Pairing Nature and Optical Control of Superconducting State in Magic-Angle Twisted Bilayer Graphene

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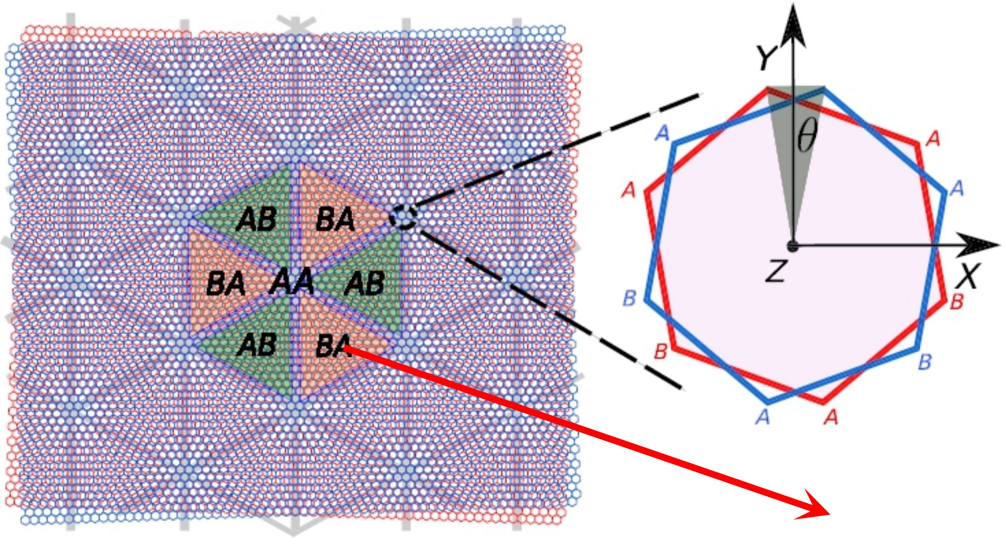
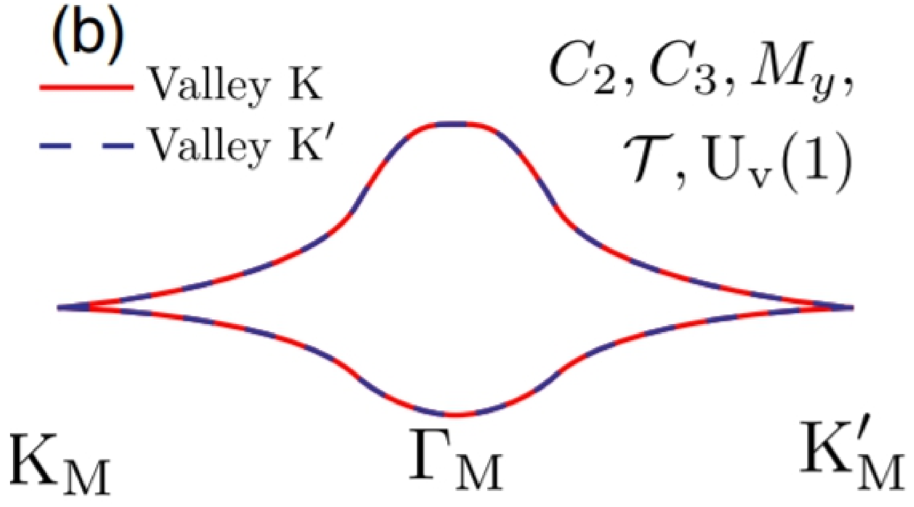
TY, D. Kennes, A. Rubio, and M. Sentef, arXiv: 2101.01426
TY, M. Claassen, D. Kennes, and M. Sentef, PRR **3**, 013253 (2021)

Sentef Lab
Light-matter control of quantum materials

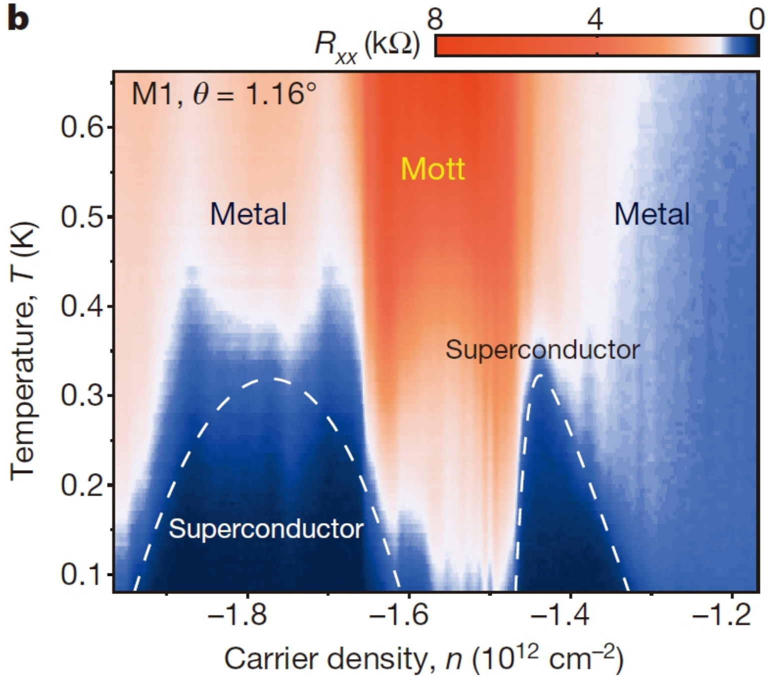
Twisted Bilayer Graphene



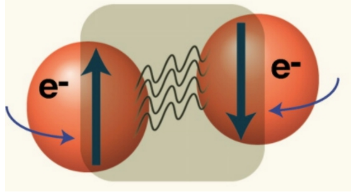
About 12000 atoms



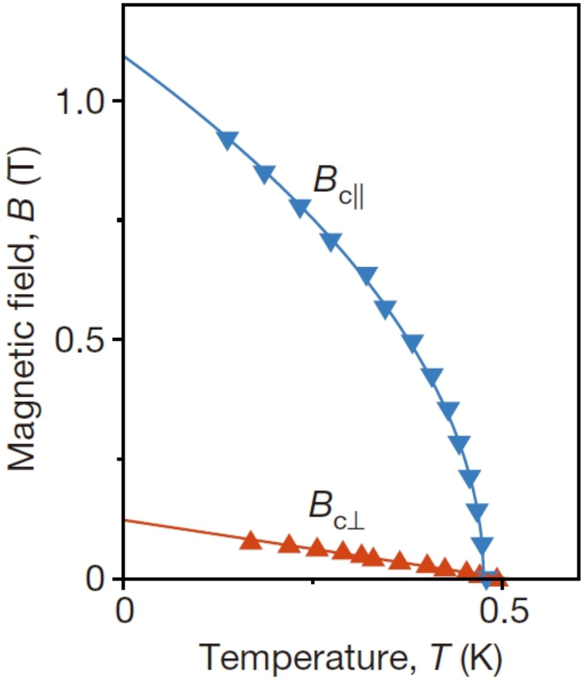
Flat band



[Cao *et al.*, Nature 556, 43 (2018)]



Pairing symmetry?
Pairing mechanisms?

