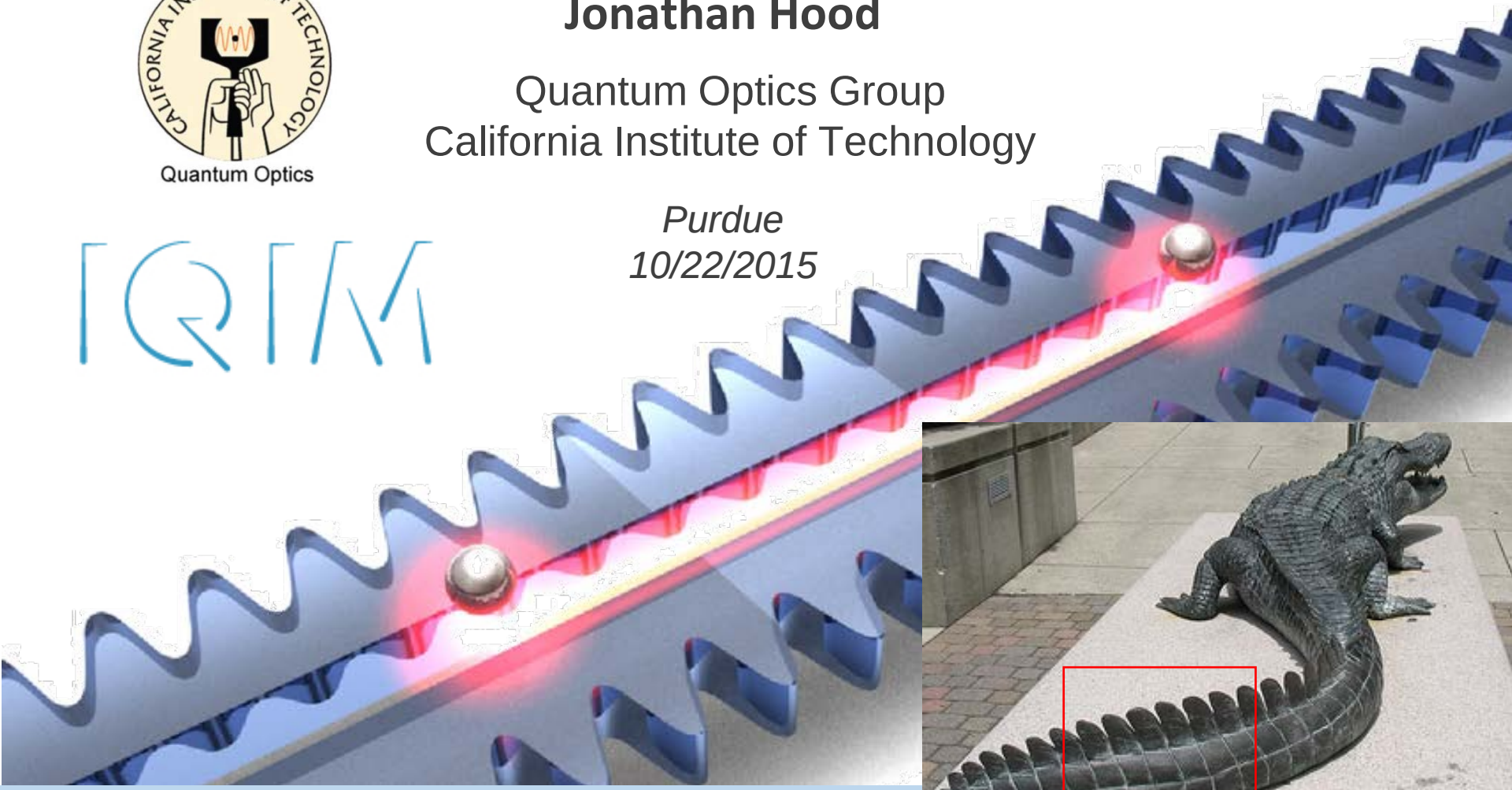
Atom-photon Interactions In 1D Photonic Crystals

From cQED to band-gap physics

Jonathan Hood

Quantum Optics Group
California Institute of Technology

Purdue
10/22/2015



IQIM/NSF/AFOSR QuMPASS MURI/DoD NSSEFF

Outline

- Strong atom-photon interactions
- ‘Alligator’ waveguide fabrication
- The experiment: atoms trapped near photonic crystals
- What next?

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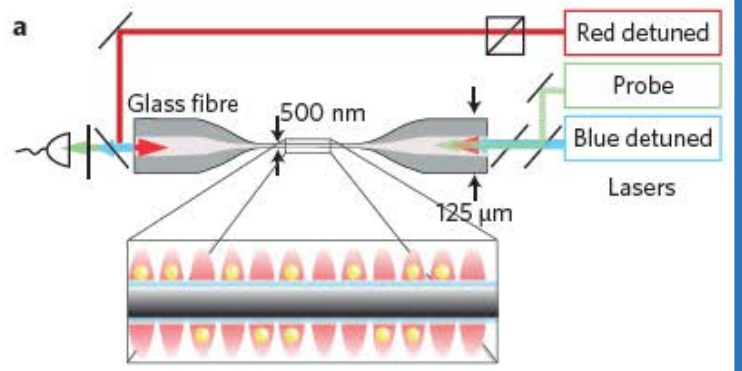
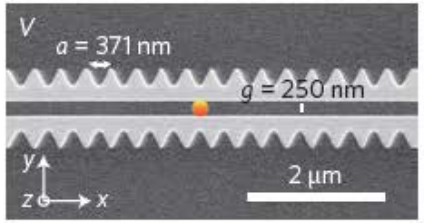
Strong atom-photon interactions

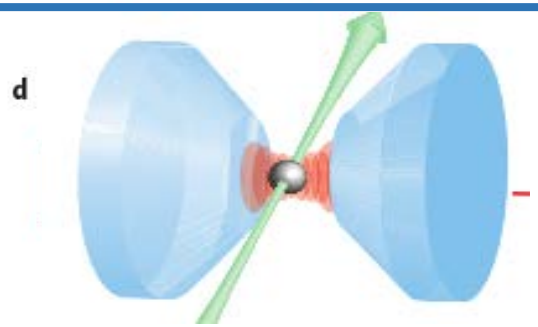
Rauschenbeutel (Vienna TU)

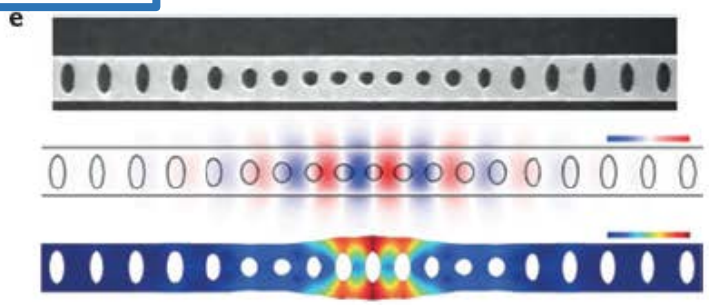


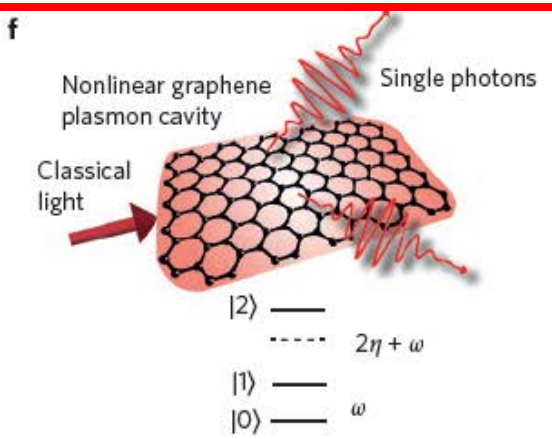
Lukin (Harvard)
Vuletic (MIT)

Kimble – Painter
(Caltech)









nature photonics

REVIEW ARTICLE

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Quantum nonlinear optics — photon by photon

Darrick E. Chang[1], Vladan Vuletić[2] and Mikhail D. Lukin[3]*

Strong atom-photon interactions

$$\Gamma_{1D}(\vec{r}_A) = \frac{1}{2}\frac{c}{v_g}\frac{\sigma_0}{A_{\text{eff}}(\vec{r}_A)}\Gamma_0$$

$$R = \left(\frac{\Gamma_{1D}}{\Gamma_{1D}+\Gamma'}\right)^2$$

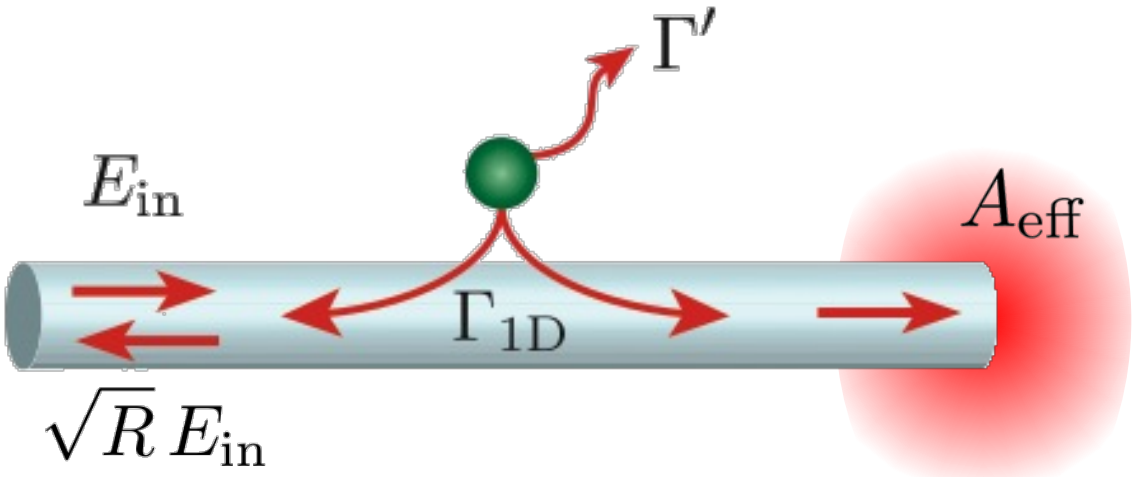
Γ_0 : Free space decay rate

v_g : group velocity

$A_{\text{eff}}(\vec{r}_A)$: effective mode area at $\vec{r}_A$

σ_0 : optical cross-section $= 3\lambda^2/2\pi$

$$\Gamma' \sim \Gamma_0$$



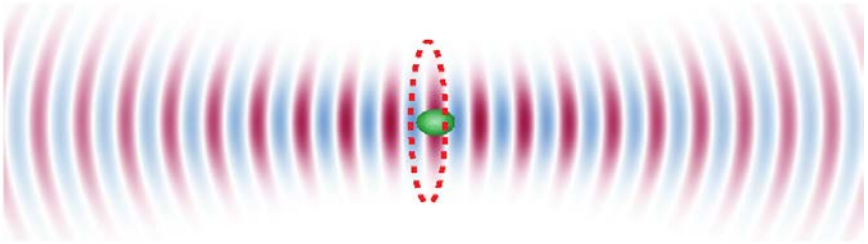
Strong atom-photon interactions

$$\Gamma_{1D}(\vec{r}_A) = \frac{1}{2}\frac{c}{v_g}\frac{\sigma_0}{A_{\text{eff}}(\vec{r}_A)}\Gamma_0$$

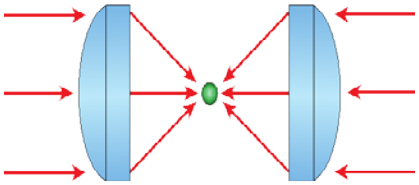
$$R = \left(\frac{\Gamma_{1D}}{\Gamma_{1D}+\Gamma'}\right)^2$$

Single atom in free space

$$A_{\text{eff}} \approx \lambda^2 \qquad \sigma_0 \approx \lambda^2$$



$$R < 1\%$$



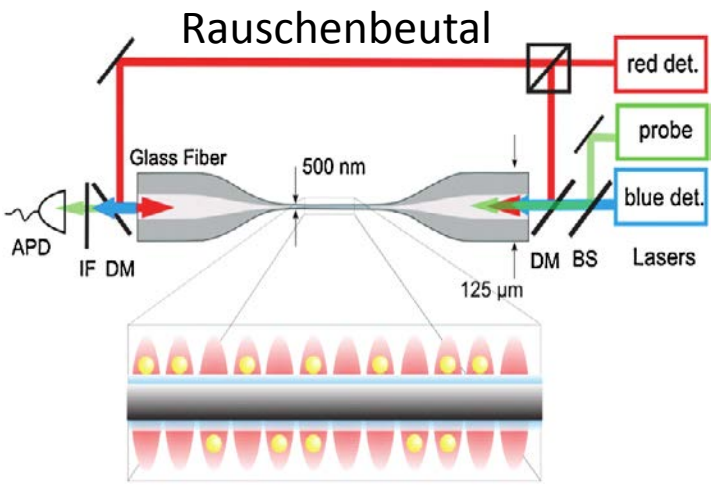
ex. C. Kurtsiefer group (Singapore)
G. Leuchs group (MPL), etc

