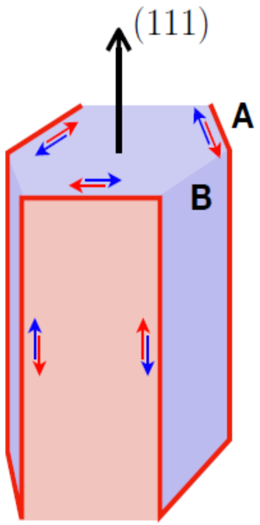
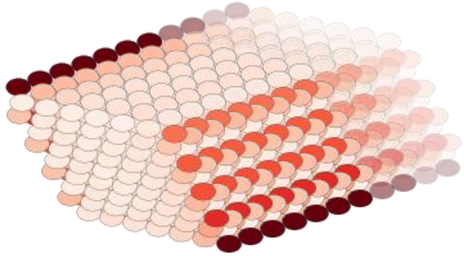
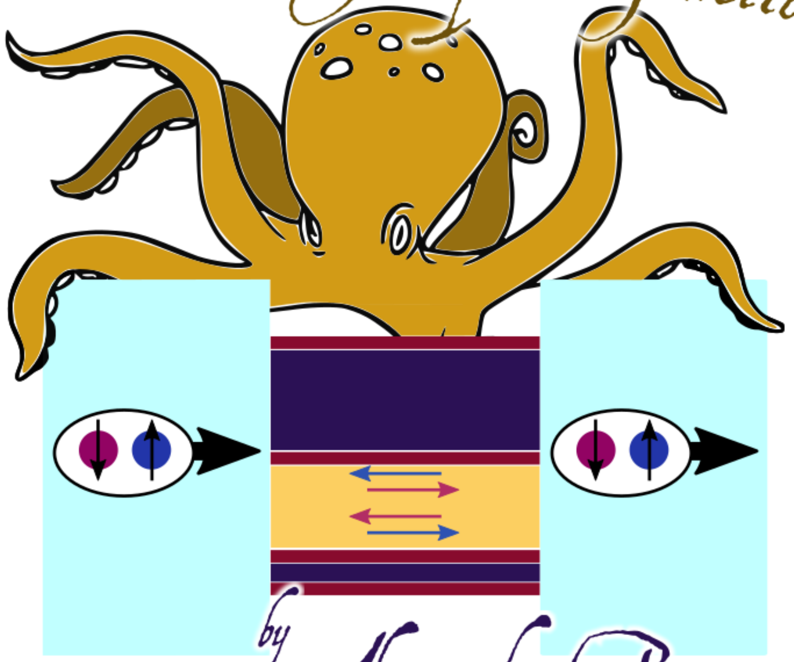
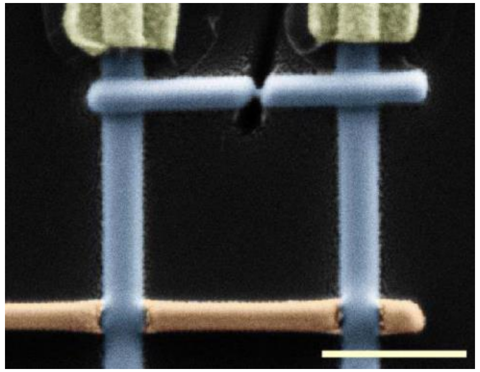
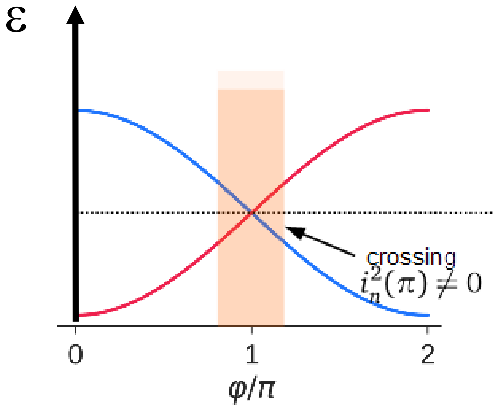




Quantum interferences in Bismuth nanowires Josephson junctions



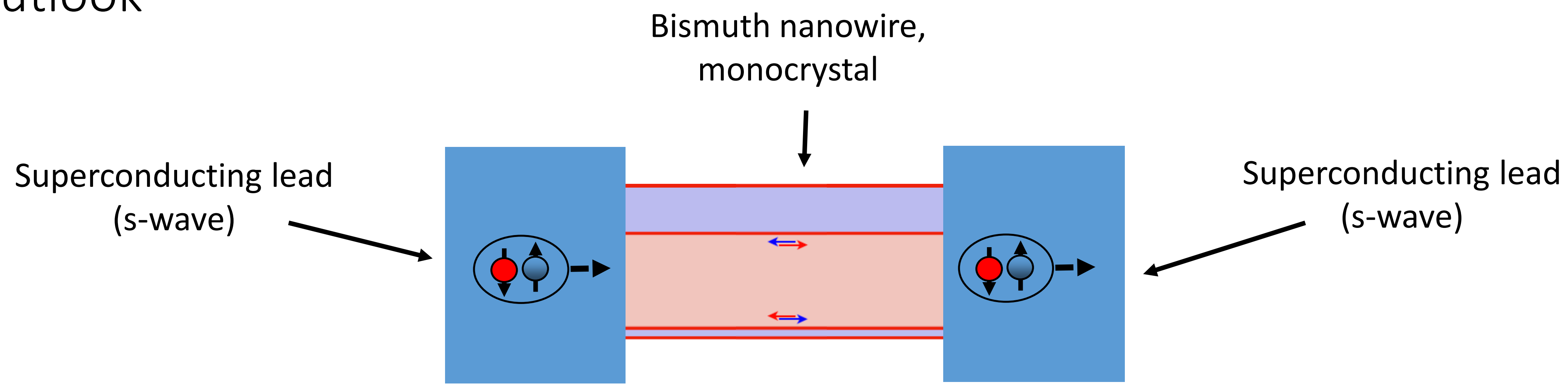




by Alexandre Bernard

and
Sophie Guéron, Anil Murani, Alik Kasumov, Hélène Bouchiat
MESO group, Laboratoire de Physique des Solides, Orsay, France

Outlook


Bismuth nanowire,
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Superconducting lead
(s-wave)
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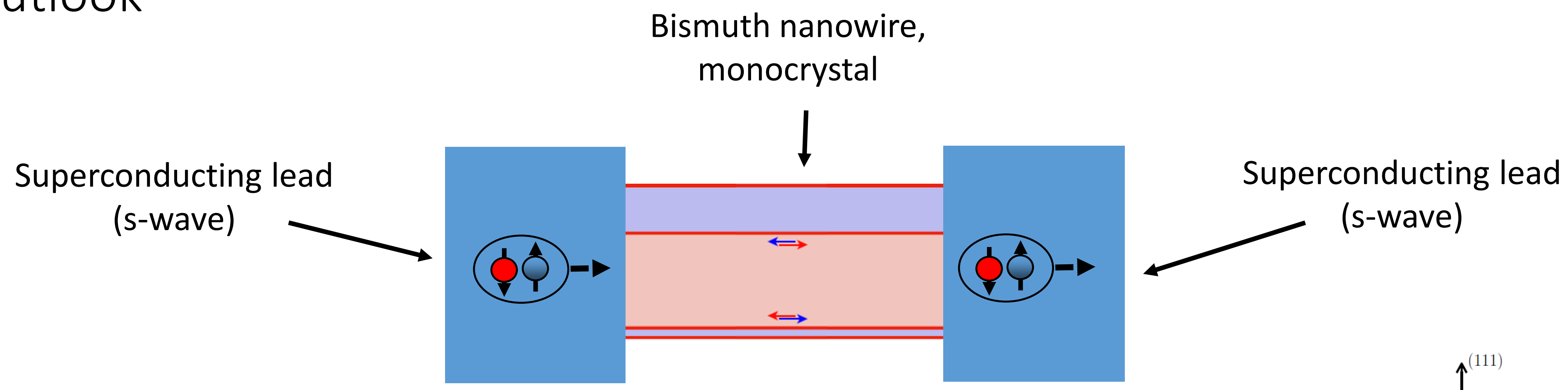
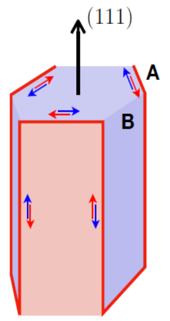


- Topological helical edge states in Bismuth, in a nutshell



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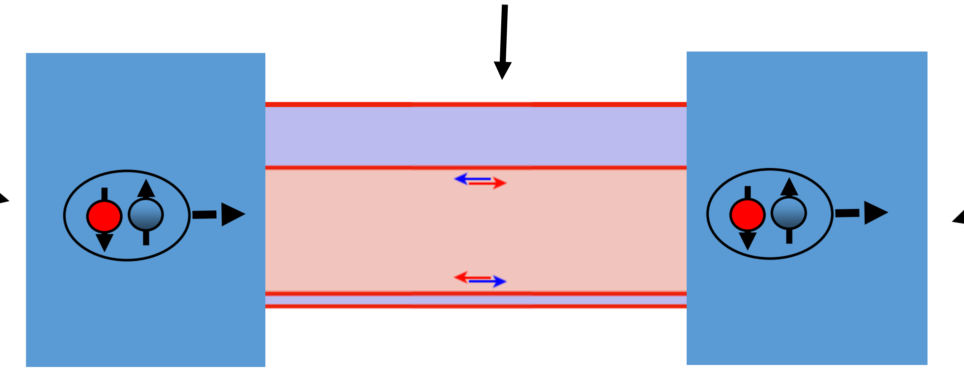

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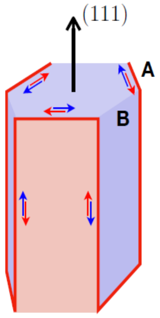

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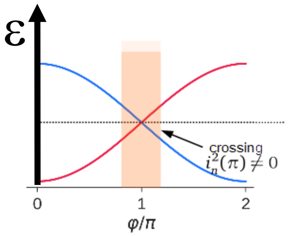
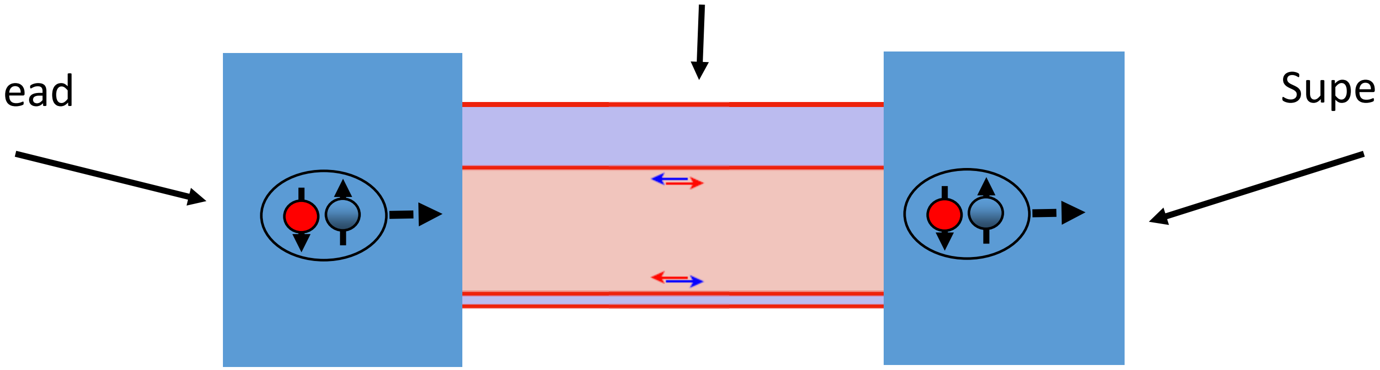
  Andreev reflexion and Andreev Bound States



Outlook

Bismuth nanowire, monocrystal

Superconducting lead (s-wave)



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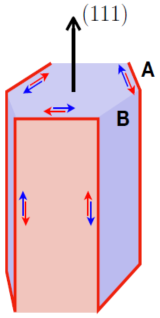

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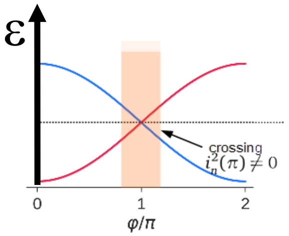

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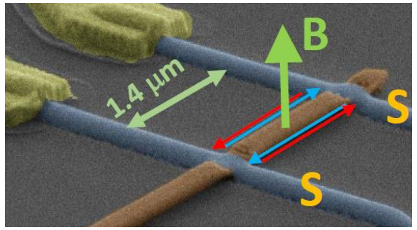

Outlook

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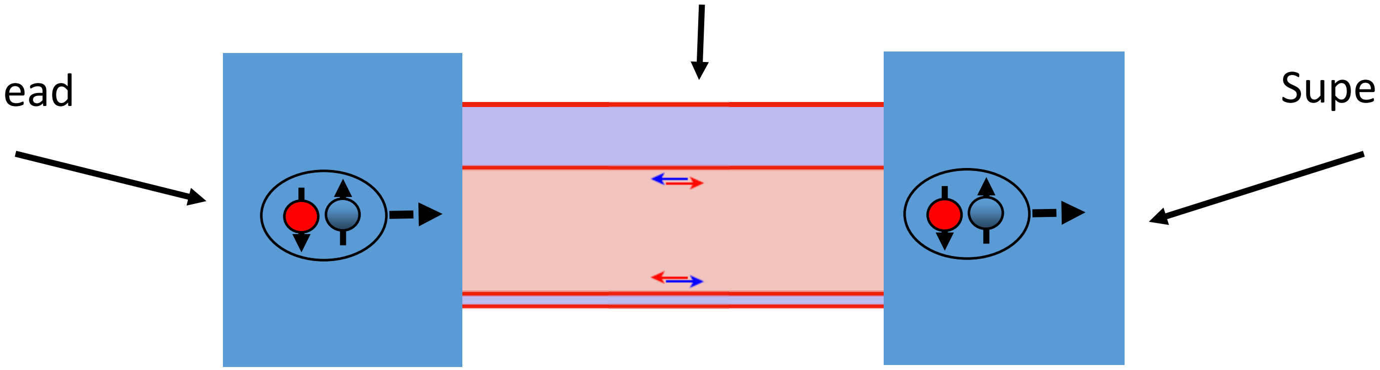

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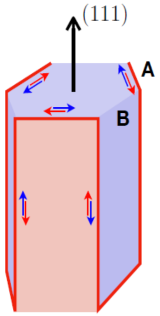

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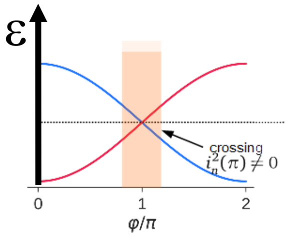

