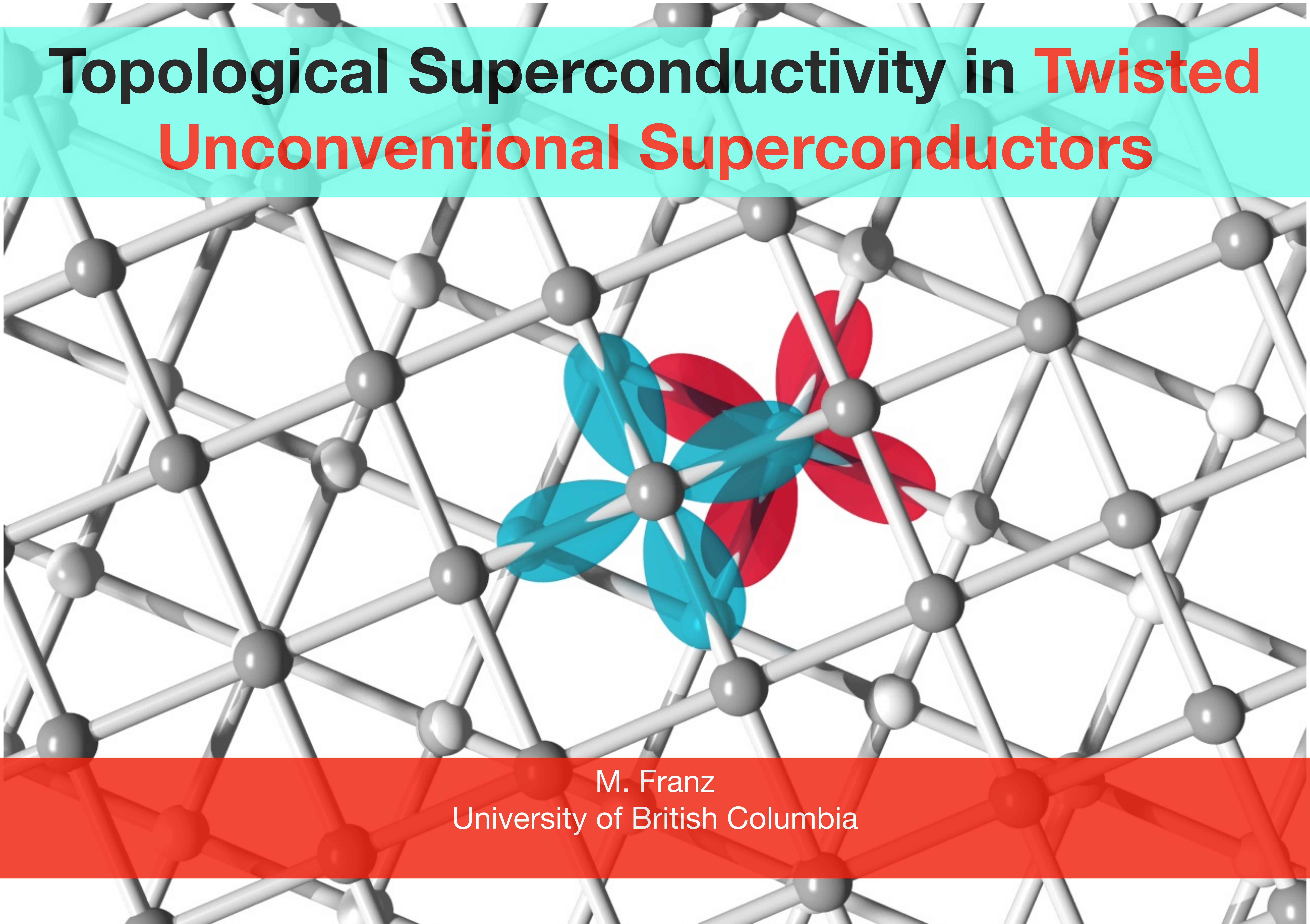
Topological Superconductivity in Twisted Unconventional Superconductors



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People involved

Theory

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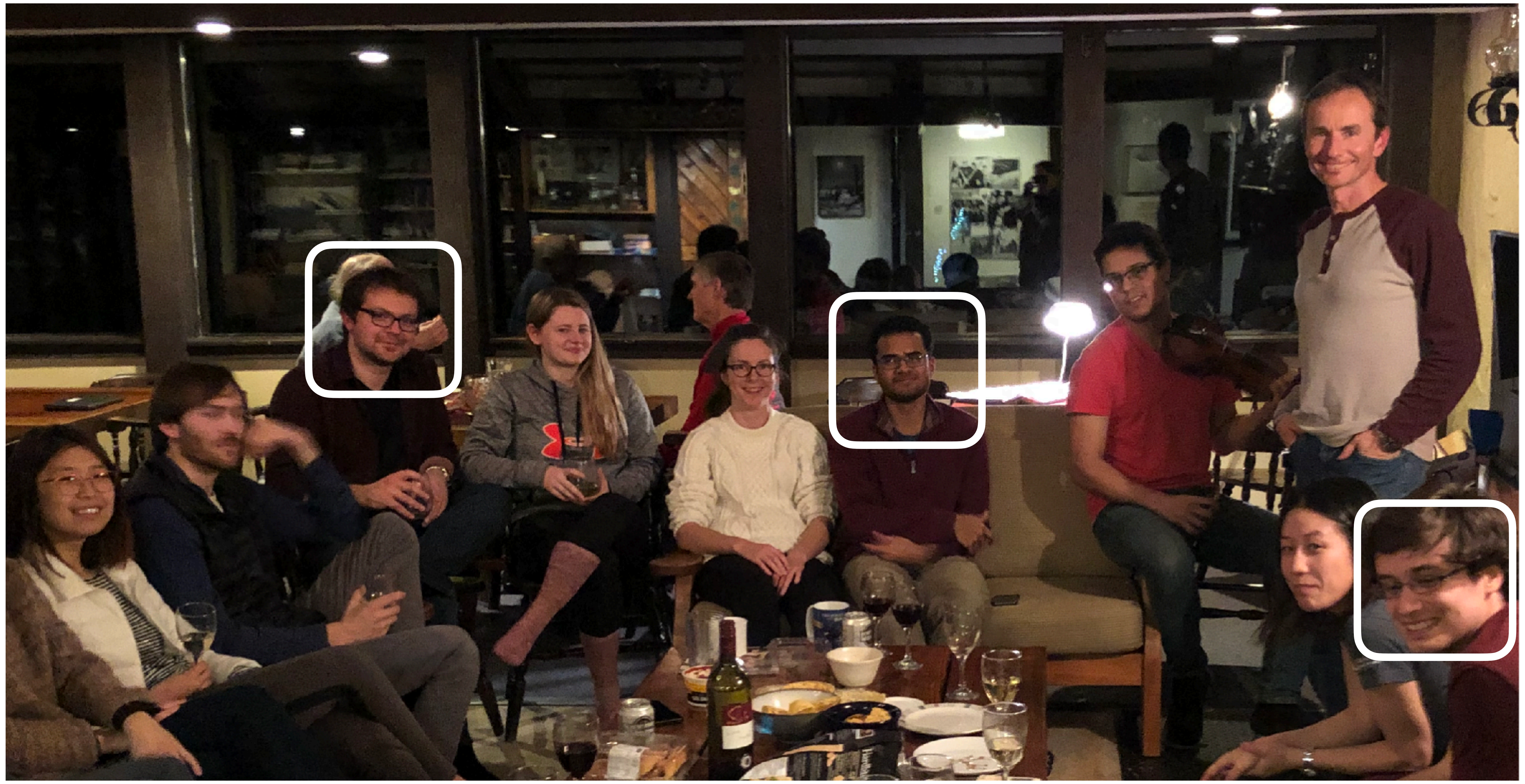

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Experiment

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

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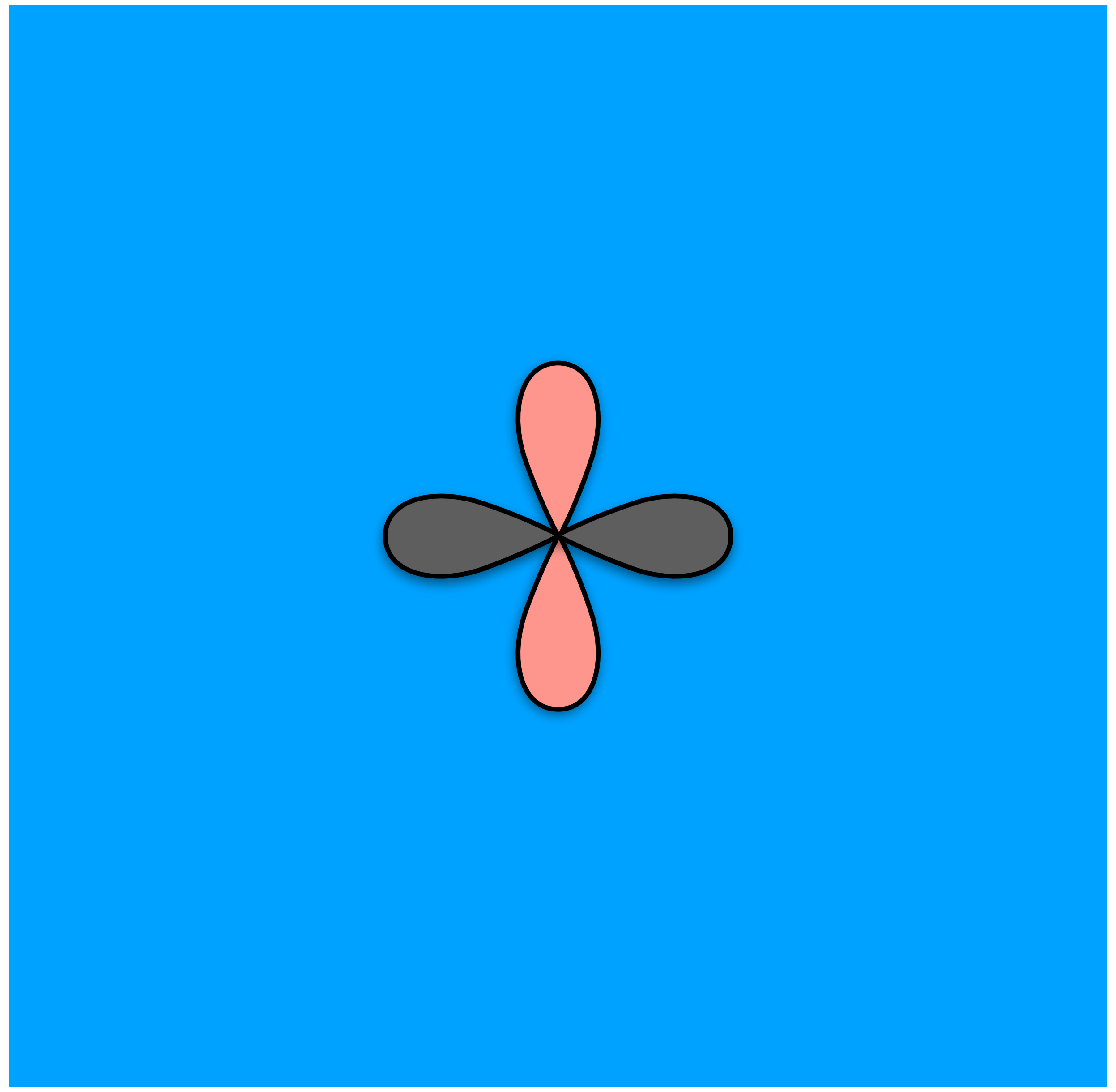
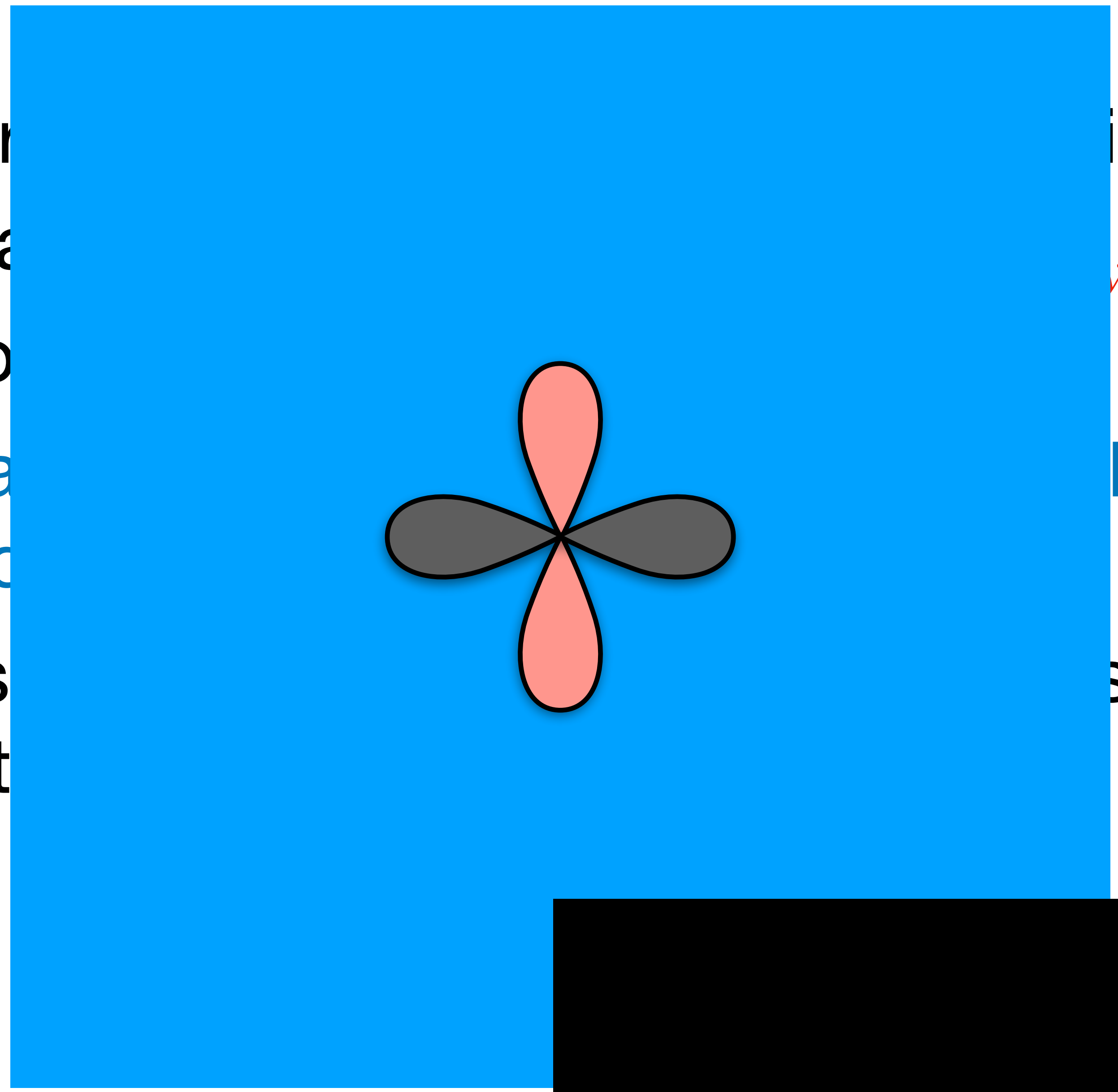
Nature Physics 17, 519 (2021); PRB Lett. 103, L100501 (2021); Phys. Rev. Lett. 127, 157001 (2021)

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





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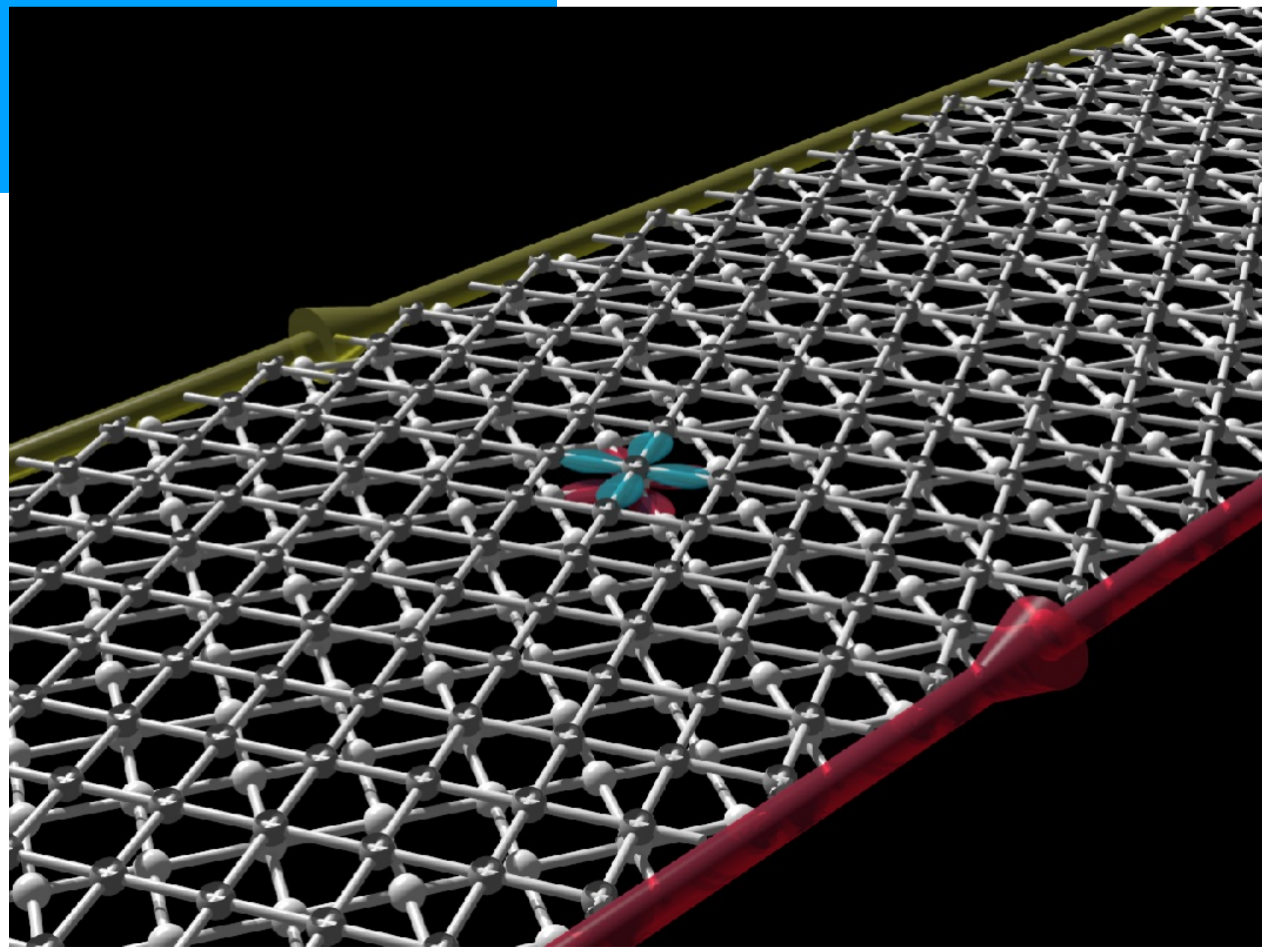
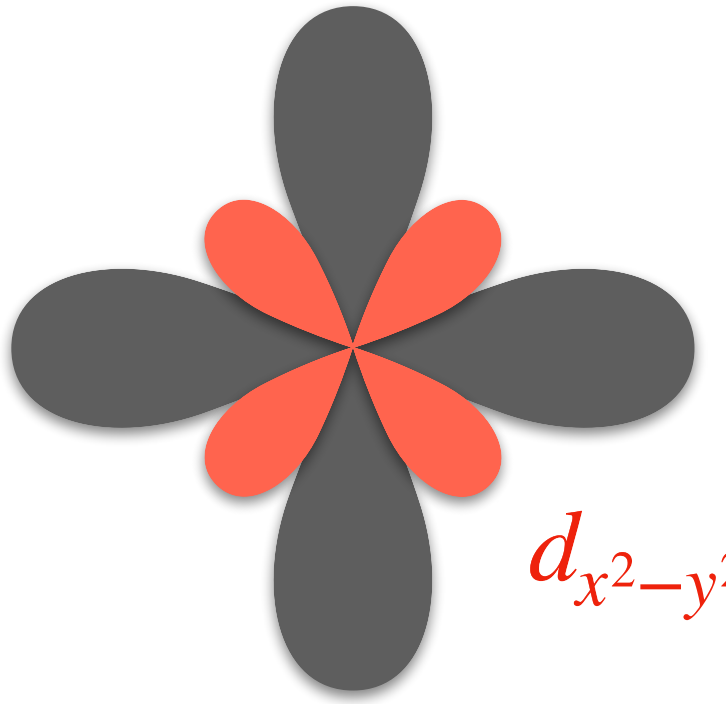


Monolayer cuprate, e.g. $Bi_2Sr_2CaCu_2O_{8+\delta}$:
$d_{x^2-y^2}$ superconductor



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

Nature Physics 17, 519 (2021)

Article

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

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Received: 2 April 2019

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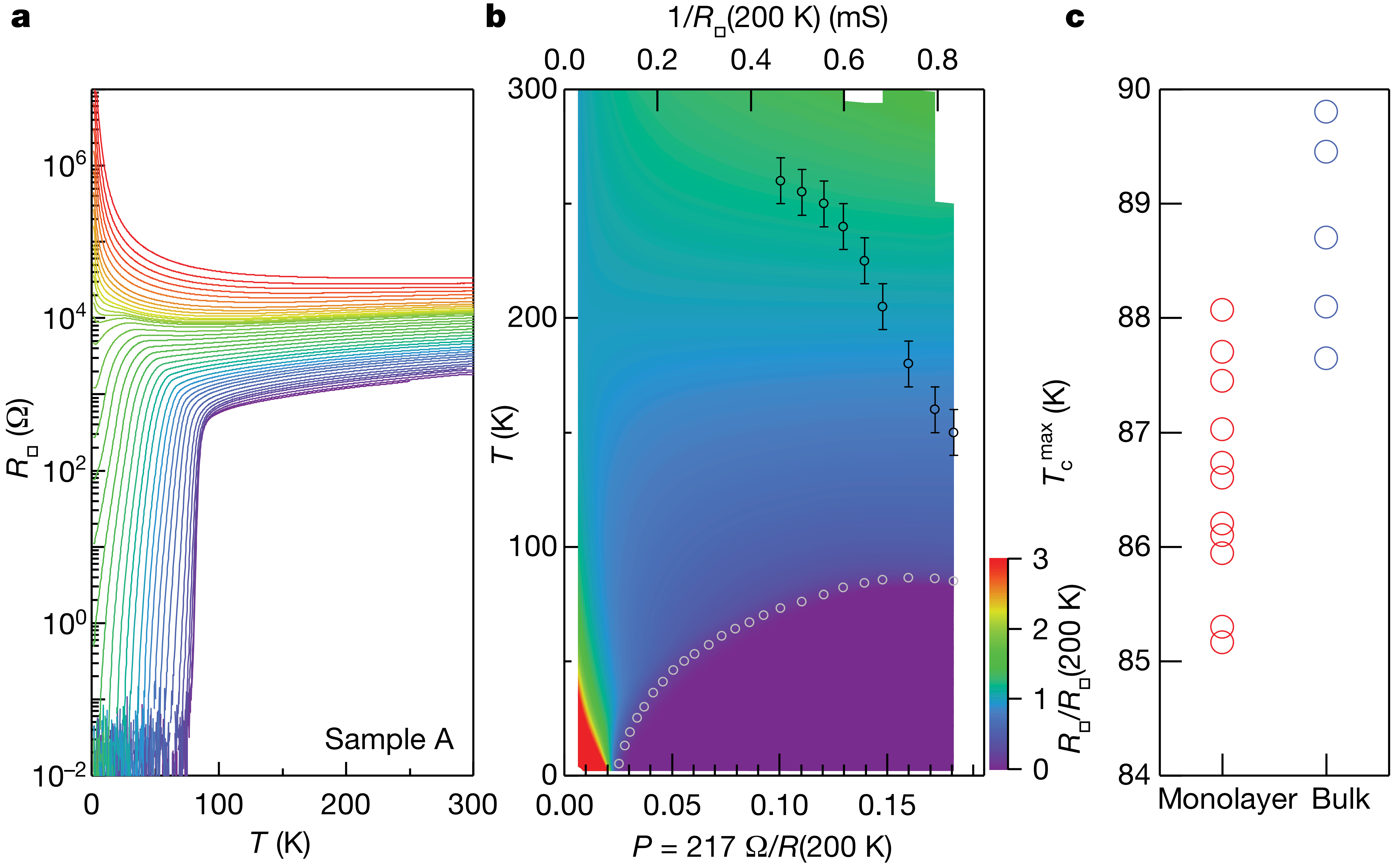
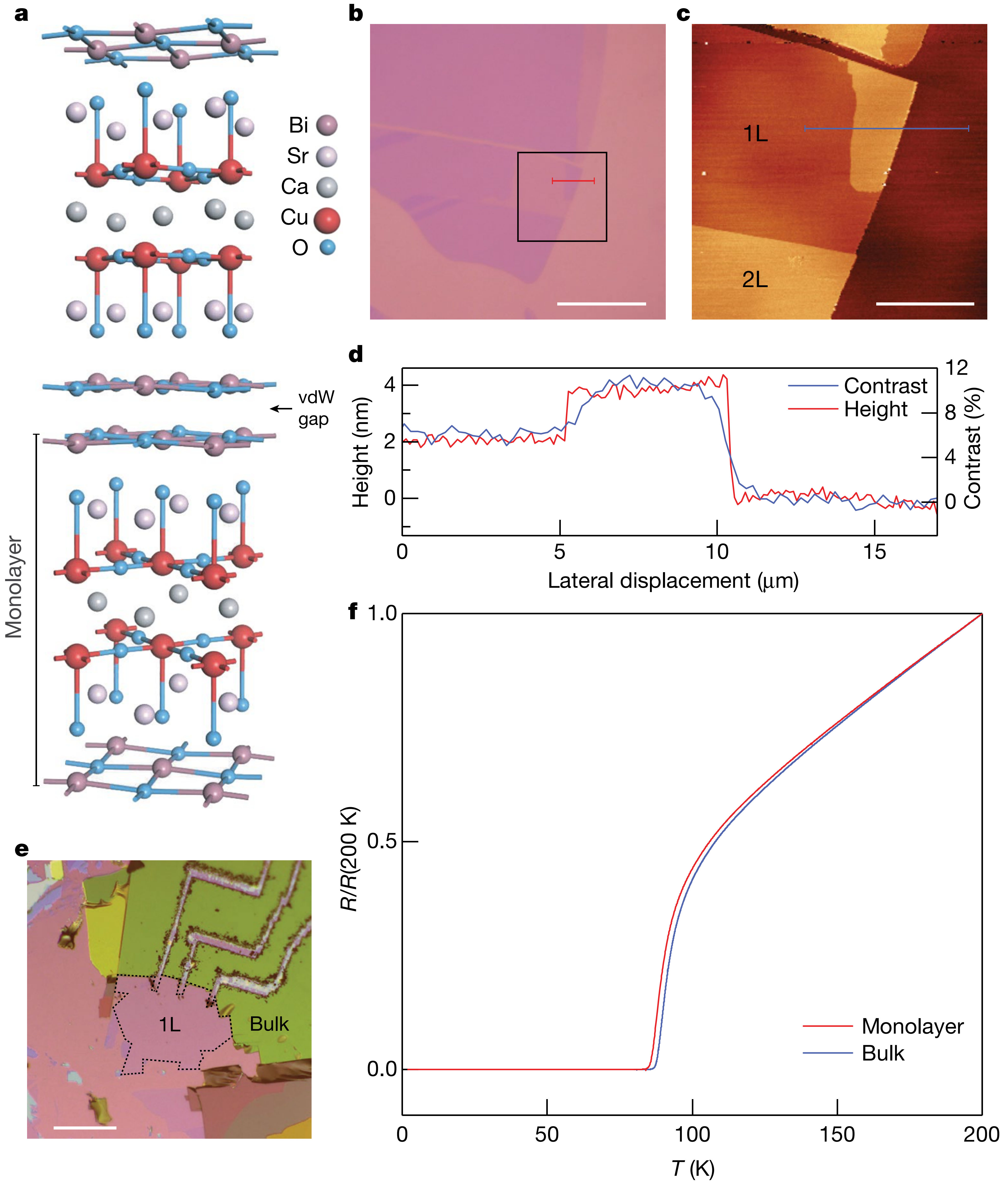