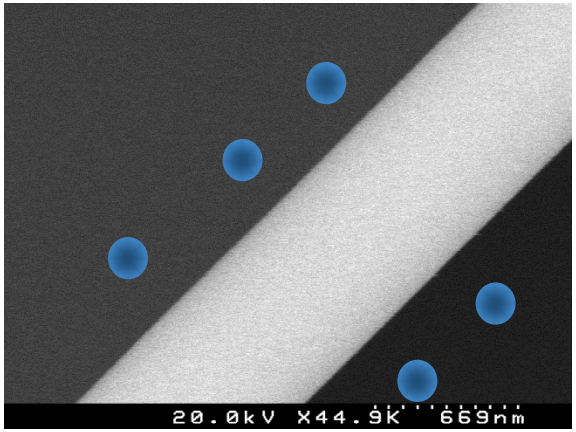
Strong atom-photon interactions

$$\Gamma_{1D}(\vec{r}_A) = \frac{1}{2}\frac{c}{v_g}\frac{\sigma_0}{A_{\text{eff}}(\vec{r}_A)}\Gamma_0$$

$$R = \left(\frac{\Gamma_{1D}}{\Gamma_{1D}+\Gamma'}\right)^2$$

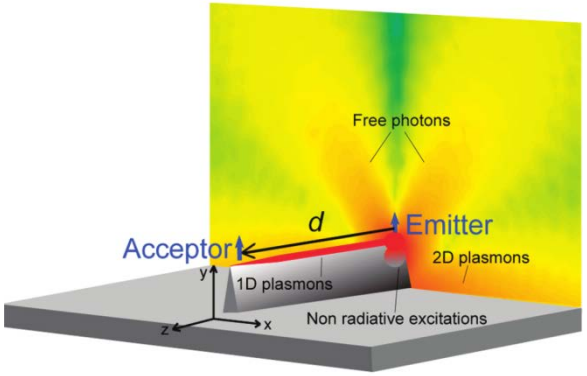
Decrease mode area

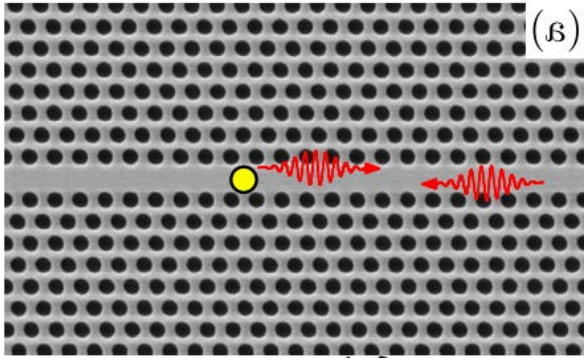




Cs atom 200nm from the surface

$R \sim 3\%$





Lodahl

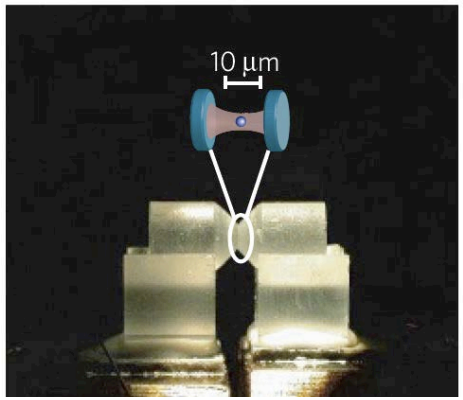
Strong atom-photon interactions

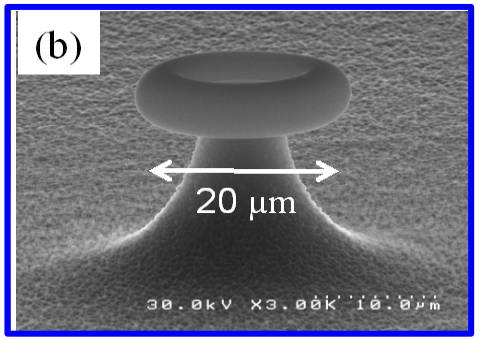
$$\Gamma_{1D}(\vec{r}_A) = \frac{1}{2}\frac{c}{v_g}\frac{\sigma_0}{A_{\text{eff}}(\vec{r}_A)}\Gamma_0\frac{\text{Finesse}}{\pi}$$

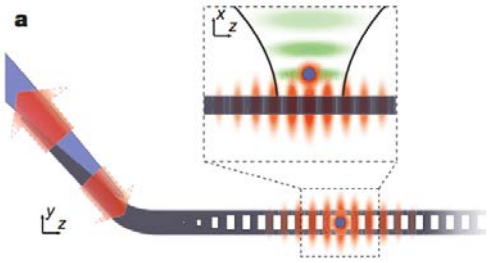
$$R = \left(\frac{\Gamma_{1D}}{\Gamma_{1D}+\Gamma'}\right)^2$$

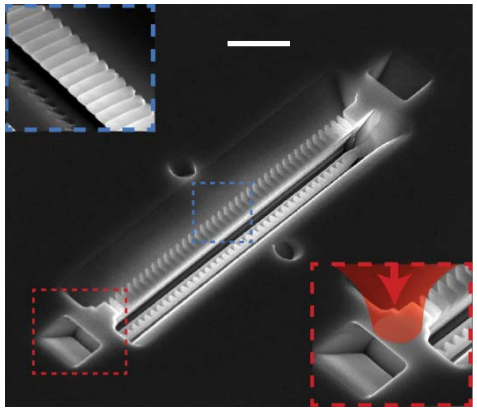
Increase by number of photon passes

Number of passes

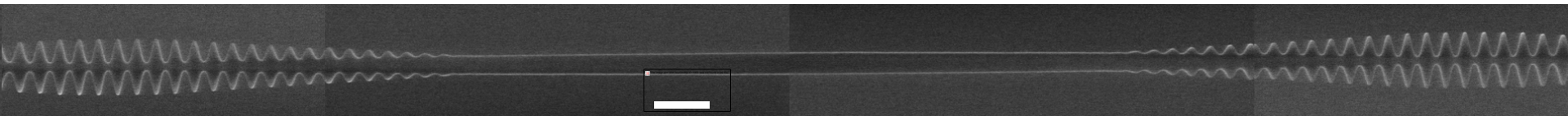








ex. Kimble,Faraon, Rempe, Lukin



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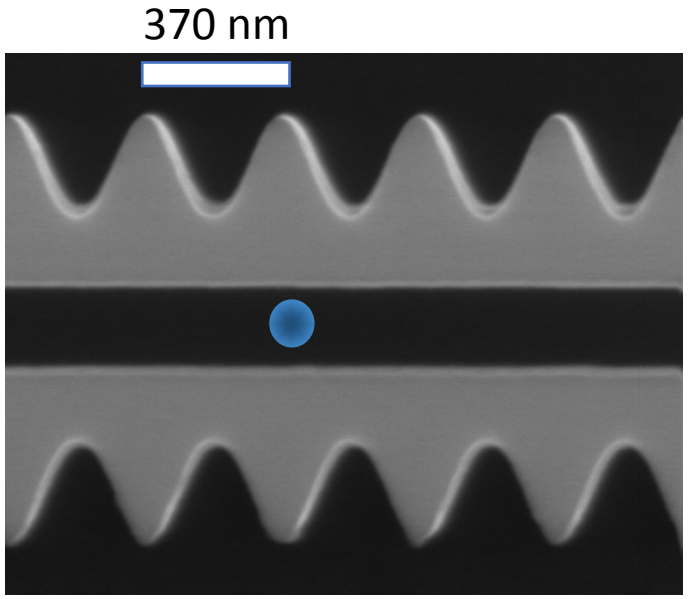
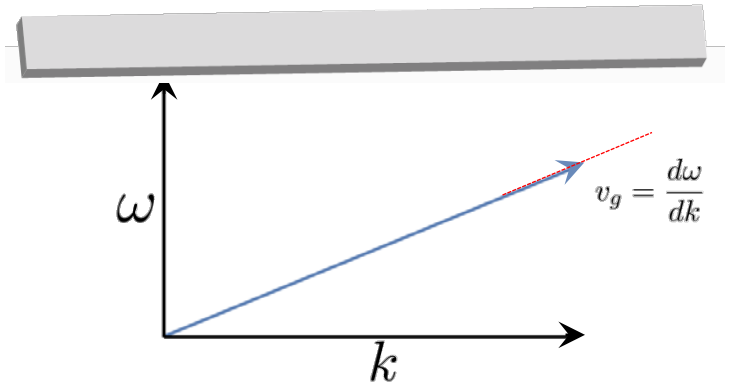
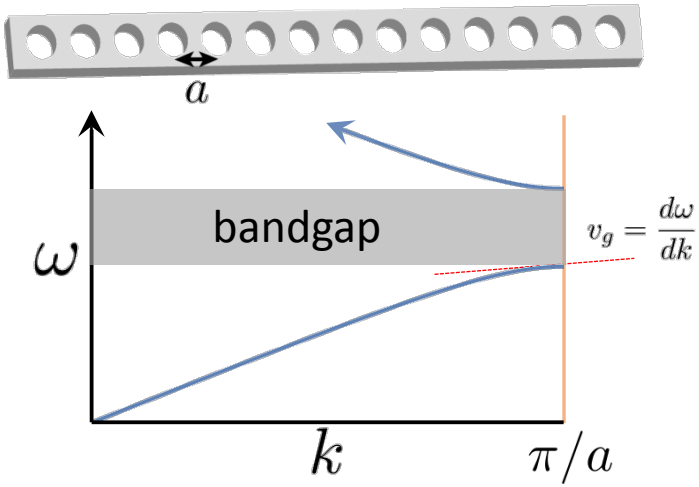
$$R = \left(\frac{\Gamma_{1D}}{\Gamma_{1D}+\Gamma'}\right)^2$$

Photonic Crystal Waveguide



$R > 95\%$



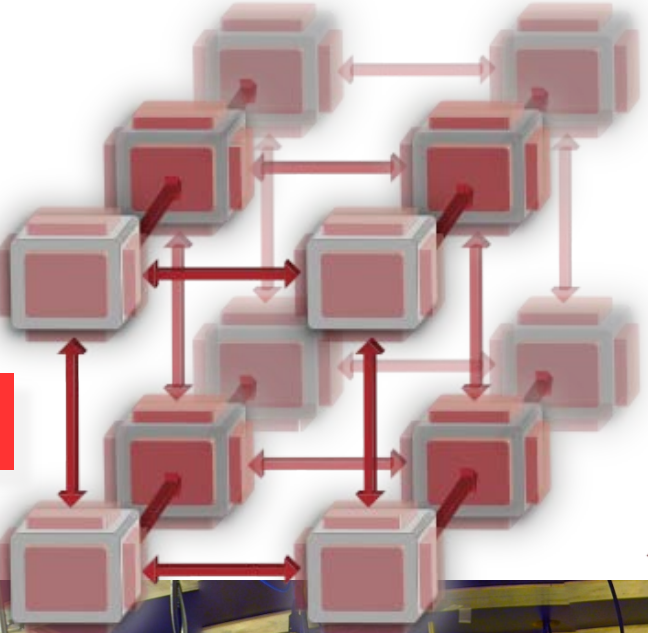


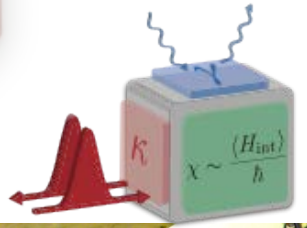
Photon mediated atom-atom interactions

“spin”

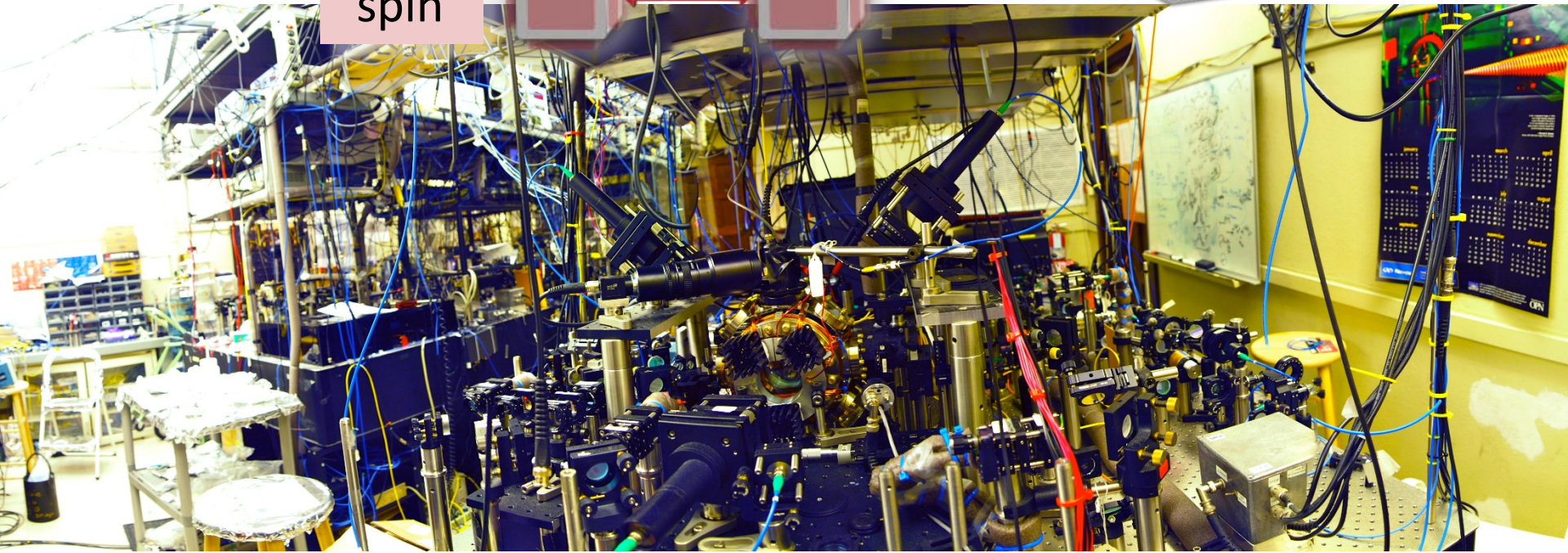
“interaction”

