Tunneling into emergent topological matter

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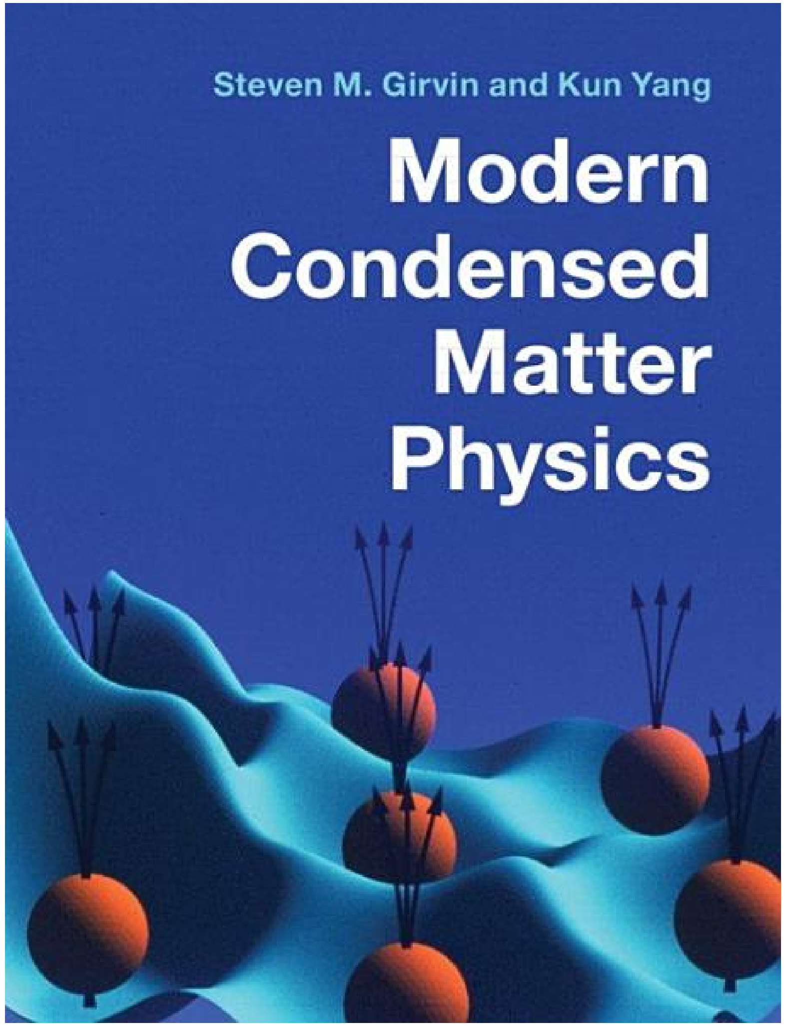
Outline

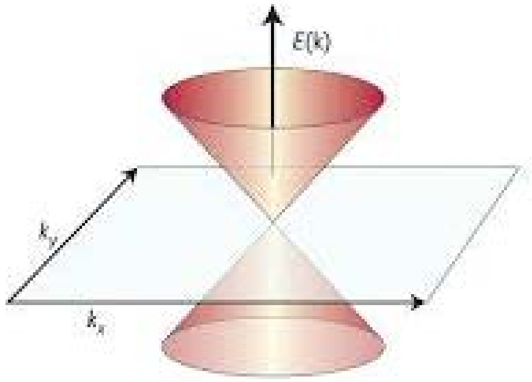
- Emergent topological matter
- State-of-the-art STM technique
- Proof-of-principle methodology
- More to discover

Topological matter

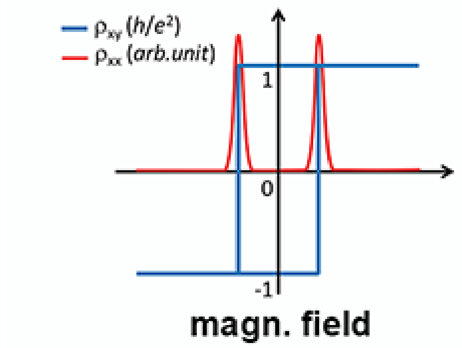
Quantum topology **Topological quantum materials**



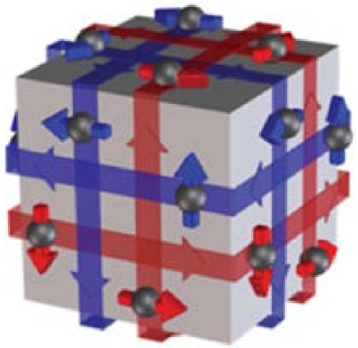
Topological fermions (Dirac, Weyl…)



Quantized electronic excitations



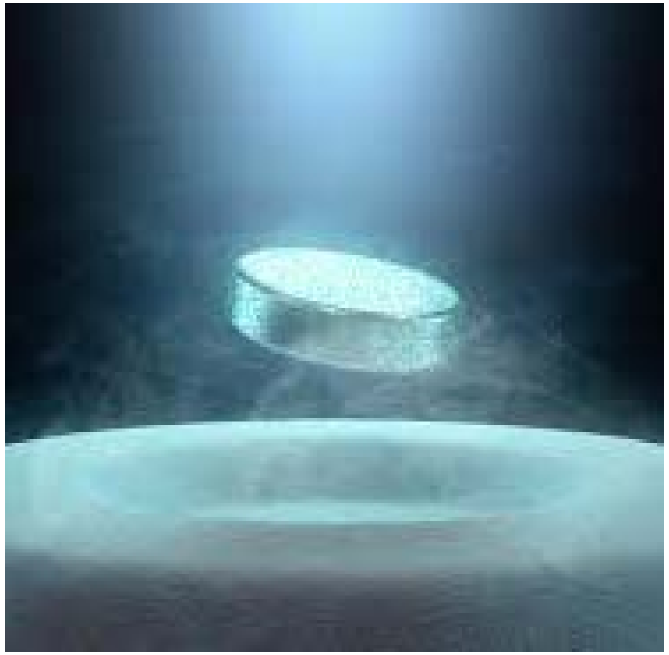
Symmetry protected bulk-boundary correspondence



J.E. Avron, et al. Phys. Today (2003)
F.D.M. Haldane. RMP (2017)
M.Z. Hasan, C.L. Kane. RMP (2010)
X.L. Qi, S.C. Zhang. RMP (2011)
B. Keimer, J.E Moore. Nat. Phys. (2017)
N.P.Armitage, E.J. Mele, A. Vishwanath. RMP (2018).
K. He, Y. Wang, Q.K. Xue, ARCM (2018)

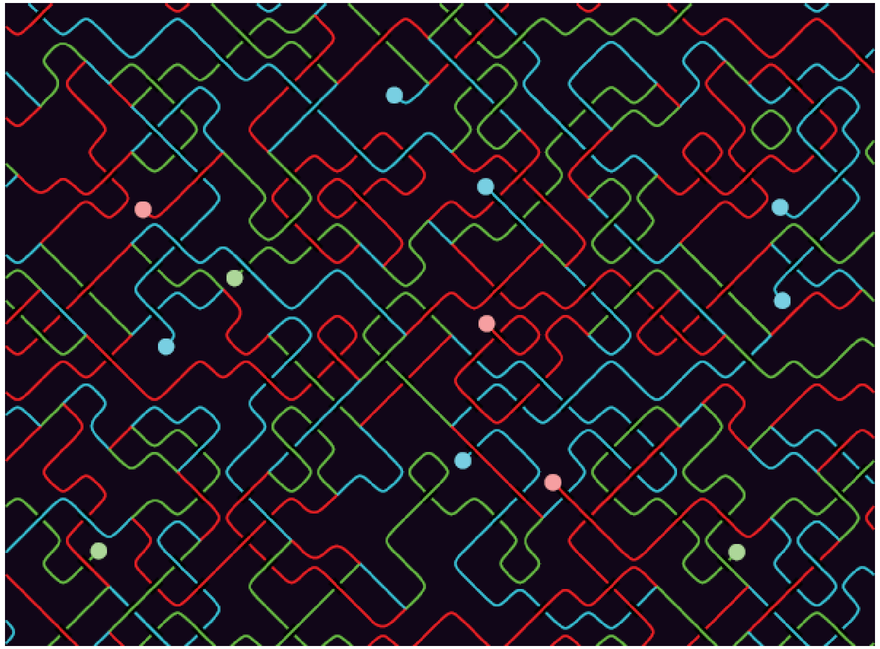
Emergent topological matter with strong interaction

Superconductivity



Magnetism

Topological order; mangy-body entanglement



Correlated electrons

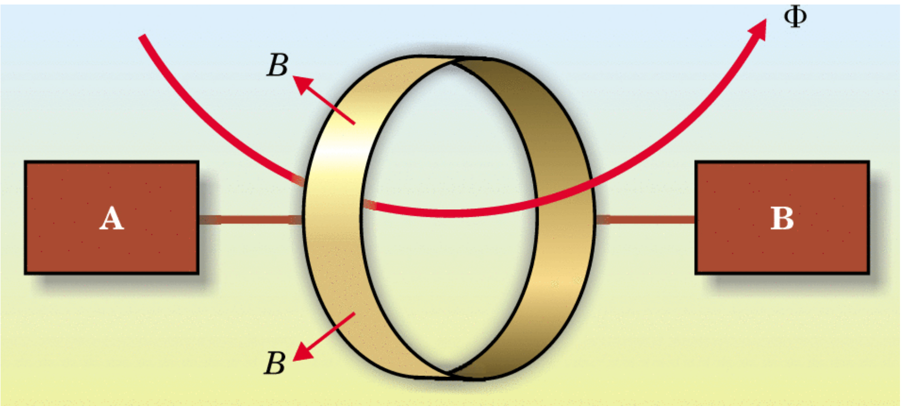
P. W. Anderson. Science (1972)
E. Dagotto. Science (2005)
A. Fert. RMP (2008)
B. Keimer, S. Kivelson, M. Norman, M. Uchida, J. Zaanen. Nature (2015)

S. Sachdev. Rep. Prog. Phys. (2019)
X.G. Wen. Science (2019)

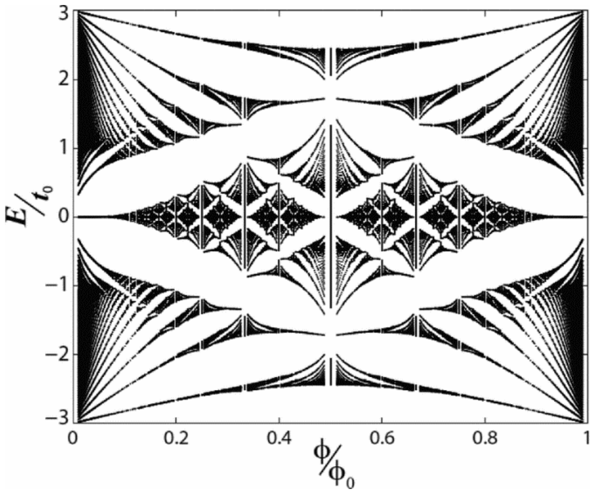
B field as strong perturbation for emergent topological matter

Quantum magnetic flux *h/e*; quantum Hall conductance ne^2/h (n is the Chern number)

Laughlin's quantum pump

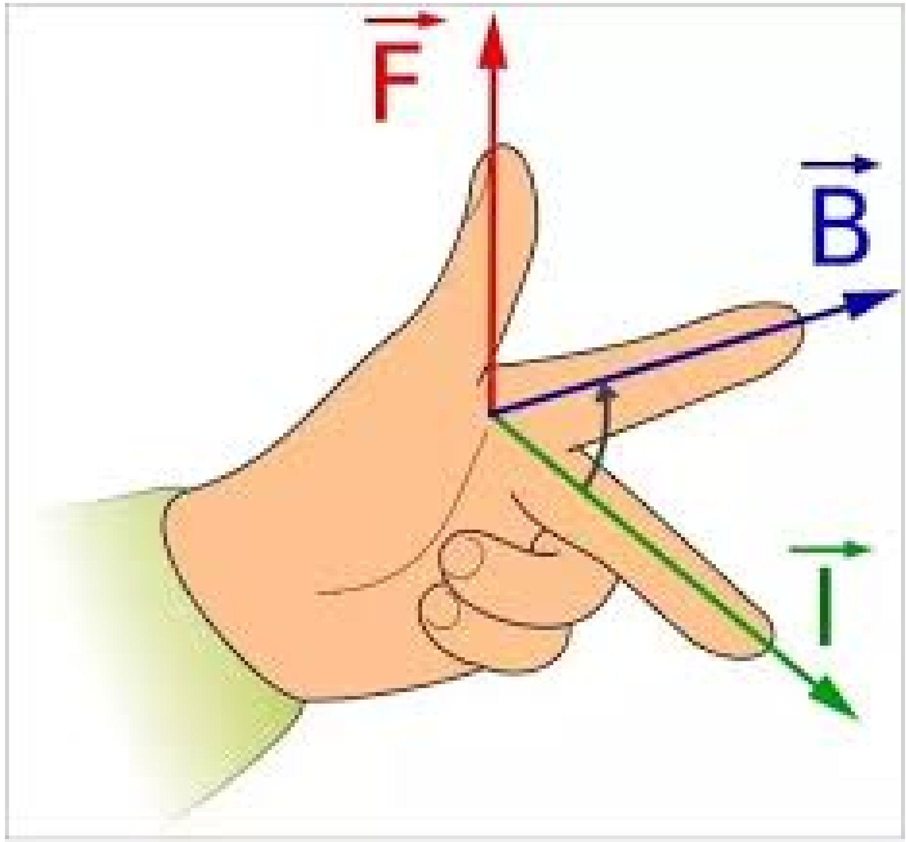


Hofstadter butterfly



R.B. Laughlin. RMP (1999)

Chirality of electronic matter



D. E. Kharzeev. Annu. Rev. Nucl. Part. Sci. (2015)

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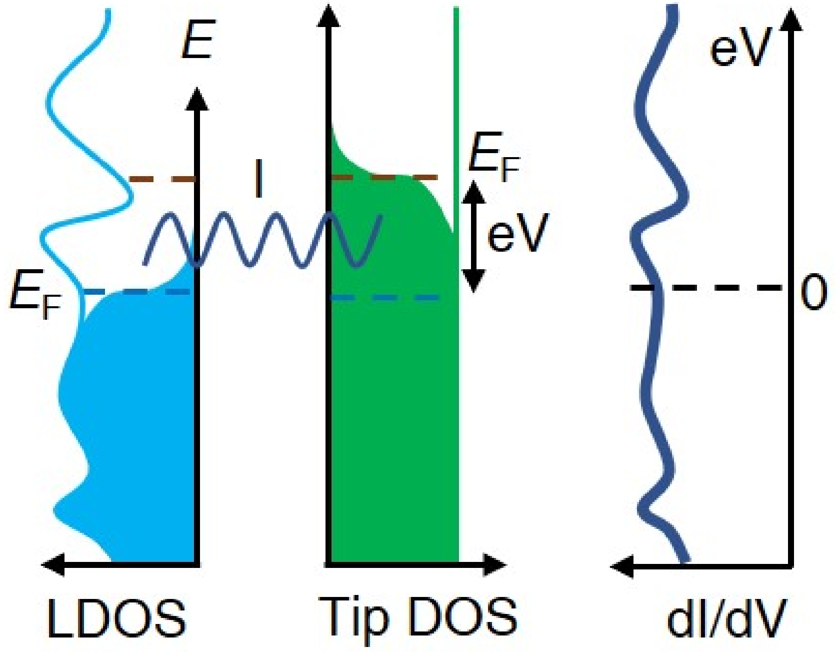
- State-of-the-art STM technique
- Proof-of-principle methodology
- More to discover

