Collective effects when photons interact with many atoms

F. Robicheaux
Purdue University

Current & Former Grad Students: Deepak Suresh , Wenqi Tong, Shihua Huang , R.T. Sutherland

Atom separation ~ 100s of nanometers

Superradiance, Subradiance

Collective control of photons: “antenna”

Recoil of atoms due to photon momentum

Support from NSF 2109987-PHY

Online talks

Virtual AMO Seminar

Ana Asenjo-Garcia “Single, few, and many photon physics in 1D atomic arrays”
https://youtu.be/_nRtoXVnoSw

Susanne Yelin “Dense arrays: a novel quantum tool”
https://youtu.be/yQws2uOchhs

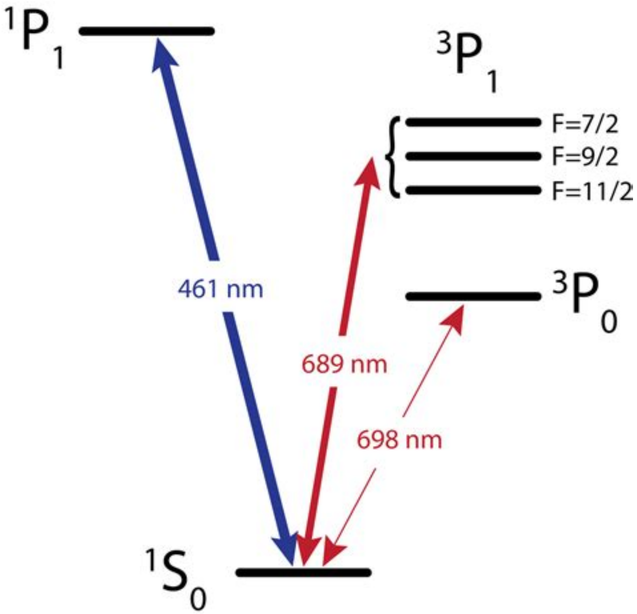
Why Optical Transitions?

Convenient wavelengths

“Easily” control which states excite

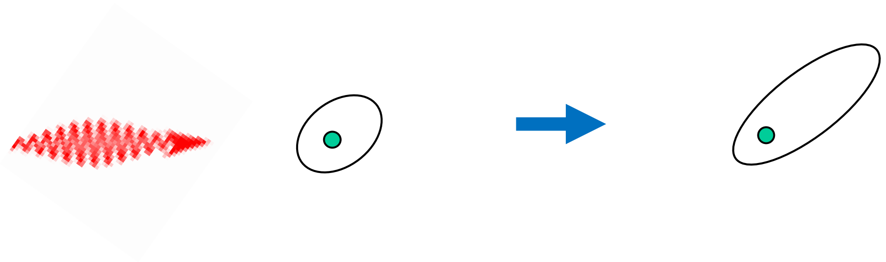
Can manipulate the internal atom states

Can manipulate the C.O.M. motion of the atom



Some transitions in ^{87}Sr

M.A. Norcia, et al



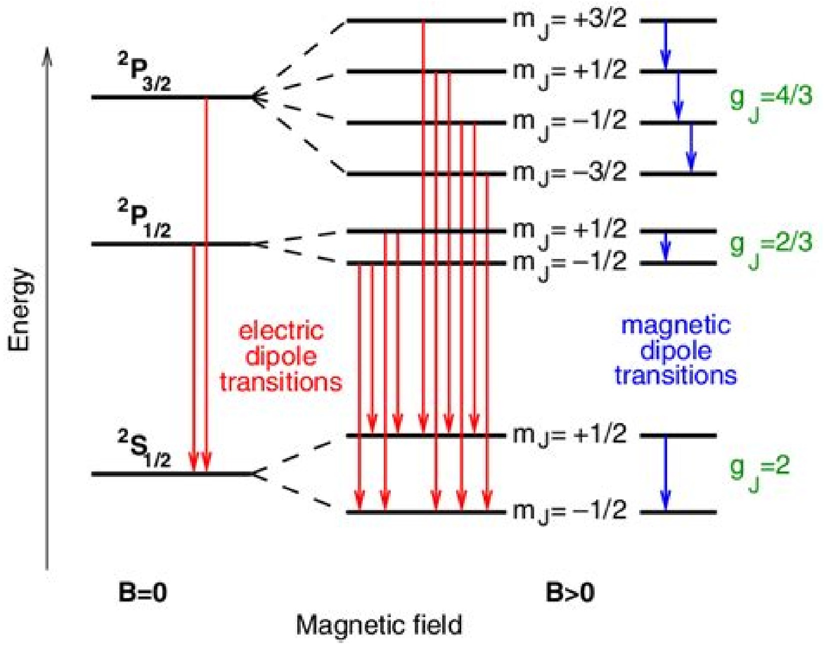
Downsides?

