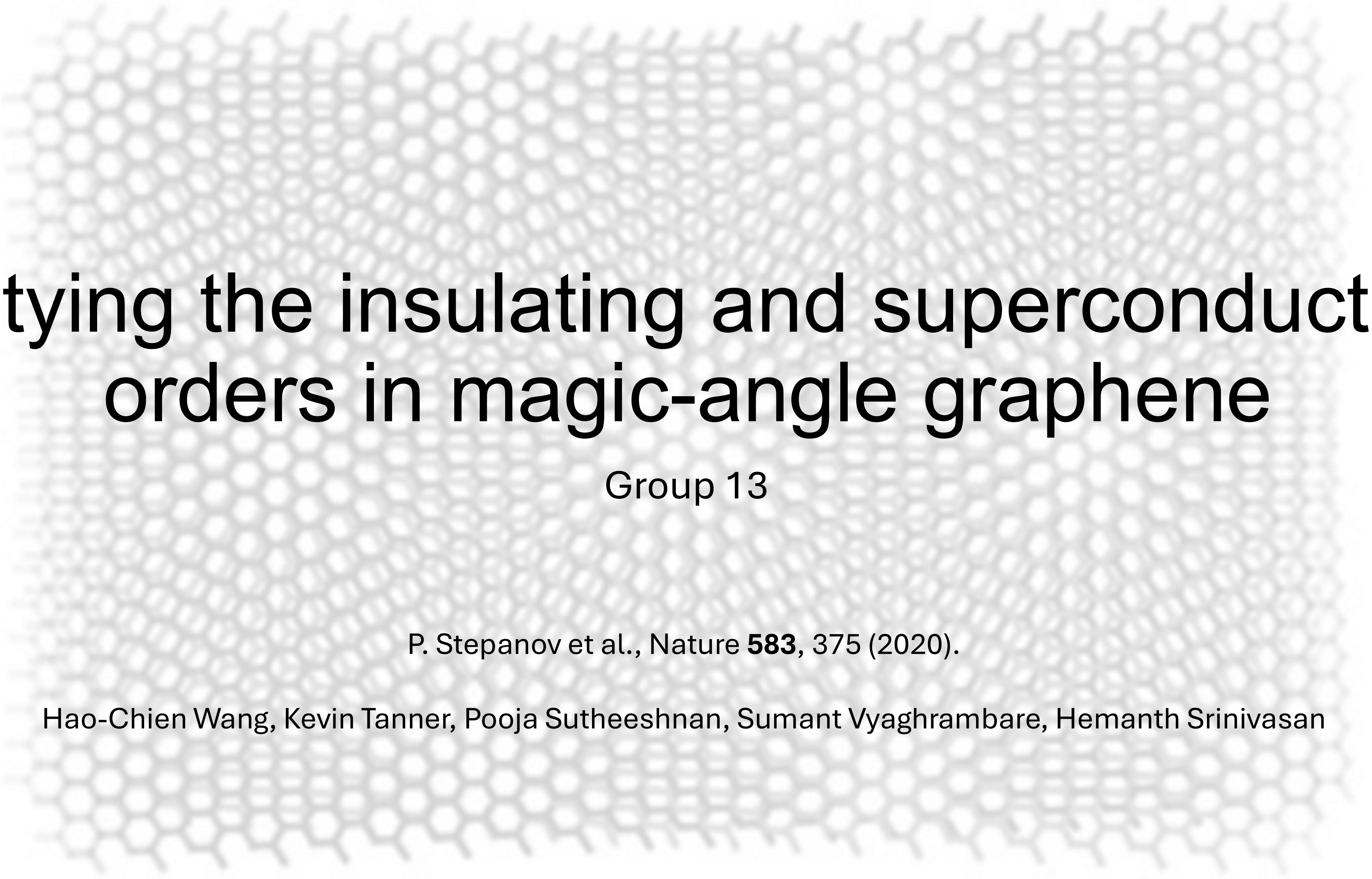


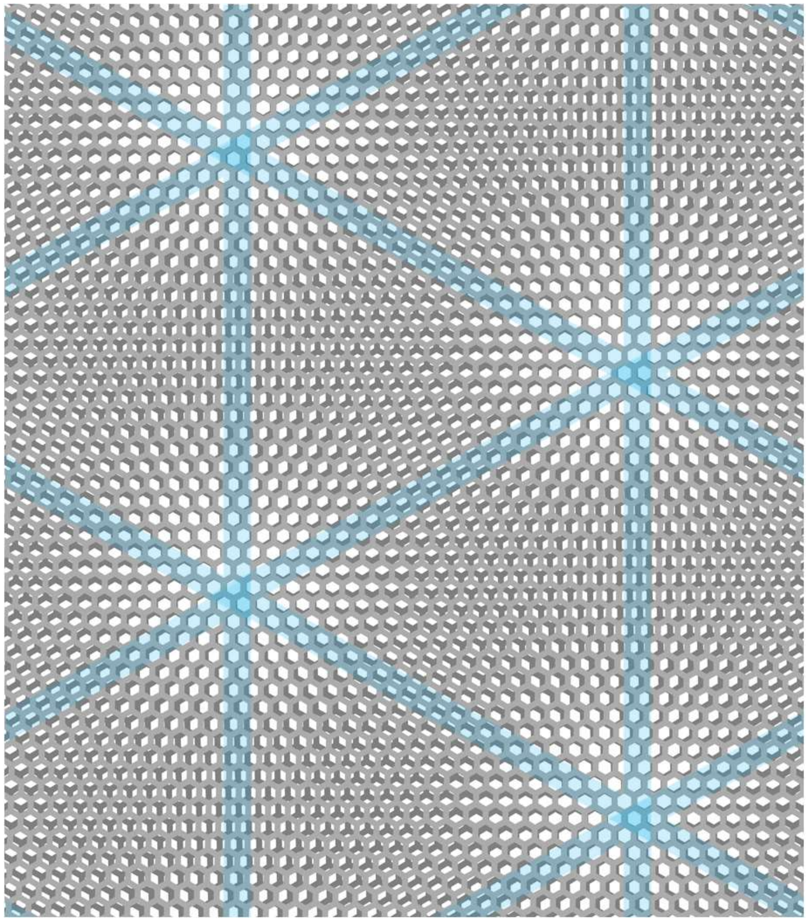
Untying the insulating and superconducting orders in magic-angle graphene

Group 13

P. Stepanov et al., Nature **583**, 375 (2020).

Hao-Chien Wang, Kevin Tanner, Pooja Sutheeshnan, Sumant Vyaghrambare, Hemanth Srinivasan

