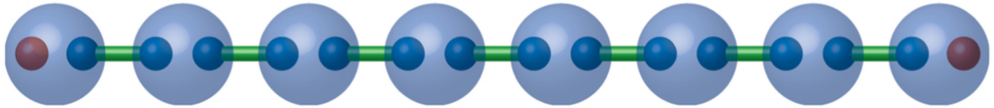
Majorana in Iron Superconductors & Pairing of Spin-Helical Electrons

Liang Fu

Majorana Fermion

Majorana
zero mode:



Kitaev (2000)

Two spatially separated Majoranas γ_1, γ_{2N} constitute a fermionic qubit

At **T=0**, zero-energy Majorana qubits are protected by spatial separation and the gap

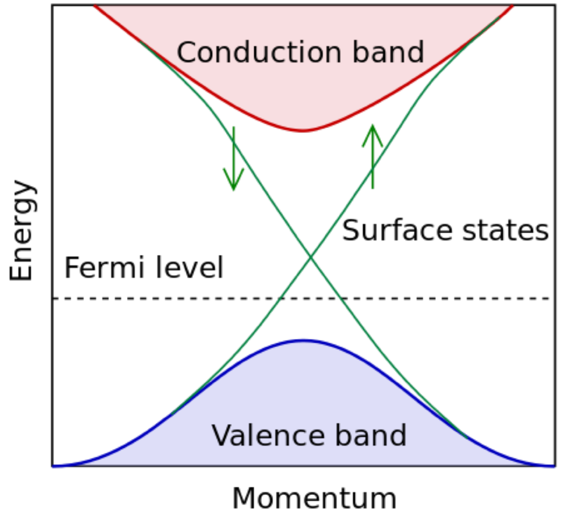
"The condition is satisfied … by proximity of a 3-dimensional p-wave superconductor"

"Physical realization … is a difficult task because electron spectra are usually degenerate with respect to spin…

Two difficulties: absence of spin degeneracy, presence of p-wave SC

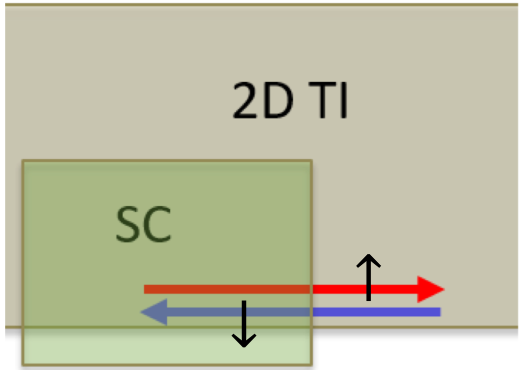
Creating Majorana from **Spin-Helical** Electrons

s-wave SC + spin-helical (instead of spin-polarized) electrons



Surface of TI:

- spin degeneracy removed
- opposite spins at k and –k; T-symmetry maintained



LF & Kane (2008)

Under π rotation $x \to -x$

- spinless: $c_k^+ c_{-k}^+ \to -c_k^+ c_{-k}^+$ p-wave
- spin-helical: $|\uparrow\rangle \to |\downarrow\rangle, |\downarrow\rangle \to -|\uparrow\rangle$ s-wave!

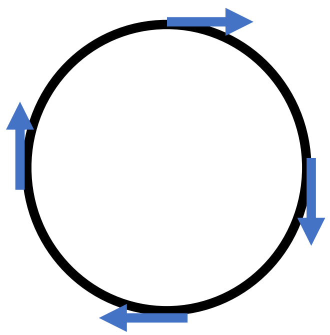
$$\Rightarrow c_{k\uparrow}^+ c_{-k\downarrow}^+ \to c_{k\uparrow}^+ c_{-k\downarrow}^+$$

(2π rotation on spin-1/2 gives -1)

Superconductivity in Topological Insulator

$$H_0 = \psi^\dagger(-iv\vec{\sigma}\cdot\nabla - \mu)\psi. \quad \Delta\psi_\uparrow^\dagger\psi_\downarrow^\dagger + h.c.$$

p-wave dispersion + s-wave pairing



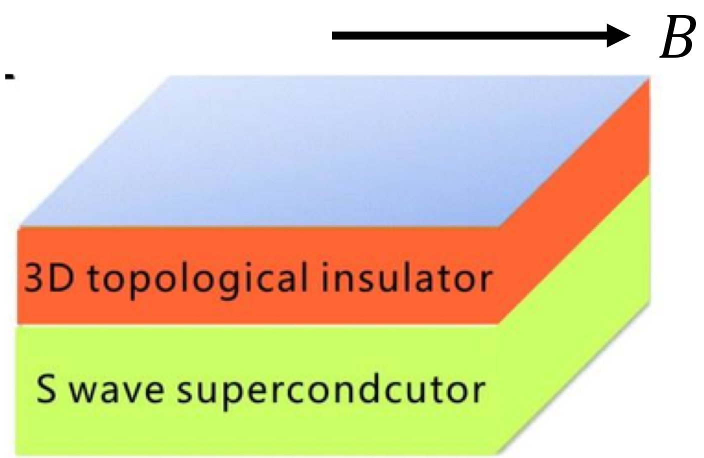
$$c_{\mathbf{k}} = (\psi_{\uparrow\mathbf{k}} + e^{i\theta_{\mathbf{k}}}\psi_{\downarrow\mathbf{k}})/\sqrt{2}$$

$$H_{\text{eff}} = \sum_k v c_{\boldsymbol{k}}^+(|\boldsymbol{k}| - k_F)c_{\boldsymbol{k}} + \Delta(e^{i\theta_{\boldsymbol{k}}}c_{\boldsymbol{k}}^+ c_{-\boldsymbol{k}}^+ + h.c)$$

resembles s-wave dispersion + p-wave pairing

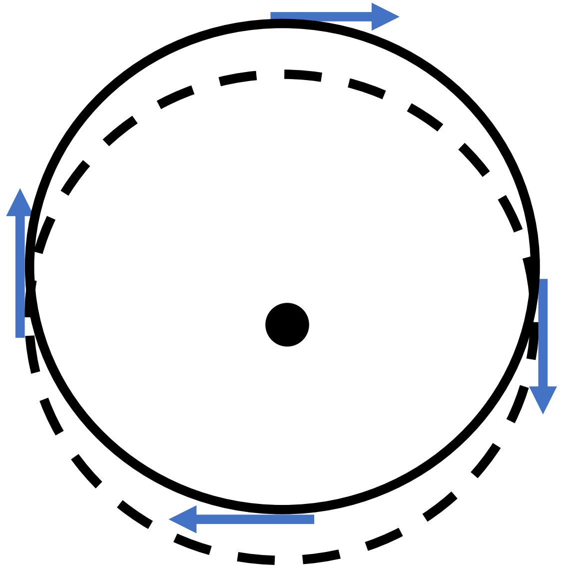
LF & Kane (2008)

Proximitized Topological Insulator under In-Plane B Field



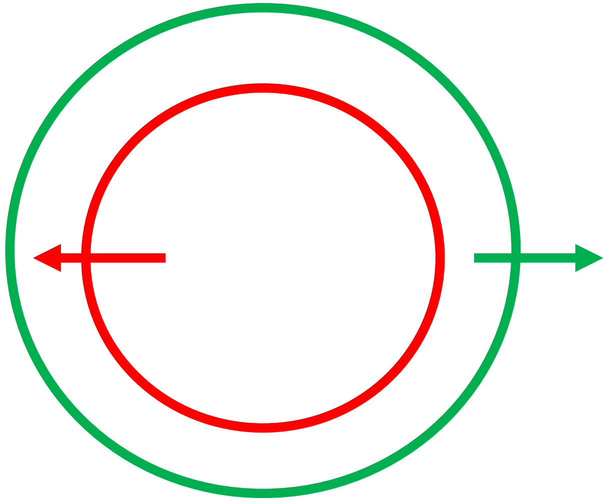
Noah Yuan & LF, PRB (2018)

Spin-Helical



Fermi surface shift in k space

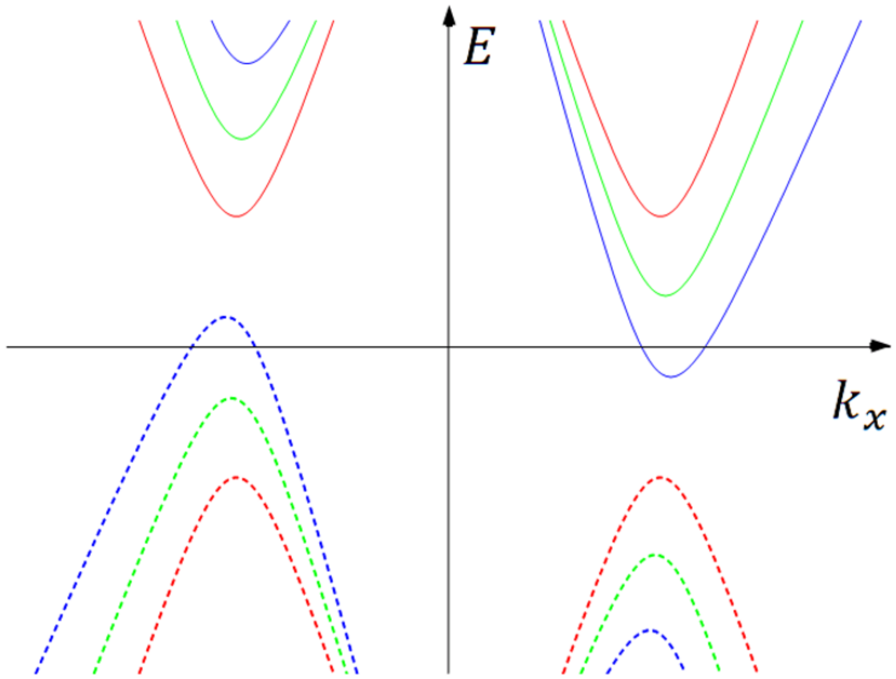
without SOC

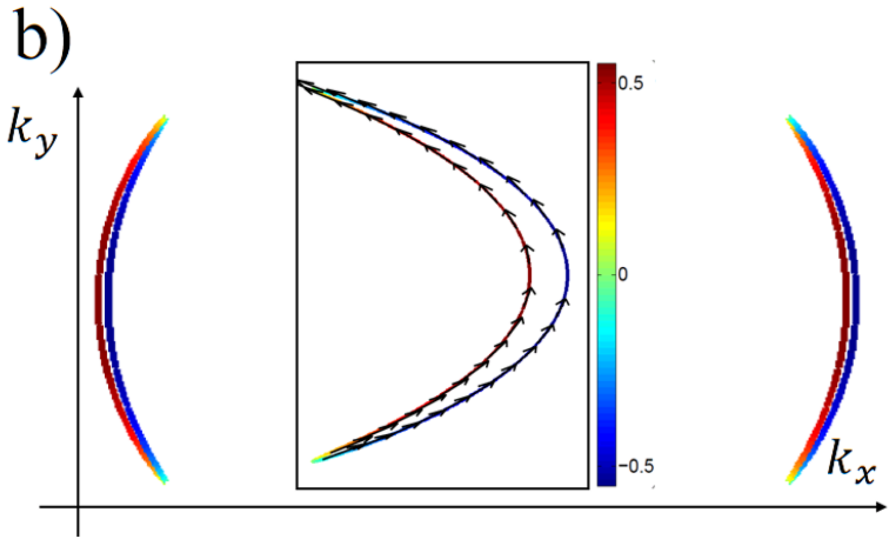


Spin splitting

- In-plane Zeeman field couples to spin-helical electrons as vector potential
- At finite $B<B_p$, the external conventional SC maintains Q=0 pairing

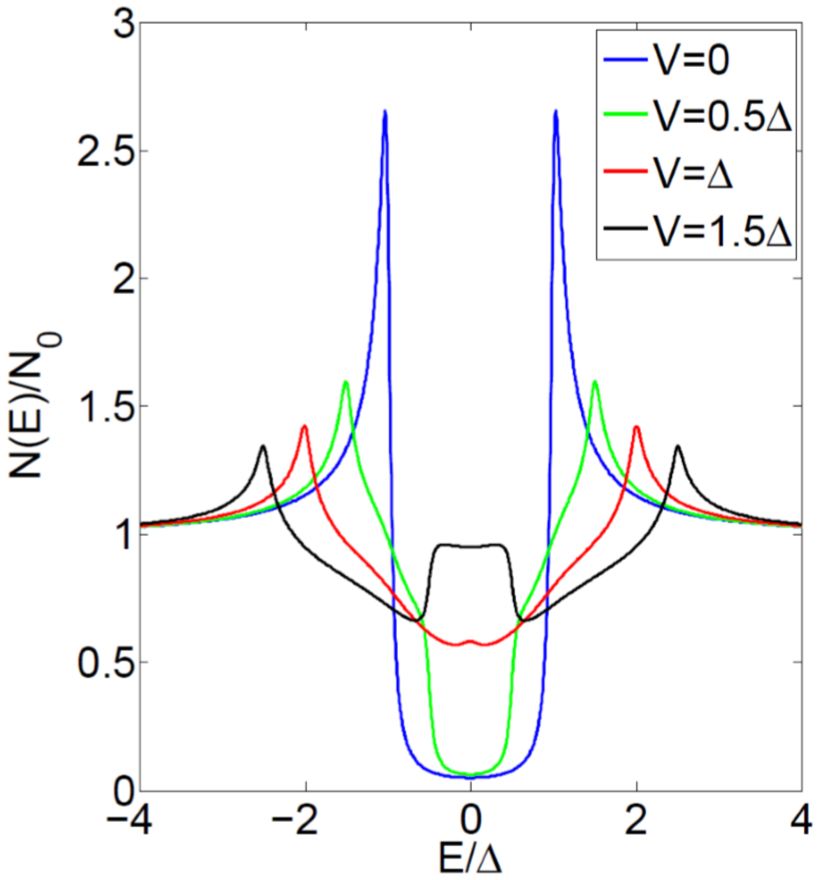
Partial Fermi Surface in Superconductor: FFLO Gap Structure at Q=0

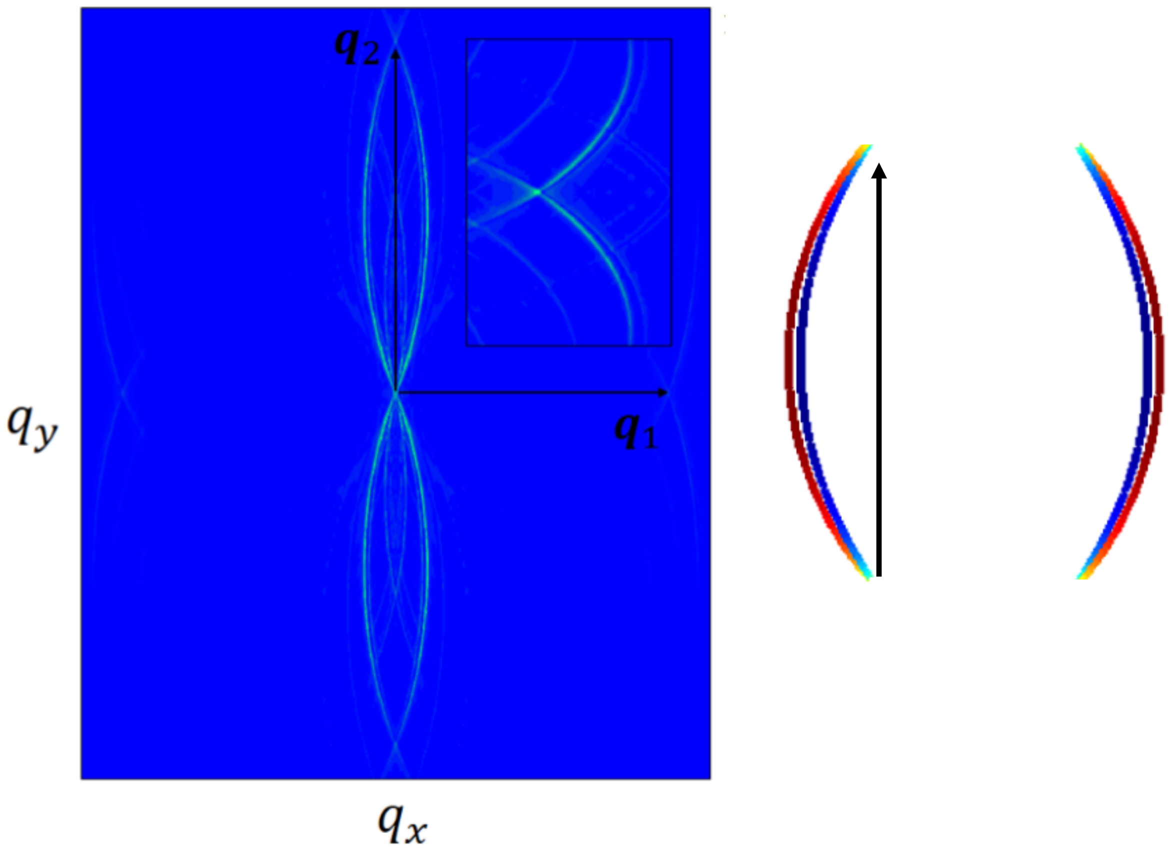




Depairing of helical electrons is strongly direction dependent.
At $B>B_0$, Fermi surface is partially gapped and partially gapless.
Gap structure is identical to FFLO SC at finite Q and ordinary SC with finite supercurrent

Quasiparticle DOS and Interference

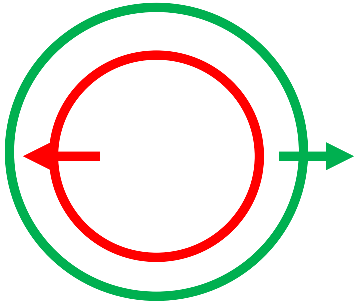


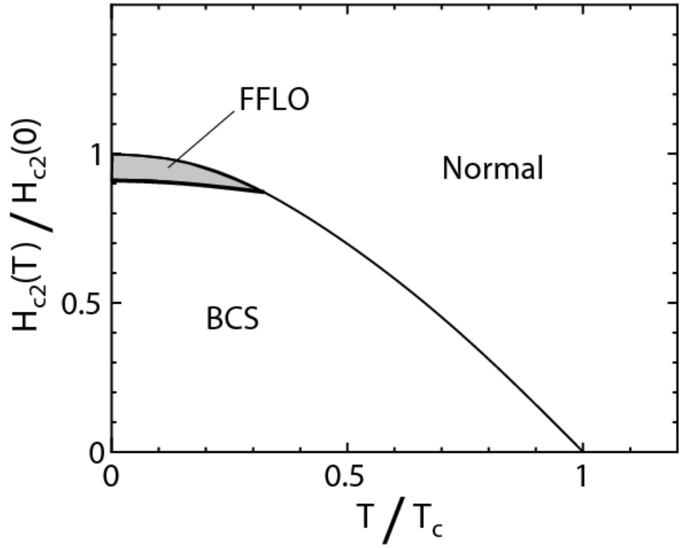


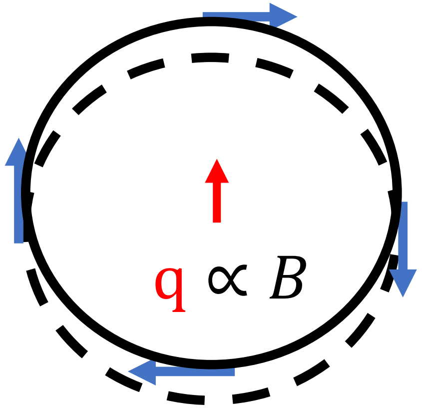
Coherence peak moves to higher energy under B !
In-gap states appear abruptly at B > B_0 (Lifshitz transition)

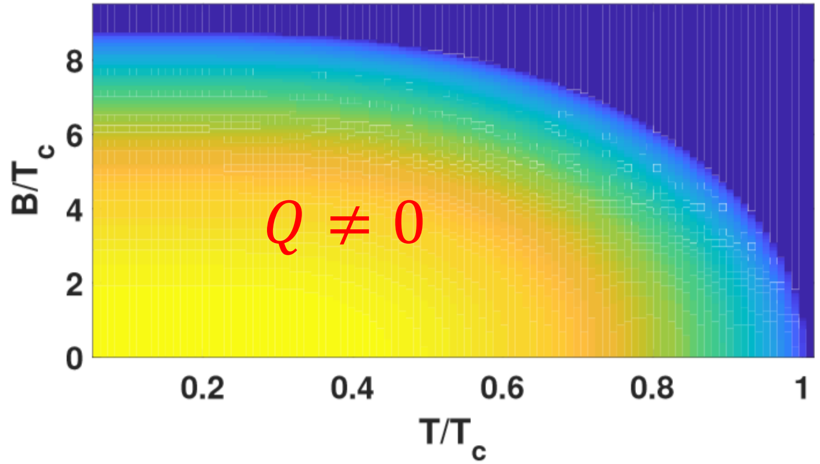
Noah Yuan & LF, PRB (2018) + in progress

