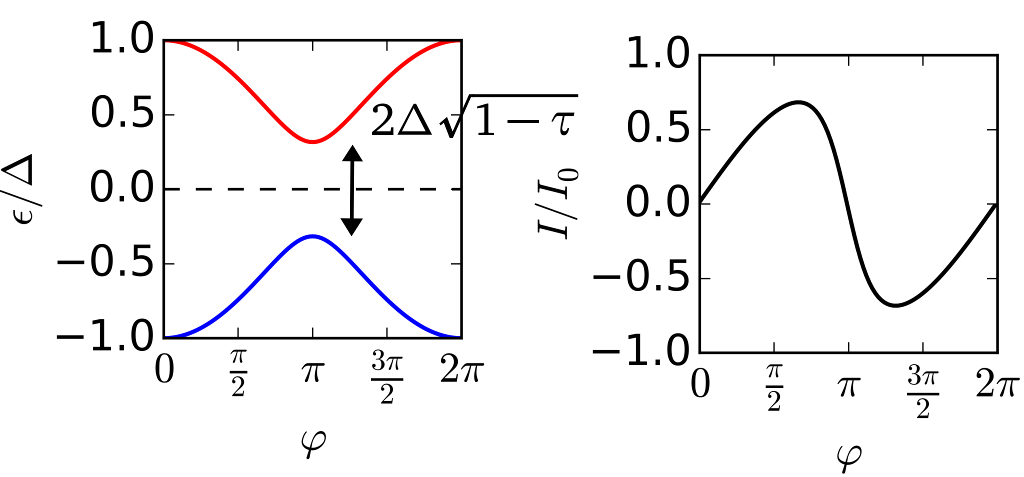


Long junction $L \gg \xi_N$

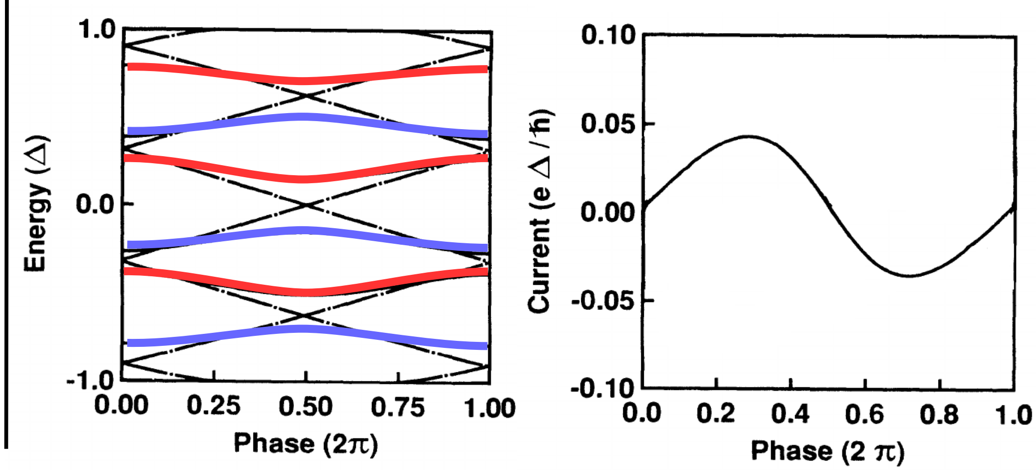


Disorder,
Finite transmission
at the interface :



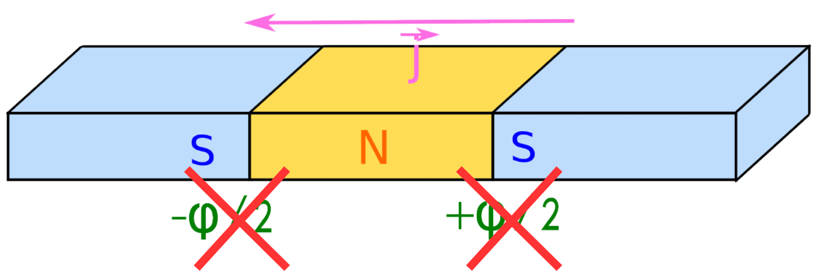


Bagwell, **Phys Rev B**, 1992



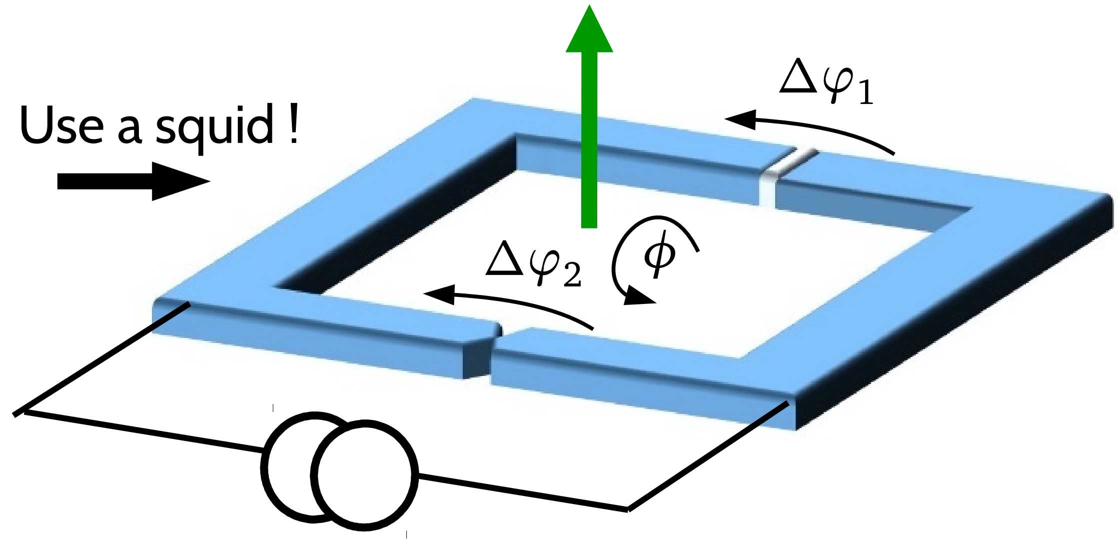
Low transparency, disorder $\Longrightarrow$ smooth current phase relation

How to phase bias the system ?



no information about the phase !

Use a squid !



$$\Delta\varphi_1 - \Delta\varphi_2 + 2\pi\frac{\phi}{\phi_0} = 2n\pi$$

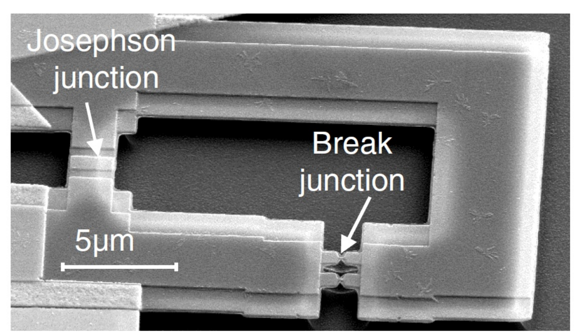
Further assumption : **assymetric SQUID** $\quad i_1 \ll i_2$

