Topological hinge states in Bismuth nanowires revealed by proximity induced superconductivity

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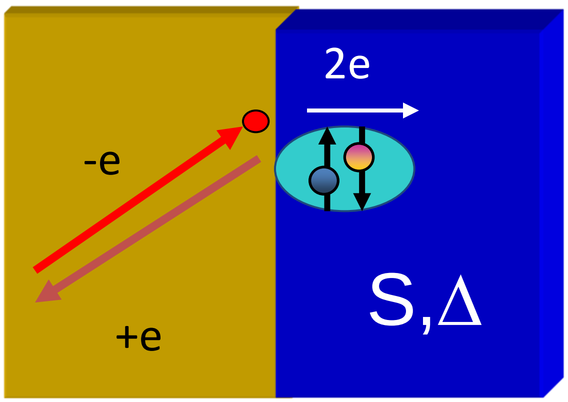
Proximity effect in material with high spin orbit coupling

LPS ORSAY

CSNSM

Institute of microelectronic tech. and High purity mat.

Normal Superconducting Interface



NS current at eV < Δ

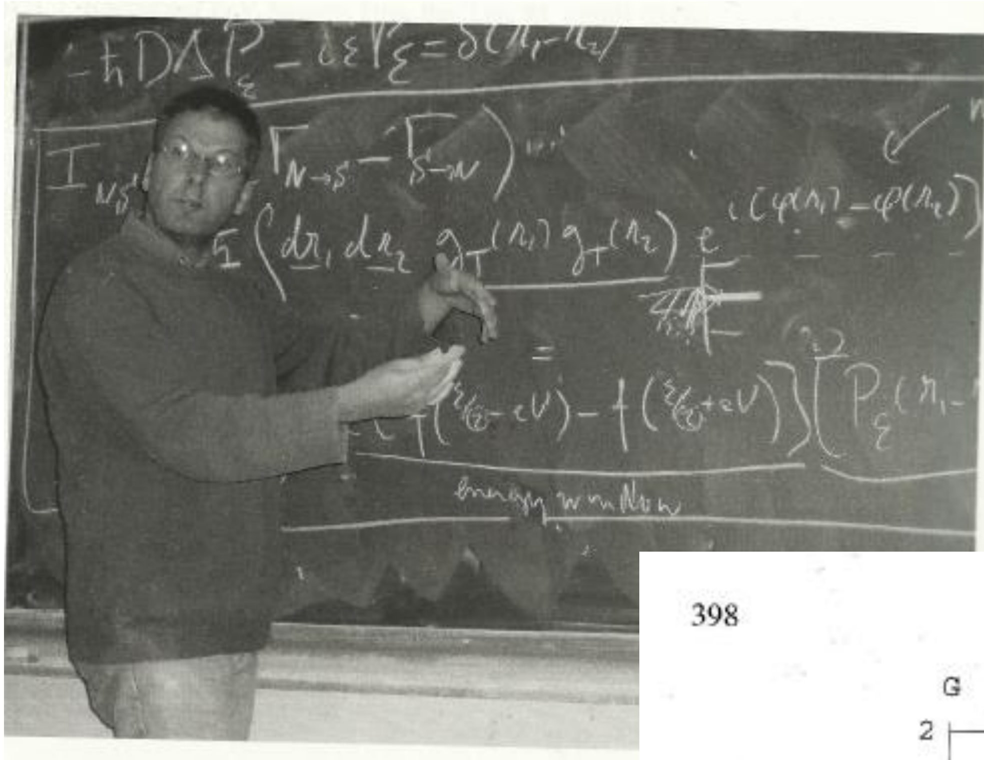
one electron retro-reflected into a hole

Andreev reflection

two electrons passing from N to S

Depends on the transmission of the NS interface

Electron subgap transport in superconducting hybrid systems



Les Houches Summer School 2004

« Nanophysics:
Coherence and Transport »

398 *F.W.J. Hekking*

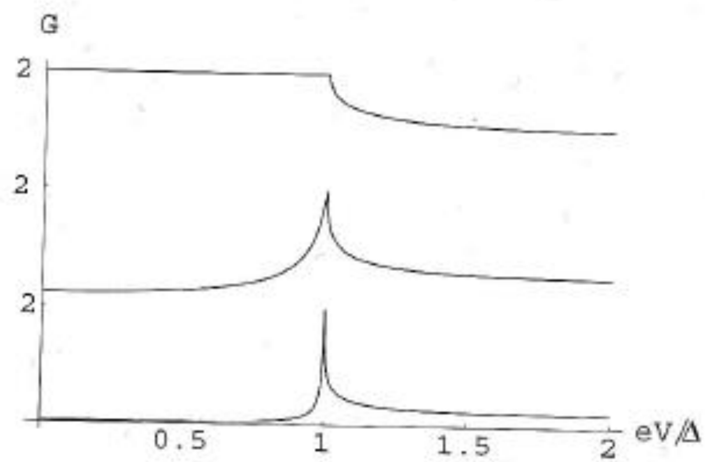
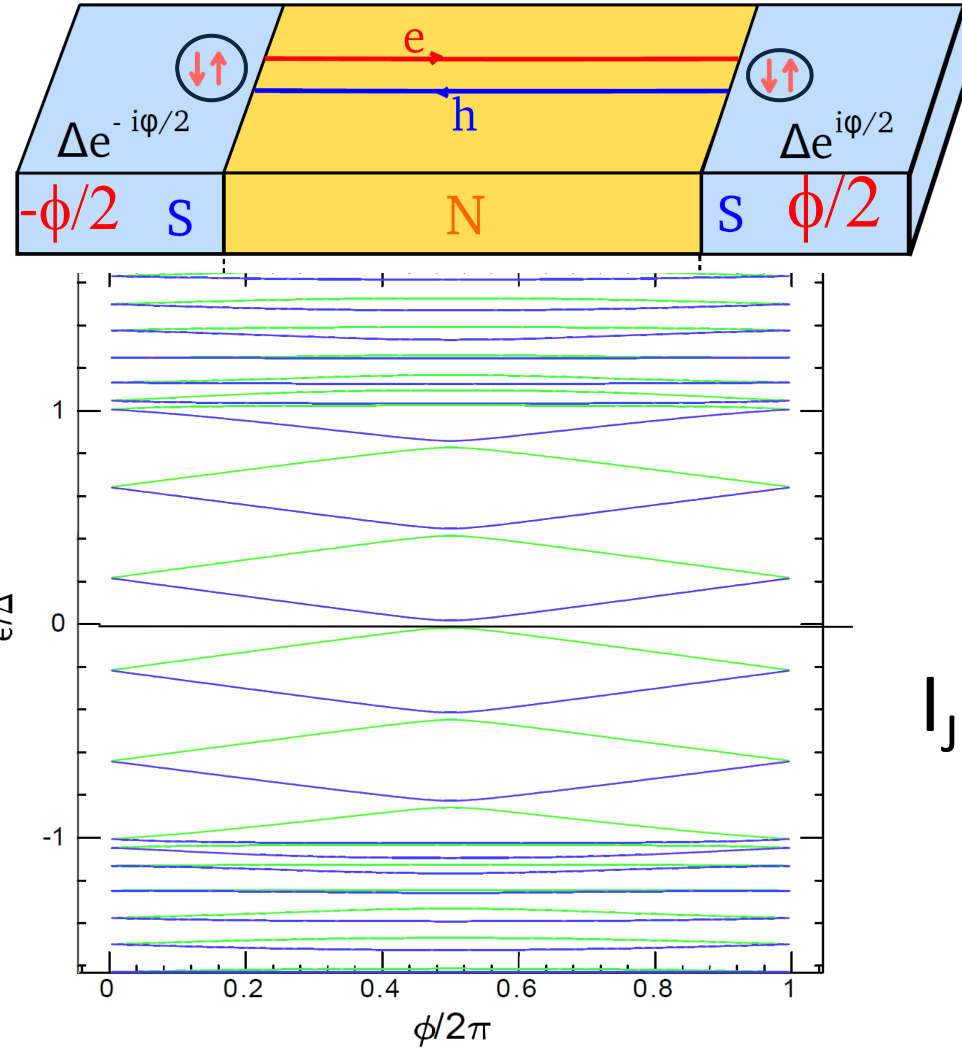


Fig. 4. Dimensionless zero-temperature differential conductance $G = dI_{NS}/G_Q dV$, where $G_Q = e^2/\pi\hbar$, as a function of voltage eV/Δ. Curves are off-set for clarity and correspond (from top to bottom) to $Z = 0.01$, 1.0, and 2.0.