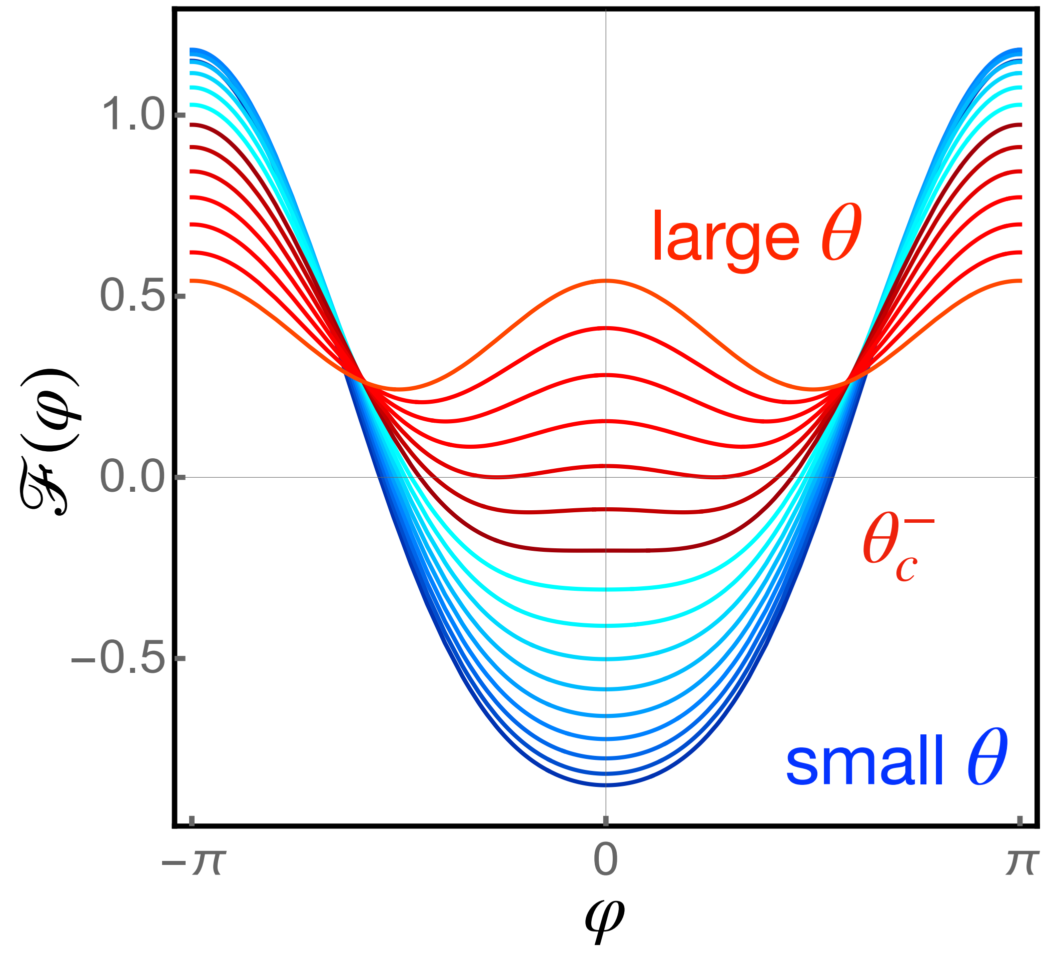
1. Ginzburg-Landau theory for twisted *d*-wave bilayers

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

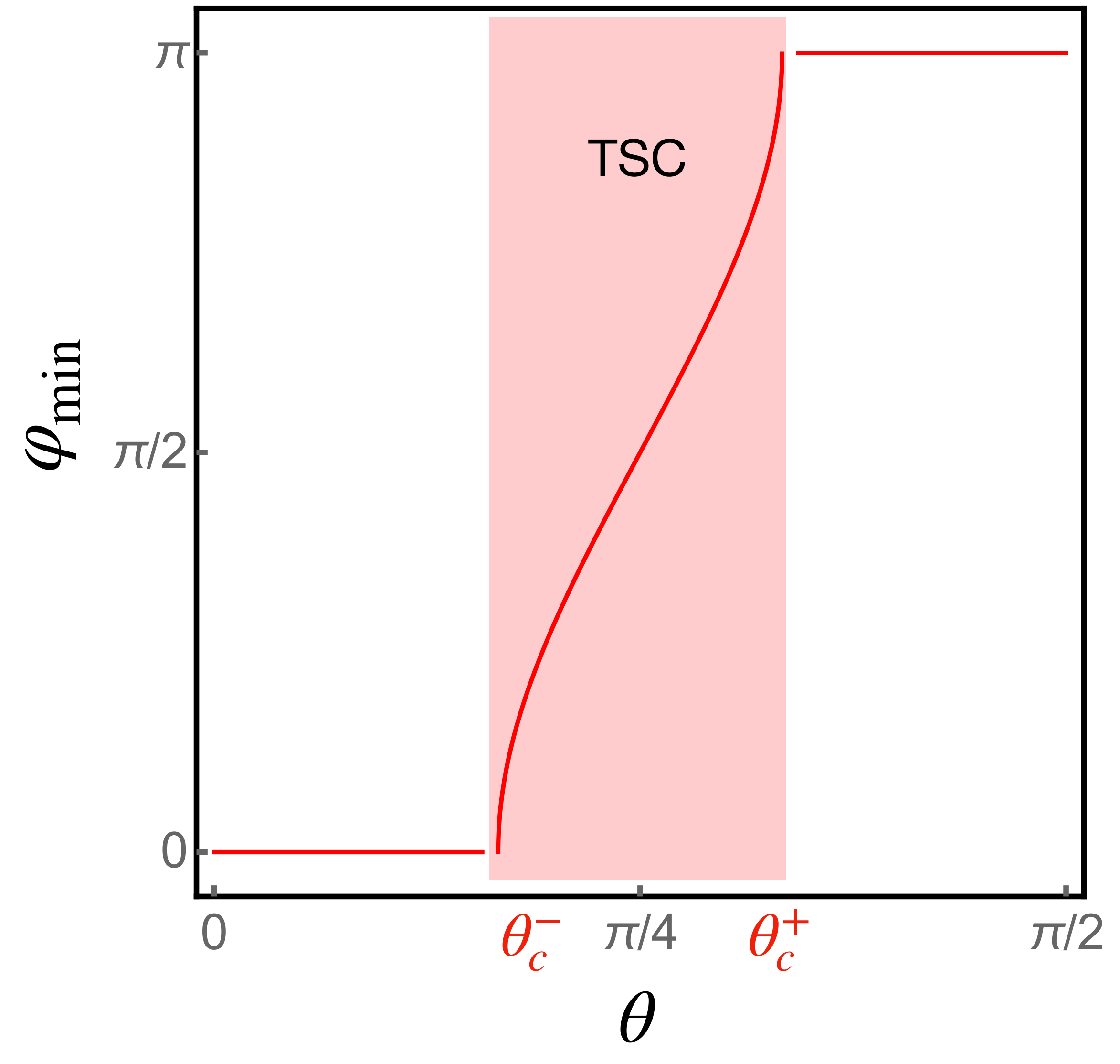
d-wave symmetry dictates $B = -B_0\cos(2\theta)$

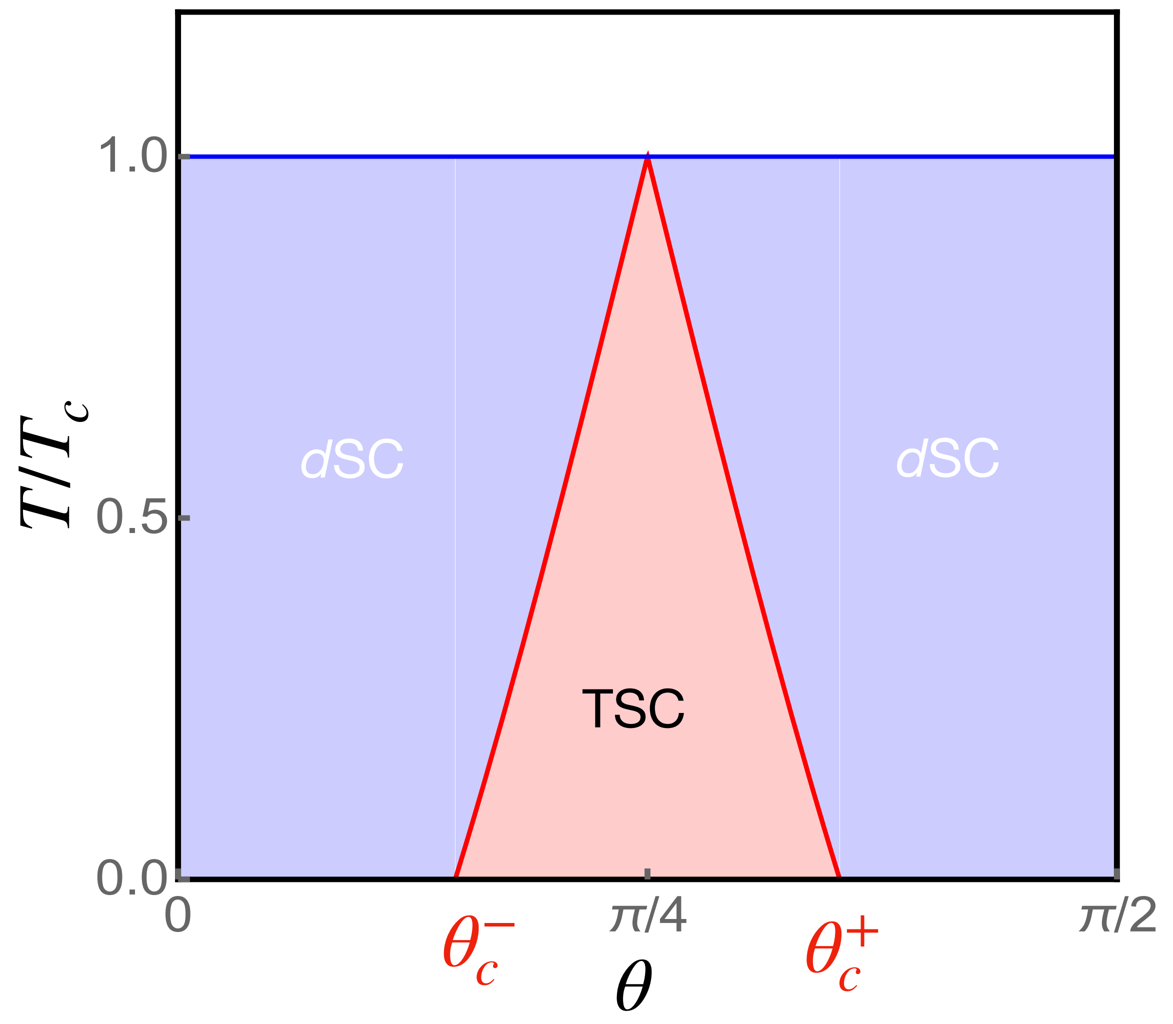
Assuming $\psi_1 = \psi, \quad \psi_2 = \psi e^{i\varphi}$ we obtain free energy as a function of the phase

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



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

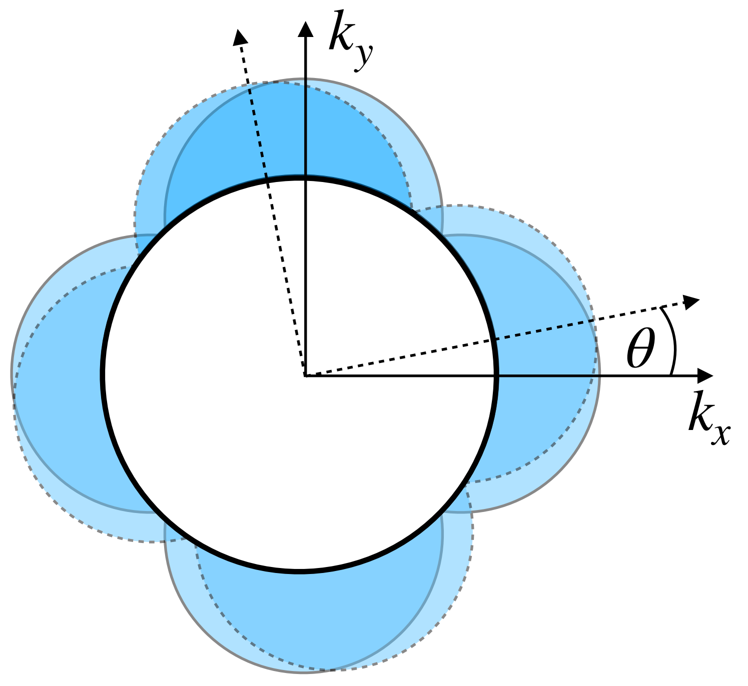




$$\tilde{T}_c(\theta) = T_c\left(1 - \frac{|\cos 2\theta|}{4\mathcal{K}_0}\right), \quad \theta_c^- < \theta < \theta_c^+$$

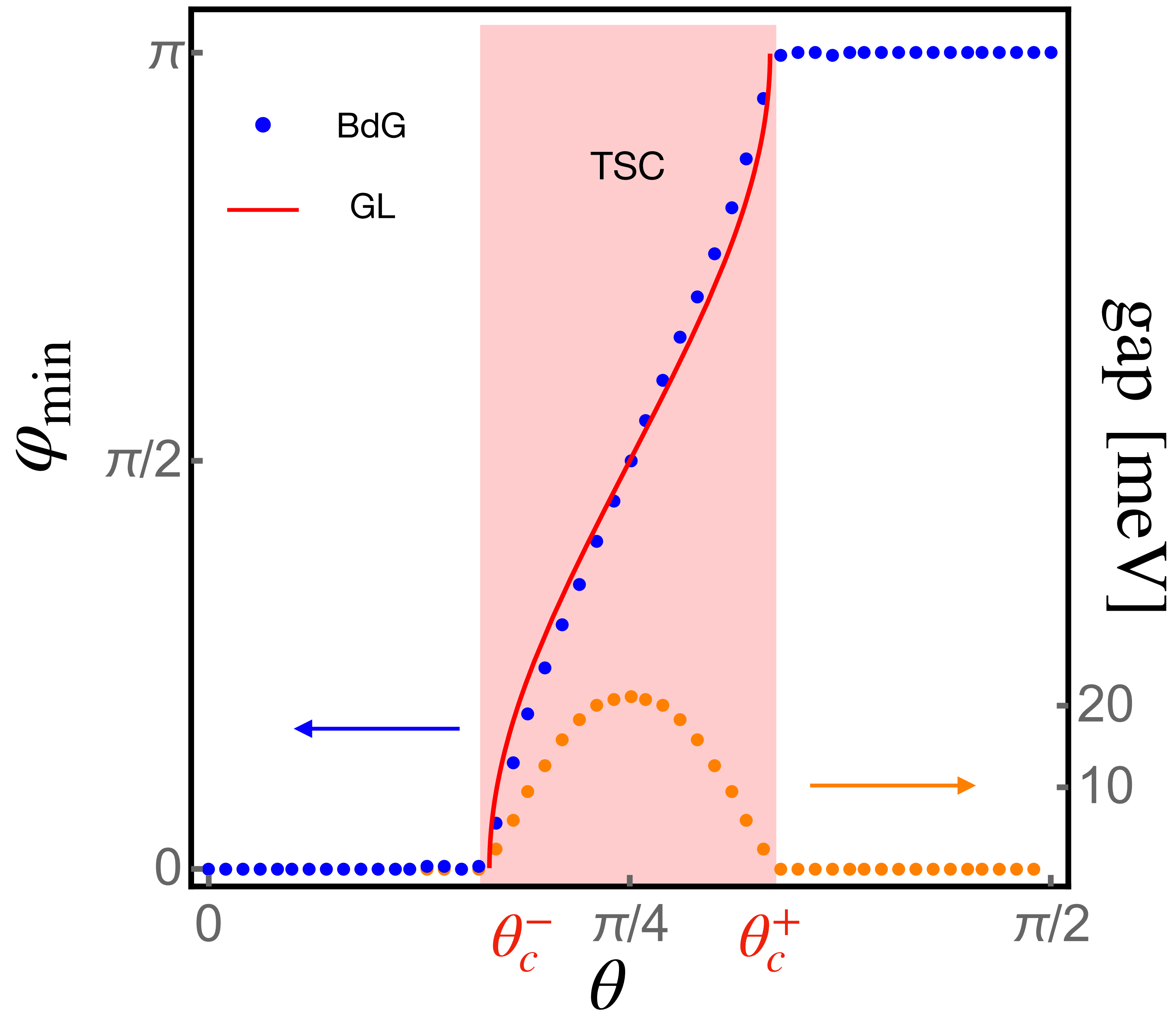
2. Microscopic theory - Continuum Bogoliubov-de Gennes

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

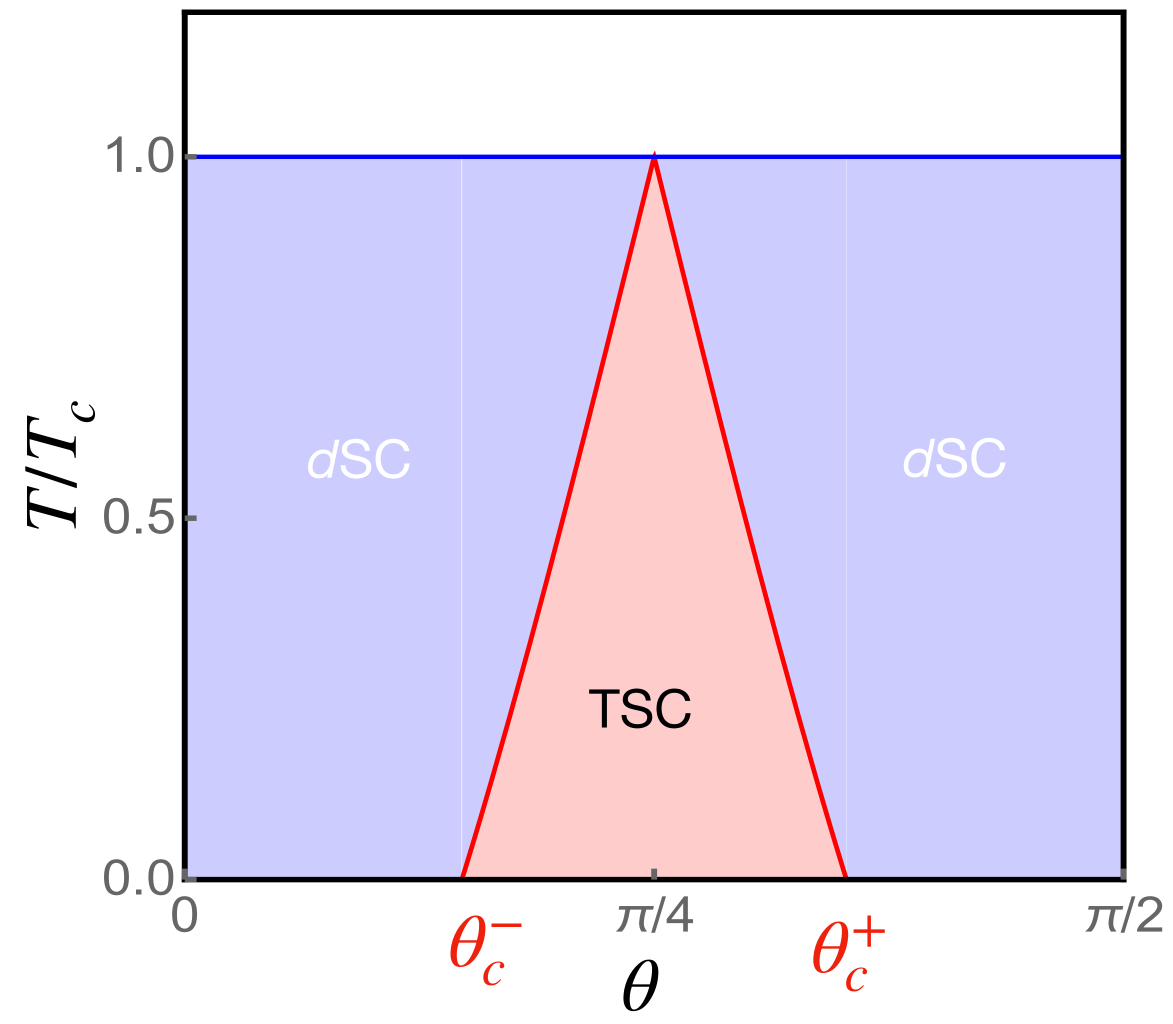


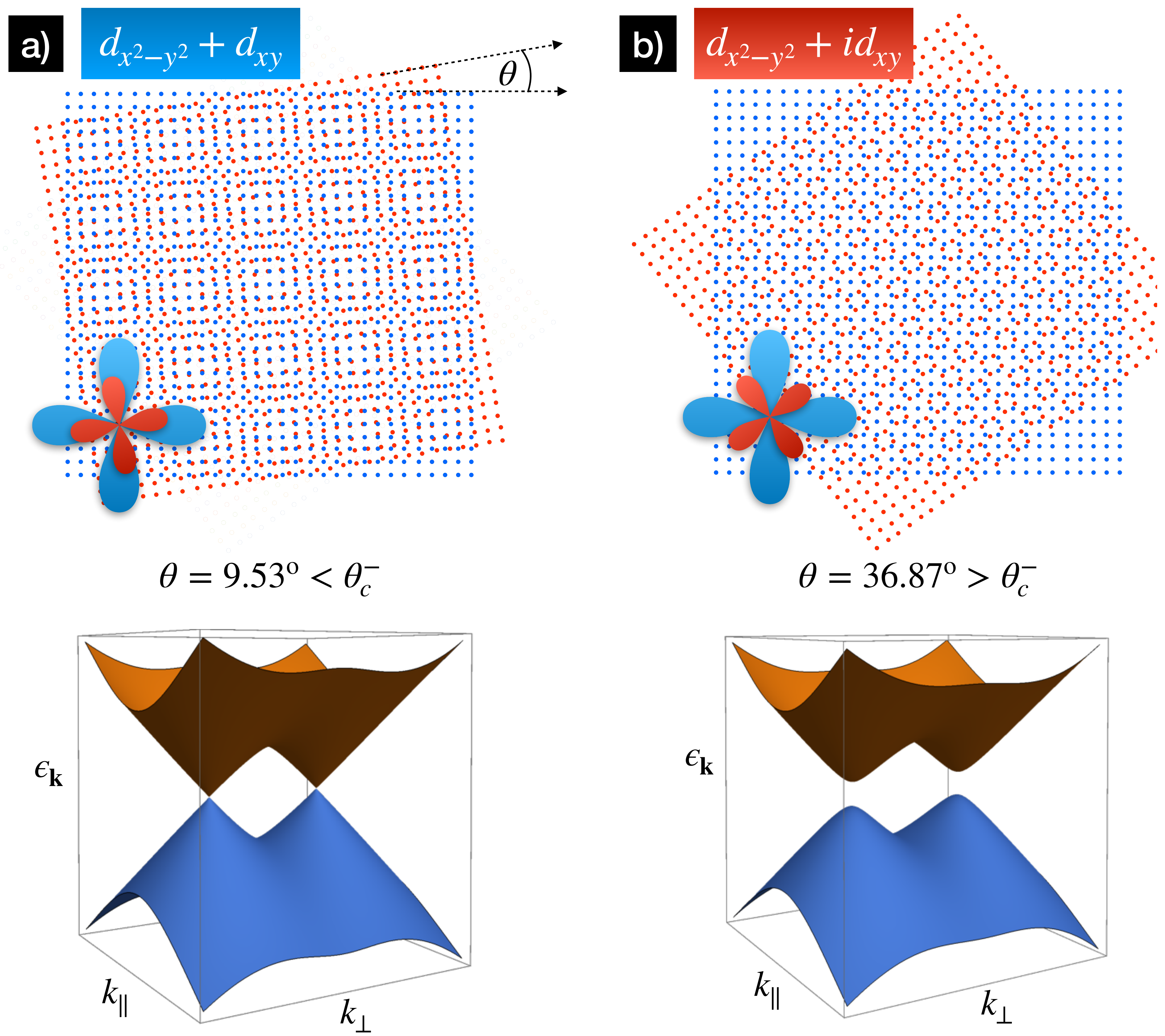
$$\mathscr{H} = \sum_{\mathbf{k}} \Psi^{\dagger}_{\mathbf{k}} h_{\mathbf{k}} \Psi_{\mathbf{k}} + E_0$$

$$h_{\boldsymbol{k}} = \begin{pmatrix} \xi_{\boldsymbol{k}} & \Delta_{\boldsymbol{k}1} & g & 0 \\ \Delta^{*}_{\boldsymbol{k}1} & -\xi_{\boldsymbol{k}} & 0 & -g \\ g & 0 & \xi_{\boldsymbol{k}} & \Delta_{\boldsymbol{k}2} \\ 0 & -g & \Delta^{*}_{\boldsymbol{k}2} & -\xi_{\boldsymbol{k}} \end{pmatrix}$$



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



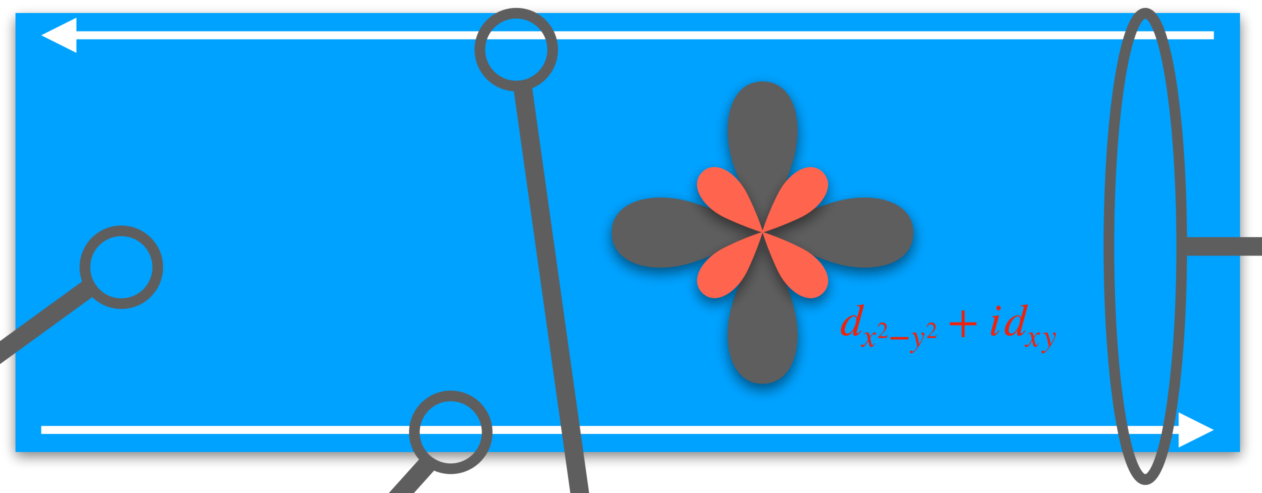


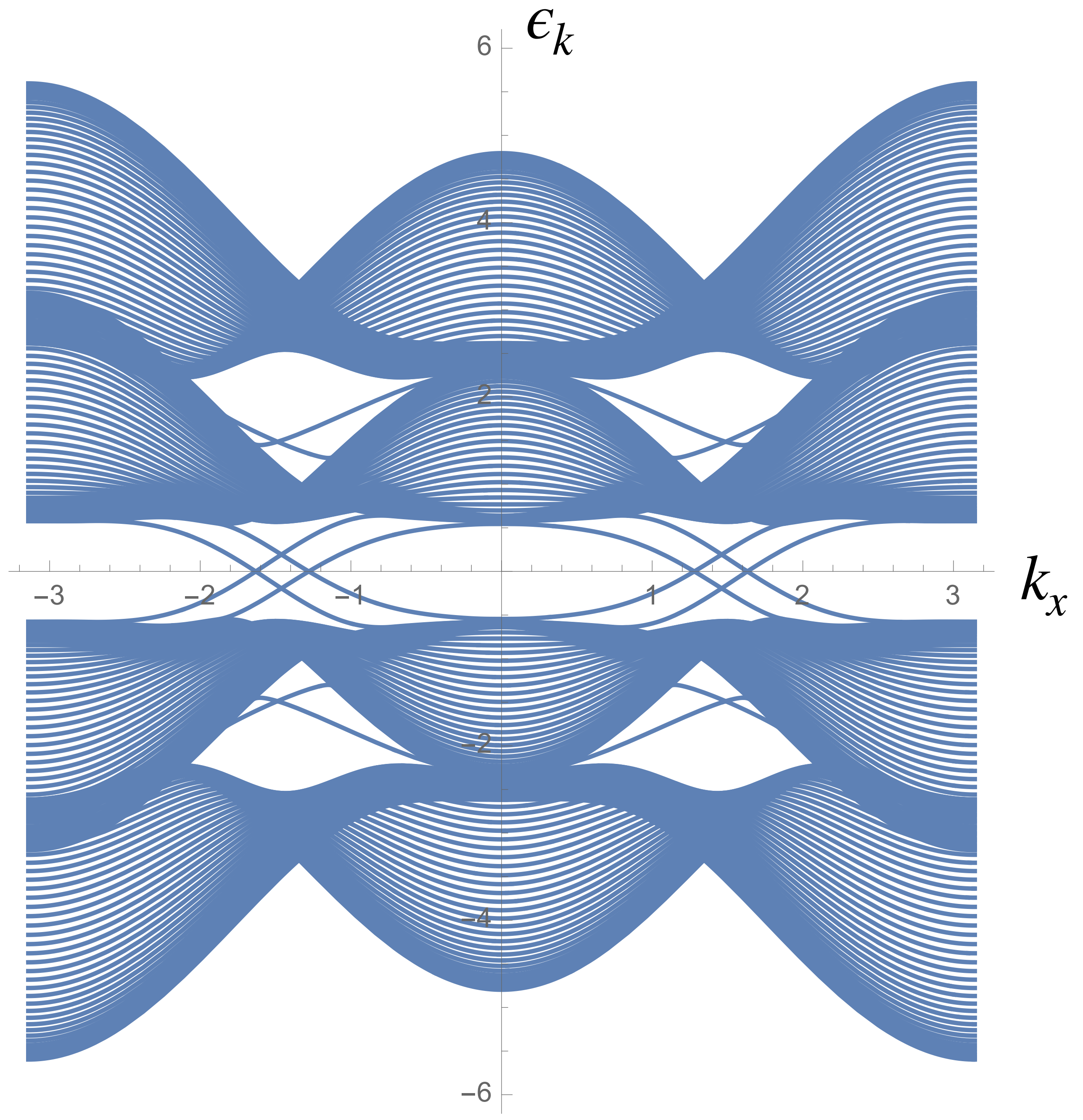
Time-reversal broken phase for any $\varphi \neq 0,\ \pi$

$$(d_{x^2-y^2} + e^{i\phi} d_{xy}) \xrightarrow{\mathcal{T}} (d_{x^2-y^2} + e^{-i\phi} d_{xy})$$

