Electron-photon Chern number in cavity-embedded 2D moiré materials

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I. Abstract

We explore theoretically how the topological properties of 2D materials can be manipulated by cavity quantum electromagnetic fields for both resonant and off-resonant electron-photon coupling, with a focus on van der Waals moiré superlattices. We investigate an electron-photon topological Chern number for the cavity-dressed energy minibands that is well defined for any degree of hybridization of the electron and photon states. While an off-resonant cavity mode can renormalize electronic topological phases that exist without cavity coupling, we show that when the cavity mode is resonant to electronic miniband transitions, new and higher electron-photon Chern numbers can emerge.

II. Cavity QED Hamiltonian

- Twisted bilayer TMD materials: Developed from single-layer tight-binding to twisted bilayer continuum model. Lattice constant goes from a_0 to a_0/θ with the twisting angle θ.
- Cavity: Split-ring resonator, consider only single-mode, spatially homogeneous field $\mathbf{A}_0$.
- Light-matter interaction: Peierls substitution with dimensionless coupling strength $g = eA_0a_0/\hbar$ **from tight-binding model**. Redevelop twisted bilayer TMD materials Hamiltonian with photonic degree of freedom.
- Single-body Hamiltonian:

$$\hat{\mathcal{H}} = \hbar\omega_c \hat{a}^\dagger\hat{a} + \frac{1}{2m^\star}\begin{pmatrix} (\hat{\mathbf{p}}+\hbar\boldsymbol{\kappa}_- - e\mathbf{A}^{(xy)}(\hat a+\hat a^\dagger))^2 & 0 \\ 0 & (\hat{\mathbf{p}}+\hbar\boldsymbol{\kappa}_+ - e\mathbf{A}^{(xy)}(\hat a+\hat a^\dagger))^2\end{pmatrix} - \begin{pmatrix}\hat V_t^v & \hat U_0^{v\dagger}\\ \hat U_0^v & \hat V_b^v\end{pmatrix} - i\frac{\omega_c e A^{(z)} d}{2}(\hat a - \hat a^\dagger)\tau_z. \quad (1)$$

- Only valid for $g \leq 0.1$.

III. Electron-photon Chern number

- Periodic boundary condition in Equation (1) $\implies$ Electron-photon eigenstates $|\Psi_{n\mathbf{k}}^{(e-p)}\rangle$.
- Electron-photon Chern number of band n:

$$\mathcal{C}_n^{(\mathrm{e-p})} = \int \frac{d^2k}{2\pi} i \sum_{\mu,\nu} \epsilon_{\mu\nu} \langle \partial_{k_\mu}\Psi_{n\mathbf{k}}^{(\mathrm{e-p})} | \partial_{k_\nu}\Psi_{n\mathbf{k}}^{(\mathrm{e-p})}\rangle . \quad (2)$$

IV. Electronic purity

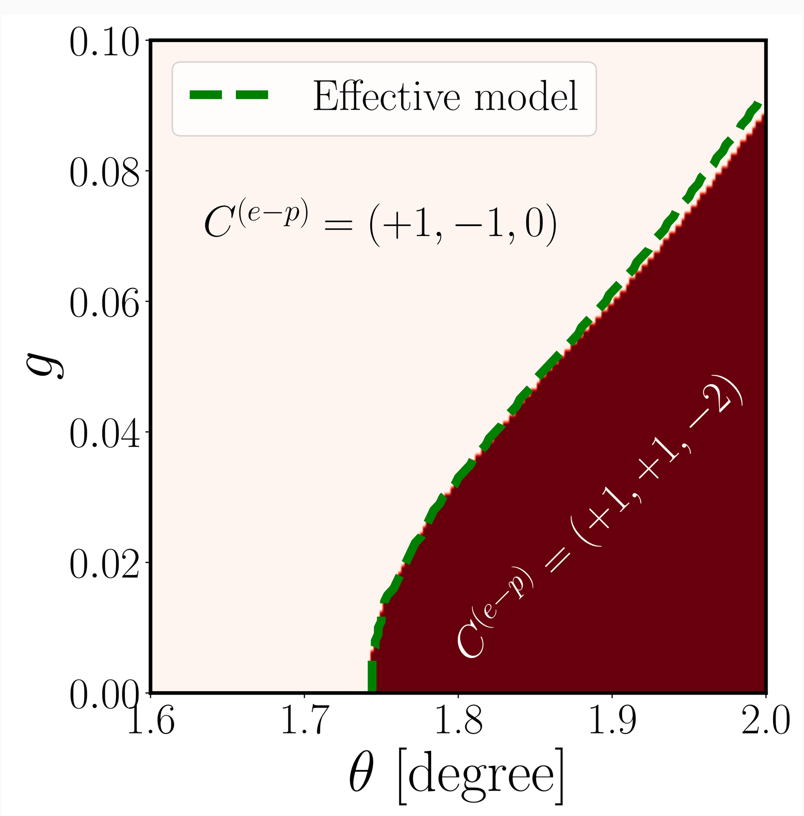
- Electronic density matrix $\hat\rho = \mathrm{Tr}_{\mathrm{phot}}\left(|\Psi^{(e-p)}\rangle\langle\Psi^{(e-p)}|\right)$.
- Electronic purity: $\mathbb{P} = \mathrm{Tr}_{\mathrm{el}}(\hat\rho^2)$.

