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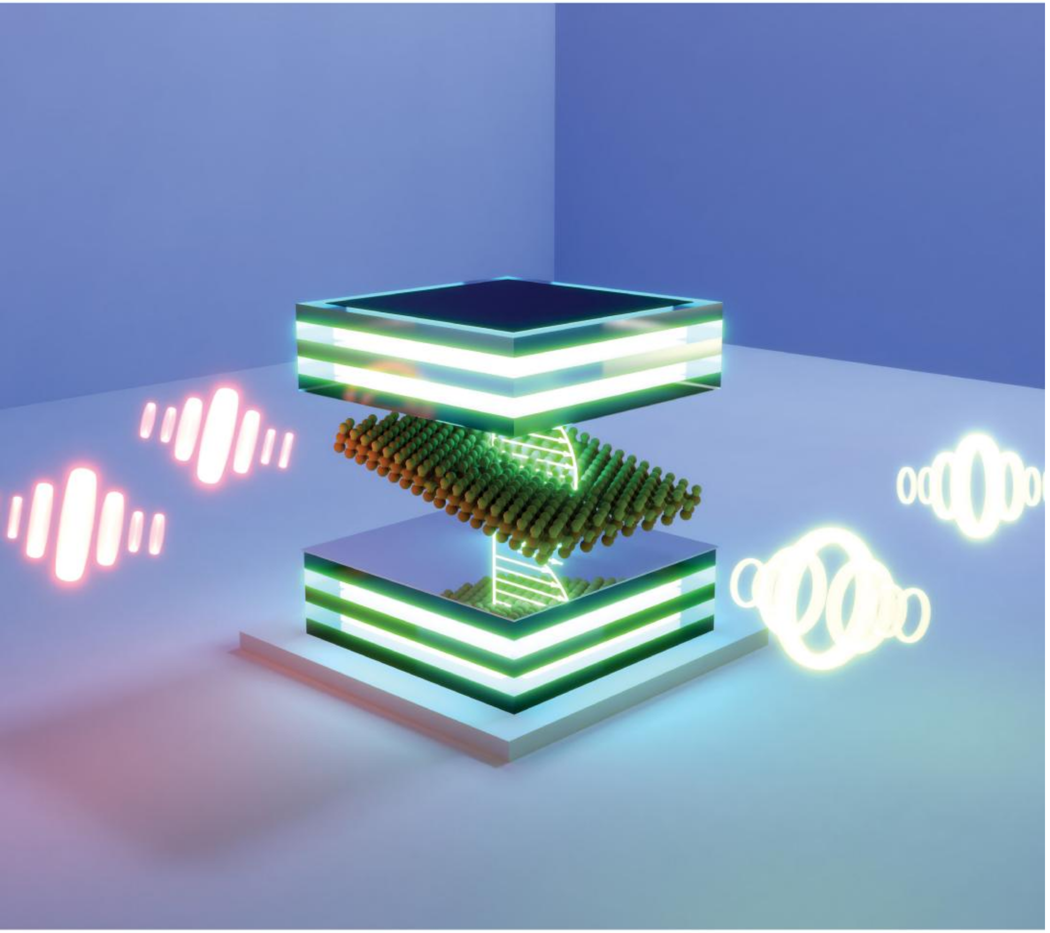
TEXAS A&M UNIVERSITY



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Tuning Quantum Dynamics *of* Materials Between two Mirrors

Arshath Manjalingal, Mandal Group, Texas A&M

Manjalingal †, Rahmanian †, Blackham, Mandal, ***ACS Photonics*** (2025)

Blackham †, Manjalingal †, Rahmanian, Mandal, ***Nano Letters*** (2025)

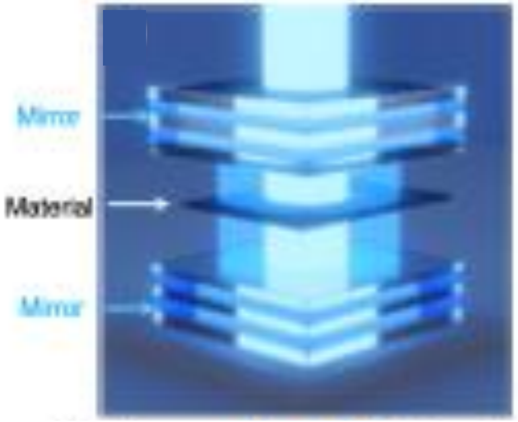
Ghosh, Manjalingal, Wickramasinghe, Rahmanian, Mandal, ***Physical Review B*** (2025)

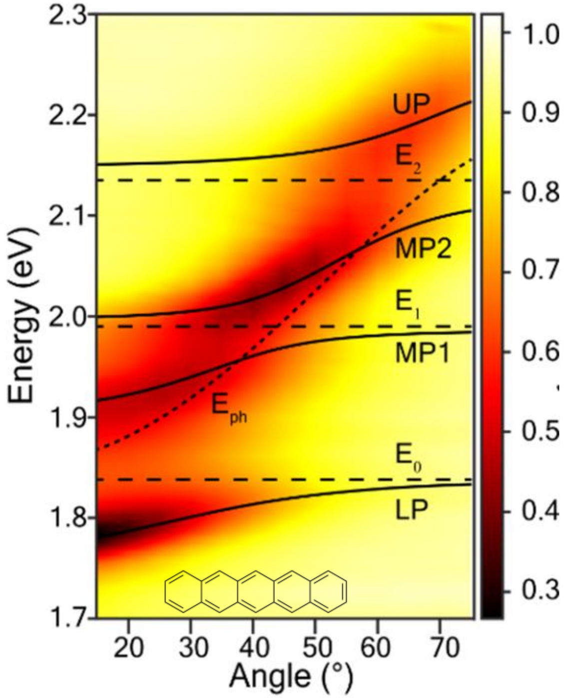
Haines †, Manjalingal †, Blackham, Rahmanian, Mandal, *arXiv* (2026)

Rahmanian, Manjalingal, Blackham, Mandal, *arXiv* (2025)

† equal contribution

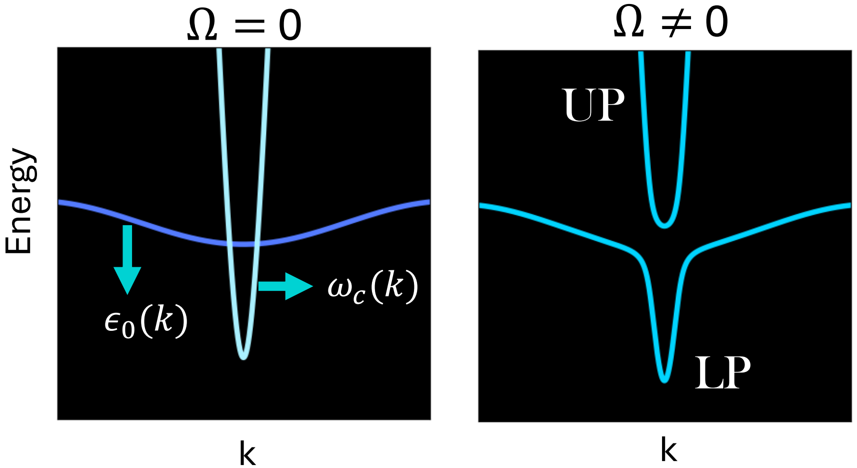
Polaron-Polariton Dispersion





Alam,... , Frontiera, arXiv. (2025)

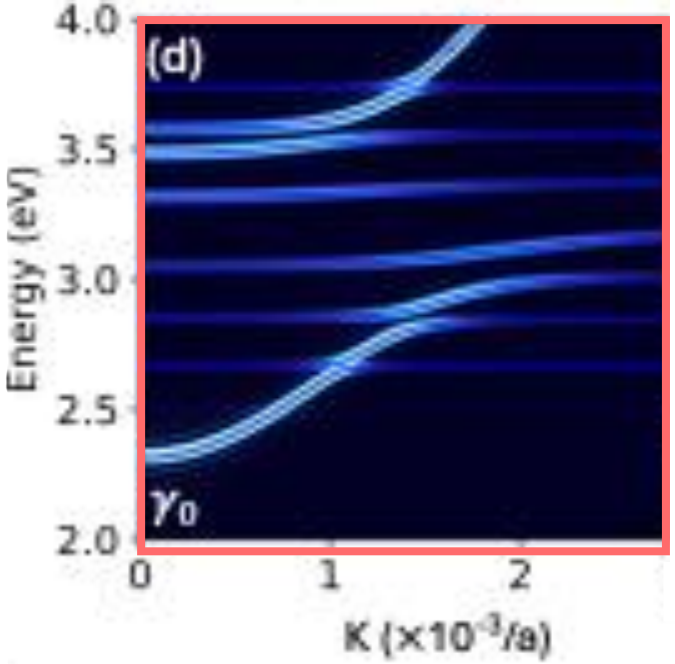
$$\tilde{\mathcal{H}}_k = \begin{bmatrix} \epsilon_0(k) & \Omega \\ \Omega & \omega_c(k) \end{bmatrix}$$



