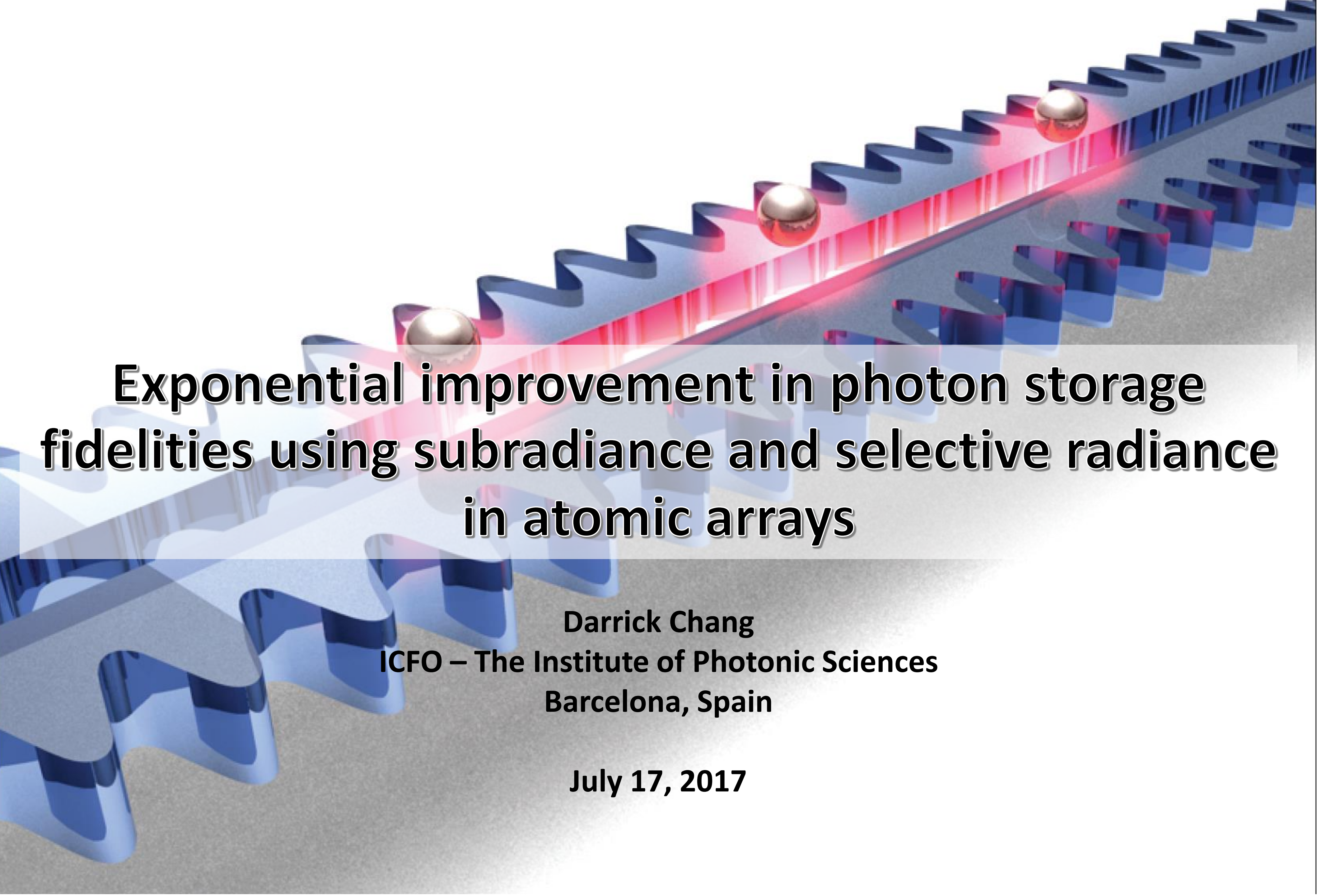


Exponential improvement in photon storage fidelities using subradiance and selective radiance in atomic arrays

Darrick Chang
ICFO – The Institute of Photonic Sciences
Barcelona, Spain

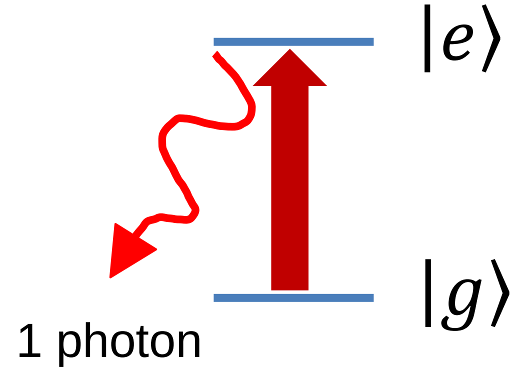
July 17, 2017

Acknowledgments

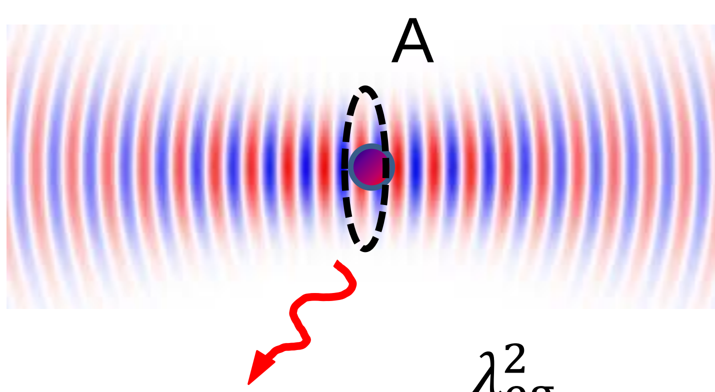
- In collaboration with Prof. Jeff Kimble (Caltech)

Atom-photon interactions

- Atoms constitute a natural quantum interface with light



  - Route toward quantum information processing, or strong interactions between photons
- Problem: single atoms and photons don't like to talk to each other



$$P_{sc} \sim \frac{\lambda_{\mathrm{eg}}^2}{A}$$

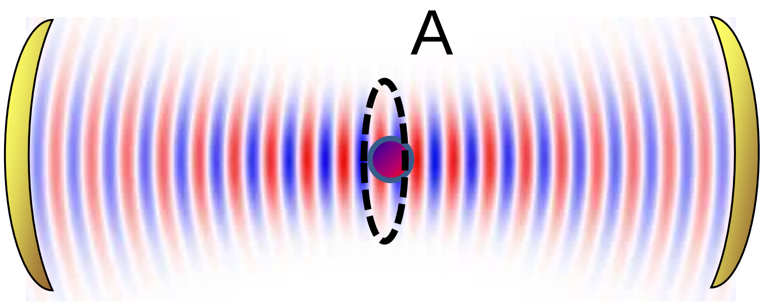
diffraction limit

$$A > \lambda_{\mathrm{eg}}^2$$

Atom-photon interactions

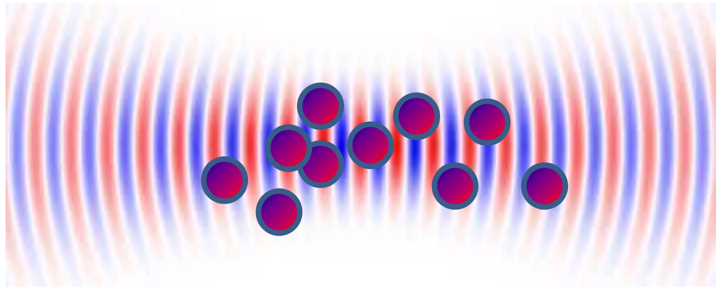
- Some fixes:

- Cavity QED



$$P_{sc} \sim \frac{\lambda_{\mathrm{eg}}^2}{A} N_{\mathrm{bounces}} \sim \frac{g^2}{\kappa\Gamma} \sim \text{Cooperativity}$$

- Atomic ensembles



$$P_{sc} \sim \frac{\lambda_{\mathrm{eg}}^2}{A} N_{\mathrm{atoms}} \sim \text{Optical depth}$$

A fundamental limit

- Cooperativity or optical depth viewed as a fundamental limit to applications of atom-light interfaces

A quantum gate between a flying optical photon and a single trapped atom

Andreas Reiserer[1], Norbert Kalb[1], Gerhard Rempe[1] & Stephan Ritter[1]

In principle, the gate mechanism presented in this work is deterministic. In our experimental implementation, the photon is not back-reflected[8] from the coupled system $|\uparrow^a\uparrow^p\rangle$ with a probability of 34(2)% (due to the finite cooperativity $C = \frac{g^2}{2\kappa\gamma} = 3$) and in the uncoupled

All-Optical Switch and Transistor Gated by One Stored Photon

Wenlan Chen,[1] Kristin M. Beck,[1] Robert Bücker,[1,2] Michael Gullans,[3] Mikhail D. Lukin,[3] Haruka Tanji-Suzuki,[1,3,4] Vladan Vuletić[1]*

stood in a simple cavity QED model: One atom in state $|s\rangle$ reduces the cavity transmission (*1*, *4*) by a factor of $T = (1 + \eta)^{-2}$, where η is the single-atom cooperativity (*30*). In the strong-coupling

Universal Approach to Optimal Photon Storage in Atomic Media

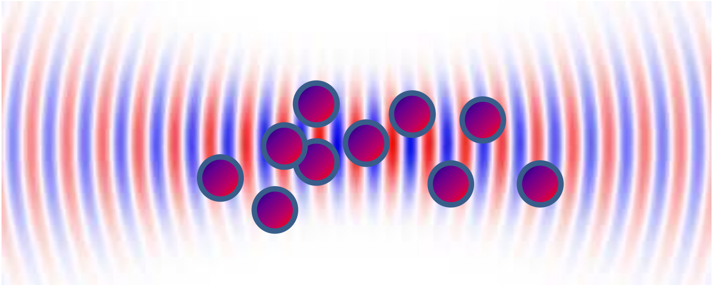
Alexey V. Gorshkov,[1] Axel André,[1] Michael Fleischhauer,[2] Anders S. Sørensen,[3] and Mikhail D. Lukin[1]

off-resonant Raman fields to photon-echo-based techniques. Furthermore, we derive an optimal control strategy for storage and retrieval of a photon wave packet of any given shape. All these approaches, when optimized, yield identical maximum efficiencies, which only depend on the optical depth of the medium.

- Errors decrease as $\frac{1}{C}, \frac{1}{OD}$ or slower

Is that the full story?

- Atomic ensembles

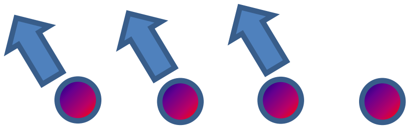


$$P_{sc} \sim \frac{\lambda_{\mathrm{eg}}^2}{A} N_{\mathrm{atoms}} \sim$$

Optical depth

- **Important assumption:** atoms interact with light independently
  - Effectiveness is multiplied by # of attempts ($\propto N_{\mathrm{atoms}}$)

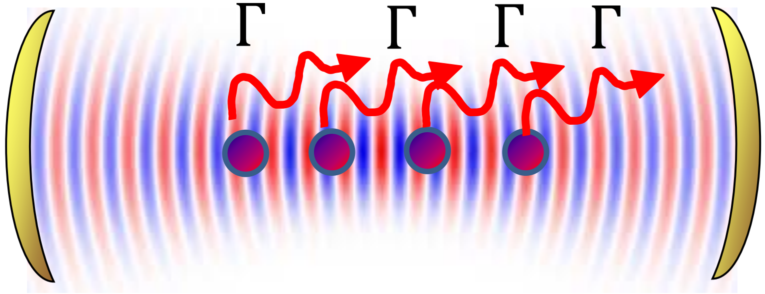
- Cannot be true – atoms emit waves, which can interfere



Physics of super- and sub-radiance

Is that the full story?