Photon spontaneous emission

Information leaves

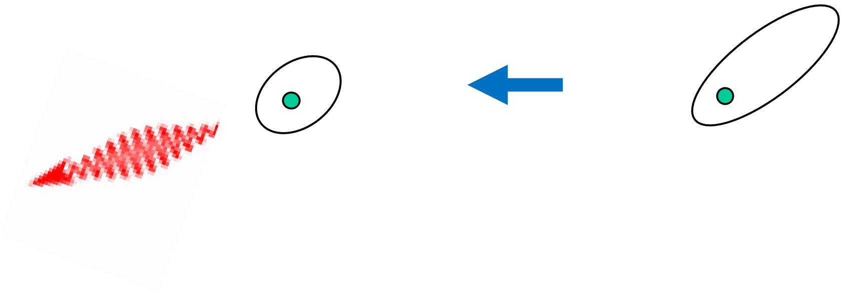
Decoherence kills some of the special quantum properties

Not super-promising for QI applications



Some transitions in H-like atom

Vit Kudrle, et al



Some Many Atom Effects

Clausius-Mossotti (Lorentz-Lorenz) corrections to χ of gas

Superradiance: many atoms emit photons with rate >> N X single atom

Subradiance: many atoms inhibit photon emission

Atom array can give 100% reflection or change propagation direction

Control emission direction using phase relation between atoms

Many others

Classical interference: 2 sources

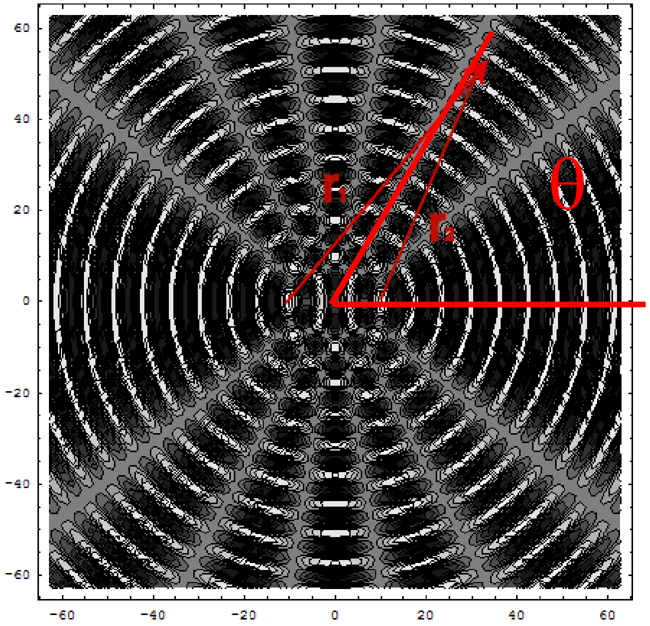
Two sources interfere depending on the phase of each source

Intensity at large distance compared to 1 source is

$4 \cos^2([\pi L \cos(\theta)/\lambda + \phi]/2)$

See web page

See iterf.plt



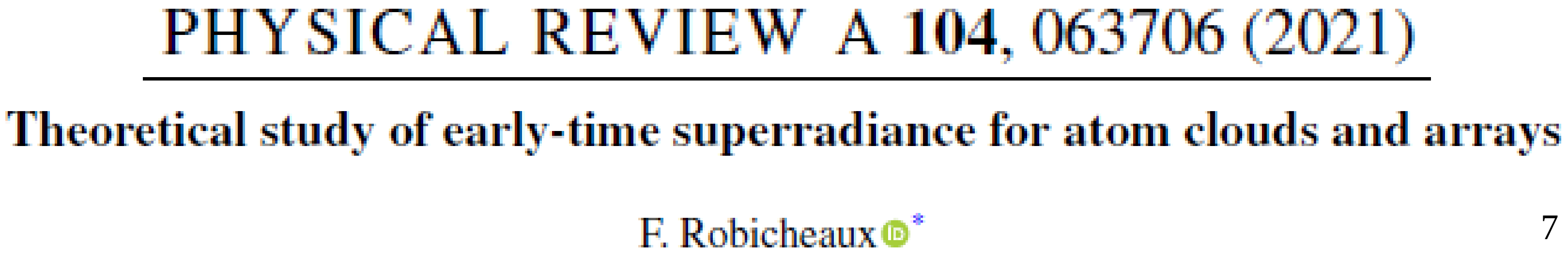
Early time Superradiance for Atom Arrays

Use early time properties of decay to determine superradiance

Inspired by Stuart J. Masson and Ana Asenjo-Garcia, “Universality of Dicke superradiance in arrays of quantum emitters,” Nat Comm 13, 1 (2022). arXiv:2106.02042 (2021).

