Ballistic edge states in Bismuth nanowires revealed by SQUID interferometry

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Proximity effect in material with high spin orbit coupling

Institute of microelectronic
tech. and High purity mat.

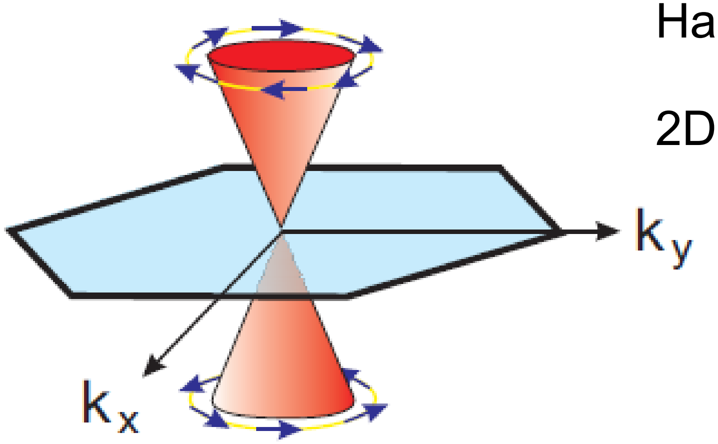
Spin orbit coupling

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

Spin orbit interactions couple spin and spatial degrees of freedom

Depends on the Crystal symmetry can lead to topological phases :

3D

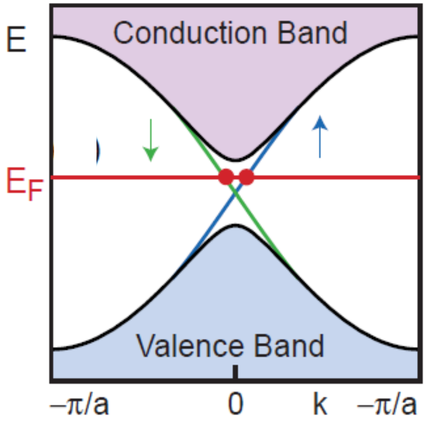


Bi_2Se_3

Hasan Kane RMP (2011)

2D conducting surface states

2D:

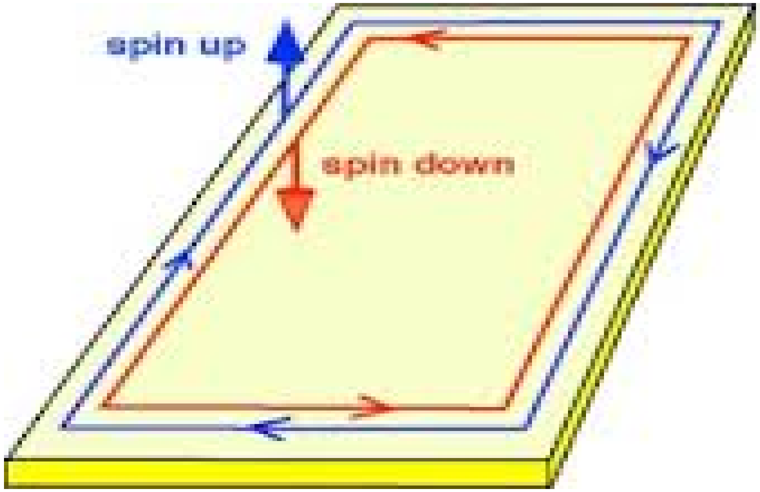


Formation of 1D

counter propagating

spin polarised edge states

Protected from disorder



Bismuth nanowires

Bulk, surface and edge states

Quantum confinement : Surface states dominant

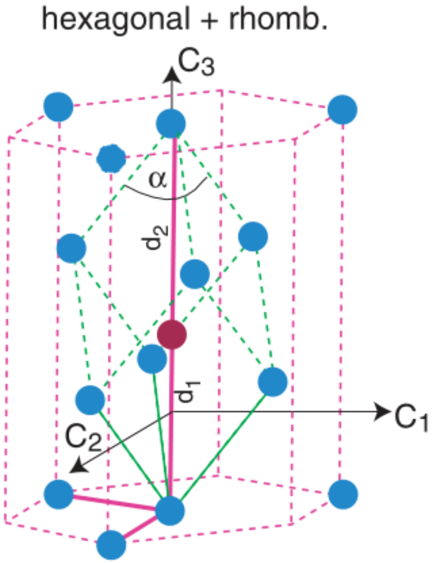
Superconducting electrodes :

Josephson supercurrent
Carried by a small number of ballistic edge states

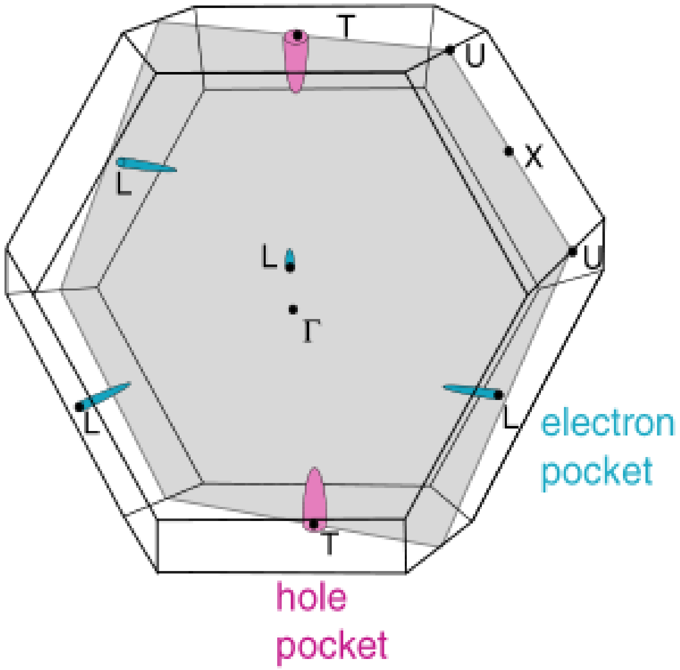
Revealed by SQUID interferometry and
Resistance to very high magnetic field

Bulk Bi

Hofmann 2006 re



Bulk Brillouin zone



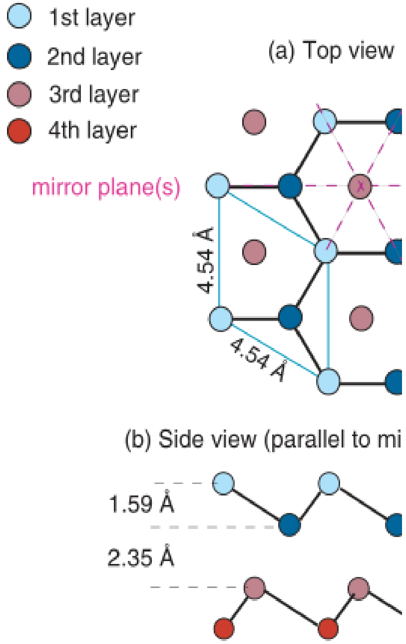
A semi-metal, with $n \approx 3\times10^{17}\ \mathrm{cm}^{-3}$, $m^* \approx 0.03m_e$ and $\lambda_F \approx 50$ nm

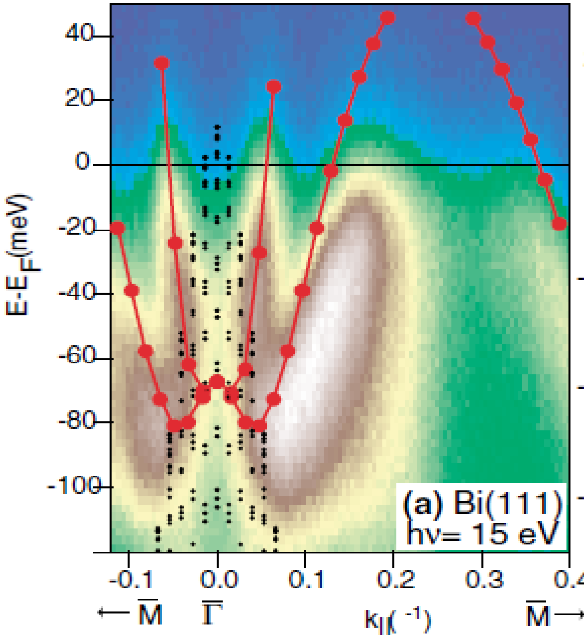
Centrosymmetric: Bulk SO averages to 0

(111)

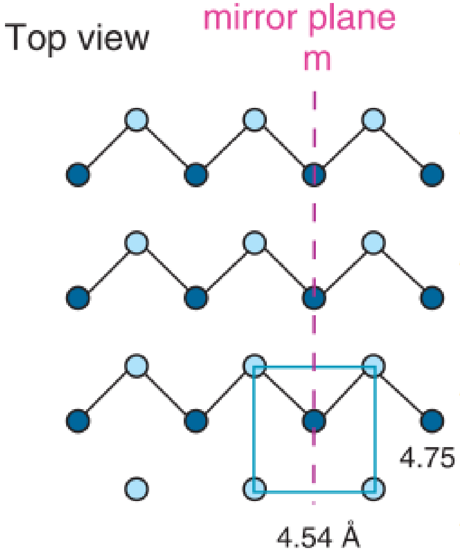
Spin split states at Bi surfaces

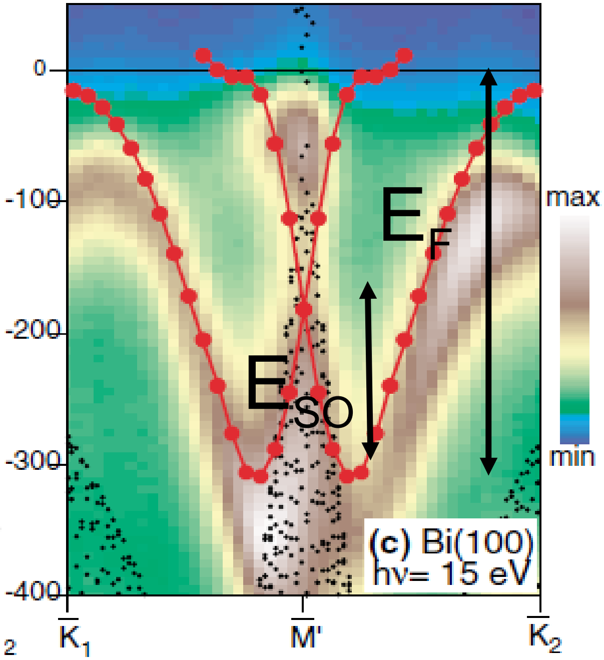
ARPES (Hoffman 2004)





(100)





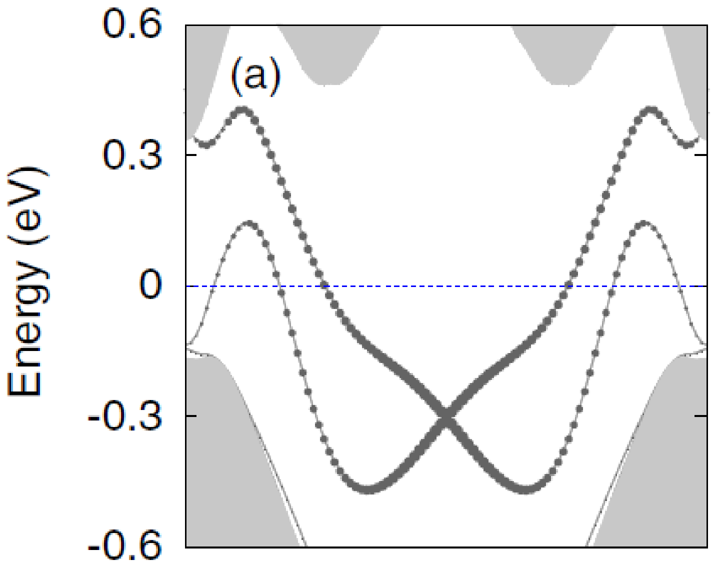
	Carrier density	λ_F	m^*
Bulk	3×10^{17} cm^{-3}	~ 50 nm	0.03
(111) surface	3×10^{13} cm^{-2}	~ nm	0.3

