Using the superconducting proximity effect to uncover topological materials : the case of Bismuth

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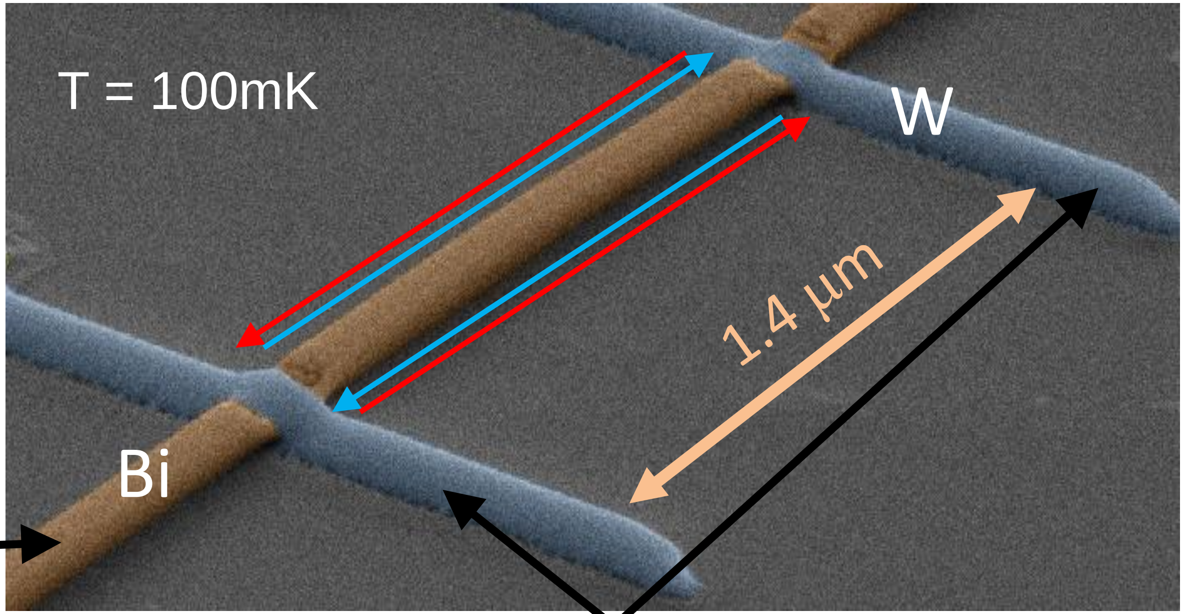
Murani et al, Phys.Rev. B 2017
Murani et al, Nature Comm. 2017
Schindler et al, Nature Phys. 2018
Murani et al, PRL 2019



Bismuth nanowire

Superconducting contacts

Atomtronics@Benasque2019

Outline

- Bismuth as it is understood today:

  a higher order topological insulator

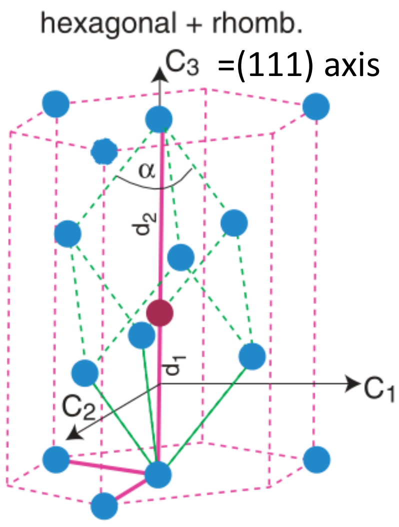
- 3 proximity effect experiments in S/Bi nanowire/S junction

  - Field-controlled Interference probe supercurrent-carrying paths : edge states

  - (dc) Supercurrent versus Phase relation (CPR) probe Andreev spectrum : edge states are ballistic

  - High frequency (ac) susceptibility χ=dI/dφ probes topological protection

Bismuth, a semi-metal



Z=83

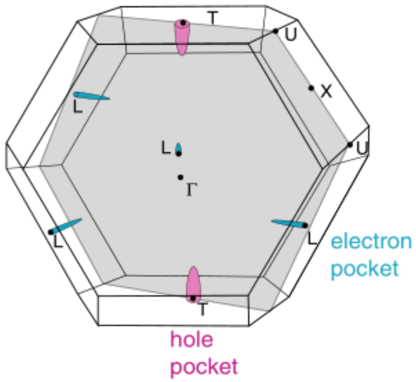
Bulk Bi: semi-metal with huge spin-orbit and $\lambda_F \approx 50$ nm

→No bulk states left in structures smaller than 50 nm

Bi surfaces: $\lambda_F \approx 1$ nm, E_{SO} ~ E_F ~ 100 meV, g_{eff}: 1~ 100

Photoemission shows that surface states are spin-split due to high spin-orbit

Bulk Brillouin zone



Better yet : Some surfaces are topological

Hofmann 2006 review

(111) Bi bilayers are predicted to be 2D topological insulators

- (111) Surface= buckled honeycomb

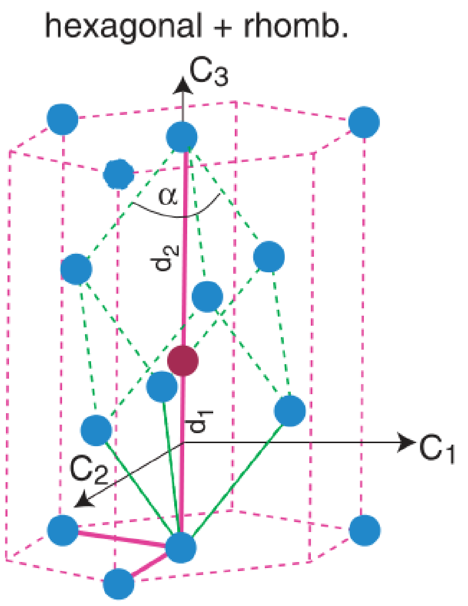
  ≈ graphene with spin-orbit !

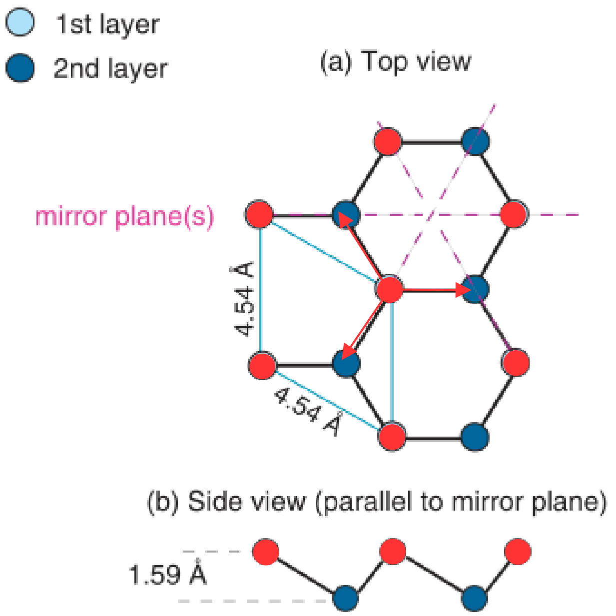
⇒predicted 2D topological insulator

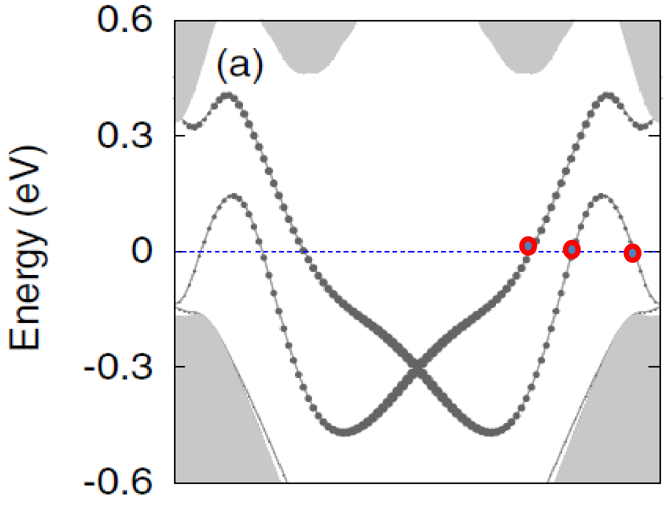
Murakami, 2006

Liu & Allen, 1991

3 edge states predicted







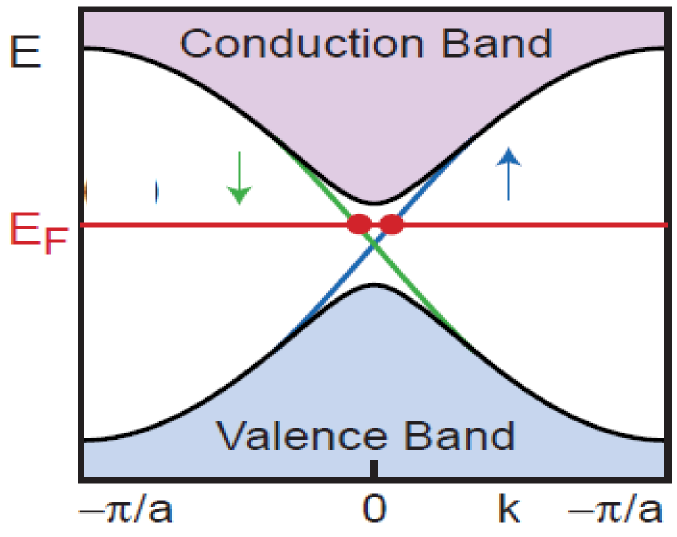
Free standing (111 bilayer)

Yemo 2016

Whether these 1D states are topological is debated

Spin orbit interactions and Topological insulators

$$V_{\mathrm{SO}} = \frac{\hbar}{4m^2c^2}\mathbf{s}\cdot(\nabla V \times \mathbf{p})$$



Depending on the crystal symmetry:

Possible electronic band inversions

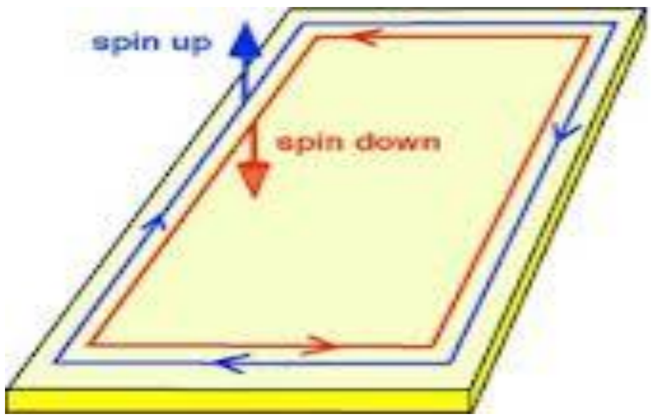
In 2D:

Formation of 1D spin polarized helical edge states

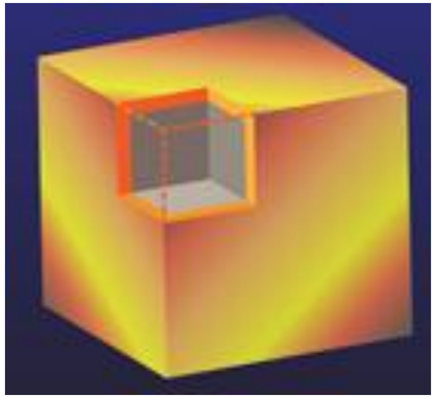
Quantum Spin Hall state

Protected from non- magnetic disorder by SO

Forbidden back scattering without spin flip



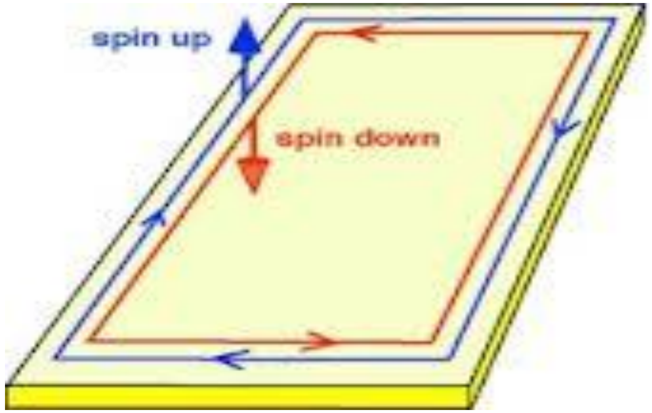
Higher order Topological Insulators



3D topological insulator

3D insulating bulk

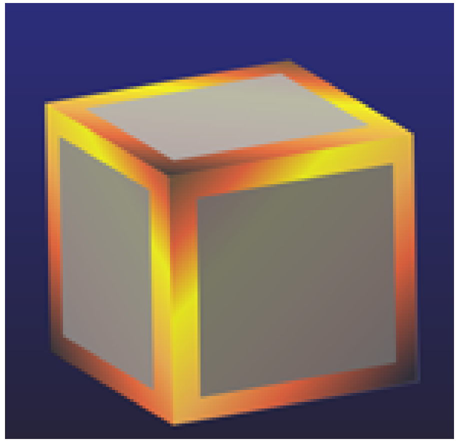
2D Conducting surfaces



2D topological insulator

2D insulating bulk

1D conducting edges



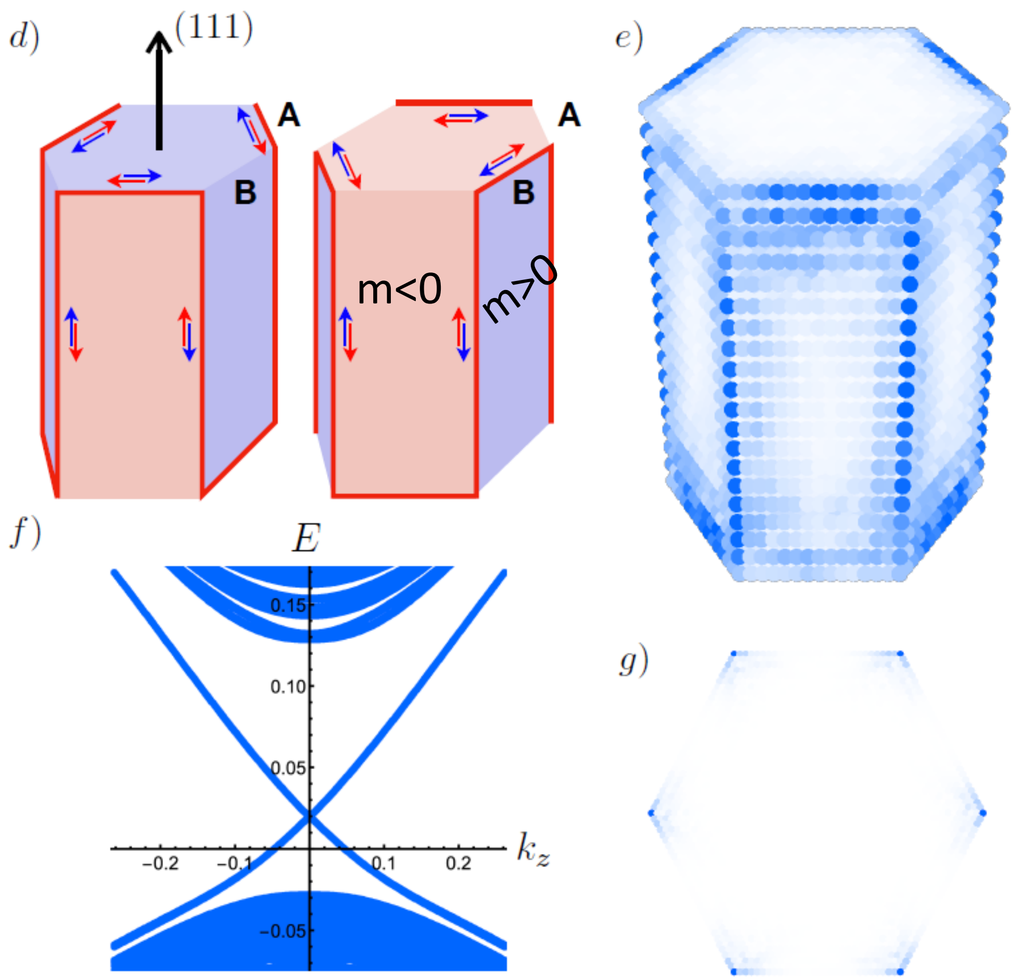
Second Order Topological Insulator

3D insulating bulk

2D insulating surfaces

1D conducting helical « hinges »

Bismuth : a High Order Topological Insulator



Topological Quantum chemistry

⇒ 6 hinge states (between six surfaces)

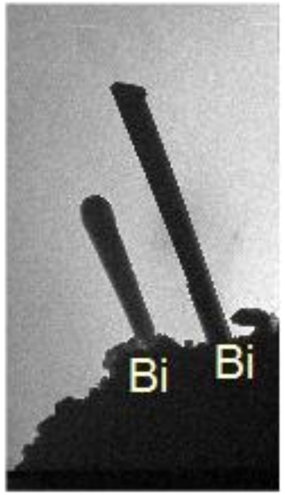
⇒ 3 Edge states on each free (111) surface