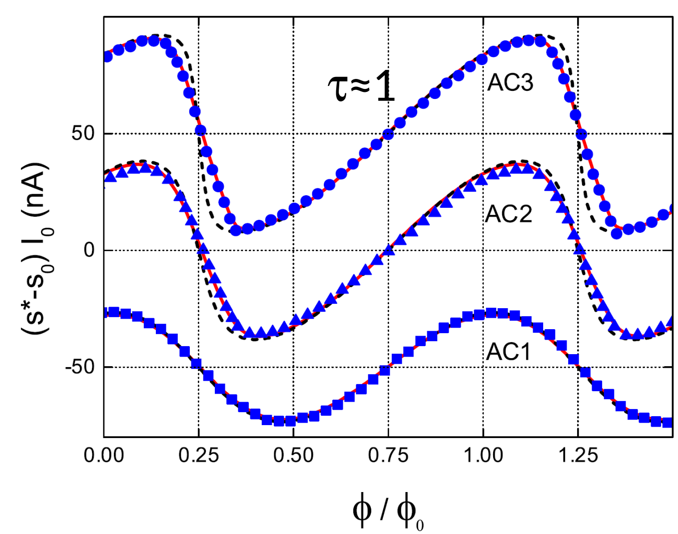
$$\Delta\varphi_2 \simeq \Delta\varphi_2^0$$

$$\Delta\varphi_1 \simeq \Delta\varphi_2^0 - 2\pi\frac{\phi}{\phi_0}$$

$$i_c \simeq i_2^0 + i_1\left(\Delta\varphi_2^0 - 2\pi\frac{\phi}{\phi_0}\right)$$

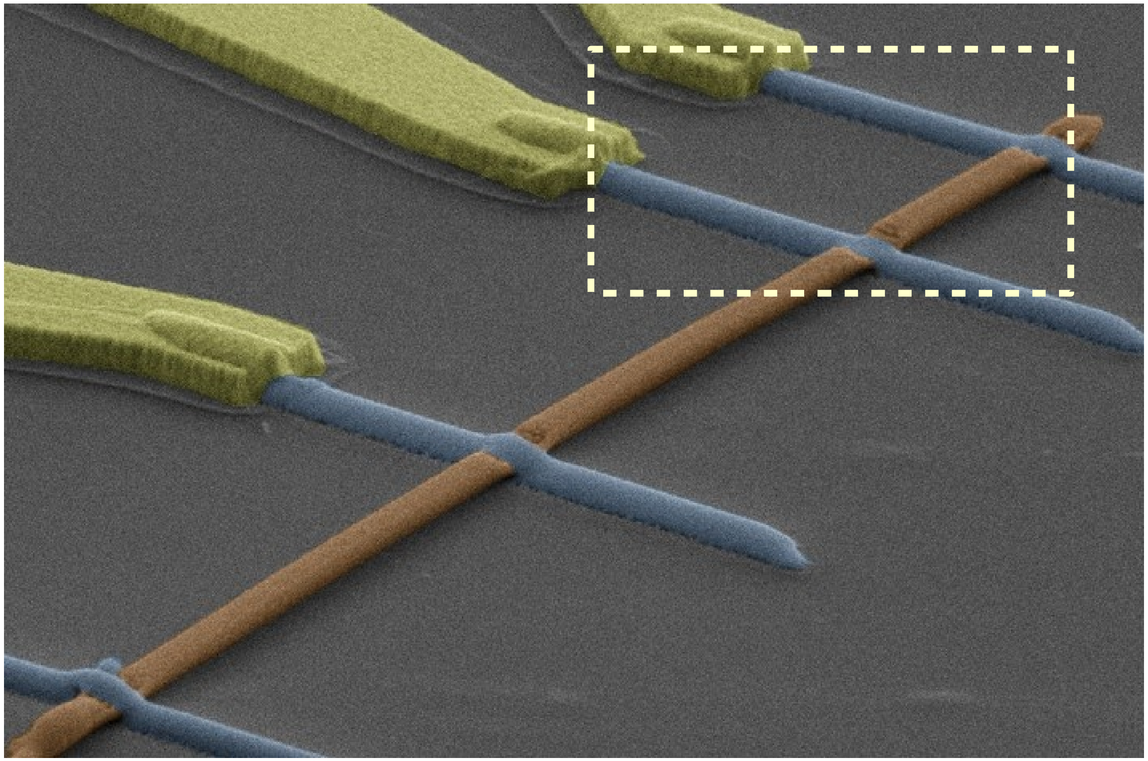
Della Rocca, 2007

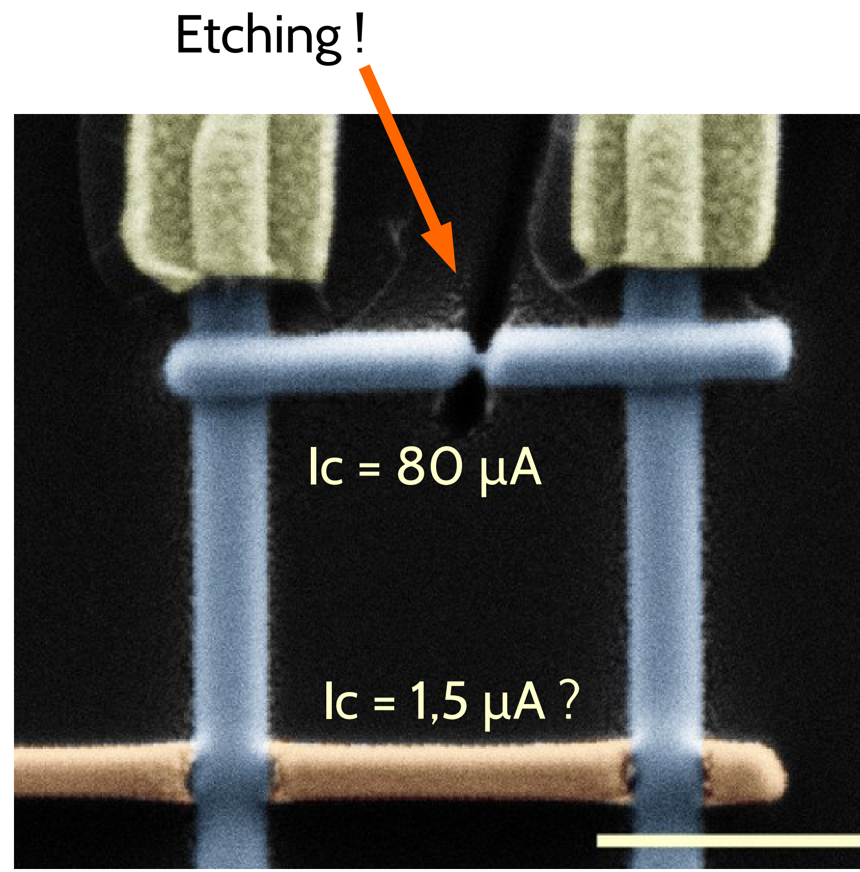




How to insert the Bi nanowire inside a SQUID ?

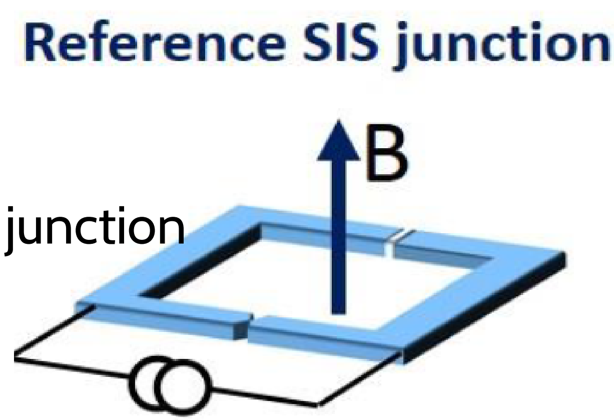
Build the SQUID around !