“spin”

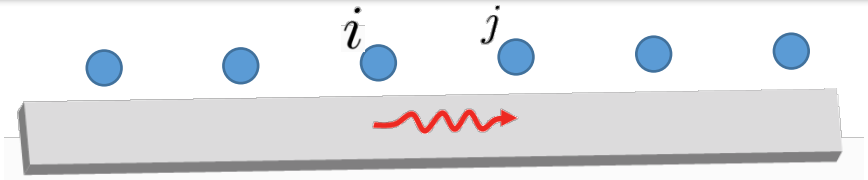




Kimble, “The Quantum Internet”



Photon mediated atom-atom interactions in a 1D system



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

Coherent dipole-dipole interactions

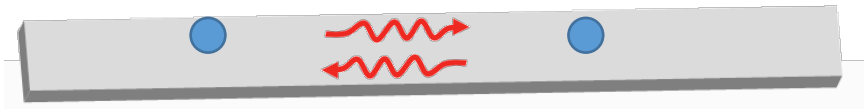
$$H = \hbar\omega_0 \sum_{ij}^{N} J_{ij}\sigma_i^\dagger \sigma_j$$

$$J_{ij} \propto \mathrm{Re}\left[G(\mathbf{r}_i, \mathbf{r}_j, \omega_0)\right]$$

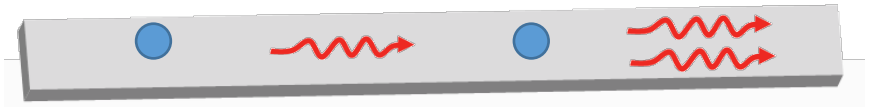
Dissipative interactions

$$\mathcal{L}[\rho] = \sum_{i,j}^{N} \frac{\Gamma_{ij}}{2}\left(2\sigma_i \rho \sigma_j^\dagger - \sigma_i^\dagger \sigma_j \rho - \rho \sigma_i^\dagger \sigma_j\right)$$

$$\Gamma_{ij} \propto \mathrm{Im}\left[G(\mathbf{r}_i, \mathbf{r}_j, \omega_0)\right]$$



Spin-exchange



Cooperative emission

Photon mediated atom-atom interactions

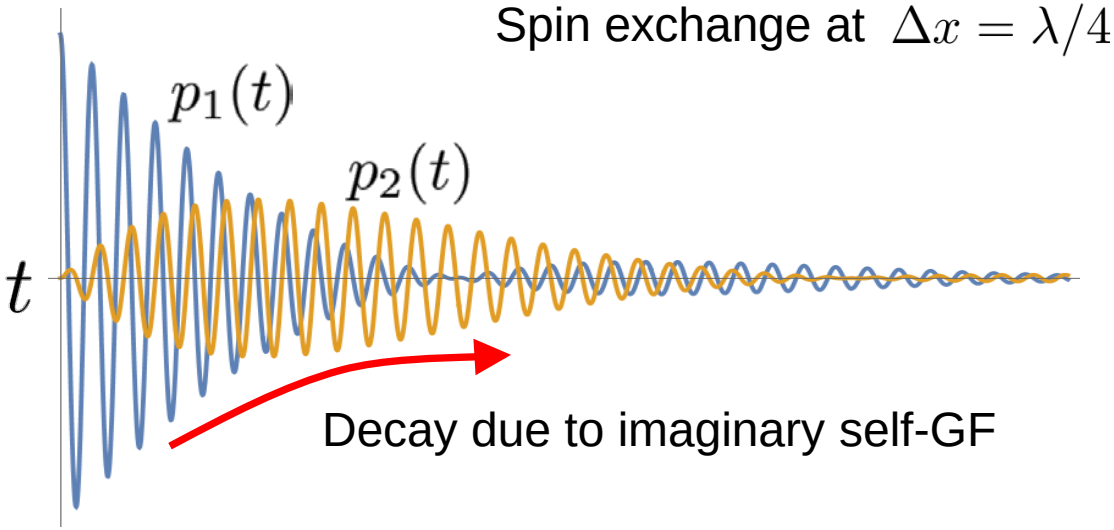
$$J_{ij} \propto \mathrm{Re}\left[G(\mathbf{r}_i, \mathbf{r}_j, \omega_0)\right] \qquad \Gamma_{ij} \propto \mathrm{Im}\left[G(\mathbf{r}_i, \mathbf{r}_j, \omega_0)\right]$$

Waveguide atom-atom interaction

$$G(x_i, x_j) \propto i\, e^{ik|x_i - x_j|}$$

Spin exchange at $\Delta x = \lambda/4$

Initial settings:
$p_1(t=0) = 1$
$p_2(t=0) = 0$

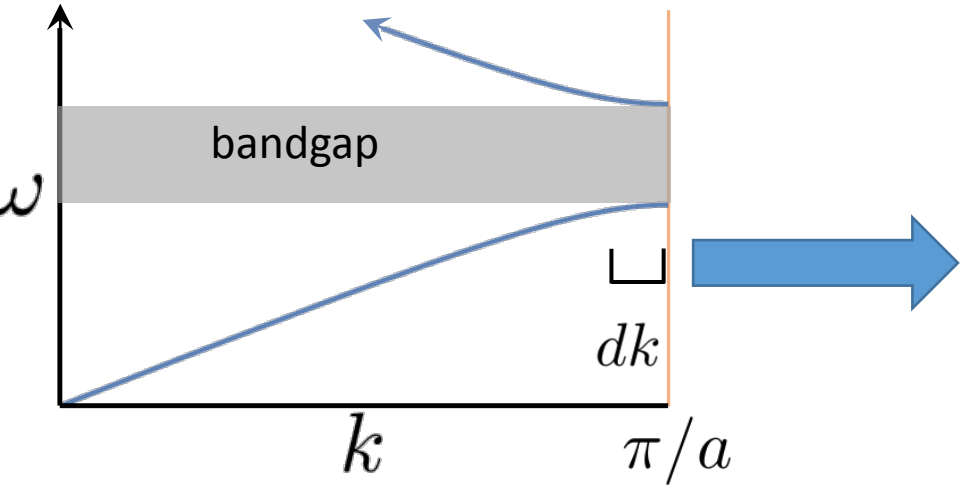


Photon mediated atom-atom interactions

$$J_{ij} \propto \mathrm{Re}\left[G(\mathbf{r}_i, \mathbf{r}_j, \omega_0)\right]$$

$$\Gamma_{ij} \propto \mathrm{Im}\left[G(\mathbf{r}_i, \mathbf{r}_j, \omega_0)\right]$$

Photonic Crystal



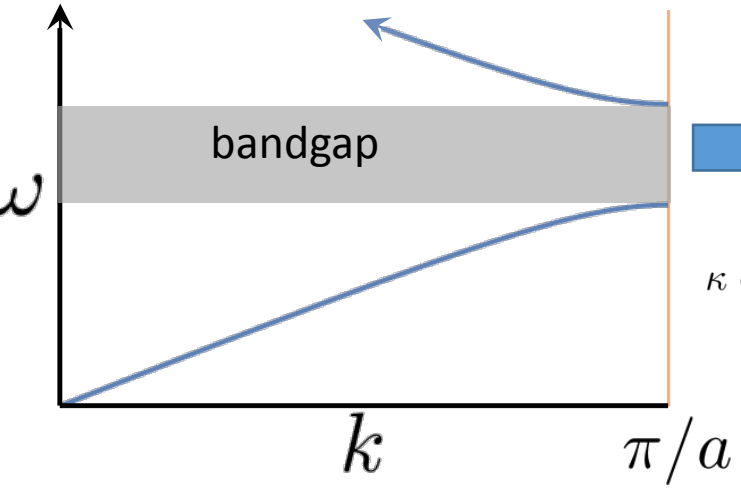
Inside band-gap same as waveguide

$$G(x_i, x_j) \propto \left(\frac{c}{v_g}\right) e^{-\kappa|x_i - x_j|}$$

Photon mediated atom-atom interactions

$$J_{ij} \propto \mathrm{Re}\left[G(\mathbf{r}_i, \mathbf{r}_j, \omega_0)\right] \qquad \Gamma_{ij} \propto \mathrm{Im}\left[G(\mathbf{r}_i, \mathbf{r}_j, \omega_0)\right]$$

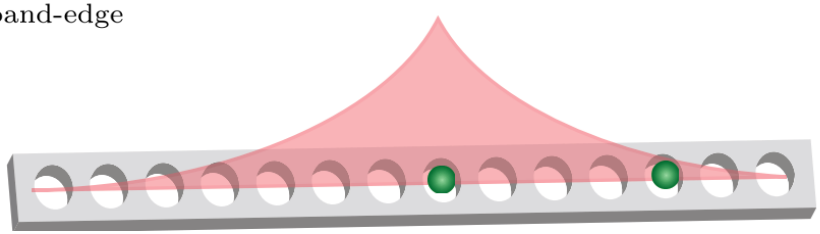
Photonic Crystal



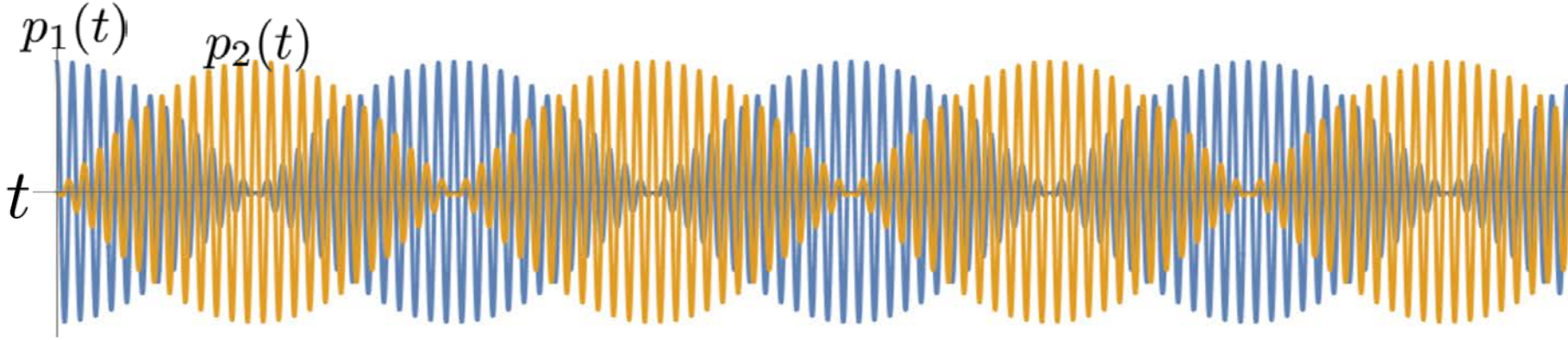
Inside band-gap:

$$G(x_i, x_j) \propto \left(\frac{c}{v_g}\right) e^{-\kappa|x_i - x_j|}$$

$$\kappa \propto \sqrt{\omega - \omega_{\text{band-edge}}}$$



Spin exchange in band-gap



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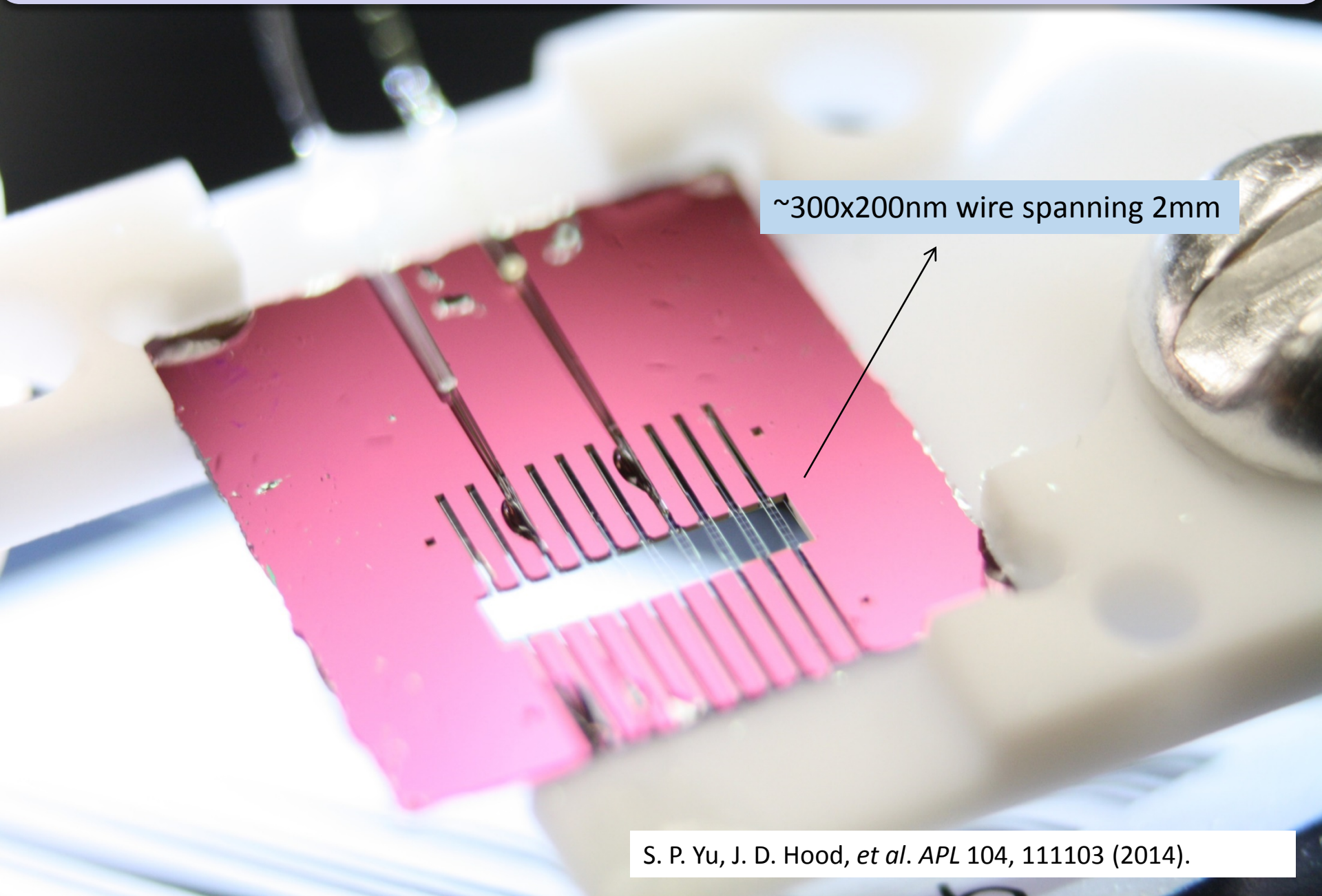
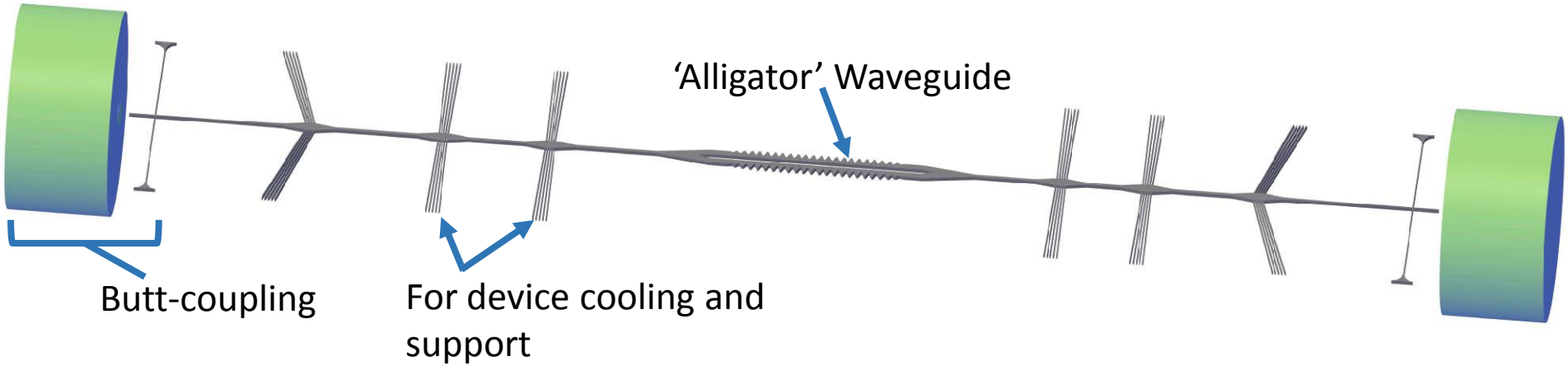
The Alligator Chip

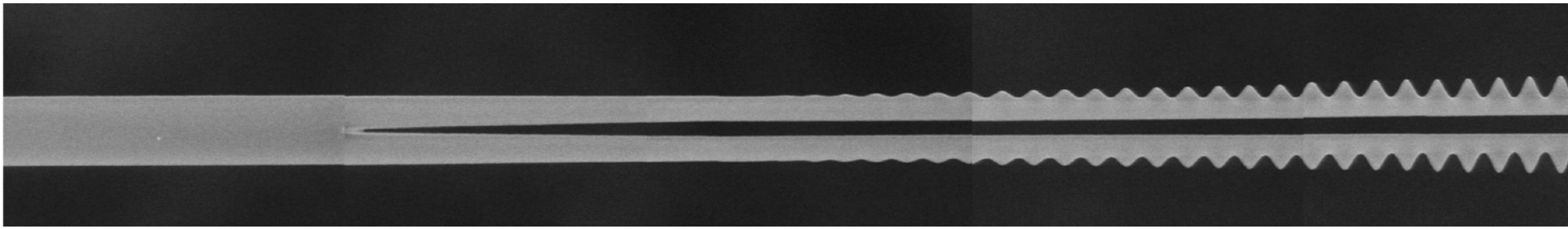


S. P. Yu, J. D. Hood, *et al*. *APL* 104, 111103 (2014).

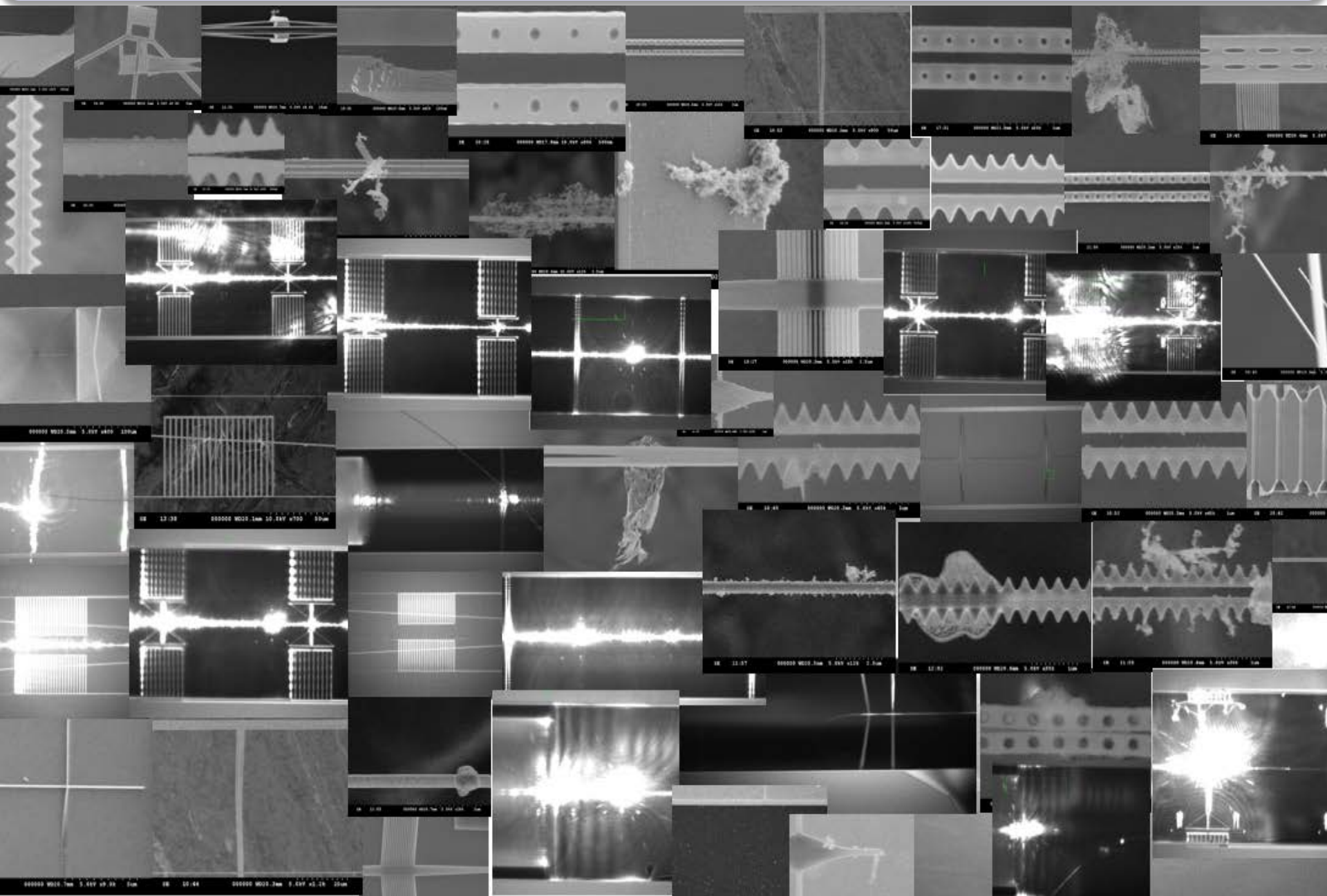
Overview of the “Alligator” photonic crystal waveguide

(Fabrication and characterization) S. P. Yu, J. D. Hood, *et al*. APL 104, 111103 (2014).