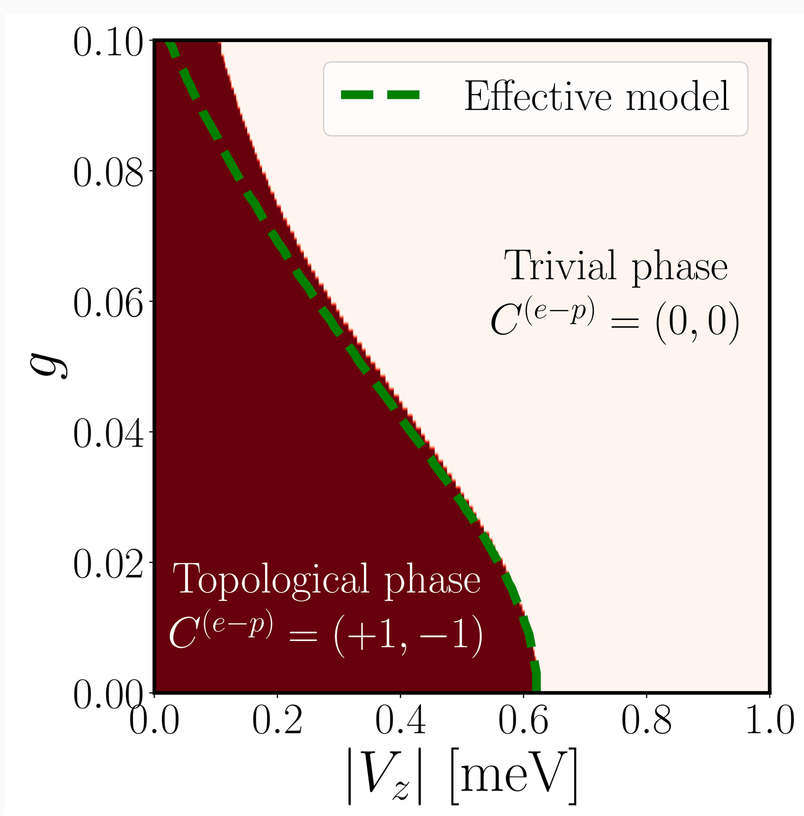
$$0 < \mathbb{P} \leq 1$$

(Maximally mixed state) (Pure state)

V. High purity regime

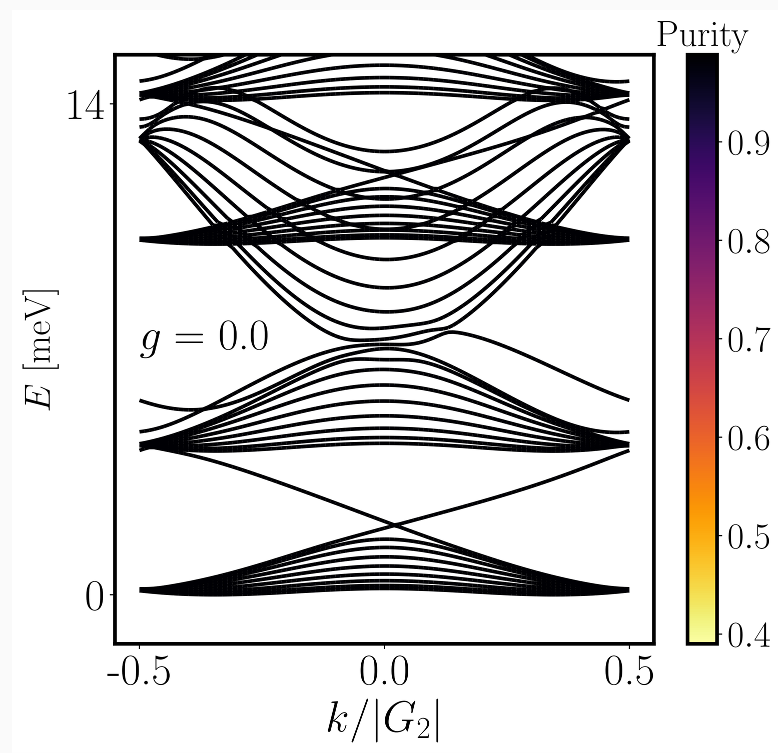
- High photon frequency.
- Shifts the phase boundary significantly.
- Can be reconstructed from effective electronic Hamiltonian.

