Charge and spin interference in Bi_2Se_3 and Bi_2Te_3 with strong spin-orbit coupling

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Outline

Part I:

Aharonov-Casher effect in Bi_2Se_3 square-ring interferometers

Part II:

Anomalous Cooper pair interference on the surfaces of Bi_2Te_3

Acknowledgements

Students:

<u>Fanming Qu</u>
Fan Yang
Jun Chen
Jie Shen
Yue Ding

Colleagues:

Guangtong Liu
Jie Fan
Yongqing Li
Zhongqing Ji
Changli Yang

Structural characterization:

Jiangbo Lu
Yuanjun Song
Huaixin Yang

Theory:

Qingfeng Sun
Xincheng Xie

Motivation

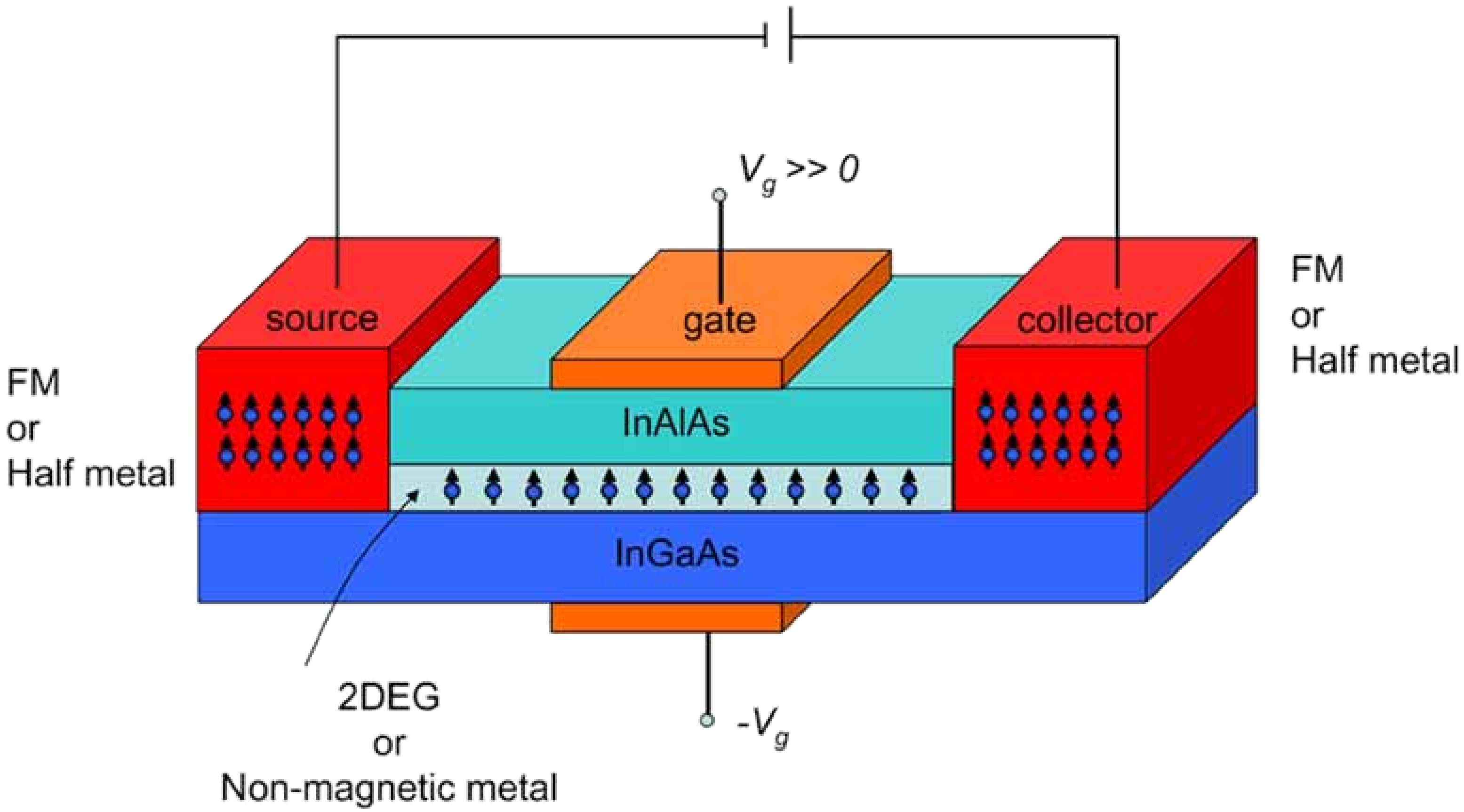
One of the main purposes of **spintronics** is to explore electrical control of spin dynamics in solid-state devices via spin-orbit coupling (SOC).

↓

Spin field-effect transistor (spin FET)

Datta-Das Transistor (Spin FET)

S. Datta, B. Das, et al., Appl. Phys. Lett. 56 665 (1990)



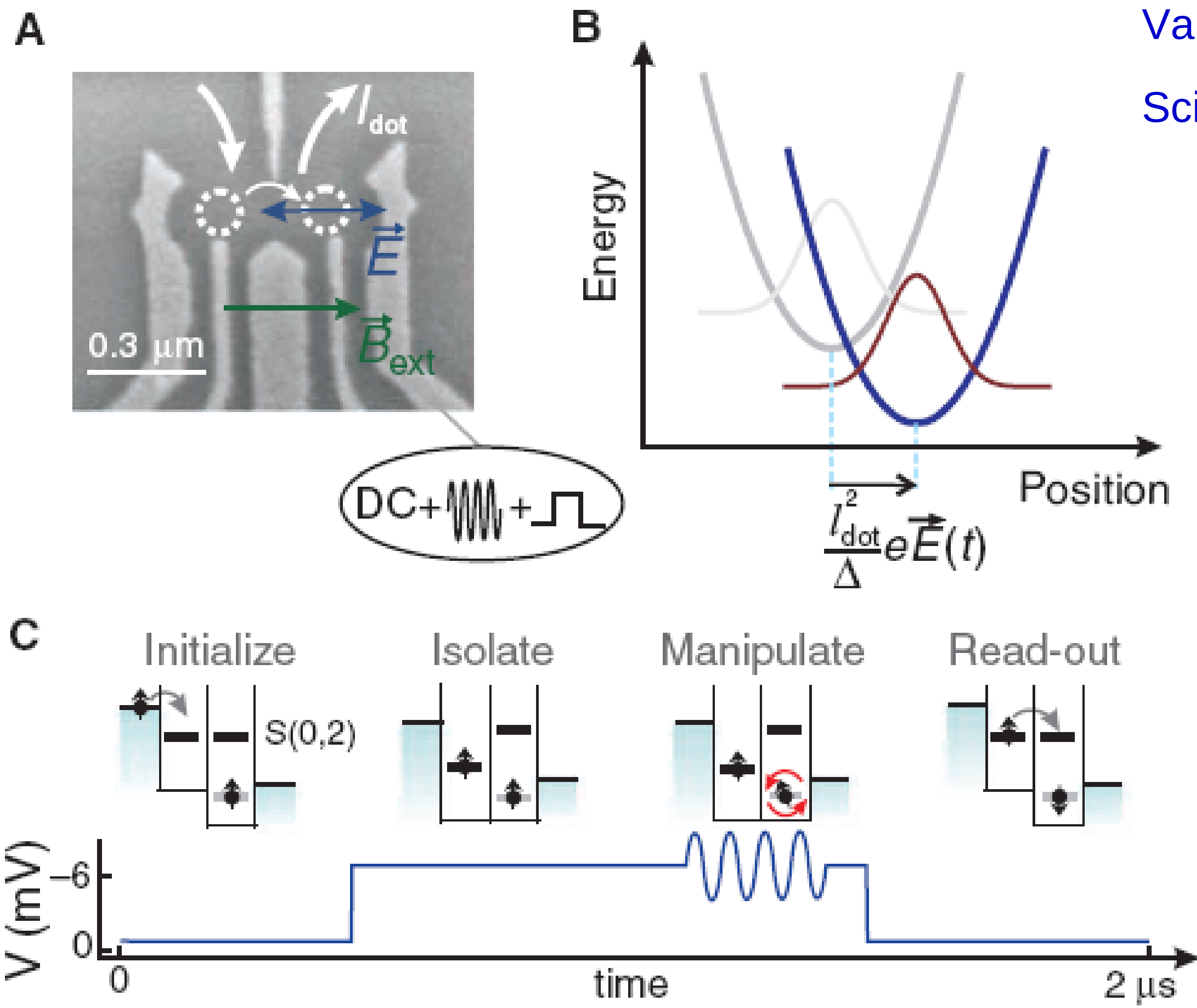
Source: http://www.nims.go.jp/apfim/SpinFET.html

Ultimate spintronics device: Spin qubits

Taurocha group, Marcus group, Vandersypen group

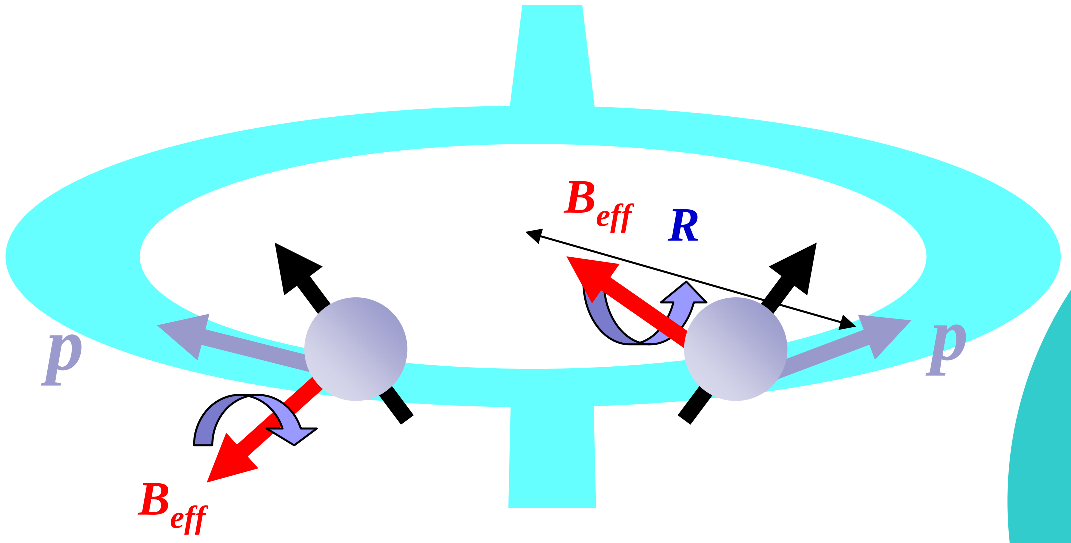
Vandersypen group

Science 2007



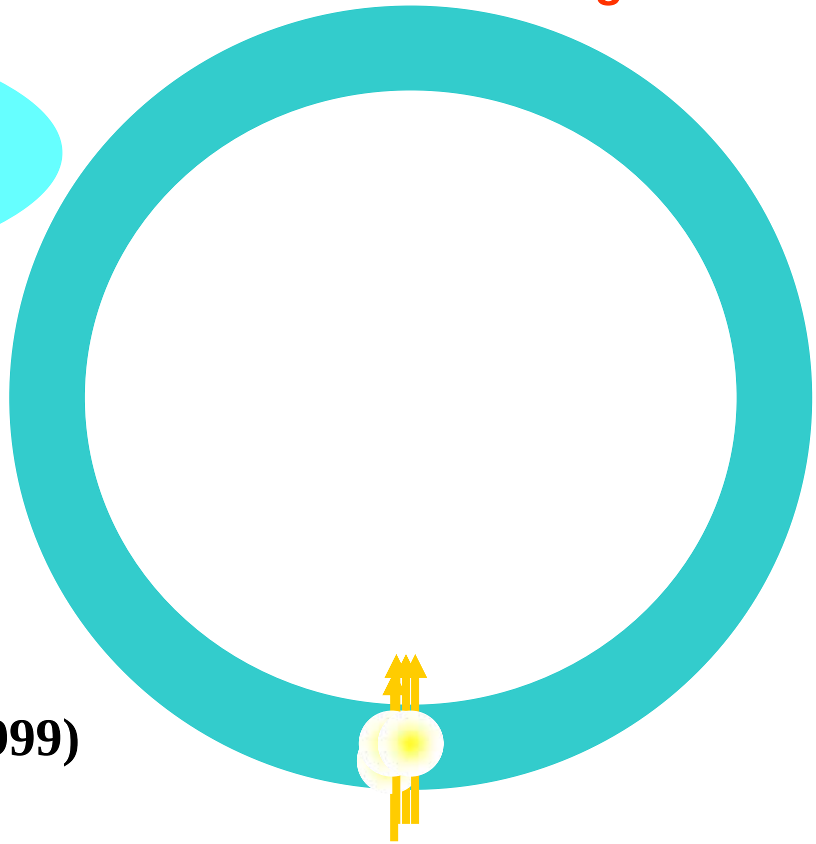
Spin FET via Aharonov-Casher effect

Y. Aharonov and A. Casher, PRL 1984



Vg= 0 V

Vg= 1 V



Spin interference device

Nitta group, Appl. Phys. Lett. 75, 695 (1999)

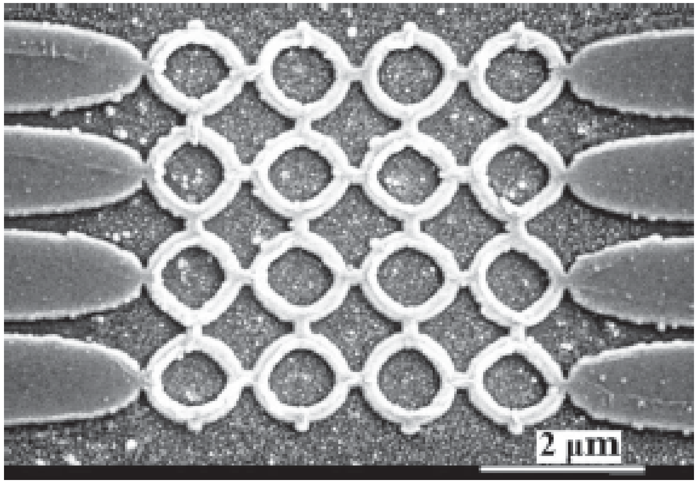
Ring conductance depends on the precession angle

from Nitta's ppt

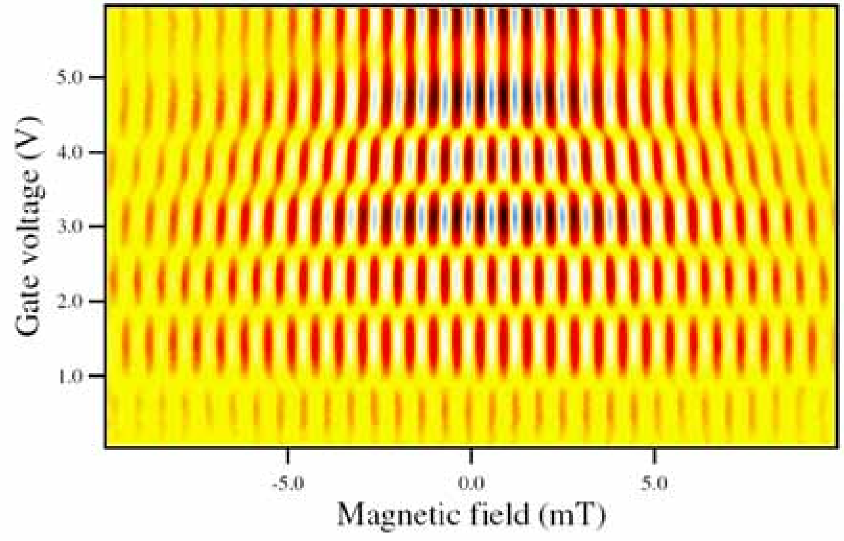
Previous Experiment on AC effect

- in InAlAs/InGaAs 2DEG (Nitta group)
- in HgTe/HgCdTe 2D TI (Molenkamp group)

