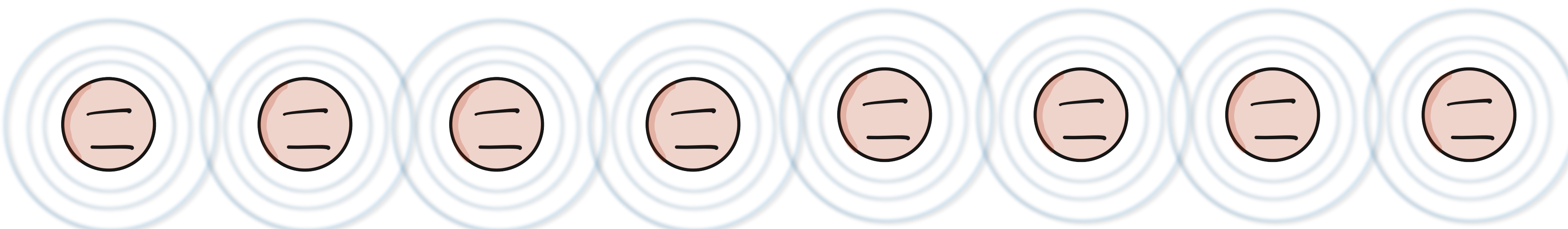
Collective phenomena in light-matter interfaces

Ana Asenjo Garcia



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Light-matter interfaces are a cornerstone of quantum optics

Quantum information science

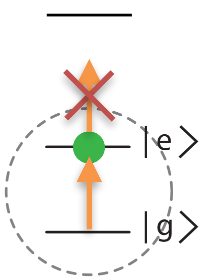
Photons in free space do not interact with each other: good candidates to transmit information

However: we need light-matter interfaces for processing that information

Quantum non-linear optics

Bulk materials are weakly non linear

However atoms are ultimate non-linear element

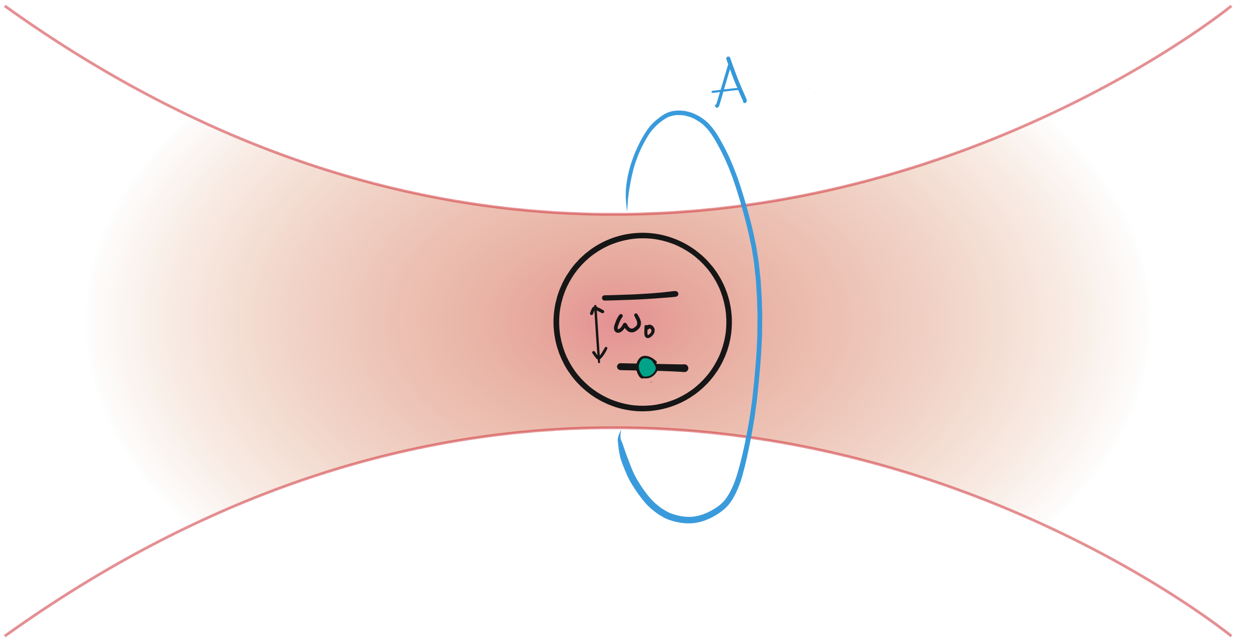


Exotic many body physics for photons and atoms

Metrology, sensing, imaging

...

In free-space, atom-photon coupling is weak

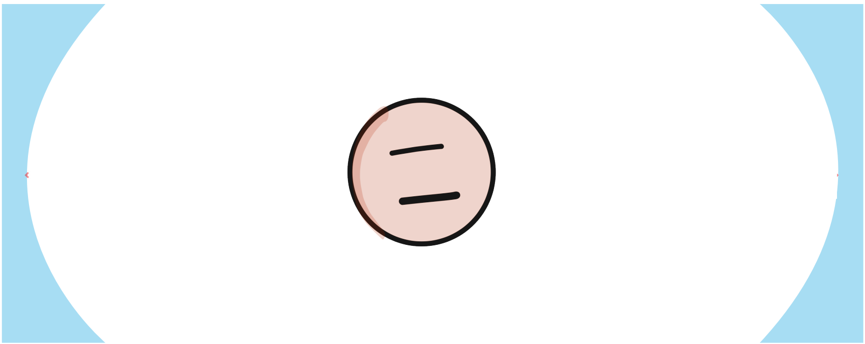


Probability of interaction
~$\lambda^2/A \ll 1$ due to diffraction limit

How to increase atom-photon interaction?

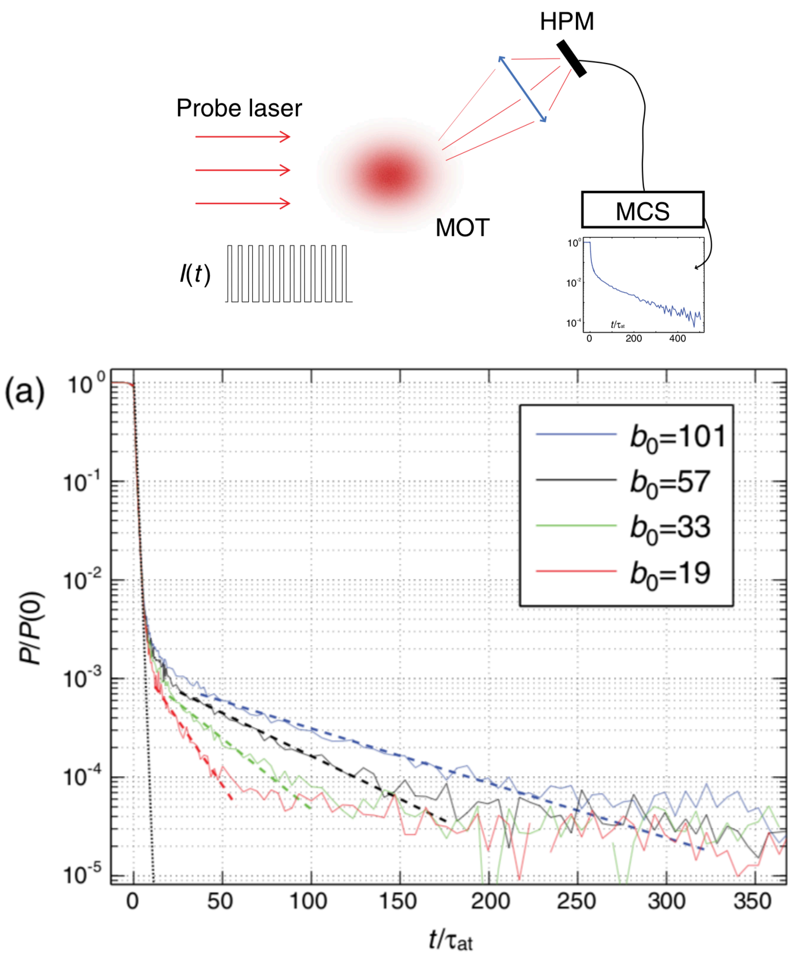
Option 1: use multiple atoms (ensemble)

Option 2: use a cavity or other nanophotonic structures

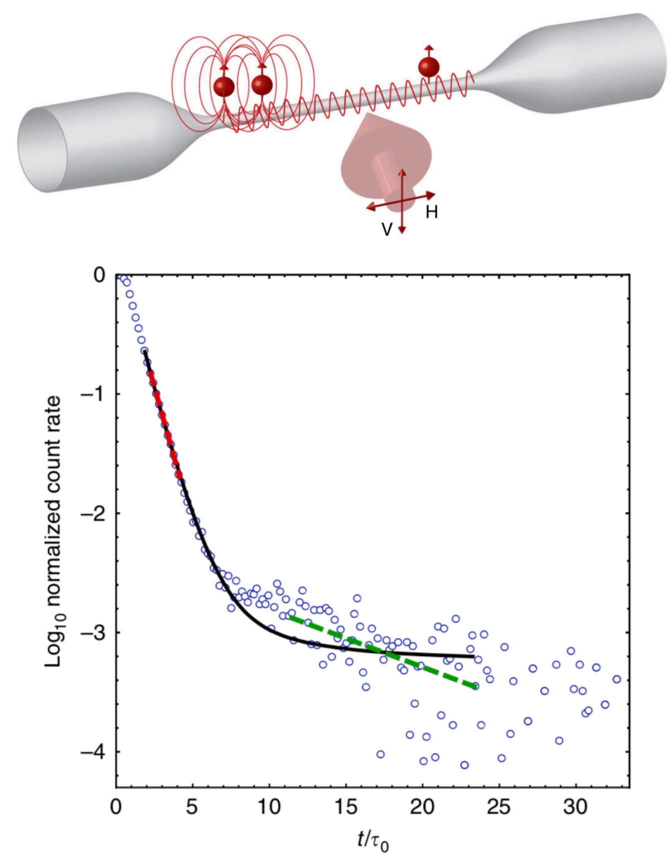


Option 3: combine both and take advantage of interactions between atoms

Disordered atomic ensembles are a very common light-matter interface



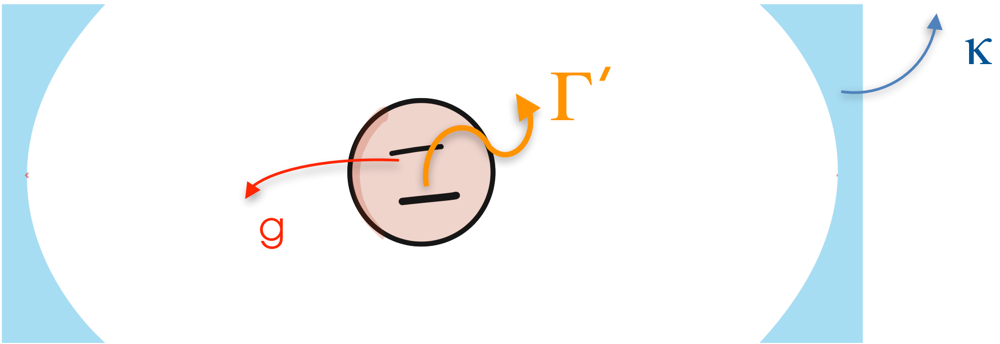
Guerin et al., Phys. Rev. Lett. **116**, 083601 (2016)



Solano et al. , Nat. Commun. **8**, 1857(2017)

Conventional ways of enhancing atom-light interactions

In cavity QED, figure of merit is $C = g^2/\kappa\Gamma'$



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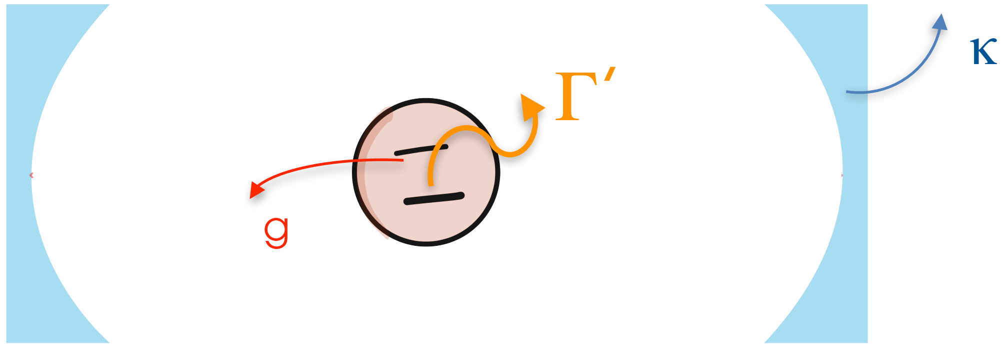
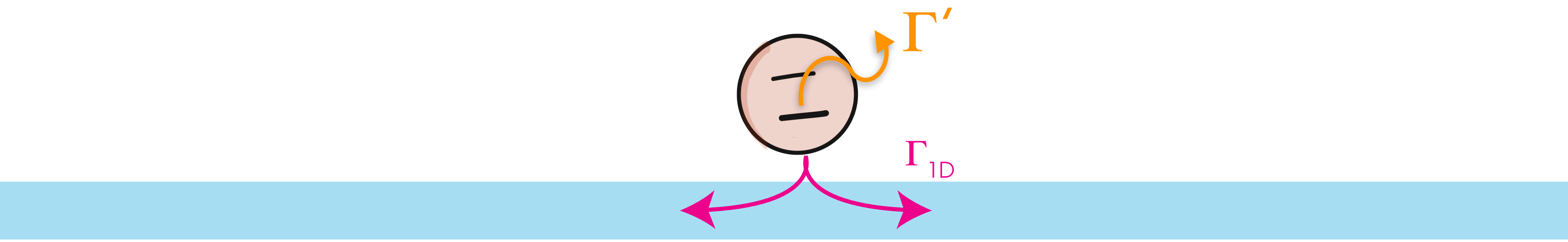
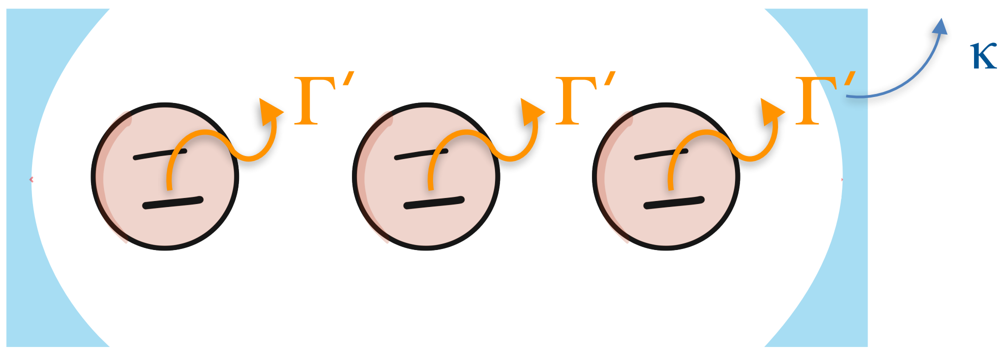


In waveguide QED, that is $D=\Gamma_{1D}/\Gamma'$

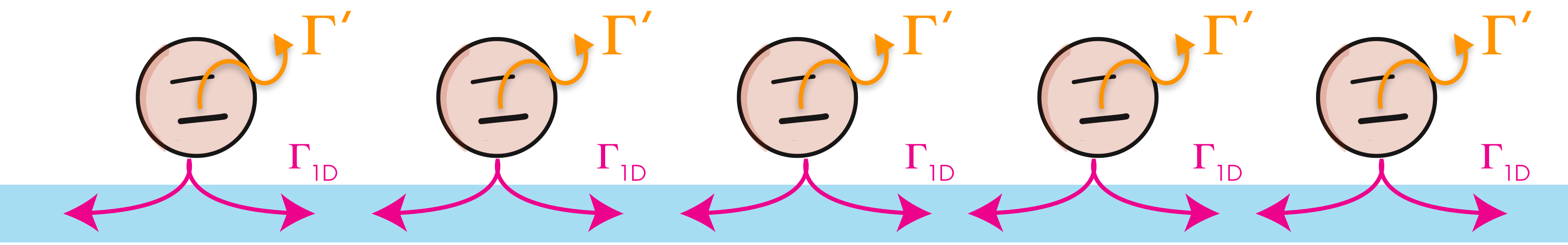


Conventional ways of enhancing atom-light interactions

In cavity QED, figure of merit is $C=g^2/\kappa\Gamma'$ → $C=Ng^2/\kappa\Gamma'$

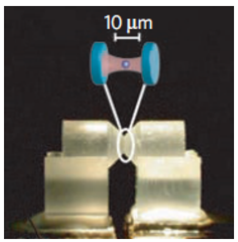


In waveguide QED, that is $D=\Gamma_{1D}/\Gamma'$ → $D=\mathbf{N}\Gamma_{1D}/\Gamma'$

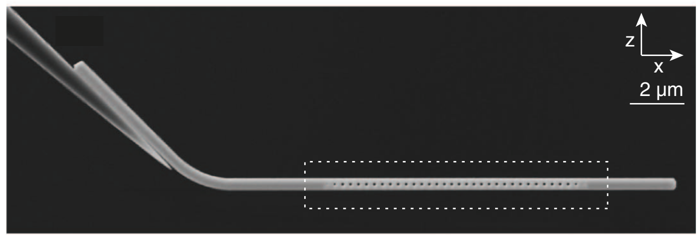


Nanophotonic structures add versatility, allowing to go beyond cavity QED

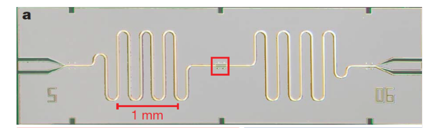
cQED: infinite interaction range between atoms inside cavity



Fabry-Perot
Kimble (2008)



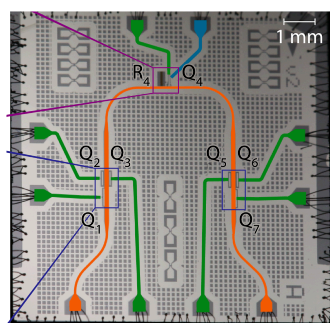
dielectric cavity
Lukin (2014)



superconducting cavity
Wallraff (2004)

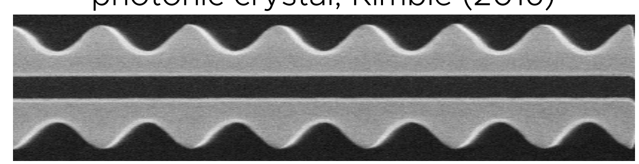
wQED: tunable interaction range, character of interaction is position dependent… dispersion engineering!

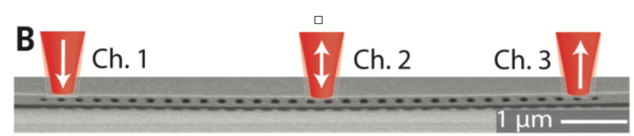
nanofiber
Laurat (2015)



SC waveguide, Painter (2019)

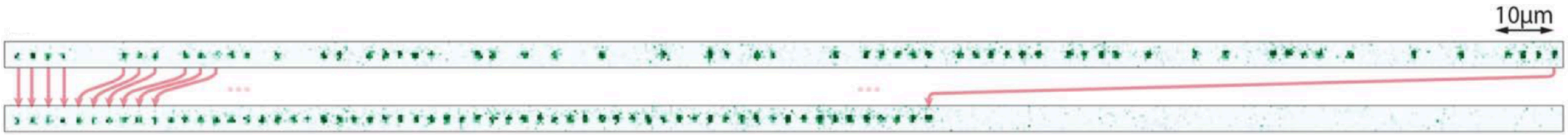
photonic crystal, Kimble (2016)





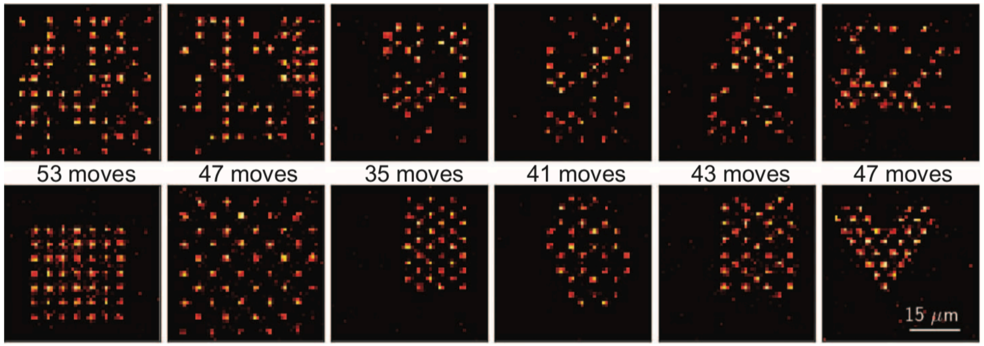
NV in diamond waveguide, Lukin (2016)

Recent development:
ordered atomic arrays with optical tweezers



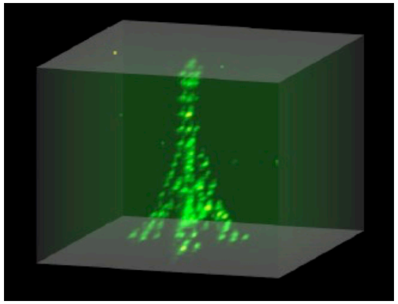
1D

Endres et al., Science **354**, 1024 (2016)



2D

Barredo et al., Science **354**, 1021 (2016)

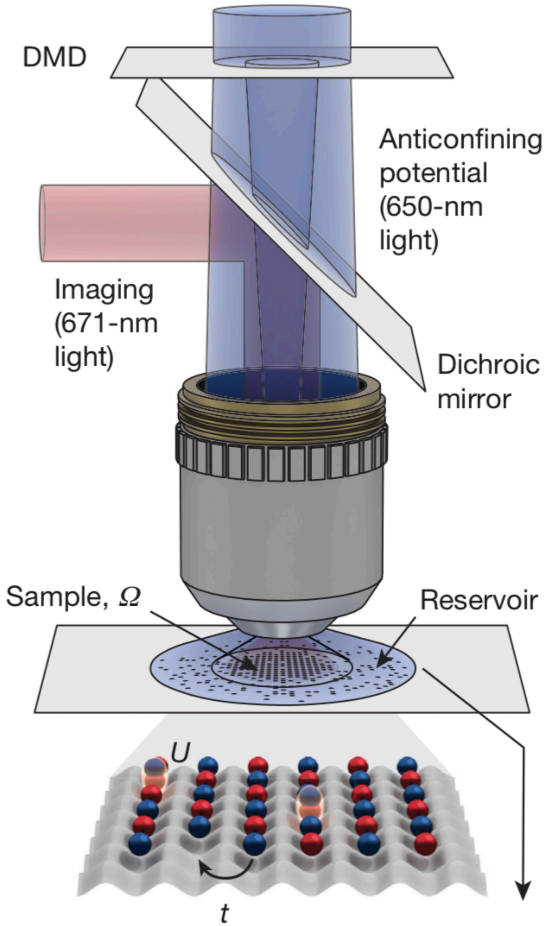


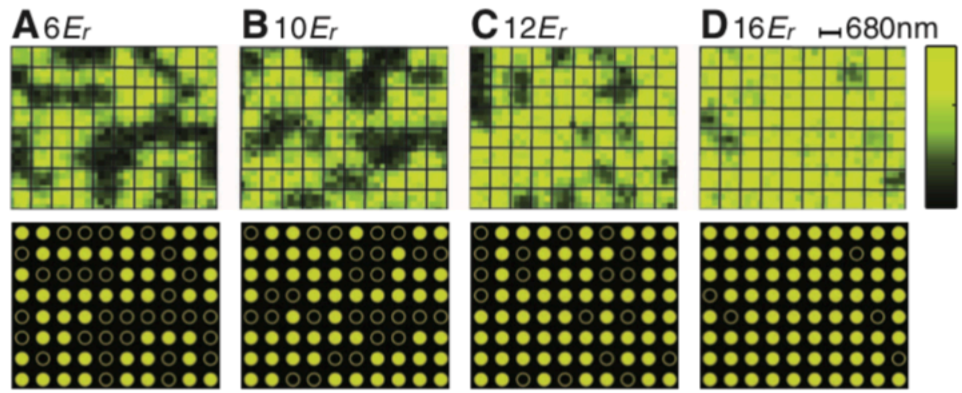
3D

Barredo et al.,
Nature **561**, 79 (2018)

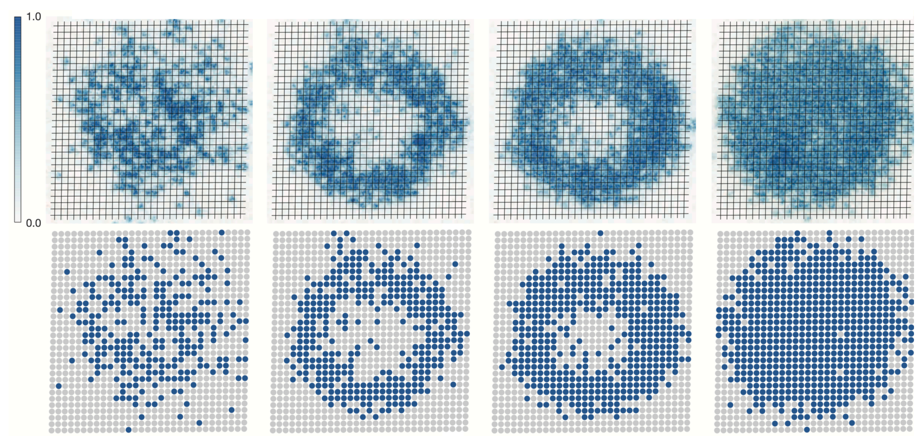
In these systems, interference in photon emission leads to correlation: atom arrays can behave as "quantum nanostructures"

Other possibility: quantum gas microscopes





Bakr et al., Science **329**, 547 (2010)

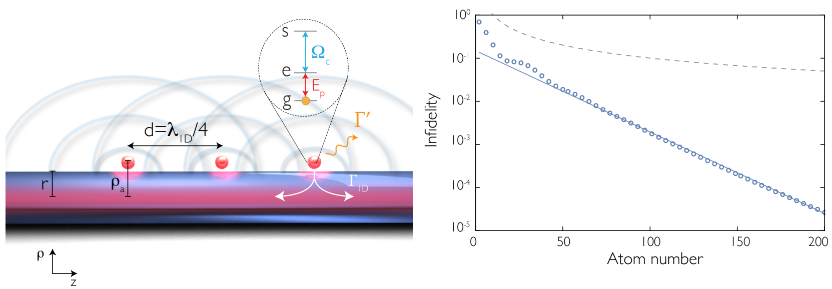


Mazurenko et al., Nature **545**, 462 (2017)

Greif et al., Science **351**, 953 (2016)

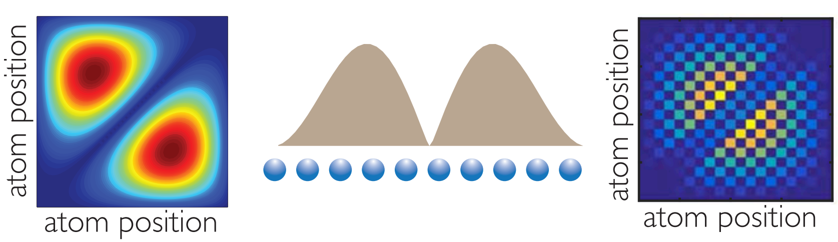
Atom arrays as light-matter interfaces

Exponential improvement in photon retrieval fidelity when coupled to 1D waveguides

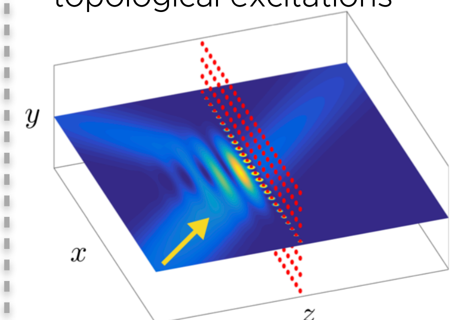


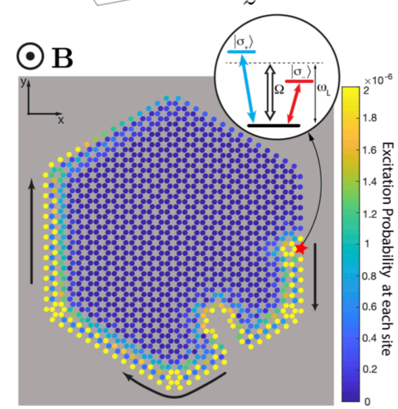
AAG et al., PRX **7**, 031024 (2017)

Many-body physics: emergence of fermionization in the dark states.



