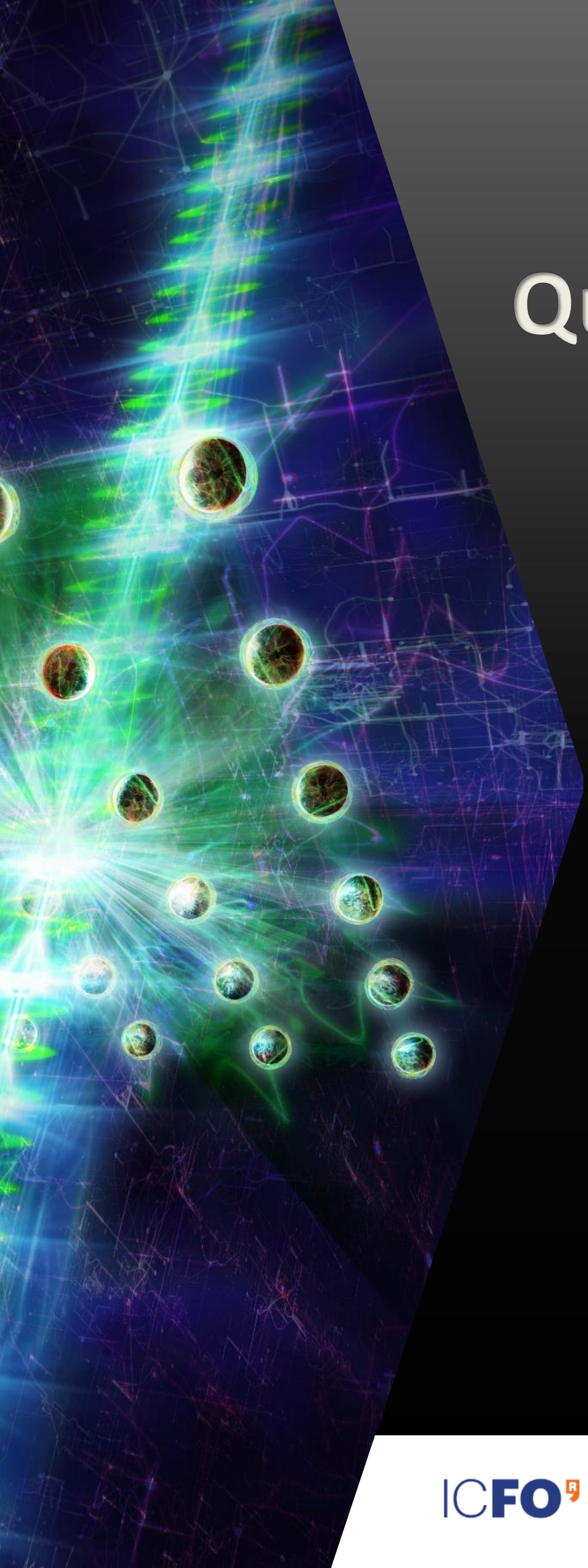


Quantum optics with atomic arrays

Tutorial talk

Darrick Chang

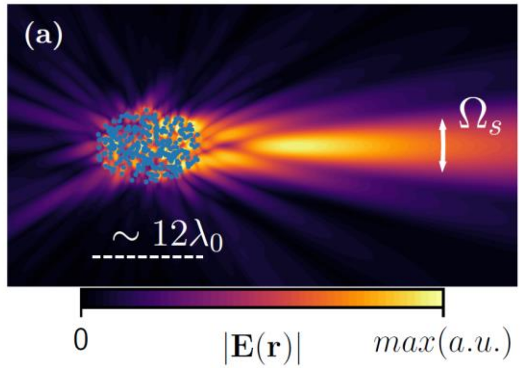
ICFO

SPICE Conference on Quantum Spinoptics

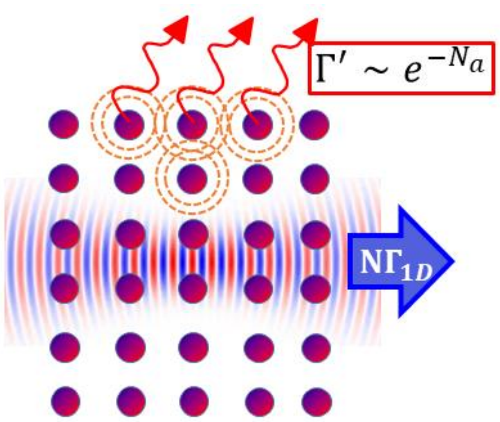
June 13, 2023

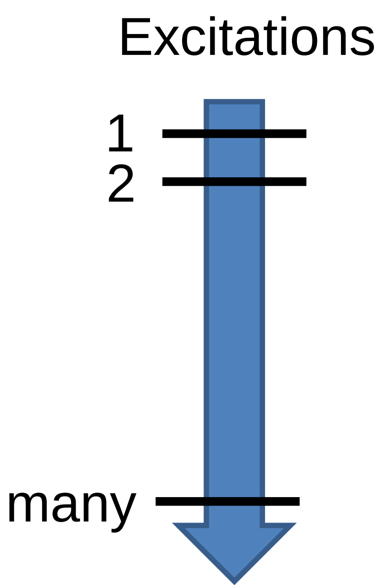
Outline

- Collective dissipation in quantum optics – why does it matter?



- Novel paradigms based on collective dissipation

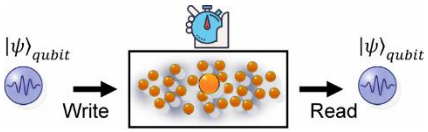




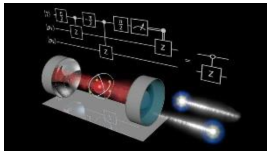
- What we don't know

Motivation

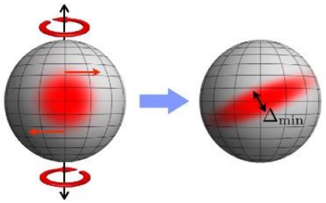
- **Goal:** realize efficient quantum atom-light interfaces



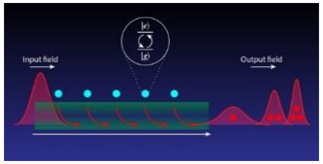
Quantum memories



Photon-photon gates

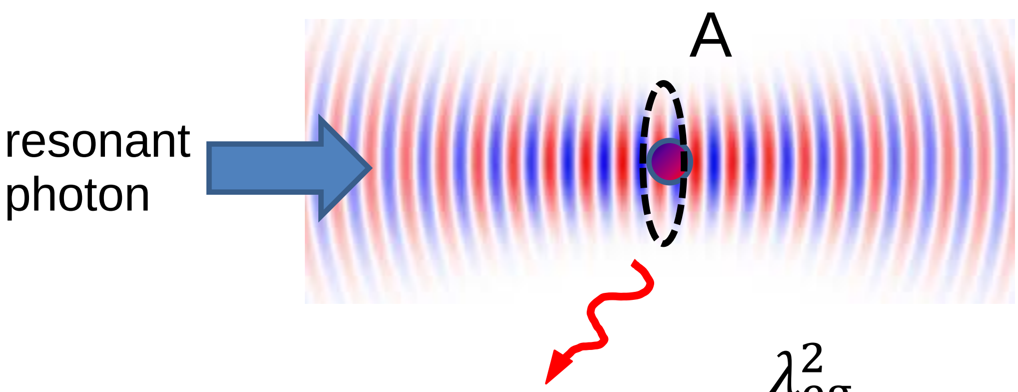


Metrology/sensing



Many-body physics with photons

- **Challenge:** hard to make a single photon and atom interact!



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

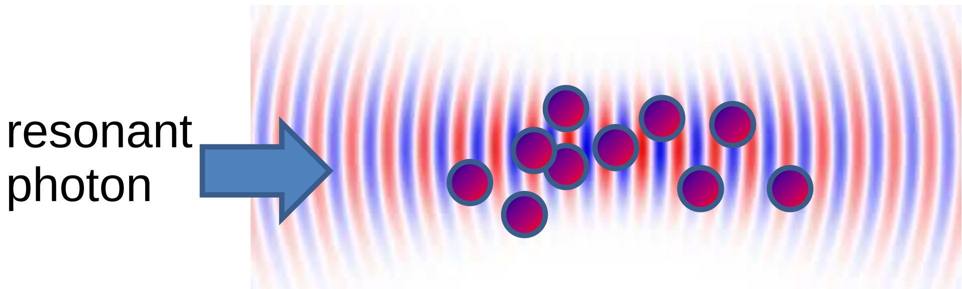
diffraction limit

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

- Record with single atoms in free space: ~10% (Kurtsiefer, Singapore)