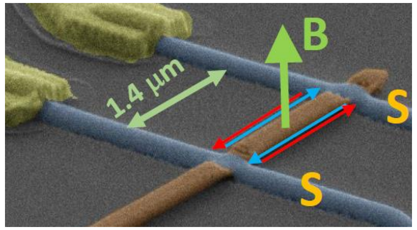

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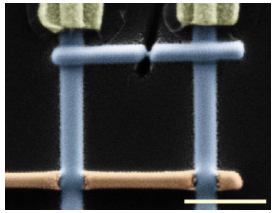
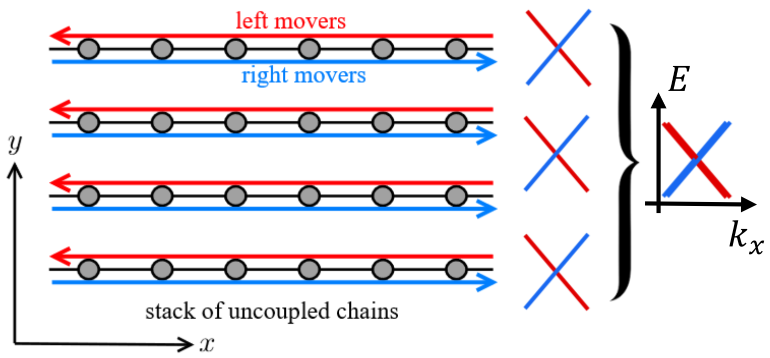
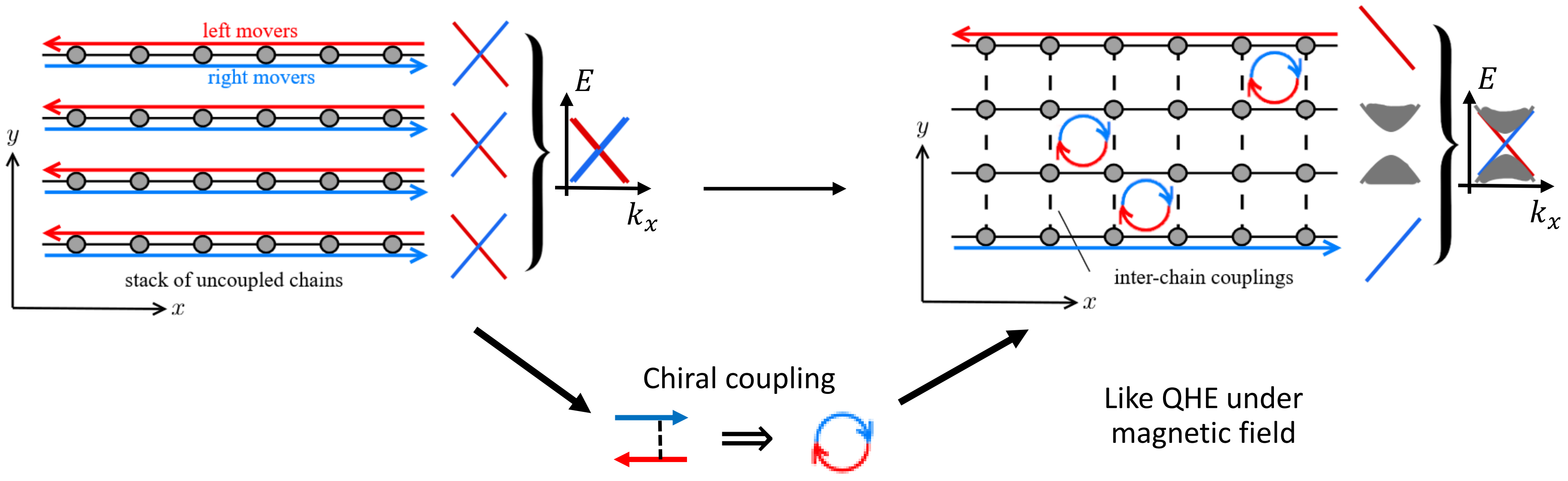


- Supercurrent vs phase, another hint for topologically protected states

Topological insulator with chiral edge state



Topological insulator with chiral edge state



Like QHE under magnetic field

$$\vec{B} = \overrightarrow{rot}\vec{A}$$

Breaks time-reversal symmetry

Topological insulator without magnetic field

$$H_{SO} = i \sum_{\langle\langle i,j \rangle\rangle, s, s'} \lambda_{SO}^{i} . \nu_{ij} . [\hat{s}_z]_{ss'} . \hat{c}_{is}^{\dagger} . \hat{c}_{js'}$$

Spin-Orbit interaction, a purely relativistic effect

2^{nd} order terms,
two 1^{st} neighbors hops,
effectively 2^{nd} neighbors hops

Topological insulator without magnetic field

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Spin-Orbit interaction, a purely relativistic effect

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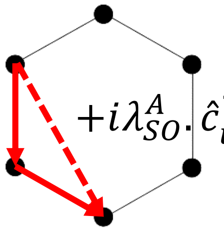
Spin up-up : $[\hat{s}_z]_{\uparrow\uparrow} = +1$

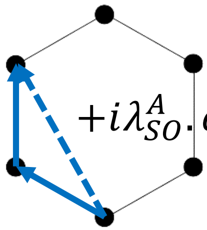
Positive rot : $\nu_{ij} = +1$



$+i\lambda^{A}_{SO}.\hat{c}^{\dagger}_{i\uparrow}.\hat{c}_{j\uparrow}$

Spin down-down : $[\hat{s}_z]_{\downarrow\downarrow} = -1$

Negative rot : $\nu_{ji} = -1$



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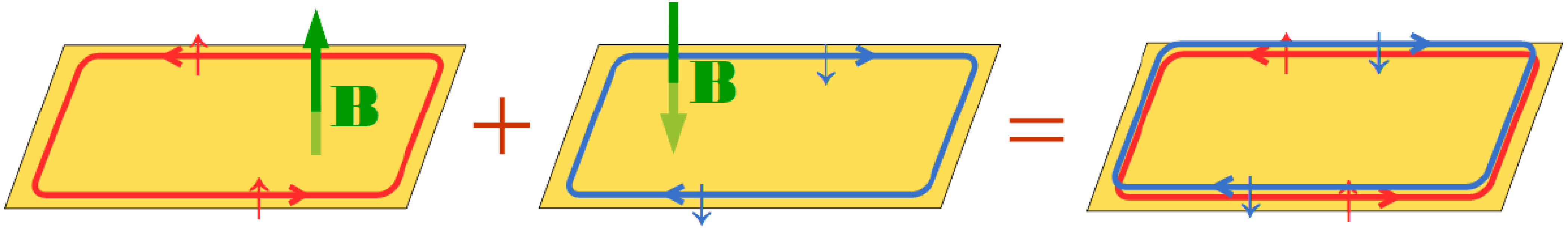
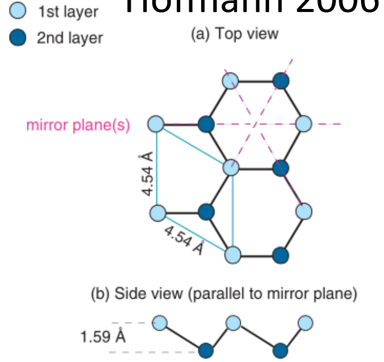


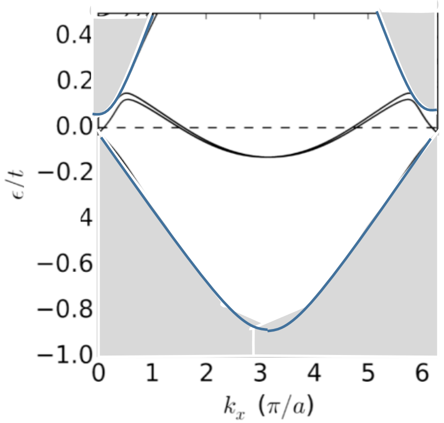
Topologically protected states in ordered Bismuth nanowires ?

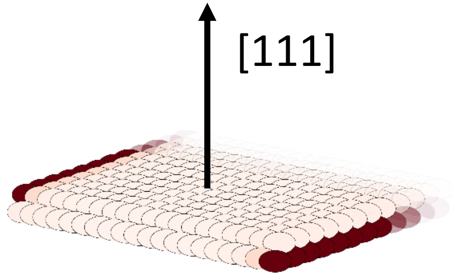
- High SOI, key ingredient for TIs with TRS
- Bi 111 bilayer ribbon is a 2D TI with helical edge states (Murakami, PRL 2006)

Hofmann 2006



(111) Bi bilayer





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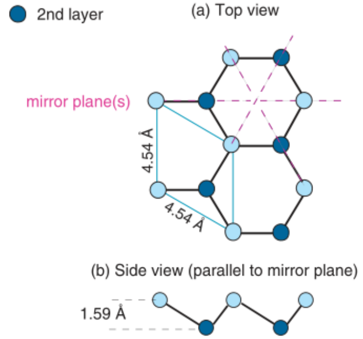
- 5 Bi 111 bilayers is somewhat a 2D TI, surface states + 1D hinge states (Murani et al., Nat. Comm. 2017)

- >8 Bi 111 bilayers predicted not TI anymore (according to Liu et al., PRL 2011)

Hofmann 2006



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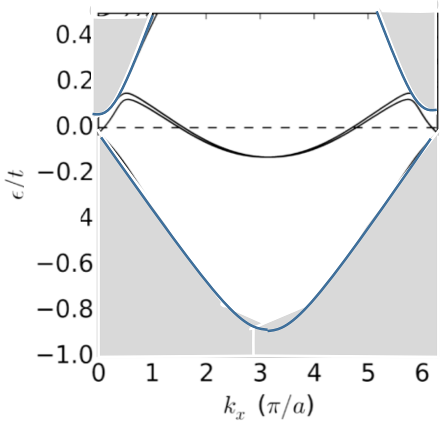
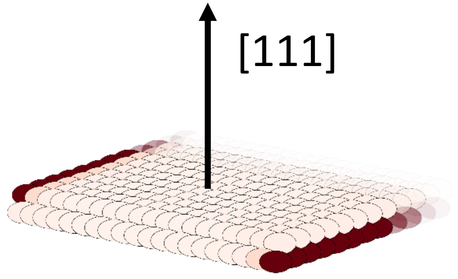
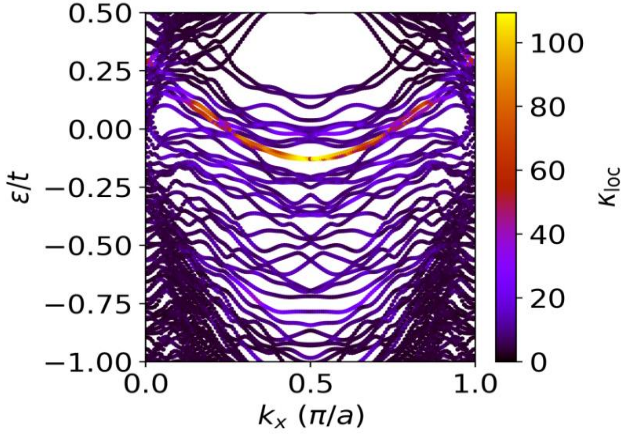
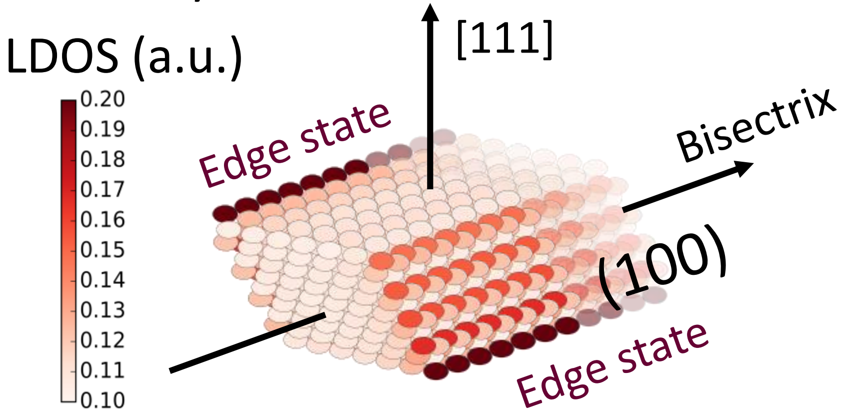




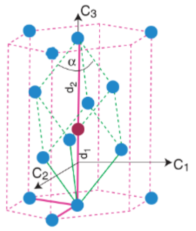
(111) Bi 5 bilayers



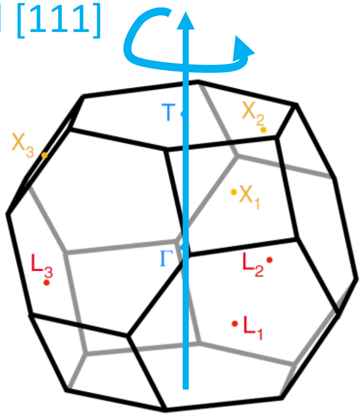


Topologically protected states in ordered Bismuth nanowires ?

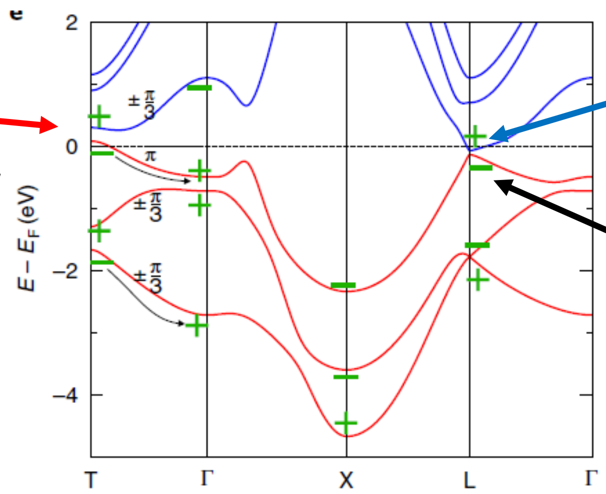
- Bulk Bi not 3D TI, semi-metal



C_3 around [111]



heavy holes pockets, ~42meV above ε_F



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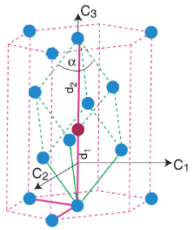

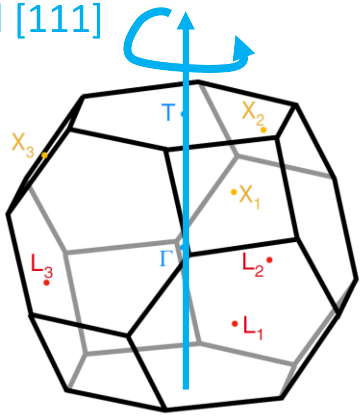

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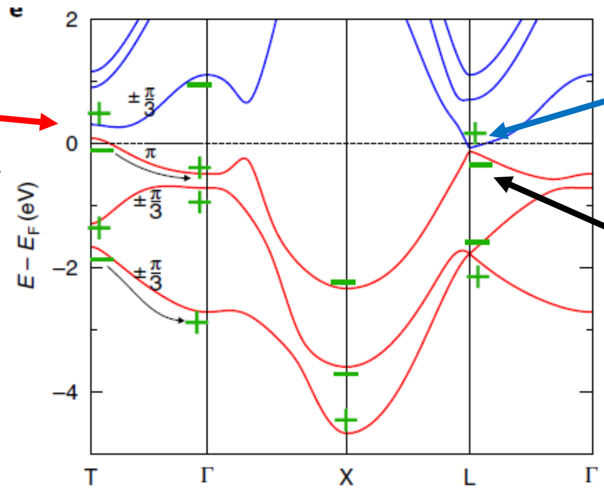

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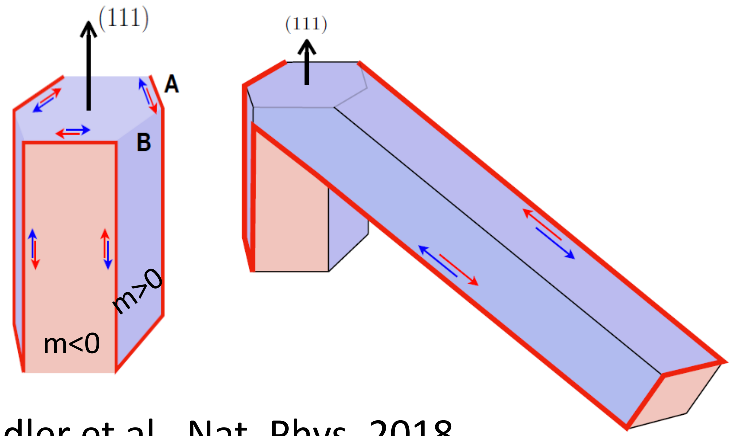
  => pure monocrystalline Bi is predicted to be a HOTI
  => no gapless surface states, but helical hinge states