Perfect mirrors and topological excitations





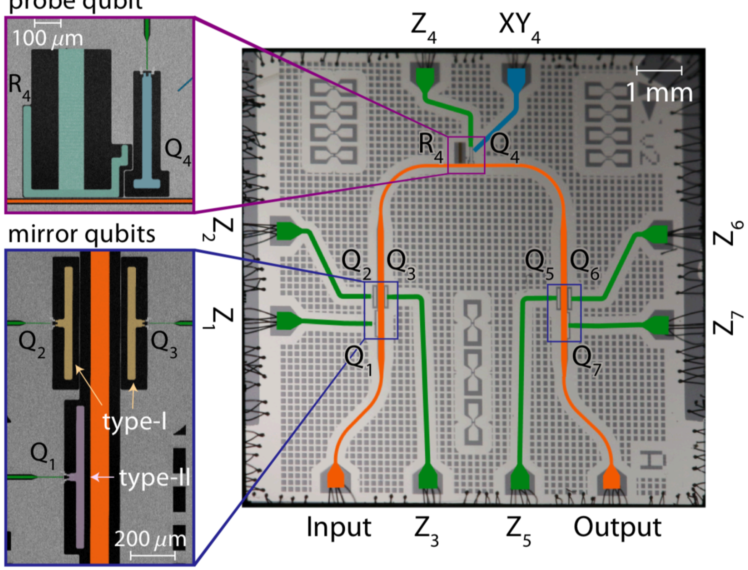
Bettles et al., PRL **116**, 103602 (2016)

Shahmoon et al., PRL **118**, 113601 (2016)

Perczel et al., PRL **119**, 023603 (2017)

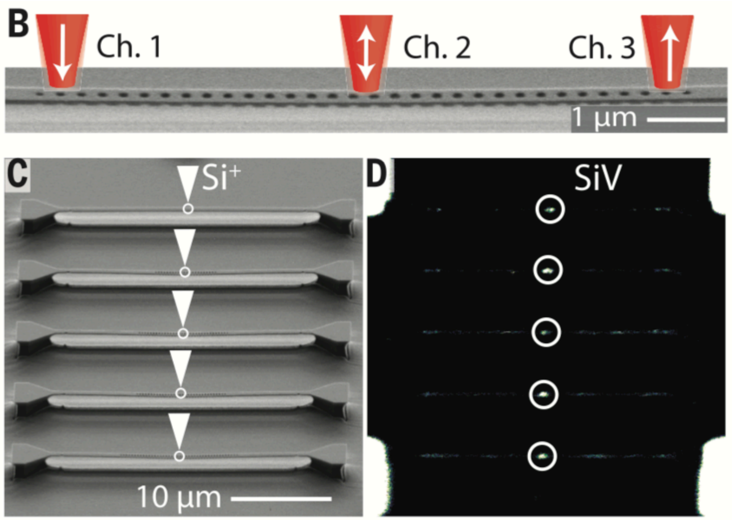
Similar physics (universality) for SC qubits and solid-state emitters

Transmon qubits



Mirhosseini et al., Nature **569**, 692 (2019)

Si-vacancies in diamond



Sipahigil et al., Science **354**, 847 (2016)

Also in quantum dots, molecules...

Outline of the lectures

Lecture 1: Atom-light interaction as a spin model

Lecture 2: Atom arrays as light-matter interfaces

Lecture 3: Atom-atom interactions in non-conventional baths

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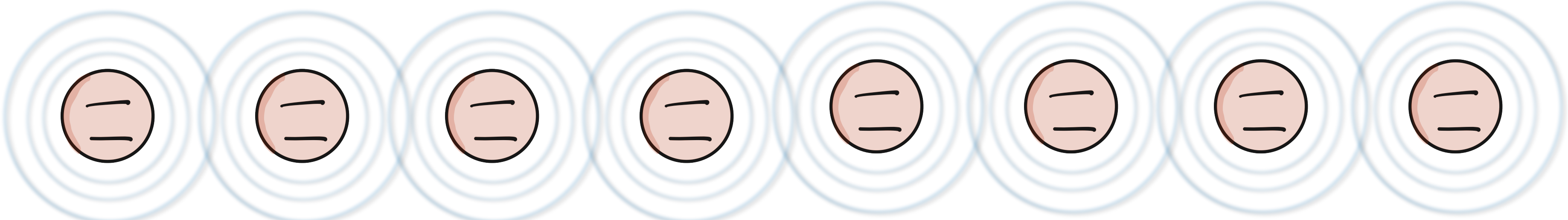

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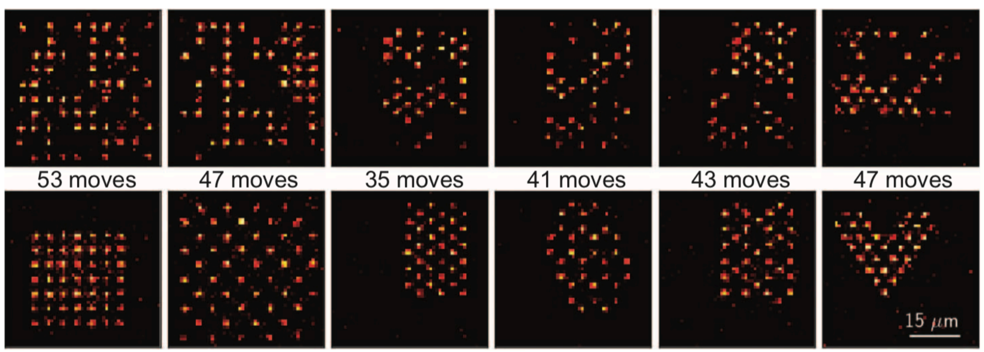
Ordered atomic arrays with optical tweezers: perfect playground for correlated dissipation

1D

Endres et al., Science **354**, 1024 (2016)



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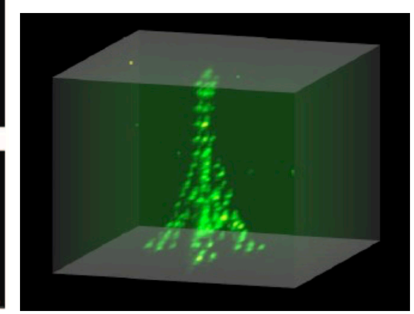

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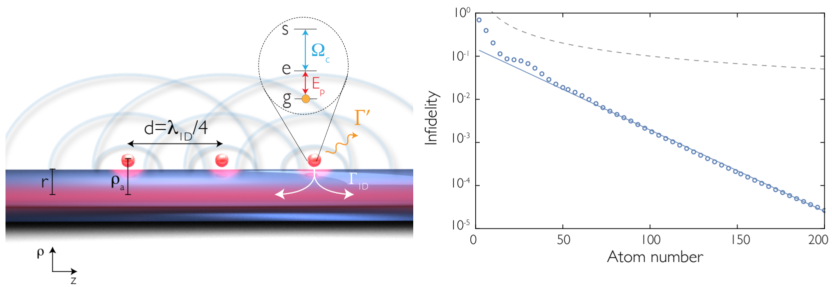

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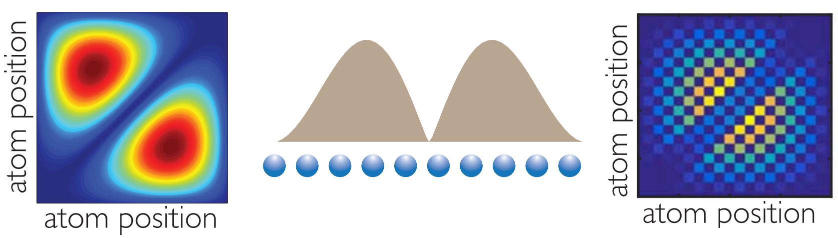

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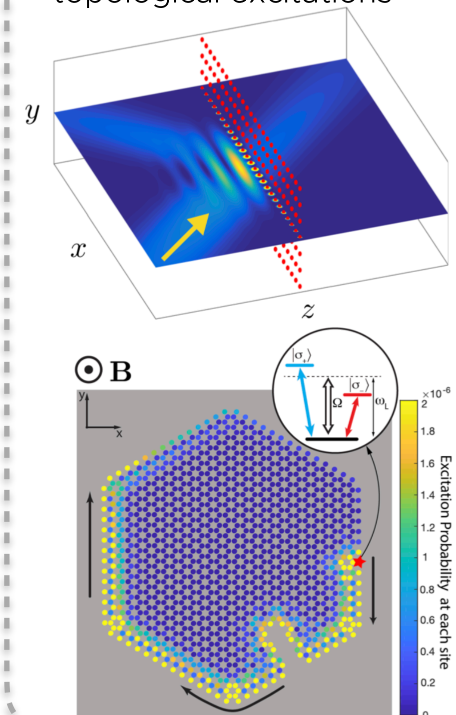


Bettles et al., PRL **116**, 103602 (2016)
Shahmoon et al., PRL **118**, 113601 (2016)
Perczel et al., PRL **119**, 023603 (2017)

Early treatment of collective effects: Dicke model

PHYSICAL REVIEW VOLUME 93, NUMBER 1 JANUARY 1, 1954

Coherence in Spontaneous Radiation Processes

R. H. Dicke
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey

(Received August 25, 1953)

IN the usual treatment of spontaneous radiation by a gas, the radiation process is calculated as though the separate molecules radiate independently of each other. To justify this assumption it might be argued that, as a result of the large distance between molecules and subsequent weak interactions, the probability of a given molecule emitting a photon should be independent of the states of other molecules. It is clear that this model is incapable of describing a coherent spontaneous radiation process since the radiation rate is proportional to the molecular concentration rather than to the square of the concentration. This simplified picture overlooks the fact that all the molecules are interacting with a common radiation field and hence cannot be treated as independent. The model is wrong in principle and many of the results obtained from it are incorrect.

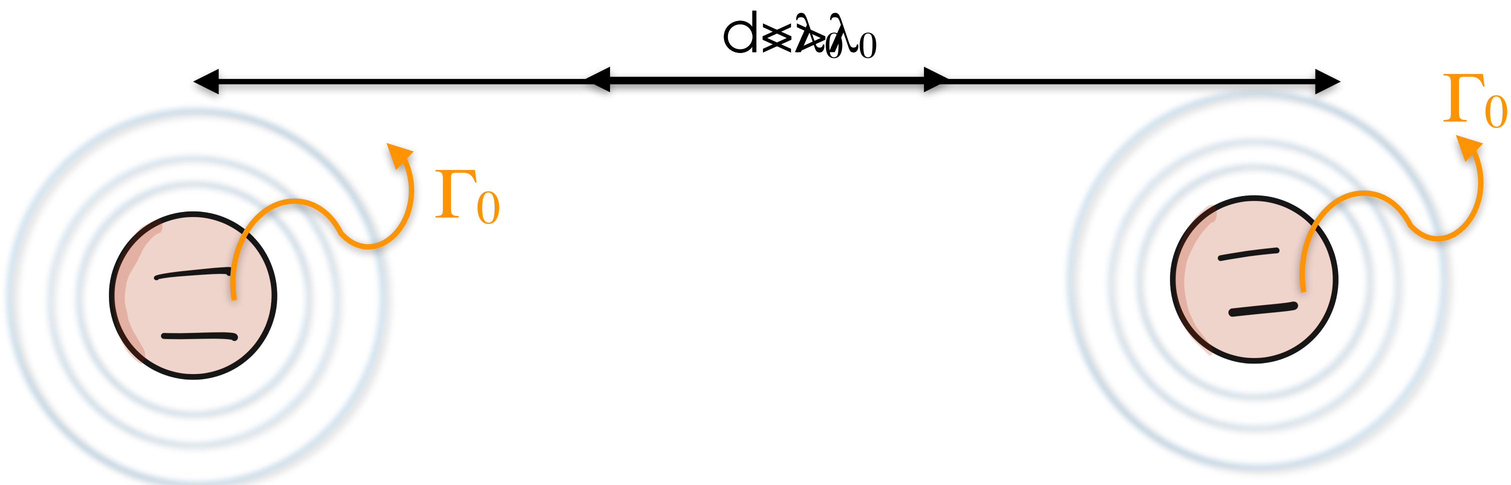
Small volume approximation:

- atoms interact with either one field mode (cavity)
- atoms are in same spatial location

Question:
what is the physics of subradiant states in ordered atomic arrays?

Photon emission is a wave phenomenon

Interference leads to correlated decay

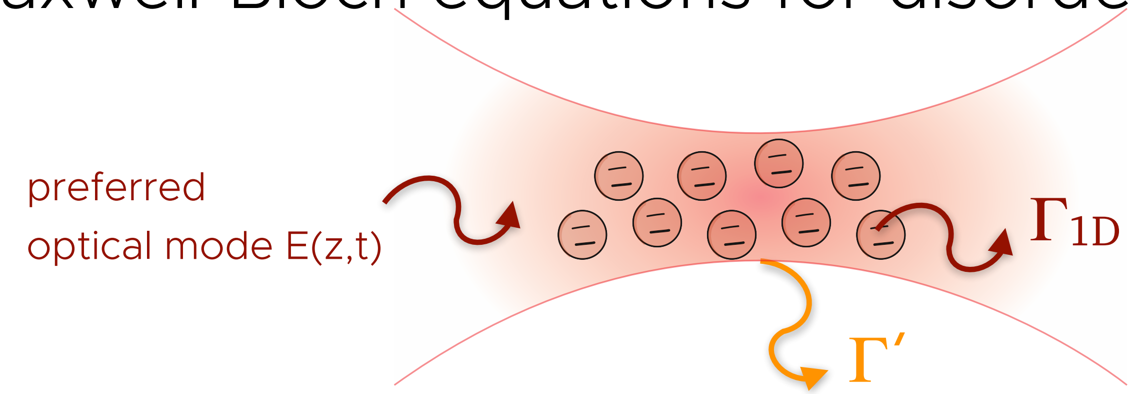


For 2 atoms, we have two atomic modes:

- One that decays faster than Γ_0: superradiant (constructive interference)
- One that decays slower than Γ_0: **subradiant (destructive interference)**

What happens for large atom number?

Conventional paradigm:
Maxwell-Bloch equations for disordered ensembles



Field equation (quasi-1D preferred mode):

$$\left(\frac{1}{c}\partial_t + \partial_z\right)\hat{E}(z,t) = i\sqrt{\frac{\Gamma_{1D}}{2}}\hat{P}_{ge}(z,t)$$

continuous atomic polarization density

Atomic equation:

$$\partial_t \hat{P}_{ge}(z,t) = -\frac{\Gamma'}{2}\hat{P}_{ge}(z,t) + i\sqrt{\frac{\Gamma_{1D}}{2}}\hat{E}(z,t)$$

independent emission into other modes!

Quantum optics 101 has a problem

Atom-light interaction as a spin model

Starting from full atom-field Hamiltonian, we integrate out the field and find that the atoms density matrix follows

$$\dot{\hat{\rho}} = -\frac{i}{\hbar}[\mathcal{H}, \hat{\rho}] + \mathcal{L}[\hat{\rho}]$$

where

$$\mathcal{H} = \hbar\omega_0 \sum_{i=1}^{N} \hat{\sigma}^i_{ee} + \hbar \sum_{i,j=1}^{N} J_{ij} \hat{\sigma}^i_{eg} \hat{\sigma}^j_{ge}$$

resonance frequency

$J_{ij} \propto \mathrm{Re}\{G(\mathbf{r}_i, \mathbf{r}_j)\}$ coherent evolution

and

$$\mathcal{L}[\hat{\rho}] = \sum_{i,j=1}^{N} \frac{\Gamma_{ij}}{2} \left(2\hat{\sigma}^j_{ge}\hat{\rho}\hat{\sigma}^i_{eg} - \hat{\sigma}^i_{eg}\hat{\sigma}^j_{ge}\hat{\rho} - \hat{\rho}\hat{\sigma}^i_{eg}\hat{\sigma}^j_{ge}\right)$$

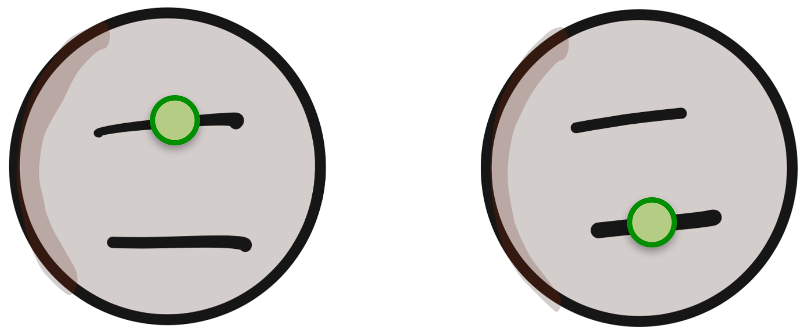
$\Gamma_{ij} \propto \mathrm{Im}\{G(\mathbf{r}_i, \mathbf{r}_j)\}$ collective dissipation

$\neq \Gamma_{ii}\delta_{ij}$

Atom-light interaction as a spin model

Equivalently: $$\mathcal{H}_{\text{eff}} = -\mu_0\omega_0^2 \sum_{i,j=1}^{N} \wp^* \cdot \mathbf{G}(\mathbf{r}_i, \mathbf{r}_j, \omega_0) \cdot \wp \; \hat{\sigma}^i_{eg}\hat{\sigma}^j_{ge}$$

+quantum jumps



Insight 1: light-matter interaction recast into a dissipative, driven, long-range spin interaction (non-unitary dynamics)

Insight 2: describes field properties even when we have integrated out the field in the first place

Collective modes of a 1D atomic chain in free space (single excitation manifold)

$$\mathcal{H}_{\text{eff}} = -\mu_0\omega_0^2 \sum_{i,j=1}^{N} \wp^* \cdot \mathbf{G}_0(\mathbf{r}_i, \mathbf{r}_j, \omega_0) \cdot \wp \; \hat{\sigma}_{eg}^i \hat{\sigma}_{ge}^j$$

$\omega_0 = k_0 c$

with $$\mathbf{G}_0(\mathbf{r}, \omega_0) = \frac{e^{\mathrm{i}k_0 r}}{4\pi k_0^2 r^3}\left[(k_0^2 r^2 + \mathrm{i}k_0 r - 1)\mathbb{1} + +(-k_0^2 r^2 - 3\mathrm{i}k_0 r + 3)\frac{\mathbf{r}\otimes\mathbf{r}}{r^2}\right].$$

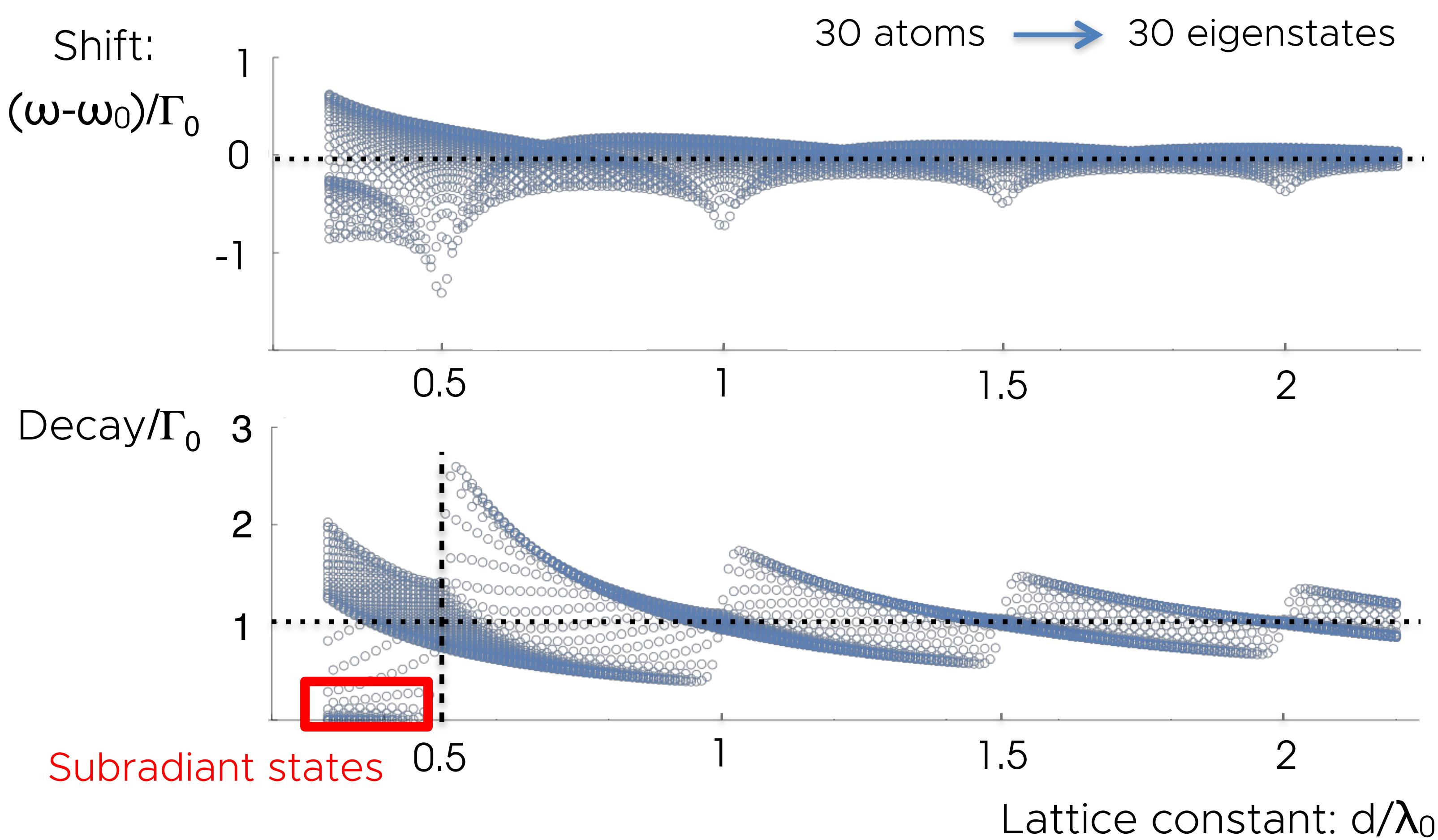
For many atoms, in the single excitation manifold, the Hamiltonian can be written as a NxN matrix, in the basis where only 1 atom is excited:

$$|egg...g\rangle, |geg...g\rangle, ..., |gg...ge\rangle$$

Eigenvalues inform about:

- Frequency shift from bare atomic resonance ω_0
- Enhanced/inhibited decay rate with respect to single atom Γ_0

Collective modes of a 1D atomic chain in free space (single excitation manifold)