Intrinsic Superconductivity of Helical Electrons under In-Plane B





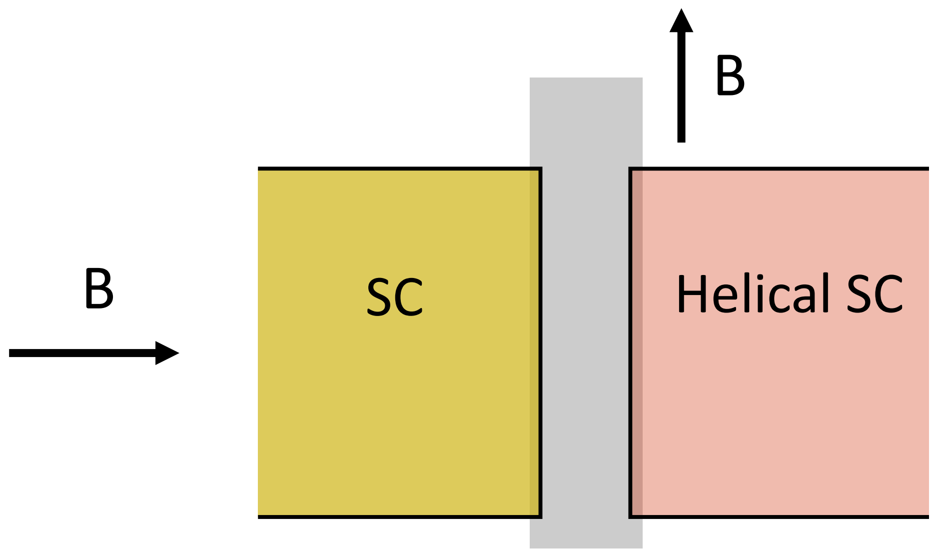




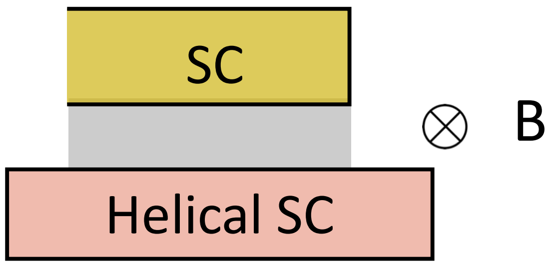
Finite momentum pairing **immediately** appears

Noah Yuan & LF, to appear

Detecting Finite-Momentum Pairing

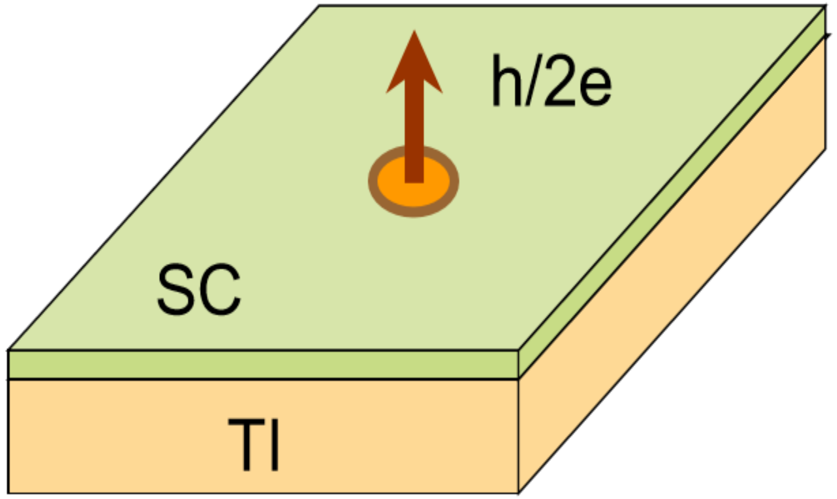


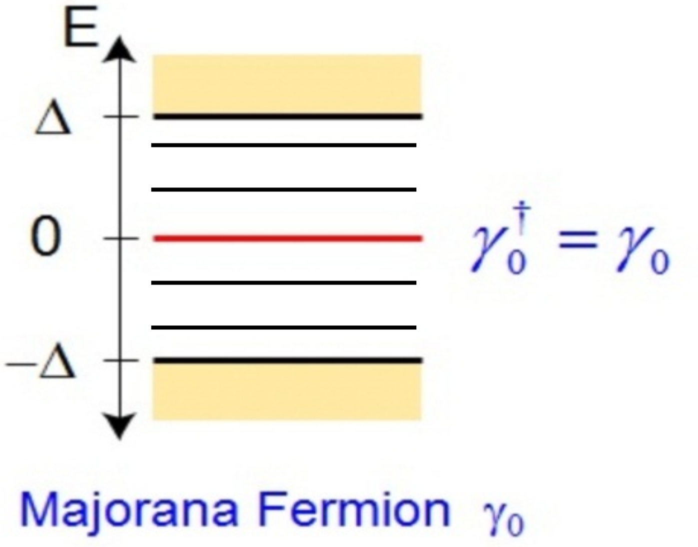
Cooper momentum and Josephson current depends on B and its orientation



Fraunhofer pattern has an anomalous period

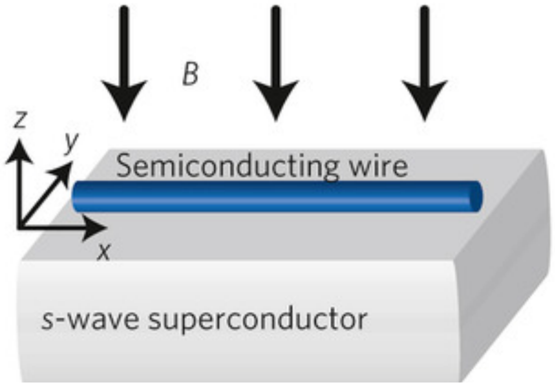
Majorana in Superconducting Topological Insulator

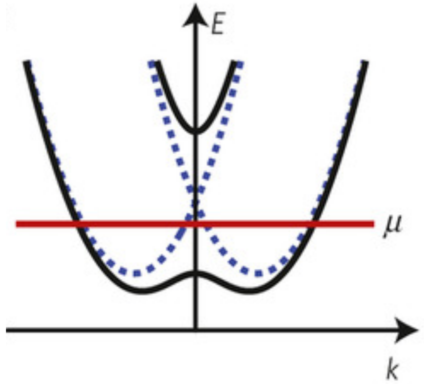




Minigap Δ^2/E_F for $E_F \gg \Delta$

Majorana Wire





Lutchyn, Sau & Das Sarma;
Oreg, von Oppen & Refael;
Potter & Lee … (since 2010)

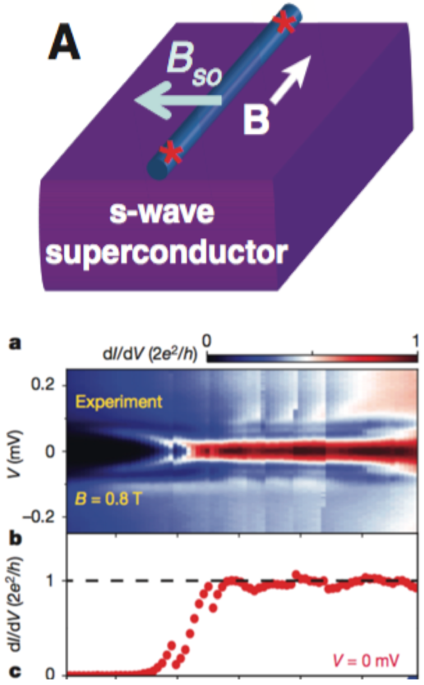
Spin-orbit-coupled nanowire under a magnetic field hosts spin-helical electrons when Fermi level is tuned into the Zeeman gap.

Platform for Majorana modes

#1: Intrinsic chiral *p*-wave (Order parameter) 2D *p*+*ip* TSC or 1D-Kitaev chain

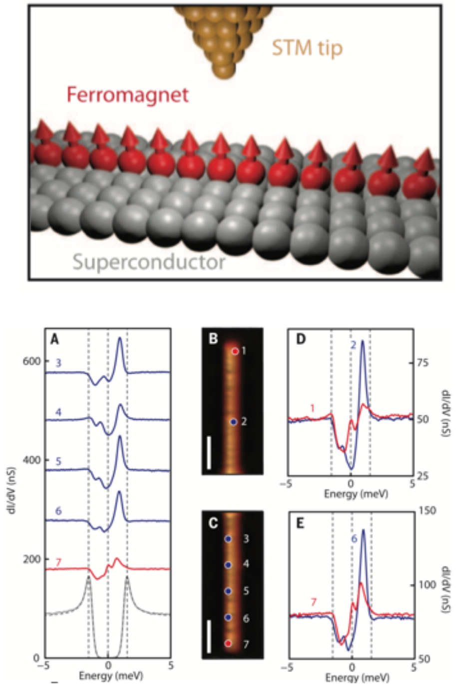
#2: Proximity effect (Single Dirac Fermi surface + full SC gap)

Nanowire / SC



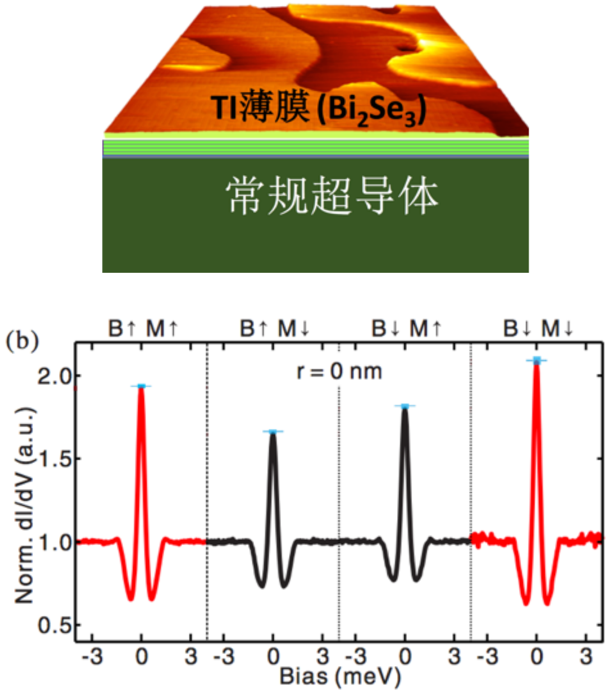
Delft, CPH and others

Atomic Chain / SC



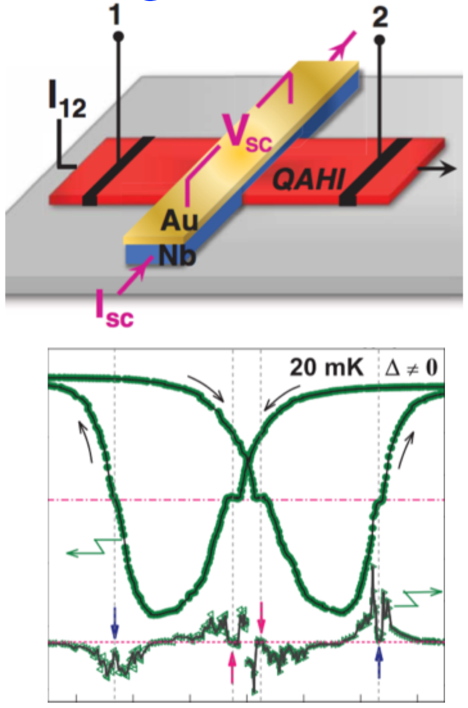
Princeton and others

TI / SC



Shanghai Jiao-Tong

QAHI / SC



UCLA and others

Common properties

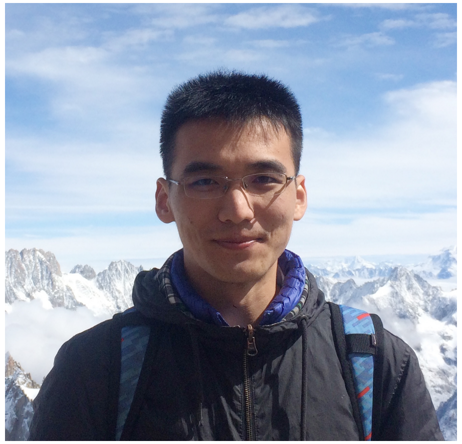
1. **Heterostructure**
2. **Ultra-low temperature**
3. **Small topological gap**

Majorana in Iron Superconductors

Institute of Physics, Beijing

Hong Ding

Hong-Jun Gao



Lingyuan Kong

+ Peng Fan, Dongfei Wang, Shiyu Zhu, Hui Chen, Lu Cao,
Wenyao Liu. Yujie Sun, Yuyang Zhang
Yuqing Xing, Fazhi Yang.

Brookhaven

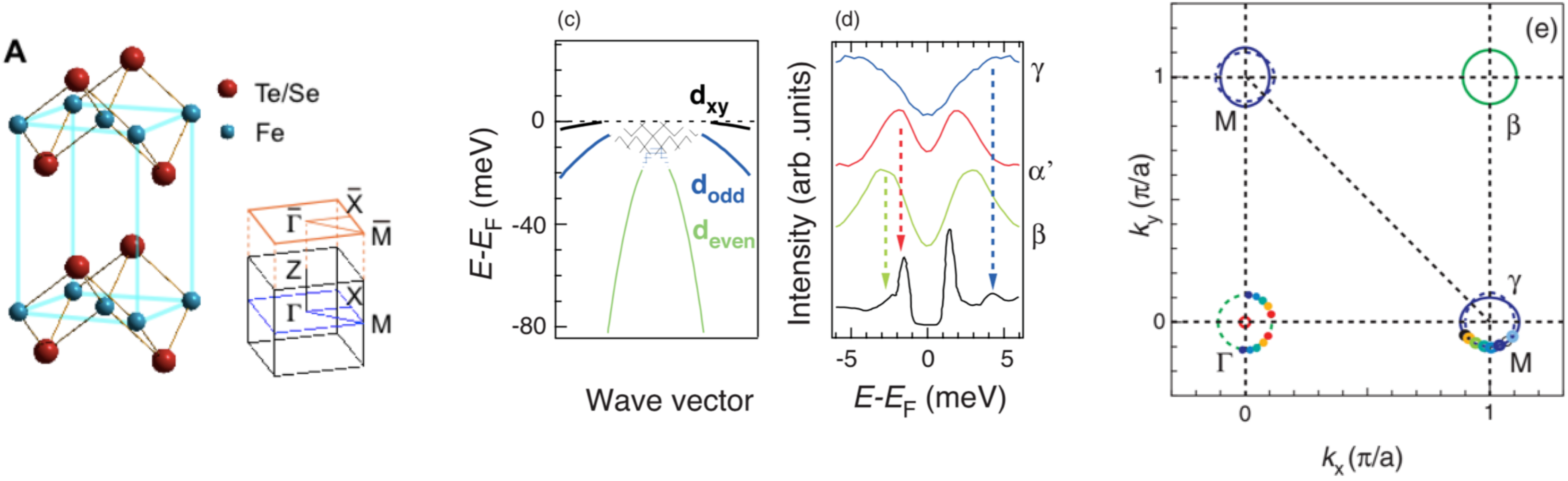
Genda Gu

+ John Schneeloch
Ruidan Zhong

MIT

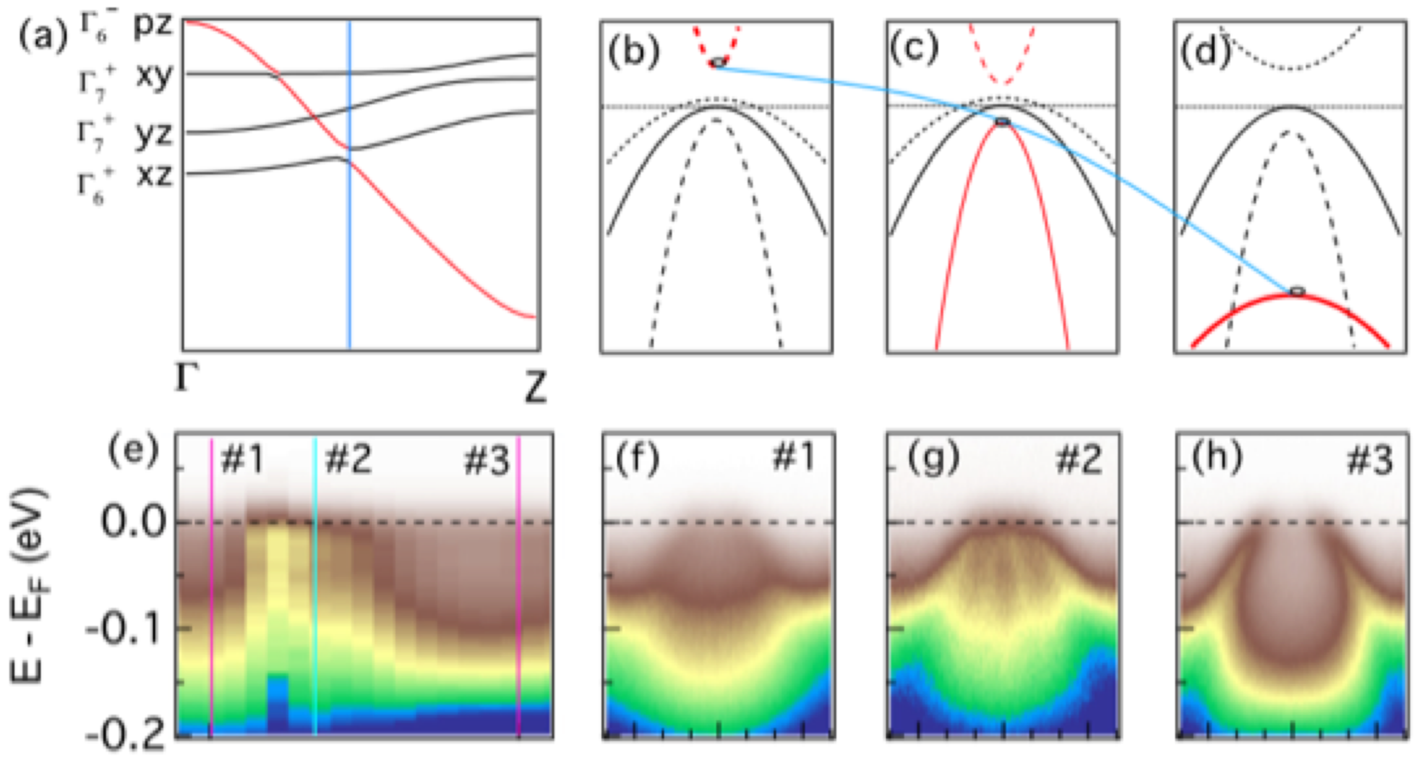
Michal Papaj

Fe(Te, Se): small E_F with large correlations



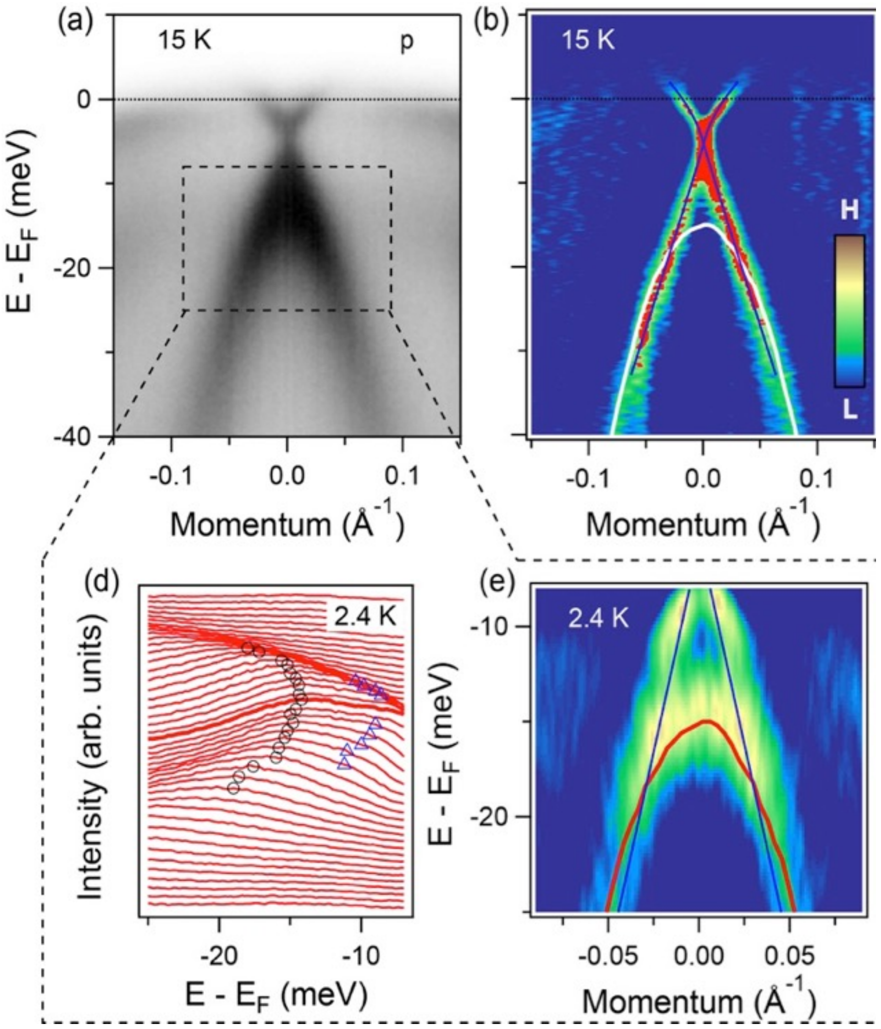
H. Miao et al., PRB 92, 1151119 (2012)

