A Multitone Mystery: Normal-State Fermiology of the Candidate Chiral Superconductor in Rhombohedral Graphene

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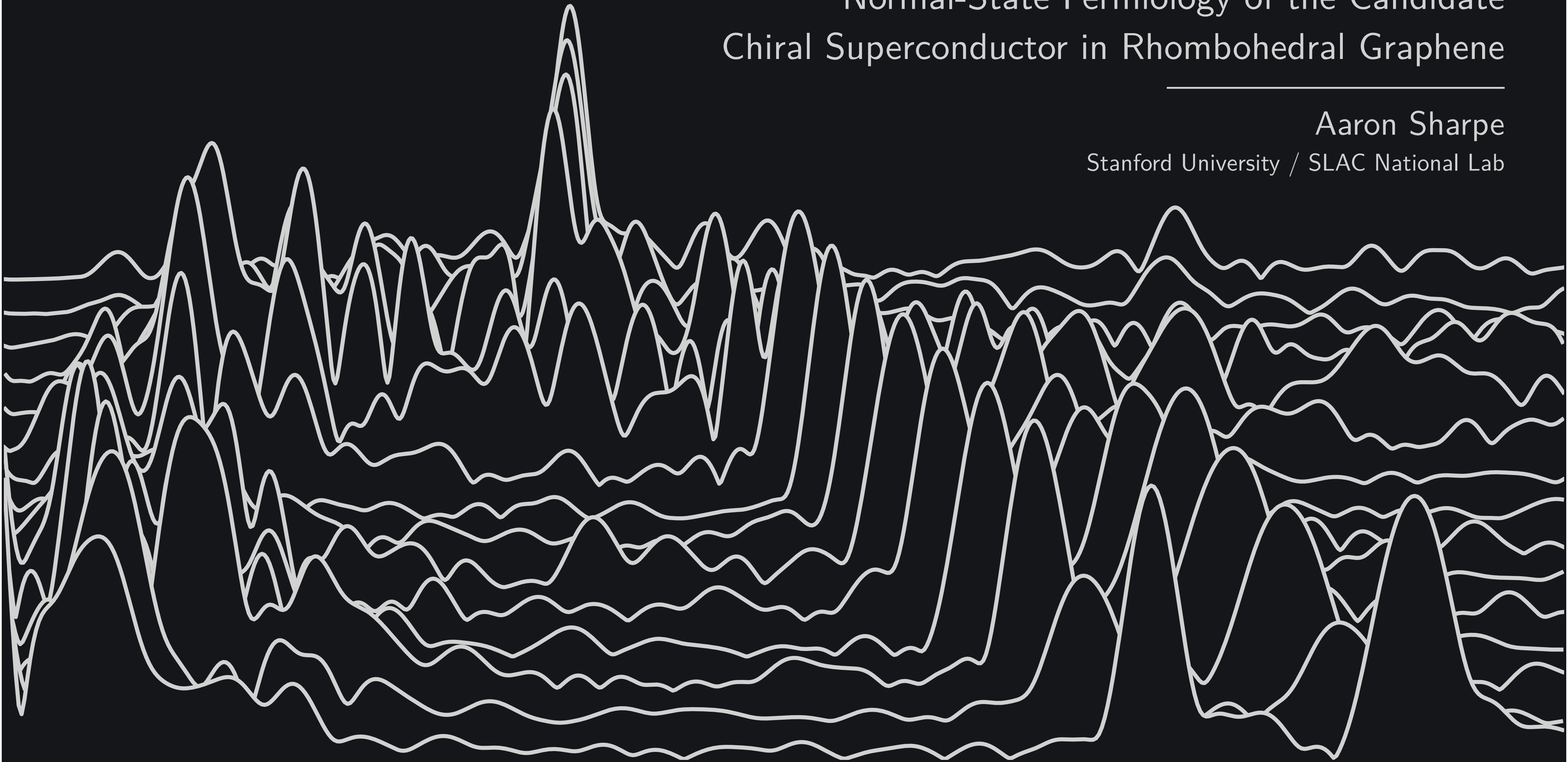
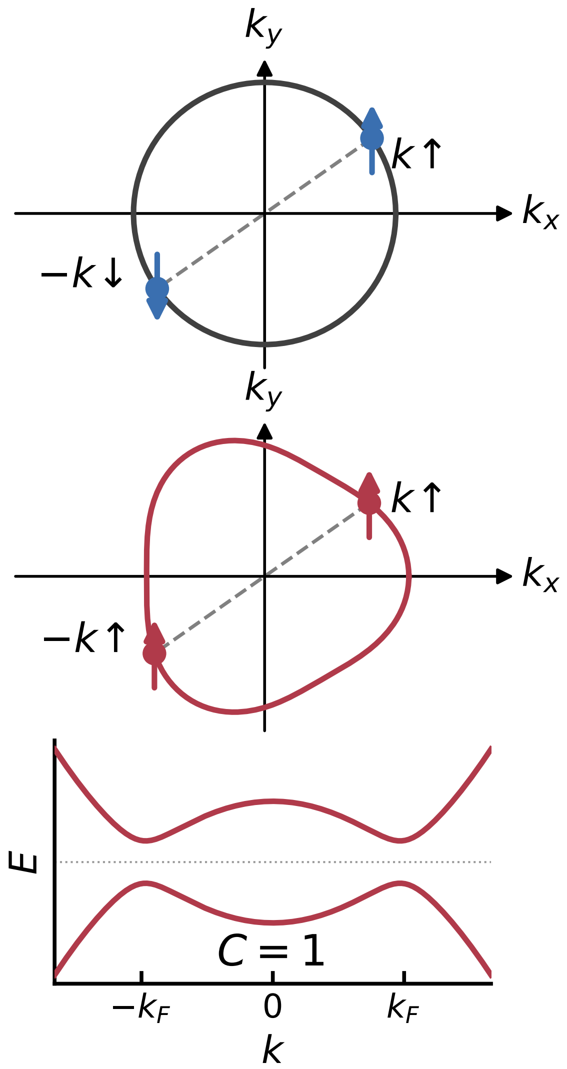


Pairing and Time Reversal

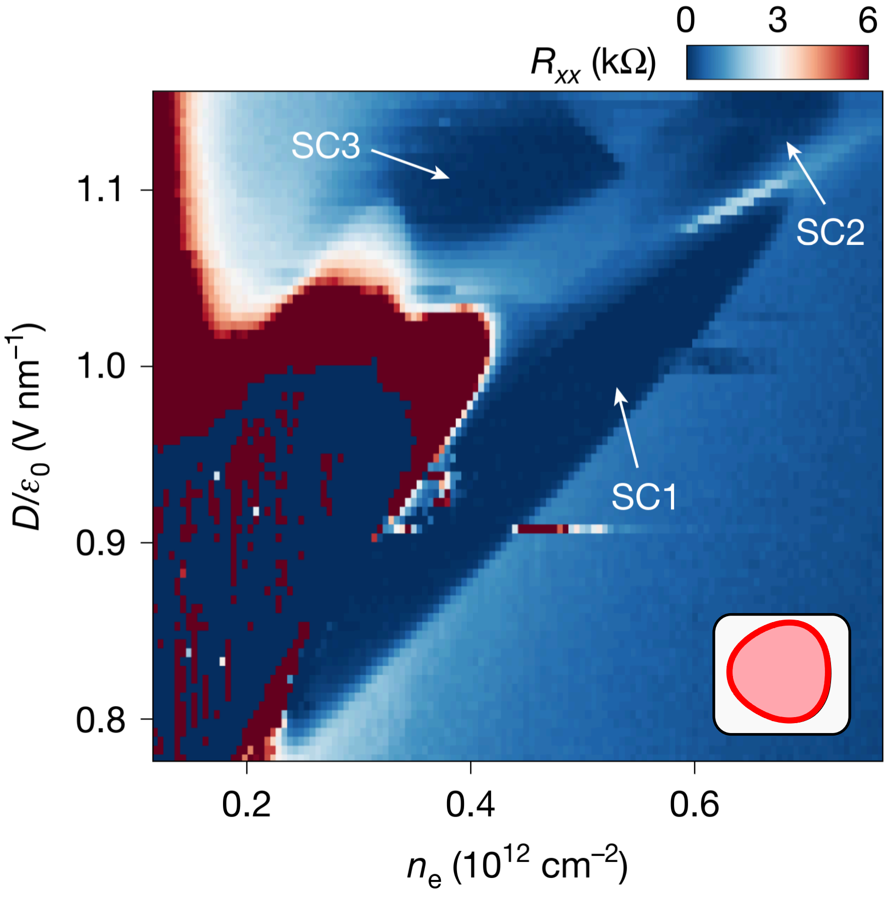
- Conventional pairing: electron at k binds its **time-reversed partner**
  - $(k\uparrow, -k\downarrow)$ degenerate at every k $\rightarrow$ weak attraction suffices
  - gap real and uniform (s-wave): $\Delta(k) = \Delta$
- **What if the metal already breaks time reversal before it pairs?**
  - no partners $\rightarrow$ $\Delta(-k) = -\Delta(k)$
  - odd gap: **nodal** (f-wave) or **fully gapped and chiral**
  - Energetics determines preferred channel
  - if fully gapped $\rightarrow$ topological



Bardeen, Cooper & Schrieffer Phys. Rev. (1957)
Slides available @ aaronsharpe.science

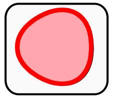
Candidate Chiral Superconductivity (CSC)

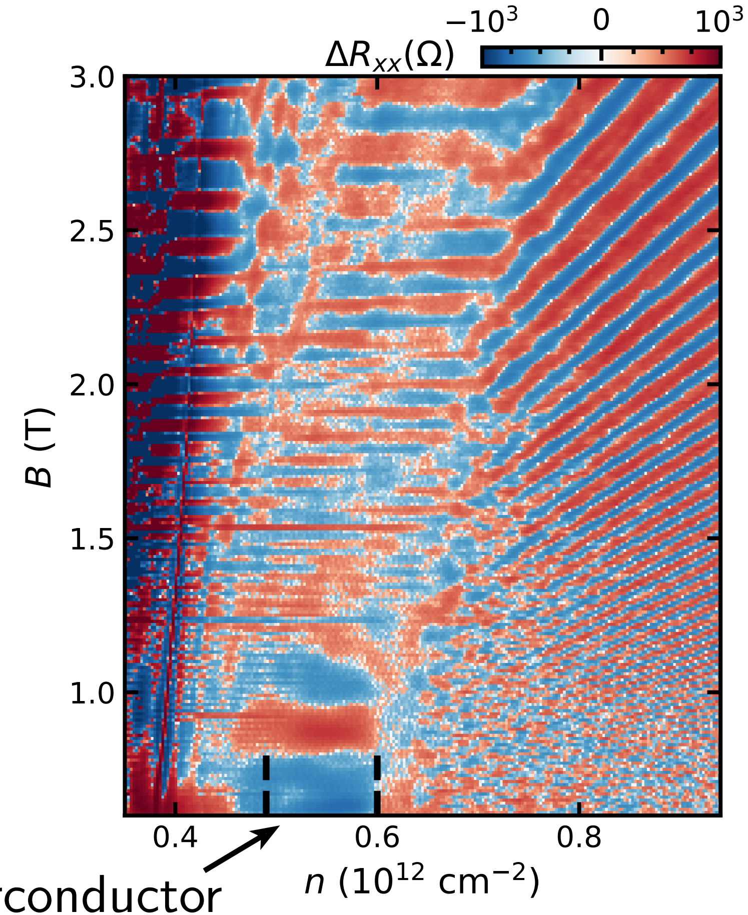
- Superconducting state in rhombohedral graphene
  - Likely spin- and valley-polarized
  - Breaks time-reversal, Chiral?
- Normal state?
- Chiral + single Fermi surface
  → topological!



