Dissipation Induced Flat Bands

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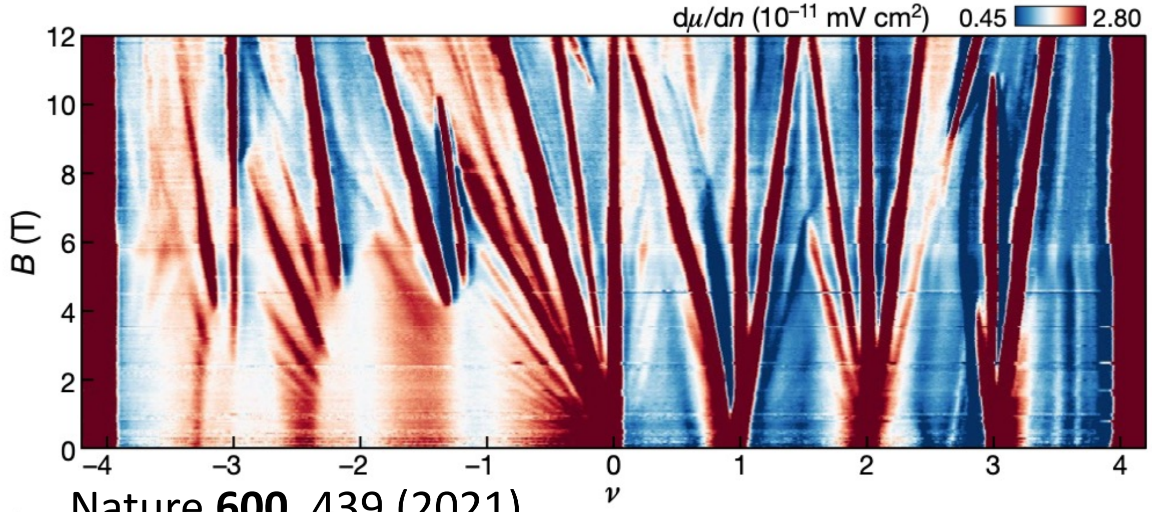
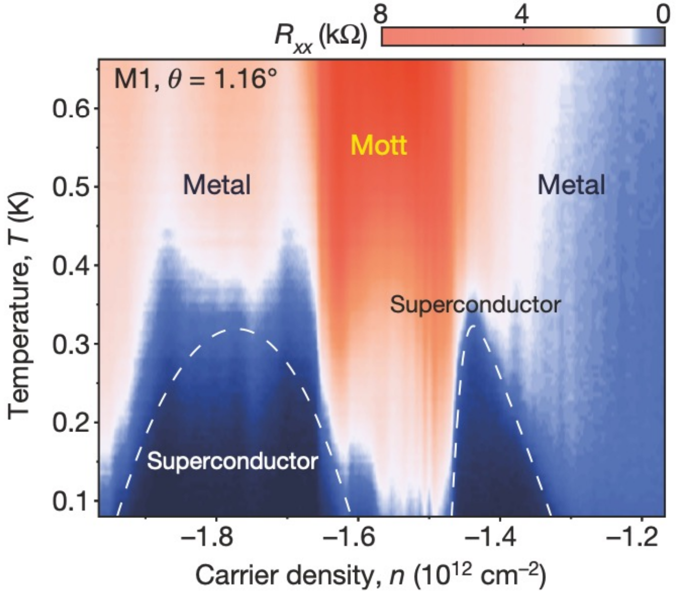
Why Flat Bands?

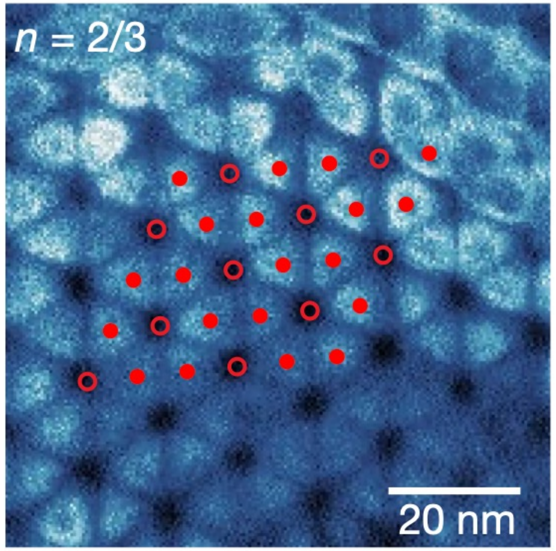
- Dominant Coulomb Interaction + Fractional Filling = Interesting Physics
  - Fractionalized states
  - Superconductivity
  - Charge orders
  - And more!



