Kavli ITS workshop on “topological matter & quantum computation”

Majorana zero mode inside vortex of topological superconductors

Jinfeng Jia

School of Phys. & Astronomy, Shanghai Jiao Tong University, Shanghai 200240, China

Email: jfjia@sjtu.edu.cn

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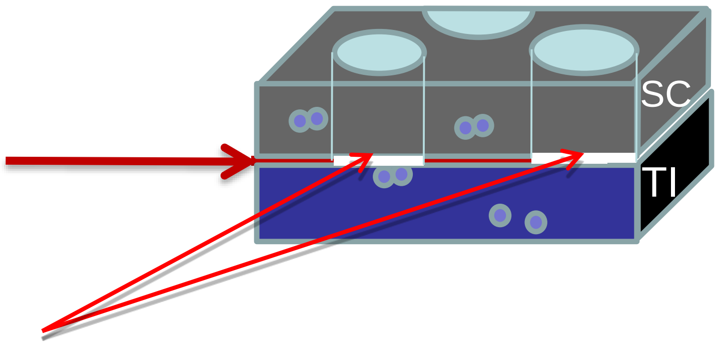
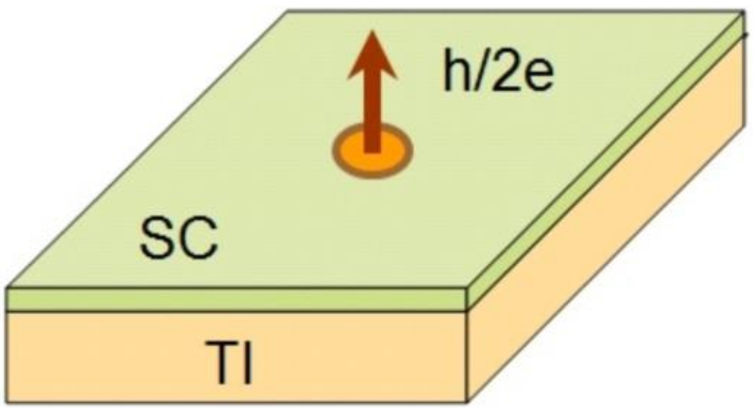
Content

- Introduction
- Topological superconductor by proximity effects
- Majorana fermion in the vortex
- Summary

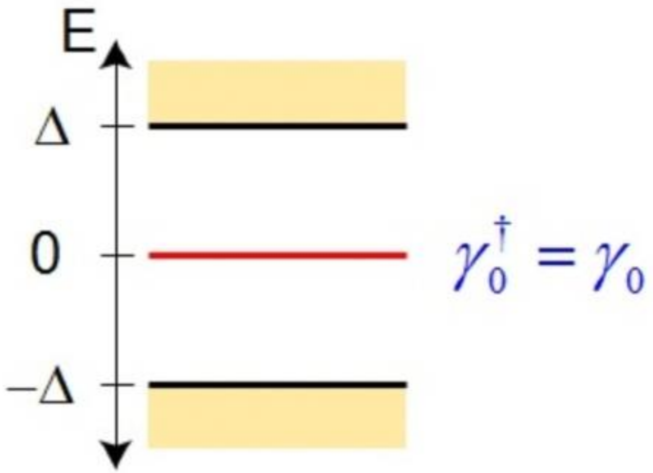
TSC by Proximity effect

- Proximity effect between SC and TI leads to „p_x+ip_y“ SC-like-state
- Majorana Bound States (MBS) at magnetic vertices





Quasiparticle Bound state at E=0

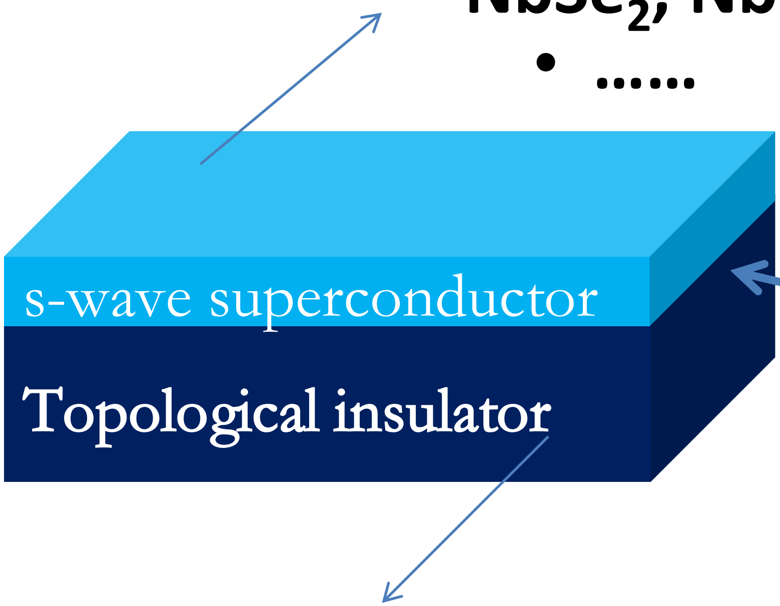


Majorana Fermion γ_0

L. Fu and C.L. Kane PRL 100, 096407 (2008)

MBE growth to obtain sharp interface.

- **Pb, Nb, Al, ……**
- **$NbSe_2$, NbS_2……**
- **……**



Sharp interface!

S-SC on TI,
difficult to realize in practice.

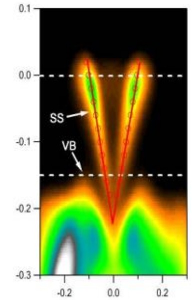
Bi-Sb, Bi_2Te_3,Sb_2Te_3,Bi_2Se_3， ……

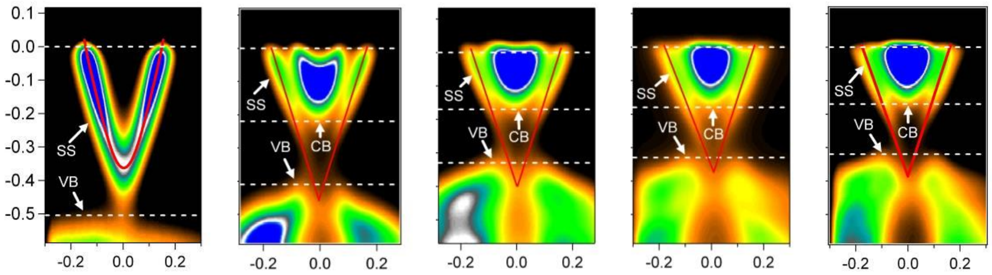
- heavy atoms
- Stable at T<300 ^{o}C

TSS is covered by superconductor ☹

Our previous work on TI fims

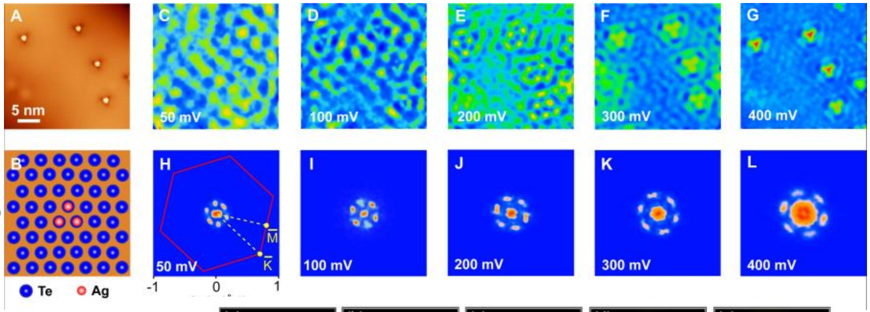
- High quality Bi_2Te_3, Bi_2Se_3, Sb_2Te_3 thin films by MBE

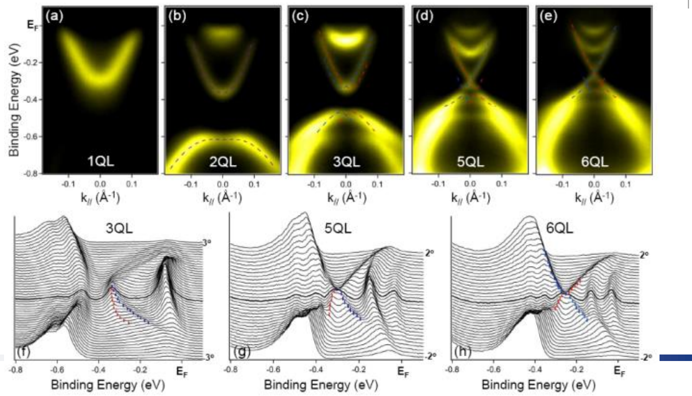




Adv. Mater. 22, 4002-4007 (2010)
Adv. Mater. 23, 1162-1165 (2011)

- Thinnest limit

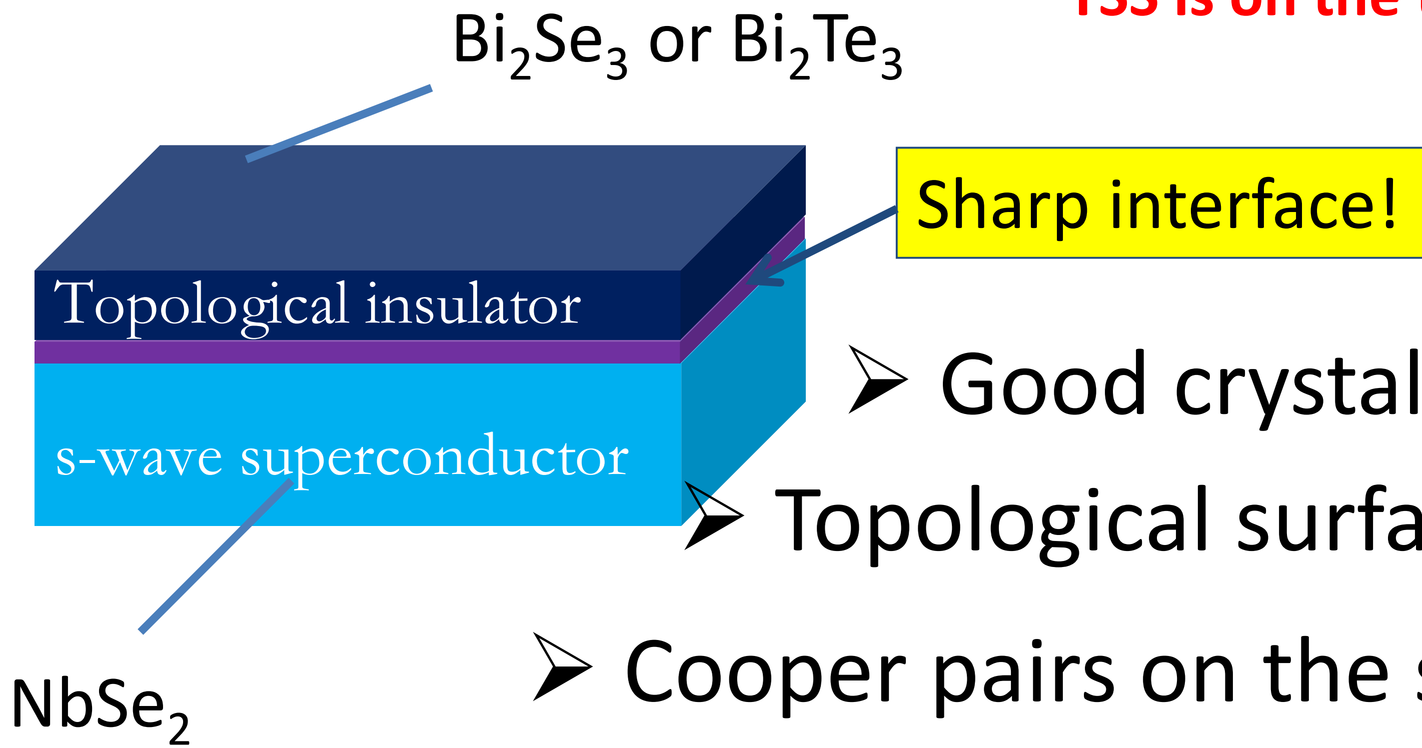




- Control the type of Bi_2Te_3 films
- Studies by LTSTM & ARPES
  - Standing wave **PRL 103**, 266803 (2009)
  - Landau levels **PRL 105**, 076801 (2010)
  - Formation of DC
    - **Nature Phys. 6**, 584 (2010)

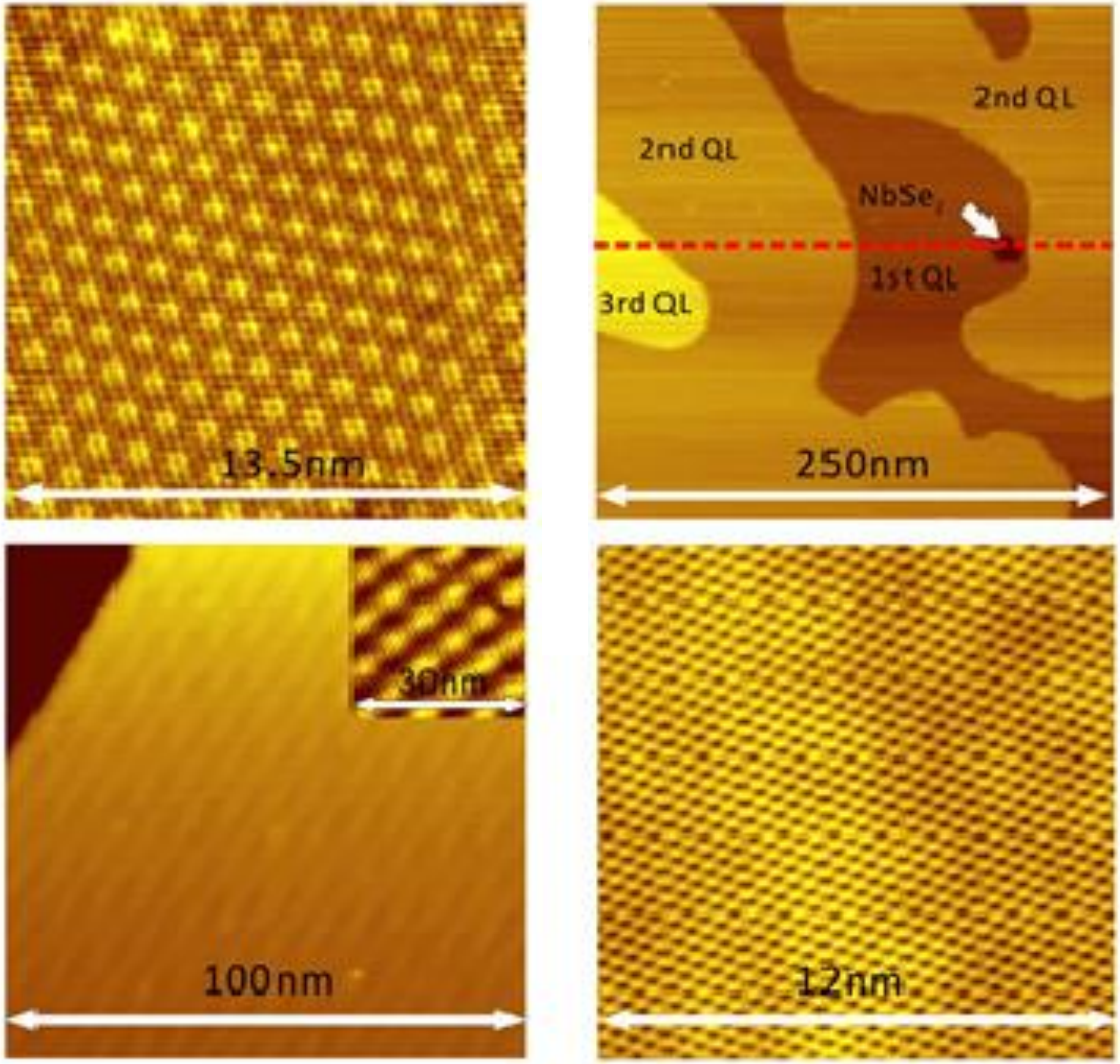
TI on SC, much easier to achieve

TSS is on the top ☺



- Good crystallization?
- Topological surface state?
- Cooper pairs on the surface?
- Topological SC?
- Vortex?
- Bound states & Majorana?