Han et al. Nature (2025)

Main Message

- Use **quantum oscillations** to probe normal-state Fermi surface
- High n: single simply-connected Fermi surface 
- Lower n: **“multitone”** state
  - Likely the normal state of CSC
  - No obvious Fermi liquid picture for oscillations 
  - Normal state is interesting in its own right



superconductor

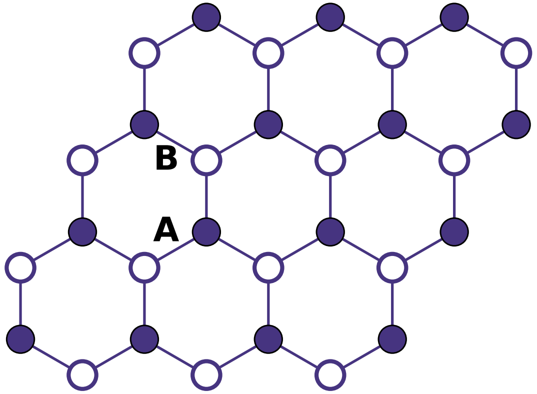
Outline

0. Introduction: rhombohedral graphene

1. Superconductivity in tetralayer rhombohedral graphene

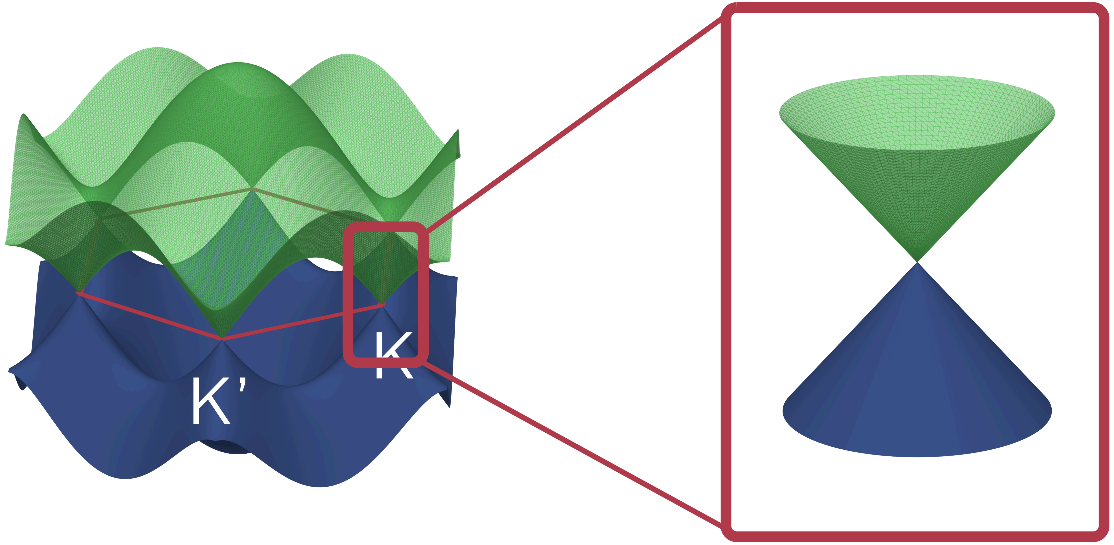
2. Fermiology from quantum oscillations

Our Building Block: Monolayer Graphene



$$H(\mathbf{k}) = \begin{pmatrix} 0 & f(\mathbf{k}) \\ f^*(\mathbf{k}) & 0 \end{pmatrix}$$

$$f(\mathbf{k}) = -\gamma_0 \sum_{j=1}^{3} e^{i\mathrm{k}\cdot\delta_j}$$

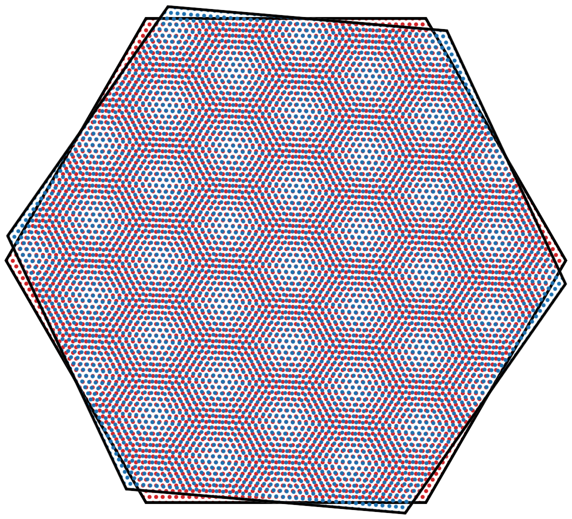


$$H(\mathbf{K}+\mathbf{q}) \approx \hbar v_F\, \mathbf{q}\cdot\boldsymbol{\sigma}$$

Xiao et al. PRL (2007)
Slonczewski & Weiss PR (1958)
McClure PR (1957)

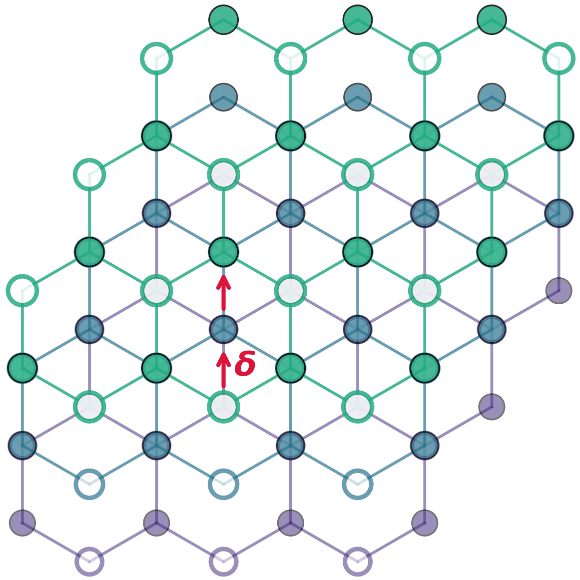
Designer Strongly Interacting Systems

moiré multilayers



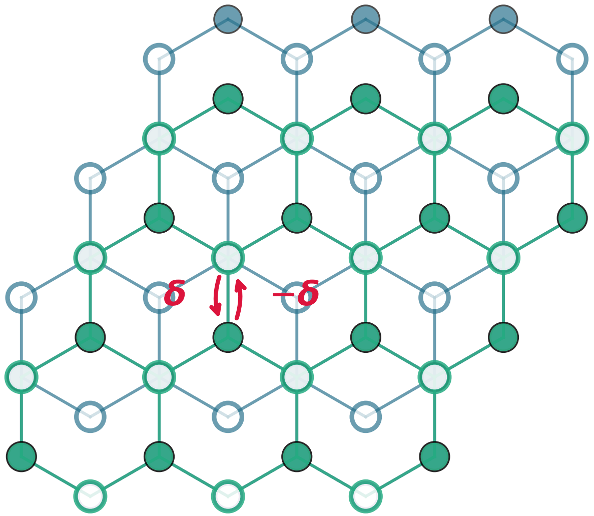
Bistritzer & MacDonald PNAS (2011)

crystalline multilayers

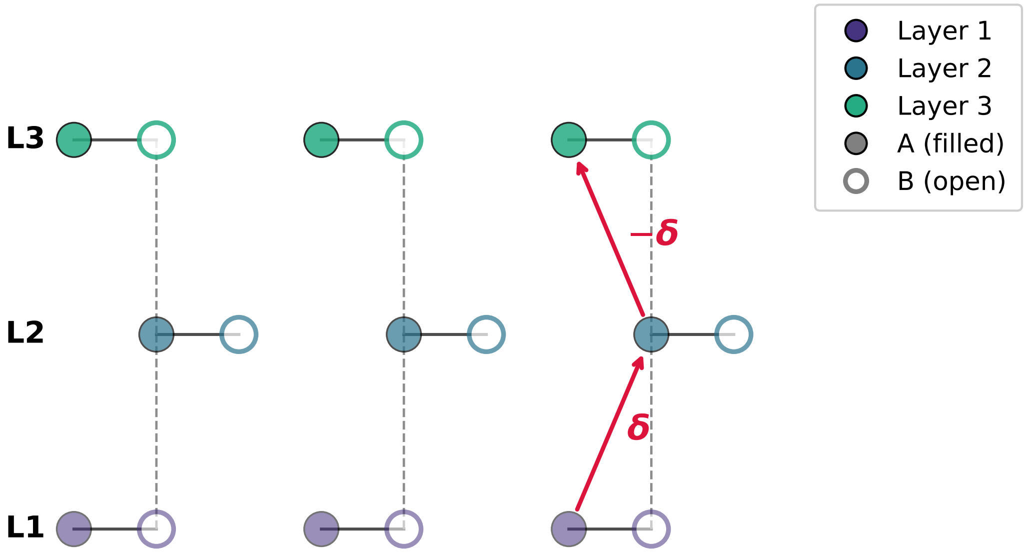


Min & MacDonald PRB (2008)

Bernal (AB) Stacking

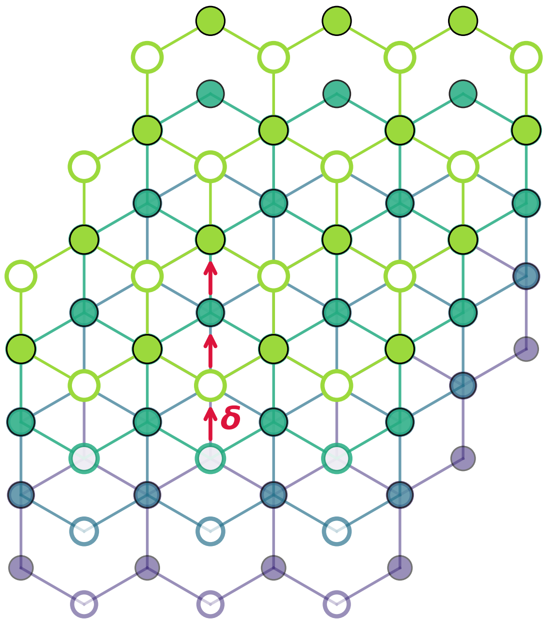


Top view

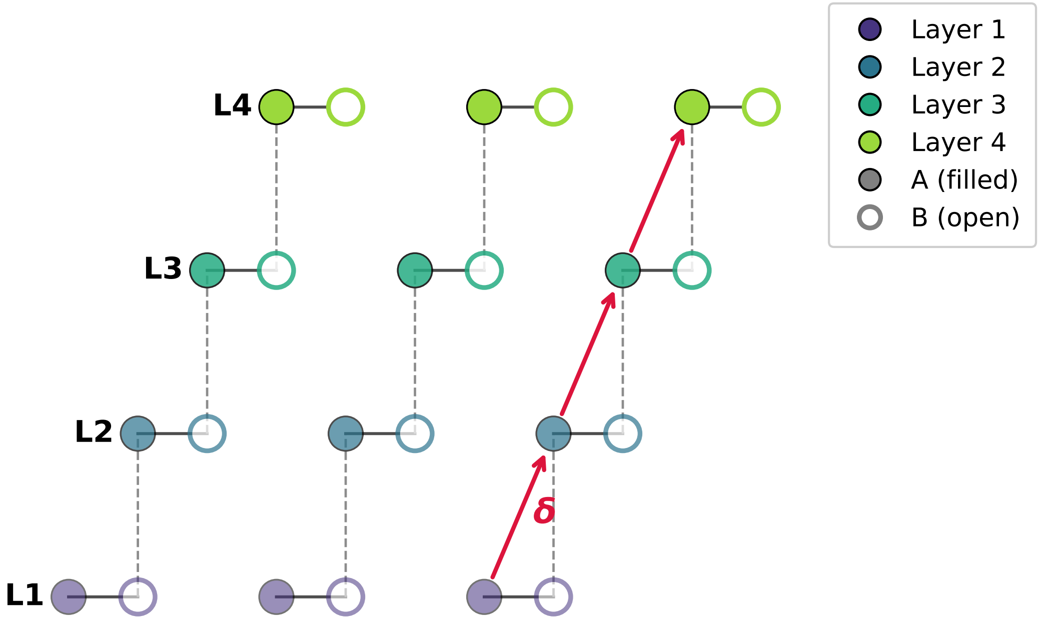


Side view

Rhombohedral Multilayer Graphene (RMG)

