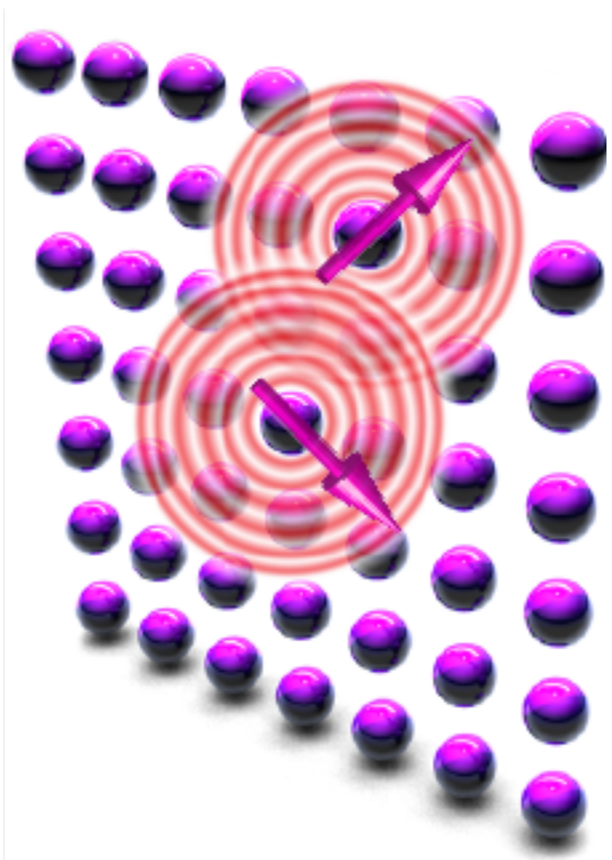
ICFO Institut de Ciències Fotòniques

UAB Universitat Autònoma de Barcelona

Exploiting Subradiance and Selective Radiance in Dense Atomic Arrays



M. Moreno-Cardoner

UAB, ICFO (Barcelona, Spain)

D. E. Chang

ICFO (Barcelona, Spain)

cost EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

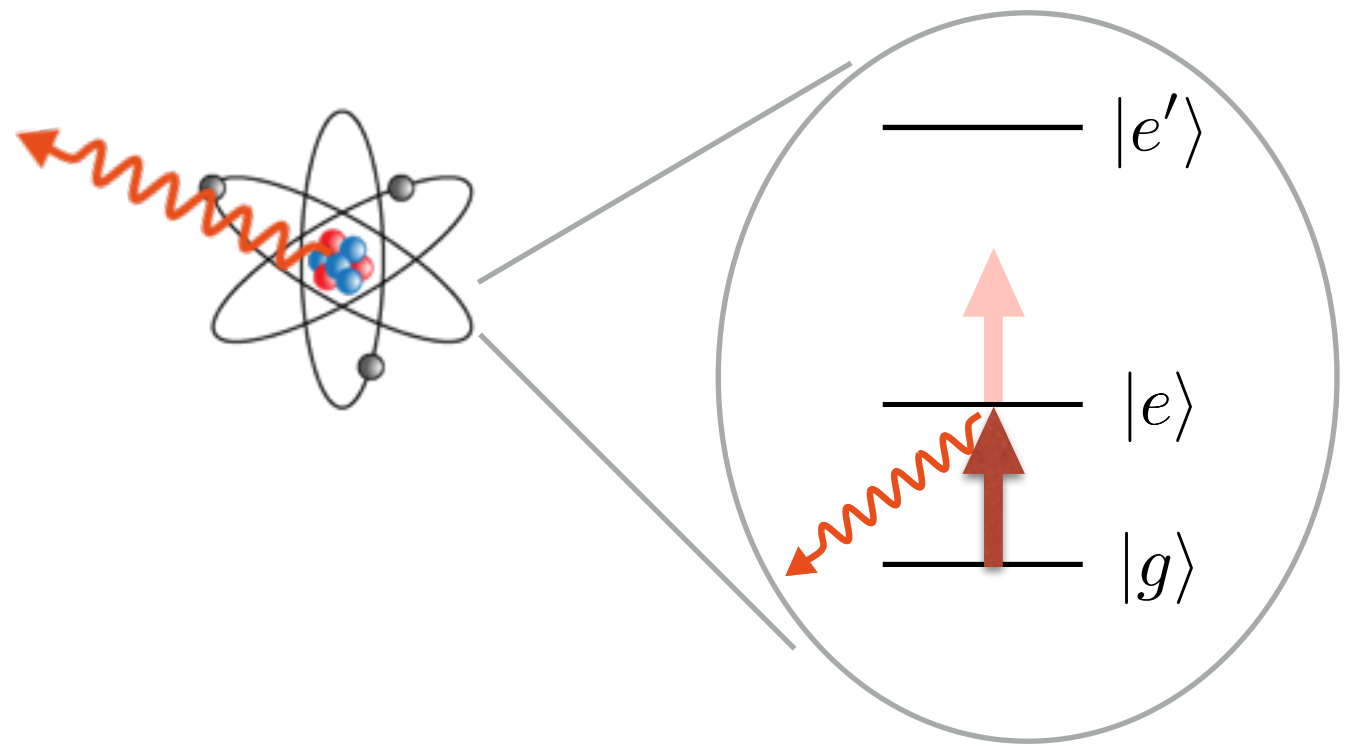
Nanoscale Quantum Optics Cost Action Meeting
Working Group 4
April 4th 2019, Brussels

Atom-Photon Interactions

A Single Atom

Ultimate non-linear optical element

non-classical states of light,
quantum information processing



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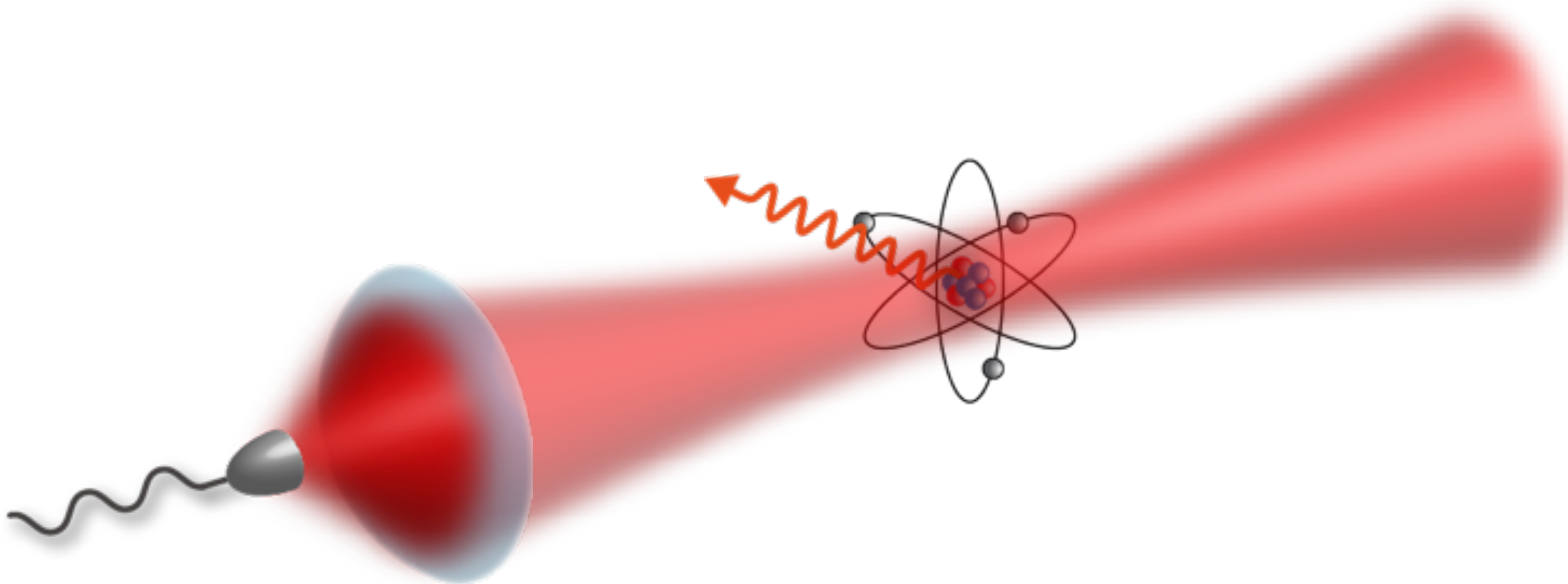
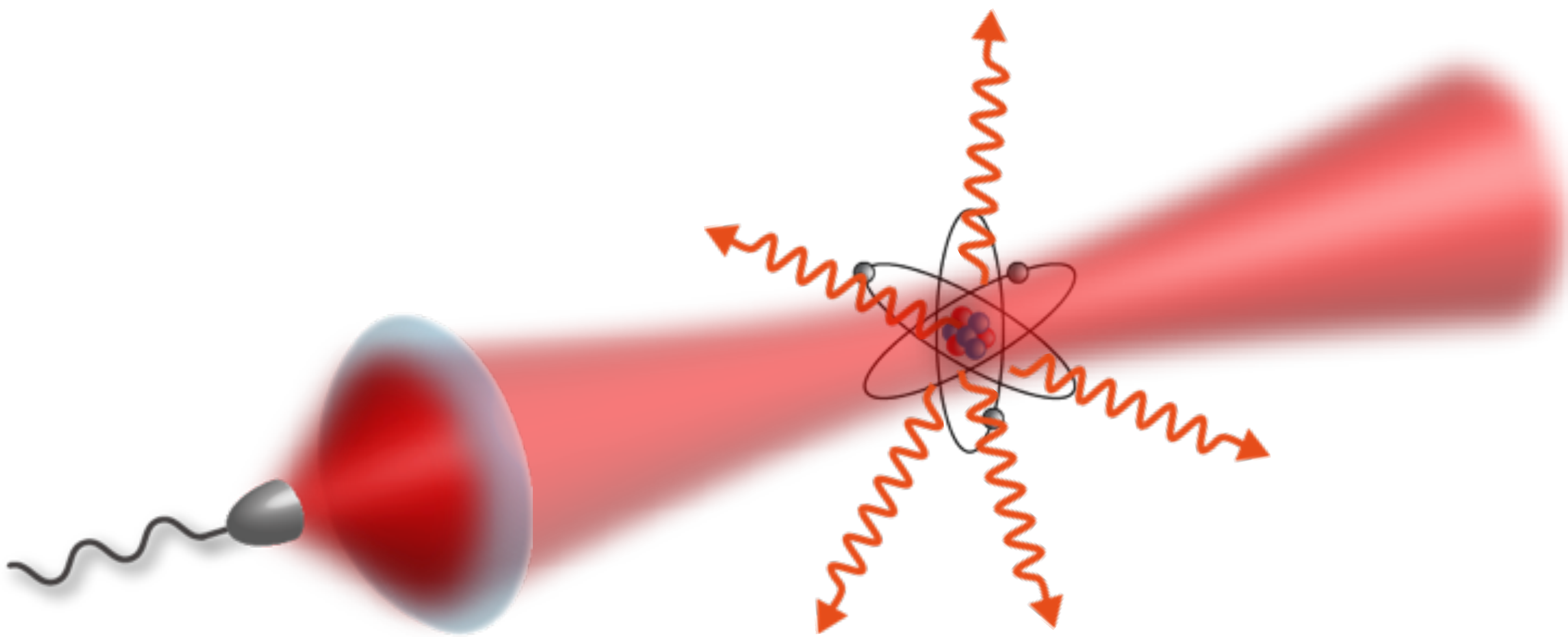


