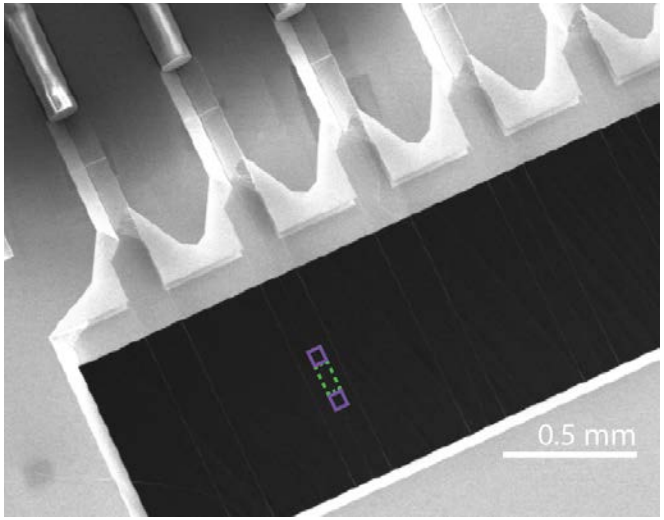
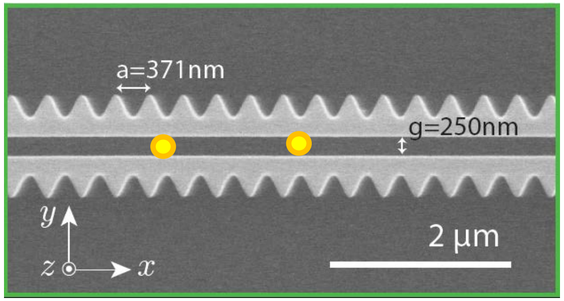
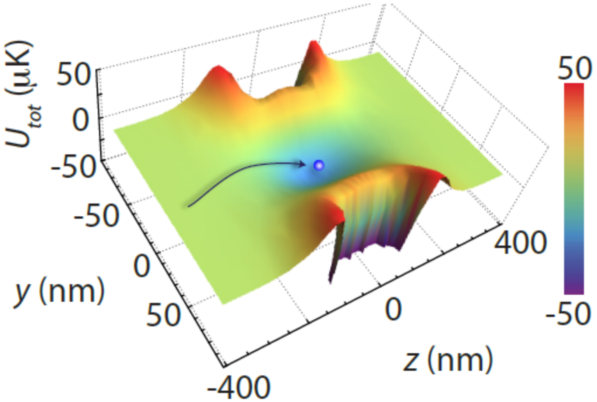
Overview on atom-nanophotonics interfaces







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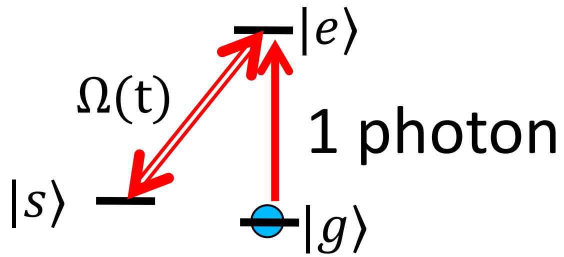
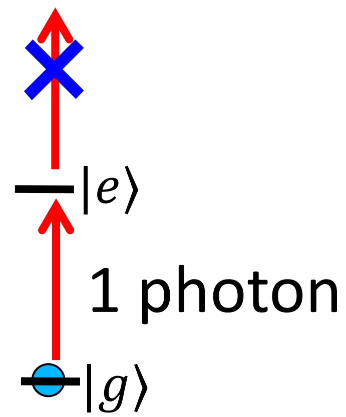
Motivation

- Efficient interaction between a single photon and atom
    - Quantum memory (flying qubit ↔ stationary qubit)

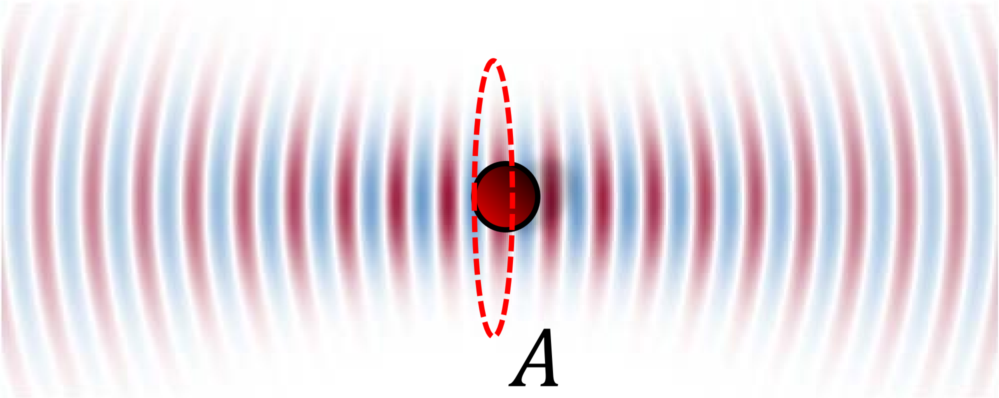


- Nonlinear optics with single-photon pulses



The problem

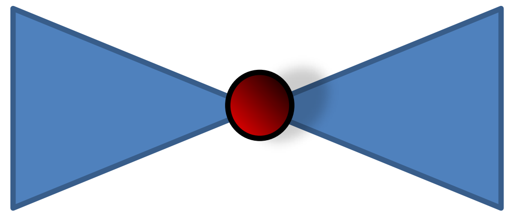
- Single photons and atoms do not easily interact