State-of-the-art STM technique

F. Hund, Z. Phys. (1927) J. R. Oppenheimer, Phys. Rev. (1928)
L. Nordheim, Z. Phys. (1927). W. Schottky, Z. Phys. (1931)

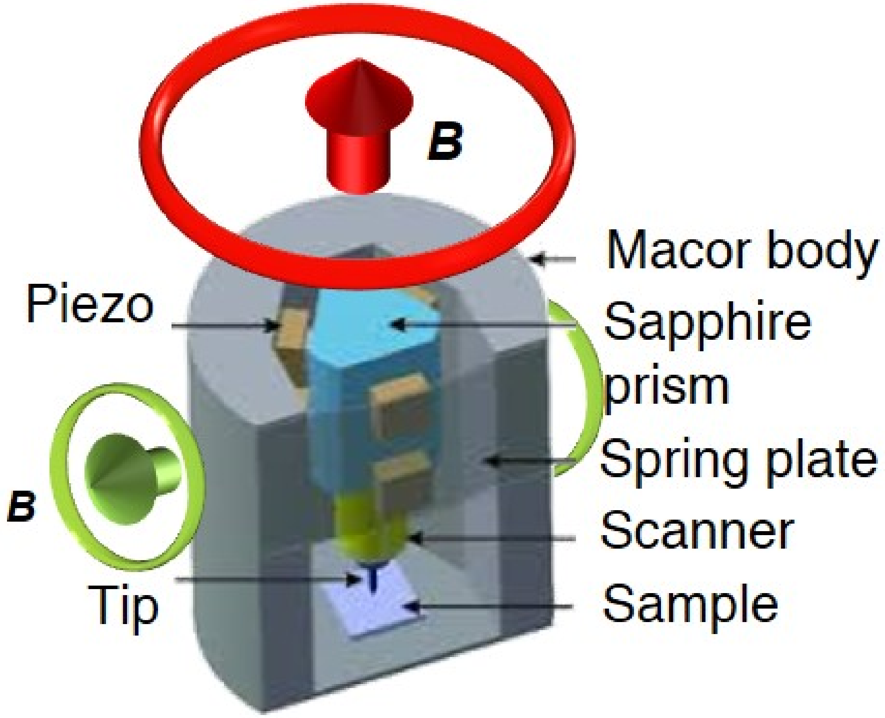
Quantum tunneling principle



J. Tersoff, D.R. Hamann. PRB (1985)

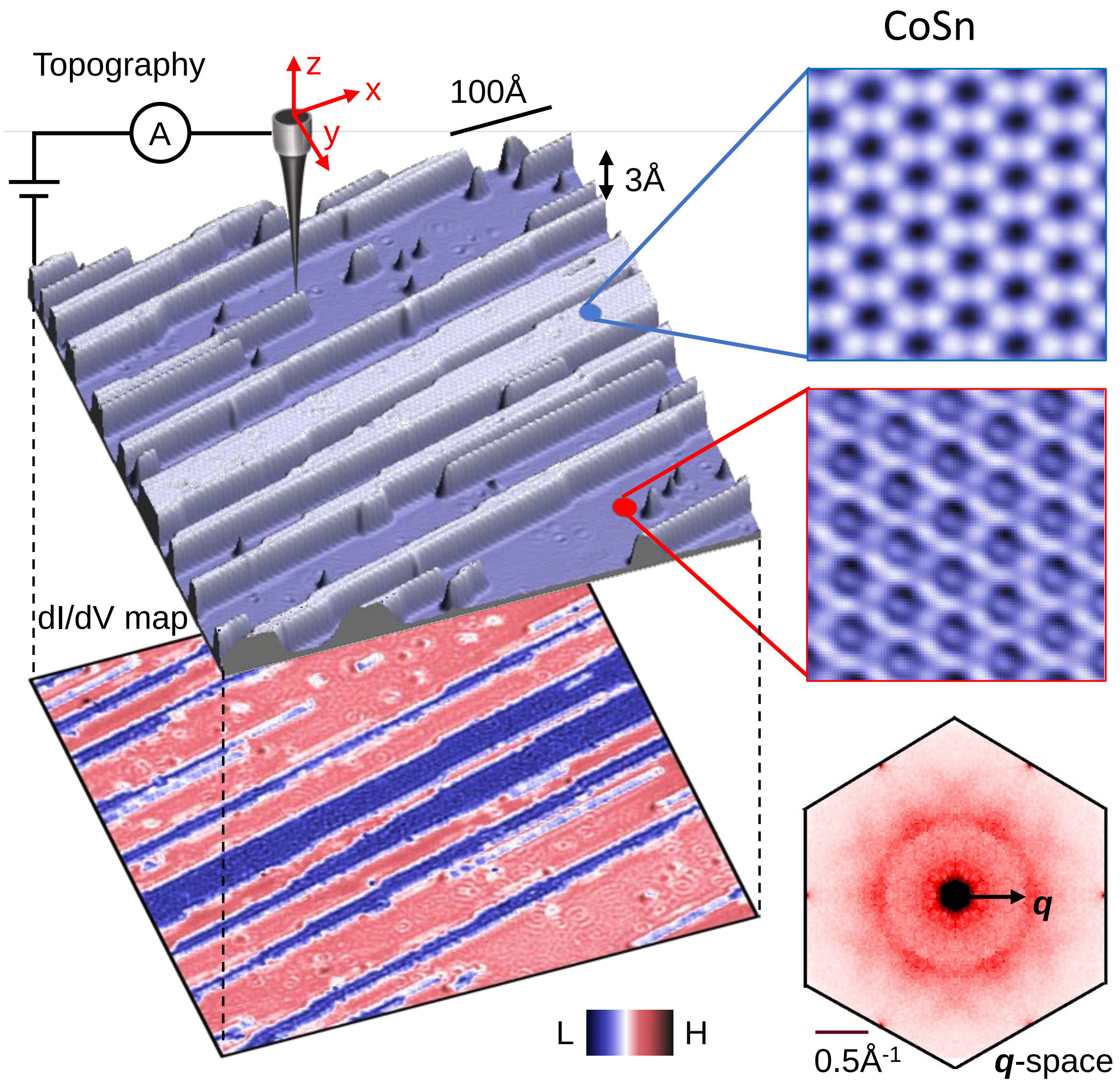
B. Voigtländer, Scanning Probe Microscopy. (Springer, 2015)

Pan-STM under a vector magnetic field



S. H. Pan. International Patent (1993)

STM data structure



Topography (Atomic resolution)

dI/dV spectrum (Sub-meV resolution)

dI/dV map
Quasi-particle interference (QPI)

O. Fischer. Rev. Mod. Phys. (2007)
R. Wiesendanger. Rev. Mod. Phys. (2009)
J. E. Hoffman. Reports Prog. Phys. (2011)
A. R. Schmidt, J.C. Davis et al. New Journal of Physics (2011)
A. Gyenis, A. Yazdani et al. New Journal of Physics (2016)
H. Zheng, M. Z. Hasan. Advances in Physics X (2018)

Comparison with other techniques in probing topological matter

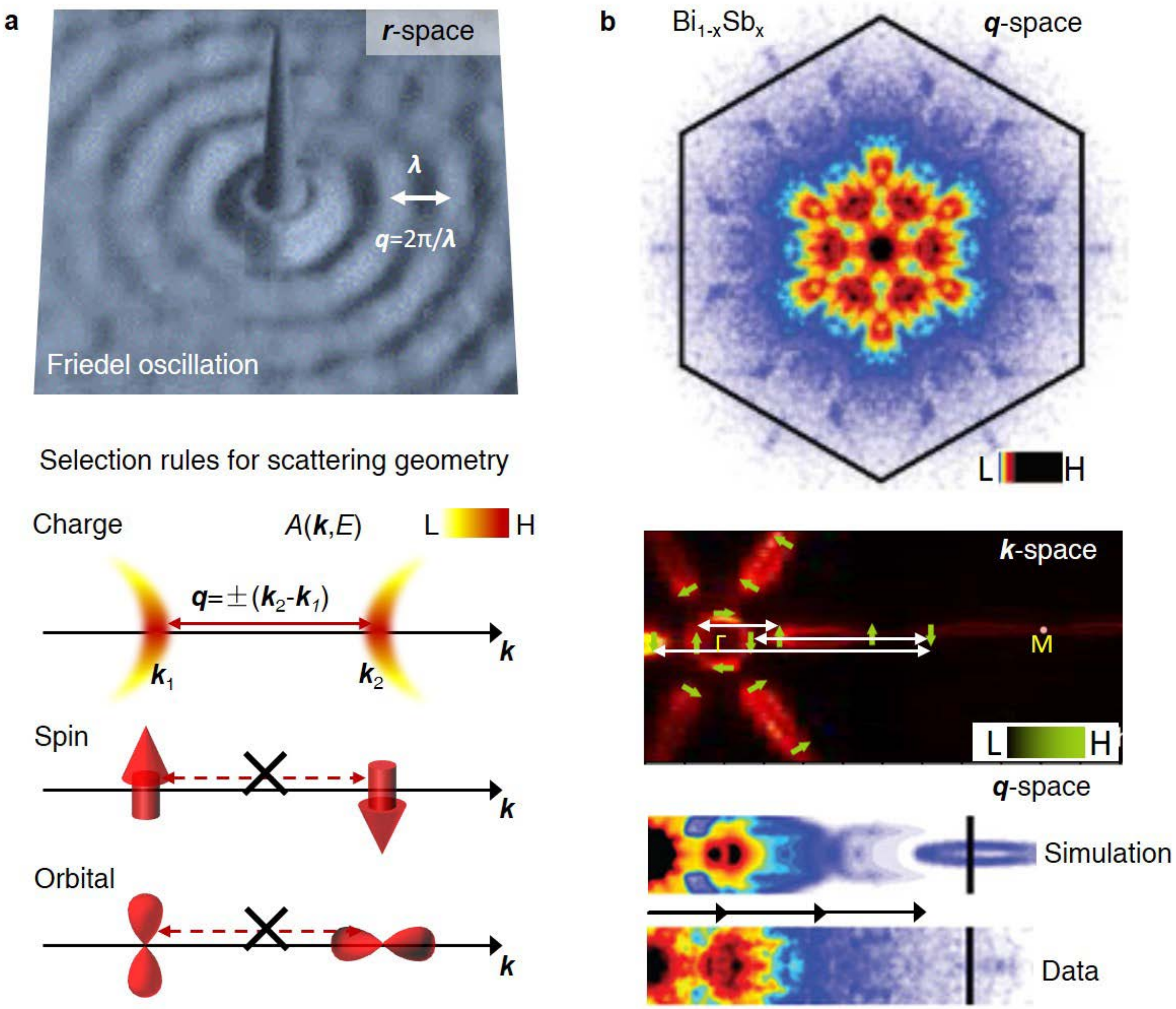
Technique	STM	ARPES	Magneto-transport
Key parameter	Local density of states	Spectral function	Conductivity tensor
Variables	Location; energy; magnetic field; magnetic or nonmagnetic tip; gating; temperature.	Momentum; energy; photon wavelength; photon polarization; spin polarization; gating; temperature.	Vector magnetic field; Landau level sequence; pressure; electrical field; gating; Temperature.
Unique aspects	Probing the scattering geometry; sub-meV energy resolution; Landau quantization; edge state; detecting zero modes.	Band crossing; spin/orbital-momentum locking and texture; probing both 2D surface and 3D bulk band structures.	Electron mobility; chiral anomaly; anomalous Hall; Hall quantization; thermal conductivity etc.
Connection with(in) scanning tunnelling microscopy	**Correspondence between single defects, vortices and local density of states; correspondence between (bulk) energy gap and edge states.**	**Correspondence to momentum integrated photoemission signal; energy gaps; charge/spin/orbital texture; band dispersion; inter/intra- band structure scattering.**	**Effective quasi-particle dispersion and Fermi surface geometry; magnetic field response; effective mass, Fermi velocity, and Fermi length; phase transition.**
Limitation	Momentum resolution; atomically flat surfaces; probing surface states and surface-projected bulk states; thermal smearing from tip.	Spatial resolution; fresh and flat surface; occupied states; energy resolution; magnetic field.	No energy, spatial, momentum or spin resolution; extrinsic scattering mechanism can contribute to the signal.

Proof-of-principle methodology

- Quasi-particle interference and Landau quantization
- Topological correspondence as a guideline for STM discovery
- Magnetic field control and engineering of topological matter
- Probing extreme local effect at the atomic scale

QPI method to probe scattering geometry

Early QPI method references: M. F. Crommie et al Nature, Science (1993). Y. Hasegawa et al PRL (1993). P. T. Sprunger. Science 275, 1764 (1997). L. Petersen et al. PRB (1998). J. E. Hoffman. et al. Science (2002).

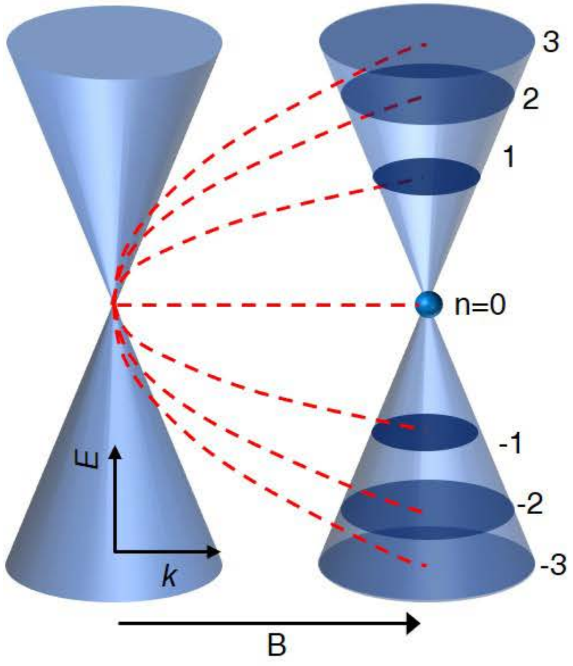


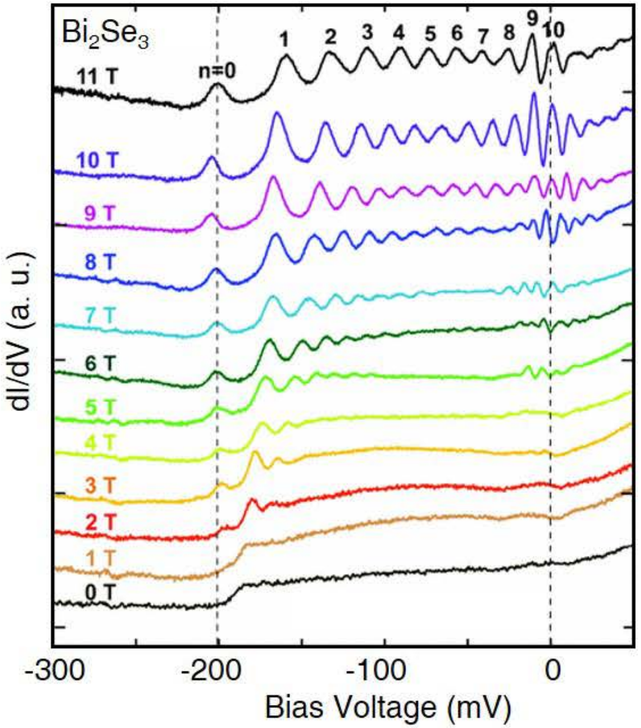
P. Roushan, A. Yazdani et al. Nature (2009); D. Hsieh, M.Z. Hasan et al. Nature (2008).

