Revealing ballistic edge states in Bismuth nanowires

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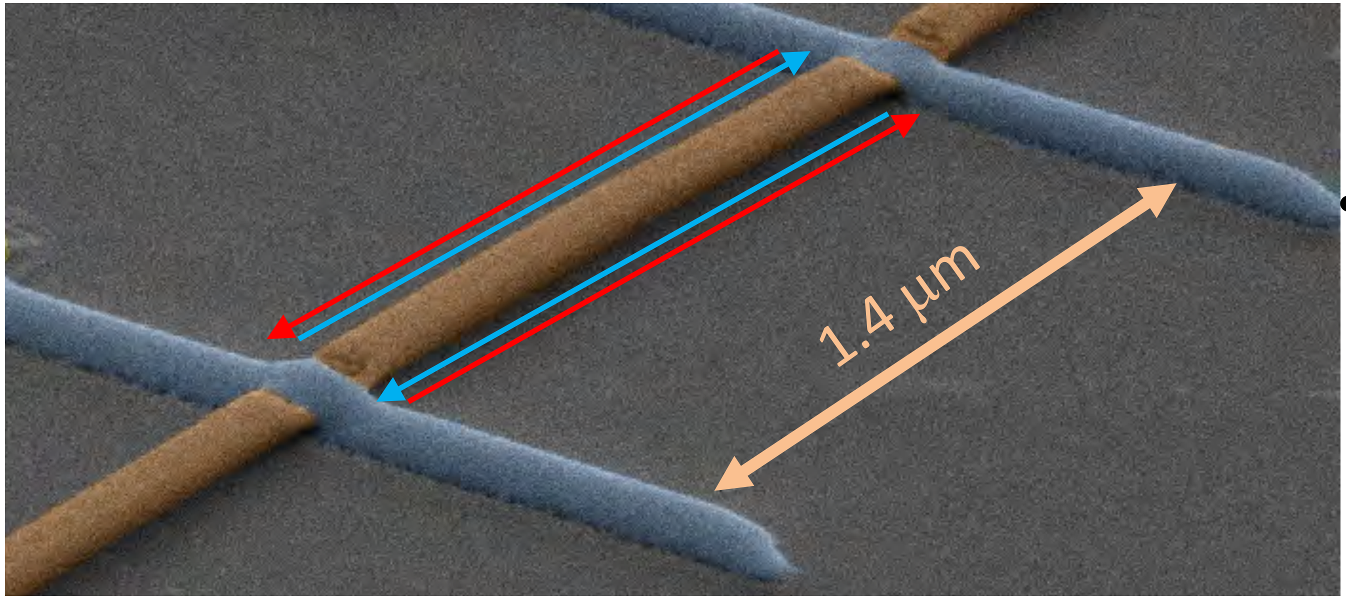


- 3D nanowire
- 2D topological insulator surfaces
- (topologically protected ?) 1D edge states

Goal : probe the 1D edge states with best tools of mesoscopic physics (using superconducting contacts)

Li et al., Phys. Rev. B 90, 245427 (2014)
Murani et al, Arxiv 1609.04848
Murani et al, Arxiv 1611.03526 (Nature Comm. July 2017)

Probing edge states in bismuth nanowires with mesoscopic superconductivity

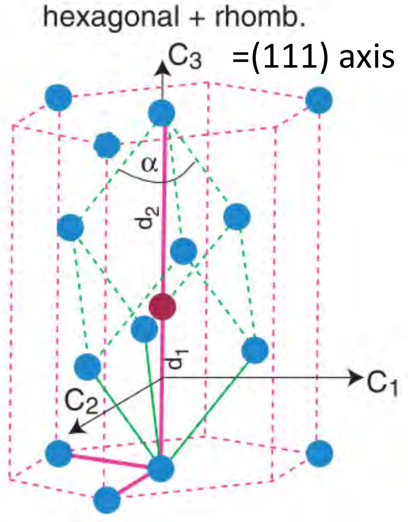
1 Our Quantum Spin Hall candidate: Bismuth nanowire

2 Induced critical current and its field dependence to detect edge states

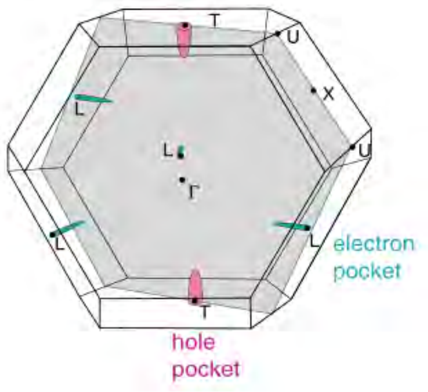
3 Are those edge states ballistic? The supercurrent-versus-phase relation

4 Beyond: High frequency probing to test topological protection

Bismuth, from bulk to surfaces to edges



Bulk Brillouin zone



Hofmann 2006 review

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

Better yet : Some surfaces are topological

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

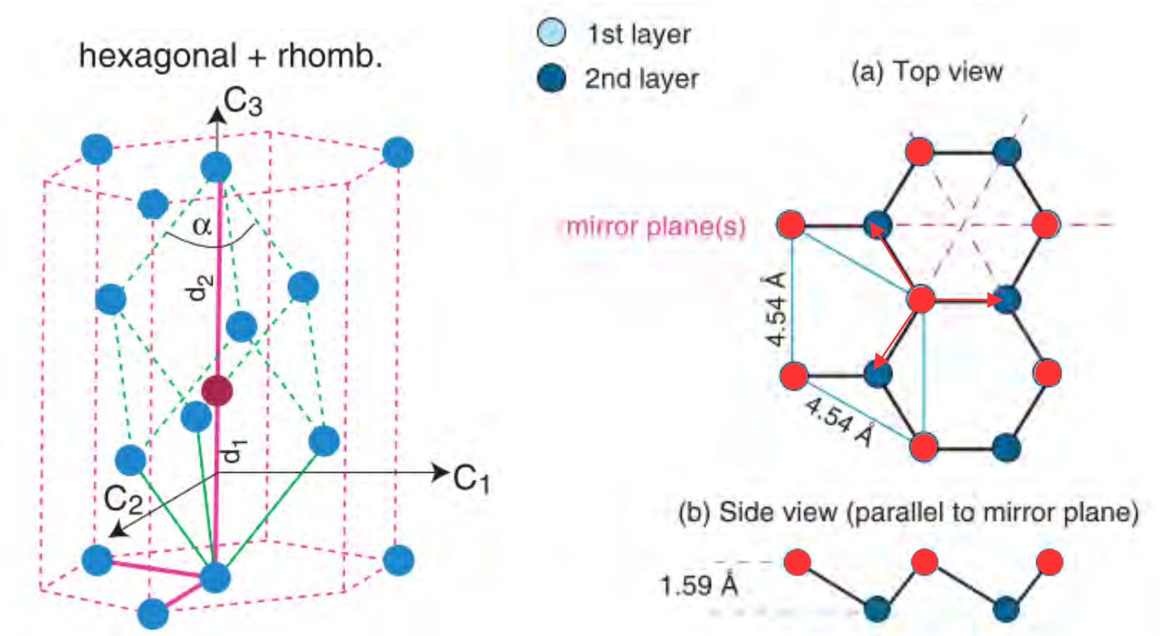
- (111) Surface= buckled honeycomb
  ≈ graphene with huge spin-orbit!

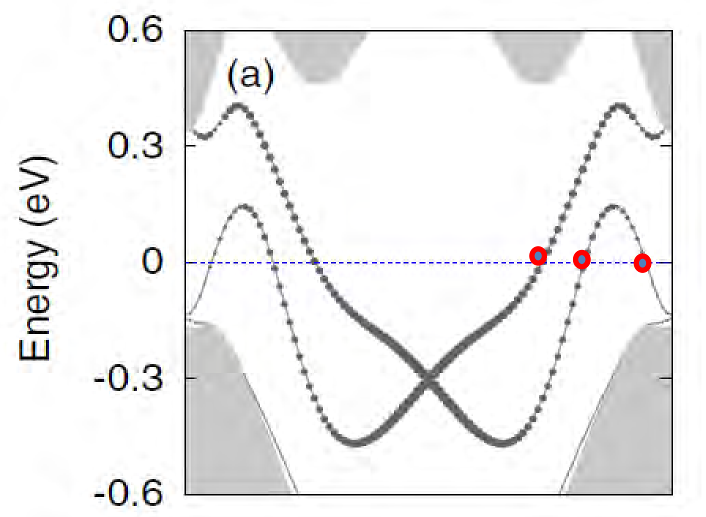
⇒predicted 2D topological insulator

Murakami, 2006

Liu & Allen, 1991

3 edge states predicted





Free standing (111 bilayer)

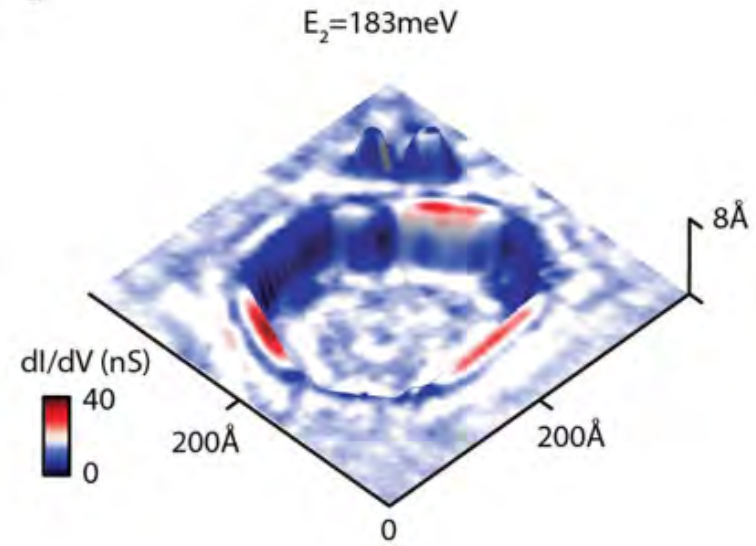
Yemo 2016

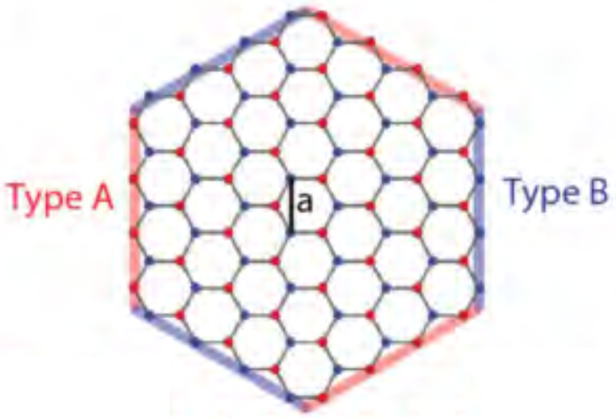
Whether these 1D states are topological is debated

1D edge states observed by STM! (decoupled from bulk Bi)

Bilayer pits in (111) bulk Bi crystals

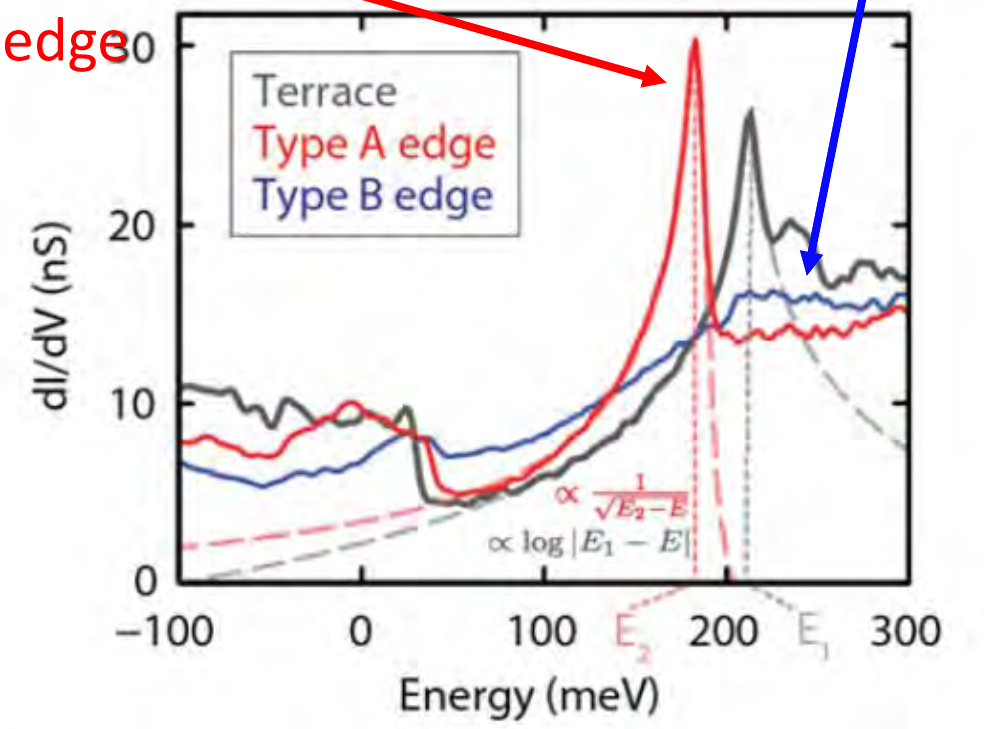
Drozdov Yazdani (2014)

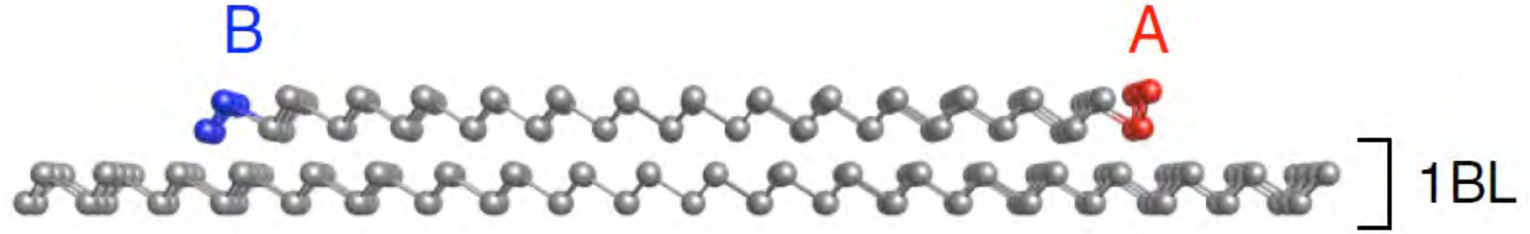




Van Hove singularity on type A edge

No van Hove on type B edge



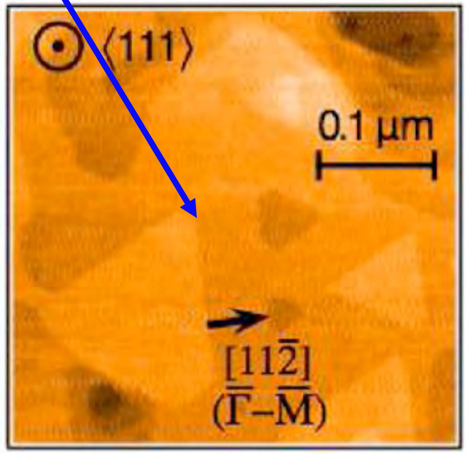


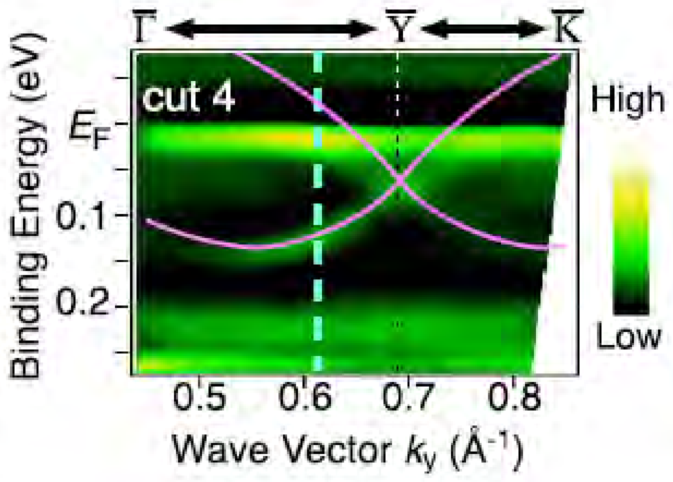
- Only A-type edges show 1D features
- Suppressed backscattering

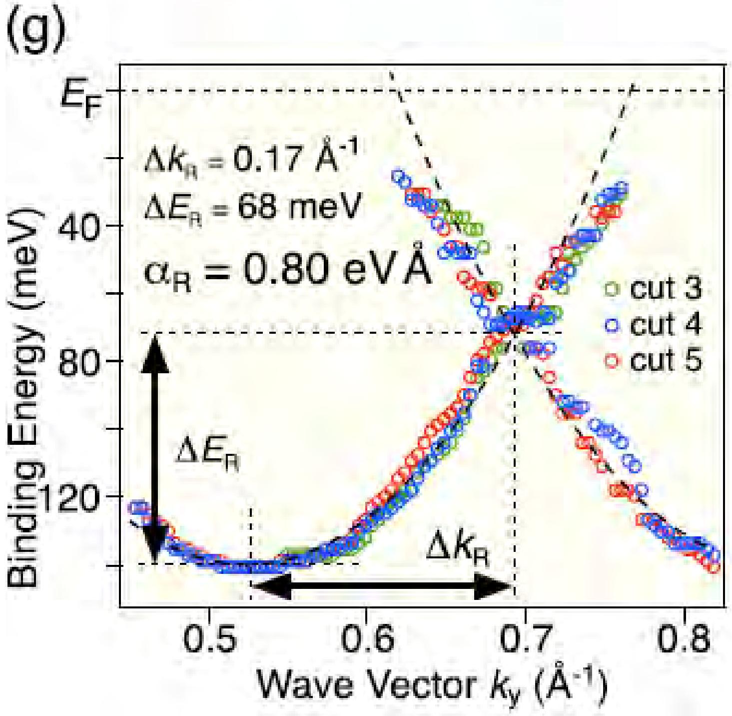
Indications of spin-polarized 1D states at (some) edges of 111 surfaces

Takayama PRL 2015

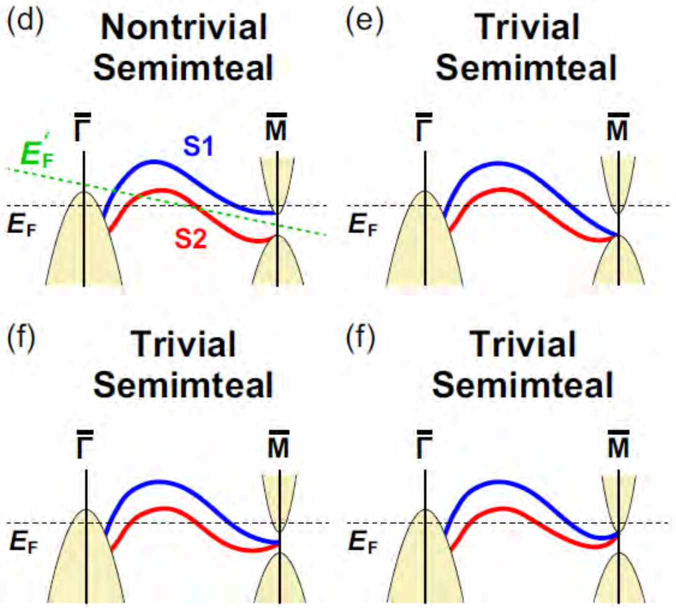
Photoemission on many A-type structures







- 1D dispersion
- Huge spin-spitting of 0.8 eV Ang (larger than surface!)
- Debated: are these 1D states topological or not?



