Superabsorption of light via quantum engineering

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About this research group...

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Superabsorption of light via quantum engineering

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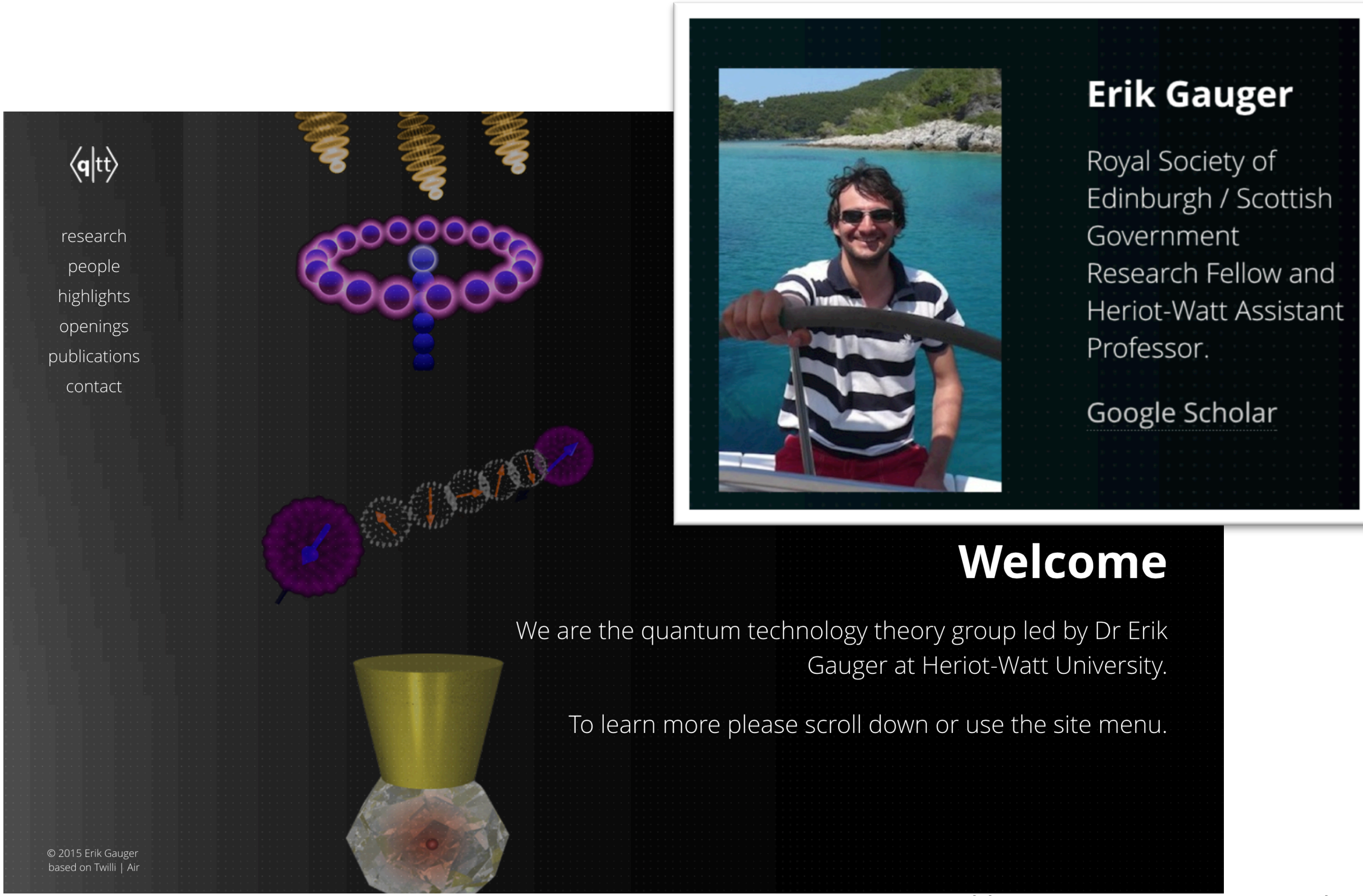
Almost 60 years ago Dicke introduced the term superradiance to describe a signature quantum effect: N atoms can collectively emit light at a rate proportional to N^2. Structures that superradiate must also have enhanced absorption, but the former always dominates in natural systems. Here we show that this restriction can be overcome by combining several well-established quantum control techniques. Our analytical and numerical calculations show that superabsorption can then be achieved and sustained in certain simple nanostructures, by trapping the system in a highly excited state through transition rate engineering. This opens the prospect of a new class of quantum nanotechnology with potential applications including photon detection and light-based power transmission. An array of quantum dots or a molecular ring structure could provide a suitable platform for an experimental demonstration.

