Topological superconductivity revealed by nanoscale Josephson junctions

S. Charpentier, L. Galletti, G. Kunakova, R. Arpaia, Y. Song, R. Baghdadi, A. Kalabouchov, E. Olsson D. Golubev, J. Linder, S. M. Wang, F. Tafuri, T. Bauch and F. Lombardi

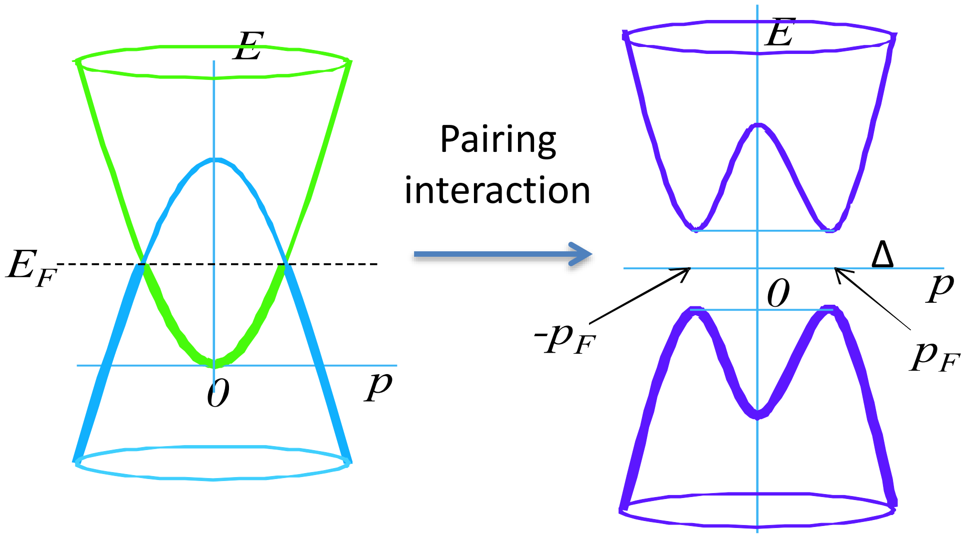
Vetenskapsrådet

Knut och Alice Wallenbergs Stiftelse

Notion of Topological Superconductivity has been identified with the proof of existence of Majoranas bound states → Topological Quantum Computation

In particle physics Majorana fermion are described by $\gamma^{+} = \gamma$

Why can we get Majoranas in Superconductors?



BCS pairing with spinless fermion Bogoliubov quasiparticle:

$$\gamma_E^{+} = \gamma_{-E}$$

Zero energy states are required !

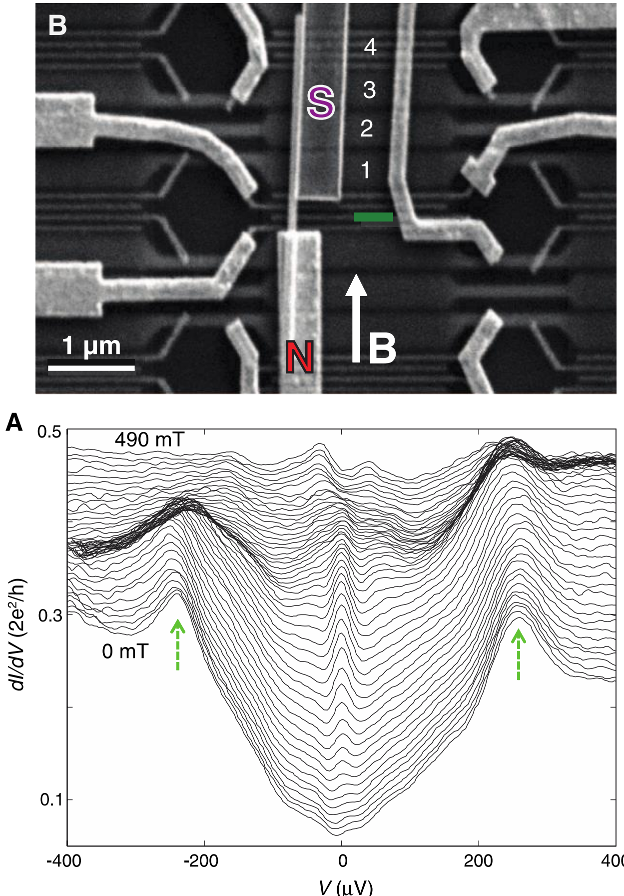
Search for Majoranas in Condensed Matter:

1) Hybrid systems with semiconductors and superconductors:
R. Lutchyn,J. Sau, S. Das Sarma PRL, 105 077001 (2010) ,
Y. Oreg, G. Refae, F. Von Oppen lPRL, 105 177002(2010)

www.sciencemag.org SCIENCE VOL 336 25 MAY 2012

Signatures of Majorana Fermions in Hybrid Superconductor-Semiconductor Nanowire Devices

V. Mourik,[1*] K. Zuo,[1*] S. M. Frolov,[1] S. R. Plissard,[2] E. P. A. M. Bakkers,[1,2] L. P. Kouwenhoven[1†]



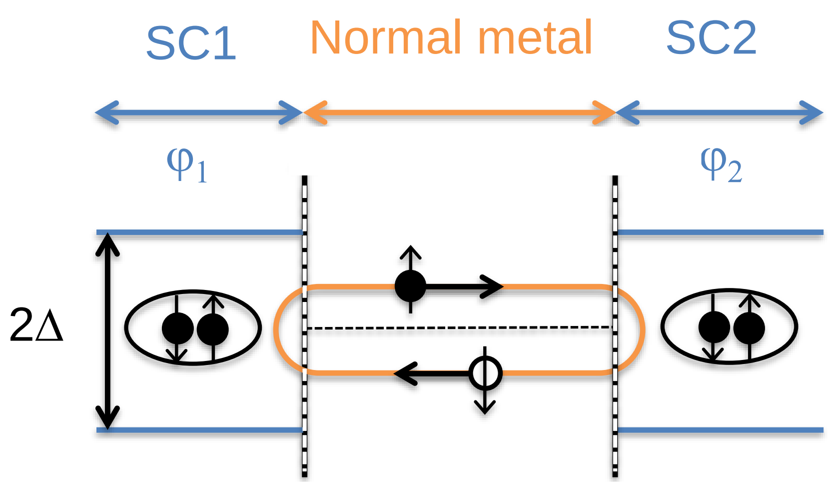
Zero bias peak phenomenology

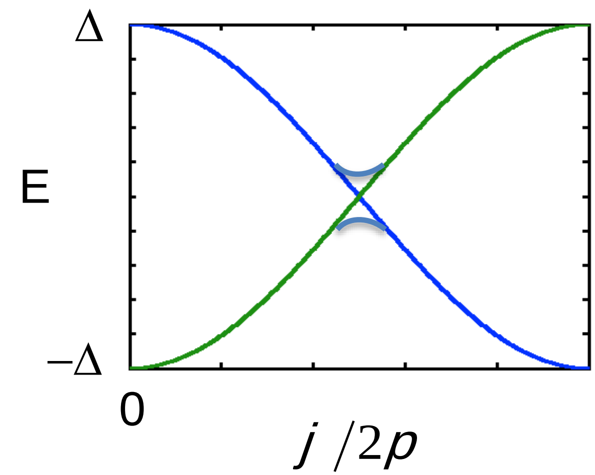
2) Hybrid systems with topological insulators and superconductors

Signature of Majoranas bound states in the Josephson effect phenomenology

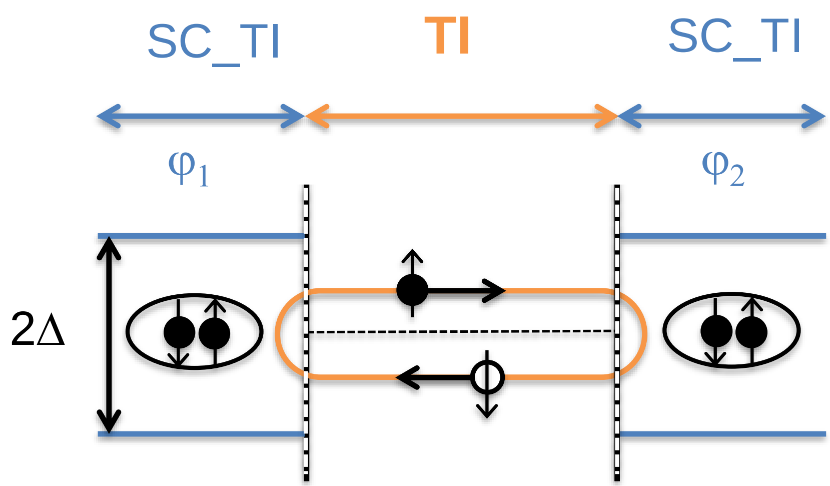
3) Topological /unconventional superconductors, ferromagnetic atomic chains on superconductors……..

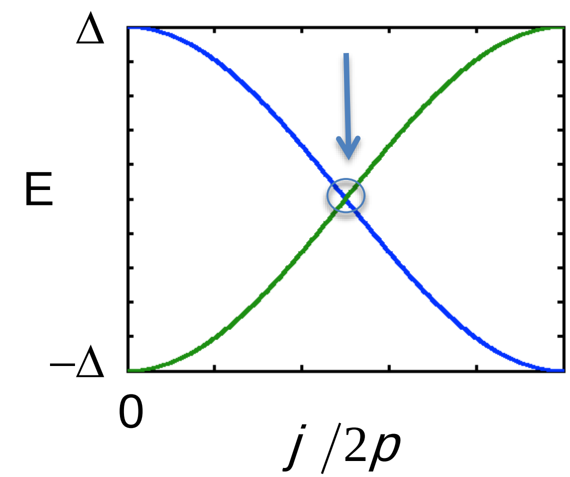
Why Josephson junctions with Topological insulators ?