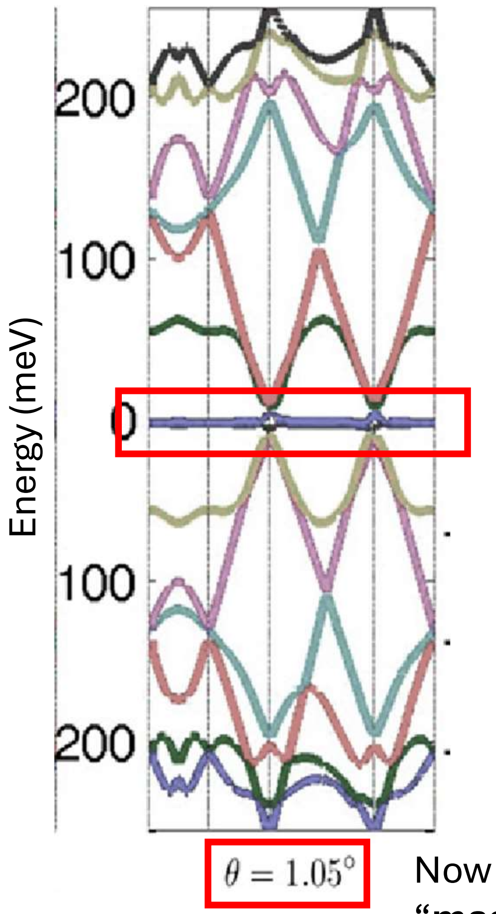
What is twisted bilayer graphene?



Graphene lattice, stacked with another layer, but **twisted** by a small angle!

The new superlattice is called the moiré lattice.

Why twisted bilayer graphene: prediction of flat bands

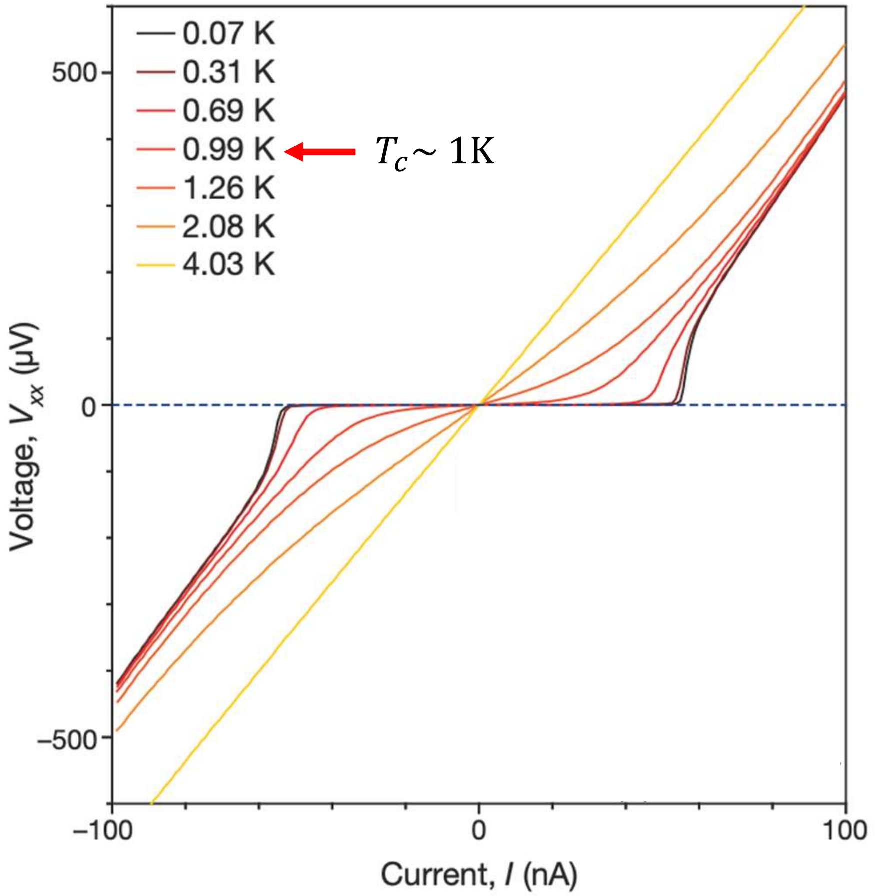


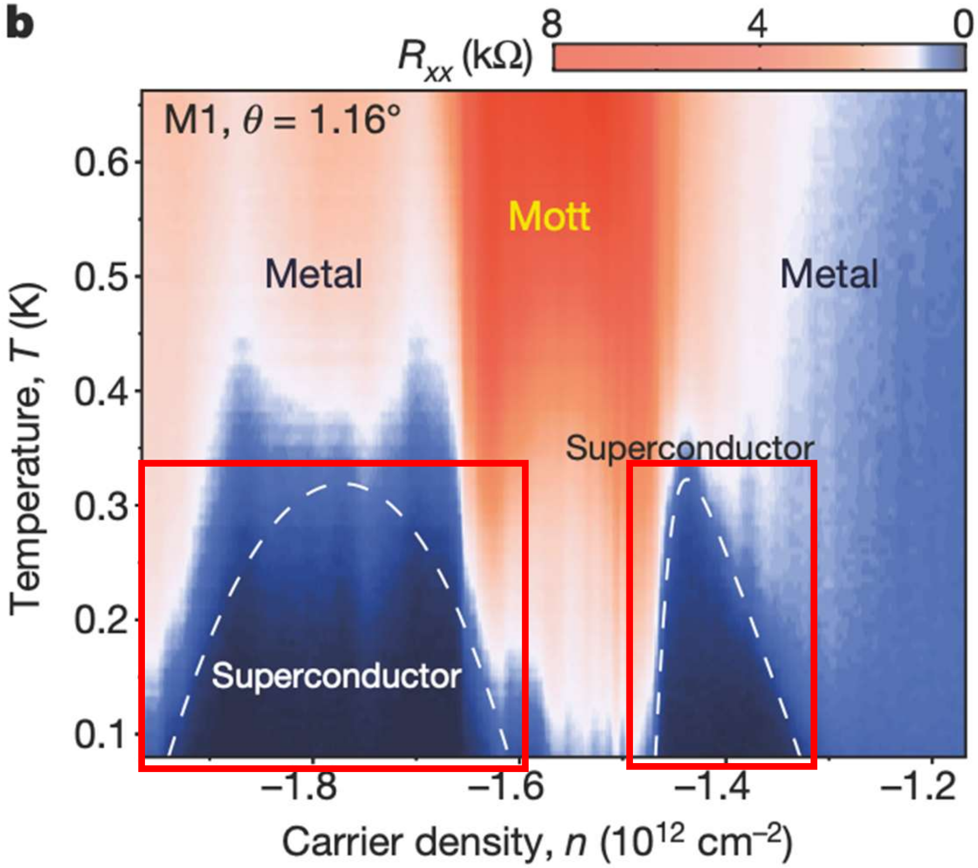
Flat bands: imply low kinetic energy, (relatively) **strong interaction**!