Nature **600**, 439 (2021)



Nature **556**, 43 (2018)



Nature **597**, 650 (2021)

Gross Tuning vs Fine Tuning

- Key question: “how do we make Coulomb interactions dominant?”
  - Solution: flatten the band
- Moiré flat bands are seen as “finetuned” solution

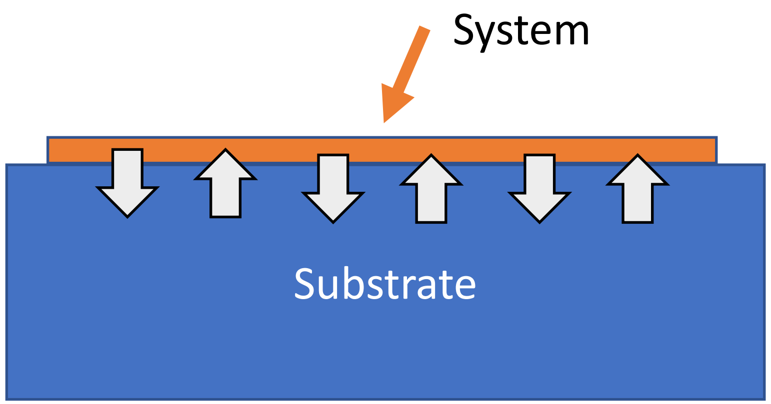
Session D44: Flatbands: Finetuning and Interactions

Invited | Live Streamed

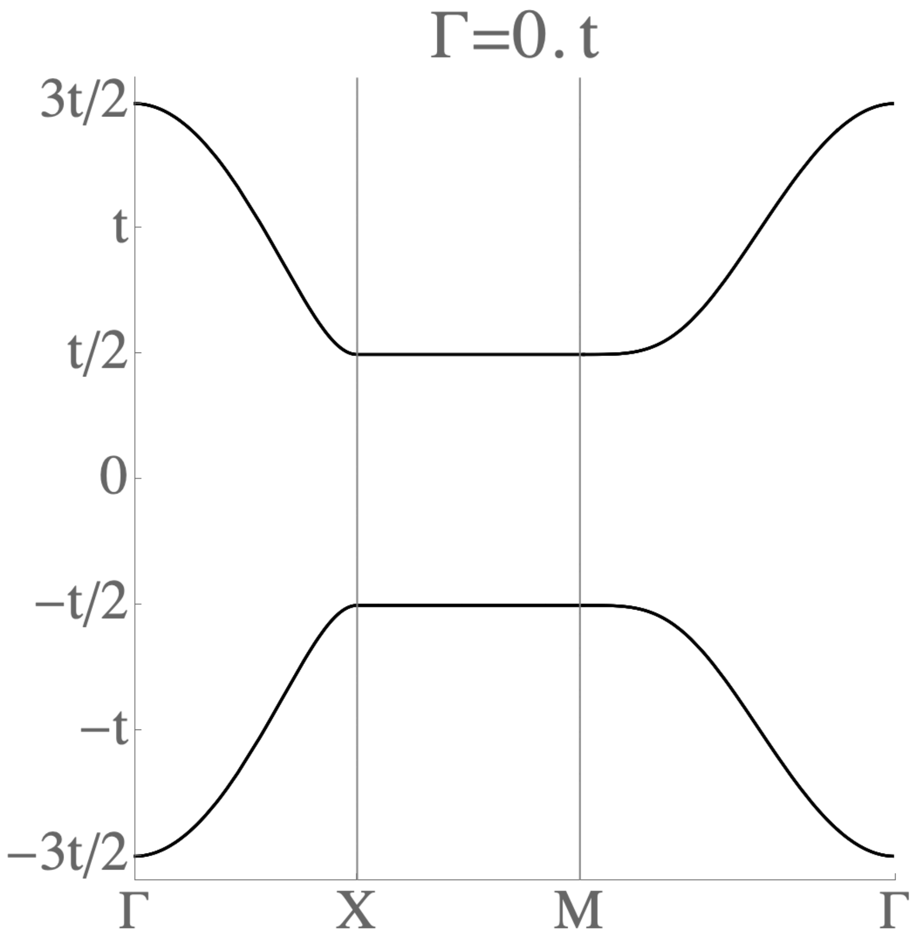
- Other prominent flat bands have limitations
  - Kagome lattice flat band is not isolated
  - Atomic insulators don’t exhibit interesting collective behavior
- Here: a new, robust mechanism to flatten bands