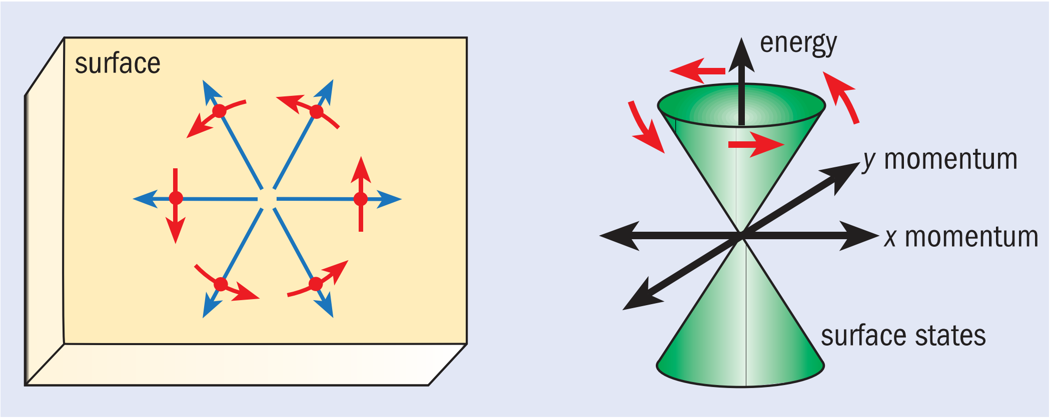


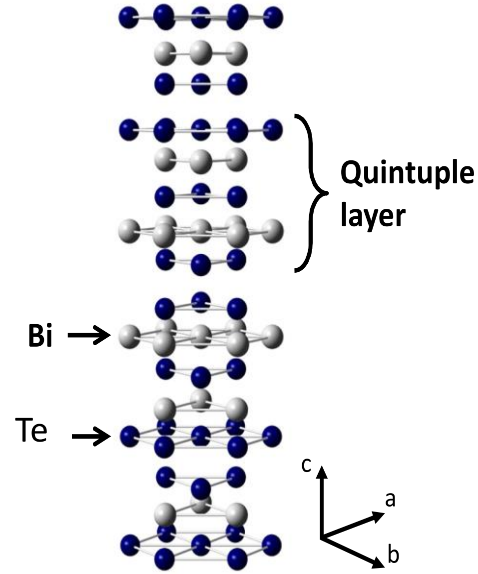
Crossing is protected



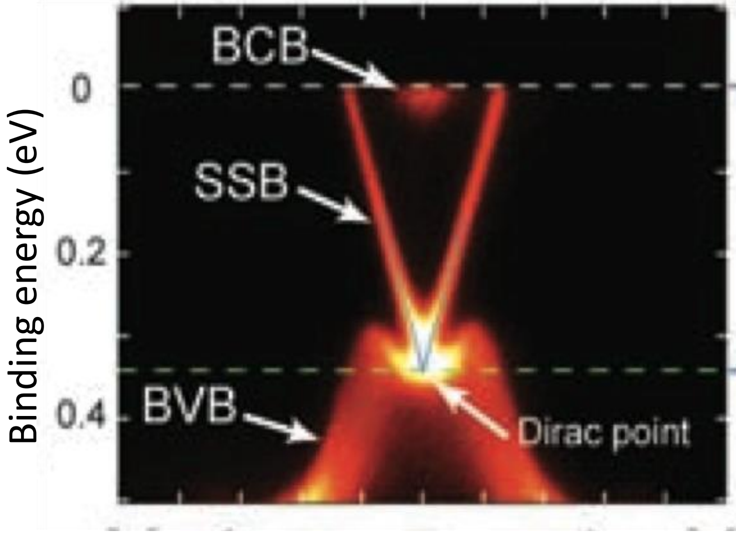


3D Topological insulators: Bi-based compounds





The surface states of a 3D TI supports electronic motion in any direction along the surface , but the direction of the electron's motion uniquely determines its spin direction and viceversa (spin momentum locking) → **backscattering is forbidden.**



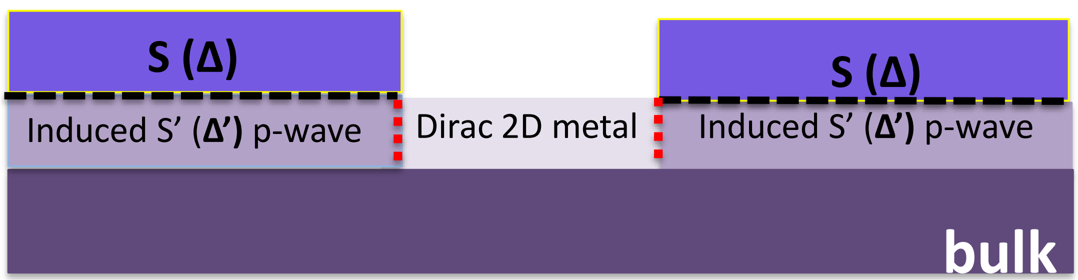
Z.X.Shen group **Science** 325, 178 (2009)

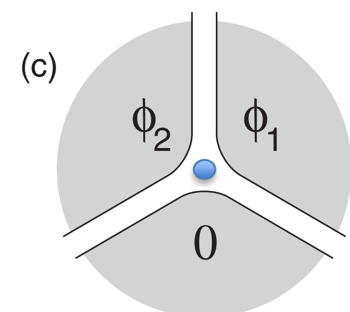
PRL **100,** 096407 (2008) PHYSICAL REVIEW LETTERS week ending 7 MARCH 2008

Superconducting Proximity Effect and Majorana Fermions at the Surface of a Topological Insulator

Liang Fu and C. L. Kane
Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA
(Received 11 July 2007; published 6 March 2008)

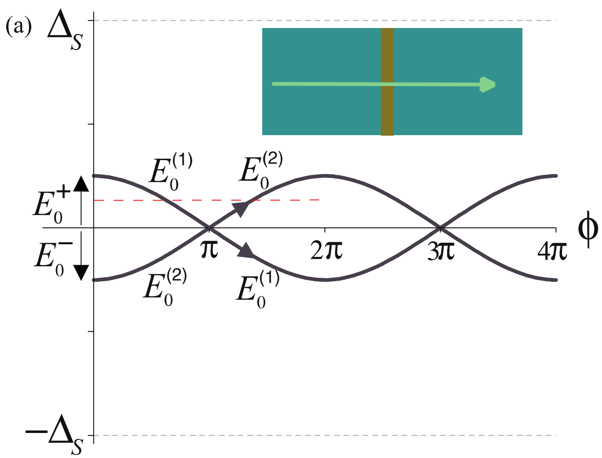
We study the proximity effect between an s-wave superconductor and the surface states of a strong topological insulator. The resulting two-dimensional state resembles a spinless $p_x + ip_y$ superconductor, but does not break time reversal symmetry. This state supports Majorana bound states at vortices. We show that linear junctions between superconductors mediated by the topological insulator form a nonchiral one-dimensional wire for Majorana fermions, and that circuits formed from these junctions provide a method for creating, manipulating, and fusing Majorana bound states.



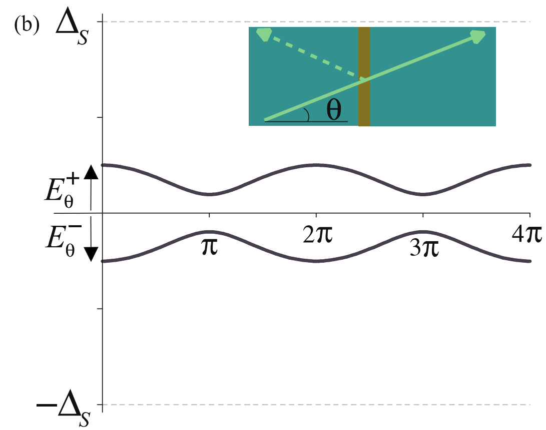


Majoranas localized at the trijunction

Perpendicular and off perpendicular trajectories in multimode TI Josephson junctions



4π-periodic CPR



2π-periodic CPR

G. Tkachov , E.M. Hankiewicz
PRB 88 074401 (2013)
similar results shown by:
M. Snelder et al.
PRB **87,** 104507 (2013)

$$J(\varphi) = \frac{2\pi}{\Phi_0}\frac{dE_J}{d\varphi}$$

$J_S(\varphi)$ Is **non sinusoidal** even for low transparency junction

Order parameter symmetry is of the type ***p+s*** where the p term consists of chiral $p_x + ip_y$ and $p_y - ip_y$ which sum up to the s term through Pauli matrices

Signature of sin(φ/2) CPR associated to Majorana bound states

nature COMMUNICATIONS

ARTICLE

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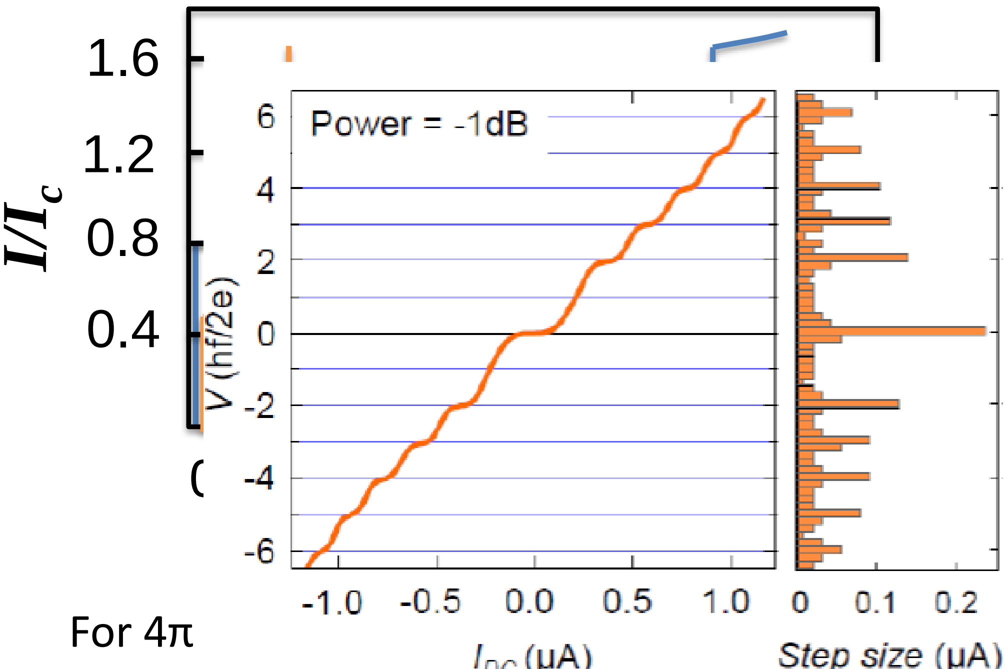
DOI: 10.1038/ncomms10303 OPEN

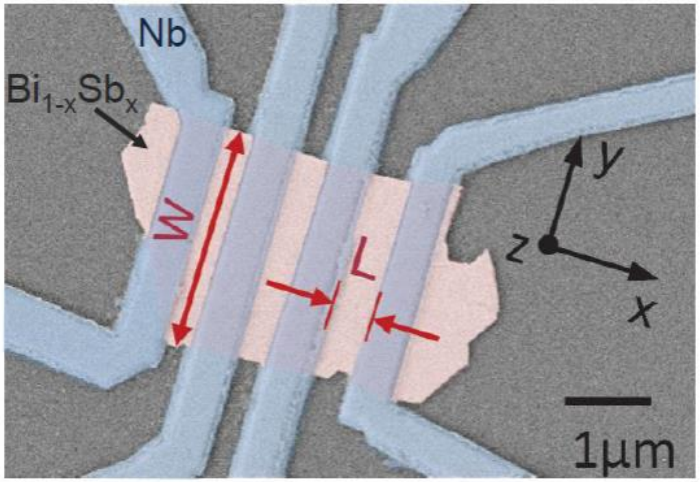
4π-periodic Josephson supercurrent in HgTe-based topological Josephson junctions

J. Wiedenmann[1,*], E. Bocquillon[1,*], R.S. Deacon[2,3,*], S. Hartinger[1], O. Herrmann[1], T.M. Klapwijk[4,5], L. Maier[1], C. Ames[1], C. Brüne[1], C. Gould[1], A. Oiwa[6], K. Ishibashi[2,3], S. Tarucha[3,7], H. Buhmann[1] & L.W. Molenkamp[1]