Conclusion: There is a helical edge state that winds around the cristal

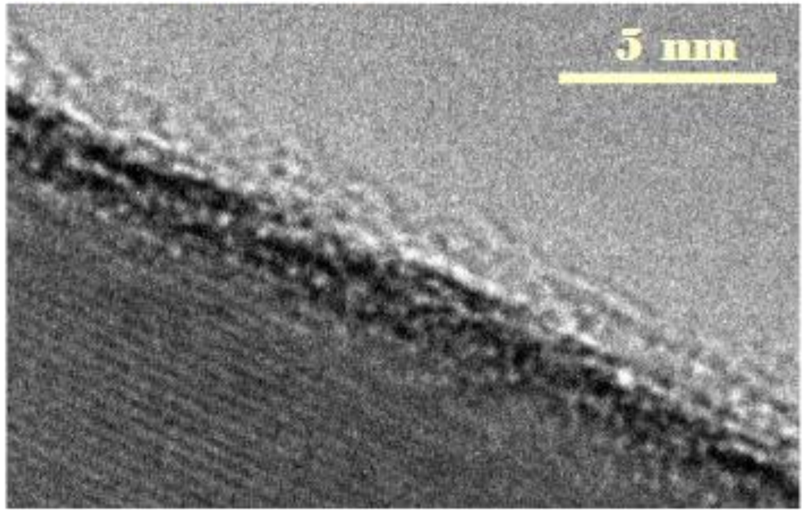
Schindler et al, Nature Phys. 2018

Our samples: Monocrystalline Bismuth nanowires

Growth : Sputtering on a hot surface High resolution TEM

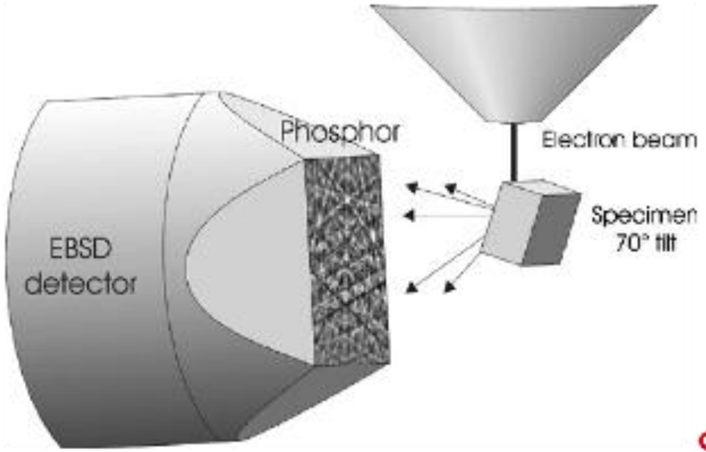


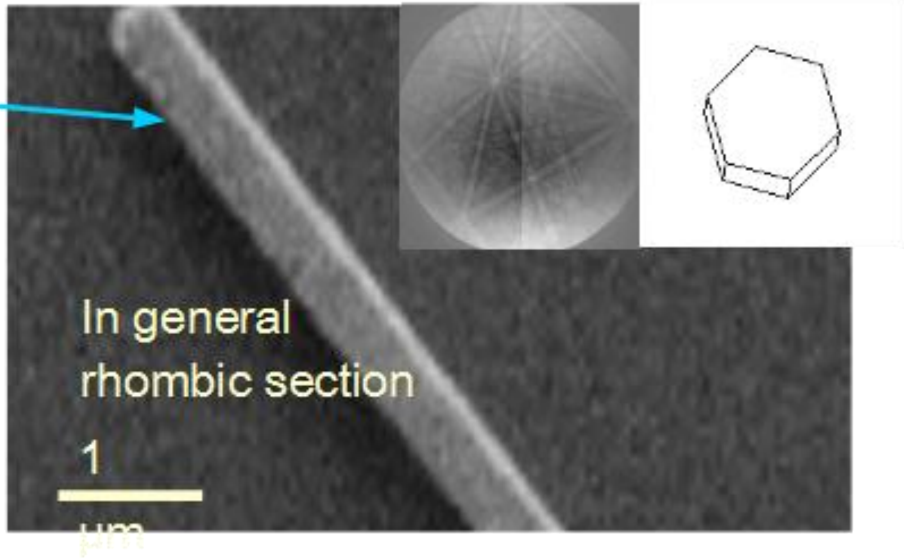
High quality
single
crystals
$\varnothing \sim 100\,\mathrm{nm}$



Alik Kasumov

Select desired orientation using EBSD





Top (111) surface

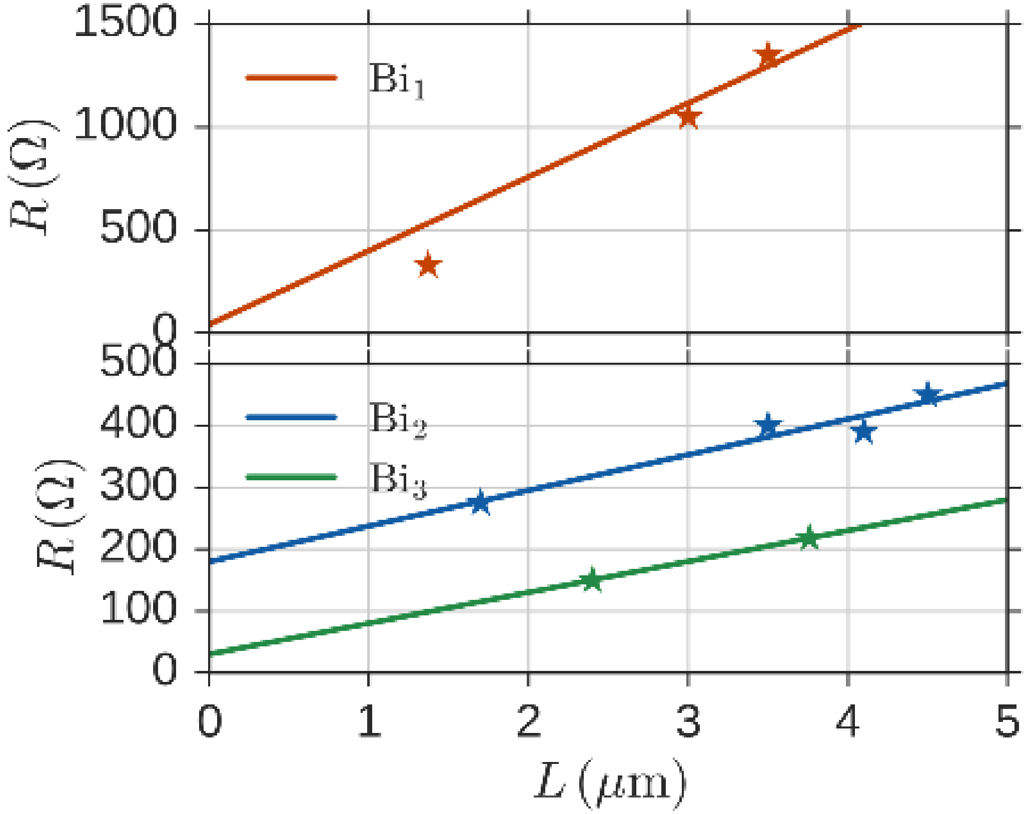
Select nanowires with (111) top surface

Bulk, surfaces and edges in our wires

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

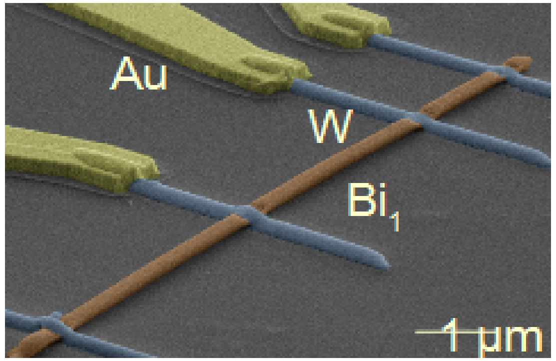
Surface $\lambda_F \simeq 5\,\mathrm{nm}$

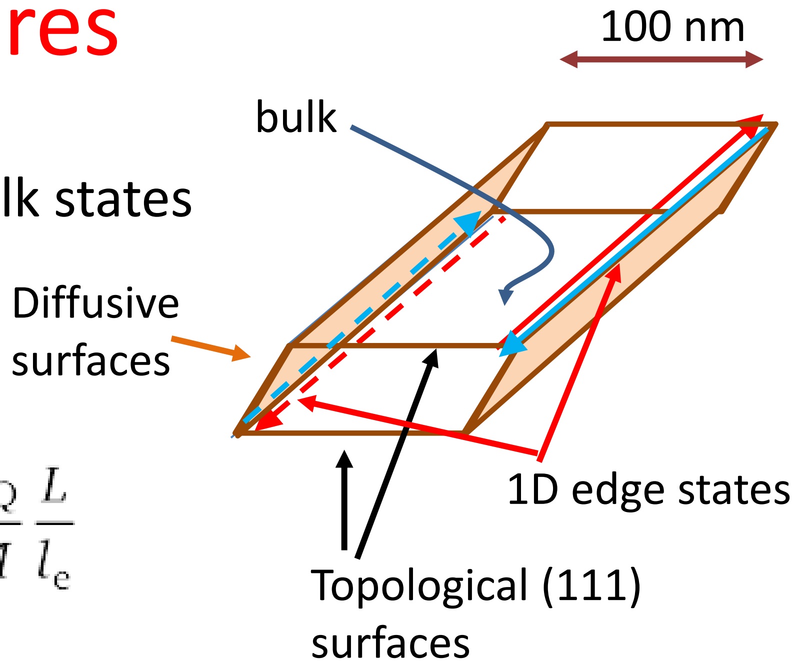
$\Big\}$ Roughly 50 times more surface states than bulk states



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

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





Diffusive surfaces states carry the normal current

We will see that all the supercurrent is carried by edge ballistic states

Proximity effect experiments in S/Bi nanowire/S junction

1- Field-controled Interference probe supercurrent-carrying paths : edge states

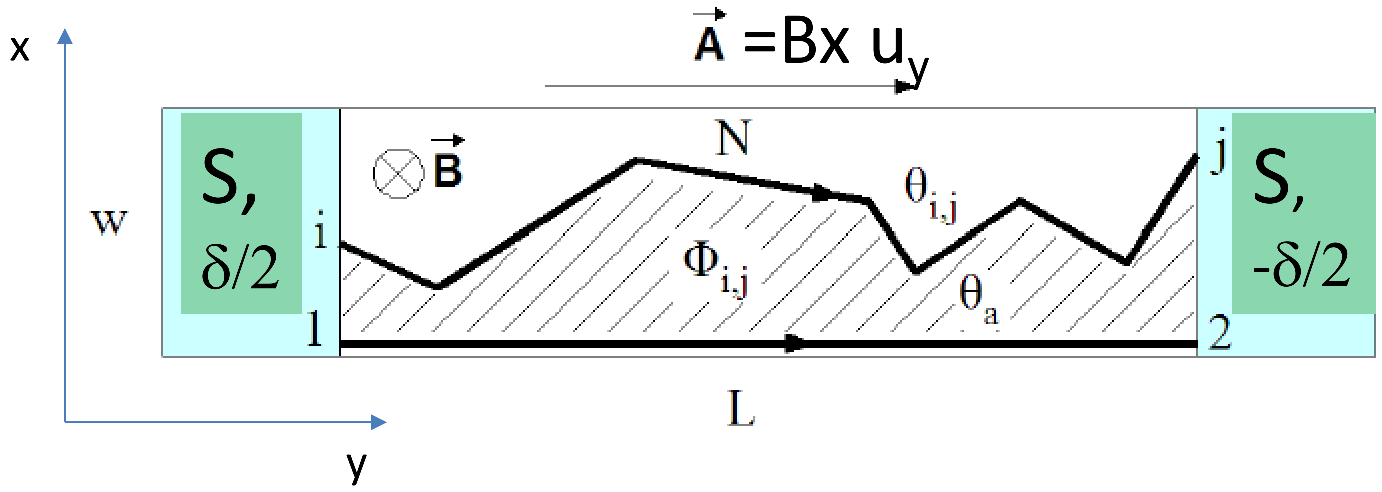
2- (dc) Supercurrent versus Phase relation (CPR) probe Andreev spectrum : edge states are ballistic

3- High frequency (ac) susceptibility $\chi = dI/d\varphi$ probes topological protection

Superconducting contacts to exploit macroscopic wavefunction (and its phase): Interference experiments will reveal supercurrent paths

Gauge invariant Josephson relation:

$$I(\delta) = I_0 \sin\left(\delta - \frac{2e}{\hbar}\int \boldsymbol{A}\cdot d\boldsymbol{l}\right)$$

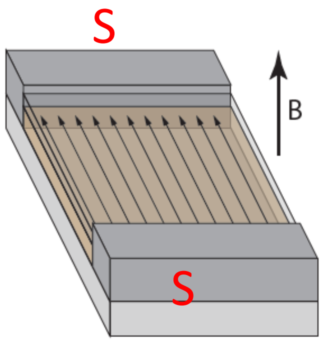


Critical current $I_c(B)$=max of integral over all supercurrent paths: interference terms!

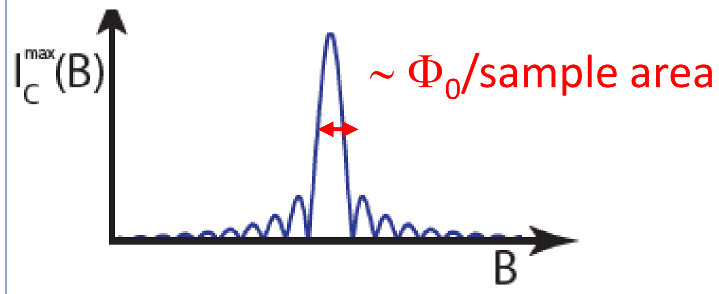
$$I_c(B) = \left|\int_{-W/2}^{W/2} J(x)\cdot e^{2\pi i L B x/\Phi_0}\,dx\right|$$

Critical current $I_c(B)$=|Fourier transform of supercurrent distibution J(x)|

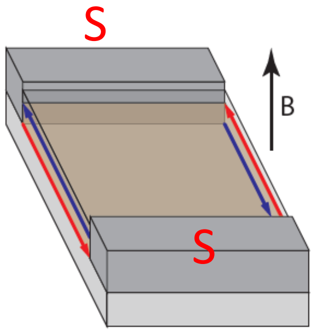
Critical supercurrent reveals paths taken by pairs (via interference)



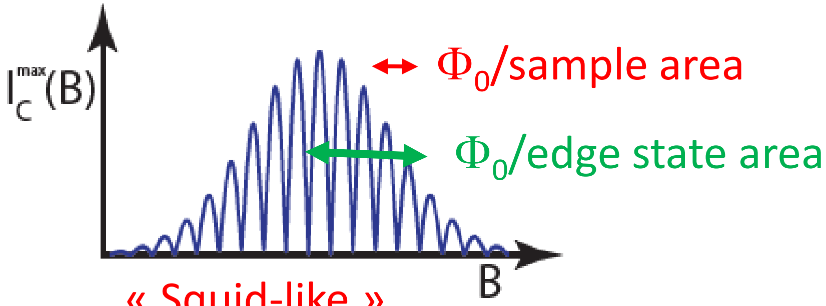
Many paths WIDE
(ballistic or diffusive)



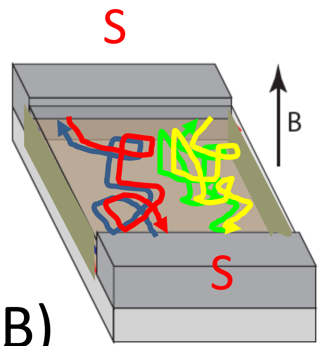
« Fraunhoffer pattern »



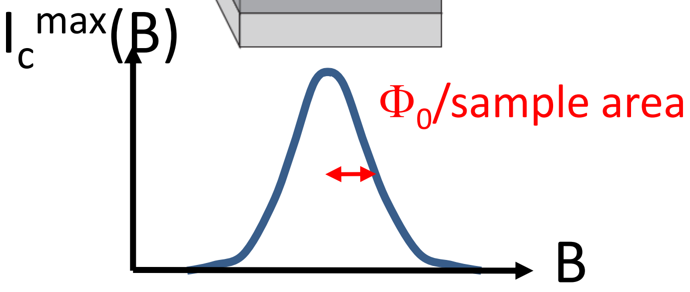
Only 2 paths (edges)
ballistic



« Squid-like »

