Chiral Topological Superconductivity, Charge-4e Superconductivity, and Chiral Metal in the Twisted-Bilayer Quasicrystals

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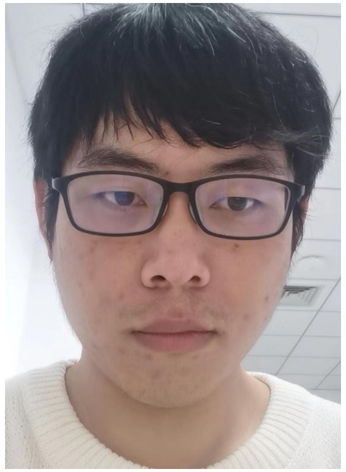

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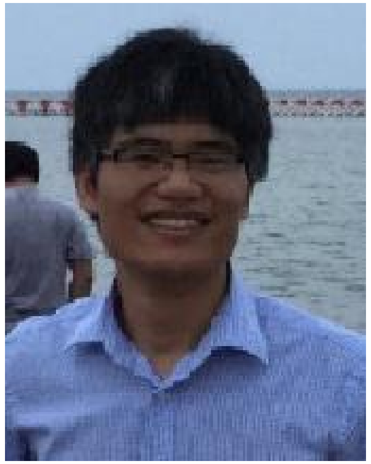

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Outline

- Introduction
- Twisted-bilayer quasi-crystals carrying chiral TSC
- Low-energy effective model for phase fluctuations
- The charge-4e SC & chiral metal
- Discussions & Conclusion

Ref: Y.B.Liu, et al, arXiv: 2301.06357;
Y.B.Liu, et al, arXiv: 2301.07553;
Y.B.Liu, et al, Phys. Rev. B 107, 014501 (2023)

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Introduction

- Chiral topological superconductivity (TSC)

U(1)-gauge symmetry
time-reversal symmetry

spontaneous breaking

nonzero Chern number $\Rightarrow$

Majorana Fermion: boundary
Majorana zero mode: vortex core

can be used in topological quantum computation

Introduction

- Mechanism: the 1:i mixing of two degenerate pairings (2D IRRP of a point-group)

D_4 E_1 IRRP : $(p_x , p_y) \longrightarrow p_x+ip_y$, p_x-ip_y (p+ip)

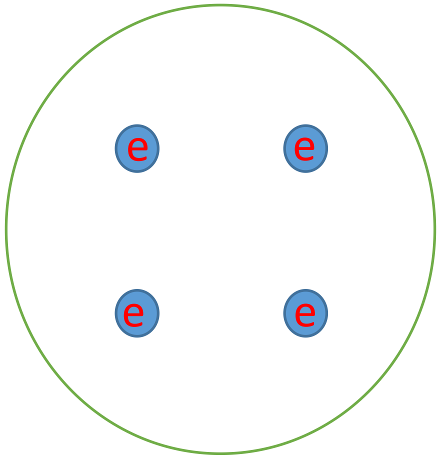
D_6 E_1 IRRP :$(p_x , p_y) \longrightarrow$ (p+ip) ; E_2 IRRP: $(d_{x^2-y^2} , d_{xy}) \longrightarrow$ (d+id)

- The material realization of chiral TSC is still a big challenge

candidates: Sr_2RuO_4; 1/4-doped graphene; MA-TBG ...... (to be verified)

Introduction

- The charge-4e SC



4e -- bound state

BEC condensation

SC with fractionalized flux

half flux quanta: hc/4e

- Can be realized as vestigial phase of degenerate-pairing ground state

Introduction

- Incommensurate PDW fluctuation $\longrightarrow$ charge-4e SC & CDW

  (U(1)*U(1) symmetry breaking)

$$\Delta(\mathbf{r}) = \Delta_{\mathbf{Q}}(\mathbf{r})\, e^{i\mathbf{Q}\cdot\mathbf{r}} + \Delta_{-\mathbf{Q}}(\mathbf{r})\, e^{-i\mathbf{Q}\cdot\mathbf{r}}$$

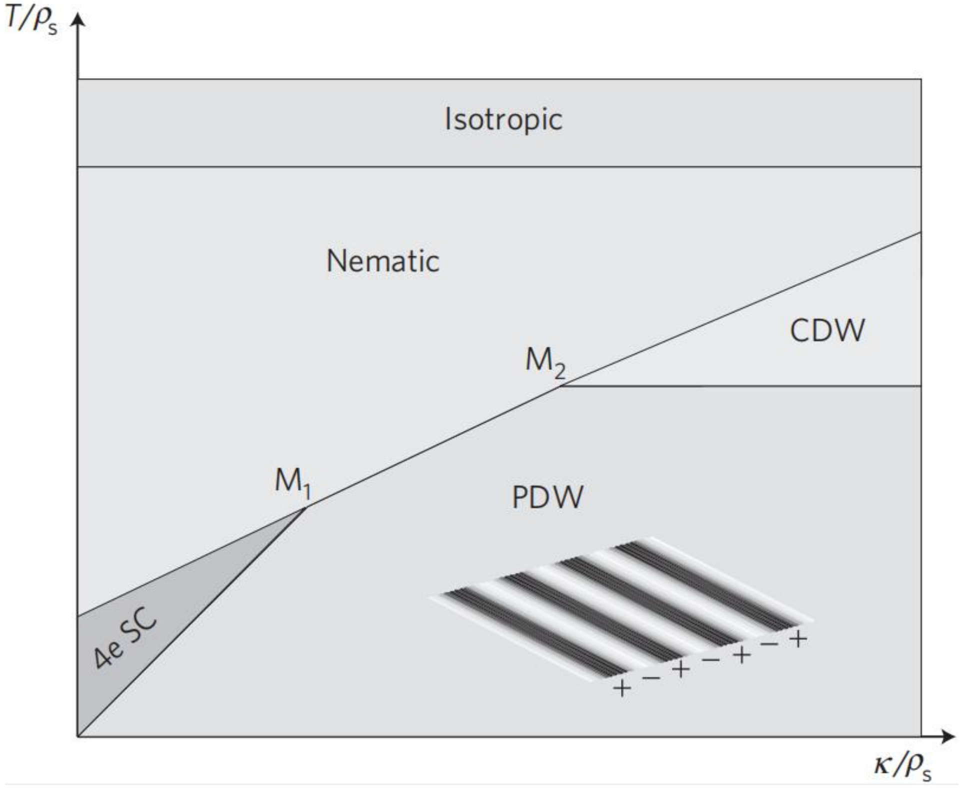
$$\Delta_{\pm\mathbf{Q}}(\mathbf{r}) = \Delta_{SC}\exp\{i(\theta(\mathbf{r}) \pm \phi(\mathbf{r}))\}$$

$$\Delta_{4e}(\mathbf{r}) \propto \Delta_{-\mathbf{Q}}(\mathbf{r})\Delta_{\mathbf{Q}}(\mathbf{r}) = \Delta_{4e}\exp[i2\theta(\mathbf{r})]$$

$$\rho_{\mathbf{K}}(\mathbf{r}) \propto \Delta^{\star}_{-\mathbf{Q}}(\mathbf{r})\Delta_{\mathbf{Q}}(\mathbf{r}) = \rho_K \exp[i2\phi(\mathbf{r})]$$

$\theta(\mathbf{r})$ -- unilateral ordering: charge-4e SC

$\phi(\mathbf{r})$ -- unilateral ordering: CDW with $\mathbf{K} = 2\mathbf{Q}$



E. Berg, et al, Nat. Phy. 5, 830 (2009).

Introduction

- Nematic pairing fluctuation → charge-4e SC & nematic metal

  (U(1)*Z(3) SB)

$$\Delta = (\Delta_x, \Delta_y)^T$$: E_u IRRP of D_{3d}

$$\Delta_\pm = \Delta_x \pm i\Delta_y$$: basis trsf

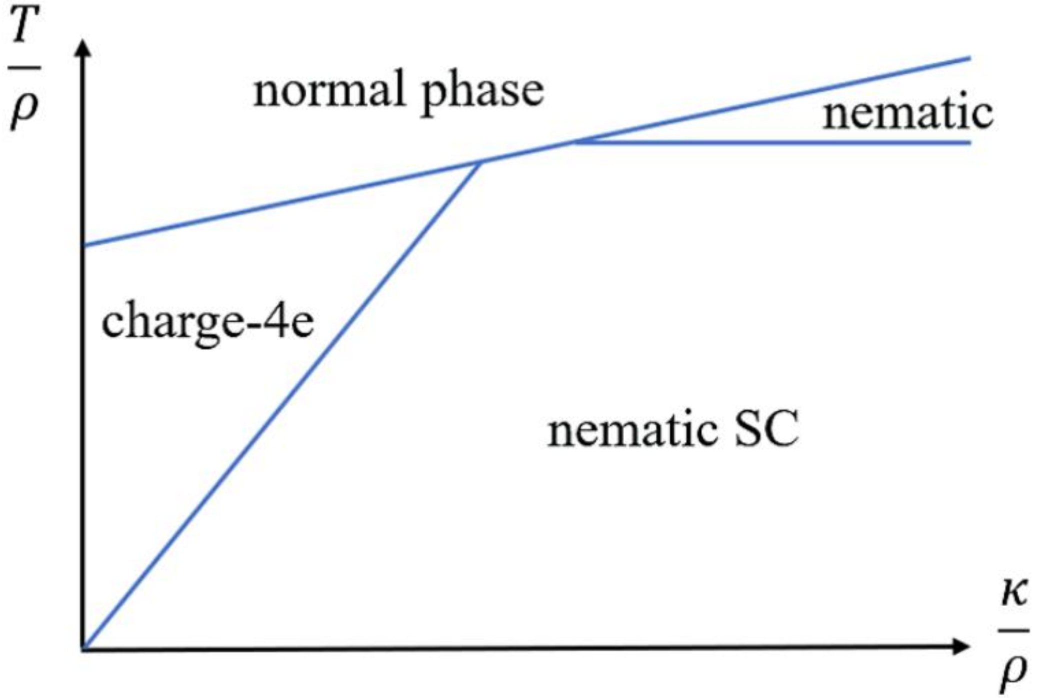
$$\Delta_+ = |\Delta| e^{i(\theta+\phi)}, \quad \Delta_- = |\Delta| e^{i(\theta-\phi)}$$

$$\Delta_{4e} \sim \Delta_+ \Delta_- \rightarrow \Delta_{4e} e^{2i\theta}$$

$$Q \sim \Delta_-^\dagger \Delta_+ \rightarrow Q e^{2i\phi}$$

$\theta(\mathbf{r})$ -- unilateral ordering: charge-4e SC

$\phi(\mathbf{r})$ -- unilateral ordering: nematic metal



S.K.Jian, et al, PRL127,22701 (2021).
R. M. Fernandes, et al, PRL127,047001 (2021)