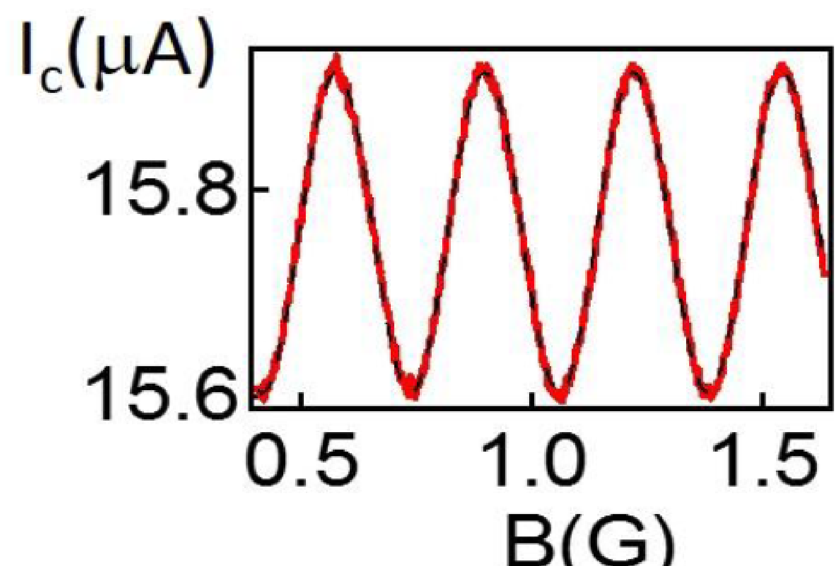




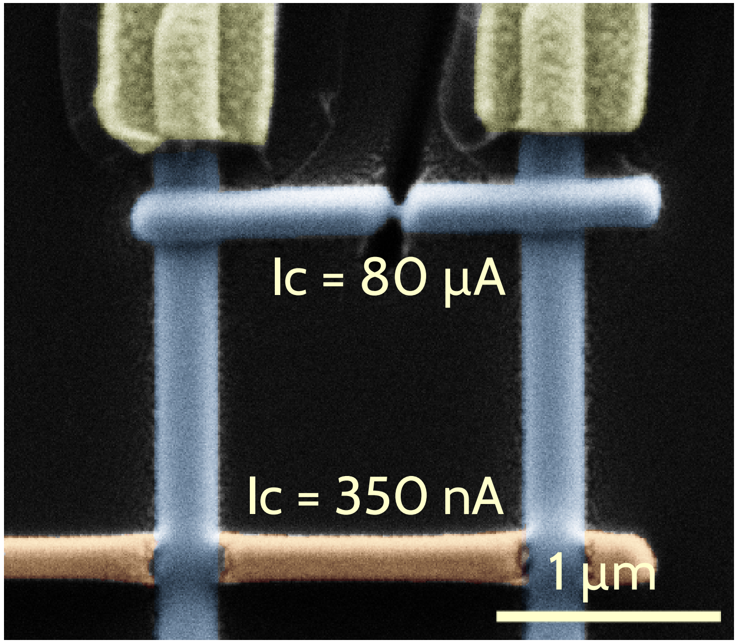
Tungsten constriction

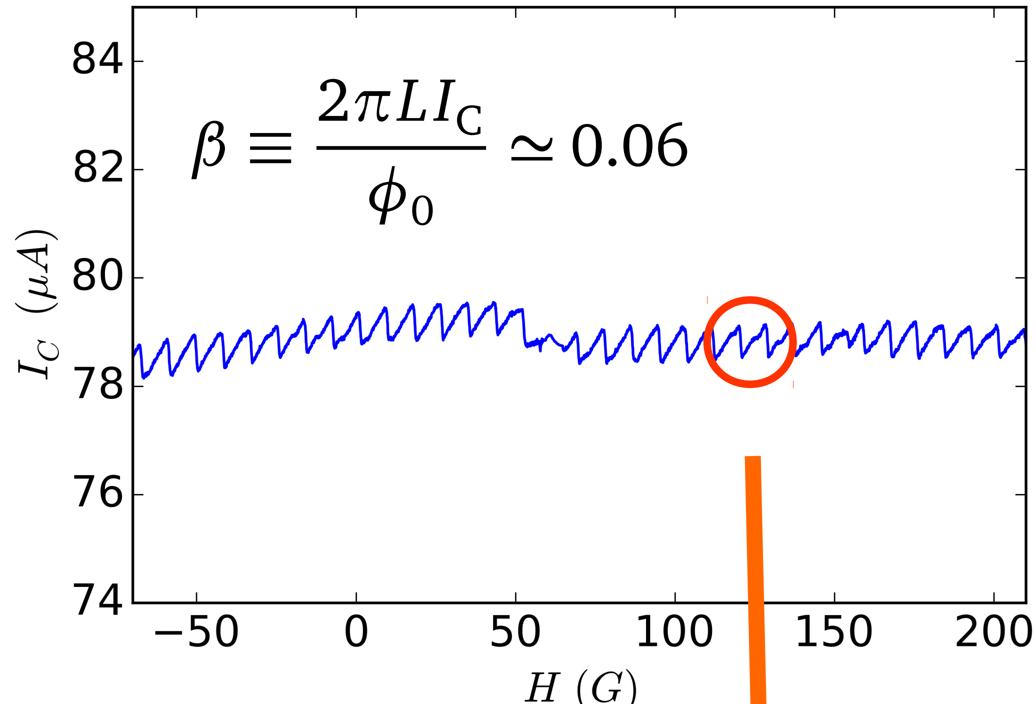
Testing with a tunnel junction (R. Delagrange)