- Starting equations for quantum optics already have an issue!
  - Jaynes-Cummings model for multiple emitters



$$H_{\text{eff}} = \sum_j g(x_j)(\sigma_{eg}^j a + h.c.) - \frac{i\kappa}{2} a^\dagger a - \underbrace{i\frac{\Gamma}{2}\sum_j \sigma_{ee}^j}_{\text{Independent emission}}$$

  - Maxwell-Bloch equations for atomic ensembles

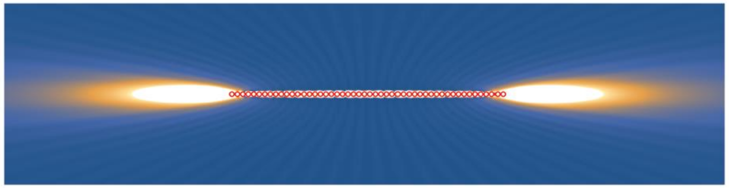
Continuous medium

$$\big((1/c)\partial_t + \partial_z\big)\mathrm{E(z,t)} \sim iP_{ge}(z,t)$$

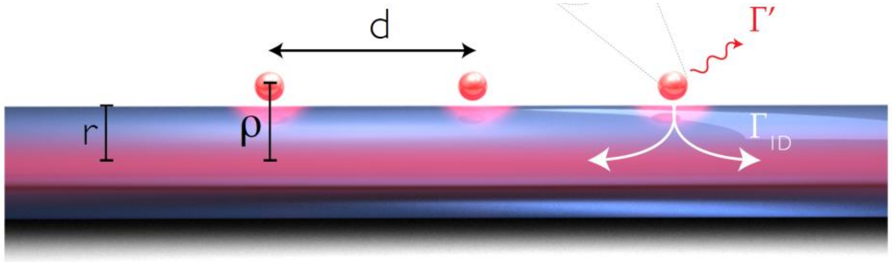
$$dP_{ge}/dt = \underbrace{-(\Gamma/2)P_{ge}}_{\text{Independent emission}} + \cdots$$

Outline

- **Big question:** can we exploit interference to enhance atom-light interfaces? **(Yes!)**
- Formalism to treat atom-light interfaces including subradiance
- Origin of subradiance in atomic arrays in free space



- “Selective” radiance: atoms coupled to a nanofiber



Light-matter interactions as a spin model

Electromagnetic Green's function

- Formal definition:

- G describes the electric field at point r, of a (normalized) oscillating dipole at r'

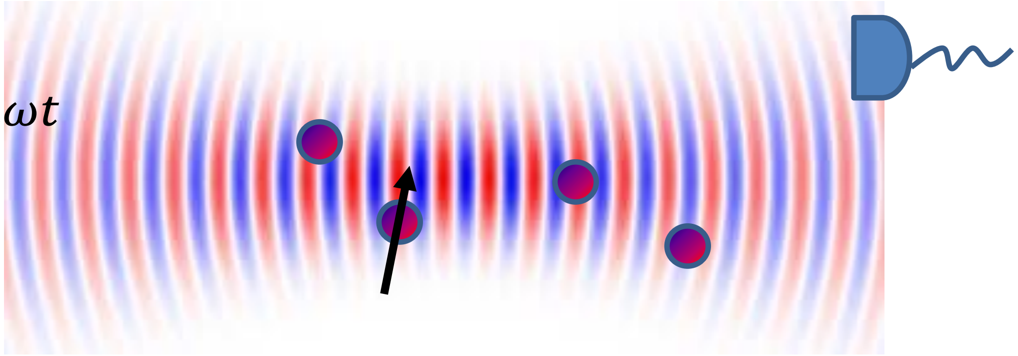
- Tensor quantity ($\alpha, \beta = x, y, z$): source dipole can have three orientations, and the electric field at r is a vector

- Simple case: free space

Getting rid of the light

- Scattering from polarizable particles

$E_{\text{in}}(r)e^{-i\omega t}$



- Know the radiation pattern for a dipole
- Can formally write down the total field
- Generalized "input-output" equation for atoms

Field encoded in atoms!

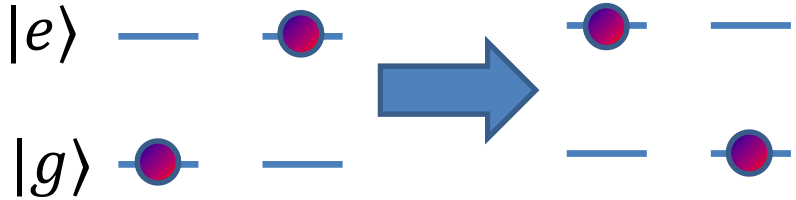
$$\hat{E}(r,t) = \hat{E}_{in}(r,t) + \left(3\pi\hbar c\Gamma_0/d_0\omega_{eg}\right)\sum_i G\left(r,r_i,\omega_{eg}\right)\sigma_{ge}^i(t)$$

- Quantum and classical fields propagate the same way

What about the atoms?

- Atoms interact with fields, but fields are dependent on the atoms themselves
- Effective "spin" Hamiltonian involving atoms alone

$$H_{\text{eff}} = -(3\pi\hbar\Gamma_0 c/\omega_{eg}) \sum_{i,j} G(r_j, r_i, \omega_{eg}) \sigma_{eg}^i \sigma_{ge}^j$$



What about the atoms?

- Atoms interact with fields, but fields are dependent on the atoms themselves
- Effective "spin" Hamiltonian involving atoms alone

$$H_{\text{eff}} = -\left(3\pi\hbar\Gamma_0 c/\omega_{eg}\right)\sum_{i,j} G(r_j, r_i, \omega_{eg})\sigma_{eg}^{i}\sigma_{ge}^{j}$$

- Strength depends on how field propagates from j to i

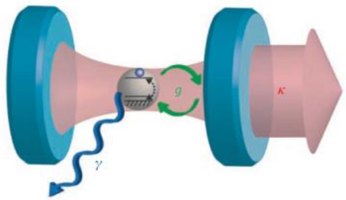
- Non-Hermitian Hamiltonian – describes both coherent interactions and (collective) spontaneous emission

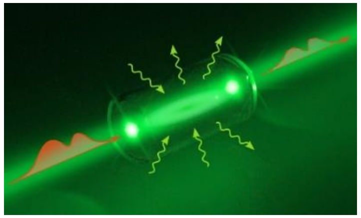
Quantum "spin model" of atom-light interactions

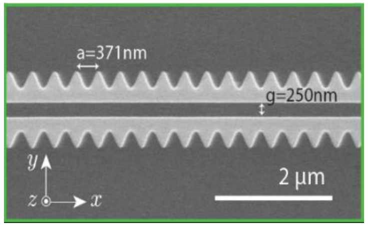
$$H_{\text{eff}} = -(3\pi\hbar\Gamma_0 c/\omega_{eg}) \sum_{i,j} G(r_j, r_i, \omega_{eg}) \sigma_{eg}^i \sigma_{ge}^j$$

$$\hat{E}(r,t) = \hat{E}_{in}(r,t) + \left(3\pi\hbar c\Gamma_0/d_0\omega_{eg}\right) \sum_i G\left(r, r_i, \omega_{eg}\right) \sigma_{ge}^i(t)$$

- Long history of these equations: Gross and Haroche (superradiance review, 1982); Kurizki (dipole-dipole interactions, 1990's); Welsch and Buhmann (quantization of dielectrics, 1990's); …
- Equally captures any system of atoms interacting with light, and treats them on equal footing



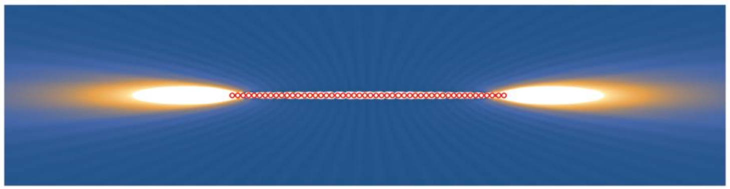




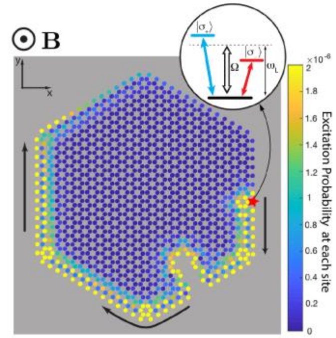
- All of atom-light interactions are formally encoded in a spin model!

Light-atom interactions as a spin model

- Subradiance, edge states in free-space atomic arrays

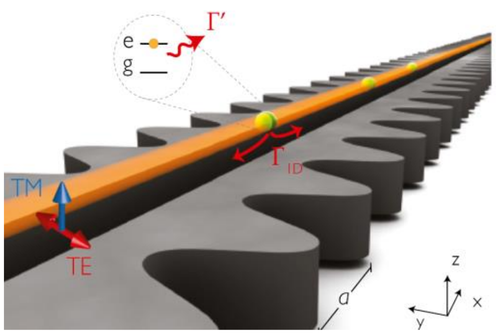


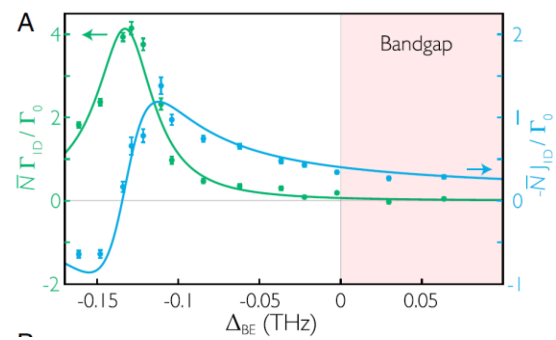
arXiv:1703.03382



J Perzcel et al, PRL 119, 023603 (2017)

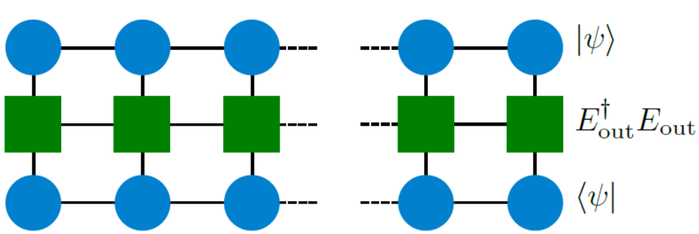
- Quantitative modeling of atoms near complex structures

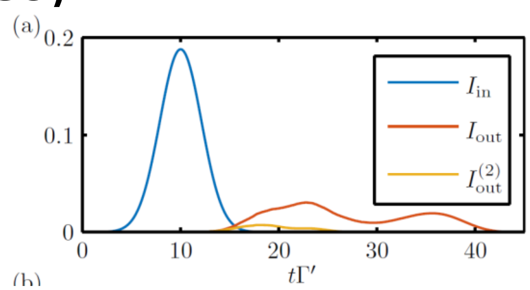




JD Hood et al, PNAS 113, 10507 (2016)

