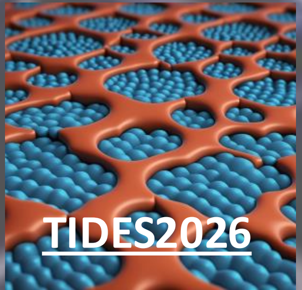
Superconductivity in flatland

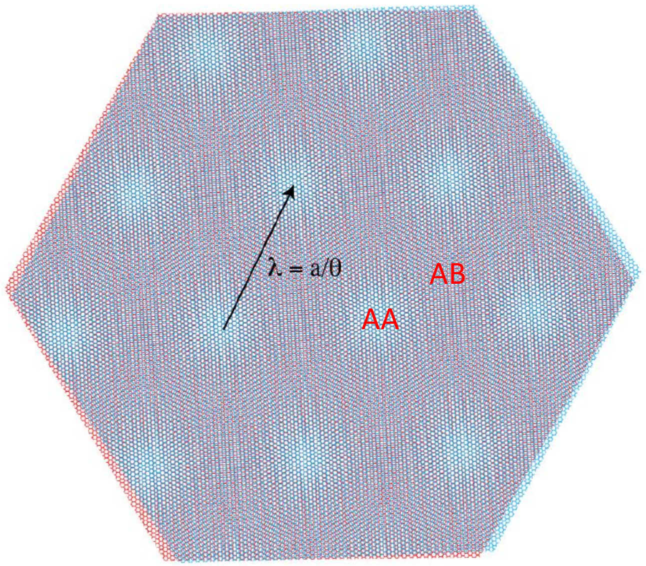
Mitali Banerjee

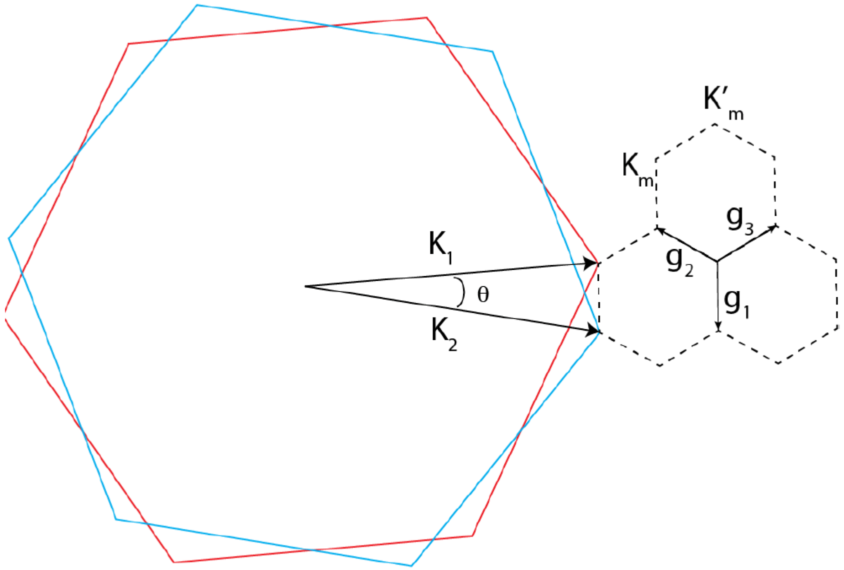
Laboratory of Quantum Physics:
Topology and correlations

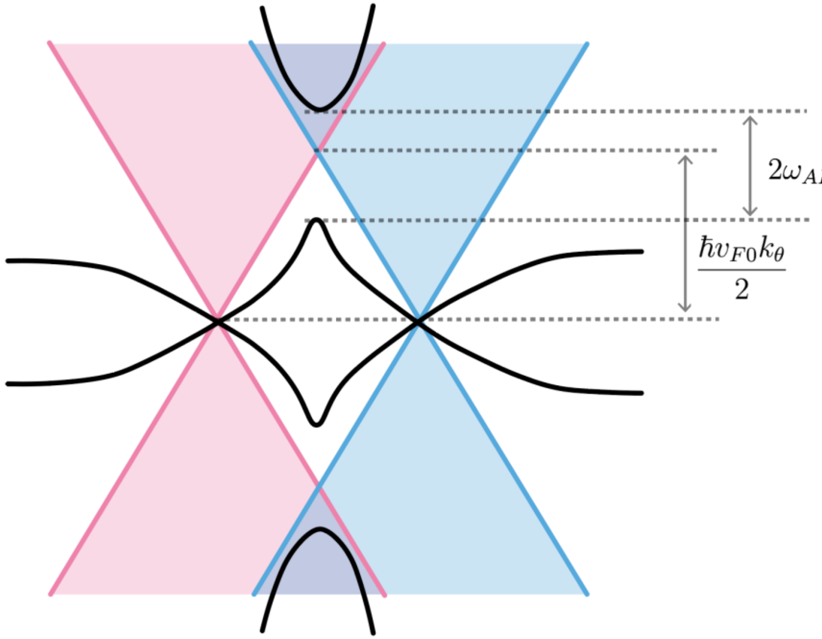


EPFL

Introduction—the formation of flat bands in MATBG

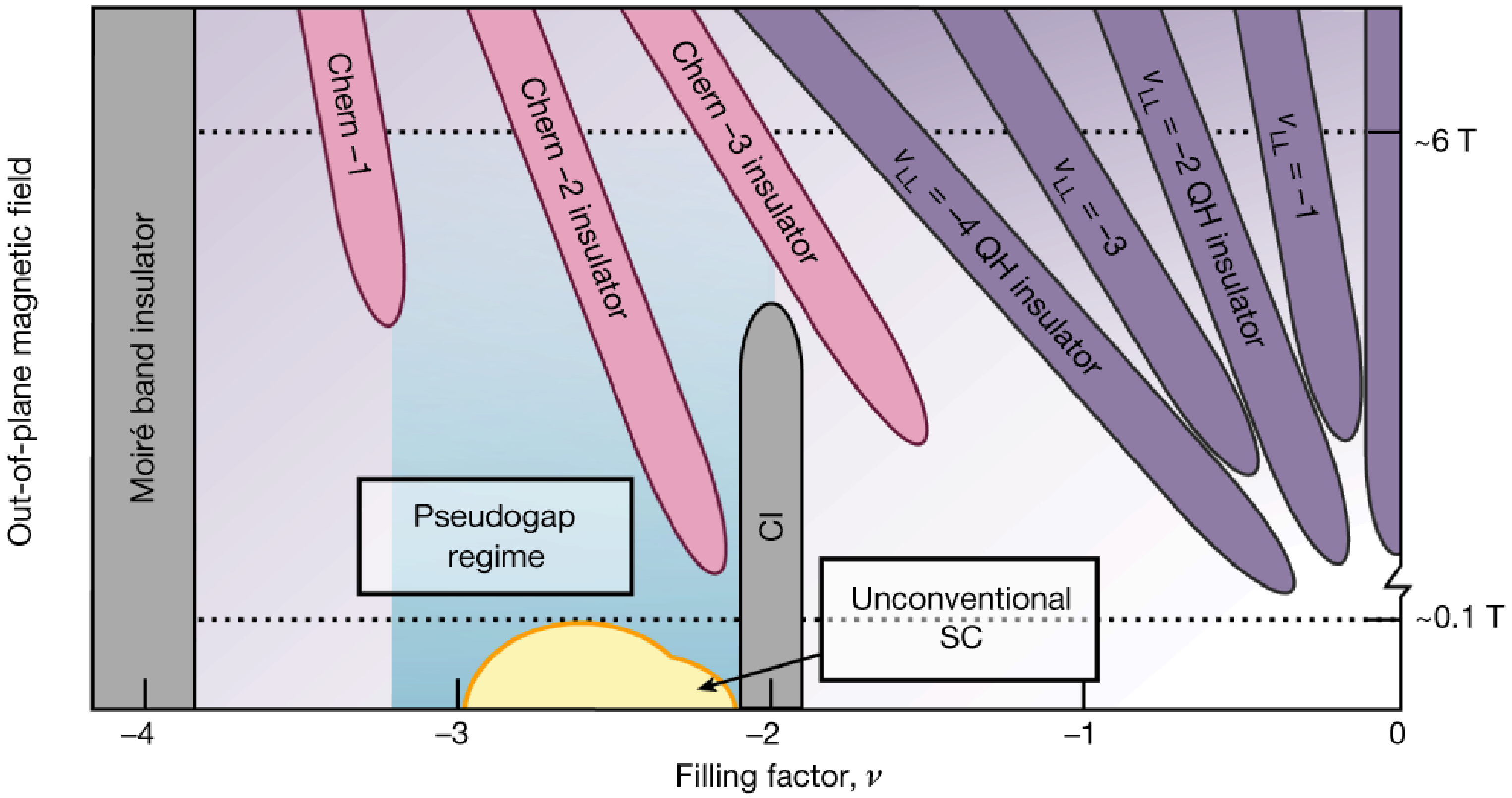






- $2\omega_{AB} \sim \hbar v_{F0} k_\theta / 2$, Fermi velocity is largly reduced and band is flat.
- Each flat band has four fold degeneracy (2 valleys and 2 spins).

Introduction—phase diagram of MATBG



K. P. Nuckolls et al.: Nat. Rev. Mater. 9, 460 (2024)

- Superconductivity

  Y. Cao et al.: Nature 556, 43 (2018)

  M. Yankowitz et al.: Science 363, 1059 (2019)

  X. Lu et al.: Nature 574, 653 (2019)

- Ferromagnetism/QAH

  A. L. Sharpe et al.: Science 365, 605 (2019)

  M. Serlin et al.: Science 367, 900 (2020)

- Pomeranchuk effect

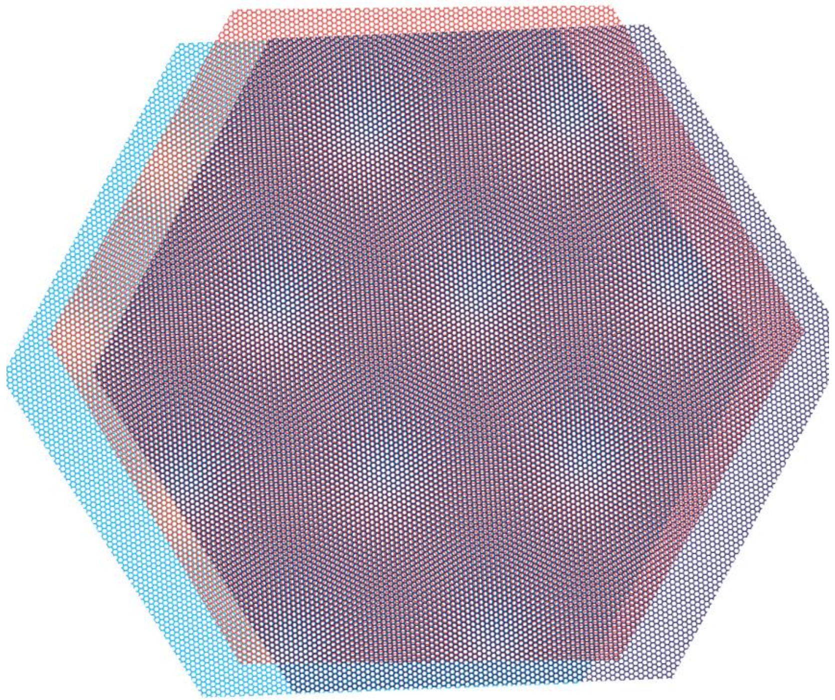
  Y. Saito et al.: Nature 592, 220 (2021)

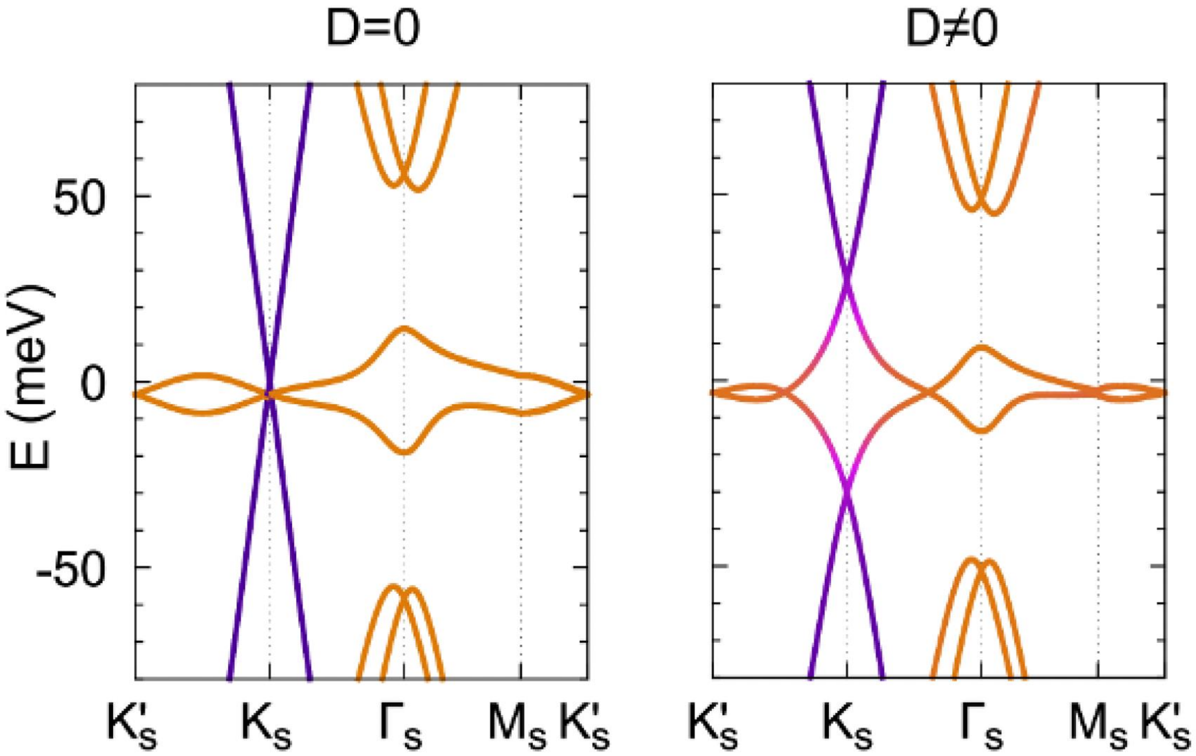
  A. Rozen et al.: Nature 592, 214 (2021)

- ……

Introduction—the motivation of studying on MATTG

Is it possible to tune these interesting quantum phases *in situ*?

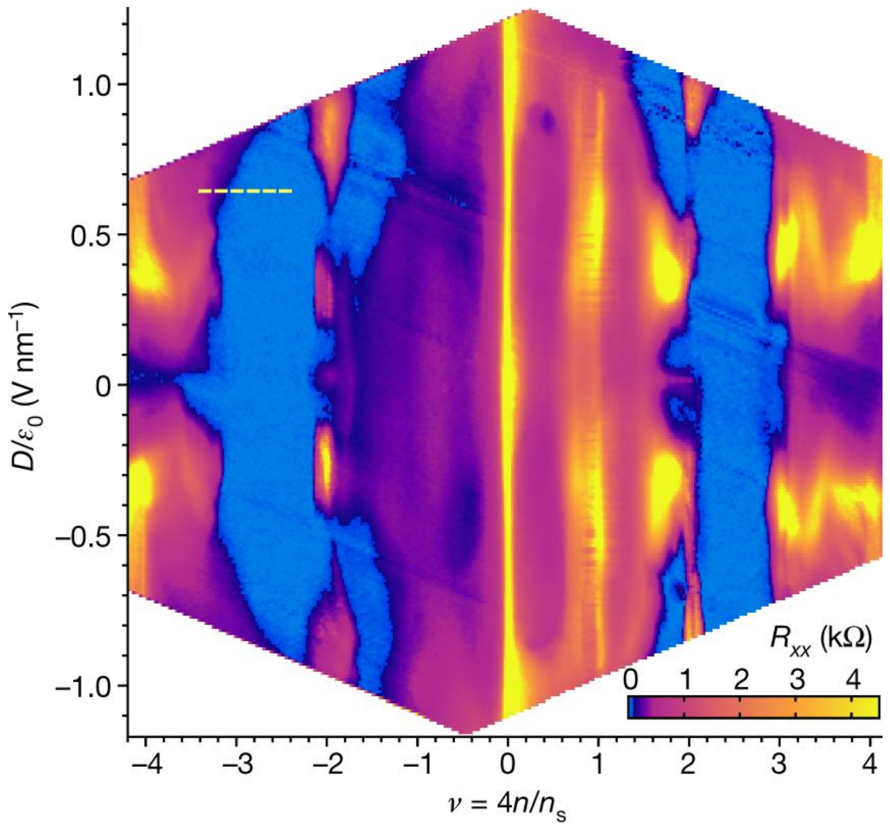


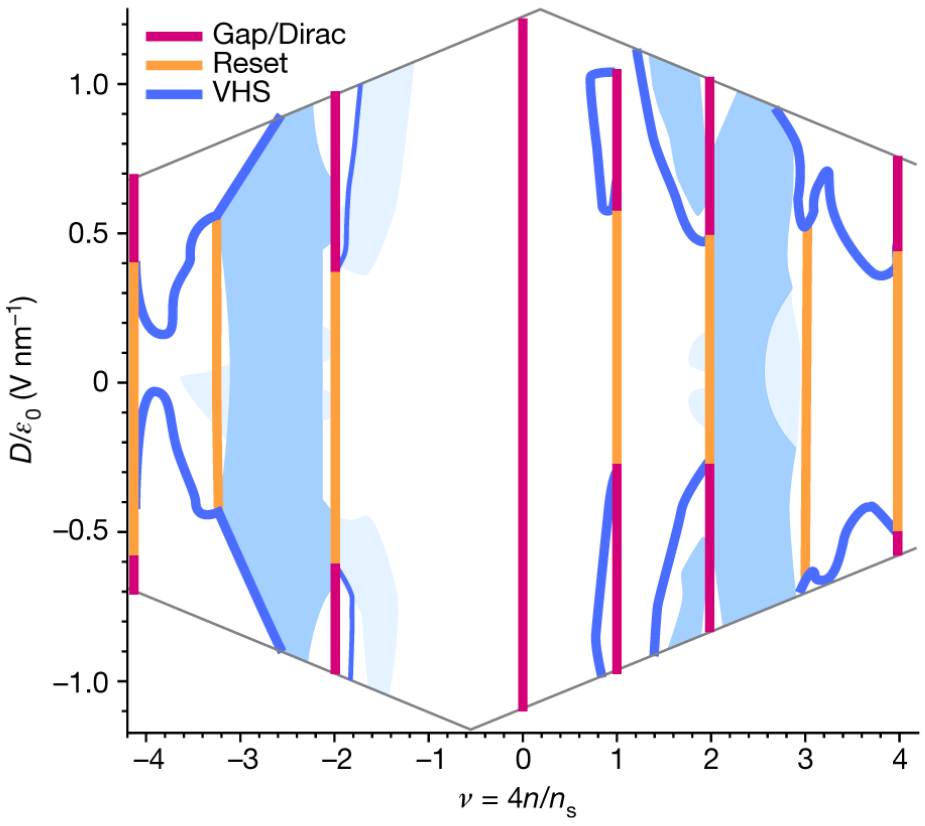


J. M. Park et al.: Nature 590, 249 (2021)

- Flat band coexists with Dirac band.
- Gate tunable band structure.

Introduction—gate tunable phase diagram of MATTG

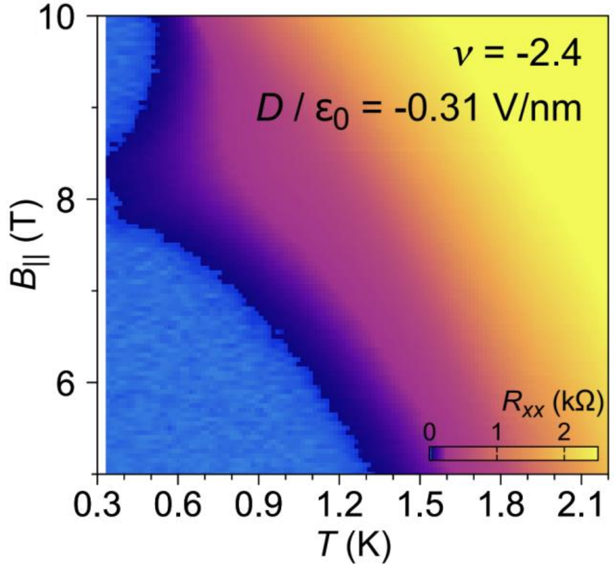




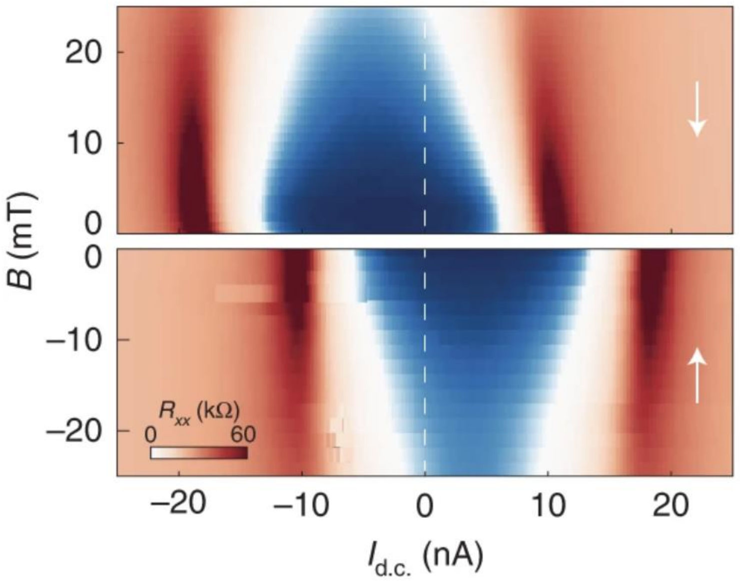
J. M. Park et al.: Nature 590, 249 (2021)

- Robust superconductivity exist in both hole and electron side.
- Superconductivity and correlated states are tunable by the displacement field.