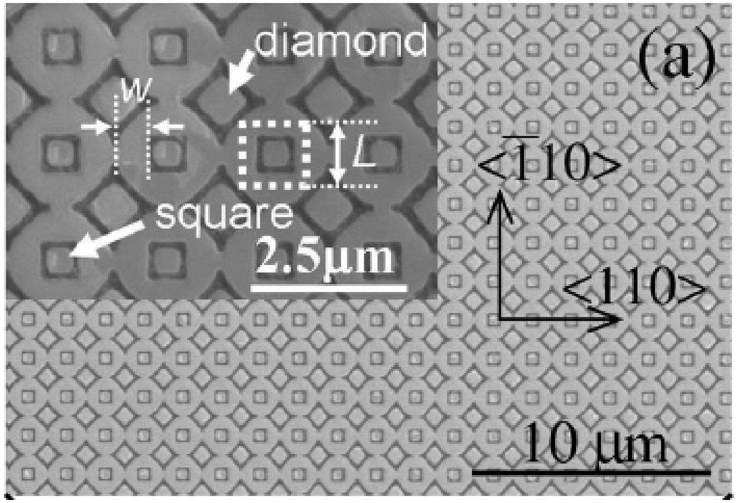
Aharonov-Casher effect in 2DEG InAlAs/InGaAs



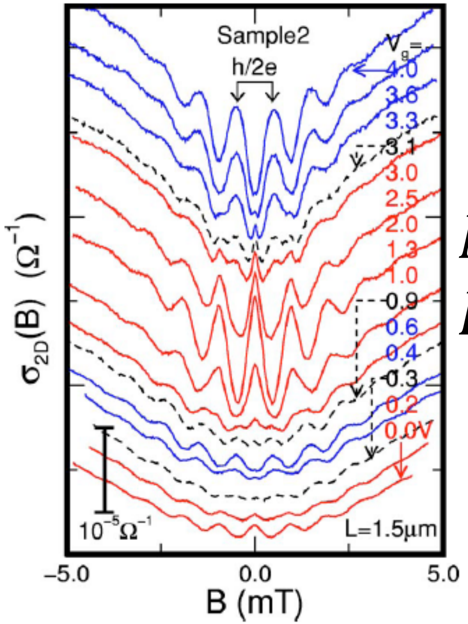
InAlAs/InGaAs



Nitta group PRL 97,196803(2006)

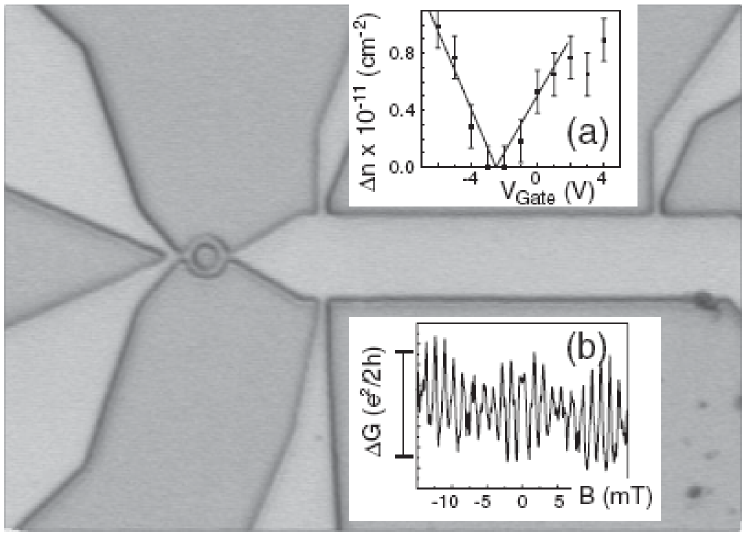


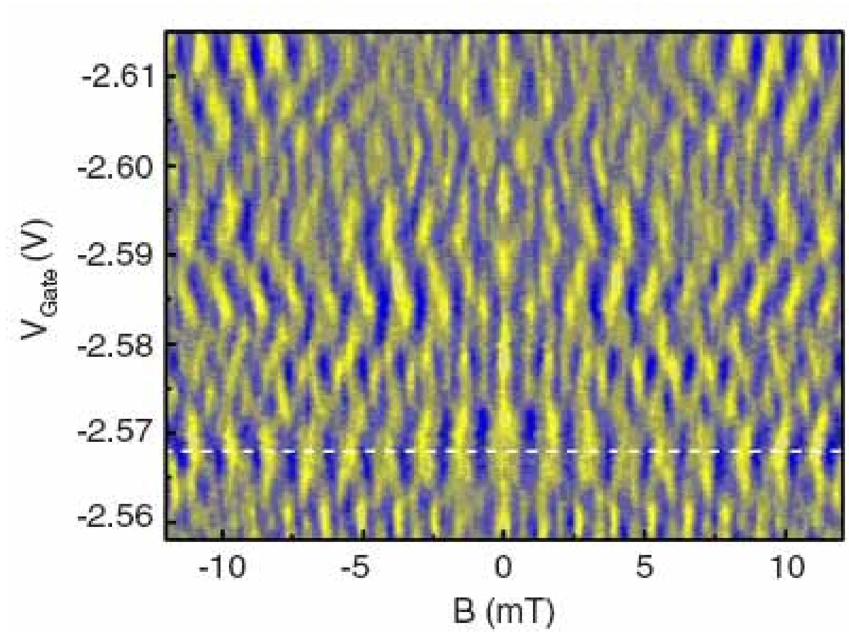
InAlAs/InGaAs



Nitta group
PRB 74, 041302(2006)

Aharonov-Casher effect in 2D TI HgTe/HgCdTe





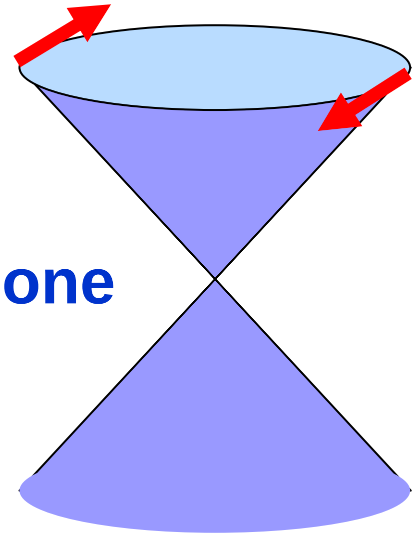
Molenkamp group PRL 96, 076804(2006)

Our Experiment on Bi_2Se_3 square rings

--- The 1st observation of AC effect on 3D TI

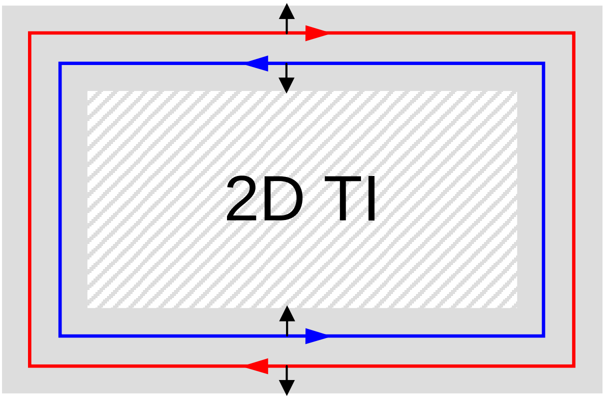
What is a topological insulator?

