Title: Topological superconductivity in twisted double-layer high-Tc cuprates: Theory and experimental signatures

Speakers: Marcel Franz

Collection: Quantum Matter Workshop

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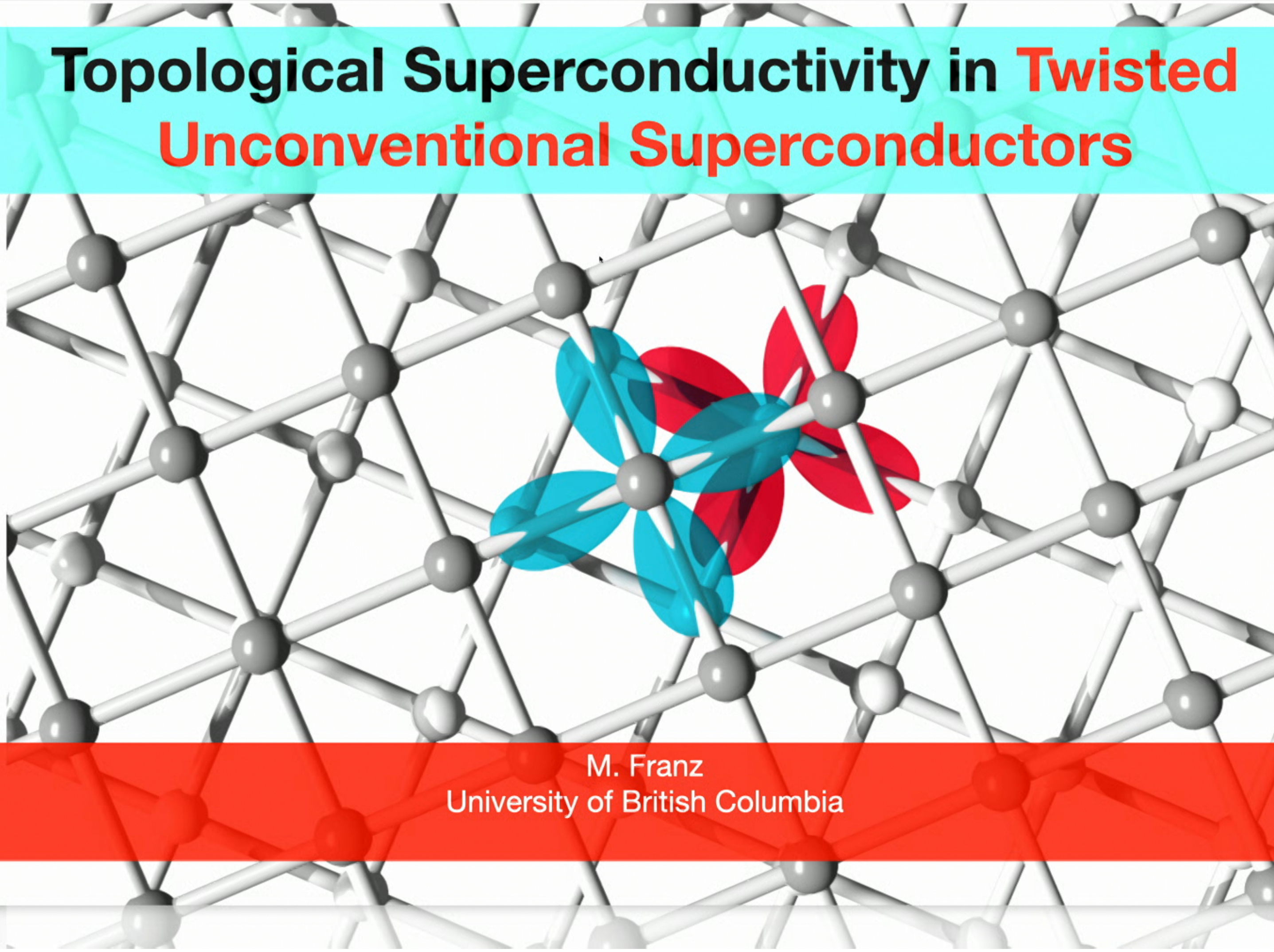
Abstract: Structures composed of two monolayer-thin d-wave superconductors with a twist angle close to 45° are predicted to form a robust, fully gapped topological superconducting phase with spontaneously broken time-reversal symmetry and protected chiral edge modes. In this talk I will briefly review the theory behind the topological phase and discuss recent experimental efforts to fabricate and probe twisted flakes of high-Tc cuprate Bi2Sr2CaCu2O8+?. Signatures of d-wave symmetry and of spontaneous T-breaking are indeed visible in the device Josephson current response, as detected through Fraunhofer pattern and Shapiro step analysis, and, very recently, a pronounced superconducting diode effect observed in samples near 45° twist but absent in untwisted samples.

Topological Superconductivity in Twisted Unconventional Superconductors



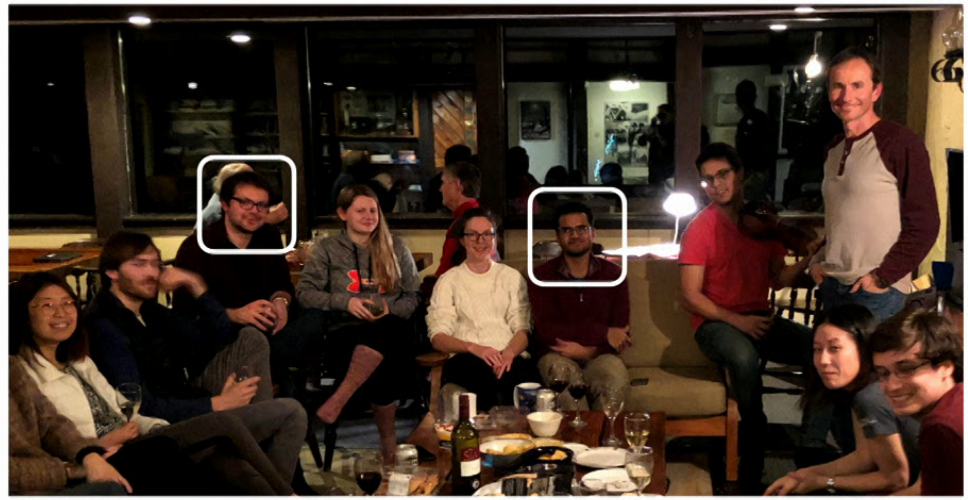
M. Franz
University of British Columbia

People involved

Theory

- Marcel Franz (UBC & QMI)
- Oguz Can (Franz group)
- Tarun Tummuru (Affleck & Franz group)
- Ryan Day (Damascelli group)
- Ilya Elfimov (QMI)
- Andrea Damascelli (QMI)

- Rafael Haenel (Franz group)
- Etiene Lantagne-Hurtubise (Caltech)
- Stephan Plugge (Leiden)
- Xiao-Xiao Zhang (MPI/QMI)
- Catherine Kallin (McMaster)
- Stephan Plugge (QMI/Leiden)
- Jed Pixley, Pavel Volkov (Rutgers)



Stewart Blusson Quantum Matter Institute
THE UNIVERSITY OF BRITISH COLUMBIA

UBC

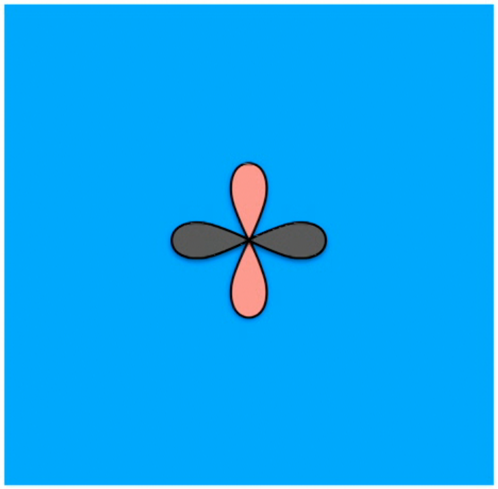
MAX PLANCK – UBC – UTokyo
CENTRE FOR QUANTUM MATERIALS
STUTTGART • VANCOUVER • TOKYO