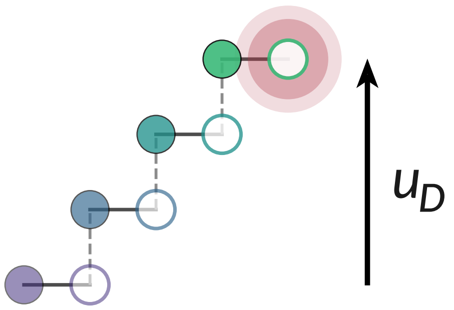


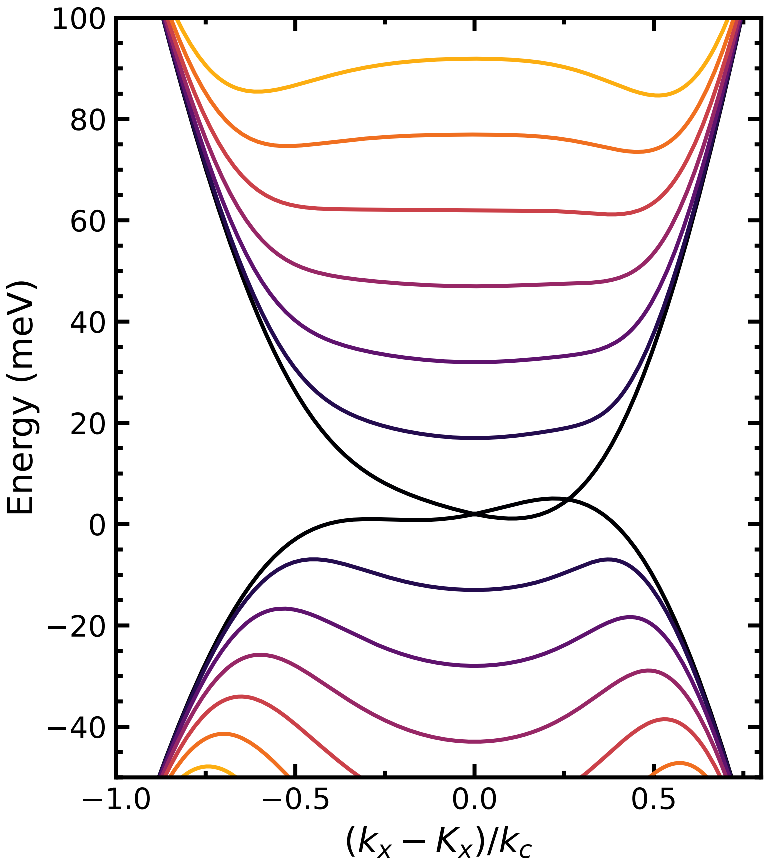
Top view

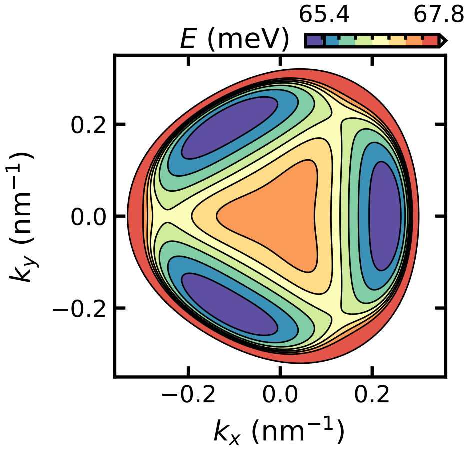


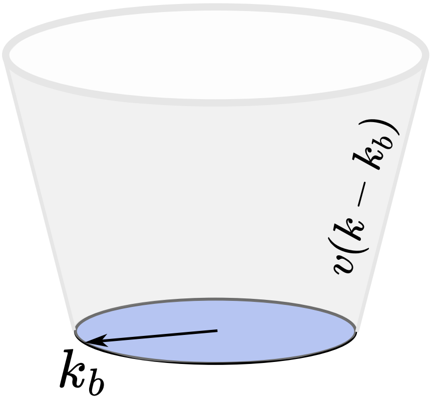
Side view

Rhombohedral Bandstructure (R4G)







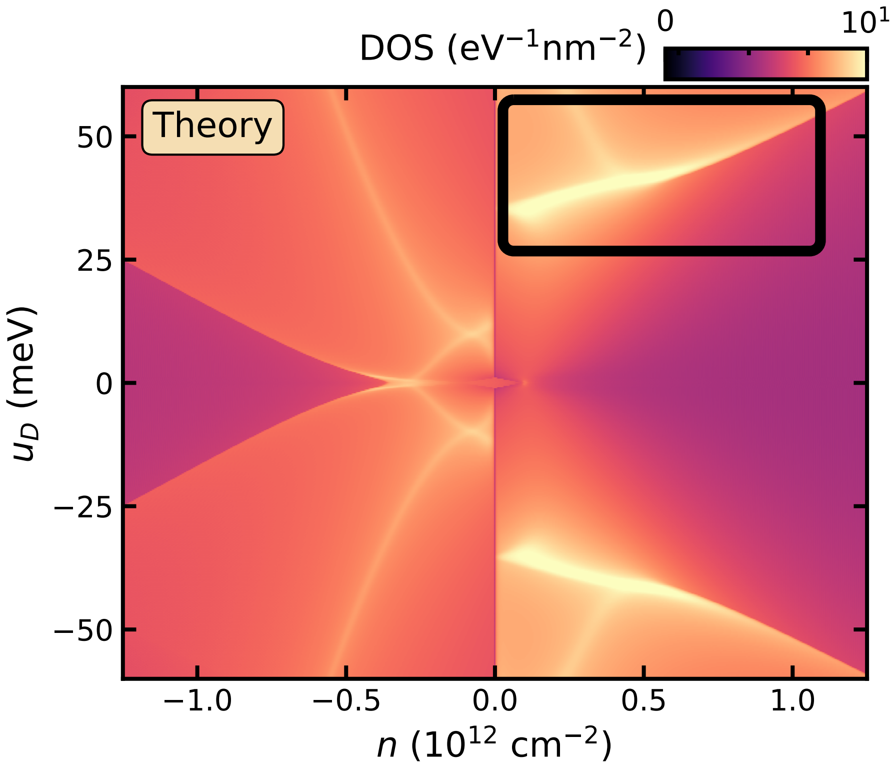


With **increasing** u_D (applied D), dispersion evolves:

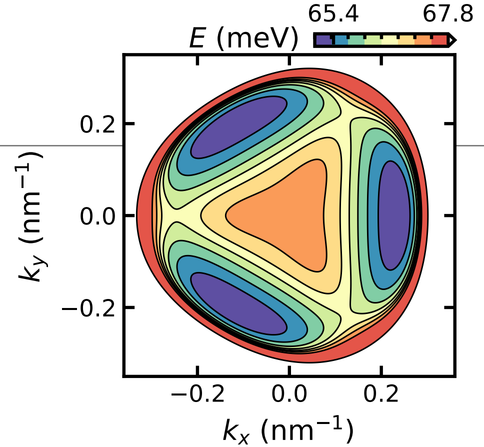
- U-shaped
- → flat minima
- → to a Mexican hat

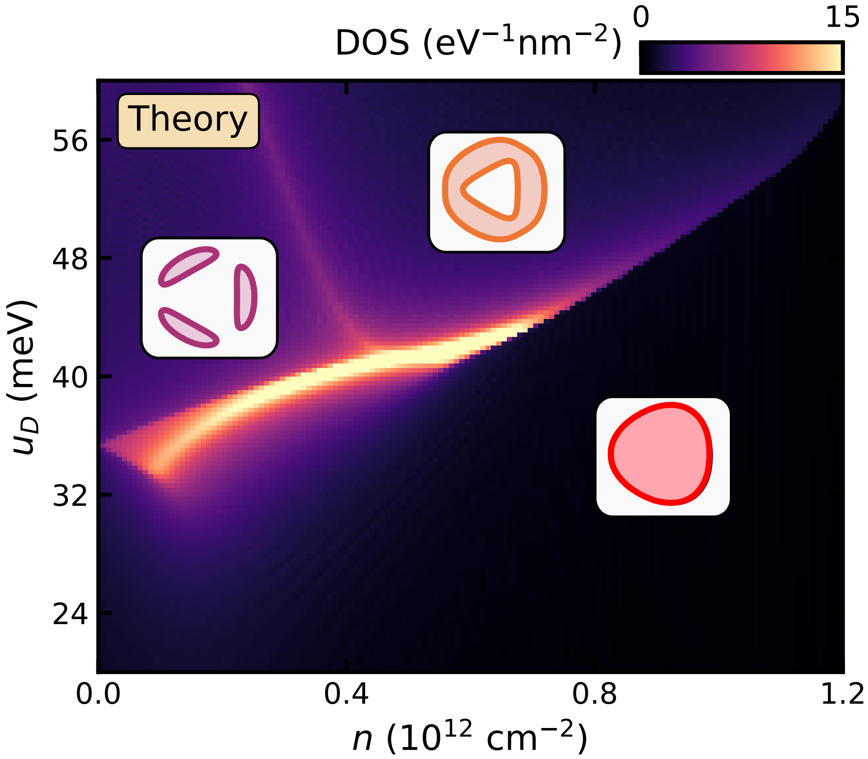
Koshino & McCann PRB (2009)
Auerbach et al. Nat. Phys. (2025)
Bernevig & Kwan arXiv:2503.09692
Patri & Franz PRB (2025)

R4G Conduction Band Fermiology



Assume spin- and valley-polarized





Outline

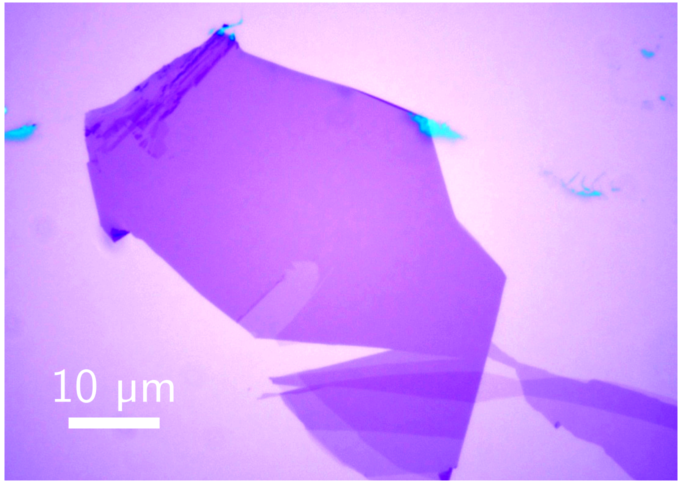
0. **Introduction: rhombohedral graphene**