Bi_2Se_3 films grown on $NbSe_2$



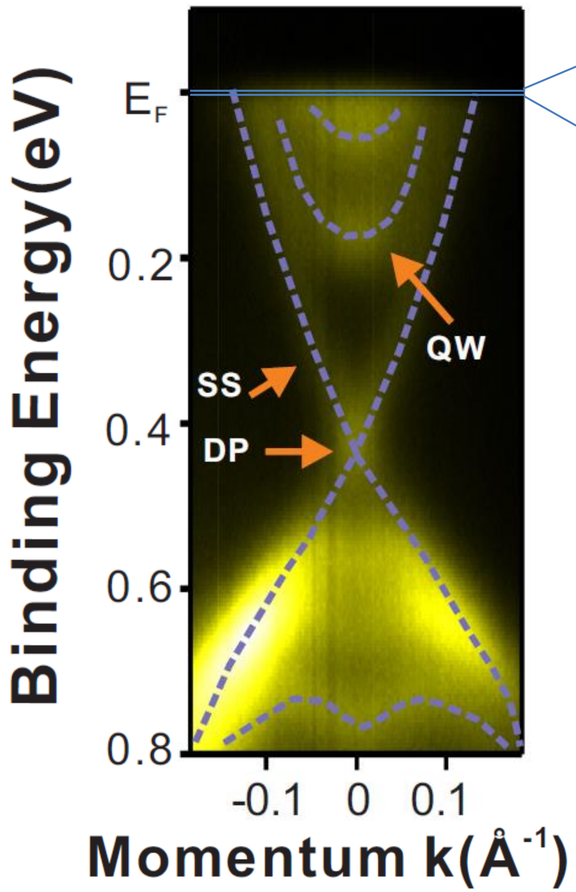
SC

Sharp interface

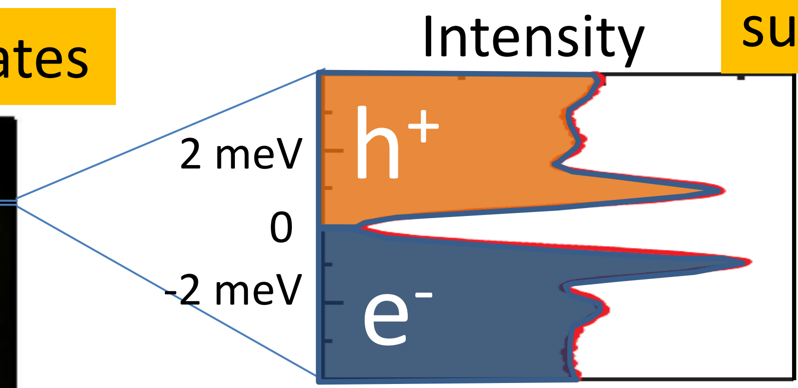
Less defects

A platform for searching Majorana Fermions

Topological surface states



superconductivity




REPORTS

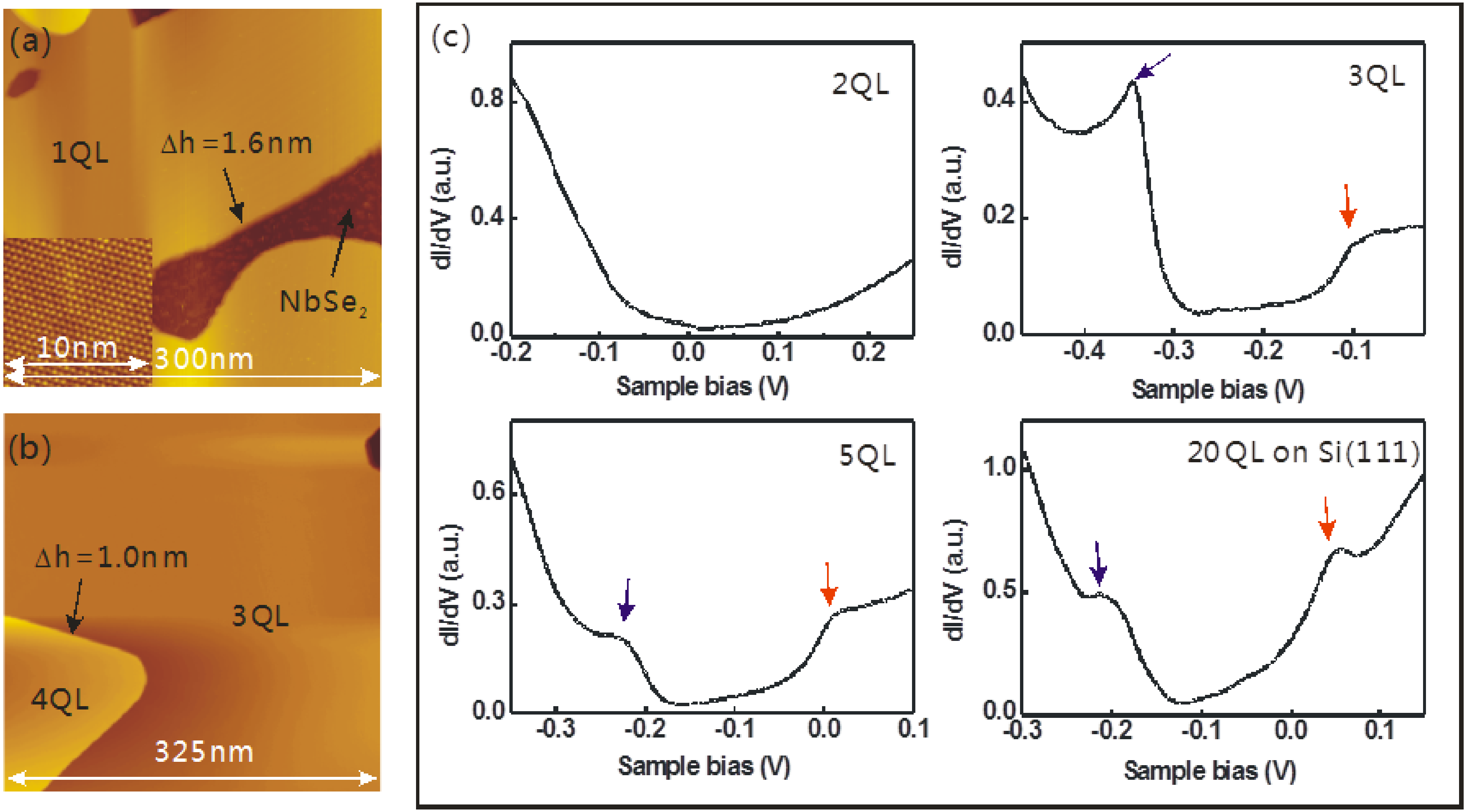
The Coexistence of Superconductivity and Topological Order in the Bi_2Se_3 Thin Films

Mei-Xiao Wang,[1]* Canhua Liu,[1]* Jin-Peng Xu,[1] Fang Yang,[1] Lin Miao,[1] Meng-Yu Yao,[1] C. L. Gao,[1] Chenyi Shen,[2] Xucun Ma,[3] X. Chen,[4] Zhu-An Xu,[2] Ying Liu,[5] Shou-Cheng Zhang,[6,7] Dong Qian,[1]† Jin-Feng Jia,[1]† Qi-Kun Xue[4]

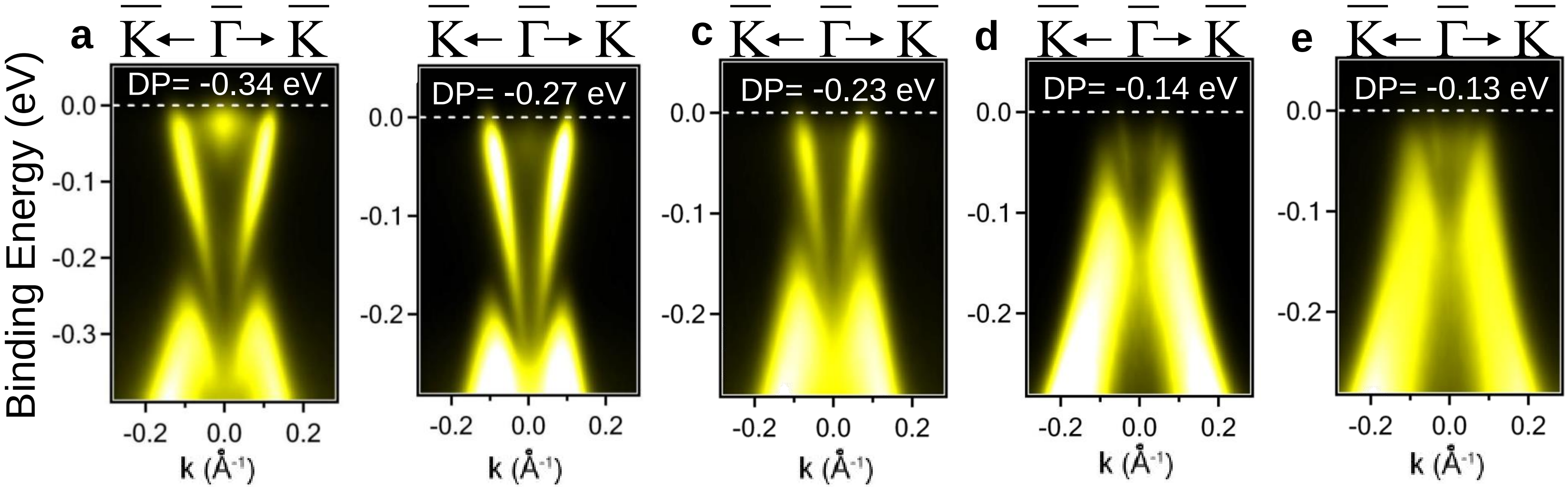
6 APRIL 2012 VOL 336 SCIENCE

Science 336, 52-55 (2012)

Bi_2Te_3 on $NbSe_2$



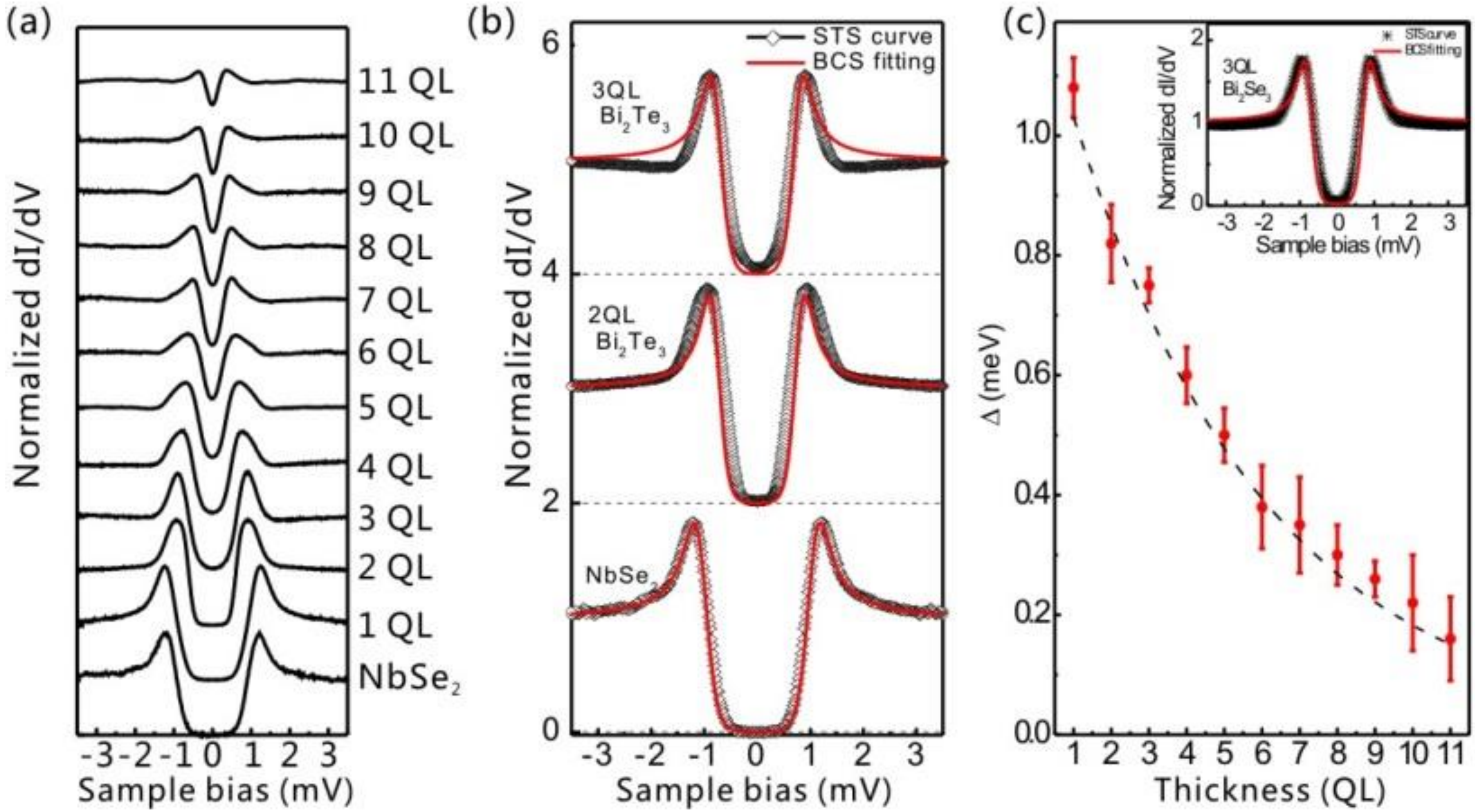
Fermi levels of Bi_2Te_3 films grown at different temperatures



Fermi level	Fermi level			
CBM = -0.06 eV	-0.02 eV	Fermi level	Fermi level	Fermi level
VBM = -0.24 eV	-0.18 eV	-0.14eV	-0.04 eV	-0.02 eV
DP = -0.34 eV	-0.27 eV	-0.23 eV	-0.14 eV	-0.12 eV
V_F= 4.3 x 10^5 m/s	4.2 x 10^5 m/s	4.8 x 10^5 m/s	4.7 x 10^5 m/s	4.7 x 10^5 m/s
T_{Si}=560 K	580 K	600 K	625 K	630 K

Adv. Mater. 22(36), 4002-4007 (2010)

Topological superconductor



Full gap topological superconductor!

Content

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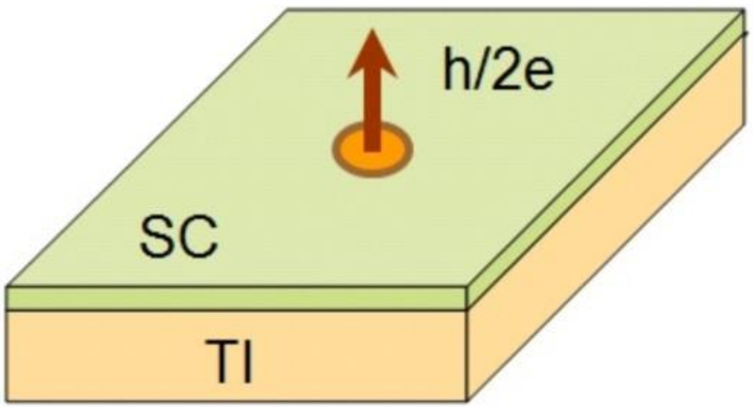
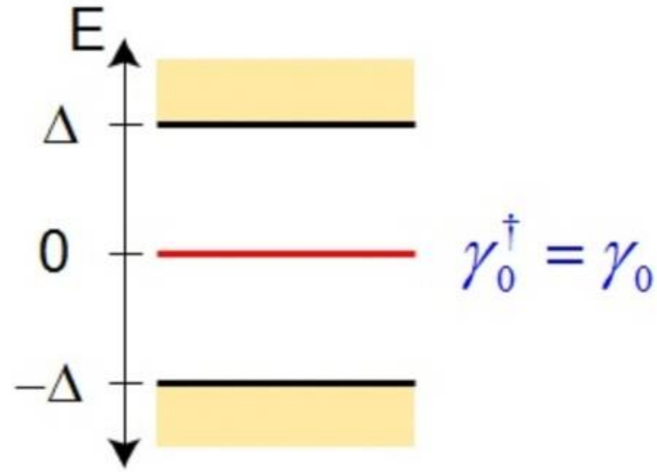
- **Majorana fermion in the vortex**
- **Summary**

MF: Zero energy



Quasiparticle Bound state at E=0

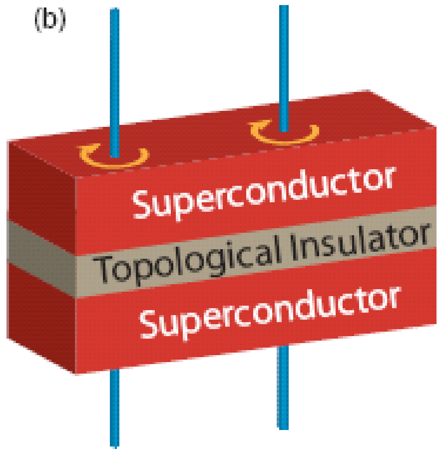


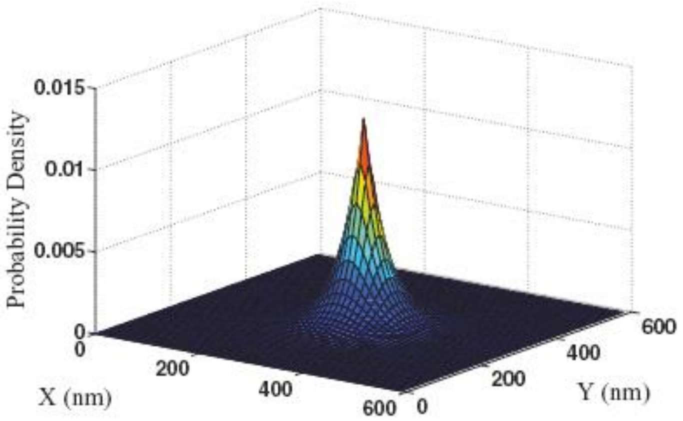
Majorana Fermion γ_0

L. Fu and C.L. Kane PRL 100, 096407 (2008)

C.W.J. Beenakker, Ann. Rev. Conden. Matter Phys., 4:113-136 (2013)

