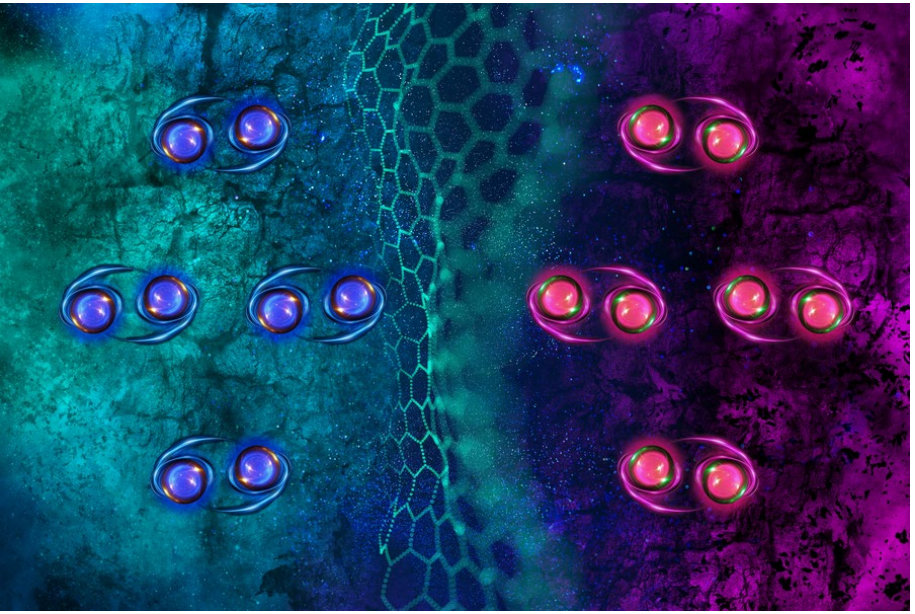
Massachusetts Institute of Technology

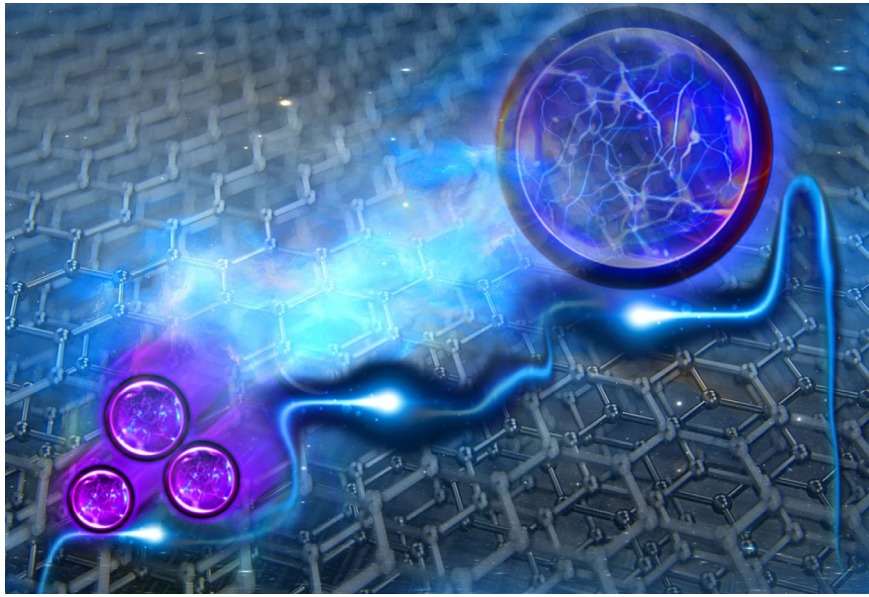
Chiral and Other Unconventional Superconductivities in Graphene



Long Ju, MIT

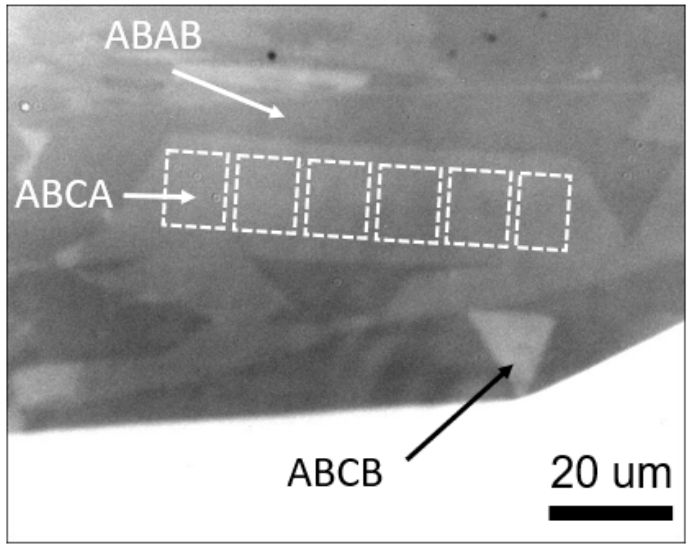
Unconventional Superconductors And Magnets Workshop, SPICE

05-14-2026

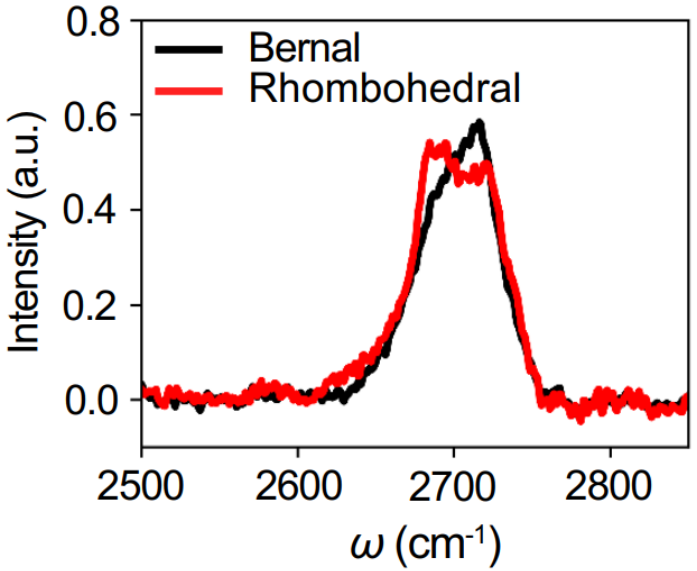


Seeing Stacking Orders in Crystalline Multilayer Graphene

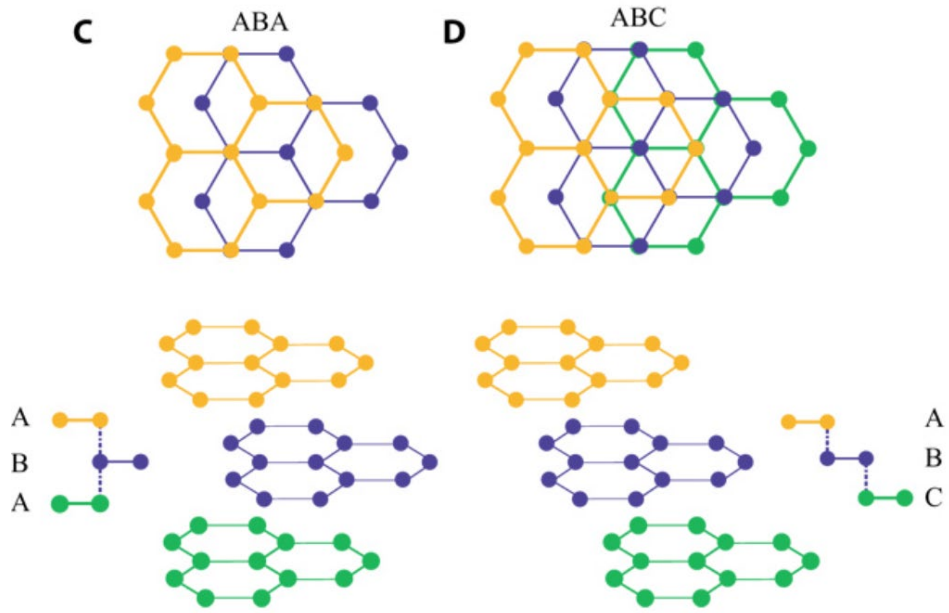
Infrared contrast by InGaAs camera



Raman signatures



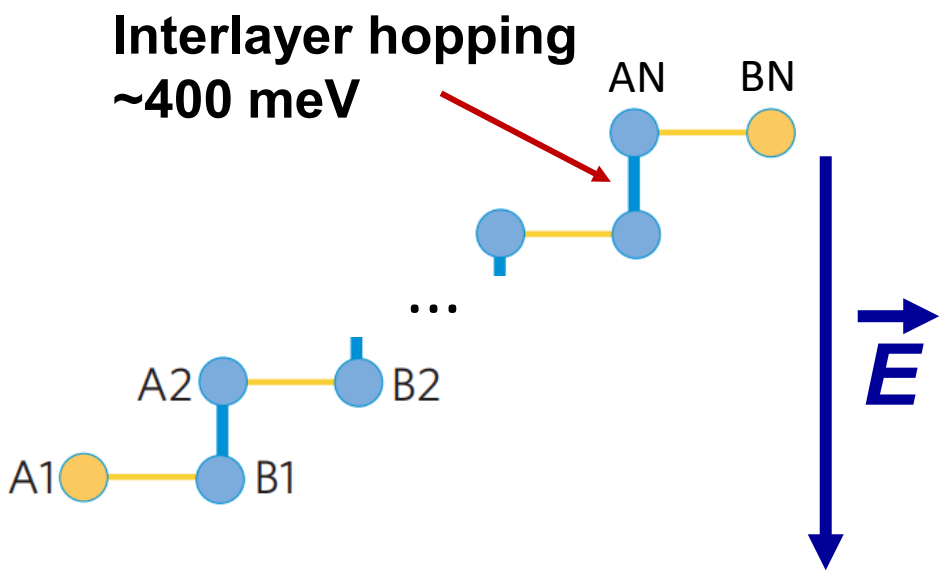
Z. Lu… LJ, *Nature* 2025



Bernal (stable) **Rhombohedral (meta-stable)**

Lui, C.H., Heinz, T.F. *Nano letters*, *11*(1) (2011).

Gate-Tunable Flat Bands in Crystalline Rhombohedral Graphene

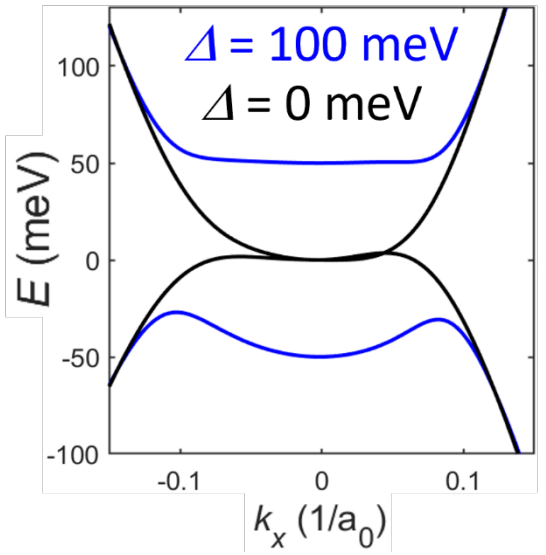


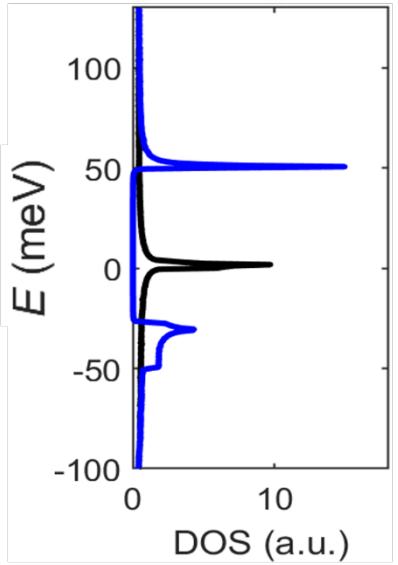
$E \sim \pm |k|^N$

Min, H. and MacDonald, A.H. *PRB* (2008)

Zhang, F. et al. *PRB* (2010)

Semi-metal $\xrightarrow{E}$ Semi-conductor



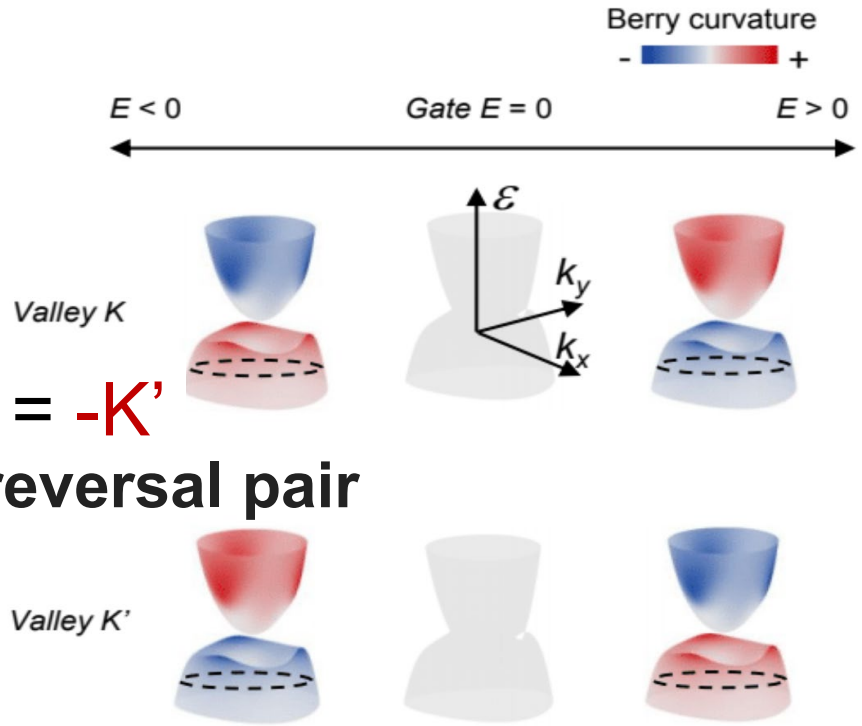


1. **Pristine flat bands**
2. **Gate-induced flat bands**

Gate-Tunable Quantum Geometry/Berry Curvature ('Magnetic field' in k-space)