1. **Superconductivity in tetralayer rhombohedral graphene**

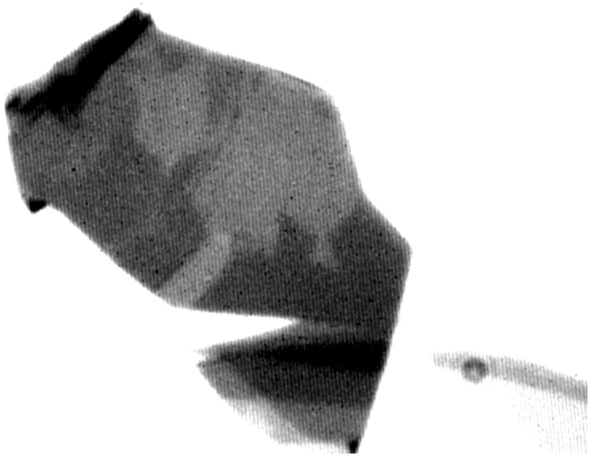
2. **Fermiology from quantum oscillations**

Identifying Rhombohedral

Optical



Near-IR

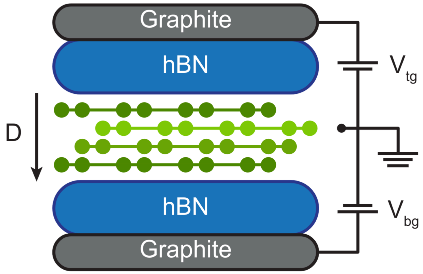


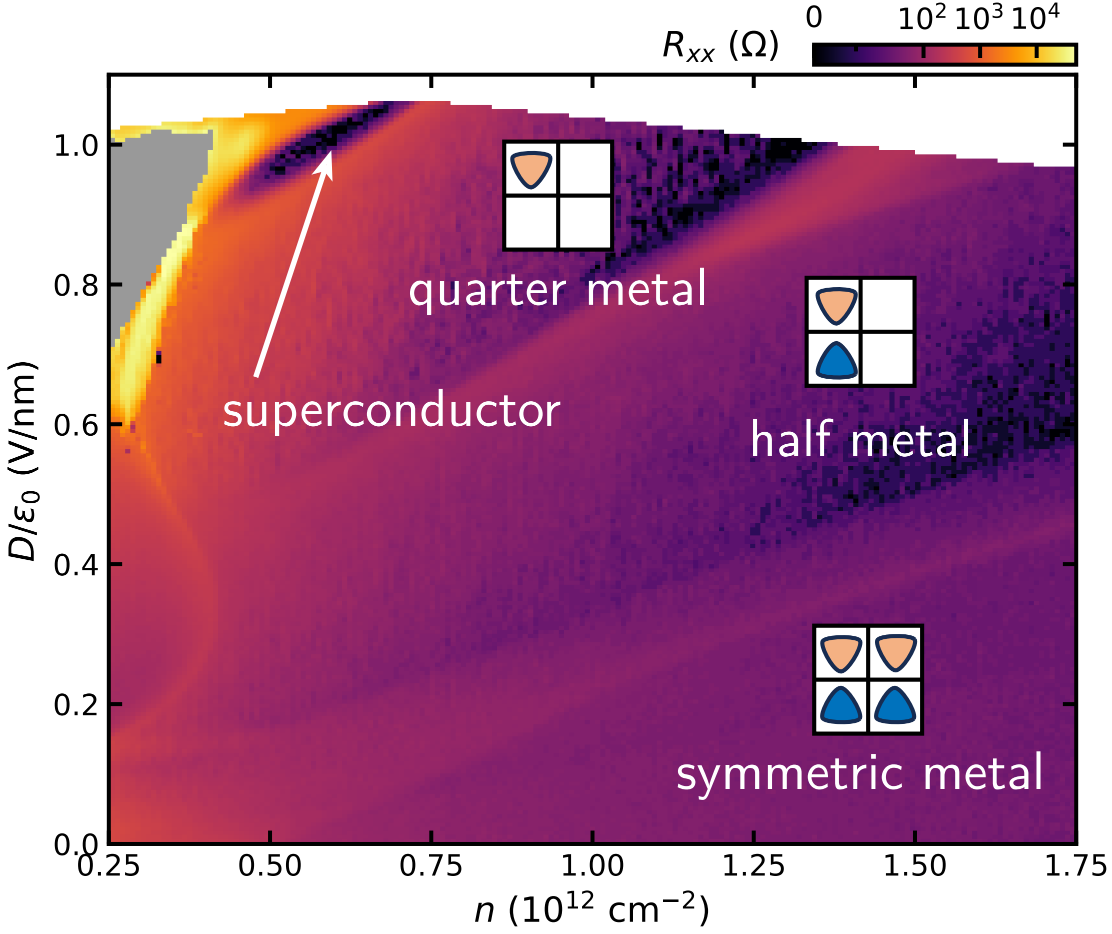
Cross reference in:

- Raman
- Various scanned probes

Li et al. Nano Lett. (2018)
Feng et al. Phys. Rev. Applied (2025)
Holleis et al. arXiv:2604.21912

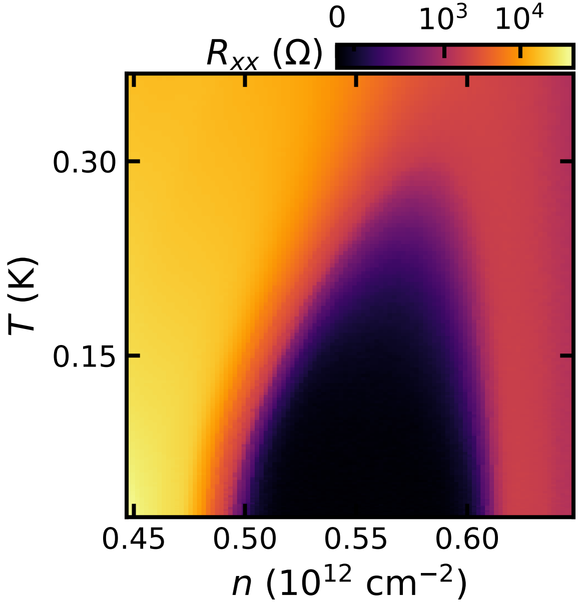
Experimental Phase Diagram of 4-layer Rhombohedral



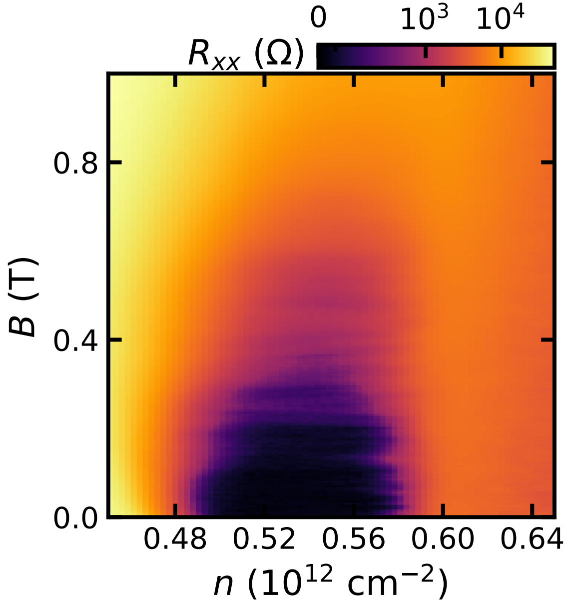


Zhou et al. Nature (2021) and many others
Han et al. Nature (2025)
Kalantre, ..., **Sharpe** arXiv:2606.05356

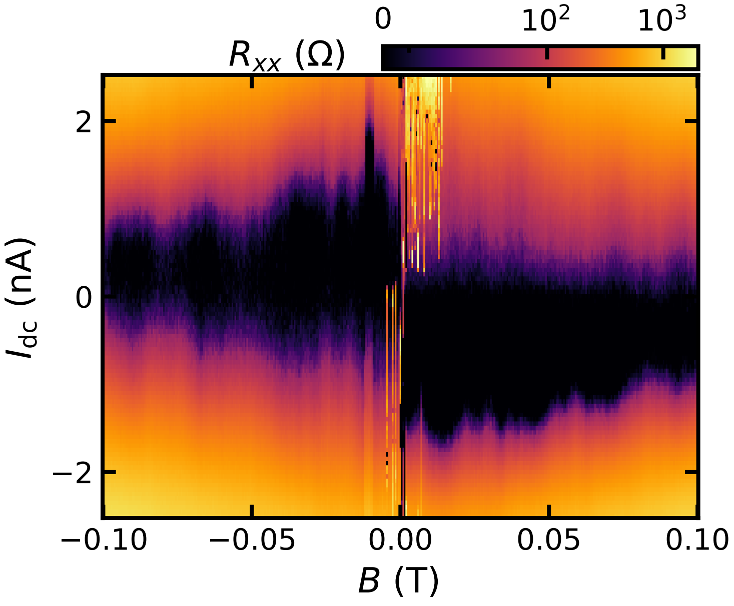
Basic Phenomenology of the Candidate CSC



