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Light-matter interface based on dense, ordered atomic lattices

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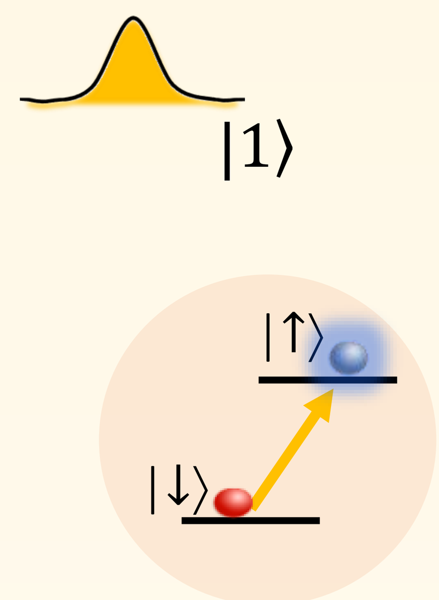
Abstract

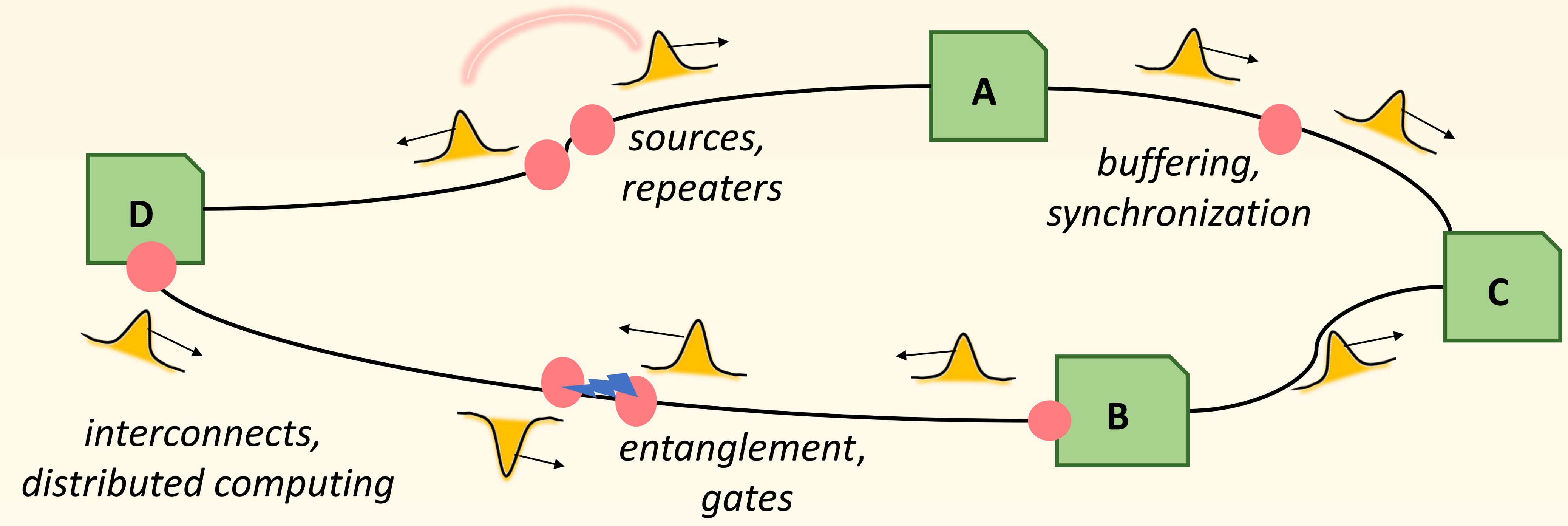
Strong coupling between a single propagating mode of light and defect-free atomic 2D arrays was recently demonstrated with subwavelength (`microscopic') inter-atomic separation. To benefit from the simplicity, flexibility, and scalability of optical tweezers arrays, we propose to extend this scheme to atomic arrays with `mesoscopic' separations, slightly above the optical wavelength. We will develop and construct such mesoscopic atomic arrays and, by exploiting either several atomic layers or an additional moderate-finesse cavity, suppress their coupling to high-order diffraction modes and maximize the coupling (cooperativity) to a single optical mode, such that quantum state transfer from light to the collective excitation of the atomic array can be realized.

