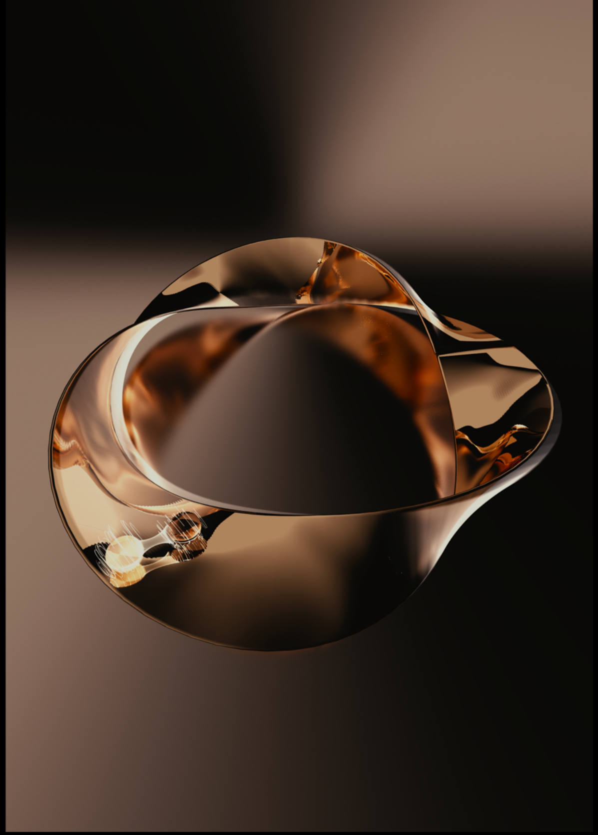


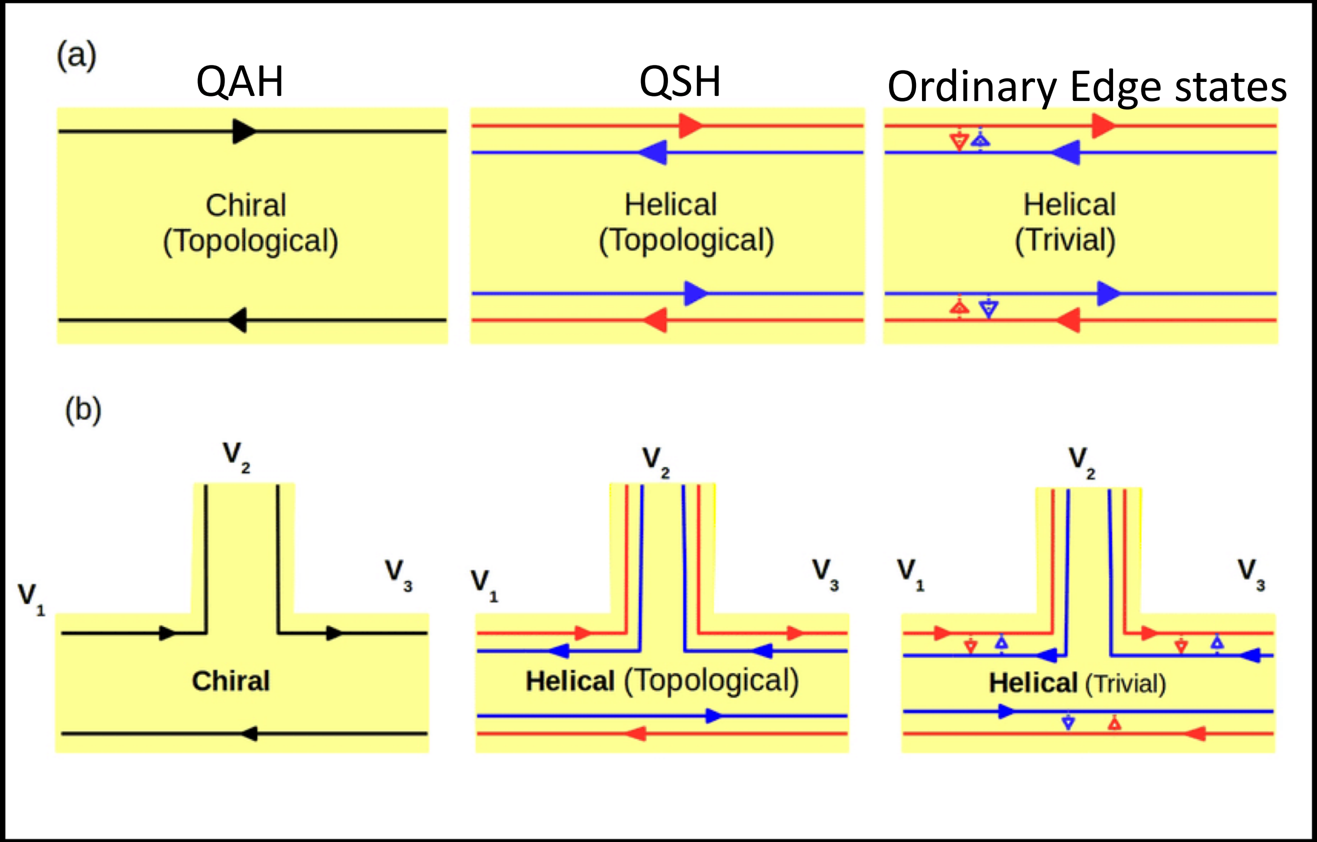
STM studies of UTe_2

Vidya Madhavan

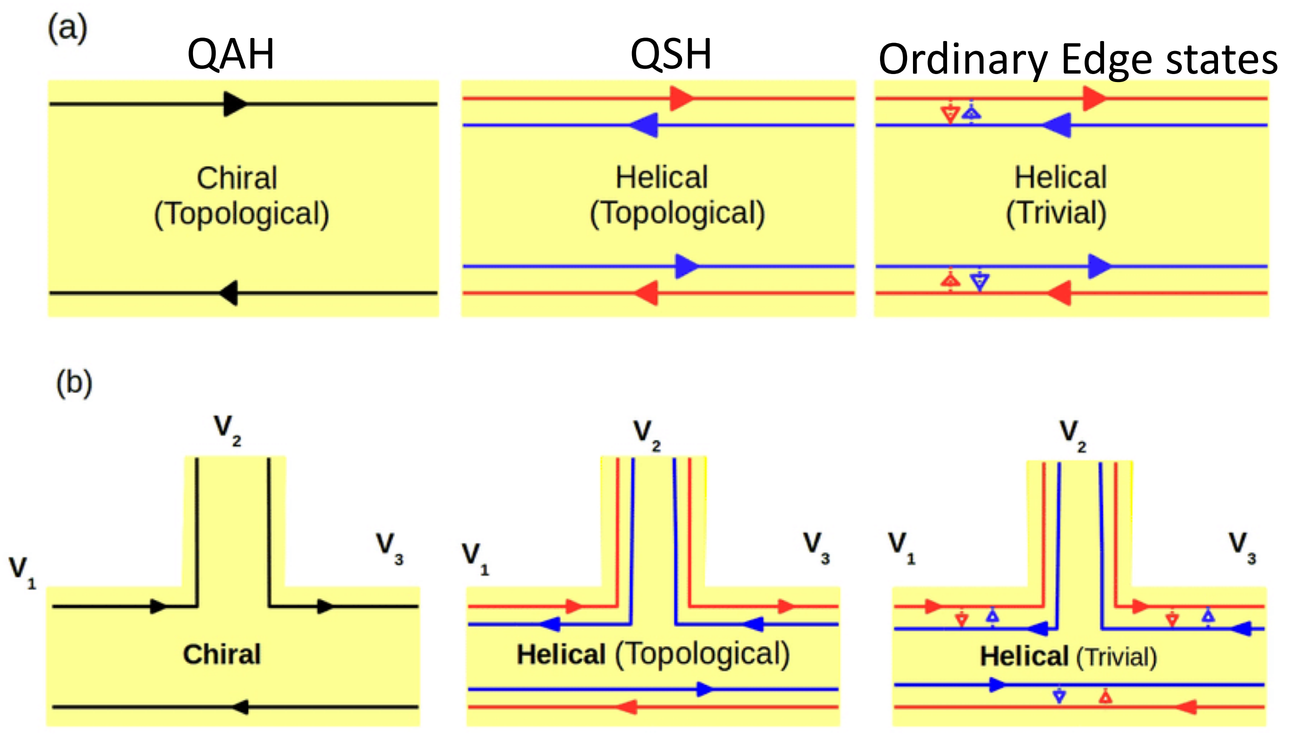
University of Illinois, Urbana-Champaign

GORDON AND BETTY MOORE FOUNDATION
NSF
U.S. DEPARTMENT OF ENERGY

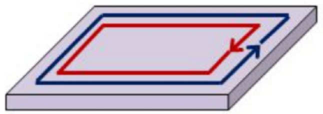
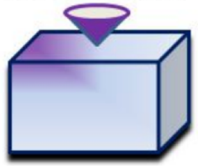
The search for Topological superconductivity



The search for Topological superconductivity



Different bulk topological # → Different gapless boundary states

2+1D time-reversal breaking SC	2+1D time-reversal invariant SC	3+1D time-reversal invariant SC
1st Chern # (TKNN82, Kohmoto85)	Z_2 number (Kane-Mele 06, Qi et al (08))	3D winding # (Schnyder et al (08))
1+1D **chiral** edge mode 	1+1D **helical** edge mode 	2+1D **helical** surface fermion 

Fundamentally New Phase of Matter

From talk of Masatoshi Sato

Chiral/Helical Majorana Modes

Chiral triplet superconductors: Majorana Fermions

- $\gamma^{\dagger}(E) = \gamma(-E)$

  particle-hole symmetry $\Rightarrow$

  Use a superconductor!!

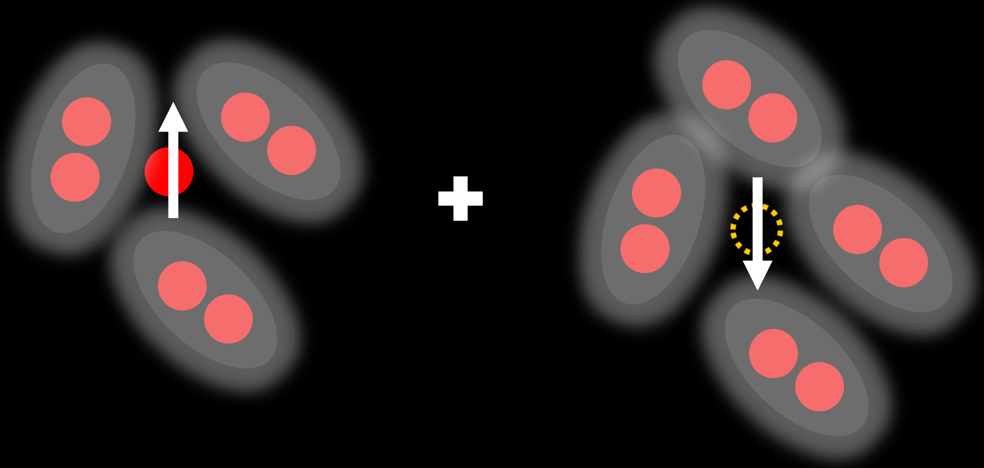
- The excitations of a SC are Bogoliubov quasiparticles which are a superposition of particles and holes

  $$\boldsymbol{\gamma_{k\downarrow}^{\dagger} = u_k\, c_{k\downarrow}^{\dagger} + v_k c_{-k\uparrow}}$$

  $$\boldsymbol{\gamma_{-k\downarrow} = v_k\, c_{k\uparrow}^{\dagger} + u_k c_{-k\downarrow}}$$

- Even if $|u_k|$= $|v_k|$ we still have a problem..**Spins are flipped!**

  So $\gamma^{\dagger}(E) \neq \gamma(-E)$

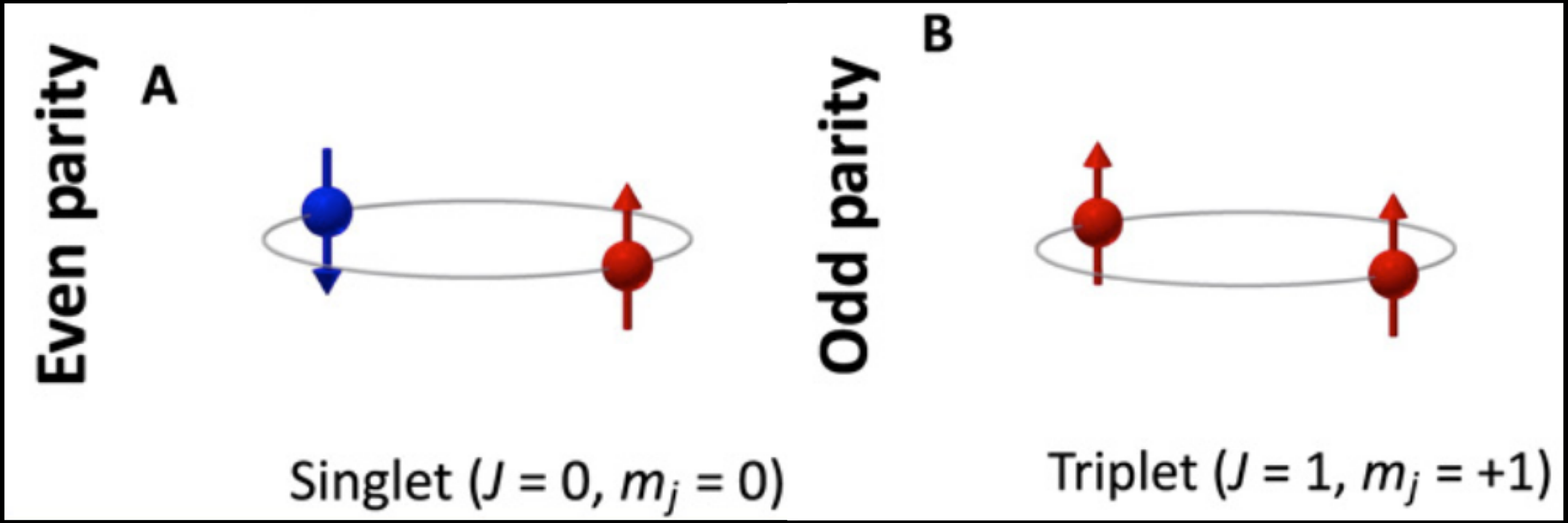


Eliminate spin as a separate degree of freedom

Triplet superconductors: Platform for Majorana Modes

How do we eliminate spin as a separate degree of freedom?

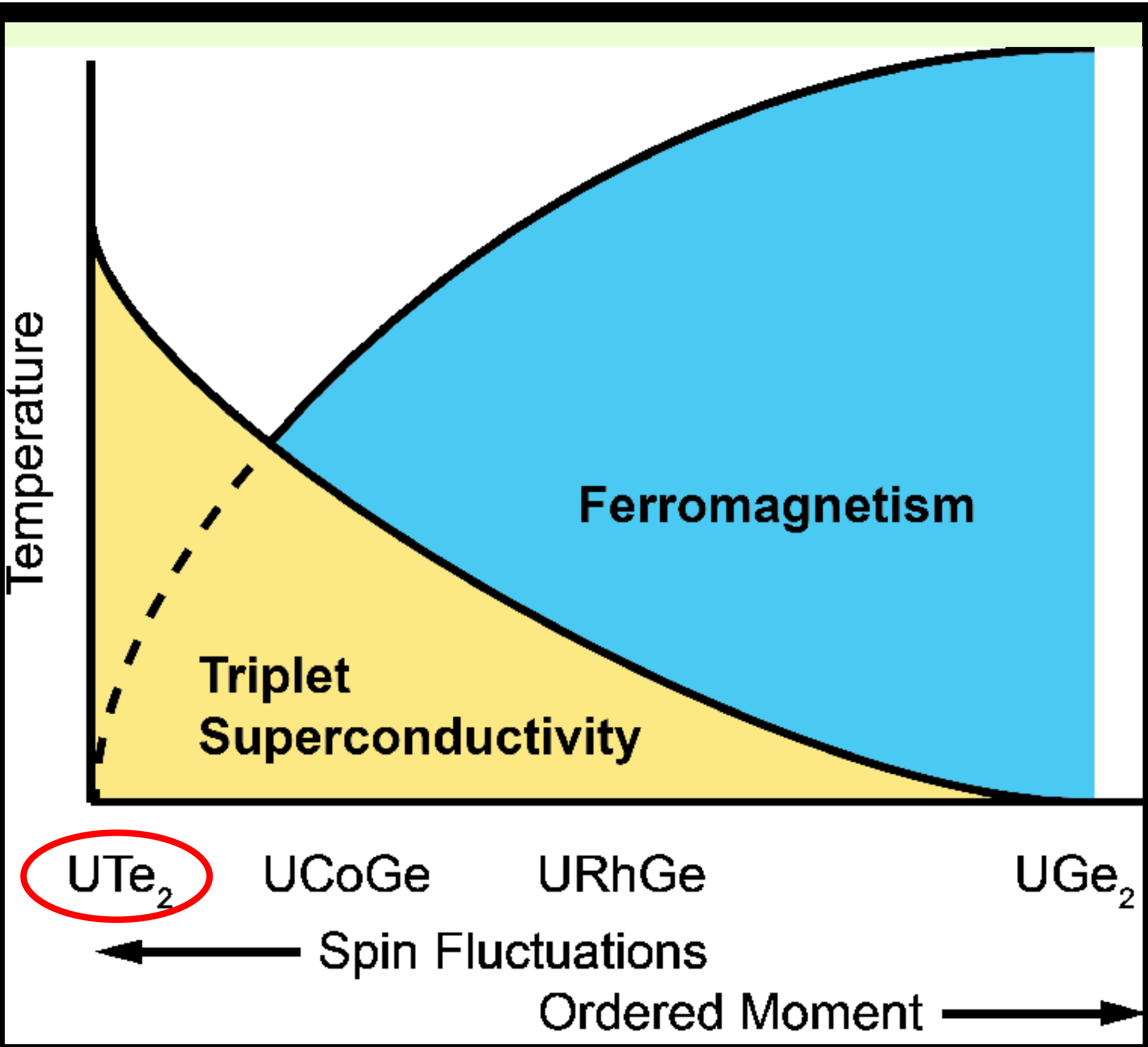
- Use an intrinsic spin-triplet p-wave SC



Very few intrinsic spin-triplet SC in ambient solids

Candidates: UCoGe, UPt_3, Sr_2RuO_4

Uranium based compounds

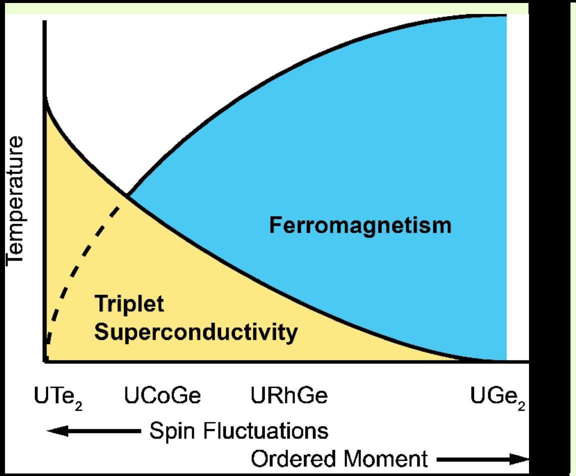


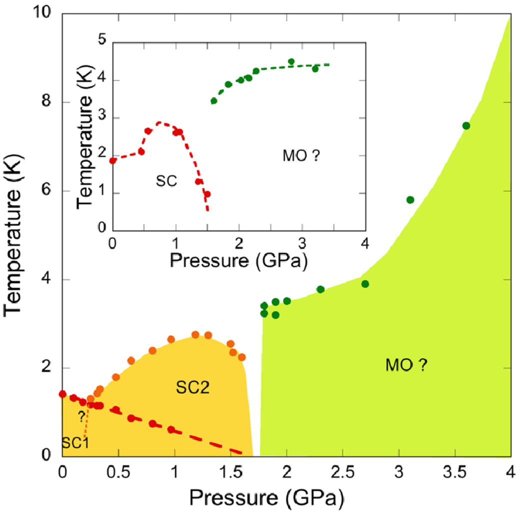
Fey, D. & Appel, J. Coexistence of p-state superconductivity and itinerant ferromagnetism. Phys. Rev. B 22, 3173-3182 (1980)

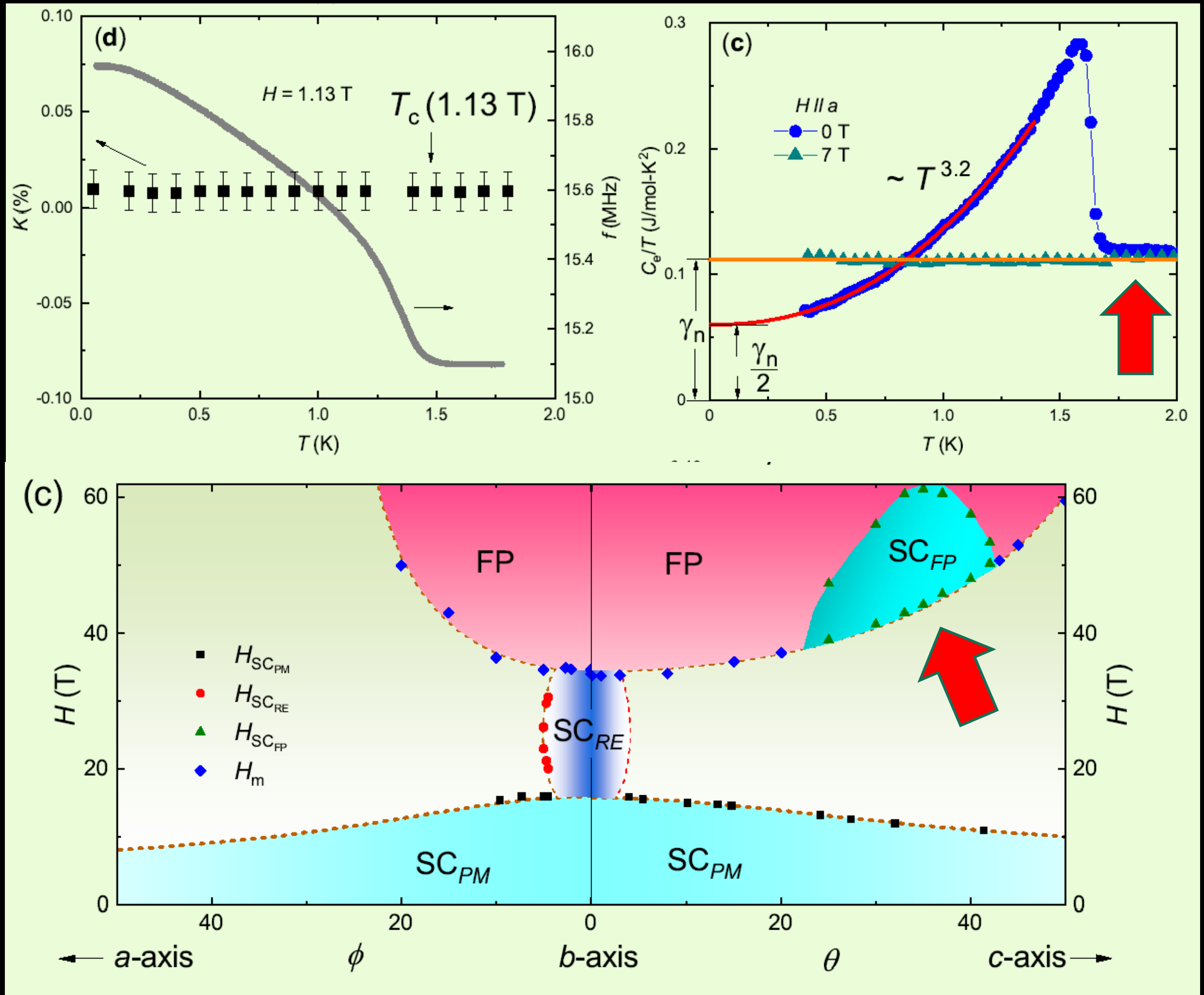
Hirsch, J. E. Attractive interaction and pairing in fermion systems with strong on-site repulsion. Phys. Rev. Lett. 54, 1317-1320 (1985)

Ran et.al., Science 365, 684 (2019)
Ran et. al Nat.Phys. (2019)

UTe_2: strong evidence for triplet paring



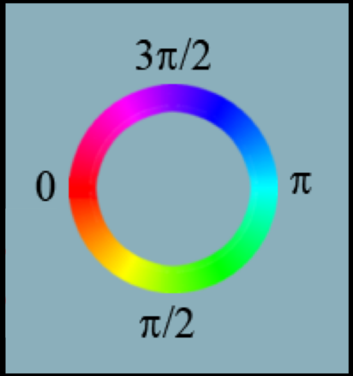




Triplet: Equal spin pairing (symmetric)

Spatial wavefunction: angular momentum 1; p- or f-wave (anti-symmetric)

Is UTe_2 a chiral p-wave (p_x+ip_y) superconductor?



Ran S, et al., Science **365**, 684 (2019)
Ran S, et al., Nat. Phys. **15**, 1250 (2019)
Braithwaite D, et al., Commun. Phys. **2**, 147 (2019)

UTe_2: Publications (not ordered!)