Schindler et al., Nat. Phys. 2018

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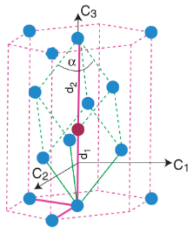

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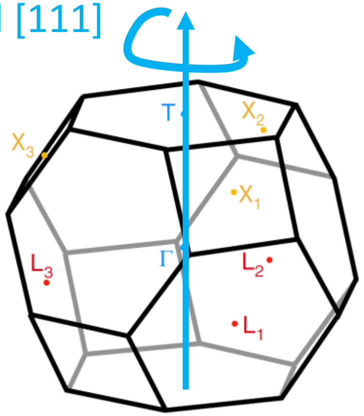

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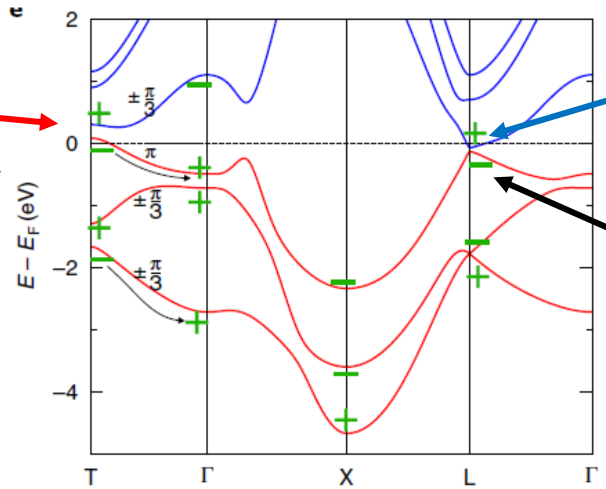

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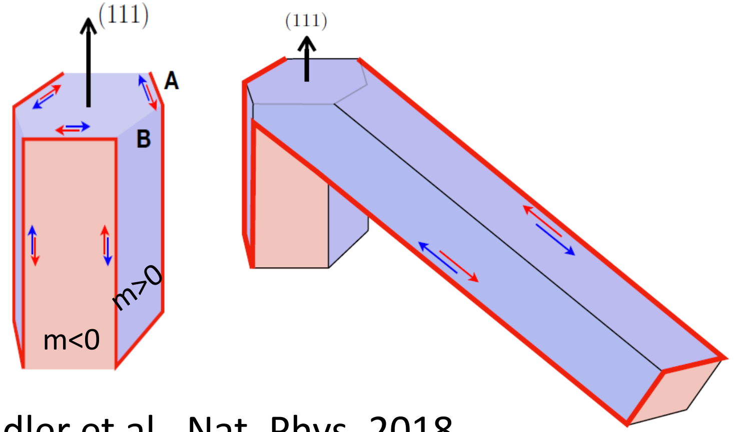
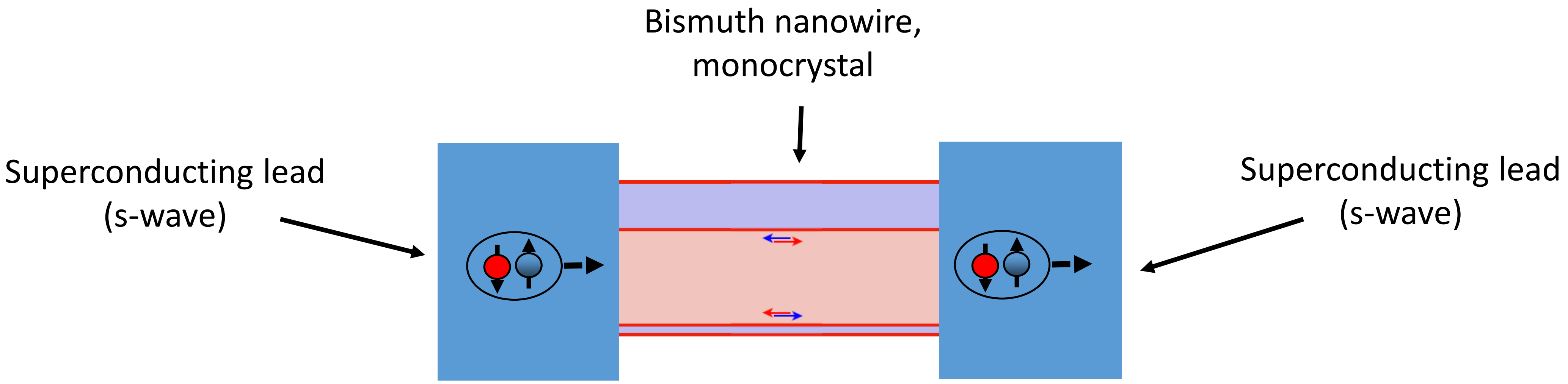


Schindler et al., Nat. Phys. 2018

- But… Bi is still a semi-metal and not an insulator
- The geometry of the samples is difficult to control, and electron transport may be affected by various finite size effects
- The HOTI picture is recent, and it is not clear what to expect experimentally

Why using superconducting proximity effect ?



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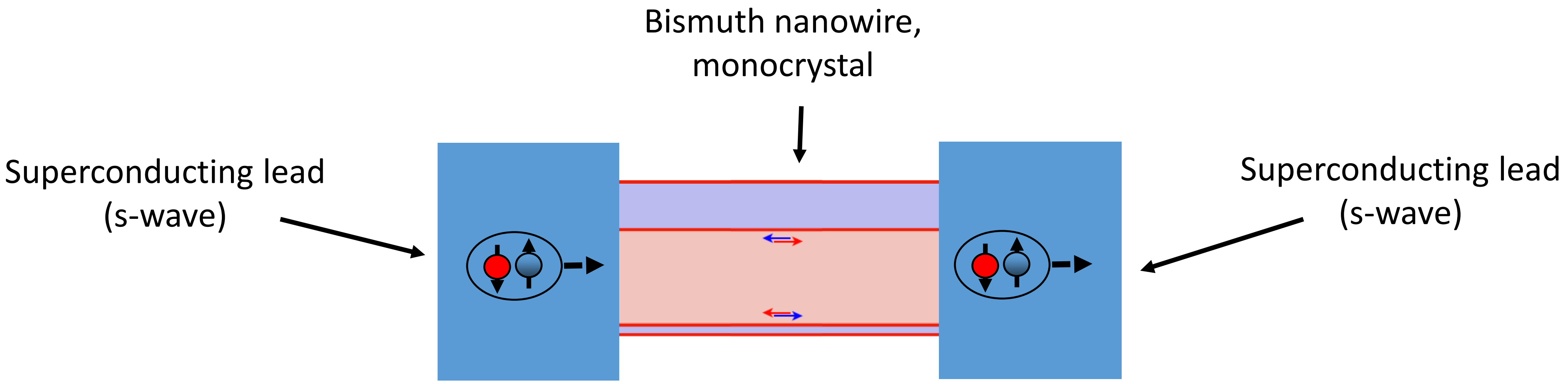
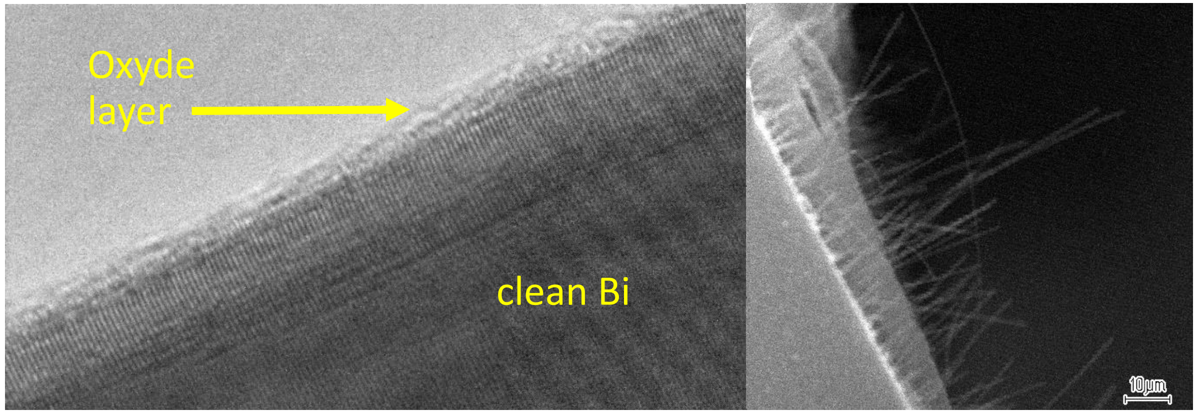


Allow to:

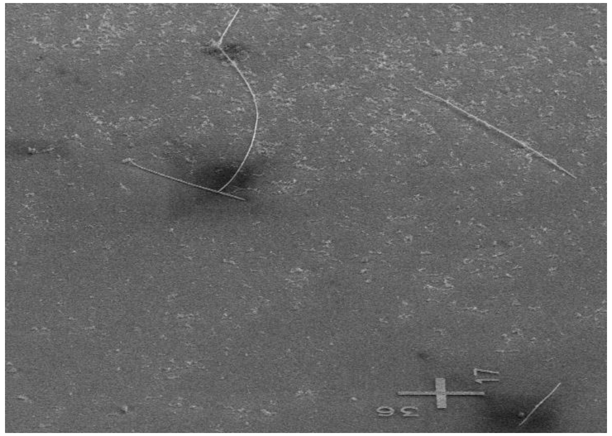
- Reduce the contribution of diffusive states compared to the ballistic ones (phase coherence of the e-h pair required)
- Spatial distribution of the supercurrent through the junction with criticalcurrent-flux relation
  => is there 1D states ? Where ?
- Dependence of the energy on the superconducting phase with supercurrent-phase relation
  => are the states perfectly transmitted, with perfect crossing at $\varphi = \pi$ as expected for topologically protected states ?

Sample fabrication



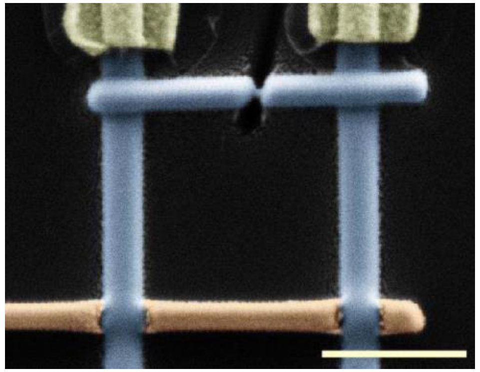
Bismuth nanowires:

- Previously grown by sputtering on a hot SiO2 substrate covered with a thin wetting layer and picked up and droped with a clean piece of wiper
  => nice ordered nanowires of D~200nm L~10um (IMT RAS, Chernogolovka)
- Now grown by sputtering on a cold substrate (reach ~70°), deposited with 10ns UV laser pulses
  => nice ordered nanowires of D~100nm L~20um, but potentially some strain
- Checked with Transmission Electron Microscope on the edges (IMT RAS, Chernogolovka)
- Selected and checked with Electron BackScattering Diffraction (ICMMO, Orsay)

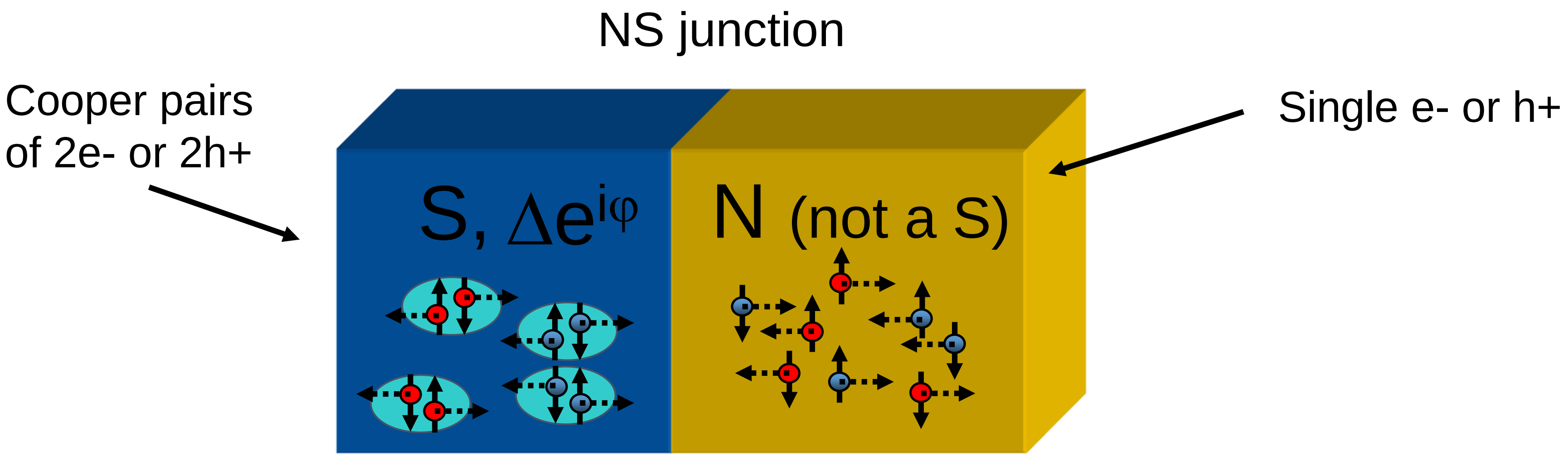


Contacts:

- Superconducting contacts with disordered W deposited with Ga+ Focused Ion Beam, after etching
  => $T_c \lesssim 5\ K, \Delta_0 \lesssim 1\ meV$ (CSNSM, Orsay)
- Larger metalic contacts with 200nm evaporated Au on top of 4nm of Ti



Superconducting proximity effect: Andreev reflexion



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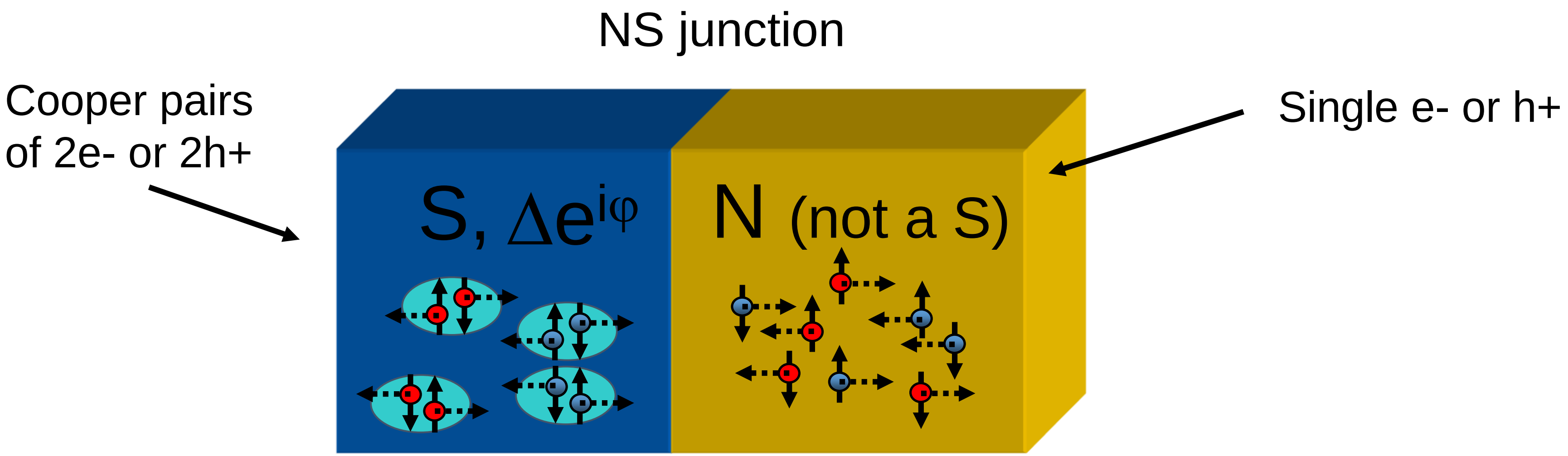