Our Analytical Theory

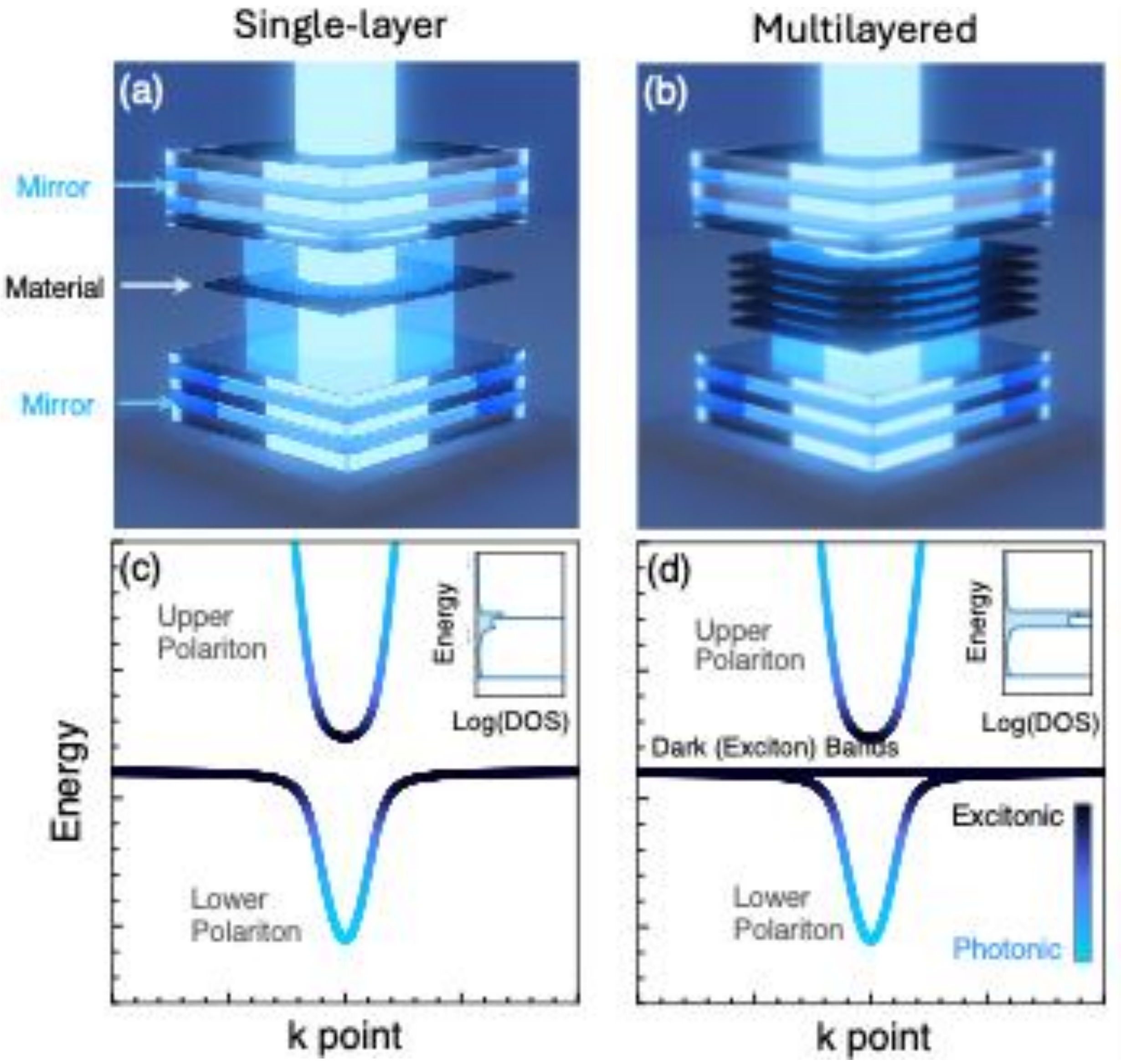
$$\tilde{\mathcal{H}}_k = \begin{bmatrix} \ddots & \vdots & \vdots & \vdots & & \vdots \\ \cdots & \tilde{\varepsilon}-\omega_0 & 0 & 0 & \cdots & \sqrt{\frac{S^{[0]}_{-1}}{N}}\Omega_k \\ \cdots & 0 & \tilde{\varepsilon} & 0 & \cdots & \sqrt{\frac{S^{[0]}_{0}}{N}}\Omega_k \\ \cdots & 0 & 0 & \tilde{\varepsilon}+\omega_0 & \cdots & \sqrt{\frac{S^{[0]}_{1}}{N}}\Omega_k \\ & \vdots & \vdots & \vdots & \ddots & \vdots \\ \cdots & \sqrt{\frac{S^{[0]}_{-1}}{N}}\Omega_k & \sqrt{\frac{S^{[0]}_{0}}{N}}\Omega_k & \sqrt{\frac{S^{[0]}_{1}}{N}}\Omega_k & \cdots & \omega_c(k) \end{bmatrix}.$$

$$S^{[j]}_{m_j} = \lim_{M\to\infty} 2\tanh\left(\frac{\beta\omega_j}{2}\right)\int_{-\infty}^{\infty} dz \frac{M!}{(M+m_j)!}\left(\frac{\gamma_j^2 z^2}{\omega_j^2 M}\right)^{m_j} \tag{14}$$
$$\times \exp\left[-\left(4\omega_j \tanh\left(\frac{\beta\omega_j}{2}\right) + \frac{z_j^2\gamma_j^4}{4\omega_j^4 M^2}\right)z^2\right]\left[L_M^{(m_j)}\left(\frac{\gamma_j^2 z^2}{\omega_j^2 M}\right)\right]^2.$$



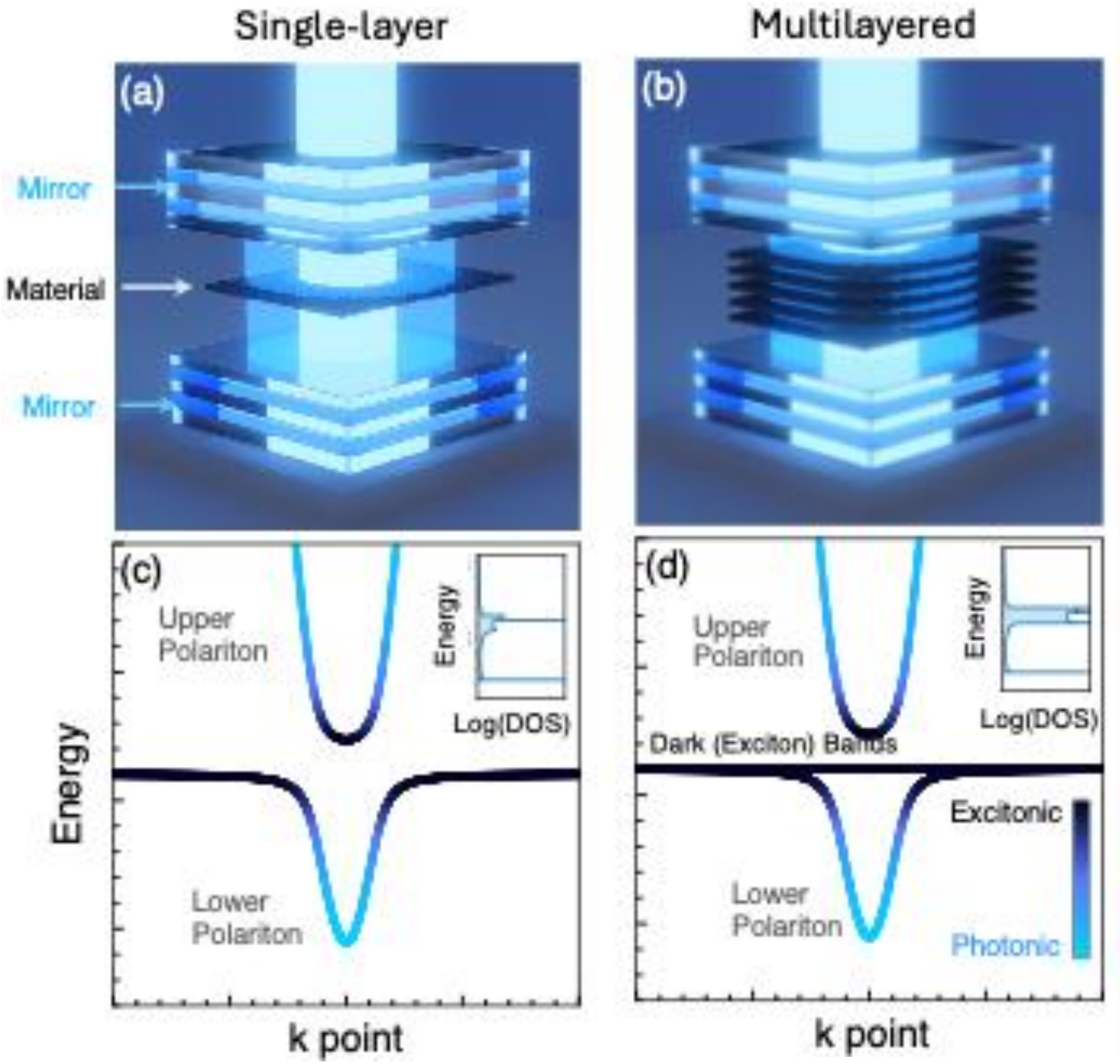
Blackham †, **Manjalingal** †, Rahmanian, Mandal, *Nano Letters* (2025)