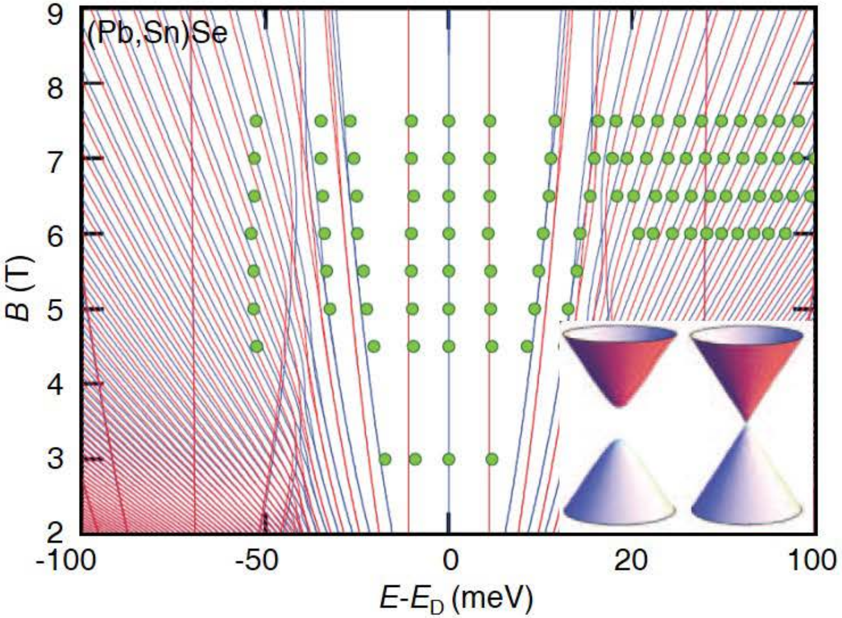
Landau quantization to detect topological fermions

Early references: J.W.G. Wildöer et al. PRB (1997). R Dombrowski et al. Applied Physics A (1998)
T. Matsuiet. et al. PRL (2005). G.H. Li. et al. Nat. Phys. (2007). D. L. Miller. et al. Science (2009).

$$E_n = \mathrm{sgn}(n) v \sqrt{2|n| e\hbar B}$$







P. Cheng, Q.K. Xue et al. PRL (2010). Y. Okada, V. Madhavan et al. Science (2013).

Transport Landau level quantization: Y. Xu, Y. P. Chen et al. Nature Phys (2014)

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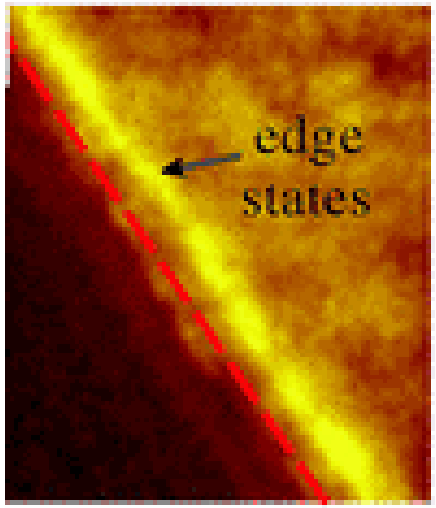
Topological correspondence

Bulk-boundary correspondence

Chern number and edge states in the integer quantum Hall effect

Y. Hatsugai. PRL (1993)



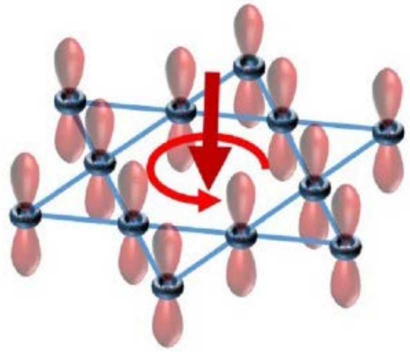
Robust edge state in Bi

F. Yang, J.F. Jia et al. PRL (2012)

Wannier–Bloch correspondence

Maximally localized Wannier functions RMP (2012)
N. Marzari, A. A. Mostofi, J. R. Yates, I. Souza, D. Vanderbilt

Topological quantum chemistry Nature (2017)
Barry Bradlyn et al, C. Felser, M. I. Aroyo, B. A. Bernevig

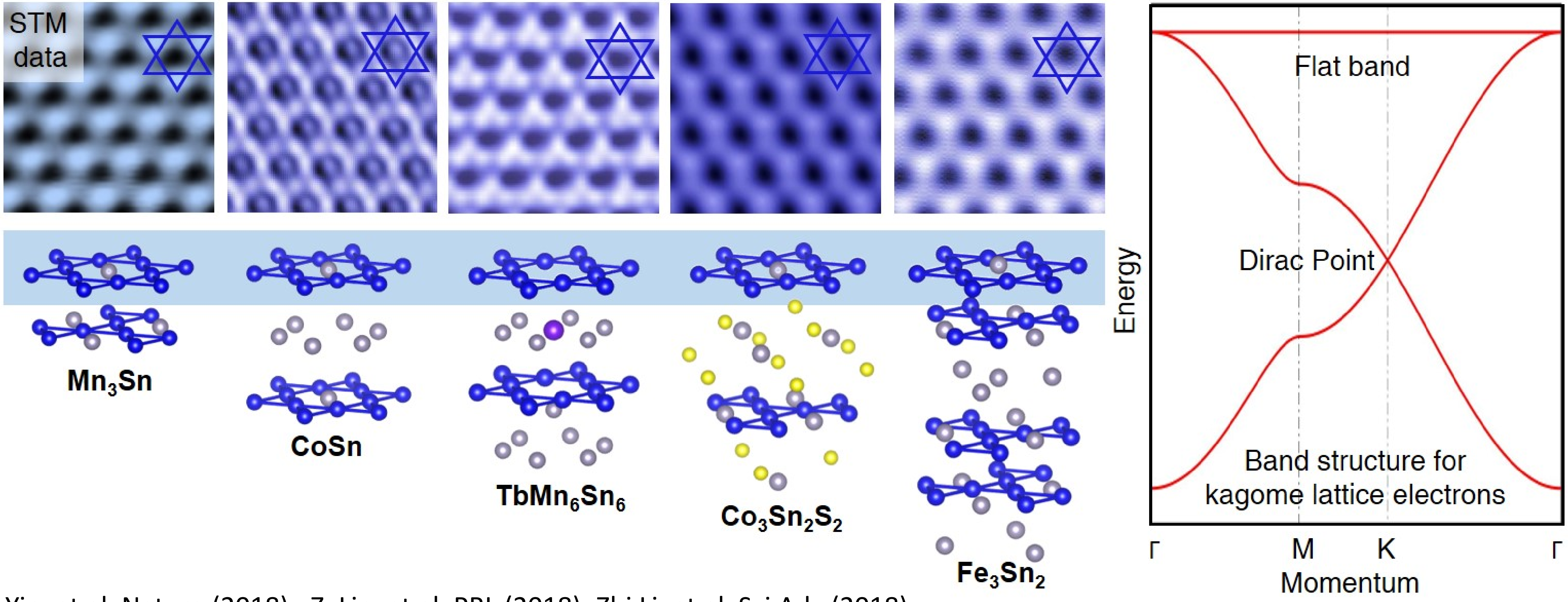


Orbital magnetism in $Co_3Sn_2S_2$

J-X Yin, M Z Hasan et al.
Nat Phys (2018)

Lattice geometry and topological correspondence

Unusual fermions arising from lattices with special geometry (honeycomb, kagome, Lieb, chiral lattice)



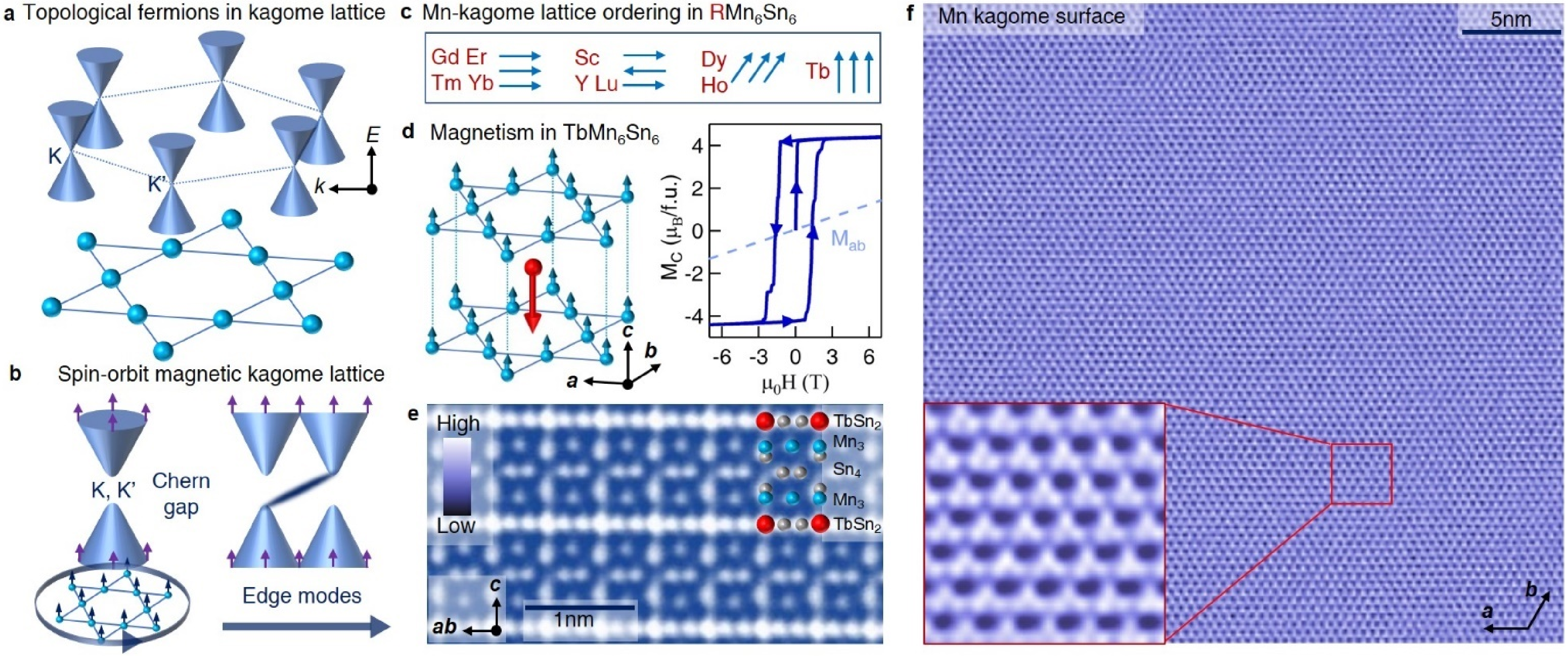
J.X. Yin, et al. Nature (2018). Z. Lin, et al. PRL (2018). Zhi Li, et al. Sci Adv (2018).
J. X. Yin, et al. Nat. Phys. (2019). N. Morali, et al. Science (2019).L. Jiao, et al. Phys. Rev. B (2019). S. Howard. Arxiv (2019).
J.X. Yin, et al. Nature (2020). S.S. Zhang, PRL (2020). J.X. Yin, et al. Nat. Commun. (2020).
J.X. Yin, et al. Nat. Commun. (2020). Y. Xing, et al. Arxiv (2020). Z. Guguchia. et al. Nat. Commun. (2020). Z. Liu. et al. Nat. Commun. (2020)

Quantum limit Chern magnetism in $TbMn_6Sn_6$

Theoretical concept for kagome Chern magnet:
F.D. Haldane PRL (1998).
C.L. Kane & E.J. Mele. PRL (2005).
G.Xu, B. Lian, S.C. Zhang. PRL (2015).

Known unknown

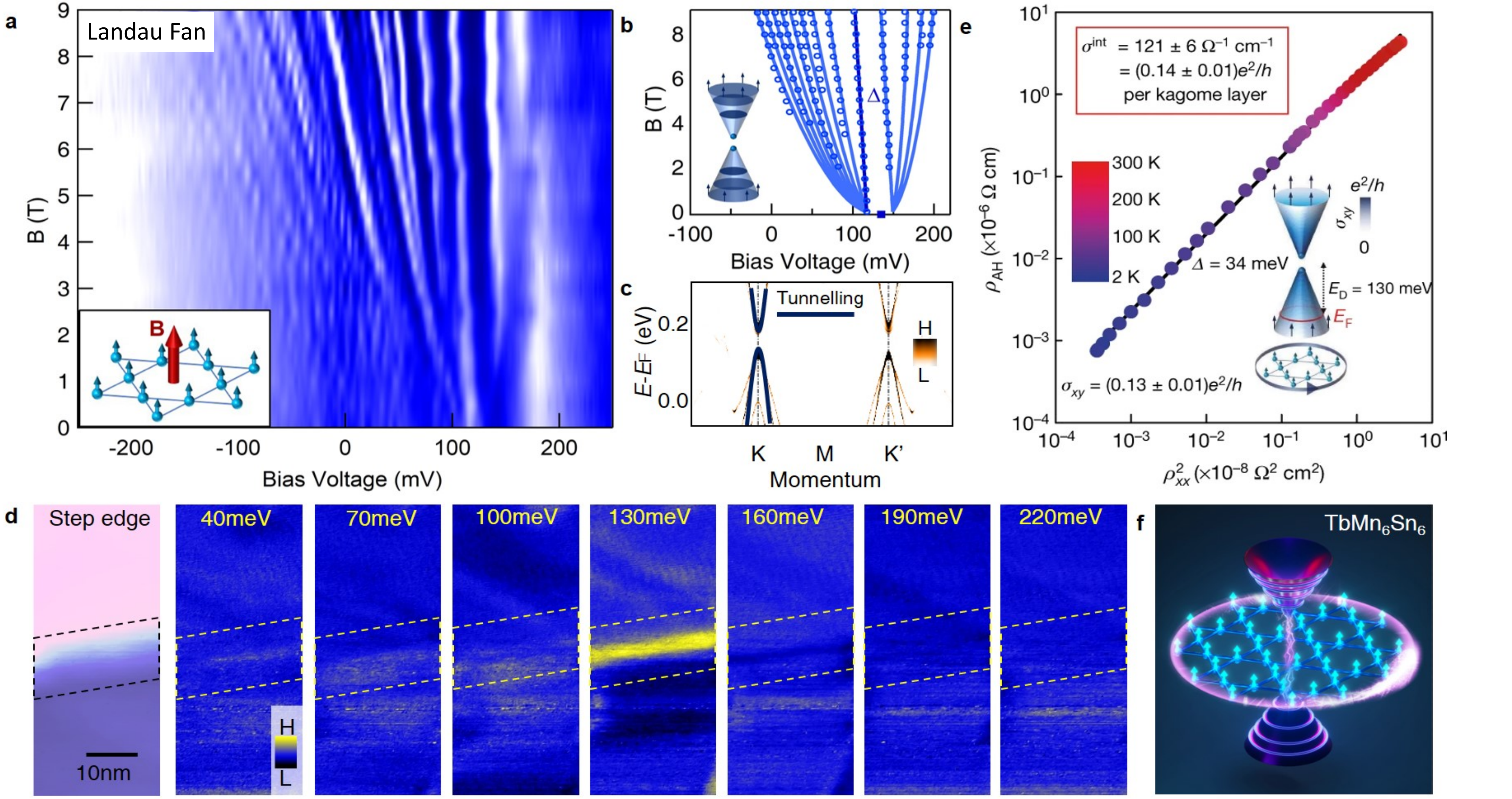
J.X. Yin, M.Z. Hasan et al. Nature (2020)