Critical temperature



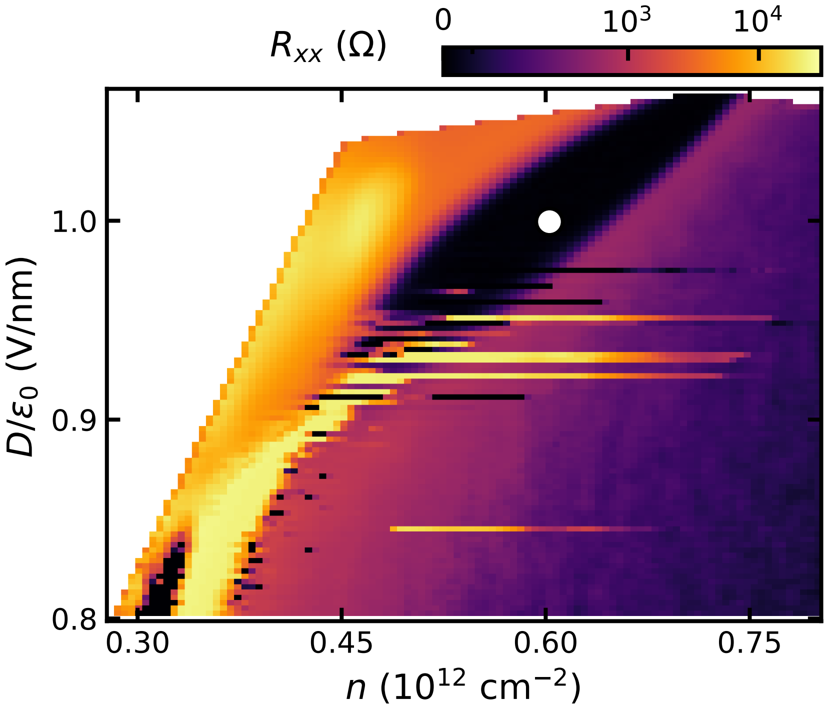
Critical field

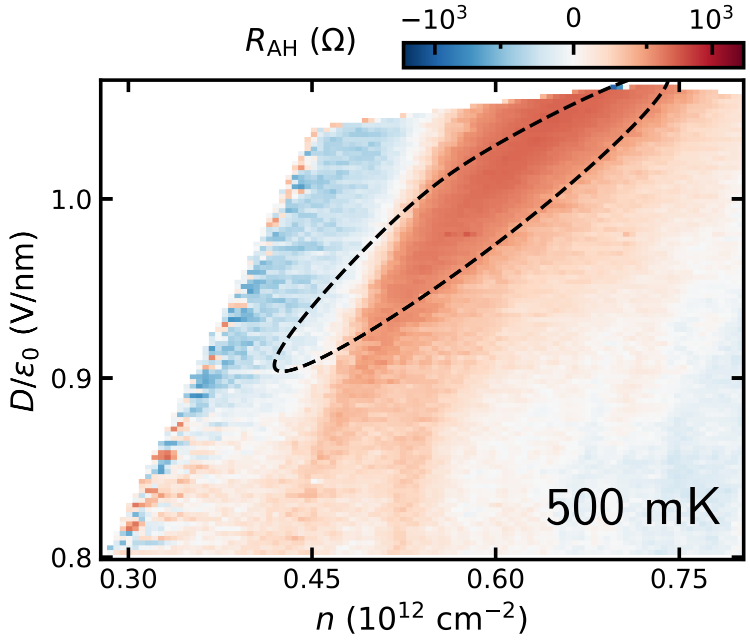


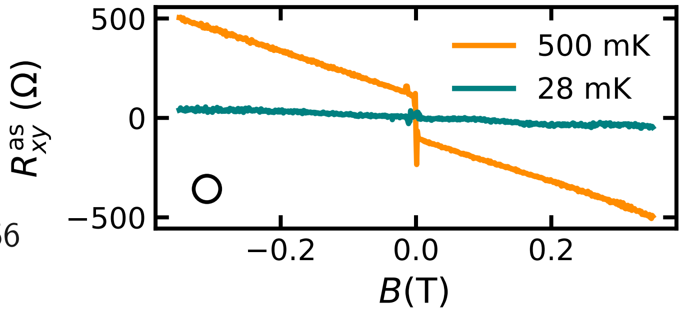
Phase coherence

Han et al. Nature (2025)
Kalantre, ..., **Sharpe** arXiv:2606.05356

Time-Reversal Symmetry Breaking



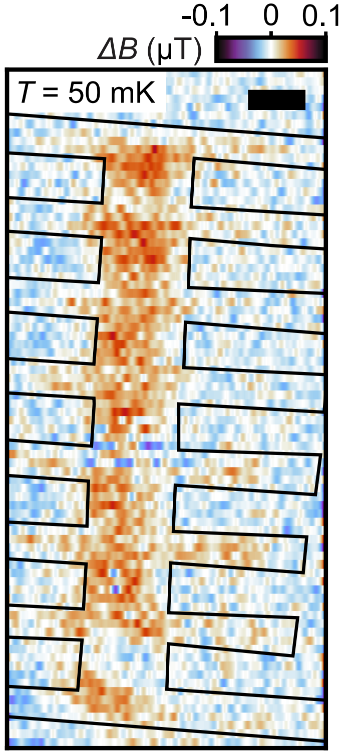


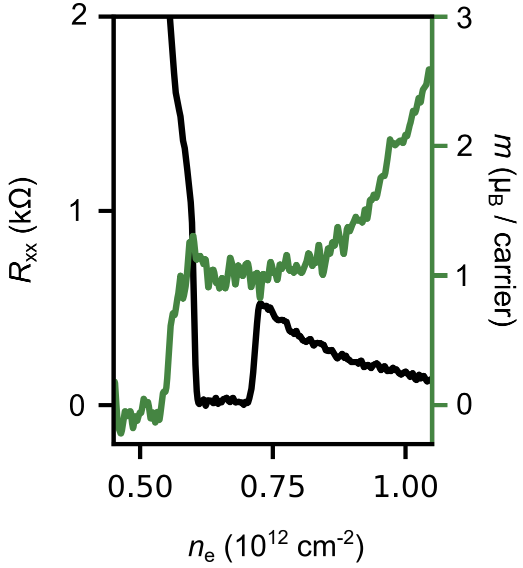


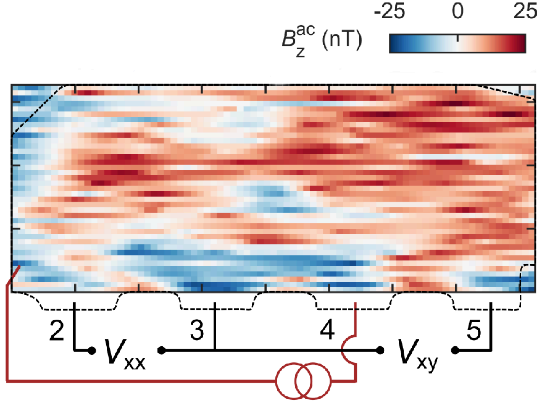
Time reversal is broken in normal state

Han et al. Nature (2025)
Kalantre, ..., **Sharpe** arXiv:2606.05356
Dutta et al. arXiv:2605.13303
Sheekey et al. arXiv:2605.30316

Time-Reversal Symmetry Breaking (cont.)





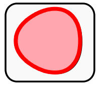


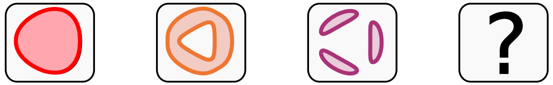
1. Time reversal is broken in CSC
2. Domains exist in the CSC

Han et al. Nature (2025)
Kalantre, …, **Sharpe** arXiv:2606.05356
Dutta et al. arXiv:2605.13303
Sheekey et al. arXiv:2605.30316

Superconductivity in a Spin- and Valley-Polarized State?

Questions:

- Symmetry of the SC pairing function?
  - Chiral vs nodal?
- Is the SC topological?
  - e.g. $p_x \pm ip_y$ pairing of 
- Mechanism driving superconductivity?
- Normal state? → quantum oscillations!



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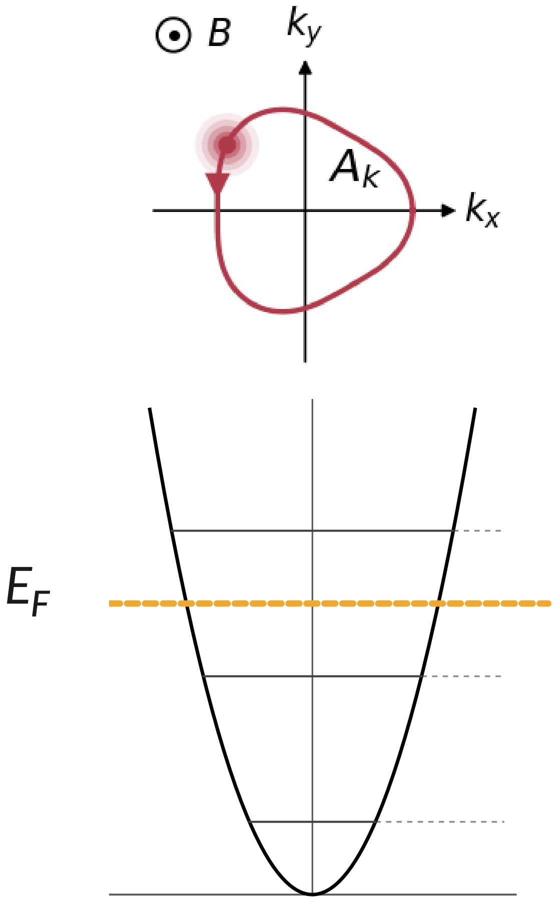
Lightning review of QOs in 2D



Landau levels evolve with magnetic field
→ DOS at E_F periodically with $1/B$

$$f = \frac{h}{e} \frac{A_k}{(2\pi)^2}$$

- de Haas-van Alphen (dHvA): magnetic susceptibility
- **Shubnikov-de Haas (SdH):** resistivity

Schubnikow & de Haas Nature (1930)
de Haas & van Alphen Proc. KNAW (1930)

Semiclassical (Onsager) Quantization

- Effective density enclosed by orbit:

$$n_{\mathrm{SdH}} = \frac{A_k}{(2\pi)^2} = \frac{ef}{h}$$

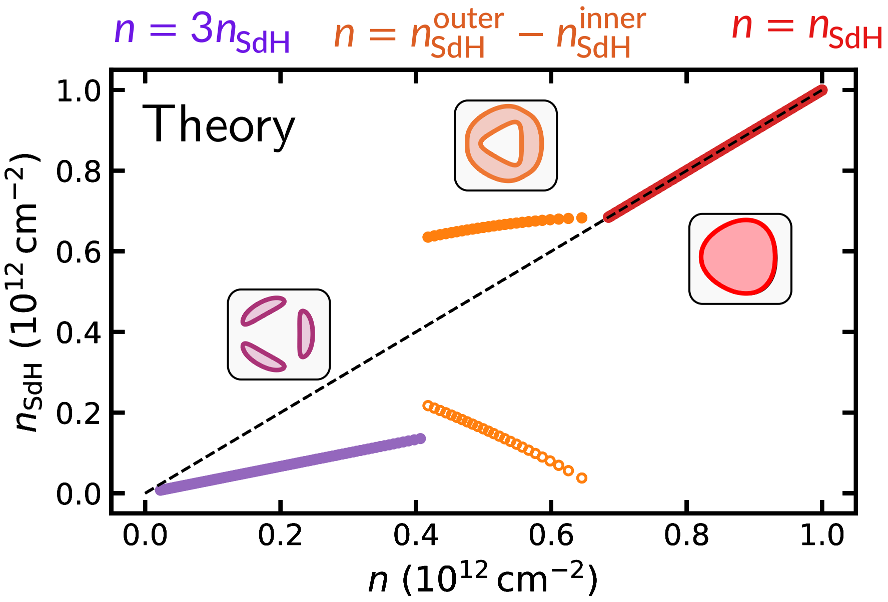
- All carriers participating in quantum oscillations → **Luttinger sum rule**