1. S. Ran, C. Eckberg, Q. Ding, Y. Furukawa, T. Metz, S. R. Saha, I. Liu, M. Zic, H. Kim, J. Paglione, N. P. Butch., *Science* **365**, 684 (2019).
2. D. Aoki, A. Nakamura, F. Honda, D. Li, Y. Homma, Y. Shimizu, Y. J. Sato, G. Knebel, J. Brison, A. Pourret, D. Braithwaite, G. Lapertot, Q. Niu, M. Vališka, H. Harima, J. Flouquet. *J PHYS SOC JPN* **88**, 43702 (2019).
3. Ran, S. *et al*., arxiv:1905.04343 (2019)
4. A. Miyake, Y. Shimizu, Y. J. Sato, D. Li, A. Nakamura, Y. Homma, F. Honda, J. Flouquet, M. Tokunaga, D. Aoki. J PHYS SOC JPN 88, 63706 (2019).
5. G. Knebel, W. Knafo, A. Pourret, Q. Niu, M. Vališka, D. Braithwaite, G. Lapertot, M. Nardone, A. Zitouni, S. Mishra, I. Sheikin, G. Seyfarth, J. Brison, D. Aoki, J. Flouquet. *J PHYS SOC JPN* **88**, 63707 (2019).
6. Hutanu, V. *et al*., arxiv 1905.04377 (2019)
7. S. Imajo, Y. Kohama, A. Miyake, C. Dong, M. Tokunaga, J. Flouquet, K. Kindo, D. Aoki. *J PHYS SOC JPN* **88**, 83705 (2019).
8. S. Sundar, S. Gheidi, K. Akintola, A. M. Cote, S. R. Dunsiger, S. Ran, N. P. Butch, S. R. Saha, J. Paglione, J. E. Sonier. *arXiv e-prints*, 1905-6901 (2019).
9. V. Hutanu, H. Deng, S. Ran, W. T. Fuhrman, H. Thoma, N. P. Butch. *arXiv e-prints*, 1905-4377 (2019).
10. Y. Tokunaga, H. Sakai, S. Kambe, T. Hattori, N. Higa, G. Nakamine, S. Kitagawa, K. Ishida, A. Nakamura, Y. Shimizu. *arXiv e-prints*, 1303-1906 (2019).
11. D. Braithwaite, M. Valiska, G. Knebel, G. Lapertot, J. P. Brison, A. Pourret, M. E. Zhitomirsky, J. Flouquet, F. Honda, D. Aoki. *arXiv e-prints*, 1909-6074 (2019).
12. J. Ishizuka, S. Sumita, A. Daido, Y. Yanase. *arXiv e-prints*, 1908-4004 (2019).
13. T. Metz, S. Bae, S. Ran, I. Liu, Y. S. Eo, W. T. Fuhrman, D. F. Agterberg, S. Anlage, N. P. Butch, J. Paglione. *arXiv e-prints*, 1069-1908 (2019).
14. Q. Niu, G. Knebel, D. Braithwaite, D. Aoki, G. E. R. Lapertot, G. Seyfarth, J. Brison, J. Flouquet, A. Pourret. *arXiv e-prints*, 1907-11118 (2019).
15. G. Nakamine, S. Kitagawa, K. Ishida, Y. Tokunaga, H. Sakai, S. Kambe, A. Nakamura, Y. Shimizu, Y. Homma, D. Li, F. Honda, D. Aoki. *arXiv e-prints*, 1909-8853 (2019).
16. S. Fujimori, I. Kawasaki, Y. Takeda, H. Yamagami, A. Nakamura, Y. Homma, D. Aoki. *J PHYS SOC JPN* **88**, 103701 (2019).
17. Y. Xu, Y. Sheng, Y. Yang. *arXiv e-prints*, 1908-7396 (2019).
18. B. Shick, W. E. Pickett. arXiv e-prints, 1558-1908 (2019).
19. S. Ran, H. Kim, I. Liu, S. Saha, I. Hayes, T. Metz, Y. S. Eo, J. Paglione, N. P. Butch. *arXiv e-prints*, 1909-6932 (2019).
20. S. Bae, H. Kim, S. Ran, Y. S. Eo, I. Liu, W. Fuhrman, J. Paglione, N. P. Butch, S. Anlage. *arXiv e-prints*, 1909-9032 (2019).
21. Lin Miao, S.Z. Liu, Y.S. Xu, E.C. Kotta, C.-J. Kang, S. Ran, J. Paglione, G. Kotliar, N.P. Butch, J.D. Denlinger, and L. A. Wray, *arXiv e-prints*, 1911.10152 (2019).

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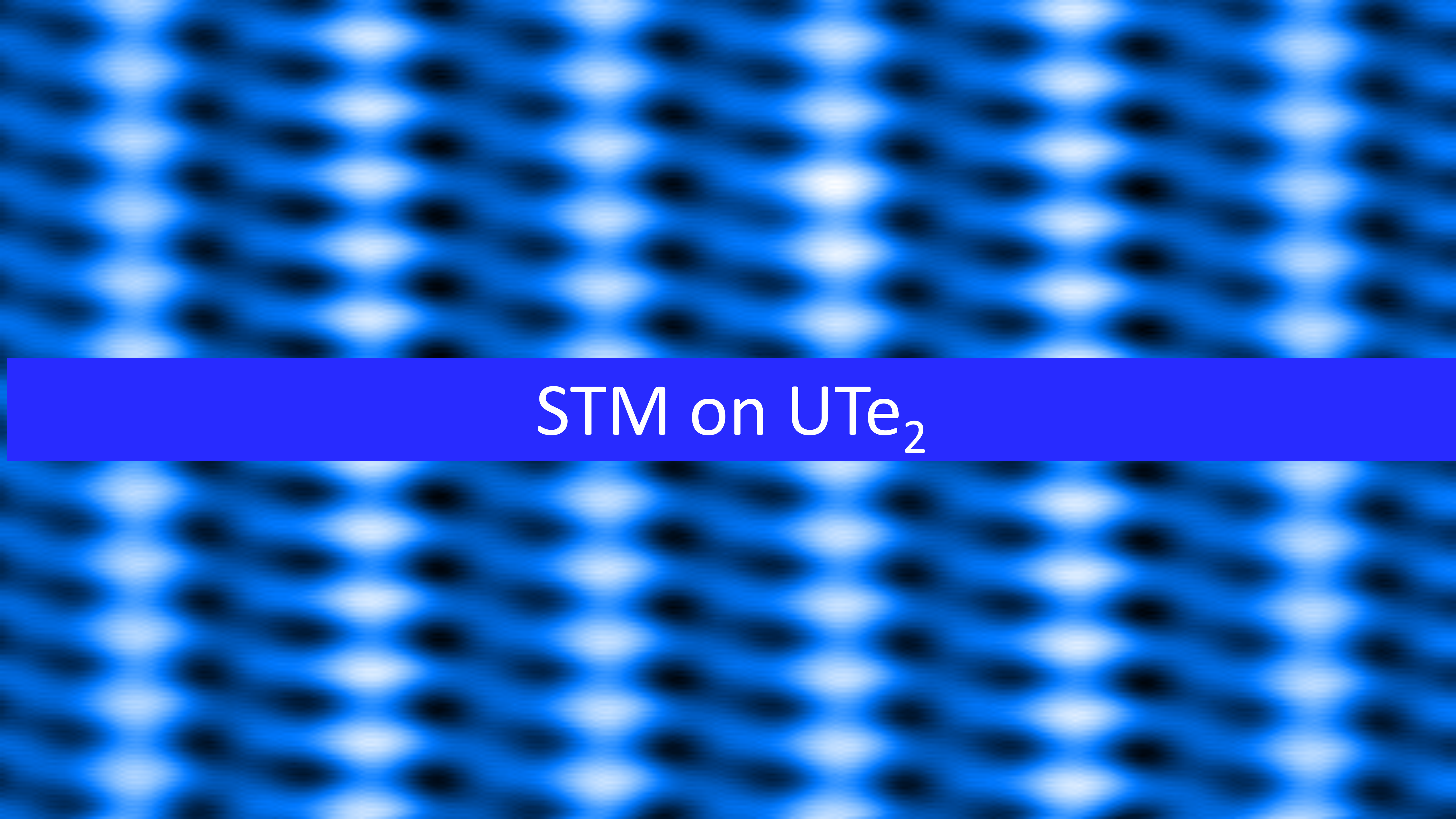


STM on UTe_2

Collaborators

STM (UIUC)

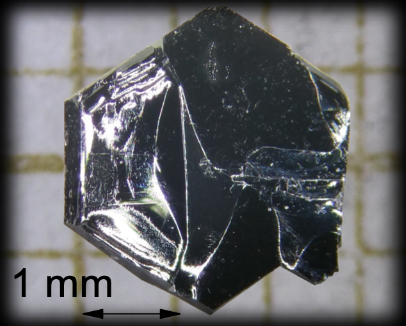
Lin Jiao
Sean Howard
Zhenyu Wang
Jorge Olivares Rodriguez
Anuva Aishwarya

Theory

Ziqiang Wang (BC)
Manfred Sigrist (ETH)
Barry Bradlyn (UIUC)

Single crystals (NIST)

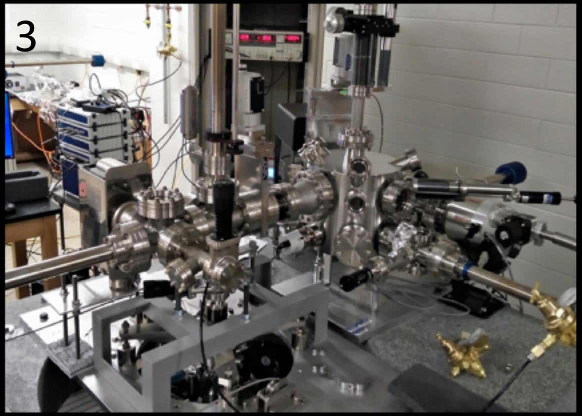
Sheng Ran
Nicholas P. Butch



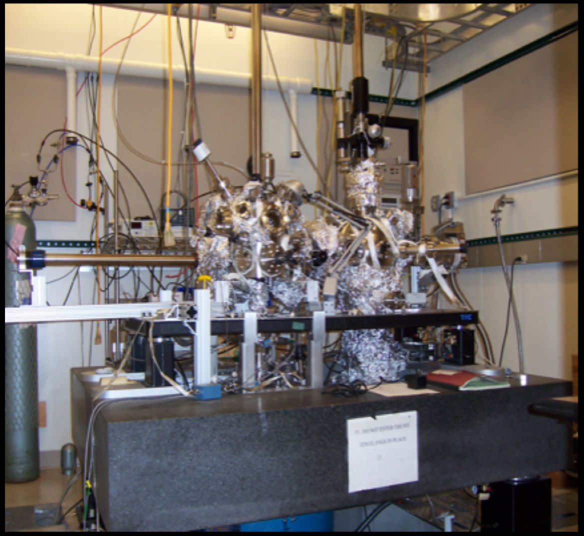
Ultra-high vacuum, low-temperature STMs

1

3



2



4

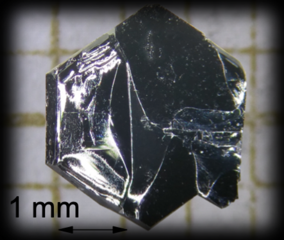
STM1: 300mK, 11T
Custom Unisoku STM

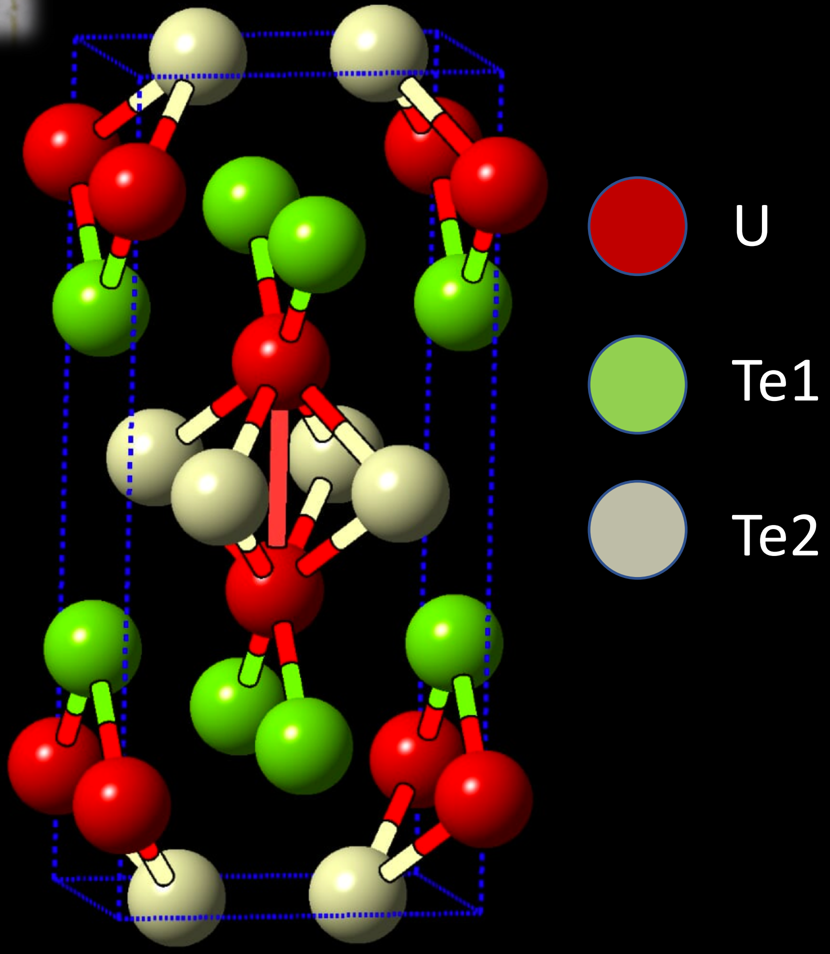
STM 2: 4K, Homebuilt system

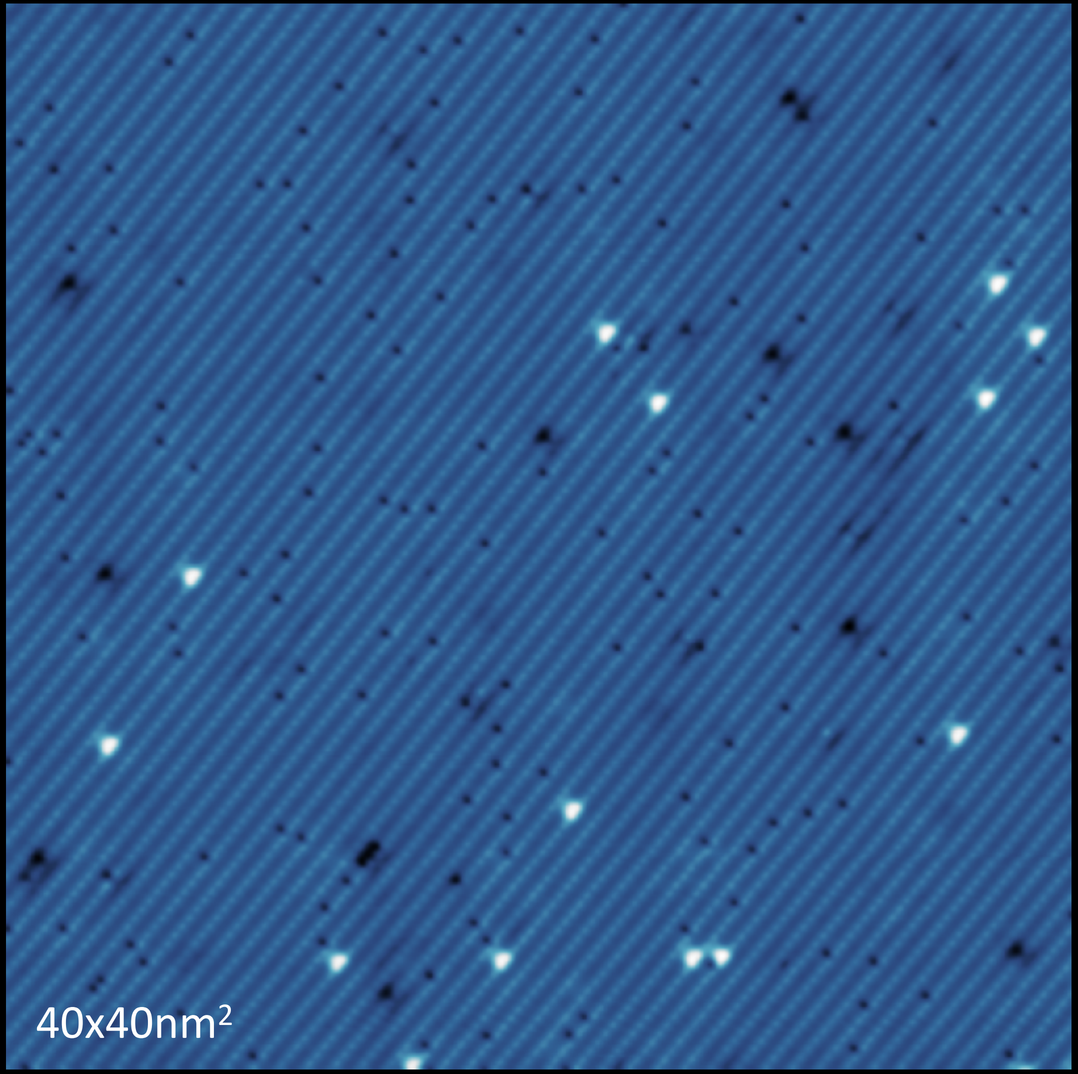
STM 3: 1K, 7T Hybrid STM

STM 4: 4K, Tabletop low boil off STM

UTe_2: Crystal Structure and STM topography





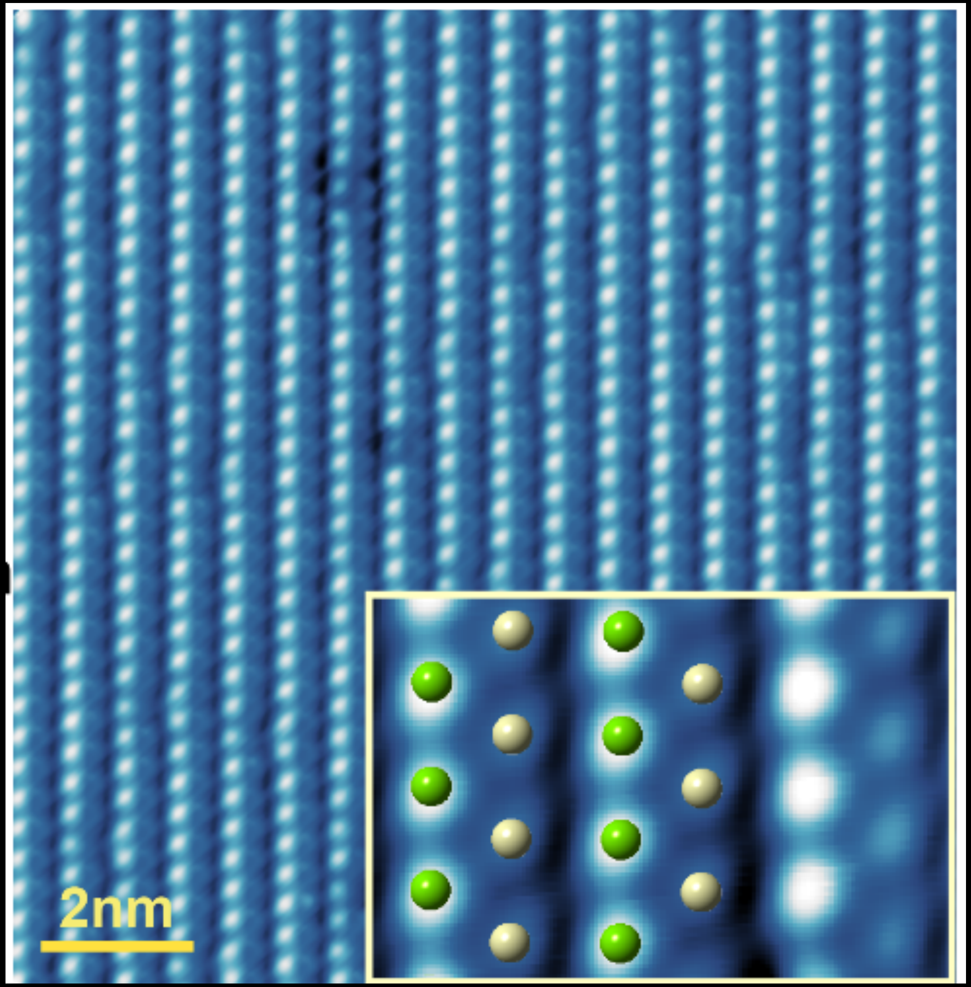


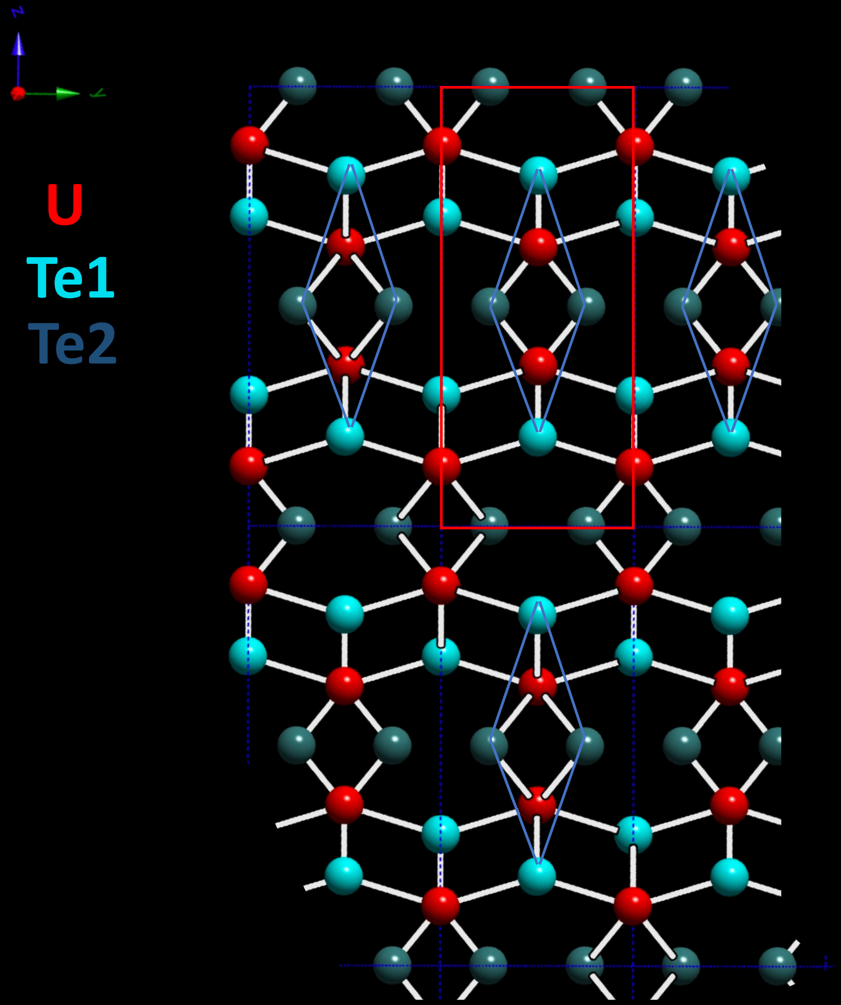
orthorhombic **structure** , space group Immm

$a = 4.1617$; $b = 6.1276$; $c = 13.965$ Å

Nature 579, 523-527 (2020)

UTe_2: STM Topography and cleave plane

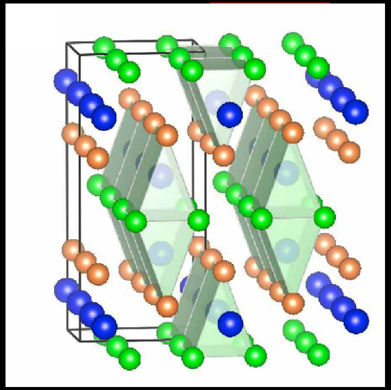




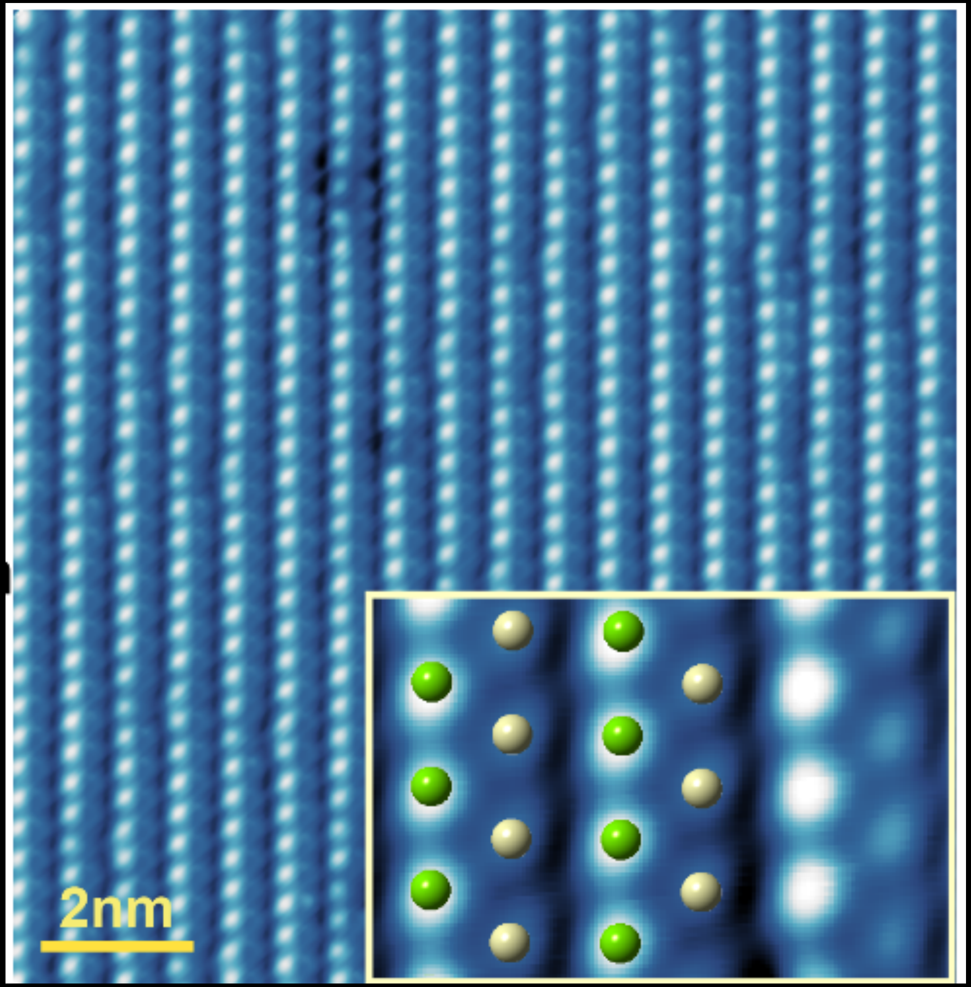
U

Te1

Te2



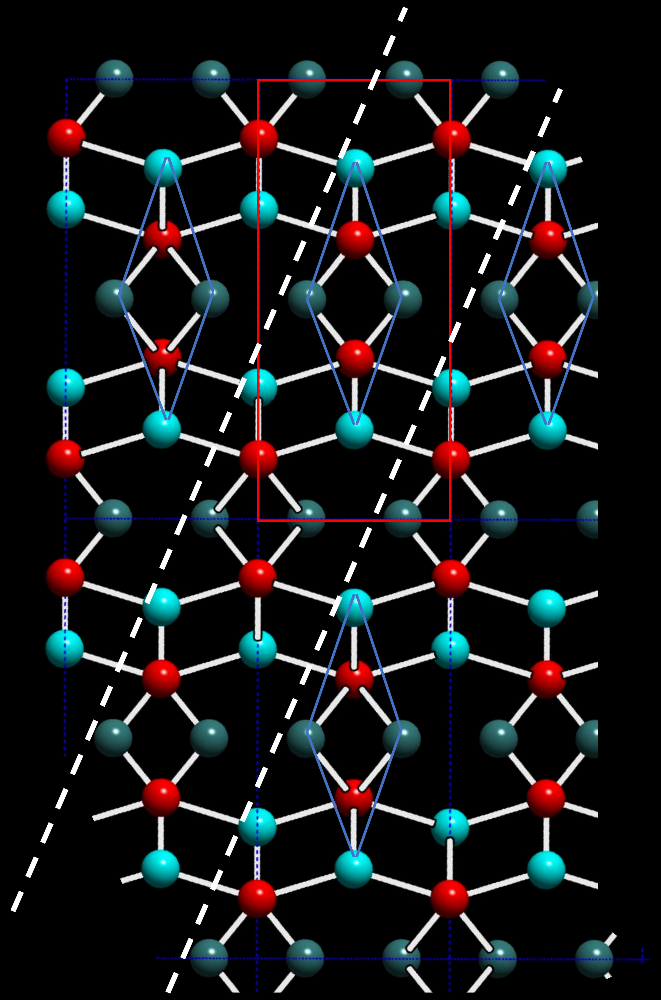
UTe$_2$: STM Topography and cleave plane