Substrate Engineering

- Couple low-D system and high-D substrate
- Coupling strength Γ
- “Dark space” coupling symmetry



Band Flattening in QWZ Model



Lindbladian Approach to Coupled Systems

- Introduce a superoperator $\mathcal{L}$

$$i\dot{\rho} = \mathcal{L}[\rho]$$

- Expressed as

a and b encode substrate and coupling

$$J_m(\boldsymbol{k}) = \sum_{\alpha} a_{m,\alpha}(\boldsymbol{k}) c_{\boldsymbol{k},\alpha} + b_{m,\alpha}(\boldsymbol{k}) c^{\dagger}_{-\boldsymbol{k},\alpha}$$

$$\mathcal{L}[\rho] = [H, \rho] - i\frac{\Gamma}{2}\sum_m \left(\{J_m^{\dagger} J_m, \rho\} - 2 J_m \rho J_m^{\dagger}\right)$$

Non-Hermitian jump operators

- Normal modes of $\mathcal{L}$
  - Particle-like
  - Hole-like
  - Generalized (dissipative) band structure

Matrix Representation of Lindbladian

- We want the normal modes of $\mathcal{L}$
- Express in terms of "left" and "right" superfermions

$$\ell_{\boldsymbol{k},\alpha}\rho = c_{\boldsymbol{k},\alpha}\rho\mathcal{P} \qquad r_{\boldsymbol{k},\alpha}\rho = \rho c^{\dagger}_{\boldsymbol{k},\alpha}\mathcal{P}$$

Fermion parity operator $(-1)^N$

  - Generalization of Prosen's "third quantization" *New J. Phys.* **10**, 043026 (2008)
- With $\mathcal{L} = \boldsymbol{\Phi}^{\dagger}[L_{\text{coh}}(\boldsymbol{k}) - iL_{\text{dis}}(\boldsymbol{k})]\boldsymbol{\Phi}$ for $\boldsymbol{\Phi}_{\boldsymbol{k}} = (\boldsymbol{\ell}_{\boldsymbol{k}}, \boldsymbol{r}_{\boldsymbol{k}}, \boldsymbol{\ell}^{\dagger}_{-\boldsymbol{k}}, \boldsymbol{r}^{\dagger}_{-\boldsymbol{k}})$

$[A_{\boldsymbol{k}}]_{\alpha,\beta} = a^{*}_{m,\alpha}(\boldsymbol{k})a_{m,\beta}(\boldsymbol{k})$, etc

BdG form

$$L_{\text{coh}} - iL_{\text{dis}} = \begin{pmatrix} H_{\boldsymbol{k}} & 0 & 0 & 0 \\ 0 & H_{\boldsymbol{k}} & 0 & 0 \\ 0 & 0 & -H^{\top}_{-\boldsymbol{k}} & 0 \\ 0 & 0 & 0 & -H^{\top}_{-\boldsymbol{k}} \end{pmatrix} - i\frac{\Gamma}{2}\begin{pmatrix} A_{\boldsymbol{k}} - B_{\boldsymbol{k}} & -2B_{\boldsymbol{k}} & C_{\boldsymbol{k}} - C^{\top}_{-\boldsymbol{k}} & 2C^{\top}_{-\boldsymbol{k}} \\ -2A_{\boldsymbol{k}} & B_{\boldsymbol{k}} - A_{\boldsymbol{k}} & -2C_{\boldsymbol{k}} & C_{\boldsymbol{k}} - C^{\top}_{-\boldsymbol{k}} \\ C^{\dagger}_{\boldsymbol{k}} - C^{*}_{-\boldsymbol{k}} & -2C^{*}_{-\boldsymbol{k}} & B^{\top}_{-\boldsymbol{k}} - A^{\top}_{-\boldsymbol{k}} & 2A^{\top}_{-\boldsymbol{k}} \\ 2C^{\dagger}_{\boldsymbol{k}} & C^{\dagger}_{\boldsymbol{k}} - C^{*}_{-\boldsymbol{k}} & 2B^{\top}_{-\boldsymbol{k}} & A^{\top}_{-\boldsymbol{k}} - B^{\top}_{-\boldsymbol{k}} \end{pmatrix}$$

Symmetries of the Lindbladian Matrix Rep.