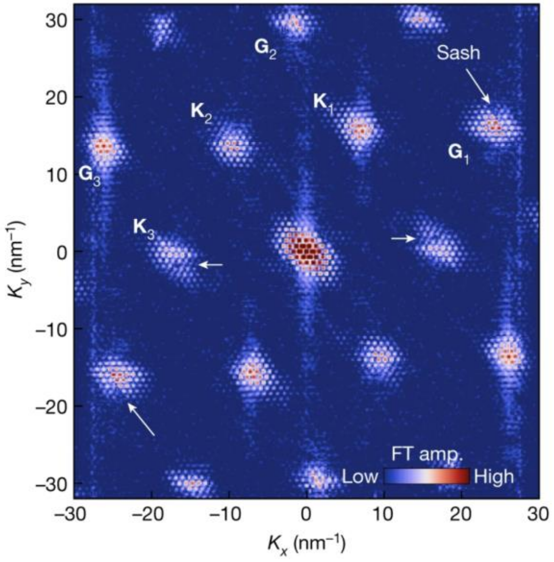
Introduction— emergent quantum phases in MATTG



Y. Cao *et al.*: Nature 595, 526 (2021)



J.-X. Lin et al.: Nat. Phys. 18, 1221 (2022)



H. Kim et al.: Nature 623, 942 (2023)

……

- A versatile platform for exploring diverse and intriguing quantum phenomena!

Introduction— uncoventional superconductivity

- Strange metal

  Y. Cao et al.: Phys. Rev. Lett. 124, 076801 (2020)

  A. Jaoui et al.: Nat. Phys. 18, 633 (2022)

- Nodal gap

  M. Oh et al.: Nature 600, 240 (2021)

  H. Kim et al.: Nature 606, 494 (2022)

  J. M. Park et al.: arXiv 2503.16410 (2025)

- Pseudogap

  M. Oh et al.: Nature 600, 240 (2021)

  H. Kim et al.: Nature 606, 494 (2022)

  Y. Han et al.: arXiv 2503.04083 (2025)

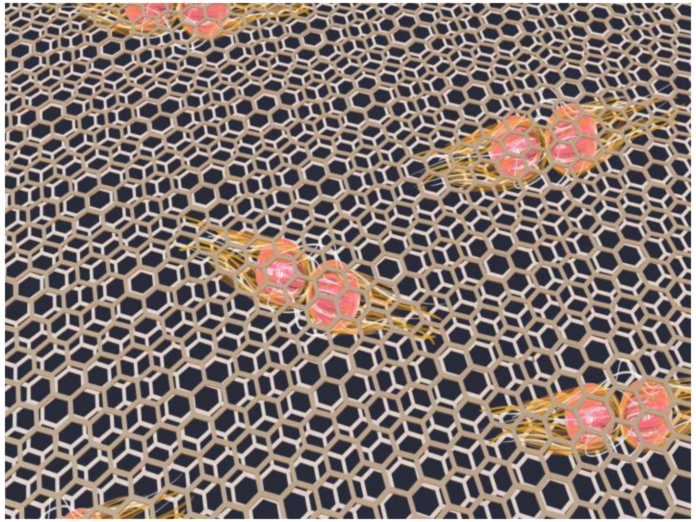
  J. M. Park et al.: arXiv 2503.16410 (2025)

- Nematicity

  Y. Cao et al.: Science 372, 264 (2021)

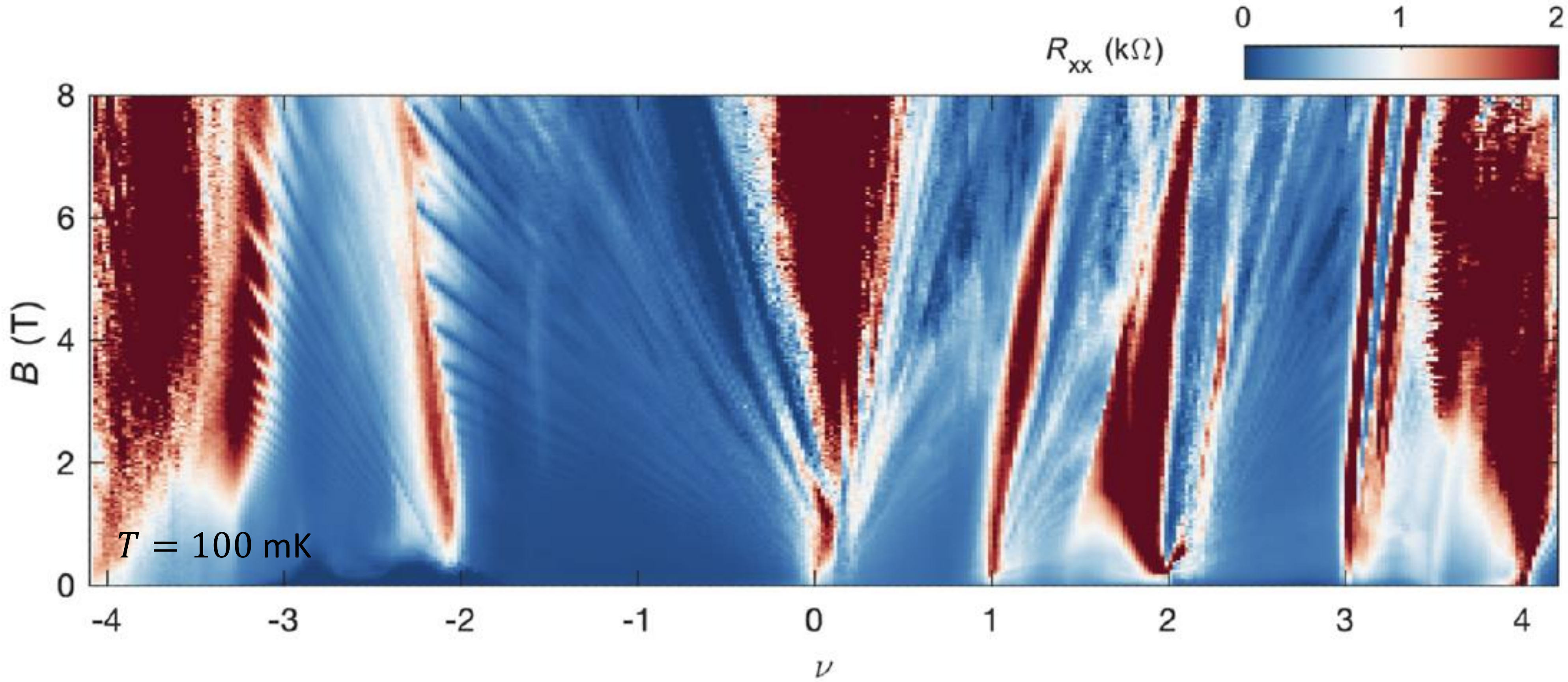
- Re-entrant SC in MATTG

  Y. Cao et al.: Nature 595, 526 (2021)

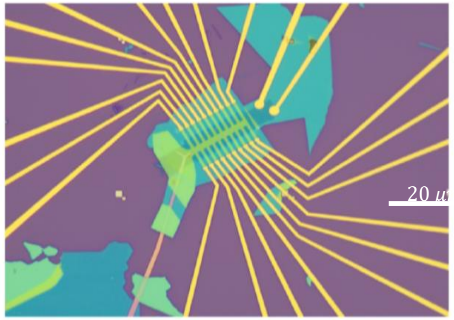


- Order parameter
- The relation between correlated state and SC.
- The role of e-ph interaction?
- ....

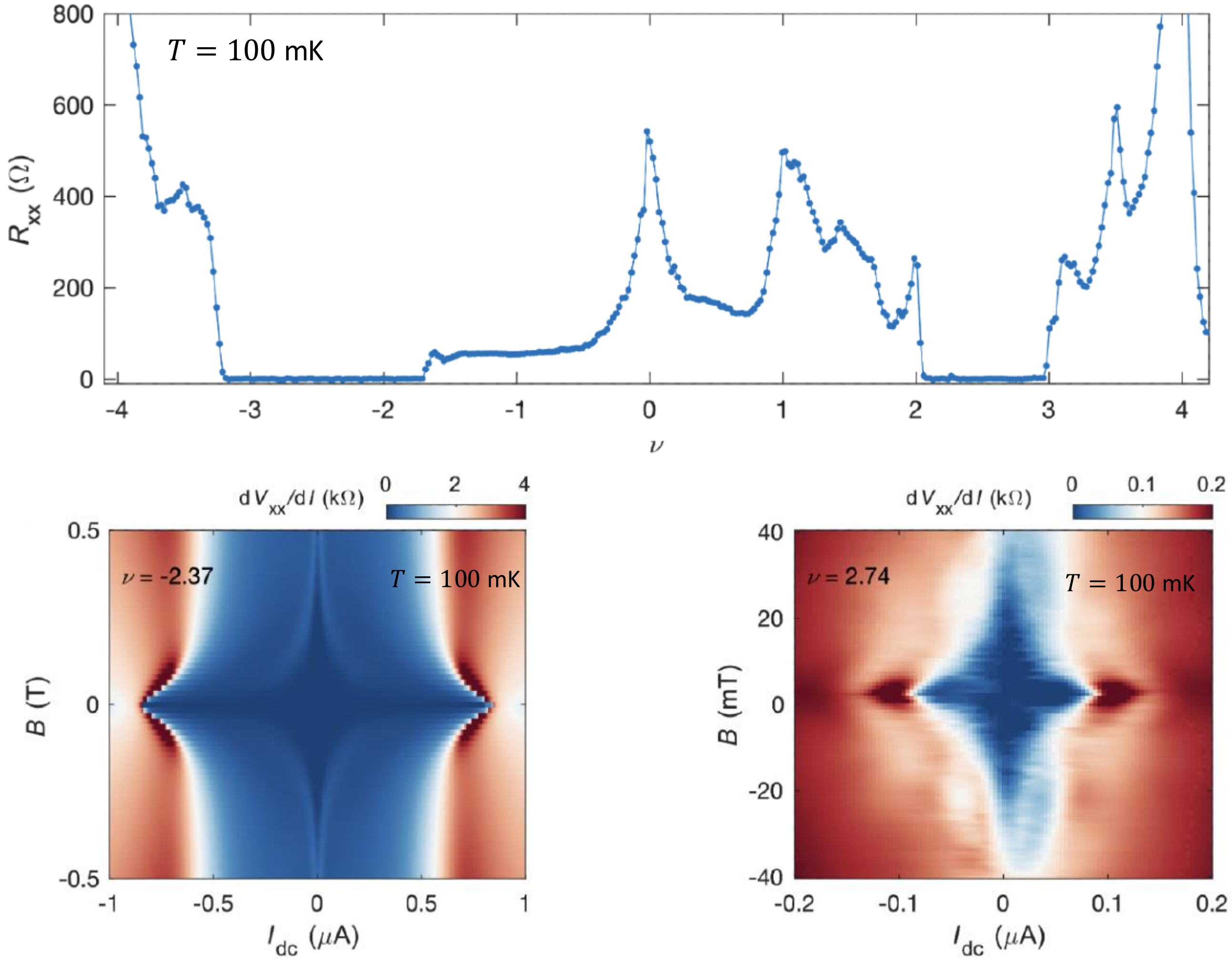
Double-dome—Landau fan diagram



- The twisted angle is 1.55°!
- The fan diagram agrees well with the reported MATTG results.

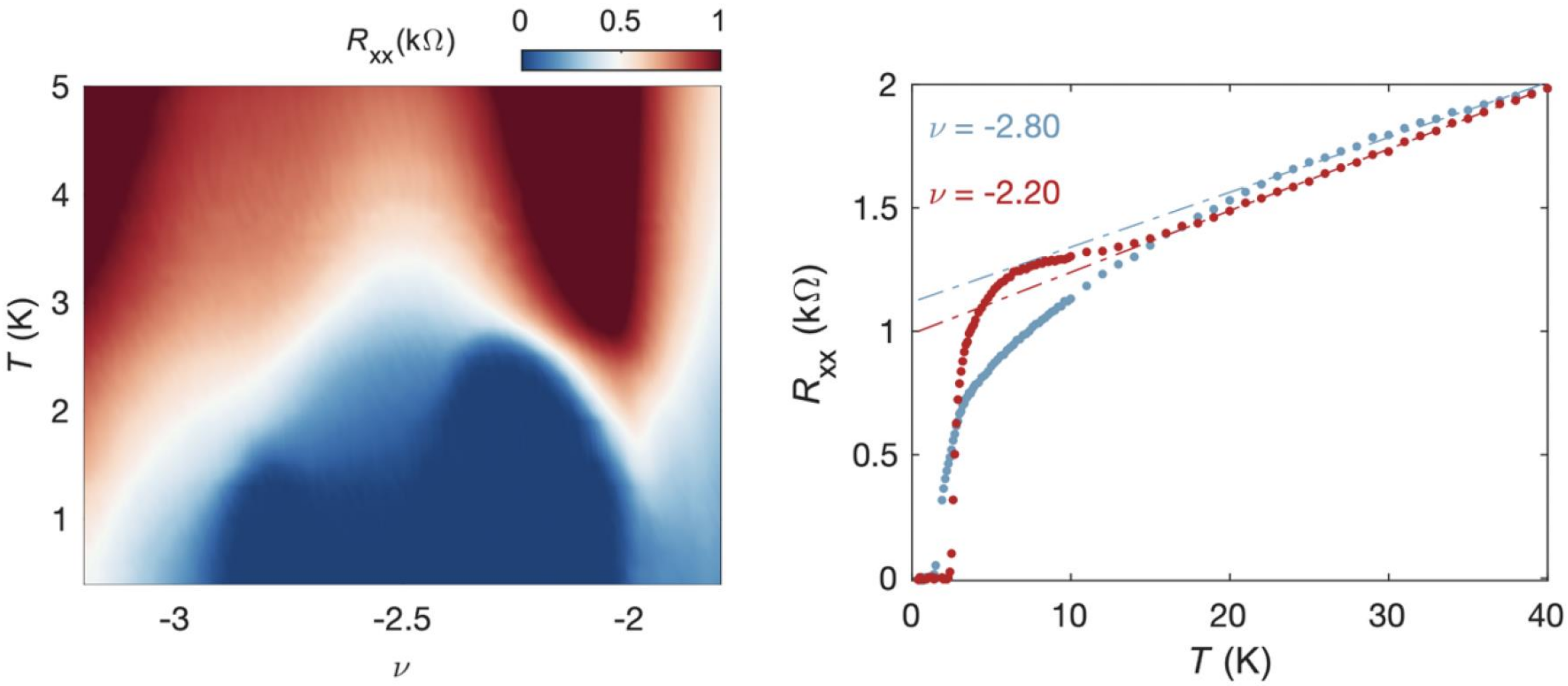


Double-dome—superconductivity



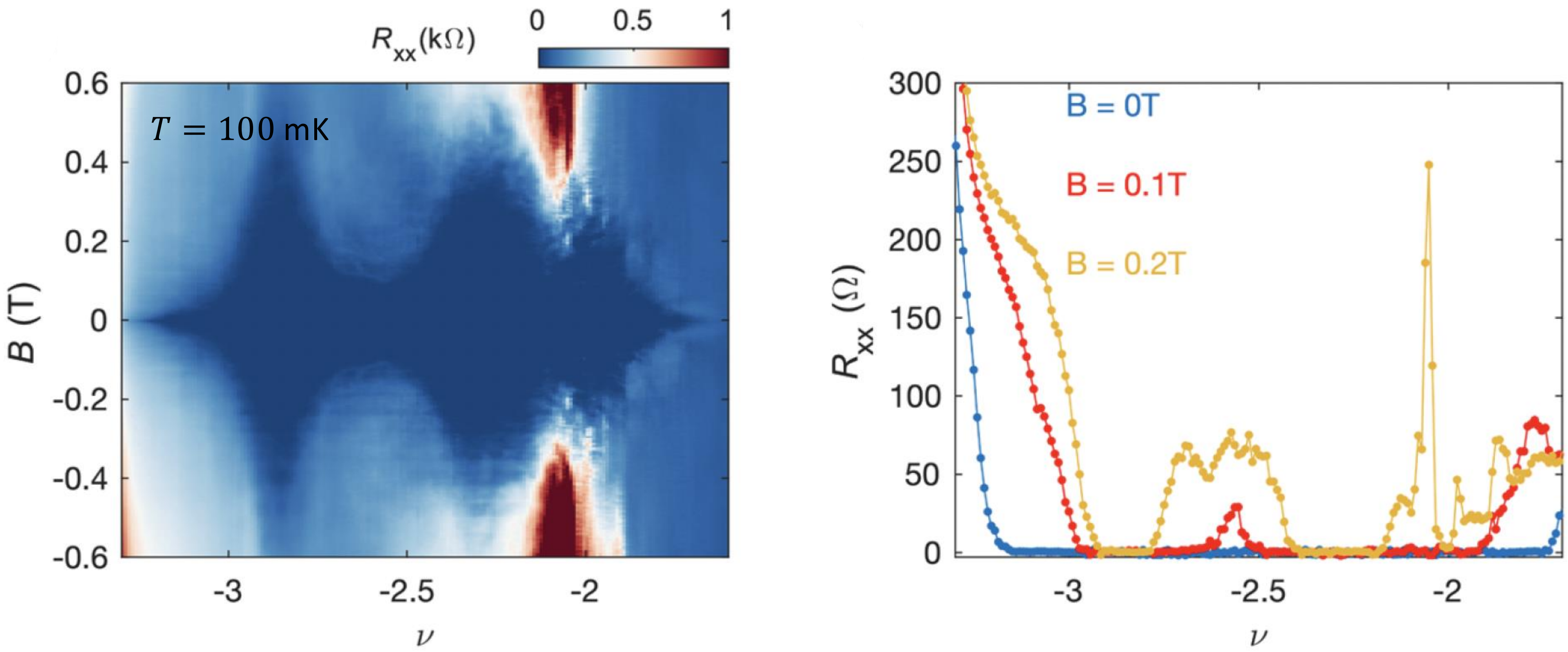
- Superconductivity exists in both electron side and hole side and hole side is much stronger.

Double-dome—temperature dependence



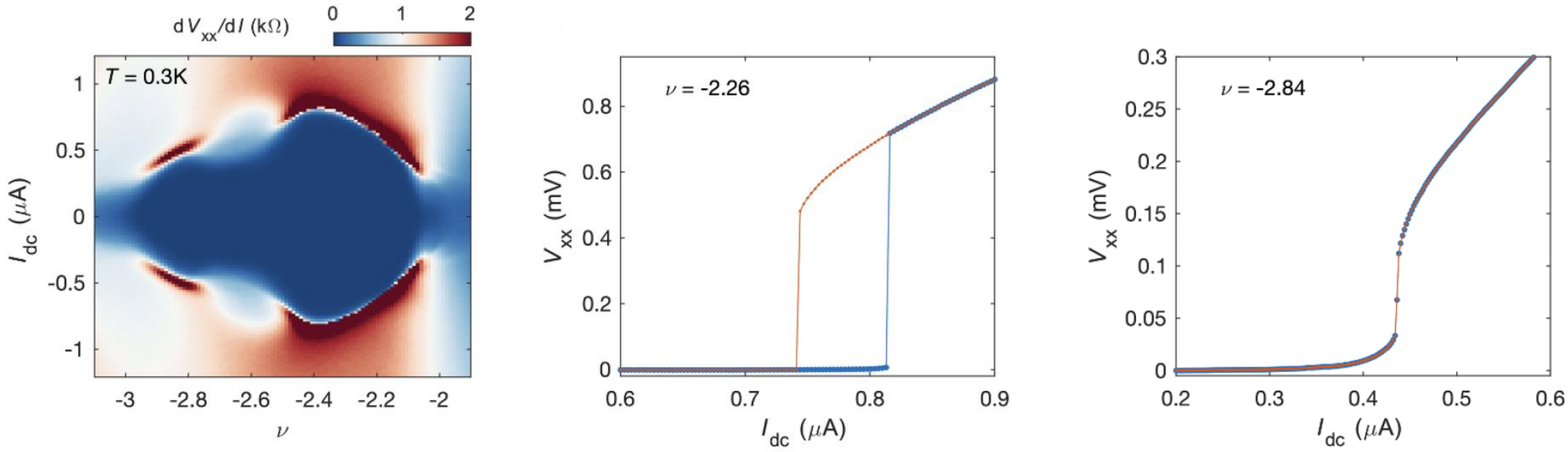
- Superconductivity is supressed near $\nu = -2.6$ and shows a double-dome feature.
- The right dome's normal-state resistance is linear in temperature.
- The right dome's transition to superconductivity is sharper than the left's.