g_{eff}: 1~ 100

All surfaces are different, $E_{SO} \sim E_F \sim 100$ meV

Dominate transport for thin layers or wires d < 90nm

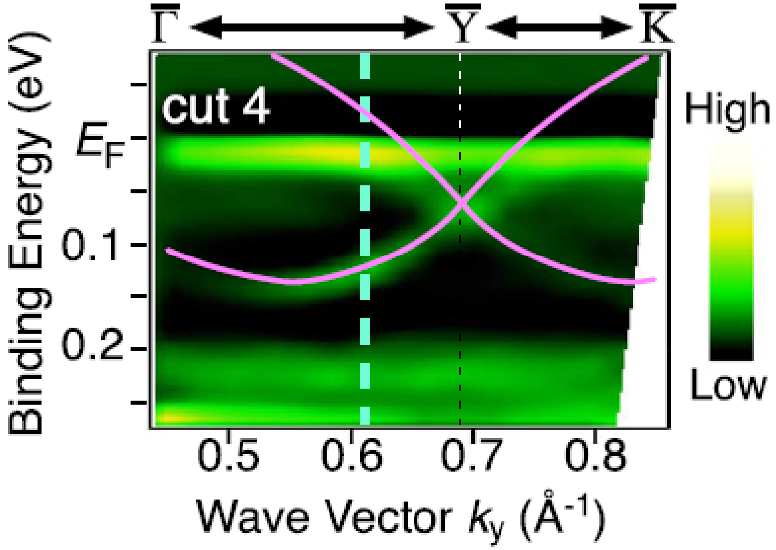
Edge states on certain surfaces

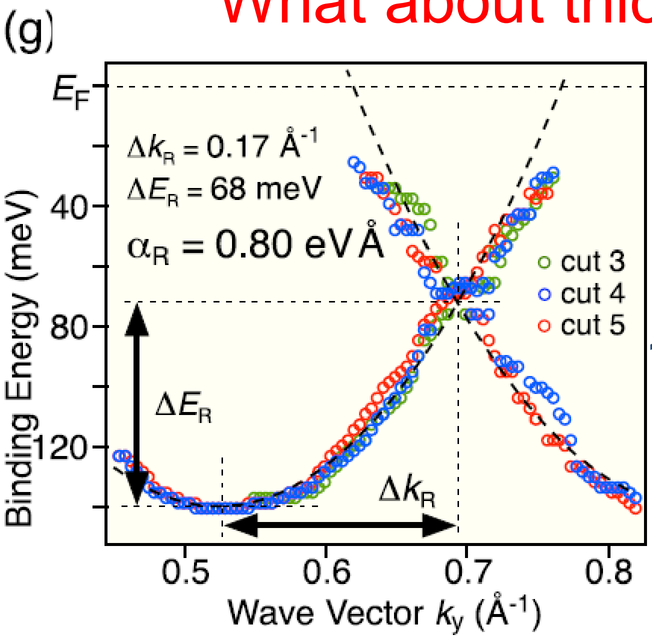


Bi(111) bilayer
Topological 2D
insulator

Murakami 2006

What about thicker layers?





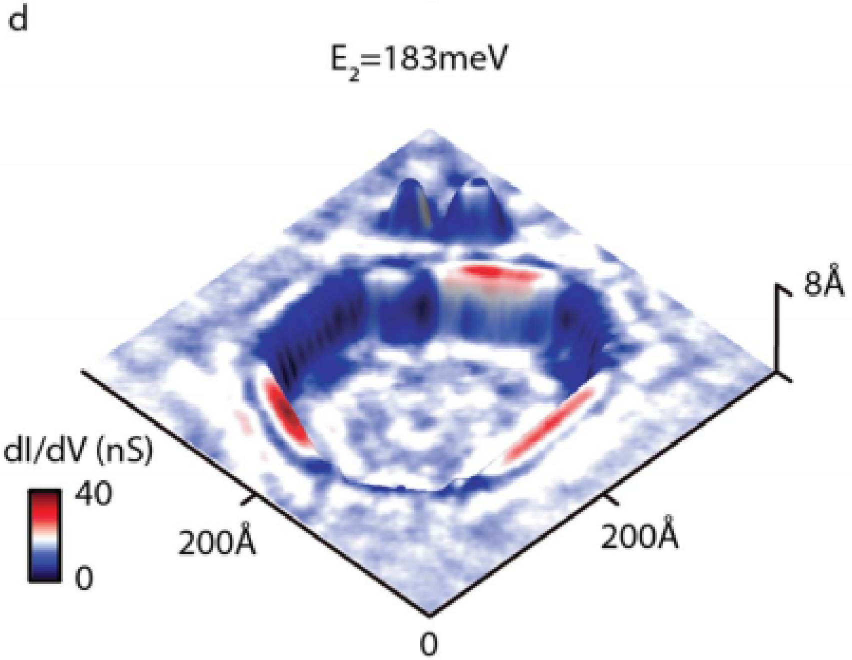
ARPES
Takayama et al

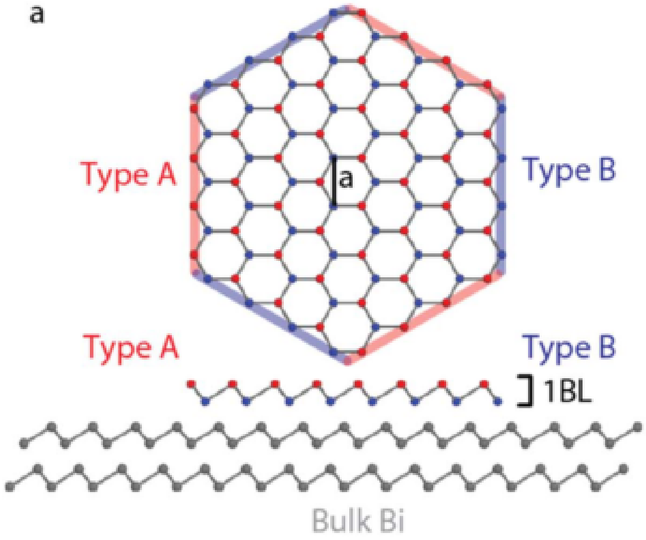
- PRL 2015

15 nm Bi (111) Layer

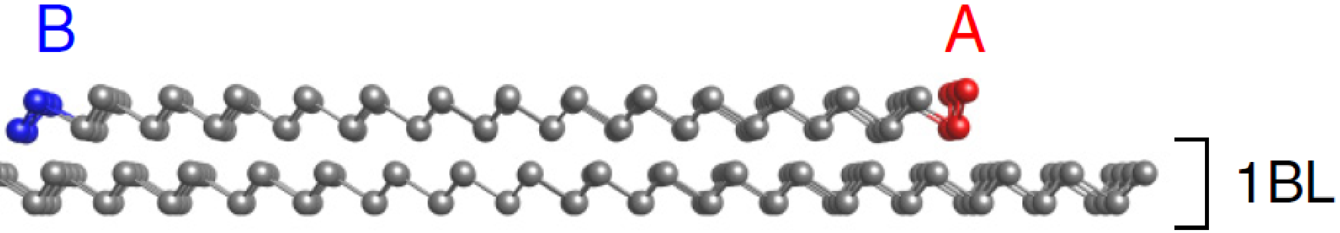
Edge states but possibly
not topological

Bismuth edge states on (111) surface



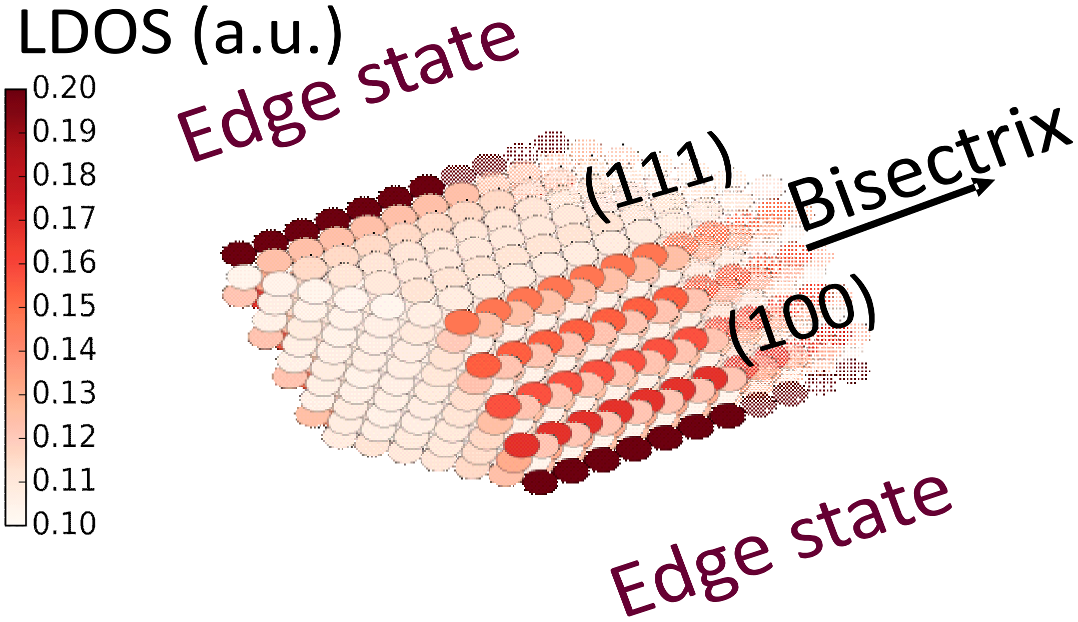


STM on Bi(111) bilayer small pit: 1D **edge states at some edges** (Drozdov Yazdani, 2014)



3D nanowire : presence of edge states along 111 surfaces

Coexist with surface states !

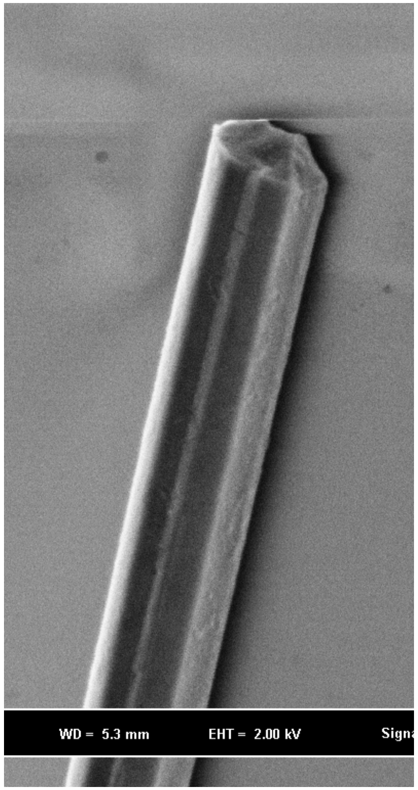


Anil Murani 2016 :
Tight binding simulations
Atomic spin orbit (no Rashba)

Conclusion: confined Bi 3D semi metal → 2D metal
with possibly 1D edges

Normal transport dominated by diffusive surface states
1D edge Revealed by proximity induced superconductivity