Bulk-boundary-Berry correspondence in Chern magnet

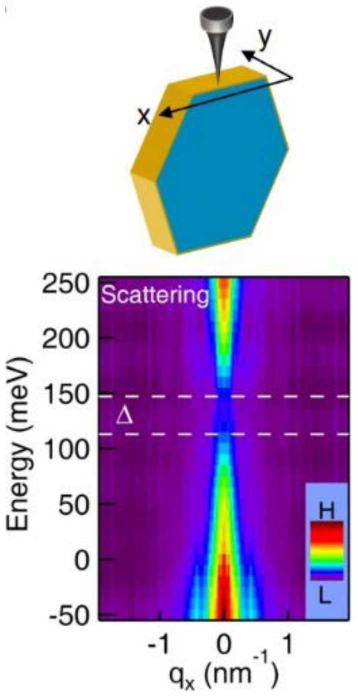
$$E_n = E_D \pm \sqrt{(\Delta/2)^2 + 2|n|e\hbar v^2 B} - \frac{1}{2} g\mu_B B$$

J.X. Yin, M.Z. Hasan et al. Nature (2020)

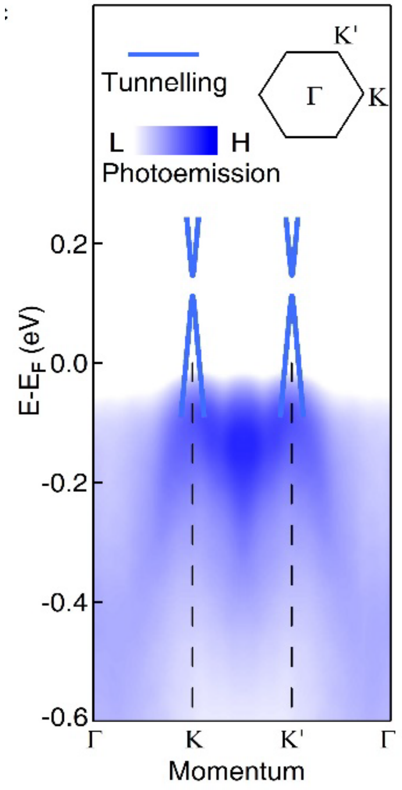


Additional features of Chern magnet

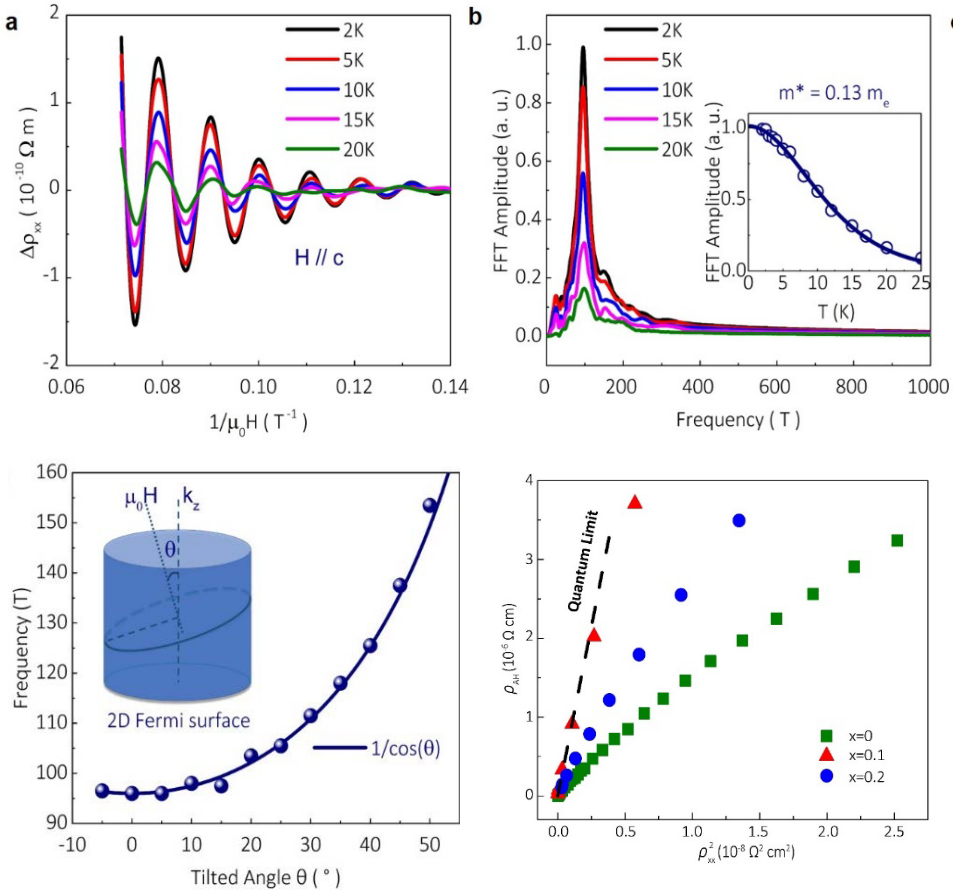
Side surface QPI imaging



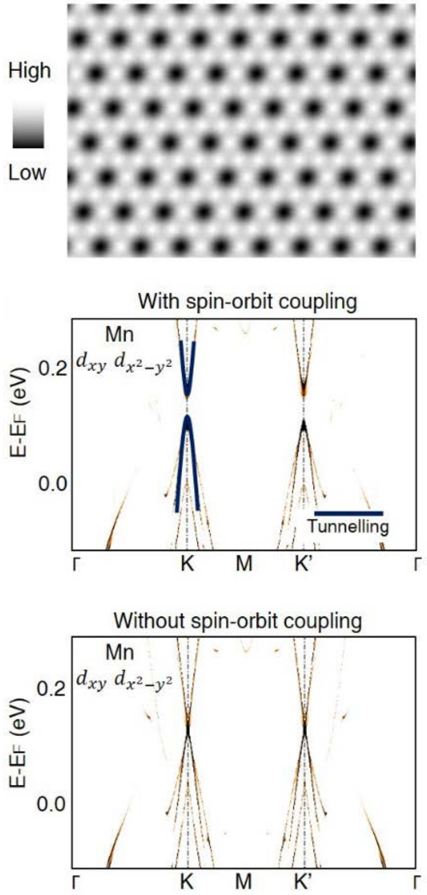
ARPES



Transport quantum Oscillations



First-principles



Proof-of-principle methodology

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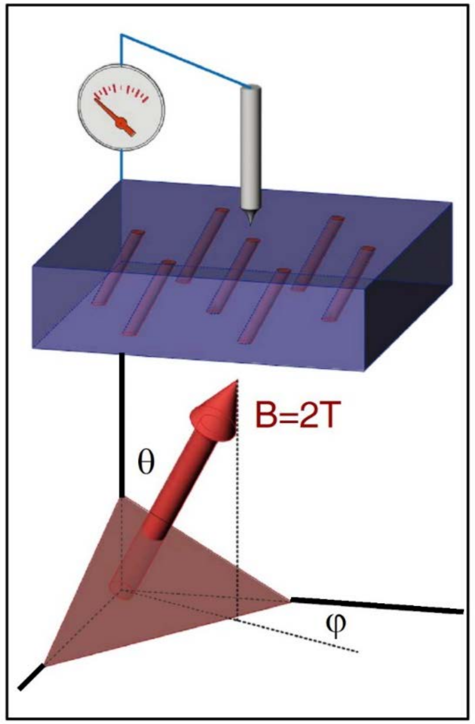
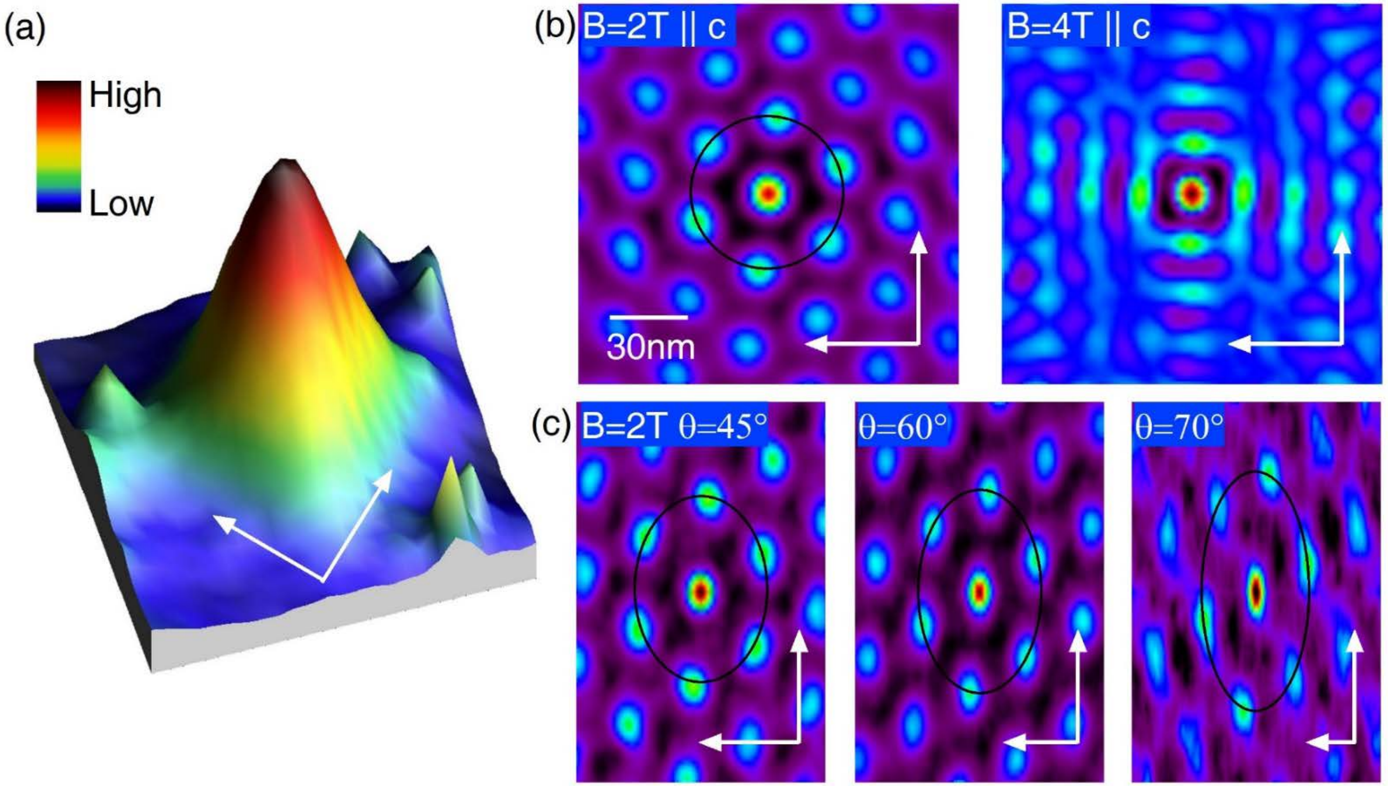
Vector magnetic field STM

Early reference: H. F. Hess. et al. PRL (1992).

Princeton Work
J.X. Yin, S.S. Zhang PRL (2019).
S.S. Zhang, J.X. Yin PRB (2019).
S.S. Zhang, J.X. Yin PRB (2020).
LiFeAs (Tc=17K)

9-2-2T 380mK-77K

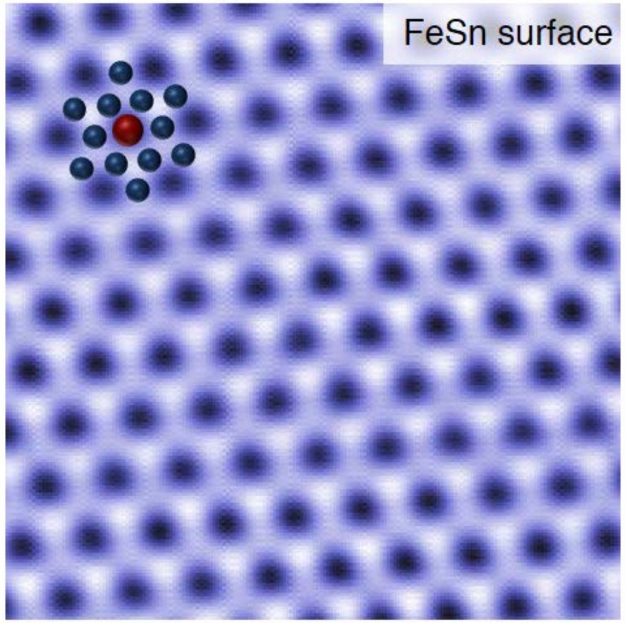




Giant spin-orbit tunability in topological magnet

Unknown unknown: **How would a topological magnet response to vector magnetization?**