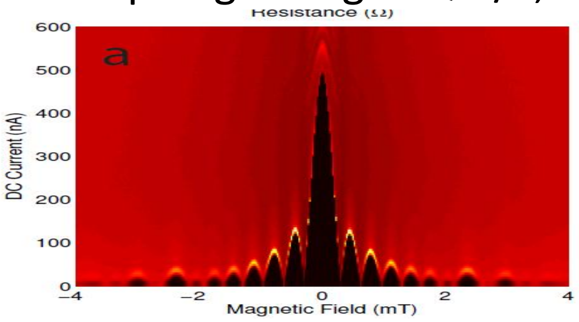


Many paths
NARROW,
diffusive

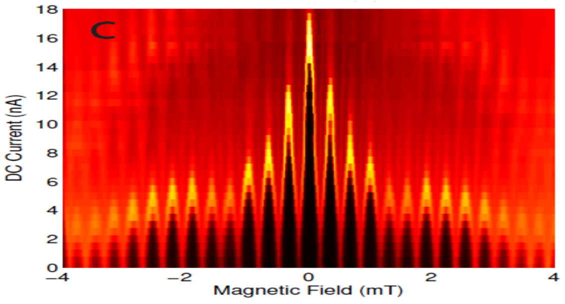


Many diffusive paths
Gaussian decay

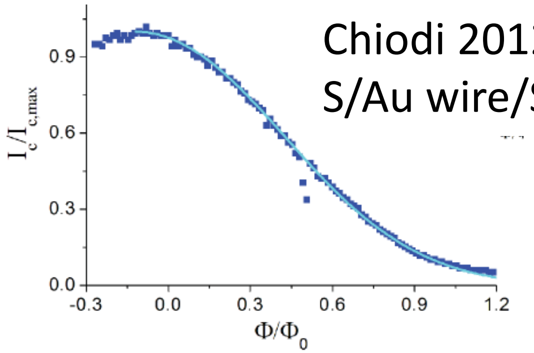
S/Non topological HgTe QW/S, Hart 2014



S/Topological/S HgTe QW, Hart 2014

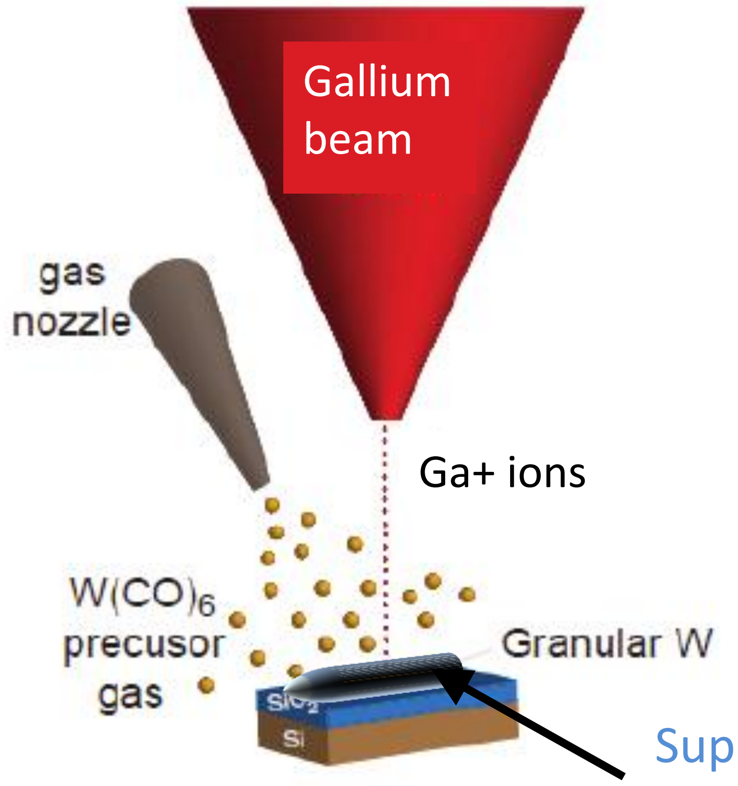


Chiodi 2012
S/Au wire/S

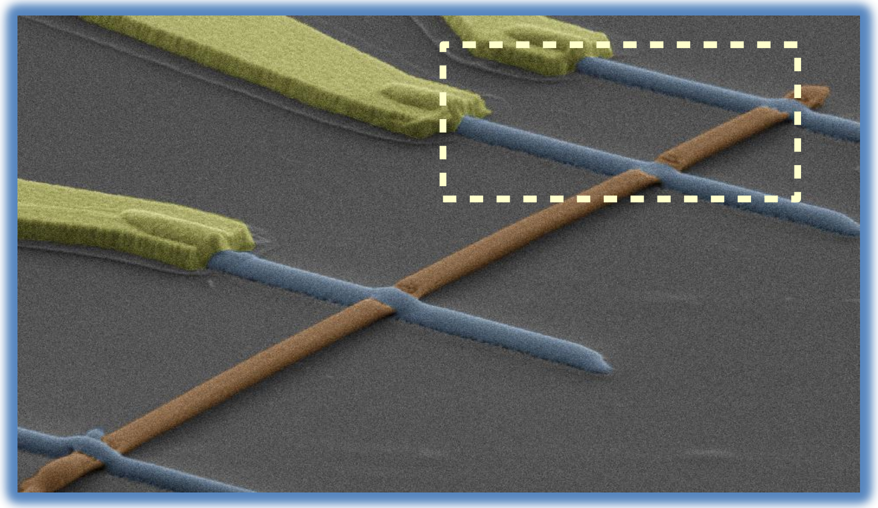


Contacting our Bi(111) wires with focused ion beam-assisted deposition to induce superconductivity

Kasumov 2005



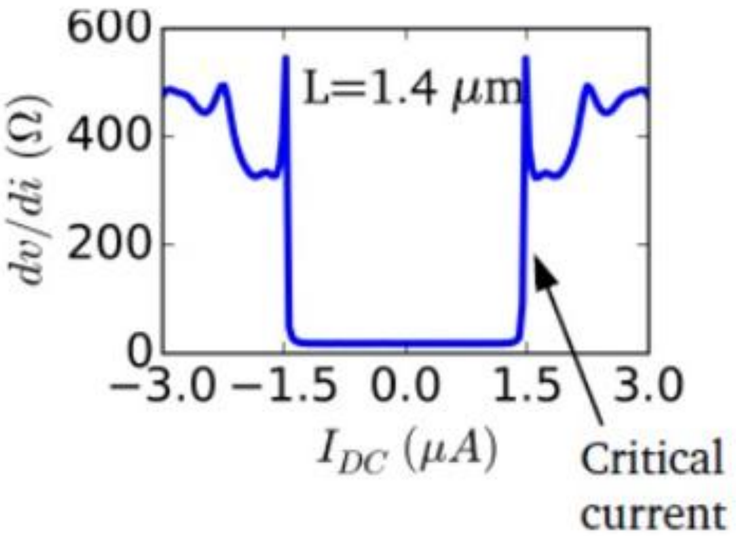
Superconducting W compound



Bismuth nanowire with (111) surfaces

Superconducting W electrodes

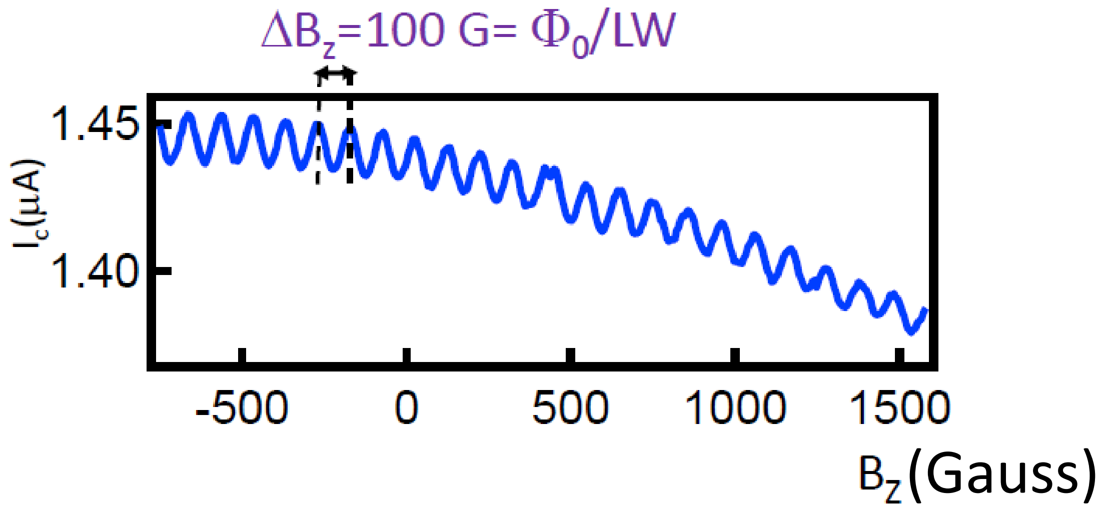
W/Bi/W junction

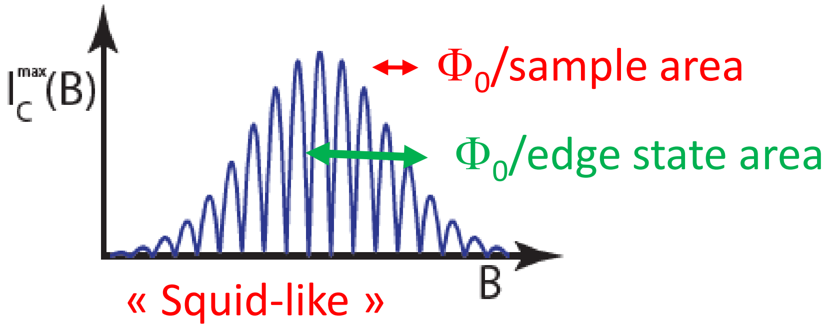


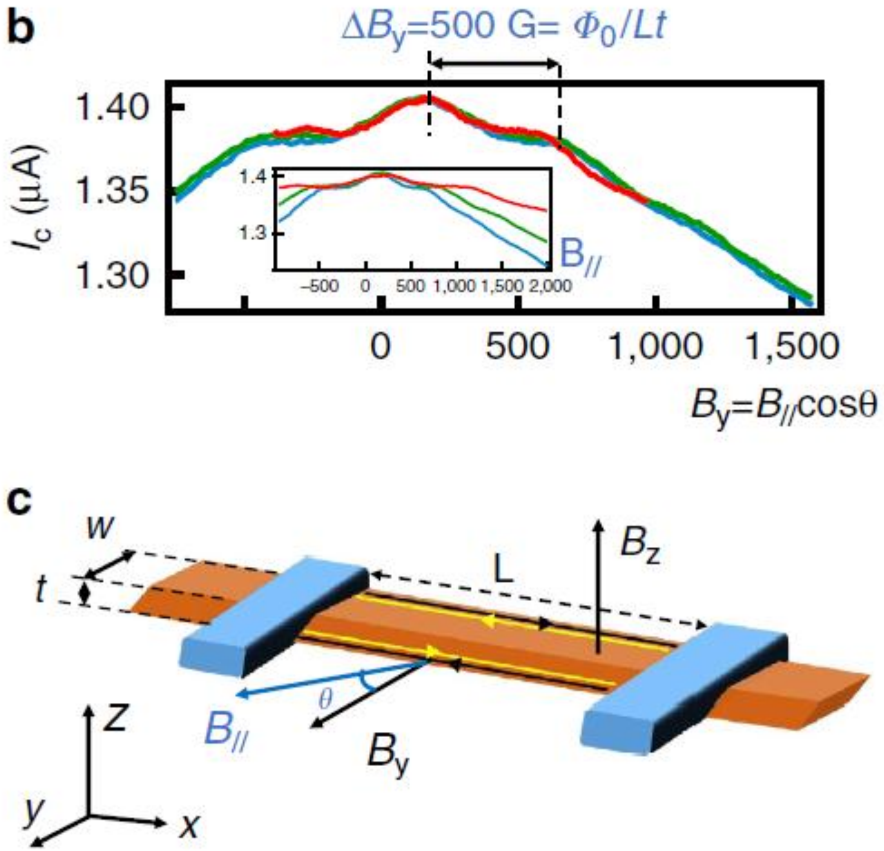
Superconducting electrodes:

- C and Ga-doped amorphous W
- ~ 200 nm thick and wide
- Great superconducting properties: T_c~4 K, Δ~0.8 meV, H_c~12 Tesla!

Field-dependence of critical supercurrent reveals paths taken by pairs







- Oscillations with field: very few states
- Field direction dependence and period: supercurrent travels at the two acute wire edges
- High field decay scale (oscillations up to 10 Tesla in some samples): narrow channels (nm!).
- High critical current : well transmitted channels.

Proximity effect experiments in S/Bi nanowire/S junction

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2- (dc) Supercurrent versus Phase relation (CPR) probe Andreev spectrum : edge states are ballistic

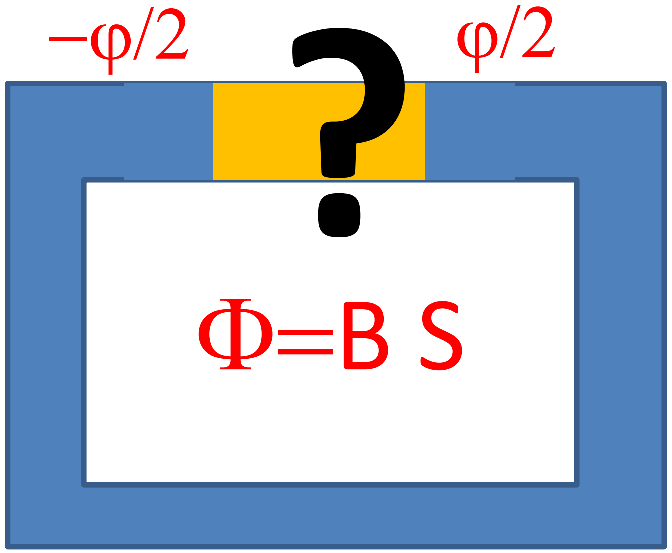
3- High frequency (ac) susceptibility $\chi = dI/d\varphi$ probes topological protection

Better than critical current: supercurrent versus phase relation

Usual two contact SNS configuration

I_c= max I(φ), φ not controlled

Better: Ring geometry allows «phase biasing»



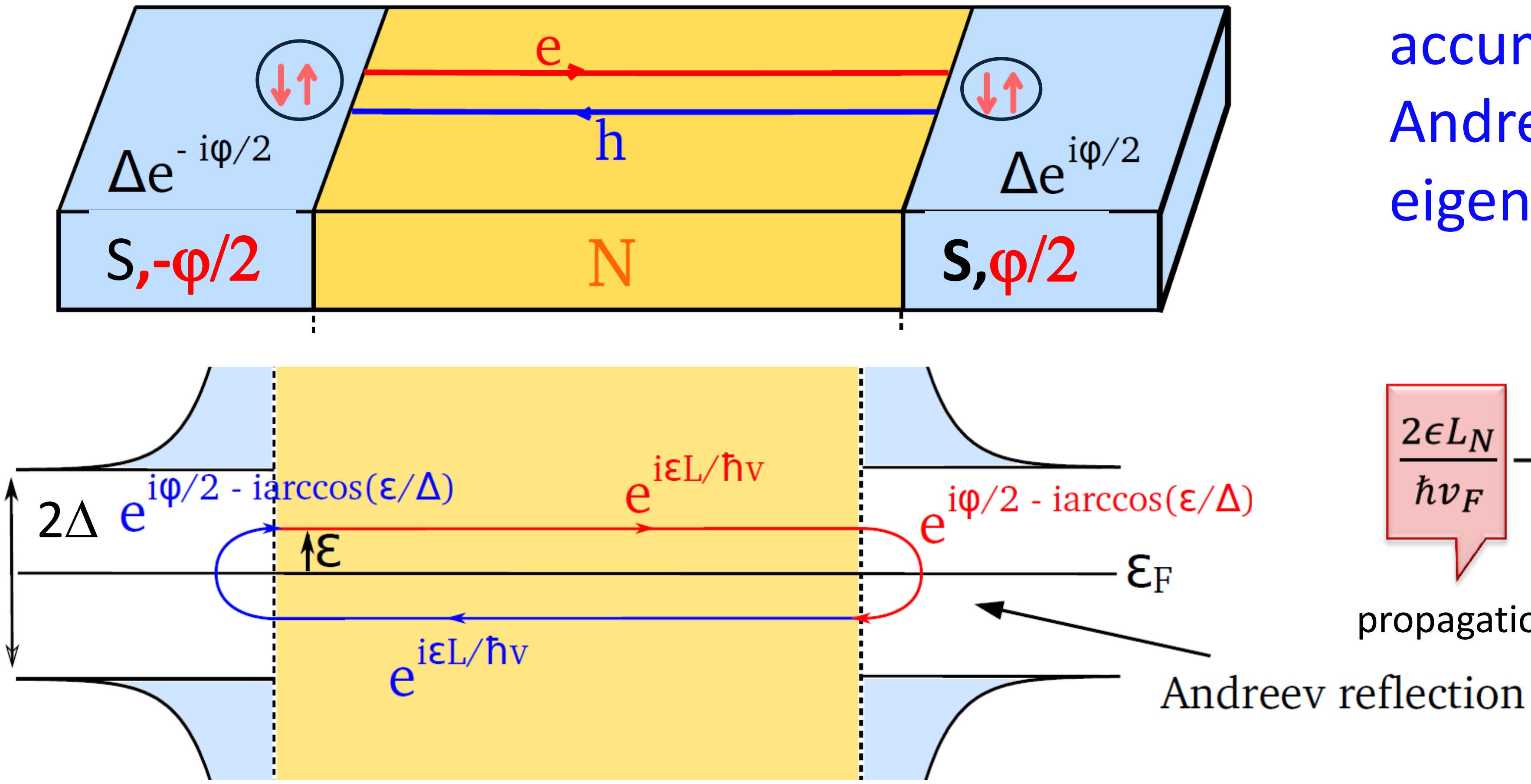
$\varphi = -2\pi\Phi/\Phi_0$

φ controlled, proportional to applied magnetic flux

I(φ) =?