Apply to various arrays and random atom cloud

Similar results to E. Sierra, S.J. Masson, and A. Asenjo-Garcia, “Dicke superradiance in ordered lattices: dimensionality matters,” Phys. Rev. Res. 4 023207 (2022). arXiv:2110.08380 (2021)

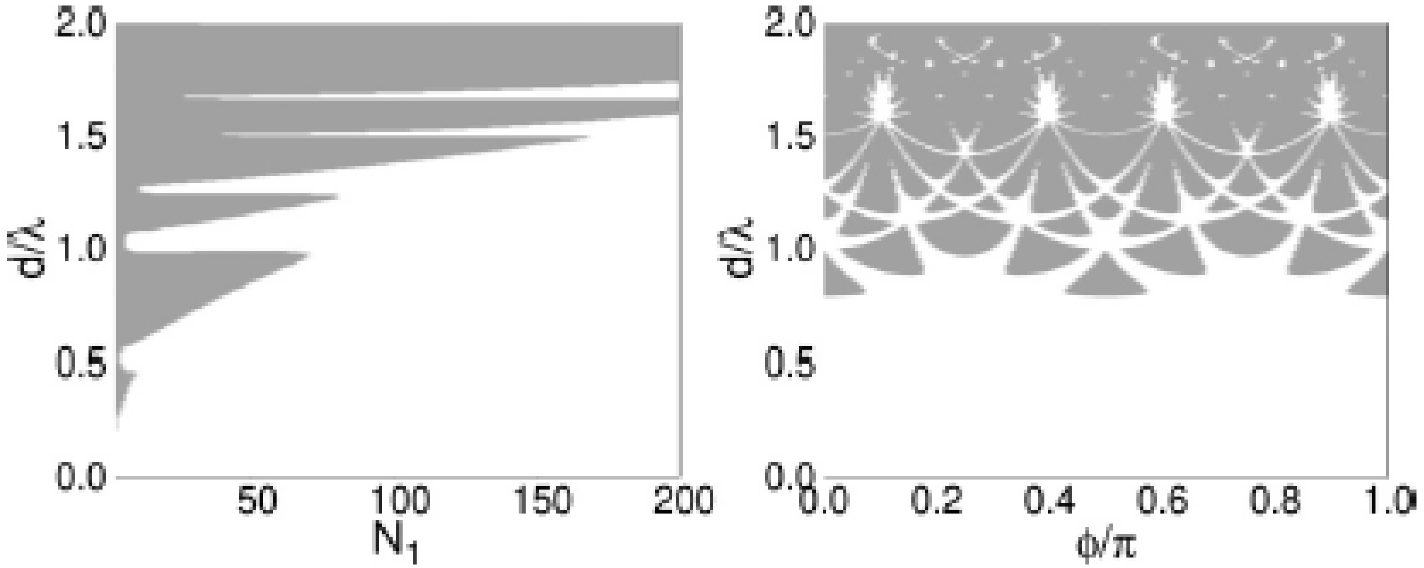


PHYSICAL REVIEW A **104**, 063706 (2021)

Theoretical study of early-time superradiance for atom clouds and arrays

F. Robicheaux*

Square array, Directional decay



$\phi = 0.0\,\pi$ $N_1 = 40$

d = spacing of atoms

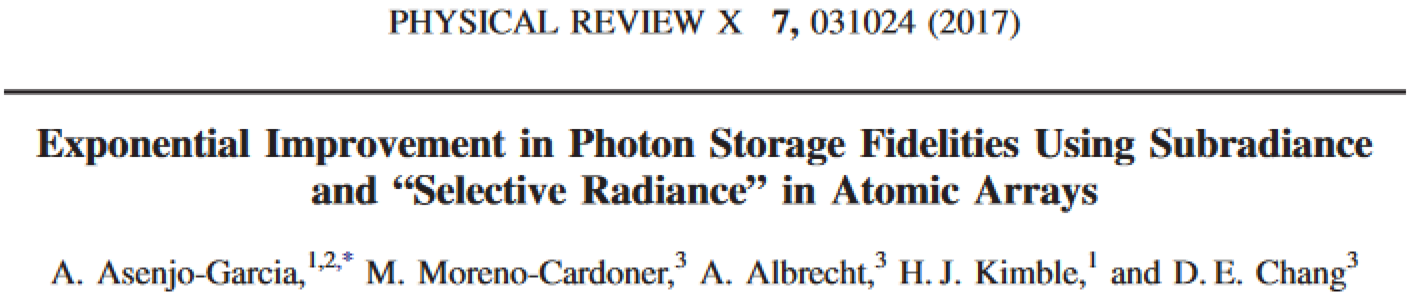
Left plot for emission into 0.0 π, Right plot for fixed number