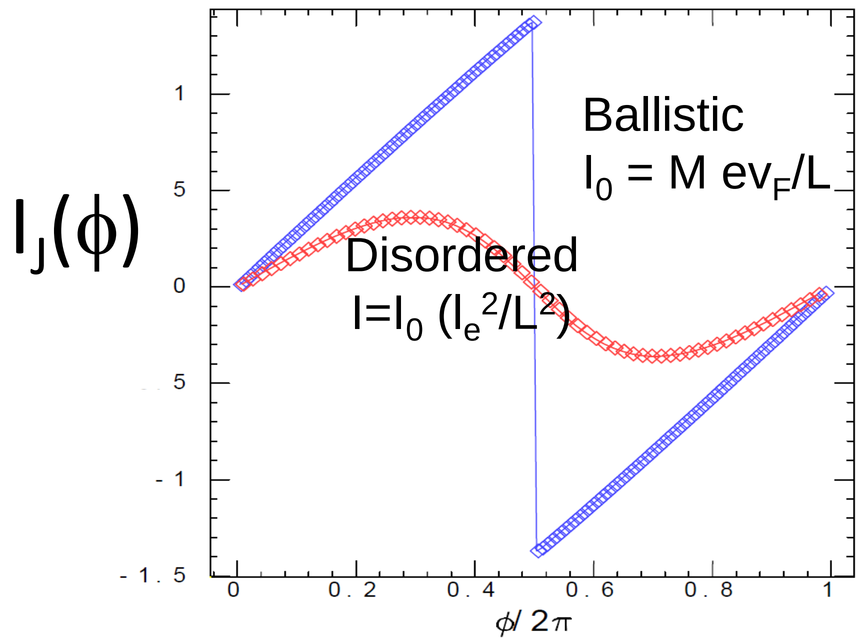
Andreev Spectrum of a long SNS junction $L_N > \xi_S$



$\sim\pi$

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

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



Level crossing at π and $\varepsilon=0$
lifted with disorder

Sawtooth $I(\varphi)$ characteristic of
ballistic junctions rounded with disorder

Revealing topological tranport in Bismuth nanowires

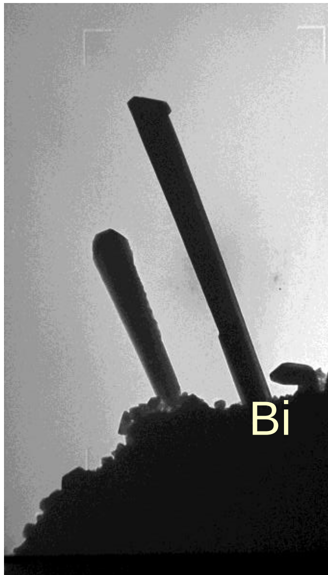
Bulk, surface and edge states

Normal transport: Bulk and Surface states dominant

Superconducting electrodes :

Josephson supercurrent
Selects a small number of ballistic edge states

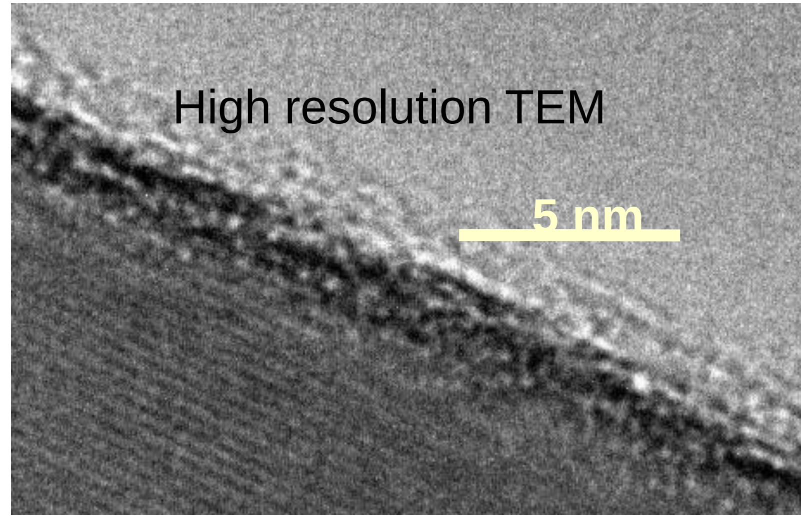
A.Murani PHD thesis april 2017, Nat.Com 2017