Main Idea

- Charge-4e SC as a vestigial phase of multi-component pairing state.
- Extra symmetry breaking besides U(1)-gauge in the ground state

  PDW: translation ;   nematic SC: rotation ;

  unilateral U(1)-gauge breaking $\Rightarrow$ charge-4e SC

  unilateral extra symmetry breaking: CDW, nematic order ......
- The TB-QC consists of two superconducting monolayers

  interlayer Josephson coupling $\Rightarrow$ chiral TSC
- Vestial phases of the chiral TSC (U(1)*Z_2 SB)

  total phase order $\Rightarrow$ charge-4e SC (U(1)-gauge SB)

  relative phase order $\Rightarrow$ chiral metal (Z_2 time-reversal SB)

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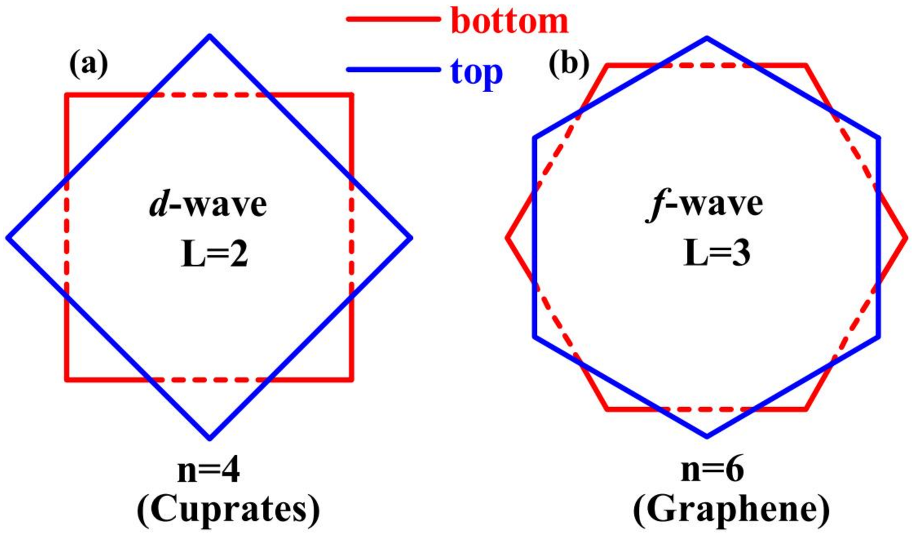
Twisted-Bilayer Quasi-Crystal (TB-QC)

- Two D_n-symmetric monolayers stacked with the largest twist angle π / n

45°-twisted bilayer cuprates



30°-twisted bilayer graphene

layer exchange

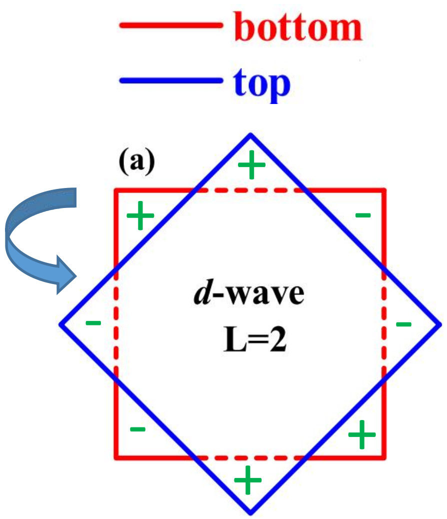
- Moireless quasi-crystal structure.
- Enlarged point group $D_{nd} \sim D_{2n}$. New symmetry generator $\widetilde{C}_{2n}^{1} \equiv C_{2n}^{1} * P$
- Suppose : each monolayer carries SC with angular momentum $L = n/2$
- What pairing can be driven by interlayer Josephson Coupling (IJC) in the TB-QC?

Y.B.Liu, et al, arXiv: 2301.07553; Y.B.Liu, et al, Phys. Rev. B 107, 014501 (2023)

Ginzburg-Landau Theory

- Pairing gap $\Delta^{(\mu)}(\mathbf{k})$; fixed form factor $\Gamma^{(\mu)}(\mathbf{k})$; complex amplitude ψ_μ

$$\Delta^{(\mu)}(\mathbf{k}) = \psi_\mu \Gamma^{(\mu)}(\mathbf{k}) \;,\; \mu = \mathrm{t/b}\ (\mathrm{top/bottom})$$



- The fixed form factor $\Gamma^{(\mu)}(\mathbf{k})$ for $L = n/2$ satisfies

$$\Gamma^{(\mathrm{b})}(\mathbf{k}) = \hat{P}_{\frac{\pi}{n}} \Gamma^{(\mathrm{t})}(\mathbf{k}), \quad \hat{P}_{\frac{2\pi}{n}} \Gamma^{(\mu)}(\mathbf{k}) = -\Gamma^{(\mu)}(\mathbf{k})$$

- The G-L free energy functional

$$F(\psi_\mathrm{t}, \psi_\mathrm{b}) = F_0(|\psi_\mathrm{t}|^2) + F_0(|\psi_\mathrm{b}|^2) + F_J(\psi_\mathrm{t}, \psi_\mathrm{b})$$

$$F_J(\psi_t, \psi_b) = F_J^{(1)}(\psi_t, \psi_b) + F_J^{(2)}(\psi_t, \psi_b) + \ldots\ldots$$

O. Can, et al, Nat. Phys. 17, 519(2021); Y.B.Liu, et al, arXiv: 2201.01656; ibid 2301.07553; B. T. Zhou, et al, arXiv: 2206.05599;

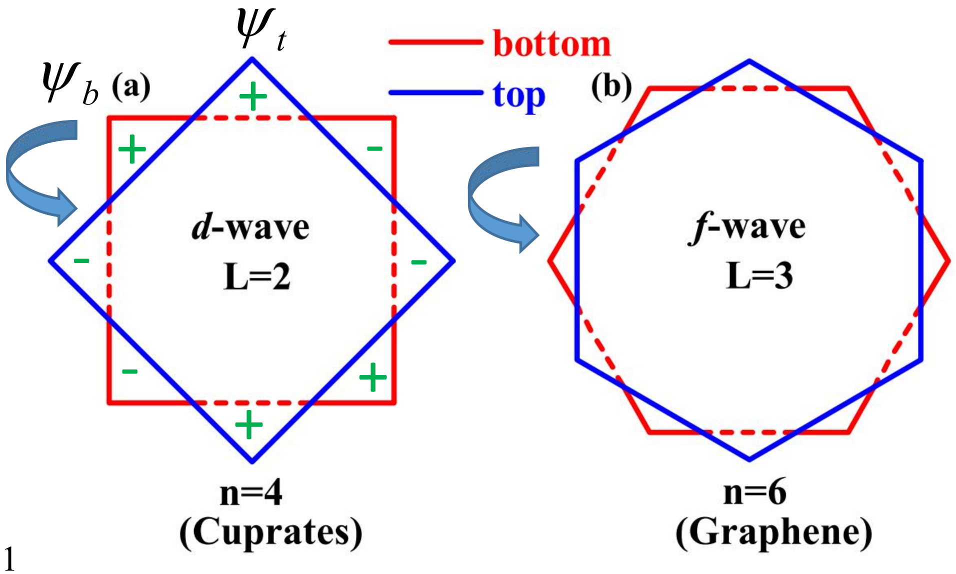
Ginzburg-Landau Theory

- The first-order IJC : satisfies U(1)- and TR

$$F_J^{(1)}\left(\psi_{\mathrm{t}},\psi_{\mathrm{b}}\right)=-A\left(\psi_{\mathrm{t}}\psi_{\mathrm{b}}^{*}+c.c\right)$$

- Invariance of $F_J^{(1)}$ under $\widetilde{C}_{2n}^{1}$ dictates $A=0$

$$\widetilde{C}_{2n}^{1}:\left.\begin{array}{l}\psi_b\rightarrow\psi_t\\ \psi_t\rightarrow-\psi_b\end{array}\right\}\Rightarrow F_J^{(1)}(\psi_t,\psi_b)\rightarrow-F_J^{(1)}(\psi_t,\psi_b)$$



- The second-order IJC: satisfies U(1), TR, $\widetilde{C}_{2n}^{1}$

$$F_J\left(\psi_{\mathrm{t}},\psi_{\mathrm{b}}\right)=A_0\left(\psi_{\mathrm{t}}^2\psi_{\mathrm{b}}^{2*}+\mathrm{c.c.}\right)$$

- Minimization of free energy:

$\psi_t=\pm i\psi_b,\qquad A_0>0,$ chiral d+id/f+if TSC

$\psi_t=\pm\psi_b,\qquad A_0<0.$ nematic d/f SC

determined by microscopic calc

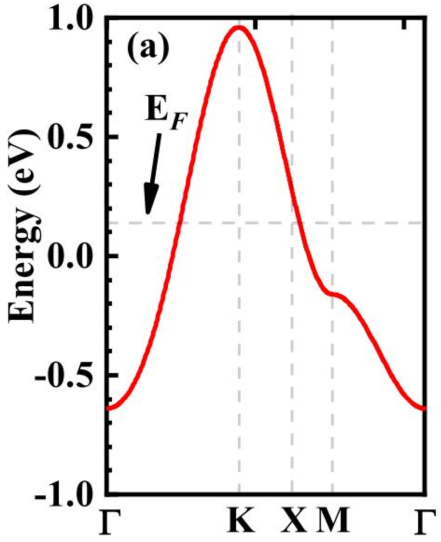
O. Can, et al, Nat. Phys. 17, 519(2021); Y.B.Liu, et al, arXiv: 2201.01656; ibid 2301.07553; B. T. Zhou, et al, arXiv: 2206.05599;

