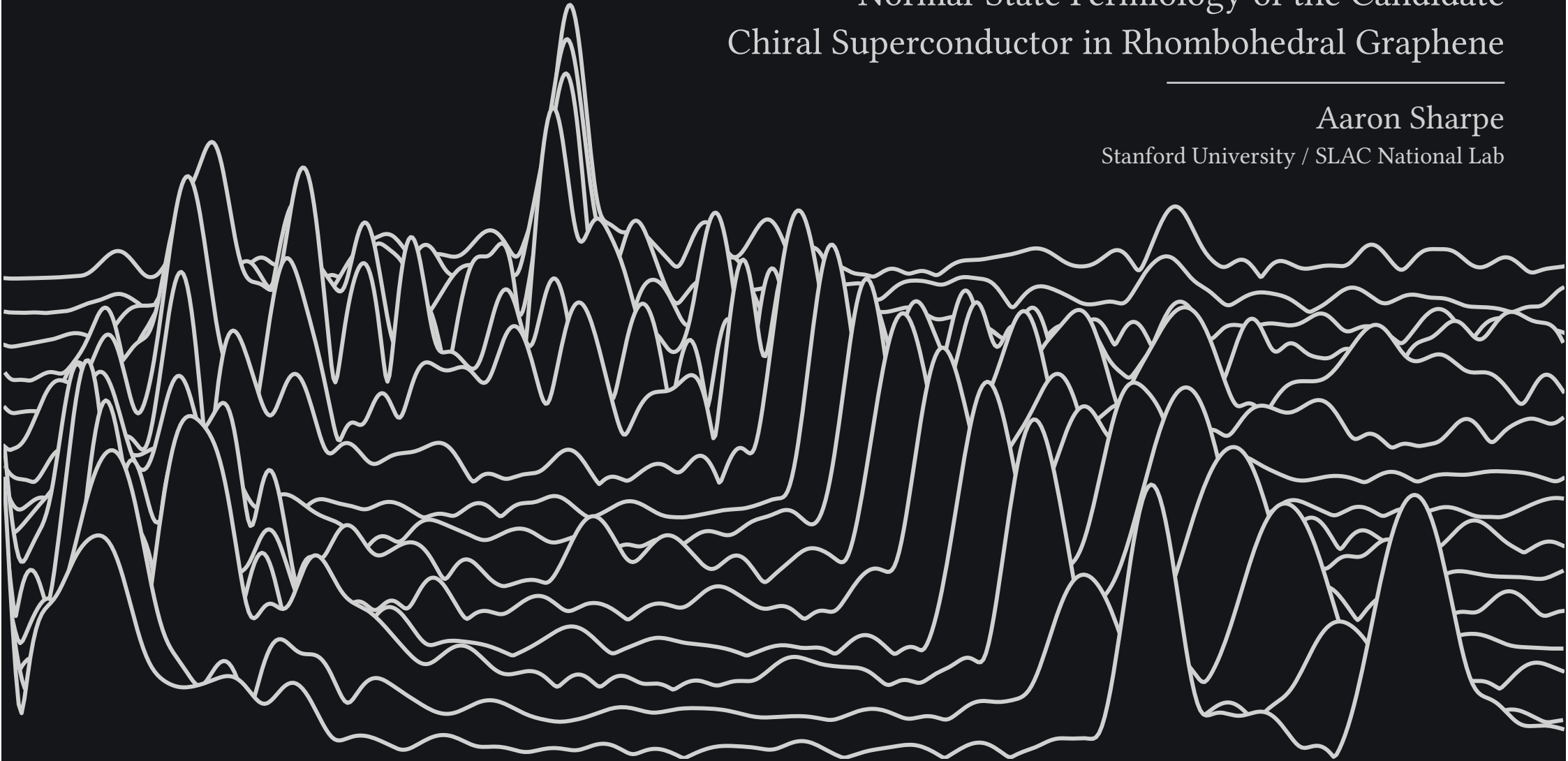


A Multitone Mystery:
Normal-State Fermiology of the Candidate
Chiral Superconductor in Rhombohedral Graphene

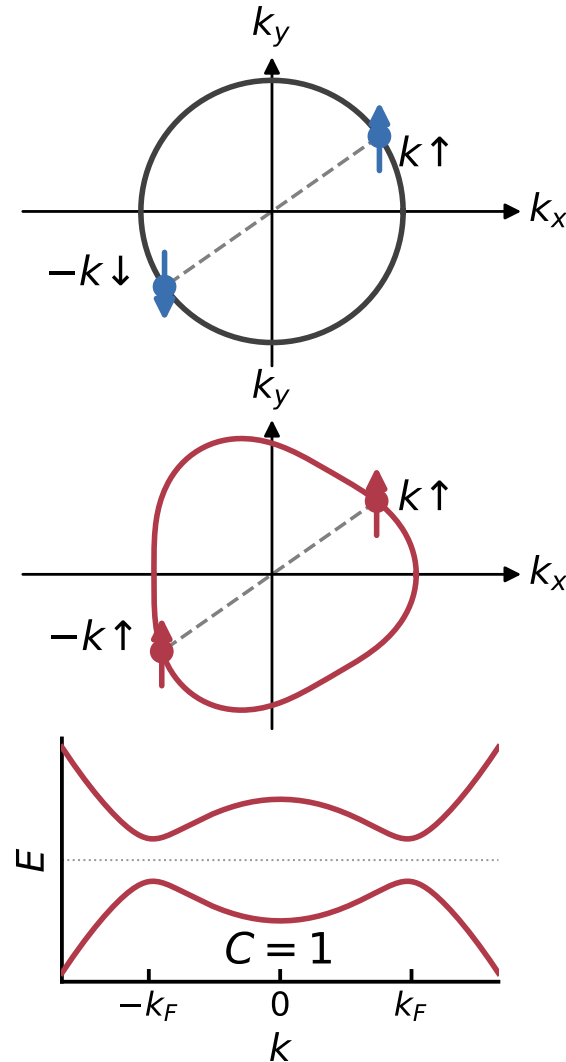
Aaron Sharpe

Stanford University / SLAC National Lab



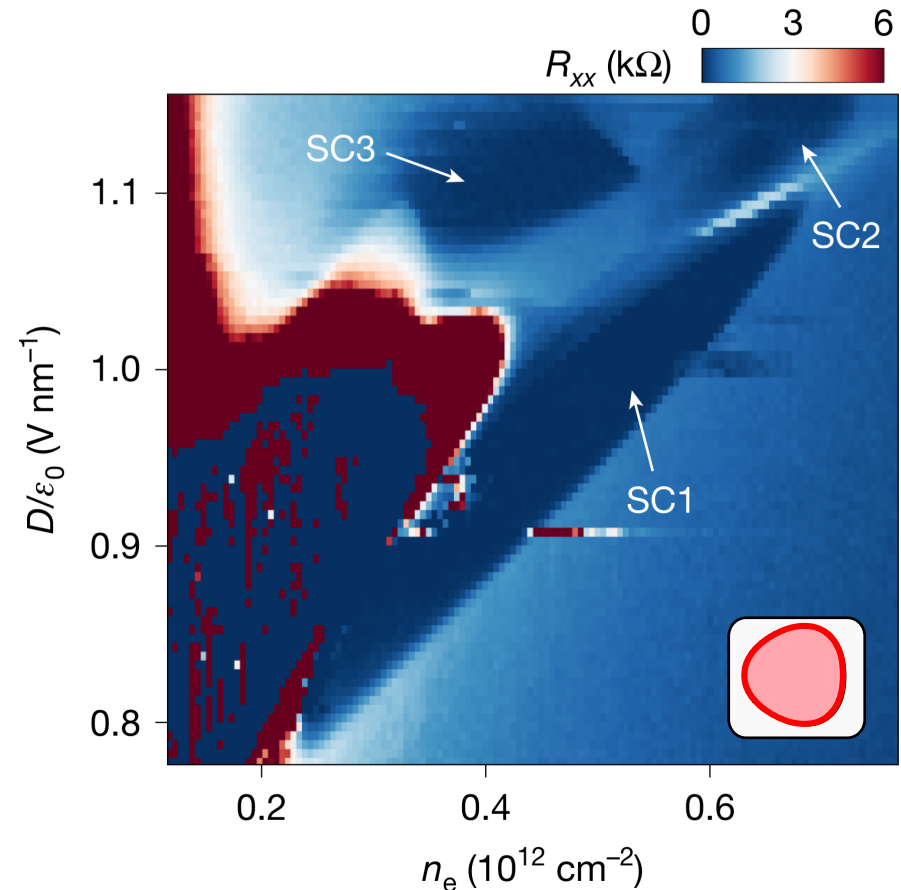
Pairing and Time Reversal

- 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** (nematic f -wave) or **fully gapped and chiral**
 - Energetics determines preferred channel
 - if fully gapped $\rightarrow$ topological



