LMC3 – Cavity Quantum Materials

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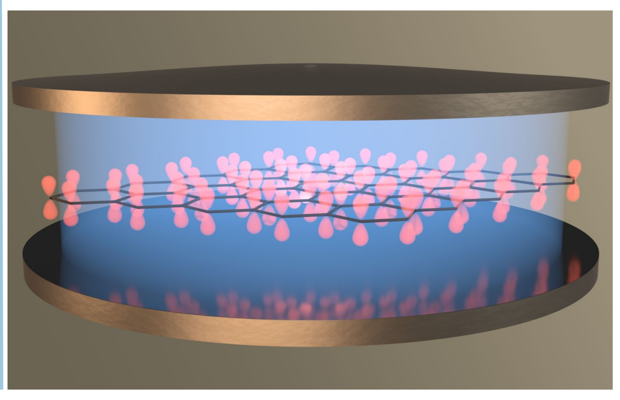
Background



Instead of irradiating materials with strong lasers, control over materials using the vacuum fluctuations of the electromagnetic field that can be shaped using optical resonators has been proposed [1]. We explore the coupling between band electrons and light [2], study an exactly solvable model for band electrons coupled to a cavity [3] and further investigate control over electron-electron interactions by coupling a cavity to optical phonons [4].

Light-matter coupling in multi-band systems

The coupling between band electrons and light is intrinsically related to the geometry of the electronic wave functions rather than only to the band structure [2].

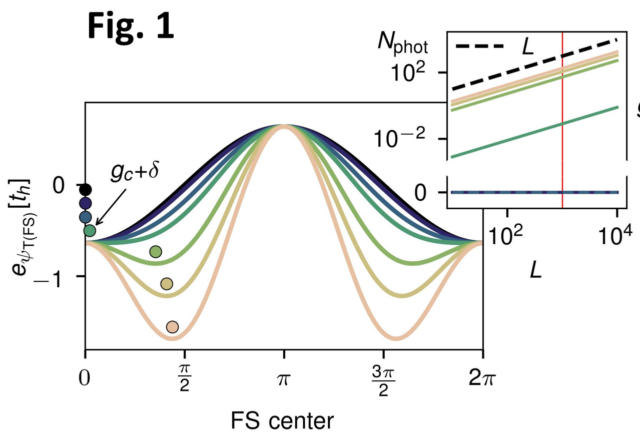
	Linear (A_μ)	**Quadratic** $(A_\mu A_\nu)$
Intra-band (n)	$\partial_\mu \varepsilon_n$	$\partial_\mu\partial_\nu\varepsilon_n - \sum_{n\neq n'}(\varepsilon_n - \varepsilon_{n'})\left(\langle\partial_\mu n\,\vert n'\rangle\langle n'\,\vert\partial_\nu n\rangle + \text{h.c.}\right)$
Inter-band $(n,\, m)$	$(\varepsilon_n - \varepsilon_m)\langle m\,\vert\partial_\mu n\rangle$	$\Big[(\partial_\mu\varepsilon_n - \partial_\mu\varepsilon_m)\langle m\,\vert\partial_\nu n\rangle + \frac{1}{2}\varepsilon_m\langle\partial_\mu\partial_\nu m\,\vert n\rangle + \frac{1}{2}\varepsilon_n\langle m\,\vert\partial_\mu\partial_\nu n\rangle + \sum_{n'}\varepsilon_{n'}\left(\langle\partial_\mu m\,\vert n'\rangle\langle n'\,\vert\partial_\nu n\rangle\right)\Big] + (\mu\leftrightarrow\nu)$

This has striking consequences in flat-band systems: Here the linear intra-band coupling vanishes. The quadratic intra-band coupling contains a quantum-geometric term together with the linear coupling to other, potentially dispersive bands. We show that these features are particularly relevant in moire systems featuring flat bands with nontrivial quantum geometry.

1D chain inside a cavity - an exactly solvable model

We study an exactly solvable model to understand interactions between a single cavity mode and band electrons – a 1D chain coupled to a single mode of an optical resonator [3].

