Strongly Interacting Polaritons in Moiré Quantum Materials

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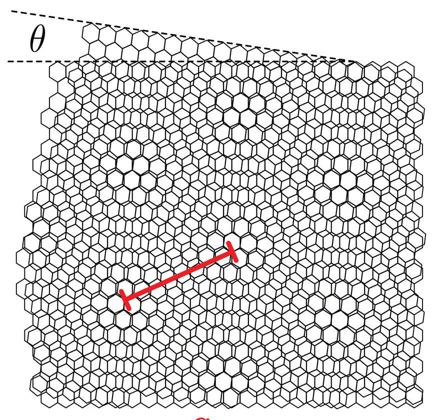
Introduction - Moiré Excitons in a Nutshell

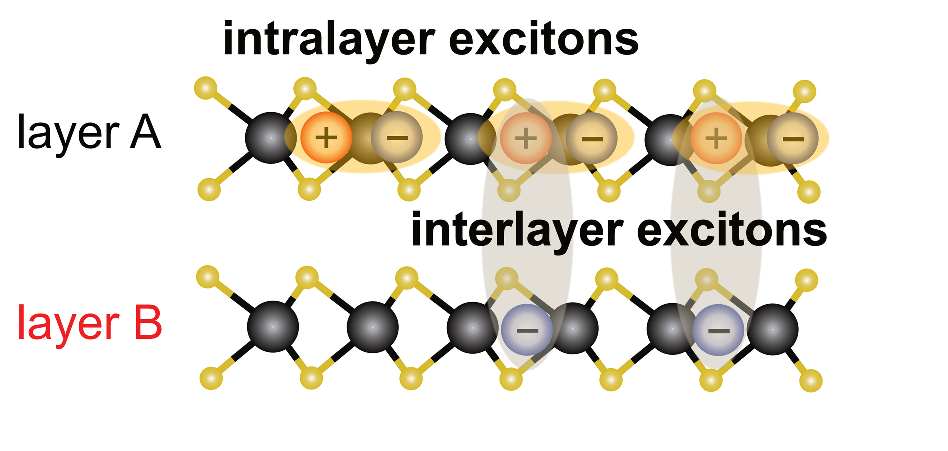
Quantum Materials with a Twist

- Twisting two layers of a two-dimensional quantum material leads to an effective moiré potential where excitons localise at the minima



$$a_\mathrm{M} \approx \frac{a}{\sqrt{\delta^2+\theta^2}} \gg a$$

lattice constant mismatch — twist angle



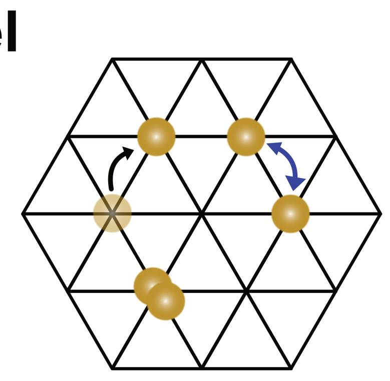
- **intralayer excitons:** strong light-matter coupling, short lifetimes (~ps)
- **interlayer excitons:** indirect excitons (long lifetime ~ns), weak light-matter coupling, strong dipole-dipole interactions (~meV)