Berry curvature

$$\Omega(k) = \nabla_k \times < u_k | i\nabla_k | u_k >$$

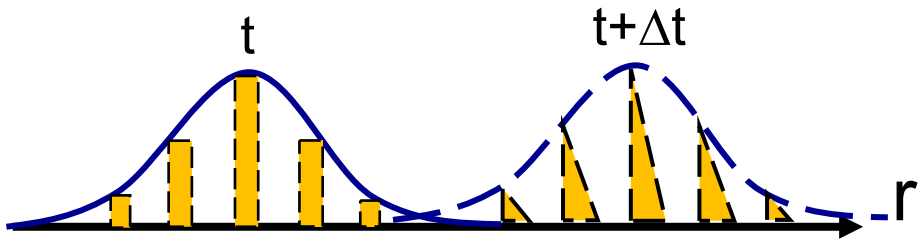


K = -K'

Time-reversal pair

T. Han, Z. Lu … LJ. *Nature* (2023)

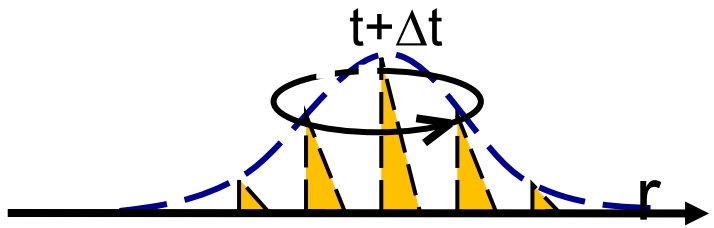
Xiao, D., Yao, W. and Niu, Q. *PRL* (2007)



$$\sigma_{xy} = \frac{e^2}{2\pi h} \int \Omega(k)\, dk$$

Anomalous Hall Effect

Karplus & Luttinger, 1954



Angular momentum & Orbital magnetic moment

Chang & Niu, 1996

Spontaneous Valley Symmetry Breaking: Correlation Helps Topology

Without flat band

$$\sigma_{xy} = 0$$

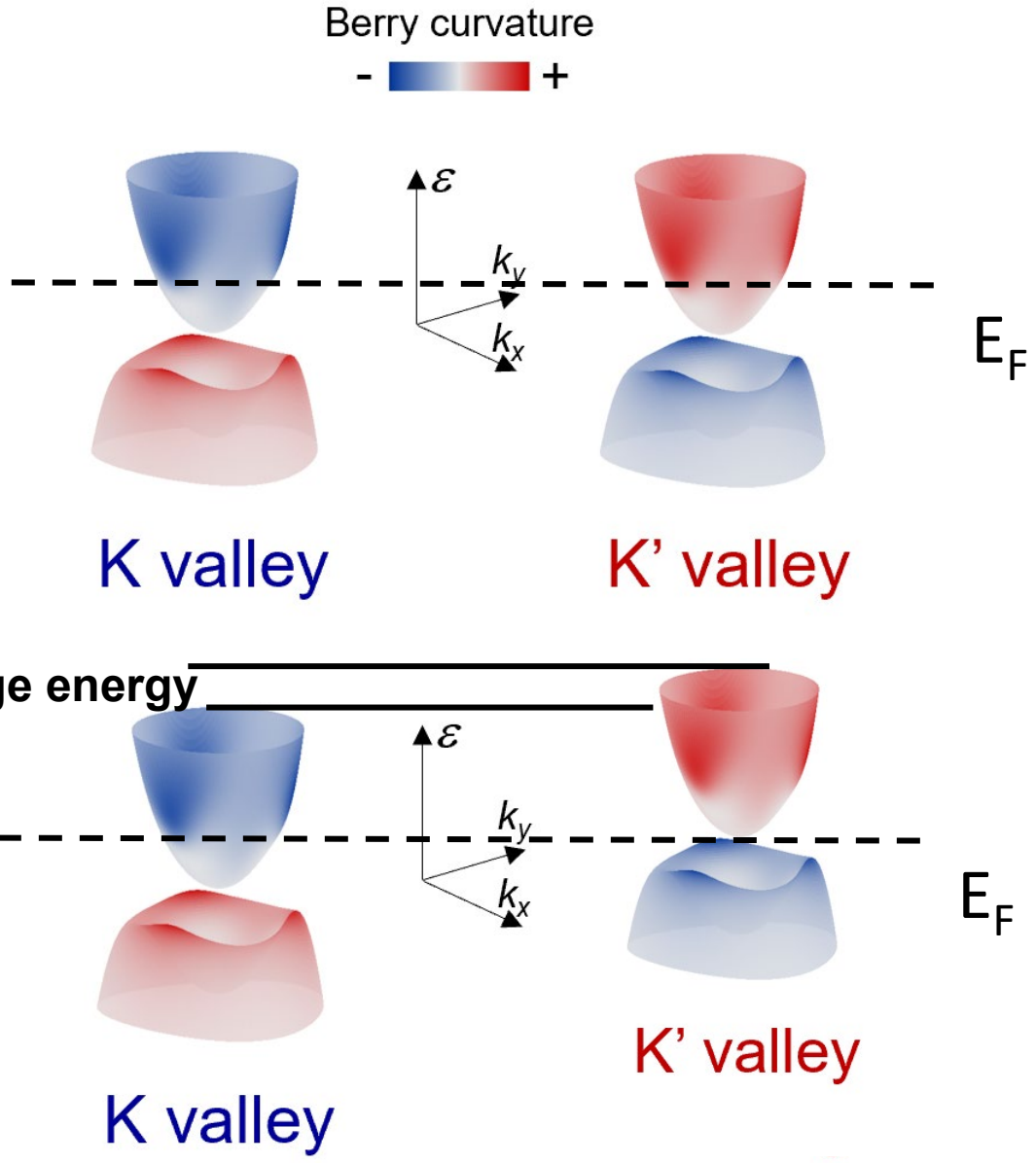
$$m = 0$$

With flat band

$$\sigma_{xy} \neq 0$$

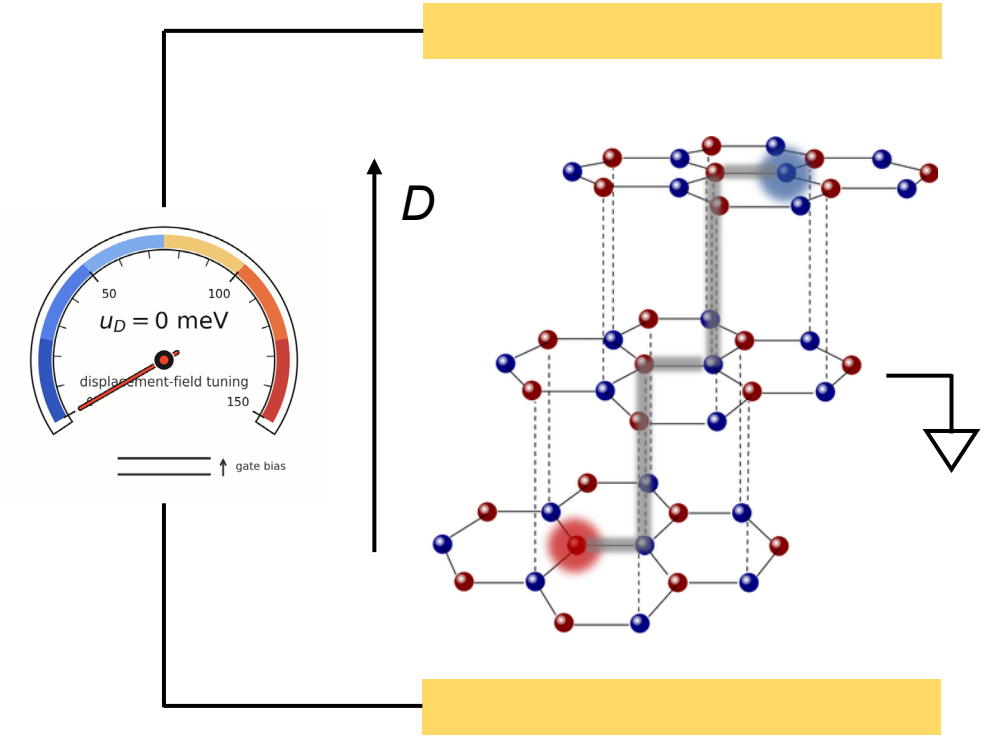
$$m \neq 0$$

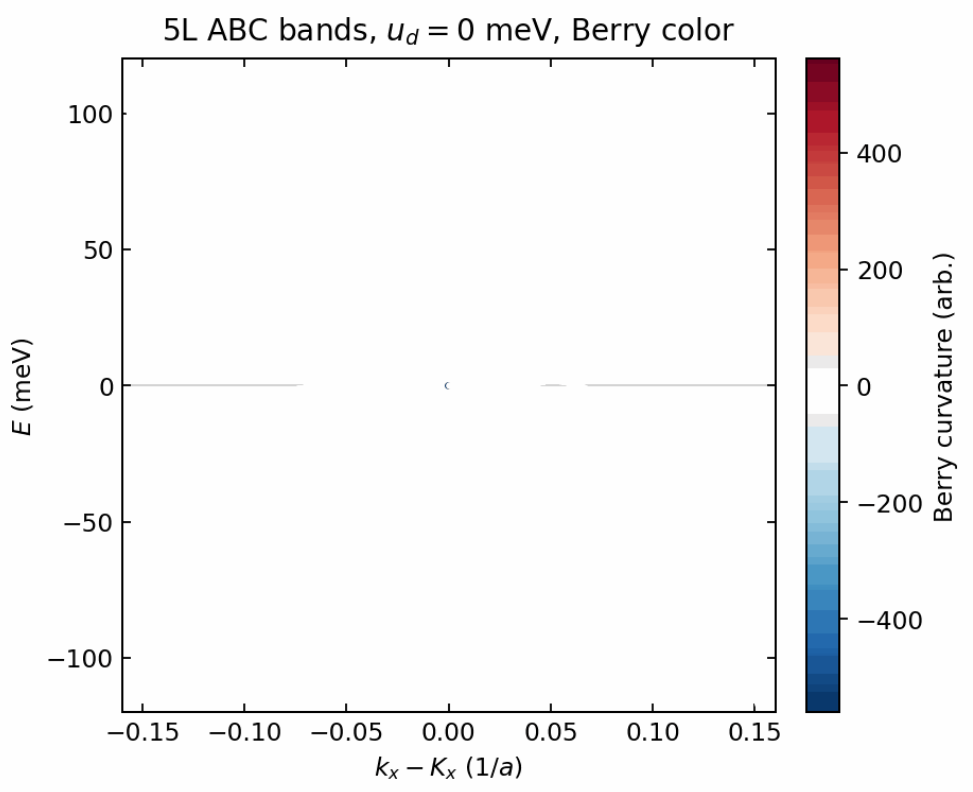
Similar to the Stoner Mechanism for ferromagnet

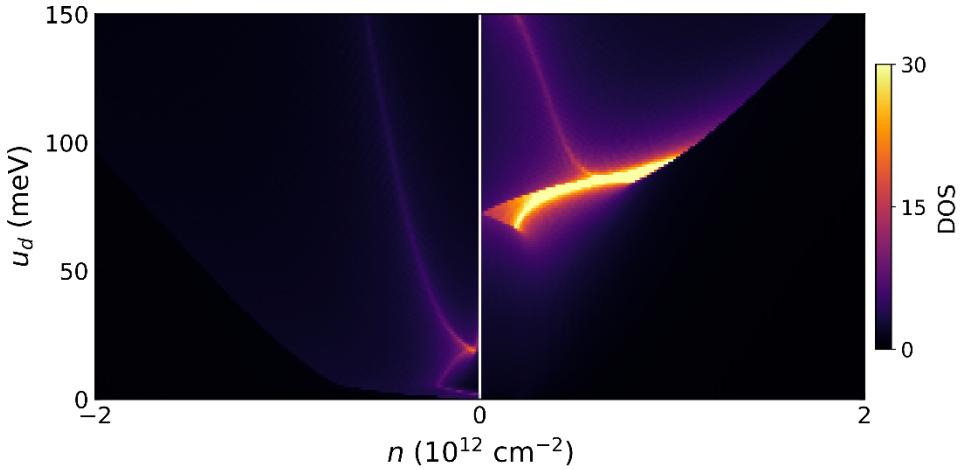


Zhou. H. et al. *Nature* 598.7881 (2021): 429-433.

