

# Atoms trapped within Photonic Crystals: using quantum optics to simulate coherent and dissipative many-body physics.

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Nanophotonics provides us with structures such as Photonic Crystals (PhCs) that allow to control and mold light at subwavelength scales [1], i.e., confining light to reduced dimensionalities (2d, 1d and 0d). Recently, the integration of atomic systems with 1d and 0d nanophotonic structures has been experimentally achieved [2–7]. In this talk, we show how to exploit some characteristics of this new hybrid system (atom-nanophotonics) for the simulation of closed & open quantum systems [8].

First we show how to use PhCs waveguides to build high-density 2d optical lattices for ultra cold atoms by using combination of optical and Casimir Polder forces. The reduced atomic spacing yields larger energy scales for the simulation of Bose-Hubbard (see Fig. 1) and spin models [8] and therefore less stringent temperature requirements. Moreover, when the atoms are trapped close within the dielectric, they exchange interactions with the photonic modes of the structure that give rise to collective couplings dependent on the dimensionality and density of modes of the photon reservoir, described by a master equation:

$$\dot{\rho} = \sum_{i,j} \sum_{\beta=xy,z} \Gamma_{ij}^{\beta} (\mathcal{O}_i^{\beta} \rho (\mathcal{O}_j^{\beta})^{\dagger} - (\mathcal{O}_j^{\beta})^{\dagger} \mathcal{O}_i^{\beta} \rho) + \text{h.c.} \quad (1)$$

where  $\Gamma_{ij}^{\beta} = \gamma_{ij}^{\beta}/2 + iJ_{ij}^{\beta} = h_{\beta} \Gamma_{2d} F^{\beta}(r_{ij})$  and  $\mathcal{O}_i^{\beta}$  is a spin operator that can be both  $\sigma_i$  and  $\sigma_i^z$  for  $\beta = xy, z$ , respectively.  $F^{\beta}(r_{ij})$  is a function whose form depends on the detuning of the atomic transitions to the bandgaps, e.g., when  $\Delta_{\beta} > 0$ ,  $F^{\beta}(r_{ij})$  has both real and imaginary components given by

$$\Gamma_{ij}^{\beta} |_{\Delta_{\beta} > 0} = \frac{\pi}{2} h_{\beta} \Gamma_{2d} H_0^{(1)}[r_{ij}/\xi_{\beta}], \quad (2)$$

where  $H_0^{(1)}(x)$  is a Hankel function of the first kind, and the length scale  $\xi_{\beta}$  can be controlled independently via the detuning,  $\Delta_{\beta}$ . By contrast, when  $\Delta_{\beta} < 0$ ,  $\Gamma_{ij}^{\beta}$  are purely imaginary:  $\Gamma_{ij}^{\beta} |_{\Delta_{\beta} < 0} = iJ_{ij}^{\beta}$ , with  $J_{ij}^{\beta}$ . Ultimately, the modified Bessel function  $K_0(x)$  is damped by an exponential factor controlled by  $\xi_{\beta}$ , that can be tuned dynamically through the detuning  $\Delta_{\beta}$  and made large enough to guarantee that we reach the limit  $x = r_{ij}/\xi_{\beta} \ll 1$ , where  $J_{ij}^{\beta}$  is of strongly long-range character as depicted in Fig. 1(c). In this regime, we engineer then the following general class of XXZ spin Hamiltonians:

$$H = \sum_{i,j} [J_{ij}^z \sigma_i^z \sigma_j^z + J_{ij}^{xy} \sigma_i^{\dagger} \sigma_j], \quad (3)$$

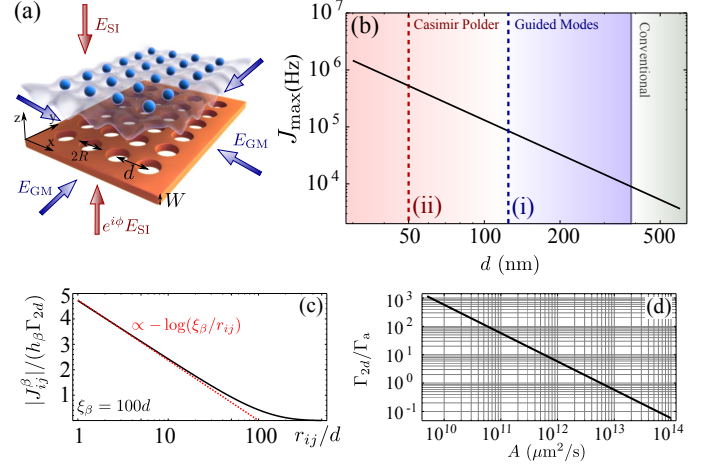


FIG. 1. (a) General scheme for a nanophotonic lattice. (b) Scaling of maximum tunneling as a function of lattice periodicity  $d$  for Rb. (c) Spatial dependence of spin-spin interaction,  $J_{ij}^{\beta}/(h_{\beta} \Gamma_{2d})$ , as a function of distance  $r_{ij}/d$ . (d) Scaling of  $\Gamma_{2d}/\Gamma_a$  with guided mode band curvature  $A$ .

where  $J_{ij}^{z(xy)}$  can be tuned independently by changing the laser intensities,  $\Omega_l$  or effective detunings,  $\Delta_{\beta}$ .

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