Vortex lines in topological insulator-superconductor heterostructures



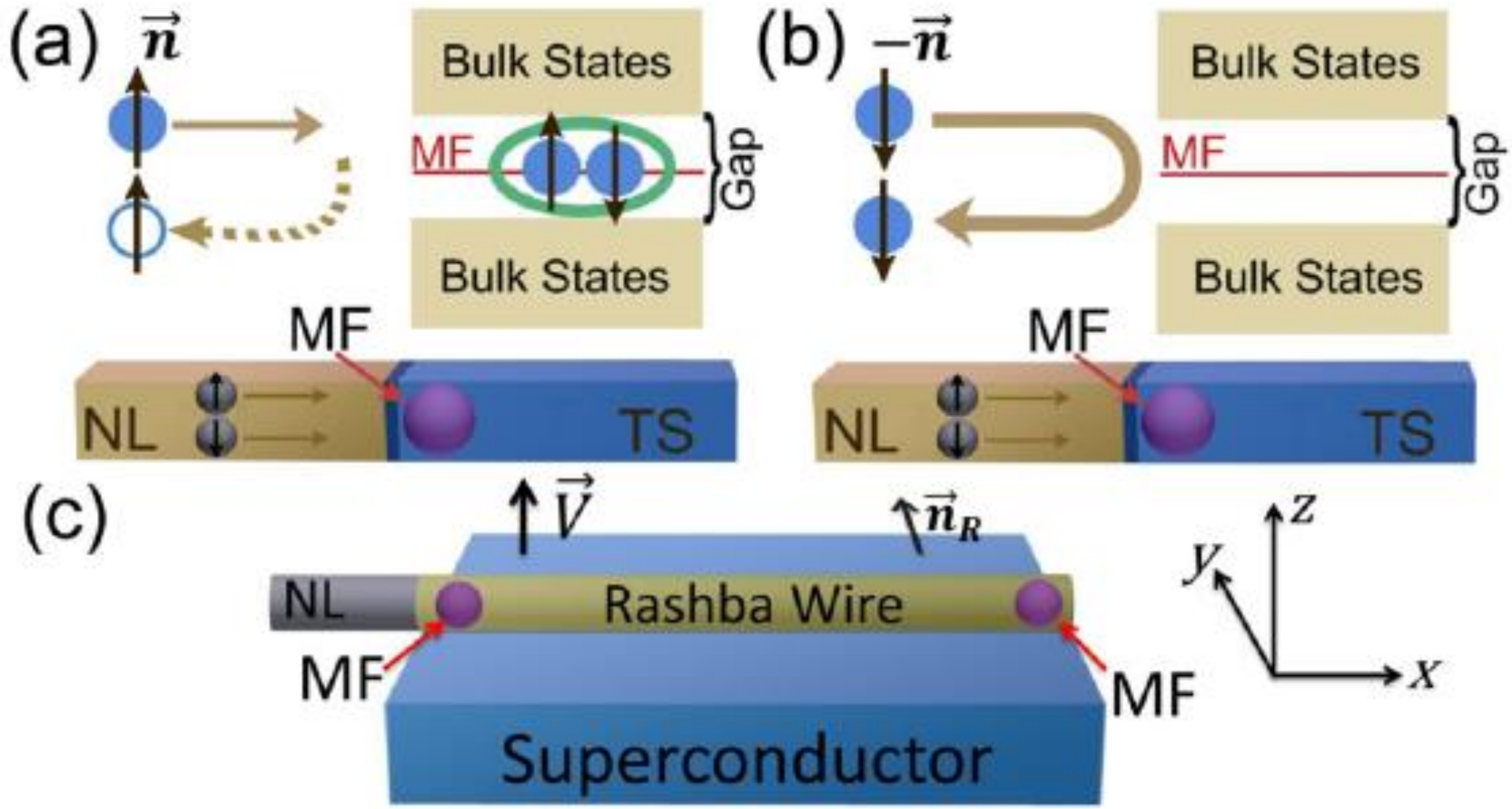


- In most case, the bulk effects can be ignored
- A Majorana fermion is stable with a spatial extent~40nm
- Chemical potential & Majorana states
- Majorana fermions can survive for thick samples

Hughes group, **PRB 84**, 144507 (2011)
PRB 87, 035401 (2013)

Selective Equal-Spin Andreev Reflections Induced by Majorana Fermions

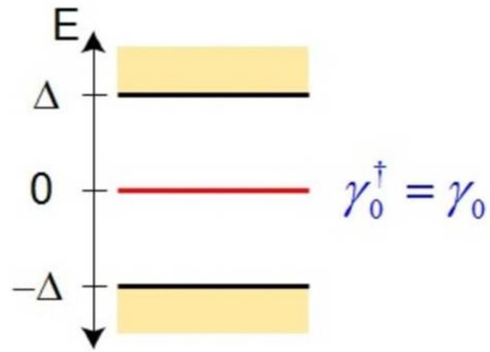
P. A. Lee, K. T. Law, PRL 112, 037001 (2014)



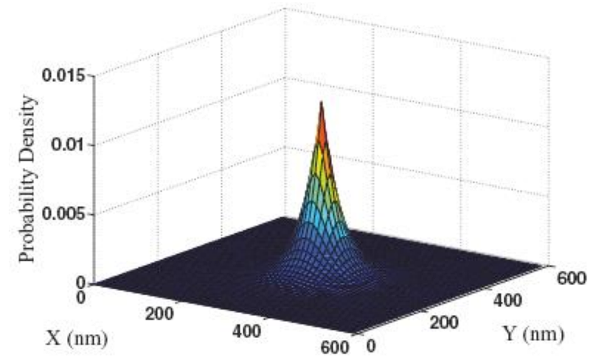
The SESARs can also be used to detect MFs if spin-polarized leads are used.

Features of MF

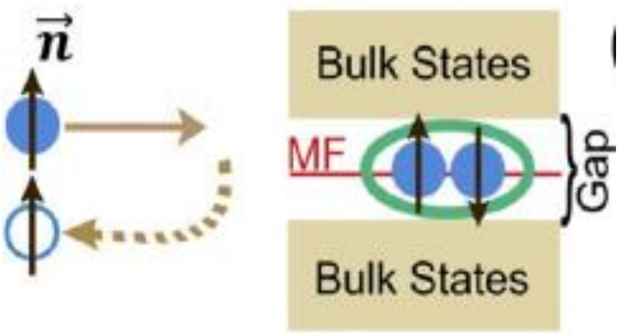
- Zero energy



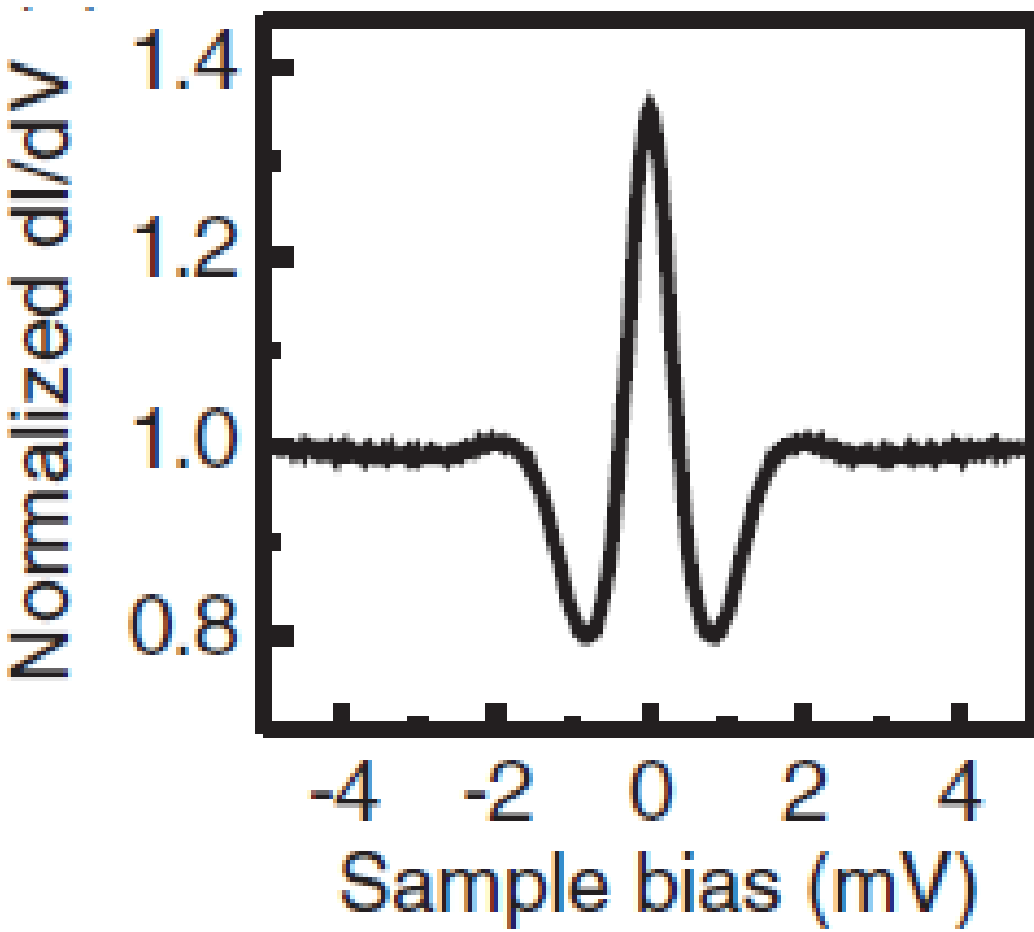
- Cone shape distribution



- SSAR or SESAR



Detect Majorana fermion by zero-energy peak



ning Fermi energy

$\sqrt{\Delta^2 + E_D^2}$

or 5QL Bi_2Te_3/$NbSe_2$

w:

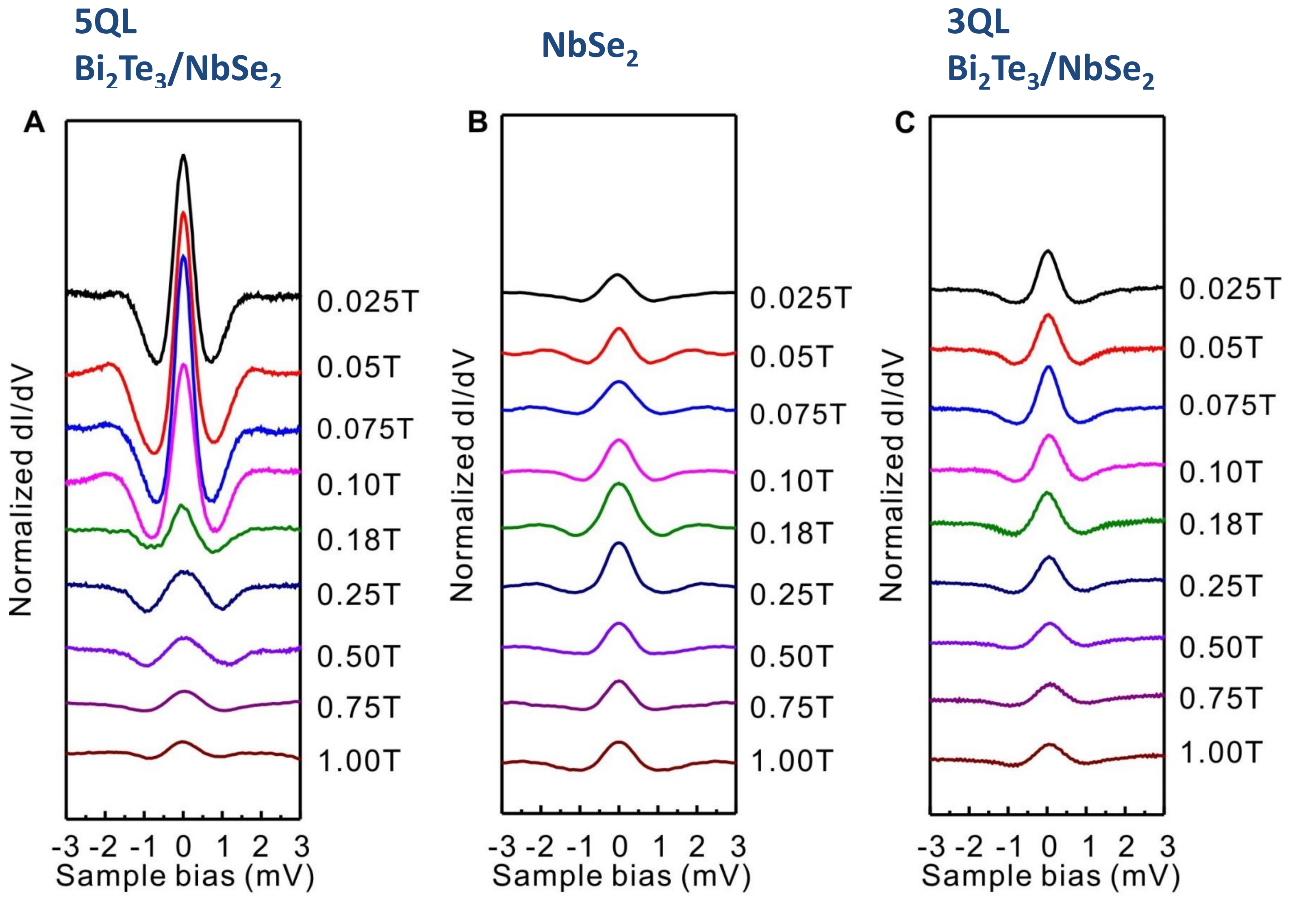
0.8meV $E_D \sim 200\text{meV}$

$E_g \approx 0.028\text{meV} \sim 30\text{mK}$

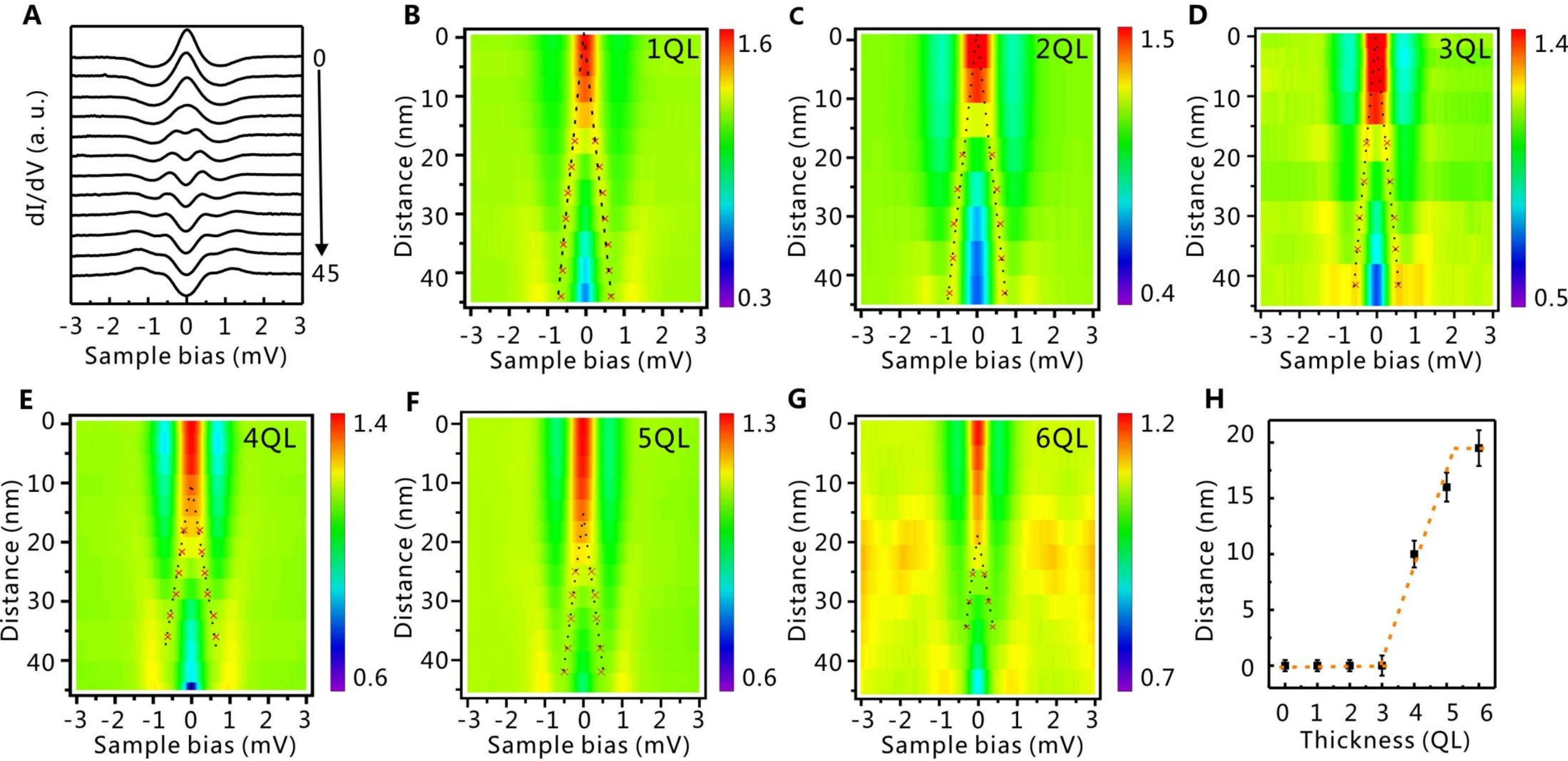
$E_D \sim 5\text{meV}$ ⇒ $E_g \approx 0.1\text{meV}$

$T \sim 300\text{mK}$ ⇒ Thermo energy ~ 0.026 mV

Magnetic field dependence of ZBP



Spatial distribution of Majorana fermion



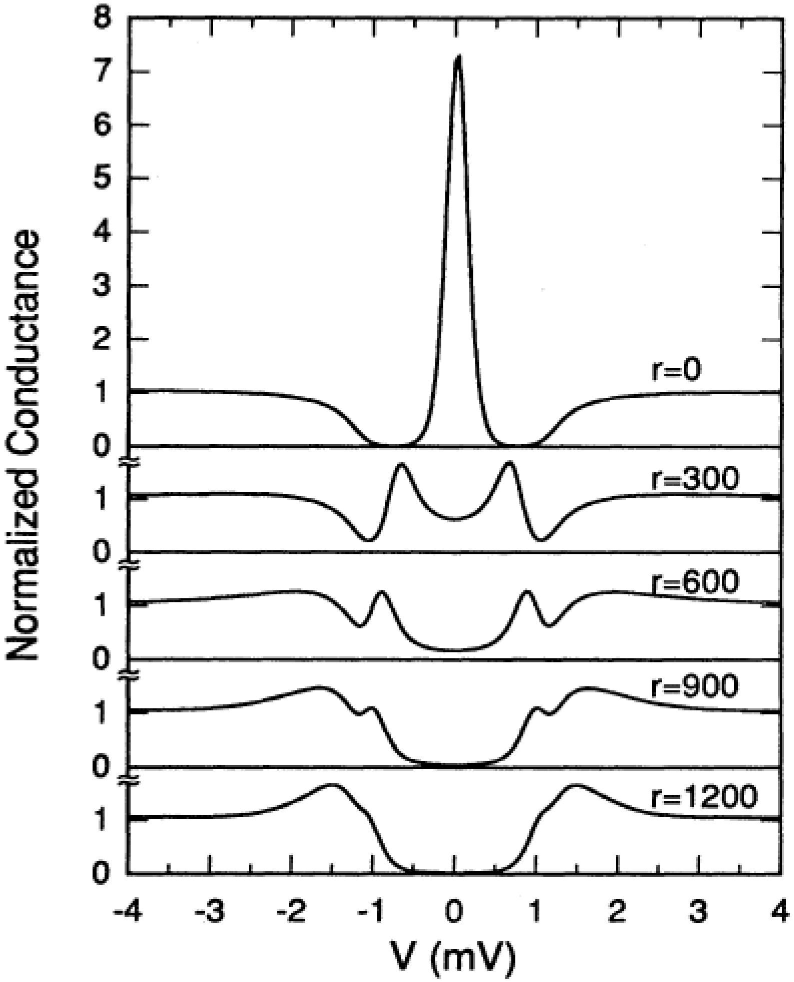
PRL 114, 017001 (2015)