$$P \sim \frac{\lambda^2}{A}$$

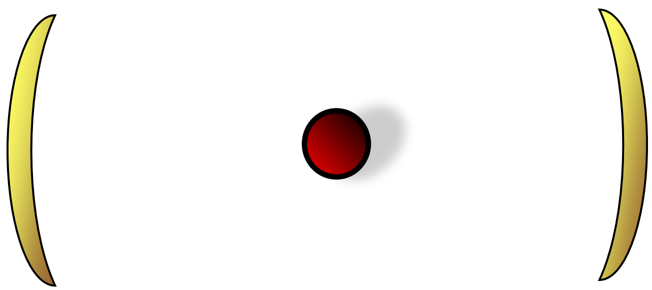
Possible solutions

- Free-space focusing (beyond paraxial optics)



$$P_{\text{limit}} = 100\%$$
$$P_{\text{actual}} \sim 10\%$$

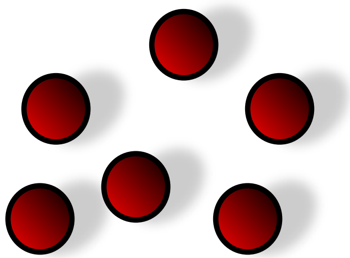
- Cavity-enhanced interaction



$$P \sim \frac{\lambda^2}{A} N_{\text{bounces}} \sim \frac{Q\lambda^3}{V} \sim \frac{g^2}{\kappa\Gamma}$$

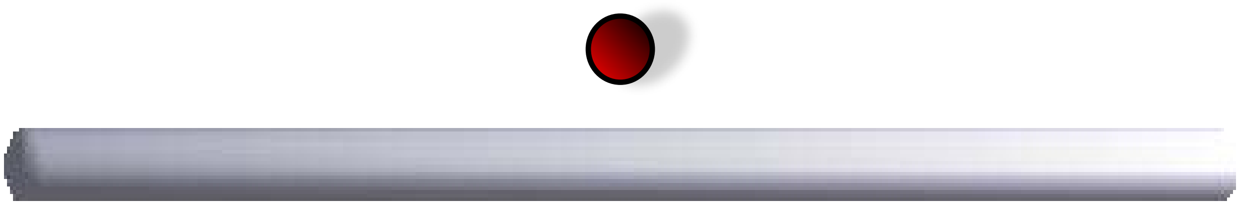
Possible solutions

- Many atoms*
  * usually decreases the nonlinearity of the system



$$P \sim \frac{\lambda^2}{A} N_{\text{atoms}} \sim OD$$

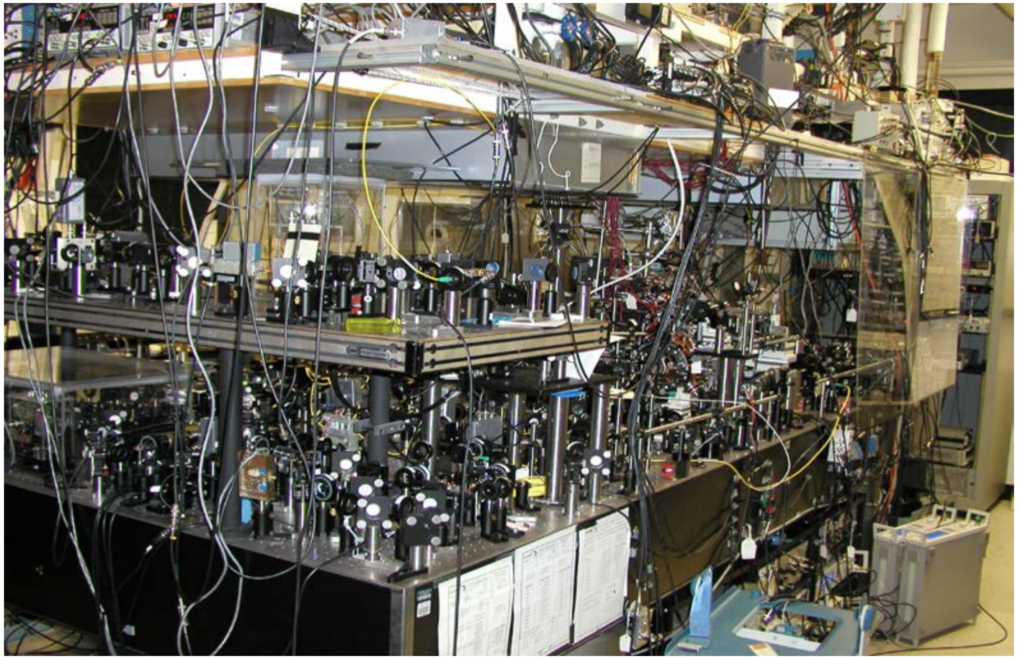
- Focusing below diffraction limit (plasmonics)



$$P \sim \frac{\lambda^2}{A}, A \ll \lambda^2$$

Why nanophotonics?