I(φ) depends on the transport regime in the N (diffusive, ballistic)

Andreev Bound States in a phase-biased SNS junction



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

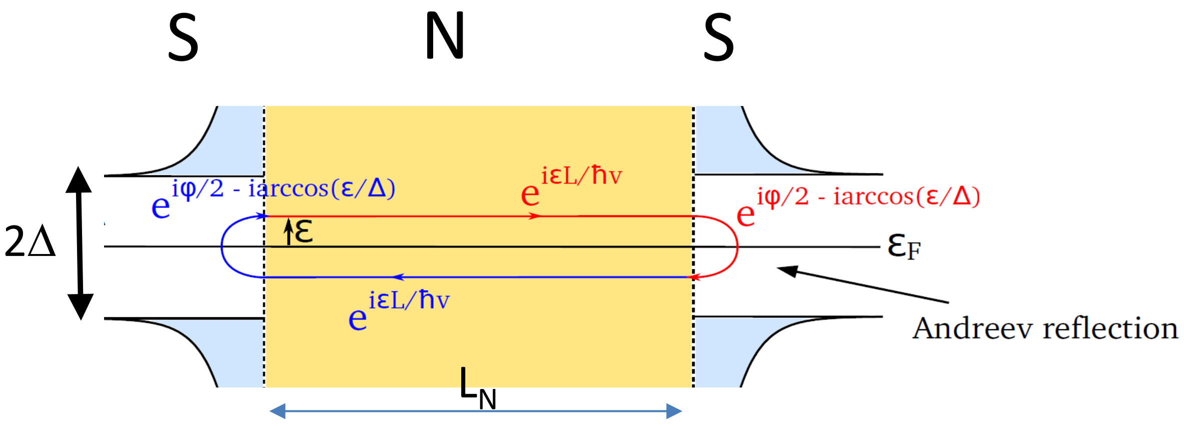
Interface reflection

Superconducting phase difference

Andreev bound states carry the supercurrent.

Spectra and supercurrent depend on the transport regime in N

Andreev spectrum and supercurrent in **short ballistic** junction

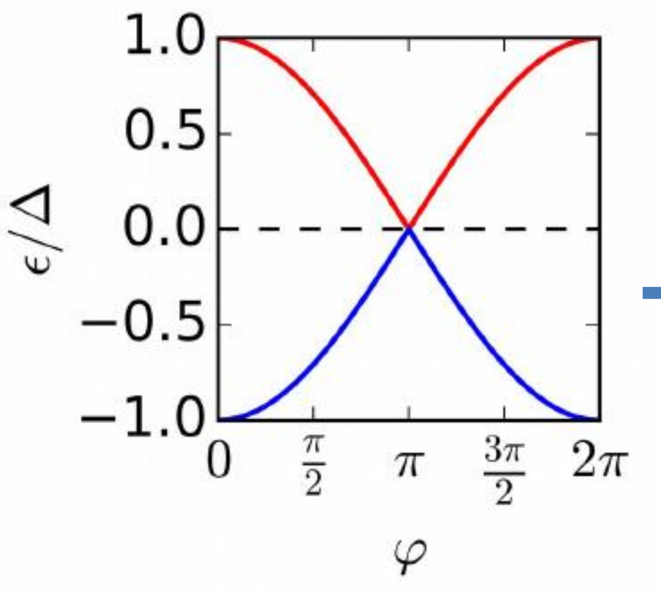


$$\cancel{\frac{2\epsilon L_N}{\hbar v_F}} - 2\,arccos\,\frac{\epsilon}{\Delta_0} \pm \Delta\phi = 2\pi m$$

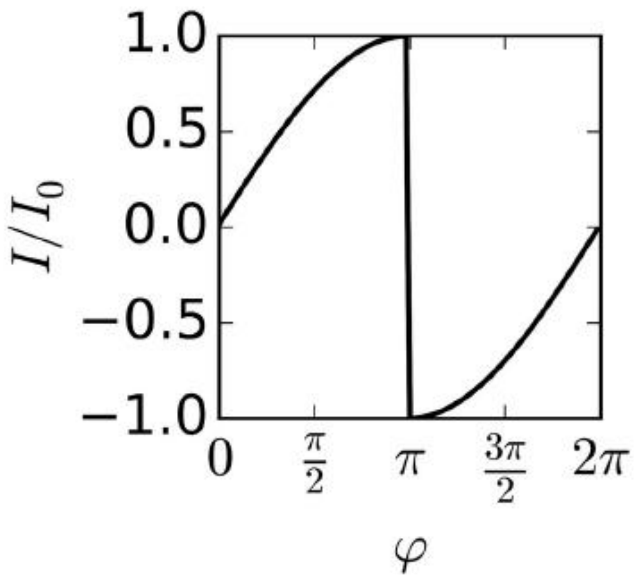
propagation

supercurrent

$\varepsilon_n(\varphi)$~branches of $\cos(\varphi/2)$

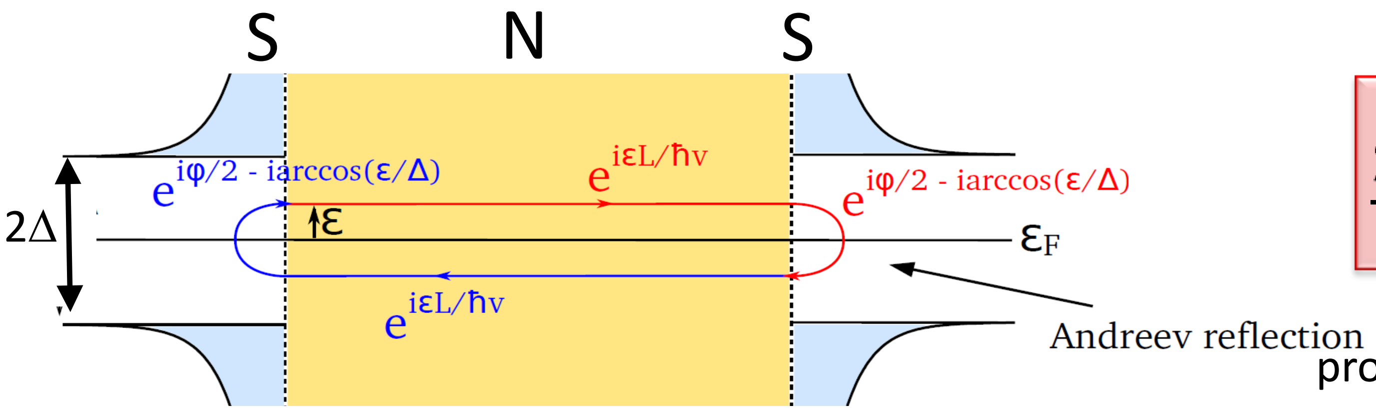


$$I = \sum_{-\infty}^{0} \frac{\partial \epsilon_n}{\partial \varphi} f(\epsilon_n)$$



$I(\varphi)$~branches of $\sin(\varphi)$ with jump at π

Andreev spectrum and supercurrent in **long ballistic** junction

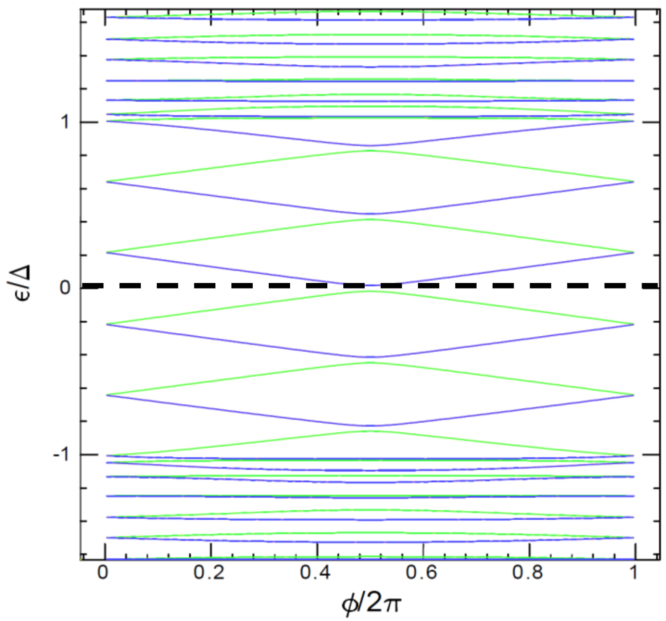


$L \gg \xi_s = \frac{hV_F}{\Delta}$

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

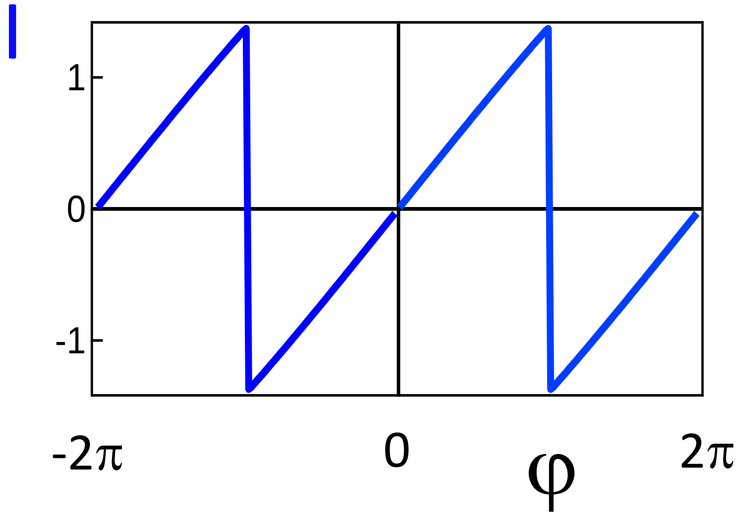
propagation

$\varepsilon_n(\varphi) \sim \varphi$: linear segments



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

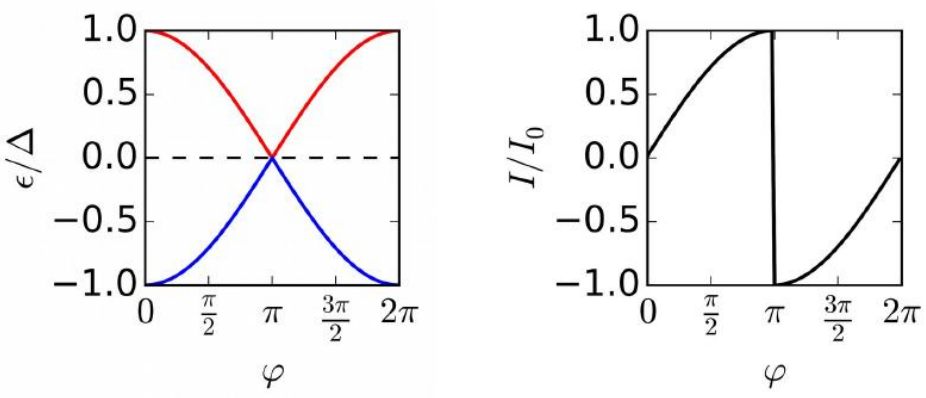
$I(\varphi)$ ~ linear segments with jumps at π



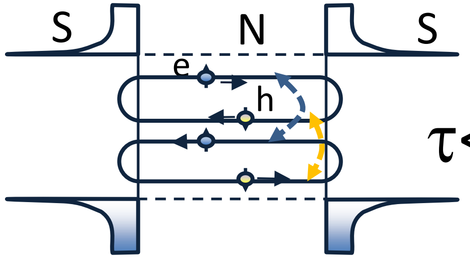
Sawtooth $I(\varphi)$ characteristic of long ballistic

Disorder softens the proximity effect

Short ballistic SNS junction (perfect Andreev reflection)

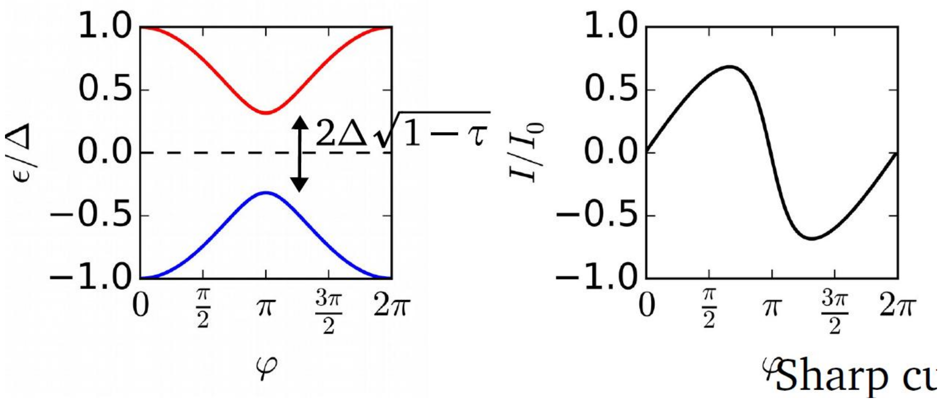


Short disordered

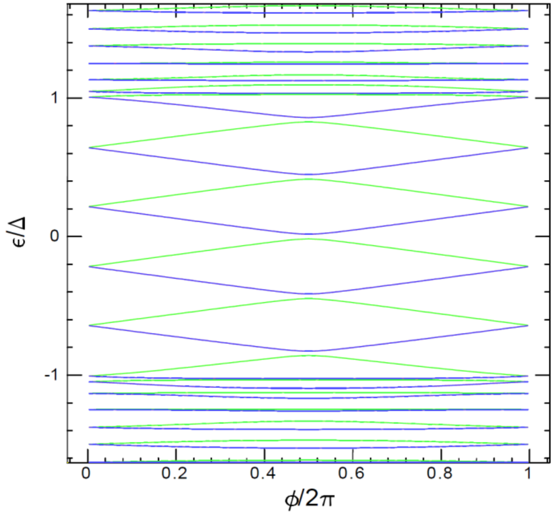


$\tau<1$

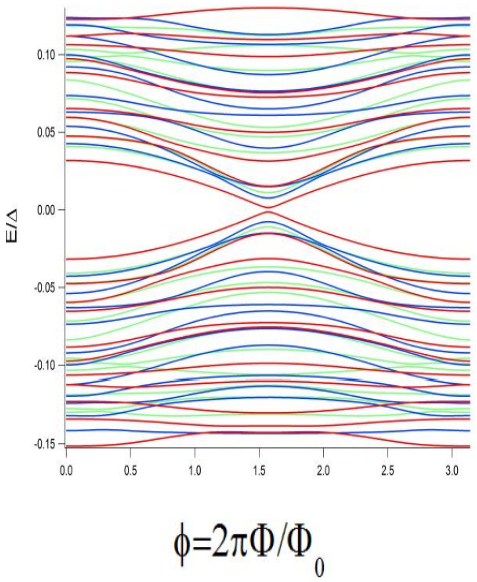
$1-\tau$ proba to backscatter



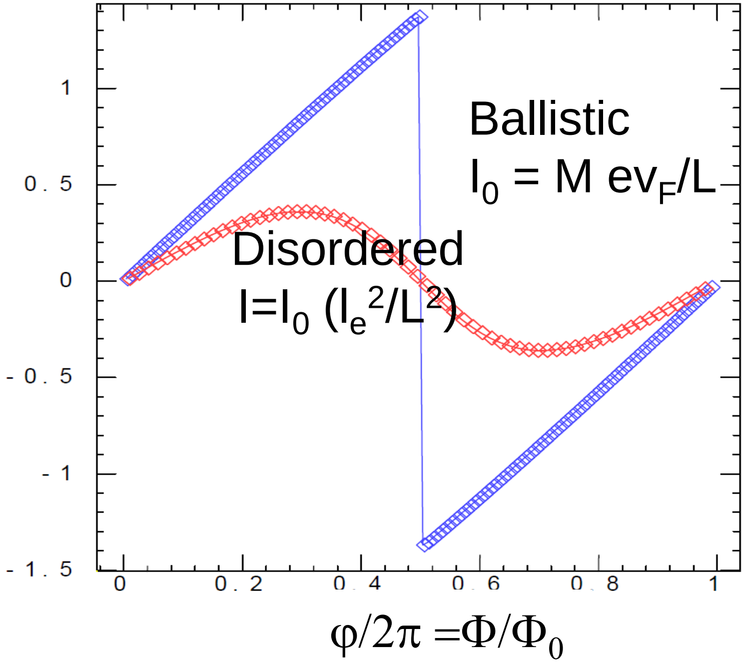
Long ballistic SNS junction



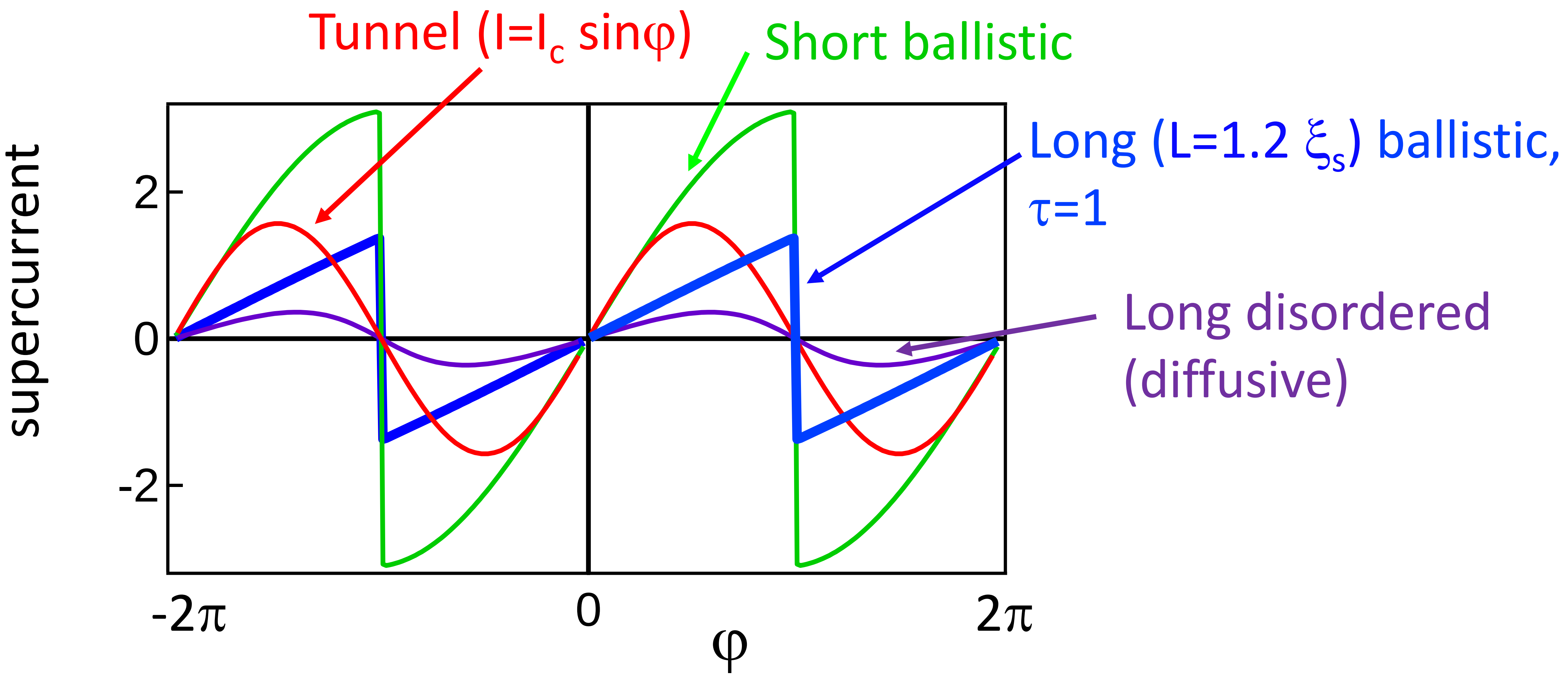
long disordered (diffusive)