Now referred to as the "**magic angle**."

R. Bistritzer and A. H. MacDonald, Proc. Natl. Acad. Sci. U. S. A. **108**, 12233 (2011).

First demonstration of superconductivity (SC)

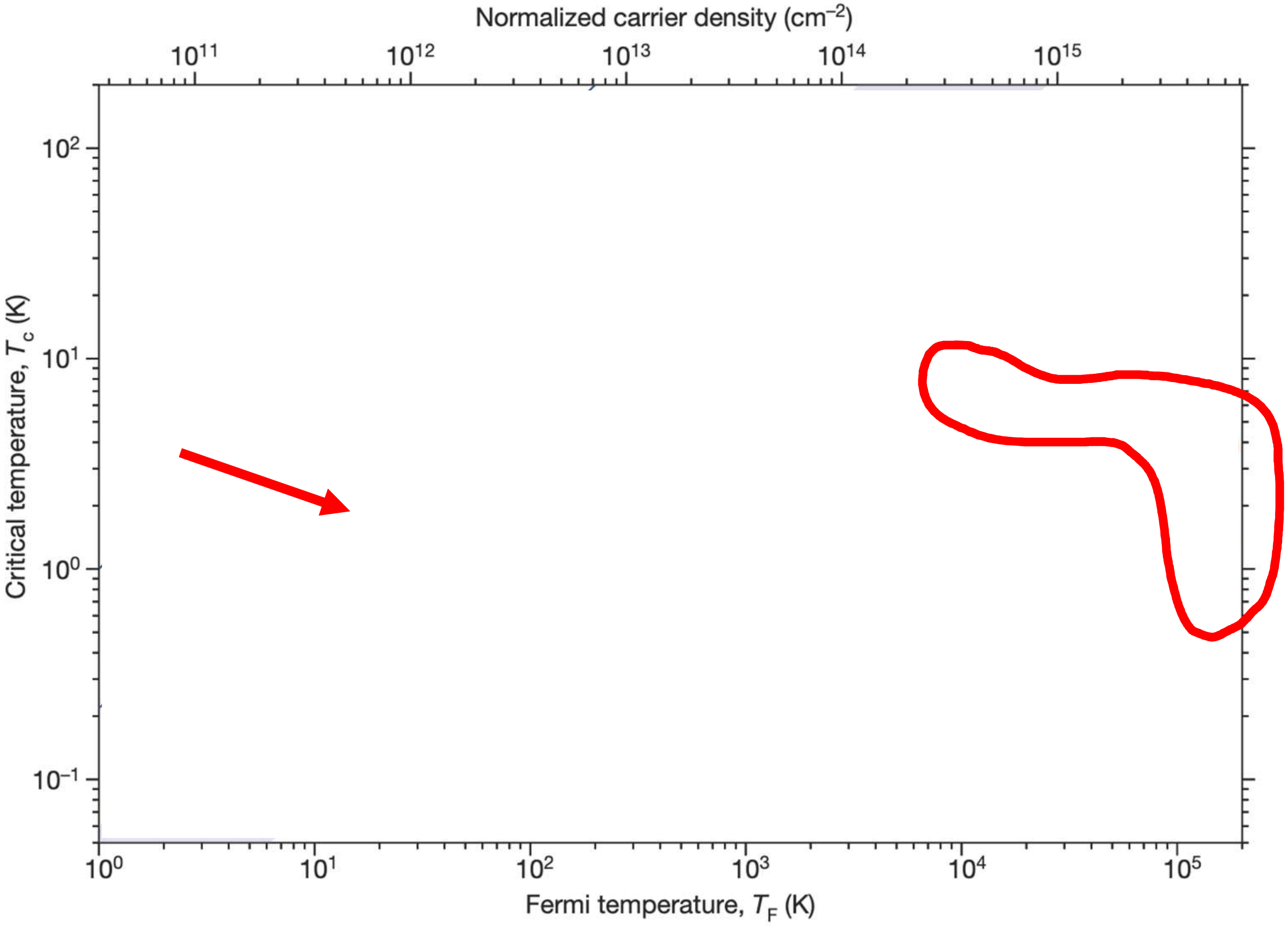




Y. Cao et al., Nature **556**, 43 (2018).

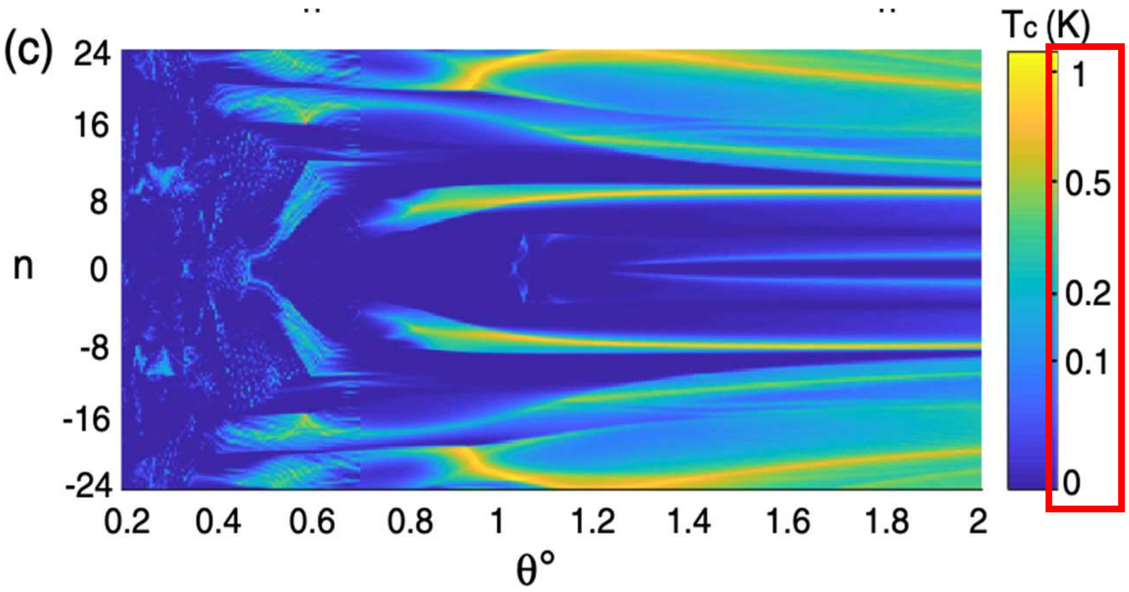
Strong pairing suggests unconventional SC.