Gate-Tunable Flat Bands and Berry Curvatures





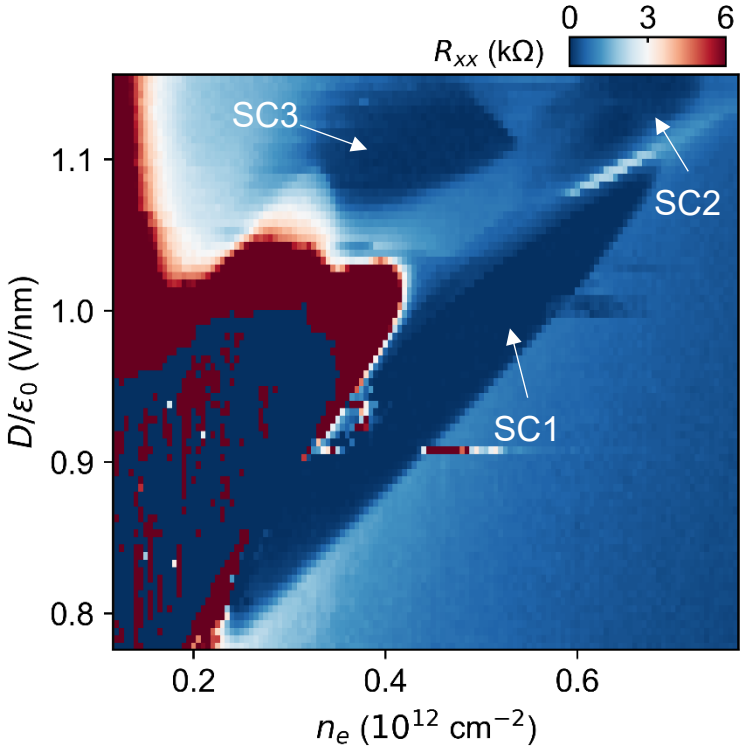


Tonghang Han

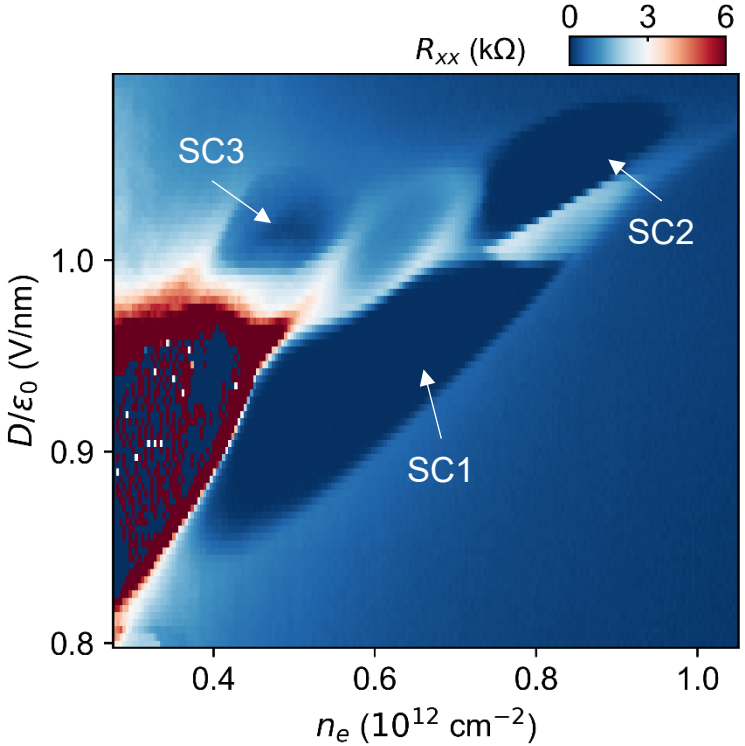
Superconductivity in Electron-Doped 4-6L RG

Zhengguang Lu @FSU

4LG - ABCA

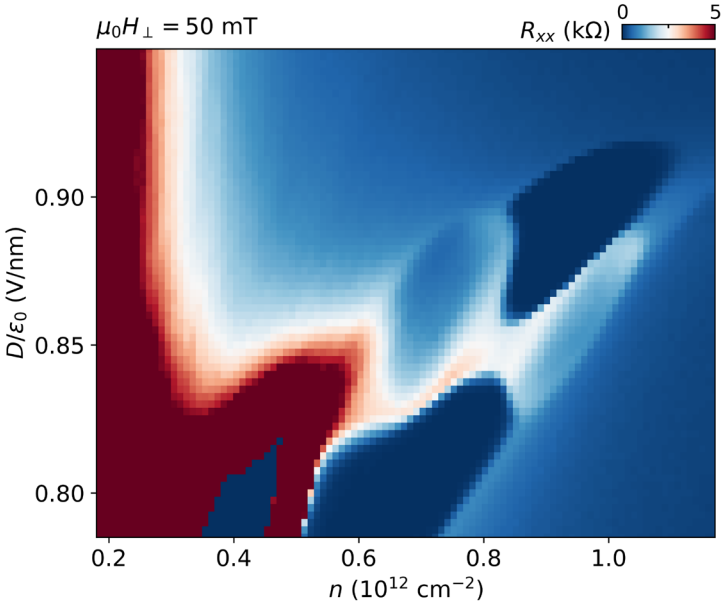


5LG - ABCAB



T. Han, Z. Lu, Z. Hadjri… LJ, Nature (2025)

6LG - ABCAB



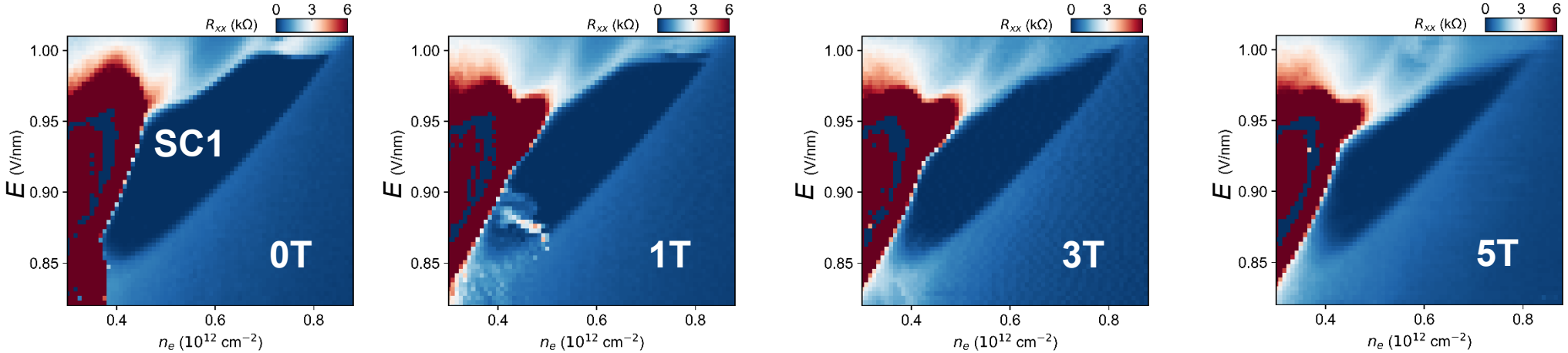
Unpublished

See also 6L work From Leo Li @UT Austin

Magnetic Field Dependence

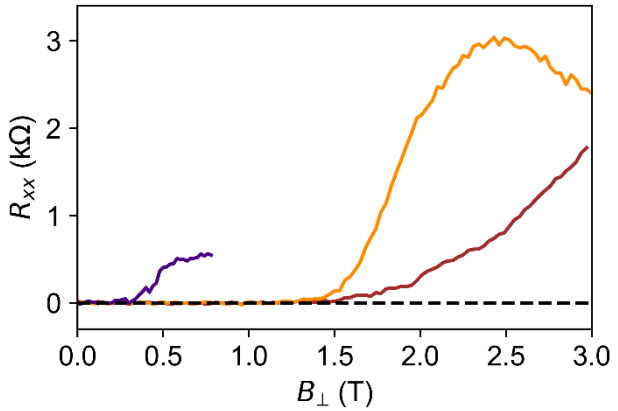
5L Device: T_c = 180mK, B_{Pauli} ~0.34 T

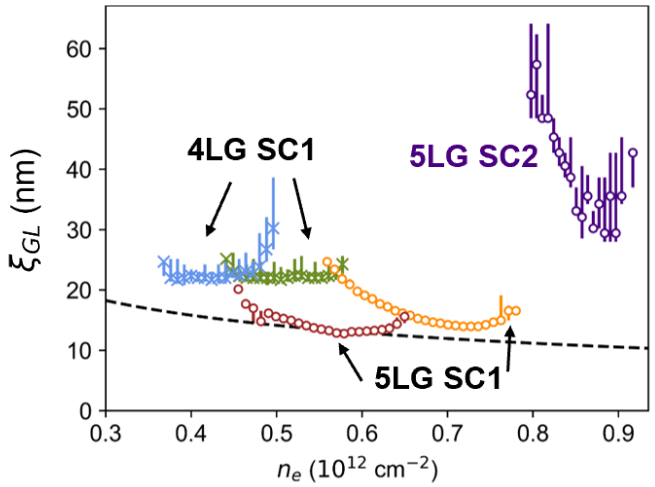
In-plane Field $B_{//}$



Exceeding the Pauli limit by at least 15 times **suggests spin-polarization**

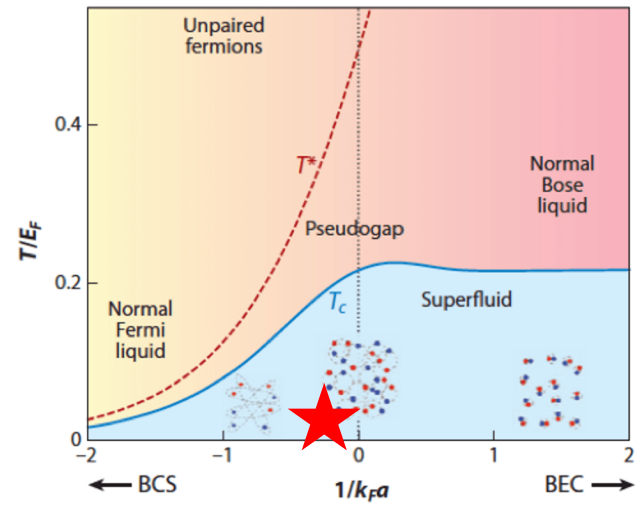
Out-of-plane Field $B_\perp$





$$\xi_{GL} = \left(\frac{\Phi_0}{2\pi B_{\perp,c}}\right)^{\frac{1}{2}} \qquad \Phi_0 = \frac{h}{2e}$$

BCS-BEC cross-over

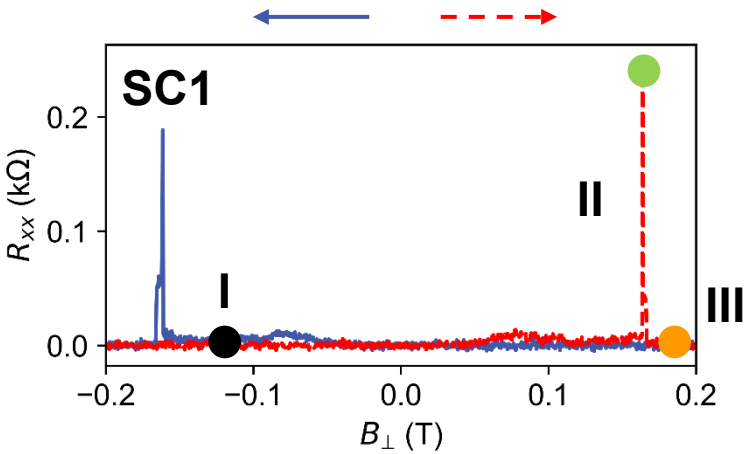


VOLUME 71, NUMBER 19 PHYSICAL REVIEW LETTERS 8 NOVEMBER 1993

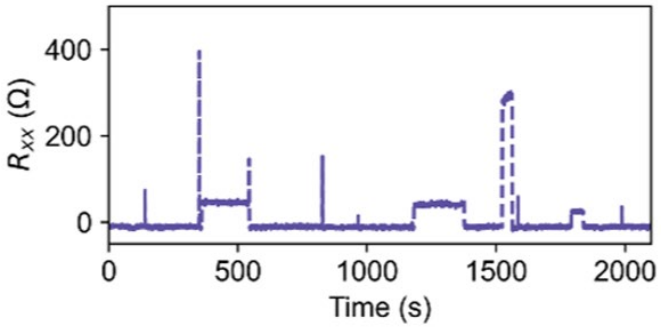
Crossover from BCS to Bose Superconductivity: Transition Temperature and Time-Dependent Ginzburg-Landau Theory

C. A. R. Sá de Melo,[1] Mohit Randeria,[2] and Jan R. Engelbrecht[3]

Magnetic Hysteresis and Fluctuations



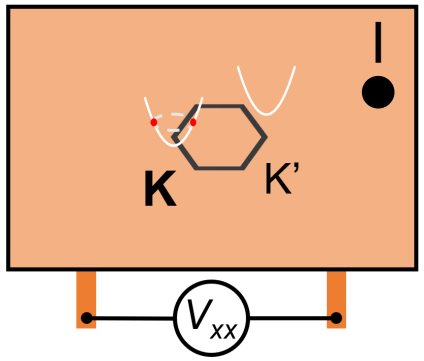
Hysteresis

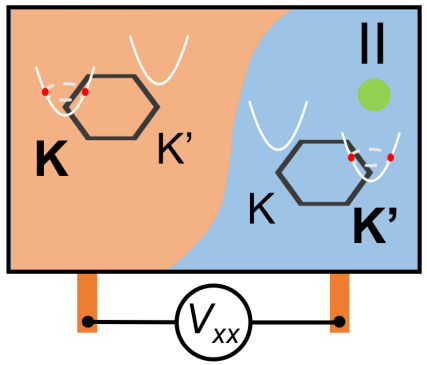


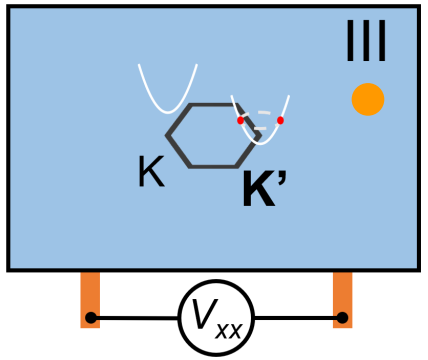
Fluctuations

Behaves like a magnet!