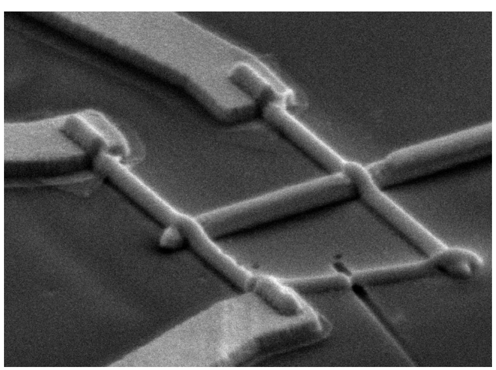


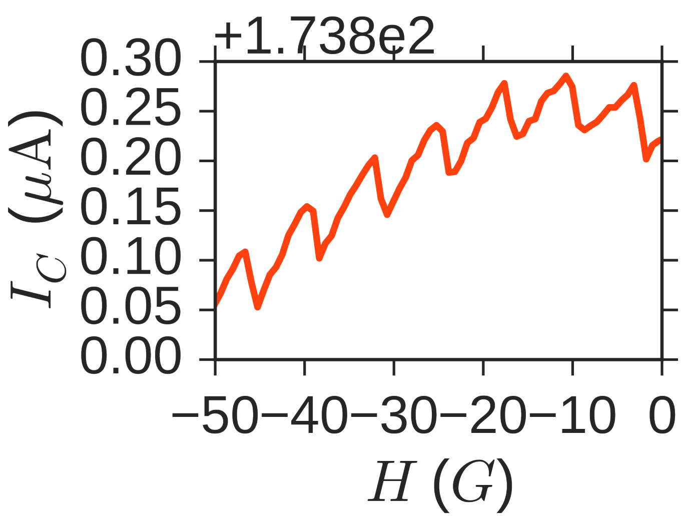
Revealing the nature of the edge states

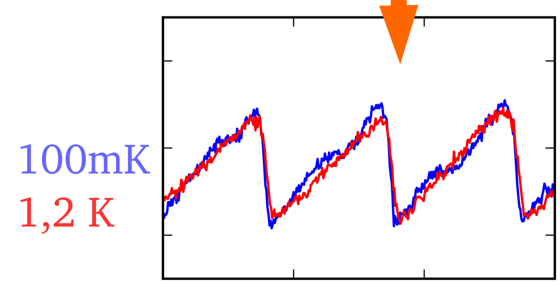




Other squid







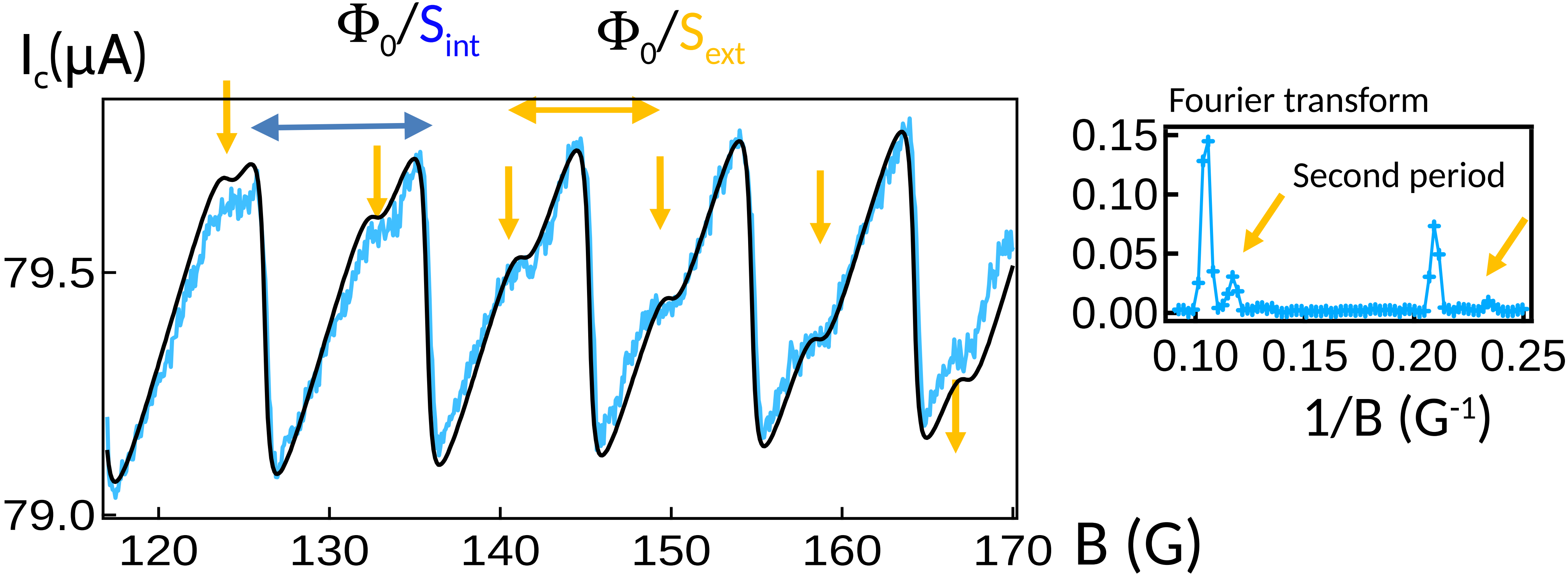
Sawtooth shaped !

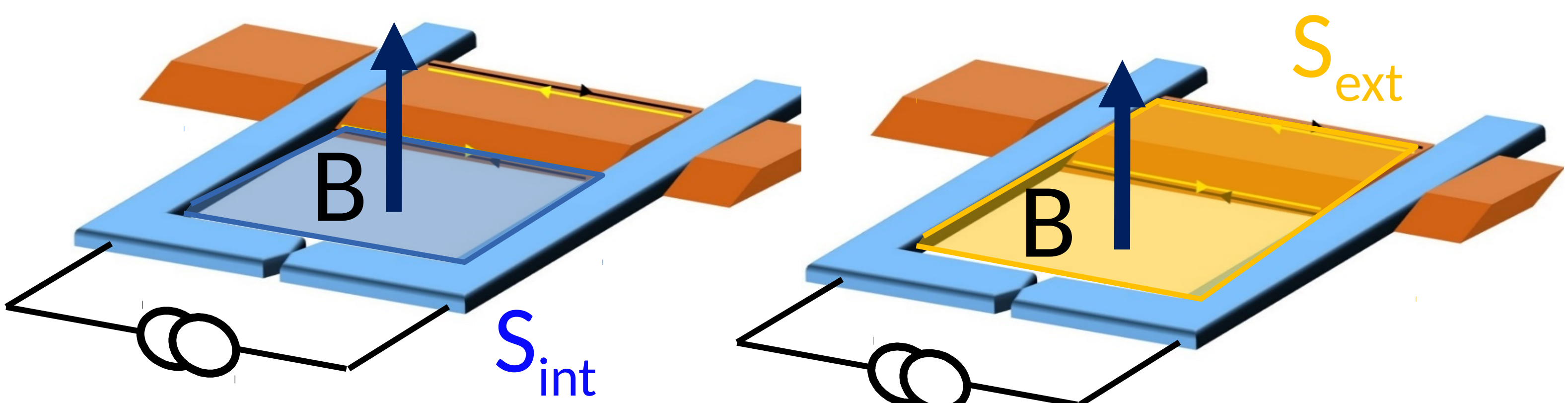
Ic = 350 nA

$\frac{e v_F}{L} \simeq 120\,\mathrm{nA}$ M = 3 channels

Current phase relation of a <u>long ballistic junction</u>

The interfering channels are visible

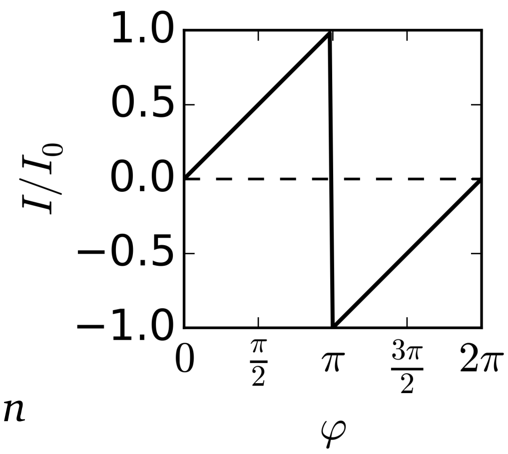




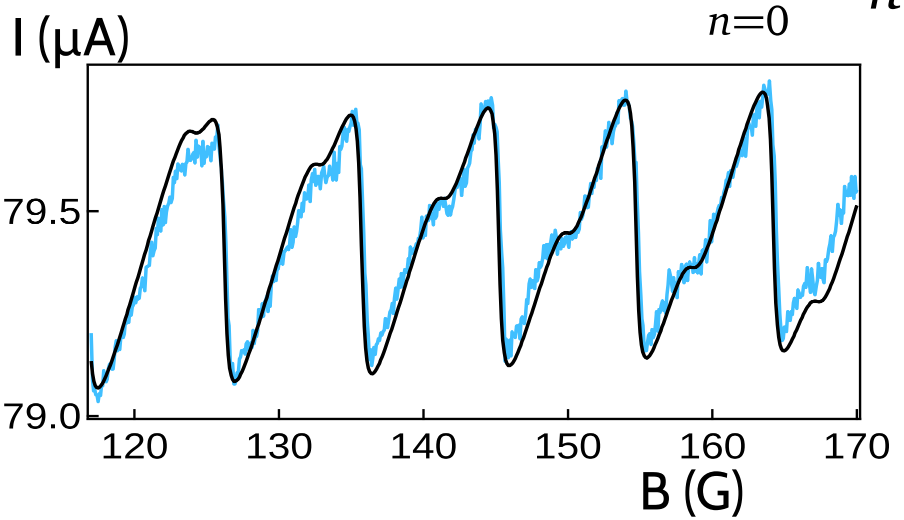
Phase modulation of the current-phase relation
= signature of edge states !