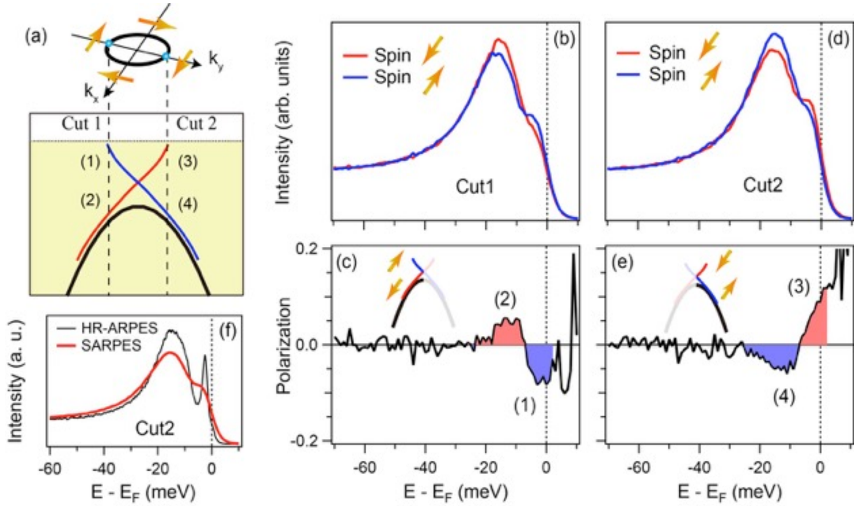
Band Inversion by Te/Se Composition

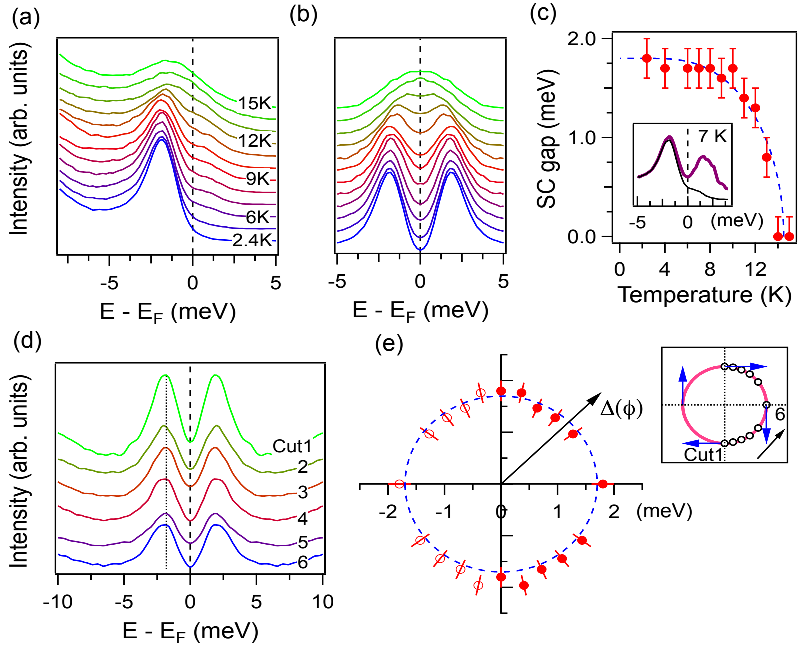


Z. J. Wang et al., PRB 92, 1151119 (2015)

Topological Surface States on $FeTe_{0.55}Se_{0.45}$

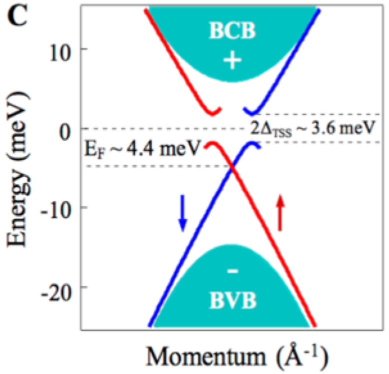






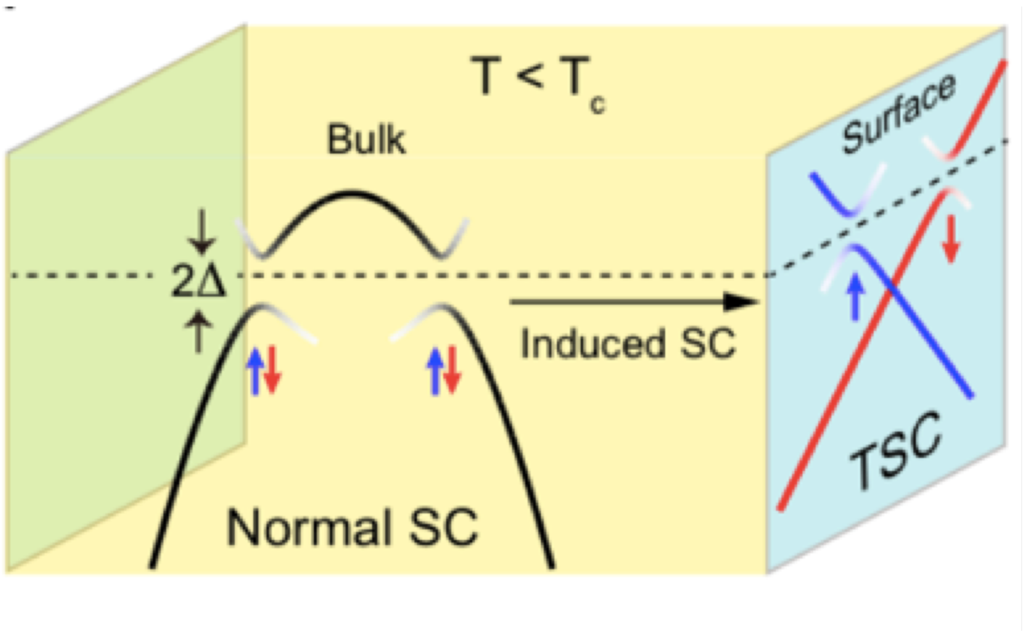
- **#1. Linear dispersion of surface states.**
- **#2. Spin-momentums locking.**
- **#3. s-wave SC gap on the surface states.**
- **Small Fermi energy comparable to SC gap**

C



P. Zhang et al., Science 360, 182 (2018)
(IOP + ISSP +Brookhaven)

Fe(Te,Se): Nature's Gift



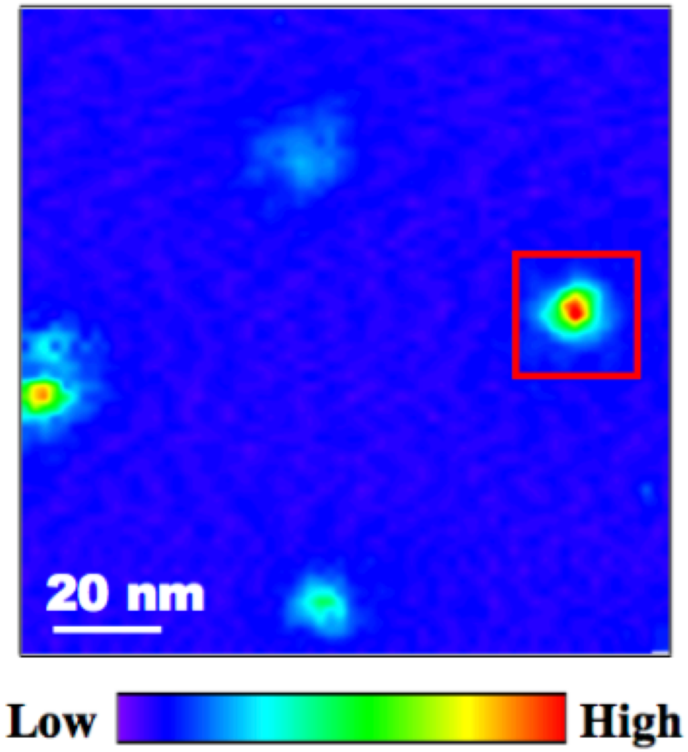
S-wave + spin-helical

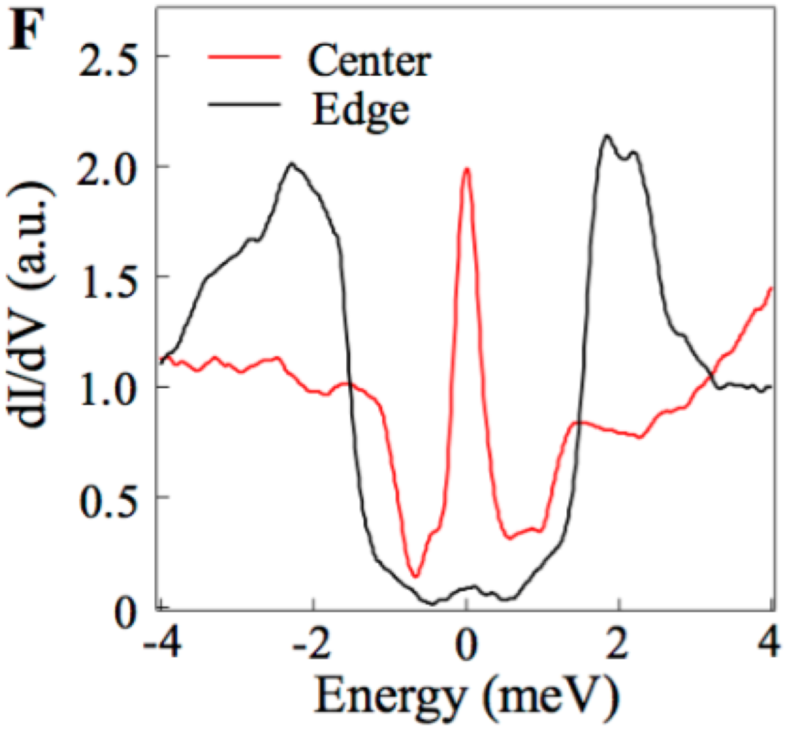
High-T_C SC

Small E_F, Large gap

Single Material

Zero-bias conductance Peak

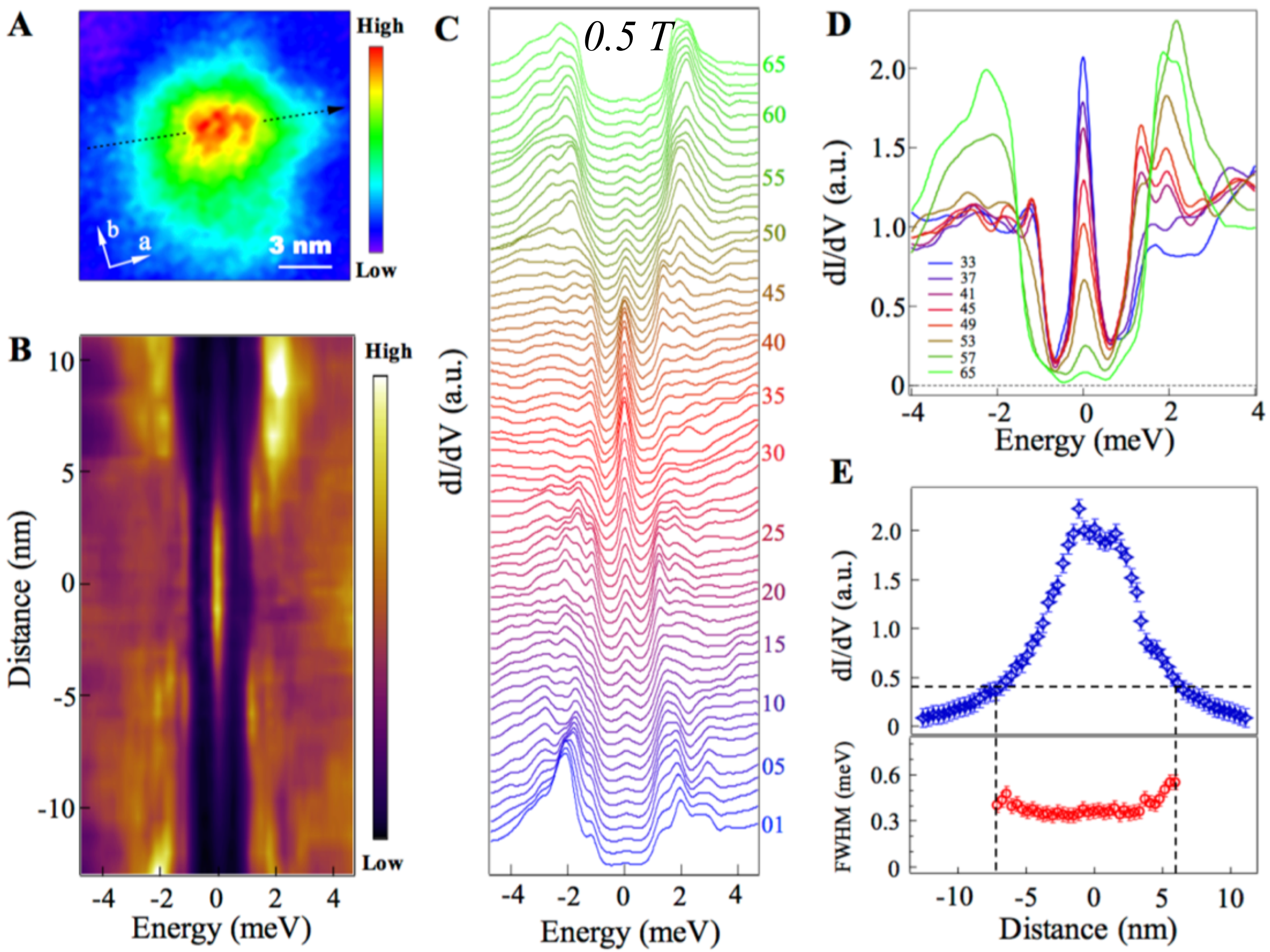




Science **362,** 333 (2018)

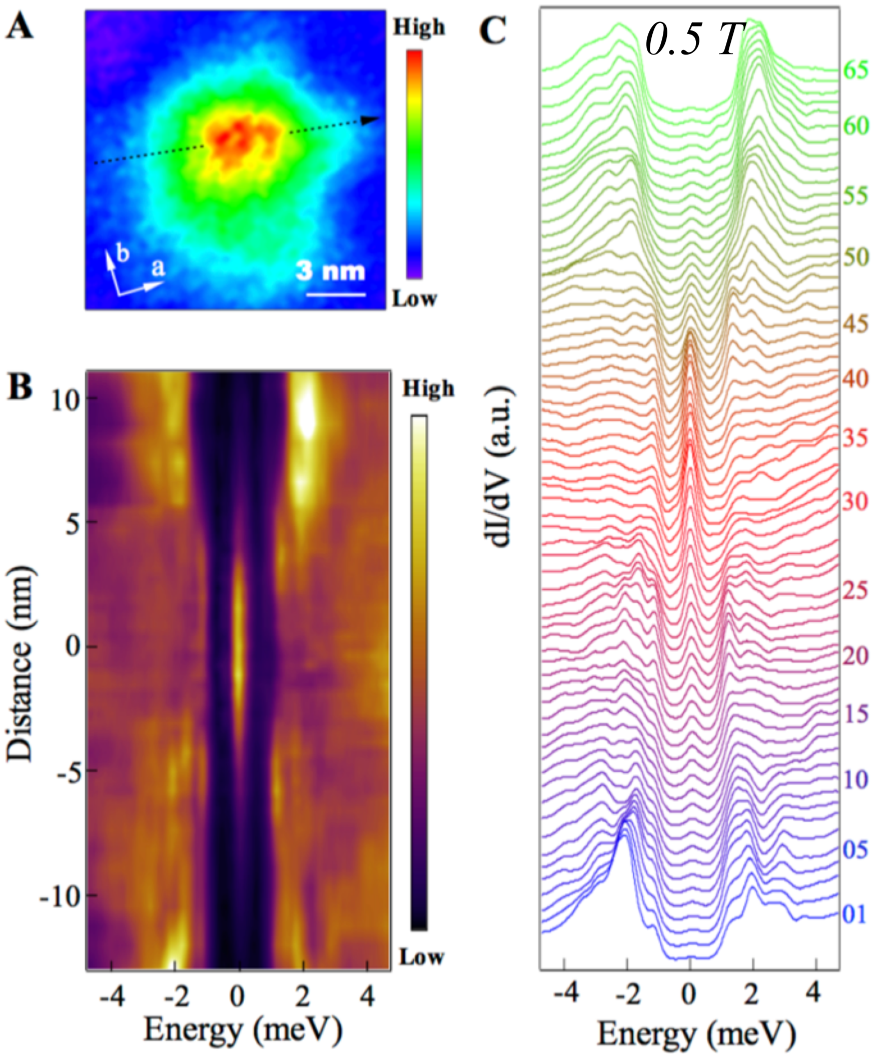
Spatial Line Profile

➢ ***Majorana: Non-split spatial dispersion (Pure)***



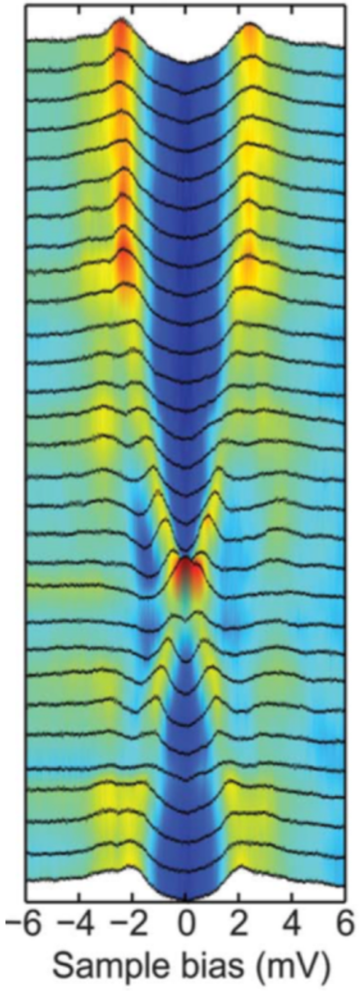
Spatial Line Profile

➢ *Majorana: Non-split spatial dispersion (Pure)*



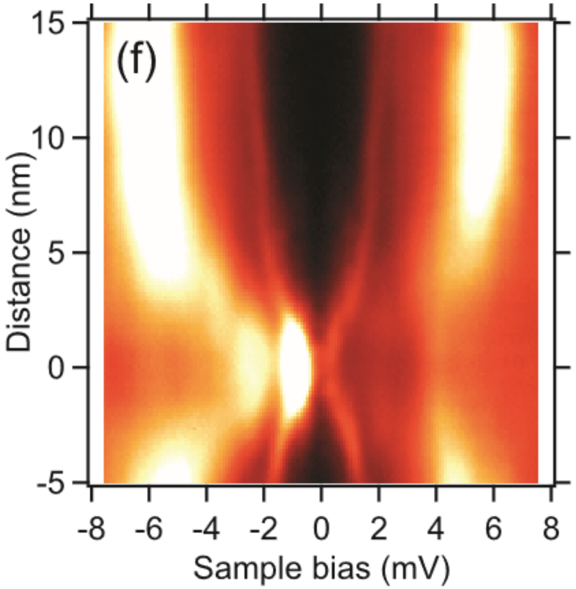
➢ *CdGM split*

FeSe



Science 332,1410

LiFeAs



Hanaguri et al (2012)

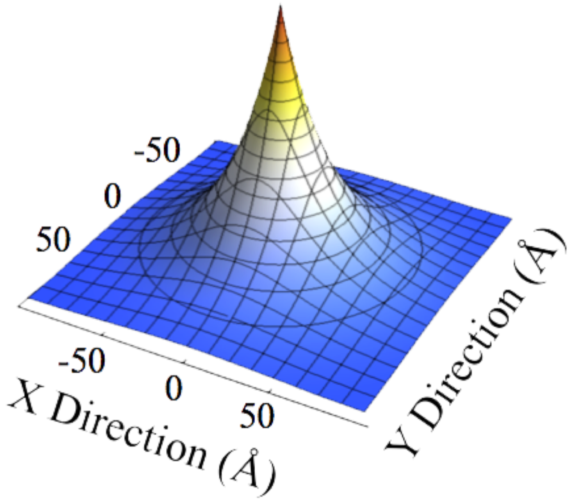
Majorana Bound State Wavefunction

Majorana Wavefunction Calculation

$$|u|^2 = |f(r)|^2 + |g(r)|^2$$

$$f(r) = J_0\left(\tfrac{E_F r}{v_F}\right)\exp\left[-\int^r \tfrac{\Delta(r')}{v_F}dr'\right](i+1)$$

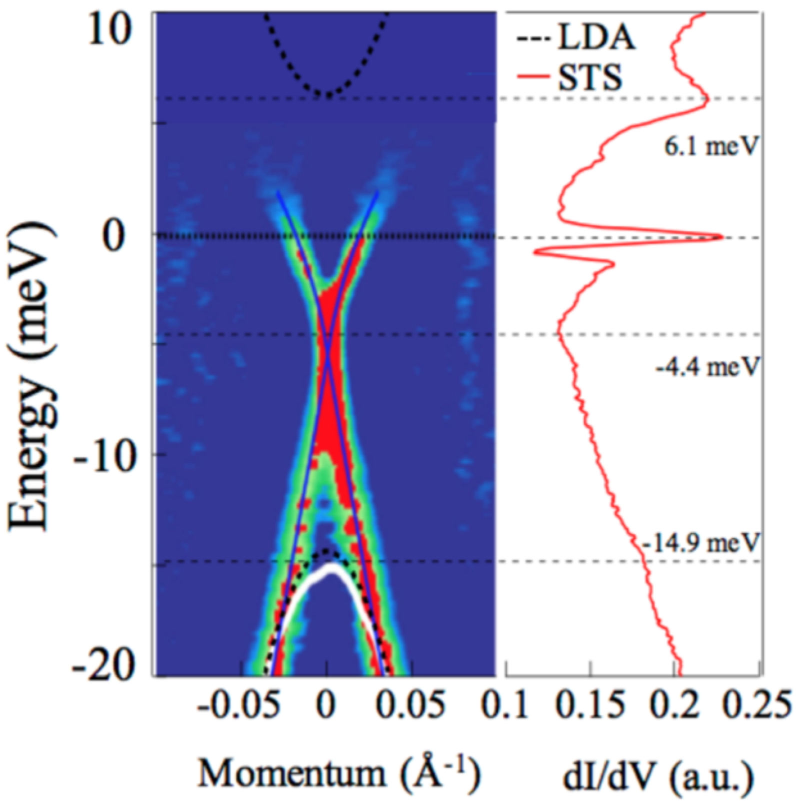
$$g(r) = J_1\left(\tfrac{E_F r}{v_F}\right)\exp\left[-\int^r \tfrac{\Delta(r')}{v_F}dr'\right](i-1)$$



