Quantum interferences in Josephson junctions with large spin orbit coupling

A. Murani, A. Kasumov, Chuan Li, Shamashis Sengupta, F. Fortuna, R. Deblock, M. Ferrier,, A. Chepelianskii ,S. Guéron and H. Bouchiat (Orsay, France)

K. Napolskii, D. Koshkodaev, G. Tsirlina, Y. Kasumov, I. Khodos (Moscow and Chernogolovka)

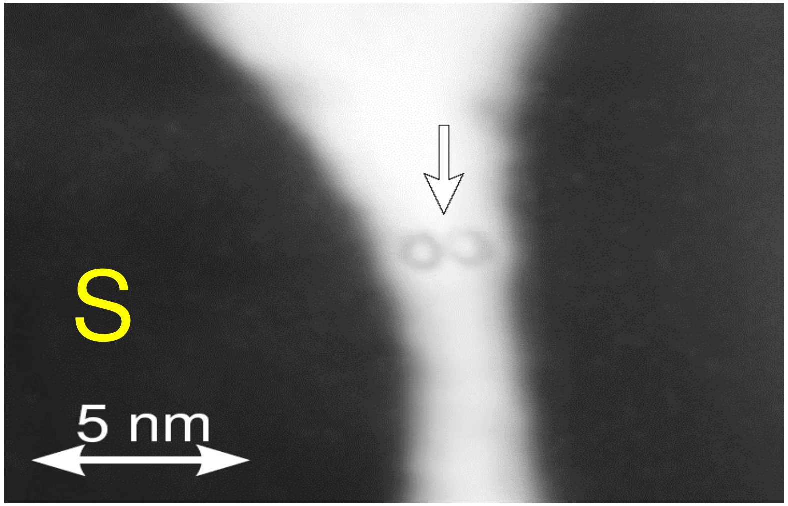
Proximity effect in material with high spin orbit coupling

Faculty of Materials Science

Faculty of Chemistry

Institute of microelectron
tech. and High purity ma

Guessing game… What's what?



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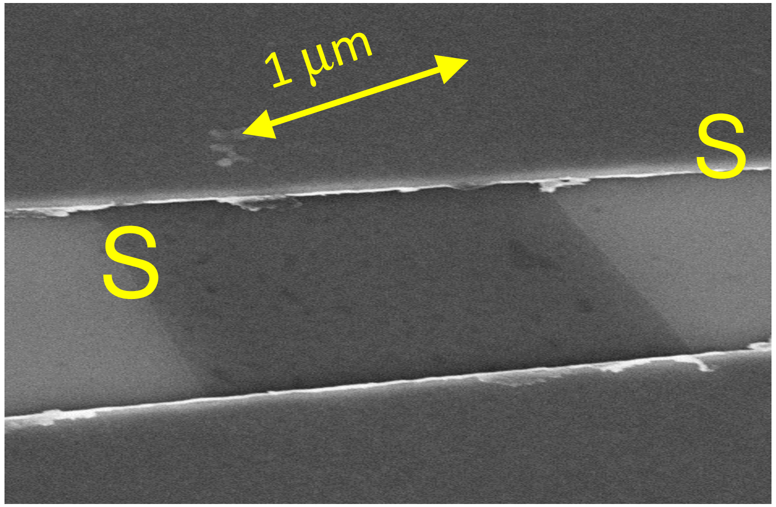

Physique mésoscopique LPS Orsay

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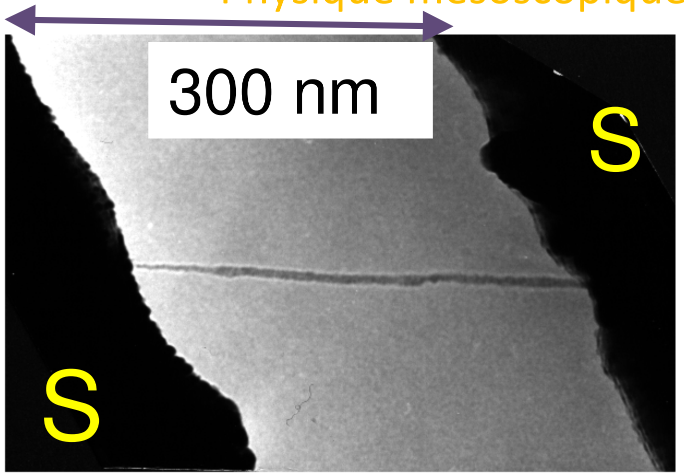
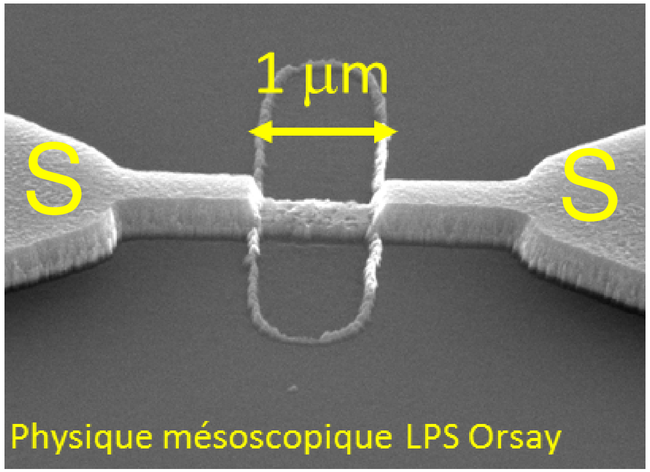




oximity effect reveals spin dynamics, intrinsic pairing, atomic orbitals, dephasing, interference, band stru

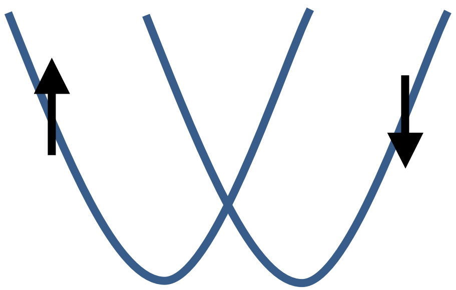
Spin orbit coupling

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

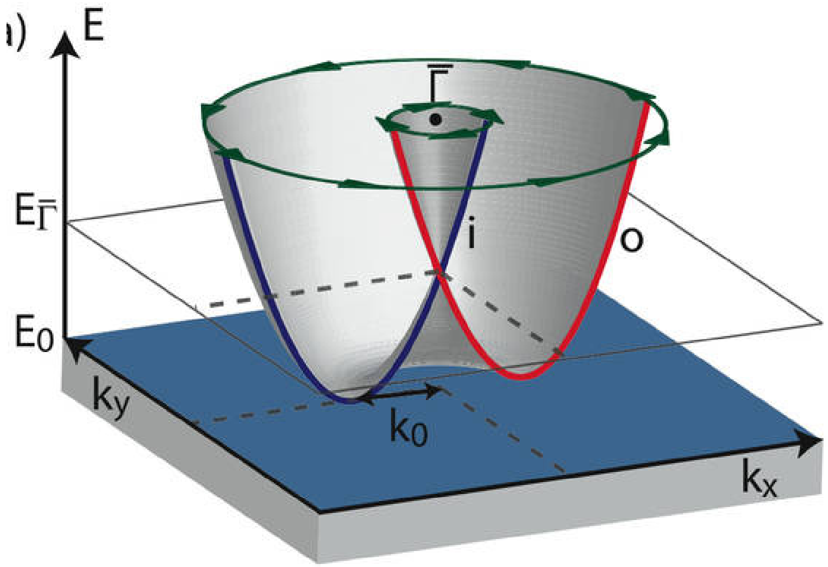
Spin orbit interactions couple spin and spatial degrees of freedo

$$H_{so} = \gamma_D(k_x\sigma_y + k_y\sigma_x) + \alpha_{BR}(k_x\sigma_y - k_y\sigma_x)$$

D_{2d} Dresselhaus | C_{4v} Bychkov-Rashba



Spin Split bands



Spin orbit coupling

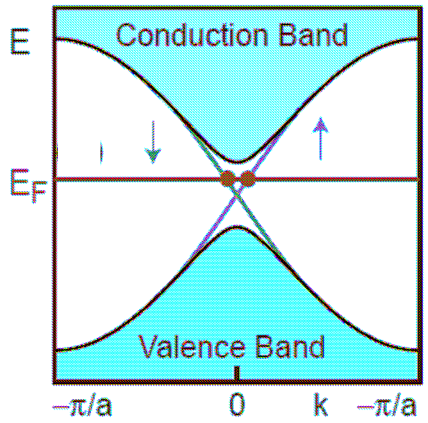
$$= \frac{\hbar}{4m^2c^2}\mathbf{s}\cdot(\nabla V \times \mathbf{p})$$ Spin orbit interactions couple spin and spatial degrees of freedo

$$H_{so} = \underbrace{\gamma_D(k_x\sigma_y + k_y\sigma_x)}_{D_{2d}\ \text{Dresselhaus}} + \underbrace{\alpha_{BR}(k_x\sigma_y - k_y\sigma_x)}_{C_{4v}\ \text{Bychkov-Rashba}}$$

ends on the Crystal symmetry:

ibility to create a topological insulator

2D:



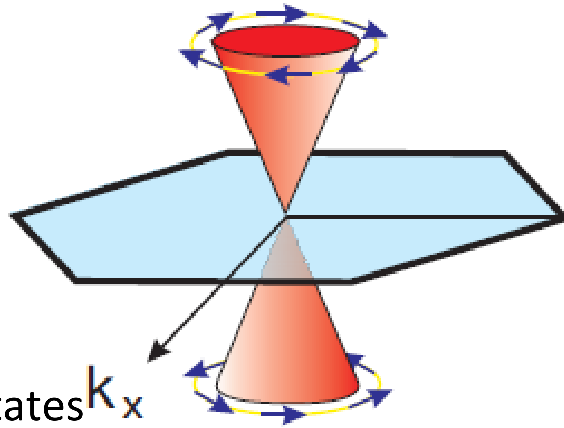
Formation of 1D

counter propagating

spin polarised edge states

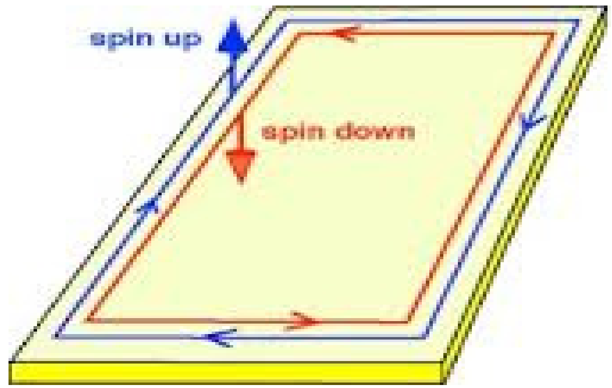
Protected from disorder

Topological Insulator



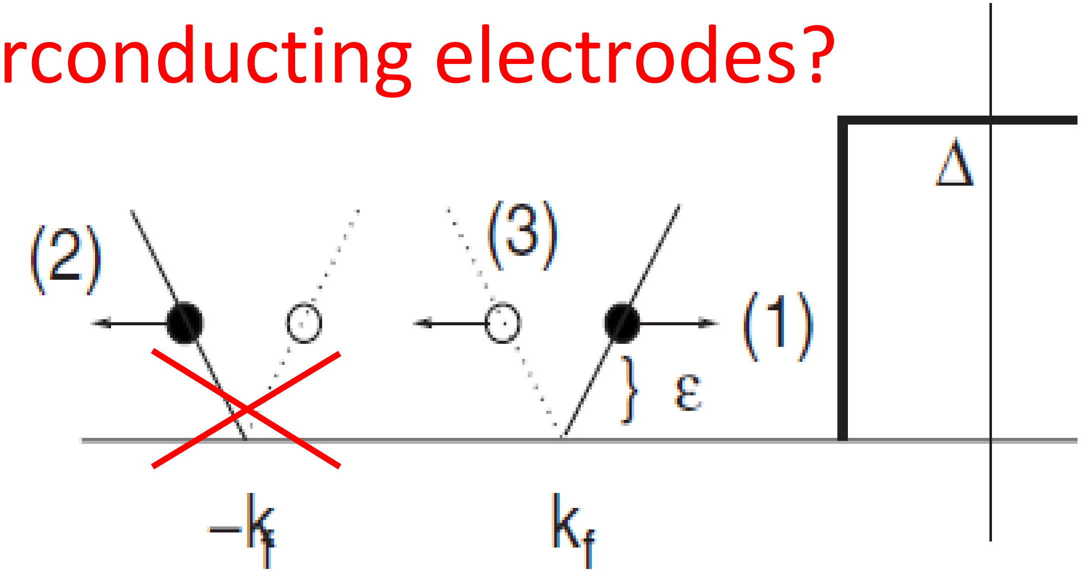
Hasan Kane RMP (2011)
2D conducting surface states

Bi_2Se_3

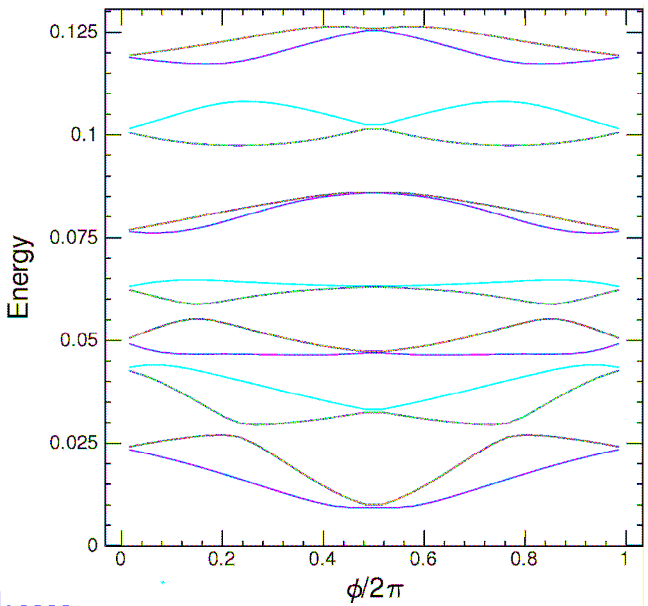


What happens with superconducting electrodes?

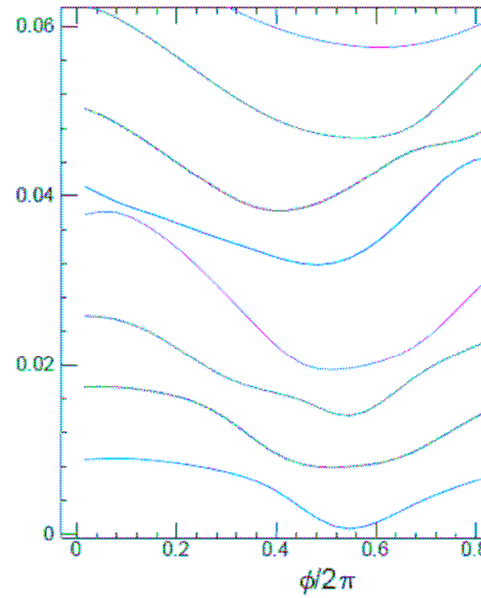
anced Andreev reflection



Backward scattering (2) vorbidden
Perfect Andreev reflection (3)



$E_{SO} = E_F /2$



$Ez = E_{SO}/2$

n split Andreev states
osephson junctions in Zeeman field

sibility of mixed singlet triplet correlation…

ge states: inhomogeneous current distribution

Bismuth nanowires

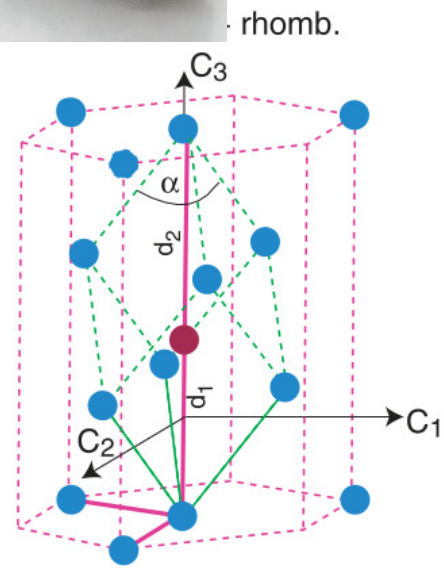
Bulk, surface, edge states

Josephson effect :

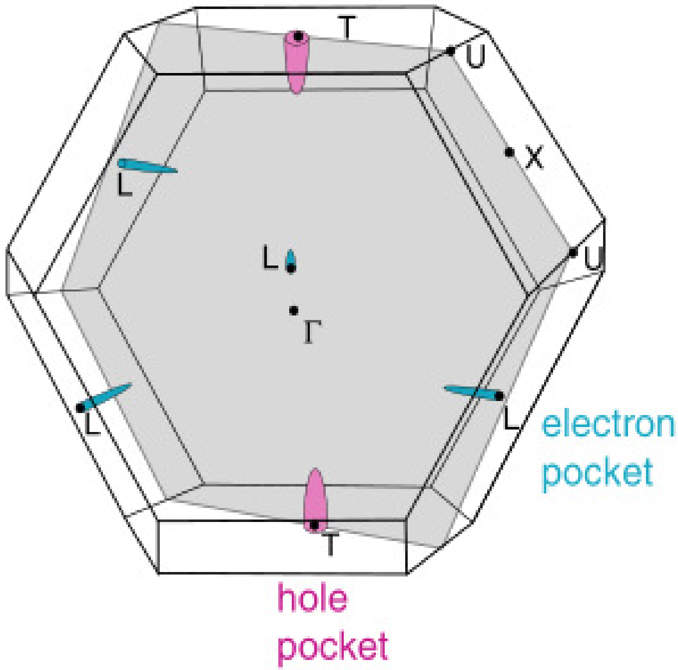
- High critical current: ballistic transport ?
- Field resistant induced superconductivity:
- Explanation via orbital and spin effects, and topological edge channels?
- Investigation of the Andreev spectrum

Bulk Bi

Hofmann 2006 review



Bulk Brillouin zone

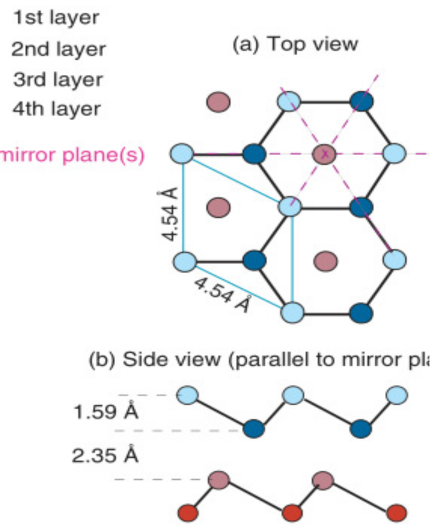


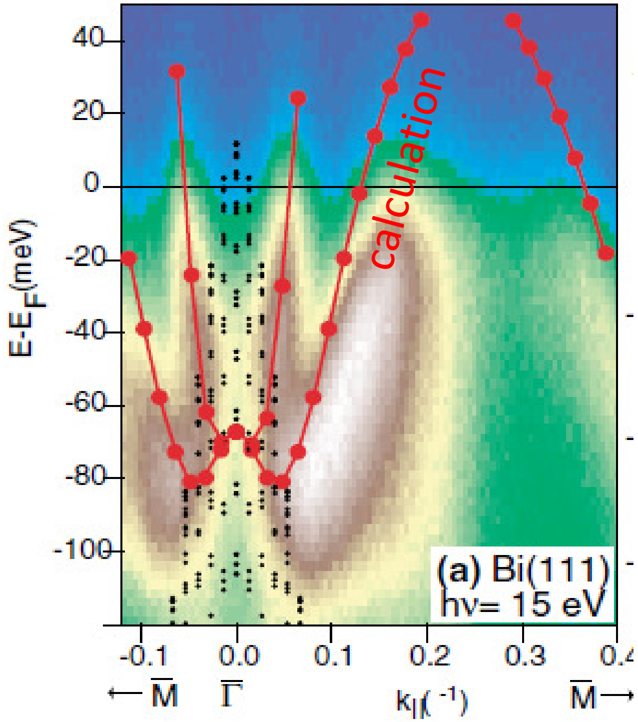
A semi-metal, with $n \approx 3x10^{17}$ cm^{-3} , $m^* \approx 0.03m_e$ and $\lambda_F \approx 50$ nm

Centrosymmetric: Bulk SO averages to 0

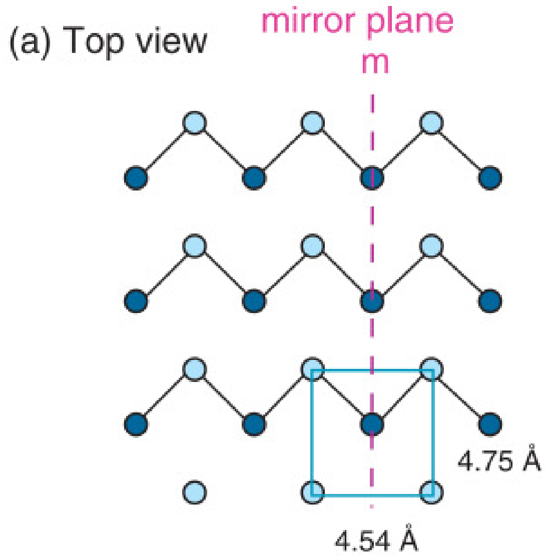
Spin split states at Bi surfaces

(111)

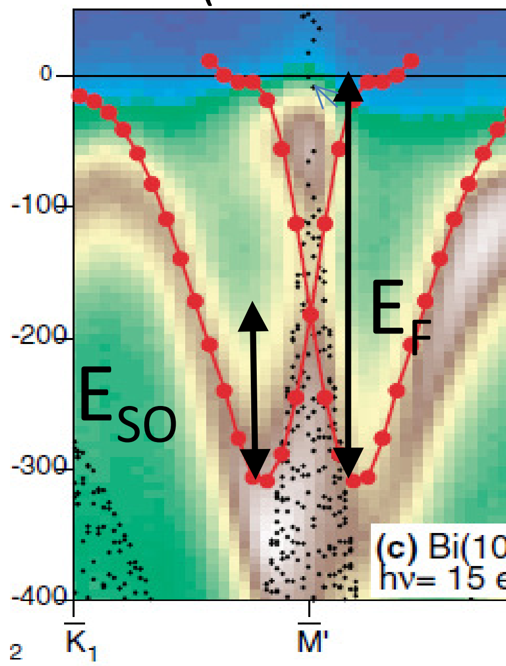




(100)



ARPES (Hoffman 2004



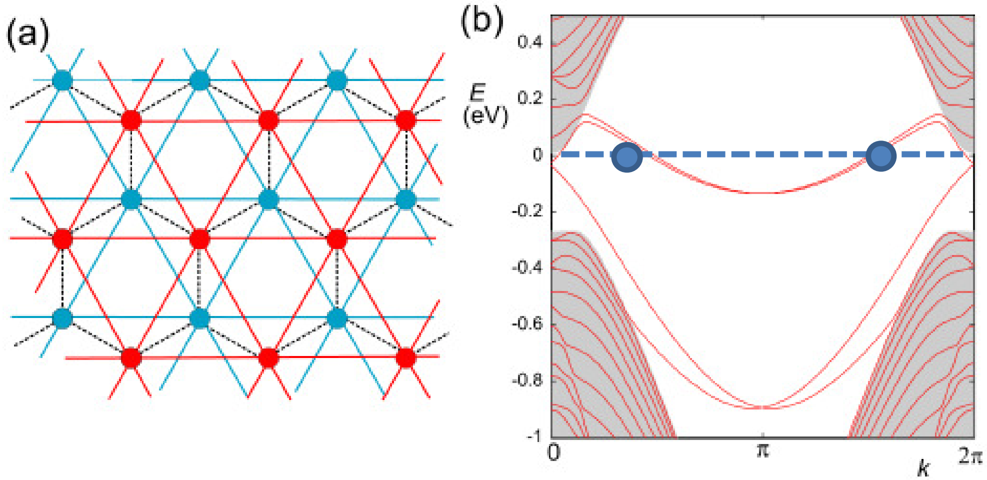
	Carrier density	λ_F	m^*
Bulk	3×10^{17} cm^{-3}	~ 50 nm	0.03
(111) surface	3×10^{13} cm^{-2}	~ nm	0.3

g_{eff}: 1~ 100

All surfaces are different, but E_{SO} ~ E_F ~ 100 meV

Dominate transport for this layers or wires d < 90nm

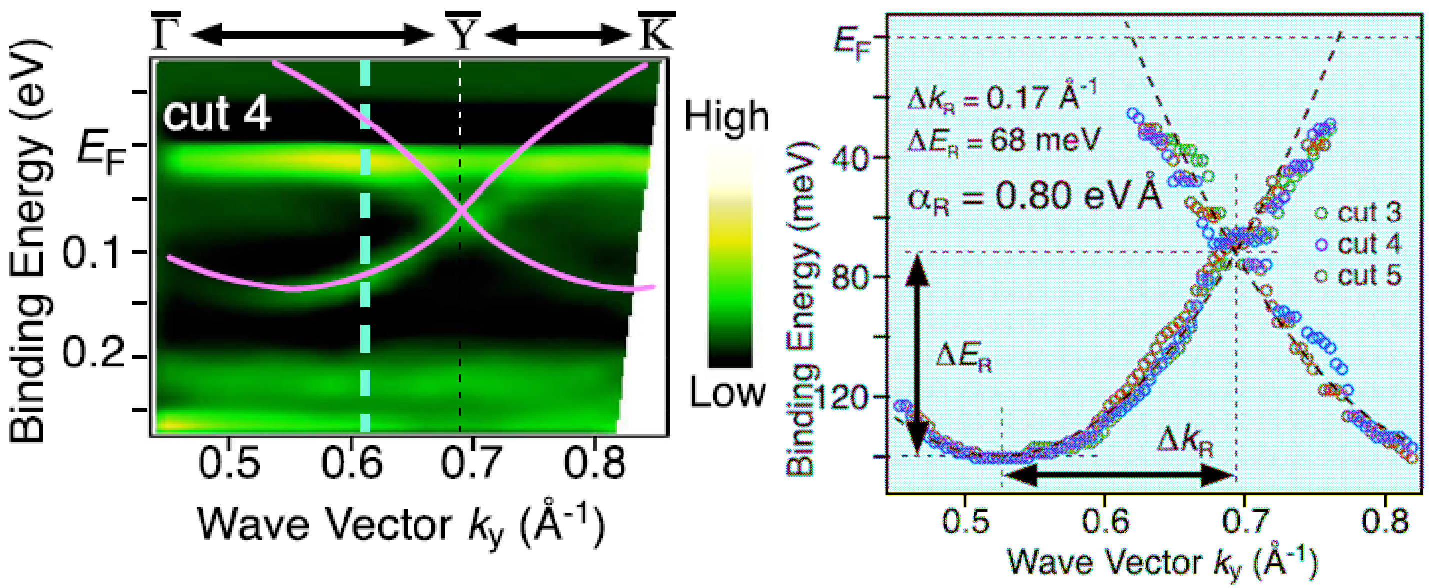
Edge states on certain surfaces



Murakami 2006

Bi(111) bilayer
Topological 2D insulator

What about thicker layers?