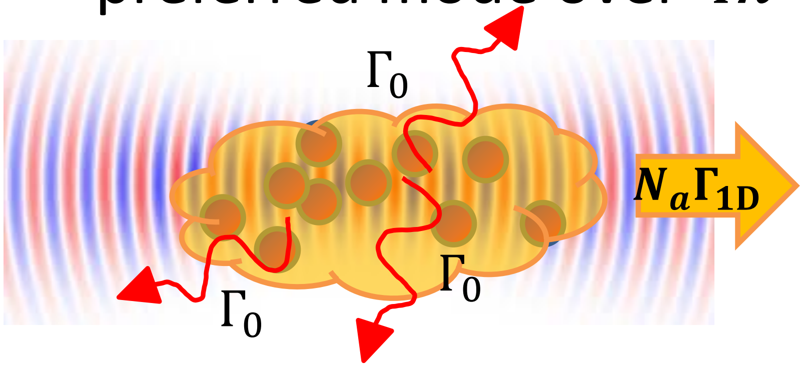
A possible fix: collective enhancement

- Common approach: collective enhancement



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

- Complementary viewpoint: branching ratio of emission into preferred mode over 4π



$$D \sim \frac{N_a \Gamma_{1\mathrm{D}}}{\Gamma_0}$$

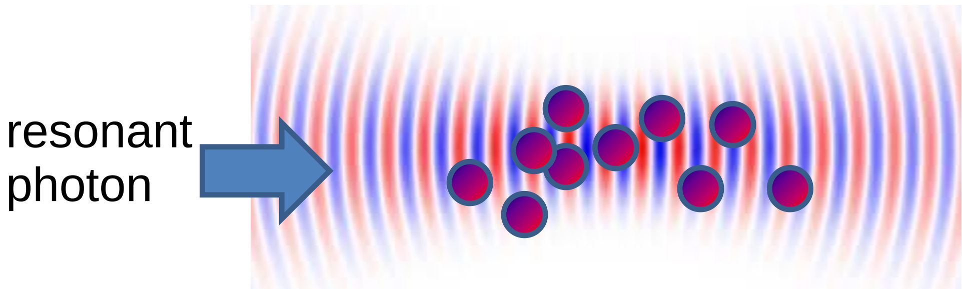
A.A. Svidzinsky et al, PRA 81, 053821 (2010)

Single collective excitation $|\psi\rangle \sim \sum_j e^{ik\cdot r_j}|e_j\rangle$

- Branching ratio of information imposes fundamental limits on the errors of any application

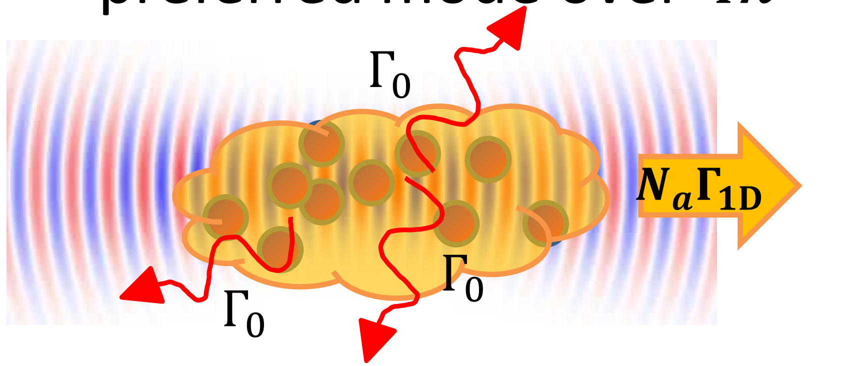
A possible fix: collective enhancement

- Common approach: collective enhancement

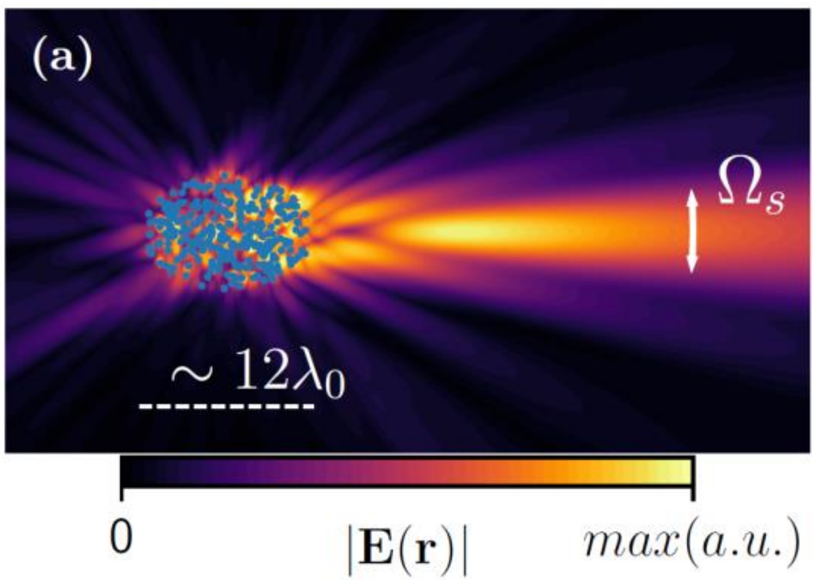


$P_{sc} \sim \frac{\lambda_{eg}^2}{A} N_a \sim$ Optical depth D

- Complementary viewpoint: branching ratio of emission into preferred mode over 4π



Single collective excitation $|\psi\rangle \sim \sum_j e^{ik\cdot r_j}|e_j\rangle$

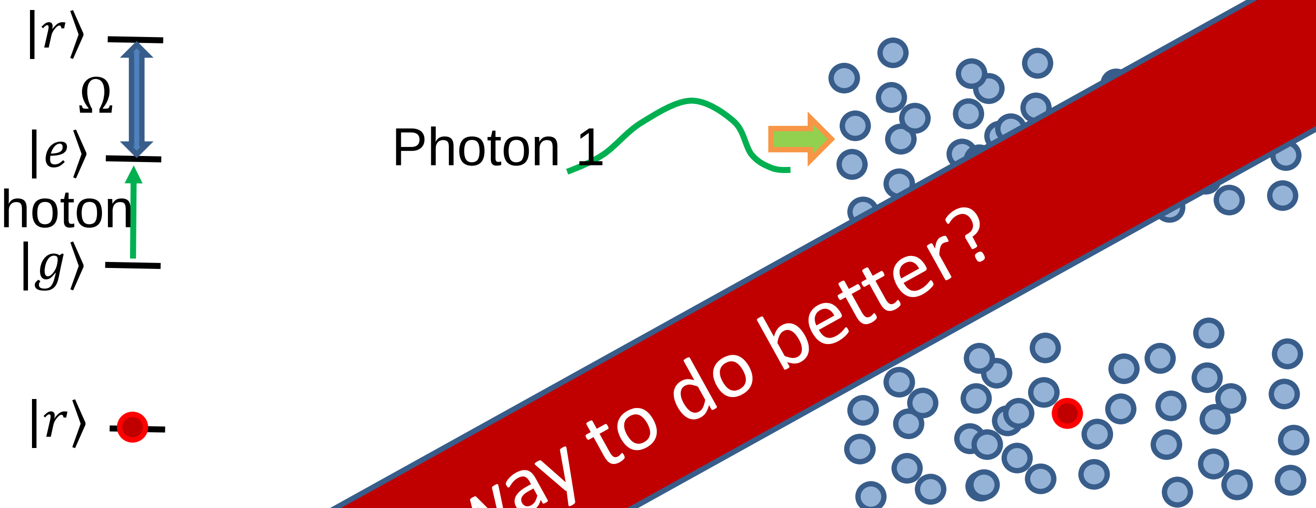


- Branching ratio of information imposes fundamental limits on the errors of any application

Photon-photon gate

- Typical protocol:
  - Quantum memory / photon storage

Error

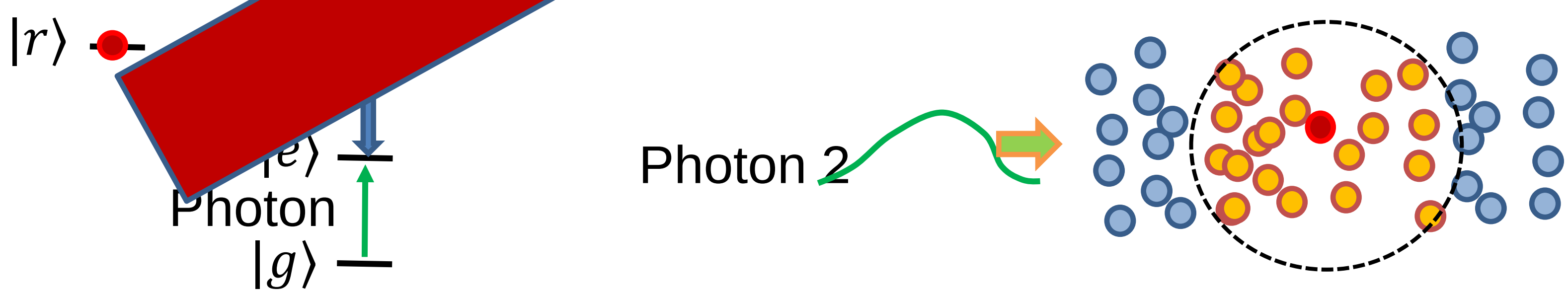


$\approx \frac{5.8}{\mathrm{D}}$

A way to do better?

  - Conditi se shift for second photon

ade



$\approx \frac{7.5}{D_b^{3/2}}$

Thompson et al, Nature 542, 206 (2017)

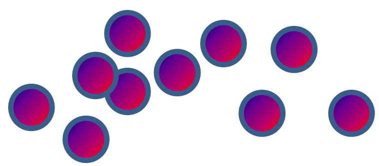
- Current error ~ 60%

T. Stolz et al, PRX 12, 021035 (2022)

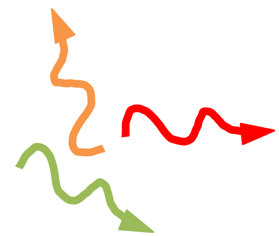
Complexity of atom-light interactions

- How did we arrive at these physical conclusions? What is the underlying theory?

- **Full microscopic** quantum theory?