Unique among all superconductors!

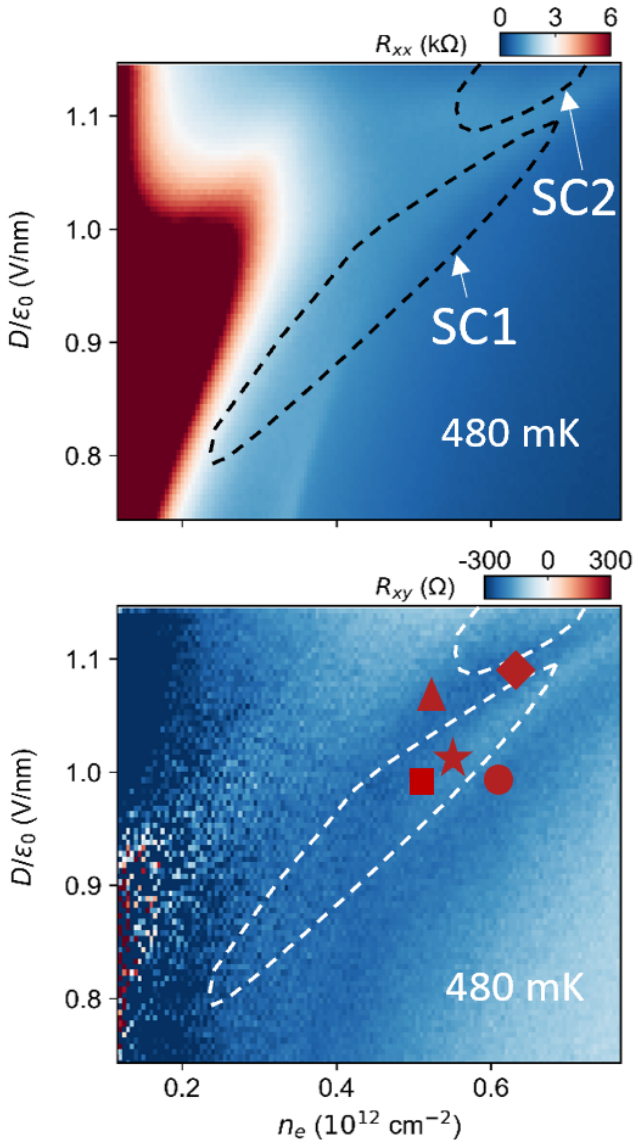


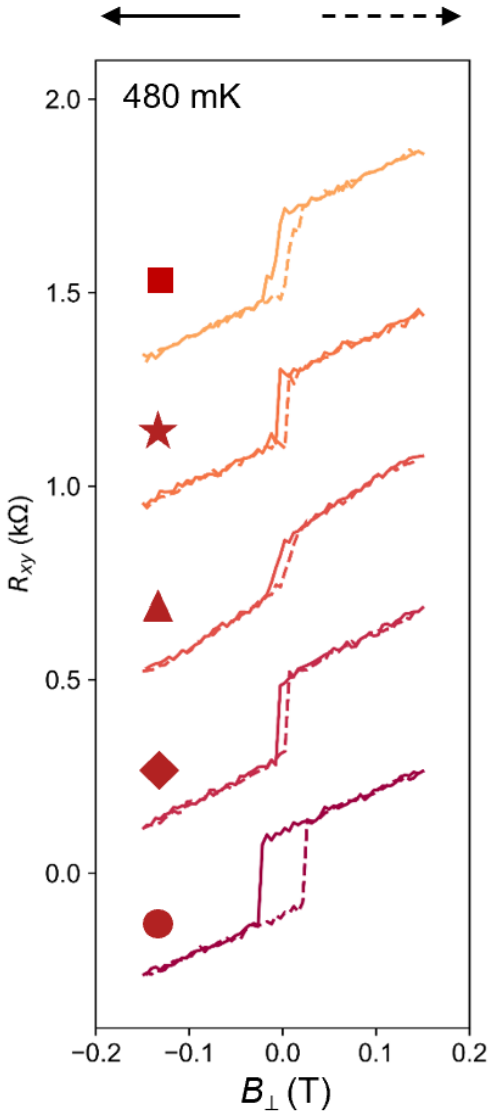


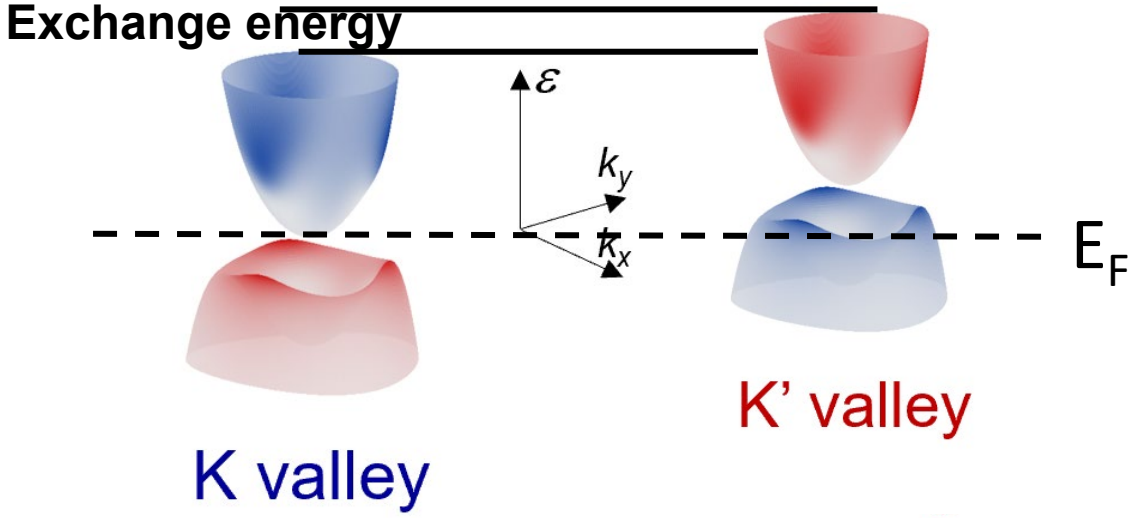


Superconducting state is valley polarized

Anomalous Hall and Hysteresis Above T_c







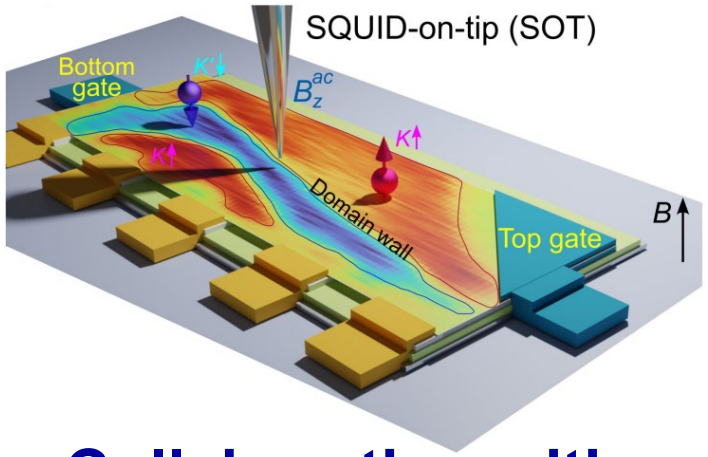
Unique among all superconductors!

Parent state of SC is orbital magnetic (valley polarized)

Direct Imaging of Magnetism and Domains in SC State

Eli Zeldov

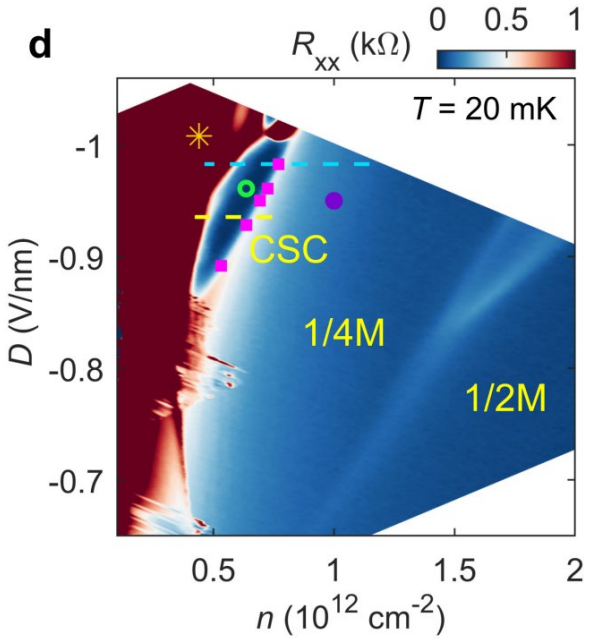
Surajit Dutta

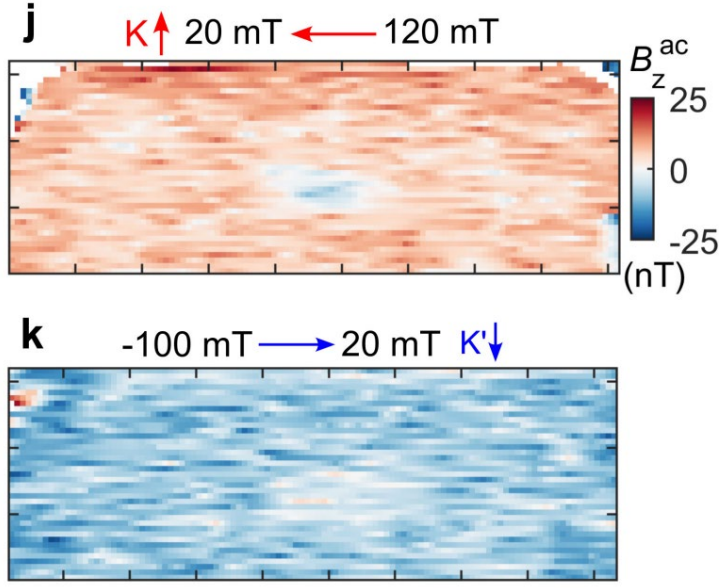


Collaboration with Zeldov group

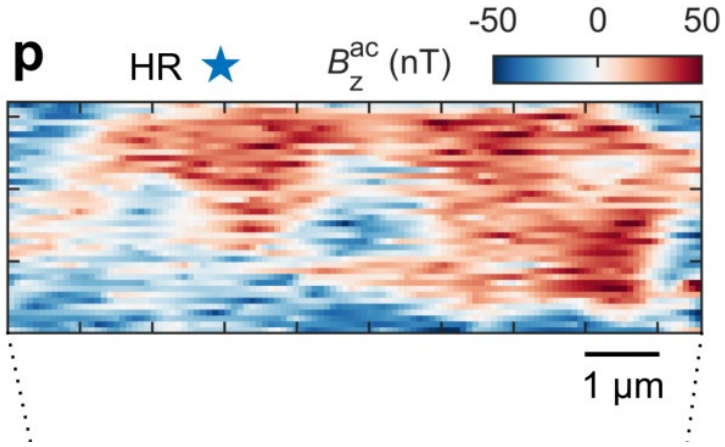
arXiv:2605.13303

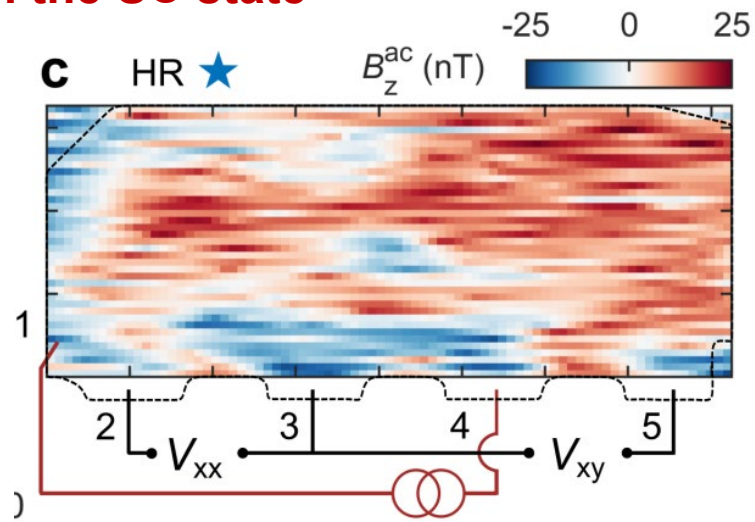
Direct detection of magnetic field from the SC state



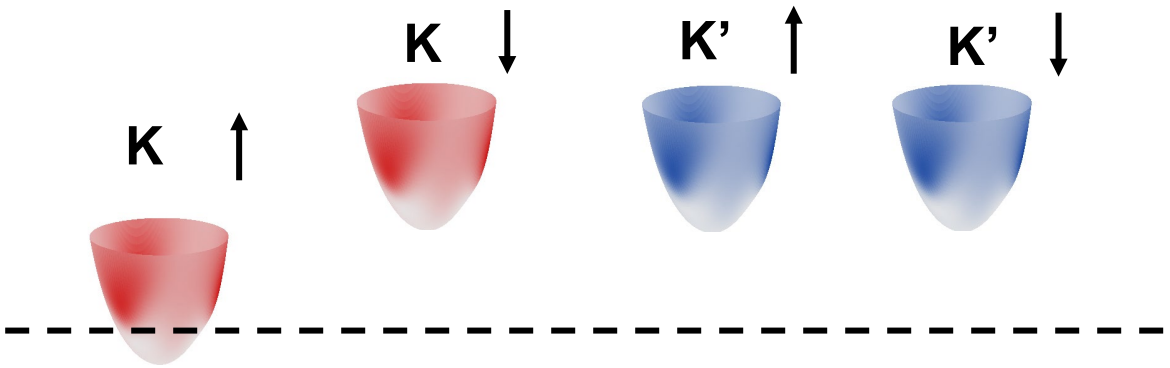


Magnetic domains in the SC state





Spin- and valley-polarized superconductivity?!