Single vs Multilayer Materials in Cavities



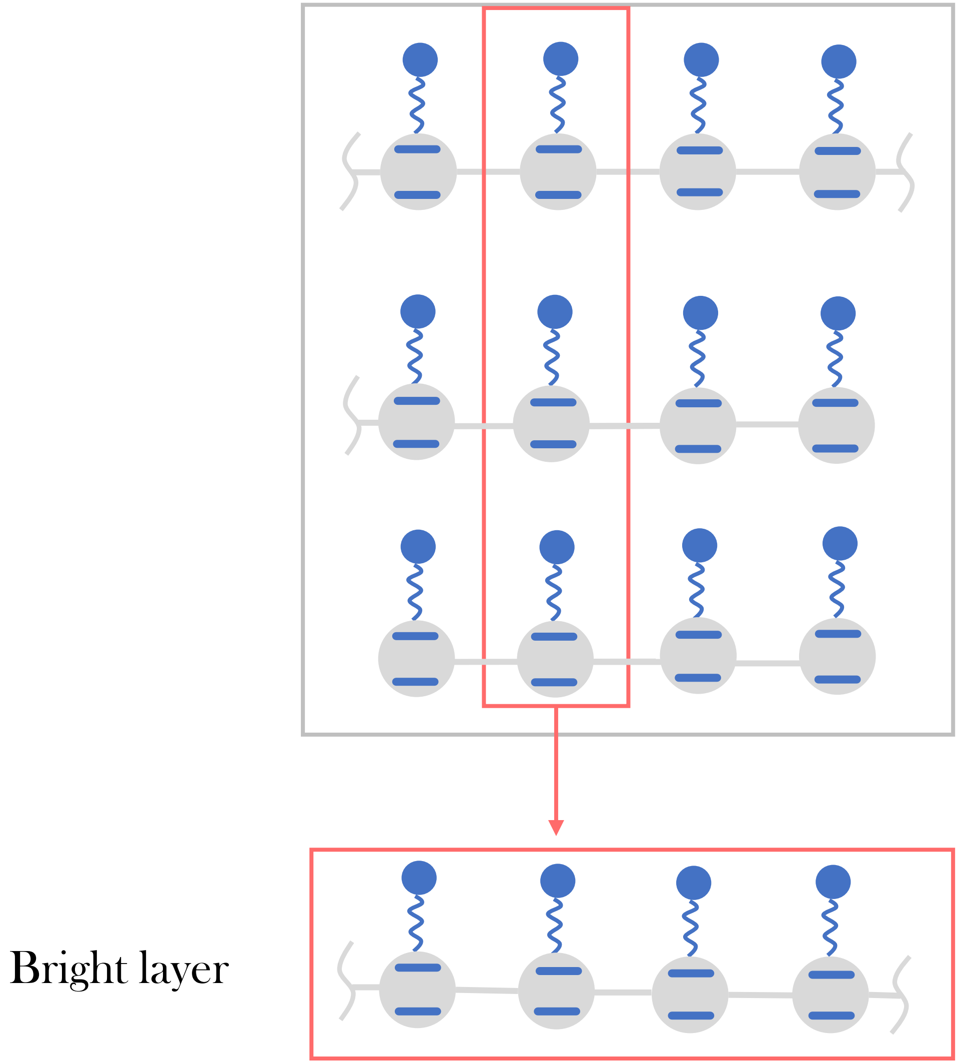
Rahmanian, **Manjalingal**, Blackham, Mandal, *arXiv* (2025)

Single vs Multilayer Materials in Cavities

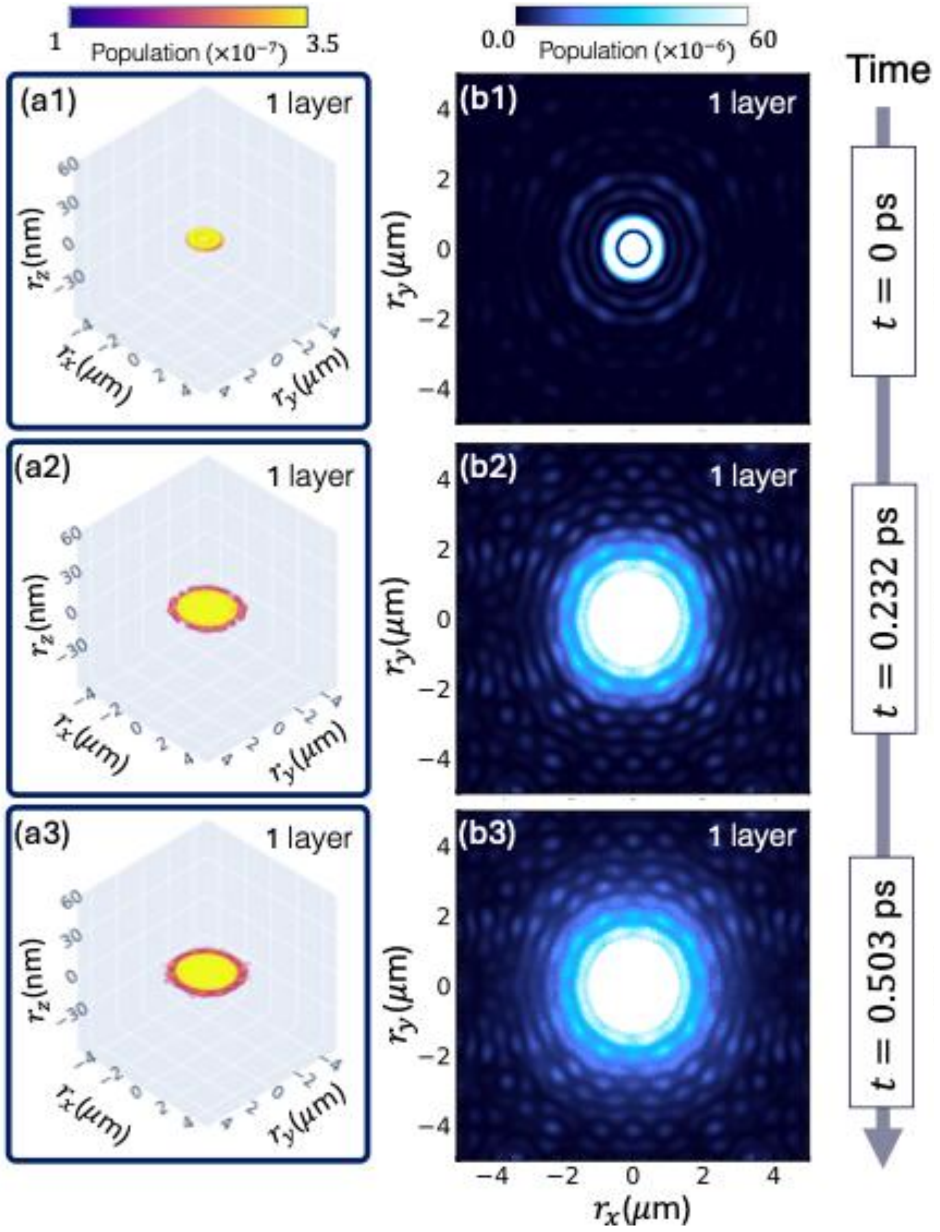


Rahmanian, **Manjalingal**, Blackham, Mandal, *arXiv* (2025)

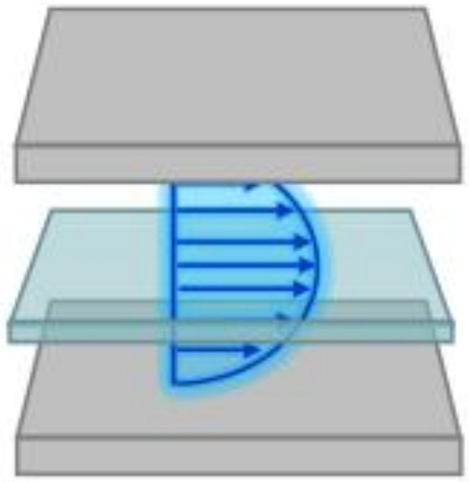
Phonon Fluctuation Synchronization Effect

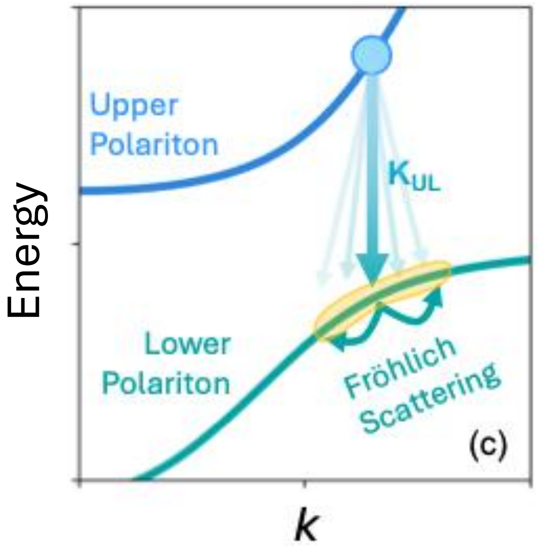


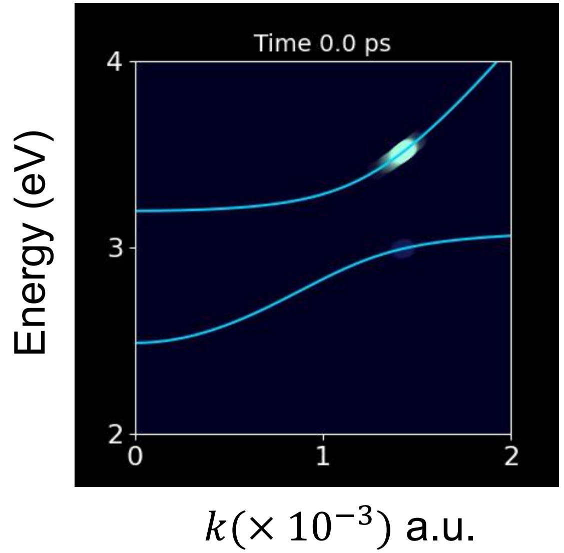
Single Layer Vs Multi-Layer with 3D Cavity-Material Architecture

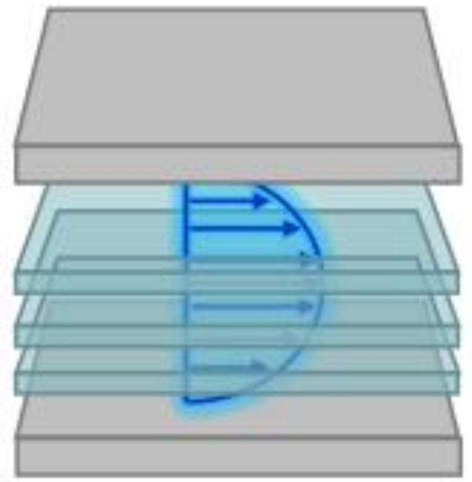


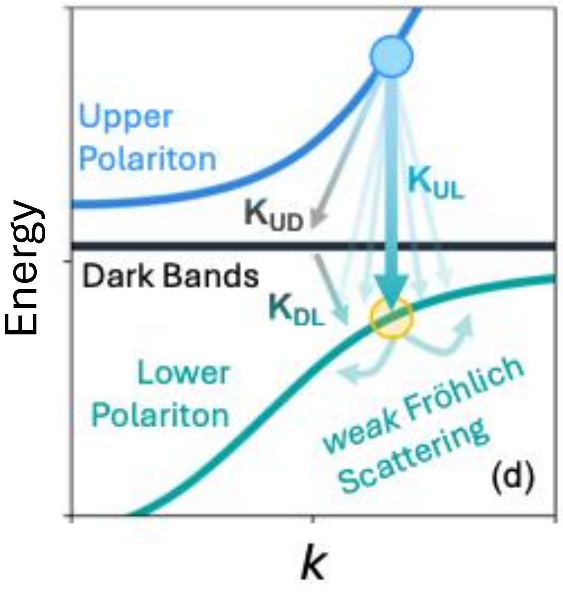
Mechanistic Principles of Exciton–Polariton Relaxation