Many regions of superradiance due to constructive interference

For some angles superradiant for d ~ 2 λ

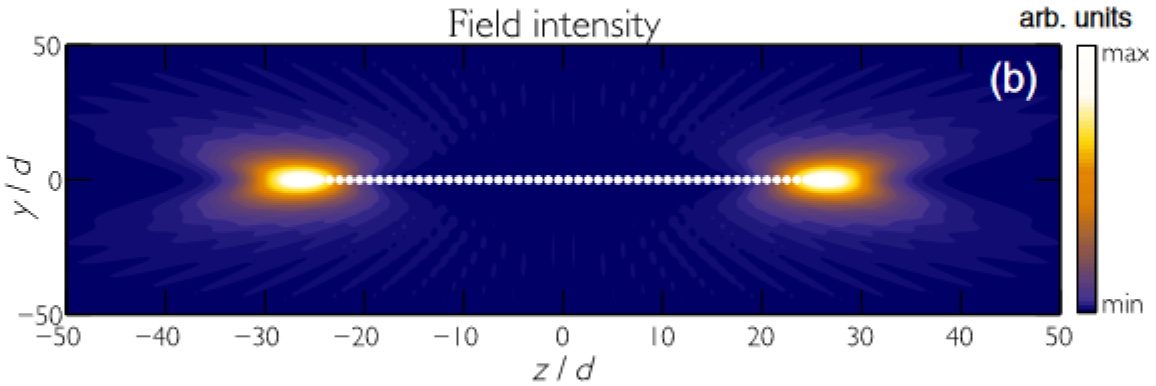
Apparently doesn’t converge with increasing number of atoms

Dipole moment perp to plane, direction in plane

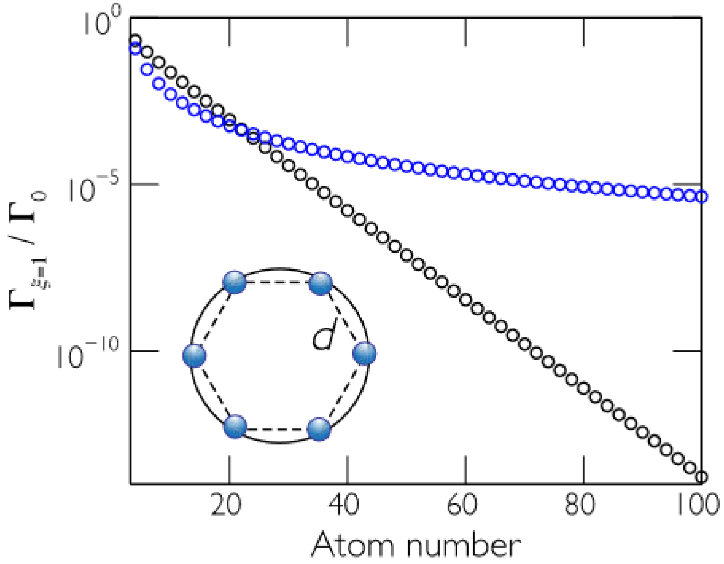

PHYSICAL REVIEW X **7,** 031024 (2017)

Exponential Improvement in Photon Storage Fidelities Using Subradiance and "Selective Radiance" in Atomic Arrays

A. Asenjo-Garcia,[1,2,*] M. Moreno-Cardoner,[3] A. Albrecht,[3] H. J. Kimble,[1] and D. E. Chang[3]



Line of atoms with subwavelength spacing only emits from the end



Atoms in a circle have increasingly long lifetime with more atoms if separation less than λ