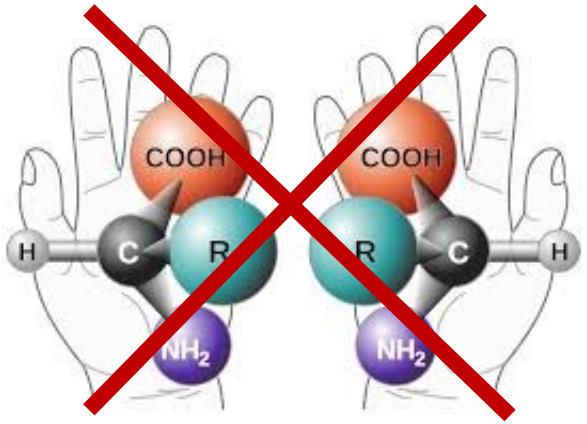
Valley polarized quarter-metal

Implications:

1. **Spin triplet**
2. **Finite momentum pairing**

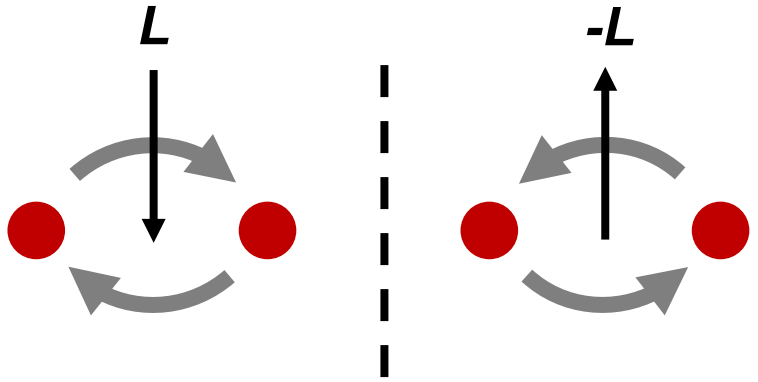
3. **Chiral superconductor (time-reversal-symmetry breaking at the orbital level)**

Chiral molecules



Break mirror symmetry

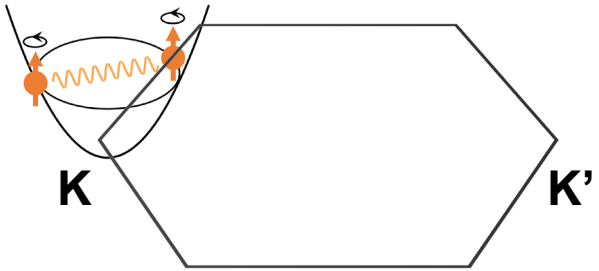
Chiral superconductor



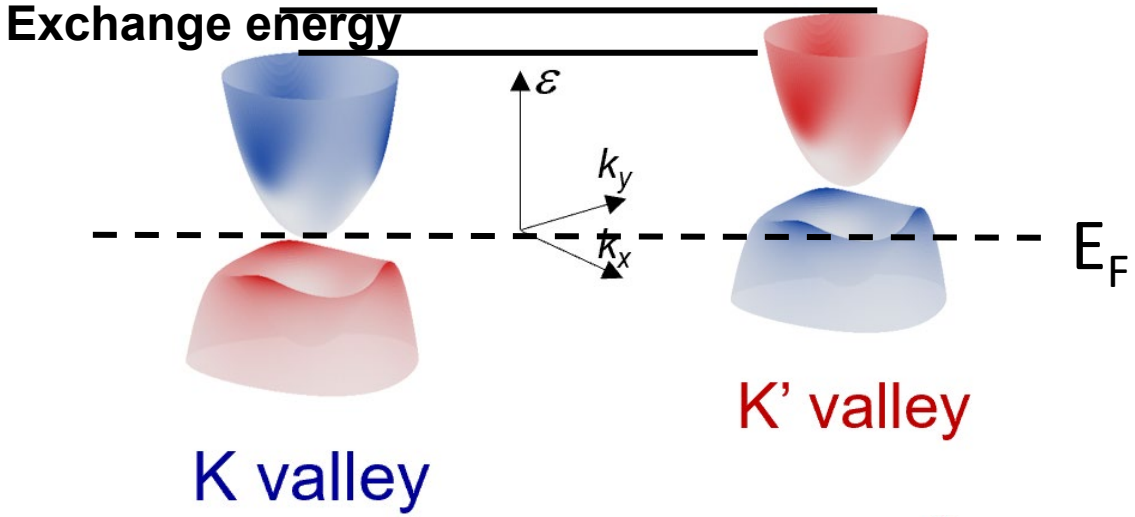
Break mirror symmetry (P)

Break time-reversal symmetry (T)

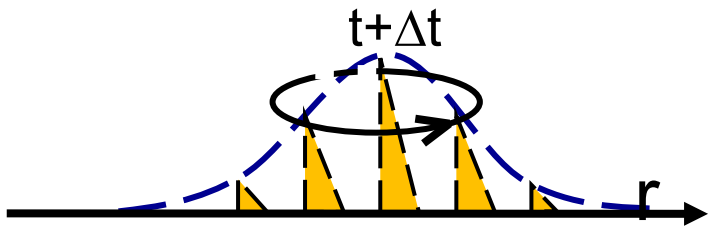
Chiral Superconductivity in Rhombohedral Graphene



Kallin, Catherine, and John Berlinsky. "Chiral superconductors." *Reports on Progress in Physics* 79.5 (2016): 054502.



Spontaneous time-reversal-symmetry broken at the orbital level (finite angular momentum)



To be explored:

1. **Is it topological? p_x+ip_y?**
2. **Pairing mechanism?**

Theory Developments Suggest Topological SC

arXiv:2409.06701 [pdf, other] cond-mat.supr-con cond-mat.mes-hall cond-mat.mtrl-sci cond-mat.str-el

Intravalley spin-polarized superconductivity in rhombohedral tetralayer graphene

Authors: Yang-Zhi Chou, Jihang Zhu, Sankar Das Sarma

arXiv:2409.13829 [pdf, other] cond-mat.supr-con cond-mat.mes-hall

Chiral and topological superconductivity in isospin polarized multilayer graphene

Authors: Max Geier, Margarita Davydova, Liang Fu

arXiv:2409.18067 [pdf, other] cond-mat.str-el cond-mat.supr-con doi 10.1103/PhysRevB.111.014508

Topological chiral superconductivity beyond pairing in a Fermi liquid

Authors: Minho Kim, Abigail Timmel, Long Ju, Xiao-Gang Wen

arXiv:2411.02503 [pdf, other] cond-mat.supr-con cond-mat.str-el

Topological incommensurate Fulde-Ferrell-Larkin-Ovchinnikov superconductor and Bogoliubov Fermi surface in rhombohedral tetra-layer graphene

Authors: Hui Yang, Ya-Hui Zhang

arXiv:2412.07145 [pdf, ps, other] cond-mat.supr-con cond-mat.str-el

Chiral finite-momentum superconductivity in the tetralayer graphene

Authors: Qiong Qin, Congjun Wu

arXiv:2502.17555 [pdf, other] cond-mat.mes-hall cond-mat.str-el cond-mat.supr-con

Quarter Metal Superconductivity

Authors: Chiho Yoon, Tianyi Xu, Yafis Barlas, Fan Zhang

arXiv:2502.19474 [pdf, other] cond-mat.str-el

Band Renormalization, Quarter Metals, and Chiral Superconductivity in Rhombohedral Te Graphene

Authors: Guillermo Parra-Martinez, Alejandro Jimeno-Pozo, Vo Tien Phong, Hector Sainz-Cruz, Daniel Kaplan, Peleg Yuval Oreg, Pierre A. Pantaleon, Jose Angel Silva-Guillen, Francisco Guinea

arXiv:2503.15471 [pdf, other] cond-mat.str-el cond-mat.supr-con

Finite-momentum pairing and superlattice superconductivity in valley-imbalanced rhombohedral graphene

Authors: Maine Christos, Pietro M. Bonetti, Mathias S. Scheurer

Spontaneous vortex lattice due to orbital magnetization in valley polarized superconductors

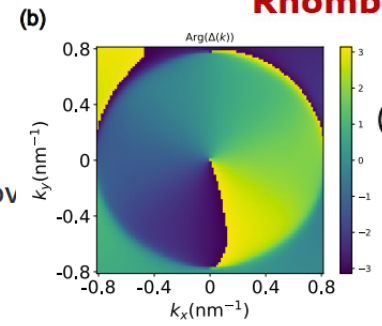
Ammar Jahin, Shi-Zeng Lin

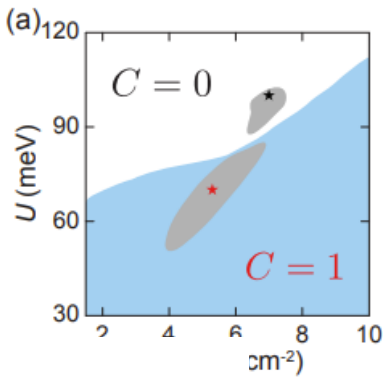
Journal Club for Condensed Matter Physics

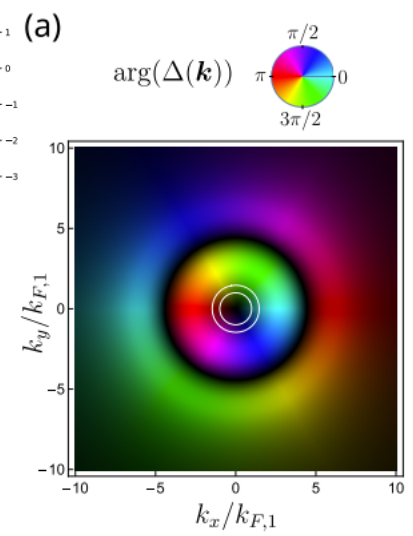
A Monthly Selection of Interesting Papers by Distinguished Correspondents

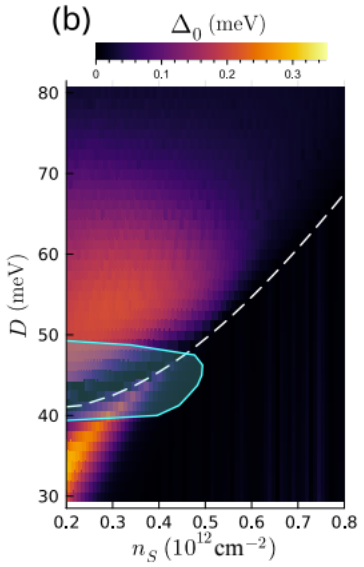
Home Organization Current Selections Archives Subscribe Guest Book

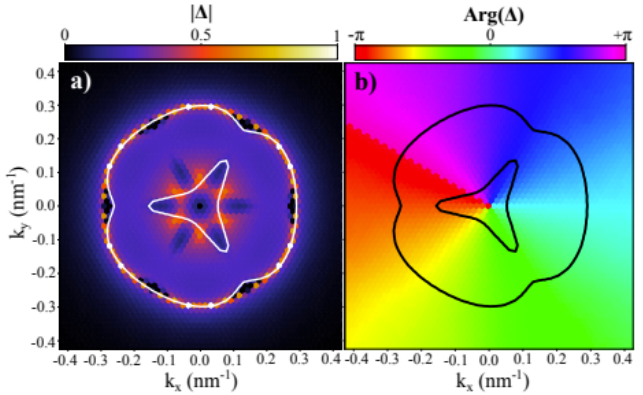
Chiral Superconductivity in the Flat bands of Rhombohedral Graphene











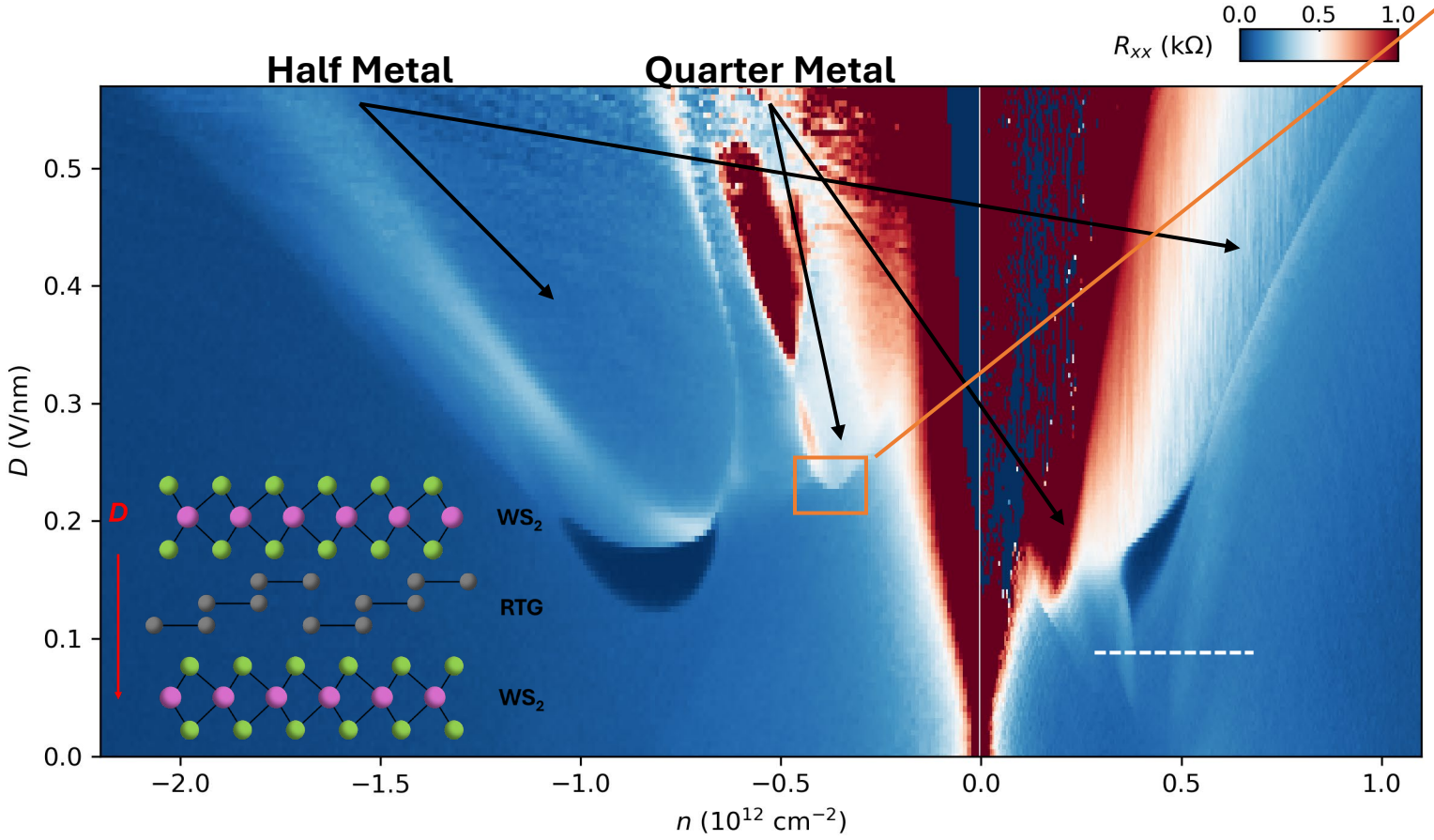
Superconductivities in TMD-Proximitized R3G