Shapiro steps occur at:

$$V_n = n\frac{\Phi_0}{p}\omega_1$$





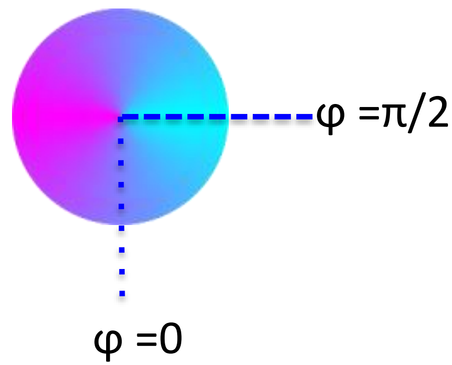
For 4π

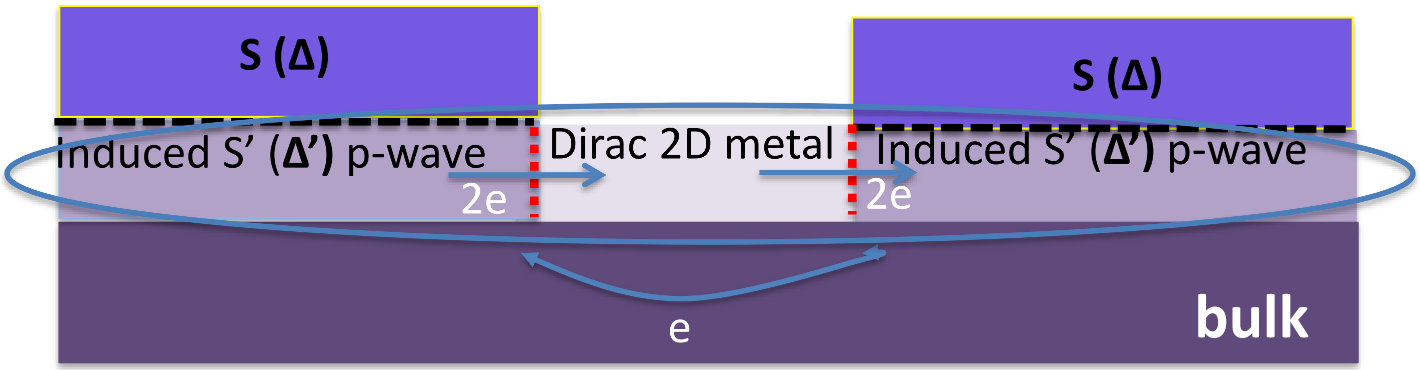
steps

Courtesy Brinkman Group Twente University

Searching for the chiral p_x+ip_y induced order parameter: phase sensitive experiments

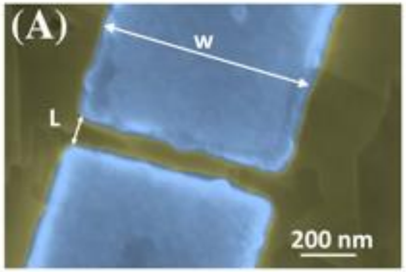
chiral p_x+ip_y

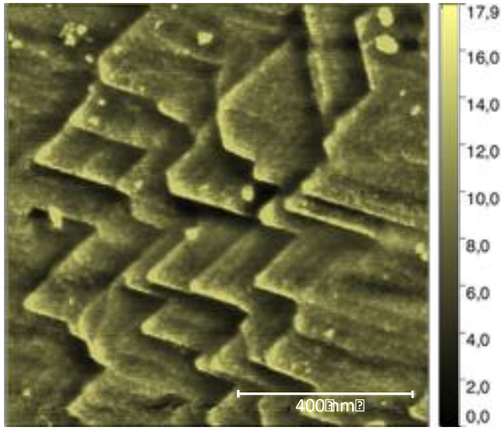




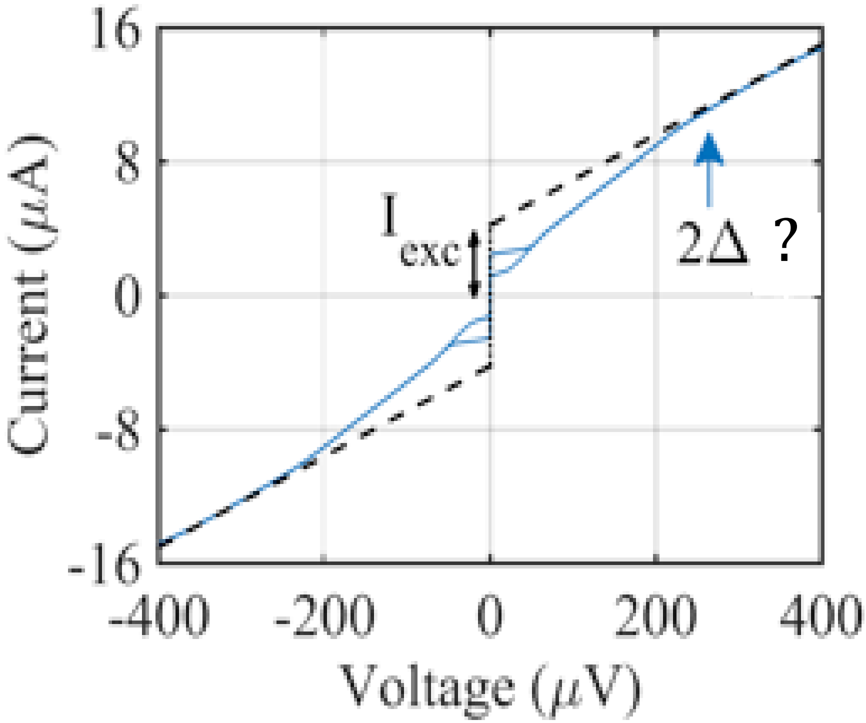
Engineer high transparent interfaces (Δ' ≈ Δ) between the S/TI and understand the physical system under study

Al-Bi_2Te_3-Al Josephson junction using flakes from MBE films

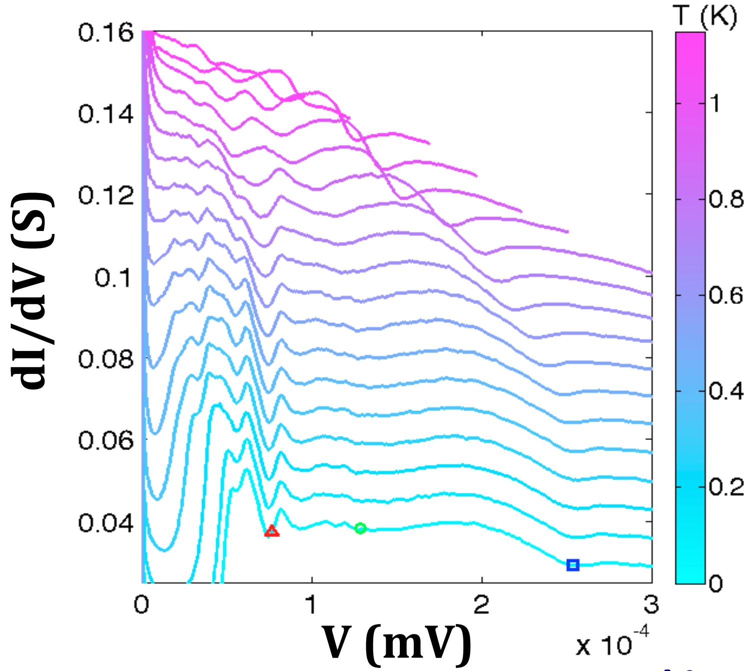


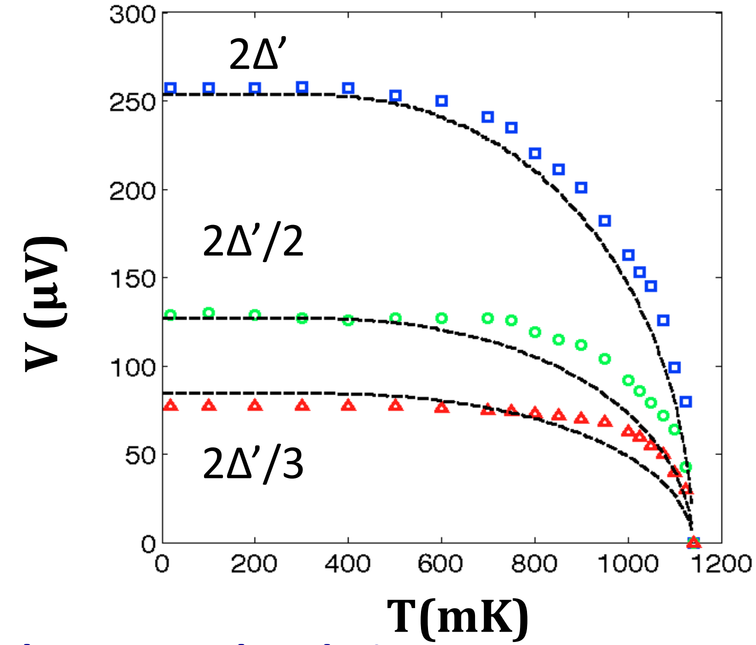


GaAs(111) 1° vicinal cut (-1,-1,2)
n_{2D}= 10^{13} cm^{-2} , μ= 2000 cm^2 V^{-1} s^{-1}