Double-dome—magnetic field dependence



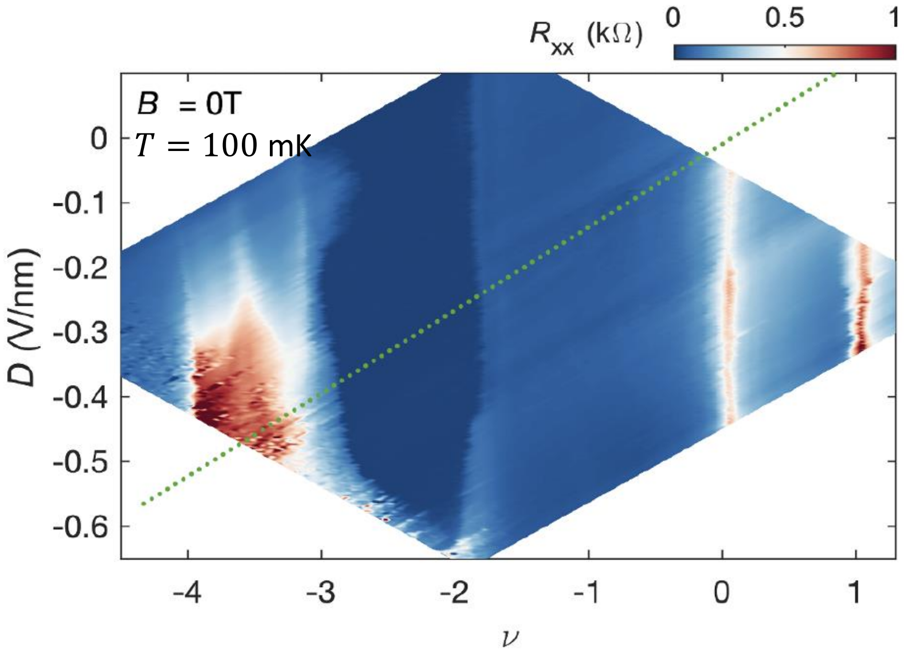
- Superconductivity is strongly supressed near $\nu = -2.6$ by magnetic field.
- The left and right domes share a similar maximum critical field.

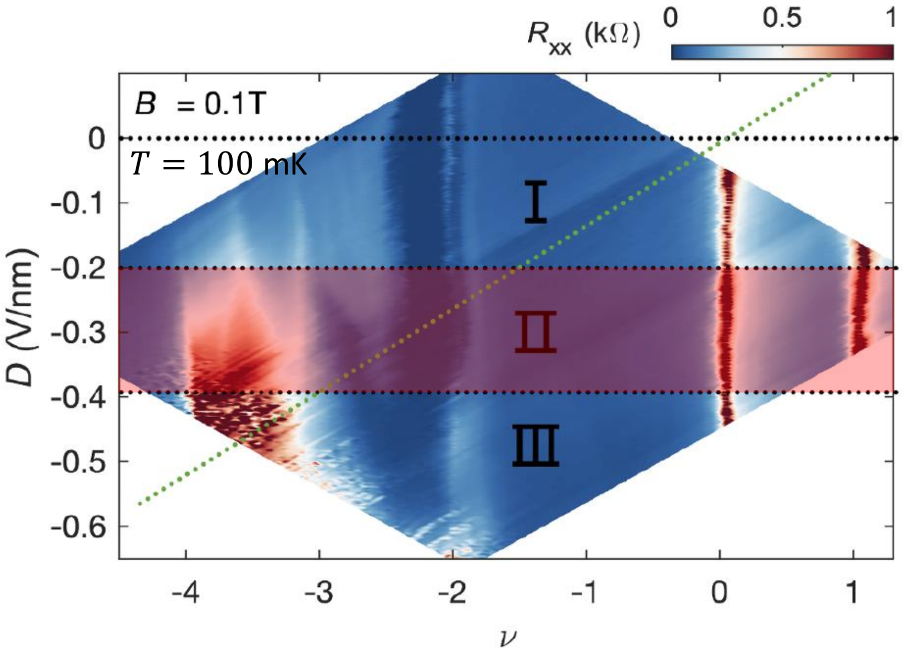
Double-dome—bias current dependence



- DC current strongly suppresses superconductivity near $\nu = -2.6$.
- I-V curve exhibits hysteresis only in the right dome.

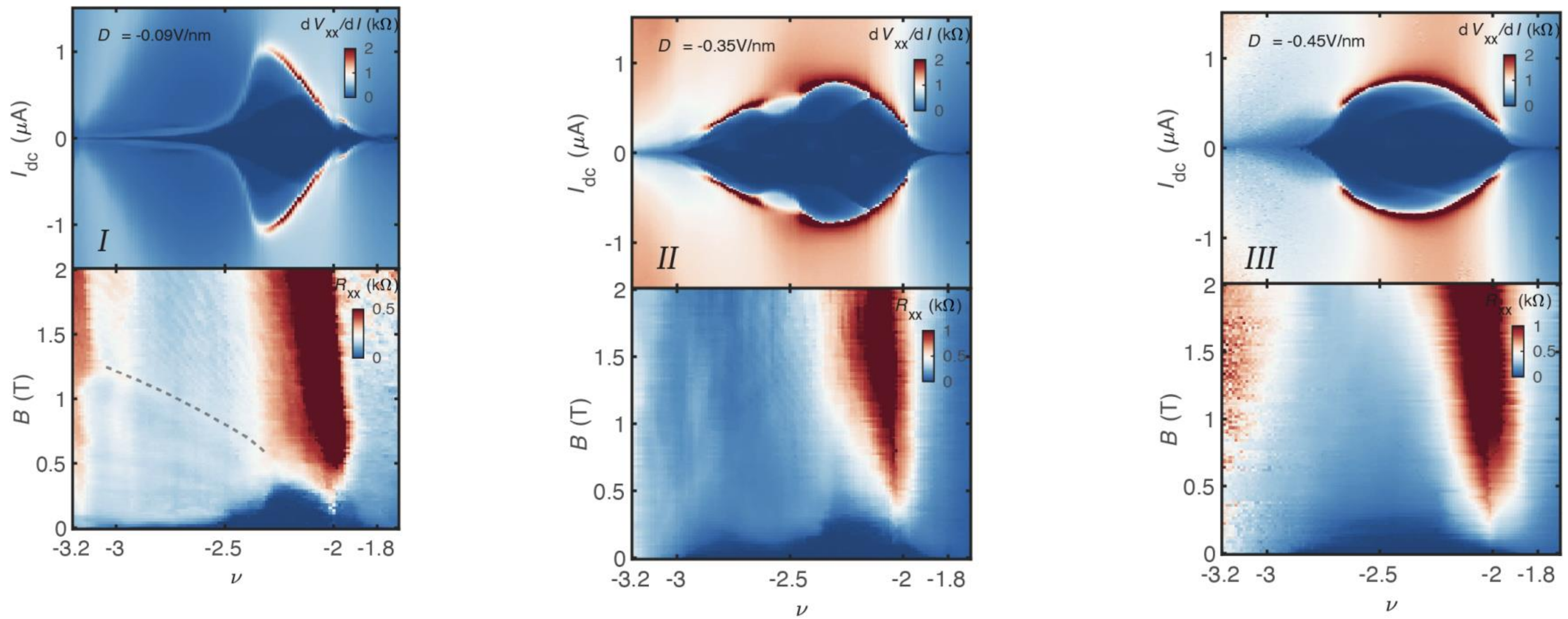
Double-dome—gate-tunable double-dome superconductivity





- Double-dome superconductivity only appears in a small displacement field window.

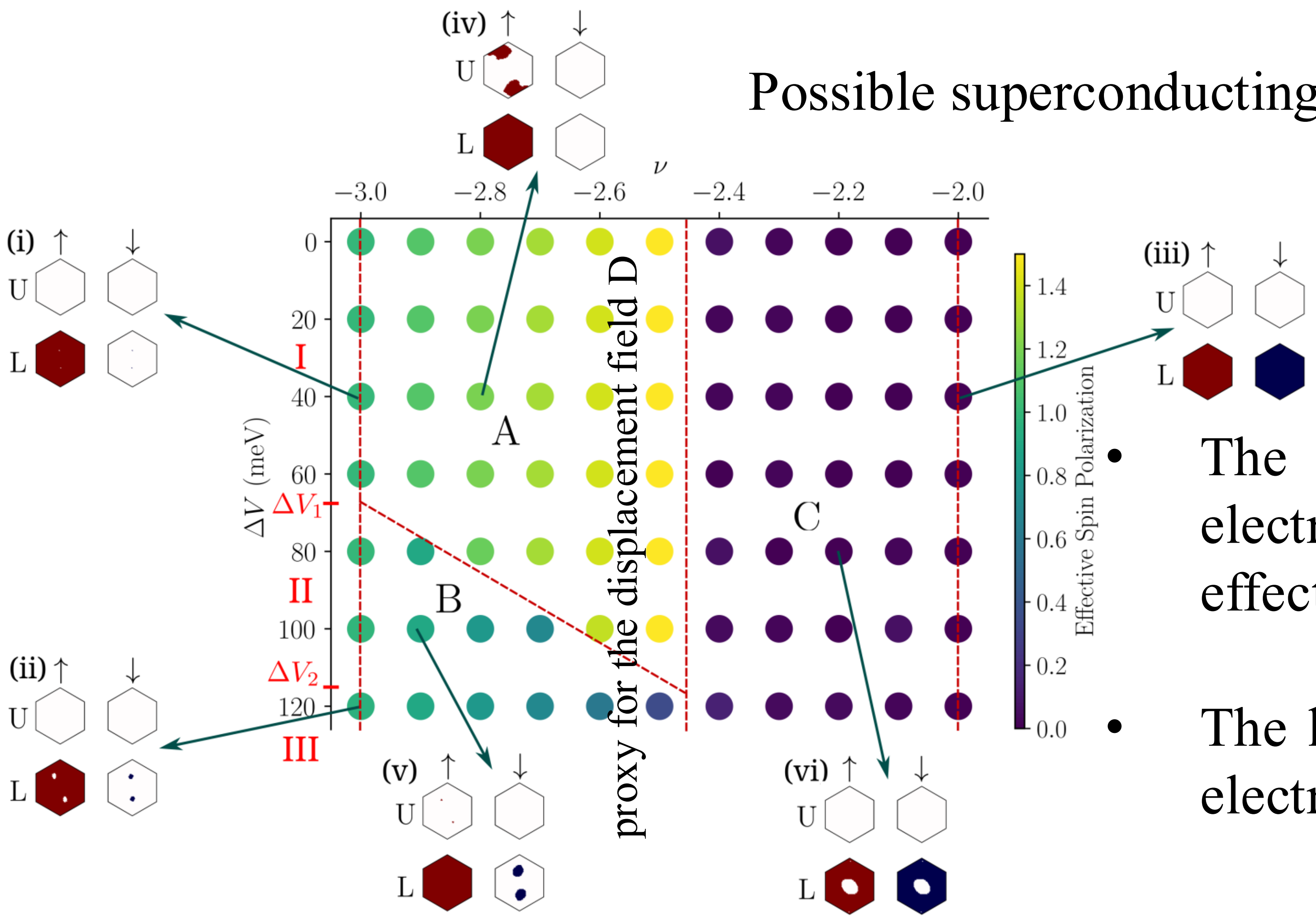
Gate-Tunable Double-Dome Superconductivity



- At a low displacement field, only one superconducting dome appears, and the Dirac band coexists with the flat band.

- At a high displacement field, one dome exists, and its behavior differs from that in the low displacement field region.

Hartree-Fock calculation of Normal-State Properties Across ν^*



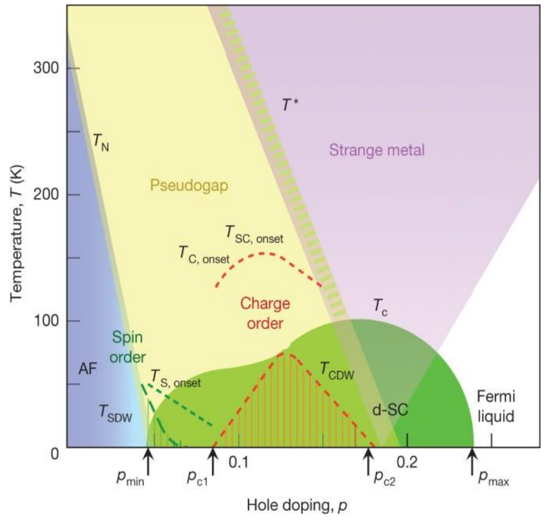
Possible superconducting pairing states in the two domes:

- The right dome admits pairing between electrons with the same and opposite effective spins
- The left dome only admits pairing between electrons with the same effective spins

Fermi surface reconstruction across the SC domes

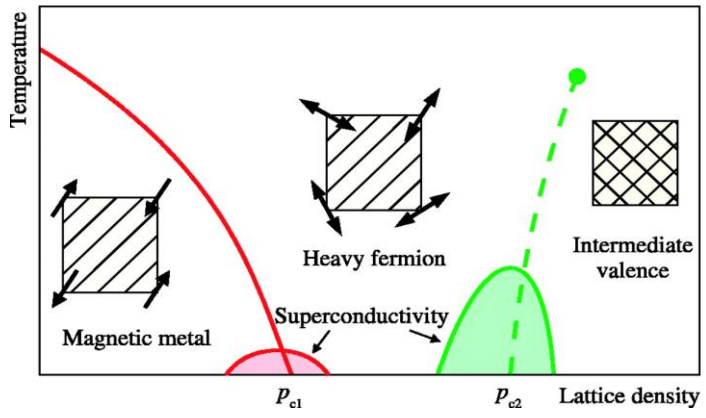
Double-dome—conclusion

Copper based unconventional superconductor



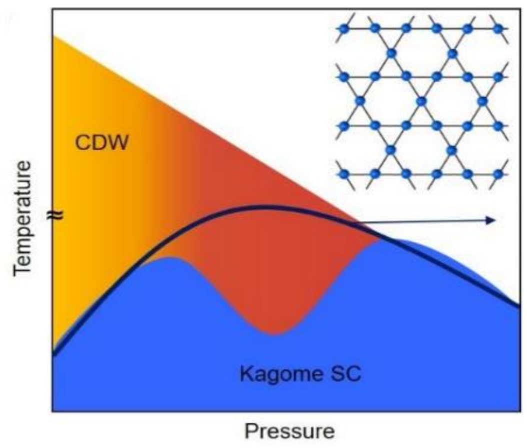
B. Keimer et al.: Nature 518, 179 (2015)

Heavy fermion superconductor



H. Q. Yuan et al.: Science 302, 2104 (2003)

Kagome superconductor



J.-X. Yin: Science Bulletin 68, 568 (2023)

- MATTG is another member of the double-dome superconductivity family.
- Do the double domes share the same origin and order parameter?
- Why does double-dome superconductivity appear only in a small displacement field window?

What does displacement fields do in MATTG?

Double dome superconductivity only exists in a small displacement field window

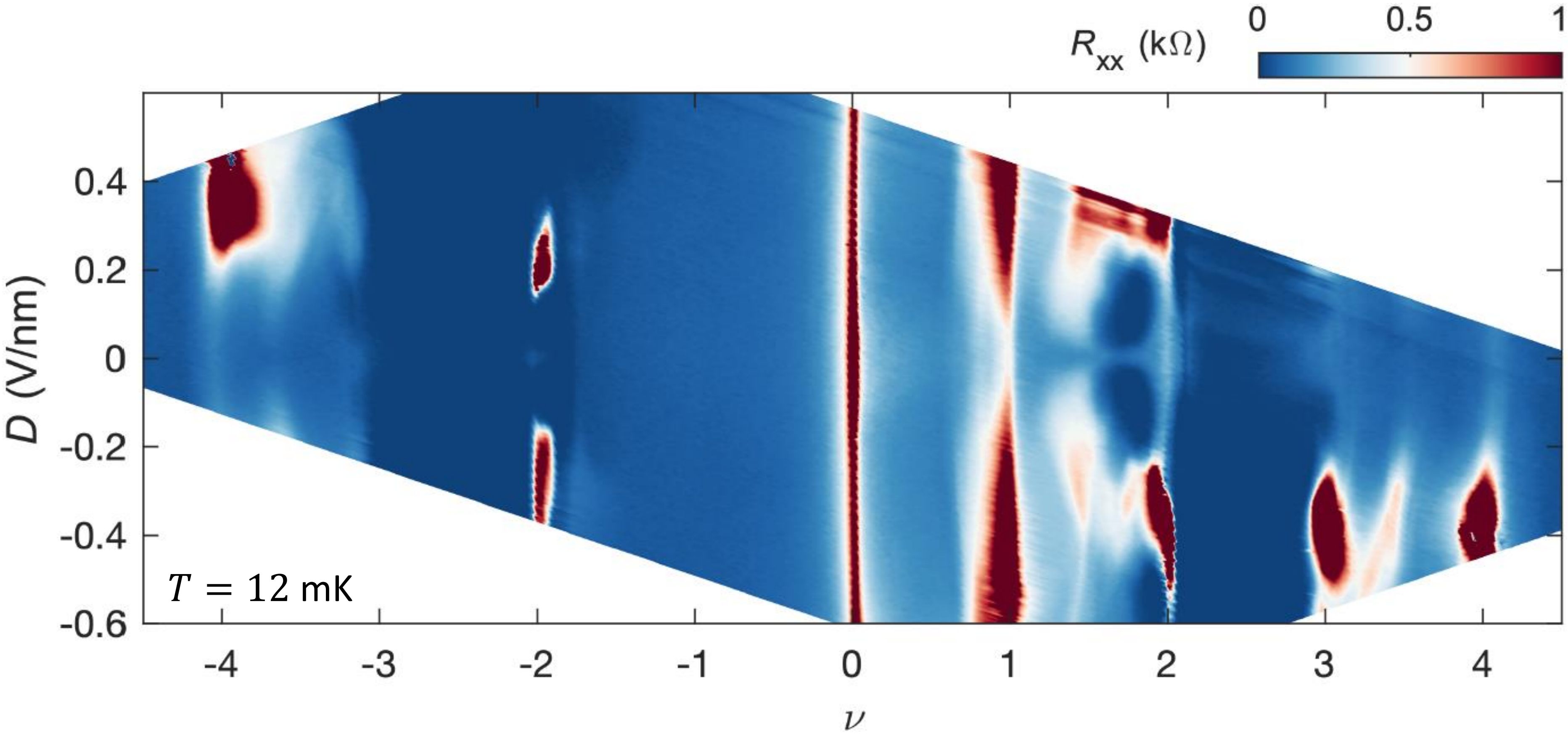
The most direct concequence of displacement field — band structure change

Hybridzation of Dirac band and flat band

Change of flat band width (electron interaction)

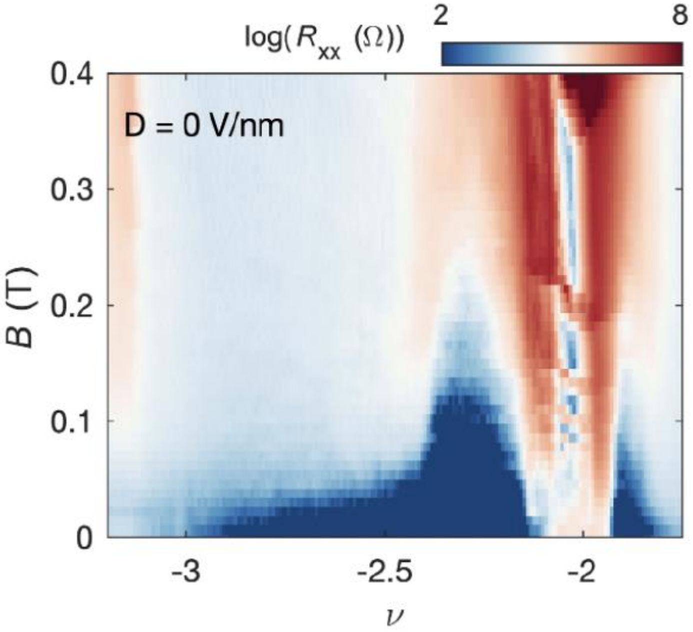
Other effect by the displacement field

Three critical displacement fields—n-D mapping

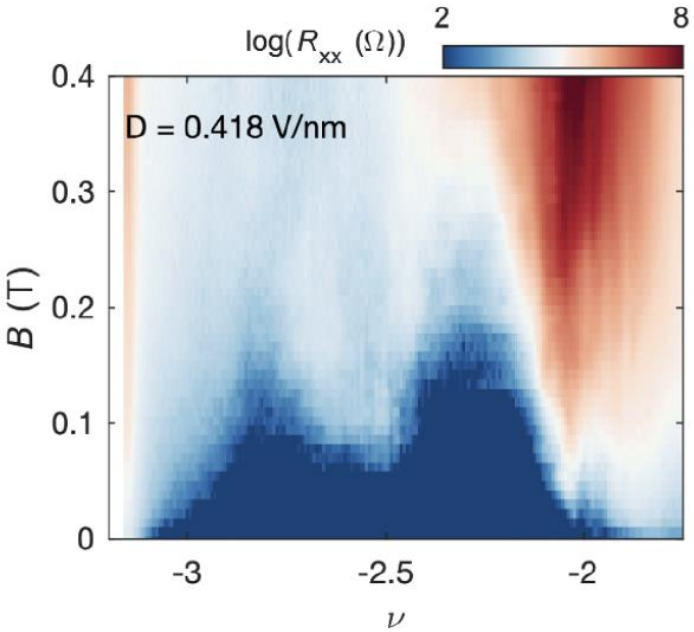


- Robust superconductivity exists on both hole side and electron side.
- Correlated states and superconductivity can be tuned by the displacement field.