- New techniques for dynamics of strongly interacting photons (e.g., matrix product states)



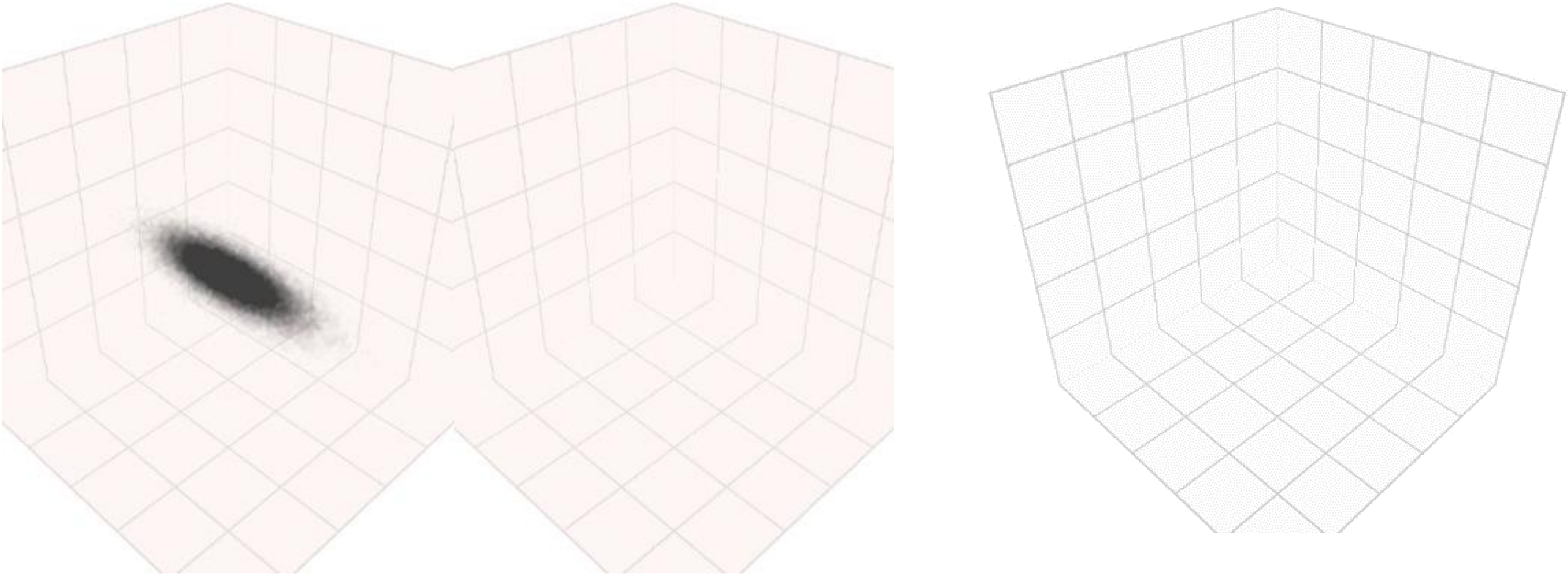


arXiv:1702.05954

Light-atom interactions as a spin model

- Direct modeling of 3D atomic ensembles (James Douglas)

Electromagnetically induced transparency
N=50000 atoms in Gaussian cloud, OD~50



Atomic distribution **Field intensity** **Spin population**

1D chain of atoms in free space

Green's function for 1D atomic chain

- Spin model in general:

$$H_{\text{eff}} = -\left(3\pi\hbar\Gamma_0 c/\omega_{eg}\right)\sum_{i,j} G(r_j, r_i, \omega_{eg})\sigma_{eg}^{i}\sigma_{ge}^{j}$$

- Simple case: atoms in free space

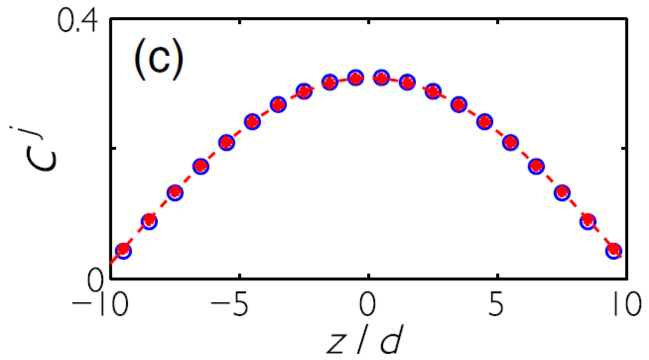
- Must specify a geometry: 1D chain of atoms (but living in 3D)

- Considering just one excitation, there are N possible states

- Hamiltonian becomes N x N matrix in this subspace, $H_{ij} \propto G(r_j, r_i)$

Exact diagonalization

- Numerically diagonalize H
  - Each eigenstate α is a superposition of different atoms excited



$$|\psi_\alpha\rangle = \sum_j c_\alpha^{(j)} |e_j\rangle$$

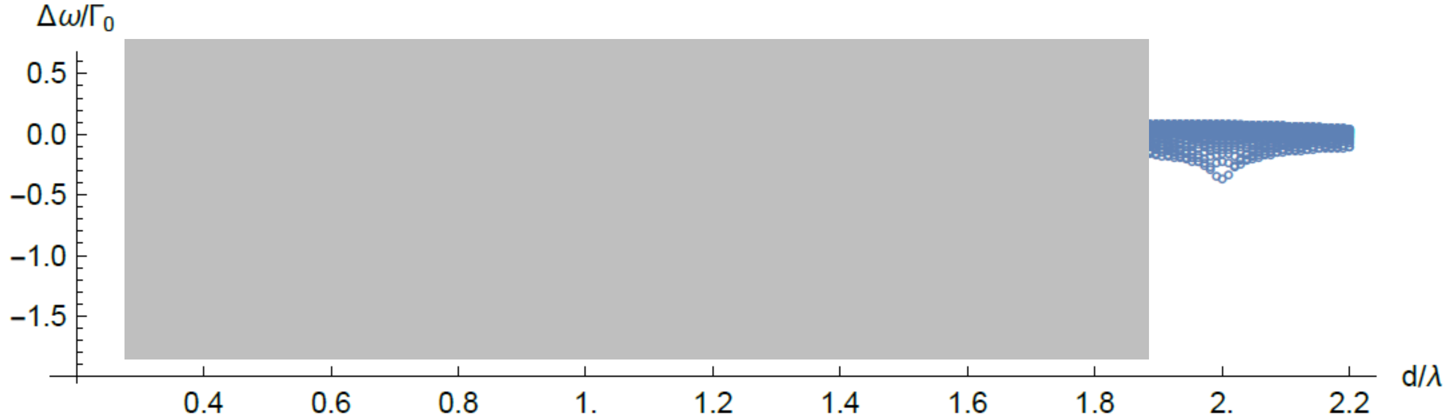
- Eigenvalues reveal:
  - Resonance frequency shift $\Delta\omega_\alpha$ away from bare atomic frequency ω_{eg}
  - Enhanced/suppressed decay rate Γ_α relative to single-atom rate Γ_0

Energy shifts and decay rates

- Shifts and decay rates vs. lattice constant

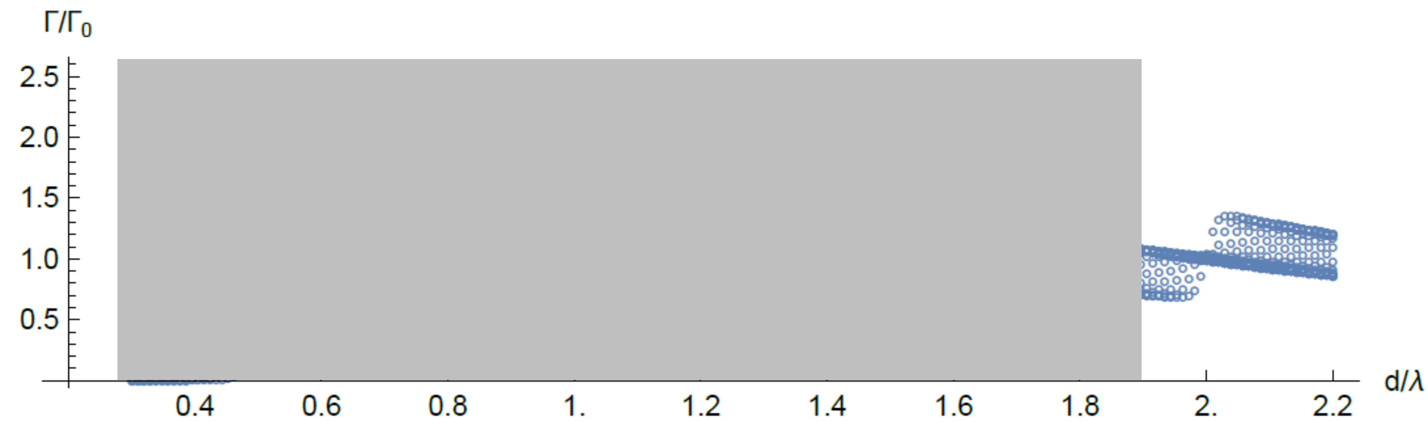
Frequency shift vs. d (N=30 atoms)

Shift normalized by free-space linewidth ($\Delta\omega_\alpha/\Gamma_0$)



Decay rate vs. d (N=30 atoms)

Decay rate normalized by free-space linewidth (Γ_α/Γ_0)



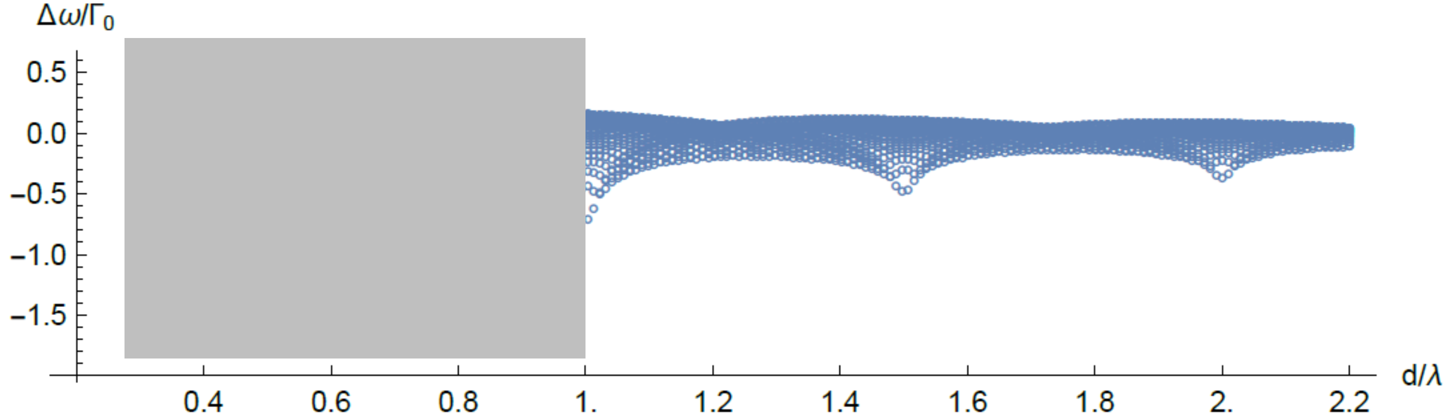
- Minimal effect of interactions at large distances