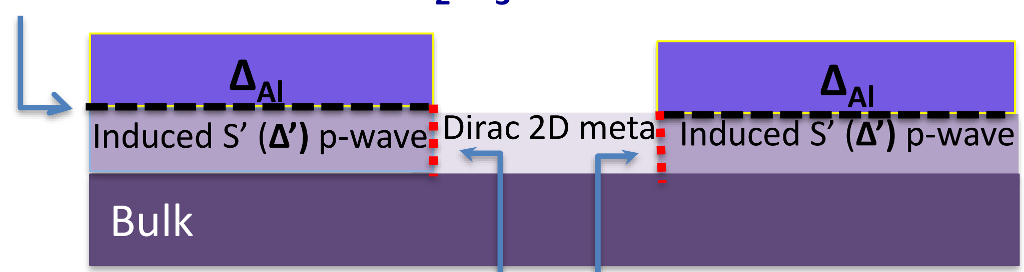


Gap structures in the IV characteristic





Good interface between Al and Bi_2Te_3



1) $\Delta_{Al} \approx 175$ μeV we observe $\Delta' \approx 125$ μeV

2) MAR at $2\Delta'/n$ at n=2, 3

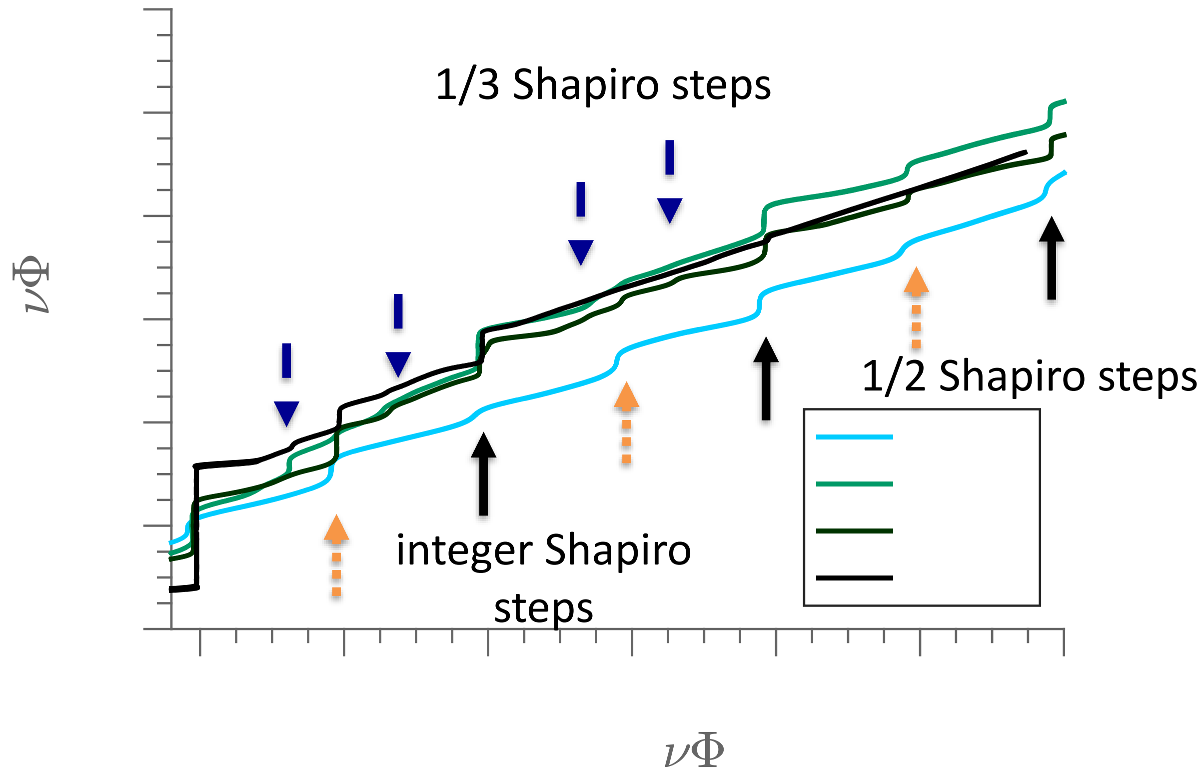
3) From I_{exc} we get a transparency $\tau \approx 0.8$-0.9

4) $I_cR_N \approx 100$ μeV

Highly transparent Josephson junctions interfaces !

The physical system is very similar to epitaxial Al/InAs hererostructures PRApp 7, 034029 (2017)

High order harmonics in the CPR $I_c = I_I \sin\varphi + I_{II} \sin 2\varphi + I_{III} \sin 3\varphi$…… : fractional Shapiro steps

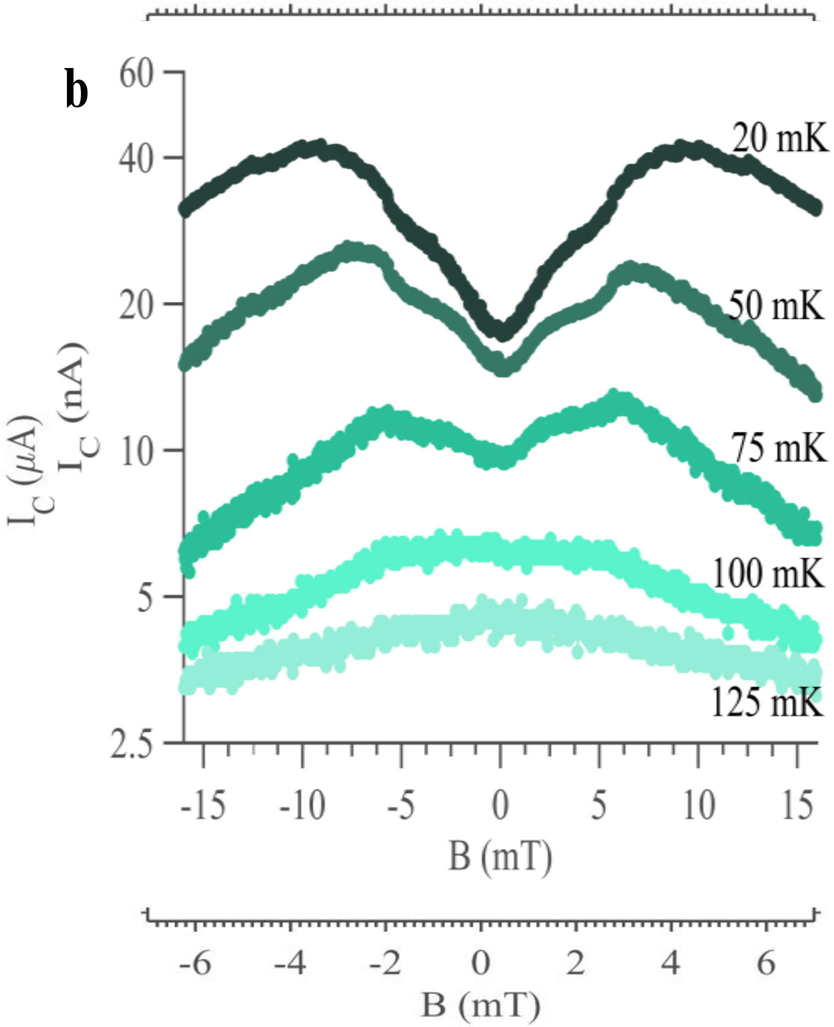


Fractional Shapiro steps:

1) interfaces S'/TI/S' are highly transparent
2) helical nature of ABS giving a skewed CPR

→ Let's search for signature of a p-wave order parameter

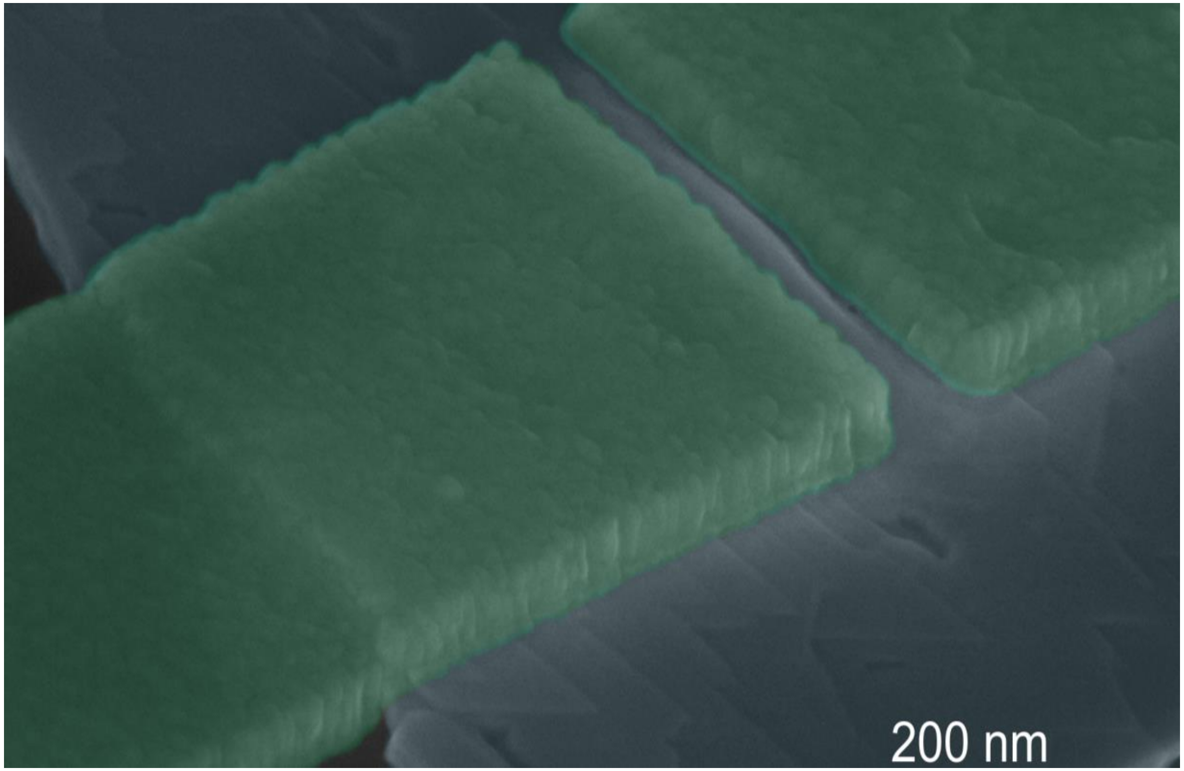
Magnetic field dependence of the Josephson current at the first cool down and second cool down (T=20mK)



After termal cycling the Ic varies between 2 to 3 order of magnitude

For the devices, which undergo the most dramatic changes, the value of the I_{exc} is zero signifying a very low transparency

1) What is the origin of the "dramatic" change of I_c behavior upon thermal cycling?



Huge difference in the thermal expansion coefficient of Bi_2Te_3, much higher than that of the SiO_2/ Si substrate: upon warming up compressive strain induces plastic deformation and a buckling

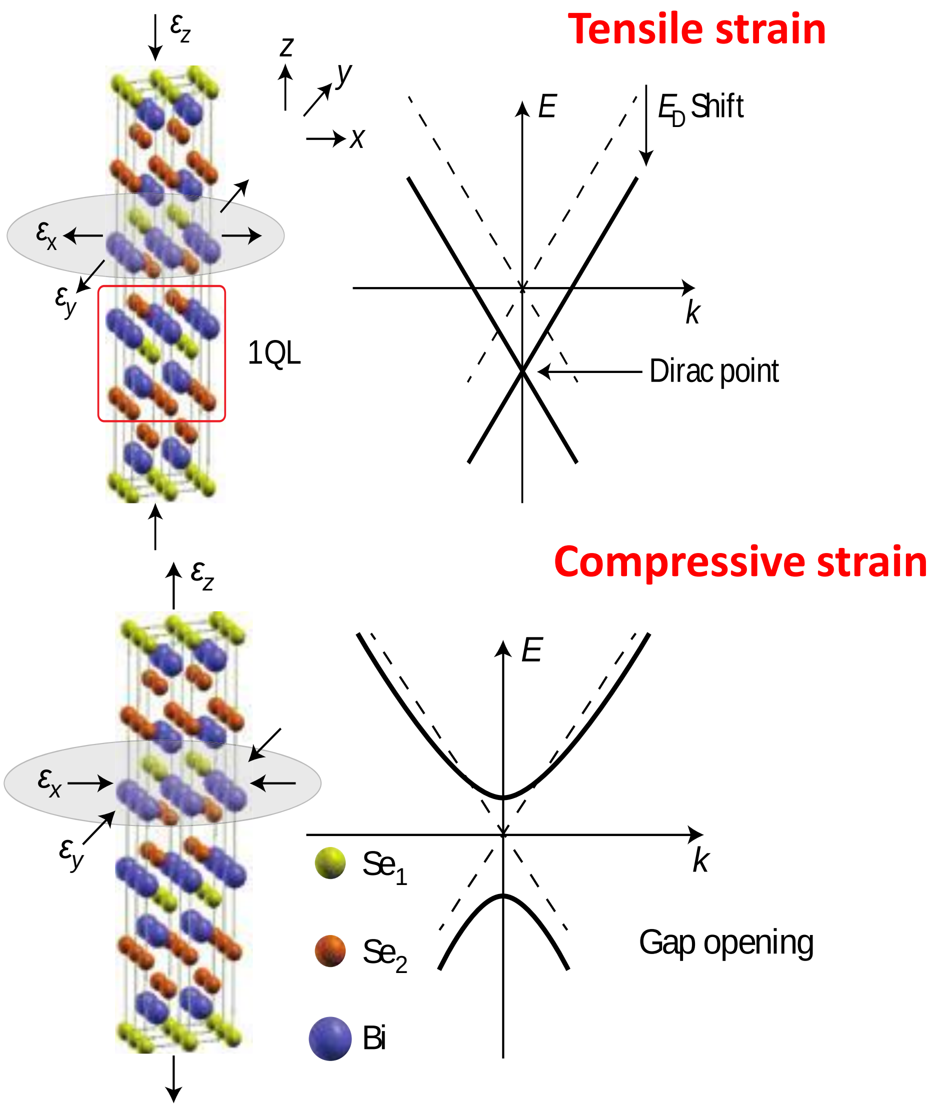
At the Bi_2Te_3 nanogap compressive strain leads to the formation of a "local buckling structure"