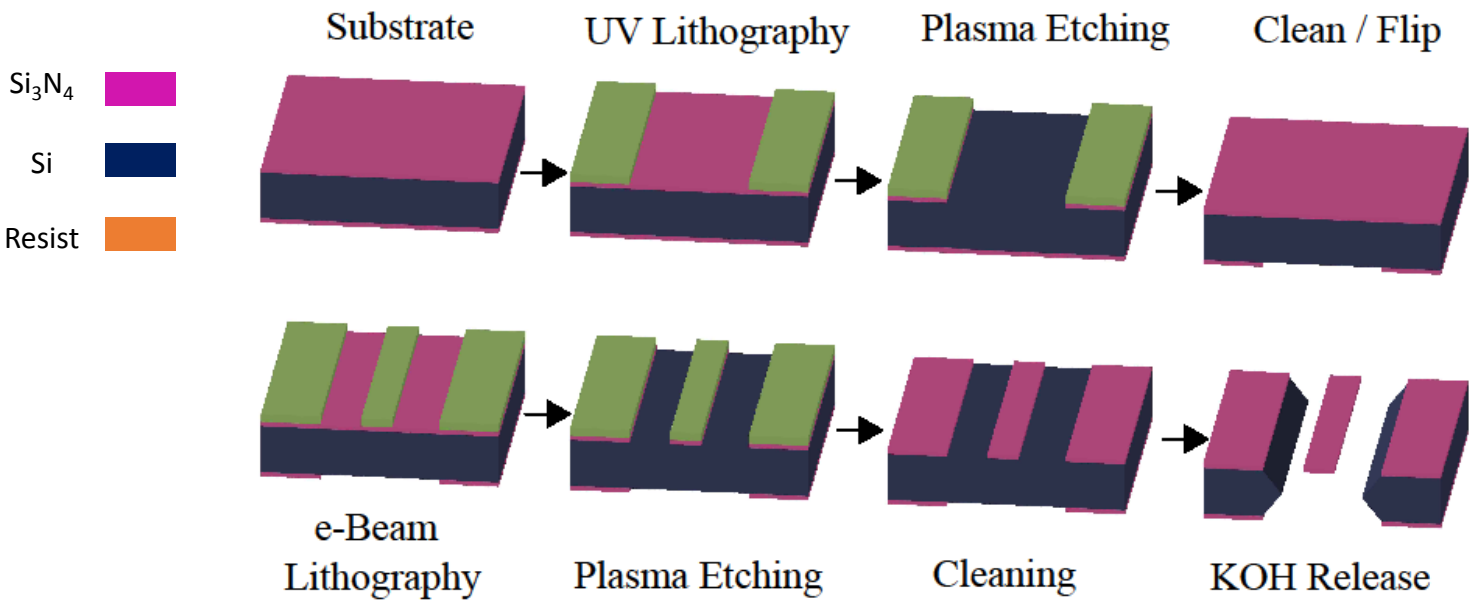




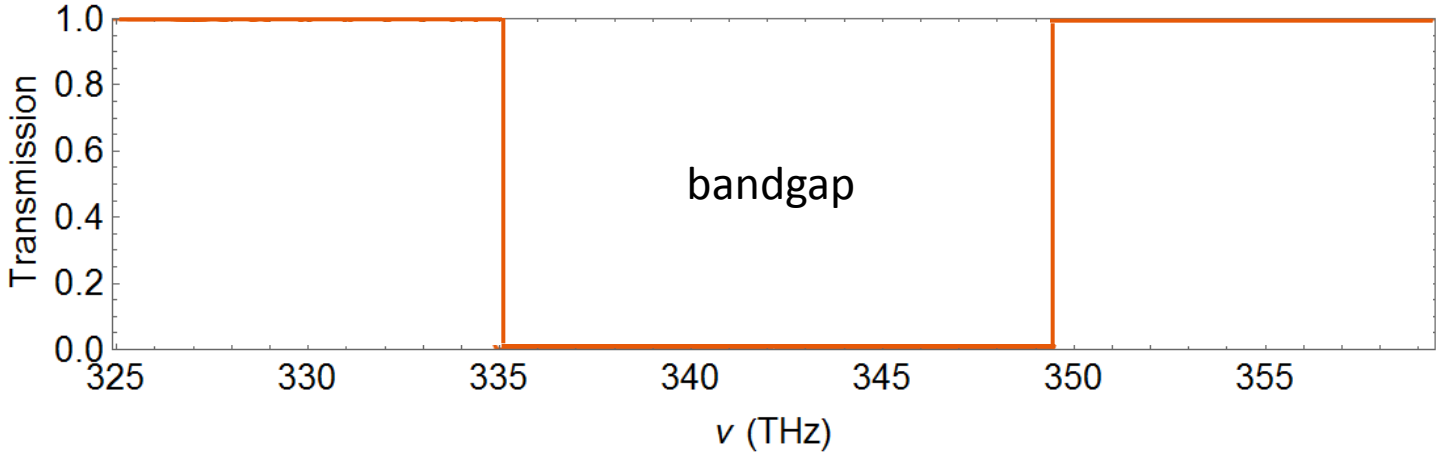
The Graveyard

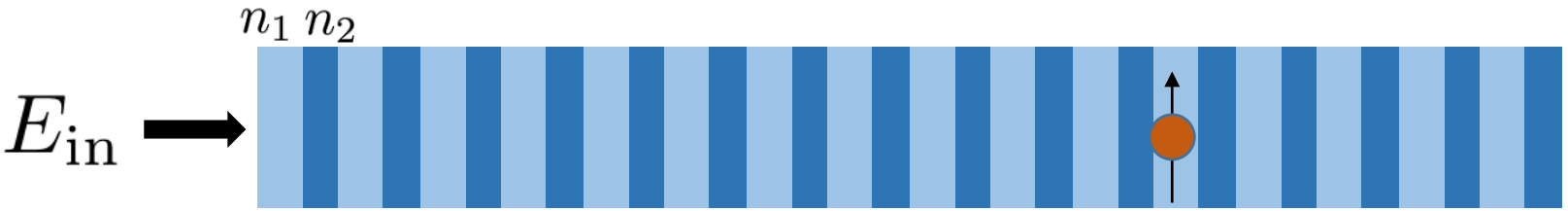


Fabrication

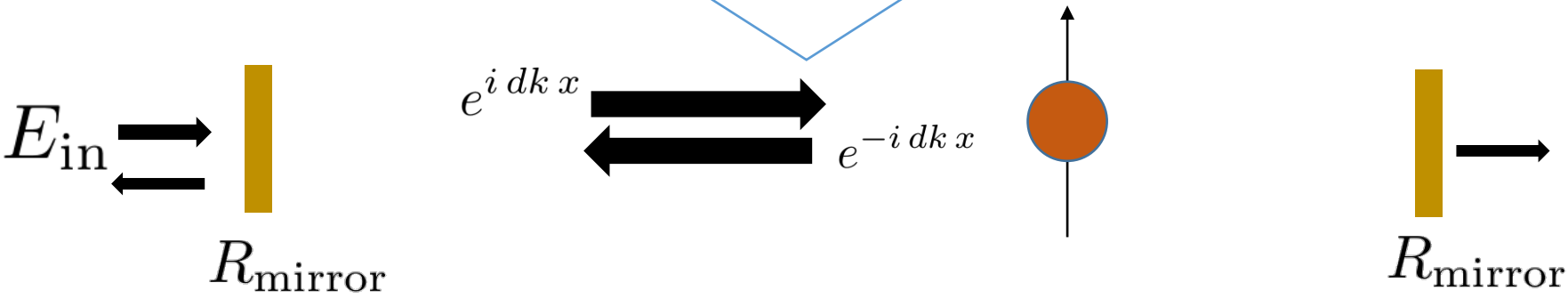


Finite photonic crystal model

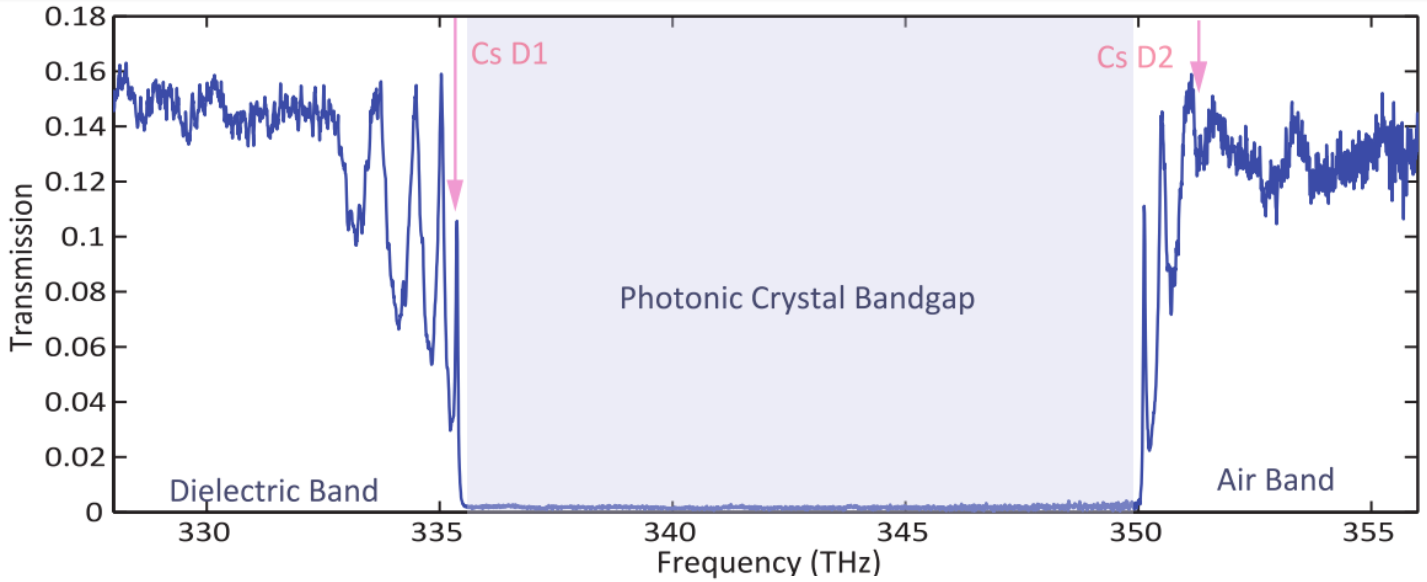


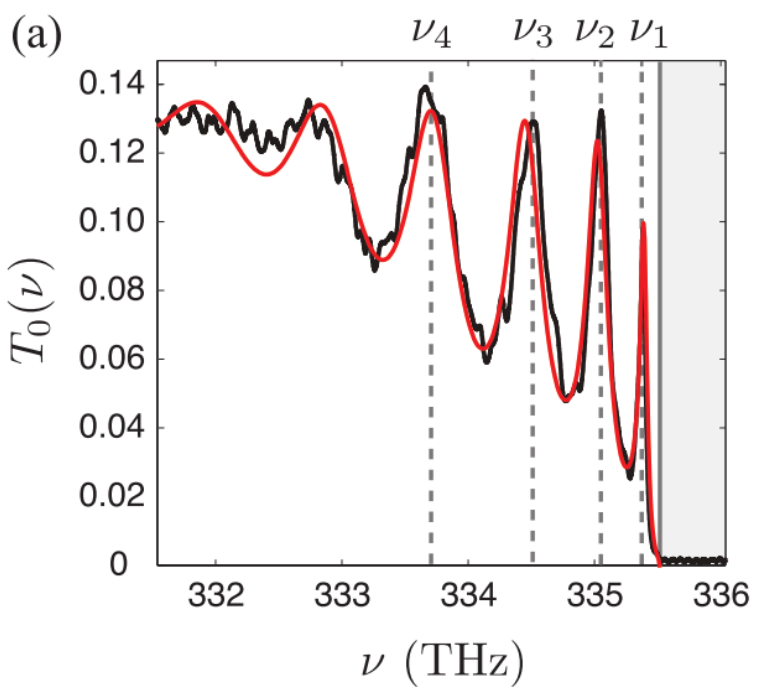


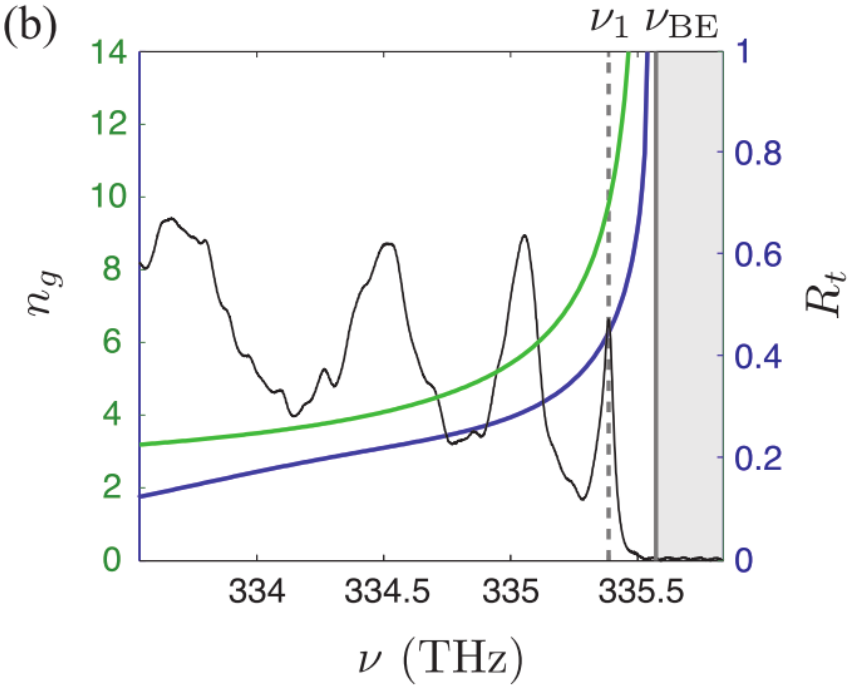
transformation



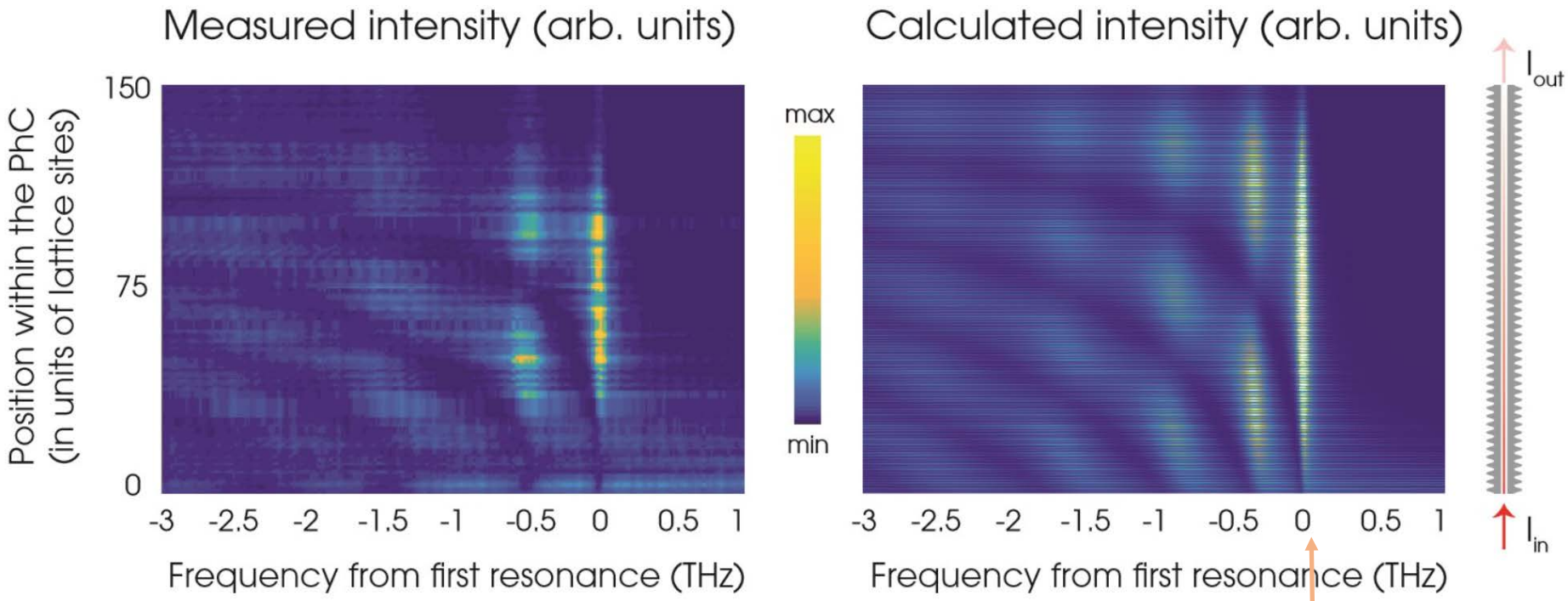
Measured photonic crystal transmission signal