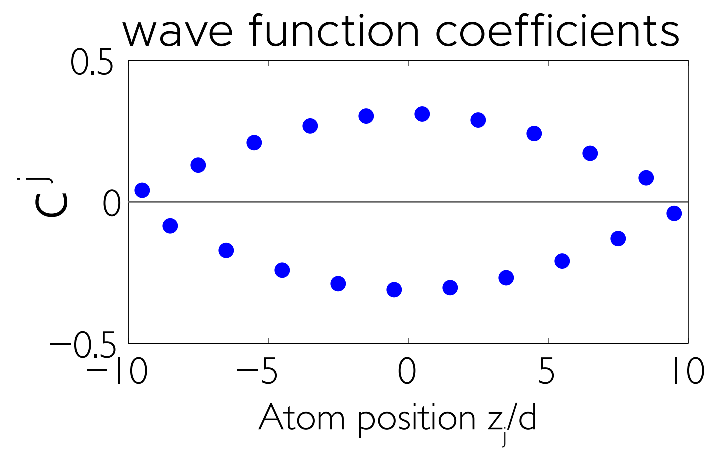


Spatial profile of most subradiant atomic mode

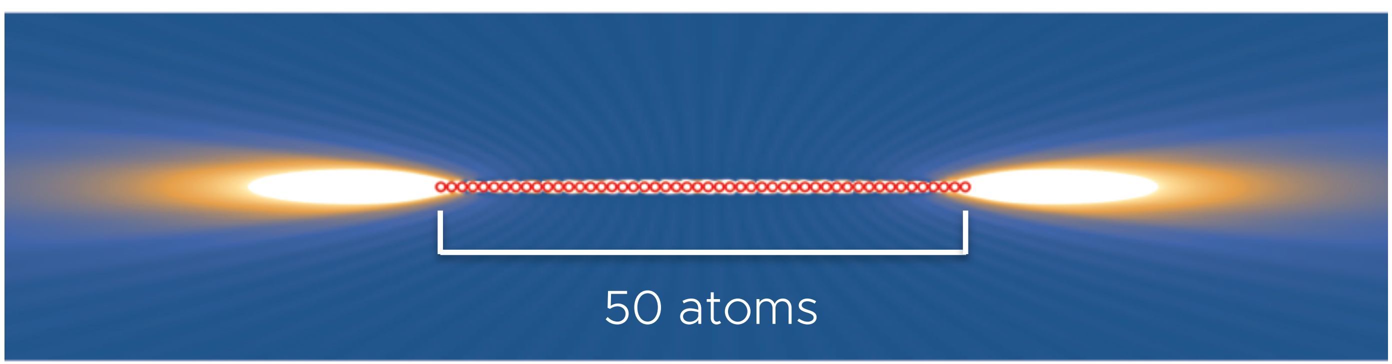
Spatial profile of most subradiant eigenstate

$$|\psi\rangle = \sum_j c_j \sigma_{eg}^j |g\rangle^{\otimes N}$$

dipole phases anti-align

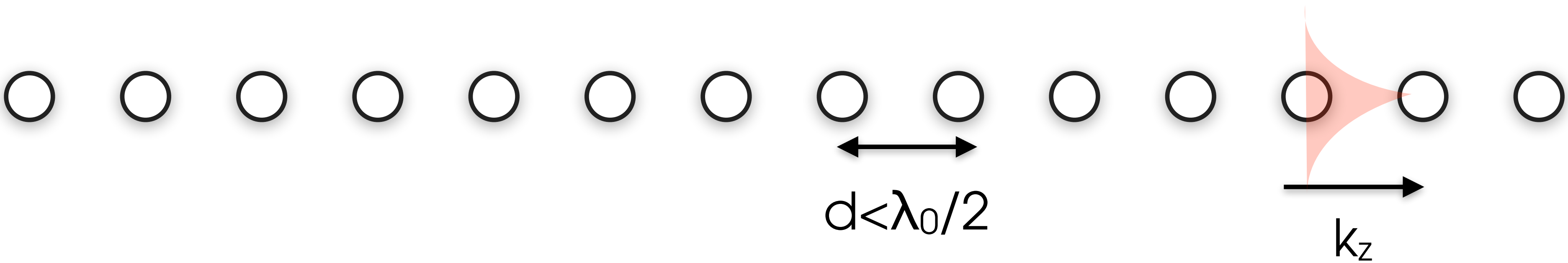


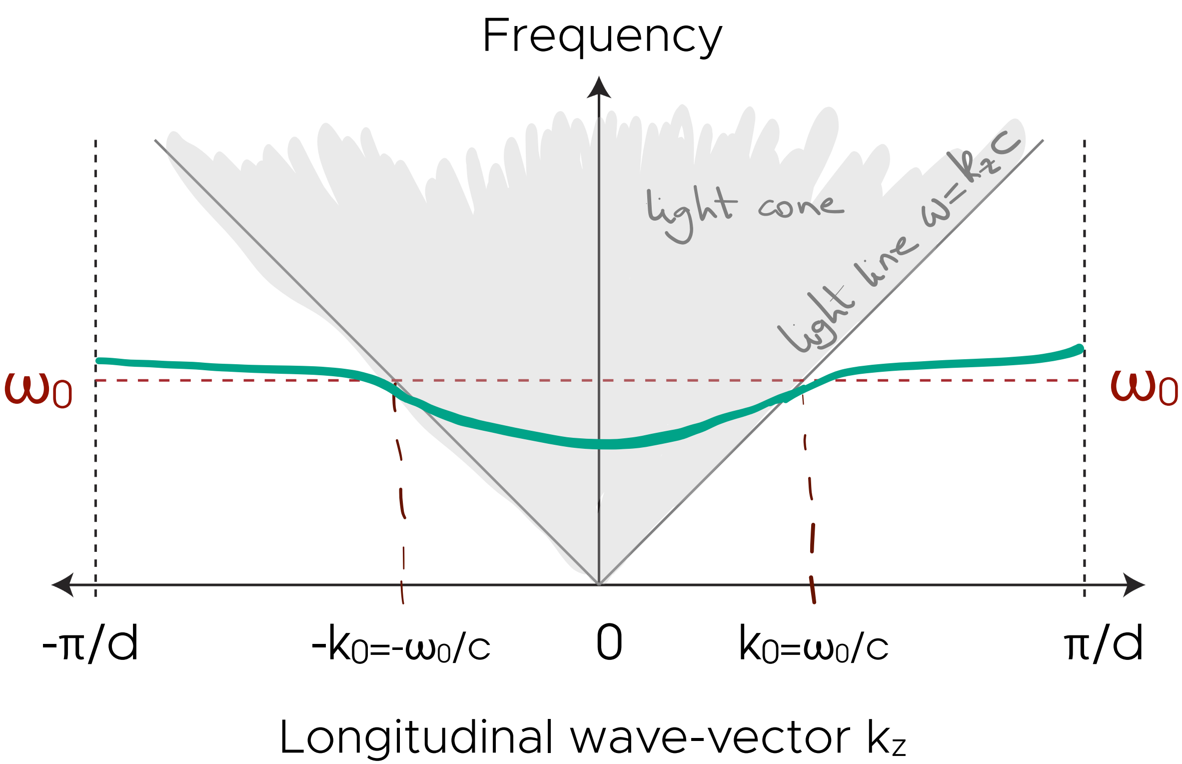
For a finite chain, radiative losses occur only at the edges



Intensity profile generated by most subradiant eigenstate

Atoms guide light perfectly (if the chain is infinite)

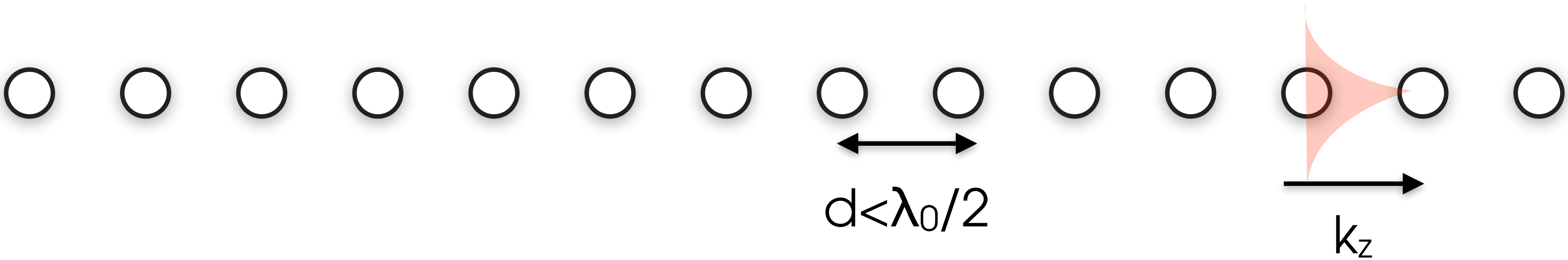


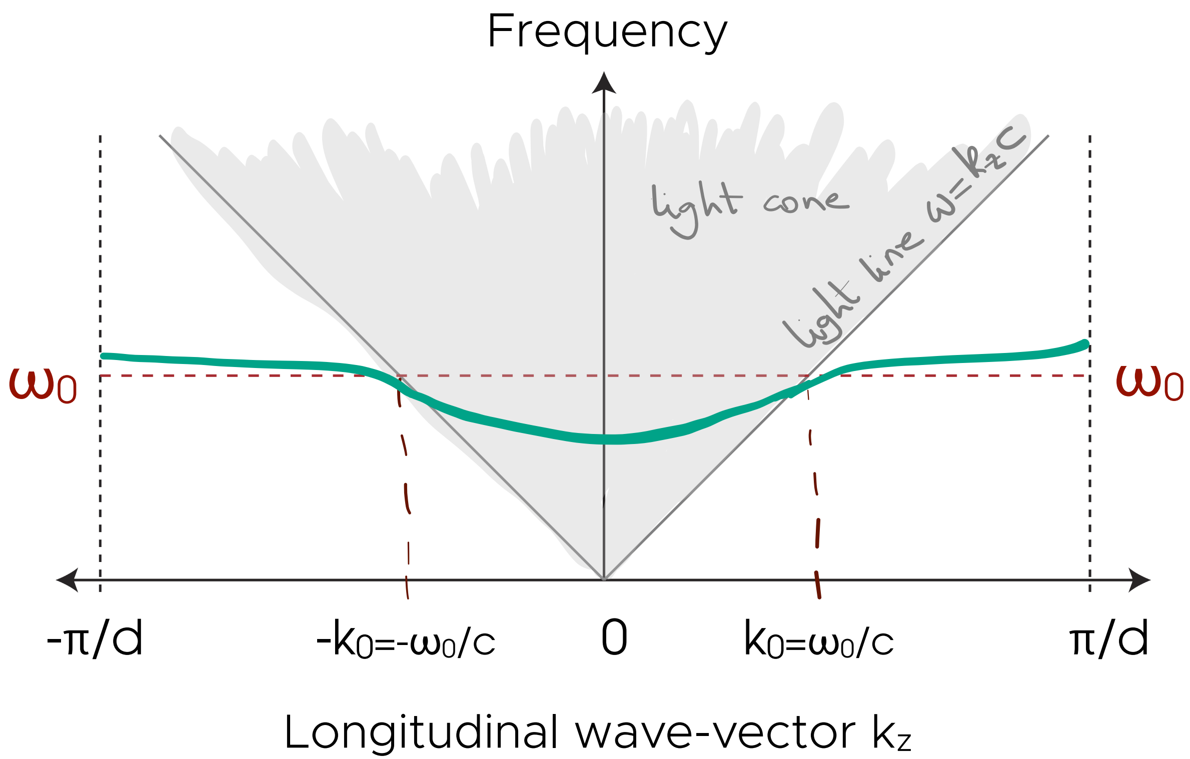


In an infinite chain, the eigenstates are Bloch modes

$$|\psi_{k_z}\rangle \sim \sum_j e^{ik_z z_j} |e\rangle_j$$

Atoms guide light perfectly
(if the chain is infinite)





$$E \sim e^{ik_z z} e^{ik_\perp x}$$

Since:

$$k_z^2 + k_\perp^2 = \frac{\omega_0^2}{c^2}$$

the atomic guided mode is evanescent along perpendicular direction

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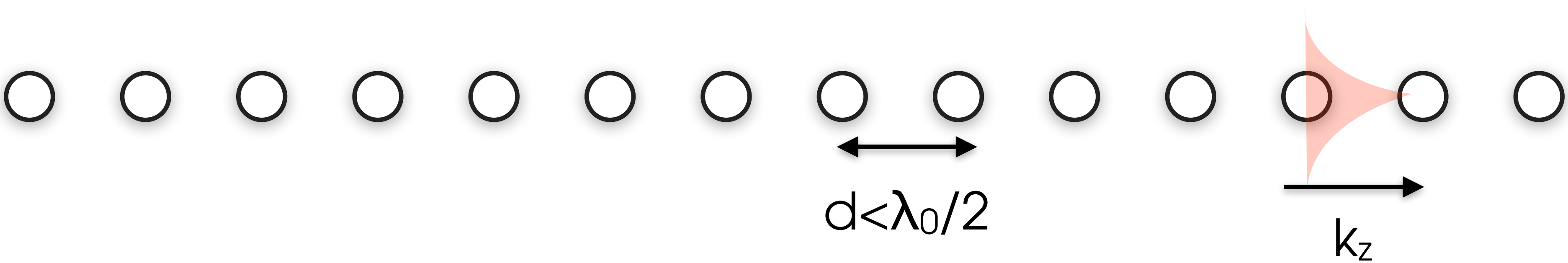

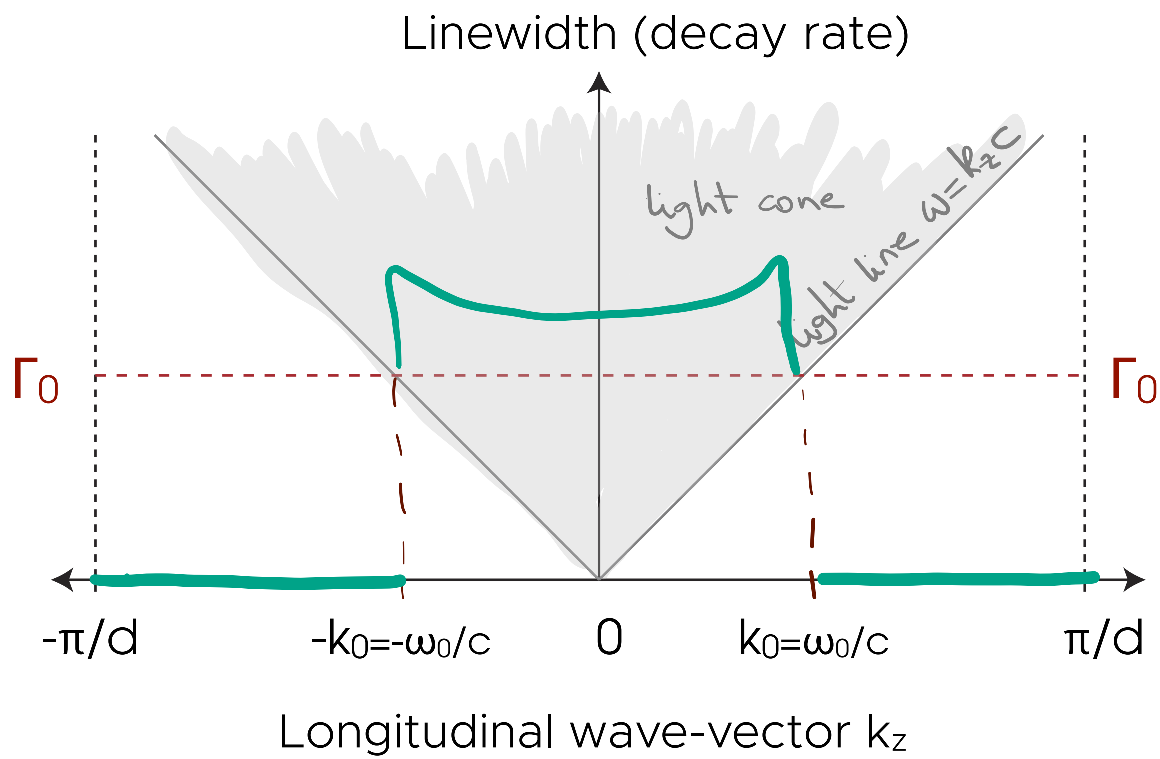

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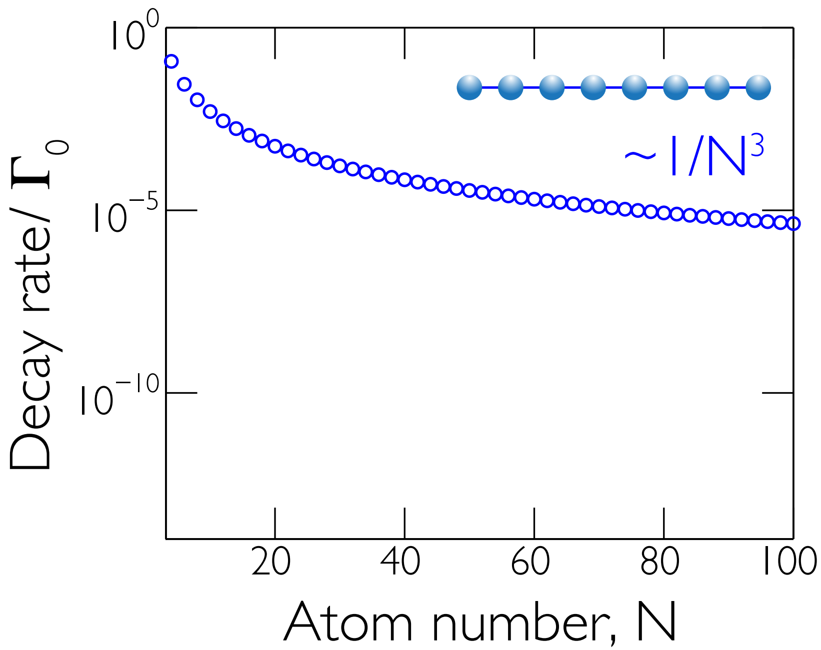
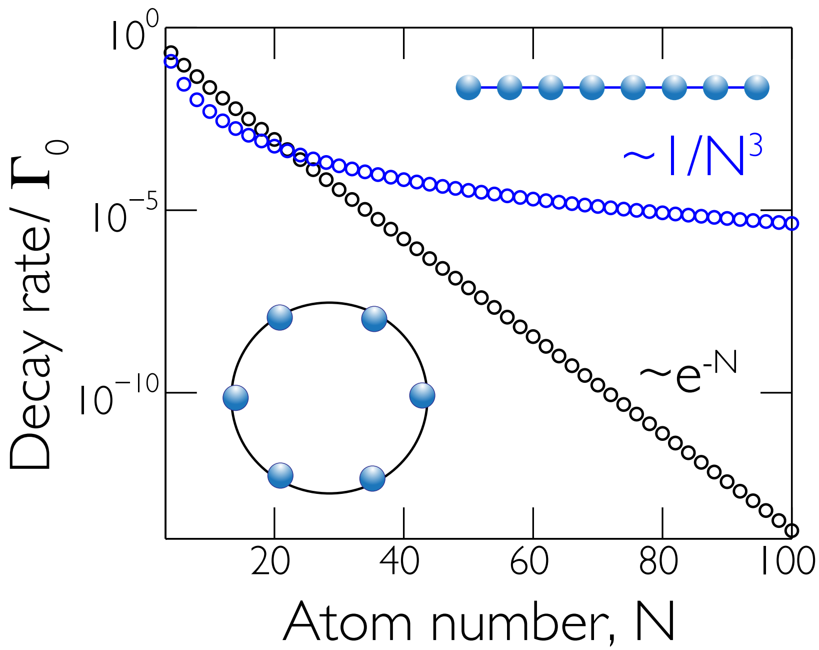
Emergent power law behavior in the decay rates and lifetimes



Universality: $1/N^3$ scaling seems to be universal for 1D arrays

- similar scaling found in generic open quantum systems with boundary dissipation, Znidaric (2015)

Emergent power law behavior in the decay rates and lifetimes

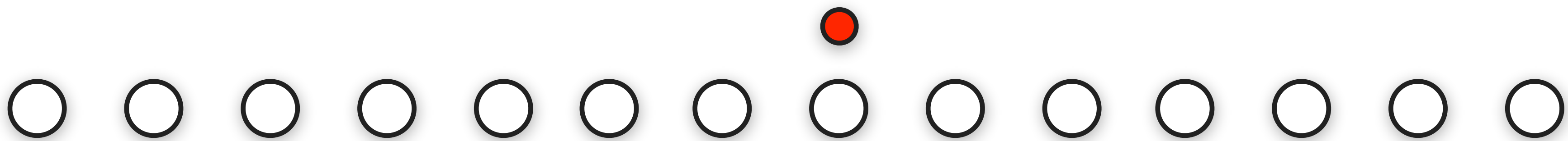


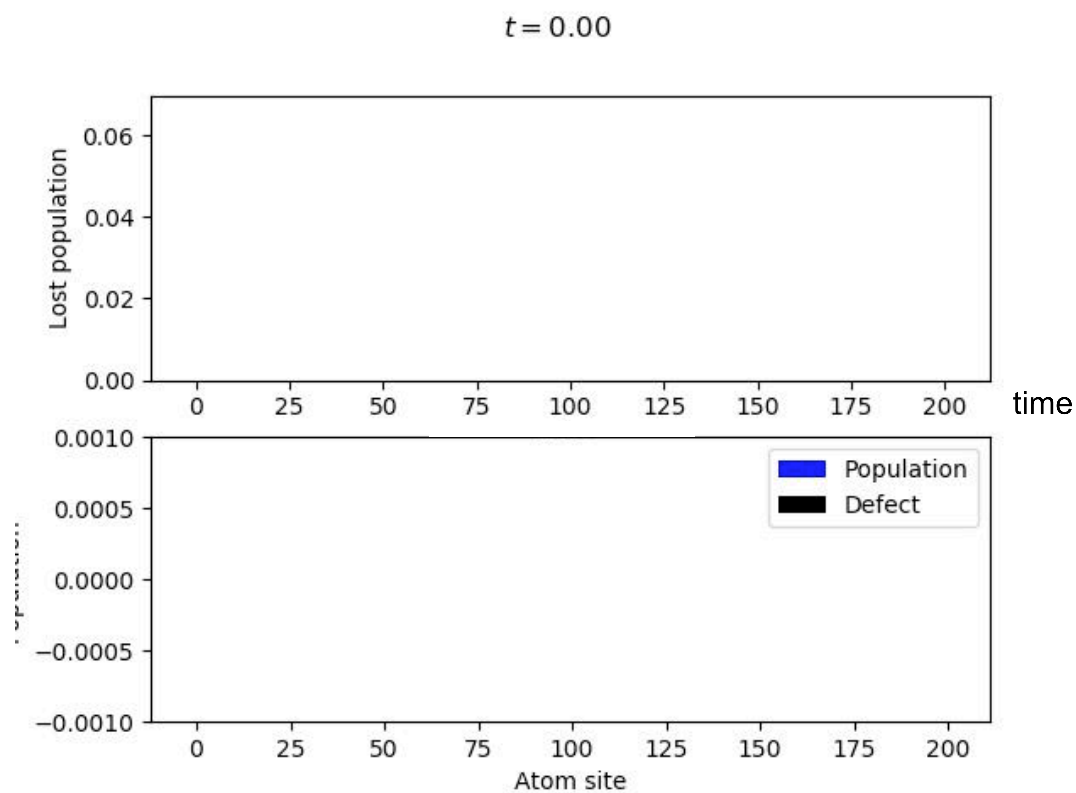
Universality: $1/N^3$ scaling seems to be universal for 1D arrays

- similar scaling found in generic open quantum systems with boundary dissipation, Znidaric (2015)

Depends on array dimensionality and topology

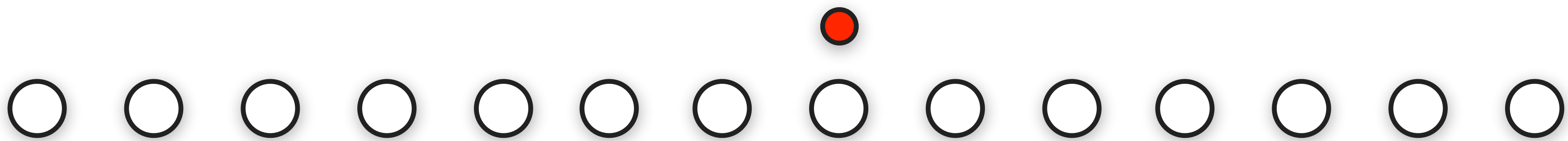
Guiding light in an atomic waveguide: reflection

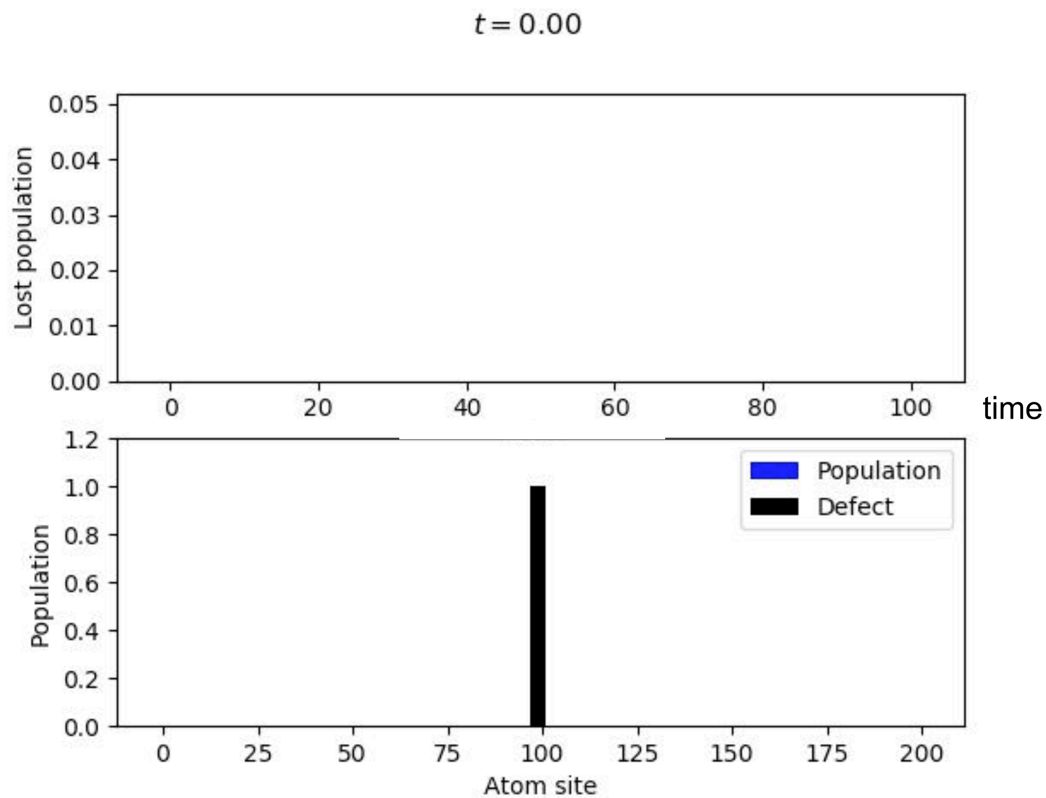




d=0.1 λ_0, ρ=0.5 d (preliminary)

Guiding light in an atomic waveguide: flipped atom



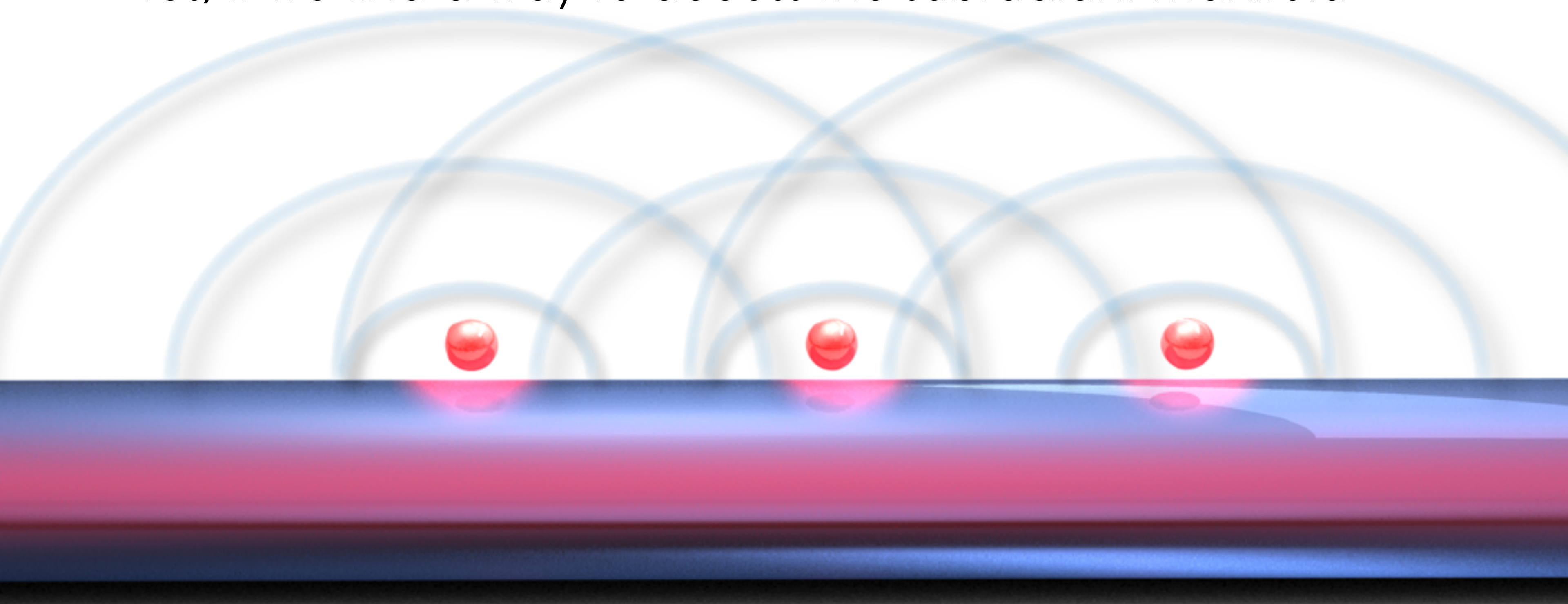


$d=0.1\,\lambda_0$, $\rho=0.5\,d$ (preliminary)

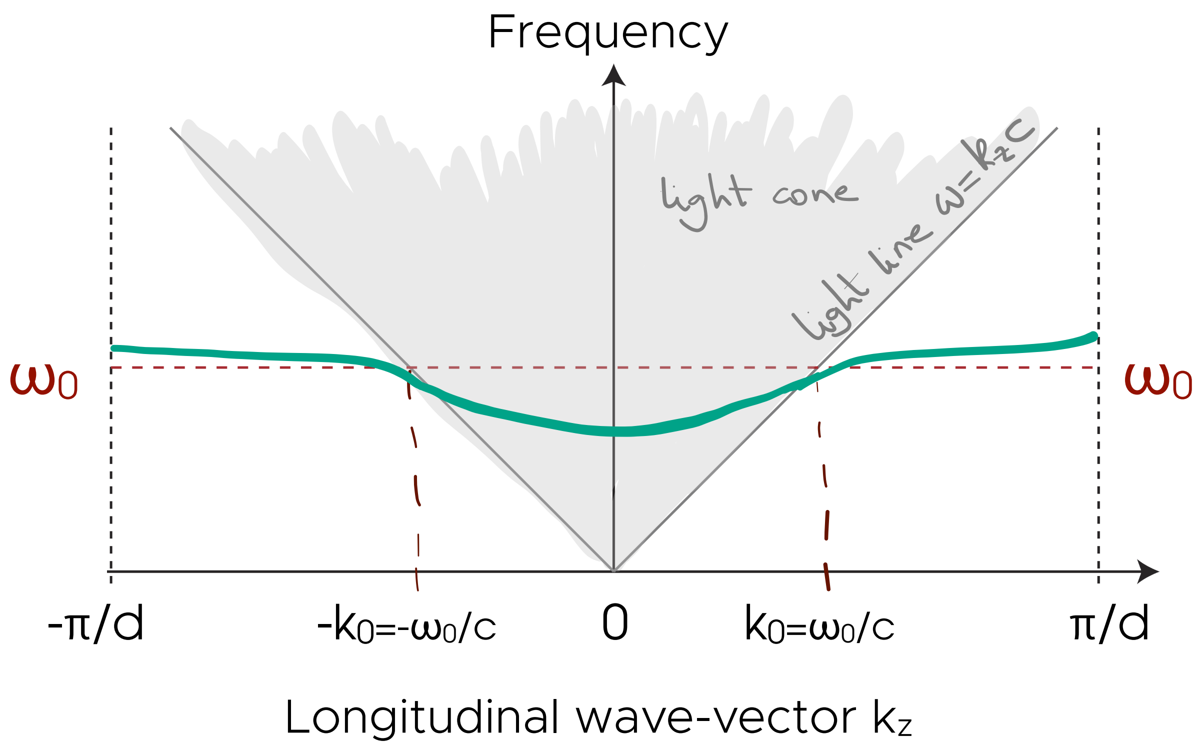
The problem of subradiant modes is that they are hard to excite

What does that imply for light-matter interactions? Can we use subradiance to our advantage?