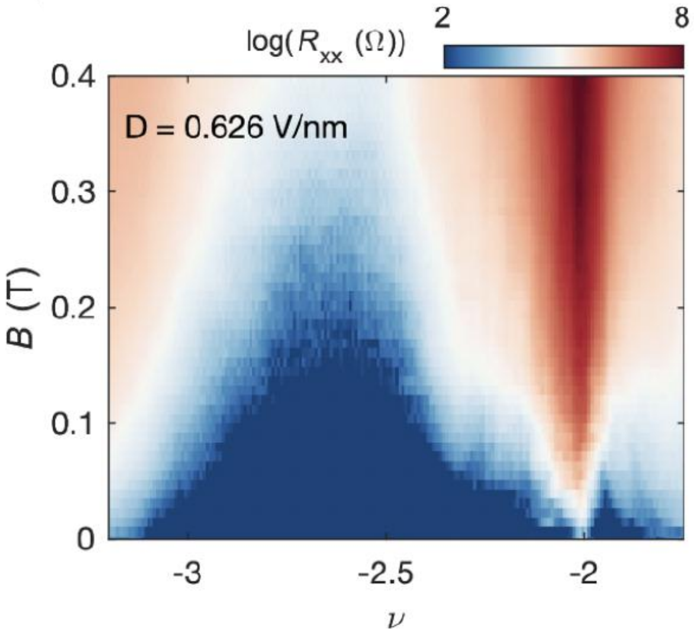
Three critical *D*—double-dome SC (magnetic field dependence, 12 mK)



Only right dome



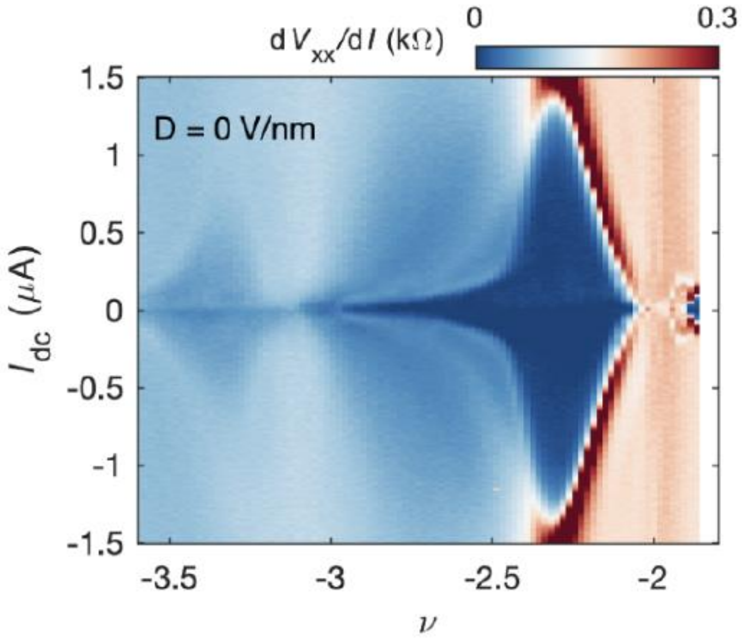
Double-dome



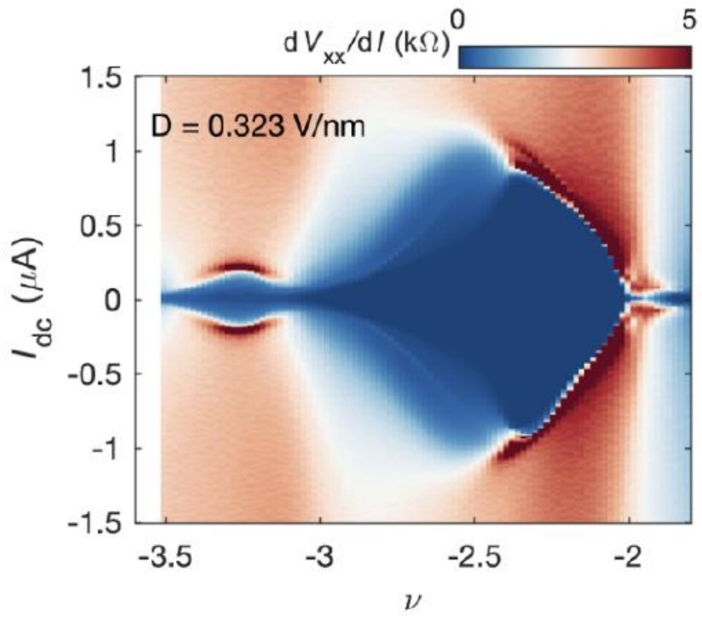
Enhanced left dome

- Superconductivity is tunable by displacement field, with double domes only in the intermediate window.

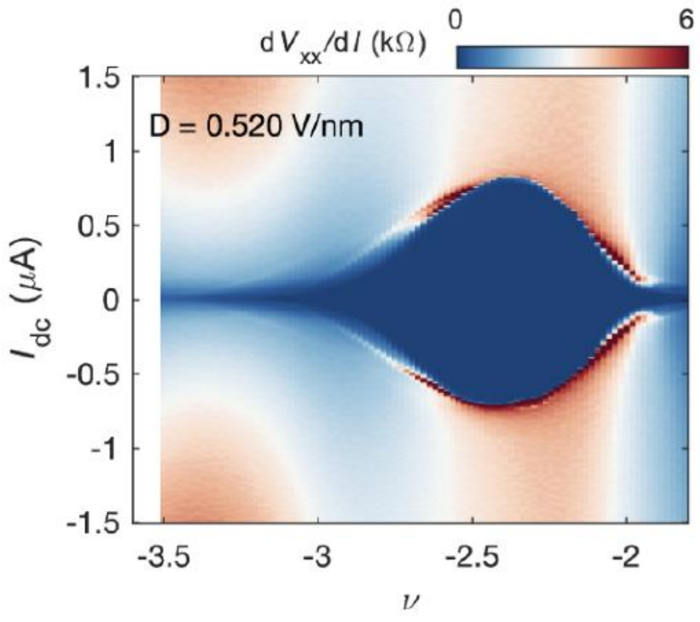
Three critical *D*—double dome SC (bias current dependence, 12 mK)



Only right dome



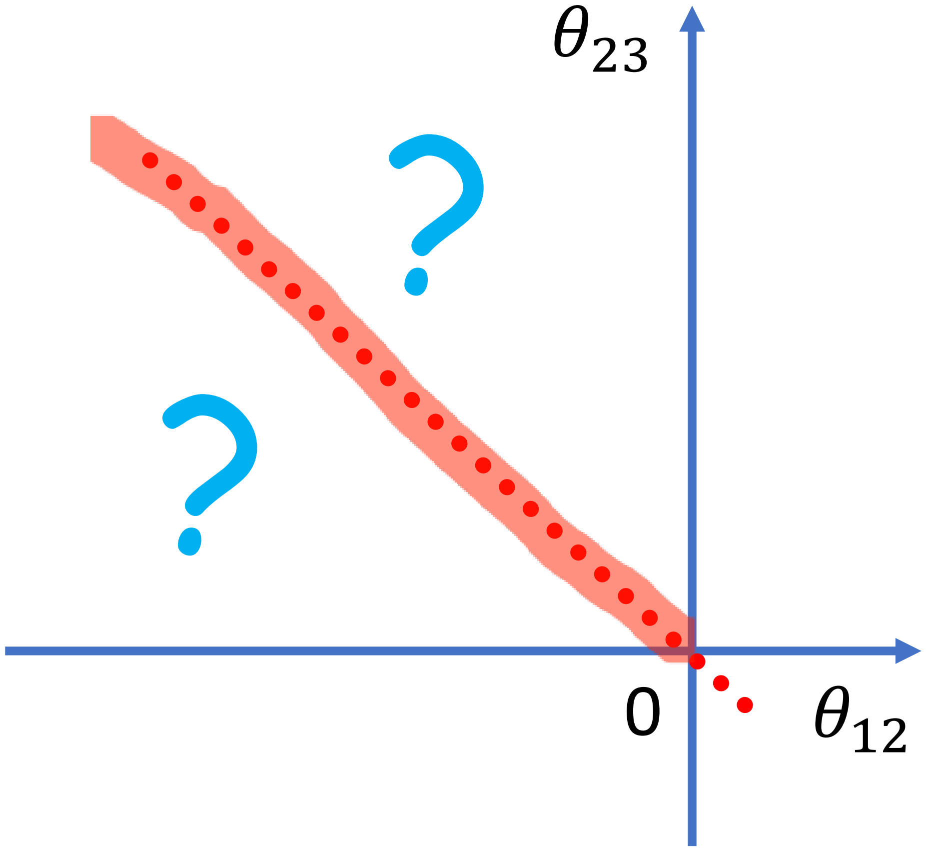
Double-dome



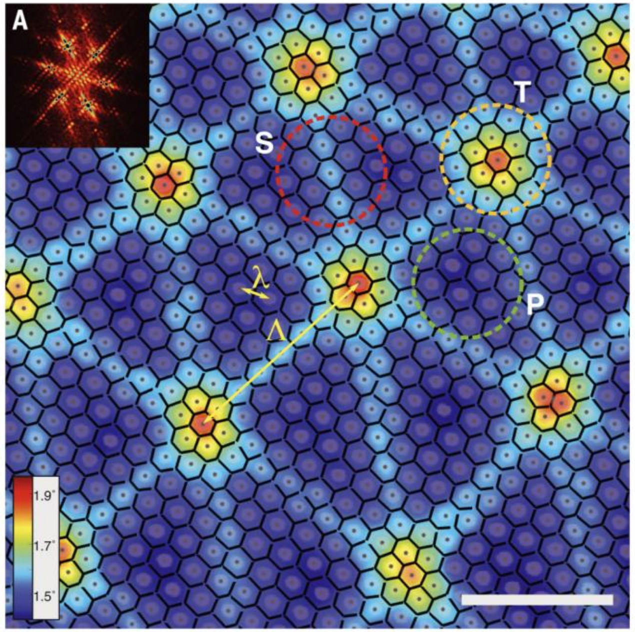
Enhanced left dome

Z. Zhou et. al. Gate-tunable double-dome superconductivity in twisted trilayer graphene, ***Nature Physics*** 21, 1773 (2025).

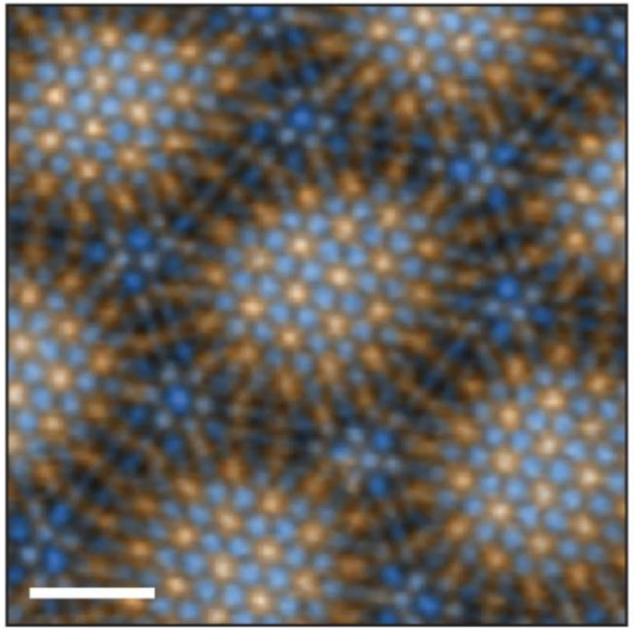
What happens when angles are different?



Supermoiré—supermoiré lattice by spectroscopic measurement



S. Turkel *et al.*: Science 376, 193 (2022)

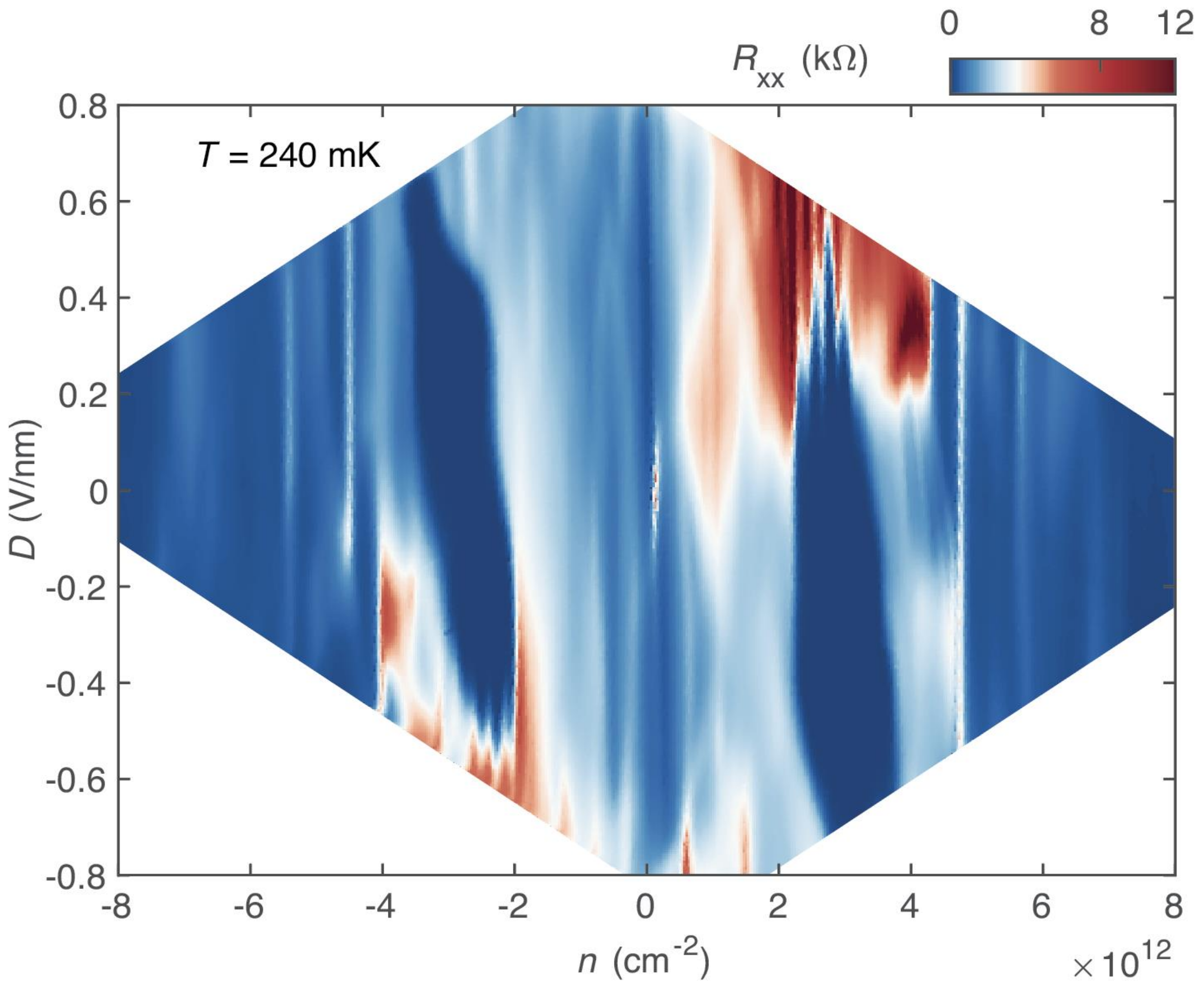


I. M. Craig *et al.*: Nature Materials 23, 323 (2024)

Interference of two moiré lattices can result in a supermoiré lattice!

See also:
Y. Li et al.: Nano Letters 22, 6215 (2022),
D. Park et al.: arXiv 2402.15760 (2024),
C.-Y. Hao et al.: Nature Communications 15, 8437 (2024),
J. C. Hoke et al.: arXiv 2410.16269 (2024)
……

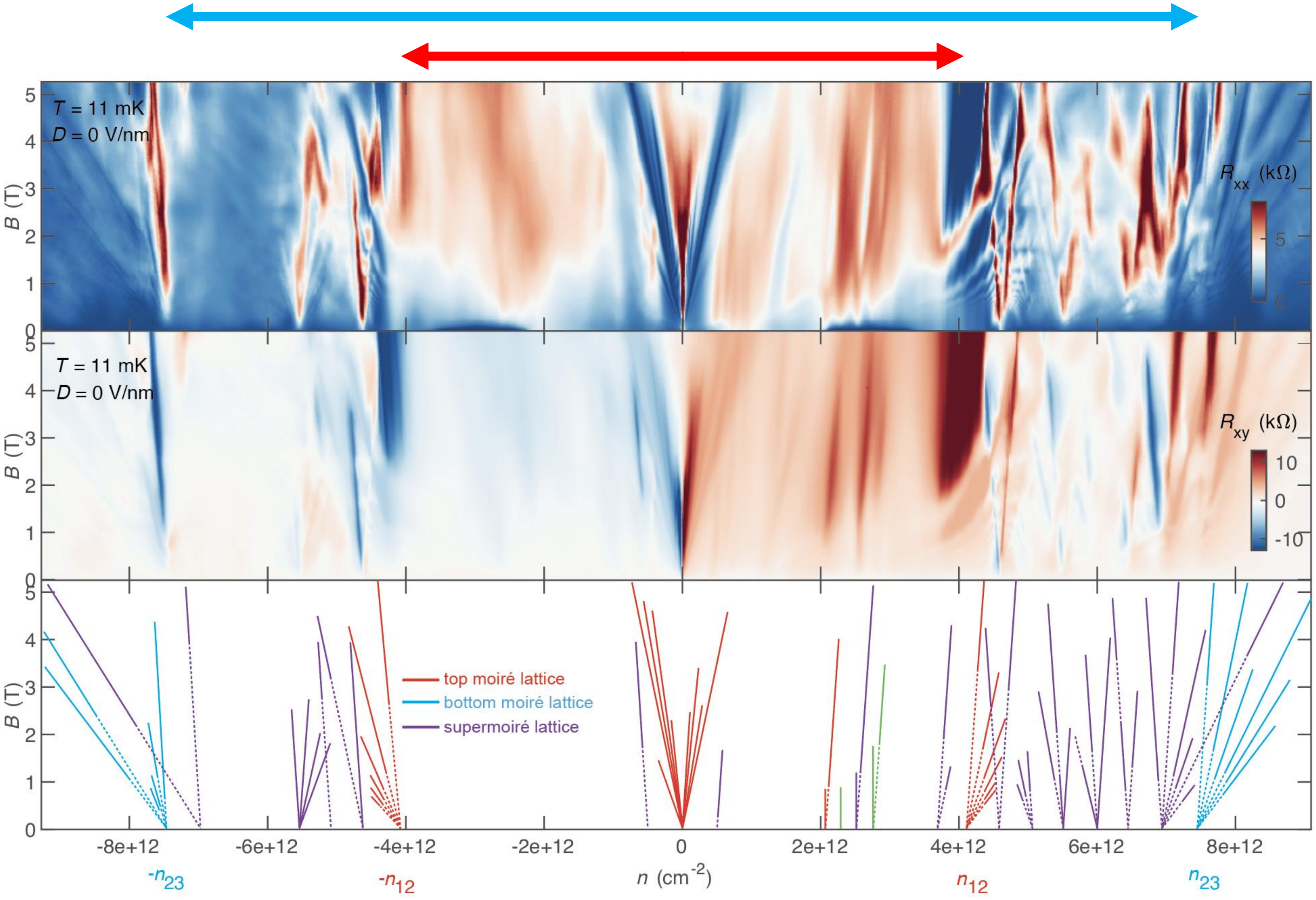
Supermoiré—mirror symmetry broken TTG



- The n-D mapping is asymmetric with respect to D = 0 V/nm.
- Superconducting states and many other resistive states exist in the n-D mapping.