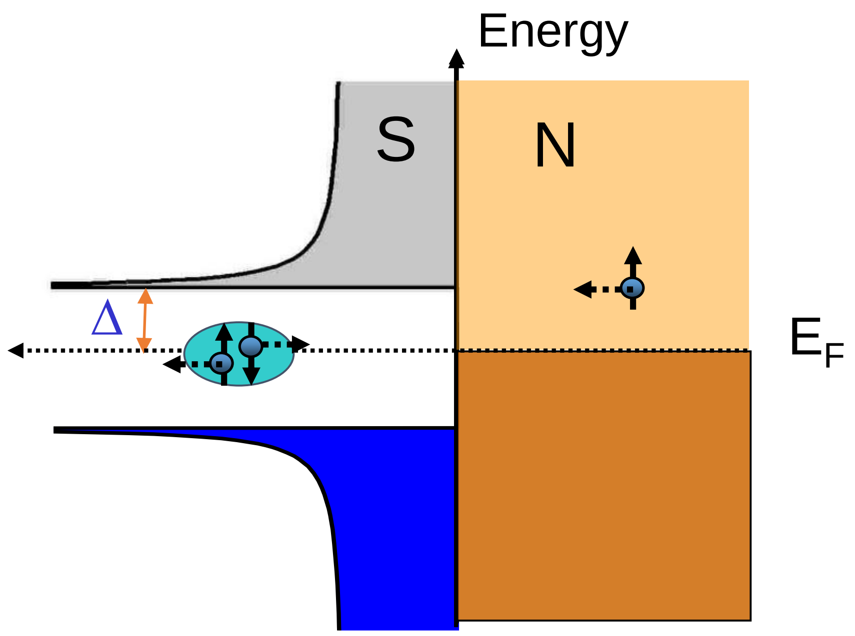

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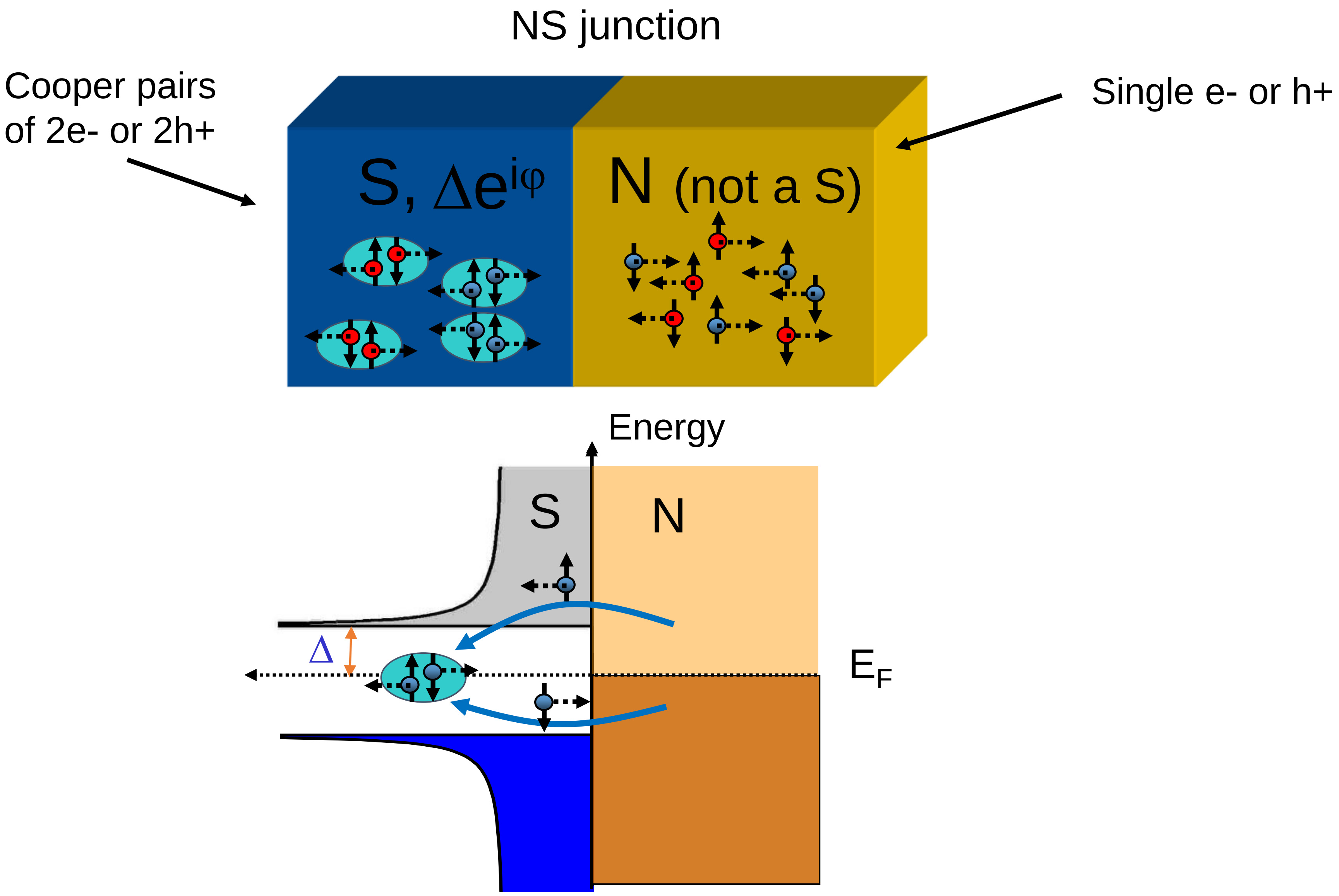
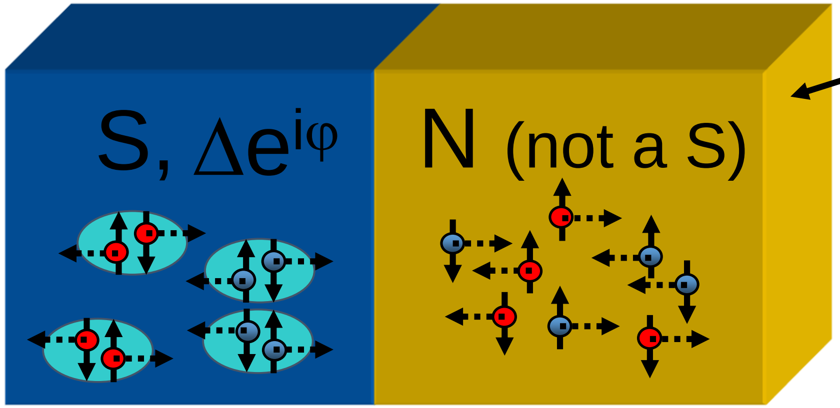


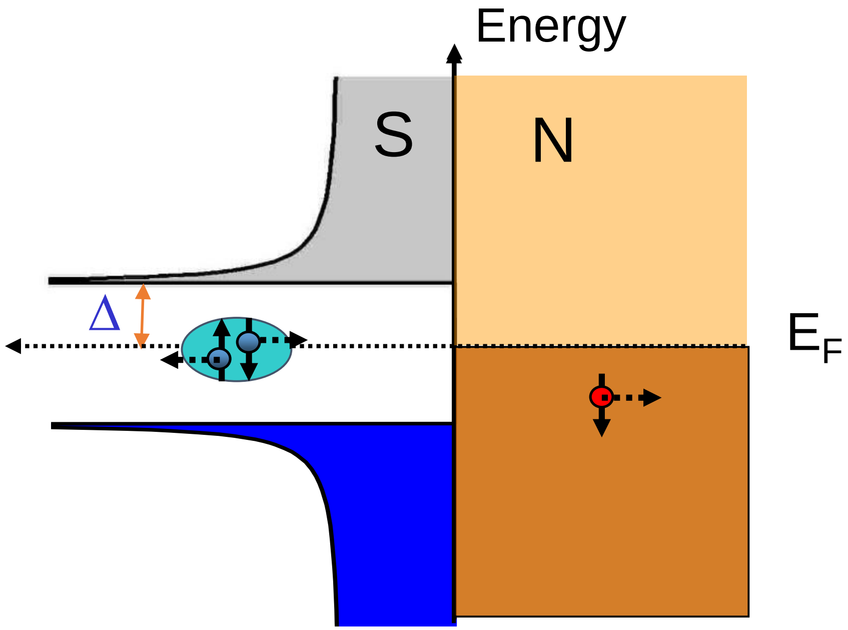
Superconducting proximity effect: Andreev reflexion

NS junction

Cooper pairs
of 2e- or 2h+



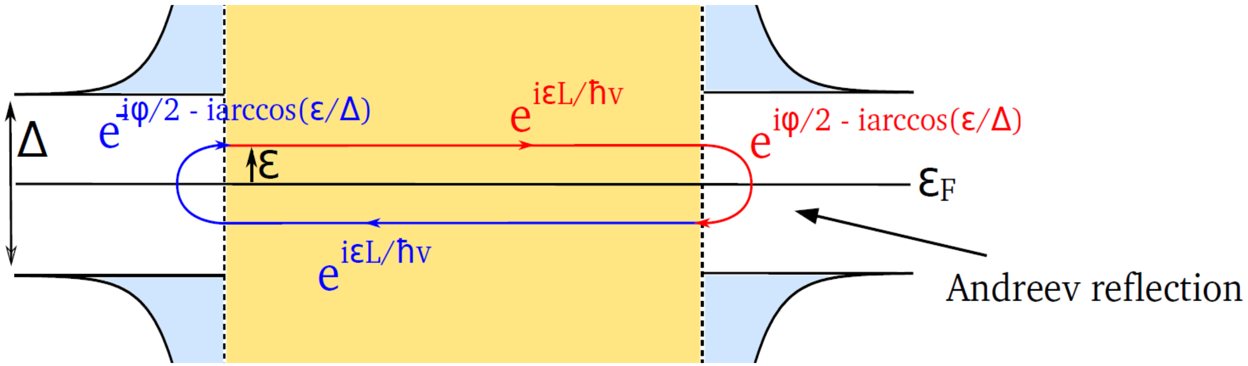
Single e- or h+



Single e- reflected as a
h+ with opposite spin

Superconducting proximity effect: Andreev Bound States

Resonance condition on accumulated phase: Andreev Bound States with eigenenergies ϵ_m



$$\frac{2\epsilon L_N}{\hbar v_F} - 2\,arccos\,\frac{\epsilon}{\Delta_0} \pm \Delta\phi = 2\pi m$$

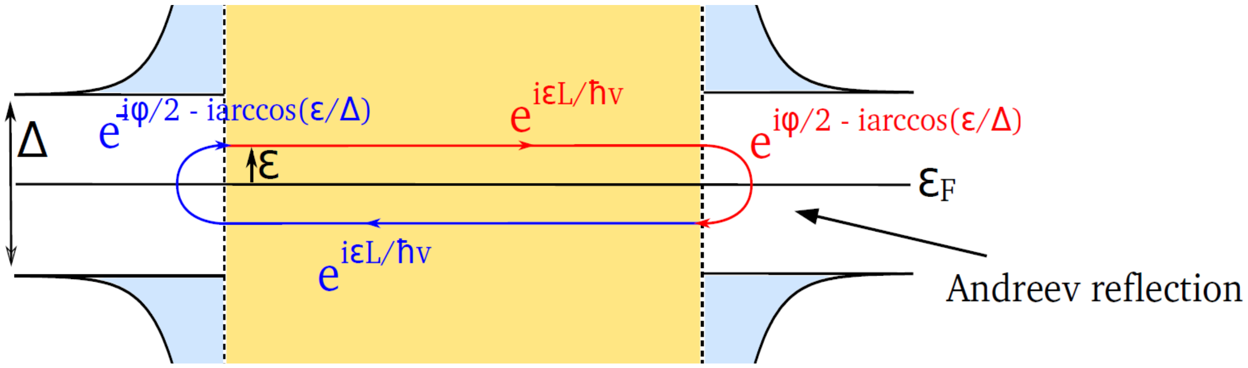
Propagation Through N

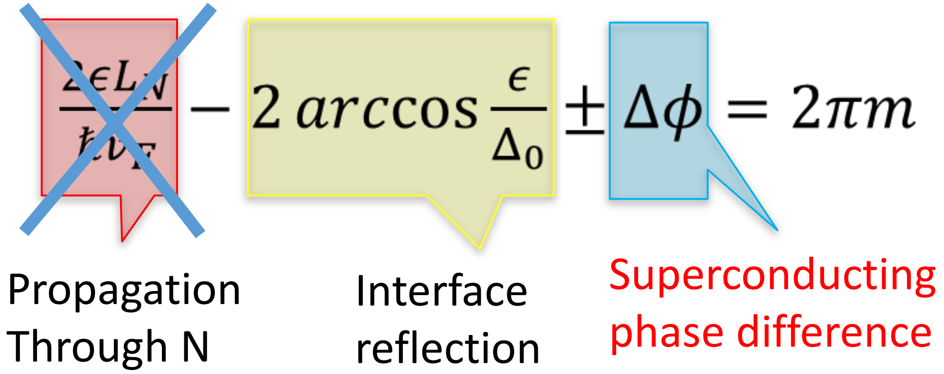
Interface reflection

Superconducting phase difference

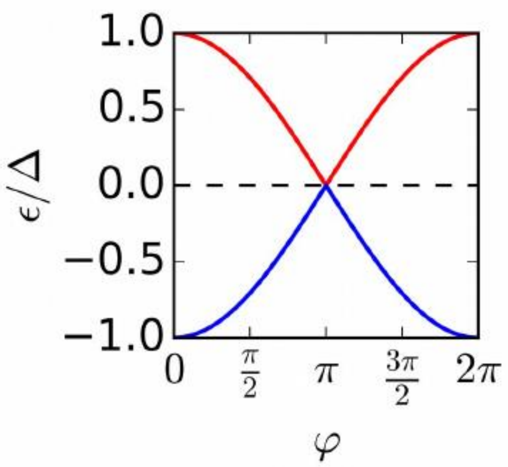
Superconducting proximity effect: Andreev Bound States

Resonance condition on accumulated phase: Andreev Bound States with eigenenergies ϵ_m