$\otimes$

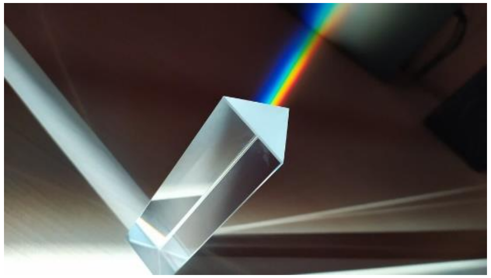


$N \sim 10^4$ atoms
Dim $\mathscr{H} \sim 2^{10000}$
Positions $\{r_i(t)\}$

Continuum of photon modes
(frequency, direction, number)
Dim $\mathscr{H} \sim \infty$

Standard approach: macroscopic theory

- Classical optics analogy:

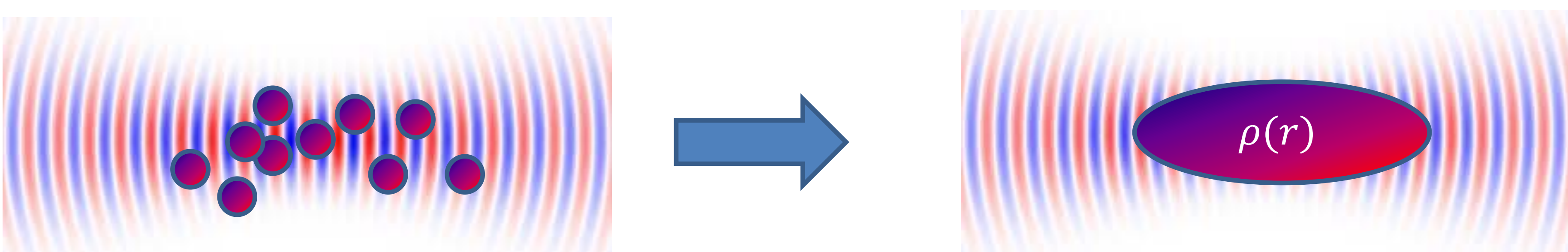


$\sim 10^{23}$ degrees of freedom

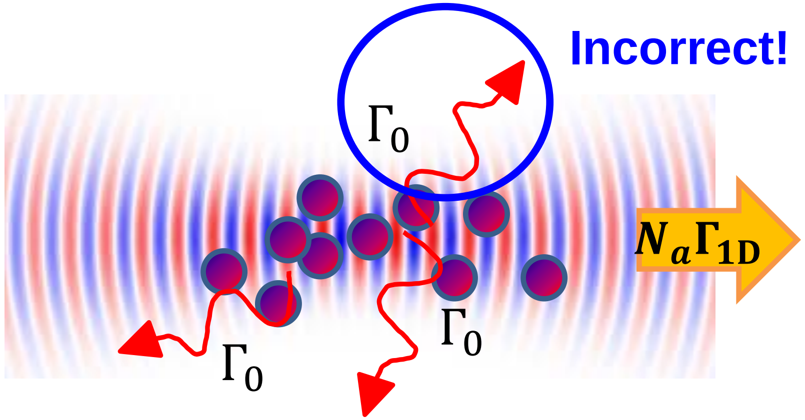
optics

Smooth material, refractive index n

- Conventional quantum optics (Maxwell-Bloch equations):
  - Quantum interaction between light and a **smooth, uniform** medium



What physics is left out?



$$D \sim \frac{N_a \Gamma_{1D}}{\Gamma_0} \sim \frac{\lambda_{eg}^2}{A} N_a$$

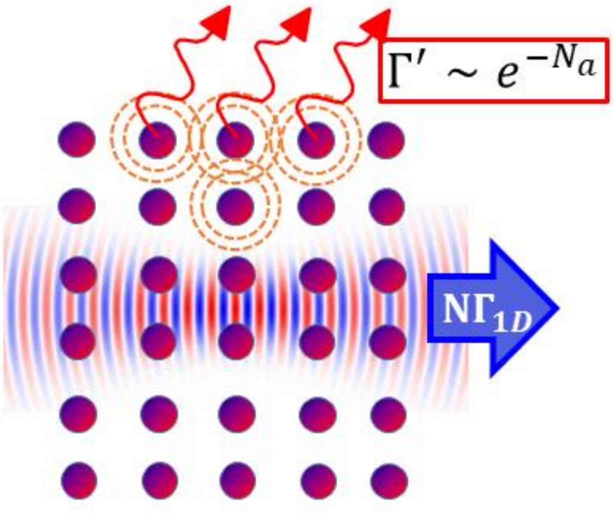
- **What is associated with granularity:**
  - Multiple scattering and wave interference!
  - Should be strong (non-perturbative) once $d < \lambda_{eg}$

- Light emitted into 4π can interfere… spontaneous emission must be a form of correlated dissipation

A new opportunity

- Can we exploit wave interference in protocols?

- Combine **collective enhancement** into good directions with **collective suppression** into 4π



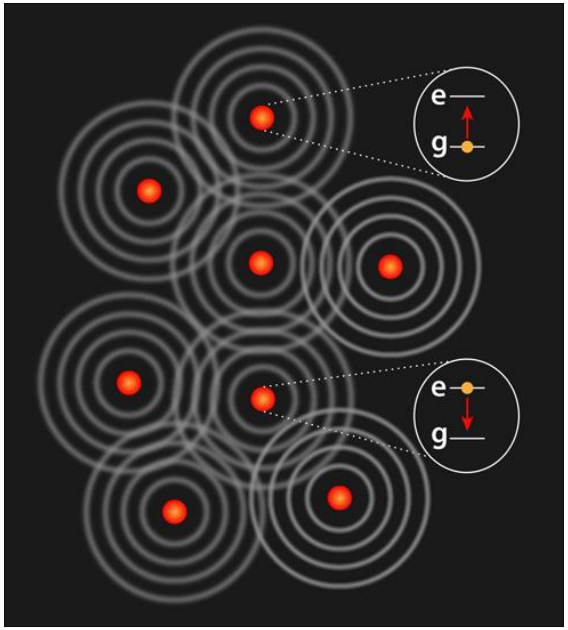
$$\text{Branching ratio} \sim \frac{N\Gamma_{1\text{D}}}{\Gamma'(N)} \gg D$$

- New concept: **“selective radiance”**

A. Asenjo Garcia et al, PRX 7, 031024 (2017)

A new opportunity

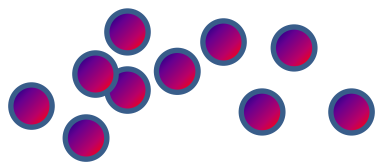
- Can we exploit wave interference in protocols?
- Suppress emission altogether and allow coherent interactions to build up: **“subradiance”**



Theory: Ritsch, Ruostekoski, Asenjo, Adams, Yelin, Shahmoon, Lukin, Genes, Mølmer, Pohl, Cirac, Sheremet, Olmos, Podubbny, …
Experiment: Zeiher/Bloch, Browaeys, Kaiser, Lodahl, Wallraff, Painter, Mirhosseini, …

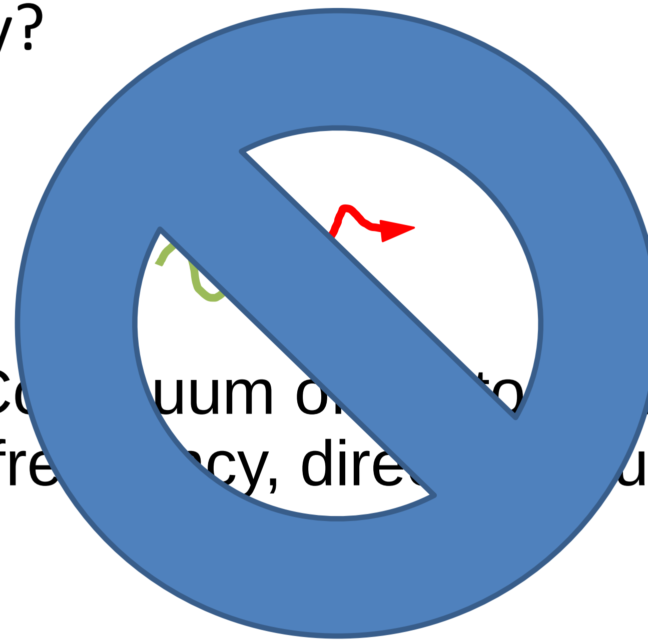
Spin model of atom-light interactions

- **Full microscopic** quantum theory?



$N \sim 10^4$ atoms
Dim $\mathscr{H} \sim 2^{10000}$
Positions $\{r_i(t)\}$

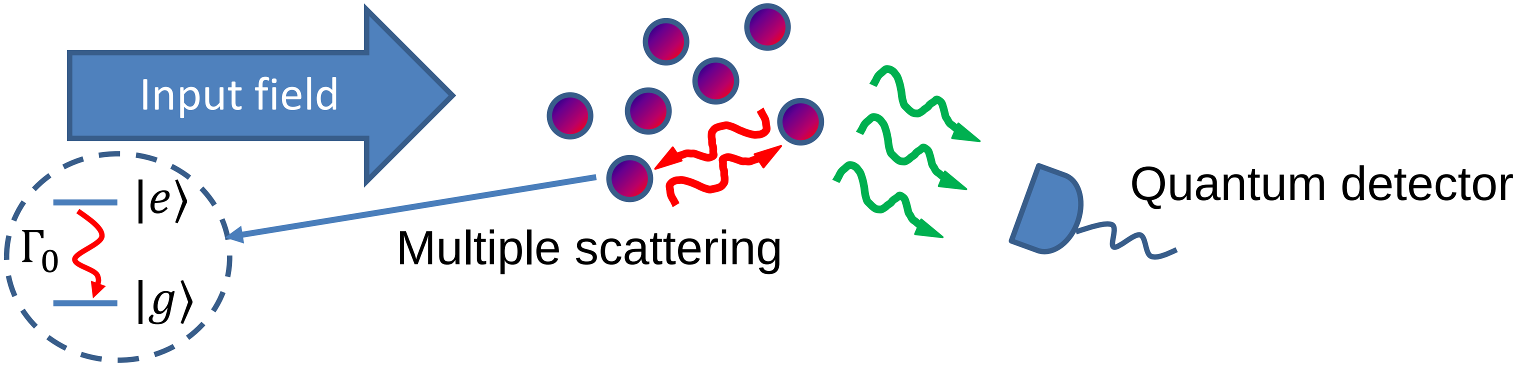
$\otimes$



Co uum o to odes
(fre cy, dire umber)