***Problem*:** A single atom and a single photon **do not like to talk** to each other

Atom-Photon Interactions

A Single Atom

Ultimate non-linear optical element



Spontaneous Emission into undesired directions is a fundamental limitation: Source of ***(quantum) information loss***

Optical Depth as a Fundamental Limit

Error of most applications is bounded by the
“***Cooperativity***" or “***Optical Depth***"

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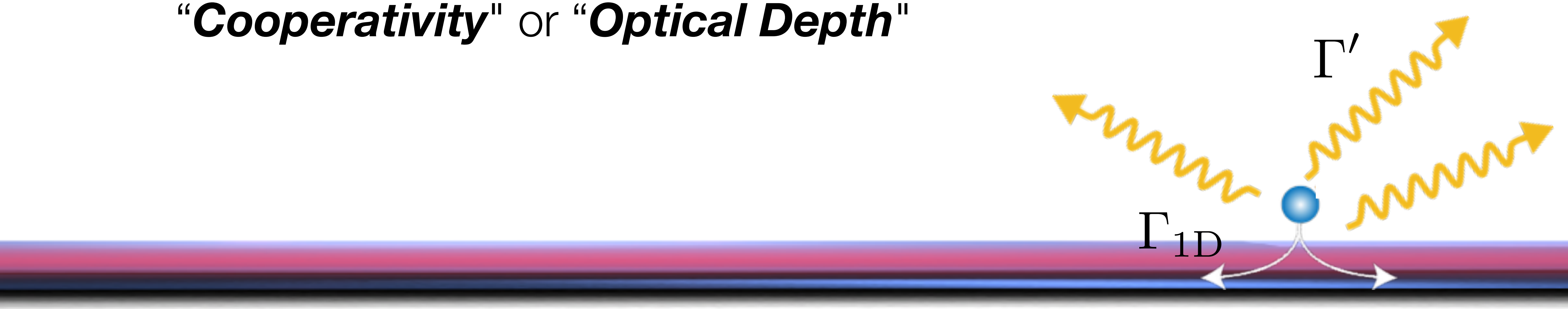

$$OD = \frac{\Gamma_{\mathrm{1D}}}{\Gamma'}$$

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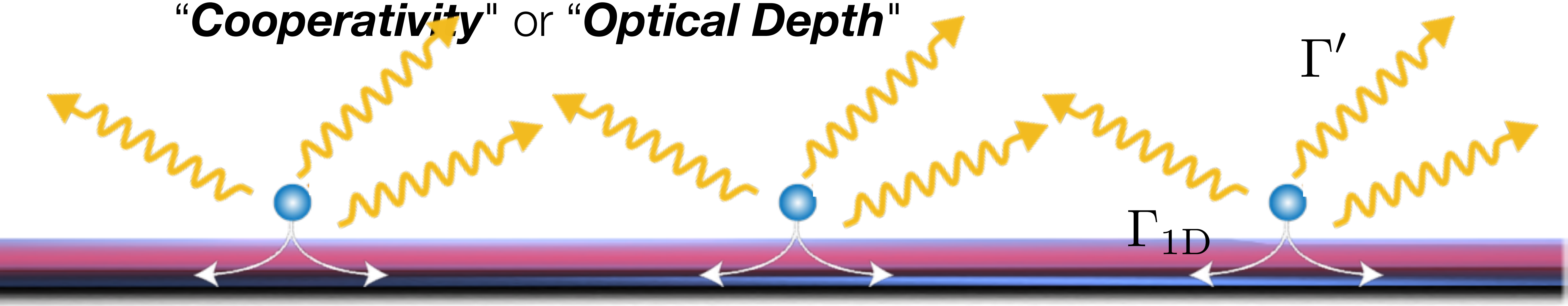

$$OD = \frac{\Gamma_{\mathrm{1D}}}{\Gamma'} \times N$$

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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.

Single Photon Storage

Error ~ 1/OD

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Single Photon Storage

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Quantum interface between light and atomic ensembles

Klemens Hammerer

Institute for Theoretical Physics, University of Innsbruck, and Institute for Quantum Optics and Quantum Information, Austrian Academy of Science, Technikerstrasse 25, 6020 Innsbruck, Austria

Anders S. Sørensen and Eugene S. Polzik

Niels Bohr Institute, Copenhagen University, Blegdamsvej 17, Copenhagen 2100, Denmark

The bound on the achievable squeezing is not so surprising, given that the state of atoms suffered essentially a decay by a fraction η_A. Due to the relation $\kappa^2 = d\eta_A$, cf. Eq. (59), there is always an optimal choice for the decay η_A given a certain optical depth d (Hammerer *et al.*, 2004). For the decoherence model adopted here the limit to spin squeezing by QND measurement and feedback is $\Delta P^2_{A,\text{final}} \geqslant (1+\sqrt{1+d})^{-1} \sim d^{-1/2}$, for large optical density. For a detailed discussion on the limits of spin

Spin Squeezing

$$\mathbf{Error} \sim \frac{\mathbf{1}}{\mathbf{OD^{0.5}}}$$

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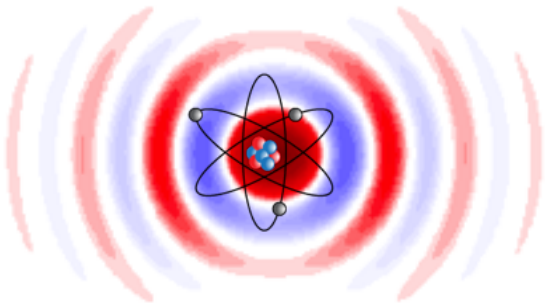
Spin Squeezing

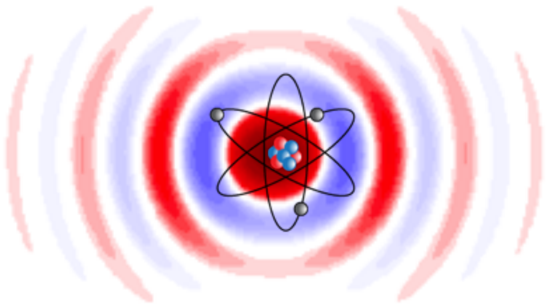
$$\textbf{Error} \sim \frac{\textbf{1}}{\textbf{OD}^{\textbf{0.5}}}$$

Error decreases as 1 / OD or slower

A Loophole

Linear scaling of optical depth with atom number
ignores ***Wave Interference***





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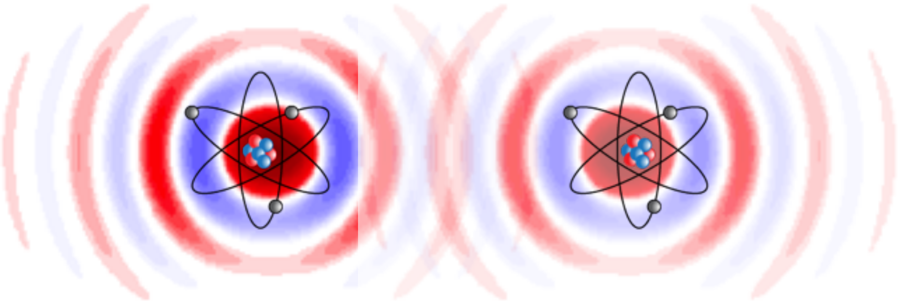

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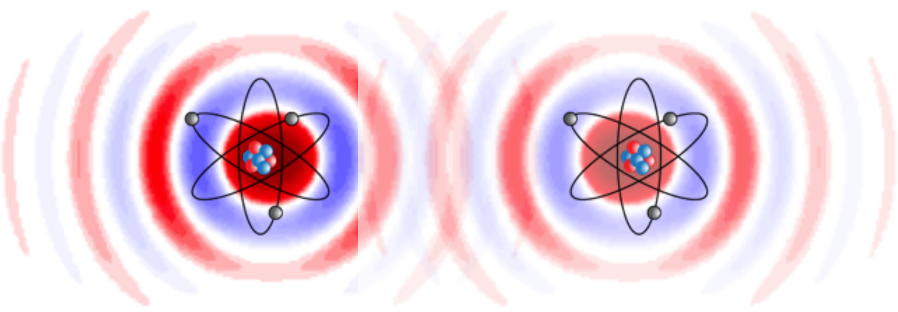

rich and engineerable emission pattern into 4π

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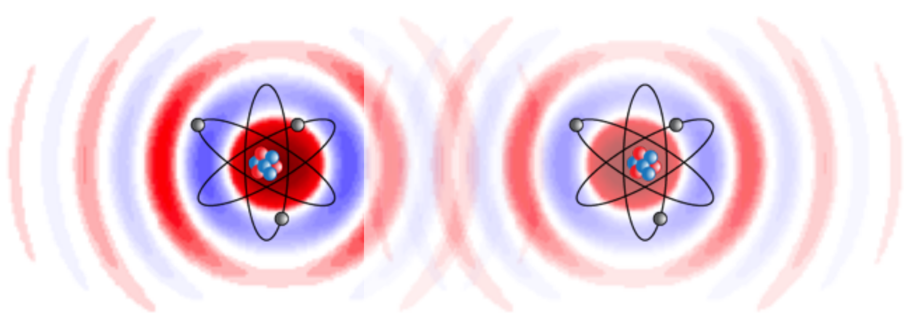