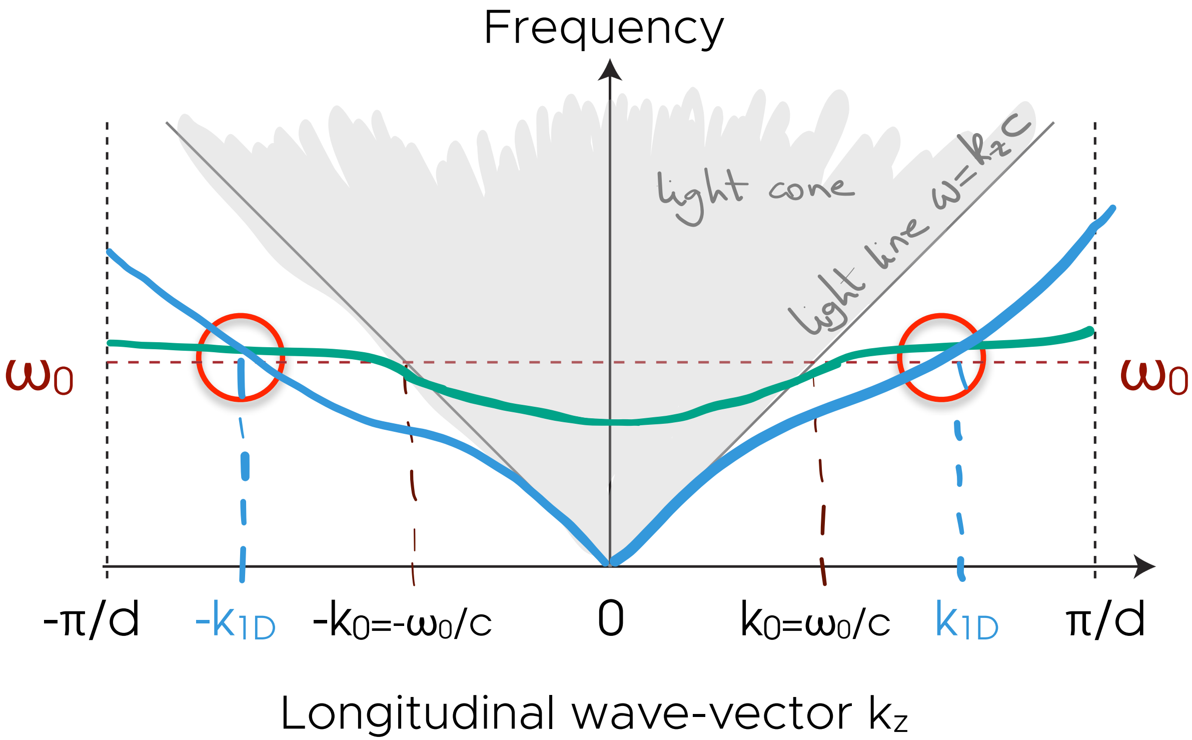
Yes, if we find a way to access the subradiant manifold



The problem of subradiant modes is that they are hard to excite



The presence of a fiber allows to excite selectively radiant modes



The presence of a fiber allows to excite selectively radiant modes:

- superradiant to fiber
- subradiant to free-space

Application: a quantum memory for light

PRL **98,** 123601 (2007) PHYSICAL REVIEW LETTERS week ending 23 MARCH 2007

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]

[1]*Physics Department, Harvard University, Cambridge, Massachusetts 02138, USA*

[2]*Fachbereich Physik, Technische Universität Kaiserslautern, 67633 Kaiserslautern, Germany*

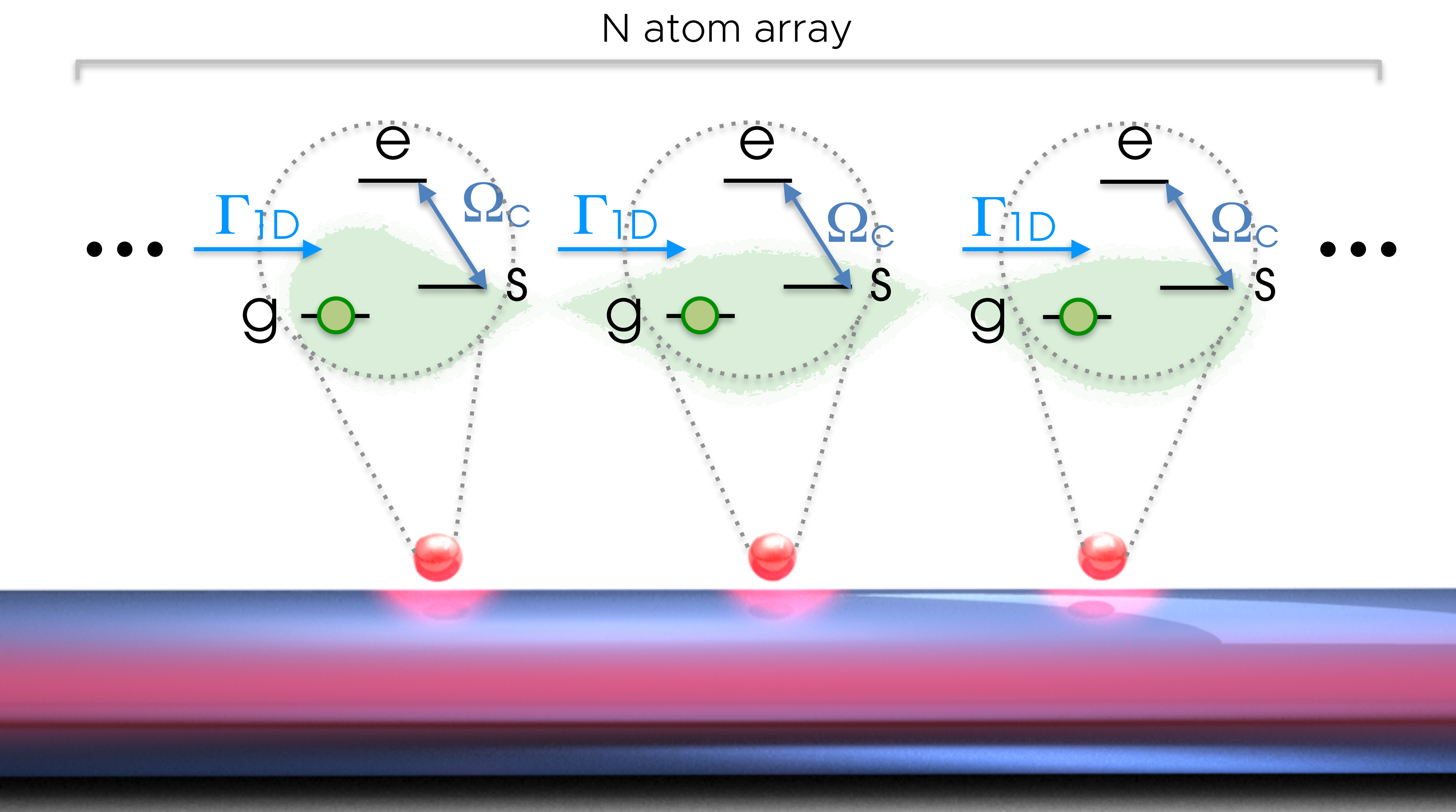
[3]*QUANTOP, Danish National Research Foundation Centre of Quantum Optics, Niels Bohr Institute, DK-2100 Copenhagen Ø, Denmark*

(Received 6 April 2006; published 19 March 2007)

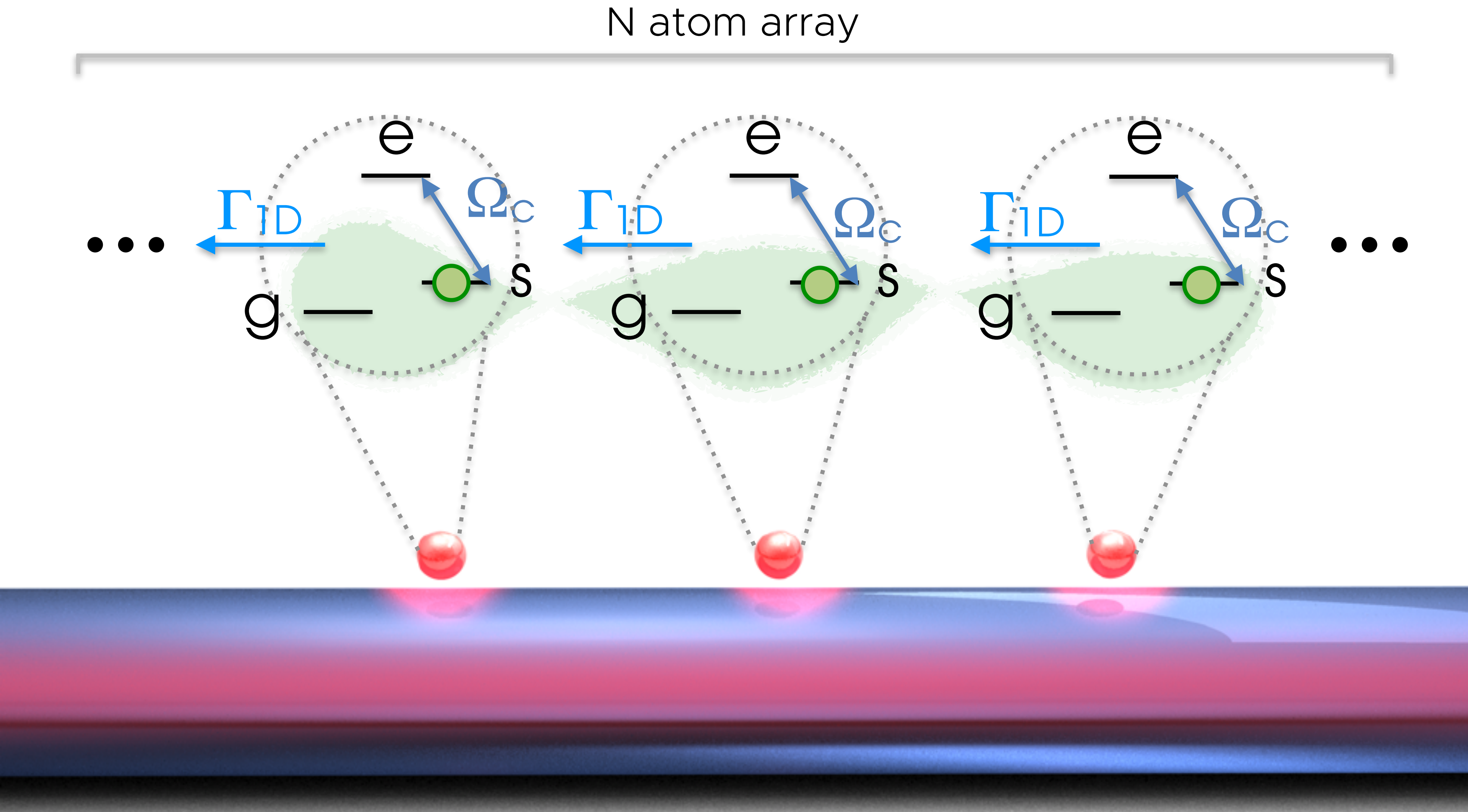
We present a universal physical picture for describing storage and retrieval of photon wave packets in a Λ-type atomic medium. This physical picture encompasses a variety of different approaches to pulse storage ranging from adiabatic reduction of the photon group velocity and pulse-propagation control via 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.

infidelity ~ 1/D, with optical depth $D=N\Gamma_{1D}/\Gamma'$

Quantum memories require three level atoms: photon storage



Quantum memories require three level atoms: photon retrieval



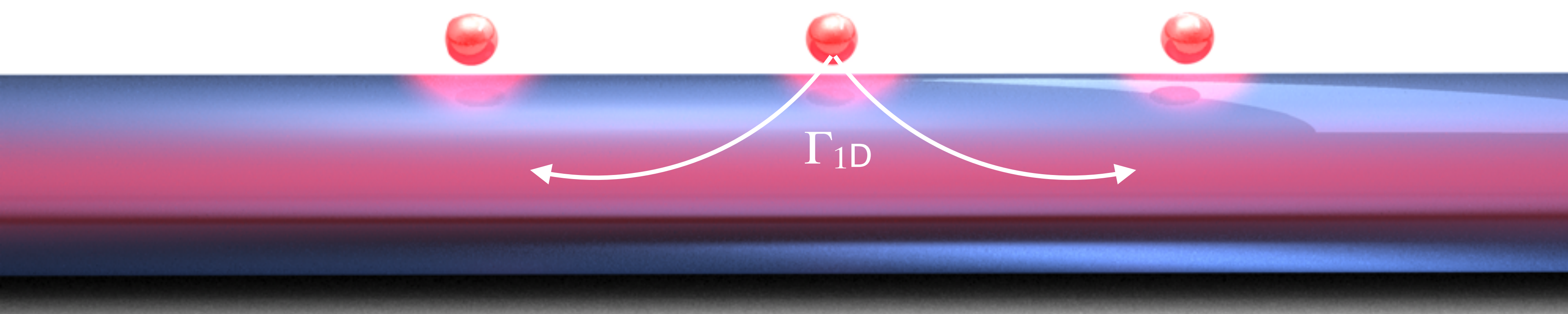
Atoms now interact both through free space and through the fiber

Coupling through guided modes:

$$\mathcal{H}_{1\mathrm{D}} = -\mathrm{i}\frac{\hbar\Gamma_{1\mathrm{D}}}{2}\sum_{i,j=1}^{N} e^{\mathrm{i}k_{1\mathrm{D}}|z_i - z_j|}\hat{\sigma}^i_{eg}\hat{\sigma}^j_{ge}$$

decay into guided mode

guided mode wave vector

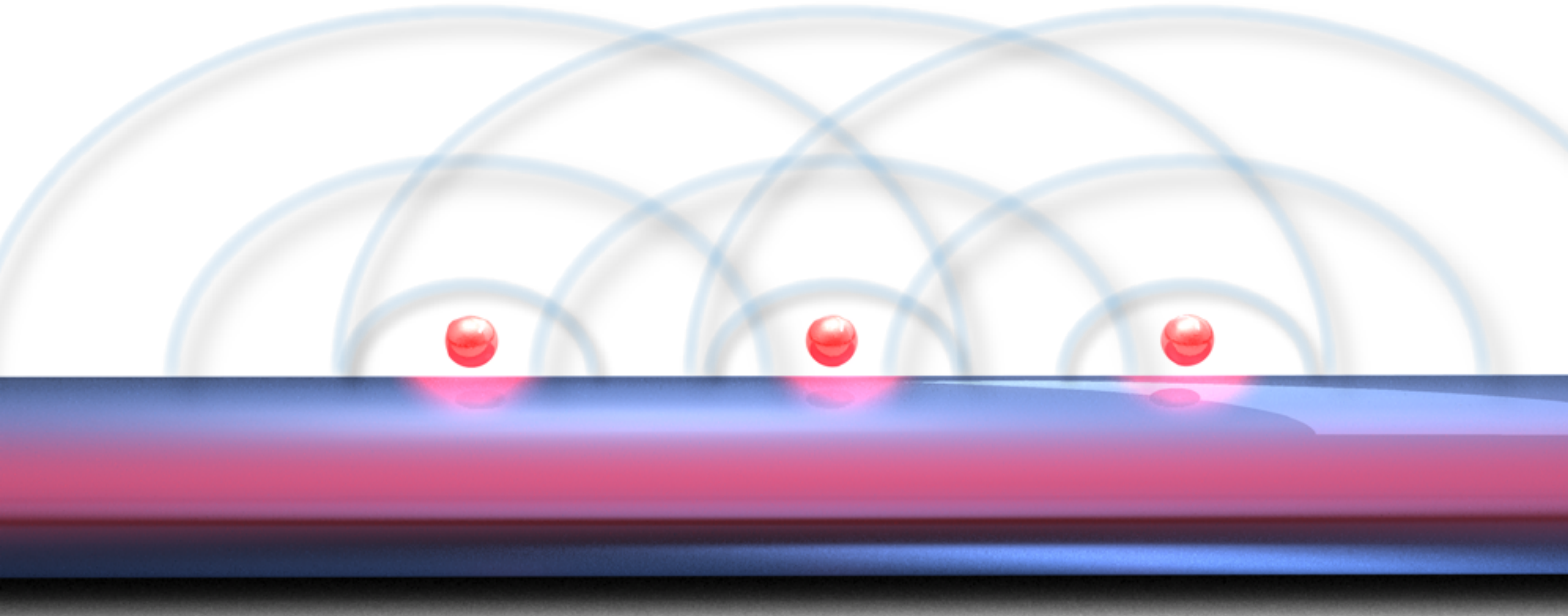


Atoms now interact both through free space and through the fiber

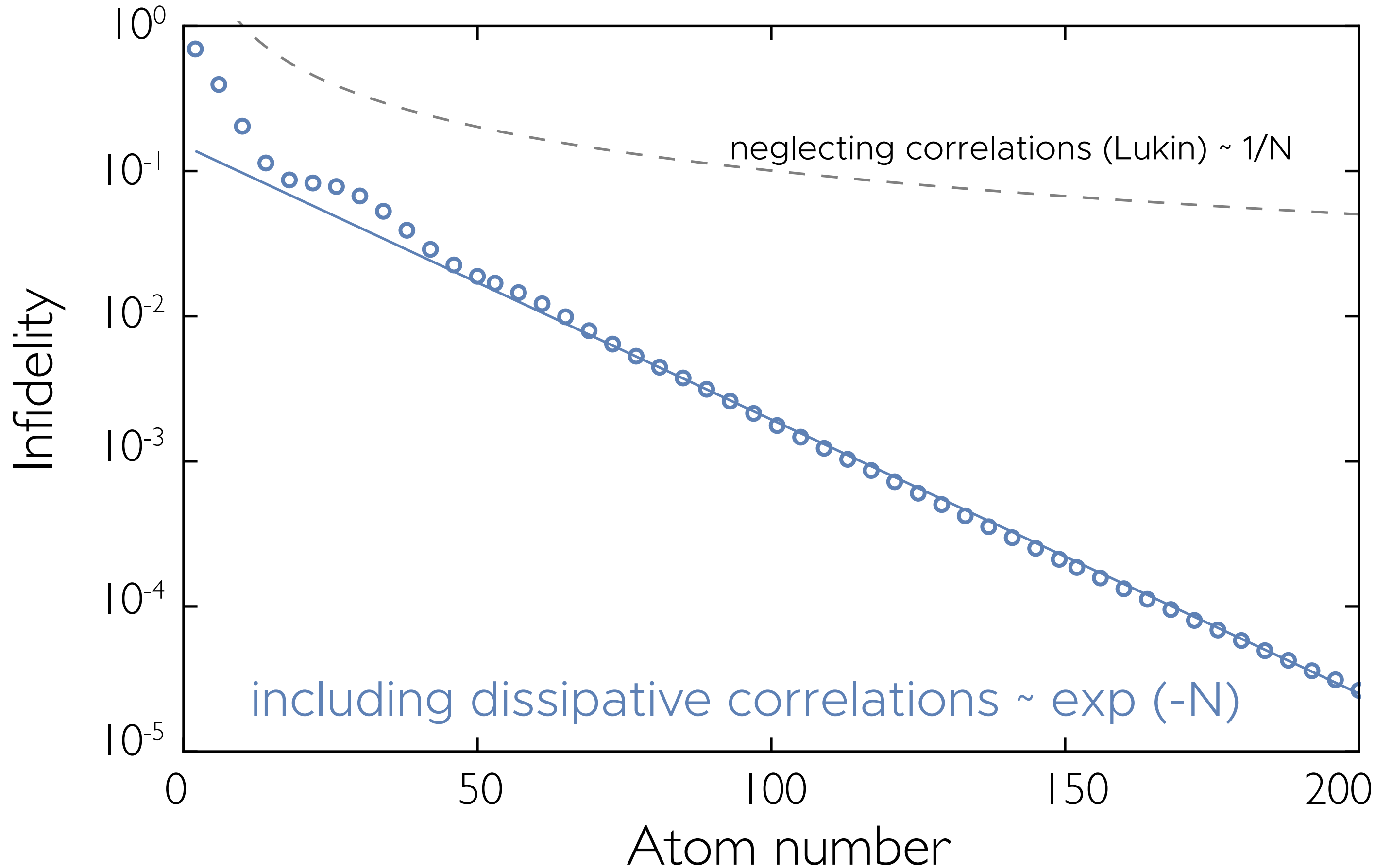
non- guided Green's function (calculated exactly)

Coupling through non-guided modes:

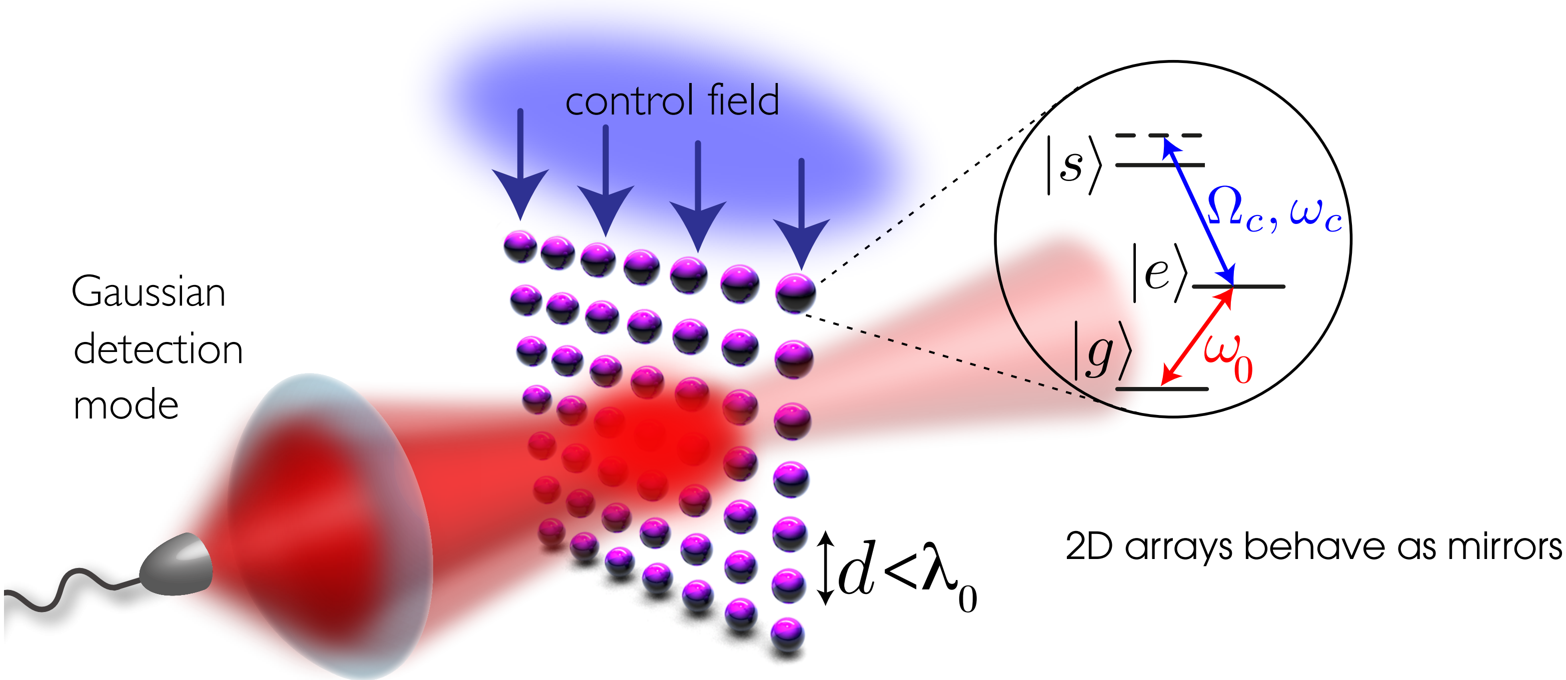
$$\mathcal{H}' = -\frac{3\pi\hbar\Gamma_0}{k_0}\sum_{i,j=1}^{N} G'_{\rho\rho}(\mathbf{r}_i, \mathbf{r}_j, \omega_0)\,\hat{\sigma}^i_{eg}\hat{\sigma}^j_{ge}$$

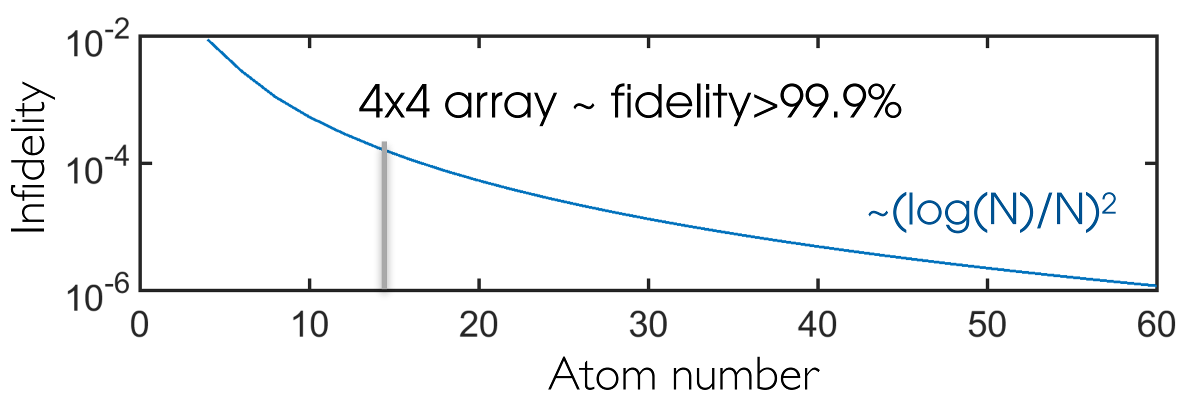


Correlated dissipation improves the fidelity of photon retrieval exponentially, well beyond previously known bounds



2D atomic arrays also work as good memories





Debate:
is subradiance a classical or a quantum phenomena?