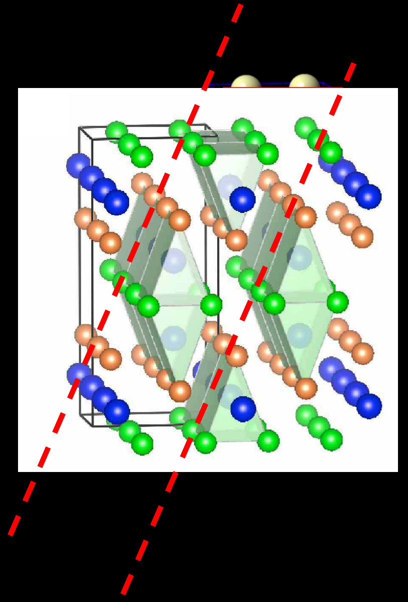


U

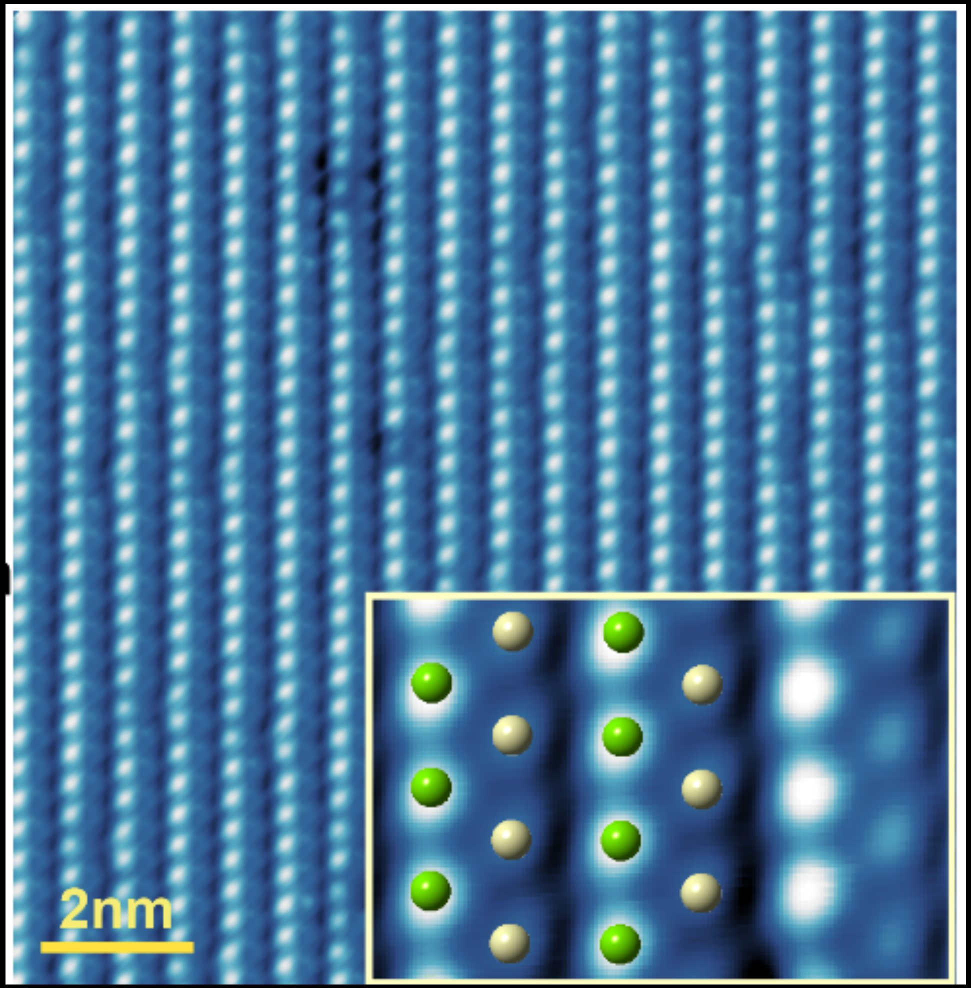
Te1

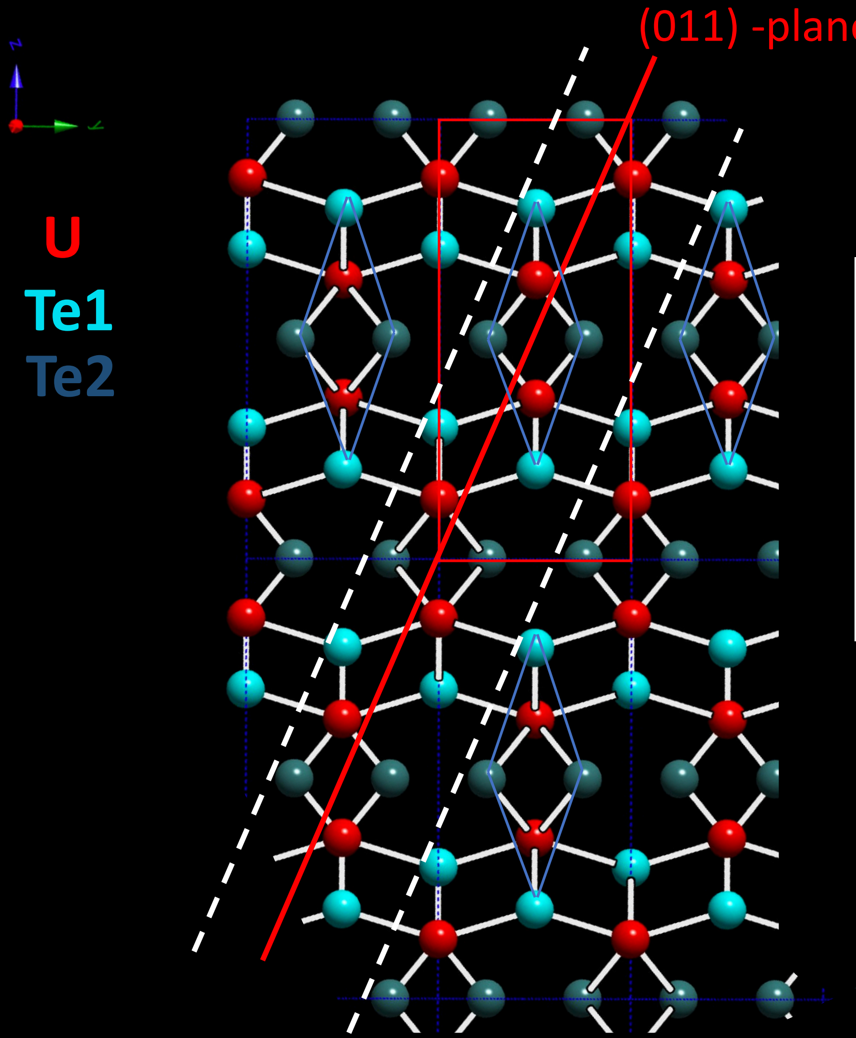
Te2

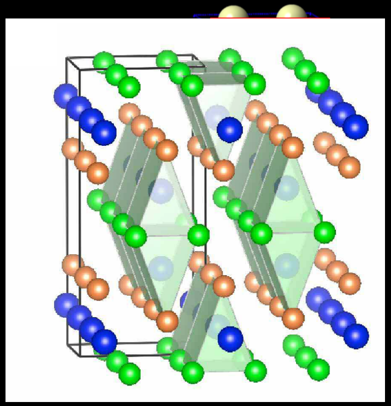




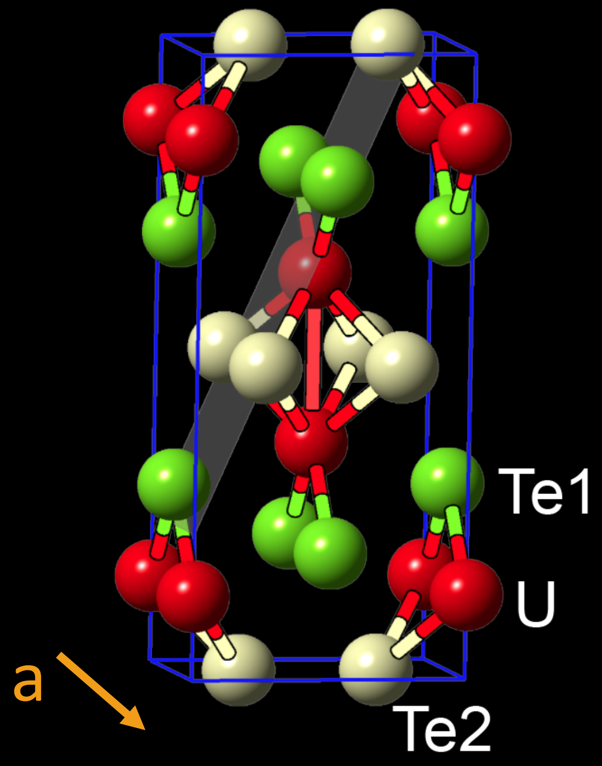
UTe_2: STM Topography and cleave plane



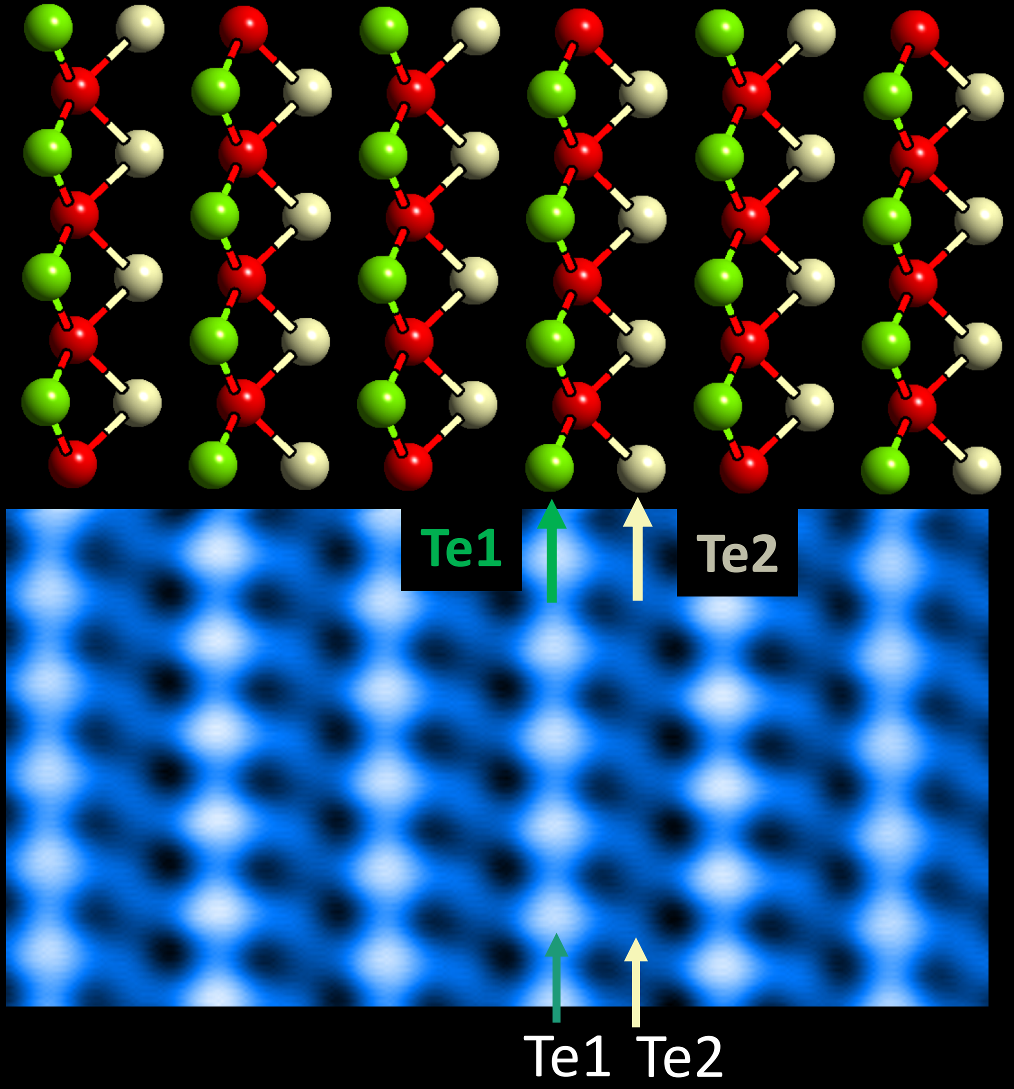




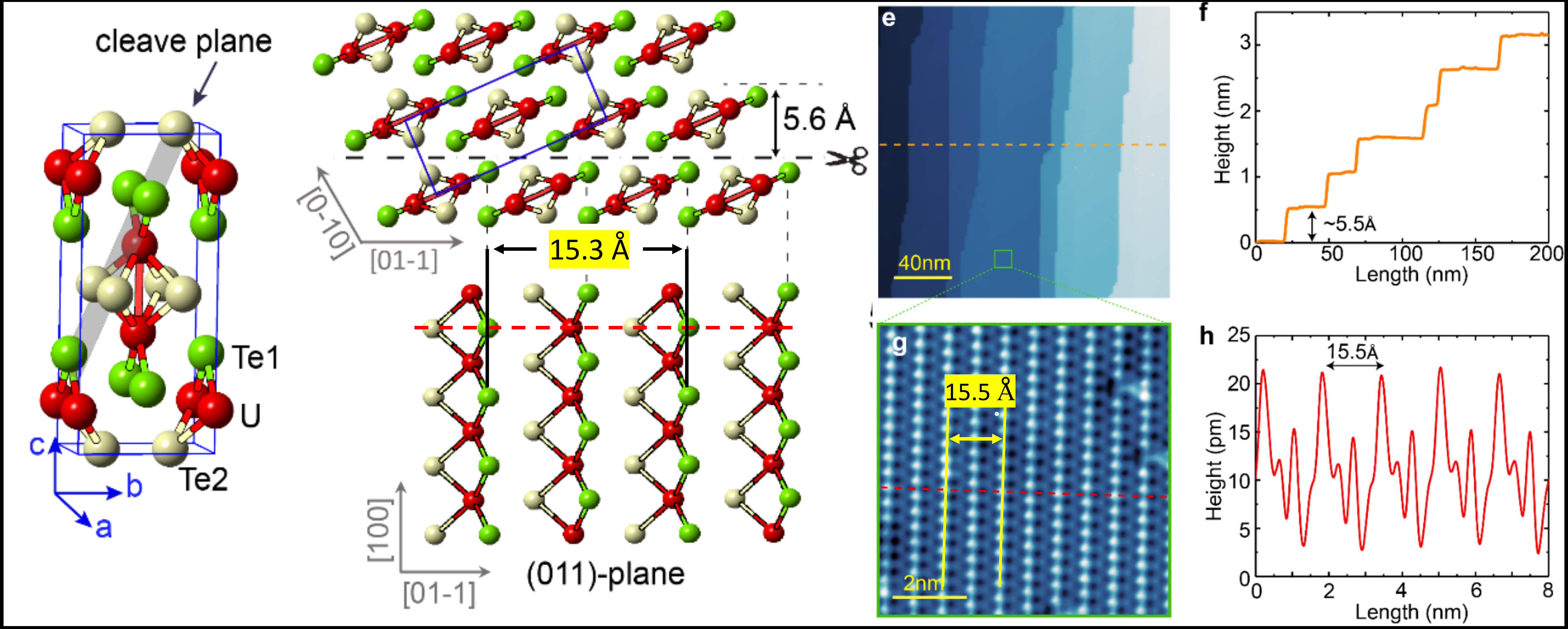
Crystal structure of UTe$_2$



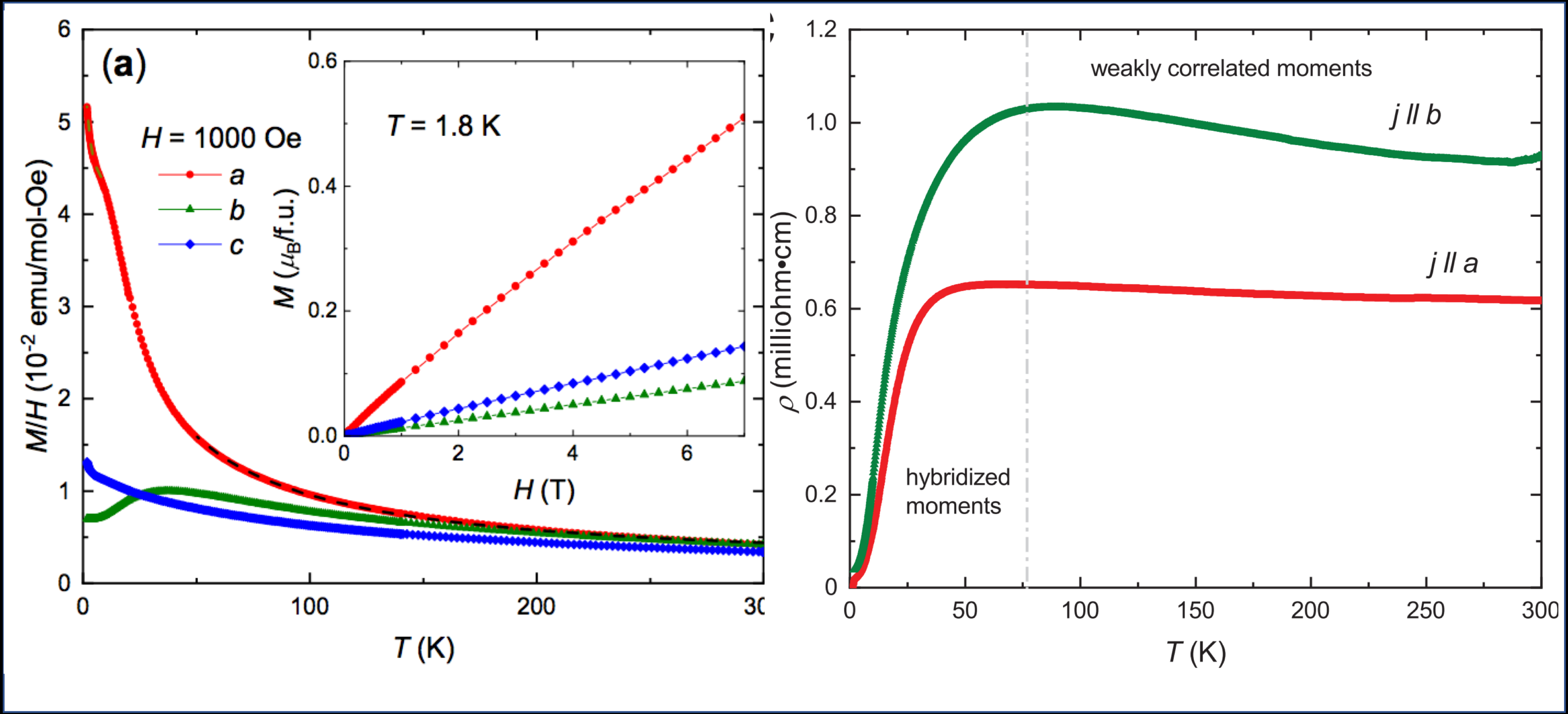
space group *Immm*


(011)-plane

UTe_2: STM Topography and cleave plane



Normal State: Heavy Fermion Metal



Ran et.al., Science 365, 684 (2019)

Normal State: Heavy Fermion Metal

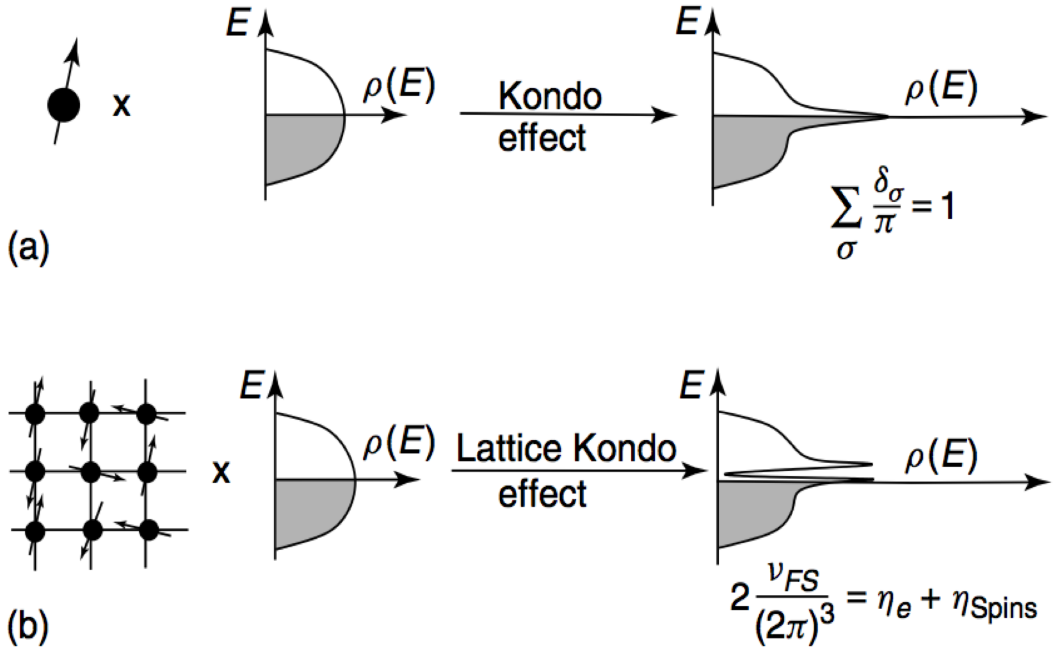
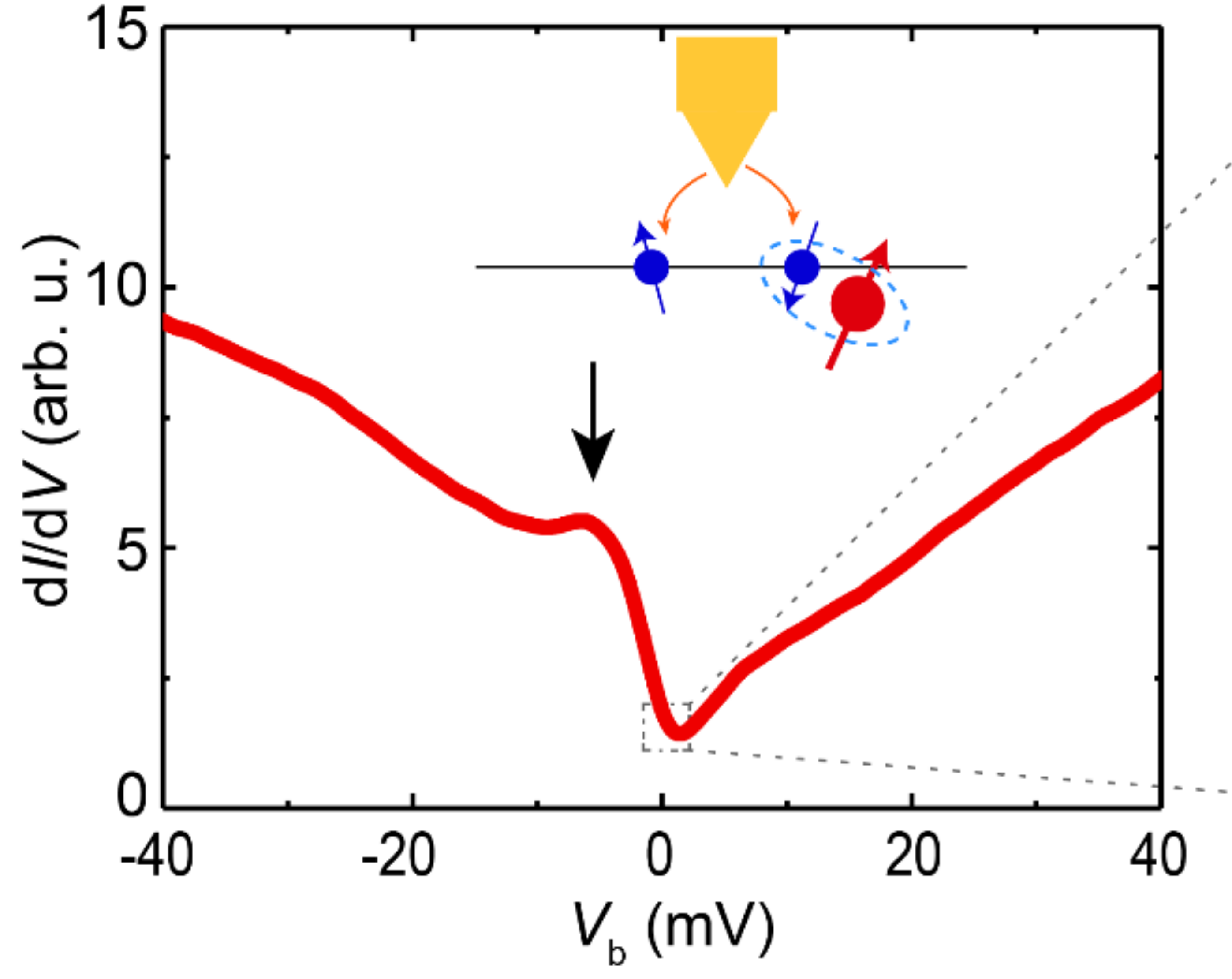


Figure 2. (a) Single-impurity Kondo effect builds a single fermionic level into the conduction sea, which gives rise to a resonance in the conduction electron density of states. (b) Lattice Kondo effect builds a fermionic resonance into the conduction sea in each unit cell. The elastic scattering of this lattice of resonances leads to the formation of a heavy-electron band, of width T_K.