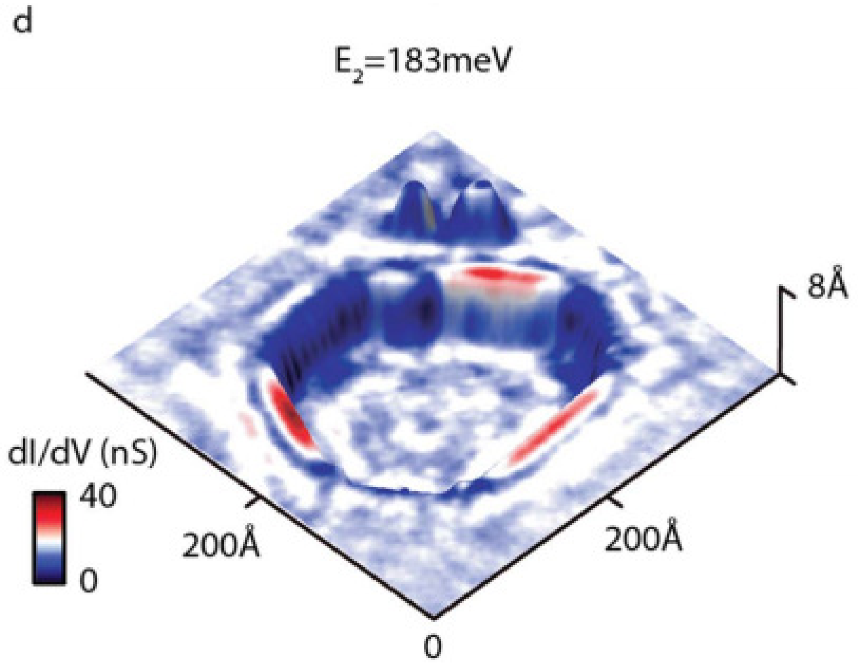


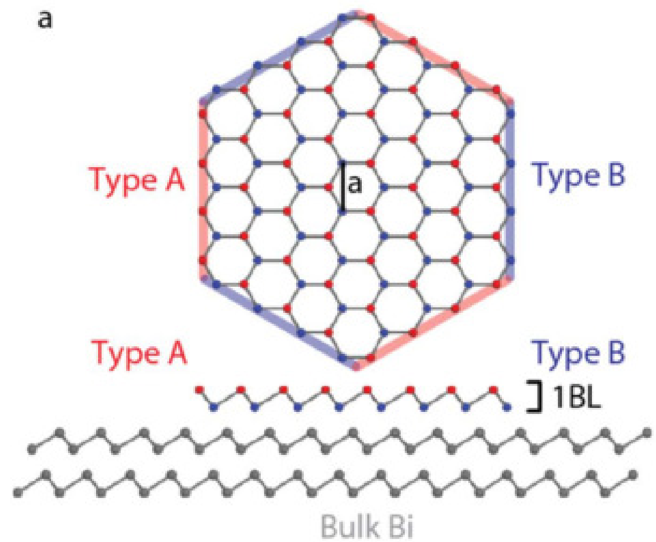
ARPES Takayama et al PRL

15 nm

Edge states but possibly not topological

Bismuth edge states on (111) surface





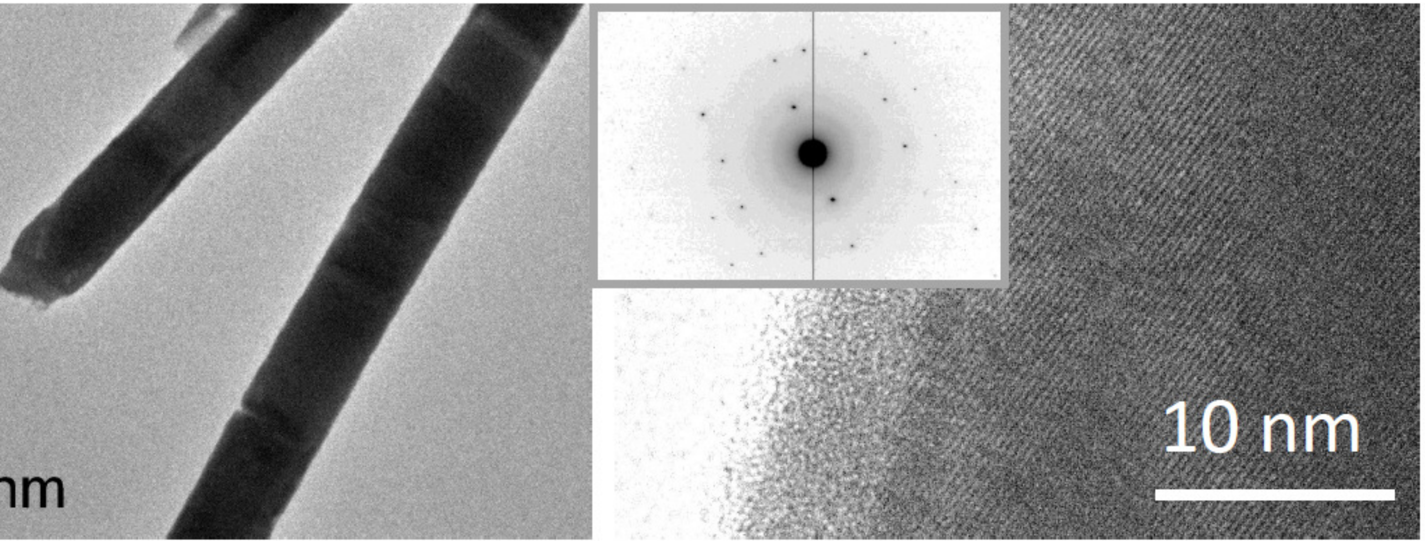
STM on Bi(111) bilayer small pit: 1D **edge states at some edges**
(Drozdov Yazdani, 2014)

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

Bi nanowires

rochemically grown in 90 nm-wide pores of polycarbonate membrane.

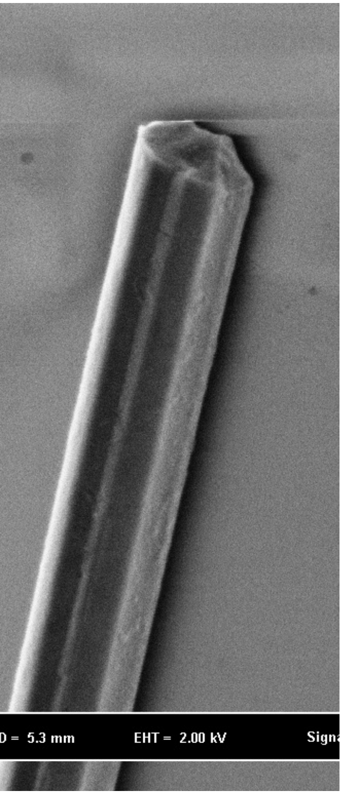
image of similar wires grown in nanopores (G. Tsirlina)

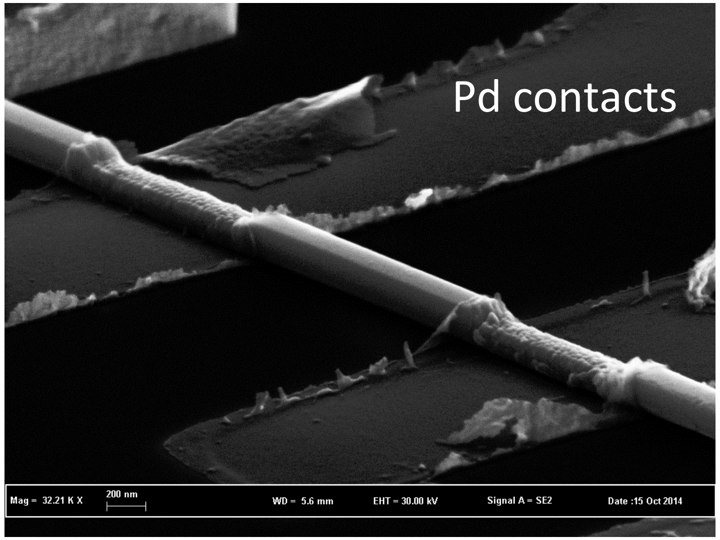


- probably facetted, with seve orientations
- Practically monocrystalline (r high angle boundary)
- Protected by membrane residues

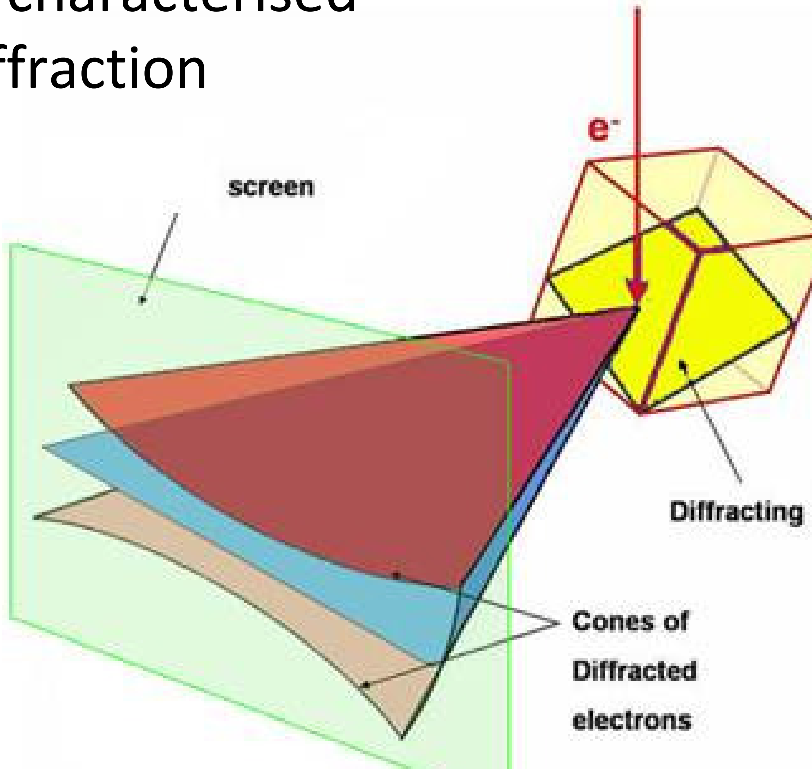
No possible caracterisation of a selected wire for transport measurements

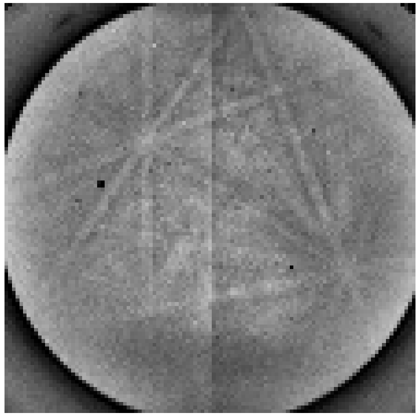
Bi nanowires grown with sputtering





Orientation of Bi nanowire facets
Can be characterised
By e diffraction

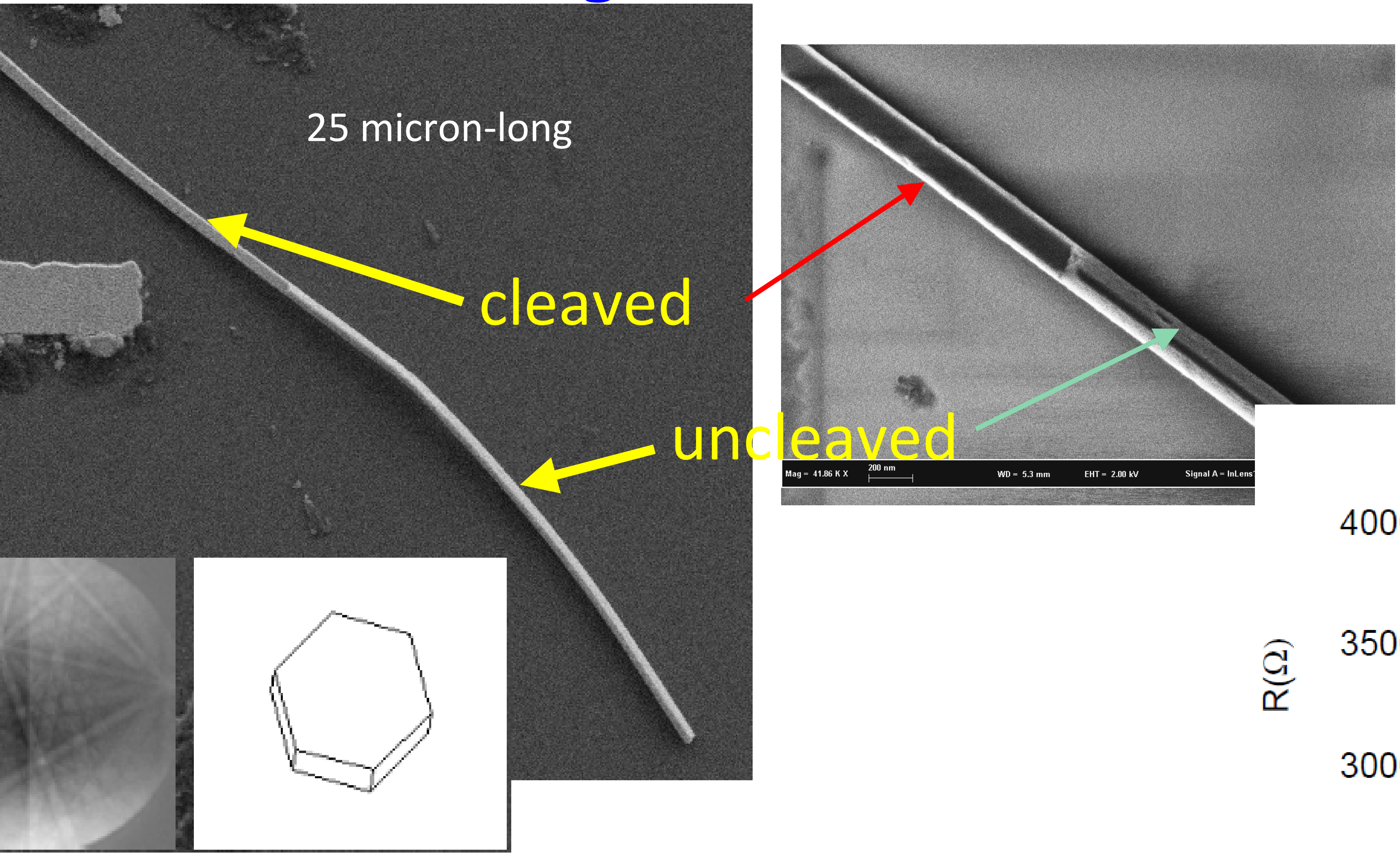


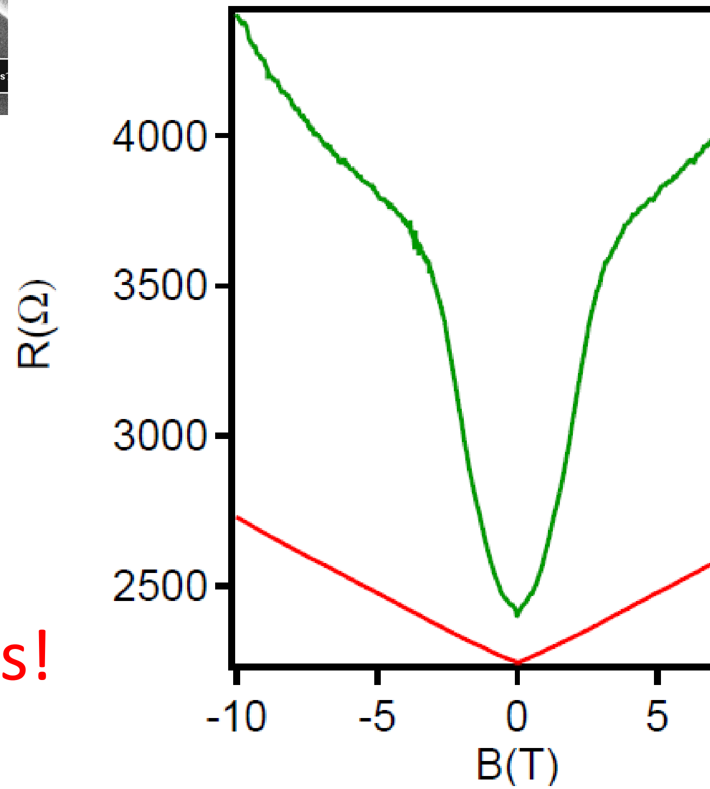


Kasumov 2015

(F. Brisset ICMMO, Anil Murani

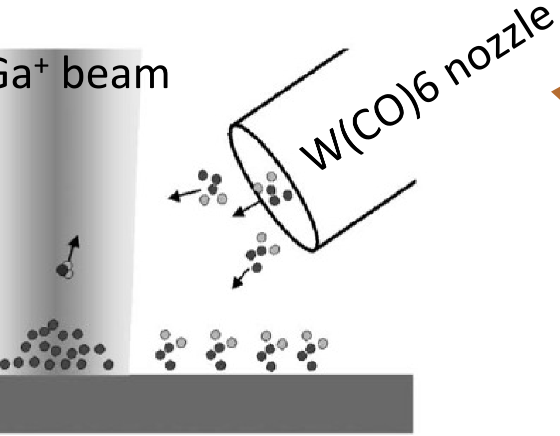
Two segments with (111) facets

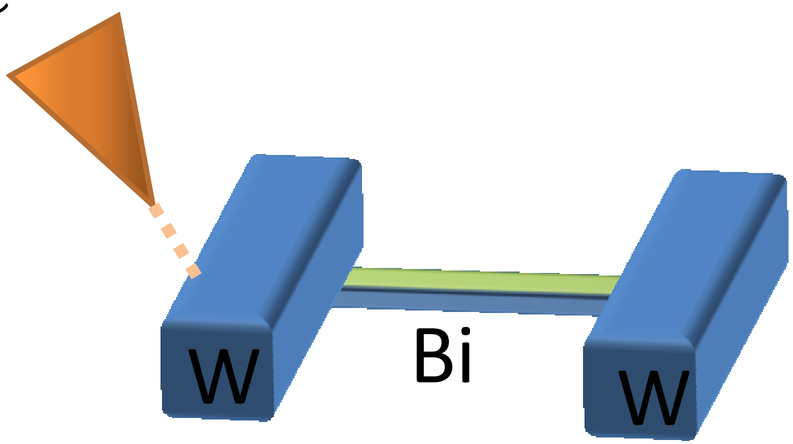




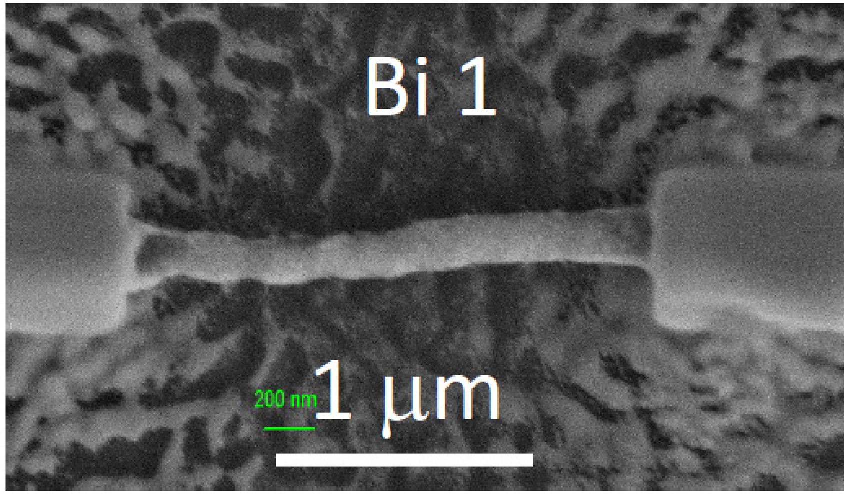
Give different magnetoresistances!