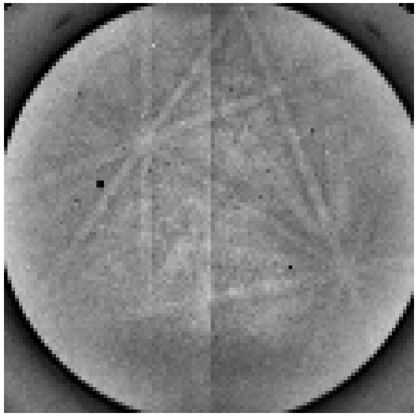
Bi nanowires grown with sputtering

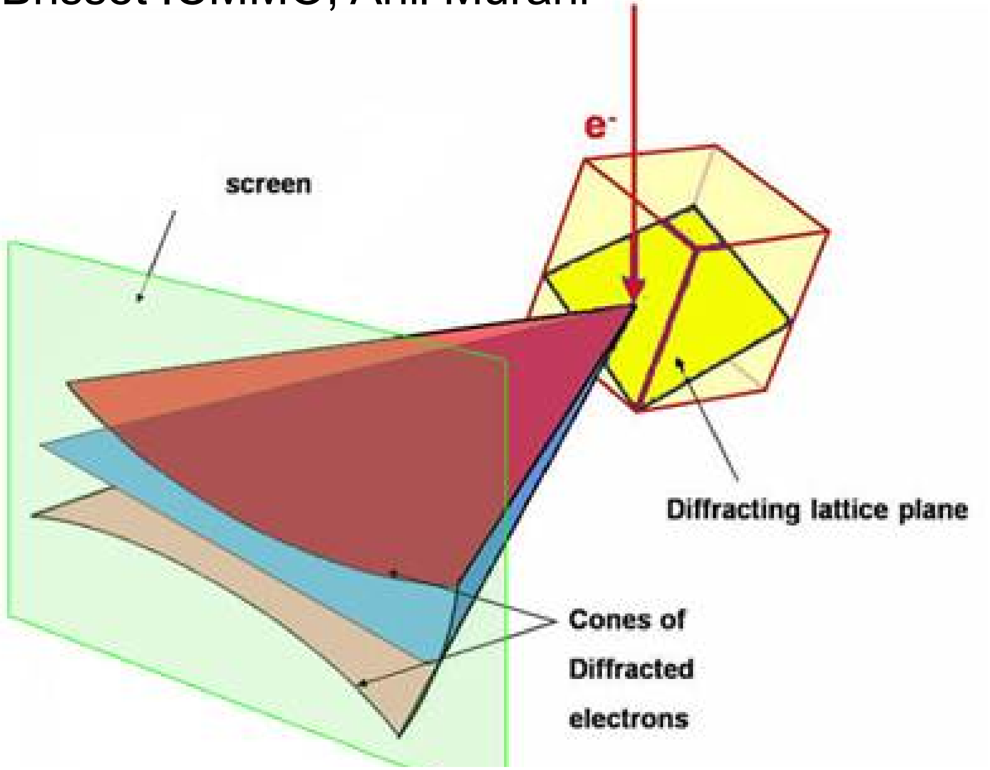


A. Kasumov 2015

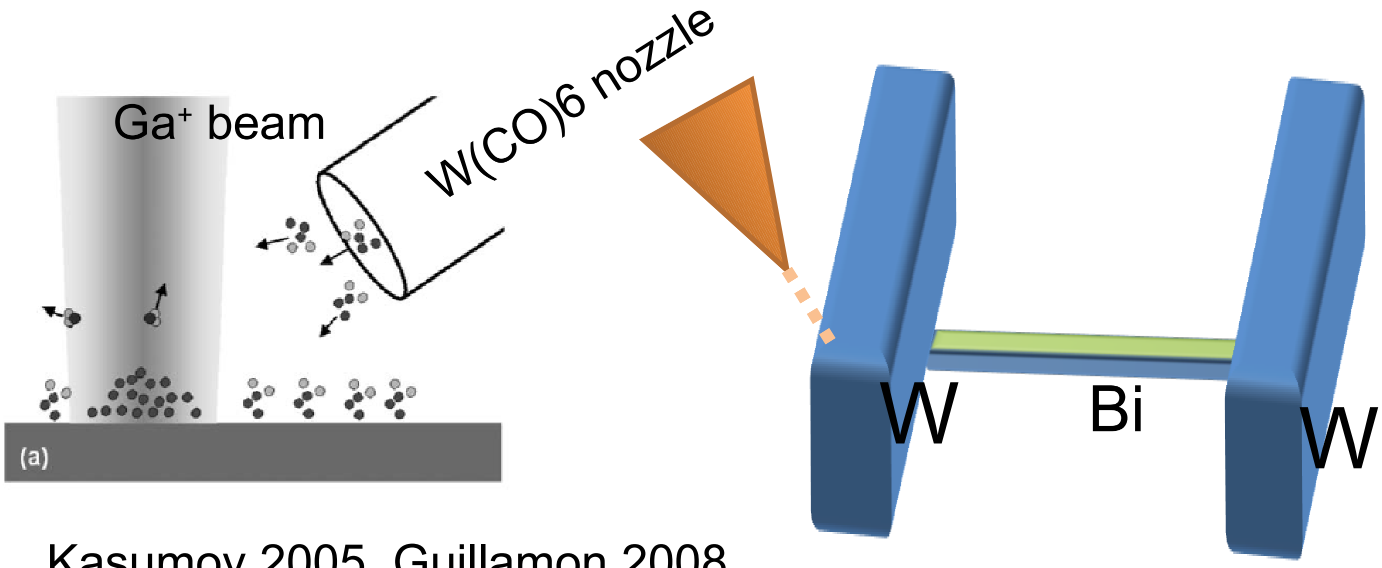
Orientation of Bi nanowire facets
Can be characterised
By backscattered e diffraction

(F. Brisset ICMMO, Anil Murani



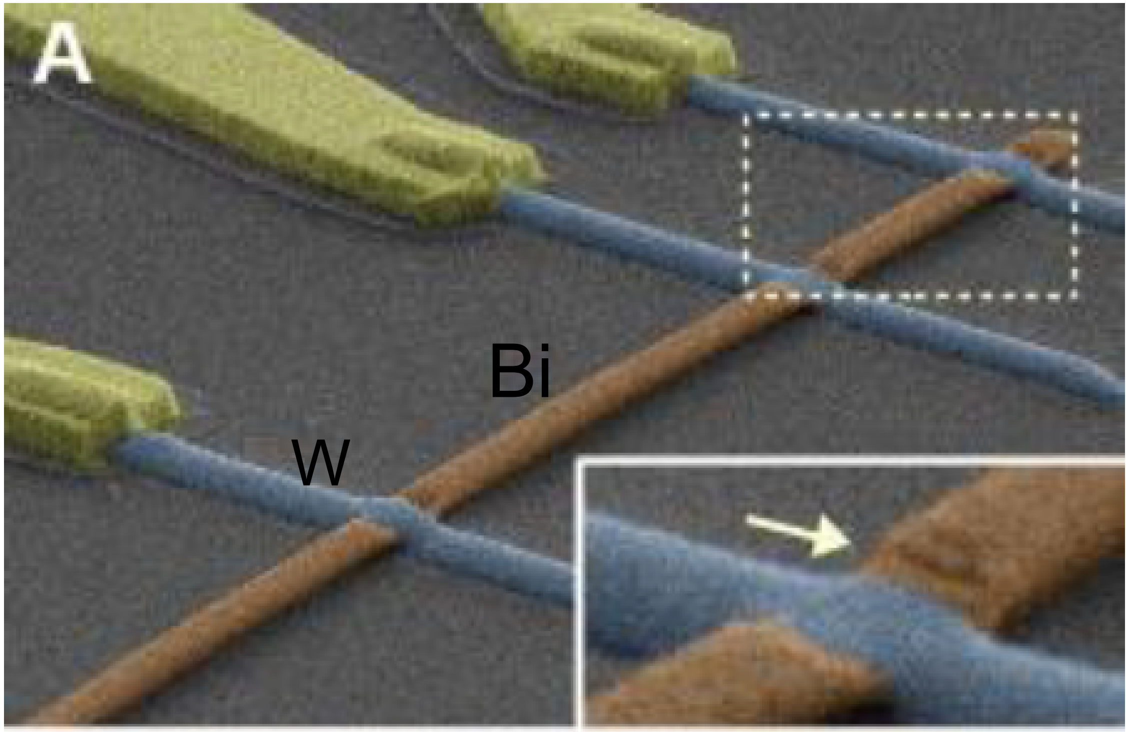


Superconducting contacts by focused ion beam-assisted deposition



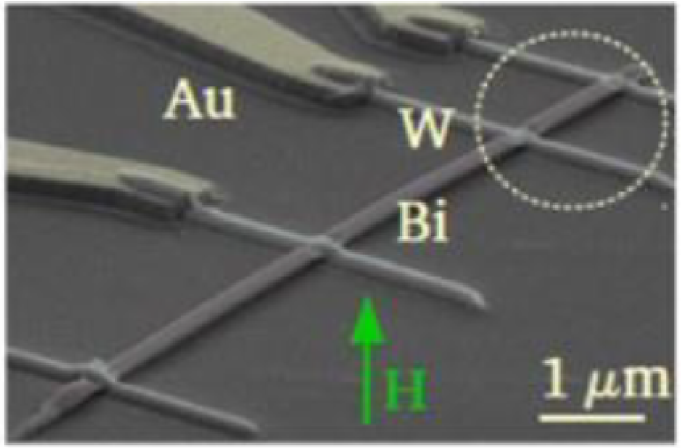
C and Ga-doped amorphous W wire
~ 200 nm diameter
great superconducting properties:
T_c~4K, Δ~0.8 meV,
H_c~12 Tesla!

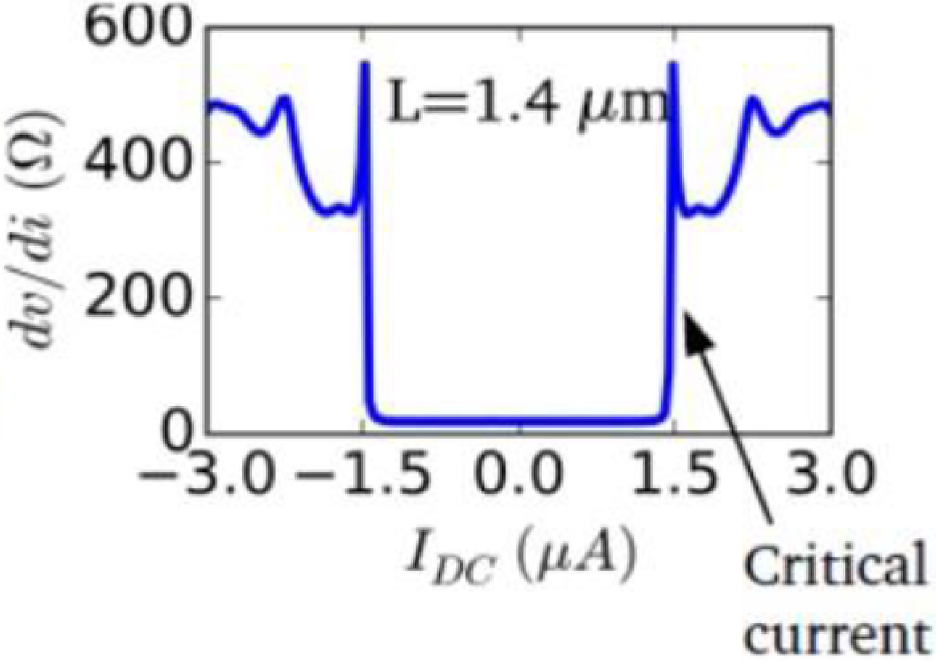
Kasumov 2005, Guillamon 2008



Oriented Bi nanowire
with in plane 111 surface
Rhombohedric shape

Supercurrent in W/Bi/W junctions





10 samples :

N resistance between 0.3 and 10kΩ

Ic between 0.1 and 2μA

Max $I_C \sim 1\text{-}2\ \mu A$

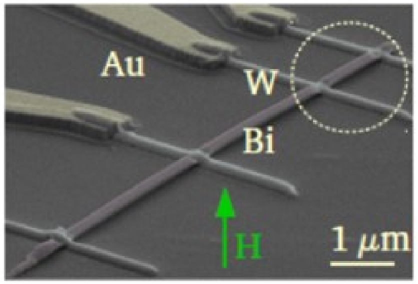
High critical current at zero field , much higher than for Ag nanowires

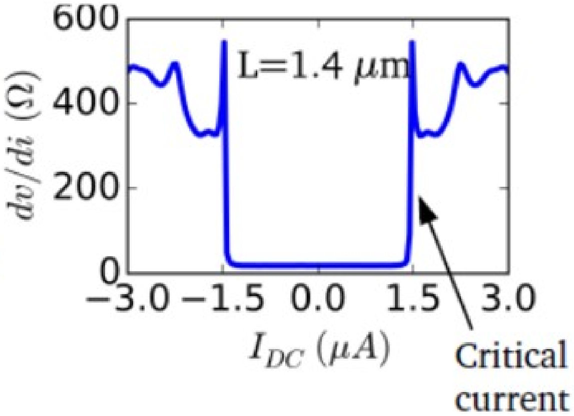
Not simply correlated to normal state resistance

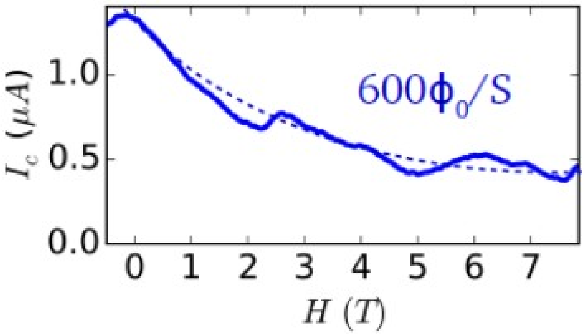
Nearly perfect Andrev reflection in spite of interface barriers ?

Supercurrent up to very high magnetic field !