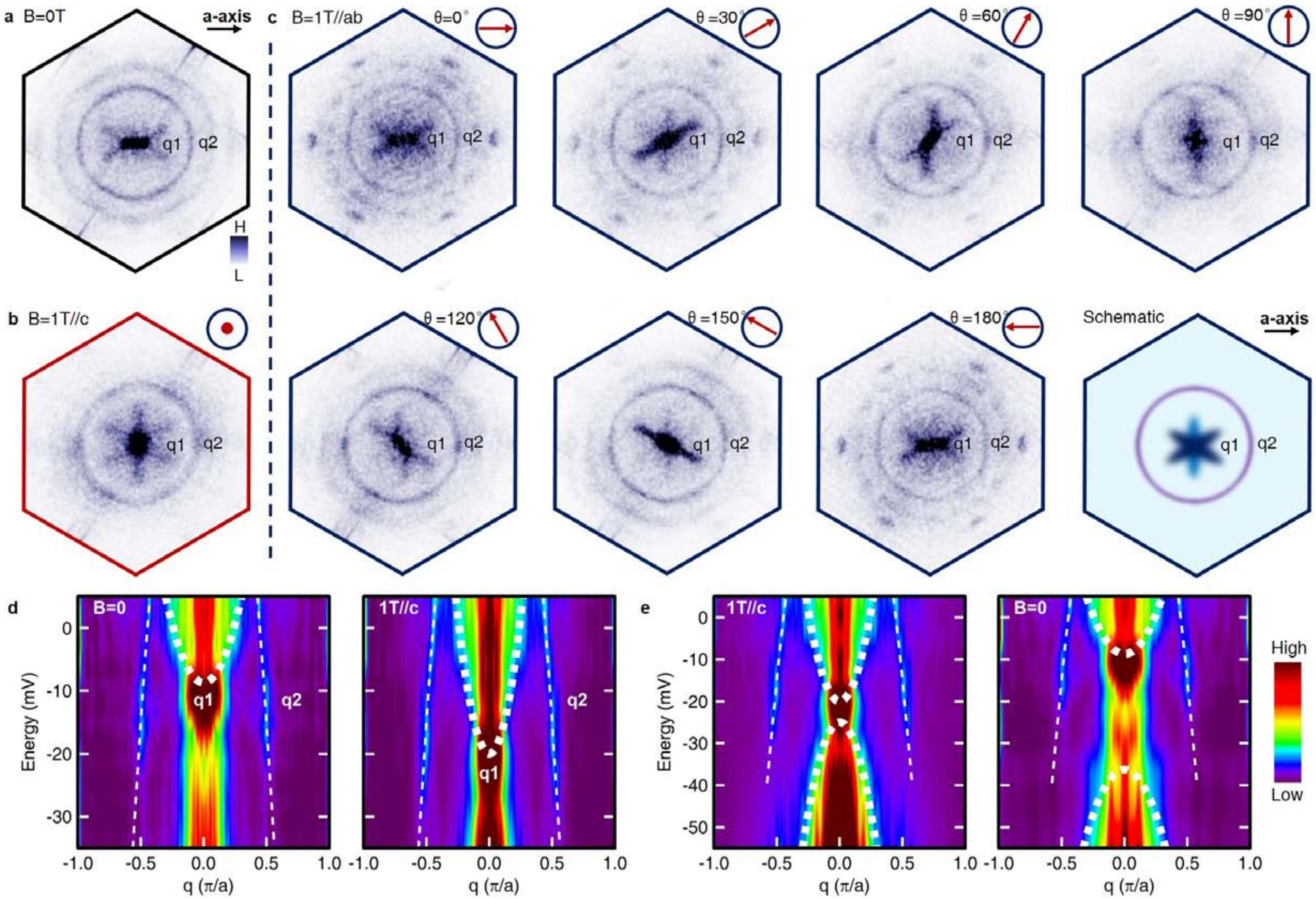
Kagome magnet Fe_3Sn_2



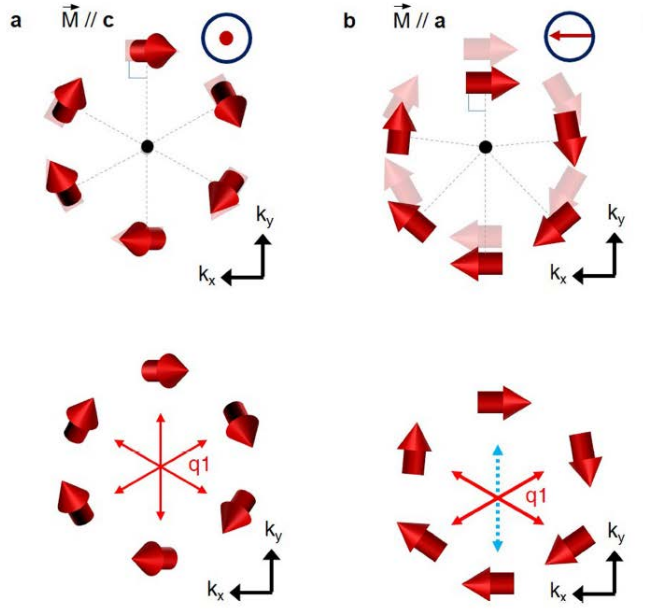
Quantum state from kagome lattice

J X Yin, M Z Hasan et al Nature (2018)
Y Li, J M Tranquada et al PRL (2019)

Vector field controlled scattering symmetry

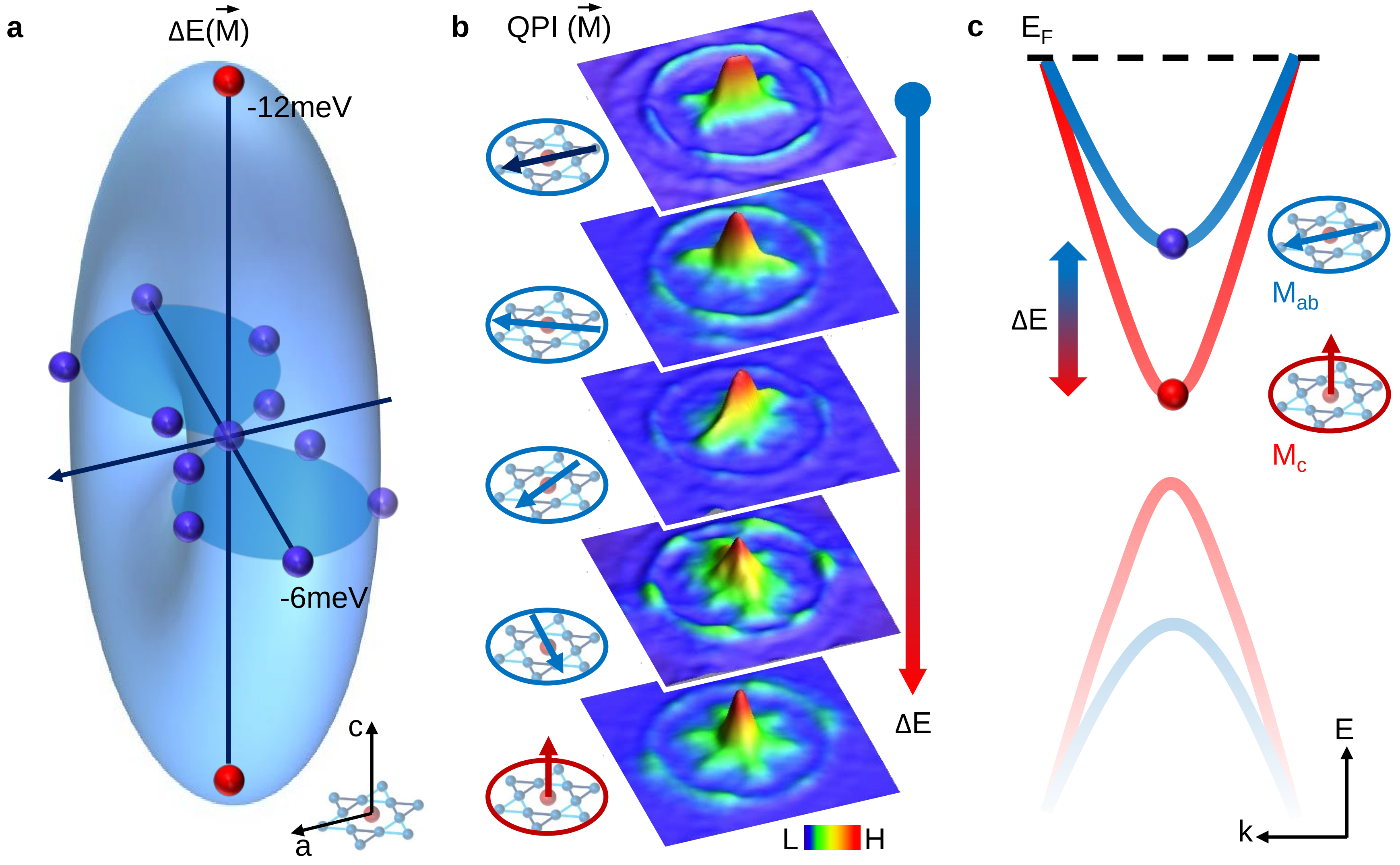


QPI anisotropy~ $\cos^2 \theta$
θ is the in-plane angle with respect to the magnetization direction.
By Lian Biao et al.



J X Yin, M Z Hasan et al Nature (2018)

Spin-orbit tunability through vector field magnetization

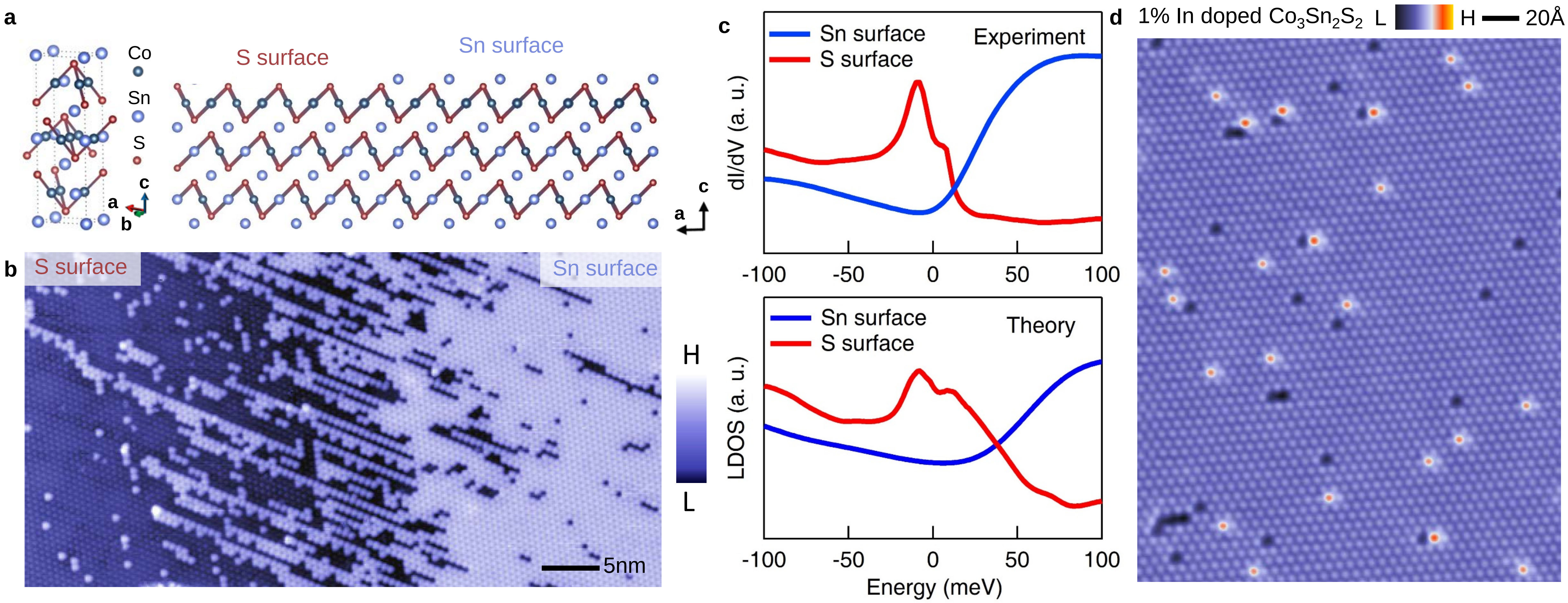


J X Yin, M Z Hasan et al Nature (2018)

Surface identification for $Co_3Sn_2S_2$

Crystalline symmetry and **layer selective chemical marker**

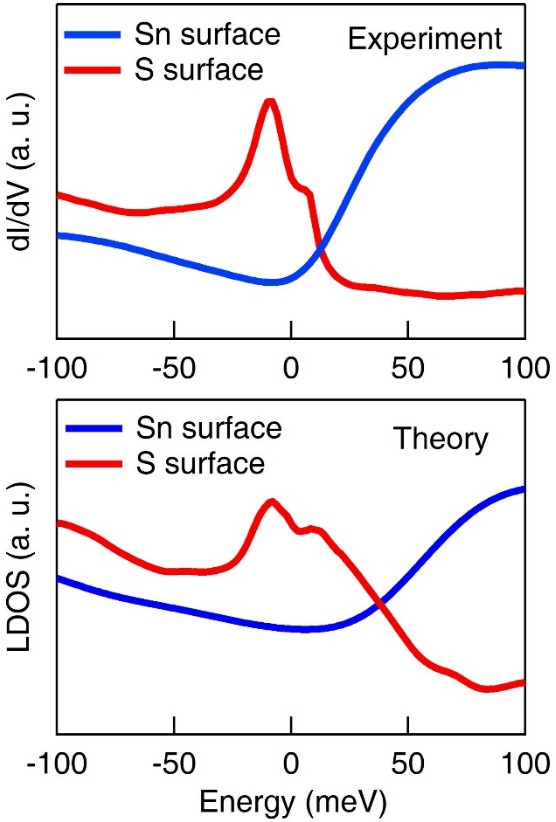
Early reference: A. Li, S.H. Pan et al. PRB (2019); P. Aynajian, A. Yazdani et al. Nature (2012)

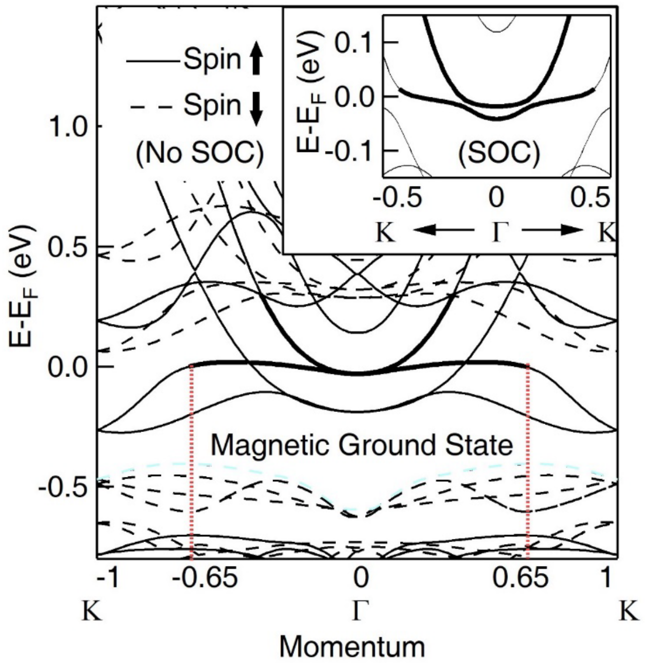


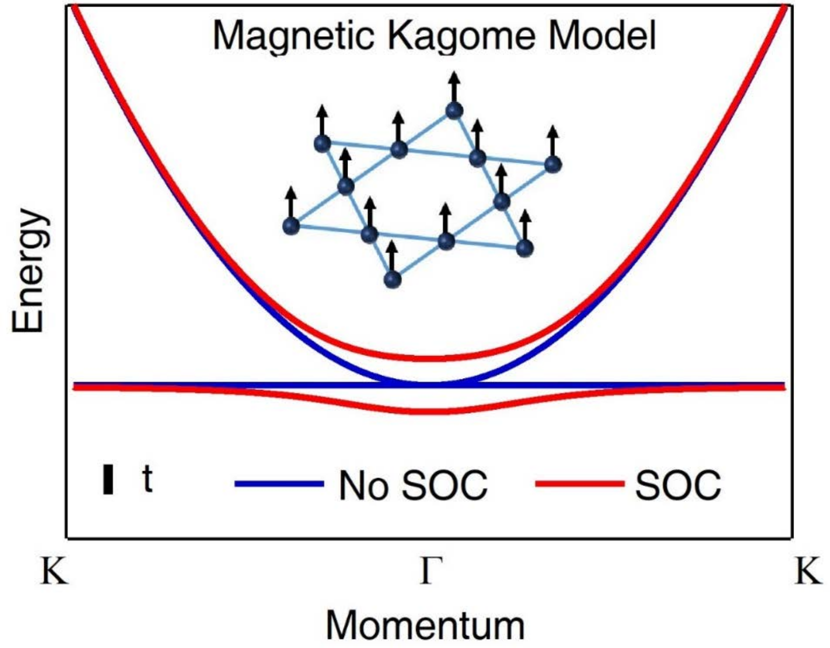
J. X. Yin, M. Z. Hasan et al. Nat Phys (2019); J. X. Yin, M. Z. Hasan et al. Nat Commun (2020).