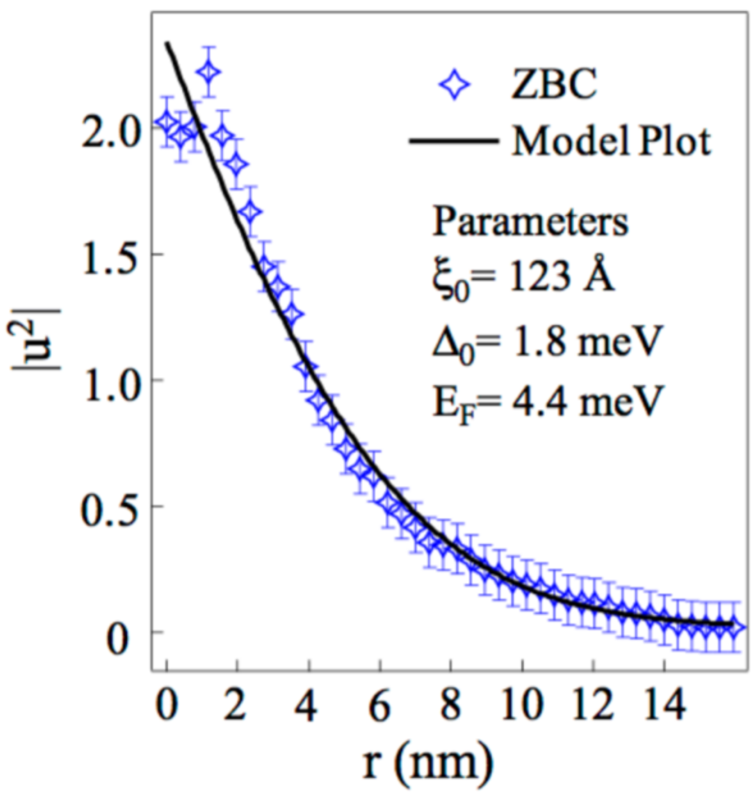
Fu & Kane PRL 100, 096407 (2008)
Wang & Fu PRL 119, 187003 (2017)
Hughes et.al., PRB (2011)

Weak tunneling regime: $\Gamma \ll k_B T$

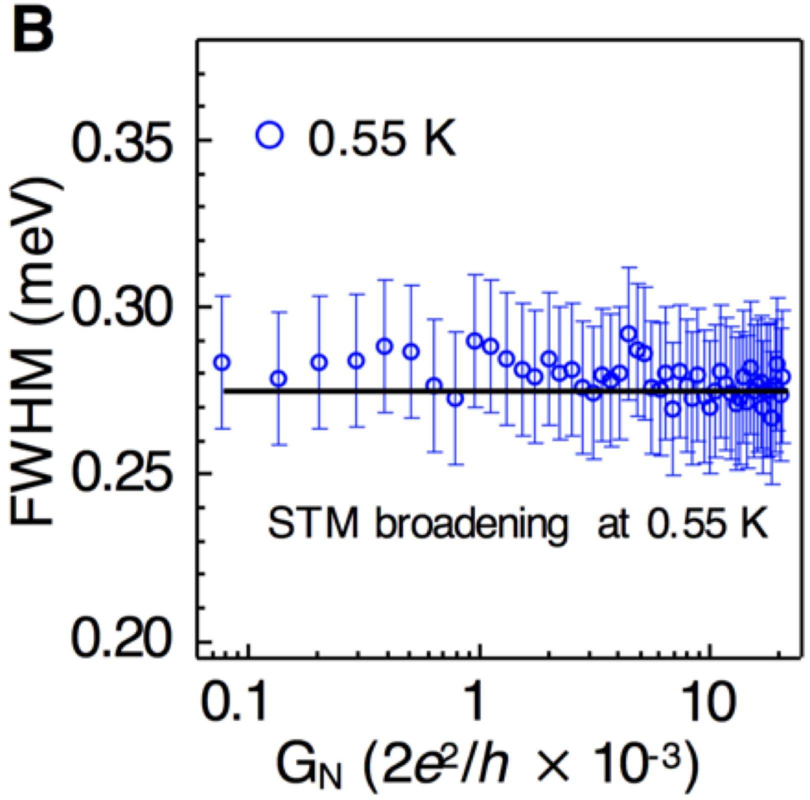
$$\frac{dI}{dV} \propto |u|^2$$



No Fitting Parameters



Linewidth



$$SysWidth = \sqrt{(0.23^2)_{STM} + (0.16^2)_{Tem}}$$
$$= 0.28 meV$$

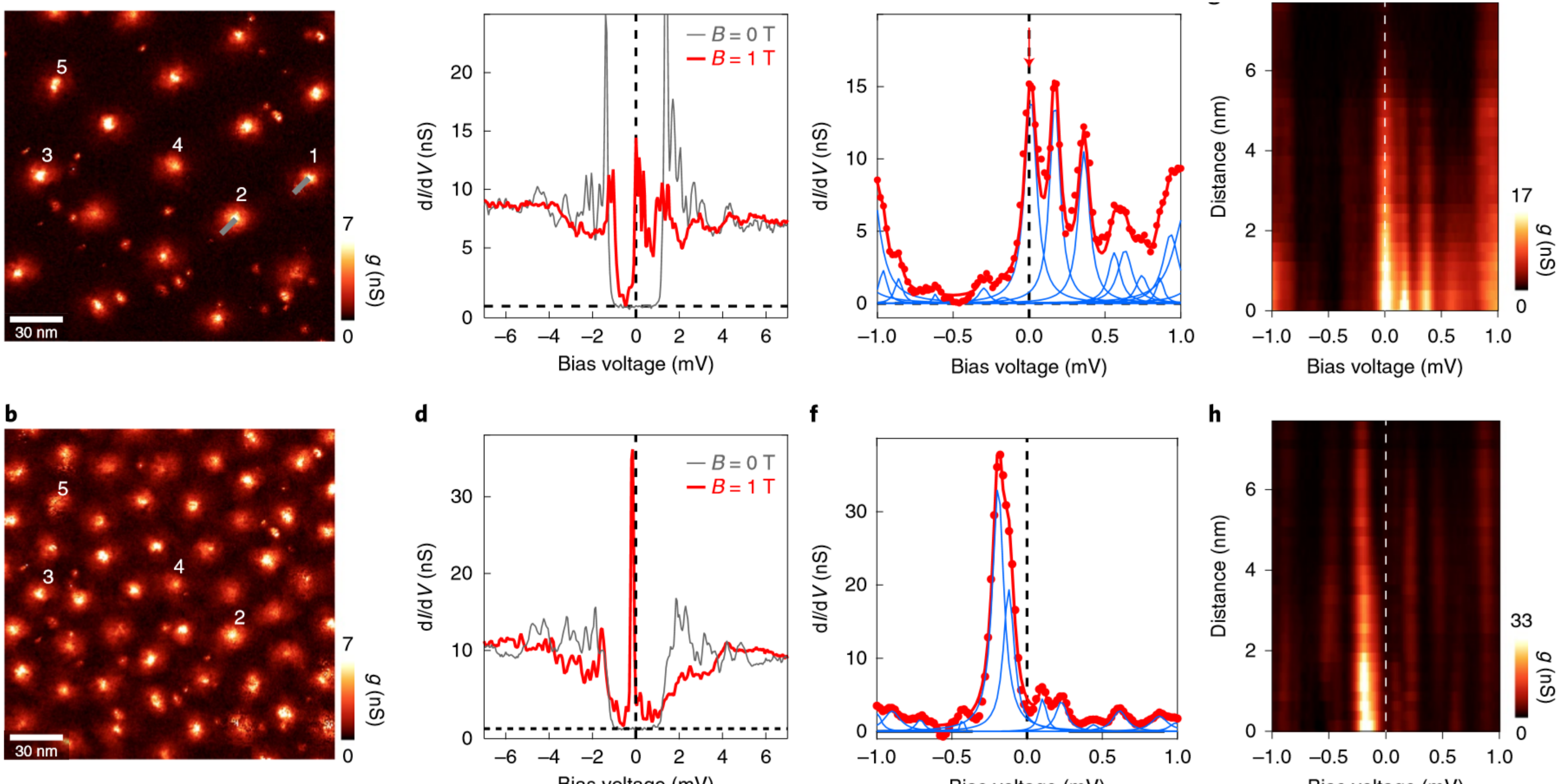
- FWHM of ZBP ***approaches resolution limit*** in good cases.
- In bad cases extra broadening related to quasiparticle poisoning

Topological and Ordinary Vortex

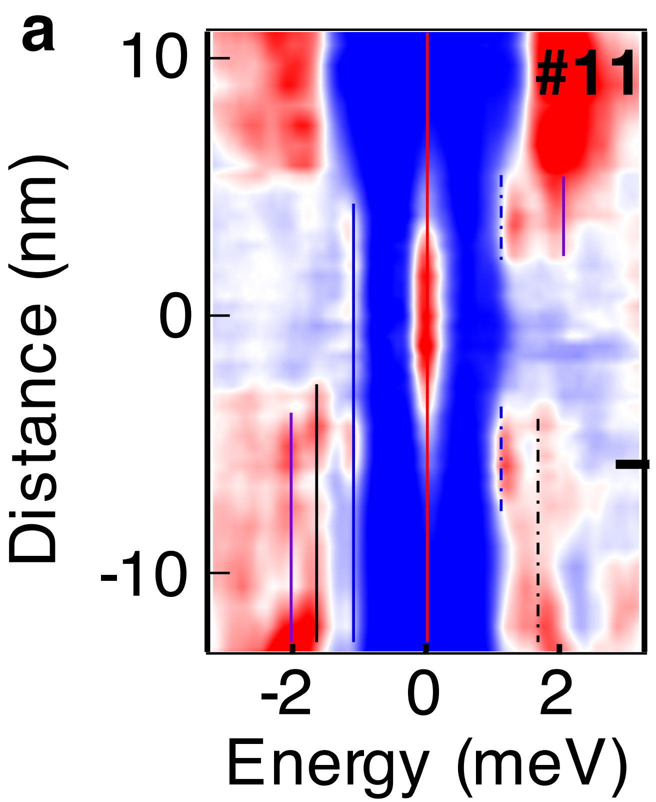
T_{eff} ≈ 85 mK, ultrahigh energy resolution of ~20 μeV.

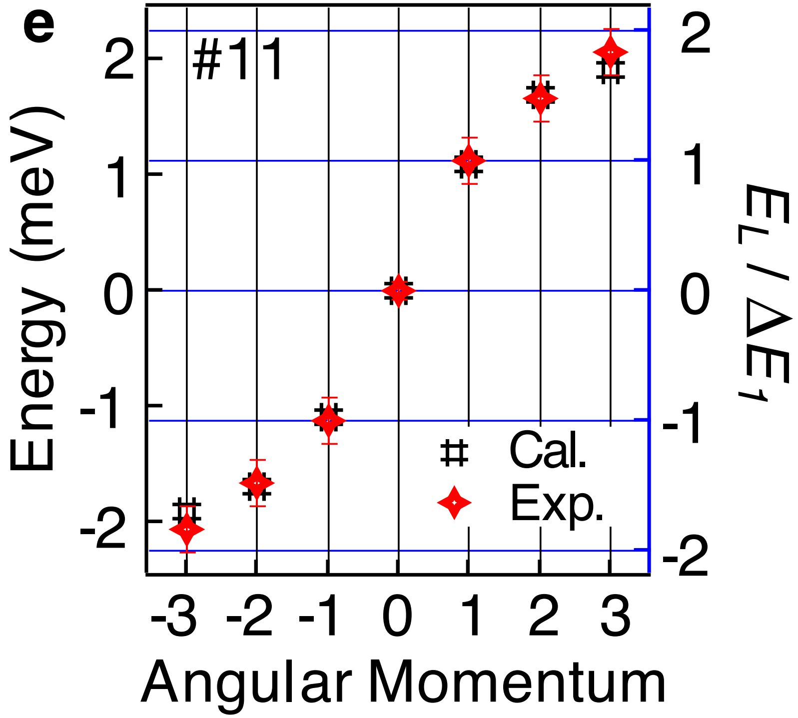
Hanaguri et.al., Nat. Mat (2019)

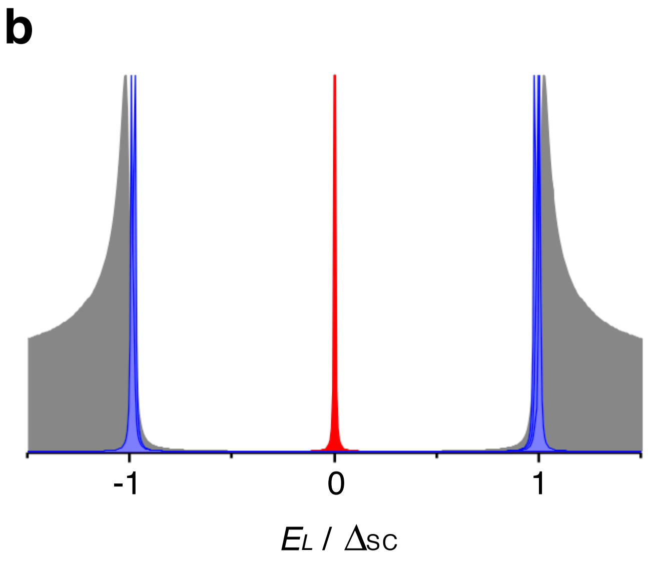
"80% and 40% of the vortices host the ZVBS (peak energy |E| < 20 μeV) at B = 1 and 3 T, respectively"



To approach the 'sweet spot': zero-doping limit

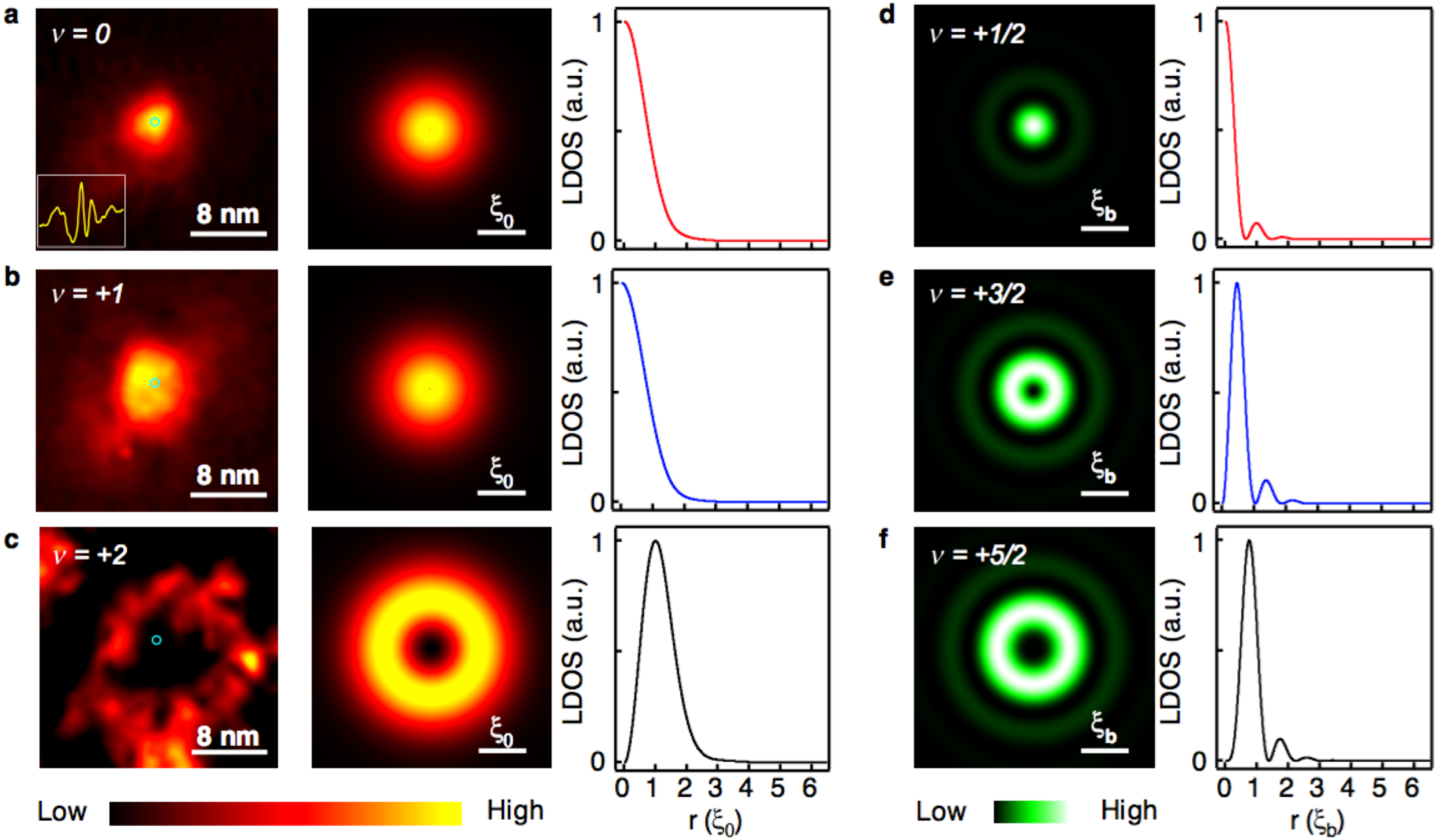


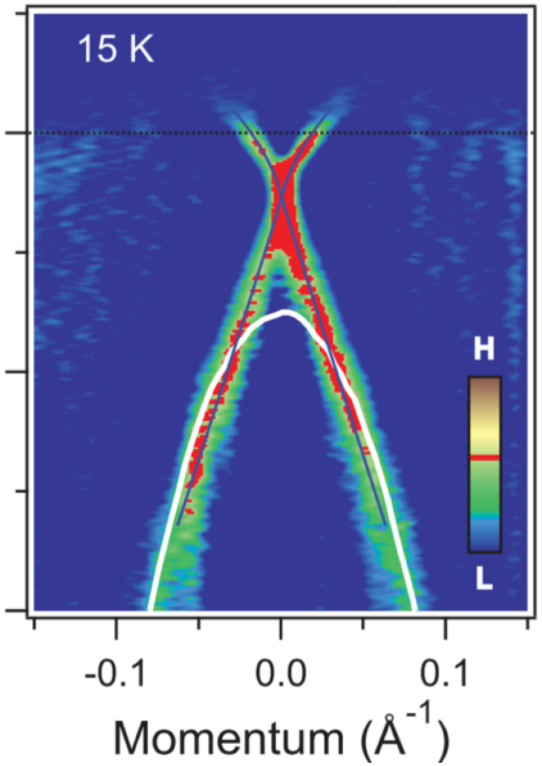




Kong et al, *Nature Physics* (2019).