$I_J(\varphi)$



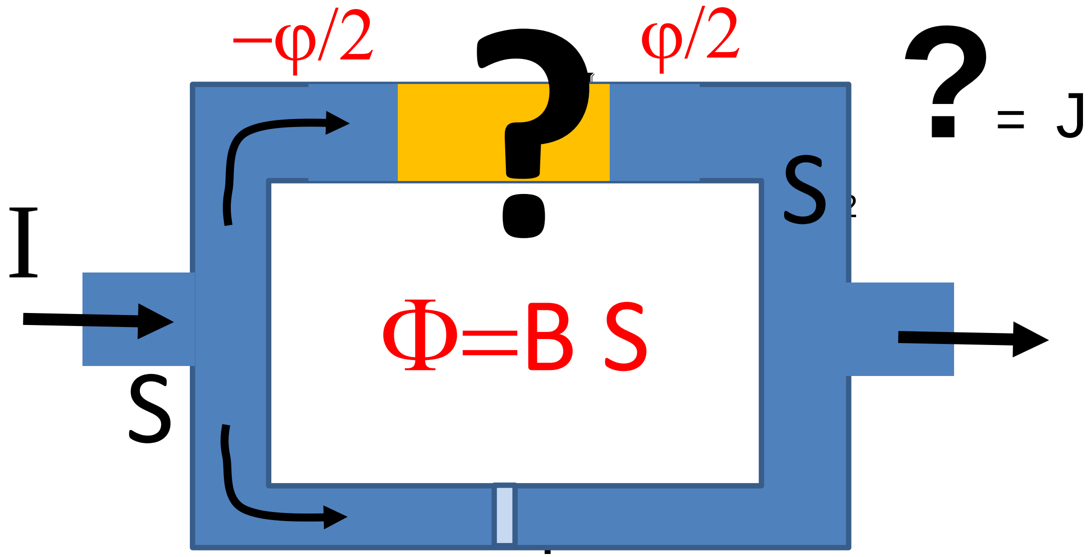
Supercurrent Vs phase relation can pinpoint transport regime



Our goal is to measure such a « Current-Phase Relation »

Current-phase measurement with an asymmetric SQUID

Della Rocca et al 2007



? = Josephson junction with smaller I_{c2}, $I_2=I_{c2}f(\varphi)$

$$I=I_{c1}\sin\varphi_1+I_{c2}f(\varphi_2)$$

$\varphi_1 - \varphi_2 = -2\pi\Phi/\Phi_0$

I_c achieved for $\varphi_1=\pi/2$

Josephson junction with high I_{c1}

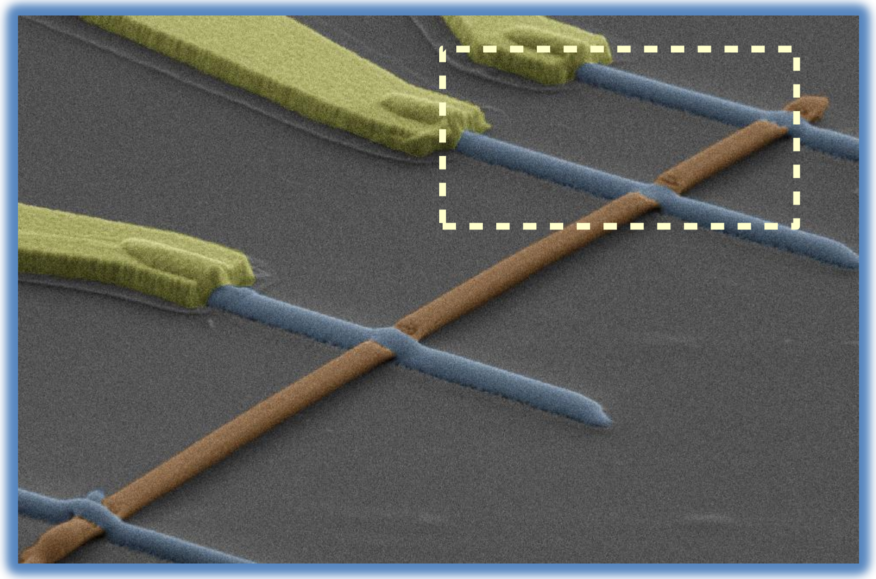
$I_1=I_{c1}\sin\varphi_1$

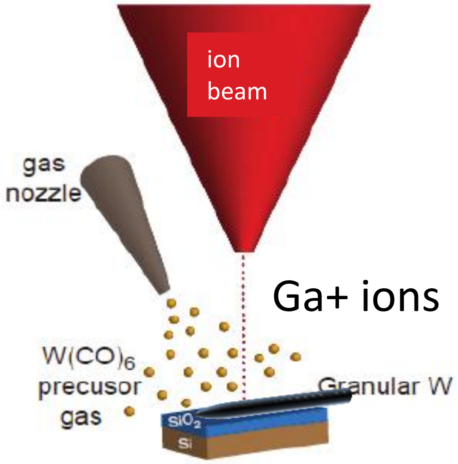
$$I_c=I_{c1}+I_{c2}f(\pi/2+2\pi\Phi/\Phi_0)$$ to first order in I_{c2}/I_{c1}

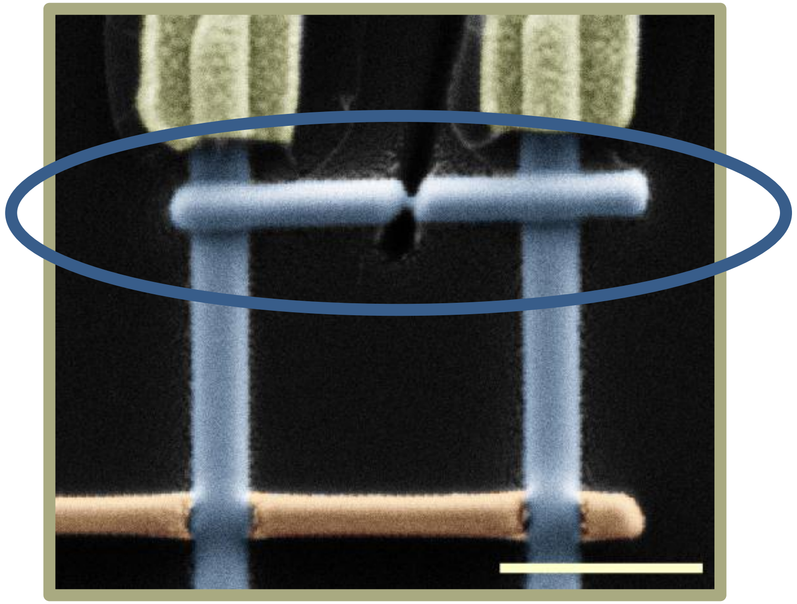
Critical current of asymmetric SQUID yields current-phase relation of junction with smallest critical current

Measurement of current-phase relation to test channels that carry the supercurrent (on very same sample)

Add superconducting constriction in parallel



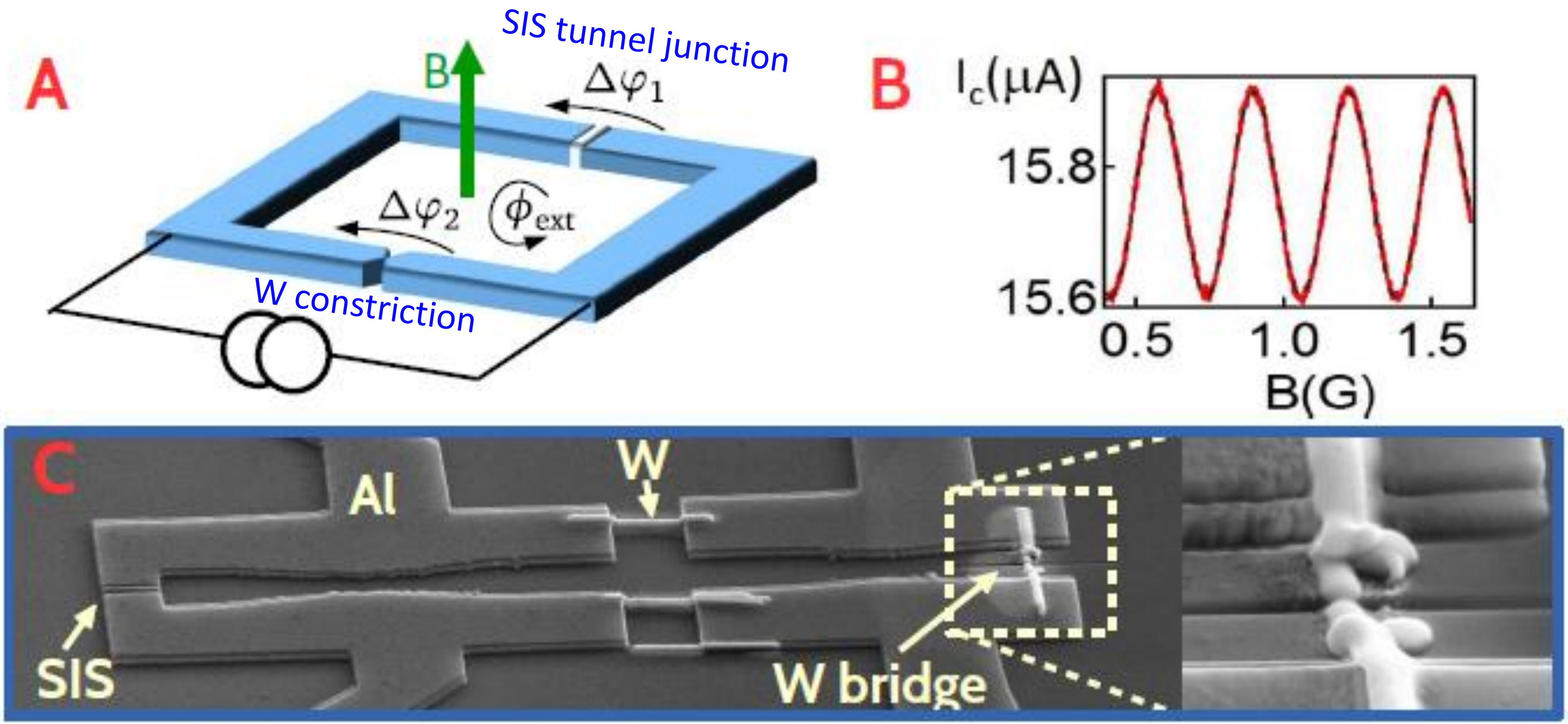




1 μm

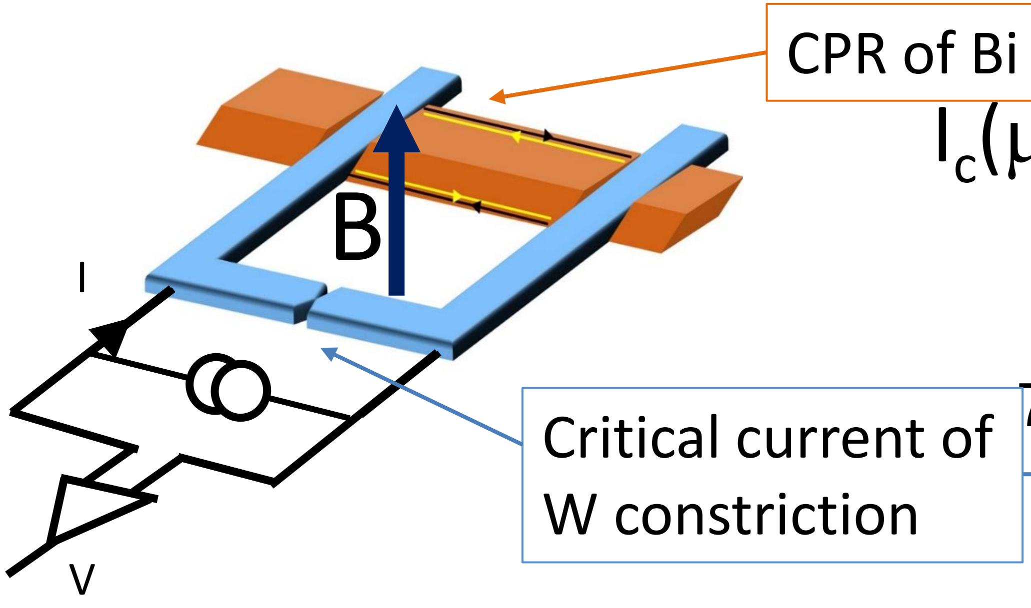
Build an asymmetric SQUID to measure the I(φ) relation

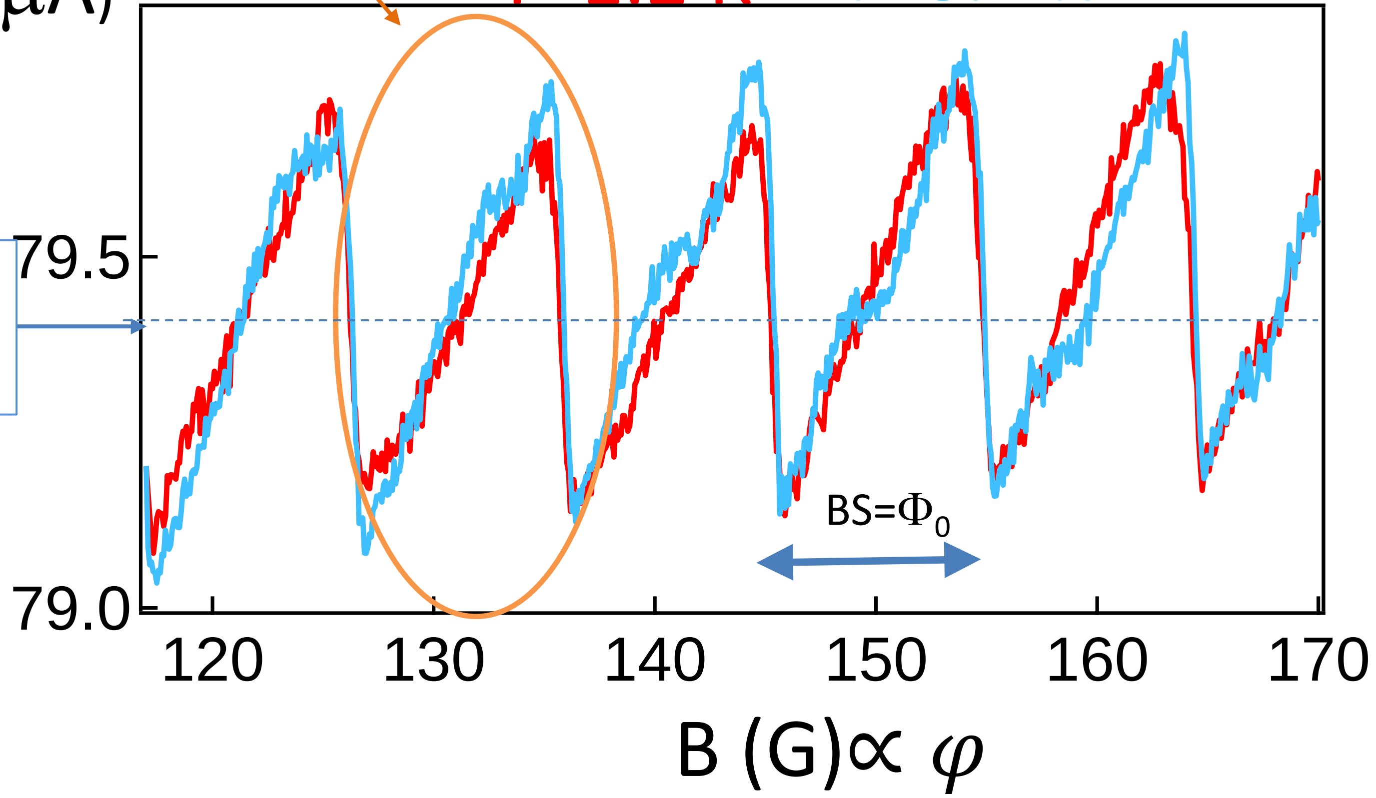
Check method with the Current Phase Relation of a SIS tunnel junction