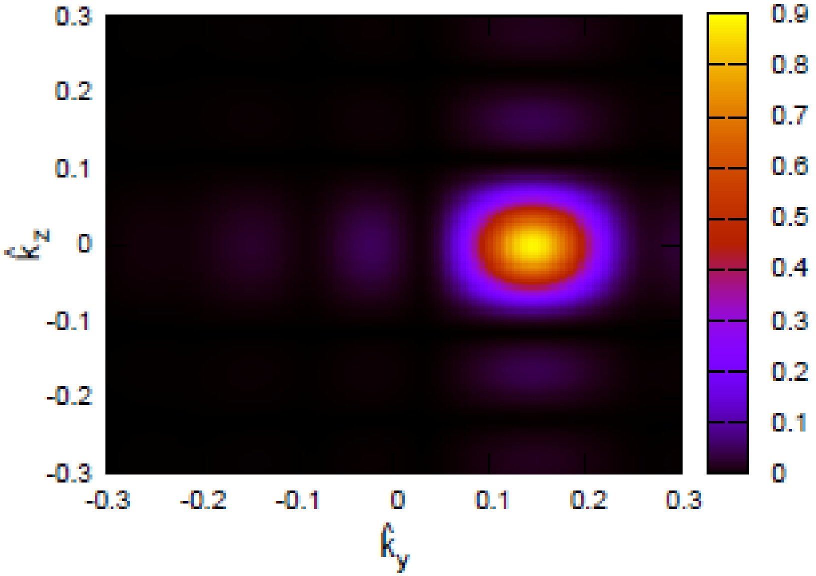
Control the propagation of light

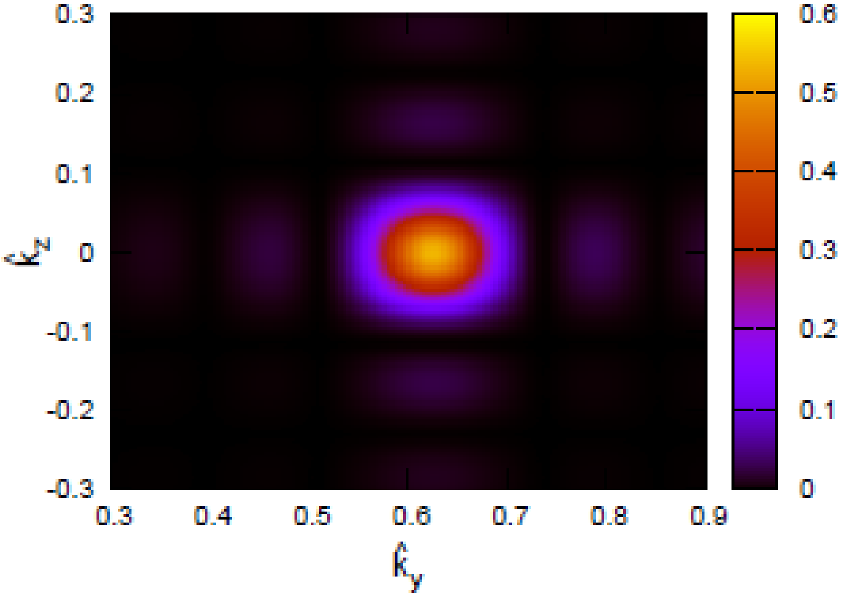
Can you use atoms to control where the light goes?

Seems impossible because the spontaneous gives random direction and phase

Many atoms with regular spacing suppress spontaneous emission

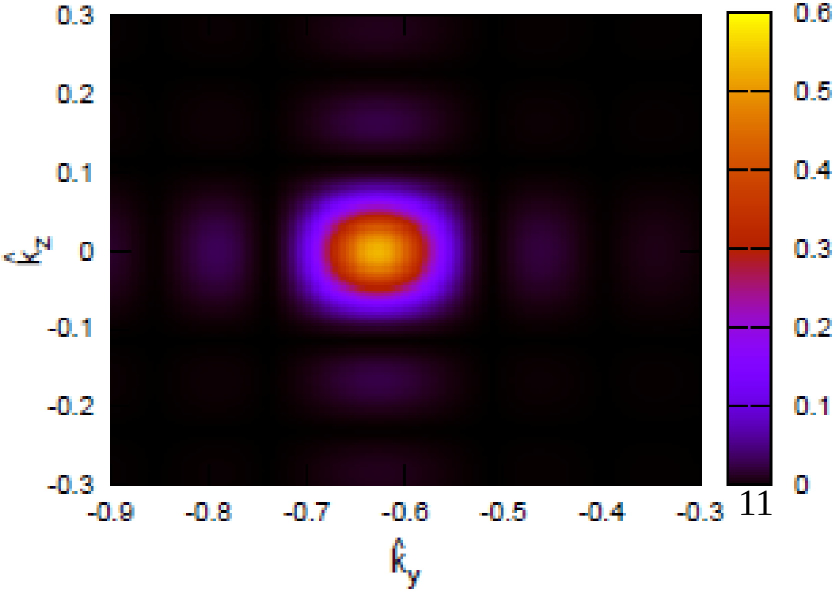
Phased Planar Arrays: a = 0.8 λ





Left is $\phi_b = 0.15\, k\, y_b$

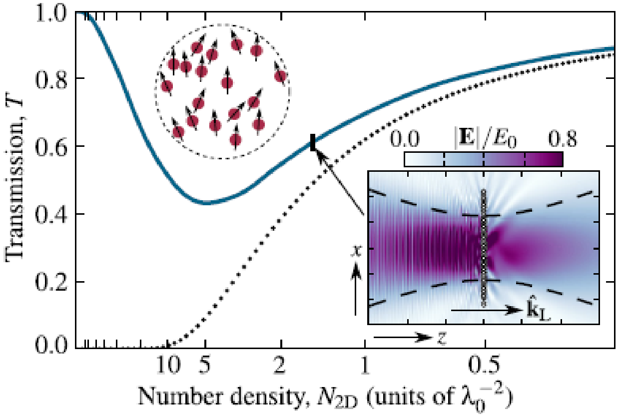
Right is $\phi_b = 0.625\, k\, y_b$
Chosen to give mirrored photons

