Correlation Effects and Exotic Superconductivity in Graphene Multilayers

Erez Berg

Uri Zondiner, Asaf Rozen, Raquel Queiroz, Felix von Oppen, Yuval Oreg, Ady Stern, Shahal Ilani, Pablo Jarillo-Herrero, Mati Bocarsly, Jiewen Xiao, Sameer Grover, Aviram Uri, Keshav Pareek, Binghai Yan, Dmitry Efetov, Eli Zeldov, Johannes Hofmann, Debanjan Chowdhury, Jong-Yeon Lee, Eslam Khalaf, Ashvin Vishwanath, Ari Turner, Ohad Antebi, Gal Shavit, Tobias Holder, Areg Ghazaryan, Maksym Serbin, Andrea Young, Taige Wang, Shubhayu Chatterjee, Michael Zaletel, Eyal Cornfeld, Mark Rudner

מכון ויצמן למדע
Weizmann Institute of Science

CRC183
ENTANGLED STATES OF MATTER

erc
European Research Council

מכון ויצמן למדע
WEIZMANN INSTITUTE OF SCIENCE

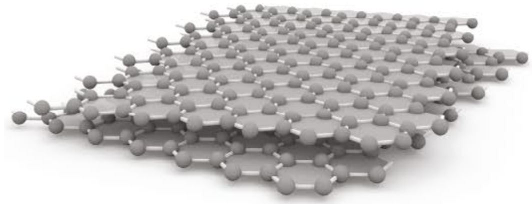
TOPOLOGICAL QUANTUM MATTER

tqm.course@weizmann.ac.il

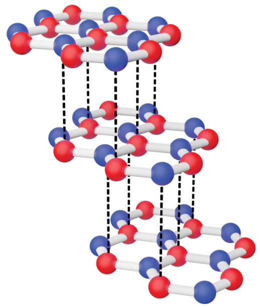
Available on: edx.org, campus.org.il
youtube.com (*coming soon!*)

Outline

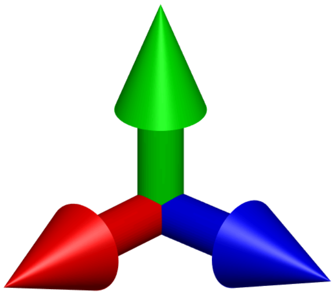
- What do we know about correlation effects in magic angle twisted bilayer graphene?



- MATBG: Open Questions



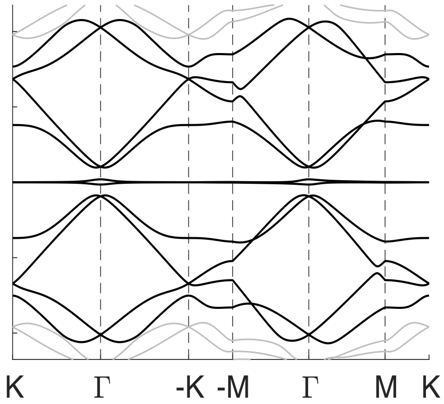
- Correlations and Exotic superconductivity in Rhombohedral trilayer graphene

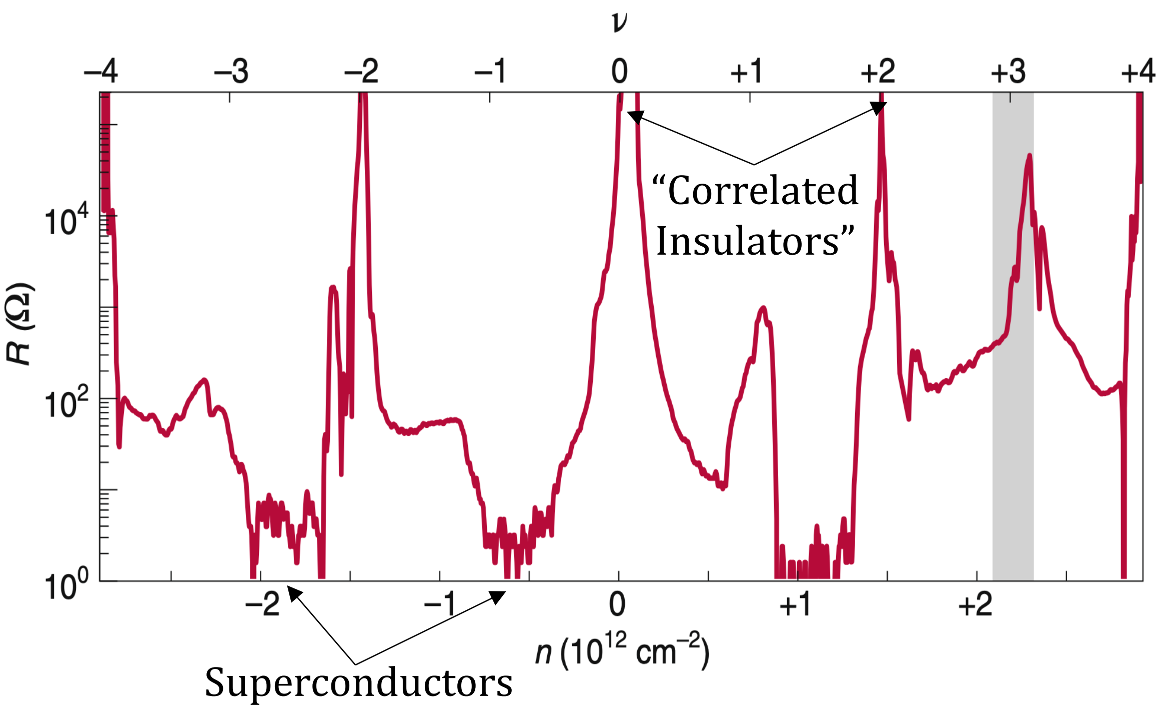


- Spin-polarized triplet superconductors: Order parameter topology and current dissipation

MATBG, Four years on

$\theta \approx 1.1^o$



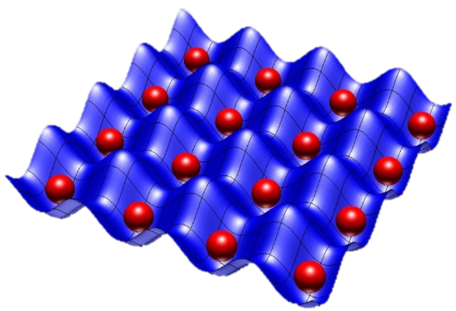


From: Balents, Dean, Efetov, Young (Nat. Phys. 2020)

What do we know for certain?

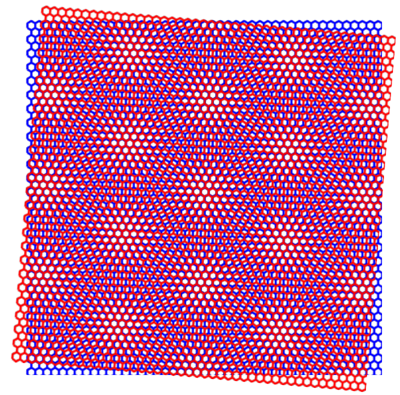
R. Bistritzer, A. MacDonald (PNAS, 2011); Y. Cao,…,P. Jarillo-Herrero (Nature, 2019); …