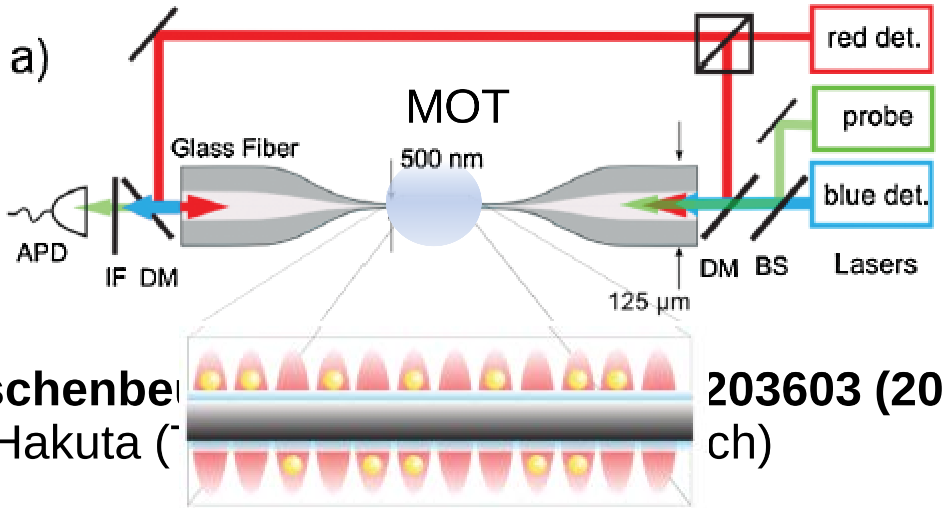
- Increase atom-light interaction by tightly confining light
- Get nanoscale control over atomic position
- Efficient probability to retrieve the photon into a fiber
  - "Scalability"



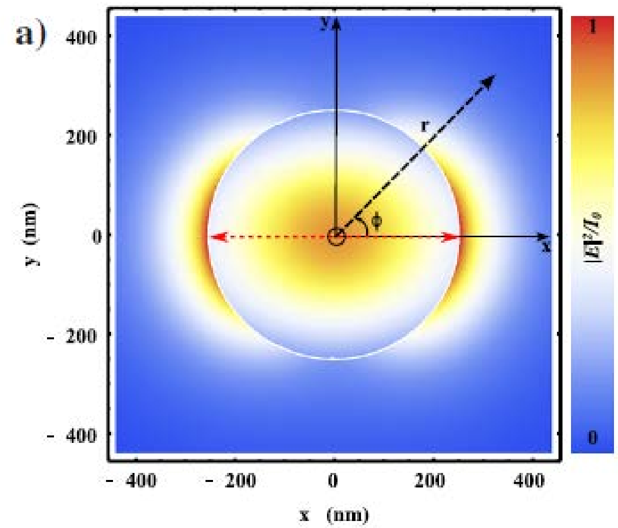
Kimble (Caltech)

Tapered nanofiber

- Tapered optical nanofibers



Rauschenbe **203603 (2010),**
also Hakuta (ch)

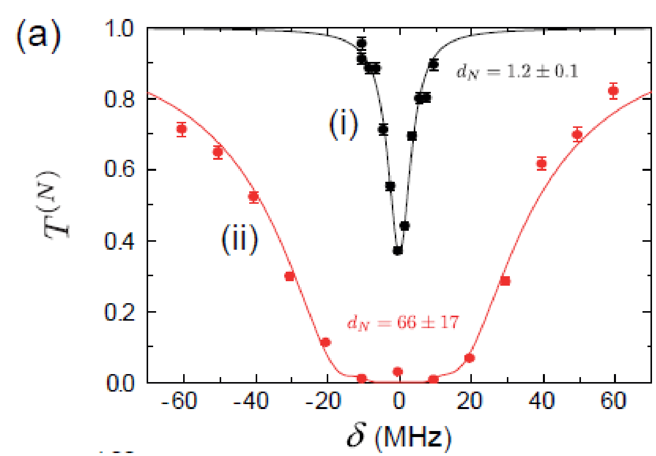


Evanescent field profile
Lacroute et al., NJP 14, 023056 (2012)

- Current parameters:

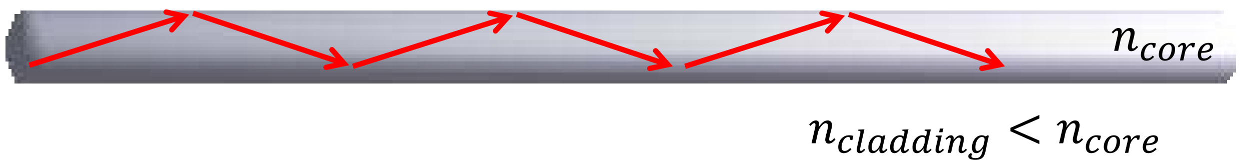
$$\frac{\Gamma_{1D}}{\Gamma_{total}} \sim 0.08 \text{ for single atom}$$