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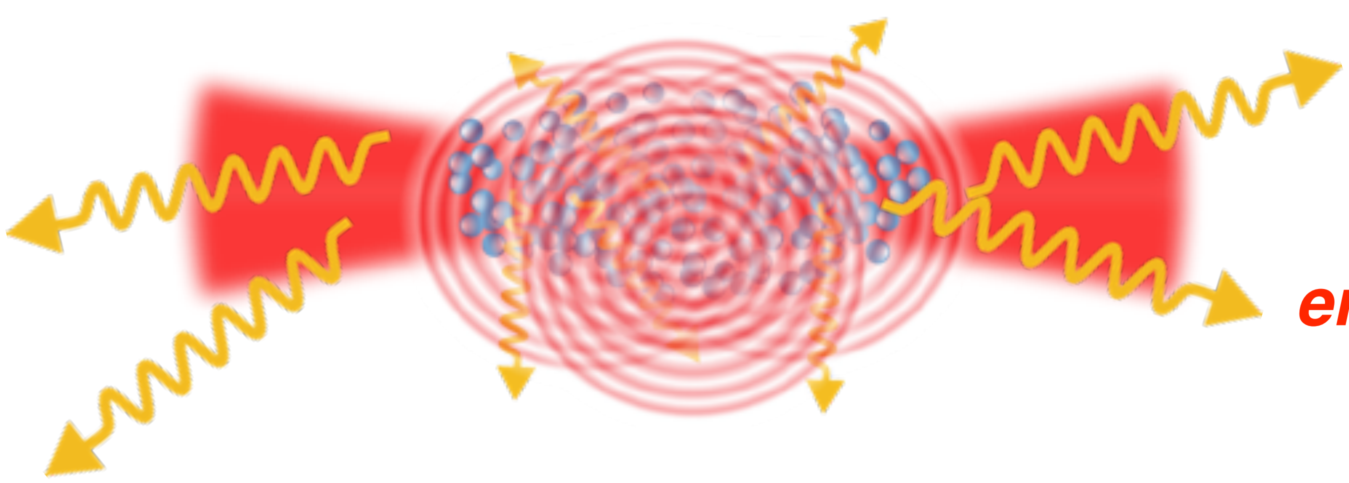

superradiance
enhancement of decay rate

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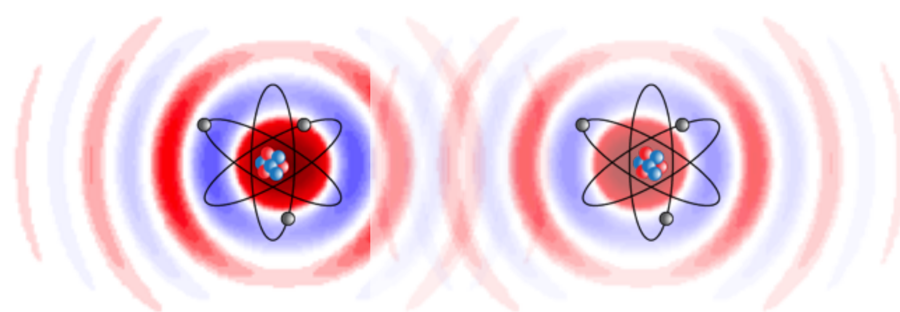

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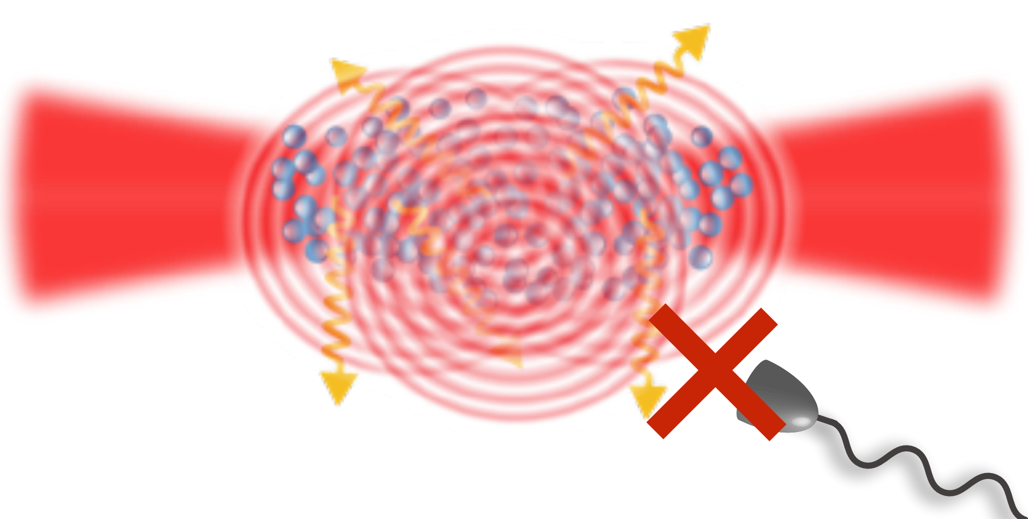
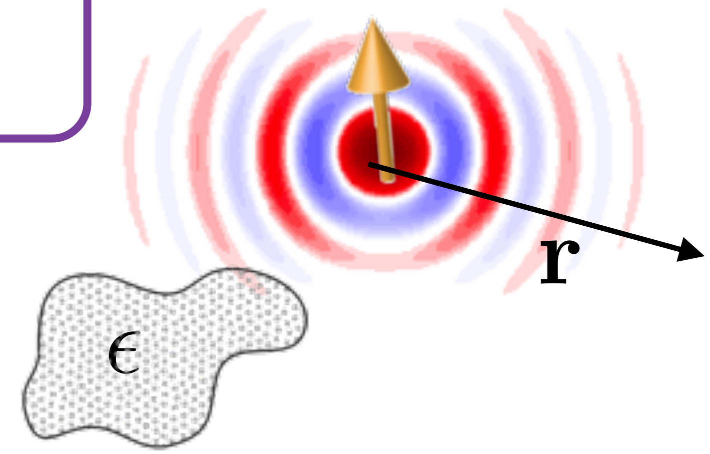


subradiance
suppression of decay rate

Formalism for Atom-Light interactions including Wave Interference

field created by a single dipole is given by Green's function



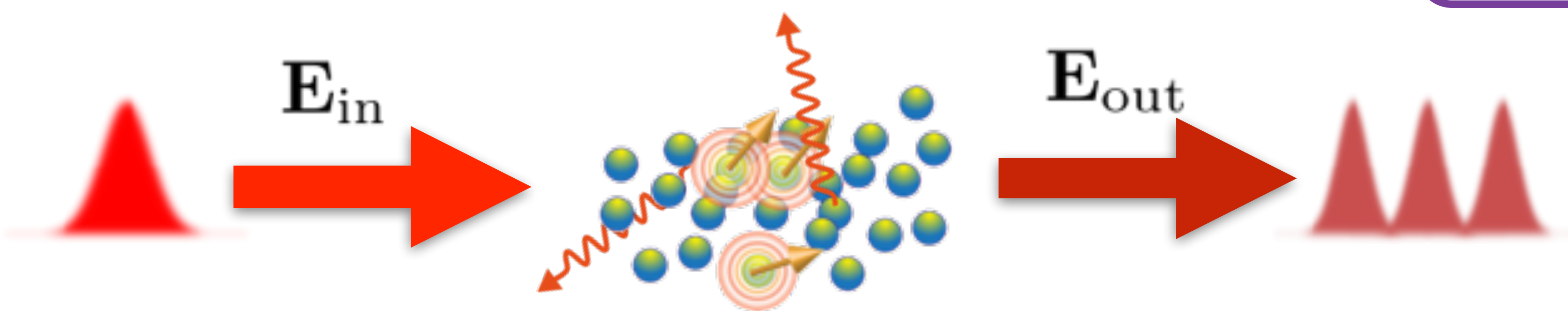
$$\mathbf{E}(\mathbf{r}) = \mu_0 \omega^2 \mathbf{G}(\mathbf{r}, 0, \omega) \cdot \wp$$

Formalism for Atom-Light interactions including Wave Interference

scattered field

input-output equation

$$\hat{\mathbf{E}}_{\mathrm{out}}(\mathbf{r}) = \hat{\mathbf{E}}_{\mathrm{in}}(\mathbf{r}) + \boxed{\mu_0 \omega_{eg}^2 \wp \sum_i \mathbf{G}(\mathbf{r}, \mathbf{r}_i, \omega_{eg}) \hat{\sigma}_i^{ge}}$$



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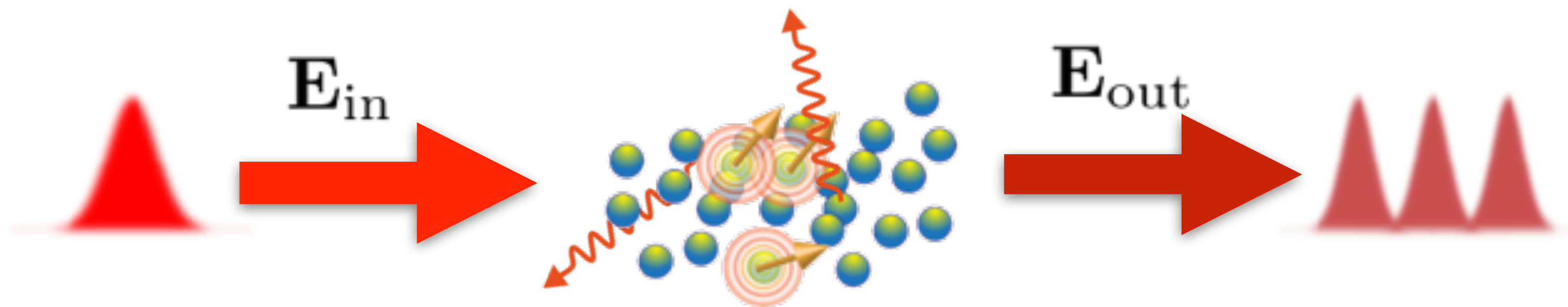

atomic dynamics
effective Hamiltonian

$$\hat{H}_{\text{eff}} = -\mu_0 \omega_{eg}^2 \wp^2 \sum_{i,j} G(\mathbf{r}_i, \mathbf{r}_j, \omega_{eg}) \hat{\sigma}_i^{eg} \hat{\sigma}_j^{ge}$$

"open quantum spin model"

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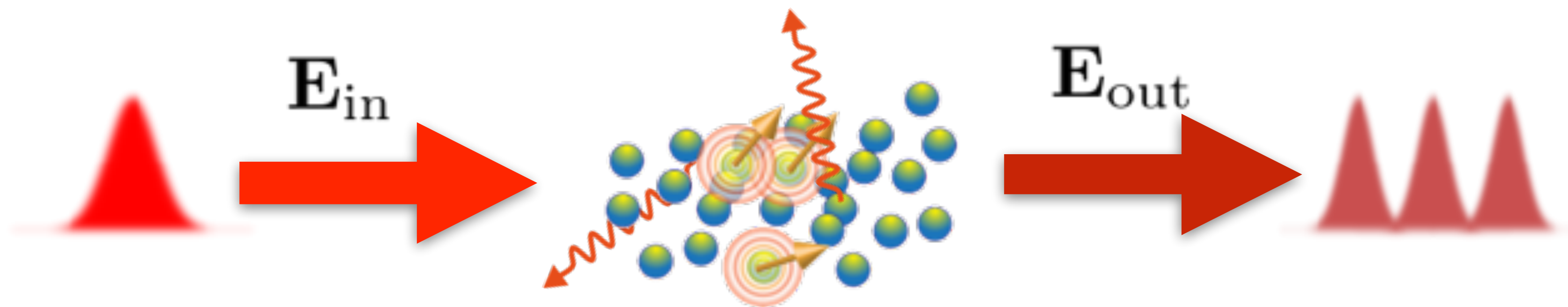