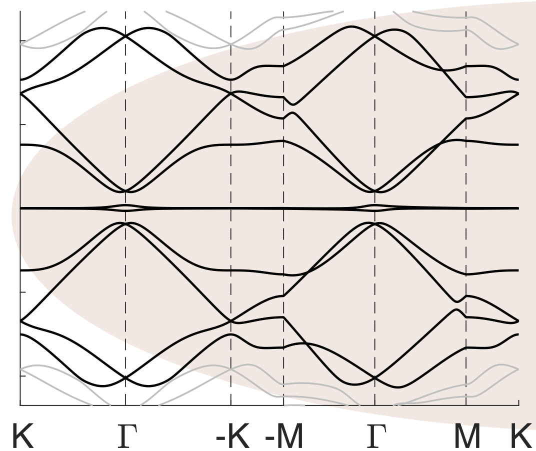
Flat Bands in MATBG

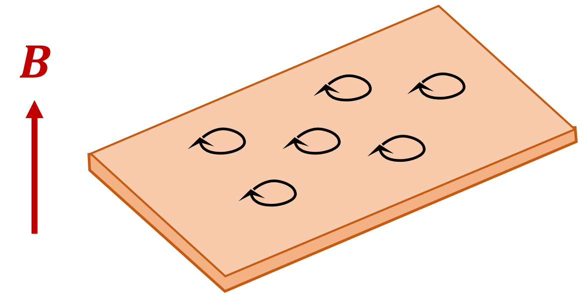


Strong periodic potential

- Mott insulators
- Antiferromagnetic interactions (superexchange)
- Localized moments, unconventional superconductivity, …



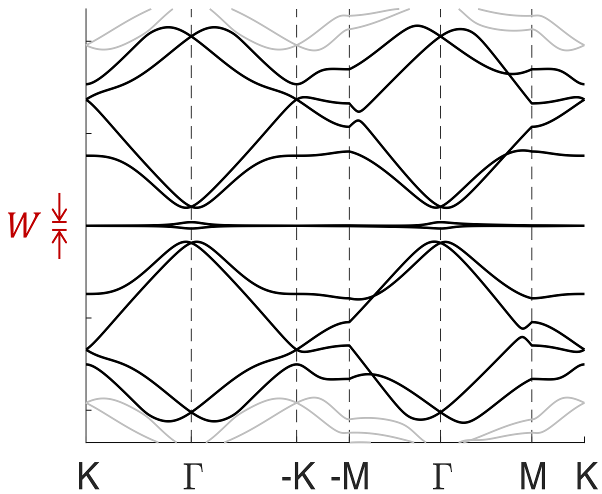




Landau levels

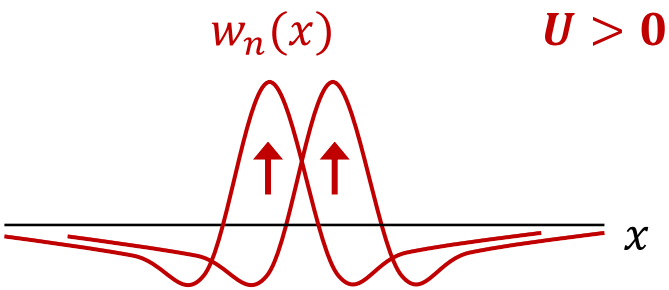
- Quantum Hall Insulators
- (Generalized) Ferromagnetism
- Skyrmions, fractional QH phases, …

Why Generalized Ferromagnetism?



Topological bands

Wannier orbitals overlapping in space



$$H = \sum_{\langle \boldsymbol{r},\boldsymbol{r}' \rangle} \left(-J_F + \frac{\alpha W^2}{U} \right) \boldsymbol{S}_{\boldsymbol{r}} \cdot \boldsymbol{S}_{\boldsymbol{r}'}$$

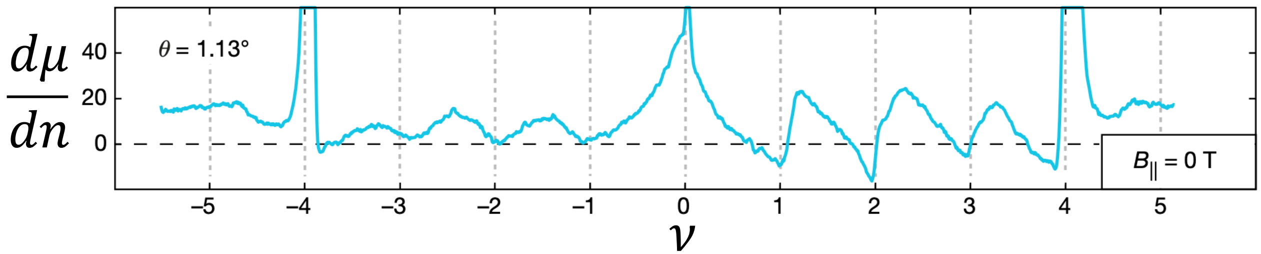
$J_F = gU,$ $g \propto$ Wannier function overlap

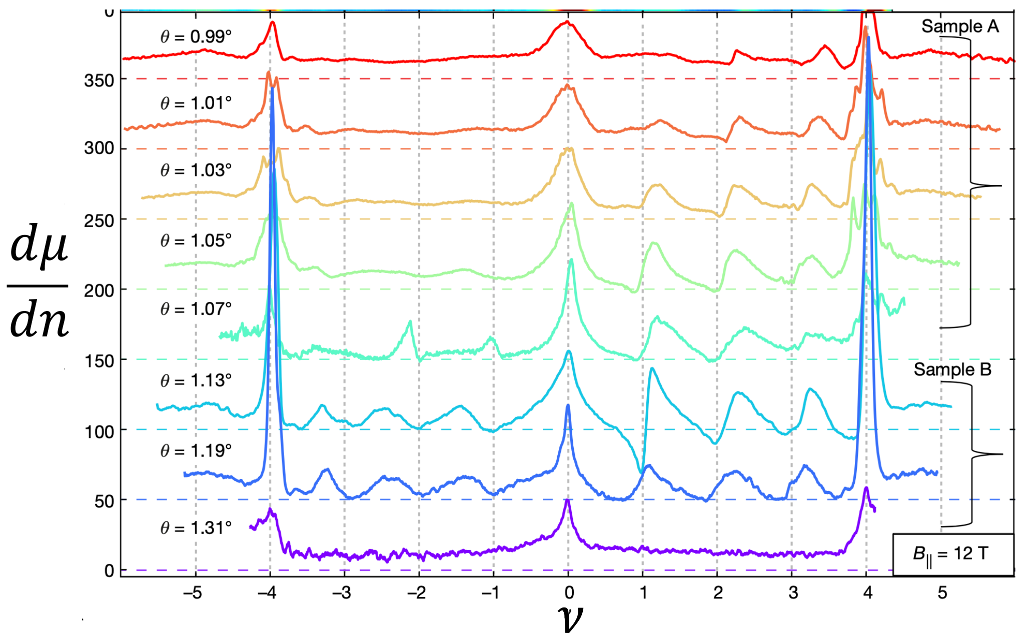
$gU > \frac{\alpha W^2}{U}$: spin/valley ferromagnetism!

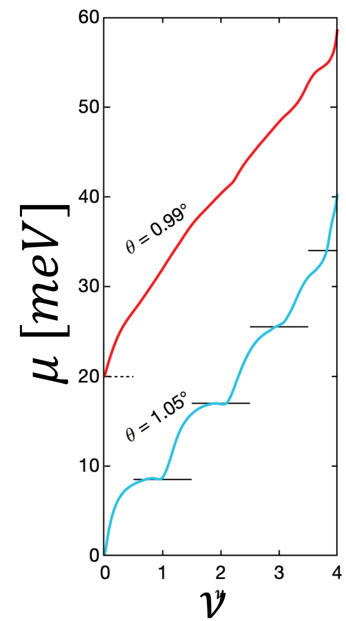
Repellin, Dong, Zhang, Senthil (PRL, 2020)

Cascade of Phase Transitions

Measurements of μ and $\frac{d\mu}{dn}$ by scanning SET







"Sawtooth" features survive at least to $T \approx$ 50K!