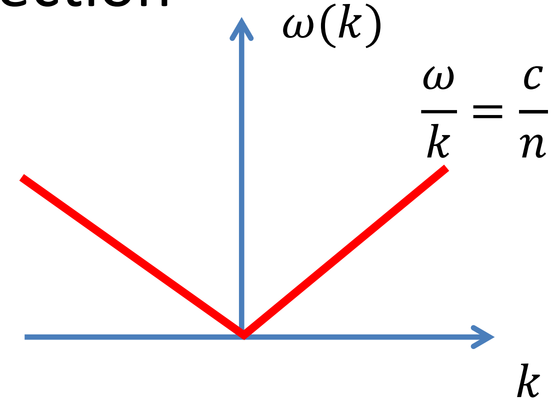
$$N_{atom} \sim 10^3$$



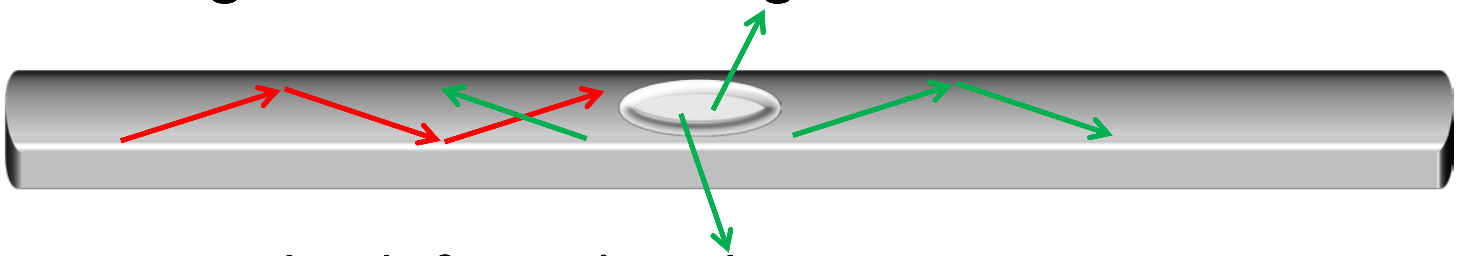
Photonic crystals

- Normal fiber: light guided by total internal reflection

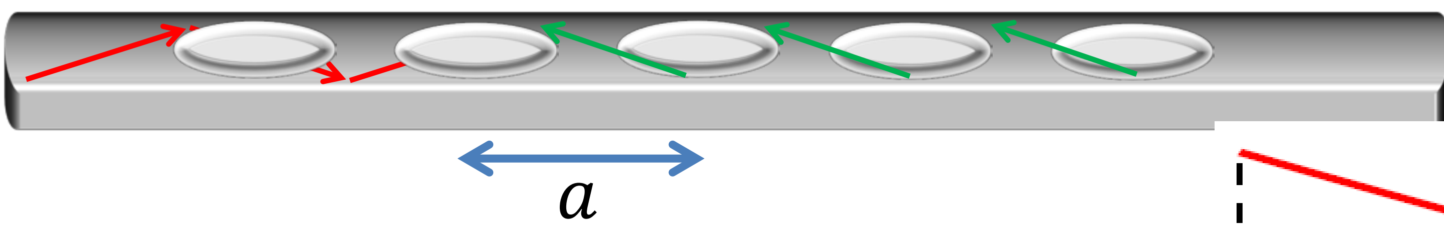




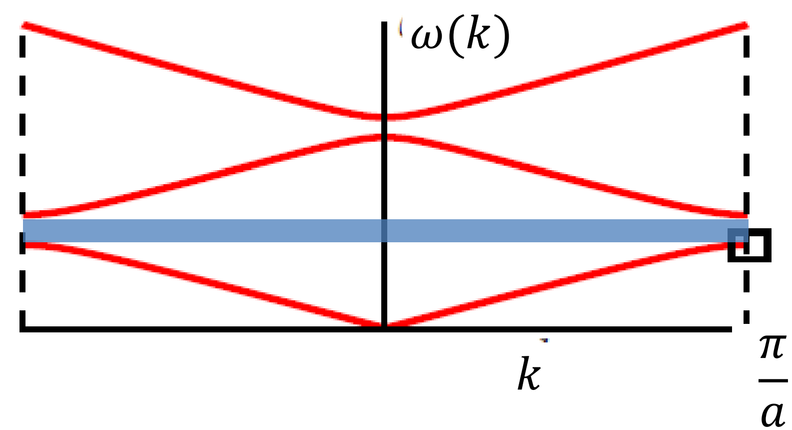
- Single defect: scattering



