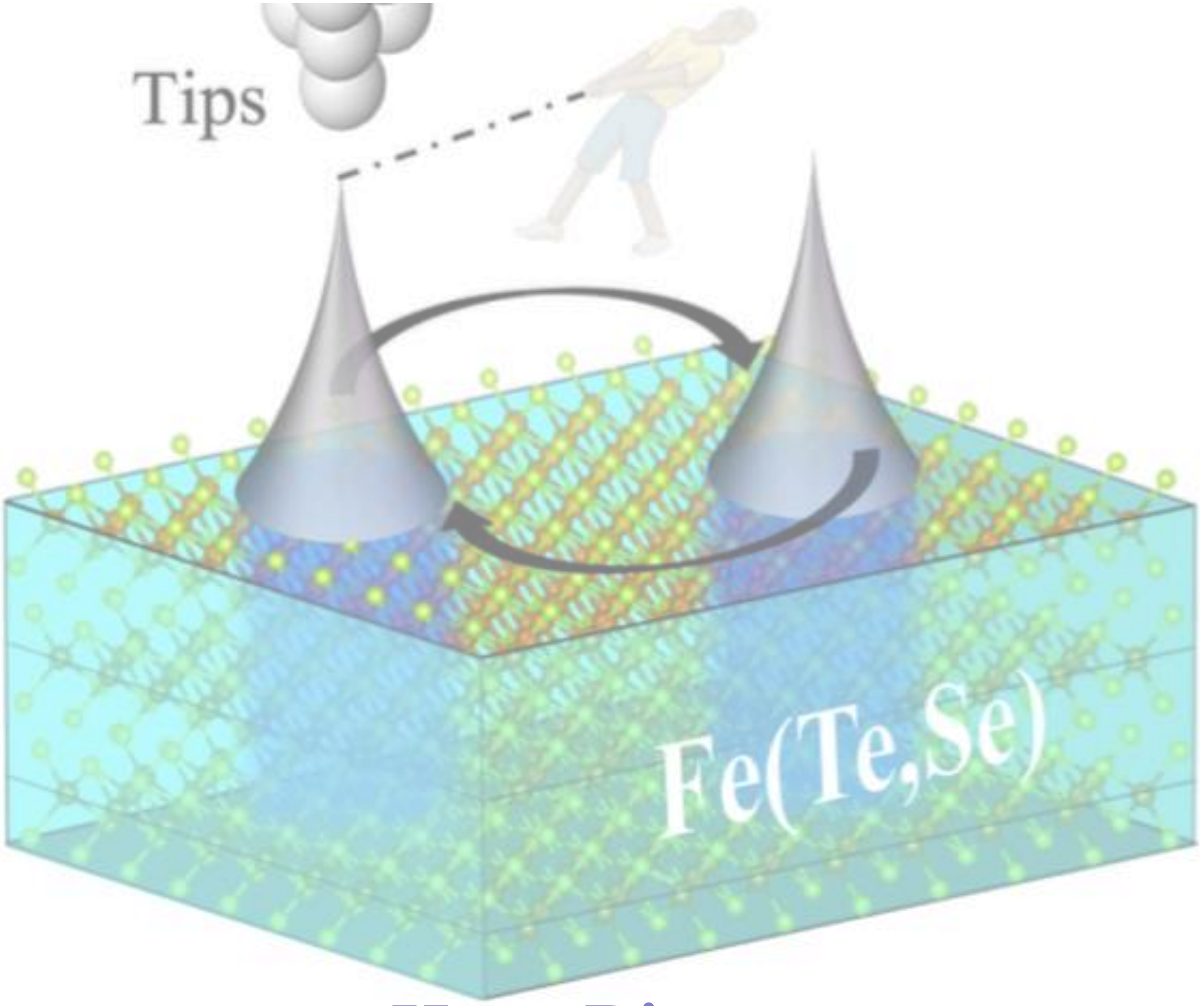
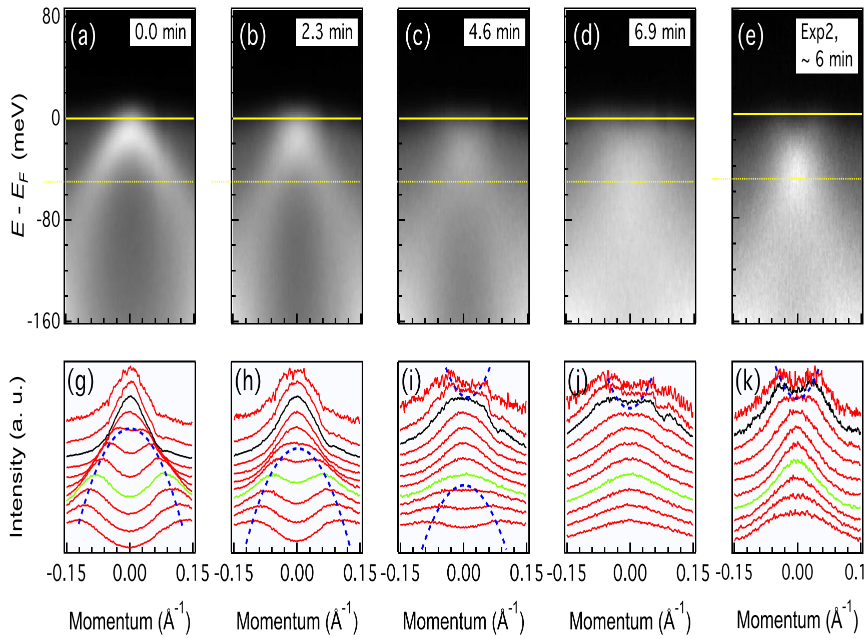
Iron-based topological superconductors & Majorana bound states

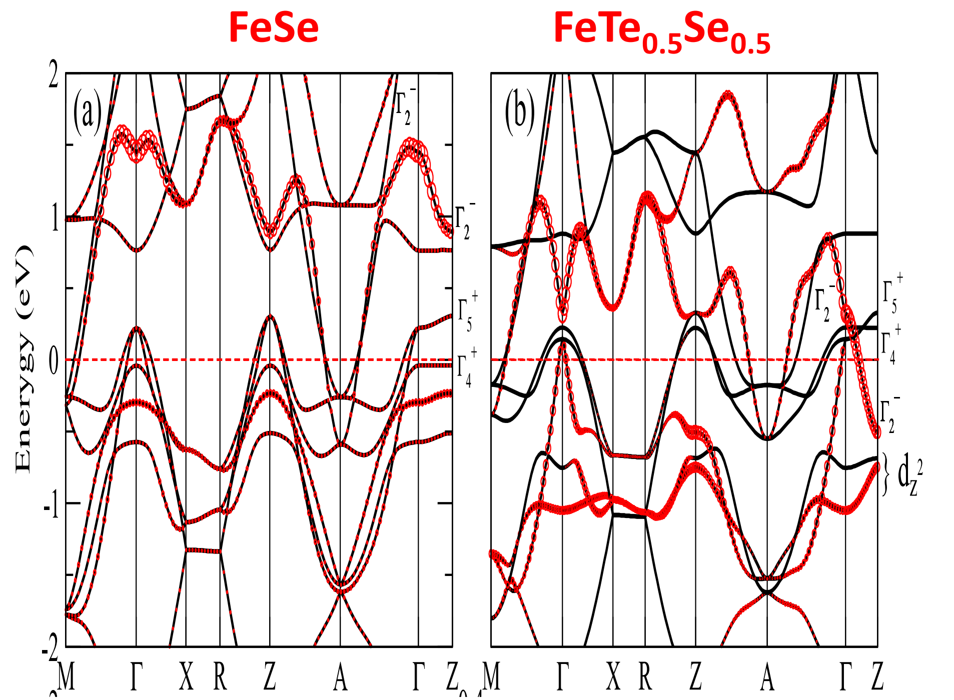


Hong Ding

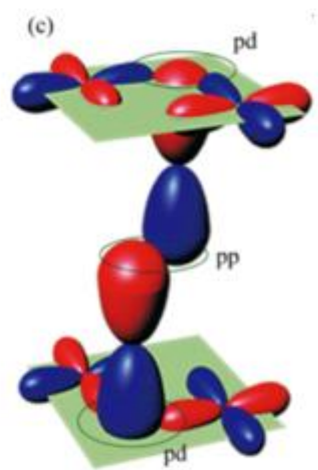
Institute of Physics, Chinese Academy of Sciences

Earlier evidence: nontrivial band inversion in Fe(Te,Se)



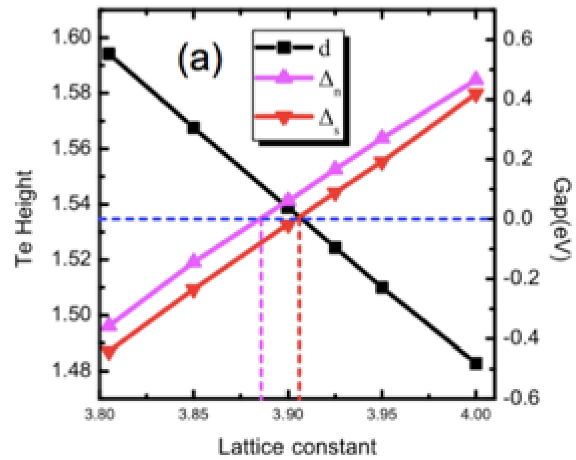


P. Zhang et al., APL 105, 172601 (2014) *Z. J. Wang et al., PRB 92, 1151119 (2015)*

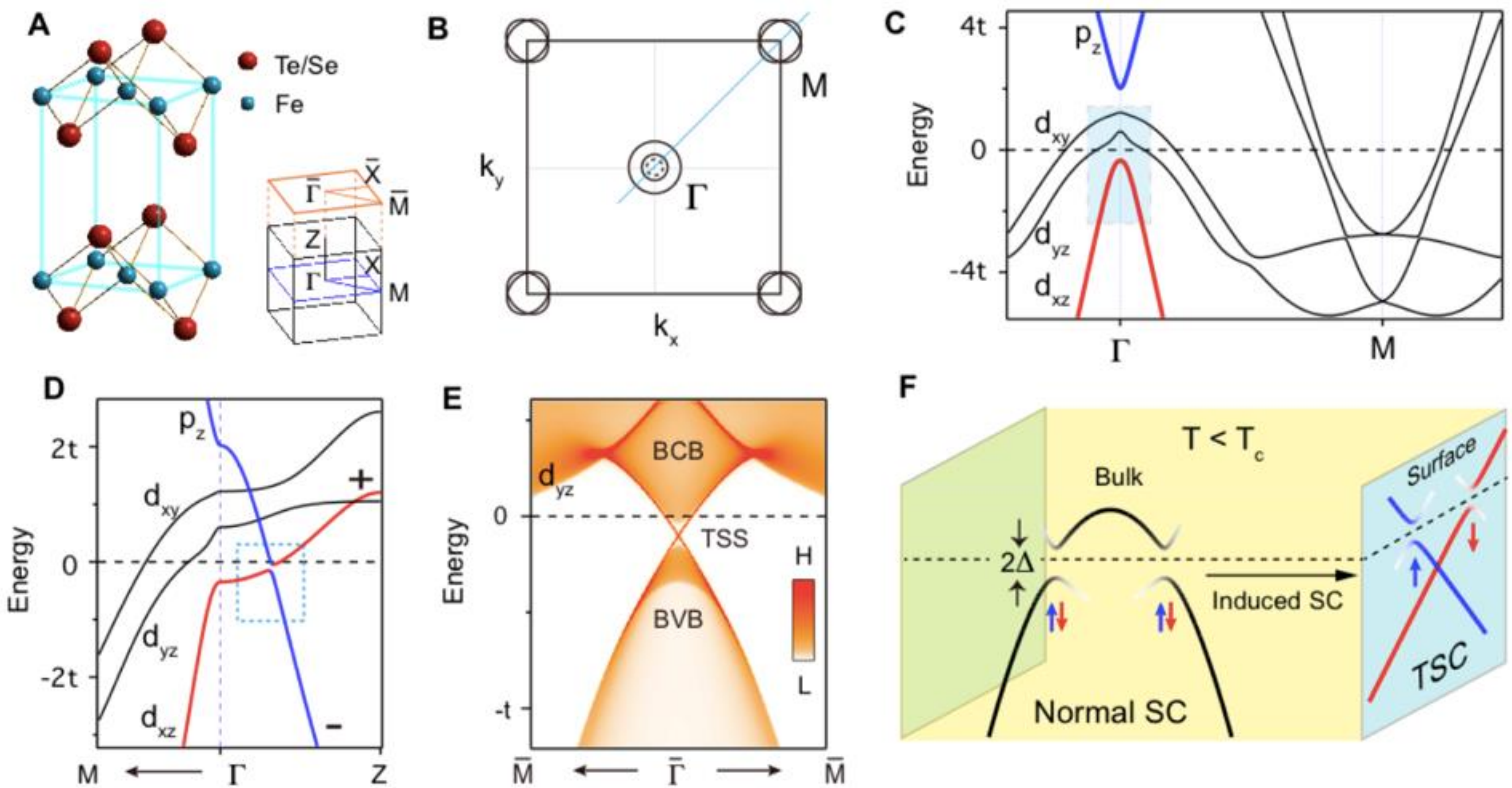


Se heights in FeSe and $FeTe_{0.5}Se_{0.5}$ are 1.46Å and 1.589Å , shifting p_z-d_{xy} down to induce a band inversion