Spatial pattern of topological vortices



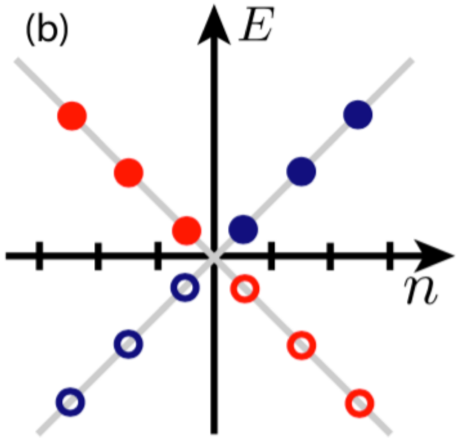


$k_F \sim 1/R \sim 0.014\ A^{-1}$

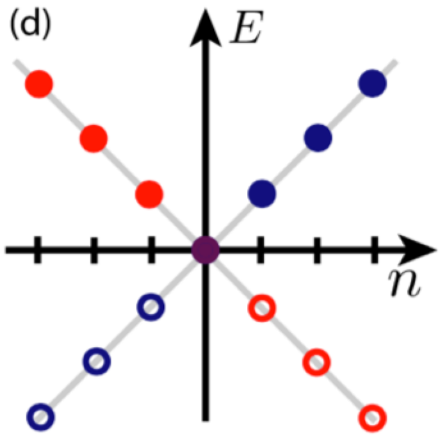
Ultra-small k_F of TSS enables directly observation of spatial pattern of vortex bound states

Half-integer level shift by Dirac surface state

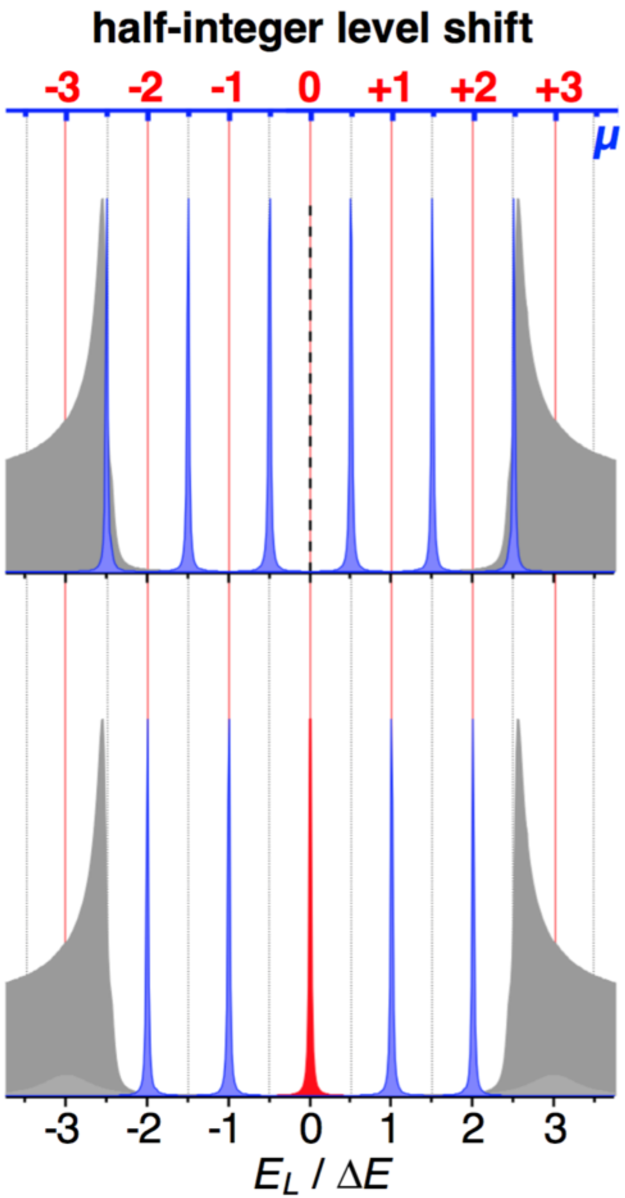
Ordinary vortex



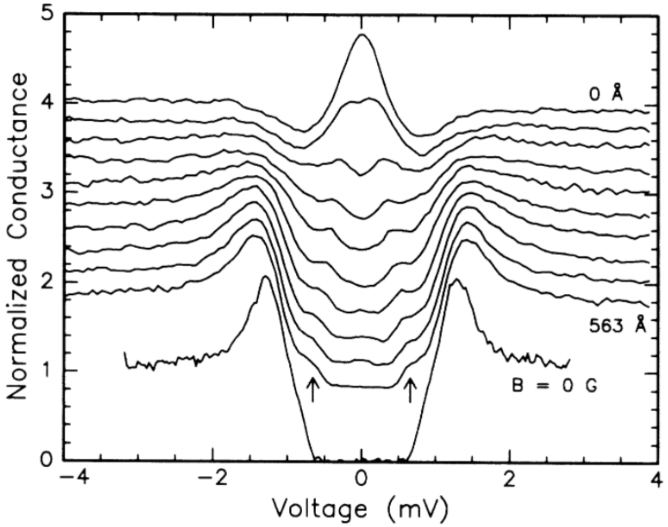
Topological vortex



Additional π flux from Dirac surface states

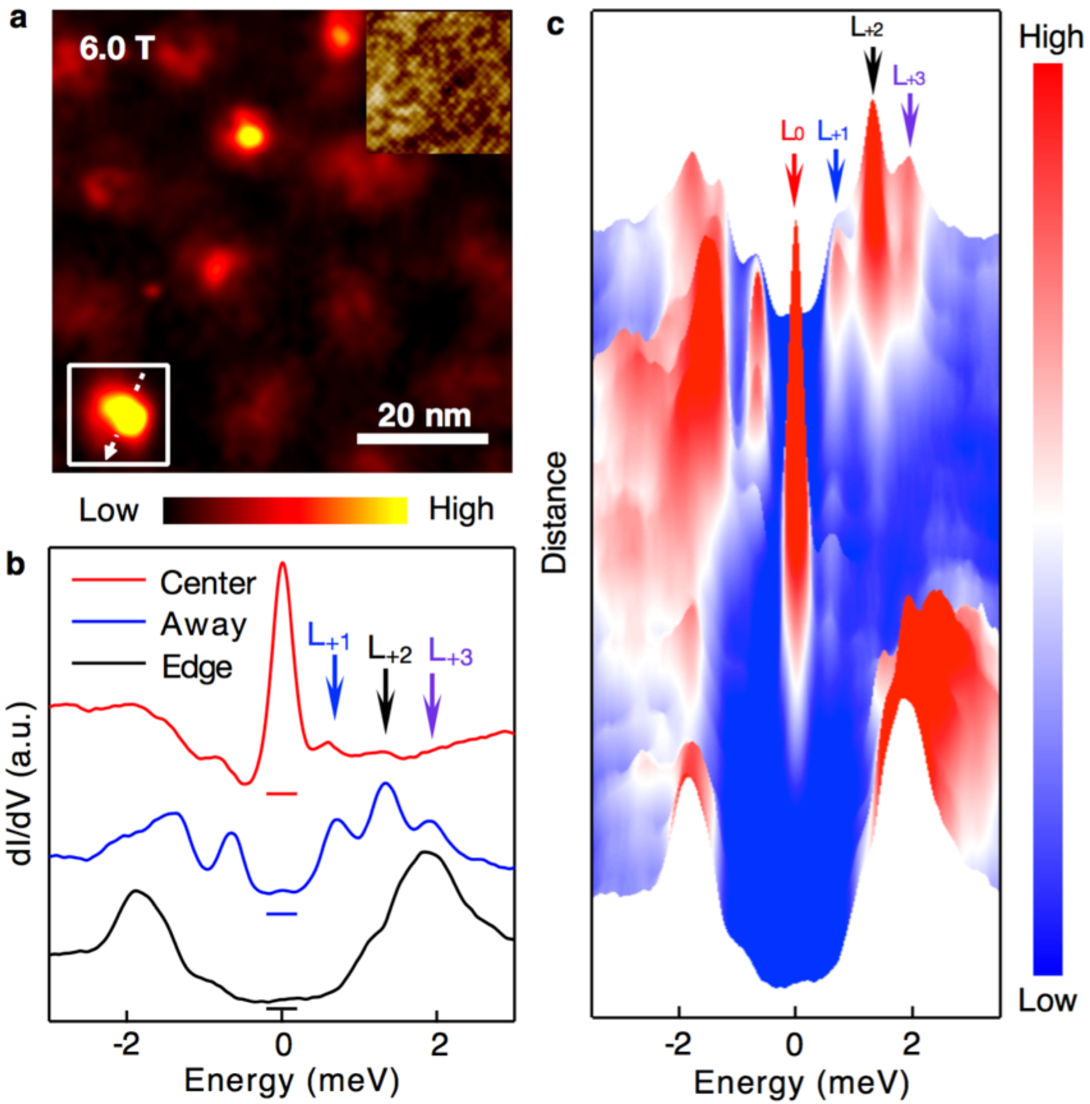


Quantum-limit vortex bound states



NbSe2: Hess et al (1990)

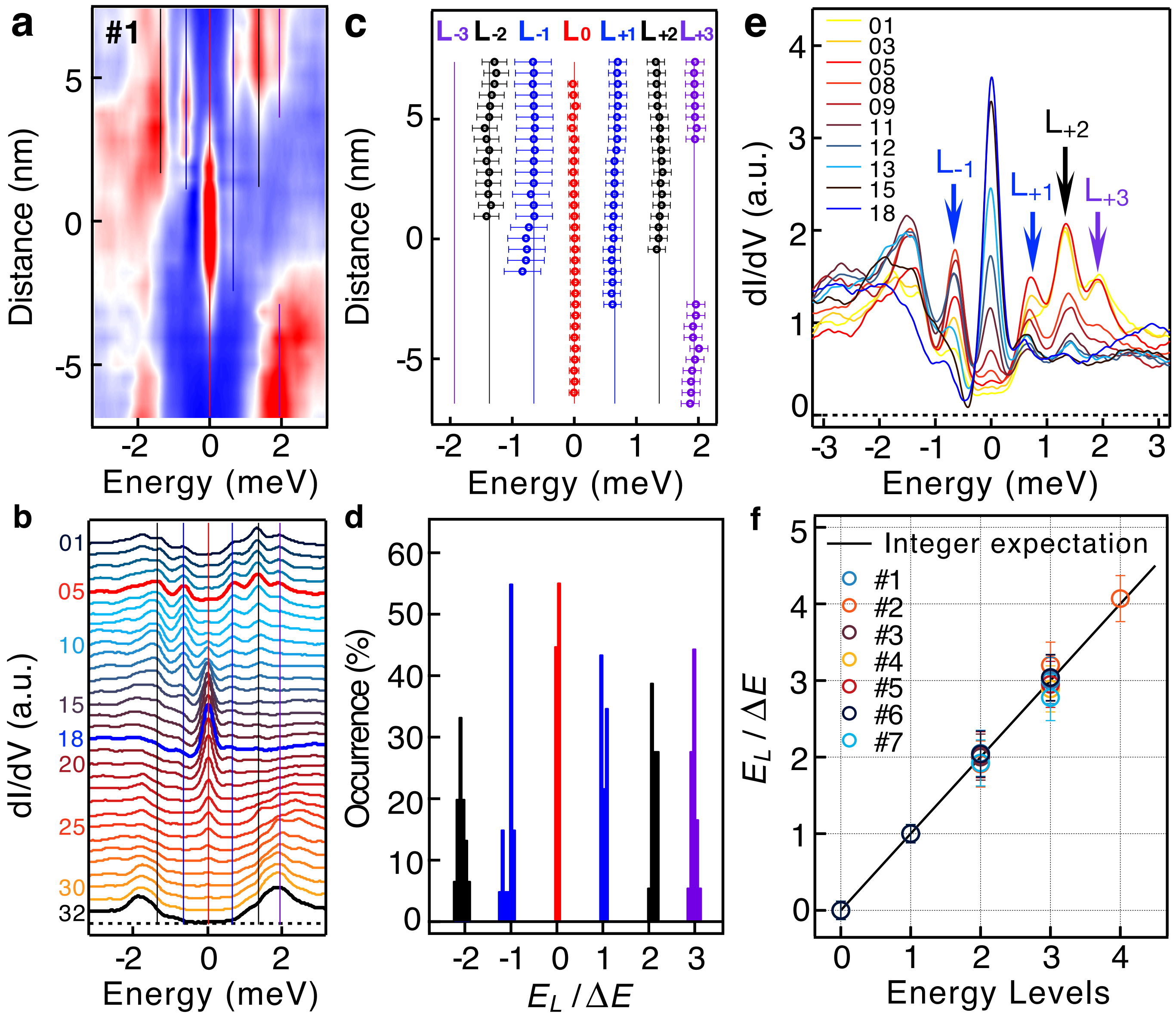
Fe(Te,Se) satisfies quantum limit in our experiments



Parameters on Fe(Te, Se)

T_{exp}= 0.4 K	Δ (meV)	E_F (meV)	T_{QL} (K)
TSS	1.8	4.4	5.9
Γ (bulk)	2.5	5 ~ 30	1.2 ~ 7.25
M(bulk)	4.2	15 ~ 40	1.5 ~ 4.1

Topological vortices and integer quantized CdGM states

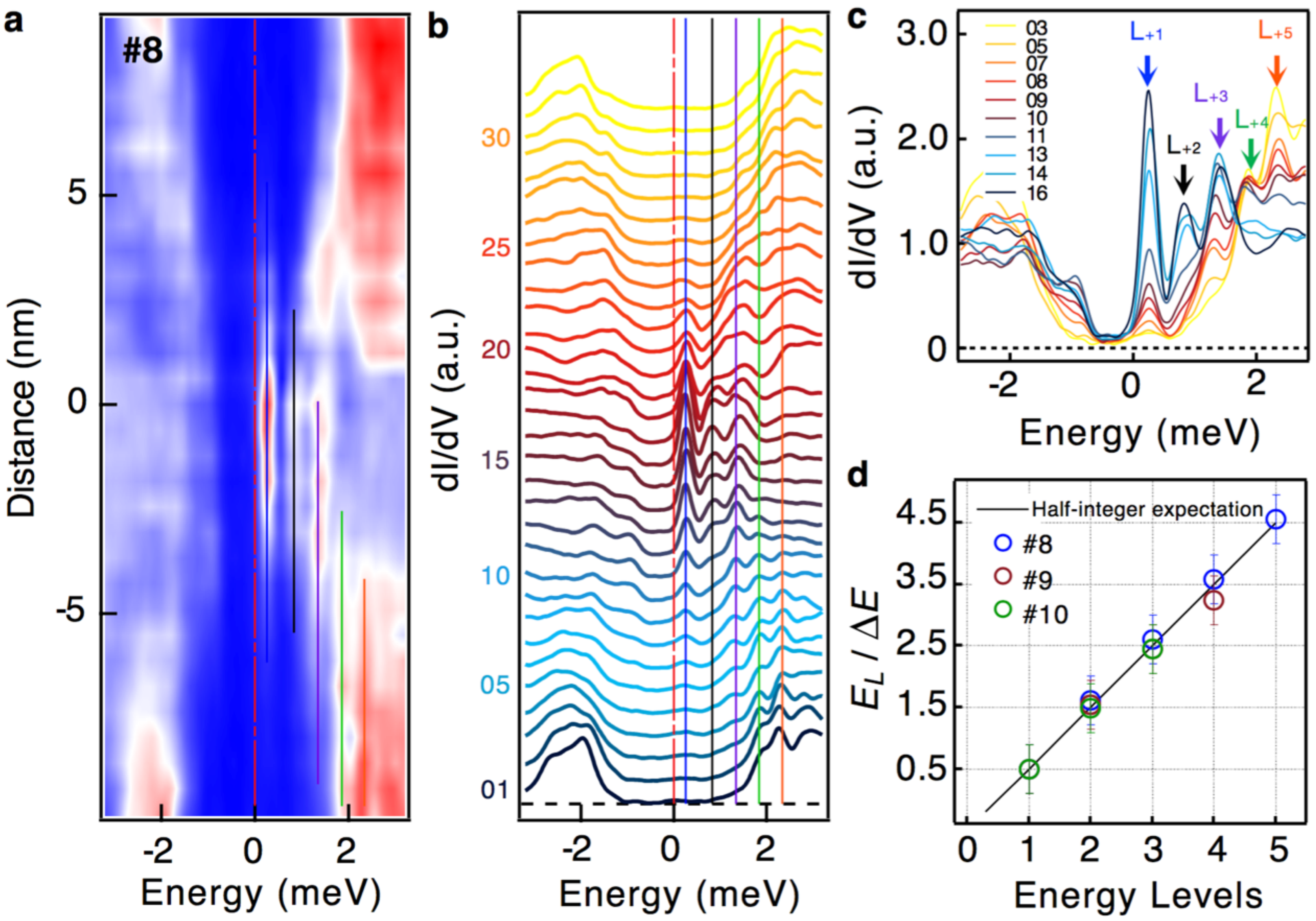


#1_6.0 T
Sample#1_STM#2

	E_L(meV)	$E_L / \Delta E$
E_0	0	0
E_1	0.65	1.00
E_2	1.37	2.11
E_3	1.93	2.97

MBS is the 0th level of the integer-quantized CdGM states

Ordinary vortices: half-odd-integer quantized CdGM states



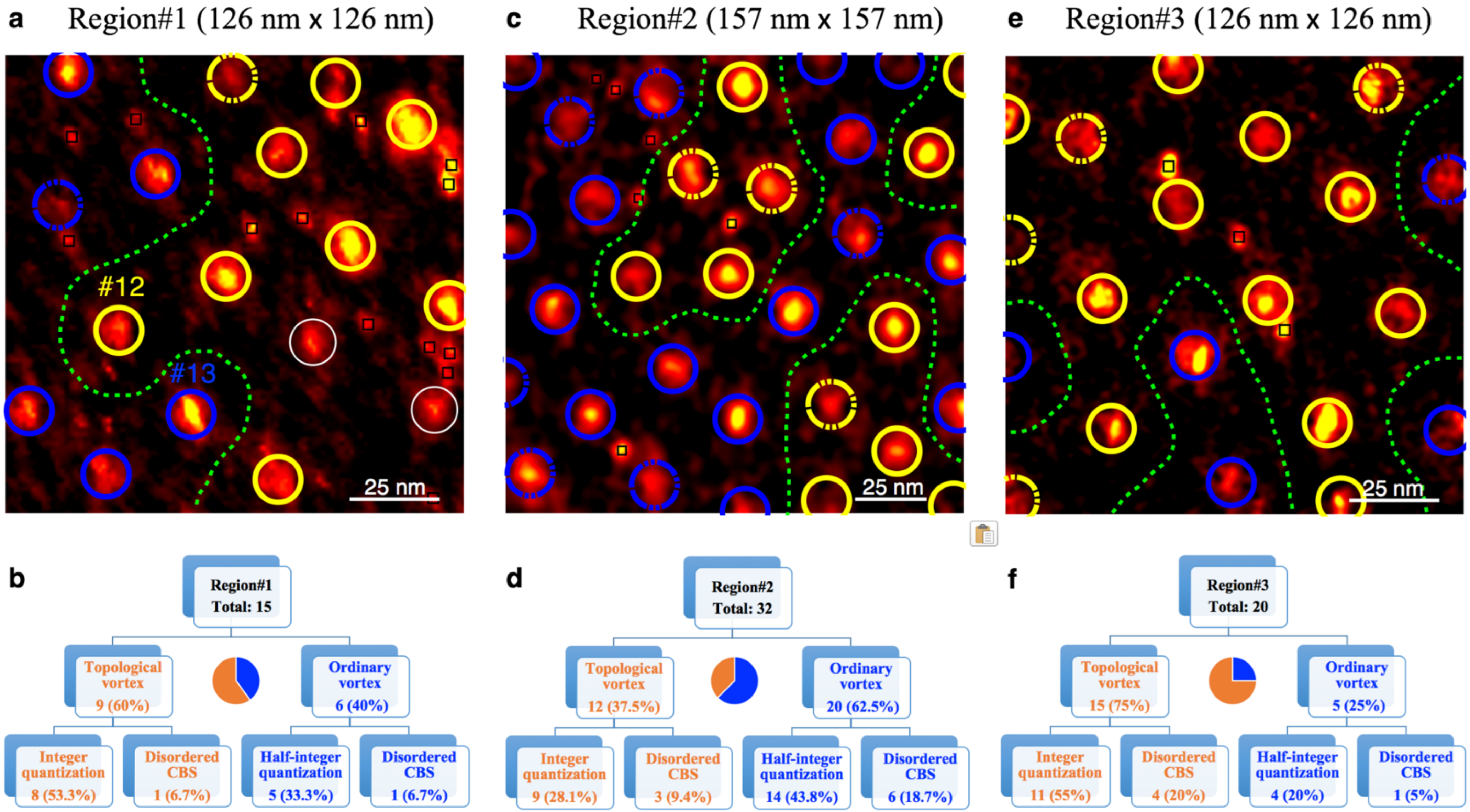
b

#8_2.0 T

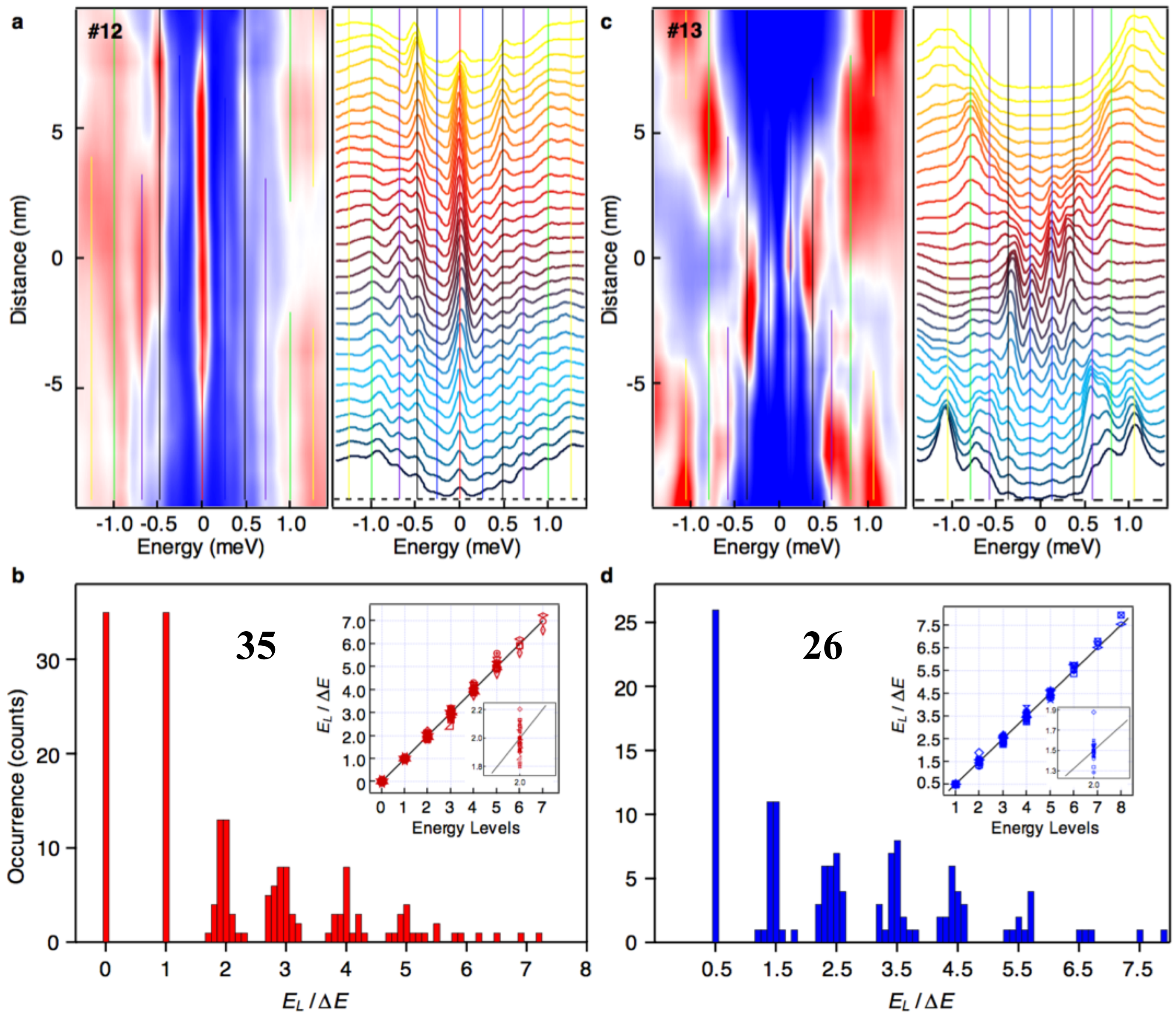
Sample#3_STM#2

	E_L (meV)	$E_L/\Delta E$
E_1	0.26	0.50
E_2	0.83	1.60
E_3	1.34	2.58
E_4	1.84	3.54
E_5	2.34	4.5