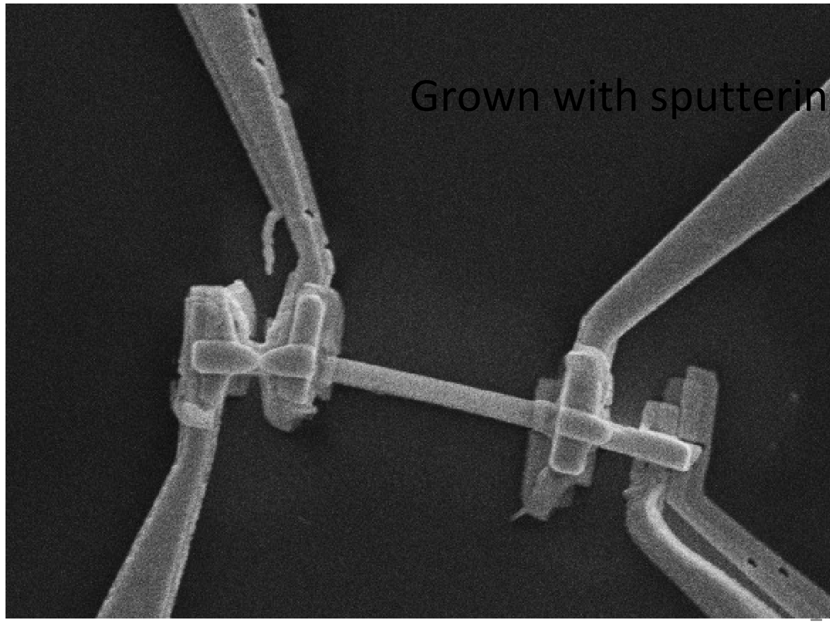
Superconducting contacts by focused ion beam-assisted deposition





Electrodeposit

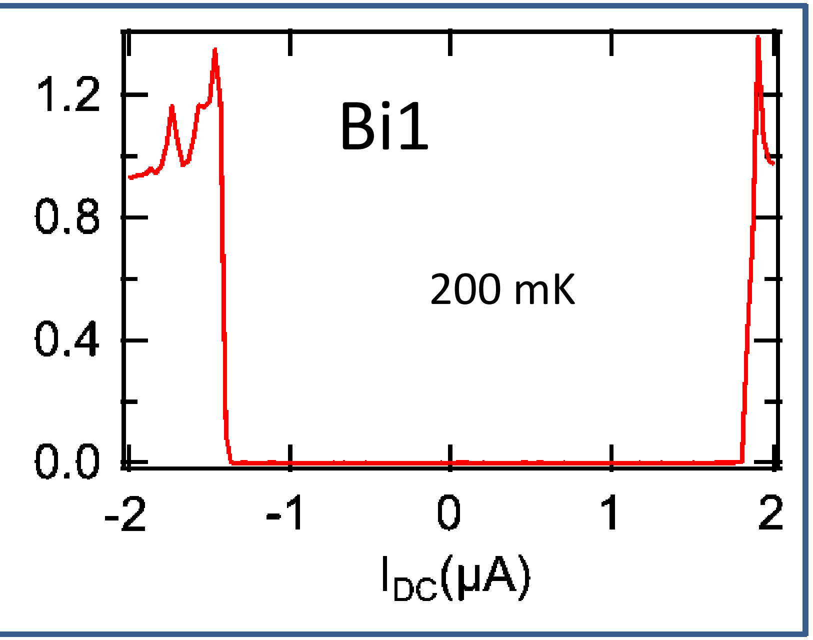


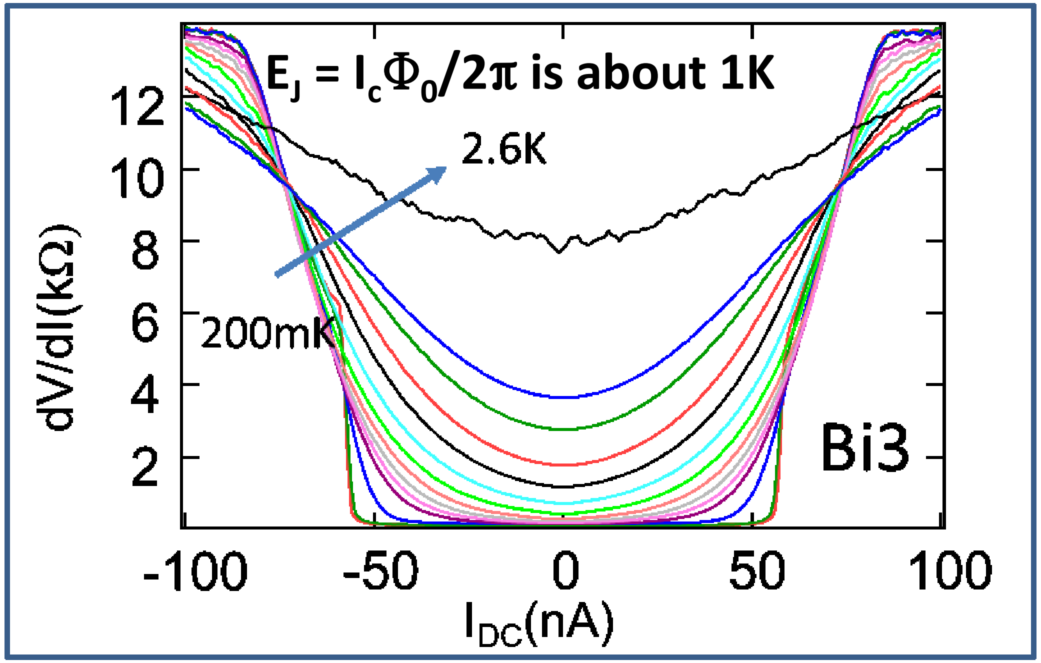


and Ga-doped amorphous W wire,
ughly 200 nm thick and wide, with great
uperconducting properties:
$_c$~4K, Δ~0.8 meV, H_c~12 Tesla!

asumov 2005, Guillamon 2008

Supercurrent in W/Bi/W junctions





	Bi1	Bi2	Bi3	Bi4
	1 kΩ	10 kΩ	16 kΩ	1,2 kΩ
	1,8 µA	140 nA	70 nA	750 nA
ngth	1.9 µm	2 µm	1.6 µm	1.4 µm

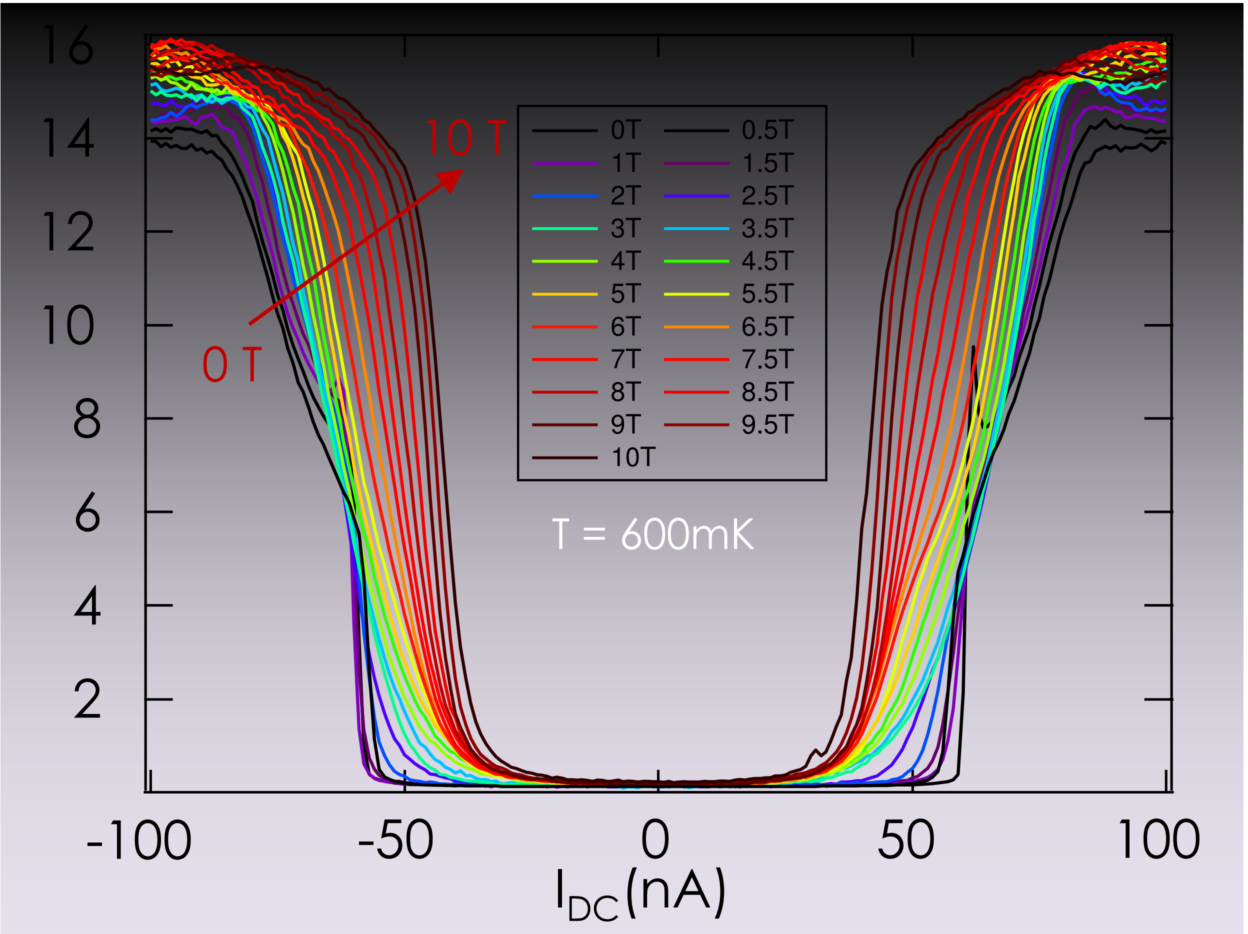
$R_N I_C \sim$ 1-2 meV~ Δ_W:

maximum critical current possible for SNS junction !

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

Nearly perfect Andrev reflection in spite of interface barriers

ack to S/Bi/S: Supercurrent persists to huge ⊥ field!

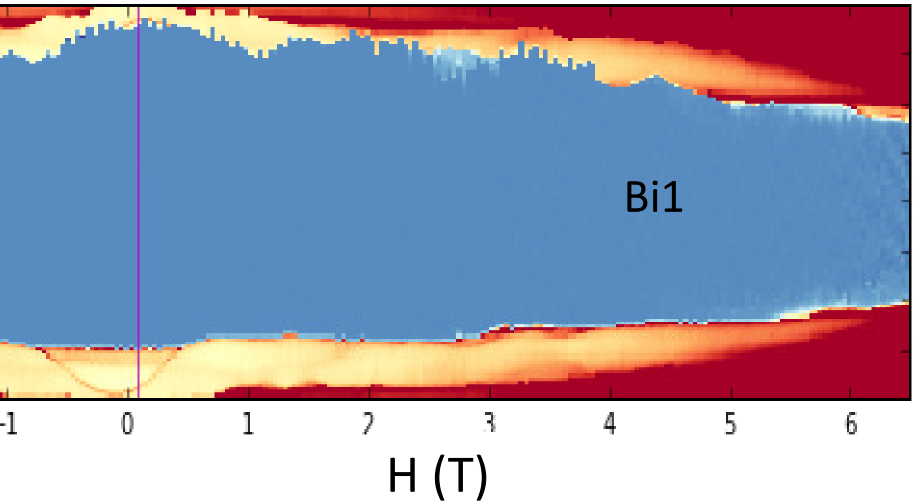


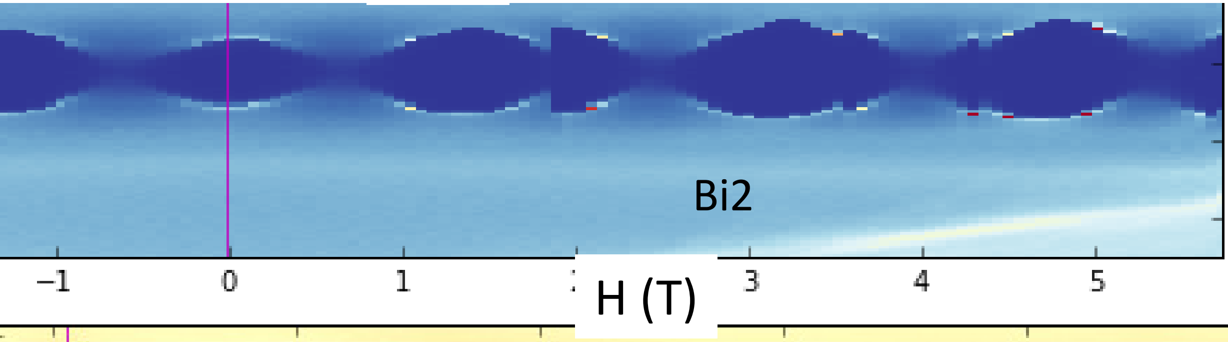
10 T corresponds to 1000 Φ_0 in the 100 nm x 2 µm wire!

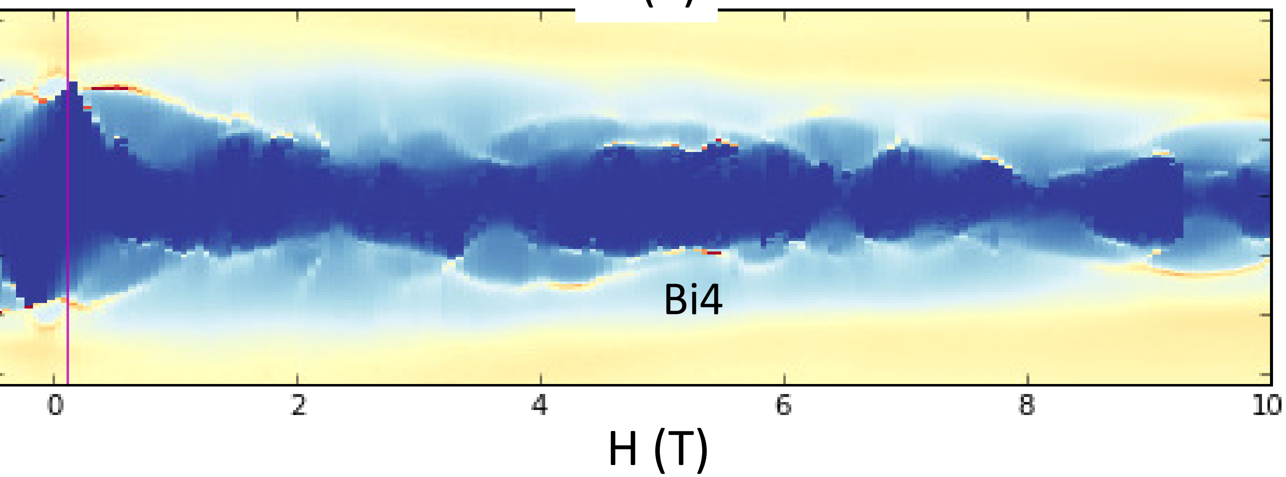
Diffusive multichannel model doesn't work.

Field dependence implies: few ballistic channels!

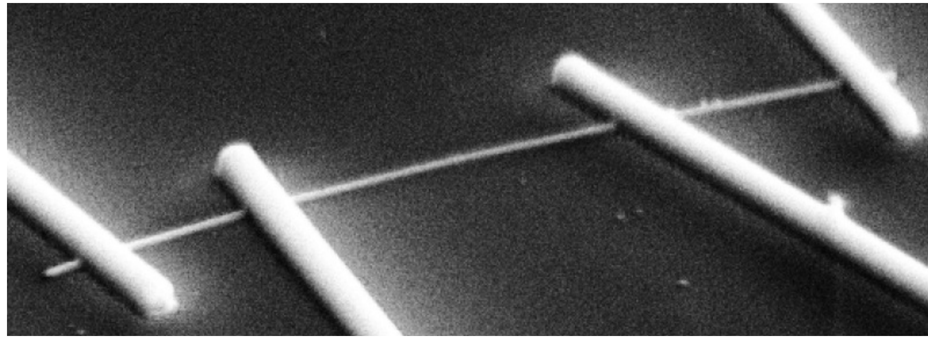
Bi nanowires

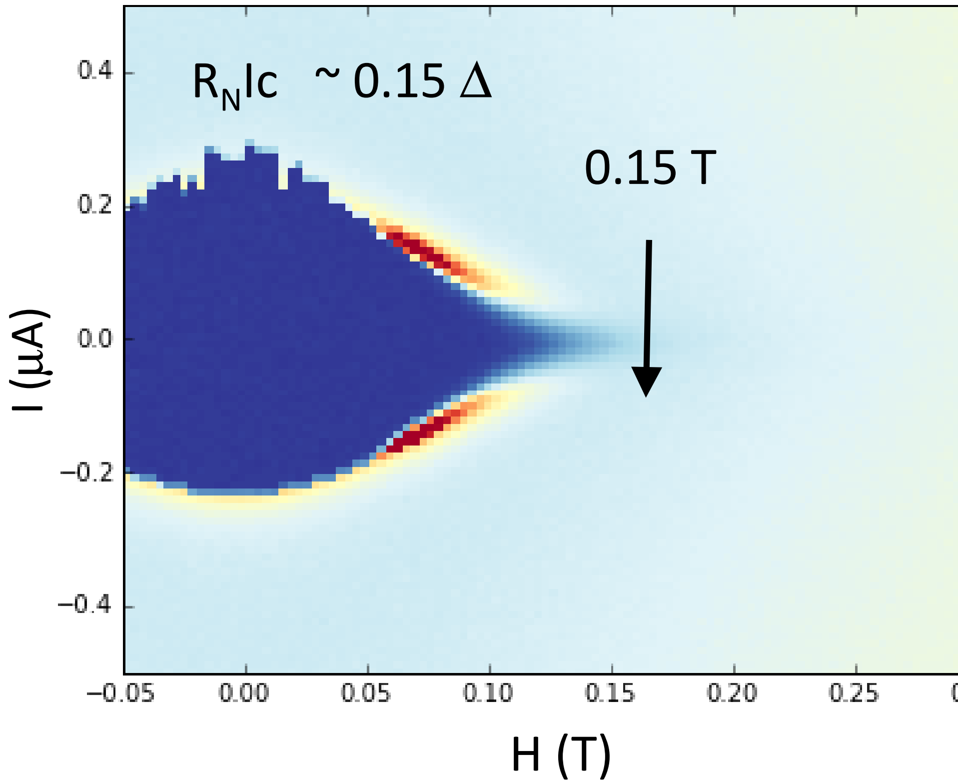






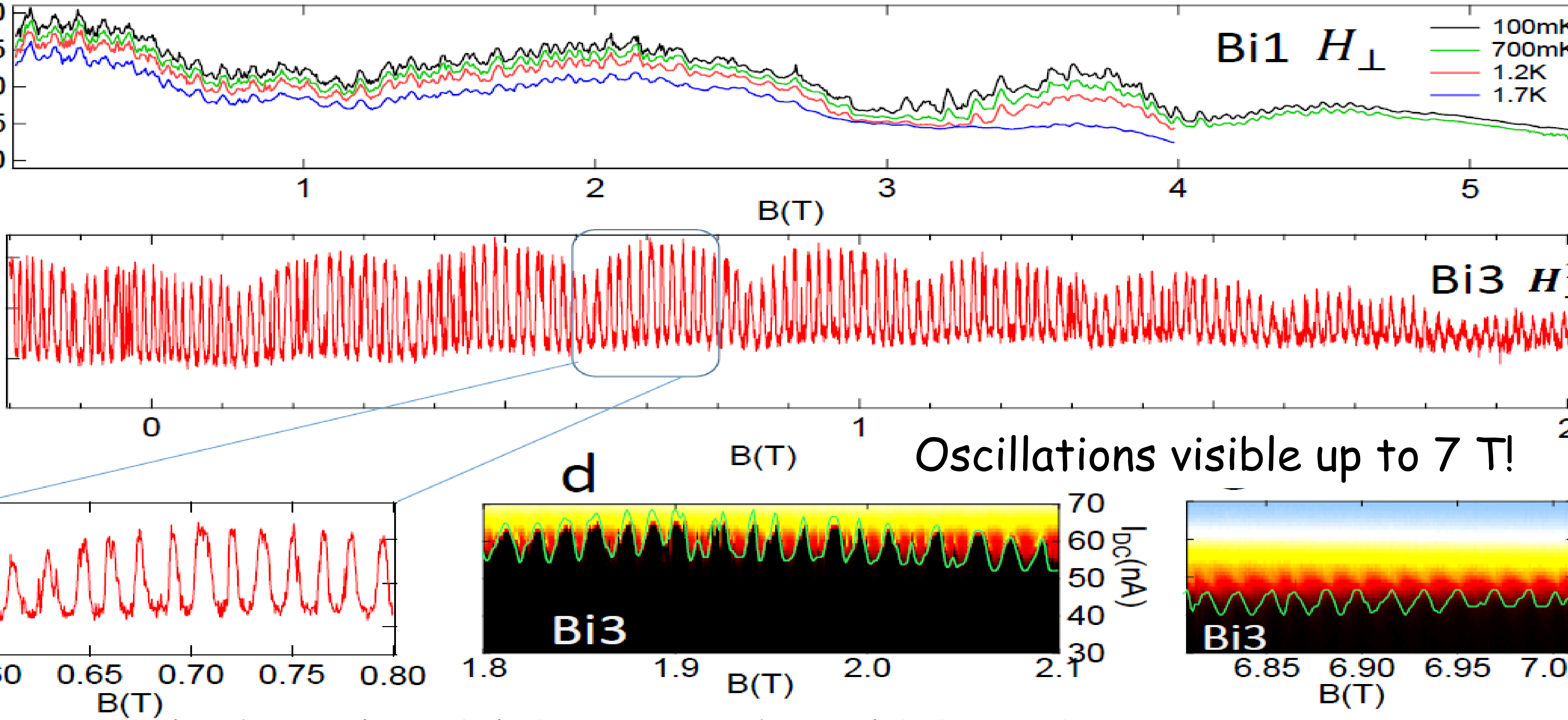
Ag nanowire





Very different behavior

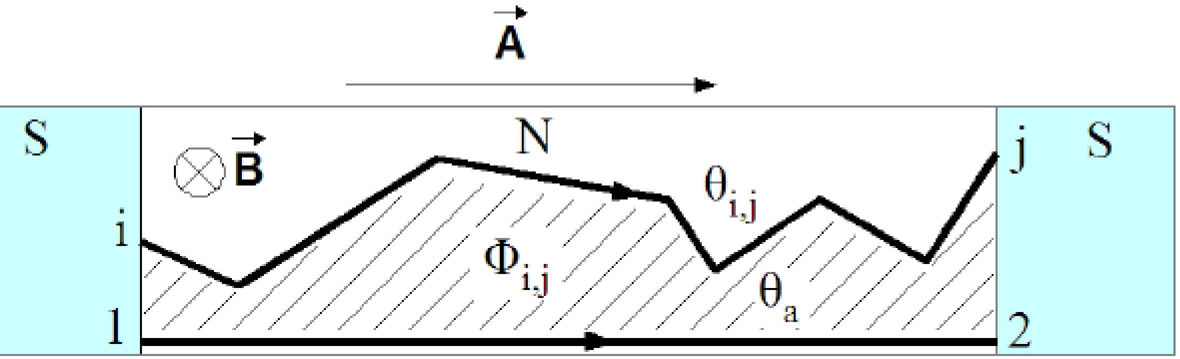
Small period field oscillations of the switching current



Oscillations visible up to 7 T!

usive multichannel model doesn't work. Field dependence
es: few ballistic channels!