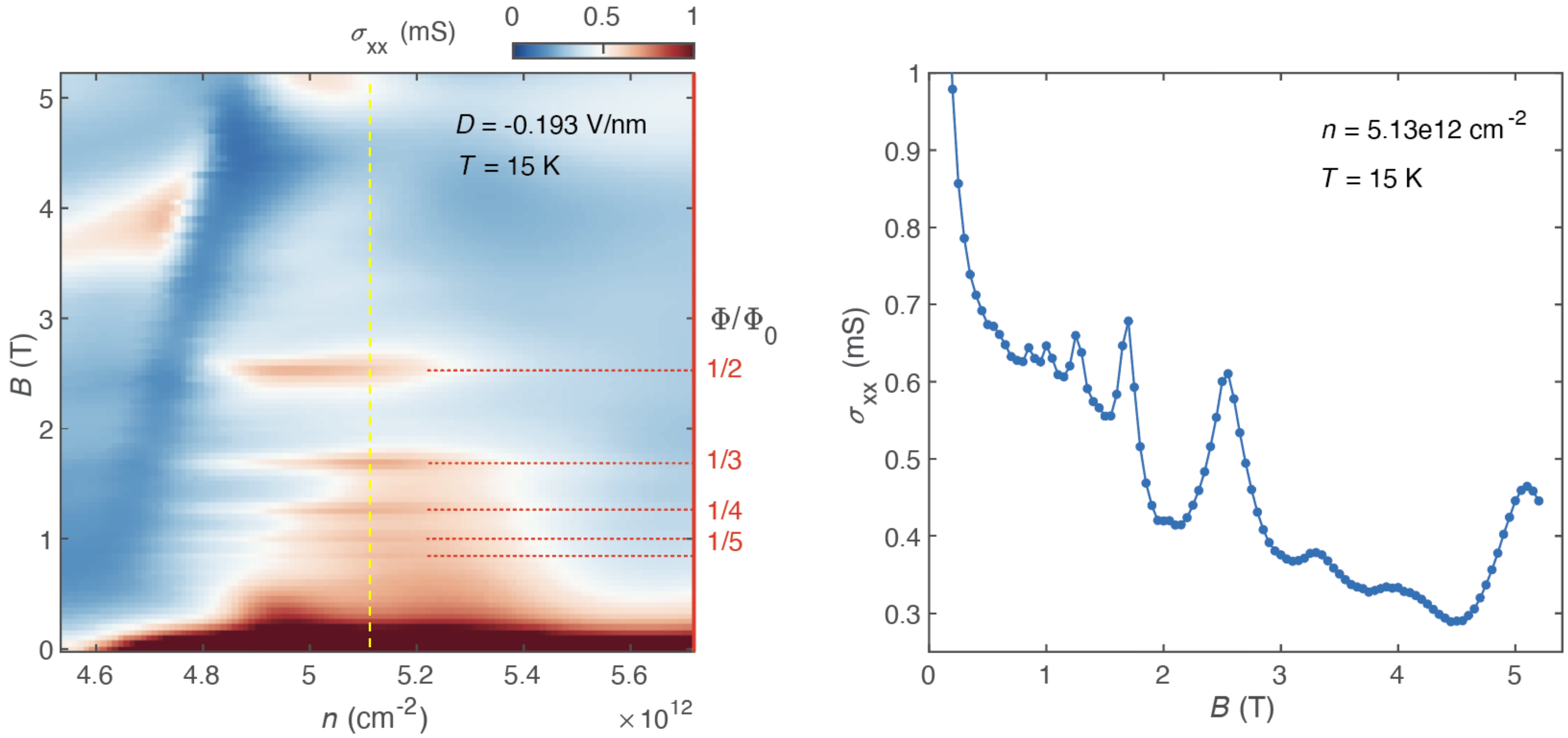
Two twist angles are different!

Supermoiré—extraction of two twist angles



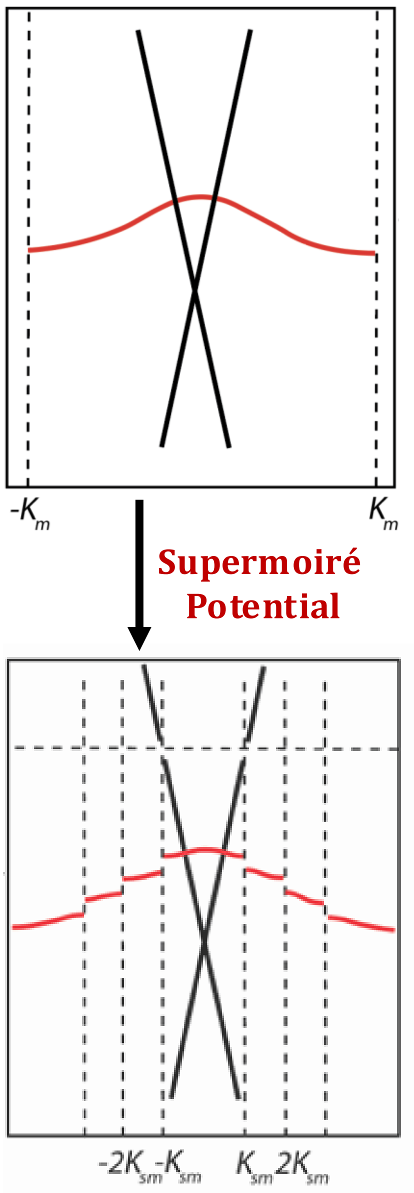
- $\theta_{12} = 1.328^{\circ}$
- $\theta_{23} = -1.785^{\circ}$

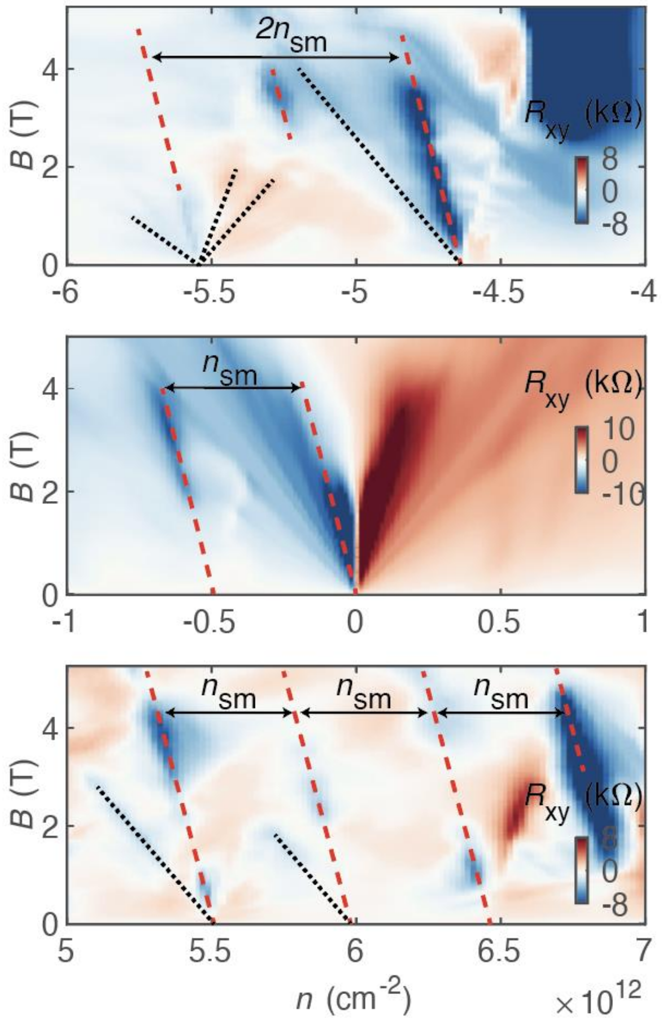
Supermoiré—Brown-Zak oscillations due to supermoiré lattice

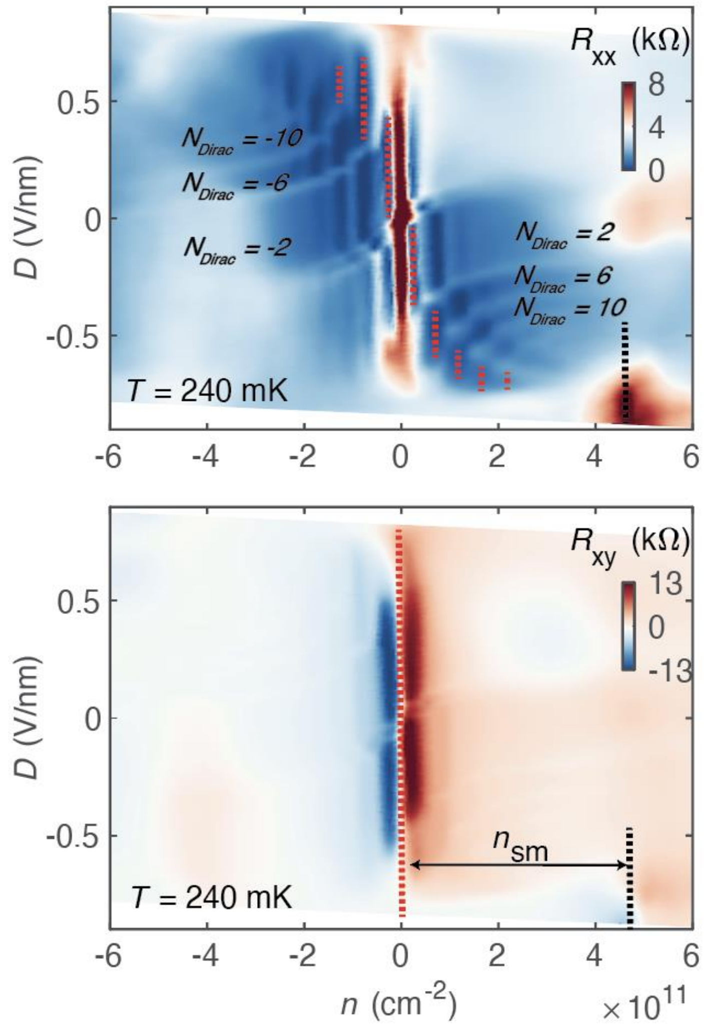


- $B \sim 5$ T corresponds to the unit Φ_0 of the supermoiré lattice with $\lambda_{sm} = 30.6$ nm.
- The expected supermoiré lattice length is $\lambda_{sm-cal} = \frac{a}{\theta_{12}+\theta_{23}} = 30.8$ nm.

Supermoiré—band folding by the supermoiré lattice

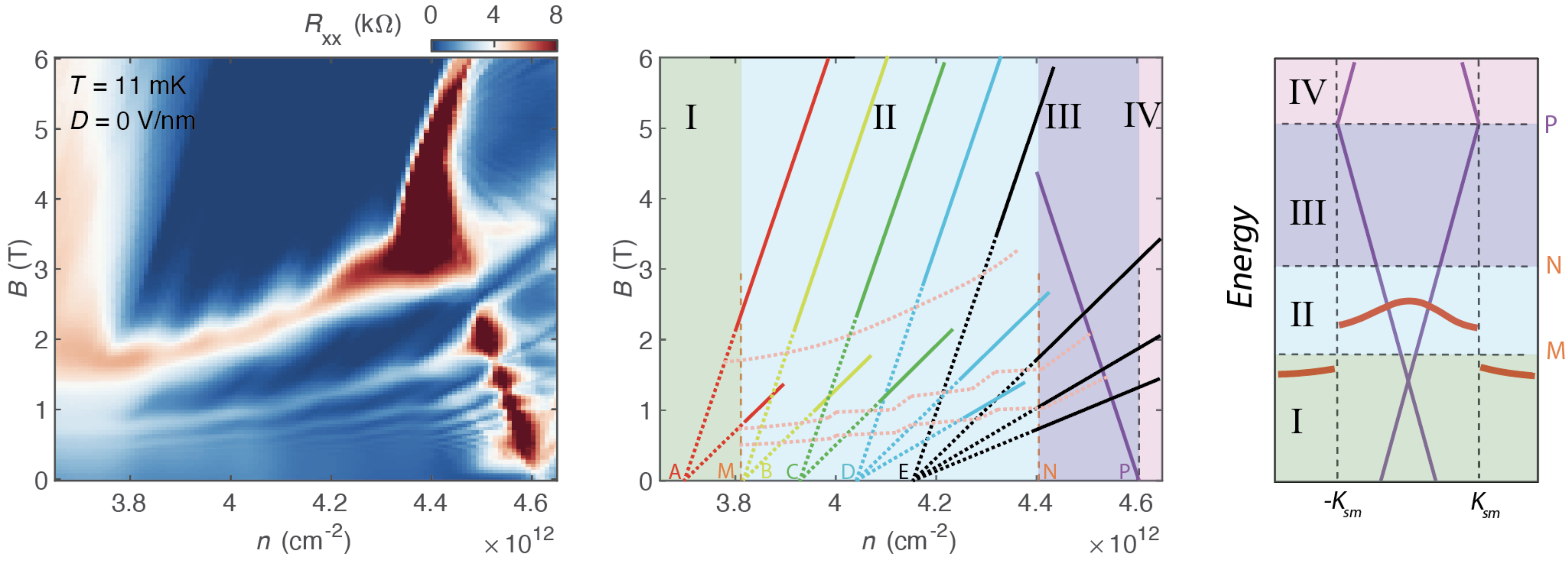






Supermoiré lattice dices both the flat band and Dirac band!

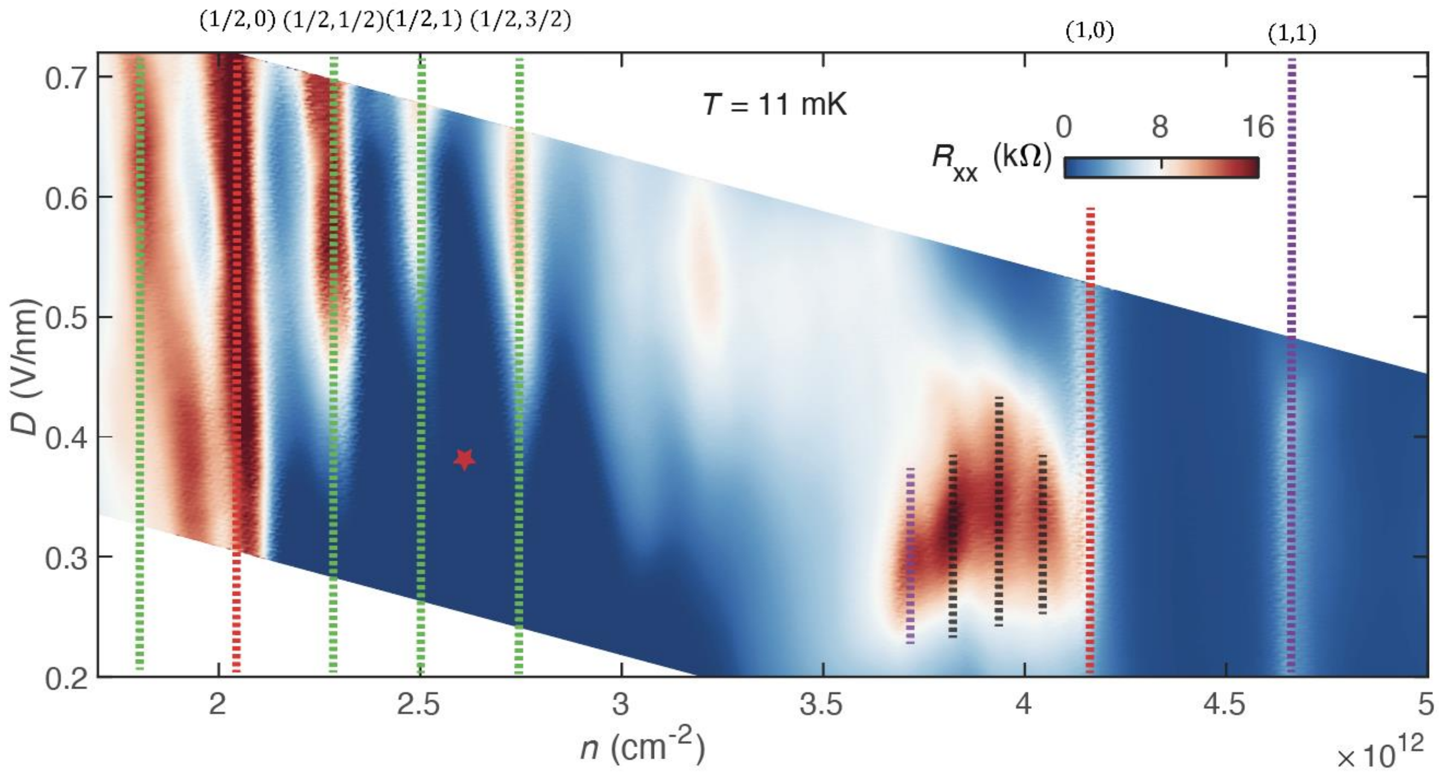
Supermoiré—interaction-driven iso-spin symmetry breaking



The strong interaction results in iso-spin symmetry breaking states!

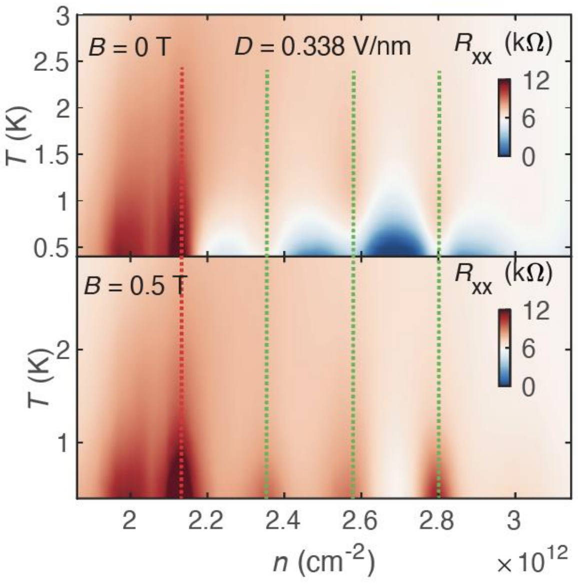
Supermoiré—cascade of superconductor-insulator transitions

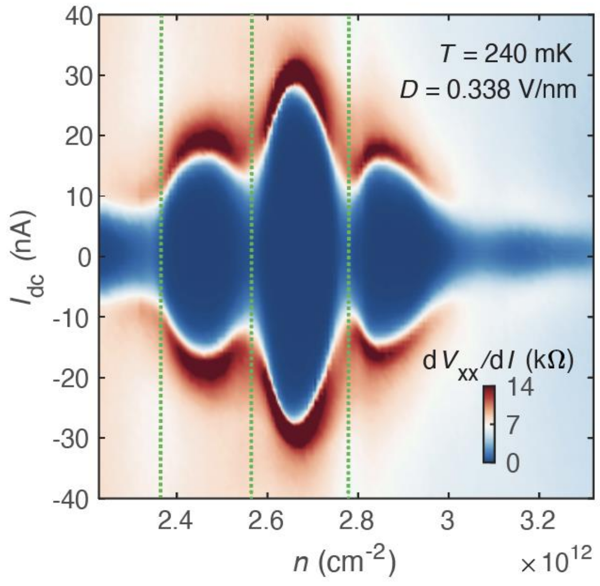
$$1/2 \cdot n_{12} + 1/2 \cdot N \cdot n_{sm}$$

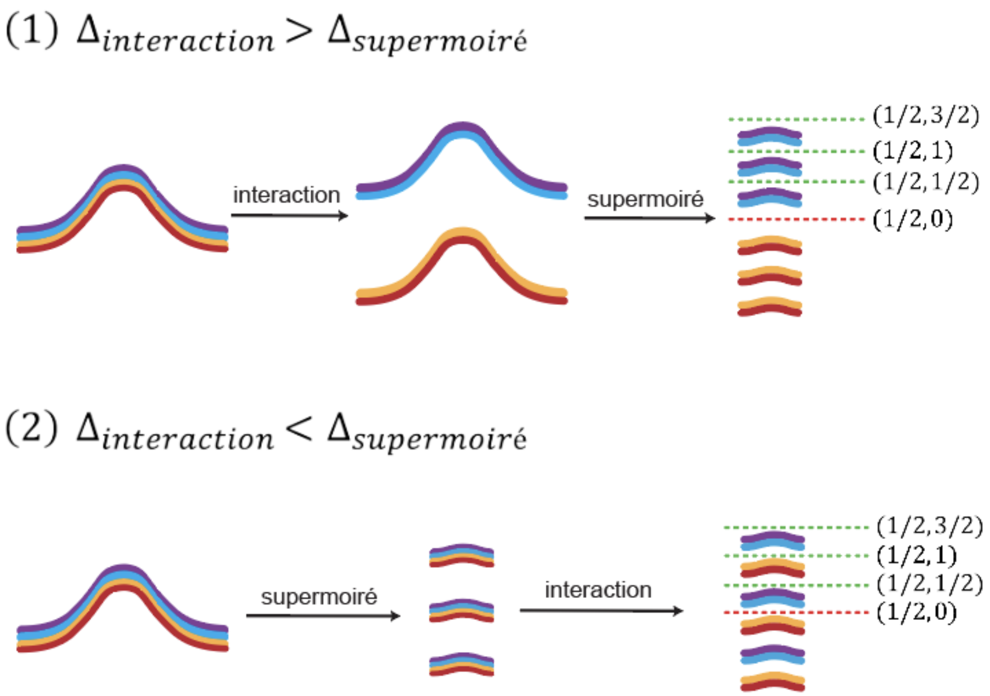


Resistive states slice the superconducting dome into smaller domes!