Splitting of Zero-bias peaks

Non-zero splitting

Core states splitting in CSC

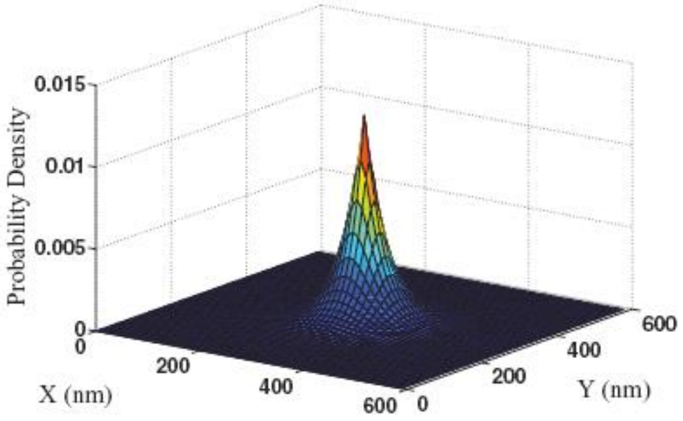
$NbSe_2$

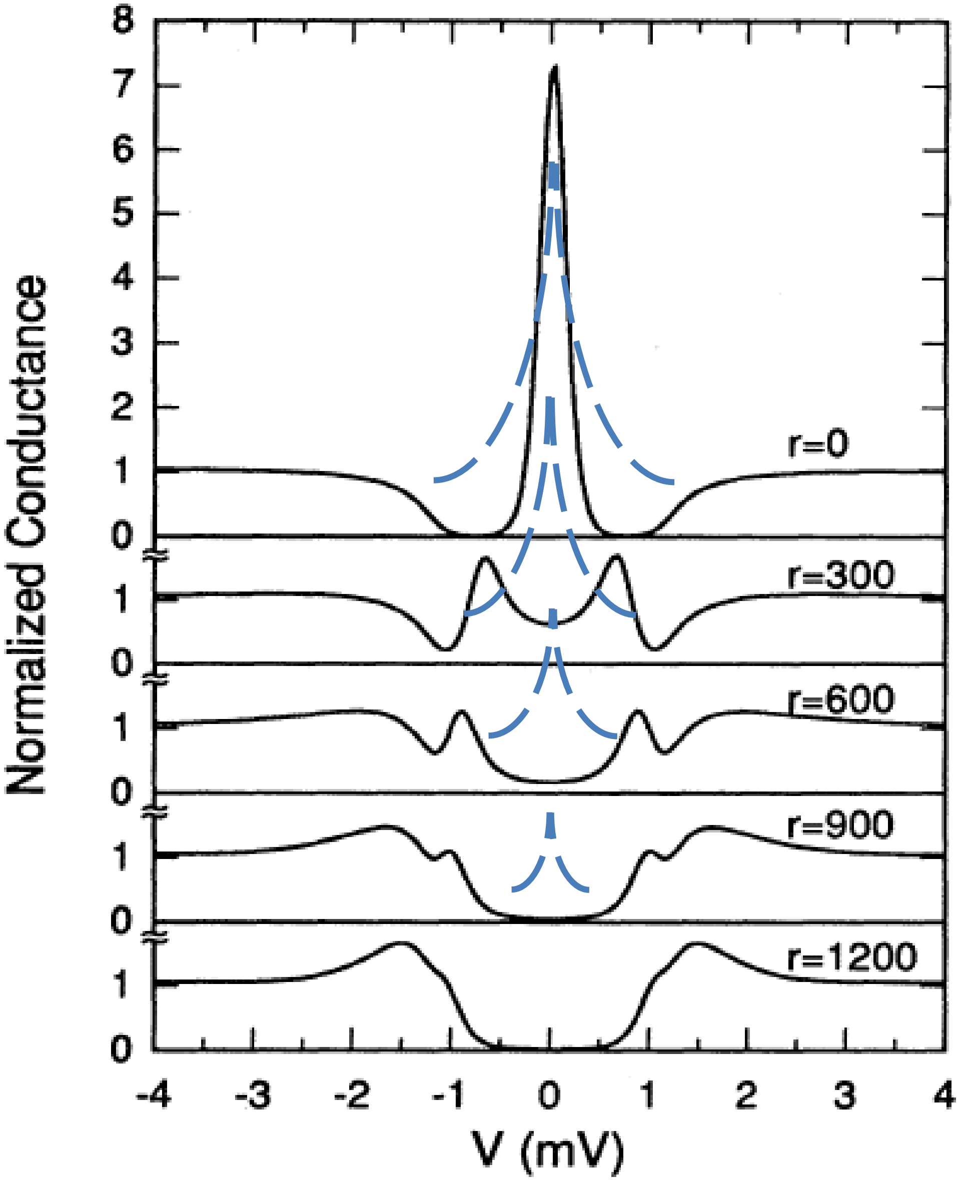


Hess et al., Phys. Rev. Lett. 62, 214 (1989)

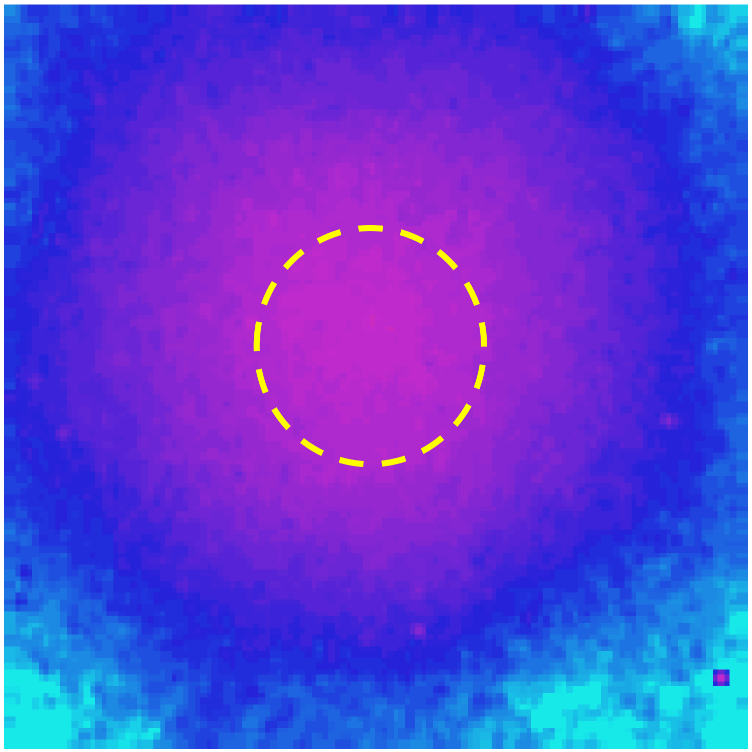
F. Gygi, M. Schluter, PRB 43, 7609 (1991)

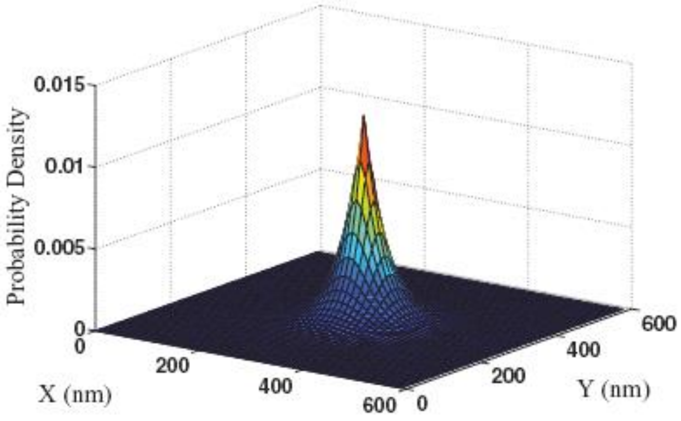
Core states splitting in TSC





Spatial extent of Mojorana fermion





- A Majorana fermion in a spatial extent~40nm

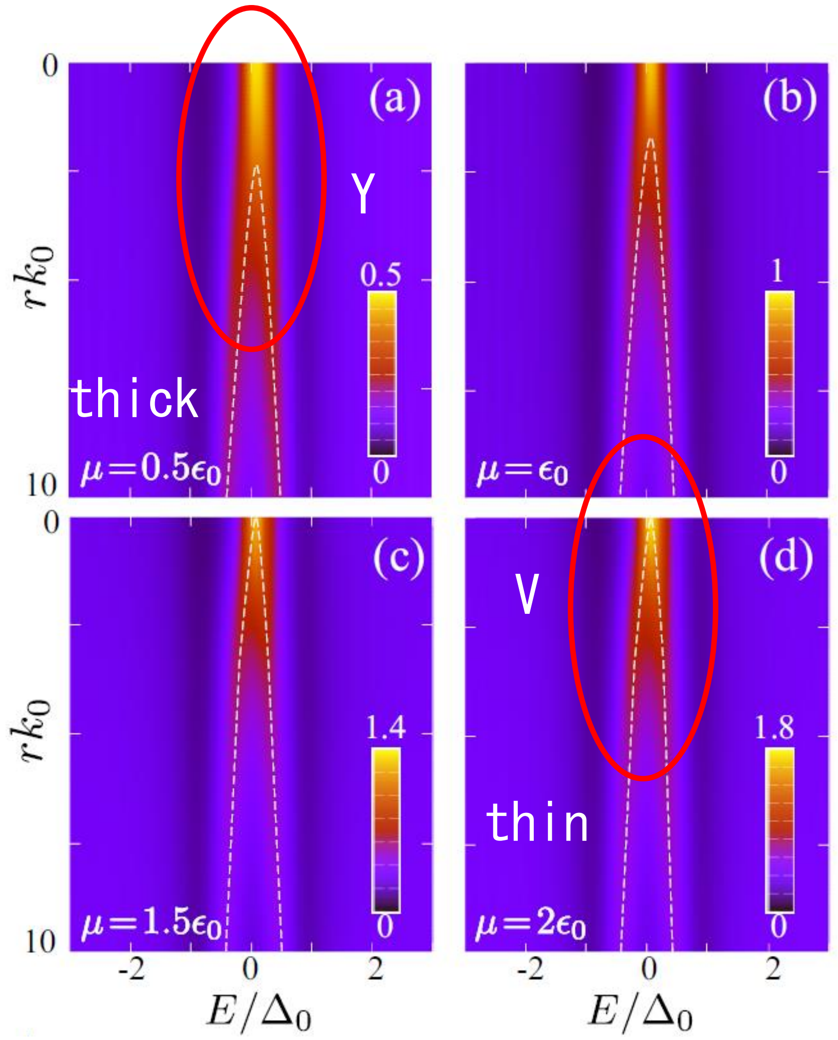
Hughes group,
PRB 84, 144507 (2011)
PRB 87, 035401 (2013)

Strong evidence for existence of Majorana mode

Evolution of DOS with thickness

PRL 115, 177001, 2015

- Energy-space distribution of DOS of quasiparticles: dI/dV in experiments



smearing factor
in energy

$\eta = 0.2\Delta_0$~4K

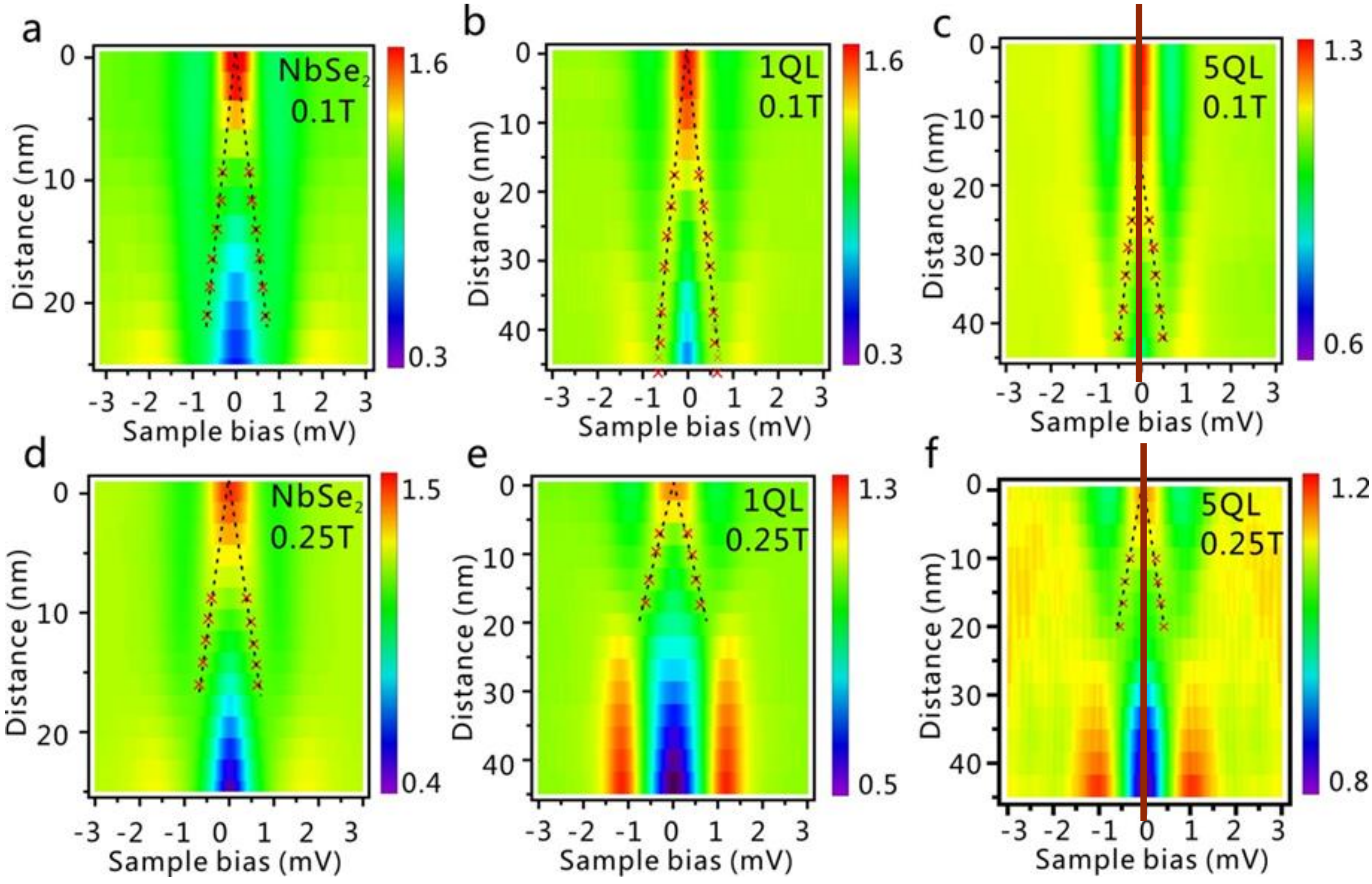
Y shape ⇔ w MBS
V shape ⇔ w/o MBS

full agreement with experiments !

- Thickness vs. chemical potential

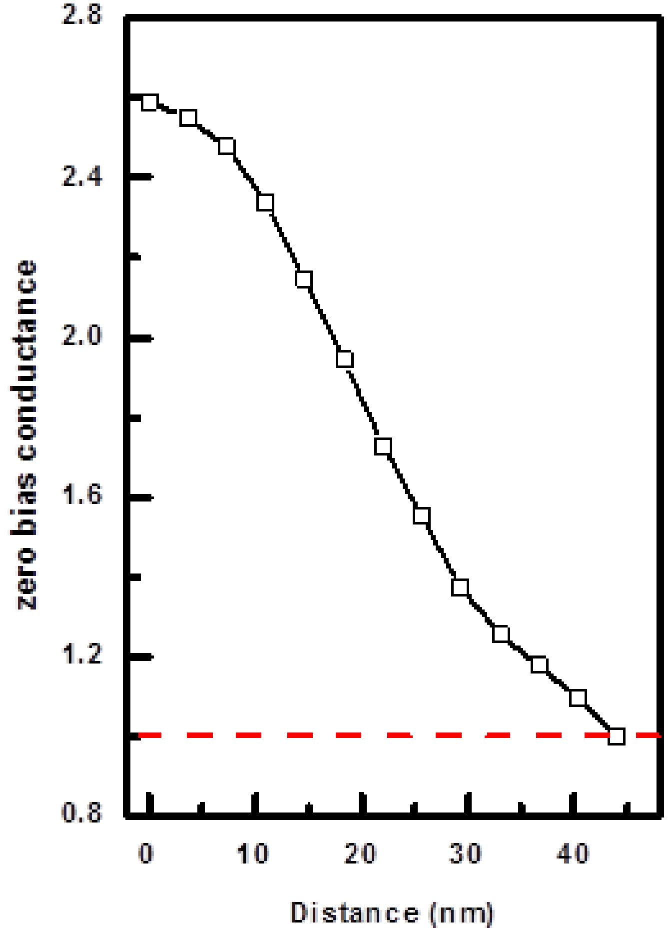
theoretically thickness only cannot induce phase transition, but μ can.