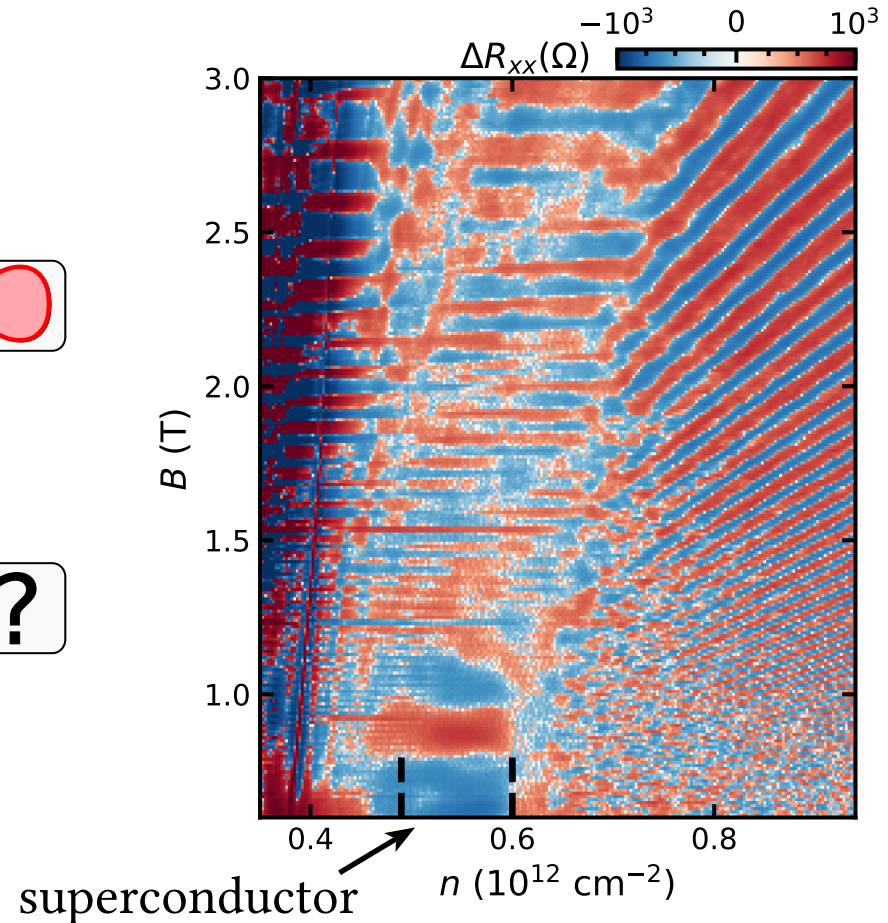
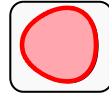
Candidate Chiral Superconductivity (CSC)

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



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



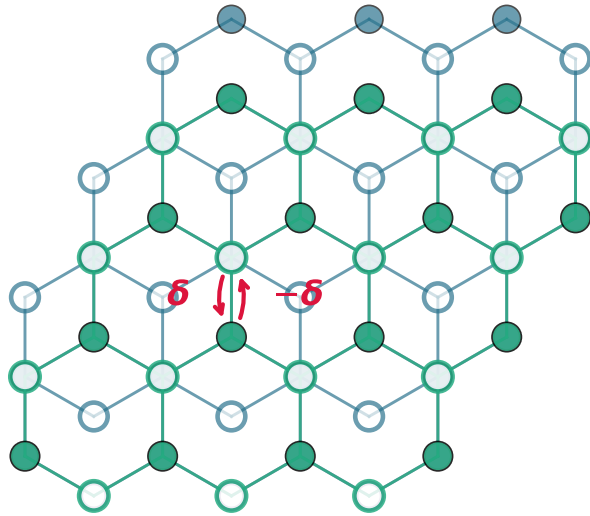
Outline

0. Introduction: rhombohedral graphene

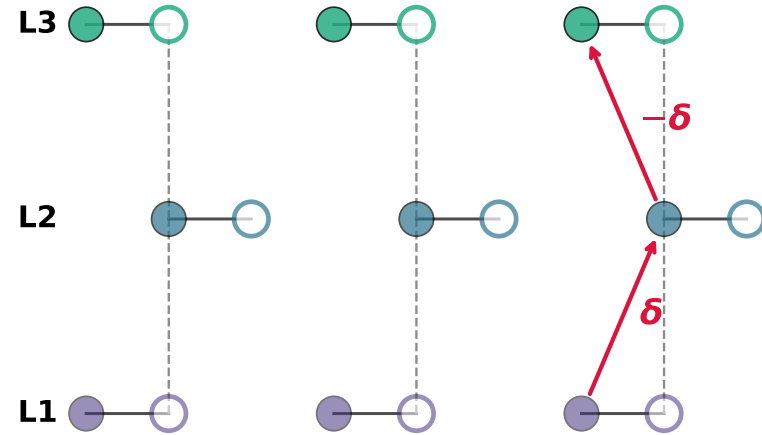
1. Superconductivity in tetralayer rhombohedral graphene

2. Fermiology from quantum oscillations

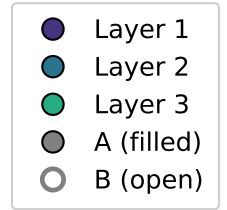
Bernal (AB) Stacking



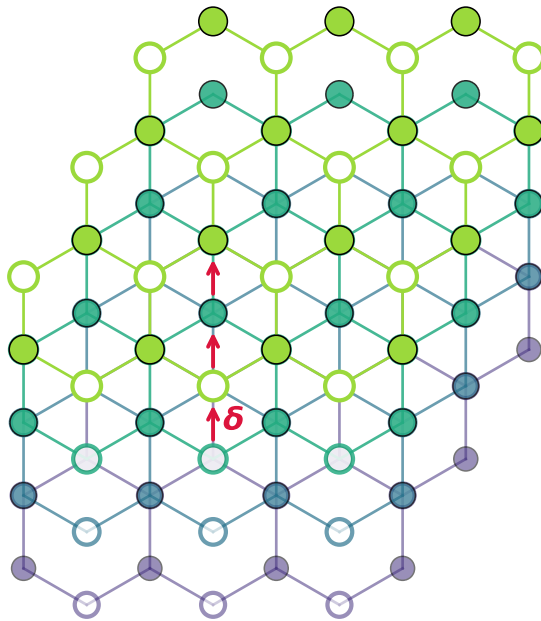
Top view



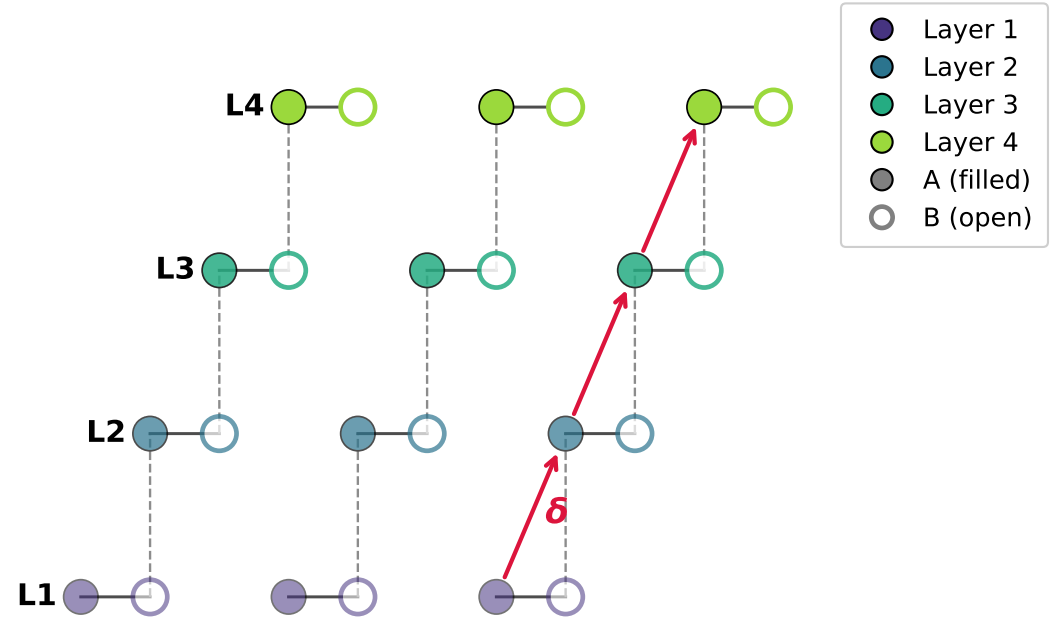
Side view



Rhombohedral Multilayer Graphene (RMG)