insulating bulk + conducting surface/edge



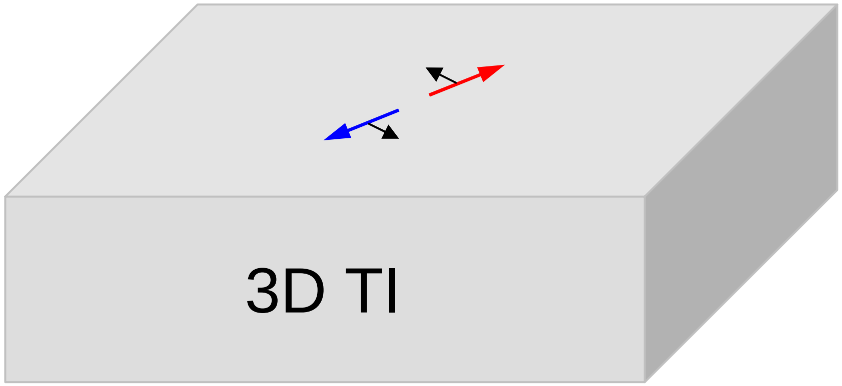
Dirac cone

Helical electrons



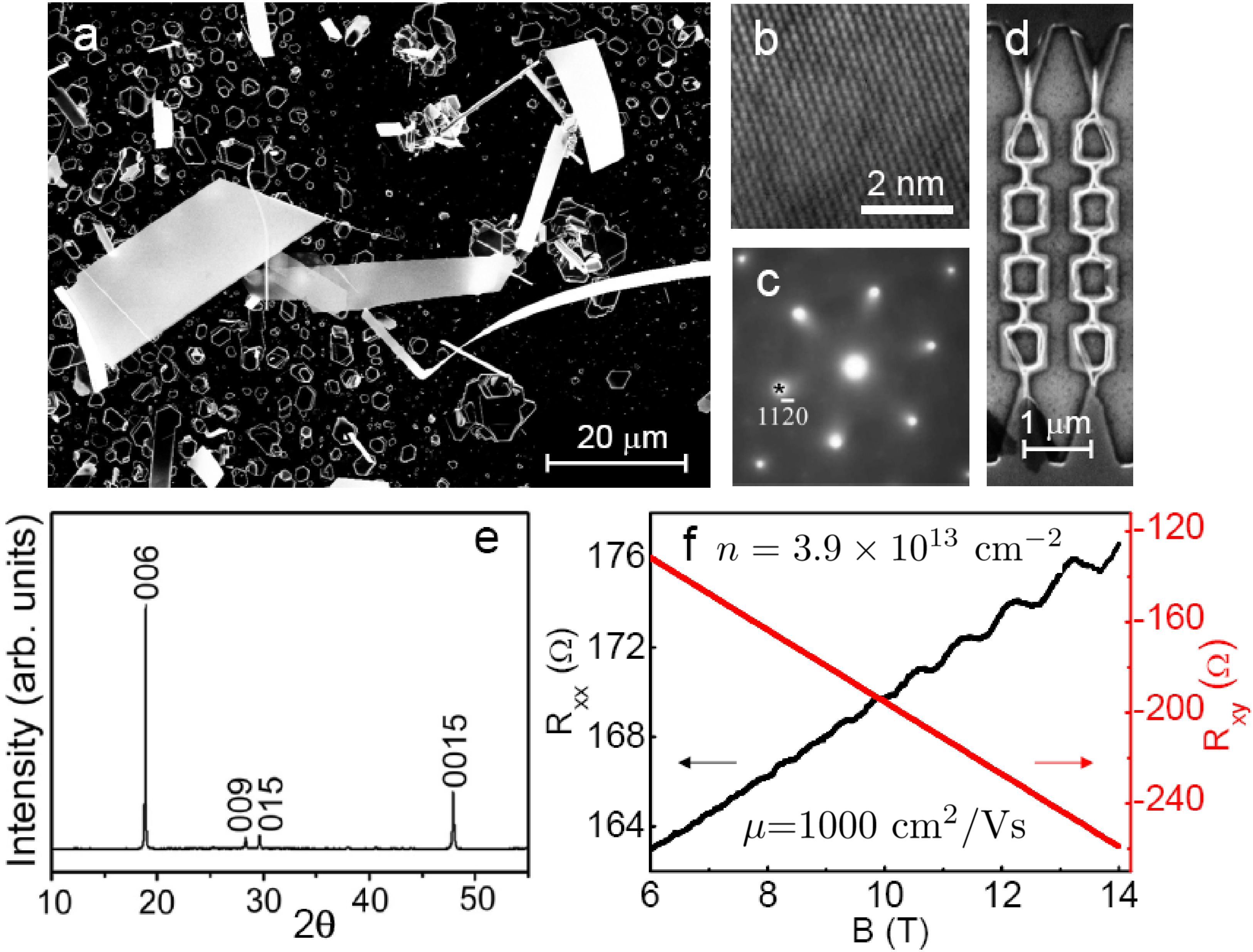
strong SOC

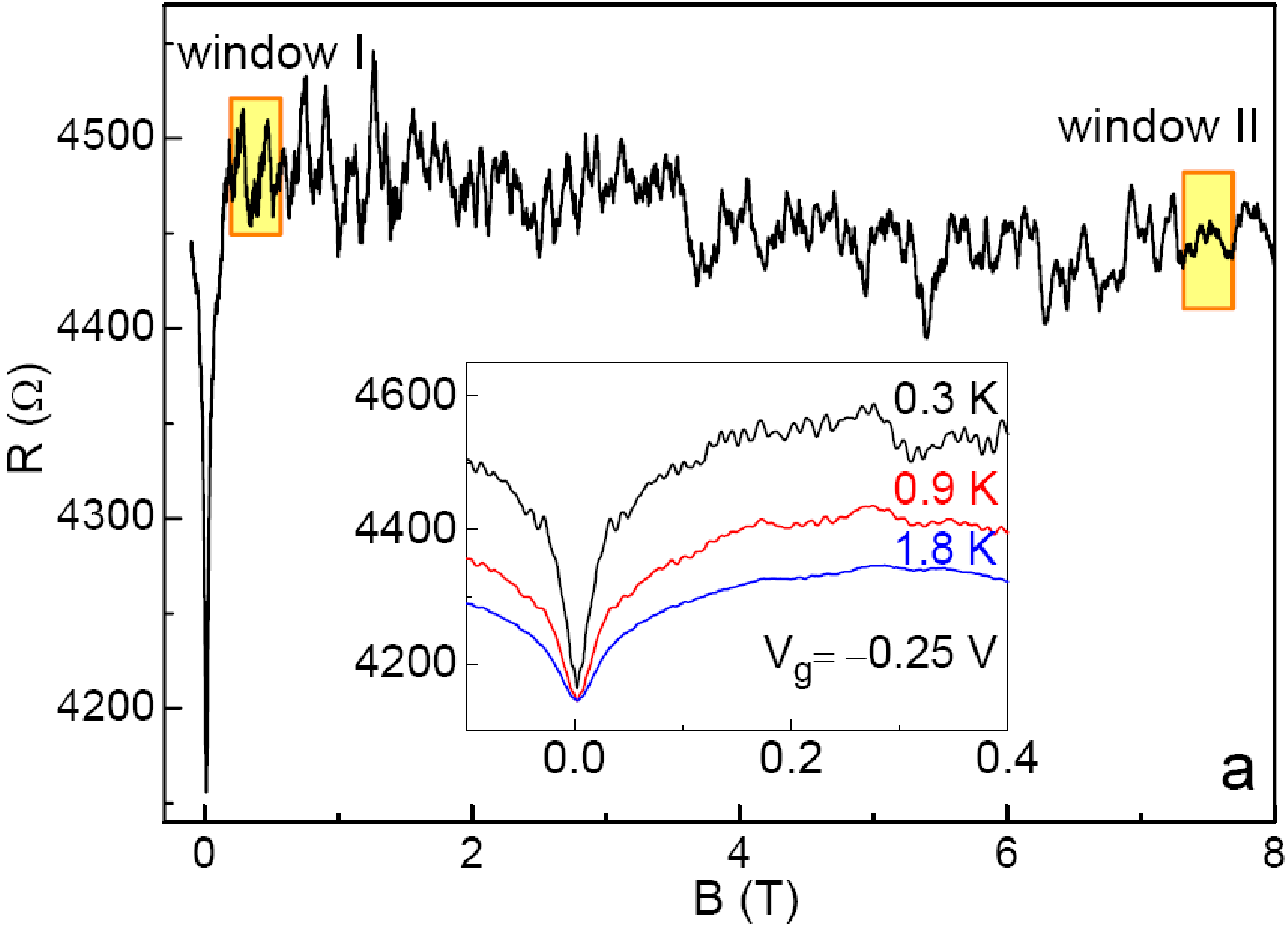
spin-momentum locking



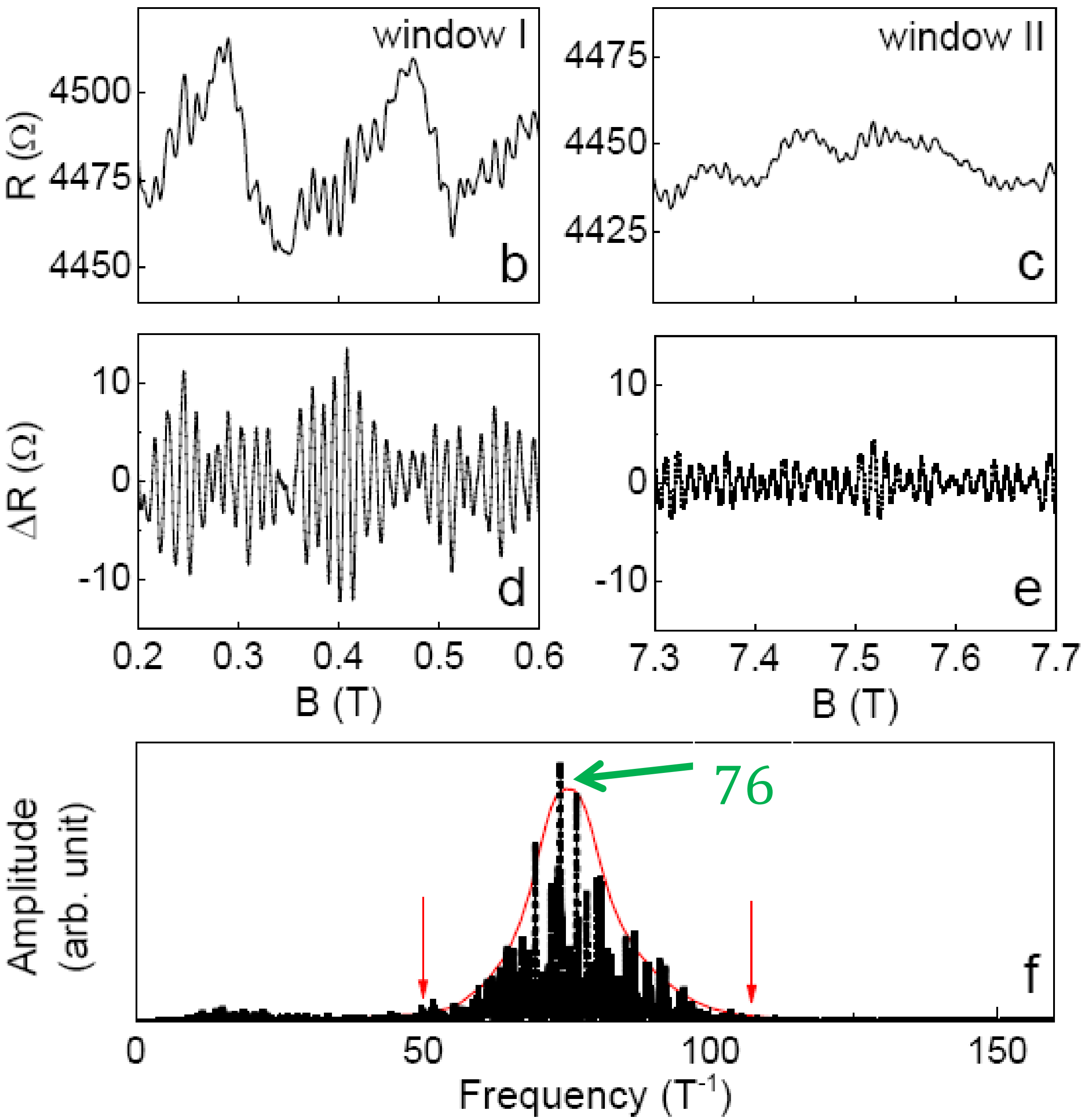
- Band inversion and Dirac cone (momentum space)
- Helical electrons (real space)

Our Experiment on Bi_2Se_3 square rings





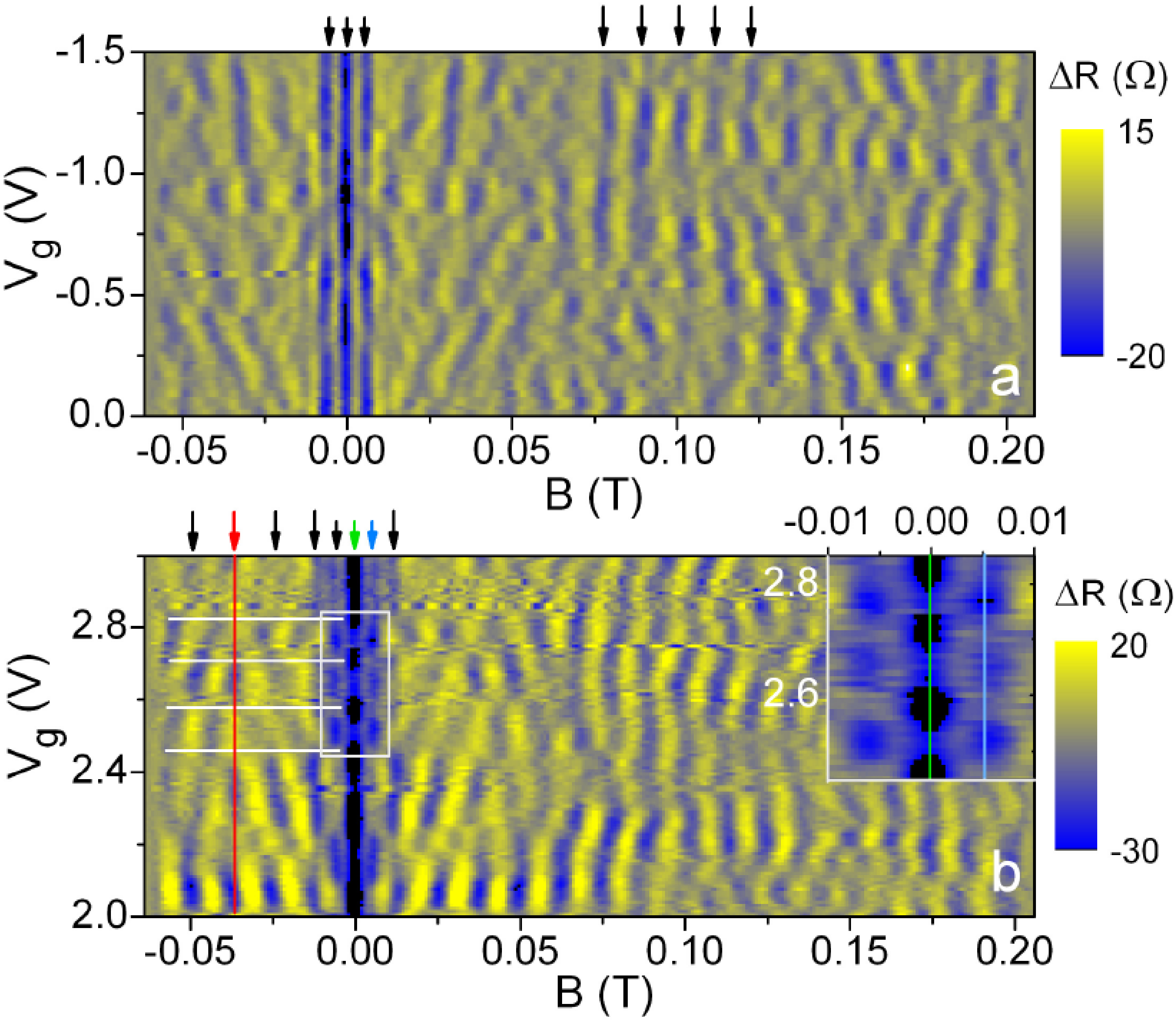
window I
window II
4500
4400
4300
4200
R (Ω)
0
2
4
6
8
B (T)
4600
4400
4200
0.3 K
0.9 K
1.8 K
V_g= –0.25 V
0.0
0.2
0.4
a



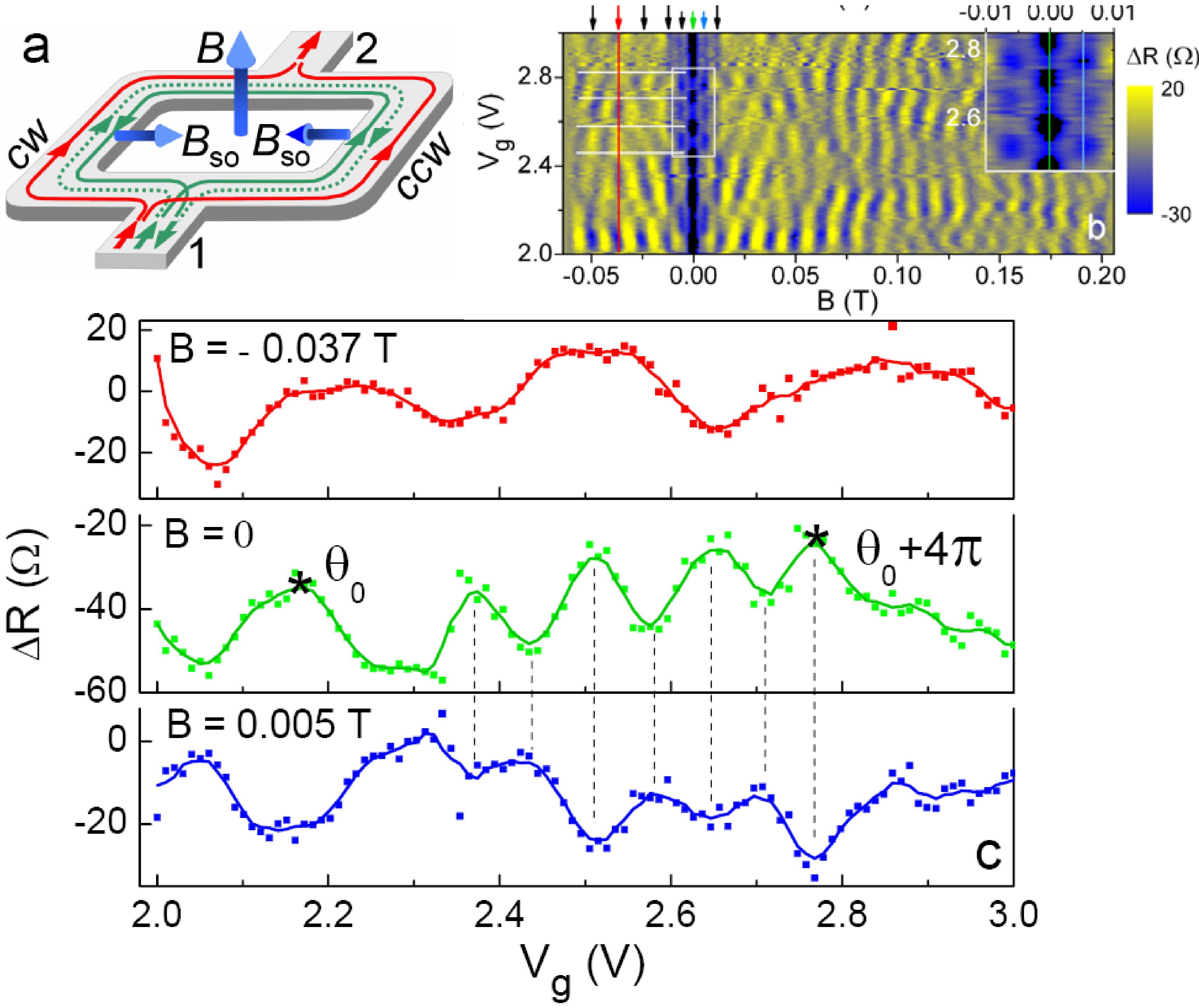
$S = 560\ \mathrm{nm} \times 560\ \mathrm{nm}$

$(\Delta B)^{-1} = S/\phi_0 = 75\ \mathrm{T}^{-1}$

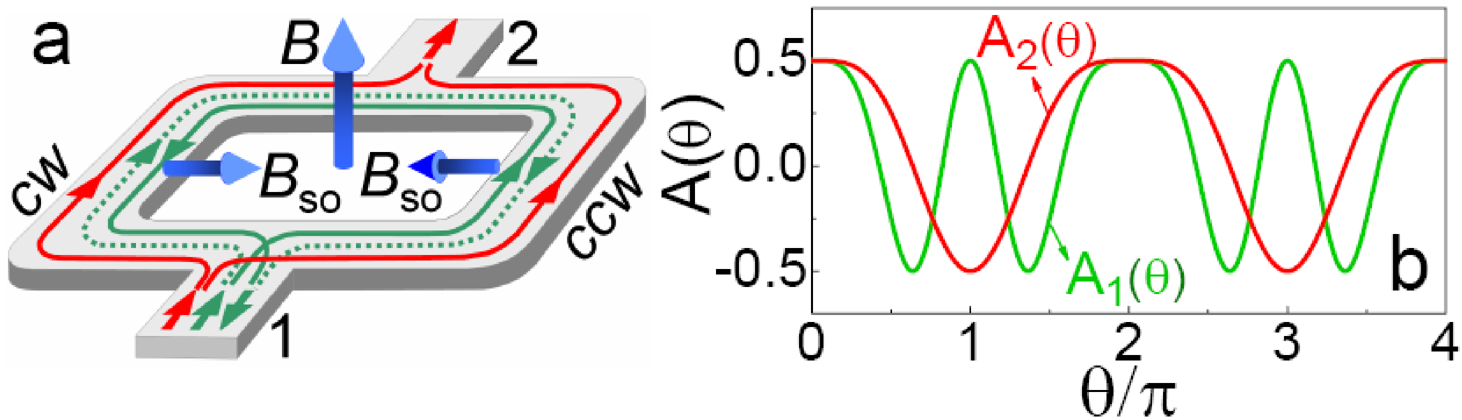
Width of the ring: 120 nm



-1.5
-1.0
-0.5
0.0
V_g (V)
-0.05
0.00
0.05
0.10
0.15
0.20
B (T)
ΔR (Ω)
15
-20
a
2.8
2.4
2.0
-0.01
0.00
0.01
2.8
2.6
ΔR (Ω)
20
-30
b



a
B
2
cw
ccw
B_{so}
B_{so}
1
b
-0.01 0.00 0.01
2.8
2.6
ΔR (Ω)
20
-30
V_g (V)
B (T)
c
B = - 0.037 T
B = 0
θ_0
$\theta_0+4\pi$
B = 0.005 T
ΔR (Ω)
V_g (V)