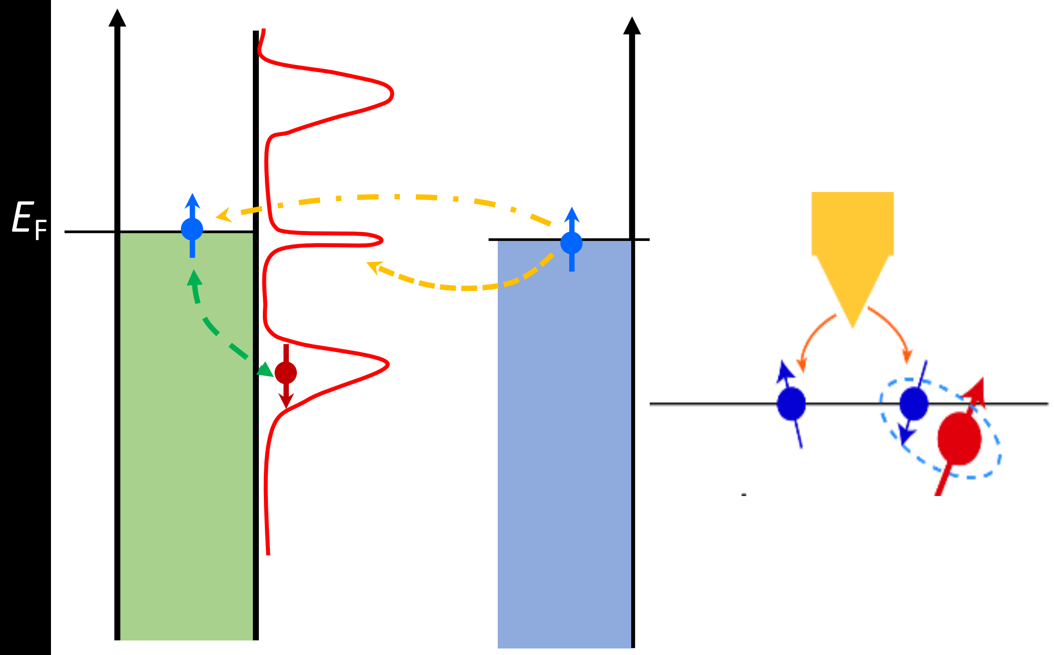
- A Fermi surface volume which counts the f electrons as itinerant quasiparticles.
- Effective masses often in excess of 100 free electron masses. Higher mass quasiparticle orbits, though inferred from thermodynamics, cannot be observed with current measurement techniques.
- Often, but not always, the Fermi surface geometry is in accord with band theory, despite the huge renormalizations of the electron mass.

https://www.physics.rutgers.edu/~coleman/682A/electrons_on_the_brink.pdf : Piers Coleman

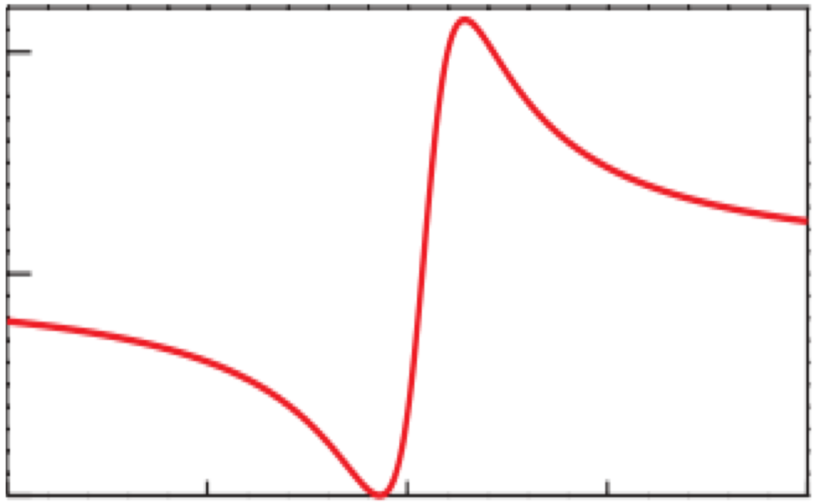
dI/dV (V) spectrum: strange lineshape



Fano lineshape of Kondo resonance



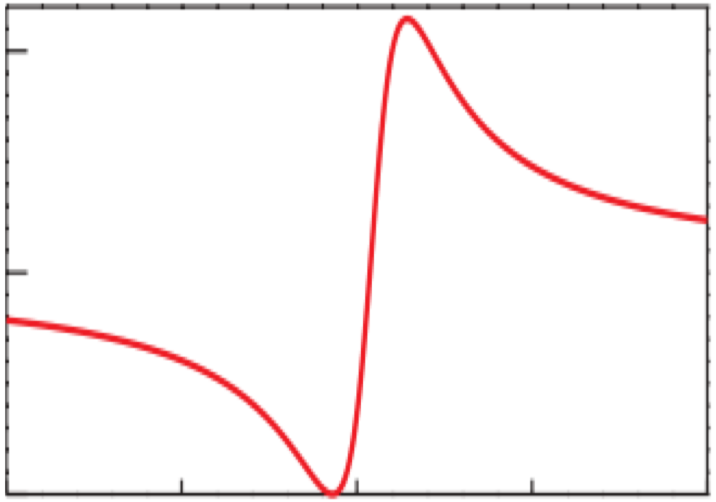
$$g(\mathbf{r}, E) \propto \frac{(q+E')^2}{E'^2+1} \text{ where } E' = \frac{(E-\varepsilon_0)}{\Gamma/2}$$



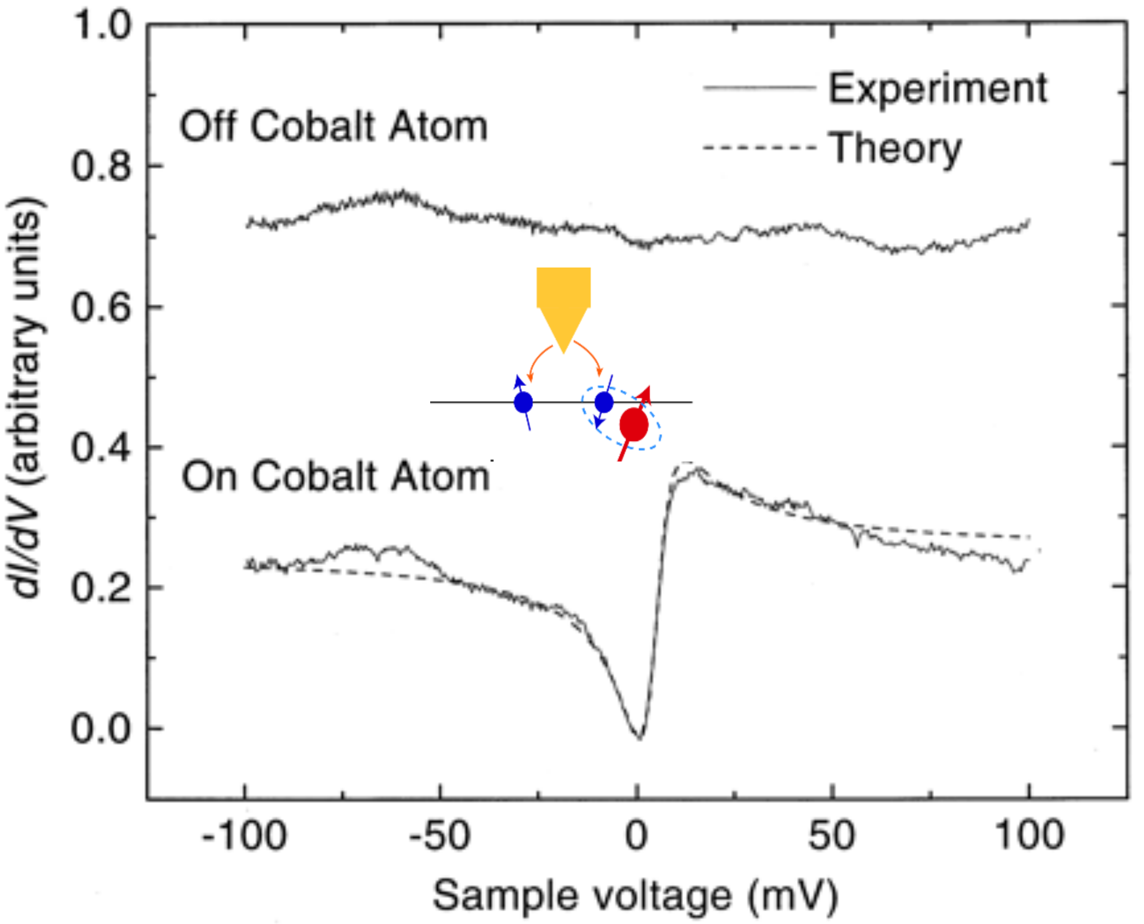
U. Fano, Physical Review. 124 (6) 1866–1878, (1961)

Fano lineshape of Kondo resonance

$$g(\mathbf{r}, E) \propto \frac{(q + E')^2}{E'^2 + 1} \text{ where } E' = \frac{(E - \varepsilon_0)}{\Gamma/2}$$

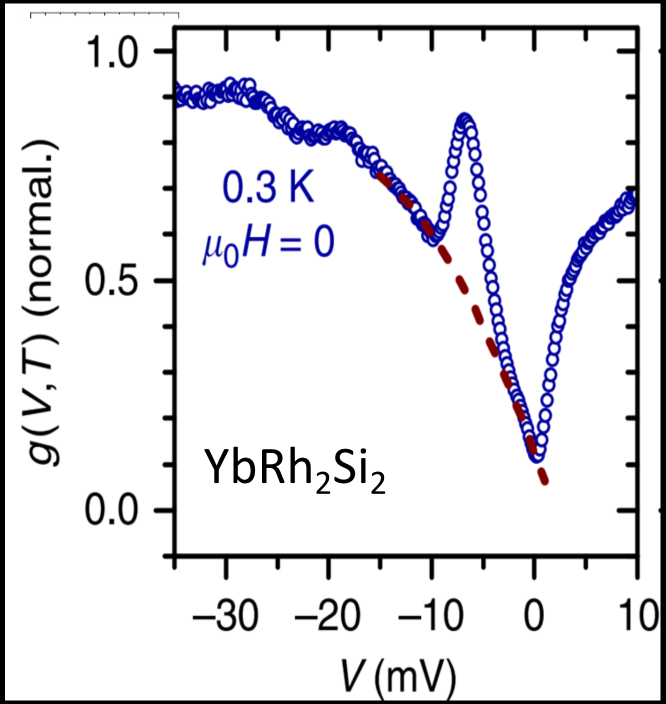


U. Fano, Physical Review. 124 (6) 1866–1878, (1961)

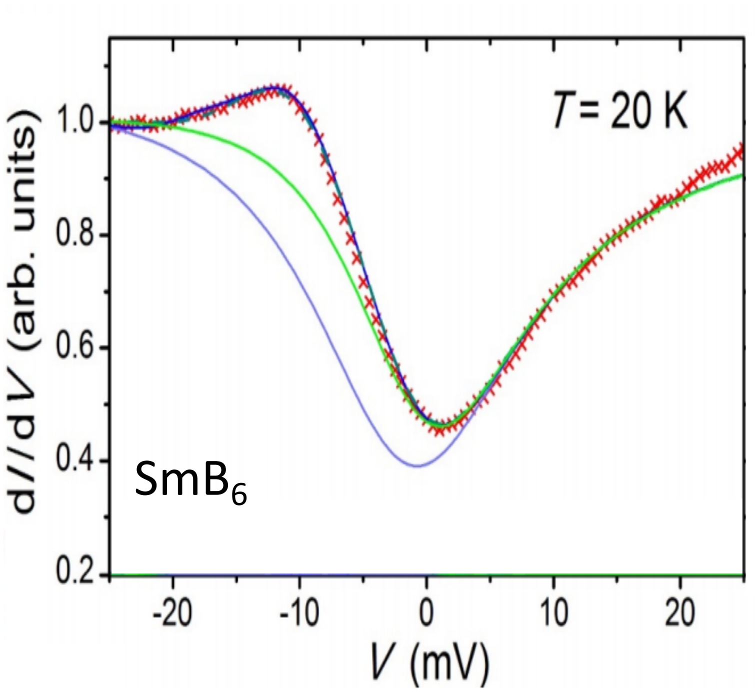


Science 280, 567-569 (1998)

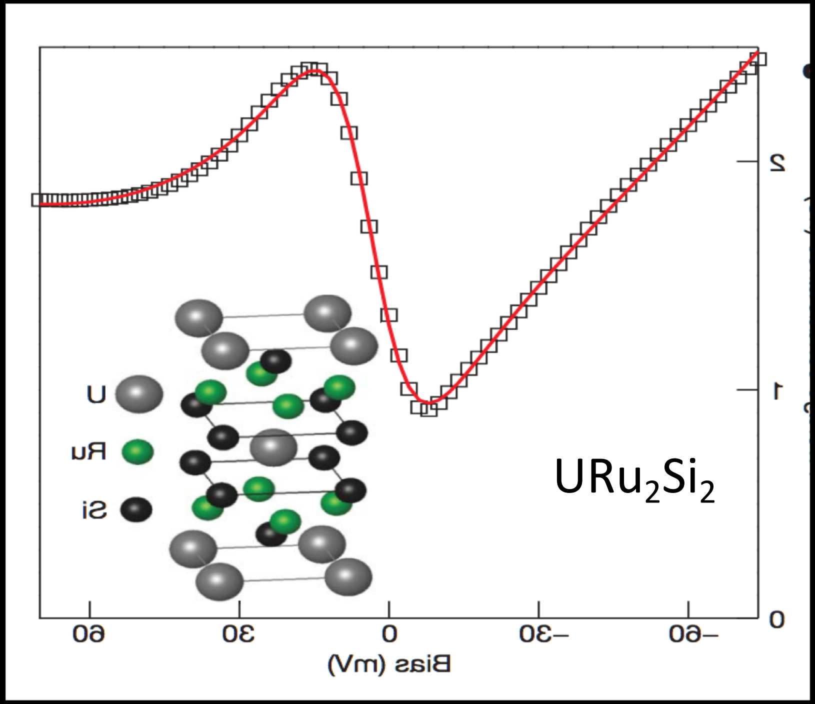
STM on Heavy Fermion Compounds: Fano resonance



S. Seiro, L. Jiao et al.
Nat. Commun. (2018)

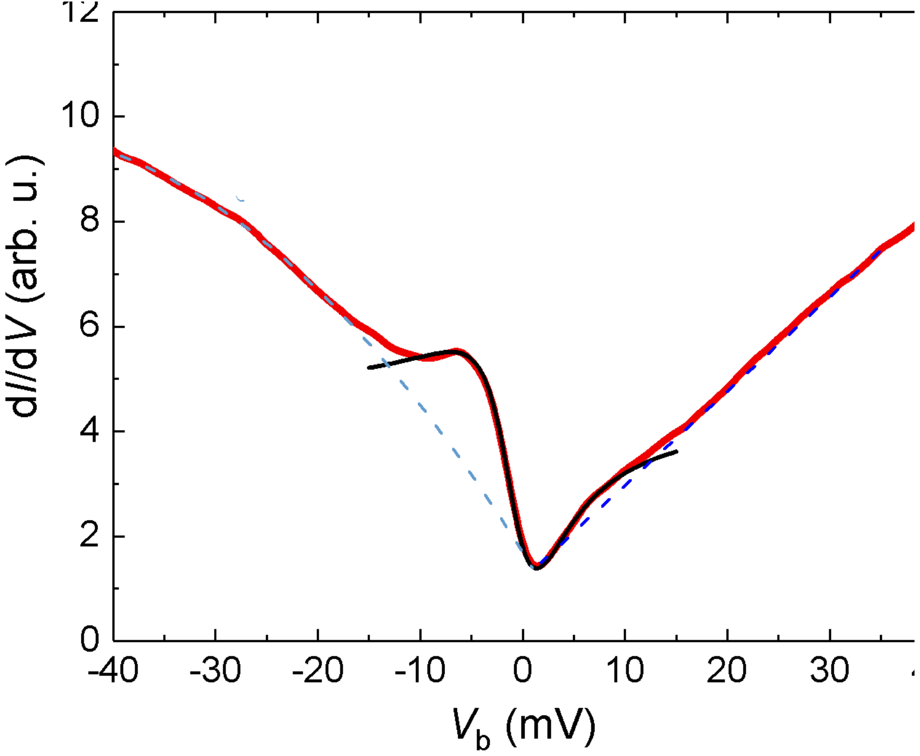


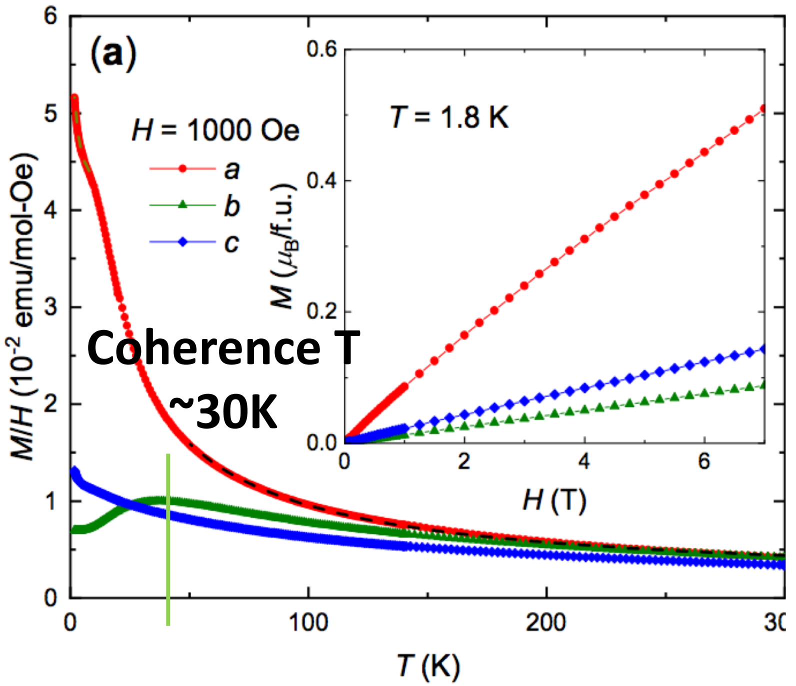
L. Jiao et al.
Nat. Commun. (2016)



Nature 465, 570 (2010)

Fitting Fano lineshape to resonance at E_F





Coherence T ~30K

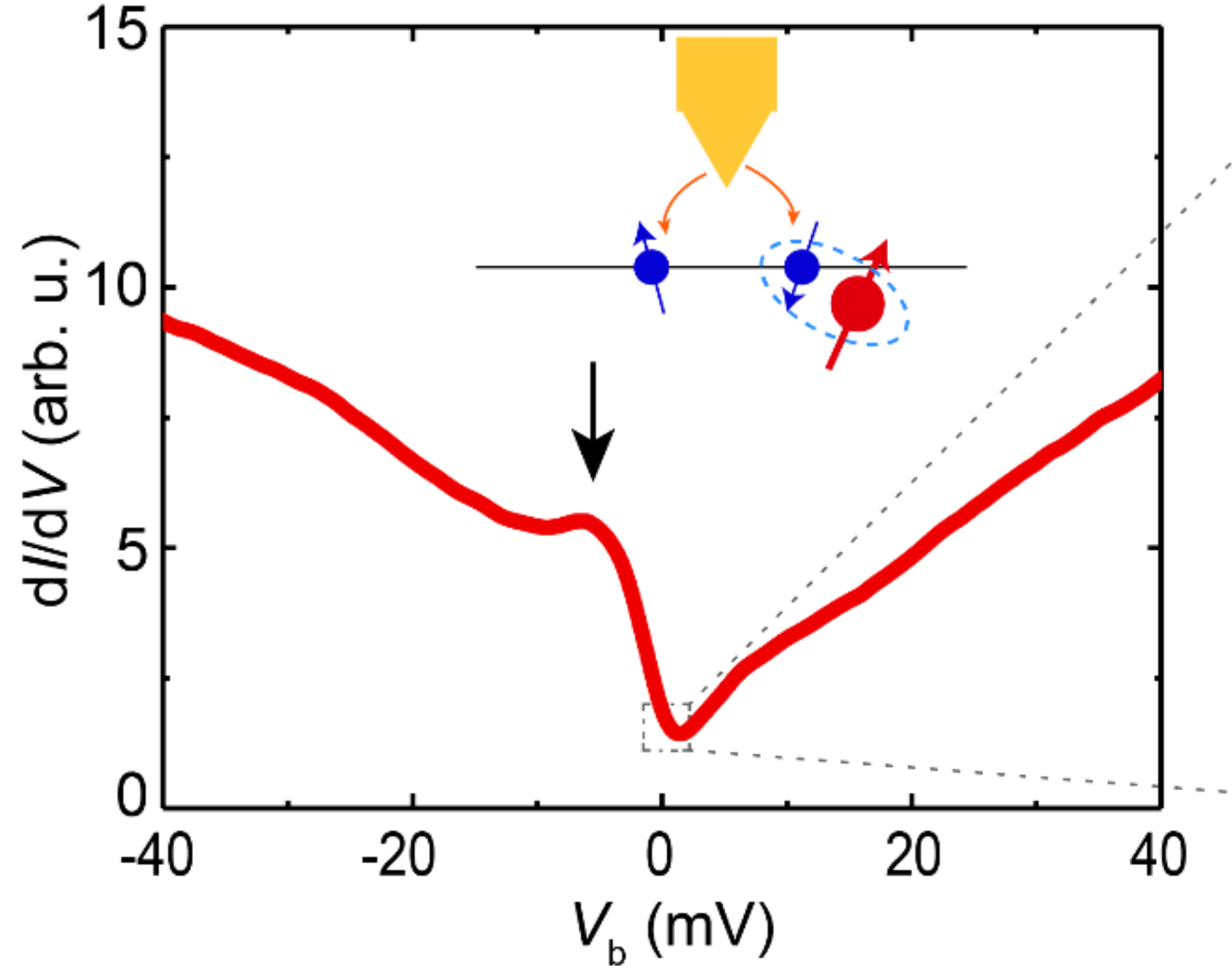
$$\left[\mathrm{d}I/\mathrm{d}V(V) \propto \frac{((V+E_0)/\Gamma+q)^2}{1+((V+E_0)/\Gamma)^2}\right]$$

Red and black curves are the raw data and the fitted curves

The fitting parameters are $q = 0.57\ (2)$, $E_0 = 0.70(8)$ meV and $\Gamma = 3.60\ (6)$ meV

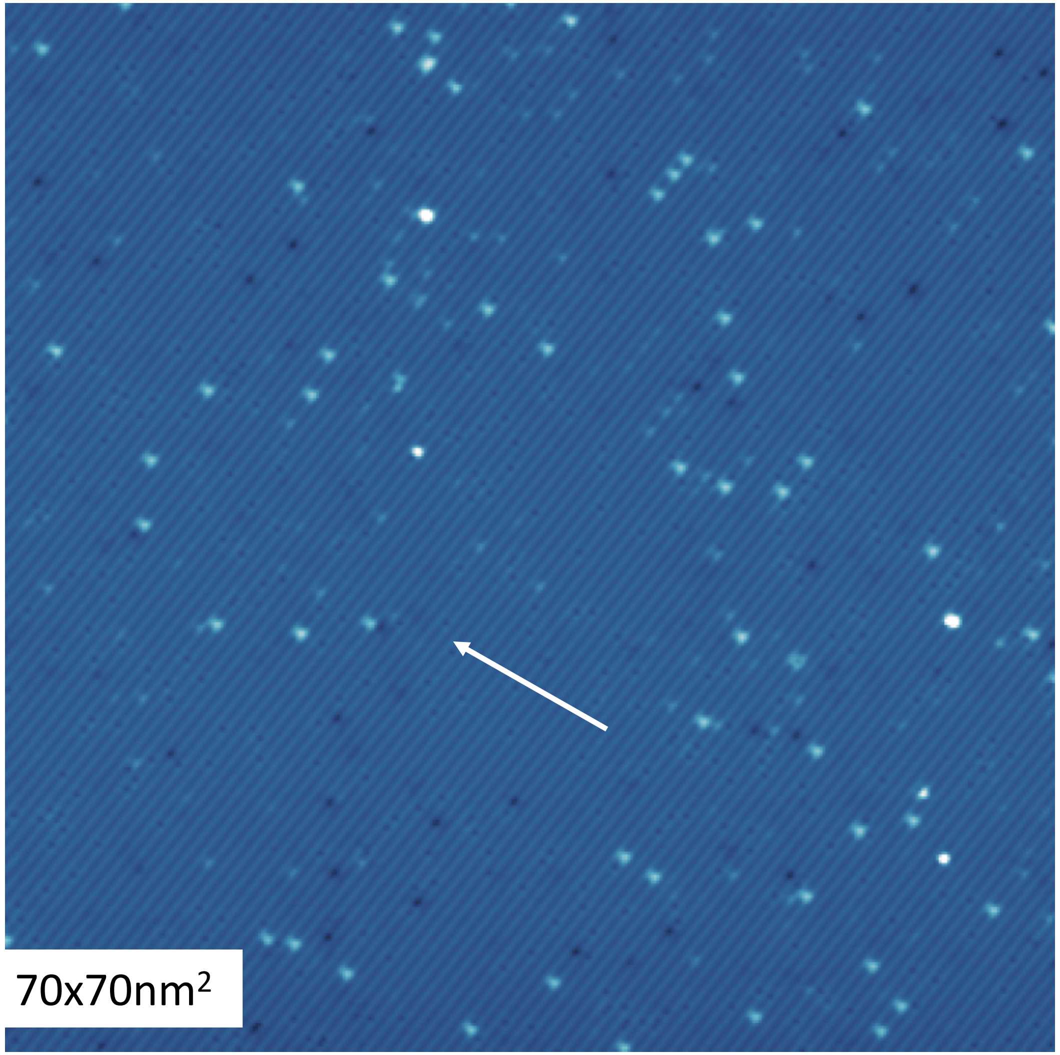
T_K from width ~ 30K

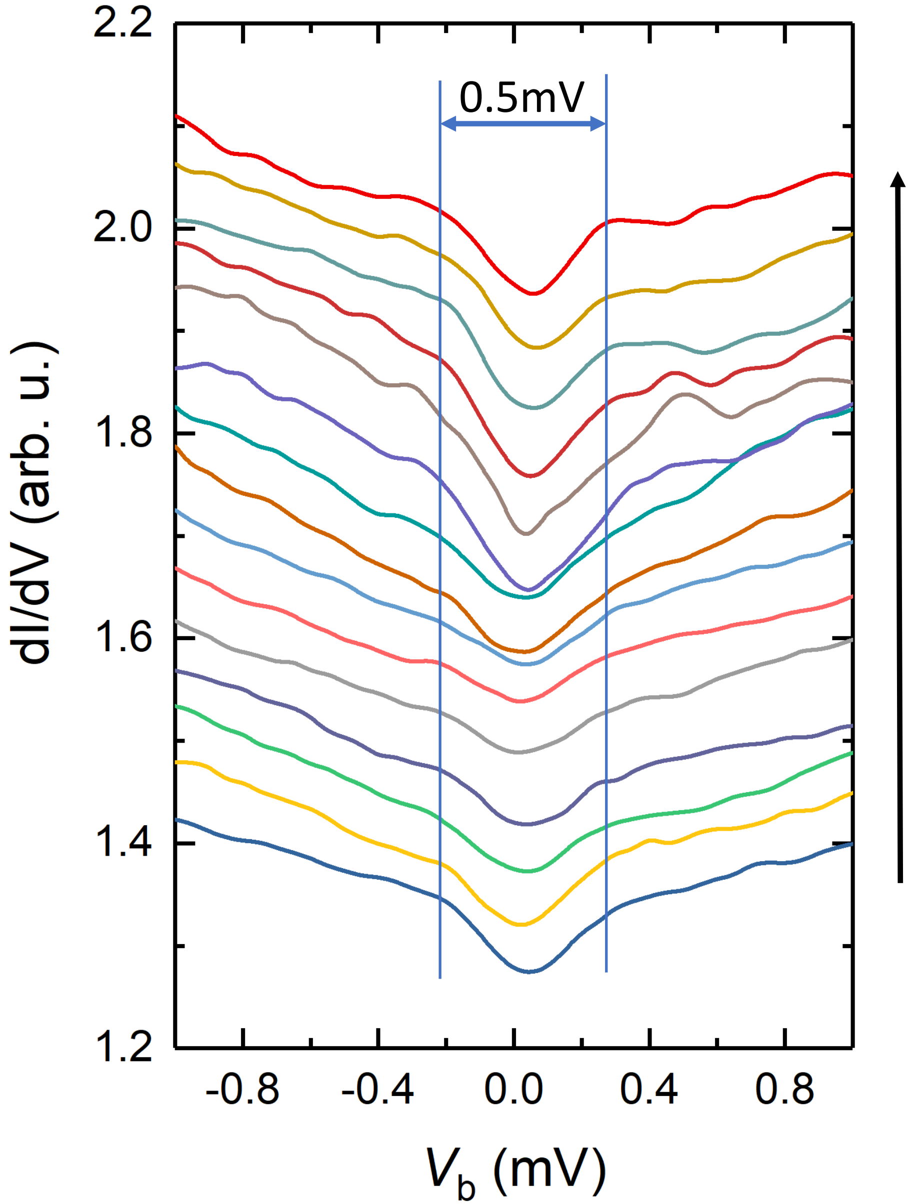
dI/dV (V) spectrum



Nature 579, 523-527 (2020)