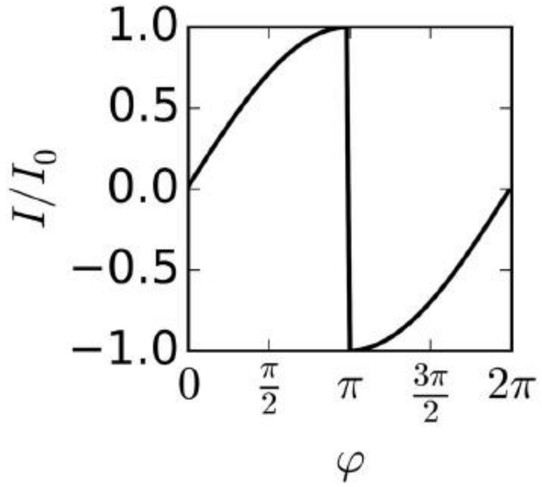


ABS spectrum



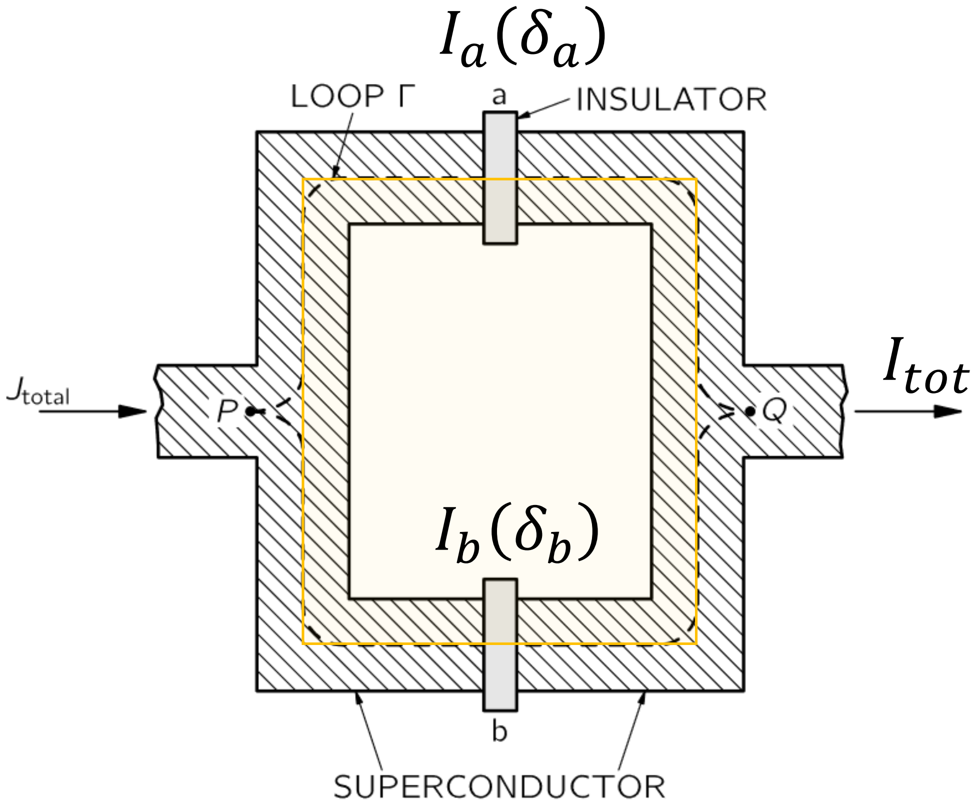
$$I = \sum_{-\infty}^{0} \frac{\partial \epsilon_n}{\partial \varphi} f(\epsilon_n)$$

ABS supercurrent
at thermodynamic limit



Show a behaviour in sinus with sharp jumps at π

Supercurrent vs magnetic flux: SQUID



$$I_{tot}(\delta_a, \delta_b) = I_a(\delta_a) + I_b(\delta_b)$$

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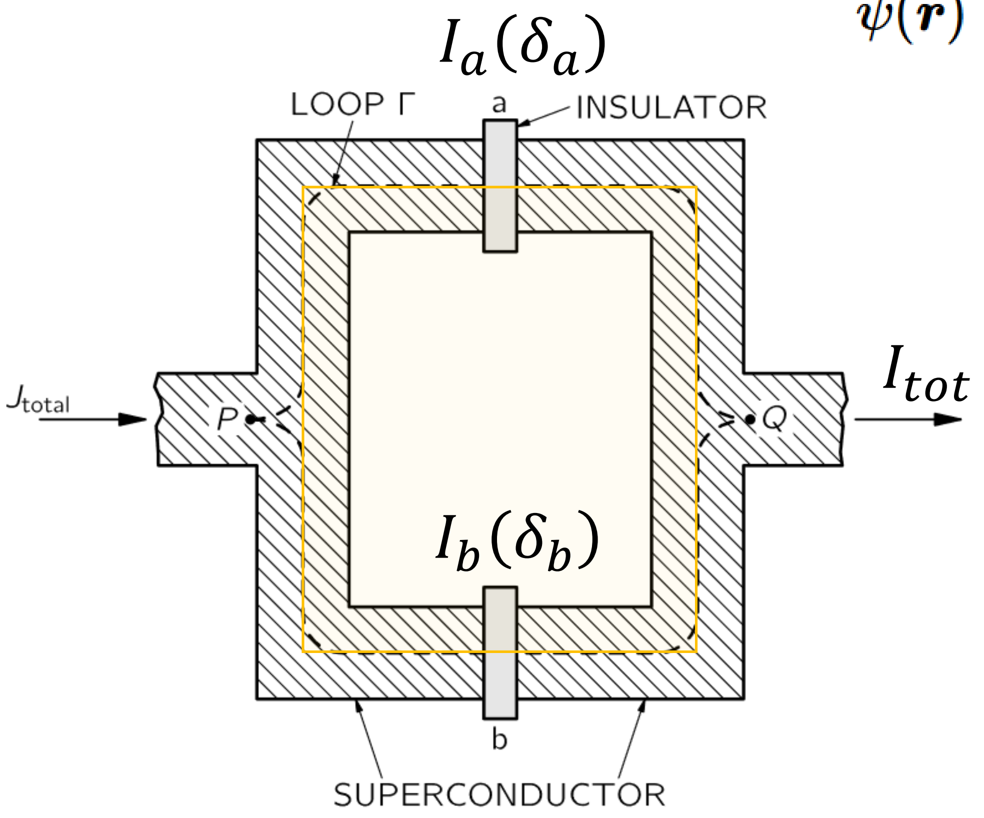


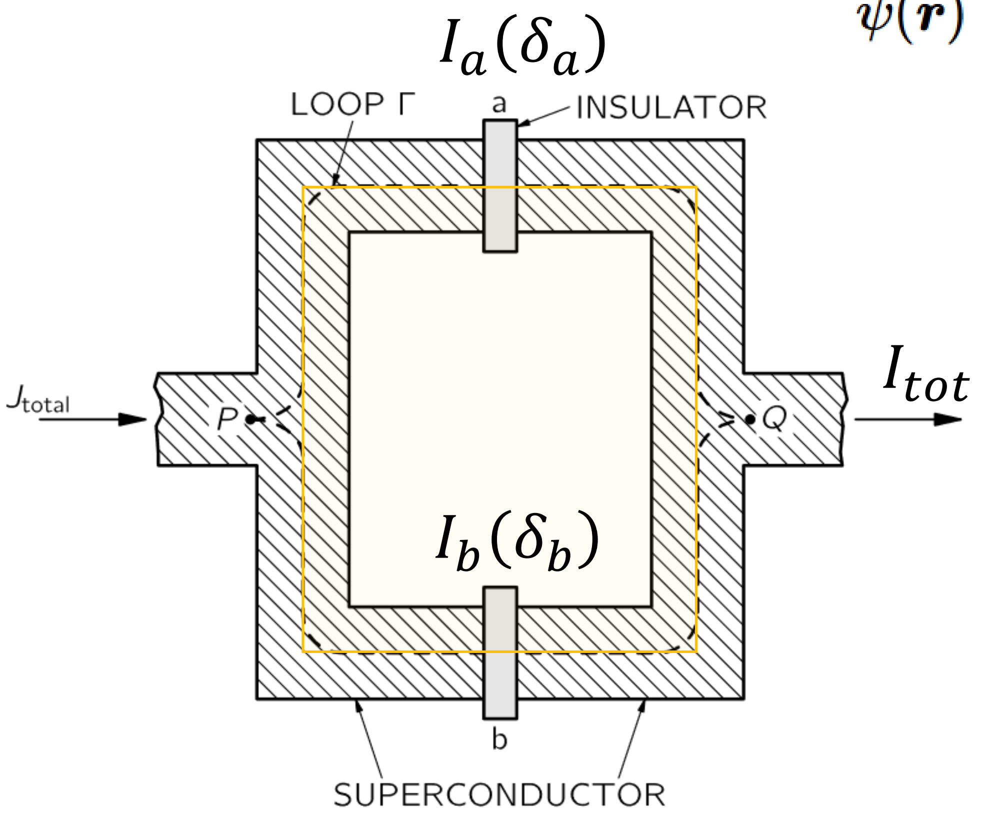
$$\psi(\boldsymbol{r}) = \rho^{1/2}(\boldsymbol{r}) e^{i\theta(\boldsymbol{r})}$$

$$\boldsymbol{J} = \frac{\hbar}{m}\left(\nabla\theta - \frac{q}{\hbar}\boldsymbol{A}\right)\rho$$

Relate the quantum phase to the geometrical path

$$I_{tot}(\delta_a, \delta_b) = I_a(\delta_a) + I_b(\delta_b)$$

Supercurrent vs magnetic flux: SQUID



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$$= 0$$ in the bulk of the superconductor

$$\delta_b - \delta_a = \frac{2q_e}{\hbar}\oint_\Gamma \boldsymbol{A}\cdot d\boldsymbol{s} = 2\pi\frac{B.S}{\phi_0}$$

Phase difference controlled by magnetic flux (Aharonov-Bohm effect), analog to interferences in optics

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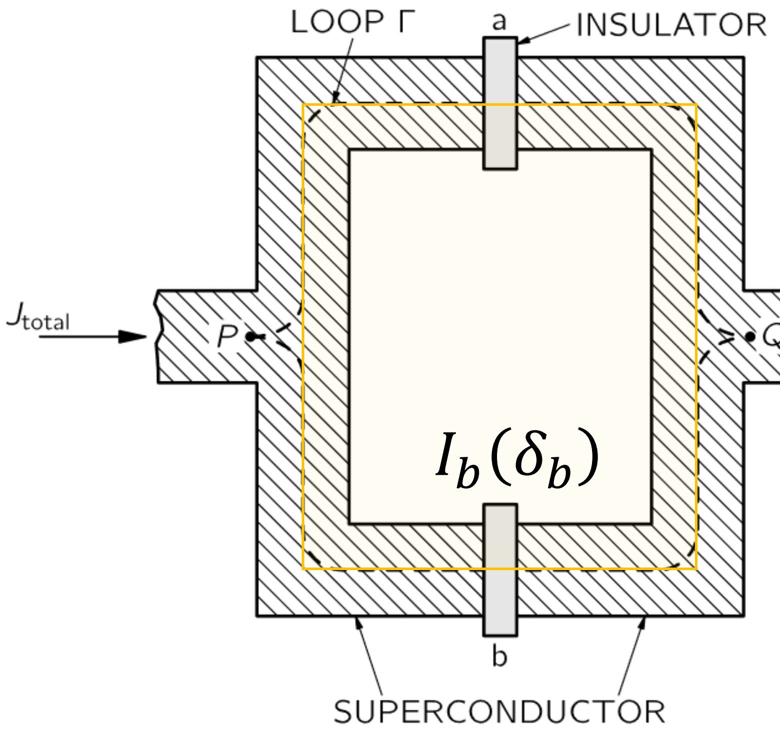
Supercurrent vs magnetic flux: SQUID

$I_a(\delta_a)$



I_{tot}

$I_b(\delta_b)$

$$\psi(\boldsymbol{r}) = \rho^{1/2}(\boldsymbol{r})e^{i\theta(\boldsymbol{r})}$$

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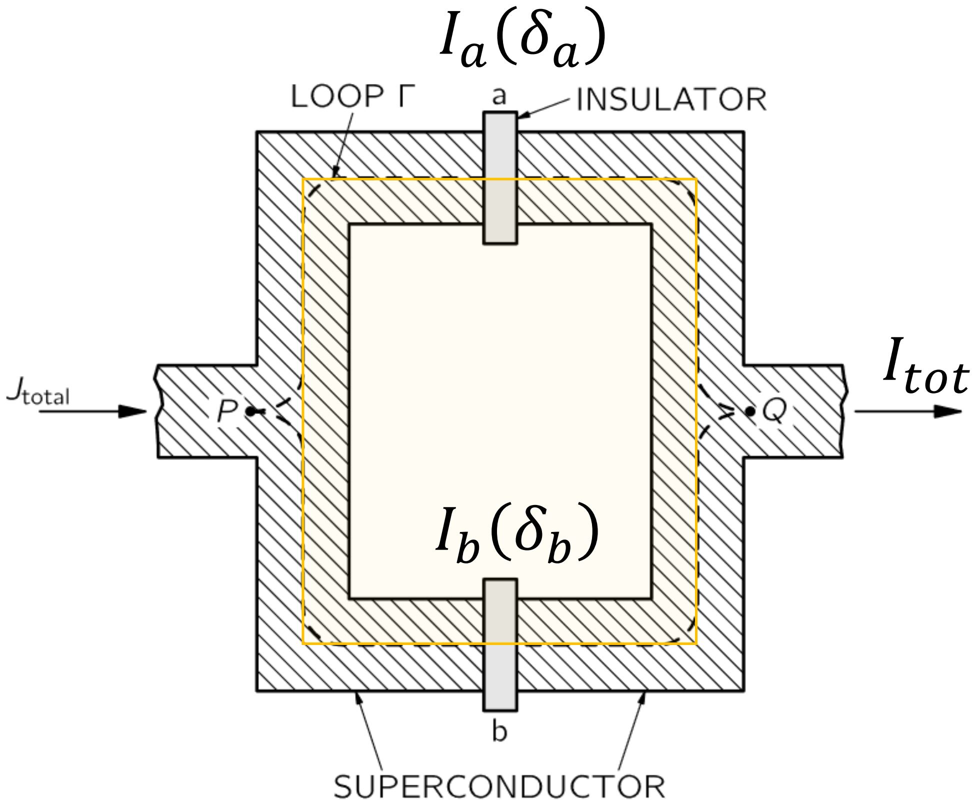
$$I_{tot}(\delta_a, \delta_b) \rightarrow I_{tot}(\delta_a, B) = I_a(\delta_a) + I_b\left(\delta_a + 2\pi\frac{B.S}{\phi_0}\right)$$