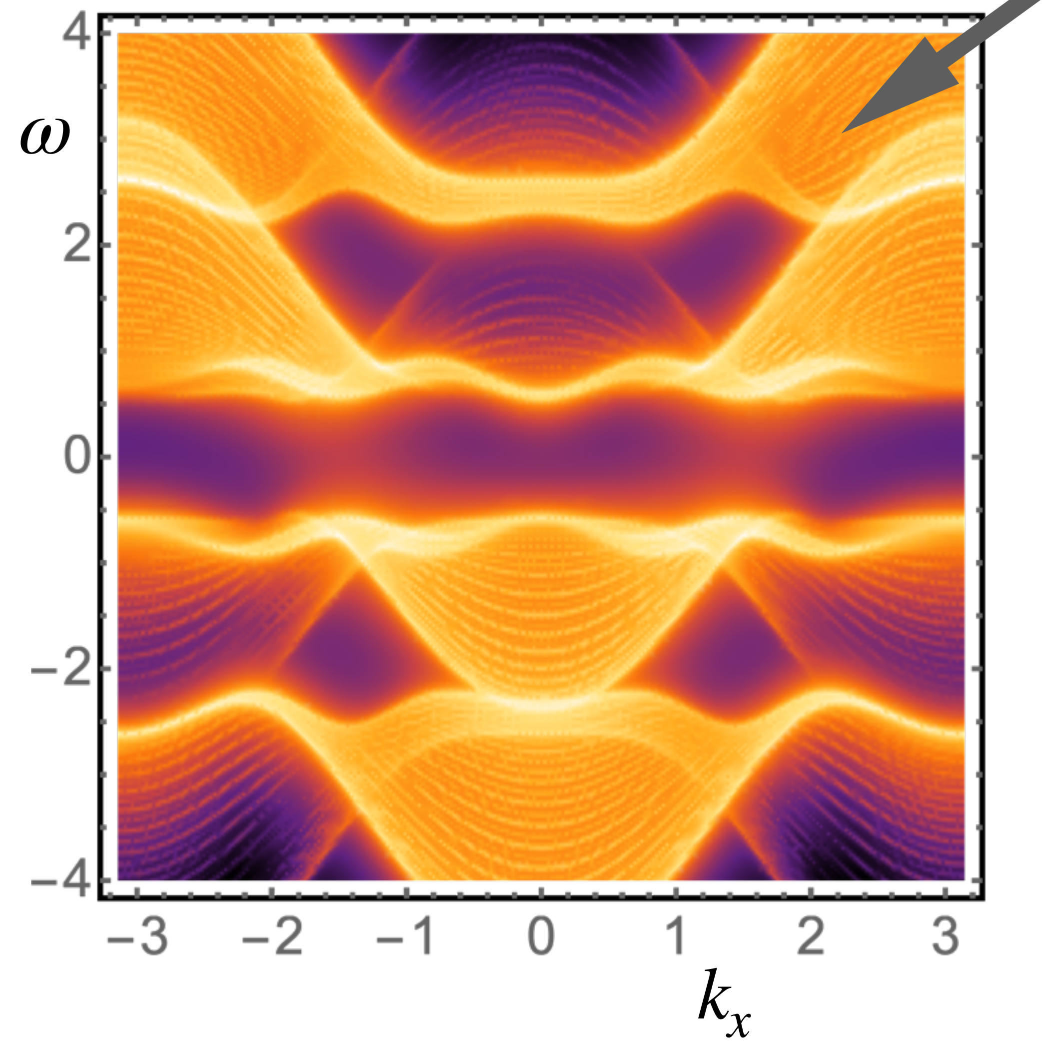
4. Topological superconductivity, protected edge modes

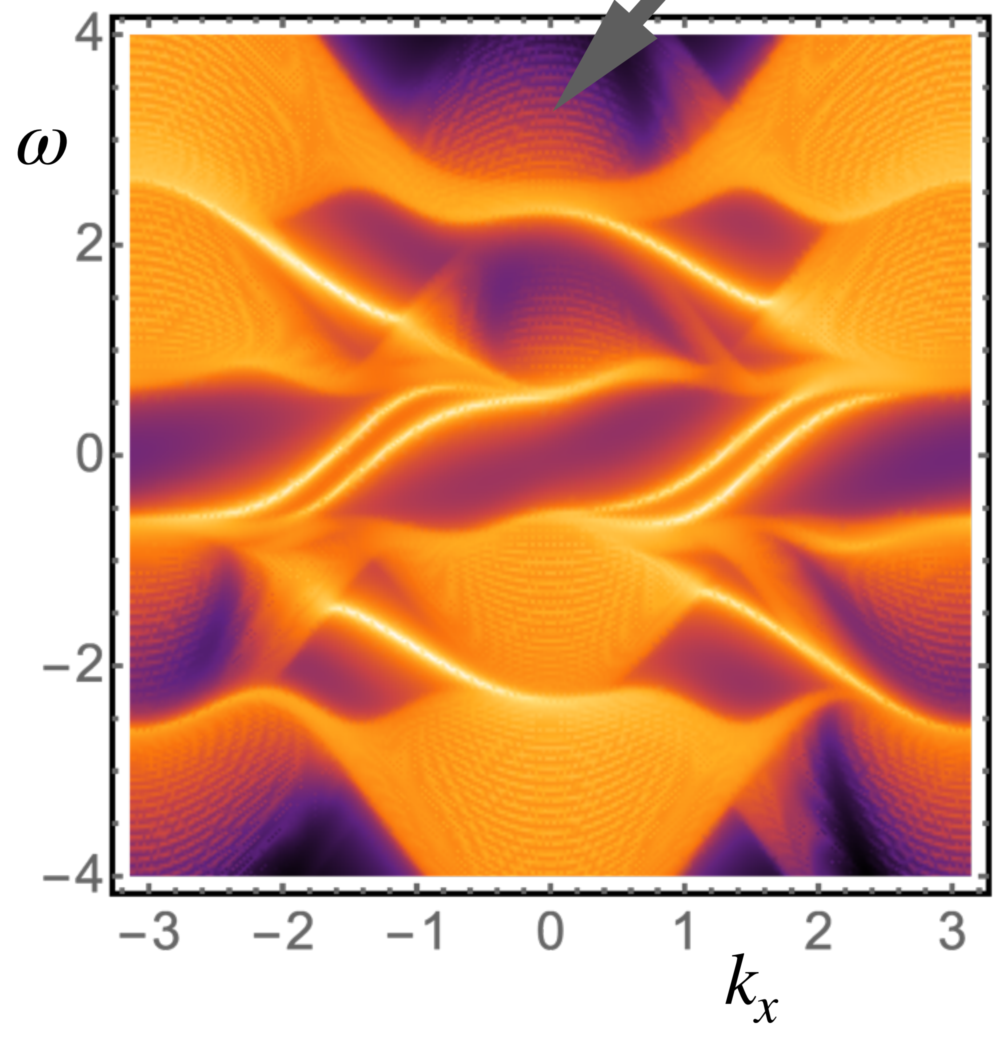
Consider a long strip geometry:

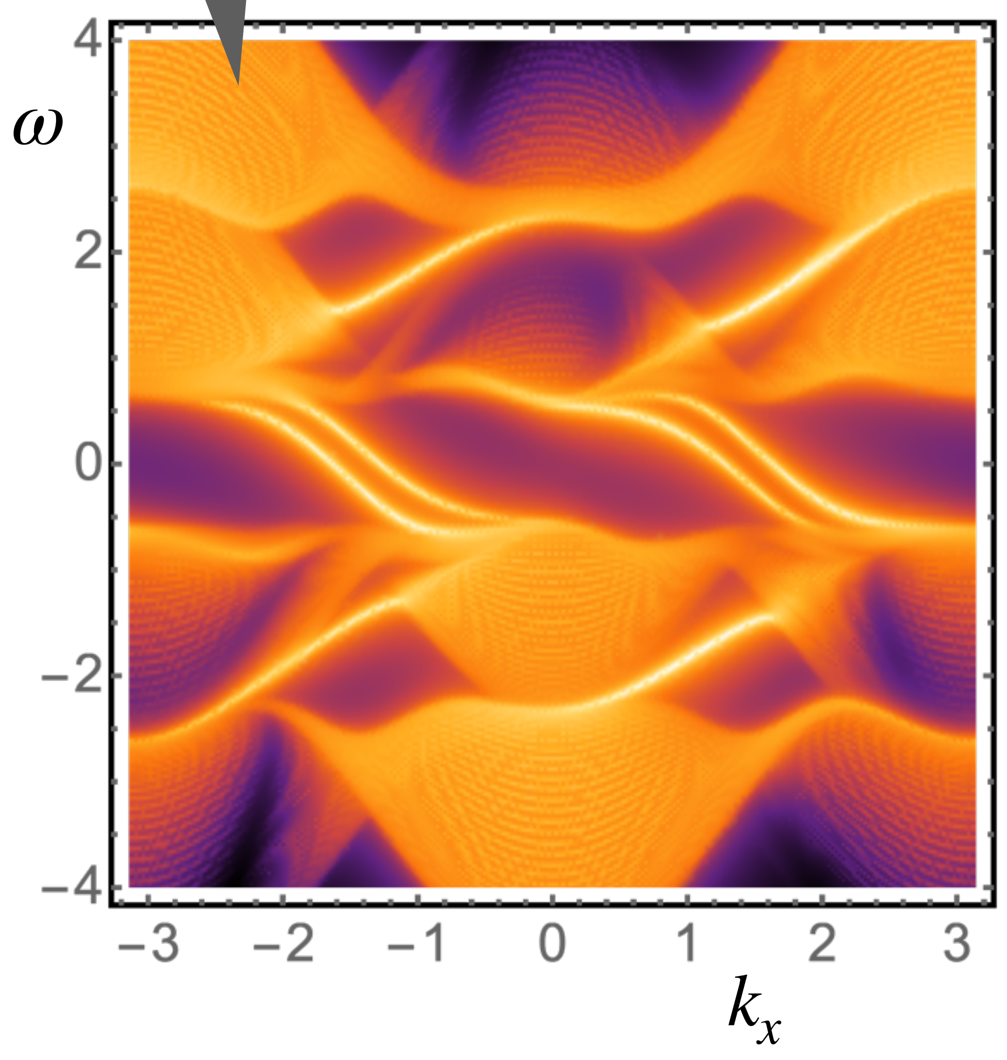


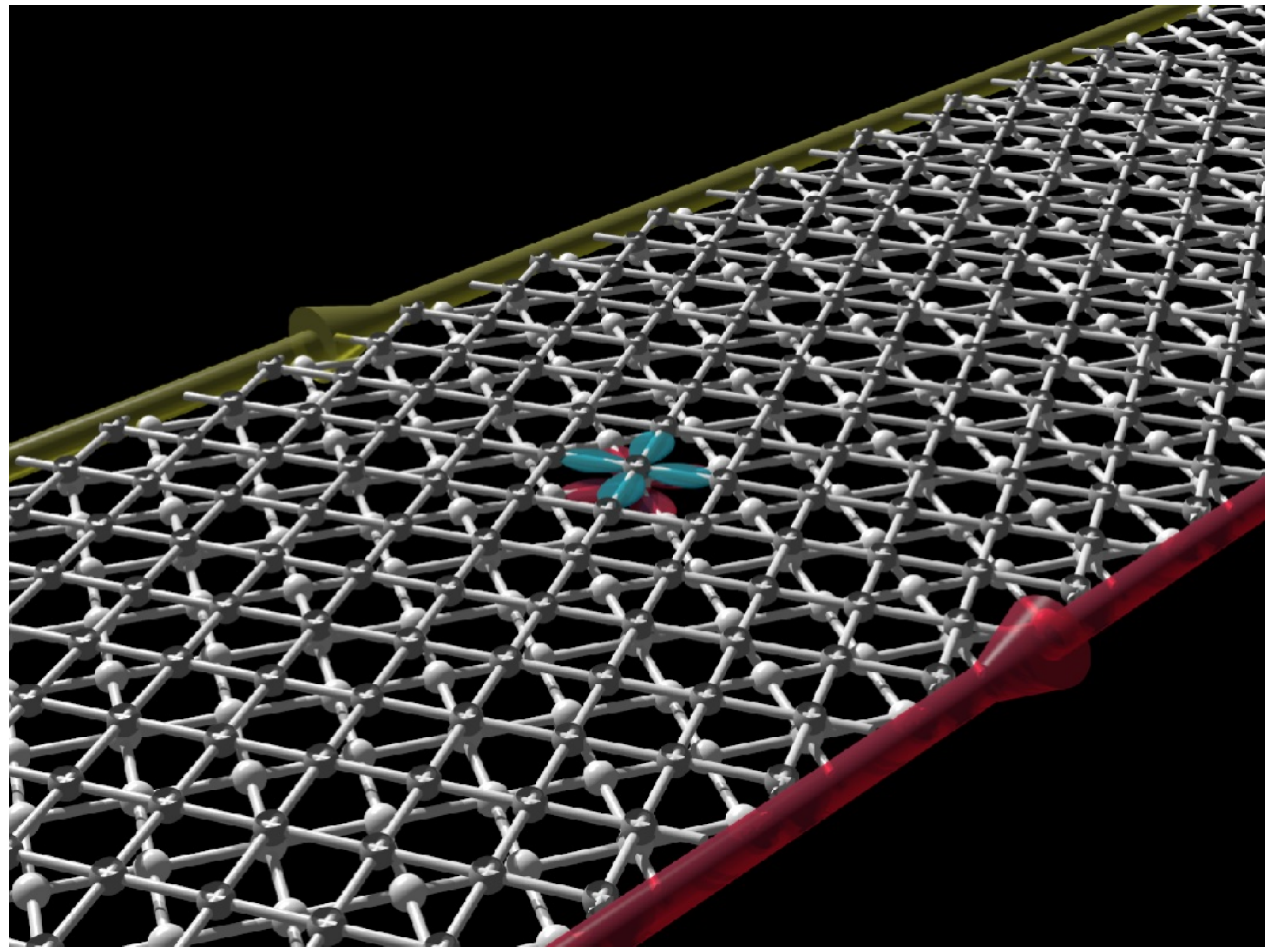


Spectral function
$A(k_x, \omega)$

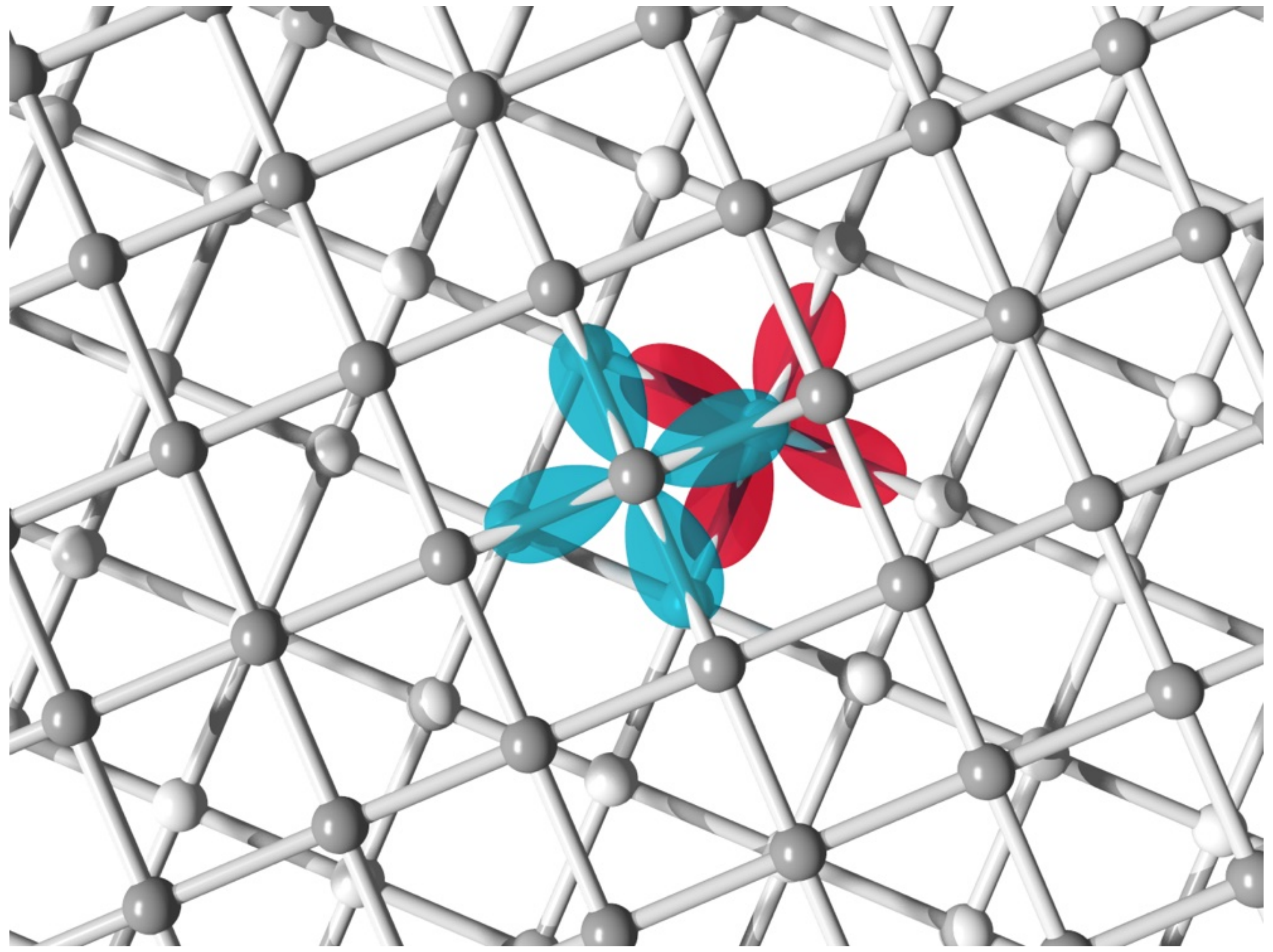






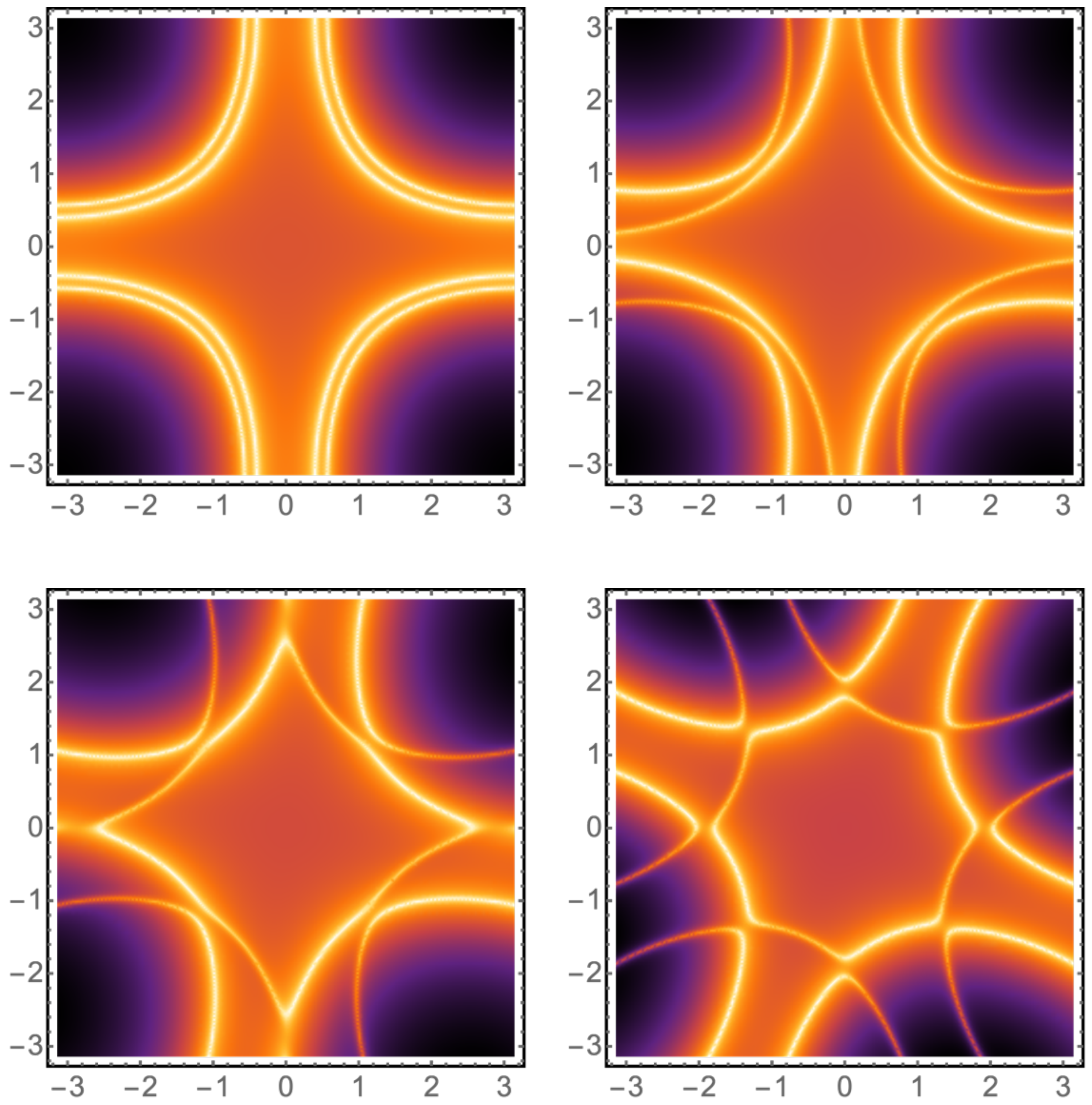


5. Self-consistent theory on the lattice



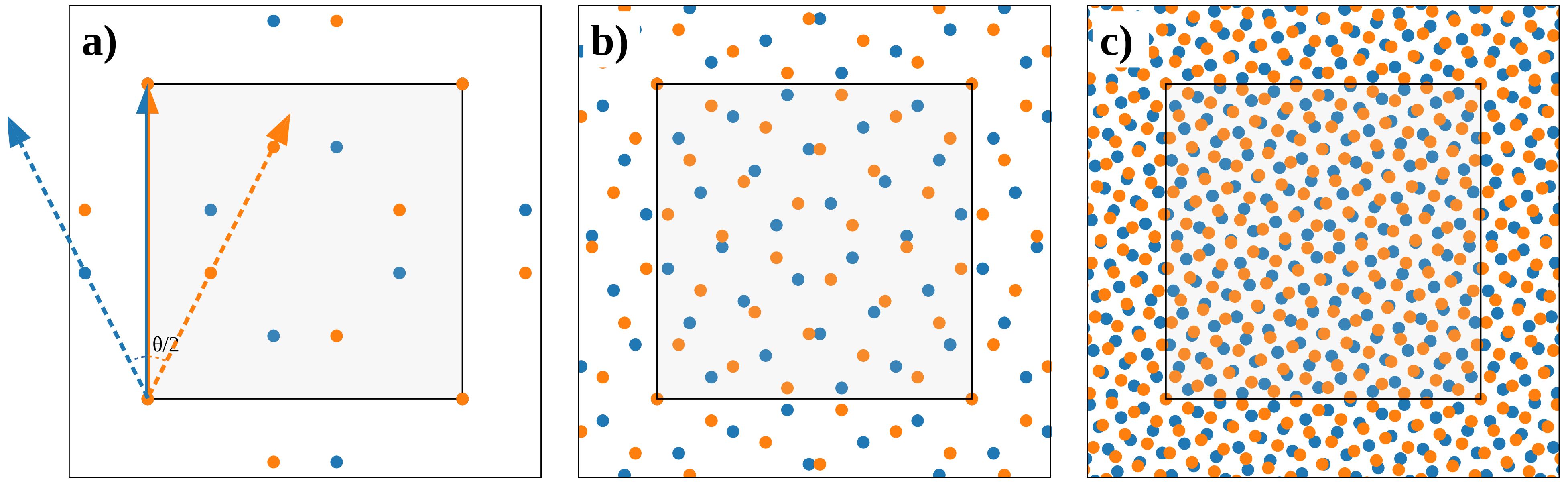
Hubbard model with nn attraction and on-site repulsion

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



Solve using standard mean-field decoupling in the pairing channel for commensurate twist angles

$$\theta_{m,n} = 2\arctan(m/n)$$



$\theta_{1,2} \simeq 53.13^{\mathrm{o}}$ $\theta_{2,5} \simeq 43.60^{\mathrm{o}}$ $\theta_{5,12} \simeq 45.24^{\mathrm{o}}$

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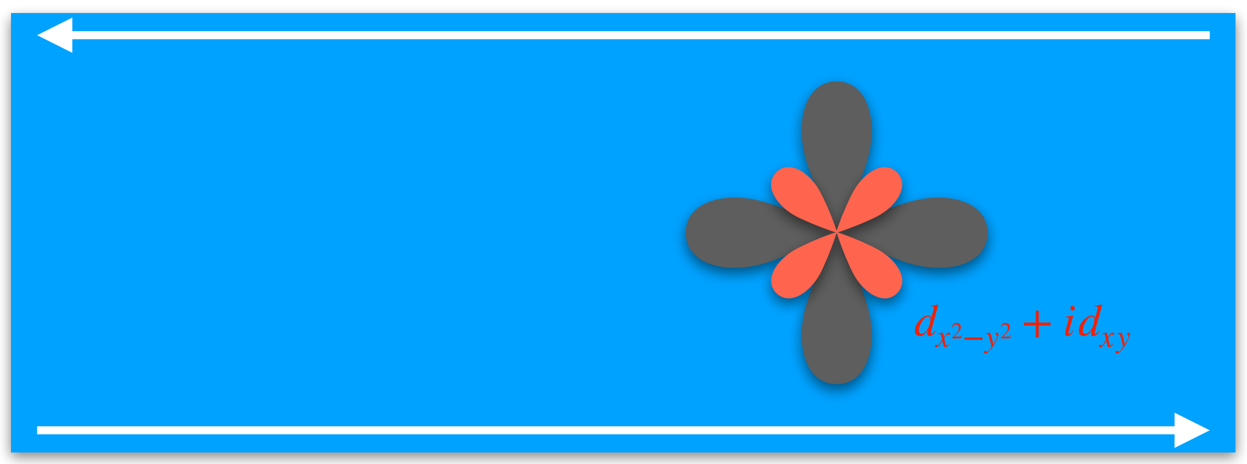
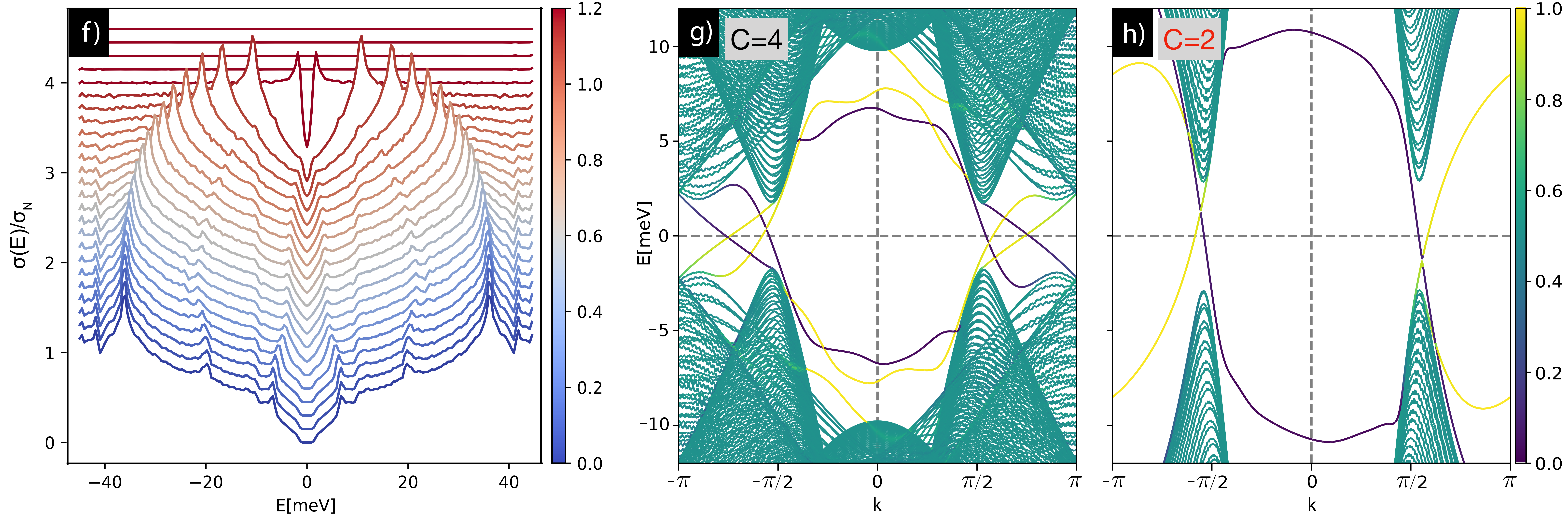
Self-consistent theory on the lattice