Supermoiré—two pictures for SC-I transitions







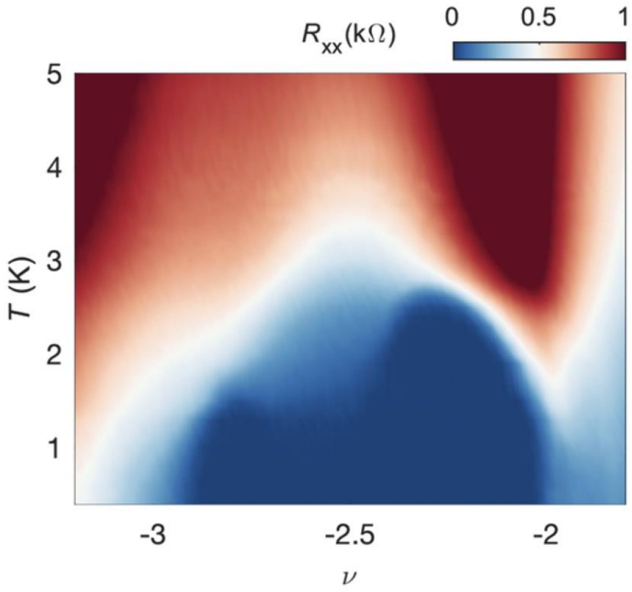
Distance between nearby insulators corresponds to half filling of supermoiré lattice!

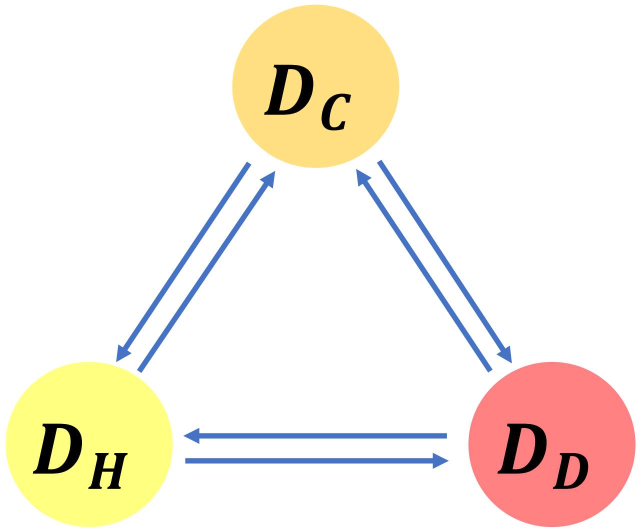
Z. Zhou et. al. Strong Correlations and Superconductivity in the Supermoiré Lattice, ***Nature Physics*** 22, 225 (2026).

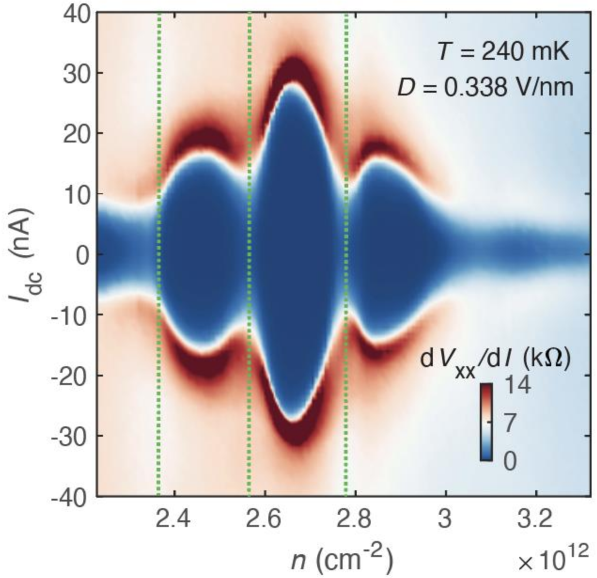
Supermoiré—conclusion

- Interference between two moiré lattices results in supermoiré lattice, strongly altering the band structure.
- Iso-spin symmetry broken states and superconductivity appear in the supermoiré mini flat bands.
- The supermoiré lattice offers a platform to discover and design unexpected electronic quantum phases.

Conclusion and outlook







- We showed the gate tunable double dome superconductivity in MATTG.
- We show there are three critical displacement fields in MATTG, which may uncover the double dome nature in MATTG.
- We observe the existence of supermoiré lattice in the mirror symmetry broken TTG.

Collaborators

Zekang Zhou, EPFL

Magic-angle | Supermoiré

Experiment

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Cheng Shen, EPFL

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Glenn Wagner, Uni Zurich

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Steve H. Simon, Oxford

Kryštof Kolář, Uni Berlin

Cyprian Lewandowski, FSU

Z. Zhou et. al. Gate-tunable double-dome superconductivity in twisted trilayer graphene, ***Nature Physics*** 21, 1773 (2025).

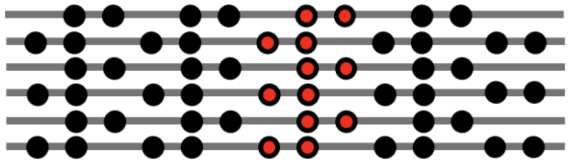
Z. Zhou et. al. Strong Correlations and Superconductivity in the Supermoiré Lattice, ***Nature Physics*** 22, 225 (2026).

Rhombohedral graphene

a

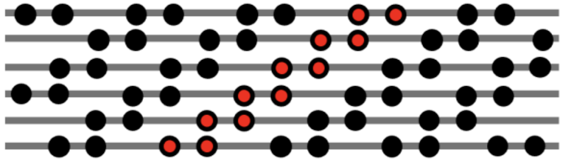
https://www.marsendustri.com/en/what-is-graphite/

ABA



Bernal graphene with alternating stacking order

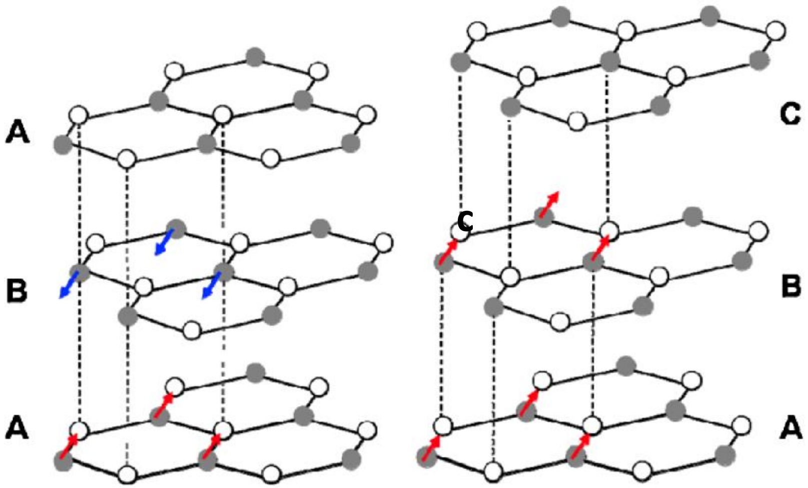
ABC



Rhombohedral graphene with stair-like stacking order

b

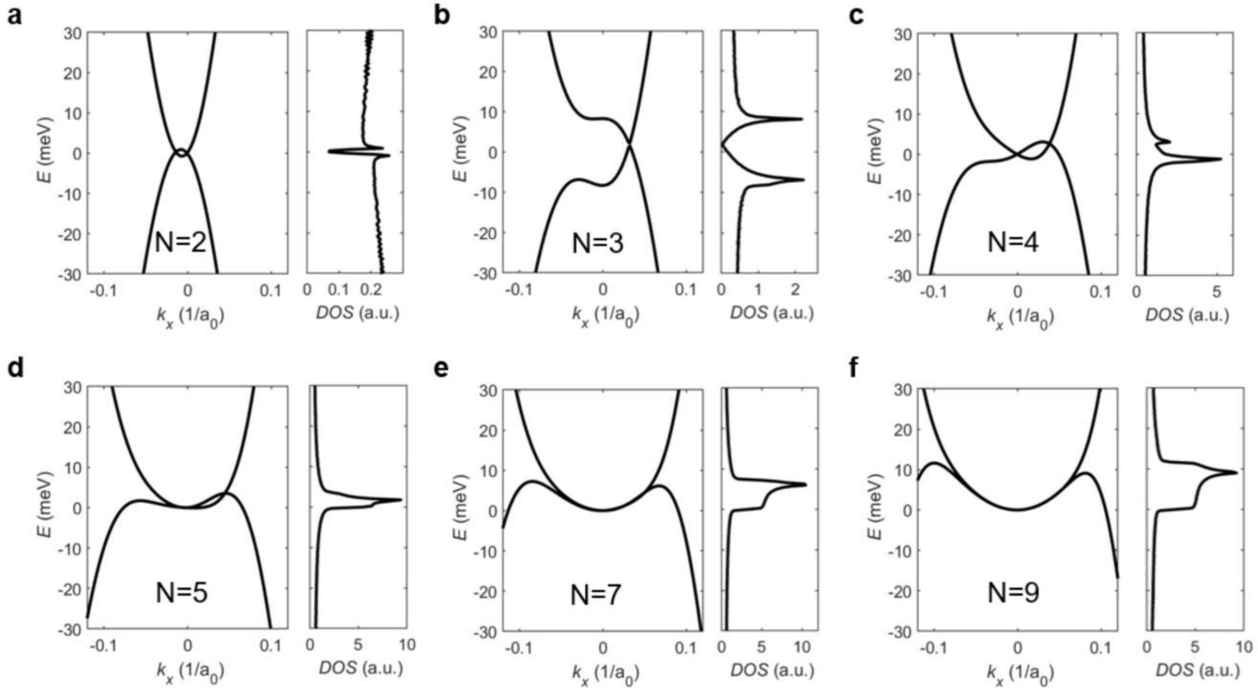
Bernal ABA Rhombohedral ABC

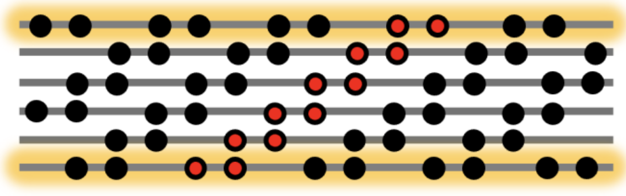


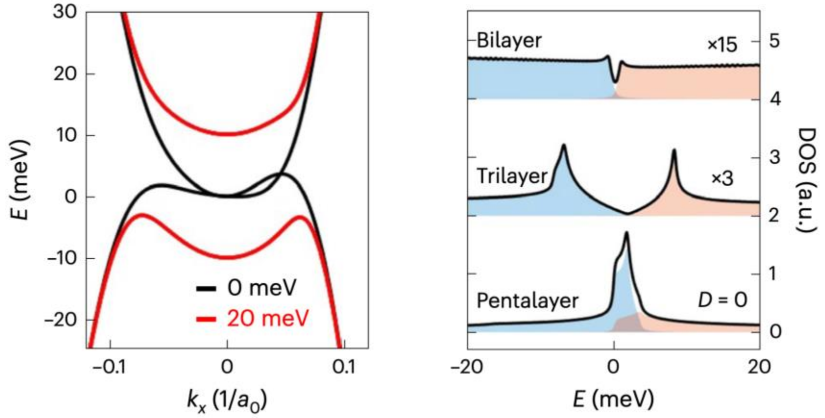
Mak K. F., Shan J., Heinz T. F., Phys. Rev. Lett. **104** (17), 176404 (2010).

Rhombohedral graphene

- Low energy and dispersion follow a power law: $E \sim k^N$
- At surface layers: Touching pair of flat conduction and valence bands + High density of states at low energies and carrier densities
- Berry curvature gives rise a Berry phase of $N\pi$ for N layers per layer at the valleys
- Flat bands and Berry curvature are gate-tunable





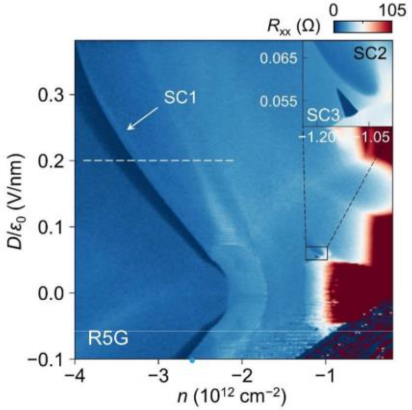


Han T., Lu Z., Scuri G, et al., Nat. Nanotechnol. **19**, 181–187 (2024).

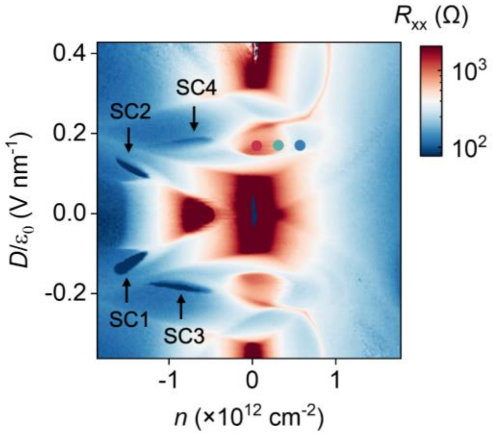
The **Zoo** of Superconductivities in RG

Crystalline:

small D

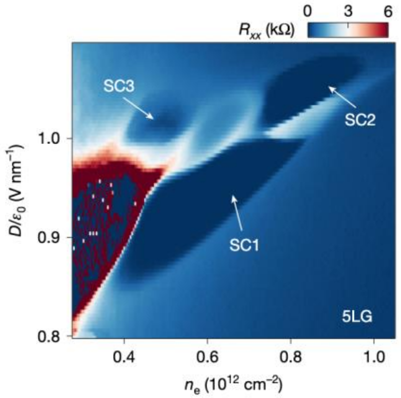


Seo, J. et al. Nature (2026).

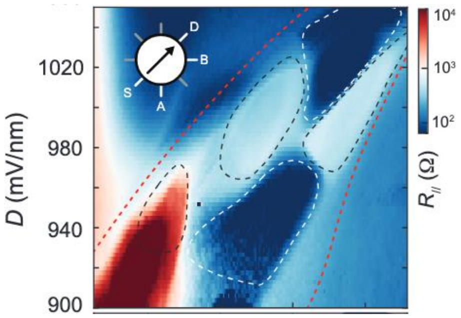


Xie, J. et al. arXiv:2512.24306 (2025).

Large D

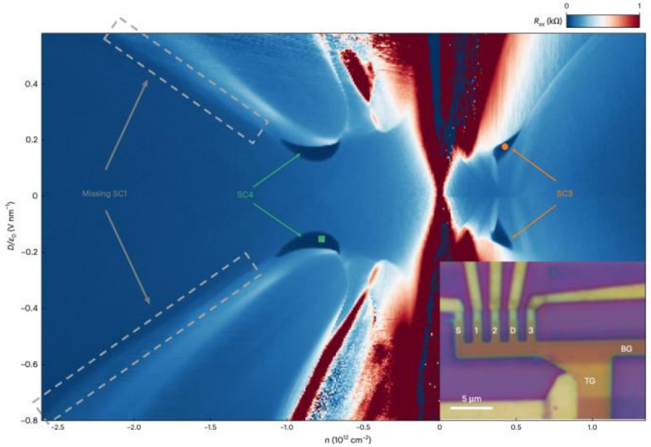


Han, T. et al. Nature 643, 654–661 (2025).

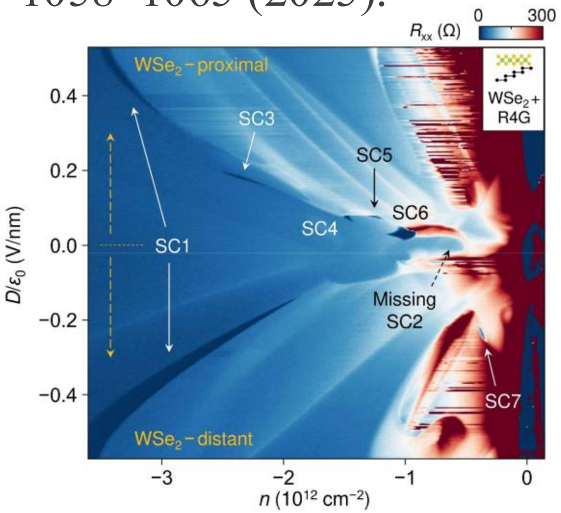


Nguyen, R. Q. et al. arXiv.2507.22026

TMD-proximized:

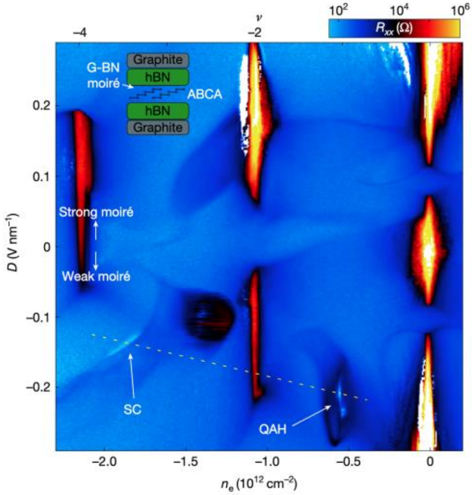


Yang, J. et al. Nat. Mater. 24, 1058–1065 (2025).