J. P. Hu, PRB 93, 115129 (2016)

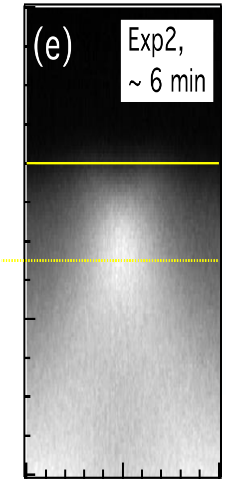


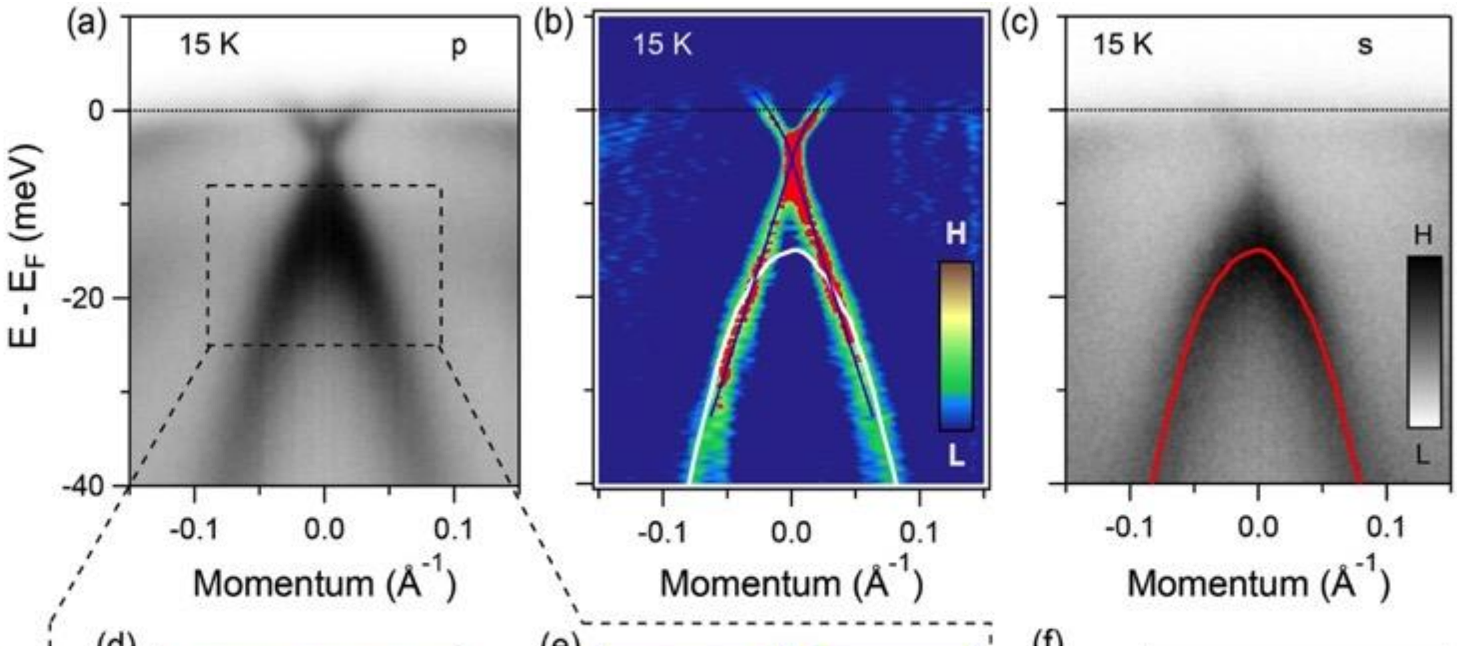
Fe(Te,Se): Connate topological superconductors through interband SC coherence

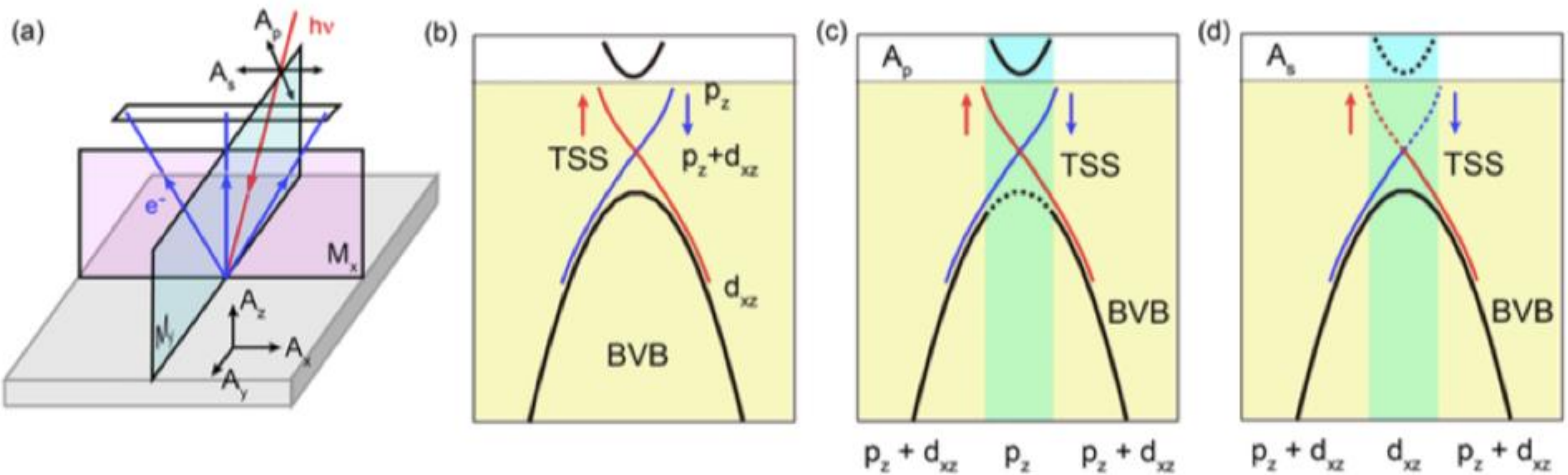


P. Zhang et al., Science 360, 182 (2018)

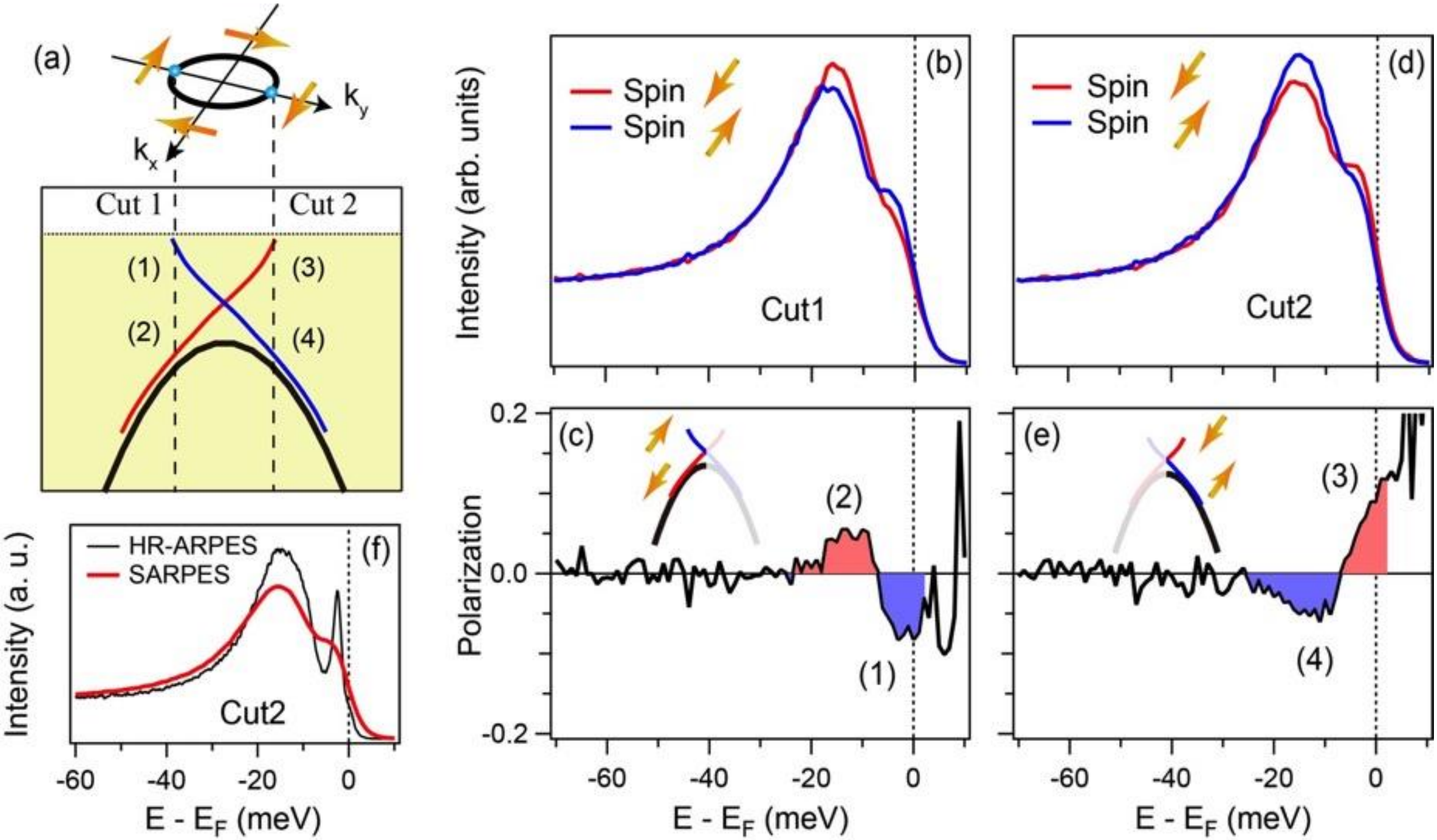
Evidence #1: Dirac cone of surface state