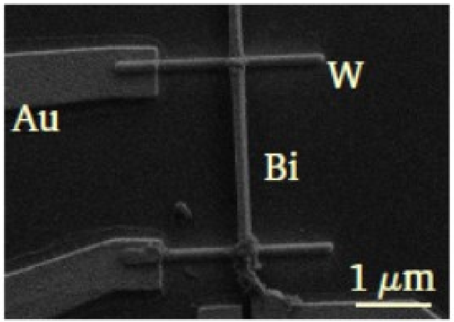
Sample
« JU »

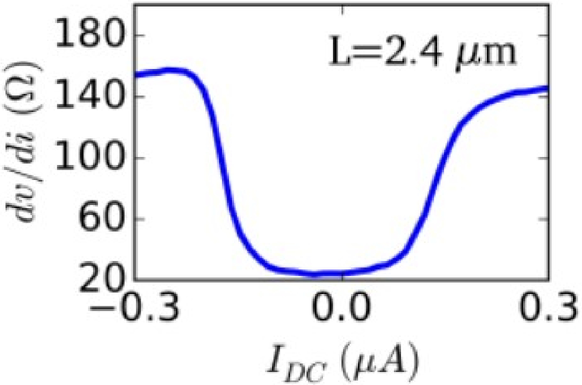


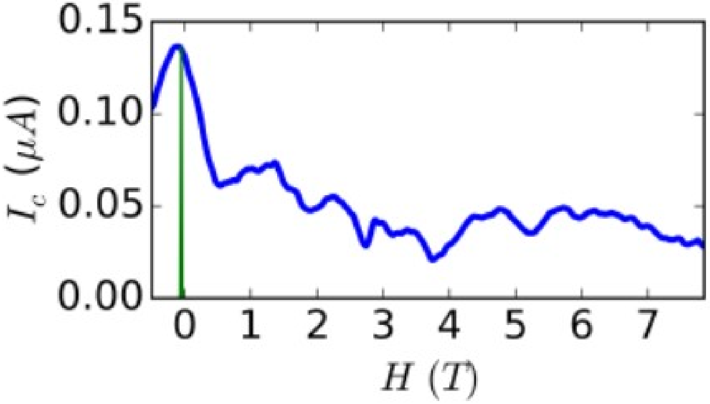




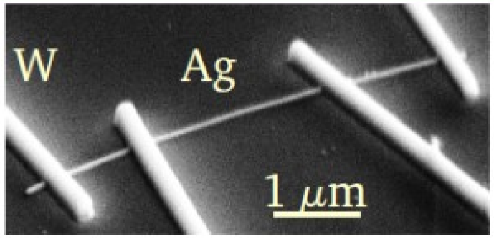
Sample
« WH »

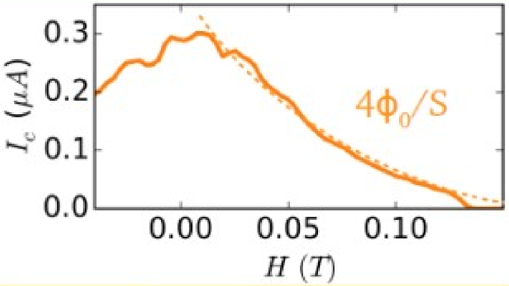






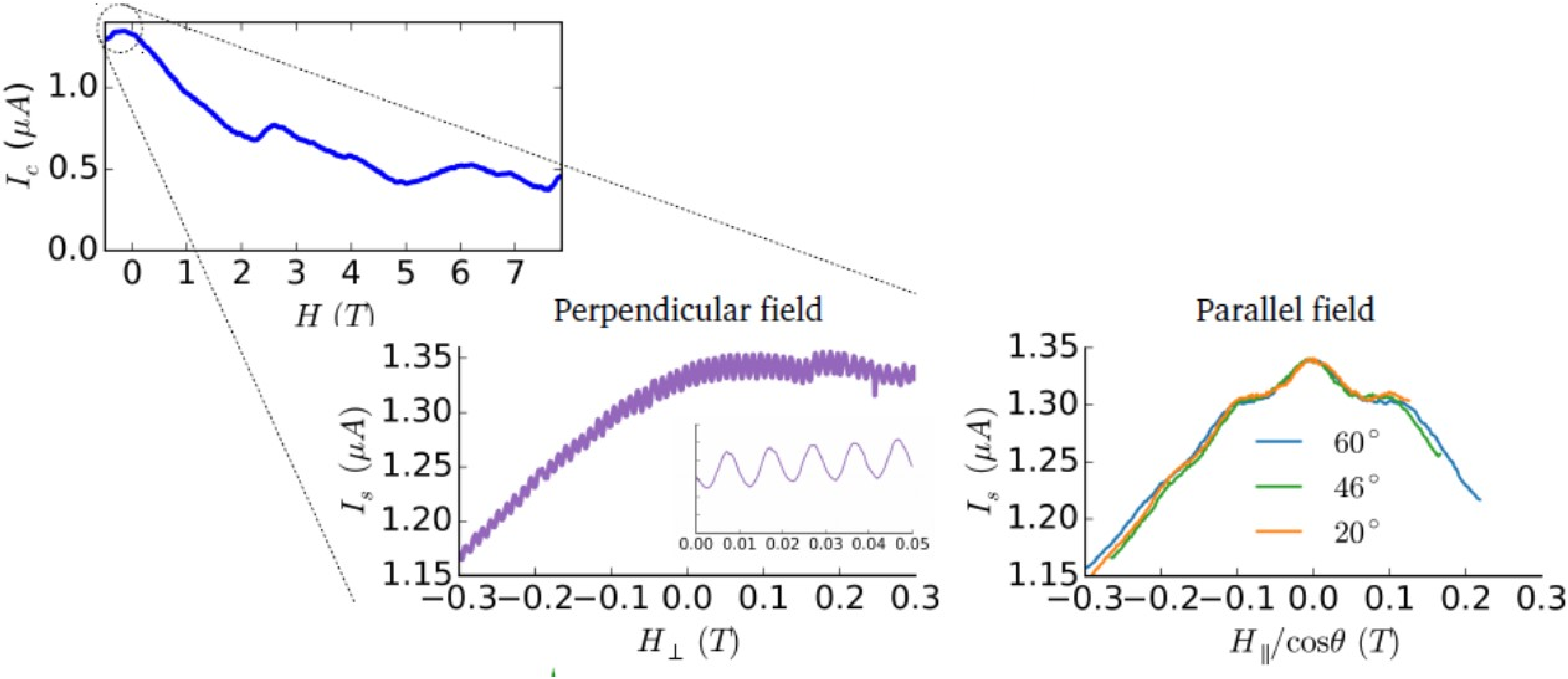
Référence junction
with Ag nanowire





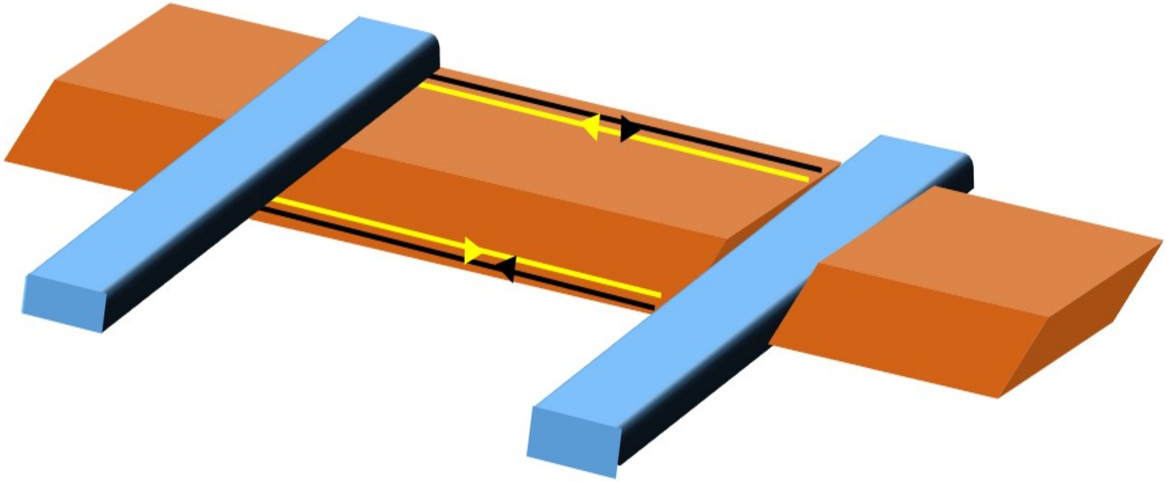
Field dependence implies: very few confined paths

Small period field oscillations of the switching current



Oscillations depend on the orientation of the magnetic field

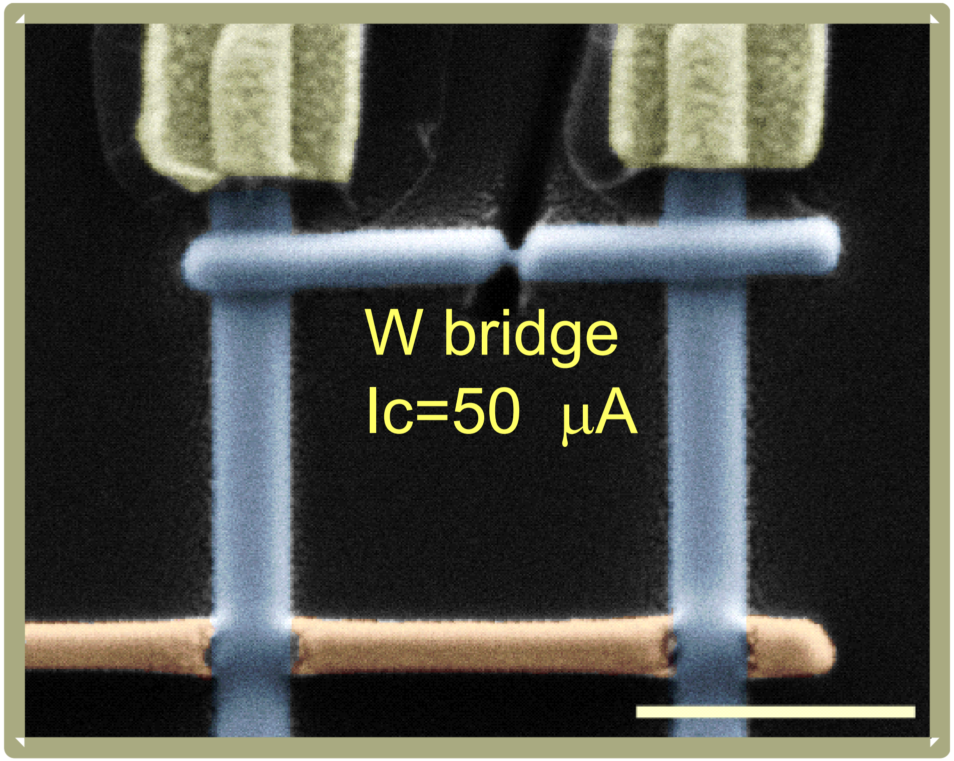
SQUID-like I_c oscillations, Very few ballistic narrow 1D channels



Period consistent with facet size

- Signature of 1D edge states on (111) facet similar to observations in SC top. Insulators HgTe /HgCd Te, InAs/GaSb
- Decay scale gives extension of edge state (nm!)

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



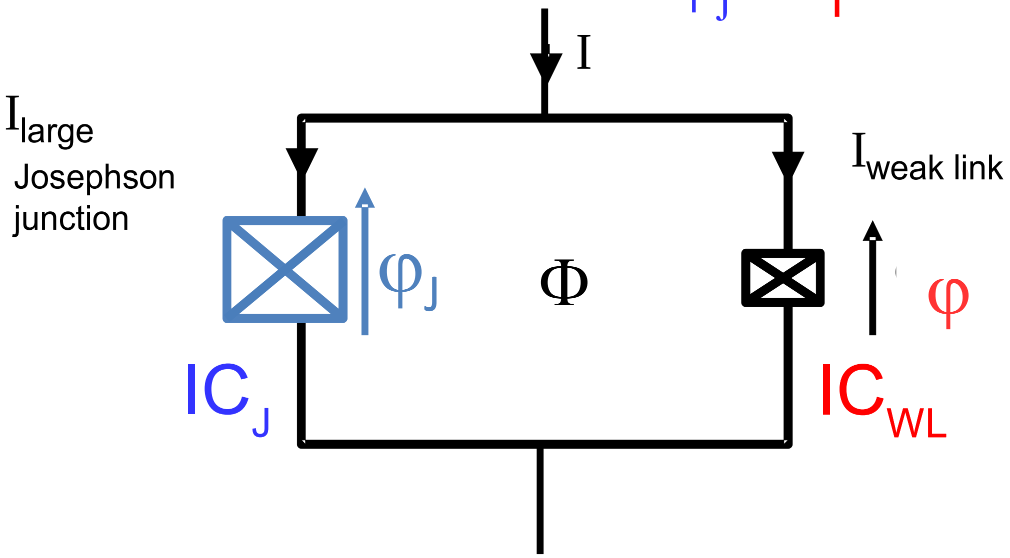
Assymetric SQUID

Bi nanowire Ic=1 μA

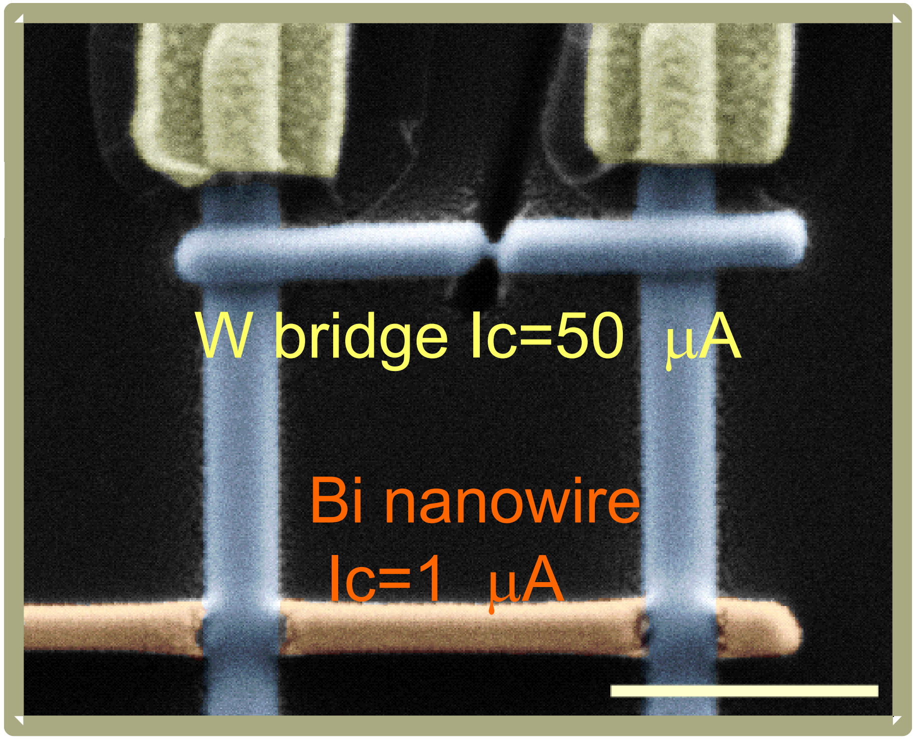
Current phase relation as a probe of the ballistic nature of transport