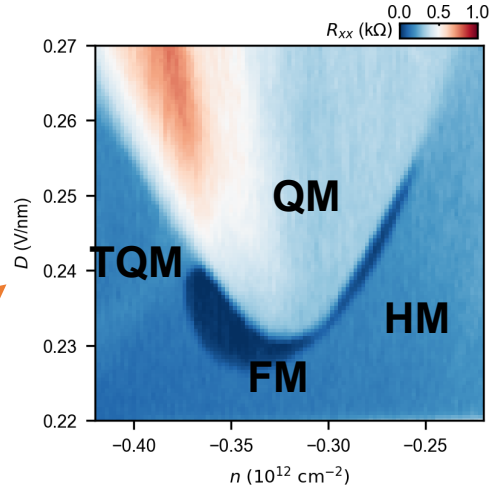
SC in ABC trilayer and AB bilayer graphene

Zhou, H… Young, A. *Nature* **598**, 434–438 (2021).

Zhou, H… Young, A. *Science* **375** (6582) (2021).

Zhang, Y… Nadj-Perge, S. *Nature* **613**, 268–273 (2023).



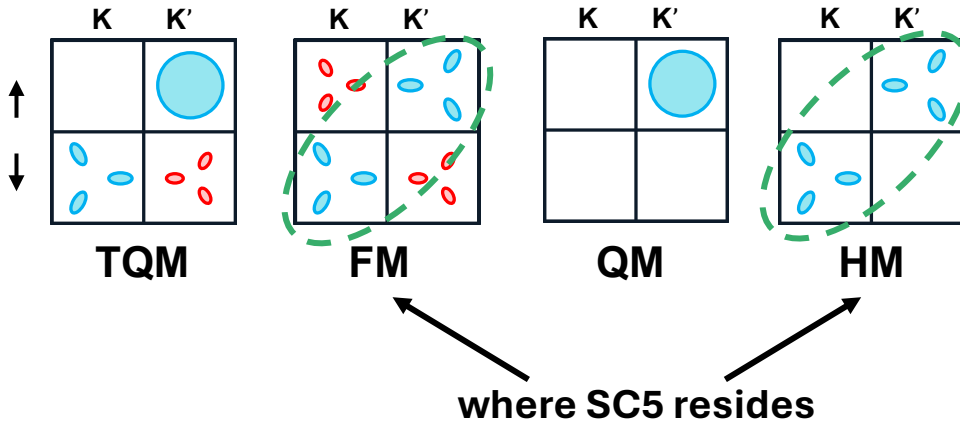


Jixiang Yang

Induced SC5 (new)

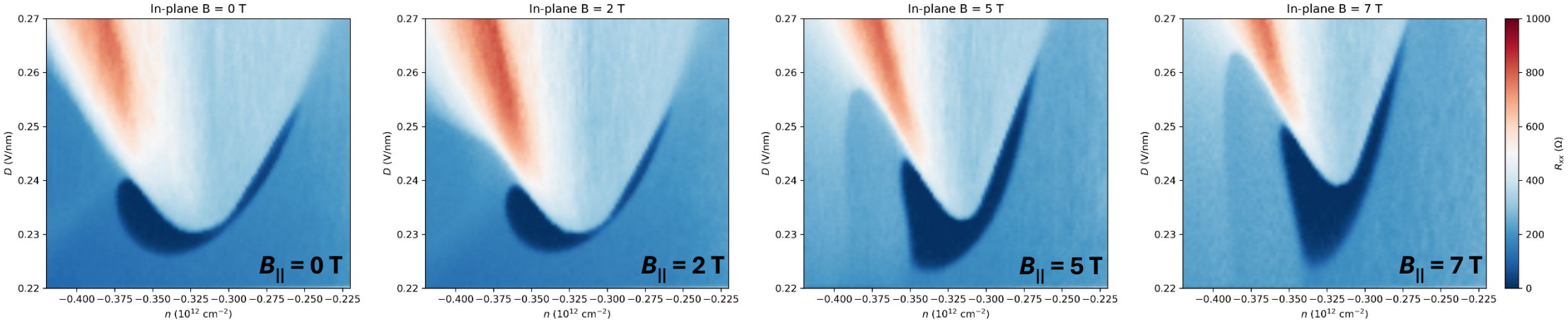
T_c ~ 70 mK

Jixiang Yang*, O. Sedeh*, C. Yoon*, S. Ye*…
D. Zumbuhl, LJ : *arXiv:2510.10873*

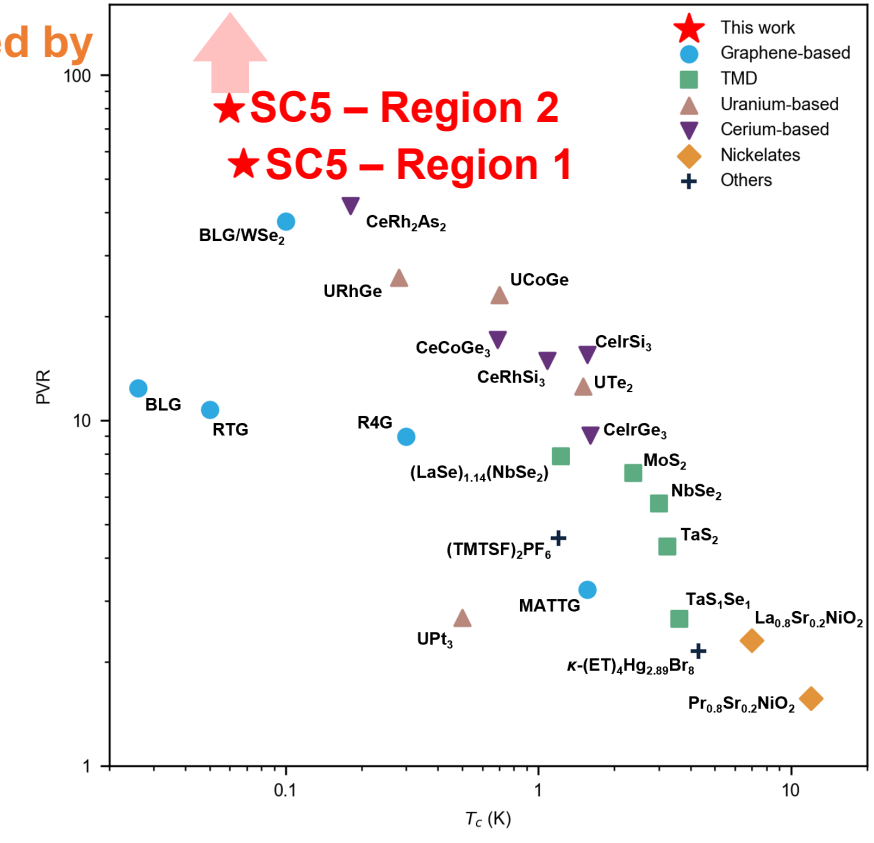


Jixiang Yang, … LJ, *Nat. Mat. 24, 1058-1065* (2025)

Enhanced SC by In-Plane Magnetic Field



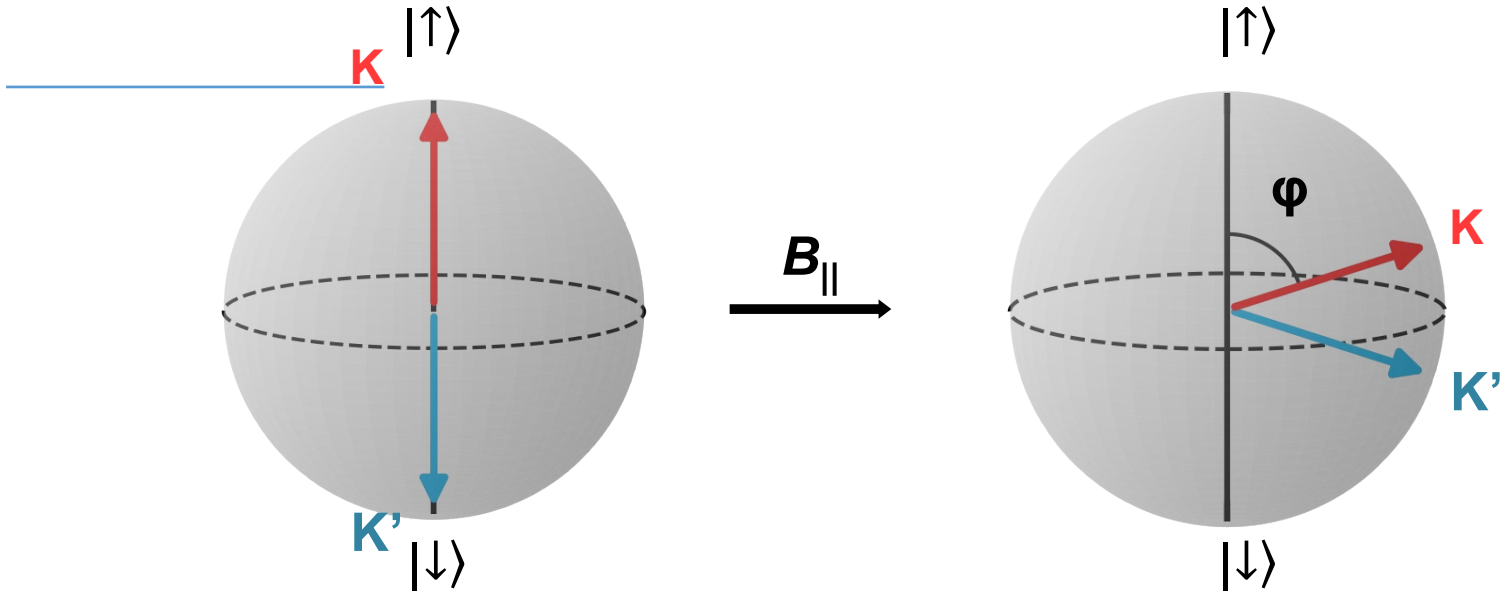
Pauli-Limit-Violated by at least 80 times



As the in-plane magnetic field increases:

- Larger area in *n*-*D* map
- Higher T_c is enhanced: 70 -> 95 mK
- Higher $B_{c\perp}$: 12 -> 25 mT

Possible Explanation



Spin-valley locking by Proximitized Ising SOC

Spin-canting

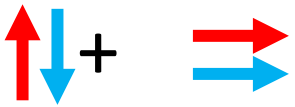
Patterson, C.L., Sheekey, O.I., Arp, T.B. *et al.* *Nature* **641**, 632–638 (2025).