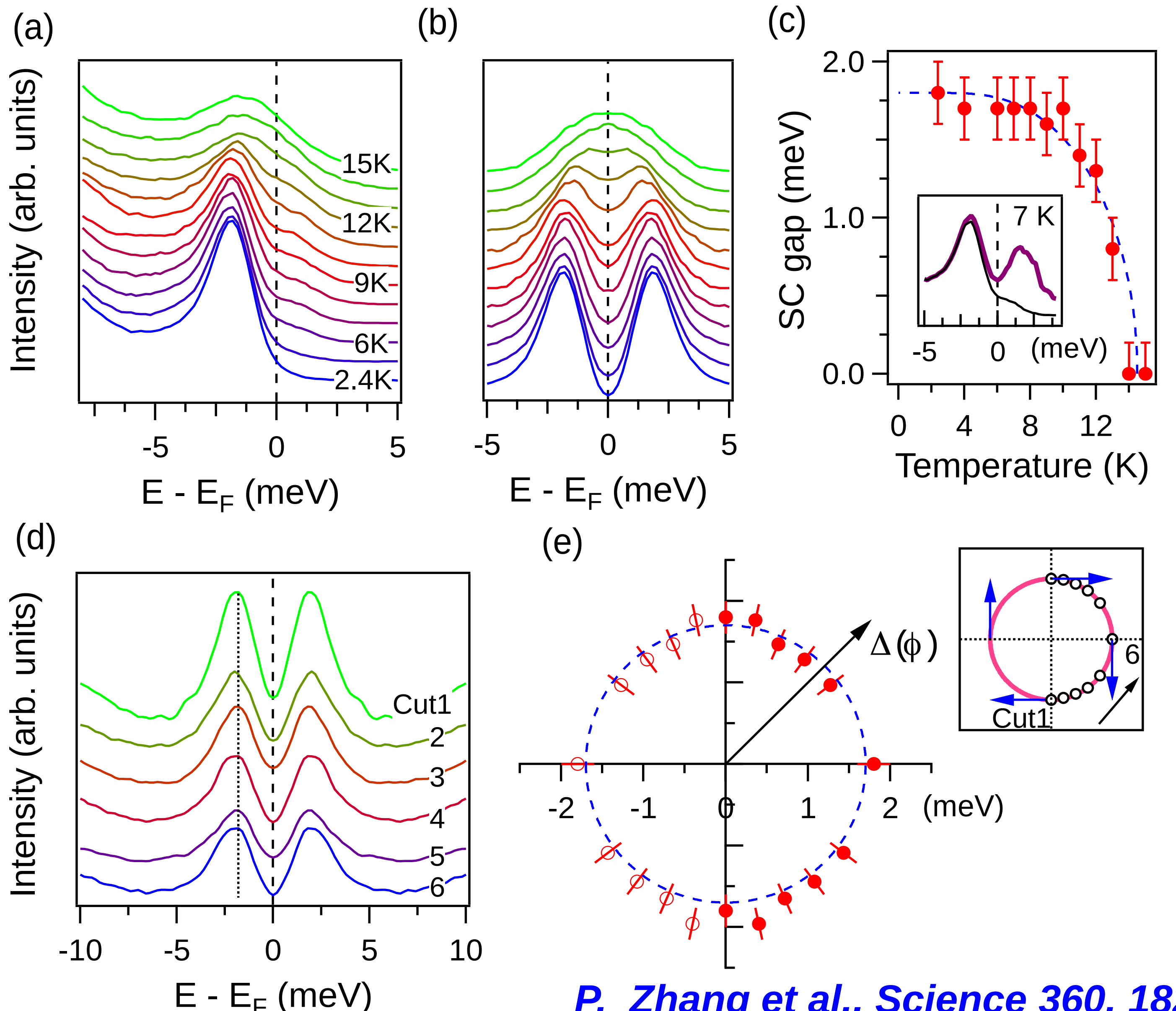


Evidence #2: helical spin structure of surface state



P. Zhang et al., Science 360, 182 (2018)

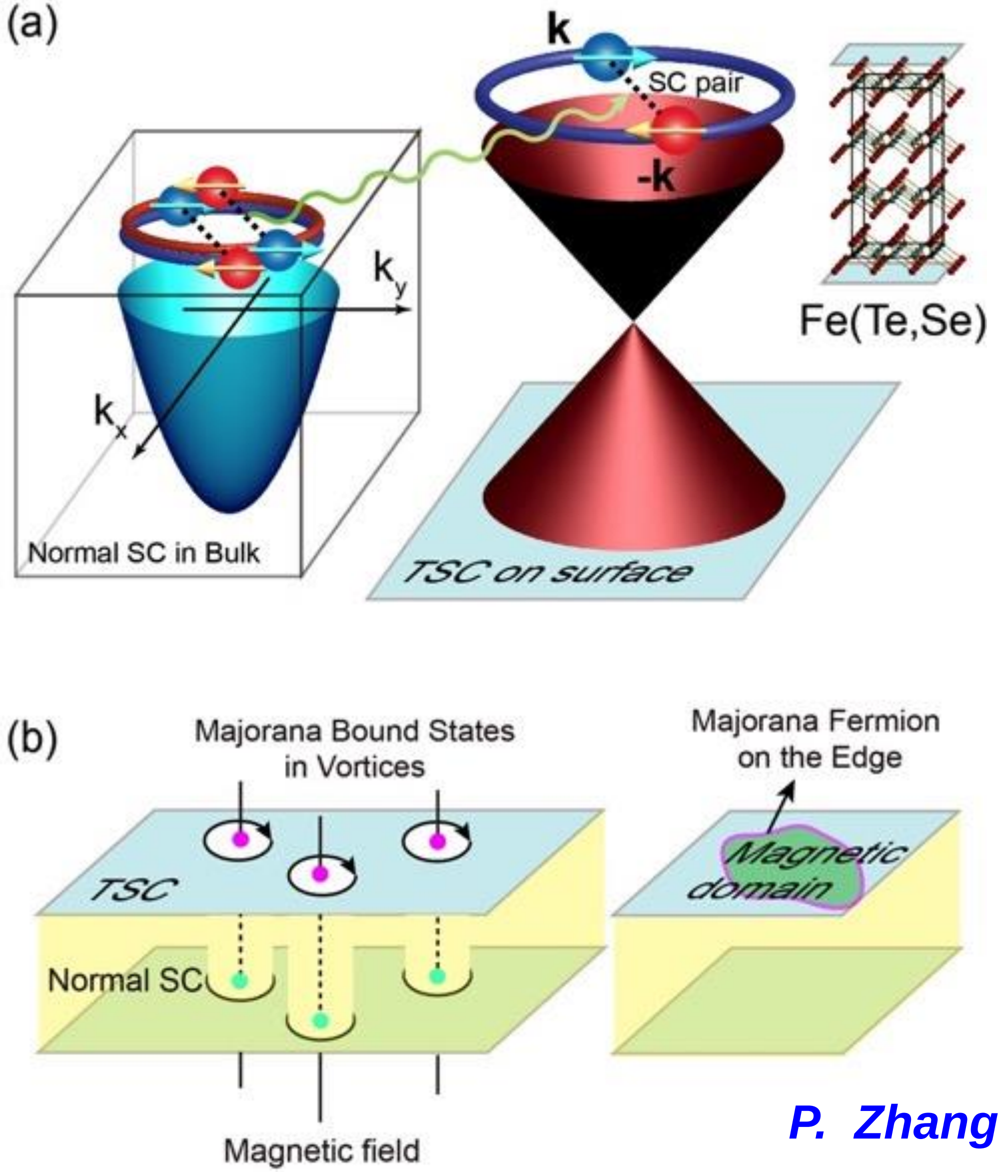
Evidence #3: *s*-wave SC gap of surface state



P. Zhang et al., Science 360, 182 (2018)

New way to find Majorana bound state

Connate topological superconductors through interband SC coherence

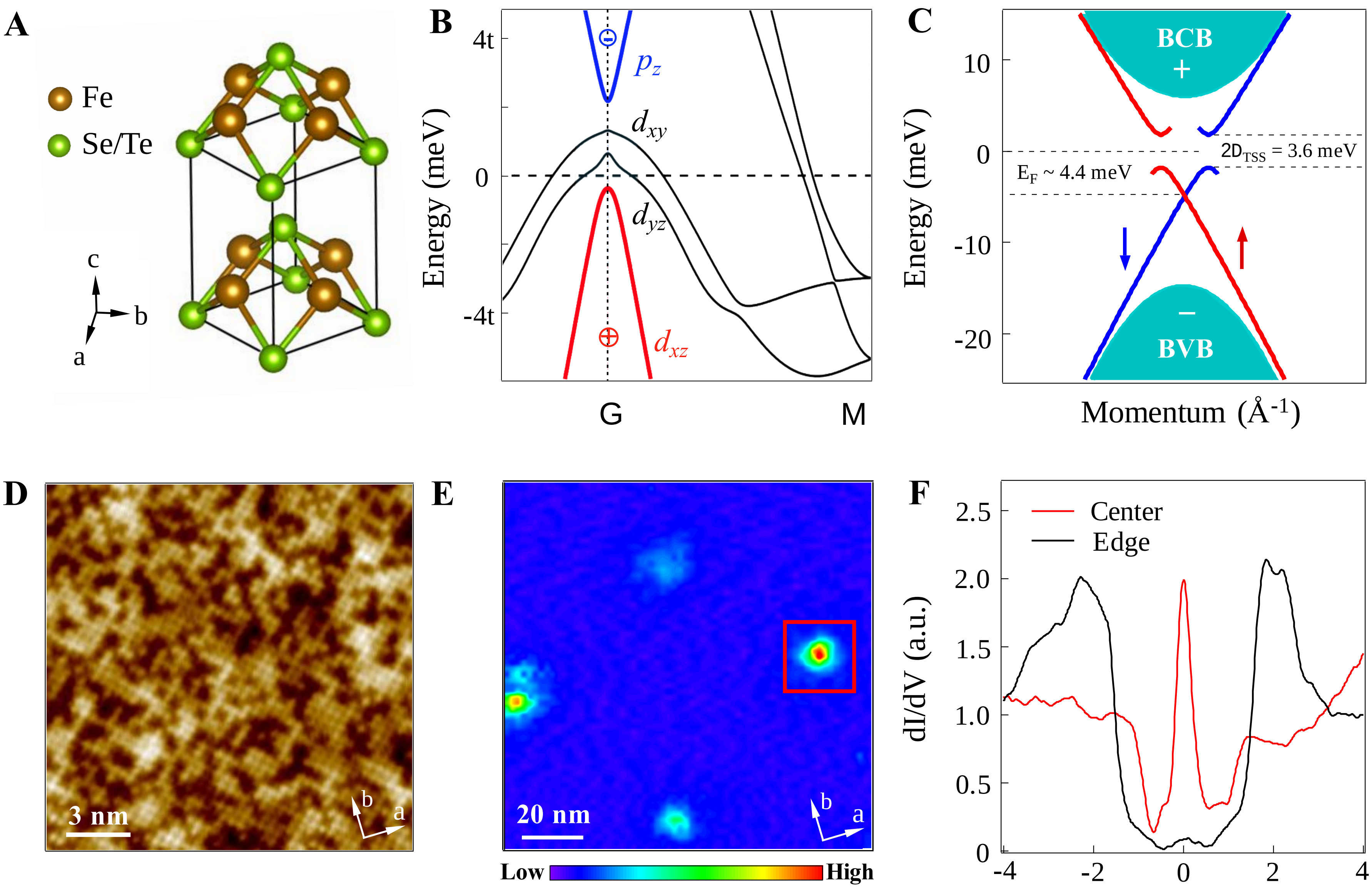


Advantages

- High Tc: single crystal (14.5K), thin film (50K?)
- Short coherence length (a few nm): high density of Majorana bound states
- Small E_F: remove other bound states