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

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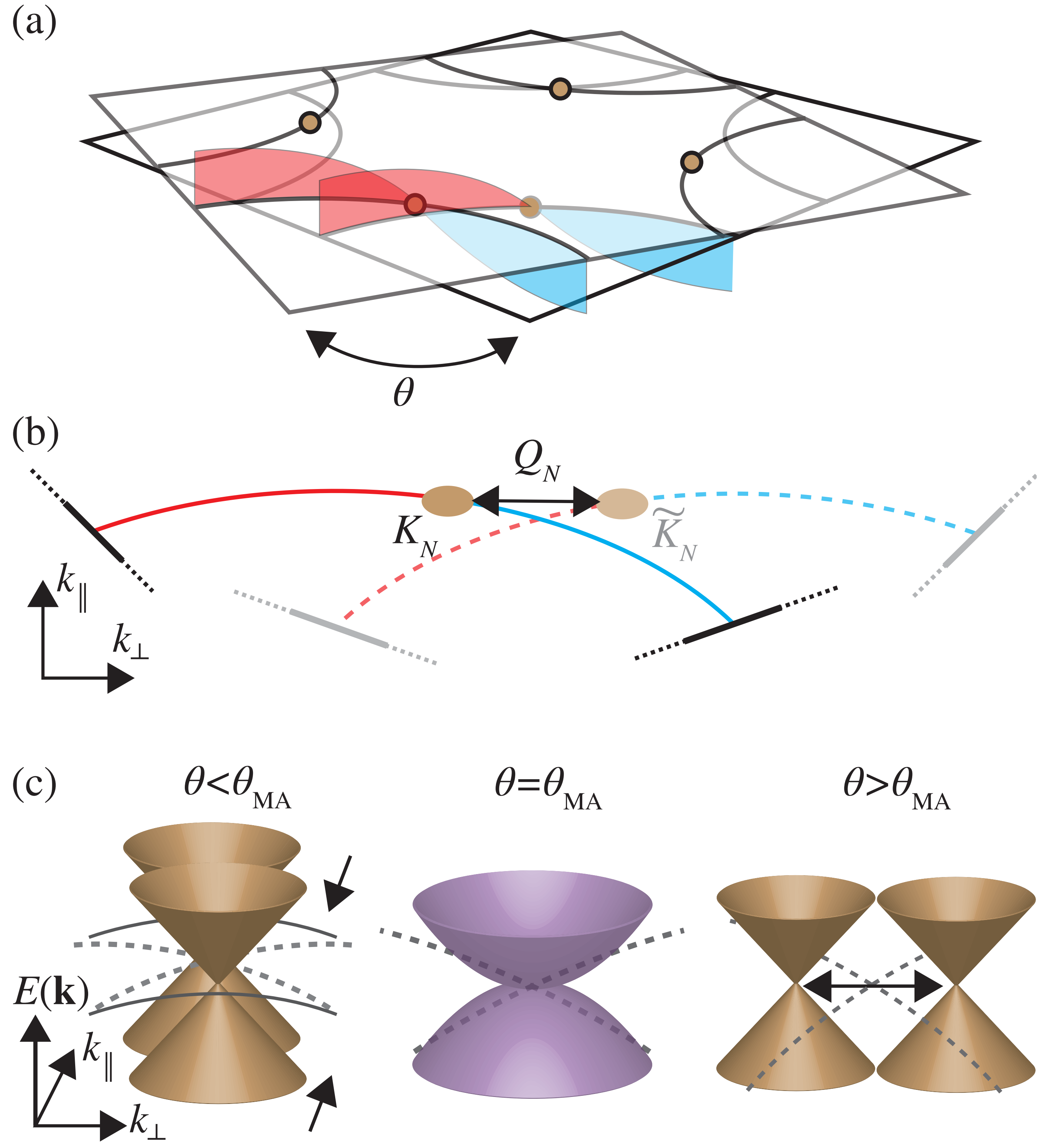
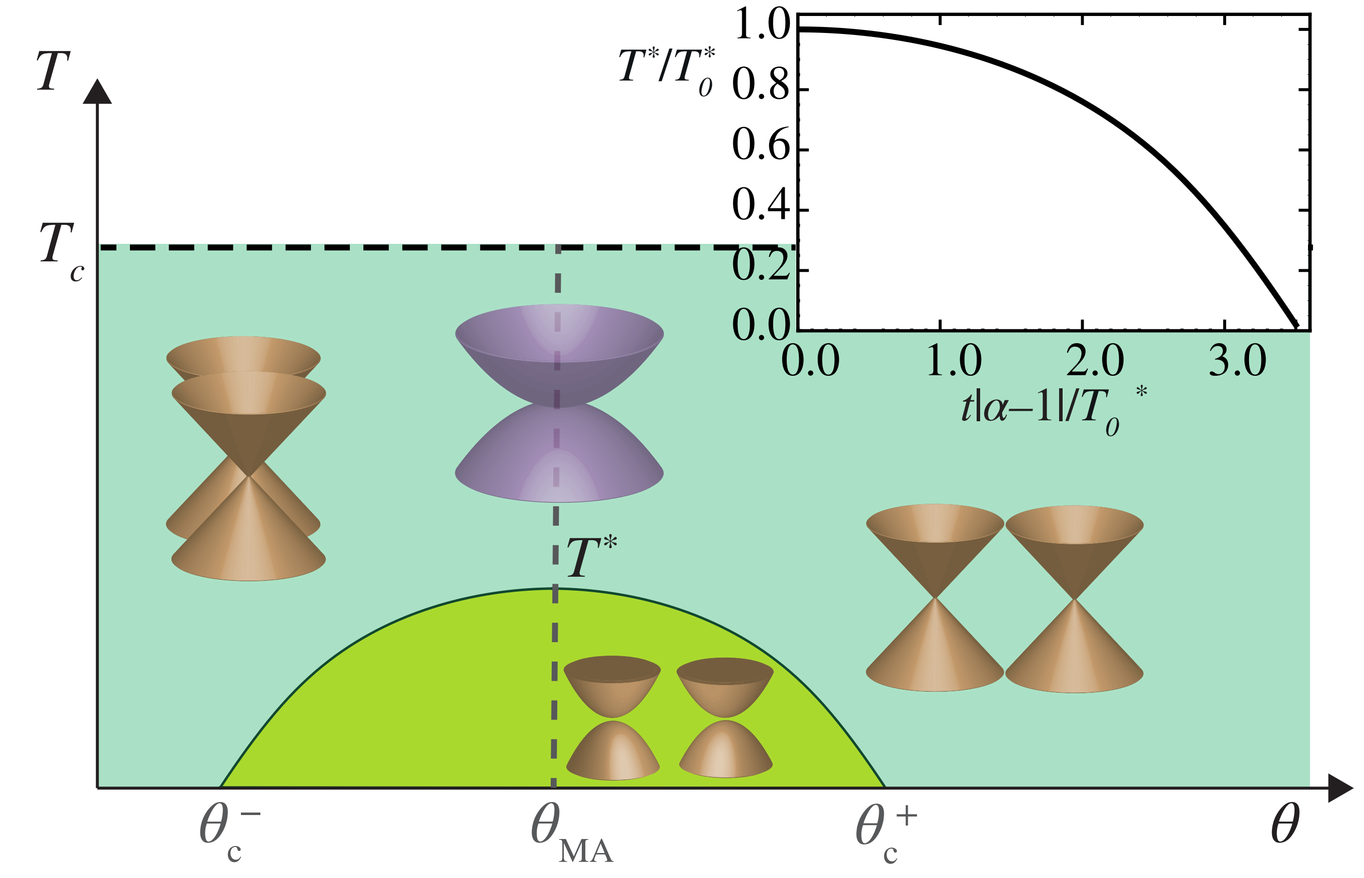
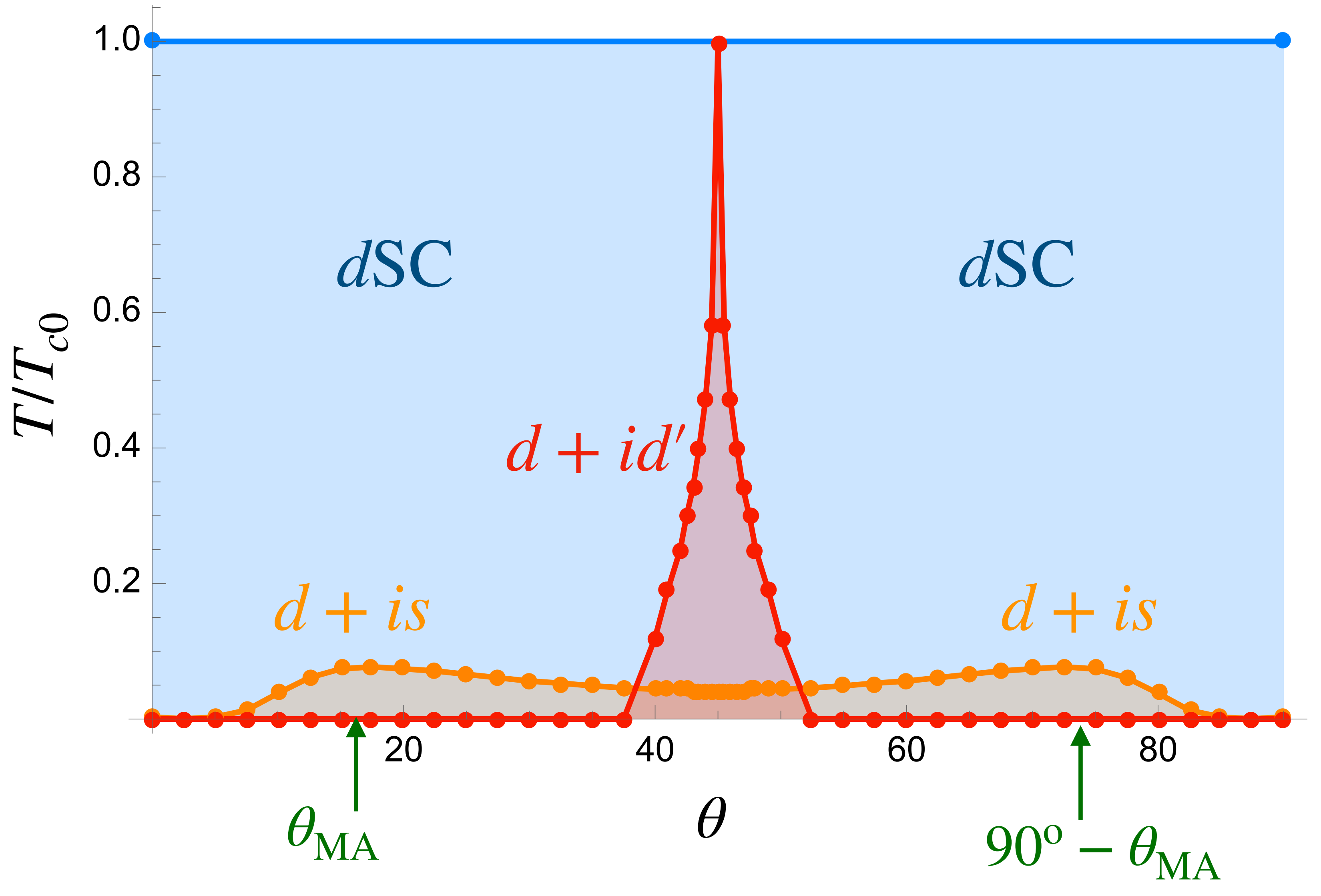
(Dated: December 16, 2020)





Self-consistently determined phase diagram - present work

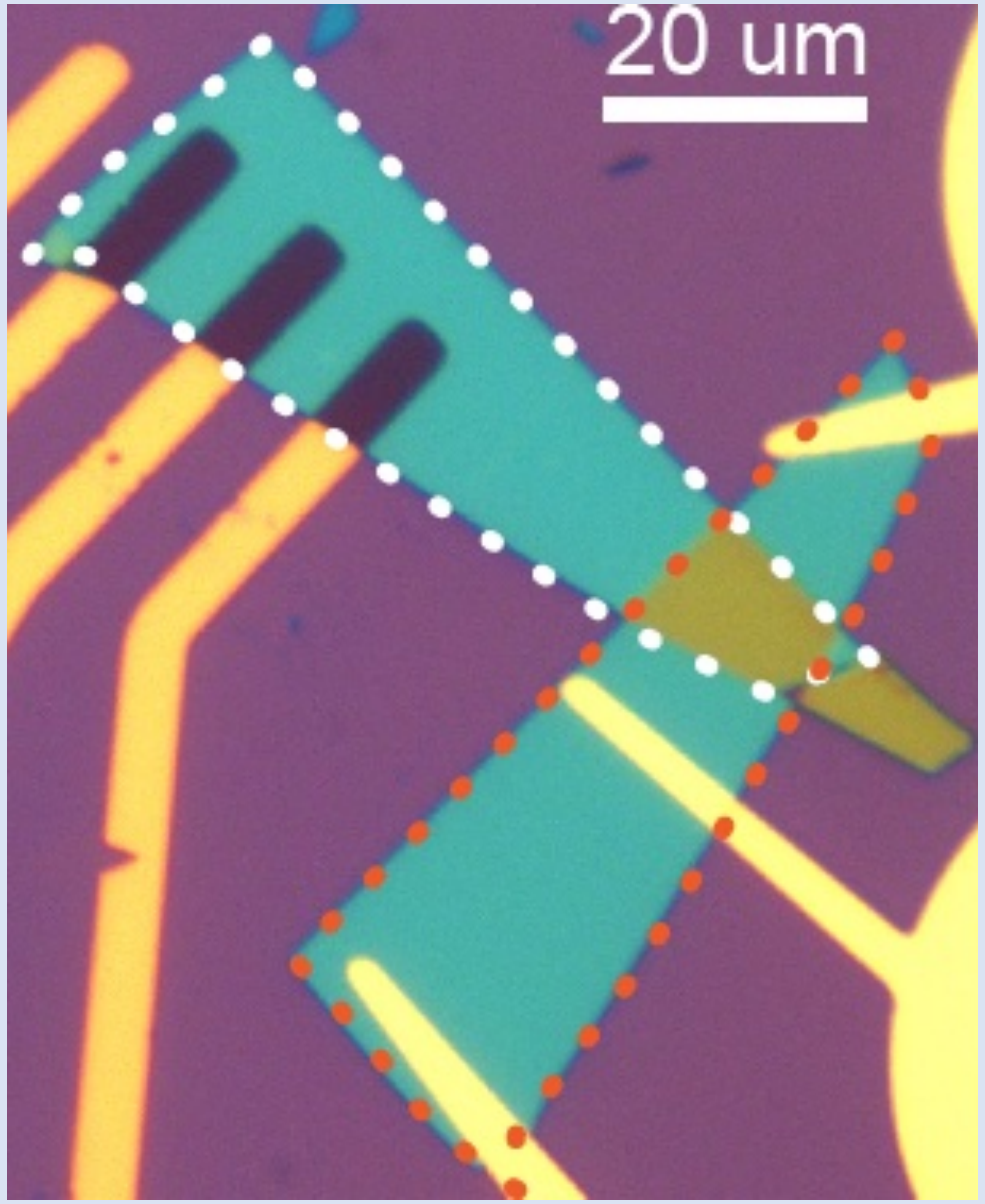
(assuming interaction-induced *s*-wave instability)

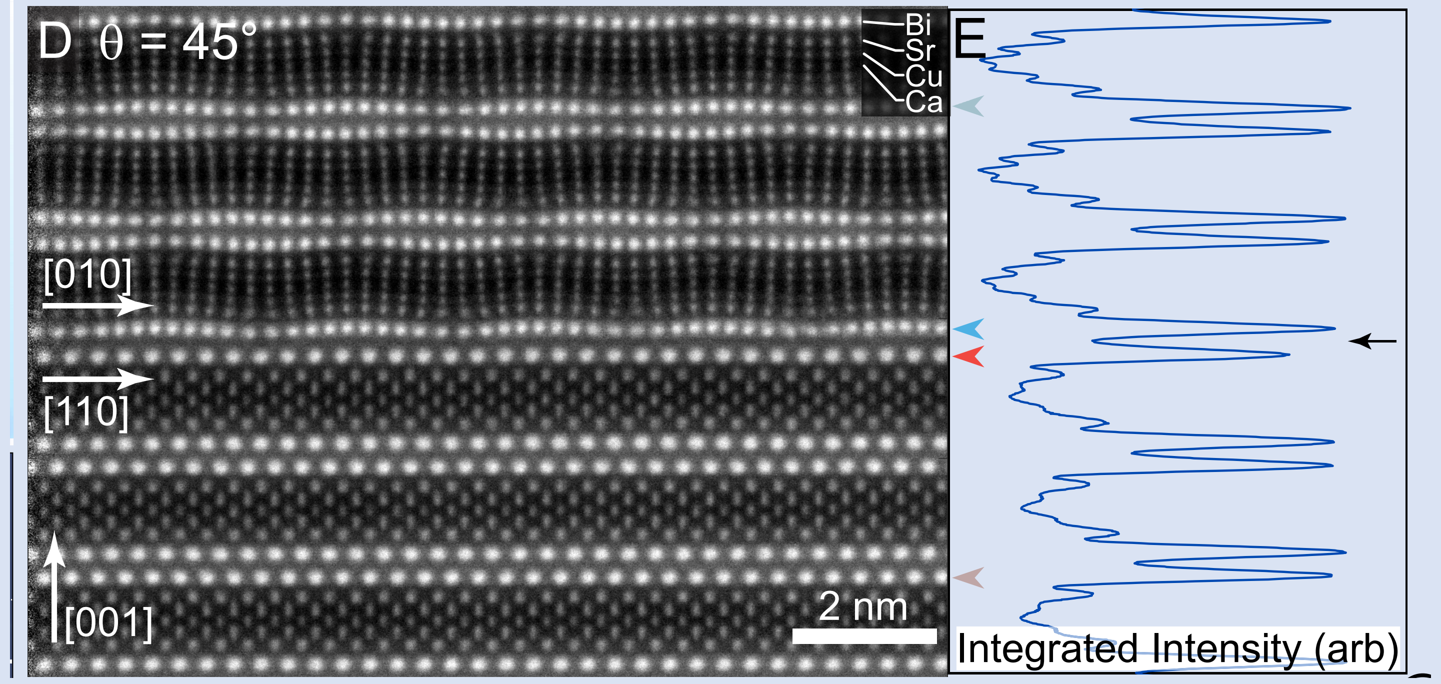


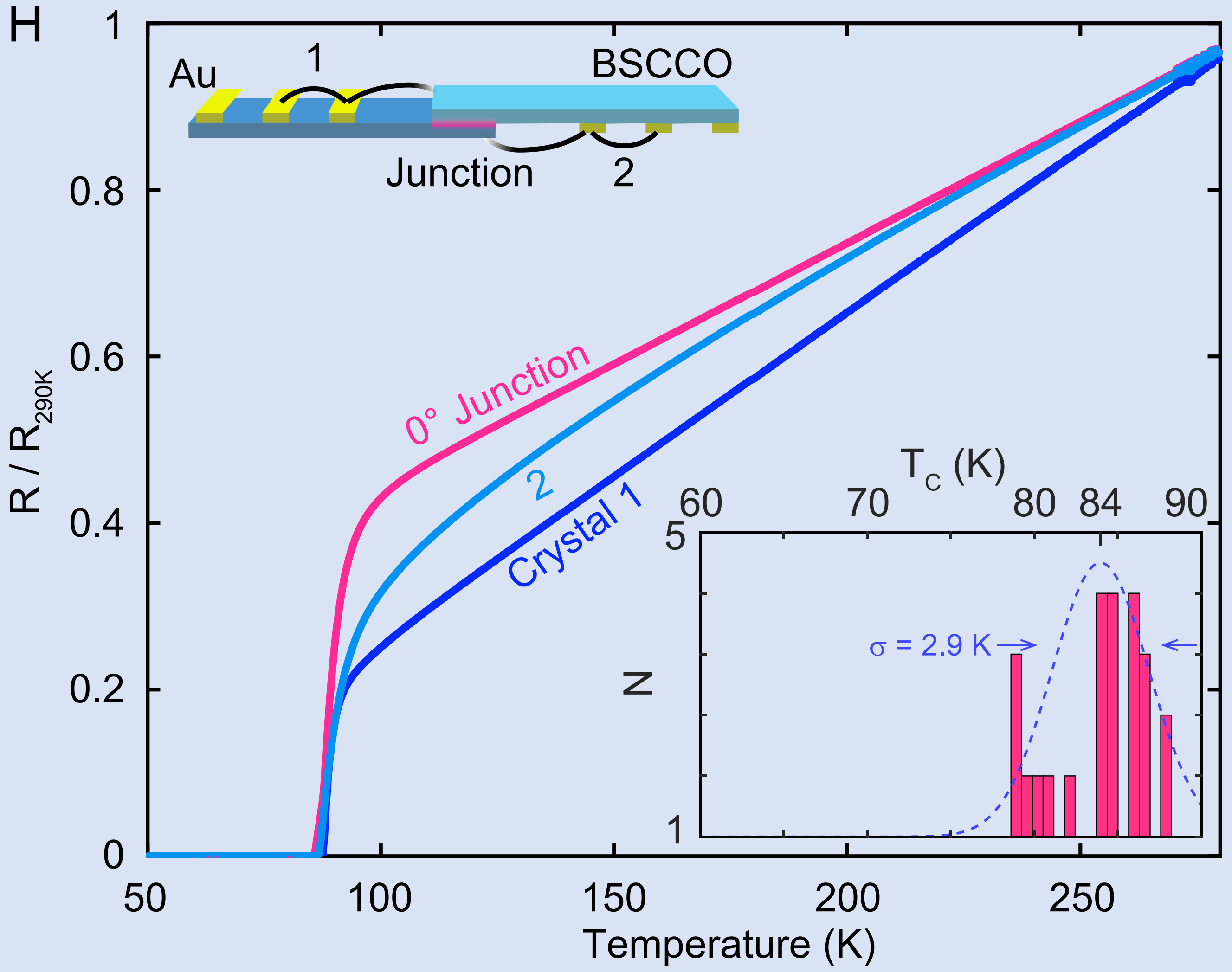
Experimental efforts

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

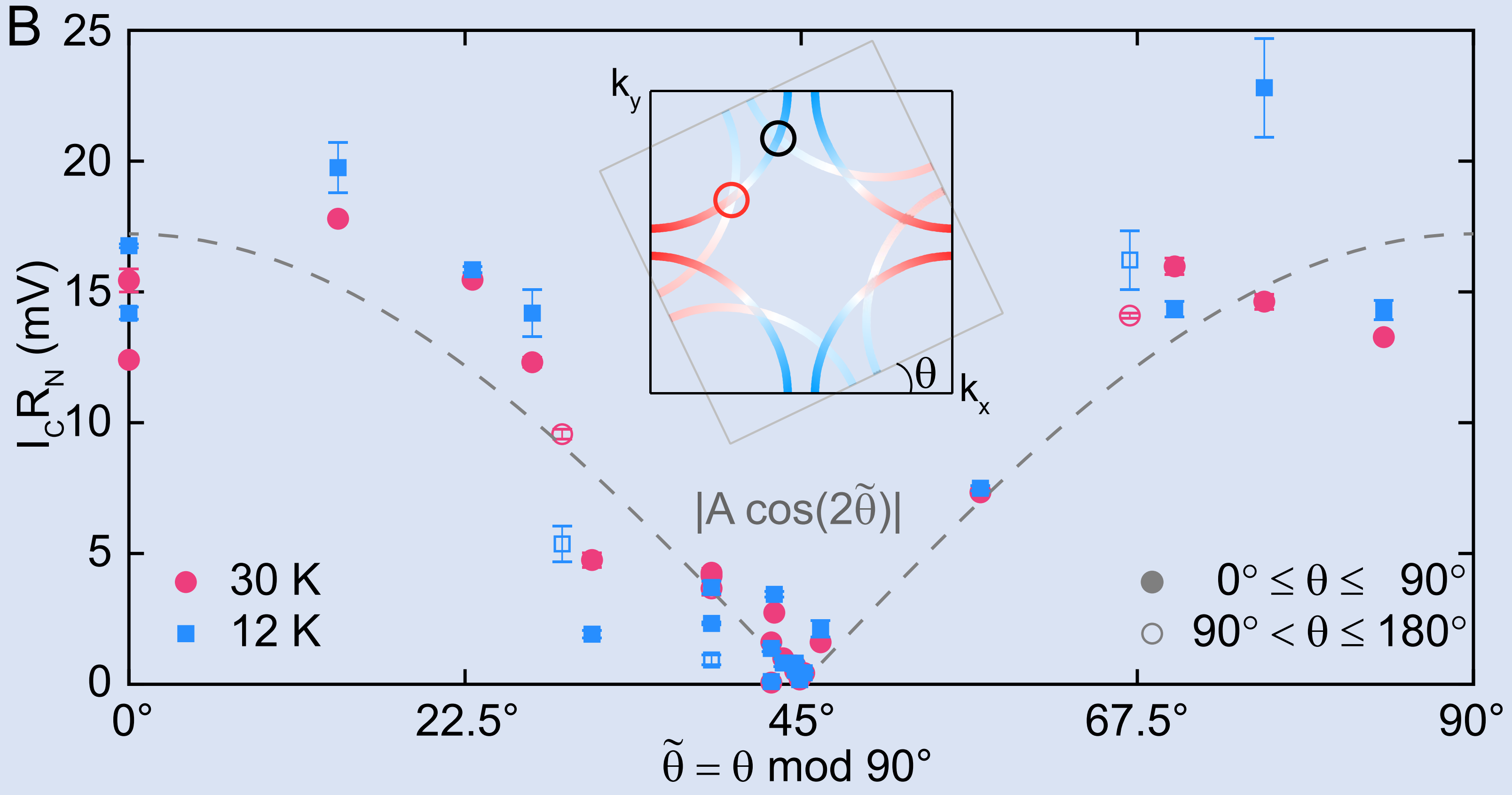
Exceptionally clean and ordered interfaces

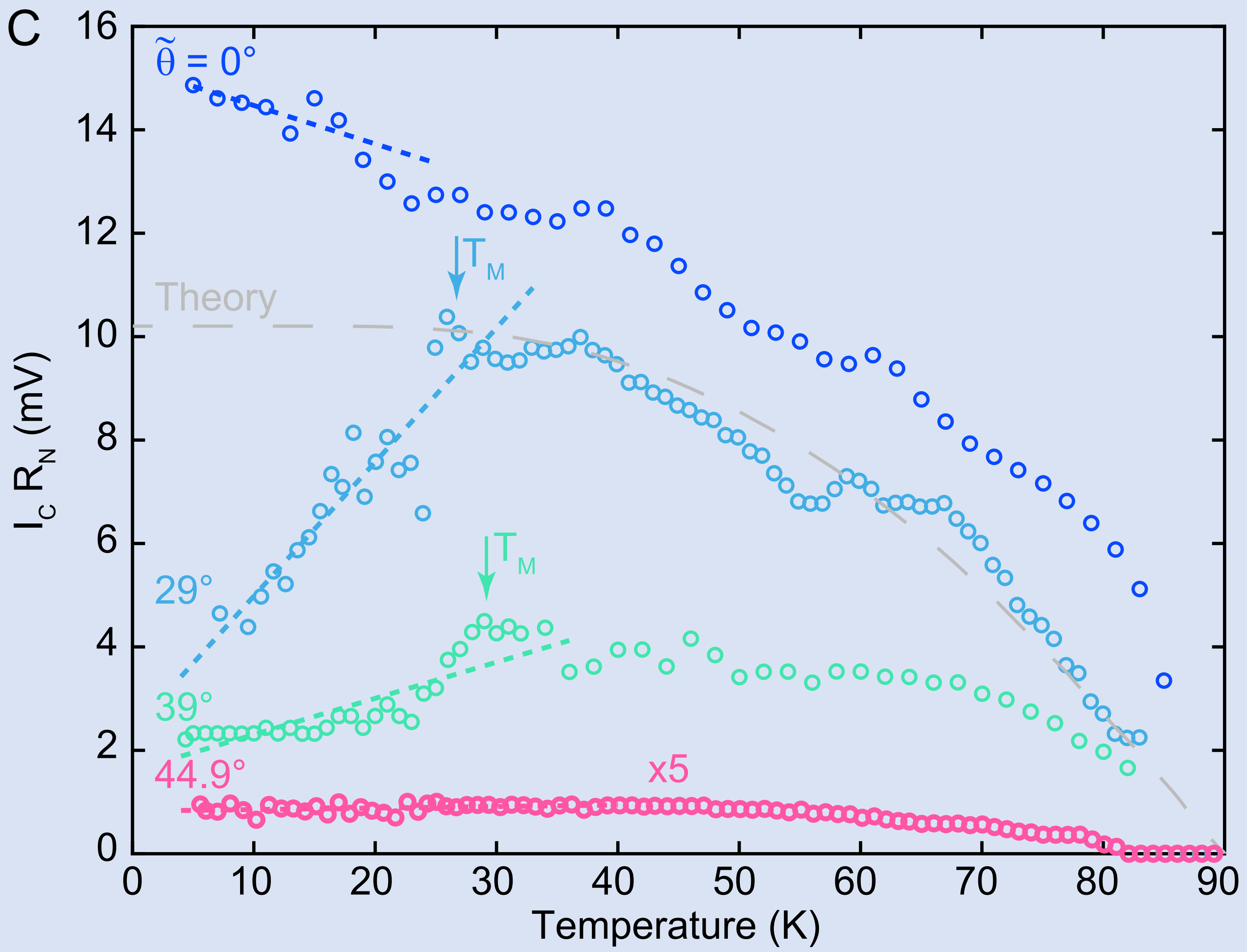






Results





Zhao et al., arXiv:2108.13455

Microscopic model - Continuum Bogoliubov-de Gennes

We wish to understand how the anomalous increase in $I_c R_N$ follows from a theory of Josephson tunnelling between twisted *d*-wave superconductors.