Della Rocca et al 2007

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



$$IC_{WL} << IC_J$$

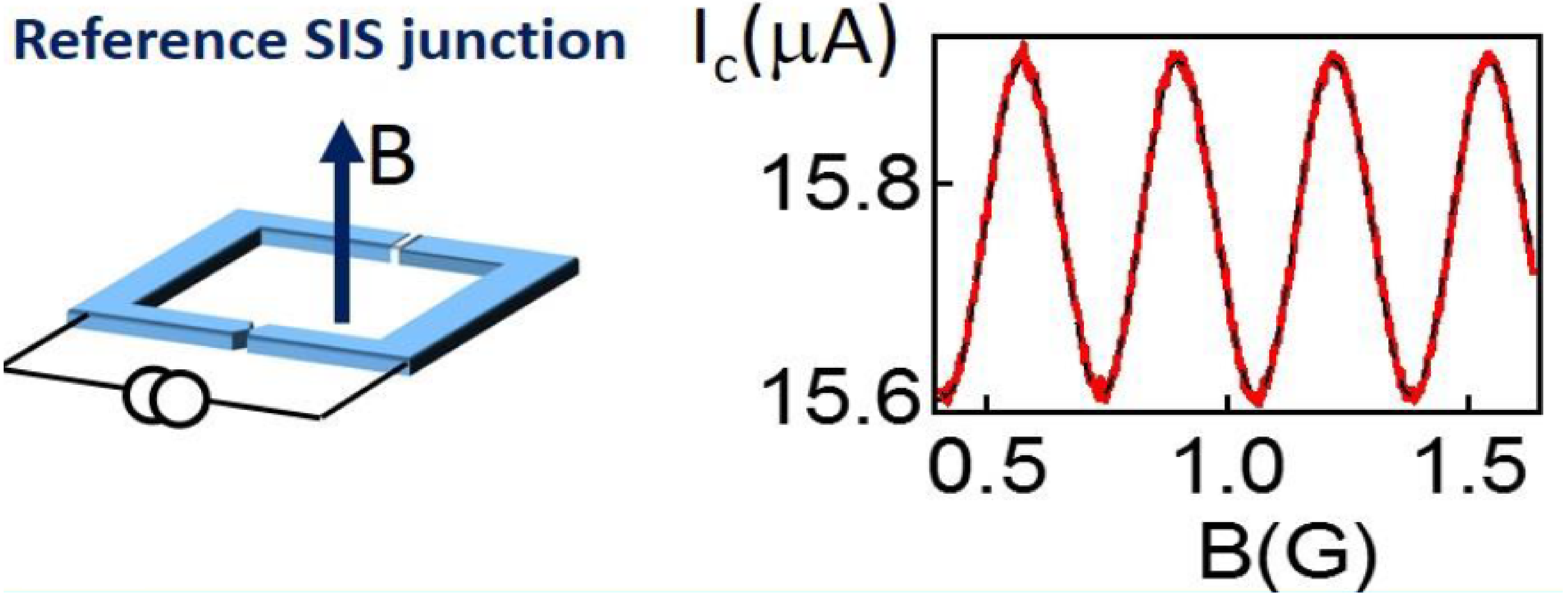


$$I_c = IC_J + IC_{WL}\, f\,(\pi/2 + \varphi)$$

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

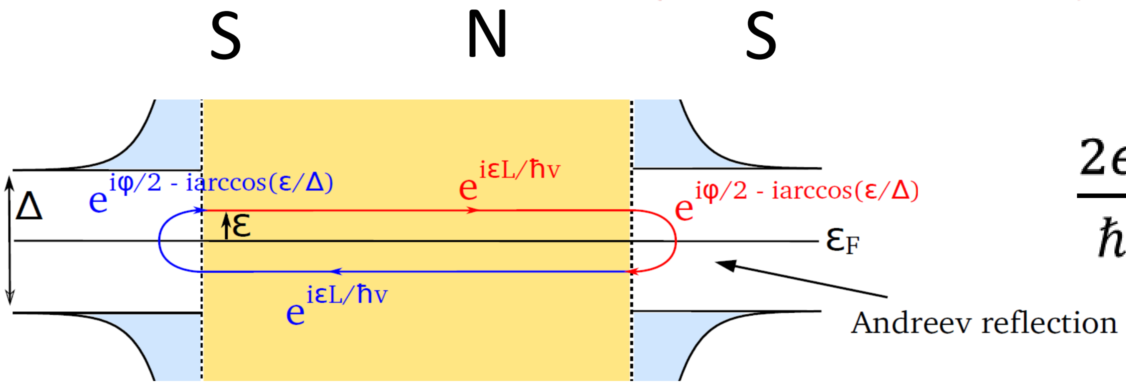
Independently of the large JJ

SIS tunnel junction



$I_J = \sin\phi$

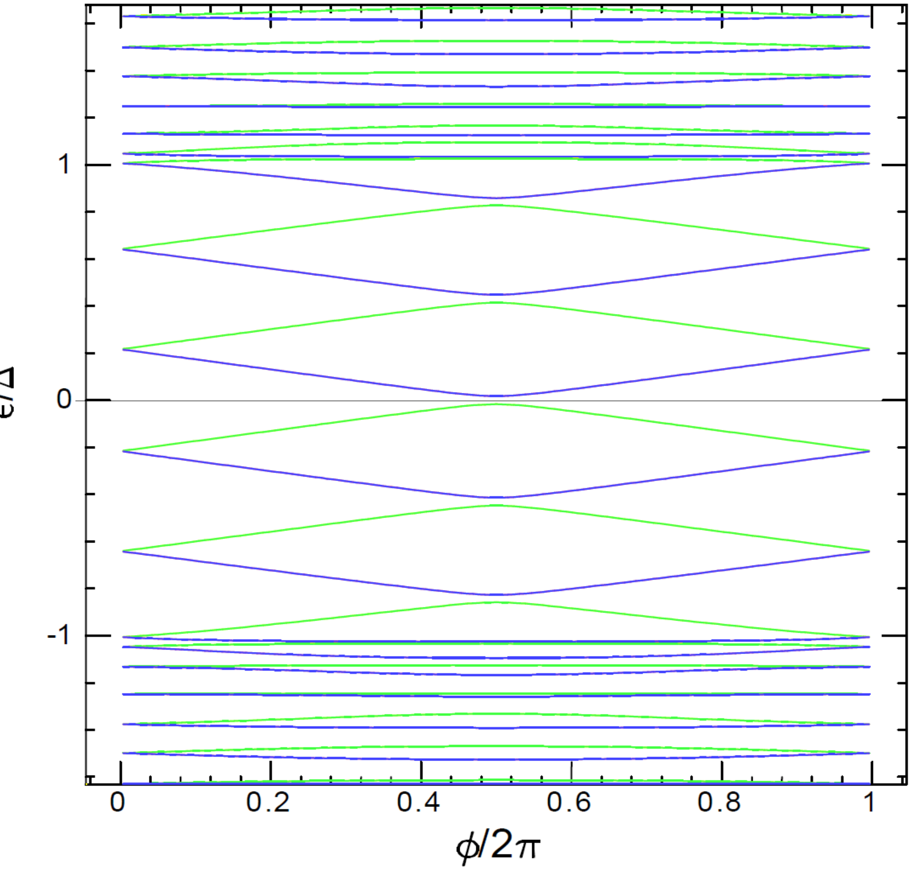
Andreev spectrum and supercurrent in long ballistic SNS junction: L>> $\xi_s = \frac{hV_F}{\Delta}$

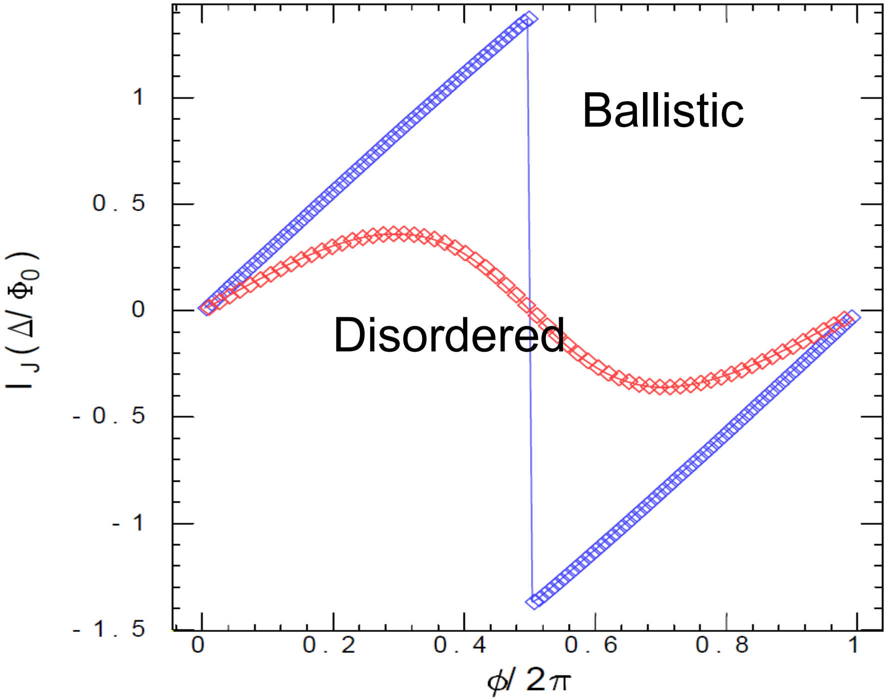


$$\frac{2\epsilon L_N}{\hbar v_F} - 2\,arccos\frac{\epsilon}{\Delta_0} \pm \Delta\phi = 2\pi m$$

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

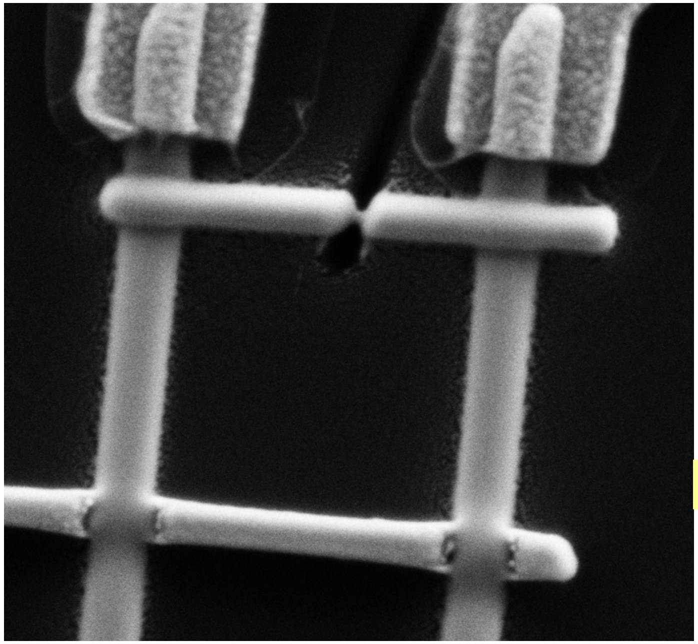
Level crossing at π and ε=0 lifted with disorder