How ballistic are the two paths ?

Perfect sawtooth : $$I(\varphi) = \sum_{n=0}^{\infty} \frac{(-1)^n}{n} \sin(n\varphi)$$



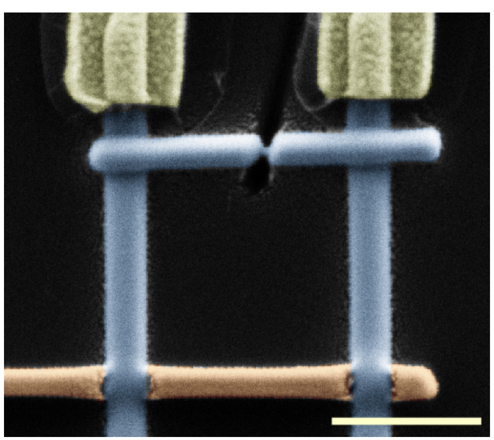
Finite transmission : $$I(\varphi) = \sum_{n=0}^{\infty} \frac{(-1)^n}{n} \sin(n\varphi) t^{2n}$$

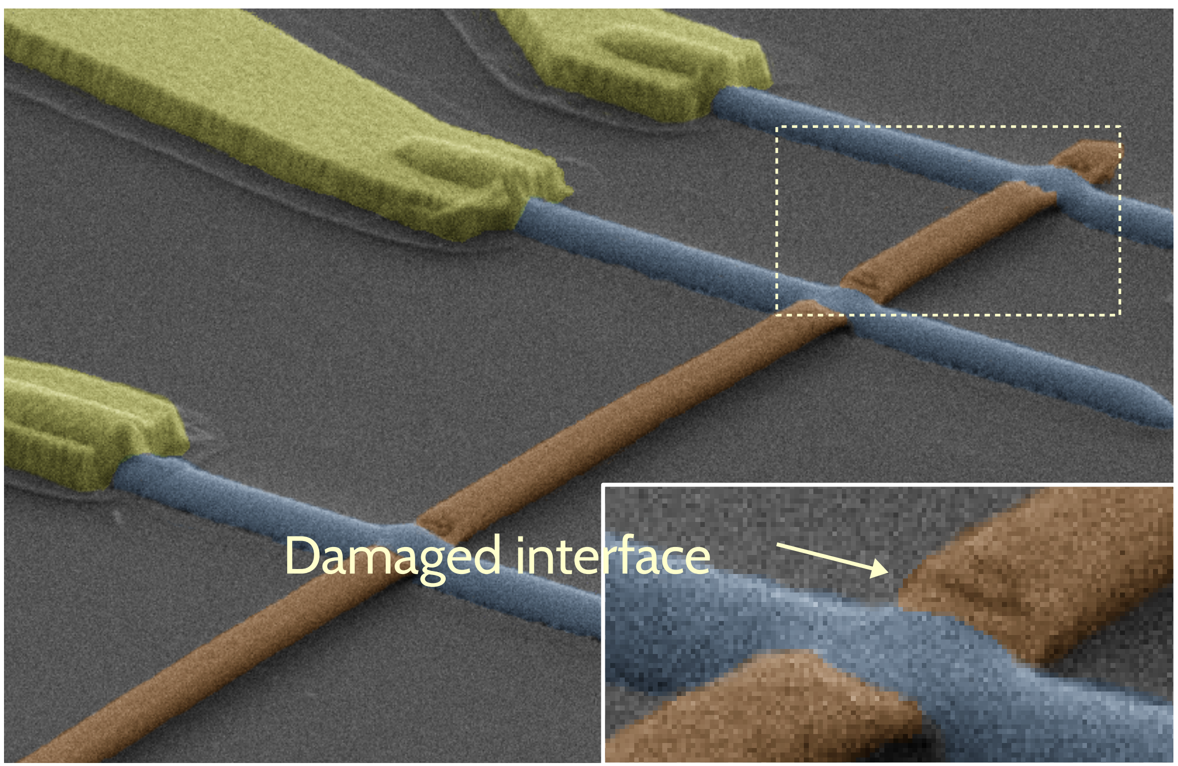


Inner edge: channels with t≈0.9

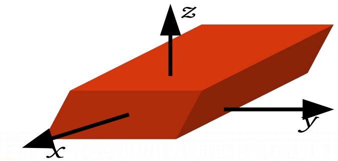
Outer edge: channels with t≈0.7

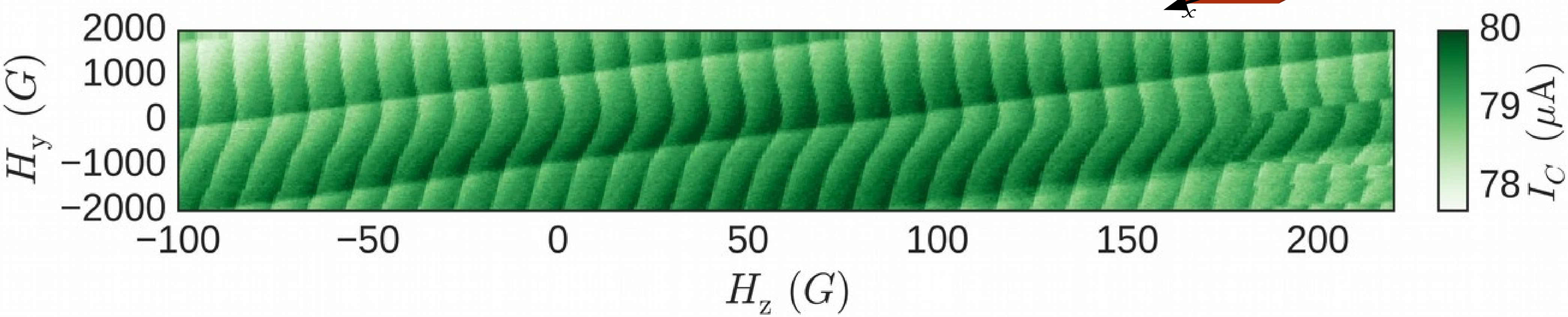
How ?