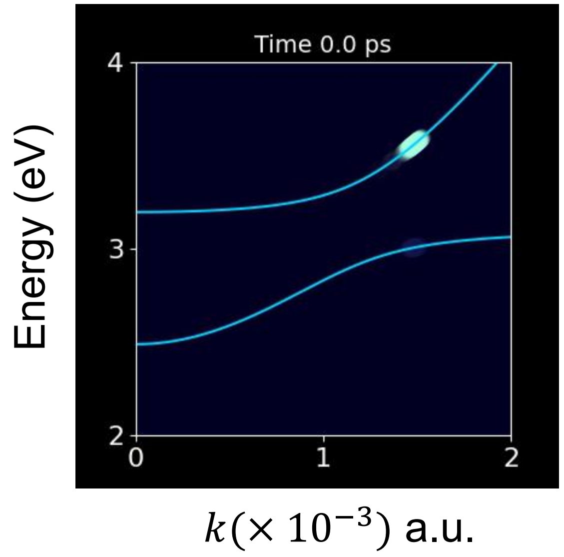


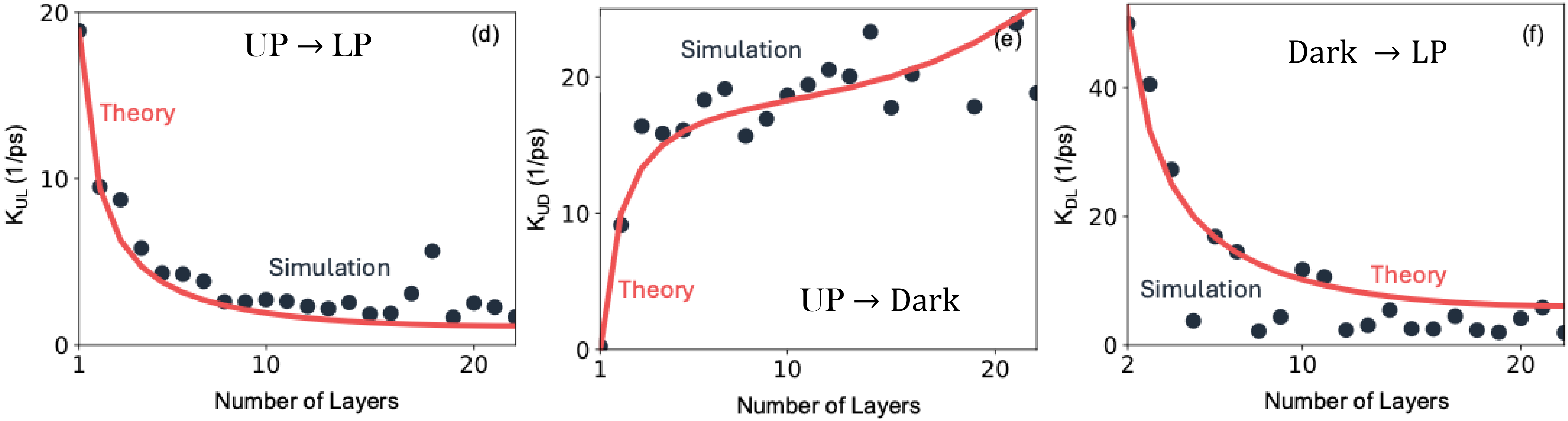












$$K_{UL}(N_L) \propto f(N_L)$$

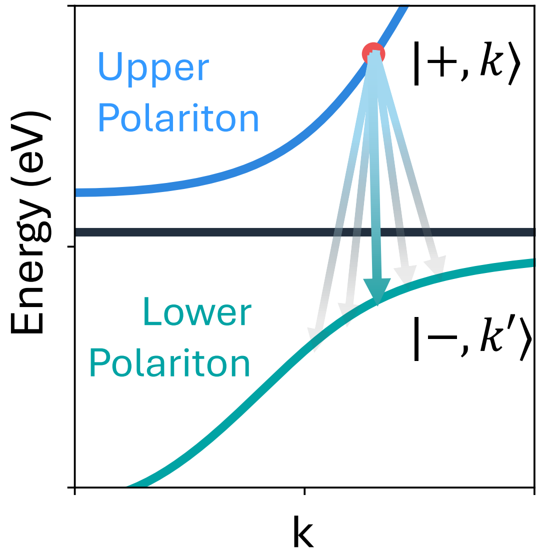
$$K_{UD}(N_L) \propto (N_L - 1) f(N_L)$$

$$K_{DL}(N_L) \propto f(N_L)$$

$$f(N_L) = \frac{1}{S^2} \sum_m^{N_L} \sin^4(k_0 \cdot y_m)$$

Haines †, **Manjalingal** †, Blackham, Rahmanian, Mandal, *arXiv* (2026)

Direct Transition from Upper to Lower Polariton



$$\mathbb{P}_{-}\hat{H}_{bX}\mathbb{P}_{+} = \gamma \sum_{k,k'} \hat{P}^{\dagger}_{k,-}\hat{P}_{k',+}\Big[\cos(\theta_k)\sin(\theta_{k'})\mathcal{Q}(t)\Big].$$

Exciton-Phonon coupling

$$\langle -, k' | e^{-i\hat{H}_{bX}\Delta t} | +, k\rangle$$

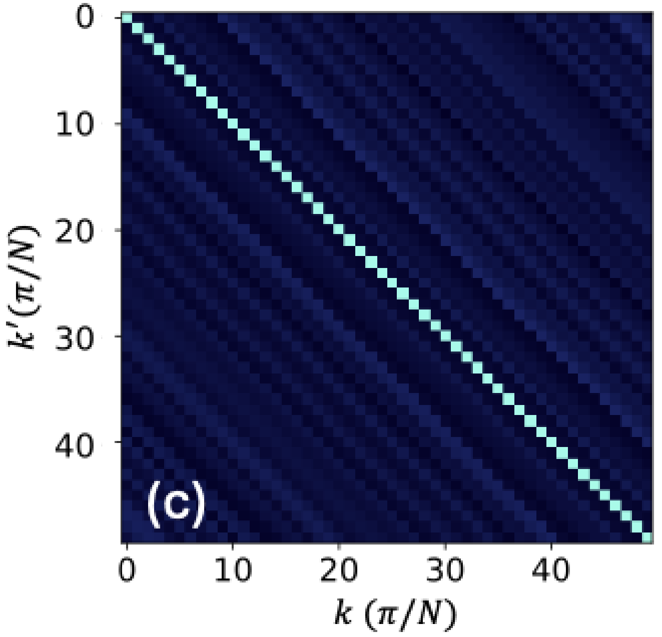
$$= C_{kk'} \sum_n \frac{e^{i(k'-k)\cdot x_n}}{N}\left(1 - e^{-i\gamma q_{n,m}\Delta t}\right)$$

$$\approx C_{kk'} \langle 1 - e^{-i\gamma q \Delta t}\rangle \sum_n \frac{e^{i(k'-k)\cdot x_n}}{N}$$

Using separation of length-scales

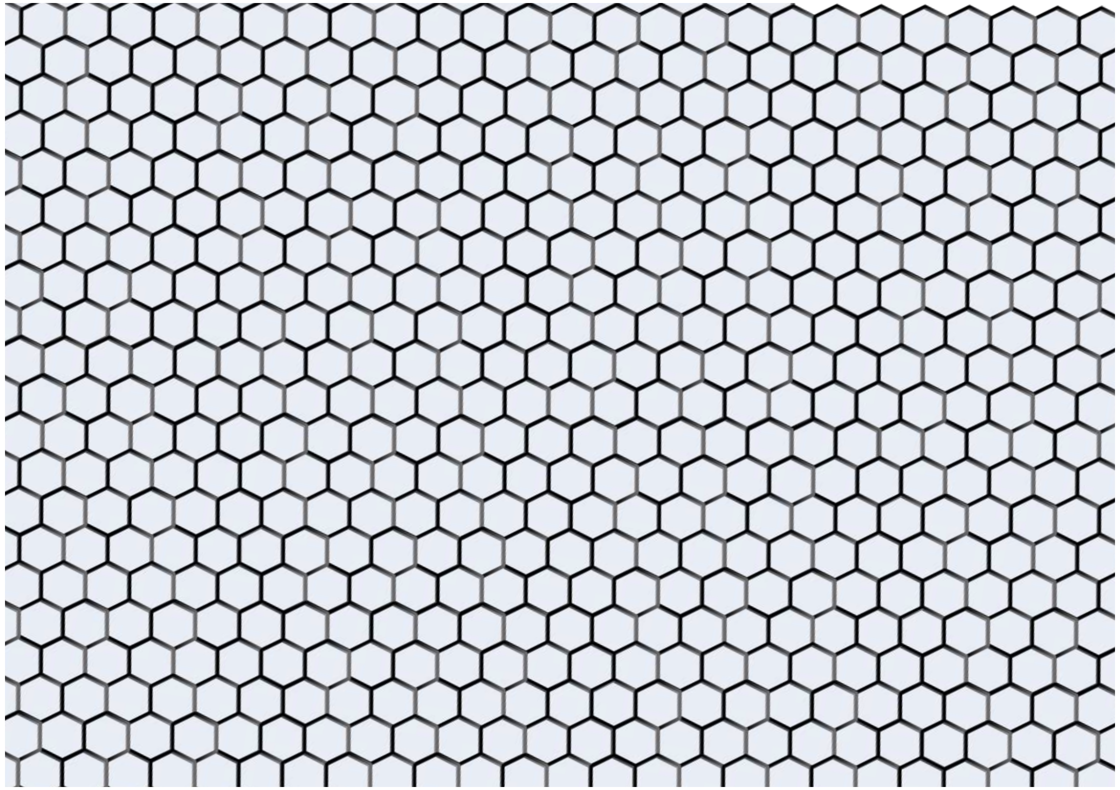
$$= C_{kk'} \langle 1 - e^{-i\gamma q \Delta t}\rangle \cdot \delta_{kk'}$$