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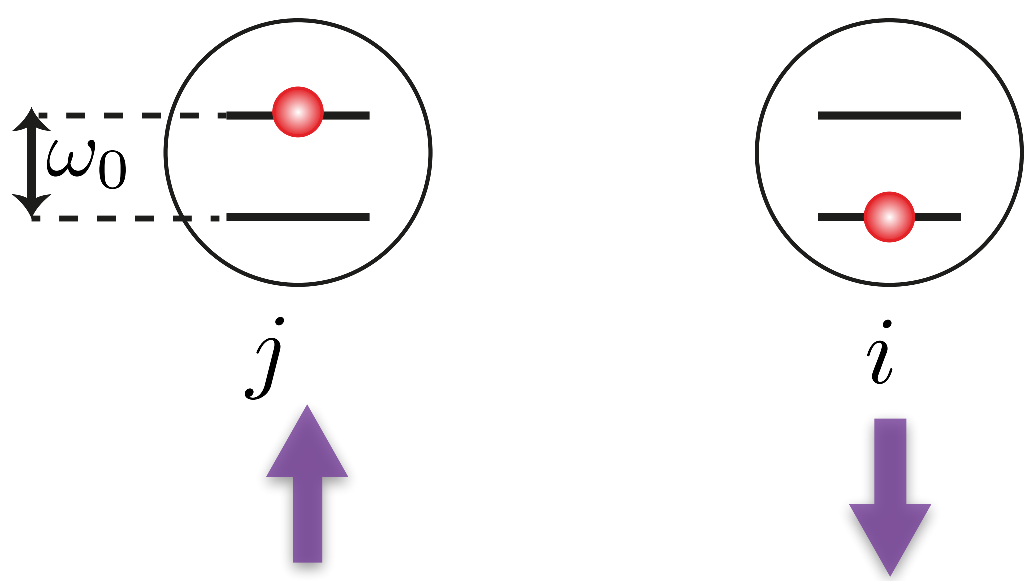

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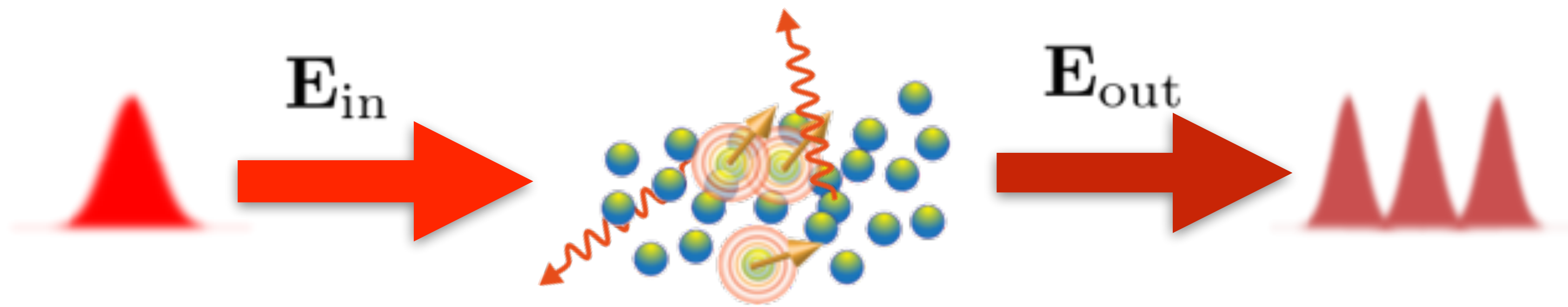

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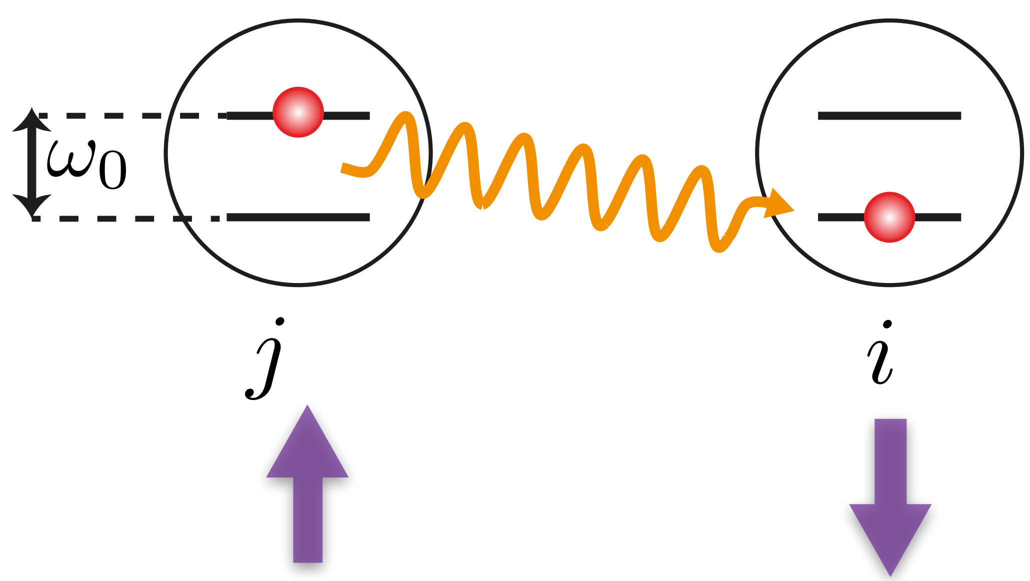

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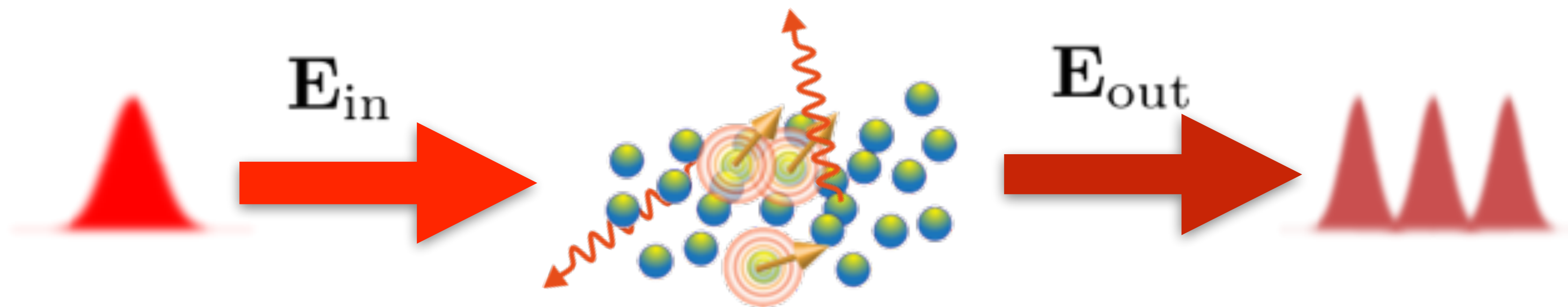

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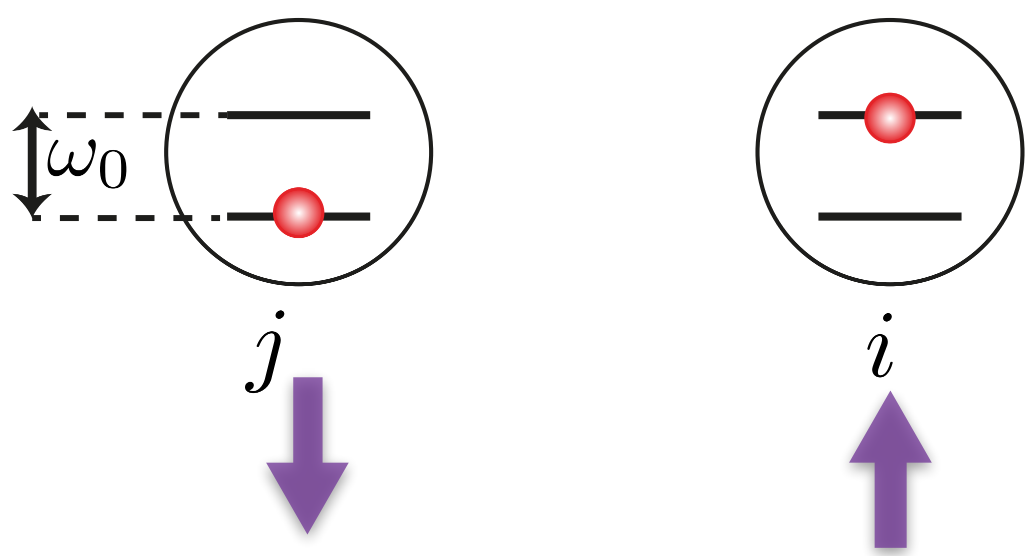

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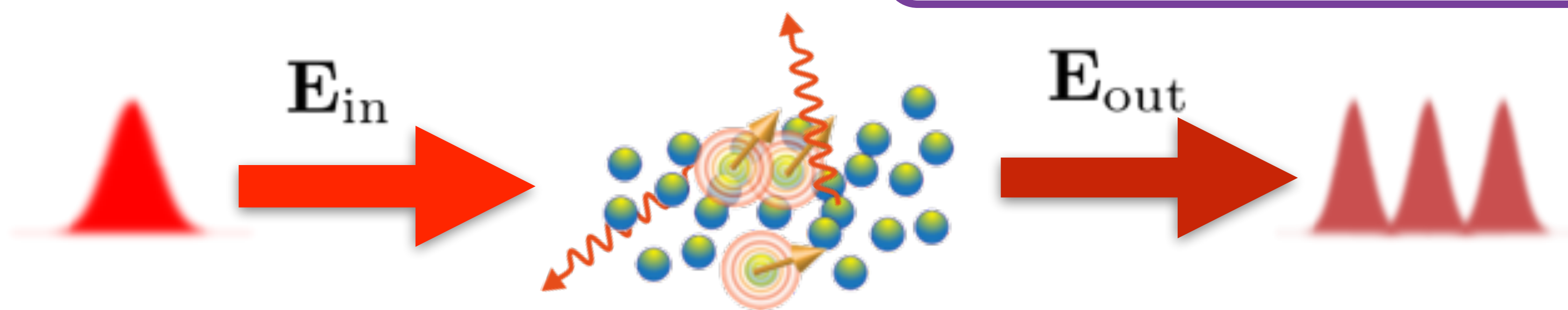