Light-Matter mapping

$$|\text{light}\rangle = \alpha|0\rangle + \beta|1\rangle$$

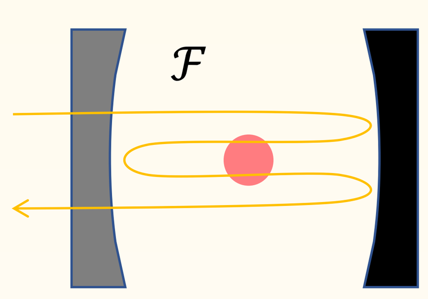
$$|\text{atom}\rangle = \alpha|\downarrow\rangle + \beta|\uparrow\rangle$$





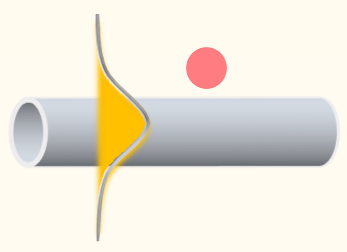
Increasing optical cooperativity

Cavity QED



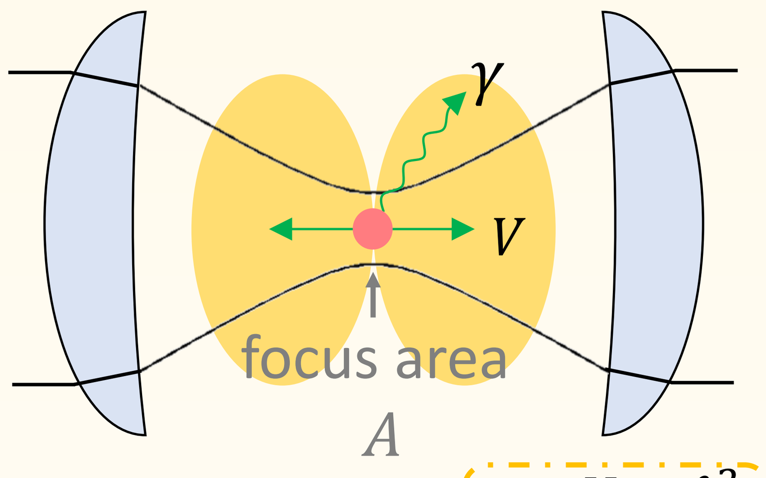
$C = \mathcal{F} \cdot \frac{\lambda^2}{A} \gg 1$

Waveguide QED



$A \ll \lambda^2$

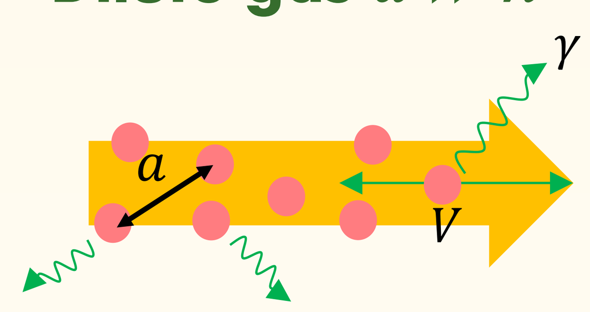
$C = \frac{\lambda^2}{A} \gg 1$



Cooperativity $C = \frac{V}{\gamma} \propto \frac{\lambda^2}{A}$

Reflectivity\Efficiency $r = \frac{V}{V+\gamma} = \frac{C}{C+1}$

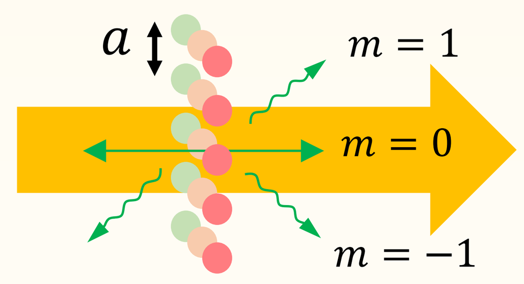
Dilute gas $a \gg \lambda$



Independent emitters (OD)