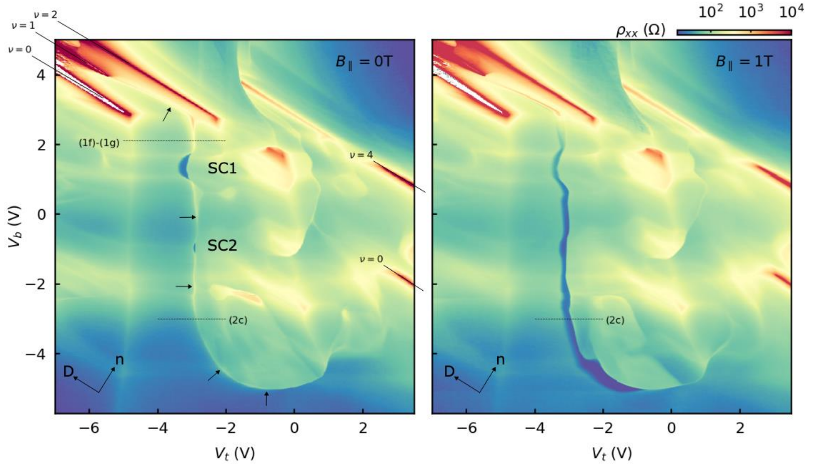


Seo, J. et al. Nature (2026).

w/ hBN-moiré:

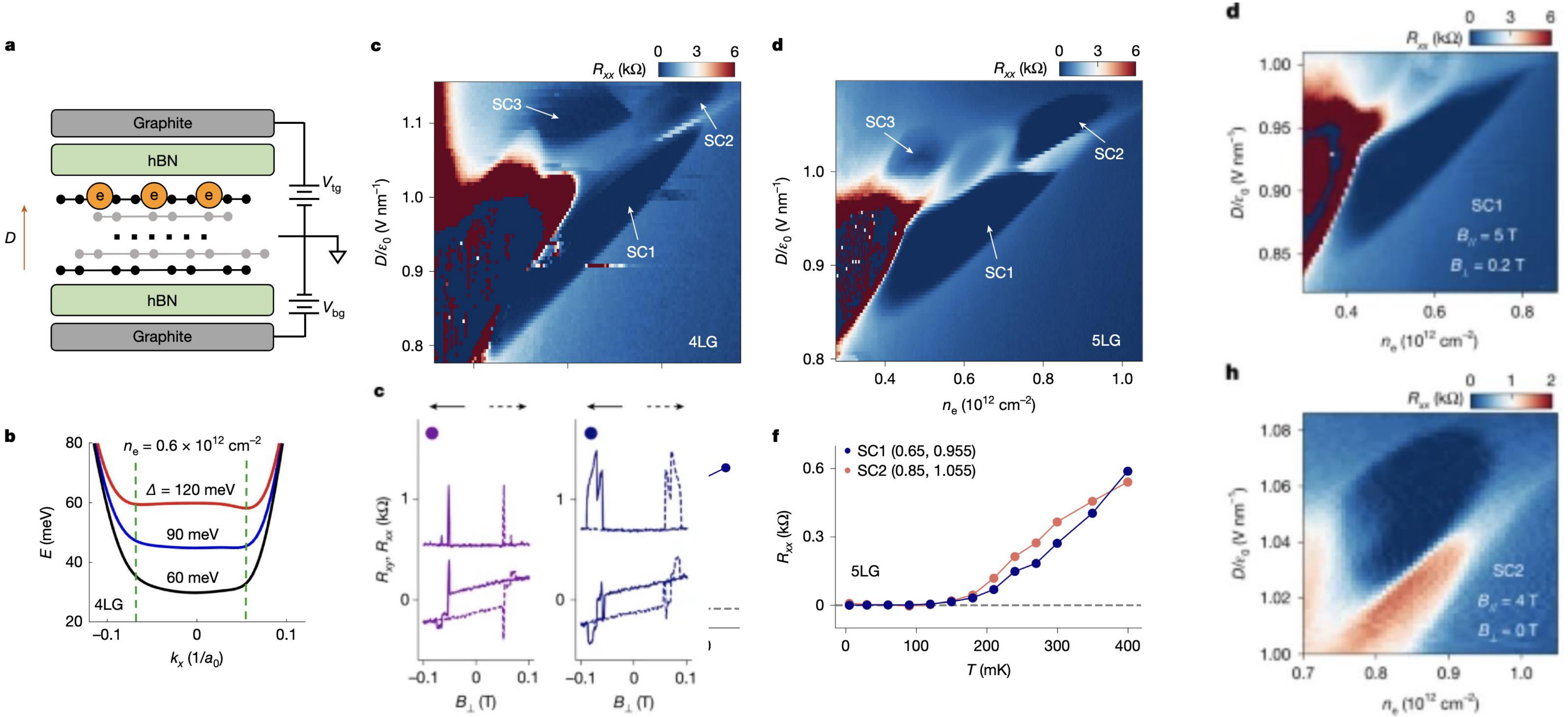


Choi, Y. et al., et al. Nature 639, 342–347 (2025).



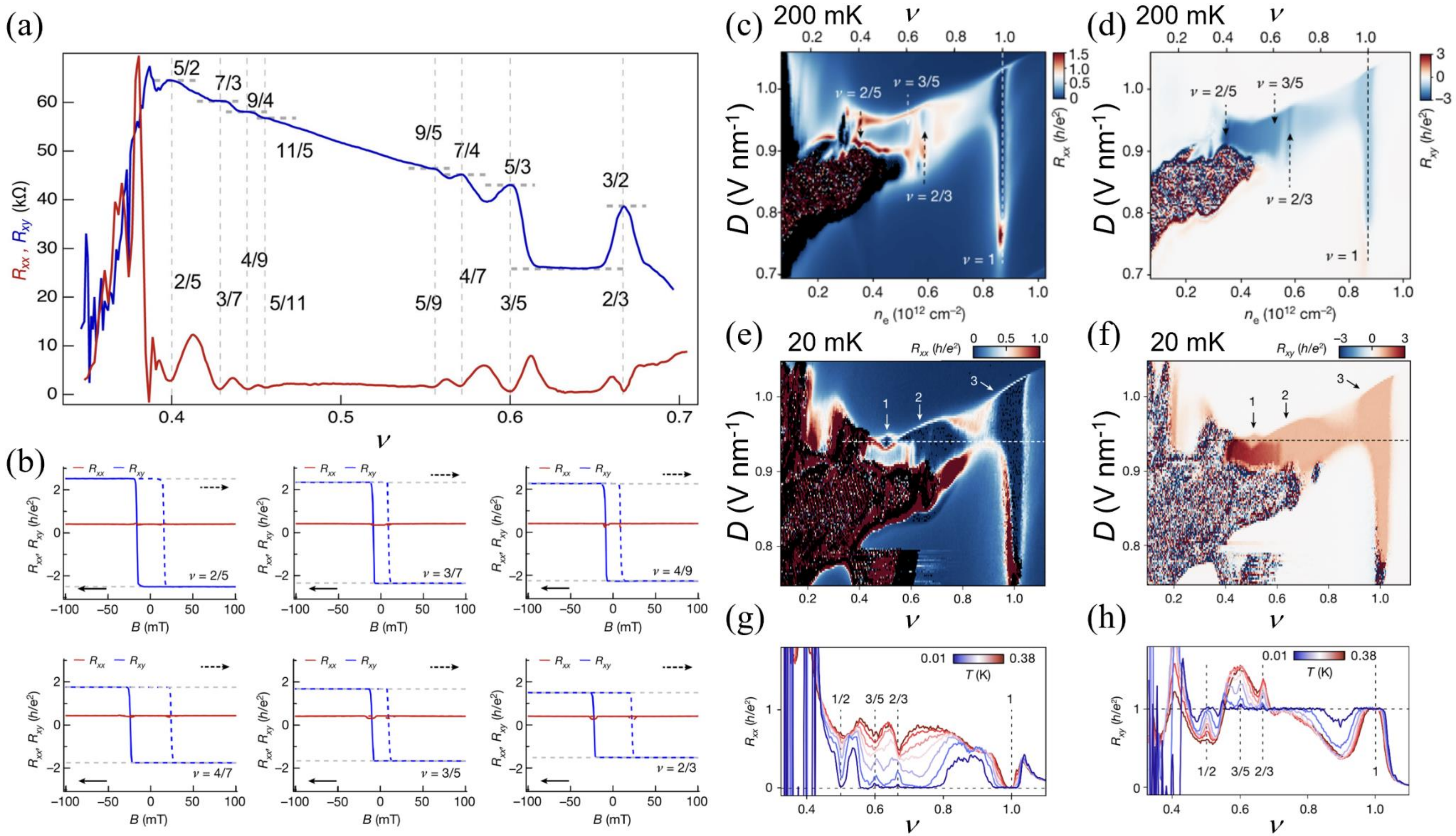
Kumar, M et al. arXiv.2511.16578 (2025).

Chiral Superconductivity in RG



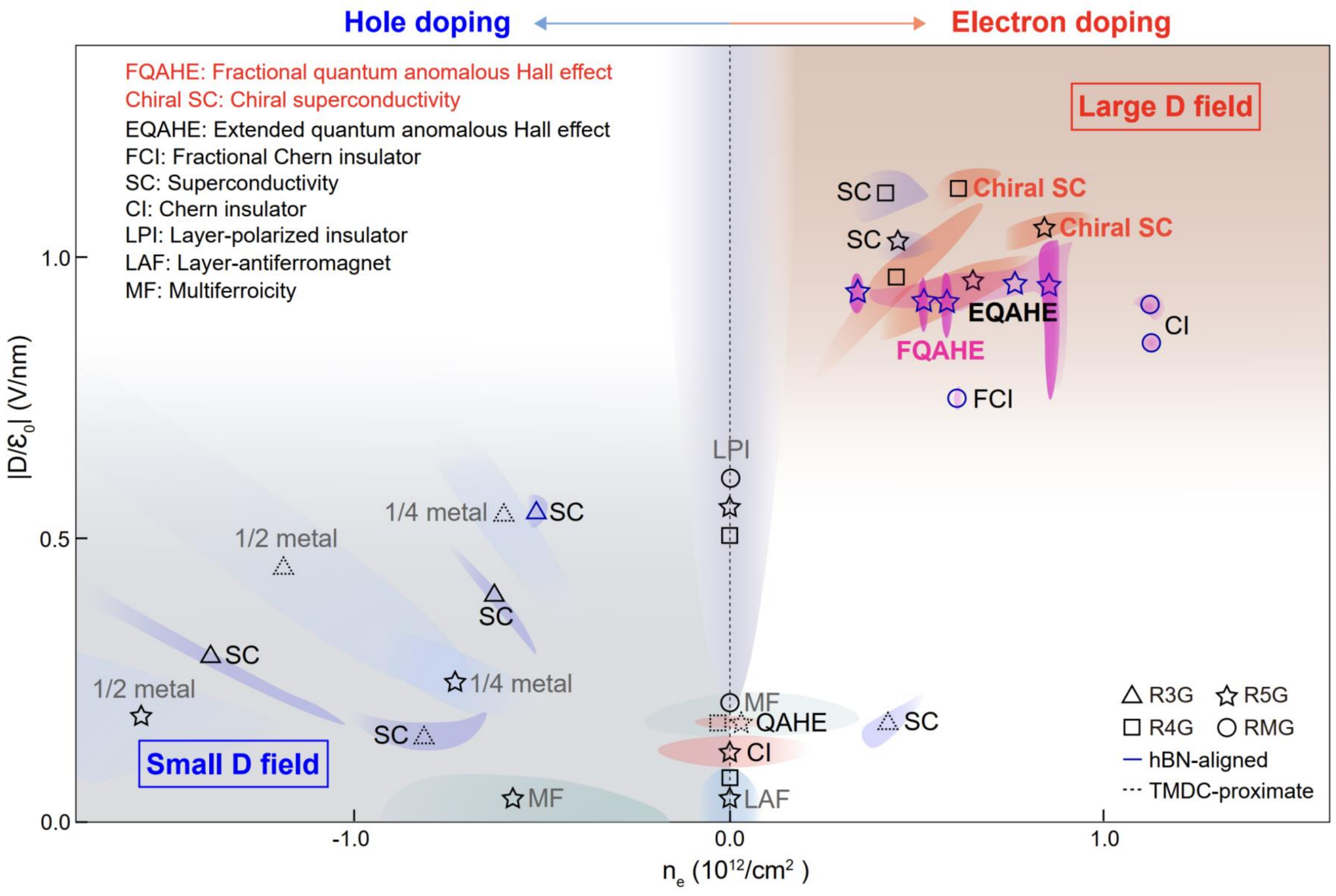
Han T., Lu Z., Hadjri Z., Ju L. et al., Nature **643**, 654–661 (2025).

Quantum anomalous Hall states RG



Lu, Z., Han, T., Yao, Y. *et al*., *Nature* **626**, 759–764 (2024) and *Nature* **637**, 1090–1095 (2025).

Phase Diagram Overview



Zhang H., Lu J., Wu S., Zhou S. et al., arXiv:2605.05199 (2026).

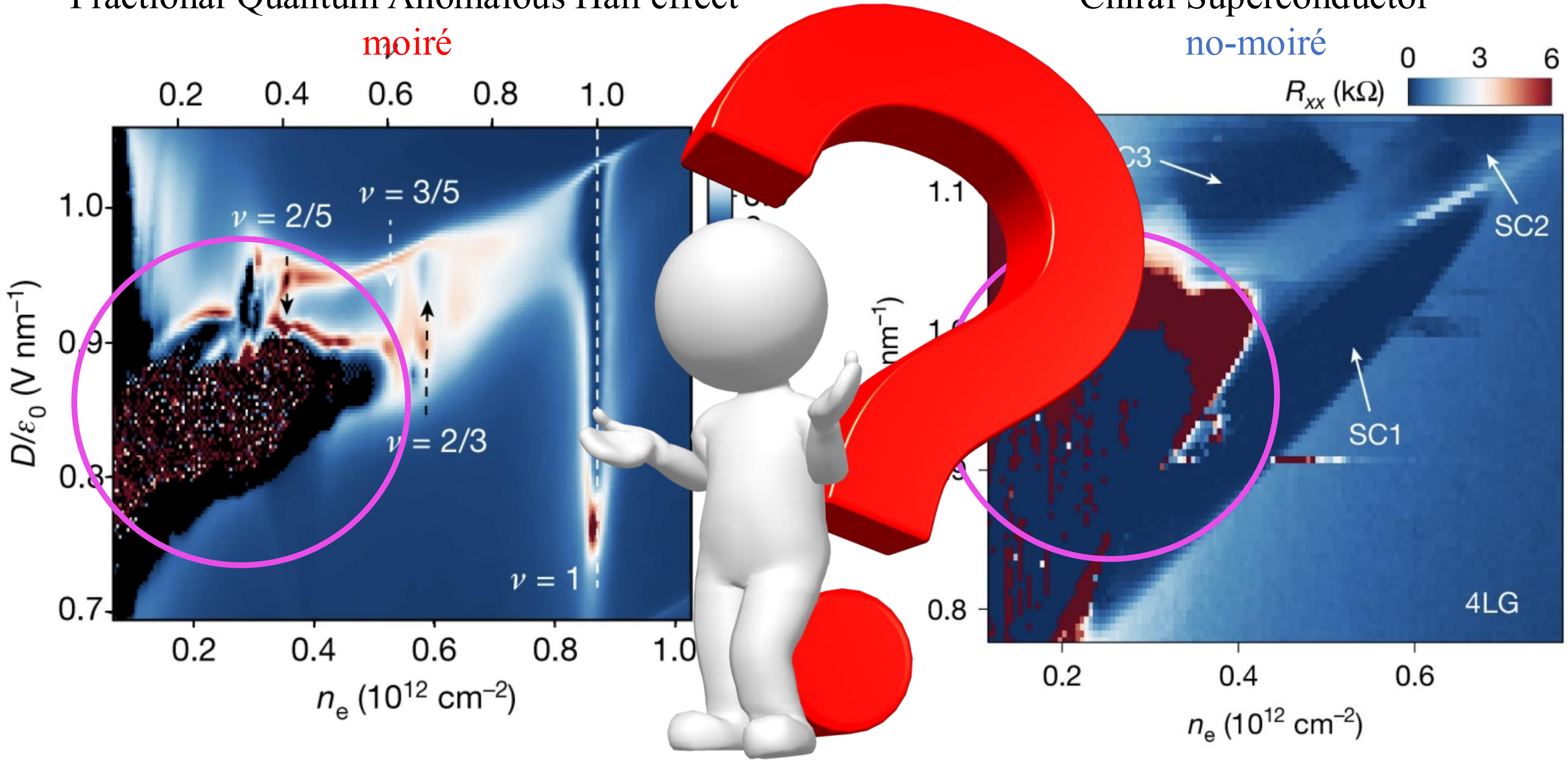
Rhombohedral graphene

Fractional Quantum Anomalous Hall effect

moiré

Chiral Superconductor

no-moiré



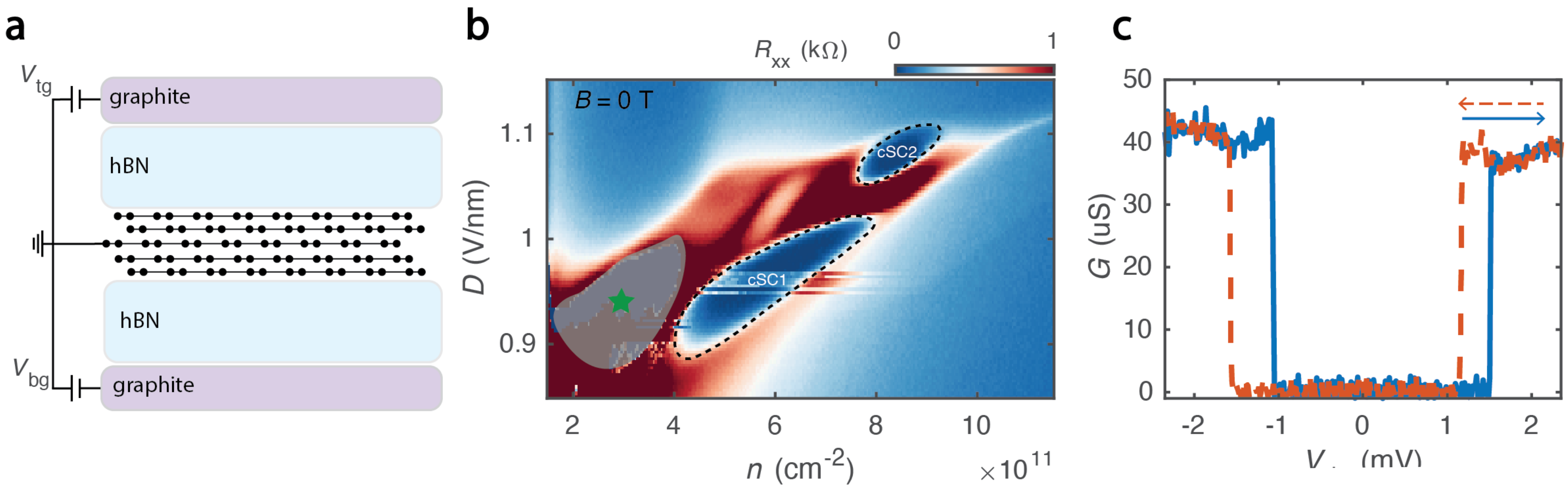
Z. Lu *et al.*, *Nature* **626**, 759–764 (2024).

T. Han *et al.*, *Nature* **643**, 654–661 (2025).

Rhombohedral graphene pentalayer

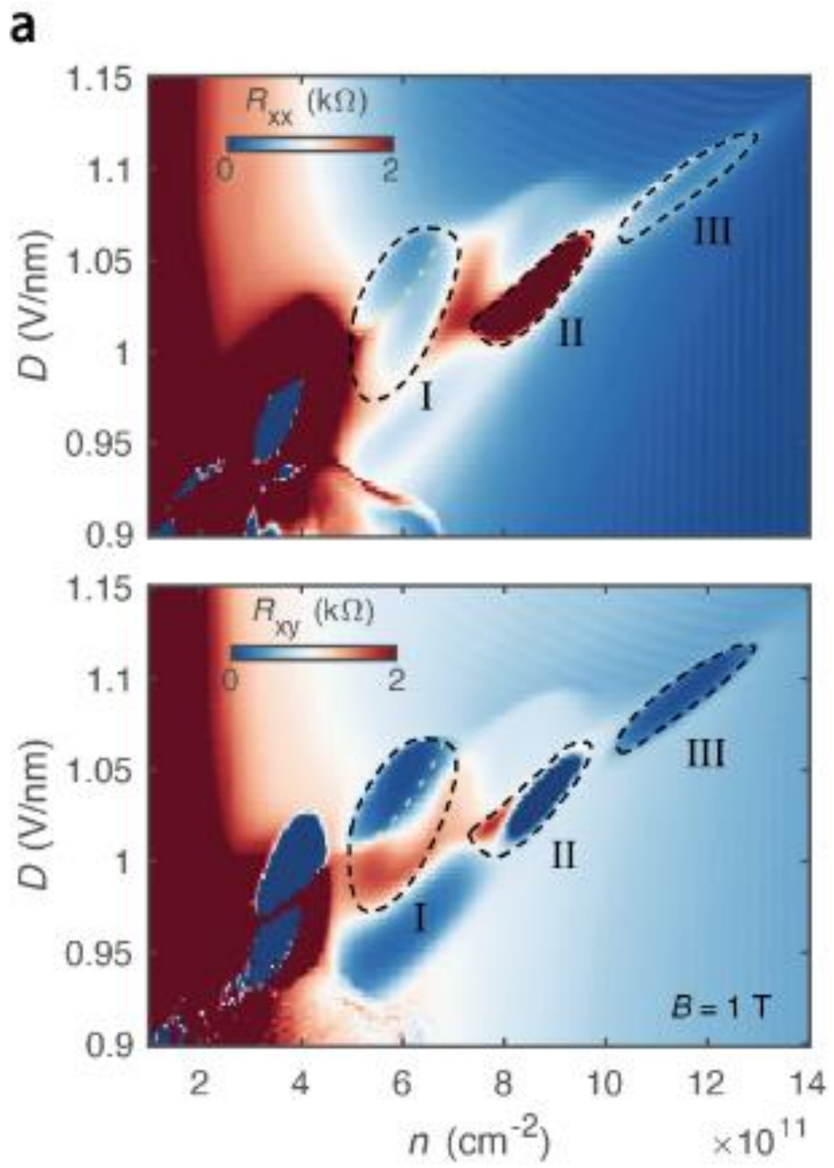
Z. Zhou et al., Submitted (2026)

See for more T. Han et al., arXiv:2604.00113 (2026).