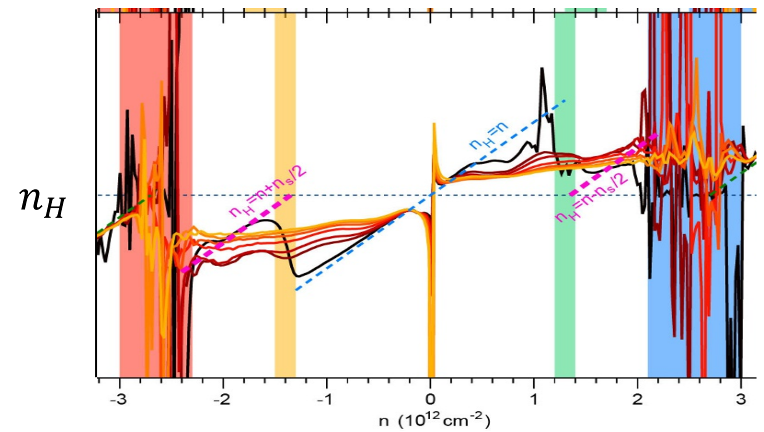
U. Zondiner, A. Rozen, D. Rodan-Legrain, Y. Cao, R. Queiroz, T. Taniguchi, K. Watanabe, Y. Oreg, F. von Oppen, A. Stern , EB, P. Jarillo-Herrero, S. Ilani (Nature, 2020)

Cascade of Phase Transitions

Fermi surface reconstruction near integer ν

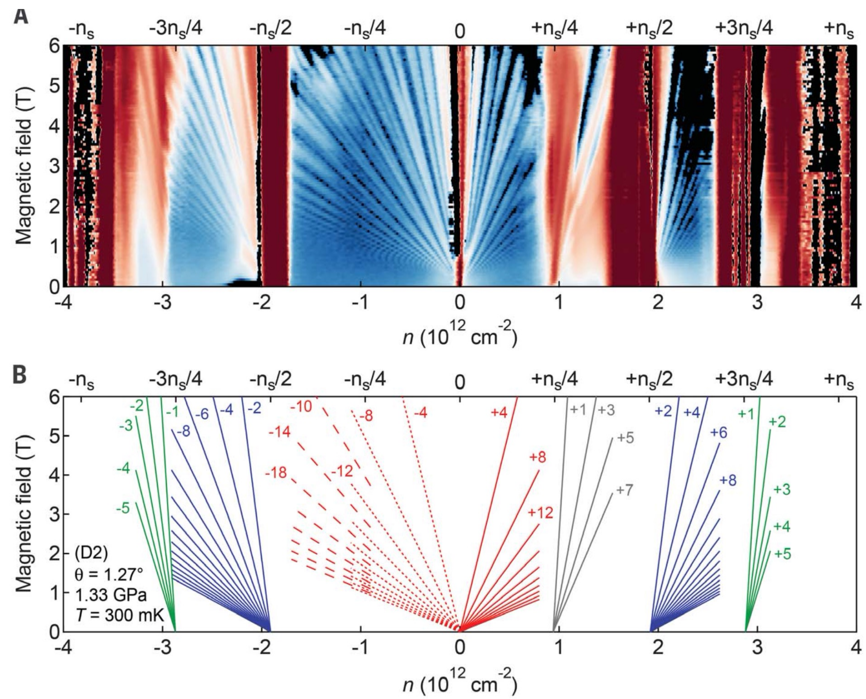
“Resets” of Hall density towards $n_H = 0$ at integer filling

Cao, …, Jarillo-Herrero (Nature, 2019)



Shubnikov-de Haas oscillations: “Landau fans” from integer ν pointing away from $\nu = 0$

Yankowitz, …, Young, Dean (Science, 2019)

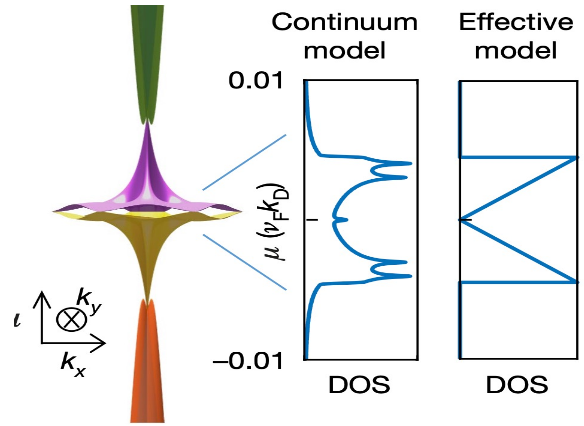


Cascade of Phase Transitions

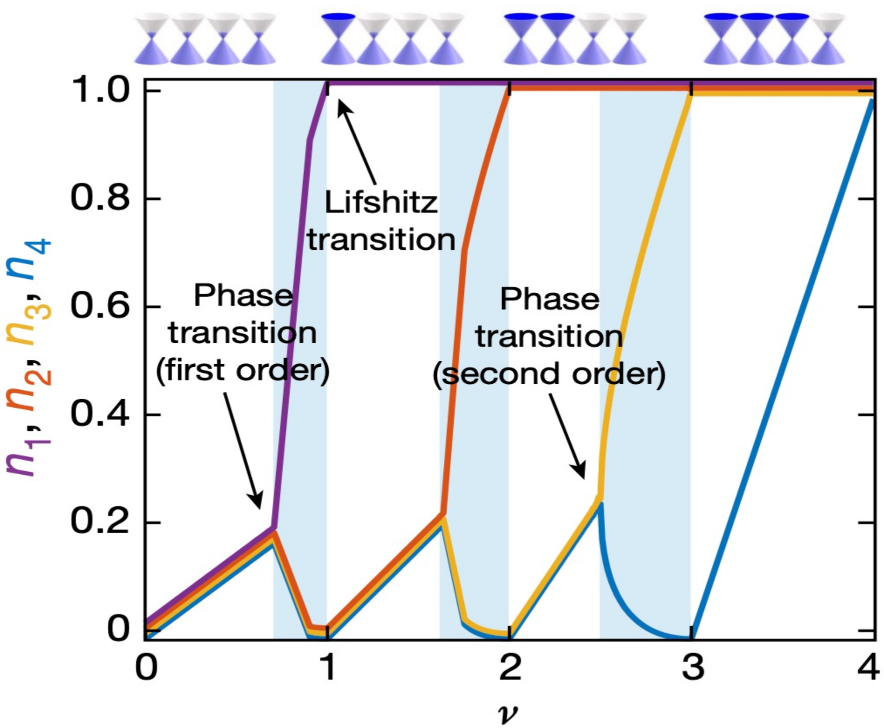
Toy model: *U. Zondiner, ..., S. Ilani (Nature, 2020)*

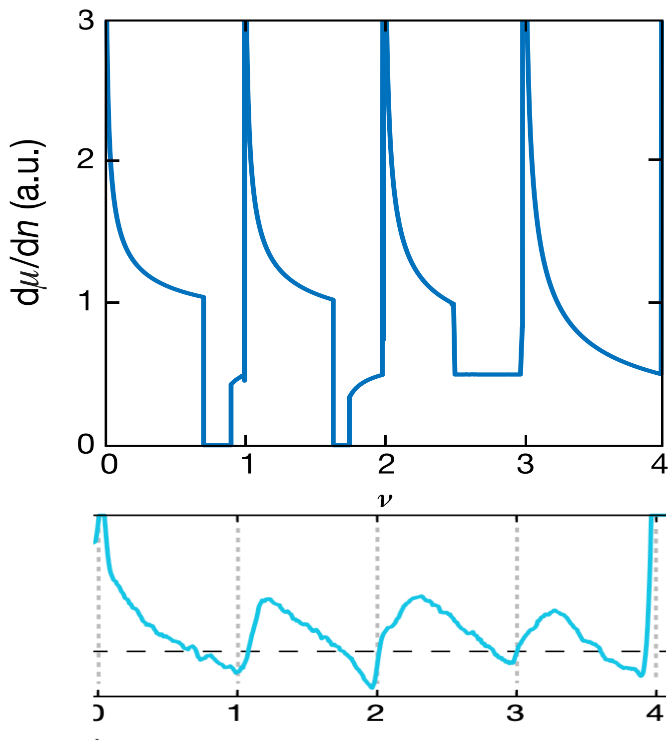
$$H = \sum_{\boldsymbol{k},\alpha} \varepsilon_{\alpha k}\, \psi^{\dagger}_{\alpha \boldsymbol{k}} \psi_{\alpha \boldsymbol{k}} + U \int d\boldsymbol{r} \sum_{\alpha \neq \beta} n_{\alpha} n_{\beta}$$