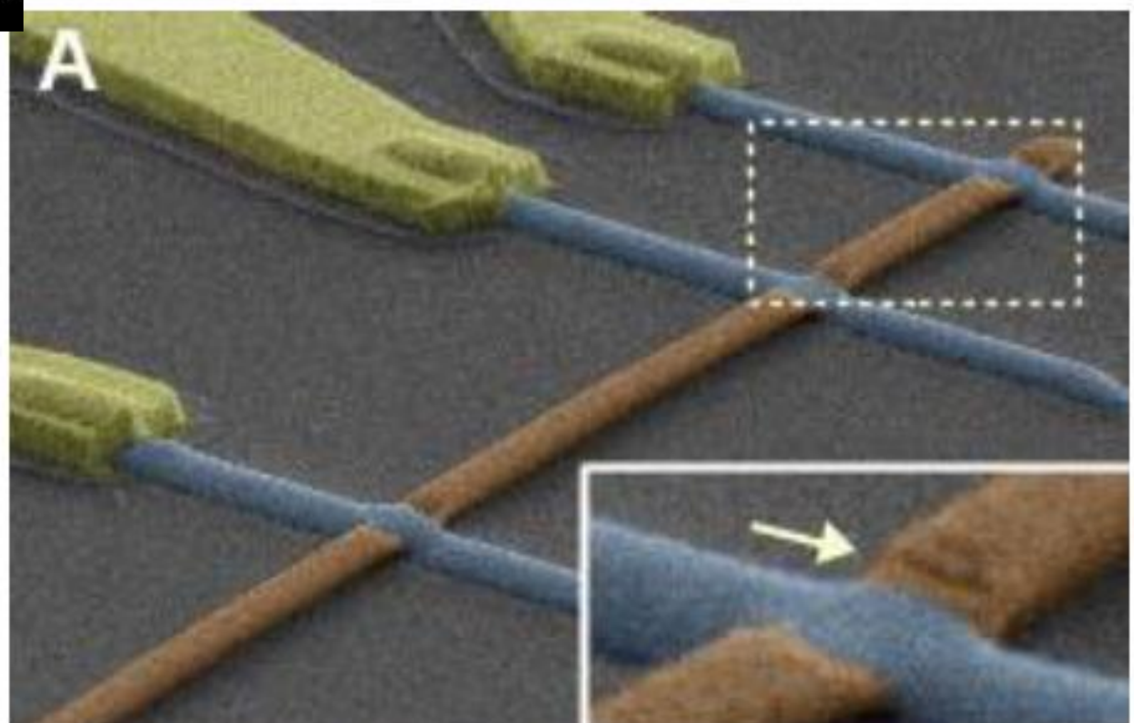


Monocrystalline Bismuth nanowires

High quality
single
crystals

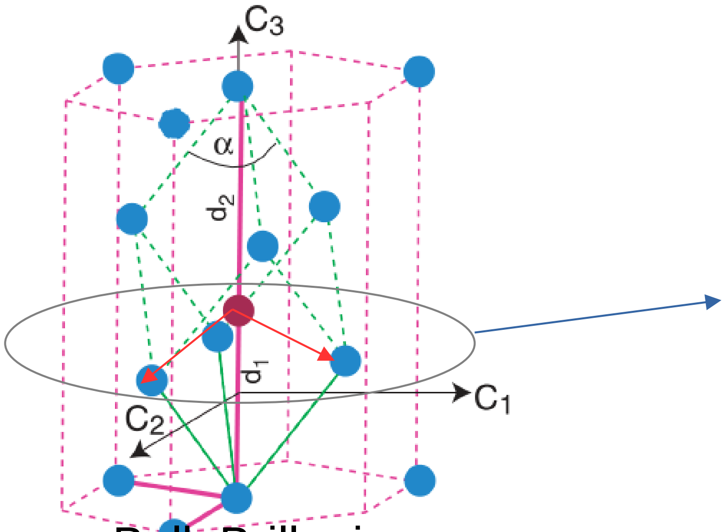
$\varnothing \sim 100\,\mathrm{nm}$



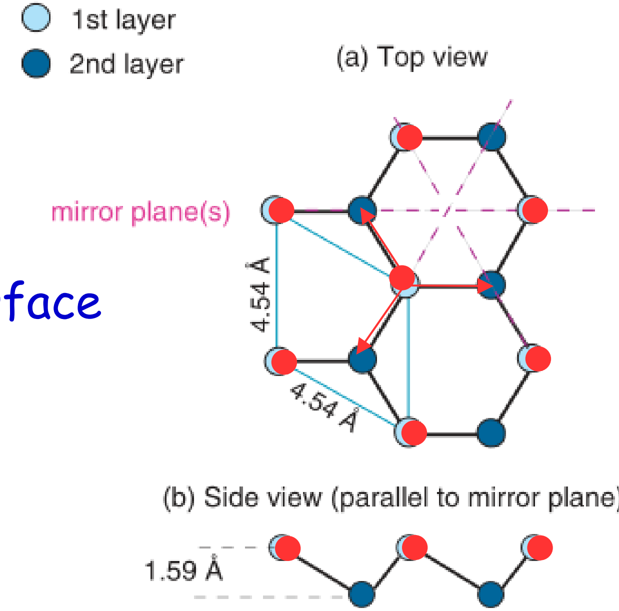


Selected Bi Nanowire with 111 surfaces connected with FIB

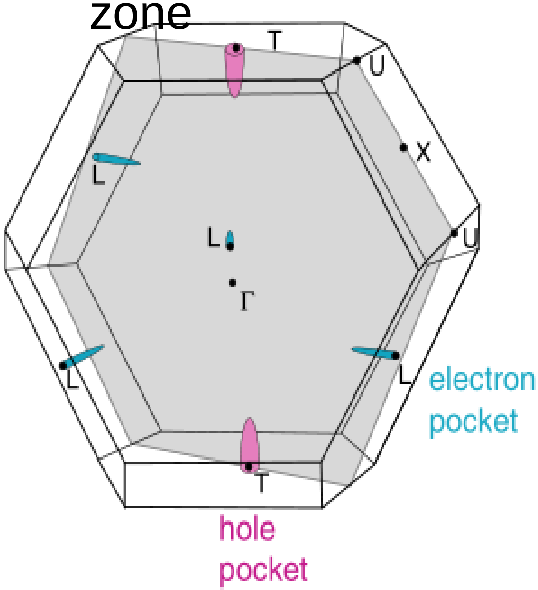
Electronic structure of Bismuth



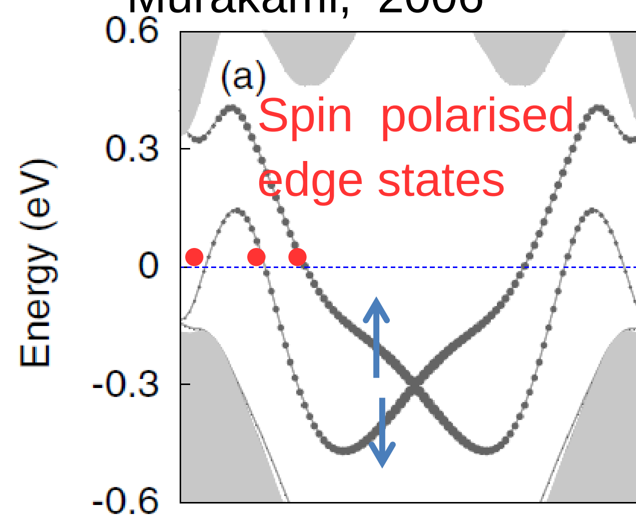
(111) surface



Bulk Brillouin zone



Murakami, 2006



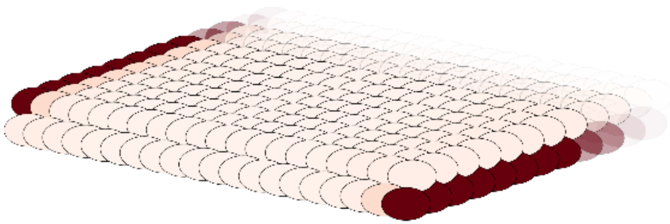
Bi (111) bilayer is a 2D quantum insulator

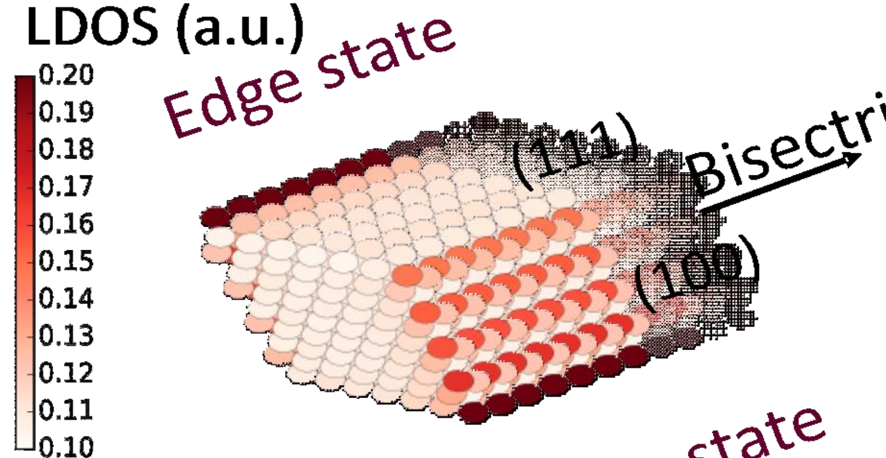
Bulk Bi is a semimetal

Bismuth nanowires

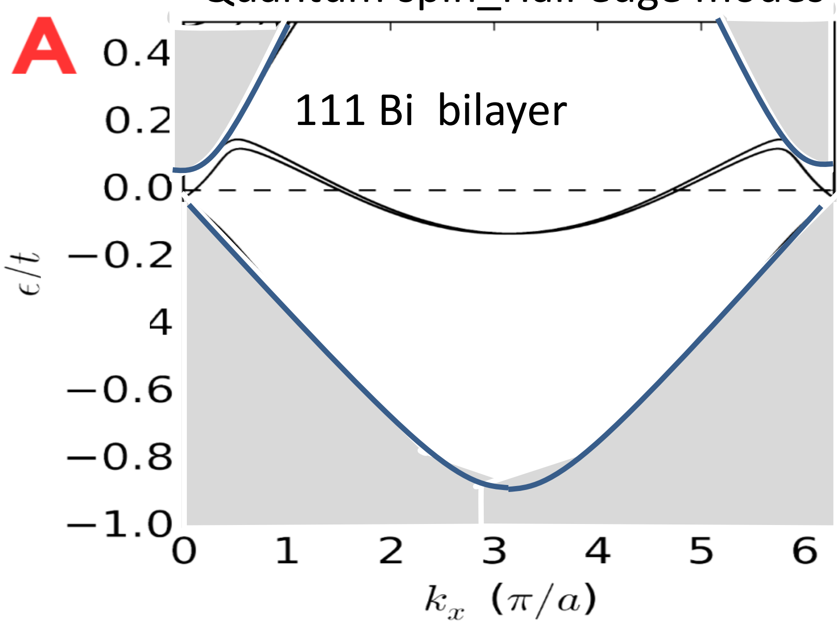
Presence of edge states along 111 surfaces

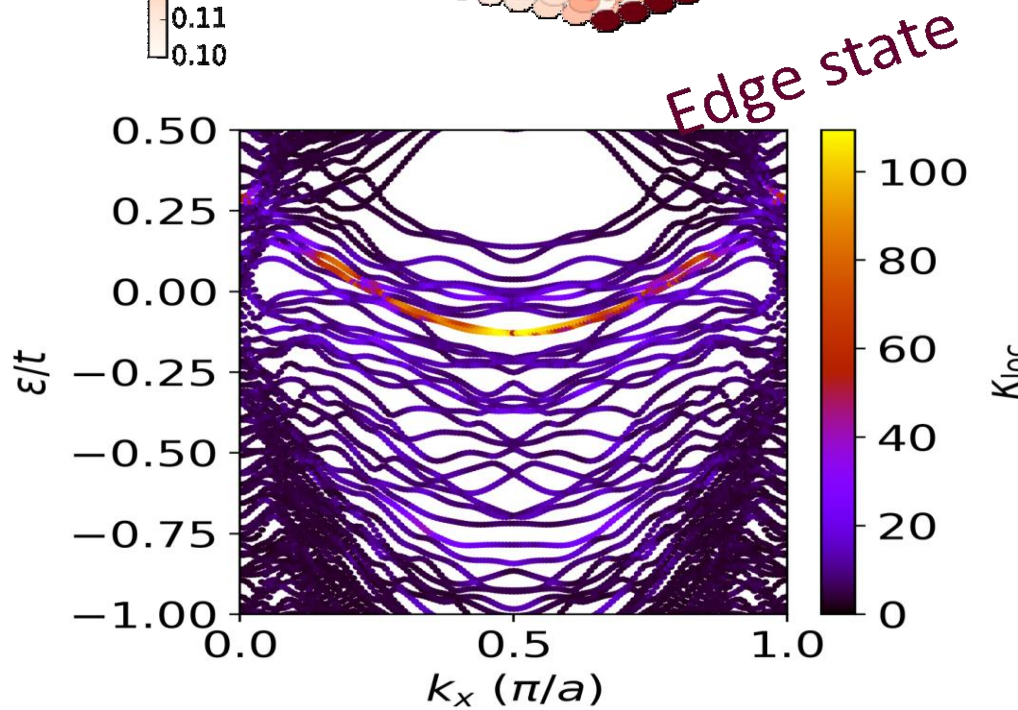
Anil Murani 2017 :
Tight binding simulations





Quantum spin_Hall edge modes





Confined Bi 3D semi metal: 2D metallic surfaces and topological 1D edges

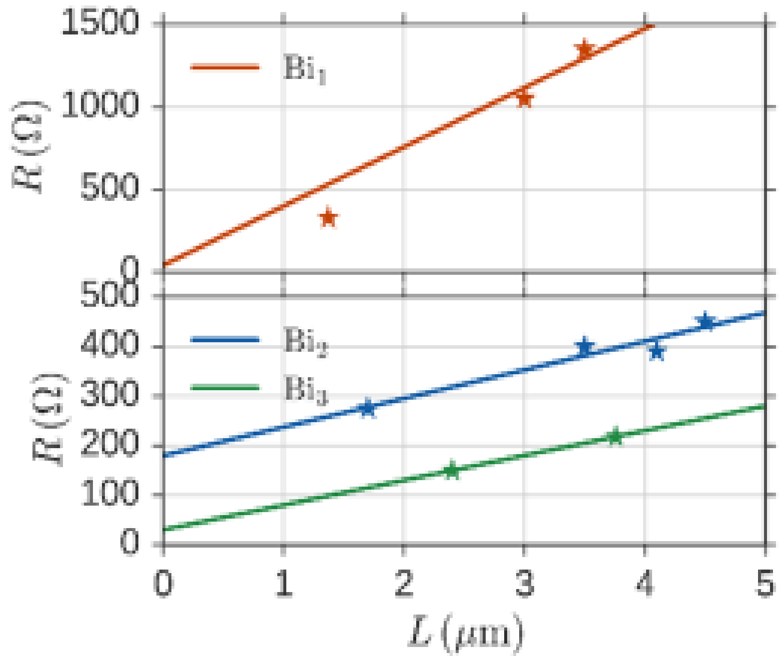
Transport in the normal state T>Tc (electrodes)