$\langle -, k' | e^{-i\Delta t \hat{H}_{bX}} | +, k\rangle$

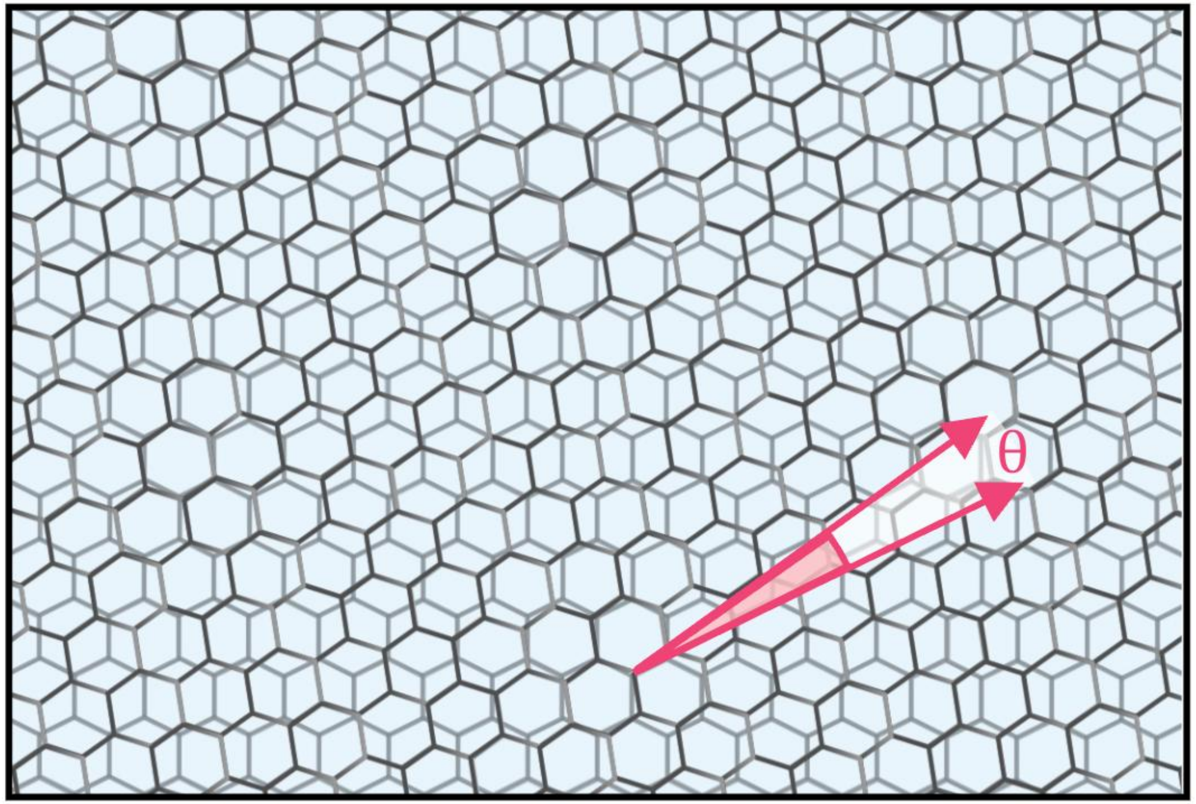


Moiré Pattern

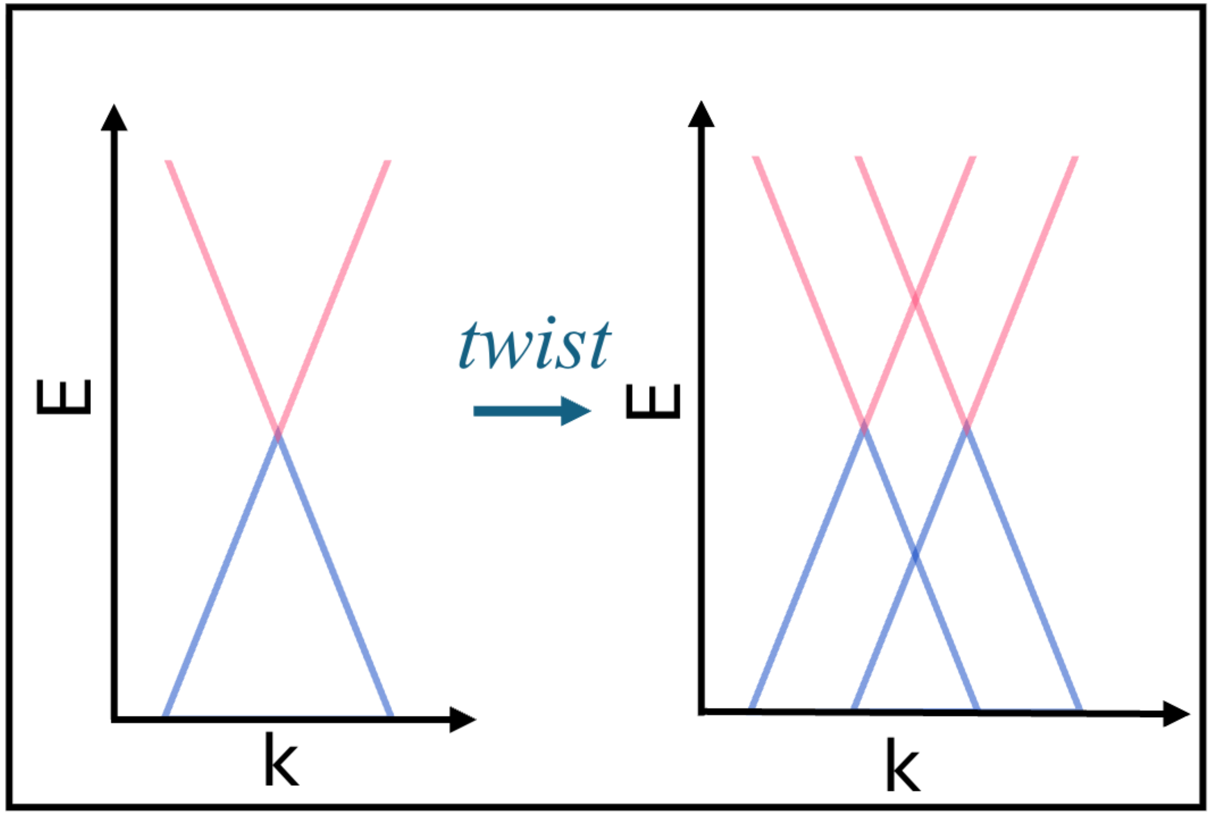
Graphene Bilayer

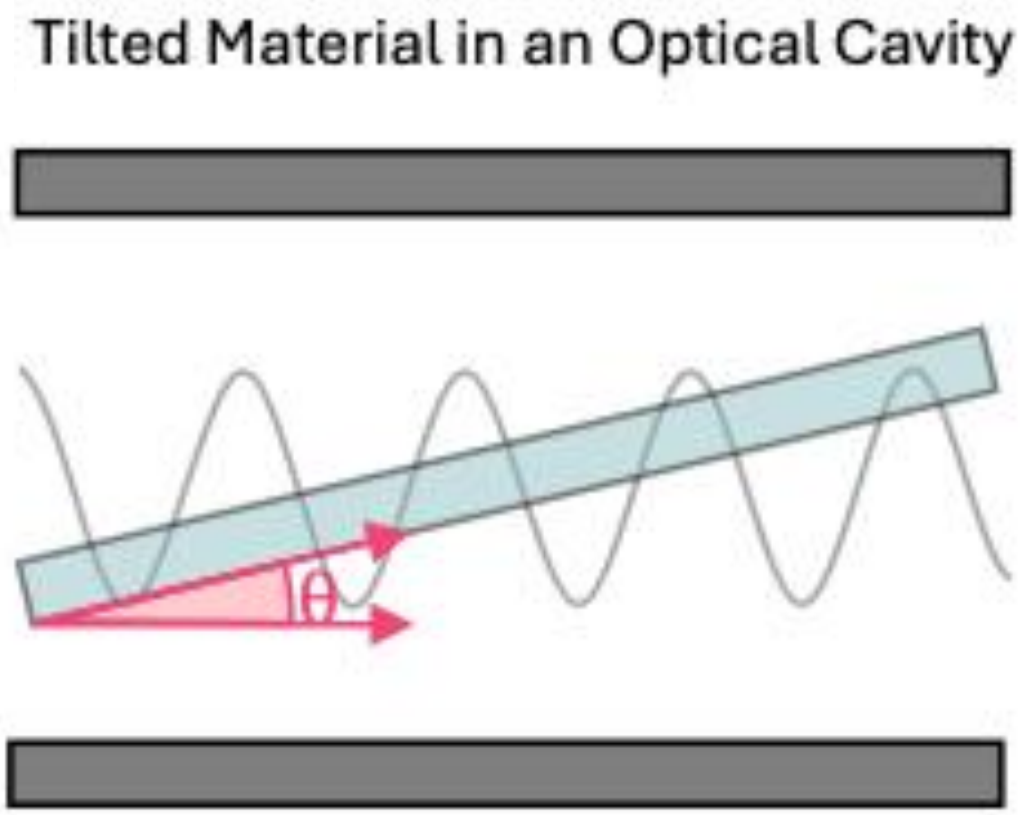


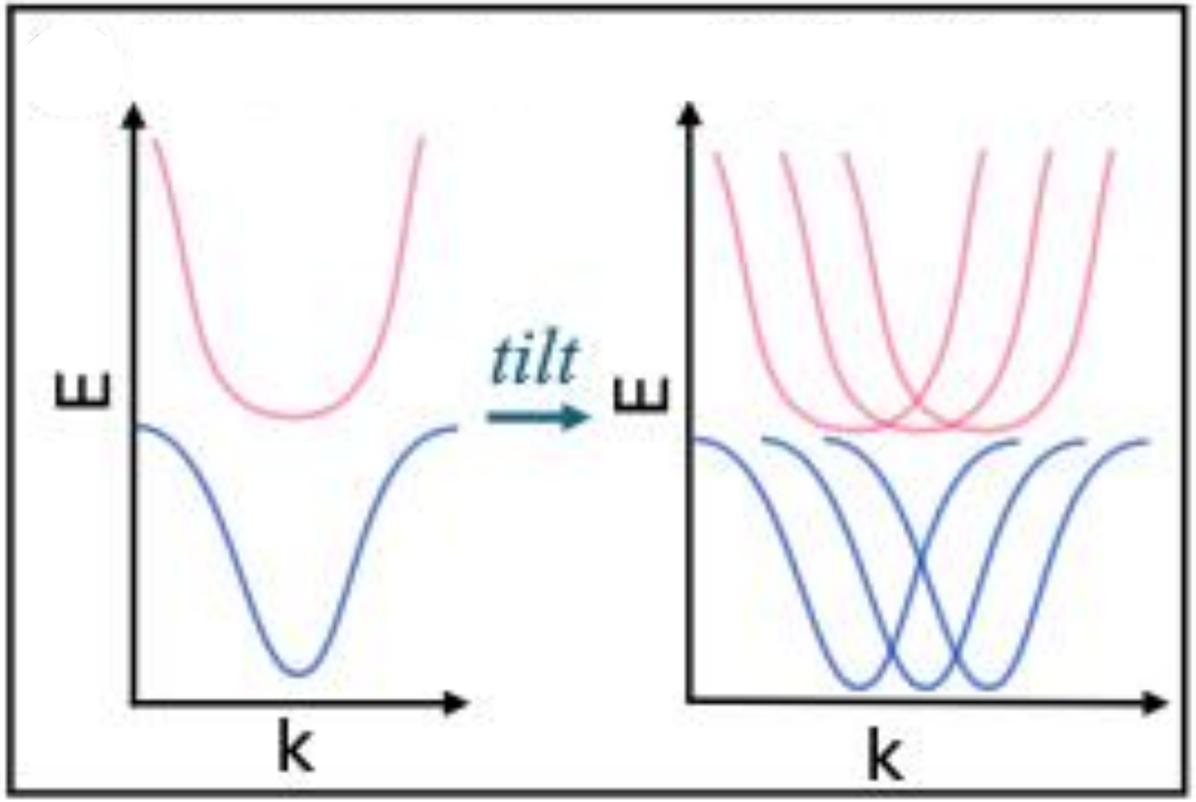
Twisted Bilayer