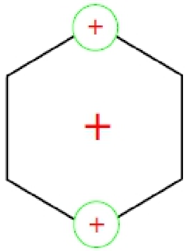
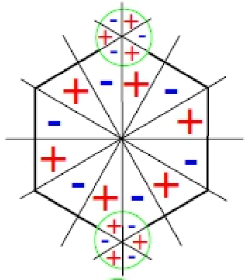
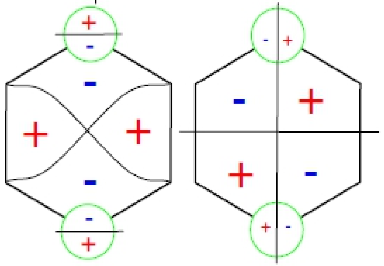


Possible superconducting pairing (s, p, d, f, g...)

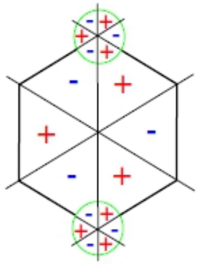
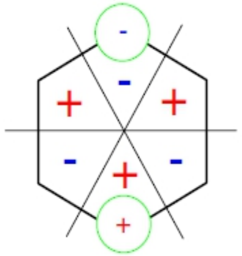
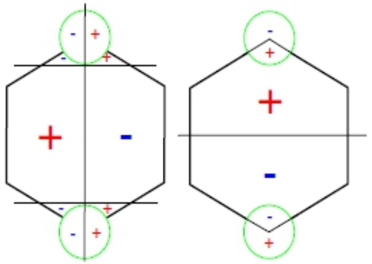
[Schaffer and Honerkamp, JPCM 26, 423201 (2014)]

D_3

even of k, singlet

Irreps	Basis function		Brillouin zone symmetry
A_{1g}	$1,\ k_x^2 + k_y^2$	s-wave	
A_{2g}	$k_x k_y (k_x^2 - 3k_y^2)(k_y^2 - 3k_x^2)$		
E_{2g}	$(k_x^2 - k_y^2,\ 2k_x k_y)$ d+id	d-wave	

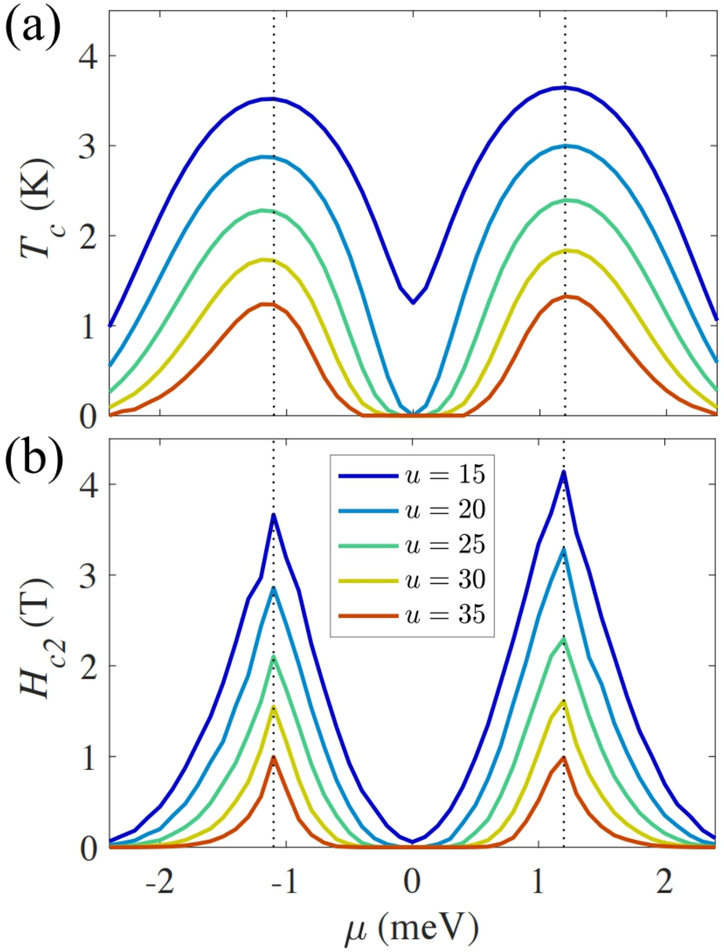
odd of k, triplet

Irreps	Basis function		Brillouin zone symmetry
B_{1u}	$k_x(k_x^2 - 3k_y^2)$		
B_{2u}	$k_y(k_y^2 - 3k_x^2)$		
E_{1u}	(k_x, k_y) p+ip	p-wave	

However, if the correlation is dominant → chiral d-wave?

Phonon

[e.g., Wu *et al.*, PRL **121**, 257001 (2018), Lian *et al.*, PRL **122**, 257002 (2019); Angeli *et al.*, PRX **9**, 041010 (2019)]

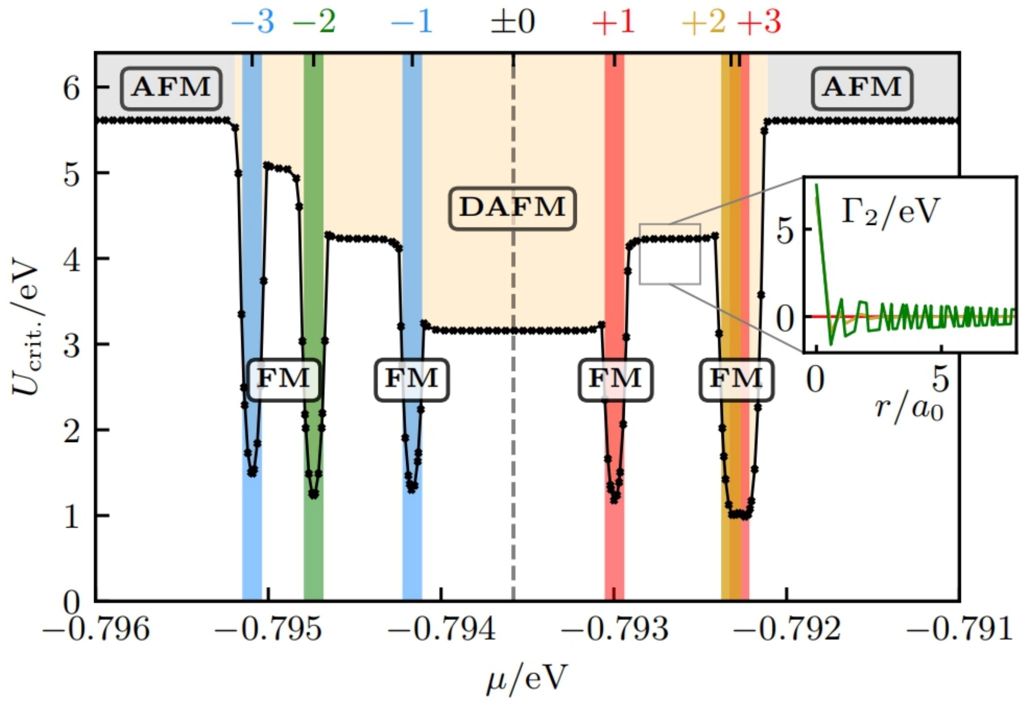


No such association is present in MATBG experimental data!