A "spin model" for multiple scattering

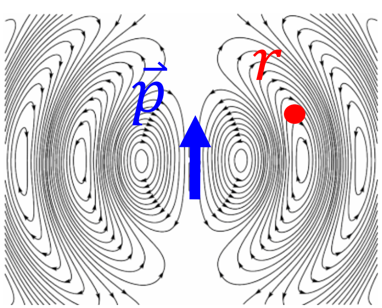
Freq. $\omega_{eg} = \frac{2\pi c}{\lambda_{eg}}$



- A quantum input-output relation:

$$\hat{E}(r,t) \sim \hat{E}_{in}(r,t) + \sum_i G(r, r_i, \omega_{eg})\hat{\sigma}^i_{ge}(t)$$

- In free space:

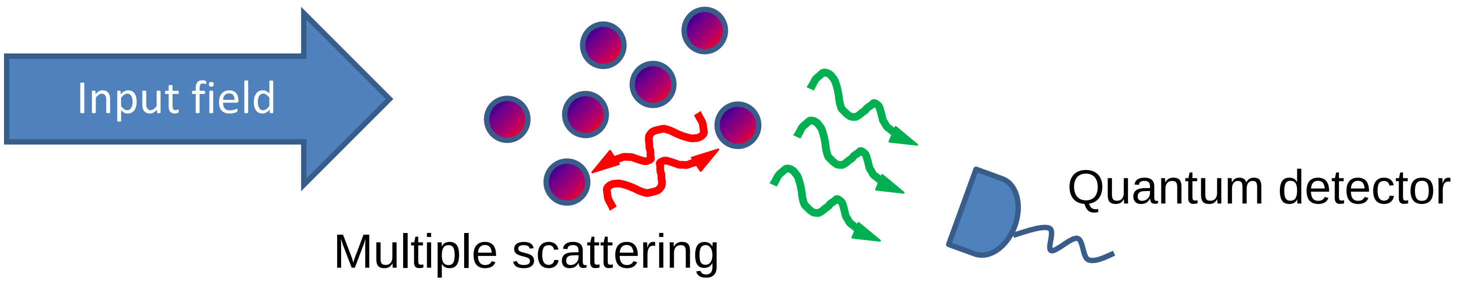


$$G(r,0,\omega) = e^{ikr}\left[\frac{k^2}{r}(\hat{n}\times\hat{p})\times\hat{n} + (3\hat{n}(\hat{n}\cdot\hat{p}) - \hat{p})\left(\frac{1}{r^3} - \frac{ik}{r^2}\right)\right]$$

$$k = \omega/c$$

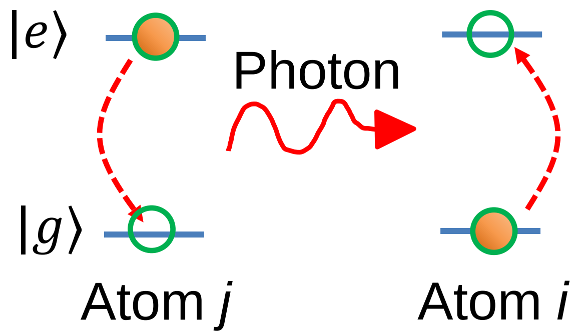
- Quantum field properties can be derived from the atoms

A “spin model” for multiple scattering



- Atomic dynamics:
  - Coherent dipole-dipole interactions

$$H = H_{in} - \sum_{i,j} \mathrm{Re}\, G(r_j, r_i, \omega_{eg}) \sigma_{eg}^i \sigma_{ge}^j$$



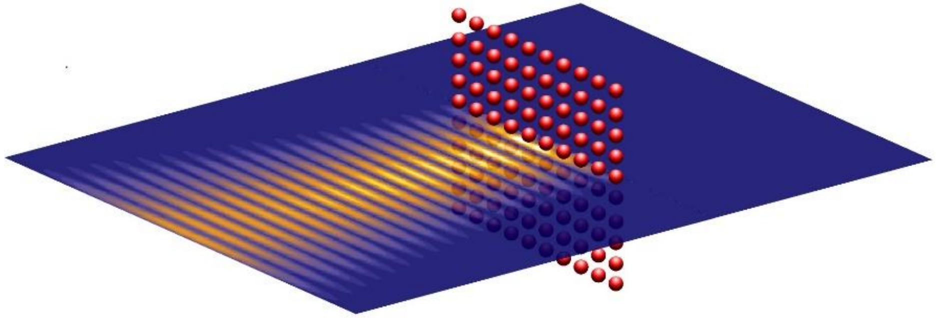
  - Correlated emission

$$d\rho_{\text{atoms}}/dt = -i[H, \rho_{\text{atoms}}] + \sum_{i,j} \mathrm{Im}\, G(r_i, r_j) \left(\hat{\sigma}_{ge}^j \rho_{\text{atoms}} \hat{\sigma}_{eg}^i - \left\{ \hat{\sigma}_{eg}^i \hat{\sigma}_{ge}^j, \rho_{\text{atoms}} \right\}/2 \right)$$

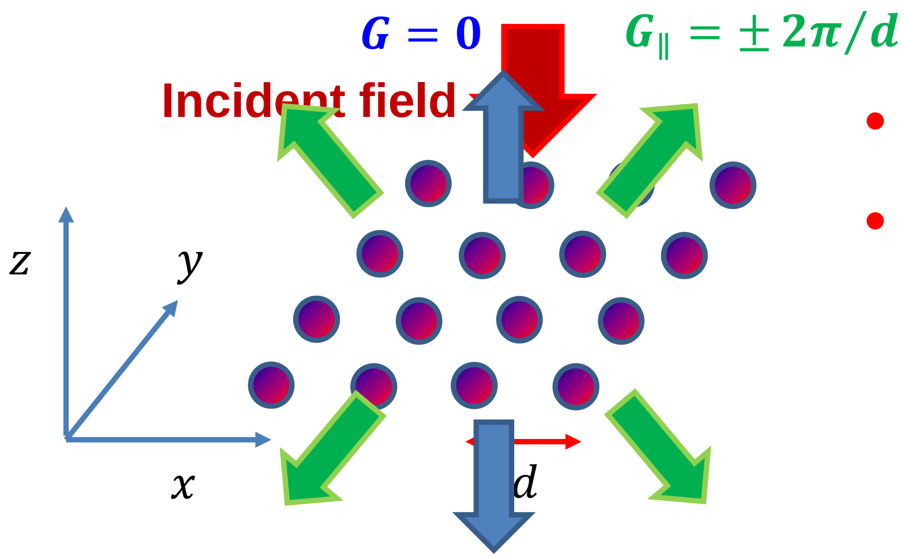
  - Encodes wave interference effects in radiation
- Quantum optics encoded in long-range, out-of-equilibrium, correlated dissipative **spin model**

A perfect mirror

- An infinite 2D array of atoms can form a perfect mirror for single, resonant photons



- Four ingredients:

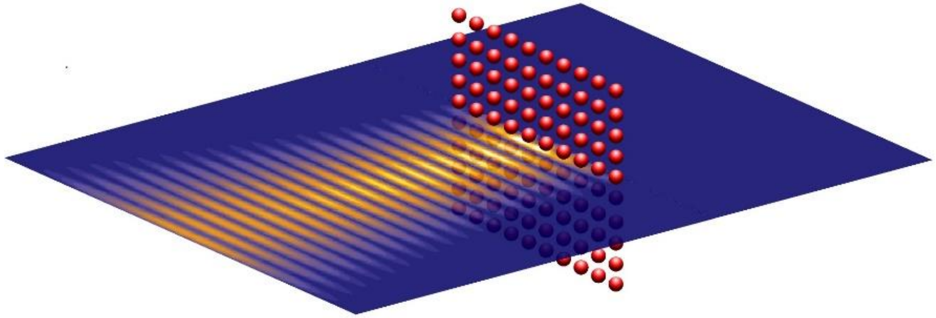


- Atoms cannot absorb (only scatter)
- Spatial order: scattering only in discrete diffraction orders

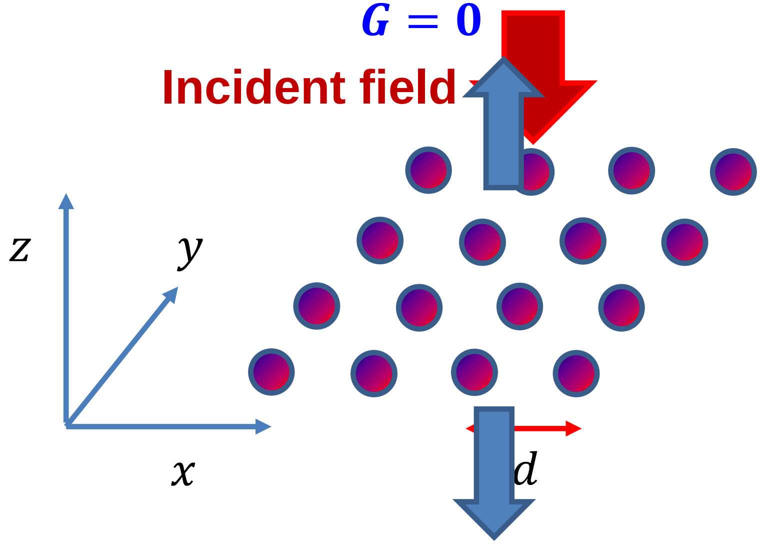
Bettles et al, PRL (2016); Shahmoon et al, PRL (2017)