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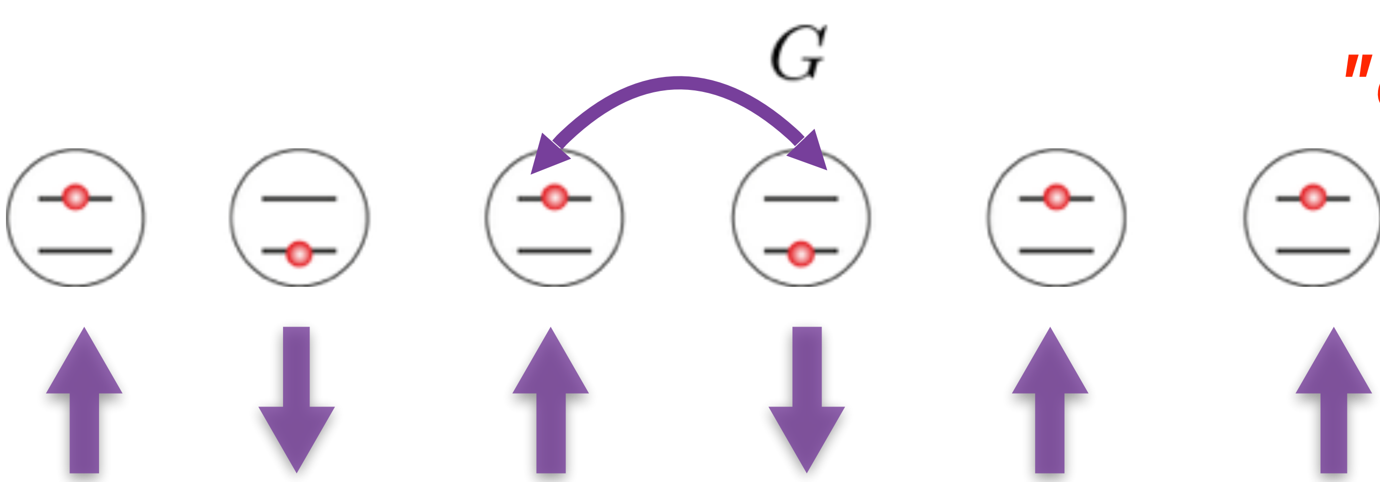
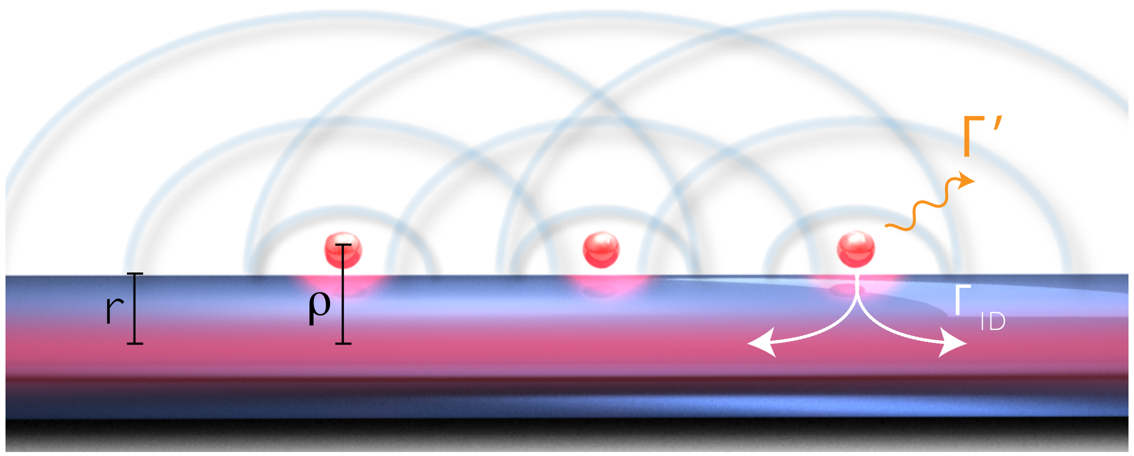
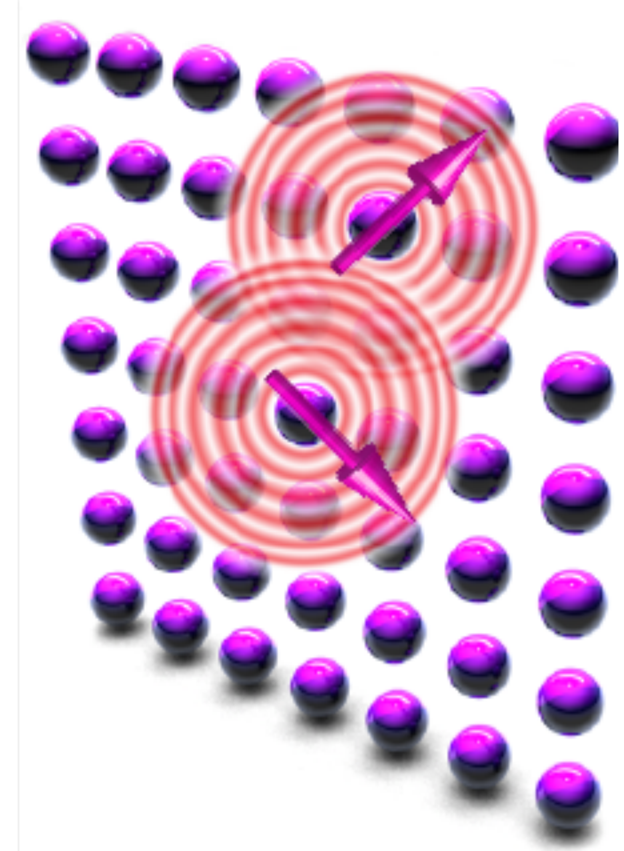


"open quantum spin model"

Exploiting Cooperative Effects in Dense Atomic Arrays

Regular and ***Dense Arrays*** maximize the effects of Wave Interference





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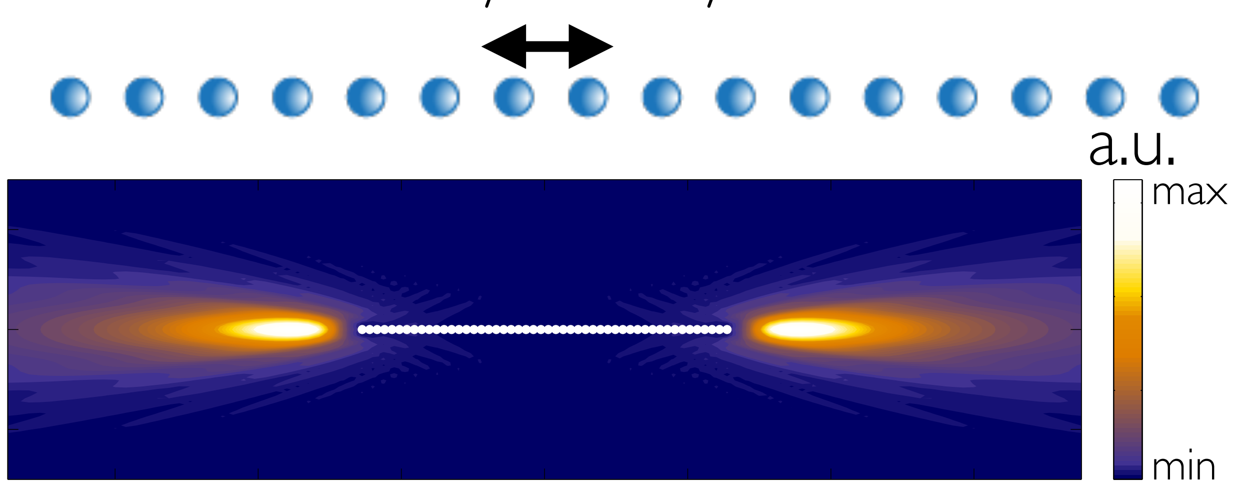
$d/\lambda < 1/2$



a sub-wavelength chain
can support
single-excitation guided modes

subradiant modes are guided

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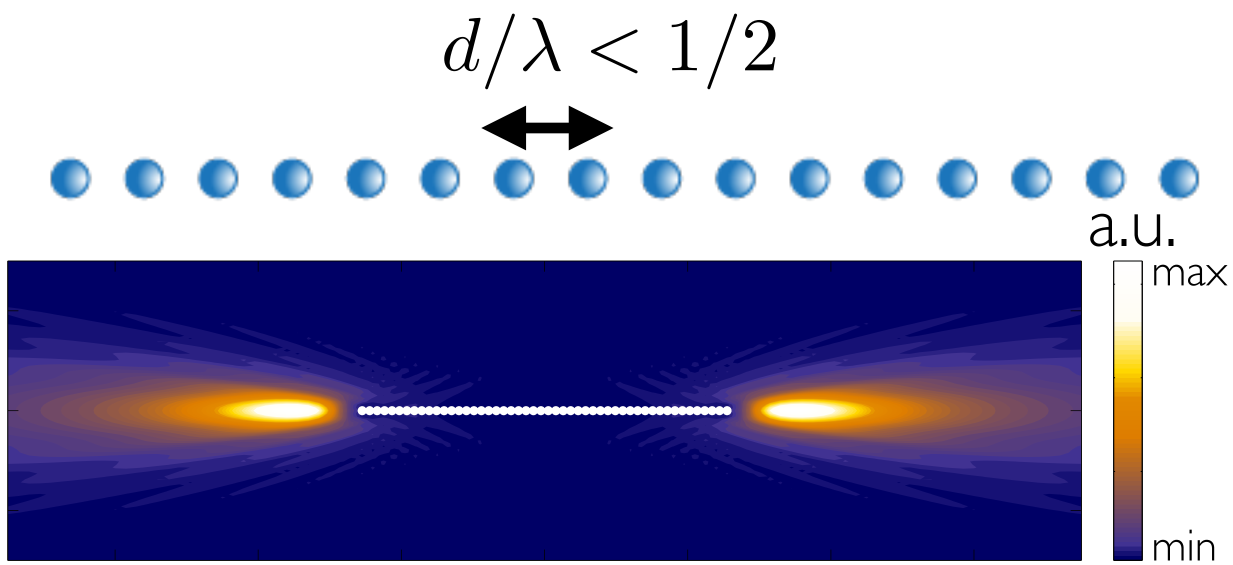