About this research group…



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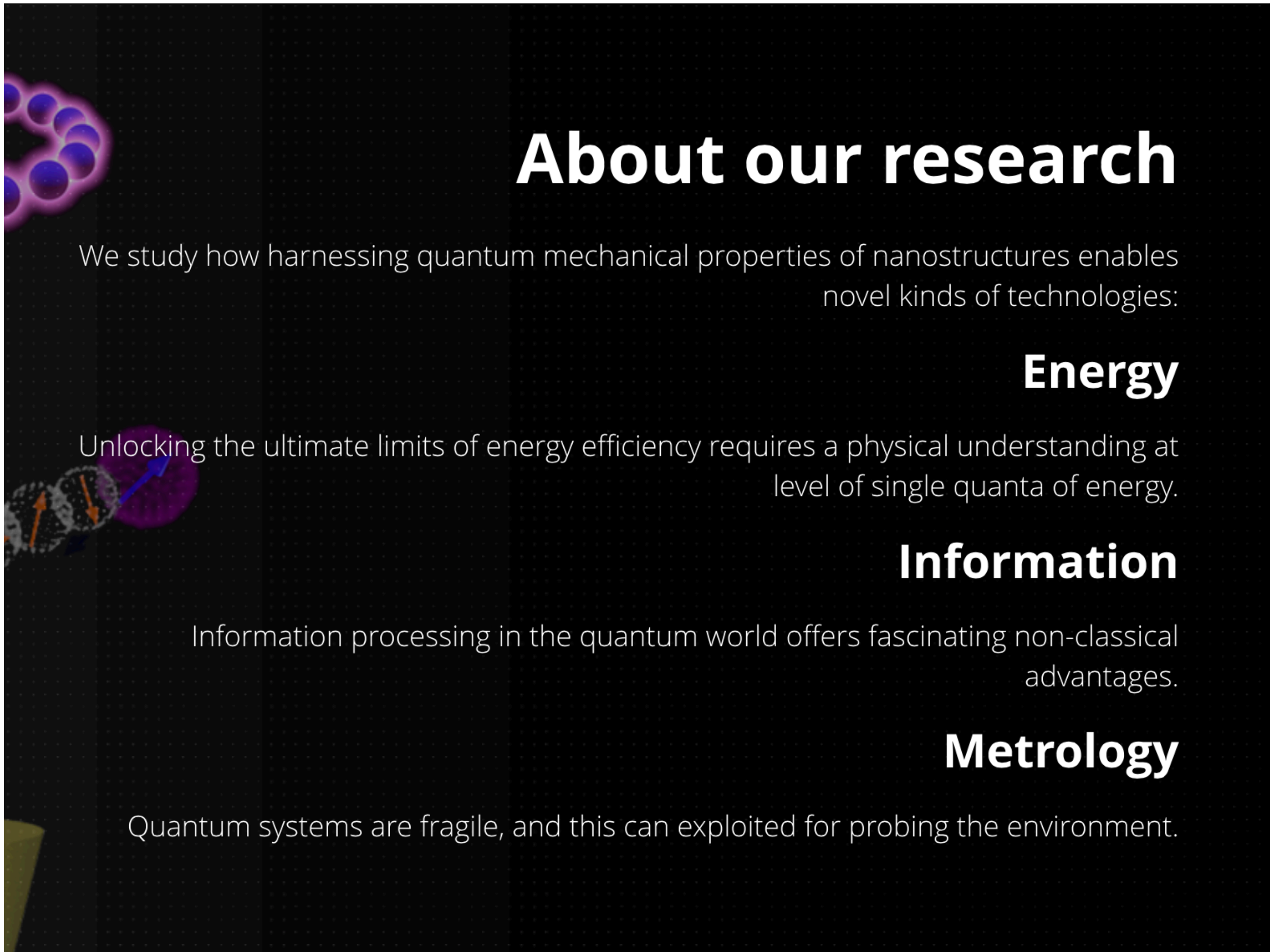

