Quantum Nanophotonics with Quantum Dots In Photonic Crystals

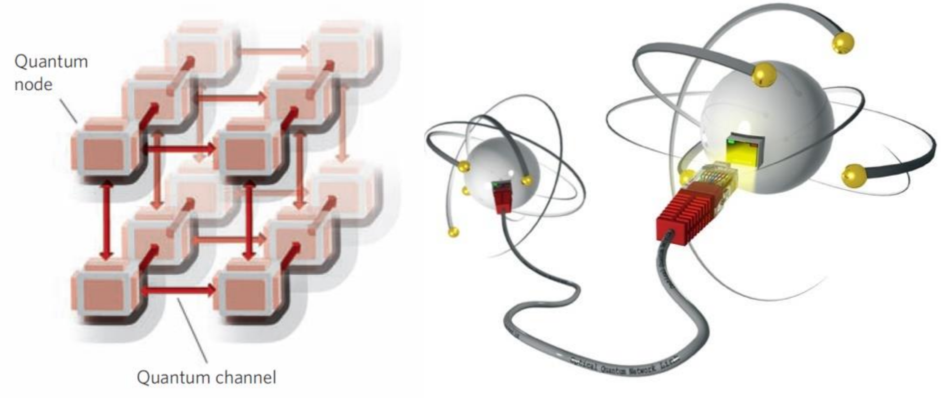
Benasque Workshop, July 2014

Peter Lodahl, Niels Bohr Institute,
University of Copenhagen, Denmark
Quantum Photonics Group
www.quantum-photonics.dk

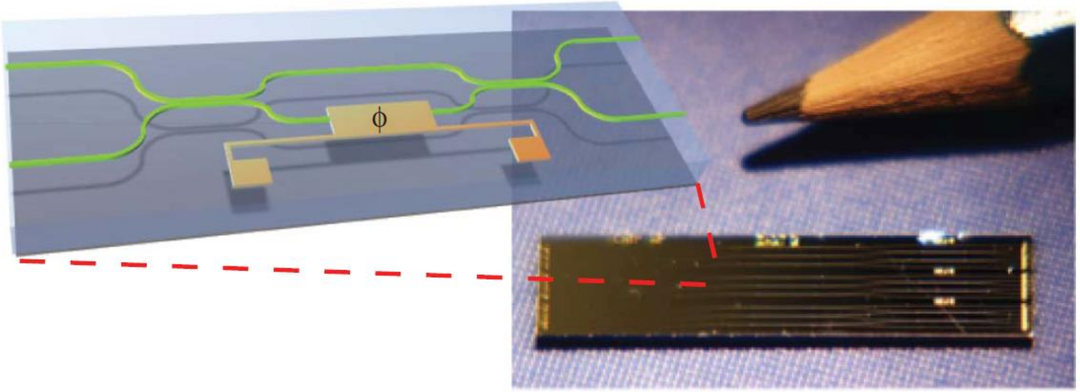
Danish Agency for Science Technology and Innovation
Ministry of Science Technology and Innovation
QUANTUM PHOTONICS
erc
VILLUM FONDEN

Photonic Quantum Networks

Outstanding challenge in quantum physics:
The scaling of small quantum systems into large architectures