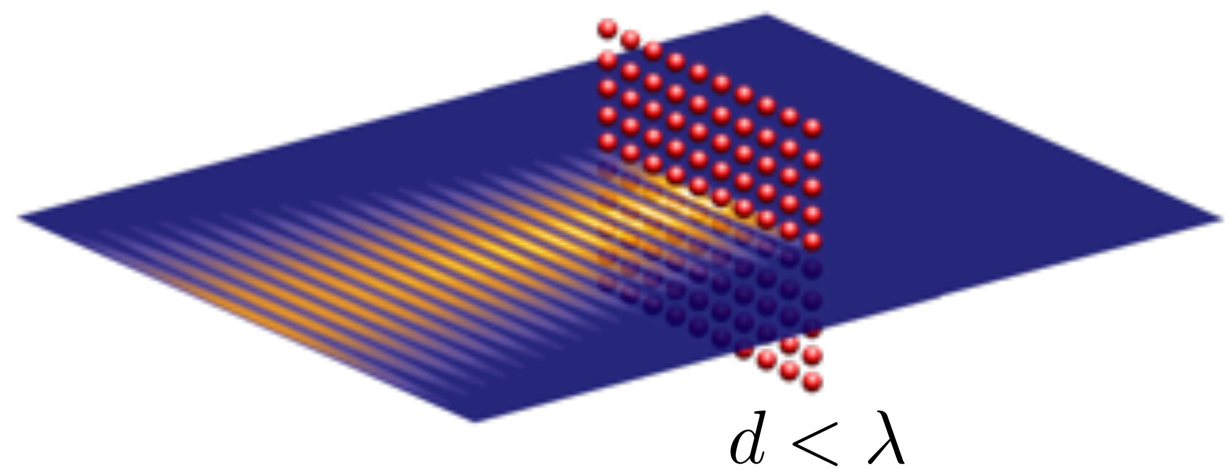

a sub-wavelength chain
can support
single-excitation guided modes

A single layer of atoms ordered
in a sub-wavelength array
behaves as a perfect mirror

subradiant modes are guided

Exploiting Cooperative Effects in Dense Atomic Arrays

No Photon Losses
Perfect Reflection

↔

Efficient Atom-Light Interface

Exploiting Cooperative Effects in Dense Atomic Arrays

We can use such effects to create a
nearly perfect quantum memory

Exploiting Cooperative Effects in Dense Atomic Arrays

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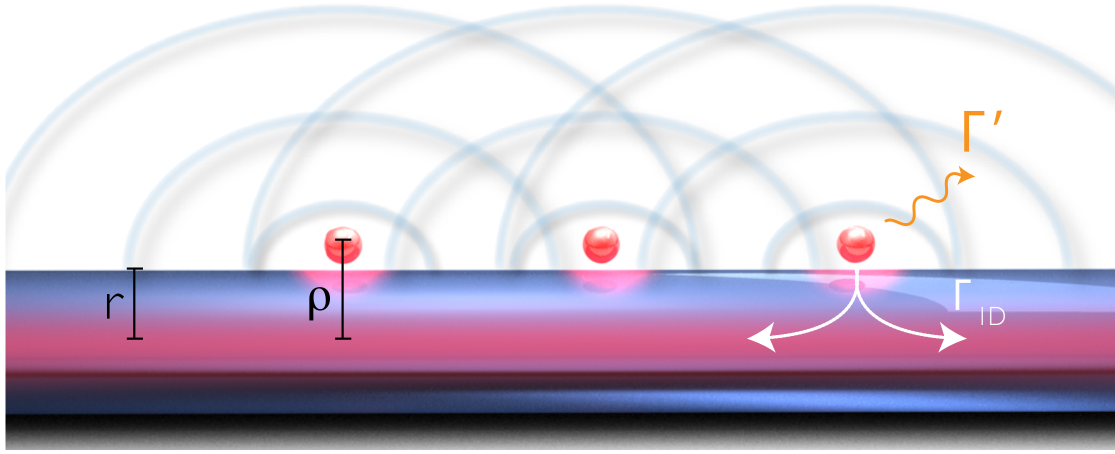

Coupling the atomic chain
with a nanofiber

Exponential Improvement in Photon Storage Fidelities using Selective Radiance
A. Asenjo-Garcia, M. Moreno-Cardoner, A. Albrecht, H. J. Kimble, D. E. Chang,
Phys. Rev. X 7, 031024 (2017)

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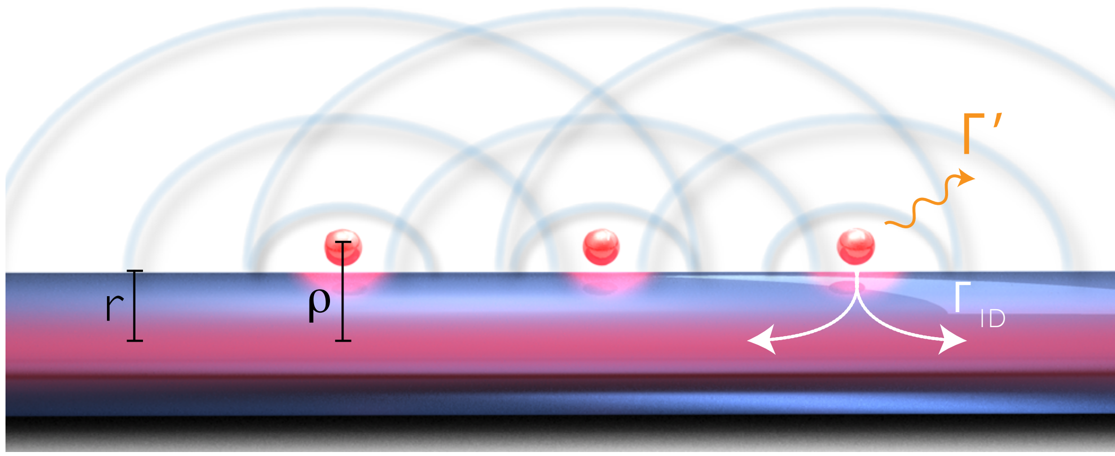

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“selectively radiant system"

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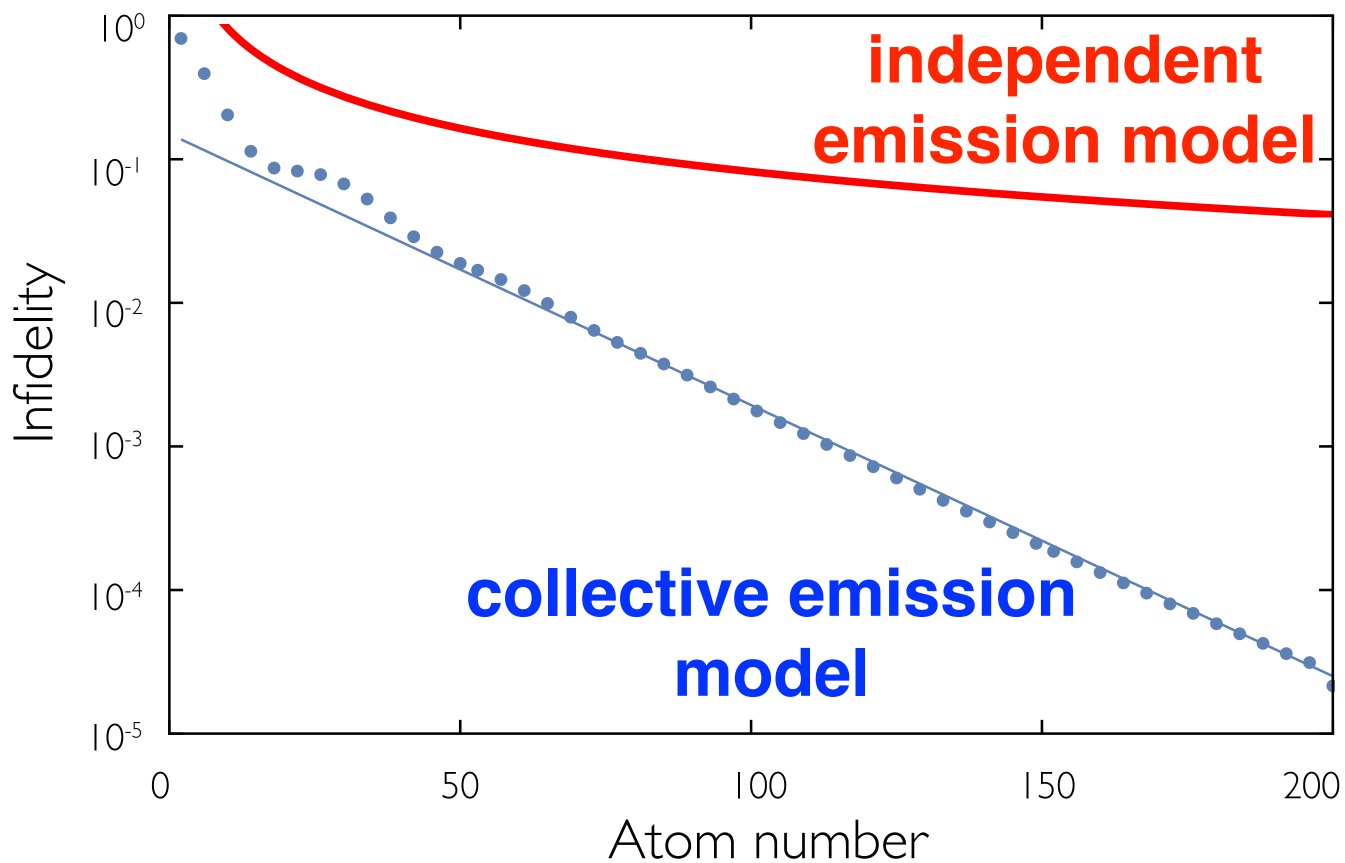