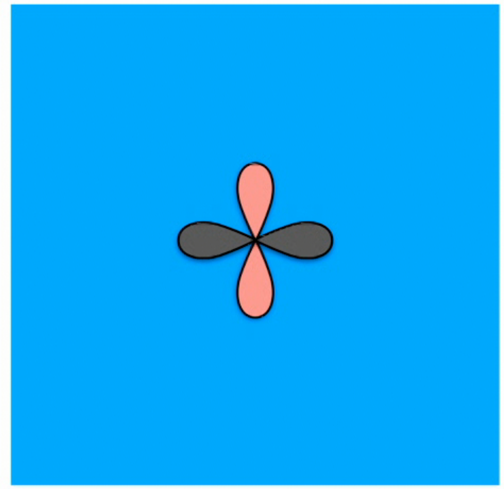
Experiment

- Ziliang Ye
- Yunhuan Xiao (Ye group)
- Yevgeny Ostroumov (QMI)
- Doug Bonn (QMI)
- Philip Kim, Frank Zhao (Harvard)

Nature Physics 17, 519 (2021); PRB Lett. 103, L100501 (2021); Phys. Rev. Lett. 127, 157001 (2021)

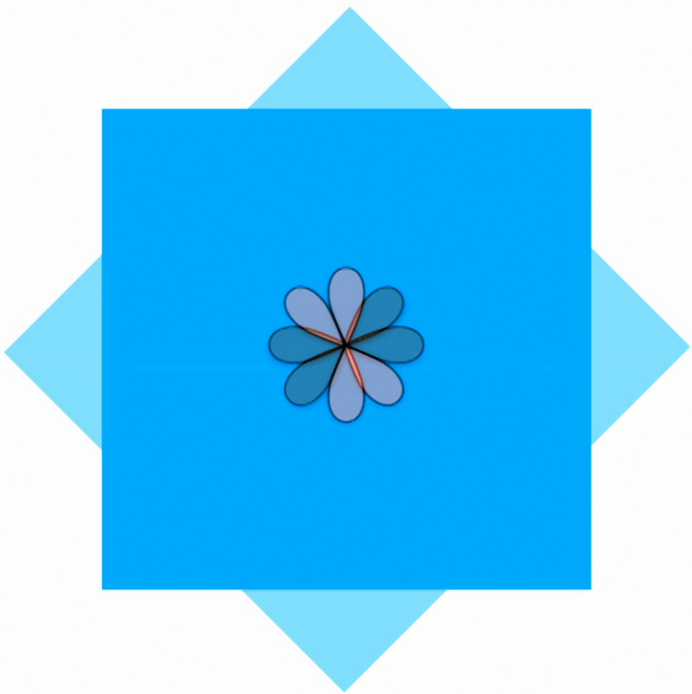
The idea: Engineer a high-T_c cuprate bilayer into a topological superconductor





Monolayer cuprate, e.g. $Bi_2Sr_2CaCu_2O_{8+\delta}$:
$d_{x^2-y^2}$ superconductor

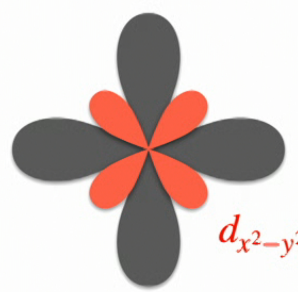
The idea: Engineer a high-T_c cuprate bilayer into a topological superconductor



Monolayer cuprate, e.g. $Bi_2Sr_2CaCu_2O_{8+\delta}$:
$d_{x^2-y^2}$ superconductor

Nature Physics 17, 519 (2021)

- In the presence of weak interlayer coupling this setup has a potential to produce a $d_{x^2-y^2} + id_{xy}$ superconductor
- This is a fully gapped topological SC with protected chiral edge modes
- Exhibits spontaneous broken time reversal symmetry