- We can write in terms of pseudospins for particles/holes η and left/right contours τ to make the symmetries manifest
- L has BdG form, so we expect
  - Charge conjugation symmetry

$$\mathcal{C}^{-1} L^{\top} \mathcal{C} = -L \qquad \mathcal{C} = \eta_1 \otimes \tau_0$$

  - Time reversal symmetry (here "contour-reversal symmetry")

$$\mathcal{T}^{-1} (iL)^* \mathcal{T} = iL \qquad \mathcal{T} = \eta_2 \otimes \tau_2$$

  - Chiral symmetry

$$\mathcal{S}^{-1} (iL)^{\dagger} \mathcal{S} = -iL \qquad \mathcal{S} = i\eta_3 \otimes \tau_2$$

(anti)-commutation relations are generalized for non-Hermitian L, see Phys. Rev. X **8**, 031079 (2018)

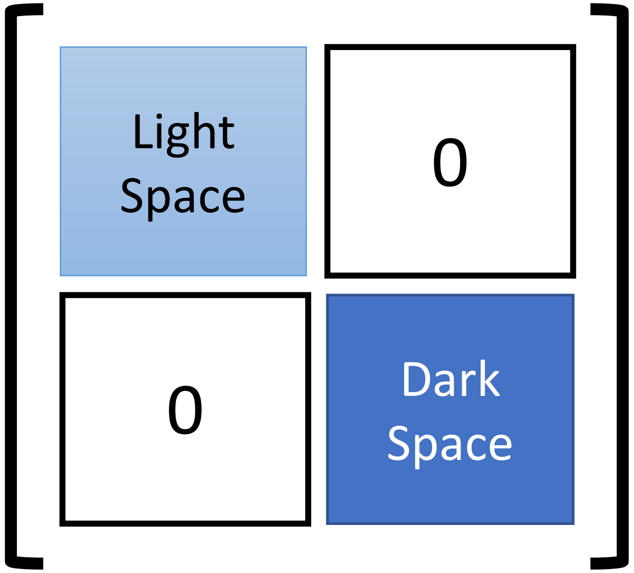
Dark Space Symmetry

- Impose one additional symmetry

$$\mathcal{D}^{-1} L \mathcal{D} = L \qquad \mathcal{D} = \eta_3 \otimes \tau_1$$

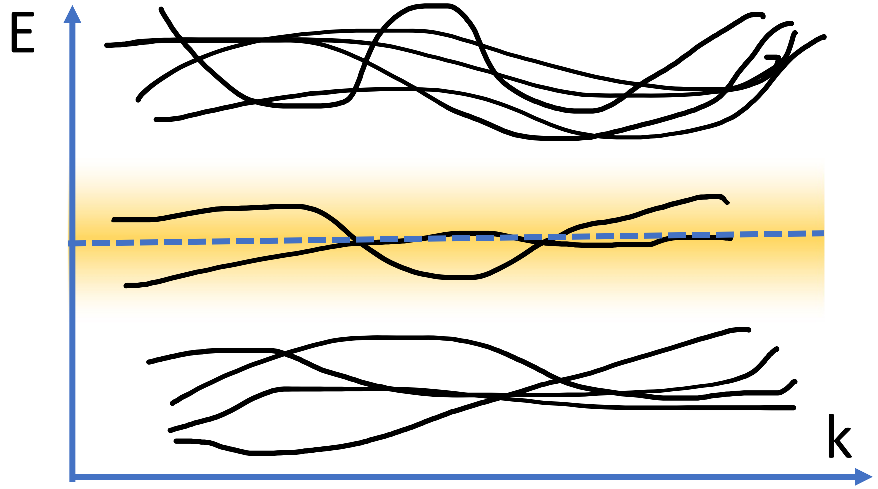
An ansatz that fulfills this symmetry is $(b_{m,1}, \ldots, b_{m,N}) = e^{iS}(a_{m,1}, \ldots, a_{m,N})$ where S is any real, symmetric matrix. This ansatz holds for a superconductor.