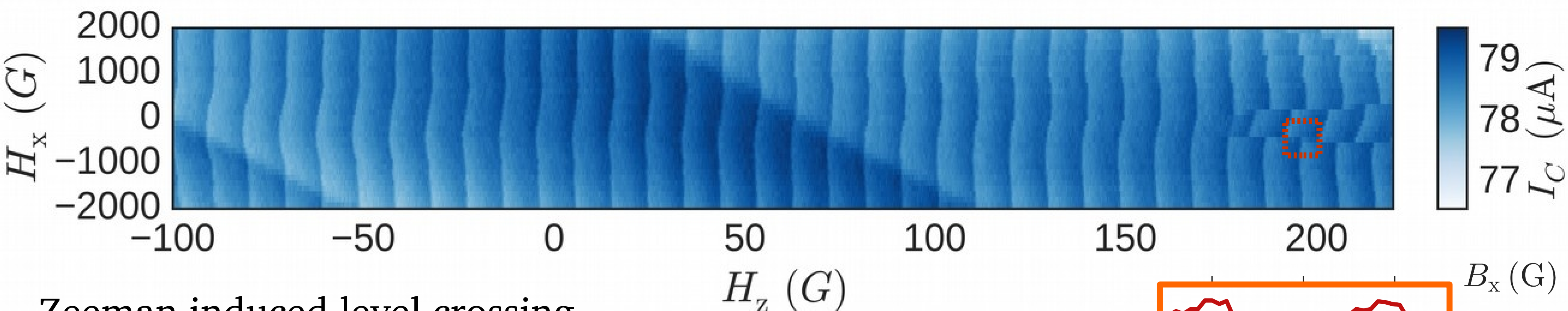




π junction in parallel magnetic field…

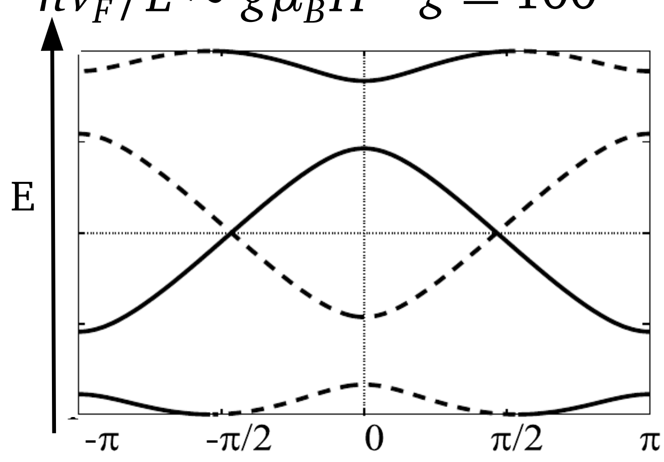


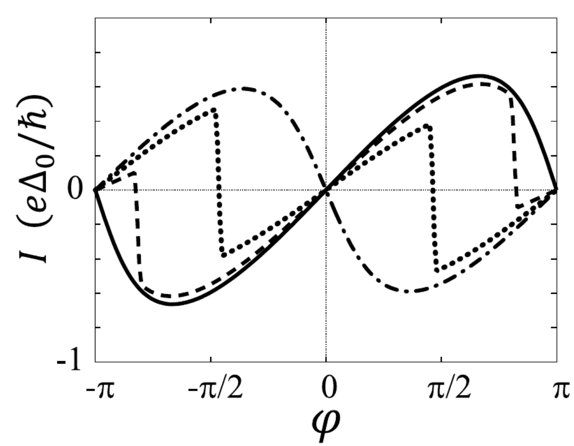




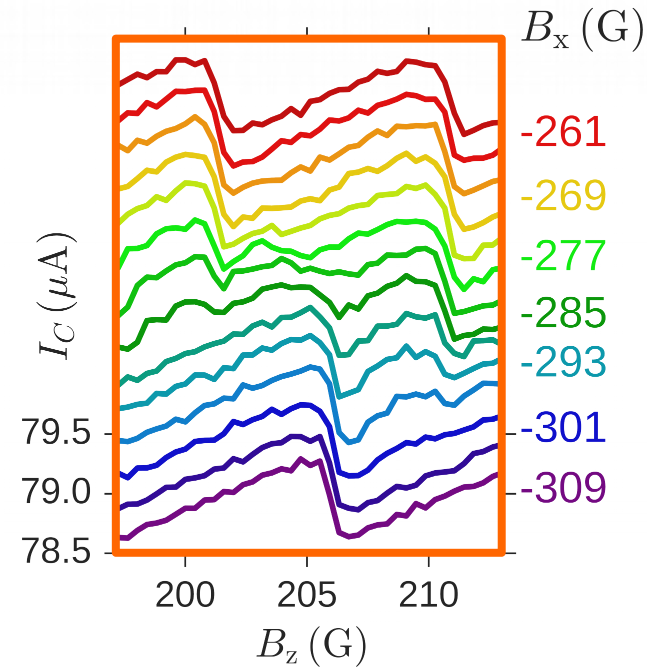
Zeeman induced level crossing

$\hbar v_F / L \sim g \mu_B H \quad g \simeq 100$

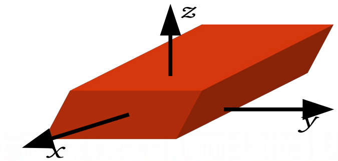


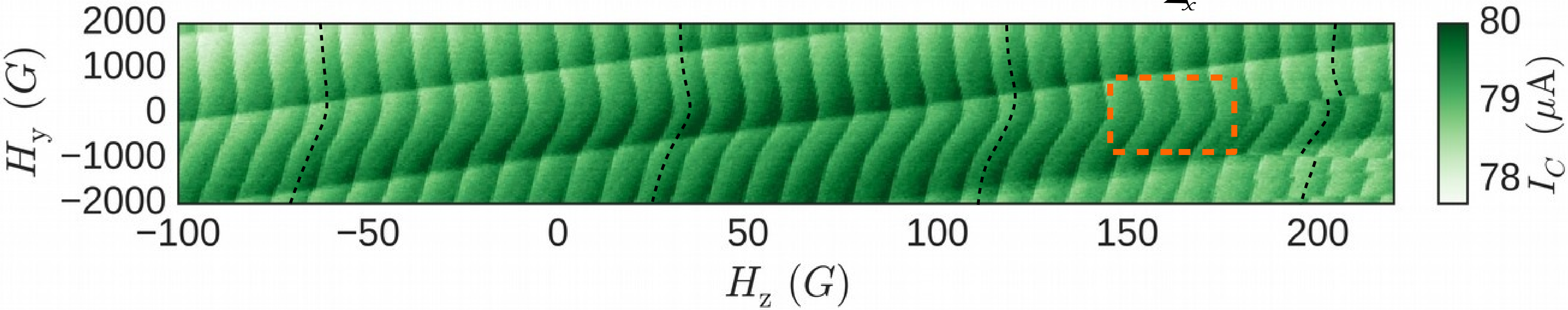


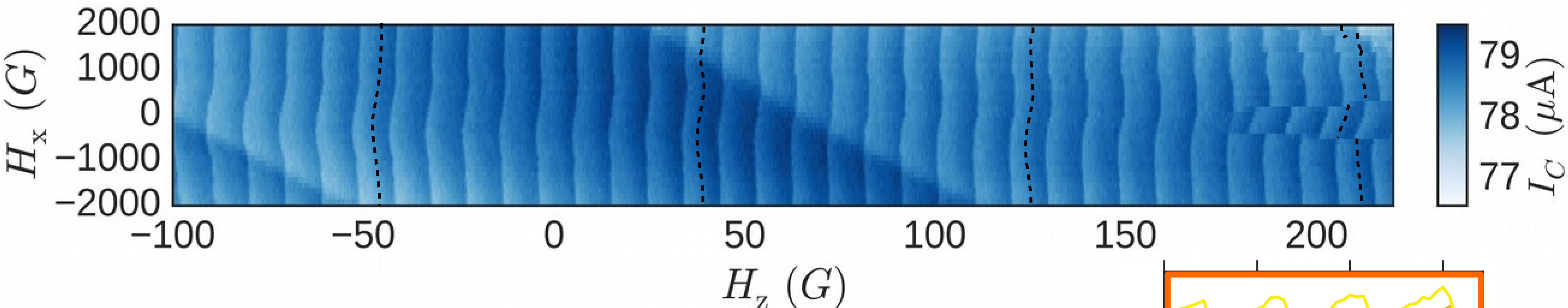