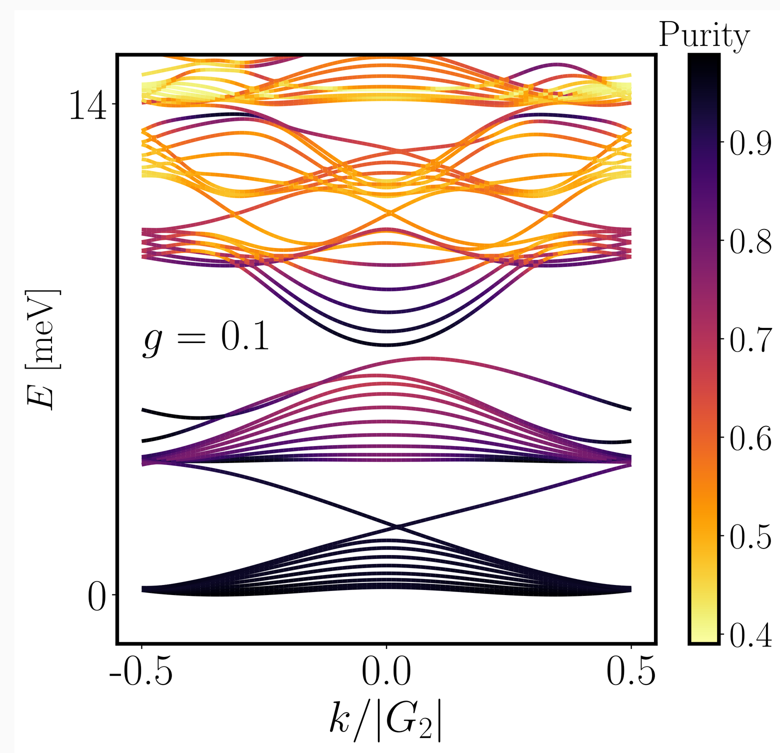


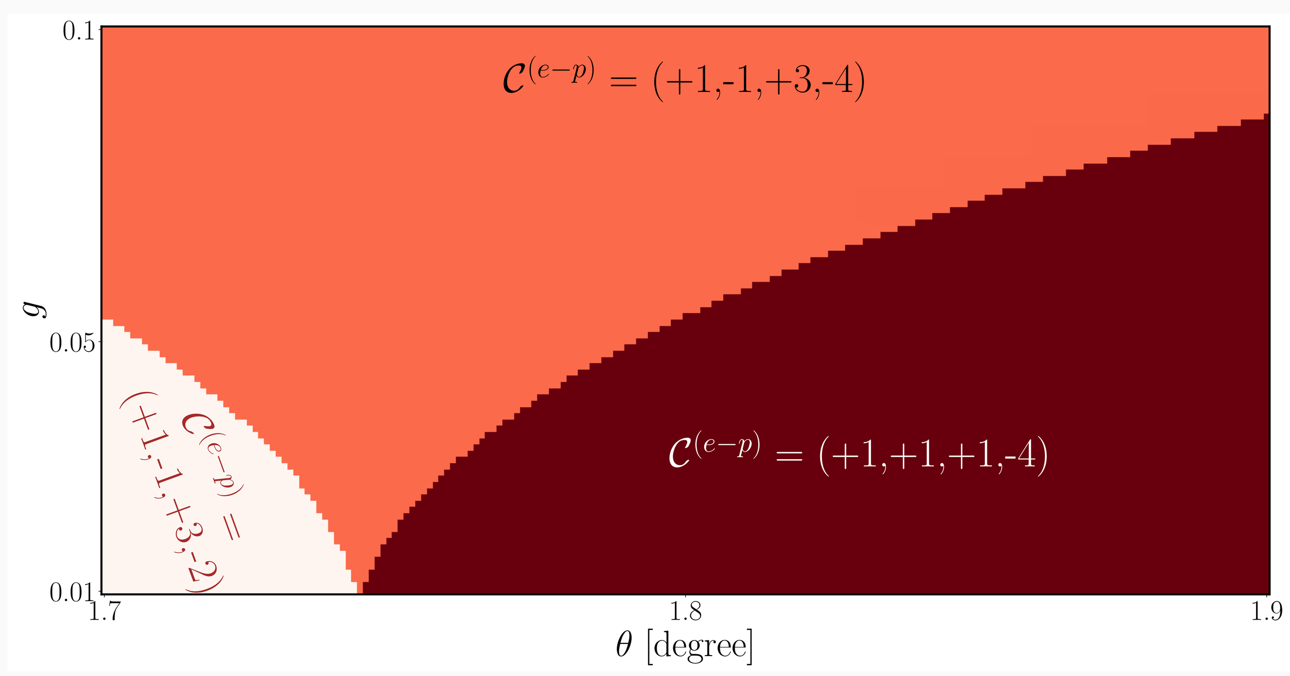


VI. Low purity regime

- Low photon frequency, therefore resonance between minibands.
- Finite coupling $\implies$ Gap opening, new bands, new **exotic** Chern numbers.







VII. Conclusion

- Light-matter interaction changes the phases significantly.
- Future work: What is the relation between electron-photon Chern number and conductance?

VIII. Bibliography

1. DP. Nguyen et. al, arXiv:2303.08804, (2023)

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