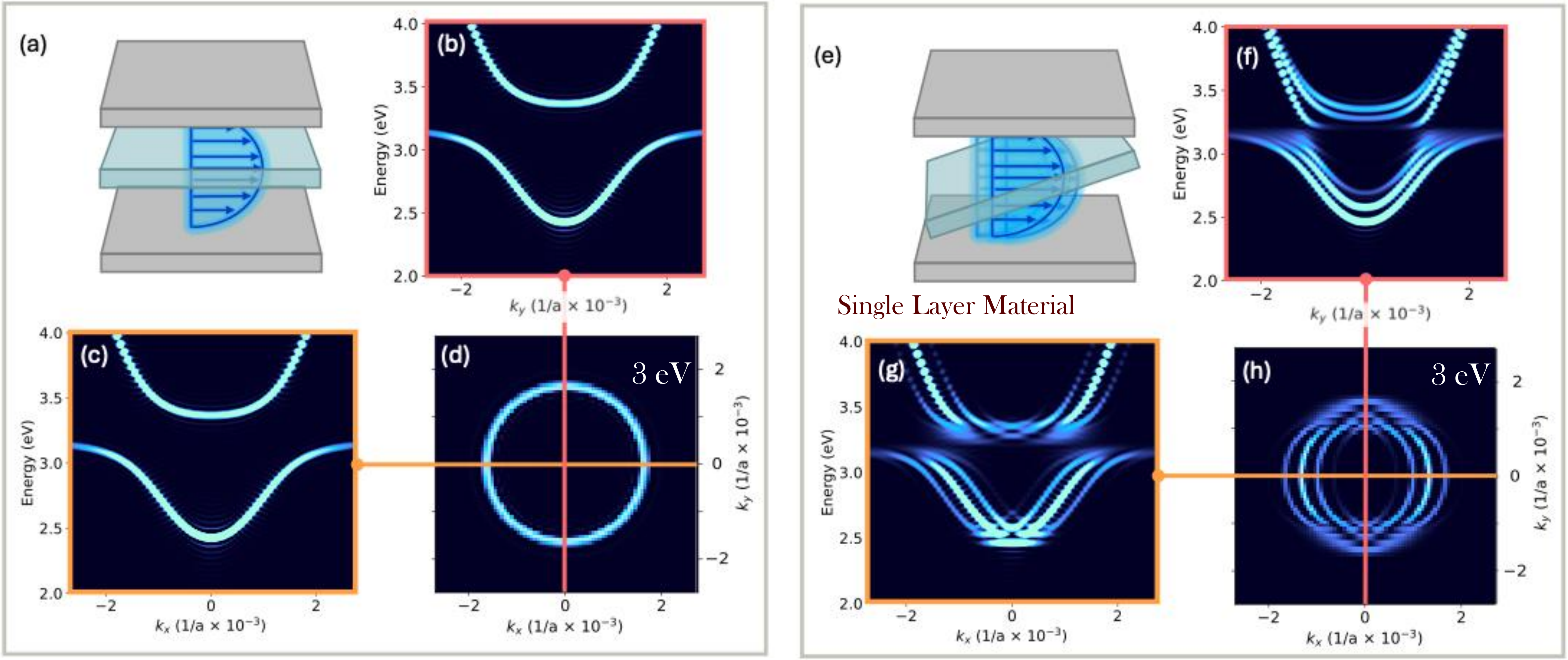
Band structure modification




Tilted Material in an Optical Cavity
θ

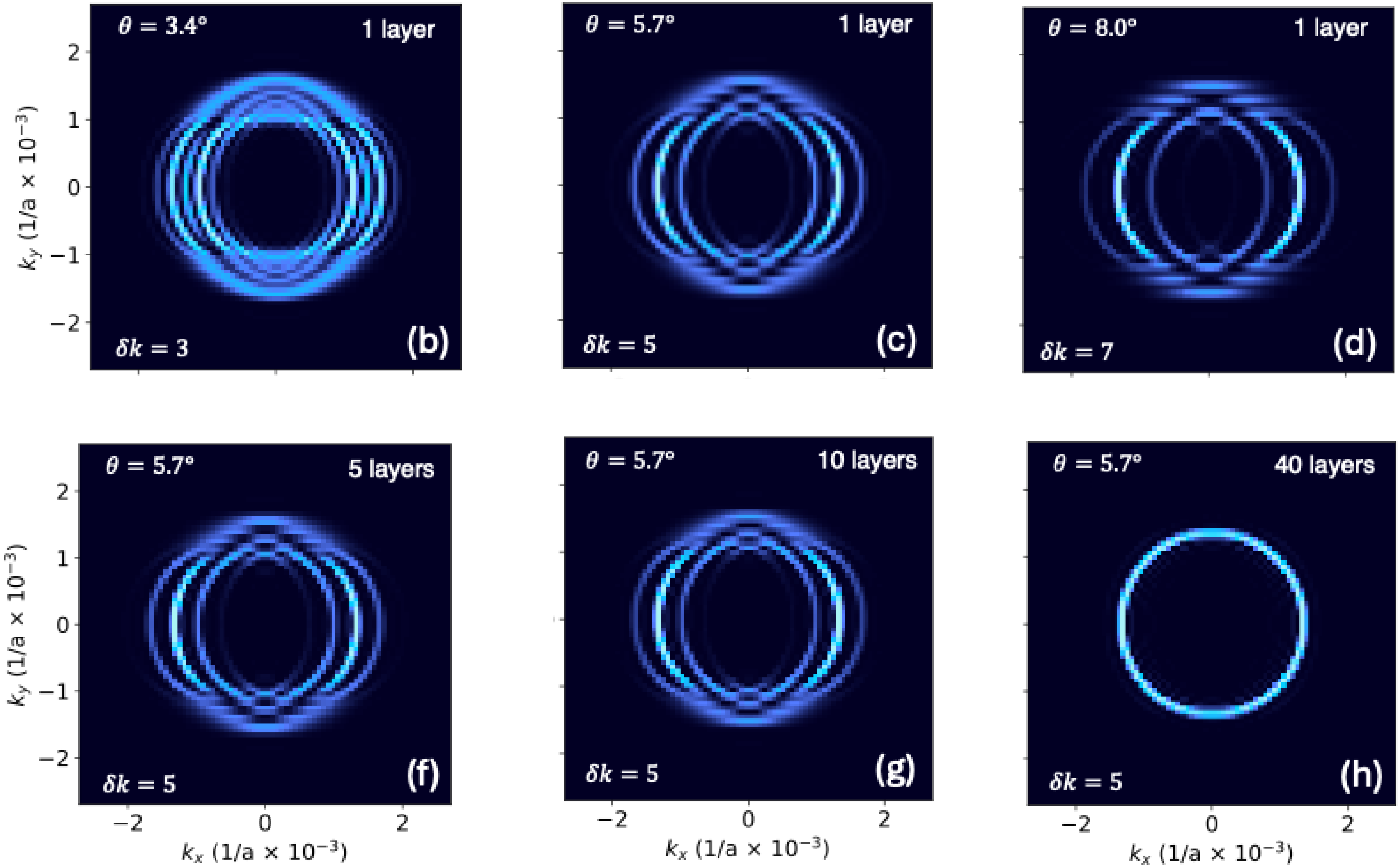

E
k
tilt
E
k

Light-Matter Moiré Effect



Manjalingal †, Rahmanian †, Blackham, Mandal, *ACS Photonics* (2025)