$\alpha, \beta = 1, \ldots, 4$ spin/valley indices



Mean-field solution:

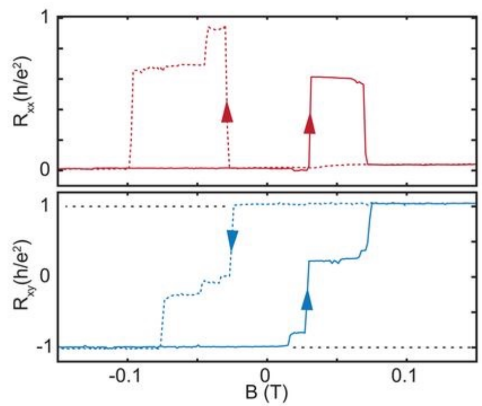


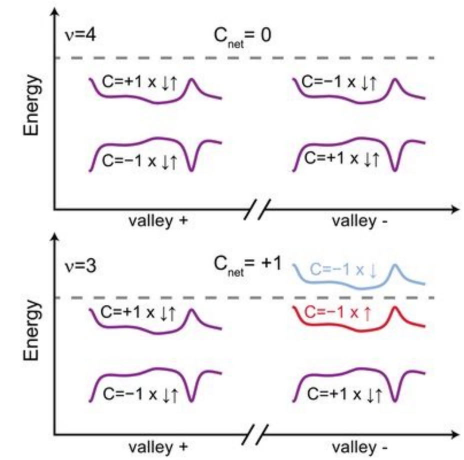


Orbital and Spin Magnetism

Quantized anomalous Hall
($\nu = 3$ with aligned hBN):

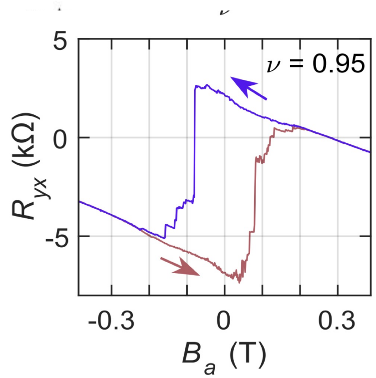
Sharpe,…,Goldhaber-Gordon (Science, 2019);
Serlin,…, Young (Science, 2020)

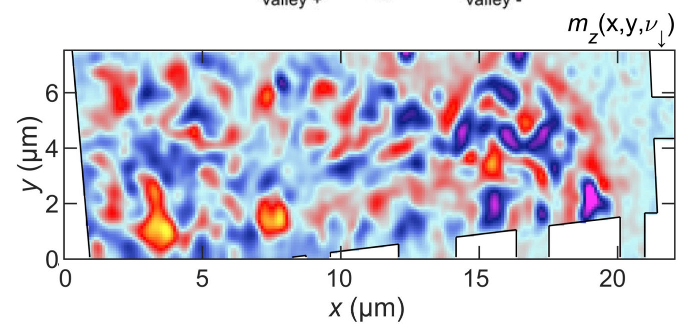




Orbital magnetism ($\nu \approx 1$):

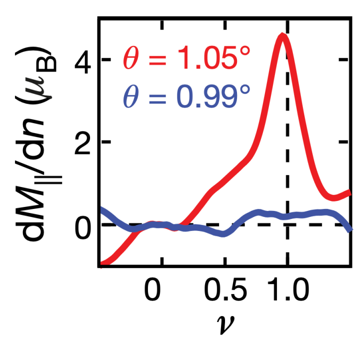
Grover, Bocarsly, Uri, Xiao, Yan, …, Stern, EB, Efetov, Zeldov (Nat. Phys., 2022)

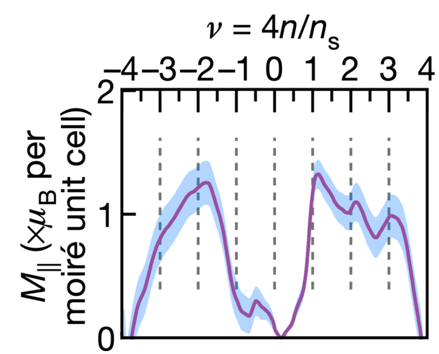




In-plane (spin?) magnetization: $\frac{dM_\parallel}{dn} = \frac{d\mu}{dB_\parallel}$

Zondiner et al. (Nature, 2020);
Park et al. (Nature, 2021)





Could have orbital component!

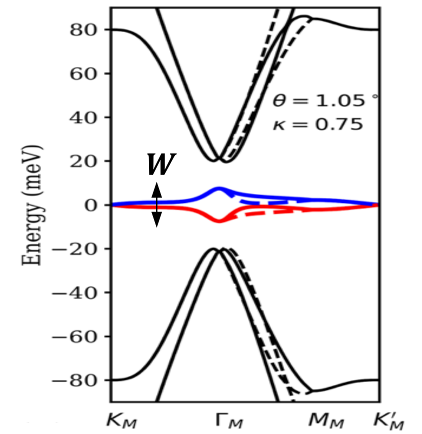
O. Antebi, A. Stern, EB (PRB, 2022)

Microscopic model

"Standard model" of TBLG

$$H = \hat{H}_{BM} + \hat{V}$$

$$\hat{H}_{\mathrm{BM}} = \int d^2r\, c^\dagger \left(H_g + H_T\right) c \qquad \hat{V} = \frac{1}{2}\sum_{\boldsymbol{q}} V_{\boldsymbol{q}} \delta\rho_{\boldsymbol{q}} \delta\rho_{-\boldsymbol{q}}$$



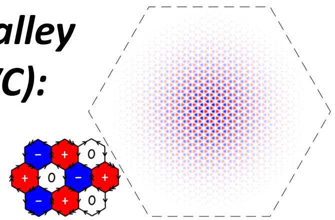
Project to narrow bands

Zero bandwidth limit ($W \to 0$)

H has low-energy U(4) symm.

$\nu = 0$: spin/valley polarized, KIVC state degenerate

Kramers Inter–Valley Coherence (KIVC):



Bultnick, Vishwanath, Zaletel et al. (PRX, 2020)

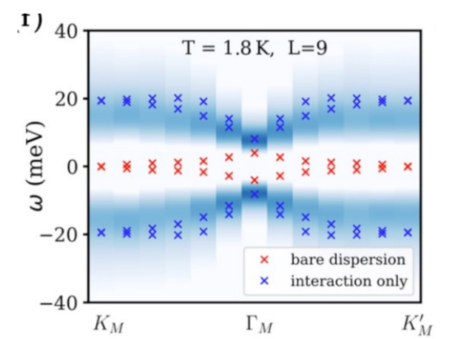
$0 < W \ll V$

Kramers Inter-Valley Coherent (KIVC) state selected

Quantum Monte Carlo (no sign problem @$\nu = 0$)

Gapped KIVC state at magic angle

Continuous transition to semi-metal at $\theta \approx 1.25^0$

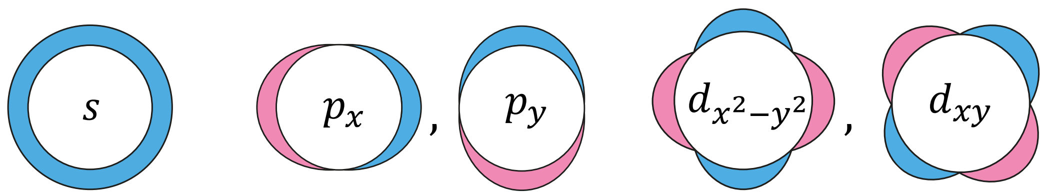


J. Hofmann, E. Khalaf, A. Vishwanath, EB, J. Y. Lee (PRX, 2022)

Challenges and Open Questions

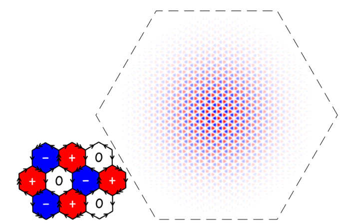
- What is the nature of superconductivity?