- Periodic defects: band structure

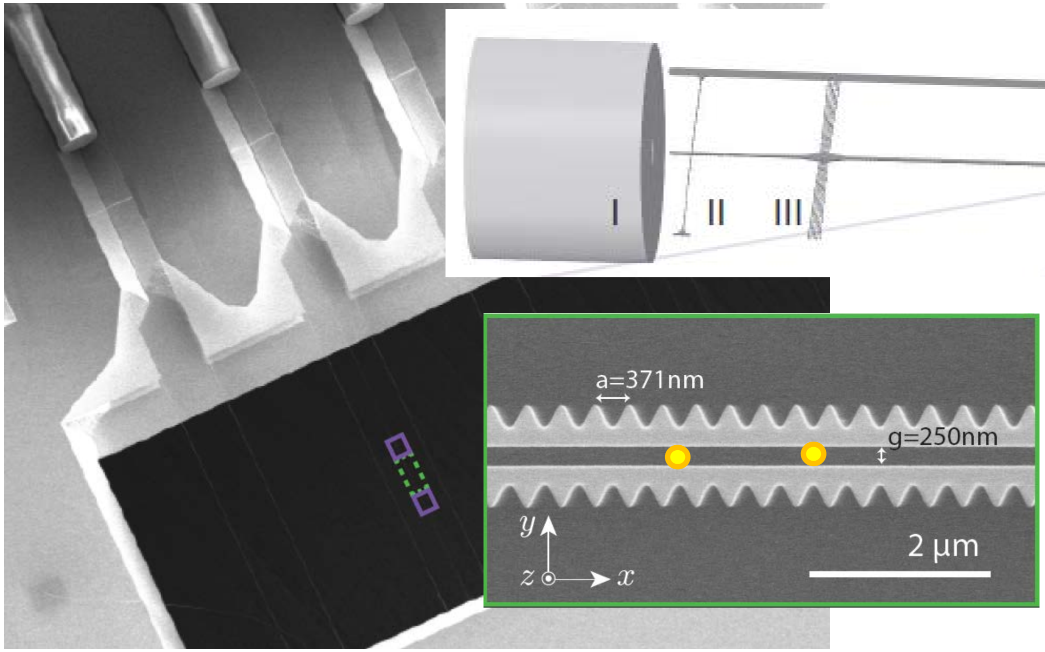


- Control over dispersion / spatial modes
- Band gaps – forbidden propagation

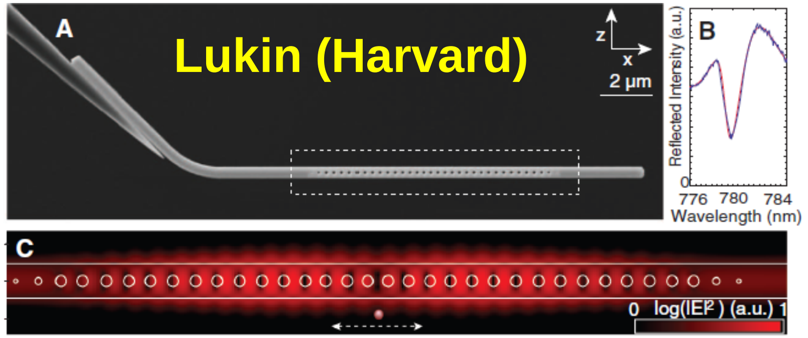


Photonic crystals

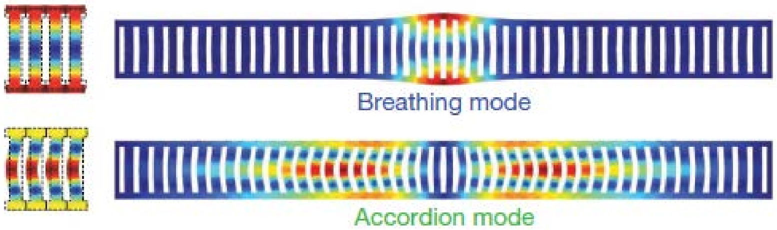
- Experiments coupling atoms to 1D beams and cavities