AAS type

$$\overline{\langle \Psi \mid \Psi \rangle} = \frac{1}{2} + \frac{1}{4}(\cos^4\theta + 4\cos\theta\sin^2\theta + \cos 2\theta)\cos\phi_1$$

$$\equiv \frac{1}{2} + A_1(\theta)\cos\phi_1 \qquad \phi_1 = 2eBL^2/\hbar$$

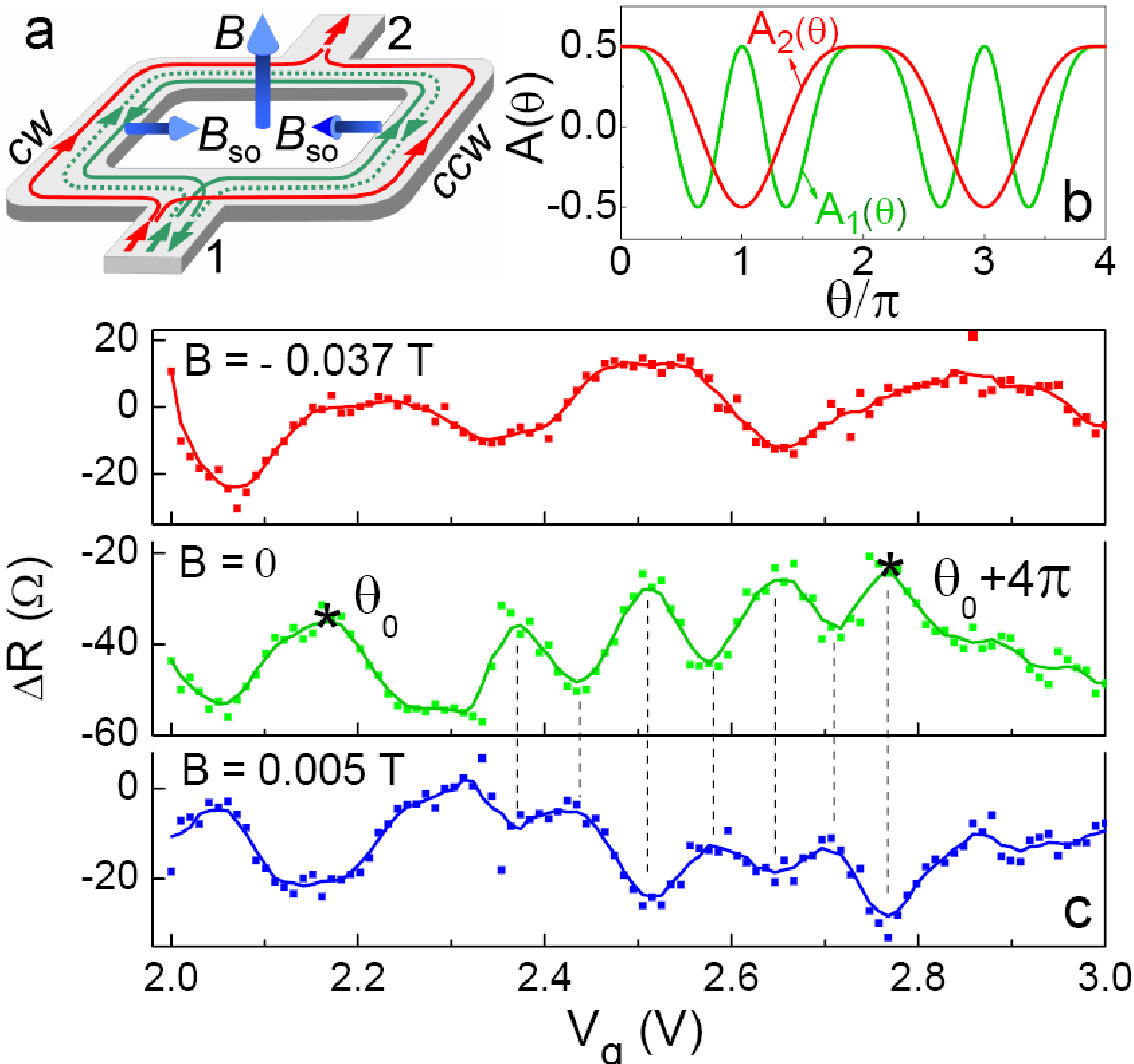
Nitta group, PRB 70, 161302(2004)

AB type

$$\overline{\langle \Psi \mid \Psi \rangle} = \frac{1}{2} + \frac{1}{4}(\sin^2\theta + 2\cos\theta)\cos\phi_2$$

$$\equiv \frac{1}{2} + A_2(\theta)\cos\phi_2 \qquad \phi_2 = eBL^2/\hbar$$

X. C. Xie group, PRB 74, 085327(2006)



a
B
2
cw
ccw
B_{so}
B_{so}
1
b
$A_2(\theta)$
$A_1(\theta)$
$A(\theta)$
0.5
0.0
-0.5
0
1
2
3
4
θ/π
c
B = - 0.037 T
B = 0
B = 0.005 T
θ_0
$\theta_0+4\pi$
ΔR (Ω)
20
0
-20
-40
-60
2.0
2.2
2.4
2.6
2.8
3.0
V_g (V)

The tunability of the Spin-FET

$$\Delta\theta/\Delta V_{\rm g} = 6.6\pi/{\rm V}$$

$$\theta = 2\alpha m^* L/\hbar^2$$

$$\Delta\alpha/\Delta V_{\rm g} = (\hbar^2/2m^*)\Delta\theta/L\Delta V_{\rm g} = 11({\rm peVm})/{\rm V}$$

The tunability in our device is the highest:

- an order of magnitude larger than that of InAlAs/InGaAs devices;
- more than two times larger than that of HgTe/HgCdTe devices.

Conclusion of Part I

- Bi_2Se_3 — A good candidate with large SOC for constructing spintronics devices.
- AC effect — A powerful tool to control spin interference.

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Part II:

Anomalous Cooper pair interference on the surfaces of Bi_2Te_3

Students:

Jie Shen   Yue Ding   Yuan Pang

Fanming Qu   Fan Yang   Jun Chen

J.Y. Feng,   J.H. Wang,   … …

Colleagues:

- Changli Yang
- Xiunian Jing
- Jie Fan
- Zhongqing Ji
- Yongqing Li
- Guangtong Liu

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- L. Fu
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- X. Dai
- G. M. Zhang
- X. C. Xie
- Q. Niu
- S. C. Zhang
- X.L. Qi
- R. Du
- S.Y. Han
- S. P. Zhao
- L. Yu

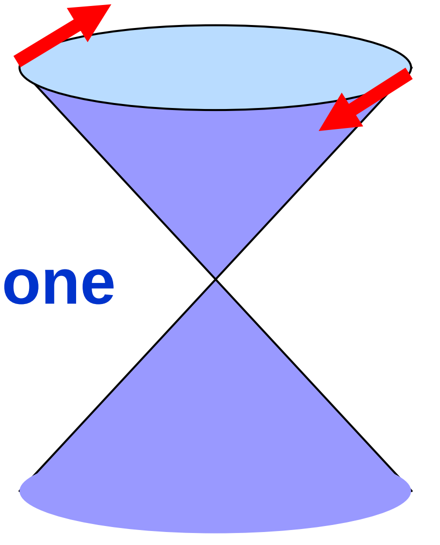
NSFC   CAS

中华人民共和国科学技术部
The Ministry of Science and Technology of the People's Republic of China

MOST

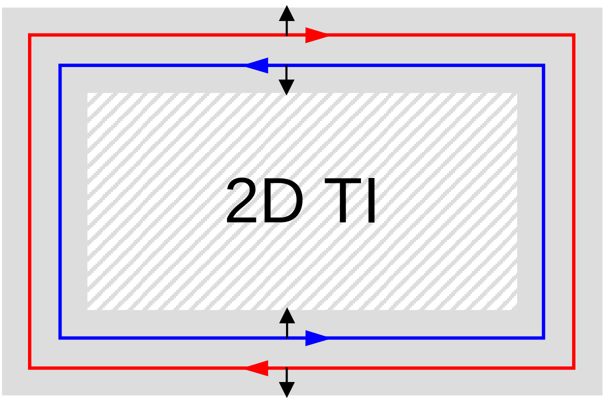
What is a topological insulator?

insulating bulk + conducting surface/edge



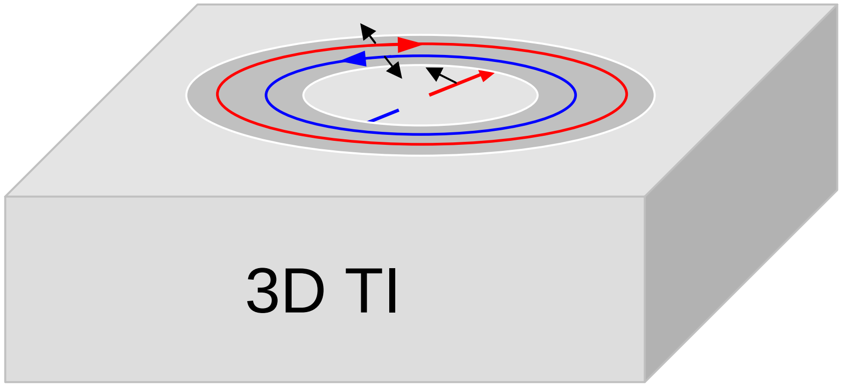
Dirac cone

Helical electrons



strong SOC

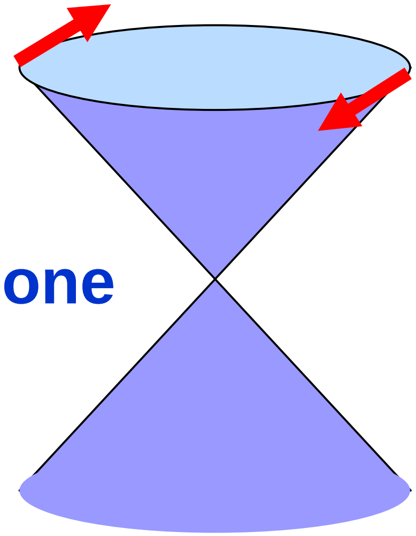
spin-momentum locking



- Band inversion and Dirac cone (momentum space)
- Helical electrons (real space)

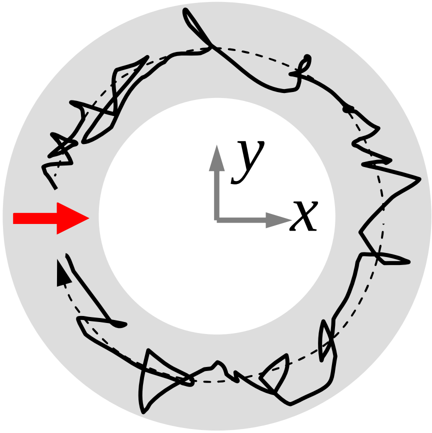
π Berry phase

Dirac cone

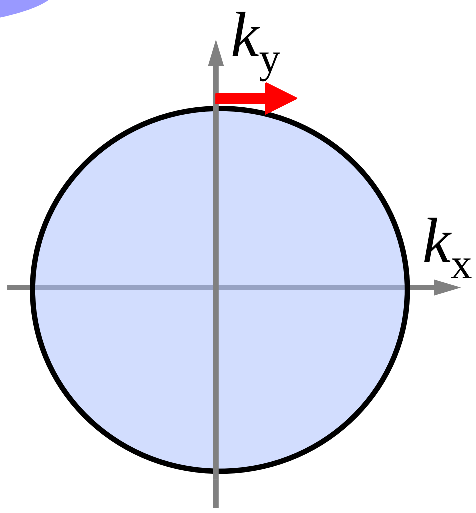


Consequences:

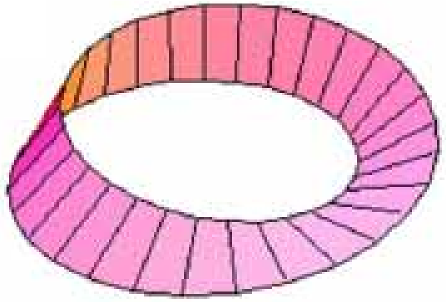
- ✓ Suppression of back-scattering
- ✓ Weak anti-localization
- ✓ … … …