  - Symmetry of the superconducting order parameter?



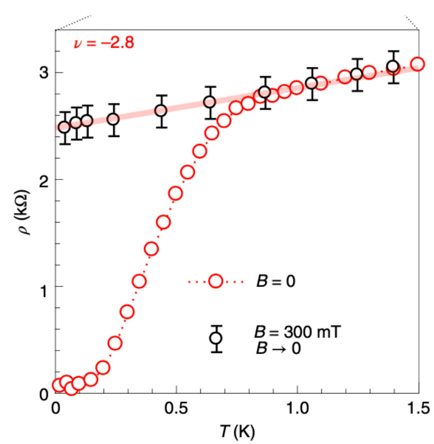
- What is the nature of the insulating states at even ν? Broken symmetry?

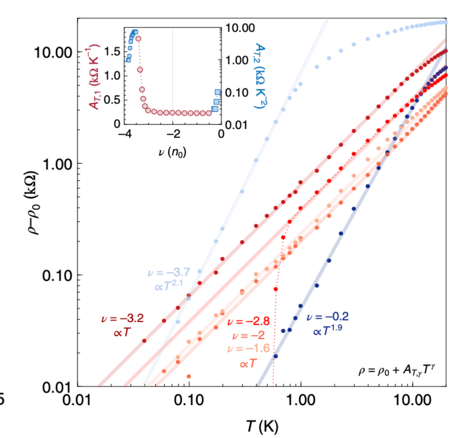
  - KIVC state?



- Normal state: Fermi liquid? "Strange metal"?

  - $\rho(T) = \rho_0 + AT$ as $T \to 0$?

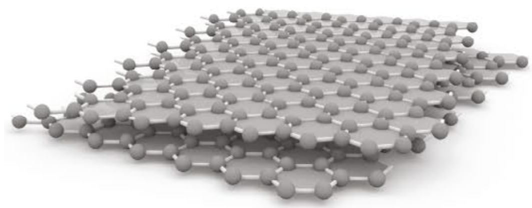




Cao, Chowdhury,..., Jarillo-Herrero (PRL, 2020);
Jauoi, Das,..., Efetov (Nat. Phys., 2022)

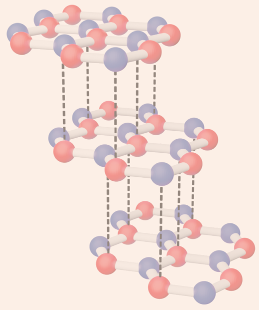
Outline

- What do we know about correlation effects in magic angle twisted graphene?

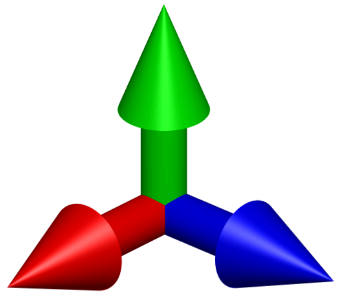


- MATBG: Open Questions

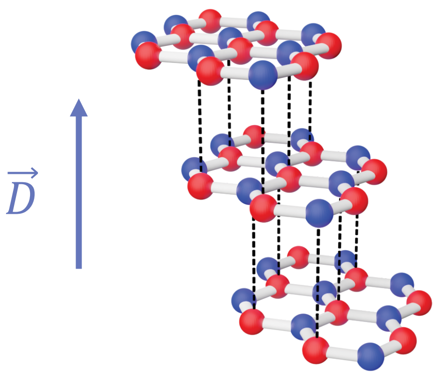
- Correlations and Exotic superconductivity in Rhombohedral trilayer graphene

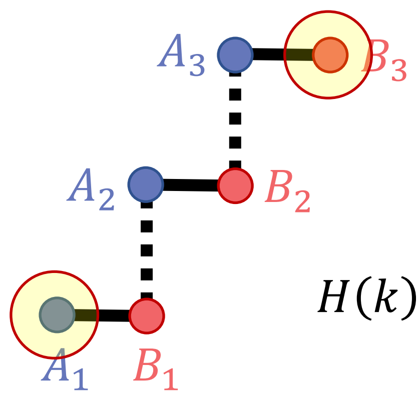


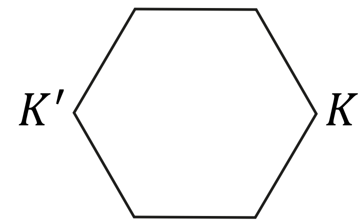
- Spin-polarized triplet superconductors: Order parameter topology and current dissipation



Rhombohedral (ABC) trilayer graphene

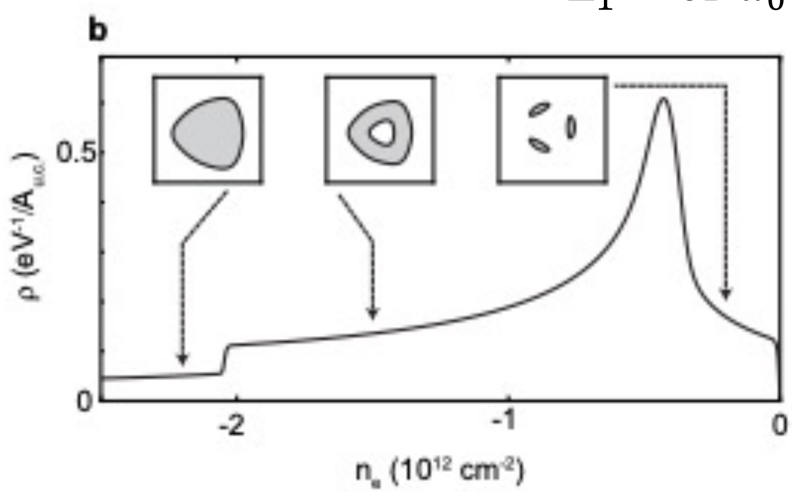






$$H(k) = \begin{pmatrix} \Delta_1 & \beta\left(k_x + \tau i k_y\right)^3 + \gamma \\ \beta\left(k_x - \tau i k_y\right)^3 + \gamma & -\Delta_1 \end{pmatrix}$$

$\Delta_1 = eDd_0$, $\tau = \pm 1$: valley index

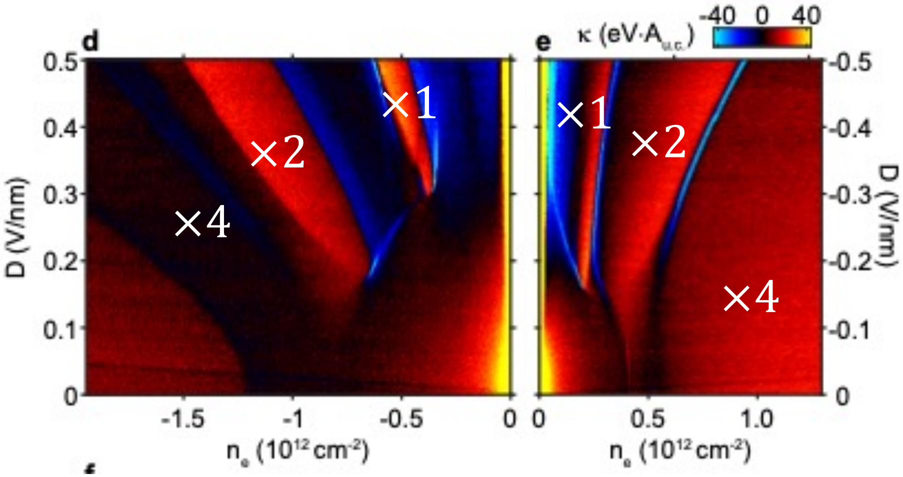


Koshino, McCann (2009); Zhang, Sahu, Min, McDonald (2010)