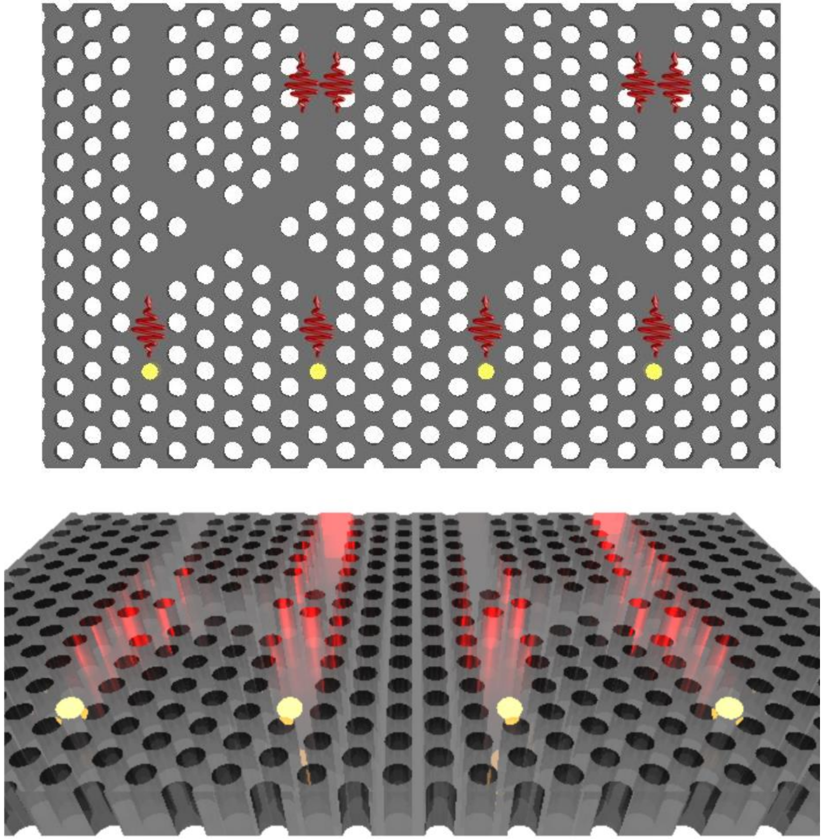
Kimble, Caltech & Rempe, Munich



Integrated photonic circuits:
Stable and easy operation of photonic networks

Bristol, Oxford, Queensland,...

Photonic Crystal Quantum Circuits with On-Chip Quantum Emitters



(Stanford, Munich, Zurich, Cambridge, Sheffield, Eindhoven, Copenhagen, …)

- Deterministic single-photon sources on chip (quantum dots)
- Tailor light-matter interaction strength
- High-efficiency channeling of photons to a single mode

→ On-chip quantum-information processing and computing

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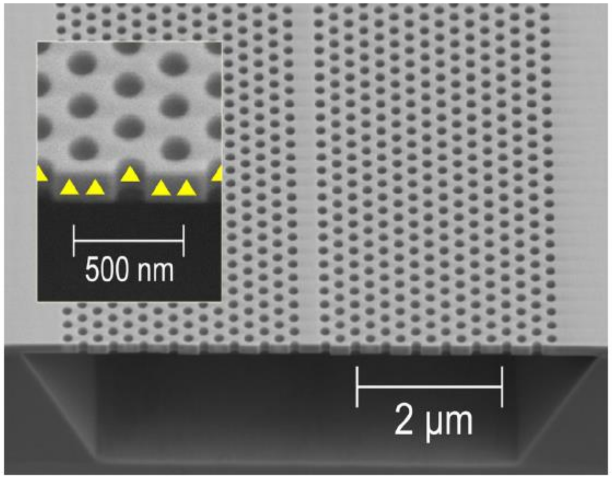
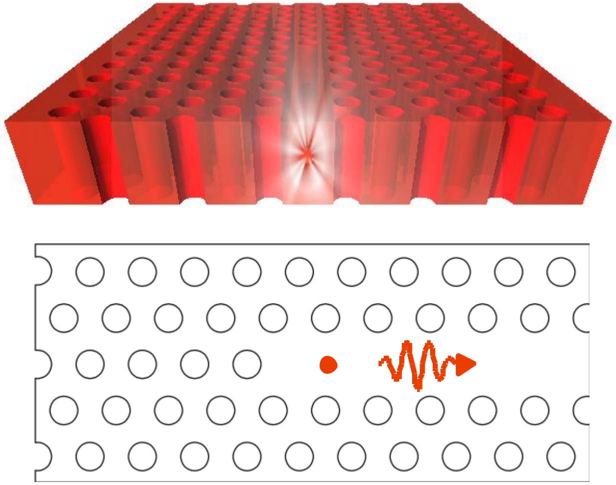
Outline

- All solid-state quantum optics with quantum dots in photonic crystals.
- Mesoscopic quantum optics effects.
- Role of fabrication imperfections.