Mixture of spin-singlet & triplet

Spin-singlet pairing

$$\Delta = \frac{\lambda_I \Delta_s + E_Z \Delta_t}{\sqrt{\lambda_I^2 + E_Z^2}}$$

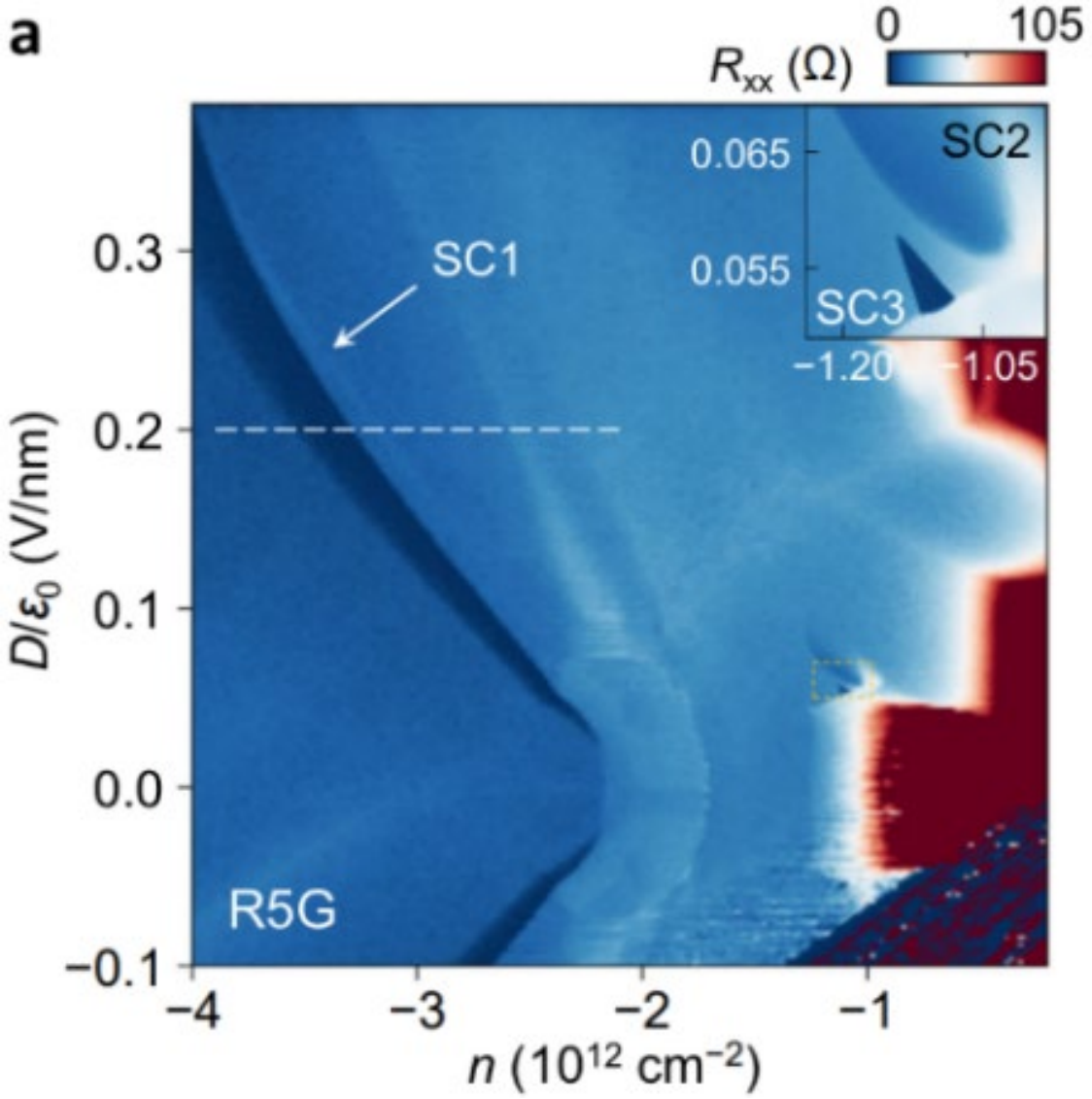
=

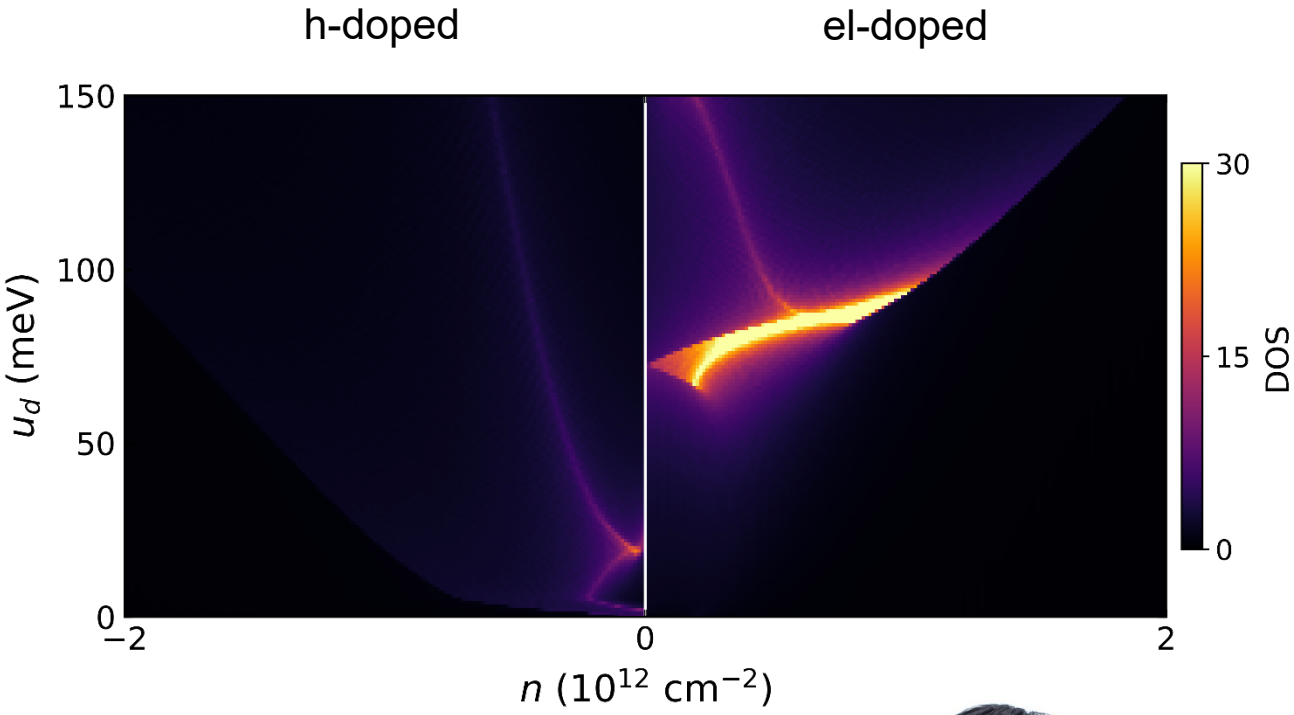


A stronger triplet pairing: $\Delta_t > \Delta_s$

Superconductivity in Hole-Doped Bare R5G

Bare R5G

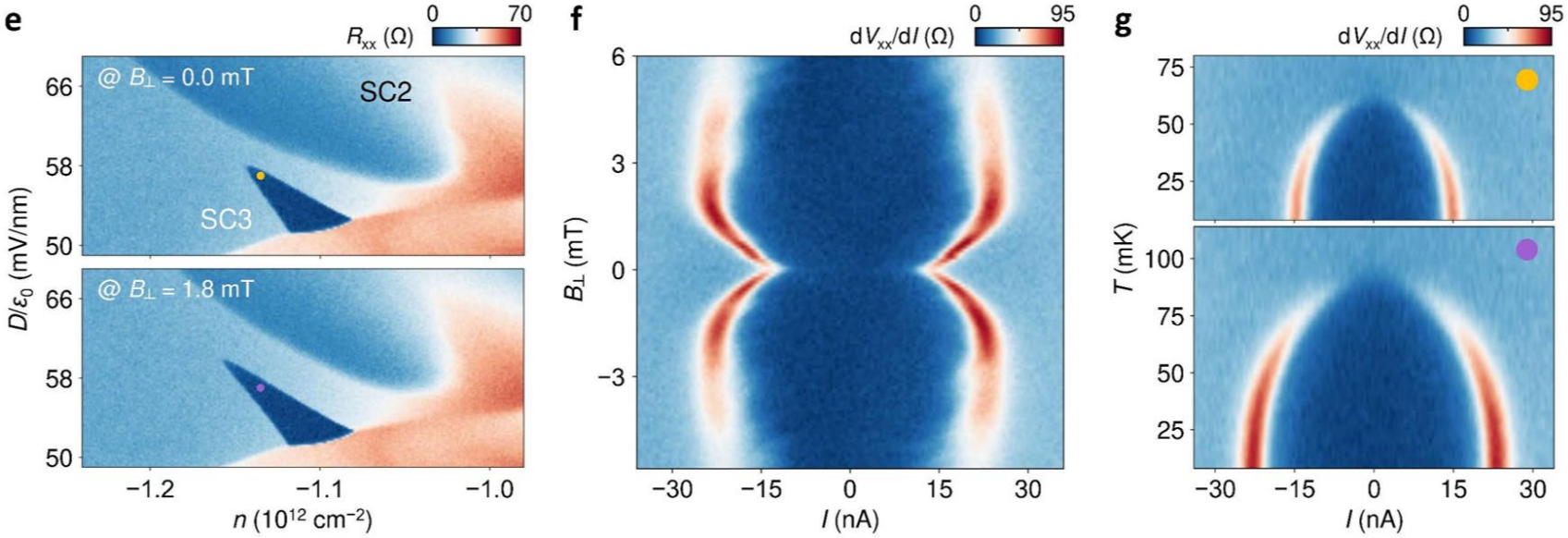




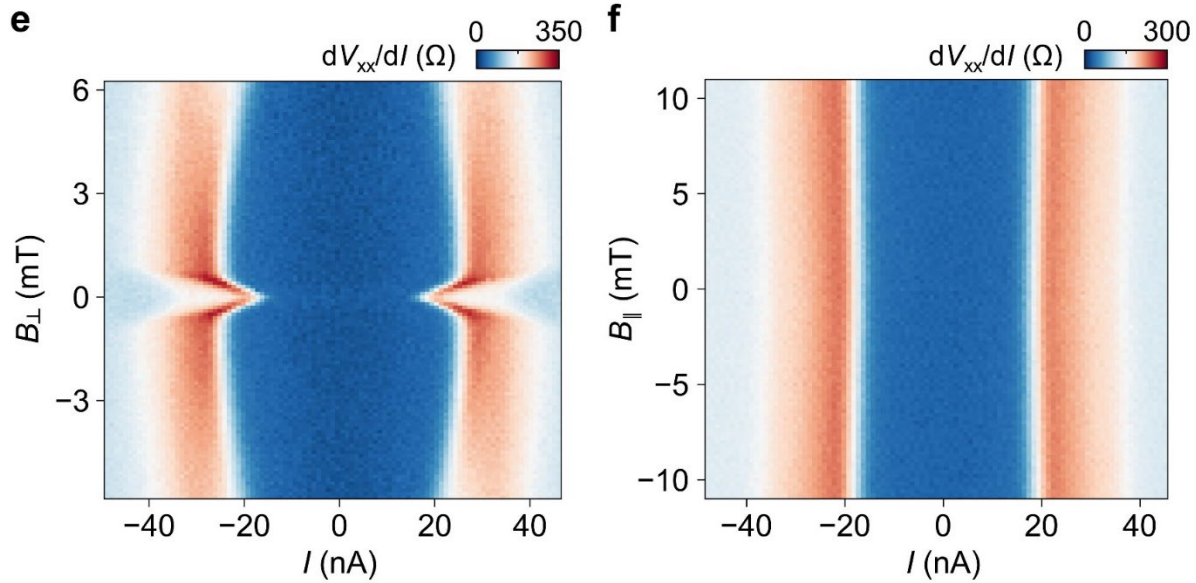
Junseok Seo

J. Seo…LJ. arXiv:2509.03295

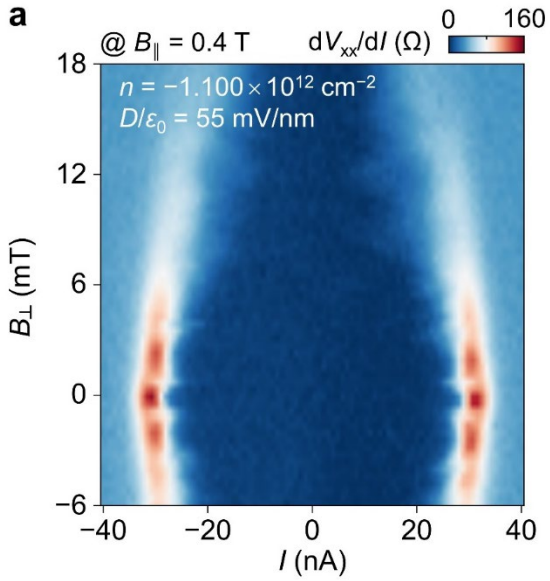
Enhanced SC3 by $B_\perp$~ mT



Spin-orbit Coupling
Ask me later



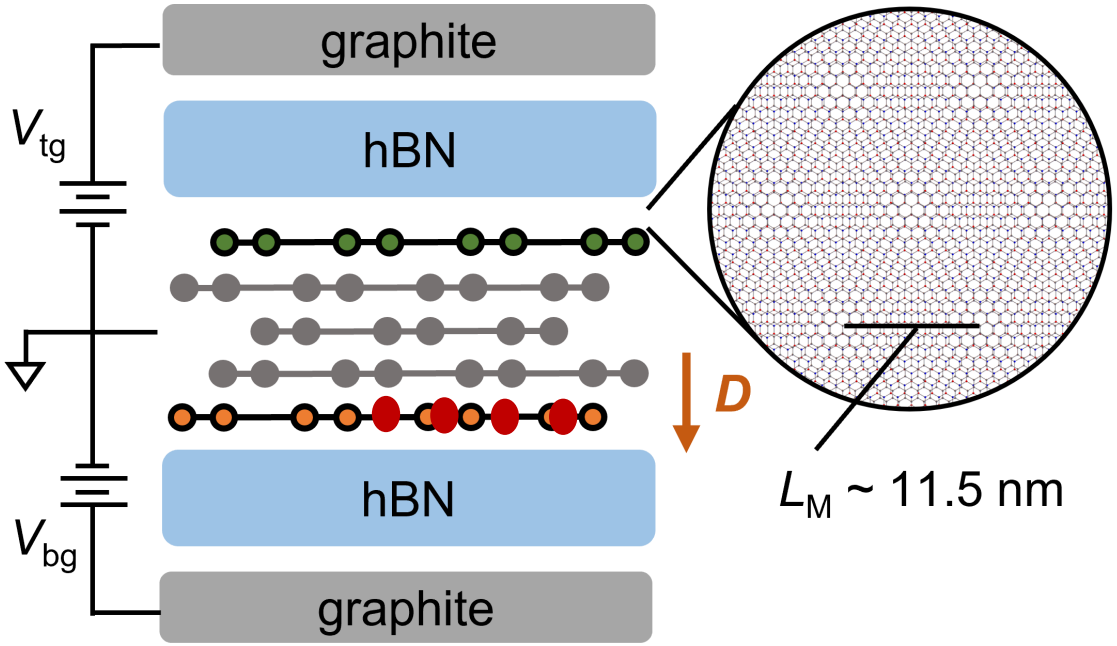
No enhancement by $B_{//}$ **(not pure spin)**