Phase diagram

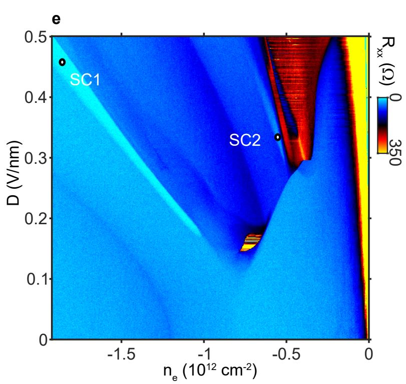
H. Zhou, …,A. Ghazaryan T. Holder, EB, M. Serbyn, A. Young, Nature (2021)

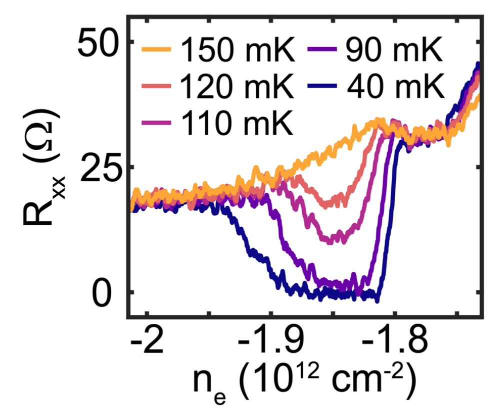
Cascade of symm-breaking transitions (analogous to TBLG: Zondiner et al., 2020)



Superconductivity!

- Two phases SC1, SC2
  $T_{c,1} \approx 100\text{mK}, T_{c,2} \approx 50\text{mK}$
- SC1: (probably) spin singlet,
  SC2: spin triplet!





Zhou, Xie, Taniguchi, Watanabe, Young, Nature (2021)

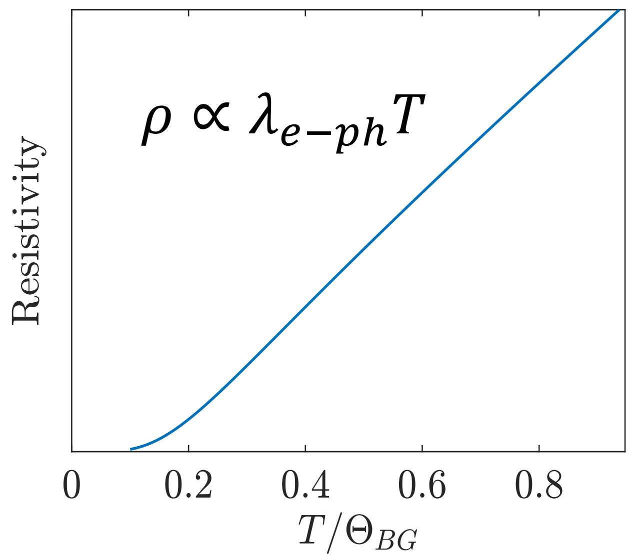
Puzzles

Conventional (acoustic phonon-mediated) s-wave?

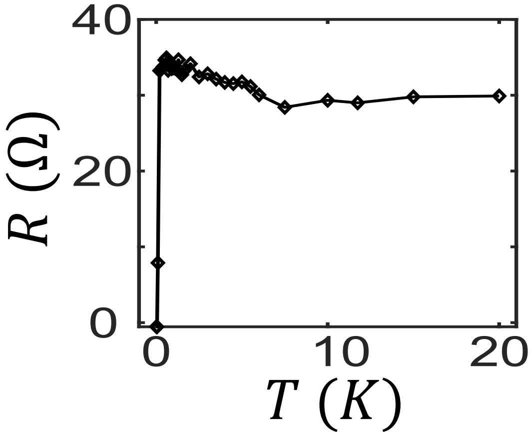
Chou, Wu, Sau, Das Sarma (2021)

$\Theta_{BG} = 2v_s k_F \approx 40\text{K}$

Resistivity should be linear in T for $T \gtrsim \Theta_{BG}/4$



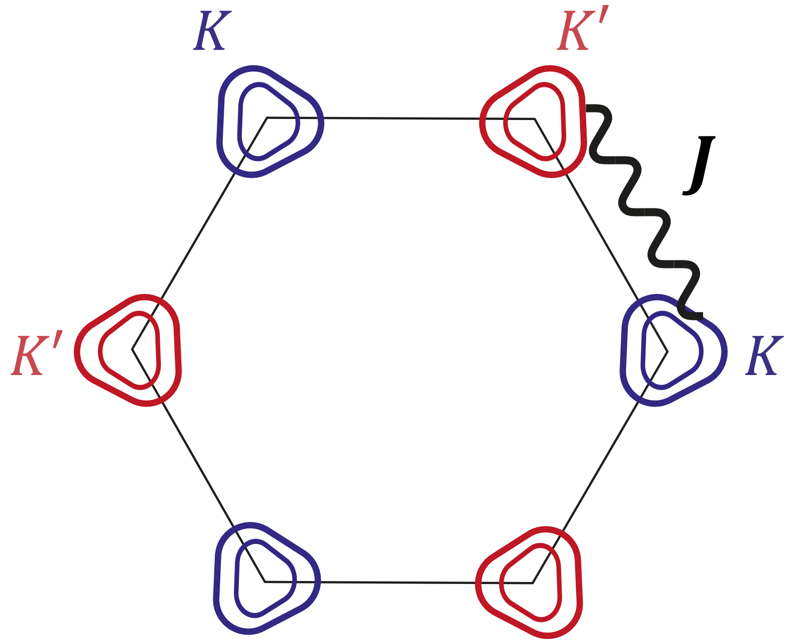
H. Zhou et al. (2021)



Puzzles (2)

Singlet or triplet?

$$H_J = -J\int d^2r\, \vec{S}_K \cdot \vec{S}_{K'}$$



SC2: normal state is spin-polarized ⇒ $J > 0$, **triplet SC**

SC1: normal state is spin-unpolarized ⇒ **singlet SC??**

Electronic mechanism

NEW MECHANISM FOR SUPERCONDUCTIVITY*

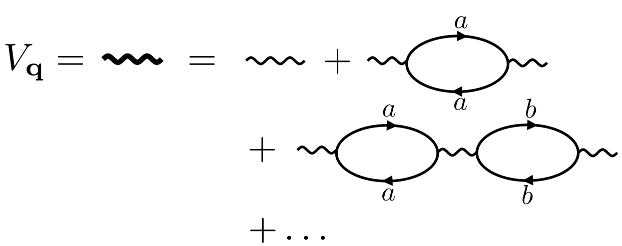
W. Kohn

University of California, San Diego, La Jolla, California

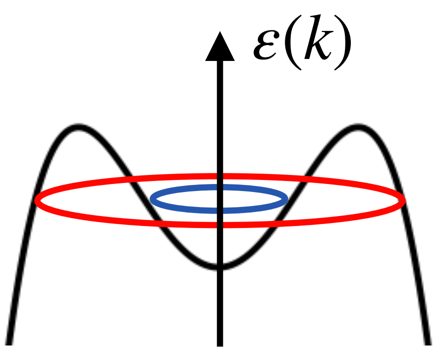
and

J. M. Luttinger (1965)

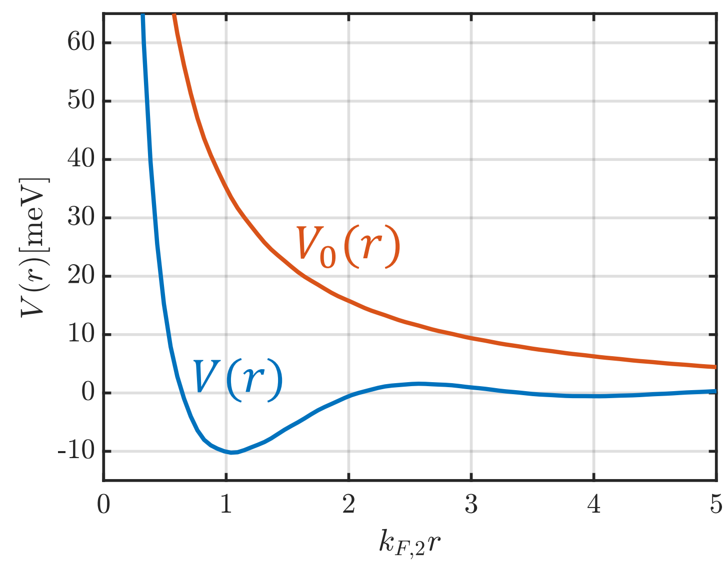
Screened Coulomb interaction (RPA):



$$= \frac{V_{0,\boldsymbol{q}}}{1 + N\,\Pi_{0,\boldsymbol{q}}\,V_{0,\boldsymbol{q}}}$$