Strain modification of the Dirac point

Liu, W. et al. *Phys. Rev. B* **84**, 245105(2011)

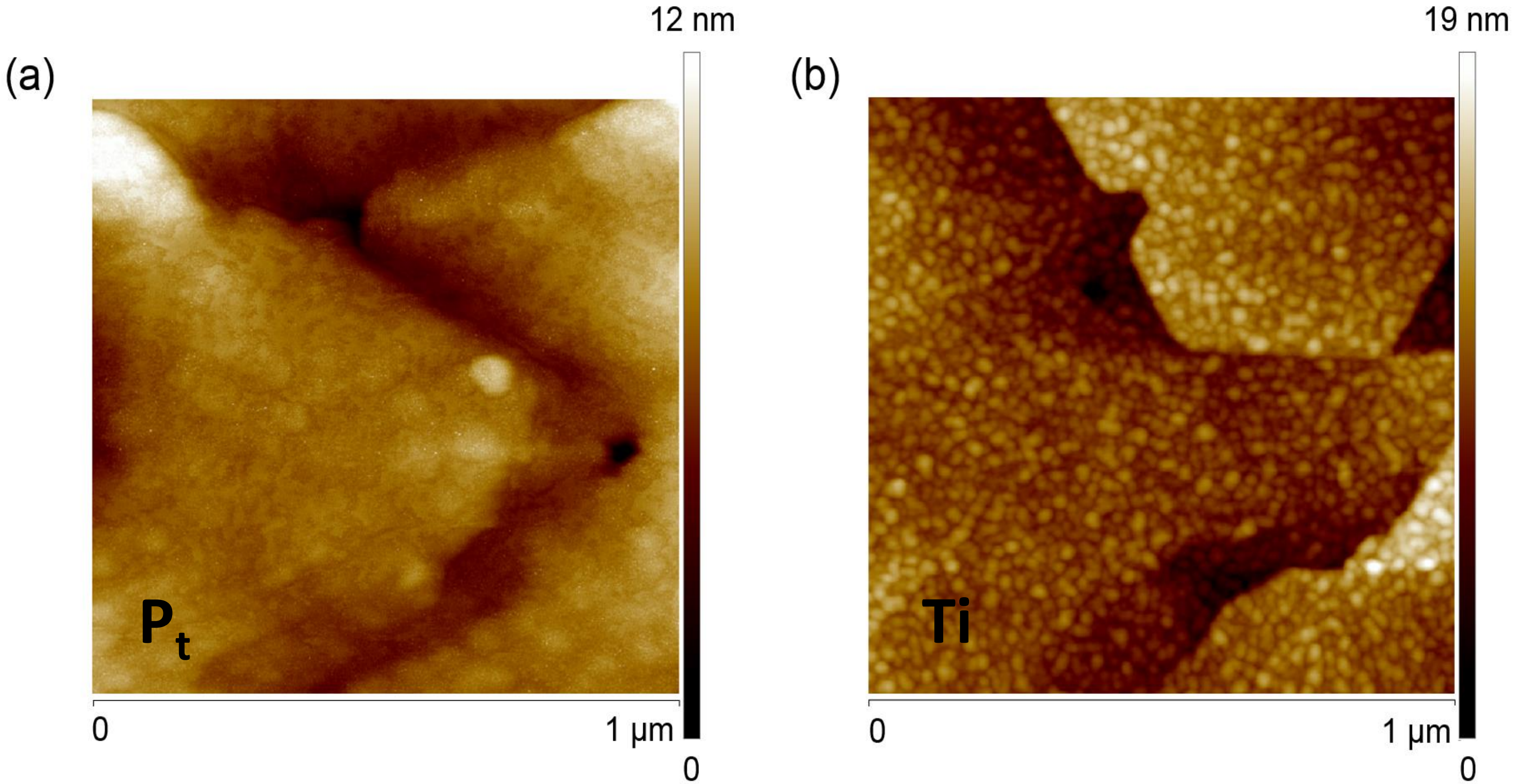
Zeljkovic, I. *et al.* Nature Nanotechnol, **10**, 849-853 (2015)

Liu, Y. *et al. Nat. Phys.* **10**, 294-299 (2014)



Gap opening at the Dirac point works as an effective tunnel barrier reducing the Josephson current

Wetting of the interlayer at the origin of buckling



Josephson junction with Ti interlayer do not change with many thermal cycles: always a Fraunhofer-like pattern.

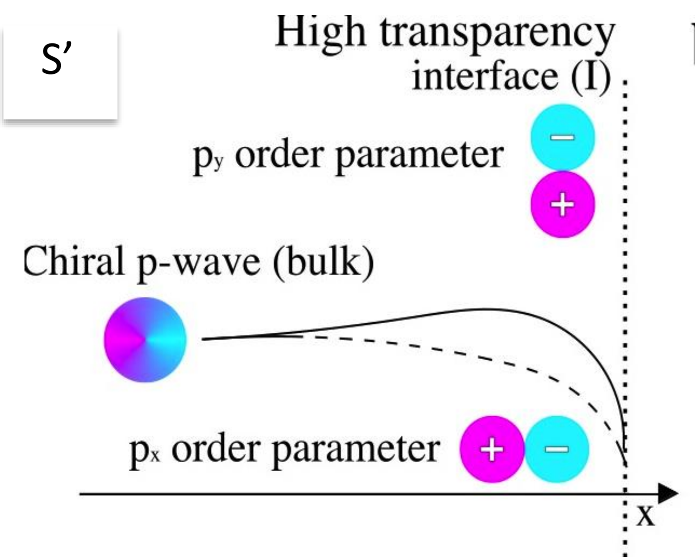
2) Origin of magnetic field pattern dip at B=0?

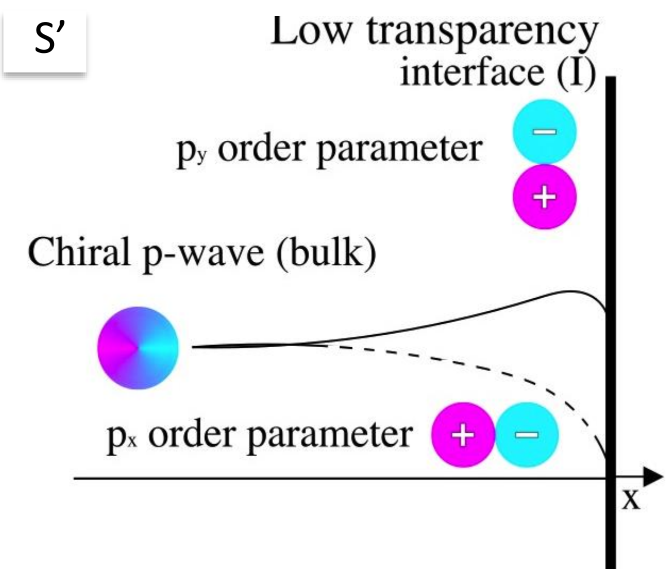
Change of the symmetry of the order parameter at the interface

Matsumoto, M. & Sigrist, *J. of the Phys. Society of Japan* **68**, 994 (1999)

First cool down

Second cool down





chiral p-wave /TI / chiral p-wave

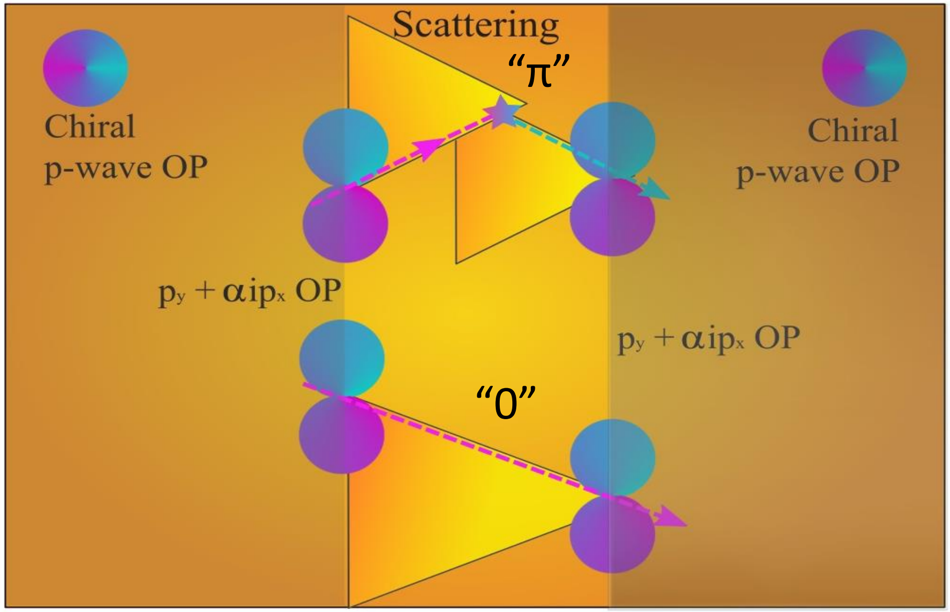
p_y-wave/ TI/p_y-wave

Fraunhofer – like Magnetic pattern except a single mode current at the nodes!