Diffusive Surface states carry most of the normal current

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

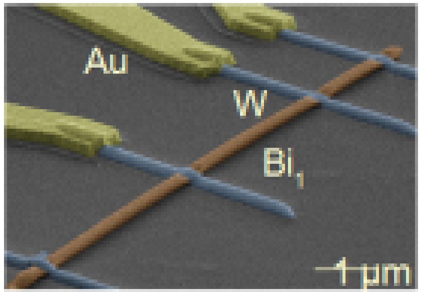
Surface $\lambda_F \simeq 5\,\mathrm{nm}$

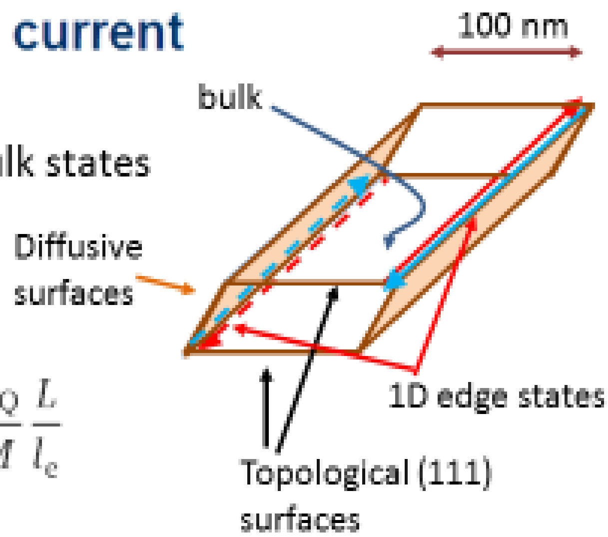
} Roughly 50 times more surface states than bulk states



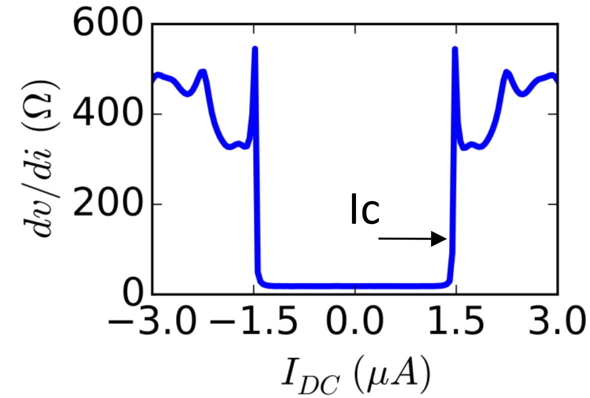
$$R(L) = R_c + \frac{R_Q}{M}\frac{L}{l_e}$$

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

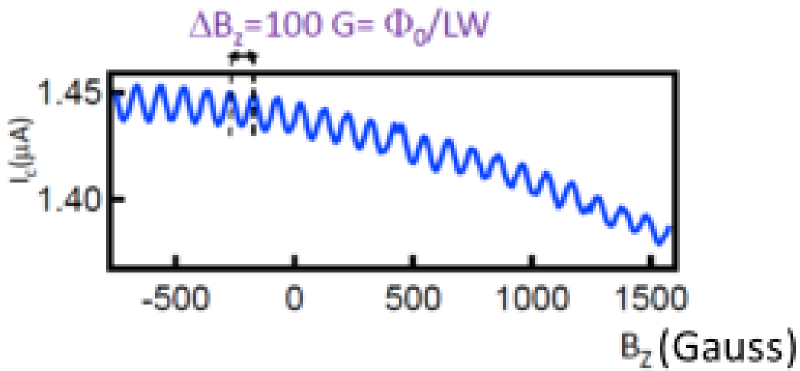


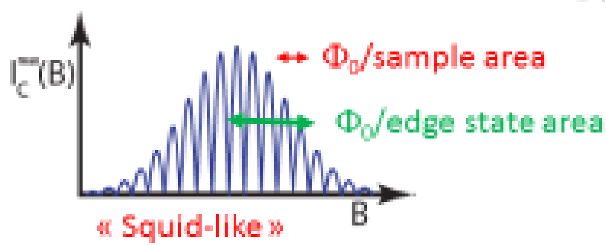


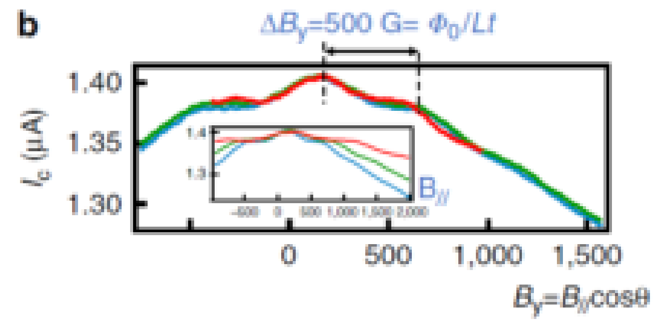
Superconducting proximity effect in Bi nanowires T<Tc (electrodes)

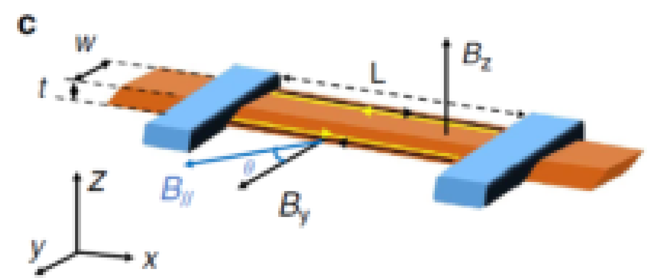


Field-dependence of critical supercurrent reveals paths taken by pairs



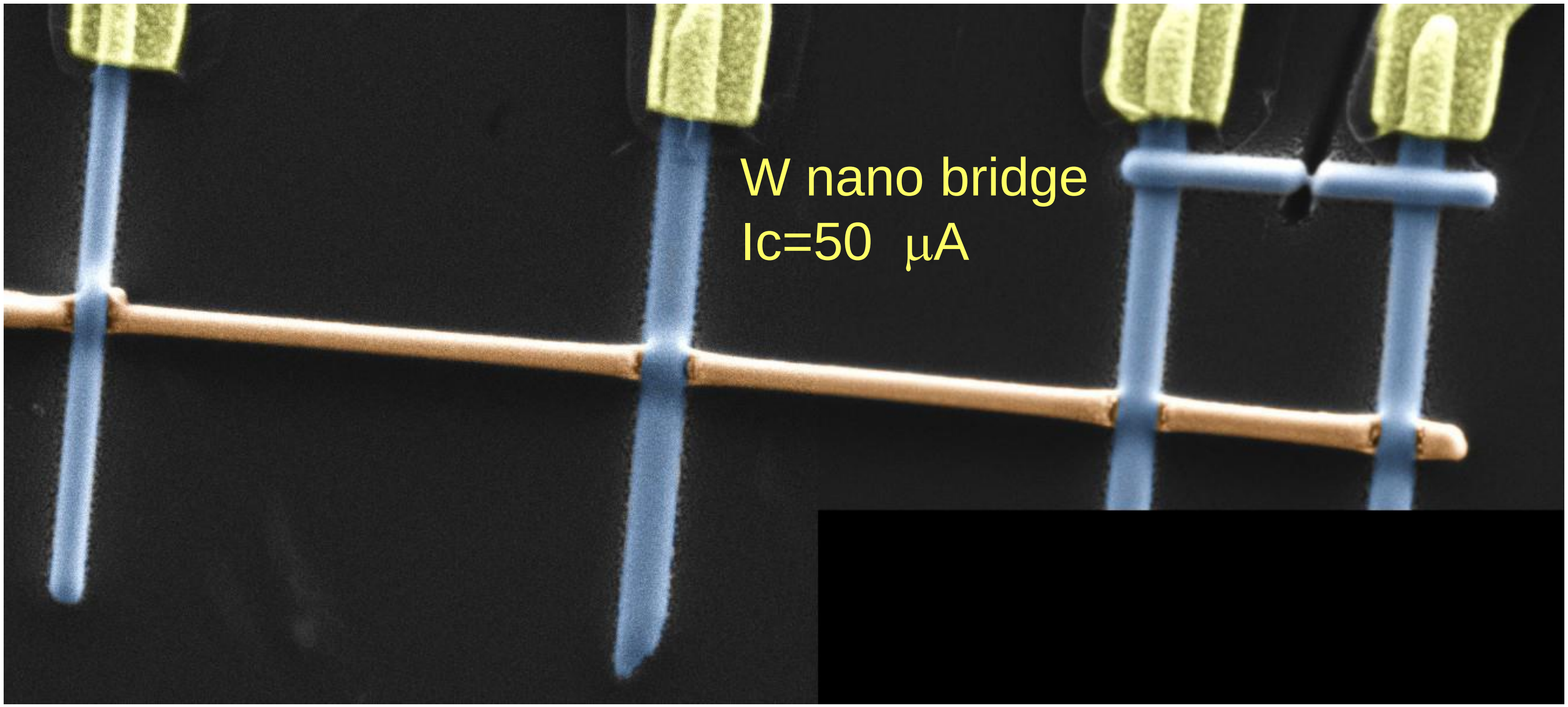






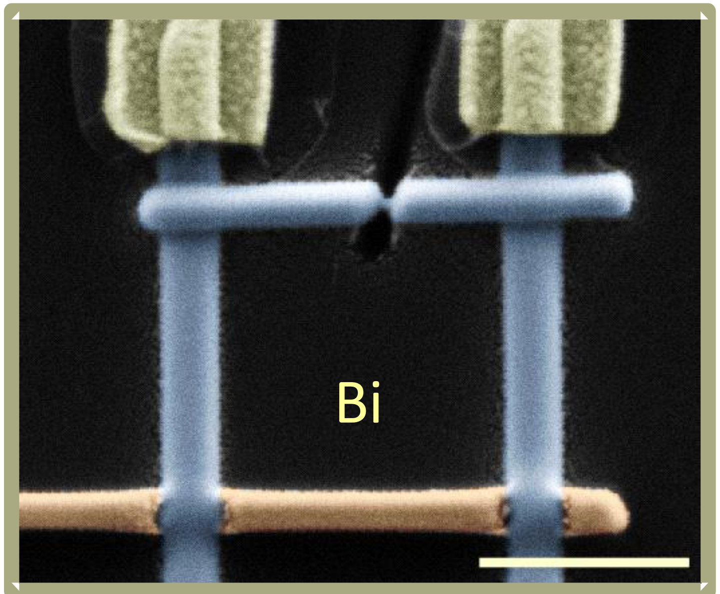
- Oscillations with field: very few states
- Field direction dependence and period: supercurrent travels at the two acute wire edges
- High field decay scale (oscillations up to 10 Tesla in some samples): narrow channels (nm!).
- High critical current : well transmitted channels.