More evidence

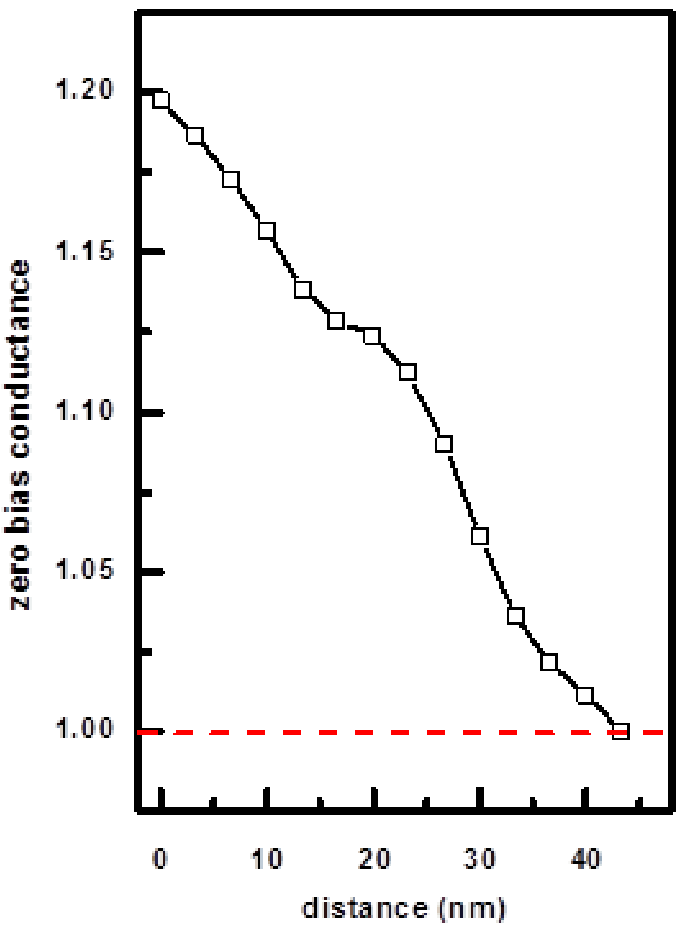


Spatial distribution at zero energy

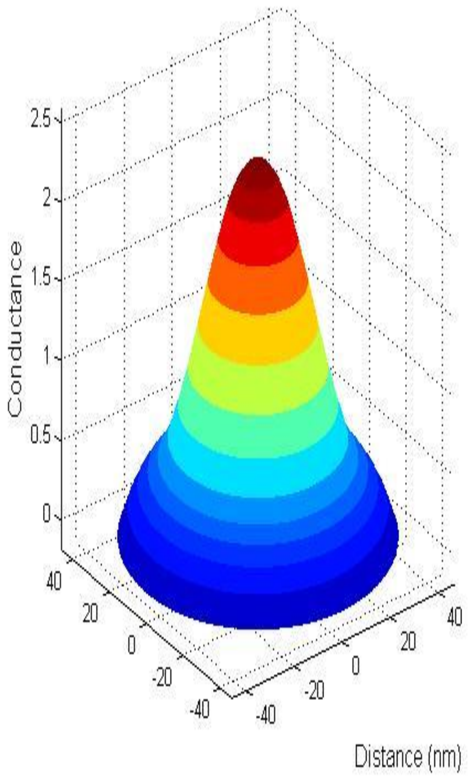
5QL@ 0.1T

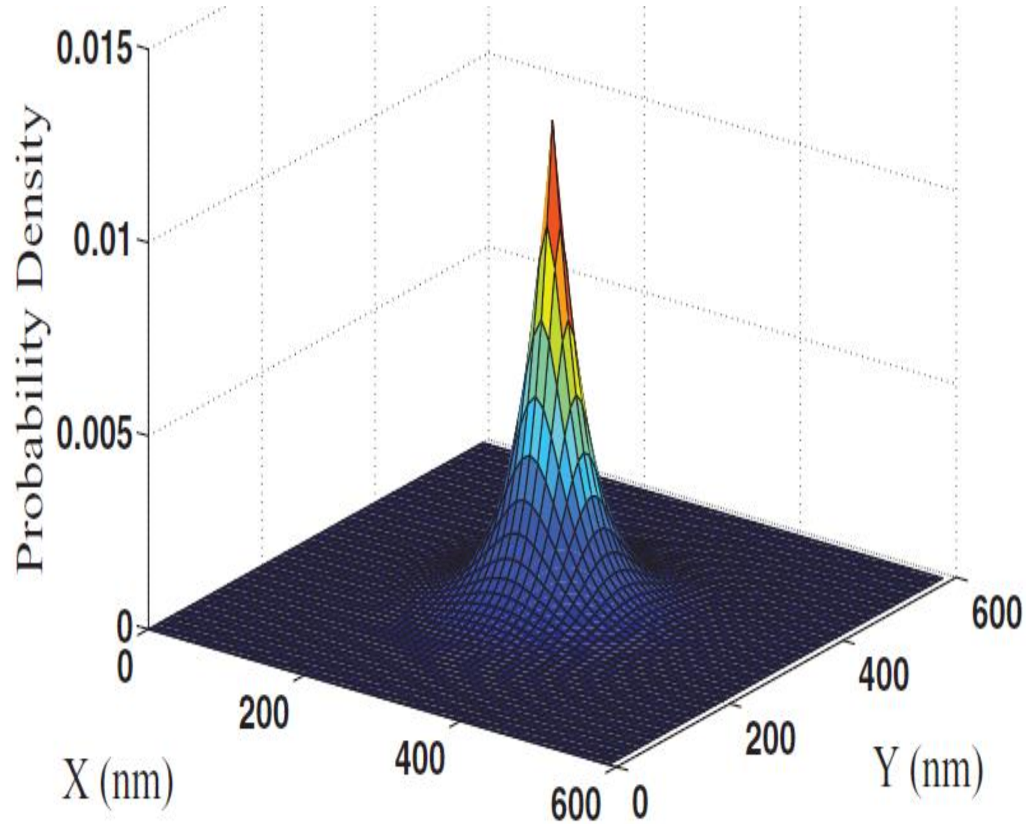


5QL@ 0.18T



Experimental spatial distribution of Majorana fermion

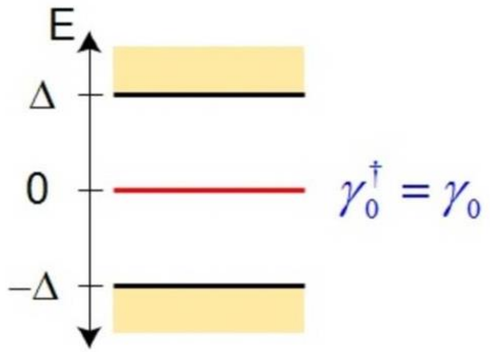




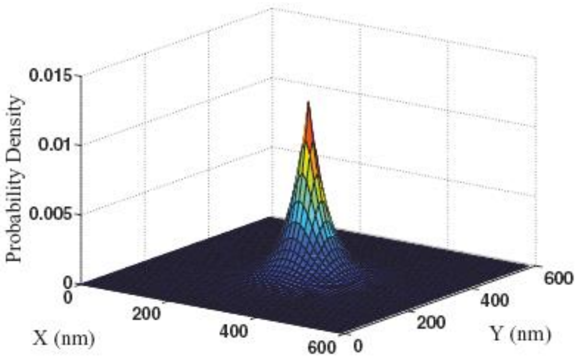
Substrate the data with MF (5QL at 0.1T) by the data without MF (5QL at 0.18T), one should get the contribution of MF (left). The right one is the calculated probability distribution of a Majorana bound state in vortex(PRB84,144507).