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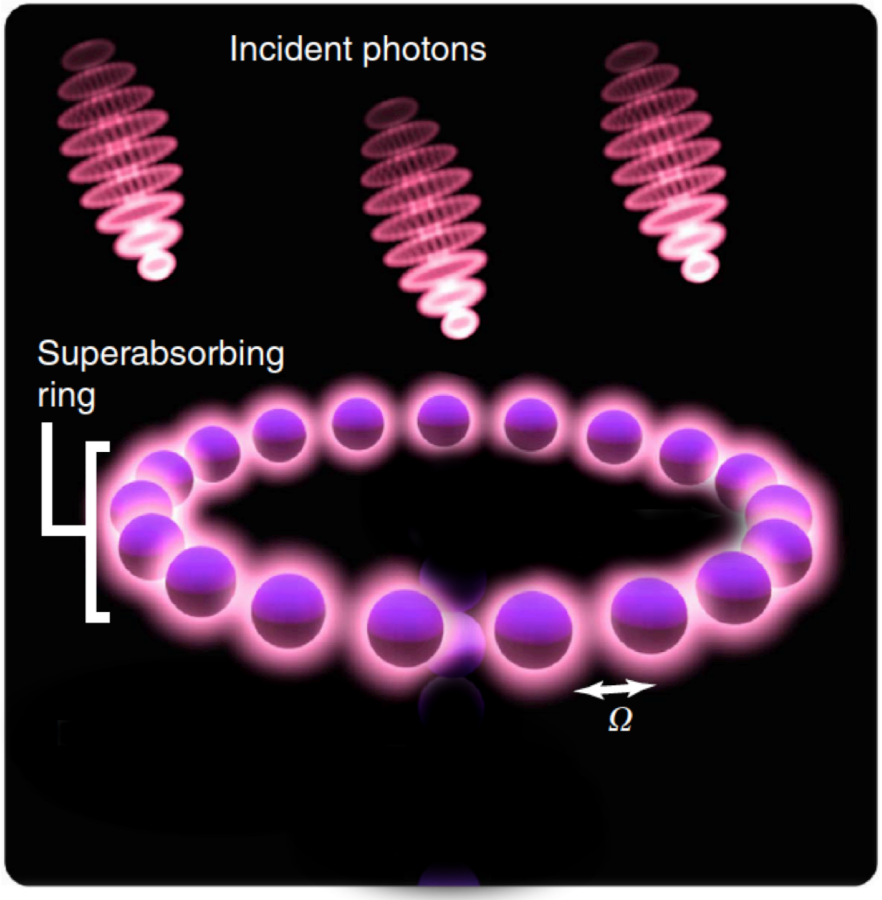
Introduction



Introduction

" **Superradiance** "

Time-reversal symmetry in QM

" **Superabsorption** "

Photon sensing &
Light-based energy transmission

Need certain interactions between the atoms…

Entities with a discrete
dipole-allowed transition

Brief review of superradiance

$$\hat{\sigma}_z^i = |g\rangle_i \langle g| - |e\rangle_i \langle e|$$
$$\hat{\sigma}_+^i = |e\rangle_i \langle g|$$
$$\hat{\sigma}_-^i = |g\rangle_i \langle e|$$

Ensemble of N identical atoms

$$\hat{H}_s = \frac{\omega_A}{2} \sum_{i=1}^{N} (\mathrm{I}^i - \hat{\sigma}_z^i) = \omega_A \sum_{i=1}^{N} \hat{\sigma}_+^i \hat{\sigma}_-^i$$

In the regime of.. $r_{ij} \ll \lambda$

$$\hat{J}_\pm = \sum_{i=1}^{N} \hat{\sigma}_\pm^i \quad , \quad \hat{J}_z = \sum_{i=1}^{N} \hat{\sigma}_z^i$$