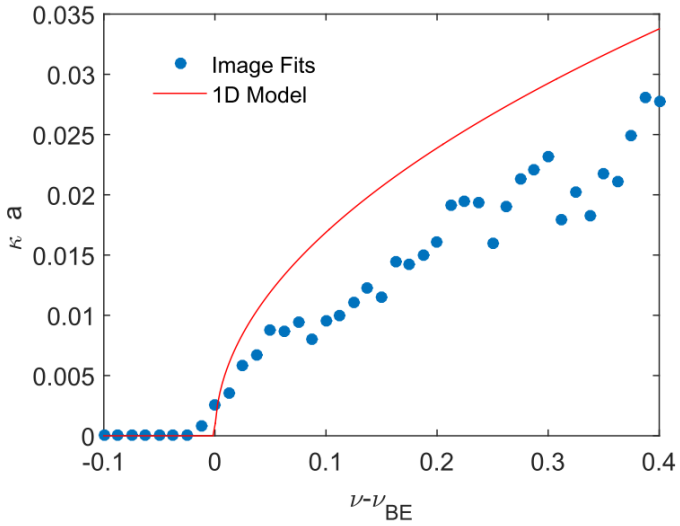






Imaged scattered light from photonic crystal





$m = 1$

Cavity resonance condition:

$$dk\,L = m\pi$$

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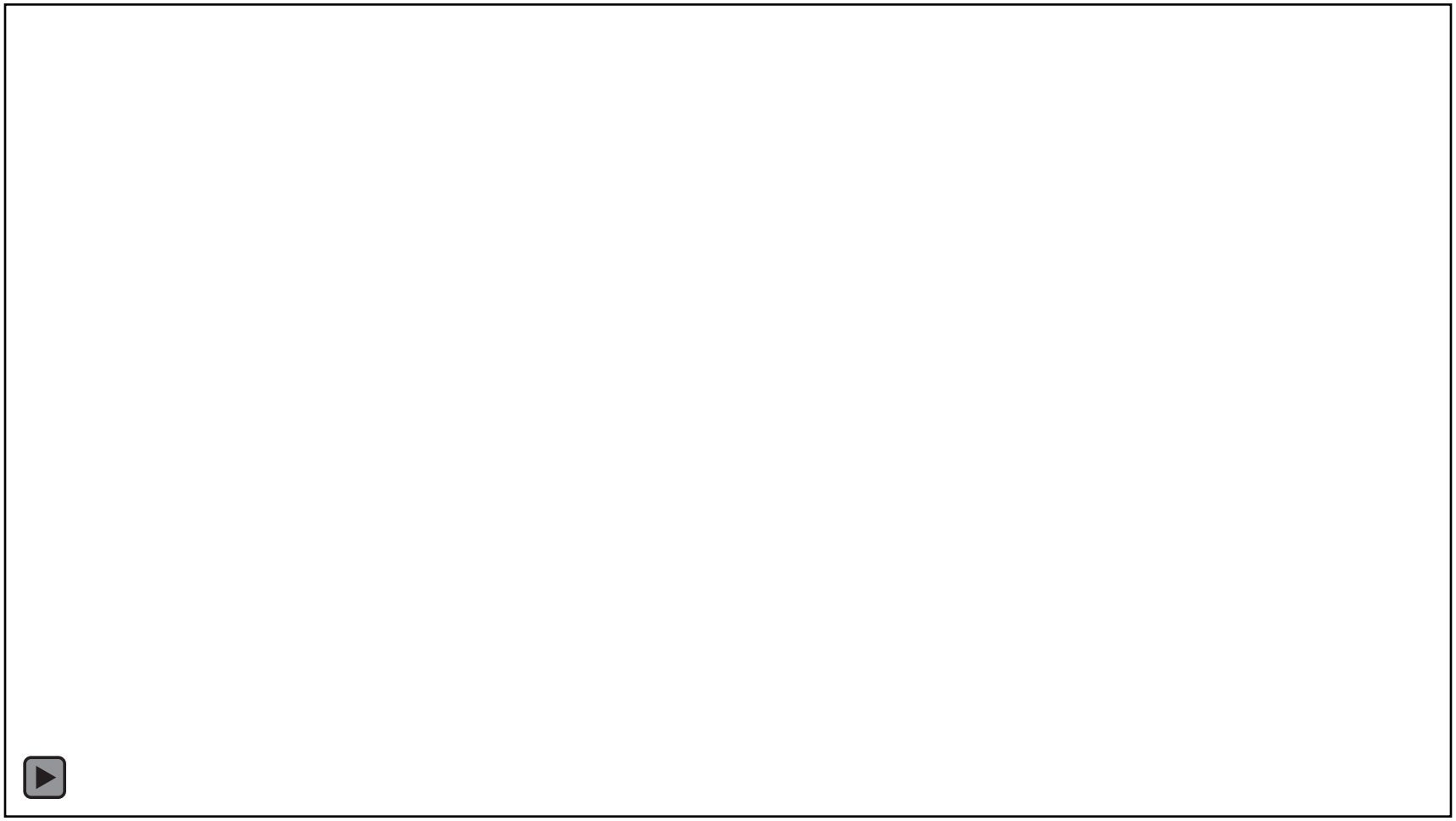
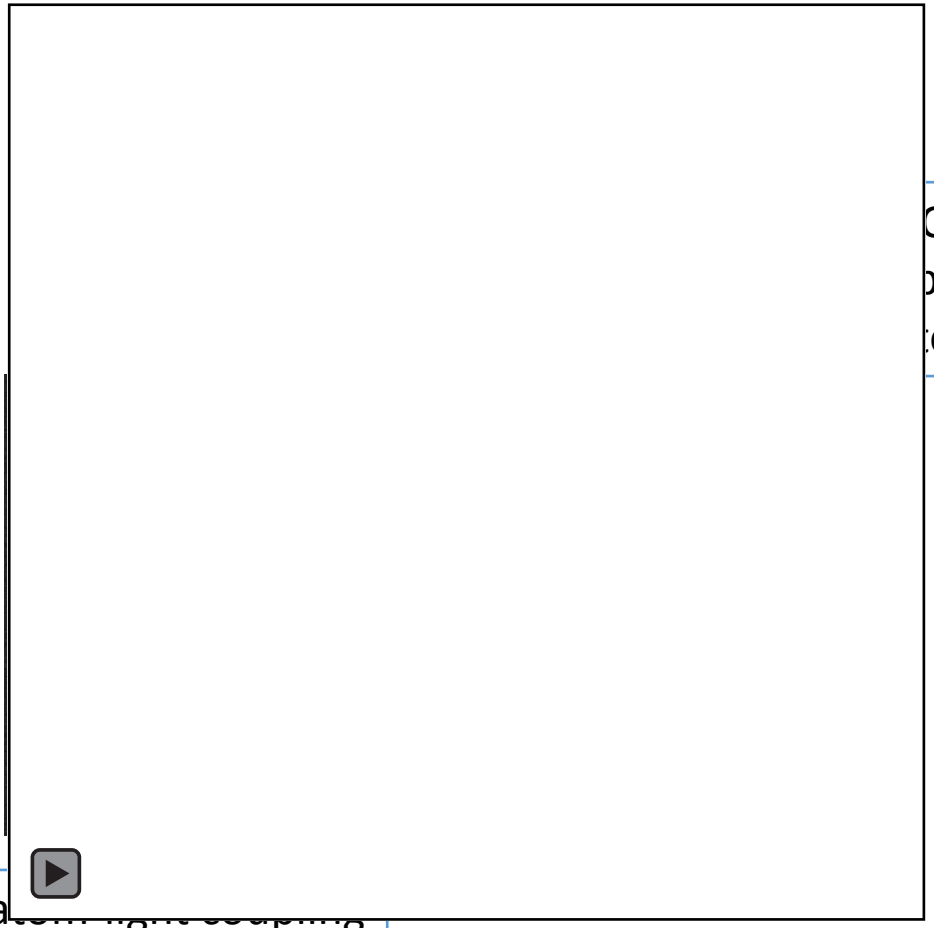
In Chen-Lung's words...



Cold atom device loading into the Alligator PCW

N_i ~ 5x10^6 Cs atoms
at ρ ~ 1x10^{11}/cm^3
T ~ 10μK



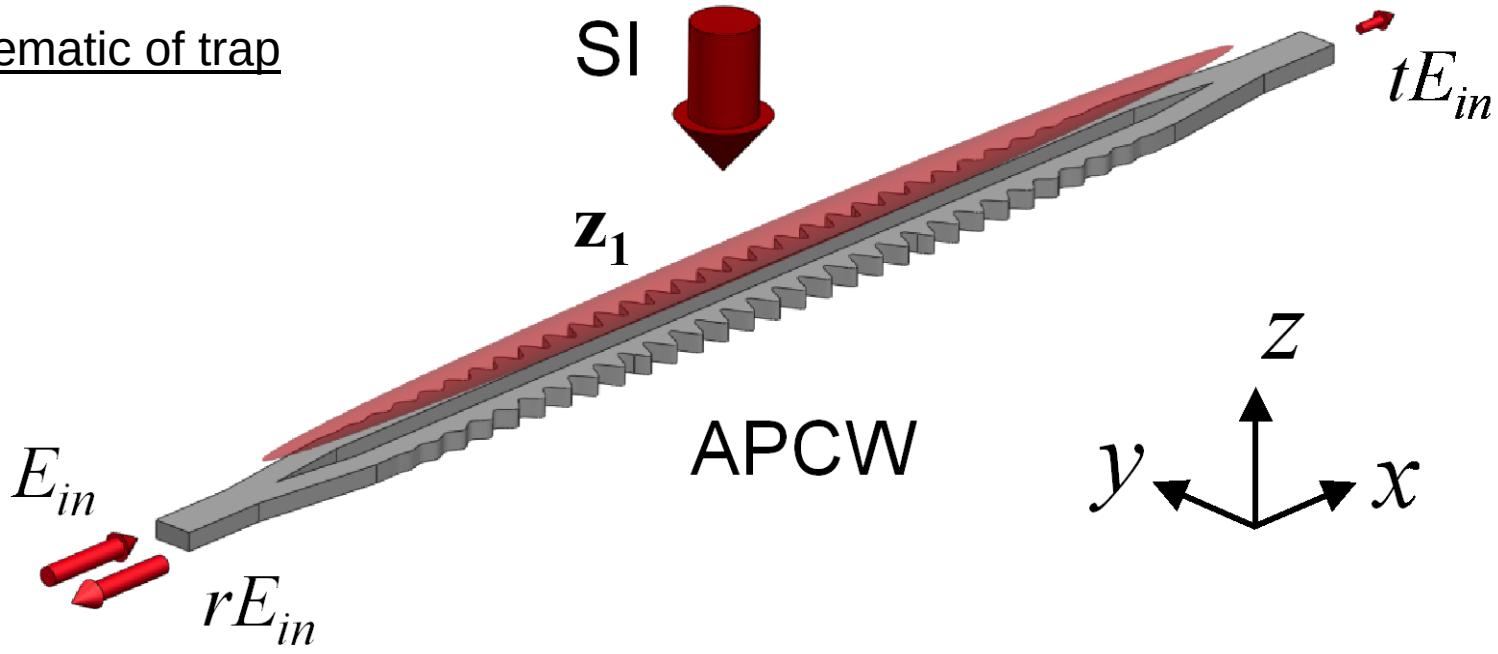
Optical fiber
butt-coupled
to SiN device

SiN device –
1d photonic
crystal
waveguide

N_f ~ 2x10^6 Cs atoms
at ρ ~ 2x10^{10}/cm^3
T ~ 20μK

Trapping atoms via side illumination

Schematic of trap

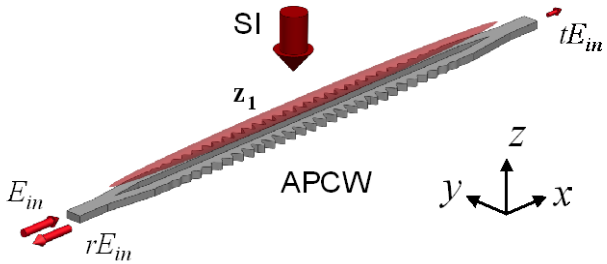


- Trapping atoms by scattering from the structure
- Superradiance from trapped atoms near the bandedge