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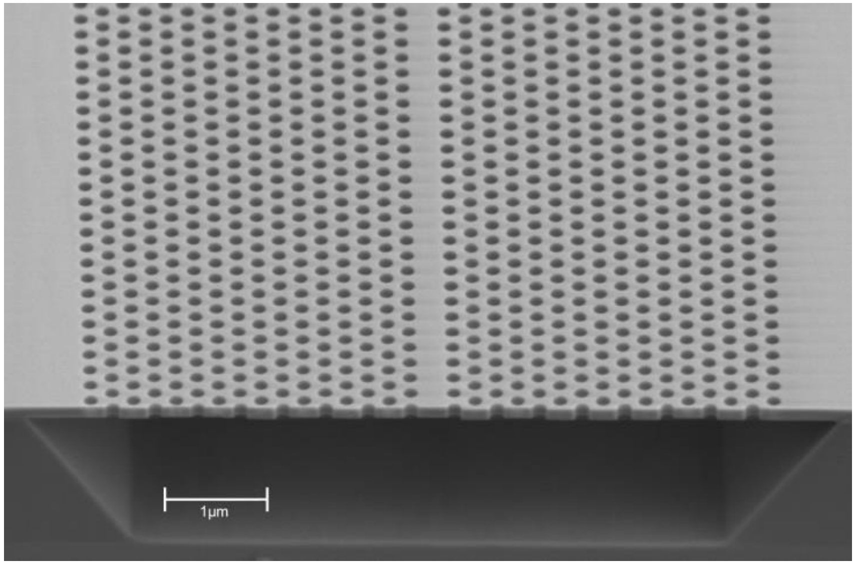
Controlling Light-Matter Interaction with Photonic Crystals



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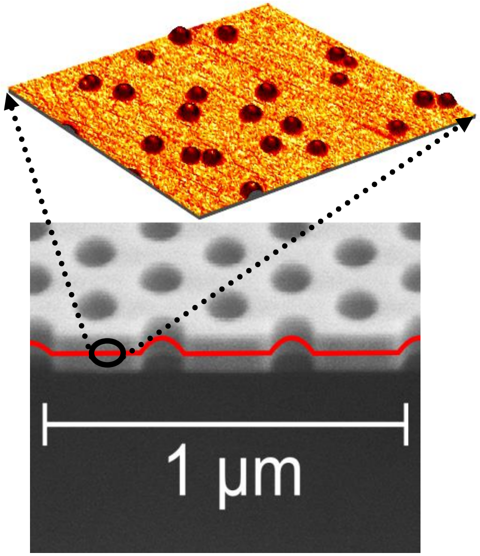
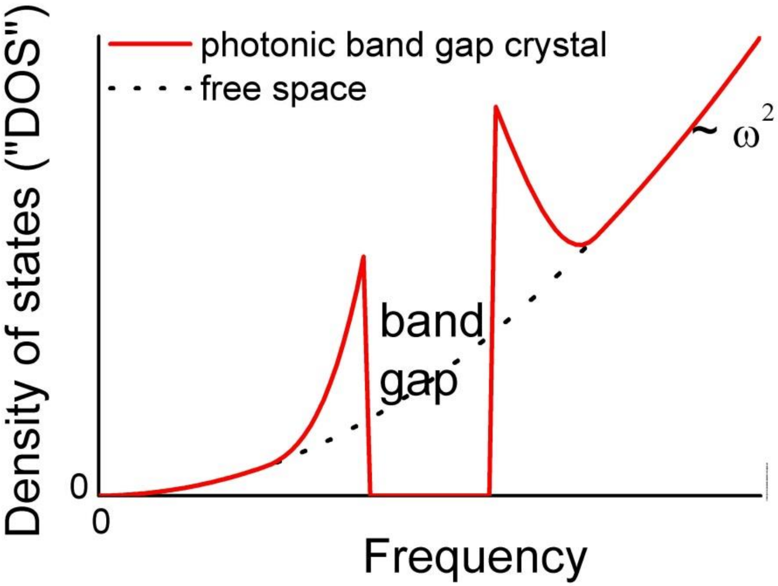
Control of Spontaneous Emission with Photonic Crystals