Vortex statistics

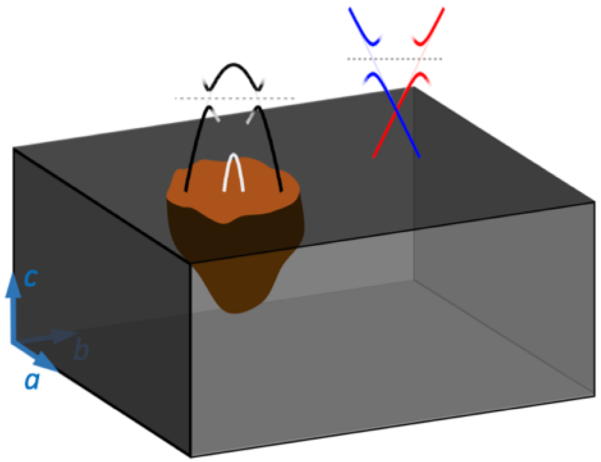


Vortex statistics



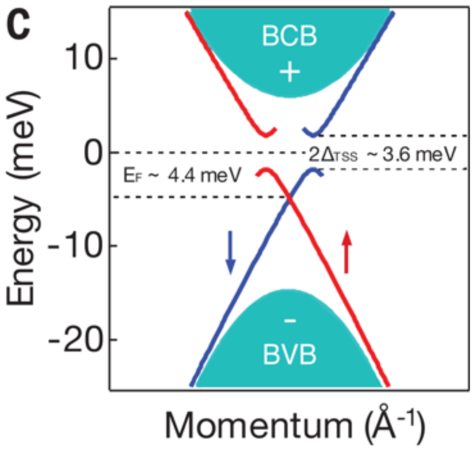
The inhomogeneity of Telluride/Selenide alloy

- **Strong inhomogeneity (break down strong-TI)**

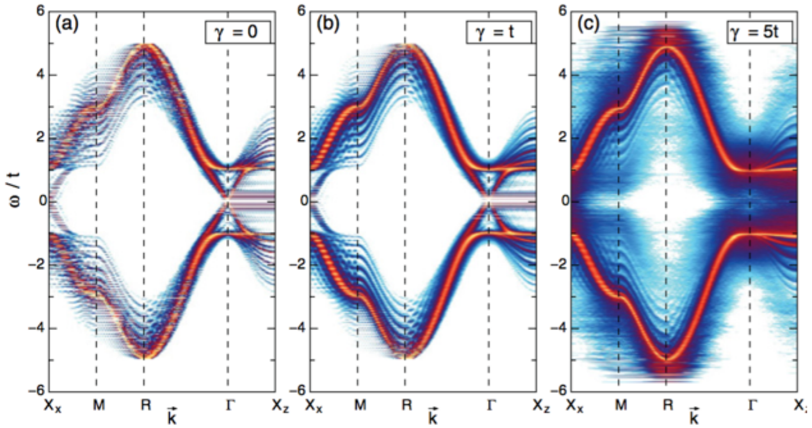


- *No TSS, Ordinary vortex, No MZM*
- *With TSS, Topo. vortex, MZM*

- ***Normal insulating state: easy to conquer 20 meV***

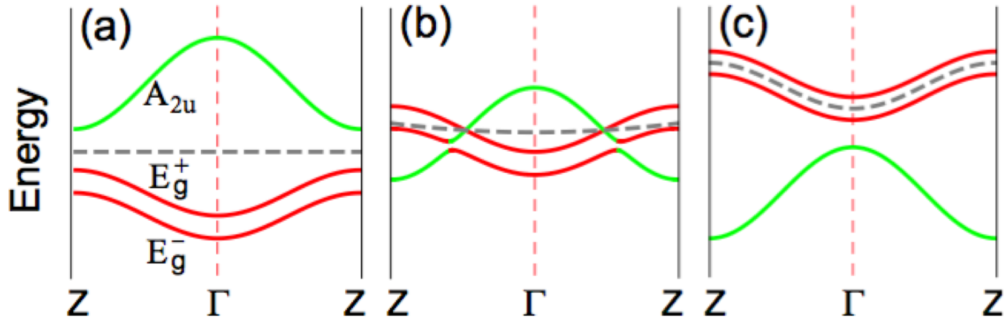


Small Topo-gap in Fe(Te,Se)



G. Schubert et al., PRB **85**, 201105(R) (2012)

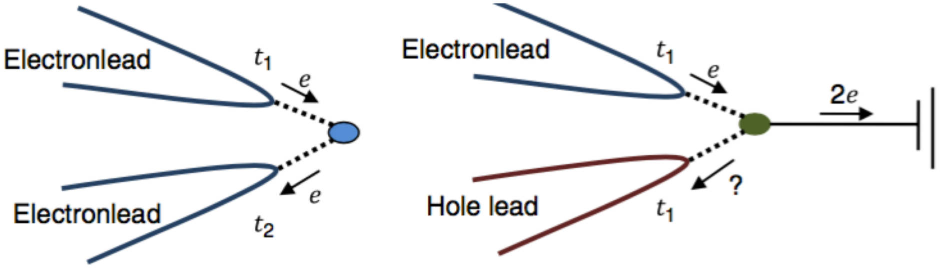
- ***Weak Topological insulator state***



S.-S. Qin, L.-H. Hu et al. arXiv:1901.03120v1

Quantized Majorana Conductance

➢ Majorana modes induced resonant Andreev reflection

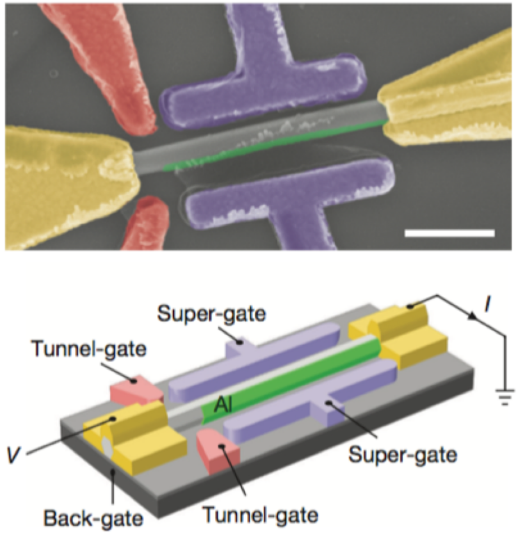


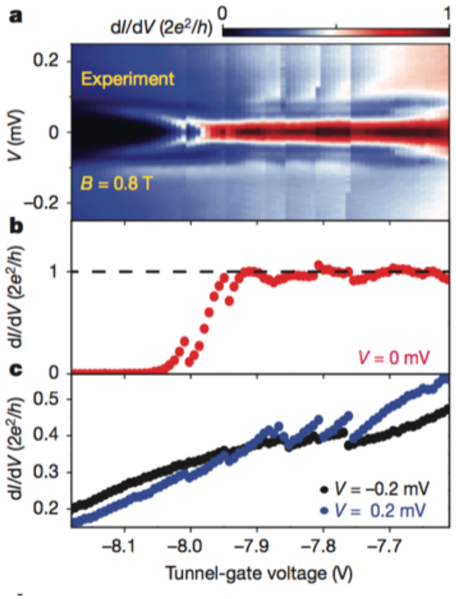
Law, Lee and Ng. PRL (2009)

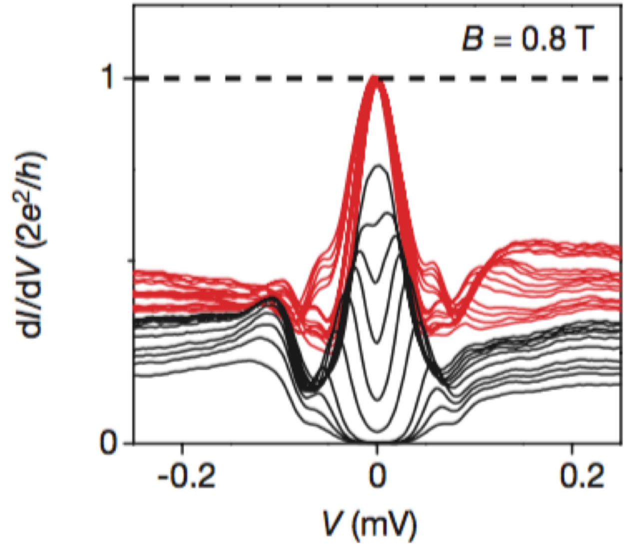
$$\frac{dI}{dV}=\frac{2e^2}{h}\frac{4\Gamma^2}{(eV)^2+4\Gamma^2}$$

On resonance (V=0), universal conductance ($2e^2/h$) regardless of tunnel barrier (Γ) at low temperature kT<Γ

➢ Majorana conductance plateau observed in nanowires





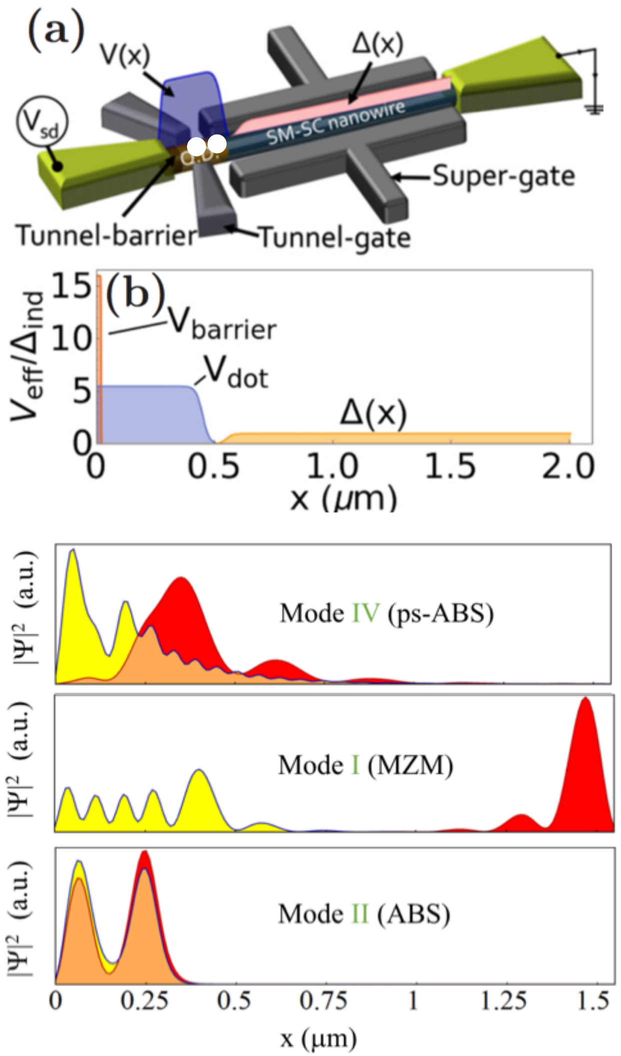


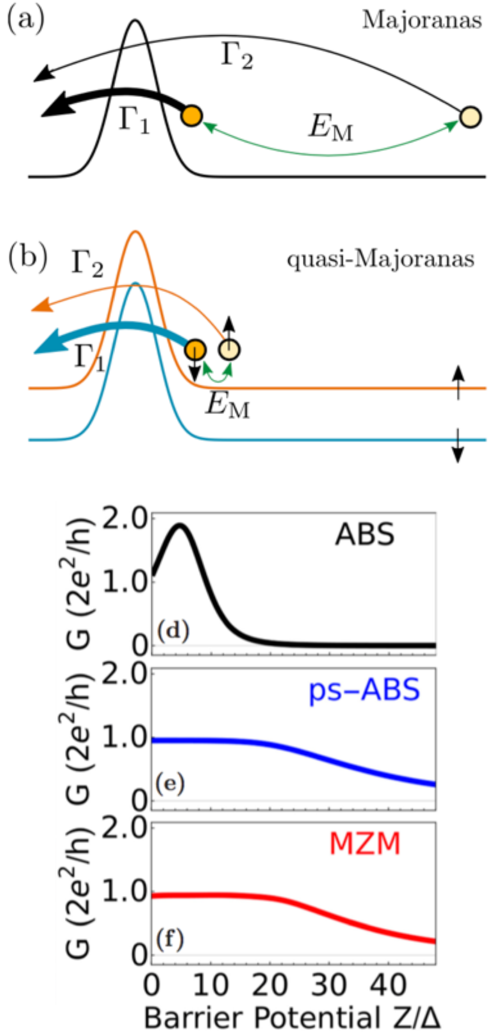
H. Zhang et al.
Nature 556, 74 (2018)

Partially separated Andreev bound state

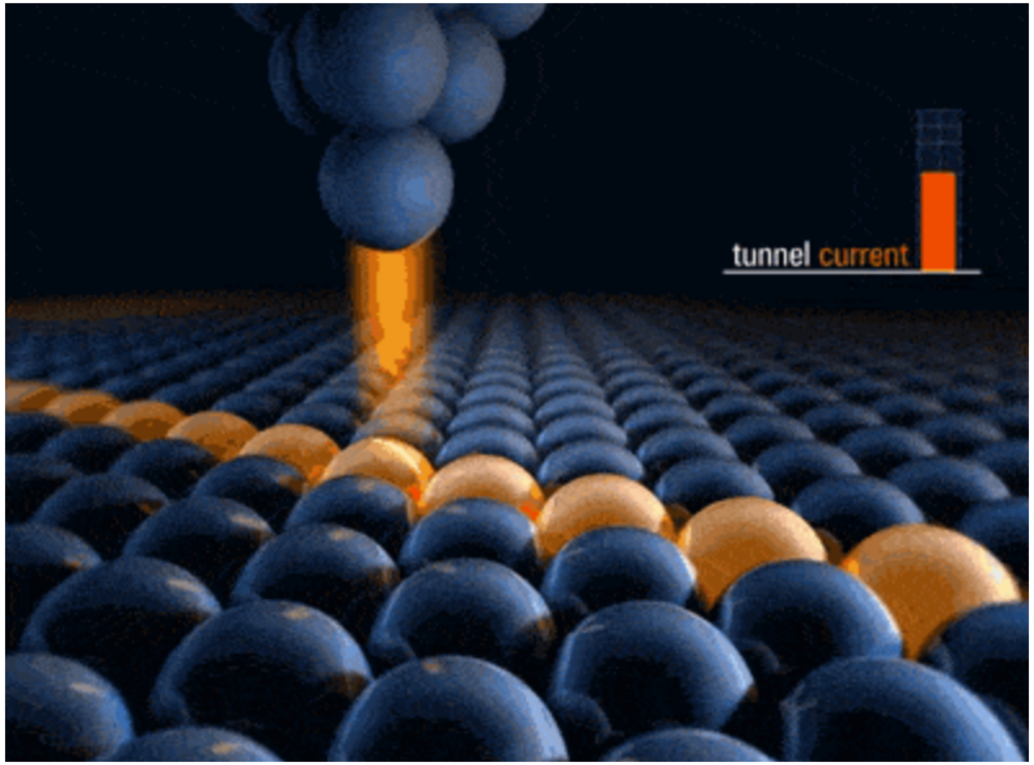
Smooth confinement potential at the end of the nanowire raise the possibility to exist a pair of spatially-overlapping MZMs localized at the same end of the nanowire arXiv:1806.02801 Phys. Rev. B 98,155314 (2018); Phys. Rev. B 97.165302 (2018)

Nanowire Devices



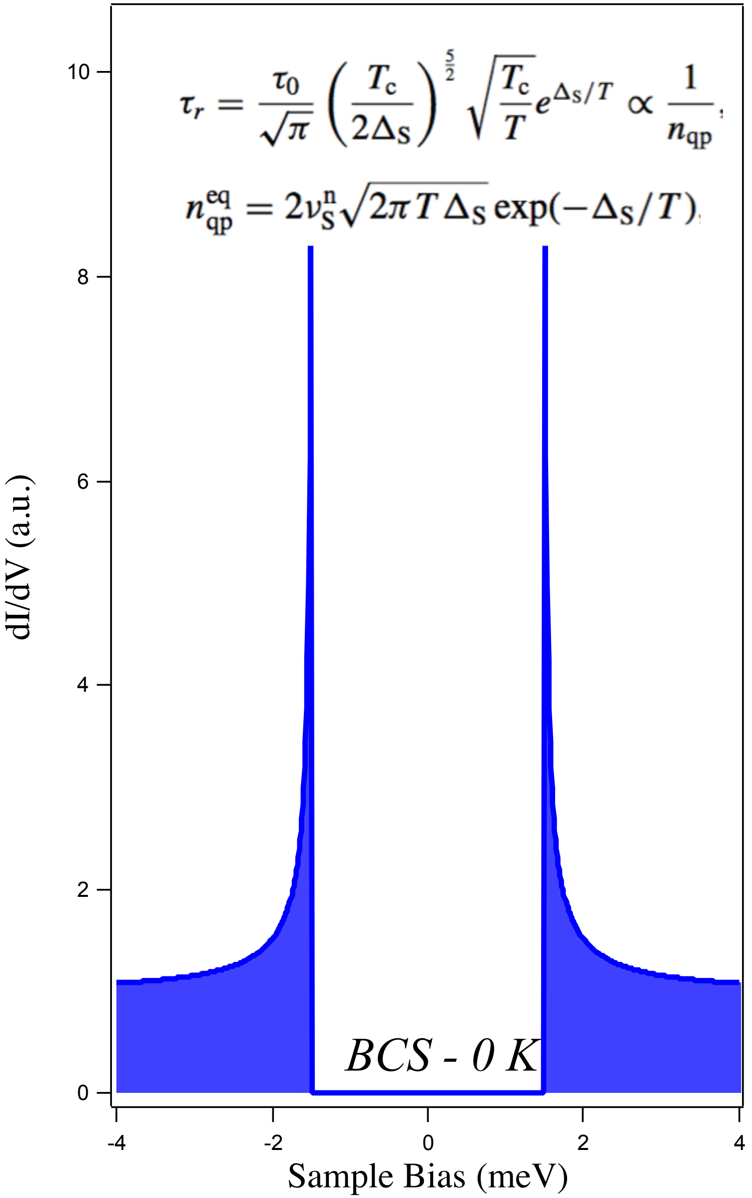


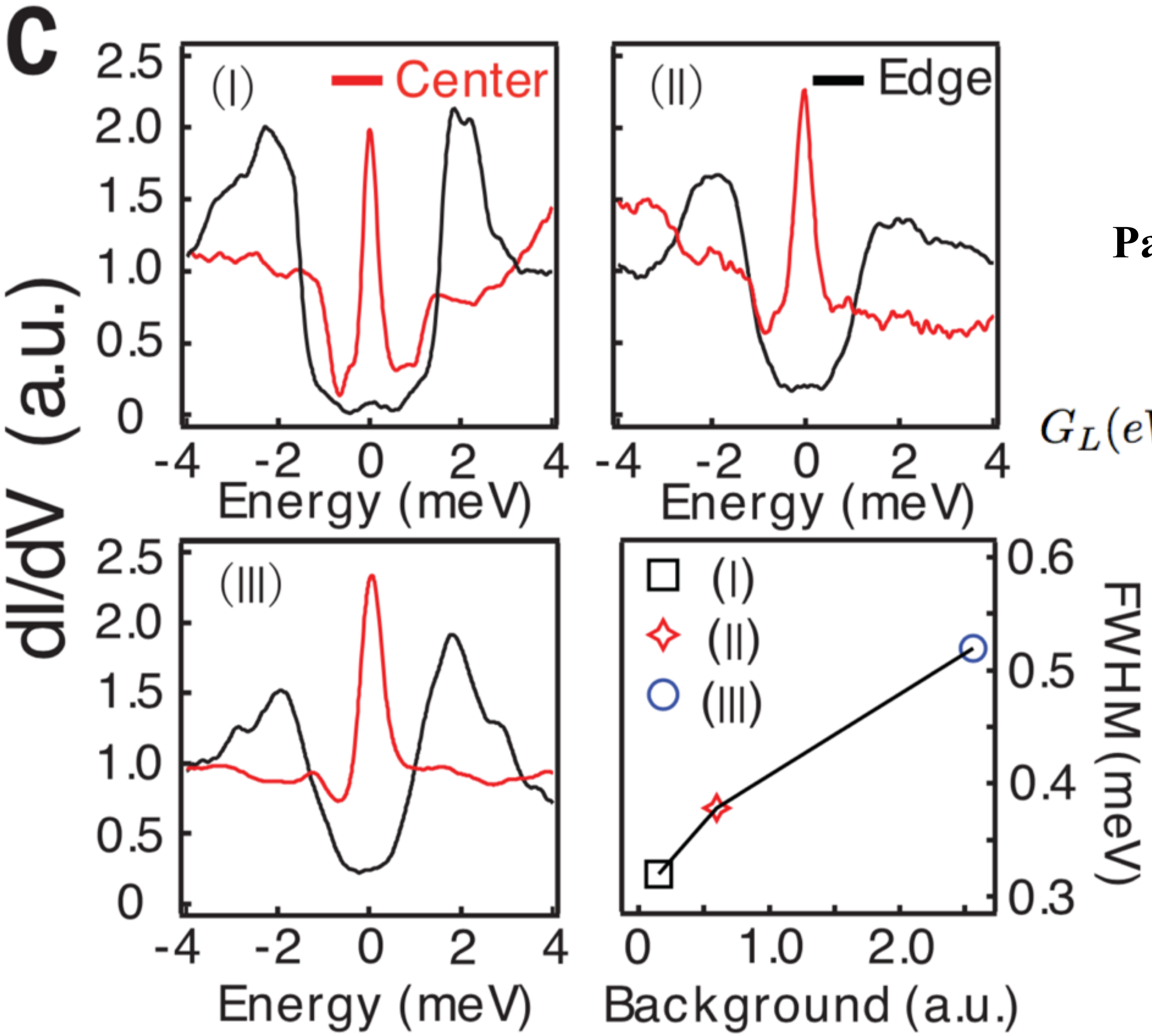
STM: vacuum tunneling



Sharp confinement tunnel-barrier remove the possibility of partially separated Andreev bound state.