Kagome flat band in $Co_3Sn_2S_2$

J. X. Yin, M. Z. Hasan et al. Nat Phys (2019)

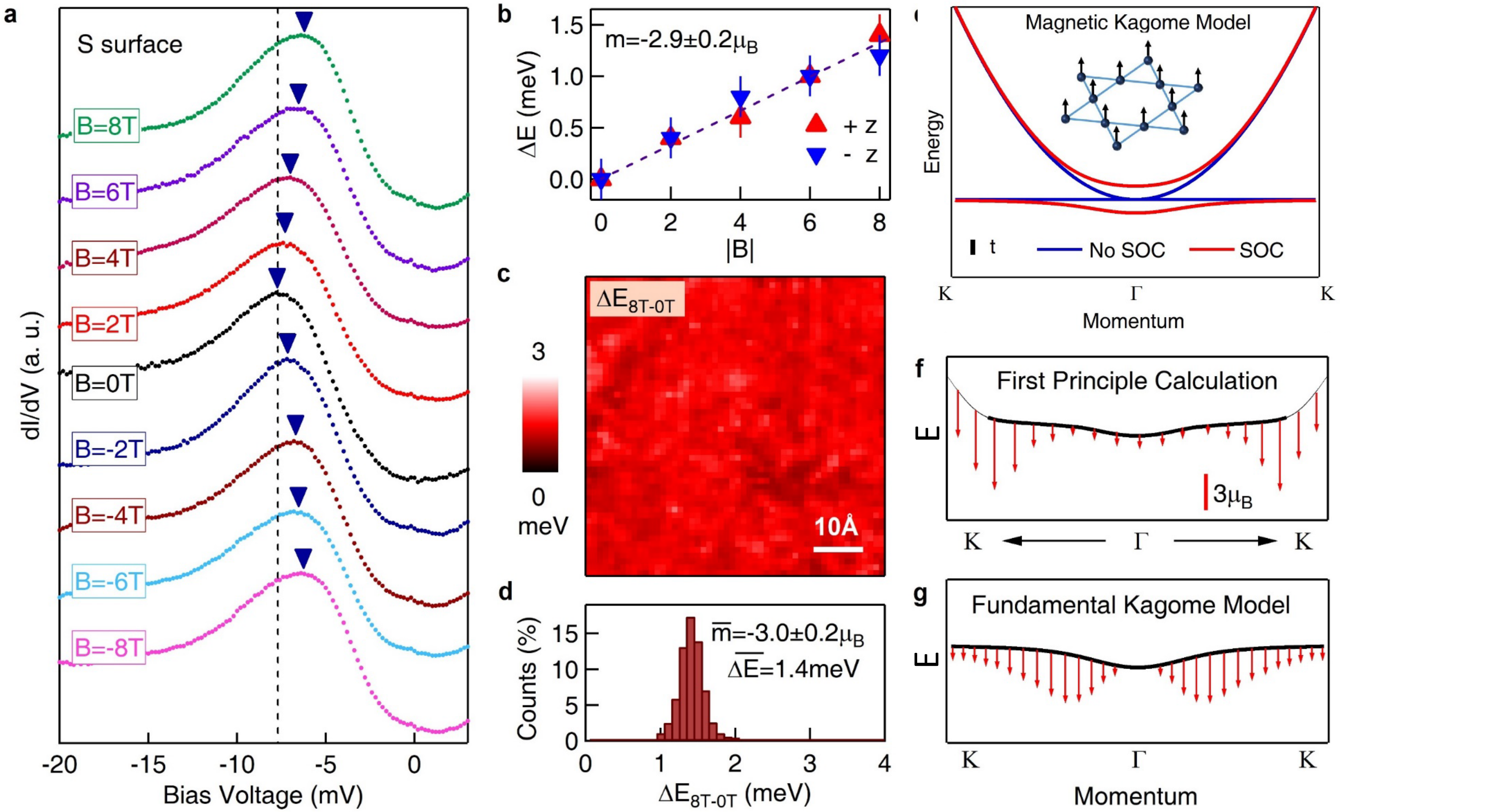






Negative flat band magnetism in $Co_3Sn_2S_2$

J. X. Yin, M. Z. Hasan et al. Nat Phys (2019)



Berry phase induced orbital magnetism: R. Karplus, J.M. Luttinger. PR (1954).
D. Xiao, M.C. Chang, Q. Niu. RMP (2010). D. Vanderbilt. Cambridge (2018).

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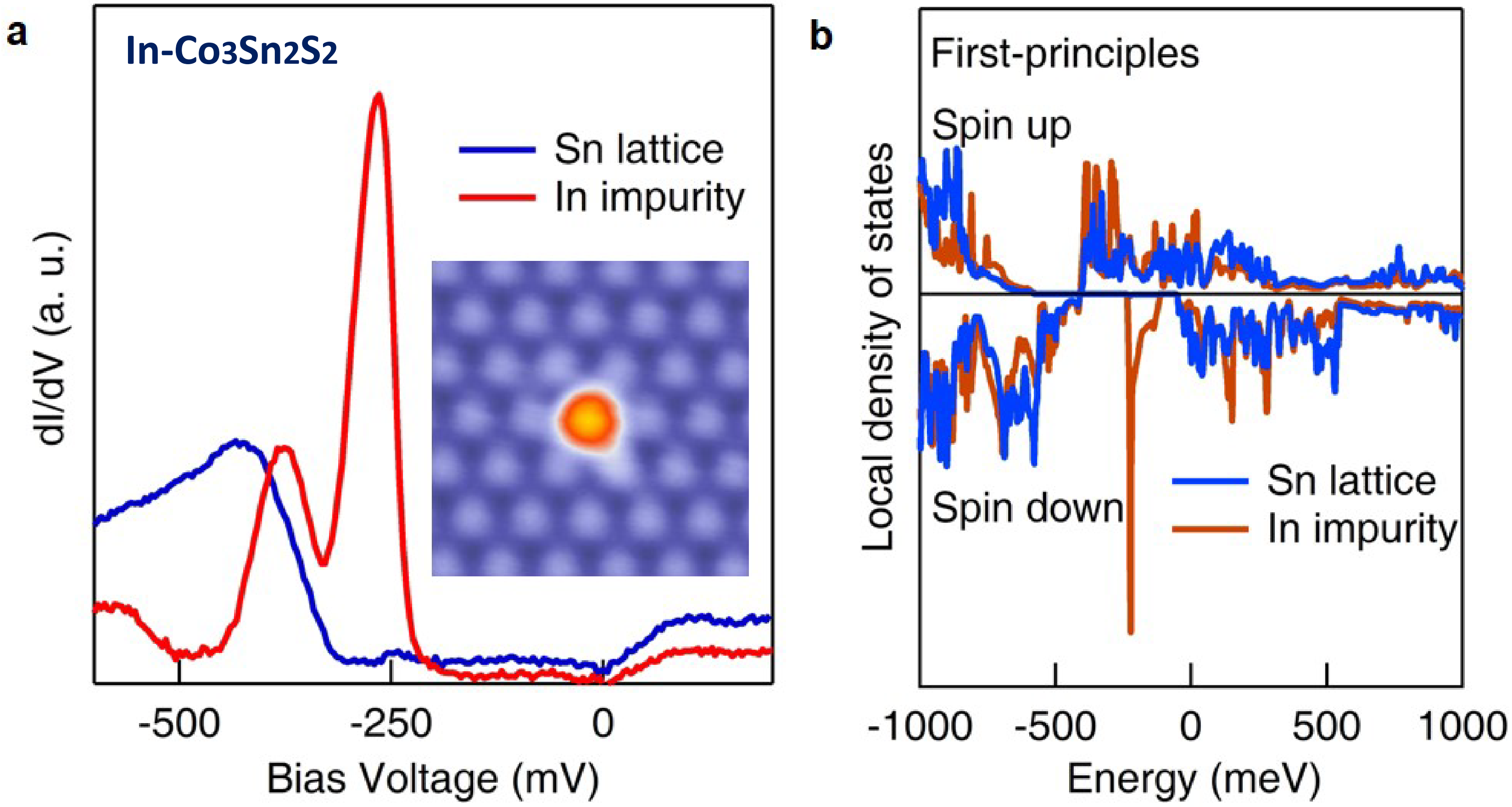
Spin-orbit quantum impurity in topological magnet

A nonmagnetic impurity can introduce spin-orbit coupled magnetic resonance in topological magnets