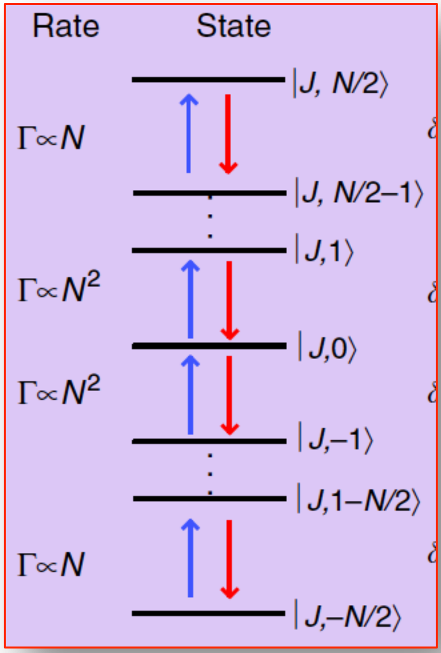
Interaction Hamiltonian between light-matter

$$\hat{H}_L = -\hat{E}d(\hat{J}_+ + \hat{J}_-)$$

Transition rate between adjacent state

$$\boxed{\Gamma_{M \to M-1} \approx \gamma \left(\frac{N}{2} \right)^2}$$

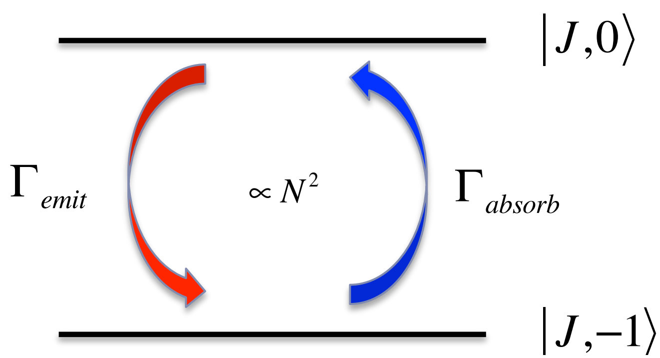
$* \ \gamma = 8\pi^2 d^2 / (3\varepsilon_0 \hbar \lambda^3)$

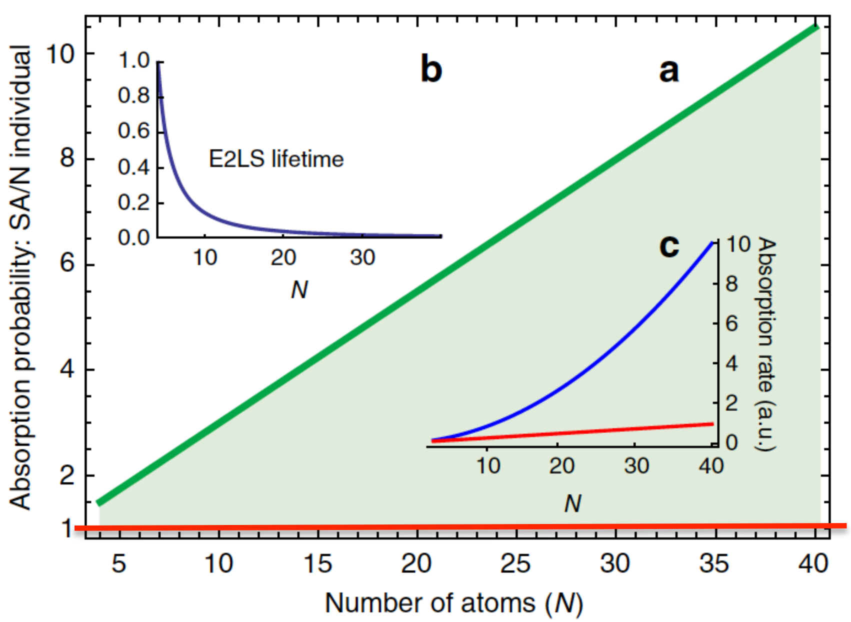


Dicke ladder state

Superabsorption

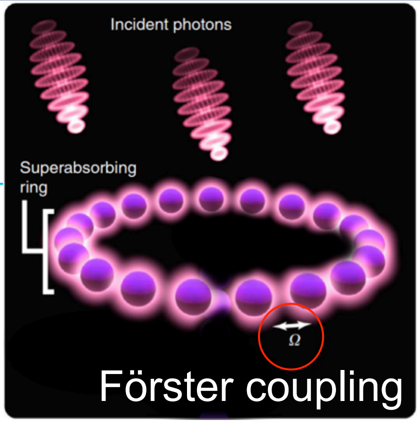
Effective two level system(E2LS) around M=0





$$\Gamma_{loss}^{-1} = (\gamma\Gamma_{-1\to-2}\kappa(\omega_{bad}))^{-1}$$

Master Equation



Quantum optical master equation

$$\dot{\rho} = -i\left[\hat{H}_s + \hat{H}_I, \rho\right] - \gamma \sum_{\beta\in\omega} \kappa(\omega_\beta)\Big((n(\omega_\beta)+1)D[\hat{L}_\beta]\rho + n(\omega_\beta)D[\hat{L}_\beta^\dagger]\rho\Big)$$