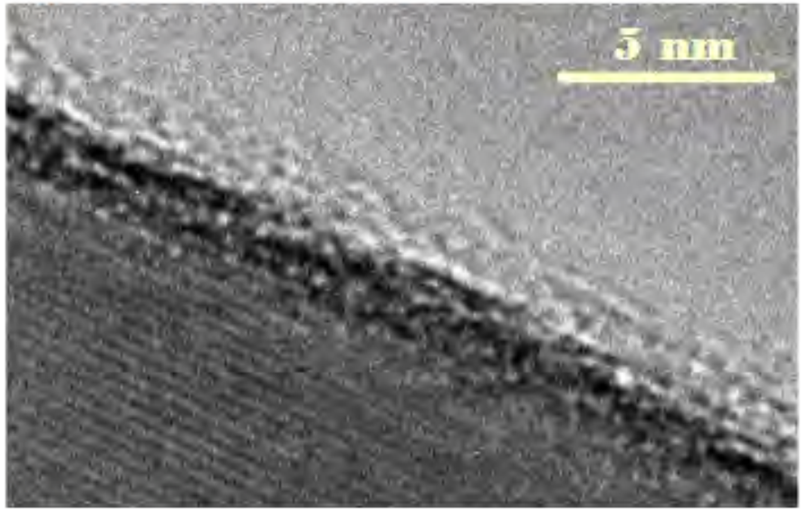
Our samples: Monocrystalline Bismuth nanowires

Growth : Sputtering on a hot surface

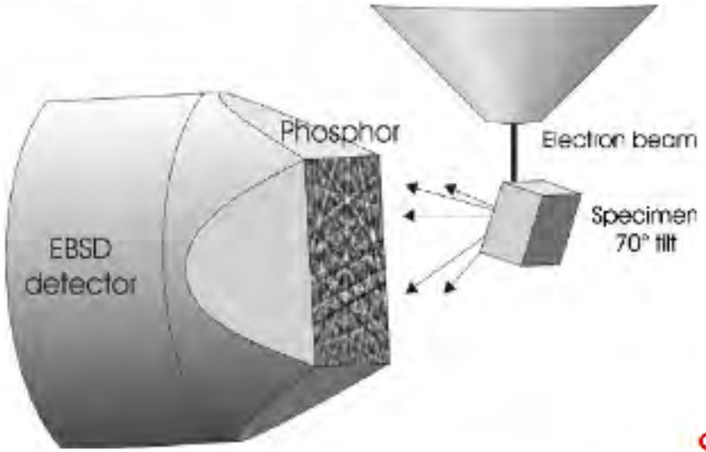
High quality
single
crystals
Ø ~ 100 nm

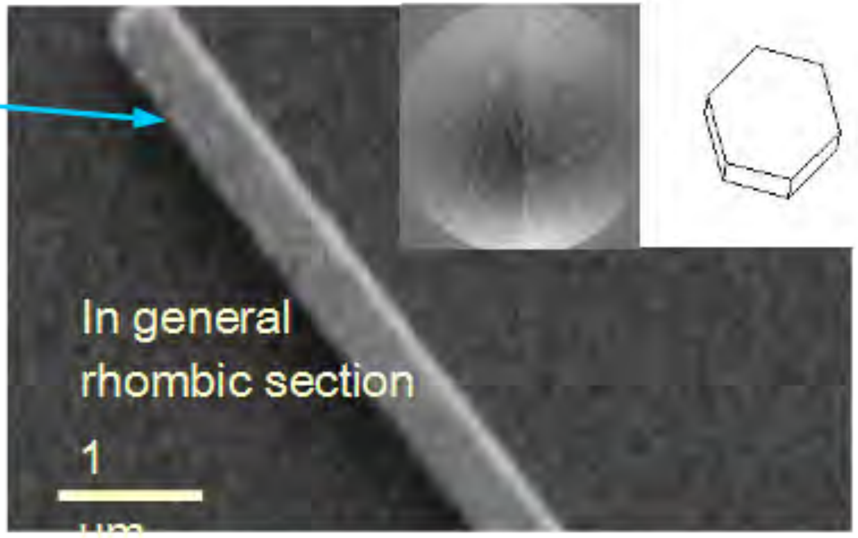
Alik Kasumov

High resolution TEM



Select desired orientation using EBSD

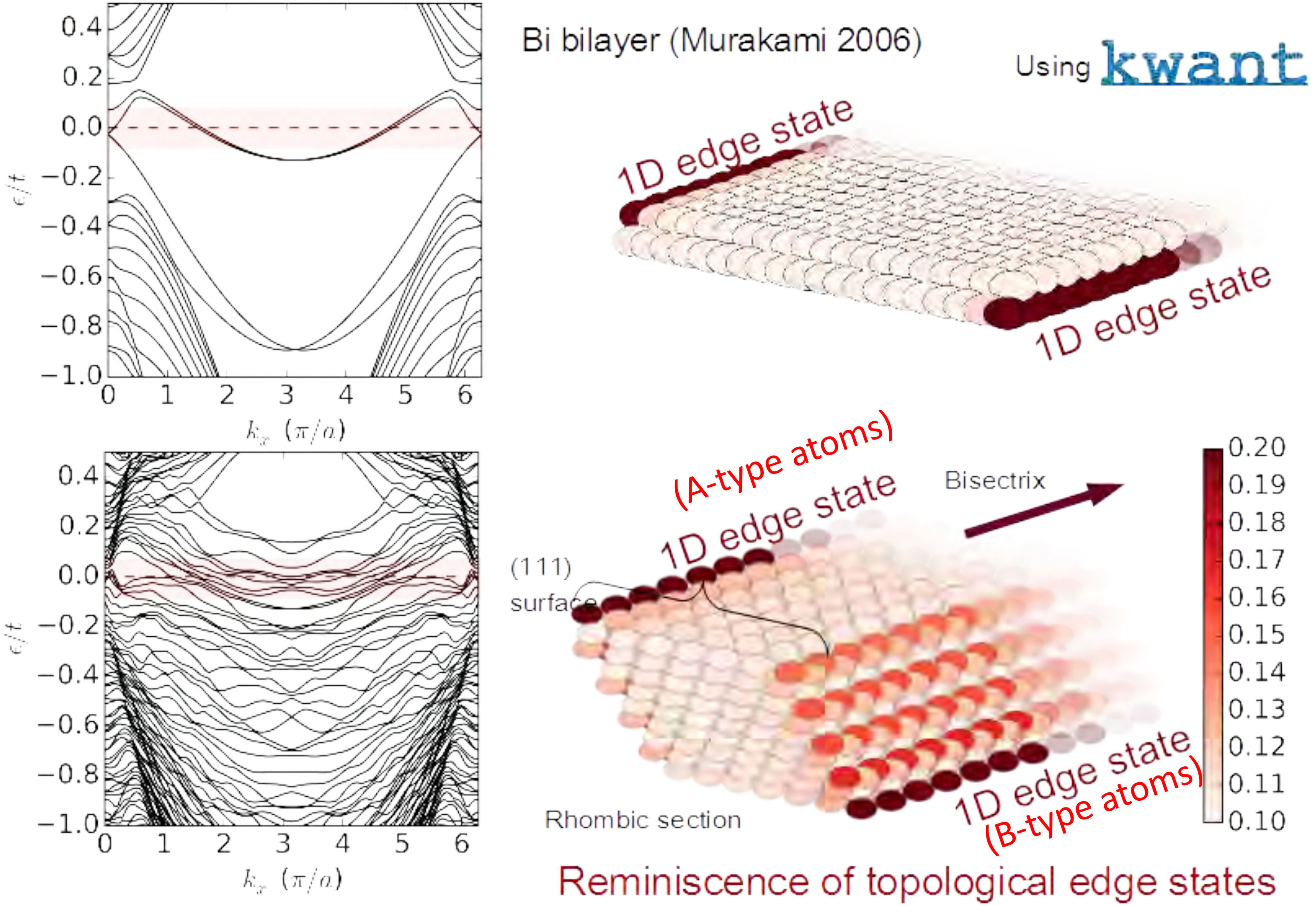




Top (111) surface

Select nanowires with (111) top surface

Simulation of bilayer and of (small) nanowire (Anil Murani)



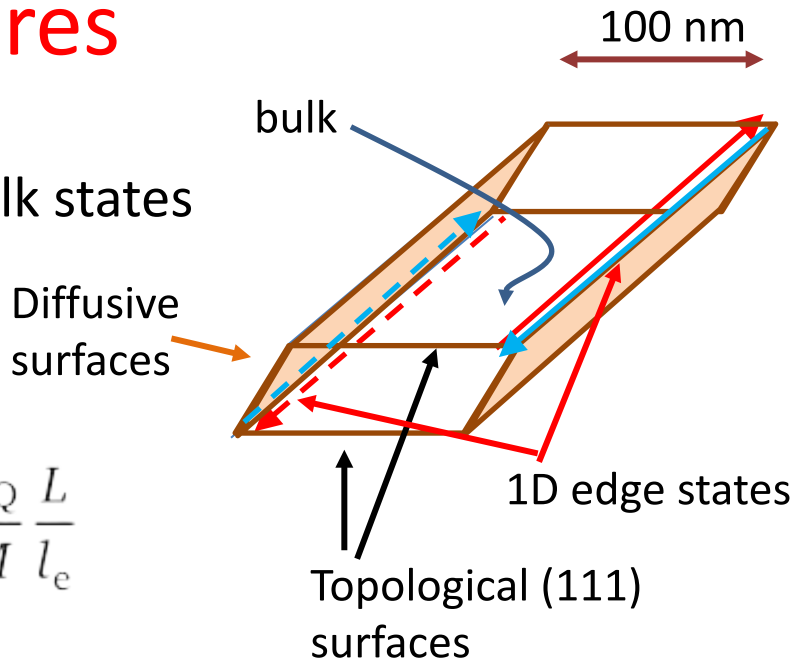
1D edge states found at sharp angles of nanowire !

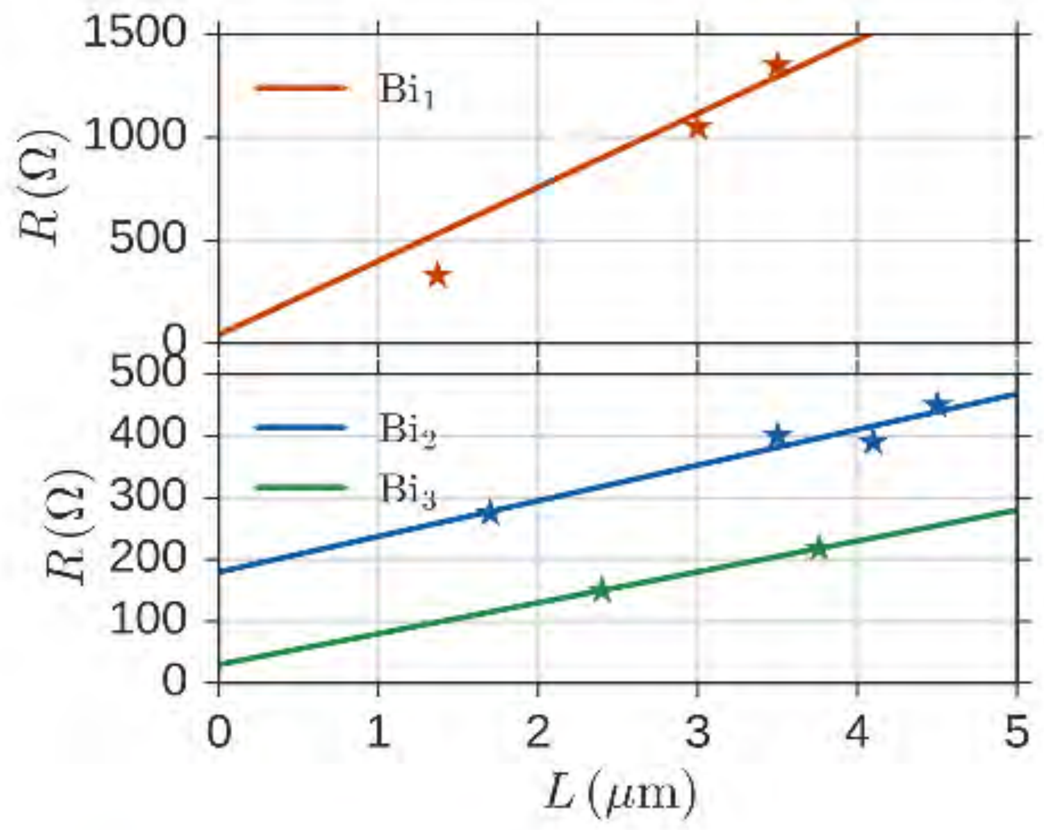
Bulk, surfaces and edges in our wires

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

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

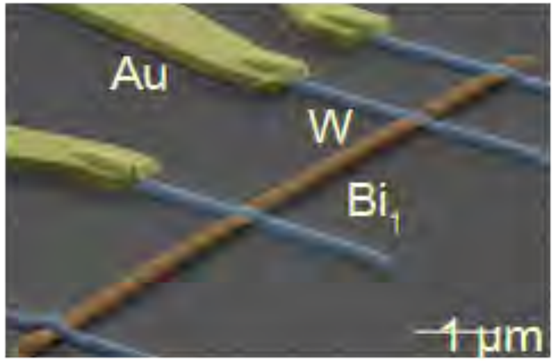
} Roughly 50 times more surface states than bulk states





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

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

Probing edge states in bismuth nanowires with mesoscopic superconductivity

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2 Induced superconductivity and its field dependence to detect edge states

3 Are those edge states ballistic? The supercurrent-versus-phase relation

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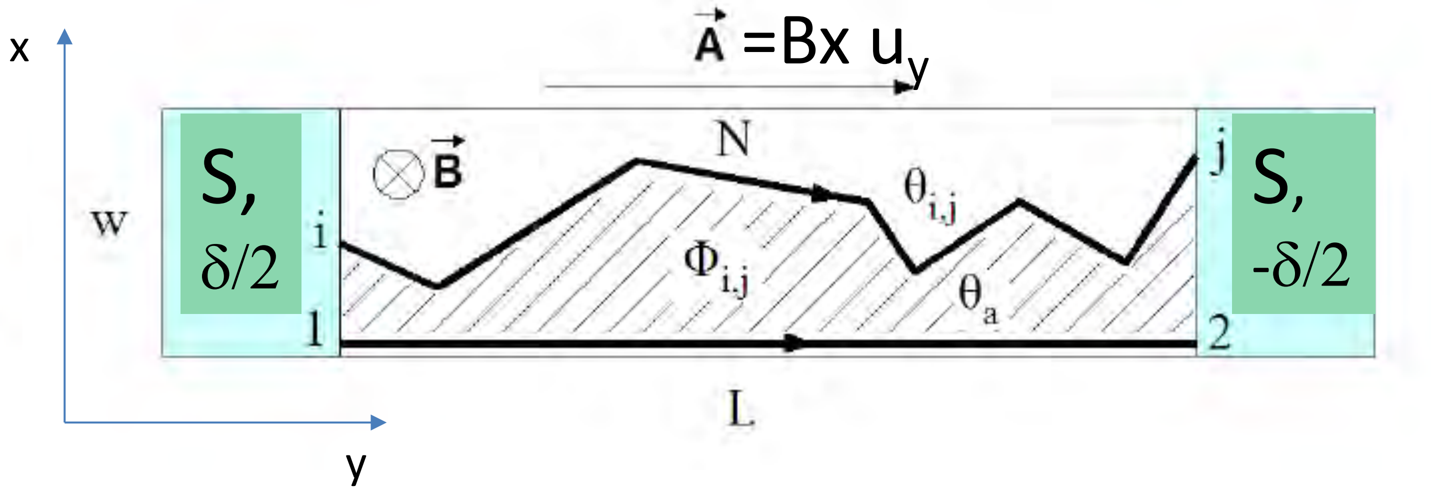
Superconducting contacts to exploit macroscopic wavefunction (and its phase): Interference experiments will reveal supercurrent paths

Gauge invariant Josephson relation:

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

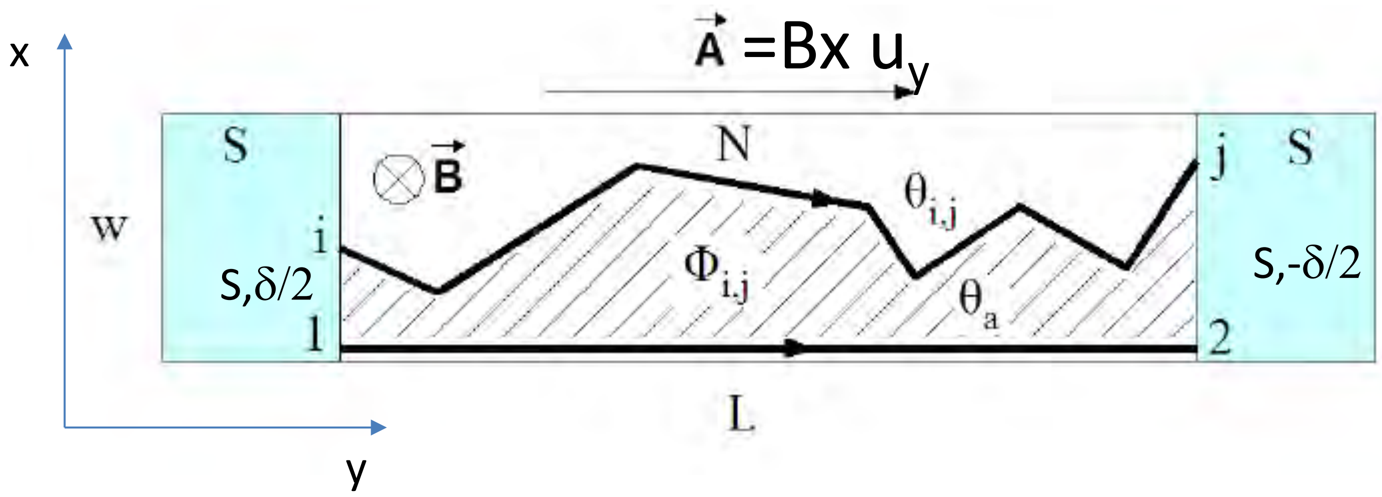


Critical current I_c(B)=max of integral over all supercurrent paths: interference terms!

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

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

Interference signature of uniform wide Josephson junction

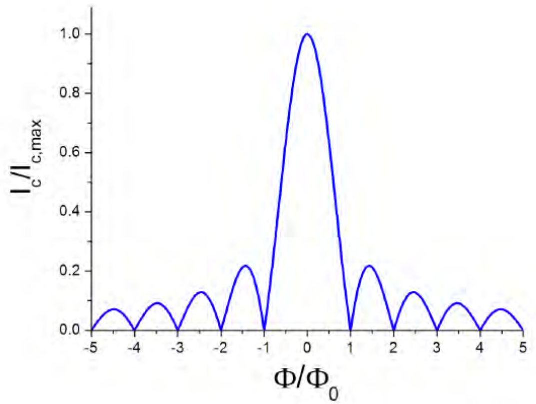


Critical current $I_c(B)$=max of integral over all supercurrent paths: interference!

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

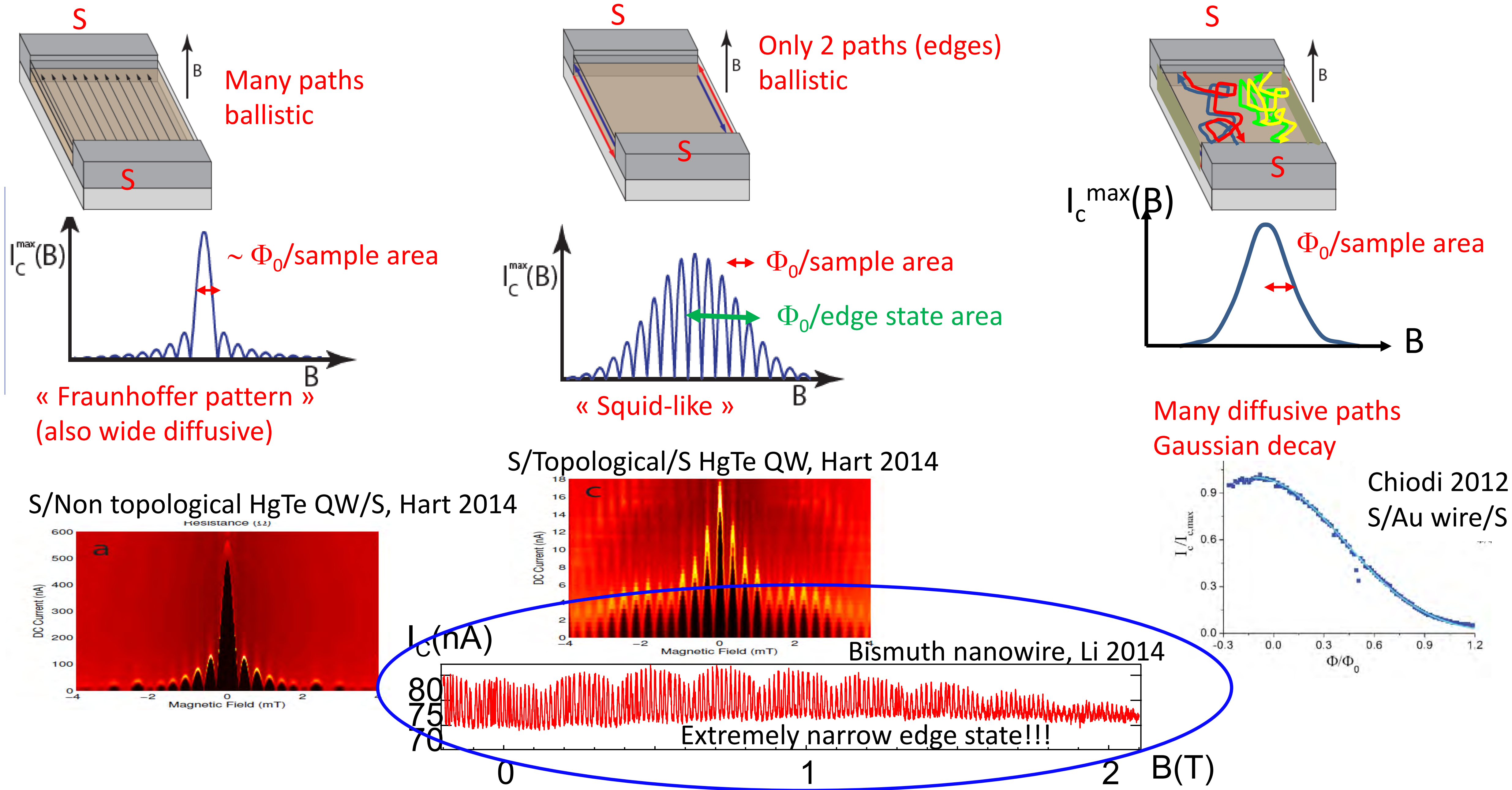
Uniform wide junction

$$I_c = I_c(0) \frac{\Phi_0}{\pi \Phi_J} \left| \sin\left(\frac{\pi \Phi_J}{\Phi_0}\right) \right|$$



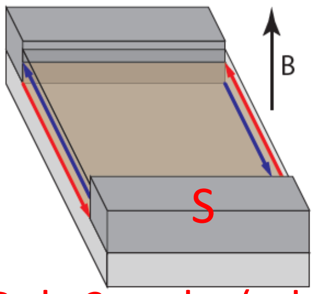
Critical current $I_c(B)$=Fraunhofer pattern in wide junction with uniform current distribution (diffusive or ballistic)

Critical supercurrent reveals paths taken by pairs (via interference)

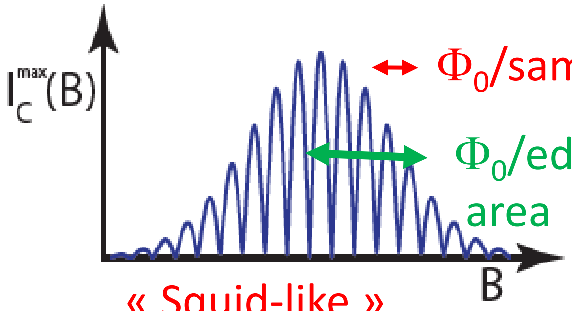


(quick) Comparison of 2 topological insulators:
Critical current through HgCdTe Quantum wells and Bismuth 111 surfaces