Yokoyama, Eto, Nazarov, **PRB** 2014



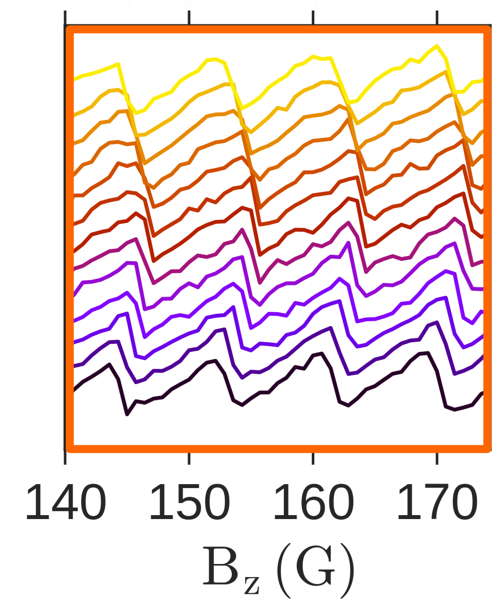
...and ϕ_0 junction in parallel field







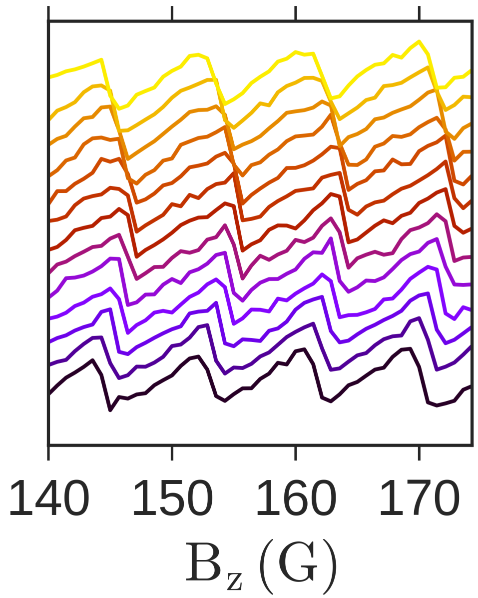
Continous ϕ_0 shift

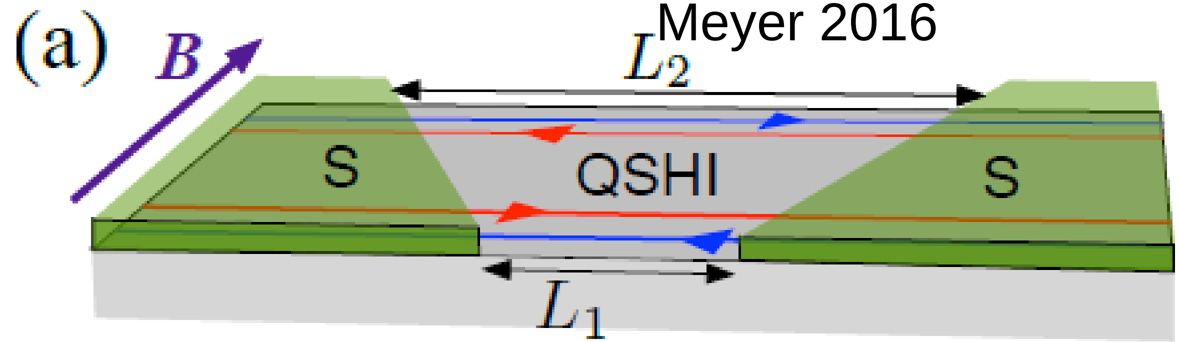


Signature of ϕ_0 junction

...and ϕ_0 junction in parallel field

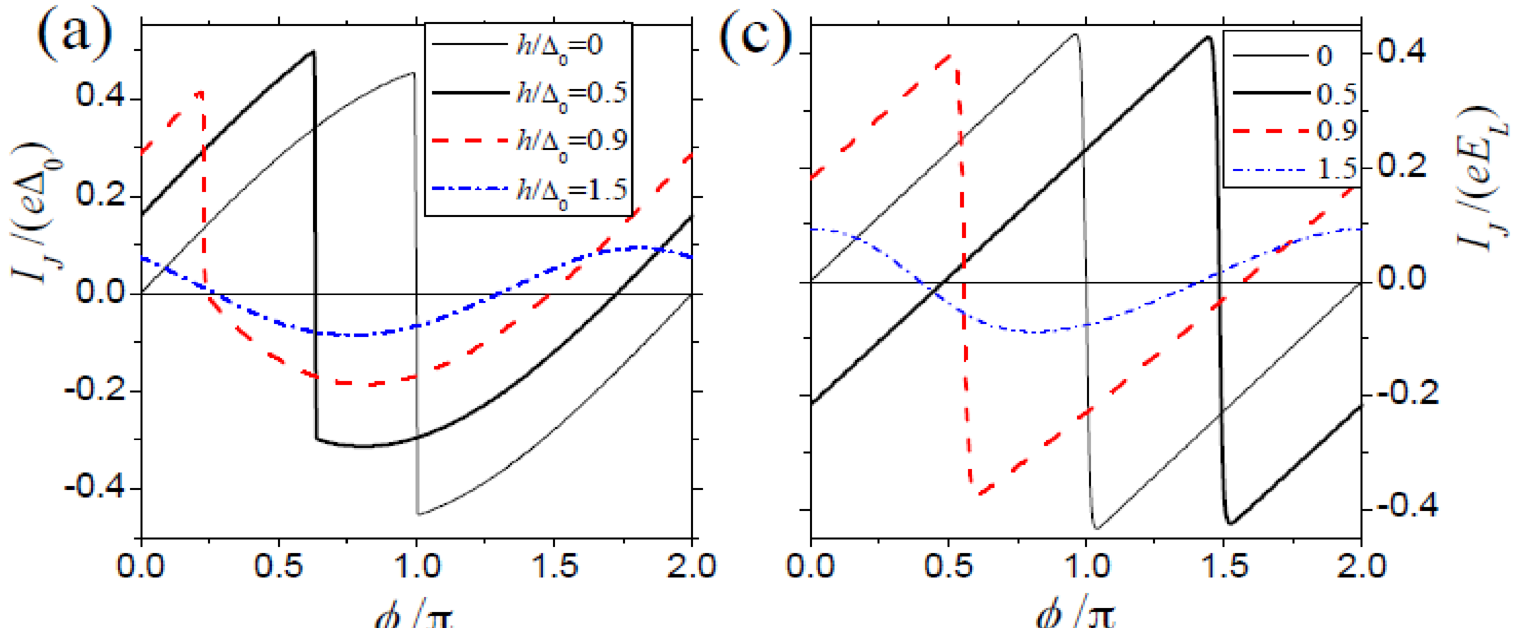
Dolcini,Houzet, Meyer 2016





$L/\xi = 0.1$ (short junction)

$L/\xi = 10$ (long junction)