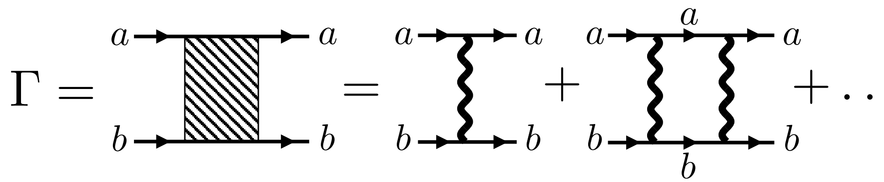


Annular 2D
Fermi surface

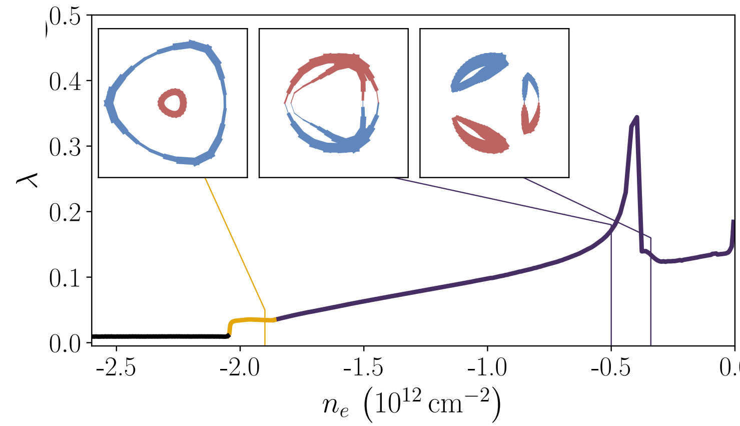


Results

Solution to the linearized BCS gap equation with $V_{\boldsymbol{q}}$

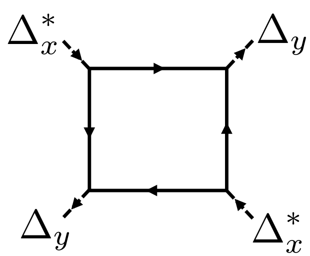


$s_{\pm}$ wave **p-wave**



$$T_c = We^{-1/\lambda}$$

$$W \sim E_F$$



Beyond the linearized BCS equation:

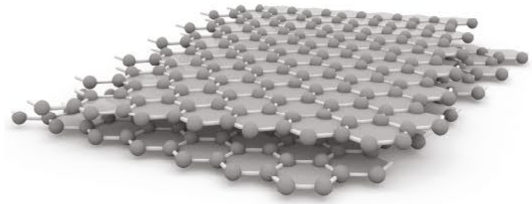
Chiral $\Delta_x + i\Delta_y$

- e-e scattering conserves momentum: $\rho(T > T_c) \approx const.$
- Coulomb interactions favor spin singlet for SC1

A. Ghazaryan, T. Holder, M. Serbyn, EB, Phys. Rev. Lett. 127, 247001 (2021)

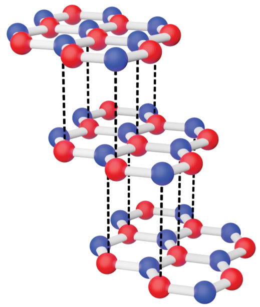
Outline

- What do we know about correlation effects in magic angle twisted graphene?

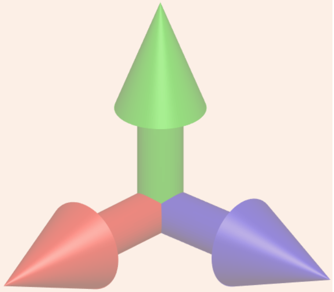


- MATBG: Open Questions

- Correlations and Exotic superconductivity in Rhombohedral trilayer graphene

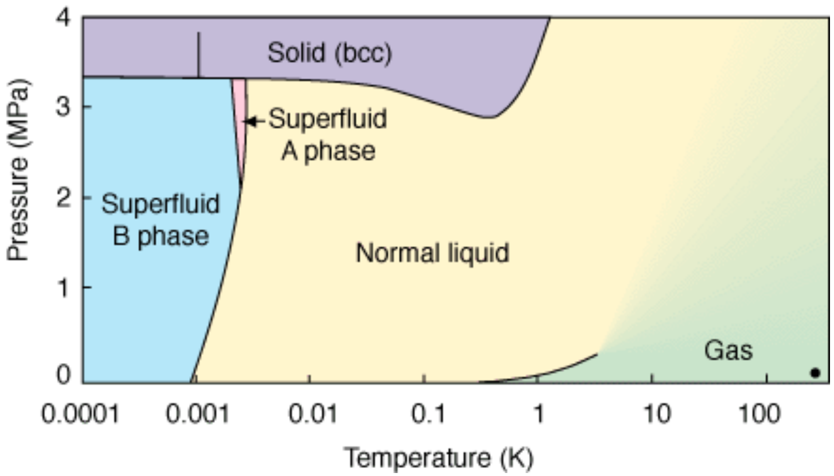


- Spin-polarized triplet superconductors: Order parameter topology and current dissipation



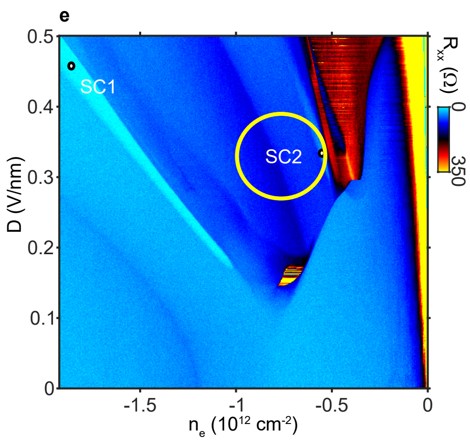
Triplet superconductivity in RTG

Solid state analogue of superfluid ^3He?



Triplet superconductivity:

- Strong electronic correlations ✅
- Nearby/coexisting ferromagnetism ✅
- Extremely clean ✅



Very small spin-orbit: SC and magnetism intertwined in interesting way?