$d_{x^2-y^2} + id_{xy}$

Article

High-temperature superconductivity in monolayer $Bi_2Sr_2CaCu_2O_{8+\delta}$

https://doi.org/10.1038/s41586-019-1718-x

Received: 2 April 2019

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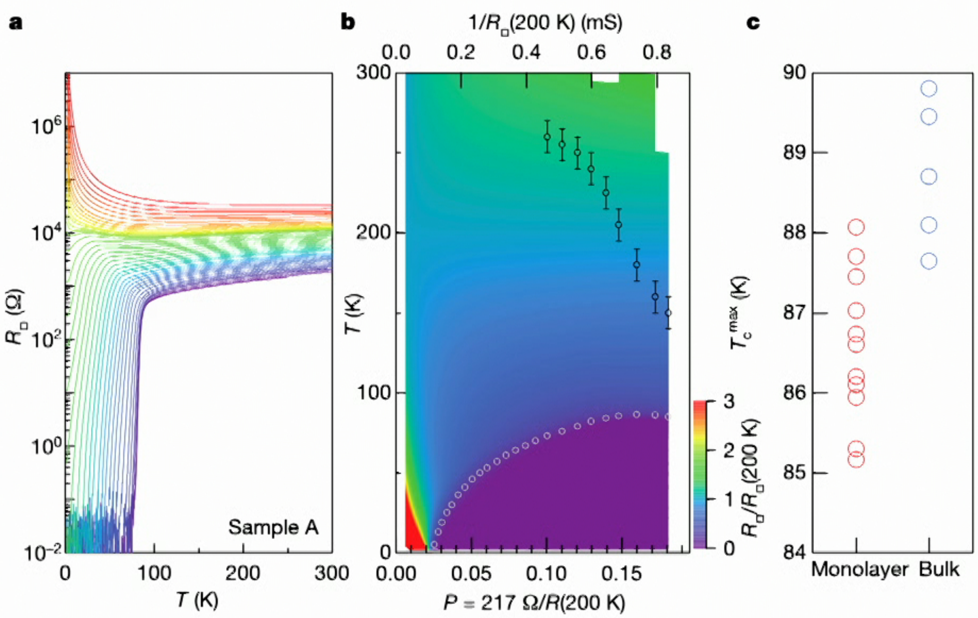
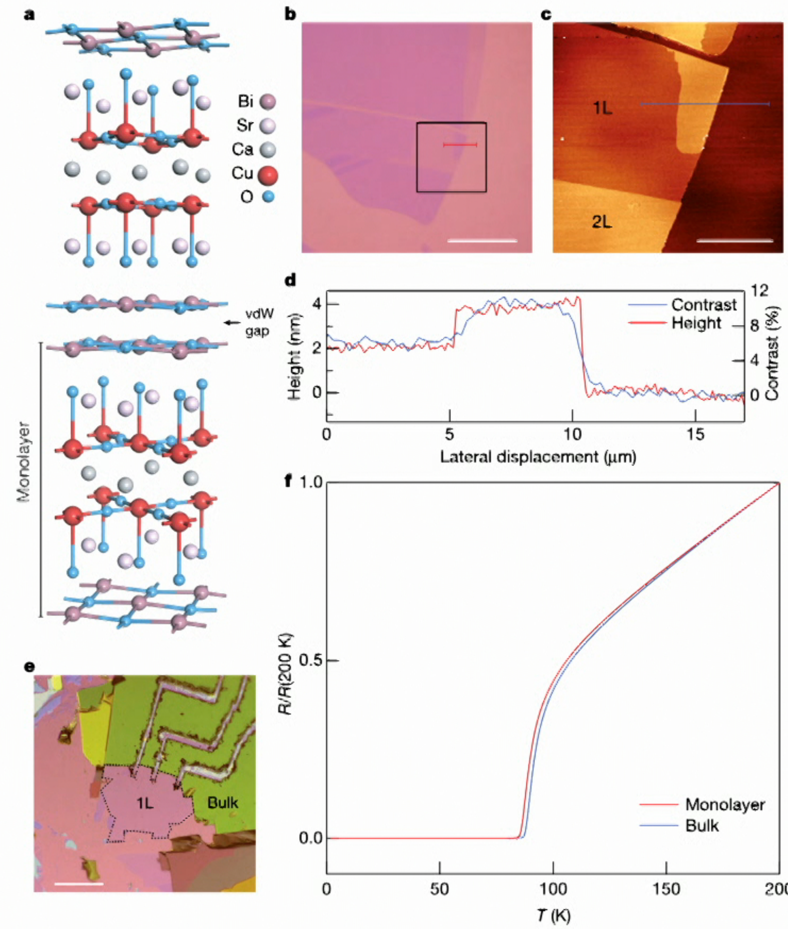
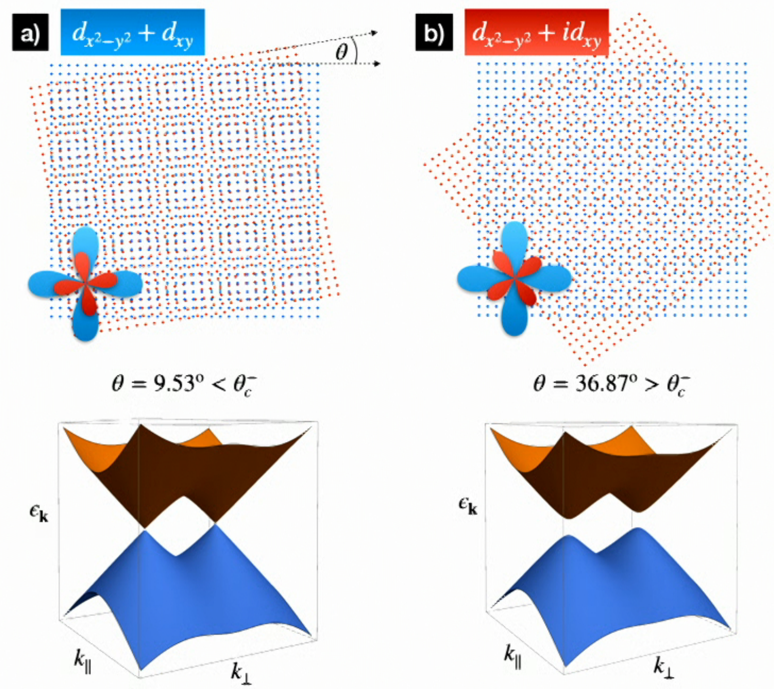




1. **Excitation spectra in the bilayer for $d_{x^2-y^2} + e^{i\phi} d_{xy}$ order parameter**



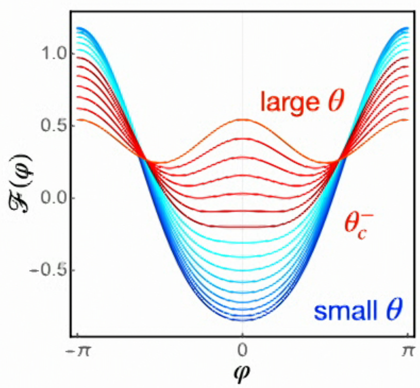
2. Ginzburg-Landau theory for twisted *d*-wave bilayers

$$\mathcal{F}[\psi_1,\psi_2] = f_0[\psi_1] + f_0[\psi_2] + A|\psi_1|^2|\psi_2|^2 + B(\psi_1\psi_2^* + \mathrm{c.c.}) + C(\psi_1^2\psi_2^{*2} + \mathrm{c.c.})$$

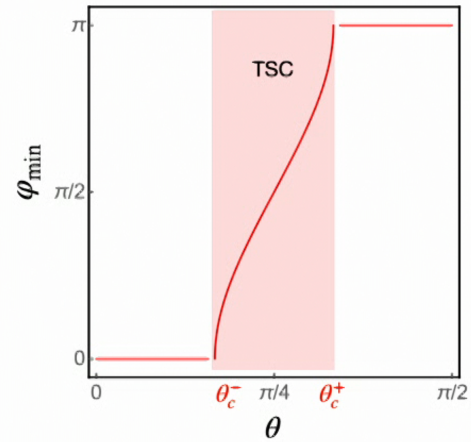
d-wave symmetry dictates $B = -B_0\cos(2\theta)$

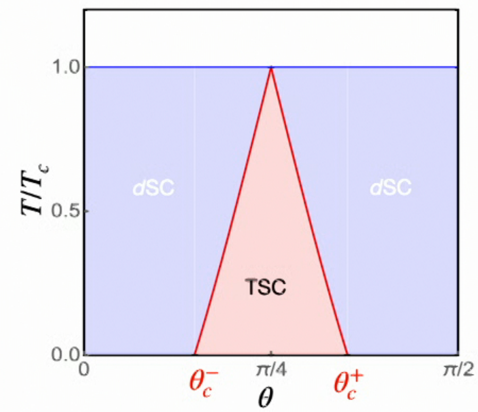
Assuming $\psi_1 = \psi, \quad \psi_2 = \psi e^{i\varphi}$ we obtain free energy as a function of the phase

$$\mathcal{F}(\varphi) = \mathcal{F}_0 + 2B_0\psi^2\left[-\cos(2\theta)\cos\varphi + \mathcal{K}\cos(2\varphi)\right]$$



$$\mathcal{K} = C\psi^2/B_0$$

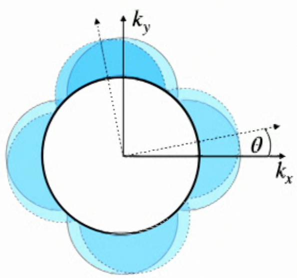


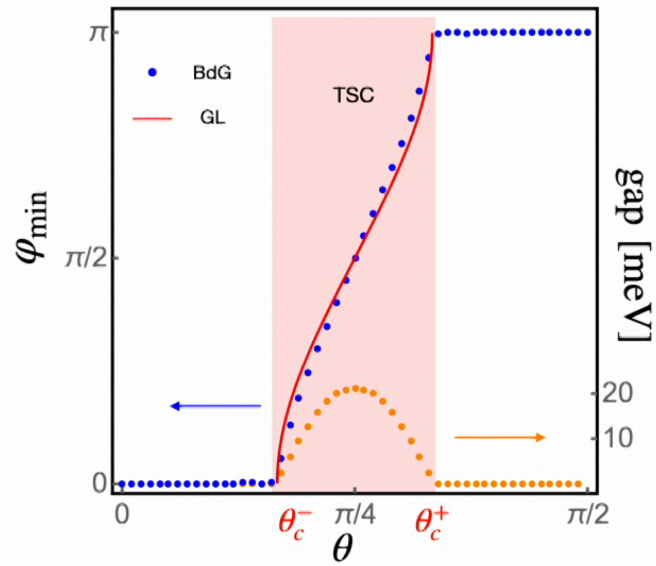


$$\tilde{T}_c(\theta) = T_c\left(1 - \frac{|\cos 2\theta|}{4\mathcal{K}_0}\right), \quad \theta_c^- < \theta < \theta_c^+$$