Potter and Fu , **PRB 88**, 121109 (R) 2013

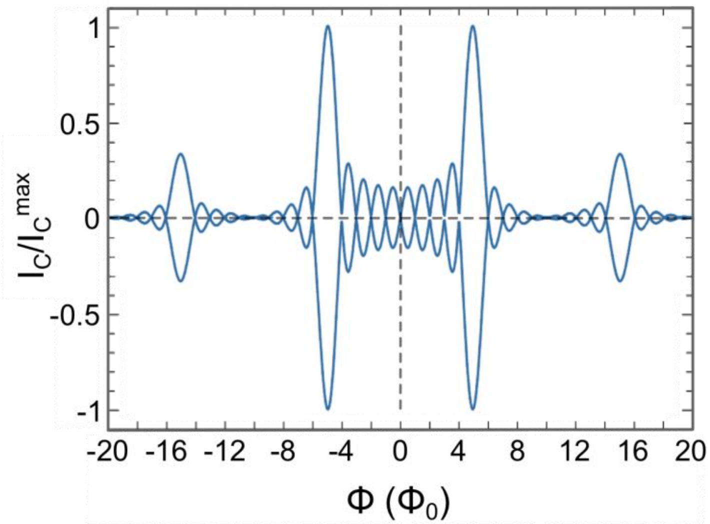
Unconventional magnetic pattern can be observed

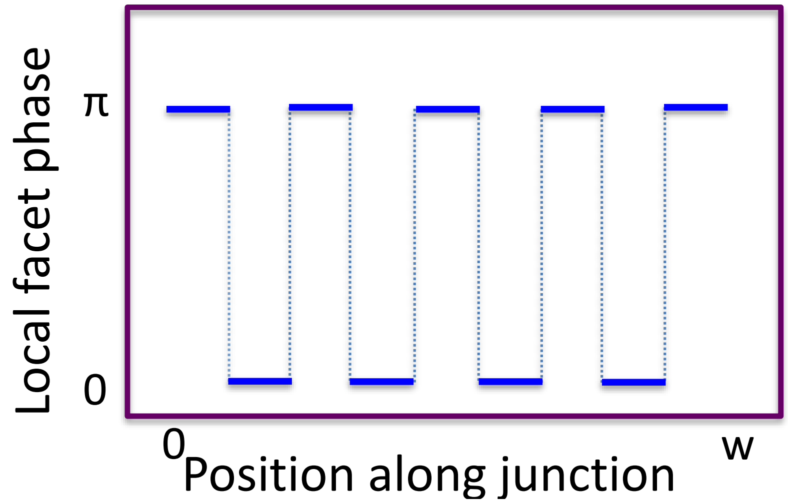
Effect of scattering center inside the TI barrier



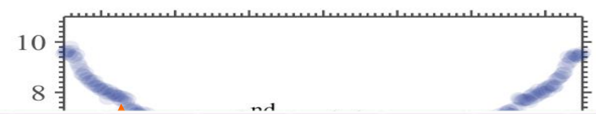
Scattering will couple quasiparticle trajectories, emerging from positive p_y, in one electrode with trajectories that probe the negative p_y lobe on the other one causing a net π-phase shift in the Josephson coupling

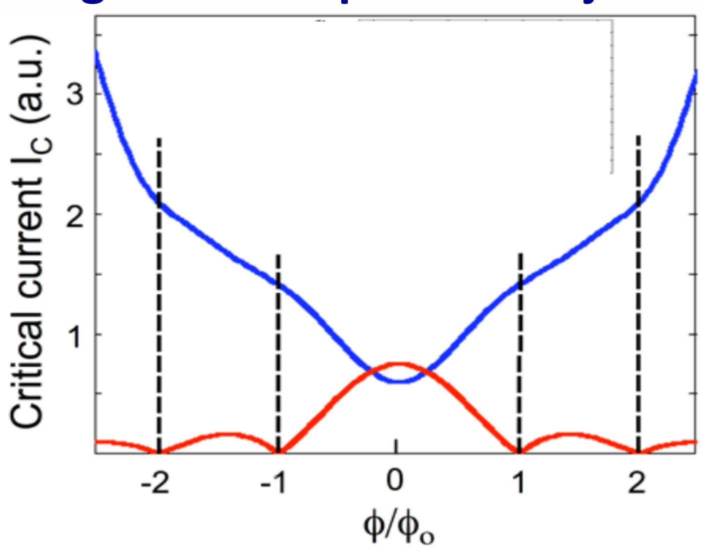
Magnetic field pattern of junction with 0 – π facets arranged in a regular way

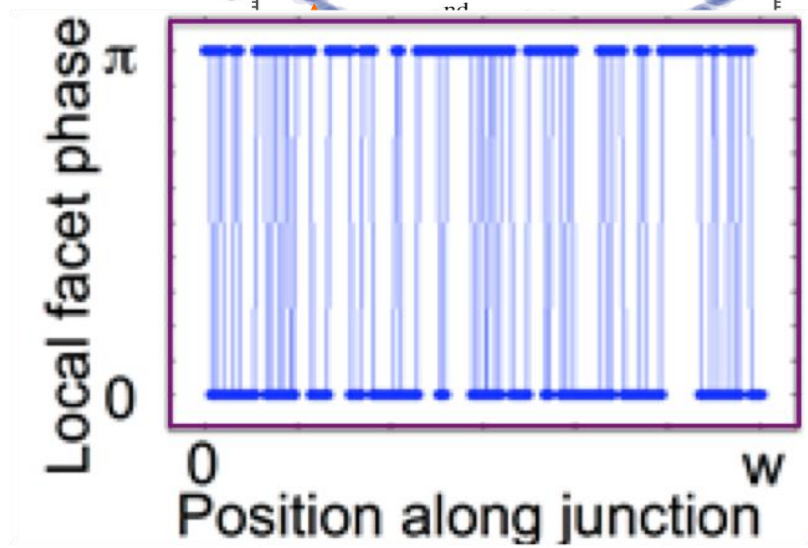




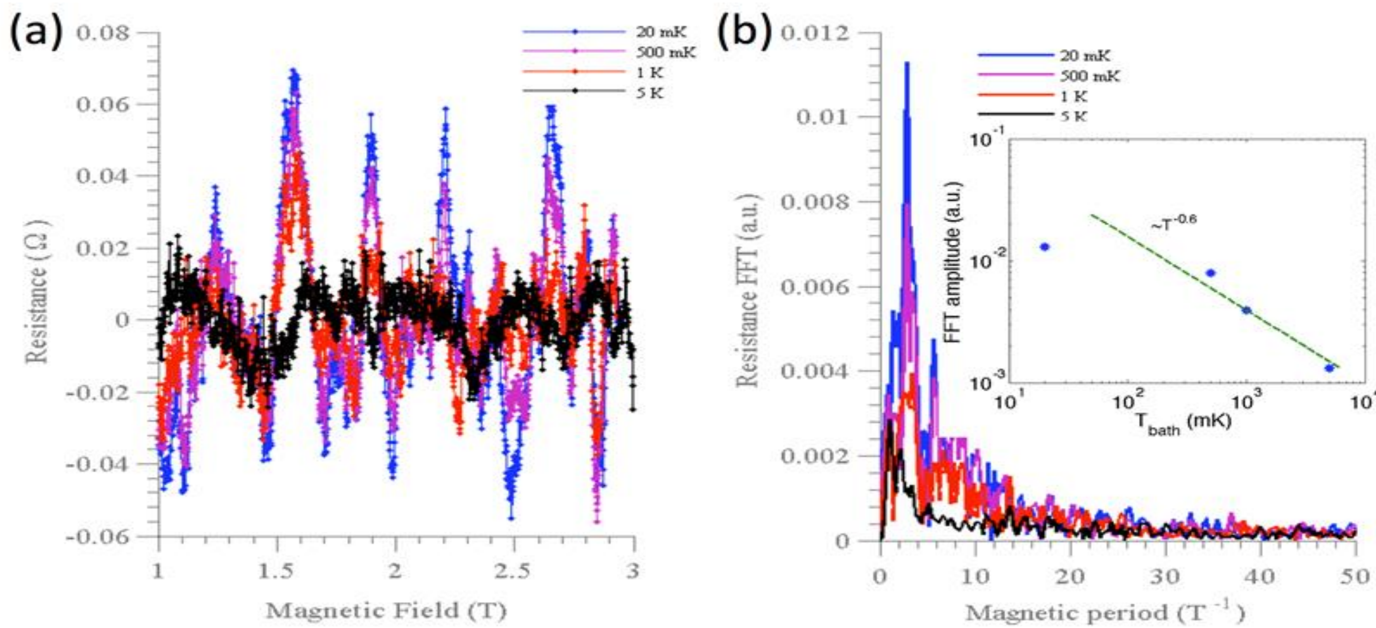
Magnetic field pattern of junction with 0 – … ic way

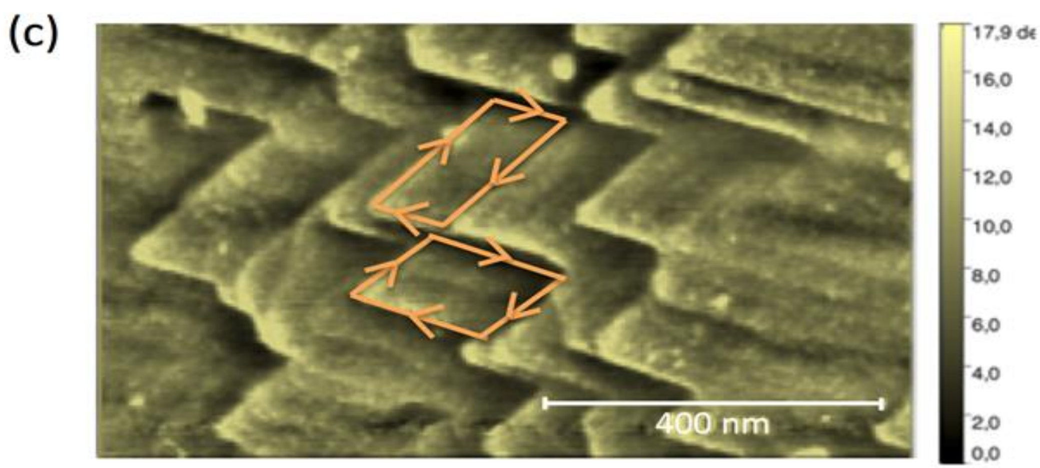






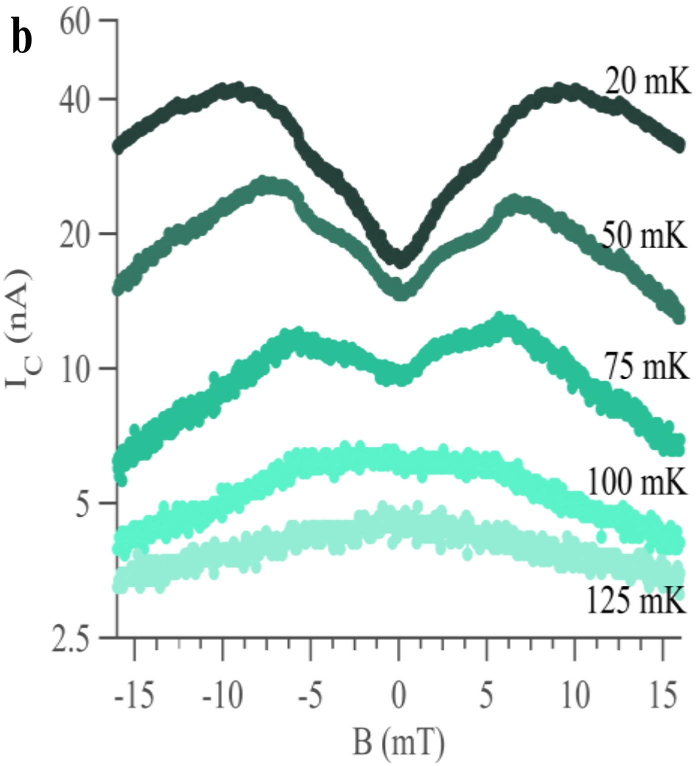
Magneto-transport in the Bi_2Te_3 flakes and scattering