Inhibited (enhanced) spontaneous emission rate in band gap (at band edge)

Yablonovitch, Phys. Rev. Lett. 58, 2059 (1987).
Lodahl, van Driel, Nikolaev, Irman, Overgaag, Vanmaekelberg & Vos, Nature 430, 654 (2004).

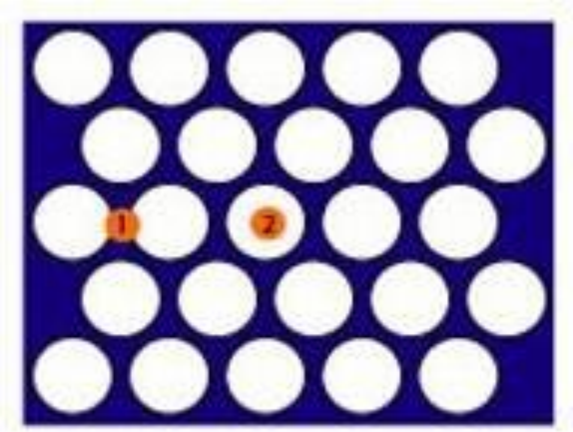
The Local Density of Optical States

The local light-matter coupling strength is determined by the projected local density of states (LDOS)

$$\rho(\omega,\vec{r})=\sum_{n}\int_{1BZ} d^{3}\vec{k}\left|\vec{e}_{\vec{d}}\cdot\vec{E}_{n,\vec{k}}(\vec{r})\right|^{2}\delta\left(\omega-\omega_{n}(\vec{k})\right)$$

The decay rate of single emitters is proportional to the LDOS

$$\gamma_{rad}(\omega,\vec{r})=\frac{\pi\omega}{3\hbar\varepsilon_{0}}d^{2}\times\rho(\omega,\vec{r})$$



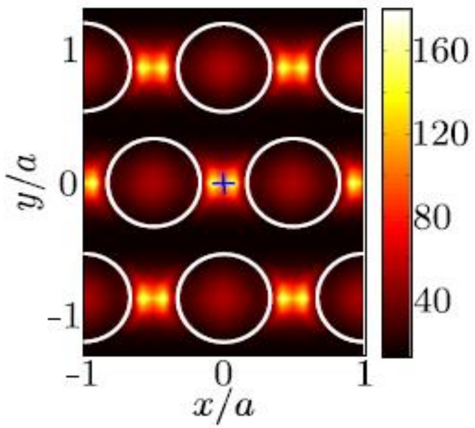
LDOS can be mapped by employing single emitters with known optical properties

Mapping the LDOS of a photonic crystal

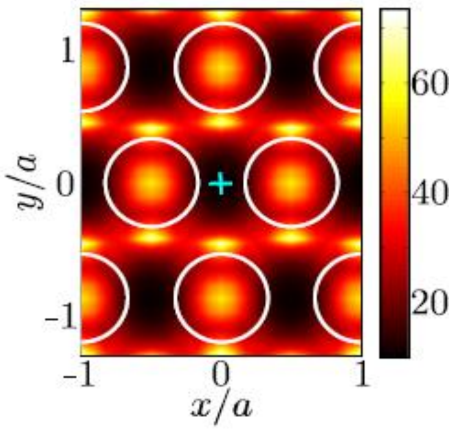
Calculated spatial variation of the inhibition factor for an ideal photonic crystal