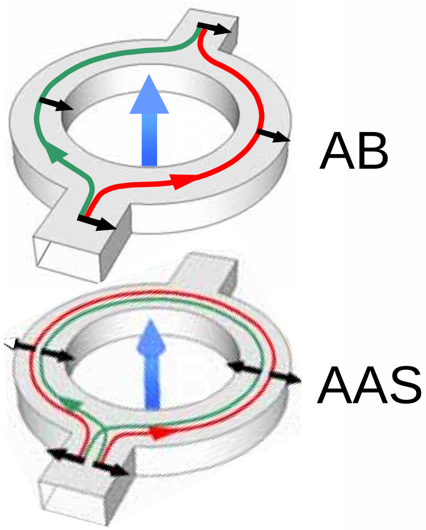
real space

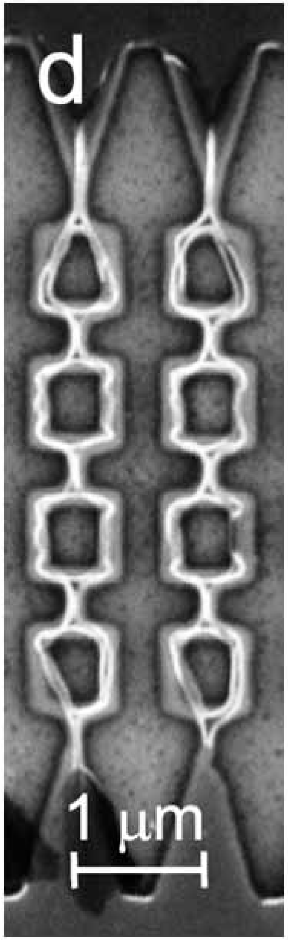


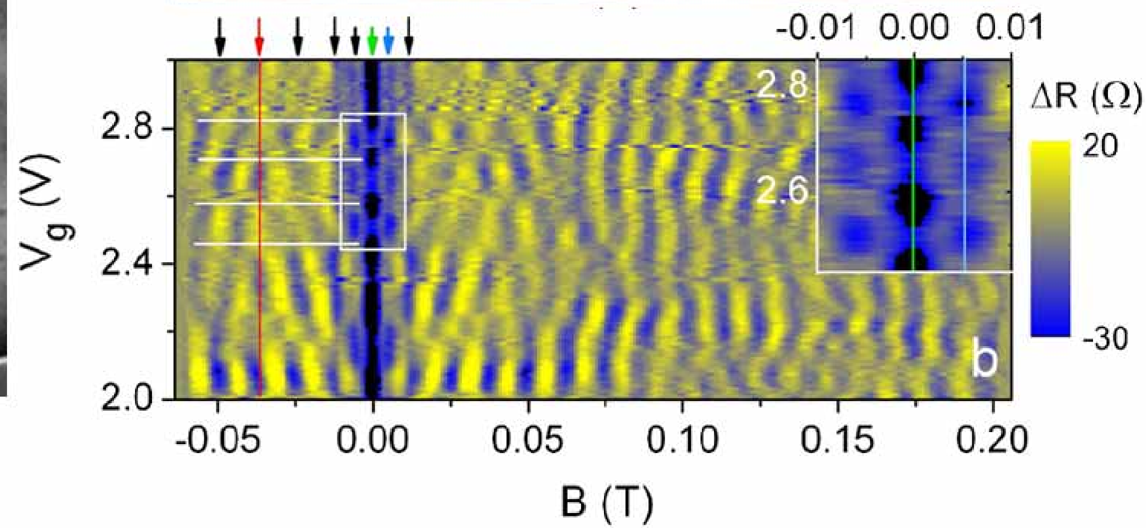
momentum space



Altshuler-Aronov-Spivak, Aharonov-Bohm, and Aharonov-Casher effects

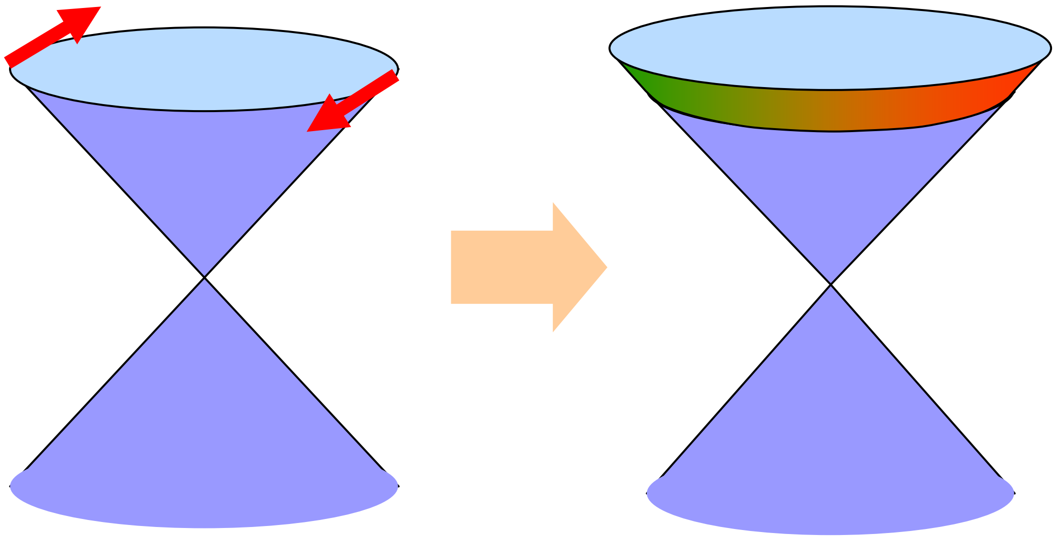






F. M. Qu, et al., PRL'2011

When helical electrons pair up …

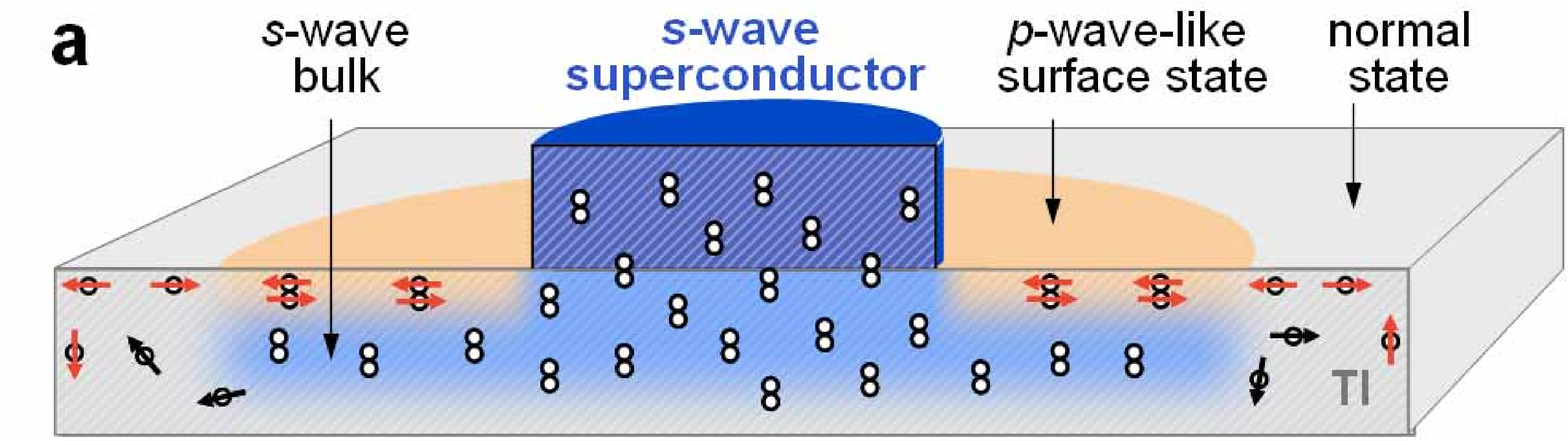


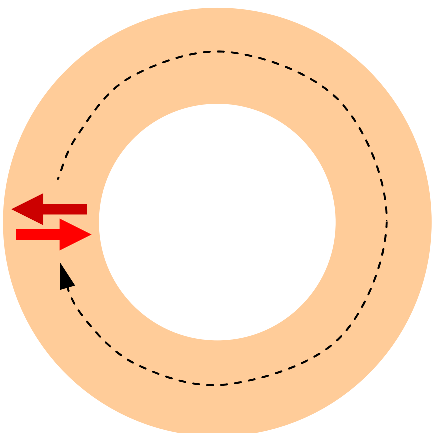
Fu & Kane (PRL 2008):

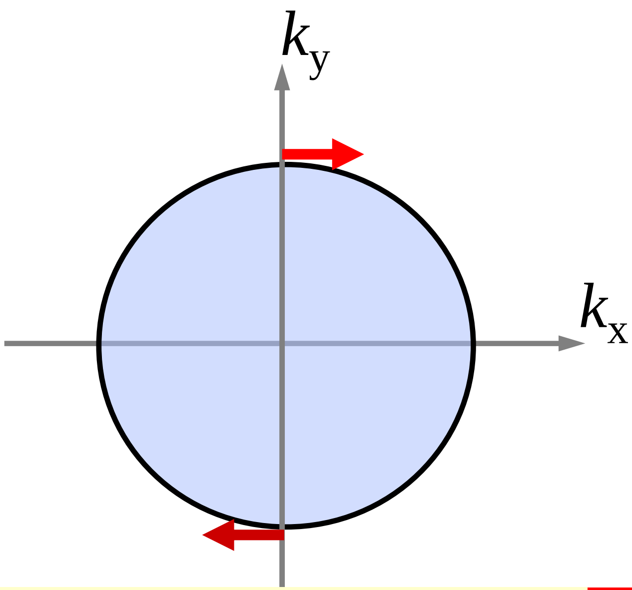
resembling a spinless p_x+ip_y-wave superconductor

$$\Delta(r,\theta) = \Delta_0(r)e^{\pm i\theta}$$

2π Berry phase







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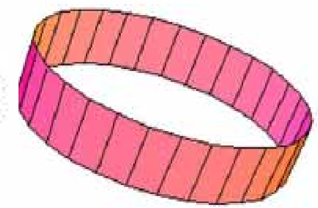
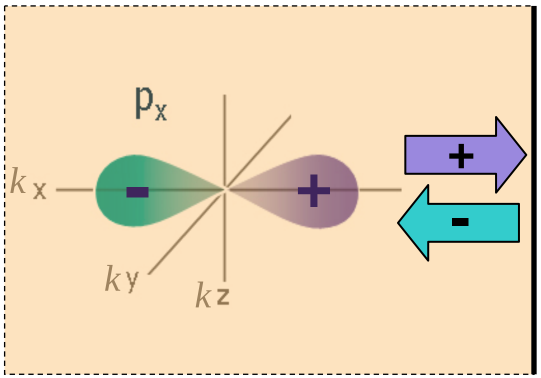


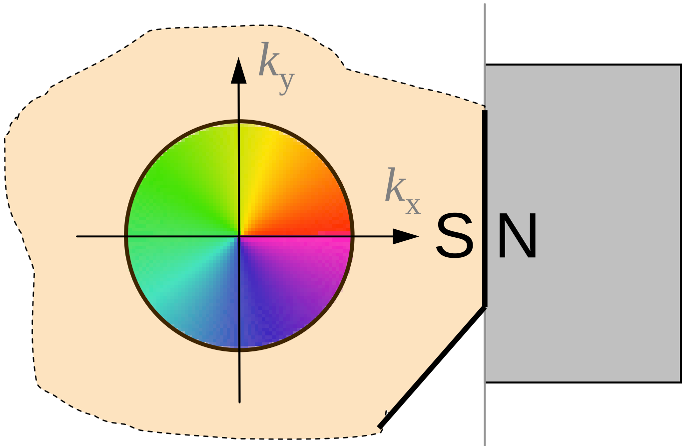
$$\Psi = \Psi_{\text{mass center}} \cdot \Psi_{\text{relative}}$$

2π Berry phase, p-like

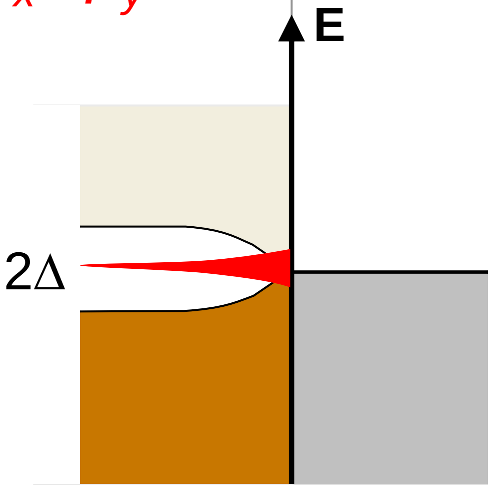
Zero-bias conductance peak (ZBCP) at S-N interface



p_x

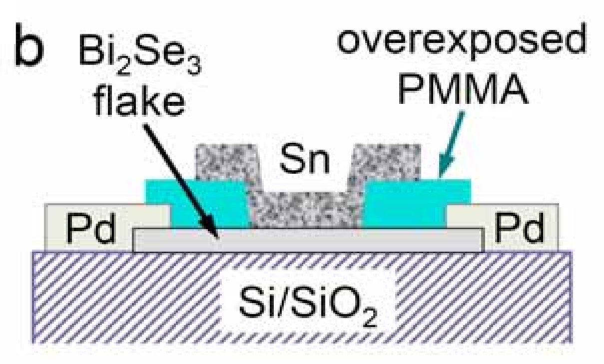


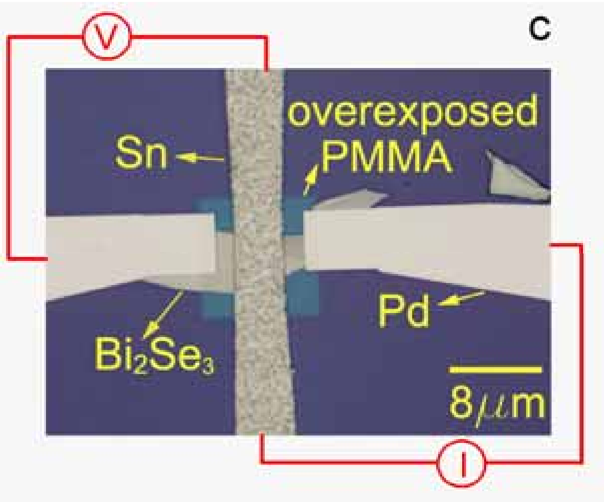
p_x+ip_y



S-N junction
ZBCP

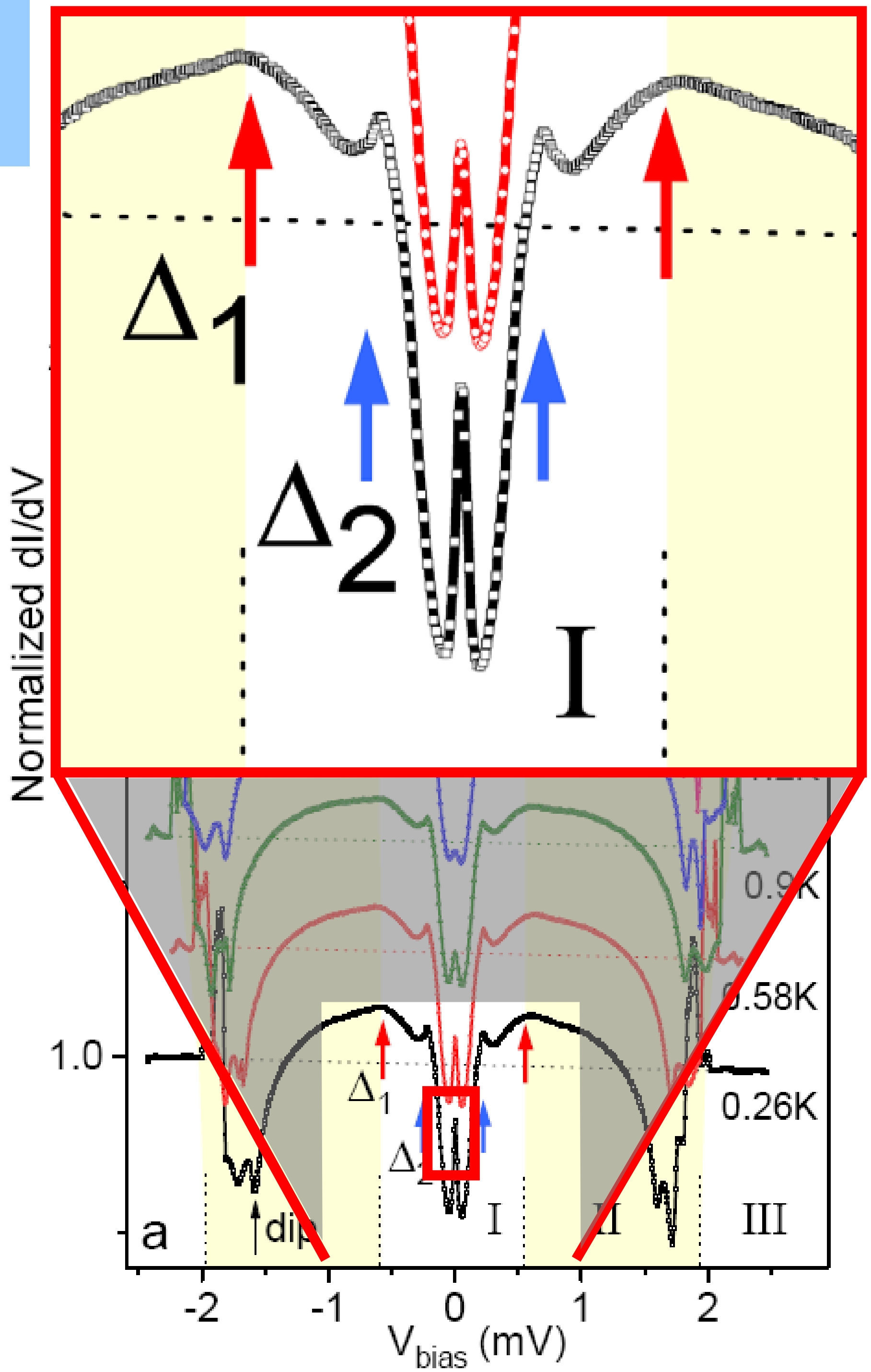
Observation of Zero-bias conductance peak





More than a dozen of devices were studied

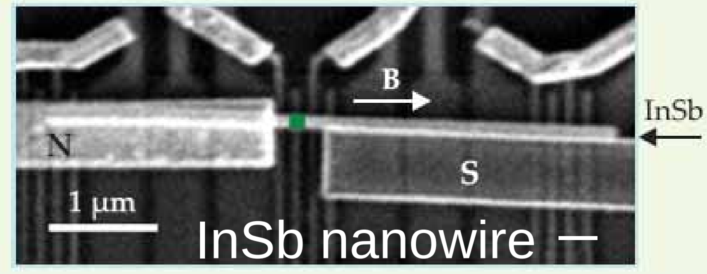
F. Yang, et al., arXiv:1105.0229v1, PRB' 2012