Quasiparticle poisoning





Patrick Lee, PRB (2014)

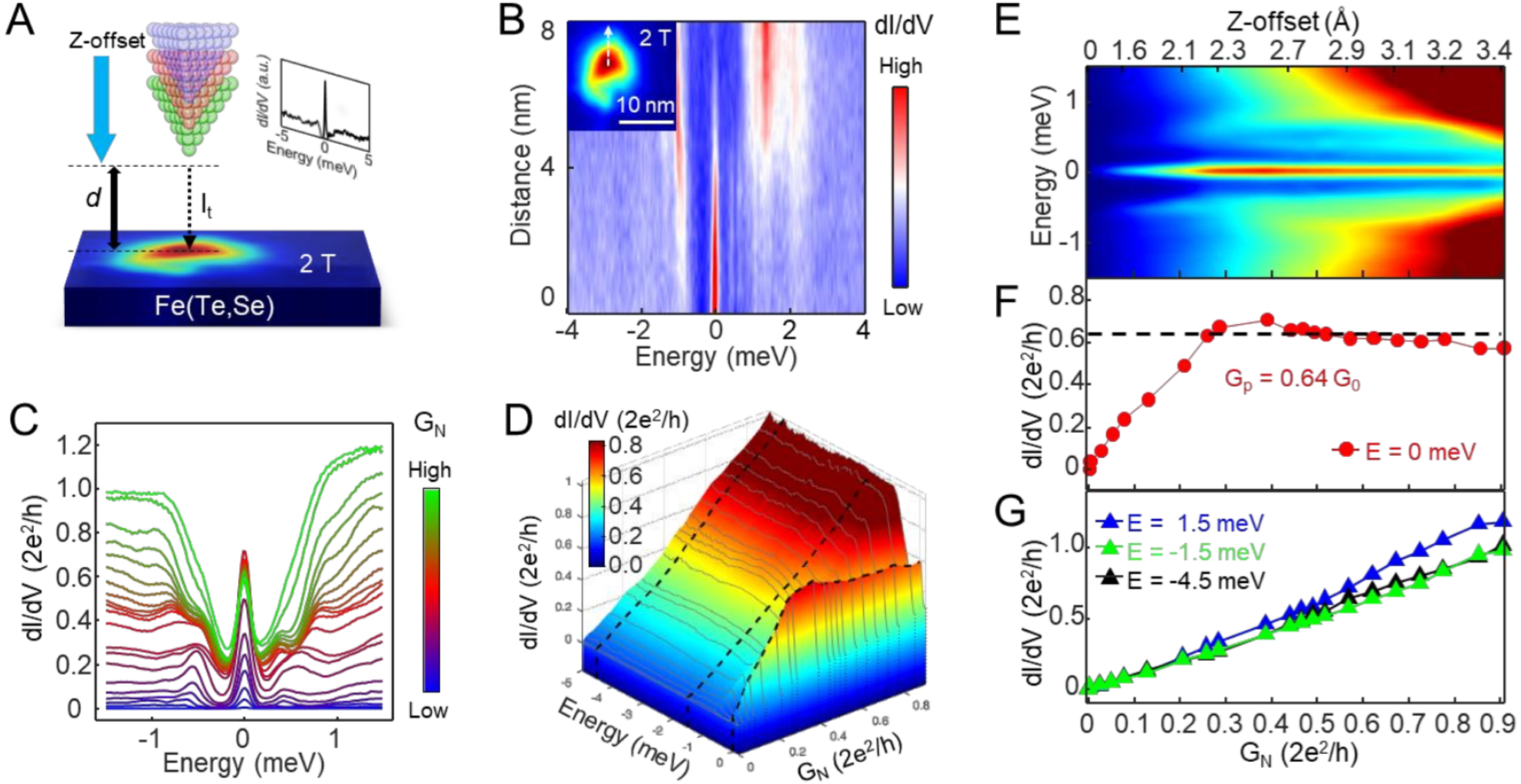
$$G_L(eV = E) = \frac{2e^2}{h} \frac{\gamma_L^t \Gamma_L}{E^2 + \Gamma_L^2}$$

$$\Gamma_L = \gamma_L^t + \gamma_L^p$$

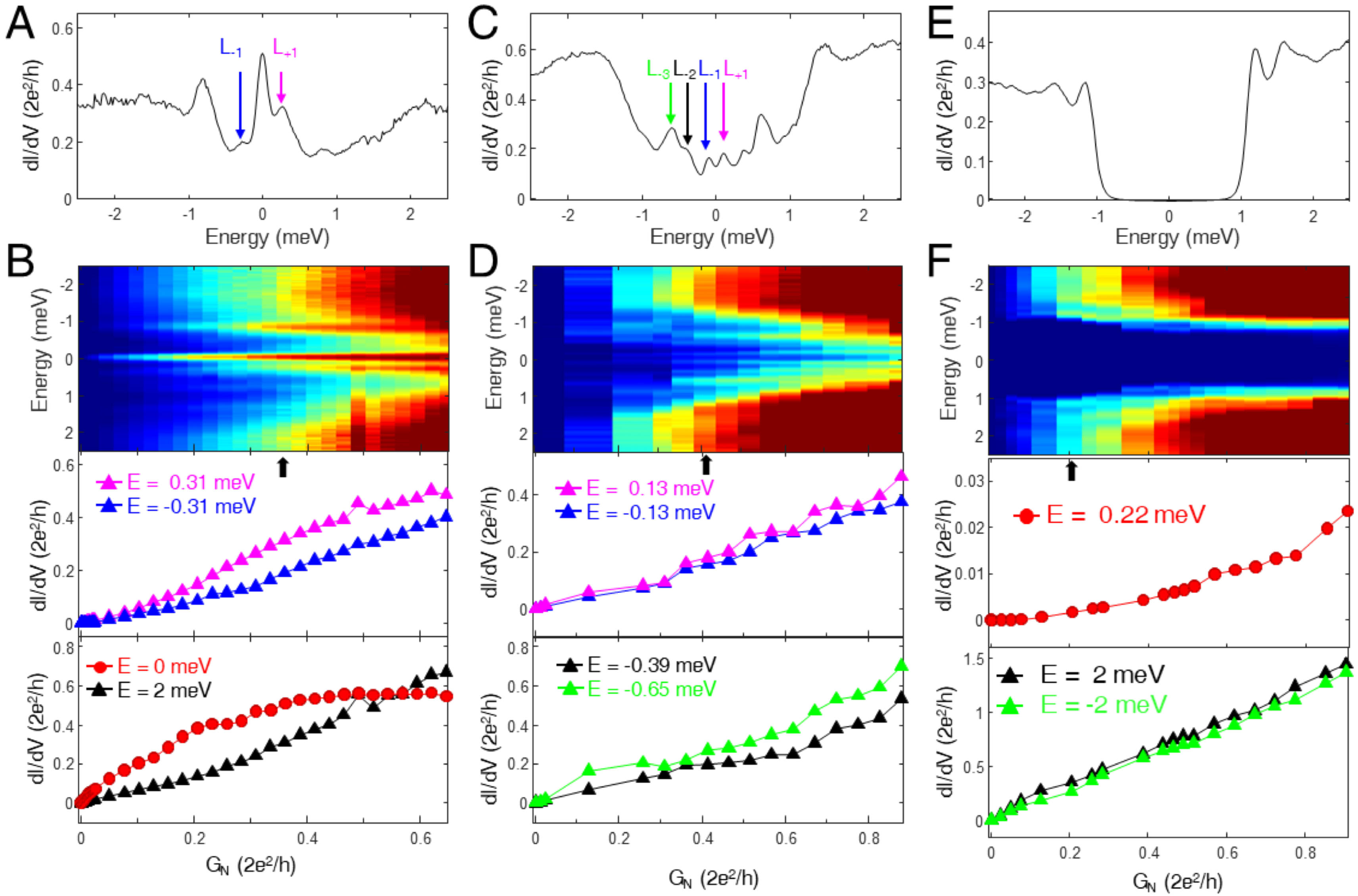
Broadening due to quasiparicle poisoning

Zero-bias conductance plateau observed on $FeTe_{0.55}Se_{0.45}$

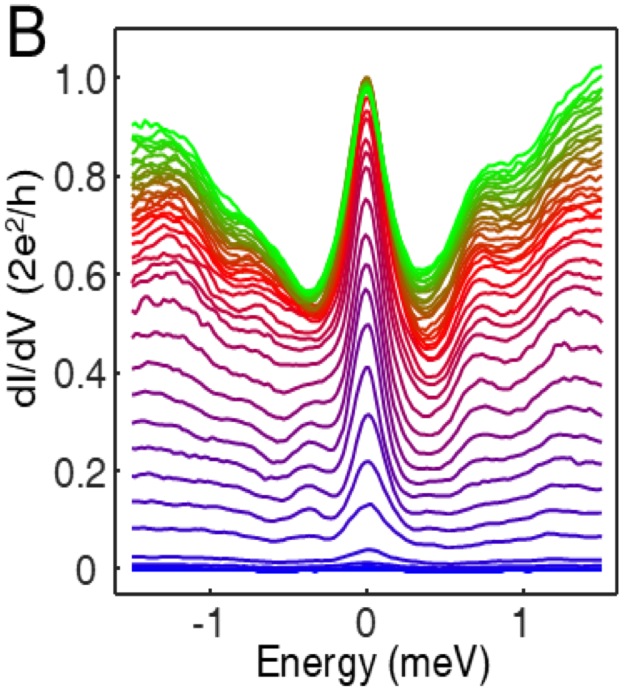
Low temperature (78 mK); Low field (2.0 T); Strong tunnel coupling ($G_N \sim e^2/h$)

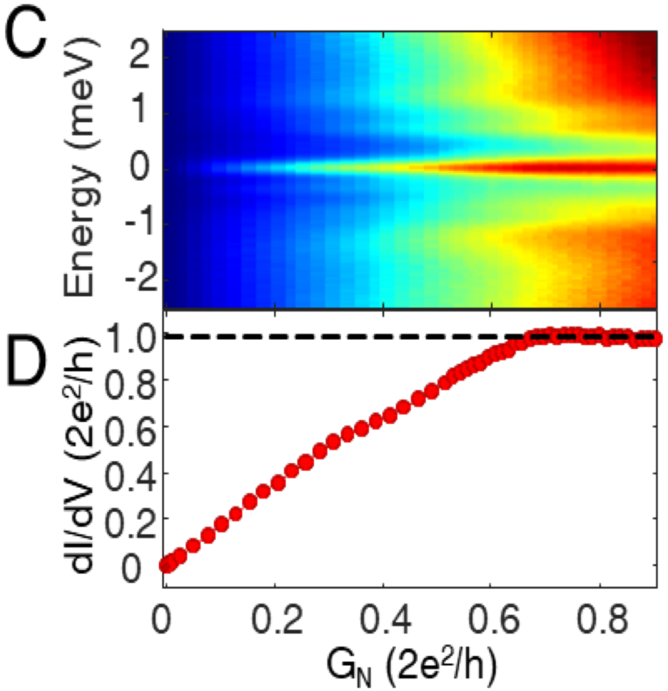


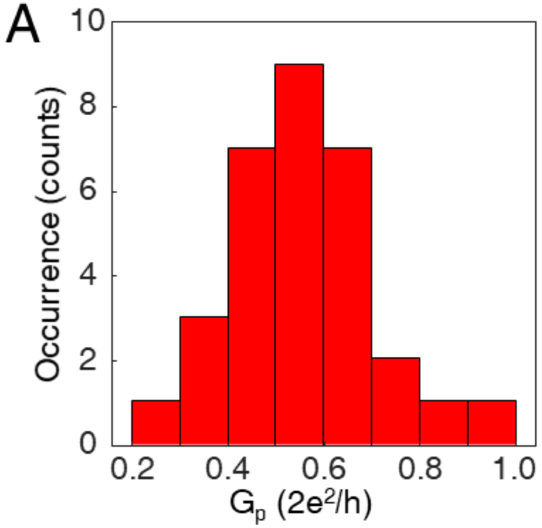
In stark contrasts with CBS and continues states