$$U\tau_\mathrm{IX} \sim 10^3 - 10^4$$

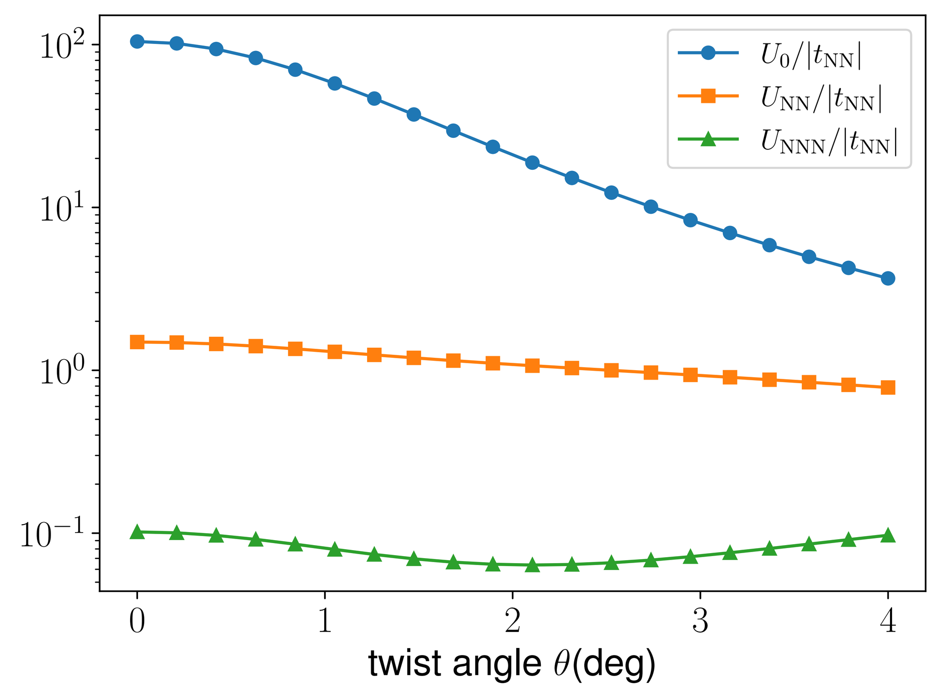
Two-dimensional bilayer materials combine deep subwavelength lattice spacing ($a_M/\lambda \sim 0.01$) with strong interactions and offer an interesting platform for (many-body) quantum optics!

Effective Bose-Hubbard Model

- The lowest band of hybridised moiré excitons can described in terms of effective (long-range) Bose-Hubbard model on a triangular lattice [1]
- The hopping and interaction strength are determined by twist angle



$$H_\mathrm{ex} = \sum_{\langle i,j\rangle} t_\mathrm{NN}\, x_i^\dagger x_j + \sum_j U_0\, x_j^\dagger x_j^\dagger x_j x_j + \sum_{i,j} U_{ij}\, x_i^\dagger x_j^\dagger x_j x_i$$



- Nearest-neighbour hopping is dominant hopping contribution
- On-site and nearest-neighbour interaction are relevant

- $|t_\mathrm{NN}| \approx 0.1 - 2.6\,\mathrm{meV}$
- $U_0 \approx 8.9 - 9.6\,\mathrm{meV}$

Exciton-Polariton Scattering and Nonlinearity

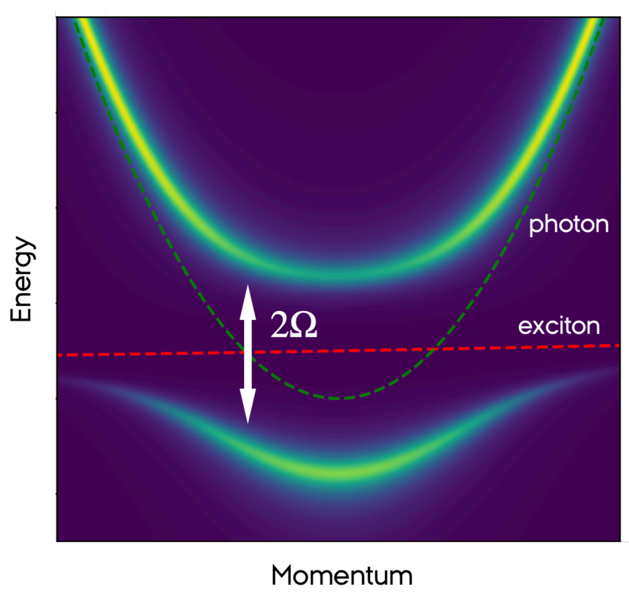
Exciton-Polaritons

$$H = H_\mathrm{ex} + \sum_{\mathbf{k}\in\mathrm{mBZ}} \left(\frac{\hbar^2|\mathbf{k}|^2}{2m_c} + \delta\right) a_\mathbf{k}^\dagger a_\mathbf{k}$$

photon dynamics in 2D plane

$$+\,\Omega\,(a_\mathbf{k}^\dagger x_\mathbf{k} + x_\mathbf{k}^\dagger a_\mathbf{k})$$