A perfect mirror

- An infinite 2D array of atoms can form a perfect mirror for single, resonant photons



- Four ingredients:

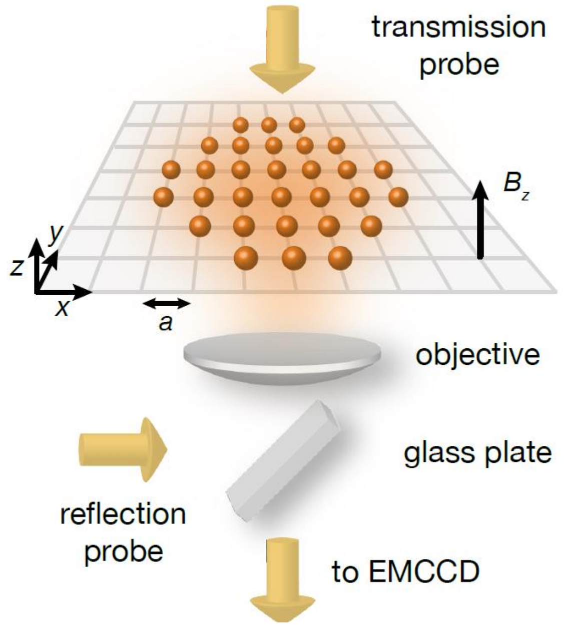


- Atoms cannot absorb (only scatter)
- Spatial order: scattering only in discrete diffraction orders
- $d < \lambda_{eg}$: only fundamental order is radiative
- Atoms have a resonance

Bettles et al, PRL (2016); Shahmoon et al, PRL (2017)

Experimental realization

- Bloch group (MPQ) (Nature 583, 369 (2020))



Nearly defect-free 2D Mott insulator

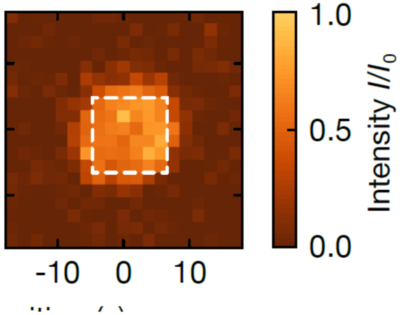
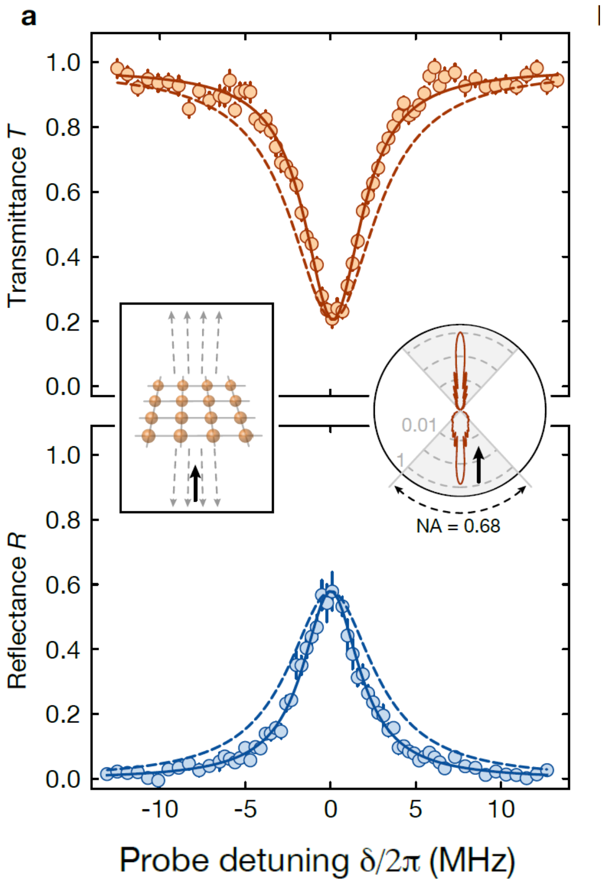


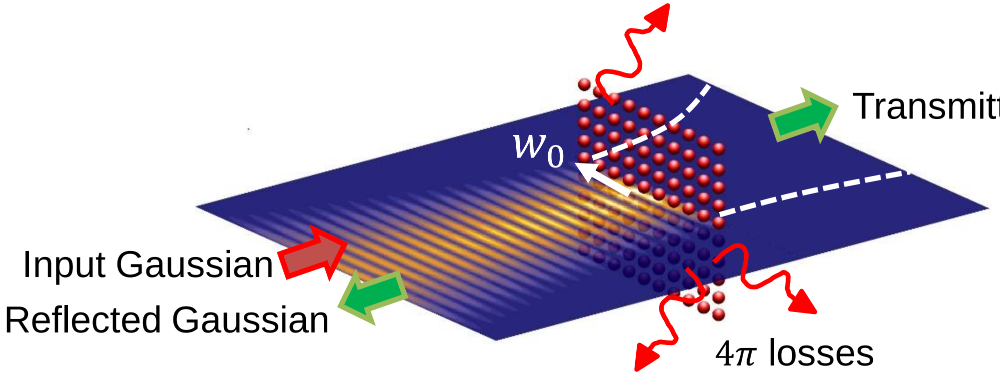
Image of reflection



- ~60% reflectance, mainly limited by non-ideal collection optics and recoil heating of atomic motion

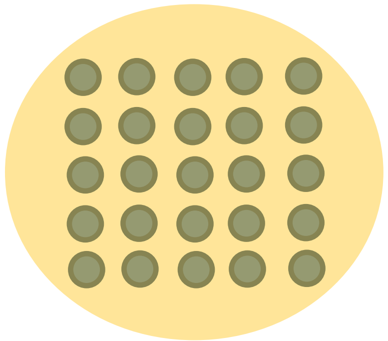
Finite systems

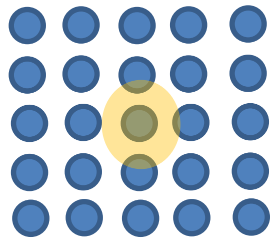
- 100% reflection $\leftrightarrow$ 100% atom-photon interaction efficiency?
- **Be careful!** Even in textbook models, infinite N (or optical depth) implies 100% fidelity/efficiency
- Need to consider finite resources (atom number N)
- Define efficiency w.r.t. a realistic mode (e.g., Gaussian)



N x N array

- Errors:

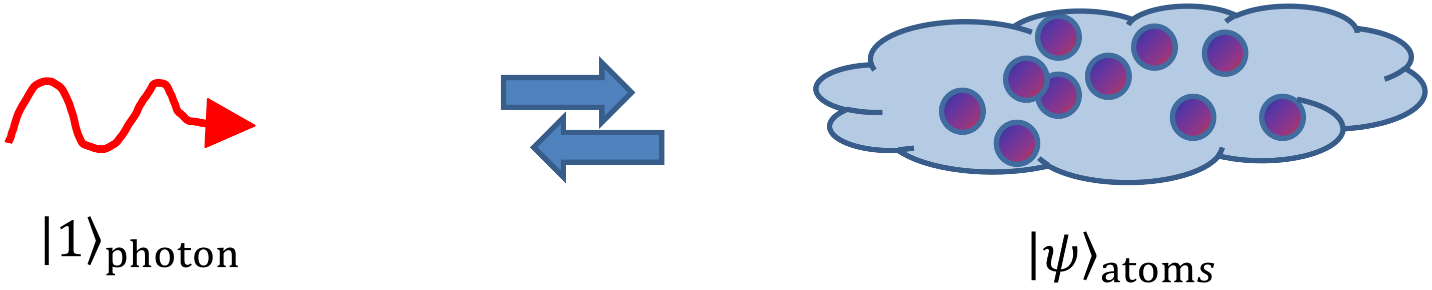




- Optimizing over beam waist: $R_{\max} \sim 1 - \frac{\log^2 N}{N^4}$

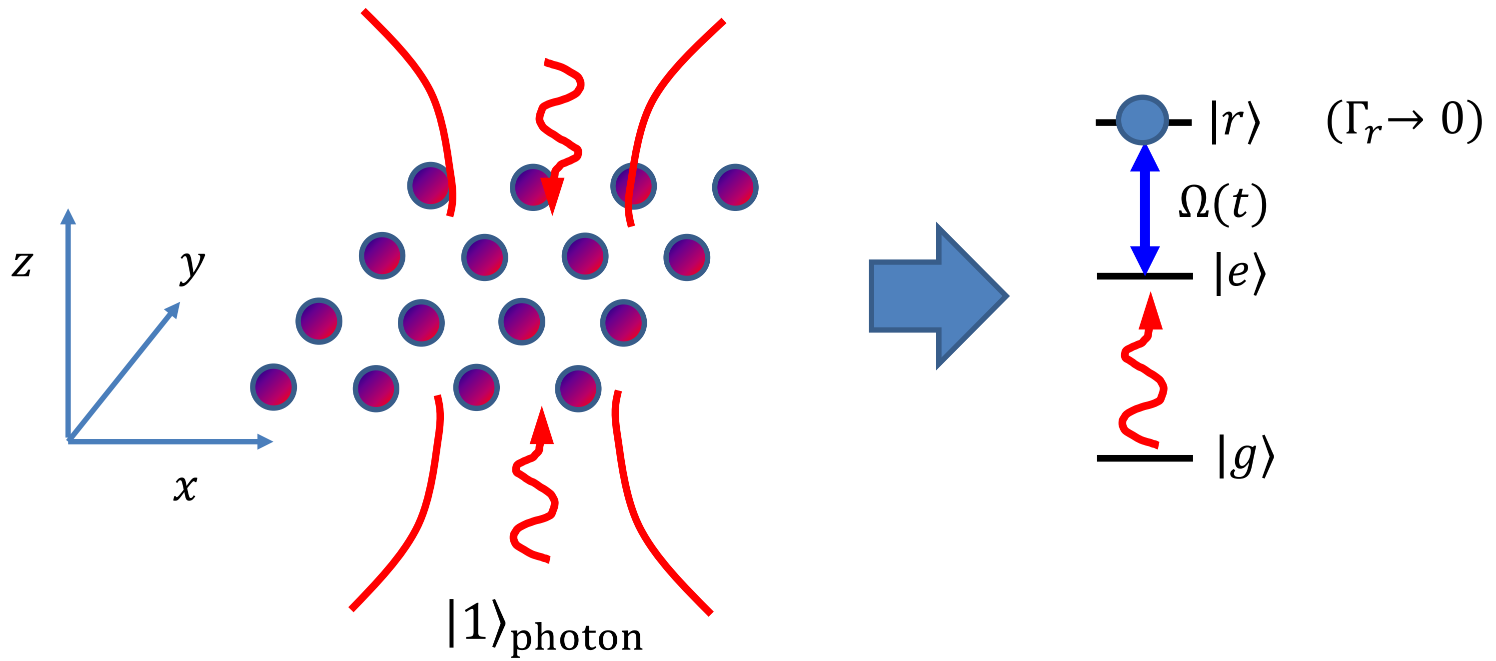
Quantum memory for light

- Analyze the error of a single-photon quantum memory based on a finite array, vs. the textbook result



Quantum memory for light

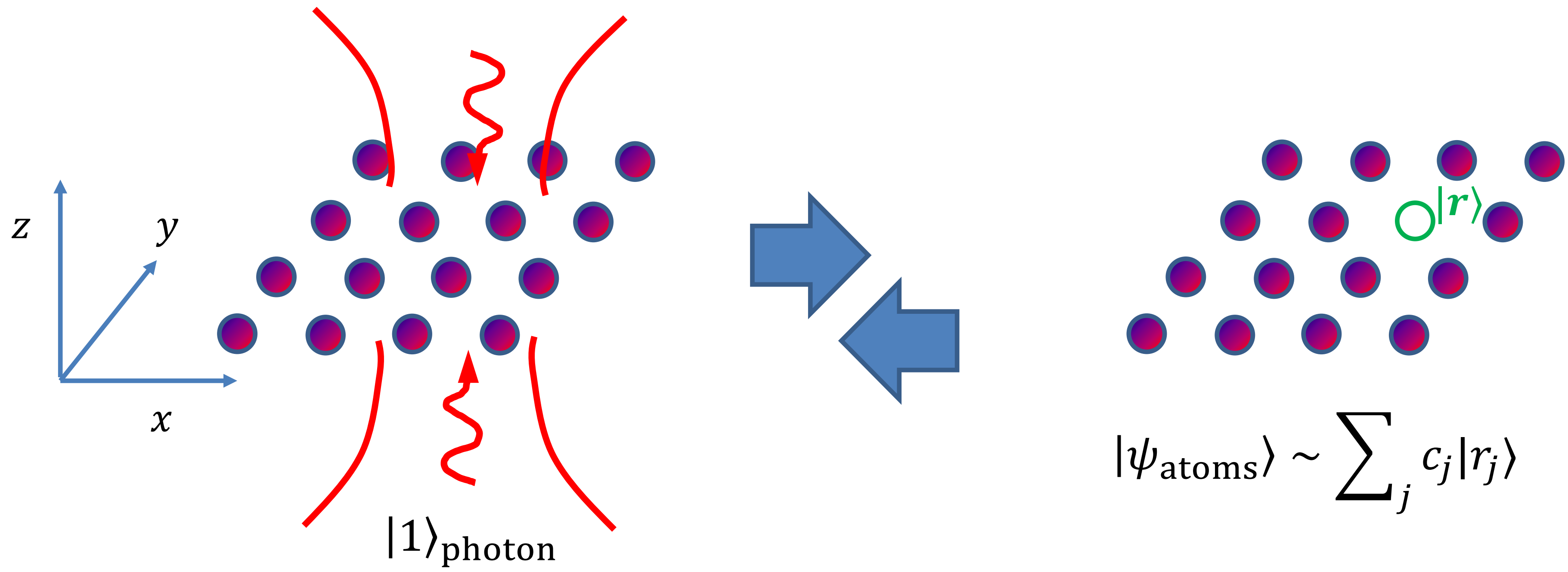
- Quantum memory protocol:



- Split photon: optimal by mirror symmetry

Quantum memory for light

- Quantum memory protocol:



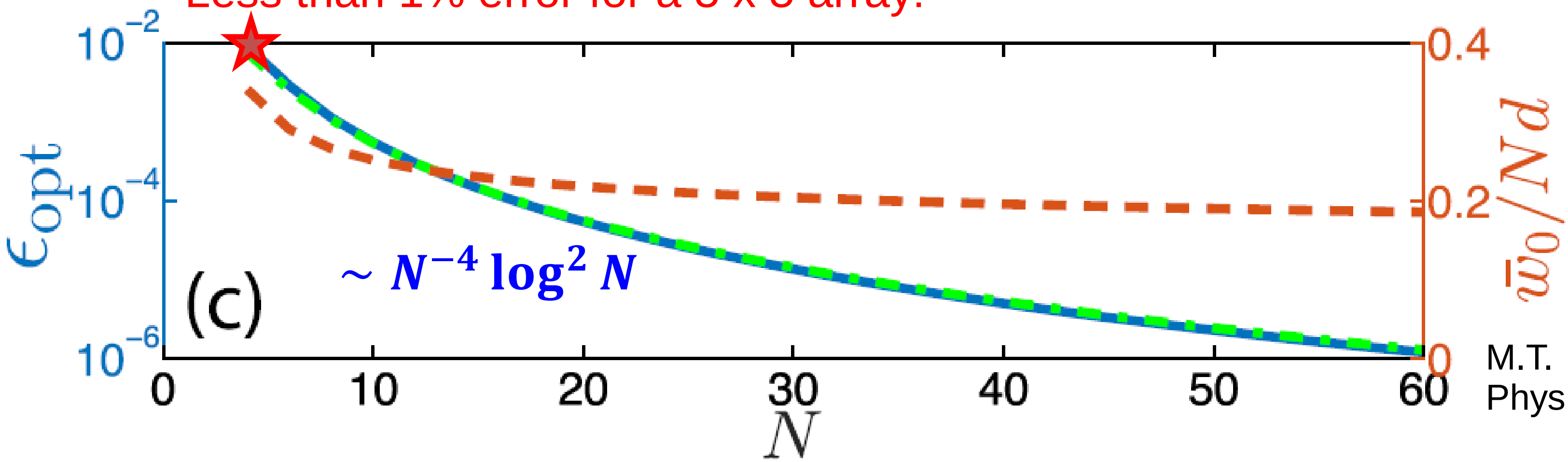
- Quantum memory has exactly the same error sources as reflection

Error $\overset{\text{optimized}}{\sim} \frac{\log^2 N}{N^4}$

Optimized retrieval efficiency

- Minimum retrieval error (N x N array):

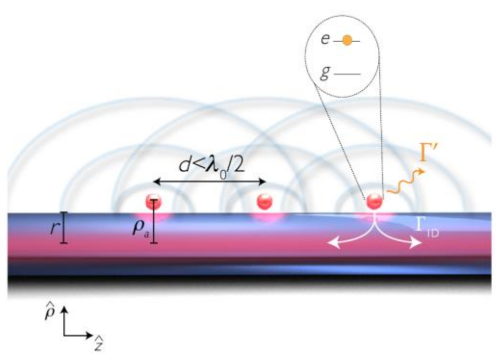
Less than 1% error for a 5 x 5 array!



Lattice constant
$\boldsymbol{d = 0.6\lambda_{eg}}$

M.T. Manzoni et al, New J. Phys. 20, 083048 (2018)

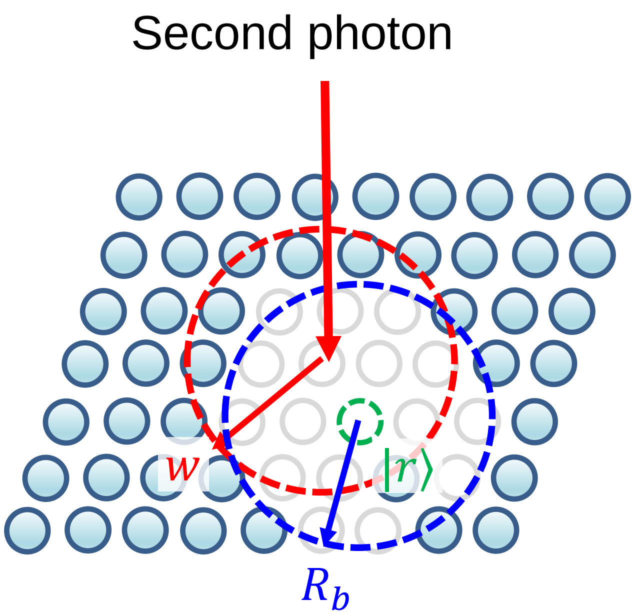
- Different array geometry (1D array coupled to nanofiber): ***exponential*** improvement, Error $\sim e^{-D}$