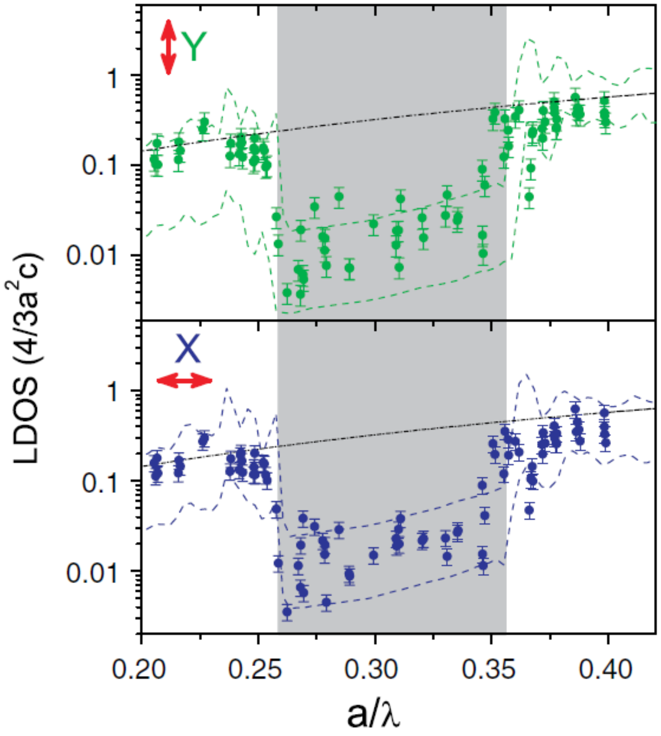
Fix lattice wavelength and vary lattice constant
→ LDOS frequency map

X dipole



Y dipole



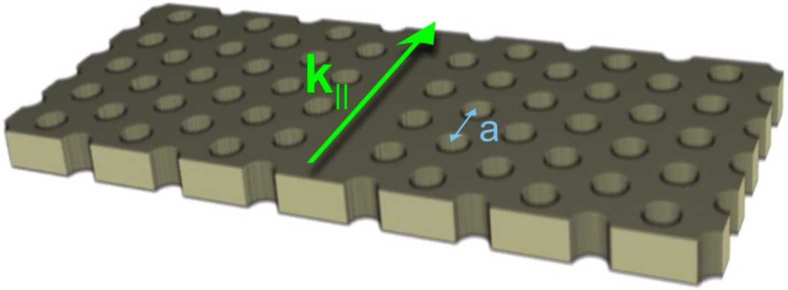


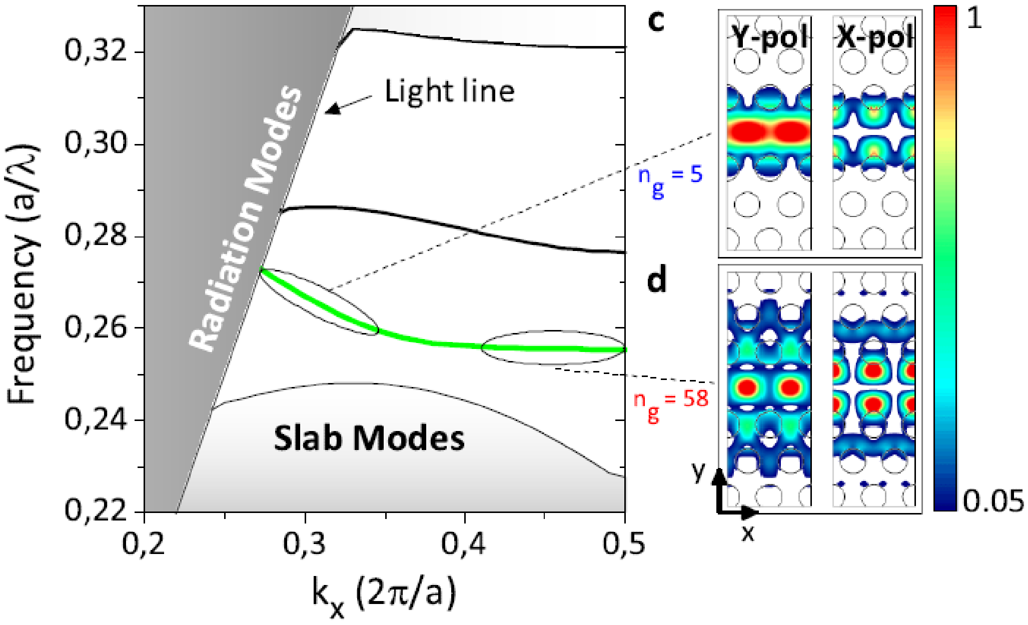
x70 inhibition of spontaneous emission rate observed