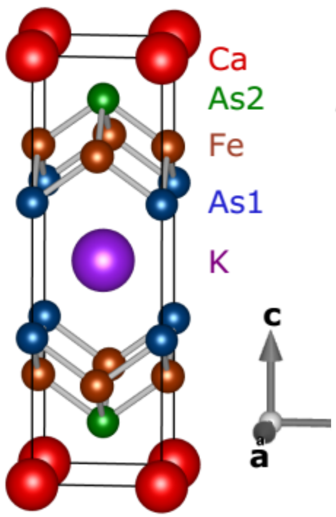
Distribution of the plateau value

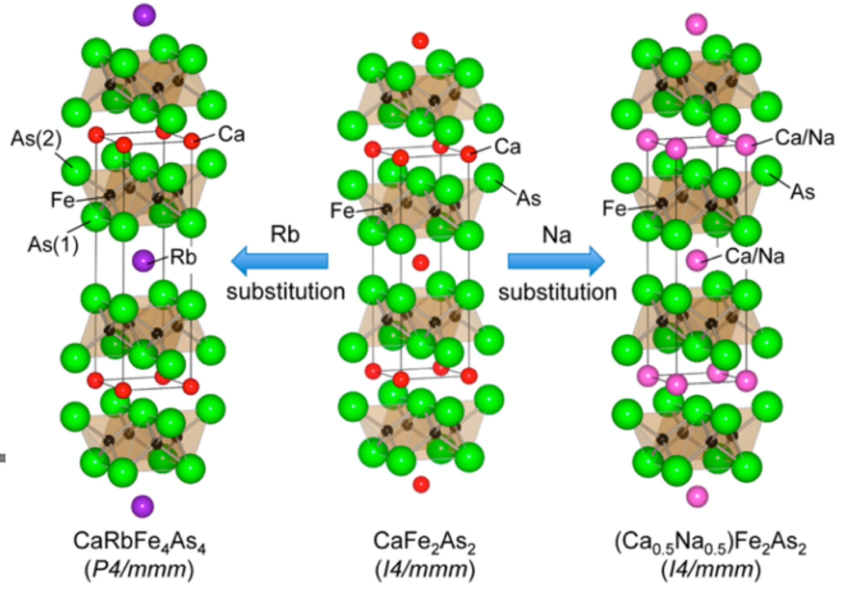


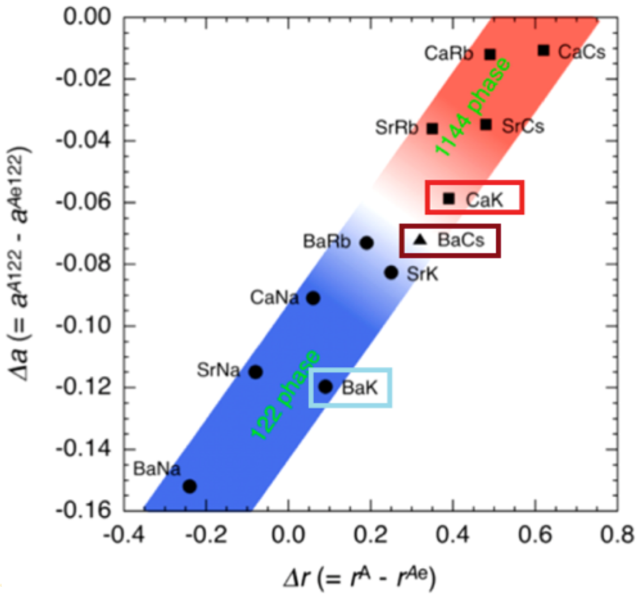




$CaKFe_4As_4$ (Tc = 33K): double Fe-As layers, self-doping



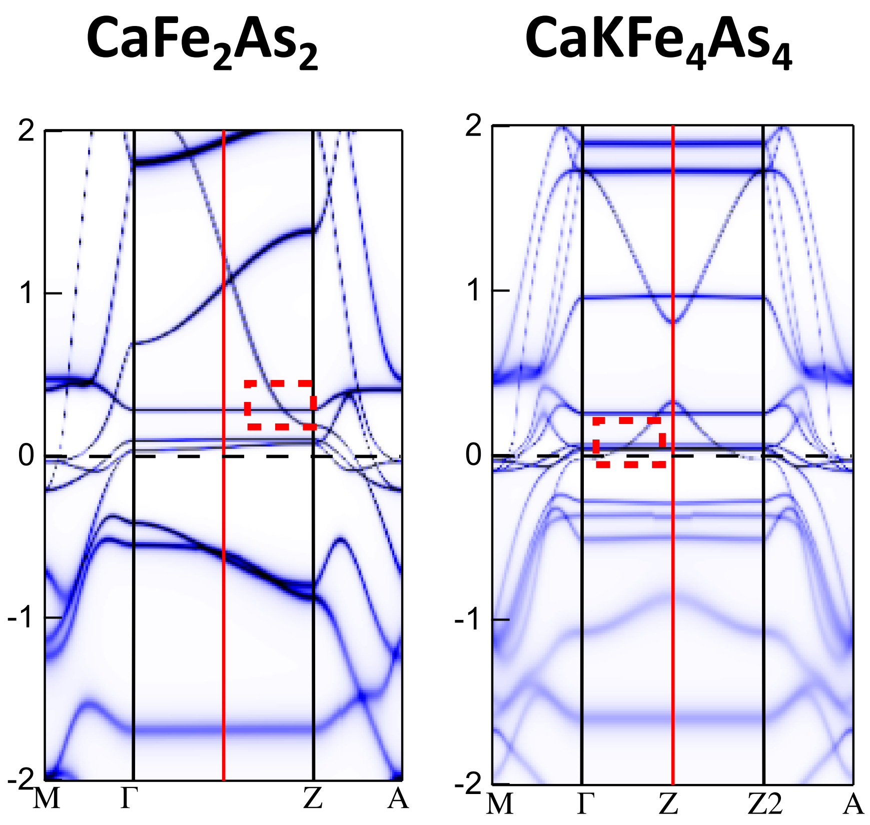


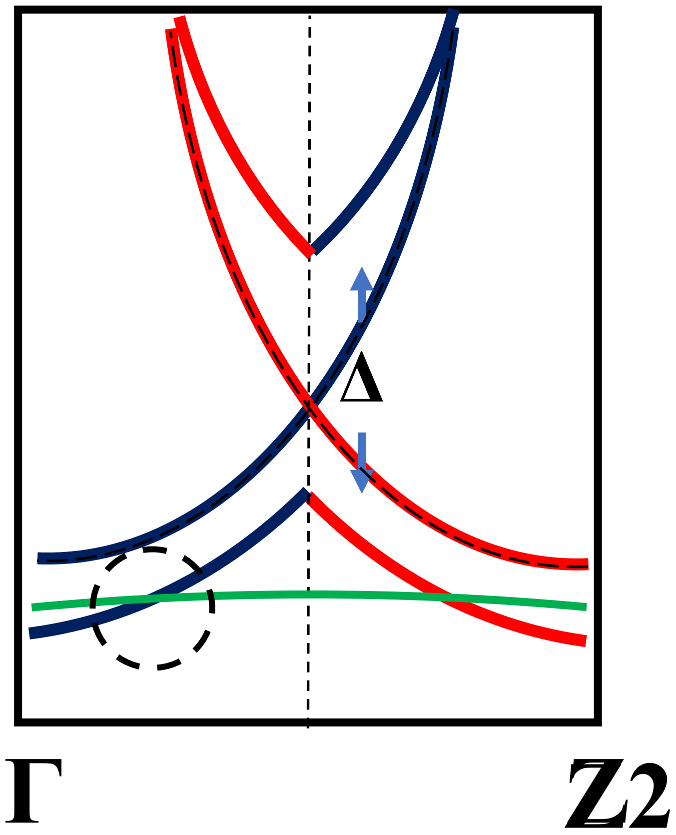


$CaKFe_4As_4$ | 1144 | 122 | 122 doping

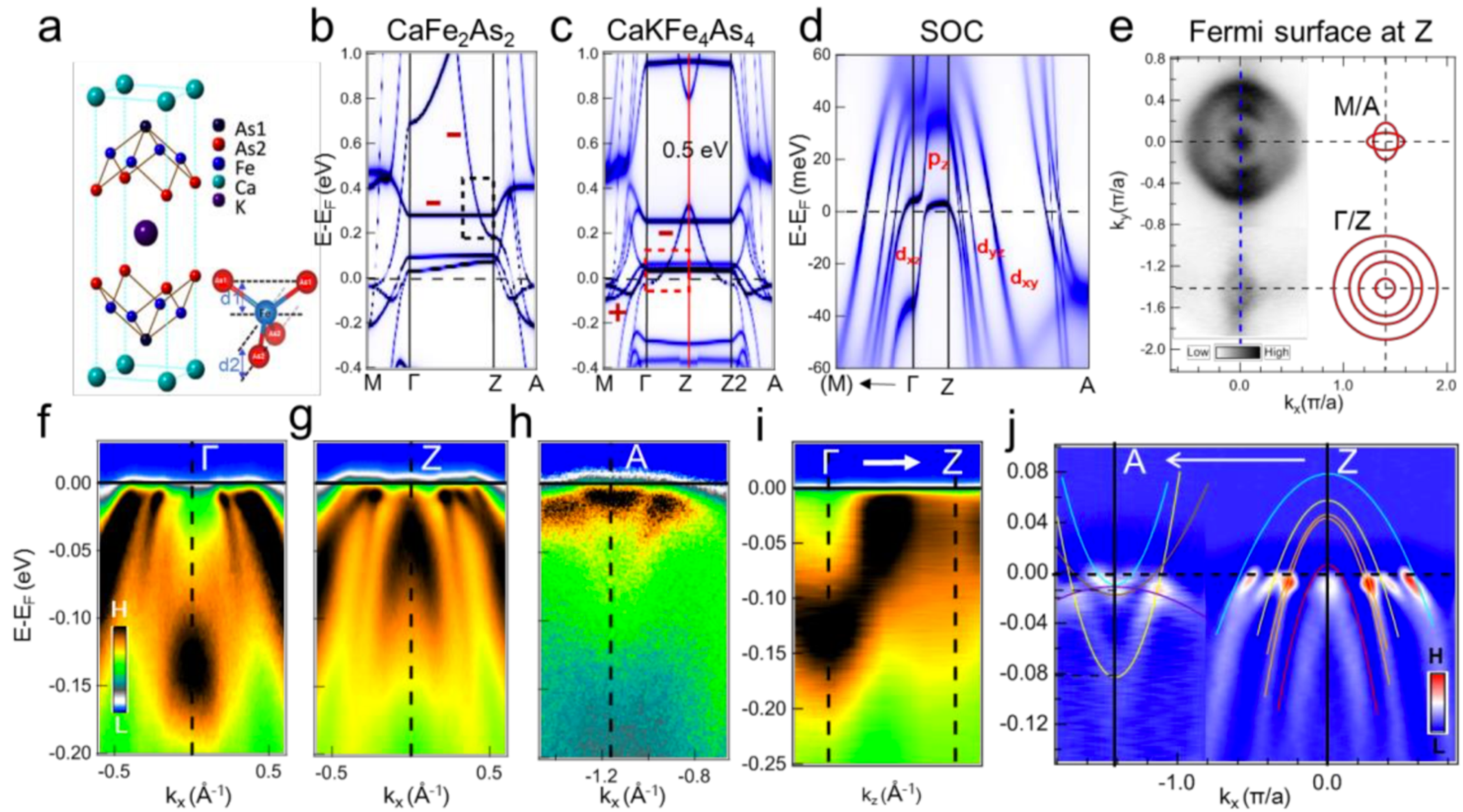
compound	space group[a]	a (Å)	c (Å)	T_c (K)
$CaKFe_4As_4$	P	3.866(1)	12.817(5)	33.1
$CaRbFe_4As_4$	P	3.8757(9)	13.104(3)	35.0
$CaCsFe_4As_4$	P	3.891 (1)	13.414(2)	31.6
$SrRbFe_4As_4$	P	3.897(1)	13.417(5)	35.1
$SrCsFe_4As_4$	P	3.910(1)	13.729(3)	36.8
$BaCsFe_4As_4$ or $(Ba,Cs)Fe_2As_2$	P or I	3.927(2)	14.134(6)	26
$CaFe_2As_2$	I	3.900(1)	11.62(1)	NS[c]
$SrFe_2As_2$	I	3.9266(5)	12.370(2)	NS[c]
$BaFe_2As_2$	I	3.9612(3)	13.006(1)	NS[c]
$NaFe_2As_2$	I	3.8090(5)	12.441(3)	25
KFe_2As_2	I	3.8414(2)	13.837(1)	3.8
$RbFe_2As_2$	I	3.888(2)	14.534(7)	2.6
$CsFe_2As_2$	I	3.8894(2)	15.066(5)	1.8

CaKFe4As4: band inversion induced by symmetry breaking

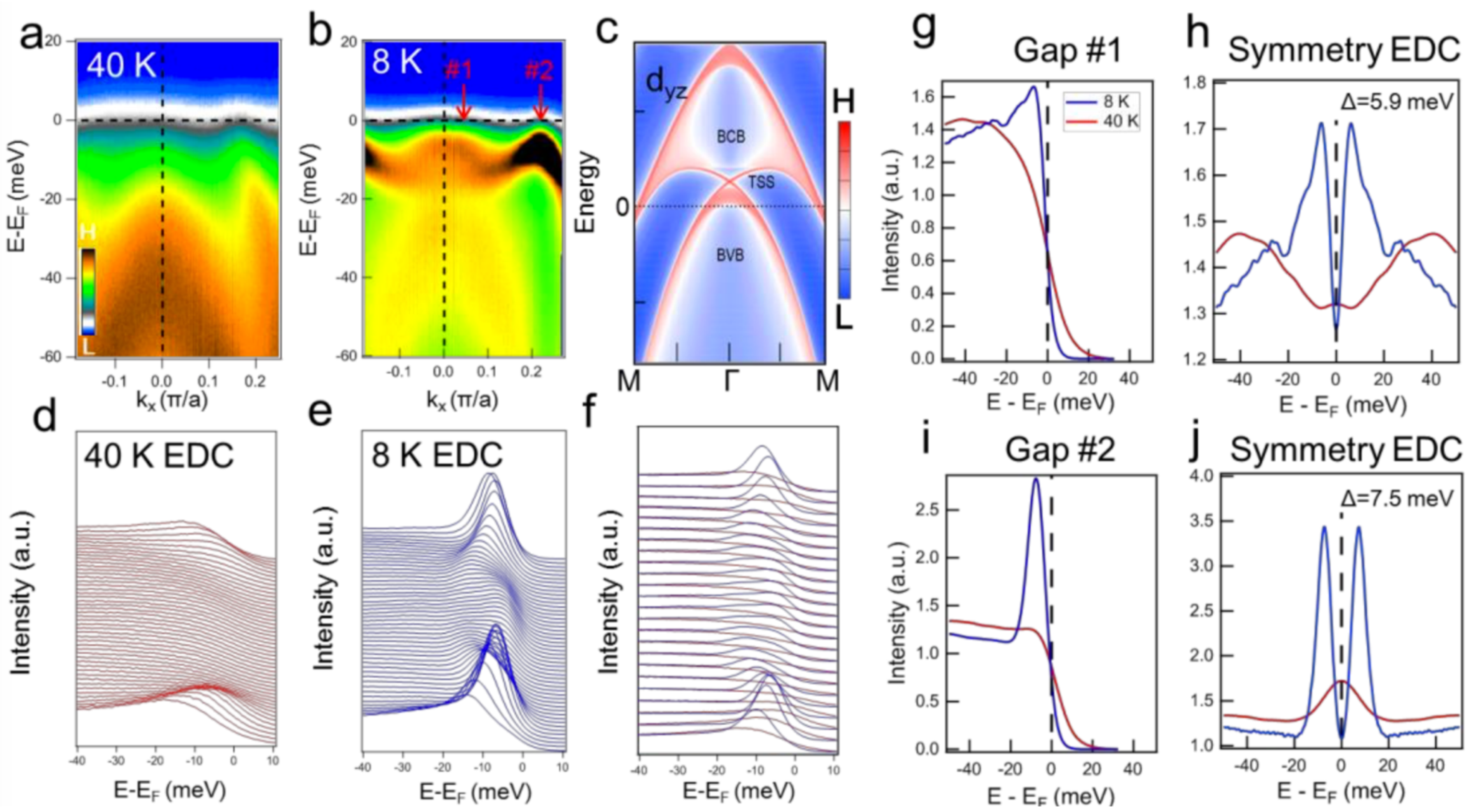




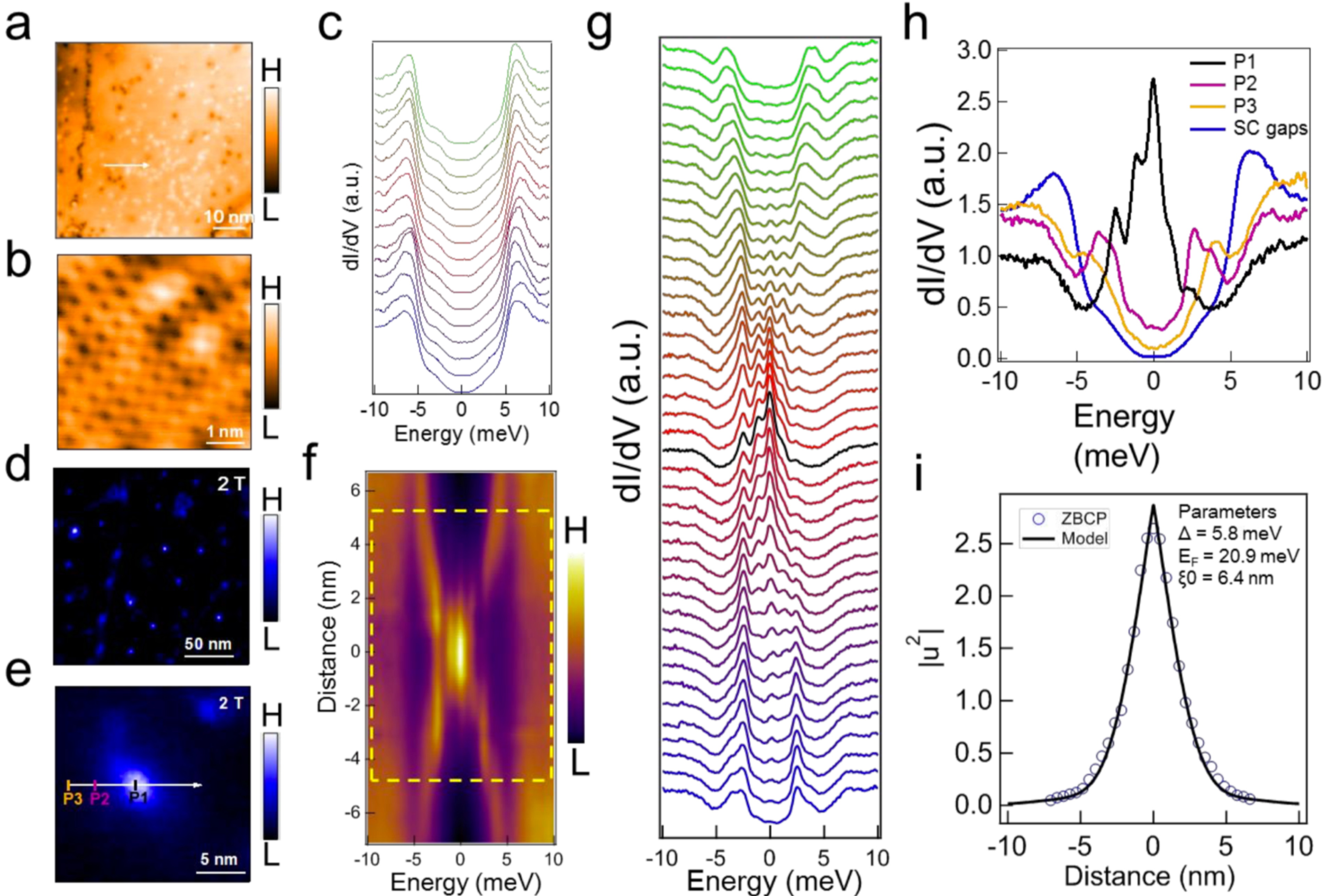
Comparison between ARPES and DMFT caculation



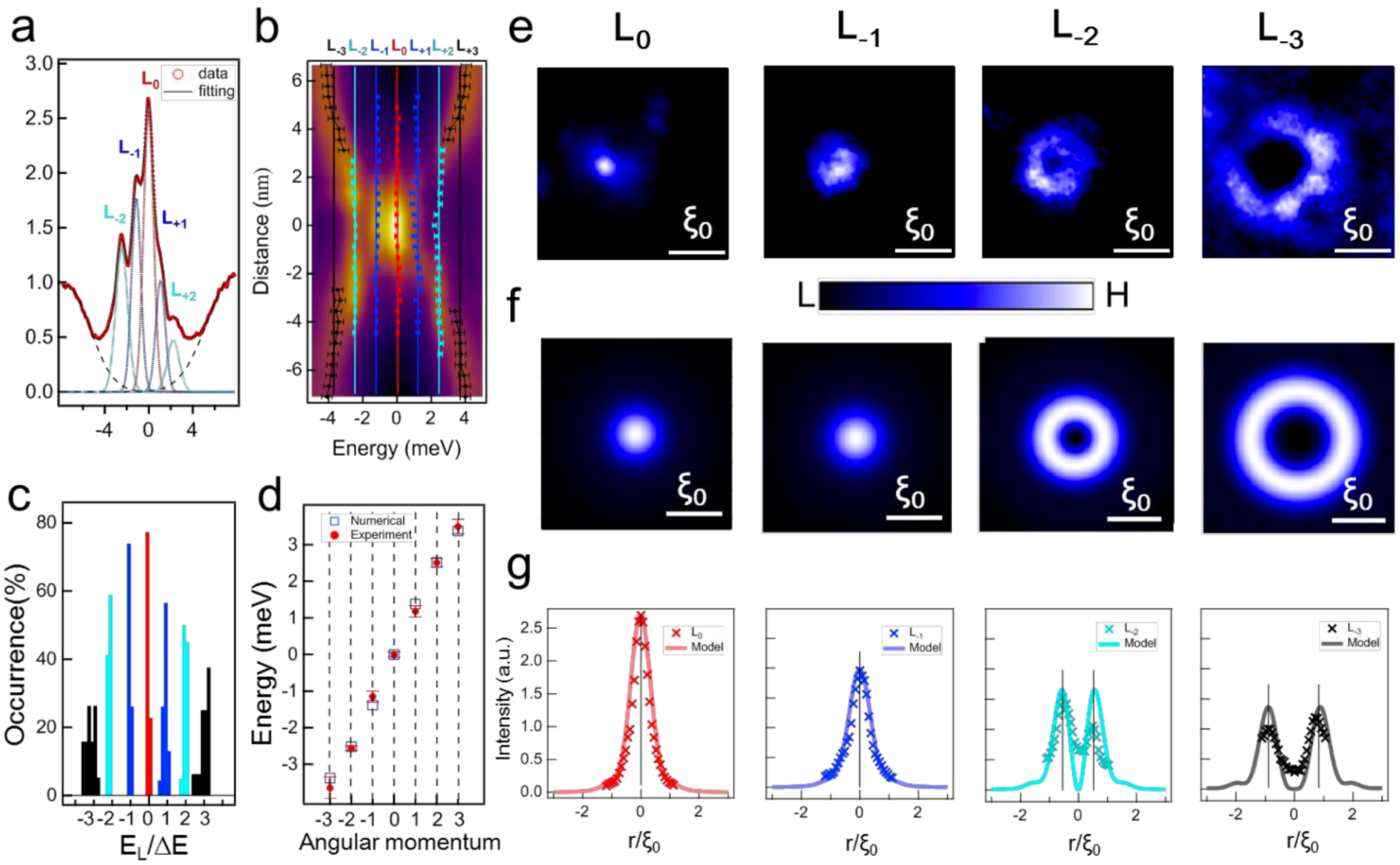
ARPES measurements of superconducting gap



STM observation of MZM and CBSs



Integer level spacing and "ring-pattern" of CBSs



An amazing new field for Majorana

Experiments:

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Yuan, Xue (WS2) et al, Nat. Phys. (2019)
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Theory:

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Qin et al. arXiv: 1901.03120 (2019)
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Journal Club for Condensed Matter Physics JCCM_January_2018_01
https://www.condmatjclub.org

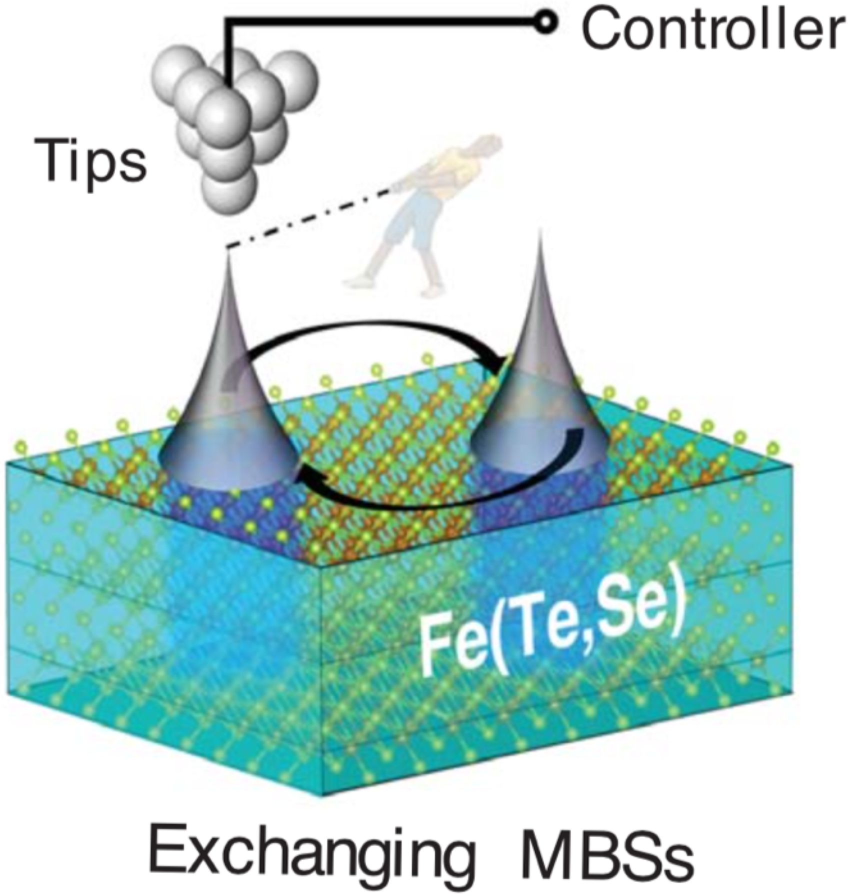
Iron-based superconductors went topological ?

Journal Club for Condensed Matter Physics JCCM_December_2018_03
https://www.condmatjclub.org

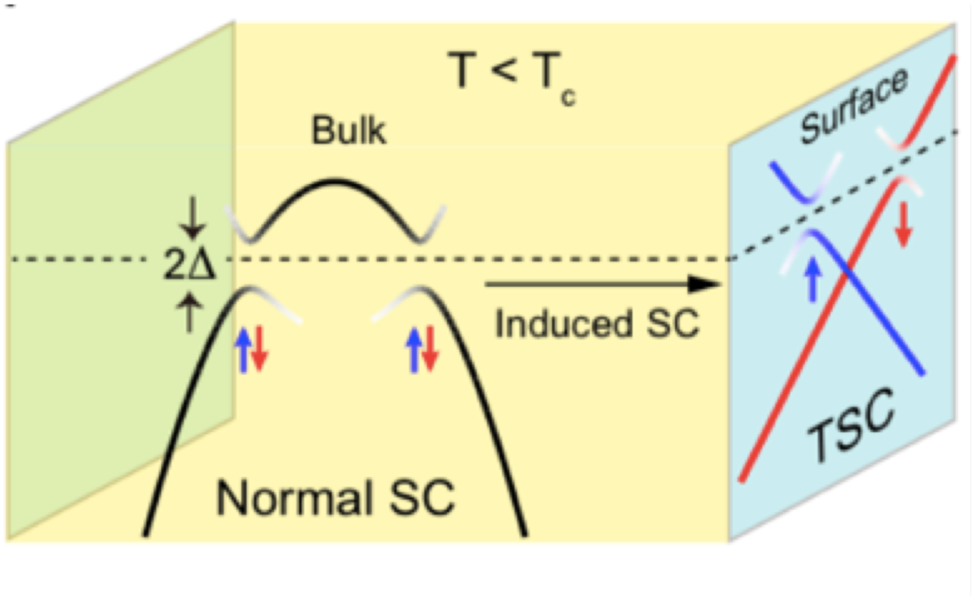
Spontaneous vortex formation and Majorana zero mode in iron based superconductor.

Journal Club for Condensed Matter Physics JCCM_June_2019_02
https://www.condmatjclub.org

Trails of Mobile Majoranas in an Iron Chalcogenide?



Iron Home for Majorana: Nature's Gift



S-wave + spin-helical

High-T_C SC

Small E_F , Large gap

Single Material