Supercurrent vs magnetic flux: SQUID



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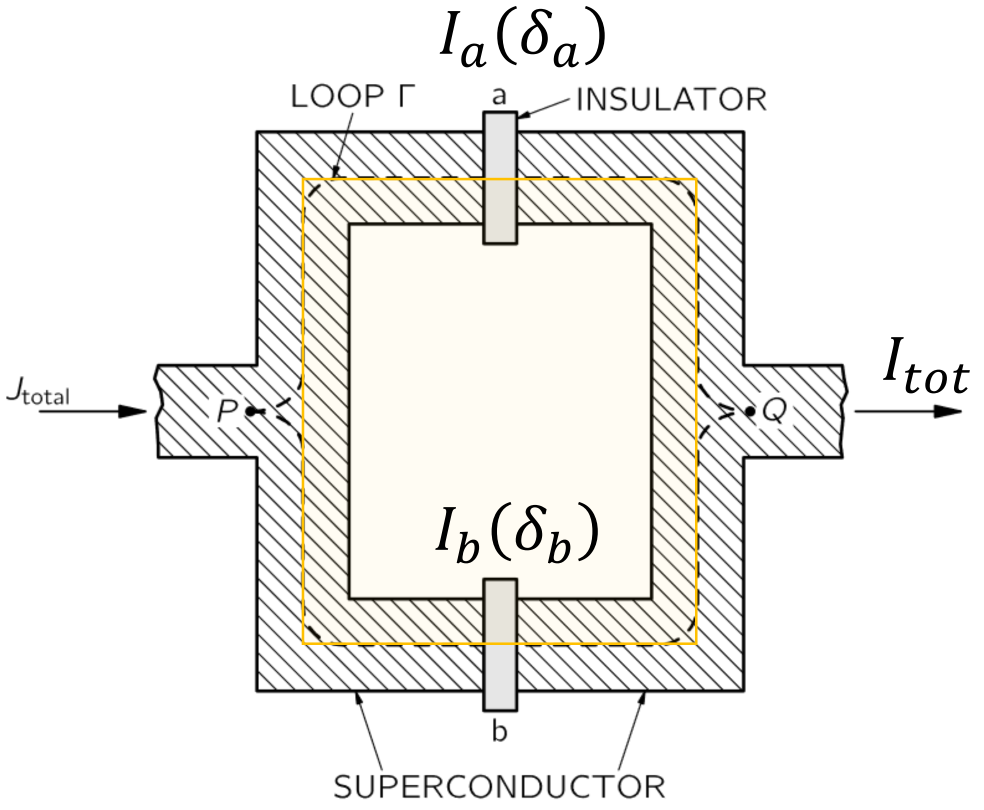
$$I_c(B) = \max_{\delta_a} I_{tot}(\delta_a, B)$$

largest current the superconducting system (symmetric SQUID) can support before becoming dissipative

Supercurrent vs magnetic flux: SQUID



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largest current the superconducting system (symmetric SQUID) can support before becoming dissipative

$$I_c\left(B + n\frac{\phi_0}{S}\right) = I_c(B)$$

$$\Delta B = \frac{\phi_0}{S}$$

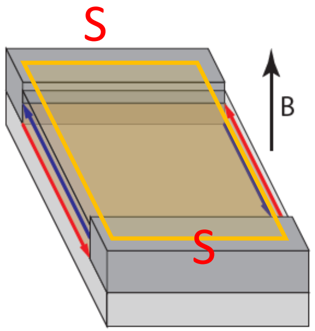
Current of the whole junctions ΔB periodic

Supercurrent vs magnetic flux: many paths

Aharonov-Bohm effect dephasing with B ⟷ time-of-flight dephasing in optics

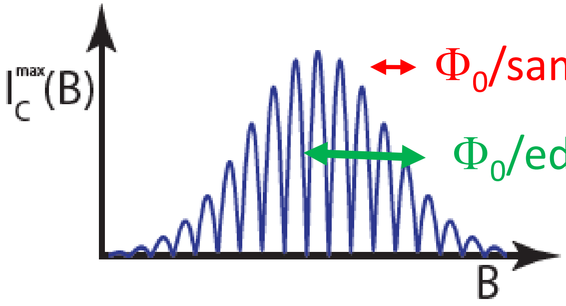
Supercurrent interferences can distinguish transport geometries

2D TI



Only 2 identical paths (edges)

$$\Delta B = \frac{\phi_0}{S}$$



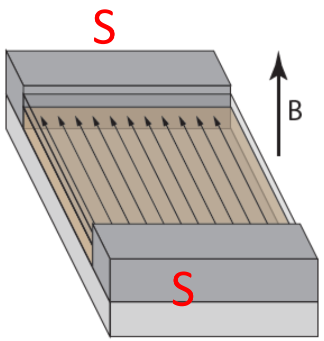
« Young pattern »

FT(narrowGate*2Dirac) = FT(narrowGate).FT(2Dirac)

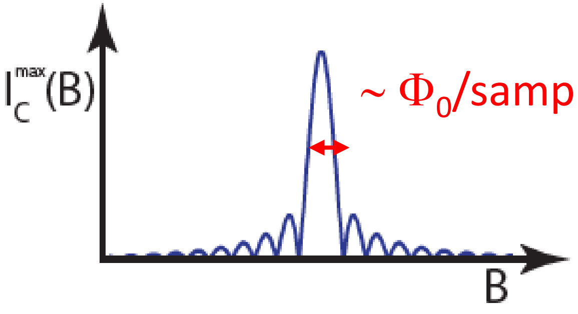
SQUID-like behaviour in a single wire

Metal

$L \ll W$



Many identical ballistic paths

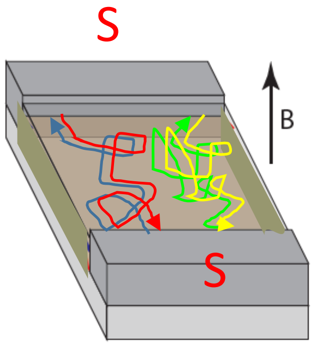


« Fraunhoffer pattern »

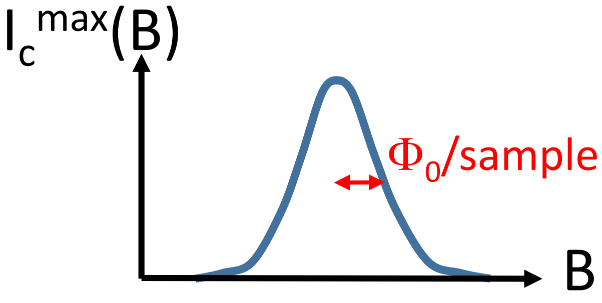
FT(wideGate)

Metal

$L \gg W$



Many diffusive paths

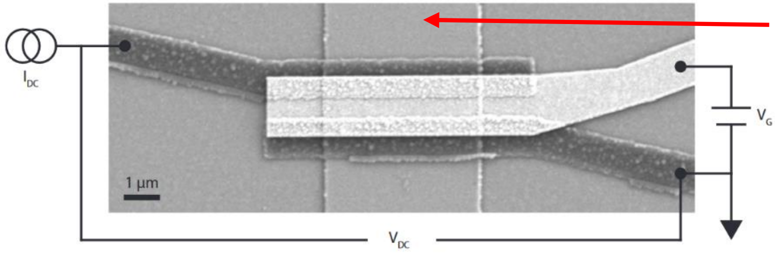


Gaussian decay

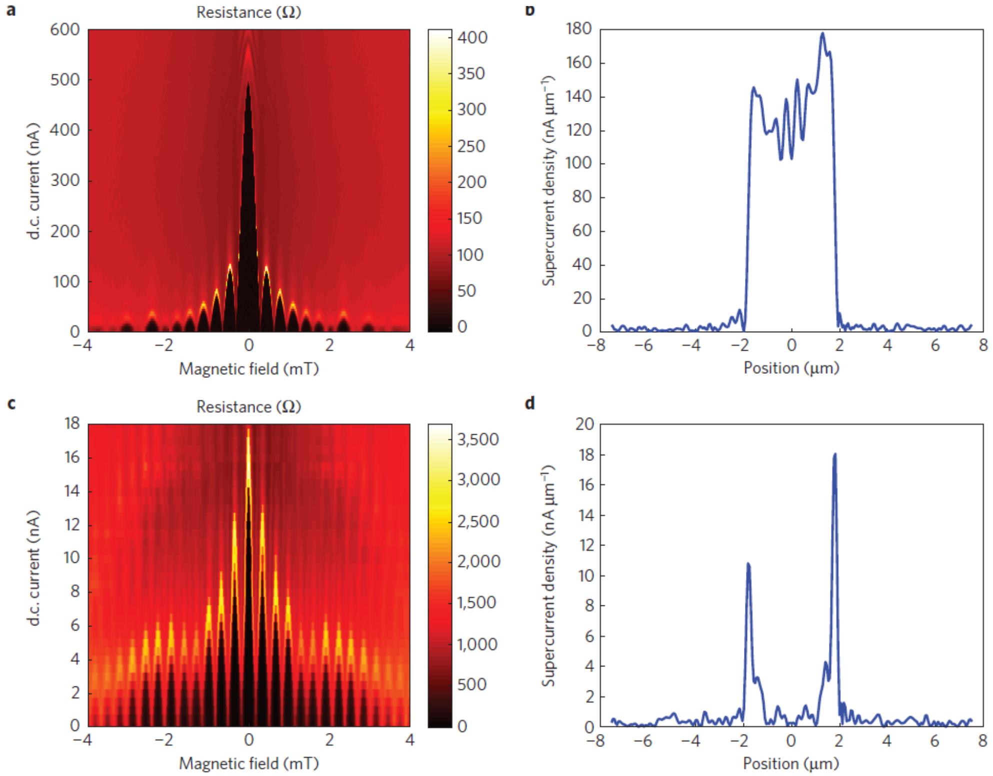
FT(narrowGate)

Critical current vs flux: experiments

$L \ll W$ case, from metal to 2D TI



HgTe/HgCdTe QW

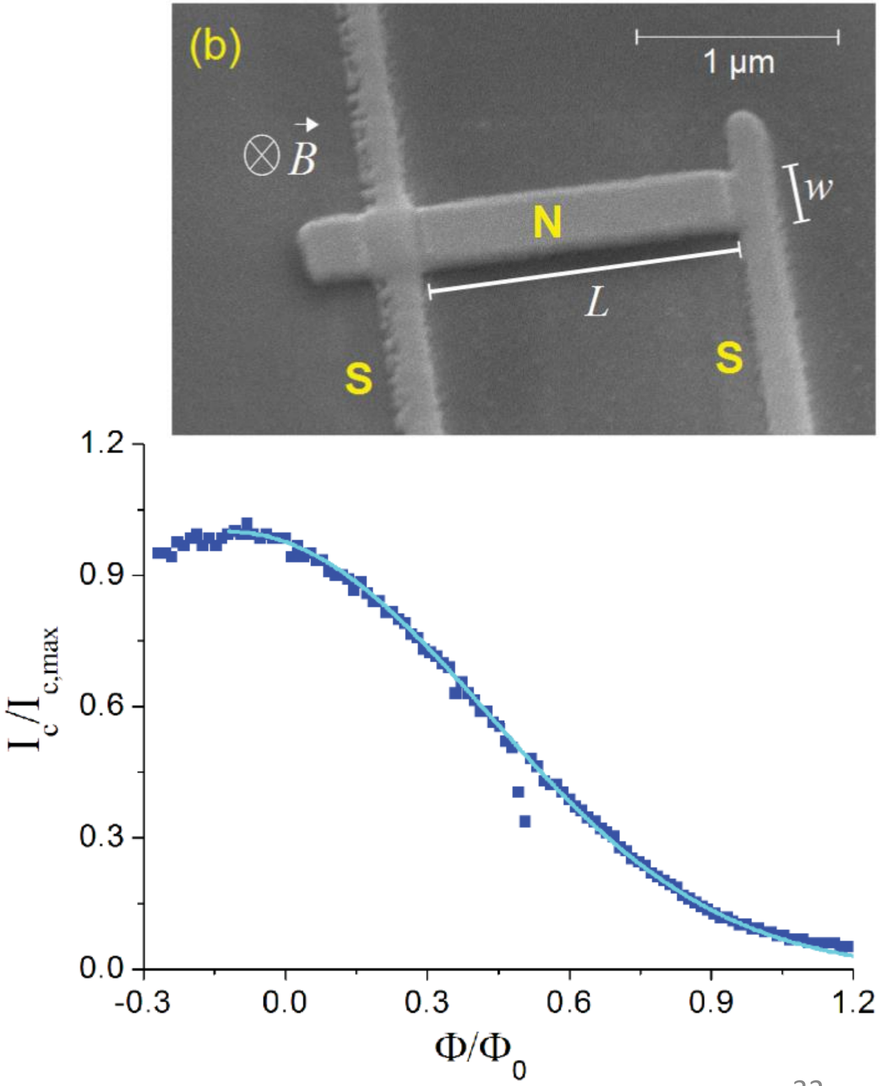


Metalic phase
Vg = 1.05V

2D TI phase
Vg = -0.42V

Hart et al., Nat. Phys. 2014

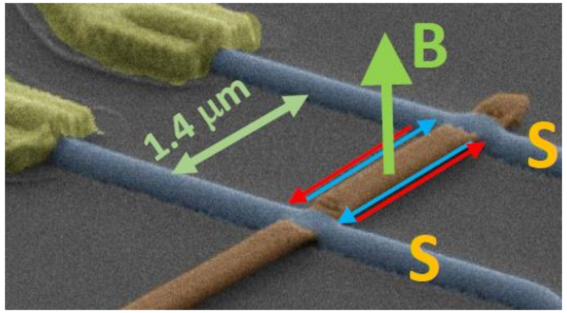
L $\gg W$ metalic case

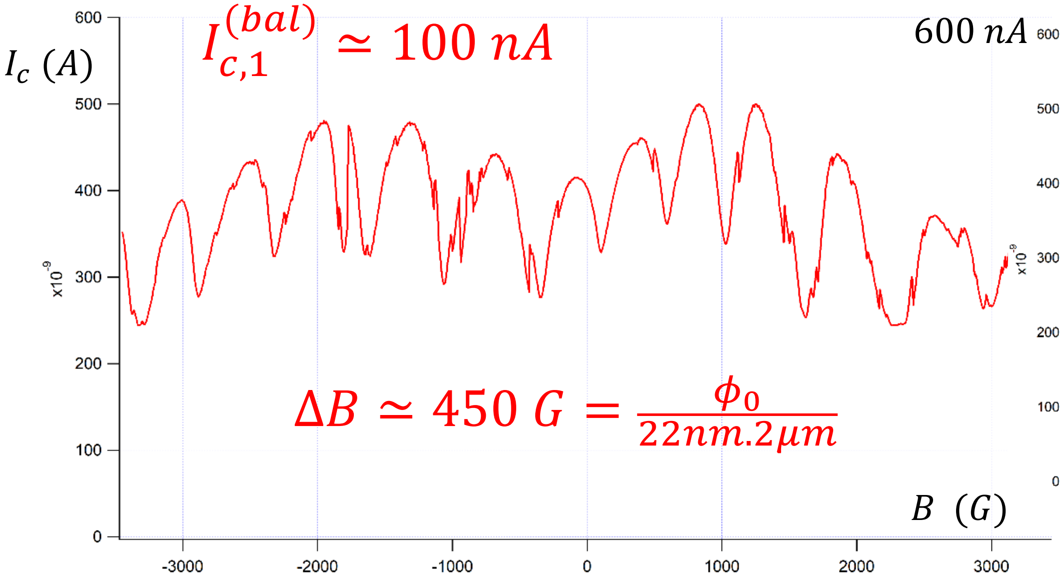


Chiodi et al., PRB 2012

Critical current vs flux: experiments on Bi

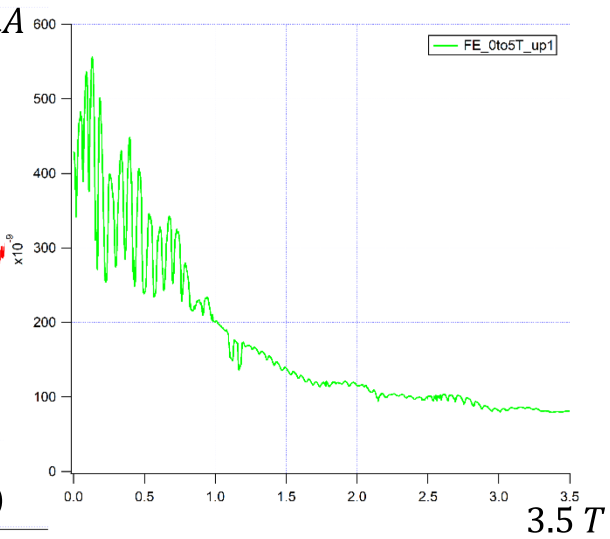
Ongoing experiment, ~100nm large Bi wire, 111 axis





$I_{c,1}^{(bal)} \simeq 100\ nA$

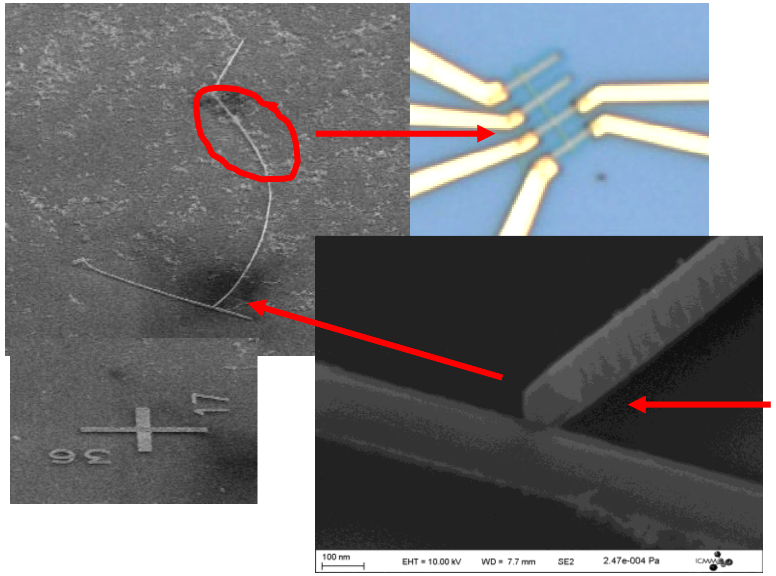
$\Delta B \simeq 450\ G = \frac{\phi_0}{22nm.2\mu m}$

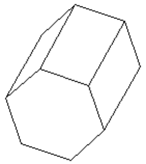


$\Delta B \simeq 1\ T = \frac{\phi_0}{1nm.2\mu m}$

SQUID-like behaviour
in a single wire

Survives at very
high magnetic field





=> Current carried by a small number of narrow paths

For previous experiments on Bi:
Murani et al., Nat. Comm. 2017

1D hinge states really topologically protected ?