$$C = \text{"\#atoms"} \cdot \frac{V}{\gamma}$$

Dense array $a \sim \lambda$

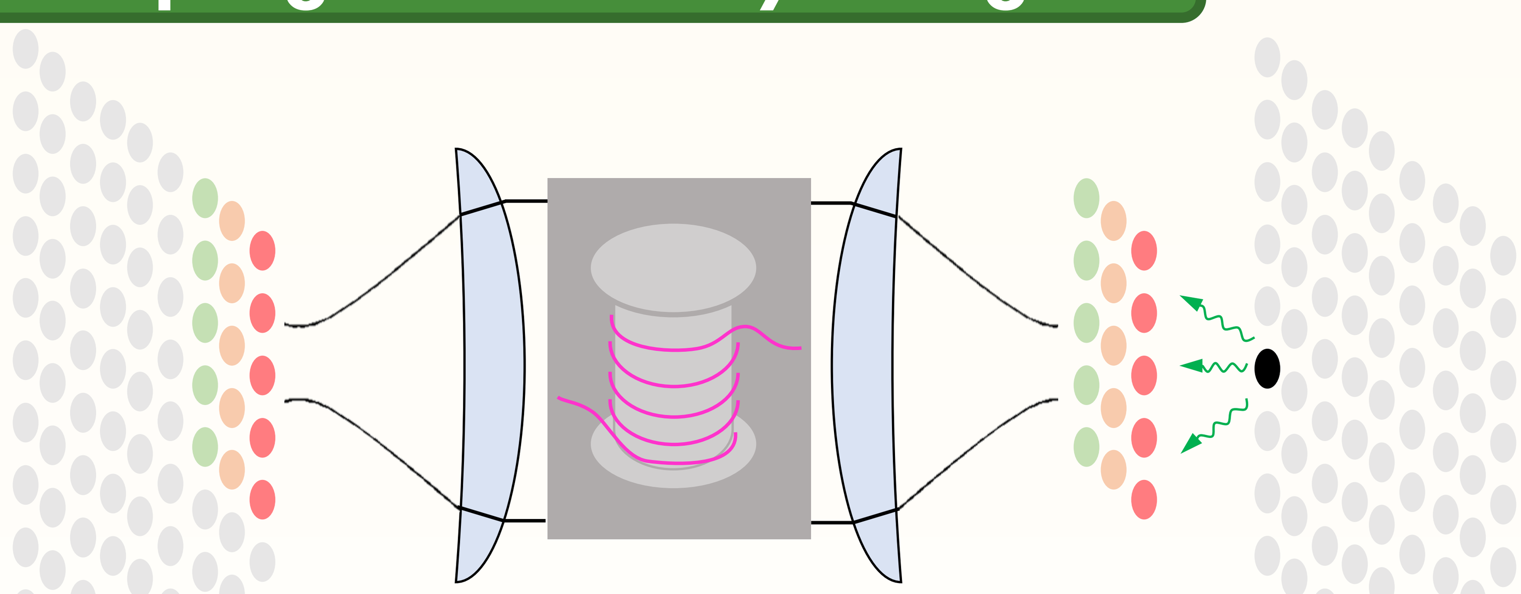


Collective response + spatial **order**

discrete scattering modes ($m = 0 \to$ "γ" $= 0$)

$$C = \frac{V}{\gamma} \to \infty$$

Coupling atomic arrays to light



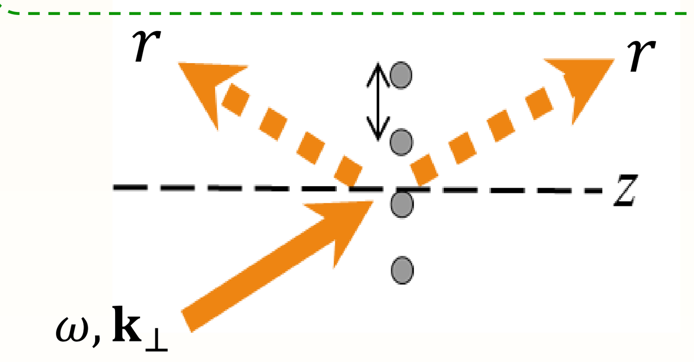
collectivity + order →

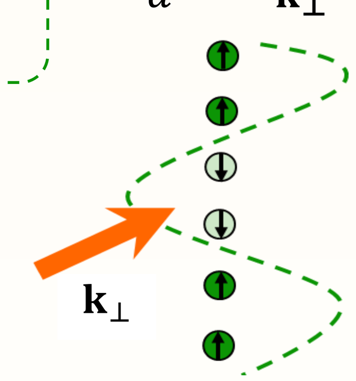
strong & directional light-matter interface