Microscopic Calculations

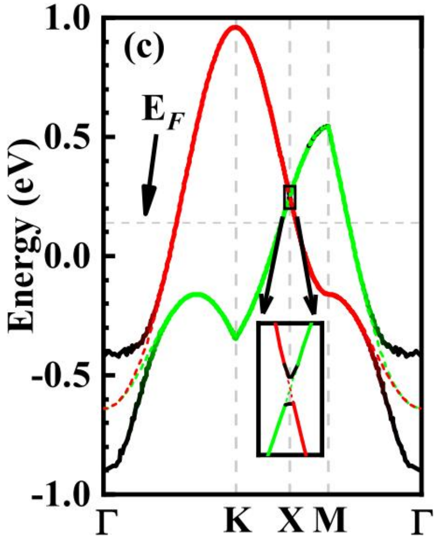
- The Moireless QC structure disables the standard band-theory study.
- Weak interlayer coupling → perturbational-band theory

$$H_0 = \sum_{\mathbf{k}\mu\alpha\sigma} c^{\dagger}_{\mathbf{k}\mu\alpha\sigma} c_{\mathbf{k}\mu\alpha\sigma} \varepsilon^{\mu\alpha}_{\mathbf{k}}, \quad H' = \sum_{\mathbf{kq}\alpha\beta\sigma} c^{\dagger}_{\mathbf{k}\mathrm{t}\alpha\sigma} c_{\mathbf{q}\mathrm{b}\beta\sigma} T^{\alpha\beta}_{\mathbf{kq}} + h.c.$$

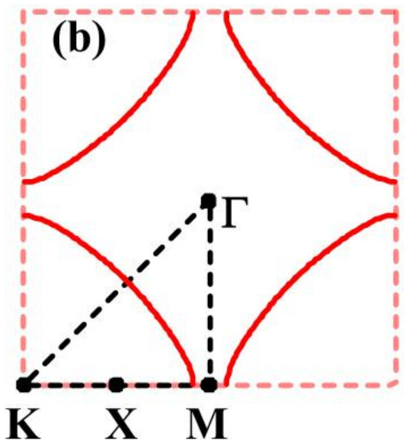
- The interlayer H'-term as perturbation: band structures and FSs



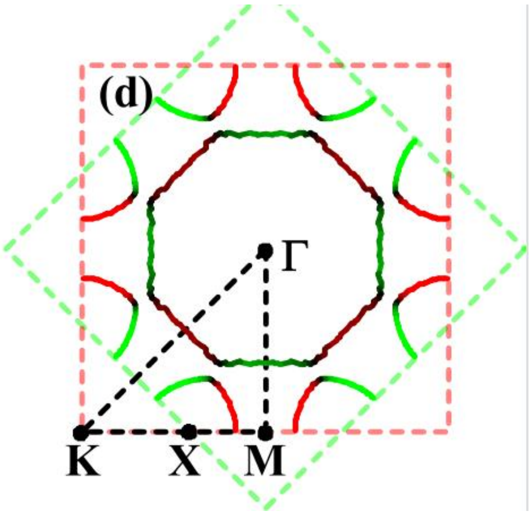
mono layer



TB-QC



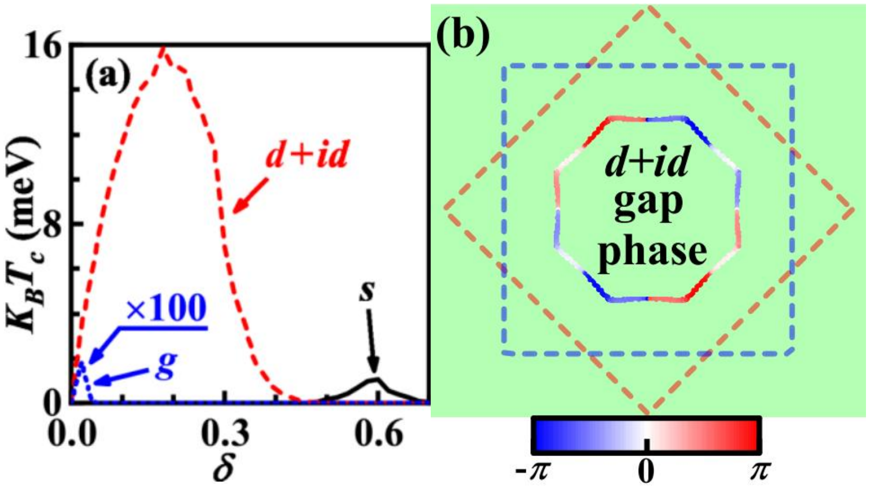
mono layer



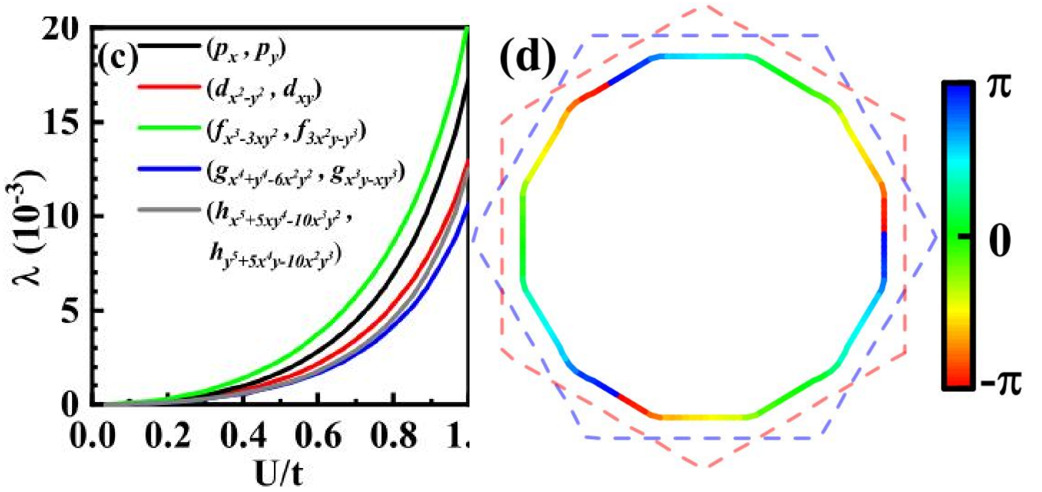
TB-QC

Microscopic Calculations

- The t-J or Hubbard interaction added: Gutzwiller MF or RPA treatment
- Effective interactions projected on the perturbation-corrected FS
- Solved gap equation classified by irreducibel representation of D_8/D_{12}
- The doubly degenerate pairing: always 1:i mixing to minimize energy



d+id TSC in 45-twisted bilayer cuprates



f+if TSC in 30-twisted bilayer graphene ($\delta = 0.15$)

- The chiral d+id / f+if TSC realized from d /f -wave SC in each monolayer.

Y.B.Liu, et al, arXiv: 2201.01656; ibid 2301.07553; ibid, Phys. Rev. B 107, 014501 (2023)

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Low-Energy Effective Model

- Fix $\Gamma^{(\mu)}$, set $\psi_\mu \to \psi_\mu(\mathbf{r})$: spatial fluctuation driven by temperature
- Focus on the phase fluctuation $\psi_{\mathrm{t/b}} = \psi_0 e^{i\theta_{\mathrm{t/b}}(\mathbf{r})}$ $\psi_0 > 0$
- The total- and relative- phase fields

$$\theta_{\mathrm{t}}(\mathbf{r}) = \theta_+(\mathbf{r}) + \theta_-(\mathbf{r}) \text{ , } \theta_{\mathrm{b}}(\mathbf{r}) = \theta_+(\mathbf{r}) - \theta_-(\mathbf{r})$$

- The low-energy effective Hamiltonian

$$H = H_0\left[\partial_\pm\theta_+, \partial_\pm\theta_-\right] + A_0\psi_0^4 \int \cos 4\theta_-(\mathbf{r})\, d^2\mathbf{r} \qquad (\partial_\pm \equiv \partial_x \pm i\partial_y)$$

$$\begin{aligned} H_0 = \frac{1}{2}\int d^2\mathbf{k}\, &\left[\theta_+(\mathbf{k})\,\theta_+(-\mathbf{k})\left(\alpha k_+^2 + \beta k_-^2 + \rho k_+ k_-\right)\right. \\ &+ \theta_+(\mathbf{k})\,\theta_-(-\mathbf{k})\left(\gamma k_+^2 + \delta k_-^2 + \eta k_+ k_-\right) \\ &\left.+ \theta_-(\mathbf{k})\,\theta_-(-\mathbf{k})\left(\epsilon k_+^2 + \xi k_-^2 + \kappa k_+ k_-\right)\right]. \end{aligned}$$

Y.B.Liu, et al, arXiv: 2301.06357

Low-Energy Effective Model

- Symmetry constraint: Under $\tilde{C}_{2n}^{1}$, $\psi_{\mathrm{t/b}}(\mathbf{r}) \to \tilde{\psi}_{\mathrm{t/b}}(\mathbf{r})$

$$\tilde{\psi}_{\mathrm{b}}(\mathbf{r}) = \psi_{\mathrm{t}}\left(\hat{P}_{\frac{\pi}{n}}^{-1}\mathbf{r}\right),\ \tilde{\psi}_{\mathrm{t}}(\mathbf{r}) = -\psi_{\mathrm{b}}\left(\hat{P}_{\frac{\pi}{n}}^{-1}\mathbf{r}\right)$$

$$\theta_{+}(\mathbf{k}) \to \theta_{+}\left(\hat{P}_{\frac{\pi}{n}}^{-1}\mathbf{k}\right),\ \theta_{-}(\mathbf{k}) \to -\theta_{-}\left(\hat{P}_{\frac{\pi}{n}}^{-1}\mathbf{k}\right)$$