Critical current vs flux measurement sensitive to the conduction channels geometry and distribution.

Signature of topology other than the interference between a few channels at the edges of the sample ?

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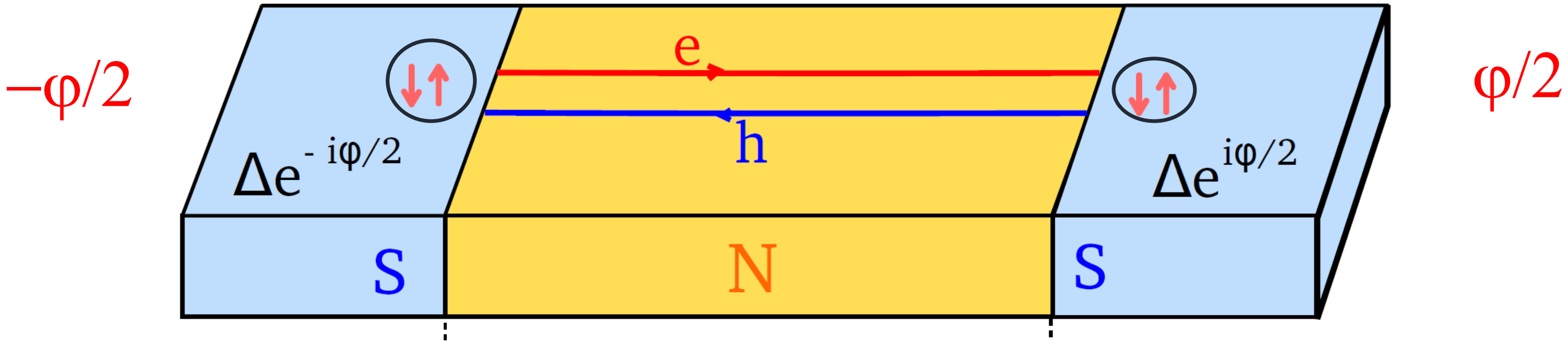
Signature of topology other than the interference between a few channels at the edges of the sample ?

Supercurrent vs phase

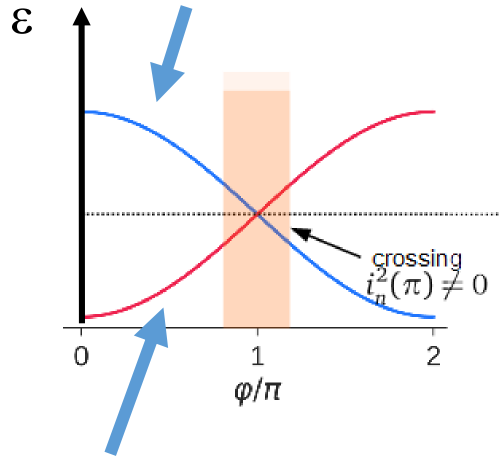
What is the behaviour of the S-Bi-S junction
when we impose a phase bias ?



Supercurrent vs phase: topo vs trivial

What happens when there is scattering ?

« left movers »



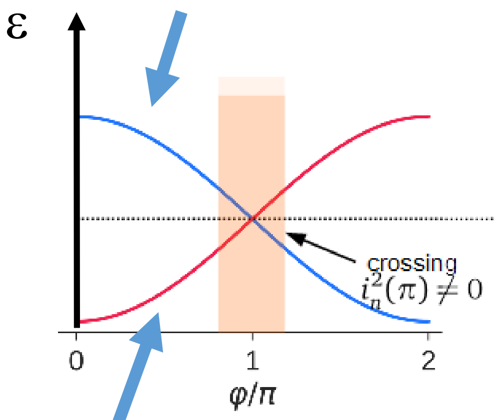
« right movers »

Supercurrent vs phase: topo vs trivial

What happens when there is scattering ?

Kwon et al., Eur. Phys. J. B 2004

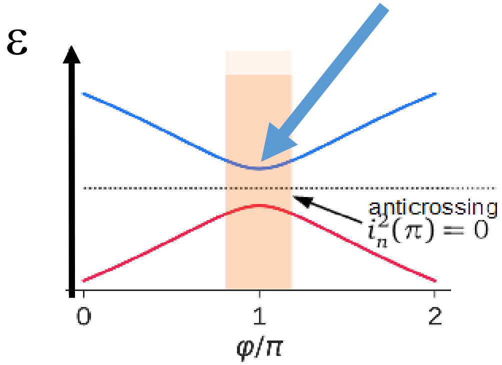
« left movers »



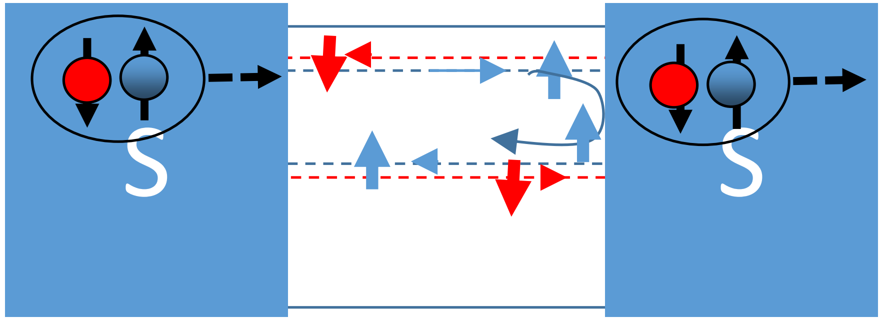
« right movers »

Trivial case

hybridization



$$E_0^{(s)}(\phi) = -\Delta_0\sqrt{1 - D\sin^2(\phi/2)}$$



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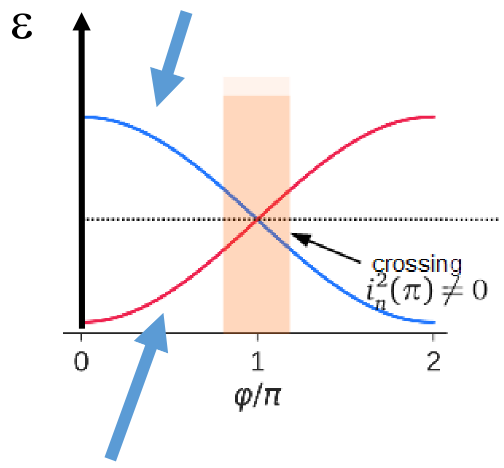

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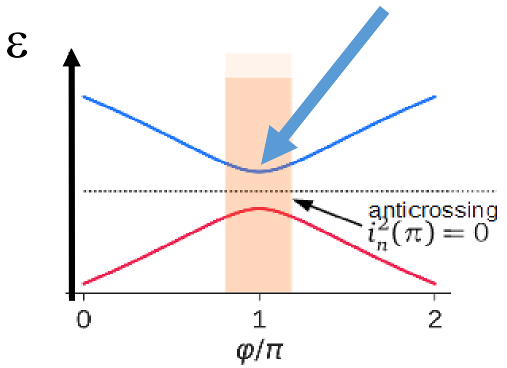
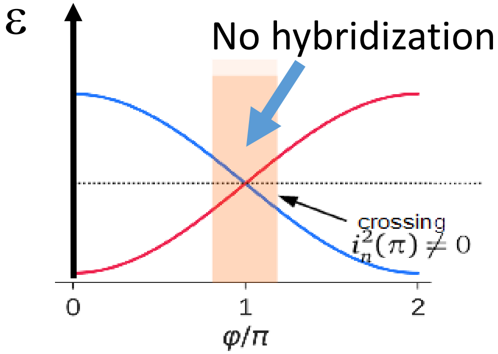


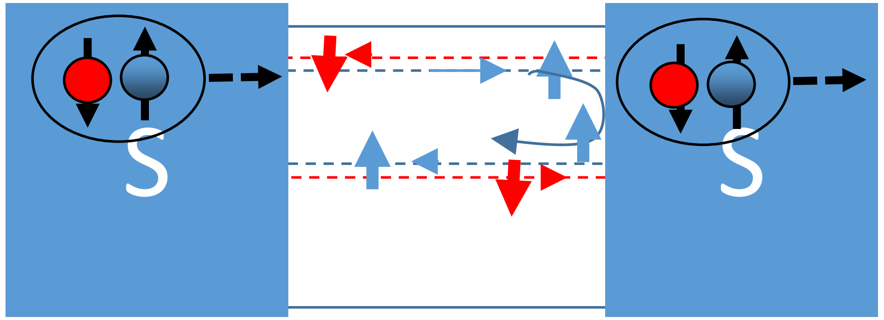
$$E_0^{(s)}(\phi) = -\Delta_0\sqrt{1 - D\sin^2(\phi/2)}$$