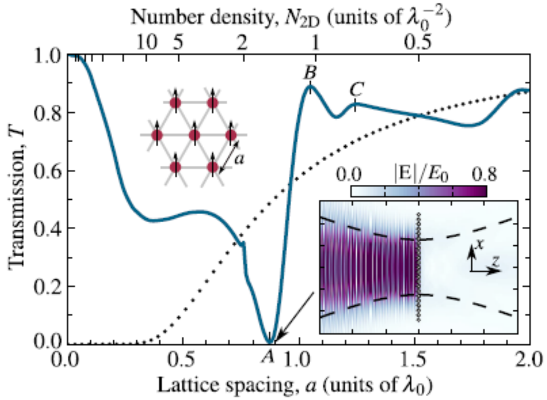


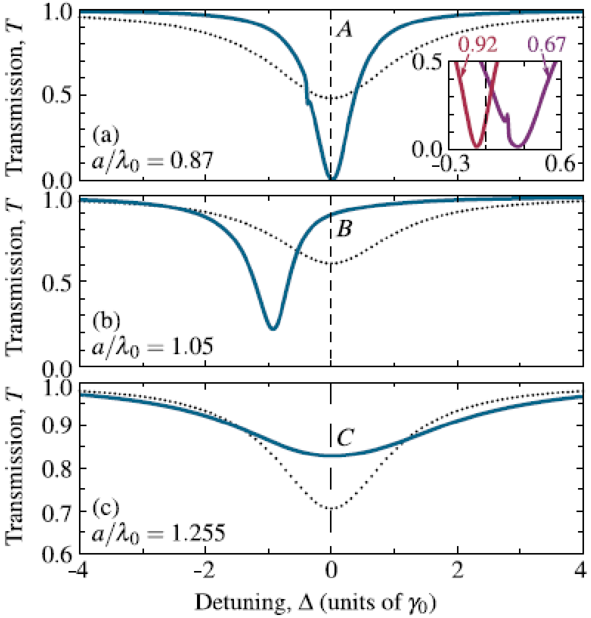
PRL 116, 103602 (2016) PHYSICAL REVIEW LETTERS week ending 11 MARCH 2016

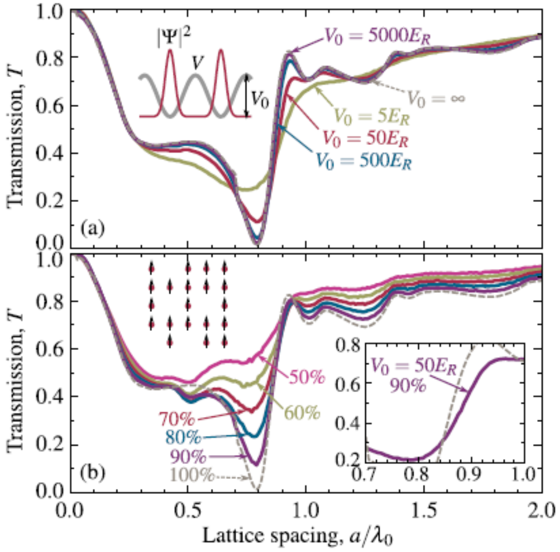
Enhanced Optical Cross Section via Collective Coupling of Atomic Dipoles in a 2D Array