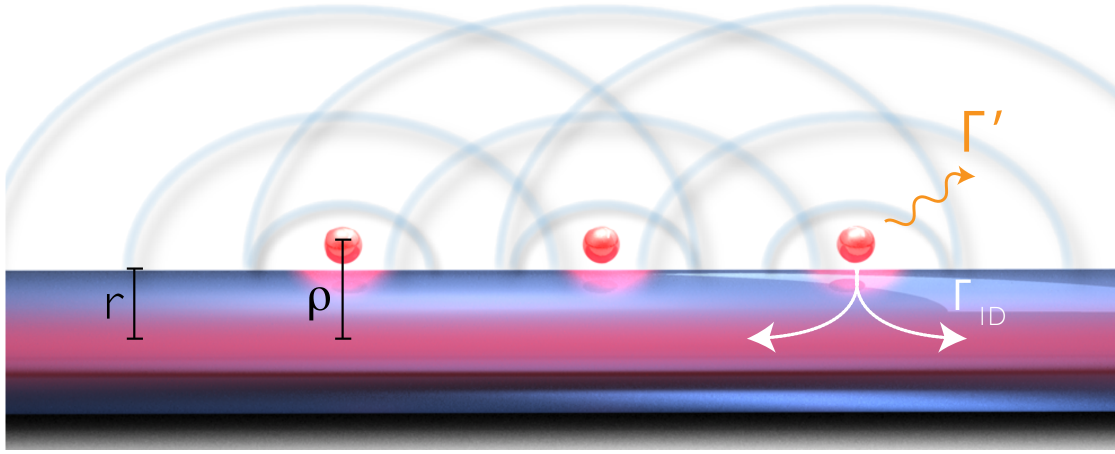

Exponential Improvement vs. Atom Number

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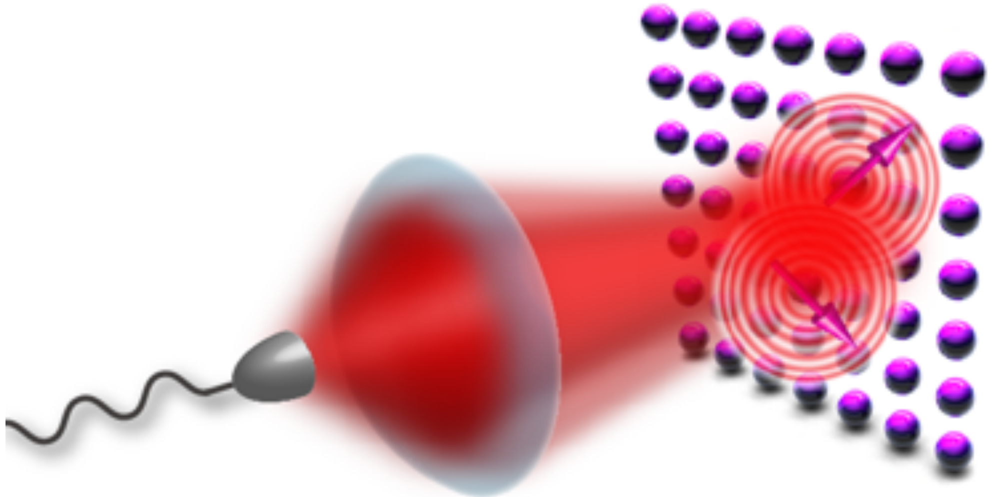
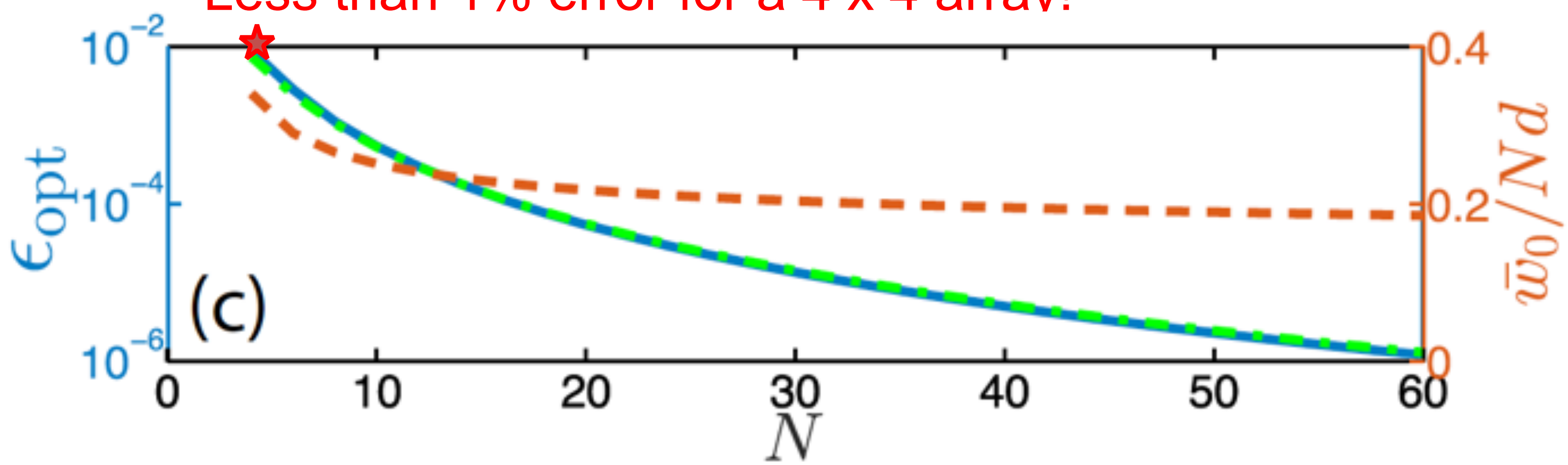
A small array of 4 x 4 atoms can be as efficient as a disordered ensemble with N = $10^6 \sim 10^7$

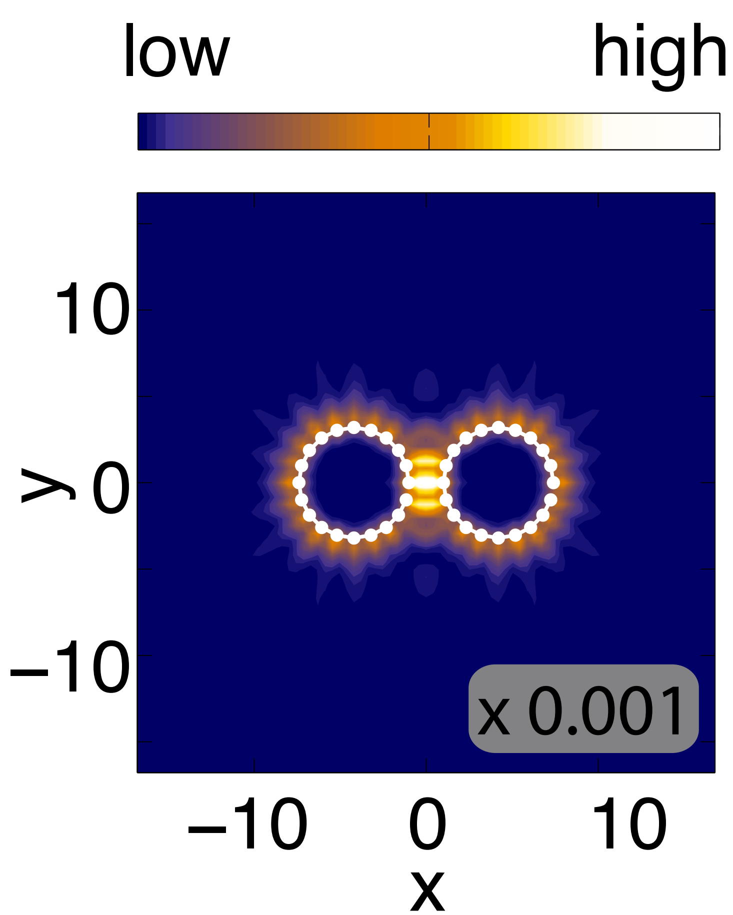


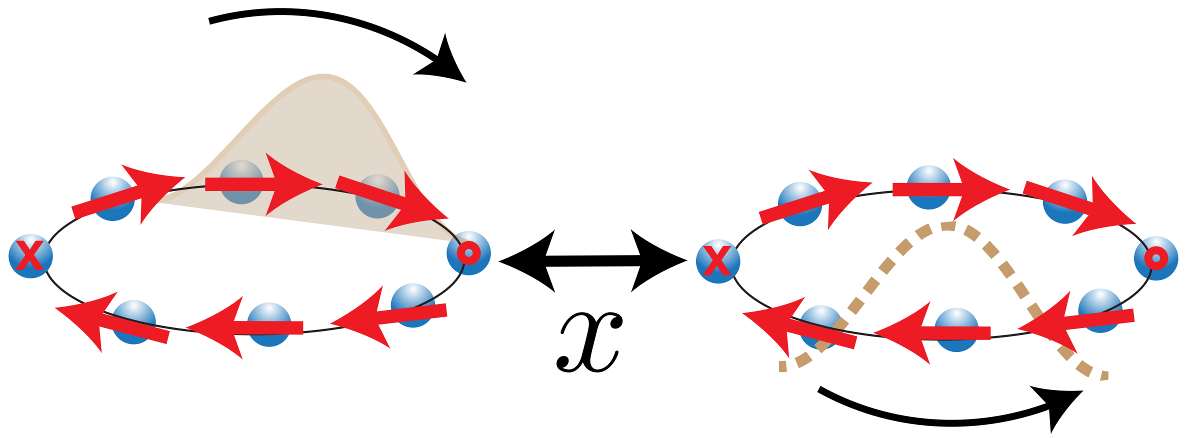


Optimization of photon storage fidelity in ordered atomic arrays
M. T. Manzoni, M. Moreno-Cardoner, A. Asenjo-Garcia, J. V. Porto, A. V. Gorshkov, and D. E. Chang,
New Journal of Physics, 20, 083048 (2018)

Exploiting Cooperative Effects in Dense Atomic Arrays

We can use such effects for an
efficient transport of excitations





two rings in a subradiant mode couple mainly dispersively

Extraordinary subradiance with lossless excitation transfer in dipole-coupled nano-rings of quantum emitters
M. Moreno-Cardoner, D. Plankensteiner, L. Ostermann, D. E. Chang, H. Ritsch, ***arXiv:***1901.10598

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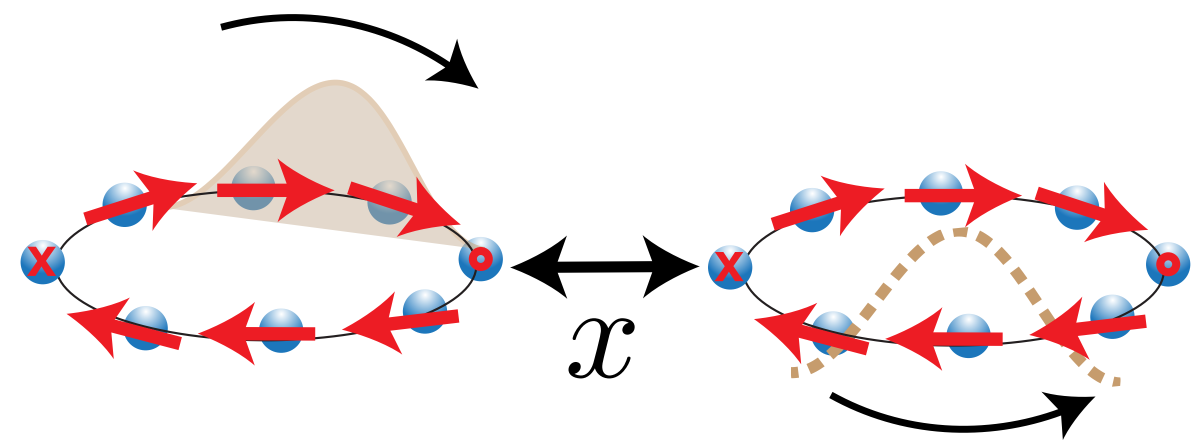