Features of MF

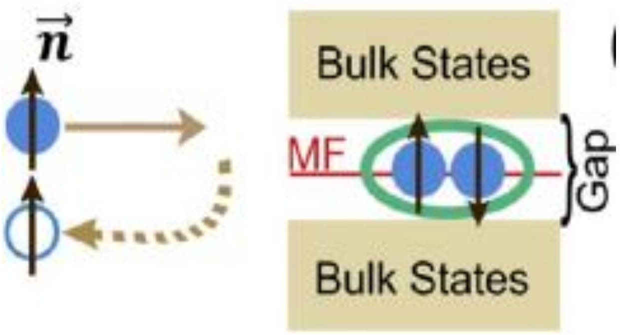
- Zero energy



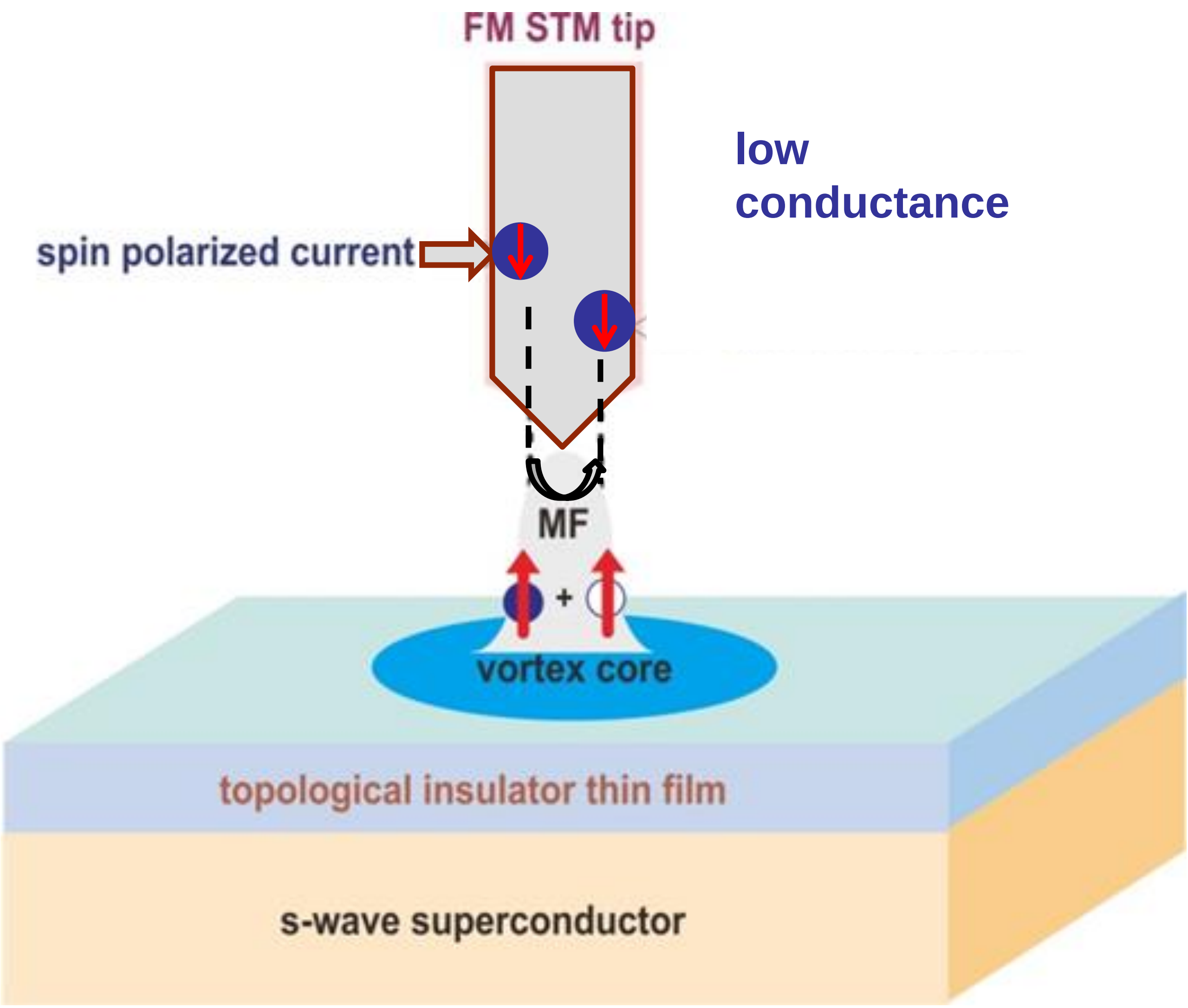
- Cone shape distribution



- SSAR or SESAR

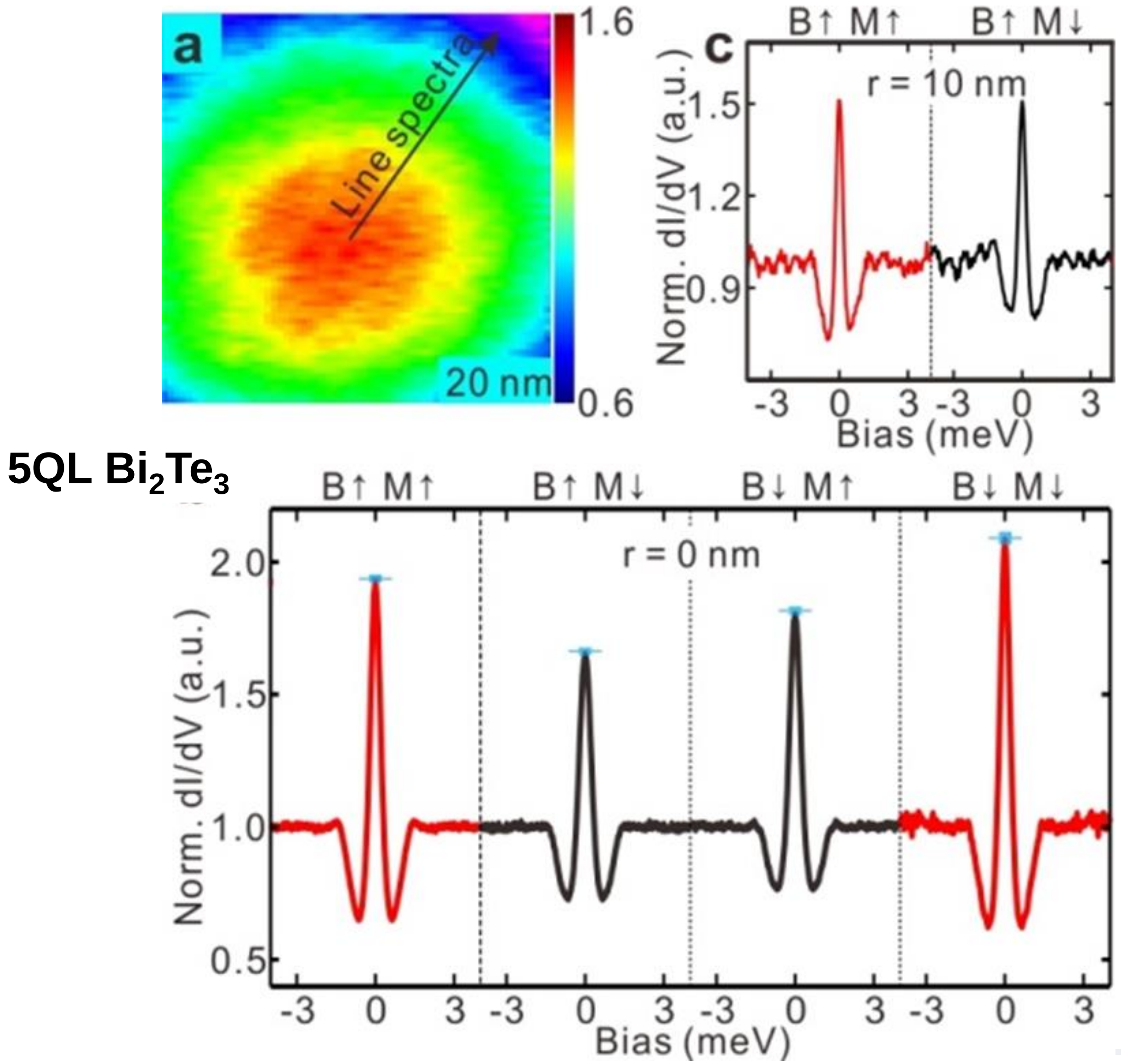


Spin selective Andreev reflection



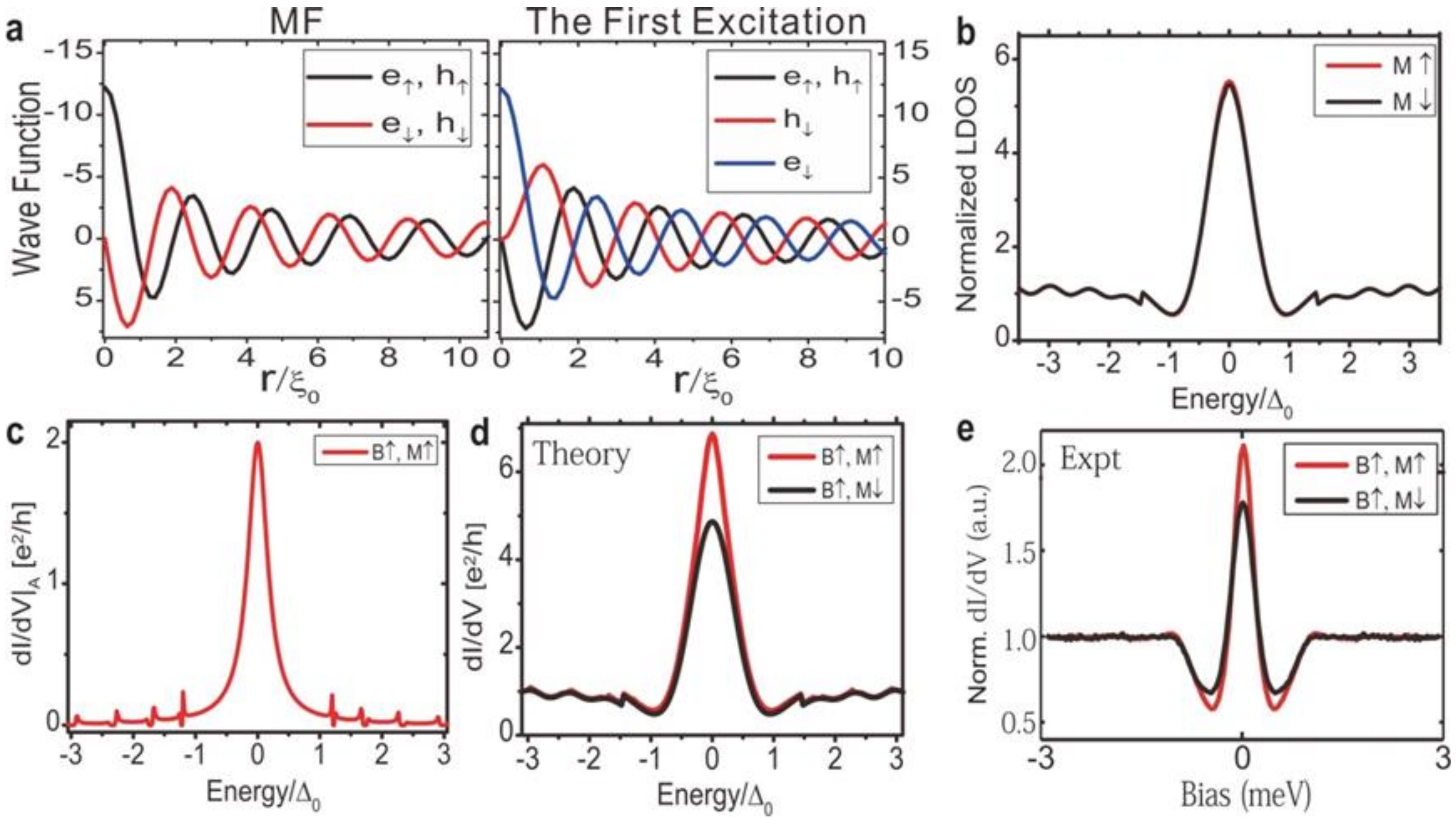
low
conductance

SSAR observed by SPSTM



- Non-magnetic
- Low applied field (0.1T)
- SSAR can only induced by MF

Comparison with model calculations



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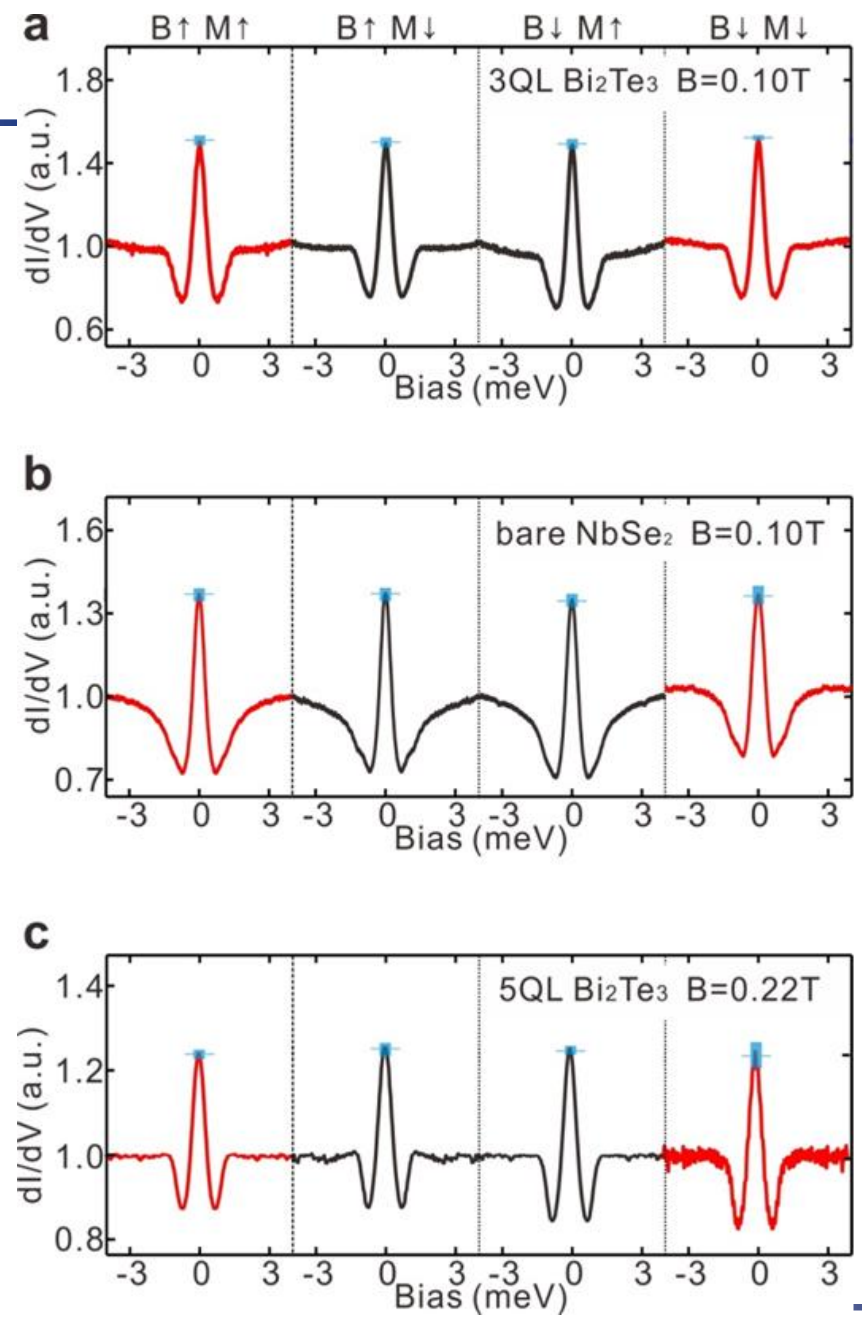
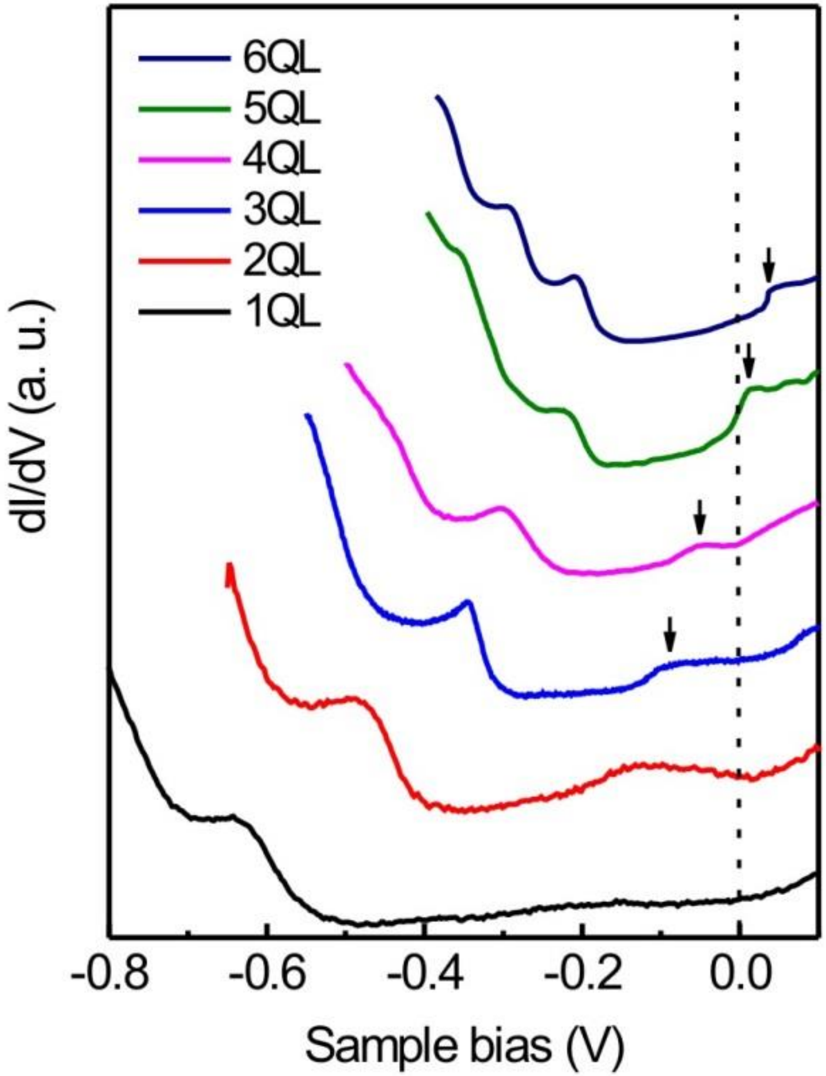
Compare with no-MF cases



arXiv:1603.02549
Phys.Rev.Lett. 116, 257003 (2016)

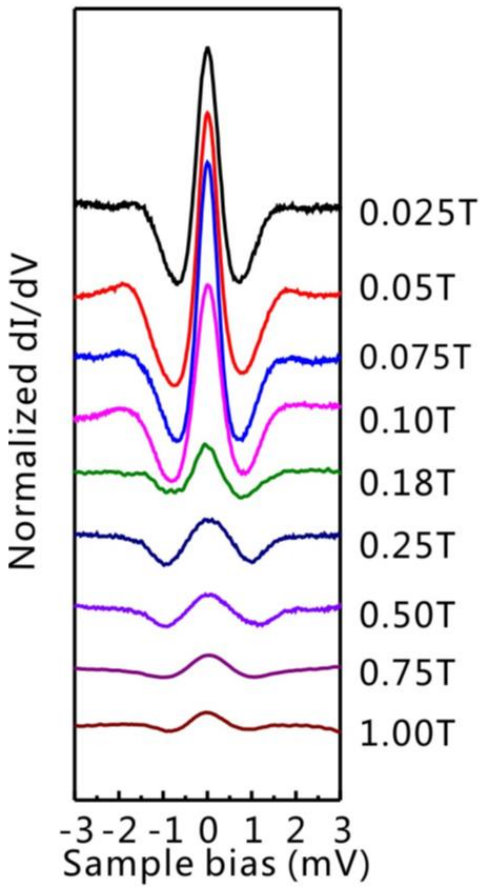
Why transition at 4QL?

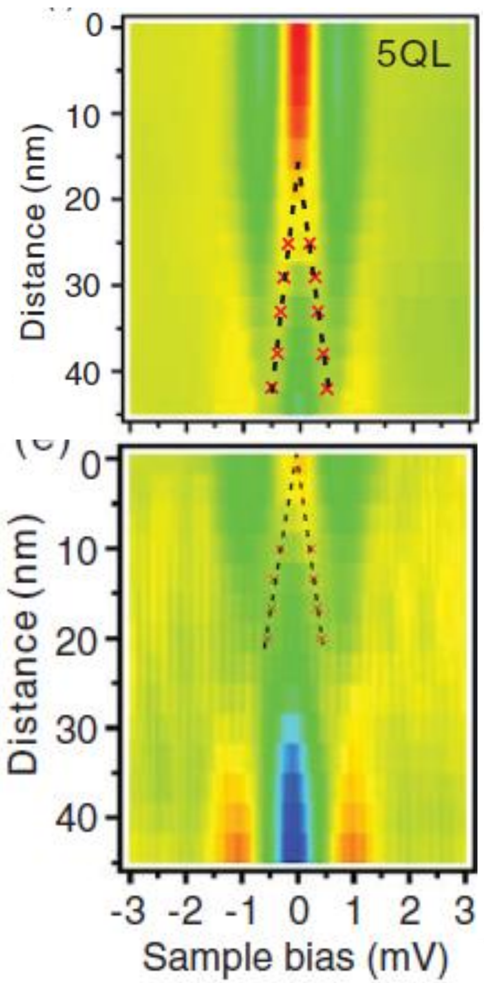


PRL 114, 017001 (2015)

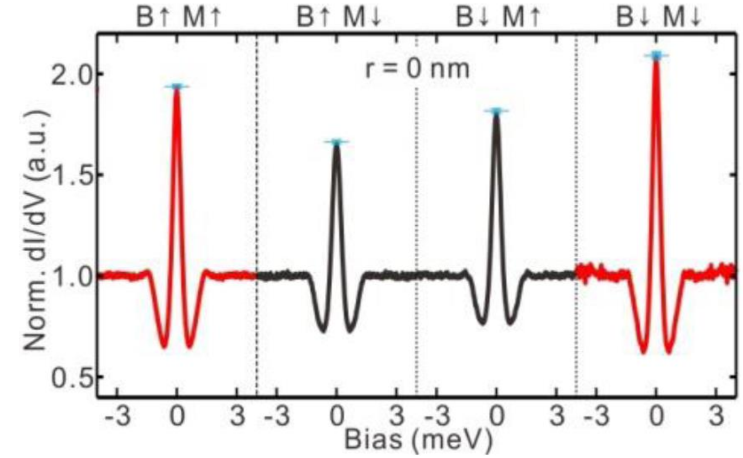
All evidences are consistent

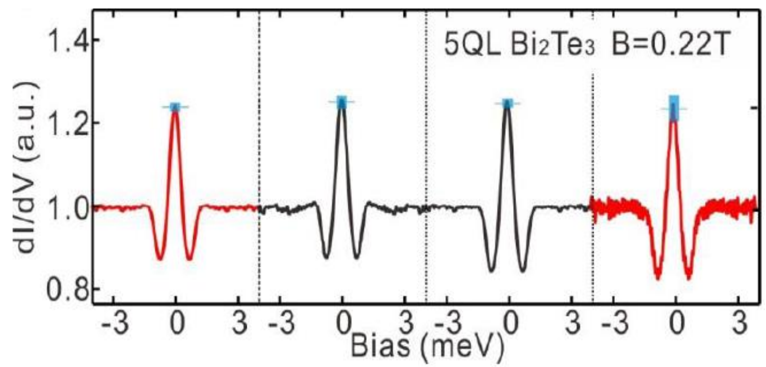
5QL Bi_2Te_3





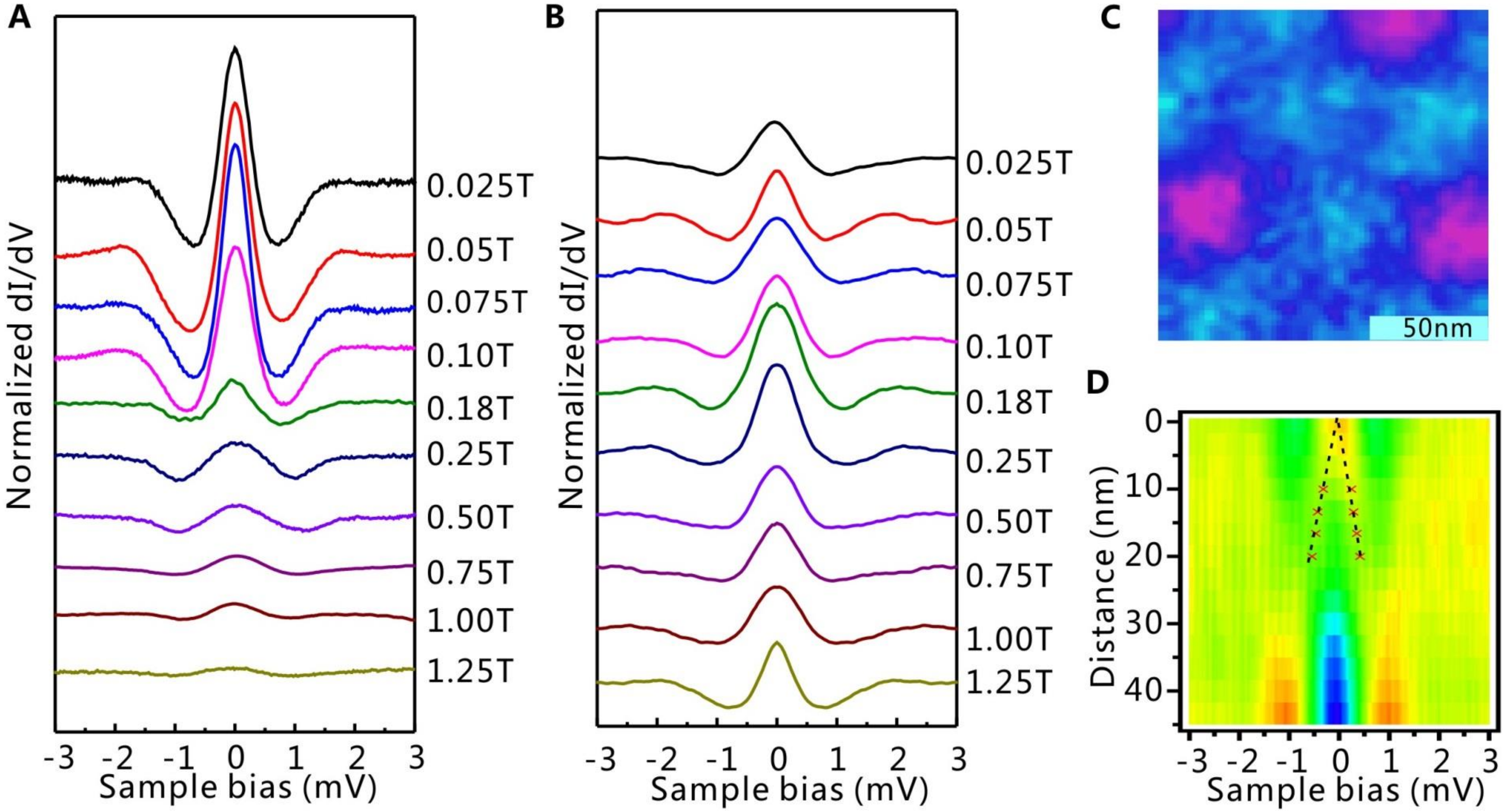
5QL Bi_2Te_3 B=0.1T





H. H Sun and J. F Jia, Sci. China-Phys. Mech. Astron. 60 (5), 057401 (2017)

Turn MF on/off



PRL 114, 017001 (2015)

npj Quantum Materials (2017) 2:34 ; doi:10.1038/s41535-017-0037-4

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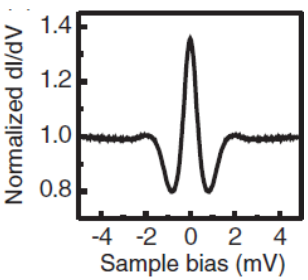
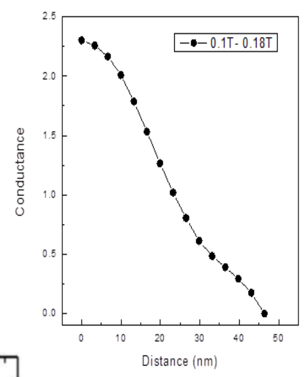
Summary

- **Artificial topological superconductor by proximity effect**
- **Zero energy** √

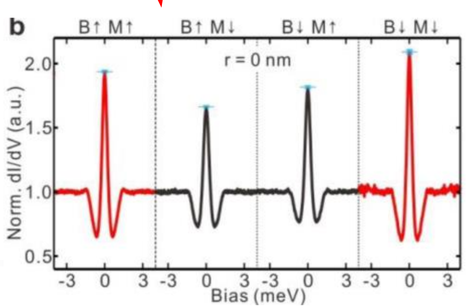


Need more work

- **Cone shape distribution** √



- **SSAR or SESAR** √



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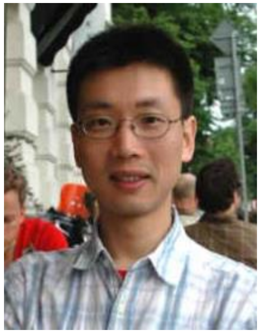
Acknowledgments