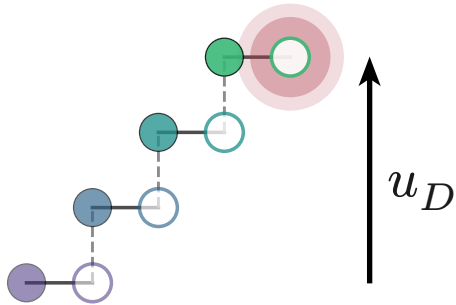


Top view



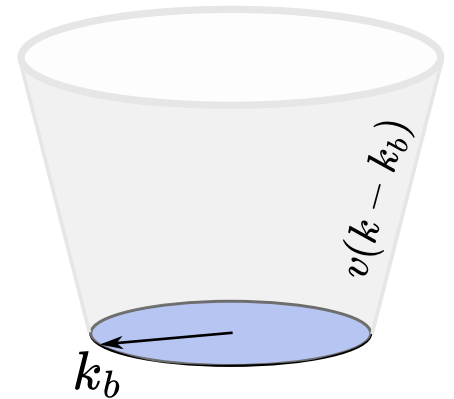
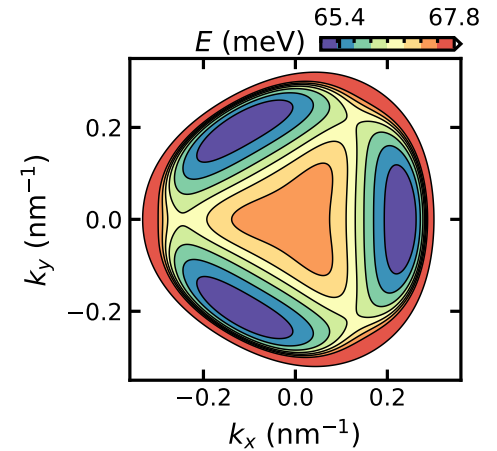
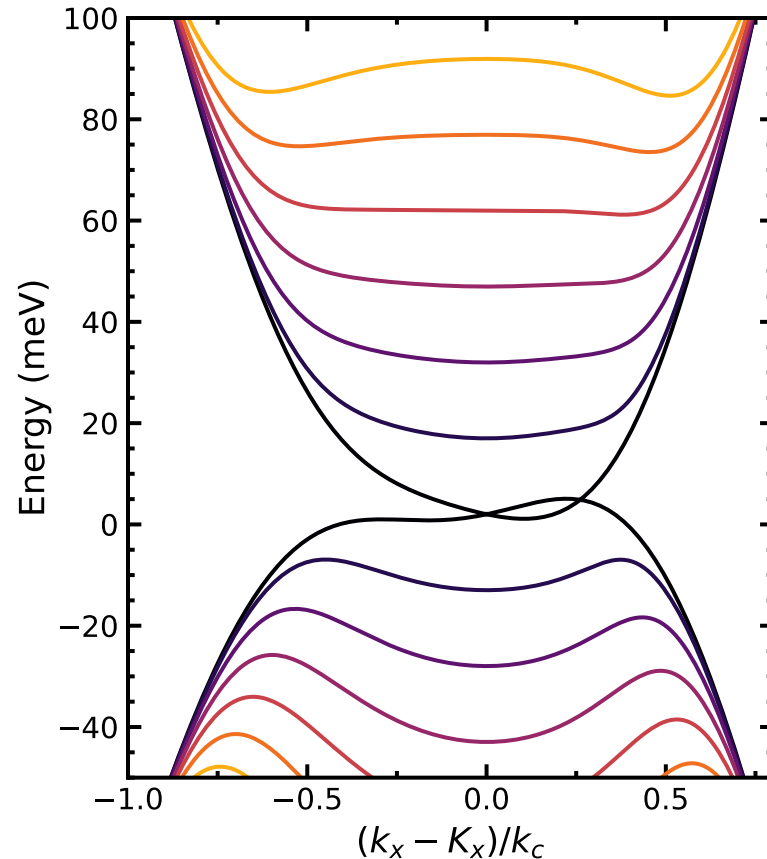
Side view

Rhombohedral Bandstructure (R4G)



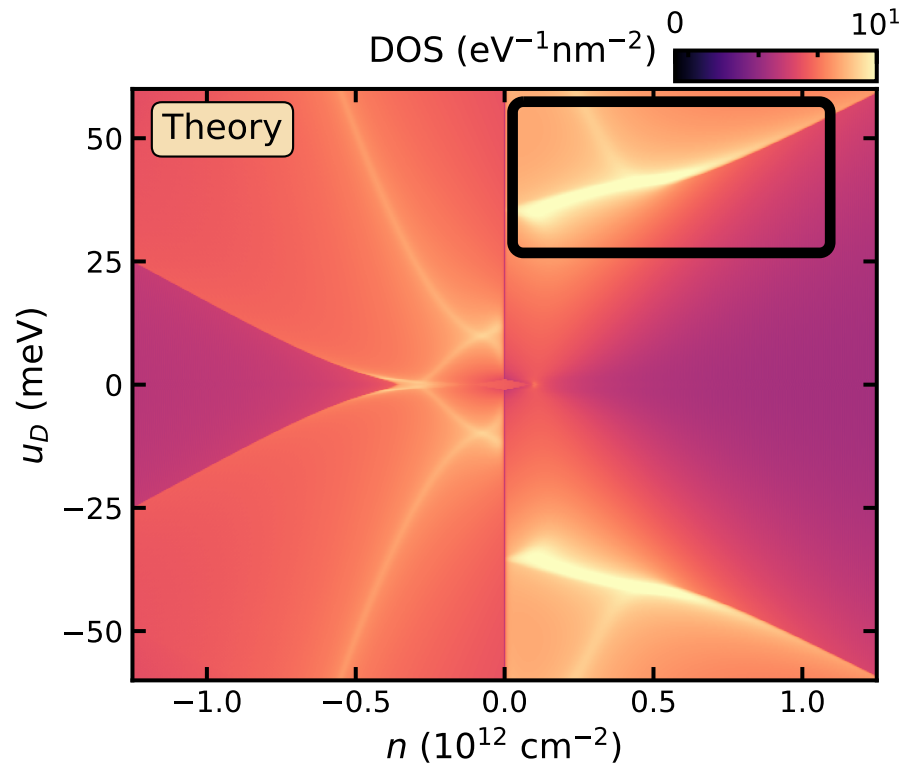
With **increasing** u_D (applied D), dispersion evolves:

- U -shaped
- $\rightarrow$ flat minima
- $\rightarrow$ to a Mexican hat

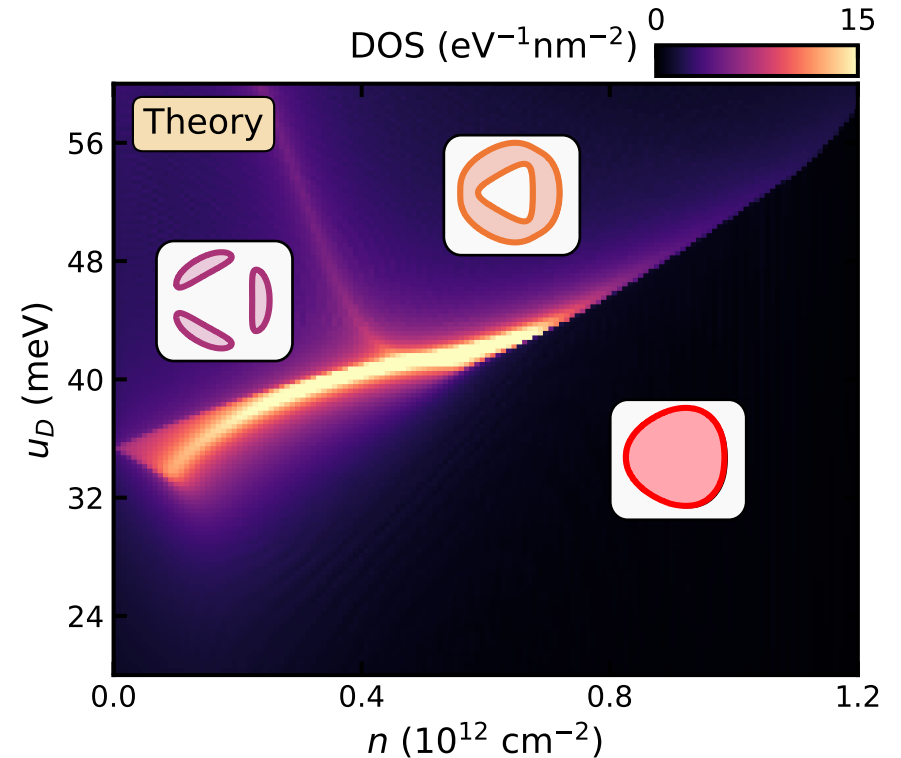
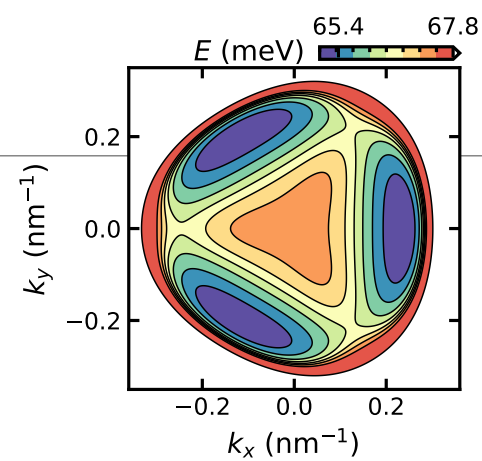


Koshino & McCann PRB (2009)
Auerbach et al. Nat. Phys. (2025)
Bernevig & Kwan arXiv:2503.09692
Patri & Franz PRB (2025)