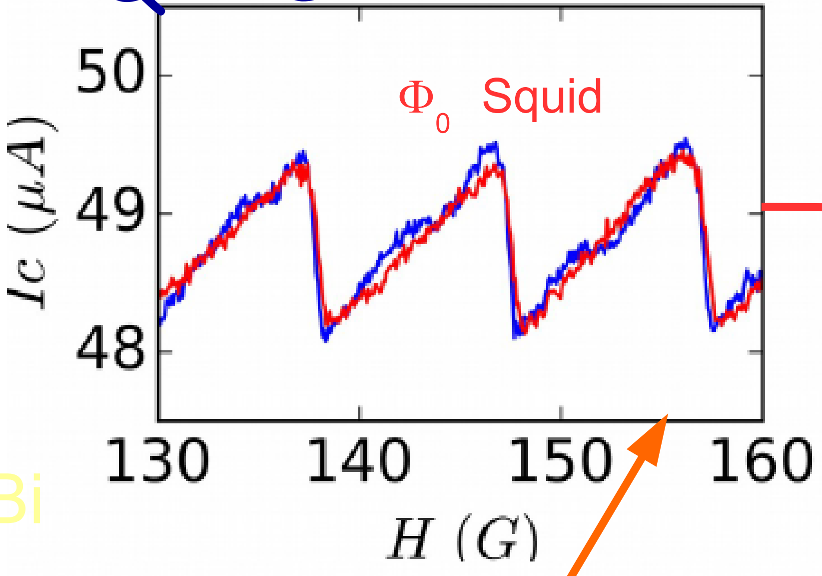




Sawtooth I(φ) characteristic of ballistic junctions rounded with disorder

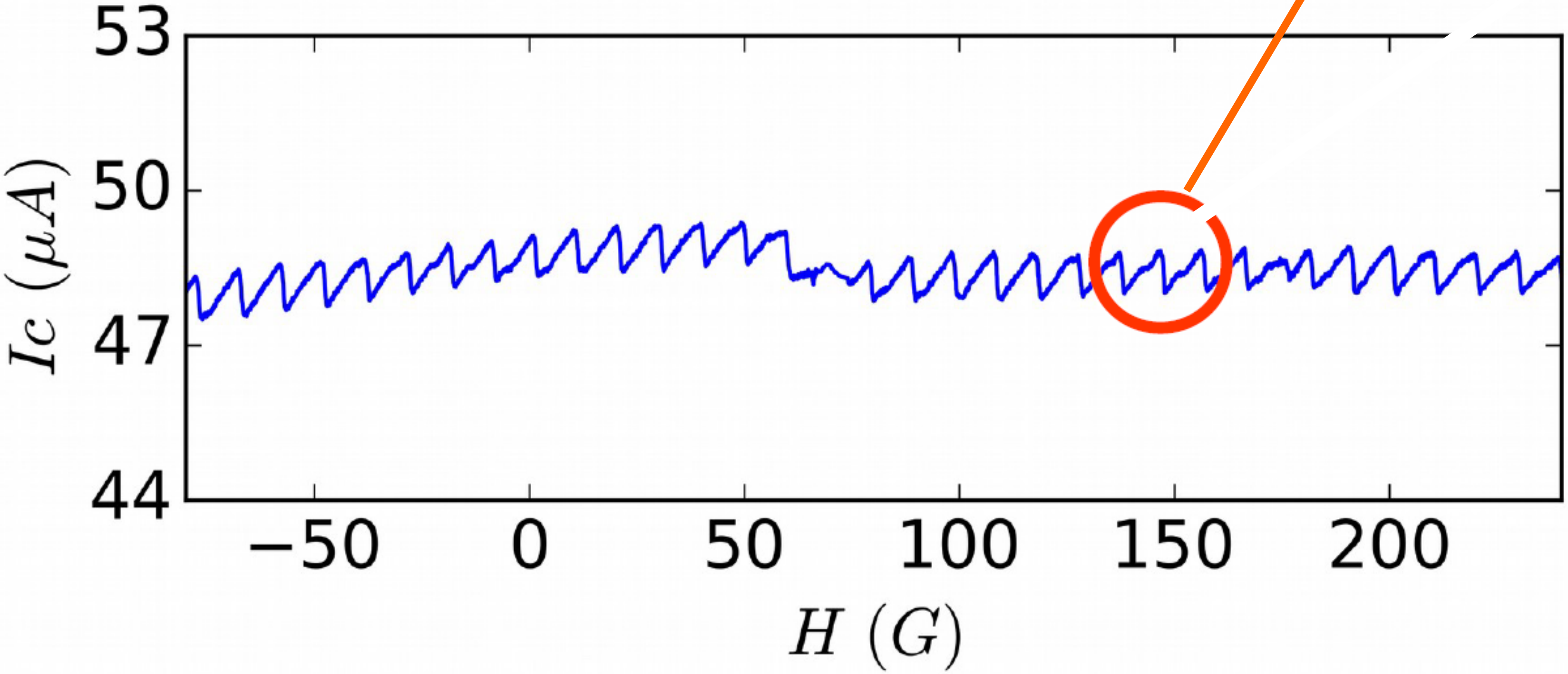
Bi nanowire based SQUID





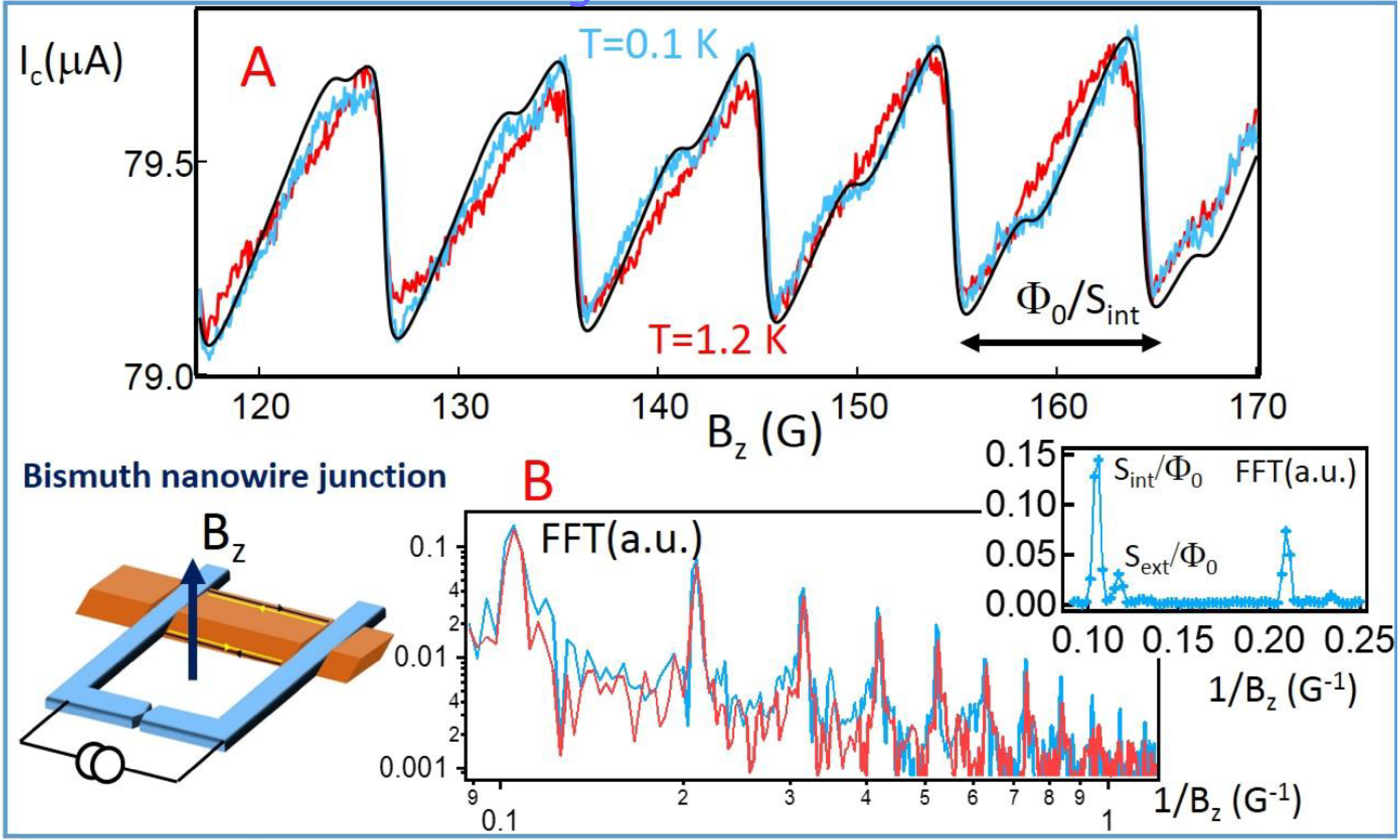
1 K
100 mK

Sawtooth shaped

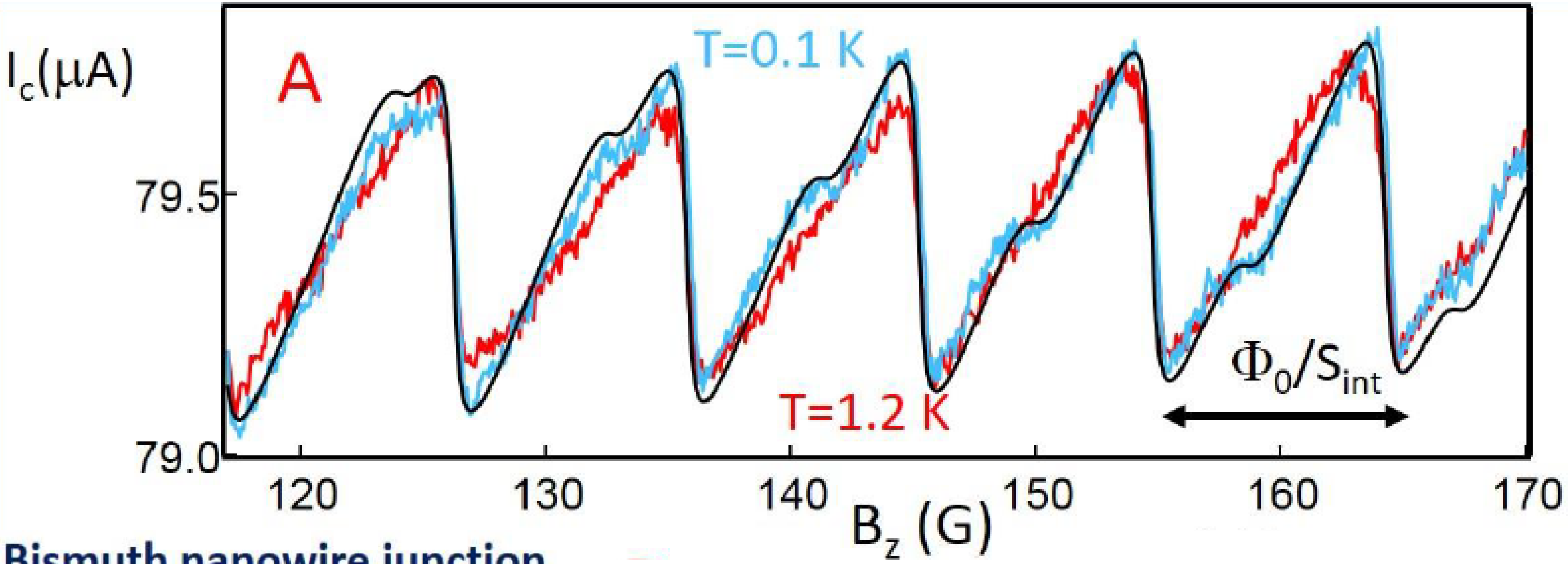


Current phase relation of a long ballistic SNS junction

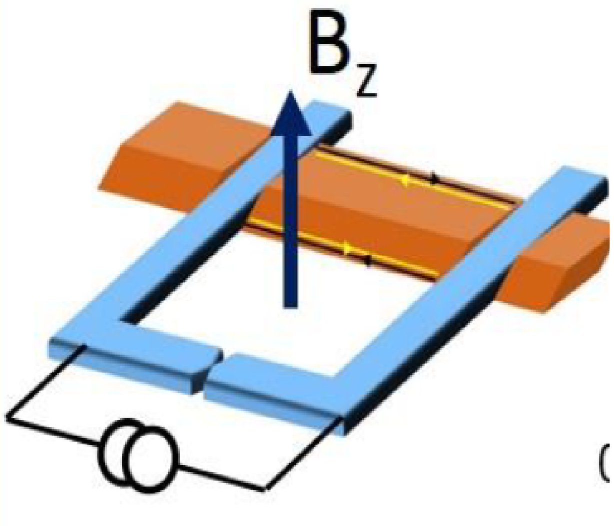
Beating between 2 saw tooth



Beating between 2 saw tooth

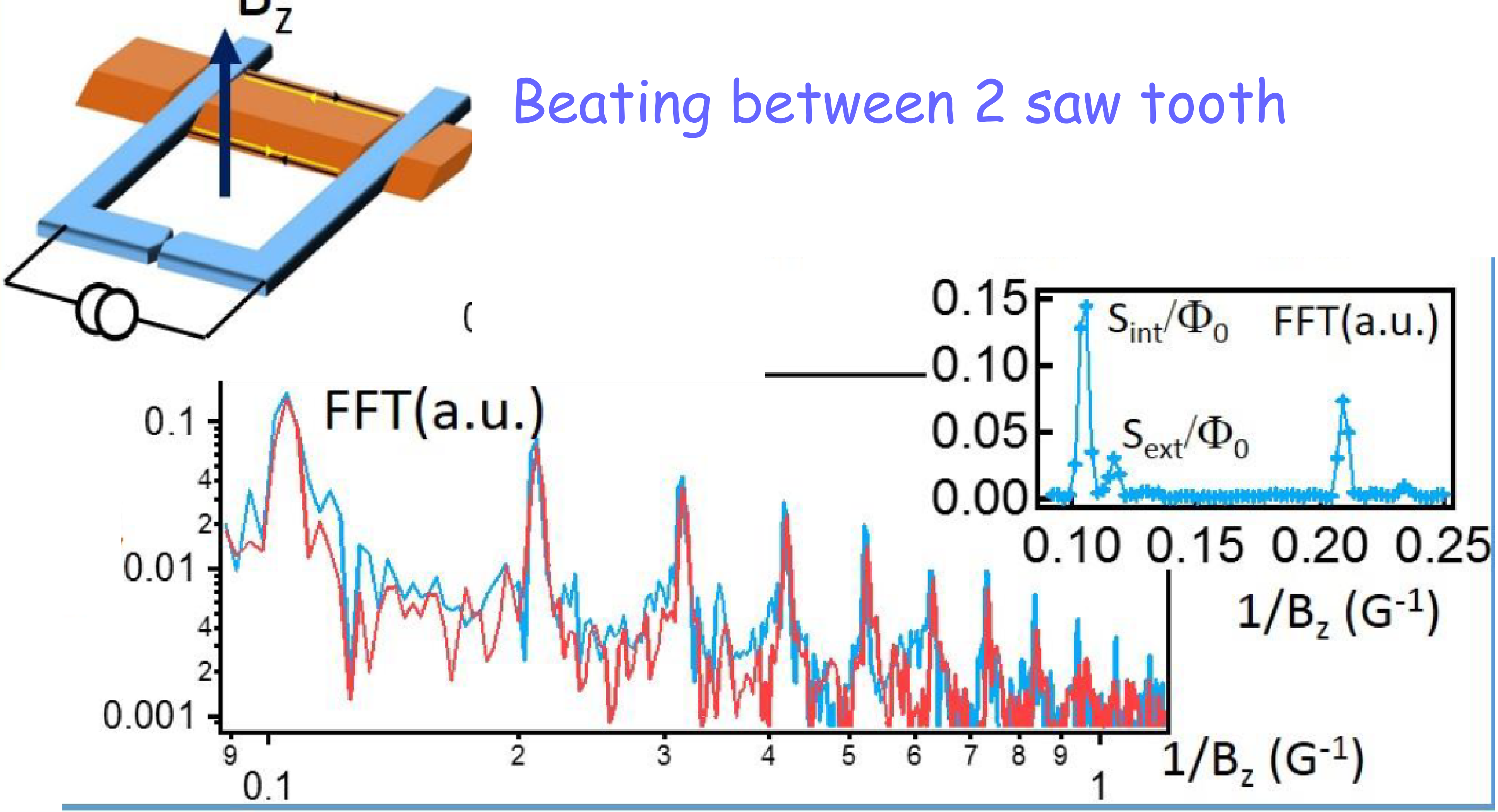


Bismuth nanowire junction



Long period = Φ_0 / area of the wire

Beating between 2 saw tooth



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

Inner edge: channels with t≈0.9

Outer edge: channels with t≈0.7