Energy shifts and decay rates

- Shifts and decay rates vs. lattice constant

Frequency shift vs. d (N=30 atoms)

Shift normalized by free-space linewidth ($\Delta\omega_\alpha/\Gamma_0$)



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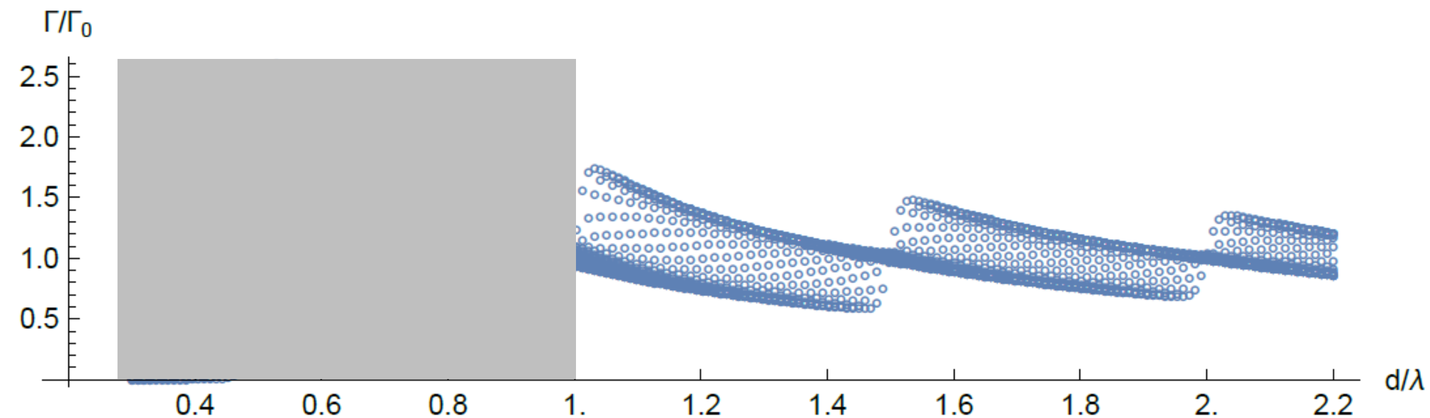

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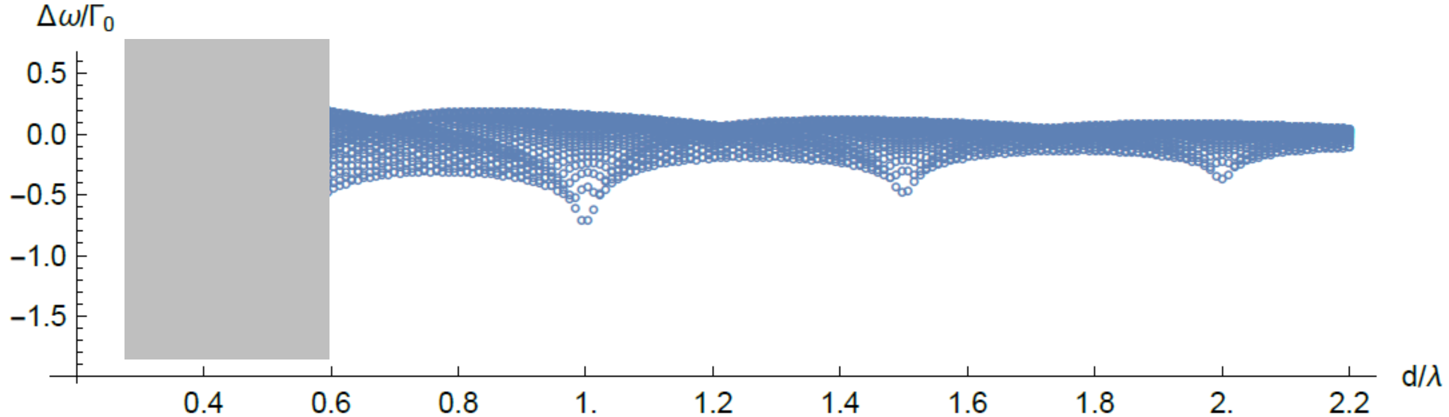

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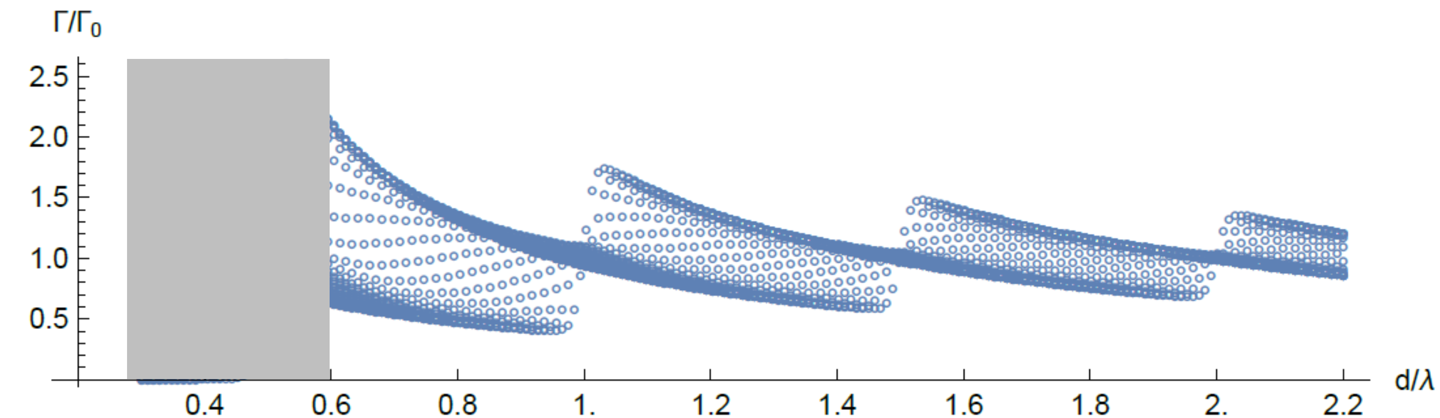
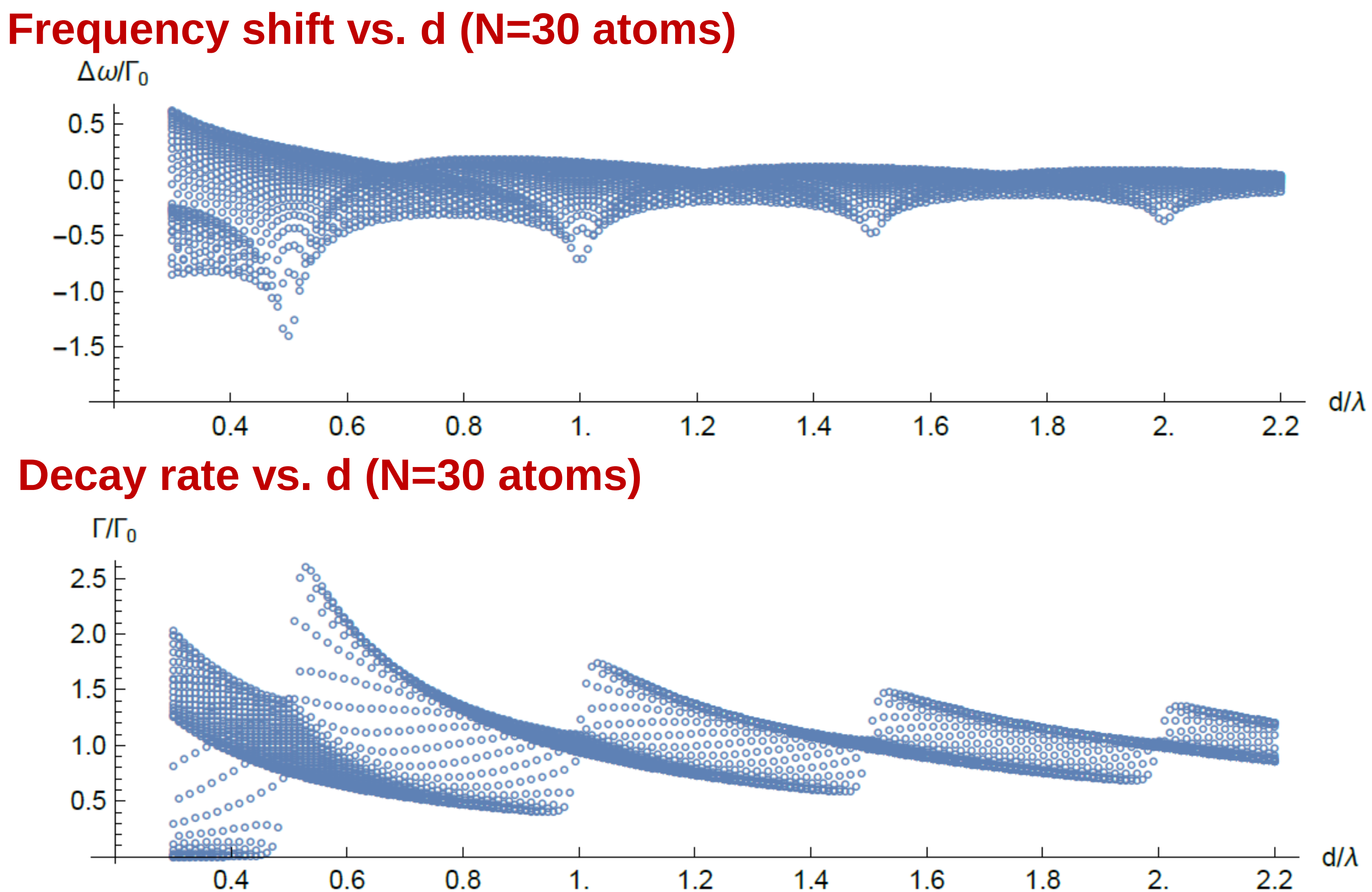


Energy shifts and decay rates

- Shifts and decay rates vs. lattice constant

Shift normalized by free-space linewidth ($\Delta\omega_\alpha/\Gamma_0$)

Decay rate normalized by free-space linewidth (Γ_α/Γ_0)



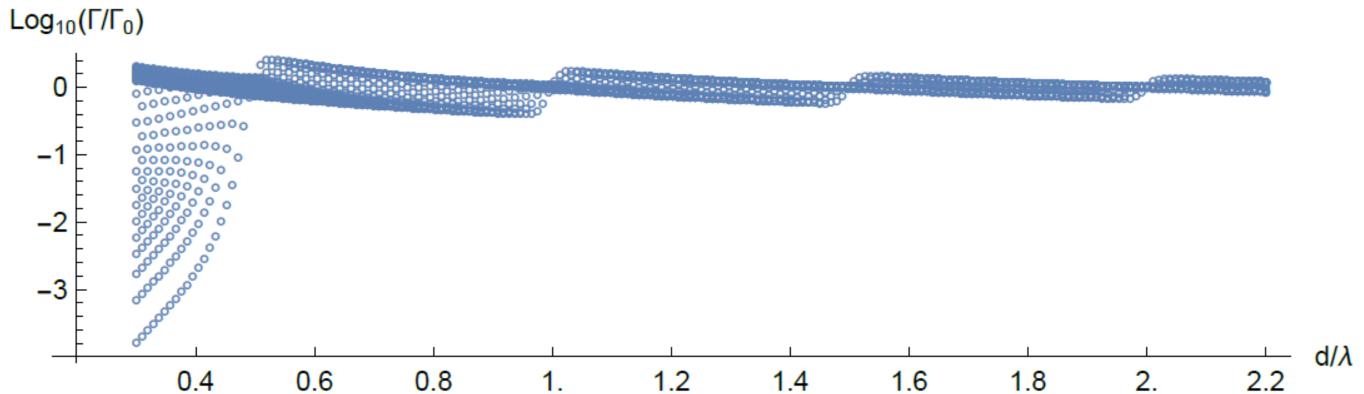
- States with nearly zero decay rate for $d < \frac{\lambda}{2}$!