(non-BCS/phonon)



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

Phonon pairing or not? No consensus among theorists



Theoretical results shows that phonon pairing is strong enough to induce SC.

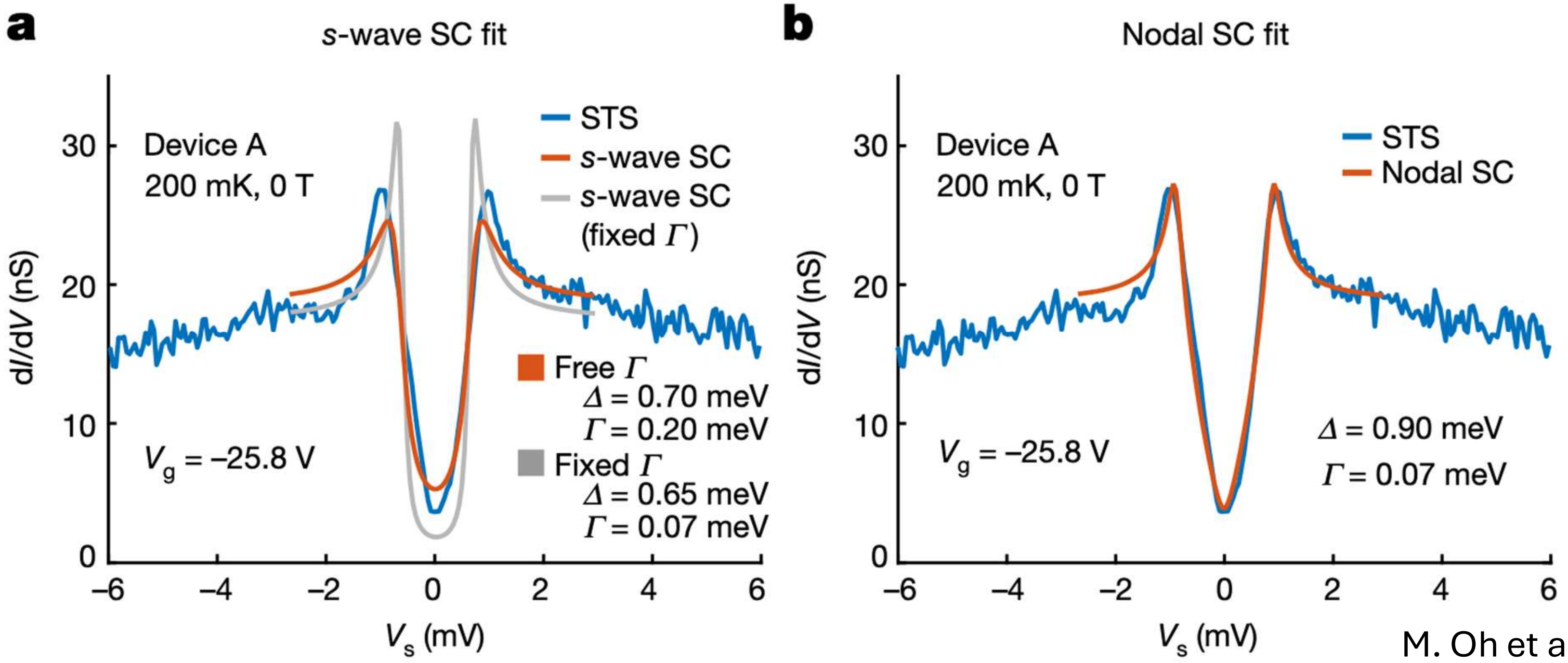
B. Lian, Z. Wang, and B. A. Bernevig, Phys. Rev. Lett. **122**, 257002 (2019).

But there are theories supporting correlation-driven SC as well:

H. Isobe, N. F. Q. Yuan, and L. Fu, Phys. Rev. X. **8**, 041041(2018).

Nodal or nodeless: also no consensus yet

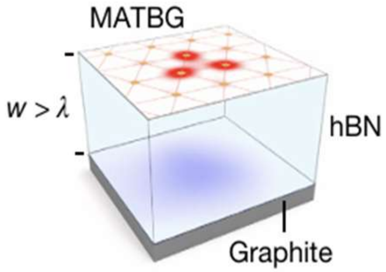
- Experiment shows tunneling spectrum *inconsistent* with s-wave pairing.
- Another experiment suggesting nodeless pairing:
    - M. Tanaka et al., arXiv:2406.13740 [cond-mat.supr-con] (2024).



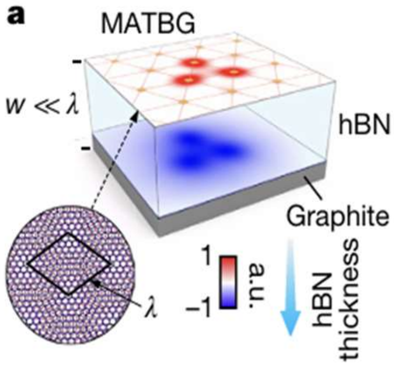
M. Oh et al., Nature **600**, 240 (2021).

Summarizing the main points of the paper

- Three graphene devices (MATBG) were studied for different spacer (hBN) thicknesses.

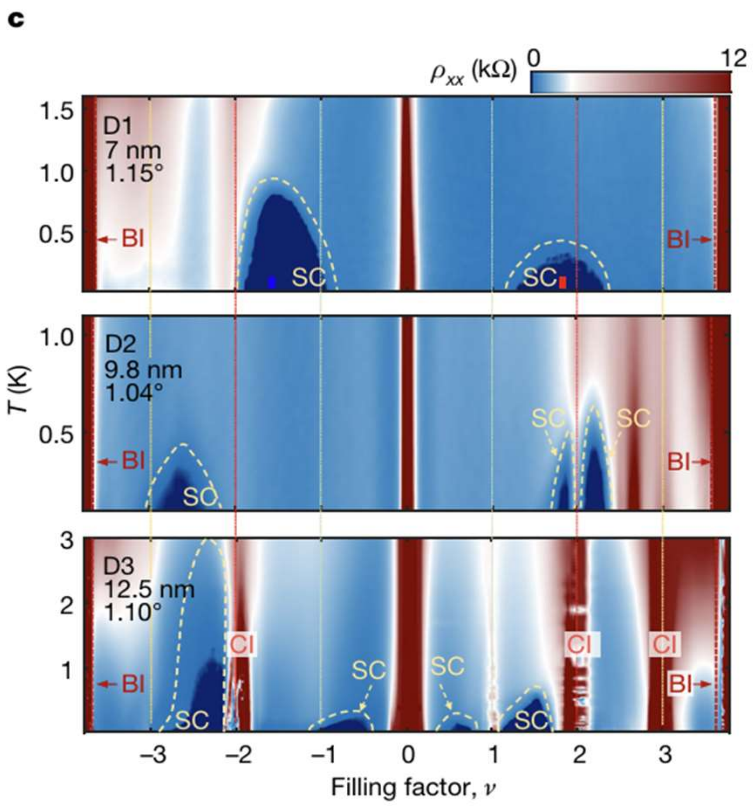


- Twisted bilayer graphene exhibits superconductivity for device thicknesses (w) less than the moiré cell size (λ ≈ 15 nm)



- Correlated insulating and superconducting orders compete rather than cooperate!