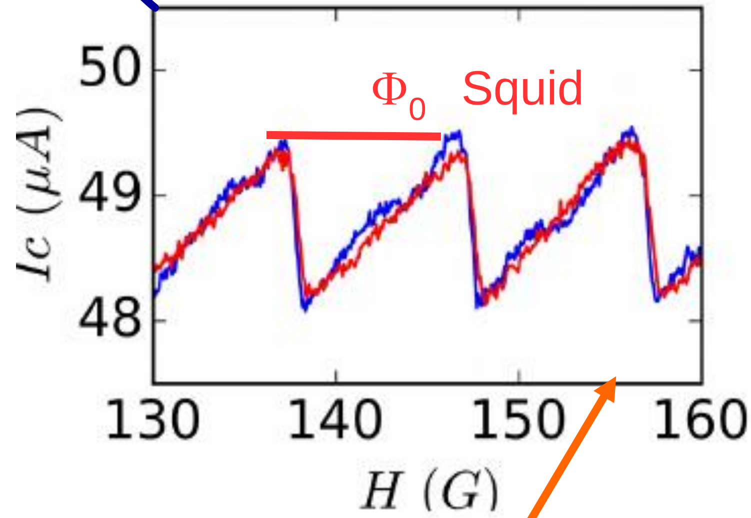
Current phase relation as a probe of the ballistic nature of transport