Energy shifts and decay rates

- Shifts and decay rates vs. lattice constant

Decay rate (log scale) vs. d (N=30 atoms)

(Log scale) Decay rate normalized by free-space linewidth (Γ_α/Γ_0)



- Smallest decay rates go like $\Gamma_\alpha \sim \Gamma_0 \alpha^2/N^3$

$\alpha = 1,2,3, \ldots$

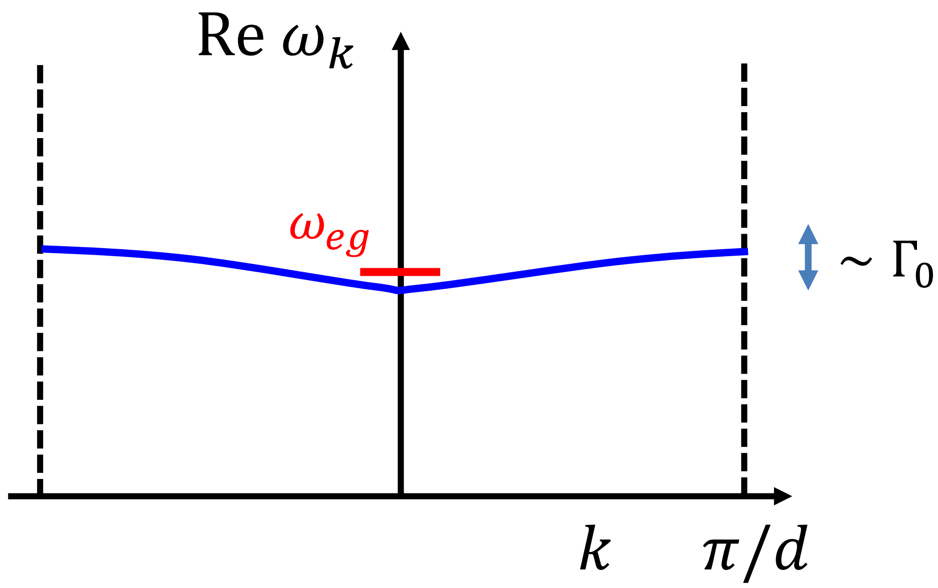
- Interference of wave emission really matters at close distances!

Band structure of infinite lattice

- Infinite chain: single-excitation eigenstates are Bloch modes

$$|\psi_k\rangle = \sum_j e^{ikz_j}|e_j\rangle$$

- Diagonalize H, represent spectrum by band structure



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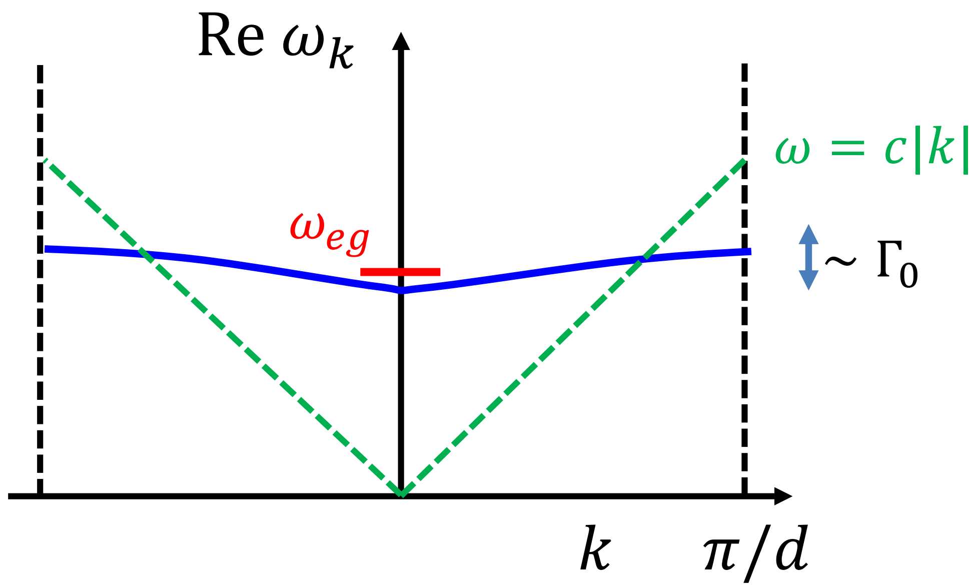

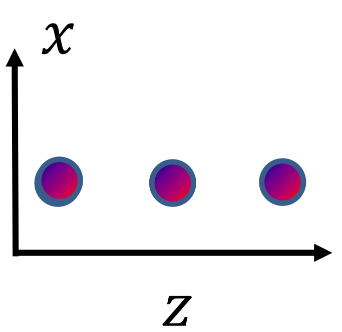

- Emitted light also has same wavevector: $E(r) \sim e^{ikz+ik_\perp x}$
  - Dispersion relation $k^2 + k_\perp^2 = (\omega/c)^2$
  - $|k| > \omega/c$ implies $k_\perp \in \mathrm{Im}$ (evanescent or guided mode)

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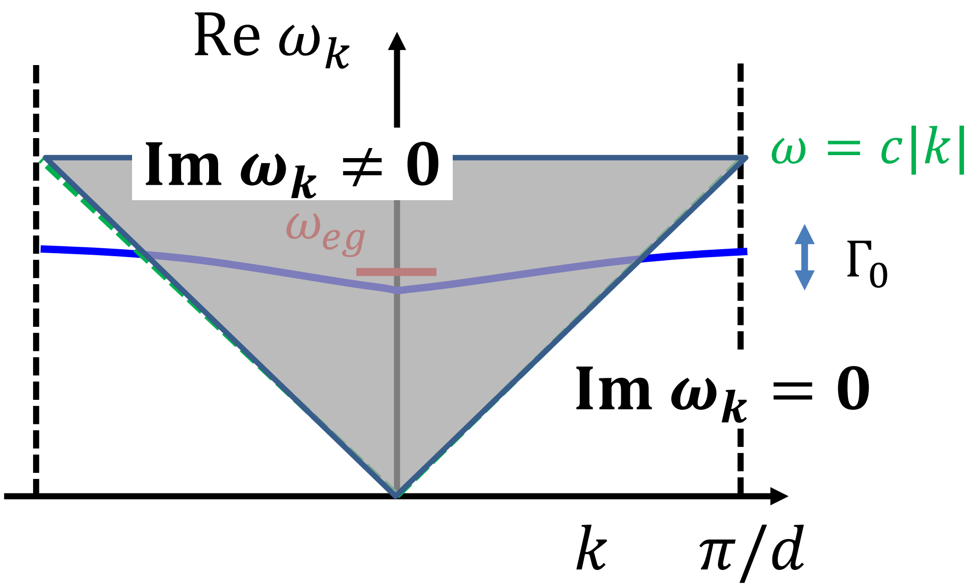

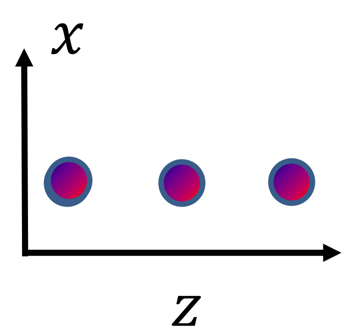

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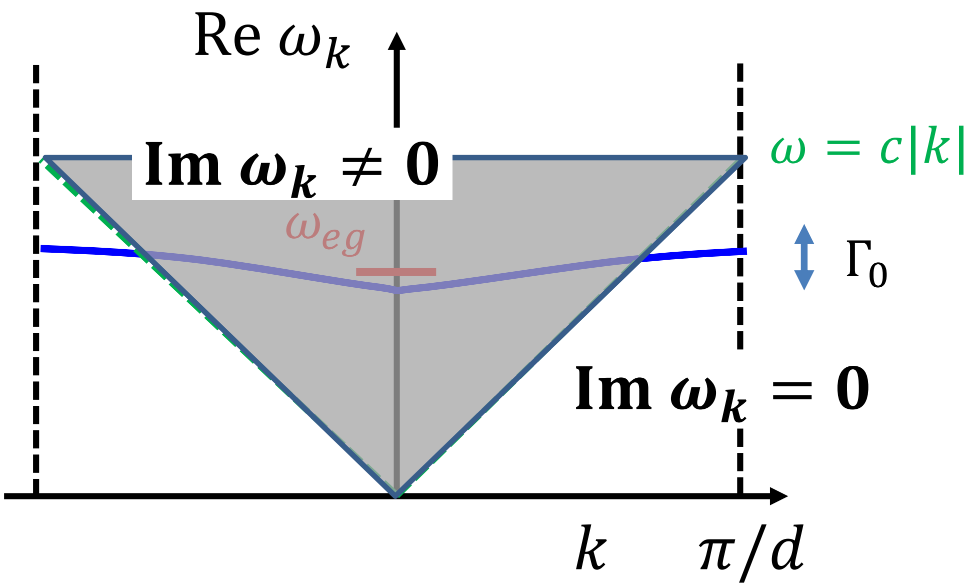
  - $|k| > \omega/c$ implies $k_\perp \in \mathrm{Im}$ (evanescent or guided mode)

Subradiant states as guided modes

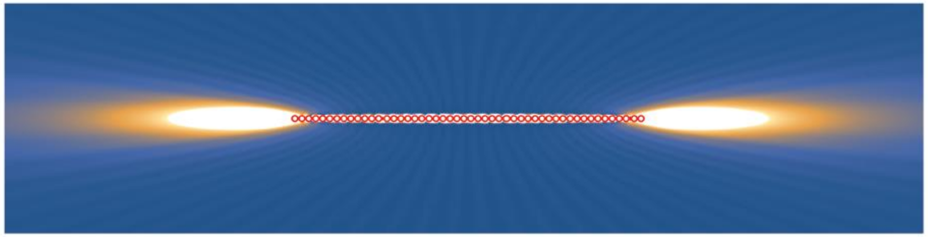
- In ordered arrays:

Subradiance = guided modes of an atomic “fiber”



- Condition: $\omega = c|k|$ intersects Brillouin zone above ω_{eg}
- Equivalent to $d < \frac{\lambda_{eg}}{2}$