R4G Conduction Band Fermiology



Assume spin- and valley-polarized



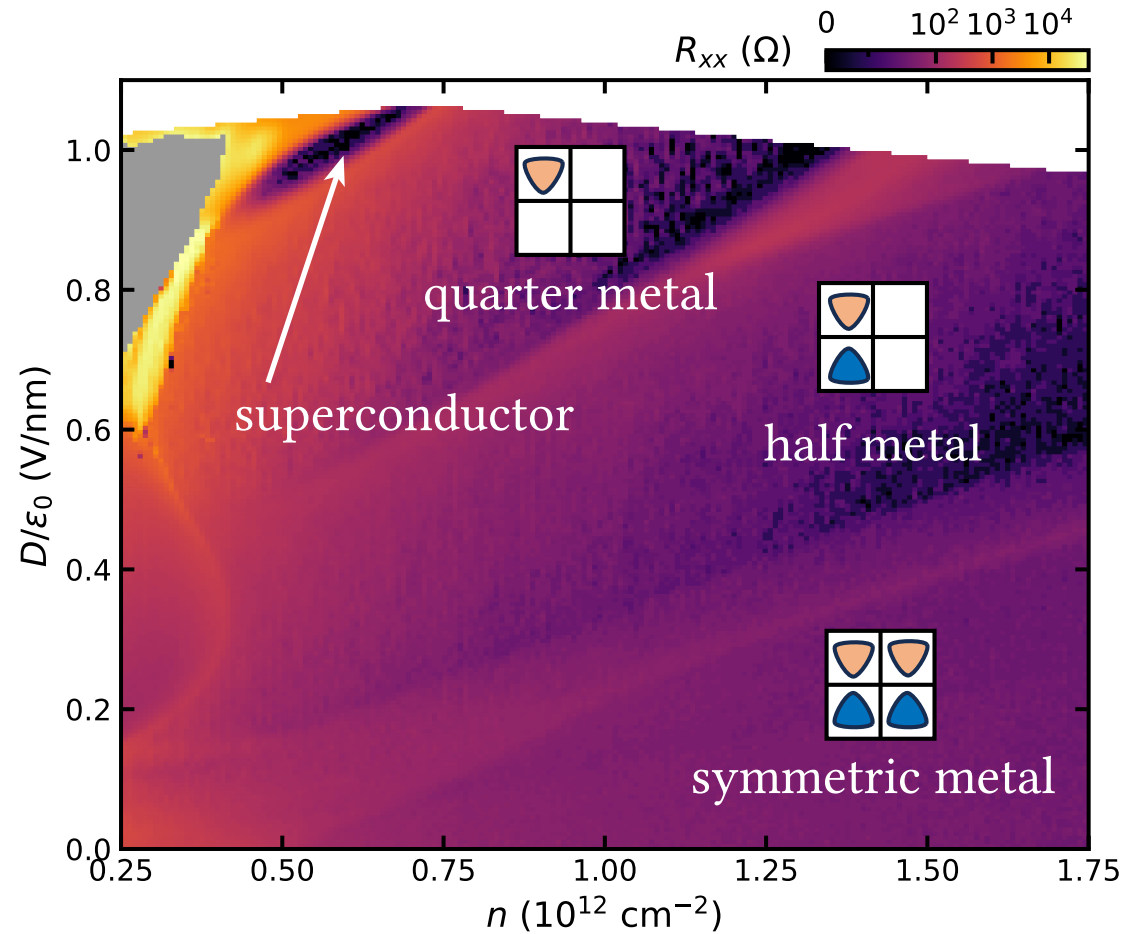
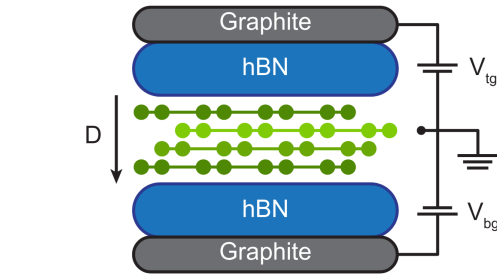
Outline

0. Introduction: rhombohedral graphene

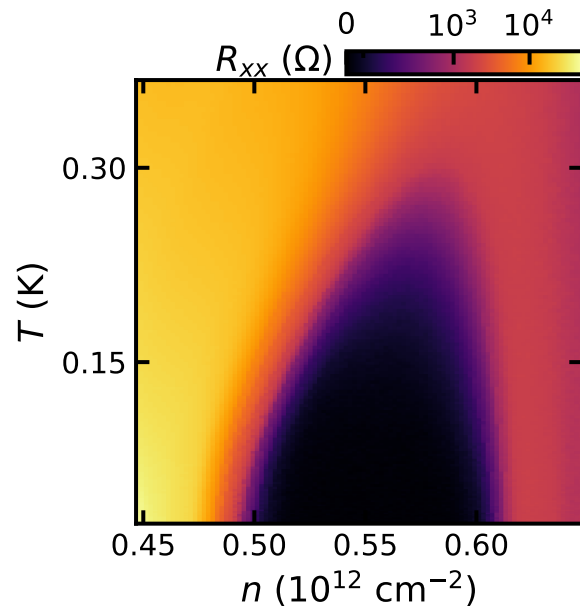
1. Superconductivity in tetralayer rhombohedral graphene

2. Fermiology from quantum oscillations

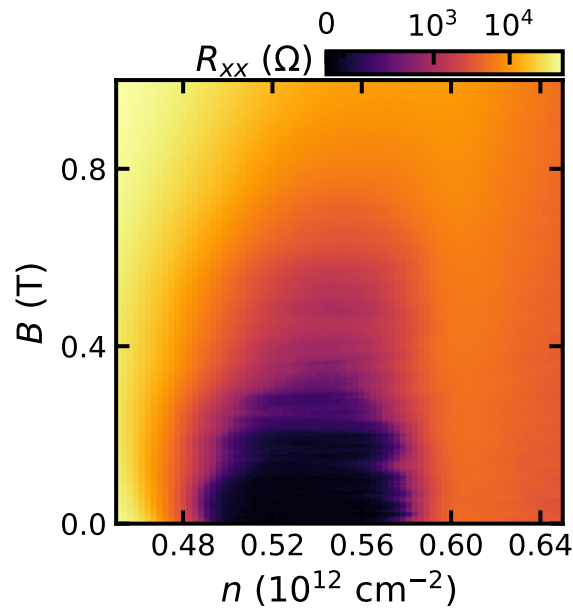
Experimental Phase Diagram of 4-layer Rhombohedral



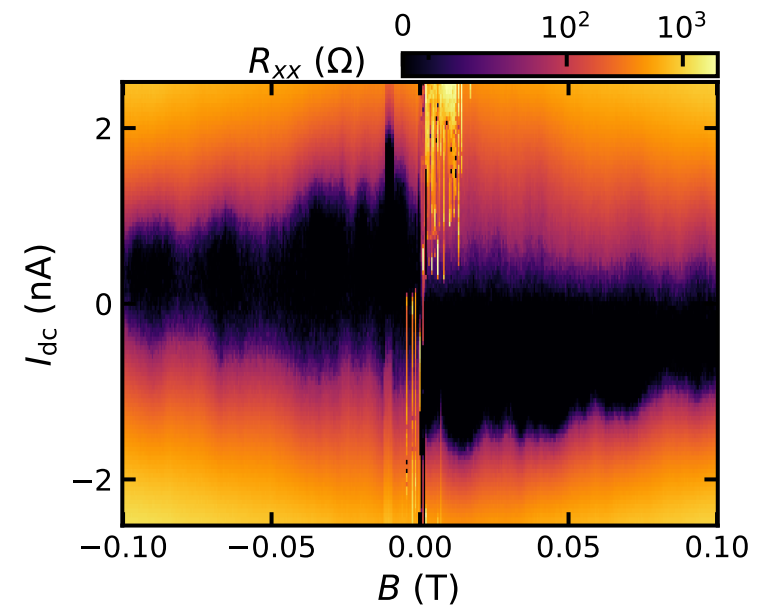
Basic Phenomenology of the Candidate CSC



Critical temperature

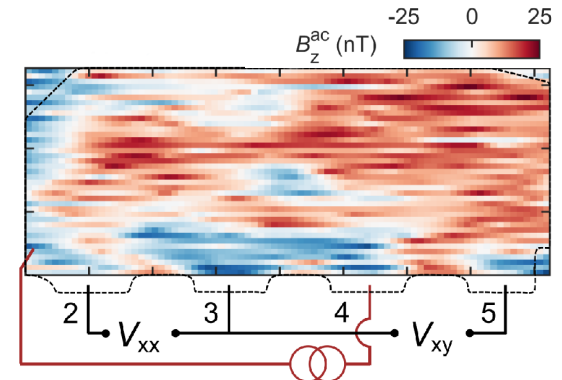
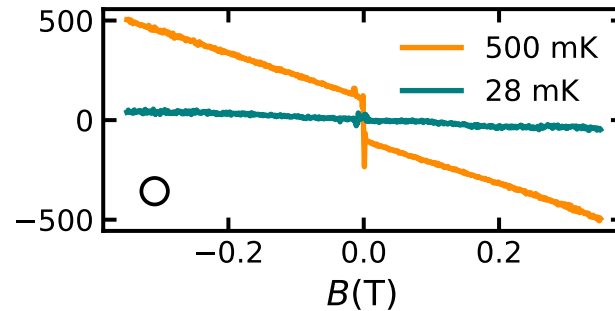
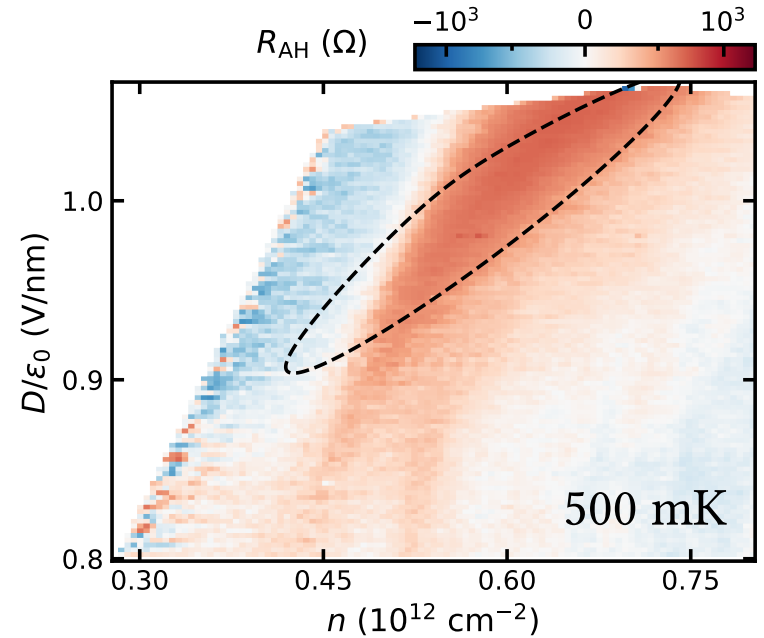
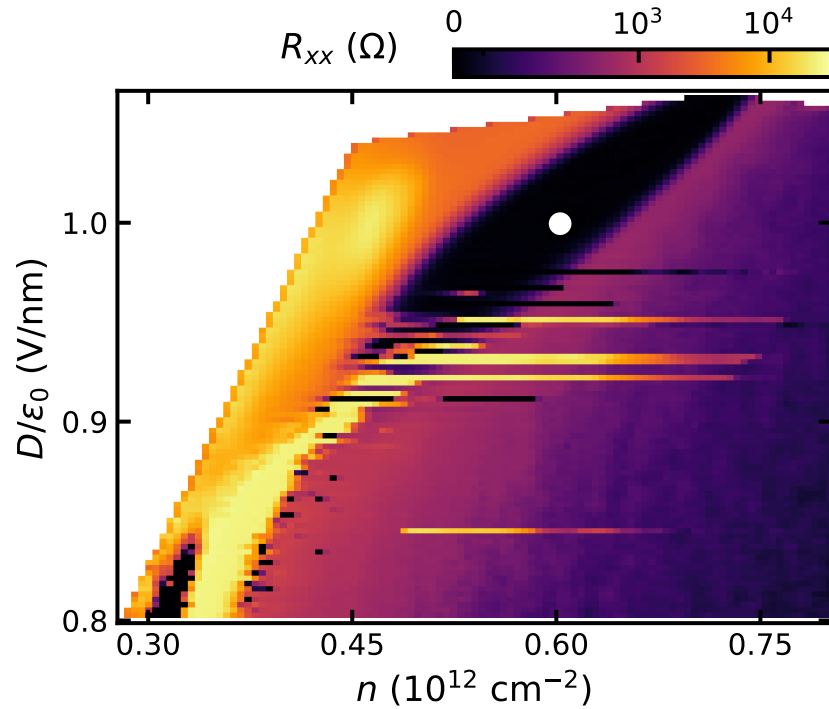