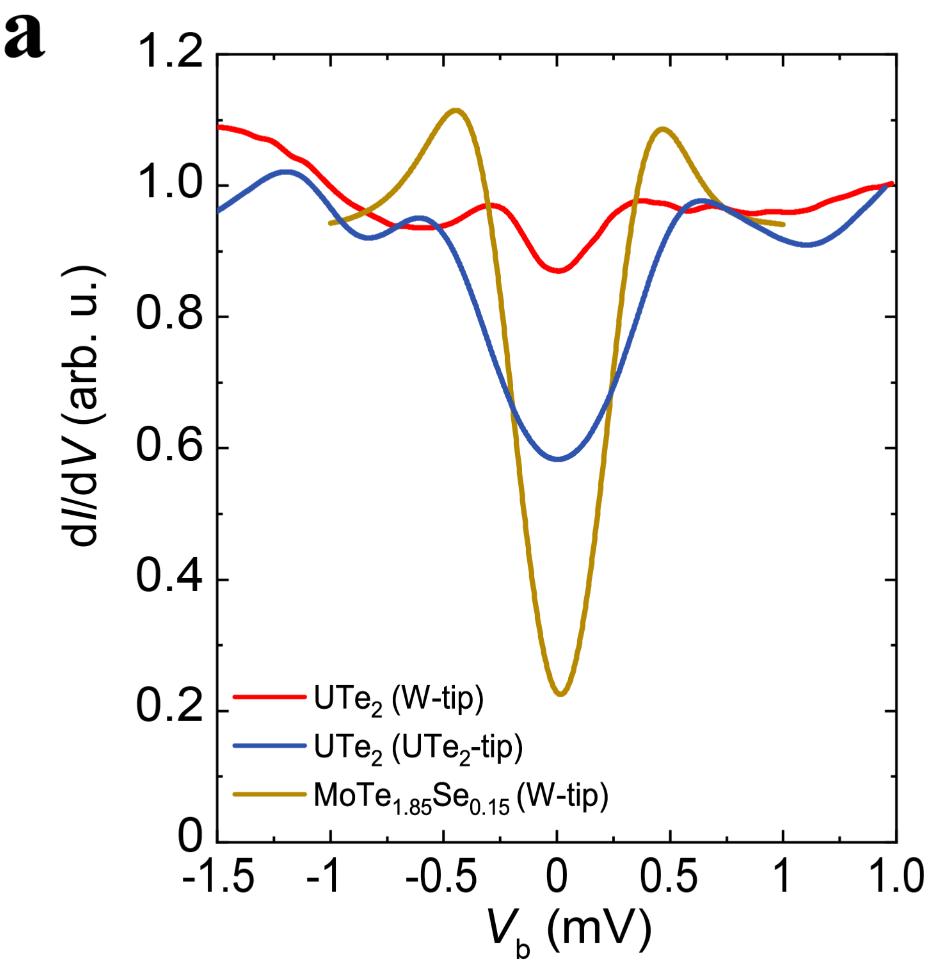
Low energy STM Spectra





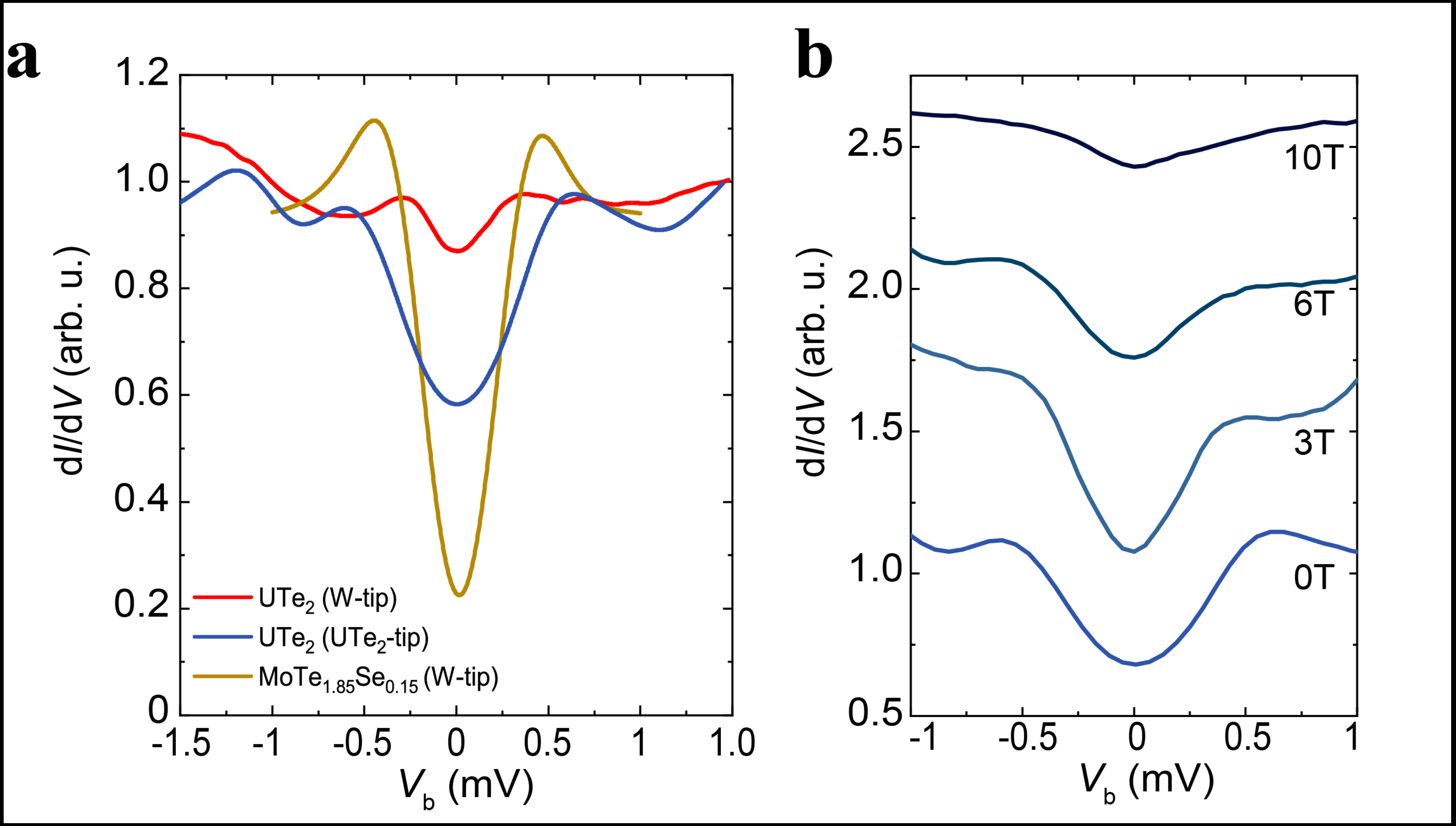
300mK

Superconducting gap



300mK

Superconducting gap

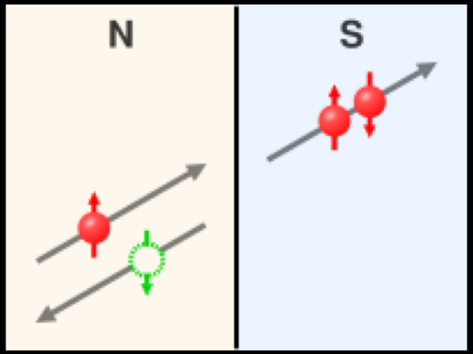


300mK

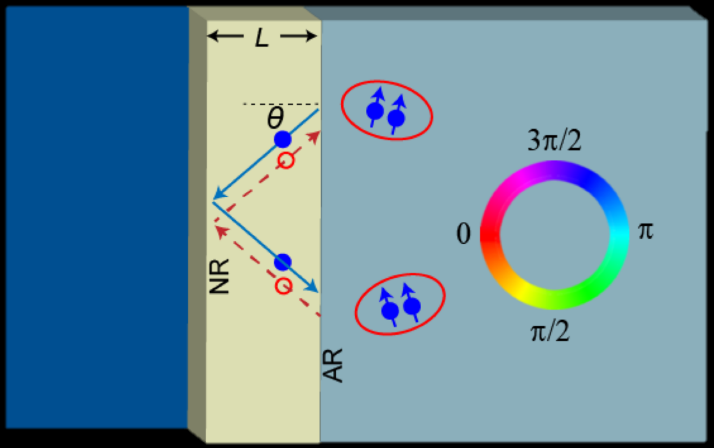
What can STM tell us about the order parameter?

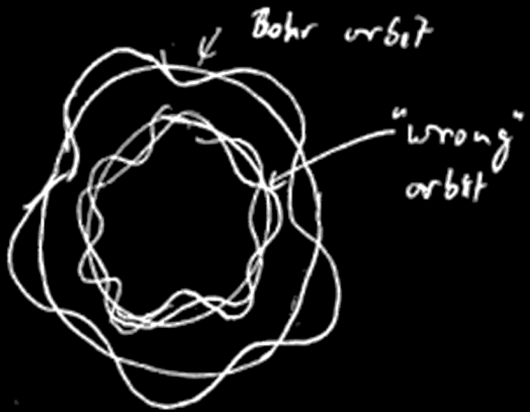
Do we see chiral boundary states?

Andreev Bound States



Electron (red) meeting the interface produces a Cooper pair in the superconductor and a retroreflected hole (green) in the normal conductor.

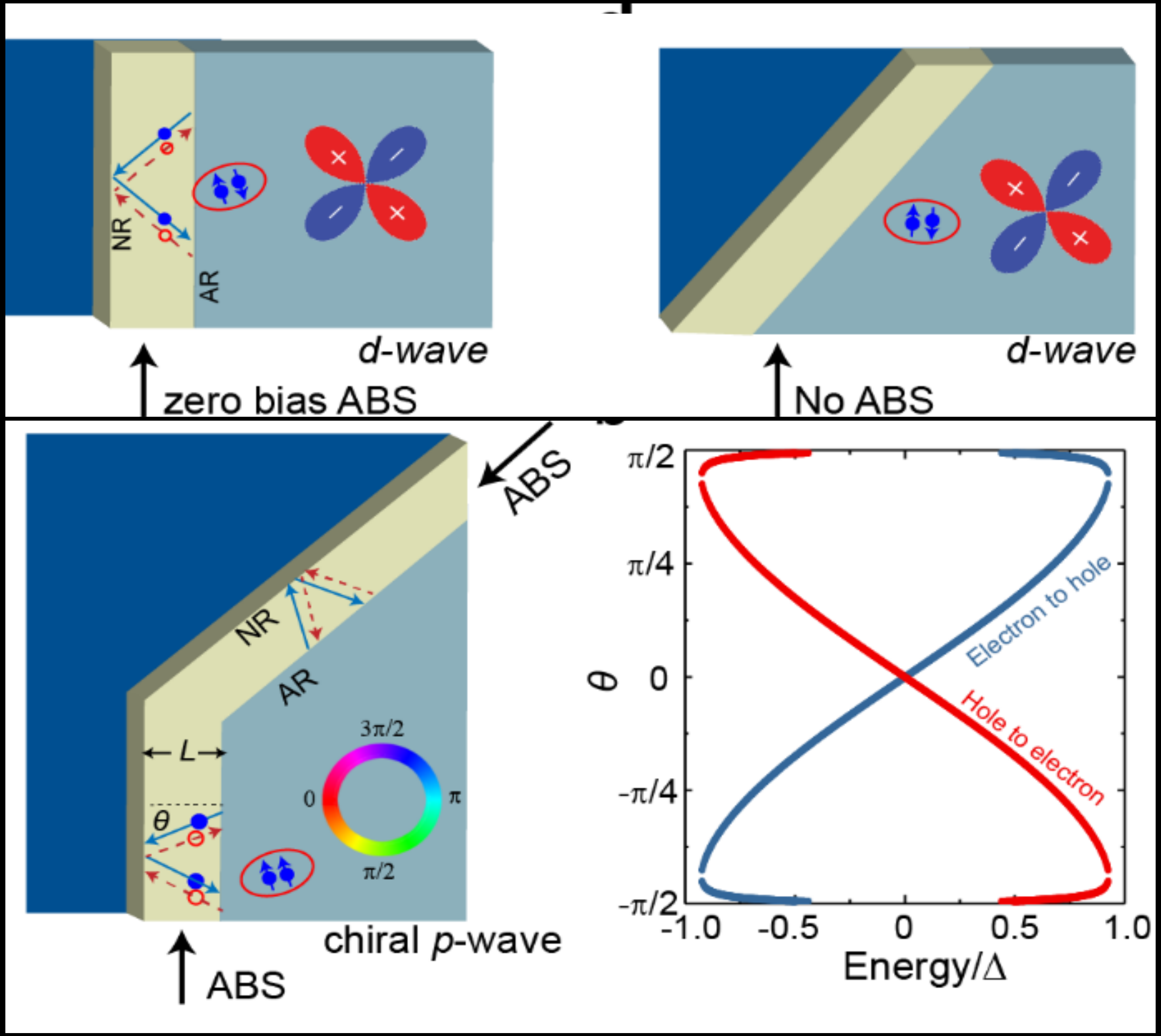




$$\text{phase} = \underbrace{2\arccos[E/\Delta]}_{=\pi \text{ @ } E=0} \pm \Phi + \beta(E) = 2n\pi$$

Bohr-Sommerfeld quantization condition

Edge Modes in Unconventional Superconductors



$$2\cos^{-1}[E/\Delta] \pm \Phi + \beta(E) = 2n\pi$$

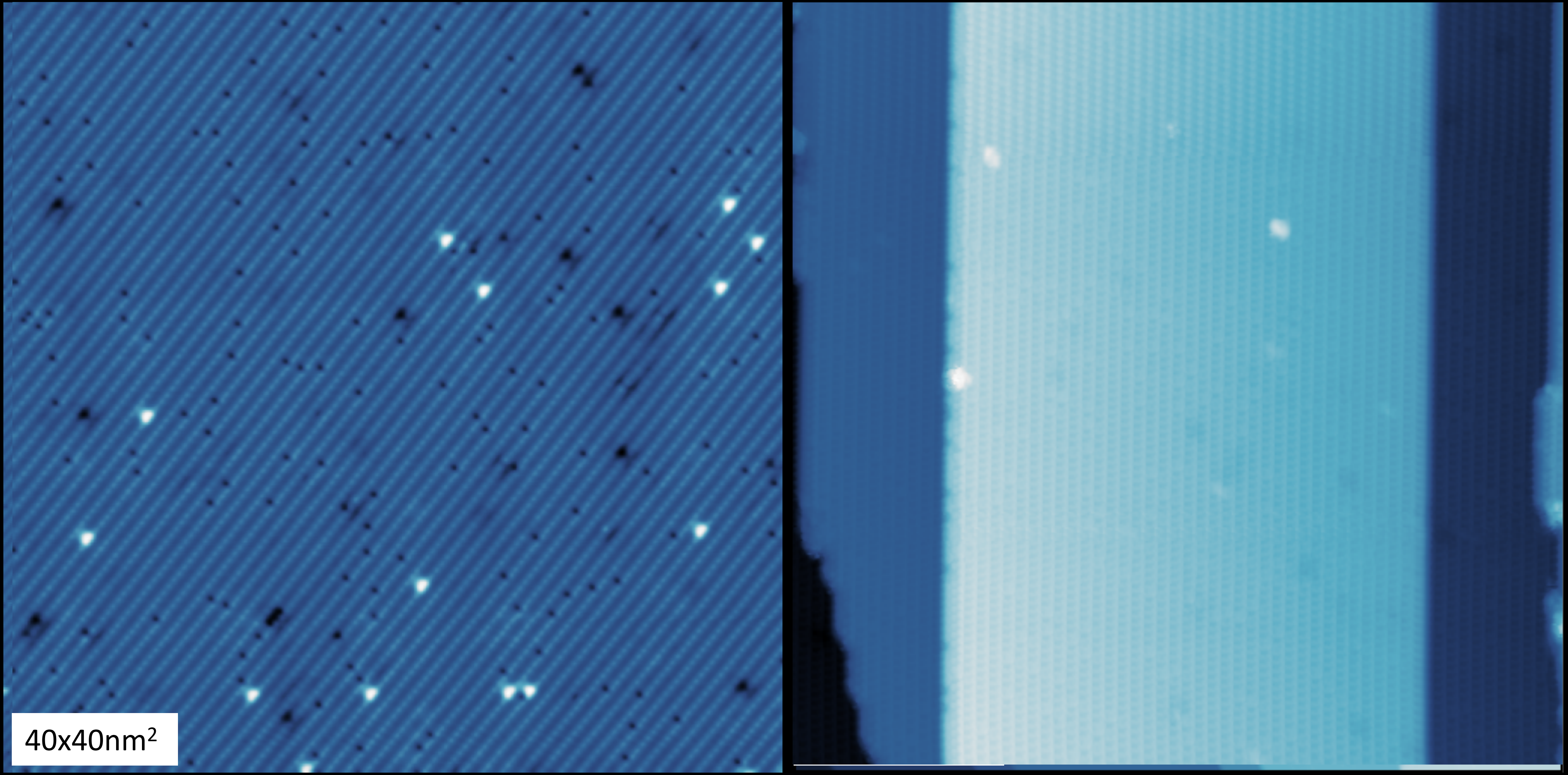
$=\pi$ @ $E=0$

$$\beta(E) \approx 4LE/\hbar v_F \cos\theta$$

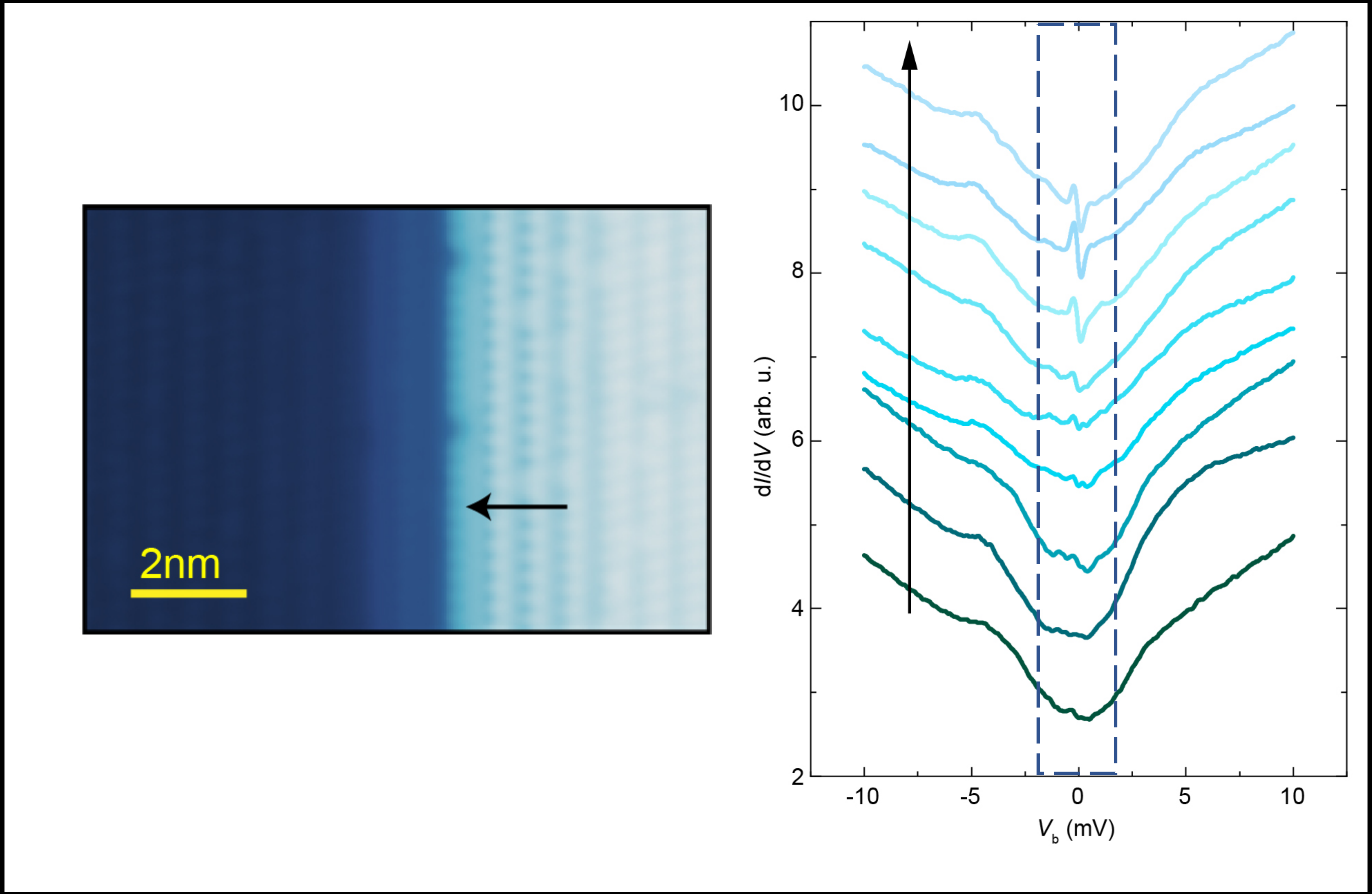
$$\Phi = \pi - 2\theta$$

Spectroscopy on boundaries: information on order parameter symmetry

Steps in UTe_2

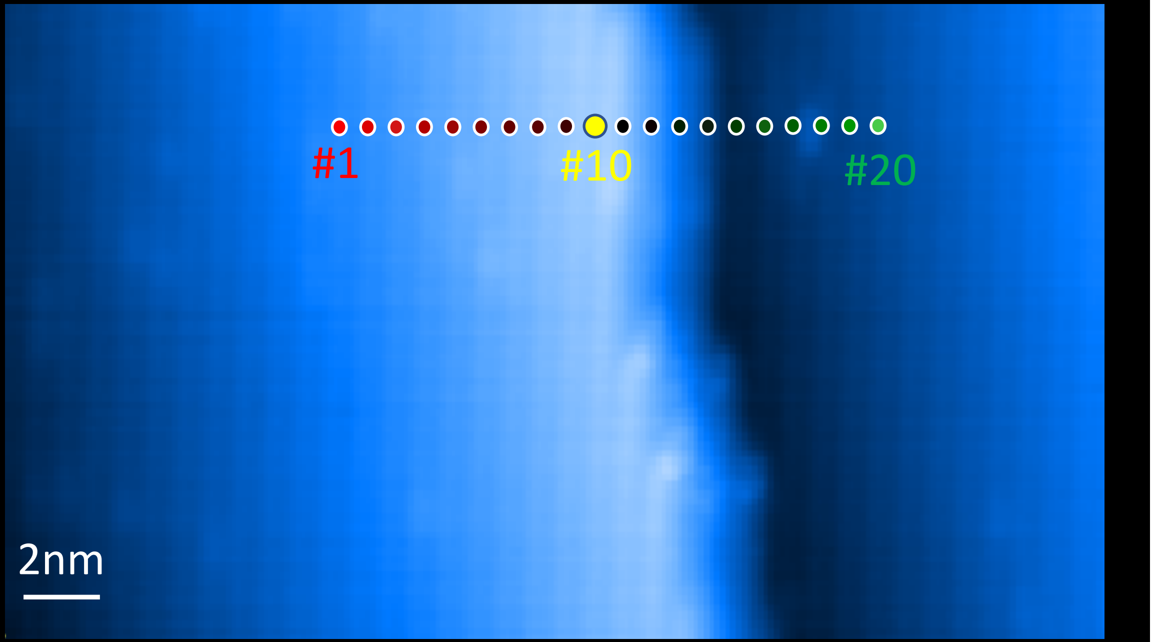


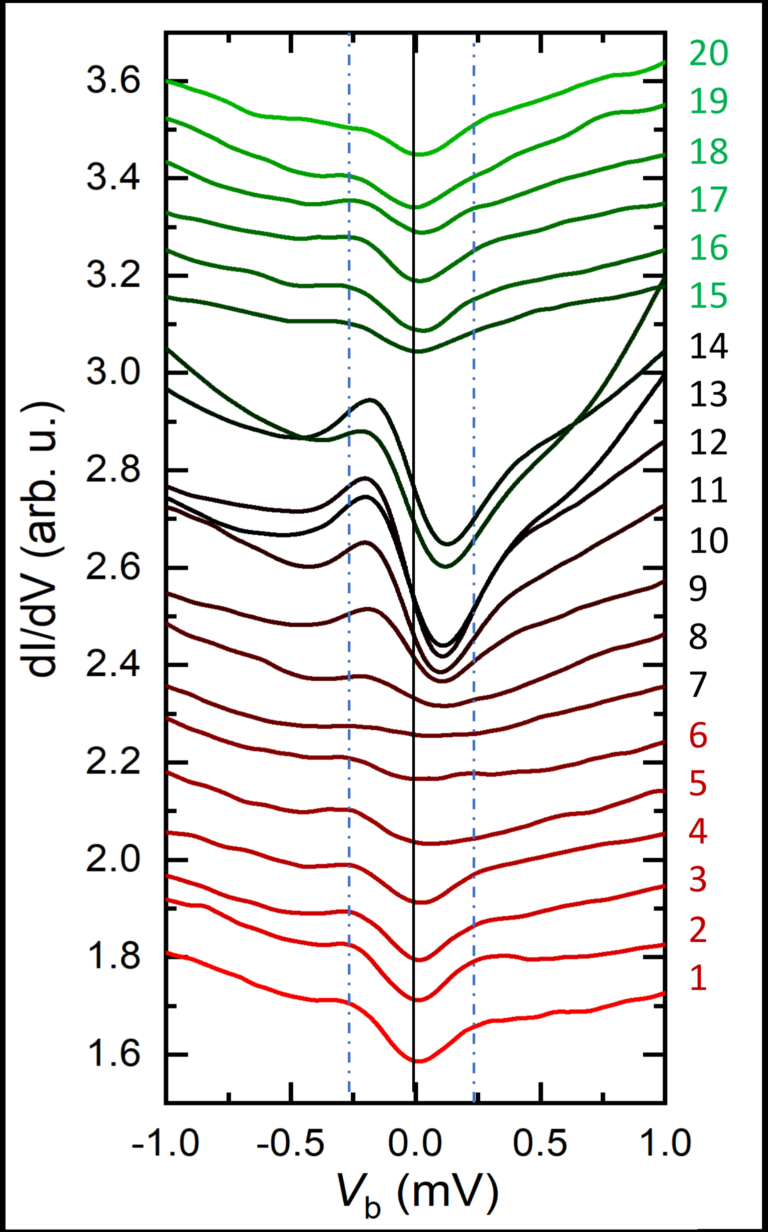
UTe_2 : Spectroscopy on step edges



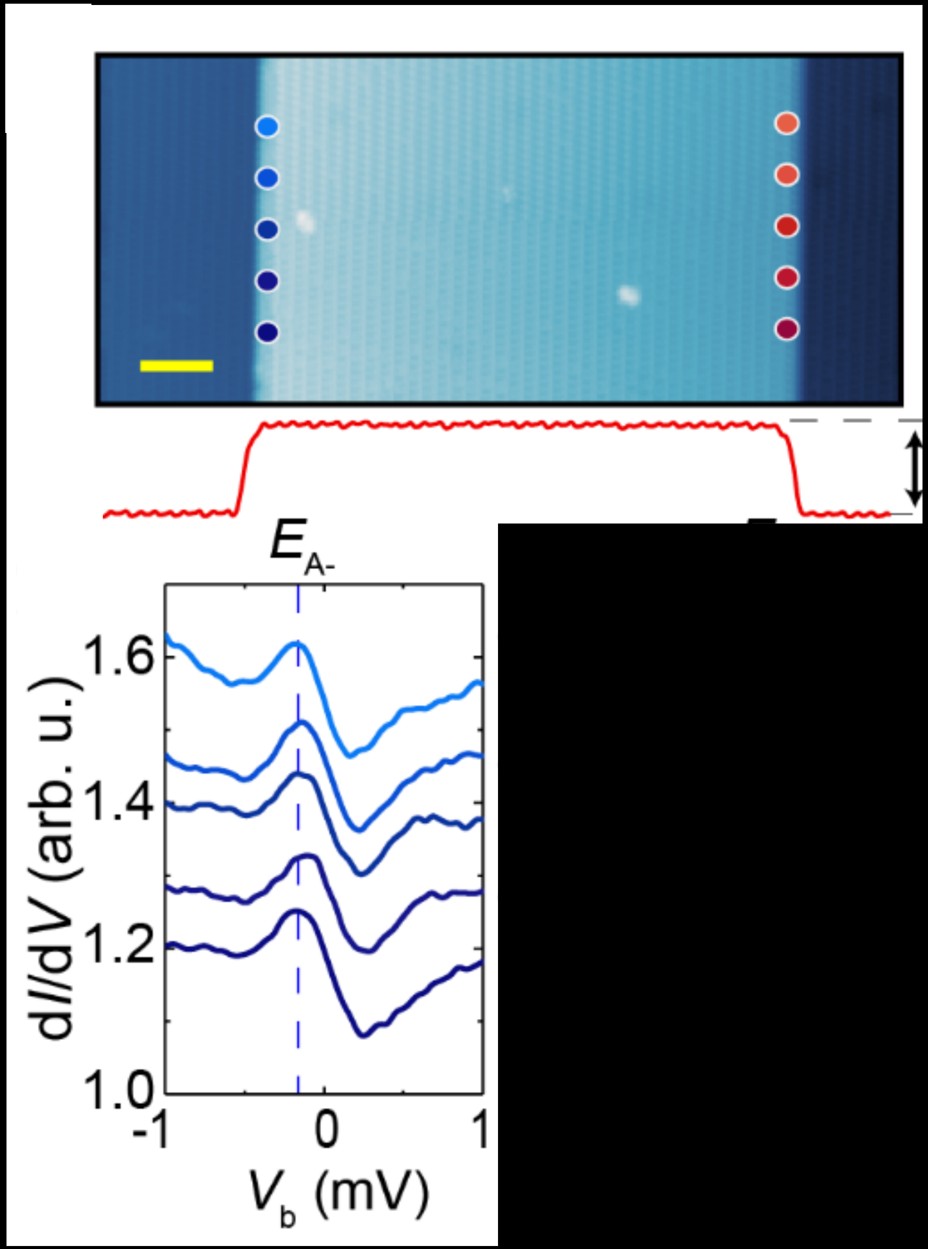
Nature 579, 523-527 (2020)