Lamb shift

with $\kappa(\omega) = \sum_k |g_k|^2 \delta(\omega - \omega_k) \equiv \chi(\omega)|g(\omega)|^2$

$$D\left[\hat{L}_\beta\right]\rho = \hat{L}_\beta \rho \hat{L}_\beta^\dagger - \frac{1}{2}\left\{\hat{L}_\beta^\dagger \hat{L}_\beta, \rho\right\}$$

$$\boxed{\hat{H}_I = \Omega_{i,j} \sum_{i\neq j}^{N} \left(\hat{\sigma}_+^i \hat{\sigma}_-^j + \hat{\sigma}_-^i \hat{\sigma}_+^j\right)}$$

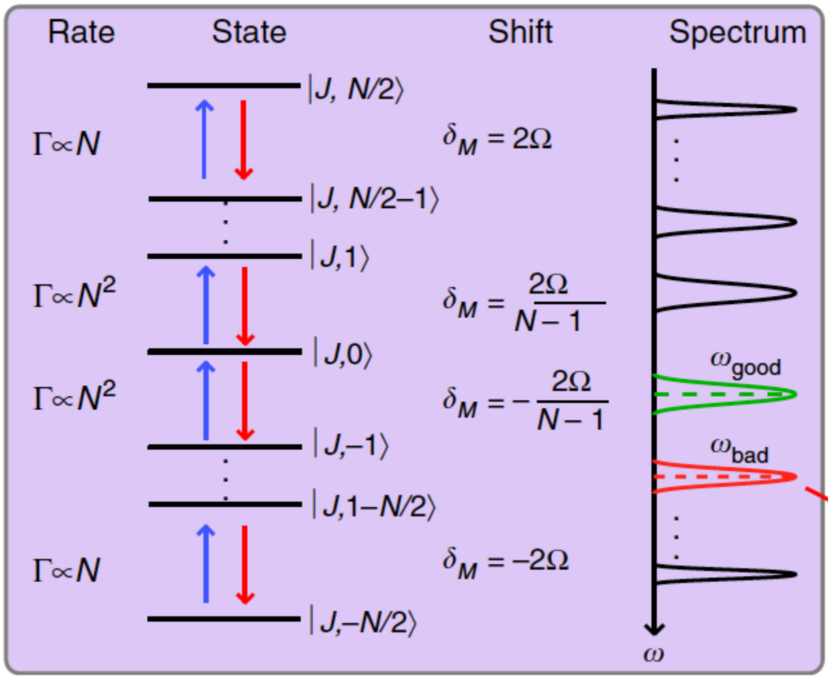
: Dipole-dipole interaction

$$\Omega(i,j) = \frac{d^2}{4\pi\varepsilon_0 r_{ij}^{\ 3}}\left[1 - \frac{3(\hat{\varepsilon}_a \cdot r_{ij})^2}{r_{ij}^{\ 2}}\right] \approx \frac{d^2}{4\pi\varepsilon_0 r_{ij}^{\ 3}}$$

For the "**ring**" structure

$$\delta E_M = \left\langle J, M \middle| \hat{H}_I \middle| J, M \right\rangle = \Omega \frac{J^2 - M^2}{J - \frac{1}{2}}$$