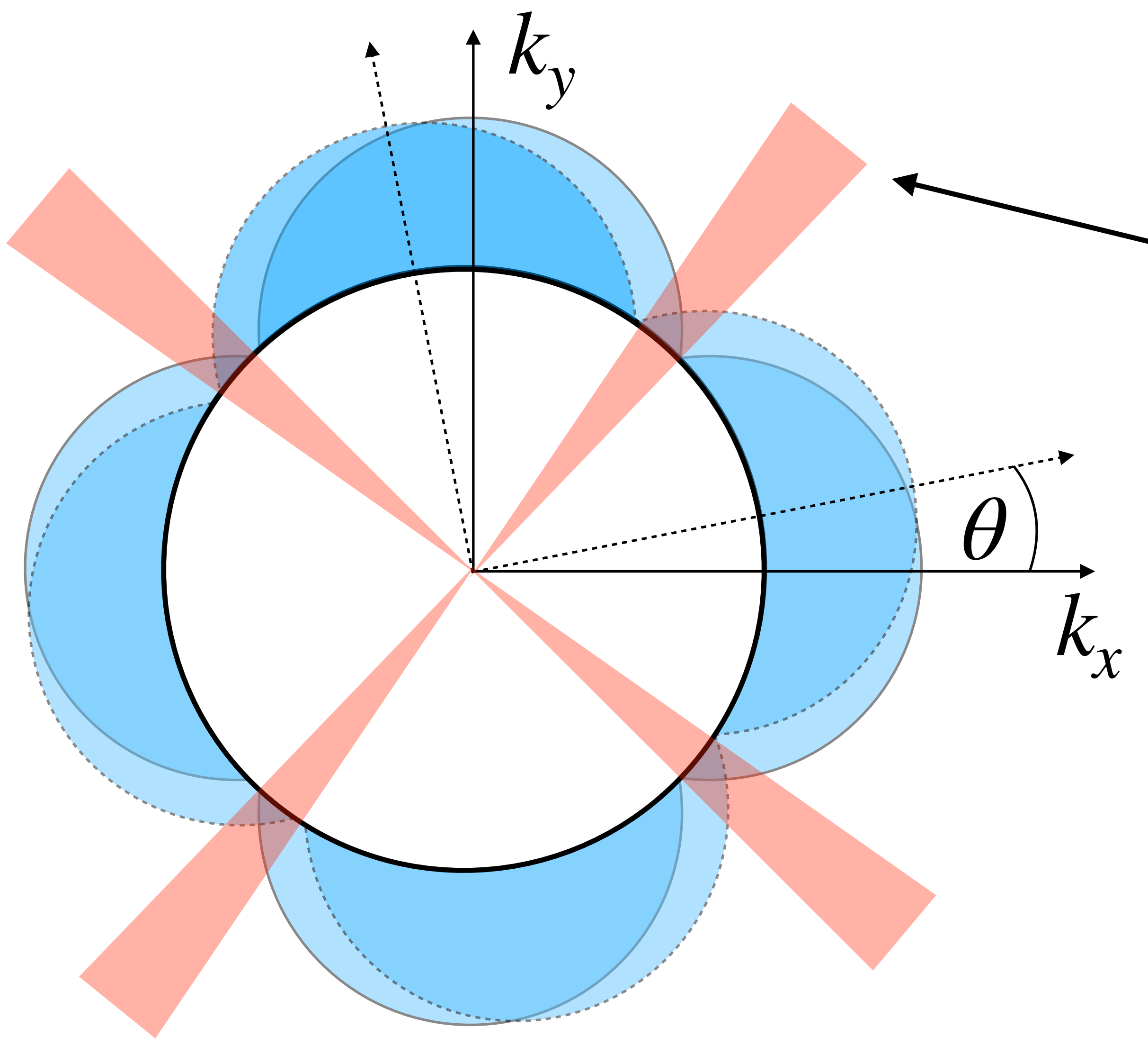
$$
\begin{aligned}
\mathcal{H} = & \sum_{\boldsymbol{k}\sigma a} \xi_{\boldsymbol{k}a} c^{\dagger}_{\boldsymbol{k}\sigma a} c_{\boldsymbol{k}\sigma a} + g \sum_{\boldsymbol{k}\sigma} \left(c^{\dagger}_{\boldsymbol{k}\sigma 1} c_{\boldsymbol{k}\sigma 2} + \text{h.c.} \right) \\
& + \sum_{\boldsymbol{k}a}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

One can show that the interlayer critical current has the form

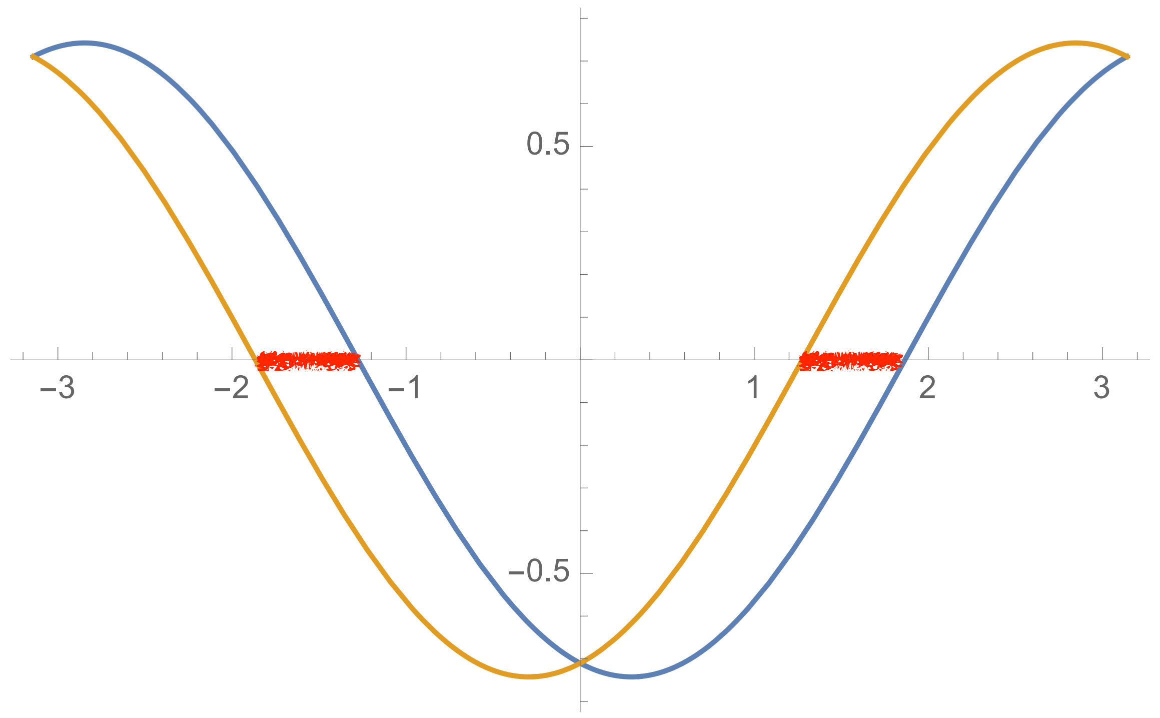
$$
I_c(T) = \sum_{\mathbf{k}} \Delta_{\mathbf{k}1} \Delta_{\mathbf{k}2} \Omega(\xi_k, T)
$$

where $\Omega(\xi_k, T) \geq 0$. In a dSC we have

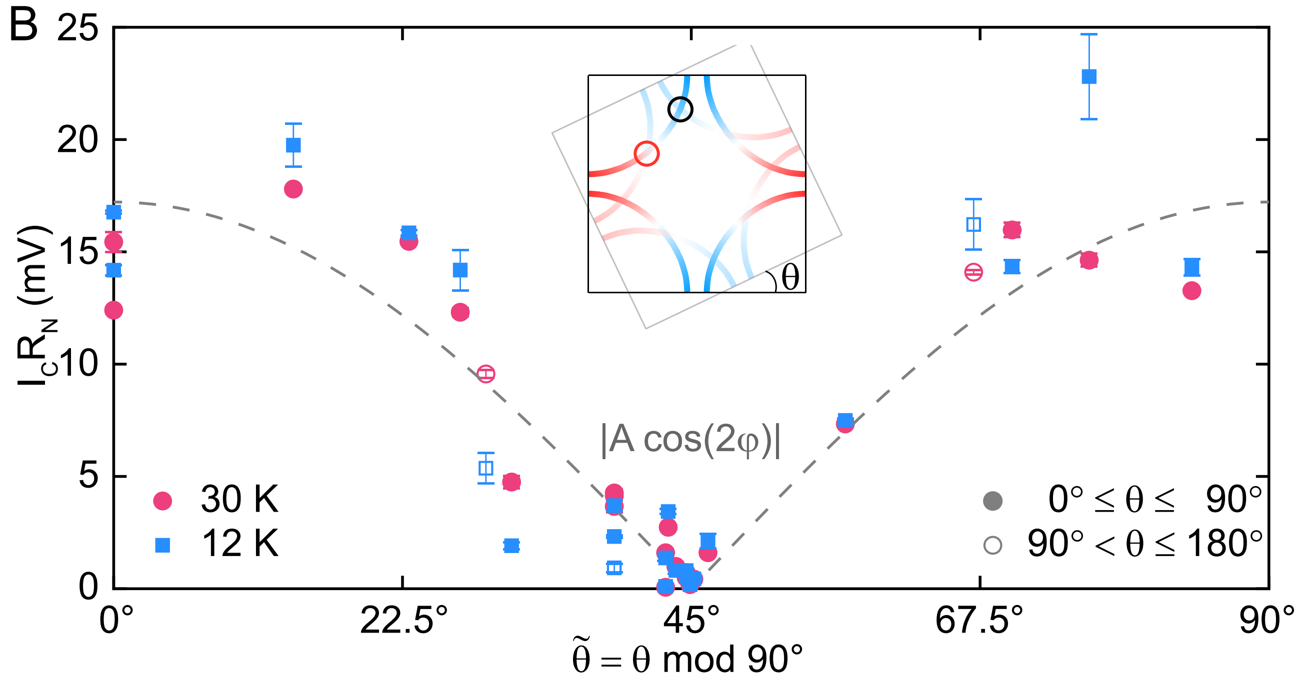
$$
\Delta_{\mathbf{k}1} \Delta_{\mathbf{k}2} = \Delta_0^2 \cos(2\alpha + \theta) \cos(2\alpha - \theta)
$$



$\Delta_{\mathbf{k}1} \Delta_{\mathbf{k}2} < 0$

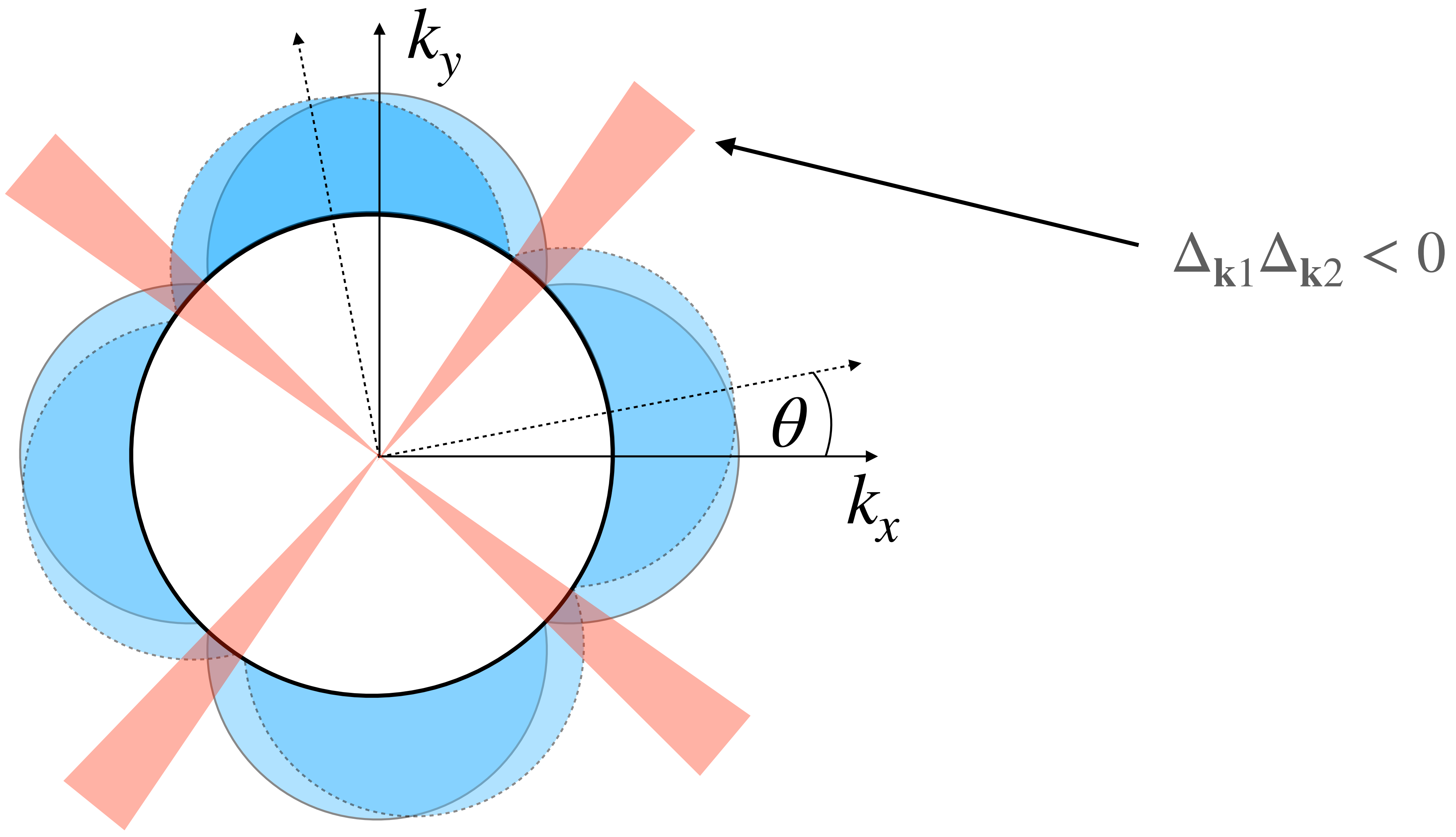


Nodal regions give NEGATIVE contribution to $I_c(T = 0)$



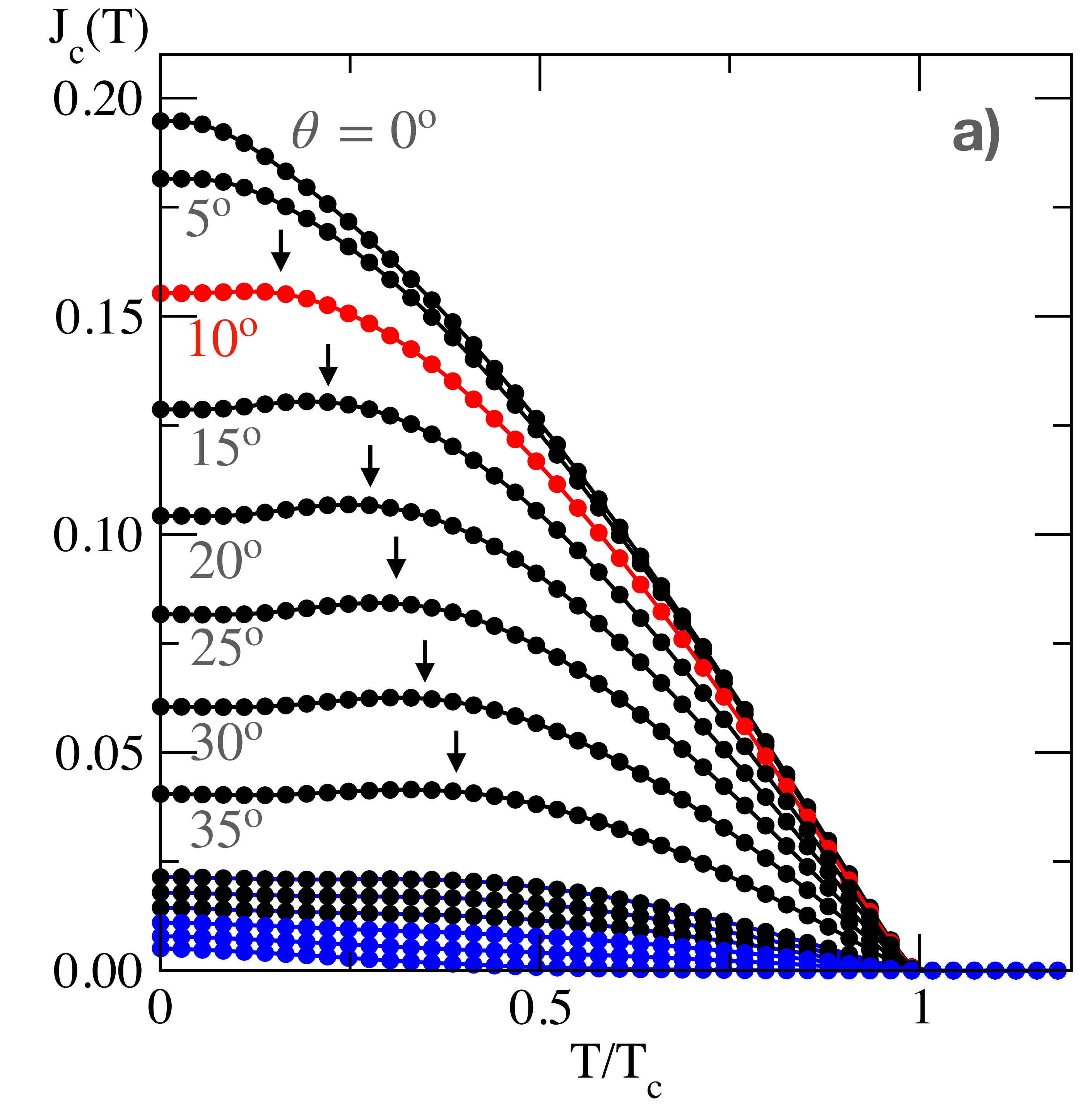
Effect of temperature

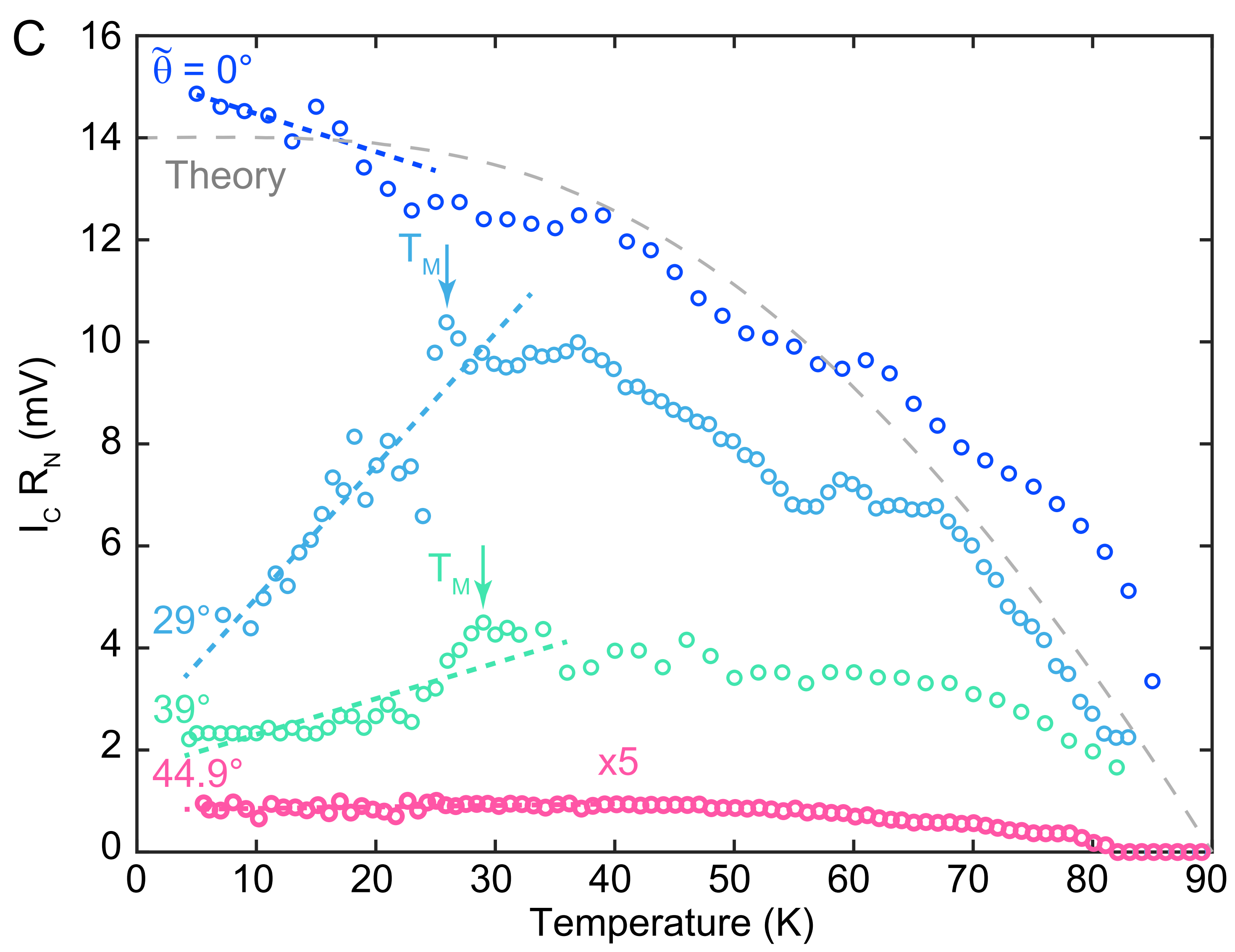
- Thermal excitations break Cooper pairs and remove their contribution to the supercurrent.
- At low *T* this happens primarily in the nodal regions
- Low-*T* thermal excitations therefore initially remove NEGATIVE contributions to I_c which is thus expected to INCREASE as a function of temperature



$$I_c(T) \simeq \frac{et^2}{2\hbar} \sum_{\boldsymbol{k}} \frac{\Delta_{\boldsymbol{k}1}\Delta_{\boldsymbol{k}2}}{D_{\boldsymbol{k}}(\pi/2)} \sum_{a=\pm} \left[\frac{-a}{E_{\boldsymbol{k}a}} \tanh \frac{1}{2}\beta E_{\boldsymbol{k}a} \right]_{\varphi\to\pi/2}$$

Calculation results:

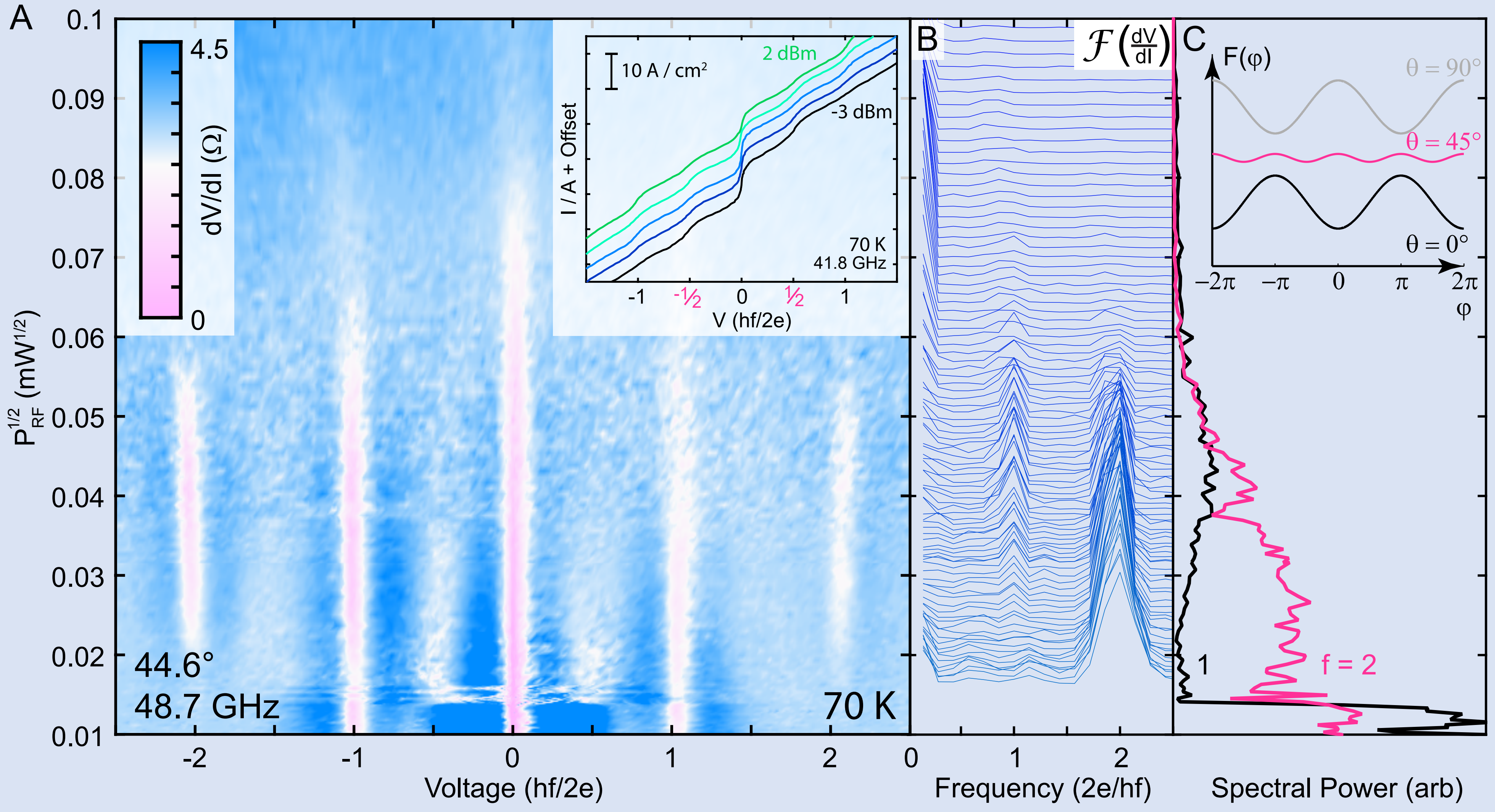




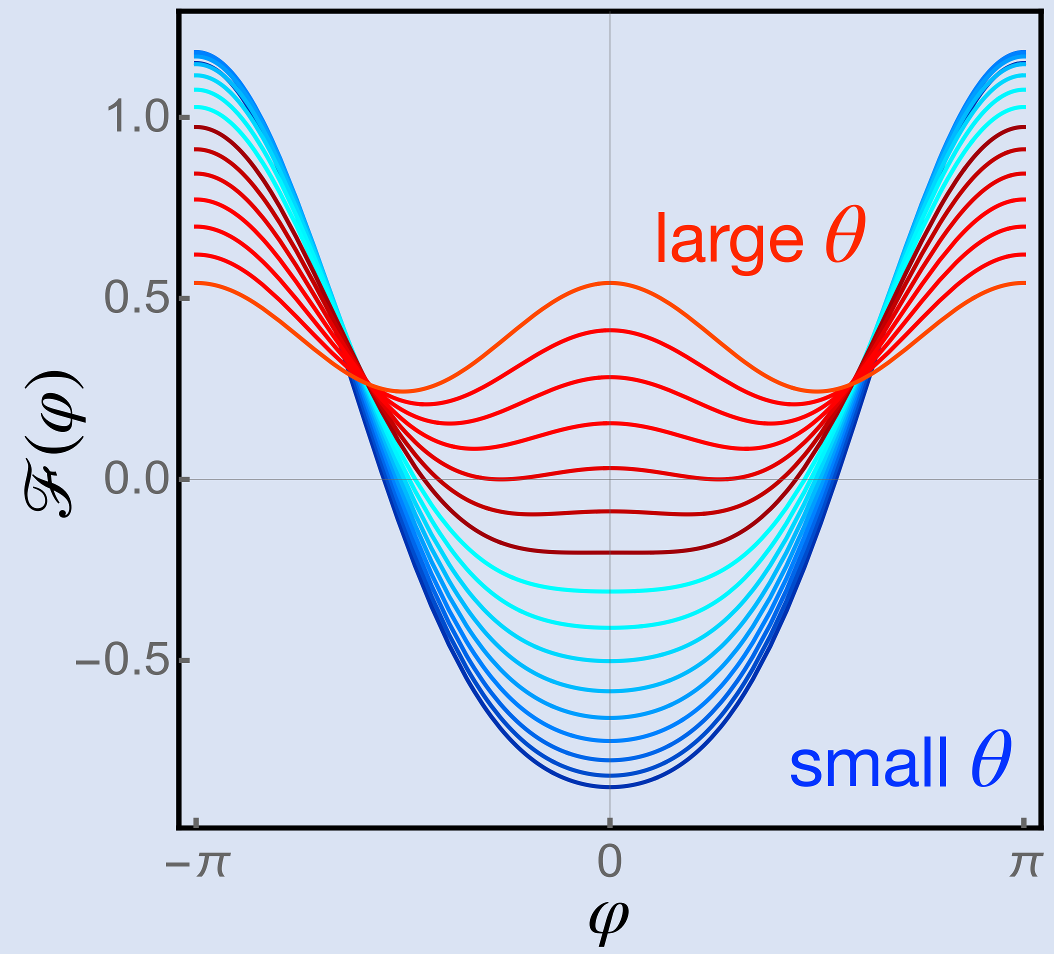
Experimental efforts: Evidence for T-broken phase