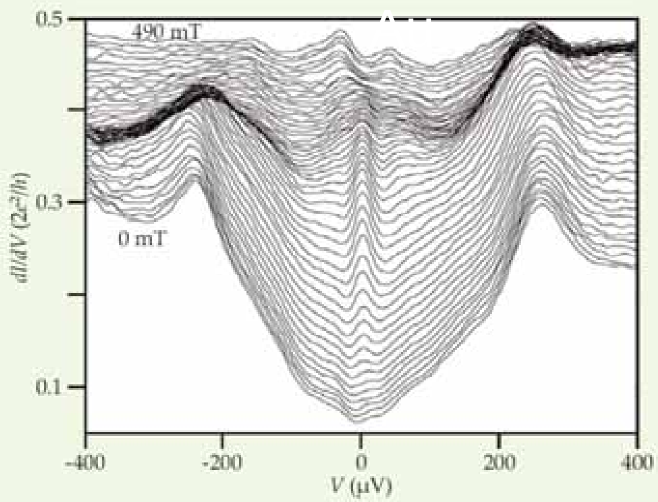


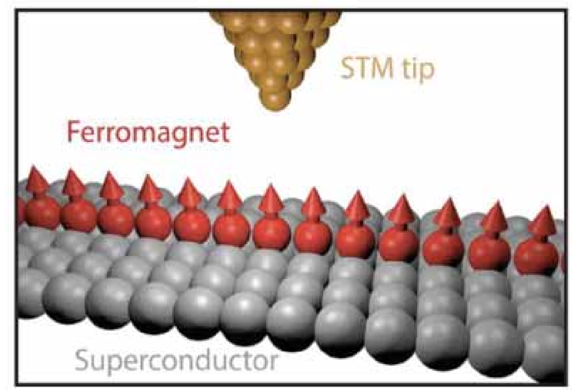
More ZBCPs

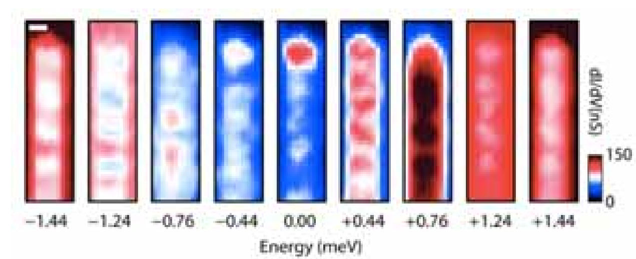
- Ando group
  $Cu_xBi_2Se_3$, PRL 2011
- Jia/Xue groups
  vortex core, Science 2012
- Kouwenhoven group
  1D wire, Science 2012
- Xu group
  1D wire, Nano Lett. 2012
- Yazdani Group
  1D Fe chain on Pb, Science 2014

Having a ZBCP is necessary but not sufficient for *p*-wave-like SC / MBS

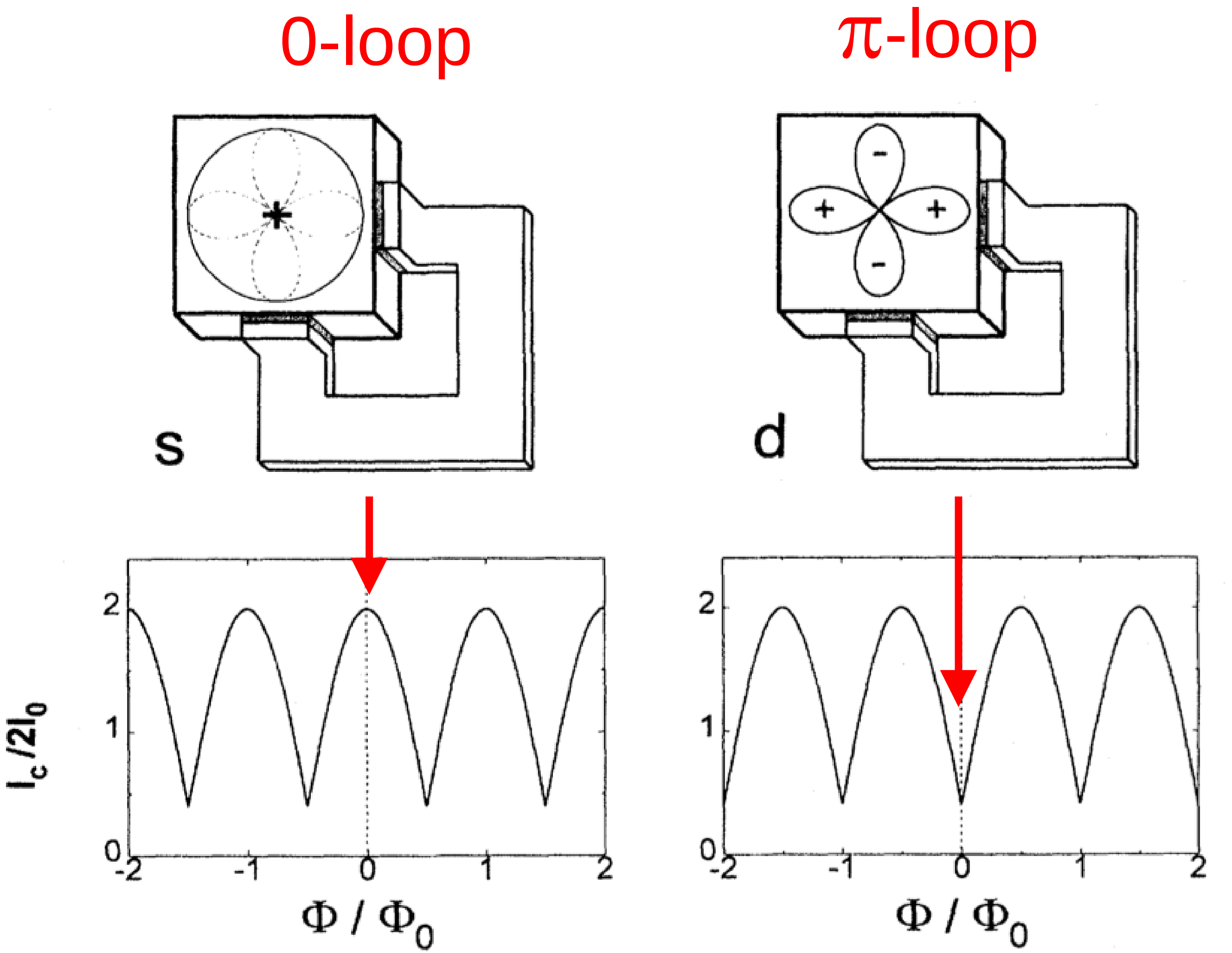






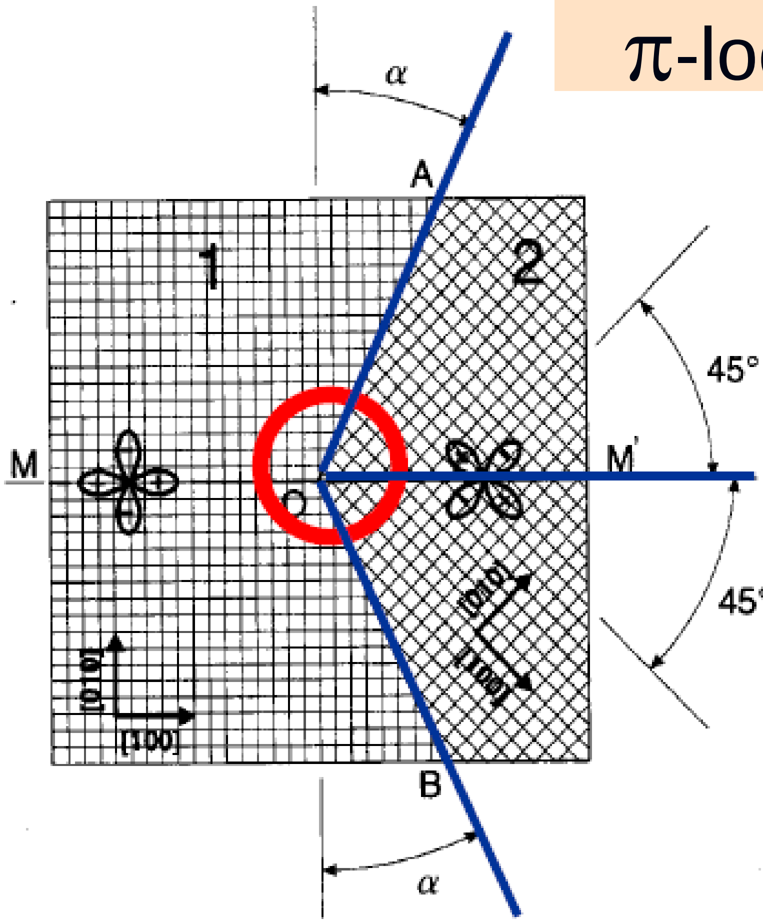


Phase-sensitive experiment (van Harlingen)

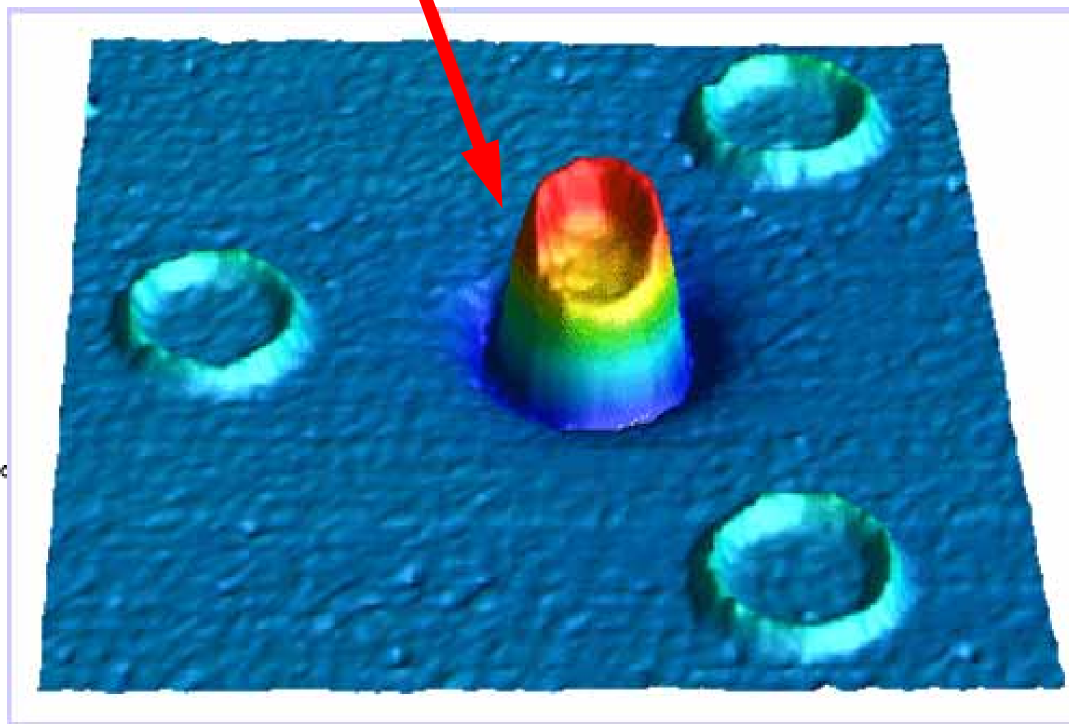


van Harlingen, Review of Modern Physics 67, 515 (1995)

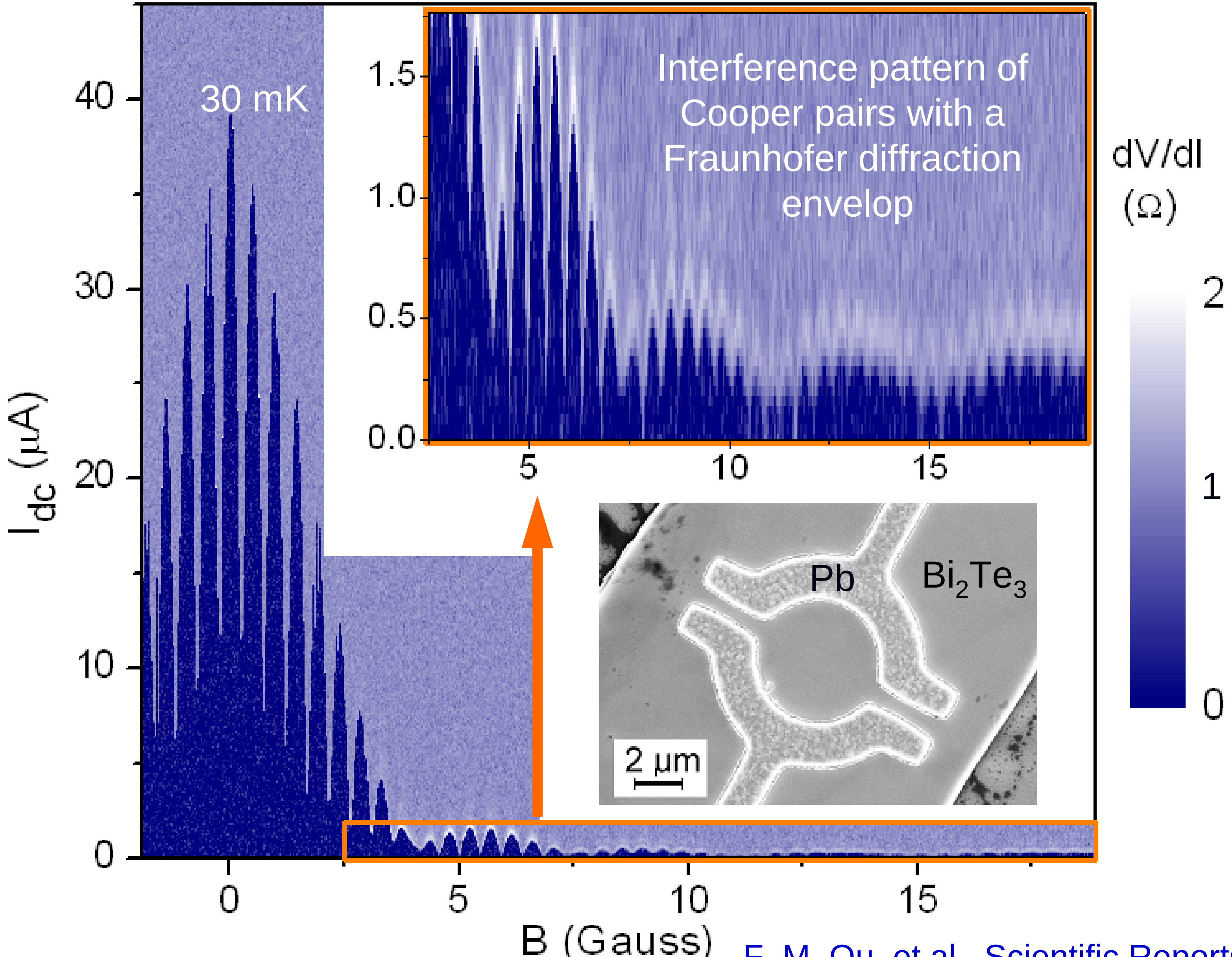
Phase-sensitive experiment (C.C. Tsuei)