[Qin, Zou, and MacDonald, arXiv: 2102.10504]

Pure electron

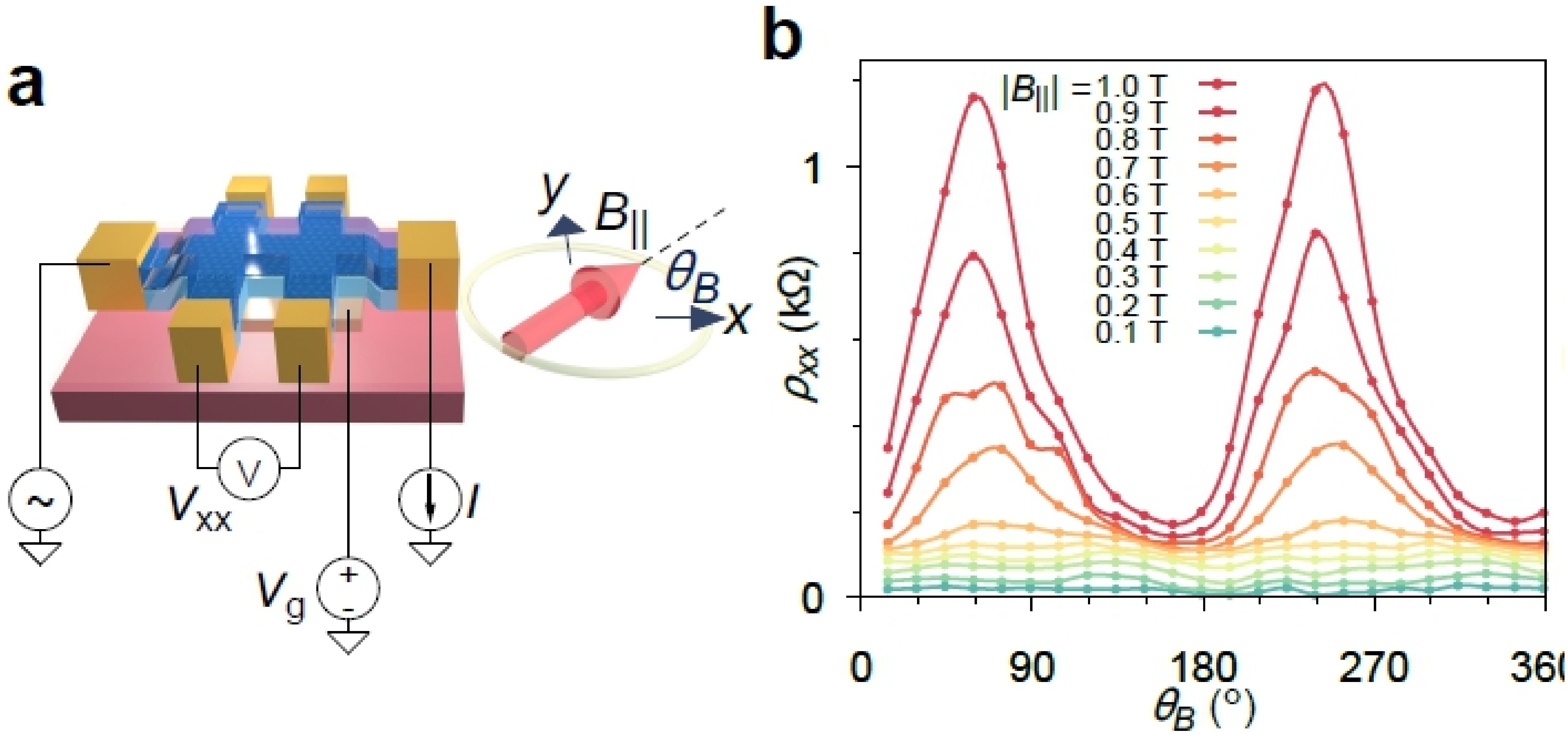
[e.g., Isobe *et al.*, PRX **8**, 041041 (2018), Po *et al.*, PRX **8**, 031089 (2018); Xu *et al.*, PRL **121**, 087001 (2018); Kennes *et al.*, PRB **98**, 241407(R) (2018)]



A large-scale tight-binding approach resolving the Ångström scale!

[Fischer, Klebl, Honerkamp, and Kennes, PRB 103, LL041103 (2021)]

Superconductivity seems nematic (Near Tc) [Cao et al., arXiv:2004.04148]



Broken rotation symmetry: two-fold anisotropy → nematic SC?

Assume chiral superconductivity → Nematicity?

[**TY**, D. Kennes, A. Rubio, and M. Sentef, arXiv: 2101.01426]

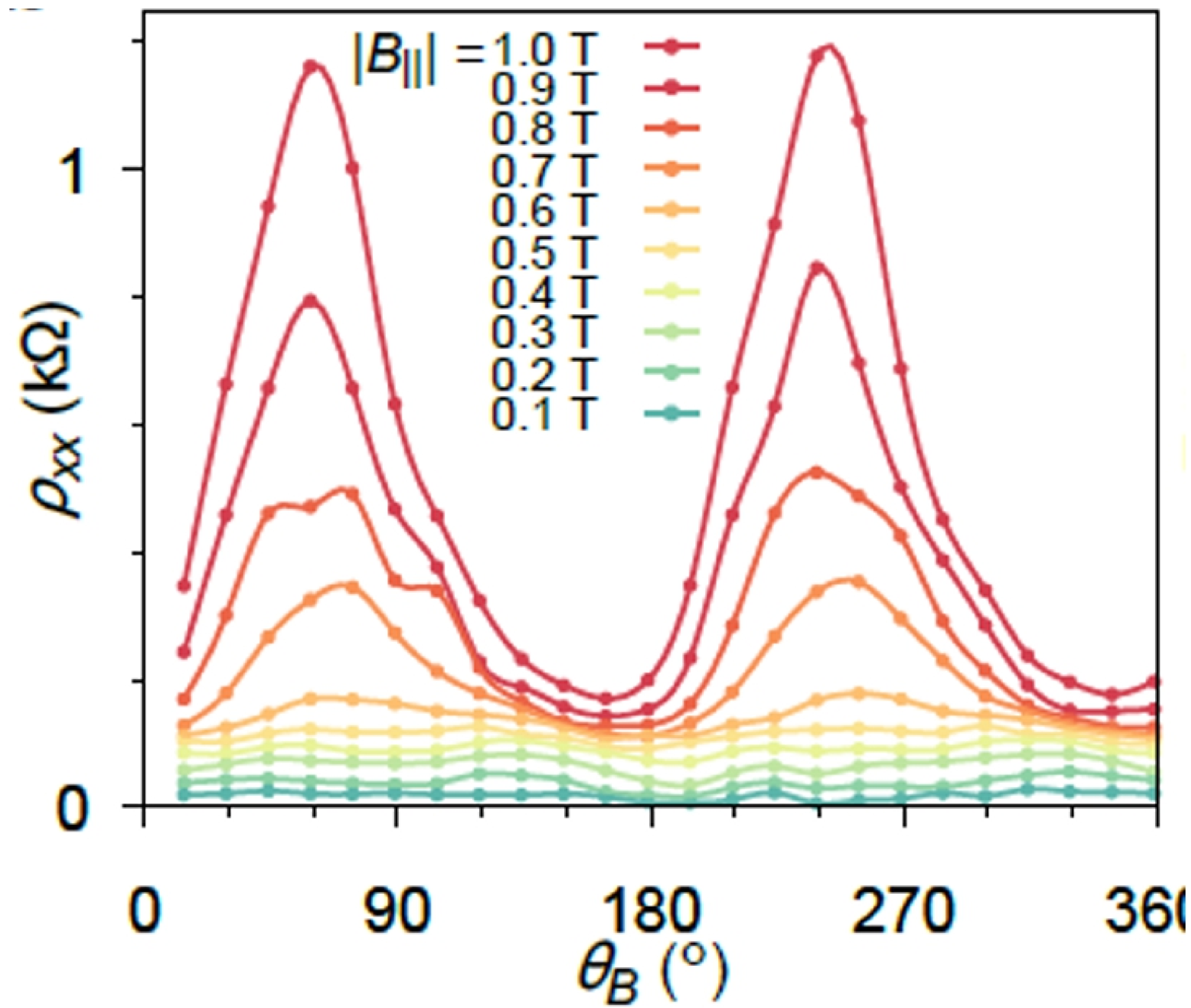
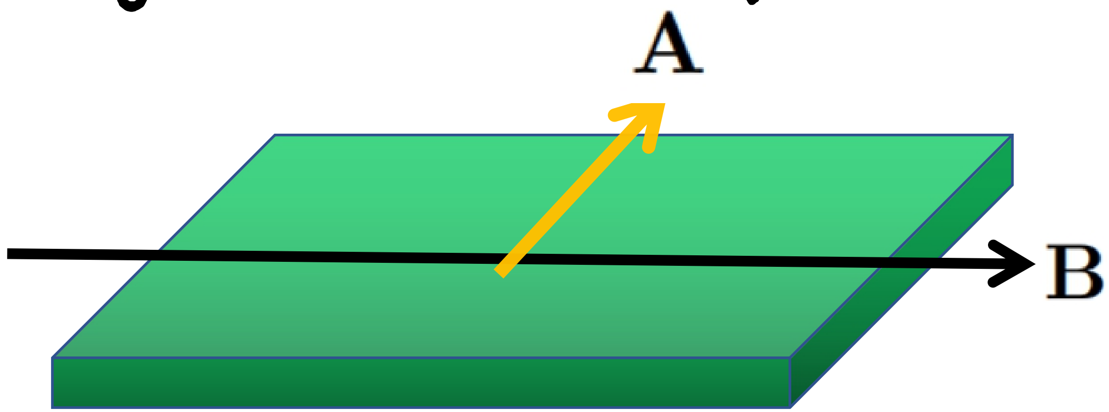