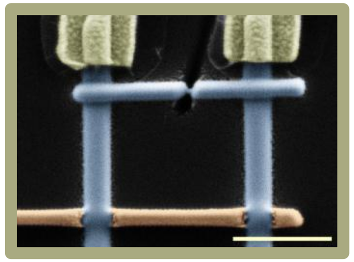
Tunnel junction has a sinusoidal Current Phase relation ✓

Current Phase relation of S/Bi/S: switching current as a function of magnetic flux





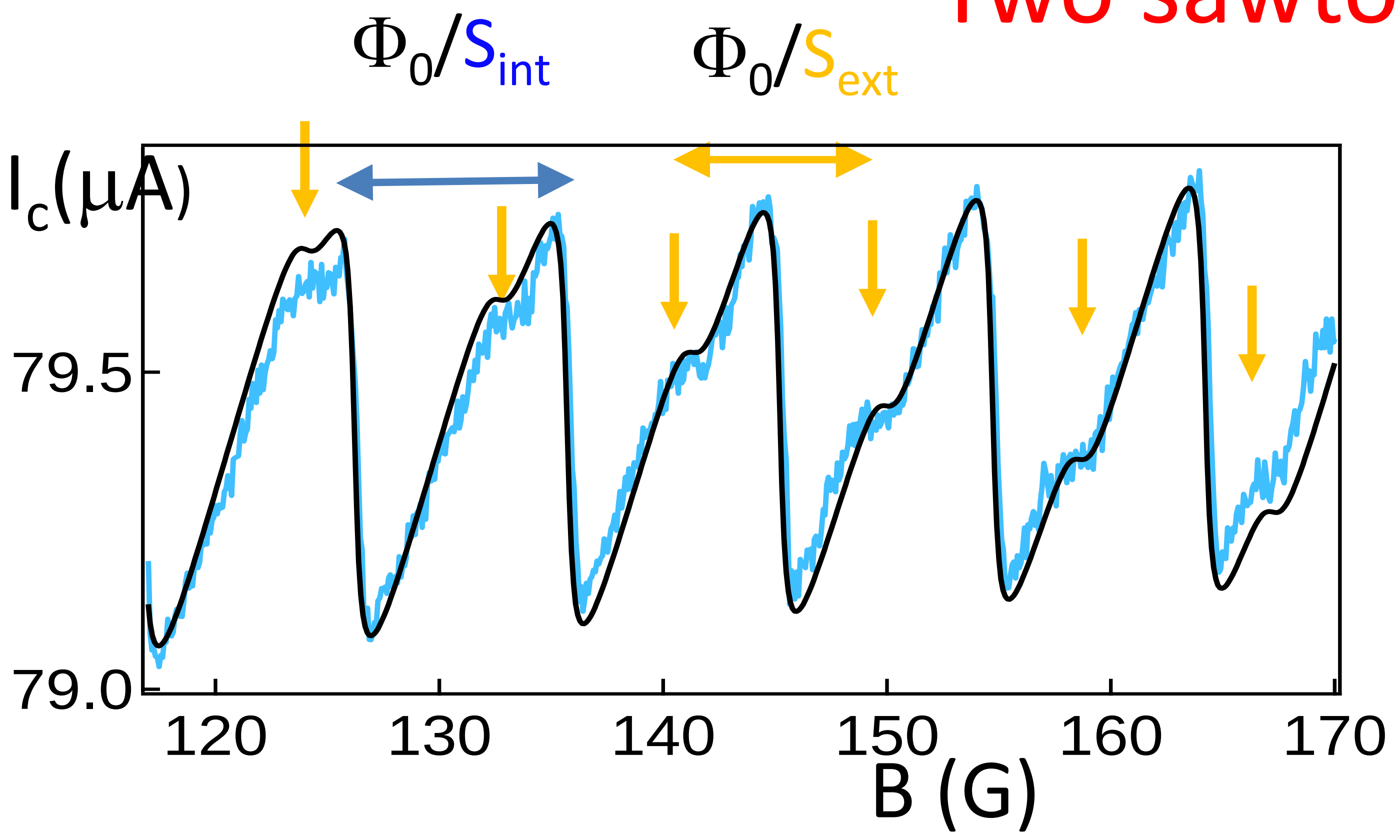
$\varphi = -2\pi BS/\Phi_0$

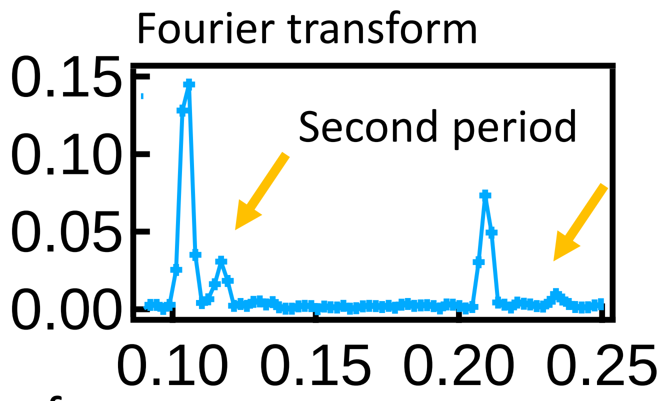


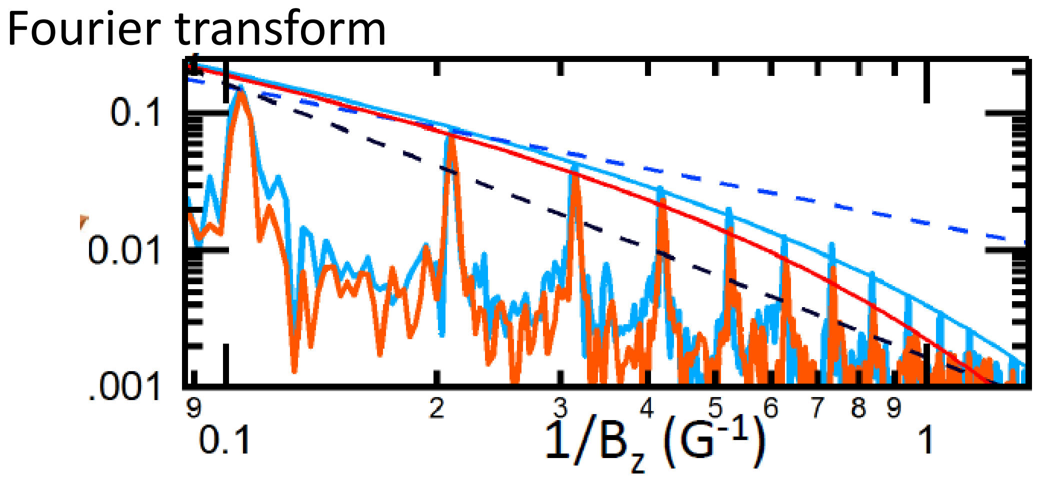
1 μm

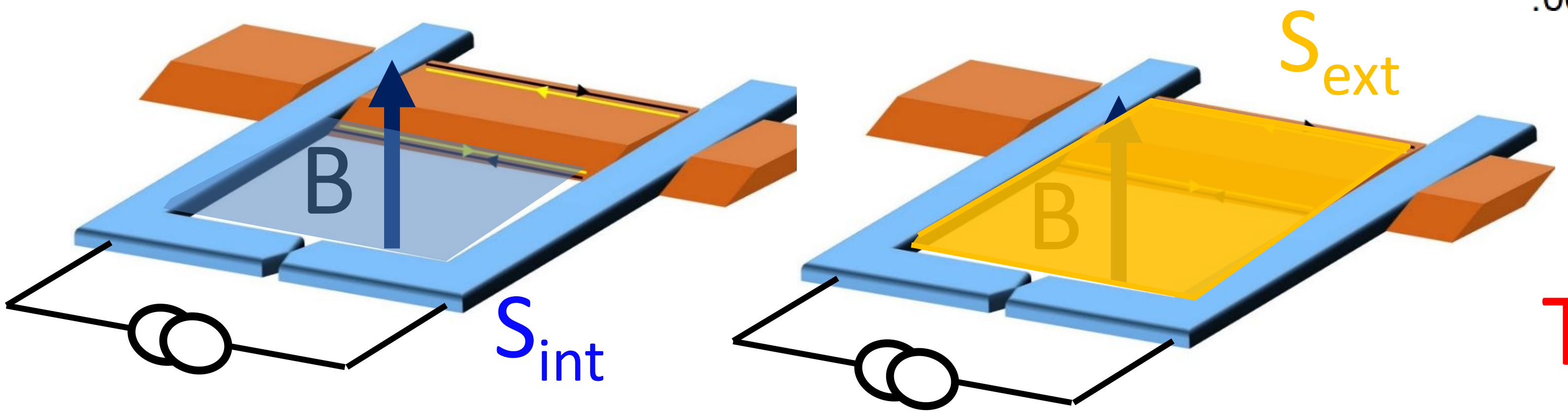
Sawtooth-shaped current phase relation: long ballistic!

Two sawtooths?



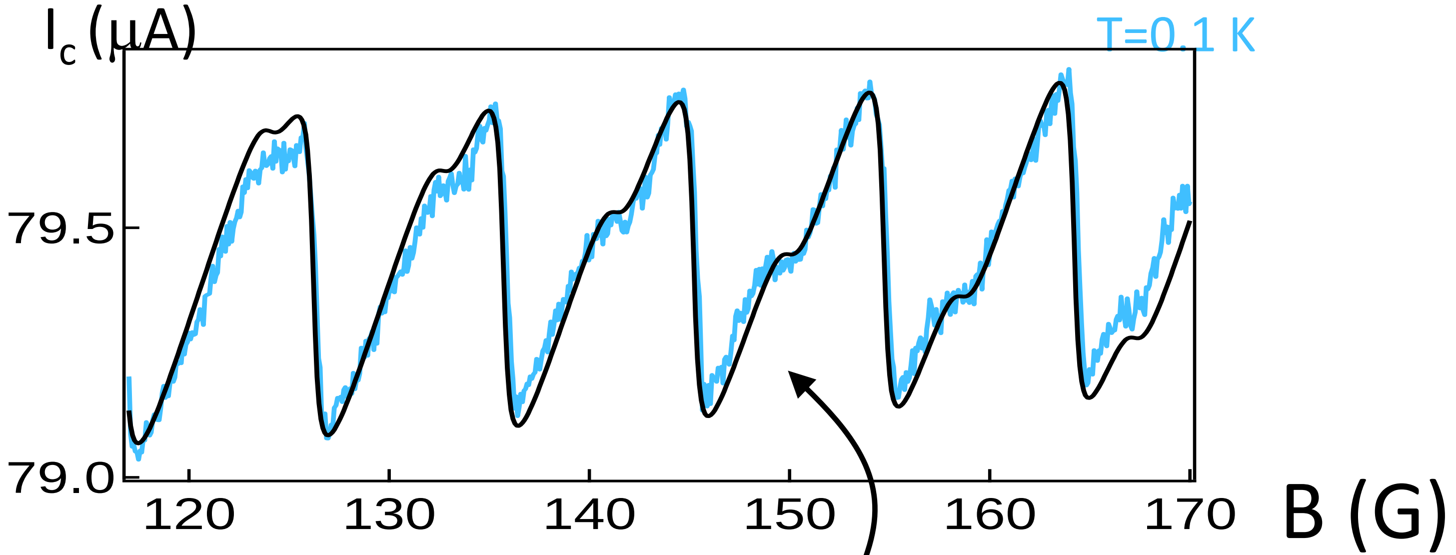






Two ballistic edges!

How ballistic are the two paths ?



I(φ) can be fit with:

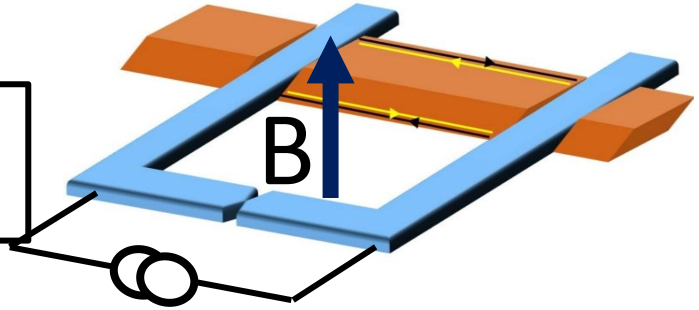
$$\boxed{\Sigma\frac{(-1)^n}{n}\sin n\varphi\, e^{-0.15n} + 0.25\,\Sigma\frac{(-1)^n}{n}\sin(1.1 * n\varphi)e^{-0.45n}}$$

$$\Sigma\frac{(-1)^n}{n}\sin n\varphi\, e^{-\alpha n} \sim \Sigma\frac{(-1)^n}{n}\sin n\varphi\, t^{2n}$$

channel transmission

Inner edge: channels with t≈0.9

Outer edge: channels with t≈0.7



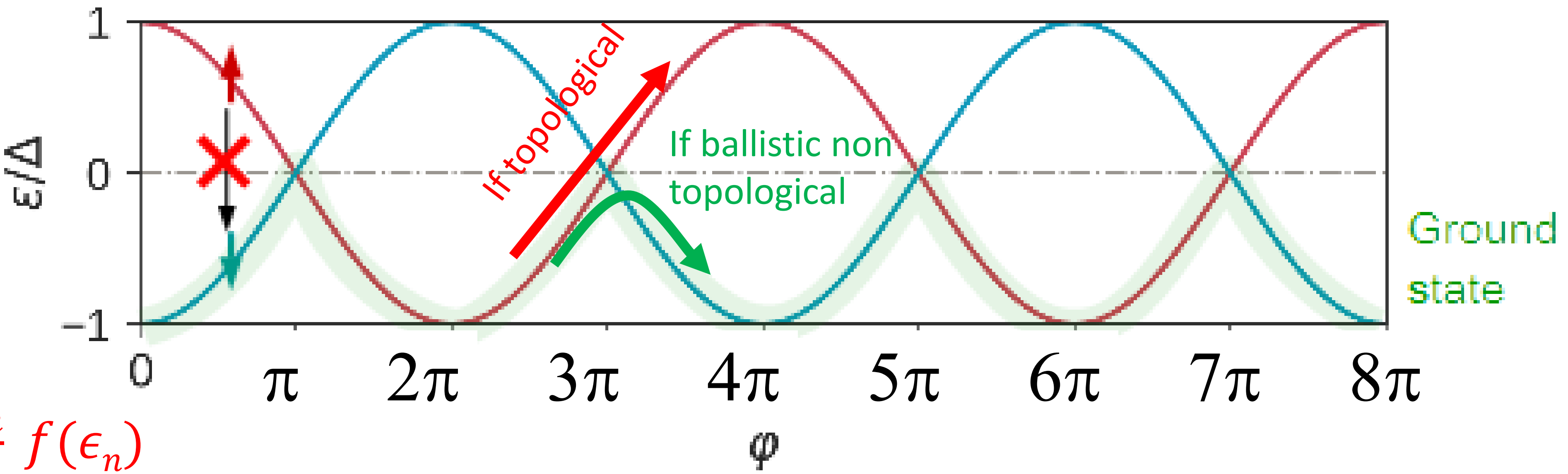
Proximity effect experiments in S/Bi nanowire/S junction

1- Field-controled Interference probe supercurrent-carrying paths : edge states

2- (dc) Supercurrent versus Phase relation (CPR) probe Andreev spectrum : edge states are ballistic

3- High frequency (ac) susceptibility $\chi = dI/d\varphi$ probes topological protection

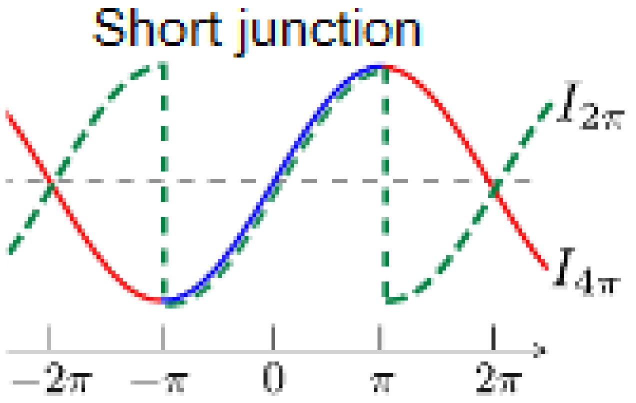
Consequence of parity protection on current phase relation?