YBCO tri-crystal SQUID
π-loop & half flux quanta

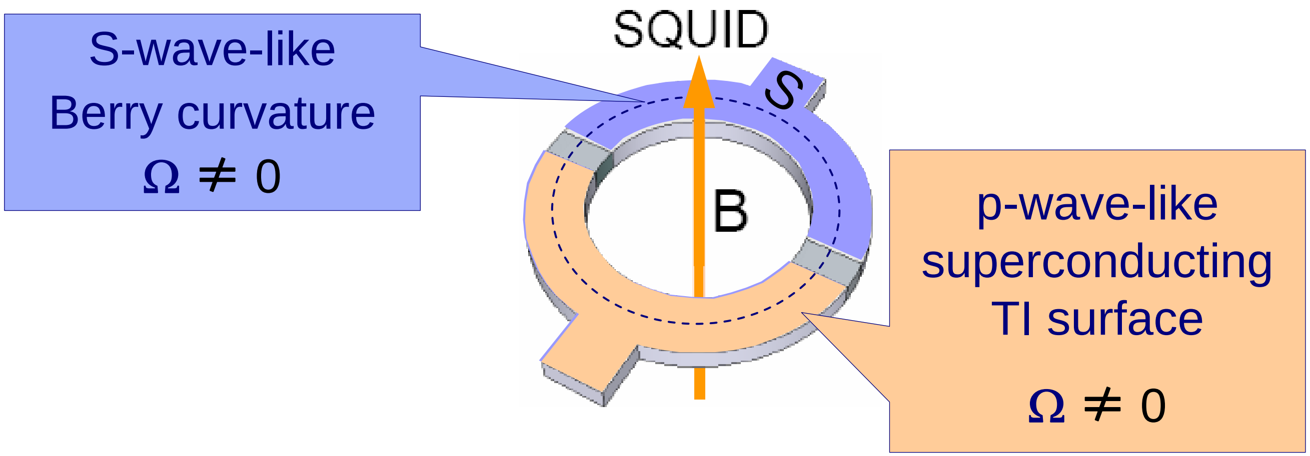


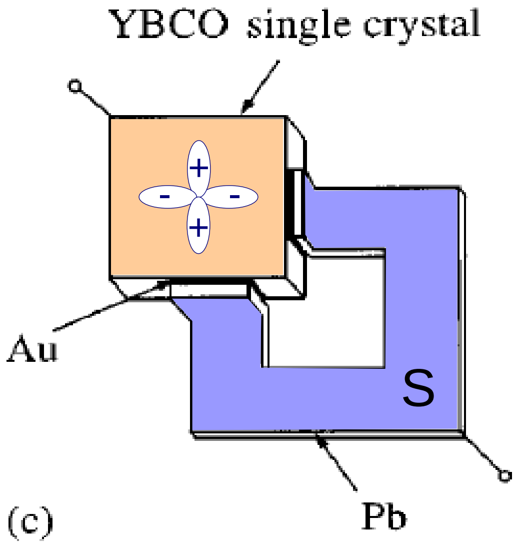
Superconducting quantum interference device (SQUID)



F. M. Qu, et al., Scientific Reports (2012)

Why I_c maximizes at B=0 in previous exp.?

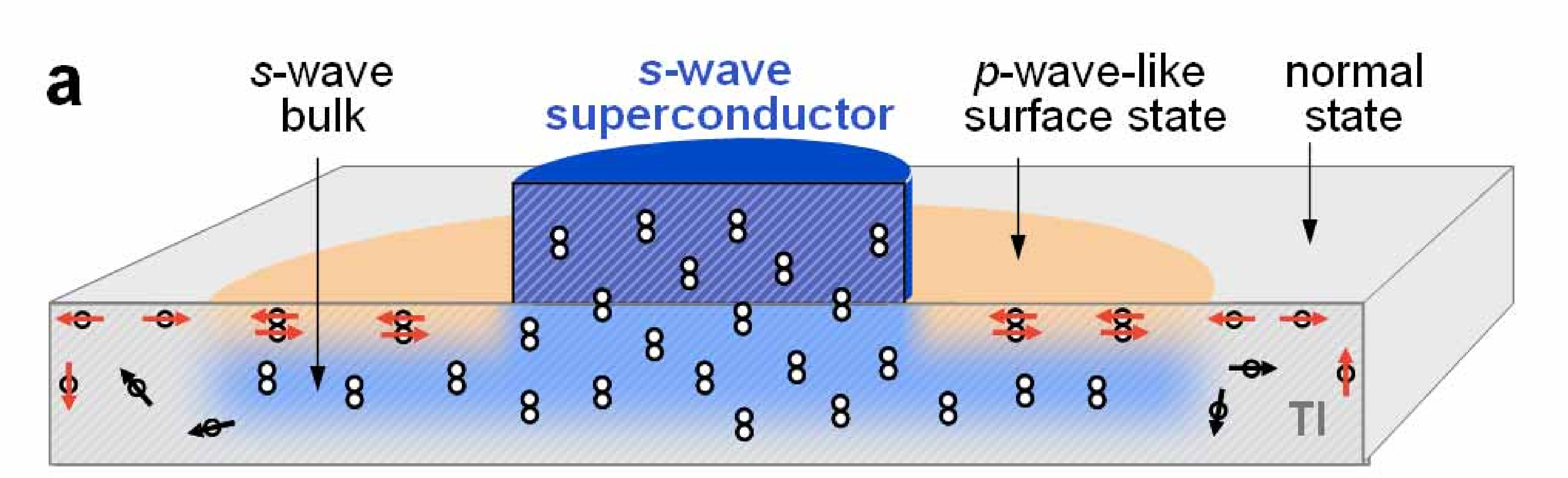




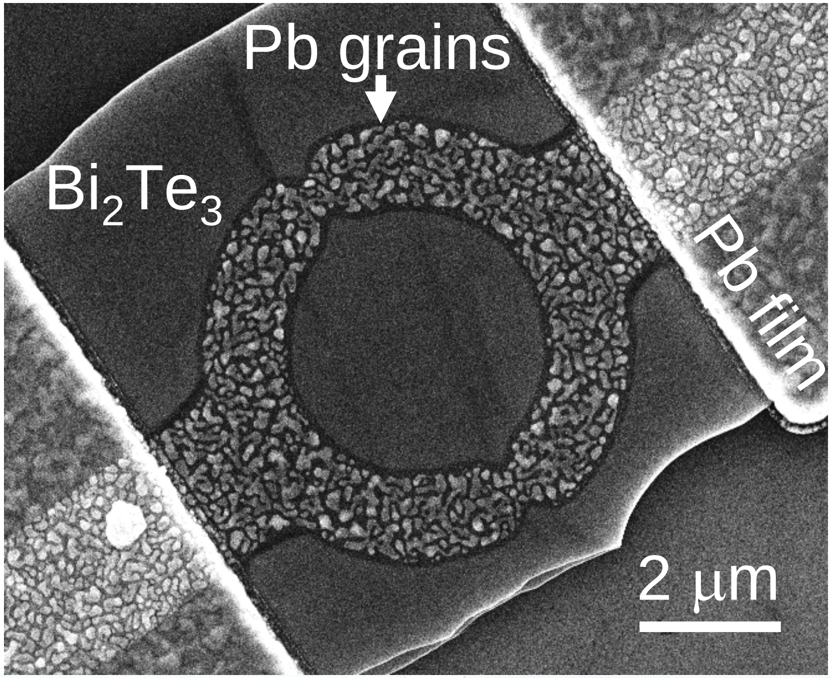
π-loops

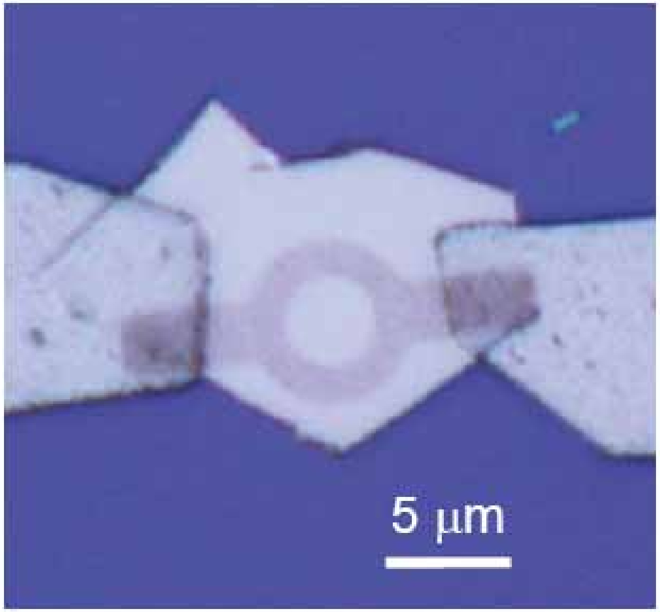
To examine the p-wave-like feature, one needs to form a loop which picks up the Berry phase of the p-like state