$$n = \sum_j \theta_j g_j n_{\mathrm{SdH},j}$$

degeneracy

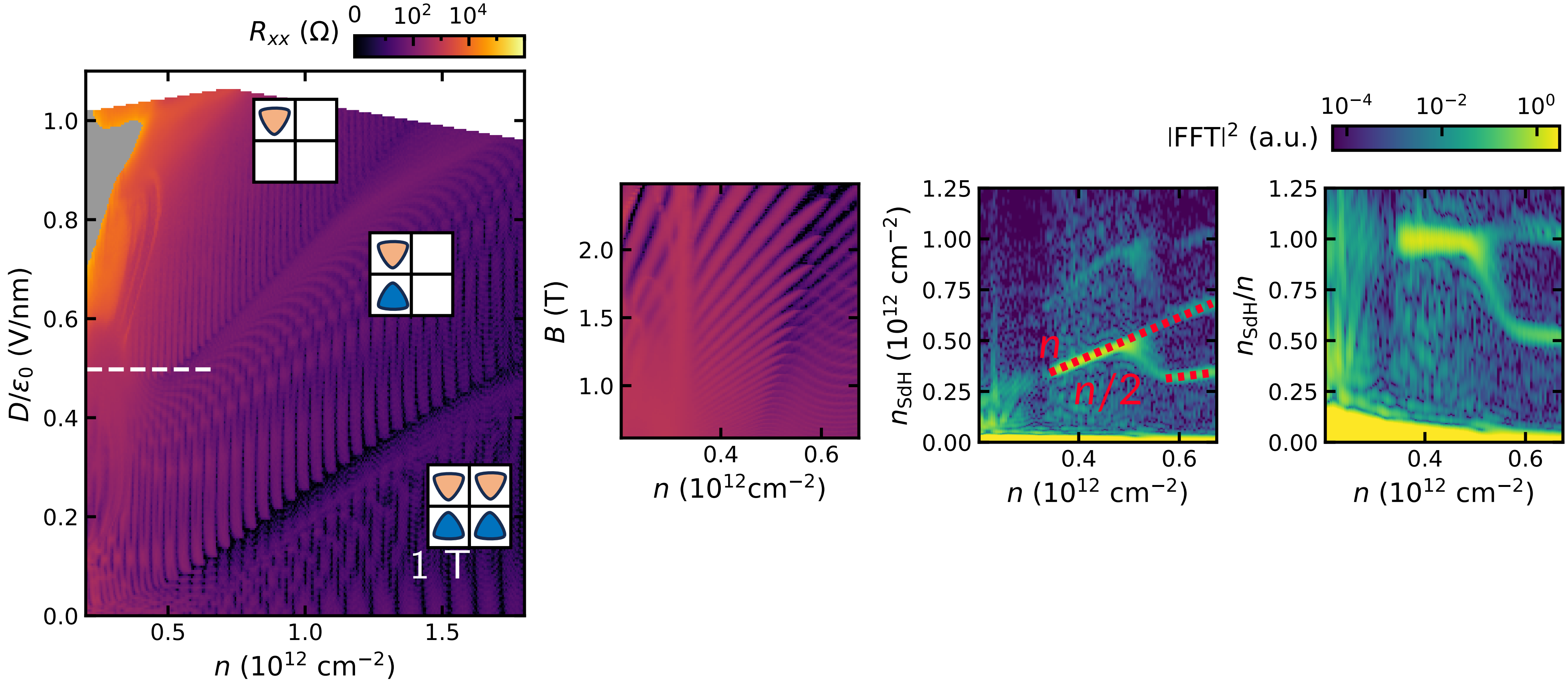
carrier sign

sum over **fundamental orbits**

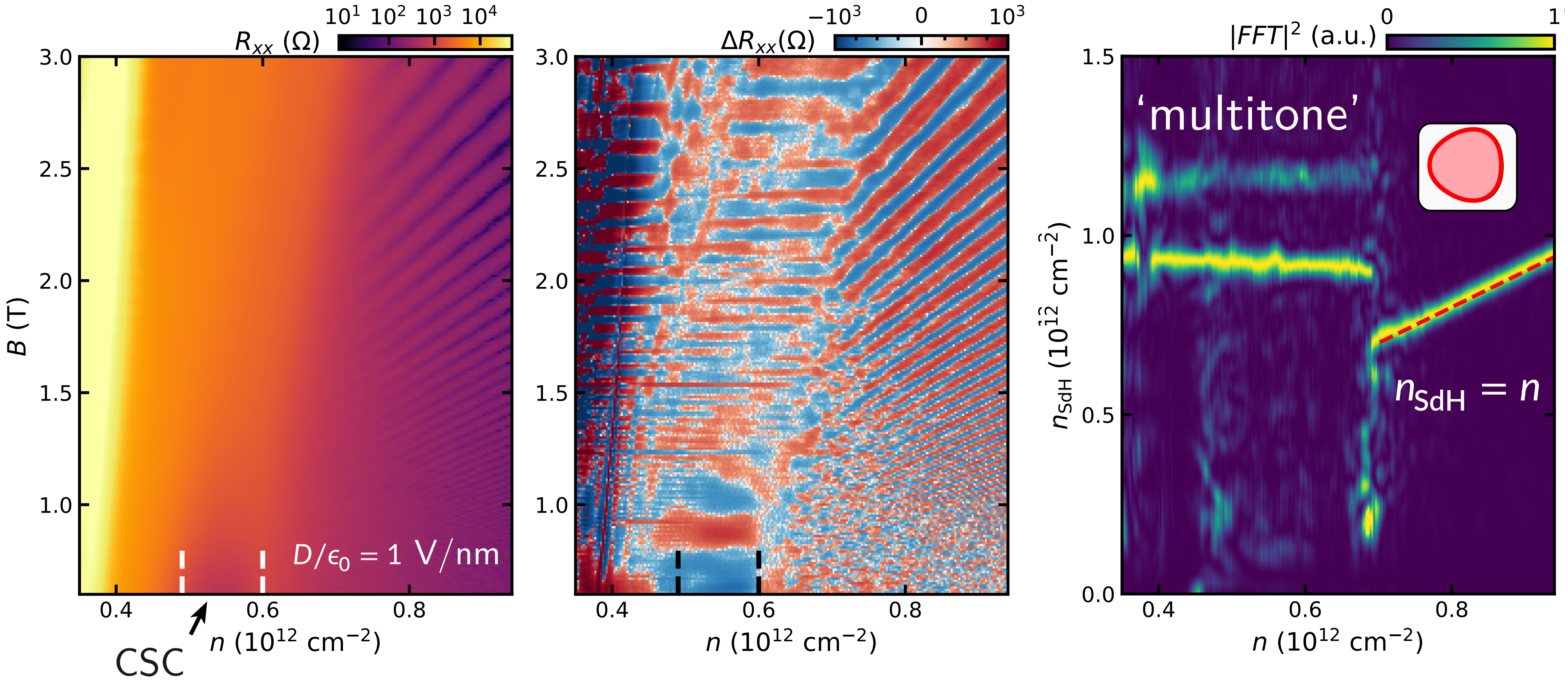


Onsager Phil. Mag. (1952)
Shoenberg Magnetic Oscillations in Metals (1984)

Flavor Transitions

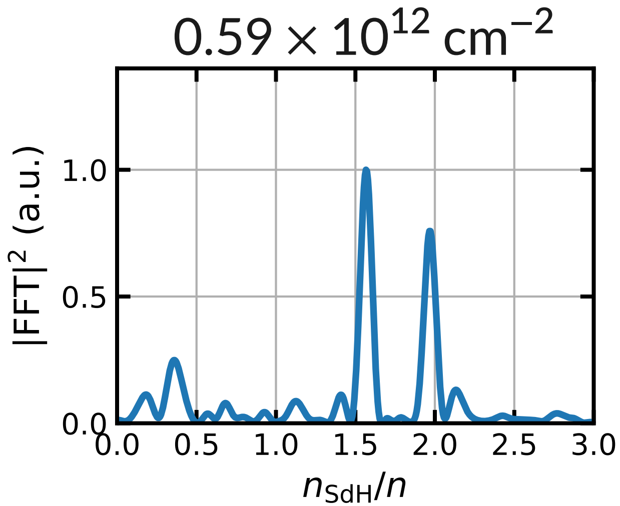


Oscillations near the CSC



Kalantre, ..., **Sharpe** arXiv:2606.05356

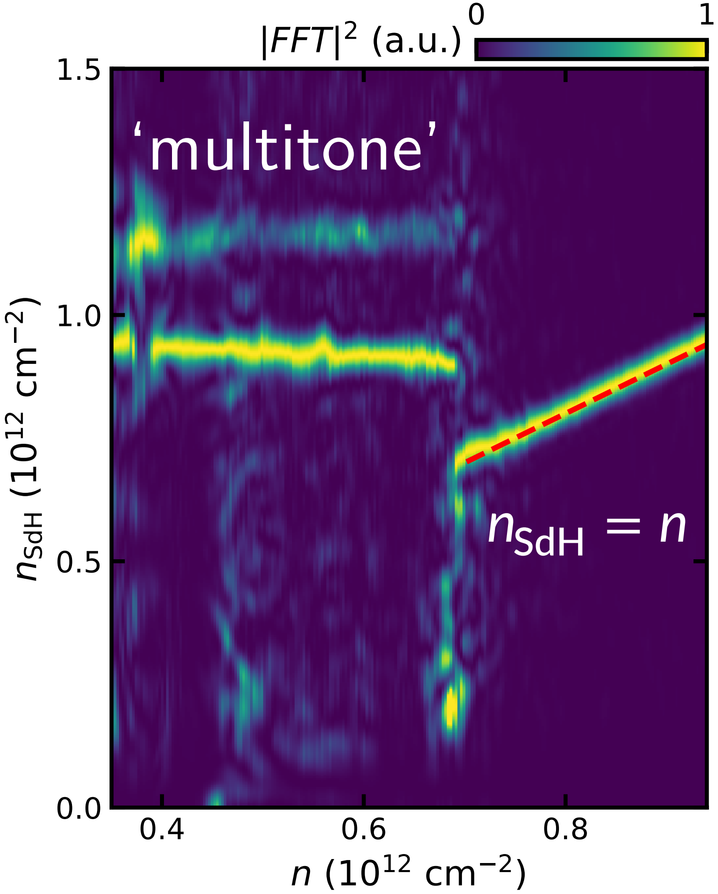
‘Multitone’ metal



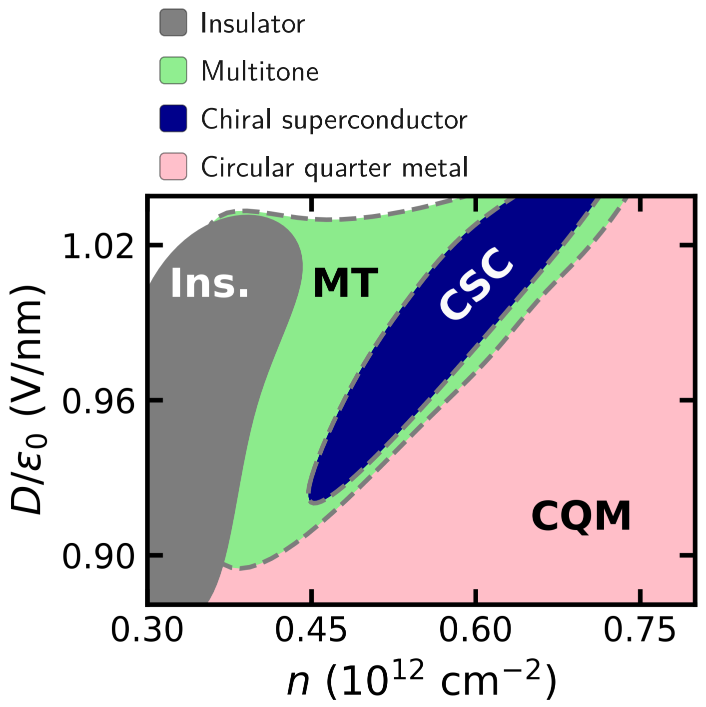
- jumps to two **high** and nearly **flat** frequencies

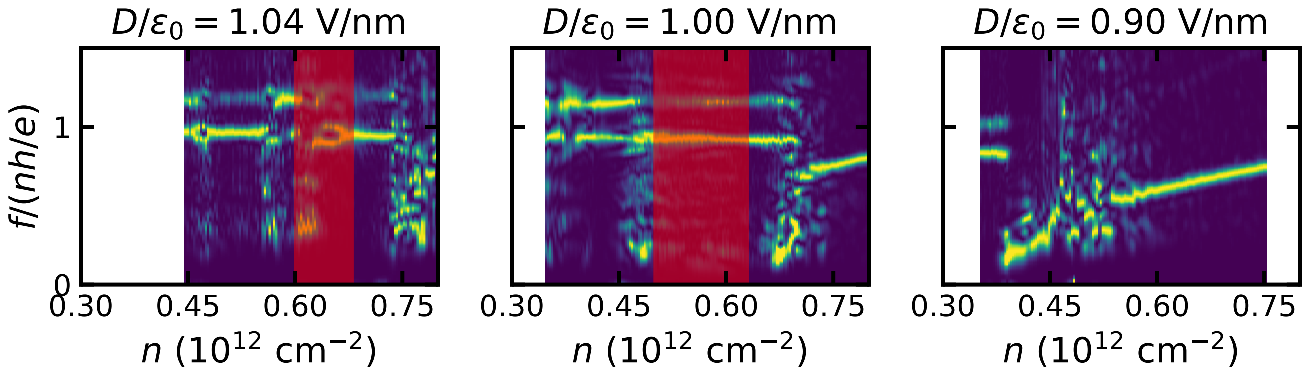
- Annulus?
  - $\Delta n_{\mathrm{SdH}}^{\mathrm{fast}} \approx 0.2 \times 10^{12}\ \mathrm{cm}^{-2}$