UTe_2 : Spectroscopy on step edges



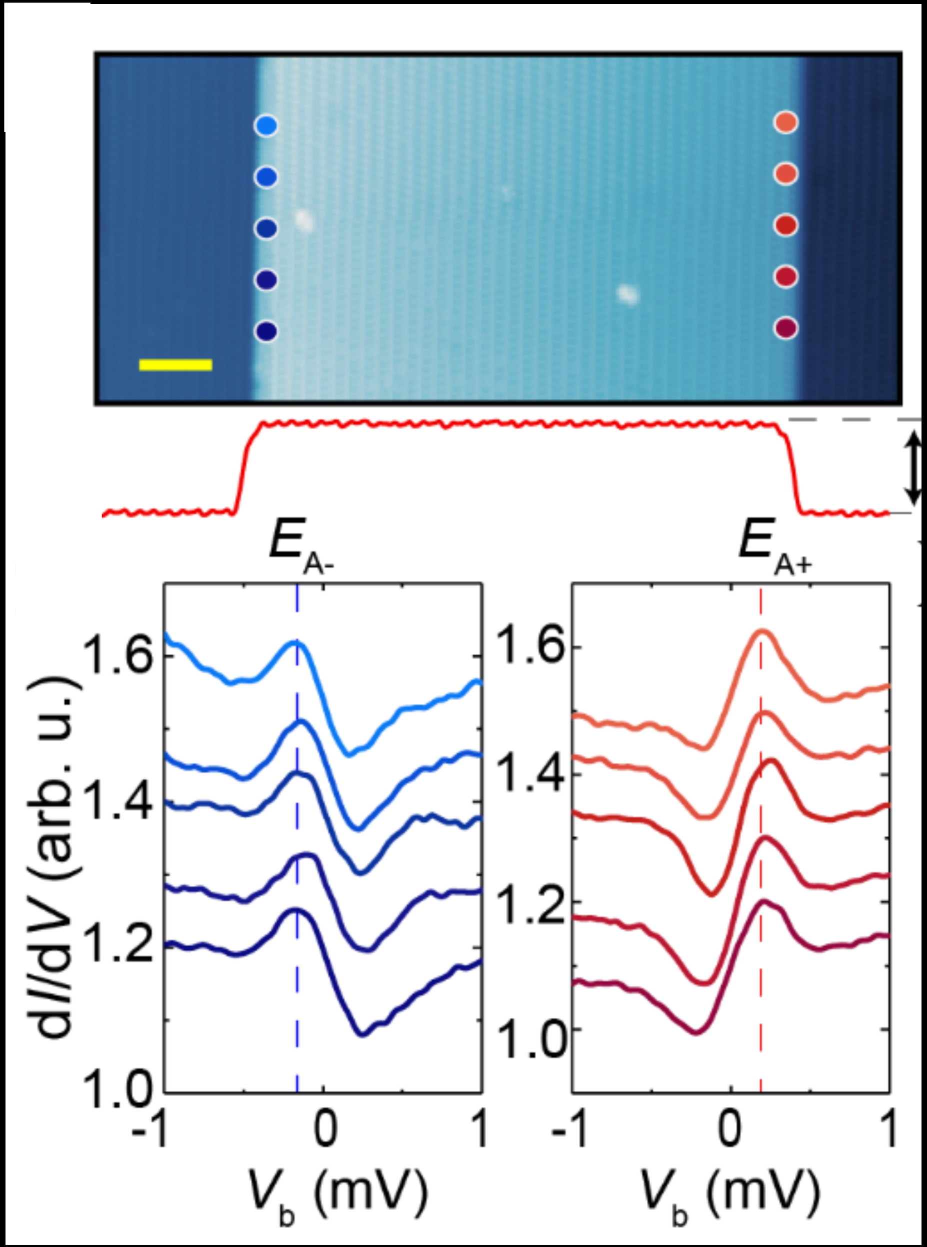


UTe_2 : Spectroscopy on step edges

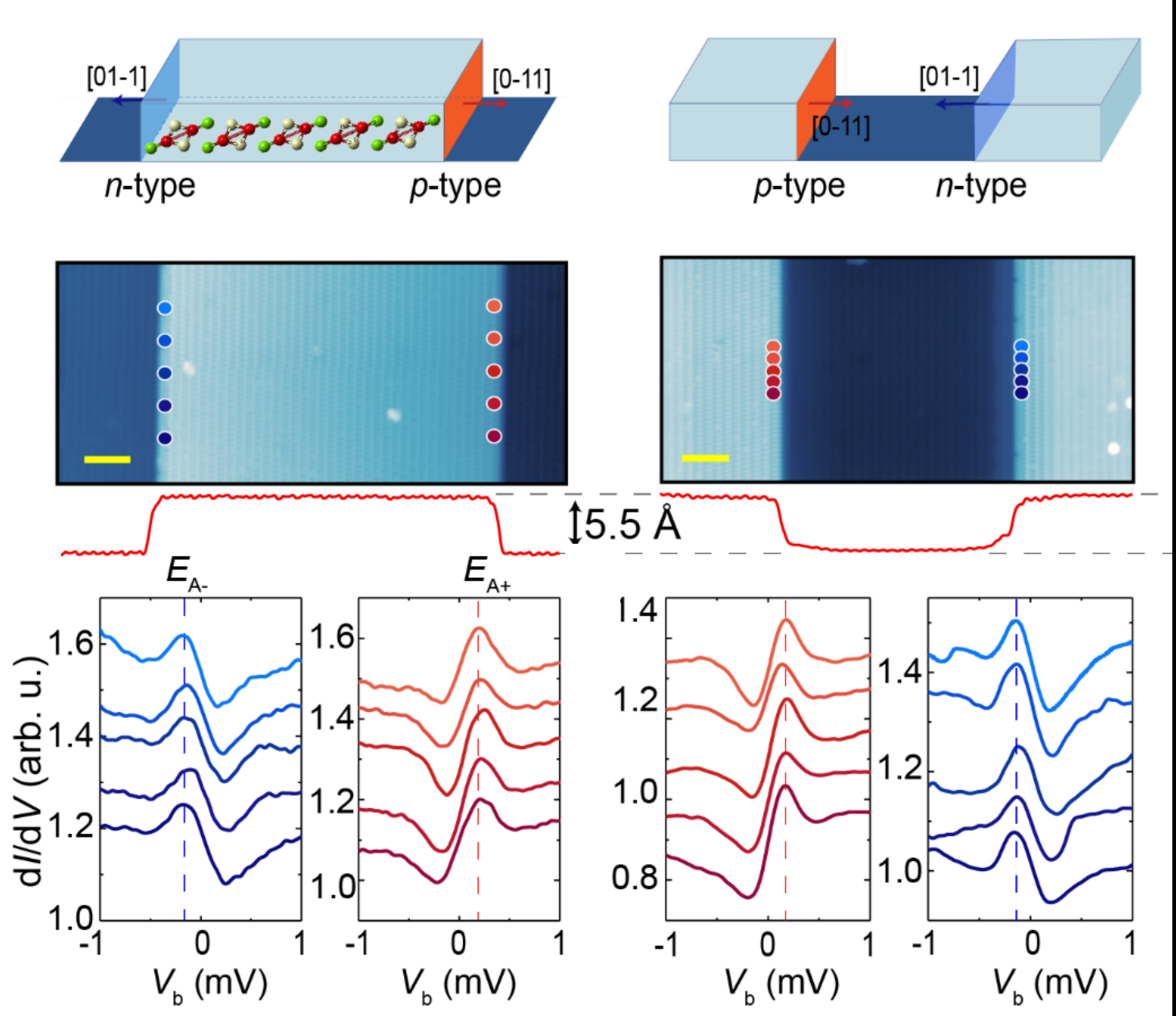


300mK

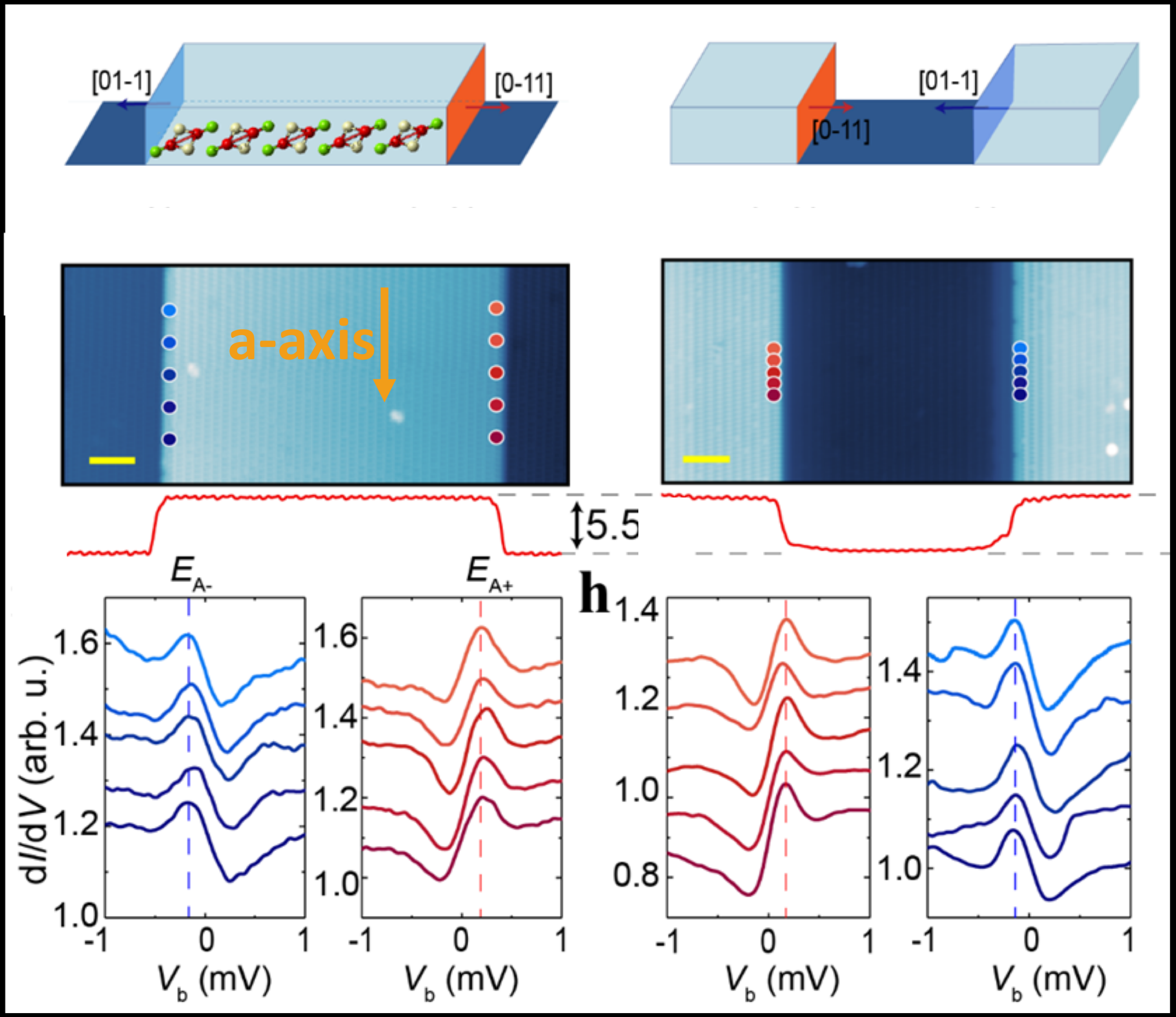
UTe_2 : Spectroscopy on step edges



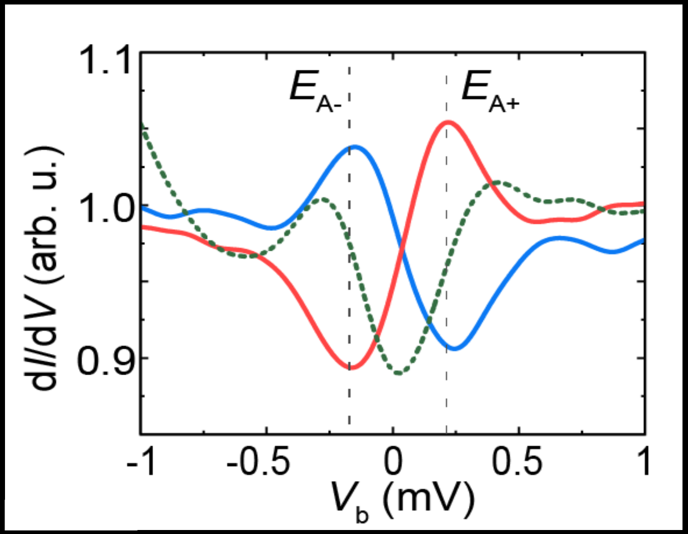
UTe_2 : Spectroscopy on step edges



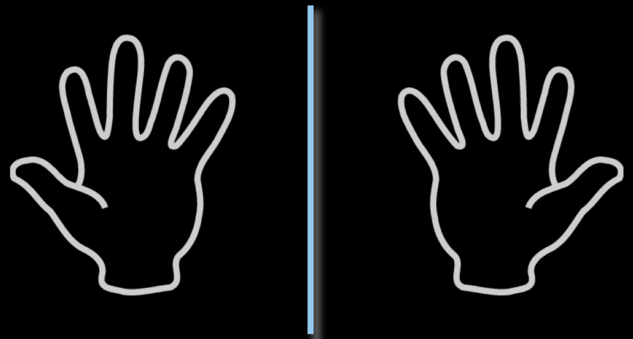
“Chiral” spectra on the step edges



Phenomenology ubiquitous in >30 step edges
4 different samples, 4 different tips

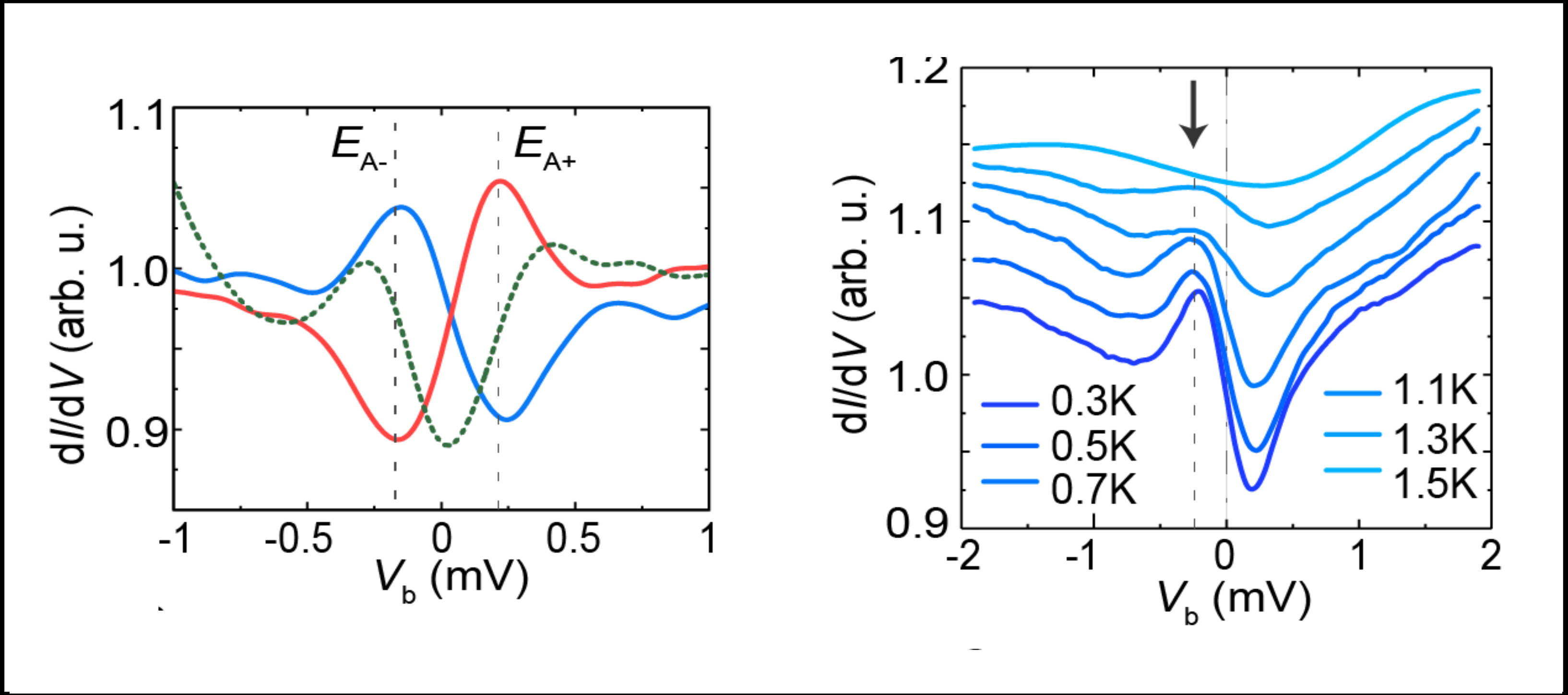


In-gap bound states with “chiral” symmetry!
i.e., they have a `handedness’

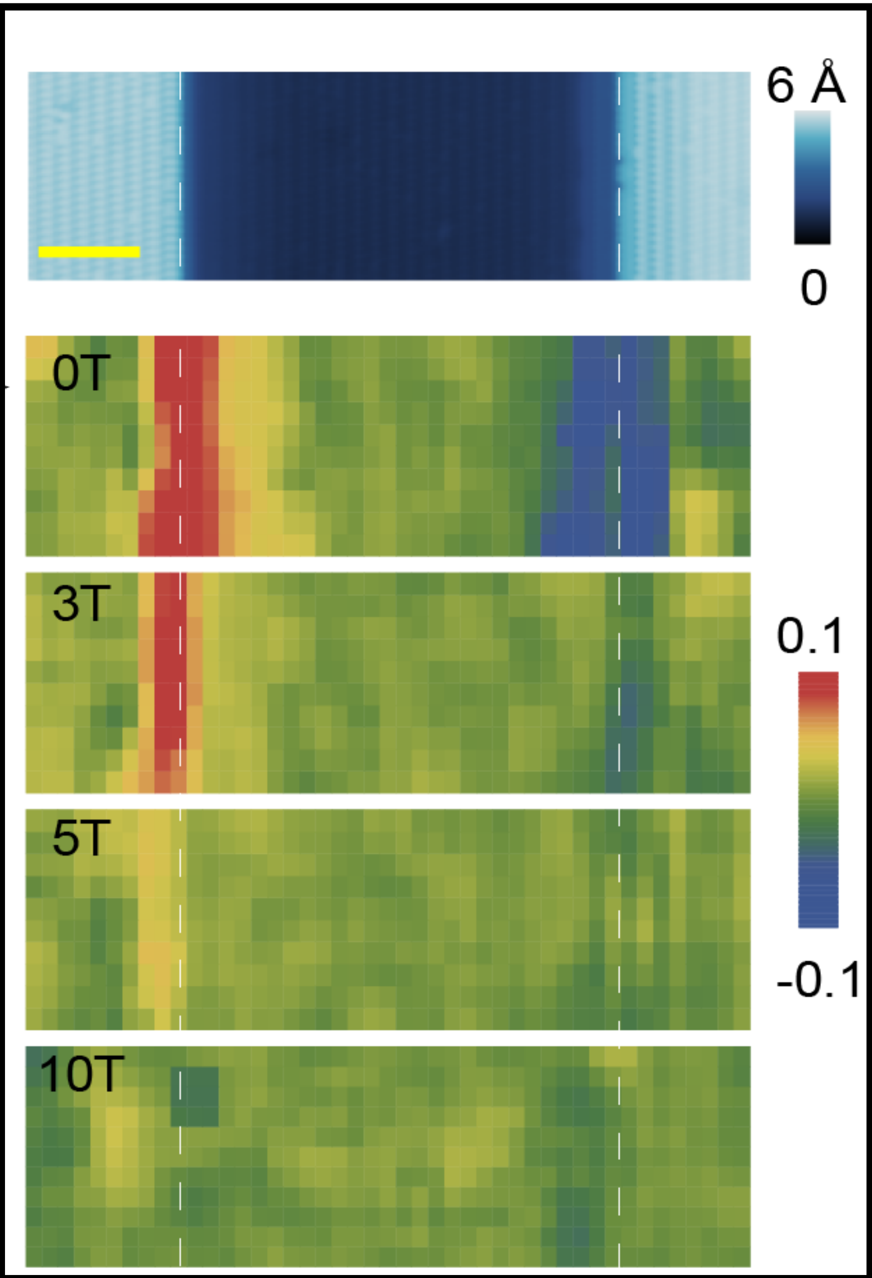


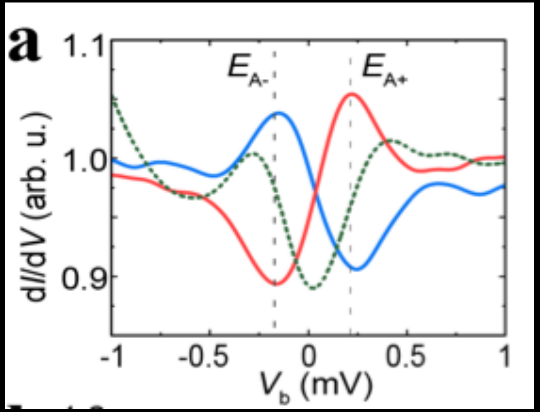
L. Jiao et.al., Nature 579, 523-527 (2020)

Chiral states: connection to superconductivity



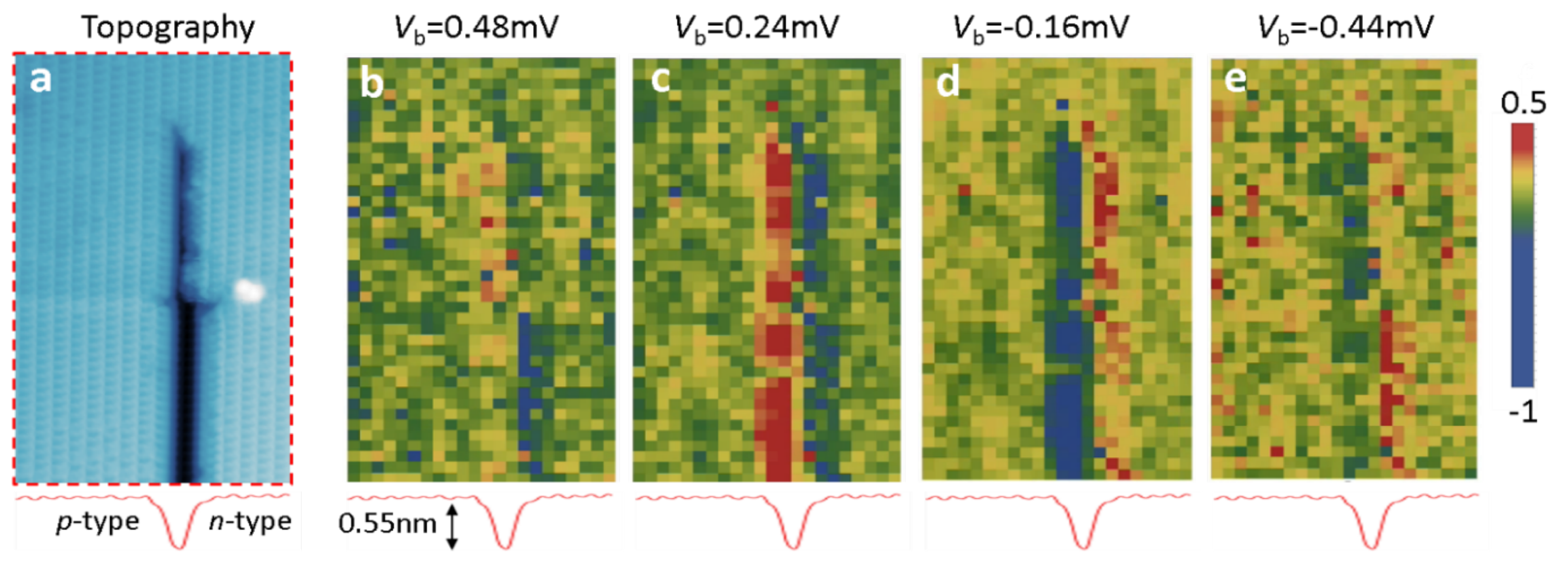
Chiral states: Magnetic field dependence