Narrow diffusive sample with many channels: Flux dependent phase variation in sample



Cuevas, Montambaux

$$I_c \propto \left| < e^{i\Delta\theta_{i,j}} >_{C_{i,j}} \right| \qquad I_c \propto \left| e^{-<(\Delta\theta_{i,j})^2>_{C_{i,j}}/2} \right|$$

Diffusive trajectories encircle different f
so pick up different phases

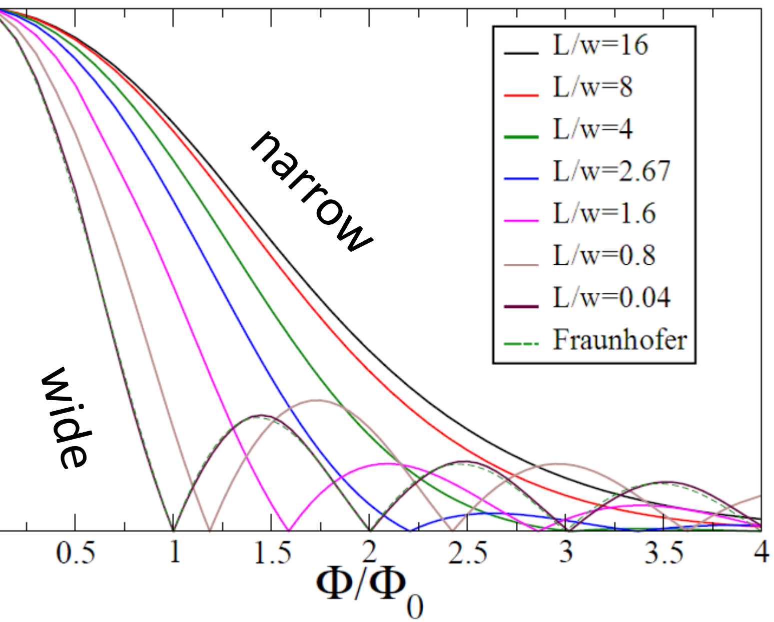
$$\Delta\theta_{i,j} = \frac{2e}{\hbar}\left[\int_i^j A_x dx - \int_1^2 A_x dx\right] = \frac{2e}{\hbar}\oint A_x dx = \frac{2\pi}{\Phi_0} H\, S_{i,j} = 2\pi\frac{\Phi_{i,j}}{\Phi_0} \quad (2.5$$

$$I_c \propto \left| e^{-2\pi^2 H^2 \alpha^2/\Phi_0^2} \right|$$

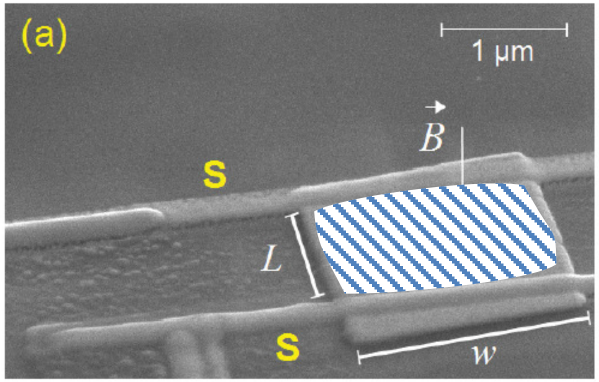
~ Gaussian decay of I_c on scale of Φ_0 because dephasing by field

Role of geometry demonstated in SNS junctions

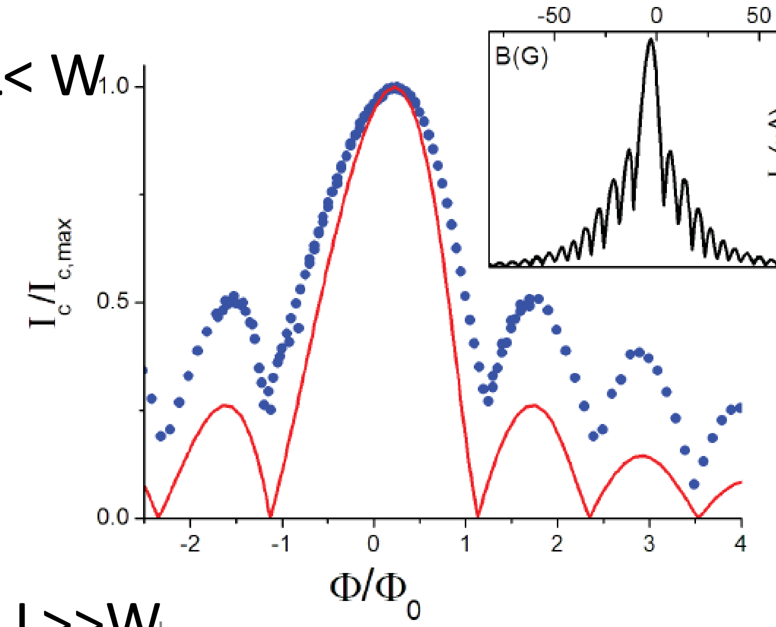
ory: Bergeret Cuevas 2008

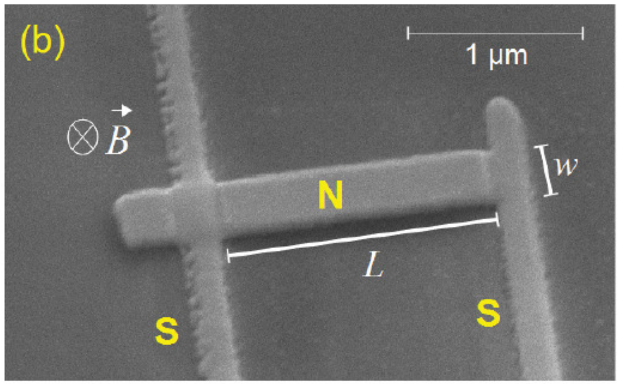


Exp: Chiodi 2012

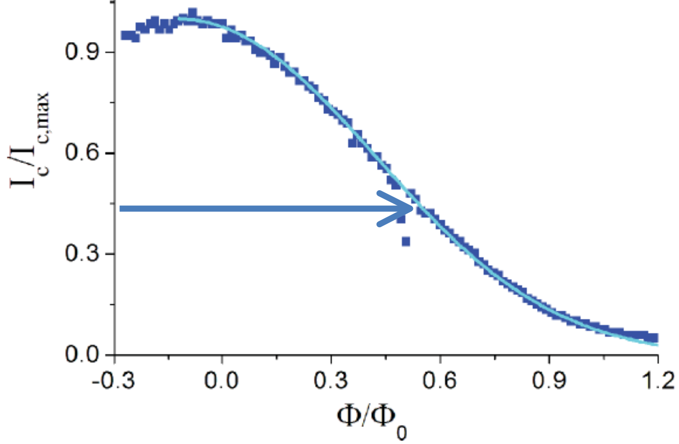


wide: L< W



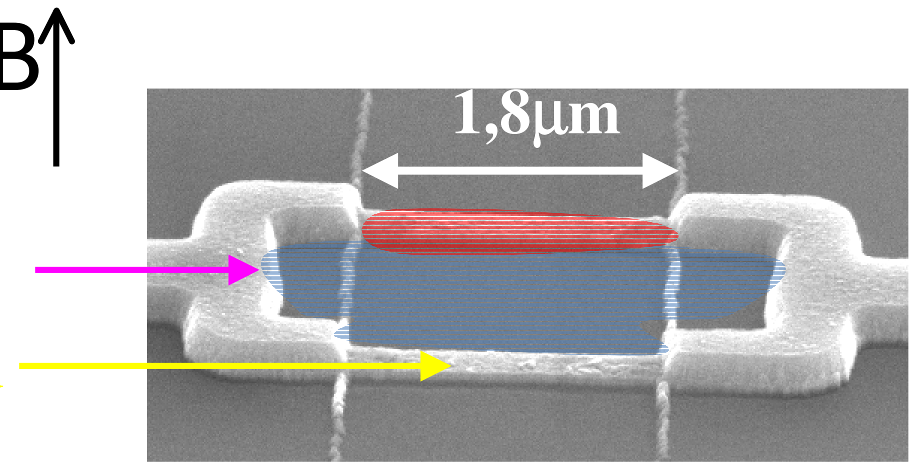


Narrow: L>>W

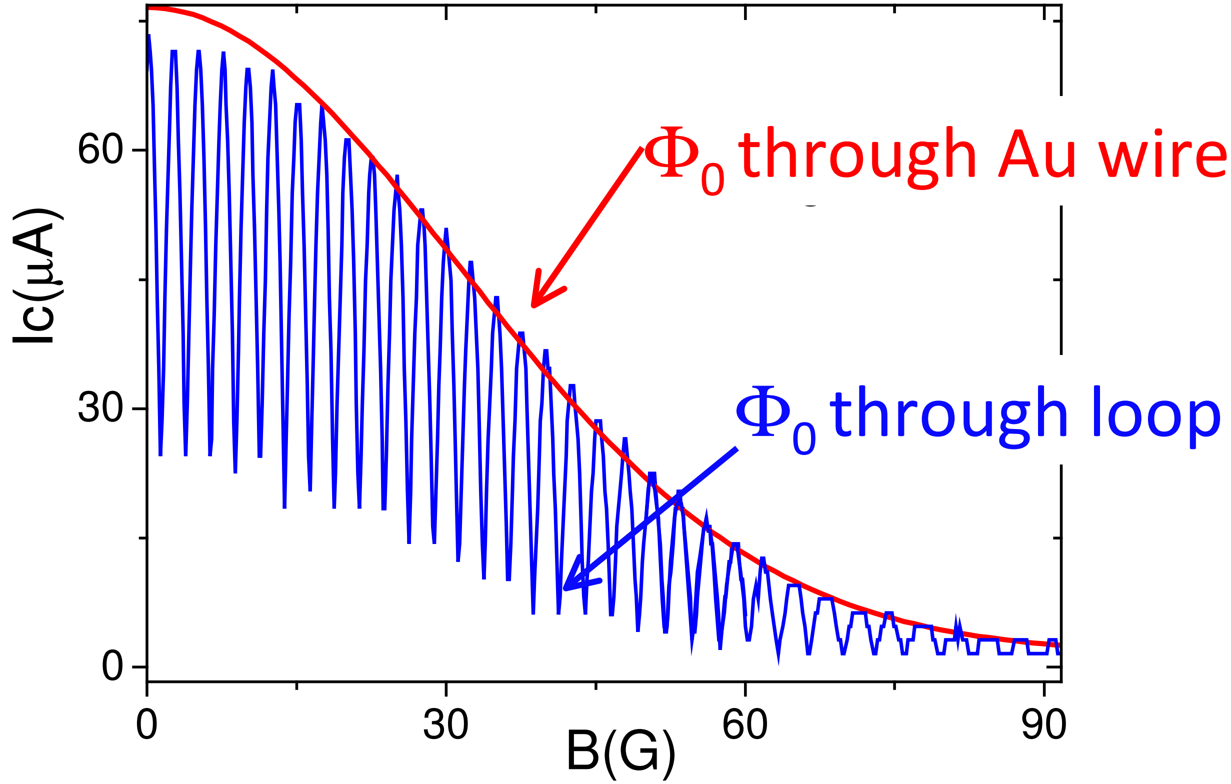


I_c decays on scale of Φ_0 through sample surface(100 G)

SNS squid junction



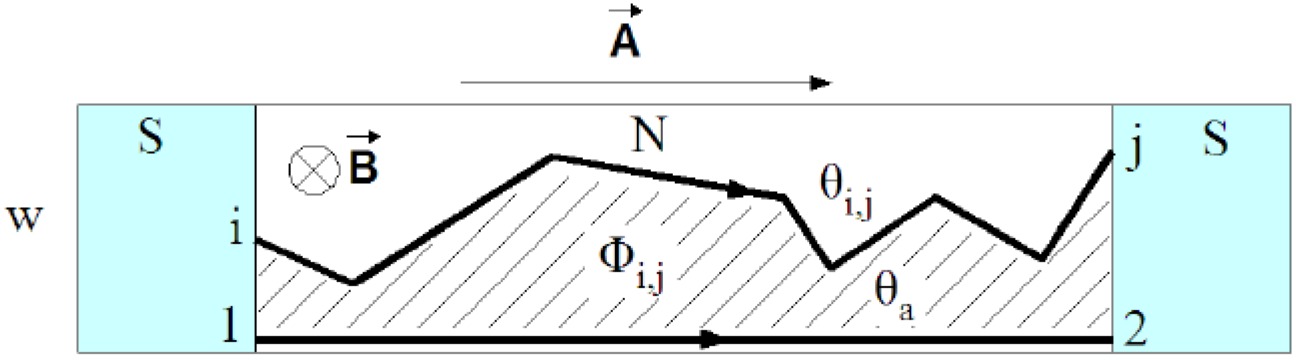
Angers 2008



Modulation period a few G, decay scale ~50 G

ack to S/Bi/S: Supercurrent persists up to huge field!

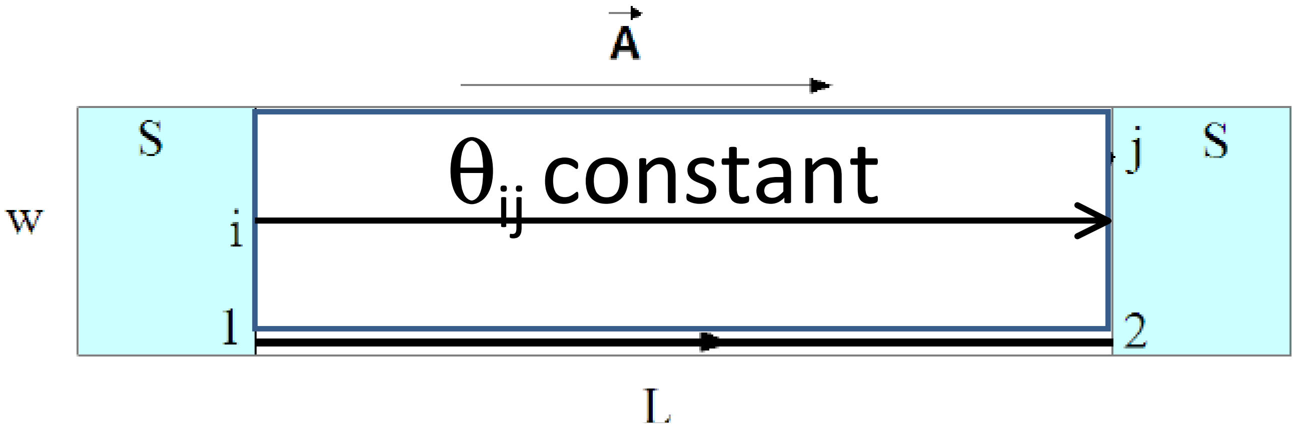
T corresponds to 1000 Φ_0 in
100 nm x 2 μm wire!



ompatible with many diffusive
nnels.

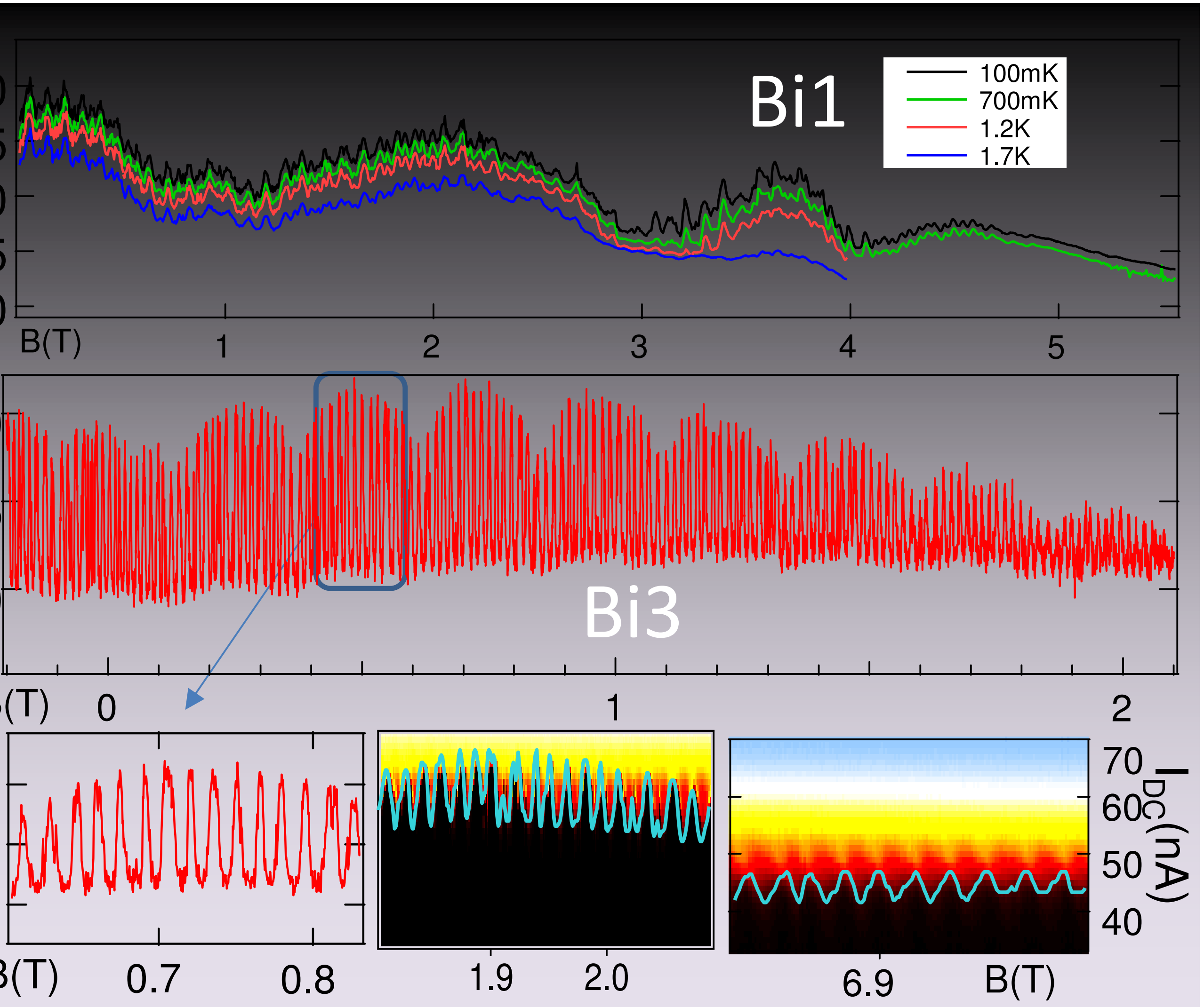
$$I_c \propto \left| < e^{i\Delta\theta_{i,j}} >_{\mathcal{C}_{i,j}} \right| \propto \left| e^{-<(\Delta\theta_{i,j})^2>_{\mathcal{C}_{i,j}}/2} \right|$$

ld dependence implies: very few ballistic 1D channels!

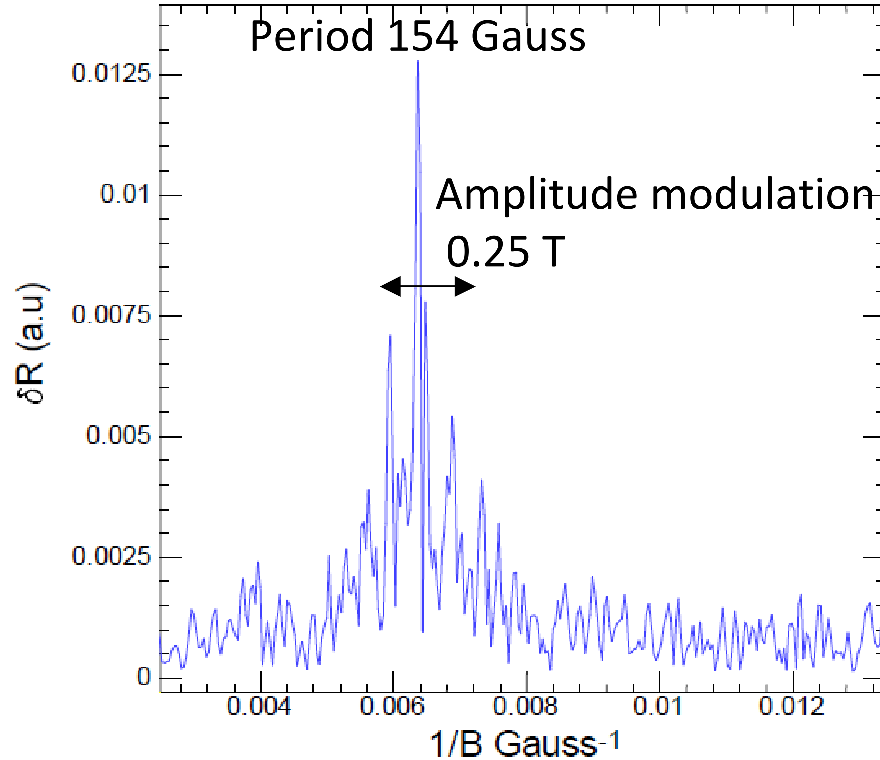


Then no decay of I_c

SQUID-like I_c oscillations, up to 10 T !



Fourier transform Bi3

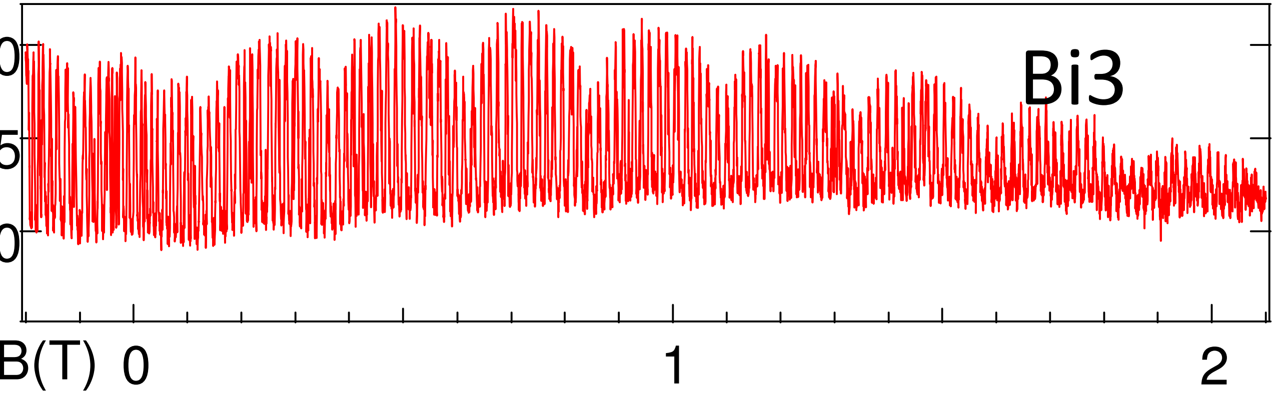


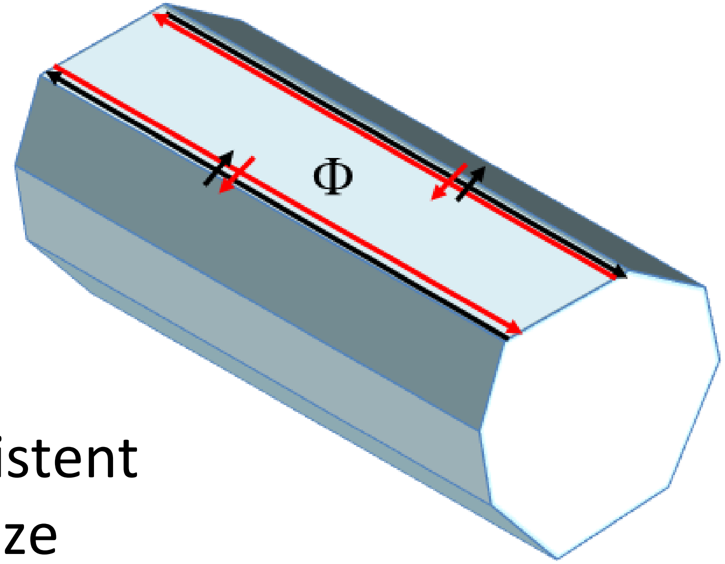
Where is the loop?

Why no extinction on the scale of $1\ \Phi_0 /S$ ~400 Gaus

SQUID-like I_C oscillations, up to 10 T : Very few ballis narrow 1D channels

(





Bi1		Bi3	
ΔB = 754G	S = 0.027 μm^2 =13nm x 2 μm	ΔB = 154G	S = 0.13 μm^2 =65nm x 2μm

Period consistent with facet size

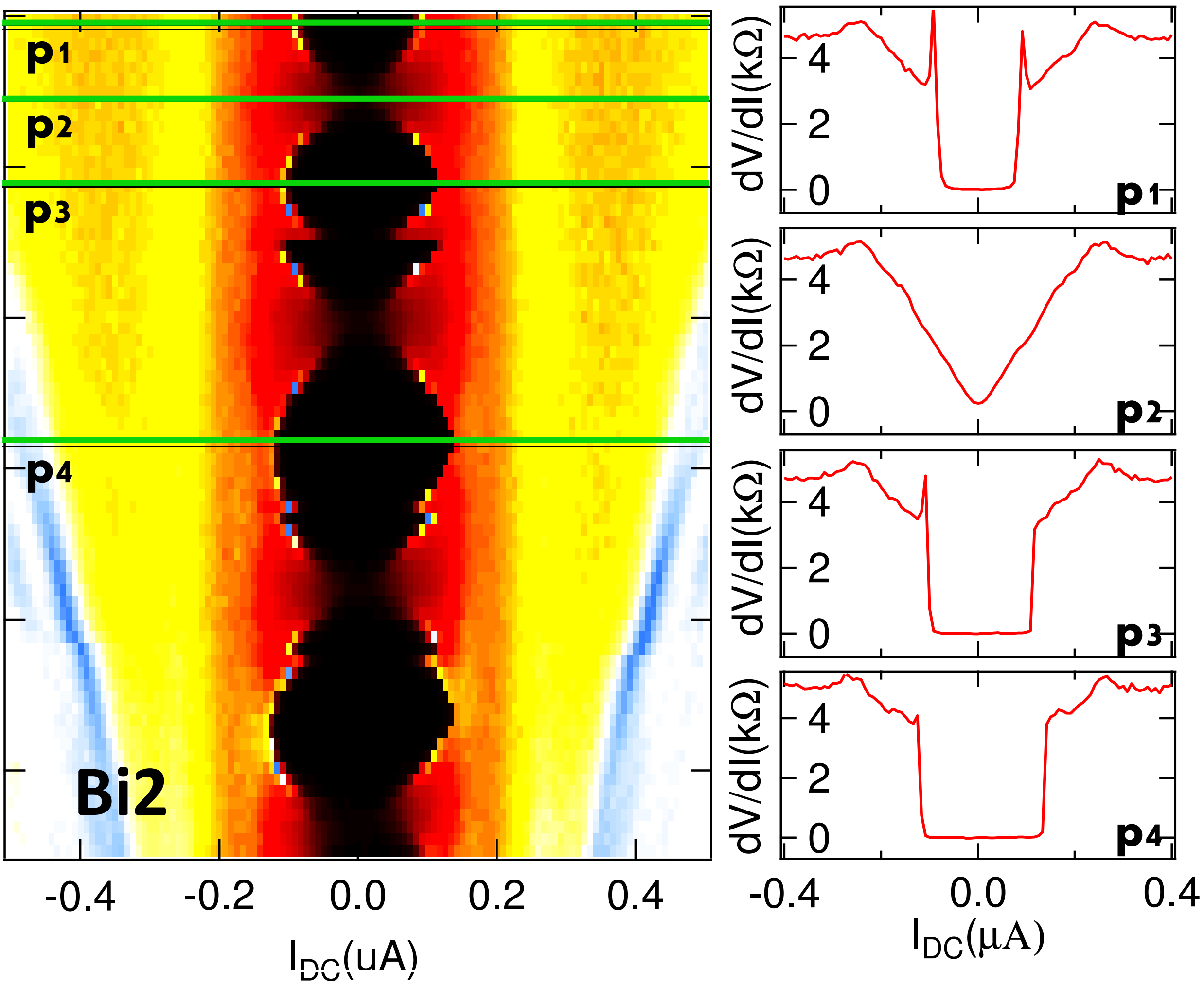
1D edge states on (111) facet (or other topological facet).

milar to observations in SC top. Insulators HgTe /HgCd Te, InAs/GaSb

Decay scale gives extension of edge state (nm!)