figure out role of inplane B



$$\mathbf{A} = \mathbf{z} \times \mathbf{B}$$

$$k = \sqrt{\langle A_x^2 \rangle} = dH/\sqrt{6}.$$

[Vadimov and Silaev, PRL **111**, 177001 (2013)]

Ginzburg-Landau Lagrange density

$$\mathbf{A} = \mathbf{z} \times \mathbf{B}$$

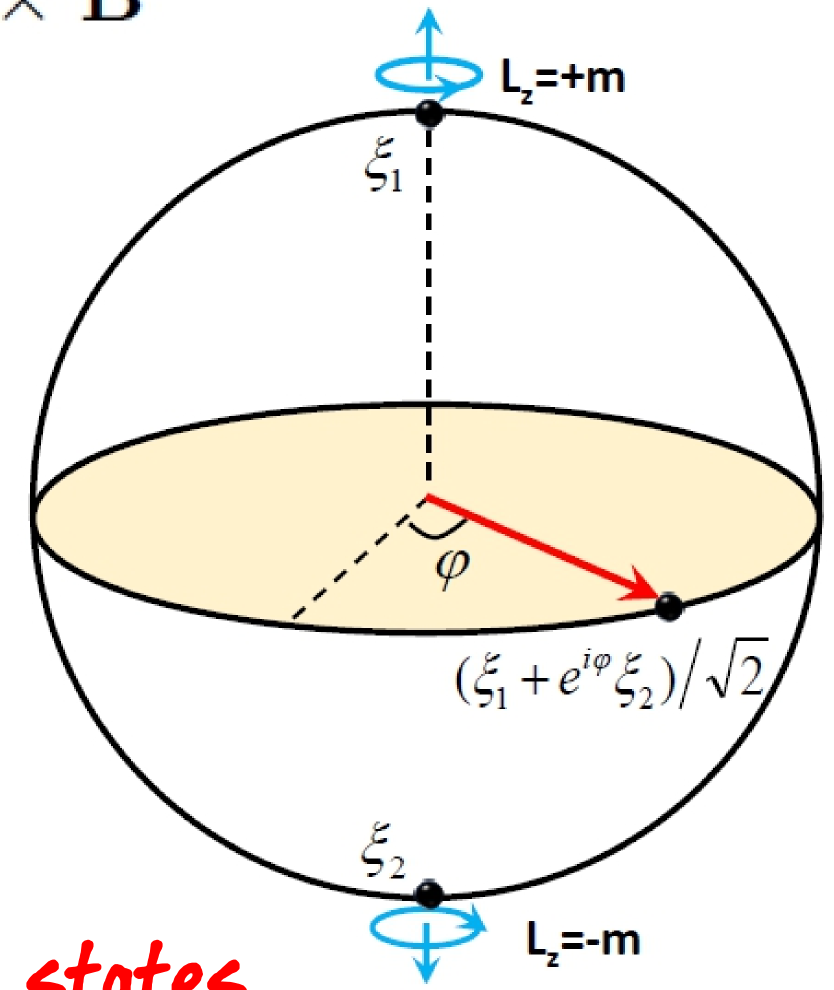
$$\mathcal{L}_{\text{eff}}(\mathbf{r}) = \alpha \sum_{\mu=1,2} |\psi_\mu(\mathbf{r})|^2$$

$$+ \beta \sum_{\nu=x,y} \sum_{\mu=1,2} \left(\partial_\nu + \frac{2e}{i\hbar}\mathbf{A}_\nu\right) \psi_\mu^* \left(\partial_\nu - \frac{2e}{i\hbar}\mathbf{A}_\nu\right) \psi_\mu$$

$$+ \gamma_1(1 - i\sqrt{3}) \left(\partial_+ - \frac{2e}{i\hbar}\mathbf{A}_+\right) \psi_2^* \left(\partial_+ - \frac{2e}{i\hbar}\mathbf{A}_+\right) \psi_1$$

$$+ \gamma_1(1 + i\sqrt{3}) \left(\partial_- + \frac{2e}{i\hbar}\mathbf{A}_-\right) \psi_2 \left(\partial_- + \frac{2e}{i\hbar}\mathbf{A}_-\right) \psi_1^*$$

$$+ \lambda_1 \left(|\psi_1(\mathbf{r})|^2 + |\psi_2(\mathbf{r})|^2\right)^2 + \lambda_2 \left(|\psi_1(\mathbf{r})|^2 - |\psi_2(\mathbf{r})|^2\right)^2$$