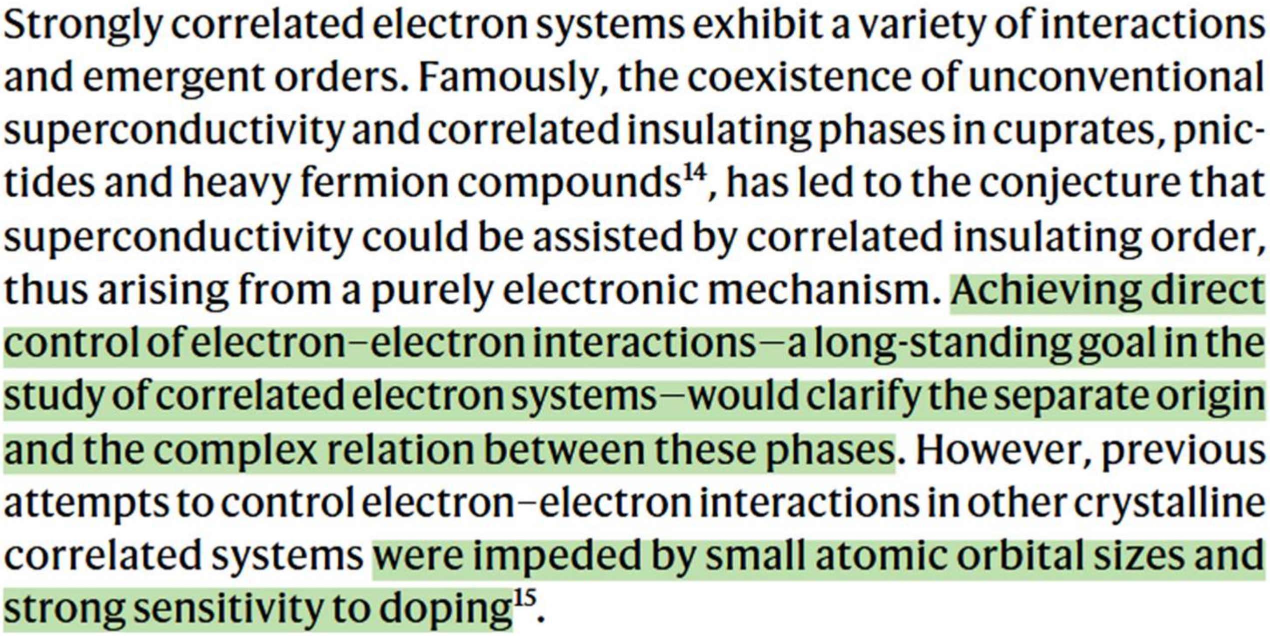
Insulating and Superconducting phases of the devices



- Superconducting regions are persistent as the device thicknesses are reduced.
- Insulating orders disappear with the same trend
- The superconducting domes extend across approximately similar temperatures

What we liked about the paper

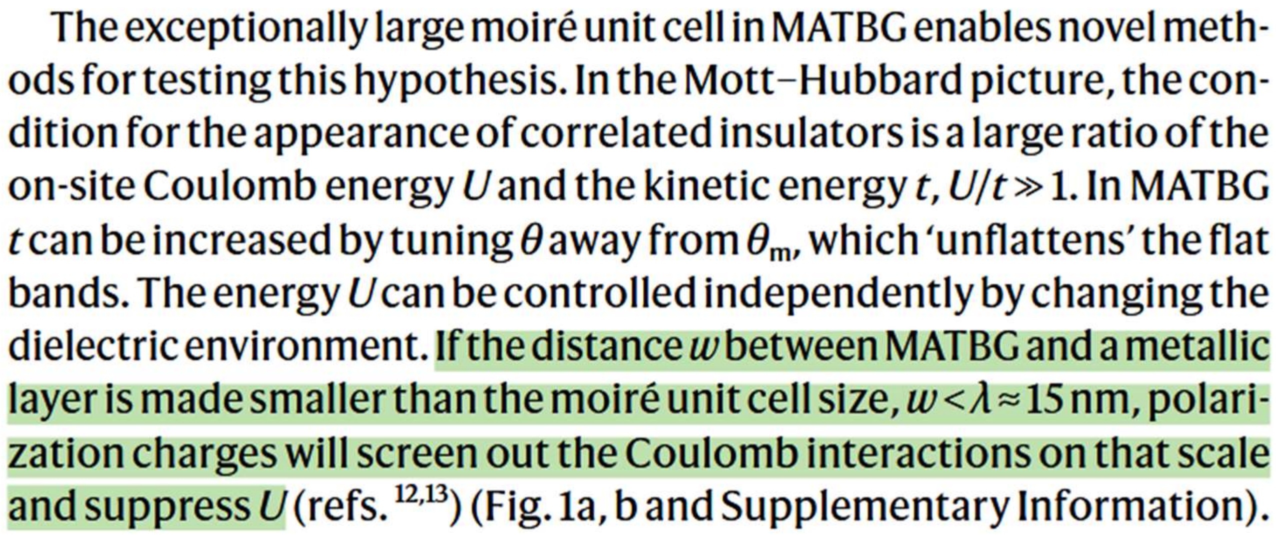
- Introduction section:
  - Main motivation clearly and concisely mentioned in the first paragraph



Strongly correlated electron systems exhibit a variety of interactions and emergent orders. Famously, the coexistence of unconventional superconductivity and correlated insulating phases in cuprates, pnictides and heavy fermion compounds[14], has led to the conjecture that superconductivity could be assisted by correlated insulating order, thus arising from a purely electronic mechanism. Achieving direct control of electron–electron interactions—a long-standing goal in the study of correlated electron systems—would clarify the separate origin and the complex relation between these phases. However, previous attempts to control electron–electron interactions in other crystalline correlated systems were impeded by small atomic orbital sizes and strong sensitivity to doping[15].