Critical field



Phase coherence

Time-Reversal Symmetry Breaking



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 nematic?
- Is the SC topological?
 - e.g. $p_x \pm ip_y$ pairing of 
- Mechanism driving superconductivity?
- Normal state? $\rightarrow$ quantum oscillations!



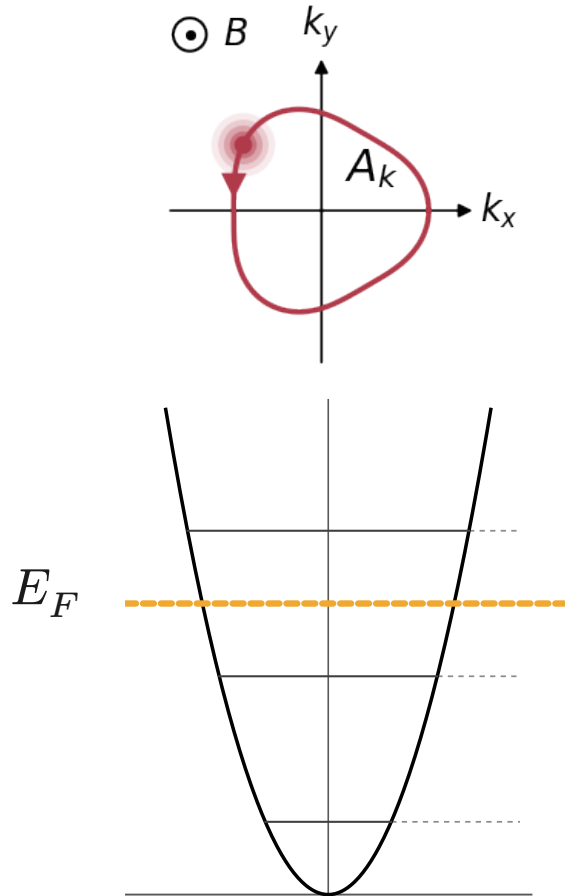
Outline

0. Introduction: rhombohedral graphene

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2. Fermiology from quantum oscillations

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

Semiclassical (Onsager) Quantization

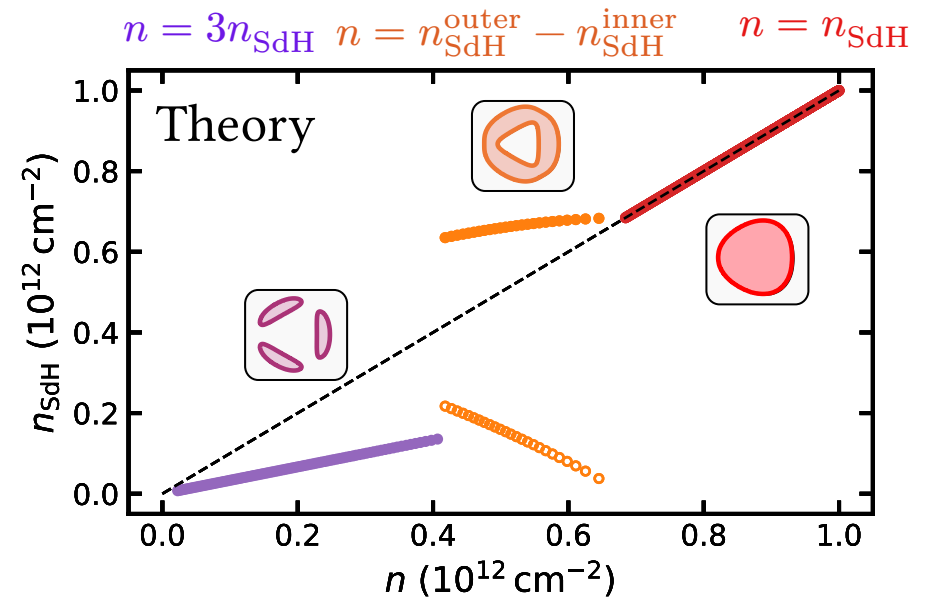
- Effective density enclosed by orbit:

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

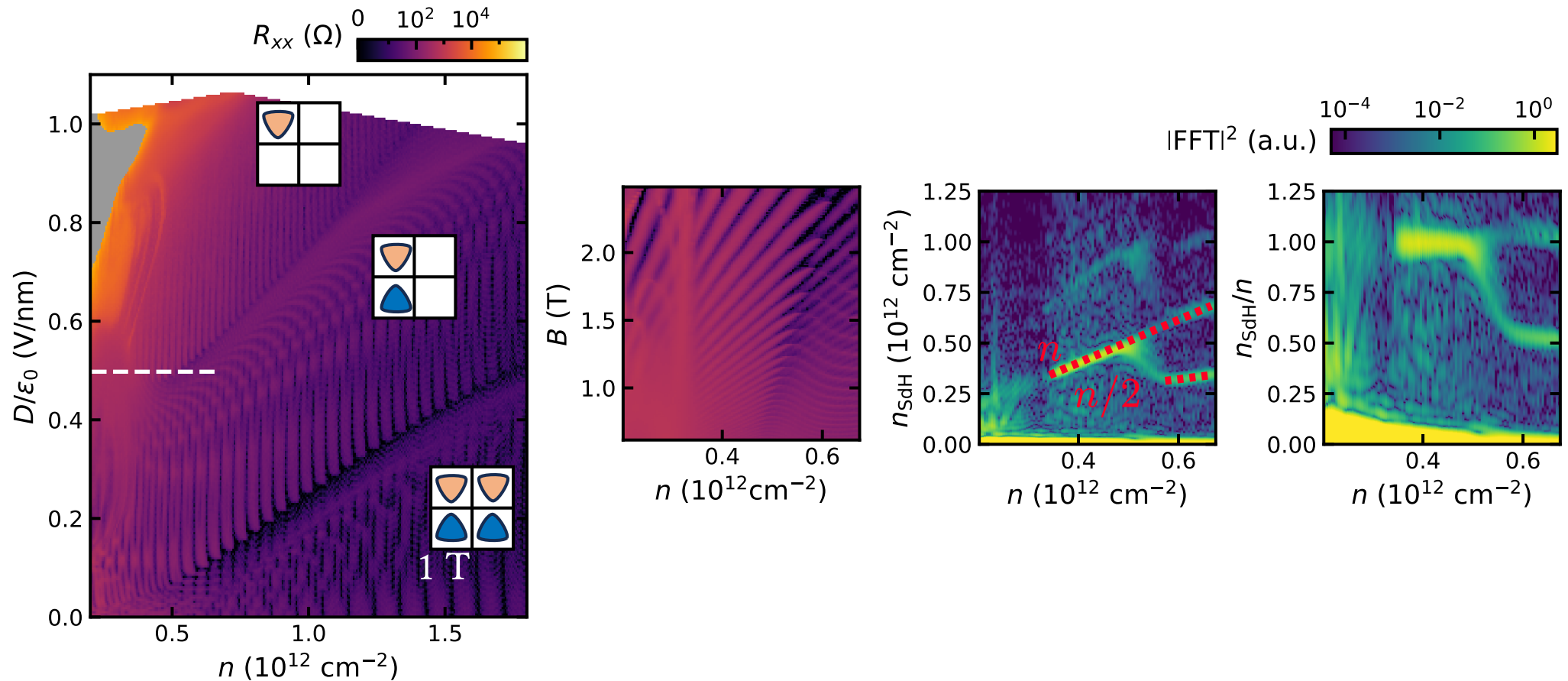
- All carriers participating in quantum oscillations → **Luttinger sum rule**