Other surface or bulk states will not contribute at such high fields

High field range modulation seen for all wires

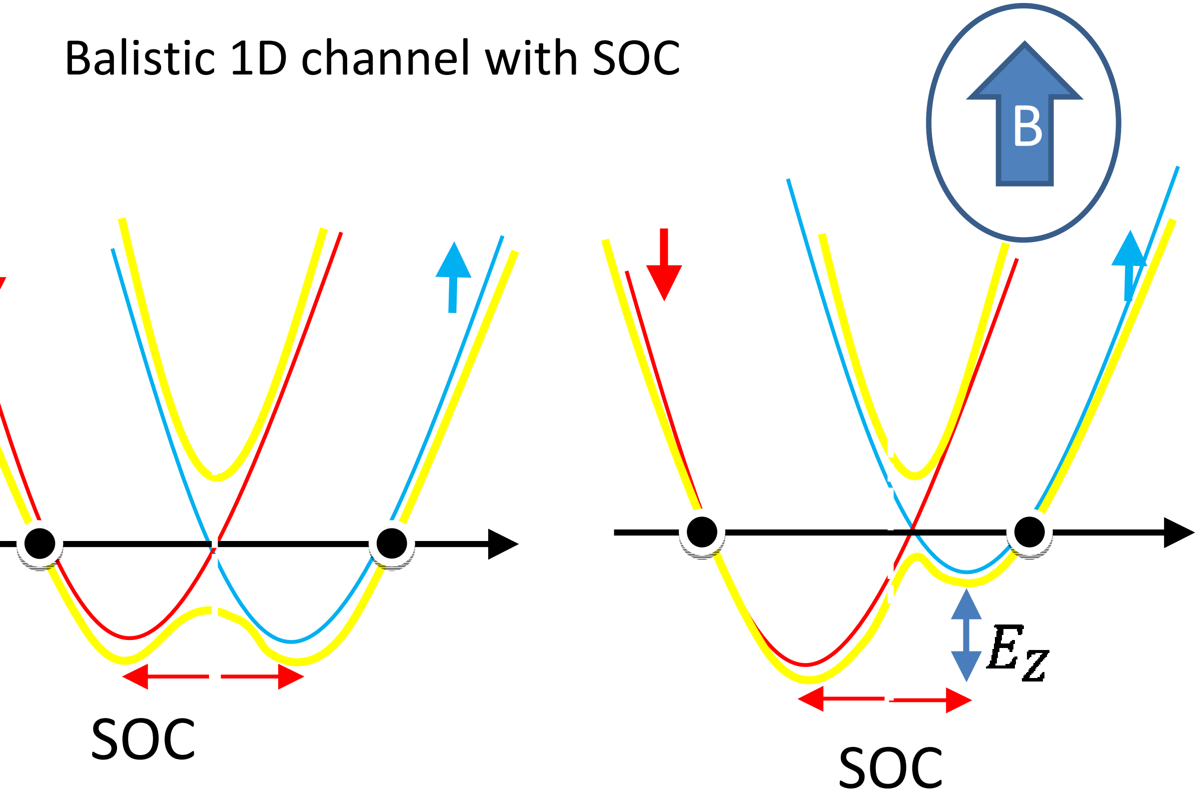


Critical current is larger in 5T than in zero field!

Slow phase modulation by Zeeman energy

gh field scale critical current modulation due to Zeeman dephasin

Balistic 1D channel with SOC



$$\Delta k = E_Z / h v_F = g_{eff}\, \mu_B\, B / h v_F$$

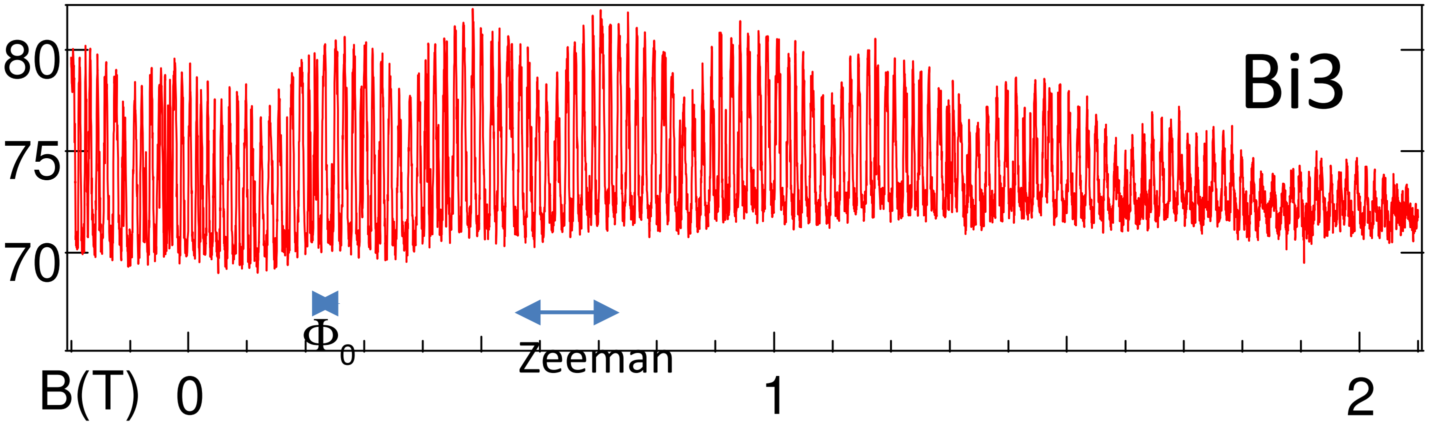
$$\delta\phi = 2\pi L \Delta k = 2\, g_{eff}\, \mu_B\, B L / v_F$$

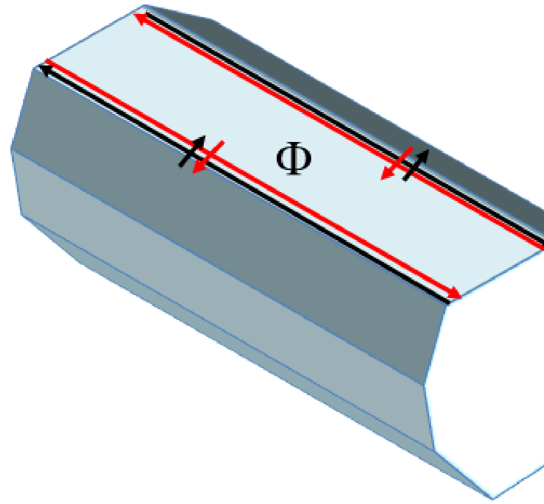
$$k_\uparrow = -k_\downarrow \qquad\qquad k_\uparrow = -k_\downarrow + \Delta k$$

$$\Delta\varphi = 0 \qquad\qquad \Delta\varphi \neq 0$$

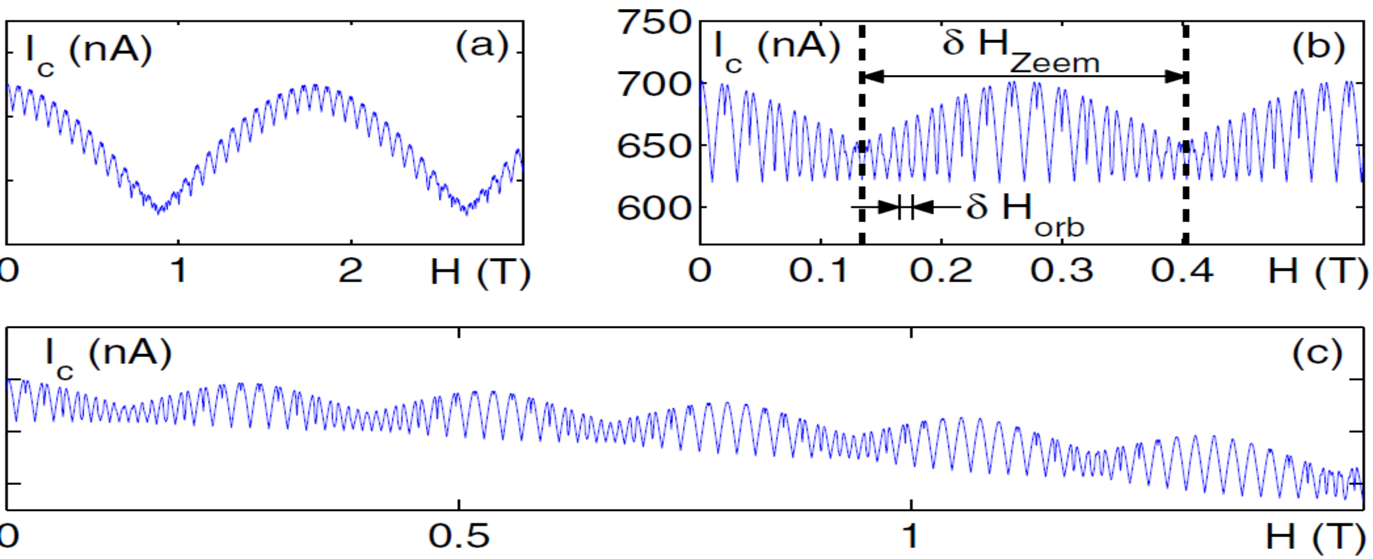
m $v_F = 3x10^5$ and $g_{eff} = 30$ yields period in Tesla range

SQUID-like I_C oscillations, and high field modulation reproduced with 2 channels





quid formula with field modulated Ic_i : $Ic^2=Ic_1(H)^2+Ic_2(H)^2+2.Ic_1Ic_2 \cos 2\pi\Phi/$



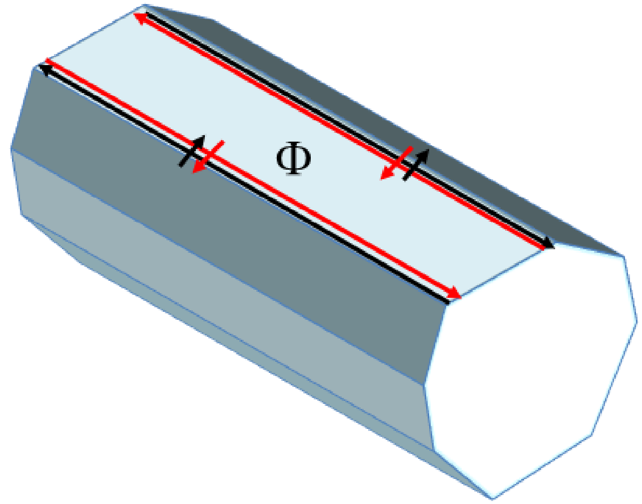
$Ic_i(H)=Ic_i\ (1-\ \alpha_i \cos g_{effi}.H$

$Ic_1=30\ Ic_2,\quad g_{eff2}=20\ g_{eff1}$

Mironov et al.PRL 2015

Conclusion: what we found in S/Bi nanowire/S junctions

Rapid squid like oscillations (due to orbital
phase modulation), and absence of decay with
ield:
Small number of narrow (<1nm) 1D ballistic
helical) edge states.



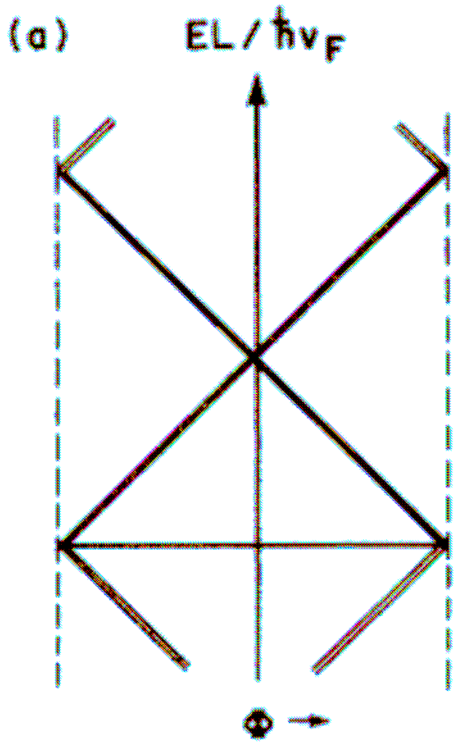
1 Tesla range modulation explained by Zeeman
spin) dephasing

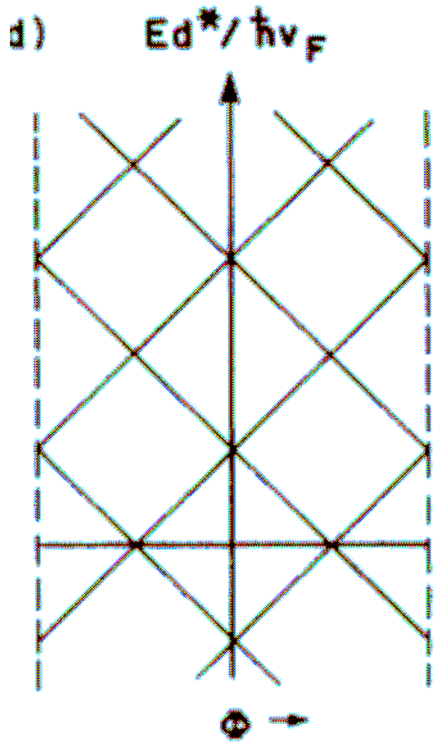
High critical current due to suppressed normal
backscattering at helical edges?

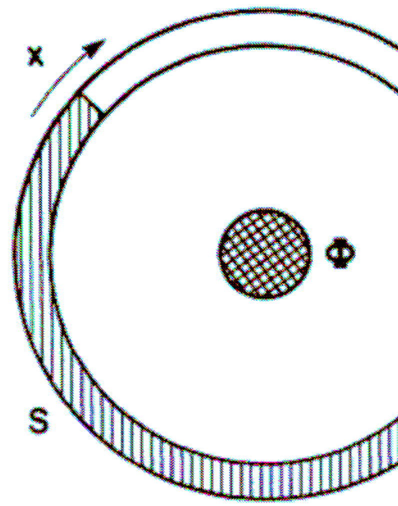
Next: Investigation of Andreev states

om single electron spectrum in a ring to Andreev states in a long SNS junction $L >> \xi_S$

Büttiker Klapwijck 1985







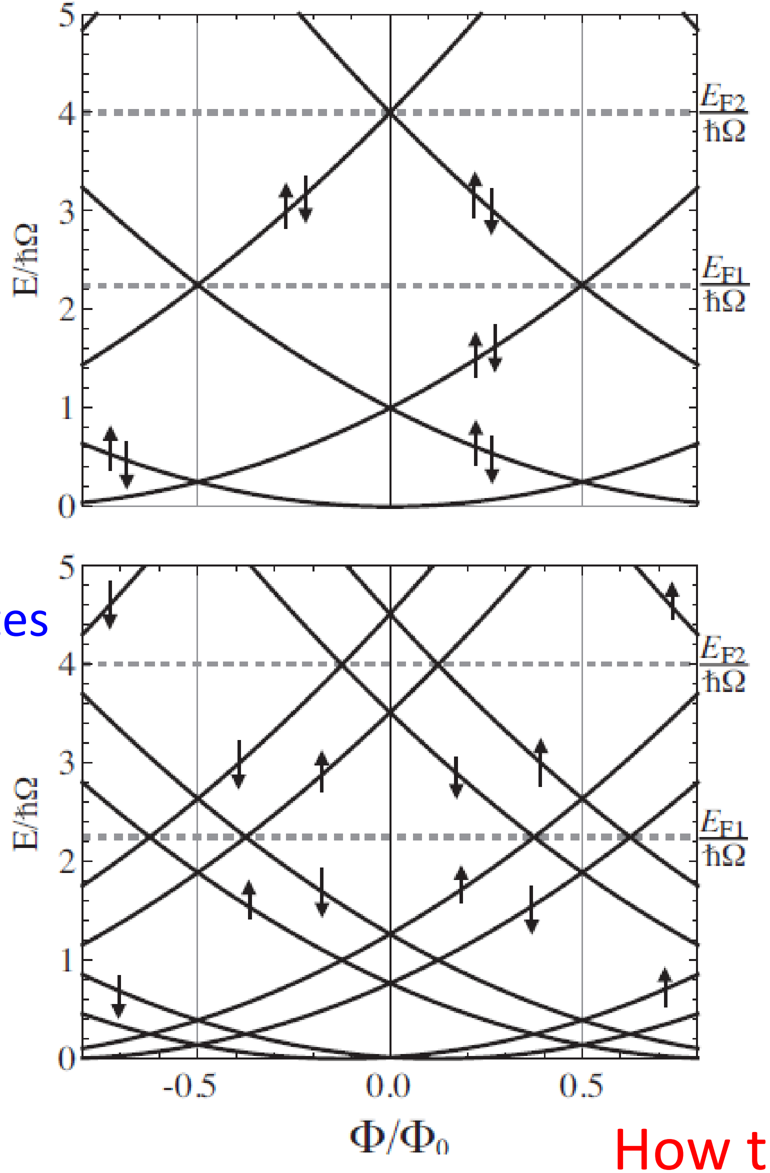
N Ring periodicity h/e

NS Ring periodicity h/2e

x dependent spectrum of a ring in the presence of spin orbit cou

1D N ring

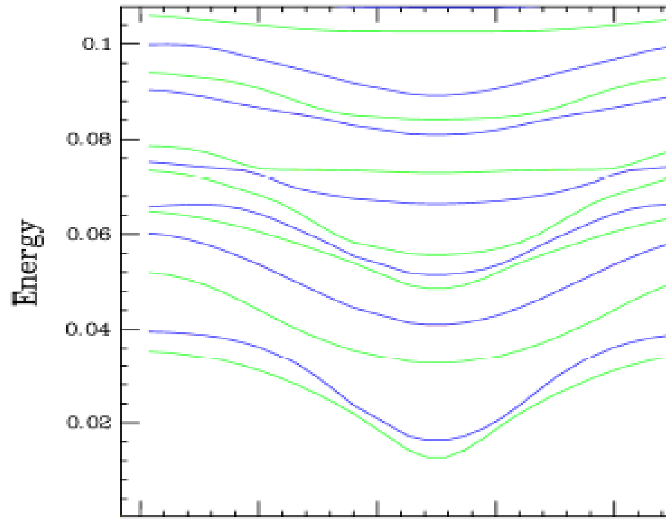
Multichannel
NS ring Andrev states invariant by



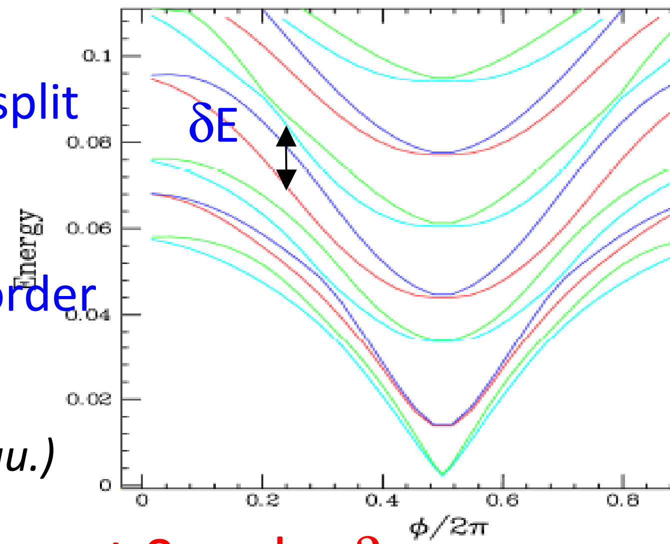
e shifted
↑ and ↓ States

$\pm k_{so}L$

No SO coupling



With Rashba SO coupling
$\lambda = E_{SO}/E_F = 0.3$



Andreev states are spin split
for $\phi \neq 0,\pi$
TRS breaking $\delta E = \lambda\Delta^2\tau_D$
decreased effective disorder

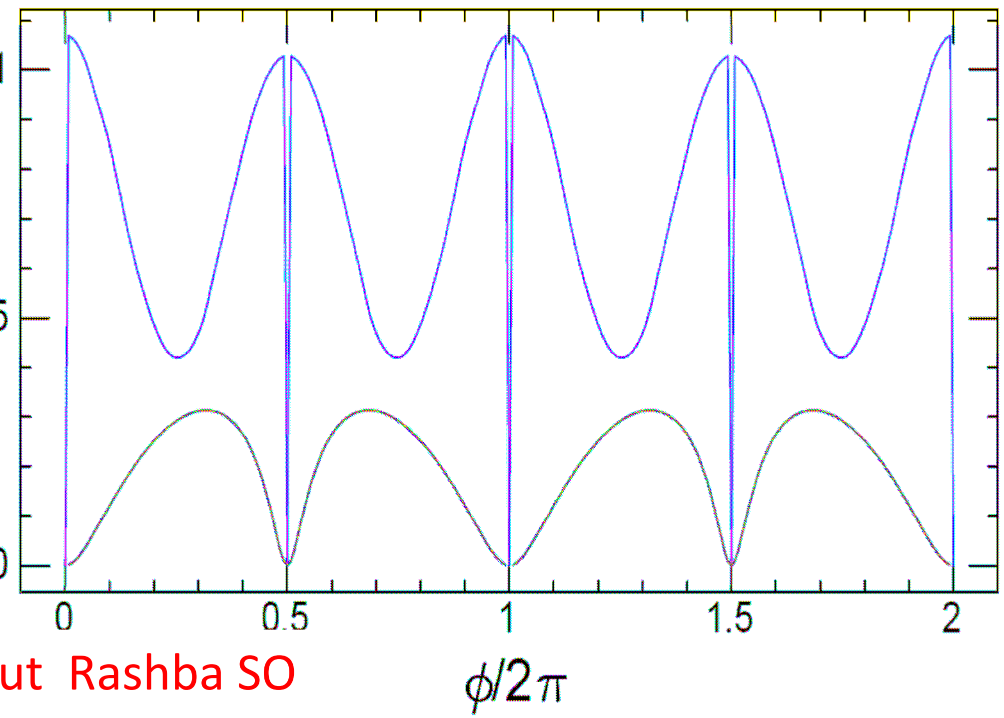
*(A.Murani A.Chepelianskii
H.B. Similations of BdG equ.)*

How to detect level crossings at 0 and π ?