Debate:
is subradiance a classical or a quantum phenomena?

My view: It is quantum for
- more than one excitation
- several ground states
- maybe other situations?

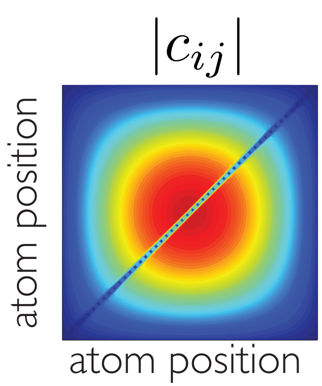
Subradiance as a many-body problem: example of two excitations

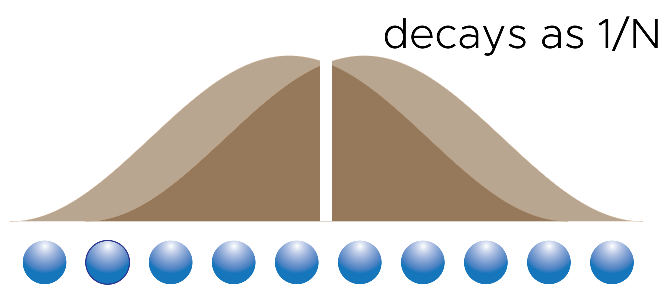
Single excitation (classical, linear optics):

$$|\psi\rangle \propto S^\dagger |g\rangle^{\otimes N} = \sum_{i=1}^{N} c_i |e_i\rangle \text{ , decays as 1/N}^3$$

Apply excitation twice: $$|\psi\rangle \propto (S^\dagger)^2 |g\rangle^{\otimes N} = \sum_{i,j=1}^{N} c_{ij} |e_i e_j\rangle$$

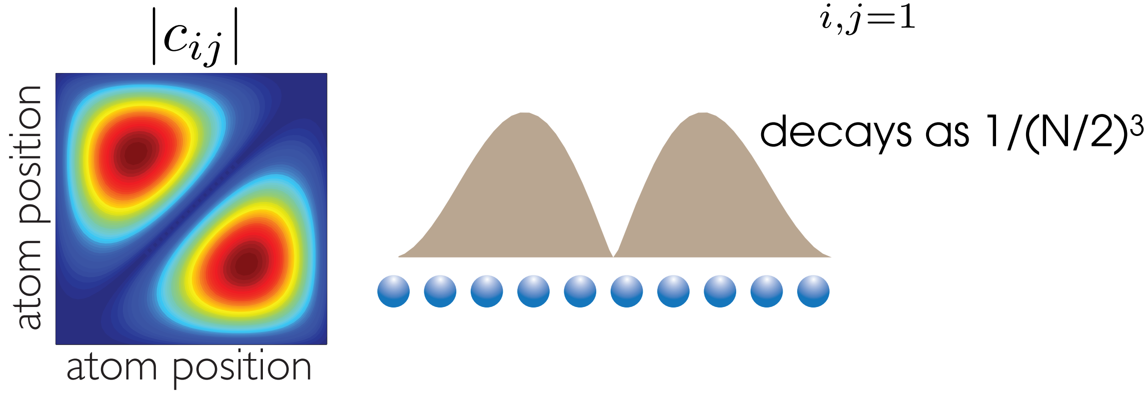
This is not an eigenstate! Spins are not bosons.





Subradiance as a many-body problem: example of two excitations

By diagonalizing the Hamiltonian we find: $|\psi^{(2)}\rangle = \sum_{i,j=1}^{N} c_{ij} |e_i e_j\rangle$



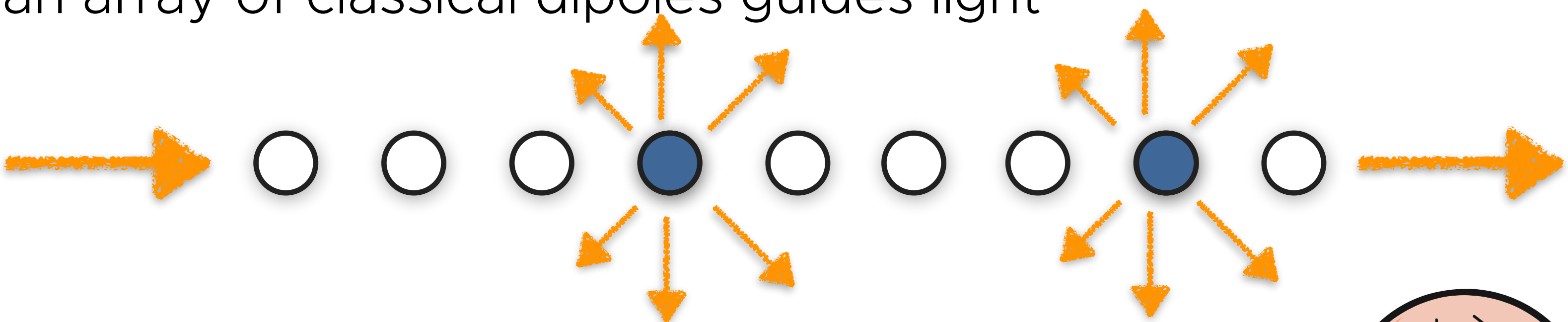
Excitations obey effective Pauli exclusion principle in space

We write ansatz for $|\psi^{(2)}\rangle$ found by "fermionizing" single-excitation wf's

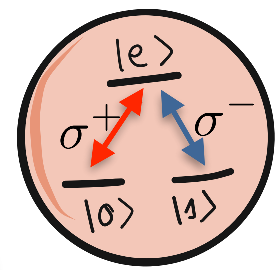
This holds whenever the number of excitations n is small (n<<N)

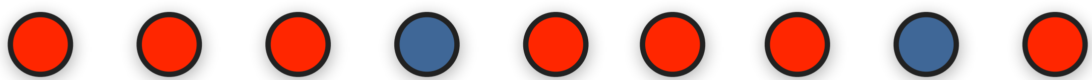
Follow up: can entanglement help guide light?

an array of classical dipoles guides light

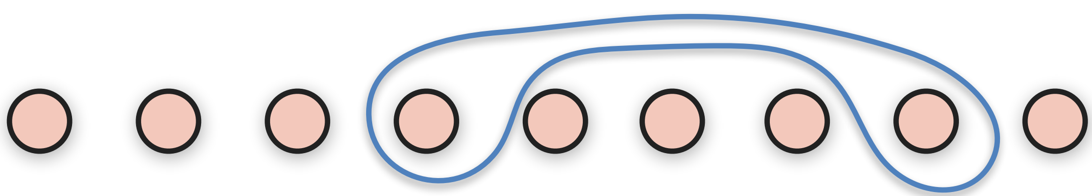


atomic ground states can behave as defects





$$|0\rangle\otimes|0\rangle\otimes|0\rangle\otimes|1\rangle\otimes|0\rangle\otimes|0\rangle\otimes|0\rangle\otimes|1\rangle\otimes|0\rangle$$



$$|0\rangle_i + |1\rangle_i \quad \otimes \quad |0\rangle_j + |1\rangle_j$$

Previous work, not applicable to arrays

PRL **118,** 143602 (2017) PHYSICAL REVIEW LETTERS week ending 7 APRIL 2017

Subradiance via Entanglement in Atoms with Several Independent Decay Channels

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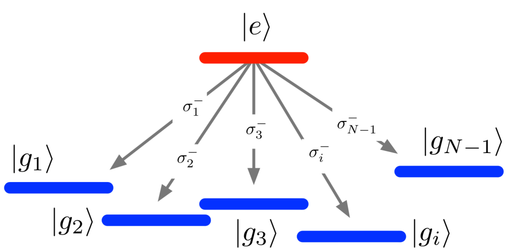
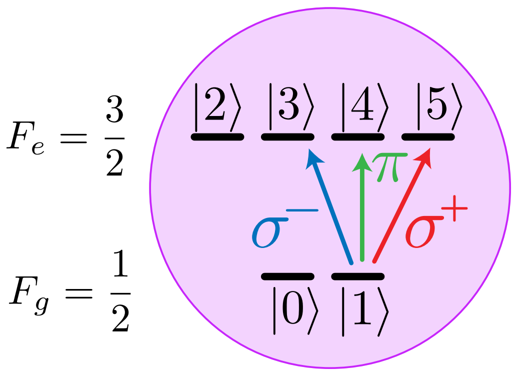
Institut für Theoretische Physik, Universität Innsbruck, Technikerstrasse 21a, A-6020 Innsbruck, Austria
(Received 17 January 2017; published 7 April 2017)

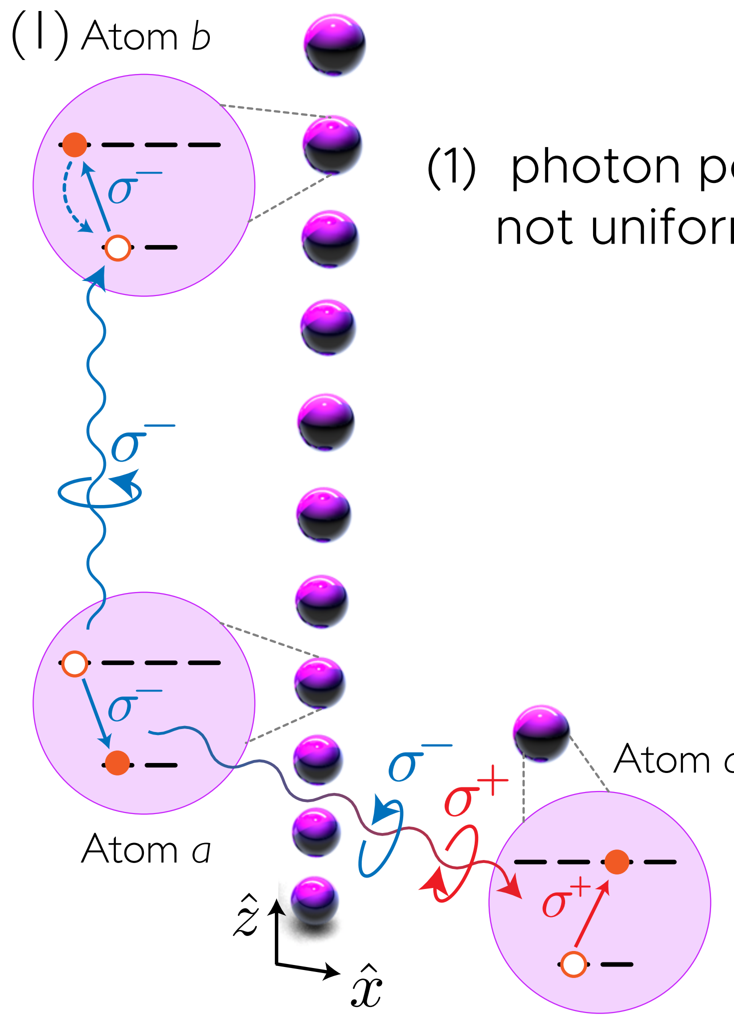


distances much smaller than the transition wavelength, all $\Gamma_j^{ik} = \Gamma_j$ become independent of the atomic indexes (i, k), reducing to a single constant Γ_j. For simplicity, we also assume equal decay rates on all transitions $\Gamma_j = \Gamma$, i.e., equal dipole moments and Clebsch-Gordan coefficients

Hyperfine "à la Dicke": small volume approximation, neglect of photon polarization

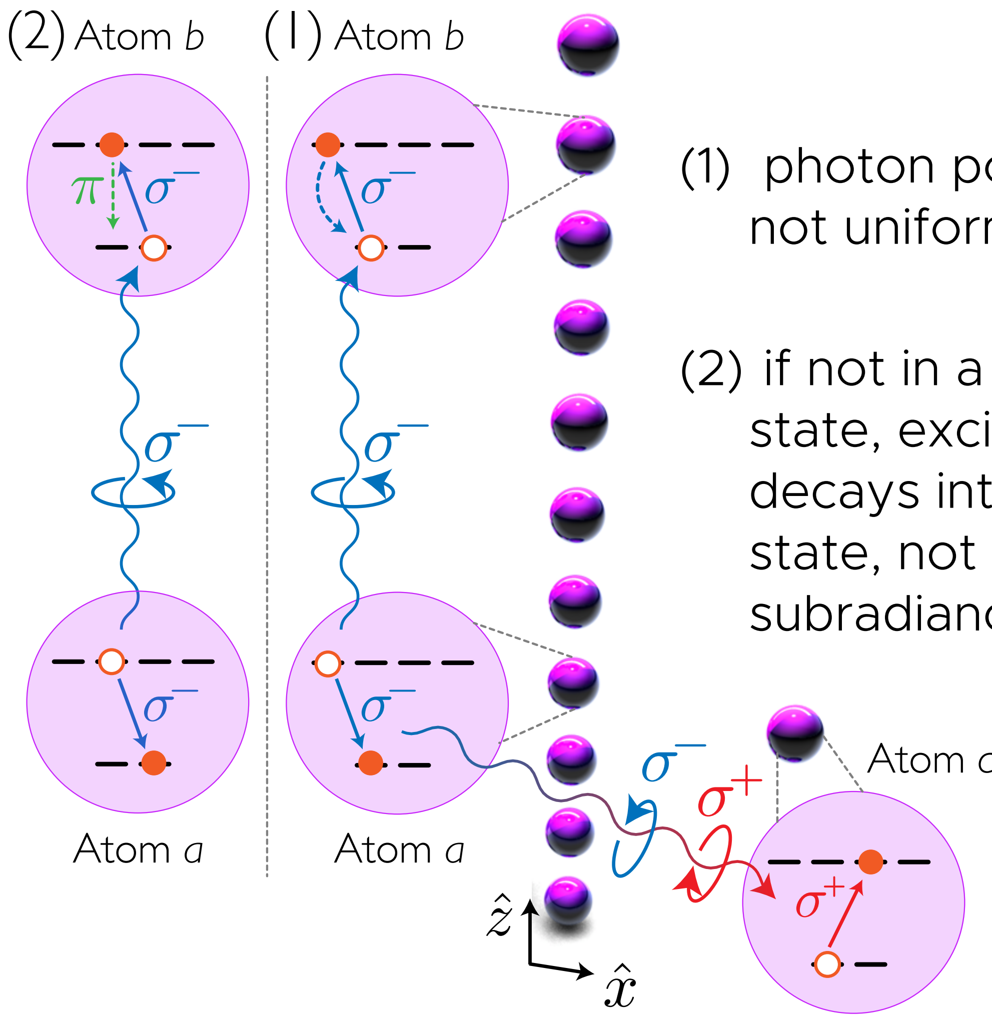
Hyperfine structure breaks down the toy-model of two-level atoms





(1) photon polarization is not uniform in space

Hyperfine structure breaks down the toy-model of two-level atoms



(1) photon polarization is not uniform in space

(2) if not in a stretched state, excited state decays into unoccupied state, not protected by subradiance

The many-body complexity of the hyperfine problem (even for single excitation)

2-level atoms

$$\mathscr{H}_{\text{eff}} = \hbar \sum_{i,j=1}^{N} (J_{ij} - \mathrm{i}\Gamma_{ij}/2)\hat{\sigma}^{i}_{eg}\hat{\sigma}^{j}_{ge}$$

unique ground state

$$dim = 1$$

$$|g\rangle^{\otimes N}$$

N=4: $|g\,g\,g\,g\rangle$

Multilevel atoms

$$\mathscr{H}_{\text{eff}} = \hbar \sum_{i,j=1}^{N} \sum_{q,q'=-1}^{1} \left(J_{ijqq'} - \mathrm{i}\frac{\Gamma_{ijqq'}}{2}\right)\Sigma^{\dagger}_{iq}\Sigma_{jq'}$$

$$\Sigma^{\dagger}_{iq} = \sum_{m_g=-F_g}^{F_g} C_{m_g q}\hat{\sigma}^{i}_{F_e m_g - q, F_g m_g}$$

degenerate ground state

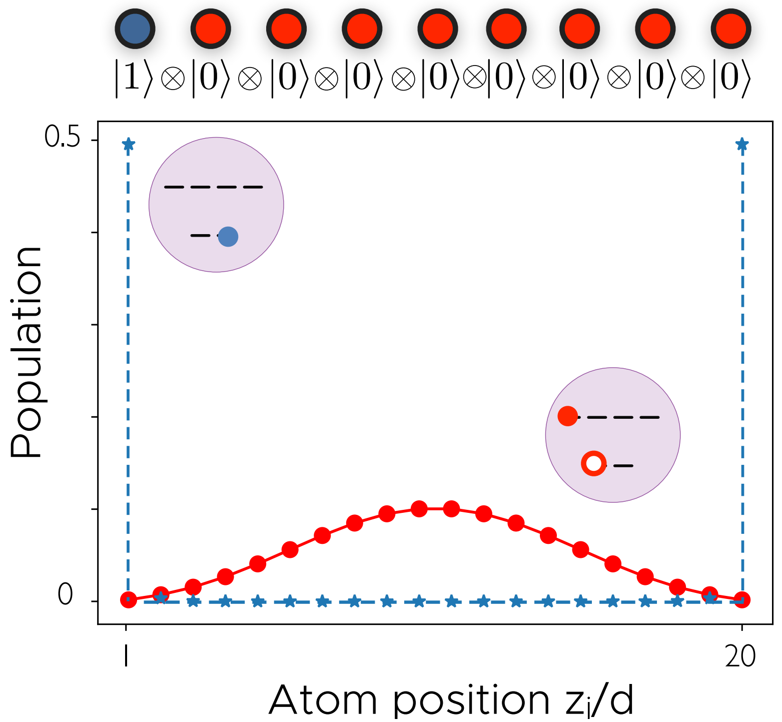
$$dim = 2^N$$

$$|0\,0\,0\,0\rangle, |0\,0\,0\,1\rangle, |0\,0\,1\,0\rangle, |0\,1\,0\,0\rangle,$$
$$|1\,0\,0\,0\rangle, |1\,0\,0\,1\rangle, |1\,0\,1\,0\rangle, |1\,1\,0\,0\rangle,$$
$$|0\,1\,1\,0\rangle, |0\,0\,1\,1\rangle, |0\,1\,0\,1\rangle, |0\,1\,1\,1\rangle,$$
$$|1\,0\,1\,1\rangle, |1\,1\,0\,1\rangle, |1\,1\,1\,0\rangle, |1\,1\,1\,1\rangle.$$

States of a 1D chain along z can be classified according to angular momentum projection F_z

Most subradiant states are “defect states”

Similar to 2-level atom subradiant states, with decay Γ ~ $1/N^3$



Defect is pushed to the edge, and does not see light intensity

For low angular momentum: emergence of domain walls

However, there are also exotic, and very non-classical subradiant states

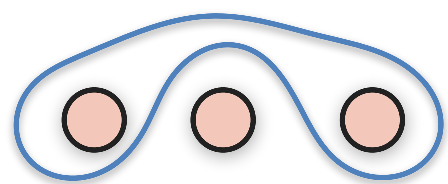
No analogy with the physics of 2-level atoms

They are highly symmetrical and appear in the minimum angular momentum subspace

In the thermodynamic limit, we have an ansatz for them, which works well for the finite chain. Decay ~$1/N^3$

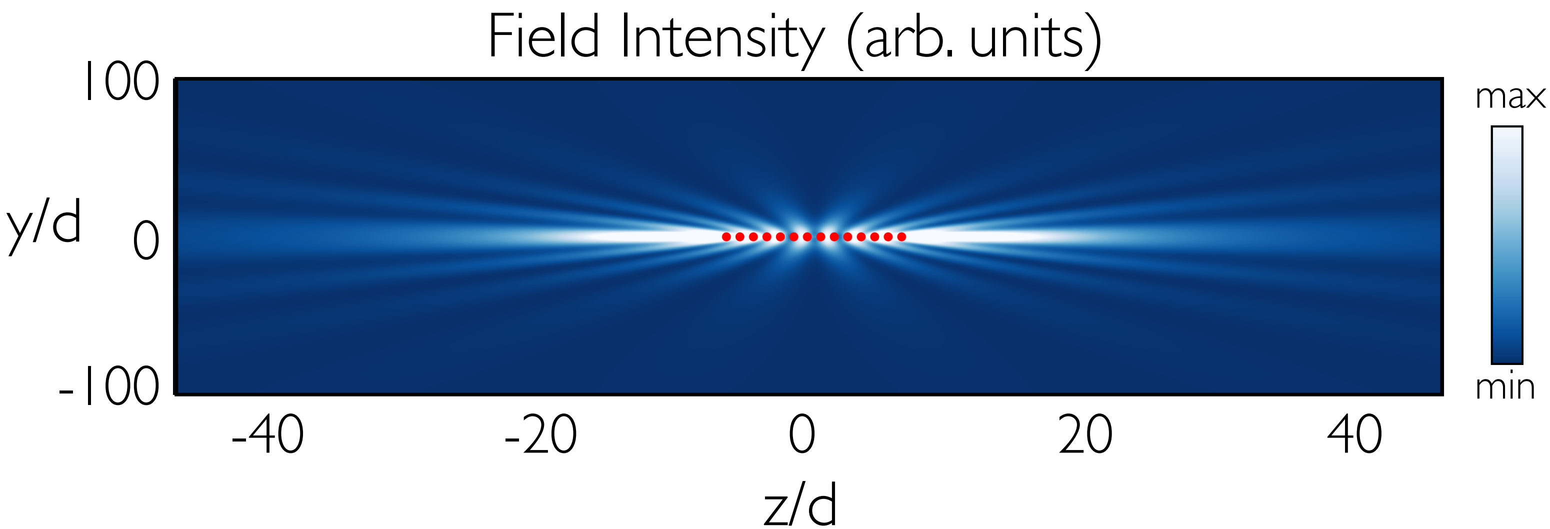
$$|\psi_{\text{dark}}\rangle \sim \sum_j e^{ik_s z_j} \left(|2_j\rangle|\mathcal{D}^j_{3/2}\rangle + |3_j\rangle|\mathcal{D}^j_{1/2}\rangle + |4_j\rangle|\mathcal{D}^j_{-1/2}\rangle + |5_j\rangle|\mathcal{D}^j_{-3/2}\rangle \right)$$

Dicke state with angular momentum projection F_z=3/2



$$|01\rangle + |10\rangle$$

However, there are also exotic, and very non-classical subradiant states



Problems:

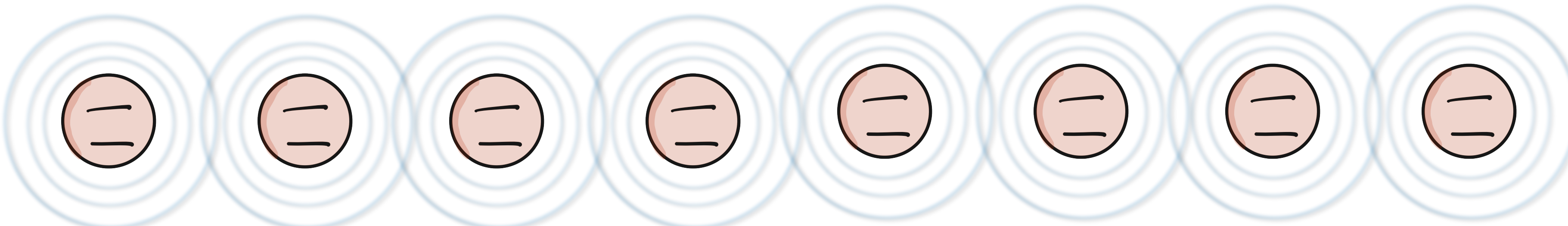
We do not know how to access them

They appear for small distances or modified dispersion relations

Experimentalists: beware

Collective phenomena in light-matter interfaces

Ana Asenjo Garcia



Columbia University

Outline of the lectures

Lecture 1: Atom-light interaction as a spin model

Lecture 2: Atom arrays as light-matter interfaces

Lecture 3: Atom-atom interactions in non-conventional baths

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Lecture 1: Atom-light interaction as a spin model

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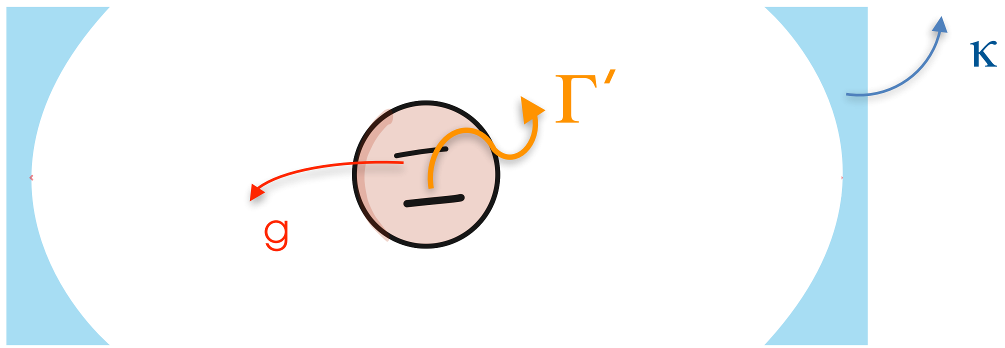
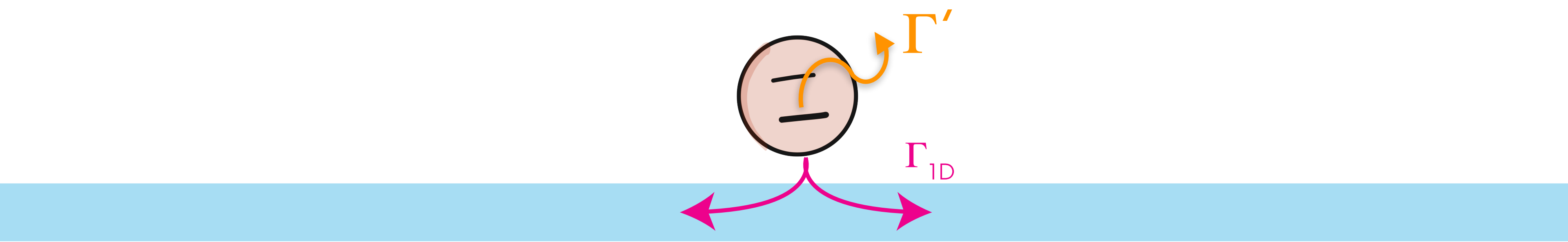
cavity QED and waveguide QED

In cavity QED, figure of merit is $C = g^2/\kappa\Gamma'$

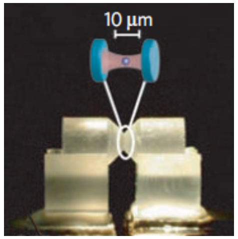


In waveguide QED, that is $D = \Gamma_{1D}/\Gamma'$

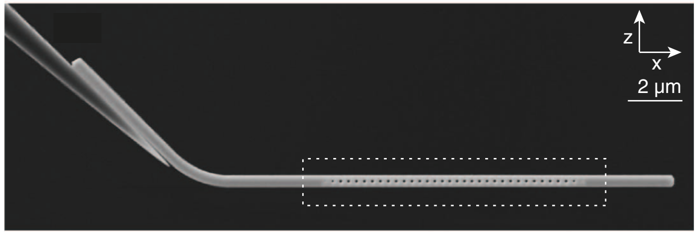


Nanophotonic structures add versatility, allowing to go beyond cavity QED

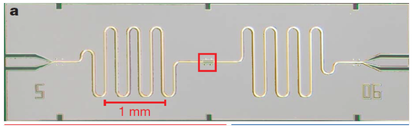
cQED: infinite interaction range between atoms inside cavity



Fabry-Perot
Kimble (2008)



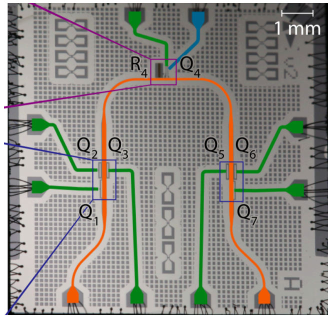
dielectric cavity
Lukin (2014)



superconducting cavity
Wallraff (2004)

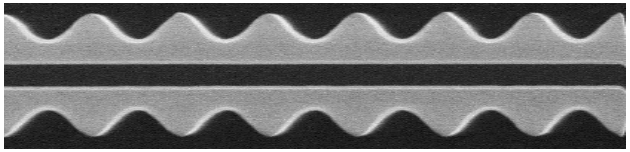
wQED: tunable interaction range, character of interaction is position dependent… dispersion engineering!