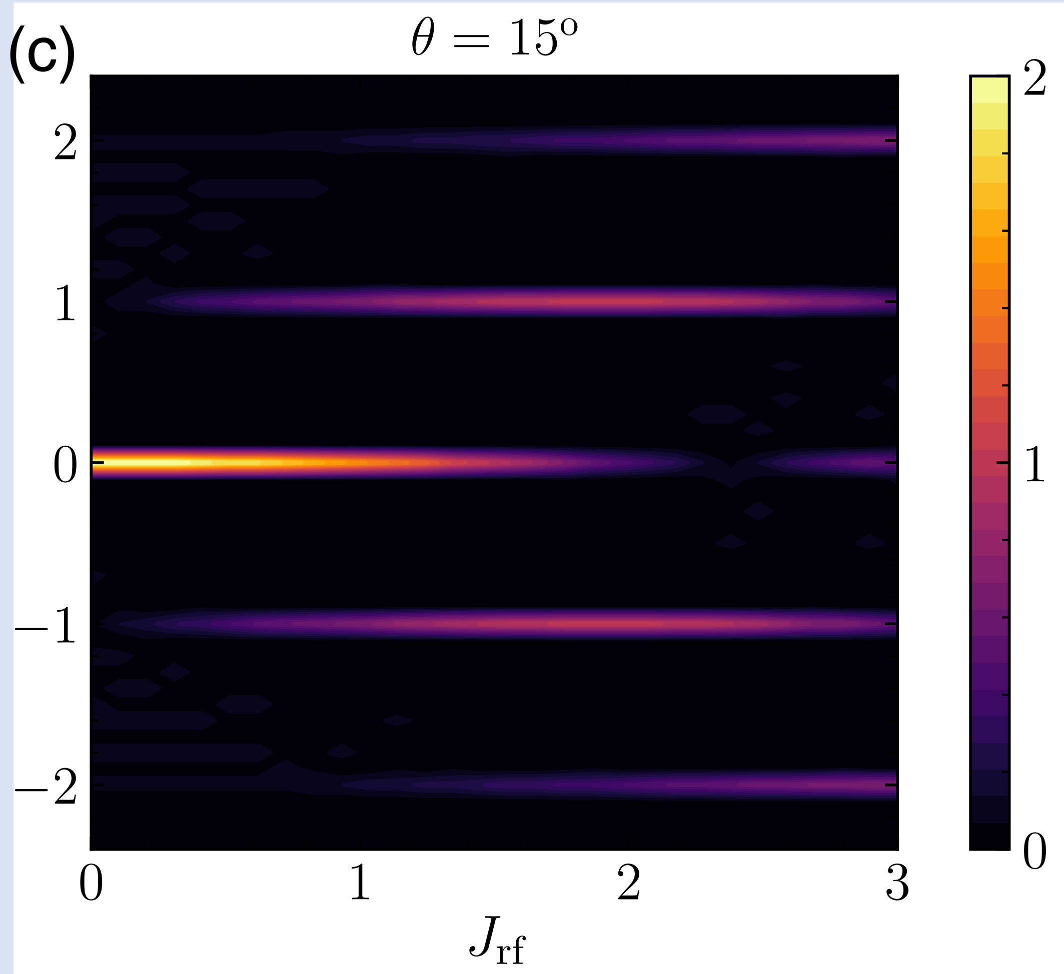
Artificial BSCCO Twist Junctions — *Philip Kim Group (Harvard)*

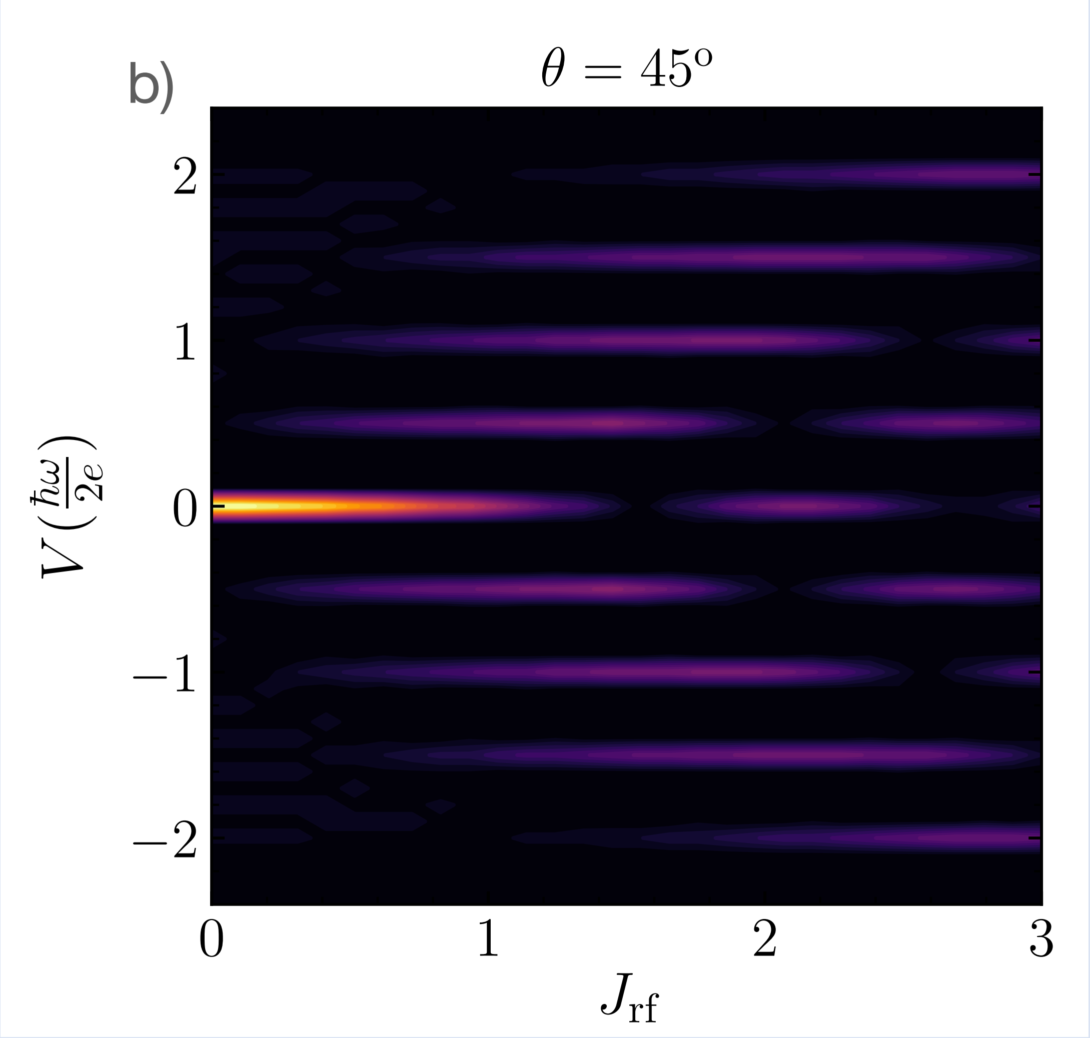
Experiment [Zhao et al., arXiv:2108.13455] observes "fractional Shapiro steps" near 45 degree twist



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



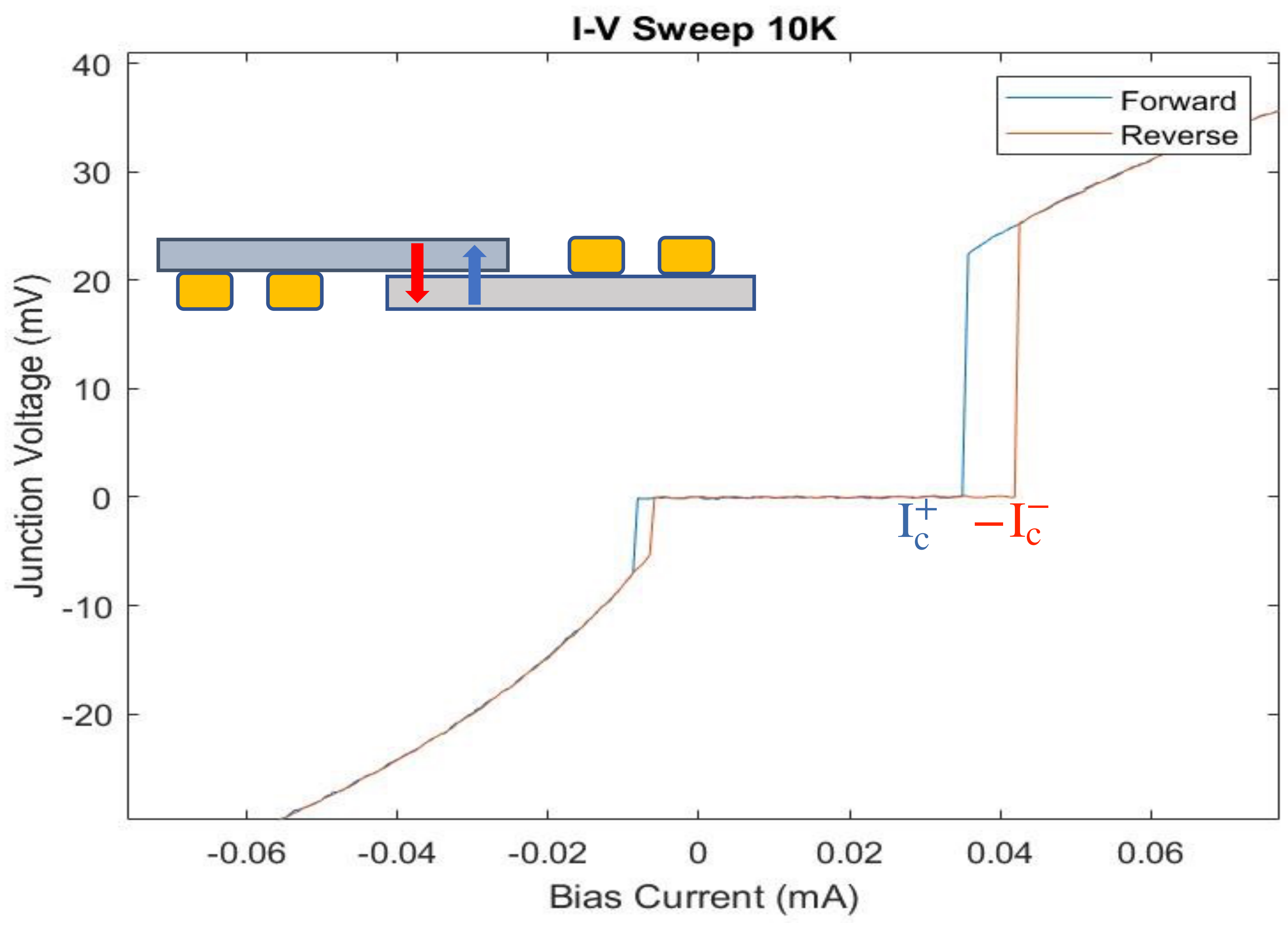




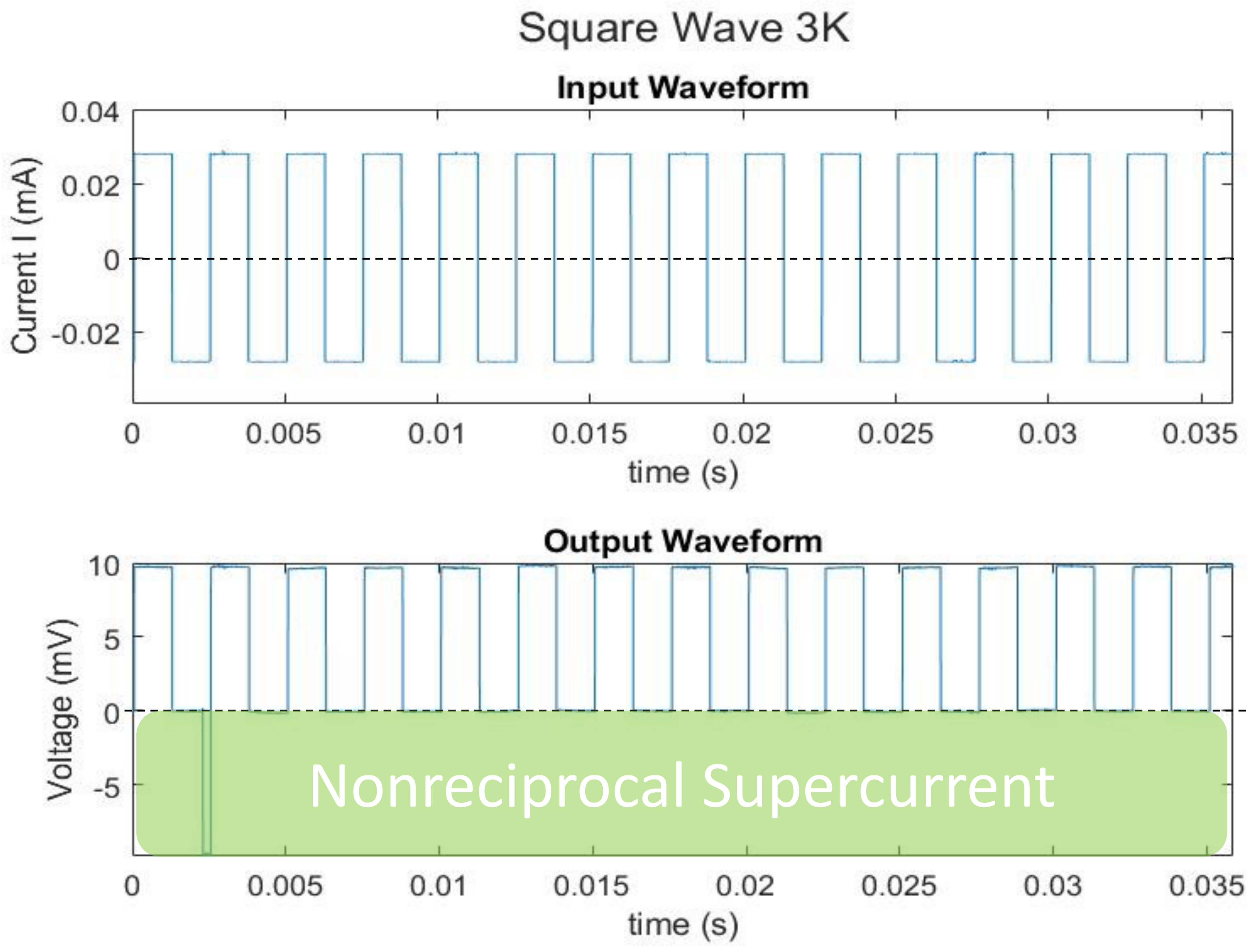
NEW: Field-Free **Josephson Diode Effect** in twisted BSCCO

(from Alex Cui, Kim Group @ Harvard)

For samples with twist **close to 45º** they observe $|I_c^+| \neq |I_c^-|$

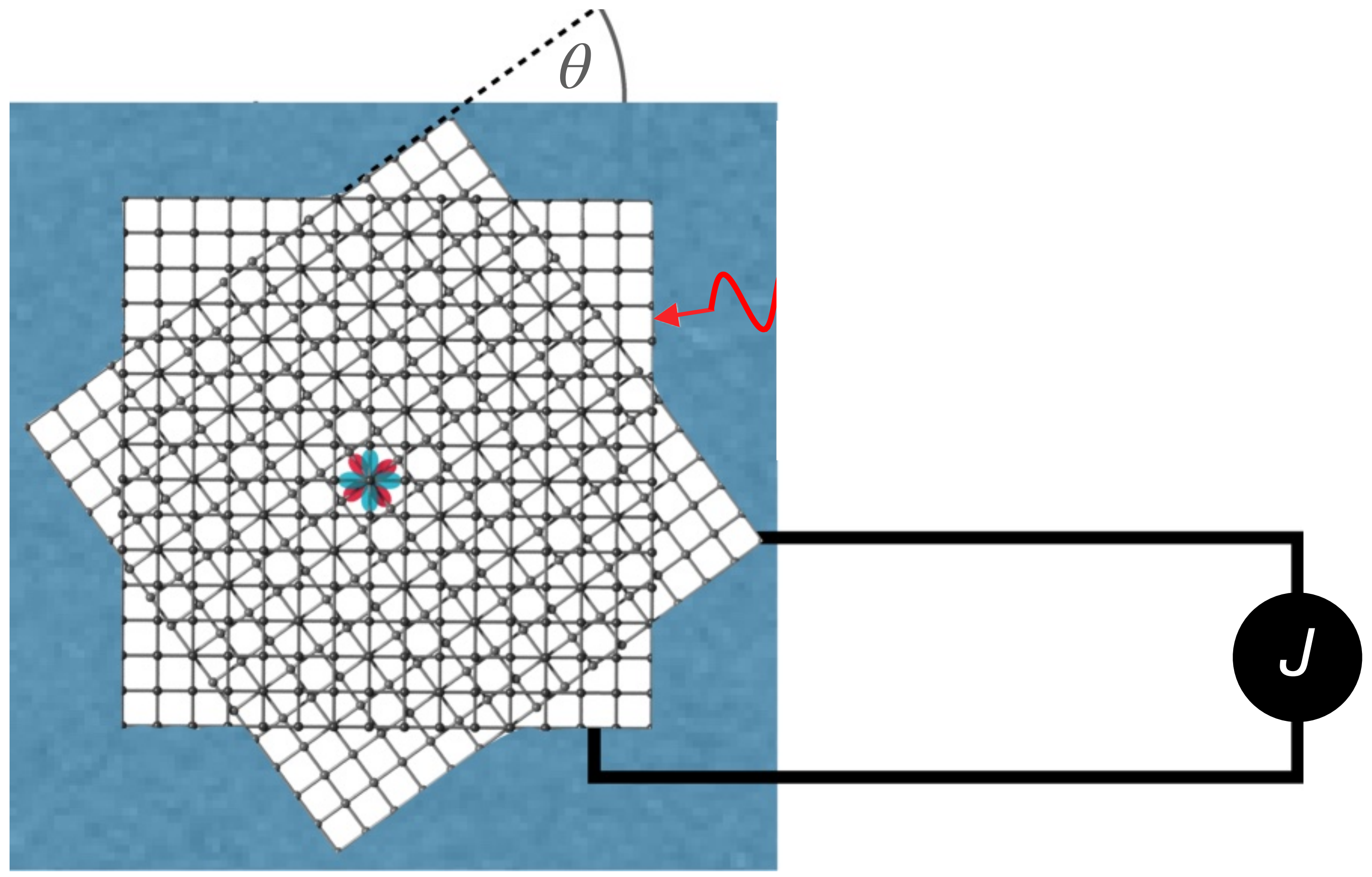


Josephson Diode: $I_c^+ < |I_{bias}| < I_c^-$



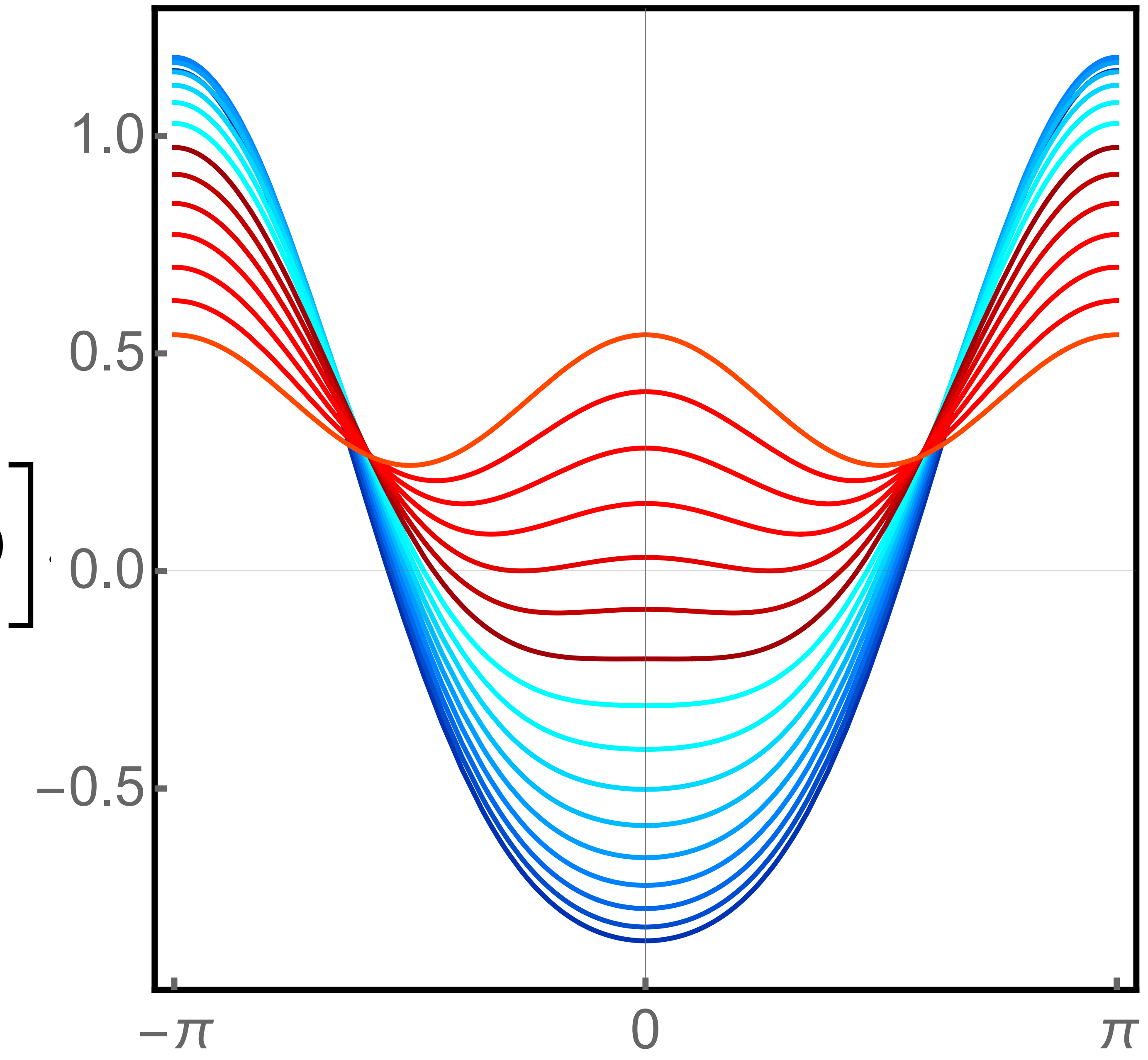
Because the current is odd under time reversal the non-reciprocal diode effect requires *broken time reversal symmetry*

Theory: Diode effect in twisted Bi2212 bilayers



$$\mathcal{F}(\varphi) = \mathcal{E}_0 - \frac{\hbar}{2e}\left[J_{c1}\cos\varphi - \frac{1}{2}J_{c2}\cos(2\varphi)\right]$$

$$J_{c1} \propto \cos(2\theta)$$

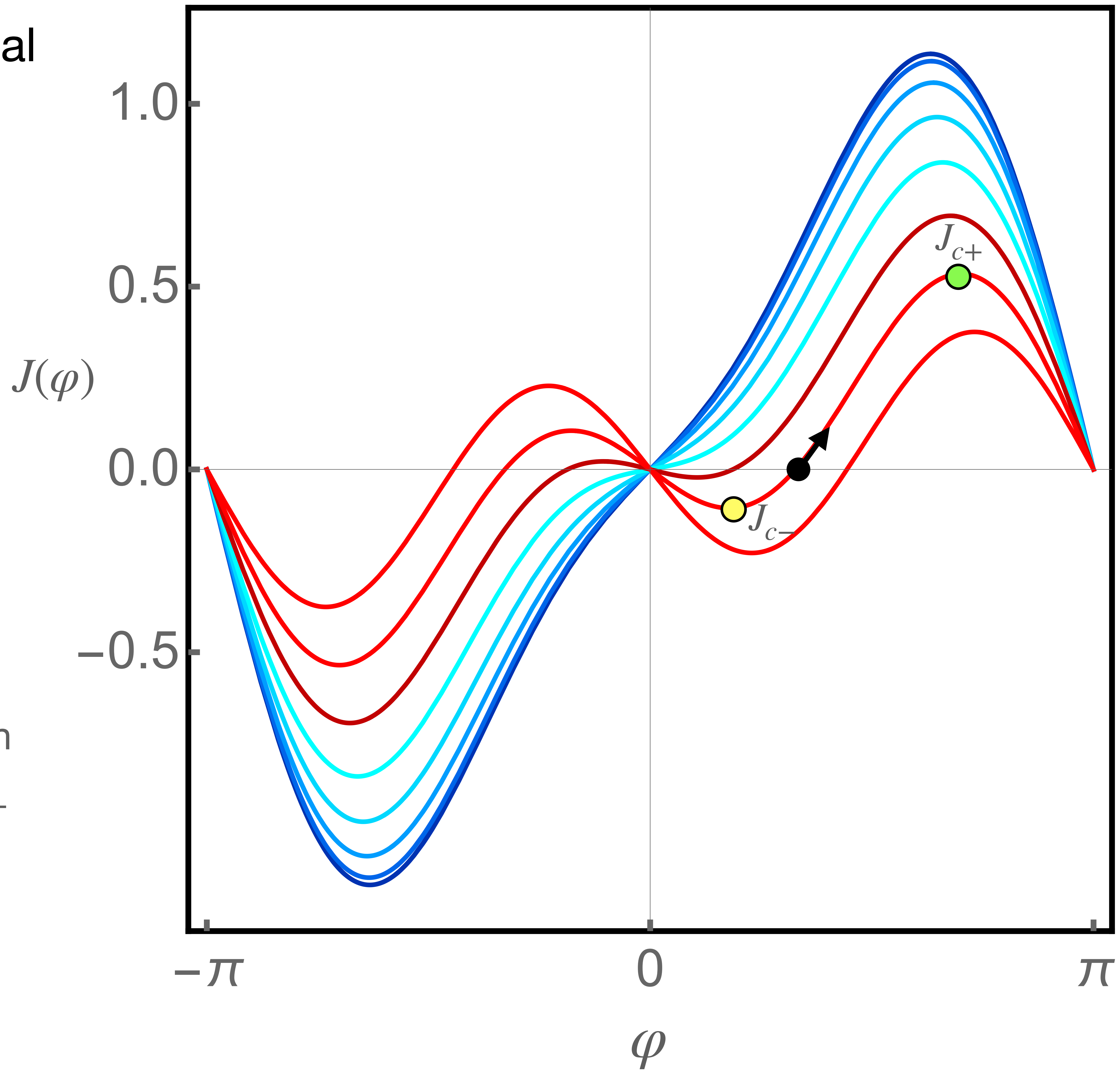


$$\mathcal{F}[\psi_1, \psi_2] = \mathcal{F}_0[\psi_1] + \mathcal{F}_0[\psi_2] + A|\psi_1|^2|\psi_2|^2$$
$$+ B(\psi_1\psi_2^* + \text{c.c.}) + C\left(\psi_1^2\psi_2^{*2} + \text{c.c.}\right)$$