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

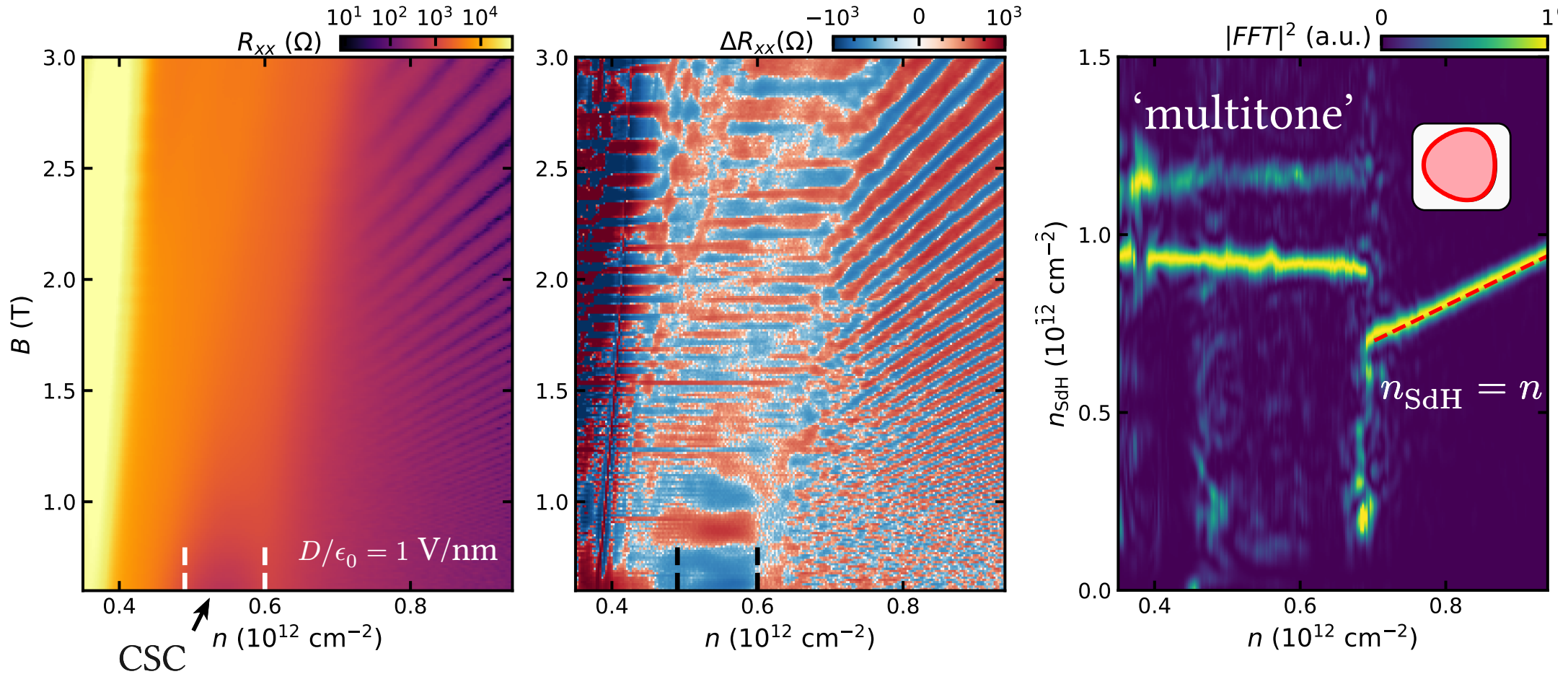
$\nwarrow$ sum over **fundamental orbits** $\nearrow$ degeneracy
 $\nearrow$ carrier sign



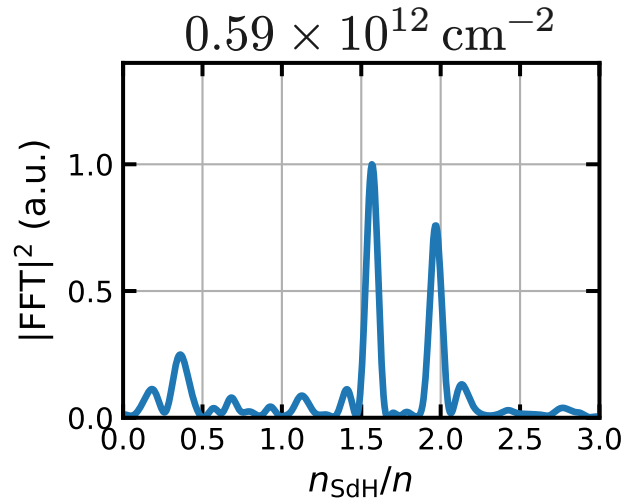
Flavor Transitions



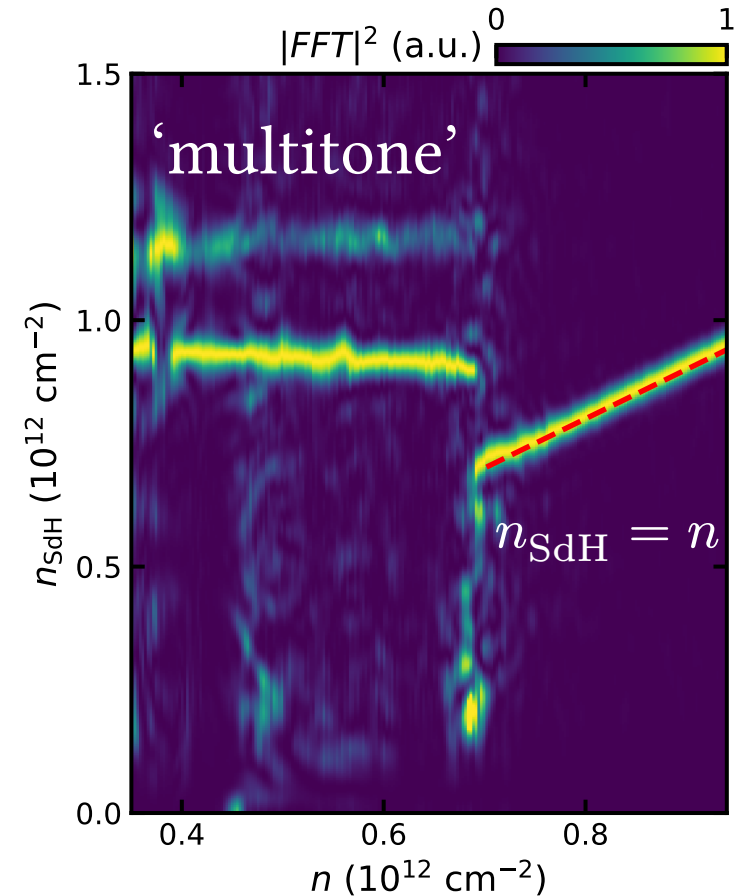
Oscillations near the CSC



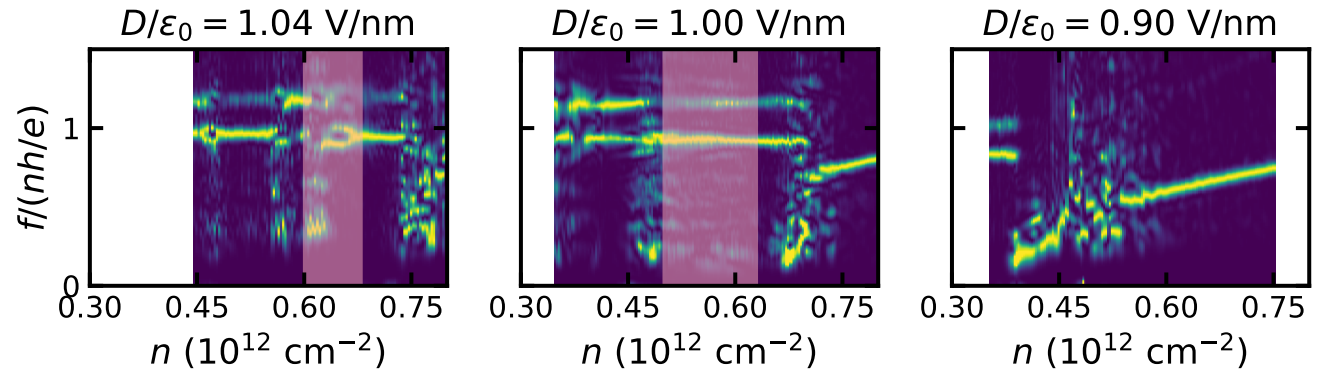
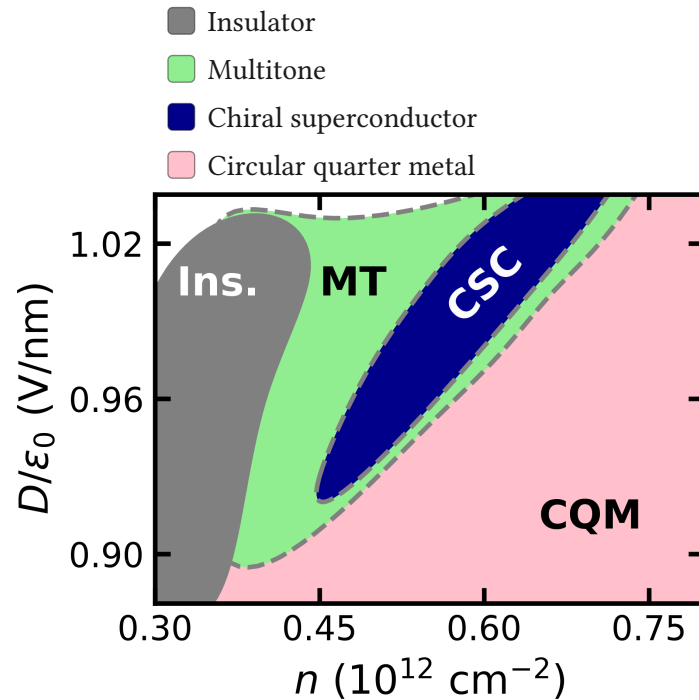
‘Multitone’ metal



- jumps to two **high** and nearly **flat** frequencies
 - Annulus?
 - $\Delta n_{\text{SdH}}^{\text{fast}} \approx 0.2 \times 10^{12} \text{ cm}^{-2}$
- high tones inconsistent with a singly degenerate annulus*