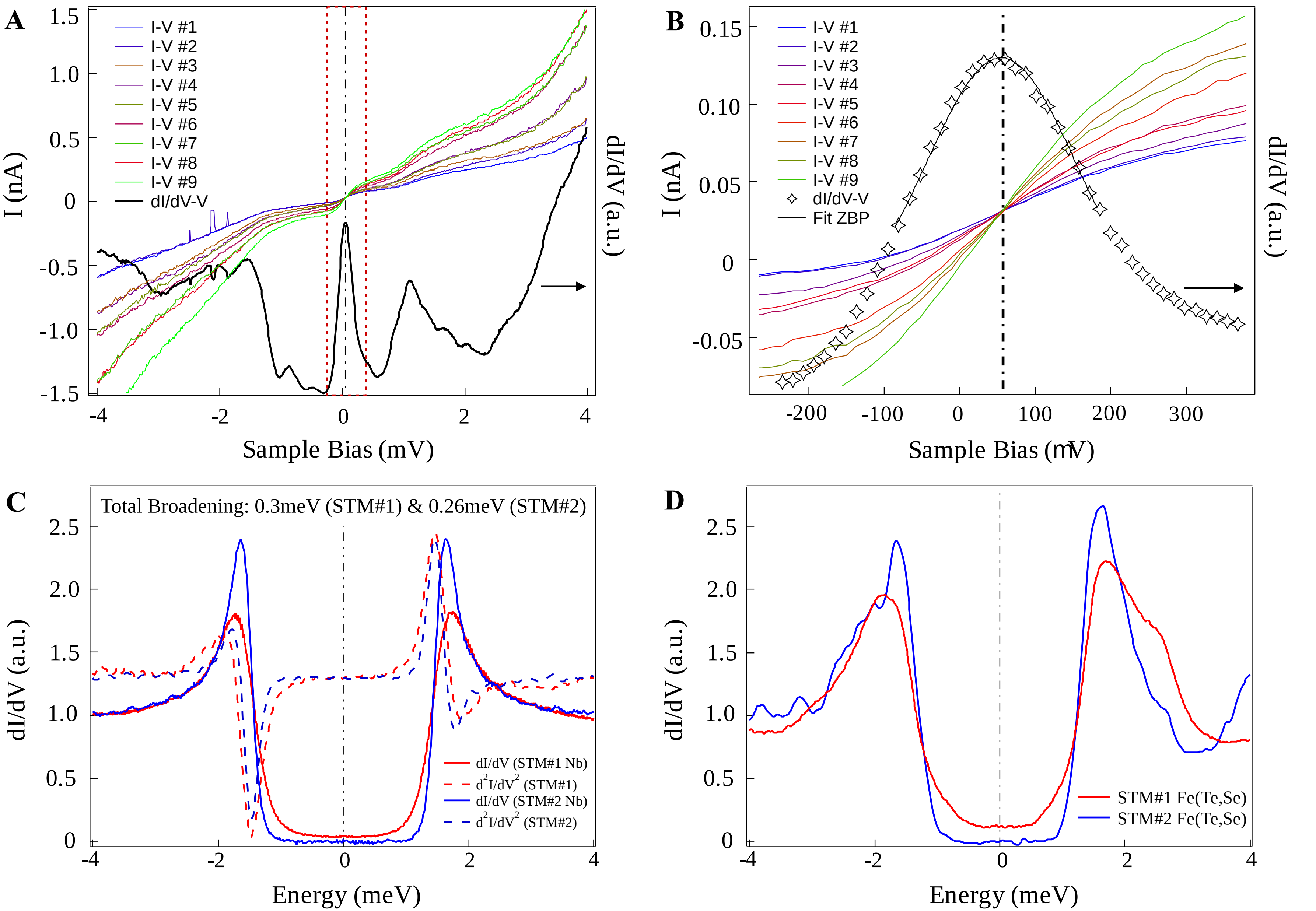
P. Zhang et al., Science 360, 182 (2018)

STM Observation of Majorana bound state in $FeTe_{0.55}Se_{0.45}$

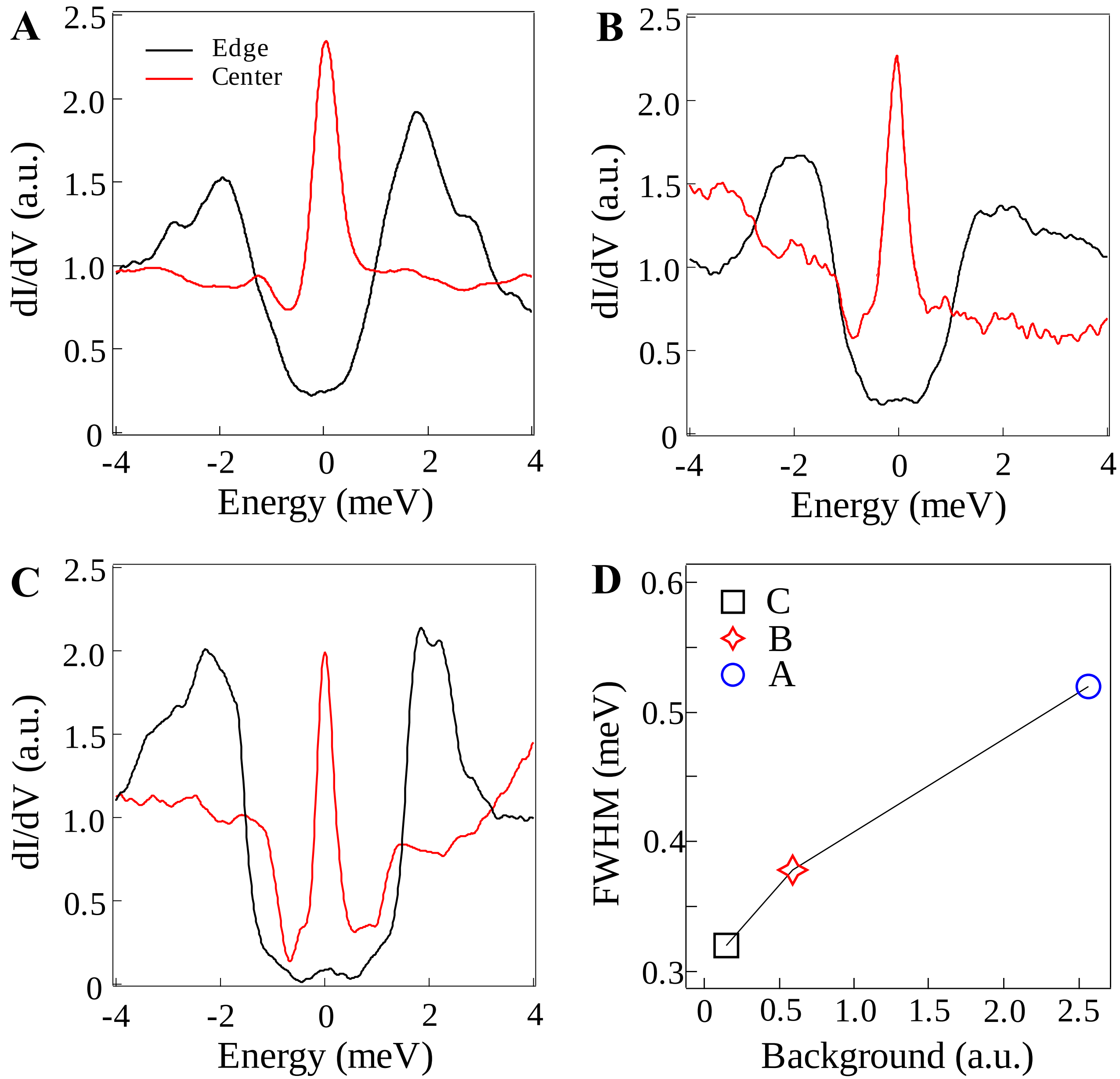


D.F. Wang et al., arXiv1706.06074

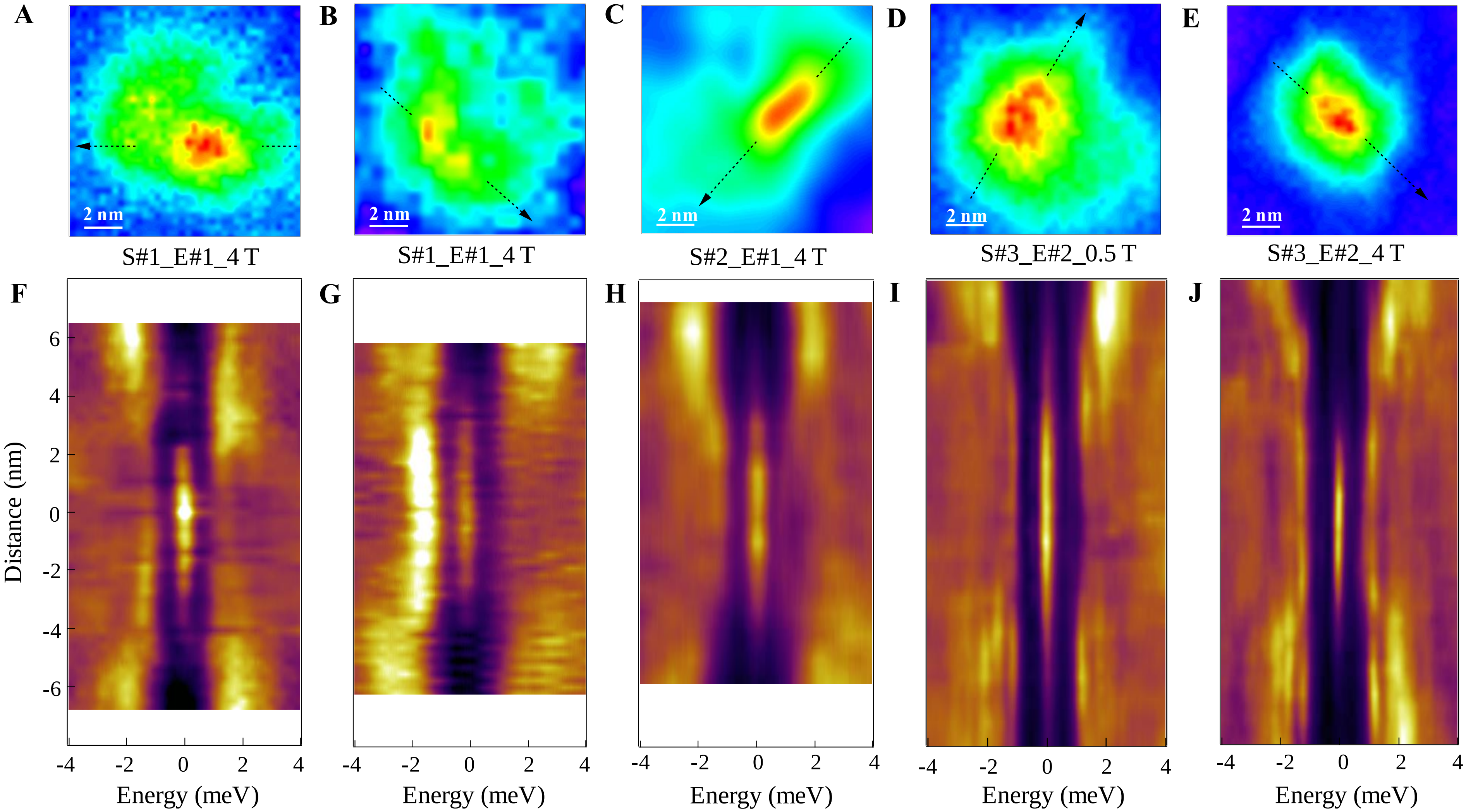
Zero energy and energy resolution calibration