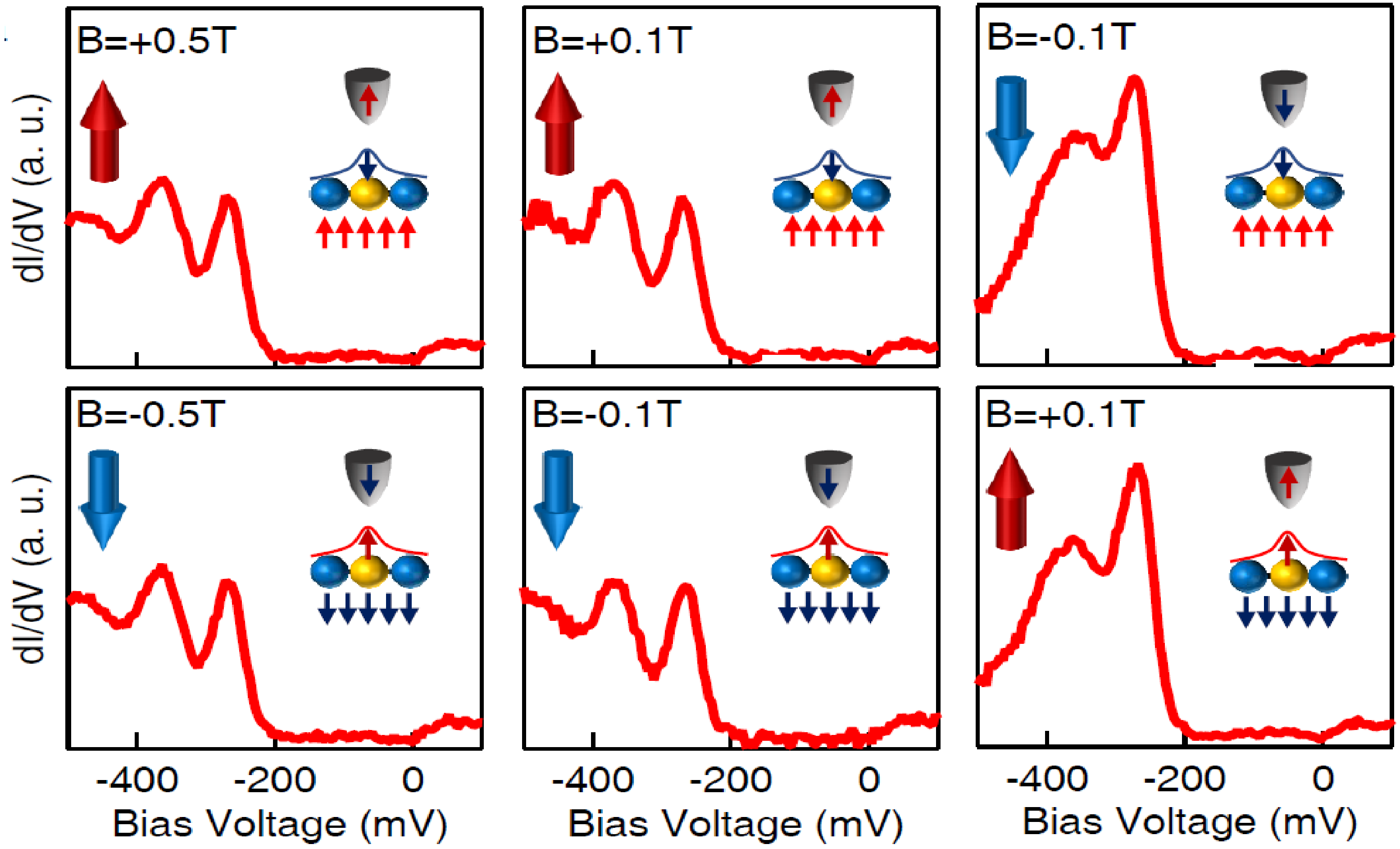


J. X. Yin, M. Z. Hasan et al
Nat Commun (2020)

Spin-orbit quantum impurity in In-$Co_3Sn_2S_2$

Spin-polarized STM

Bc(Ni tip)<<0.1T Bc(sample)~0.3T



J. X. Yin, M. Z. Hasan et al
Nat Commun (2020)

Spin-orbit quantum impurity in In-$Co_3Sn_2S_2$

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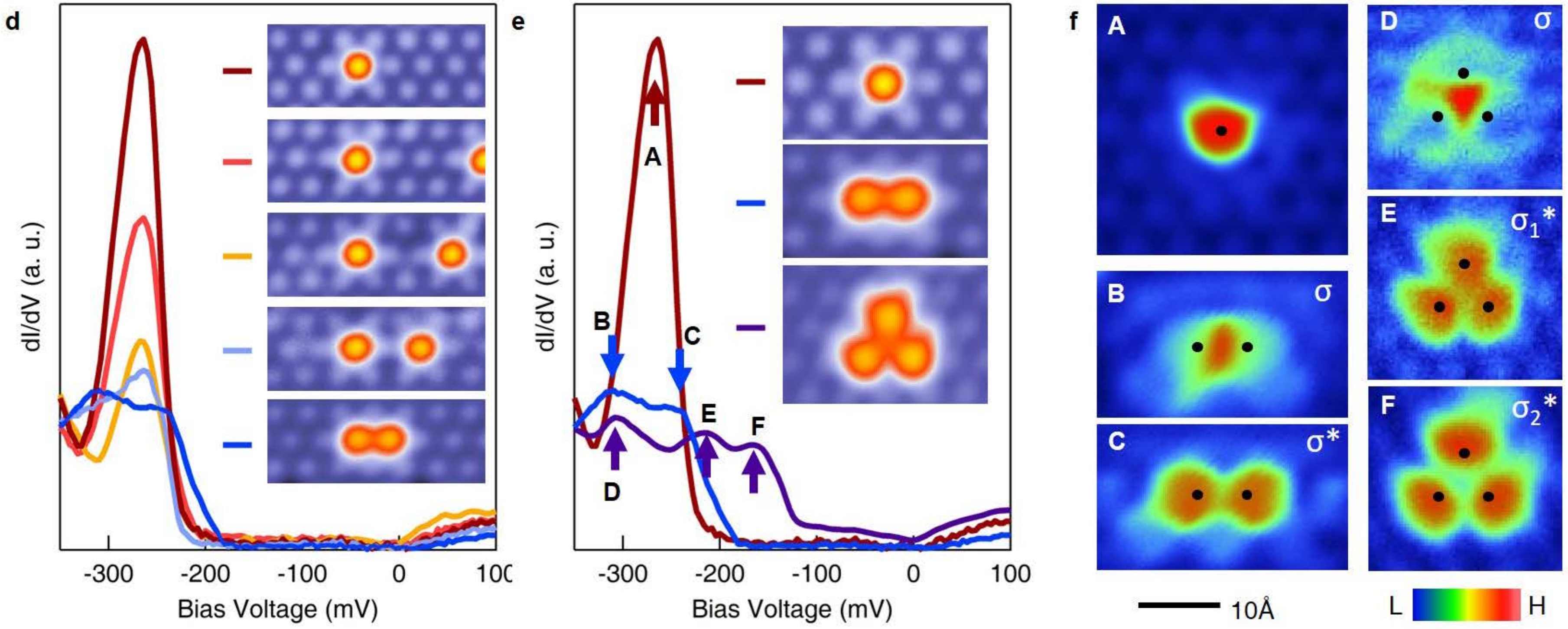
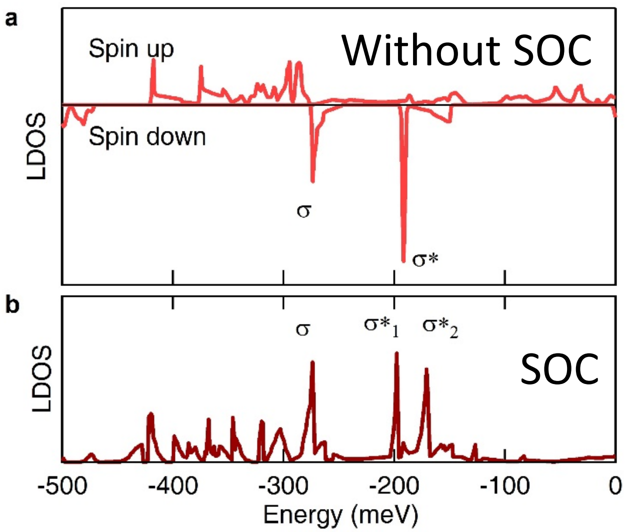


First-principles calculation



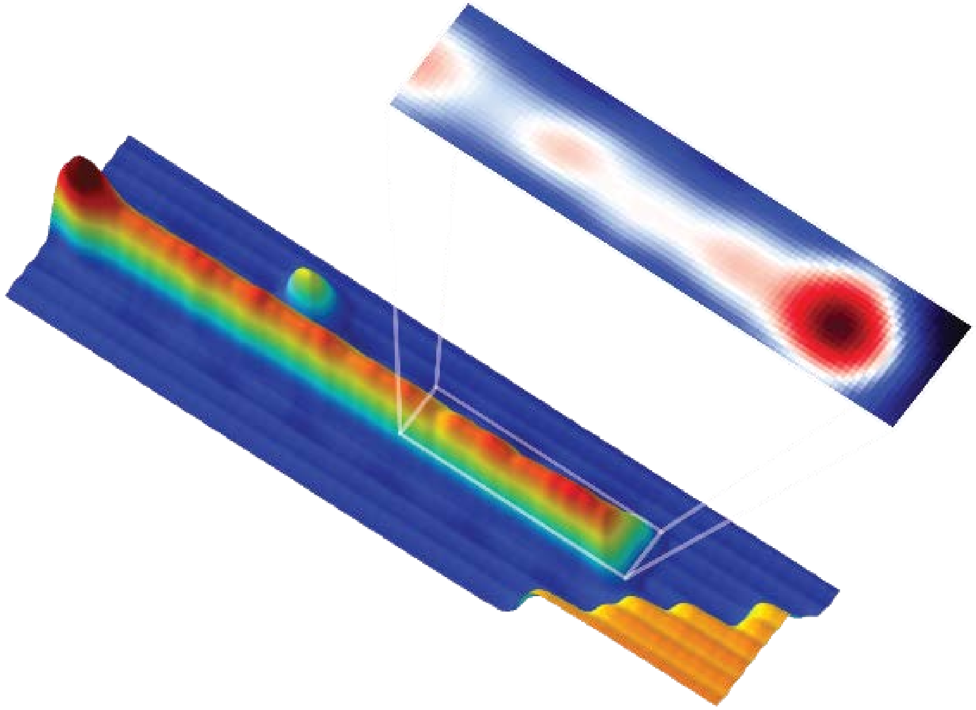
J. X. Yin, M. Z. Hasan et al
Nat Commun (2020)

Topological zero mode in artificial hybrid systems

Theory references: G. Moore,N. Read. Nucl. Phys. B (1991). G. E. Volovik. JETP Letters. (1999). A. Y. Kitaev. Phys.-Usp. (2001).

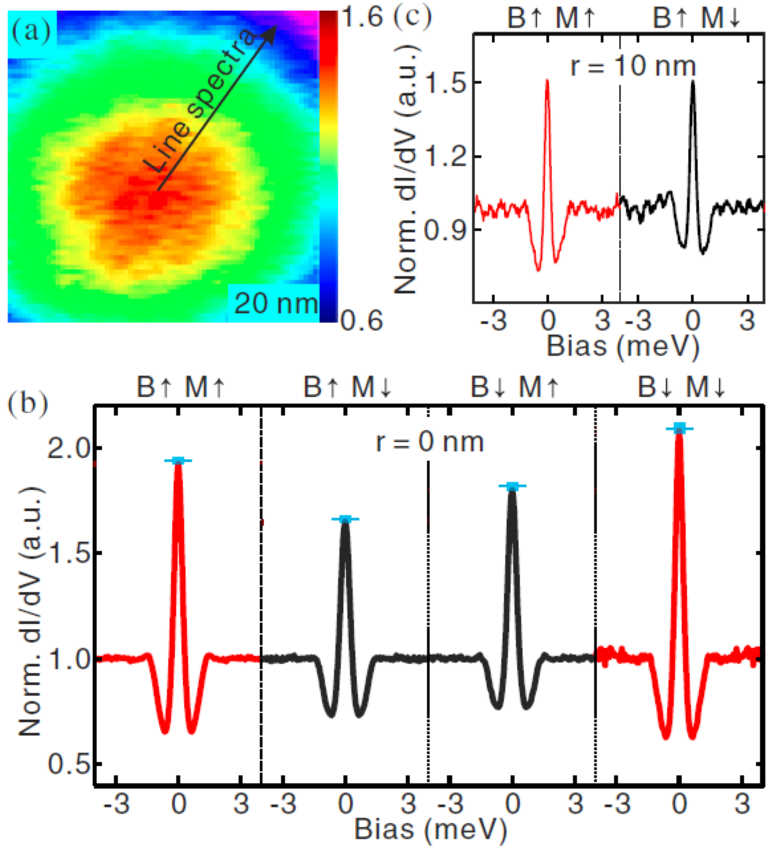
1D Chain

Ali Yazdani et al.



2D heterostructure

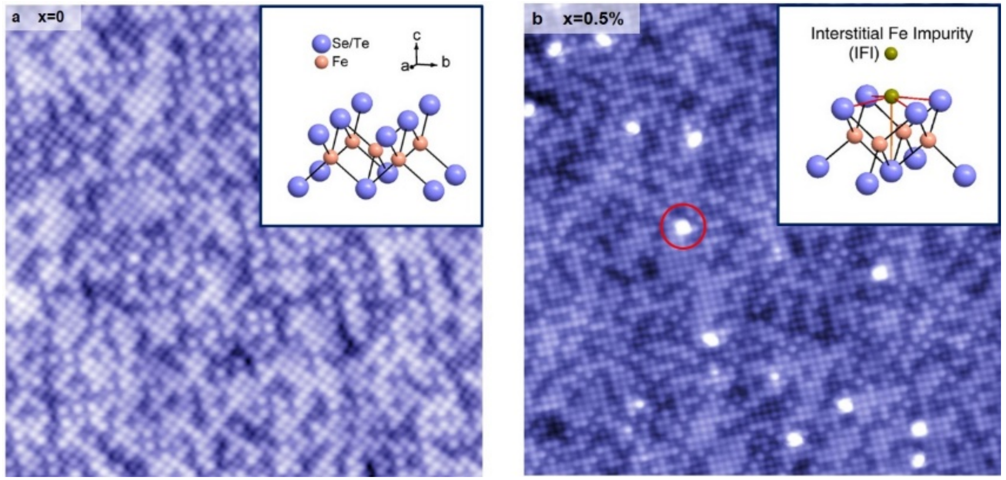
Jinfeng Jia et al.

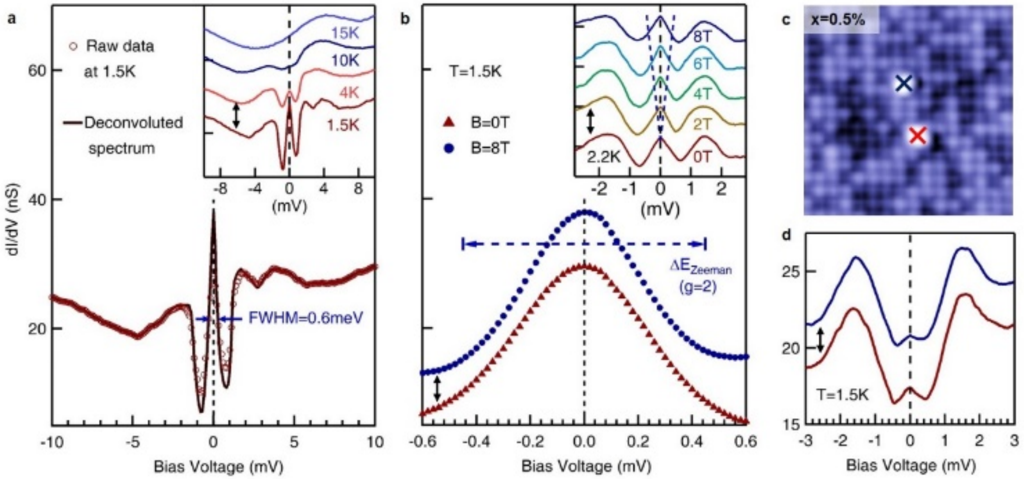


Searching for naturally occurring topological zero mode

J X Yin, S H Pan, *et al* Nat. Phys. 2015

Majorana like robust zero mode





PHYSICAL REVIEW B **92**, 115119 (2015)

Topological nature of the $FeSe_{0.5}Te_{0.5}$ superconductor

Zhijun Wang,[1,2] P. Zhang,[1] Gang Xu,[1,3] L. K. Zeng,[1] H. Miao,[1] Xiaoyan Xu,[1] T. Qian,[1] Hongming Weng,[1,4] P. Richard,[1] A. V. Fedorov,[5] H. Ding,[1,4,*] Xi Dai,[1,4,†] and Zhong Fang[1,4,‡]

PHYSICAL REVIEW B **93**, 115129 (2016)

Topological characters in $Fe(Te_{1-x}Se_x)$ thin films

Xianxin Wu,[1] Shengshan Qin,[1] Yi Liang,[1] Heng Fan,[1,2] and Jiangping Hu[1,2,3,*]

PRL **117,** 047001 (2016) PHYSICAL REVIEW LETTERS week ending 22 JULY 2016

Topological Superconductivity on the Surface of Fe-Based Superconductors

Gang Xu, Biao Lian, Peizhe Tang, Xiao-Liang Qi,[*] and Shou-Cheng Zhang[†]

PHYSICAL REVIEW X **9,** 011033 (2019)

Quantum Anomalous Vortex and Majorana Zero Mode in Iron-Based Superconductor Fe(Te,Se)

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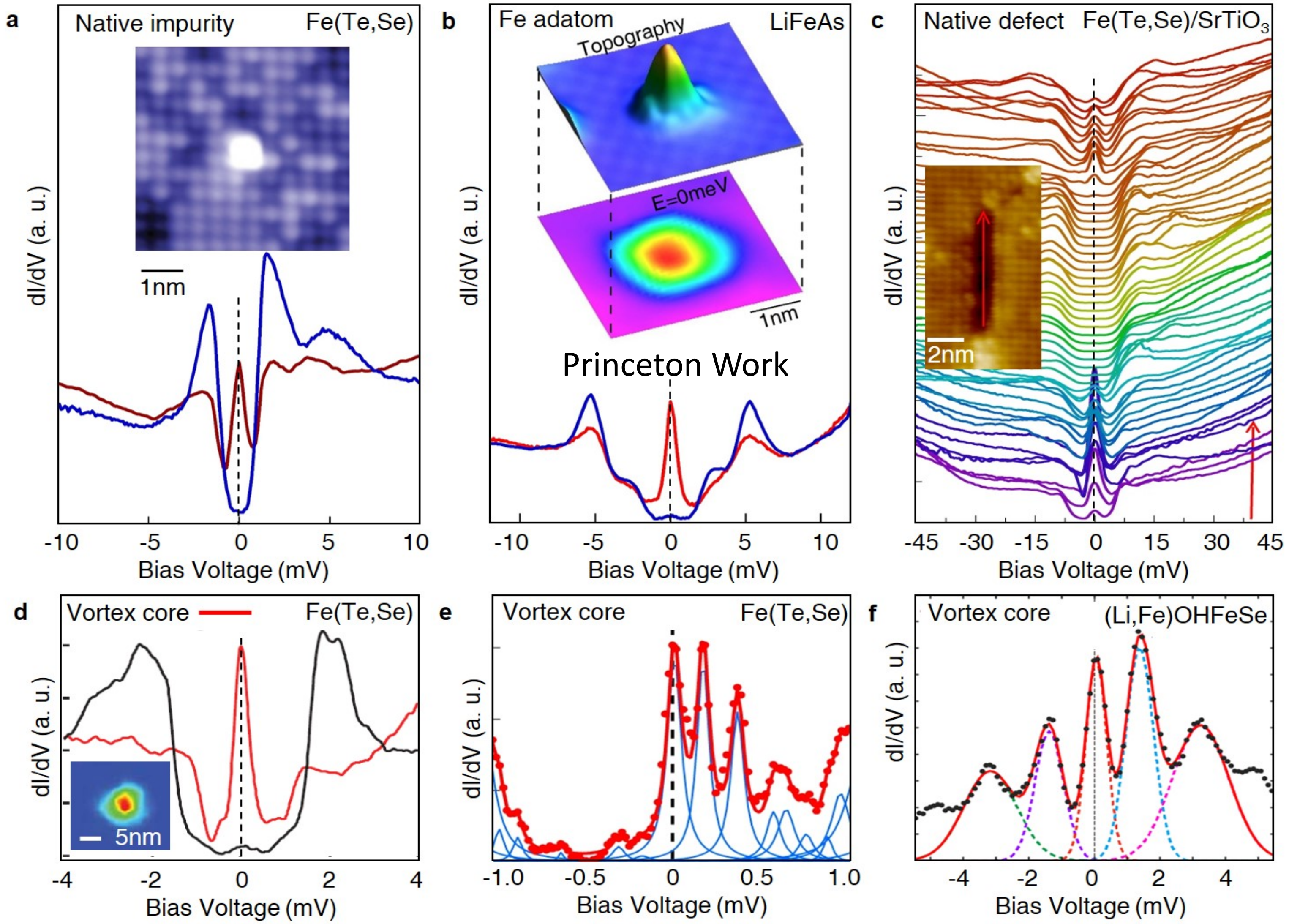
Spontaneous vortex formation and Majorana zero mode in iron based superconductor.