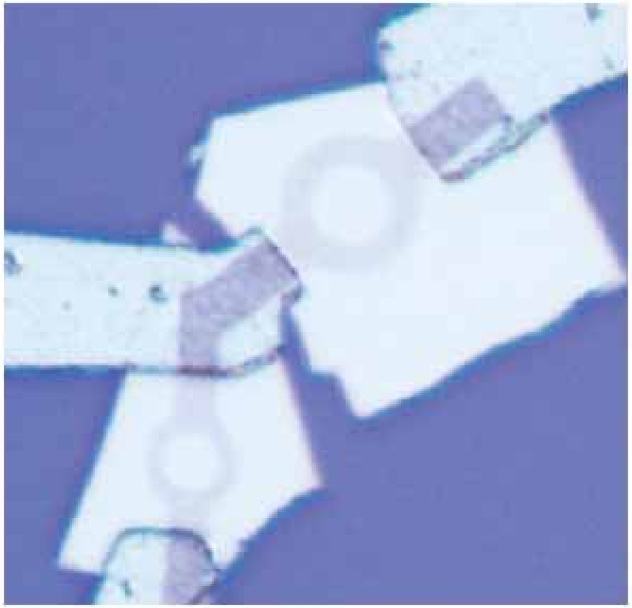
Proximity Effect at SC-TI Interface



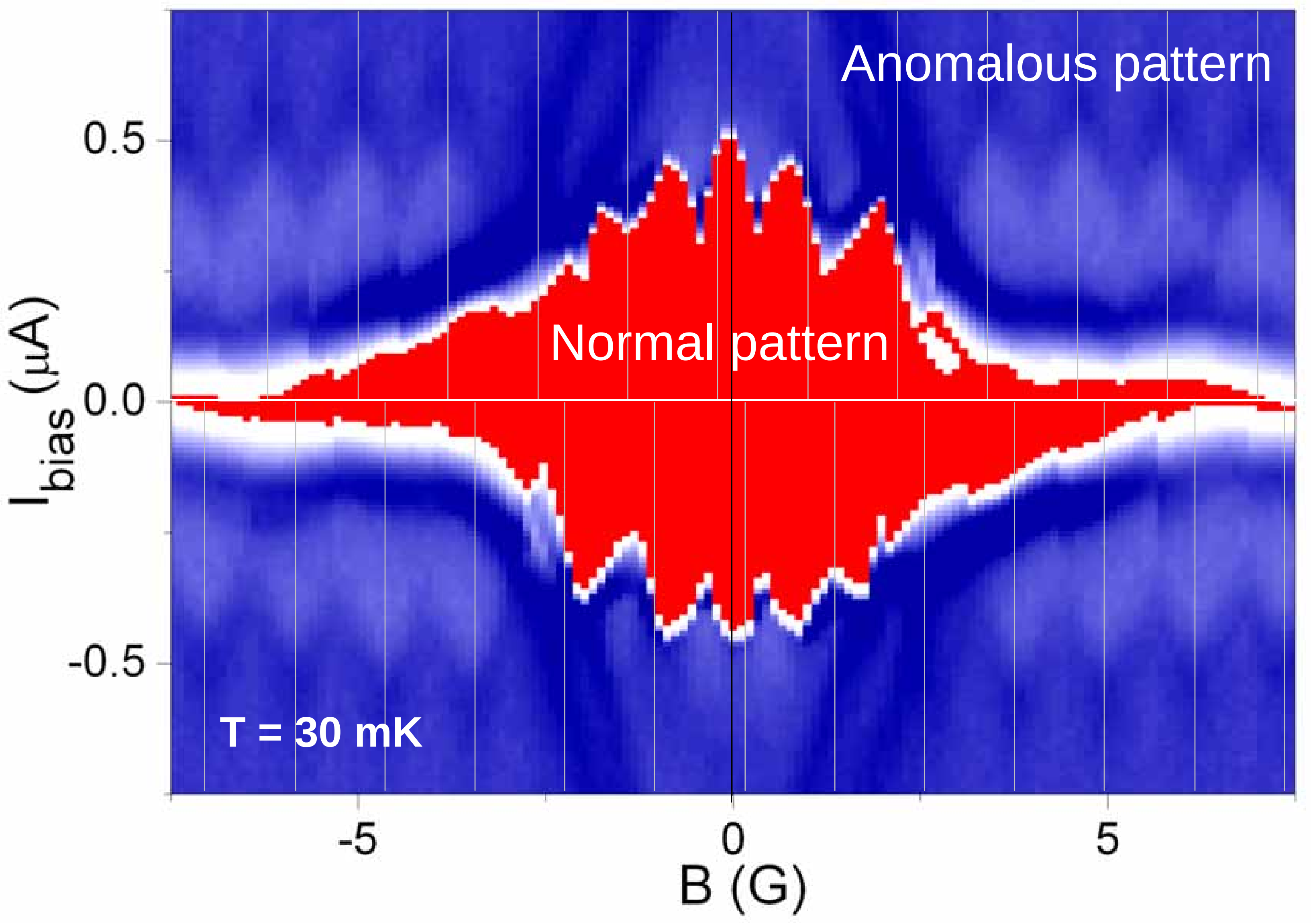
Pb-grain SQUIDs on Bi_2Te_3



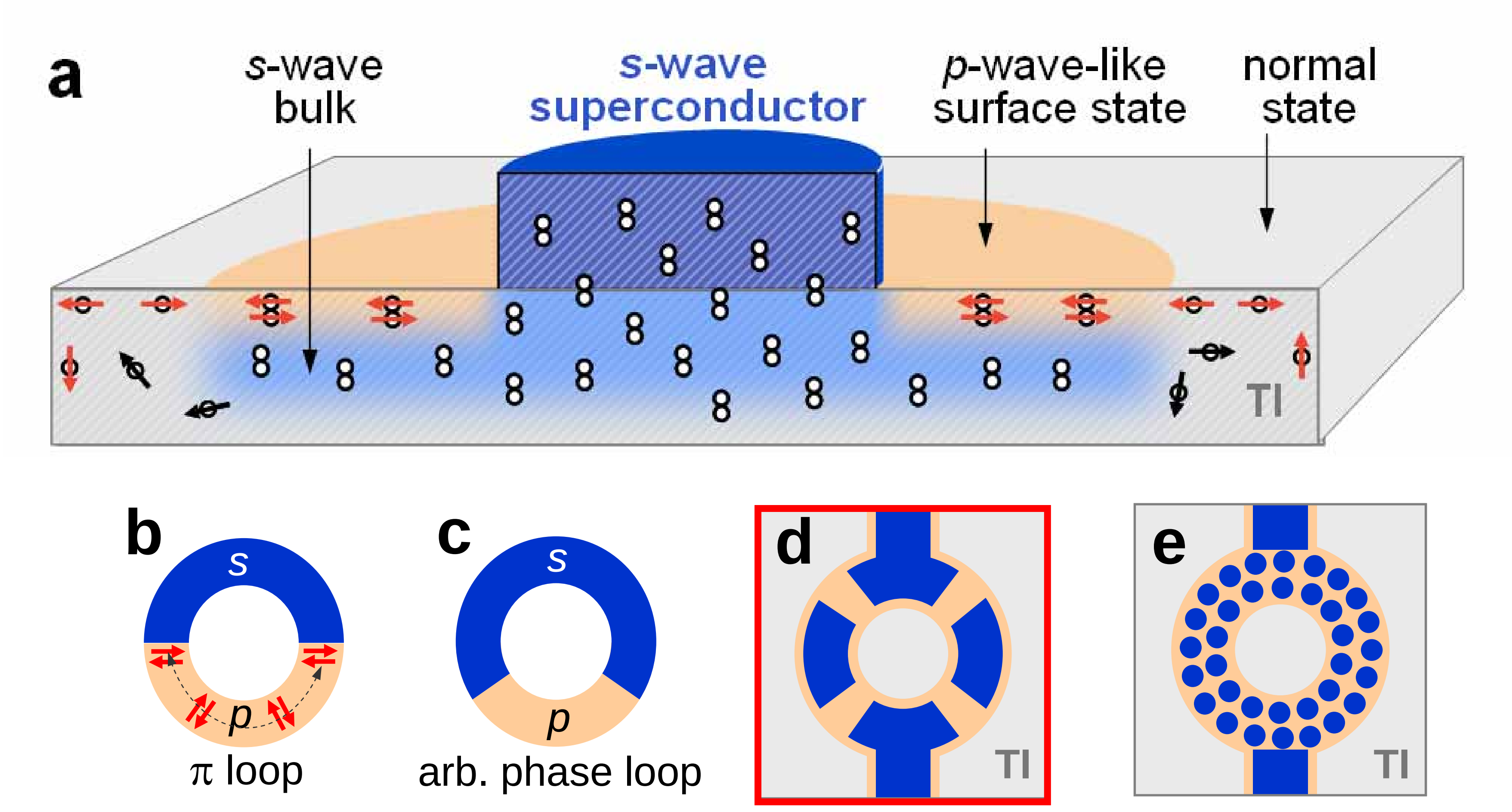




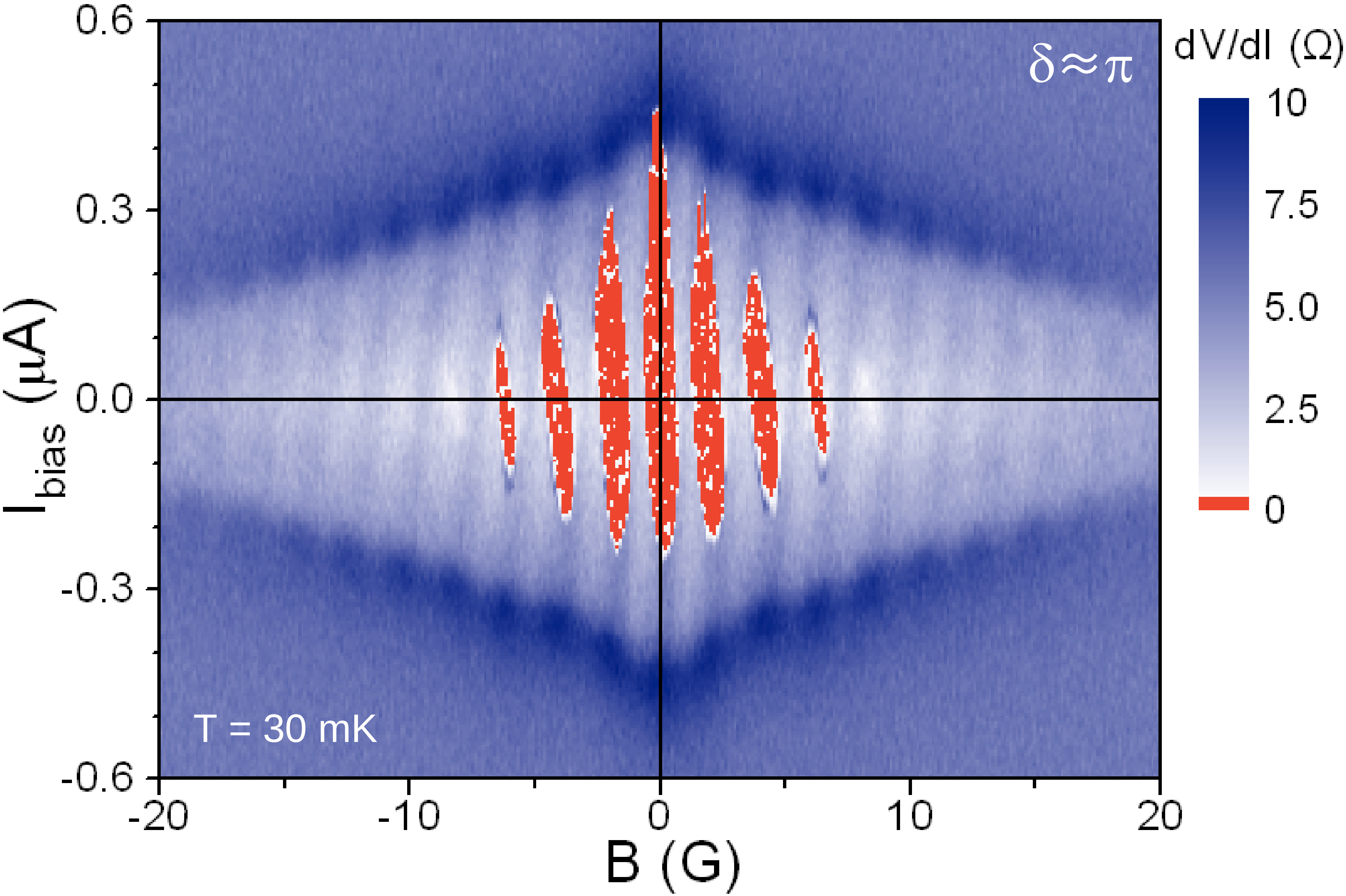
Interference Patterns



Proximity Effect at SC-TI Interface



Four Pb segments SQUIDs on Bi_2Te_3



Our picture for the anomalous pattern

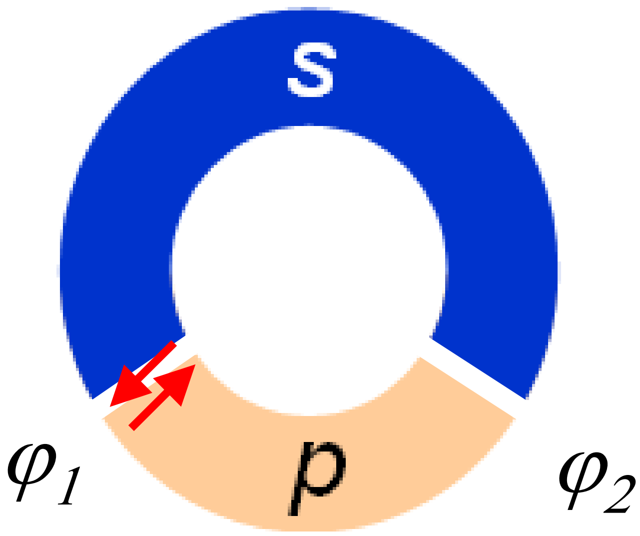
Fluxoid quantization along the loop:

$$\varphi_1 + \varphi_2 + 2\pi \Phi_{ex}/\phi_0 \pm \delta = 2\pi N$$

Berry phase ~ B_{eff}

Free energy:

$$U = (\Phi_{ex} - N\phi_0)^2/2L - E_{J1}\cos\varphi_1 - E_{J2}\cos\varphi_2$$



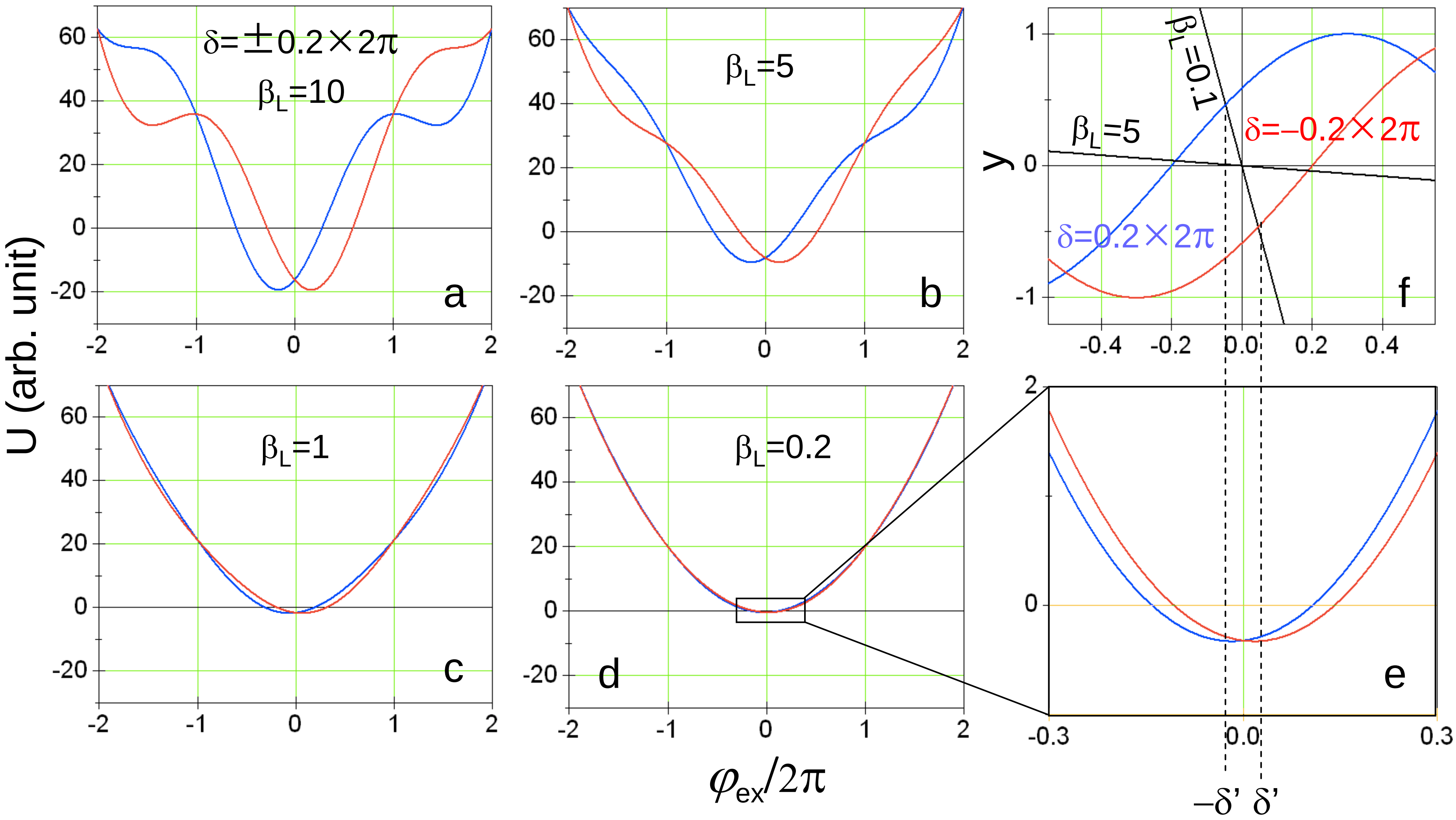
When $E_{J1} = E_{J2}$:

$$U \propto \varphi_{ex}^2/2 - 2\beta_L\cos(\varphi_{ex}/2 \pm \delta/2)$$

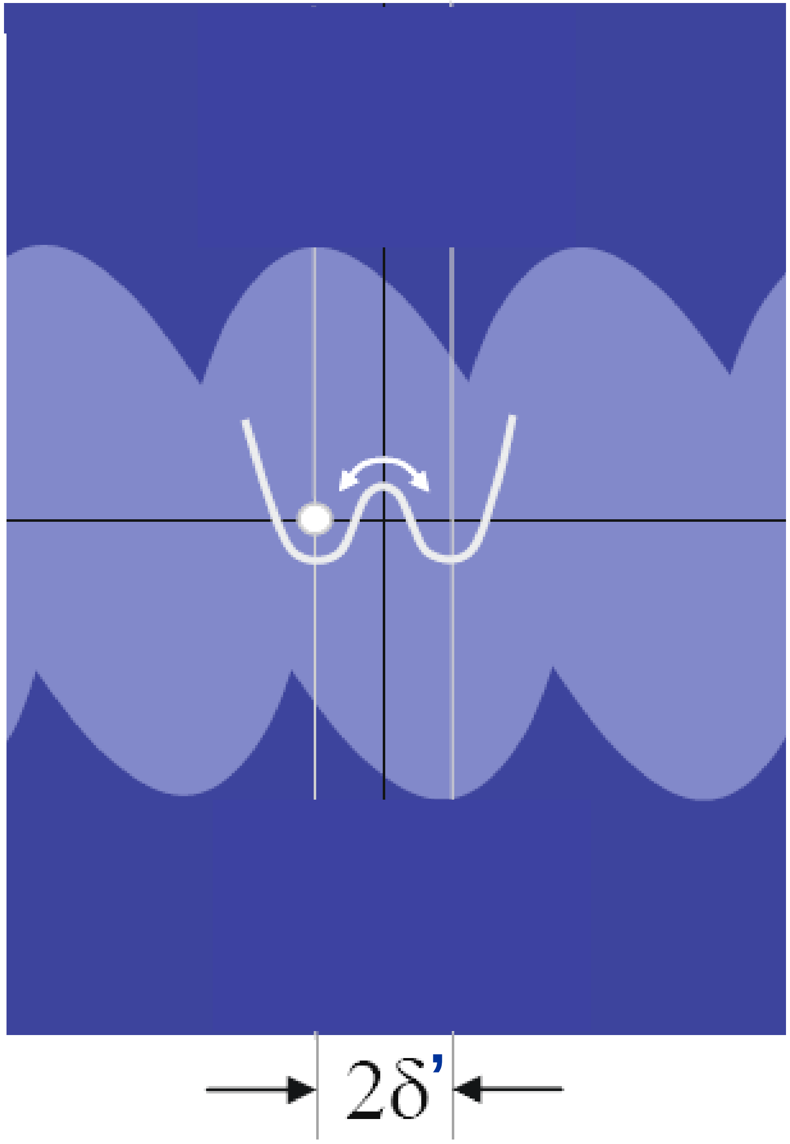
$$\beta_L = 2\pi L I_c/\phi_0$$

Formation of a double-well potential

$$U \propto \varphi_{ex}^2/2 - 2\beta_L \cos(\varphi_{ex}/2 \pm \delta/2)$$



Break the time reversal symmetry?



- cw and ccw double wells
- with inter-well tunneling, it forms a two-level system:

  $|\Psi_0\rangle = |cw\rangle + |ccw\rangle$

  $|\Psi_1\rangle = |cw\rangle - |ccw\rangle$

- The wavefunctions are ***time reversal invariant*** within the decoherence time.
- In real measurement, the system will project to |cw> or |ccw> states spontaneously.
- The projection is selected by the bias current.

Summary

- Used 2π Berry phase to describe the p-wave-like superconductivity of Cooper pairs made of helical electrons.

- Constructed two types of Cooper pair interference loops to detect the Berry phase on the surface of 3D TI.

- Observed in addition to a normal interference pattern an anomalous one, which survives in parallel magnetic field, presumably arising from the Berry phase of the Cooper pairs.

arXiv:1303.5598v3

Thank You