3. Microscopic theory - Continuum Bogoliubov-de Gennes

$$
\begin{aligned}
\mathcal{H} = \sum_{\boldsymbol{k}\sigma a} \xi_{\boldsymbol{k}a} c^\dagger_{\boldsymbol{k}\sigma a} c_{\boldsymbol{k}\sigma a} + g \sum_{\boldsymbol{k}\sigma} \left(c^\dagger_{\boldsymbol{k}\sigma 1} c_{\boldsymbol{k}\sigma 2} + \text{h.c.} \right) \\
+ \sum_{\boldsymbol{k}a} \left(\Delta_{\boldsymbol{k}a} c^\dagger_{\boldsymbol{k}\uparrow a} c^\dagger_{-\boldsymbol{k}\downarrow a} + \text{h.c.} \right) - \sum_{\boldsymbol{k}a} \Delta_{\boldsymbol{k}a} \langle c^\dagger_{\boldsymbol{k}\uparrow a} c^\dagger_{-\boldsymbol{k}\downarrow a} \rangle .
\end{aligned}
$$

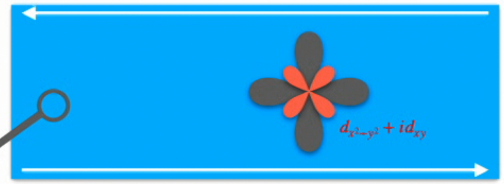




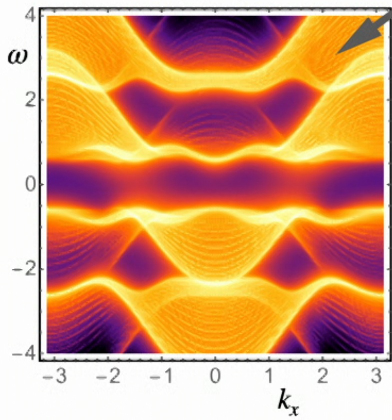
$$
\mathscr{H} = \sum_{\mathbf{k}} \Psi^\dagger_{\mathbf{k}} h_{\mathbf{k}} \Psi_{\mathbf{k}} + E_0
\qquad
h_{\boldsymbol{k}} = \begin{pmatrix} \xi_{\boldsymbol{k}} & \Delta_{\boldsymbol{k}1} & g & 0 \\ \Delta^*_{\boldsymbol{k}1} & -\xi_{\boldsymbol{k}} & 0 & -g \\ g & 0 & \xi_{\boldsymbol{k}} & \Delta_{\boldsymbol{k}2} \\ 0 & -g & \Delta^*_{\boldsymbol{k}2} & -\xi_{\boldsymbol{k}} \end{pmatrix}
$$

4. Topological superconductivity, protected edge modes

Consider a long strip geometry:



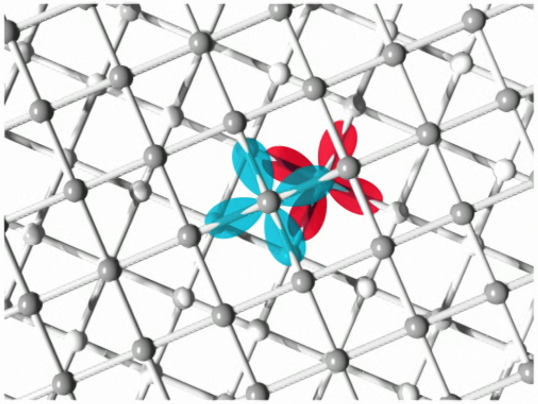
Spectral function
$A(k_x, \omega)$

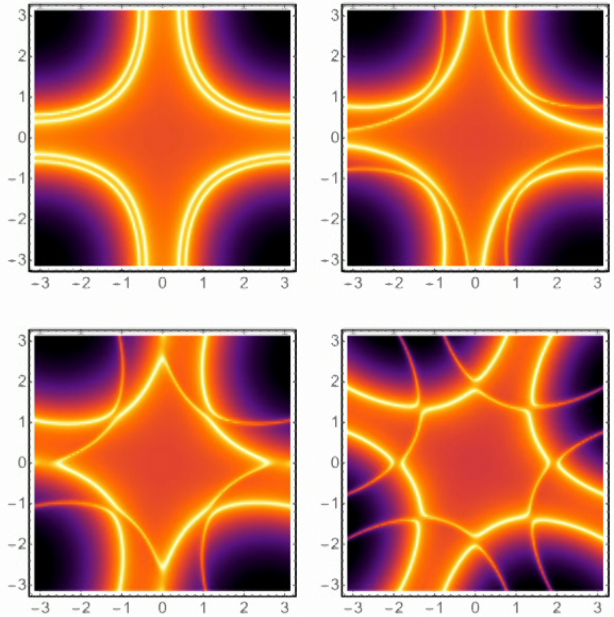


5. Self-consistent theory on the lattice

Hubbard model with nn attraction and on-site repulsion

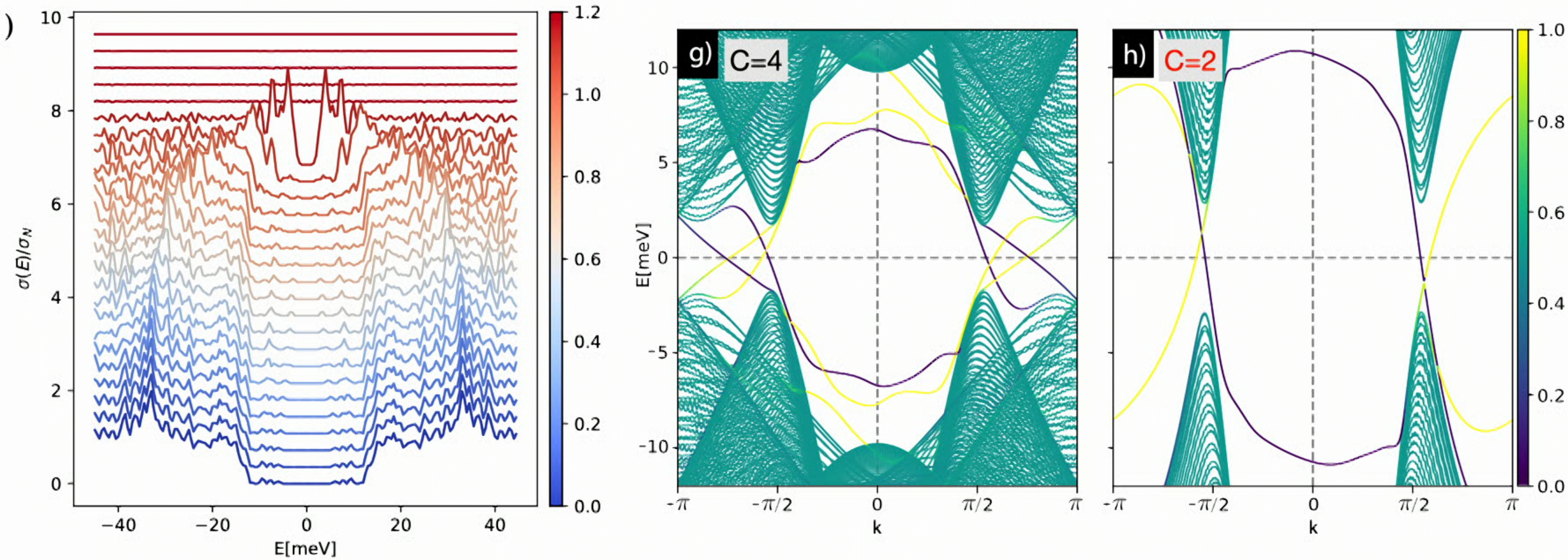
$$H = -\sum_{ij,\sigma a} t_{ij} c^{\dagger}_{i\sigma a} c_{j\sigma a} - \mu \sum_{i\sigma a} n_{i\sigma a} + \sum_{ij,a} V_{ij} n_{ia} n_{ja} - \sum_{ij\sigma} g_{ij} c^{\dagger}_{i\sigma 1} c_{j\sigma 2},$$