Topological HgCdTe QW, Hart 2014



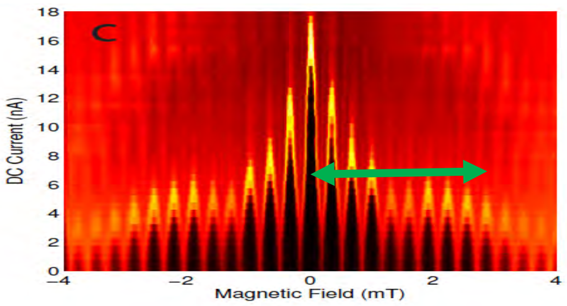
Only 2 paths (edges) ballistic



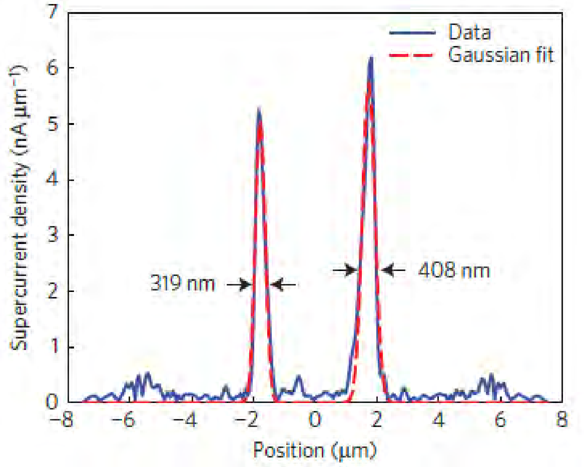
« Squid-like »

Φ_0/sample area

Φ_0/edge state area



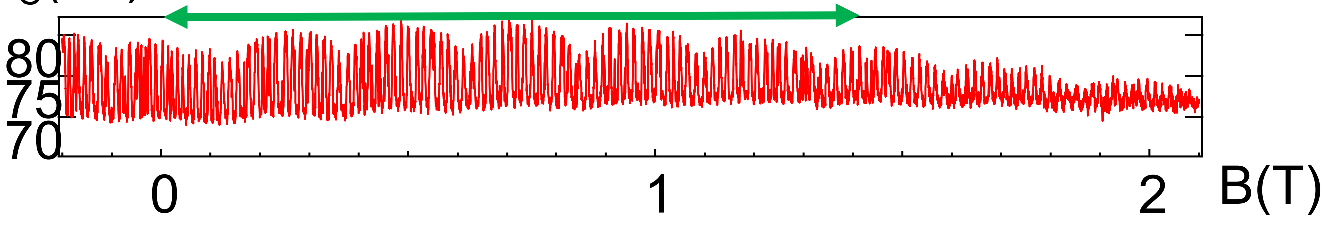
Φ_0/edge state area ~ 30 G



edge state ≈ 400 nm wide

Another 2D Topological insulator ? Surface of Bismuth nanowire, Li 2014

Φ_0/edge state area ~ 10 000 G

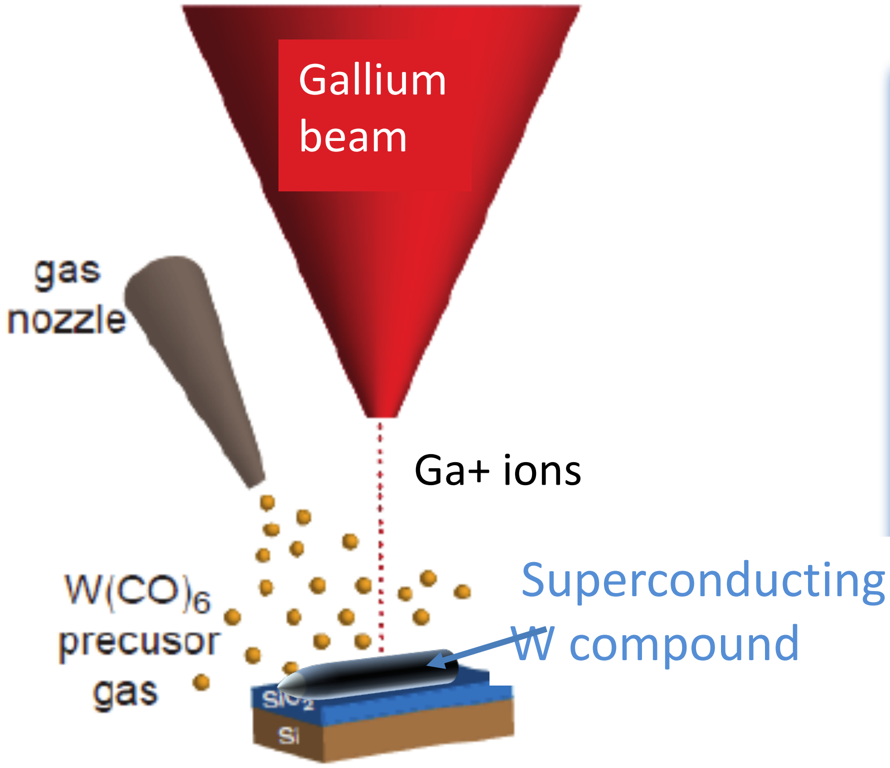


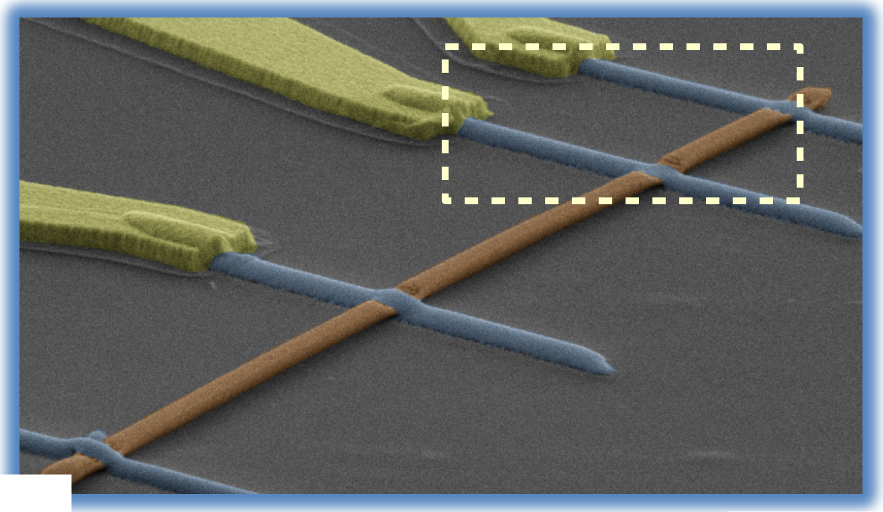
Nanometer-sized edge state, Extremely narrow!

- Squid-like (oscillating) $I_c(B)$ is proof of two paths
- But to proove ballistic transport through the two paths: need to go beyond $I_c(B)$

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

Kasumov 2005

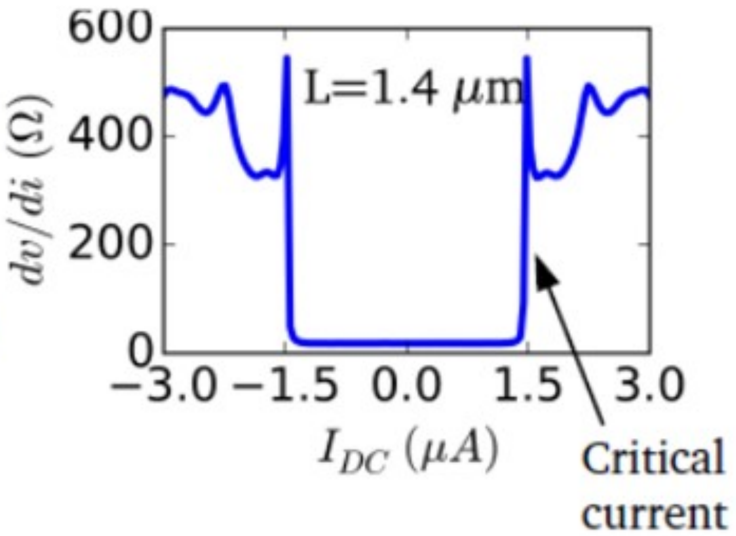




Bismuth nanowire With (111) surfaces

Superconducting W electrodes

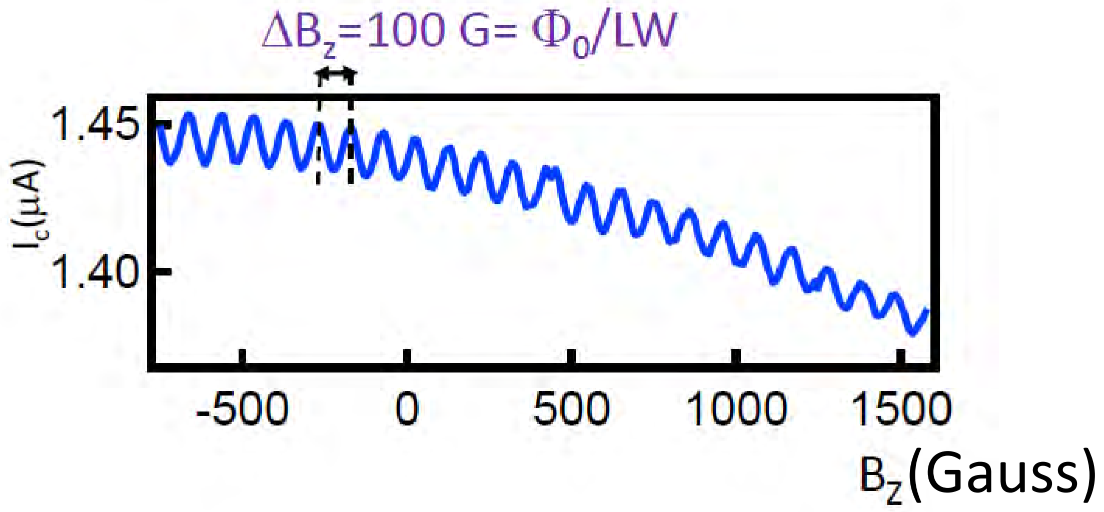
W/Bi/W junction

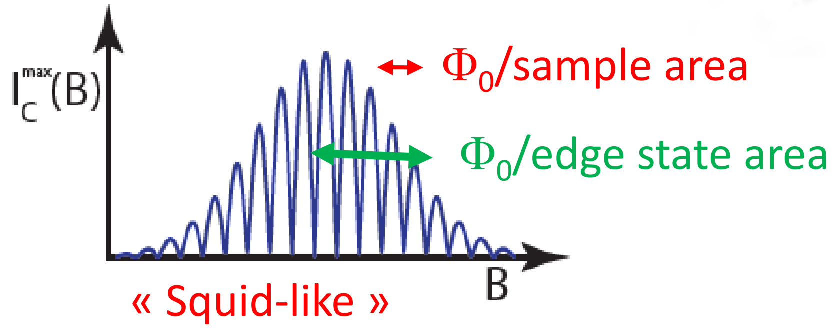


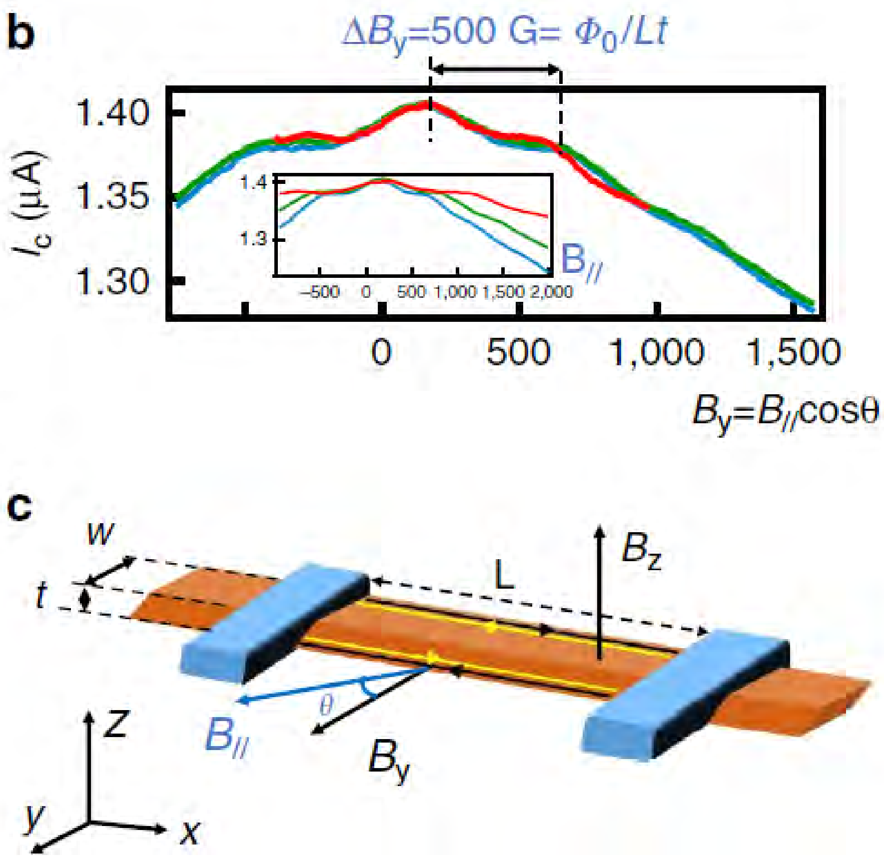
Superconducting electrodes:

- 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.

Beyond interference paths revealed by $I_c(B)$ of SNS junction

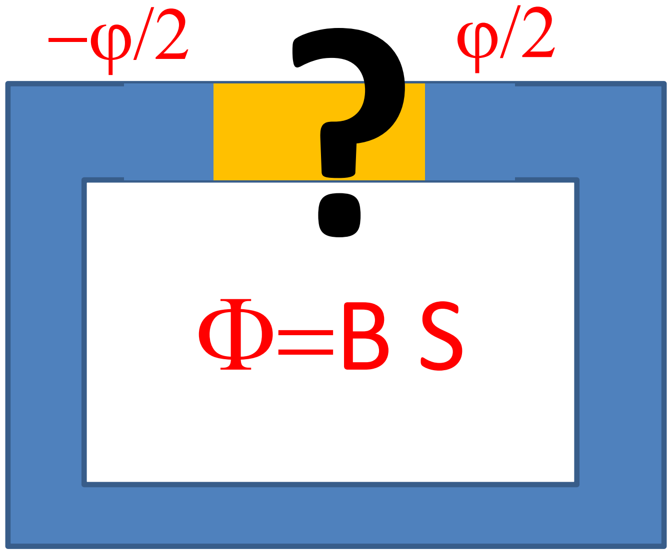
- There is a way to determine the transport regime in the N part (weak link)
- Need to reveal specific Andreev Bound States that form in weak link
- (Short) tutorial on Andreev Bound States and the supercurrent they carry
- The phase-biased configuration is essential

Better than critical current: supercurrent versus phase relation

Usual two contact SNS configuration

I_c= max I(φ), φ not controled

Better: Ring geometry allows «phase biasing»



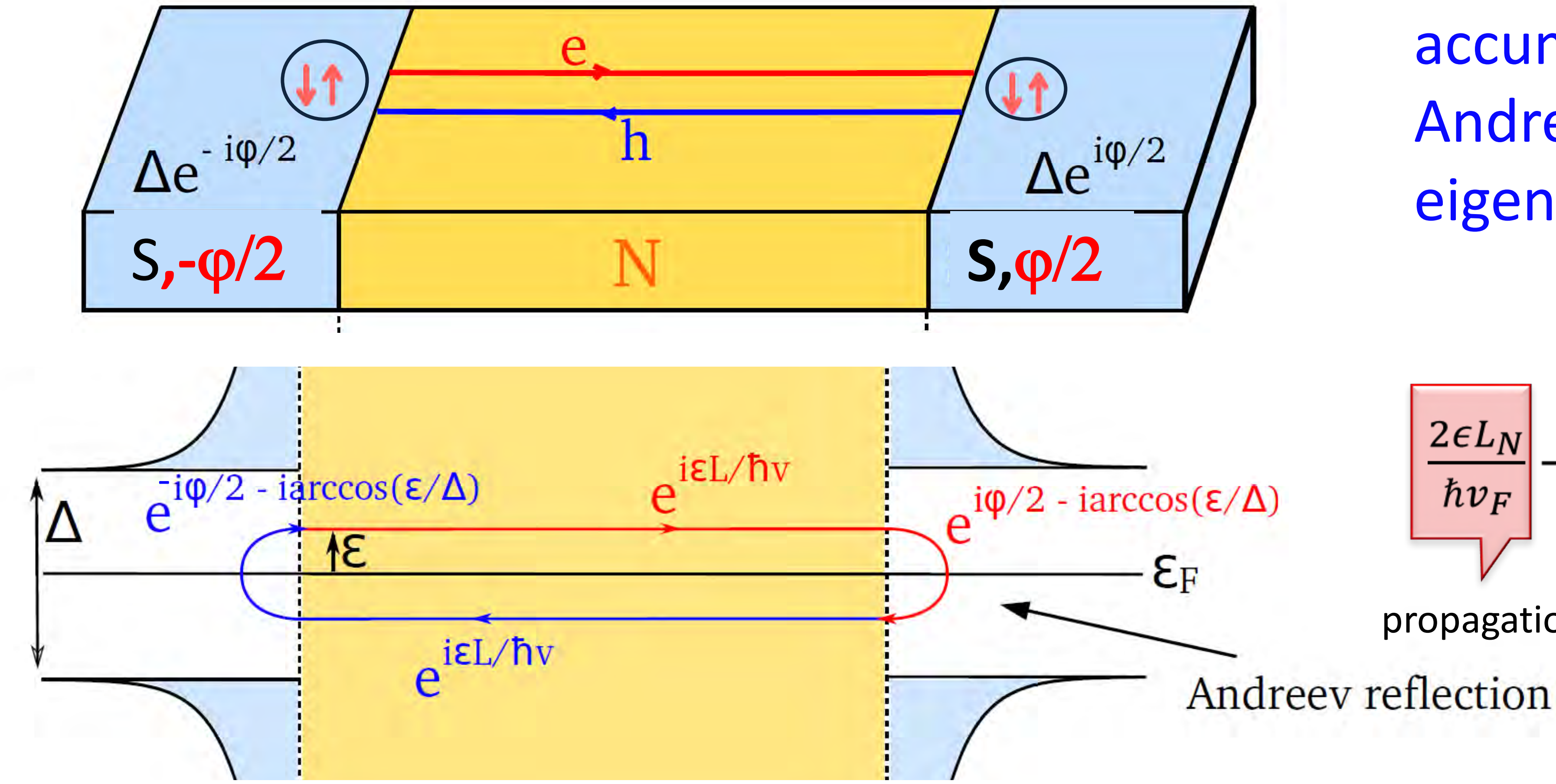
$\varphi=-2\pi\Phi/\Phi_0$

φ controled, 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

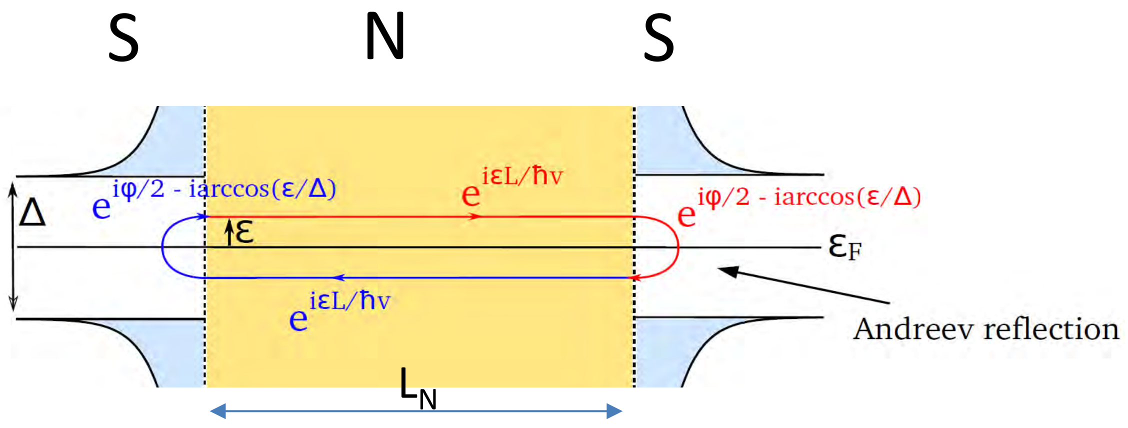
Interface reflection

Superconducting phase difference

Andreev bound states carry the supercurrent.