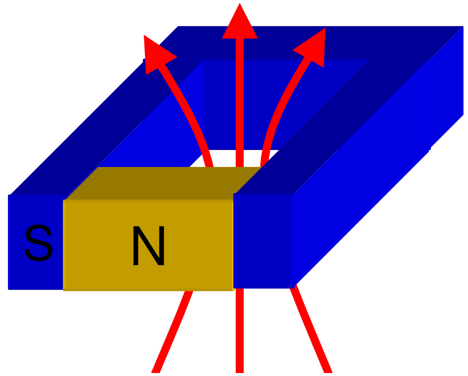
Finite frequency response

$\Phi_{ext}=\Phi_{dc}+\Phi_{ac}$ cos

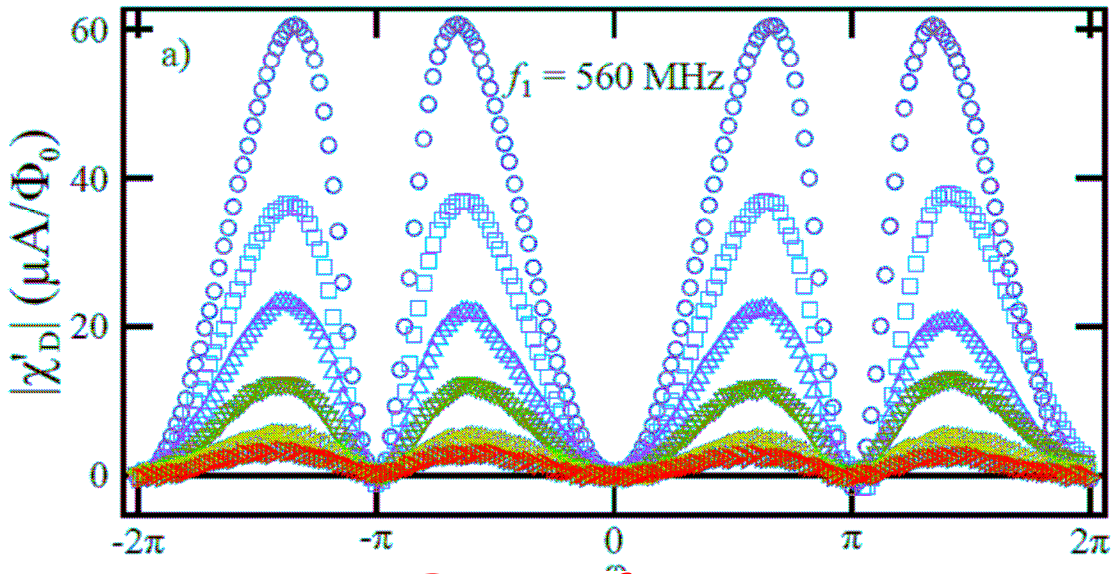
ith Rahba SO



ut Rashba SO



Au diffusive wire



Josephson current

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

Finite frequency

$$\chi_D(\omega) = -\sum_n i_n^2 \frac{\partial f_n}{\partial \epsilon_n}$$

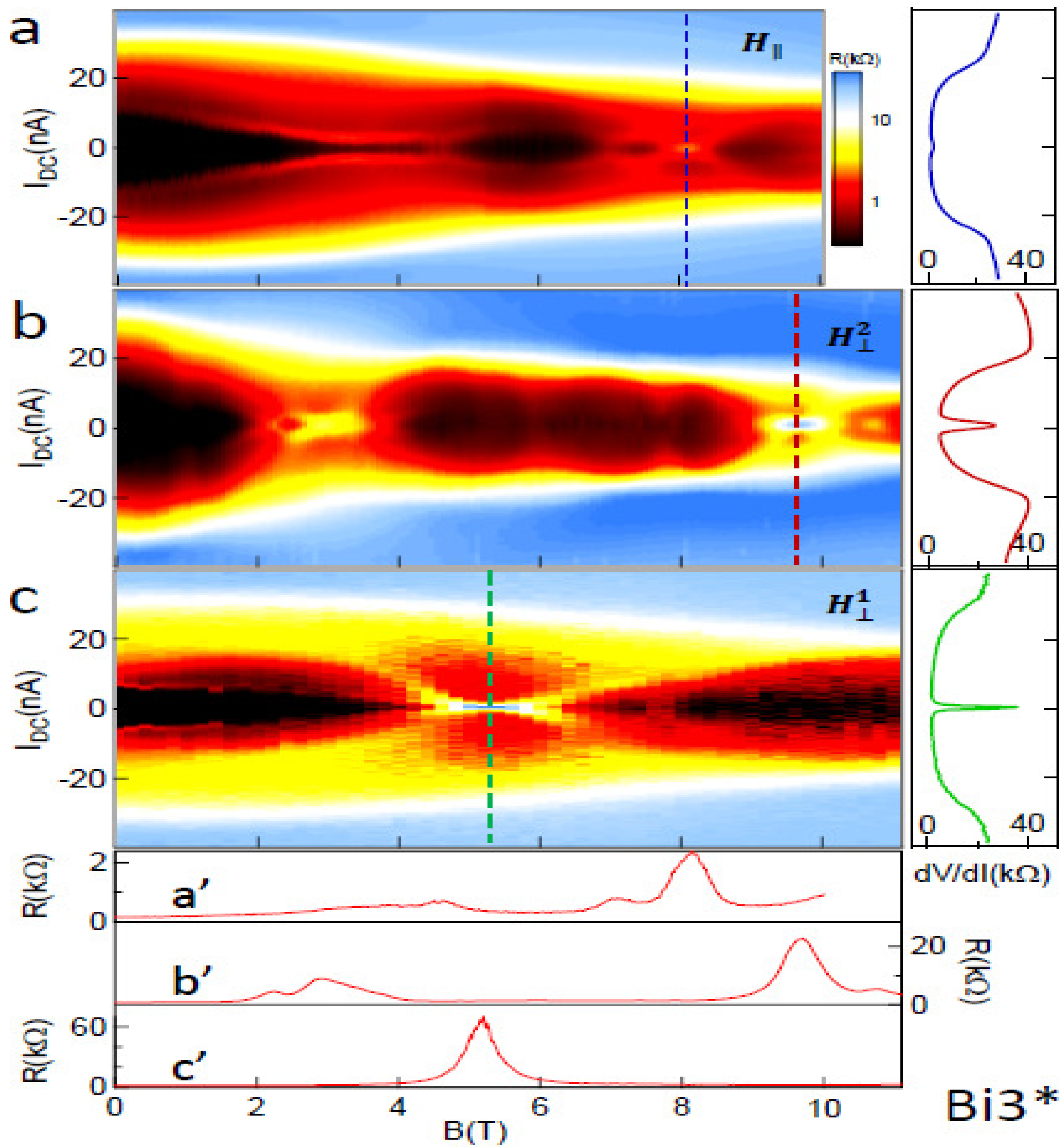
sensitive to Andreev level crossings at 0 and π

rge Field modulations of Ic, depend on the direction of magnetic field

after 1 month at room T…

ons where Ic=0 And R > R_N

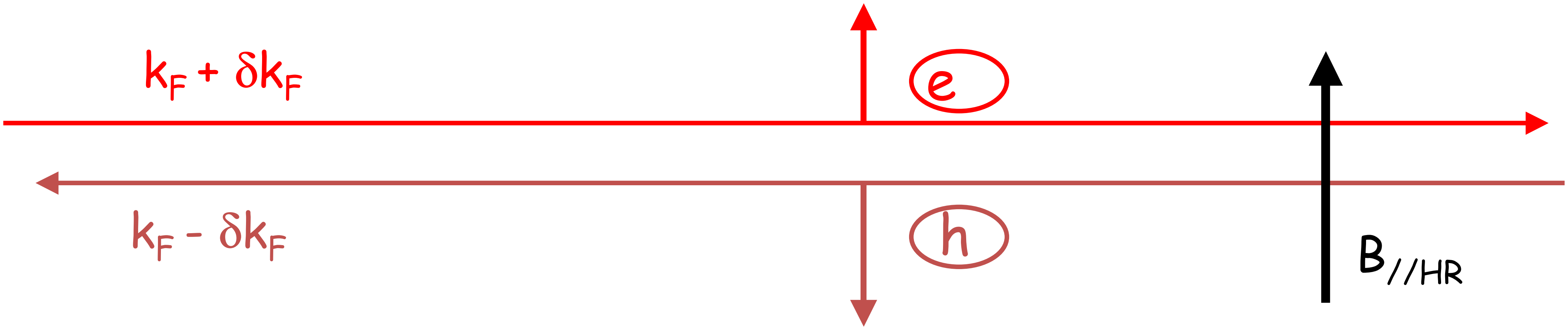
R_N = 30kΩ



Bi3*

Large field modulations of the Supercurrent

eman e/h phase shift along a ballistic channel of length L



$$\delta k_F = E_Z / h\, v_F = g_{eff}\, \mu_B\, B / v_F$$

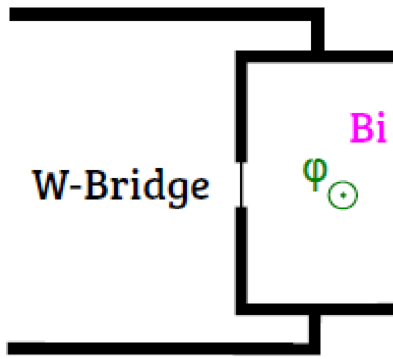
$\phi = 2\pi L\, \delta k_{F} = 2\, g_{eff}\, \mu_B\, B\, L / v_F \sim \pi$ for 1T

$_F = 10^5$ m/s $\quad g_{eff} = 10 \quad L = 2\mu m$

Large field modulations of Ic can be explained!
Full modulation in the single channel limit

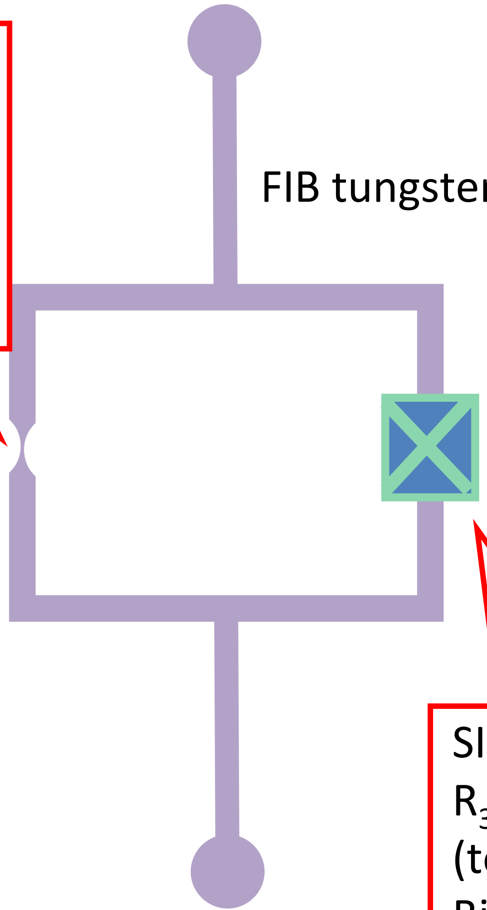
rrent-phase relation ?

be measured in asymmetric squid configuration

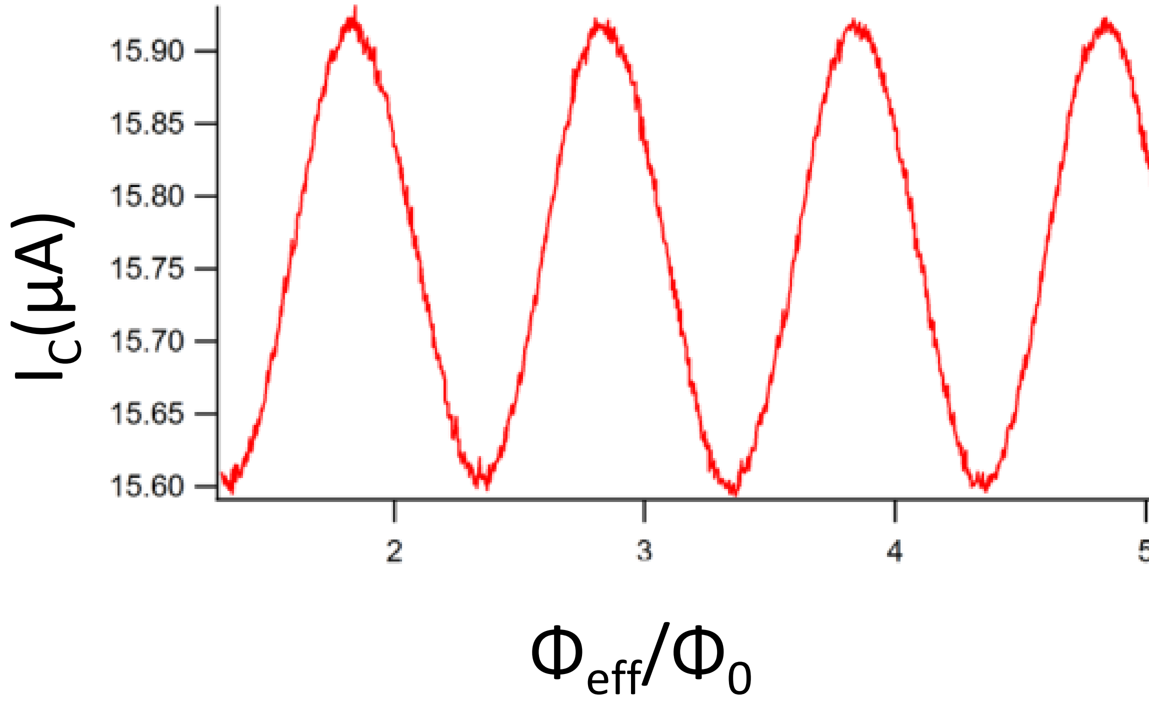


liminary experiment R. Delagrange, A. Murani, R. Deblock, A. Kasumov 2014

riction
link
400Ω

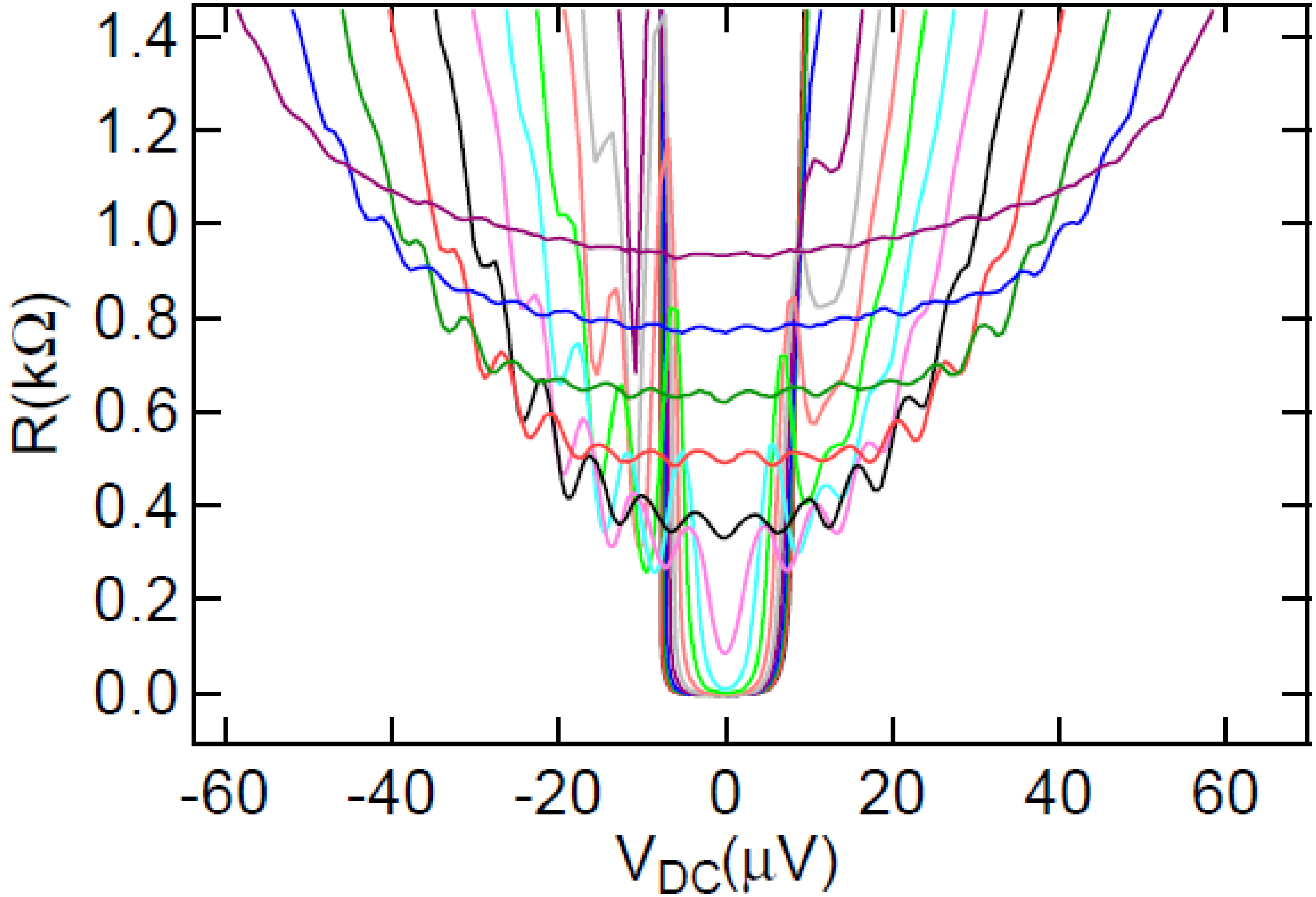


SIS tunnel junction
R_{300K}=900Ω
(to be replaced by
Bi nanowire)



Bi3

Shapiro steps ν=2.2 GHz



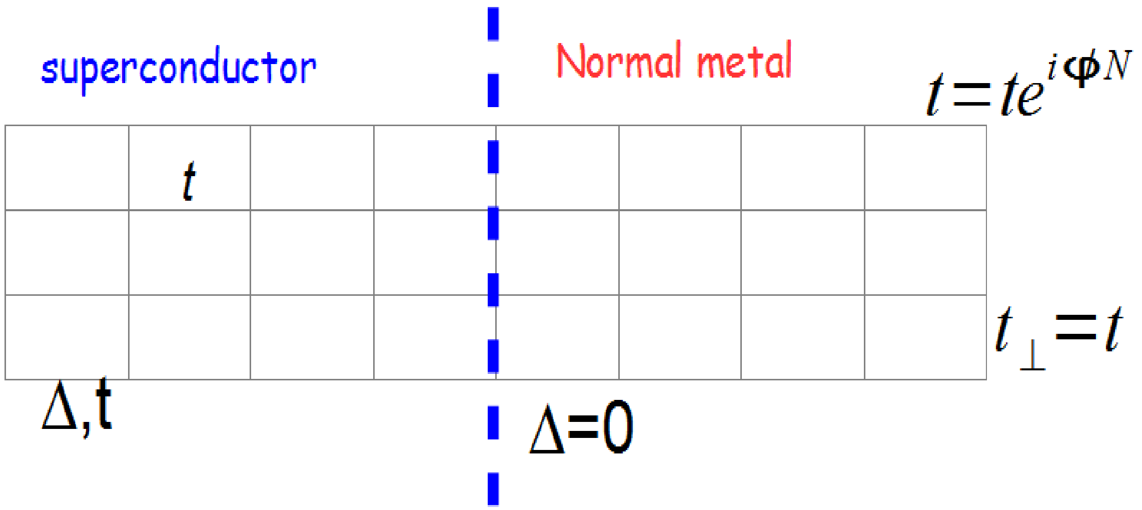
Understanding contribution of spin orbit, superconductivity, disorder, number of channels

ght binding model

uare or hexagonal lattice (H. Bouchiat, A. Chepelianskii, A. Murani, M. Ferr

just disorder, spin-orbit strength, junction length, …

$$H = \Delta c_i^\dagger c_i^\dagger - t \sum c_{i,j}^\dagger c_{i+1,j} + c_{i,j}^\dagger c_{i,j+1}$$

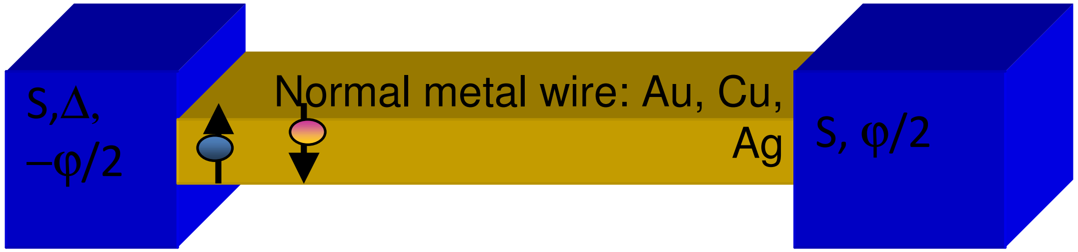


+ periodic boudary condition = SNS ring

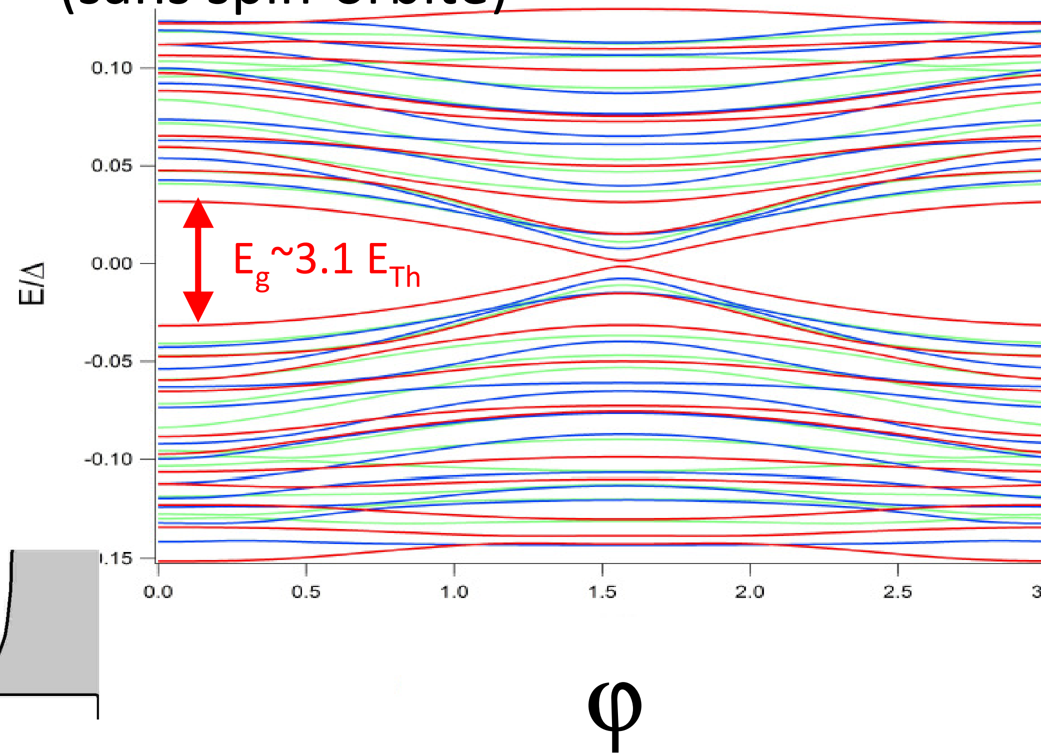
Possible to add disorder

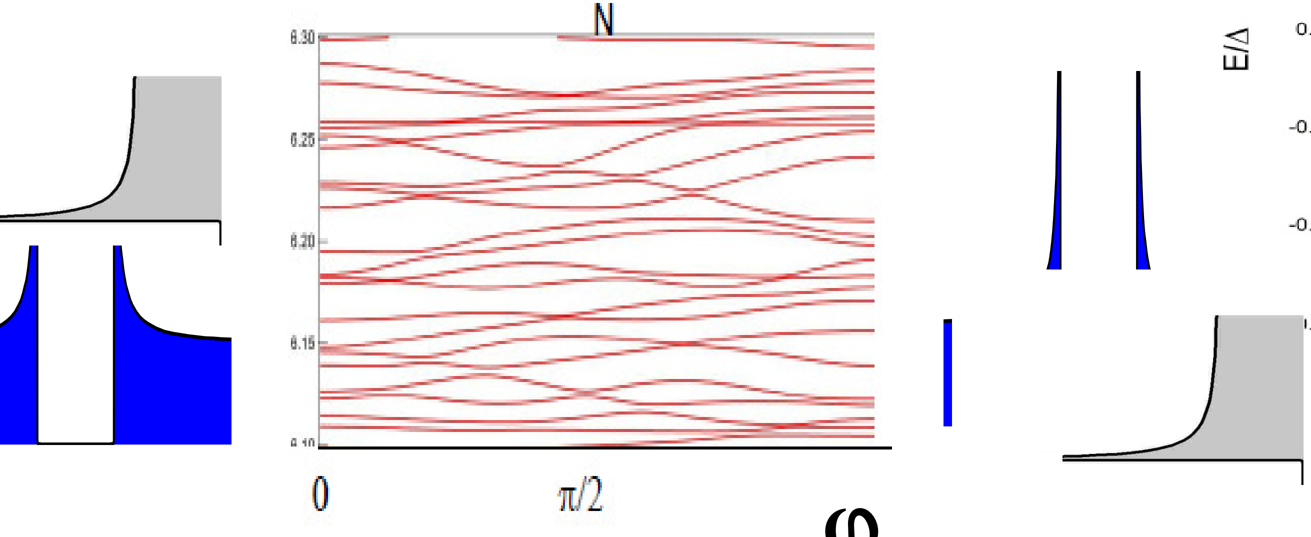
Spectre sans spin-orbite

H. Bouchiat, M. Ferrier



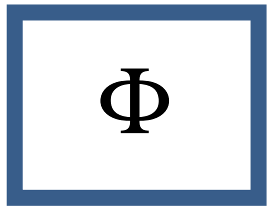
Spectre avec contacts supra
(sans spin-orbite)