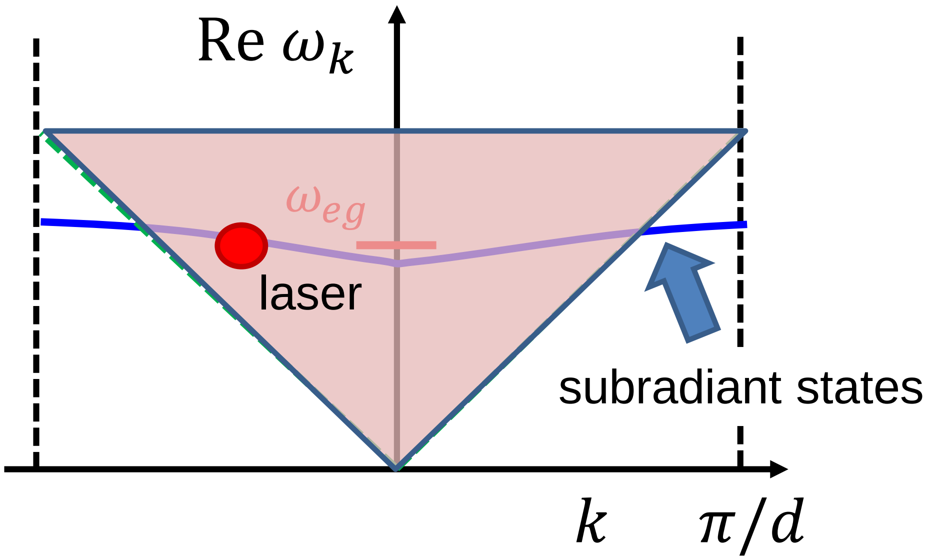
- Finite chain: non-zero decay rate $\Gamma_\alpha \propto \Gamma_0 \alpha^2 / N^3$ due to end-fire emission off the “fiber” ends



Emission pattern for most sub-radiant state, N=30 atoms

Accessing subradiant states

- Hard to couple to subradiant states from free space

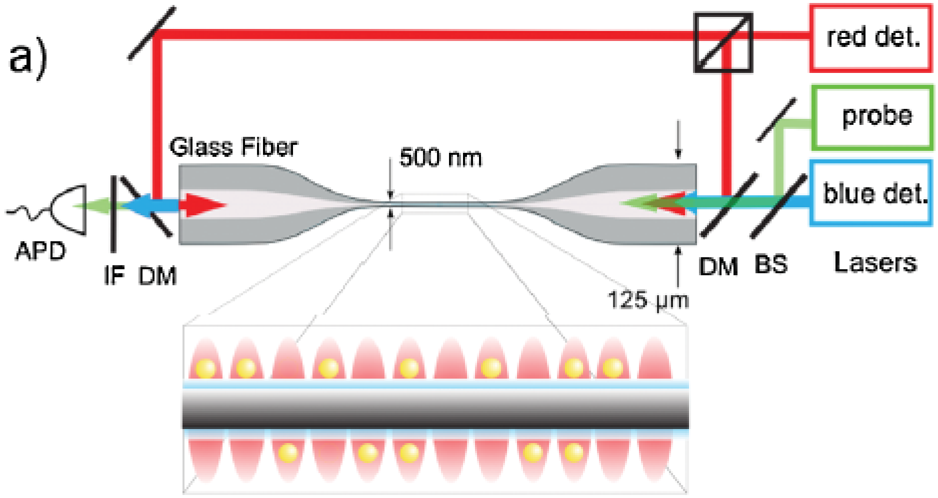


- First experimental observation in extended atomic ensembles just last year (Robin Kaiser, Nice)
- More efficient approach: excite with another set of guided modes (optical nanofiber!)

Atom-nanofiber interfaces

Atom-nanofiber interface

- Trap atoms in lattice with far off-resonant guided modes

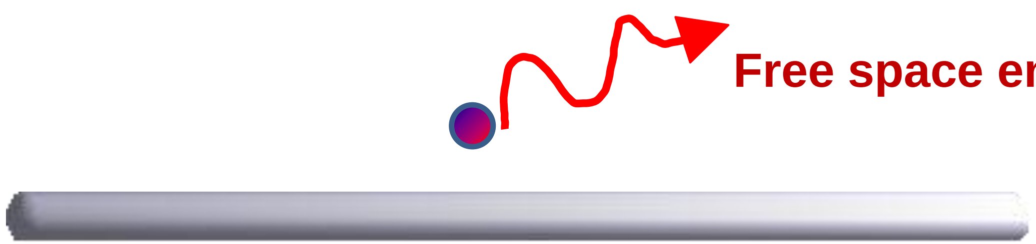


Vetsch et al, PRL 104, 203603 (2010)

- Efficient coupling of atoms with near-resonant photons

Free space emission rate $\Gamma' \sim \Gamma_0$

Single atom:

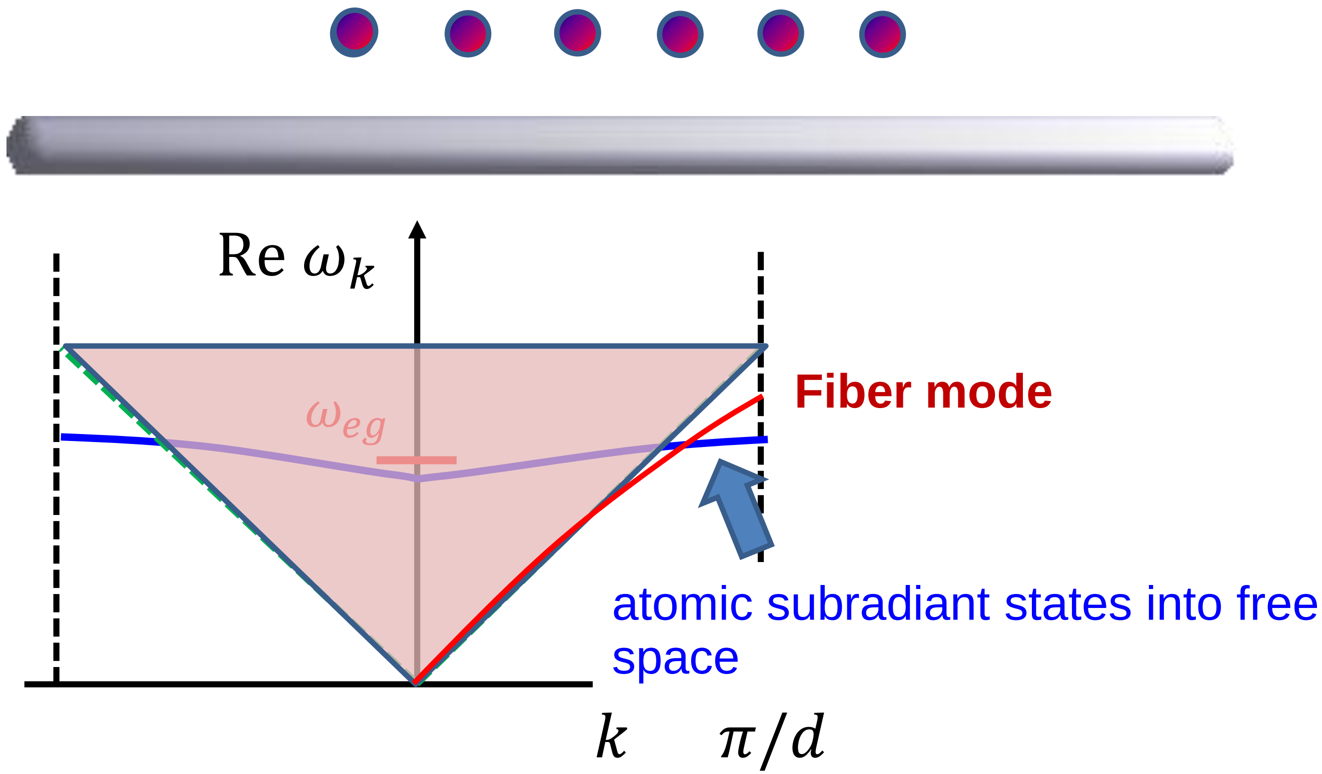


Emission into guided modes $\Gamma_{1D} \sim 0.1\Gamma_0$

- Expts: Hakuta (Tokyo), Rauschenbeutel (TU Vienna), Kimble (Caltech), Orozco (JQI), Laurat (Paris), Polzik (NBI), Nic Chormaic (OIST), …

"Selective" radiance

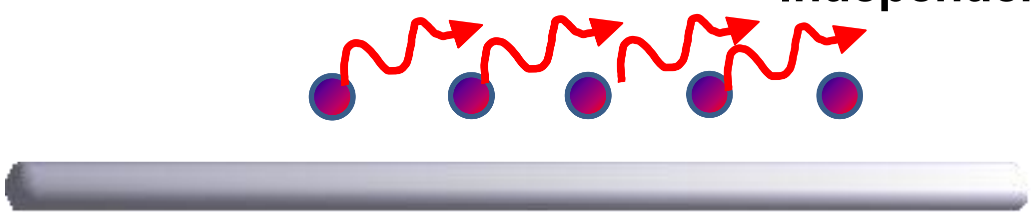
- Previously subradiant states can now couple to guided modes of the fiber



- Not subradiant, but "selectively" radiant… perfect!
- Efficient atom-light interface: atoms talk very well to modes of interest, but not to free space
  - Use this to beat the "optical depth" limit

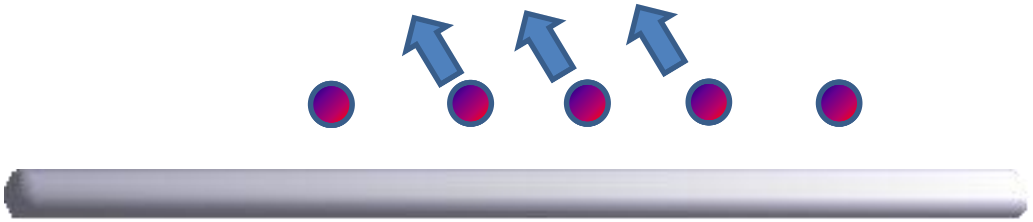
Model of atom-light interactions

- "Independent emission model"



Collective emission into guided modes $N\Gamma_{1D}$

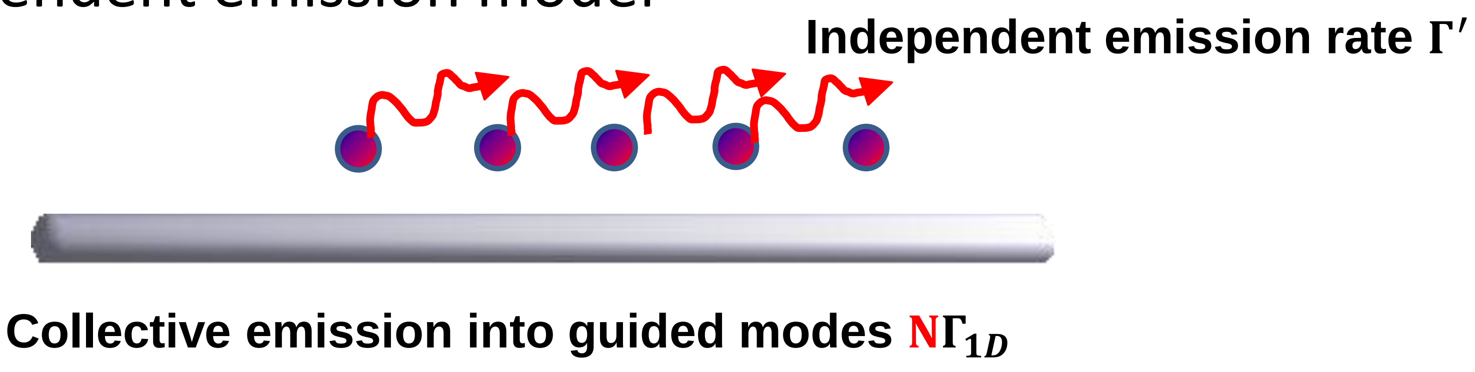
- Collective emission model



Collective emission into guided modes $N\Gamma_{1D}$

Model of atom-light interactions

- "Independent emission model"