- Invariance of Hamiltonian H under $\tilde{C}_{2n}^{1}$, requires

$$\alpha = \beta = \gamma = \delta = \eta = \varepsilon = \xi = 0$$

- The resultant Hamiltonian

$$H = \int d^2\mathbf{r}\left(\frac{\rho}{2}\left|\nabla\theta_{+}\right|^2 + \frac{\kappa}{2}\left|\nabla\theta_{-}\right|^2 + A_0\psi_0^4\cos 4\theta_{-}\right)$$

ρ, κ : stiffness parameters

Y.B.Liu, et al, arXiv: 2301.06357

Low-Energy Effective Model

- Three types of vortices

$$\theta_{\mathrm{t}}(\mathbf{r}) = \theta_{+}(\mathbf{r}) + \theta_{-}(\mathbf{r}) \;,\; \theta_{\mathrm{b}}(\mathbf{r}) = \theta_{+}(\mathbf{r}) - \theta_{-}(\mathbf{r})$$

$$\oint \nabla\theta_{t/b}(r)\bullet d\vec{l} = 2\pi n_{t/b}, n_{t/b} \in I; \quad \oint \nabla\theta_{+/-}(r)\bullet d\vec{l} = 2\pi n_{+/-}, n_{+/-} = (n_t \pm n_b)/2$$

$n_{\pm} \in I \neq 0 \Rightarrow$ integer vortex , $n_{\pm} \in I + 1/2 \Rightarrow$ half-half vortex

- Various phases and phase diagram

Y.B.Liu, et al, arXiv: 2301.06357

For T $\rightarrow$ 0, all types of vortex--anti-vortex pairs $\Rightarrow$ chiral TSC

When T $\nearrow$,
θ_- vortices first unilateral proliferate: restore TRS $\longrightarrow$ charge-4e SC
θ_+ vortices first unilateral proliferate: kill SC $\longrightarrow$ chiral metal
half θ_+- half θ_- vortices first proliferate: kill SC and restore TRS $\longrightarrow$ metal

Which phase is realized: determined by T and κ/ρ $\longrightarrow$ phase diagram

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Y.B.Liu, et al, Phys. Rev. B 107, 014501 (2023)

The RG Study

- The action describing the pairing-phase fluctuations

$$S = \int d^2\mathbf{r} \left(\frac{\rho}{2T} |\nabla\theta_+|^2 + \frac{\kappa}{2T} |\nabla\theta_-|^2 + g_4 \cos 4\theta_- \right)$$

- Map to the Sine-Gordan model via the dual representation

$$S_{\mathrm{SG}} = \int d^2\mathbf{x} \left(\frac{T}{2\rho} \left|\nabla\tilde{\theta}_+\right|^2 + \frac{T}{2\kappa} \left|\nabla\tilde{\theta}_-\right|^2 + g_4 \cos 4\theta_- - g_{2,0} \right.$$
$$\left. \times \cos 2\pi\tilde{\theta}_+ - g_{0,2} \cos 2\pi\tilde{\theta}_- - g_{1,1} \cos \pi\tilde{\theta}_+ \cos \pi\tilde{\theta}_- \right)$$

$\tilde{\theta}_+$, $\tilde{\theta}_-$: vortex fields of θ_+, θ_-

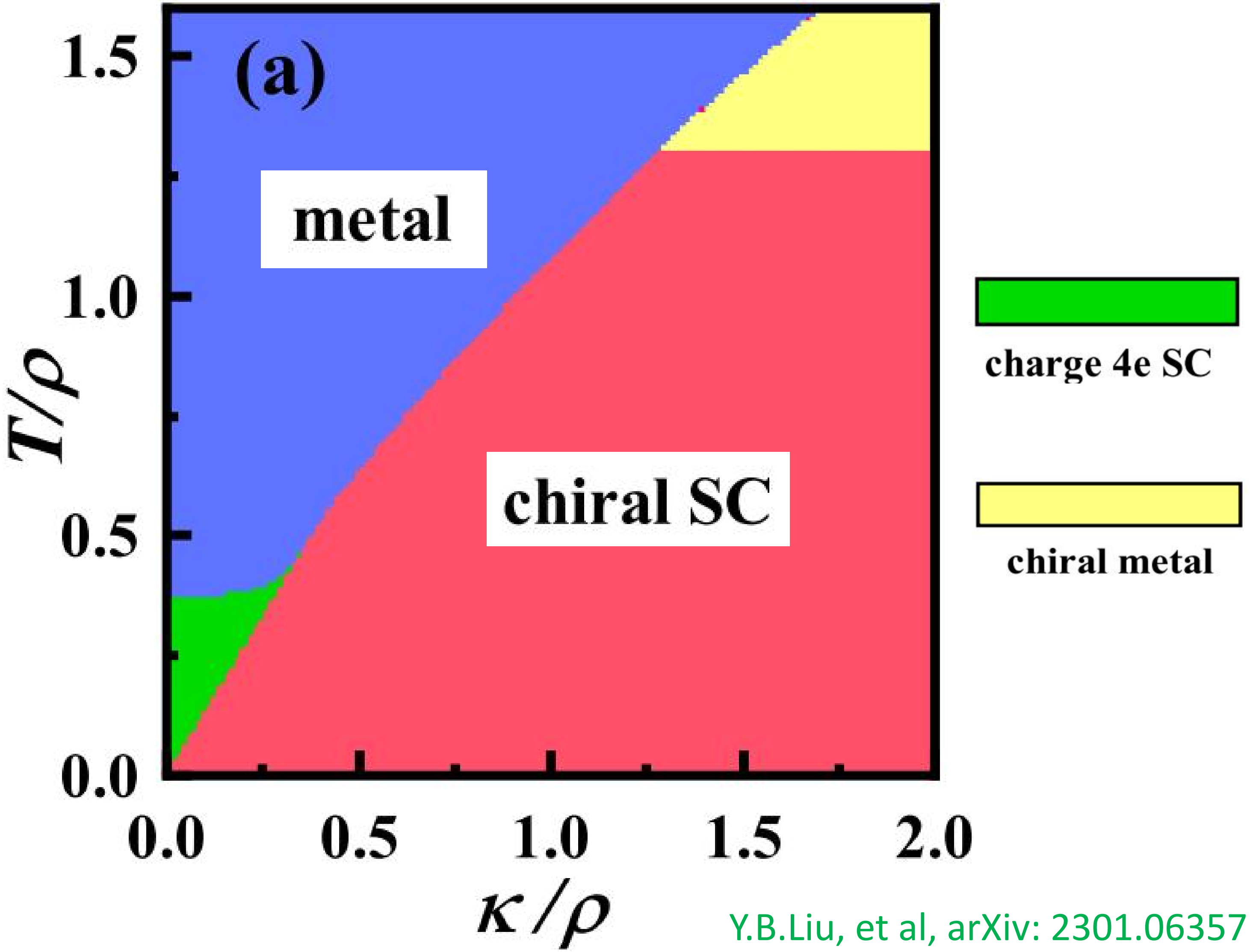
$g_{2,0}$, $g_{0,2}$, $g_{1,1}$: fugacities of θ_+ vortices, θ_- vortices, combined half θ_+ - half θ_- vortices

Y.B.Liu, et al, arXiv: 2301.06357

The one-loop RG Study

$$\frac{dg_{2,0}}{d\ln b} = (2 - \pi\rho')g_{2,0}$$
$$\frac{dg_{0,2}}{d\ln b} = (2 - \pi\kappa')g_{0,2}$$
$$\frac{dg_{1,1}}{d\ln b} = \left(2 - \frac{\pi}{4}(\rho' + \kappa')\right) g_{1,1}$$
$$\frac{dg_4}{d\ln b} = (2 - \frac{4}{\pi\kappa'})g_4$$

$g_{2,0}$	$g_{0,2}$	g_4	$g_{1,1}$	phase
∞	∞	0	∞	normal
∞	0	0	∞	normal
0	0	0	∞	normal
0	∞	0	∞	normal
∞	∞	0	0	normal
0	∞	0	0	charge 4e SC
0	0	∞	0	chiral SC
∞	0	∞	0	chiral metal



Y.B.Liu, et al, arXiv: 2301.06357

The Monte-Carlo Study

- Calculate physical quantities by MC for the discretized Hamiltonian
- The superfluid density S characterizing SC and the Ising ODP I for TRSB
- The susceptibility $\chi_{\pm}$ and correlation function $\eta_{\pm}(\Delta\mathbf{r})$ for the total- and relative- pairing phases, related to SC and TRSB.

$$S = \frac{1}{N}\frac{\partial^2 F(\Phi)}{\partial \Phi^2}$$, Φ: the insert flux; F: the free energy