Spectra and supercurrent depend on the transport regime in N

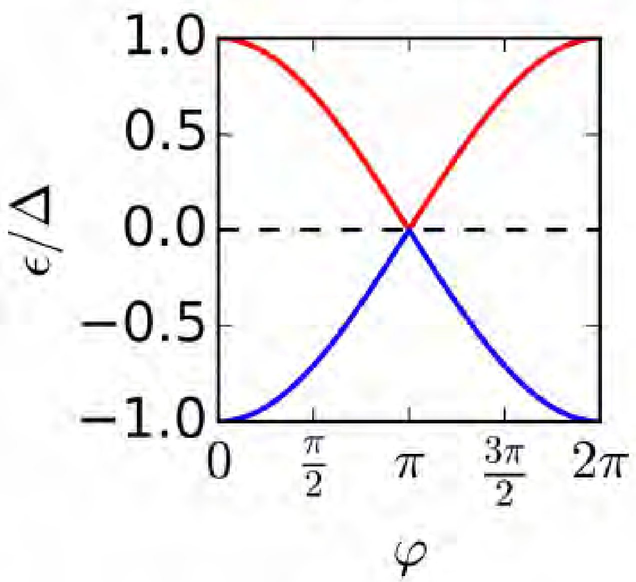
Andreev spectrum and supercurrent in **short ballistic** junction



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

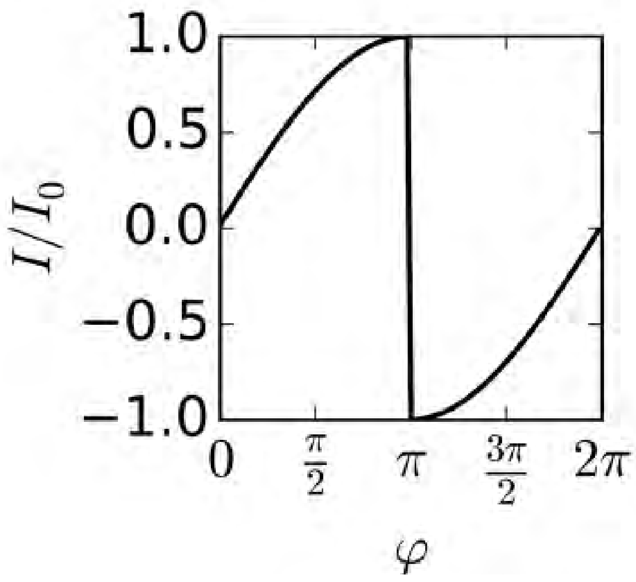
propagation

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



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

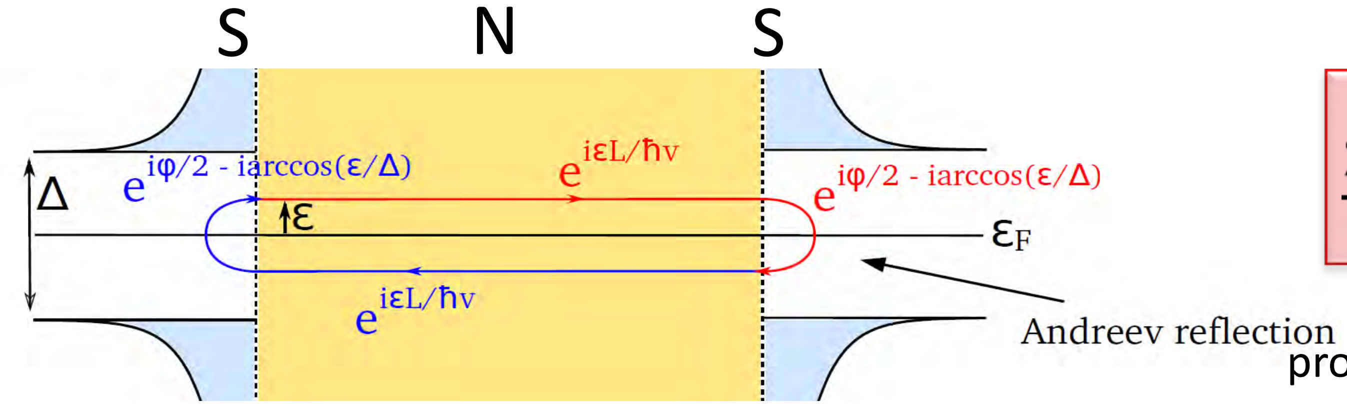
supercurrent



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

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

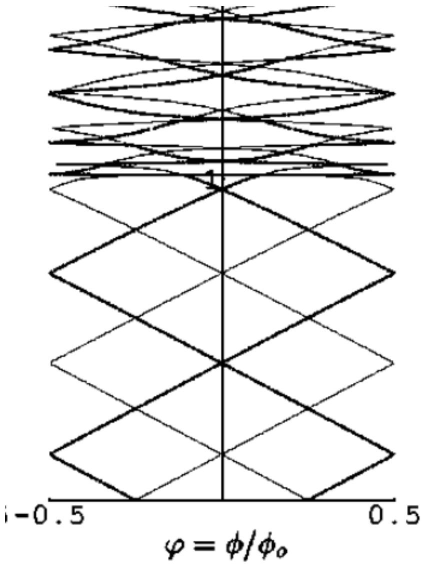
$L \gg \xi_s = \frac{\hbar V_F}{\Delta}$



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

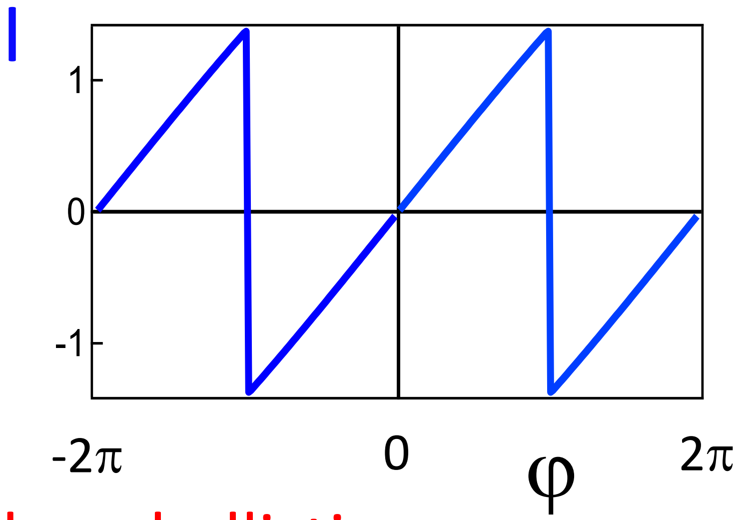
propagation

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



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

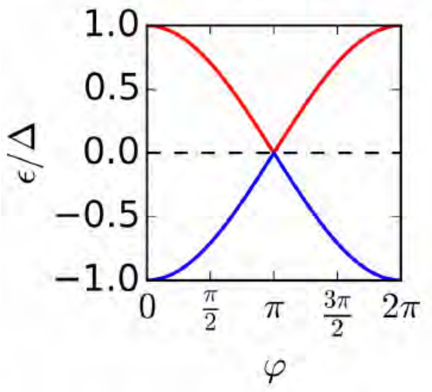
$I(\varphi)$ ~ linear segments with jumps at π

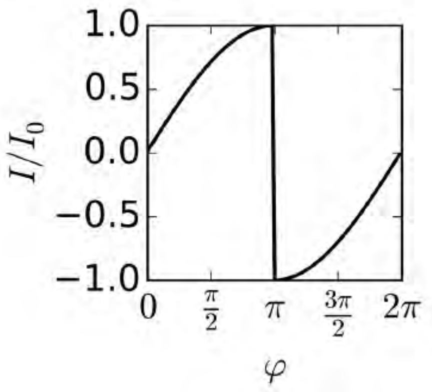


Sawtooth $I(\varphi)$ characteristic of long ballistic

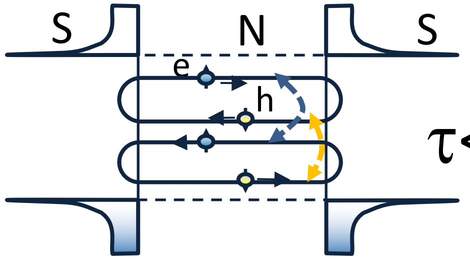
Disorder softens the proximity effect

Short ballistic SNS junction (perfect Andreev reflection)



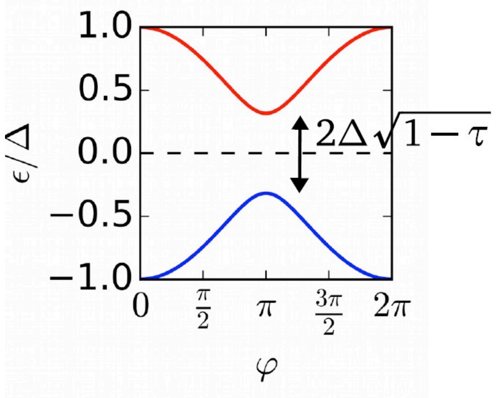


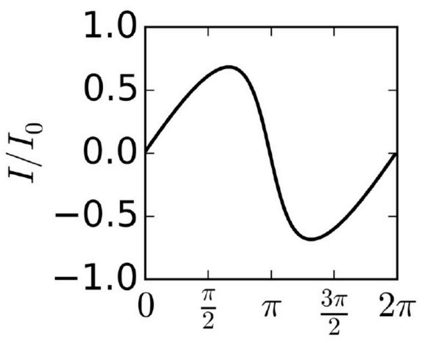
Short disordered



$\tau<1$

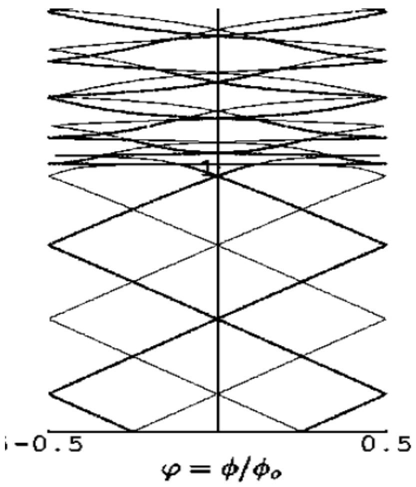
$1-\tau$ proba to backscatter



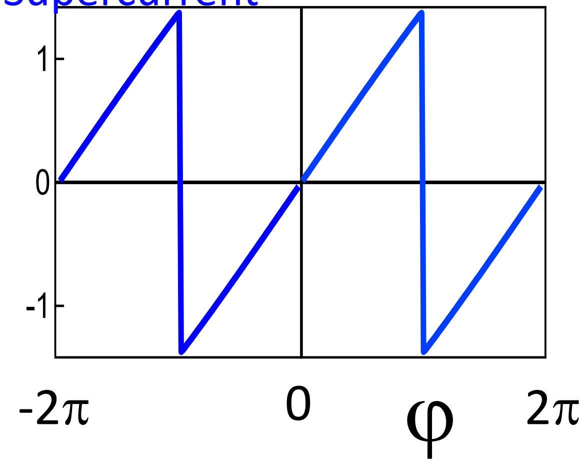


Sharp cu

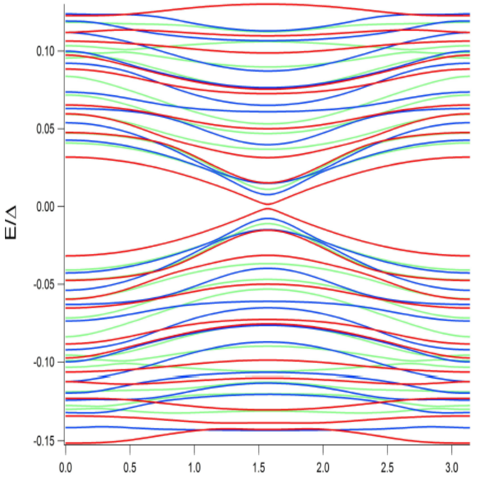
Long ballistic SNS junction



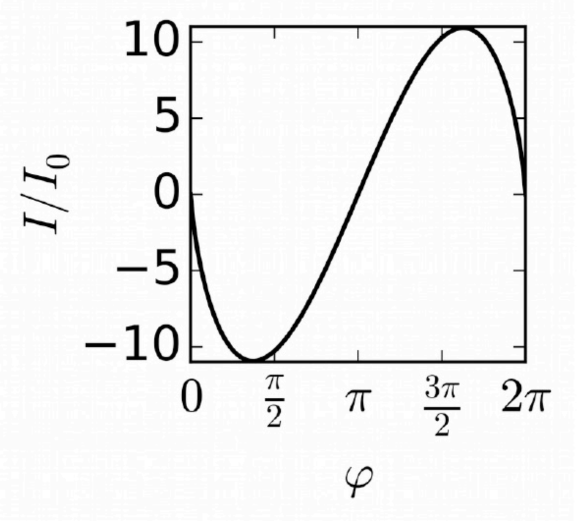
Supercurrent



long disordered (diffusive)

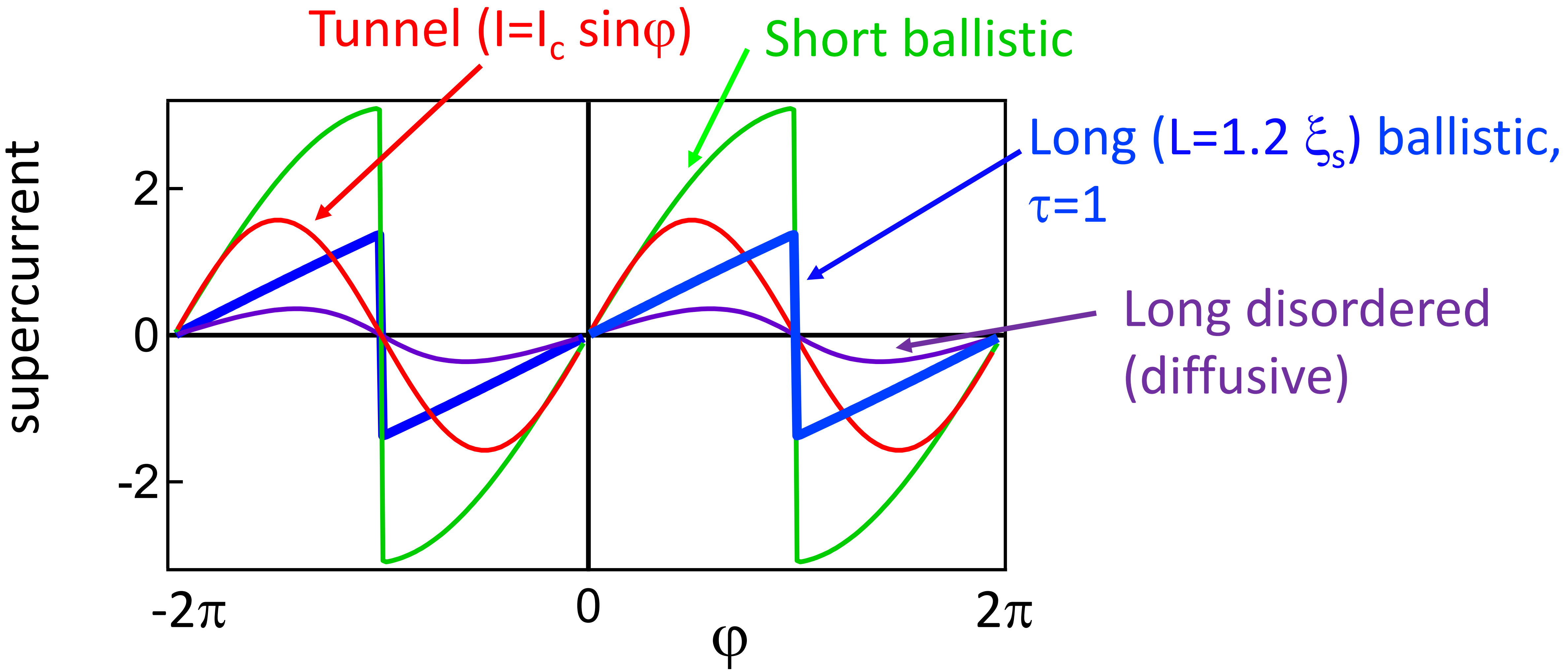


$\phi=2\pi\Phi/\Phi_0$



Skewed (almost a sine)

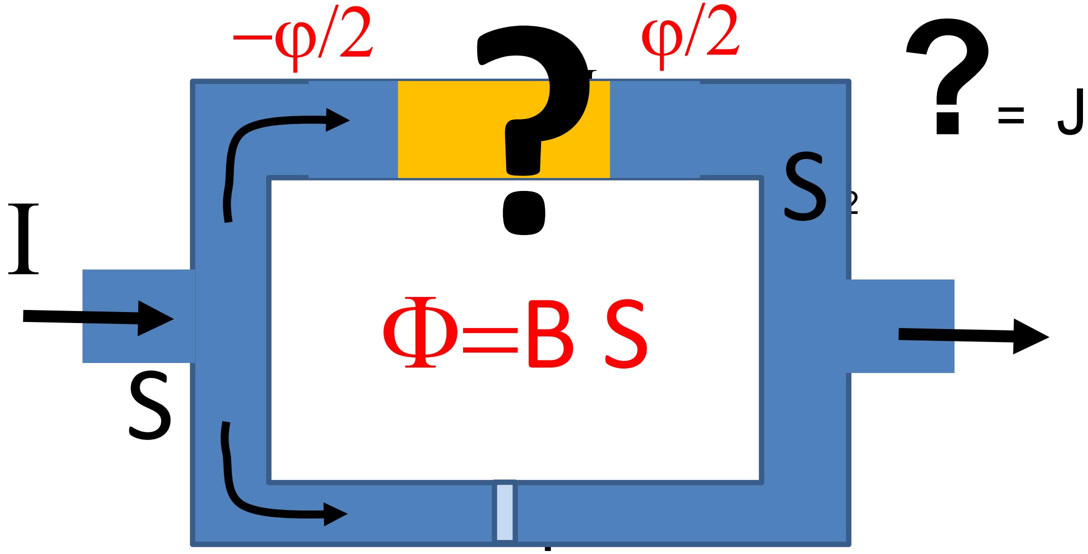
Supercurrent Vs phase relation can pinpoint transport regime



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}

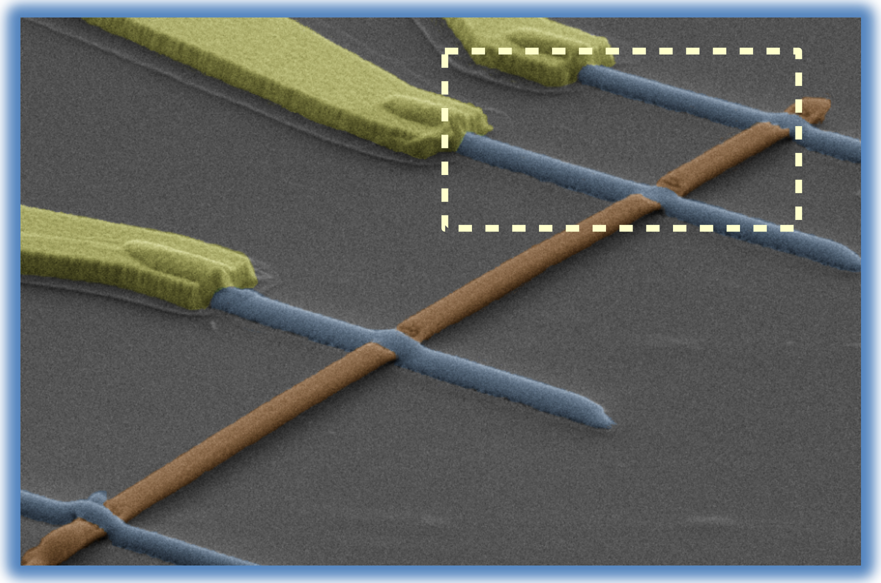
$I_1=I_{c1}\sin\varphi_1$

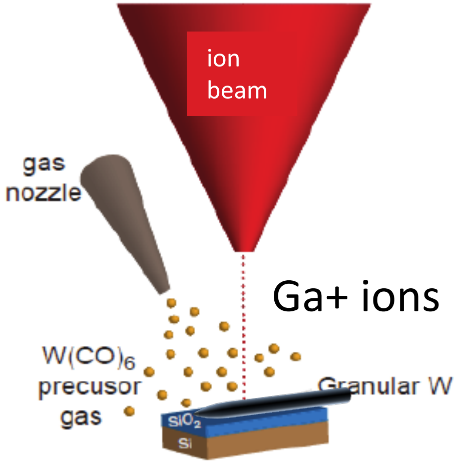
$$I_c=I_{c1}+I_{c2}f(\pi/2+2\pi\Phi/\Phi_0)$$ to first order in I_{c2}/I_{c1}

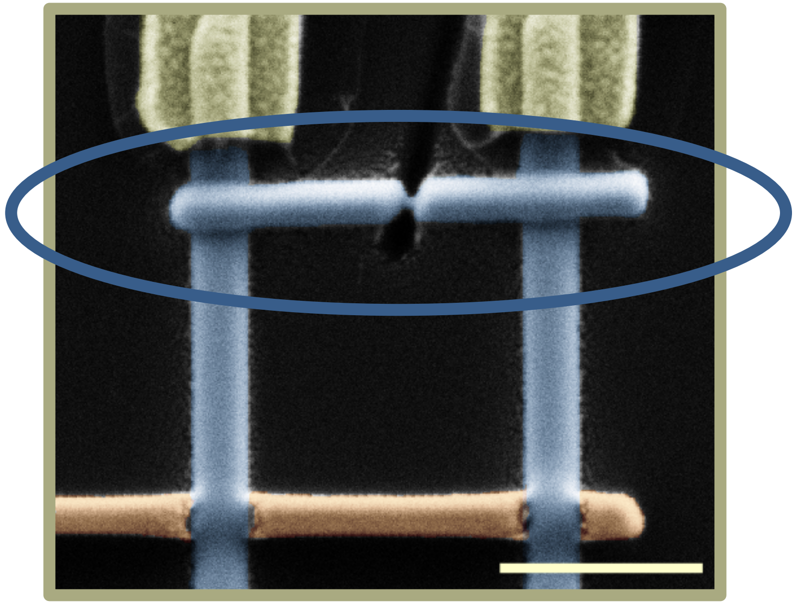
Critical current of asymmetric SQUID yields current-phase relation of junction with smallest critical current