Fig. 1



$$\hat{H} = \omega_0\left(\hat{a}^\dagger\hat{a} + \tfrac{1}{2}\right) - \sum_{j=1}^{L} t_h e^{-i\frac{g}{\sqrt{L}}\left(\hat{a}^\dagger + \hat{a}\right)}\hat{c}^\dagger_{j+1}\hat{c}_j + \text{h.c.}$$

At T=0 the system is in a product state between the electronic ground-state of the uncoupled chain and a squeezed state of photons. We warn that truncations of the light-matter coupling break gauge invariance and can lead to a false superradiant phase hosting a current in the ground-state accompanied by a photon number that scales with the system size, reminiscent of the superradiant phase transition in the Dicke model (Fig.1).

Fig. 2

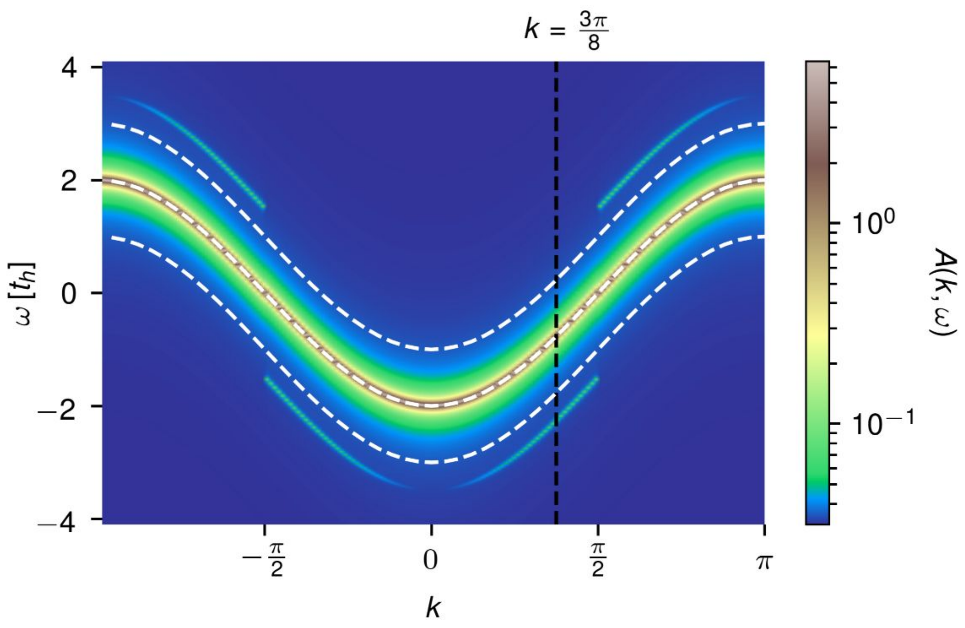
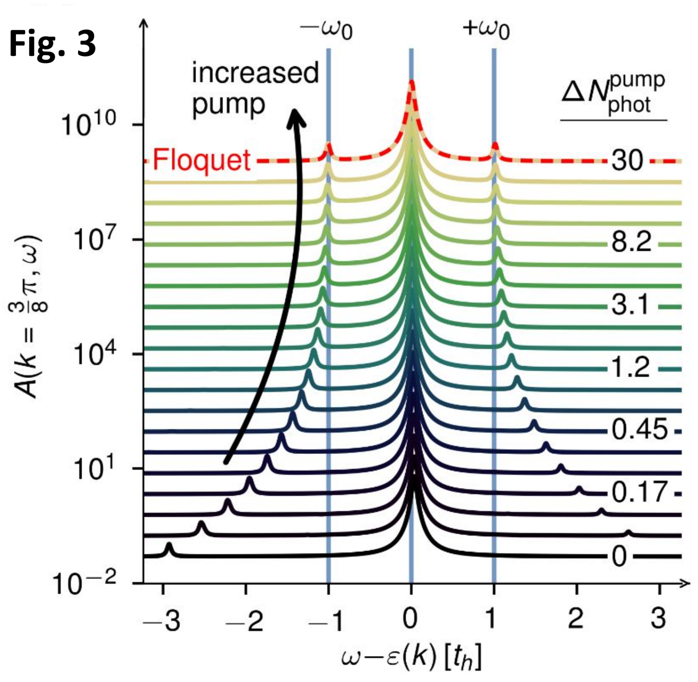


Fig. 3



The electronic spectral function shows quantum analogs to Floquet results, like quantum shake-off bands and dynamical localization induced by vacuum fluctuations (Fig. 2). The classical Floquet limit is recovered when the cavity is prepared in a coherent state with large photon number (Fig. 3). The Drude peak in the optical conductivity (not shown) is suppressed by the presence of the cavity, similarly to the free electron gas [Rokaj et al., PRResearch 4, 013012 (2022)].