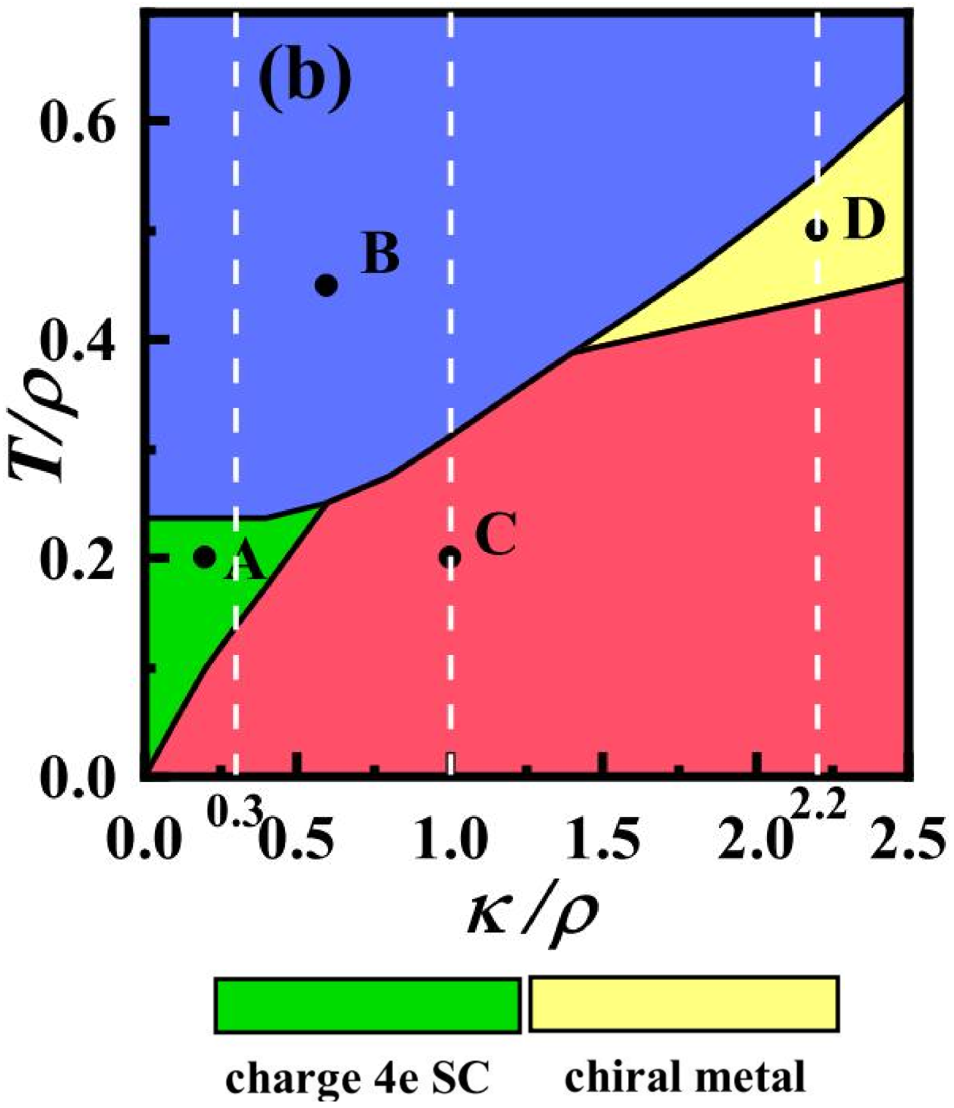
$$I \equiv \frac{1}{N^2}\sum_{ij}\langle \sin[\theta_{\mathrm{t}}(\mathbf{r}_i) - \theta_{\mathrm{b}}(\mathbf{r}_i)] \cdot \sin[\theta_{\mathrm{t}}(\mathbf{r}_j) - \theta_{\mathrm{b}}(\mathbf{r}_j)]\rangle$$

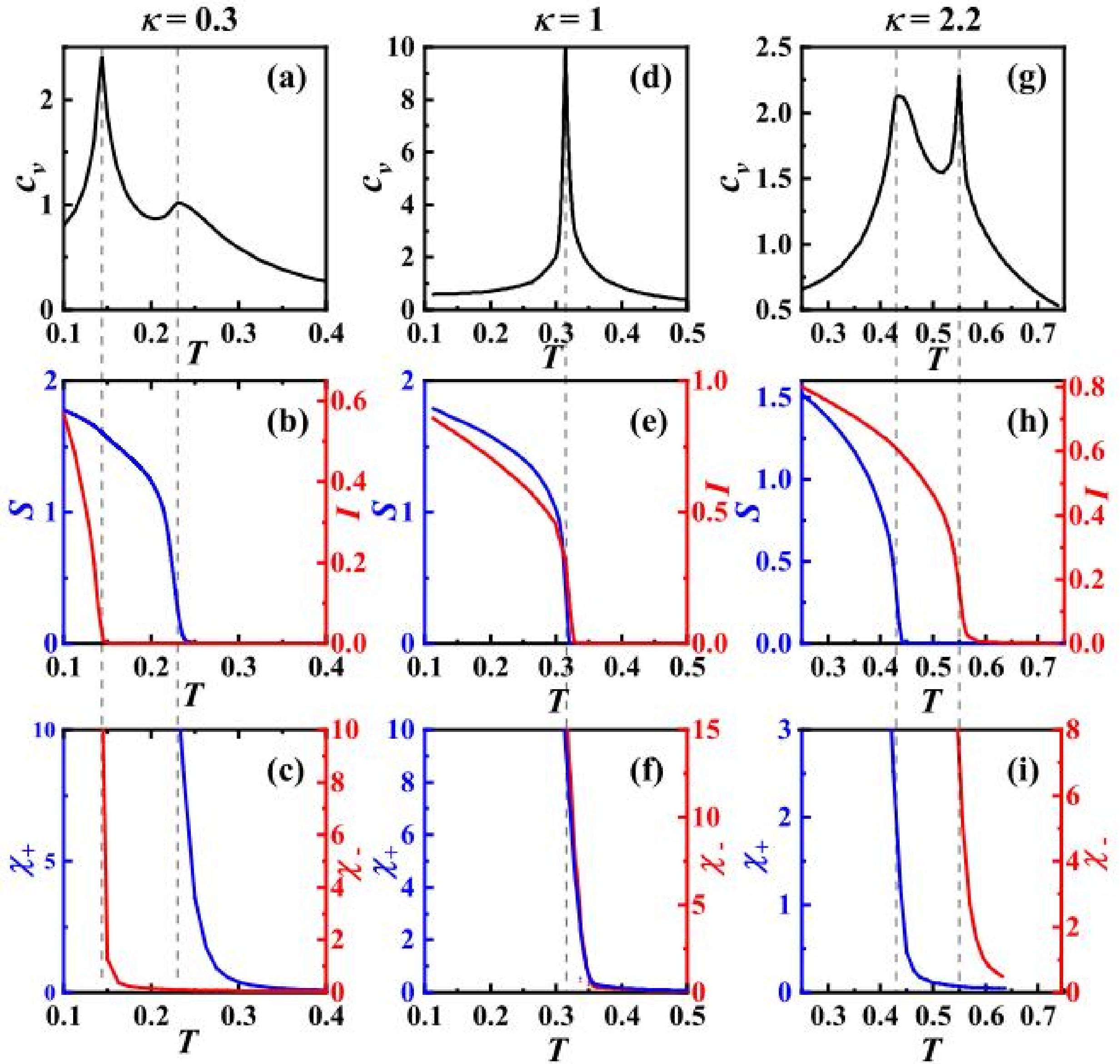
$$\chi_{\pm} \equiv \frac{1}{NT}\sum_{i}\left\langle \left| e^{i[\theta_{\mathrm{t}}(\mathbf{r}_i) \pm \theta_{\mathrm{b}}(\mathbf{r}_i)]} \right|^2 \right\rangle$$

$$\eta_{\pm}(\Delta\mathbf{r}) = \frac{1}{N}\sum_{\mathbf{r}}\left\langle e^{i[\theta_t(\mathbf{r}) \pm \theta_b(\mathbf{r}) - \theta_t(\mathbf{r}+\Delta\mathbf{r}) \mp \theta_b(\mathbf{r}+\Delta\mathbf{r})]} \right\rangle$$

Y.B.Liu, et al, arXiv: 2301.06357

The Monte-Carlo Study





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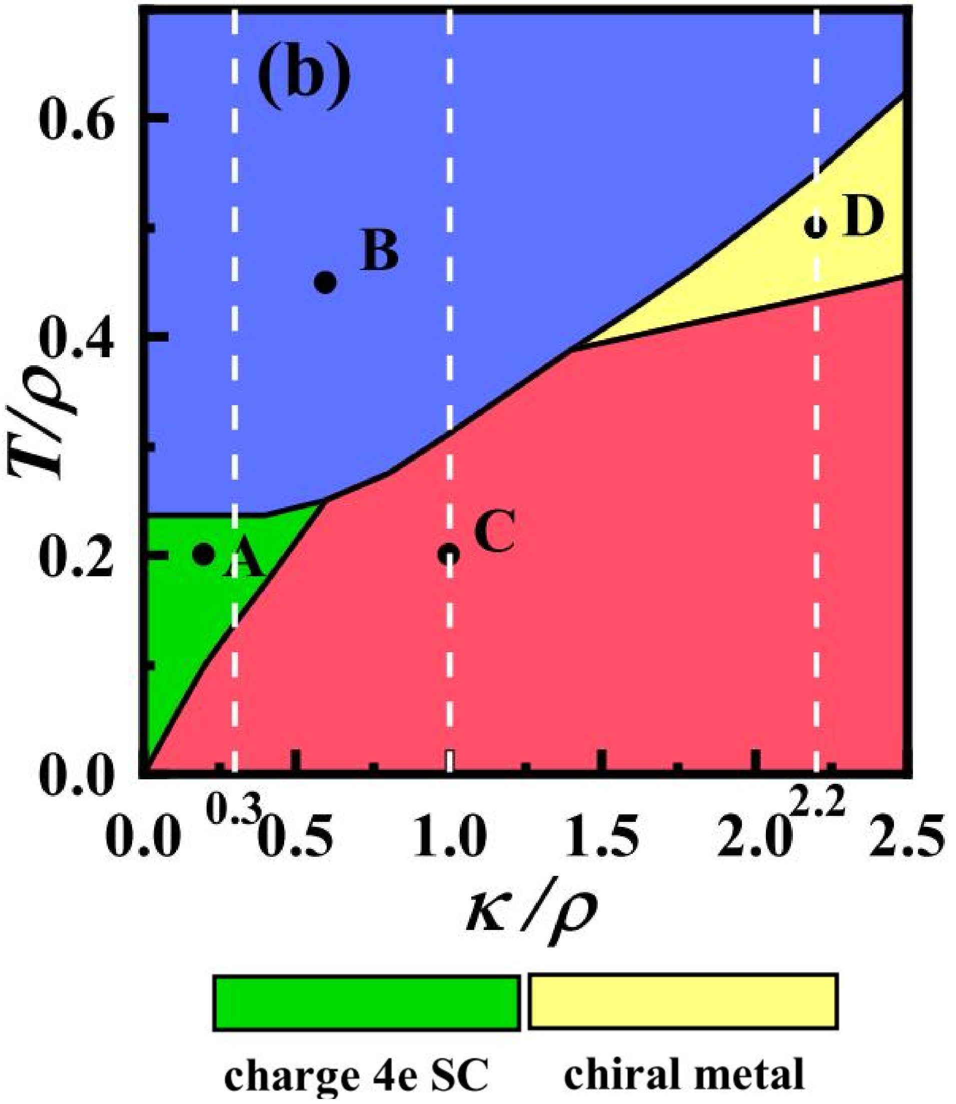