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

Add superconducting constriction in parallel





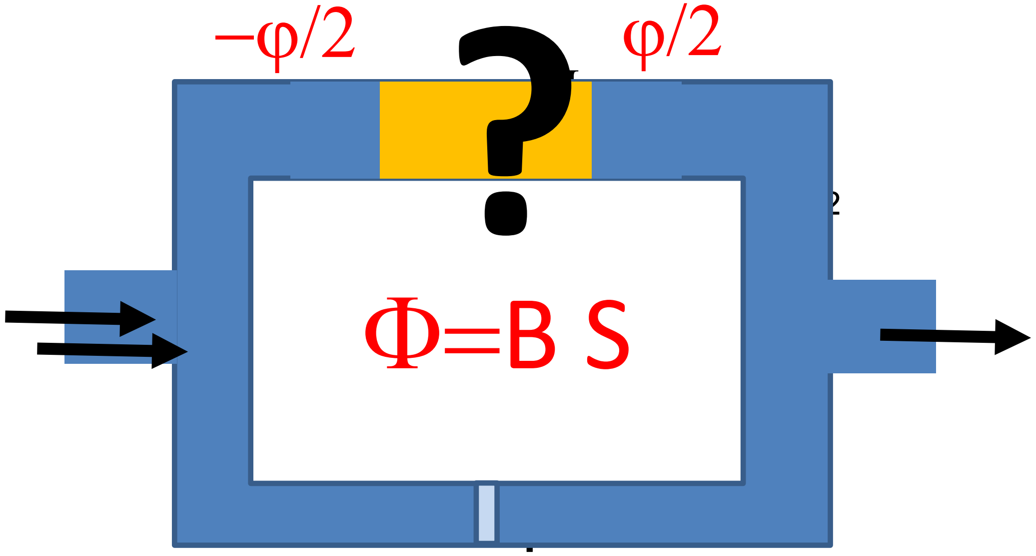


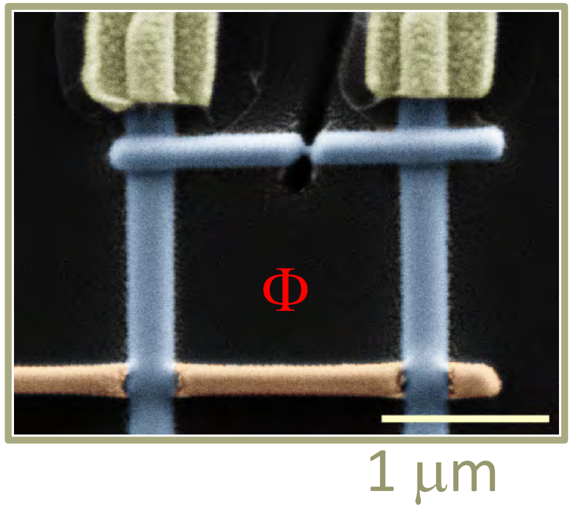
1 μm

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

Supercurrent Vs phase measurement with an asymmetric SQUID

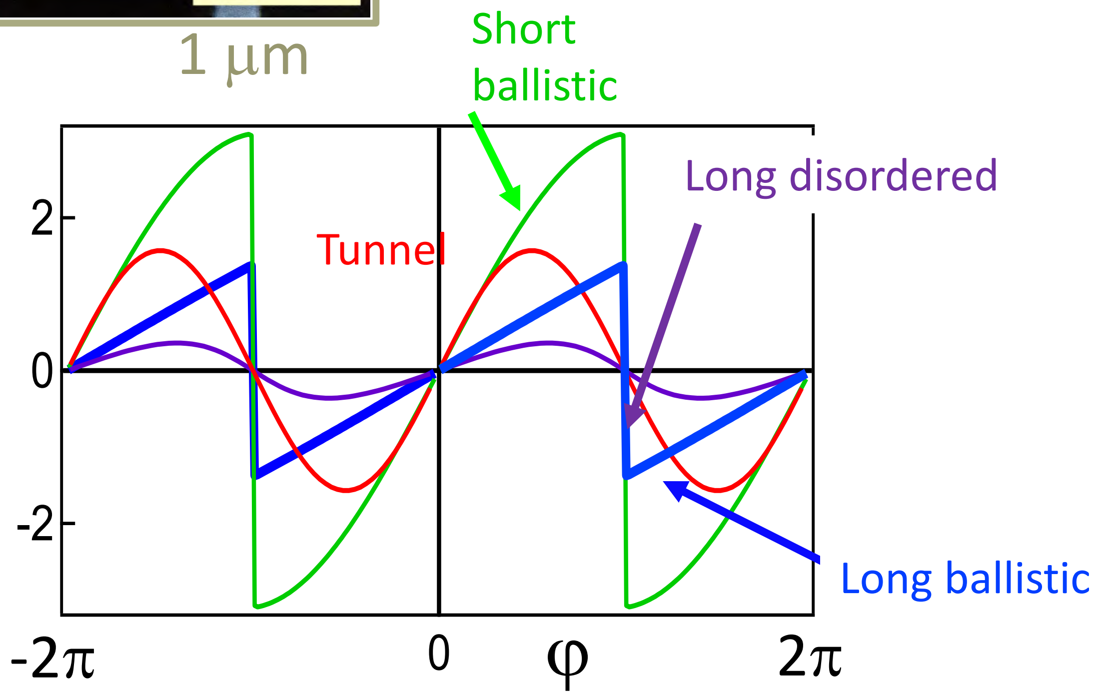
Della Rocca et al 2007





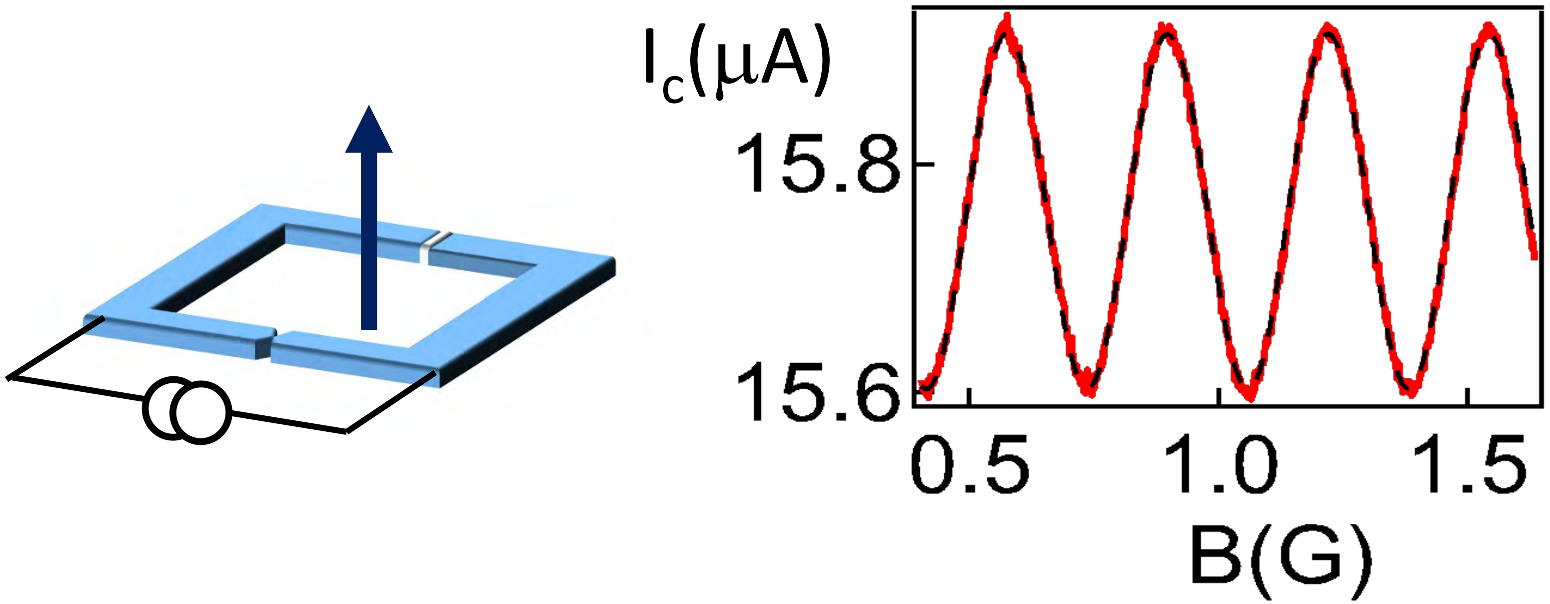
$$I_c = I_{c1} + I_{c2} f(\varphi_2)$$

f(φ)???



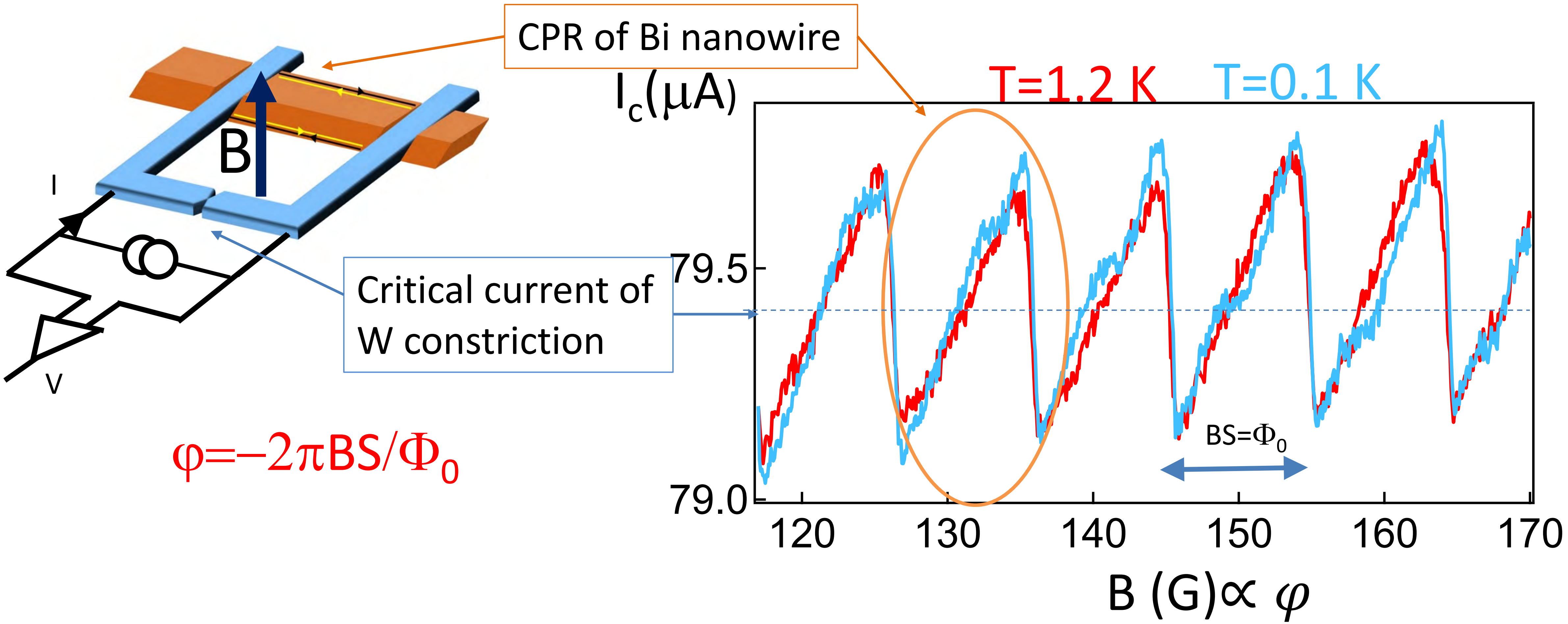
Critical current of asymmetric SQUID yields current-phase relation of weak link

Reference SIS tunnel junction



Sanity check: a tunnel junction has a sinusoidal Current Phase relation

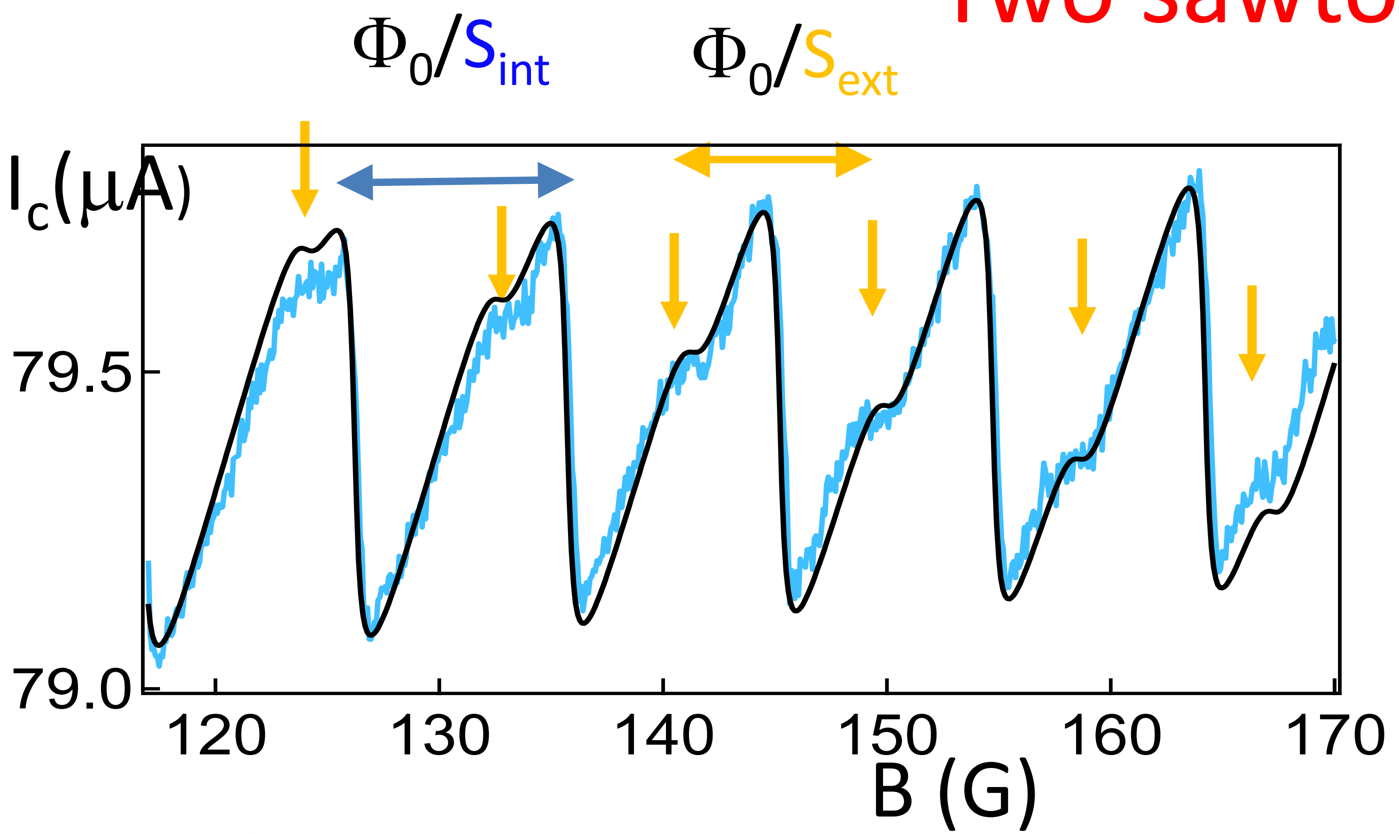
Result: switching current as a function of magnetic flux

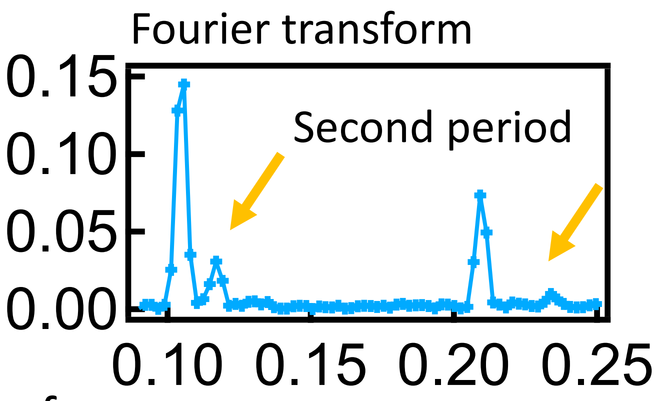


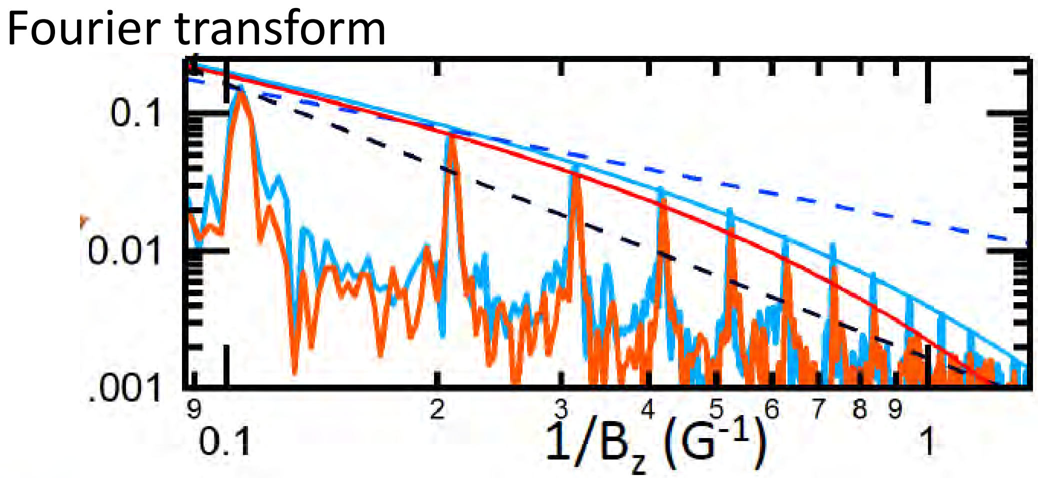
$\varphi = -2\pi BS/\Phi_0$

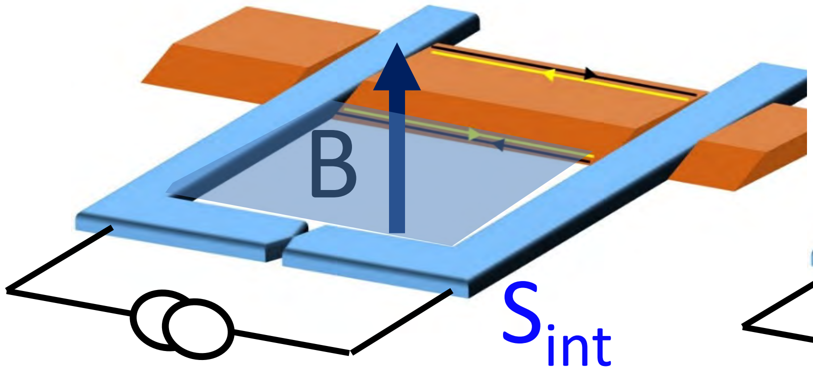
Sawtooth-shaped current phase relation: long ballistic!

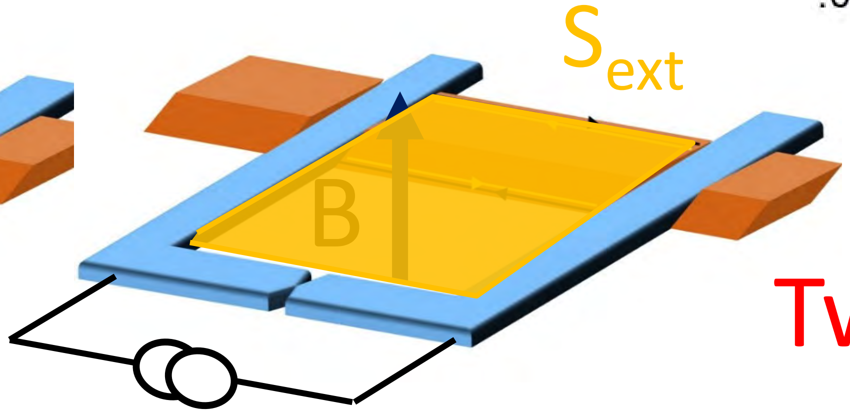
Two sawtooths?





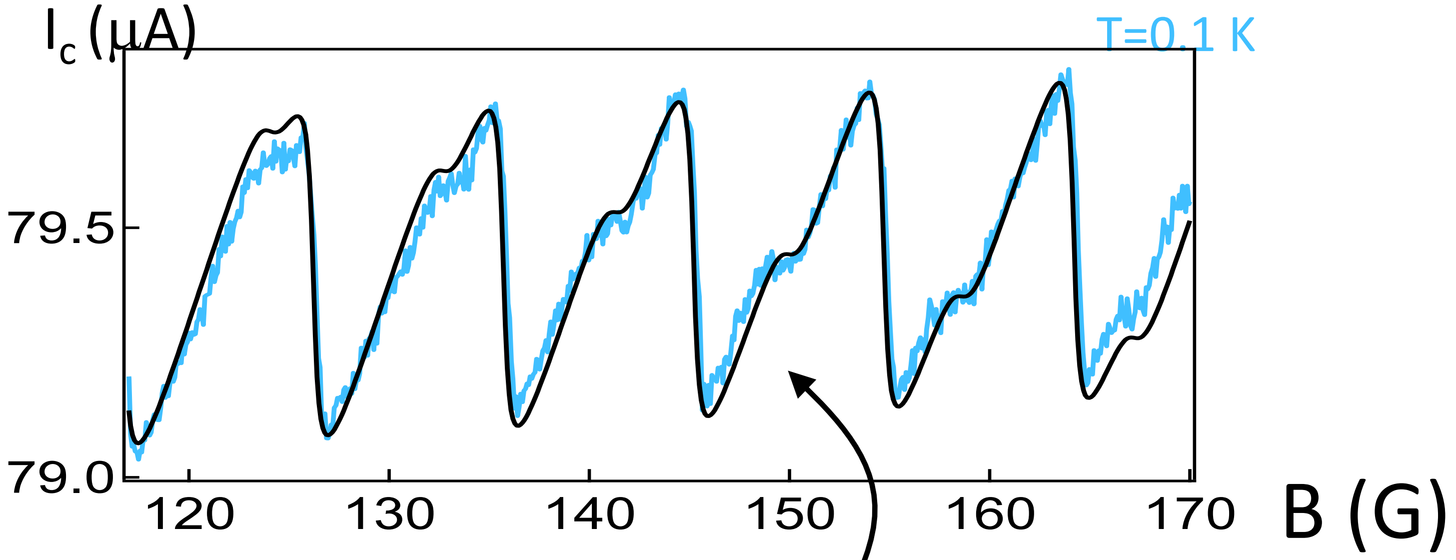






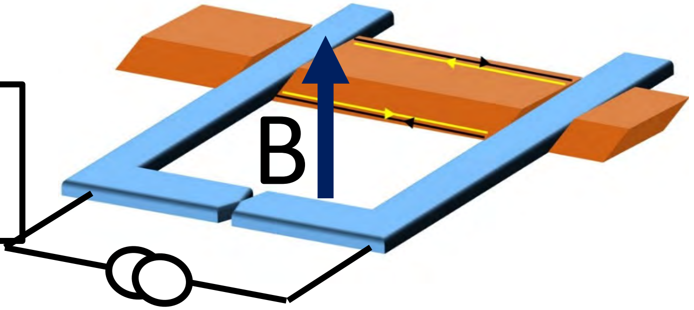
Two ballistic edges!