- Collective emission model

- Use our "spin model"

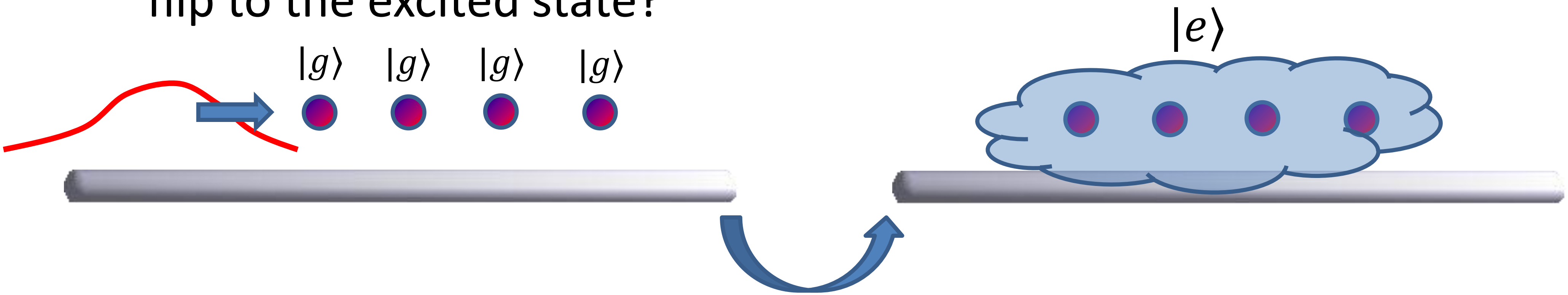
$$H_{\text{eff}} = -\mu_0 d_0^2 \omega_{eg}^2 \sum_{i,j} \underbrace{G(r_j, r_i, \omega_{eg})}_{\text{Exact for cylindrical fiber}} \sigma_{eg}^i \sigma_{ge}^j$$

- Field propagation

$$\hat{E}(r,t) = \hat{E}_{in}(r,t) + \left(3\pi\hbar c\Gamma_0/d_0\omega_{eg}\right) \sum_i G\left(r, r_i, \omega_{eg}\right)\sigma_{ge}^i(t)$$

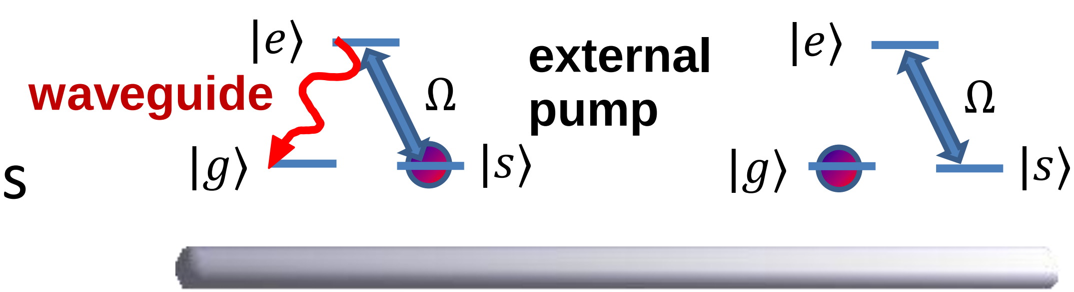
Quantum memory for light

- How well can one store an incoming photon as a collective spin flip to the excited state?



- By time reversal symmetry, can study the reverse problem of mapping an initial spin excitation into a photon

- Use three-level systems

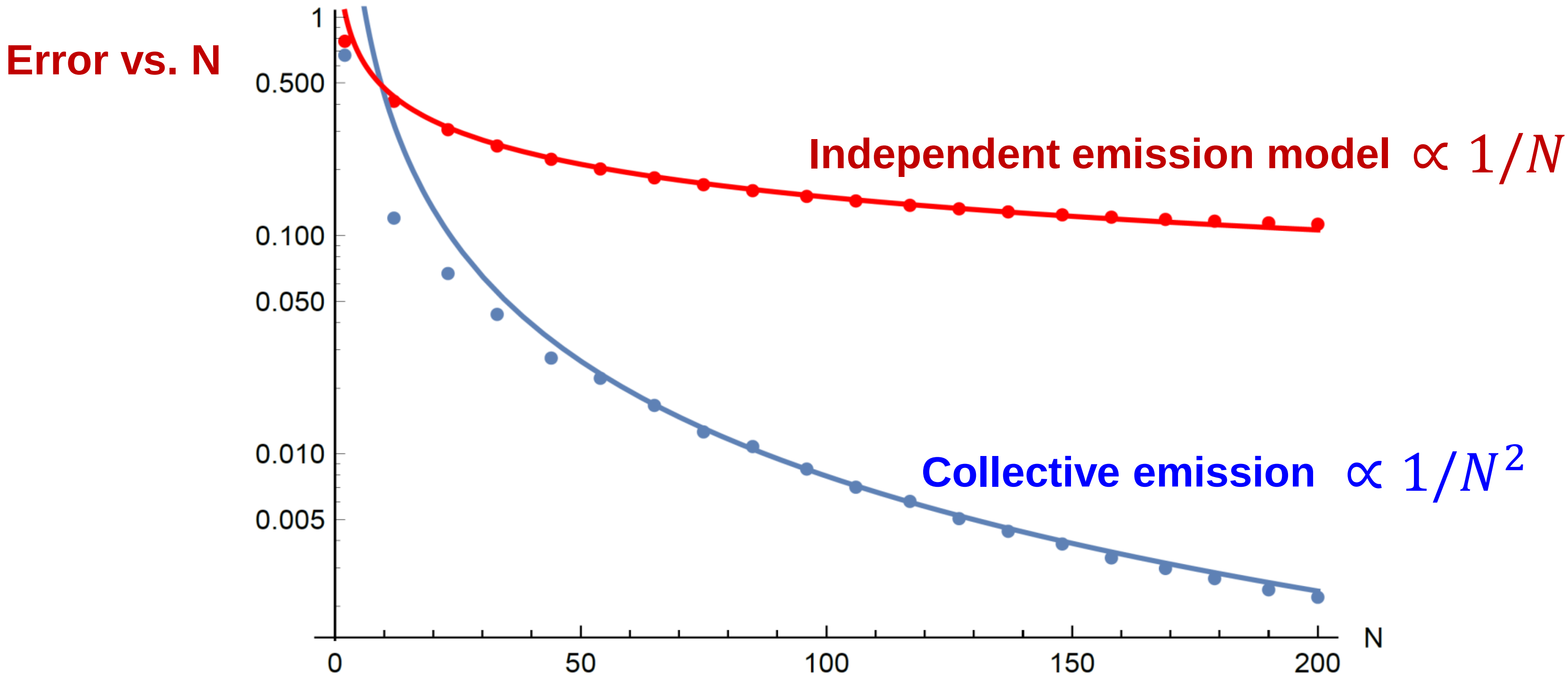


- Independent emission model: error $\sim \frac{5.8\Gamma'}{N\Gamma_{1D}} = \frac{5.8}{\mathrm{OD}}$

Same scaling as free space: AV Gorshkov et al, PRL 98, 123601 (2007)

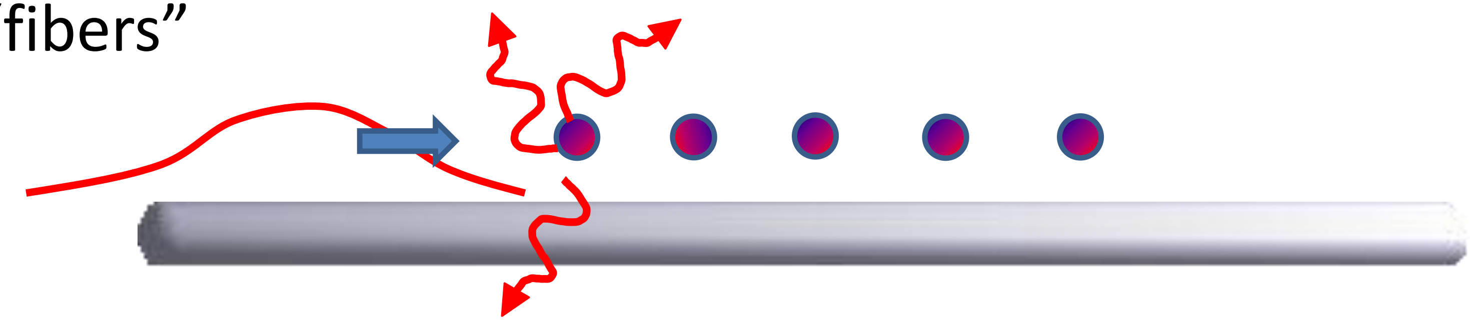
Photon storage/generation

- Collective emission:
  - Numerically diagonalize H_{eff} within manifold of single $|s\rangle$ excitation
  - Look for eigenstate with highest emission probability into waveguide



What limits the process?

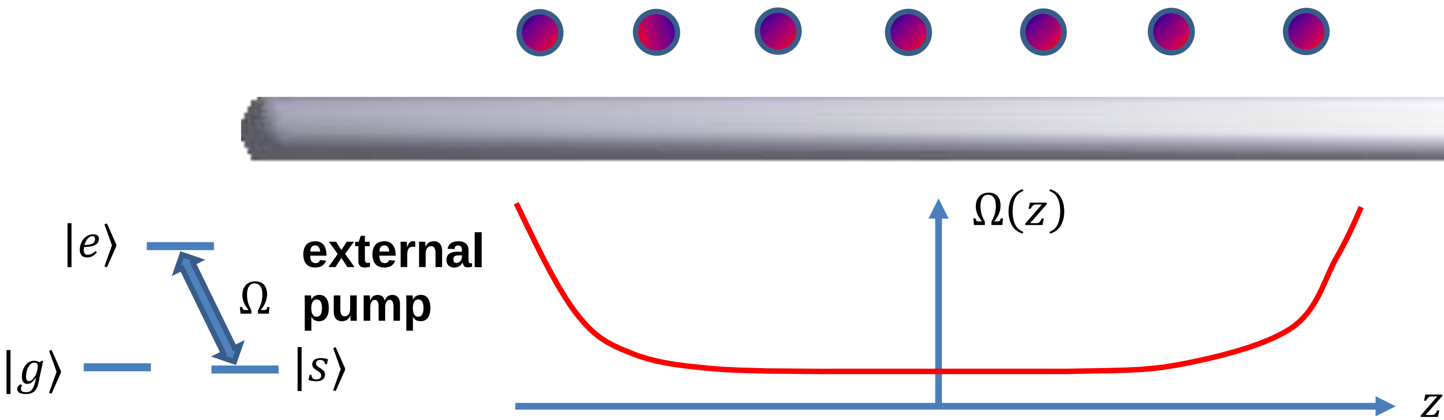
- $1/N^2$ error seems less than ideal
  - $\frac{1}{N}$ from collective enhancement into guided mode
  - “Only” $\frac{1}{N}$ suppression of emission into free space
- Origin: scattering losses at interface between two different “fibers”



- Need a fiber “connector!”