What we liked about the paper

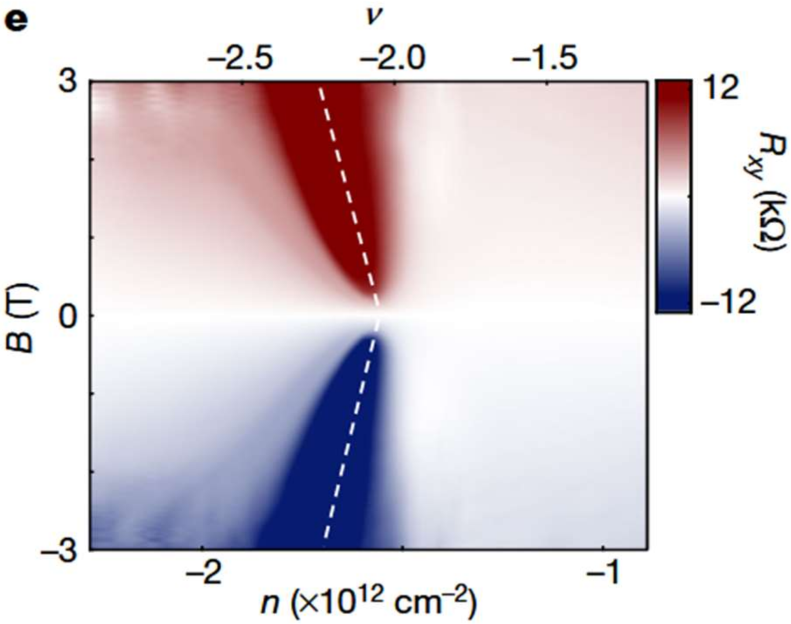
- Early connection to Mott-Hubbard model

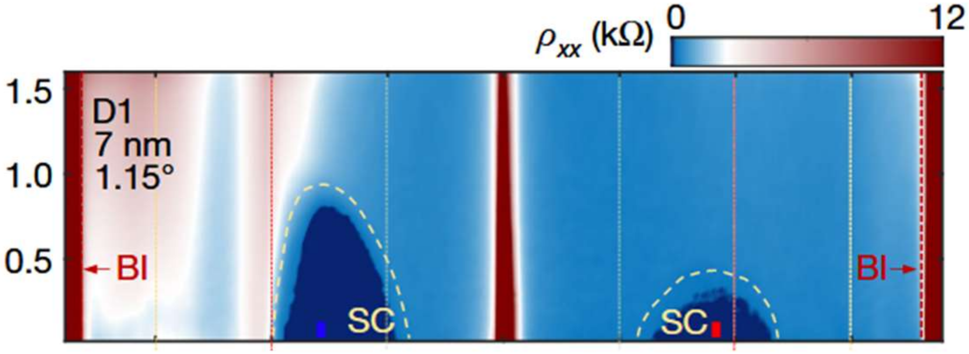


The exceptionally large moiré unit cell in MATBG enables novel methods for testing this hypothesis. In the Mott–Hubbard picture, the condition for the appearance of correlated insulators is a large ratio of the on-site Coulomb energy U and the kinetic energy t, $U/t \gg 1$. In MATBG t can be increased by tuning θ away from θ_m, which 'unflattens' the flat bands. The energy U can be controlled independently by changing the dielectric environment. If the distance w between MATBG and a metallic layer is made smaller than the moiré unit cell size, $w < \lambda \approx 15$ nm, polarization charges will screen out the Coulomb interactions on that scale and suppress U (refs. [12,13]) (Fig. 1a, b and Supplementary Information).

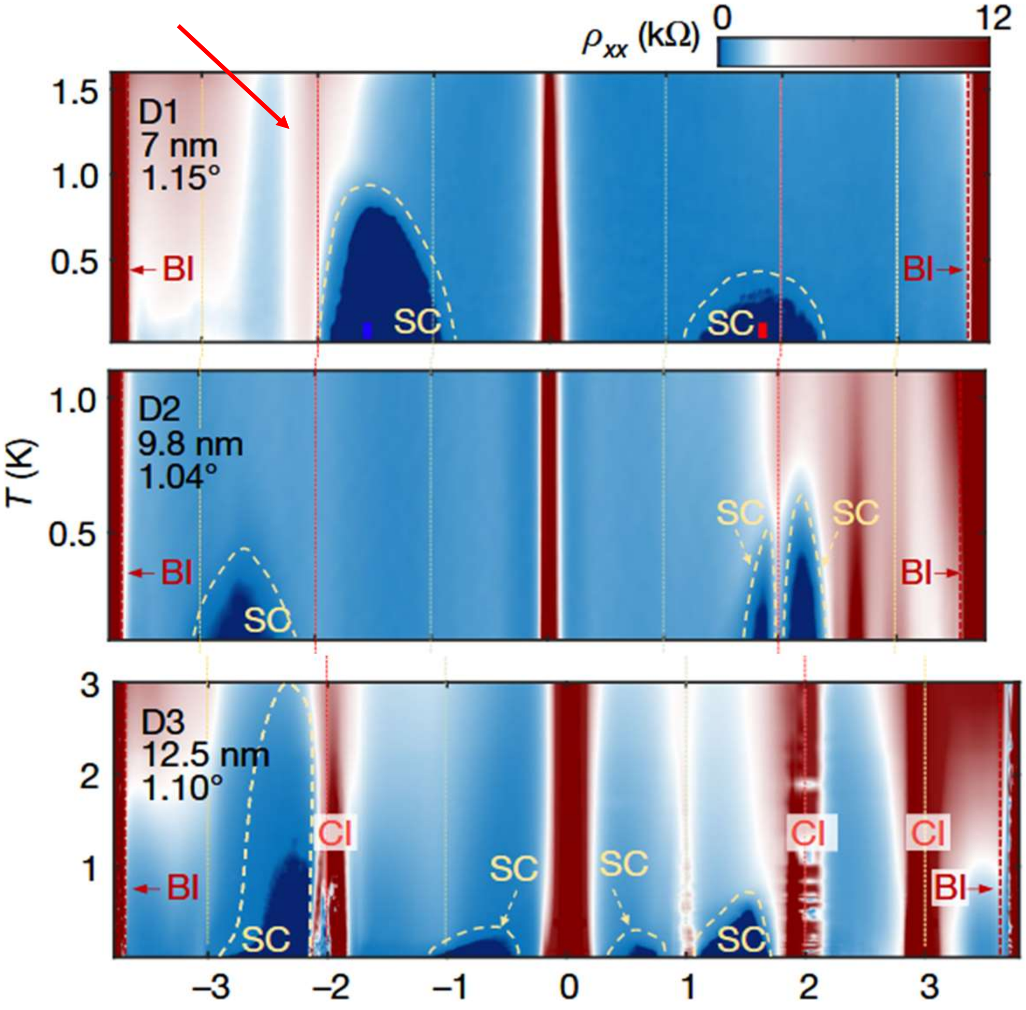
What we liked about the paper

- Good choice of colors in the density plots





Potential improvements



Weak correlated insulator phase reappears.