QK Xue



C.H. Liu

C.L. Gao

D. Qian

Zhuan Xu

S.C.Li

F.C. Zhang

Liang Fu

Theoreticians: F. Liu, S.B. Zhang, X.C. Xie, Z. Fang, X. Dai, S. Q. Shen, Xiao-Liang Qi, Shou-Cheng Zhang., Q.H. Wang, Y. Chen, Y. Zhou

M.X. Wang, J.P. Xu, H.H. Sun, G.Y. Wang, D. Xu, L. Miao, F. Yang, M.Y. Yao, Z. F. Wang, K.W. Zhang, Lun-Hui Hu, Chuang Li

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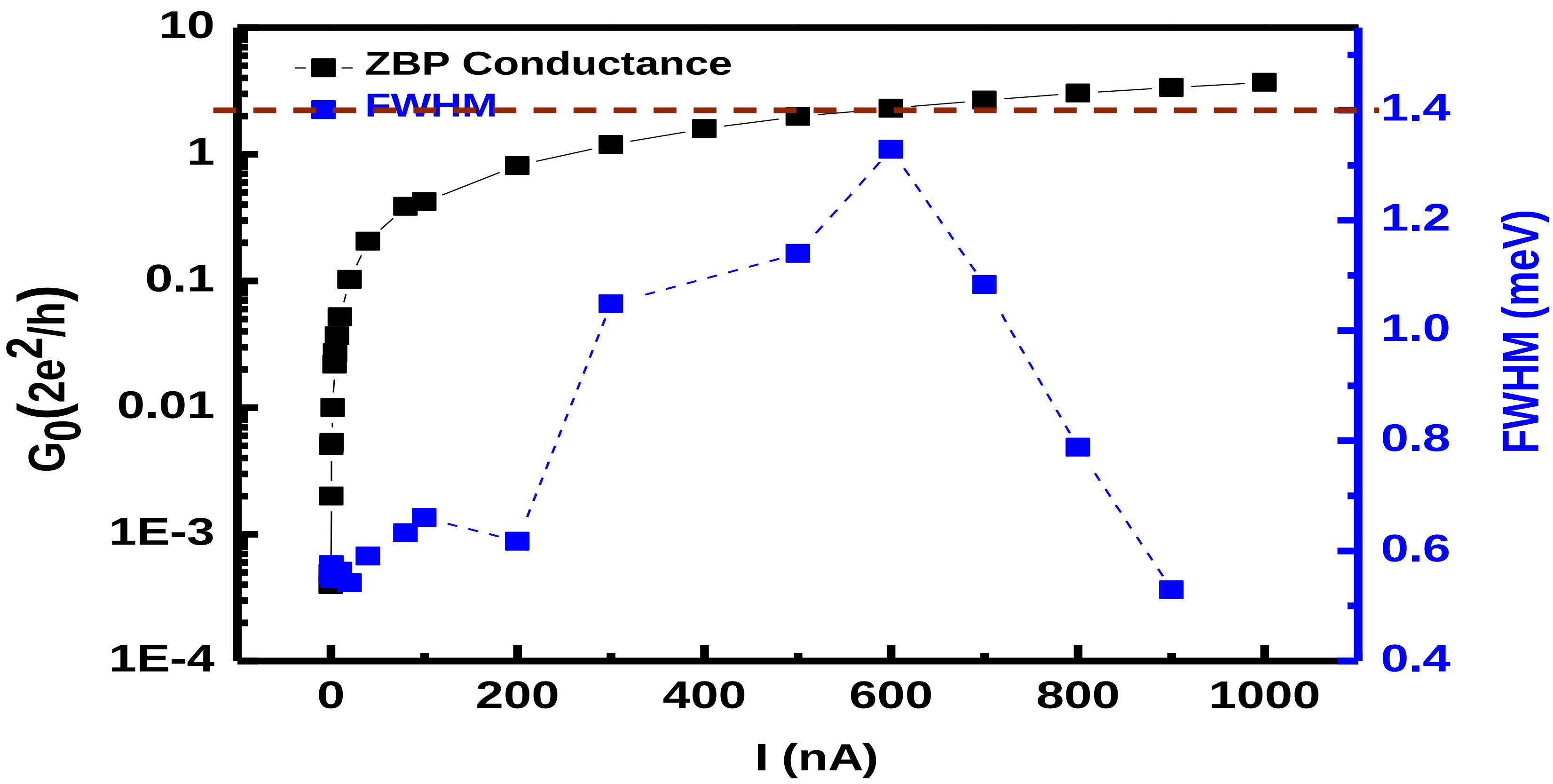
Thank you very much!

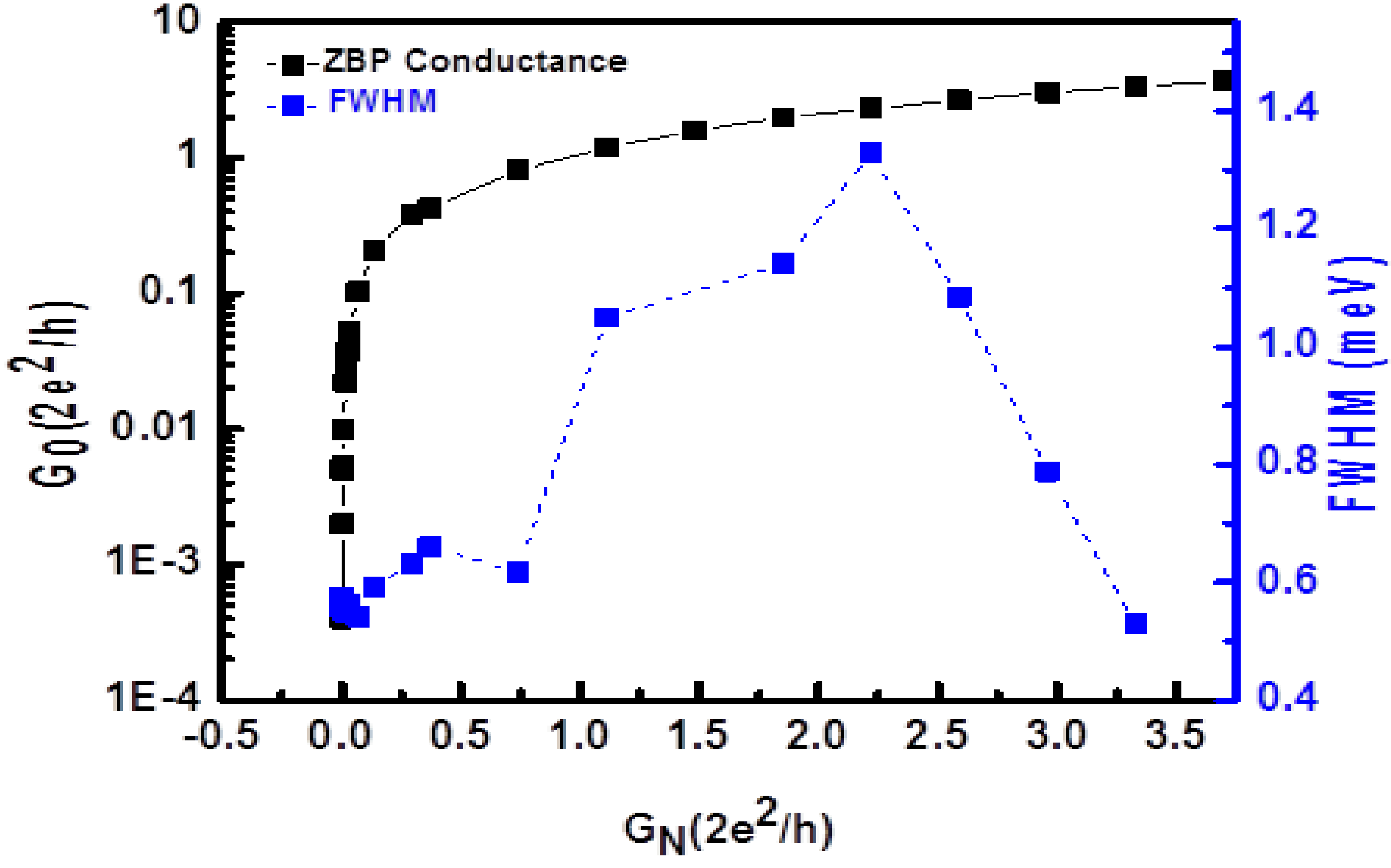
Conductance and width of ZBP VS tunneling current



Tip touchs sample ~600nA

Conductance saturate: $2G_0$

MZM+2 normal modes

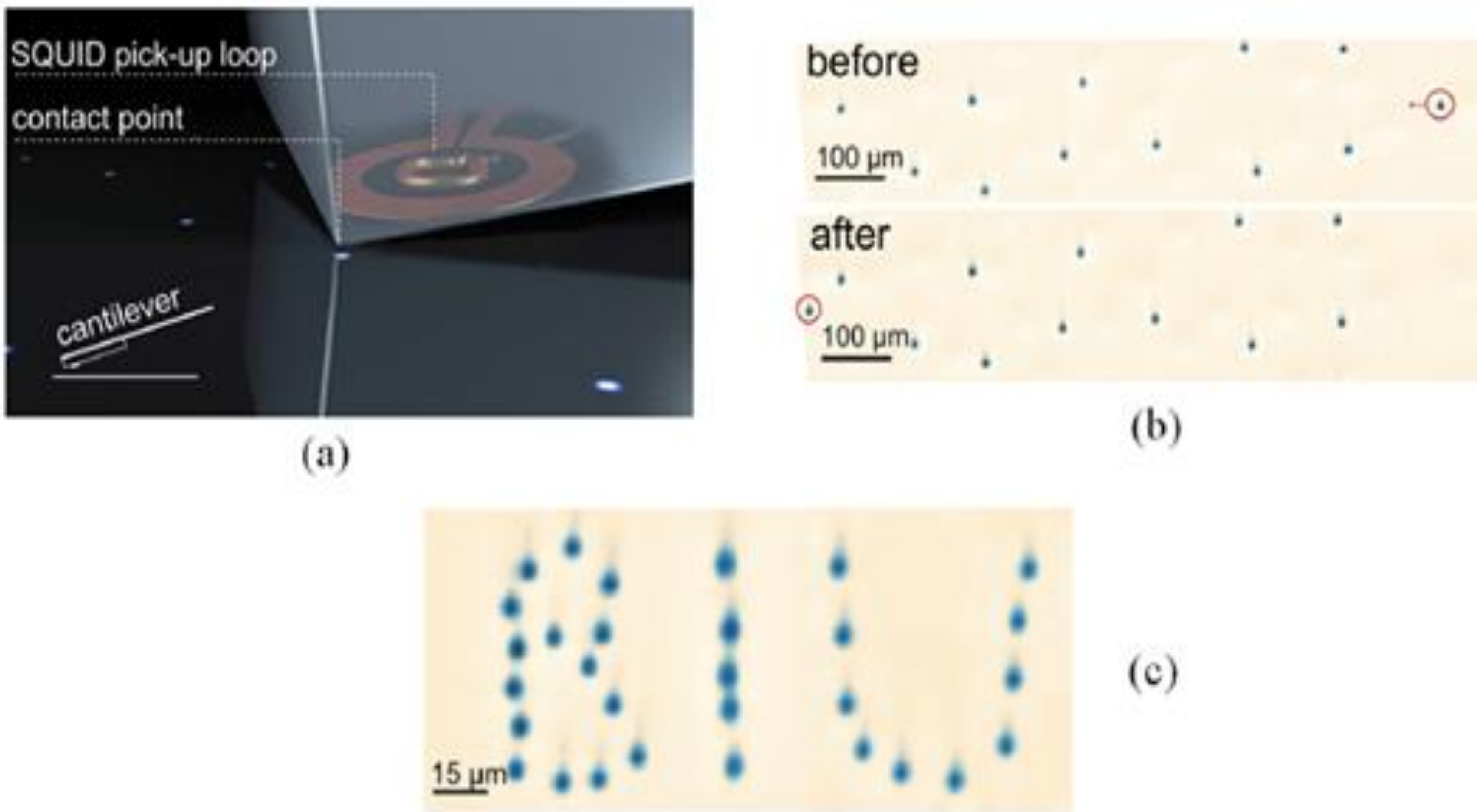

ZBP Conductance
FWHM
10
1
0.1
0.01
1E-3
1E-4
-0.5
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
1.4
1.2
1.0
0.8
0.6
0.4
G0(2e2/h)
GN(2e2/h)
FWHM (meV)

Possible application in topological quantum computing

Advantages

- Simple
- Low magnetic field ~0.1T
- E_f can be tuned, no gate is needed
- Protected by superconducting gap
- Easy to increase the temperature
- No effect by impurities
- 2D system, easy to manipulate

Braiding



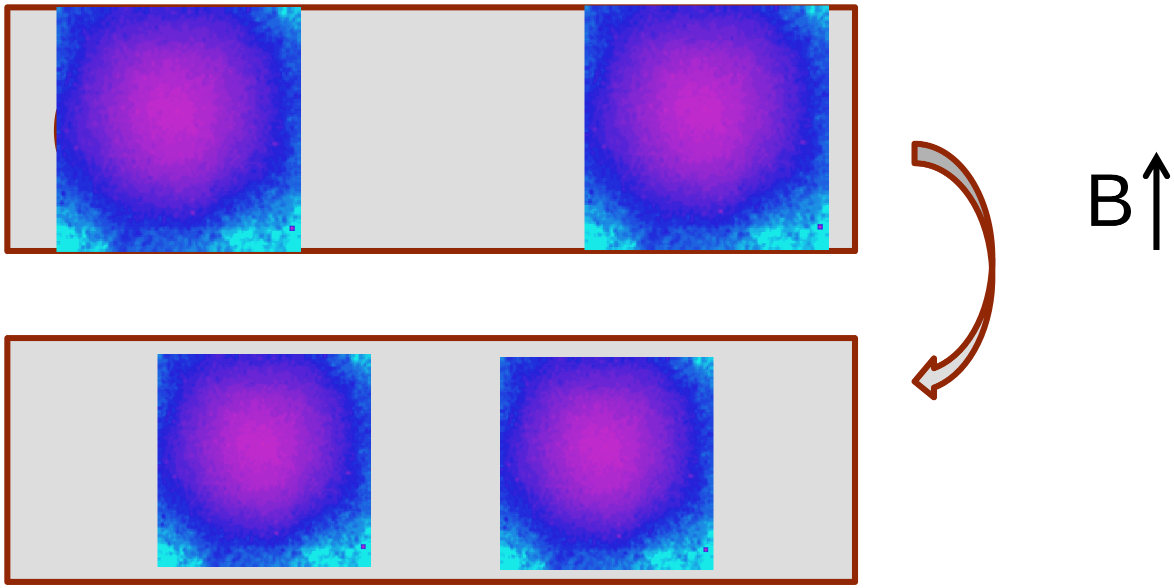
(a) (b) (c)

- Vortex can be easily moved and positioned by scanning SQUID

Nano Lett. 16, 1626 (2016)

Fusion

- Fusion = read out

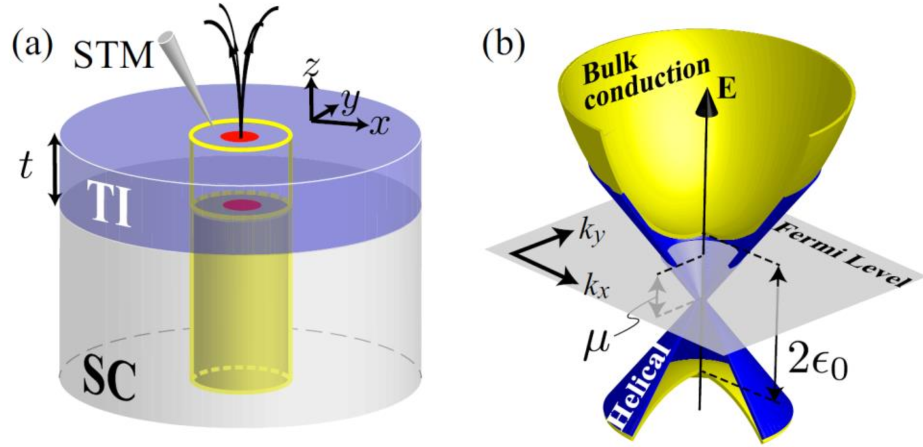


- How to detect the result?
  - Junction? Microwave? Spin?......