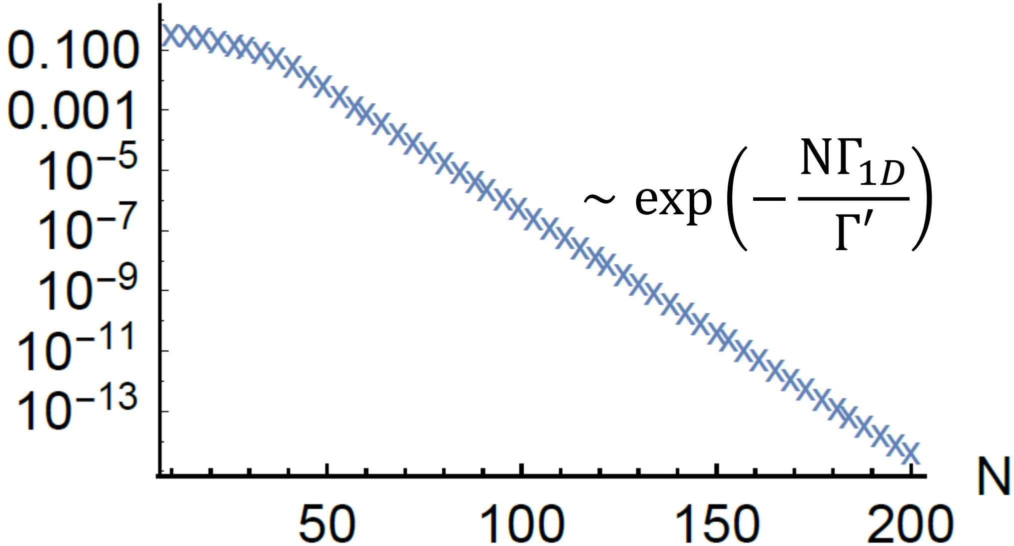
Photon storage with impedance matching

- Spatially vary the pump field profile, so that atoms at the ends "gradually" couple to fiber



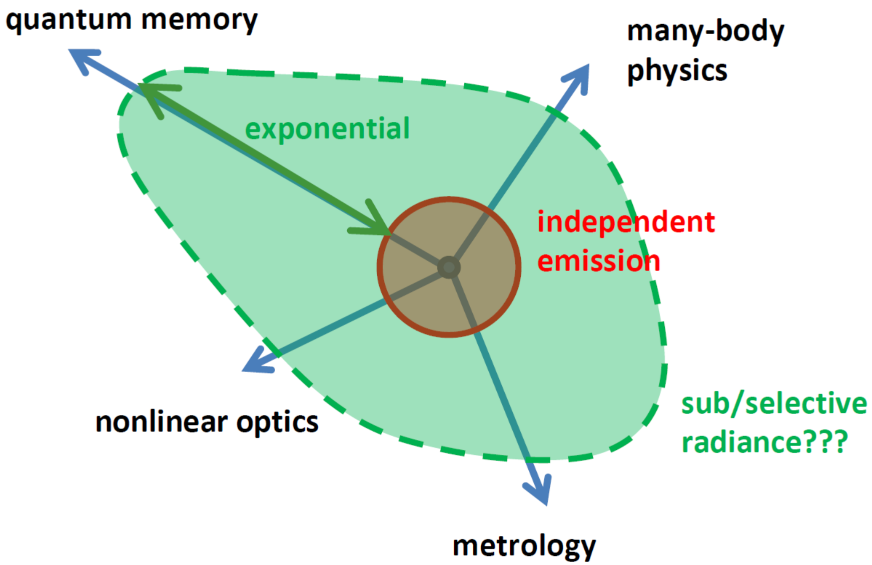
- Exponential suppression of error!

Error vs. N



Outlook

- What is the new ceiling if one exploits subradiance?



- Atom-light interactions as a quantum spin model

$$H_{\text{eff}} = -(3\pi\hbar\Gamma_0 c/\omega_{eg}) \sum_{i,j} G(r_j, r_i, \omega_{eg}) \sigma_{eg}^{i} \sigma_{ge}^{j}$$

$$\hat{E}(r,t) = \hat{E}_{in}(r,t) + (3\pi\hbar c\Gamma_0/d_0\omega_{eg}) \sum_{i} G(r, r_i, \omega_{eg}) \sigma_{ge}^{i}(t)$$

  - New insights or numerical tools for AMO physics?

Multiple excitations

- Single-excitation physics is classical
- Can we encode many excitations in sub-radiant states?

- Most sub-radiant single excitation $\Gamma_1 \propto \Gamma_0/N^3$

$$|\psi\rangle = S_1^\dagger |g\rangle^{\otimes N} = \sum_j c_j^{(1)} |e_j\rangle$$

- Example: two excitations
  - What if we create same excitation twice: $|\psi\rangle = \left(S_1^\dagger\right)^2 |g\rangle^{\otimes N}$

Eigenstate?

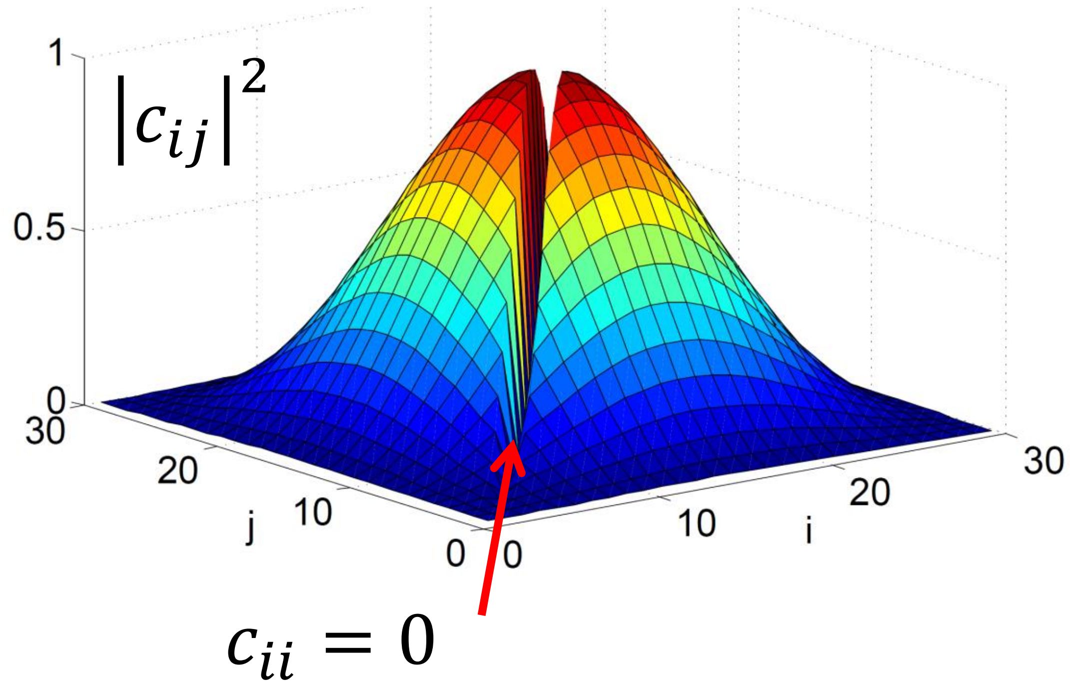
- Bosons: yes! Decay rate $2\Gamma_1$
- Spins: no!

Two-excitation wavefunction

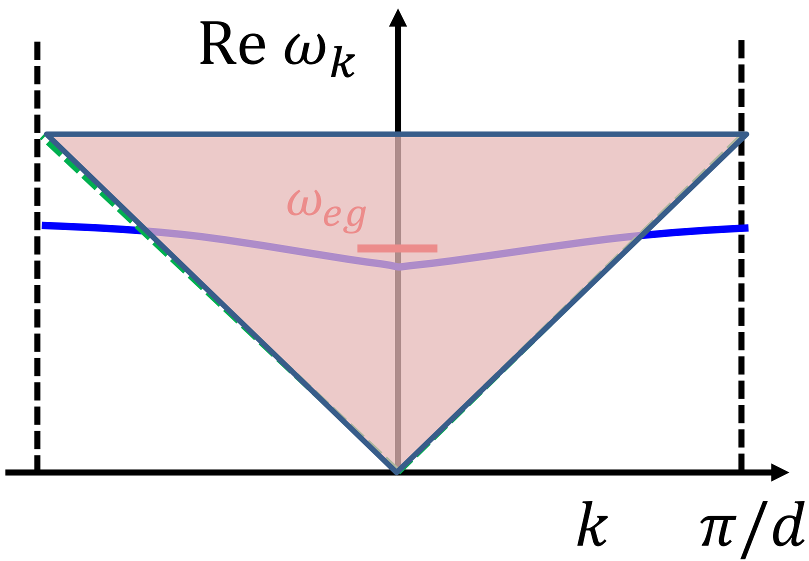
- Wave function:

$$|\psi\rangle = \left(S_1^\dagger\right)^2 |g\rangle^{\otimes N}$$

$$= \sum_{i,j} c_{ij} |e_i e_j\rangle$$



- State contains many momentum components within light cone



- Only weakly subradiant

$$\langle \Gamma \rangle \sim \Gamma_0 / N$$

Multiple excitations

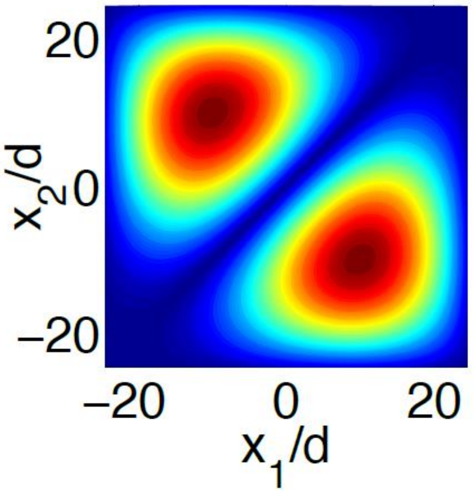
- How to construct many-excitation subradiant states?
- Single-particle eigenstates

$$\Gamma_\alpha \propto \alpha^2\,\Gamma_0/N^3, \qquad |\psi_\alpha\rangle = \sum_j c_j^{(\alpha)}|e_j\rangle$$

- Sub-radiant states should satisfy:
  - Wavevectors beyond the light line, *and* spatially non-overlapping
- Create a *fermionized* wave function (Pauli exclusion!)
- Example: two excitations

$$|\psi\rangle = \sum_{i>j} c_{ij}|e_i e_j\rangle$$

$$c_{ij} = c_i^{(1)}c_j^{(2)} - c_i^{(2)}c_j^{(1)}$$



$$\Gamma \sim \Gamma_1 + \Gamma_2 \propto \frac{1}{N^3}$$

- Subradiance itself is a rich many-body problem!