n – D under finite B

Z. Zhou et al., Submitted (2026)

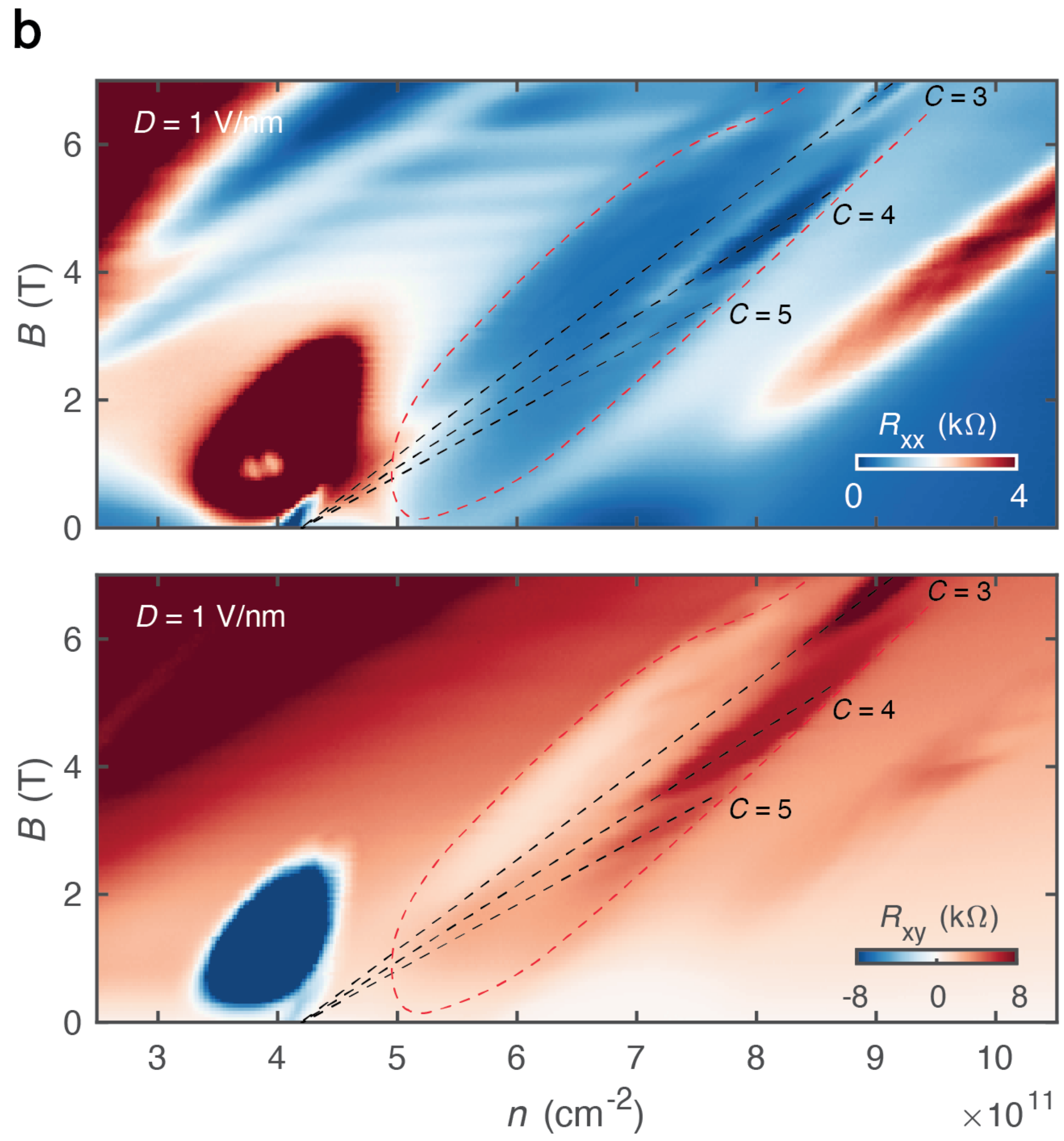


Both the cSC1 and cSC2 phases are substantially suppressed at 1T.

- Region I shows two competing states
- Region II shows RIQH
- Region III shows a low resistive state

Bifurcation of Region I

Z. Zhou et al., Submitted (2026)



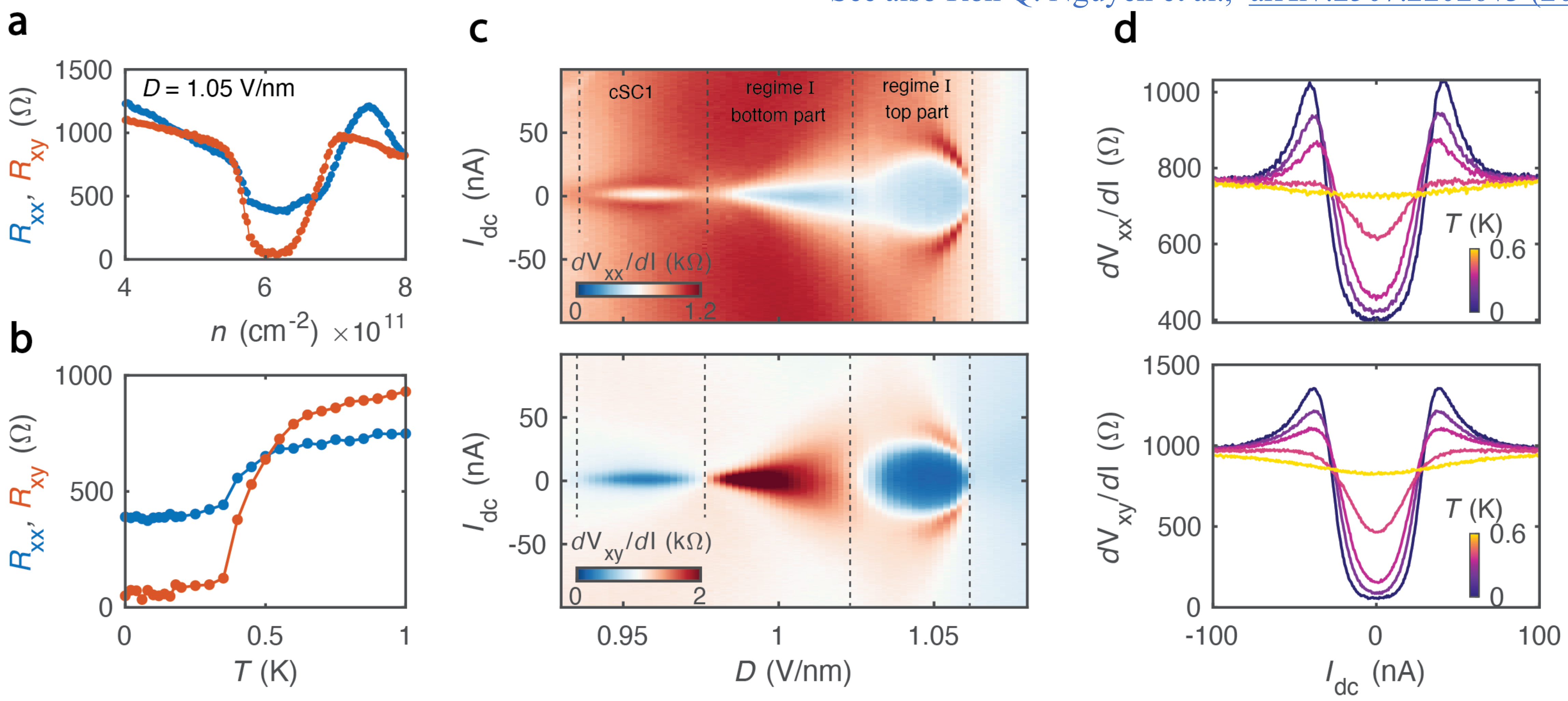
- The boundaries of Region I shift toward higher carrier density as the magnetic field increases.
- The RIQH states emerge from the Wigner crystal phase boundary.
- RIQH states deviate from the Středa formula.

Z. Zhou et al., Submitted (2026)

Superconductivity in Region I

Z. Zhou et al., Submitted (2026)

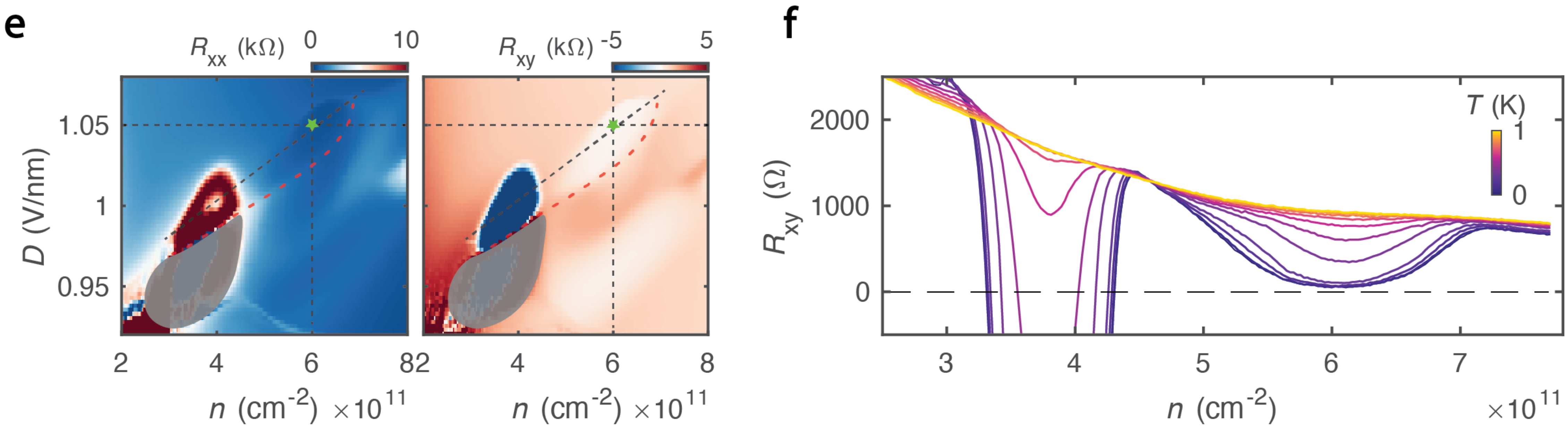
See also Ron Q. Nguyen et al., arXiv:2507.22026v3 (2025).



out-of-plane magnetic-field-stabilized superconducting phase !!!

Superconductivity Region I

Z. Zhou et al., Submitted (2026)

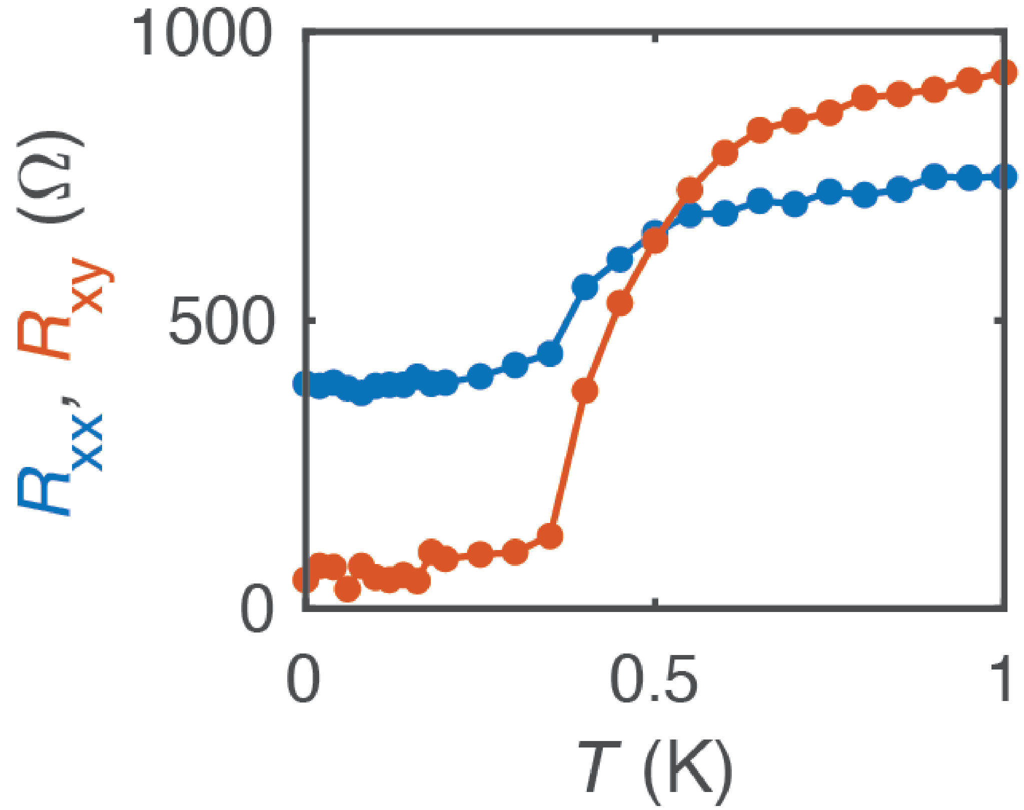


- The less electron-doped side exhibits a negative Hall resistance, the metallic WC state.
- The more electron-doped side shows a nearly zero Hall resistance, a superconducting state.

boundaries are connected!

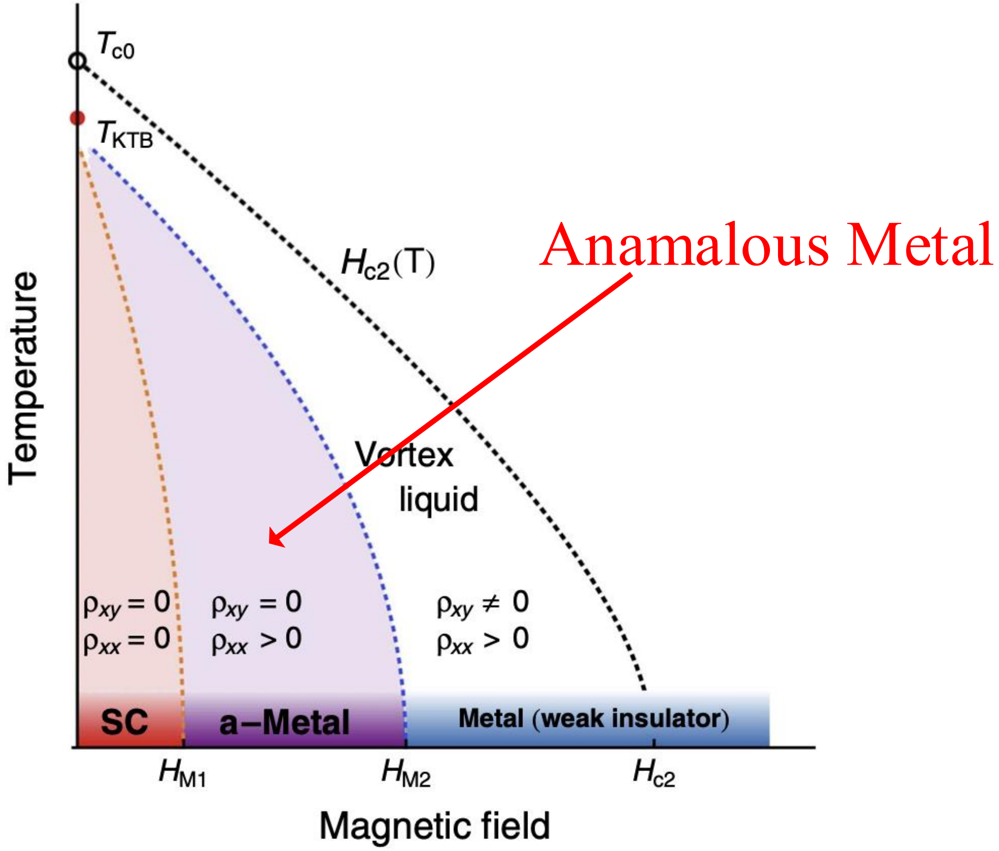
Superconductivity Region I

Z. Zhou et al., Submitted (2026)



Non- zero R_{xx} and zero R_{xy}!!

Can there be any other explanation?

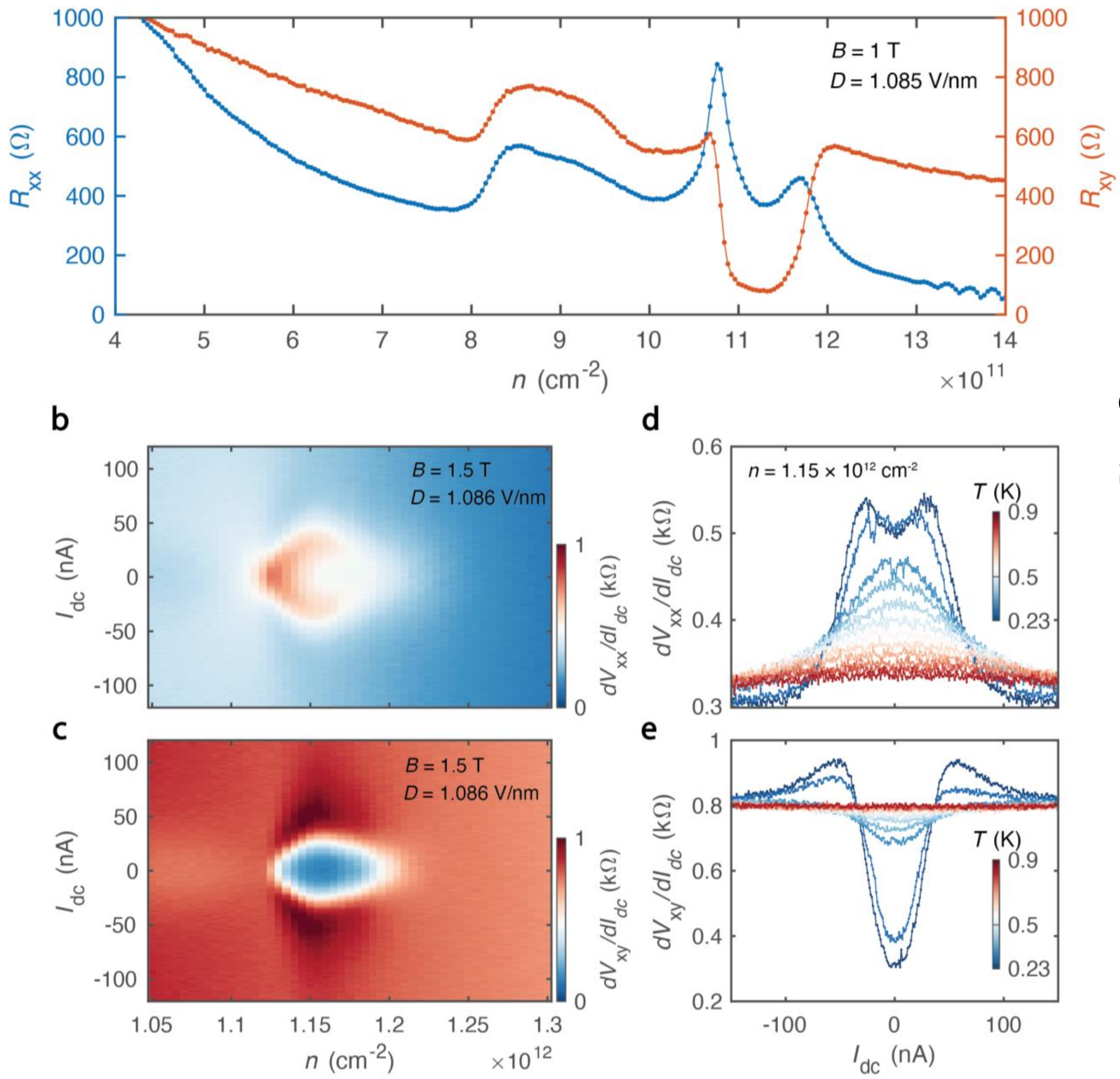


Breznay and Kapitulnik, Sci. Adv. (2017).

Also, M. Yankowitz et al., Under review (2026).

Superconductivity Region III

Z. Zhou et al., Submitted (2026)



out-of-plane magnetic-field-stabilized superconducting phase !!!

Summary

Z. Zhou et al., Submitted (2026)

Four closely intertwined emergent phases in pentalayer rhombohedral graphene.

- A hole-doped mWC phase emerging along the boundary of a WC phase.
- In an out-of-plane magnetic field, we observe an fSC phase in the upper part of region I and unconventional RIQH states in the lower part of region I.
- The phase boundary between the mWC and WC phases evolves continuously into the boundary separating the superconducting and RIQH phases.
- All four states exhibit comparable critical temperatures.
- At high displacement fields, the RIQH states in Region I can be interpreted as emerging from the Landau levels of an electron-doped mWC phase.

Collaborators

Zekang Zhou, EPFL

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hBN Crystals (NIMS Japan)
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Takashi Taniguchi

20 mK dry dilution (CEA Saclay, France)
Now doing shot noise measurements
Raphaël Ayache
Preden Roulleau

50 mK wet dilution (WIS, Israel)
Moty Heiblum

Wigner crystal discussions
Sandeep Joy (FSU)

Honorable mentions: S Kivelson, S. A. Parameswaran, Y. H. Kwan, C. Lewandowski, T. Neupert for comments, and B. Ghosh and A. K. Paul for help with measurements in WIS.

EPFL

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SWISS NATIONAL SCIENCE FOUNDATION

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