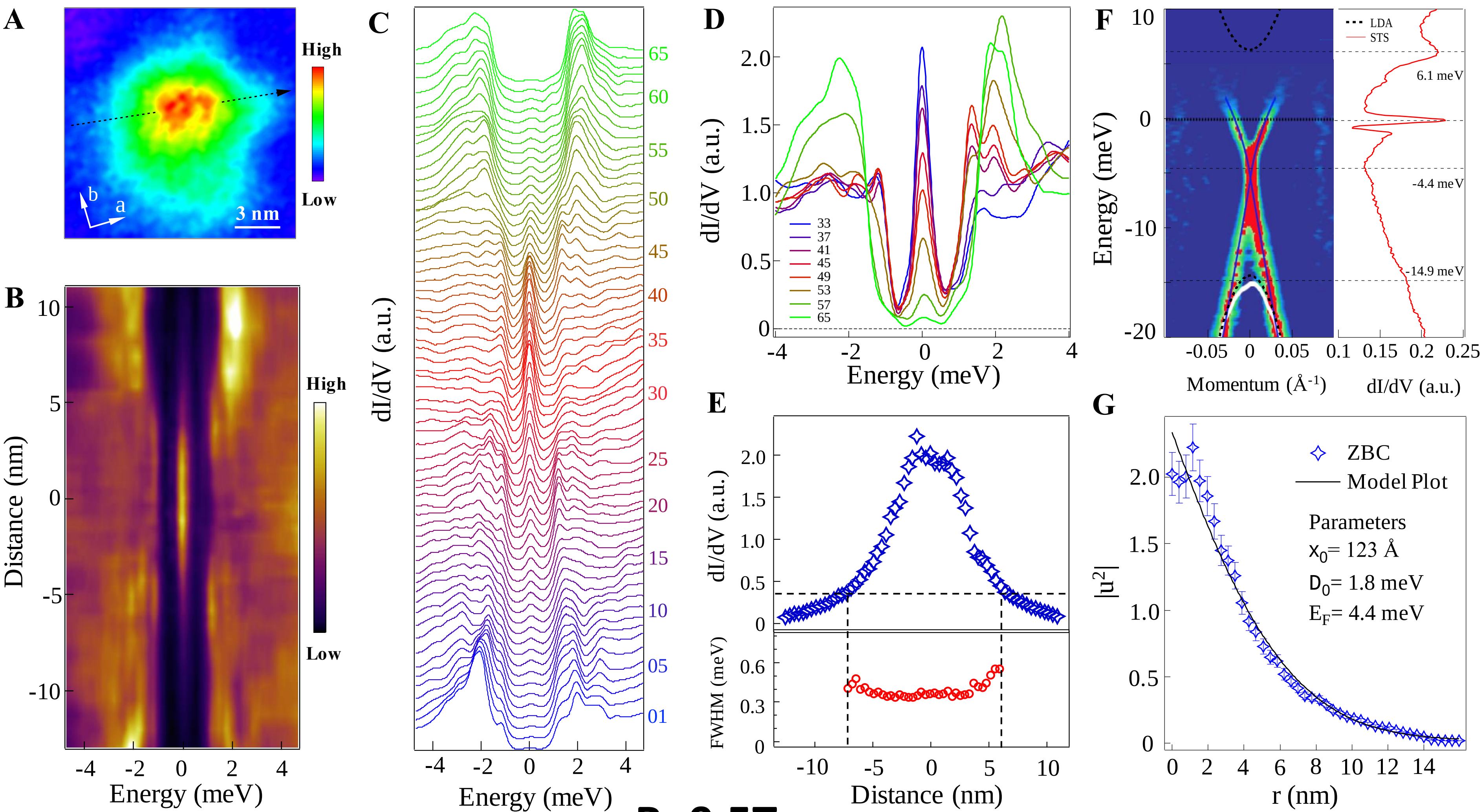
MBS broadening and background



Five examples of MBS inside vortex core



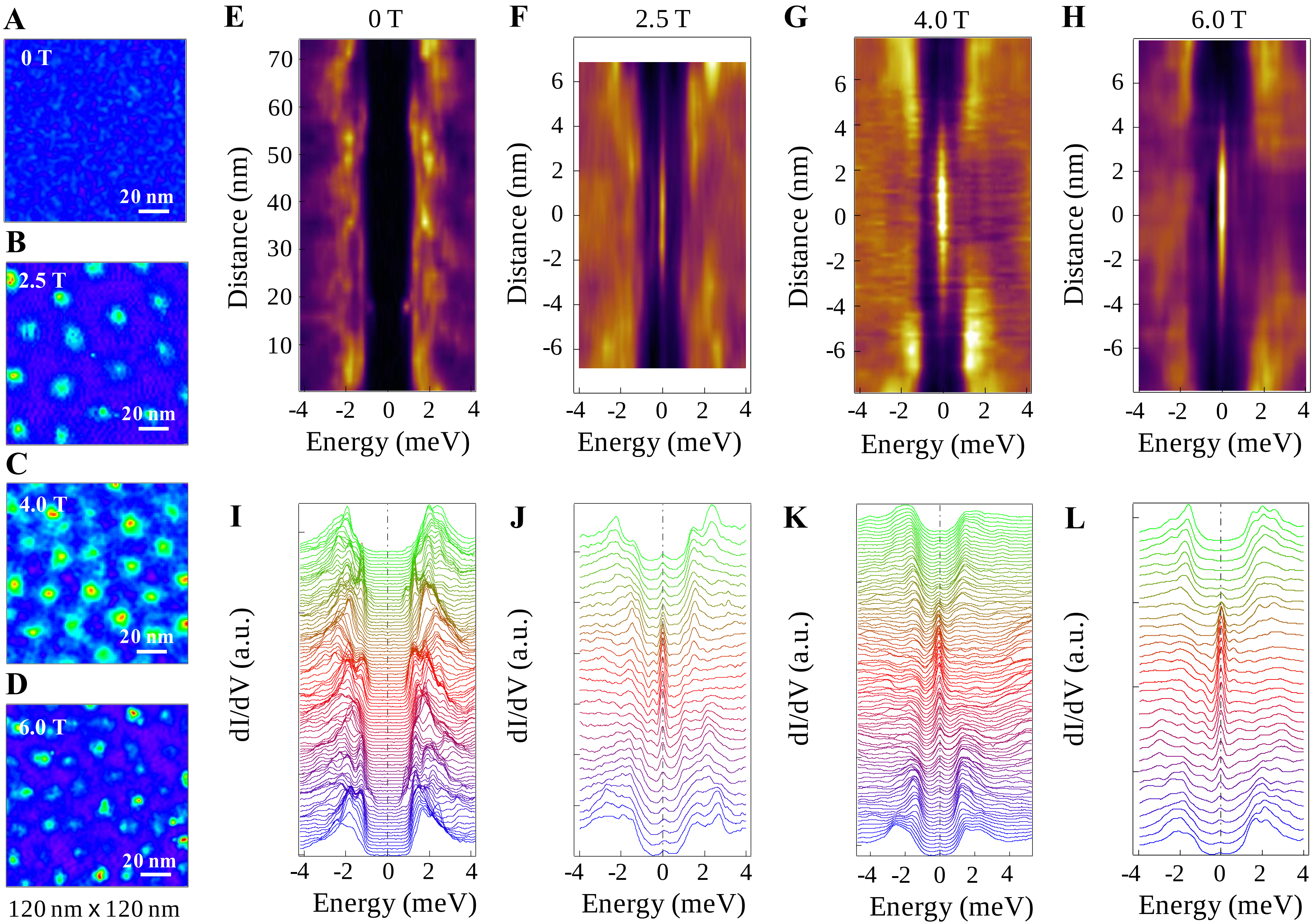
Spatial and energy distribution of MBS



B=0.5T

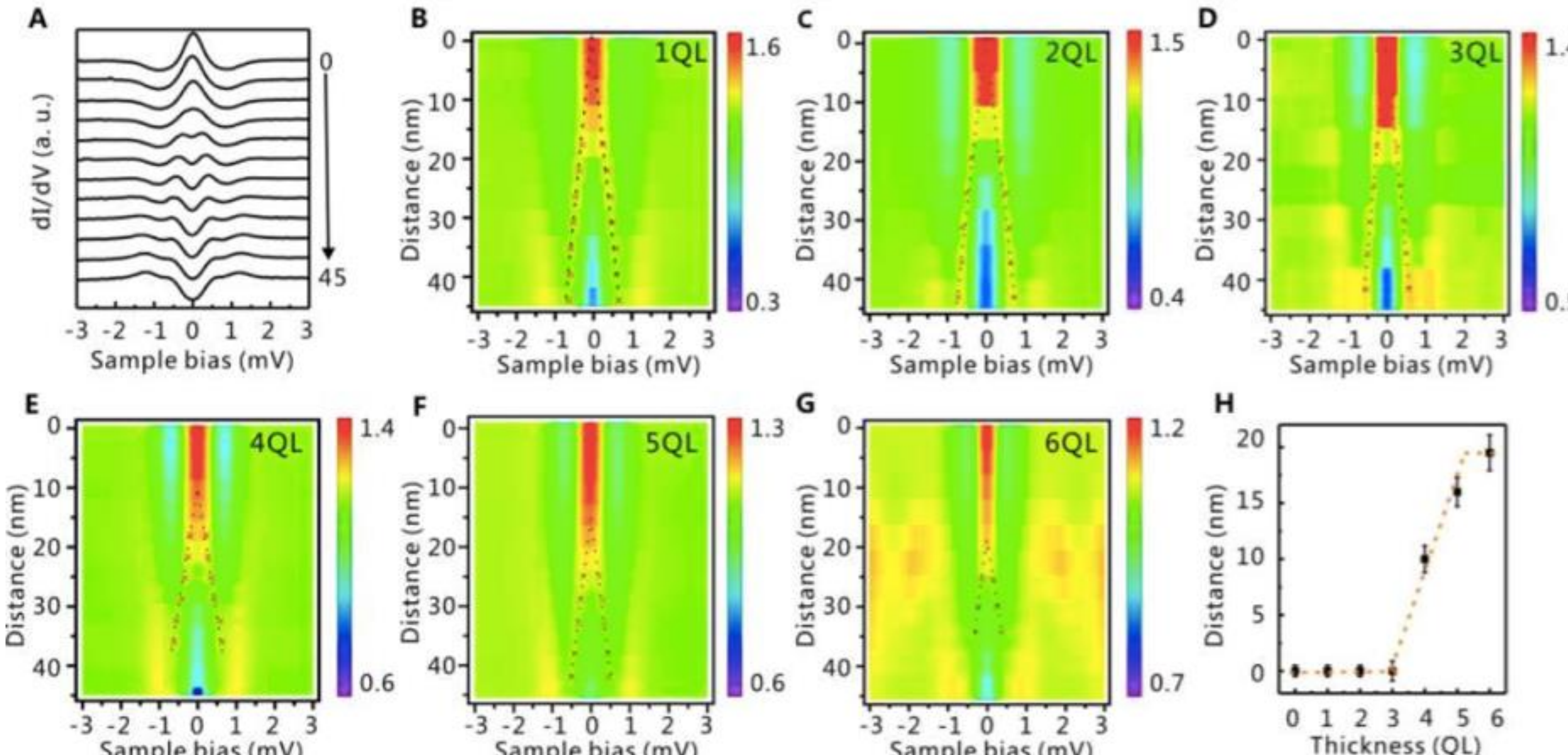
Majorana bound states never shift, they just fade away!

Magnetic field dependence



Comparison between TI/SC and connate TSC

$Bi_2Te_3/NbSe_2$



Splitting of Zero-bias peaks

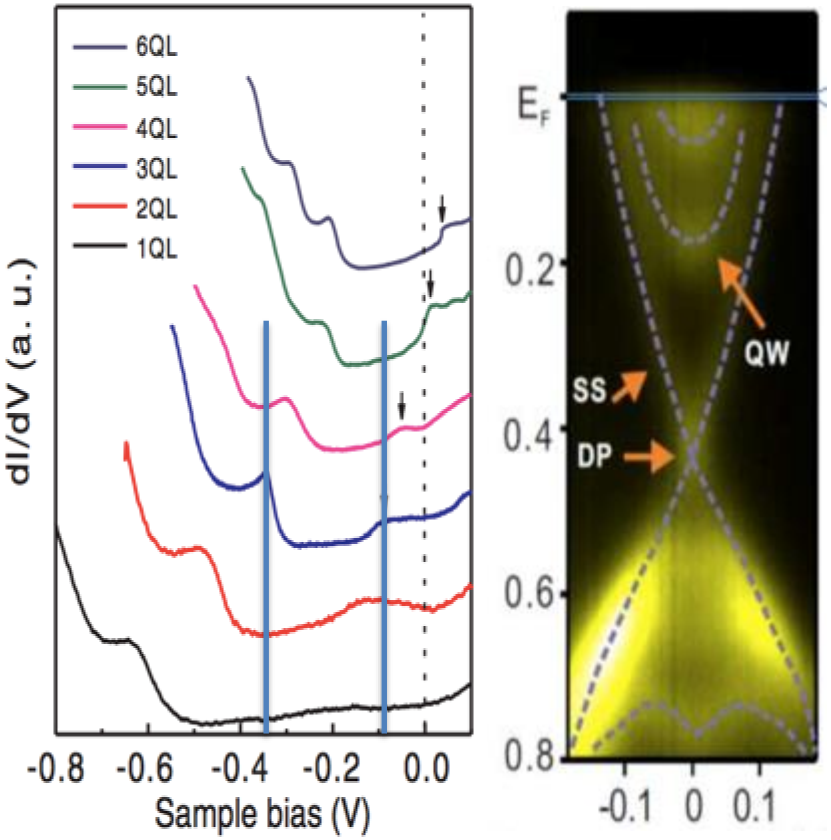
Non-zero splitting

PRL 114, 017001 (2015)