Dicke ladder and energy shifts

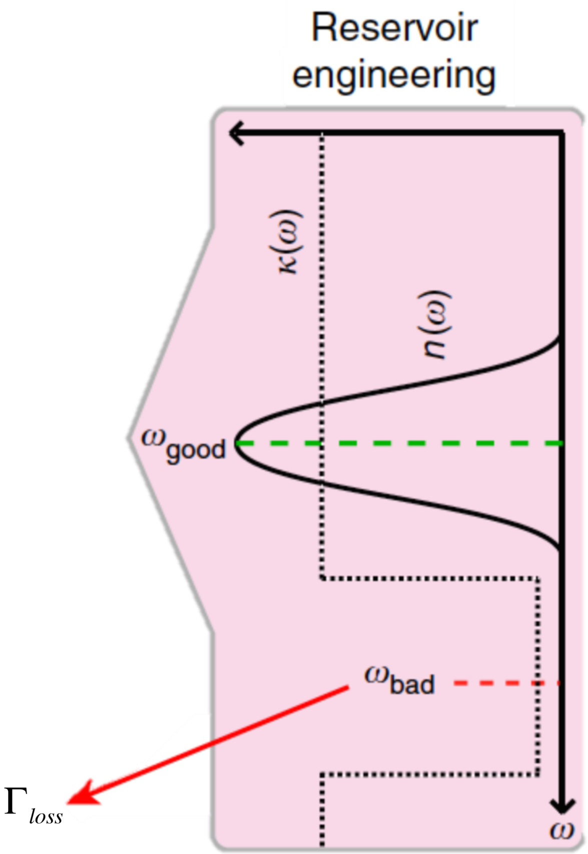


$$\omega_{M \to M-1} = \omega_A - 4\Omega \frac{M - \frac{1}{2}}{N - 1}$$

$\kappa(\omega)$ $n(\omega)$

Transition rate engineering

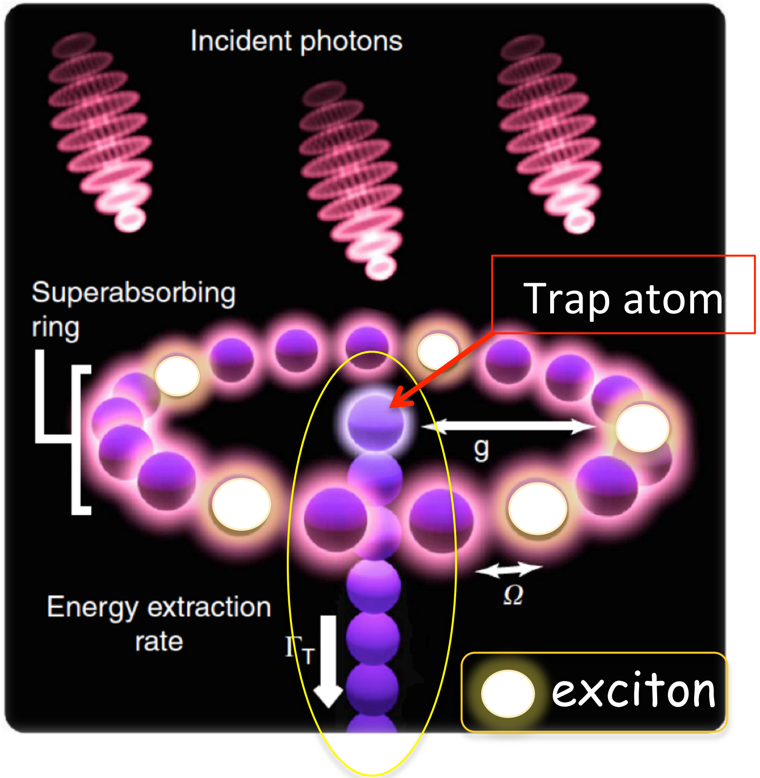
$$\kappa(\omega) \ \ \& \ \ n(\omega)$$



Rely on
Frequency selectivity

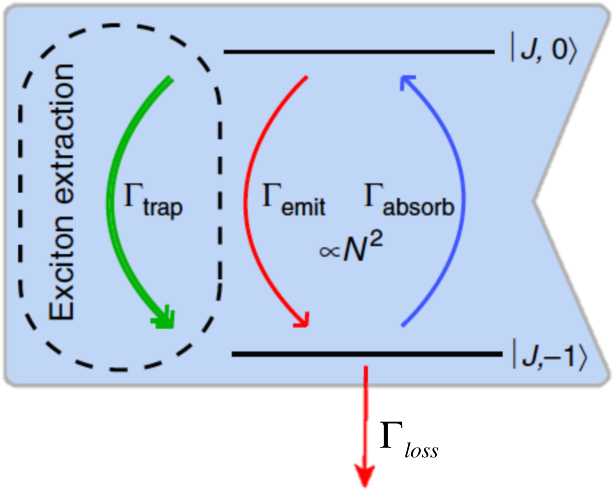
Energy harvesting

Trapping **Collective Extraction**



Non-radiative channel

E2LS



Trapping Hamiltonian..