Robert J. Bettles,* Simon A. Gardiner,† and Charles S. Adams‡







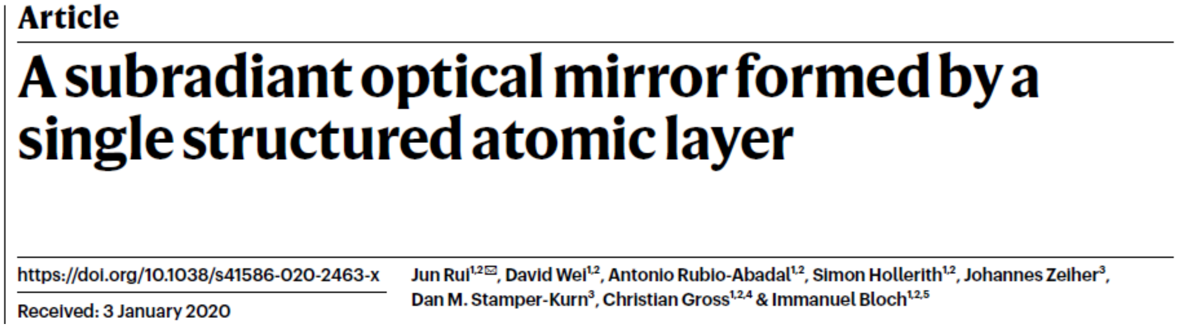


Proposal for total reflection from atom array

Weak light limit is equivalent to CM

Finite size calculations

Effects from positional disorder and fractional filling



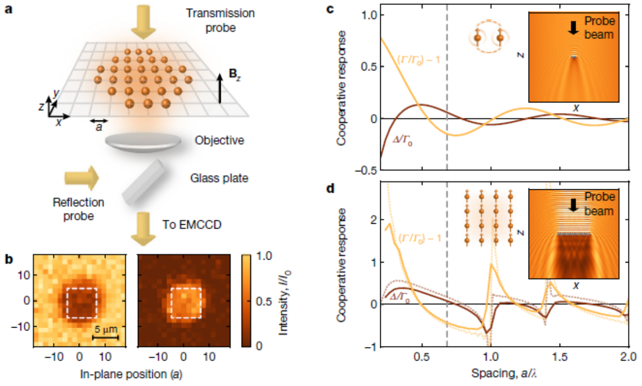
Article

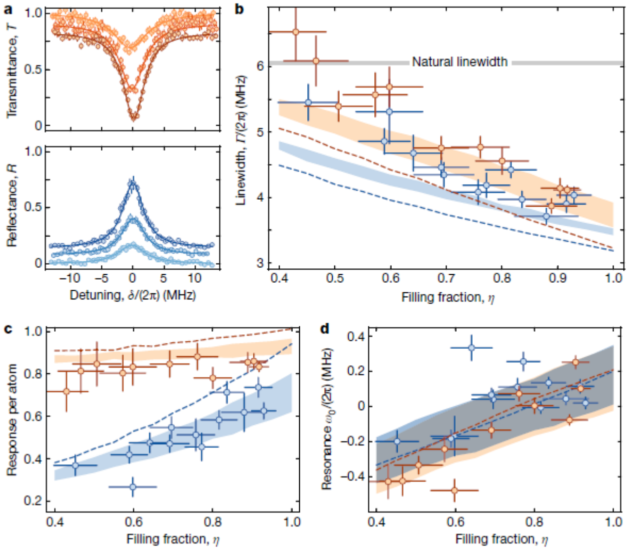
A subradiant optical mirror formed by a single structured atomic layer

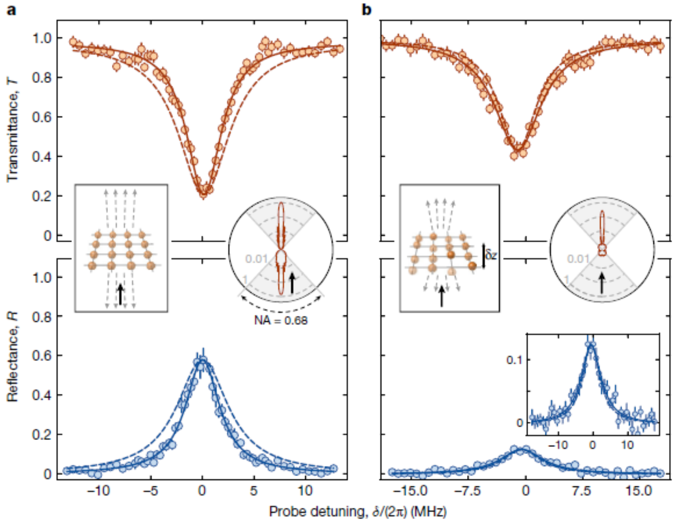
https://doi.org/10.1038/s41586-020-2463-x

Received: 3 January 2020

Jun Rui[1,2 ✉], David Wei[1,2], Antonio Rubio-Abadal[1,2], Simon Hollerith[1,2], Johannes Zeiher[3], Dan M. Stamper-Kurn[3], Christian Gross[1,2,4] & Immanuel Bloch[1,2,5]







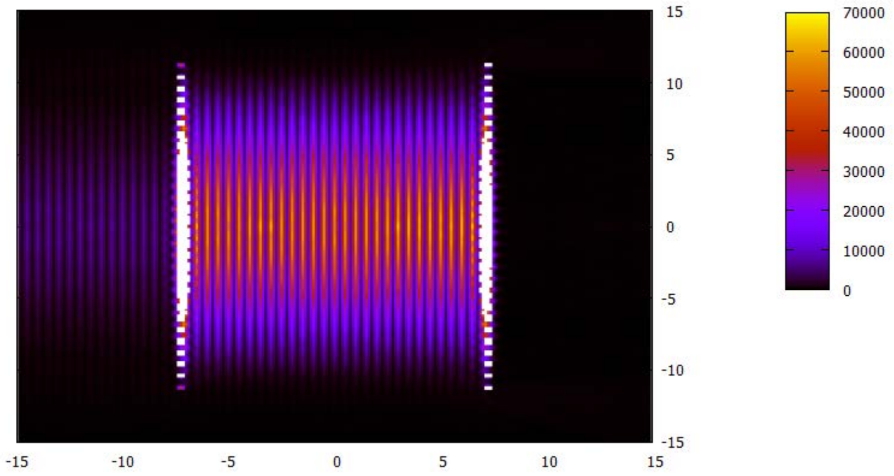
Experimental verification

Subradiant mode

Show better results as fractional filling -> 1

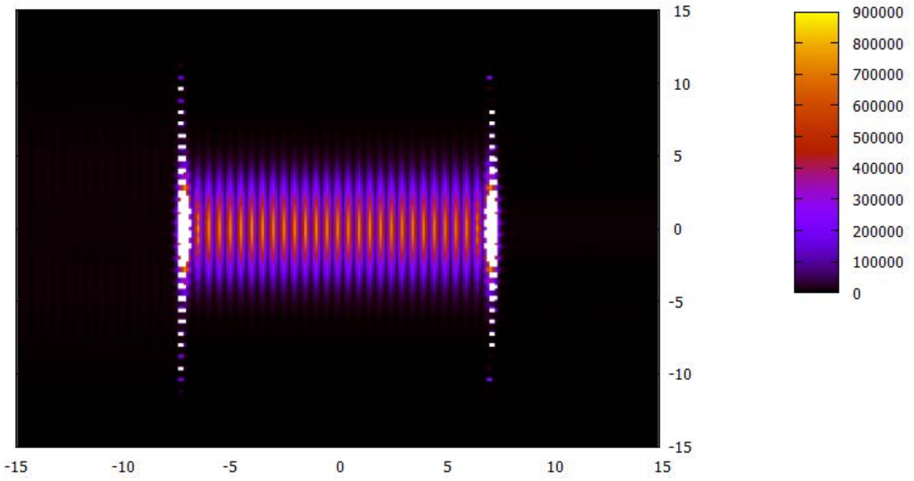
Positional disorder and not quite 100% filling