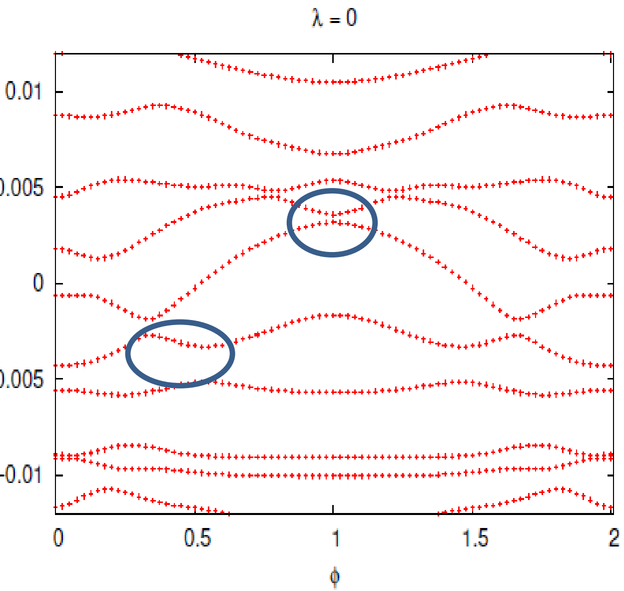


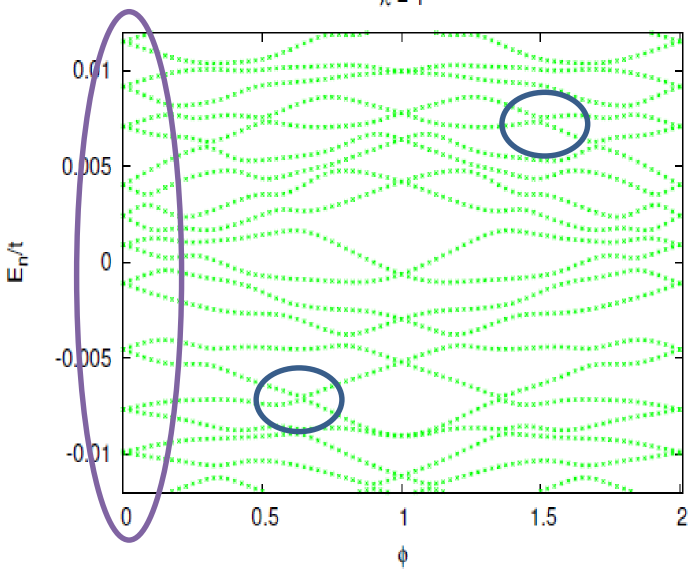
Spectre normal sans spin -orbite

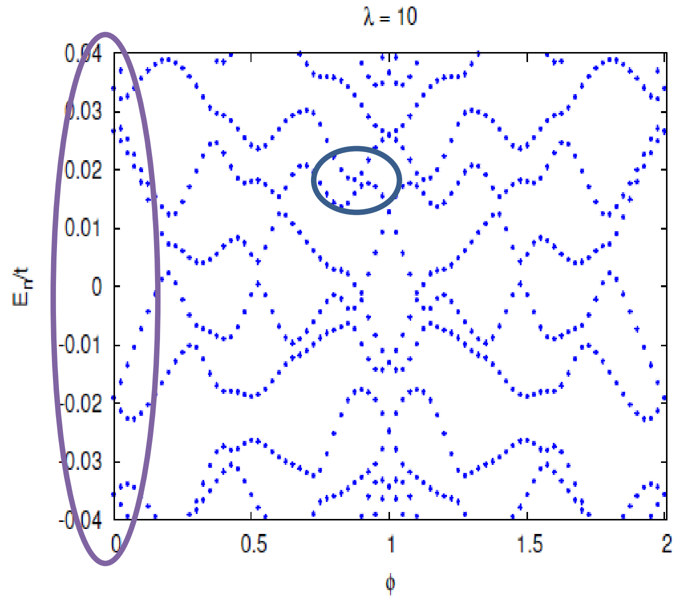
Spectre normal (anneau): effet du spin-orbite



he strength of the spin-orbit interaction, hopping $t = 4$, superconducting gap $\Delta = 0$, disorder $W = 4$, $N_x = 80$,
0, $N_{supra} = 0$.







de spin-orbite

nts dégénérés en spin

oisements évités (couplage par désordre)

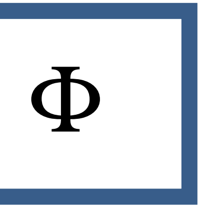
Faible spin-orbite

Fort spin-orbite

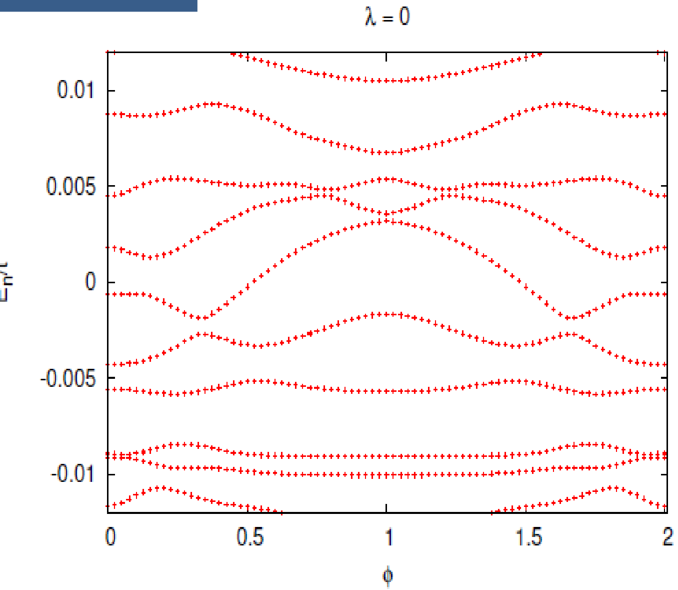
- Dégénérescence de Kramers, à phase nulle.
-« Splitting » de spin
-Certains croisement autorisés : « disparition du désordre »

. Bouchiat, A. Chepelianskii, A. Murani

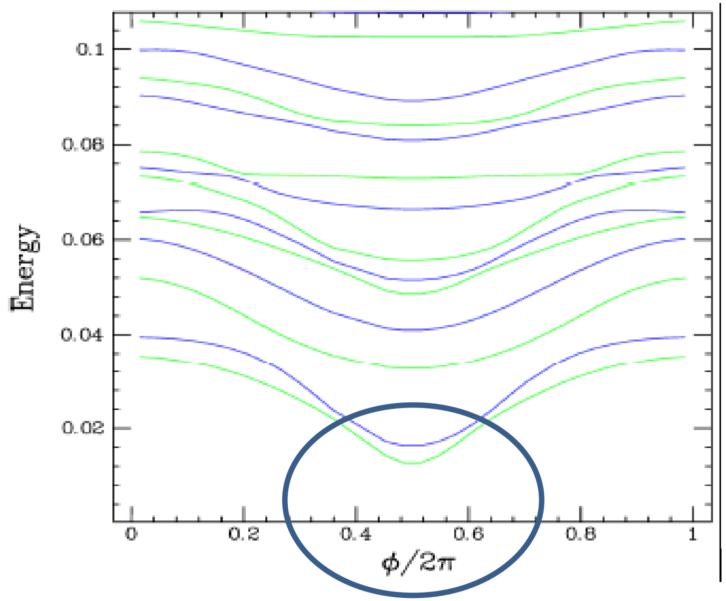
N ring



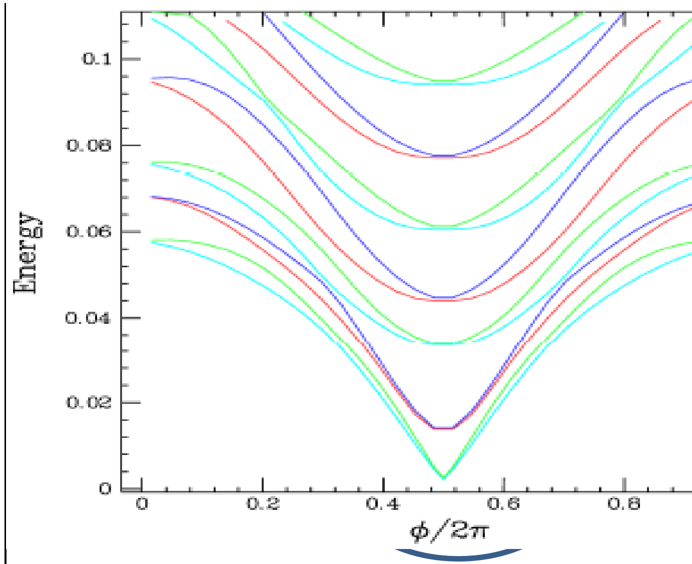
$\varphi=2\pi\Phi/\Phi_0$



SNS Junction



λ=3



N seul, Pas de spin-orbite

Etats dégénérés en spin

Croisements évités (couplage par désordre)

SNS, Pas de spin-orbite

- Etats dégénérés en spin
- Gap induit, ne se ferme pas à π

SNS, avec spin-orbite

-Kramers ,

-levée de la dégénérescence de

-Gap induit se ferme à π:

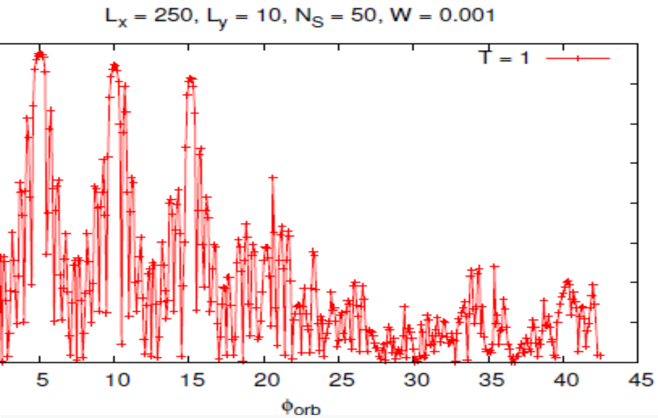
disparition du désordre! (certai

$$\text{supercurrent} \quad I_s \propto \frac{\partial \epsilon_n}{\partial \phi}$$

Chepelianskii, A. Murani, HB

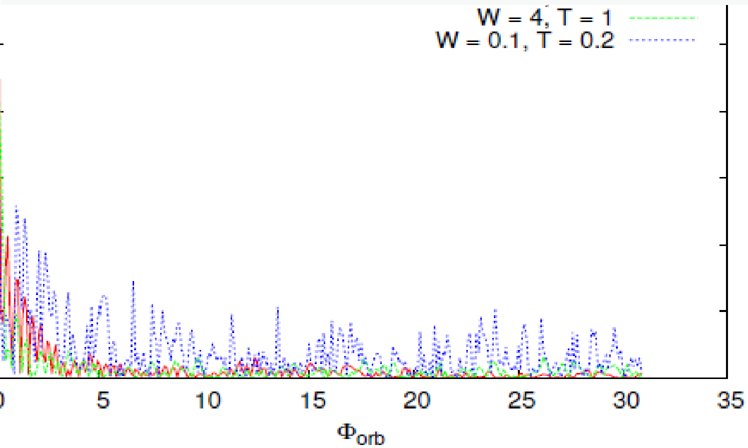
Alexei Chepelianskii: test non extinction du courant critique à fort champ

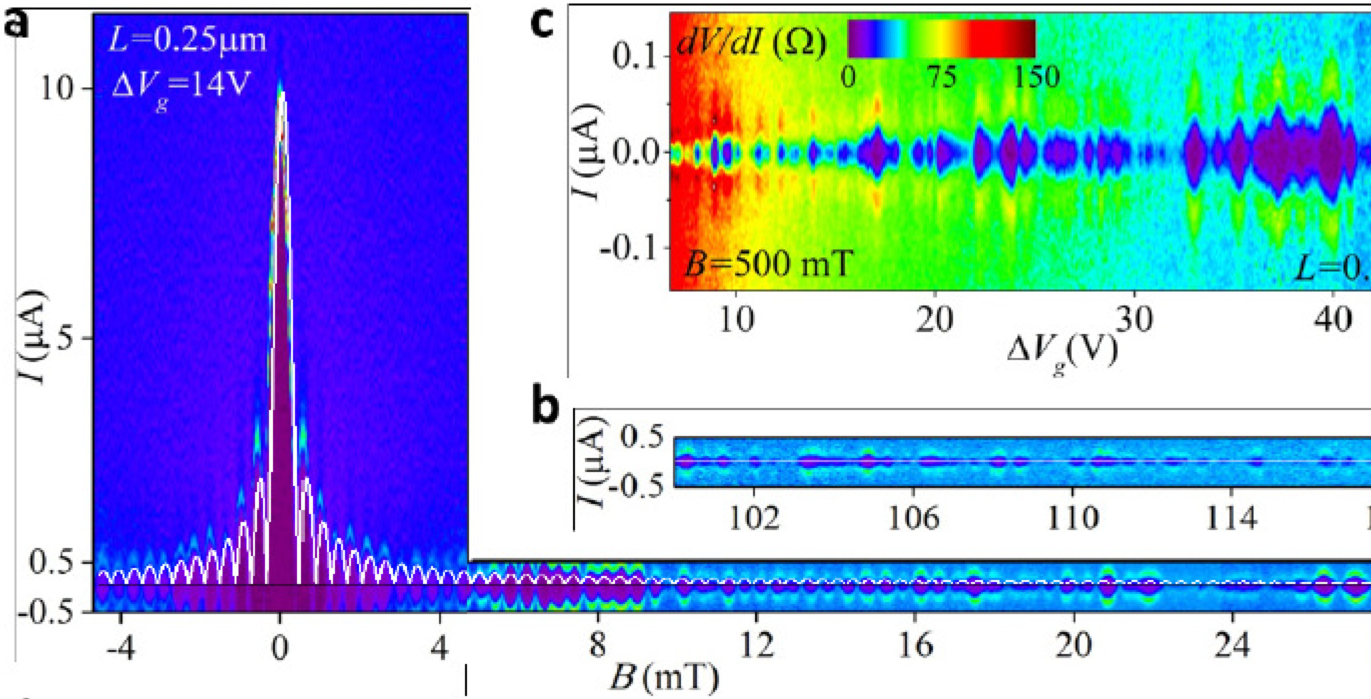
u de canaux de conduction, courant critique oscille, ne décroit pas avant 50 quanta de



Ballistique, 10 canaux

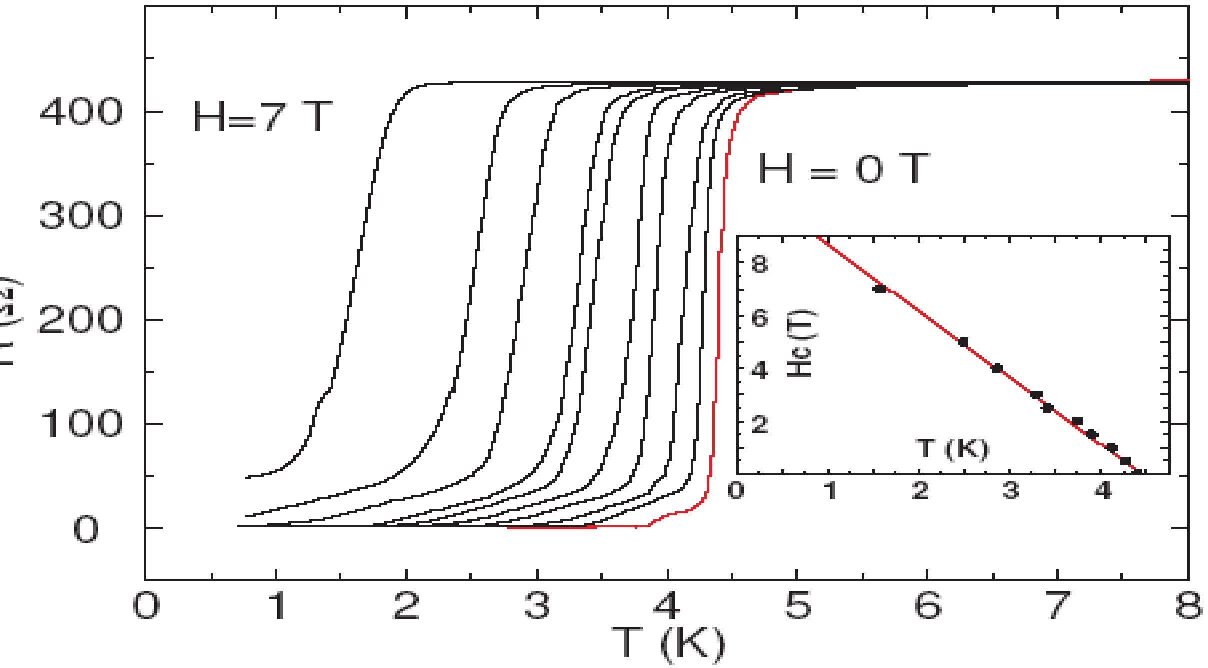
ucoup de canaux de conduction,
rant critique décroit à qq quanta, n
't courant critique subsiste jusqu'à
ucoup plus fort champ

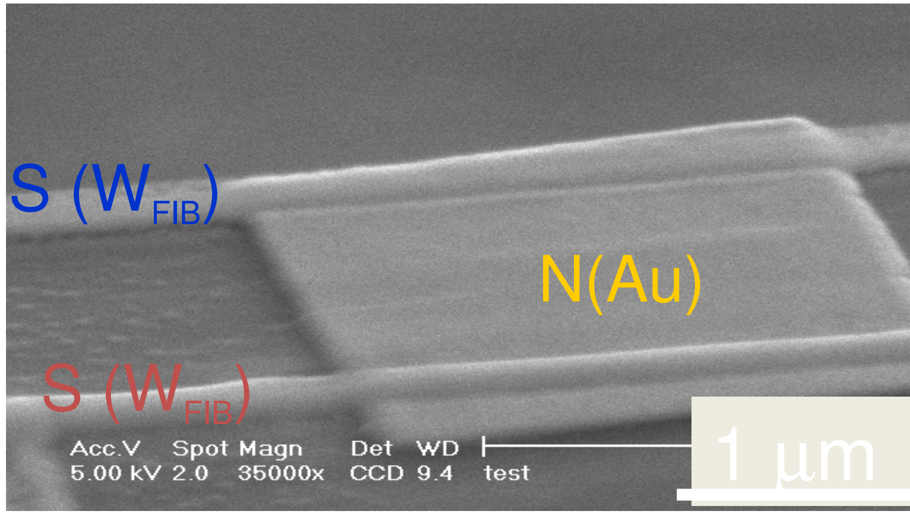




Exp S/ballistic Graphene/S, Geim, Avril 2015

operties of FIB deposited « tungsten » nanowires





ger analysis :
gsten
% carbon
% Ga
oxygen

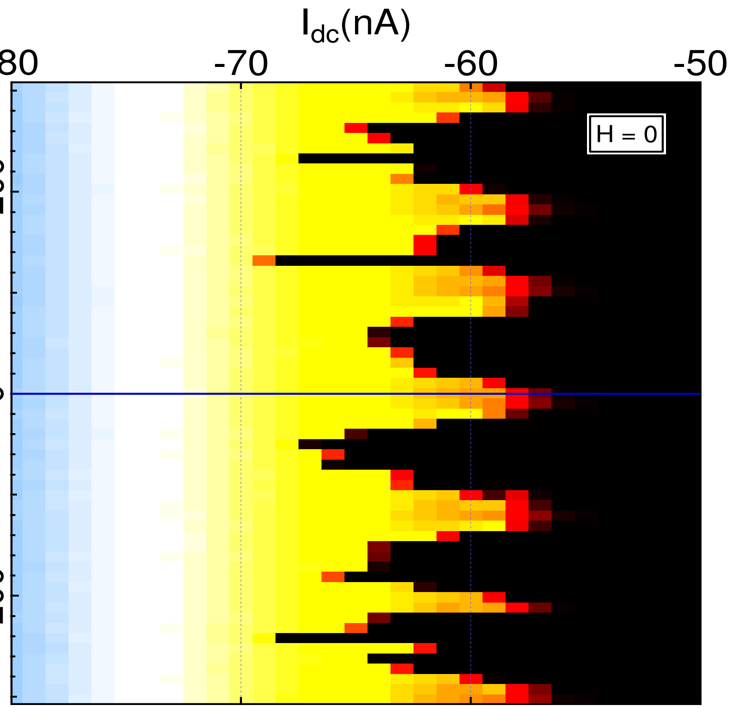
T_C = 4-5 K, H_C = 12 T (pure W has T_c of less than 100 mK !)
Length = several microns, typical width = 100 nm to 500nm

Very reproducible superconducting parameters
Nice electrodes for investigation of proximity effect…

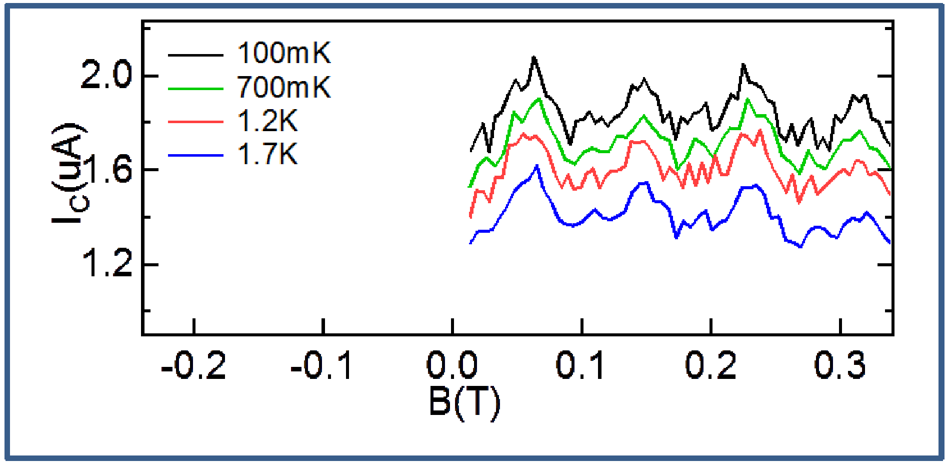
Kasumov et al: 2005

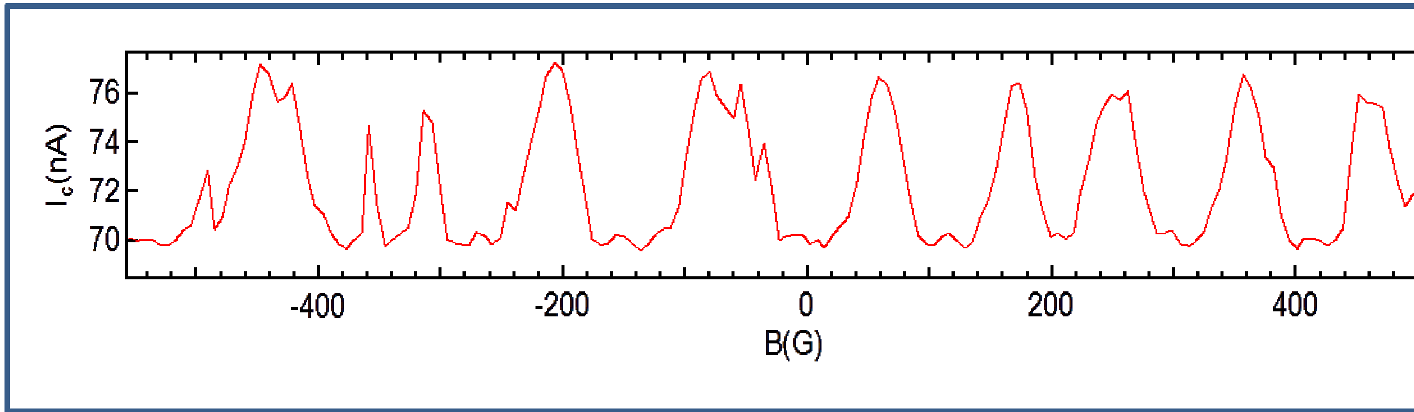
pen questions…

junction SQUID?