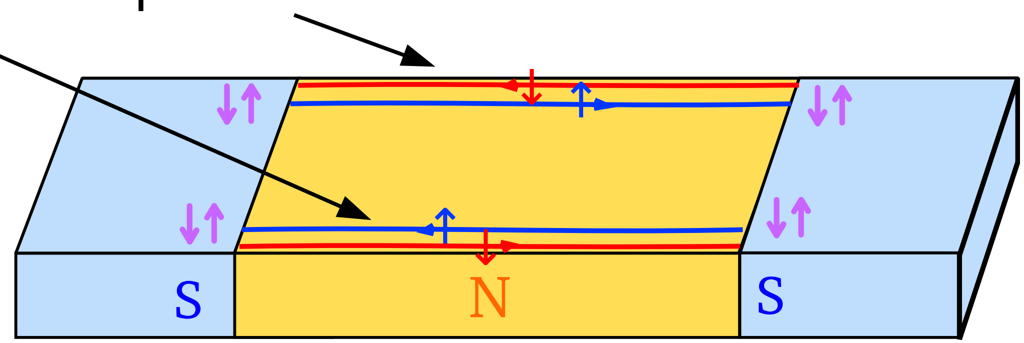


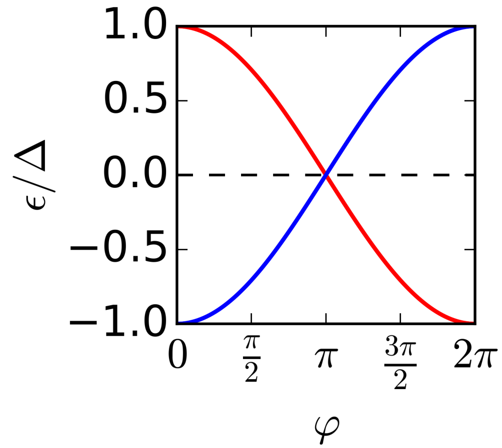
$$2\arccos\left(\frac{E_n + h}{\Delta_0}\right) - \frac{2(E_n + h)}{E_L} = \phi + 2\pi n$$

An other prediction for the current phase relation

$$\hbar\epsilon L/v_F \pm \varphi/2 + \arccos(\epsilon/\Delta) = n\pi$$

Delocalized pair of solutions



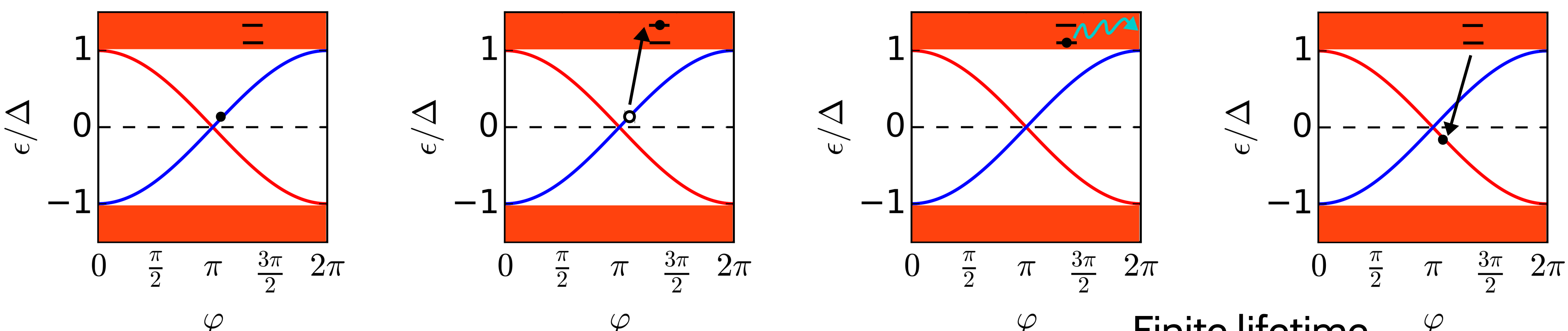


4π periodic current phase relation

Fractionnal Josephson Effect : charge e

Fu, Kane, 2007
Beenakker *et. al.*, 2013

But : quasiparticle poisonning in DC measurements...



Finite lifetime

DC measurements are not ideal for measuring a 4π supercurrent...

Summary

Arxiv 1609.04848

Ballistic edge states in Bi nanowires revealed by CPR measurement

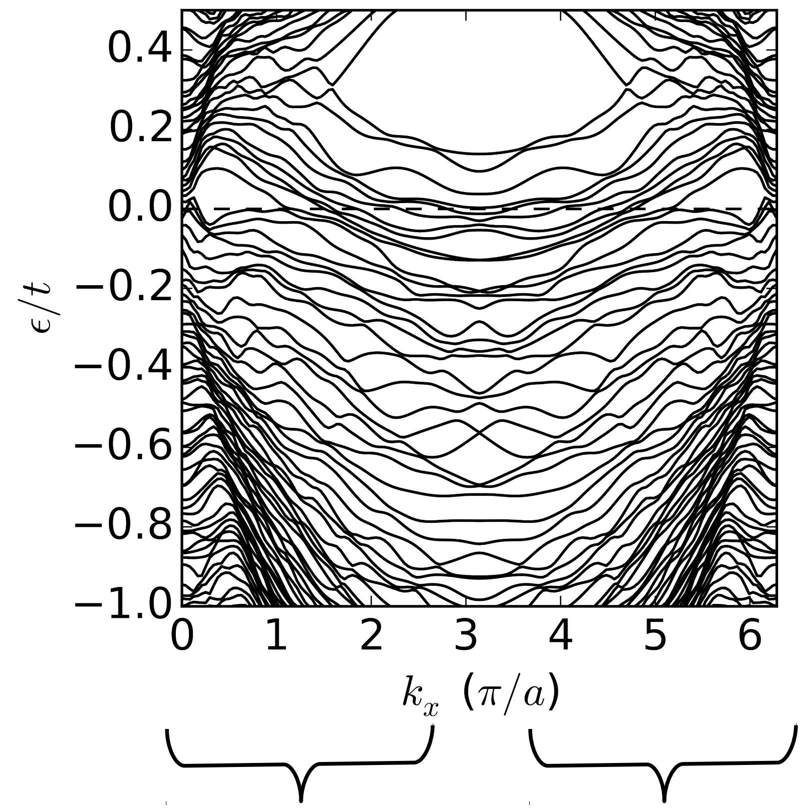
0-π transitions and ϕ_0 junction behaviour in parallel magnetic field

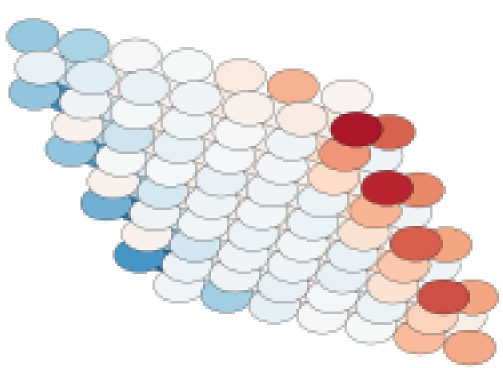
---

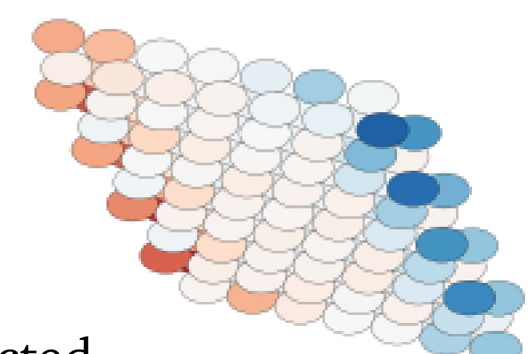
Shamashis Sengupta
Alik Kasumov
François Brisset
Raphaelle Delagrange
Alexei Chepelianski
Richard Deblock
Sophie Guéron
Hélène Bouchiat

Thank you for your attention

Local spin density of states $\langle \sigma_z \rangle$







On average, $\langle \sigma_z \rangle = 0$ as expected

AM *et al,* in preparation

Localized states are spin polarized