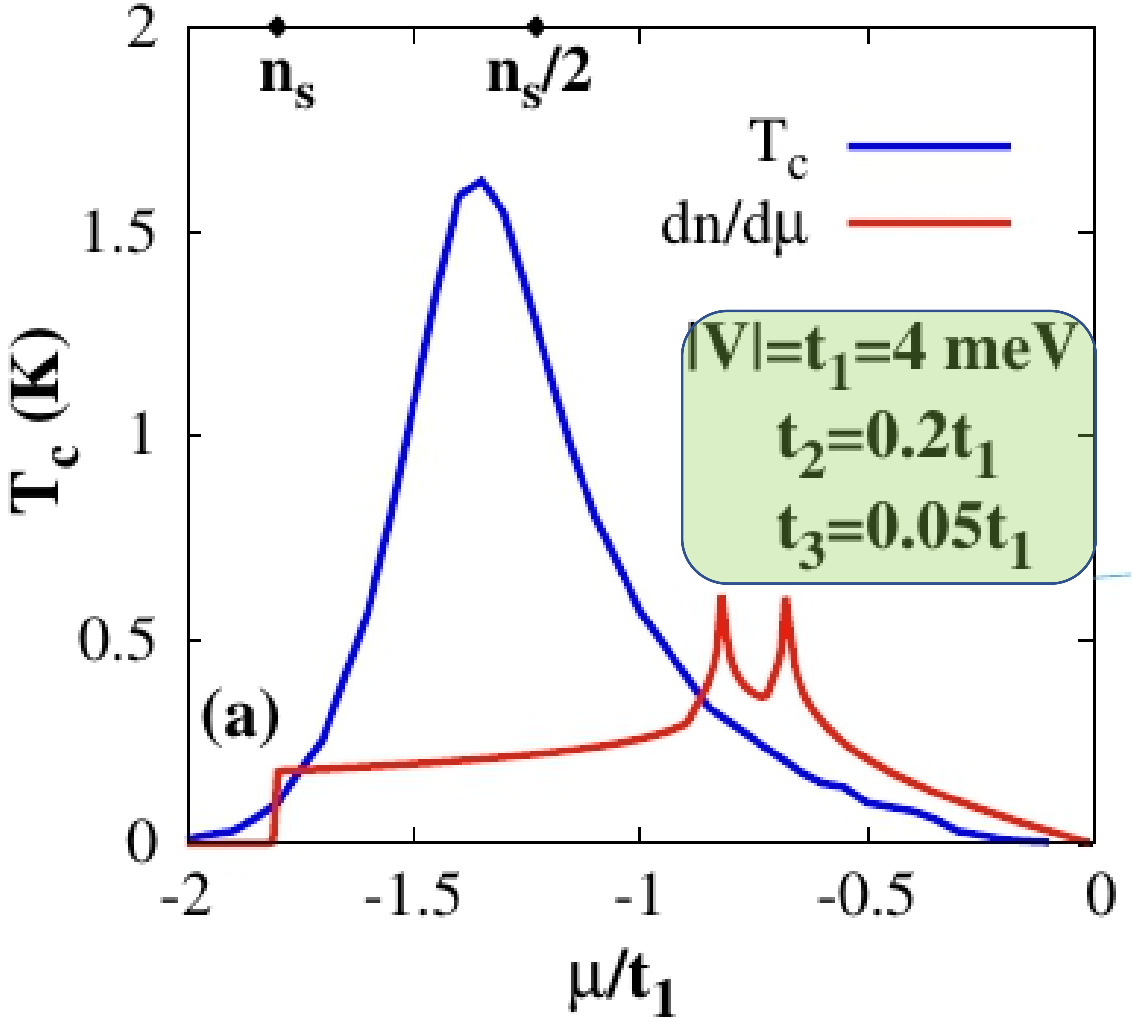


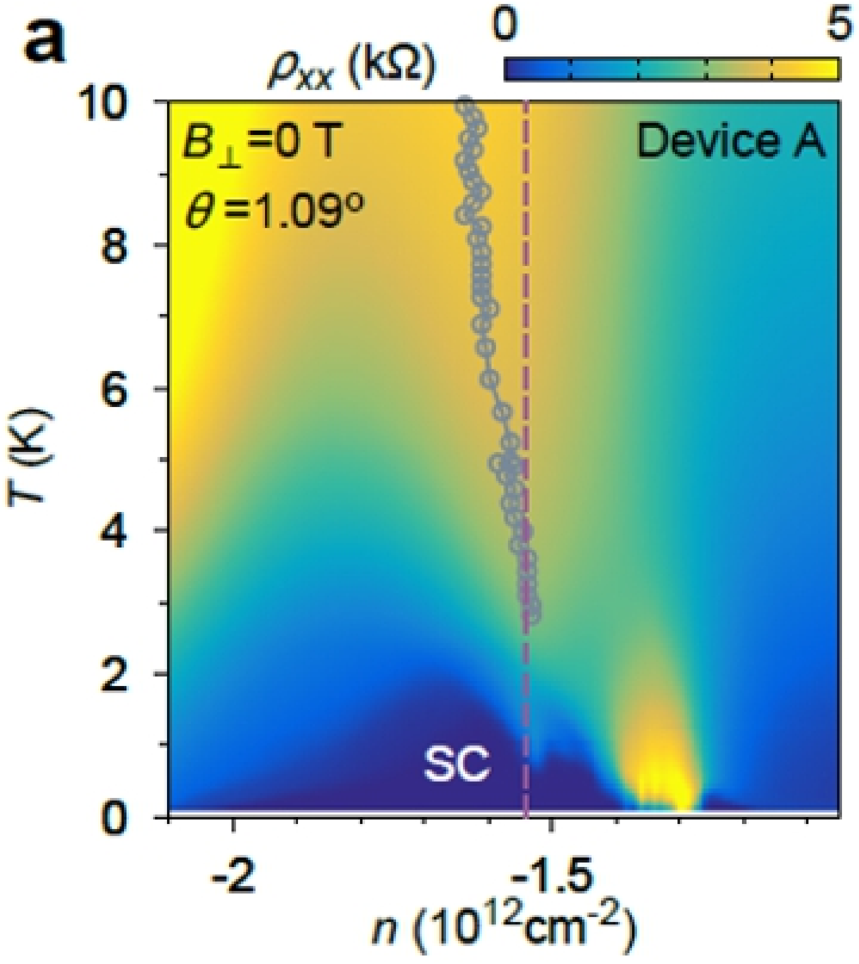
New ground state: a superposition of two chiral states

$$\psi_2 = \psi_1 e^{i\varphi} \longrightarrow 2\theta_B$$

Parameters ➡ Superconducting dome (from tight-binding model)

[**TY**, D. Kennes, A. Rubio, and M. Sentef, arXiv: 2101.01426]



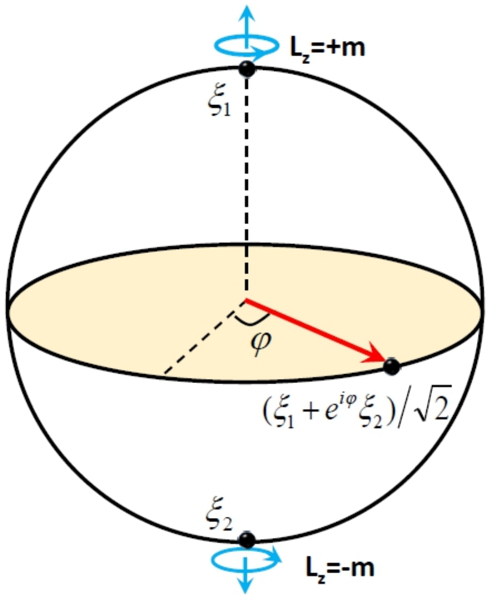


[Yuan, Fu *et al.*, PRB **98**, 045103 (2018); PRX **8**, 031087 (2018)]