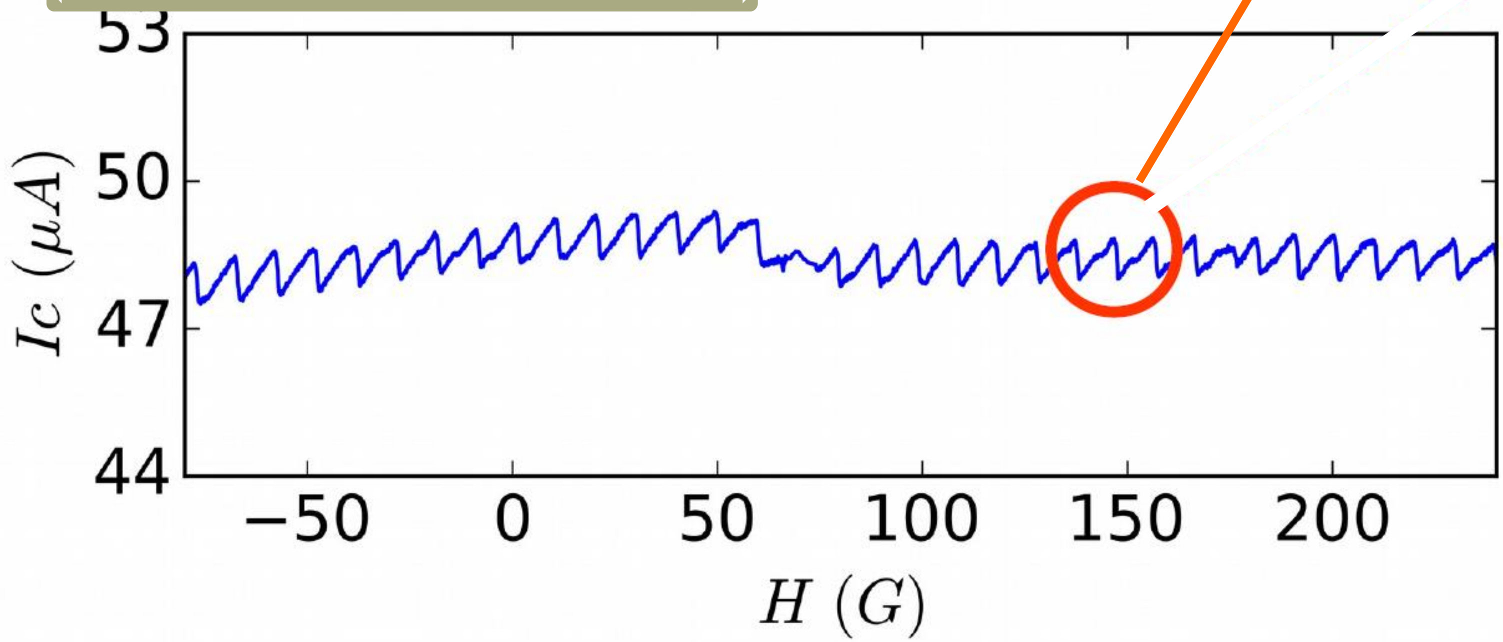


Assymetric SQUID

Bi nanowire based SQUID

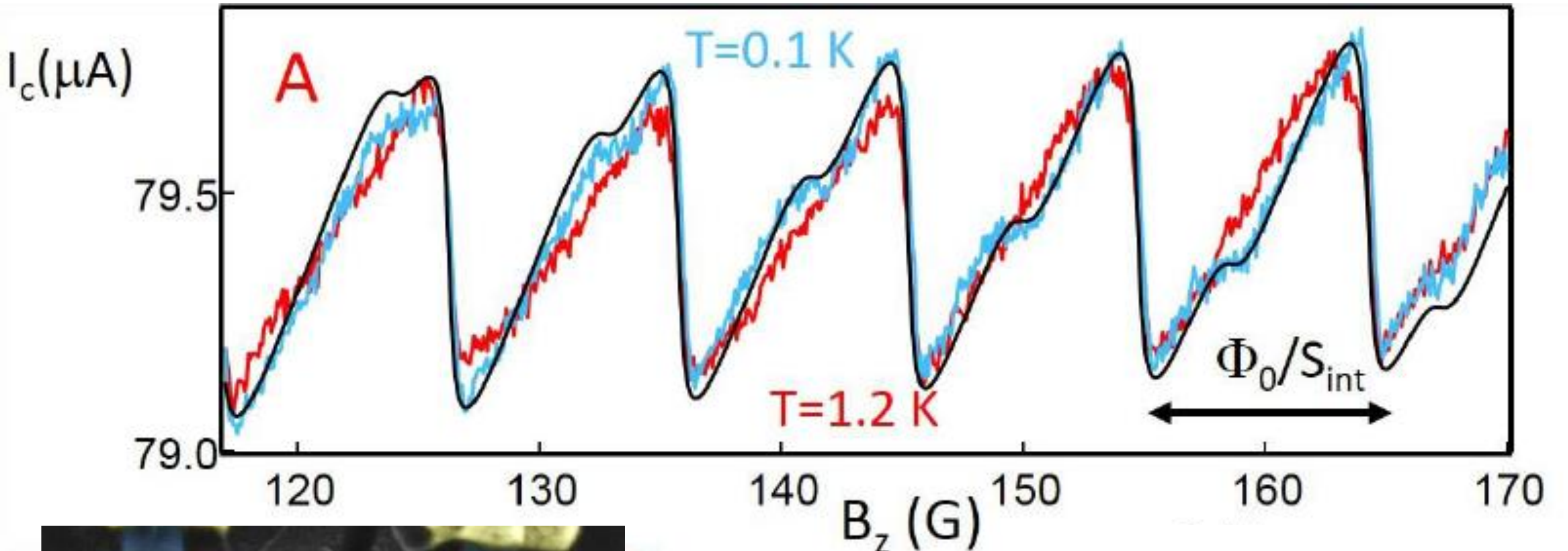


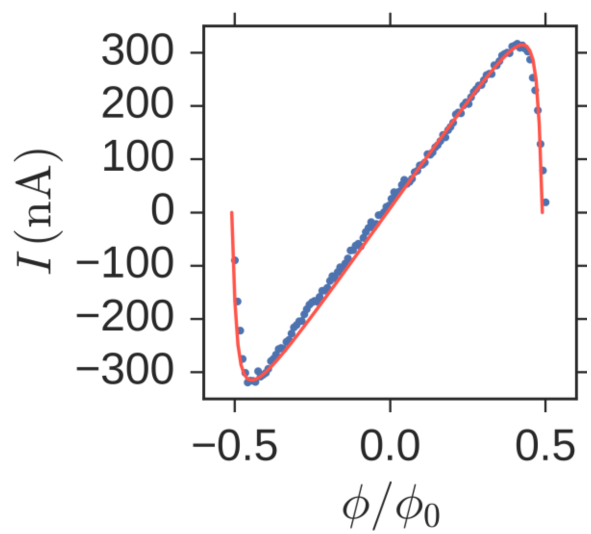


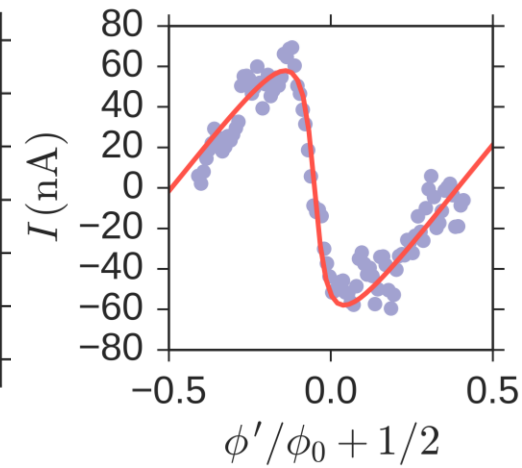


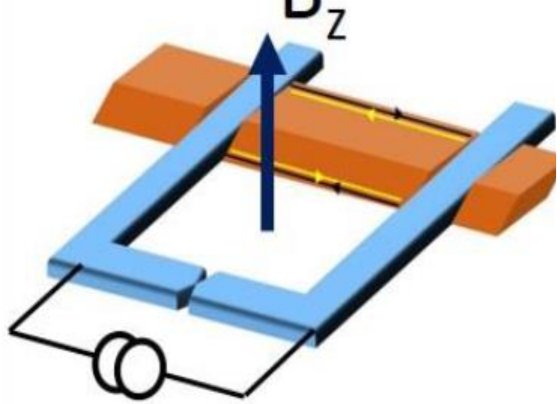
Current phase relation of a long ballistic SNS junction

Beating between 2 saw tooth

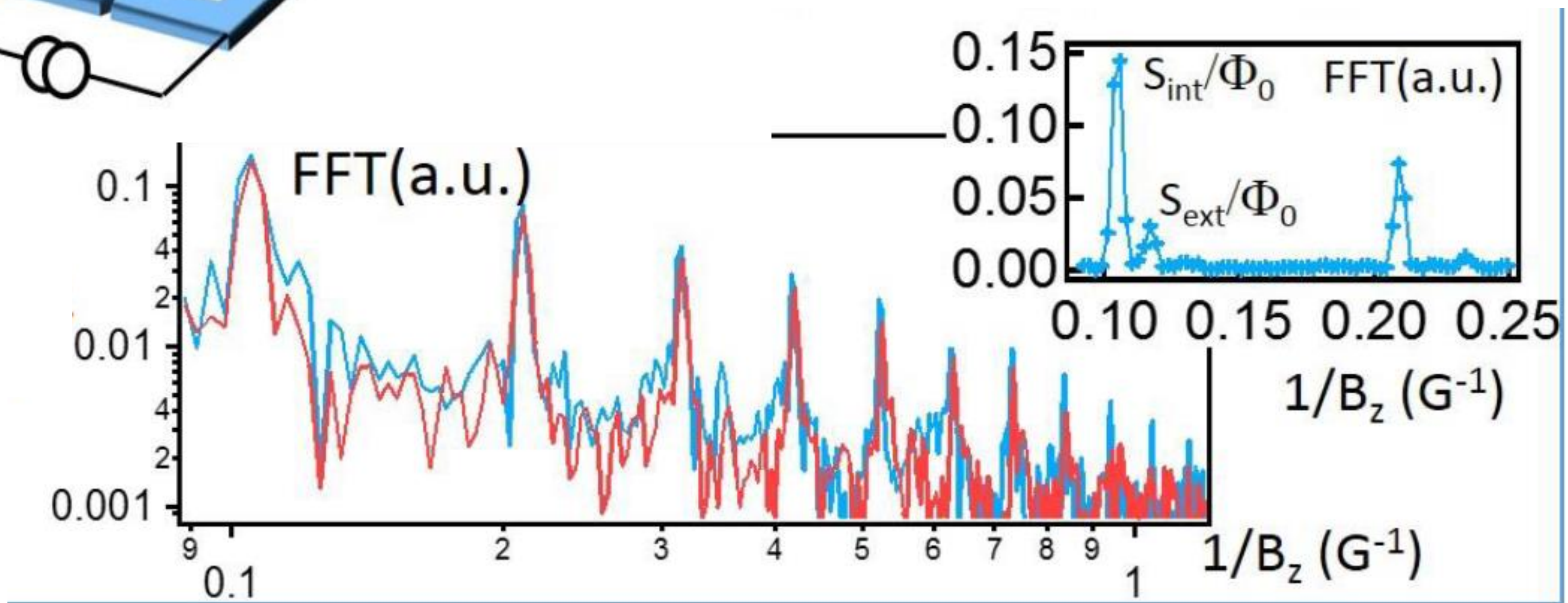








Beating between 2 saw tooth



$$I_J(\varphi) = \Sigma \frac{(-1)^n}{n} \sin n\varphi \, t^{2n}$$

Inner edge: 3 channels with t > 0.9

Outer edge: 1 channel with t > 0.7

Effective mean free path > 10 micrometers

Why is the contribution of edge states dominant ?

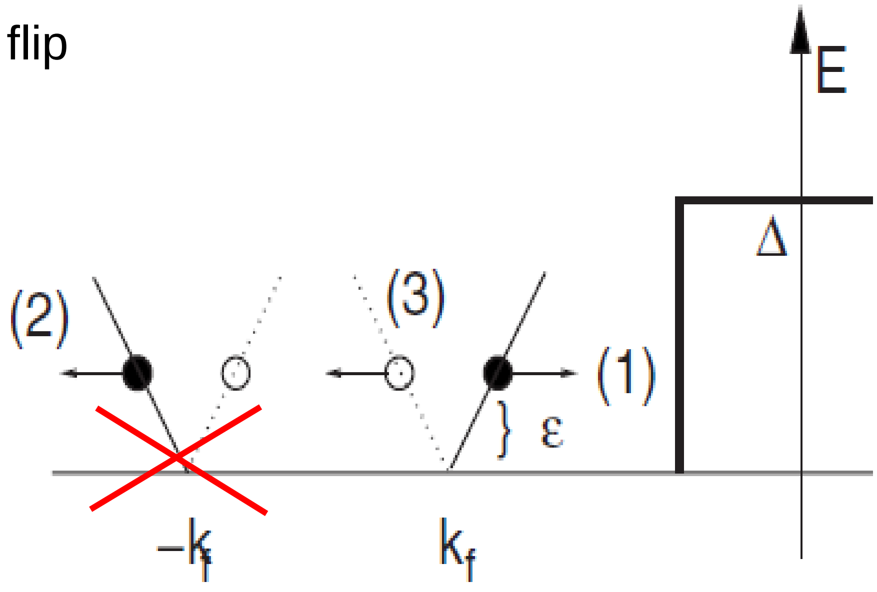
1 ballistic channel Ic = ev_F/L

1 diffusive channel Ic = $(l_e/L)^2 \; ev_F/L$

Surface states $l_e/L \sim 0.1$

NS interface enhanced Andreev reflection of topological helical states

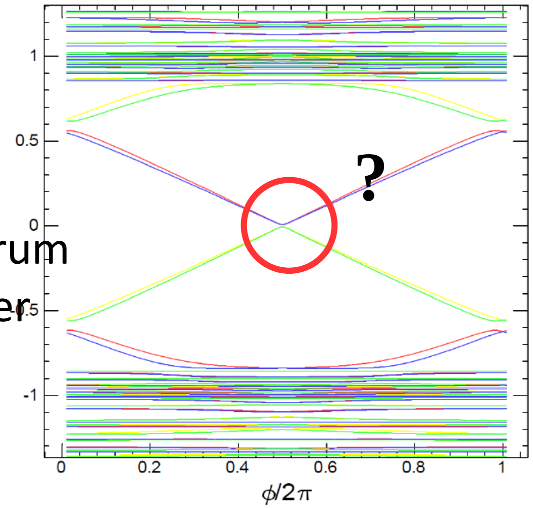
Backward scattering only possible with spin flip



Adroguer et al.

Experimental signatures of topological zero energy level crossing at π

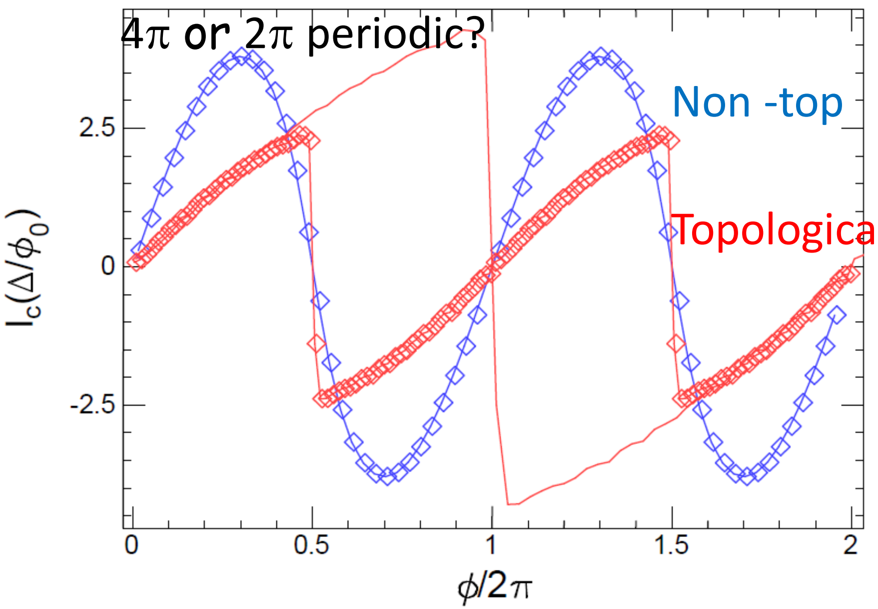
Topological
Andreev spectrum
Resit to disorder