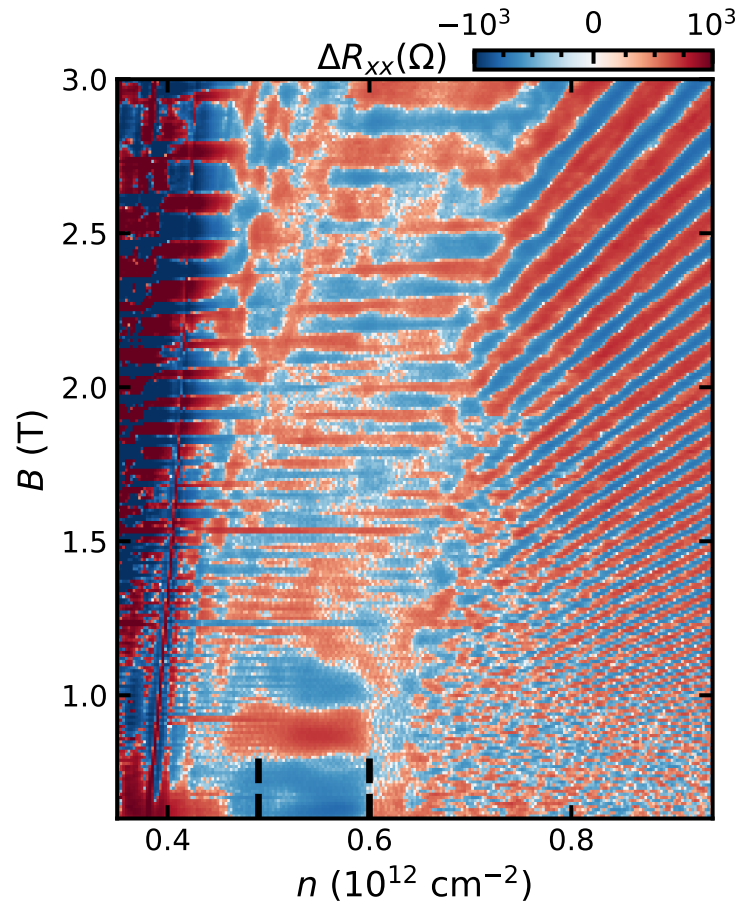
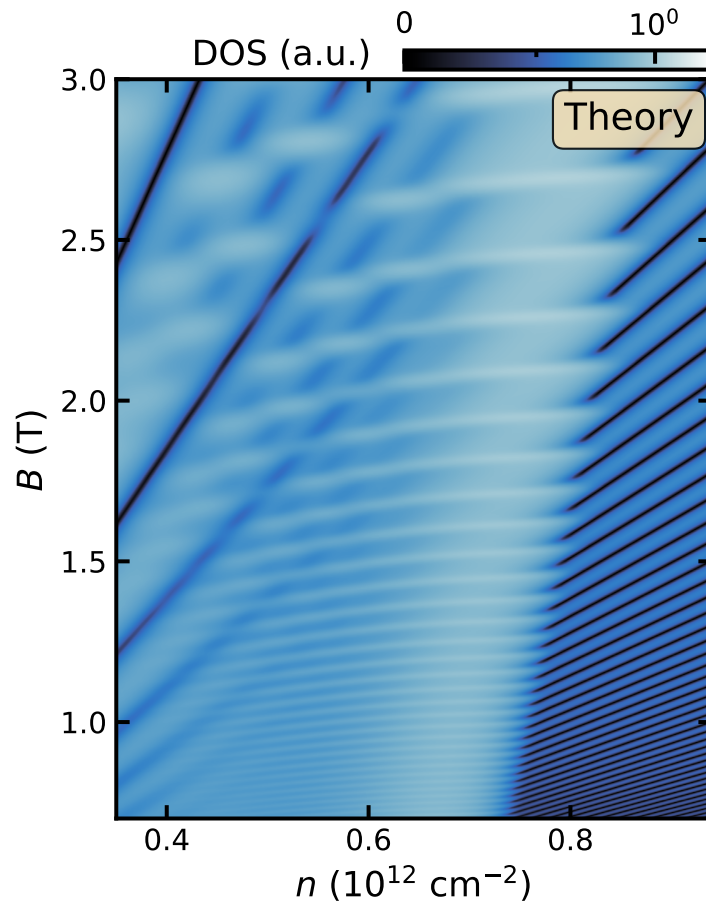
Mapping the Phase Diagram