References

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[3] CJE, G. Passetti, M. Othman, C. Karrasch, F. Cavaliere, MAS, DMK, arXiv:2107.12236 (2021), to appear in a Communications Physics Focus Collection.

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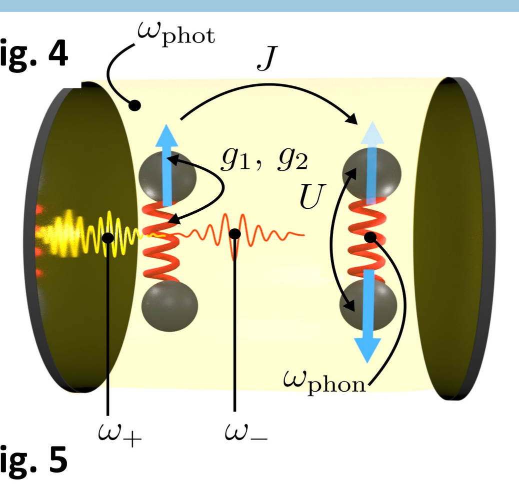
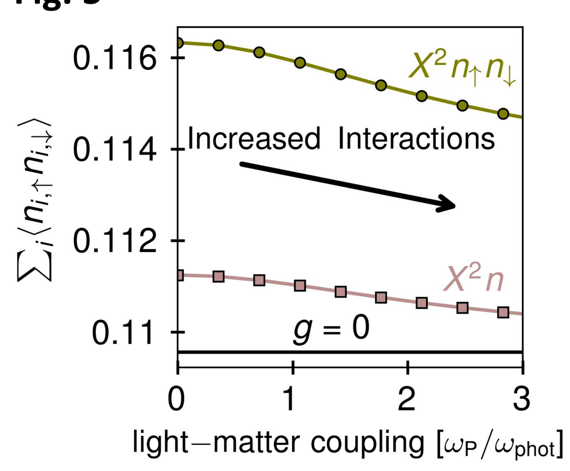
Cavity control of electron-electron interactions

Fig. 4



Control of electron-electron interactions with lasers has previously been achieved by driving an IR-active optical phonon in organic molecular compounds [Buzzi et al., PRX 10, 031028 (2020)]. IR-active phonons hybridize with photons inside a cavity to form phonon polaritons (Fig. 4). Here we explore the possibility to influence effective electron-electron interactions via phonon polaritons [4].

Fig. 5



$$\hat{H} = \hat{H}_{e^-} + \hat{H}_{phon} + \hat{H}_{phot} + \hat{H}_{e^- - phon} + \hat{H}_{phon-phot}$$

$$\hat{H}_{e^-} = -J\sum_{\sigma\in\{\uparrow,\downarrow\}}\left(\hat{c}^\dagger_{1,\sigma}\hat{c}_{2,\sigma} + h.c.\right) + U\sum_{j\in\{1,2\}}\left(\hat{n}^{el}_{j,\uparrow} - \frac{1}{2}\right)\left(\hat{n}^{el}_{j,\downarrow} - \frac{1}{2}\right)$$