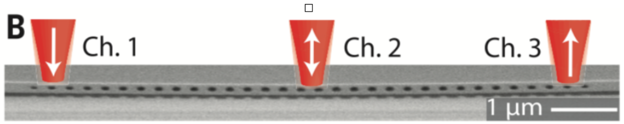
nanofiber
Laurat (2015)



SC waveguide, Painter (2019)

photonic crystal, Kimble (2016)





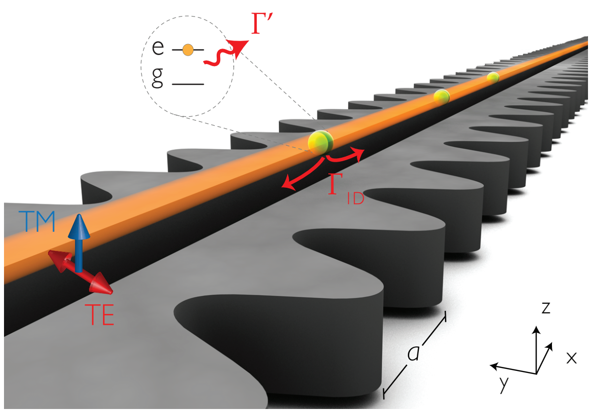
NV in diamond waveguide, Lukin (2016)

Figures of merit of different systems

atom+fiber

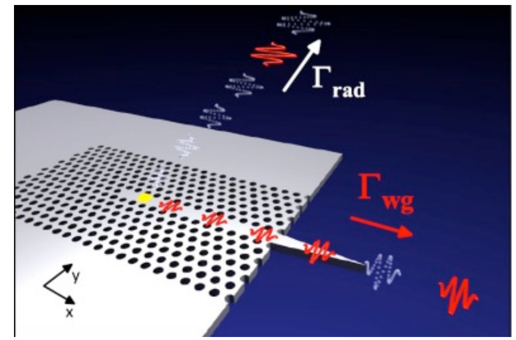
$$\Gamma_{1D}/\Gamma' \sim 0.05$$

atom+PhC



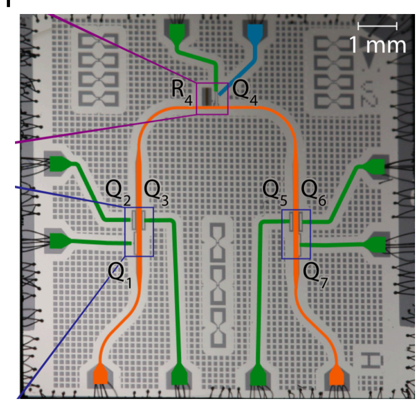
$$\Gamma_{1D}/\Gamma' \sim 1$$

QD+PhC



$$\Gamma_{1D}/\Gamma' \sim 10$$

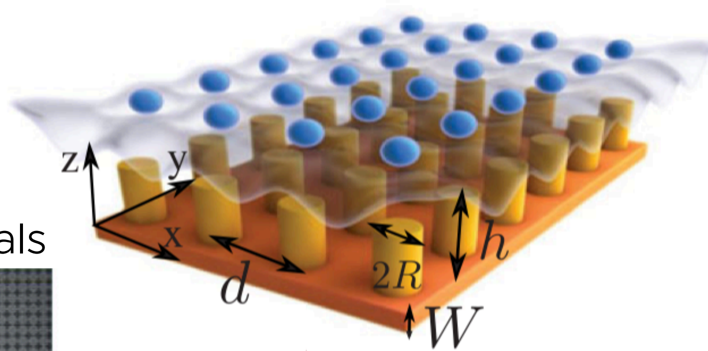
SC qubit+transmission line



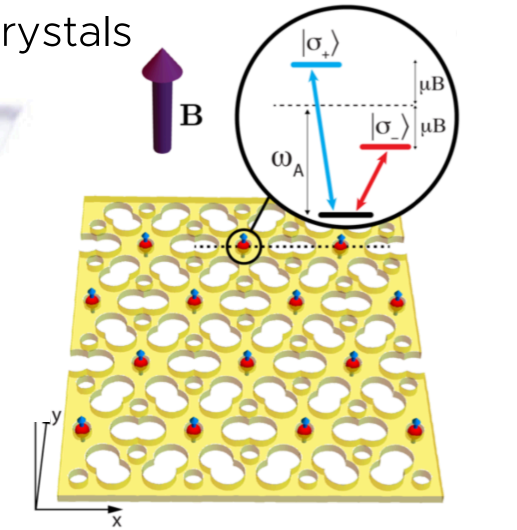
$$\Gamma_{1D}/\Gamma' \sim 100$$

Nanophotonics brings many opportunities

2D photonic crystals

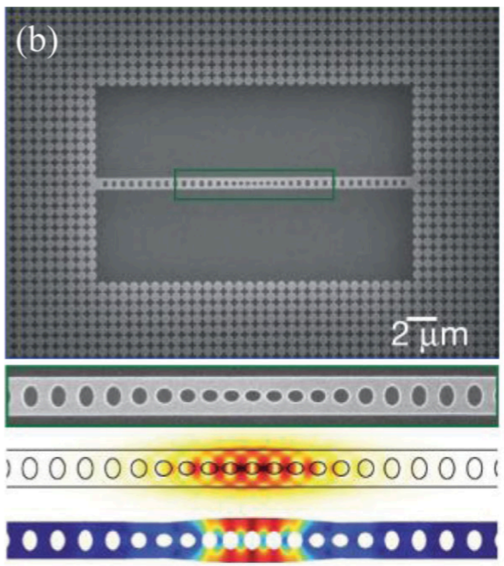


Gonzalez-Tudela et al.,
Nat. Photon. 9, 320 (2015)



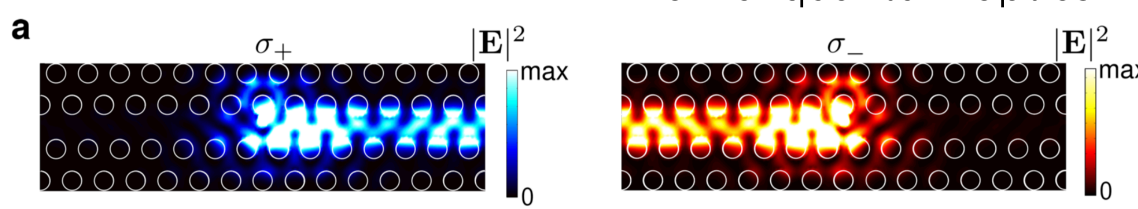
Perczel et al., arXiv:1810.12299 (2018)

optomechanical crystals



Safavi-Naeini et al., Nature 472, 69 (2011)

chiral quantum optics

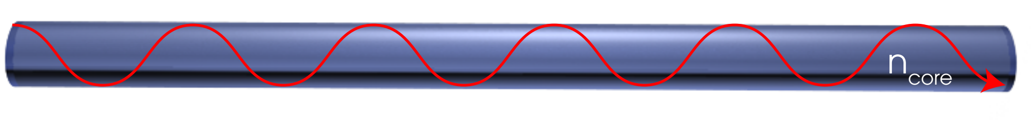


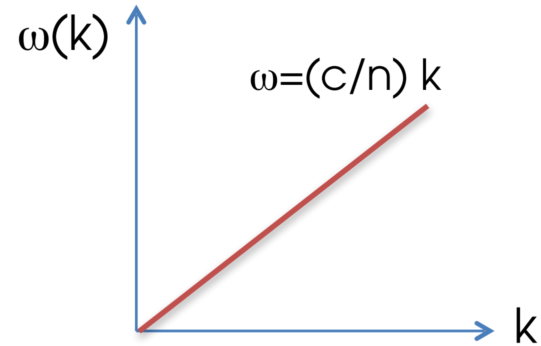
Lodahl et al., Nature 541, 473 (2017)

Review paper: Chang et al., RMP 90, 031002 (2018)

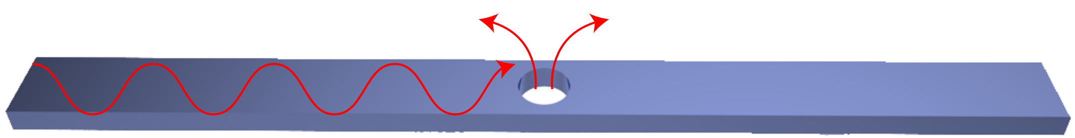
Example of dispersion engineering: Photonic crystal waveguides

Regular fiber:
light guided by total internal reflection

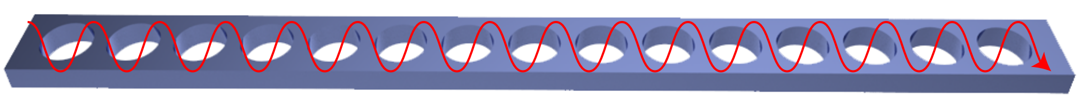


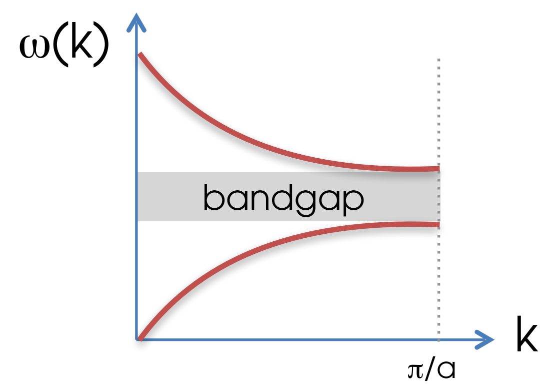


Single defect: loss by scattering into other modes

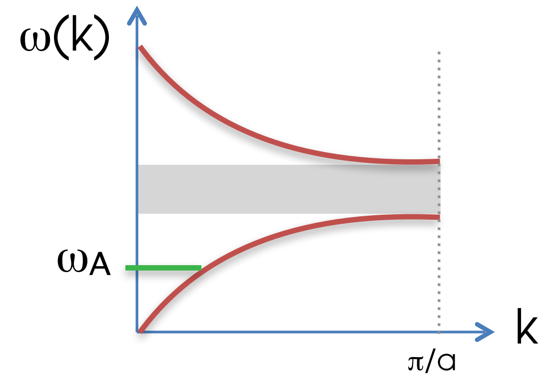


Periodic array of defects: band structure



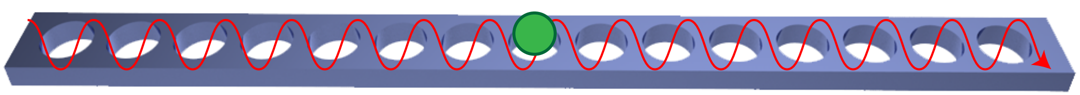


Example of dispersion engineering: Photonic crystal waveguides

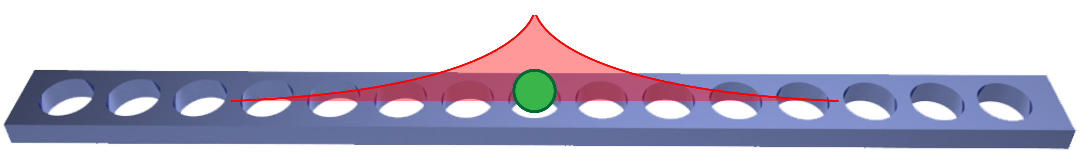


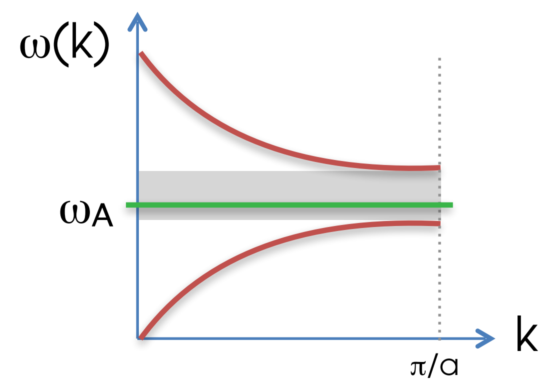
ω_A in propagating region:

infinite interaction range



ω_A in bandgap: atom dressed by photonic cloud



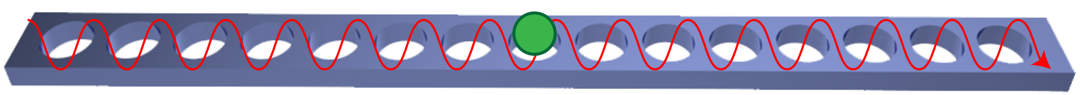


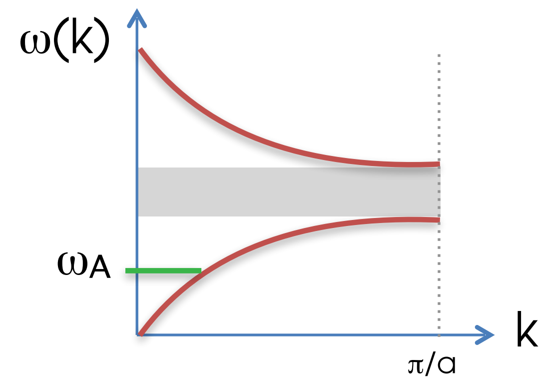
- atom carries its own cavity around

Example of dispersion engineering: Photonic crystal waveguides

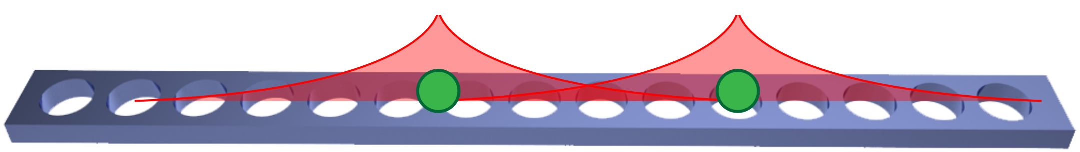
ω_A in propagating region:

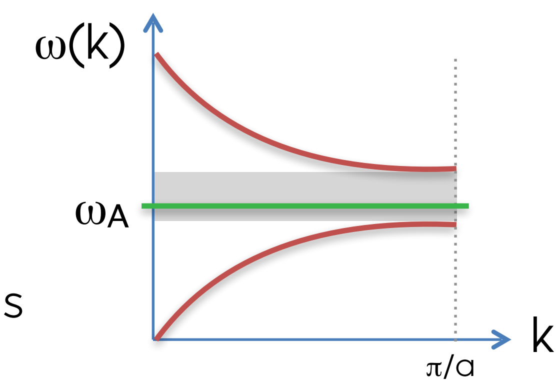
infinite interaction range





ω_A in bandgap: atom dressed by photonic cloud



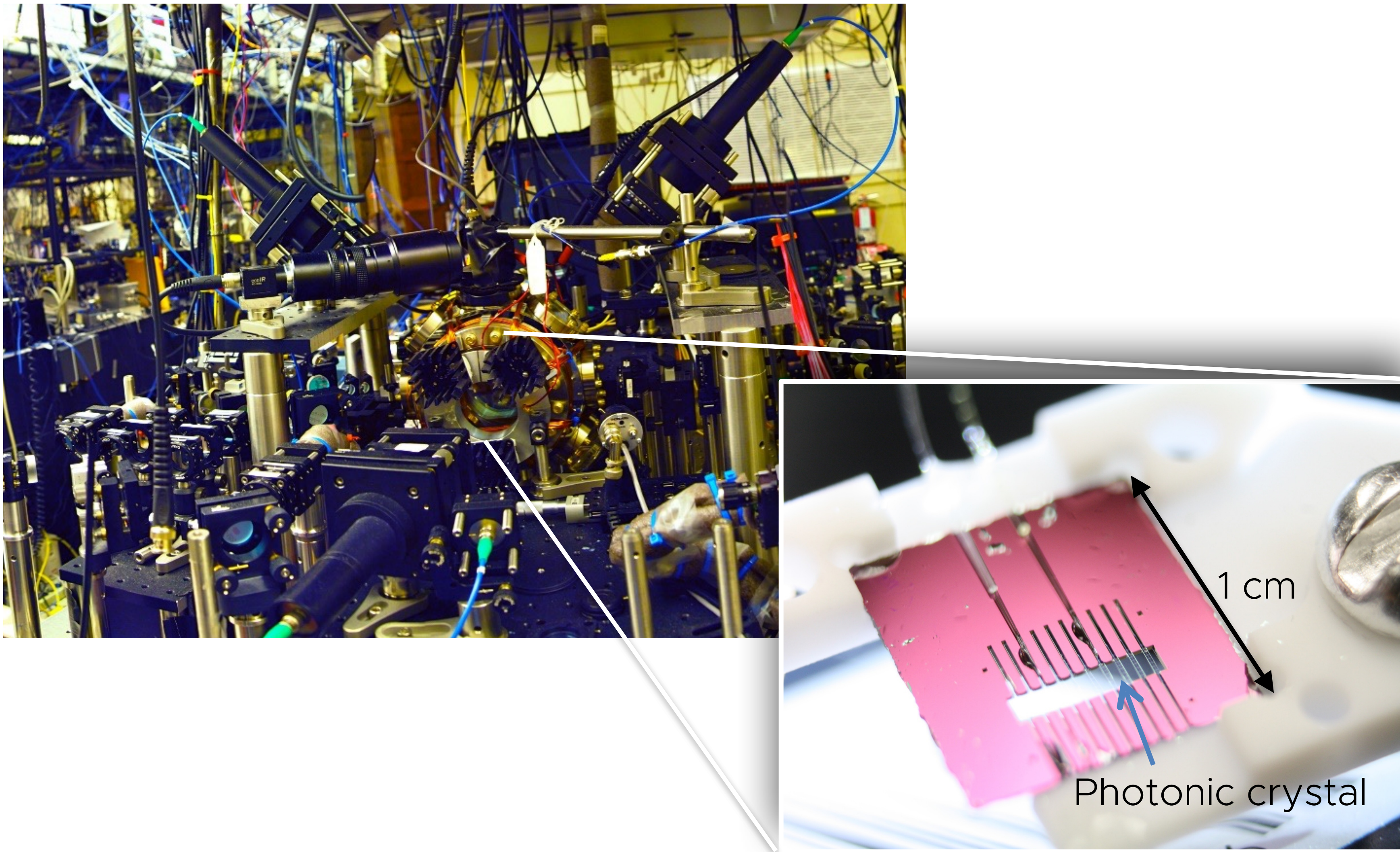


- atom carries its own cavity around
- coherent, tunable-range atom-atom interactions

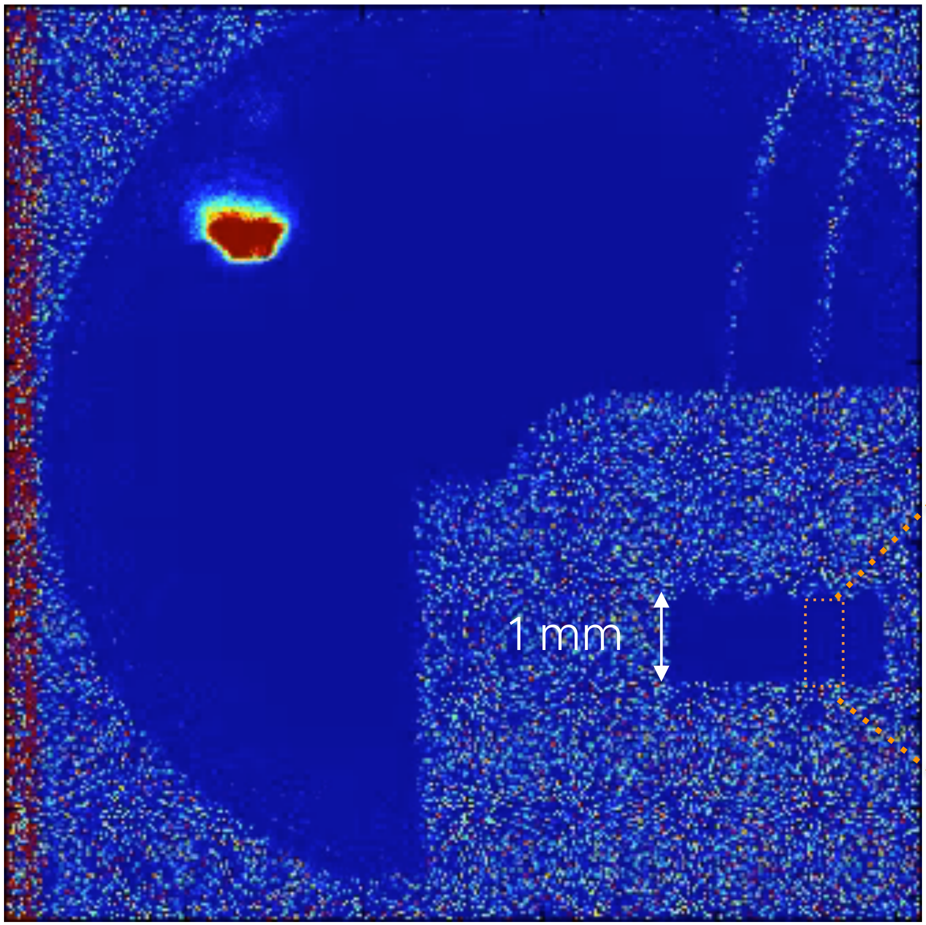
Initial work by John (1990)

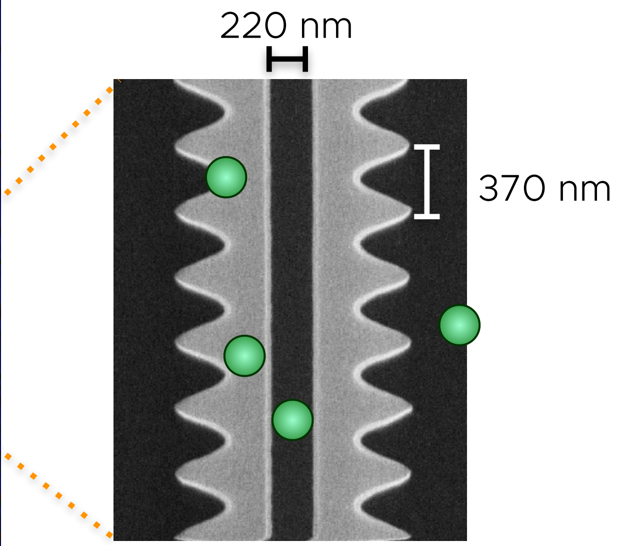
More recent: Douglas (2015), Gonzalez Tudela (2015)