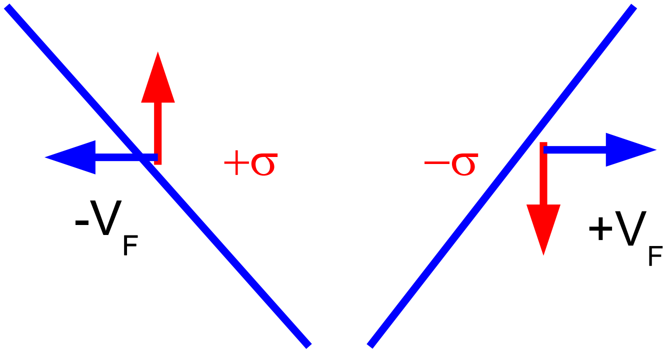
Amplitude 4 ev_F/L corresponds to ~4 conduction channels

3 orbitals /Bi atom

Why is the contribution of edge states dominant ?

N state

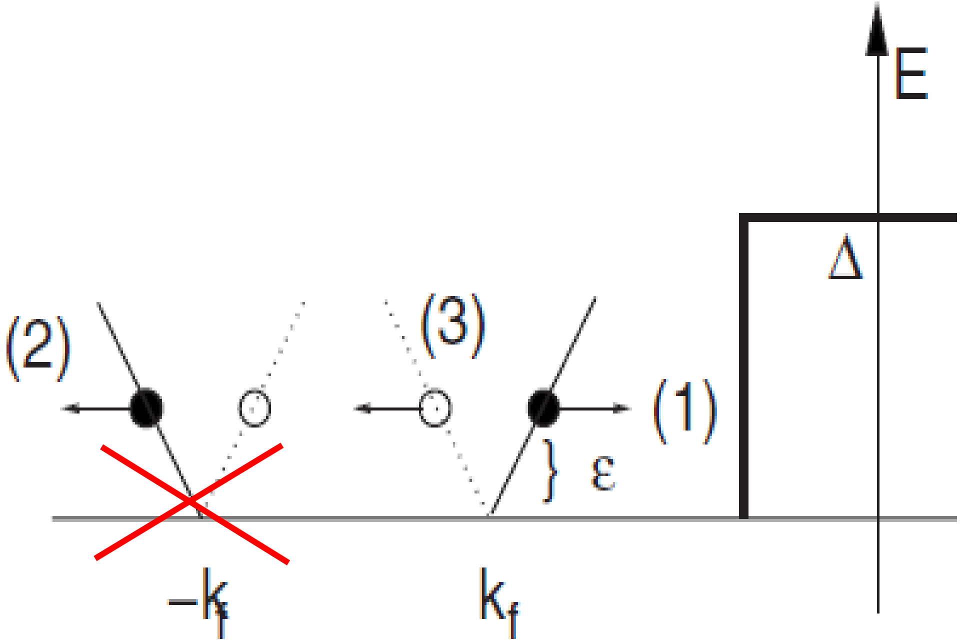
Backward scattering only possible with spin flip



NS interface

Enhanced Andreev reflection

For topological states



Backward scattering (2) vorbidden

Perfect Andreev reflection (3) favoured
Even for imperfect transmission of NS interface

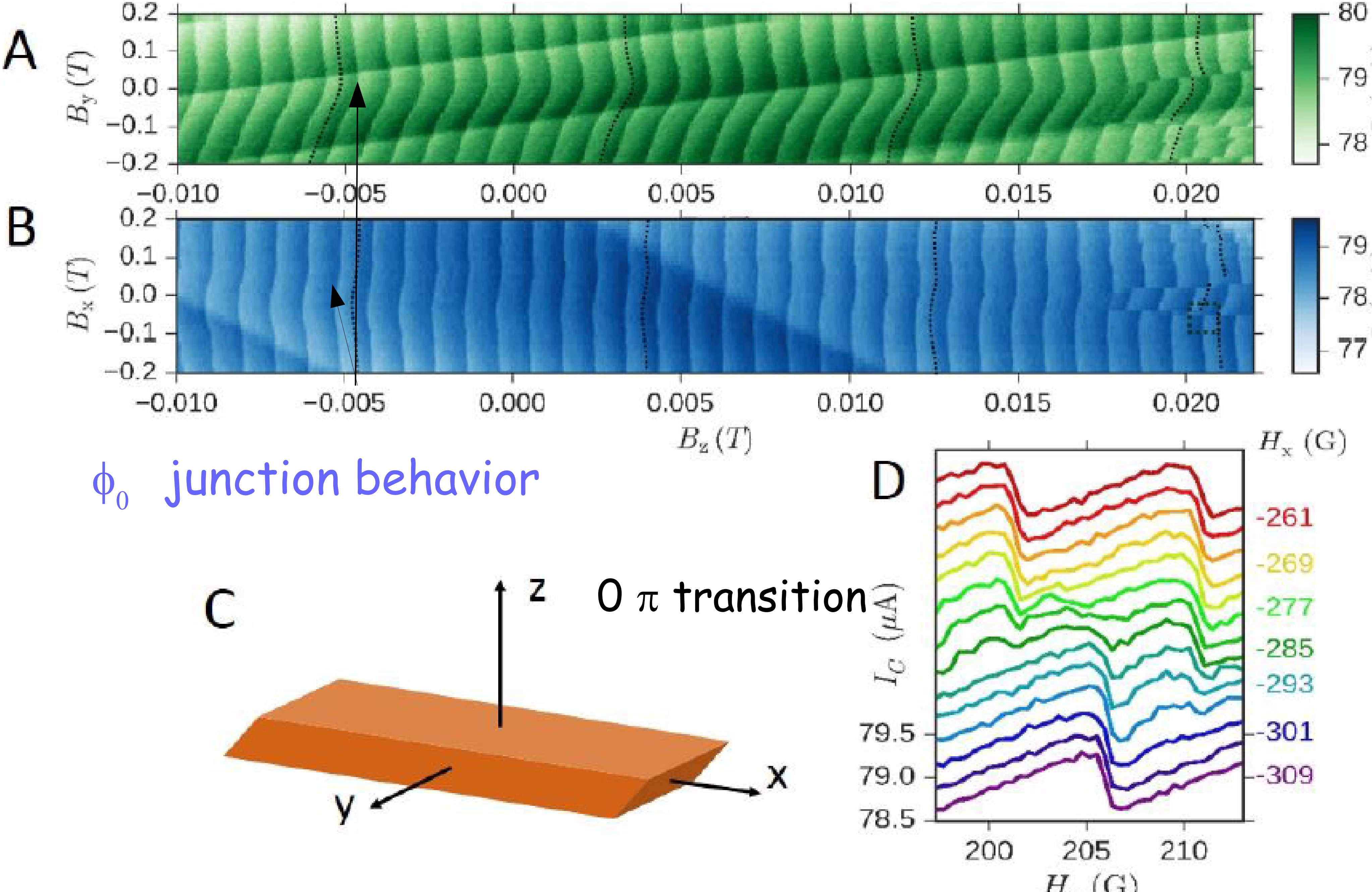
1 ballistic channel $I_c = ev_F/L$

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

Adroguer et al.

Surface states $l_e/L \sim 0.2$

Effect of in plane magnetic field (Zeeman effect)