$$\Delta K = \sin(\theta)\frac{m_z}{2L_z}$$



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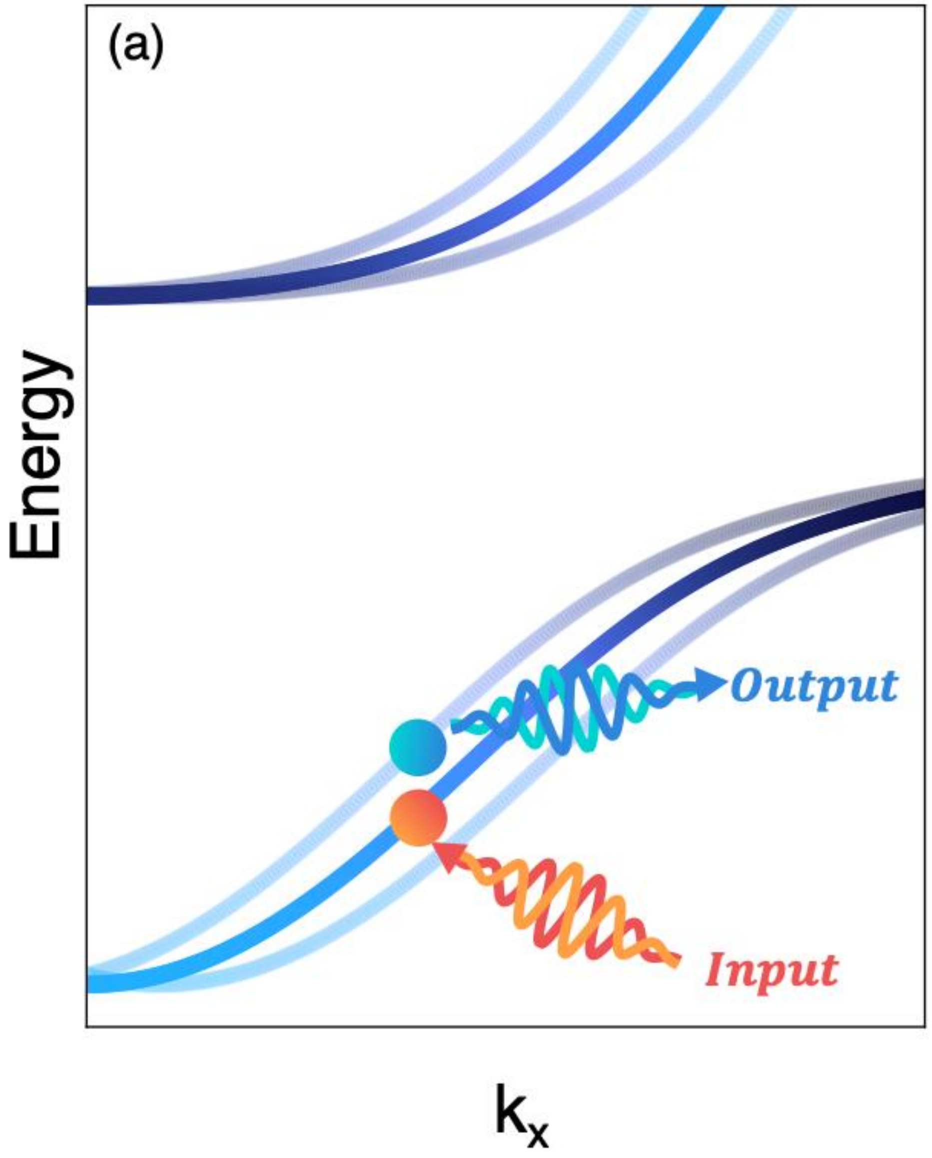
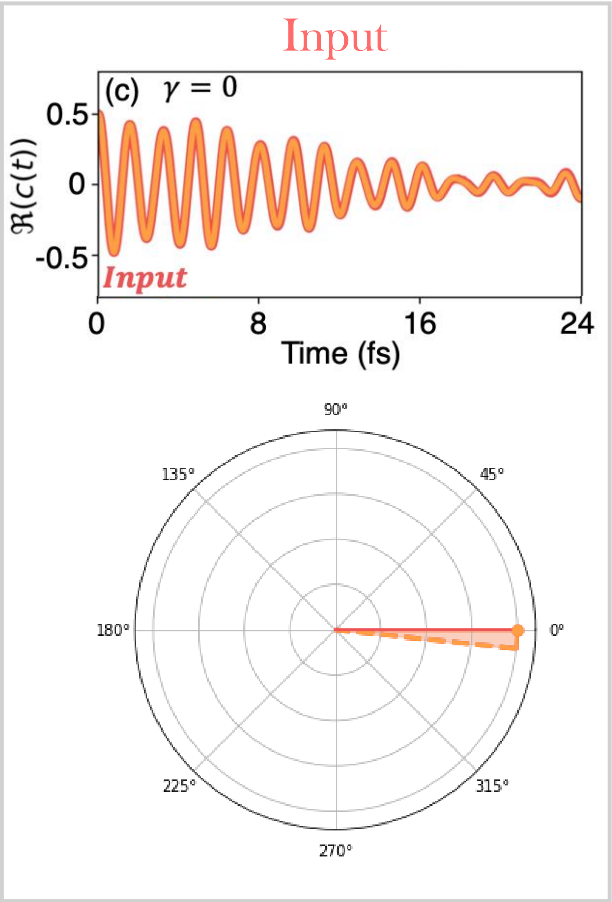
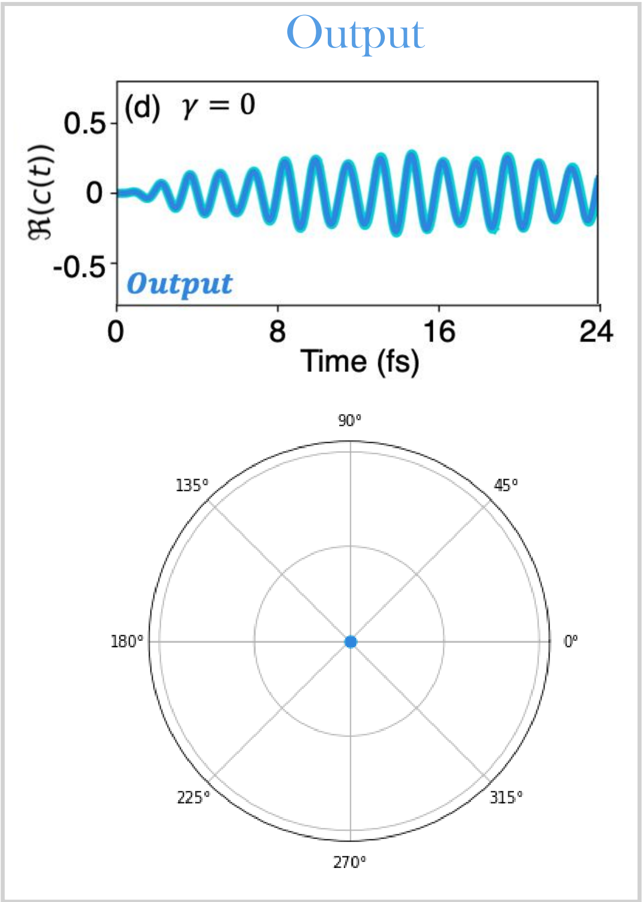
Coherent Frequency Conversion



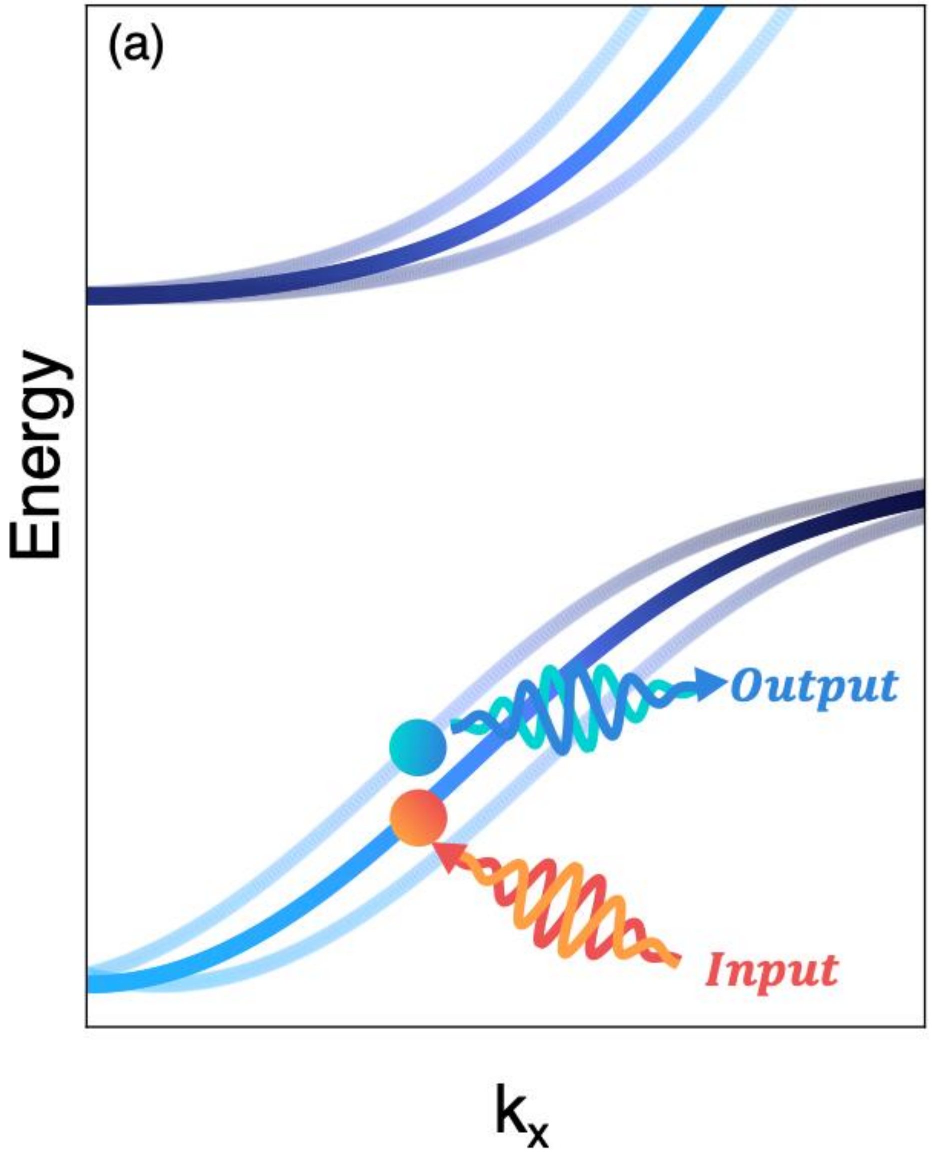
$$\frac{1}{\sqrt{2}}\left(A^\dagger_{k_1} + A^\dagger_{k_2}\right)|0\rangle$$