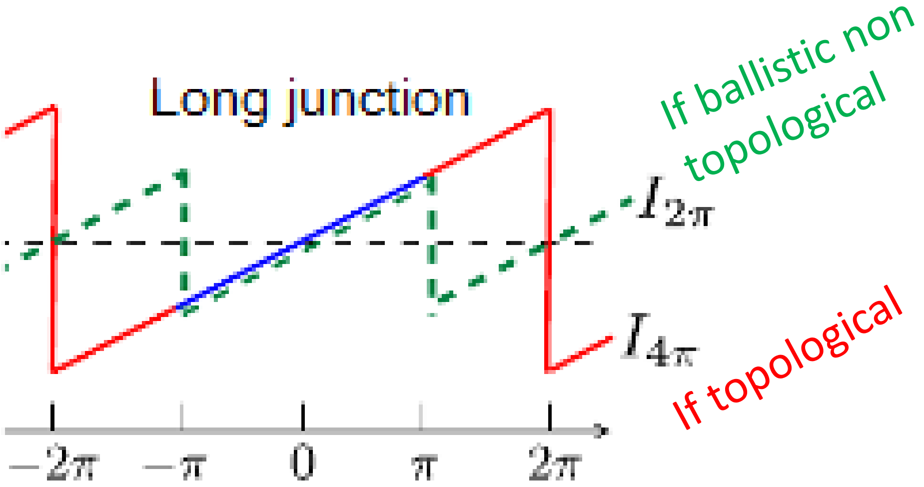


$$I = \sum_{-\infty}^{0} \frac{\partial \epsilon_n}{\partial \varphi} \, f(\epsilon_n)$$

4π periodic CPR

Beenakker 2013

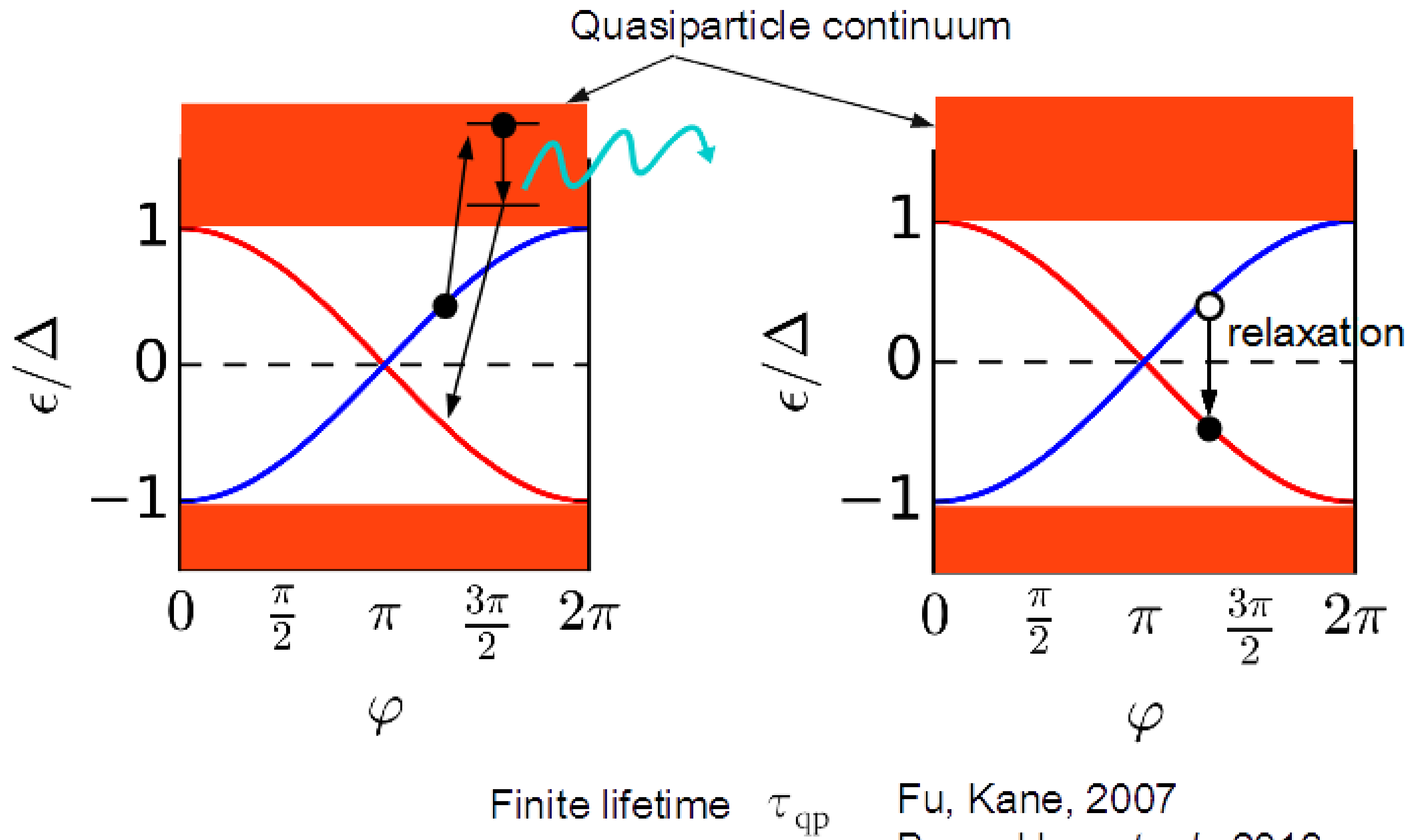




Difference easy to see?

Supercurrent through QSH edge should be 4π periodic, whereas 2π periodicity if ballistic non topological.

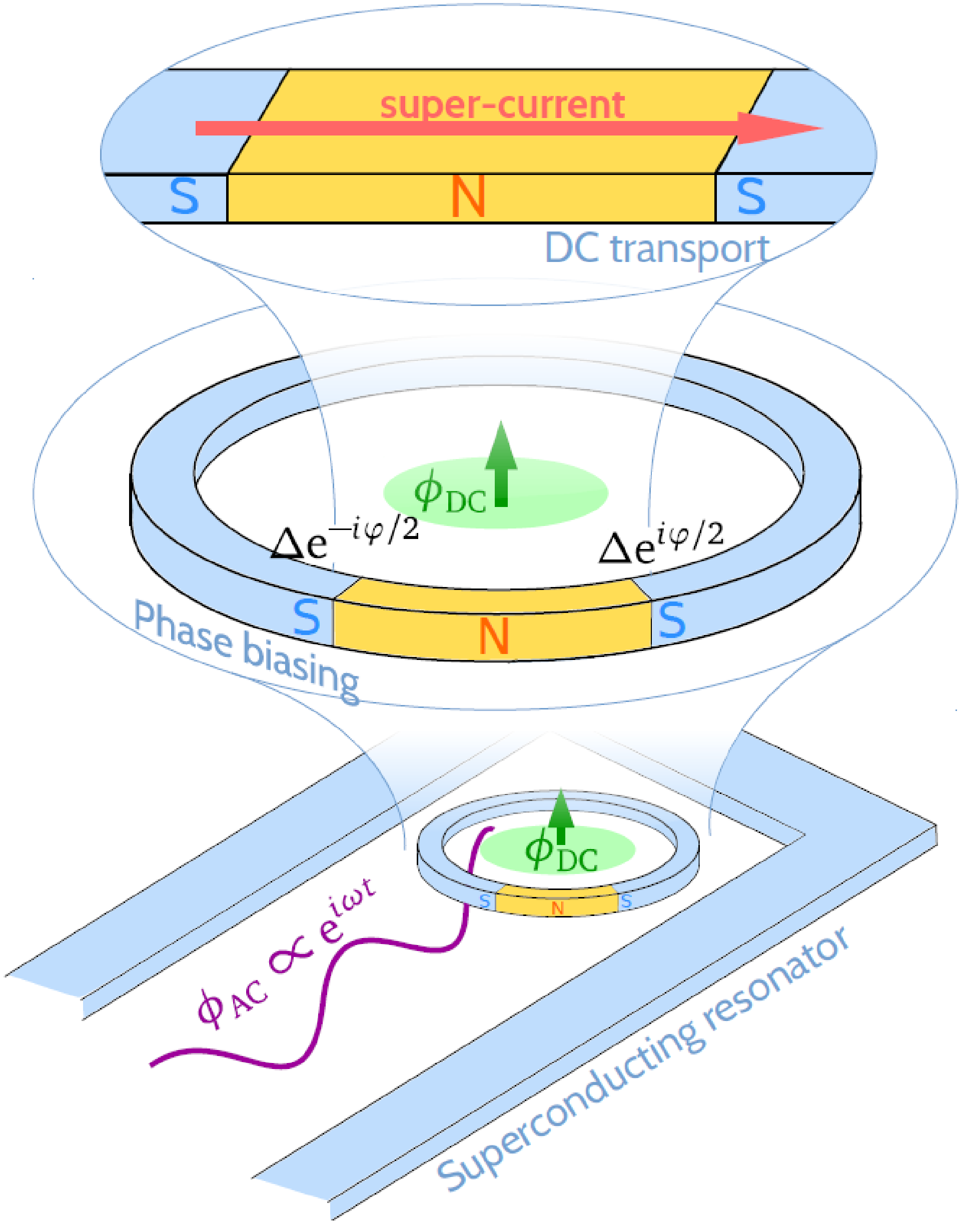
But poisoning can return periodicity to 2π



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

Need to go beyond dc current phase measurements:
Measure high frequency response (especially near crossings) to beat poisoning/relaxation rate: measure at $\omega >> \gamma_p$!

How to determine the topological character of the Bi SNS junction: finite frequency driving



<u>Finite frequency driving</u>:

$\varphi(t) = \varphi_{dc} + \varphi_{ac} \cos \omega t$

Linear response

$\delta I(\omega) = \chi(\omega)(\varphi_{ac} \exp{-i\omega t})$

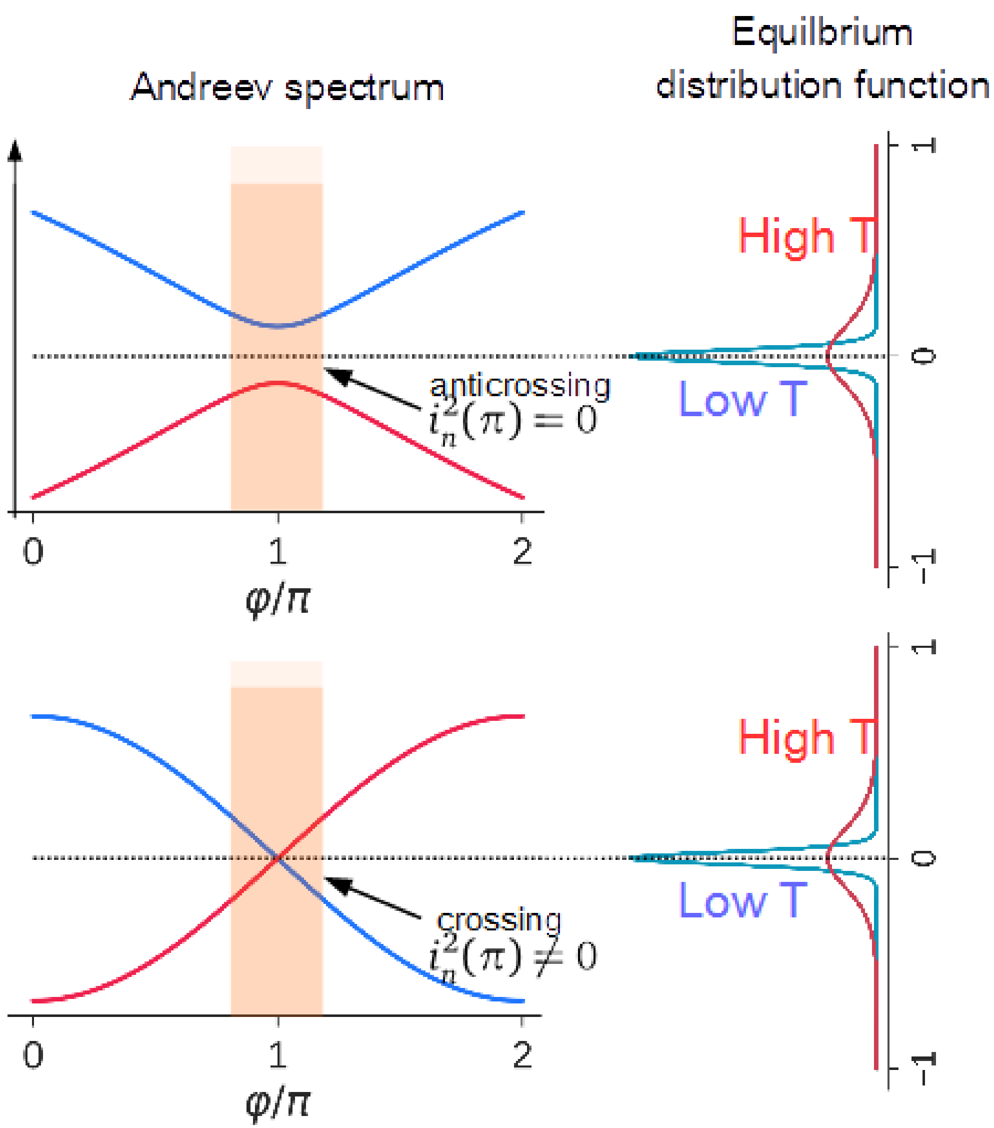
$\chi = \chi' + i\chi''$

Probing dynamics of SNS junctions close to equilibrium

ac susceptibility could distinguish topo/non topological states

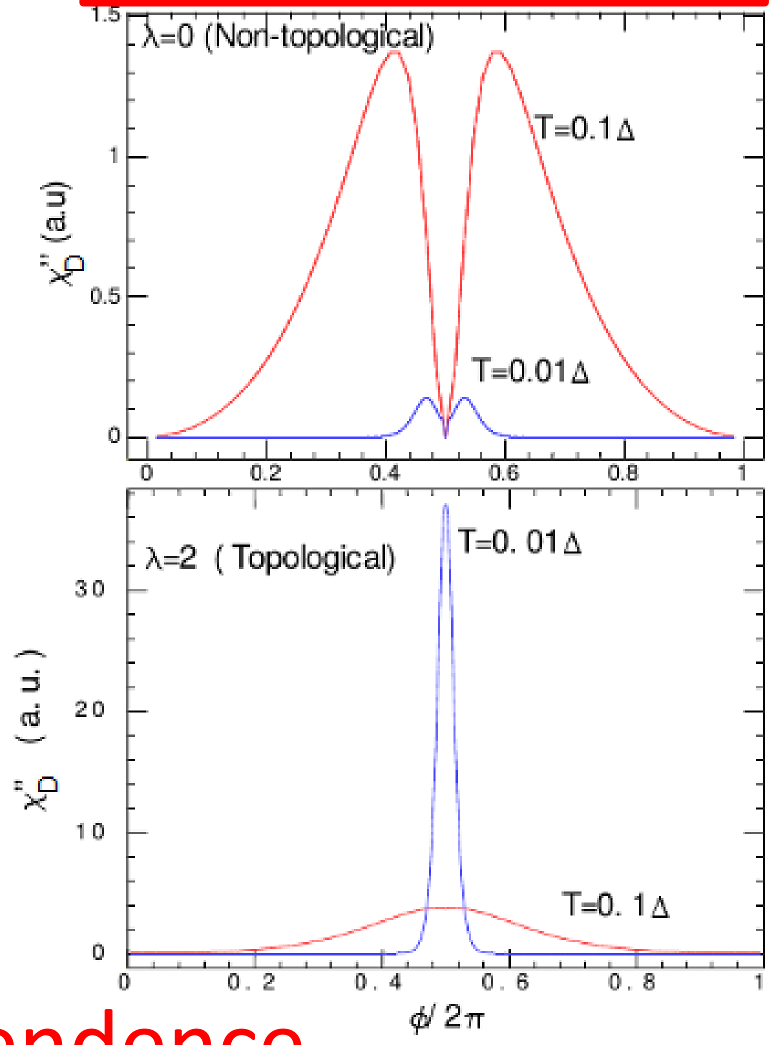
Without topological protection

With topological protection



Diagonal absorbtion (imaginary part)

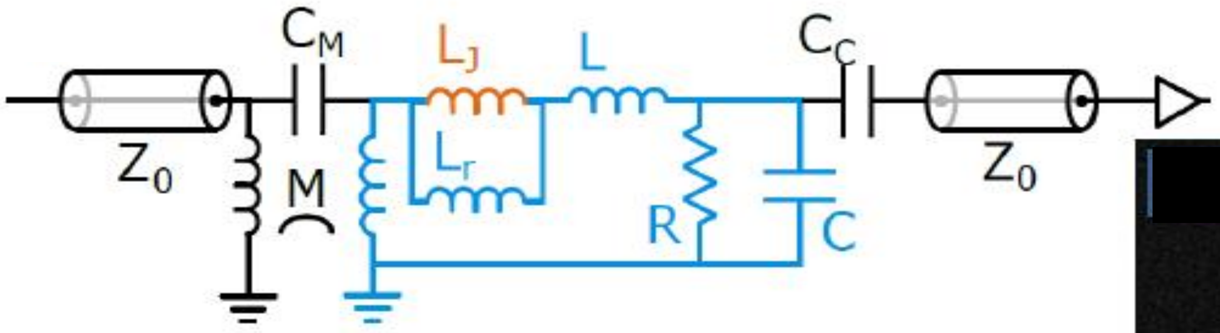
$$\chi''_{\mathrm{D}} = \frac{\omega\tau_{\mathrm{in}}}{1+(\omega\tau_{\mathrm{in}})^2}\sum_n (\partial_\epsilon f_n)\, i_n^2$$