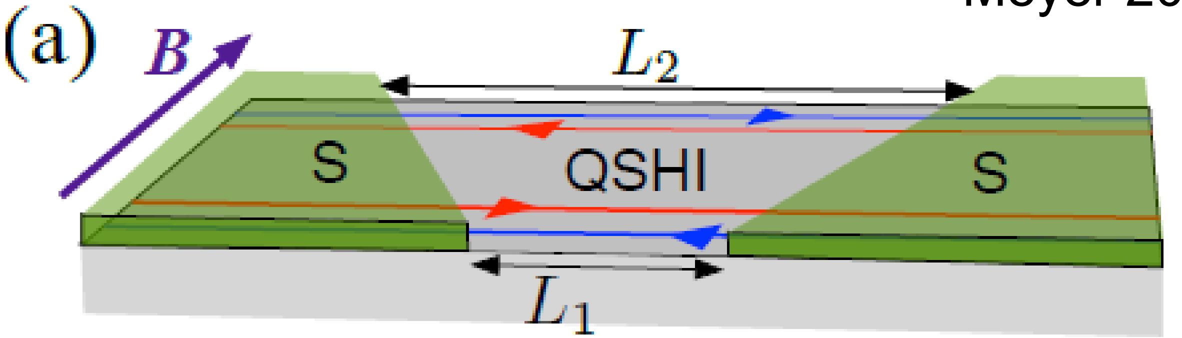


ϕ_0 junction behavior

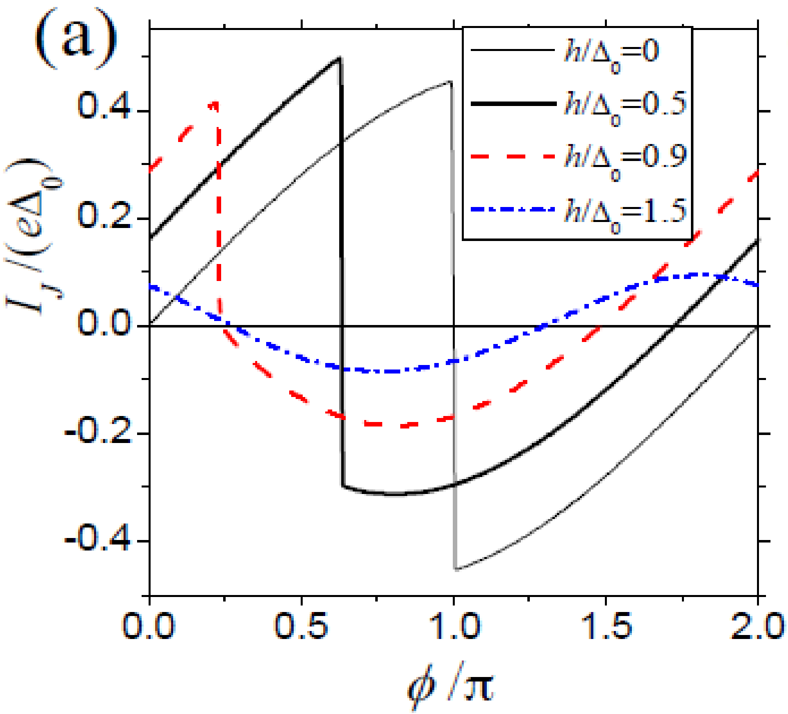
0 π transition

Topological Josephson ϕ_0 junction

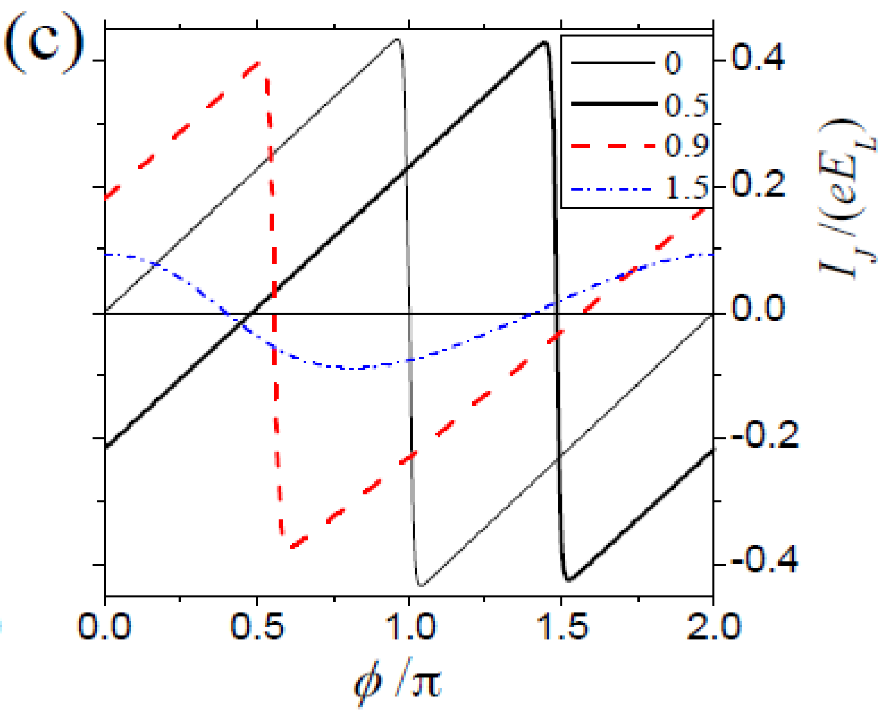
Dolcini,Houzet,
Meyer 2016



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



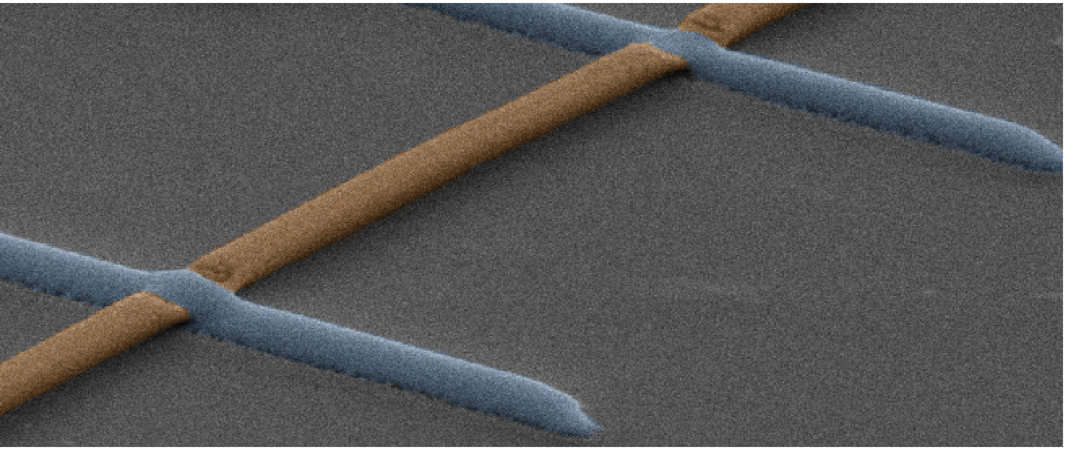
$L/\xi = 10$ (long junction)



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

Bismuth nanowires with 111 facets

Josephson supercurrent



Carried by a small number of ballistic edge states

Murani et al, Arxiv 1609.04848

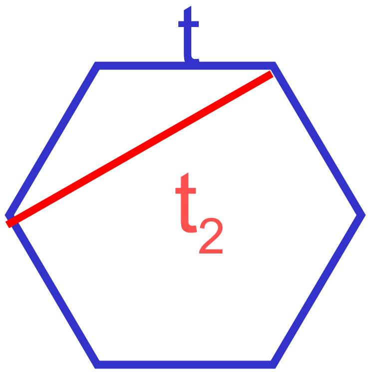
Revealed by SQUID interferometry

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

Topological nature of the edges not proven yet
AC experiments in progress

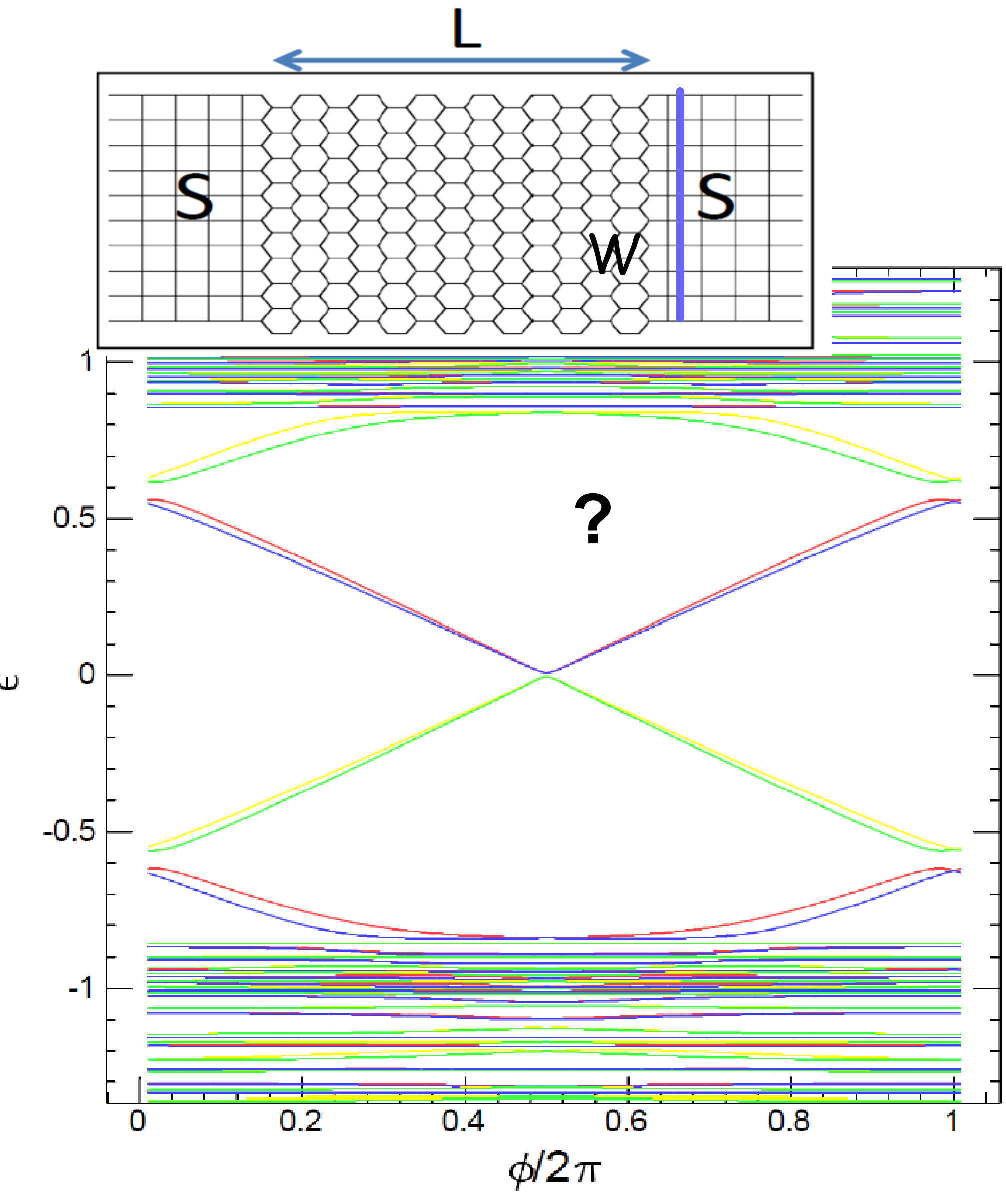
Andreev spectrum of a 2D topological insulator

$$\mathcal{H} = \sum_{\langle ij\rangle\alpha} t c^{\dagger}_{i\alpha} c_{j\alpha} + \sum_{\langle\langle ij\rangle\rangle\alpha\beta} i t_2 \nu_{ij} s^{z}_{\alpha\beta} c^{\dagger}_{i\alpha} c_{j\beta}.$$

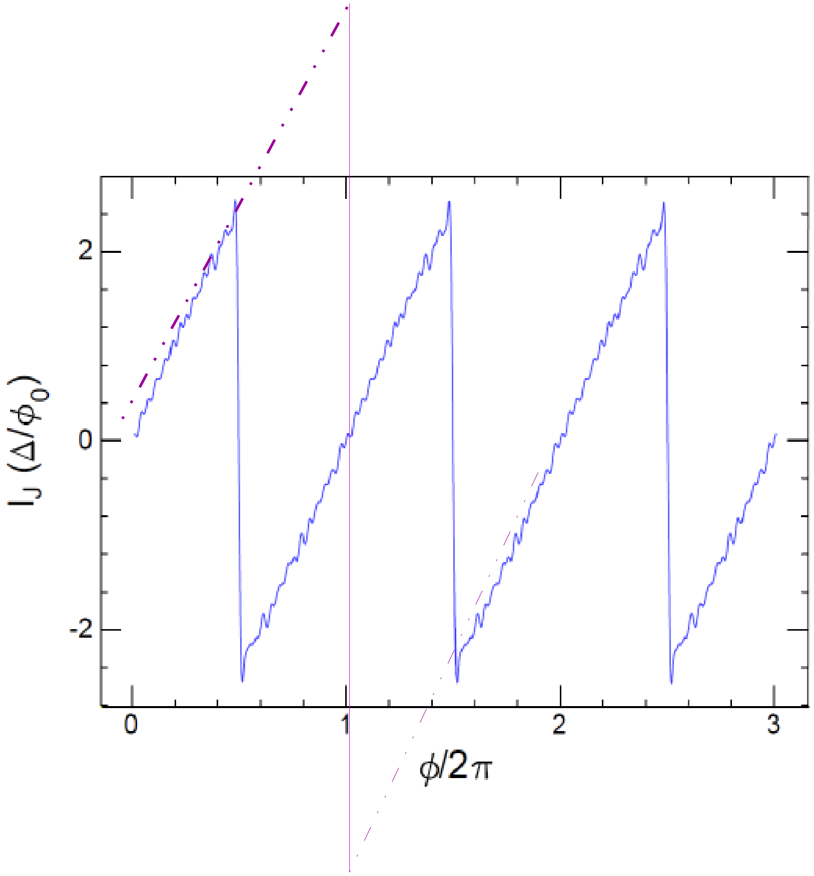


Kane and Mele model

$$\nu_{ij} = -\nu_{ji} = \pm 1$$



2 edge states independent for W>>ξ_S



How to detect the protected crossing at pi ?

4π periodicity ? *Pikulin Beenakker 2013*

Investigating the topological nature of edge states

AC non adiabatic response

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