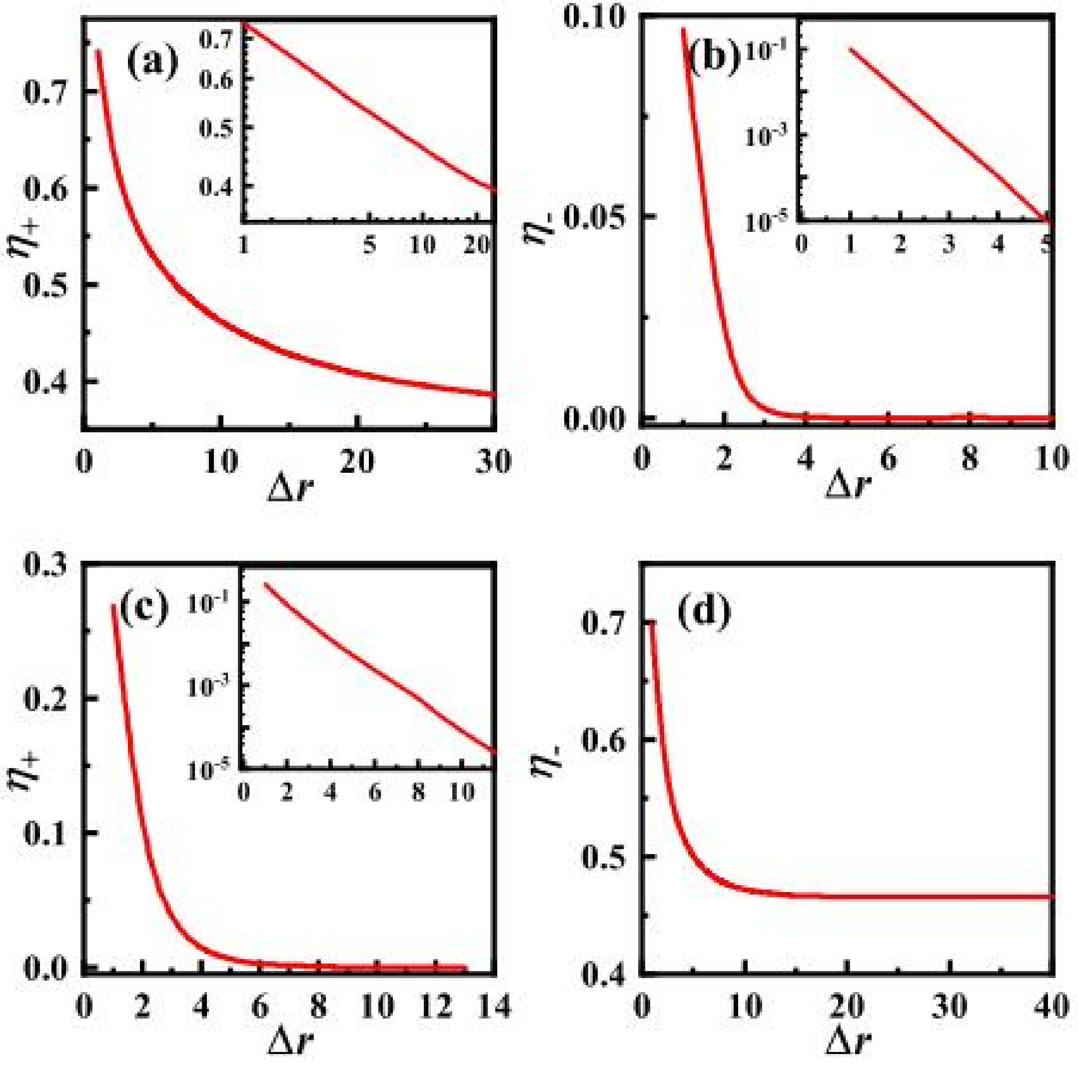

point A

point D

Y.B.Liu, et al, arXiv: 2301.06357

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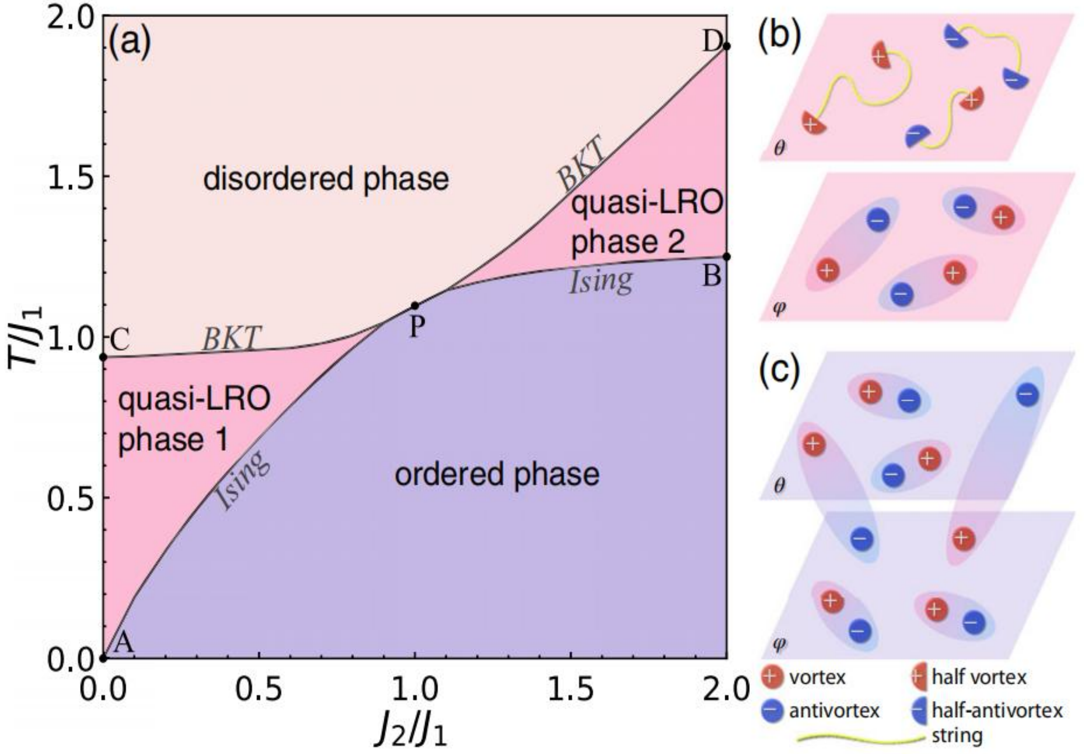
Comparison with charge-4e SC in hetostructure bilayer

- Charge-4e SC in one layer induced by charge-2e SC in the other through IJC.

$$H = -J_1 \sum_{\langle i,j \rangle} \cos(\theta_i - \theta_j) - J_2 \sum_{\langle i,j \rangle} \cos(\varphi_i - \varphi_j) + K \sum_i \cos(2\theta_i - 2\varphi_i),$$

$J_{1/2}$: phase stiffness in layer 1/2; $J_2<J_1$

K: second-order IJC



For T ⟶ 0, both layers host SC

When T ↑, SC2 is killed, SC1 maintains

$\theta(\mathbf{r})$ -- unilateral quasi-ordering: SC1

$\phi(\mathbf{r})$ -- Z_2 fluctuation by the IJC: kill SC2

$\phi(\mathbf{r})$*2 -- quasi-ordering: charge-4e SC in layer2

F. F. Song, et al, PRL128, 195301 (2022)

Comparison with Other chiral TSCs

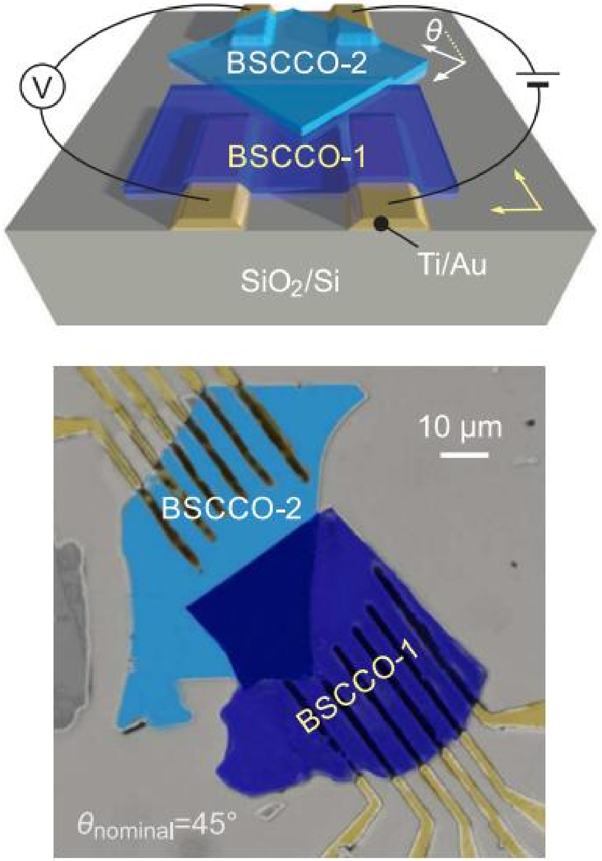
- The p+ip/d+id chiral TSCs can emerge on conventional D_4 or D_6 lattices.
- U(1)-gauge and TRSB might also be unilateral broken to get vestigial phases
- The symmetry allows such term to appear in the Hamiltonian density