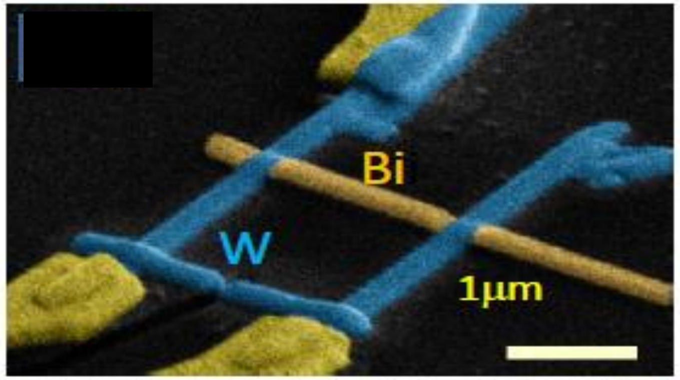


absorption decreases as T increases

…Measure absorption and T dependence

High frequency experiments: SQUID in a multimode resonator





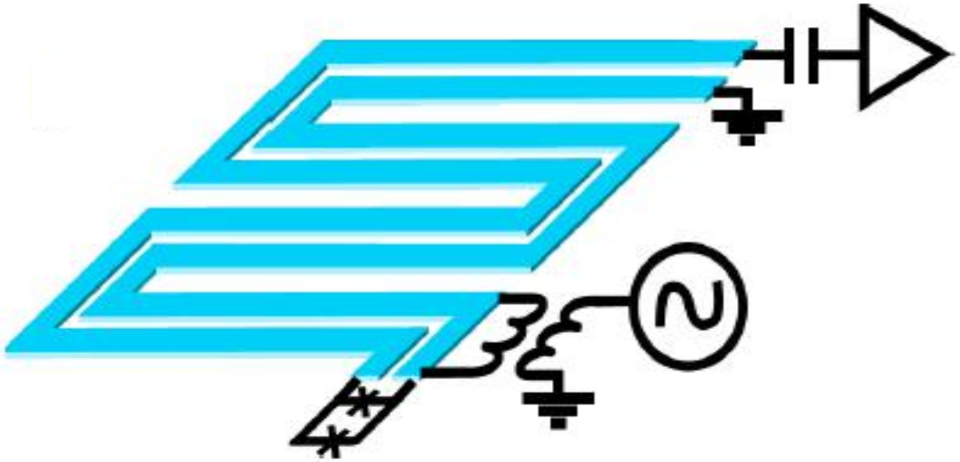
$$\boxed{\delta(1/Q) = -\delta Q/Q^2 = L_c^2 / L_R \chi''}$$

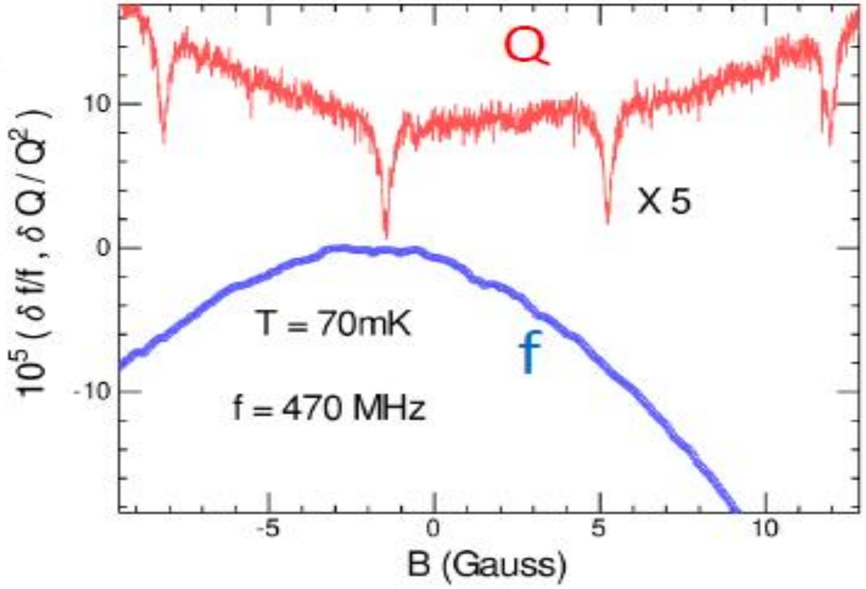
Coupling inductance

L_c ~ 100pH

Resonator inductance

L_R ~ 1µH



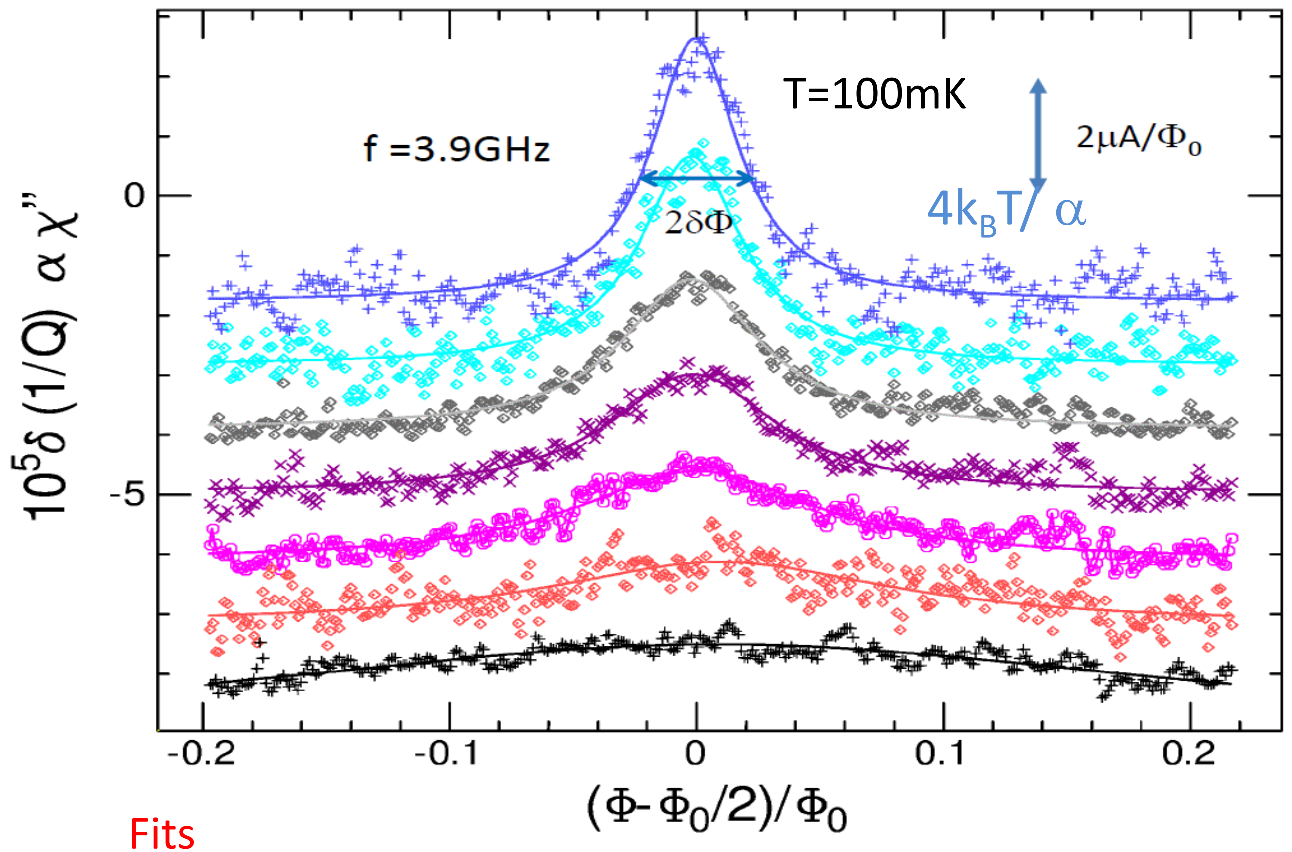


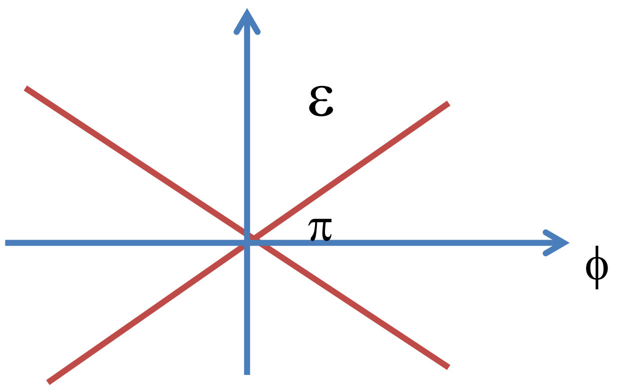
$$\boxed{L = (2n+1)\lambda_n/4}$$

Periodic absorption peaks around 2n+1 $\phi_0/2$

Signature of zero energy Andreev level crossing

$$\chi''_D = \frac{-\ \omega\tau_{in}}{(1+\omega^2\tau_{in}^2)} i^2(\varphi) df/d\epsilon$$





$$\boxed{\varepsilon = \pm\,\alpha(\phi-\pi)}$$

$i^{\pm} = \partial\,\varepsilon^{\pm}(\phi)\,/\,\partial\,\phi$

$\boxed{i^2 \text{ finite} = (ev_F/L)^2}$

Fits

$$\boxed{\chi''_D = I^2\frac{\partial f}{\partial\epsilon} = \frac{(ev_F/L)^2}{4k_BT\cosh^2[\alpha(\phi-\pi)/2k_BT]}}$$

$\alpha = ev_F/4L\pi$

Only adjustable parameter

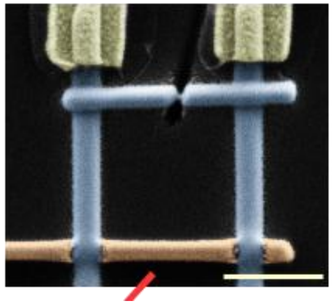
$v_F = 4\ 10^5$ m/s

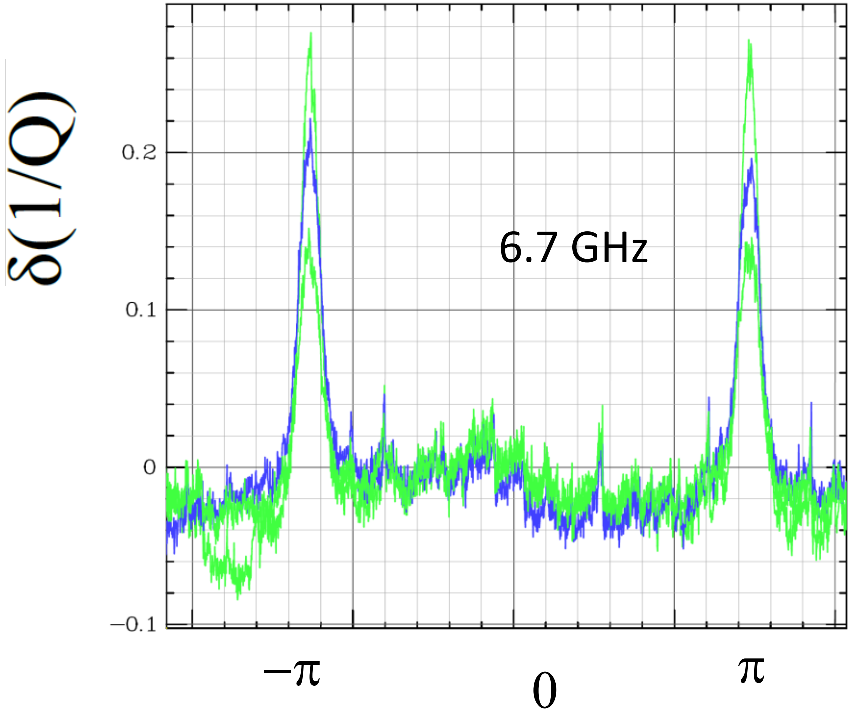
Compatible with dc measurements

Compare ac susceptibility of S/Bi/S and S/diffusive Au/S

S/Bi/S

A. Murani, B. Dassonneville



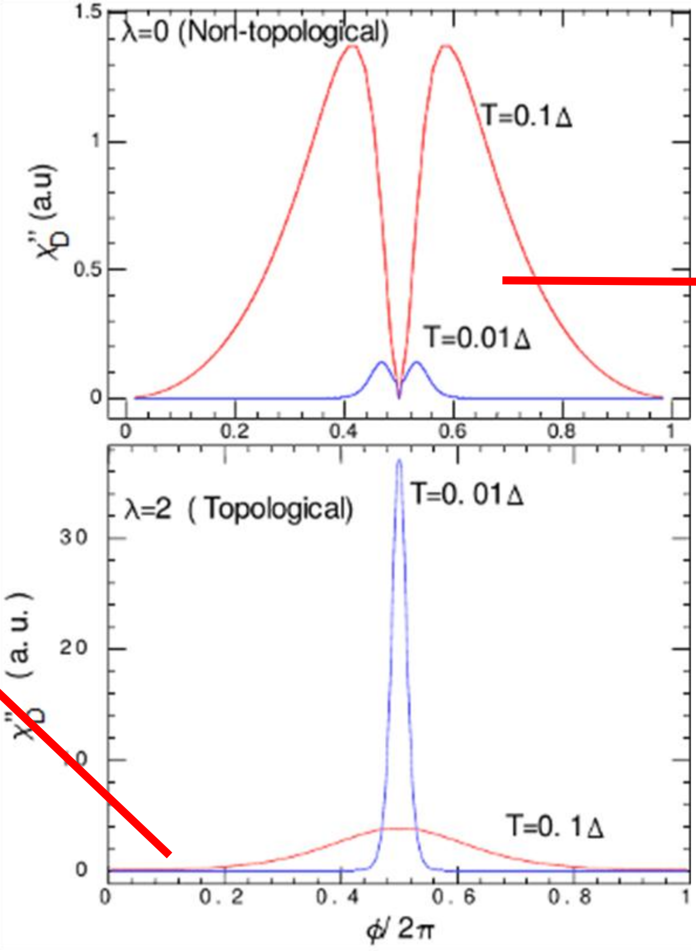


In S/Bi/S:

max absorption at π!

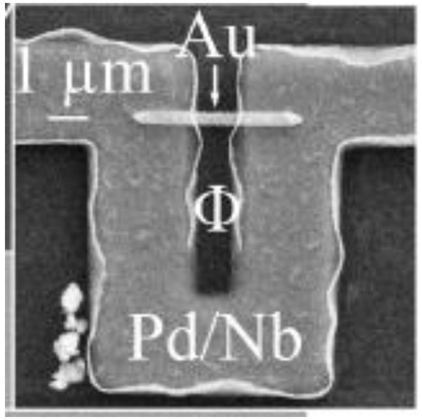
Diagonal absorbtion
(imaginary part)

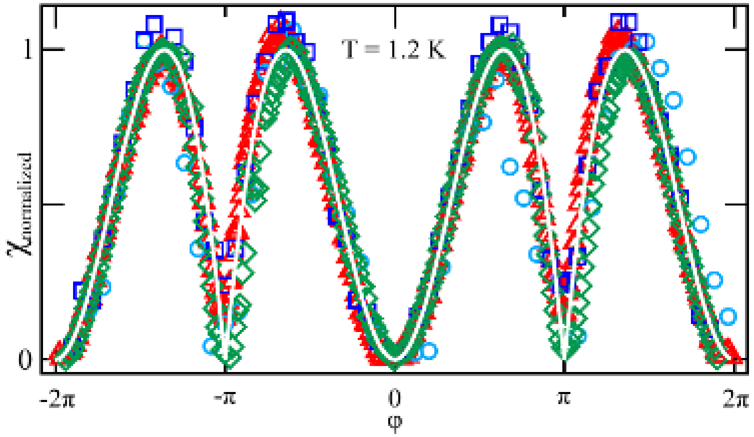
$$\chi''_D = \frac{\omega\tau_{in}}{1+(\omega\tau_{in})^2}\sum_n (\partial_\epsilon f_n)\, i_n^2$$



S/diffusive Au/S

B. Dassonneville PRL 2013





In SNS:

zero absorption at π!

Experimental conclusion: Probing edge states in bismuth nanowires with mesoscopic superconductivity

Edge states revealed in Bismuth nanowires with (111) surfaces

« Edge » :revealed by interference pattern of critical current

« Ballistic edge » : revealed by sawtooth-shaped current-phase relation

« Topologically protected edge state » suggested by shape of dissipation peaks in ac response measurement.

Murani et al, Phys.Rev. B 2017
Murani et al, Nature Comm. 2017
Schindler et al, Nature Phys. 2018
Murani et al, PRL 2019