$$\hat{H}_T = g\left(\hat{J}_+\hat{\sigma}_-{}^T + \hat{J}_-\hat{\sigma}_+{}^T\right) + \omega_{trap}\hat{\sigma}_+{}^T\hat{\sigma}_-{}^T$$

From the master equation…

Add,

$$D\left[\hat{L}_{trap}\right]\rho \qquad \hat{L}_{trap} = \sqrt{\Gamma_{trap}}\,|J,-1\rangle\langle J,0|$$

The rate of exciton extraction

$$I_{trap}(t) = \Gamma_{trap} Tr\left[|J,0\rangle\langle J,0|\,\rho(t)\right]$$

For, $\Gamma_{trap} \gg \Gamma_{emit}$

$$I_{trap}(t) = I_{\max} \approx \Gamma_{absorb} \approx \mu\left(\frac{N}{2} + \frac{N^2}{4}\right)$$

$$\mu = \gamma\kappa(\omega_{good})n(\omega_{good})$$

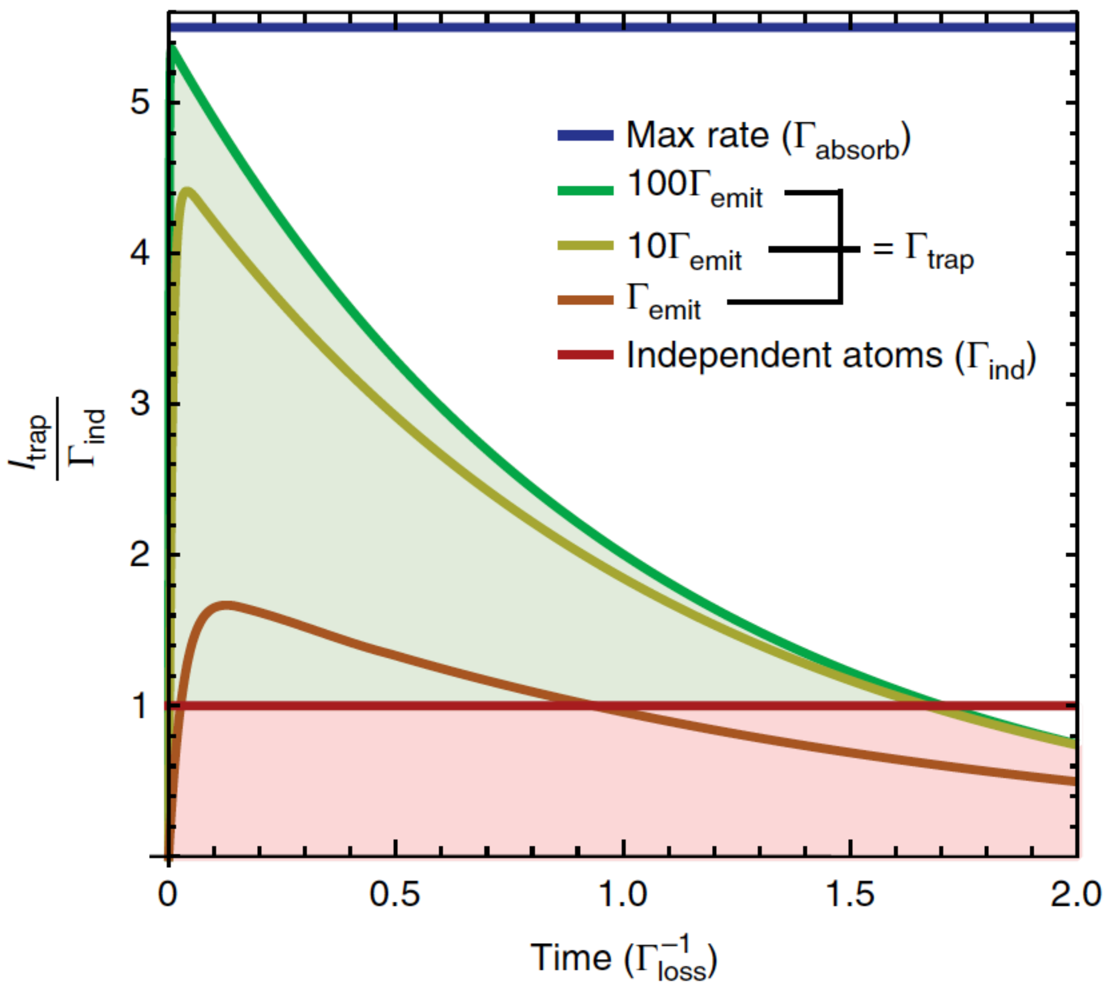
$$\cancel{\Gamma_{loss} \equiv \kappa(\omega_{bad})(n(\omega_{bad})+1)\Gamma_{-1\to-2}} \quad \text{E2LS}$$

$$\cancel{\Gamma_{emit} \equiv \kappa(\omega_{good})(n(\omega_{good})+1)\Gamma_{0\to-1}} \quad \Gamma_{trap} \gg \Gamma_{emit}$$