Work at Caltech: the alligator photonic crystal waveguide



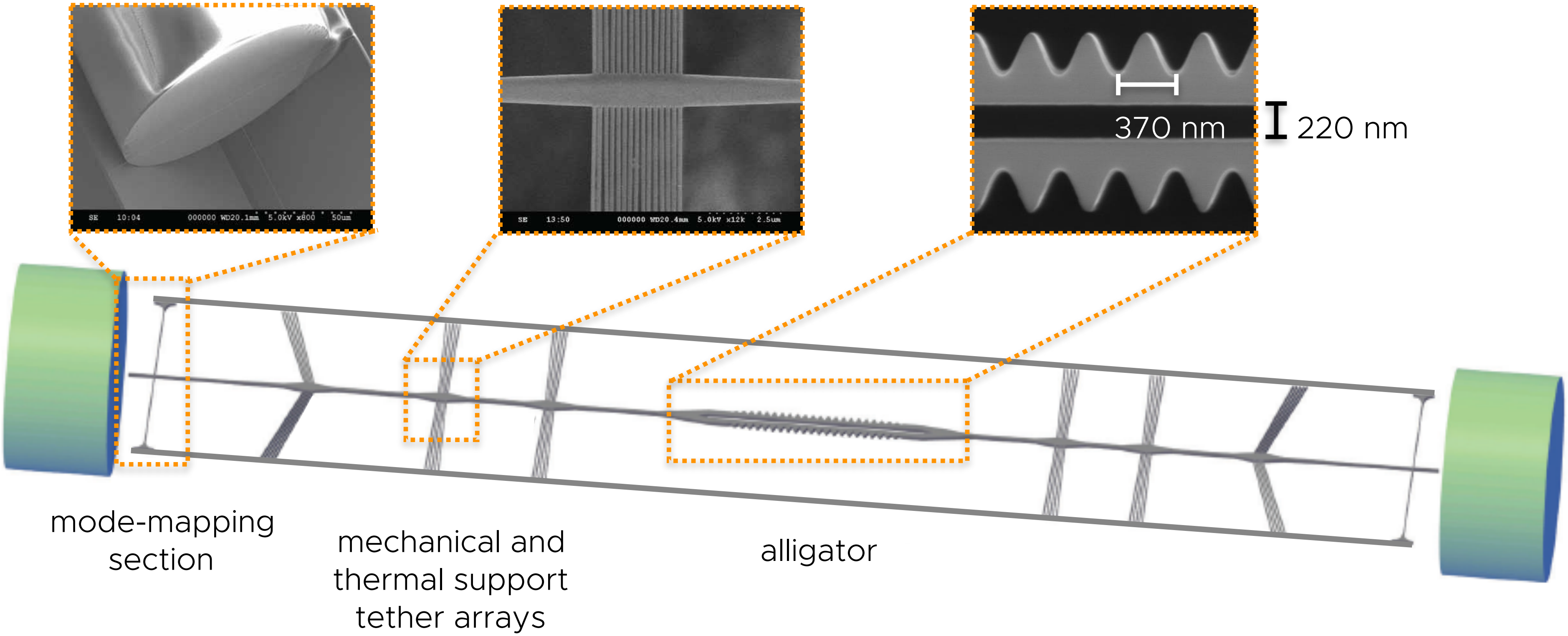
Feeding the atoms to the alligator



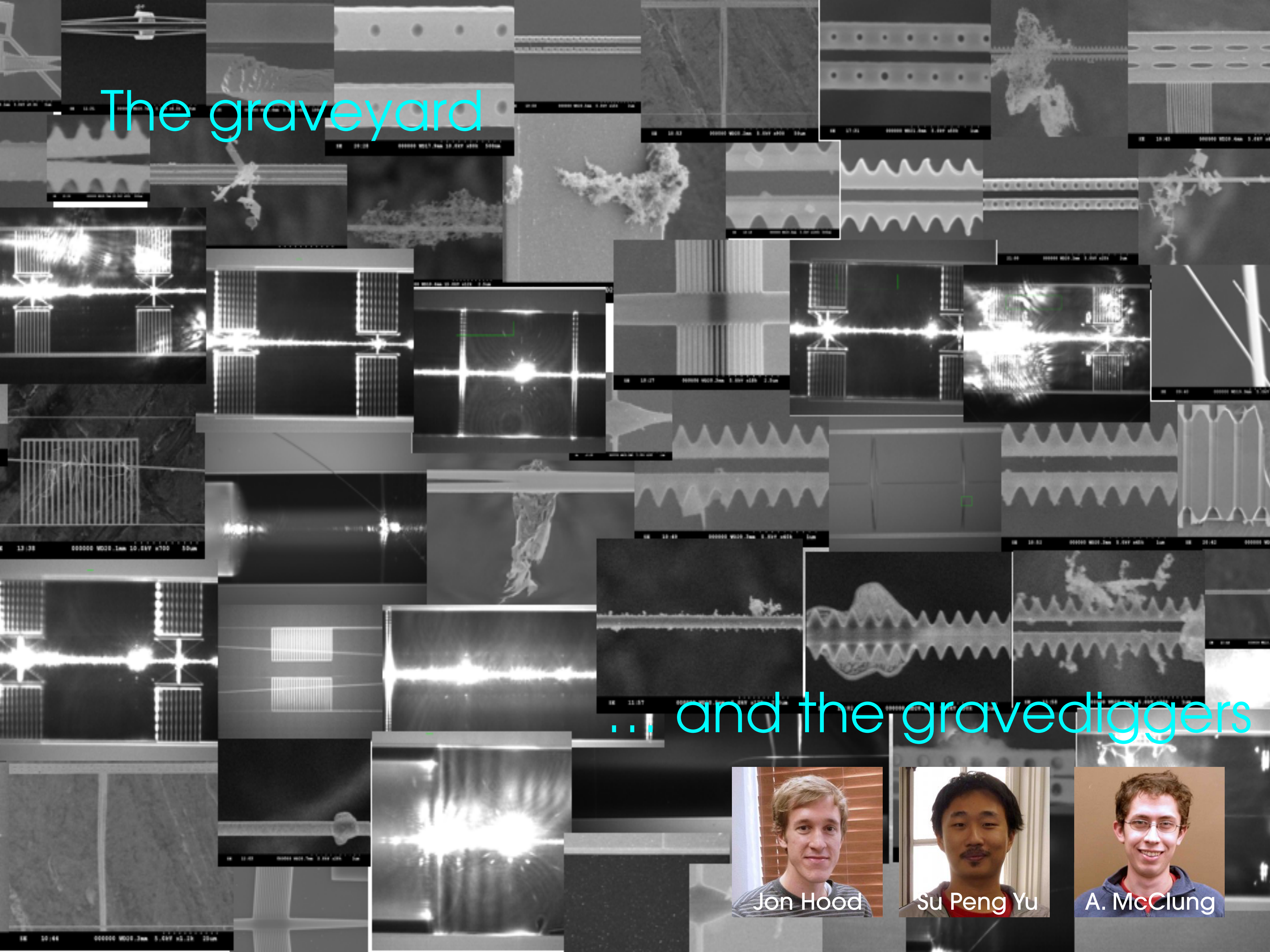


N~ 10^6 Cs atoms
at ρ ~ 10^{10}/cm^3
T ~ 30μK

The alligator photonic crystal waveguide

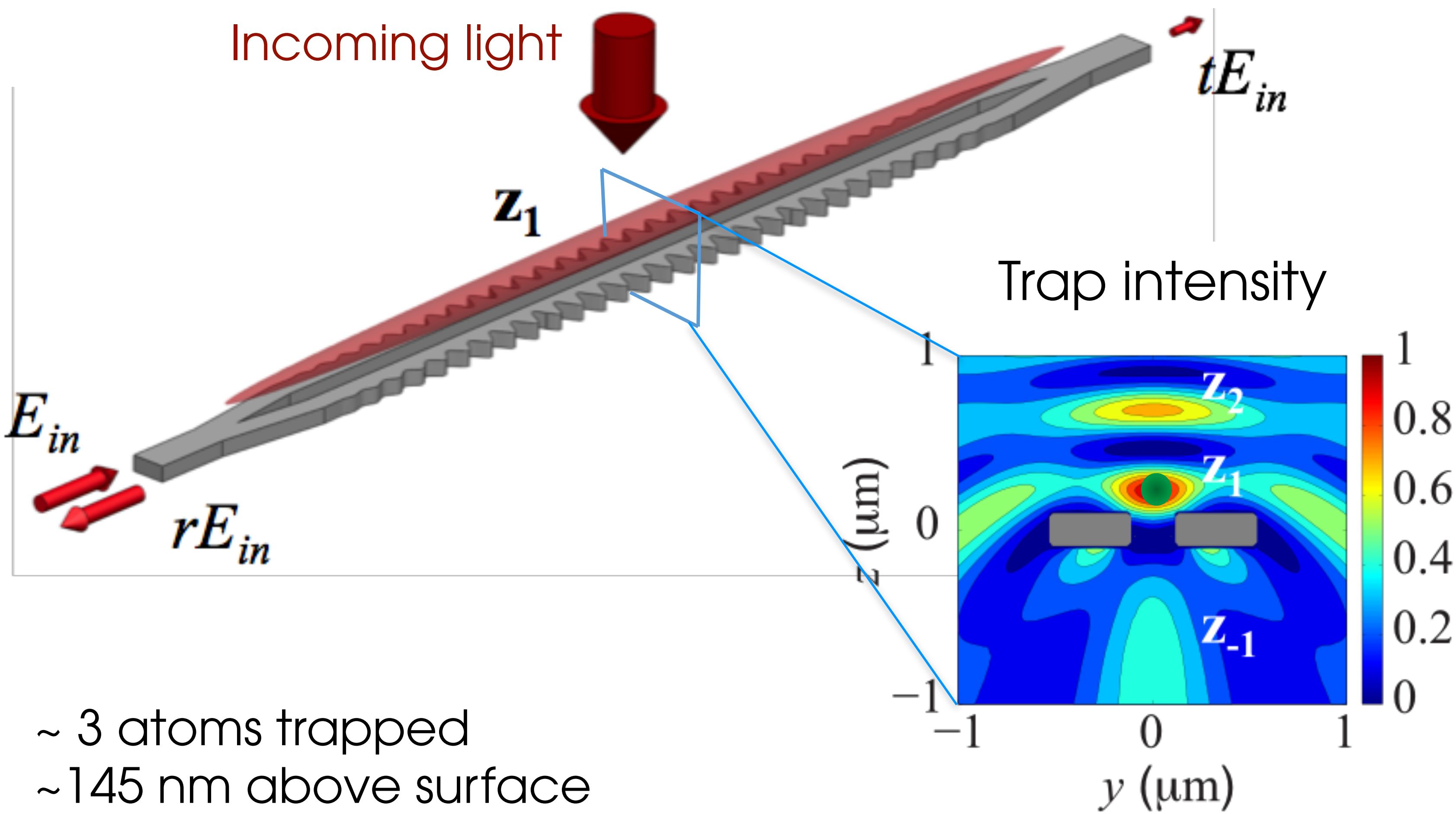


The graveyard



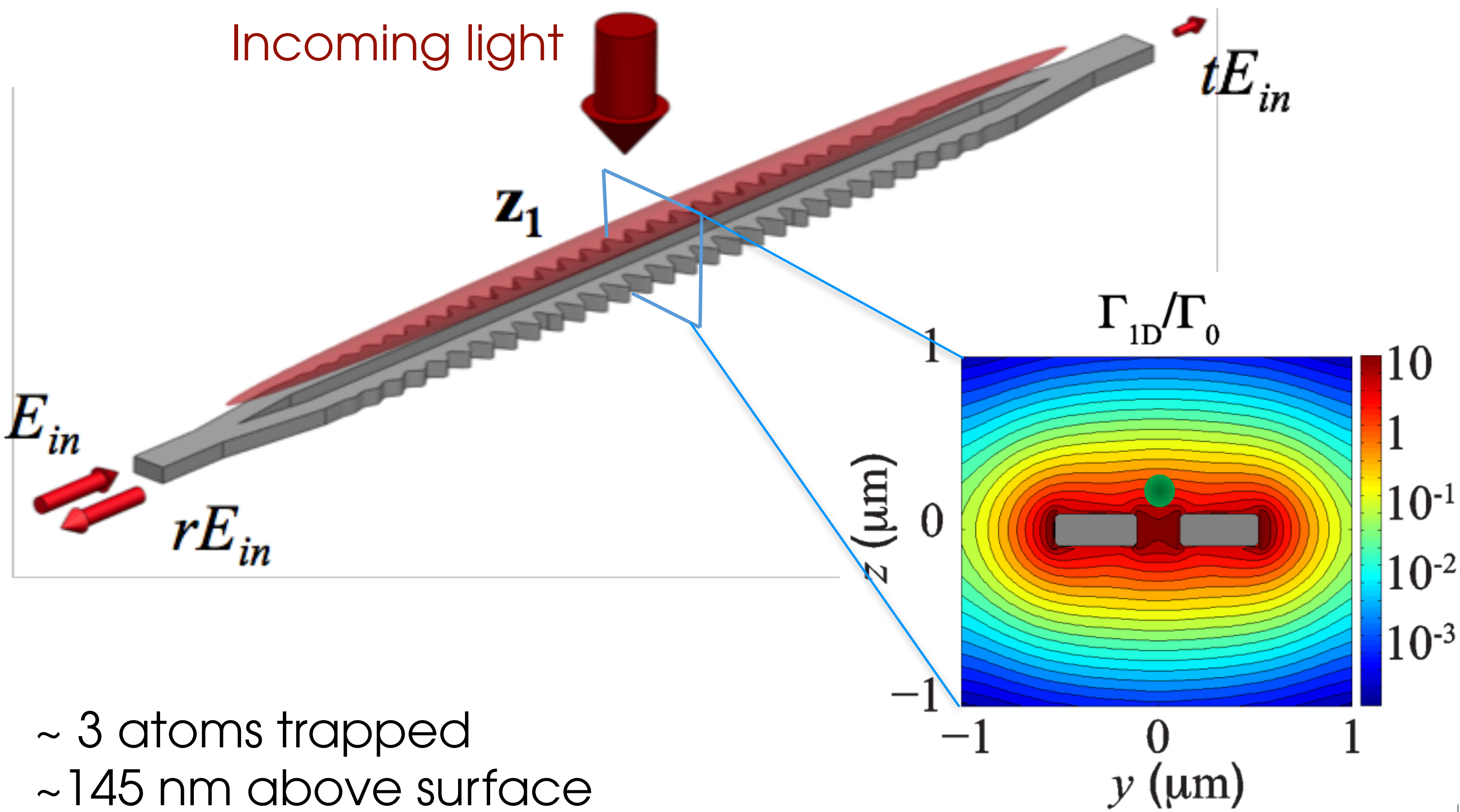
... and the gravediggers

The atoms are trapped above the alligator



~ 3 atoms trapped
~145 nm above surface

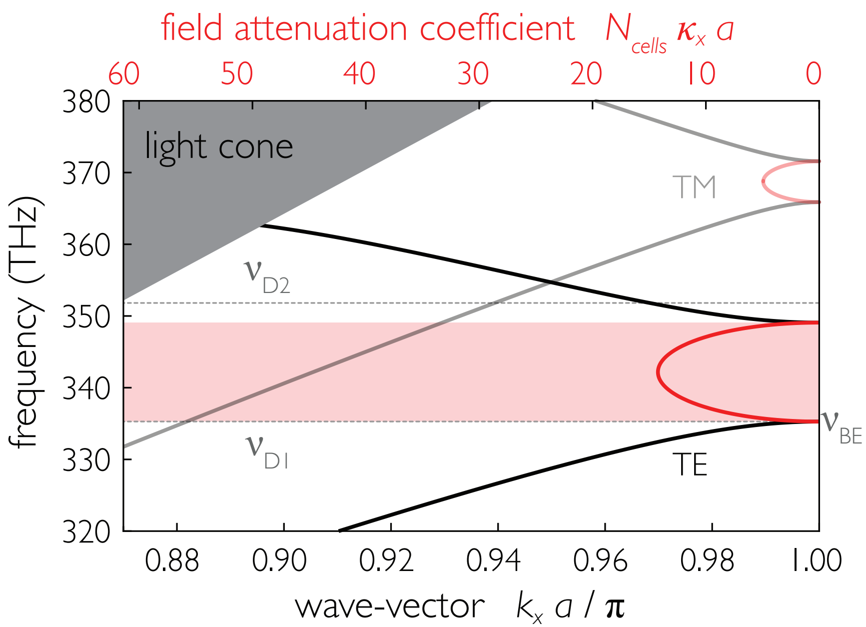
The atoms are trapped above the alligator

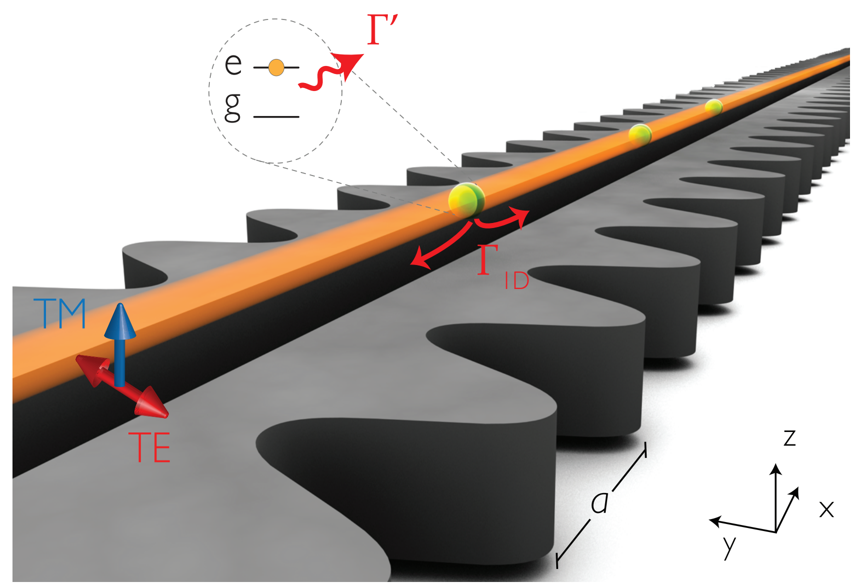


~ 3 atoms trapped
~145 nm above surface

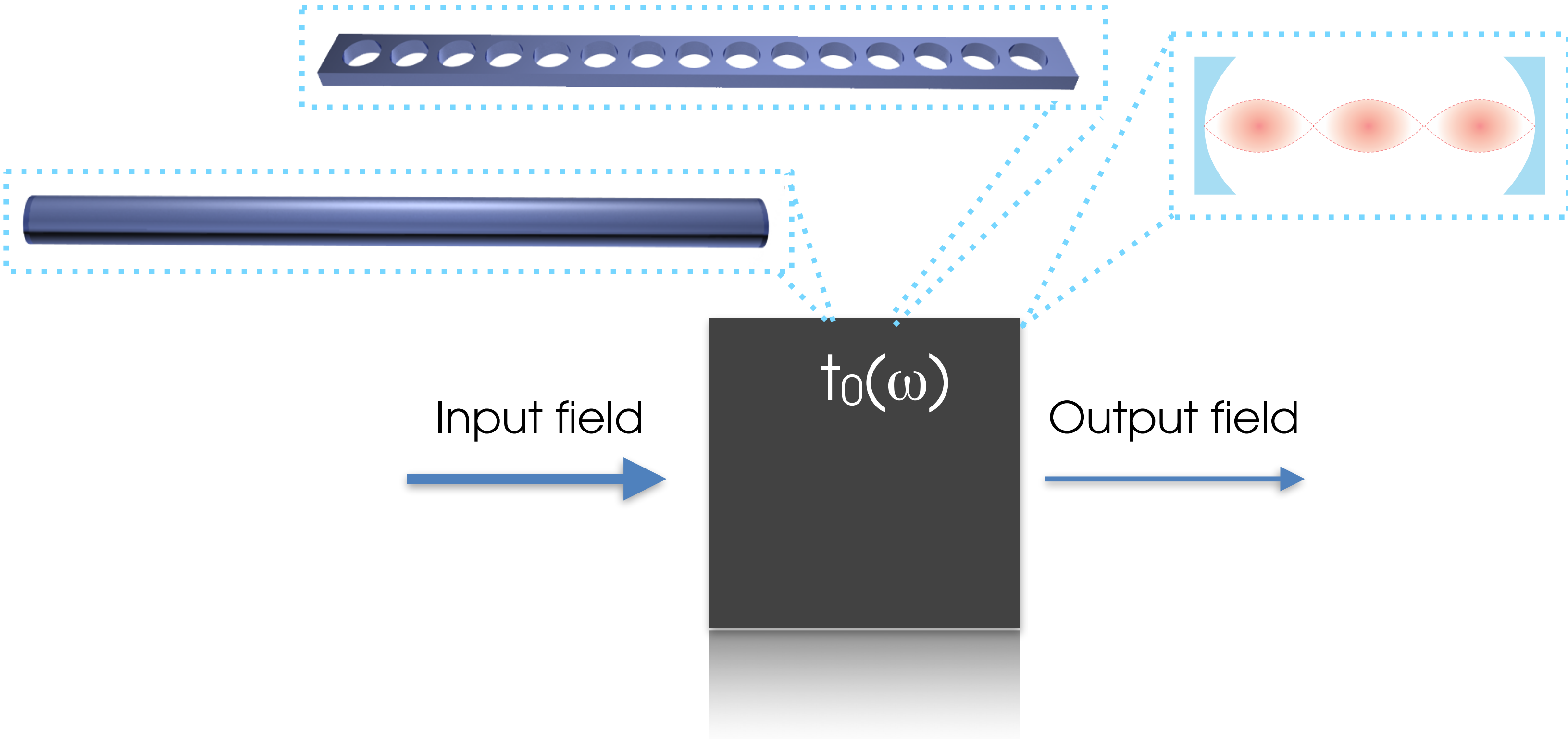
Alligator dispersion relation

Simulated dispersion relation

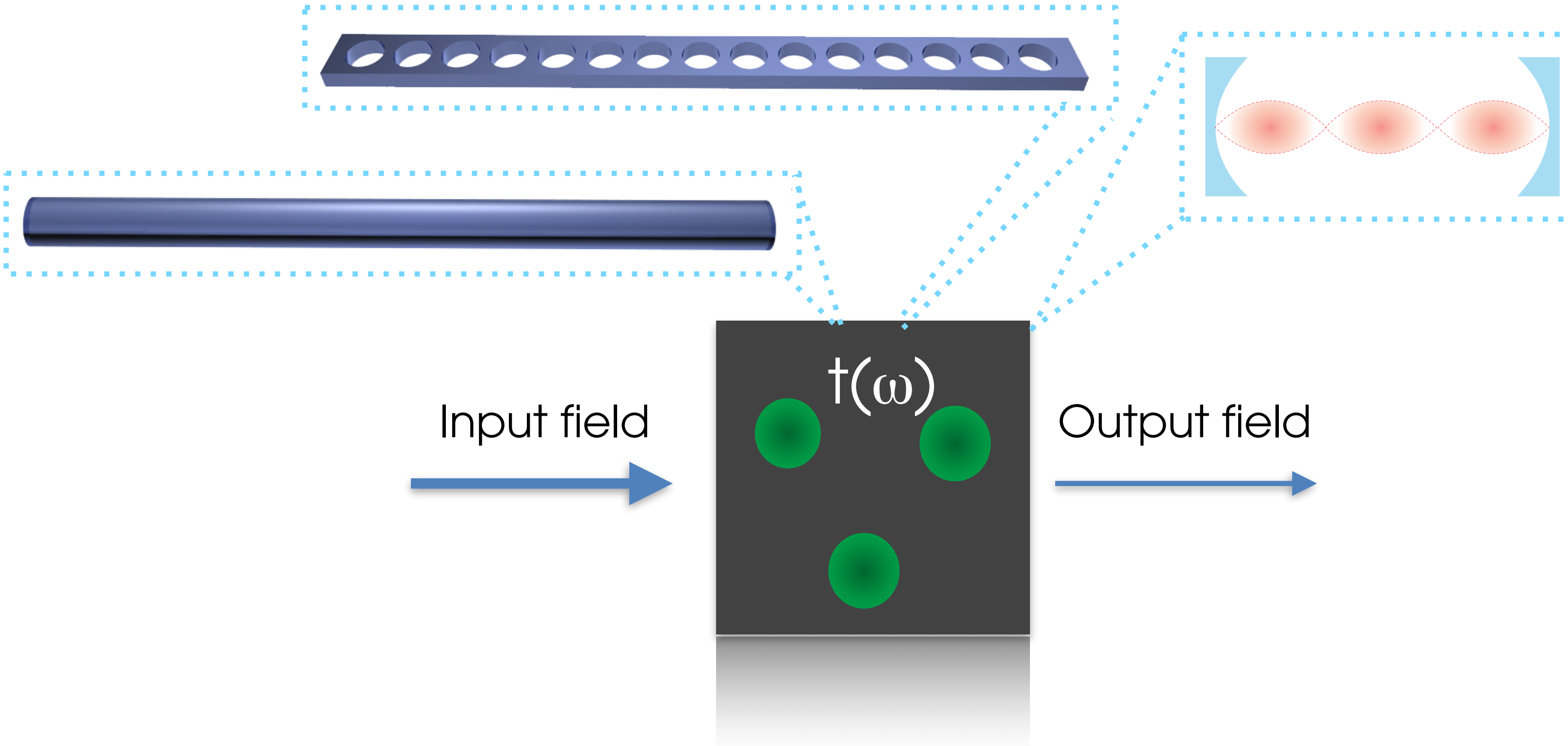




How does the coupling between atom and light relate to measurable observables?

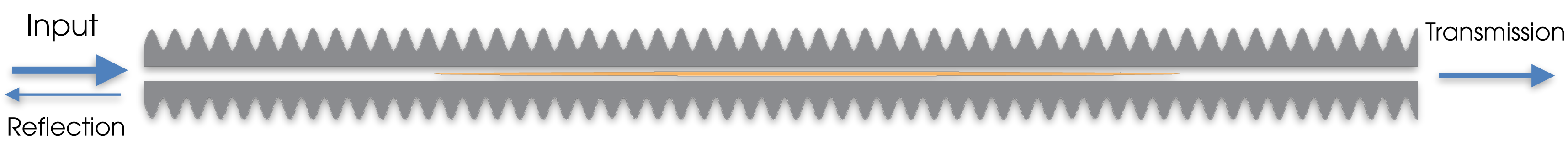


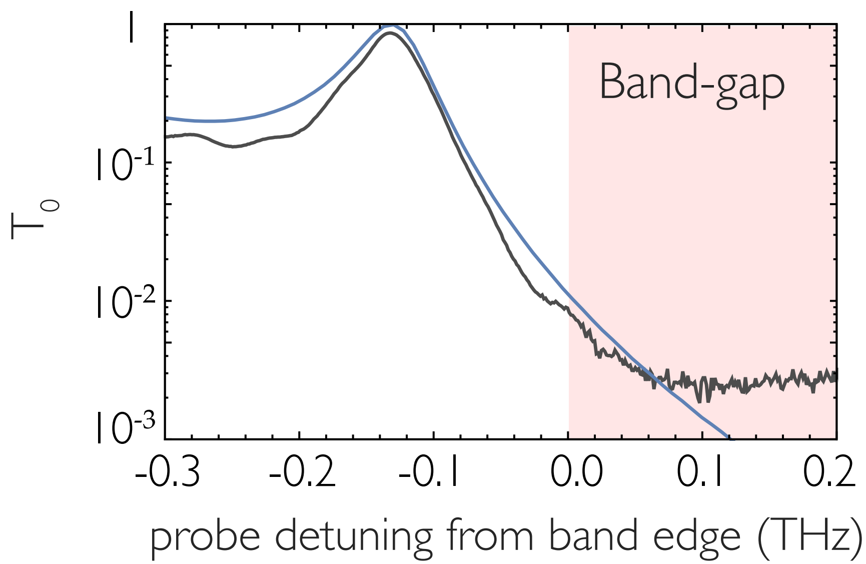
How does the coupling between atom and light relate to measurable observables?