Courtesy of Jinfeng Jia

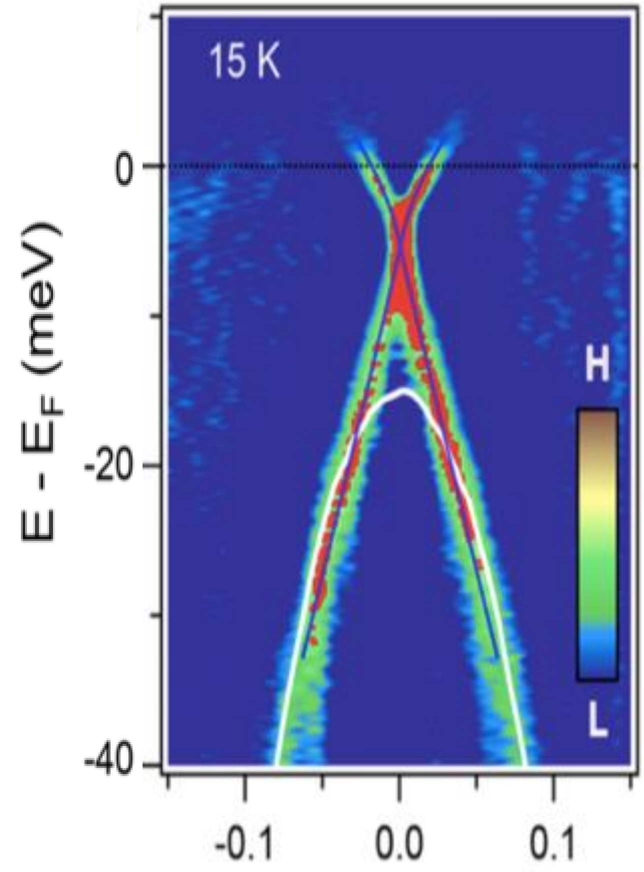
Comparison between TI/SC and connate TSC

$Bi_2Te_3/NbSe_2$



$$\frac{\Delta_{SC}}{E_F} \sim \frac{0.5\,meV}{250\,meV} \sim 2\times10^{-3}$$

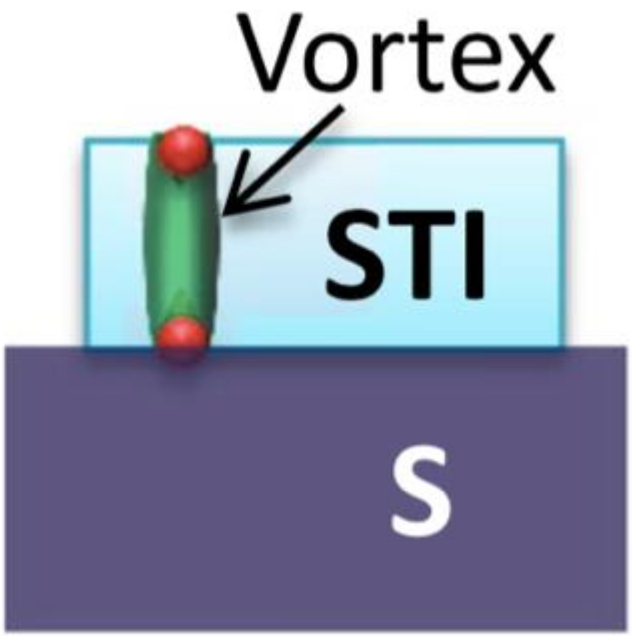
Fe(Te,Se)



$$\frac{\Delta_{SC}}{E_F} \sim \frac{2\,meV}{5\,meV} \sim 4\times10^{-1}$$

Comparison between TI/SC and connate TSC

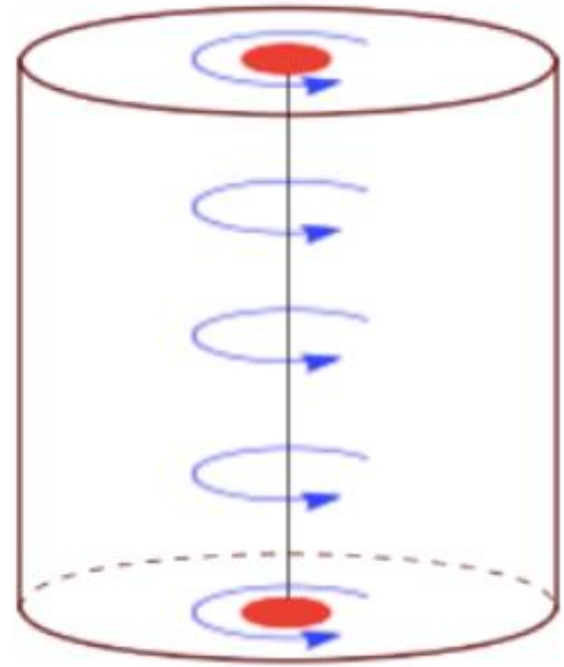
$Bi_2Te_3/NbSe_2$



Problems:

1. If TI film is too thin, then Majorana pairs interacting and annihilating
2. If TI film is too thick, then no or weak SC on top surface

Fe(Te,Se)



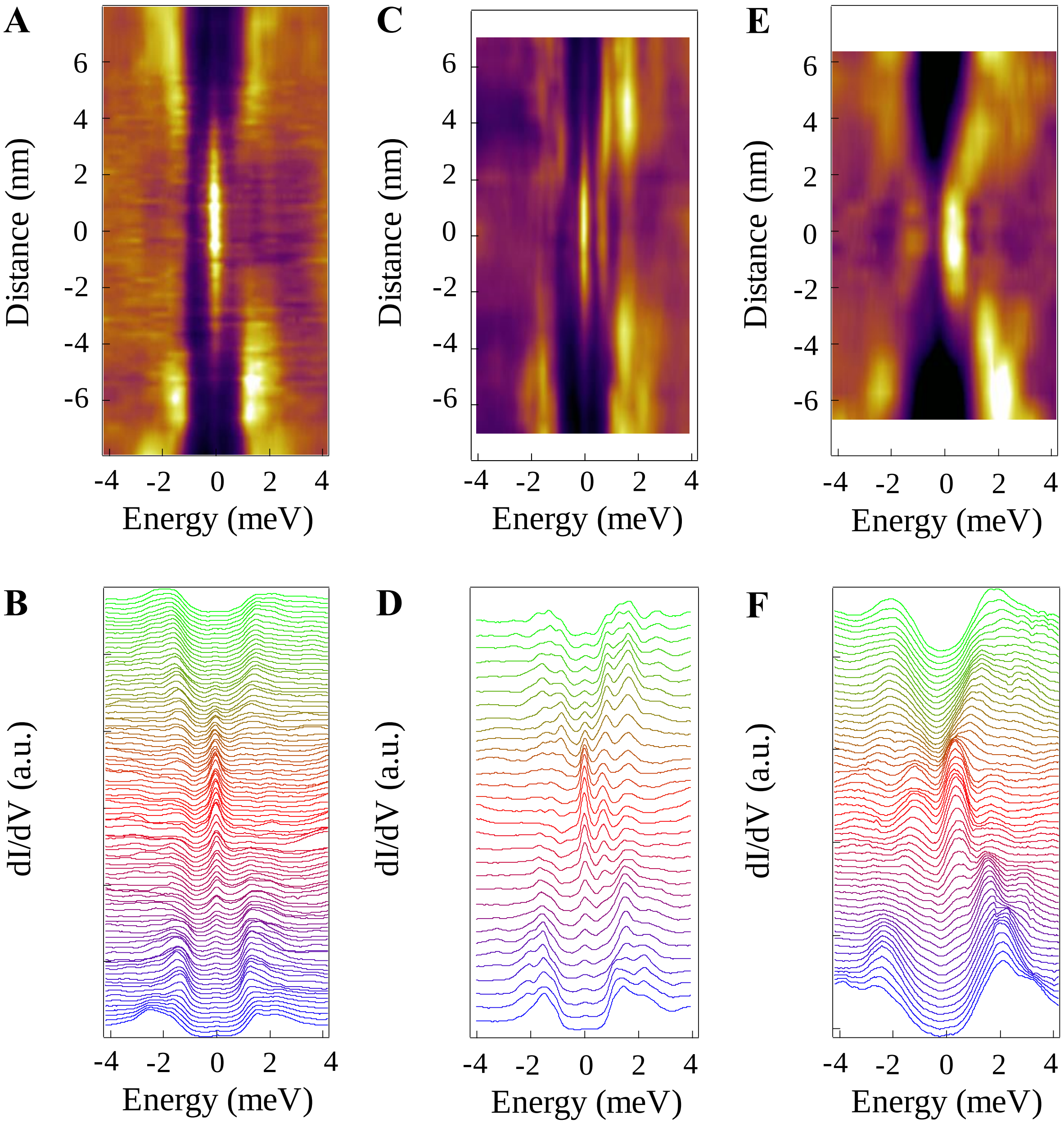
Problems:

The bulk is NOT an insulator!

Likely solution:

Localized state in the bulk vortex line

Other types of bound states



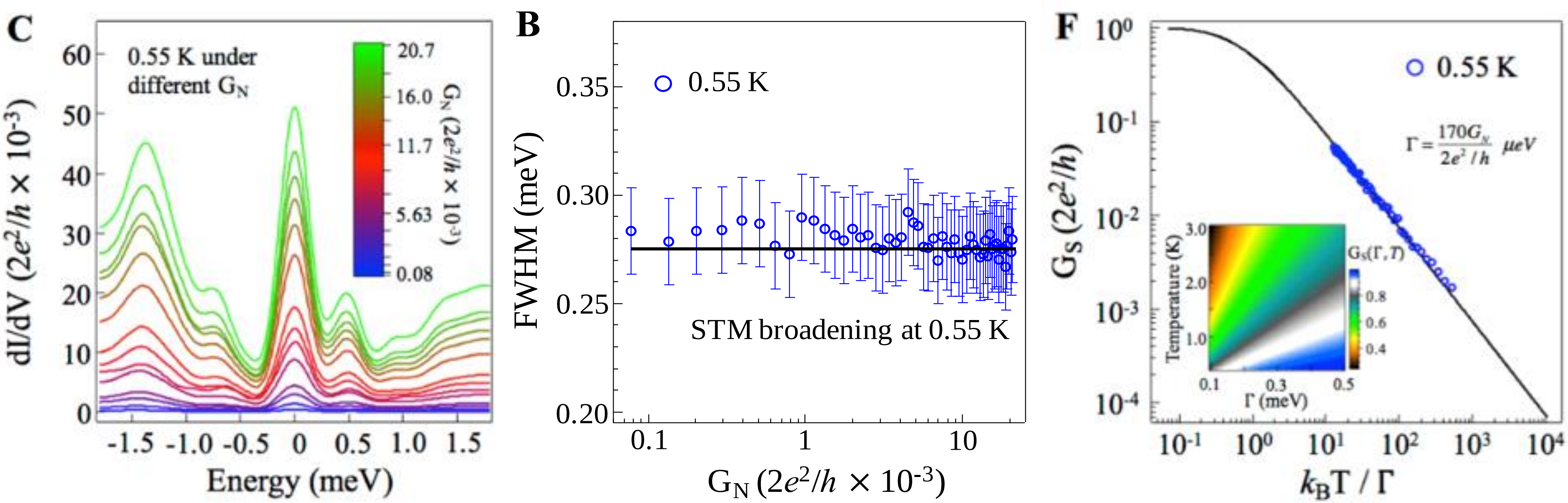
Toward quantized conductance

Scaling behavior of zero bias conductance: to achieve $2e^2/h$ plateau

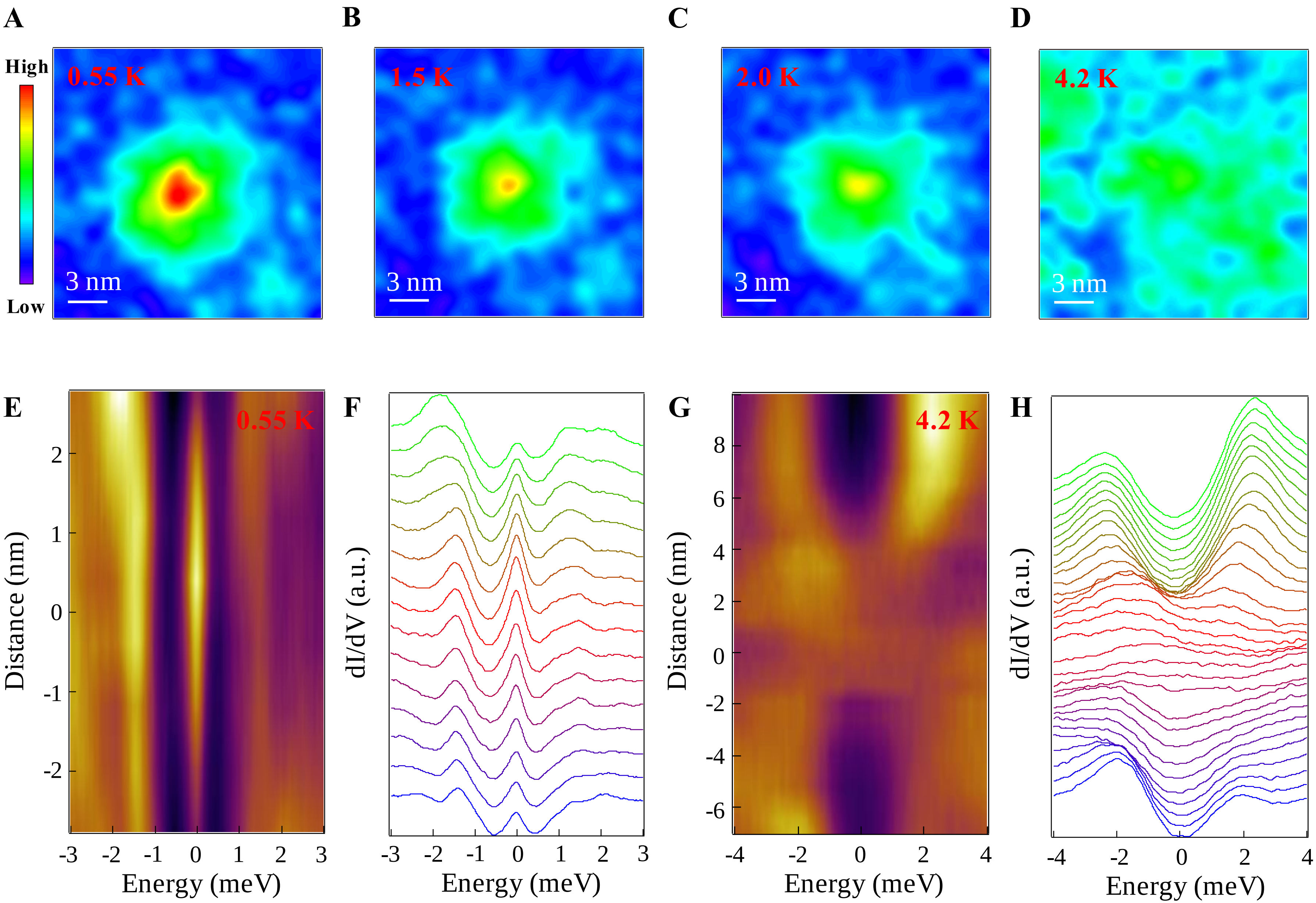
$$G_s = \frac{2e^2}{h}\int_{-\infty}^{+\infty} dE \, \frac{\Gamma^2}{E^2+\Gamma^2}\,\frac{1}{4k_BT\cosh^2(E/2k_BT)}$$

$$= \frac{2e^2}{h} f\,(k_BT/\Gamma)$$

PRL 103, 237001 (2009)
PRL **119**, 136803 (2017)
PRB **96**, 184520 (2017)

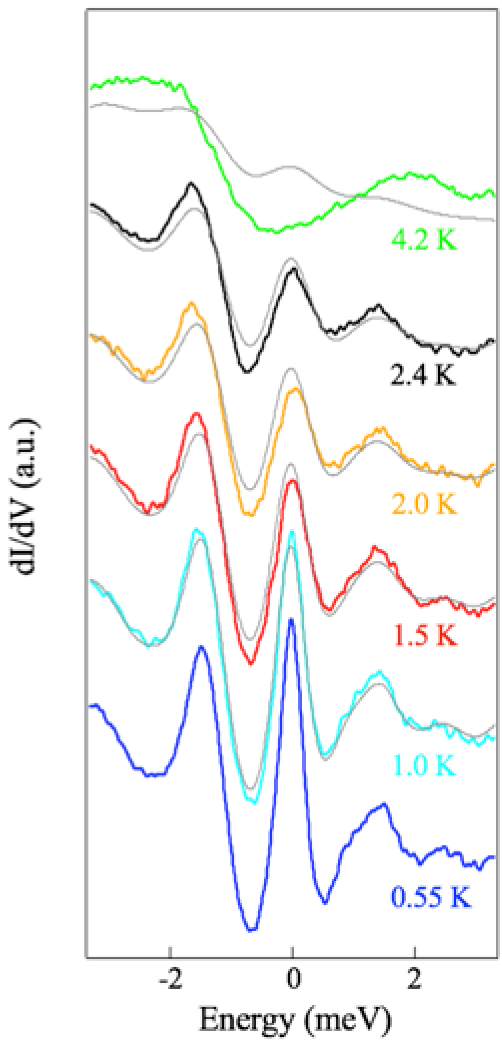


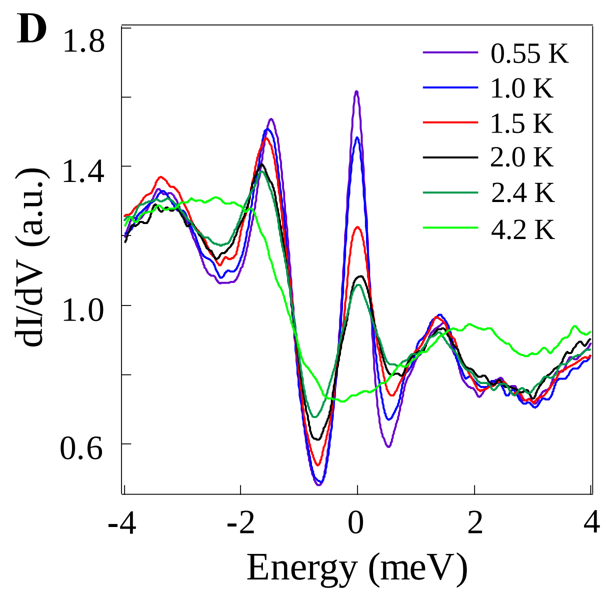
Temperature dependence

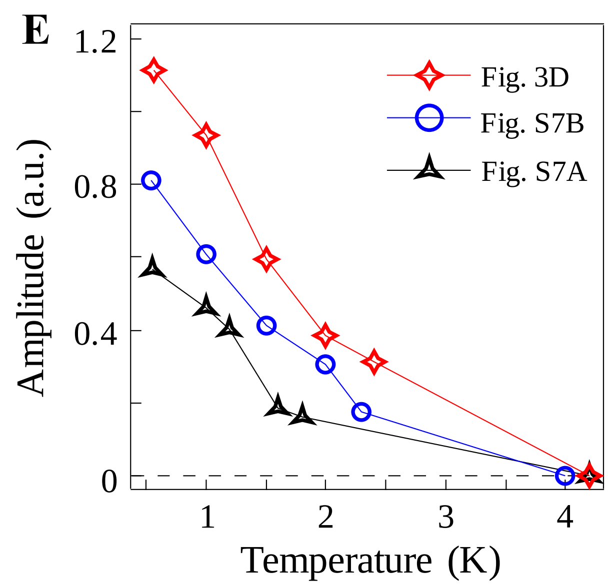


Temperature dependence

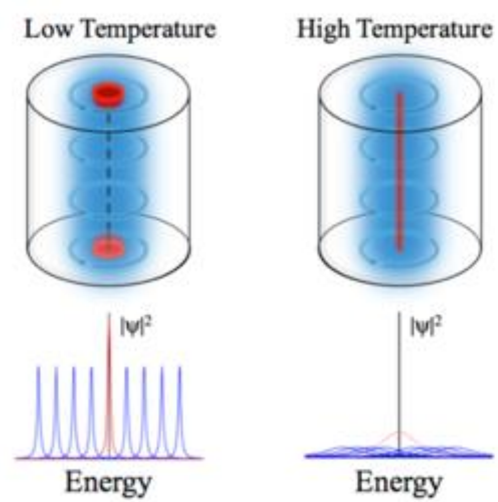
At higher T, dissipative bulk QPs can mix with surface Majorana







Orbital/Band	Δ (meV)	E_F (meV)	Δ^2/E_F (meV)
Γ (TSS)	1.8	4.4	0.74
Γ	2.5	5~30	0.21~1.25
M	4.2	15~40	0.44~1.18



$(\Delta^2/E_F)_{Bulk} \sim 3$ K

Summary of our results on Fe(Te, Se)

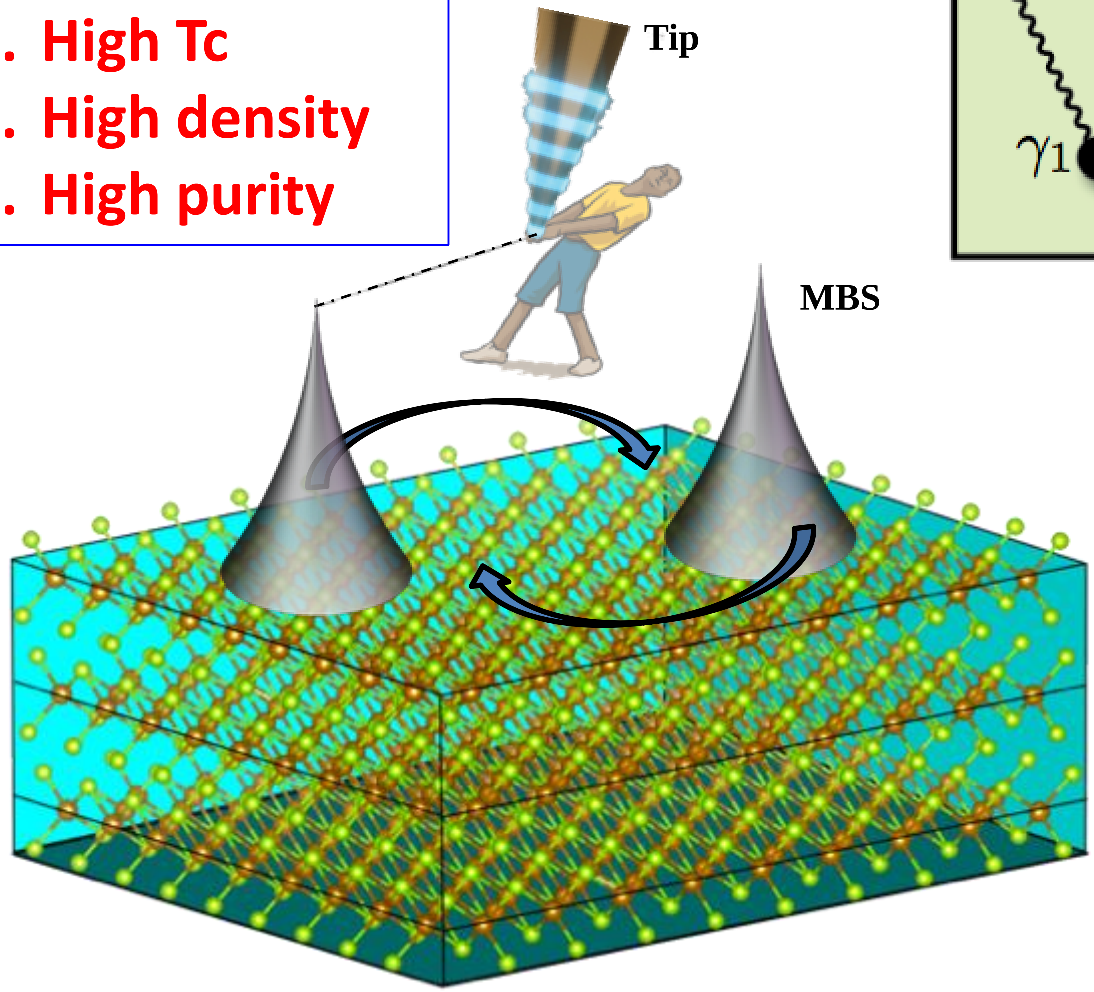
1. Band inversion and topological surface state
2. Full superconducting gap below bulk T_C of 14.5K
3. Non-splitting ZBP inside a vortex core, robust under a magnetic field of 0.1T – 6T
4. Spatial profile of ZBP fully consistent with theoretical prediction
5. Linewidth of ZBP at low-T is resolution and temperature limited (0.28 meV at 0.56K), and remains a constant under 2 orders of magnitude change in tunneling barrier
6. Temperature dependence is consistent with MBS behavior

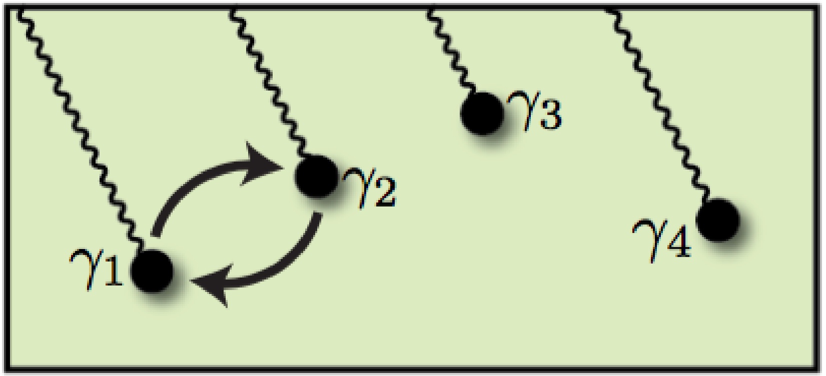
Conclusion: Tunneling to a pristine isolated MBS!