Painter, Kimble

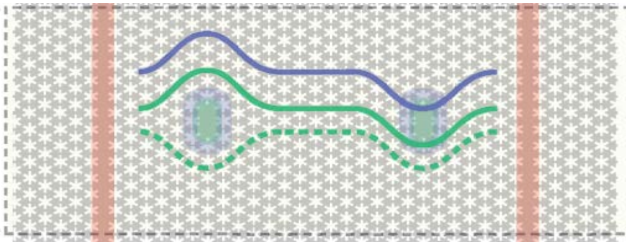


- Tremendous figures of merit and configurability



Cavities/optomechanics

$$Q > 10^6, V < \lambda^3$$



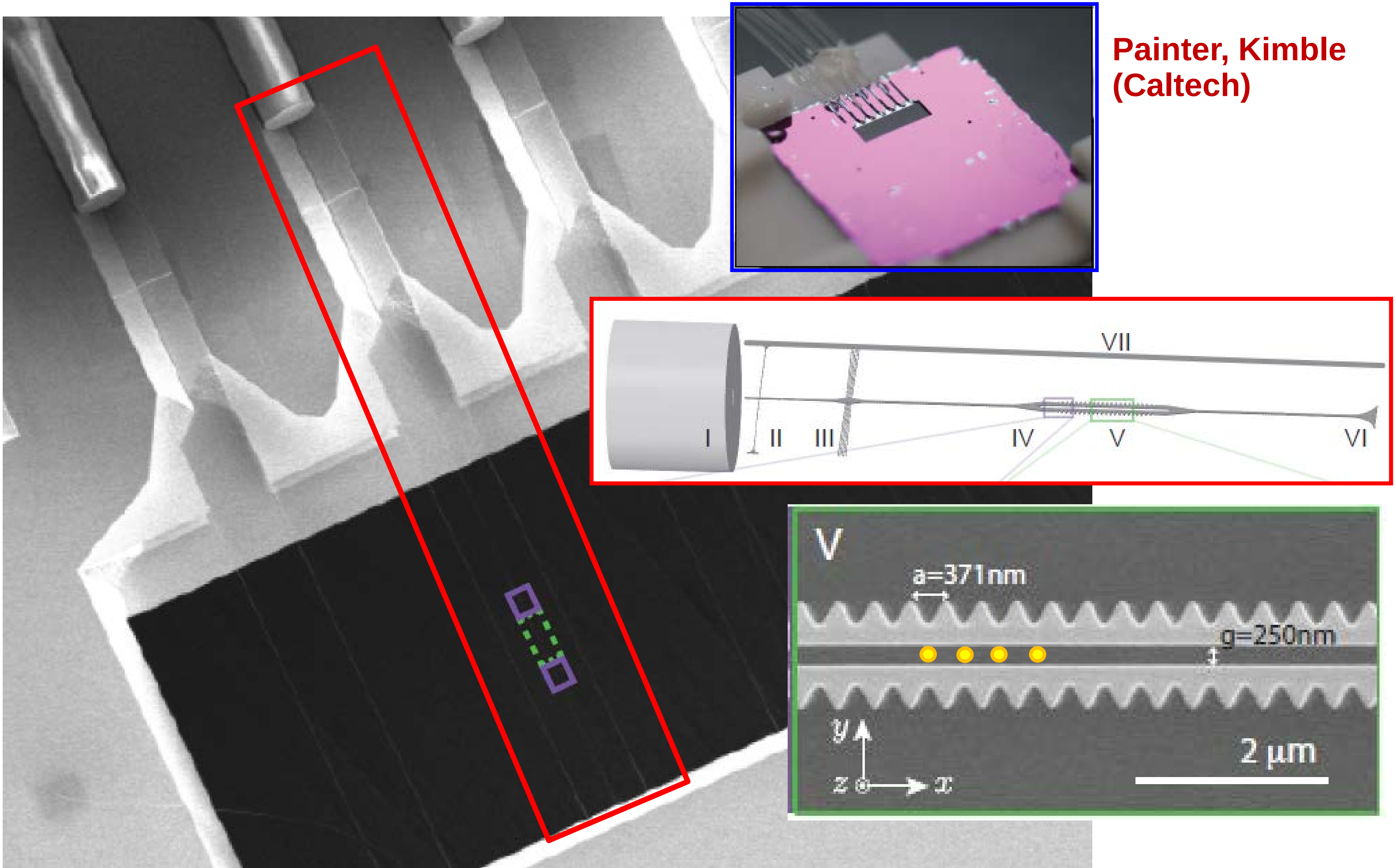
2D arrays

Painter group

Photonic crystal waveguide

- Overview of device

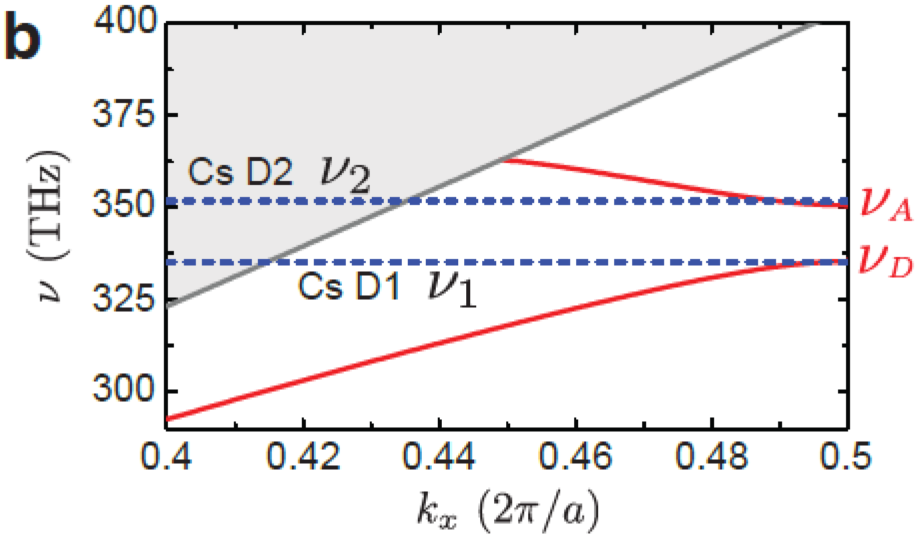
A Goban et al., Nature Commun. 5, 3808 (2014)

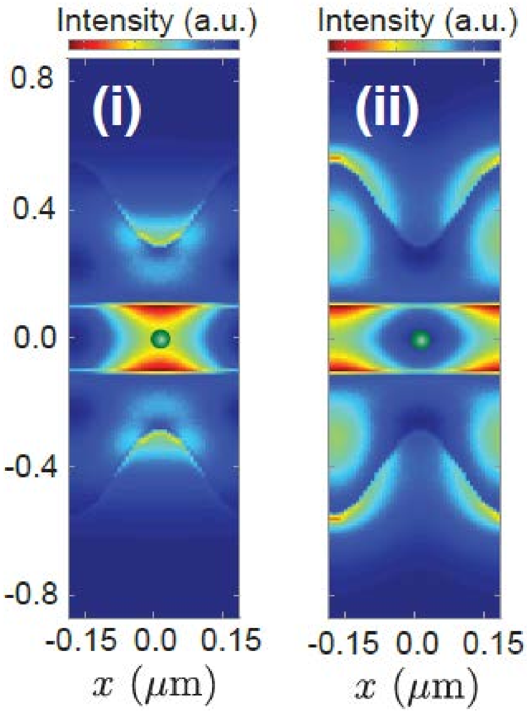


Painter, Kimble (Caltech)

Atom-light interactions

- Band structure – separation of trapping and "quantum optical" physics





- Demonstrated parameters:

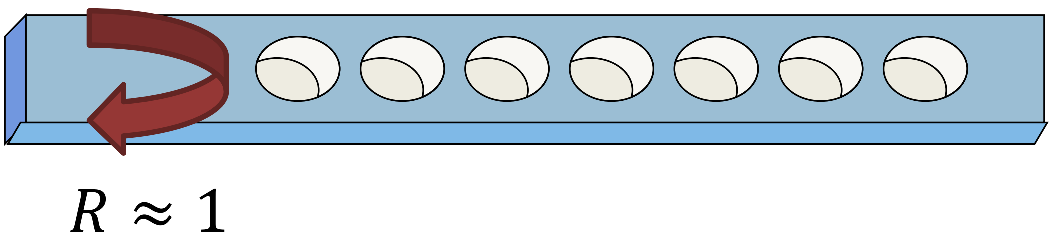
$$\langle N_{\text{atoms}} \rangle \sim 1$$

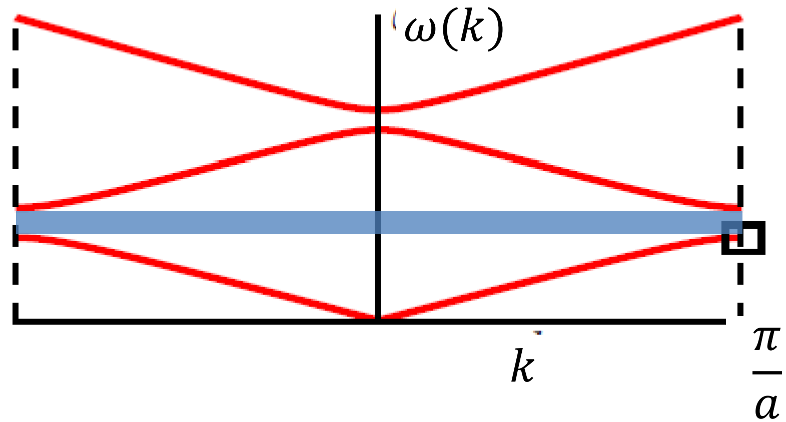
$\frac{\Gamma_{1D}}{\Gamma_{total}} \sim 40\%$ (enhanced by slow group velocity near band edge)

- Lack of efficient cooling mechanism

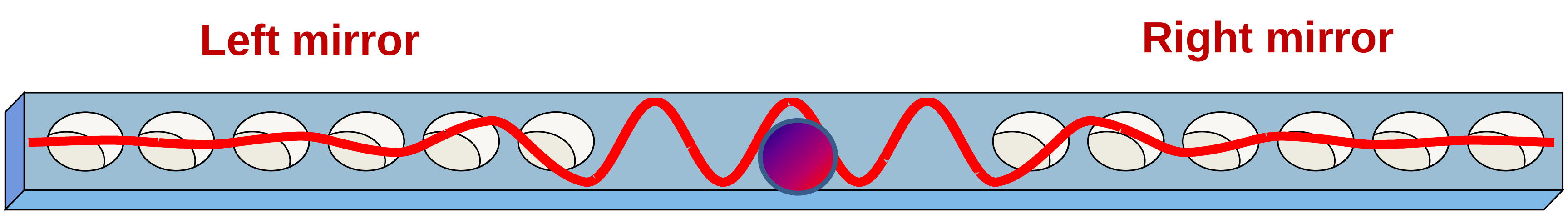
Photonic crystal cavities

- Light cannot propagate when its frequency is in a band gap
  - Nearly perfect mirror