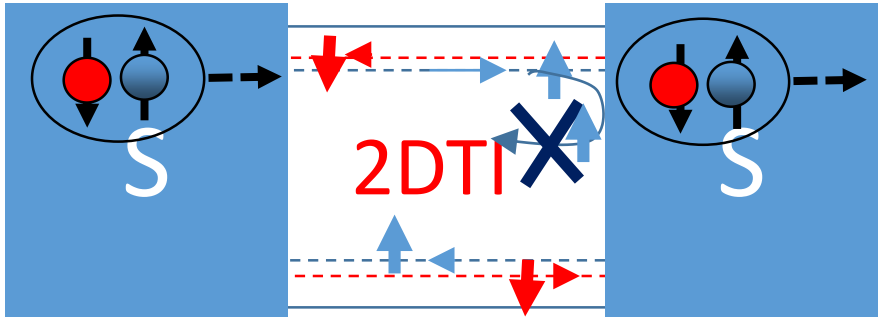
Topological case

No hybridization

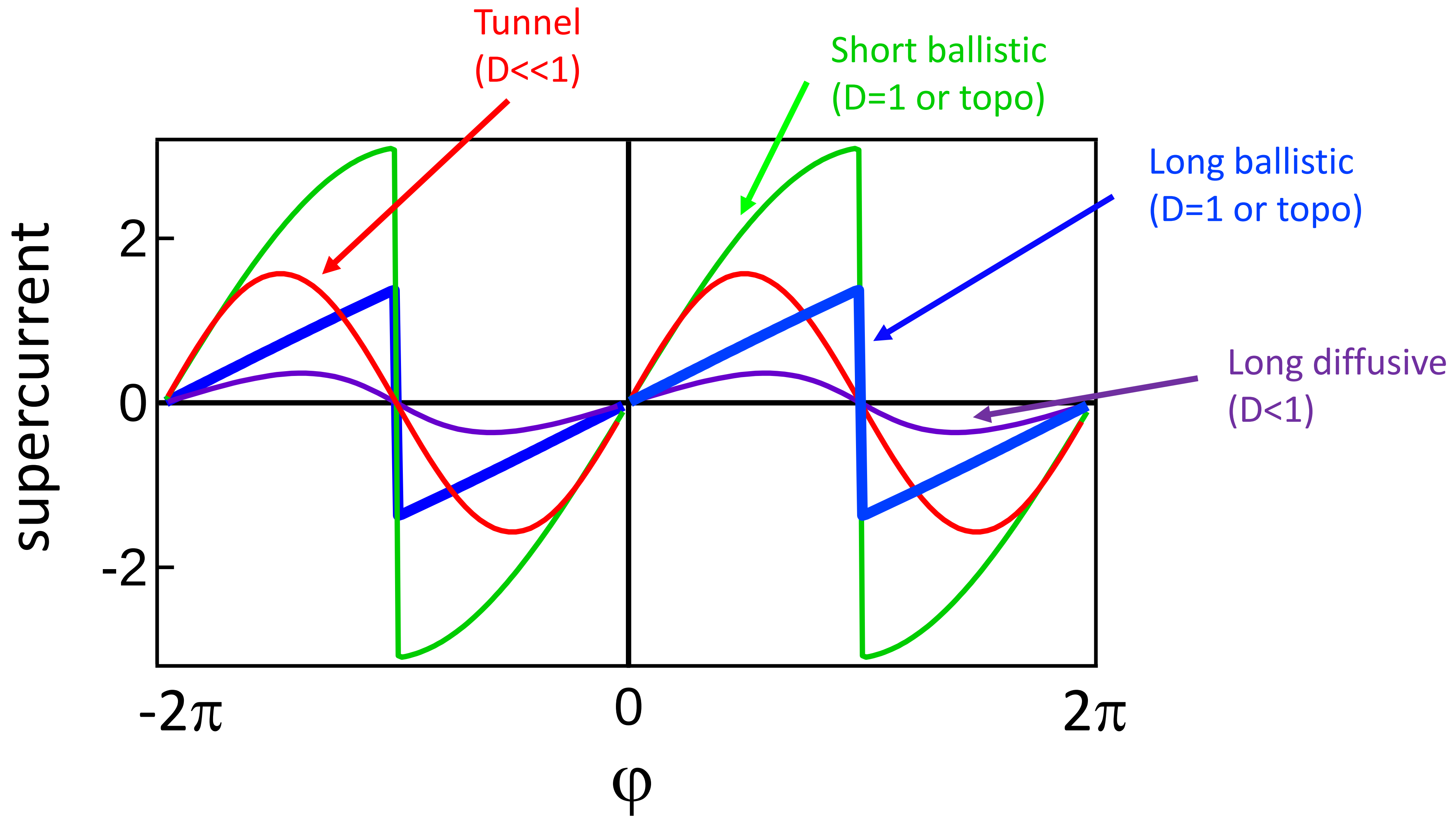


$$E_0^{(p)}(\phi) = -\Delta_0\sqrt{D}\cos(\phi/2)$$

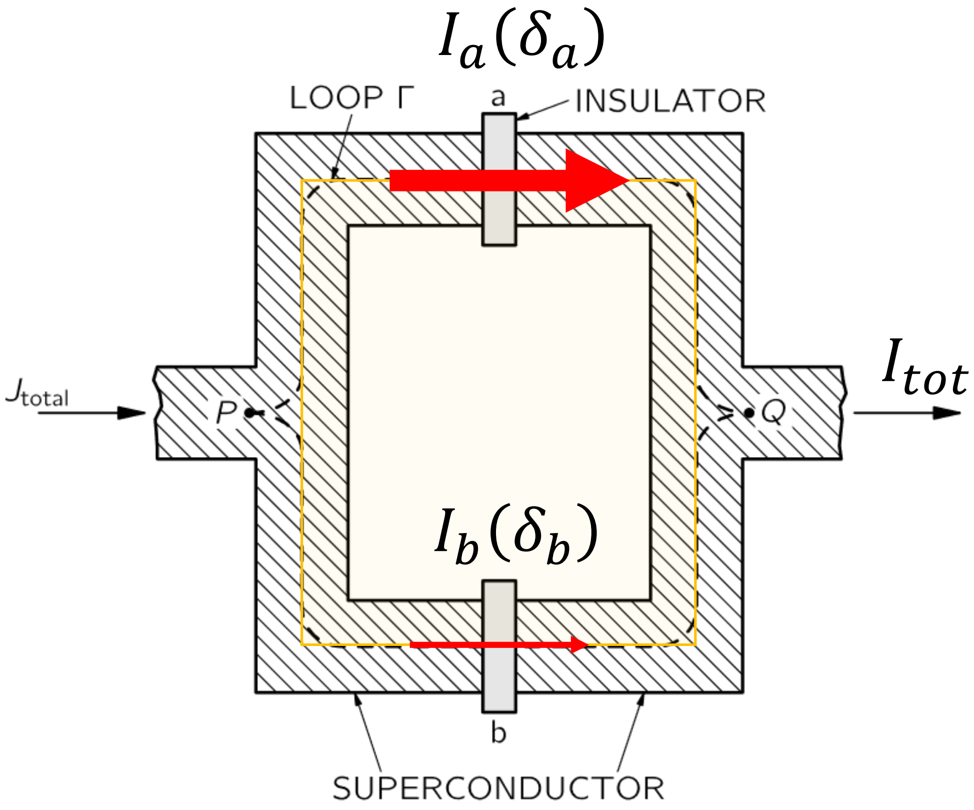




Supercurrent vs phase: expectations



Supercurrent vs phase: measurement with an asymmetric SQUID



What happens when $\max I_a(\delta_a) \gg \max I_b(\delta_b)$?

Supports the largest current when $\delta_a = \theta$ is such that the current in I_a is maximum

$$I_c(B) = \max_{\delta_a} I_{tot}(\delta_a, B) \simeq I_{tot}(\theta, B)$$

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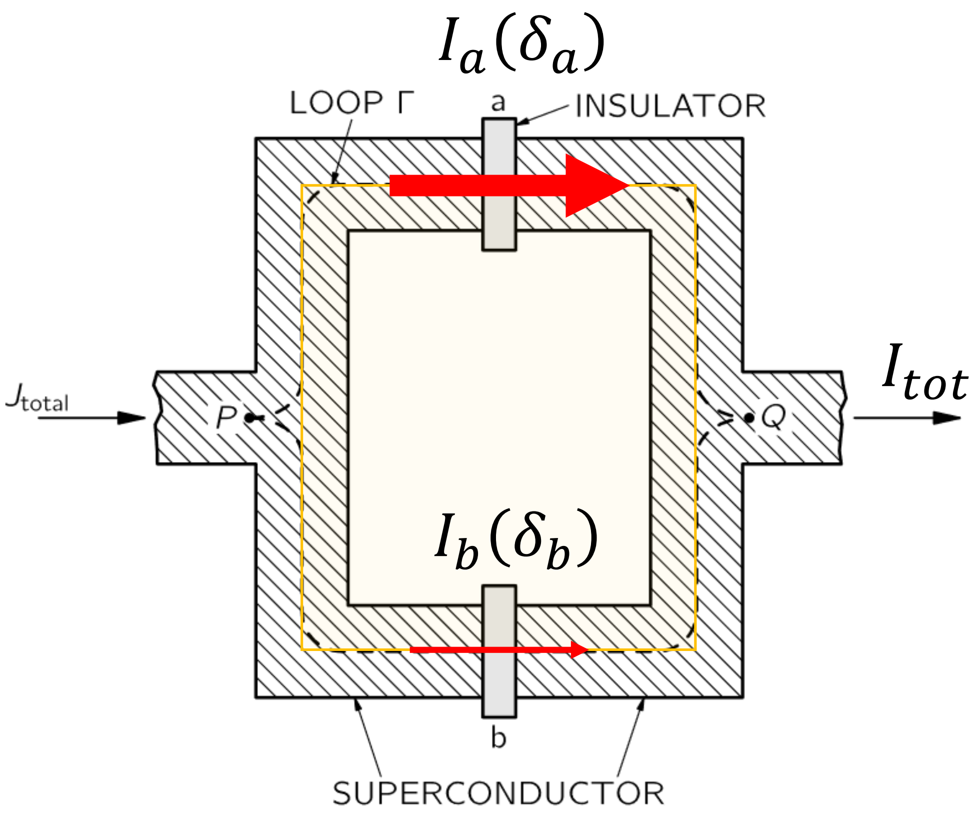

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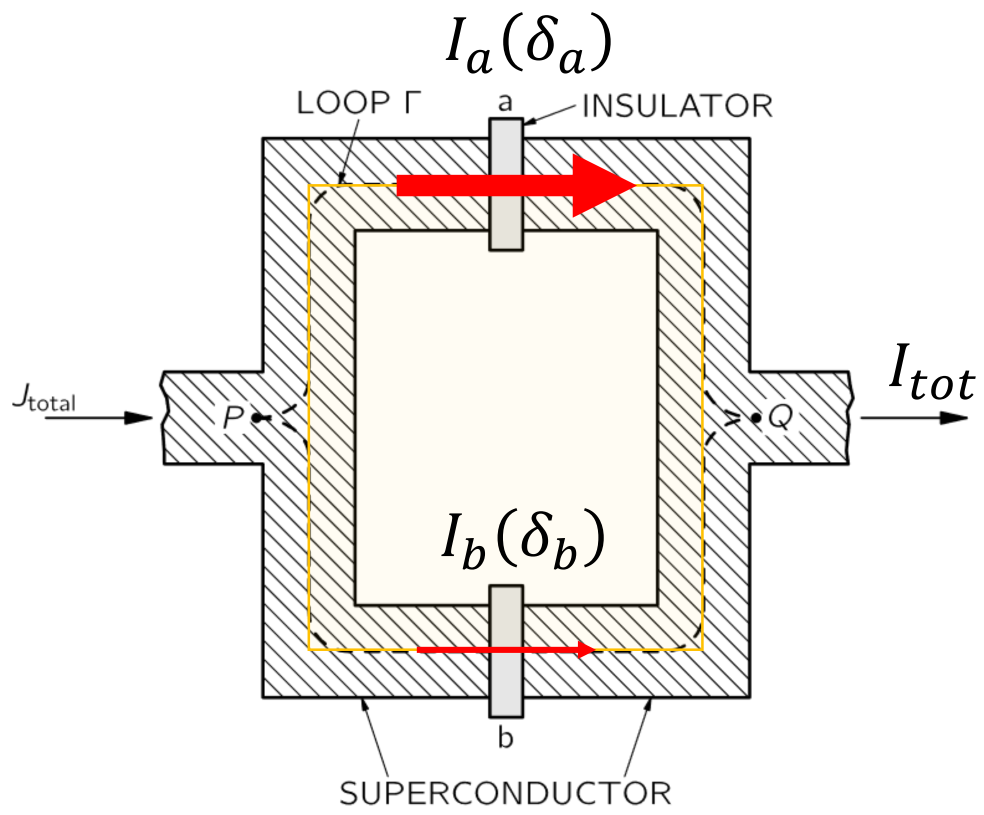
The big junction imposes $\delta_a = \theta$
and B imposes $\delta_b - \delta_a = 2\pi\frac{B.S}{\phi_0}$

Supercurrent vs phase: measurement with an asymmetric SQUID



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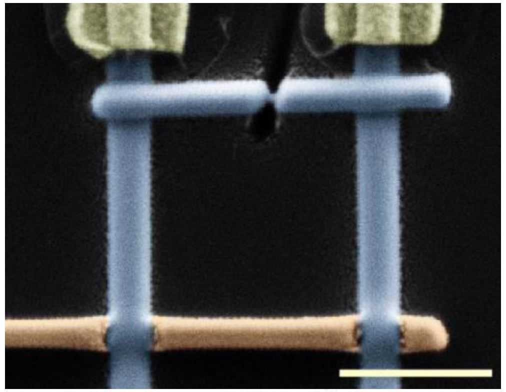
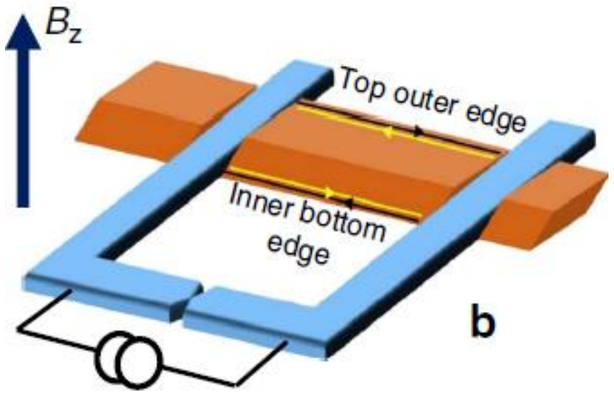
The big junction imposes $\delta_a = \theta$
and B imposes $\delta_b - \delta_a = 2\pi\frac{B.S}{\phi_0}$

=> can measure supercurrent vs phase $I_b(\varphi)$ with $I_c(B)$

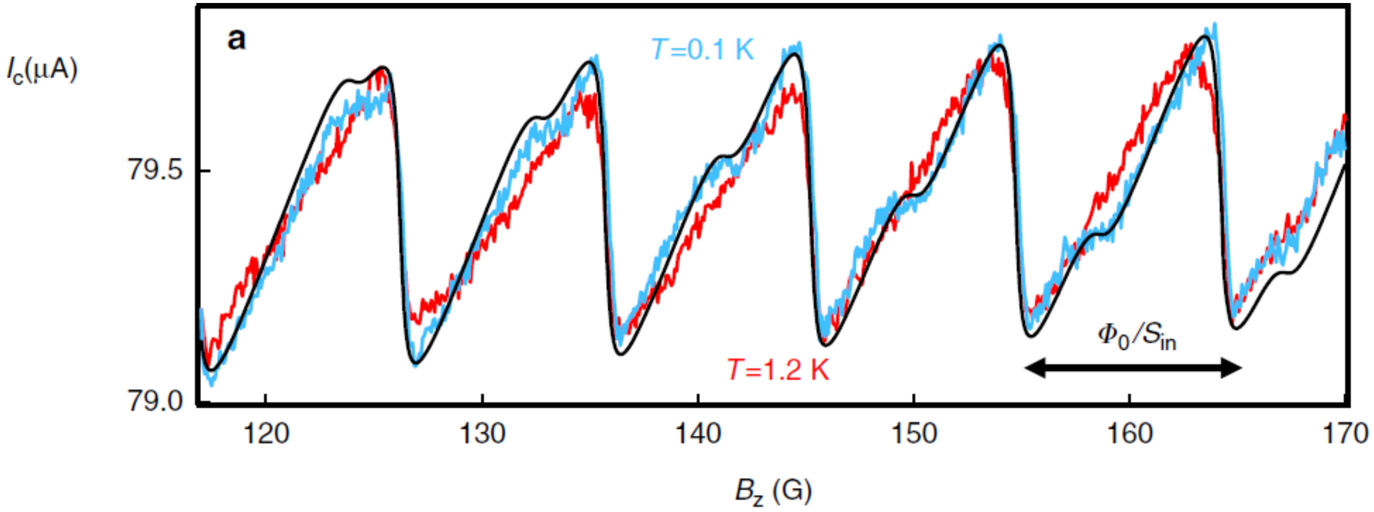
$$I_c\left(B = \varphi.\frac{\phi_0}{2\pi S}\right) \simeq I_a(\theta) + I_b(\theta + \varphi)$$

Supercurrent vs phase: previous experiments



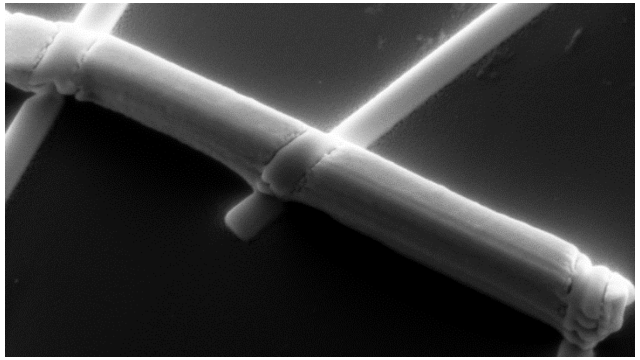


Murani et al., Nat. Comm. 2017

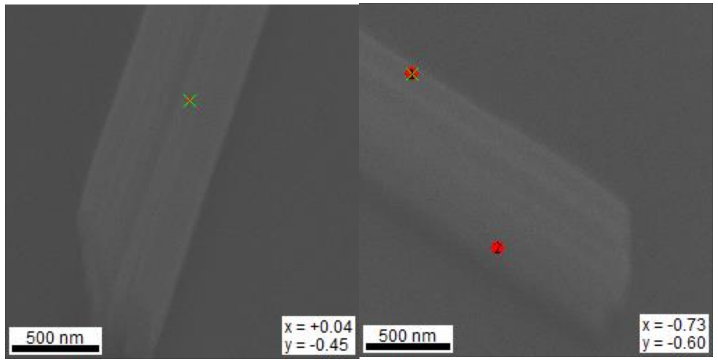


THANK YOU

Open questions

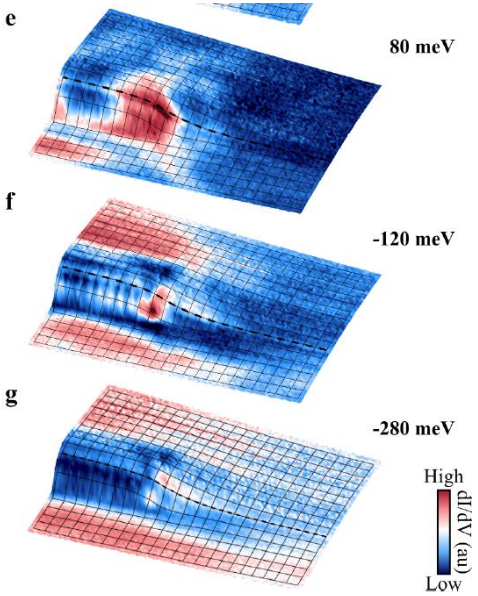


R. S. Deacon
Ishibashi's group, RIKEN



Can a big supercurrent be supported by many hinge states arranged in steps ?

What is the effect of defects on the surface of Bi ?
What about strain ?
Revealing topological nature with screw dislocations ?
(Nayak et al., Cond. Mat. 2019)



What happens at high magnetic field ?
(Queiroz and Stern, Cond. Mat. 2019)