exciton-photon coupling



- **Use exciton interaction to induce effective photon-photon interaction**

Photon Nonlinearity

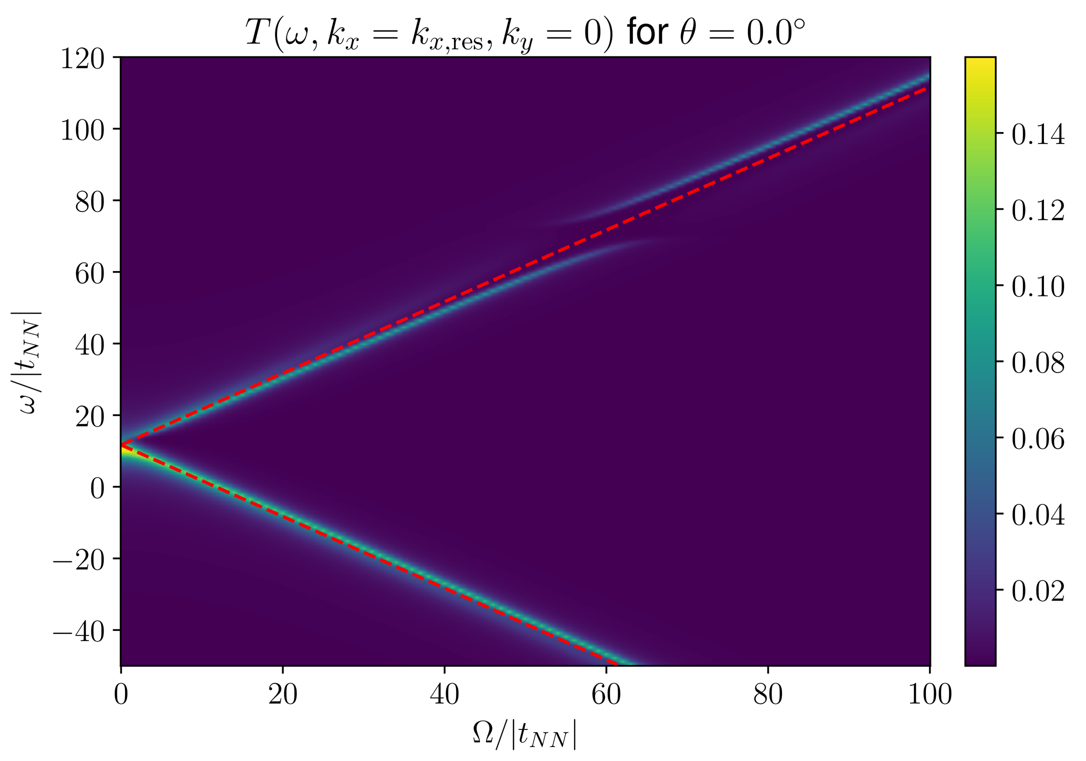
- Photon transmission is proportional to photonic part of the (many-body) Green's function $\quad T(\omega,\mathbf{k}) \propto |G_c(\mathbf{k},\omega)|^2$

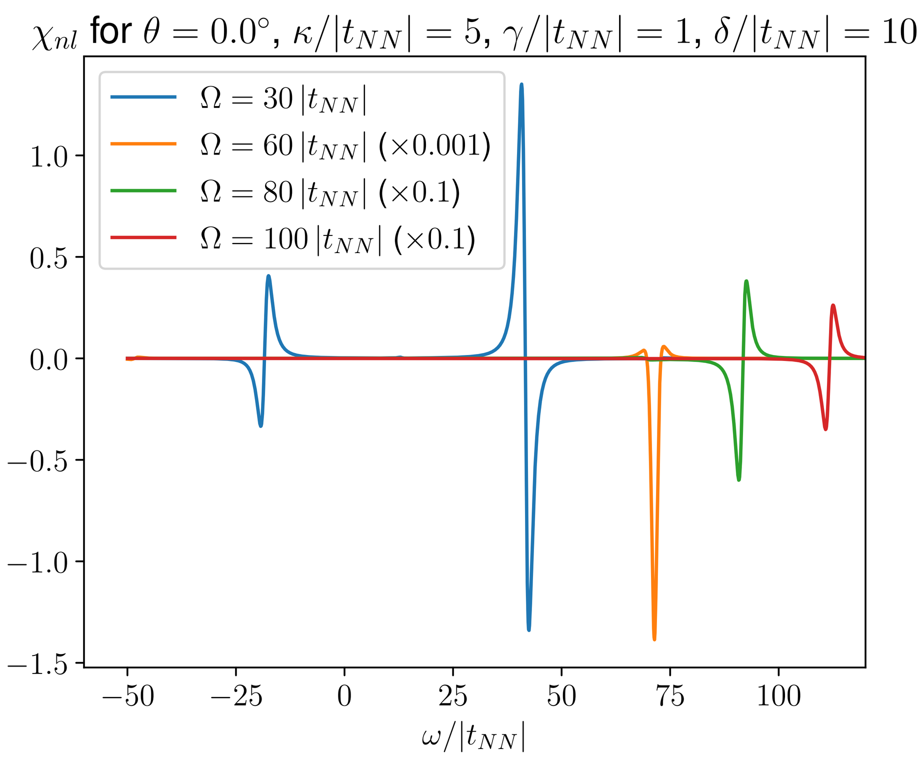
$$G_c^{-1}(\mathbf{k},\omega) = \omega - \left(\varepsilon_c(\mathbf{k}) - i\frac{\kappa}{2}\right) - \frac{\Omega^2}{\omega - \left(\varepsilon_X(\mathbf{k}) + n_X\Gamma_{XX} - i\frac{\gamma}{2}\right)}$$