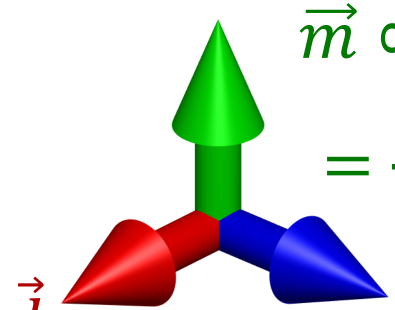
Order parameter of a spin-polarized superconductor

Order parameter of a spin-triplet SC:

$$\vec{d}_k = \langle c_k^\dagger i\sigma_2 \vec{\sigma} c_{-k}^\dagger \rangle \equiv \vec{d}_{1,k} + i\vec{d}_{2,k}$$

Fully spin polarized SC: $|\vec{d}_{1,k}| = |\vec{d}_{2,k}|$, $\vec{d}_{1,k} \perp \vec{d}_{2,k}$

Order parameter space: $SO(3)$
(*Neglecting spin-orbit coupling)*

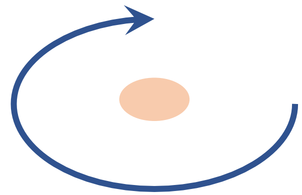


No finite T transition in $d = 2$
Mukerjee, Xu, Moore (2006)

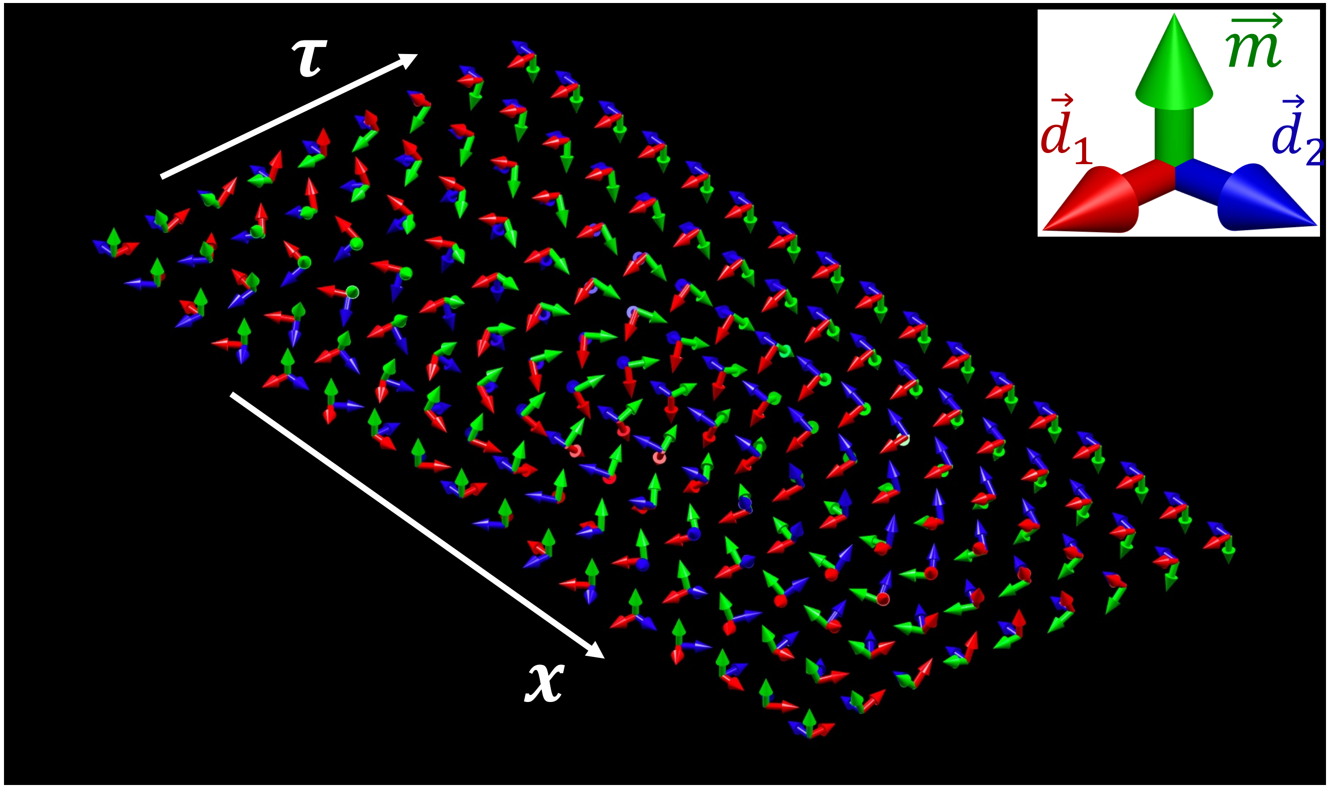
Topological defects

Polarized triplet superconductor:

$$\pi_1(SO(3)) = Z_2 \qquad (Z_2 \text{ superconducting vortex})$$

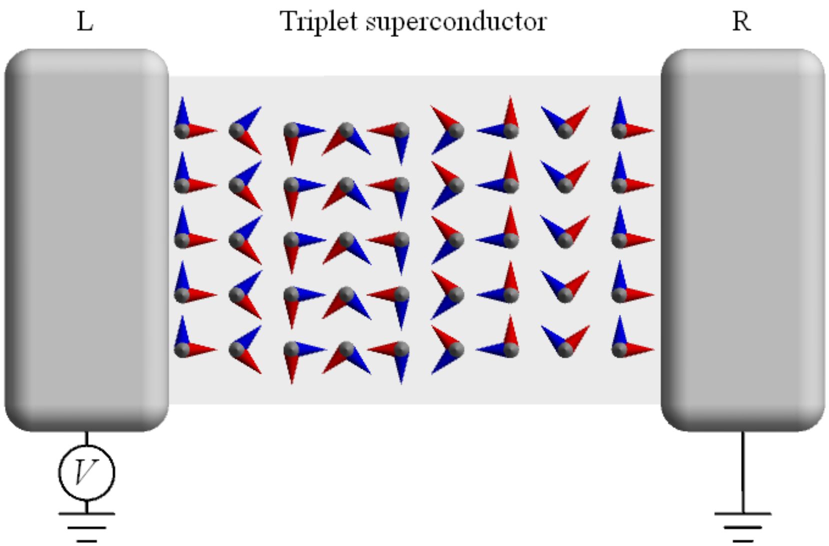


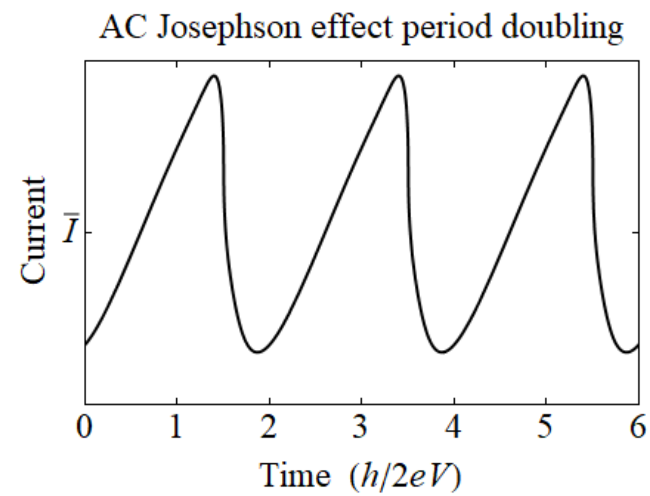
Unwinding a phase twist of 4π:



E. Cornfeld, M. Rudner, EB, Phys. Rev. Research 3, 013051 (2021)

Double-period Josephson effect





Half the usual Josephson frequency: $\omega = \frac{eV}{\hbar}$

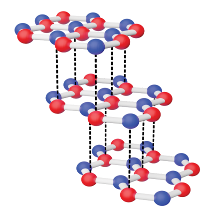
Critical current: $J_c \sim 1/\lambda \sim \sqrt{B}$

$^*T$ is low enough such that vortex-antivortex dissociation is suppressed.

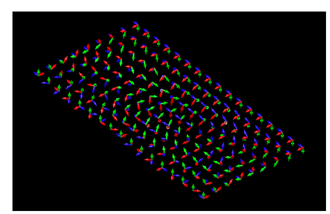
Summary

Astonishingly rich correlated electron phenomena in multilayer graphene!

- **MATBG:** Cascade of phase transitiosns, spin/valley ferromagnetism, Chern insulators
- **Open questions:** Symmetry of SC order parameter? Broken symmetry at even ν? Non-Fermi liquid?
- **Unconventional SC in ABC trilayer graphene?** Most likely state: chiral p-wave



- **Fully spin polarized SC:** fragility of supercurrent due to topology, double-period Josephson effect



Thank you!