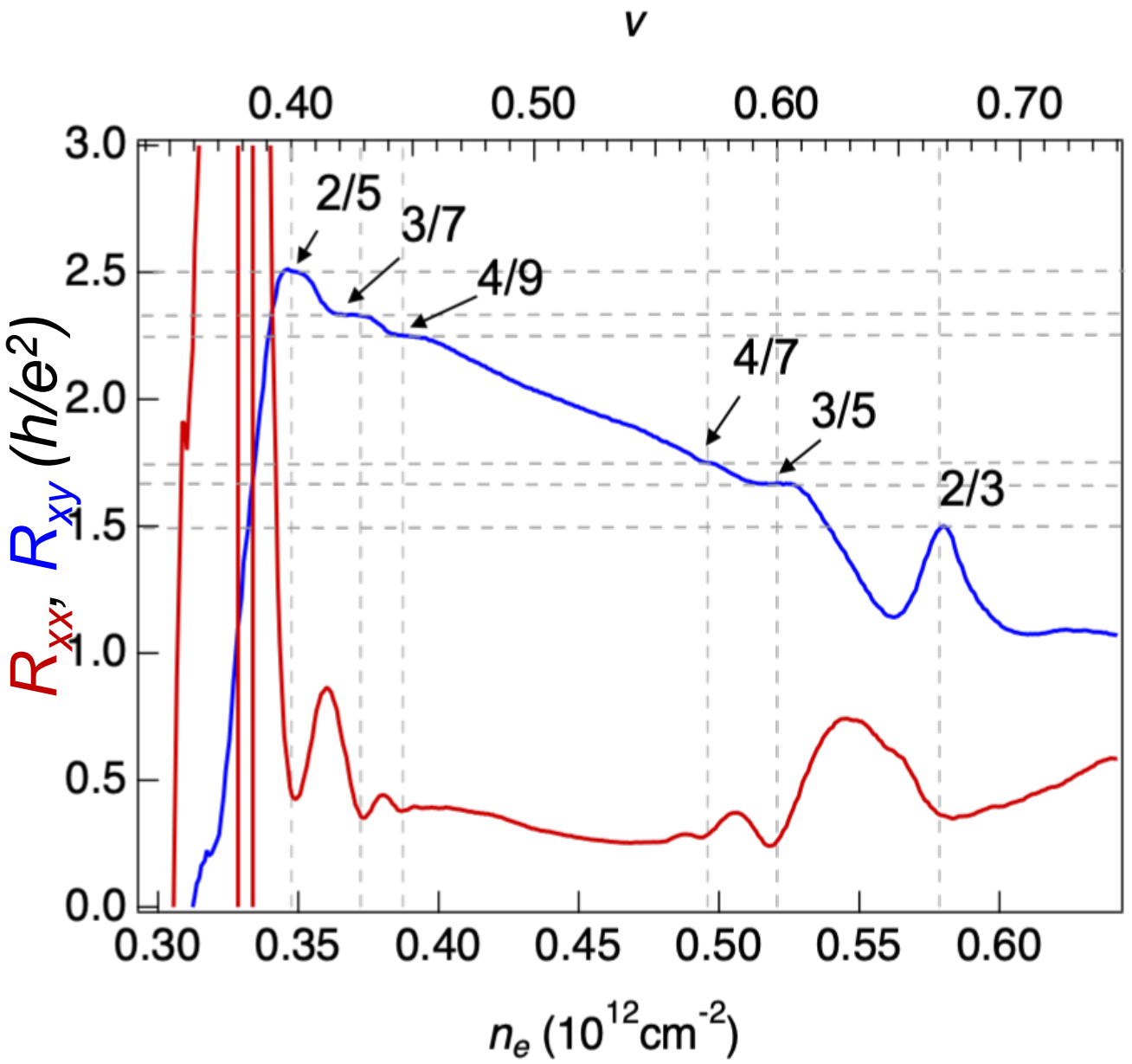


Enhancement by $B_\perp$ absent with $B_{//}$= 0.4 T

(not pure orbital)

5L RG/hBN Moiré Superlattice





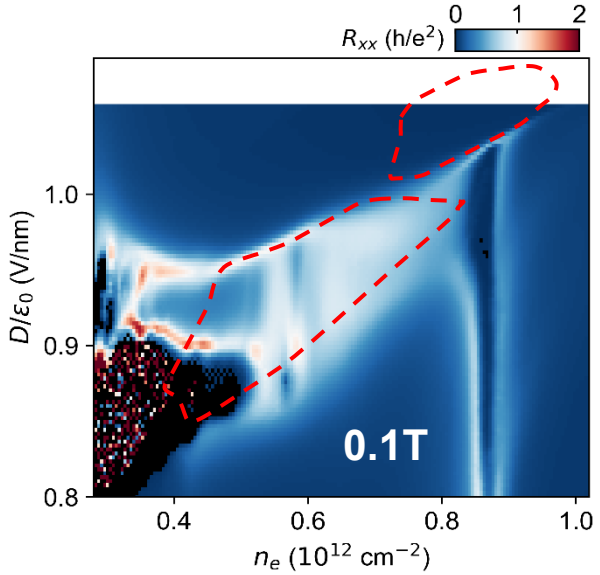
Twist angle ~0.7 degrees

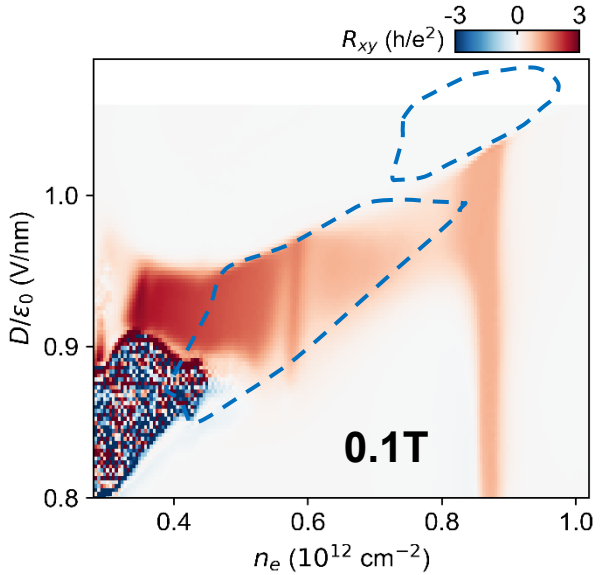
Lu Z., Han T.…LJ,

Accepted to *Nature*, Dec 19th 2023

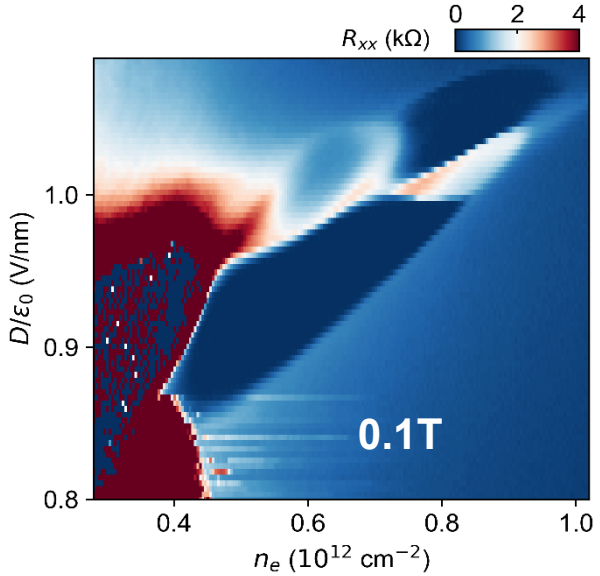
FQAHE and Chiral SC in the Same Rhombohedral Graphene!

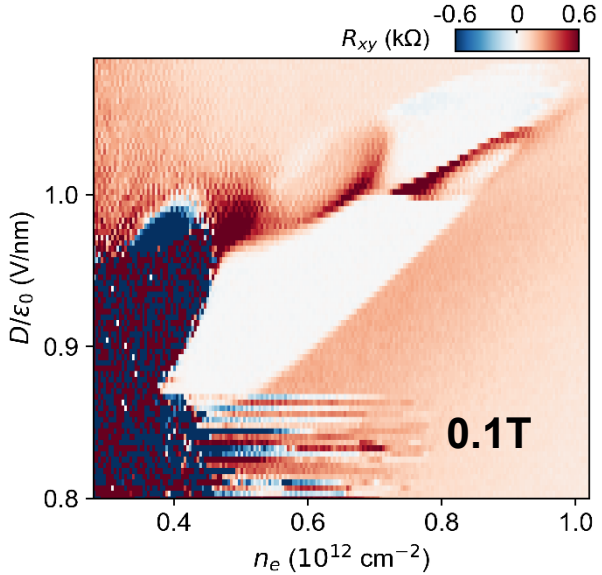
5L RG with moiré





5L RG without moiré



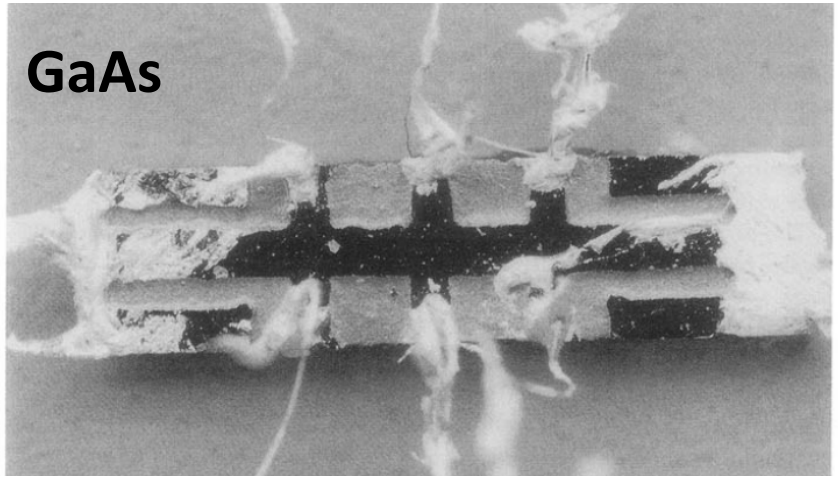


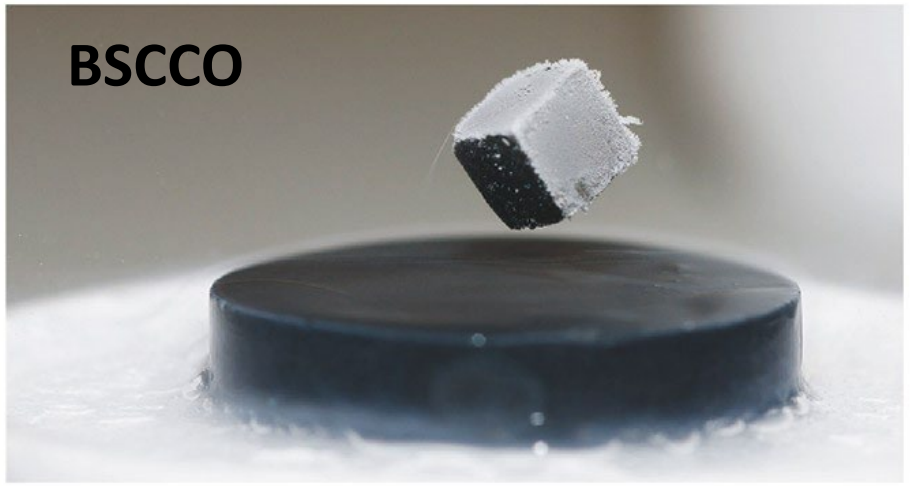
Same electrons/part of flat band

(Fractional) Quantum Hall Effect

Superconductivity

Conventional





Requires high B

Perfect diamagnetic

Un-Conventional

In Crystalline graphene

At zero B

Magnetic

Intertwined correlation, topology and magnetism

Acknowledgement

Ju Group


Tonghang Han


Jixiang Yang


Junseok Seo

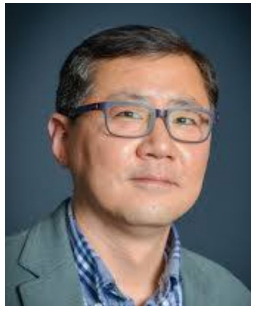

Dasol Kim


Shenyong Ye


Zacharia Hadjri


Emily Aitken

Harvard

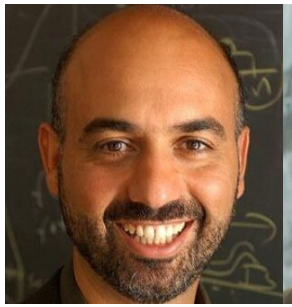

Hongkun Park

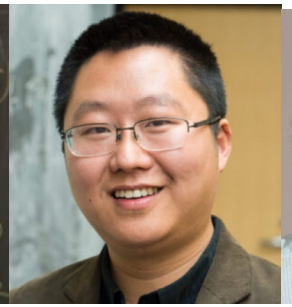
NIMS


Takashi Taniguchi


Kenji Watanabe

MIT


Ray Ashoori


Liang Fu


Senthil Todadri


Xiao-Gang Wen

U Basel


Dominik Zumbühl

FSU


Peng Xiong

UT Dallas


Fan Zhang

Weizmann Inst.


Ady Stern


Eli Zeldov

Thanks!