Recommended with a Commentary by Patrick A. Lee, MIT

Searching for naturally occurring topological zero mode

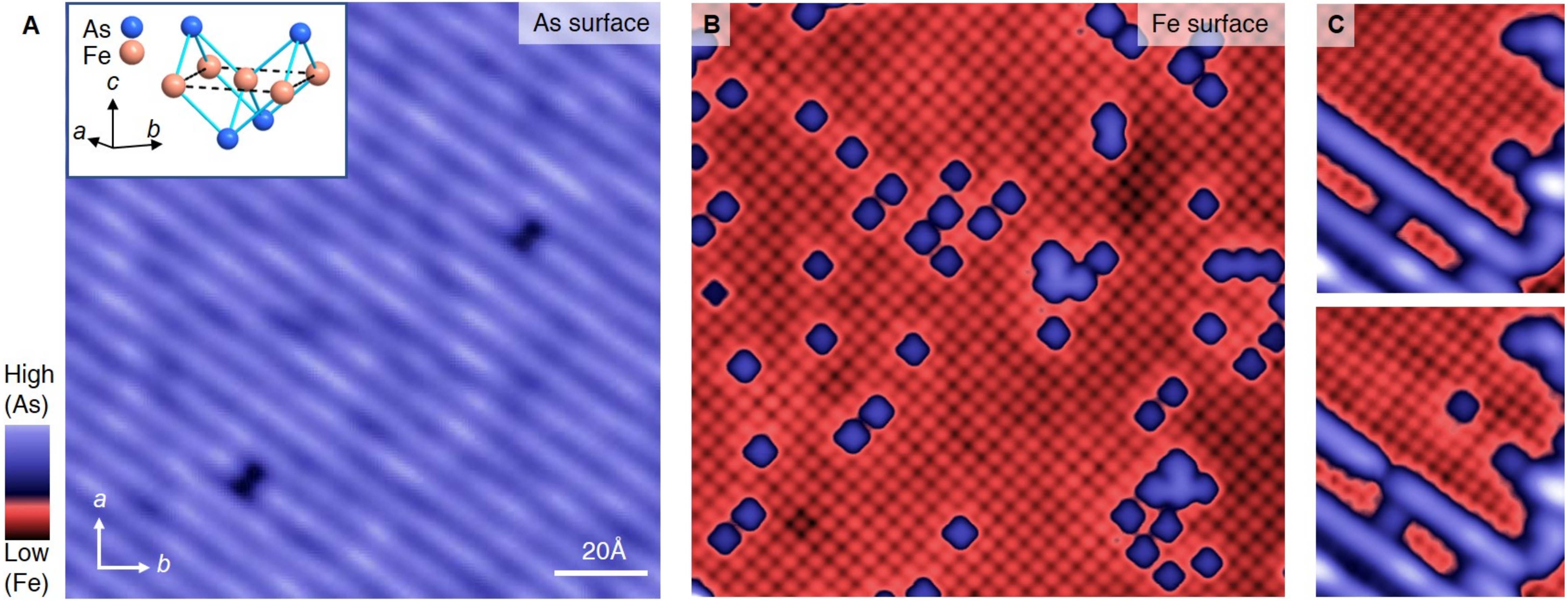


J.X. Yin, et al. Nat. Phys. (2015). S.S. Zhang, et al. PRB (2020). C. Chen, et al. Nat. Phys. (2020).
Z. Wang, et al. Science (2020). T. Machida, et al. Nat. Mater. (2019). Q. Liu, et al. PRX (2018).

Fundamental role of anion in iron-based superconductivity

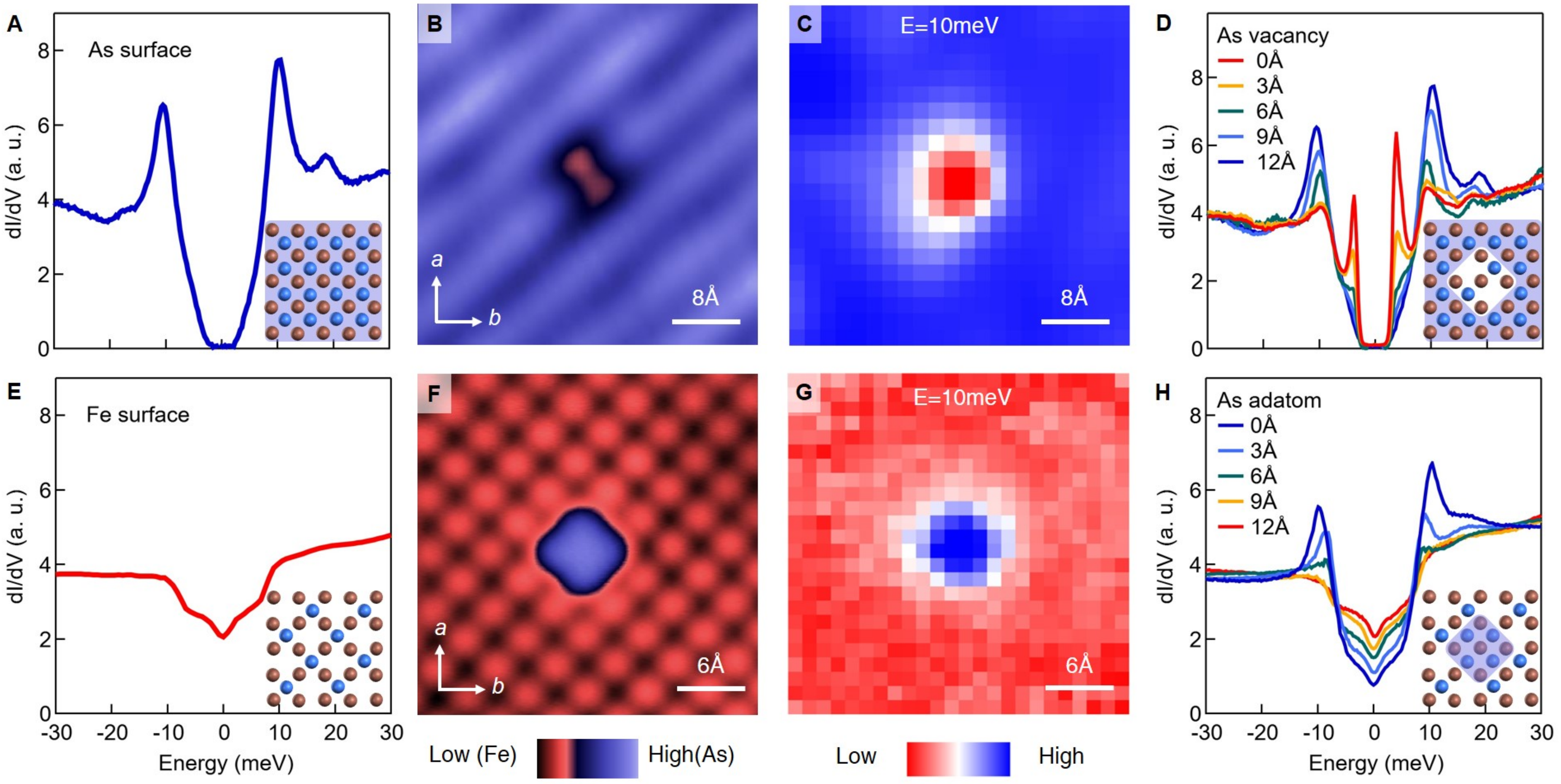
>100 cleaved $Ba_{0.4}K_{0.6}Fe_2As_2$ crystals (Tc=38K, experiments 2011~2015).
75% are disordered surfaces,
13% are Ba(K) surfaces, 11% are As surfaces,
1% are Fe surfaces (six samples).

J.X. Yin, S. H. Pan et al. arXiv:2011.07701 (2020)



Atomic switch of superconducting electronic feature

Local pairing concept: **P. W. Anderson Science (1987)**



J.X. Yin, S. H. Pan et al. arXiv:2011.07701 (2020)

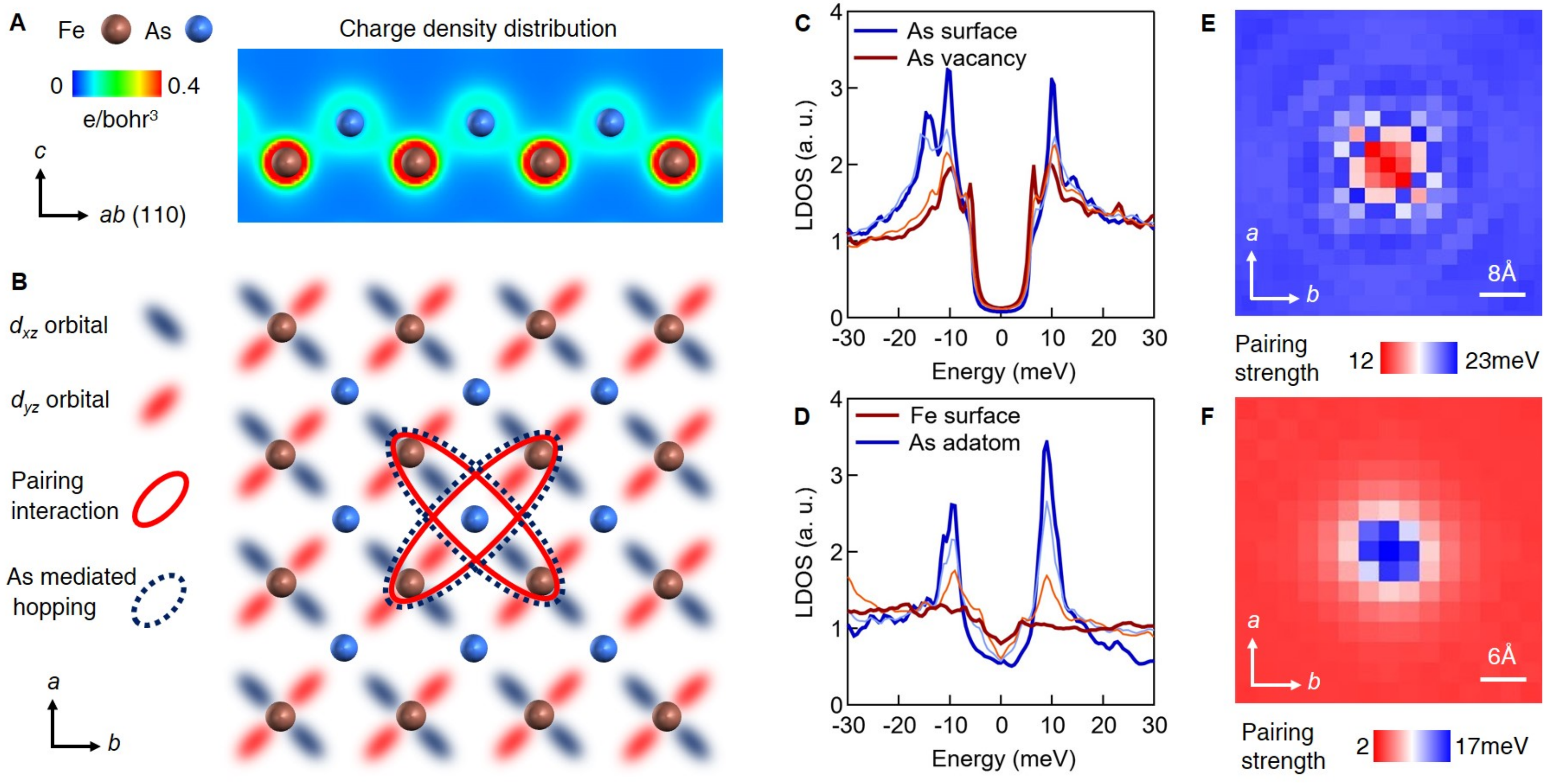
Local effects on pairing from geometry and interaction

Local pairing concept
P. W. Anderson Science (1987)

Calculations by C.S. Ting, Z. Wang, J.P. Hu, B.M. Andersen…(2011~2020)
Self-consistent Bogoliubov-de Gennes calculation

Anion mediates hopping between neighboring Fe ions

Cooper pairing S±
Δ~coskx*cosky



J.X. Yin, S. H. Pan et al. arXiv:2011.07701 (2020)

More to discover

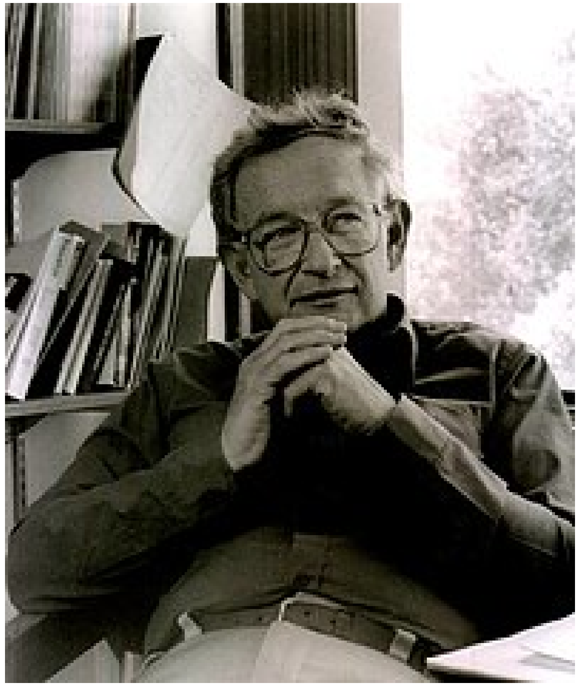
- 18T vector field
- Ramping mode map
- Vector electric field

Vector field engineering of quantum materials

RMn_6Sn_6, CeAlGe, Co_2MnGa, UTe_2,BISSCO,Fe_{1+x}(Te,Se)

Wannier–Bloch correspondence visualization

Topological protection of quantum information



P. W. Anderson (1923-2020)

Measurement of "new" :
how long it can be understood

Ong: What is your best suggestion to young researchers when they encounter a new phenomenon?

Anderson: Patience, and it can take a lifetime long.

Acknowledgement

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Sample: Shuang Jia, Pengcheng Dai, Hechang Lei, Changqing Jin, Wenhong Wang, Genfu Chen, Satoru Nakatsuji, Brian C.Sales, Youguo Shi,

Theory: Ziqiang Wang, Titus Neupert, Hsin Lin, Guoqing Chang, Tay-Rong Chang, Biao Lian, Jiangping Hu, Ching-Sen Ting, Brian Møller Andersen, Rui Wang

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