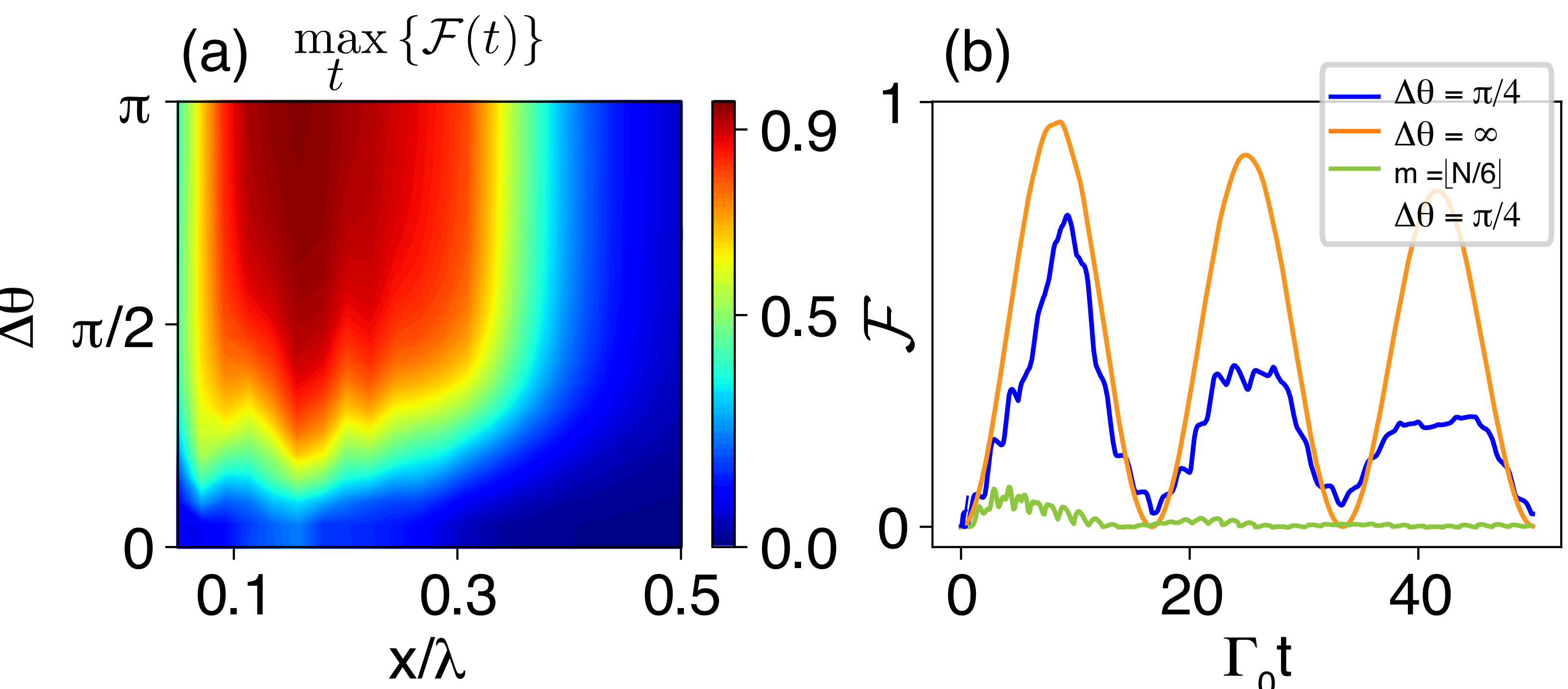

fidelities near unity of
multi-mode excitation transfer

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Outlook

- Including Wave Interference and Correlated Dissipation leads to new paradigms

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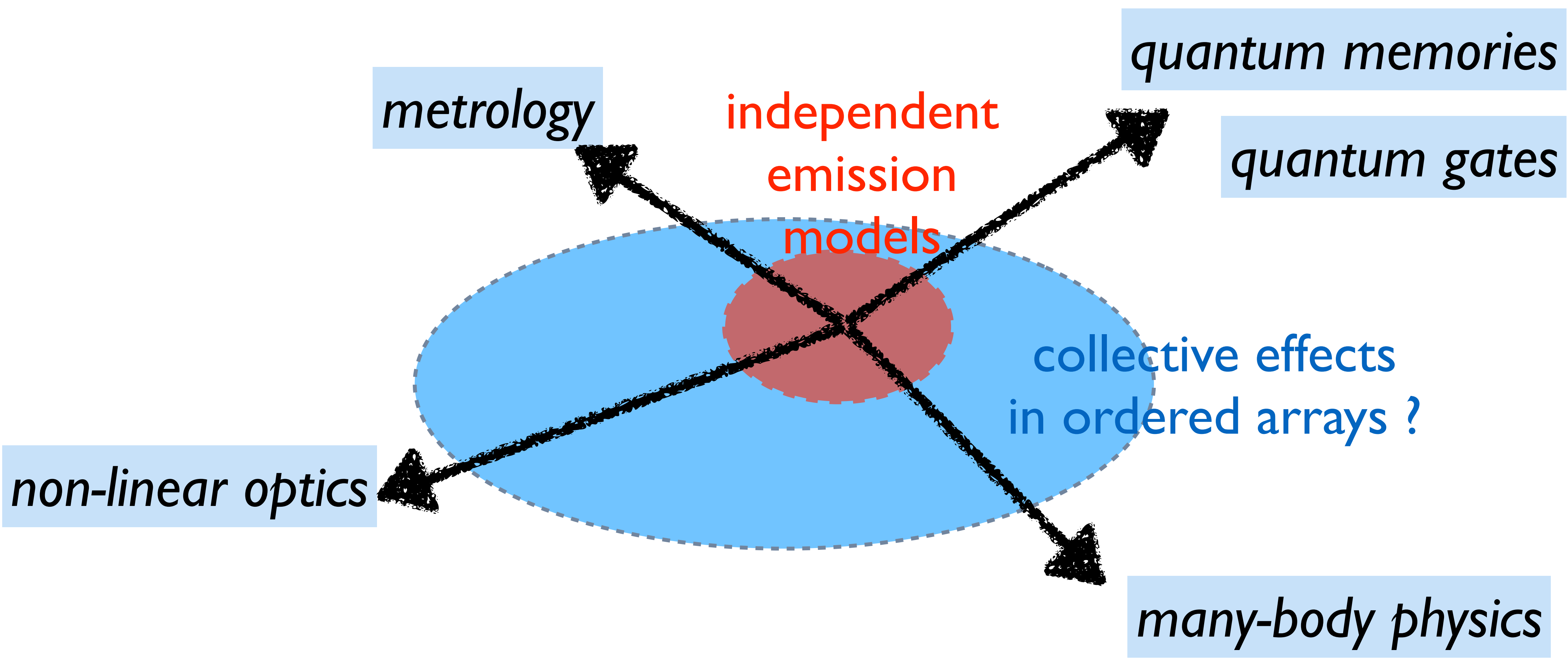
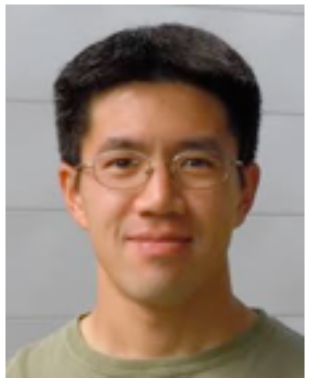
- Novel phenomena, More powerful protocols?



Acknowledgments



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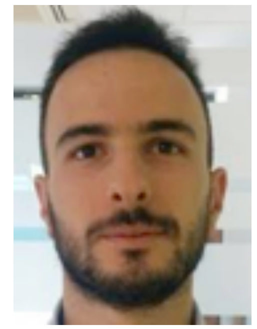
(ICFO)

H. J. Kimble (Caltech)

A. Asenjo-Garcia (Columbia Univ.)



M. T. Manzoni

A. Albrecht

T. Porto (JQI)

A. Gorshkov (JQI)

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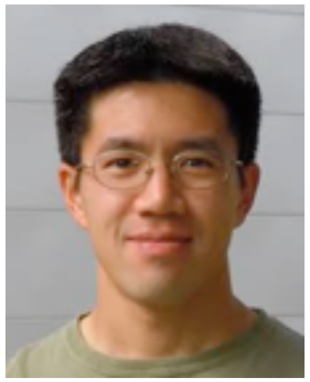

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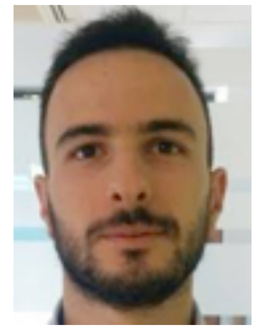

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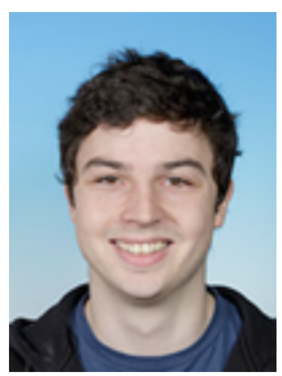
(JQI)

H. Ritsch
(Univ. Innsbruck)



D. Plankensteiner
(Univ. Innsbruck)

L. Ostermann
(Univ. Innsbruck)

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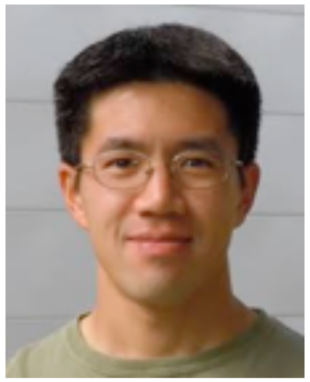

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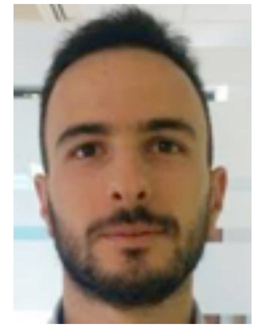

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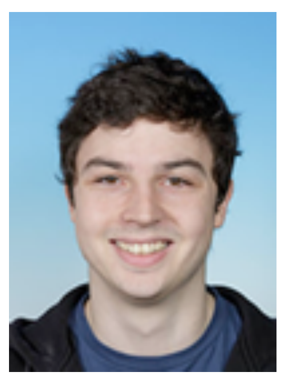

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(Univ. Innsbruck)

L. Ostermann
(Univ. Innsbruck)

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