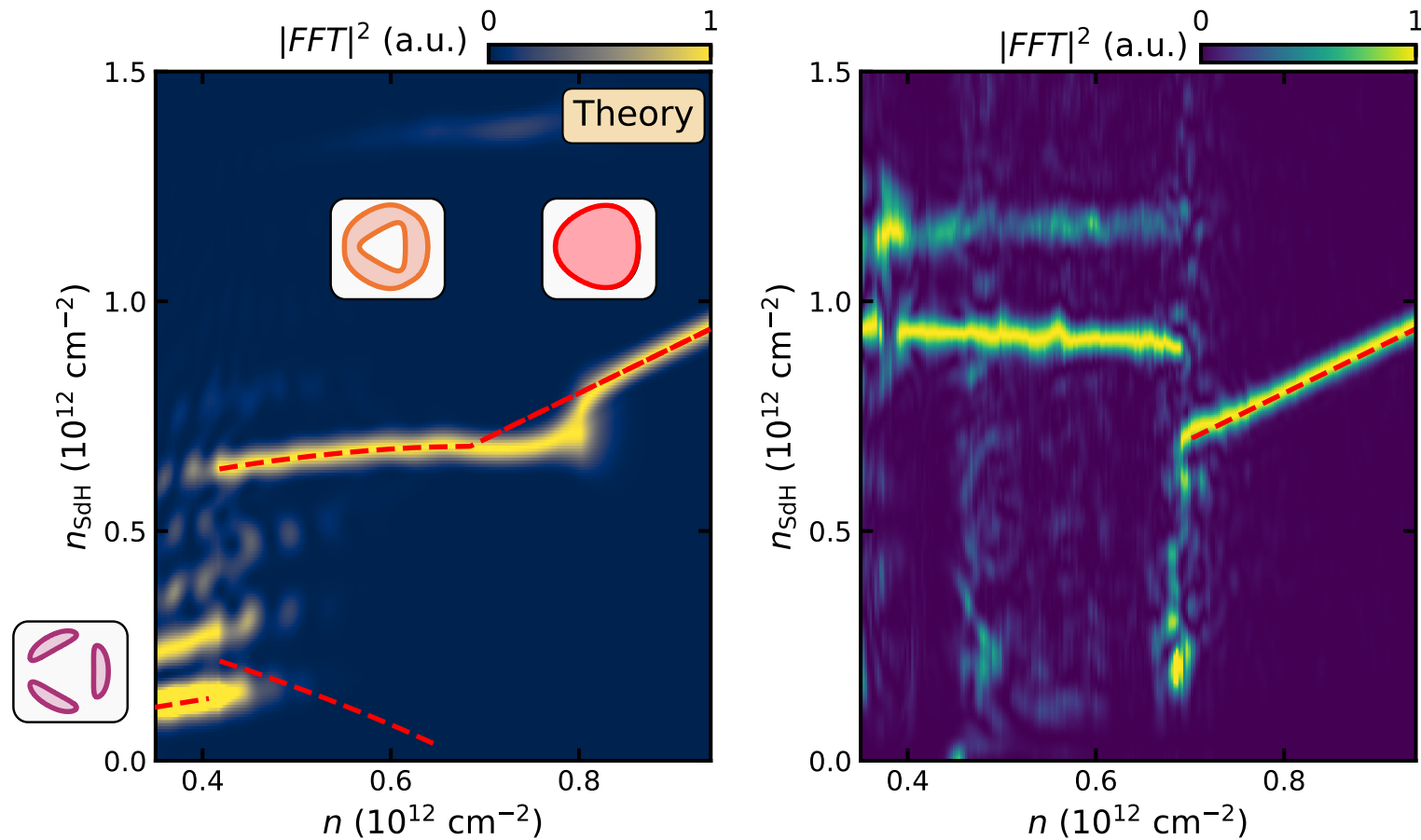
Pink: extent of CSC

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

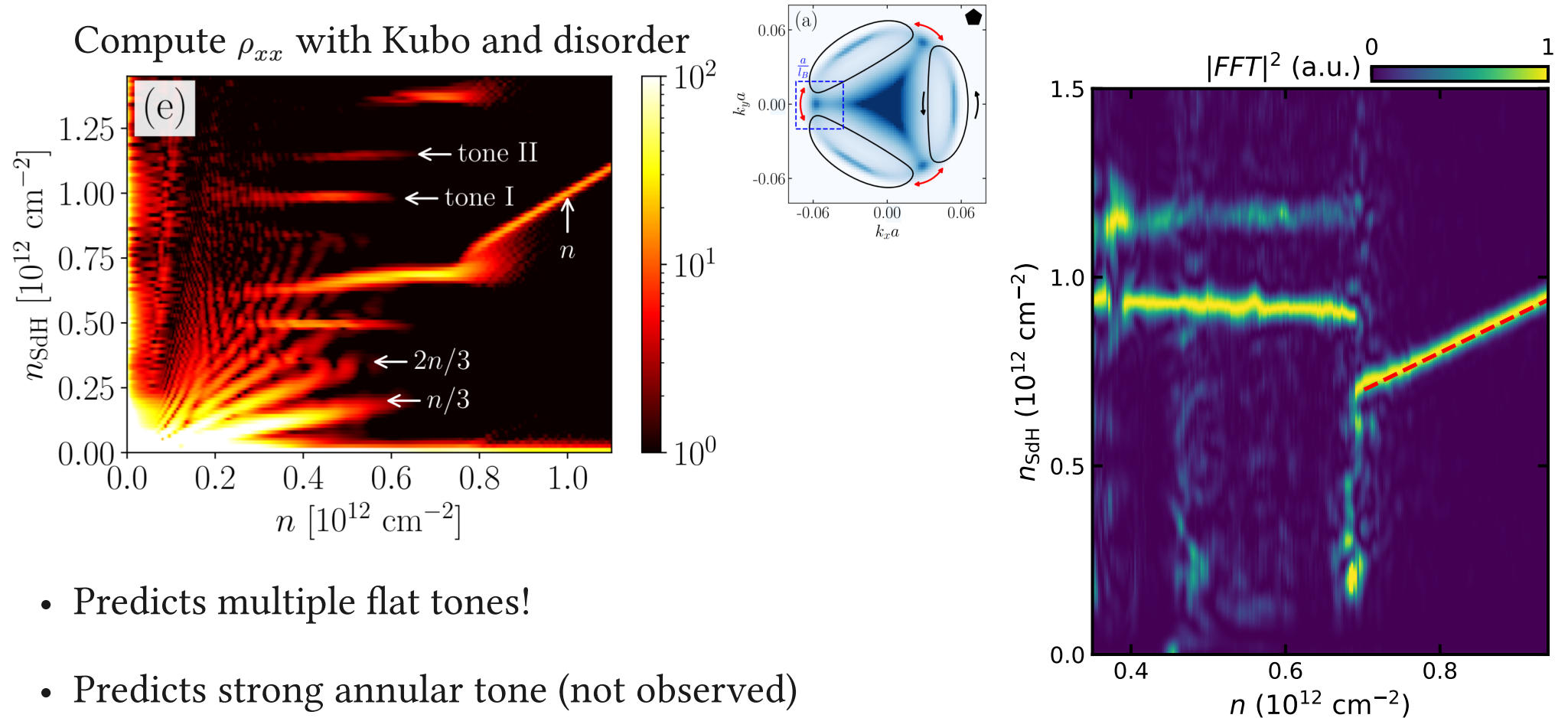
Microscopic model



Microscopic model



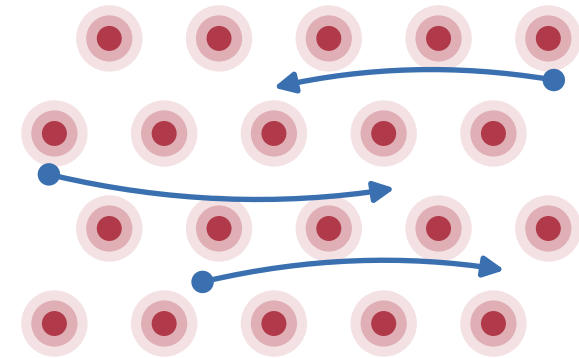
Hot Off the Press Theory



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

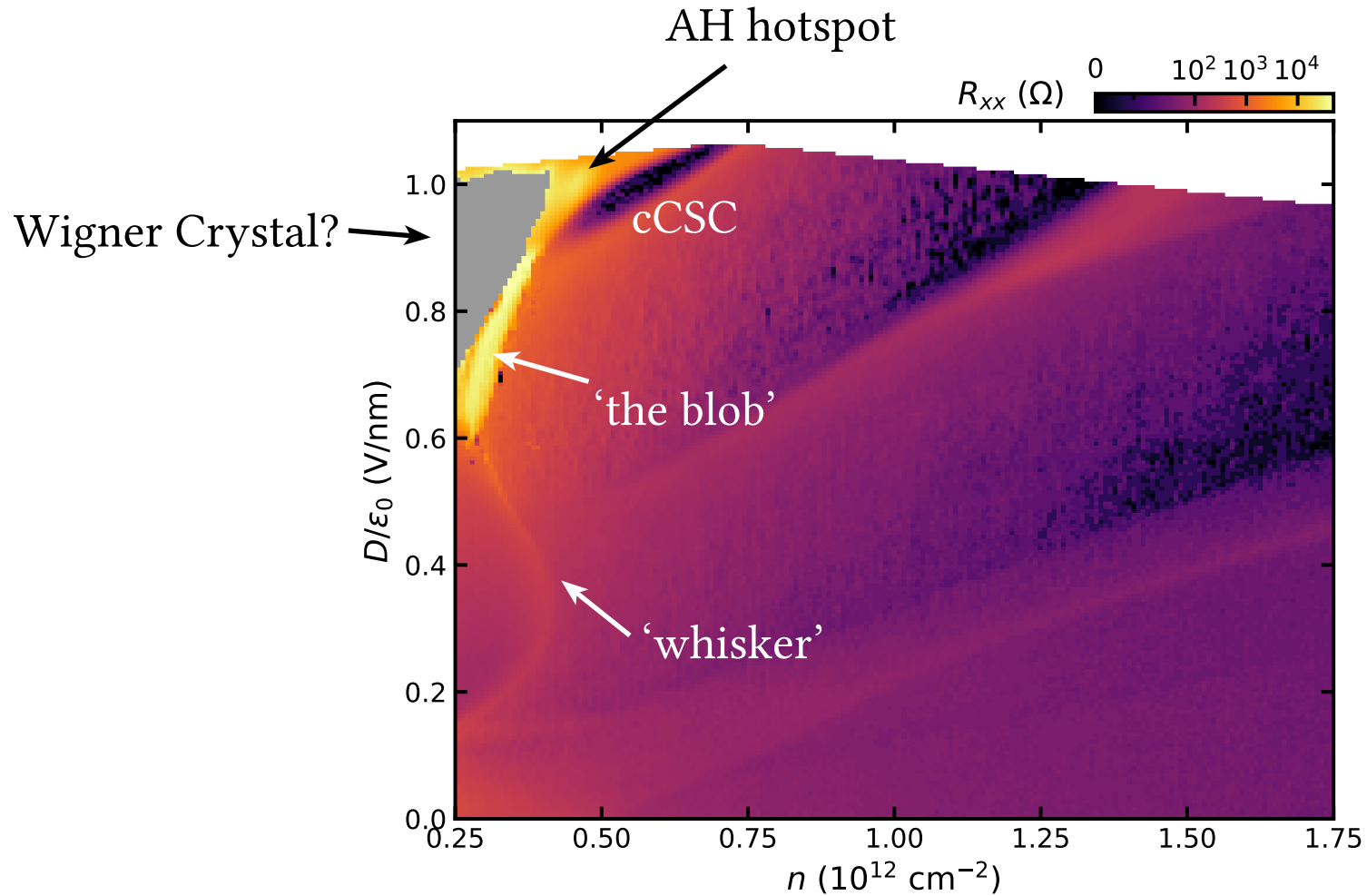
Crystallization and Onsager?

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



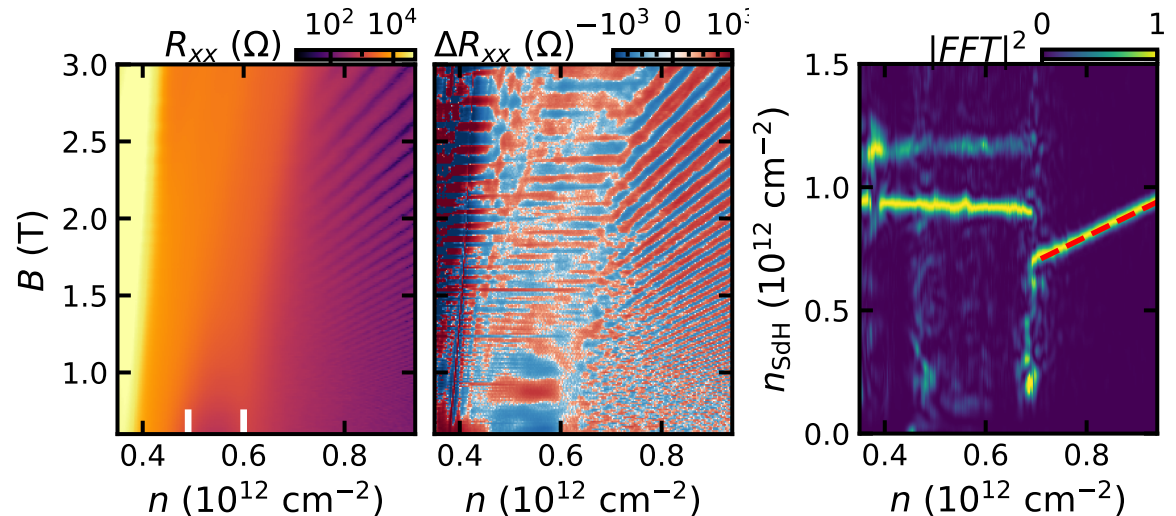
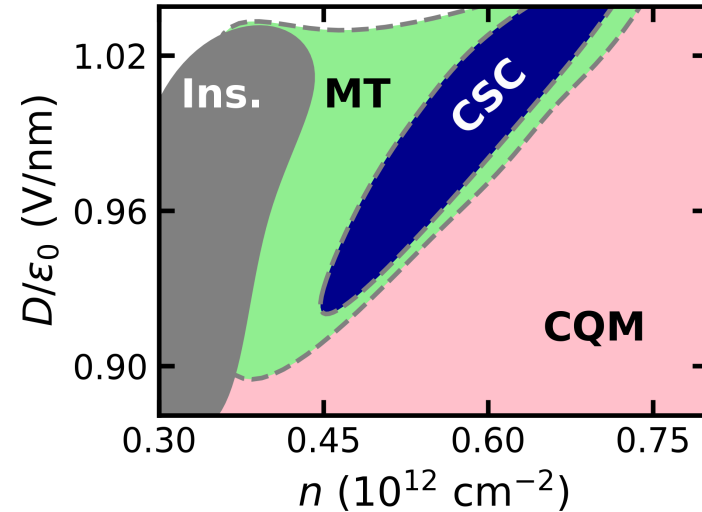
• localized carriers • itinerant carriers

Nearby Notable Features



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**



Acknowledgements



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stanford



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Dan Parker



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Trithep Devakul

Risa Hocking, Qingrui Cao,
David Goldhaber-Gordon, Andy Mannix