Self-consistent theory on the lattice
Tunneling density of states and edge modes

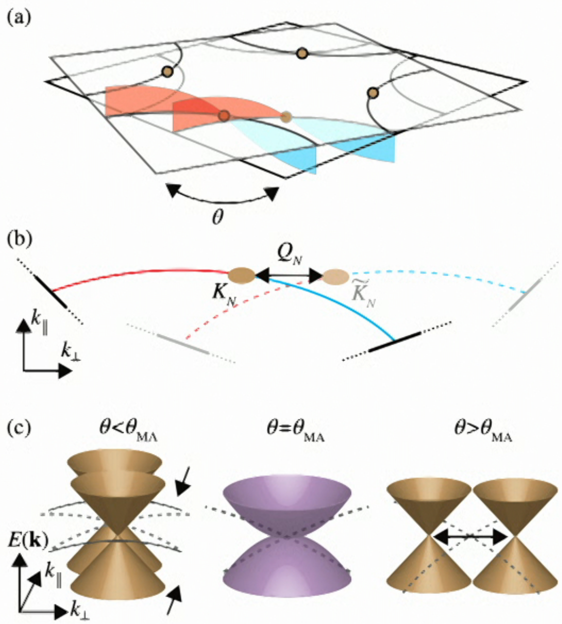
Long strip geometry

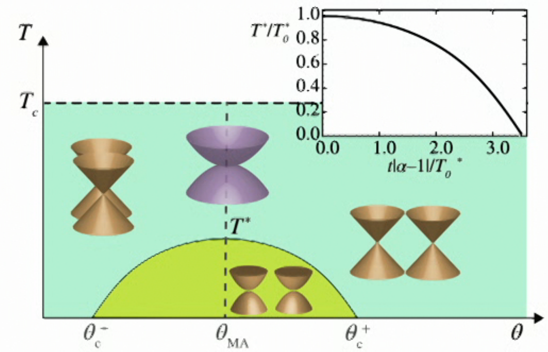


Interaction effects, flat bands, graphene similarities?

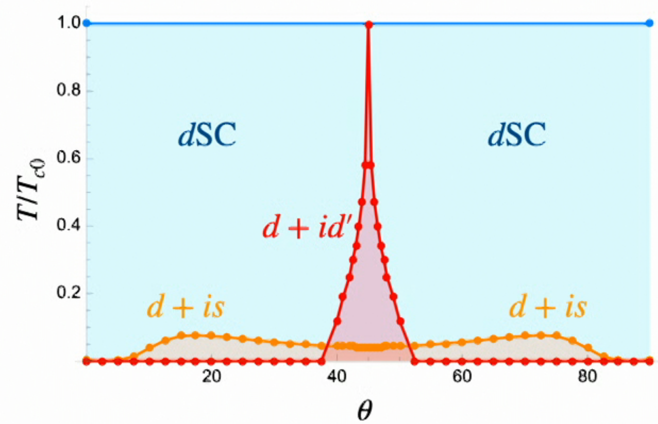
Magic angles and current-induced topology in twisted nodal superconductors

Pavel A. Volkov,* Justin H. Wilson, and J. H. Pixley
Department of Physics and Astronomy, Center for Materials Theory, Rutgers University, Piscataway, NJ 08854, USA
(Dated: December 16, 2020)





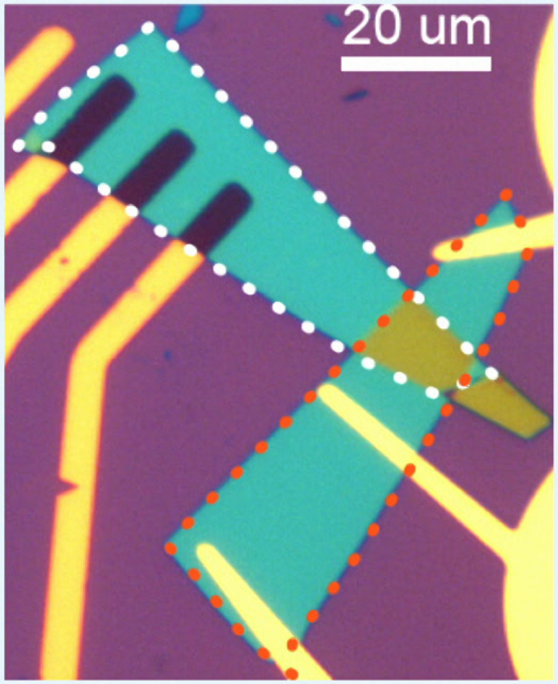
Self-consistently determined phase diagram - present work
(assuming interaction-induced s-wave instability)

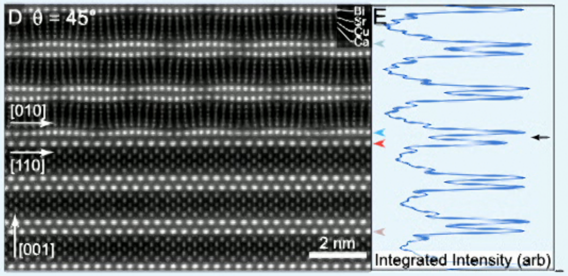


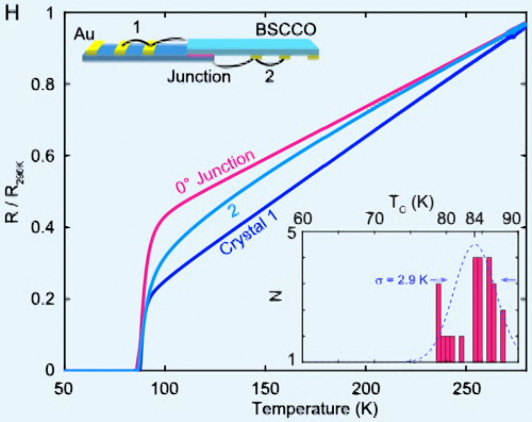
Experimental efforts

Artificial BSCCO Twist Junctions — *Philip Kim Group (Harvard)*

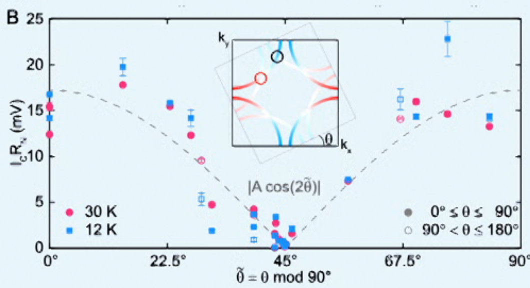
Exceptionally clean and ordered interfaces