Wang, Stobbe & Lodahl, Phys. Rev. Lett. 107, 167404 (2011).

Theory: **Koenderink, Kafesaki, Soukoulis & Sandoghdar, J. Opt. Soc. Am. B 23, 1196 (2006).**

Highly efficient photonic-crystal waveguide single-photon source



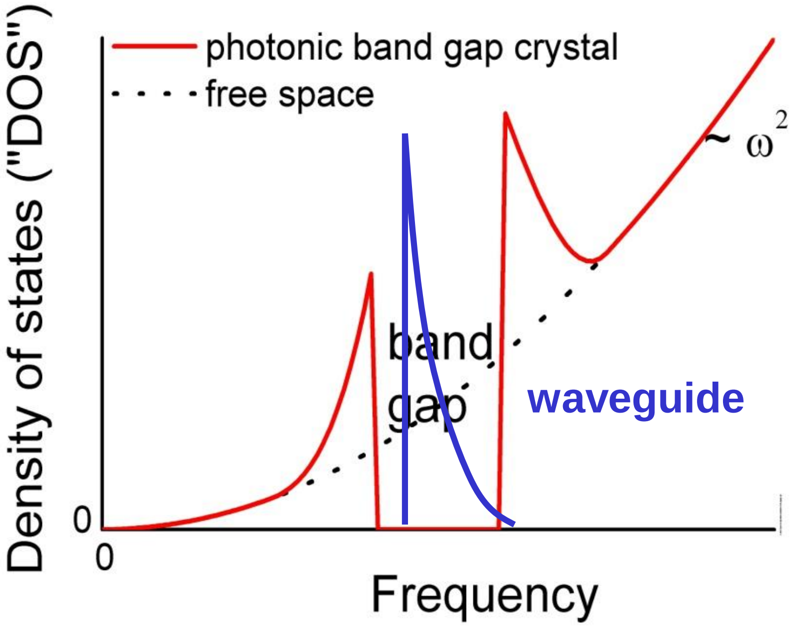


Single-photon coupling efficiency:

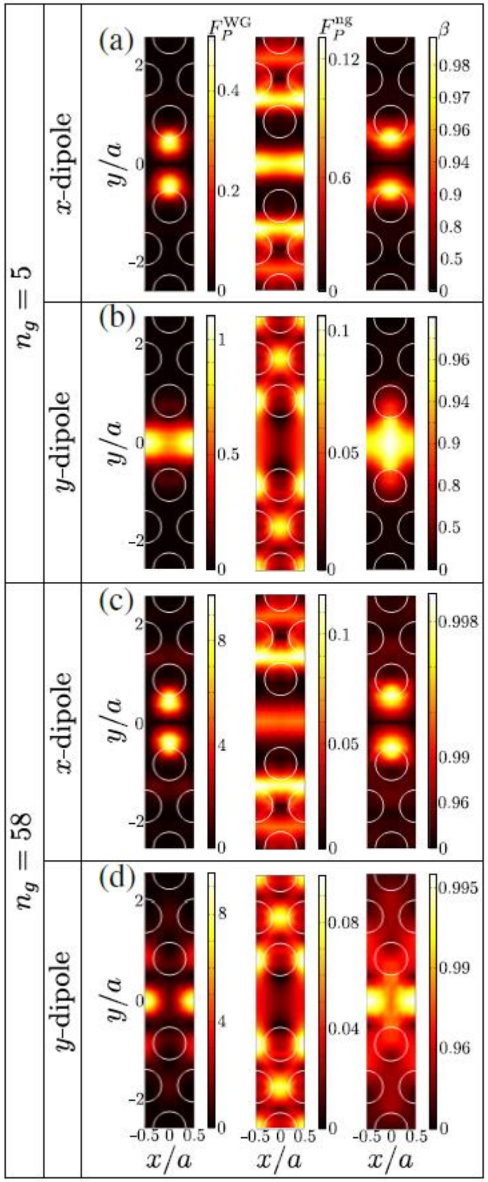
$$\beta = \frac{\gamma_{\mathrm{wg}}}{\gamma_{\mathrm{wg}} + \gamma_{\mathrm{rad}} + \gamma_{\mathrm{nrad}}}$$