$$\langle 0|\left(A^\dagger_{k_{1+2\Delta k}} + A^\dagger_{k_{2+2\Delta k}}\right)|\psi(t)\rangle$$

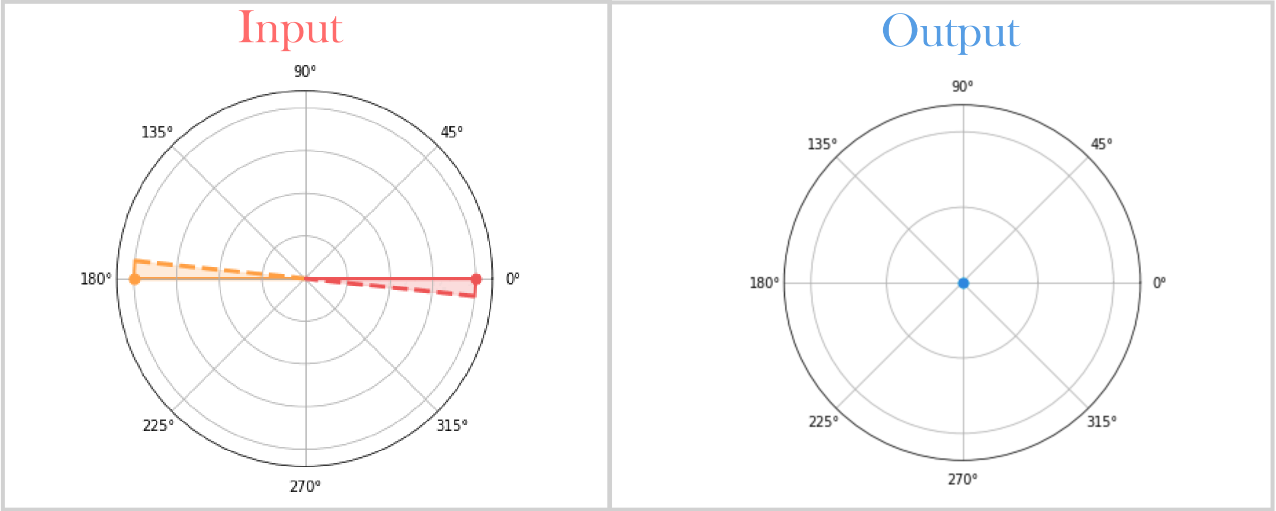




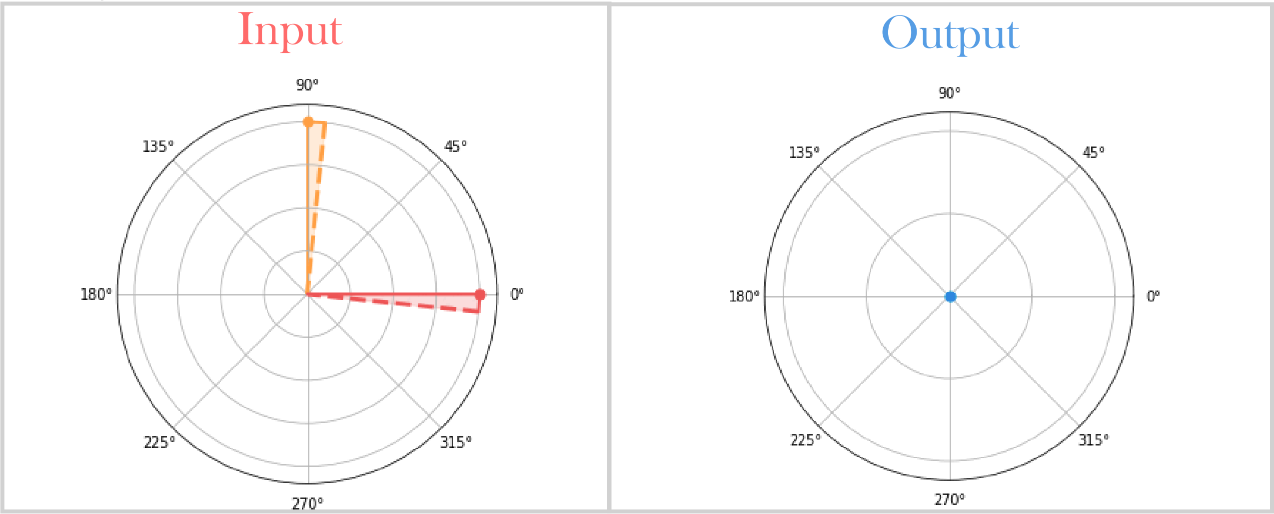
Coherent Frequency Conversion



$$\frac{1}{\sqrt{2}}\left(a_{k_1}^{\dagger} + e^{i\boldsymbol{\pi}} a_{k_2}^{\dagger}\right)|0\rangle$$



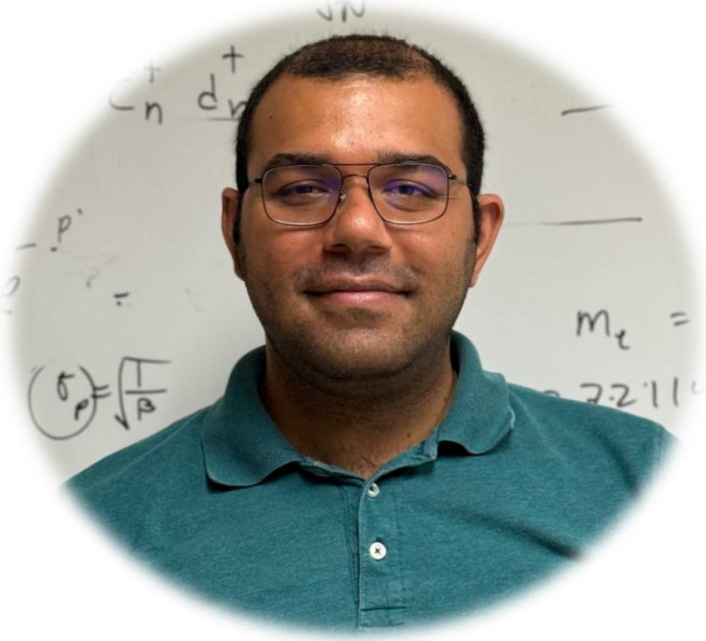
$$\frac{1}{\sqrt{2}}\left(a_{k_1}^{\dagger} + e^{i\frac{\boldsymbol{\pi}}{\mathbf{2}}} a_{k_2}^{\dagger}\right)|0\rangle$$



Summary

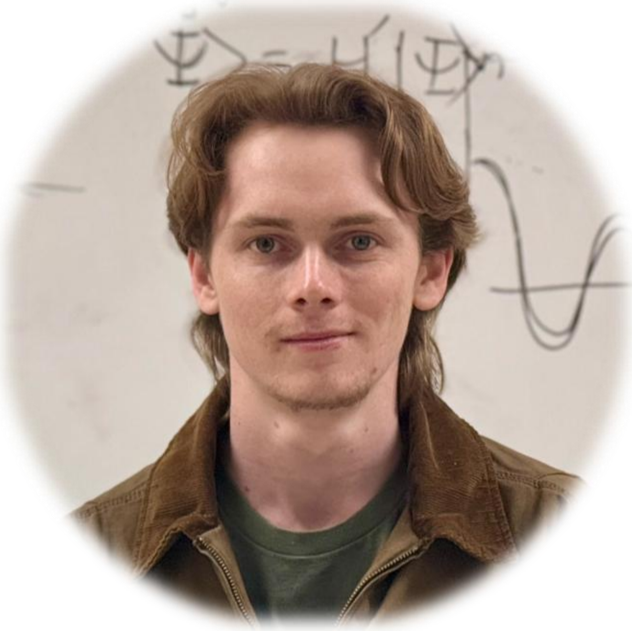
- Multilayer material-cavity configurations give rise to a **phonon-fluctuation synchronization effect**
- This synchronization leads to **enhanced quantum coherence**, accompanied by **more robust polaritonic transport properties**.
- The relaxation pathway from the upper to the lower polariton is strongly modified by the presence of **dark layers**, resulting in a **two-step relaxation mechanism**:
- Step I: A **momentum-conserving direct transition**
- Step II: **Phonon-induced Fröhlich-type intraband scattering**
- When the material is tilted inside the cavity, a **light-matter moiré effect** emerges. However, increasing the material thickness causes this effect to fade away.
- Finally, we derive simple analytical expressions that directly relate a material's finite thickness to its relaxation dynamics and coherence properties.

Acknowledgements



Saeed Rahmanian Koshkaki

Logan Blackham



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