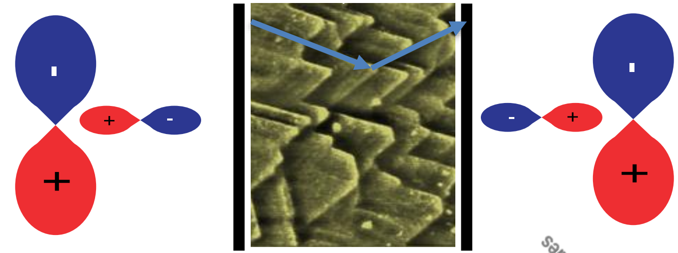


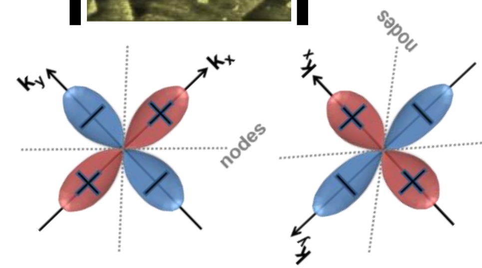


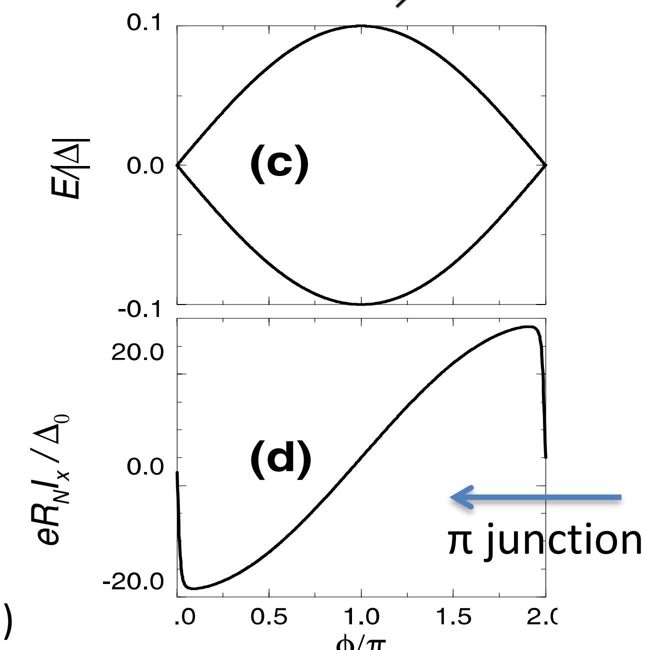
Our results are similar
to A. Kandala
Nano Lett., 13, 2471 (2013)

3) Change of order parameter symmetry and microscopic picture









T. Löfwander et al.
SUST 14, R53 (2001)

Conclusions and outlook

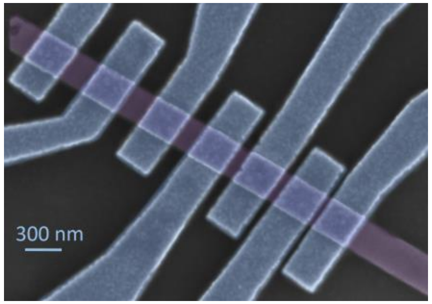
The induced OP in the surface states of the a TI has a non trivial phase compatible with a chiral p-wave.

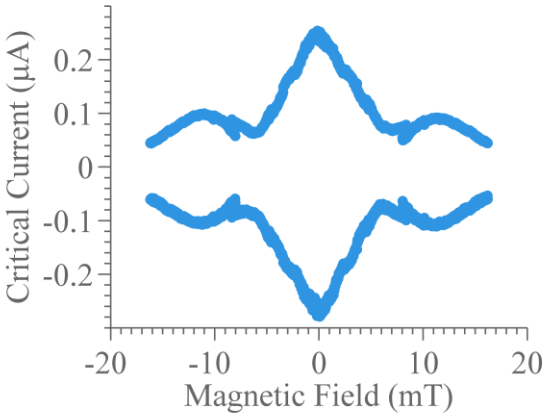
Specific interlayer choice allows strain tuning (gap opening) of the Dirac node of the Ti in the nanochannel:

a) dramatically change the Josephson properties

b) a symmetry change of the OP at the interface barrier and inverter Fraunhofer pattern

Towards Majoranas…. few channel Josephson junctions : gating+Ti nanowires

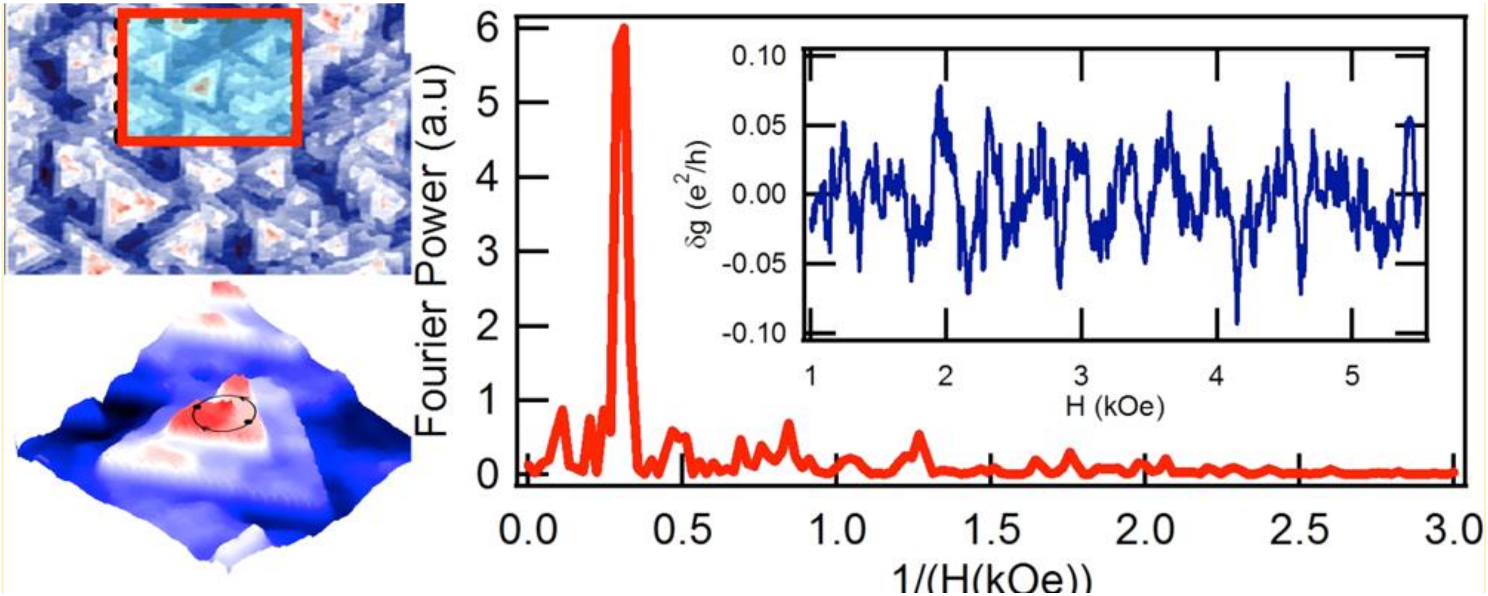




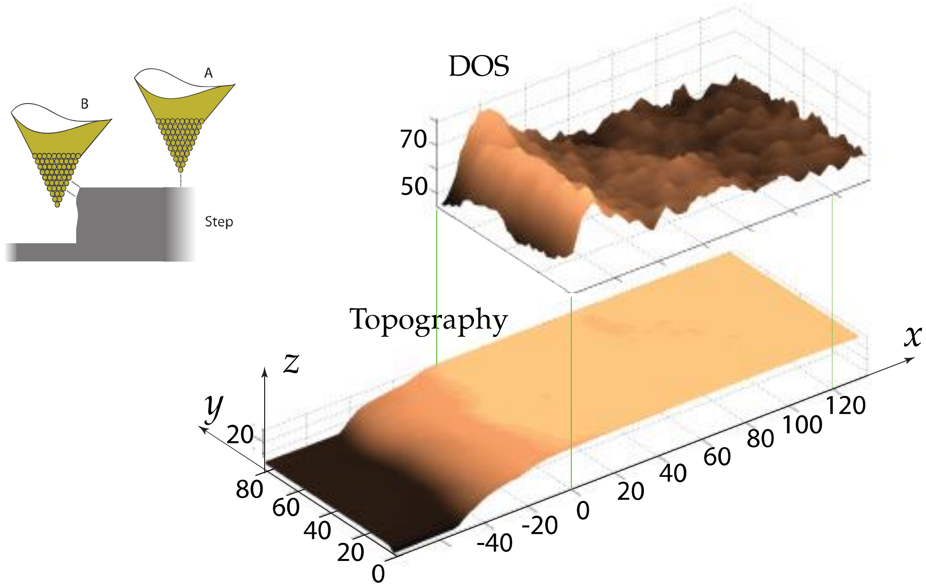
J. Andzane. G. Kunakova,…..FL and D. Erts
Nanoscale 7, 15935 (2015)

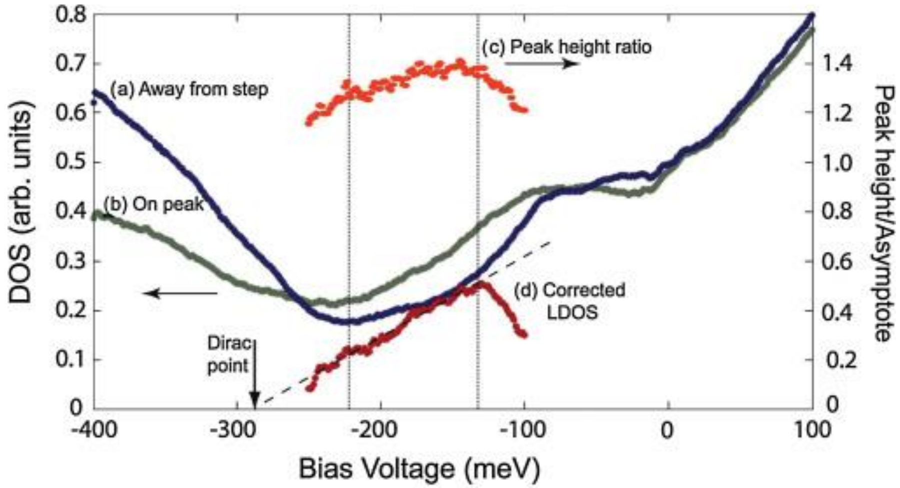
Other experimental evidences that the corners act as scattering center