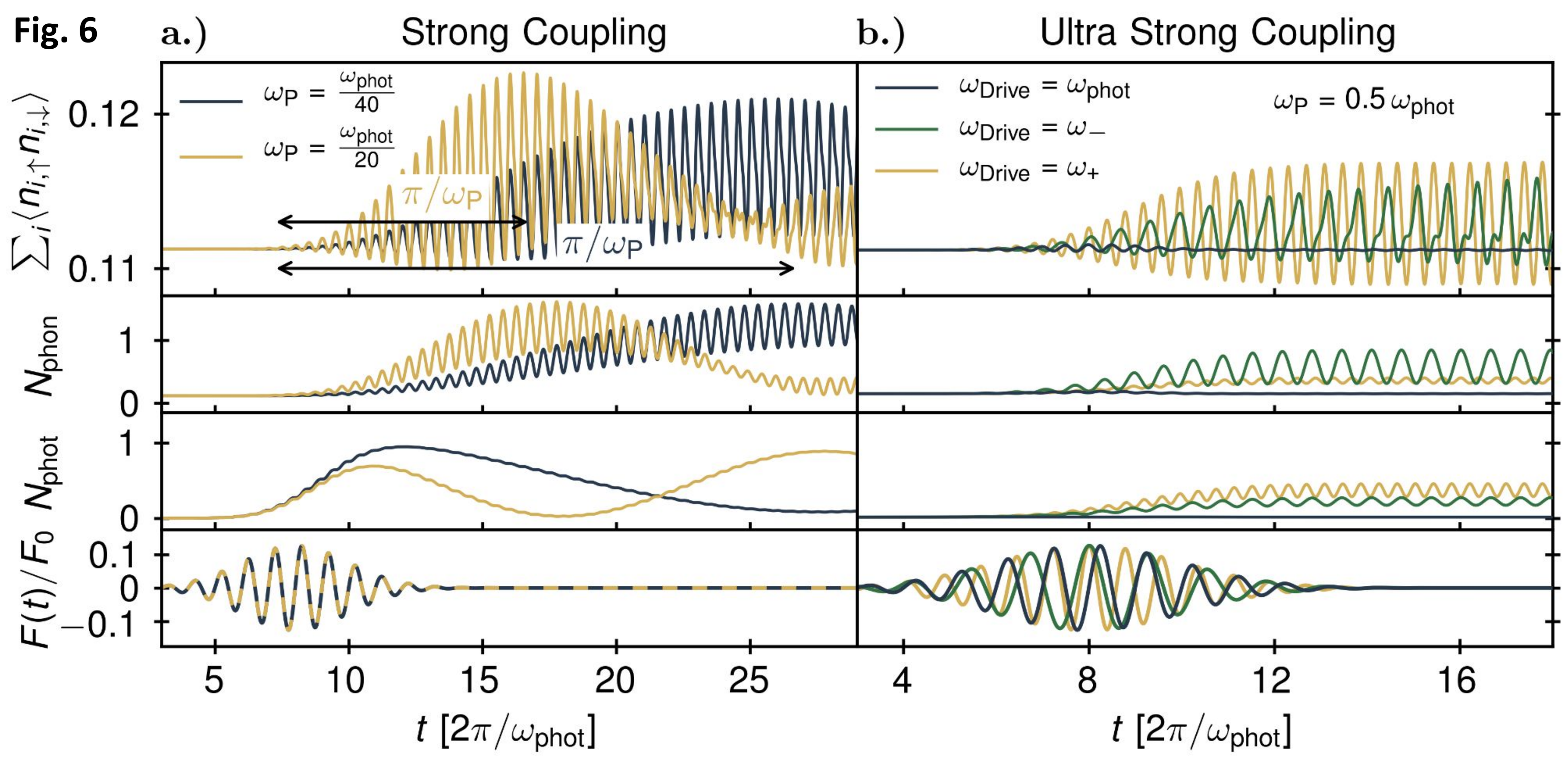
$$\hat{H}_{phon} + \hat{H}_{phot} = \sum_j \omega_{phon}\,\hat{b}^\dagger_j\hat{b}_j + \omega_{phot}\,\hat{a}^\dagger\hat{a}$$

$$\hat{H}_{phon-e^-} = \sum_j g_1\left(\hat{b}_j + \hat{b}^\dagger_j\right)^2\left(\hat{n}^{el}_{j,\uparrow} + \hat{n}^{el}_{j,\downarrow}\right) + g_2\left(\hat{b}_j + \hat{b}^\dagger_j\right)^2\hat{n}^{el}_{j,\uparrow}\hat{n}^{el}_{j,\downarrow}$$

$$\hat{H}_{phon-phot} = \sum_j\left[i\left(\frac{\omega_P\sqrt{\omega_{phon}}}{2\sqrt{2}\sqrt{\omega_{phot}}}\right)\left(\hat{a} + \hat{a}^\dagger\right)\left(\hat{b}_j - \hat{b}^\dagger_j\right)\right] + \left(\frac{\omega_P^2}{4\,\omega_{phot}}\right)\left(\hat{a} + \hat{a}^\dagger\right)^2$$

In a dark cavity, formation of phonon polaritons increases electron-electron interactions leading to a decrease in the double occupancy in the ground-state (Fig. 5).