A. Asenjo Garcia et al, PRX 7, 031024 (2017)

Photon-photon gate

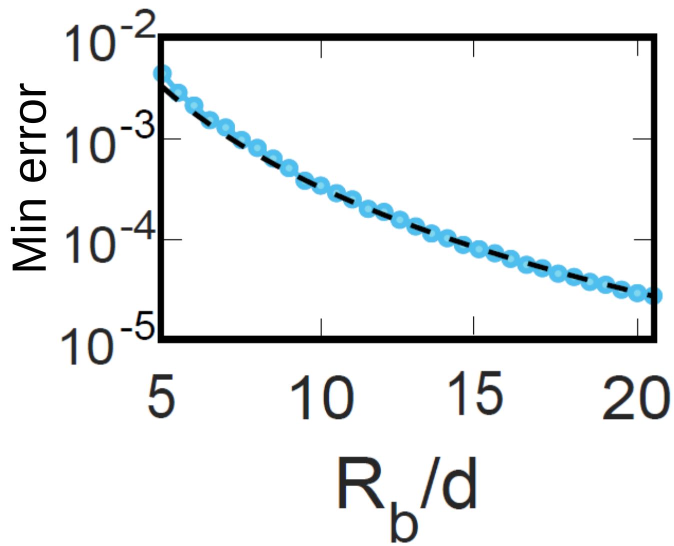
- Following storage of first photon into Rydberg excitation, send in a second photon
- Utilize Rydberg excitation to strongly shift resonance frequency of nearby atoms



- Conditional transmission of second photon, depending on presence of first

Efficient photon-photon gate

- Error as a function of "blockade radius"



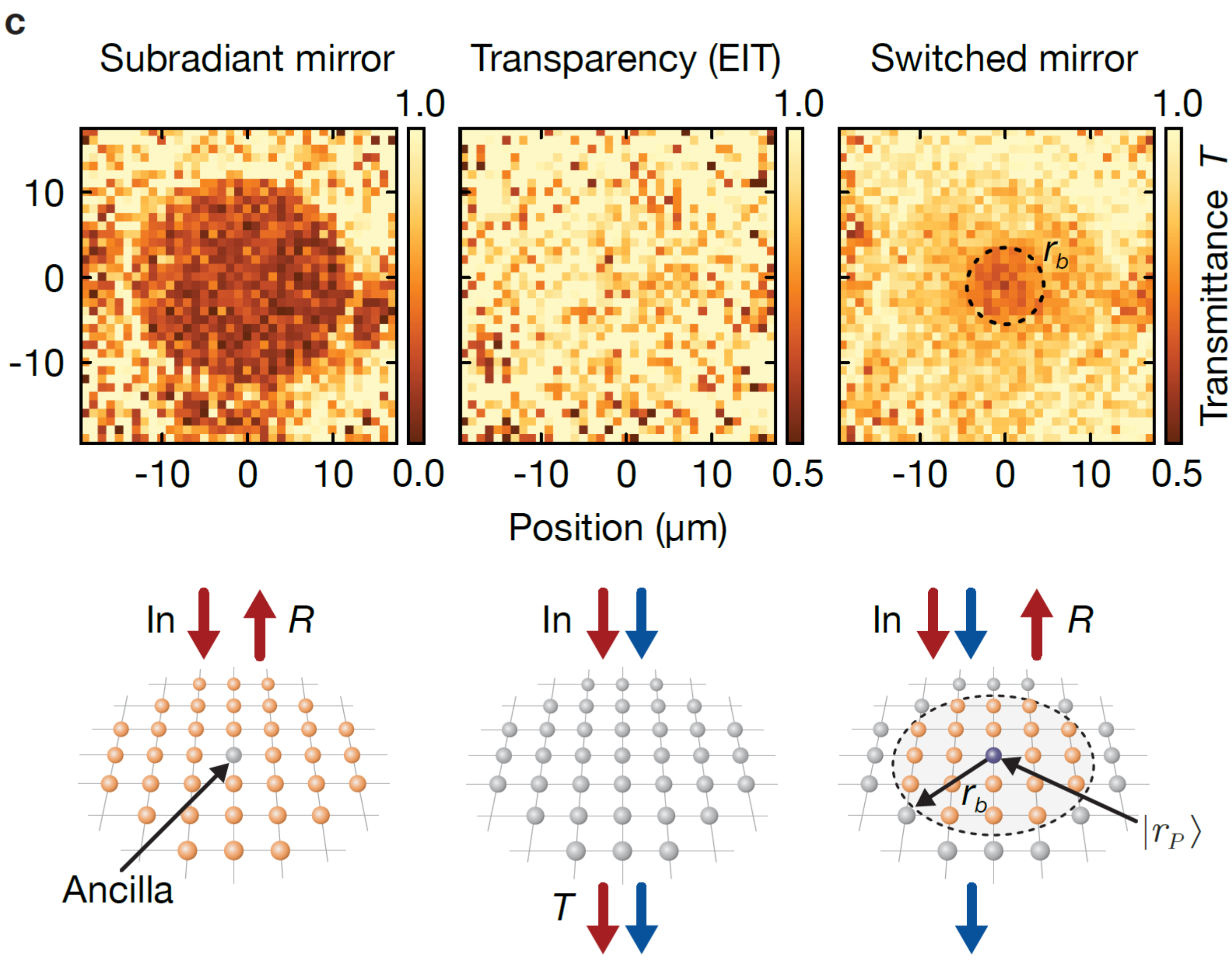
$d = 0.5\lambda_{eg}$
(assumes $Nd > R_b$)

$$\text{Error} \sim \frac{\log^2(R_b/d)}{(R_b/d)^4}$$

- **Polynomial improvement** over best known gate using Rydberg EIT in ensembles ($R_b^{-3/2}$)
- 1% error for moderate system sizes and blockade radius
- Other realistic errors (atomic motion, imperfect filling, realistic Rydberg dressing): $\sim 1\%$

Experimental observation of switched mirror

- Classically excited Rydberg atom can switch atom array

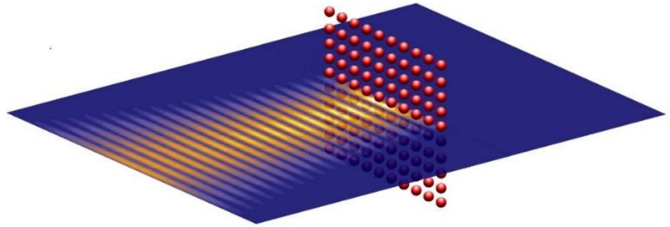


K. Srakaew et al, Nature Phys. 19, 714 (2023)

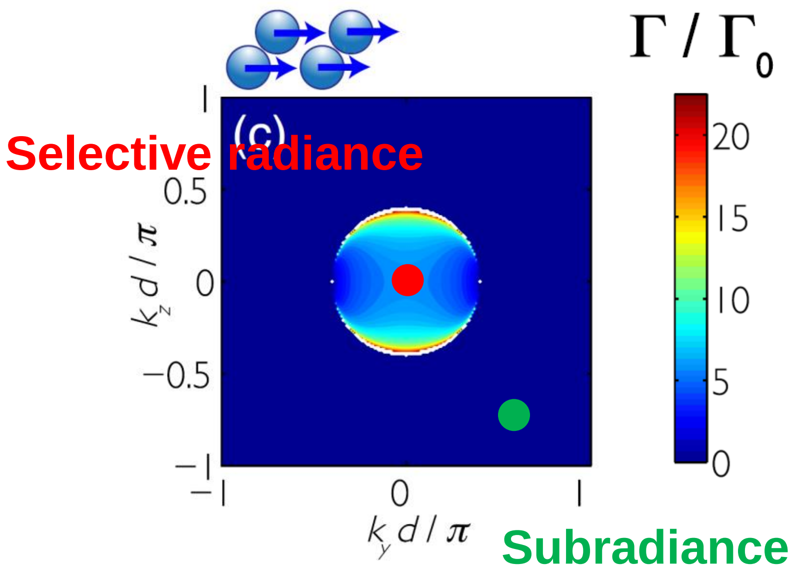
Optical band structure

- Diagonalize spin model in single excitation manifold

$$S_k^\dagger |g\rangle^{\otimes N} = \frac{1}{\sqrt{N}} \sum_j e^{i\boldsymbol{k}\cdot\boldsymbol{r}_j} |e_j\rangle$$



- Complex dispersion relation $\omega(k) - \frac{i\Gamma(k)}{2}$



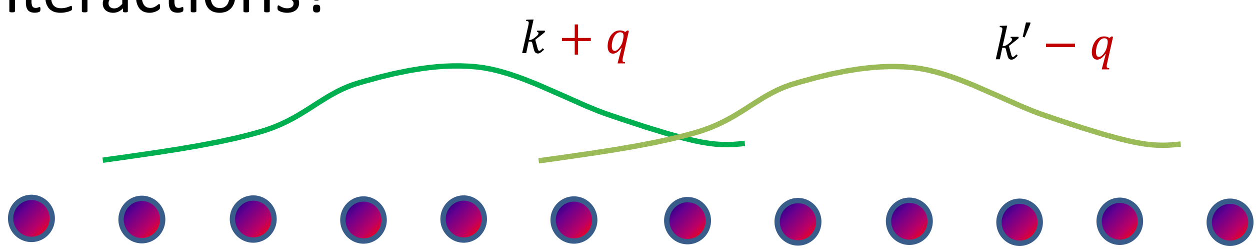
- $\Gamma(k)$ in first Brillouin zone $|k_{x,y}| < \frac{\pi}{d}$

- Subradiance: $|k| > \omega/c$, spin wave modes decouple from radiation

Exciting subradiant modes?