Pair of Planar Arrays: a = 0.8 λ



Both mirrors are flat

Laser in from left

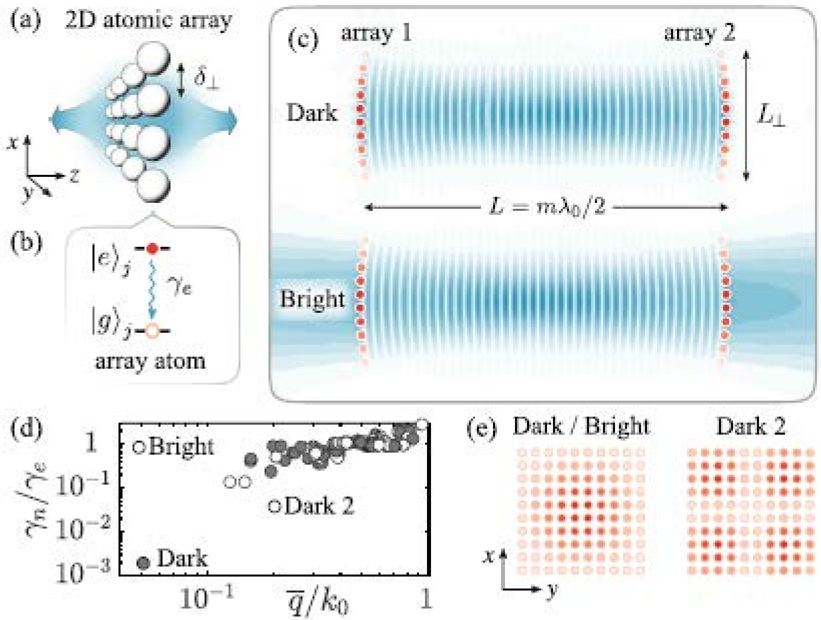


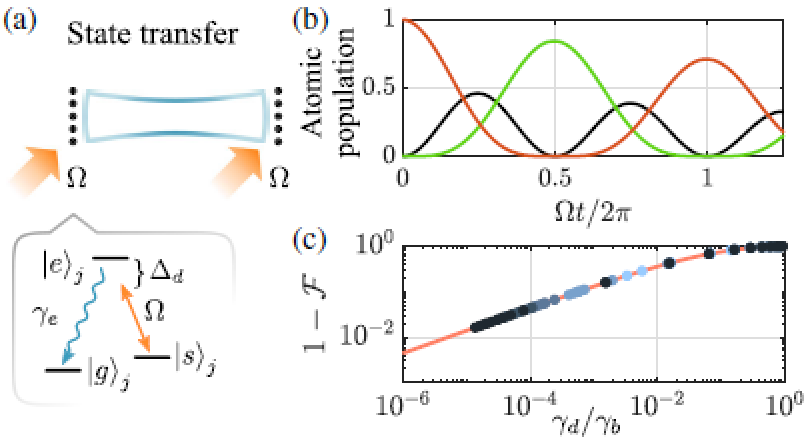
Two slightly parabolic mirrors
Laser in from left
Much higher buildup in cavity

PHYSICAL REVIEW LETTERS **122,** 093601 (2019)

Subradiant Bell States in Distant Atomic Arrays

P.-O. Guimond, A. Grankin, D. V. Vasilyev, B. Vermersch, and P. Zoller





Use curved array to make cavity

Use cavity effect to transfer bit over large distance

Outro

Interaction of photons with many atoms leads to qualitative new effects

Super-radiance and subradiance are collective effects of many atoms + photon

Possible uses for subradiant states

Possible uses to coherently control the photon propagation

Concluding Remarks

Subradiant states can have large recoil energy per photon

Superradiant states can have less than expected recoil

Amount of recoil could affect utility of atom arrays (most subradiant states are most interesting => largest recoil)

Size of an atom’s recoil roughly follows excitation probability (as expected)

What happens when not in the weak laser limit?

Concluding Remarks

Early time behavior of photon emission rate can determine whether “superradiant” but not the peak rate

Atom arrays give less dephasing: implications for Rydberg arrays?

For 2 states, the initial photon emission slope increases with number of atoms (doesn’t converge) for 2D & 3D