- L_{dis} then becomes Hermitian!
- L_{dis} has a dissipationless "dark space" with dim ≥ N
- For $\Gamma \gg t$, L_{coh} is a perturbation $\widetilde{L}_{ij} = \langle \phi_i | L_{\text{coh}} | \phi_j \rangle$
  - N long-lived (generically dispersive) bands
  - Contour reversal symmetry $\implies \epsilon(\boldsymbol{k}) \leftrightarrow -\epsilon^*(-\boldsymbol{k})$
  - $\text{Tr}(\widetilde{L}) = 0$
    - N odd (per spin) $\implies$ "dangling" zero mode guaranteed
    - N even (per spin) $\implies$ no guarantee of zero modes
- Second order corrections lead to finite lifetime



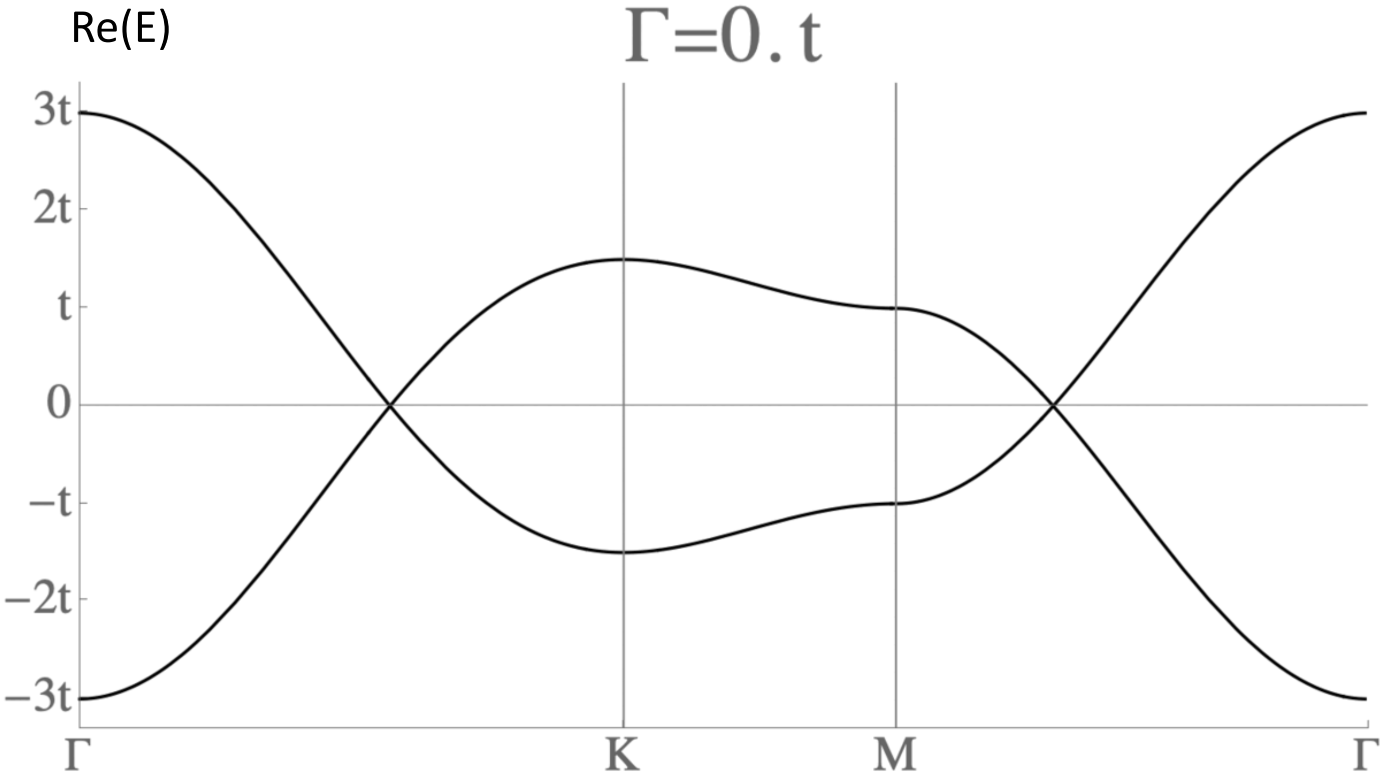
What Does it Mean to Have an Odd #?