Two-Dimensional Magneto-Fingerprint in Mesoscopic Bi_2Se_3 Channels

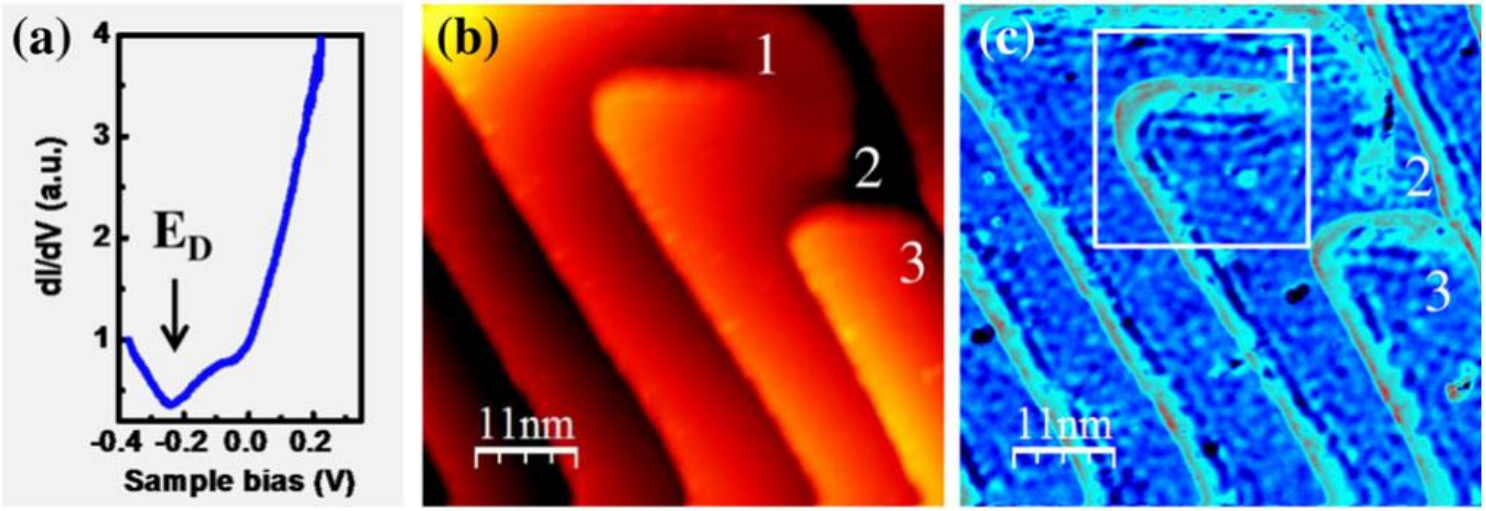


A. Kandala, A. Richardella et al. **Nano Lett., 13**, 2471, 2013

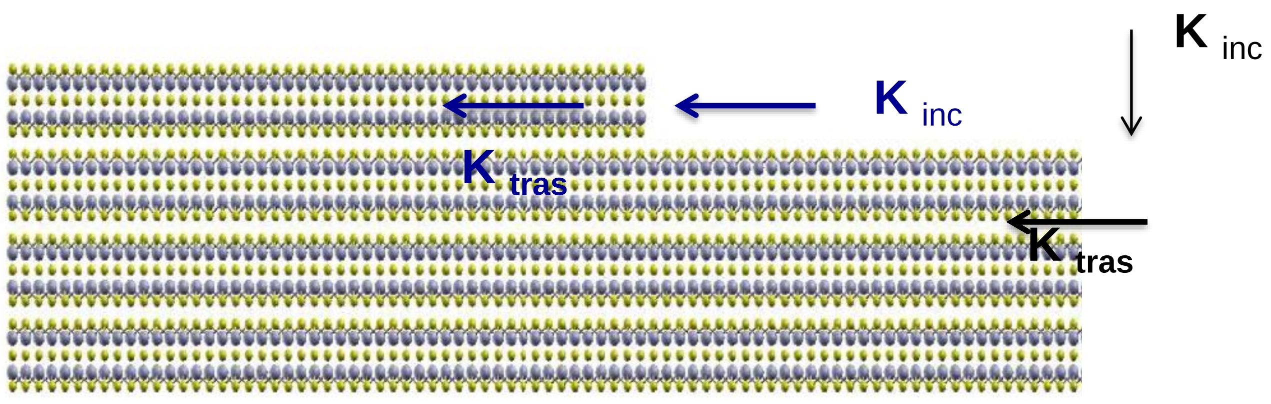




Z. Alpichshev…..A. Kapitulnik et al. PRB **84**, 041104 (R) (2011)



Y. Liu et al. PRL **108**, 115501 (2012)



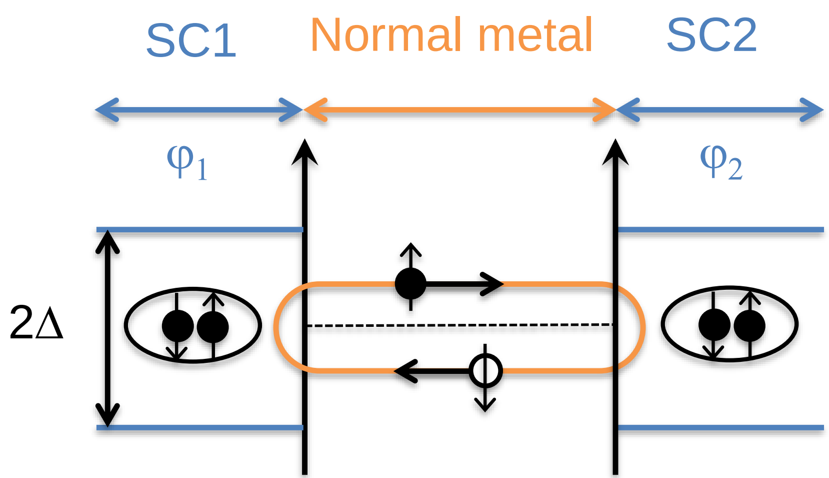
We have two effects:

1) Enhanced density of states at the step edge due to a bound state of possible " topological" nature
2) side injection does not require a change in the momentum

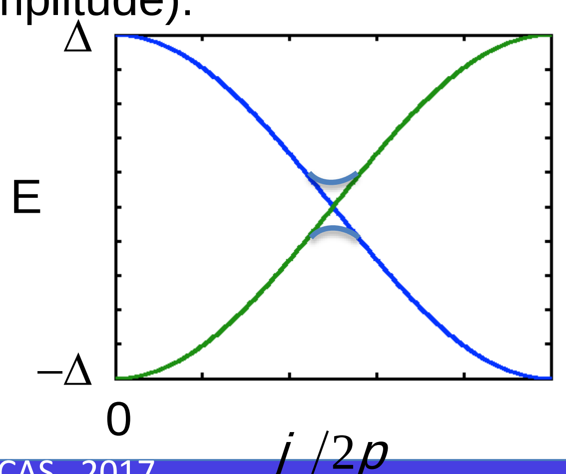
High transparency junctions on the rough flakes

Which are the signatures of Majorana fermions in Josephson effect?

Microscopic picture of the Josephson effect: Bound states in a "trivial" Josephson junction

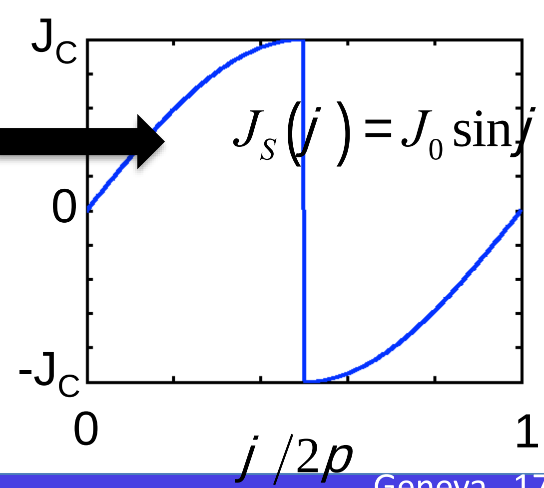


Energy dispersion and corresponding current of bound states (for unity transmission amplitude):



$$J_S(\varphi) = \frac{2\pi}{\Phi_0}\frac{dE_J}{d\varphi}$$

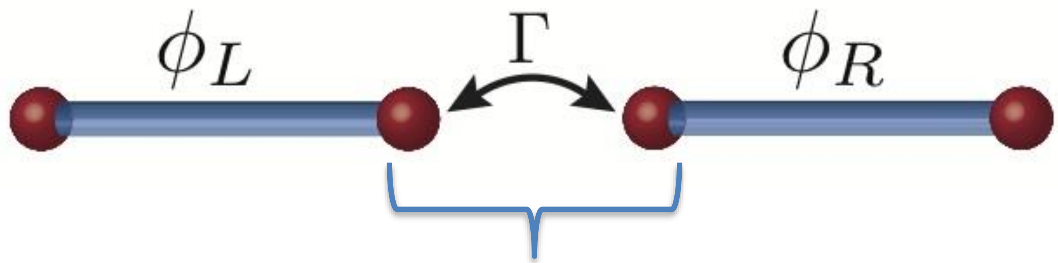
1



$$J_S(\varphi) = J_0 \sin\varphi$$

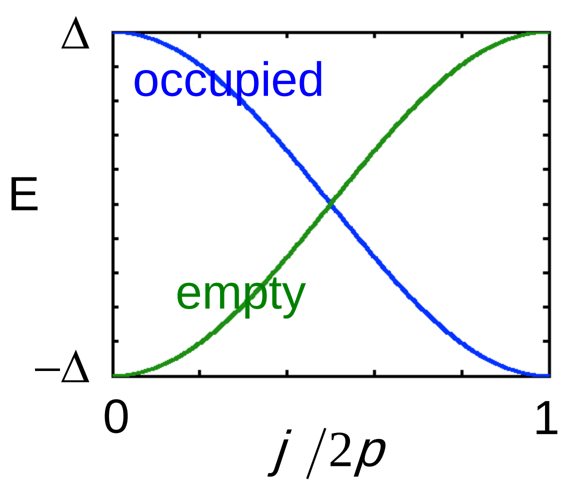
2π periodic CPR

"non-trivial"Josephson junction
e.g. between end states of two 1D spinless p-wave superconductors

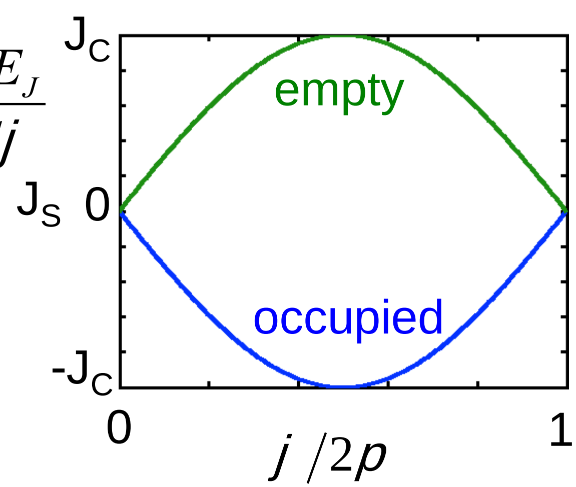


Fermionic state:
empty or occupied

Energy dispersion and corresponding current of bound state

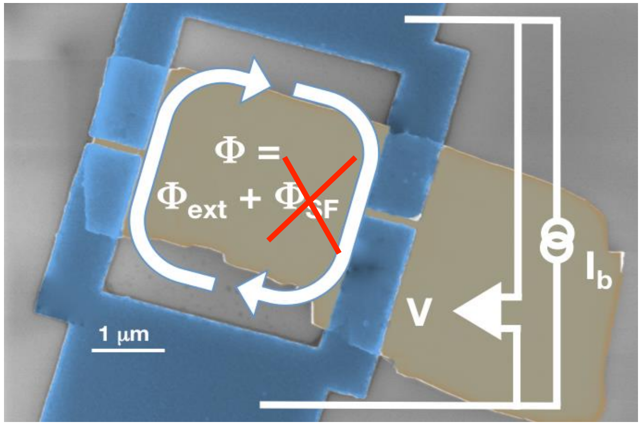


$$J_S(\varphi) = \frac{2\pi}{\Phi_0}\frac{dE_J}{d\varphi}$$



4π periodic CPR

Magnetic field dependence of a dc SQUIDs with rough flakes



The effect of the sin2φ component is enhanced in the minima of the Junction magnetic pattern