Chirality robust and insensitive to local details

Only depends on direction of normal to step edge



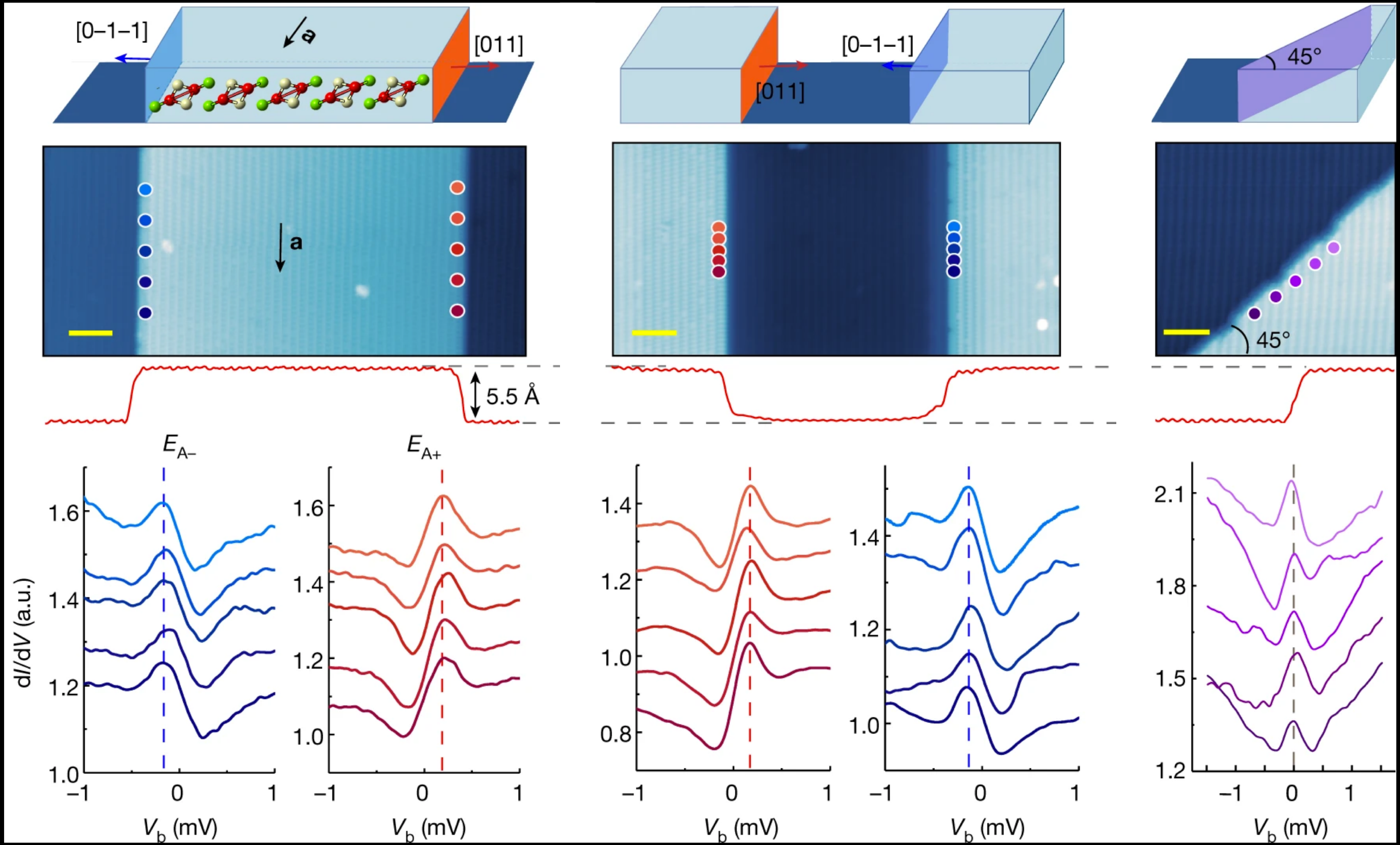
Chiral in-gap states
(direction matters)

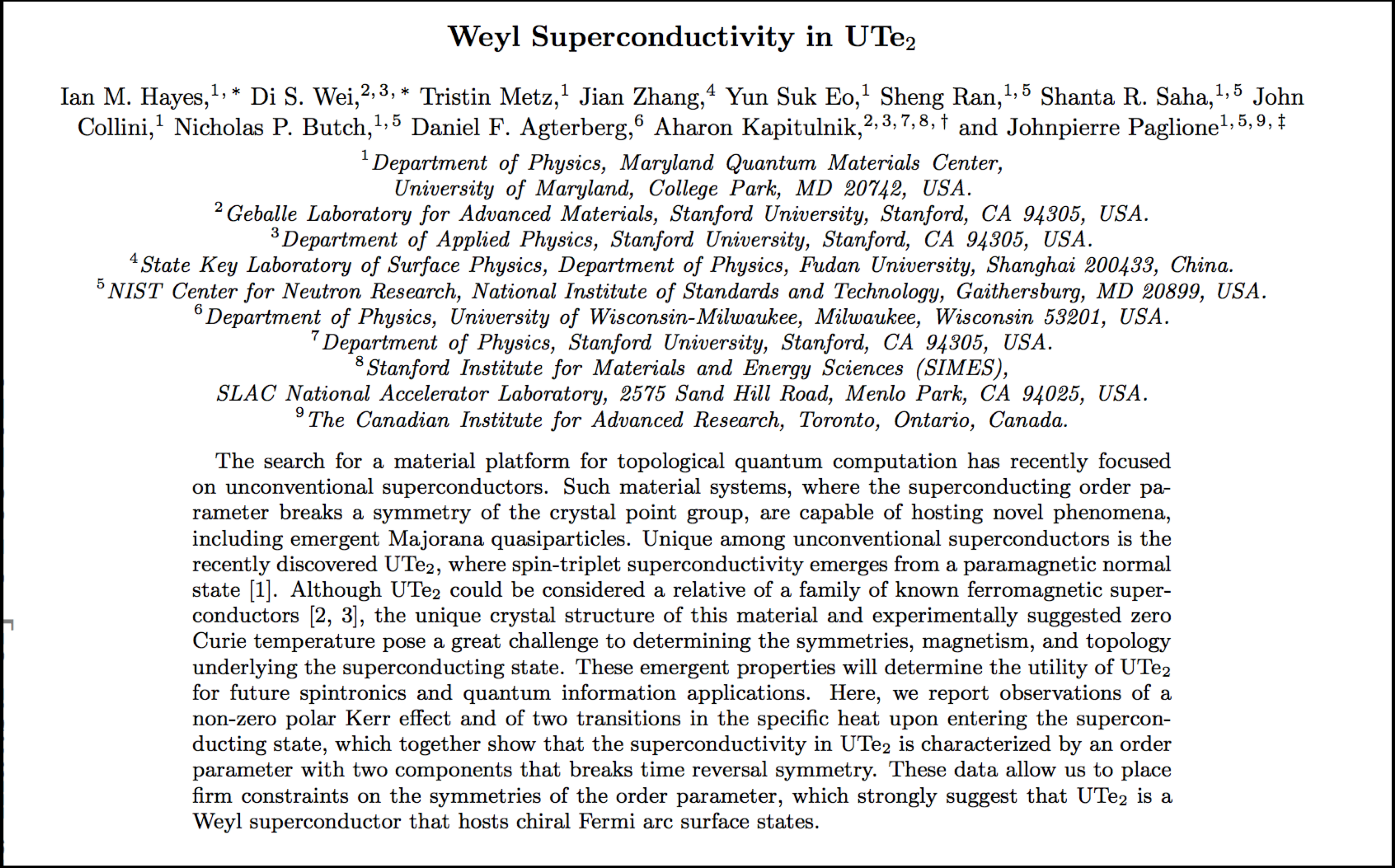
→

SC order parameter has a vector associated with it

Combined with evidence of triplet pairing, UTe_2 is a helical or chiral p-wave or f-wave superconductor

45 Deg step edges





Weyl Superconductivity in UTe_2

Ian M. Hayes,[1,*] Di S. Wei,[2,3,*] Tristin Metz,[1] Jian Zhang,[4] Yun Suk Eo,[1] Sheng Ran,[1,5] Shanta R. Saha,[1,5] John Collini,[1] Nicholas P. Butch,[1,5] Daniel F. Agterberg,[6] Aharon Kapitulnik,[2,3,7,8,†] and Johnpierre Paglione[1,5,9,‡]

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University of Maryland, College Park, MD 20742, USA.
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[4] *State Key Laboratory of Surface Physics, Department of Physics, Fudan University, Shanghai 200433, China.*
[5] *NIST Center for Neutron Research, National Institute of Standards and Technology, Gaithersburg, MD 20899, USA.*
[6] *Department of Physics, University of Wisconsin-Milwaukee, Milwaukee, Wisconsin 53201, USA.*
[7] *Department of Physics, Stanford University, Stanford, CA 94305, USA.*
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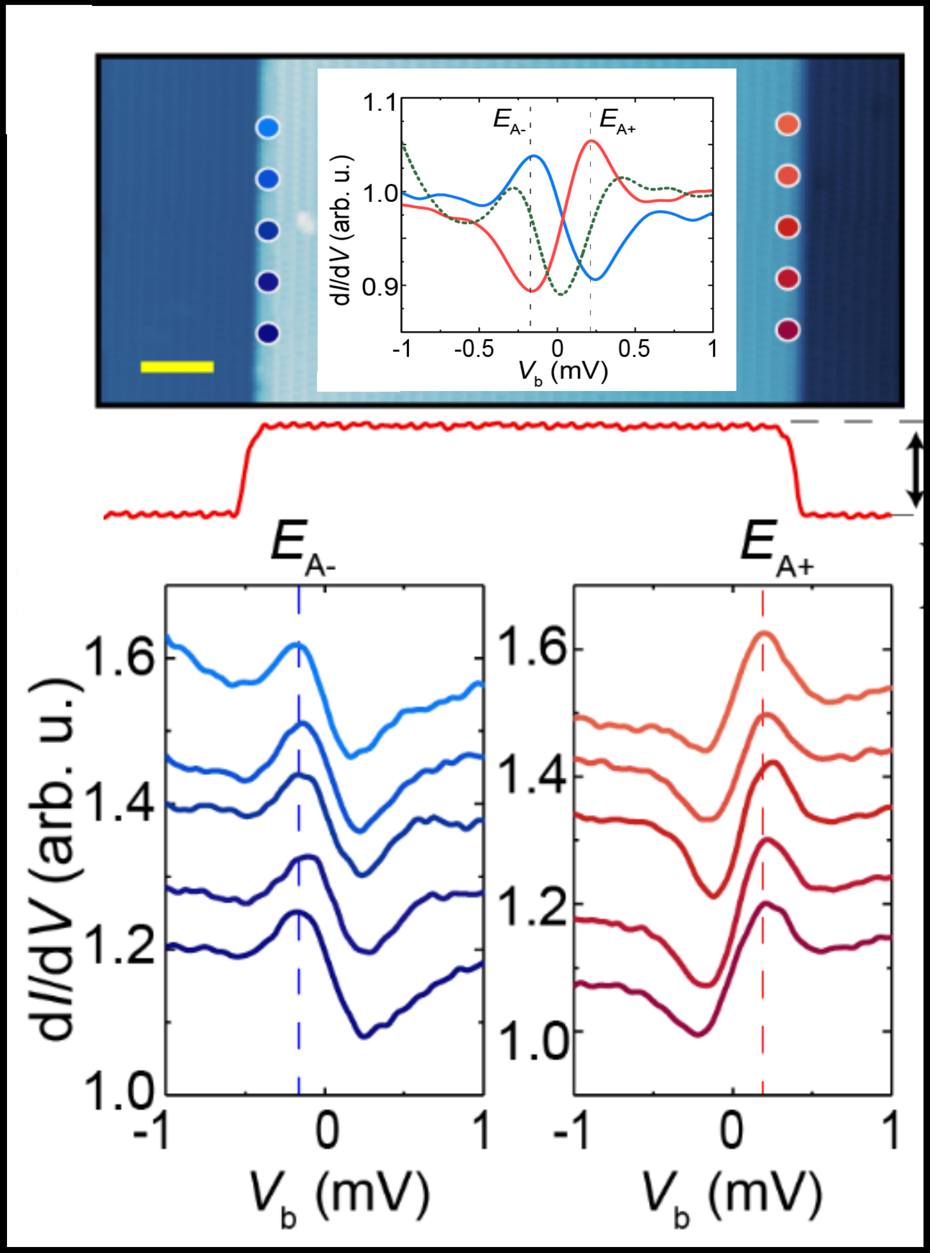
[9] *The Canadian Institute for Advanced Research, Toronto, Ontario, Canada.*

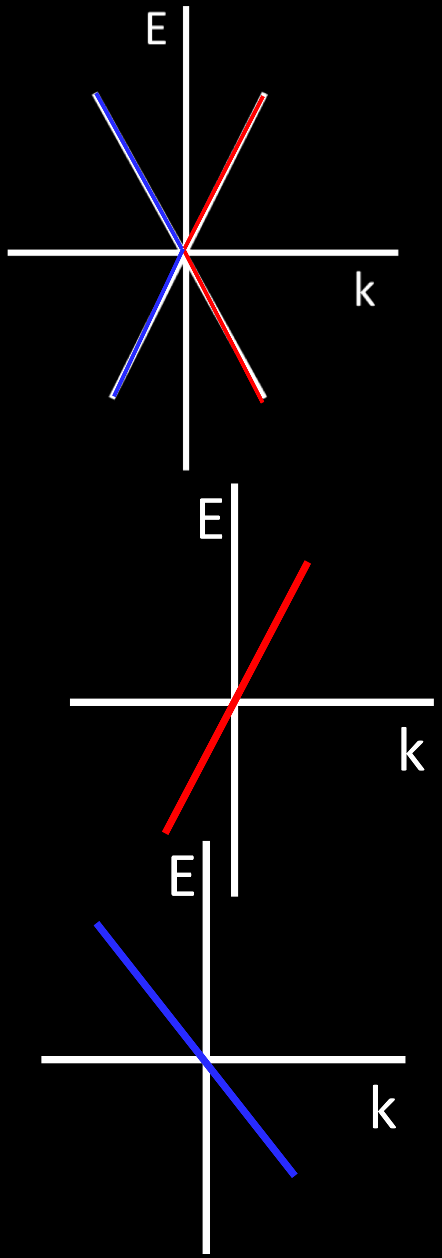
The search for a material platform for topological quantum computation has recently focused on unconventional superconductors. Such material systems, where the superconducting order parameter breaks a symmetry of the crystal point group, are capable of hosting novel phenomena, including emergent Majorana quasiparticles. Unique among unconventional superconductors is the recently discovered UTe_2, where spin-triplet superconductivity emerges from a paramagnetic normal state [1]. Although UTe_2 could be considered a relative of a family of known ferromagnetic superconductors [2, 3], the unique crystal structure of this material and experimentally suggested zero Curie temperature pose a great challenge to determining the symmetries, magnetism, and topology underlying the superconducting state. These emergent properties will determine the utility of UTe_2 for future spintronics and quantum information applications. Here, we report observations of a non-zero polar Kerr effect and of two transitions in the specific heat upon entering the superconducting state, which together show that the superconductivity in UTe_2 is characterized by an order parameter with two components that breaks time reversal symmetry. These data allow us to place firm constraints on the symmetries of the order parameter, which strongly suggest that UTe_2 is a Weyl superconductor that hosts chiral Fermi arc surface states.

arXiv:2002.02539v1

Open questions: lineshape of in-gap states

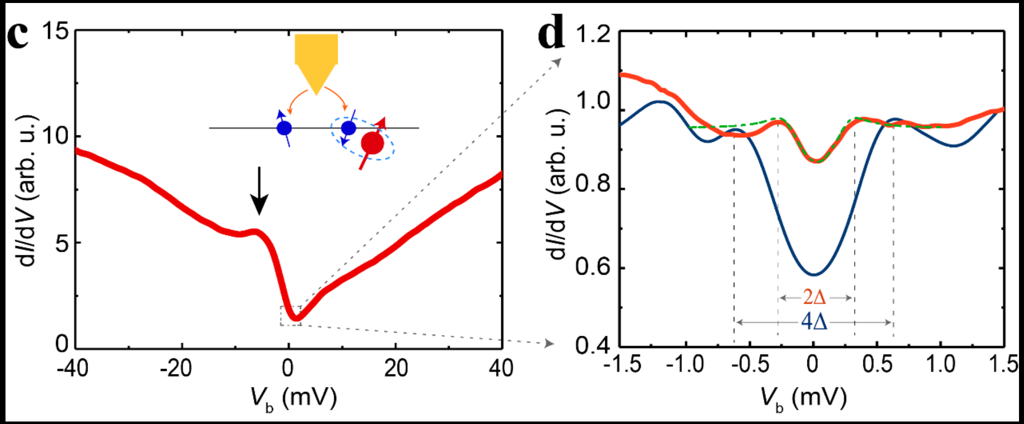


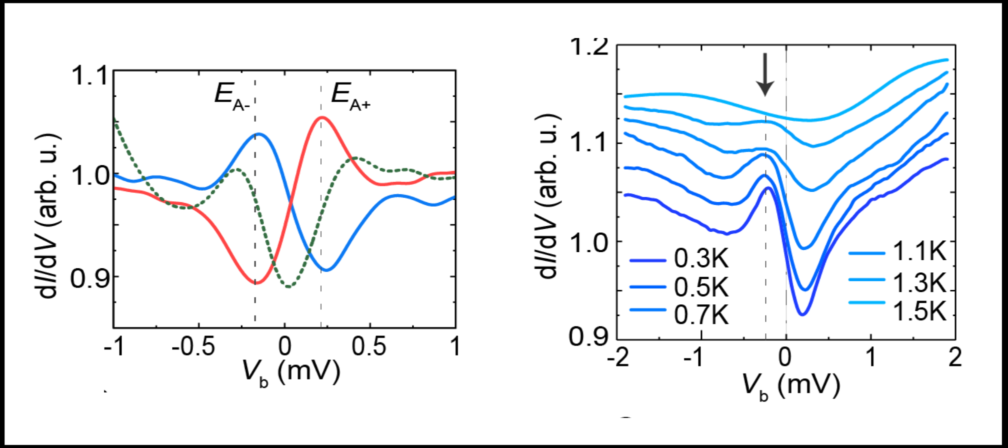
- Unusual lineshape with lots of interesting symmetry: peak on one side and dip on the other at same energy : what about p-h symmetry?
- Step edge breaks inversion symmetry but that's not enough to explain the lineshape
- Need to invoke chiral edge modes to explain the lineshape
- A full explanation of the lineshape will provide important insights into the superconducting order parameter



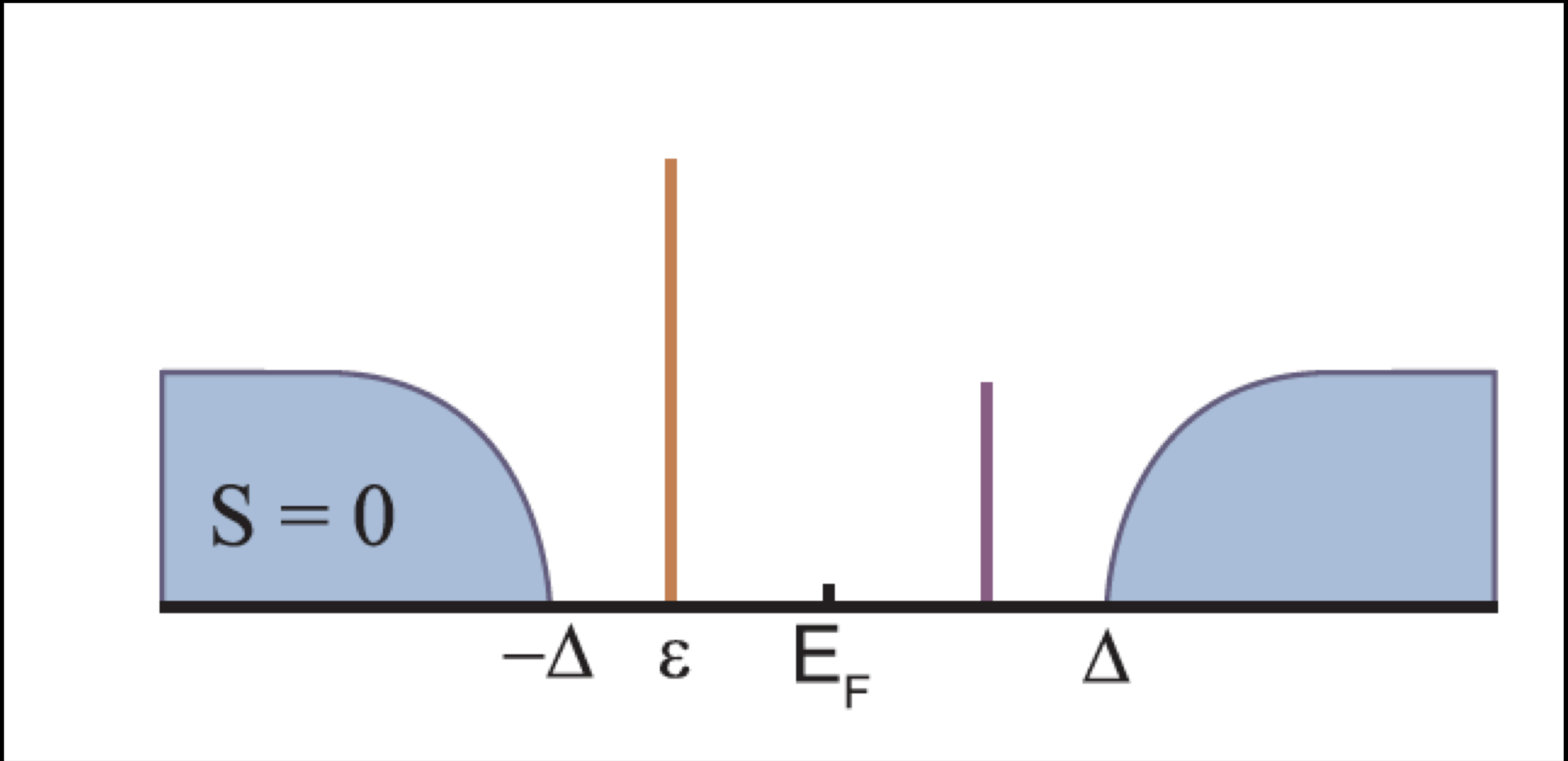
Summary/Open questions

- Kondo effect--ferromagnetic fluctuations
  - Oscillations of Kondo width and SC gap Hidden order? PDW?
  - Observation of Chiral Edge modes suggests a TR broken superconducting state
- SC Order parameter? Unitary? Non-Unitary? Residual specific heat?
- Chiral? Broken TR symmetry?
- Is SO coupling important?
- 3D or Quasi 2D?