- Real systems often have a few bands near the Fermi energy and a spaghetti of bands at large positive and negative energies
  - How can we assign a system a number of bands?
- Only count the bands in an energy window
  - E.g. The window for which Γ is large to the bandwidths and energies



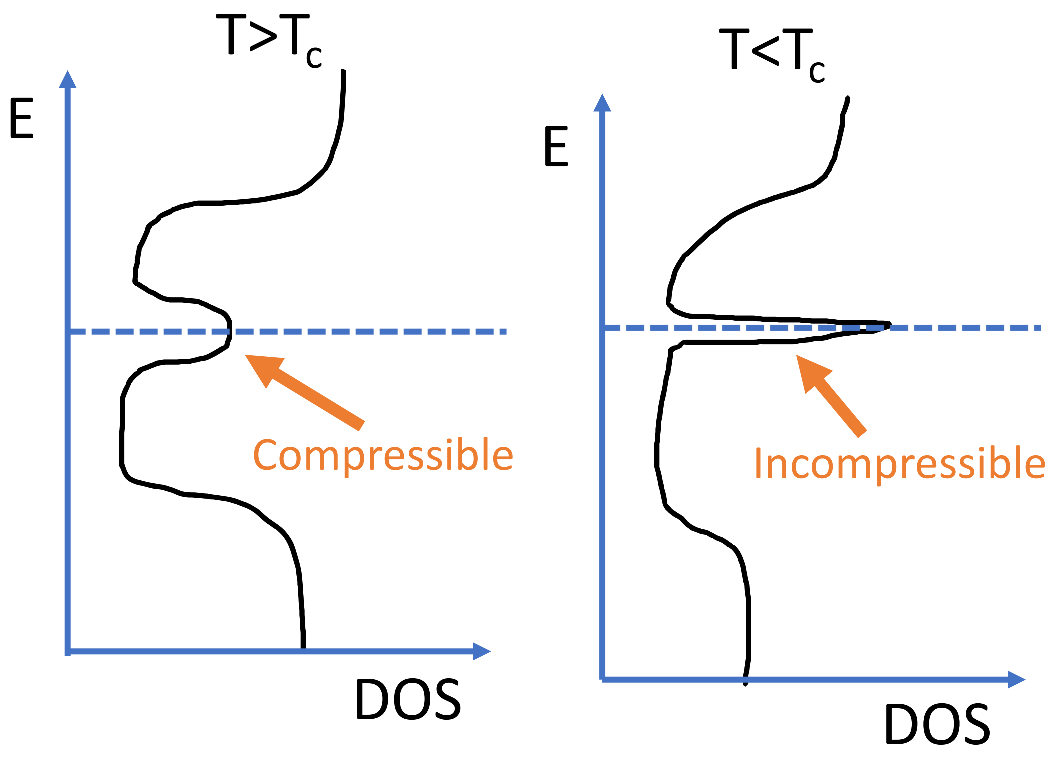
One Band Spinful Model

- Let $H(\boldsymbol{k}) = d(\boldsymbol{k})\sigma_0 + \lambda(\boldsymbol{k})\sigma_3$ with $d(\boldsymbol{k})$ even, $\lambda(\boldsymbol{k})$ odd
- Choose both jump operators of the form $J_\sigma = c_{\boldsymbol{k},\sigma} + c^\dagger_{-\boldsymbol{k},-\sigma}$
  - Both leads to TRS
- Nearest neighbor hopping
- Triangular Lattice
- Ex. isolated almost flat bands
  - Almost MA-TBLG
  - Twisted bilayer WSe_2 at ~2°
  - Twisted bilayer $PtSe_2$ at ~6°



Experimental Proposal

- Twisted bilayer
  - TBLG (near magic angle)
  - WSe_2 (~2°)
  - $PtSe_2$ (~6°)
- On top of a *s*-wave superconductor
  - Or a high-T_c superconductor
- Ex. T dependence of near-IR optics
  - Sharper absorption edge
  - Narrower Drude peak
  - Although there are issues with probing the superconductor vs probing the surface
- Could also do ARPES, pump-probe, or possibly even interferometry



Outlook

- Flat bands exhibit a panoply of fascinating strongly interacting phases
- Substrates need not be inert and can help to engineer flat bands
- We showed that this engineering can rely on the symmetries of the coupling between the system and the substrate
  - When a "dark space" symmetry holds, flat bands form above a critical dissipation rate
  - This does not rely on the crystalline properties of the system
  - This is most applicable for flattening already nearly flat bands so that Coulomb dominates over kinetic energy – this is tunable!