  → high tones inconsistent with a singly degenerate annulus*



Mapping the Phase Diagram



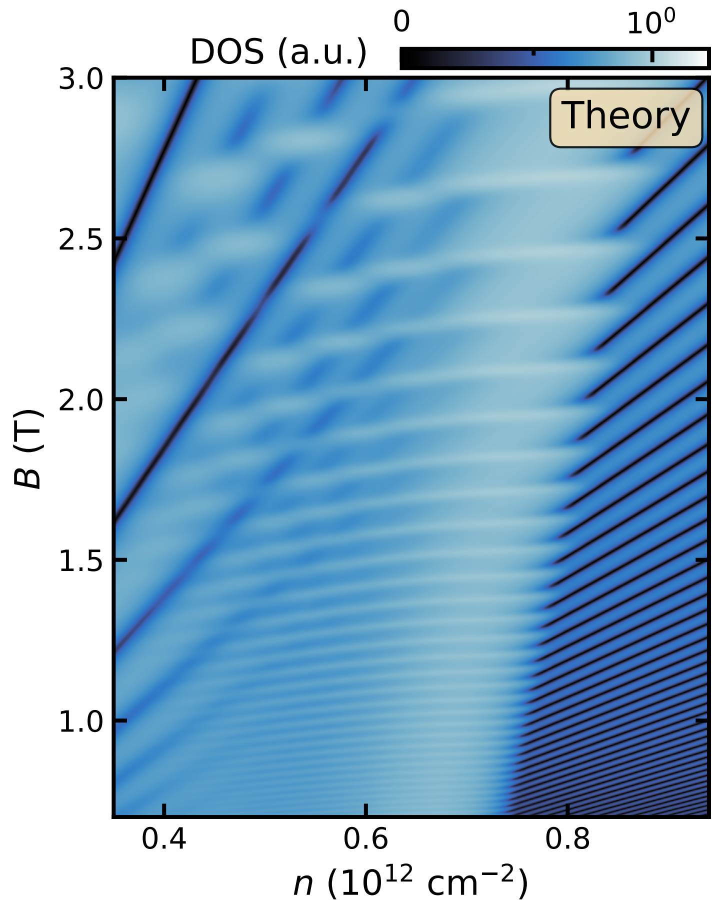


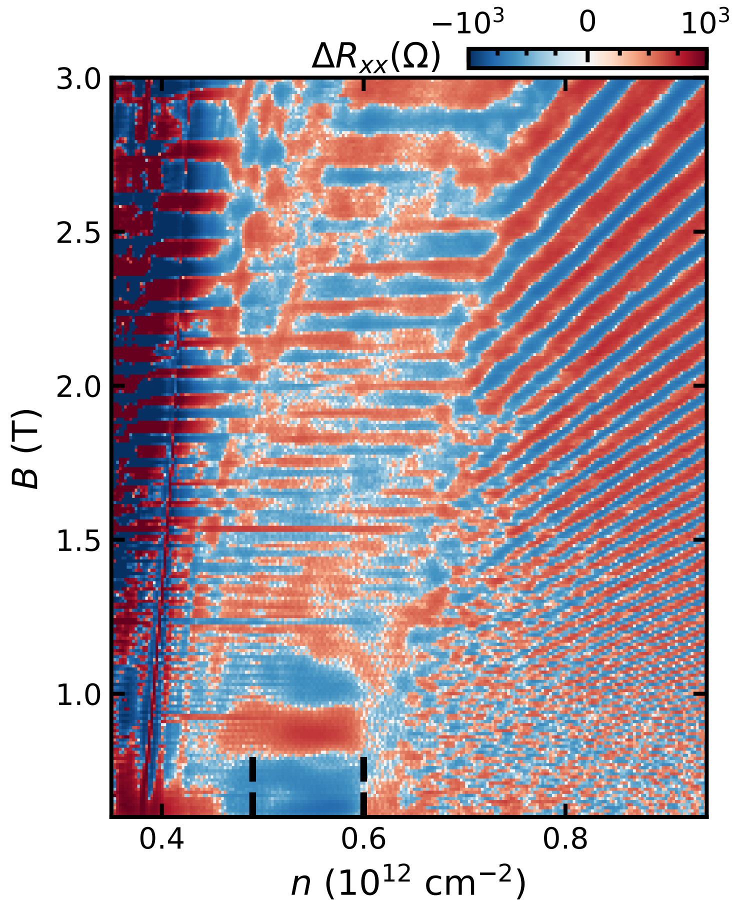
Red: extent of CSC

- CSC resides primarily within multitone
  - $\rightarrow$ multitone = normal state (assuming no finite field transition)

Kalantre, ..., **Sharpe** arXiv:2606.05356

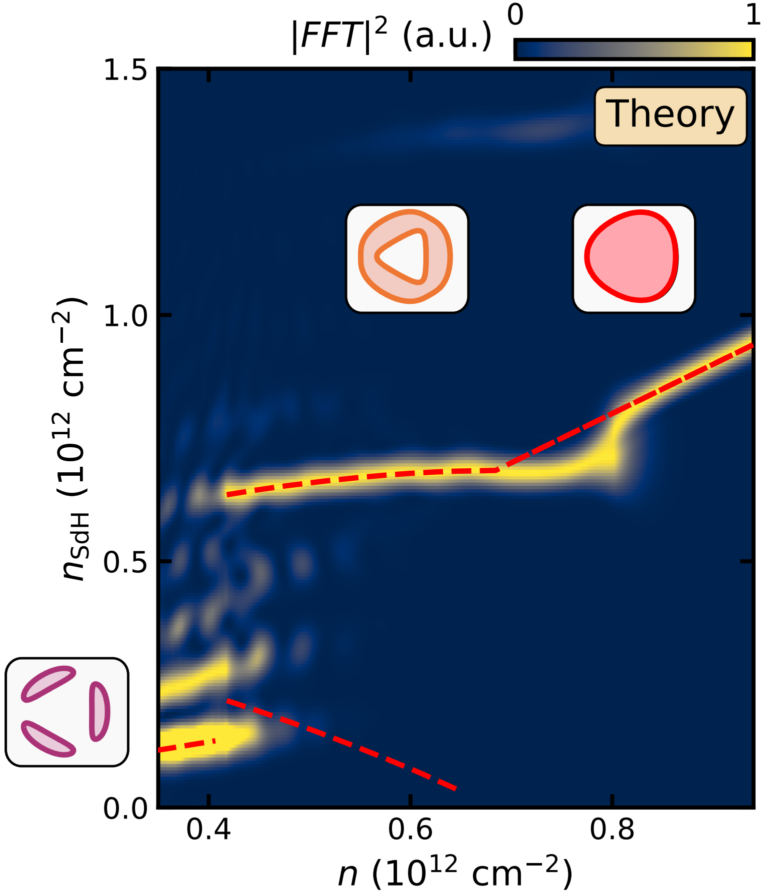
Microscopic model

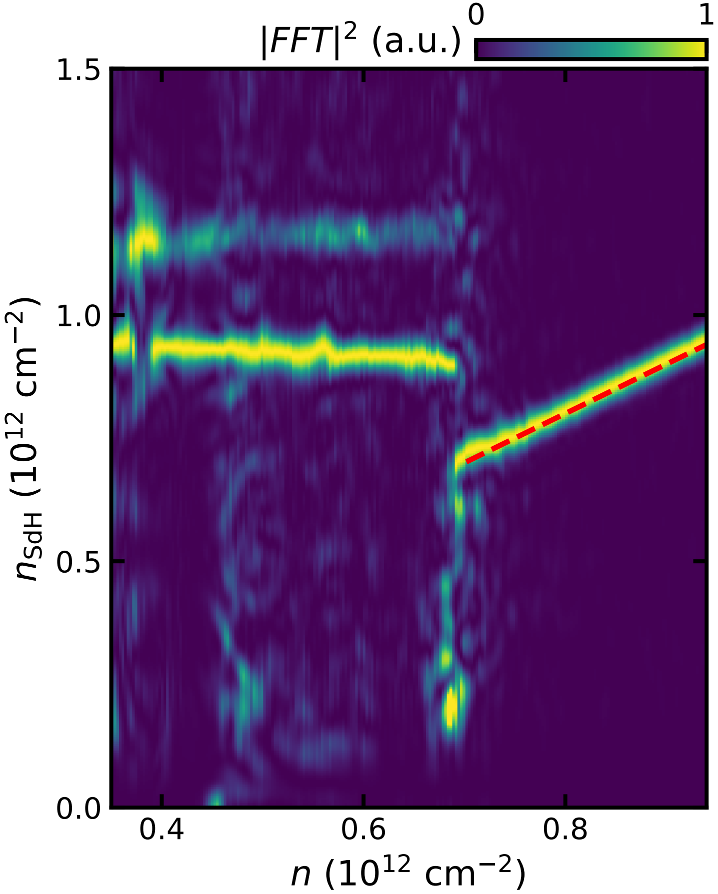




Kalantre, …, **Sharpe** arXiv:2606.05356

Microscopic model

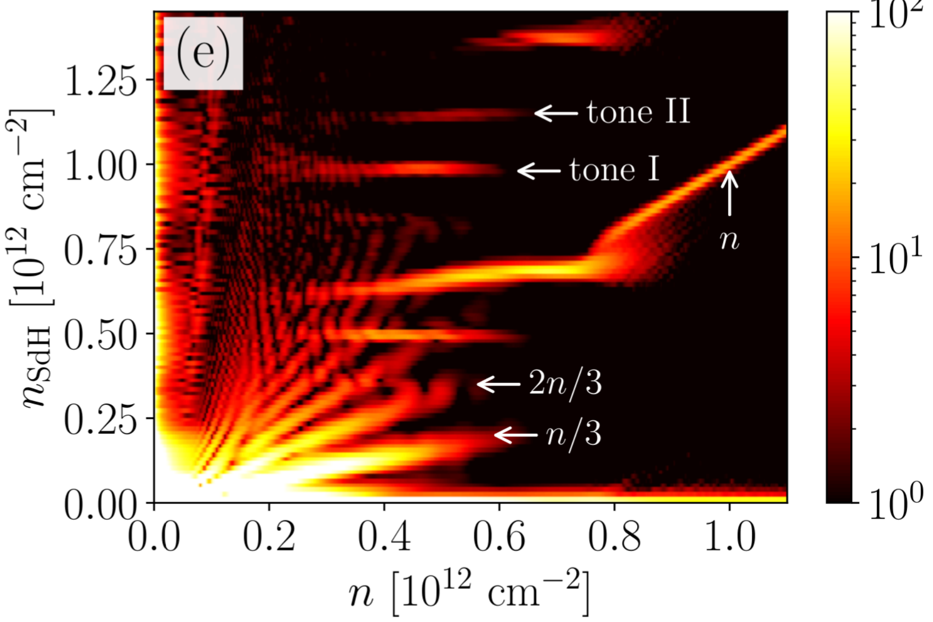


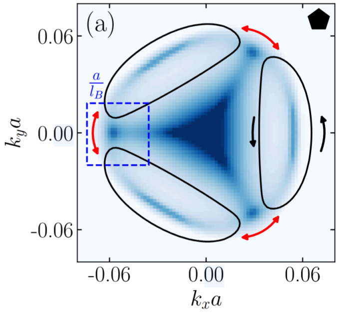


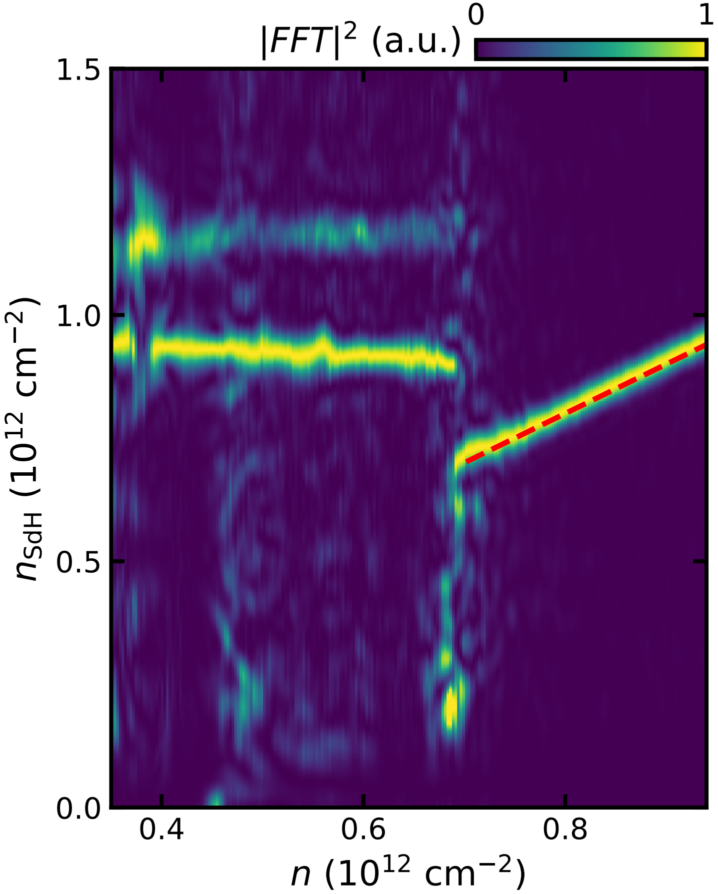
Kalantre, ..., **Sharpe** arXiv:2606.05356