New Lagrange

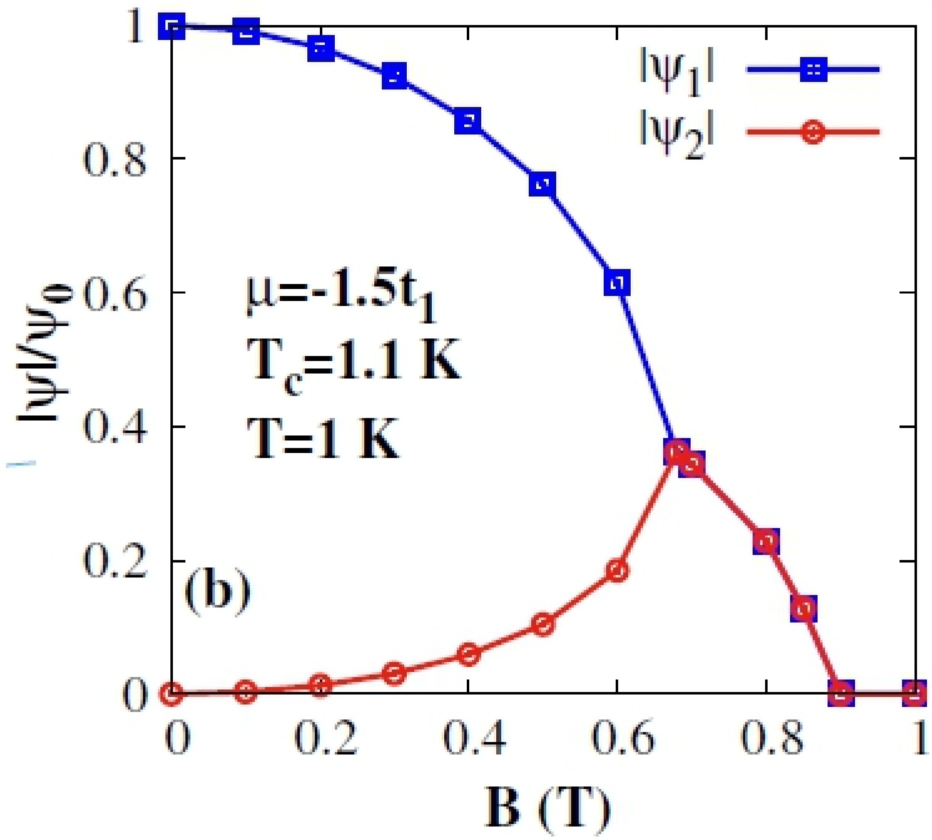
$$F = \int d\mathbf{r} \psi^*(\mathbf{r}) \mathcal{H}(\hat{\mathbf{r}}, t) \psi(\mathbf{r}).$$

$$\mathcal{H}(\hat{\mathbf{r}}, t) = \alpha - \sum_{\mu\nu} \tilde{c}_{\mu\nu} \left(\partial_\mu - \frac{2e}{i\hbar} \mathbf{A}_\mu \right) \left(\partial_\nu - \frac{2e}{i\hbar} \mathbf{A}_\nu \right)$$



stiffness is anisotropic

$$\tilde{c}_{xx} = \beta + 2\gamma_1 \cos(2\theta_B),$$
$$\tilde{c}_{yy} = \beta - 2\gamma_1 \cos(2\theta_B),$$
$$\tilde{c}_{xy} = \tilde{c}_{yx} = 2\gamma_1 \sin(2\theta_B).$$