- Scattering resonances lead to strong interaction-induced shifts of the polariton transmission line

nonlinear transmission coefficient

$$T = T_0\,(1 + \chi_{nl} I)$$



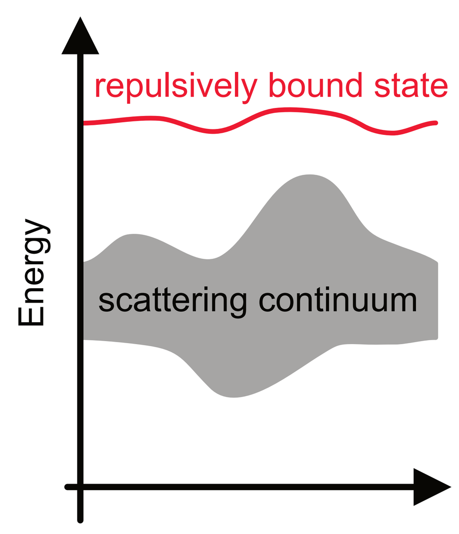


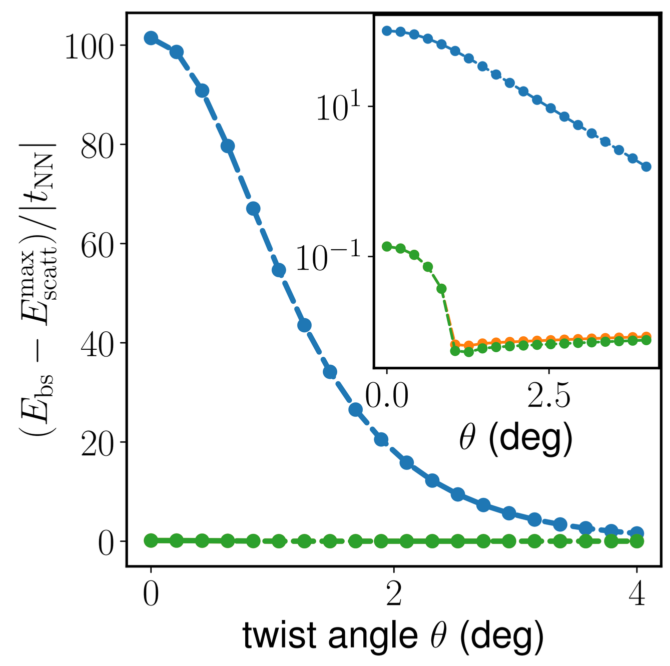
- **The upper polariton experiences splitting on resonance due to coupling to repulsively bound state, the lower polariton does not experience this splitting**
- **Below (above) resonance, the shift is attractive (repulsive)**