Hot Off the Press Theory

Compute ρ_{xx} with Kubo and disorder





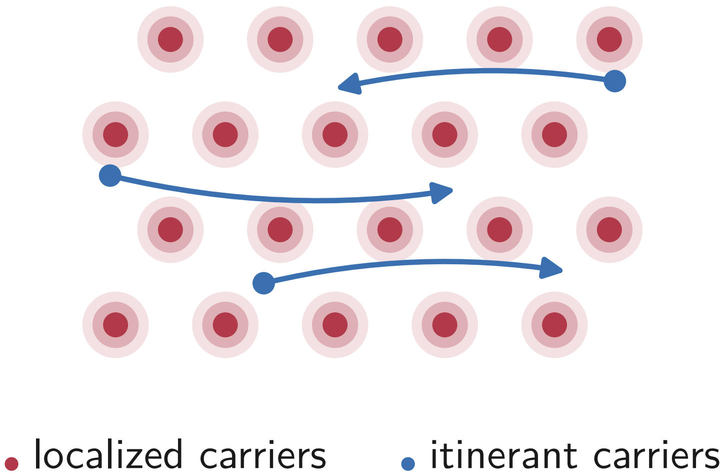


- Predicts multiple flat tones!
- Predicts strong annular tone (not observed)

Kalantre, ..., **Sharpe** arXiv:2606.05356
Zhao et al. arXiv:2607.27207

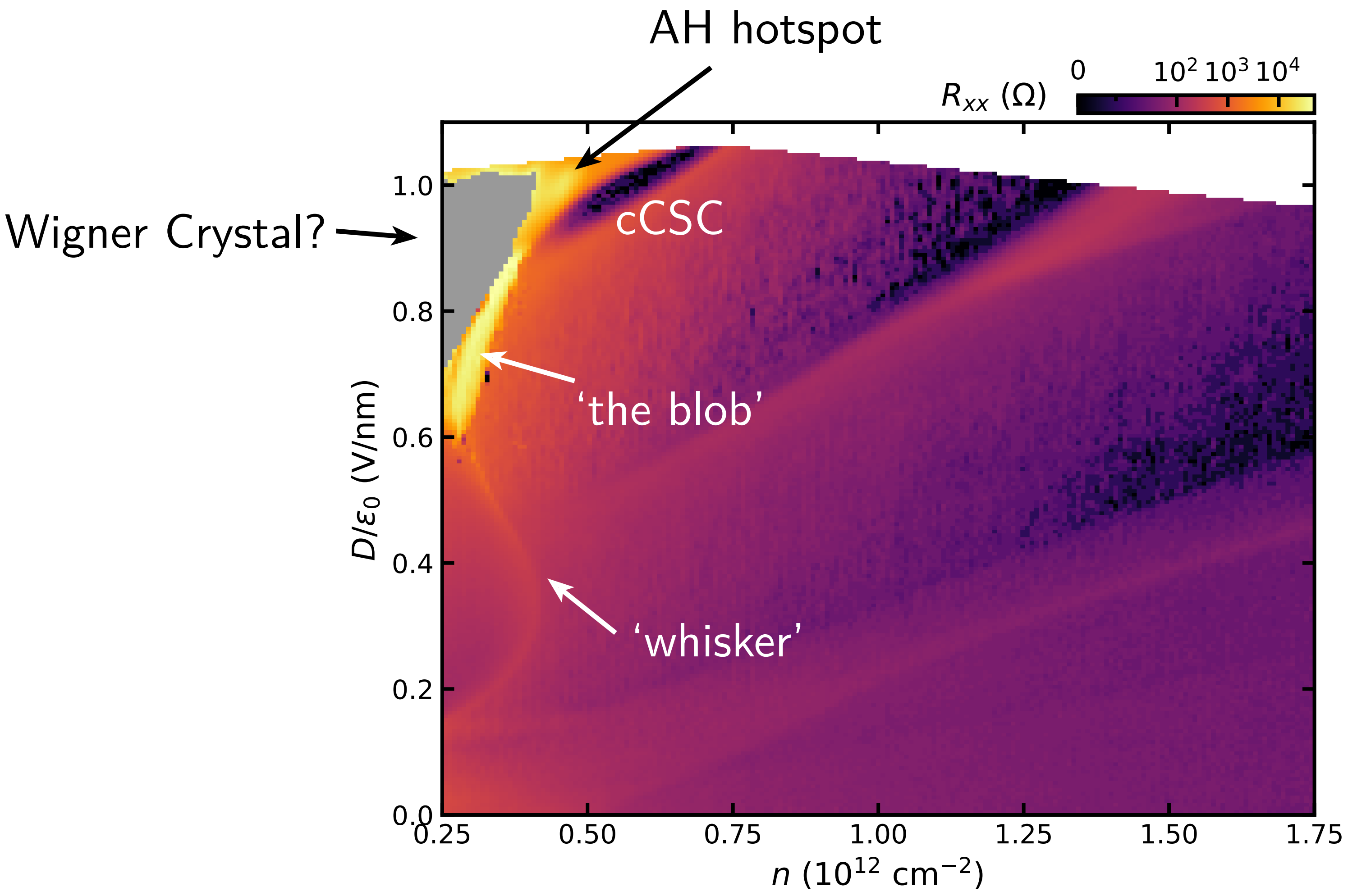
Crystallization and Onsager?

- Not all carriers are contributing to quantum oscillations?
  - $\Delta n_{\mathrm{SdH}}^{\mathrm{fast}} \approx 0.2 \times 10^{12}\,\mathrm{cm}^{-2}$
  - Tones remain flat over $\sim 0.2 \times 10^{12}\,\mathrm{cm}^{-2}$
- Disorder localization seems unlikely
- **Wigner crystal + itinerant carriers**
  - Itinerant fraction ~constant
- Need microscopic calculations!



Kalantre, ..., **Sharpe** arXiv:2606.05356
Dong et al. arXiv:2604.00114
Han et al. arXiv:2604.00113

Nearby Notable Features

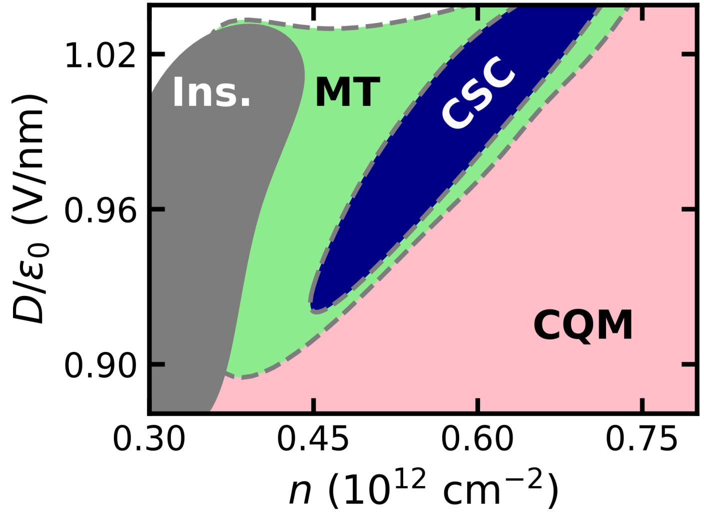


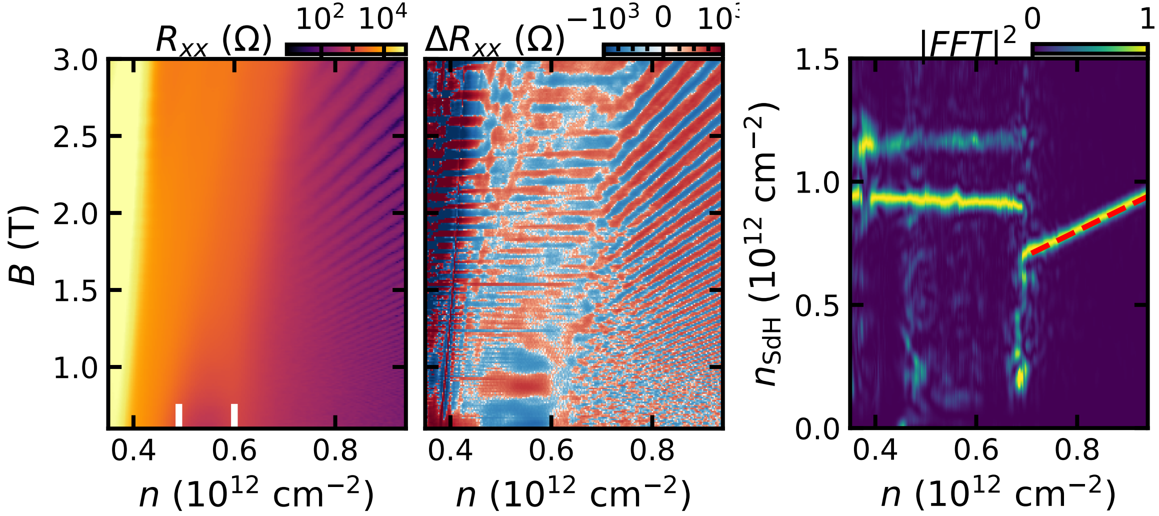
Kalantre, ..., **Sharpe** arXiv:2606.05356

Summary

- cCSC resides primarily within multitone
  - $\rightarrow$ multitone = normal state
  - **Not** circular quarter metal

- Multitone:
  1. Likely spin- and valley-polarized
  2. Two **high** and nearly **flat** tones
  3. Difference is $\sim$ constant with D
  4. No obvious Luttinger sum rule
  5. **Inconsistent with simplest candidates**





Kalantre, ..., **Sharpe** arXiv:2606.05356

Acknowledgements

Sandesh Kalantre

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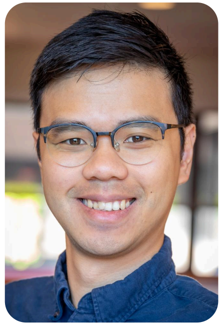
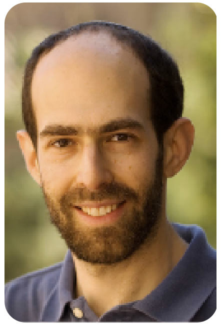


Yves Kwan

Dan Parker



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Risa Hocking, Qingrui Cao,
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