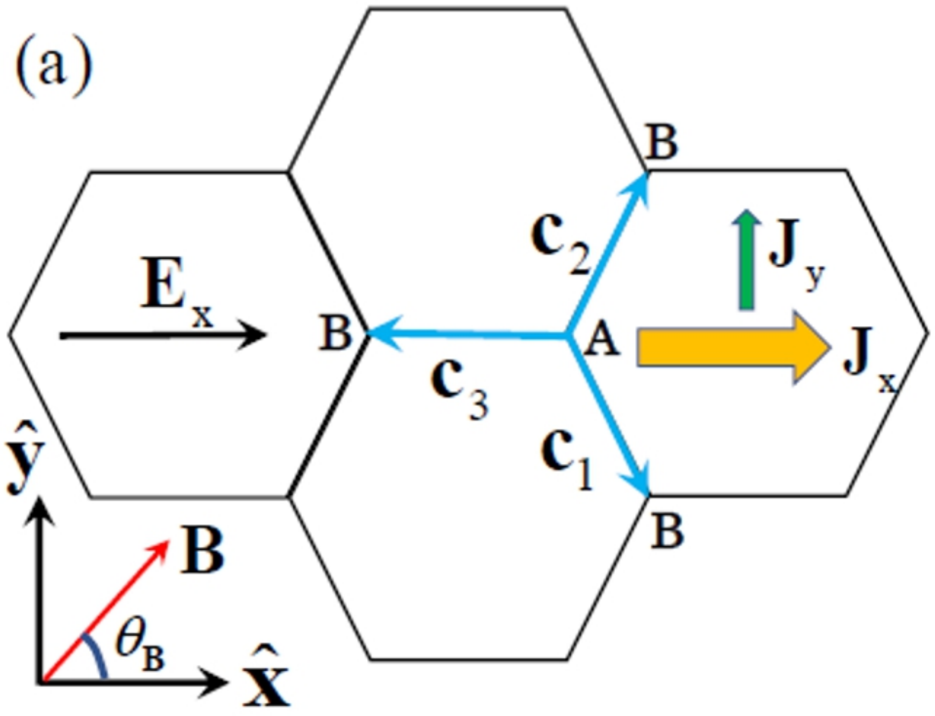
Nematic and Hall paraconductivity

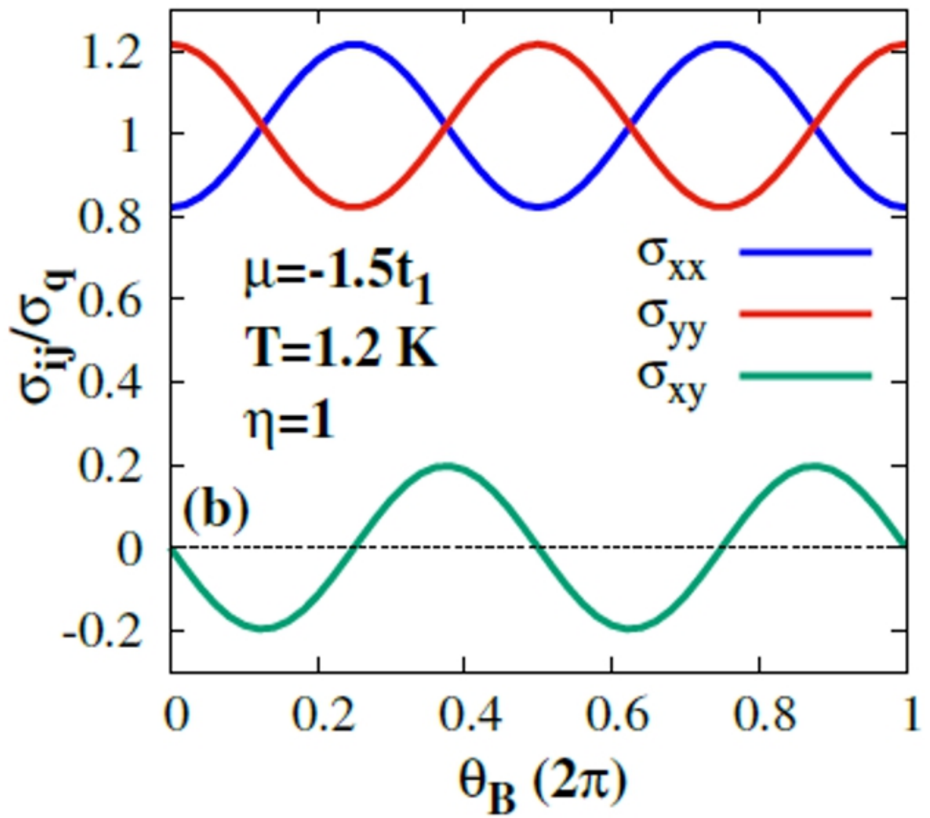
$$\Gamma\partial_t\psi(\mathbf{r},t) = -\mathcal{H}(\hat{\mathbf{r}},t)\psi(\mathbf{r},t) + f(\mathbf{r},t)$$

→ thermal noise

$$\sigma_{ij} = k_B T \frac{e^2\Gamma}{2\pi\hbar^2\alpha} \frac{\tilde{c}_{ij}}{\sqrt{\beta^2 - 4\gamma_1^2}}$$

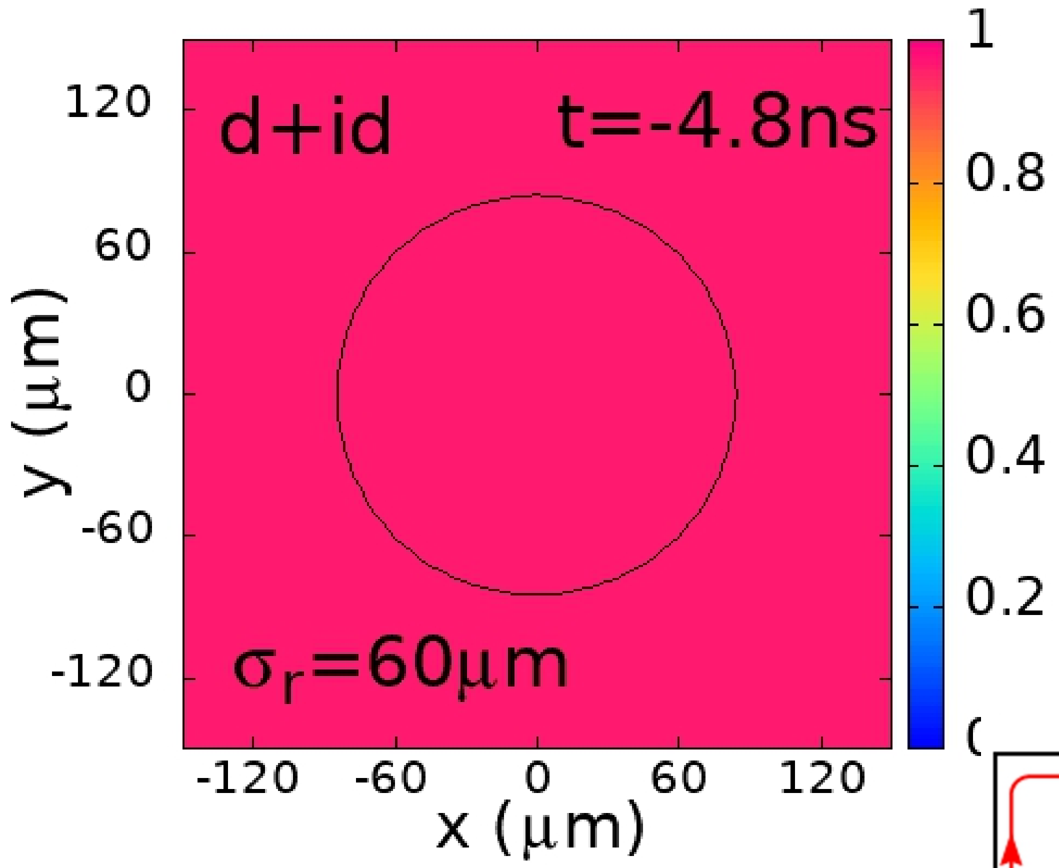
$$\tilde{c}_{xx} = \beta + 2\gamma_1 \cos(2\theta_{\mathrm{B}}),$$
$$\tilde{c}_{yy} = \beta - 2\gamma_1 \cos(2\theta_{\mathrm{B}}),$$
$$\tilde{c}_{xy} = \tilde{c}_{yx} = 2\gamma_1 \sin(2\theta_{\mathrm{B}}).$$