$$\nabla_{\pm}\theta_{+} \cdot \nabla_{\pm}\theta_{-}$$

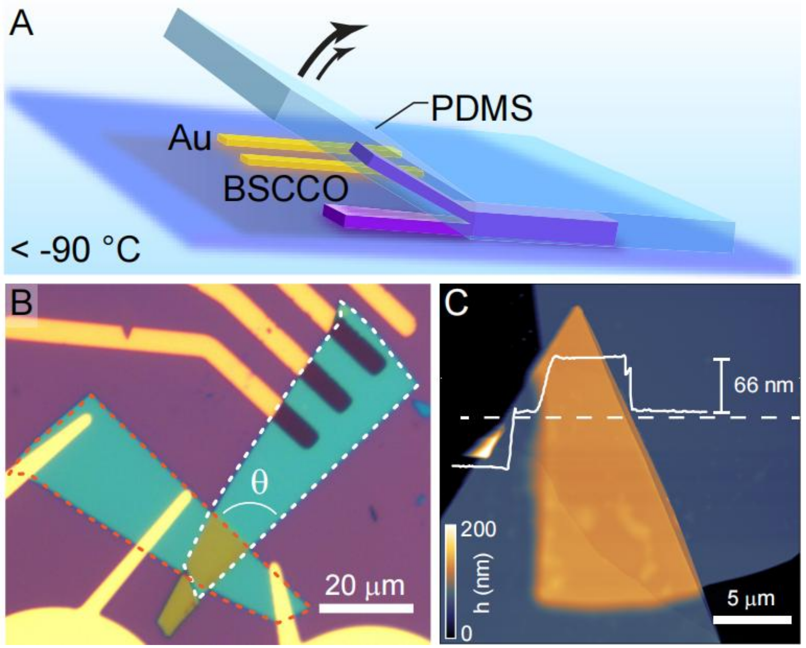
- Such dynamic coupling between θ_{+} and θ_{-} might largely shrink the regime of the vestigial phases in the phase diagram.
- The special $\tilde{C}_{2n}^{1}$ symmetry in the TB-QC forbids the term $\nabla_{\pm}\theta_{+} \cdot \nabla_{\pm}\theta_{-}$, and favors the formation of the vestigial phases.

Experiment Relevance

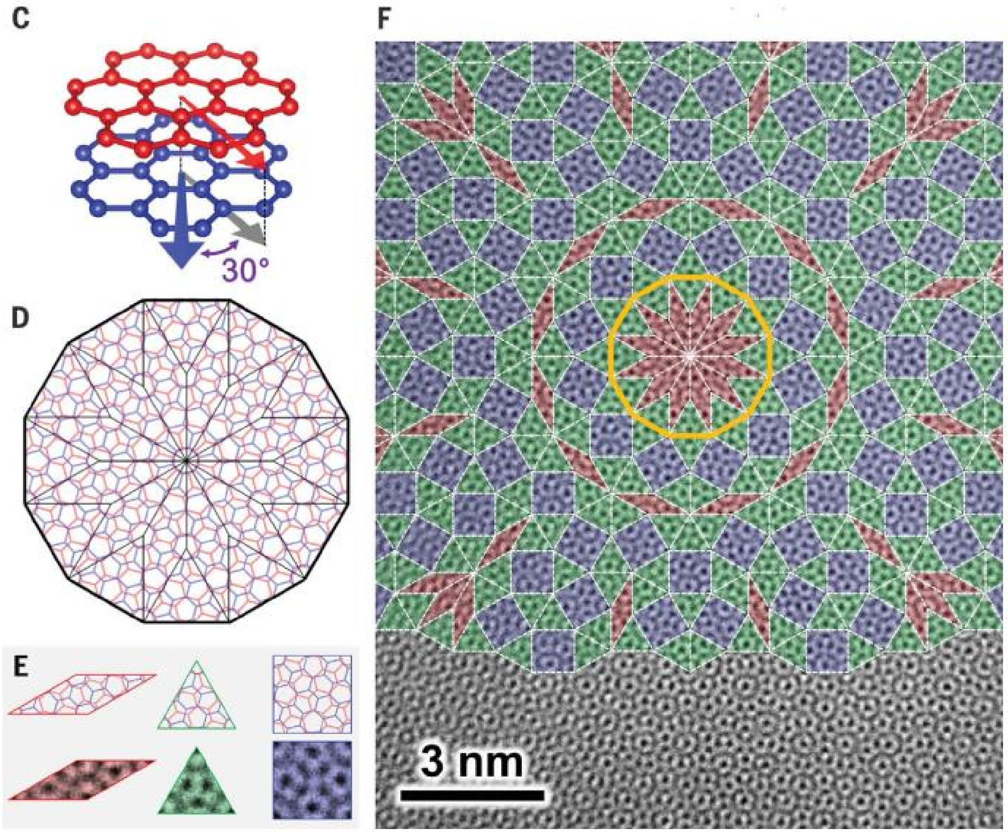
- Synthesization of 45°-twisted bilayer cuprates and 30°-twisted bilayer graphene



Y. Zhu, et al,
Phys. Rev. X 11, 031011 (2021)

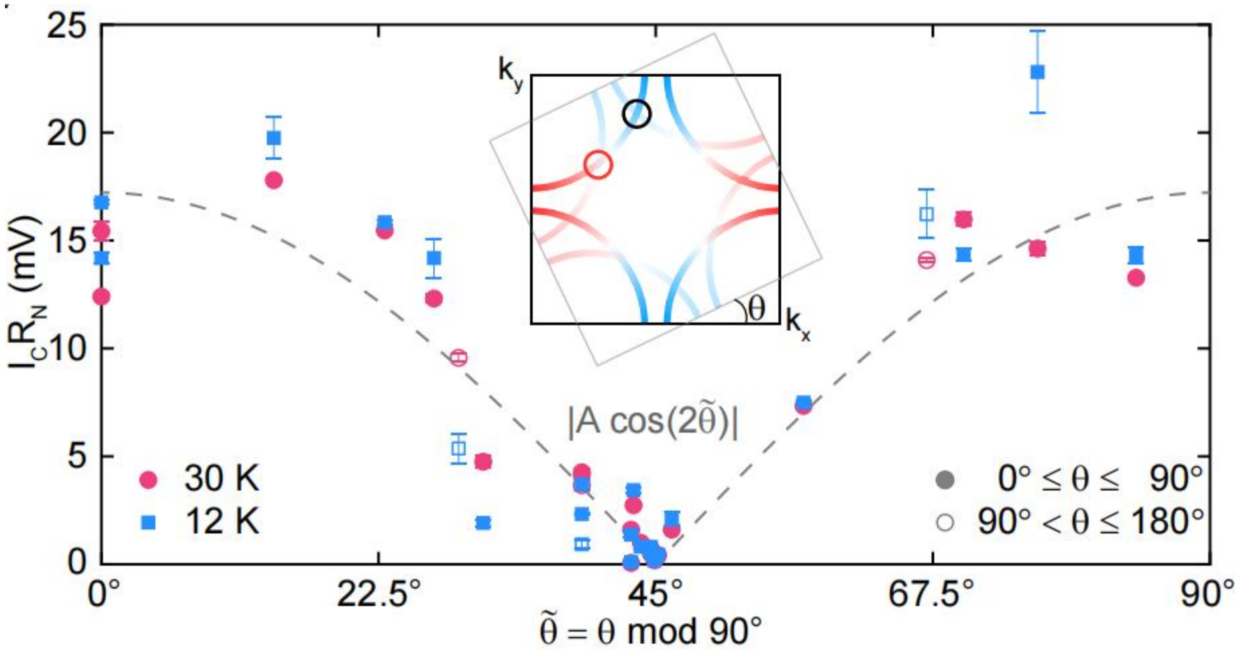


S. Y. Frank Zhao, et al, arXiv: 2108. 13455

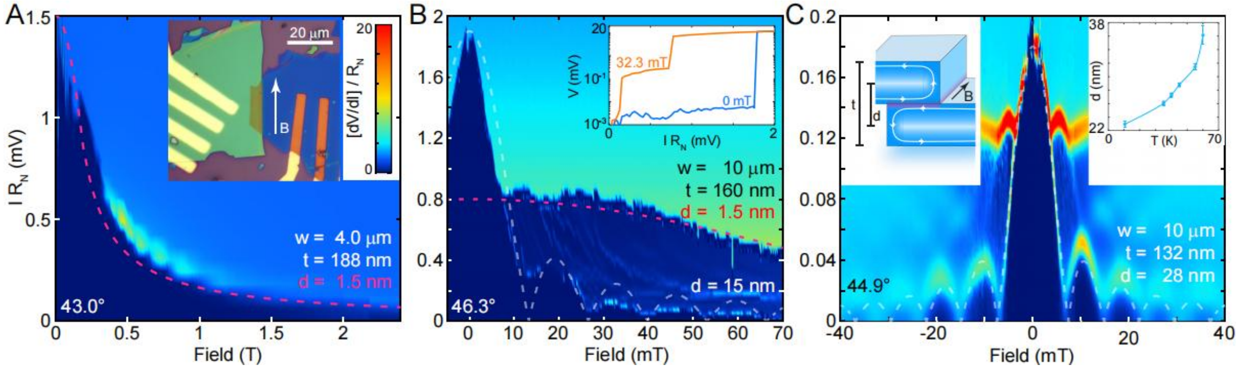


Ahn, et al., Science 361, 782–786 (2018)
W. Yao, et al, PNAS 115, 6928 (2018).