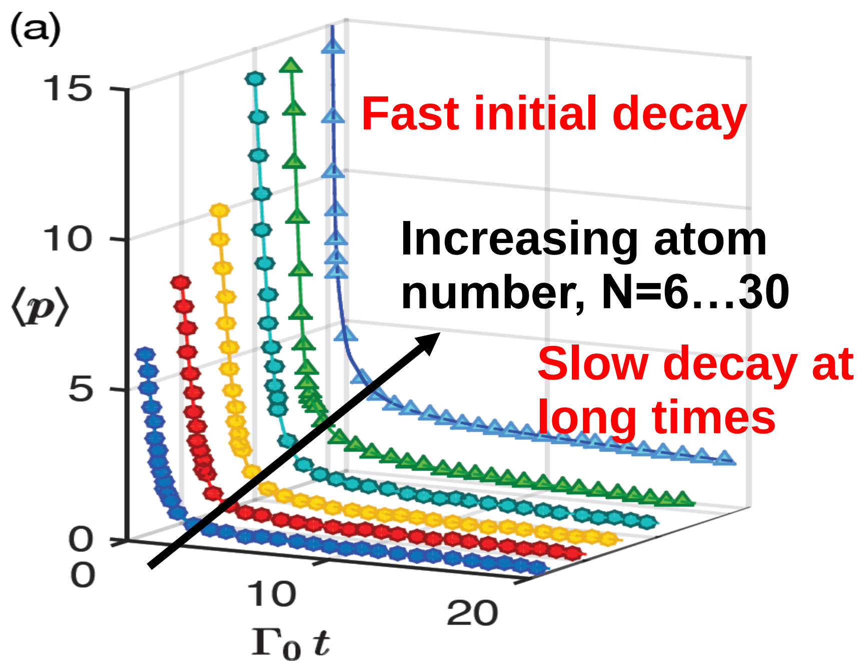
- How do we access subradiant modes, if they are decoupled from laser light?

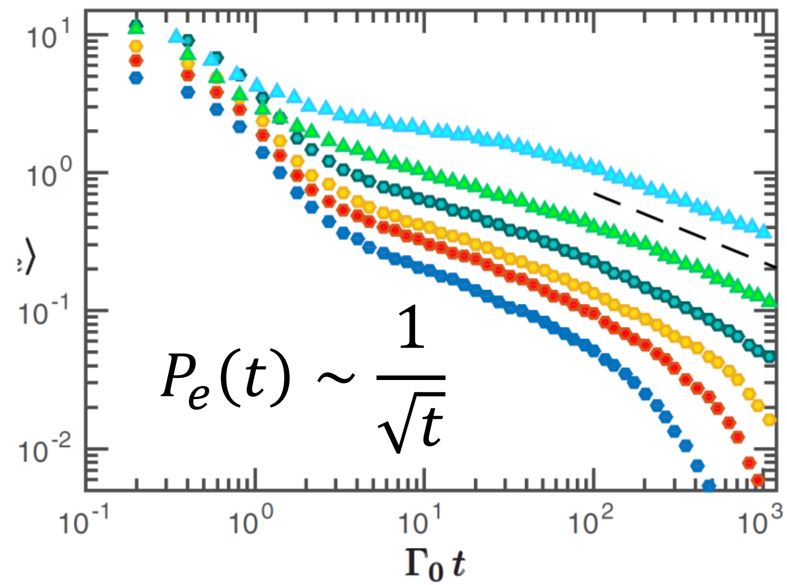
- Use interactions?



Exciting subradiant modes?

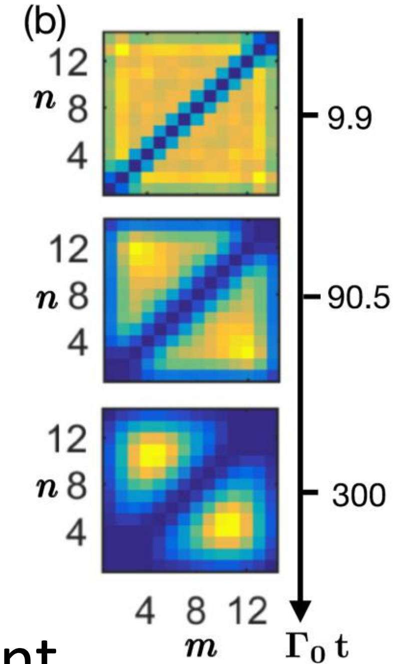
- Highly excited 1D chain: $|\psi(t=0)\rangle = |e\rangle^{\otimes N}$





- Closing Liouvillian gap
  - Continuous manifold of (many-body) states with zero decay rate as $N \to \infty$

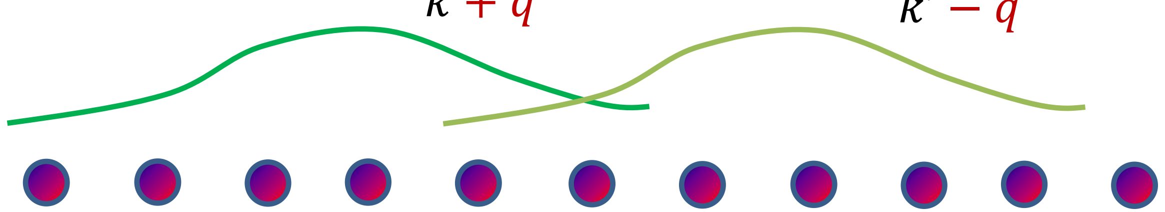
Buildup of "fermionic" correlations



- Density-density correlations of atomic excitations $\langle \sigma_{ee}^{n}(t) \sigma_{ee}^{m}(t) \rangle$

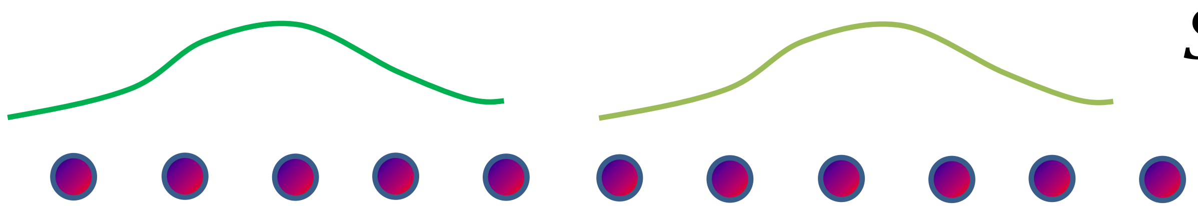
- Buildup of "Pauli exclusion" between subradiant states?

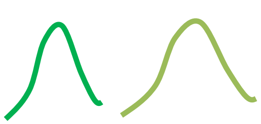
- Product of subradiant states is not subradiant



$S_k^\dagger S_{k'}^\dagger |g\rangle^{\otimes N}$

- Can protect subradiance by including a Slater determinant



$S|$  $\rangle$

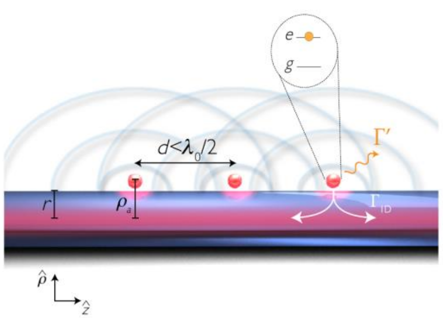
Summary

- Independent spontaneous emission is a killer for atom-light interactions
- But true physics must involve correlated dissipation
  - Encoded in a many-body dissipative spin model

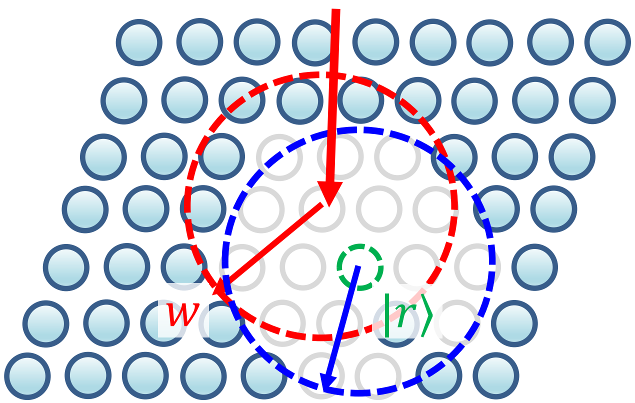
$$d\rho_{\mathrm{atoms}}/dt = -i[H, \rho_{\mathrm{atoms}}] + \sum_{i,j} \mathrm{Im}\, G(r_i, r_j) \left(\hat{\sigma}_{ge}^{j} \rho_{\mathrm{atoms}} \hat{\sigma}_{eg}^{i} - \left\{ \hat{\sigma}_{eg}^{i} \hat{\sigma}_{ge}^{j}, \rho_{\mathrm{atoms}} \right\}/2 \right)$$

- Dramatically improved building blocks for quantum information processing

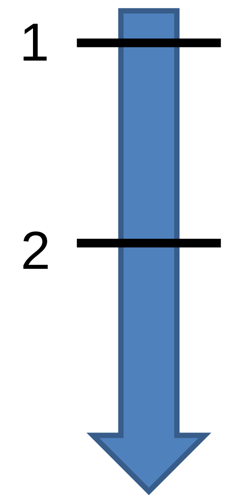
Quantum memories



Photon-photon gates



Excitations



The many-body frontier

Insight-based development of novel theoretical and numerical methods

Paradigms or universality classes

Goals:

- Use correlated dissipation to protect all applications
- New strongly correlated phenomena and states

Inspiration from and connections to other fields

Development of dedicated experimental platforms

The group