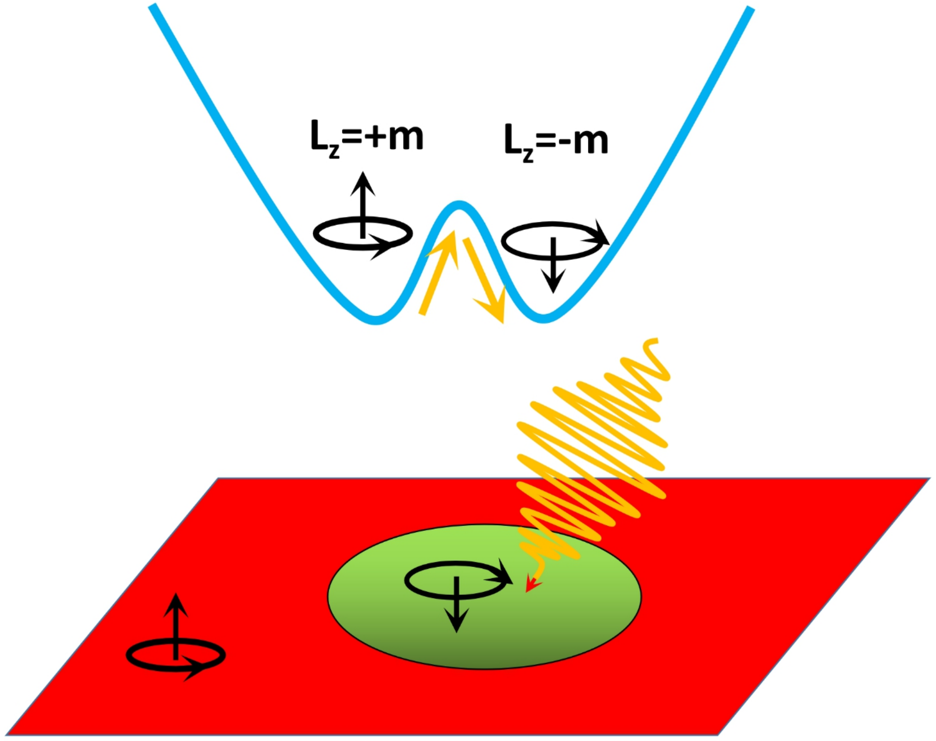




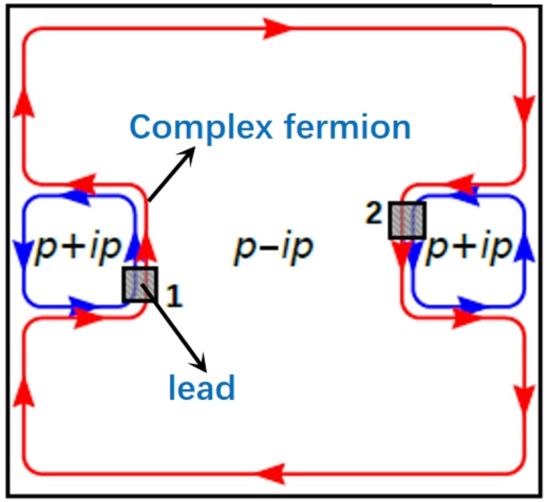
Optical pulse ⟹ chirality switching

[Classen *et al.*, NP **15**, 766 (2019); **TY**, Classen, Dante, and Sentef, PRR **3**, 013253 (2021)]



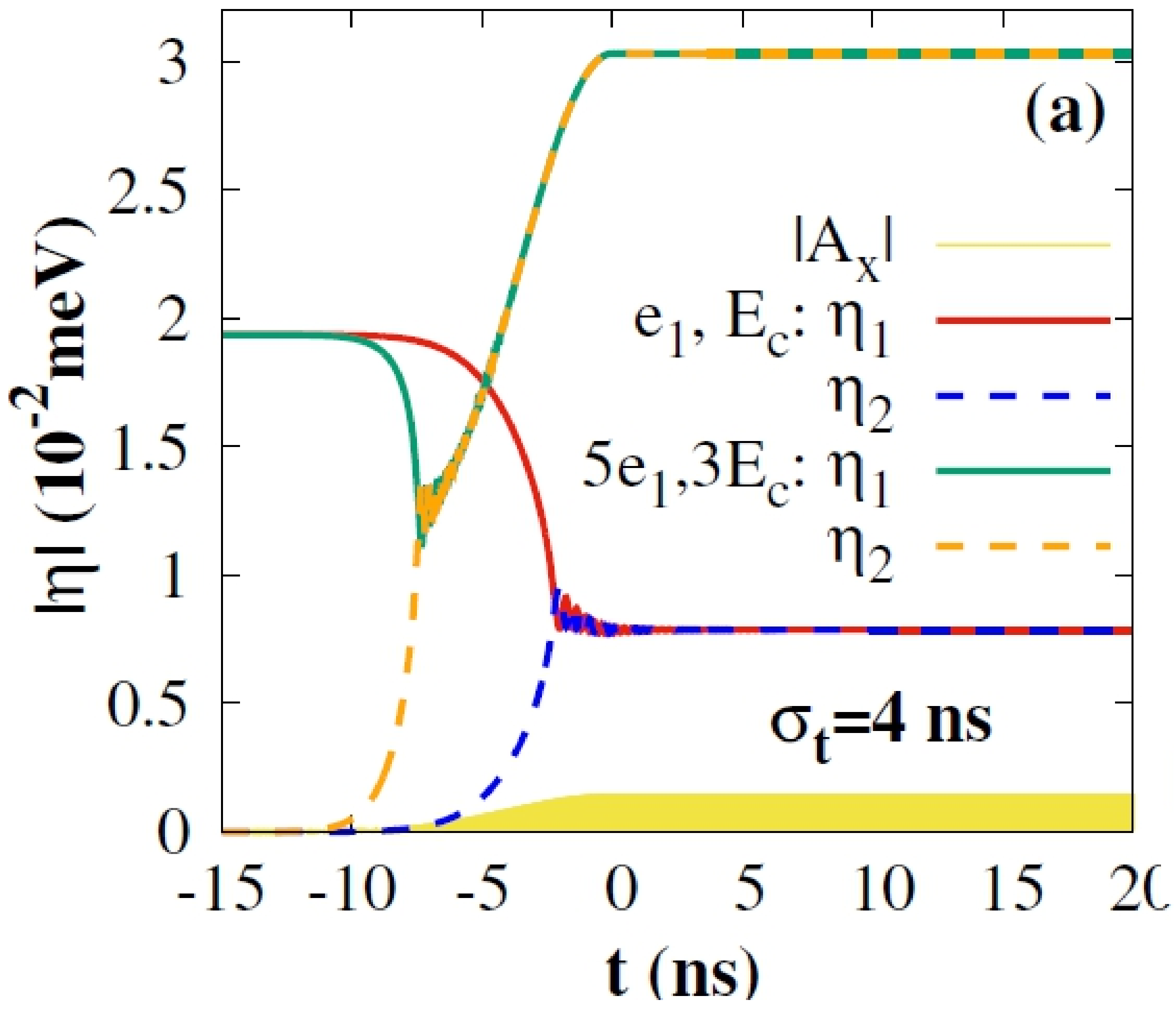


$$|1\rangle\,|0\rangle \rightarrow \frac{1}{\sqrt{2}}\left(|1\rangle\,|0\rangle + |0\rangle\,|1\rangle\right)$$



[Lian *et al.*, Proc. Natl. Acad. Sci. USA **115**, 10938 (2018)]

We can optically enhance the chiral superconductivity



$$
\begin{aligned}
\mathcal{L}_{\rm eff}(\mathbf{r}) = & \sum_{\mu=1,2} \Gamma_\mu \eta_\mu^*(\mathbf{r}) D_t \eta_\mu(\mathbf{r}) + \sum_\mu \Lambda_\mu |D_t \eta_\mu(\mathbf{r})|^2 \\
& + a \sum_\mu |\eta_\mu(\mathbf{r})|^2 + b \sum_{\alpha=x,y} \sum_\mu |D_\alpha \eta_\mu(\mathbf{r})|^2 \\
& + e_1 (1 - i\sqrt{3}) [D_+ \eta_2^*(\mathbf{r})] [D_+ \eta_1(\mathbf{r})] \\
& + e_1 (1 + i\sqrt{3}) [D_+^* \eta_2(\mathbf{r})] [D_+^* \eta_1^*(\mathbf{r})] \\
& + f_1 \left(|\eta_1|^2 + |\eta_2|^2\right)^2 + f_2 \left(|\eta_1|^2 - |\eta_2|^2\right)^2 .
\end{aligned}
$$

$$
|\tilde{\eta}_{1,2}| = \sqrt{\frac{1}{4 f_1}\left(-a + 2(2e_1 - b)\left(\frac{eE_x}{\hbar\omega}\right)^2\right)};
$$

Spatial fluctuation between different/same order parameters

Conclusions

1) Chiral superconductivity might be supported rather than ruled out by experiments in MATBG (arXiv: 2101.01426)

2) Optical field can locally switch the chirality of Cooper pairs that holds potential in quantum computing [PRR **3**, 013253 (2021)]

3) The theories are general that can be applied to other potential materials, e.g., UPt_3, UTe_2, Sr_2RuO_4.

Thank you!