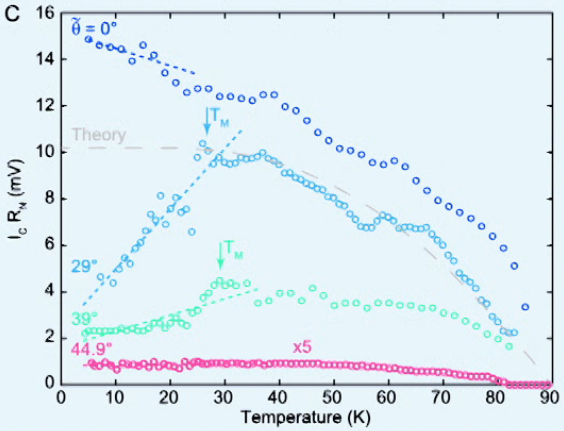






Results



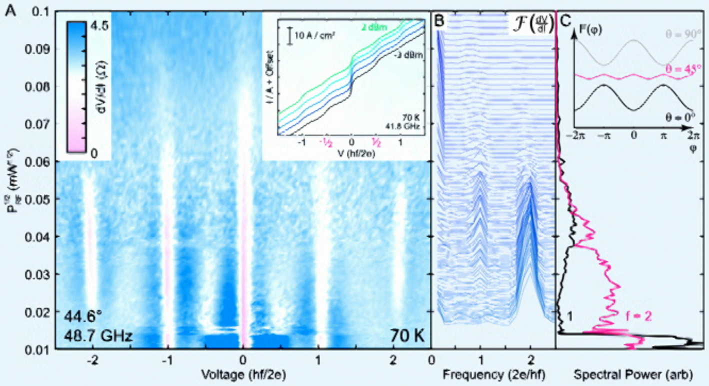


Zhao et al., arXiv:2108.13455

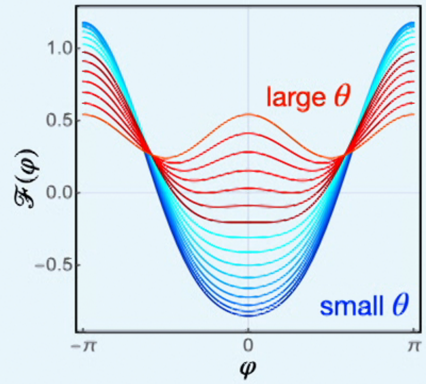
Experimental efforts

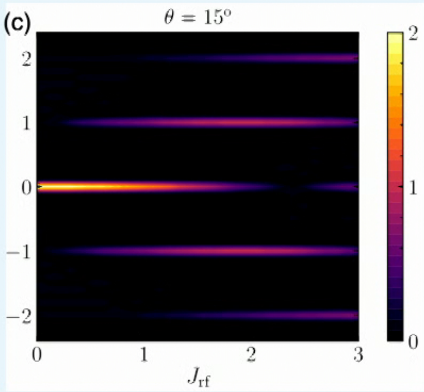
Artificial BSCCO Twist Junctions ***Philip Kim Group (Harvard)***

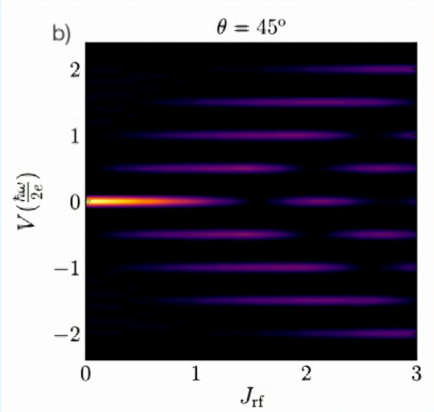
Experiment [Zhao et al., arXiv:2108.13455] observes "fractional Shapiro steps" near 45 degree twist



Fractional Shapiro steps can reflect the $\pi-$periodic I-V curves



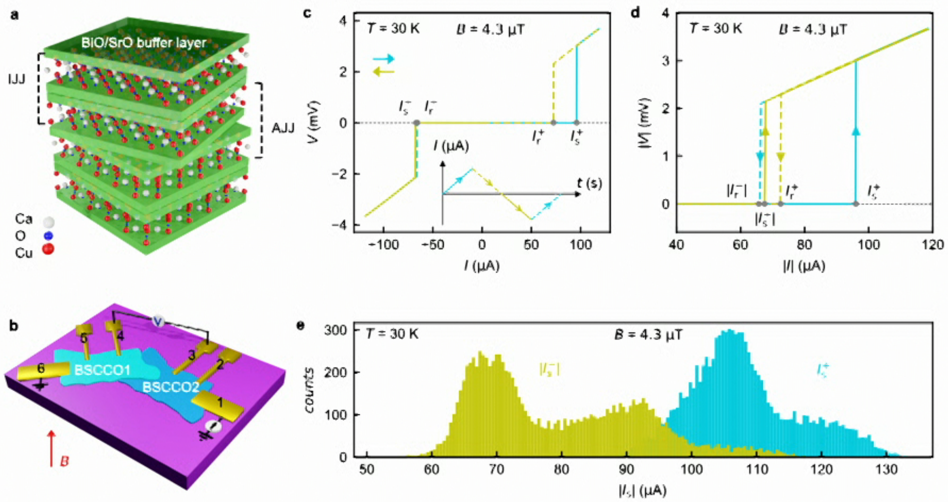


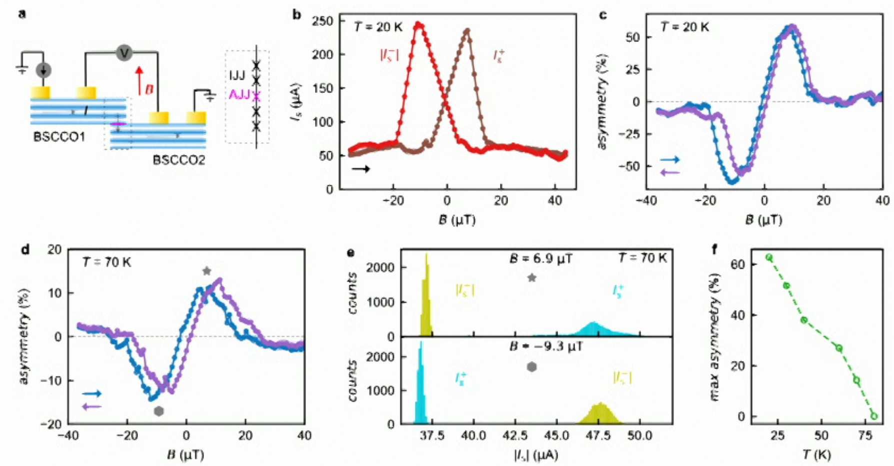


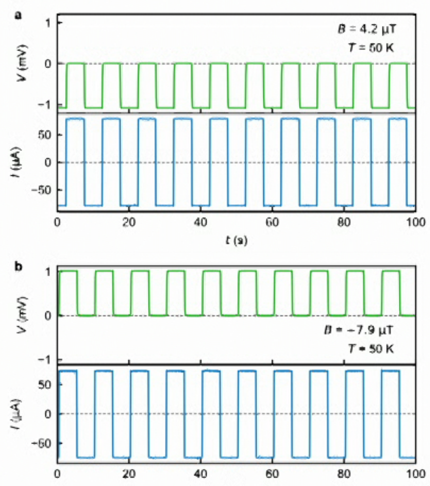
High-temperature superconducting diode

Sanat Ghosh,[1,*] Vilas Patil,[1] Amit Basu,[1] Kuldeep,[1] Digambar A. Jangade,[1] Ruta Kulkarni,[1] A. Thamizhavel,[1] and Mandar M. Deshmukh[1,†]

[1] *Department of Condensed Matter Physics and Materials Science, Tata Institute of Fundamental Research, Homi Bhabha Road, Mumbai 400005, India*