Correlated insulator phase completely absent for filling factor ~ -2.

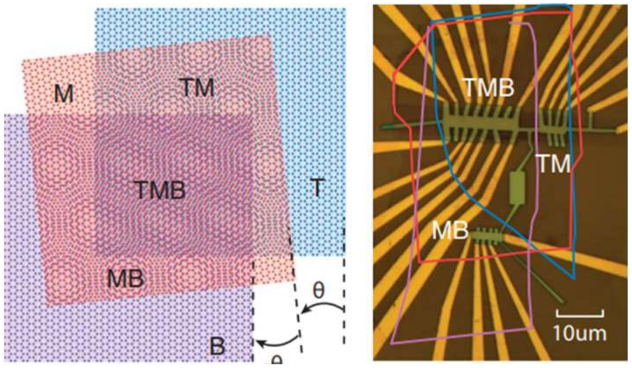
Superconducting domes get weaker, giving way to correlated insulator phase.

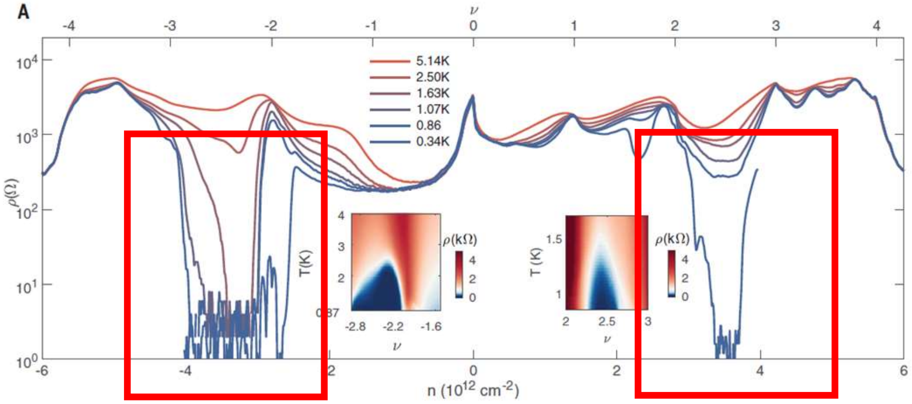
Citation Evaluation

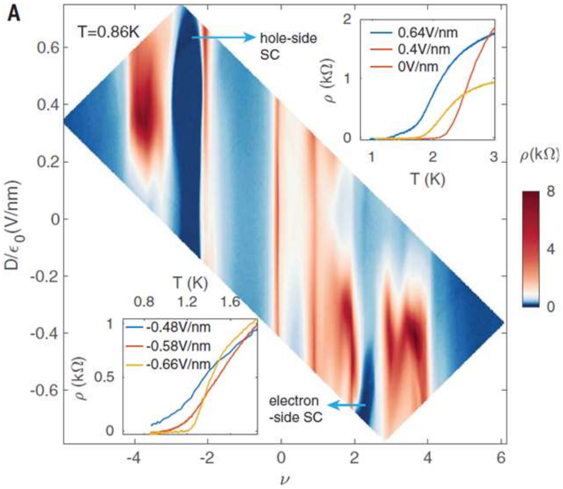
According to Google Scholar, this paper, published in 2020, has been cited 471 times.

Electric field–tunable superconductivity in alternating-twist magic-angle trilayer graphene

Zeyu Hao[1]*, A. M. Zimmerman[1]*, Patrick Ledwith[1], Eslam Khalaf[1], Danial Haie Najafabadi[1], Kenji Watanabe[2], Takashi Taniguchi[3], Ashvin Vishwanath[1], Philip Kim[1]†







- clear signature of superconductivity controlled with applied electric field.
- Tc reaches a maximum of 2.1 K, higher than most previously reported values for MA TBG.

Hao, Zeyu, et al. "Electric field–tunable superconductivity in alternating-twist magic-angle trilayer graphene." *Science* 371.6534 (2021): 1133-1138

Moiré 2D systems other than graphene ?

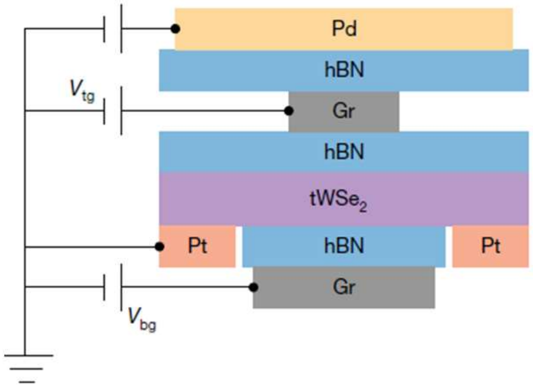
Article

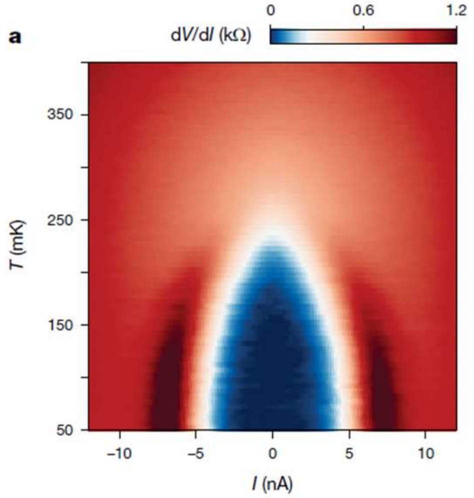
Superconductivity in twisted bilayer WSe$_2$

https://doi.org/10.1038/s41586-024-08116-2

Received: 20 May 2024

Yiyu Xia[1,5]✉, Zhongdong Han[2,5]✉, Kenji Watanabe[3], Takashi Taniguchi[3], Jie Shan[1,2,4]✉ & Kin Fai Mak[1,2,4]✉





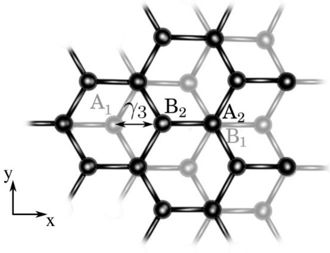
- Robust superconductivity in both 3.5° and 3.65° twisted bilayer tungsten diselenide (WSe$_2$).
- Superconductivity emerges near half-band filling and zero external displacement fields.
- The observed superconducting state has several unusual properties that deserve future studies.