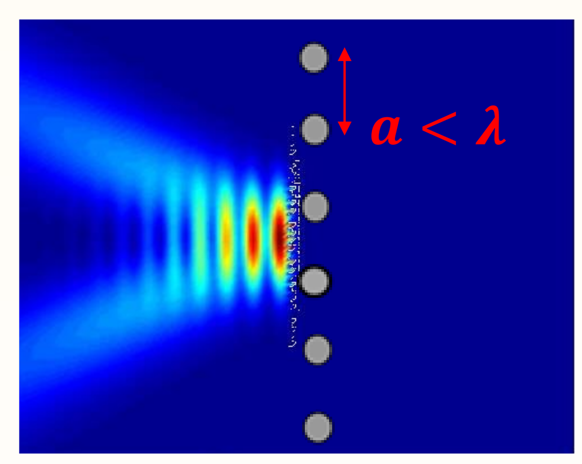
Subwavelength atom array ($a < \lambda$)

Light scattering: directional, reflectivity

$$r = -\frac{i\Gamma/2}{(\omega - \omega_a - \Delta) + i\Gamma/2}$$







ES, Wild, Lukin, Yelin, PRL (2017)
Bettles, Gardiner, Adams, PRL (2016)

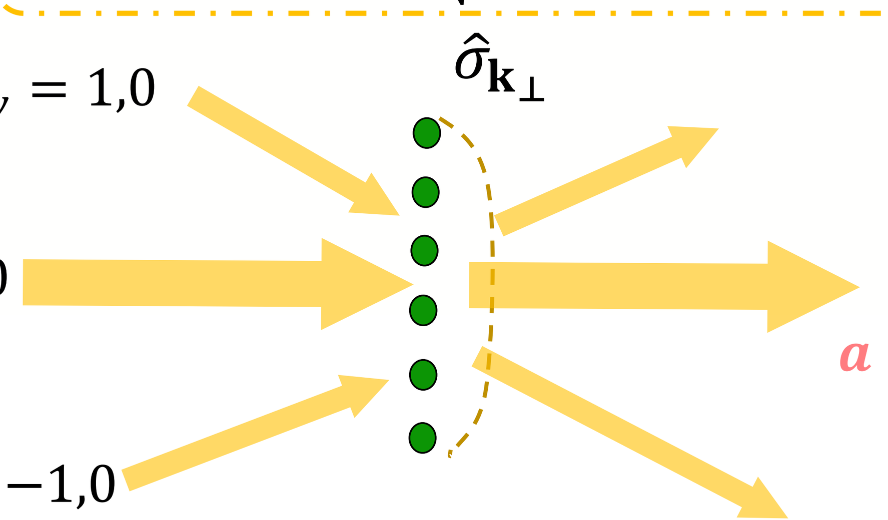
$\omega = \omega_a + \Delta_{\mathrm{k}} \to$ $\boldsymbol{r = -1}$ **"Perfect" mirror** (tunable, robust)

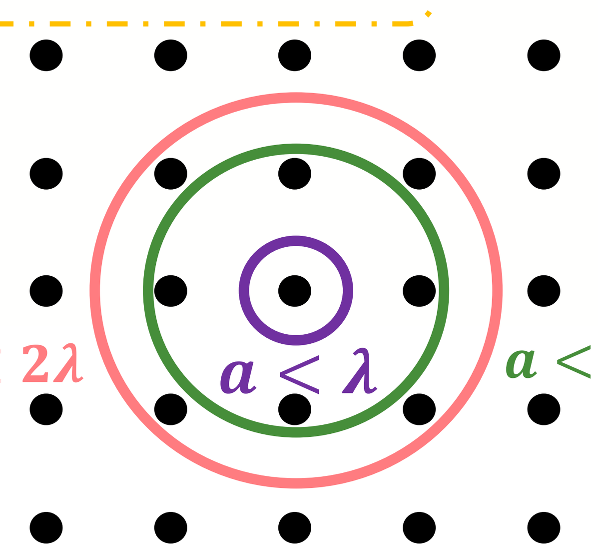
Scattering off "super-wavelength" atomic array ($a > \lambda$)

Coupling to light: $\mathbf{k}_\perp^{m_x,m_y} = \mathbf{k}_\perp + \mathbf{q}_{m_x,m_y} \quad \mathbf{q}_{m_x,m_y} = \frac{2\pi}{a}(m_x e_x + m_y e_y)$

"symmetric" dipole $\mathbf{k}_\perp = 0 \to \mathbf{k}_\perp^{(m_x,m_y)} = \mathbf{q}_{m_x m_y}$

$$k_z^{(m_x,m_y)} = \frac{2\pi}{\lambda}\sqrt{1 - (\lambda/a)^2(m_x{}^2 + m_y{}^2)} \in \text{Re}$$





Integration of Low - $\mathcal{F}$ cavity can increase C