How ballistic are the two paths ?



I(φ) can be fit with:

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



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

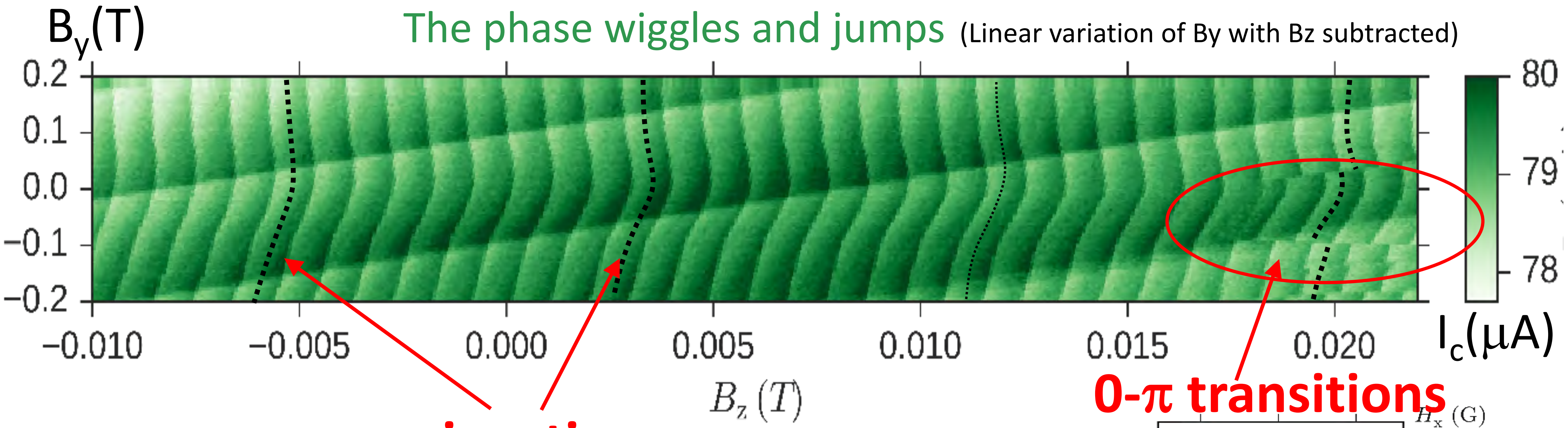
channel transmisison

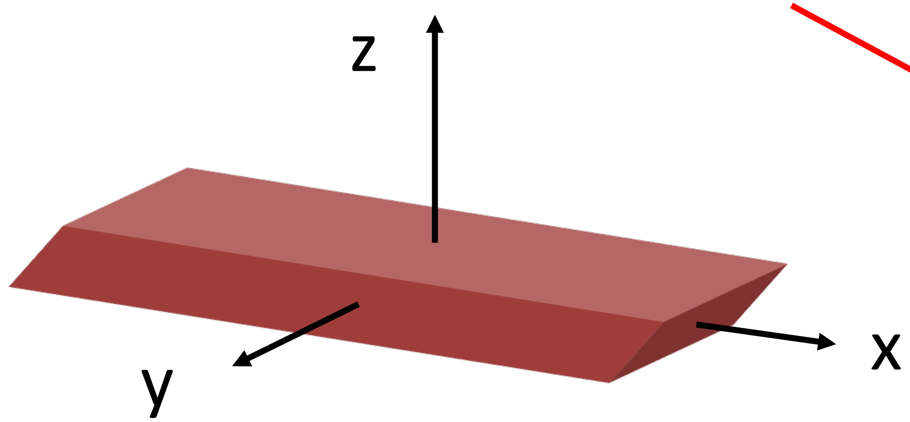
Inner edge: channels with t≈0.9

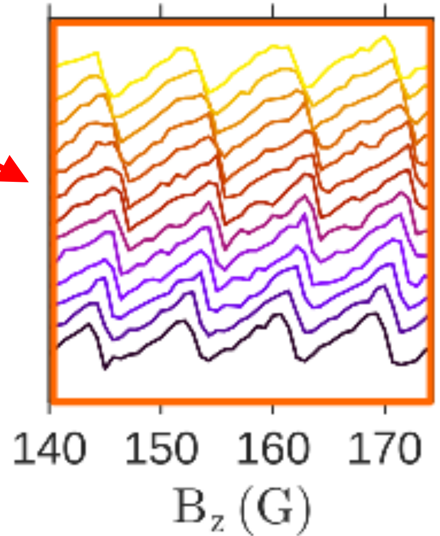
Outer edge: channels with t≈0.7

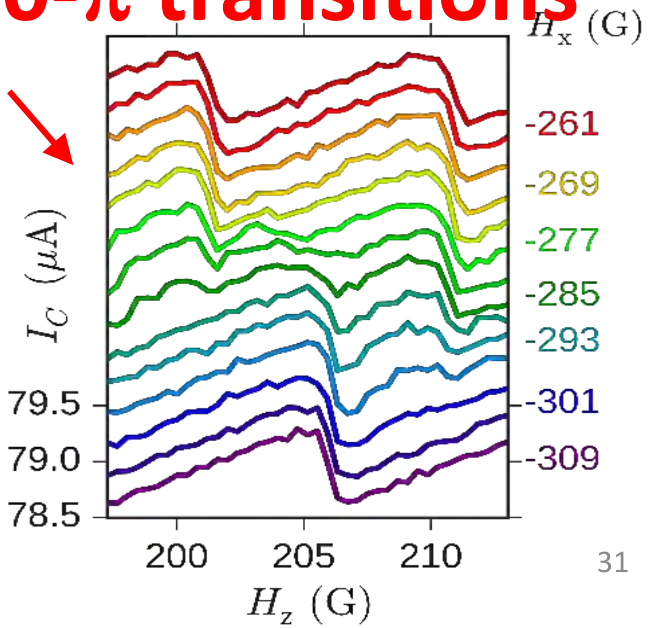
In plane magnetic field affects the phase of the I(φ)

The phase wiggles and jumps (Linear variation of By with Bz subtracted)

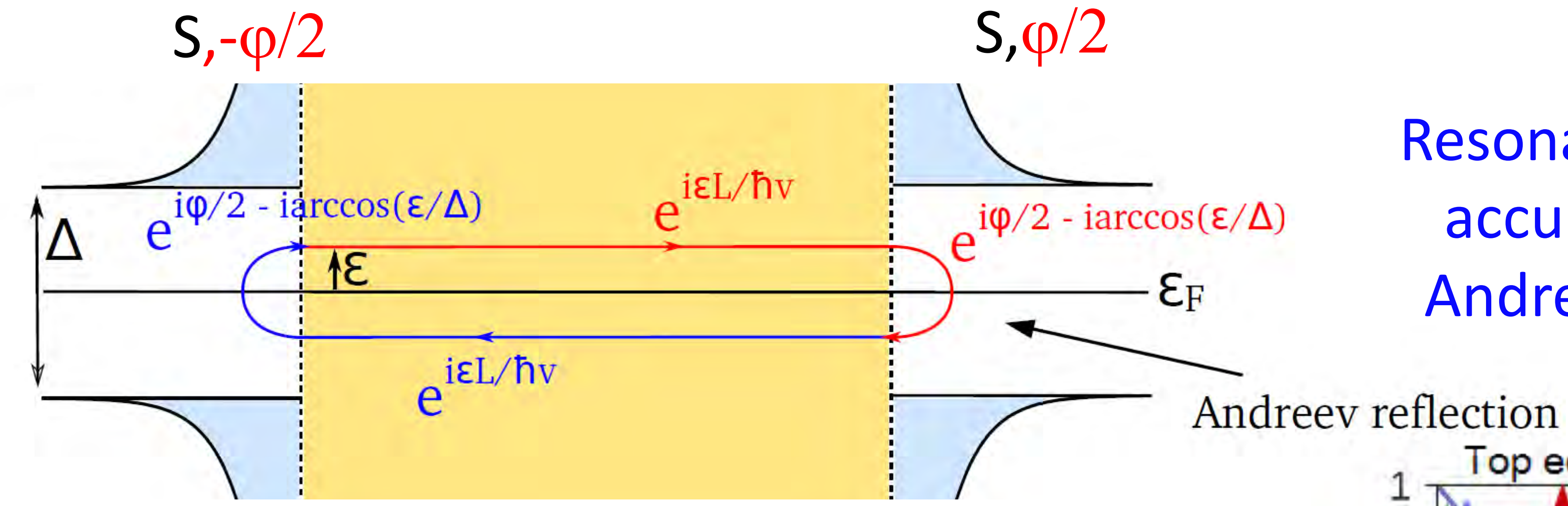








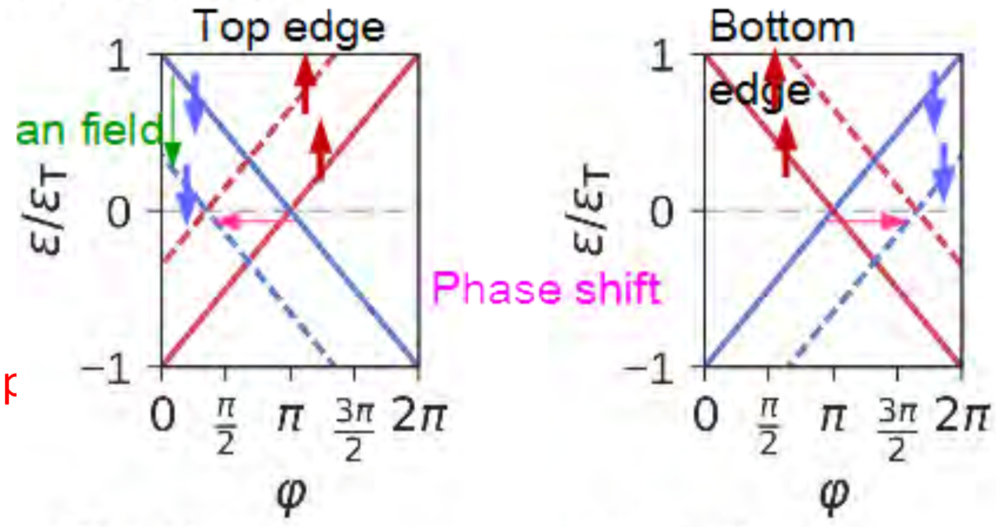
Effect of magnetic field on Andreev states



Resonance condition on accumulated phase : Andreev Bound States

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

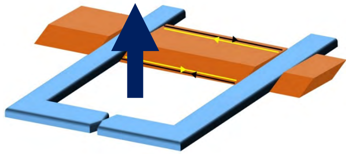
Zeeman effect — propagation — Interface reflection — Superconducting p difference



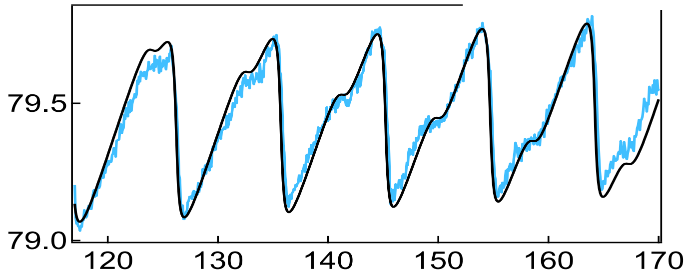
Andreev spectrum splits with field,

and shifts if spin-orbit scattering, because spin-dependent v_F

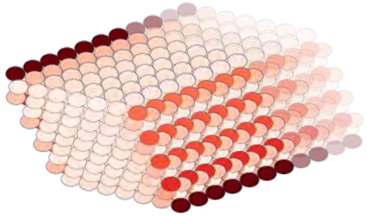
Current-phase relation of Bi (111) nanowire



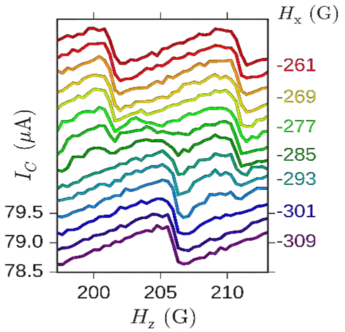
- First measurement of sawtooth current-phase relation : Ballistic long junction!

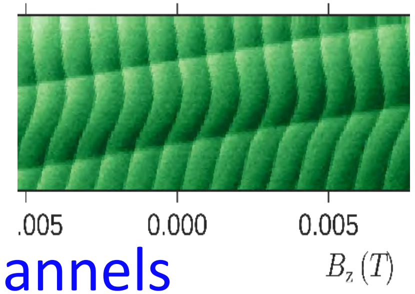


- Two spatially separated paths for Andreev pairs
- Very well transmitted 1D states confined at two specific edges of Bi nanowire



- Other (2D, 3D) states carry much less supercurrent



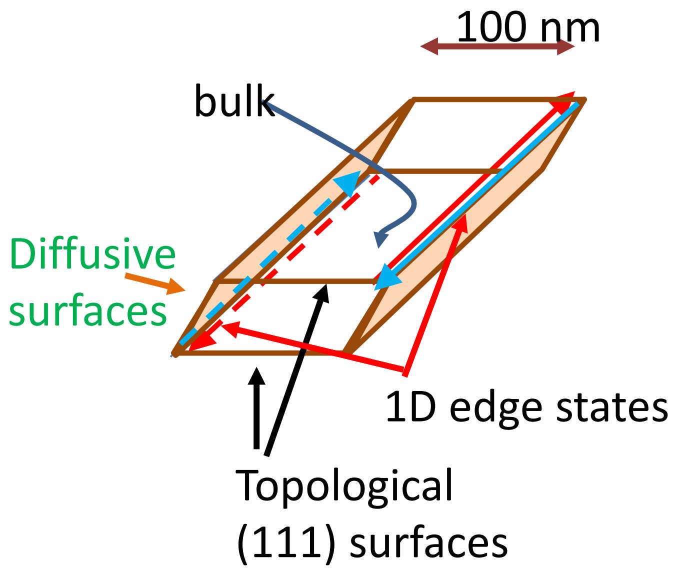


- π-junction induced by Zeeman field
- φ-junction due to spin-orbit, Zeeman field, long junction and (at least)two channels

Diffusive in the normal state.. but only see ballistic channels in the superconducting state

~ 6 ballistic edge channels, ~ 100 diffusive surface channels.

Why do we only see ballistic channels?

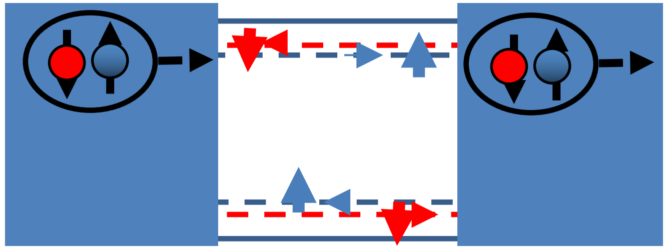


$$I_{c\ \text{1channel, ballistic}} \sim \frac{hv_F}{L}\frac{h}{e^2}$$

$$I_{c\ \text{1channel, diffusive}} \sim \frac{hv_F}{L}\frac{h}{e^2}\frac{l^2}{L^2}$$

100 to 1000 times smaller than ballisitic

+Quantum spin Hall edges should have perfect transmission into S (not true of diffusive channels)



Superconducting proximity effect singles out ballistic states (other states are amost invisible)!

Probing edge states in bismuth nanowires with mesoscopic superconductivity

1 Our Quantum Spin Hall candidate: Bismuth nanowire

2 Induced critical current and its field dependence to detect edge states

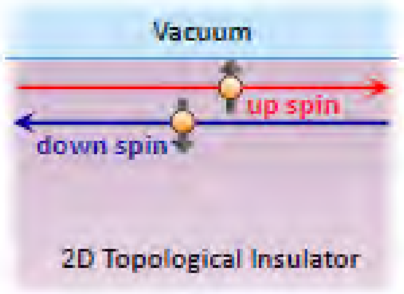
3 Are those edge states ballistic? The supercurrent-versus-phase relation

4 Beyond: High frequency probing to test topological protection

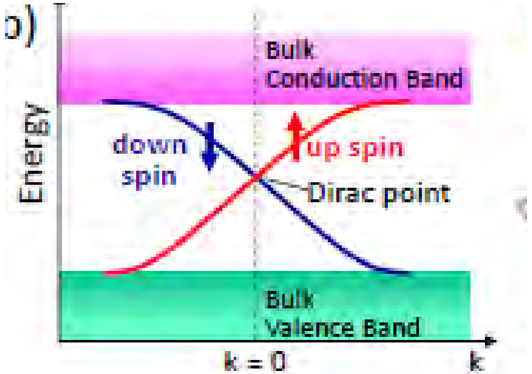
Can we distinguish ballistic edge states from topologically pretected edges states of a 2D Topological insulator ?

Ando Review 2013

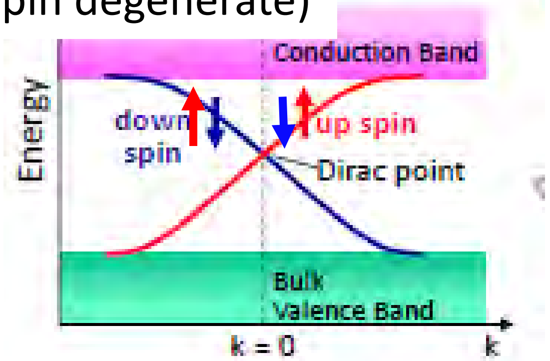
Real space



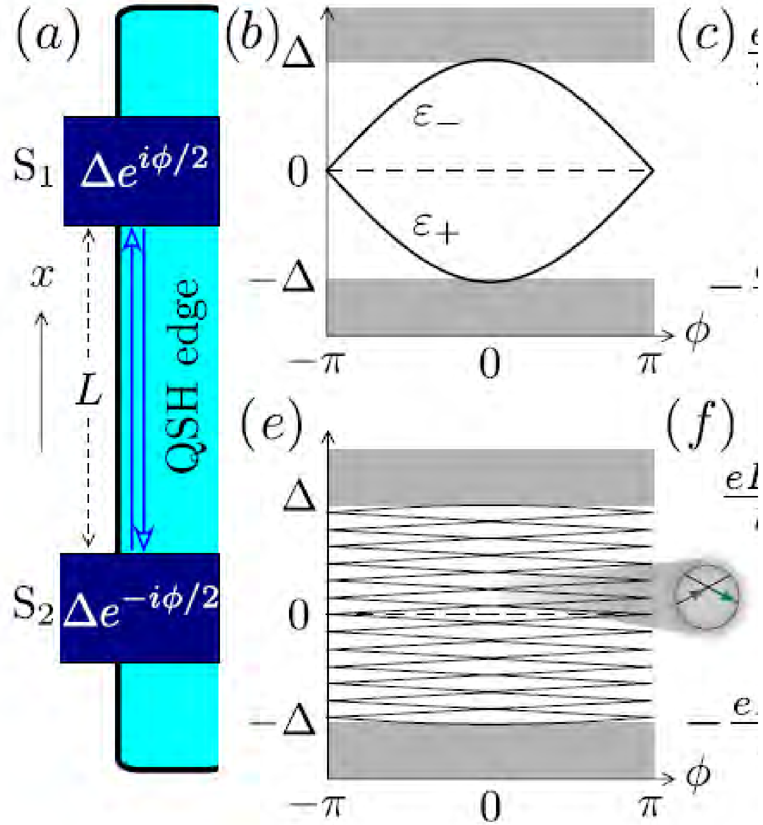
Normal state spectrum of
Quantum Spin Hall state at one edge



Normal state spectrum of
1D Ballistic edge (spin degenerate)