Josephson current:

$$I_s(\varphi) = \sum f_n(\varphi)\, \partial\, \varepsilon_n(\varphi) / \partial\, \varphi$$

Saw- tooth current phase relation



Finite quasi particle relaxation time

Finite frequency driving:

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

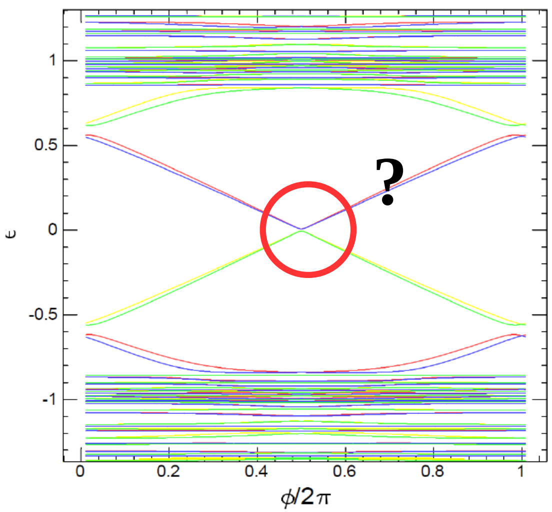
Linear response

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

$$\chi= i\omega\ Y = \chi'+i\chi''$$

Probing dynamics of SNS junctions close to equilibrium

Experimental signatures of topoogical zero energy level crossing at pi

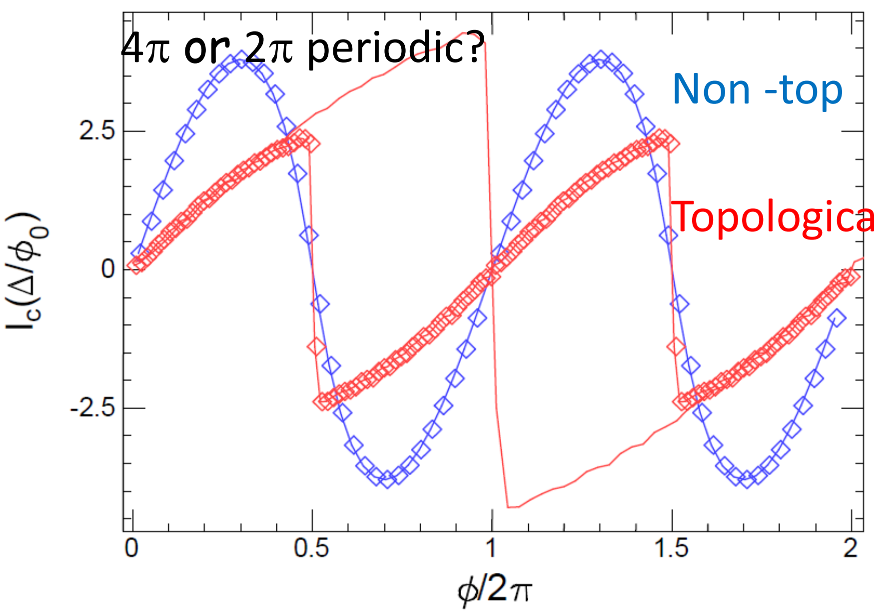


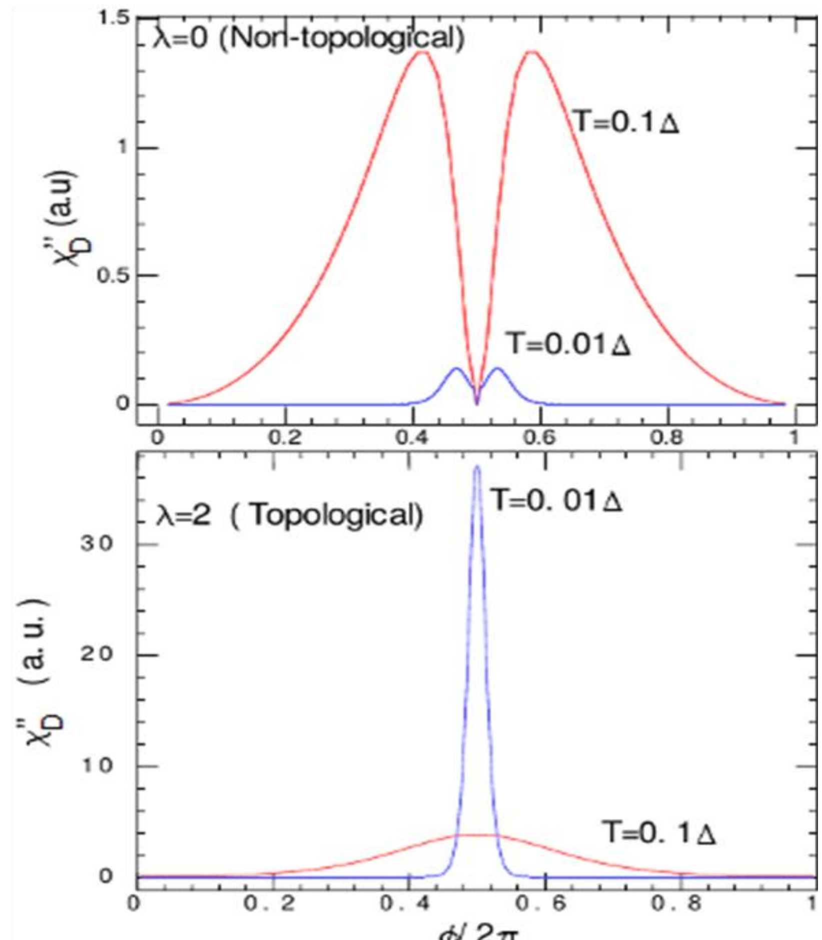
Phase dependent finite frequency admittance Y=ωχ

Diagonal contribution: relaxation of ABS populations

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

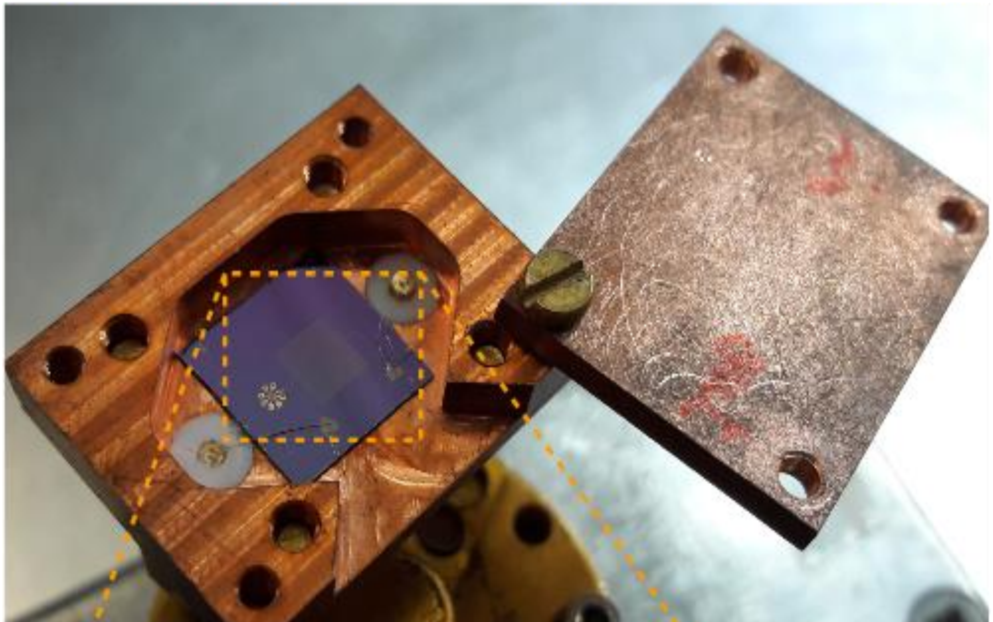
Saw- tooth current phase relation



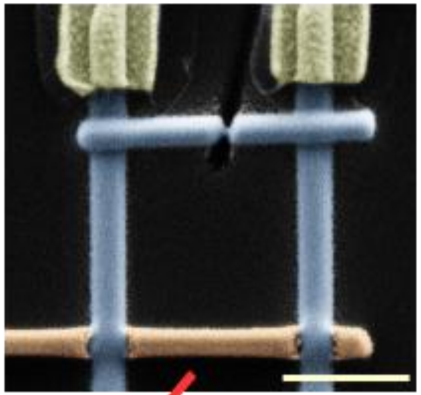


High frequency experiments

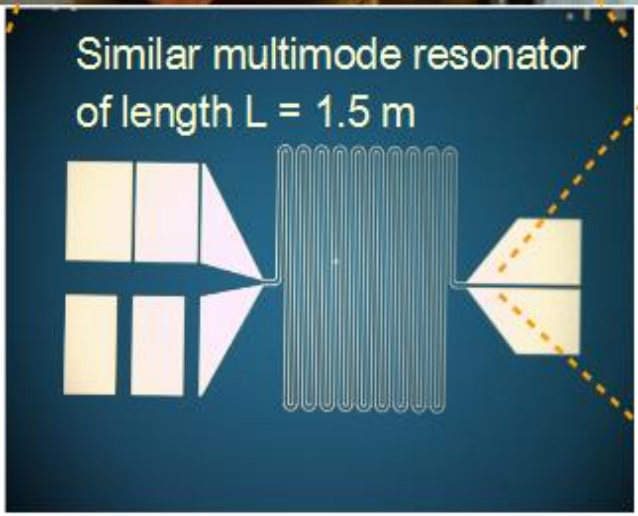
Fabrication of a resonator around the SQUID