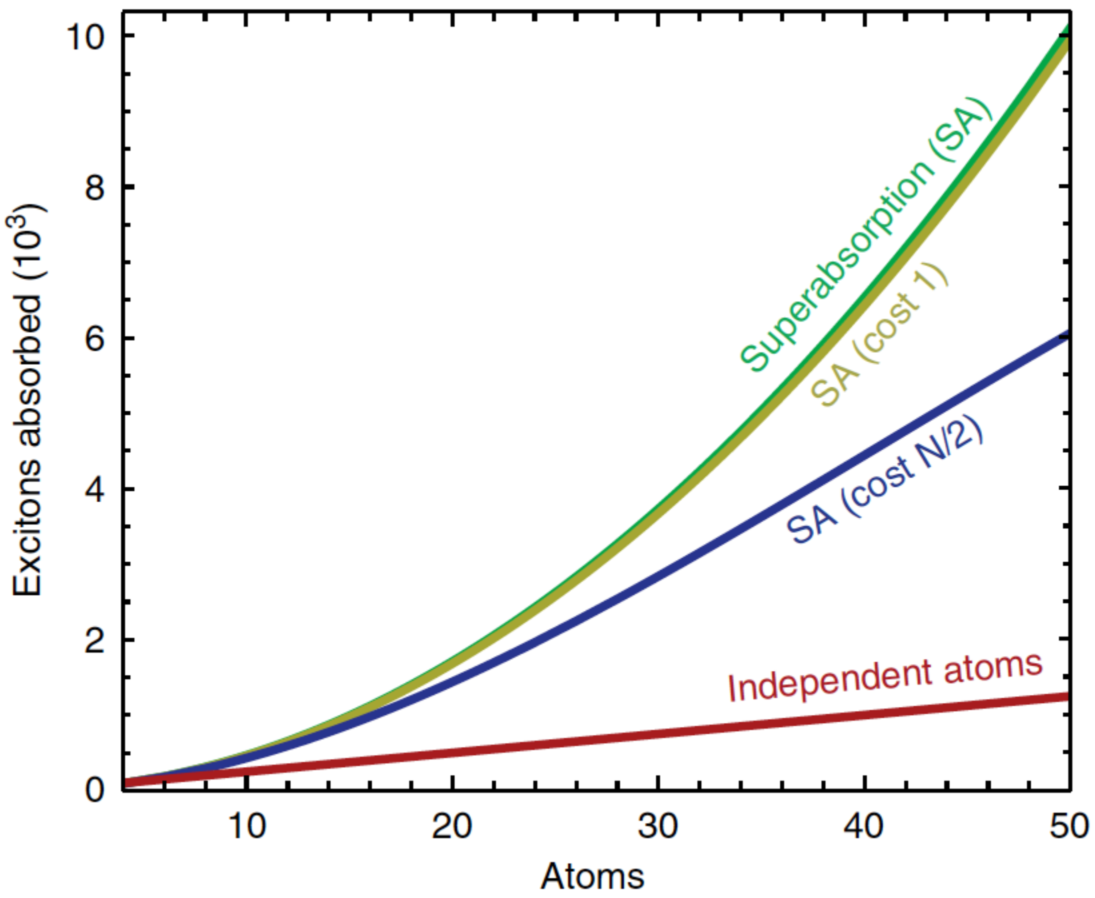
$$\Gamma_{absorb} \equiv \kappa(\omega_{good})n(\omega_{good})\Gamma_{-1\to 0}$$

$$\Gamma_{ind} = n(\omega_{good})N_\gamma$$

$$I_{trap}(t) = I_{max} \approx \Gamma_{absorb} \approx \mu\left(\frac{N}{2} + \frac{N^2}{4}\right)$$



Reinitialization



Thank you