Andreev spectrum at one edge



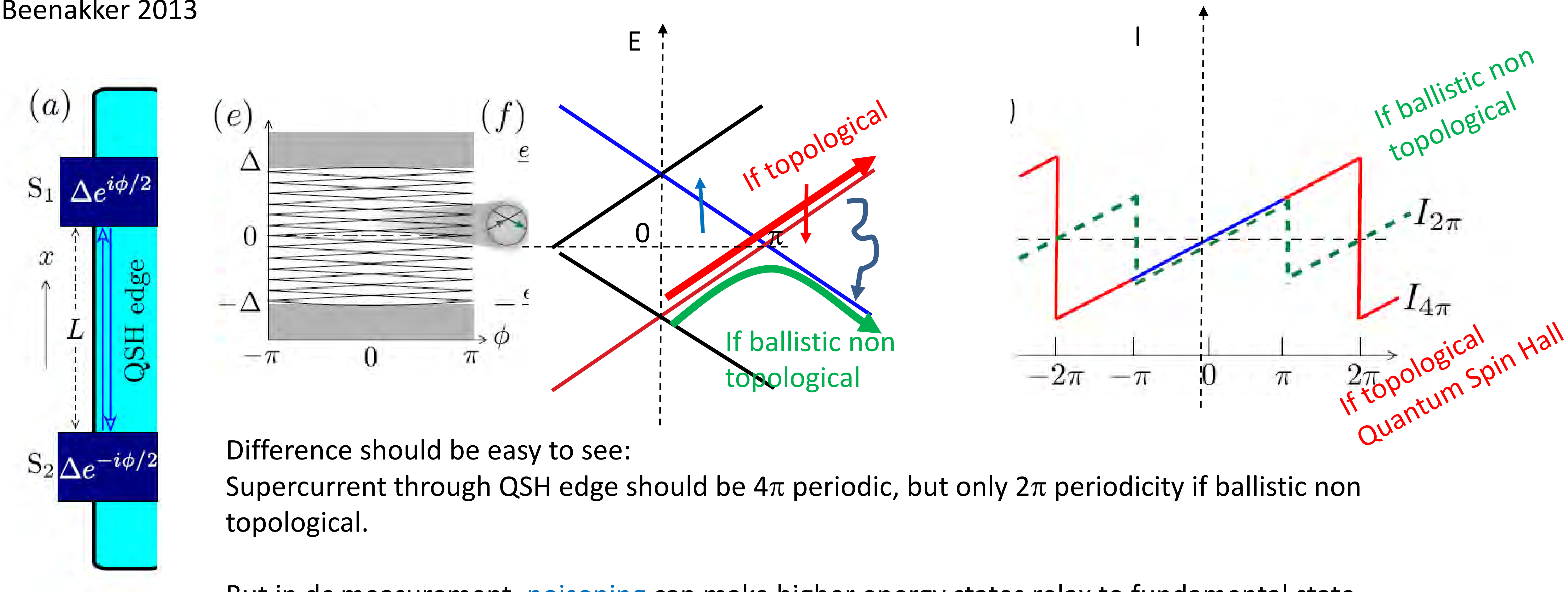
short

long

- QSH Andreev spectrum is « half » of Andreev spectrum of 1D ballistic
- Spin polarized

Difference between S/topological insulator/S and S/ballistic/S

Beenakker 2013

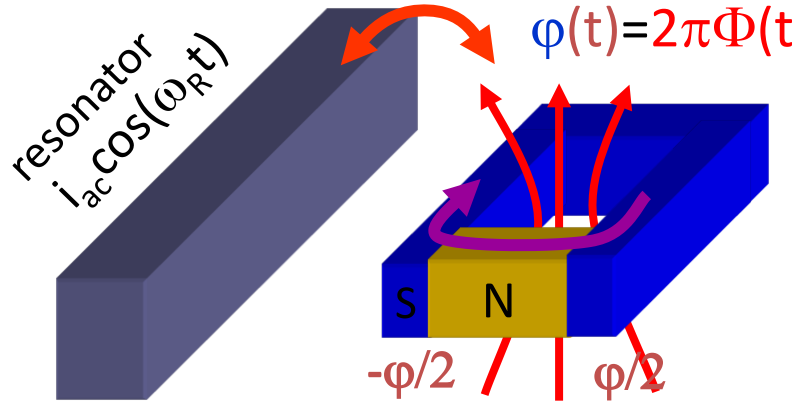


Difference should be easy to see:
Supercurrent through QSH edge should be 4π periodic, but only 2π periodicity if ballistic non topological.

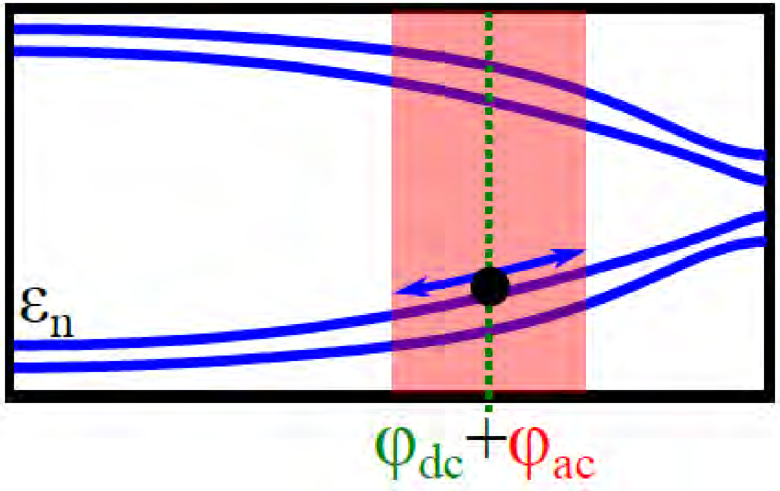
But in dc measurement, poisoning can make higher energy states relax to fundamental state, and recover 2π periodicity.

We need to go beyond dc current versus phase measurements:
Use high frequency response (to beat relaxation rate)!

ac phase-driven proximity effect



$\varphi(t)=2\pi\Phi(t)/\Phi_0=\varphi_{dc}+\varphi_{ac}\cos\omega t$



linear response

Experimentally $\quad I(t,\varphi,\omega) = I_{s,dc} + \varphi_{ac}(\chi'(\omega)\cos\omega t+\chi''(\omega)\sin\omega t)$

non dissipative dissipative

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

$I=Y(\omega)V$, $V=i\omega\Phi$,
$I=i\omega Y(\omega)\Phi$, complex admittance of system
$\chi=i\omega Y(\omega)$

Theoretically

$$\chi(\omega) = \delta I(t)/\delta\Phi(t)$$

$$\delta I(t) = \mathrm{Tr}(J\,\delta\rho(t)) + \mathrm{Tr}(\delta J(t)\rho_0)$$ (linear response theory)

$$\partial\rho(t)/\partial(t) = (1/i\hbar)[H(t),\rho] - \Gamma[\rho(t)-\rho_{eq}(t)].$$ …

What response is expected ?

The response can be computed for any system

$$\chi(\omega) = \frac{\partial I_J}{\partial \Phi} - \sum_n i_n^2 \frac{\partial f_n}{\partial \epsilon_n} \frac{i\omega}{\gamma_D - i\omega} - \sum_{n,m\neq n} |J_{nm}|^2 \times \frac{f_n - f_m}{\epsilon_n - \epsilon_m} \frac{i\hbar\omega}{i(\epsilon_n - \epsilon_m) - i\hbar\omega + \hbar\gamma_{nm}}.$$

Static

Delayed response
Population relaxation

Transition between levels

Applied to normal ring (Trivedi Browne PRB 1988), and SNS ring (Ferrier PRB 2013, Dassonneville 2014)

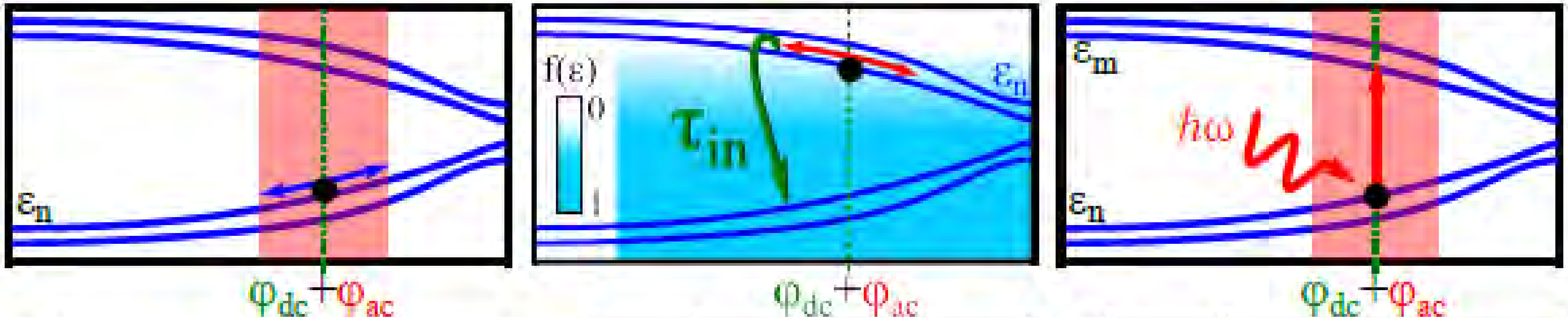
The response to an ac flux has two terms in addition to derivative of dc Josephson relation:
Population relaxation prop i^2, and transition between levels.
Both terms give rise to dissipation

$$\chi(\omega) = \frac{\partial I_J}{\partial \Phi} - \sum_n i_n^2 \frac{\partial f_n}{\partial \epsilon_n} \frac{i\omega}{\gamma_D - i\omega} - \sum_{n,m\neq n} |J_{nm}|^2 \times \frac{f_n - f_m}{\epsilon_n - \epsilon_m} \frac{i\hbar\omega}{i(\epsilon_n - \epsilon_m) - i\hbar\omega + \hbar\gamma_{nm}}.$$

Derivative of dc Josephson relations cosine

Population relaxation Prop to i^2

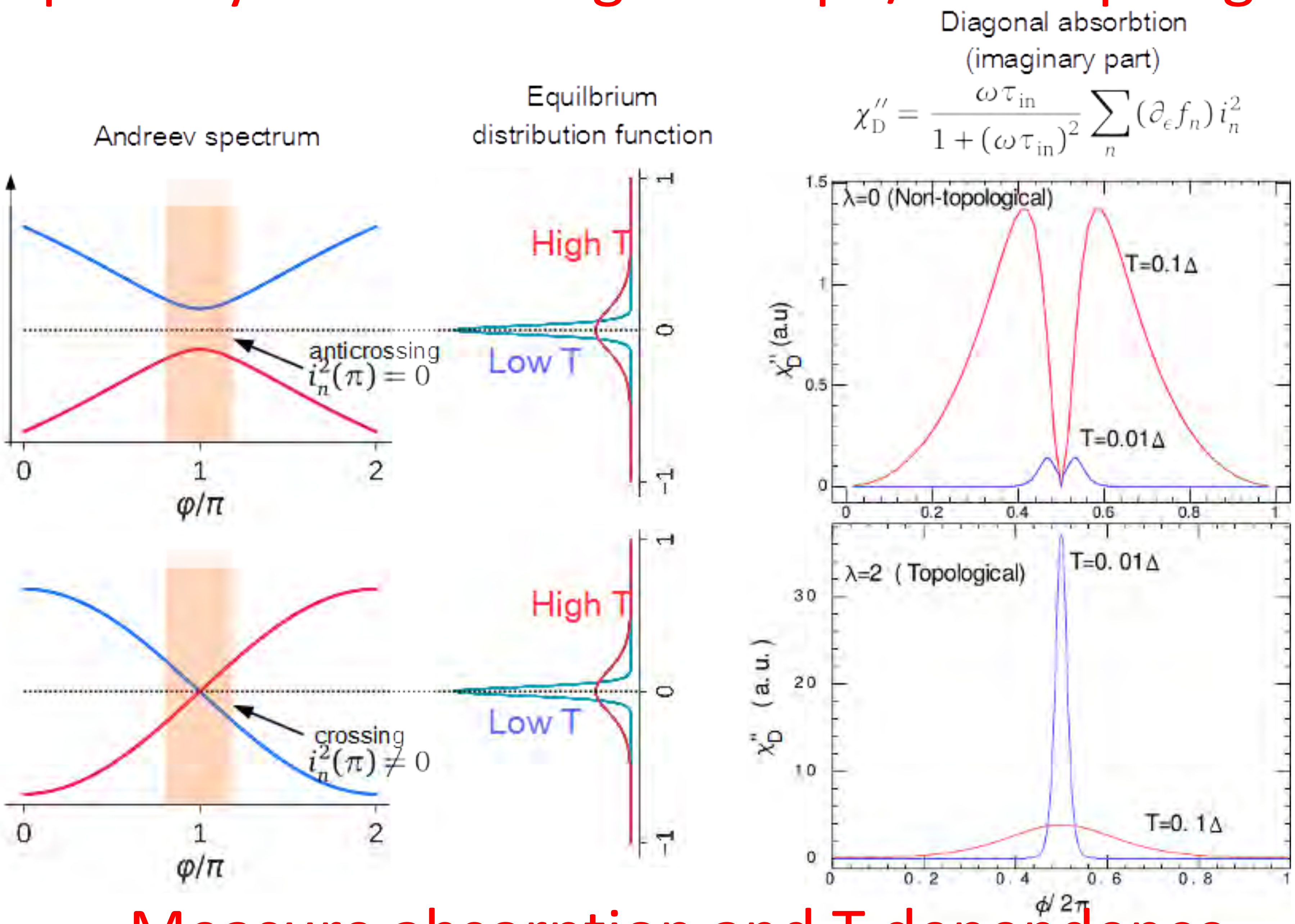
Transitions: Spectroscopy of minigap (in some range)



ac susceptibility could distinguish topo/non topological states

Without topological protection

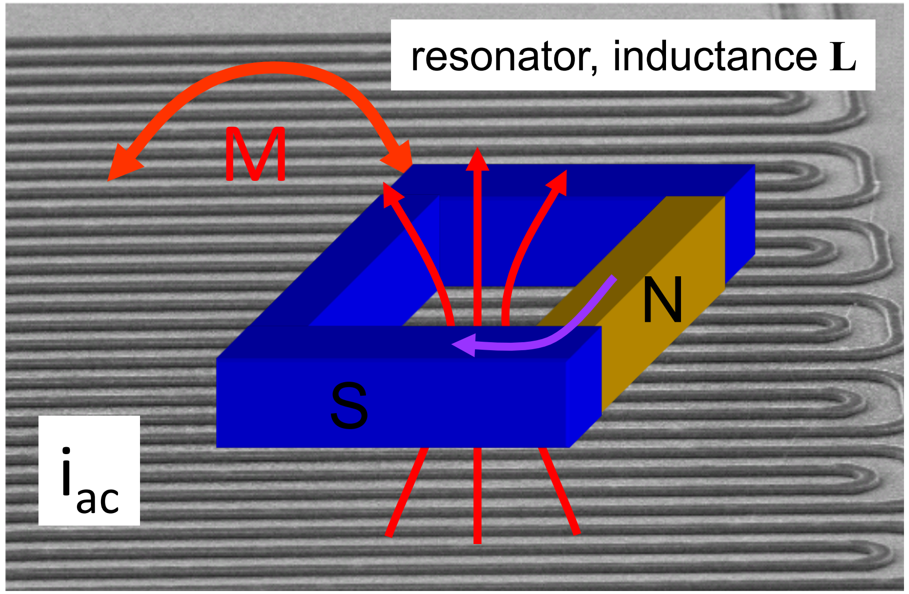
With topological protection

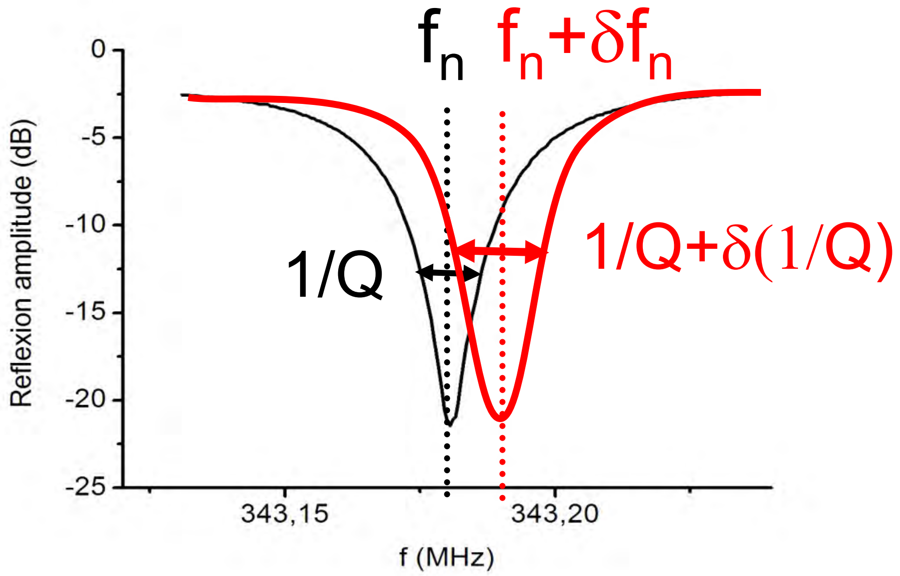


absorption decreases at T increases

...Measure absorption and T dependence

Very sensitive detection





$2\delta f/f = -\chi' M^2/L$: sensitivity 10^{-9}

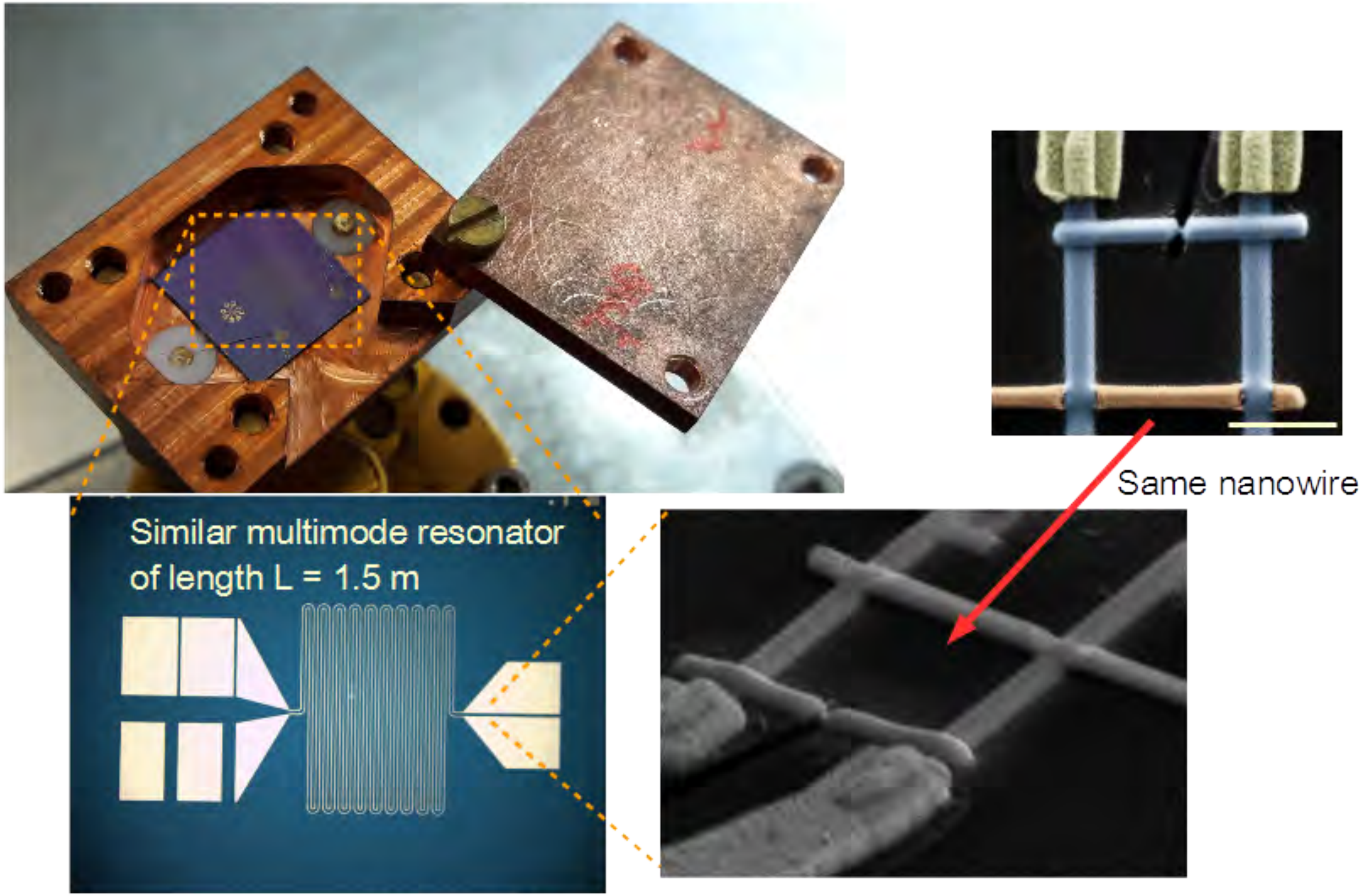
$\delta(1/Q) = \chi'' M^2/L$: sensitivity 10^{-10}

$$f = \frac{1}{\sqrt{\mathcal{L}C}}$$

$$Q = \frac{\mathcal{L}\omega}{R}$$

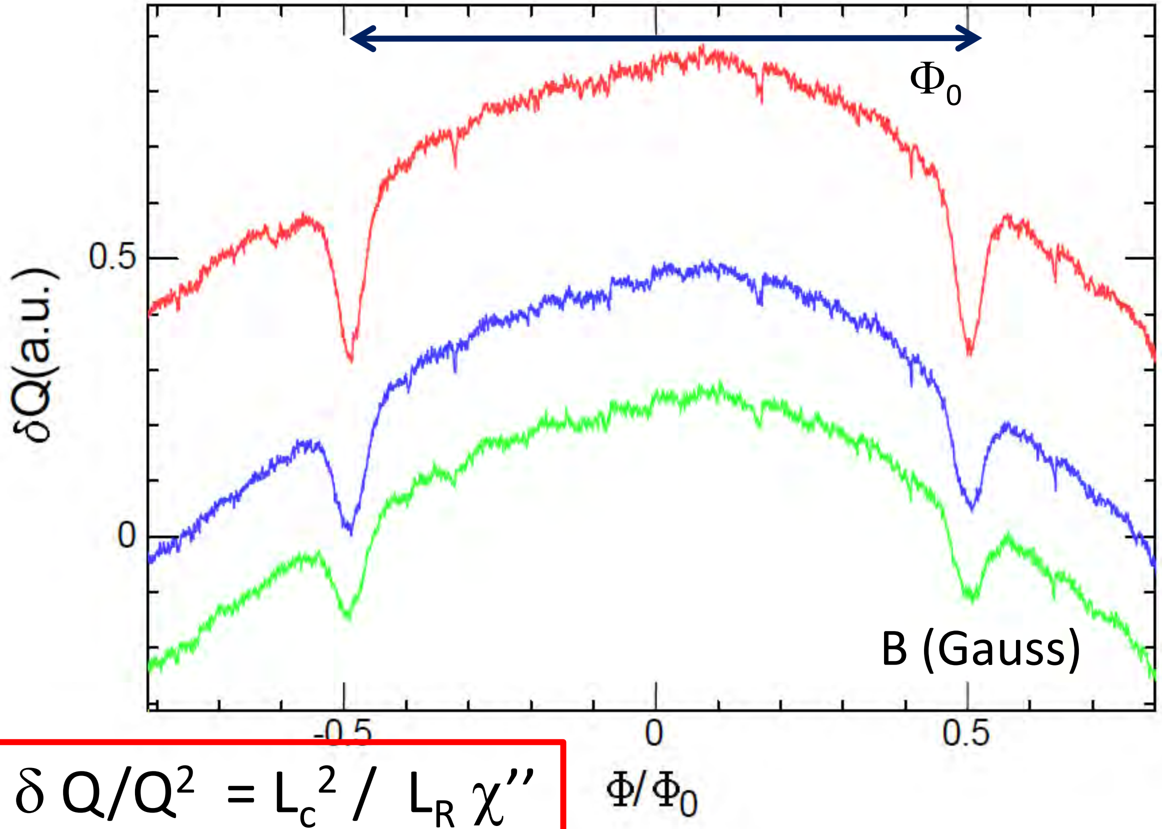
Sensitivity 10^{-10} at T= 40mK P=10^{-15} W

Fabrication of a resonator around the SQUID !