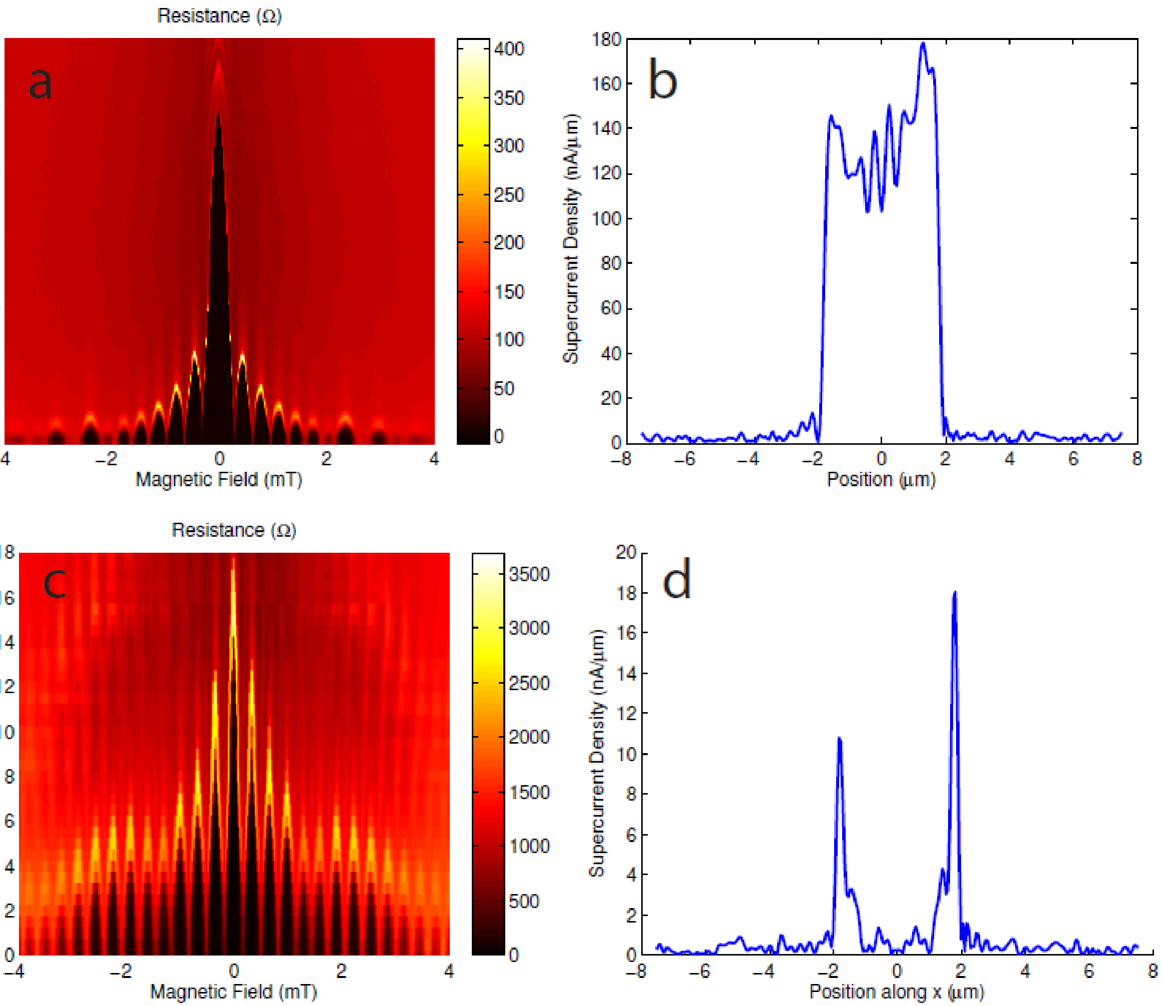
different samples which have Ic
scillations show always minimum
t zero field.

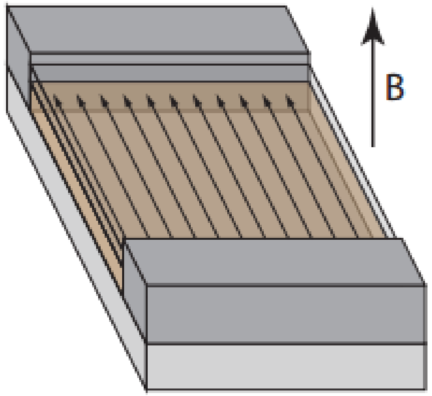




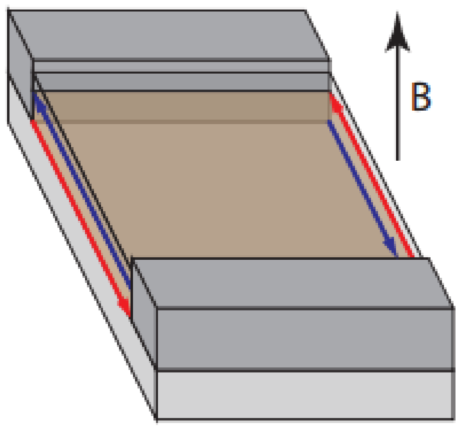
imilar to proximity effect in Quantum Spin Hall Effect

gTe/HgCdTe quantum wells, Yacoby Molenkamp, 2014



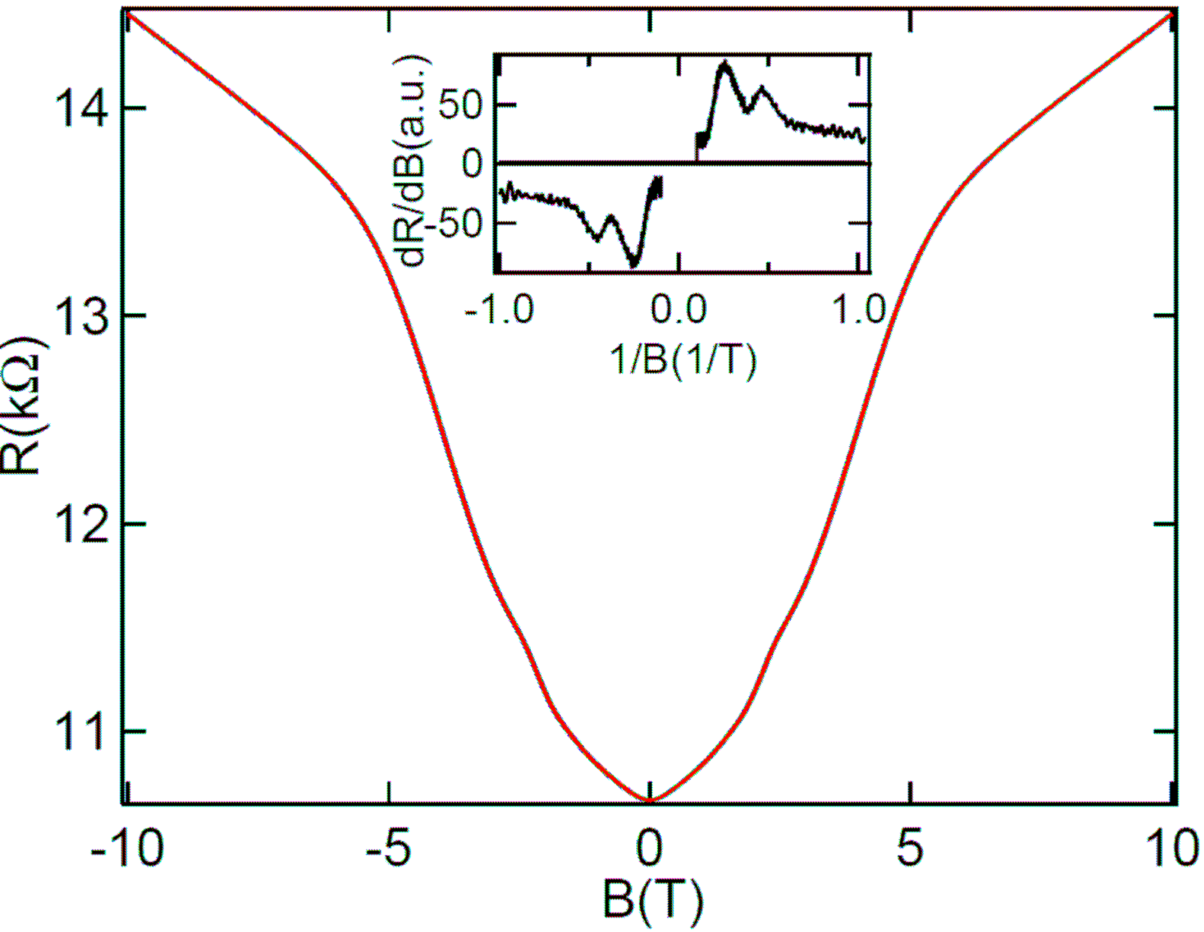


V_g=1.05V trivial transport, uniform supercurrent density



V_g=-0.425V, supercurrent flows via helical edges states!

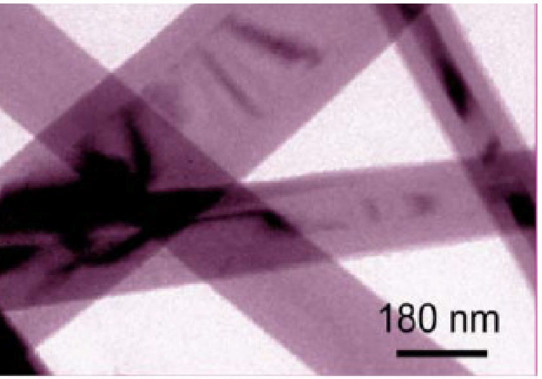
Shubnikov de Haas oscillations seen at T>Tc

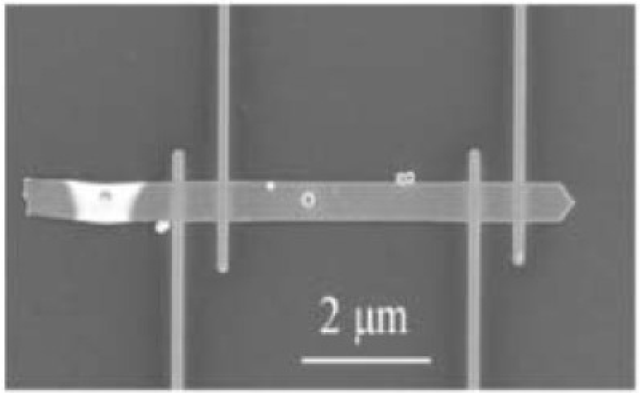


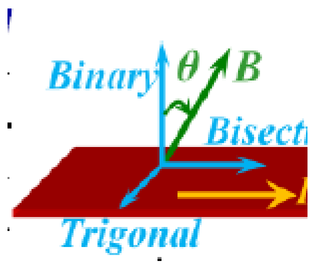
T=6K

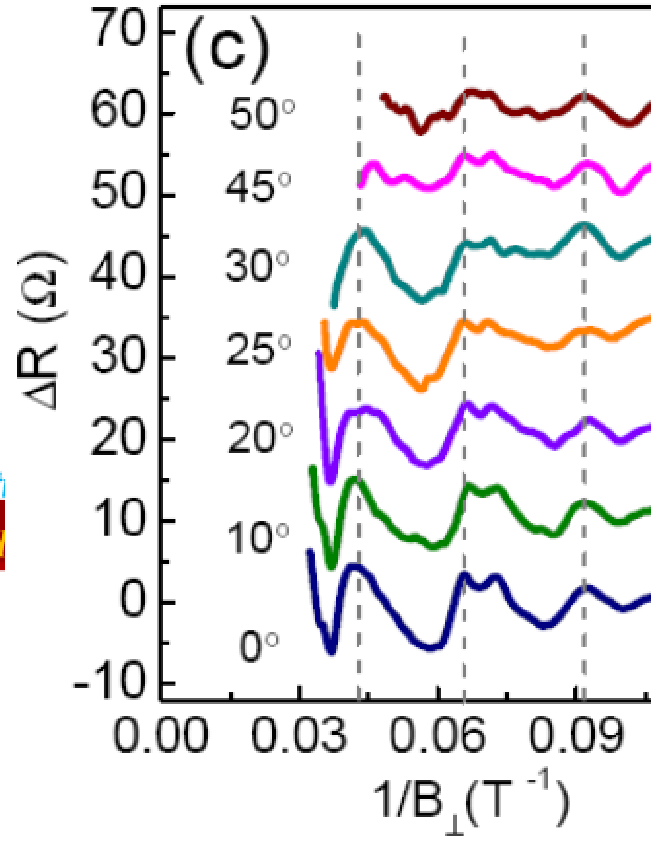
Dirac-type surface states on Bi nanoribbons

ing et al. (2014) arXiv:1404.5702:
10), 50 nm thick



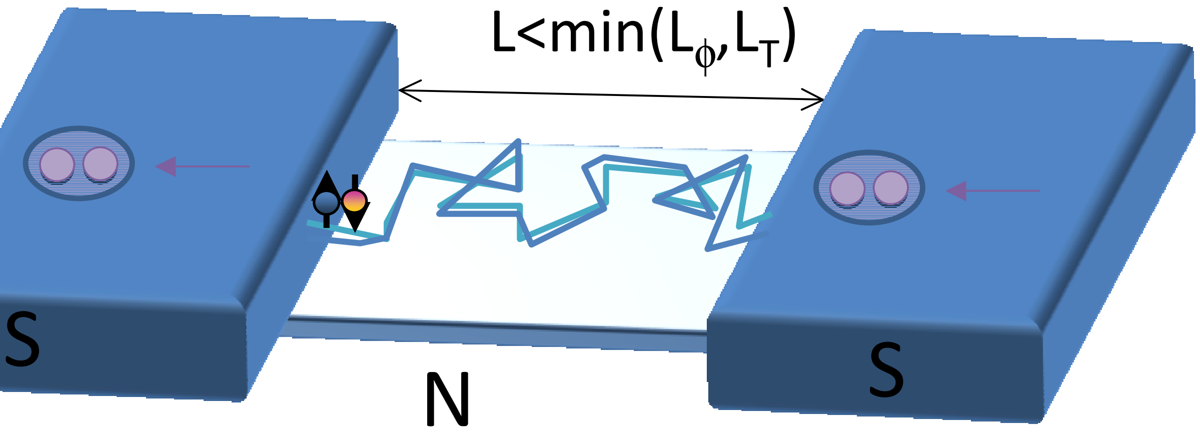






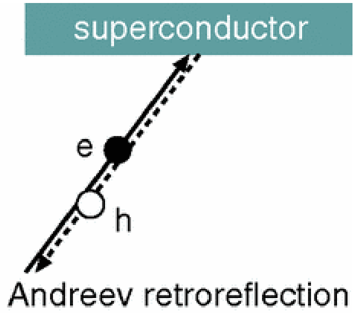
- SdH oscillations with 1/2-shifted behavior (i.e. $\gamma=1/2$): Dirac electrons on the surface

Proximity effect



$$\Delta\varphi = k\Delta l + \frac{e}{\hbar}\oint \vec{A}\cdot d\vec{l} = k\Delta l + 2\pi\frac{\phi}{\phi_0}$$

Andreev reflection



Time reversal symmetry

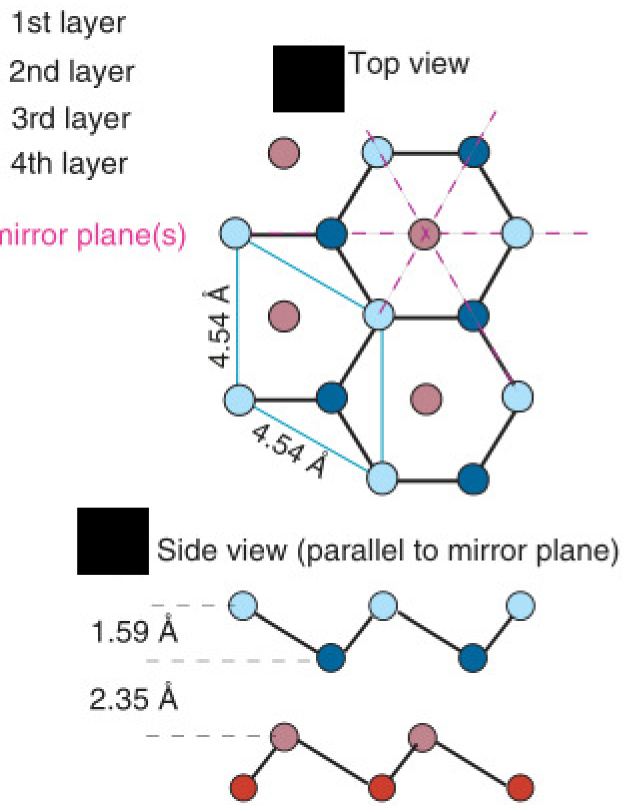
$$\Delta\varphi = \underbrace{\int \vec{k}\,\mathrm{d}\vec{l}}_{e} - \underbrace{\int (-\vec{k})\,\mathrm{d}\vec{l}}_{h} = 0$$

Constructive interferences

Proximity effect is a very sensitive probe of coherence, spin properties in different systems

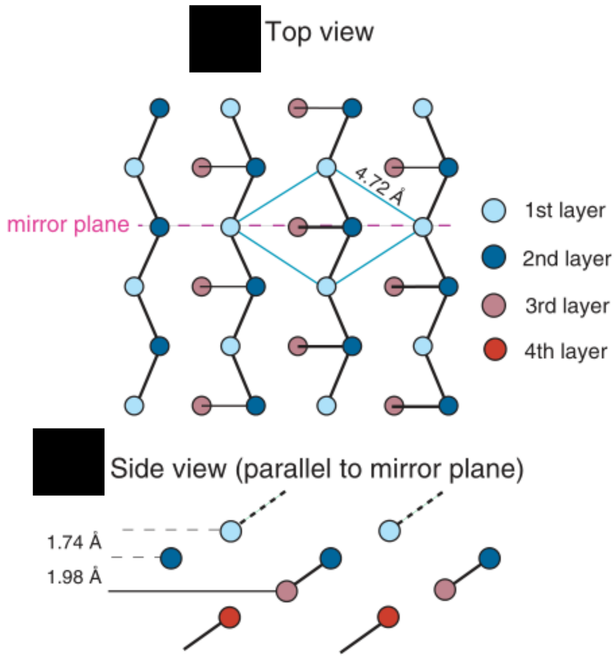
Bi thin film and surface structure

Truncated-bulk for (111)

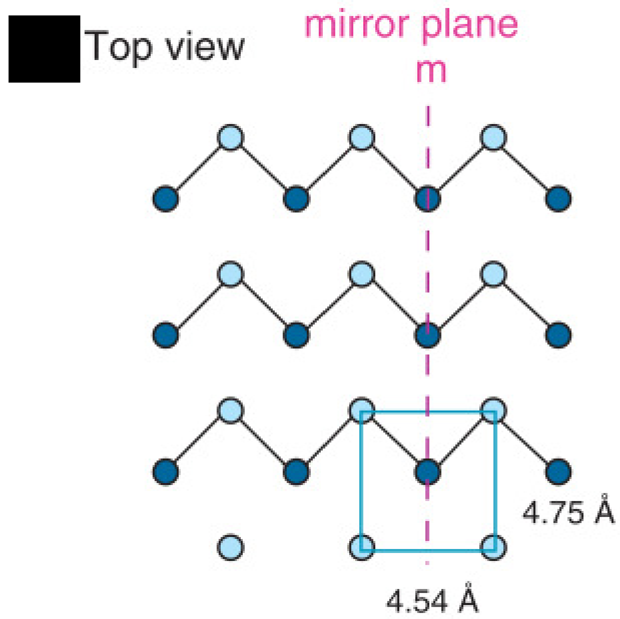


Mönig PRB 72 (2005) 085410

Truncated-bulk for (110)



Truncated-bulk for (100)



Long de Broglie wavelength ~120Å

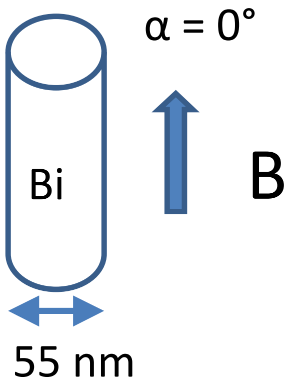
Semimetal – semiconductor transition at a critical thickness: 320Å

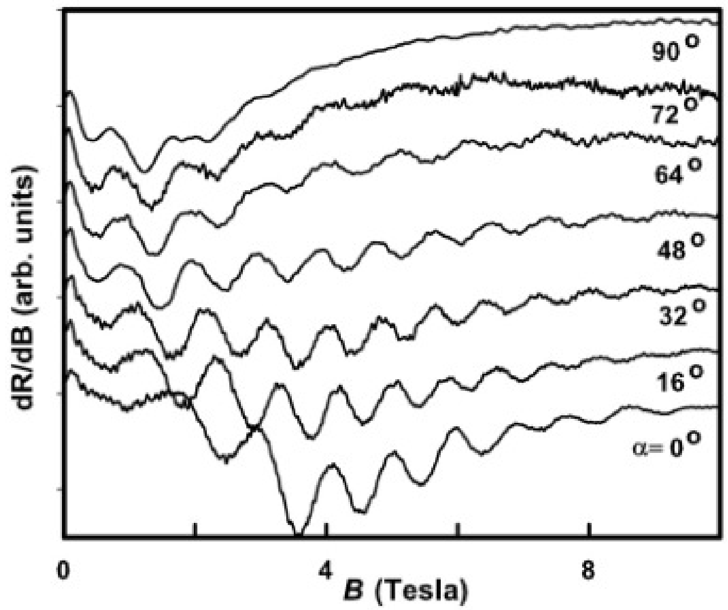
C.A. Hoffman PRB (1993)

What do you get with Bi nanowires?

liameter $\lesssim (\lambda_F^{bulk} = 50 \text{ nm})$, wire is only surface!

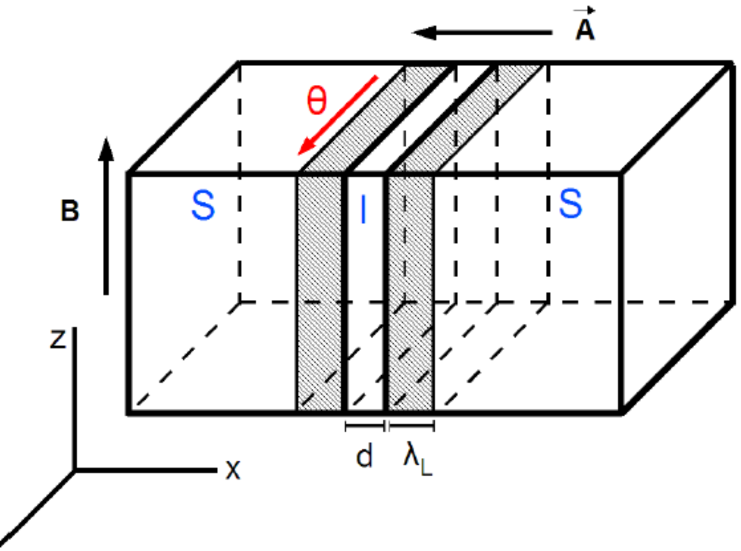
of: Aharonov-Bohm oscillations in parallel field (Nikolaeva 2008)

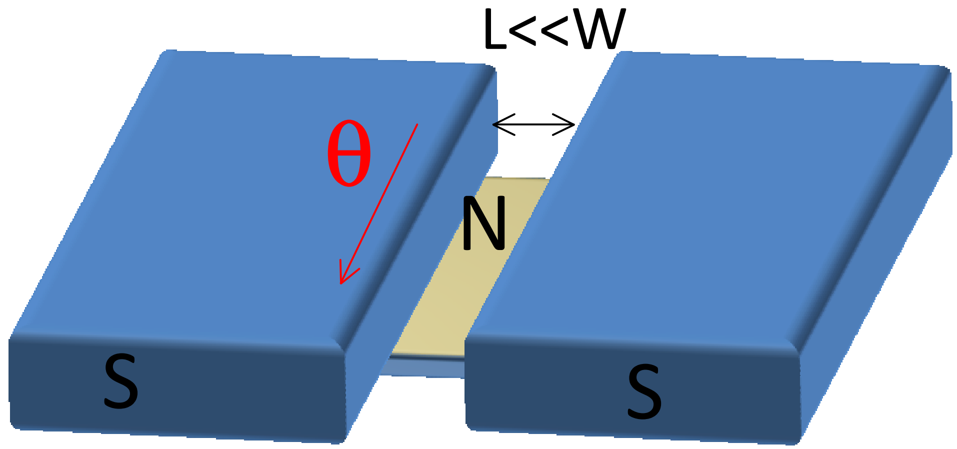




Clear period: as if cylinders are hollow: only surfaces?

Oscillatory decay for a planar SIS or **wide SNS junction**



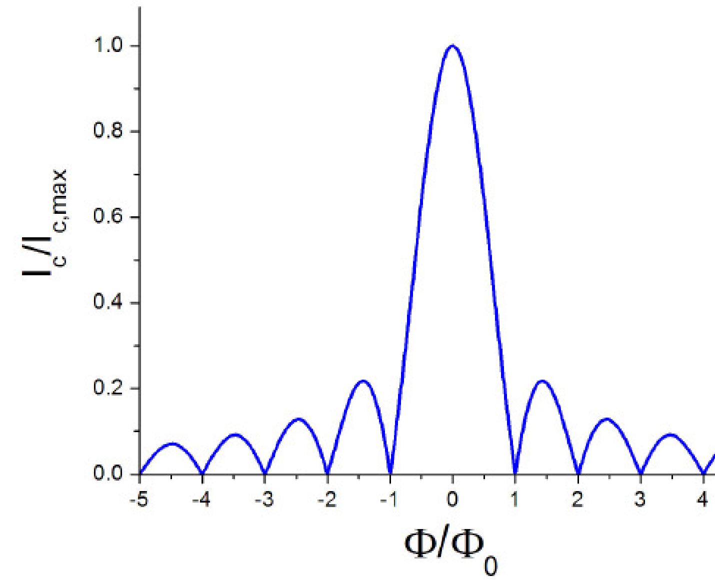


x dependent phase variation at boundary θ(y)

$$\Delta\theta = 2\pi\frac{2e}{h}\int_{-\lambda_{L,d}}^{d+\lambda_{L,d}} A_x dx = 2\pi\frac{2e}{h} B\, l\, y = 2\pi\frac{\Phi_J(y)}{\Phi_0}$$

$$j = j_c \sin\left(\delta + 2\pi\frac{\Phi_J(y)}{\Phi_0}\right)$$

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



Fraunhoffer pattern for a wide junction