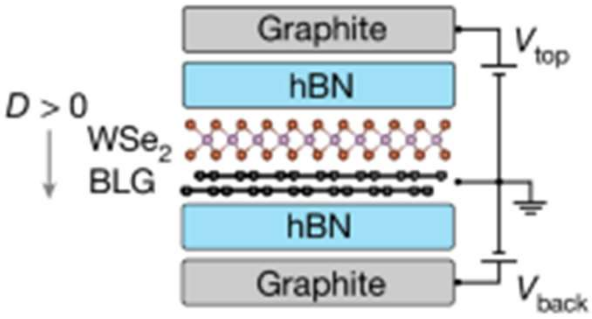
Xia, Yiyu, et al. "Superconductivity in twisted bilayer WSe2." *Nature* (2024): 1-6.

Other investigations into Bilayer Graphene

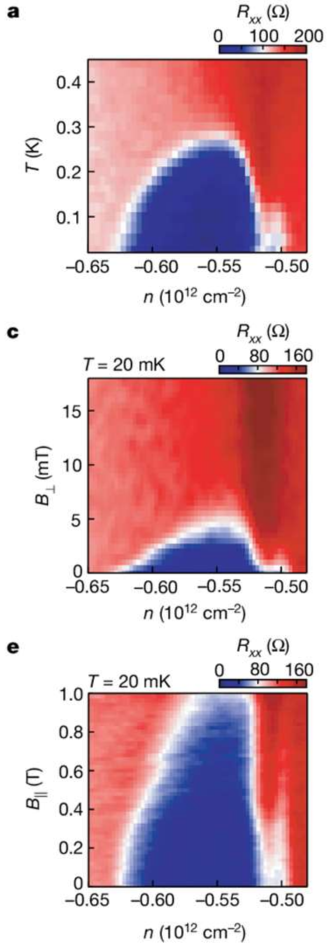
Tunable superconductivity in electron- and hole-doped Bernal bilayer graphene

First shown proof of electron-doped superconductivity in crystalline graphene





Previously, superconductivity only seen in hole-doped crystalline graphene systems and twisted graphene systems



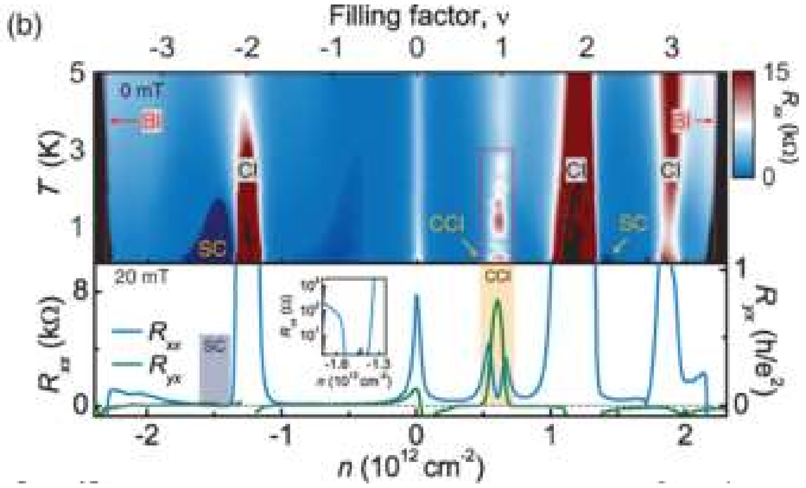
Superconductivity is **tunable** by changing temperature and the magnetic field strength

Requires much lower temperatures

Li, C., Xu, F., Li, B. *et al.* Tunable superconductivity in electron- and hole-doped Bernal bilayer graphene. *Nature* **631**, 300–306 (2024).

Further Analysis of MATBG

Competing Zero-Field Chern Insulators in Superconducting Twisted Bilayer Graphene



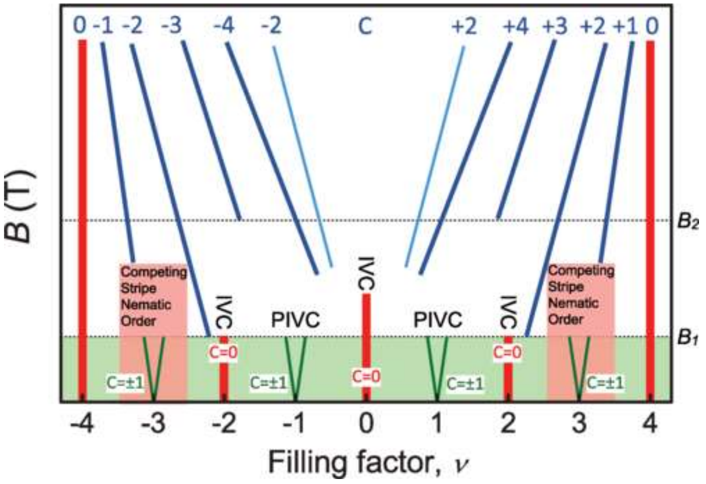
Revealed existence of a third quantum phase:

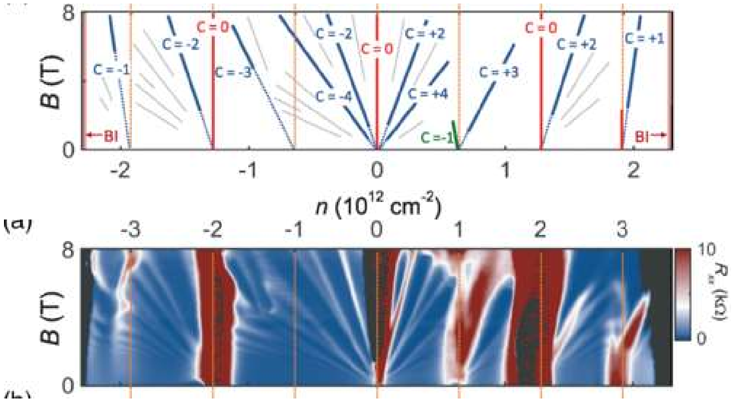
1. Super-conducters (SC)
   - At temperatures up to 3.5K!
2. Correlated insulators (CI)
3. Correlated Chern insulators (CCI)

Theoretical models only partially match the experimental results

<u>May be due to:</u>

1. Sample imperfections
2. Strain variations
3. Hard to model many-body interactions
4. Other?





Stepanov, P., Xie, M., Taniguchi, T., Watanabe, K., Lu, X., MacDonald, A., Bernevig, B., & Efetov, D. (2021). Competing Zero-Field Chern Insulators in Superconducting Twisted Bilayer Graphene. *Phys. Rev. Lett., 127, 197701*.

THANK YOU