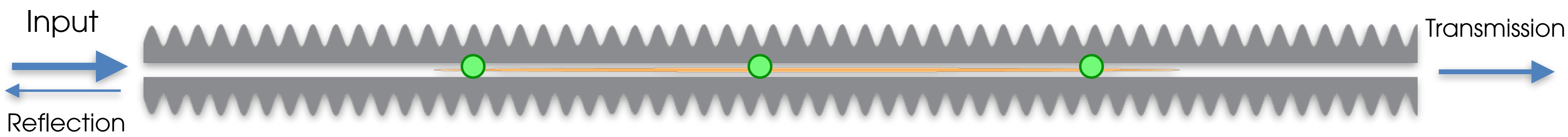
Transmission spectrum gives information about atom-light interactions.

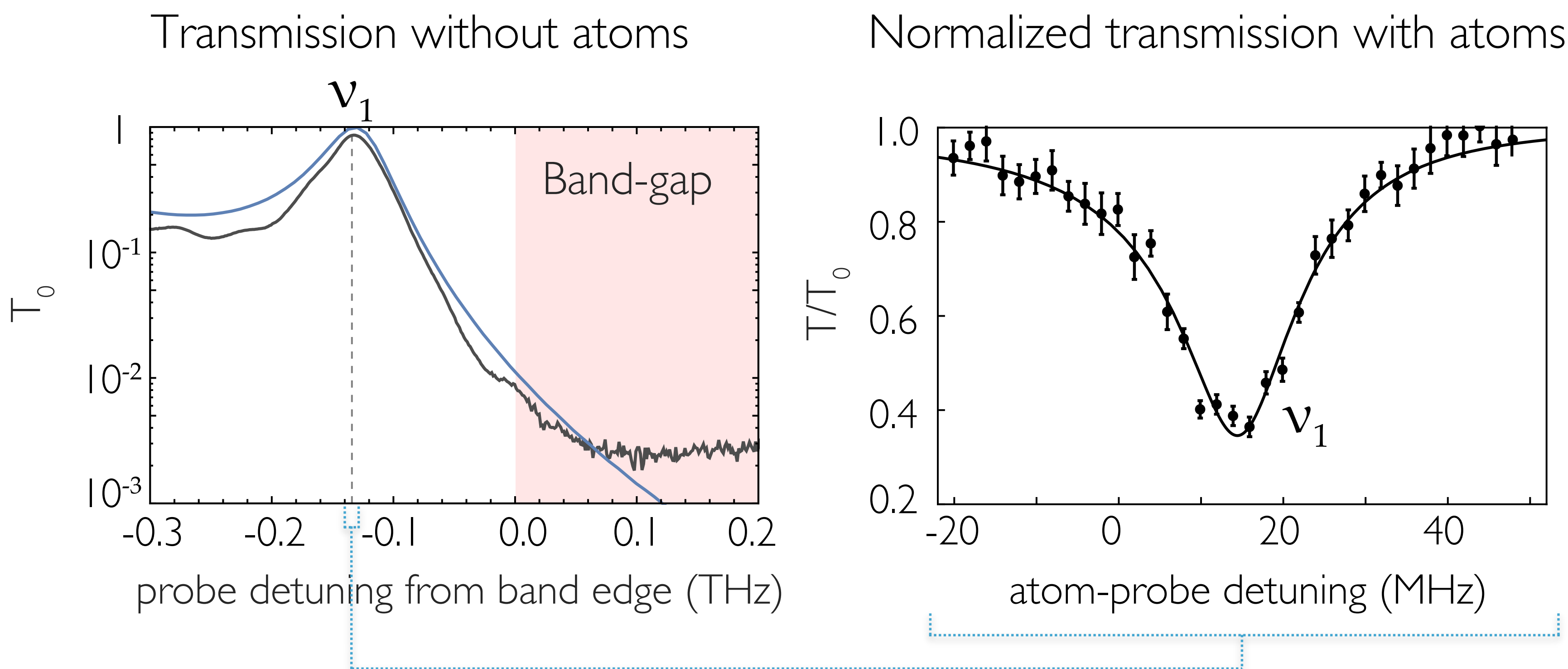
Transmission spectra without atoms





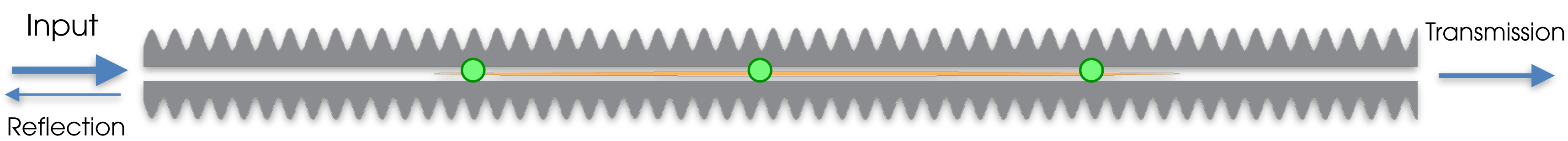
Transmission spectra with atoms





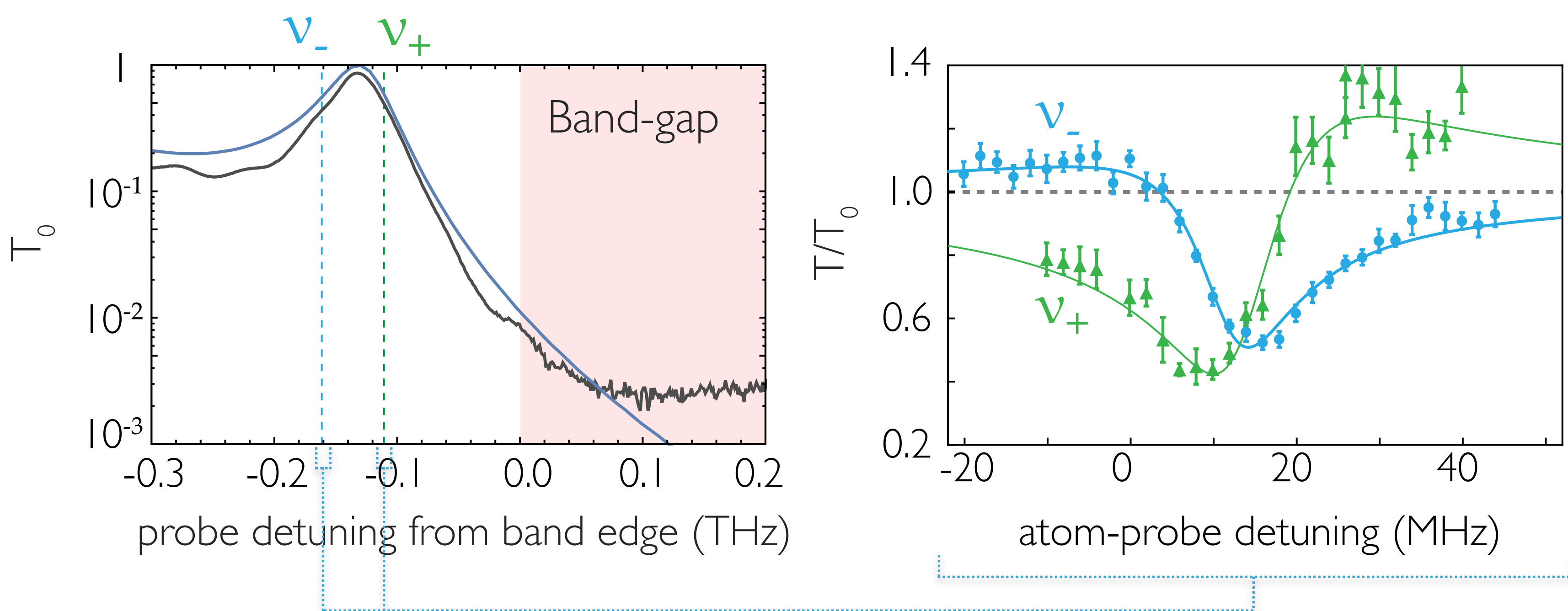
On resonance cavity, symmetric spectrum, dissipative interaction

Transmission spectra with atoms



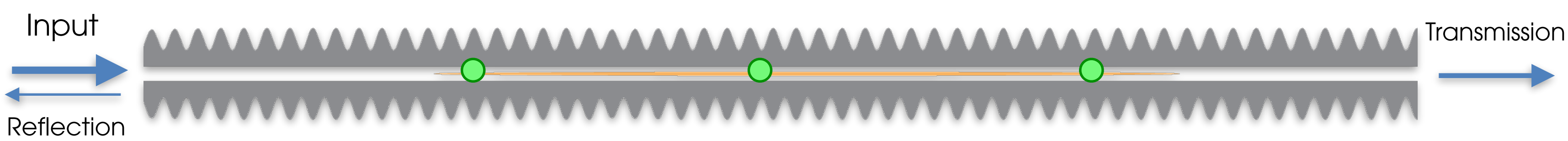
Transmission without atoms

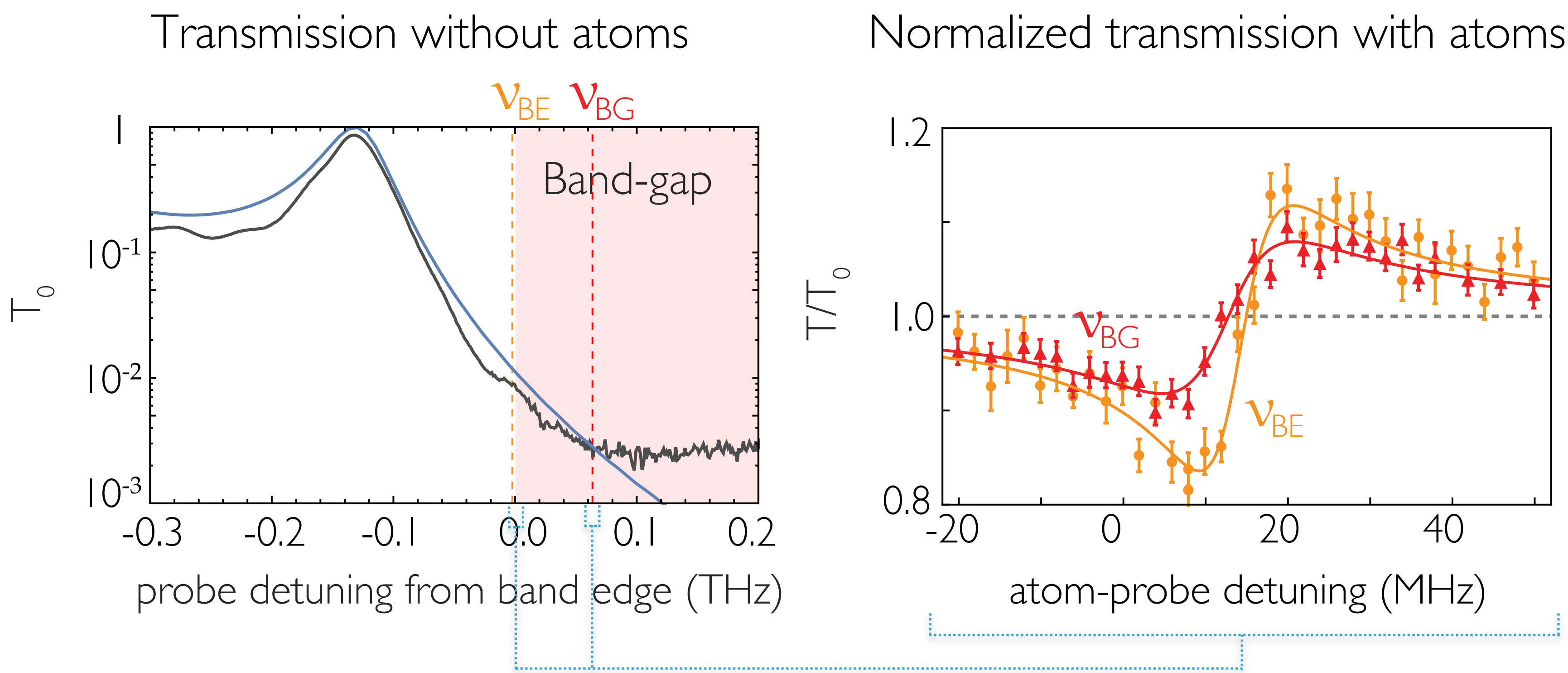
Normalized transmission with atoms



Out of resonance cavity, asymmetric spectrum, coherent interaction

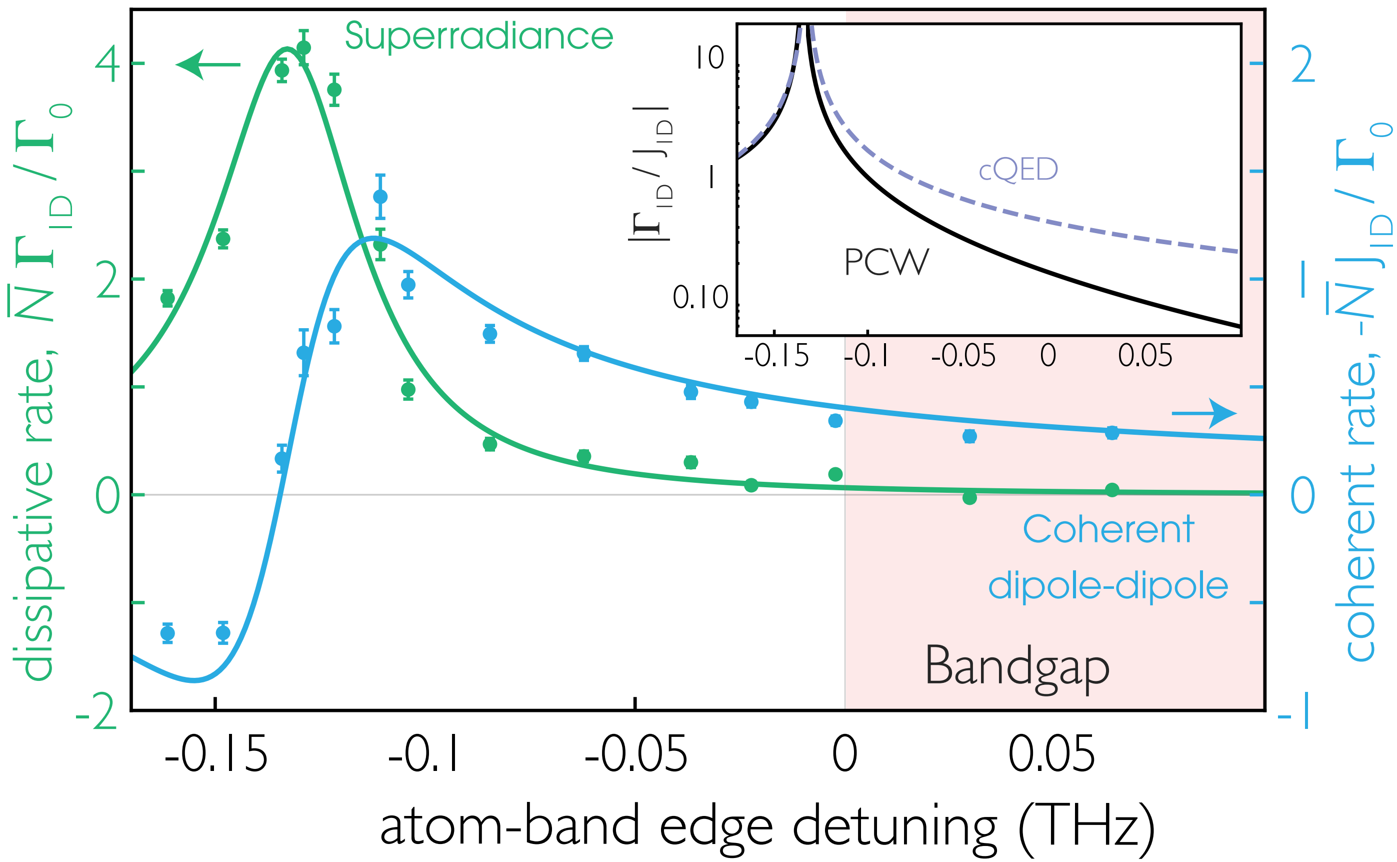
Transmission spectra with atoms



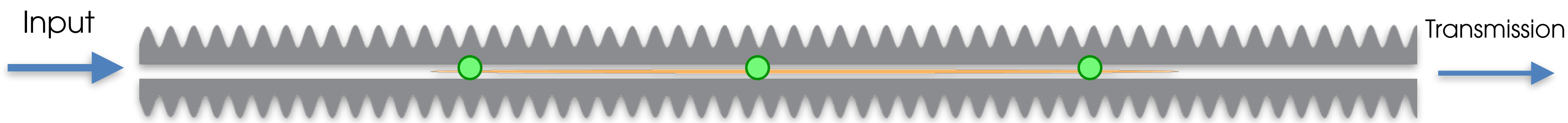


Into the bandgap, asymmetric spectrum, coherent interaction

We obtain the coherent and dissipative rates from the spectra measurements



Transmission coefficient



We obtain the transmission coefficient from plugging the solution of Heisenberg equations to the field equation

$$\mathcal{H}_{\text{eff}} = -\sum_{i=1}^{N} d\,\hat{\mathrm{E}}_{\mathrm{p}}(\mathbf{r}_i)\,\hat{\sigma}_{eg}^{i} - \sum_{i=1}^{N}\hbar\left(\Delta_{\mathrm{A}} + \mathrm{i}\frac{\Gamma'}{2}\right)\sigma_{ee}^{i} - \sum_{i,j=1}^{N}\hbar\left(J_{1\mathrm{D}}^{ij} + \mathrm{i}\frac{\Gamma_{1\mathrm{D}}^{ij}}{2}\right)\hat{\sigma}_{eg}^{i}\hat{\sigma}_{ge}^{j}$$

solve for σ_{eg}

$$\hat{\mathbf{E}}(\mathbf{r}_{\text{out}},t) = \hat{\mathbf{E}}_{\mathrm{p}}(\mathbf{r}_{\text{out}},t) + \mu_0\omega_{\mathrm{A}}^2 d\sum_{j=1}^{N}\mathrm{G}(\mathbf{r}_{\text{out}},\mathbf{r}_j,\omega_{\mathrm{A}})\,\hat{\sigma}_{ge}^{j}(t)$$

low saturation
single excitation manifold

$$\frac{t(\Delta_{\mathrm{A}})}{t_0(\Delta_{\mathrm{A}})} = \prod_{\xi=1}^{N}\frac{\Delta_{\mathrm{A}} + \mathrm{i}\Gamma'/2}{(\Delta_{\mathrm{A}} + J_{\xi,1\mathrm{D}}) + \mathrm{i}(\Gamma' + \Gamma_{\xi,1\mathrm{D}})/2}$$

transmission without atoms

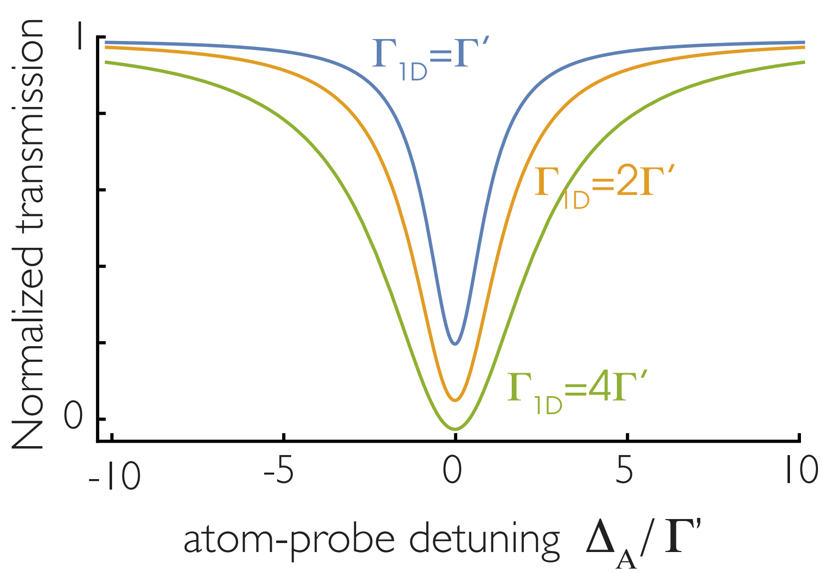
coherent rate ~Re G_{1D}

dissipative rate ~Im G_{1D}

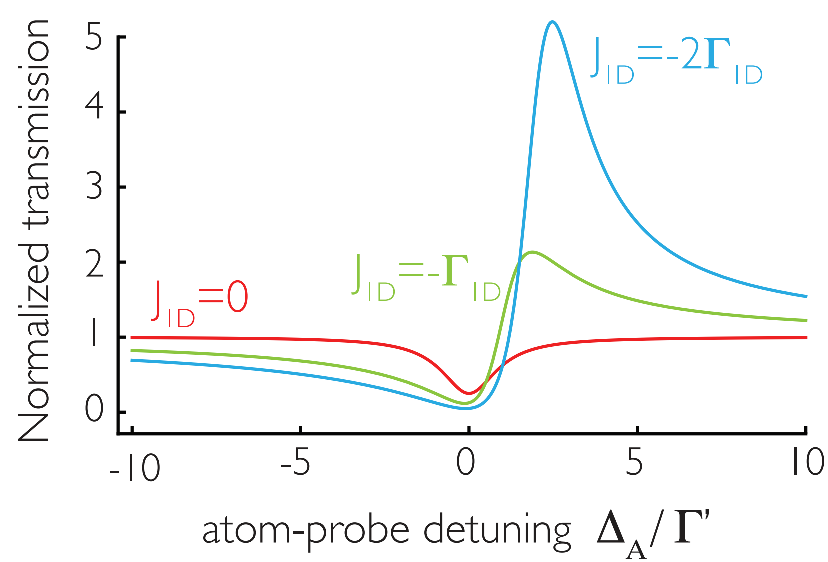
Dispersive/coherent atom-light interactions give rise to a Fano-like transmission spectrum

For a single atom: $$\frac{t(\Delta_A)}{t_0(\Delta_A)} = \frac{\Delta_A + i\Gamma'/2}{(\Delta_A + J_{1D}) + i(\Gamma' + \Gamma_{1D})/2}$$

Dissipative atom-light interaction (J_{1D}=0)

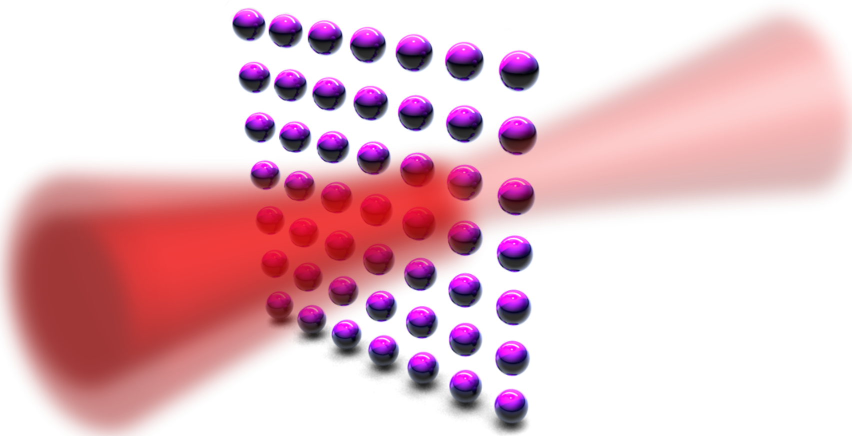


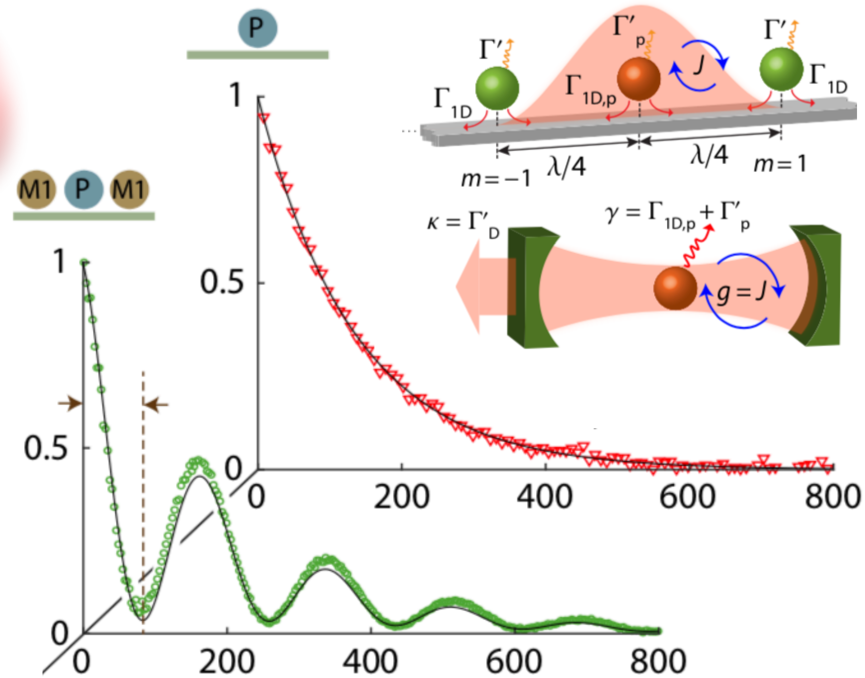
Dispersive atom-light interaction

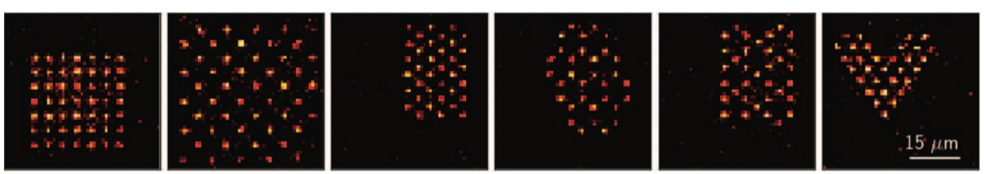


Degree of asymmetry ~J_{1D}/Γ_{1D}

The future:
atoms as quantum photonic structures







Summary

Physics of correlated quantum dipoles with dissipation and long range interactions

Not much is known, new playground for multidisciplinary physics

Correlated dissipation

Quantum info protocols

Fundamental limits and error bounds

Entanglement protocols with ensembles, quantum gates

Metrology

Increasing complexity

Open quantum many body system

Multilevel atoms , disorder

Self organization

Quantum dielectrics

nanophotonic analogues with atoms

role of topology and dimension

intrinsic quantum non-linearity

Experimental platforms

Atoms, SC qubits, solid-state emitters

Tweezers, quantum microscopes

Interface with nanophotonics