A new platform to manipulate MBSs!

Advantage:

1. Single material
2. High Tc
3. High density
4. High purity





From quantum device to quantum material!

D.F. Wang et al., arXiv1706.06074

Fe(Te, Se) monolayer may be even better!

Science Bulletin 62 (2017) 503–507

ELSEVIER

Contents lists available at ScienceDirect

Science Bulletin

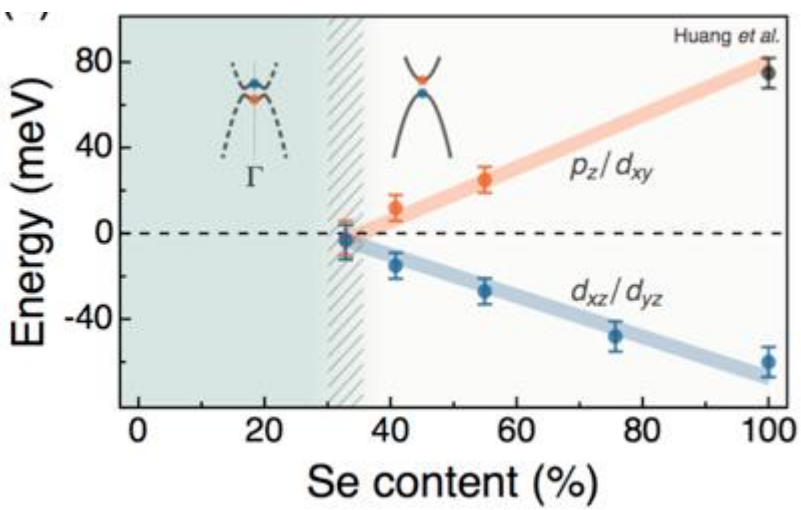
journal homepage: www.elsevier.com/locate/scib

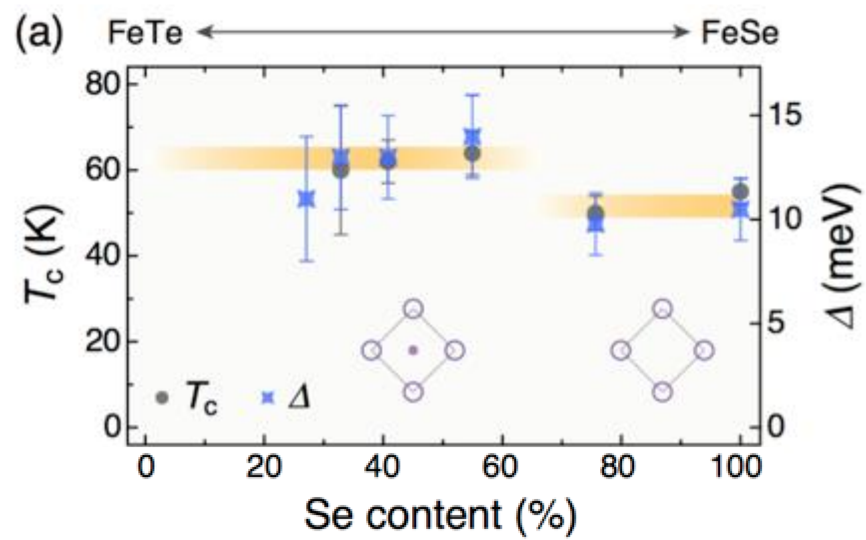
Science Bulletin
www.scibull.com

Article

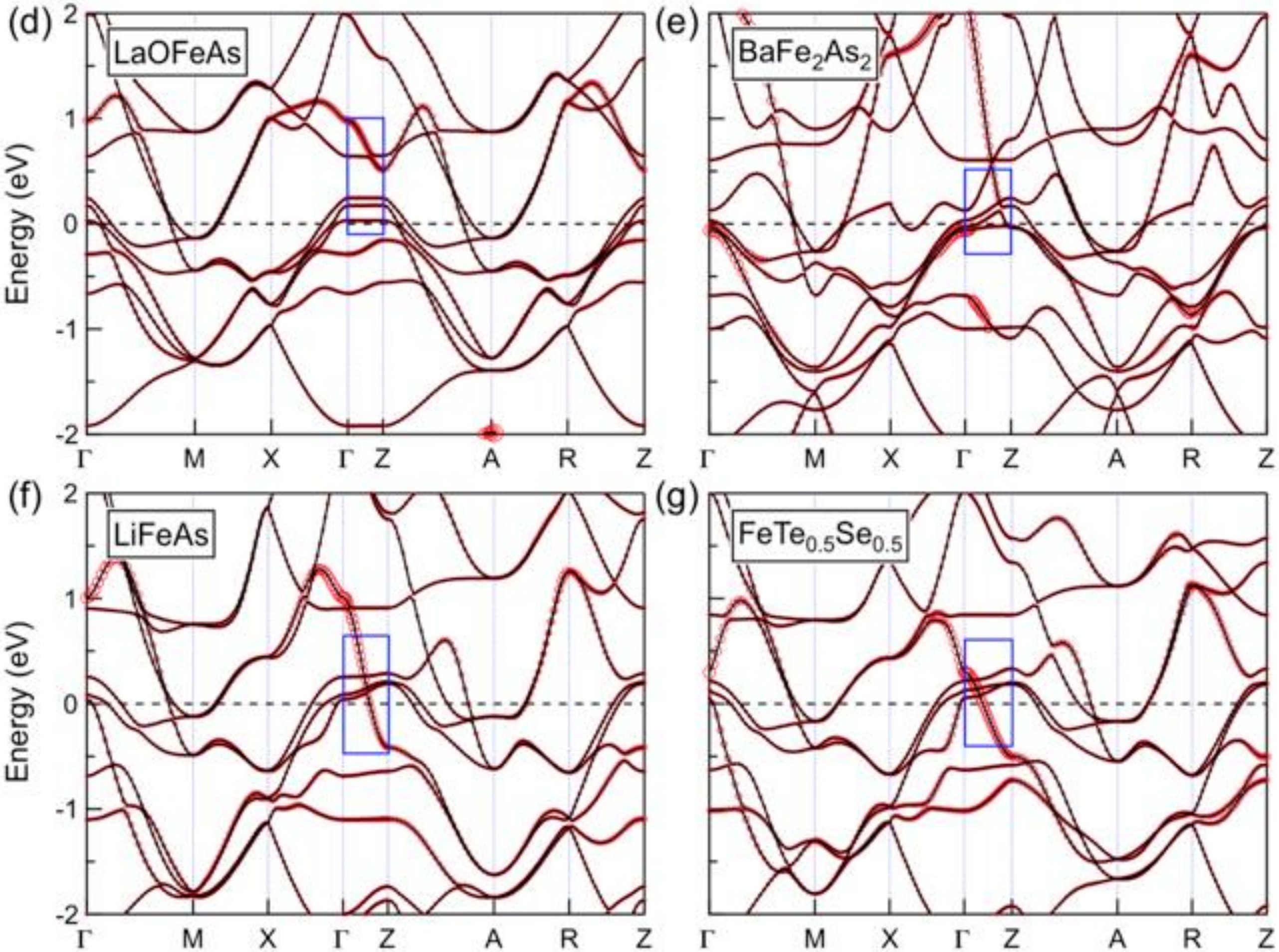
$FeTe_{1-x}Se_x$ monolayer films: towards the realization of high-temperature connate topological superconductivity

Xun Shi [a,1], Zhi-Qing Han [a,b,1], Pierre Richard [a,c,d], Xian-Xin Wu [a], Xi-Liang Peng [a], Tian Qian [a,c], Shan-Cai Wang [b], Jiang-Ping Hu [a,c,d], Yu-Jie Sun [a,*], Hong Ding [a,c,d,*]

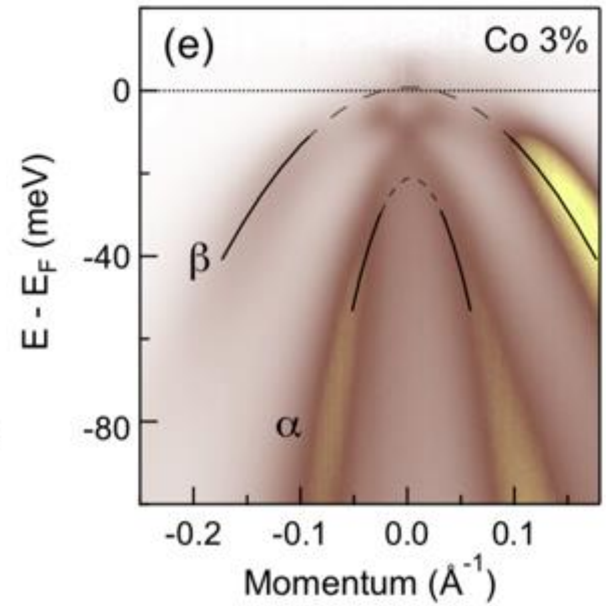


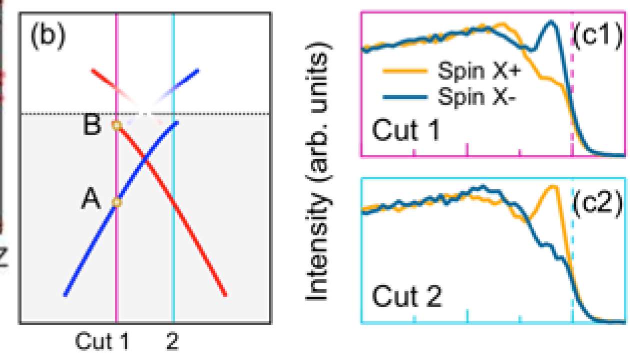


Most iron-based superconductors are topological!



LiFeAs





P. Zhang et al., arXiv: 1803.00846

Marriage of high-Tc superconductivity and topology!

Collaborators

ARPES:

IOP: P. Zhang, X. Shi, T. Qian, P. Richard, L.K. Zeng, H. Miao, N. Xu, J. Ma

ISSP: P. Zhang, K. Yaji, K. Kuroda, T. Hashimoto, Y. Ota, T. Kondo, K. Okazaki, S. Shin

STM:

IOP: D.F. Wang, L.Y. Kong, P. Fan, H. Chen, Y.J. Sun, S.X. Du, H.J. Gao

Theory:

ARPES IOP: Z.J. Wang (Princeton), G. Xu, H.M. Weng, X. Dai, Z. Fang

STM MIT: L. Fu

Thank you!

Samples:

Single crystal: G.D. Gu (**BNL**), J.S. Wen (**Nanjing U**)

Thin film: Z.-Q. Han, X.-L. Peng, Y.-J. Sun (**IOP**)