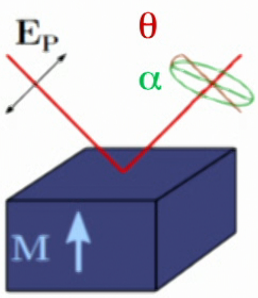






Anomalous Hall and polar Kerr effect

(with O. Can, X.-X. Zhang, C. Kallin)



Polar

Kerr angle is related to Hall conductivity

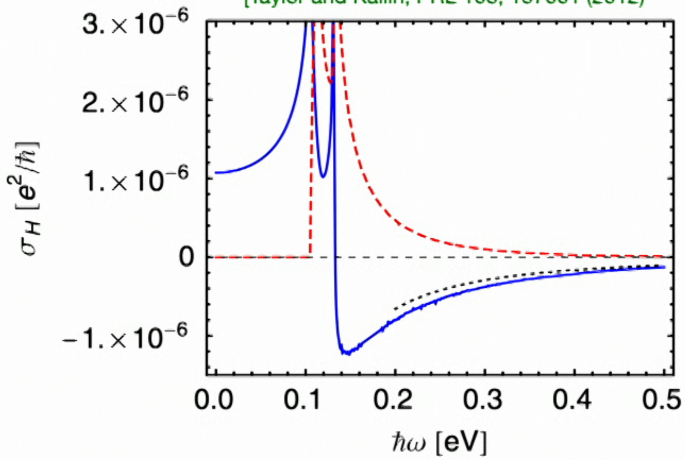
$$\sigma_{\rm H}(\omega) = [\sigma_{xy}(\omega) - \sigma_{yx}(\omega)]/2$$

with

$$\theta_{\rm K}(\omega) = \frac{4\pi}{\omega}{\rm Im}\left(\frac{\sigma_{\rm H}(\omega)}{n(n^2-1)}\right)$$

Prediction for Sr_2RuO_4

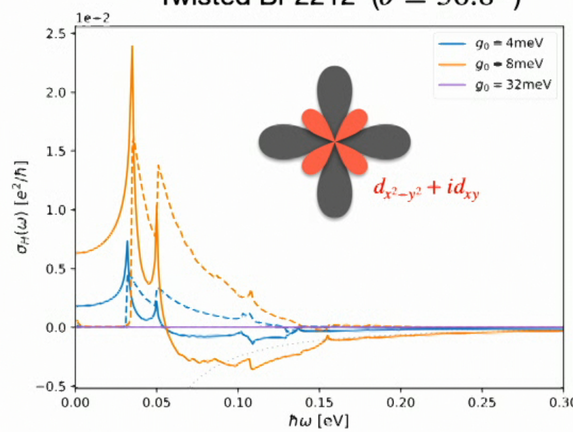
[Taylor and Kallin, PRL 108, 157001 (2012)]



This can be calculated from the standard Kubo formula

$$\sigma_{xy}(\nu_n) = \frac{ie^2T}{\nu_n}\sum_{\mathbf{k},\omega_n}{\rm Tr}[v_xG_0(\mathbf{k},\omega_n)v_yG_0(\mathbf{k},\omega_n+\nu_n)]$$

Twisted Bi-2212 ($\theta \simeq 36.8^0$)



PRL 127, 157001 (2021)

- The Hall conductivity is nonzero and large in the *d*+*id'* state of twisted Bi-2212
- The signal is about 3 orders of magnitude stronger than that predicted for Sr_2RuO_4; this is chiefly due to much larger SC gap in the cuprate.

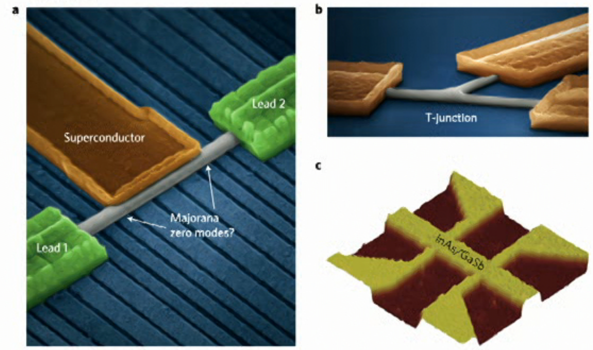
Looking ahead: Majorana Fermions?

- Topological superconductors often host Majorana zero modes at vortices, corners, or other defects.

Majorana modes materialize

Condensed-matter physicists are steadily closing in on exotic excitations known as Majorana modes that could advance both fundamental science and quantum computing.

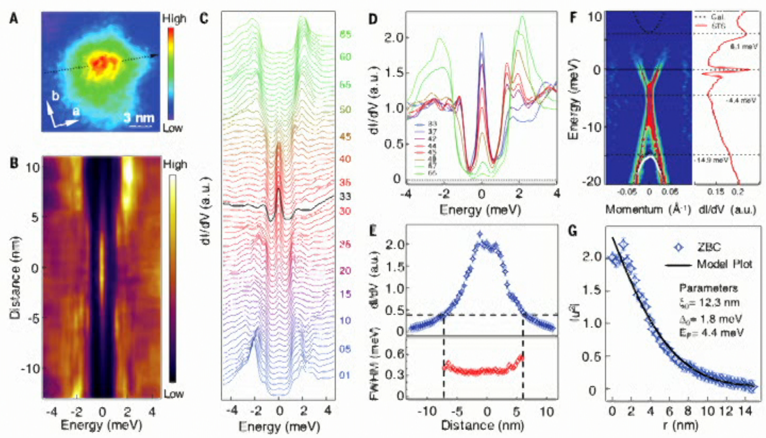
Jason Alicea



TOPOLOGICAL MATTER

Evidence for Majorana bound states in an iron-based superconductor

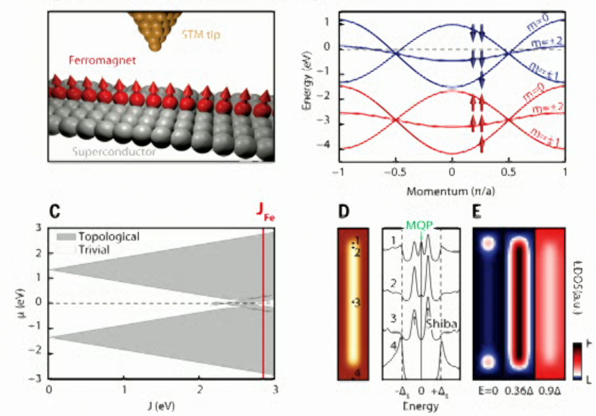
Dongfei Wang[1,2*], Lingyuan Kong[1,2*], Peng Fan[1,2*], Hui Chen[1], Shiyu Zhu[1,2], Wenyao Liu[1,2], Lu Cao[1,2], Yujie Sun[1,2], Shixuan Du[1,2,4], John Schneeloch[5], Ruidan Zhong[5], Genda Gu[5], Liang Fu[6], Hong Ding[1,2,3,4]†, Hong-Jun Gao[1,2,3,4]†



TOPOLOGICAL MATTER

Observation of Majorana fermions in ferromagnetic atomic chains on a superconductor

Stevan Nadj-Perge,[1*] Ilya K. Drozdov,[1*] Jian Li,[1*] Hua Chen,[2*] Sangjun Jeon,[1] Jungpil Seo,[1] Allan H. MacDonald,[2] B. Andrei Bernevig,[1] Ali Yazdani[1]†