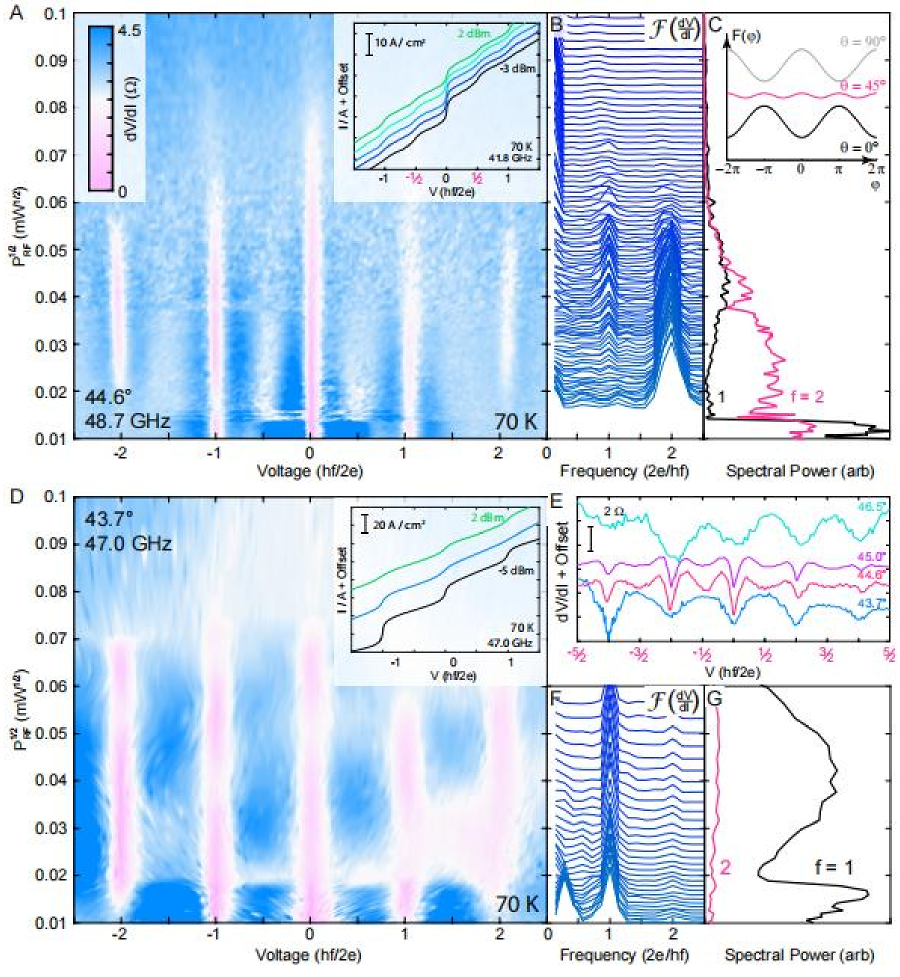
Experiment for the 45°-twisted bilayer cuprates



Twist-angle dependence of the critical current



Fraunhofer pattern near 45°

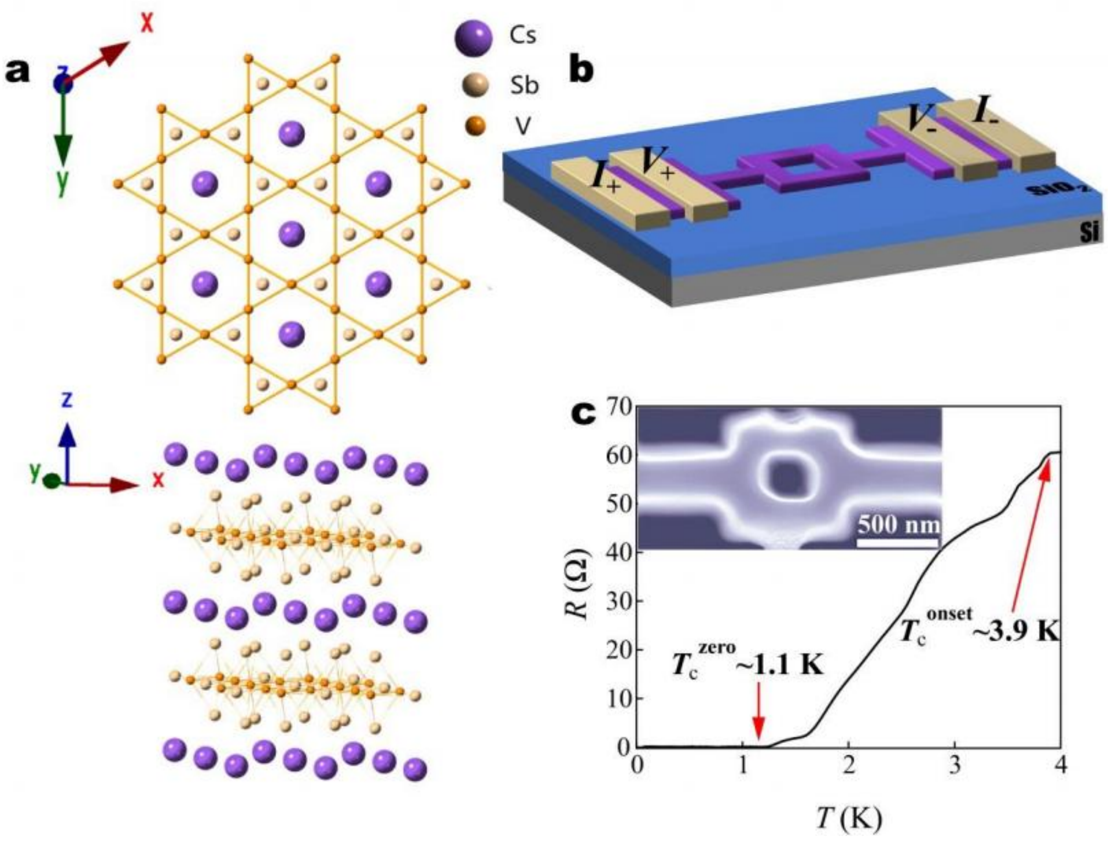


Half-integer Shapiro steps emerge close to 45°

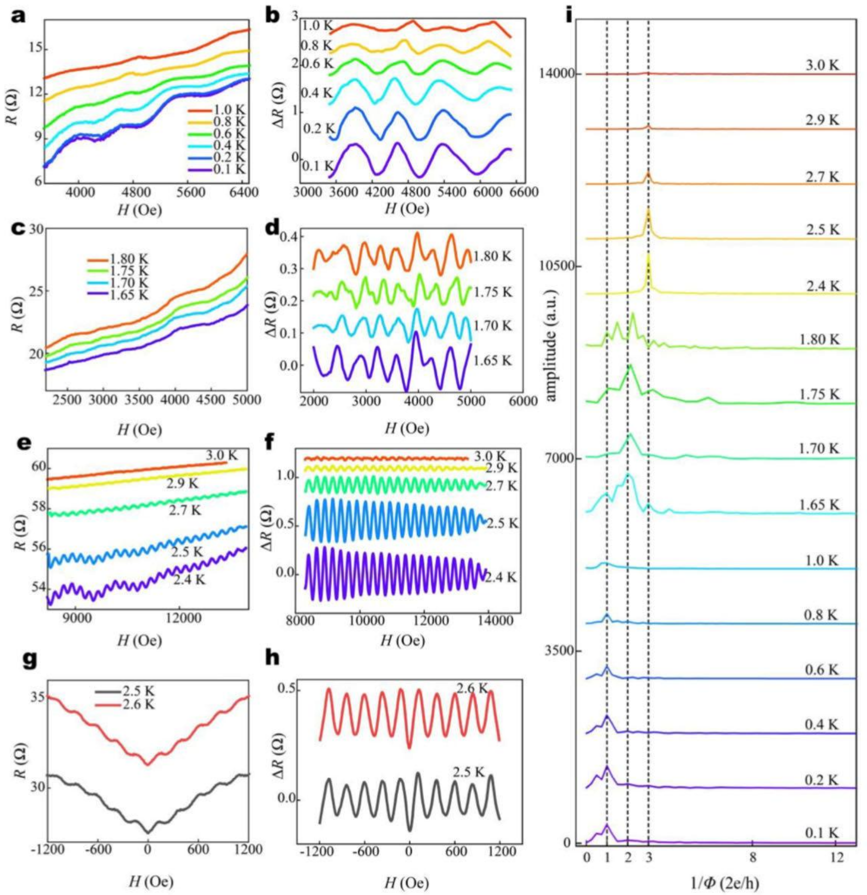
S. Y. Frank Zhao, et al, arXiv: 2108. 13455

How to detect charge-4e SC ?

- The Little-Parks experiment can detect the charge-4e/6e SC



Little-Parks experiment done for CsV_3Sb_5,
J. Ge, et al, arXiv:2201.10352



Resistance oscillations in the Little-Parks EXP

Experimental identifIcation of the chiral metal

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State with spontaneously broken time-reversal symmetry above the superconducting phase transition

Vadim Grinenko[1,2,3]✉, Daniel Weston[4], Federico Caglieris[2], Christoph Wuttke[2], Christian Hess[2,5], Tino Gottschall[6], Ilaria Maccari[4], Denis Gorbunov[6], Sergei Zherlitsyn[6], Jochen Wosnitza[1,6], Andreas Rydh[7], Kunihiro Kihou[8], Chul-Ho Lee[8], Rajib Sarkar[1], Shanu Dengre[1], Julien Garaud[9], Aliaksei Charnukha[2], Ruben Hühne[2], Kornelius Nielsch[2], Bernd Büchner[1,2], Hans-Henning Klauss[1] and Egor Babaev[4]✉

Conclusion

- We predict realization of d+id/f+if chiral TSC in the TB-QC
- The charge-4e SC or chiral metal as vestigial phases of the chiral TSC
- The vestigial phases are driven by pairing phase fluctuations
- Locking of the total pairing phase of the two layers: charge-4e SC
- Locking of the relative pairing phase : the chiral metal
- Might apply to other chiral TSCs, but with shrinked vestigial-phase regimes
- We appeal experimental realization of the prediction.

Thanks!