Model system

T. Kawakami and XH: arXiv.1506.03194

- Geometry



- Hamiltonian

$$\mathcal{H}_{\rm BdG} = \begin{pmatrix} \hat{\mathcal{H}}_{\rm TI}(\boldsymbol{k}) & \hat{\Delta} \\ \hat{\Delta}^\dagger & -\hat{\mathcal{H}}^*_{\rm TI}(-\boldsymbol{k}) \end{pmatrix}$$

$$\hat{\mathcal{H}}_{\rm TI} = \epsilon\hat{\sigma}_z - iv_{\rm F}\left[e^{-i\phi\hat{s}_z}\left(\partial_r\hat{s}_x + \frac{1}{r}\partial_\phi\hat{s}_y\right) + \partial_z\hat{s}_z\right]\hat{\sigma}_x - \mu$$

σ: orbital
s: spin

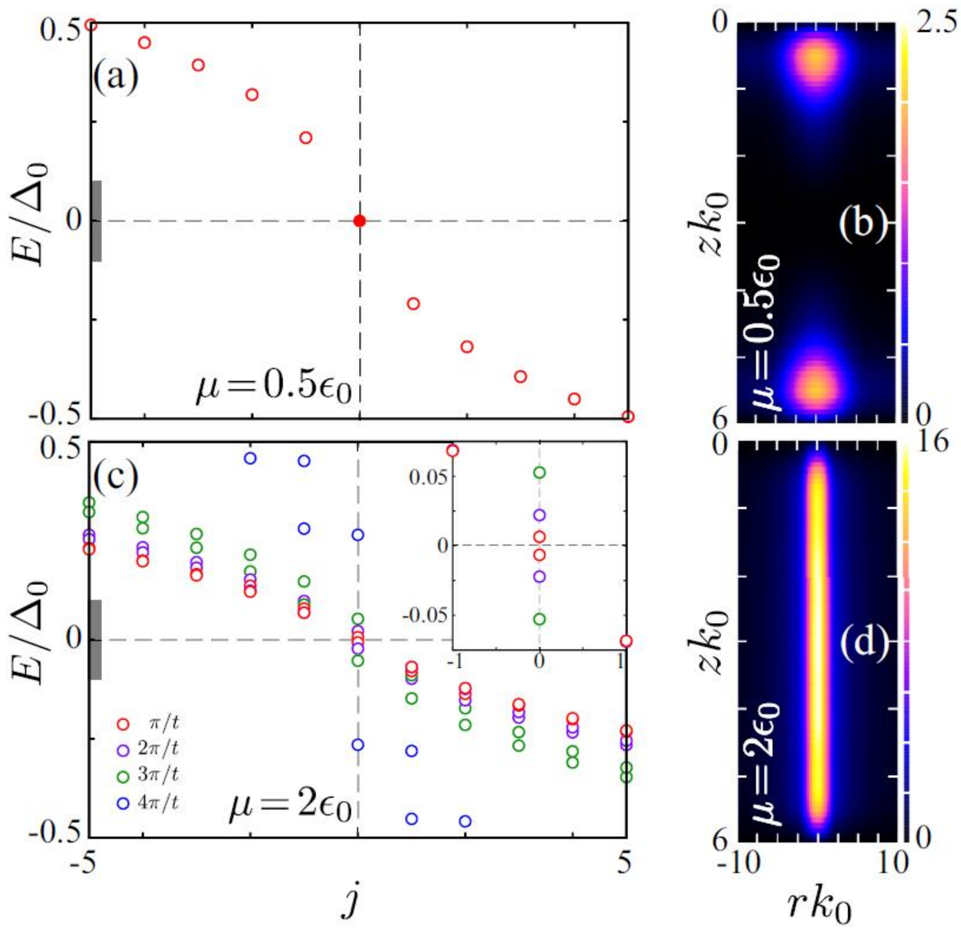
$$\epsilon = -\epsilon_0 - \frac{1}{2m}\left(\partial_r^2 + \frac{1}{r}\partial_r + \frac{1}{r^2}\partial_\phi^2 + \partial_z^2\right) \qquad \hat{\Delta} = e^{i\phi}\Delta_0 i\hat{s}_y$$

- Parameters for calculation: * Band gap of Bi_2Te_3: $2\varepsilon_0$~0.2eV

  * SC gap: $\Delta=0.02\varepsilon_0$~2meV * chemical potential: $\mu=0.5\varepsilon_0$~$2\varepsilon_0$

Majorana bound states in thick TI film

- Energy dispersion and distribution of DOS of quasiparticles



* typical length

$$k_0^{-1} = v_F/\epsilon_0 \simeq 2\text{nm}$$

* coherence length

$$\xi = v_F/\Delta_0 = 50k_0^{-1}$$

MBS at small Fermi level ⇔ thick TI film

suppression of MBS ← bulk conduction bands induce interactions in thin TI film

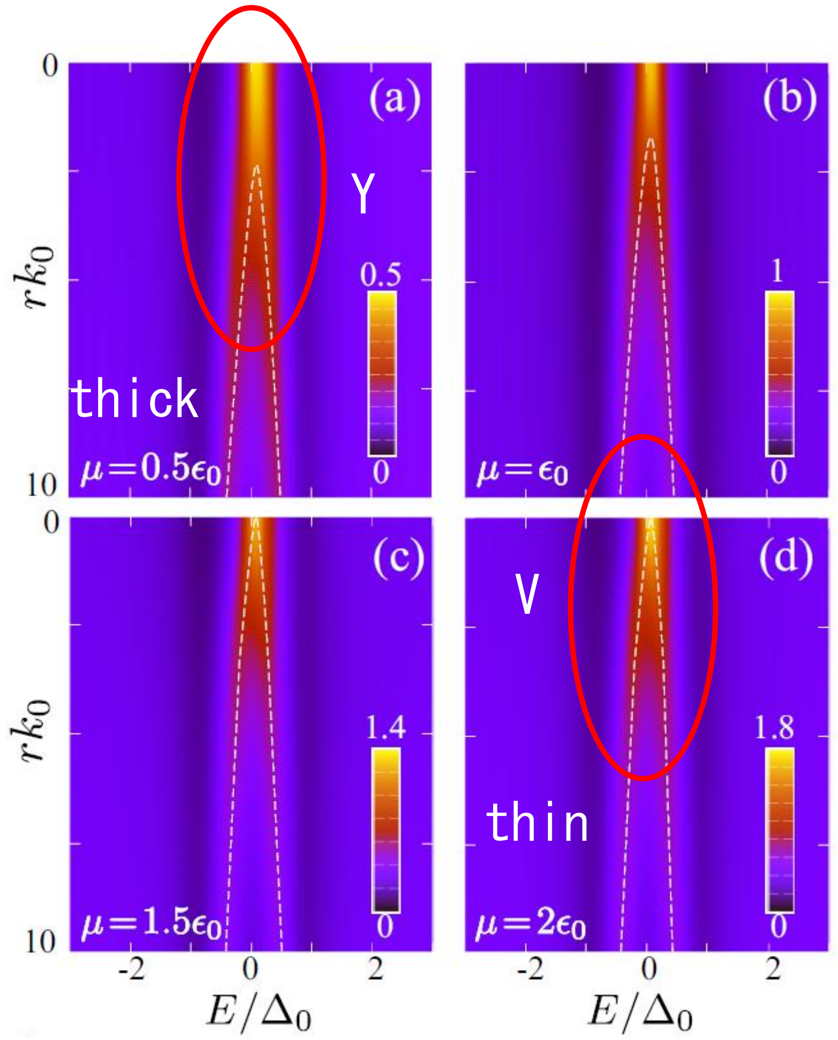
Fu and Kane, PRL **100**, 96407 (2008). Hosur, *et al.*, PRL **107**, 097001 (2011).

Z.-Z. Li, F.-C. Zhang, and Q.-H. Wang, Sci. Rep. **4**, 6363 (2014).

Evolution of DOS with thickness

PRL 115, 177001, 2015

- Energy-space distribution of DOS of quasiparticles: dI/dV in experiments



smearing factor in energy

$\eta = 0.2\Delta_0$~4K

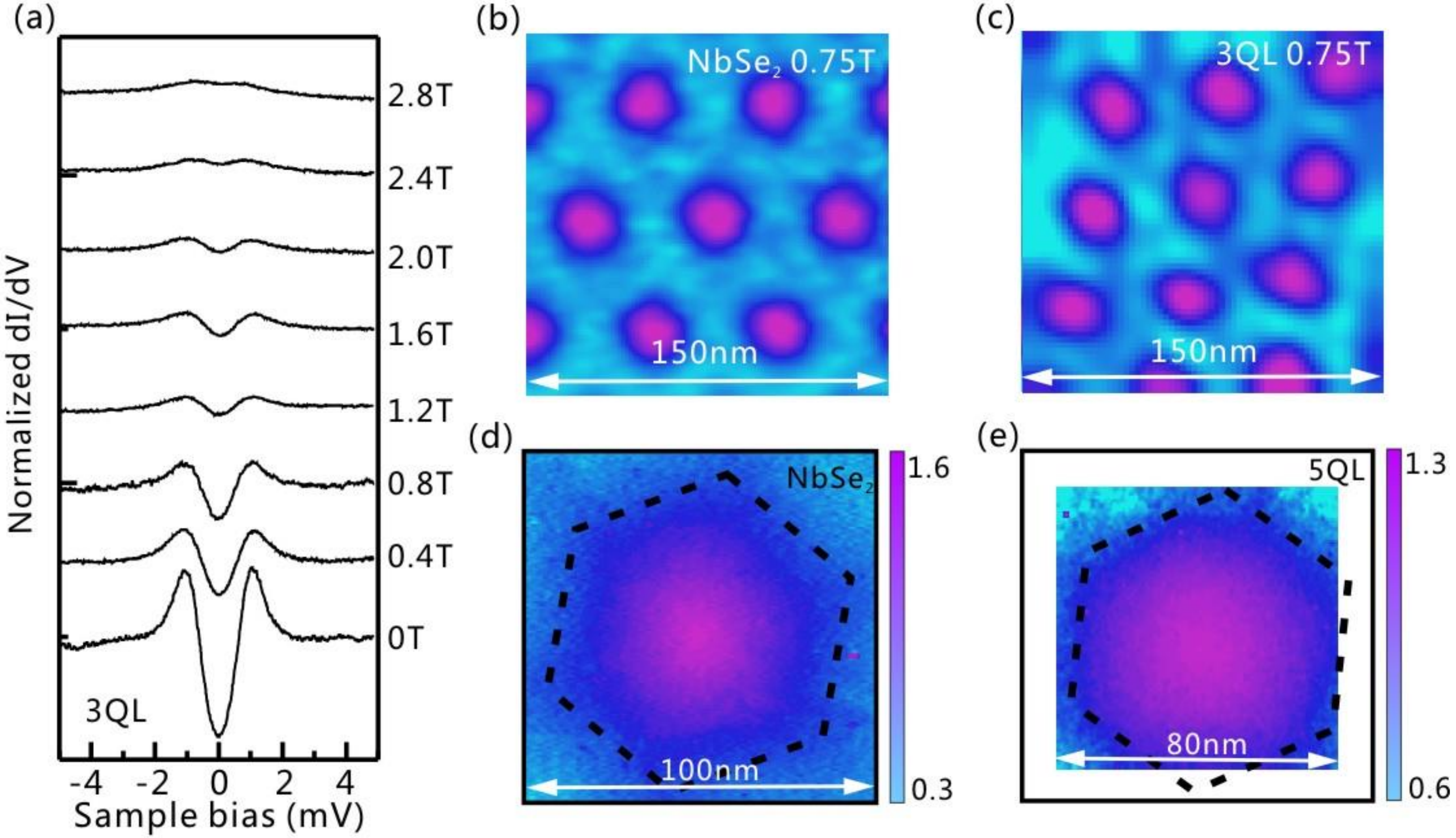
Y shape ⇔ w MBS
V shape ⇔ w/o MBS

full agreement with experiments !

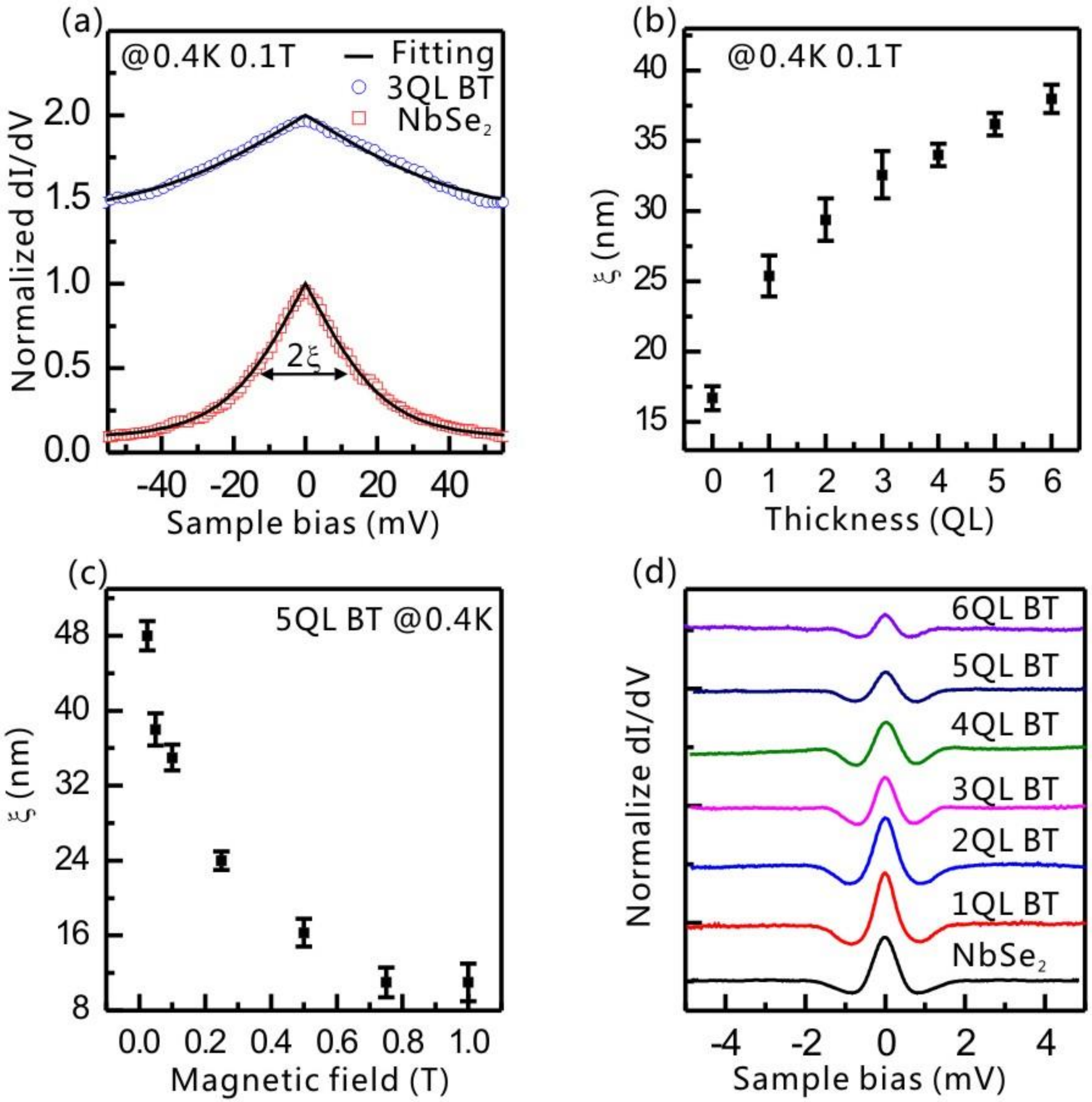
- Thickness vs. chemical potential

theoretically thickness only cannot induce phase transition, but μ can.

Vortex on topological superconductor



Coherence length and core states



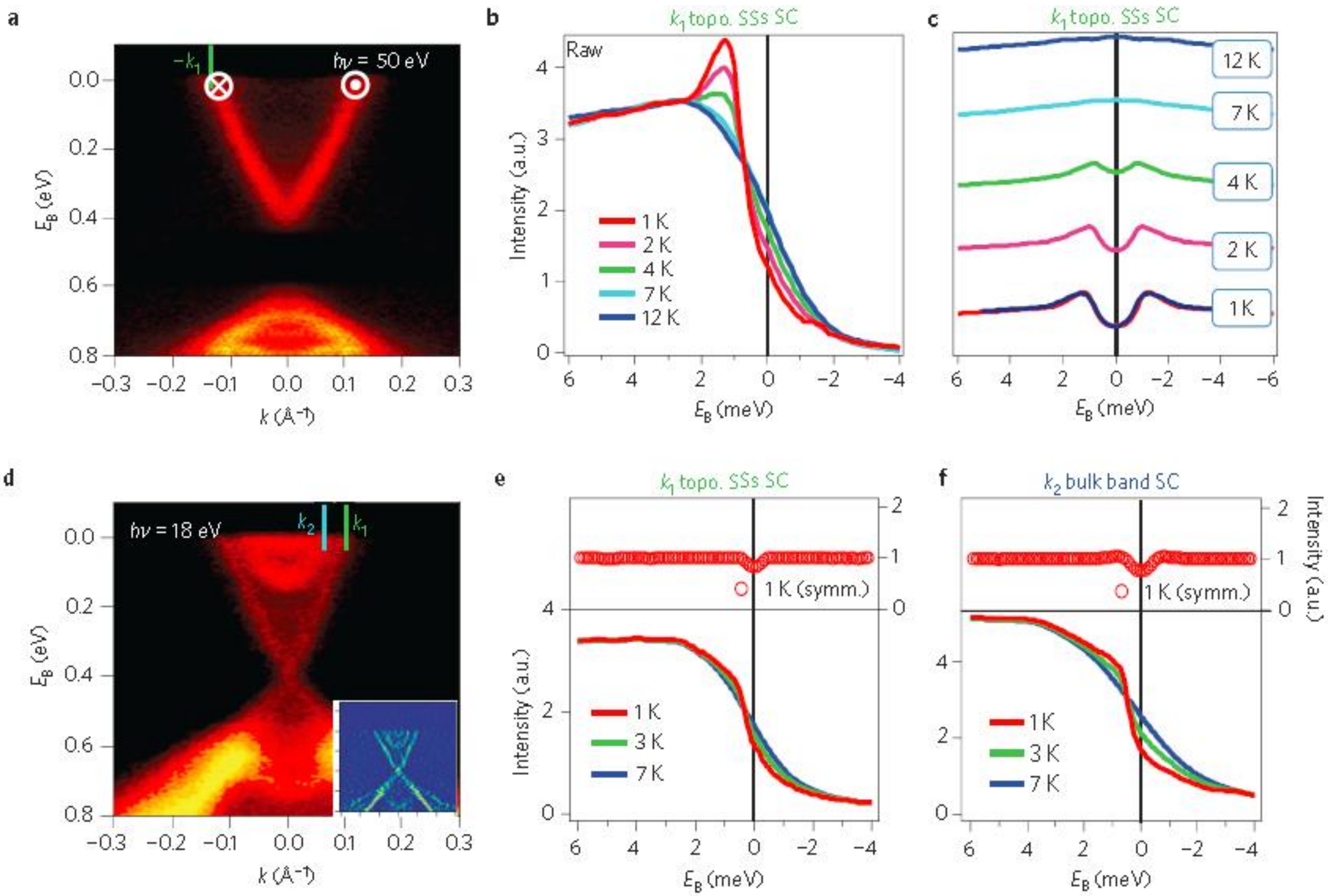
- Coherence length deduced from Vortex
- Much larger than that in $NbSe_2$
- Saturate at 3QL
- Change with magnetic field
- Saturate at ~0.7T
- Core states observed

PRL 112, 217001 (2014)

Momentum-space imaging of Cooper pairing

3QL

7QL



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