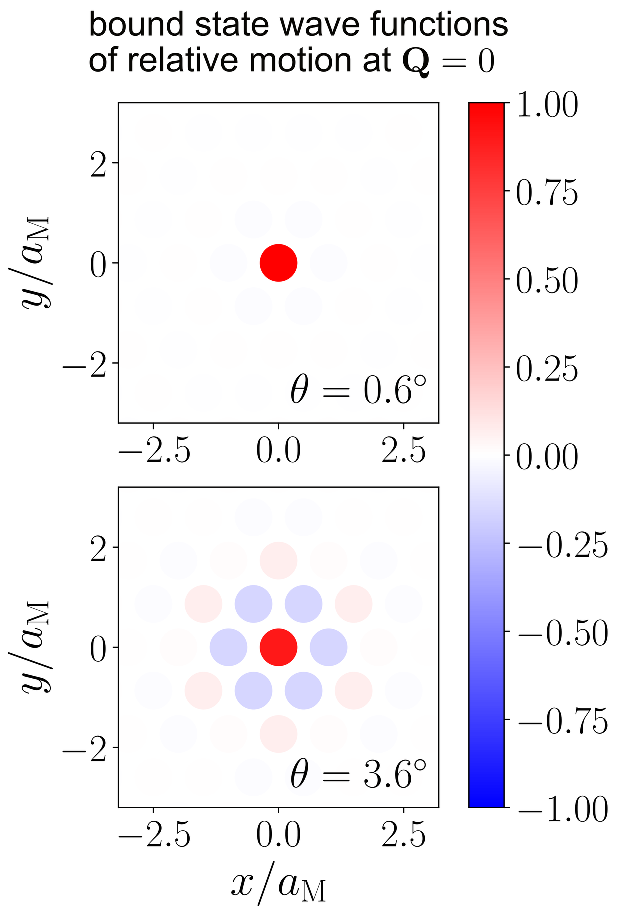
Exciton-Exciton Scattering - Bound States

Repulsively Bound Pairs in a Moiré Lattice

- Repulsively bound pair is unable to convert interaction (binding) energy to kinetic energy due to finite width of Bloch band [2]
- In one and two dimensions, repulsively bound pairs exist for arbitrarily small (on-site) interactions strengths







- **Additional (loosely) bound states appear below a critical twist angle (above critical interaction strength) due to long-range interactions**

Modified Exciton-Polariton Scattering

- Exciton scattering is modified due to the light-matter coupling (scattering in the presence of polariton background)
- We restrict the analysis to on-site interactions (still due to dipolar interactions within one moiré cell!)

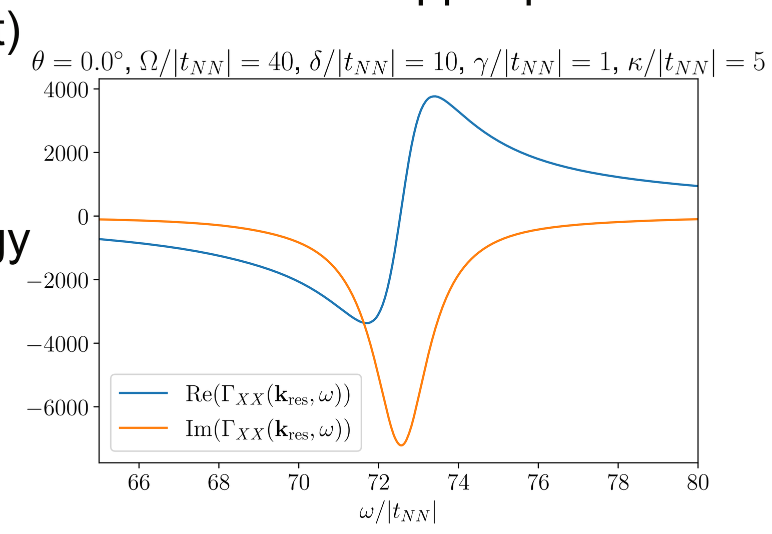
$$\Gamma_{XX}(\mathbf{Q},\omega) = \frac{U_0}{1 - U_0\Pi(\mathbf{Q},\omega)}$$

$$\Pi(\mathbf{Q},\omega) = \sum_{\mathbf{q}\in\mathrm{mBZ}} \sum_{\alpha,\beta=\mathrm{LP,UP}} \frac{\nu_\mathrm{X}^\alpha(\mathbf{Q}/2+\mathbf{q})\,\nu_\mathrm{X}^\beta(\mathbf{Q}/2-\mathbf{q})}{\omega - \varepsilon_\alpha(\mathbf{Q}/2+\mathbf{q}) - \varepsilon_\beta(\mathbf{Q}/2-\mathbf{q}) + i\eta}$$

$\varepsilon_\mathrm{LP/UP}(\mathbf{k})$: energy of lower/upper polariton

$\nu_\mathrm{X}^\mathrm{LP/UP}(\mathbf{k})$: (hybrid) exciton contribution to lower/upper polariton (Hopfield coefficient)

- Scattering matrix has narrow resonance at the bound state energy



References

[1] A. Julku, Phys. Rev. B **106**, 035406 (2022)
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