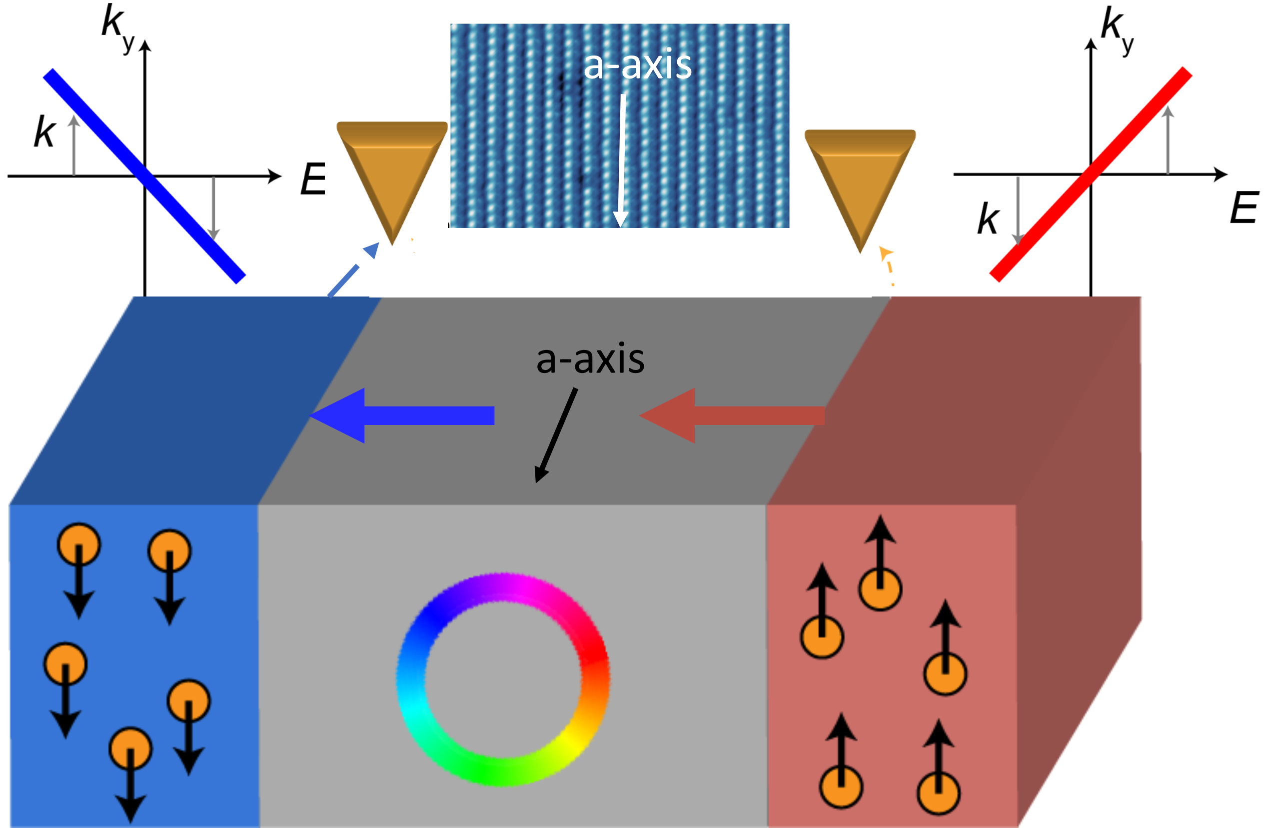


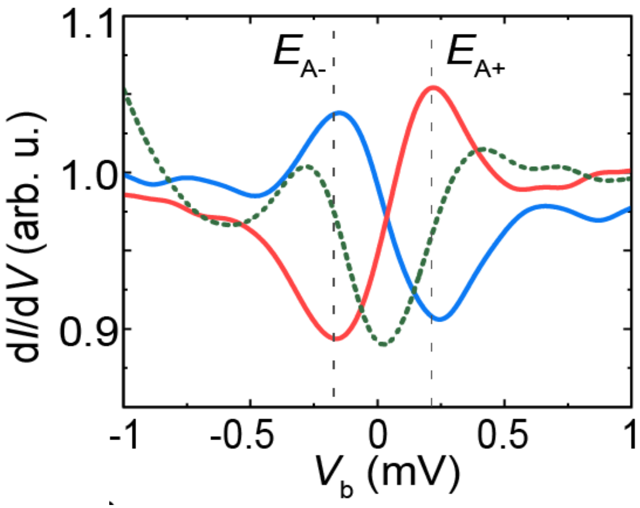
The issue of p-h asymmetry



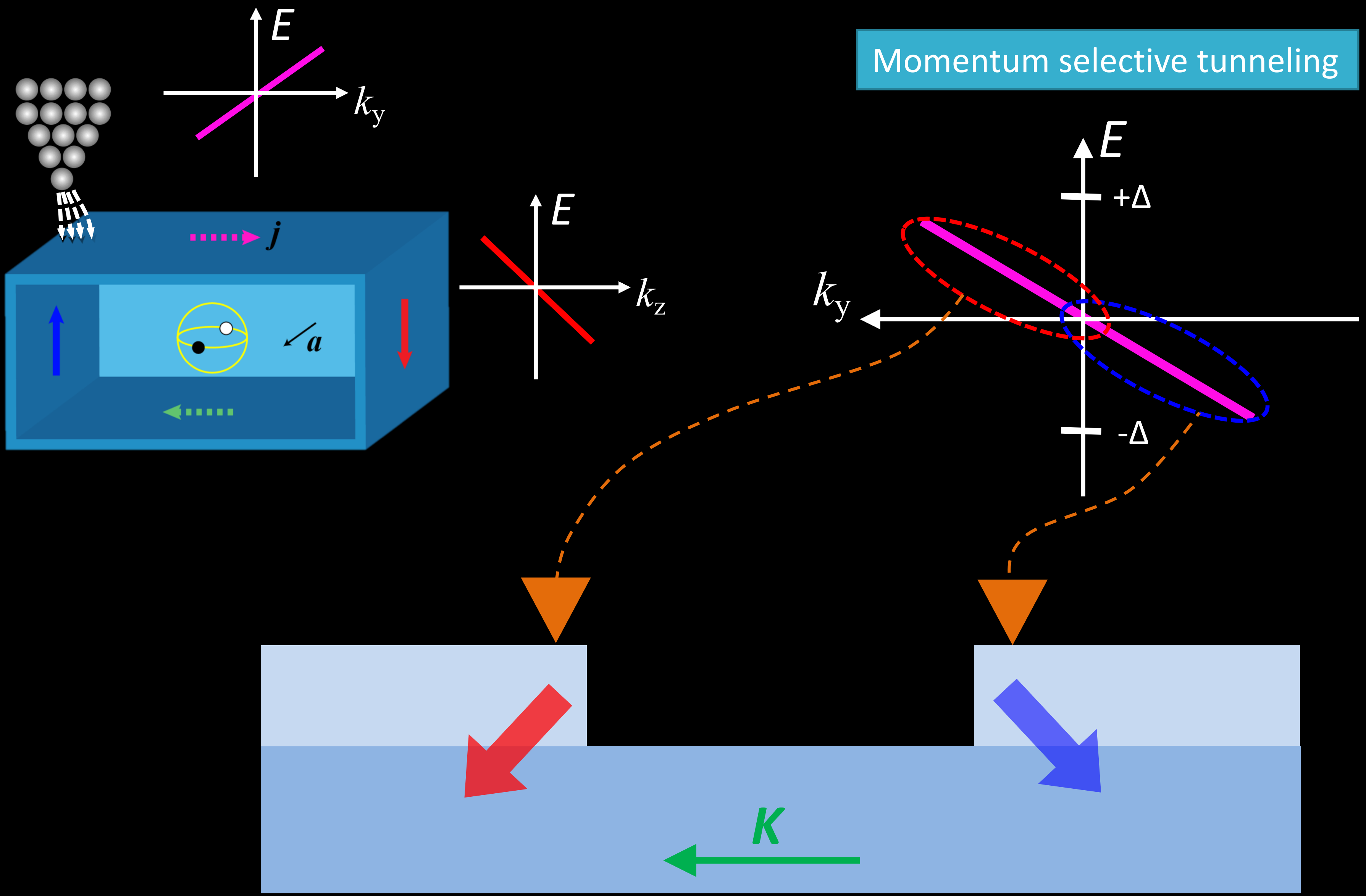
- In gap bound states could arise from potential scattering in an unconventional SC
- Expected at BOTH +ε and –ε although their relative heights could be different

How do we explain our lineshape?





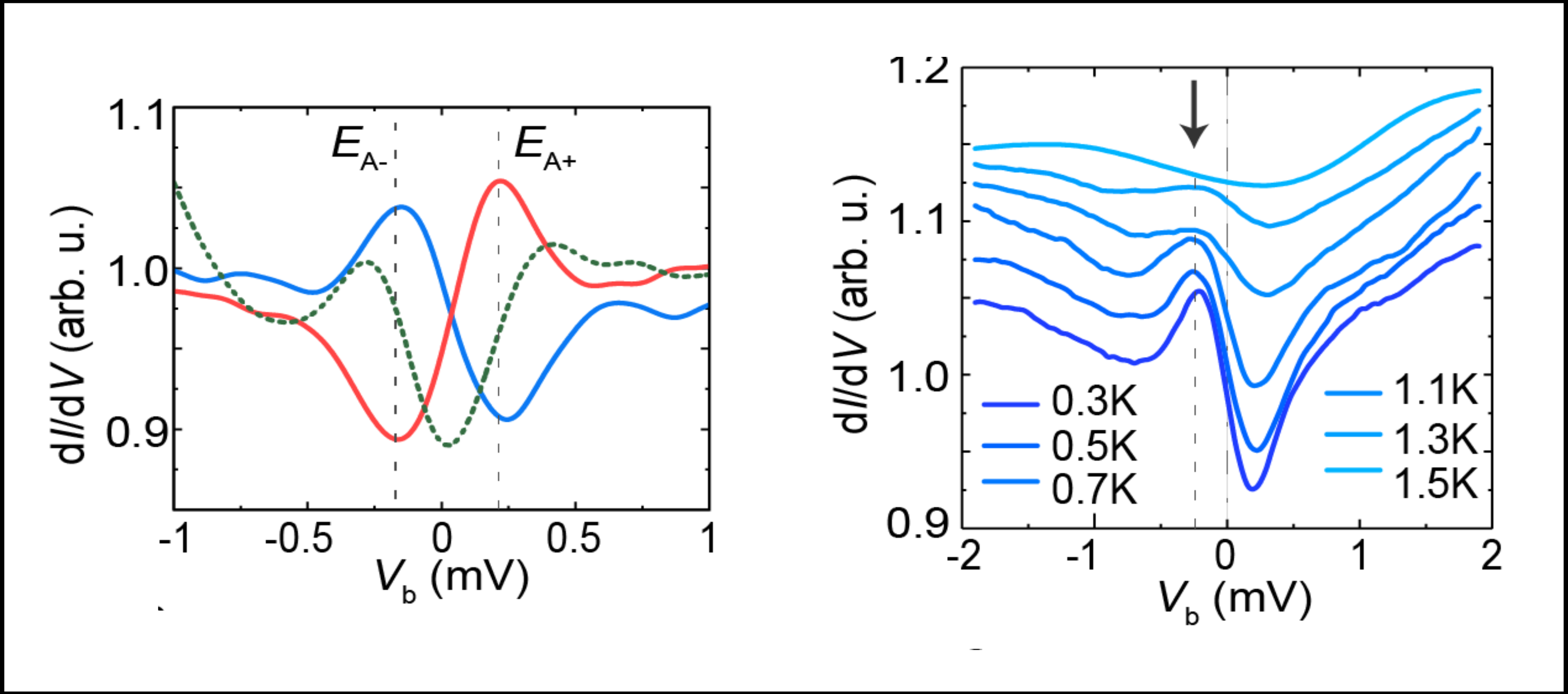
Possibility Momentum selective tunneling



Momentum selective tunneling

Lineshape not completely captured

Chiral in-gap states



How can we explain their lineshape?

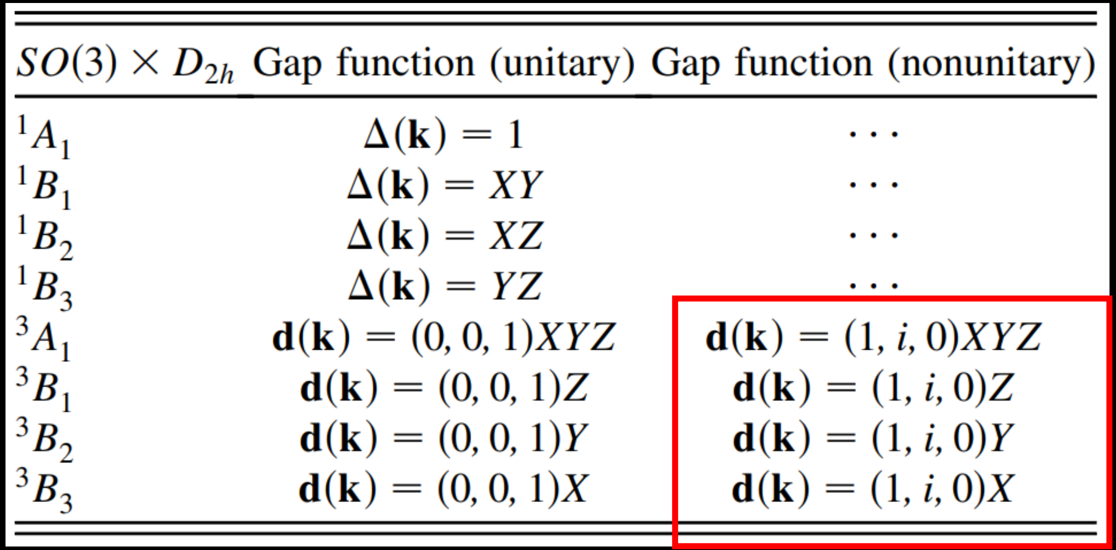
What more can we learn about SC order parameter in UTe_2?

To explain our data…

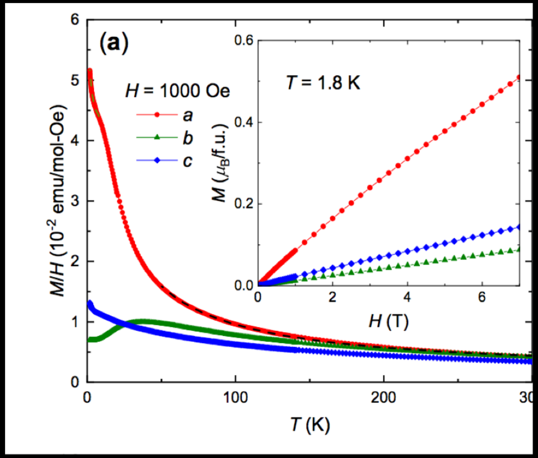
Consider a chiral superconductor

Can we have a Chiral OP with C_2 symmetry?

Orthorhombic D_{2h}
point group symmetry



$SO(3) \times D_{2h}$	Gap function (unitary)	Gap function (nonunitary)
$^1A_1$	$\Delta(\mathbf{k}) = 1$	$\cdots$
$^1B_1$	$\Delta(\mathbf{k}) = XY$	$\cdots$
$^1B_2$	$\Delta(\mathbf{k}) = XZ$	$\cdots$
$^1B_3$	$\Delta(\mathbf{k}) = YZ$	$\cdots$
$^3A_1$	$\mathbf{d}(\mathbf{k}) = (0, 0, 1)XYZ$	$\mathbf{d}(\mathbf{k}) = (1, i, 0)XYZ$
$^3B_1$	$\mathbf{d}(\mathbf{k}) = (0, 0, 1)Z$	$\mathbf{d}(\mathbf{k}) = (1, i, 0)Z$
$^3B_2$	$\mathbf{d}(\mathbf{k}) = (0, 0, 1)Y$	$\mathbf{d}(\mathbf{k}) = (1, i, 0)Y$
$^3B_3$	$\mathbf{d}(\mathbf{k}) = (0, 0, 1)X$	$\mathbf{d}(\mathbf{k}) = (1, i, 0)X$

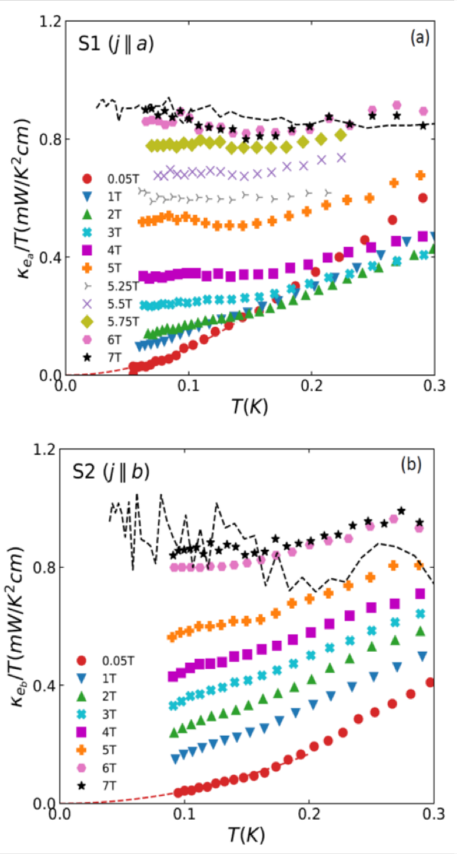


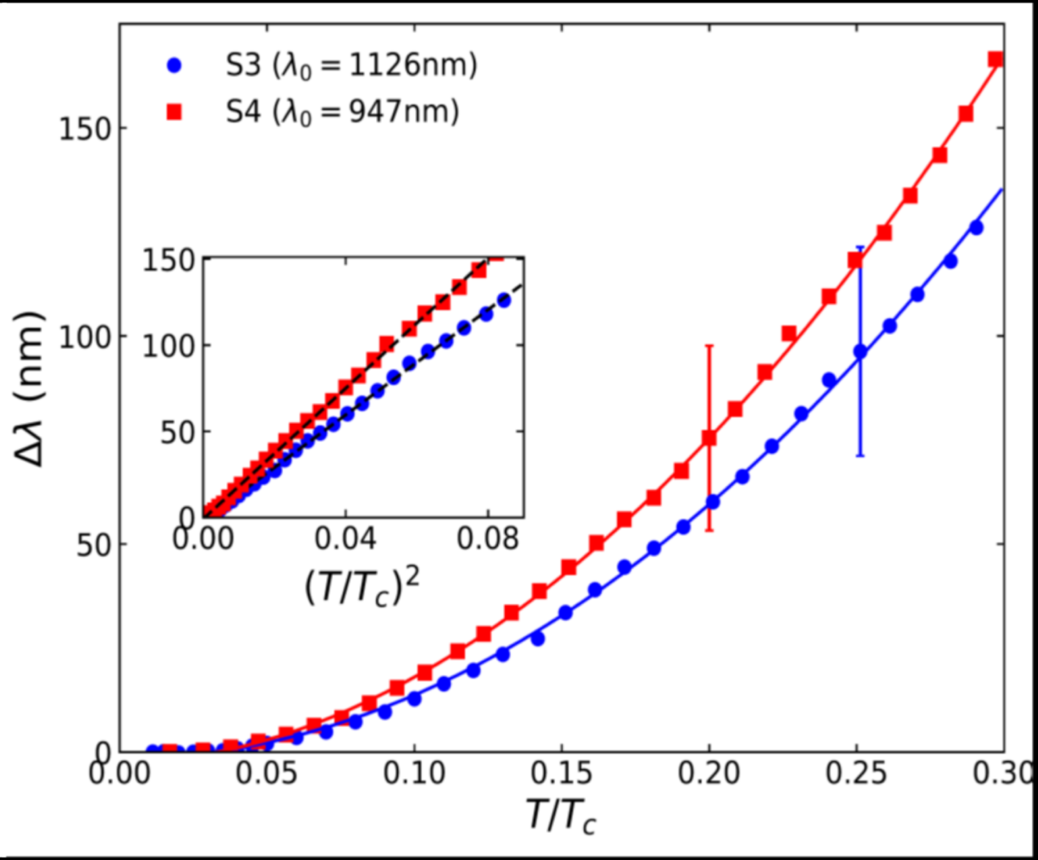
a-axis is the easy axis

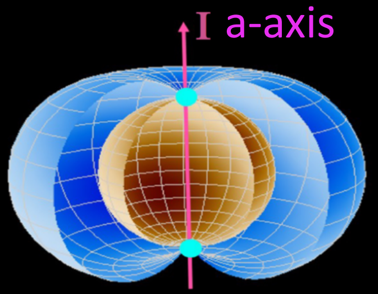
Stability of a Nonunitary Triplet Pairing on the Border of Magnetism in UTe_2, Andriy H. Nevidomskyy, arXiv:2001.02699v1

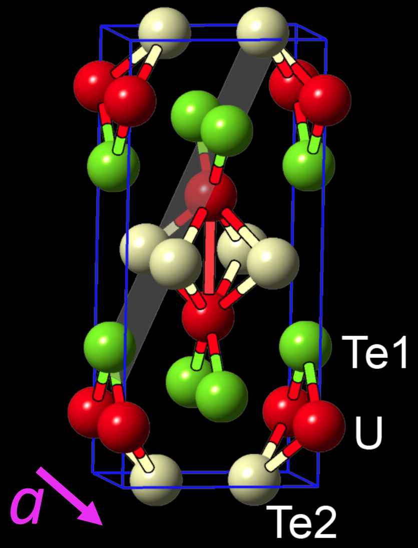
..we show that chiral nonunitary superconducting order can be stabilized on the border of ferromagnetism in UTe2, even in the absence of long-range magnetic order.

In which direction is the chiral axis?







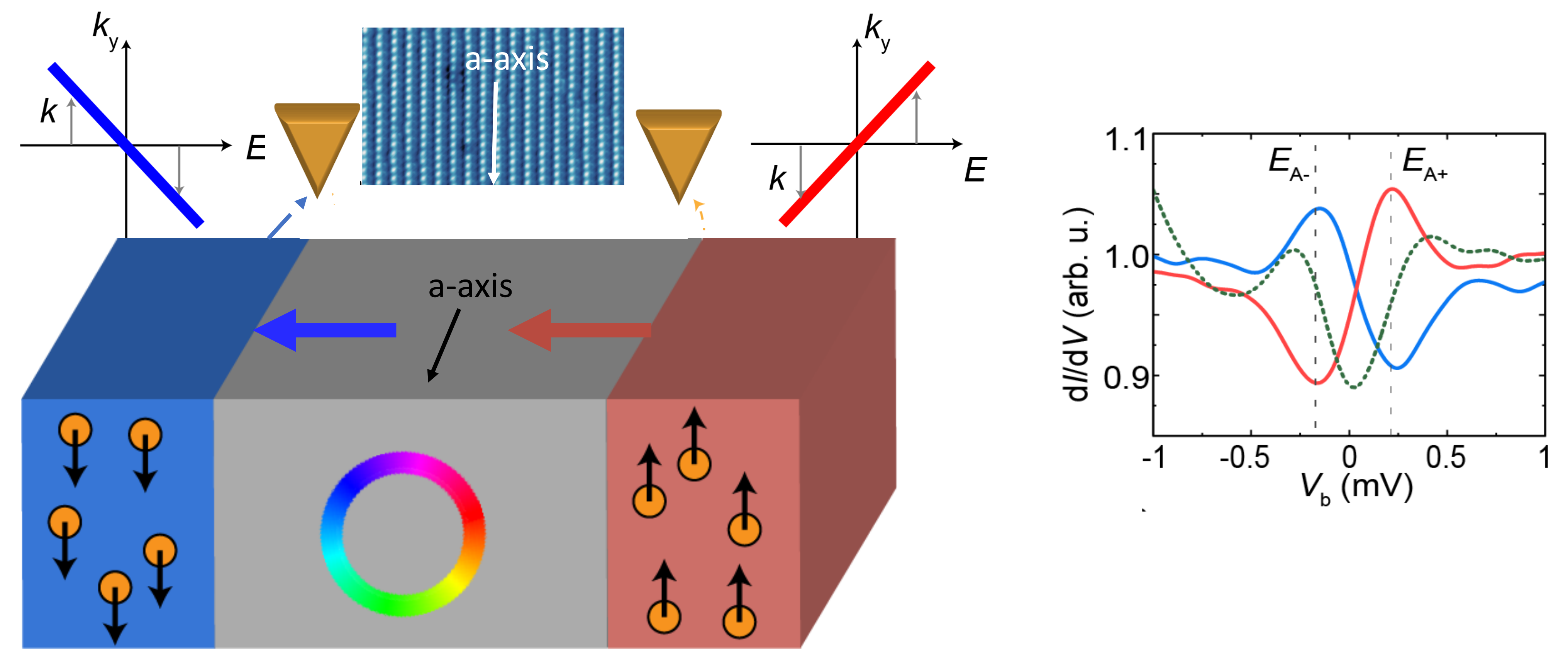


T^2 penetration depth → point nodes along a axis

By symmetry chiral axis likely to be along a-axis

T. Metz *et al*, arXiv:1908.01069
S. Bae *et al*, arXiv:1909.09032

How do we explain our lineshape?



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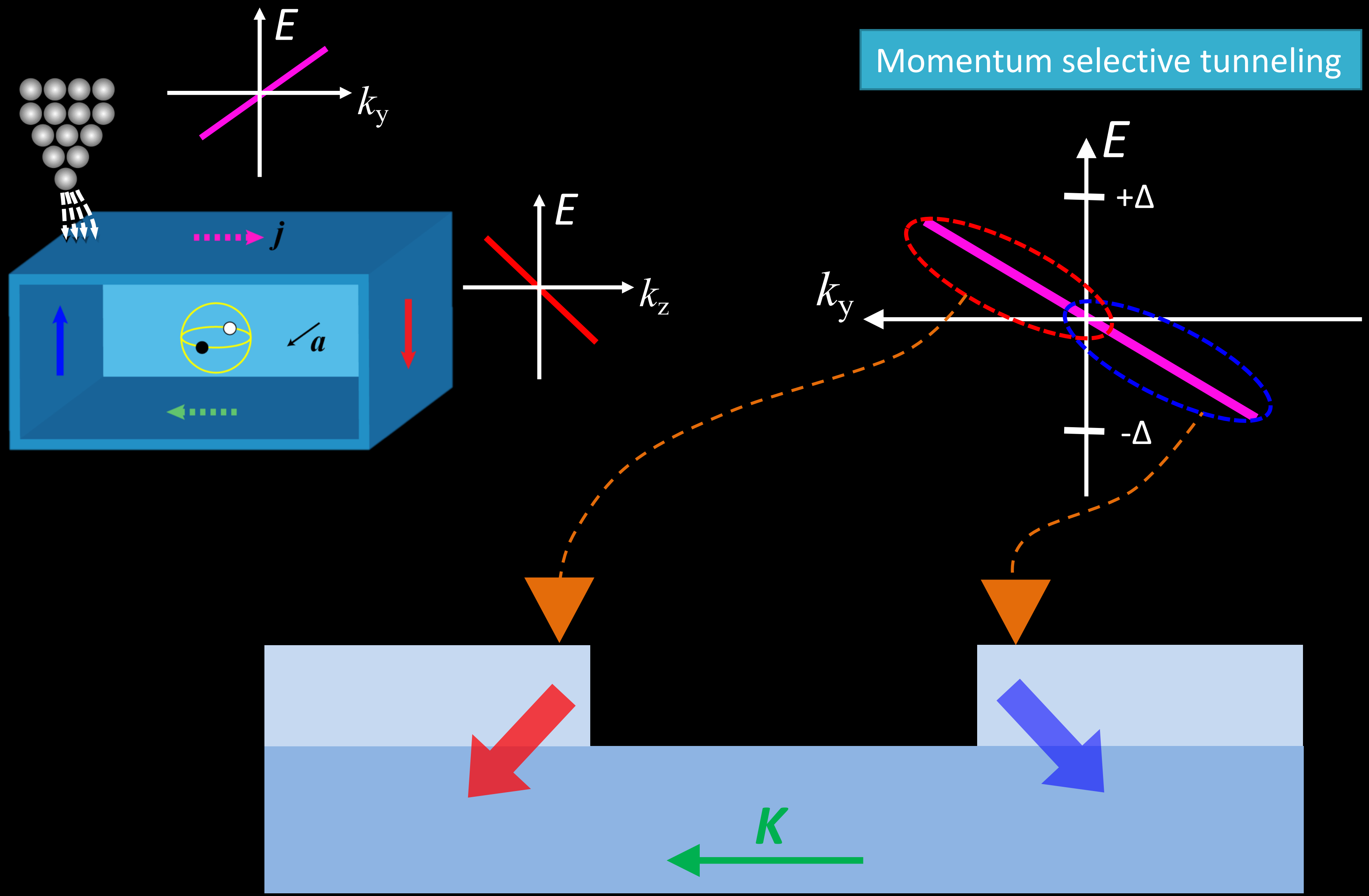

Momentum selective tunneling

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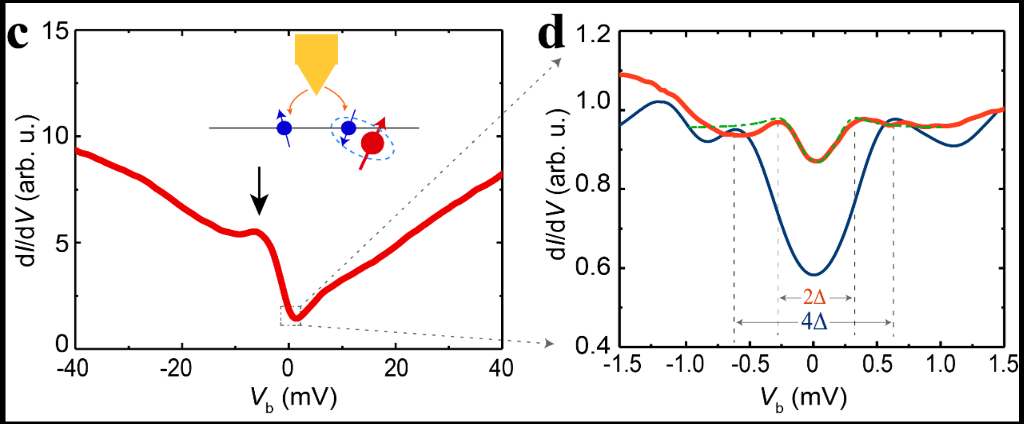

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