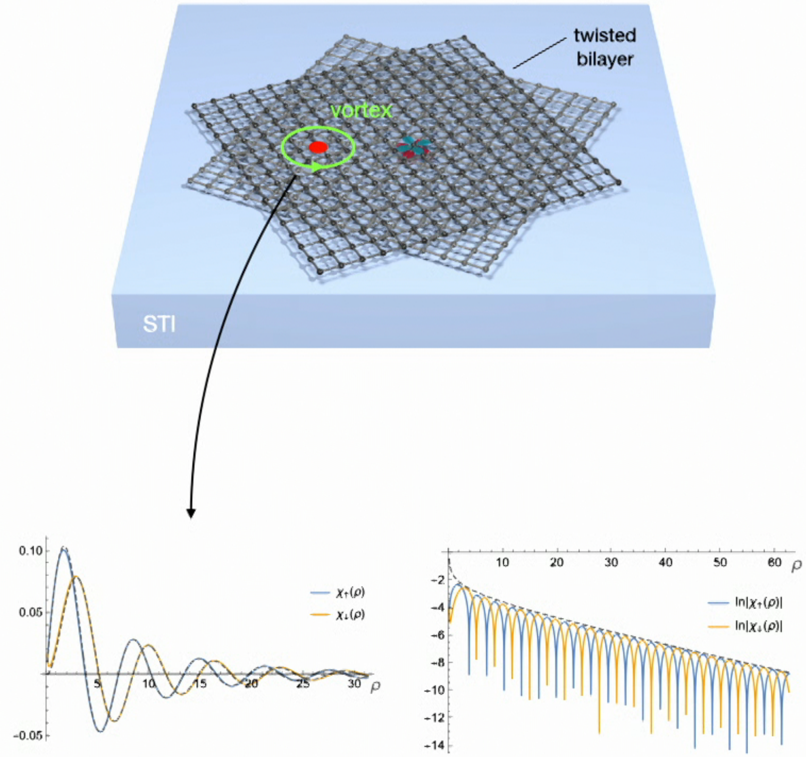


Twisted cuprate bilayer on top of a topological insulator

Variation on the Fu-Kane construction

[Mercado, Sahoo and Franz, PRL 128, 137002 (2022).

- Twisted cuprate bilayer supplies fully gapped high-T_c superconductivity
- TI surface provides the requisite spin-orbit coupling
- Will this setup host Majorana zero mode in the vortex?



- We solve the problem by an approximate analytic approach and exact numerical diagonalization
- Clear evidence for MZM bound to the vortex core

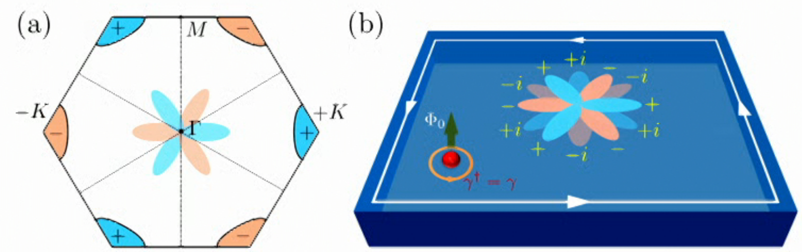
$$H = \begin{pmatrix} v\boldsymbol{\sigma}\cdot\boldsymbol{p} - \mu & \hat{\Delta} \\ \hat{\Delta}^\dagger & -v\boldsymbol{\sigma}\cdot\boldsymbol{p} + \mu \end{pmatrix}$$

$$\mu\chi_\uparrow - \left[v\left(\partial_r + \frac{l+1}{r}\right) + \hat{\Delta}_{l,l+1}\right]\chi_\downarrow = 0,$$
$$\mu\chi_\downarrow + \left[v\left(\partial_r - \frac{l}{r}\right) + \hat{\Delta}_{l+1,l}\right]\chi_\uparrow = 0,$$

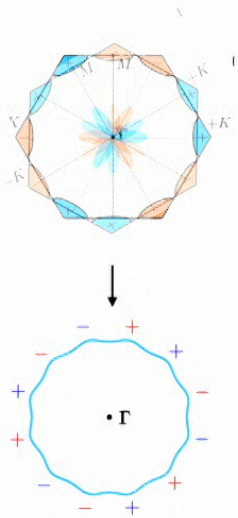
Maximally twisted double-layer spin-triplet valley-singlet superconductors

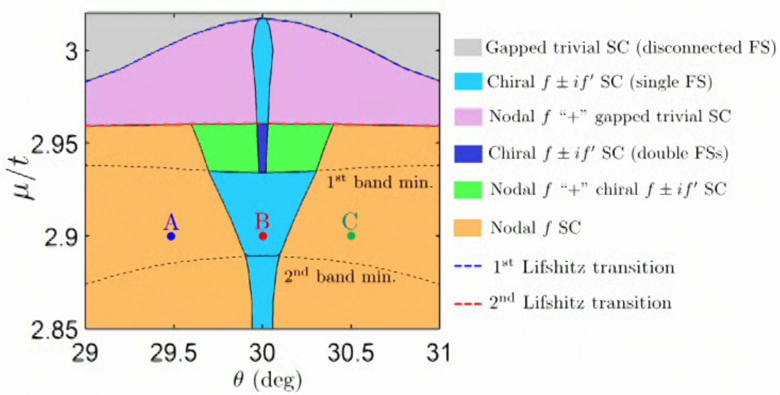
[arXiv:2206.05599]

- Rhombohedral trilayer graphene, Bernal bilayer graphene and ZrNCl are thought to be spin-triplet valley-singlet superconductors with f-wave order parameter.
- We consider a bilayer formed of such a STVS material close to 'maximal' twist angle of 30^0.



[Zhou, Egan, Kush, Franz, arXiv:2206.05599]

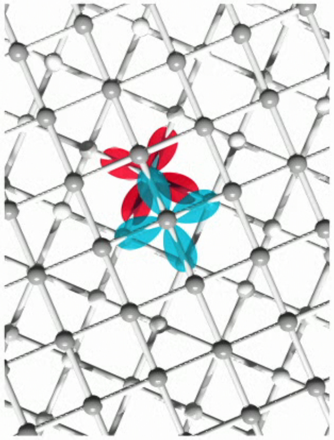


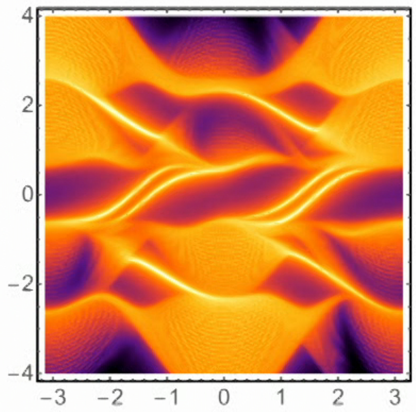


- For a range of electron density and twist angles the combined system forms a spontaneously T-broken phase with $f + if'$ order parameter.
- This chiral phase exhibits non-Abelian topology: it hosts an odd number of chiral Majorana edge modes and a single Majorana zero mode in the vortex core.

Summary and outlook

- Natural models of coupled layers of *d*-wave SC predict a T-broken phase when the twist angle is close to $45°$
- The resulting phase is fully gapped and over much of the phase diagram also topologically non-trivial
- Topological phase will show an even number of protected chiral edge modes
- Gap opening can be detected through various spectroscopies (ARPES, STM)
- T-breaking can be probed directly (polar Kerr effect, SC diode effect, fractional Shapiro steps)





Some interesting open questions:

1. What is the best way to observe the topological phase experimentally?
2. Are there any interesting uses for this novel topological superconducting phase once identified?
3. Are there other 2D systems (beyond graphene, chalcogenides, cuprates) that will produce interesting new behaviors under twist or similar geometries?