Fig. 6

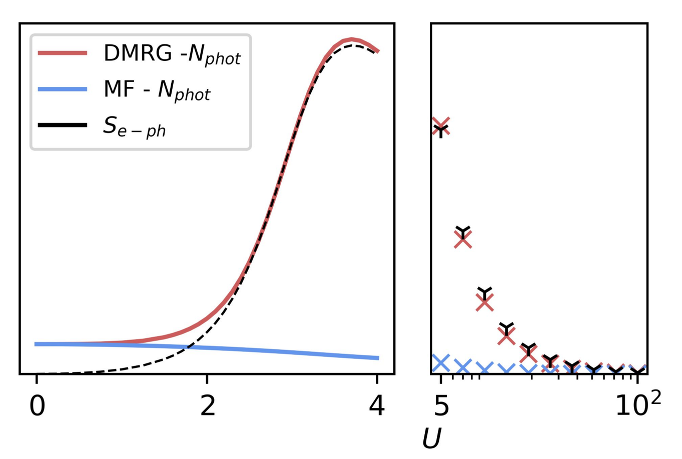


Upon weak driving of the cavity (~1 photon) electronic correlations decrease. In the strong coupling regime – where the light-matter coupling outweighs cavity losses – the em-field of the cavity and the lattice vibrations undergo a beating motion enabling complete energy transfer from the photons to the phonons irrespective of the strength of the light-matter coupling (Fig. 6a). In the ultra strong coupling regime light and matter degrees of freedom are significantly hybridized changing the resonant frequencies of the system (Fig. 6b).

Ongoing Work

Interacting electrons coupled to a cavity
Interacting spinless electrons (XXZ model) are coupled to a cavity via the Peierls substitution. Close to the critical point of the BKT transition to a charge-density wave we observe a non-trivial, entangled wave function (Fig. 7). Within our finite-size calculation, this leads to a shift of the phase transition.

Fig. 7

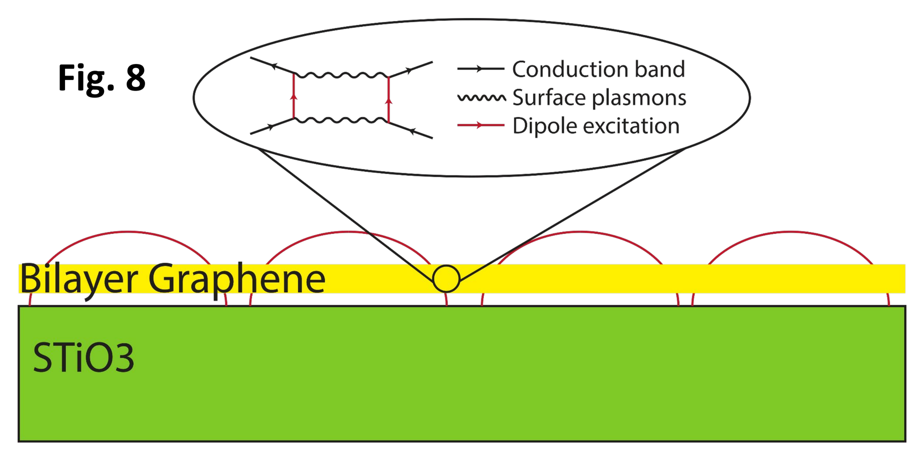


$$\hat{H} = -t_h\sum_{i=1}^{L}\left(e^{ig(\hat{a}^\dagger + \hat{a})}\hat{c}^\dagger_i\hat{c}_{i+1} + \text{h.c.}\right) + U\sum_{i=1}^{L}\left(\hat{n}_i - \tfrac{1}{2}\right)\left(\hat{n}_{i+1} - \tfrac{1}{2}\right) + \omega_{phot}\hat{a}^\dagger\hat{a}$$

Cavity-mediated superconductivity in flat band systems
Cavity-mediated superconductivity was proposed by Schlawin et al., PRL 122, 133602 (2019). We are exploring the possibility of realizing this in flat-band systems (where competing energy scales are small) via the geometric terms in the light-matter coupling.

Surface-matter hybrids
Nonlinear electron-phonon interactions, previously used to explain decreased electron-electron interactions upon optical driving, can be derived from linear coupling of a phonon to a dipole transition. We use this insight to explain how phonons can mediate an attractive electron-electron interaction. As a platform to test our predictions we propose bilayer graphene on top of a $SrTiO_3$ substrate where dipole excitations couple to the surface plasmons (Fig. 8).

Fig. 8



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