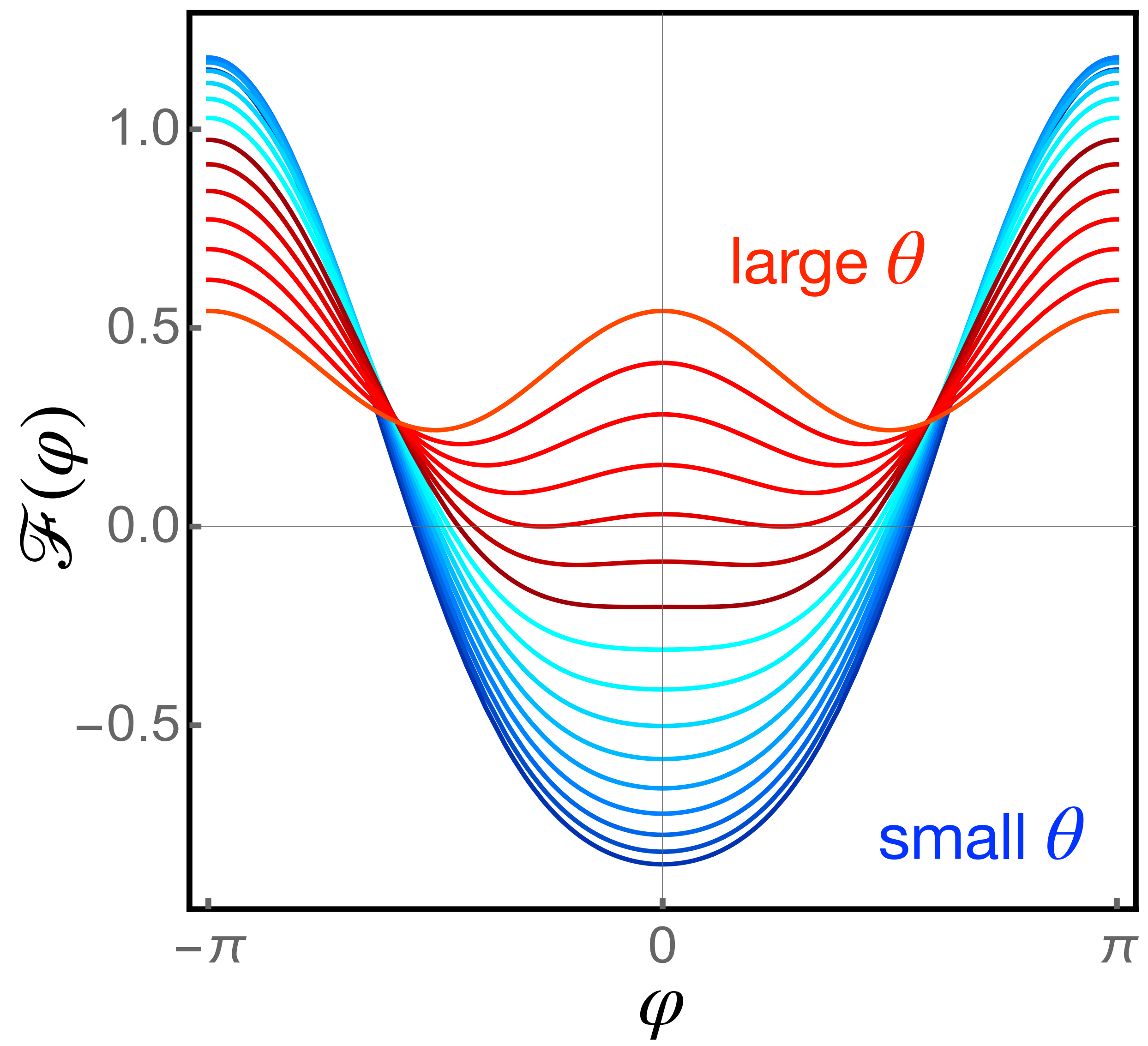
d-wave symmetry dictates $B = -B_0\cos(2\theta)$

Theory: Diode effect in twisted Bi2212 bilayers

The origin of non-reciprocal critical current



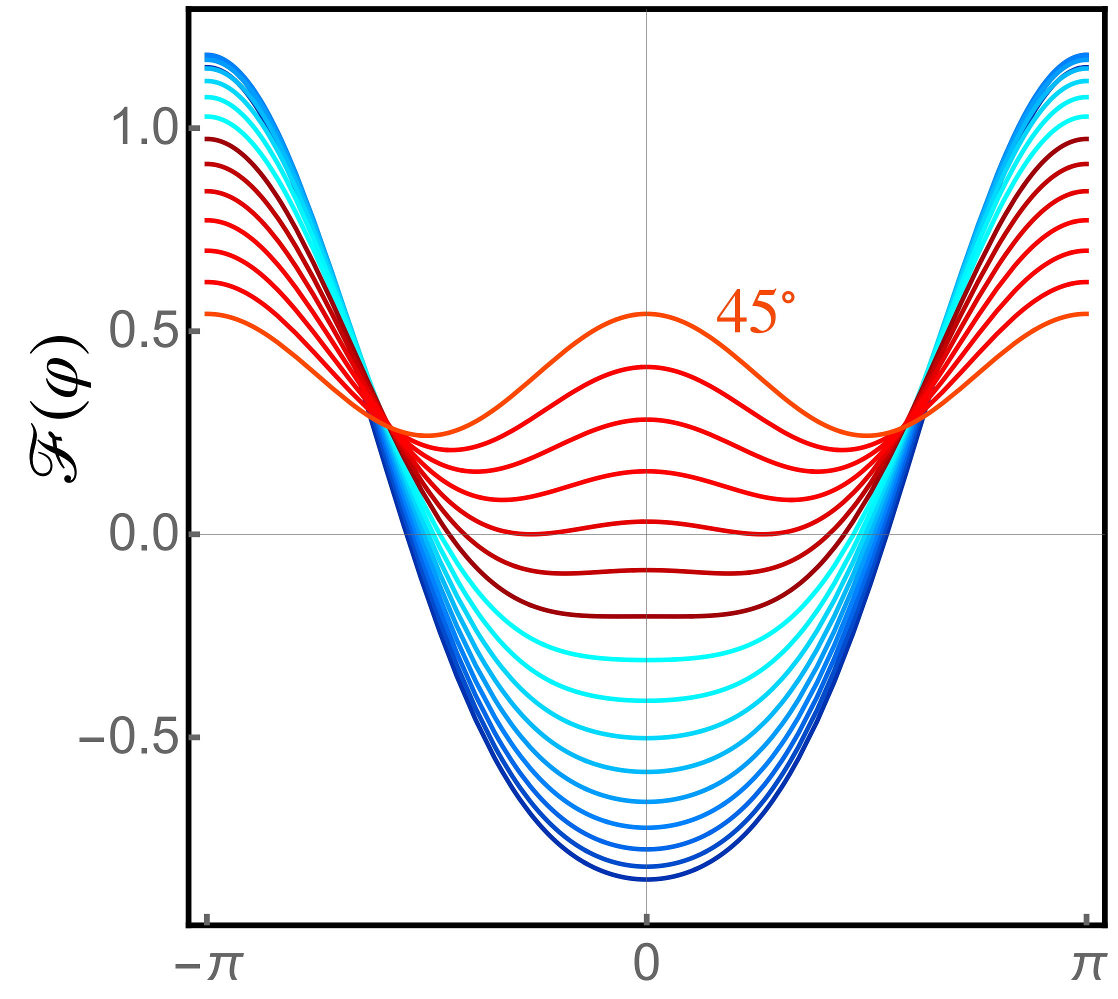
Whenever time reversal is broken AND $\theta \neq 45^{\circ}$ we have $J_{c+} \neq J_{c-}$ which implies non-reciprocal behaviour.

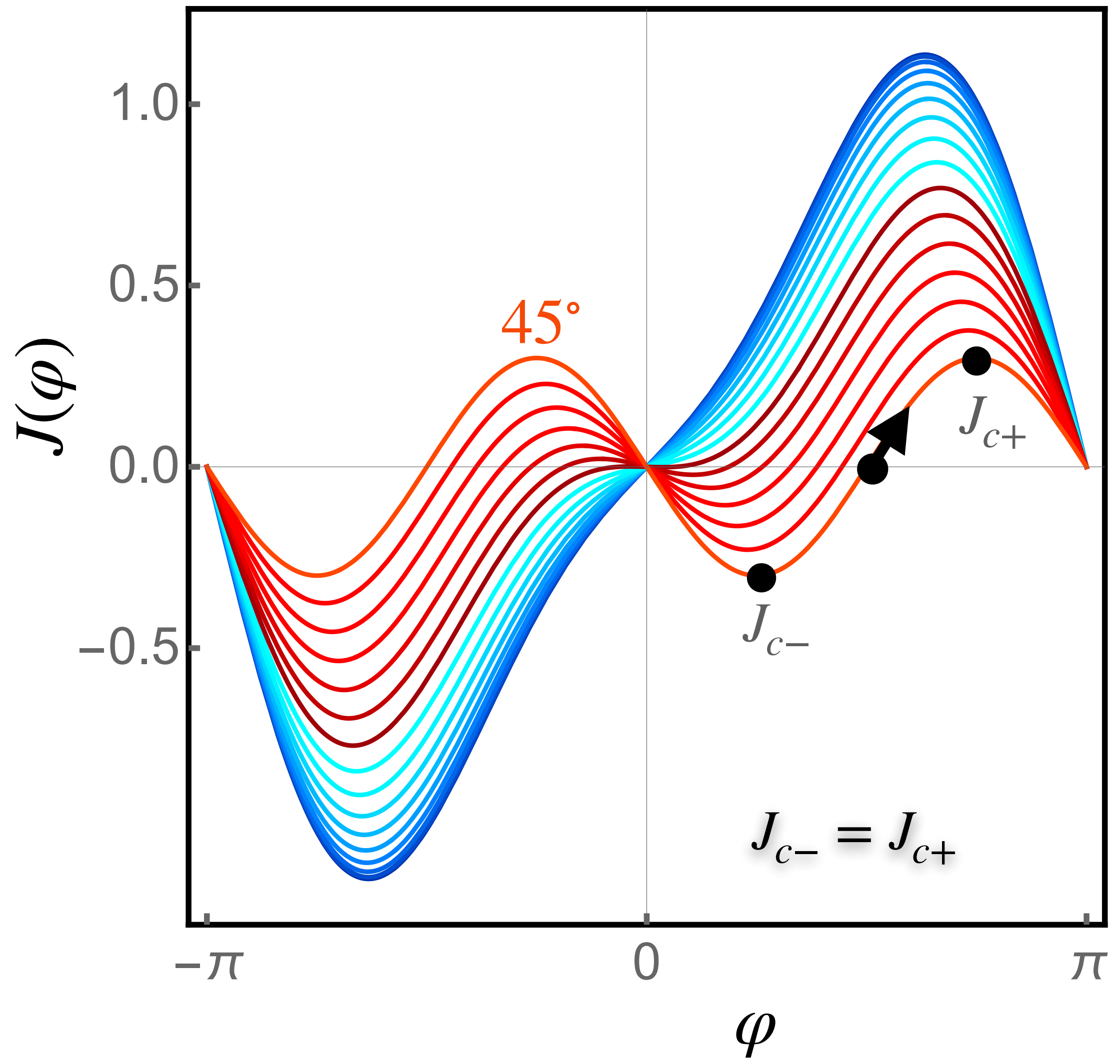


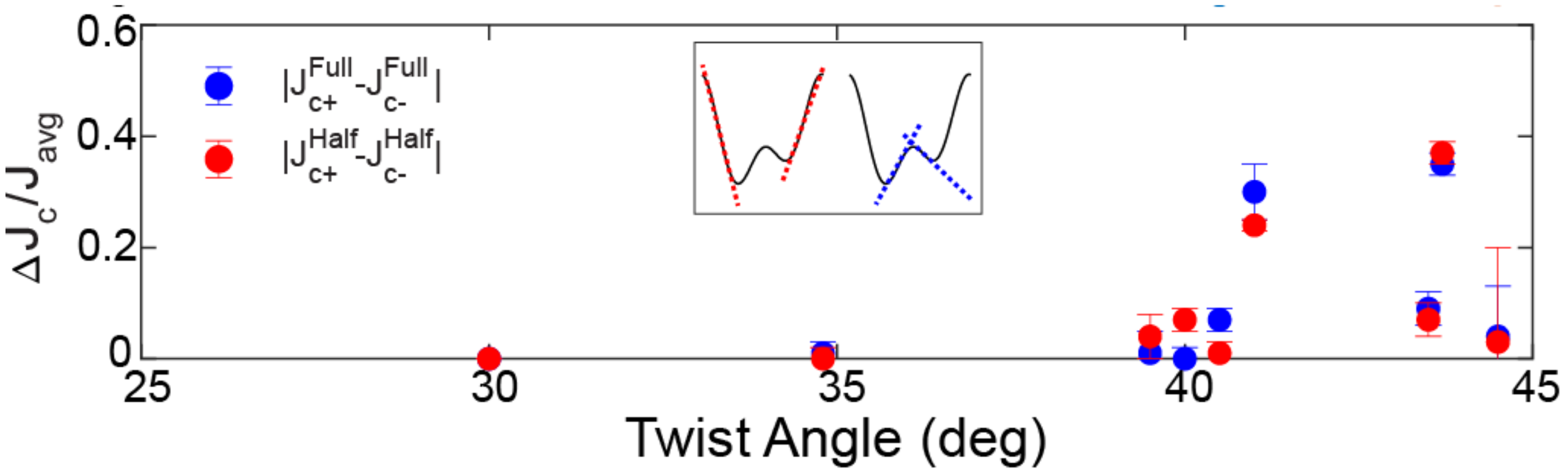
However, if the NORMAL state is $\mathcal{T}$-respecting one would expect to start randomly from either free-energy minimum.

—> One needs a measurement protocol that reproducibly initiates the system in the same minimum.

A new theory prediction: The diode effect must vanish at exact 45° twist



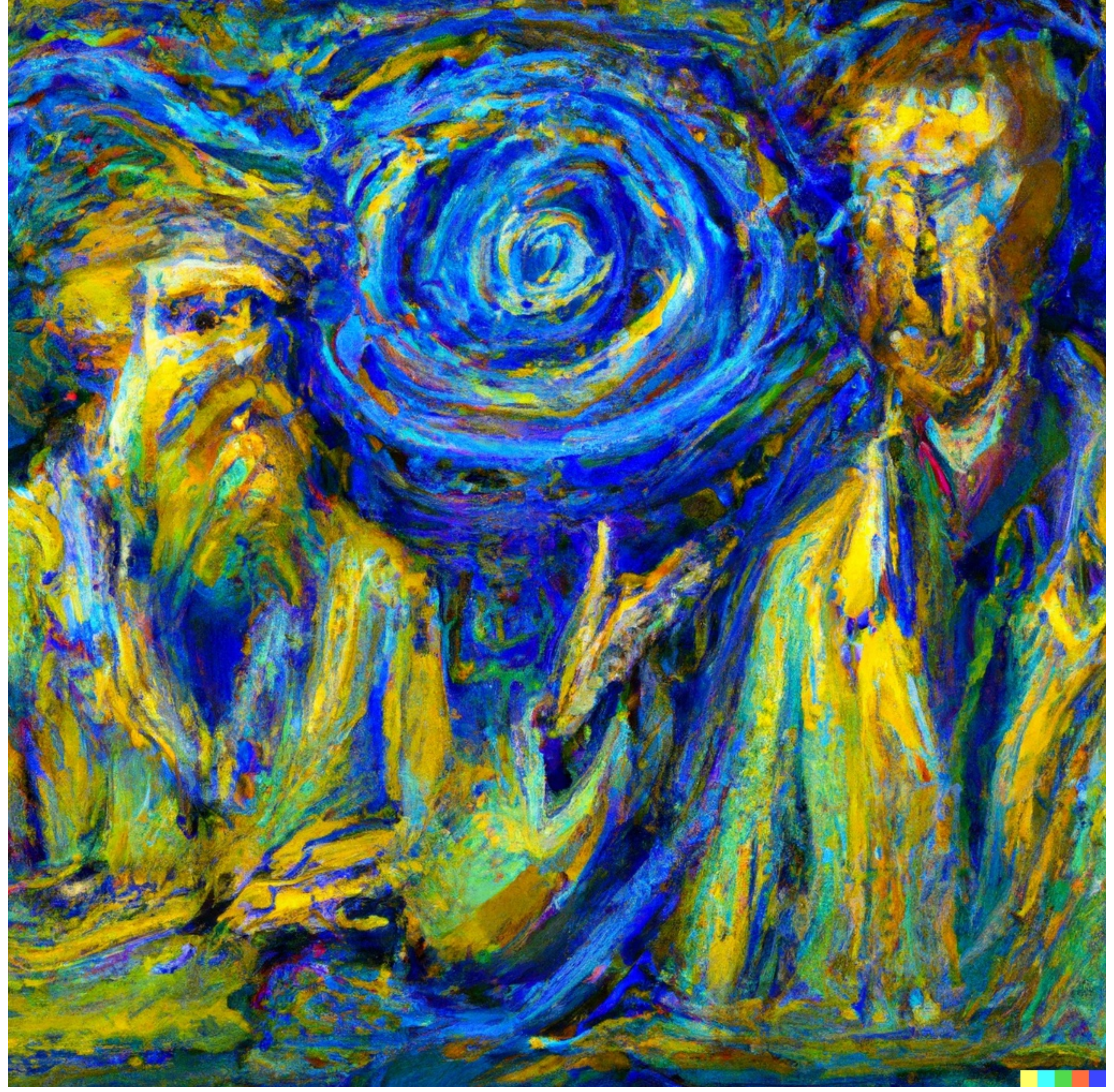




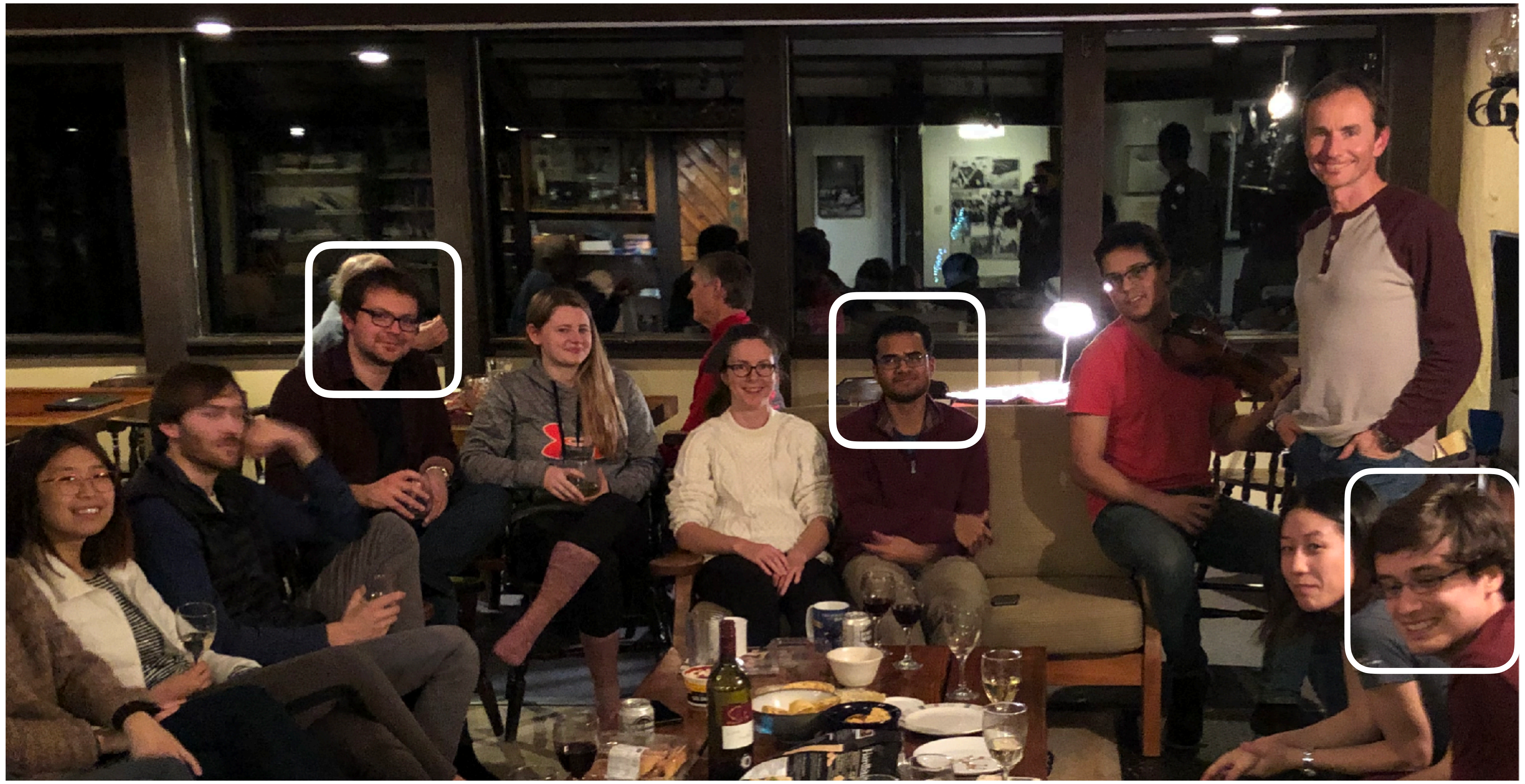
- Zero Field Diode Effect only appears near 45°
- Possible broken ground state degeneracy

Data courtesy of Alex Cui, Philip Kim group, Harvard

Thank you!



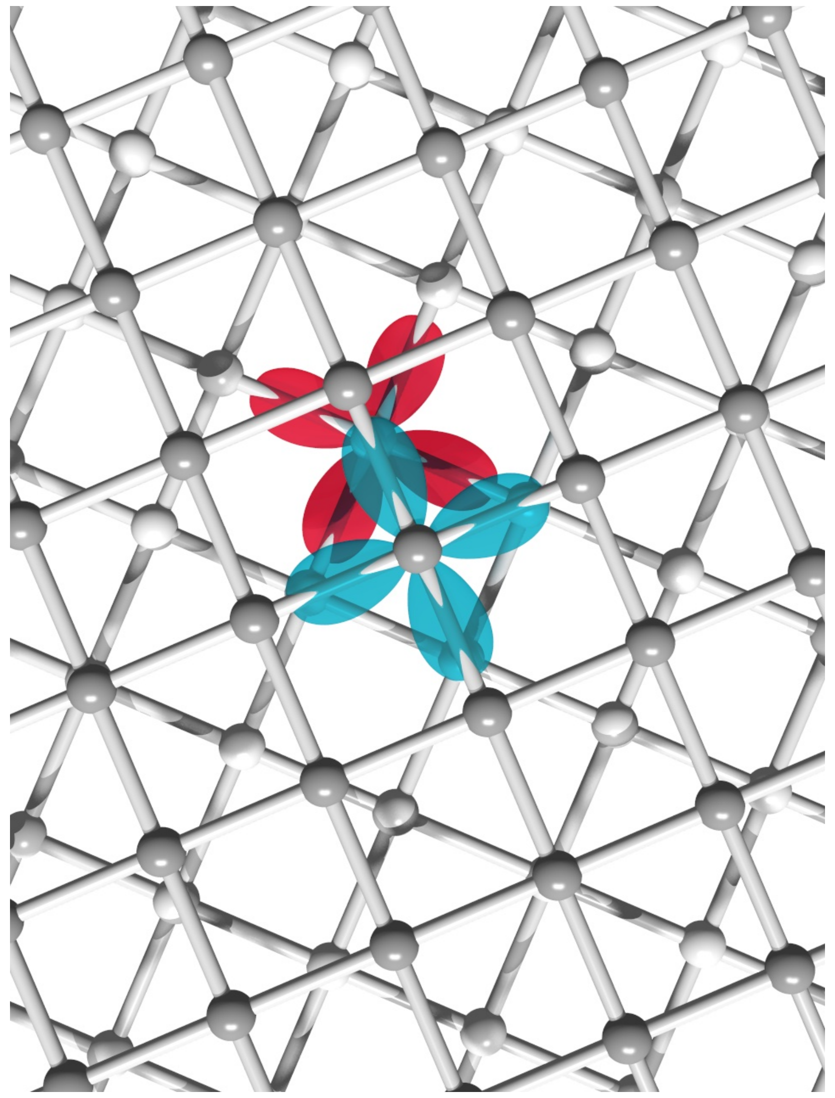
DALL-E: "Two scientists pondering twisted high-Tc cuprate superconductor"

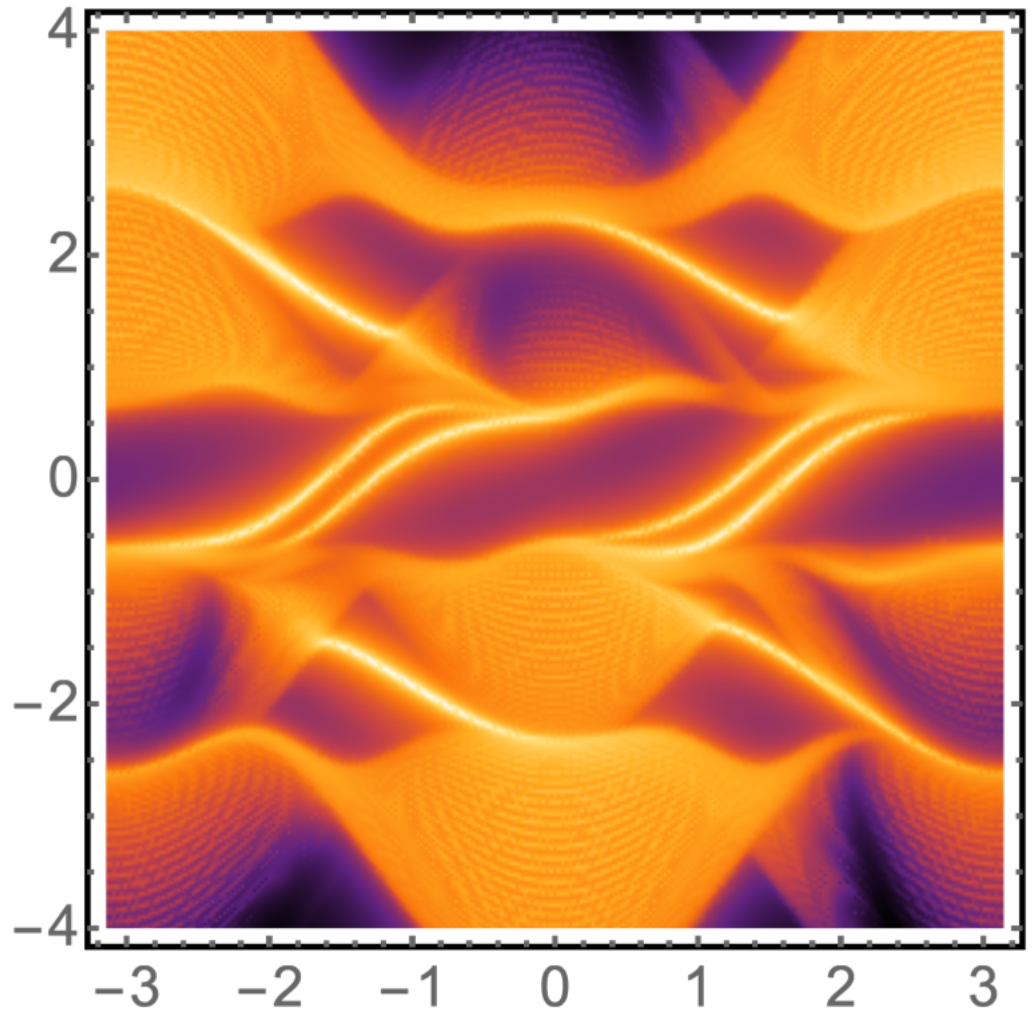


Group members:
O. Can
T. Tummuru
E. Lantagne-Hurtubise

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)