Recent results (July 2017):
Phase-dependent Quality Factor of the resonator yields absorption of Bi junction

Periodic absorption peaks at 2n+1 π over wide frequency range (between 280MHz and 6.6 GHz)



f=464MHz

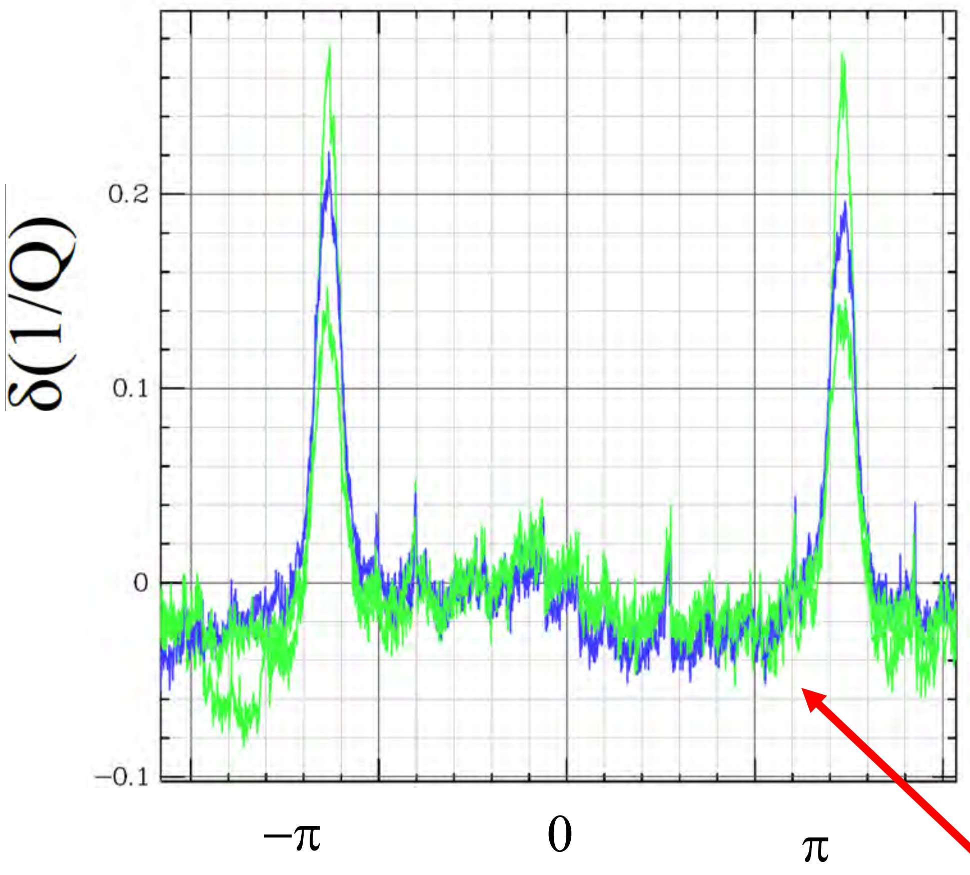
Coupling inductance L_c ~ 100pH
Resonator inductance LR ~ 1μH

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

Quality Factor variation is proportional to dissipative part of susceptibility

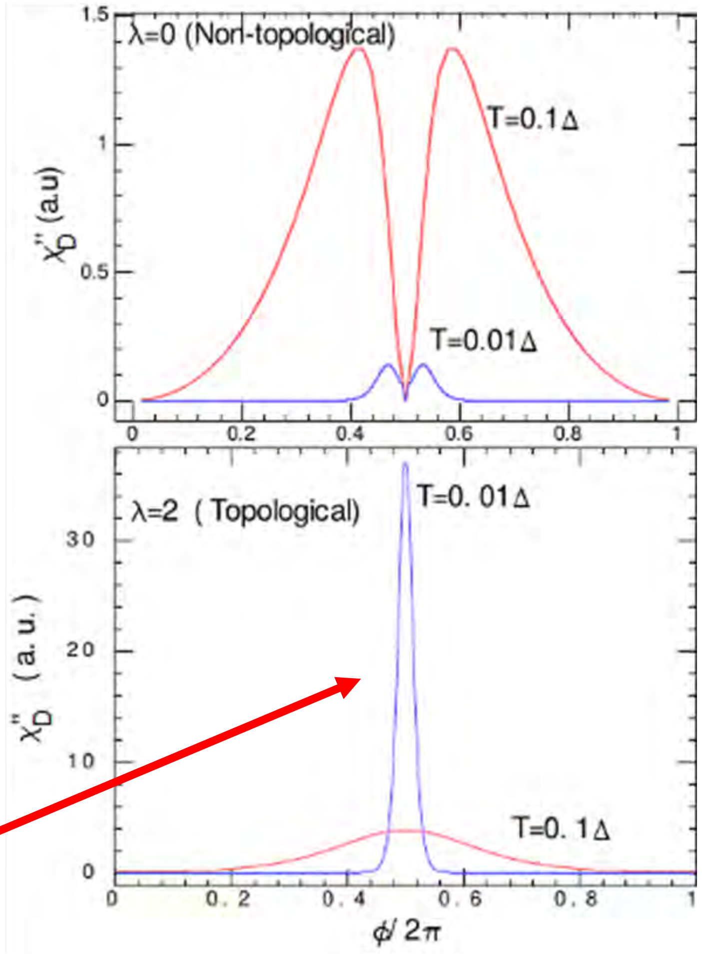
First results for Bi nanowire (July 2017)

Anil Murani, Bastien Dassonneville



Diagonal absorbtion
(imaginary part)

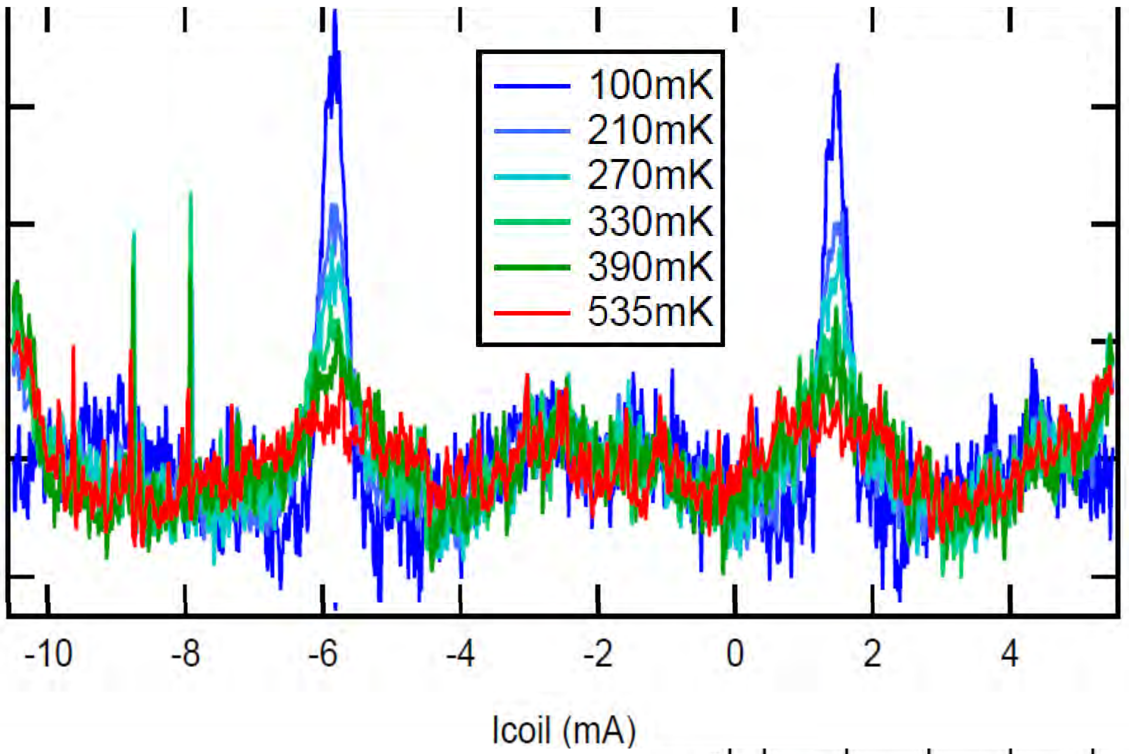
$$\chi''_D = \frac{\omega\tau_{in}}{1+(\omega\tau_{in})^2}\sum_n (\partial_\epsilon f_n)\, i_n^2$$



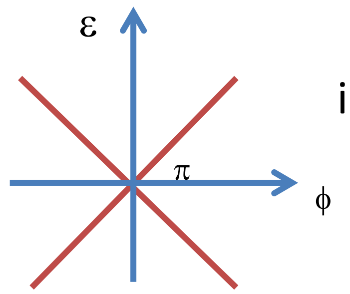
... seems promising!

Temperature dependence of absorption peaks at $\phi=\pi$

$\delta 1/Q$ $\quad \delta(1/Q) = -\delta Q/Q^2 = L_c^{\,2} / L_R\, \chi''$ $\quad$ f=4GHz



If protected crossing of two Andreev levels:

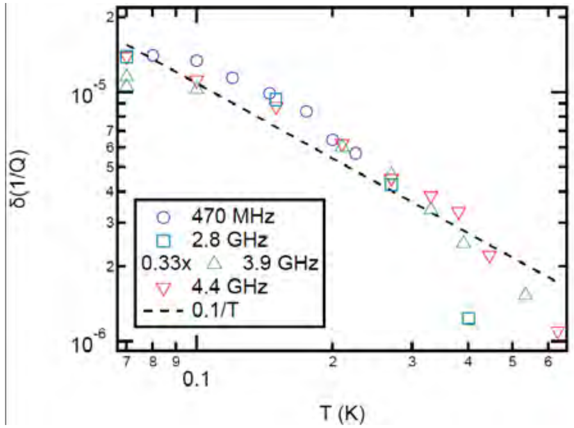


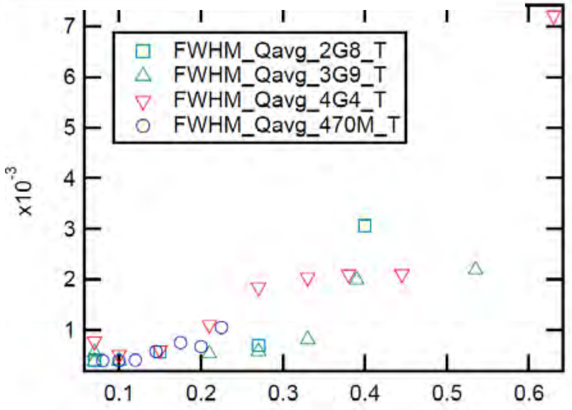
$i^{\pm} = \partial\, \varepsilon^{\pm}(\phi) / \partial \phi$

$i^{+2} = (ev_F/L)^2$

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

$$\chi''_D = I^2 \frac{\partial f}{\partial \epsilon} = \frac{(ev_F/L)^2}{4k_B T \cosh^2[\alpha(\phi-\pi)/2k_B T]}$$





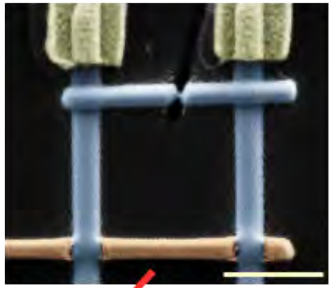
Peak intensity decreases like 1/T, width ~ T

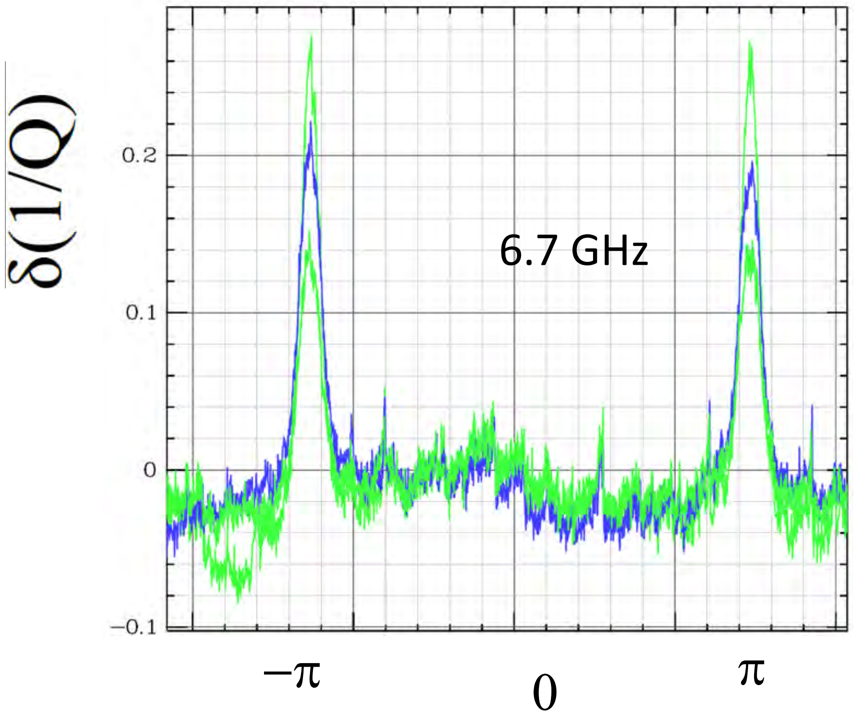
OK with protected crossing scenario!

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

S/Bi/S

A. Murani, B. Dassonneville

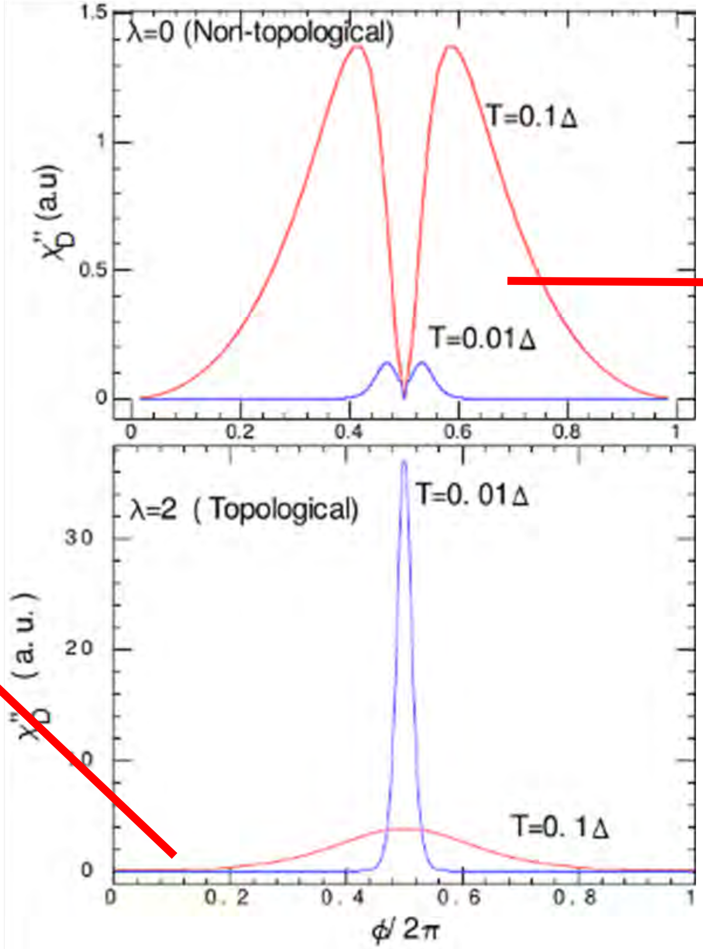




In S/Bi/S:
max absorption at π!

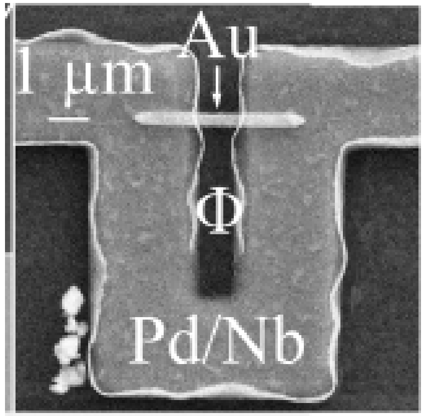
Diagonal absorbtion
(imaginary part)

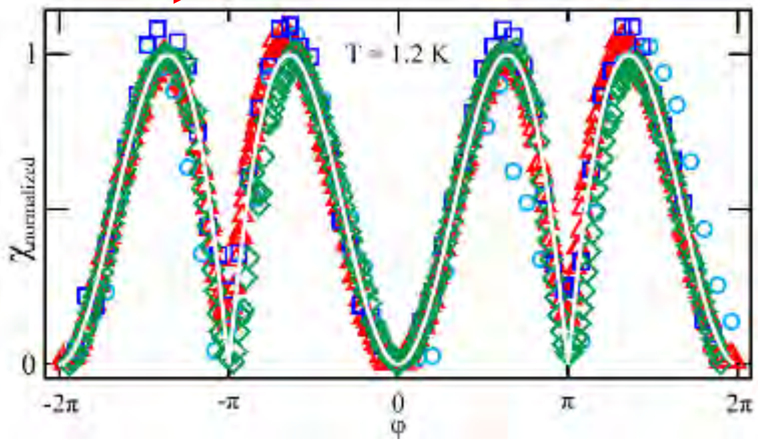
$$\chi''_D = \frac{\omega\tau_{in}}{1+(\omega\tau_{in})^2}\sum_n (\partial_\epsilon f_n)\, i_n^2$$



S/diffusive Au/S

B. Dassonneville PRL 2013





In SNS:
zero absorption at π!

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 current-phase relation

« Topologically protected edge state » suggested by ac response measurement of diagonal susceptibility

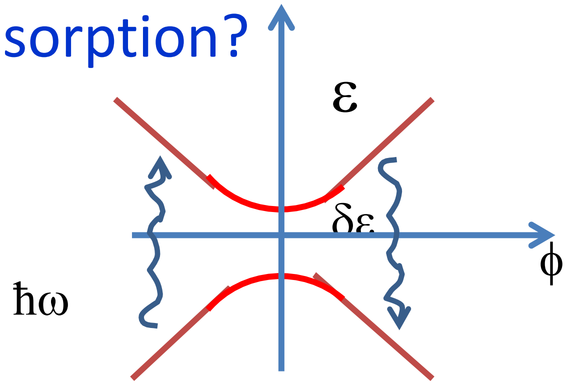
Ongoing questions:

Frequency dependence to reveal relaxation mechanisms:

Difficult to determine precisely.
Order of magnitude indicates that $\tau_{in} < 1/\omega$ up to 6GHz
Fast relaxation: subgap states in disordered W (vortices)?
Possible distribution of τ_{in} (T independent)

Do interlevel (Non Diagonal) transitions also contribute to absorption?

$$\chi_{ND} = \frac{f_n - f_m}{\epsilon_n - \epsilon_m} \frac{i\hbar\omega}{i(\epsilon_n - \epsilon_m) - i\hbar\omega + \hbar\gamma_{nm}}.$$



(small coupling $\delta\varepsilon$ between edges) $W/\xi > 10$

Should give absorbtion peaks at π of width $\delta\varepsilon$, independent of T with satellites at $\pm\hbar\omega/\alpha$ for $\omega \sim \delta\varepsilon$

Experiments still in progress!

Future plans

- Analyze ac measurements
- narrower Bi111 nanowires, gateable?
- Transition from long to short junctions?
  closer contacts with He-Focused Ion Beam
- Bismuthene???

More about the current-carrying channels

- Critical current of a ballistic channel 1 μm long ≈ ev_F/L~100 nA

Experiment: 400 nA modulation: 4 channels?
Hypothesis: 3 channels with t=0.9 at inner edge, 1 to 2 channels with t=0.7 at outer edge: degeneracy due to atomic orbitals? or three terrasses?

- v_F~ given from rounding of sawtooth with temperature

- Persistence up to 1000G of sawtooth, up to 1T of supercurrent : paths must be narrower and closer than 4 nm.

- What causes the non perfect transmission: scattering between two edges? Leakage to rest of wire?