Ref: J.D.Thompson, *et al*. *Science* 340, 1202 (2013). [Lukin]

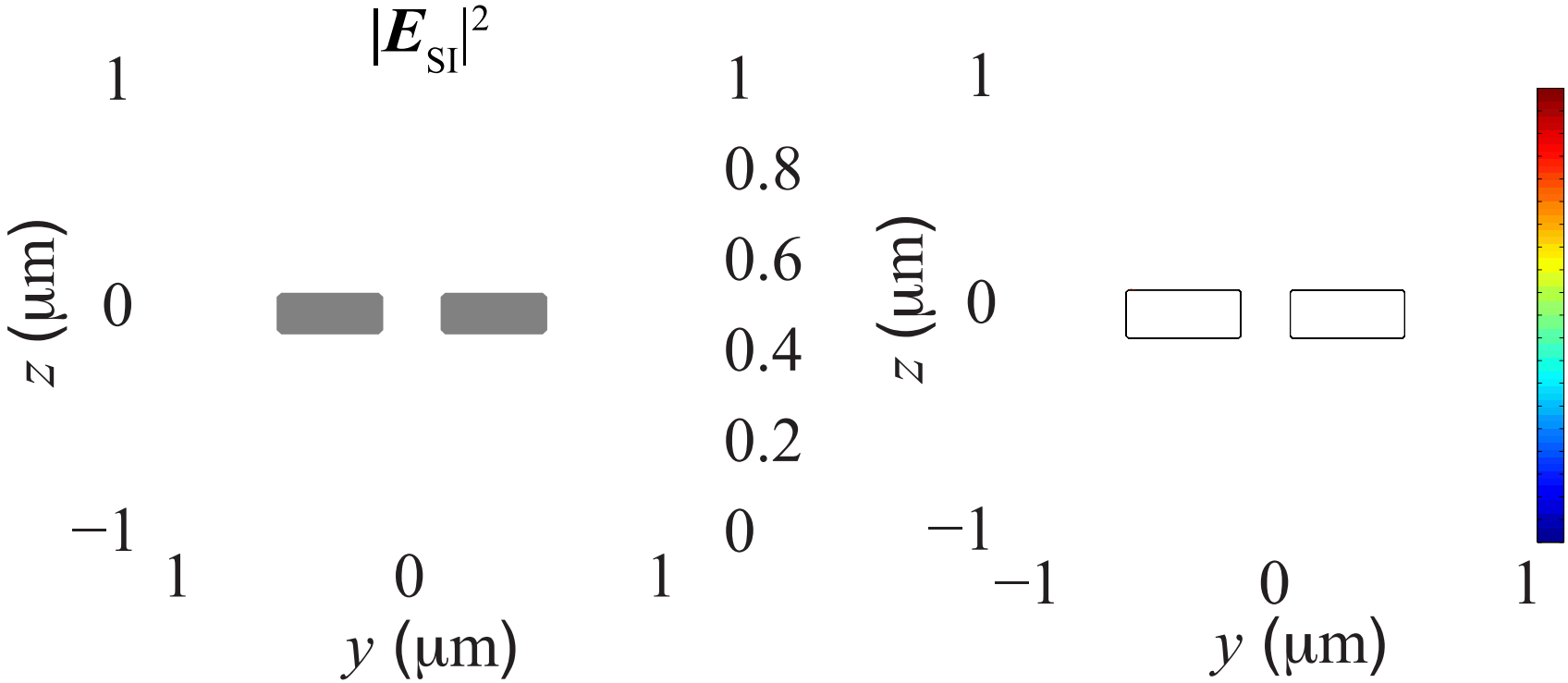
Cross section of trap and coupling rate

Cross section of scattering intensity and coupling rate

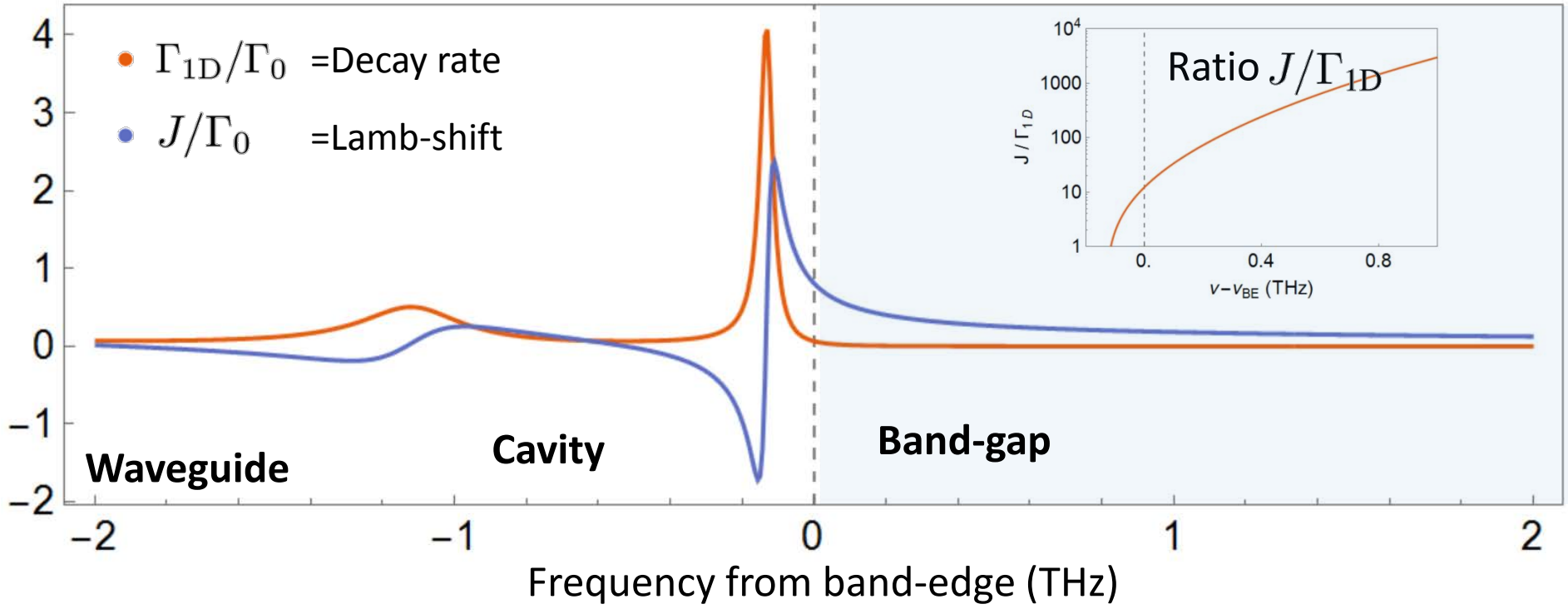


Multiple trapping sites ➔ only closest site strongly couples to the waveguide.

(e.g., $\Gamma_{1D}(z_1)/\Gamma_{1D}(z_2) \sim 100$)



Photonic crystal decay rate and lamb-shift



Coherent evolution

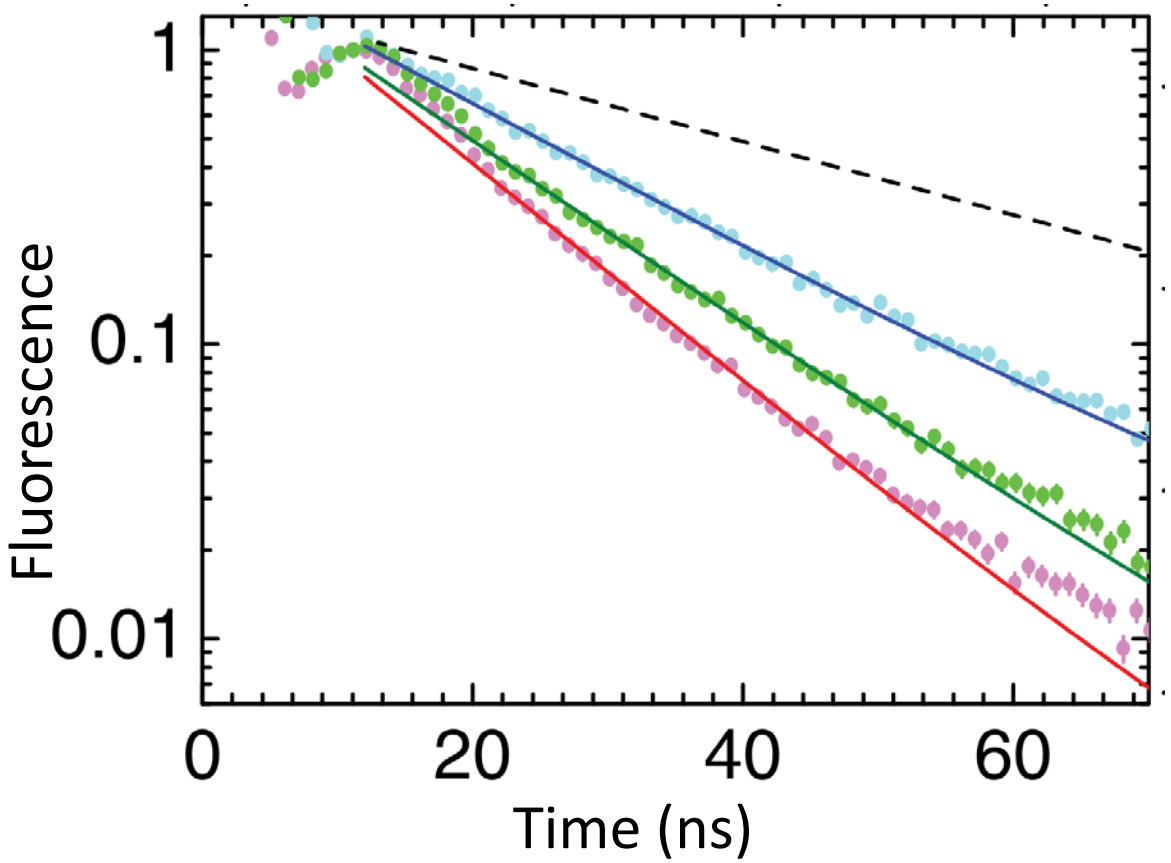
$$H = \hbar\omega_0 \sum_{ij}^{N} J_{ij}\sigma_i^\dagger\sigma_j$$

Collective dissipation

$$\mathcal{L}[\rho] = \sum_{i,j}^{N} \frac{\Gamma_{ij}}{2}\left(2\sigma_i\rho\sigma_j^\dagger - \sigma_i^\dagger\sigma_j\rho - \rho\sigma_i^\dagger\sigma_j\right)$$

Superradiance near the cavity resonance

Large collective dissipation $\mathcal{L}[\rho]$ → $\Gamma_{\rm tot} = \Gamma' + \bar{N}\,\Gamma_{\rm 1D}$



Free-space decay

$\tau_0 = 1/\Gamma_0 = 34.9\,\text{ns}$

Single atom decay rate

$\Gamma_{\rm 1D}/\Gamma' = 1.0 \pm 0.1$

Superradiant decay rate

$\Gamma_{\rm tot} = \Gamma' + \bar{N}\,\Gamma_{\rm 1D}$

Average atom number $\bar{N} \approx 2.6$

A. Goban, C.-L. Hung, J.D. Hood, S.P. Yu *et al*. *PRL 115, 063601* (2015).

Moving into the band-gap

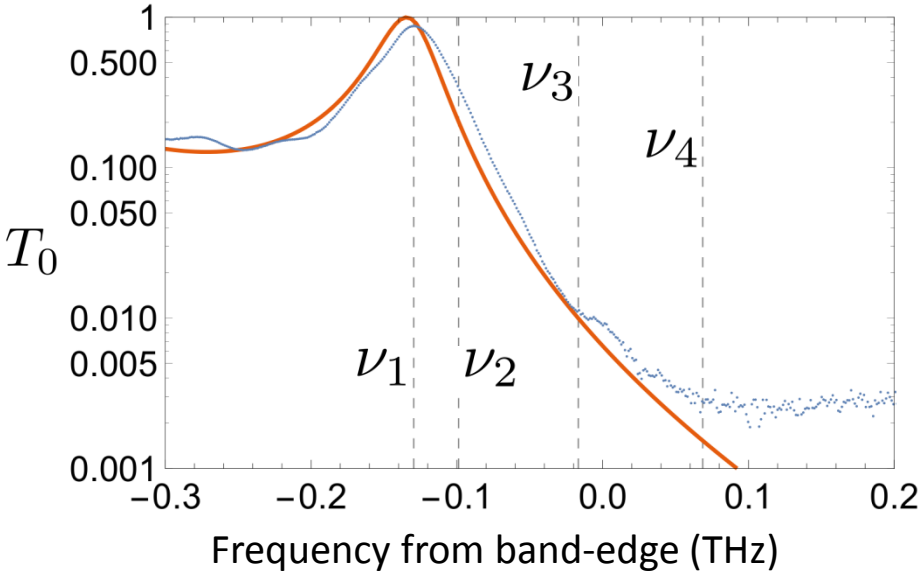
Greens function transmission model

$$T/T_0 = \frac{(2\Delta)^2 + (\Gamma')^2}{(2\Delta + \bar{N}J)^2 + (\Gamma' + \bar{N}\Gamma_{1D})^2}$$