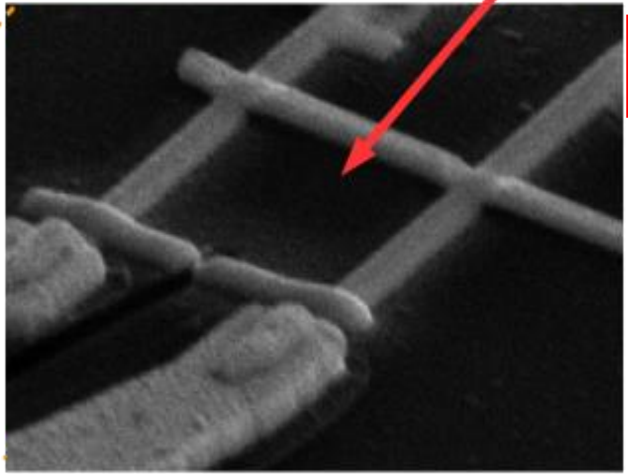


B. Dassonneville A. Murani



Same nanowire





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

$$\frac{\delta f}{f} = -\frac{1}{2} \quad k_m \chi'$$

$$\delta(\frac{1}{Q}) = \quad k_m \chi''$$

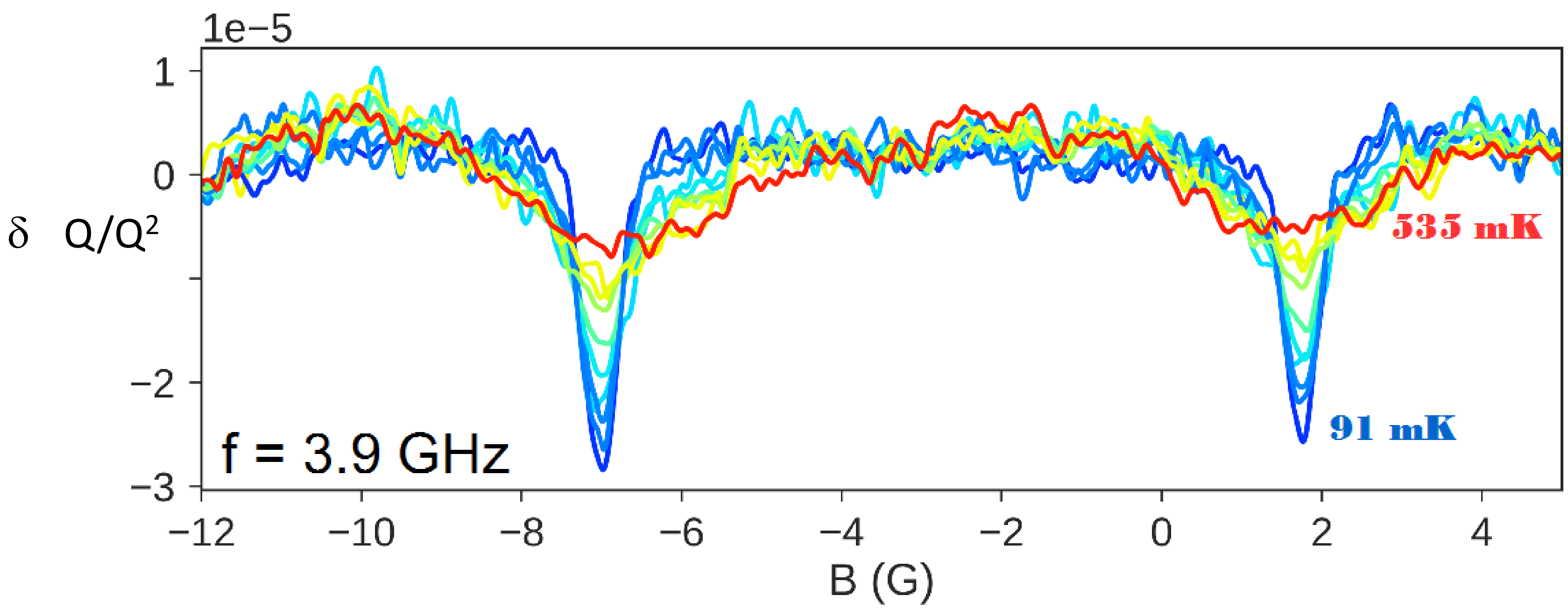
No detectable signal on $f_n(\phi)$...

Phase dependent Quality Factor

Periodic absorbtion peaks at $2n+1\ \pi$

Observed in a wide range of frequency:

f_{min} 280MHz f_{max} 6.8 GHZ



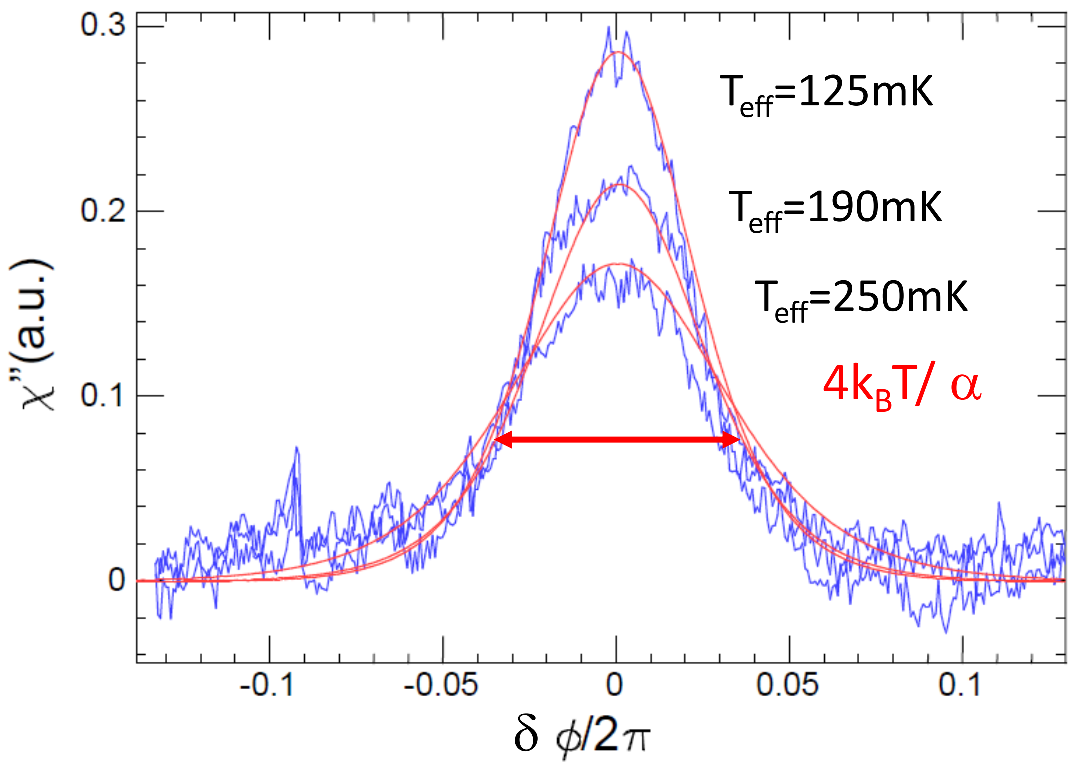
$$\delta (1/Q) = - \delta Q/Q^2 = L_c^2 / L_R \chi''$$

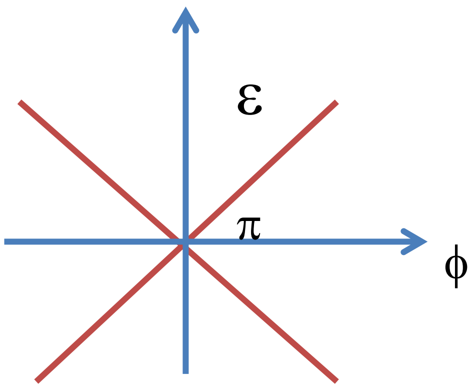
Coupling inductance $L_c \sim 100$pH

Resonator inductance LR ~ 1μH

Signature of zero energy Andreev level crossing

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





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

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

i^2 finite = $(ev_F/L)^2$

Possible fit:

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

$\alpha = ev_F/4L\pi$

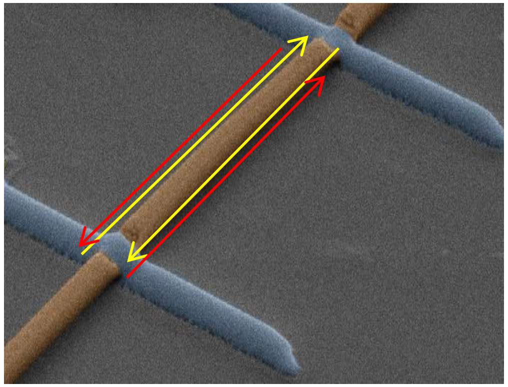
Only adjustable parameter

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

Compatible with dc measurements

Bismuth nanowires with 111 facets

Josephson supercurrent



Carried by a small number
of disorder protected edge *states*

Revealed by SQUID interferometry

Saw tooth current-phase relation
Beating between the 2 edges contributions
Zeeman field yields phase modulation and 0π transitions

Topological nature of the edges
investigated through HF experiments in progress