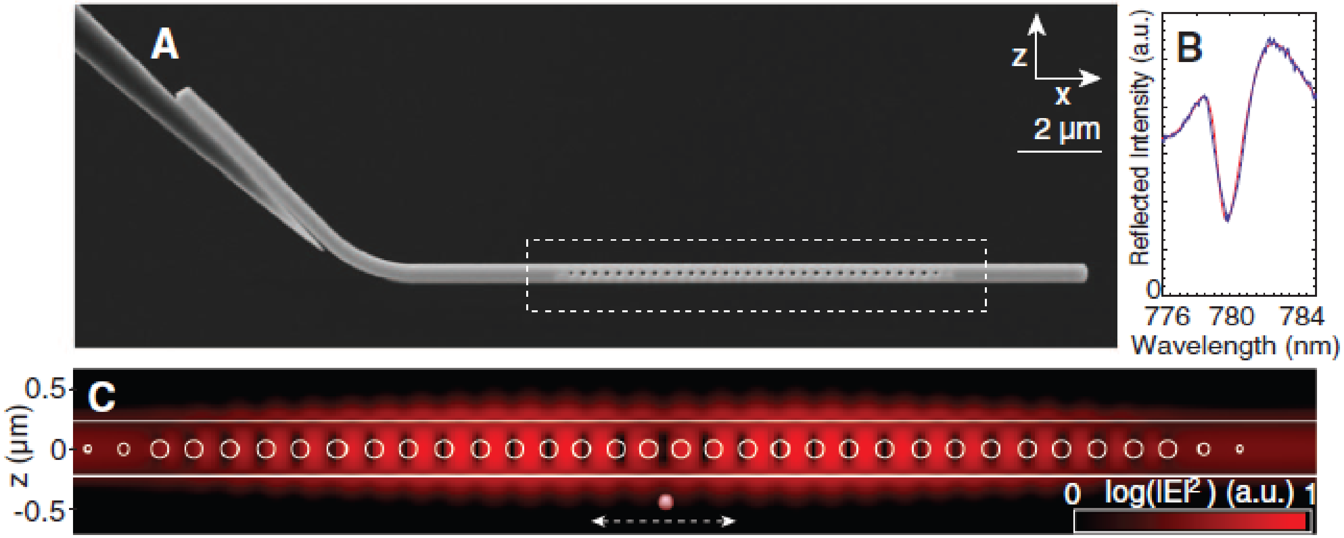


- Create a photonic crystal cavity in a dielectric defect region

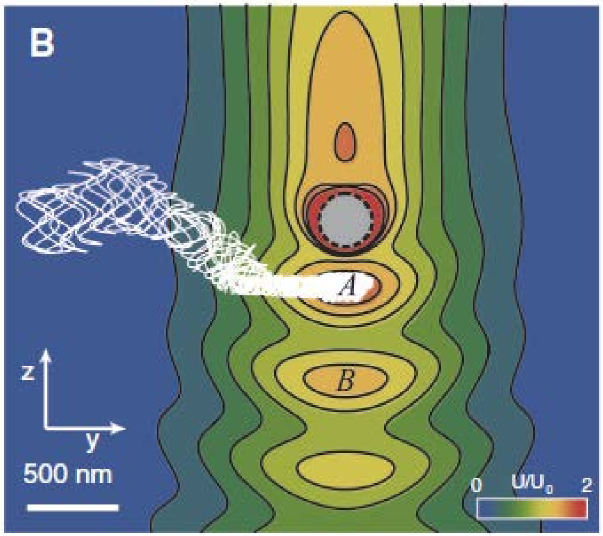


Photonic crystal cavity experiment

- Overview of device (JD Thompson et al., Science 340, 1202 (2013))



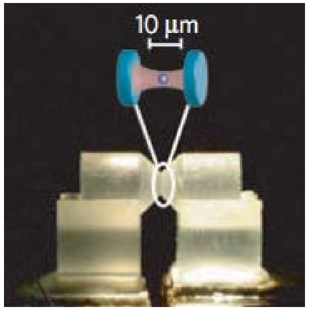
- Trapping via single-atom optical tweezer



$g \sim 2\pi \times 600$ MHz
$\kappa \sim 2\pi \times 800$ GHz
$\Gamma \sim 2\pi \times 6$ MHz

What's next?

- Does nanophotonics just enable us to do old things better?



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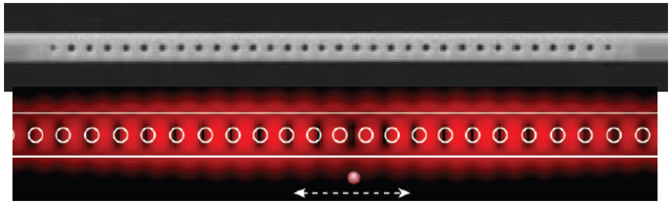

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Jaynes-Cummings model

OR

Surface & vacuum forces

Dimensionality & dispersion

Large per-photon forces

Strong atom-photon interactions

New paradigms

Quantum information processing

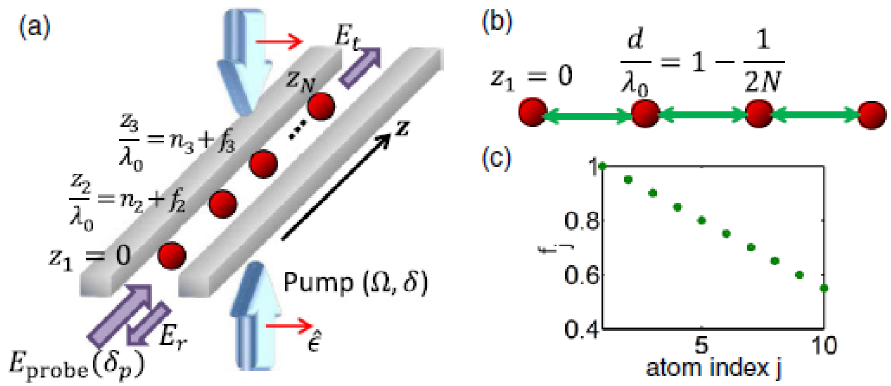
Single-photon nonlinear optics

Many-body physics

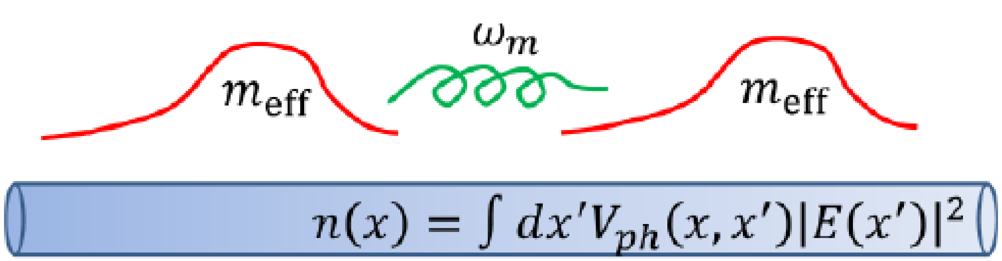
Atom trapping

My group's research

- Atom trapping using quantum vacuum (Casimir) forces
- Long-range atomic interactions mediated by photons
- Atomic self-organization



- Long-range *photonic* interactions
  - Two-photon molecules



- S-matrix techniques for strongly interacting photons