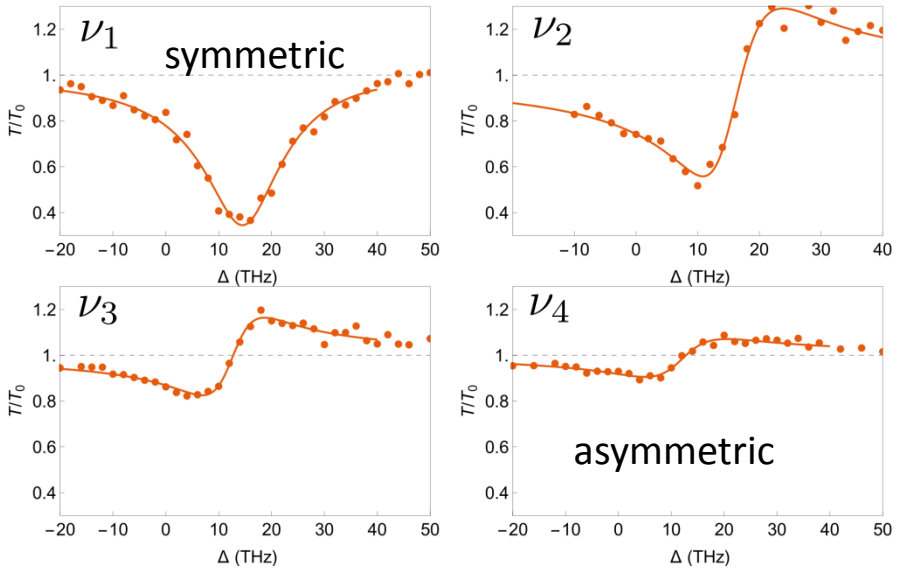
where $\Delta = \omega - \omega_{\text{atom}}$,
$\Gamma_{1D} = \text{Im}[G]/\Gamma'$, $J = \text{Re}[G]/\Gamma'$

Asymmetric Lorentzian **Lorentzian**

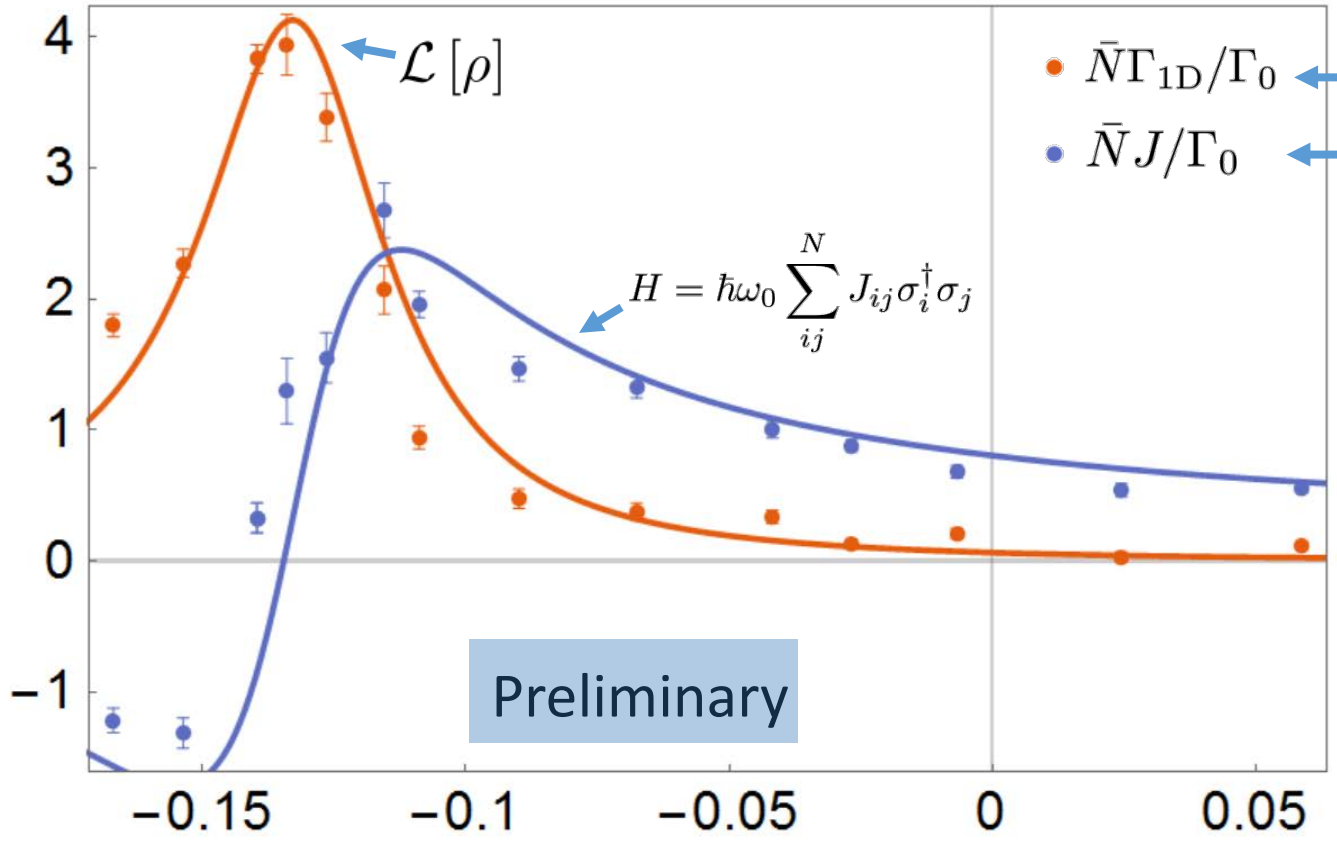
Transmission spectrum (no atoms)



Transmission spectrum with atoms



Greens function from fitted atomic spectra vs. theory (solid)



Collective decay rate

Cooperative level shift

$\bar{N} \sim 4$ atoms

Dissipation is suppressed

Outline

- Strong atom-photon interactions
- ‘Alligator’ waveguide fabrication
- The experiment: atoms trapped near photonic crystals
- What next?

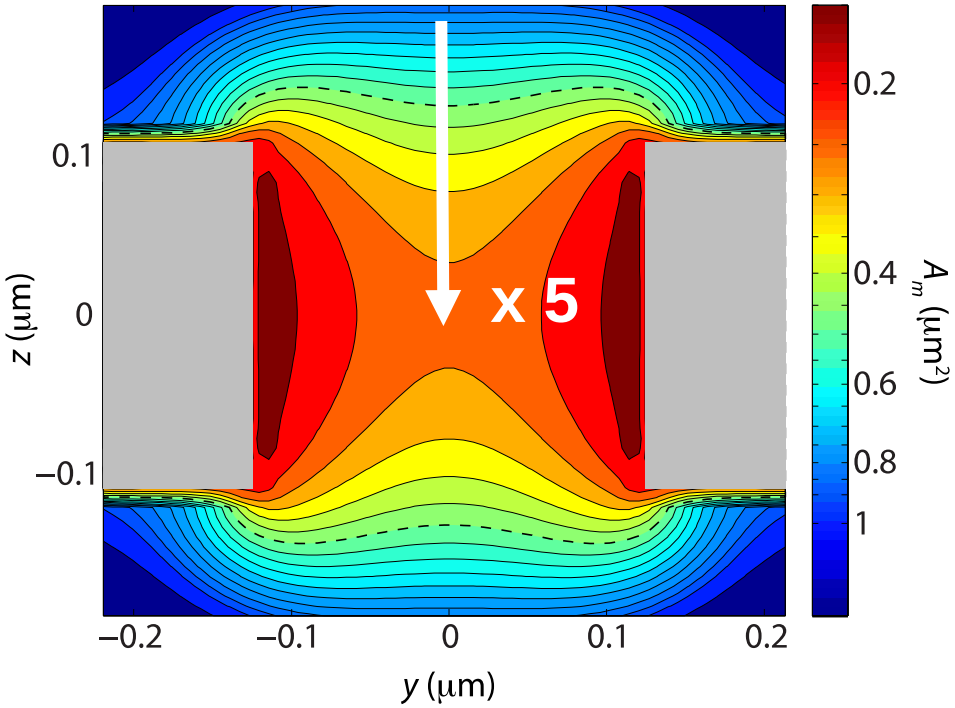
Transport of atoms into center of alligator

Stronger coupling rate

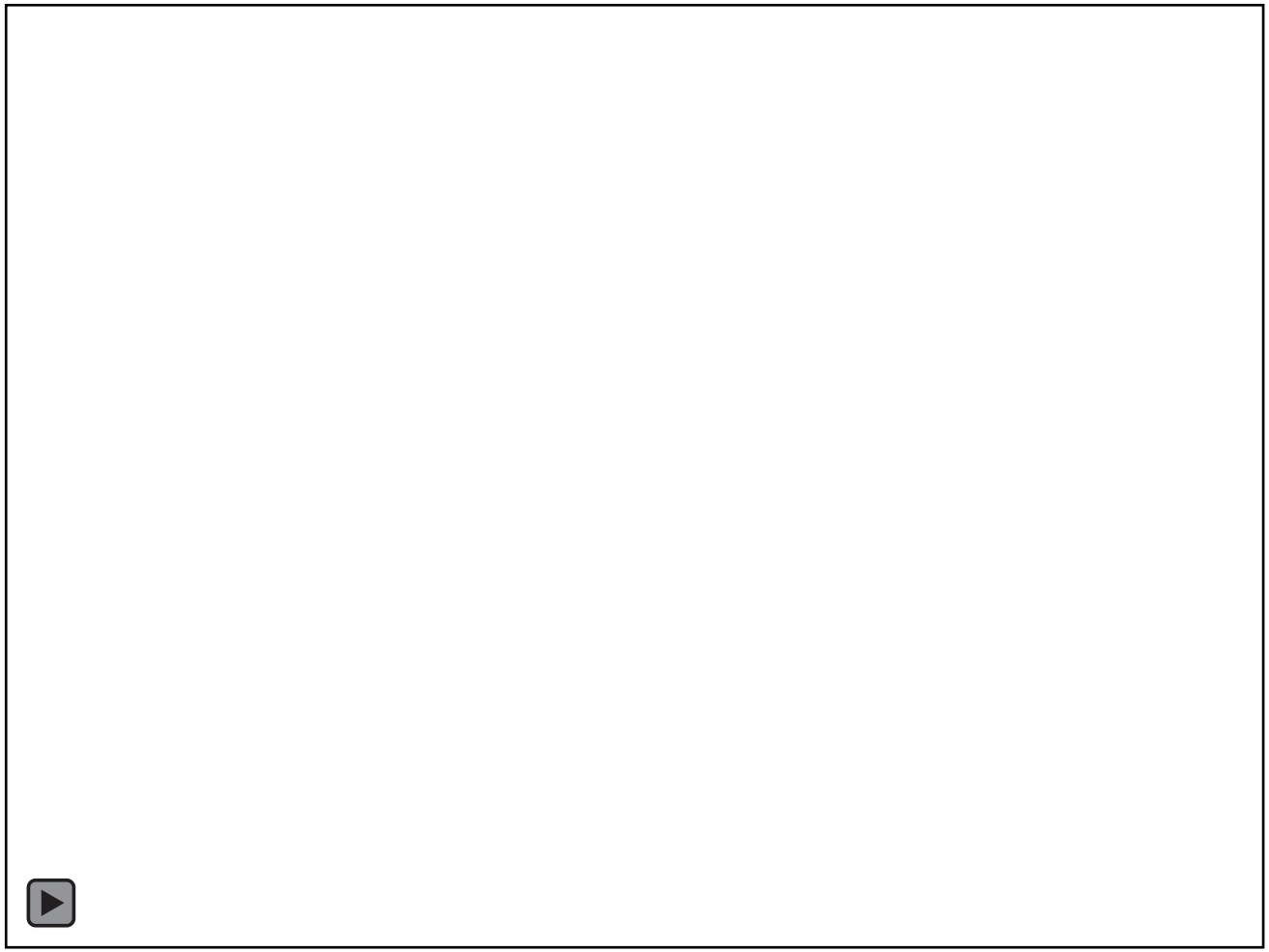
At the center of the gap:

Projected $\frac{\Gamma_{1D}}{\Gamma'} \sim 5$

Effective mode area



Transport of atoms into center of alligator



Thank you!

Jeff Kimble group

Ana Asenjo
Kevin Burdge
Aki Goban (JILA)
Jon Hood
Mingwu Lu
Jae Lee (KAIST)
Mike Martin (Sandia)
Andrew McClung
Juan Muniz
Lucas Peng
Su-Peng Yu

Senior Collaborators

Darrick Chang (ICFO)
Ignacio Cirac (MPQ)
Chen-Lung Hung (Purdue)
Oskar Painter (Caltech)

O. Painter Group

Xingsheng Luan
Justin Cohen
Richard Norte (Delft)
Sean Meenehan