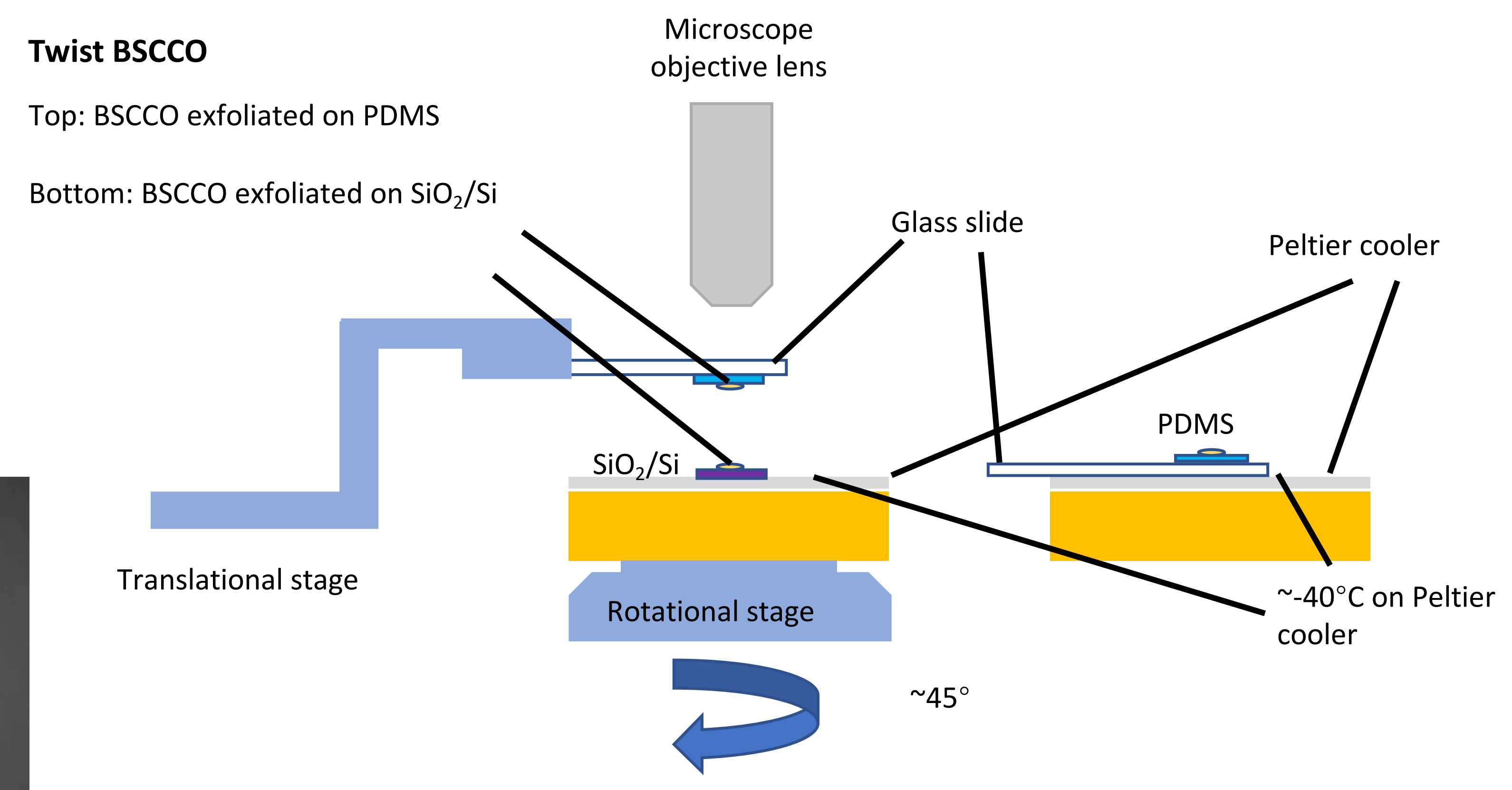


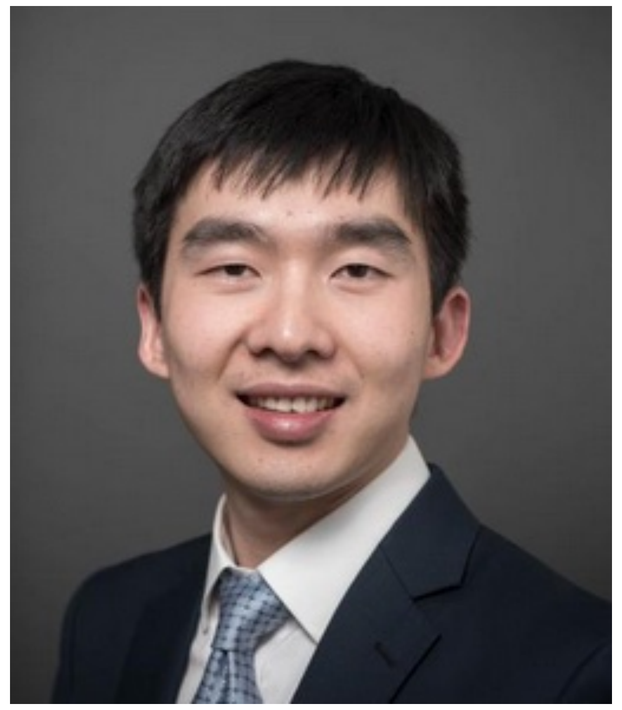


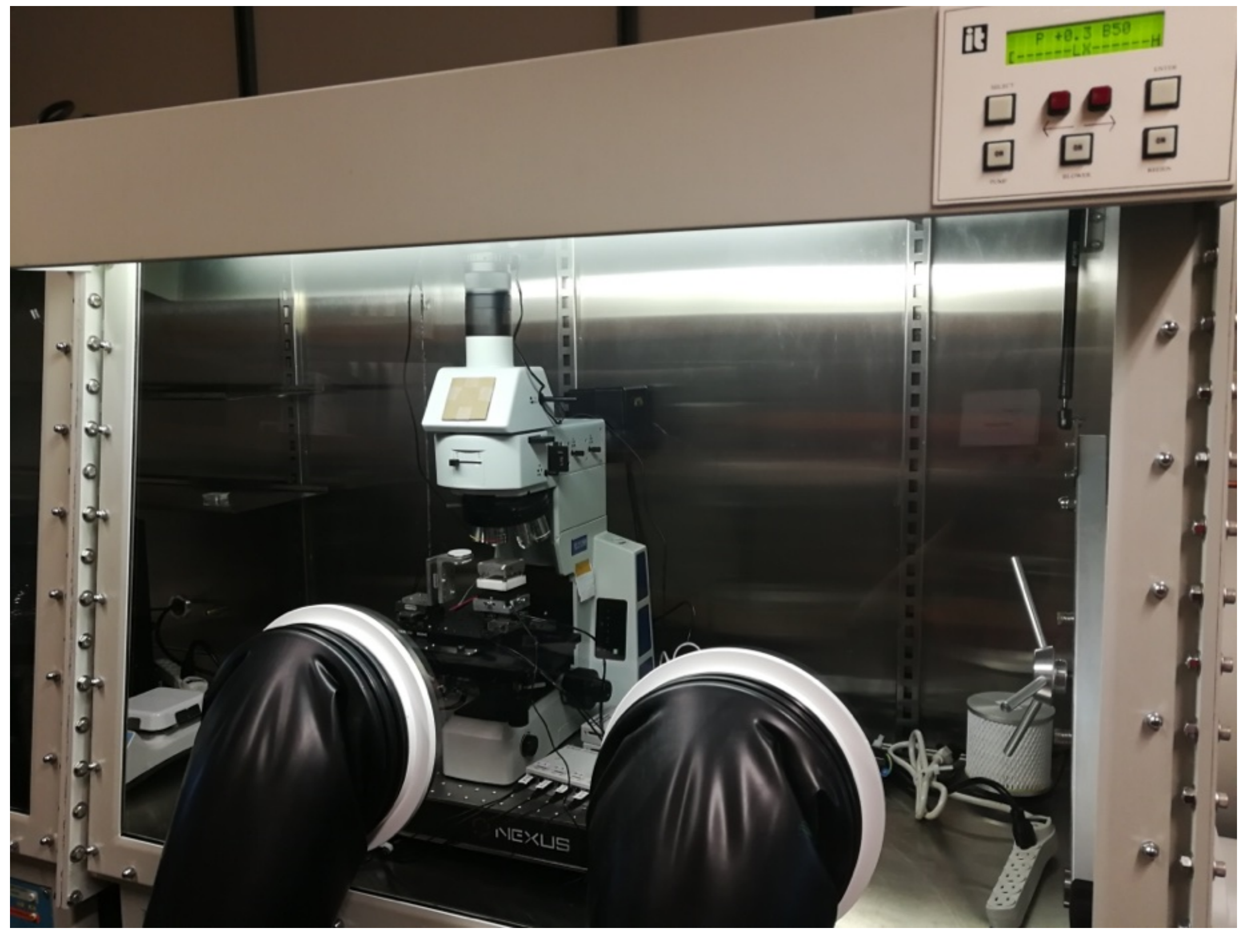
Some interesting open questions:

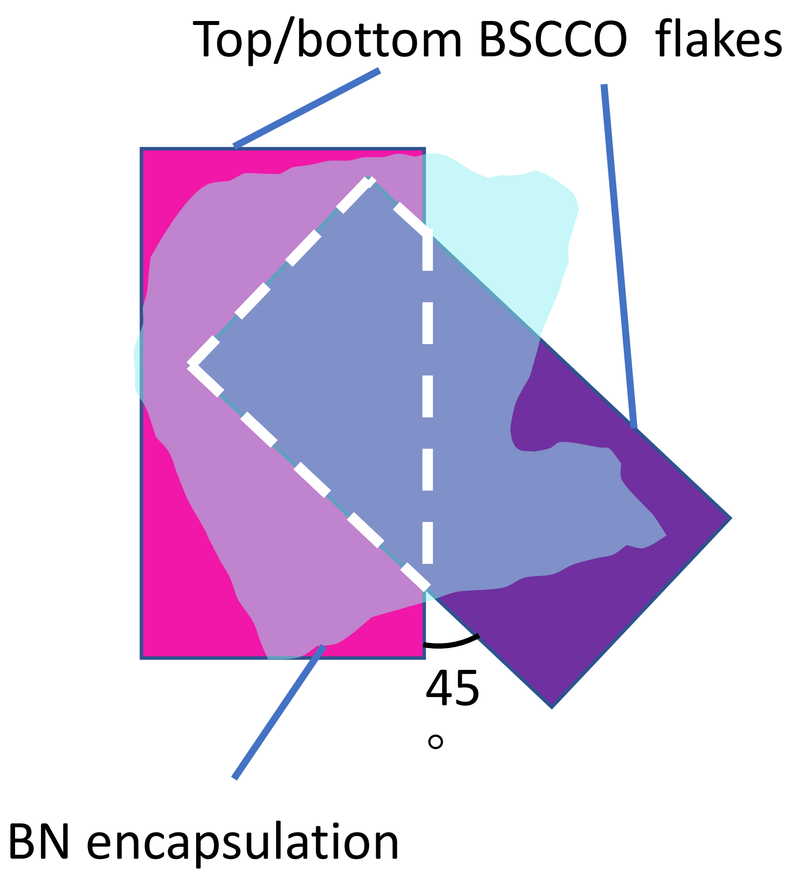
1. What is the best way to observe the topological phase experimentally?
2. Are there any interesting uses for this novel topological superconducting phase once identified?
3. Are there other 2D systems (beyond graphene, chalcogenides, cuprates) that will produce interesting new behaviors under twist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

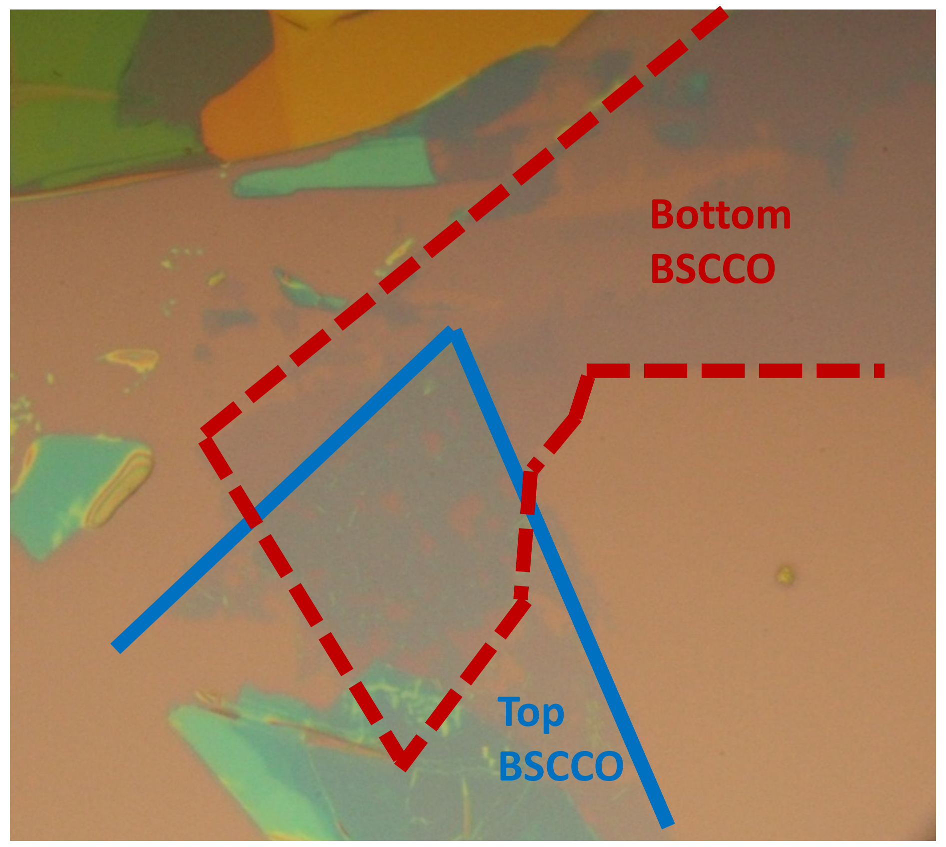
Optical probes: Preliminary results
(Ziliang Ye group, SBQMI)

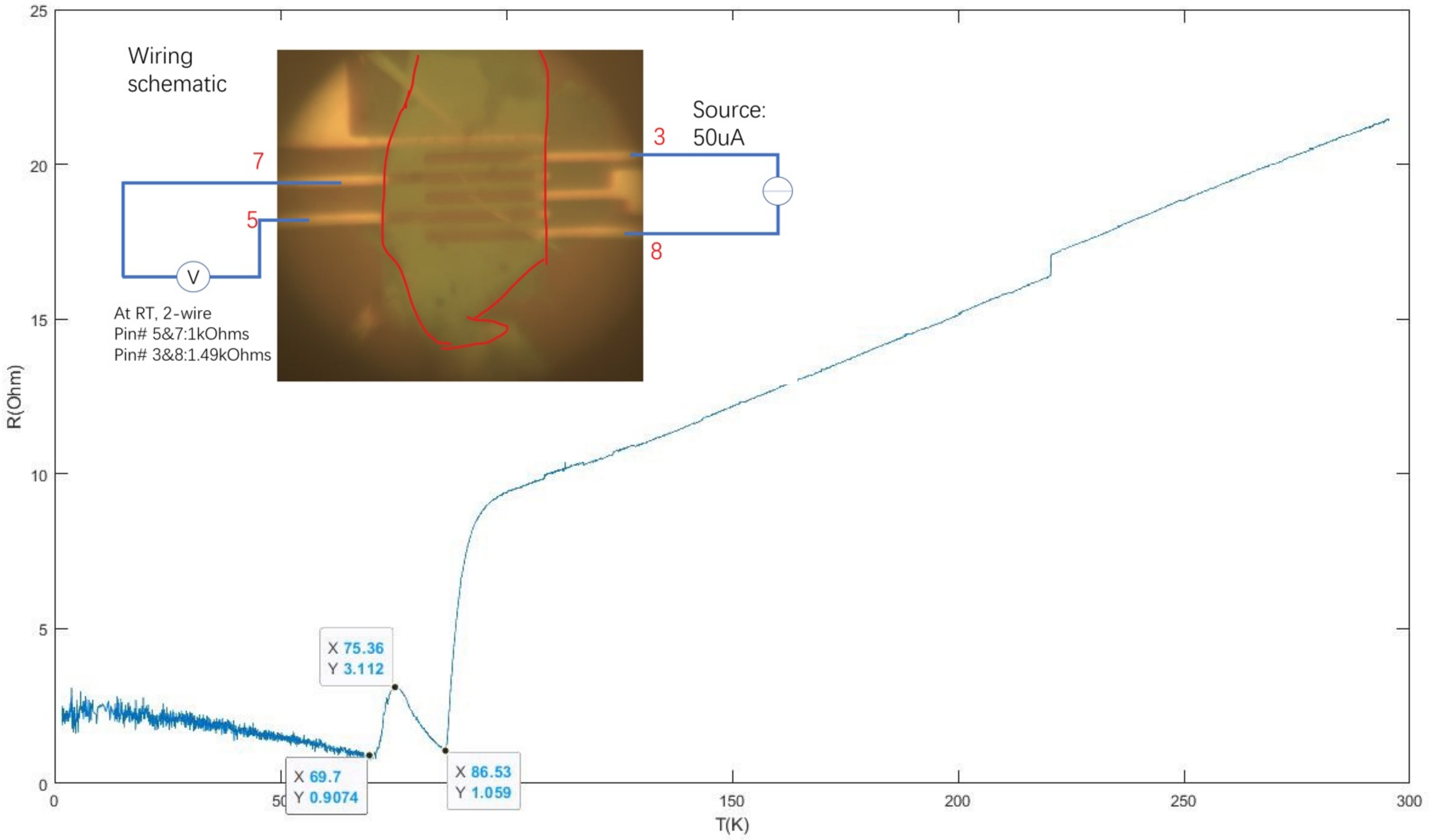






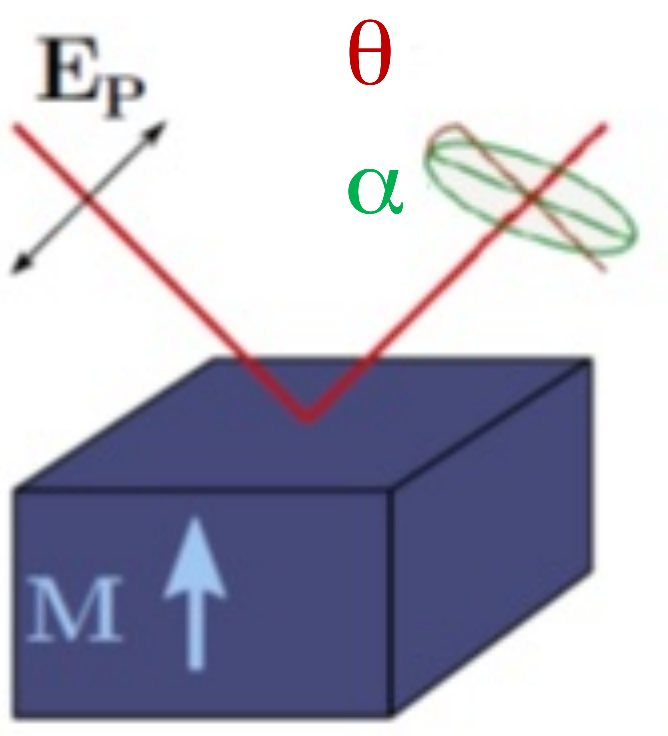






Anomalous Hall and polar Kerr effect

(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

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

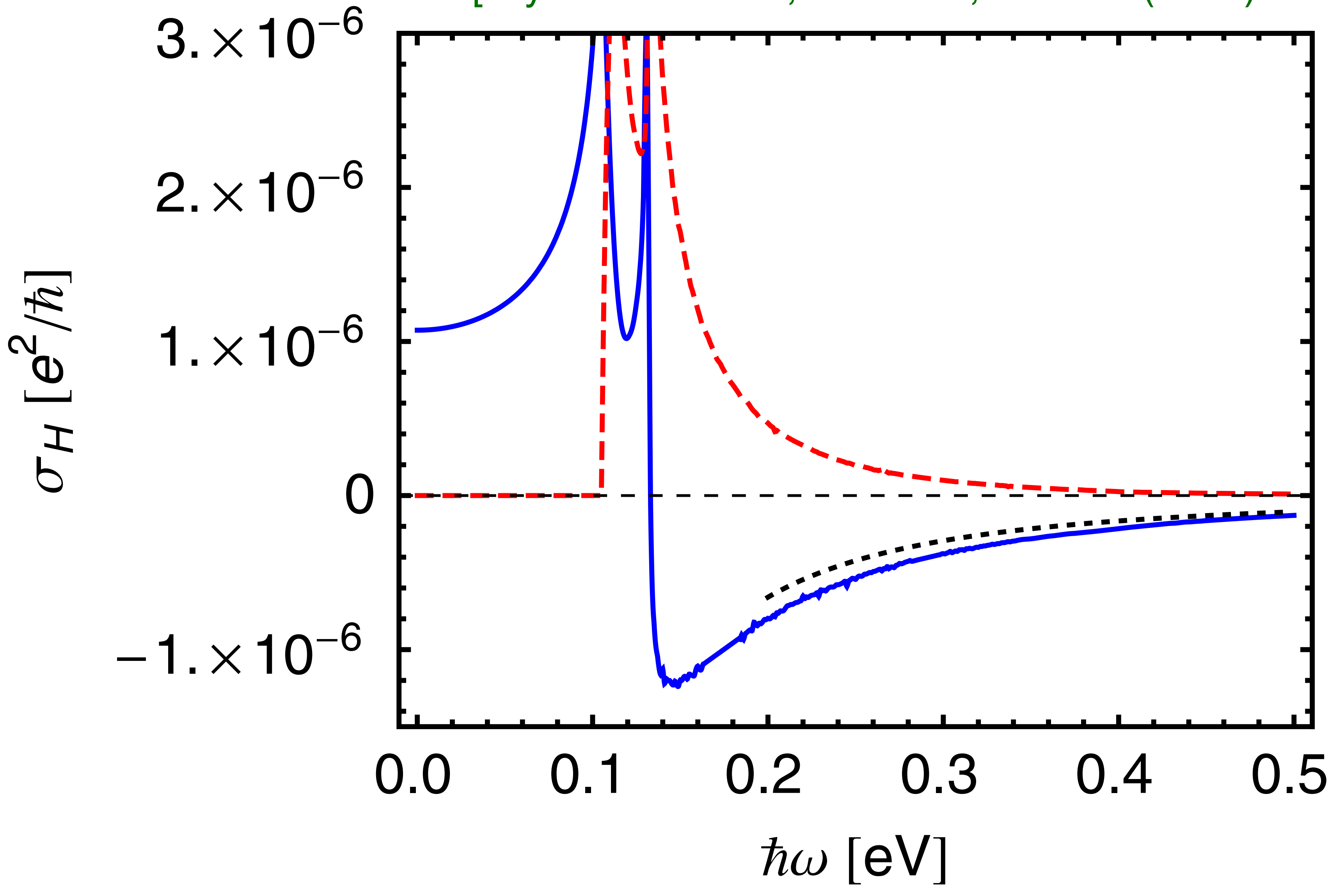
This can be calculated from the standard Kubo formula

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

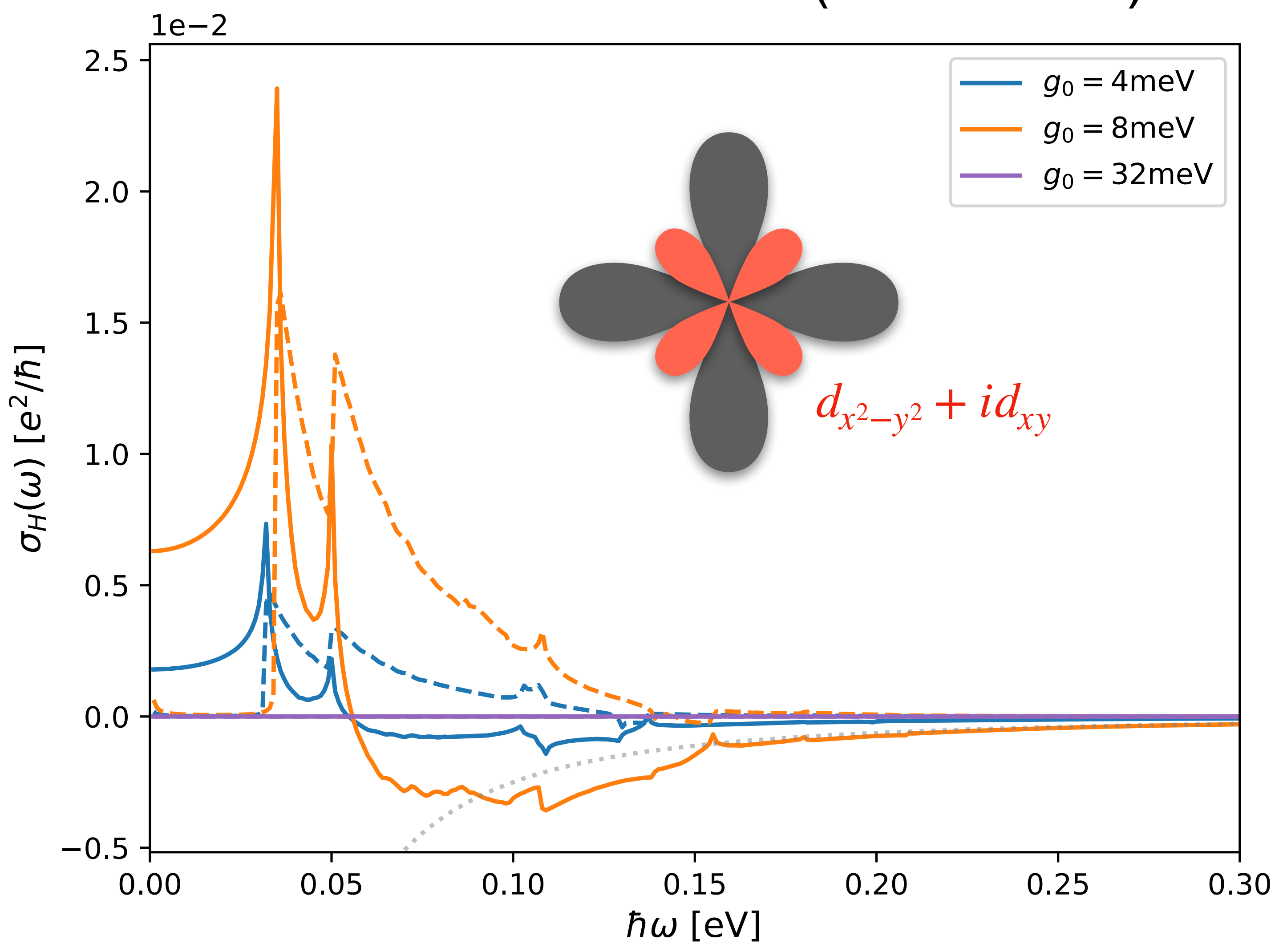
- The Hall conductivity is nonzero and large in the *d*+*id’* state of twisted Bi-2212
- The signal is about 3 orders of magnitude stronger than that predicted for Sr_2Ru0_4; this is chiefly due to much larger SC gap in the cuprate.

Prediction for Sr_2Ru0_4

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

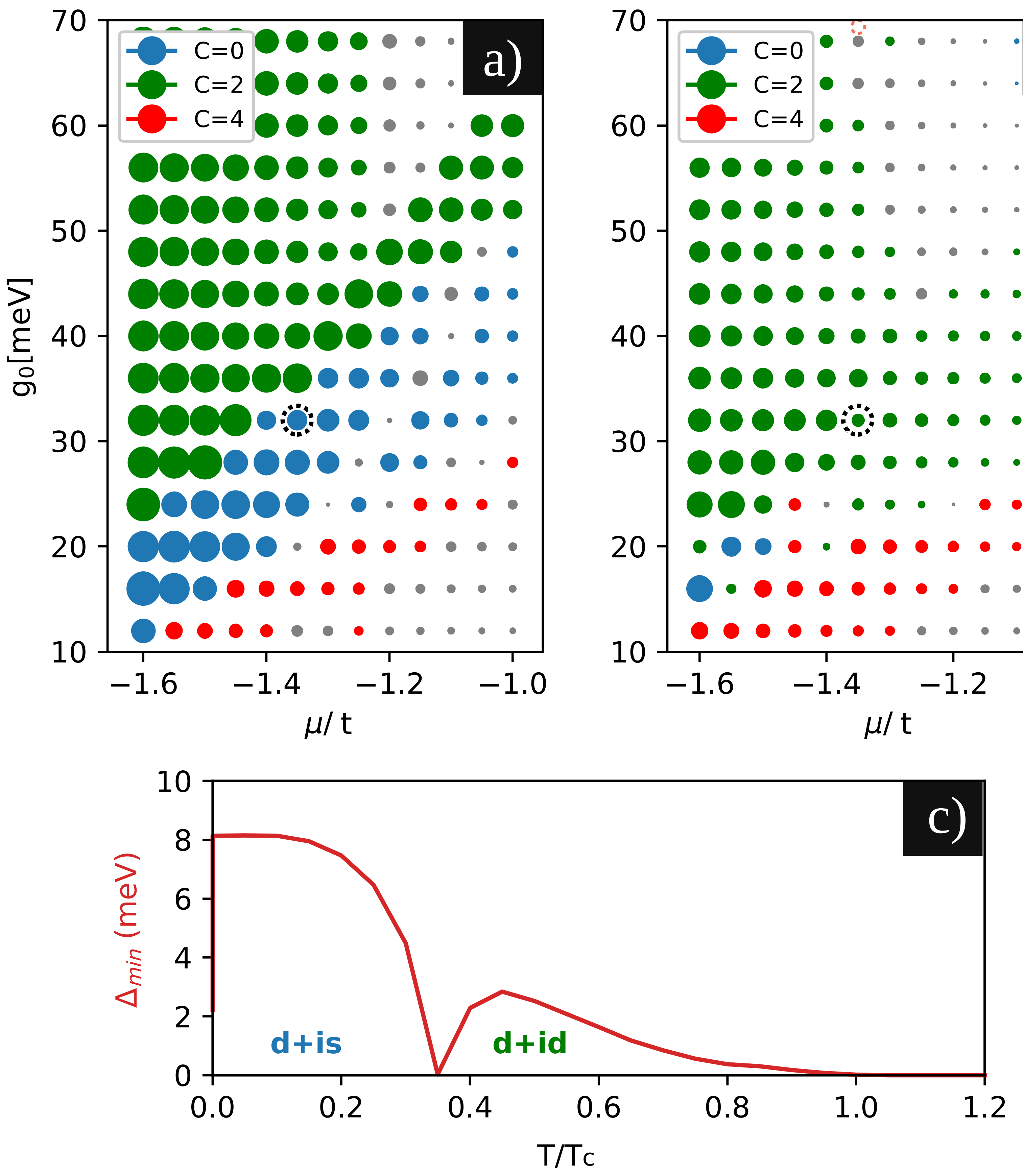


Twisted Bi-2212 $(\theta \simeq 36.8^0)$



PRL 127, 157001 (2021)

Finite *T* behavior



Real Bi2212 structure