Lund-Hansen, Stobbe, Julsgaard, Thyrrestrup, Sunner, Kamp, Forchel & Lodahl, Phys. Rev. Lett. 101, 113903 (2008).

Density of States and Purcell Factor

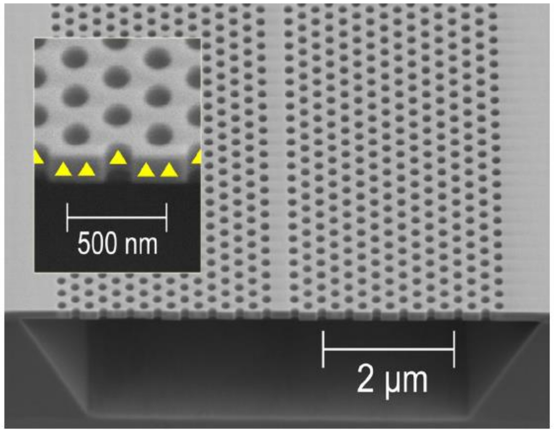


$$F_P(\vec{r}_{QD}) = \frac{\gamma_{wg}}{\gamma_{hom}} = \frac{3\pi c^3 a n_g}{n\omega^2 c} \times \left|\vec{f}(\vec{r}_{QD}) \cdot \vec{e}_{QD}\right|^2$$

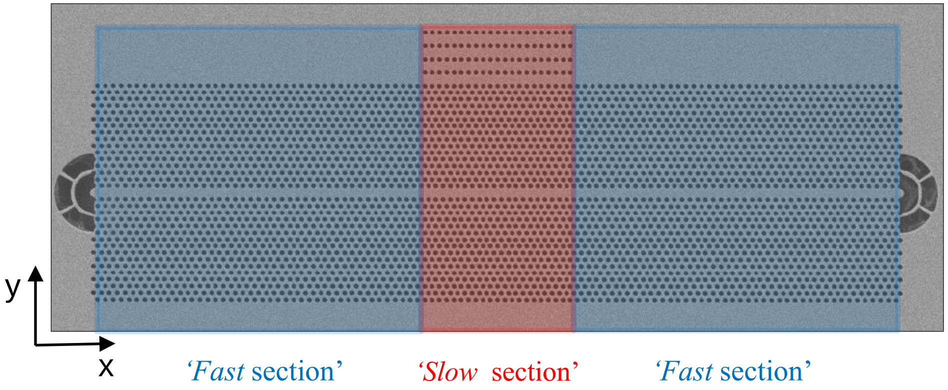


V.S.C. Manga Rao and S. Hughes, Phys. Rev. B 75, 205437 (2007).
Lodahl, Mahmoodian & Stobbe, submitted to Rev. Mod. Phys. (2013).
arXiv:1312.1079

Engineered samples for efficient outcoupling



PC waveguide with a single layer of quantum dots embedded in the center of the membrane



Lattice constant tailored for efficient outcoupling

$$a_f = 1.07 \cdot a_s$$

+ four row long transition region between slow and fast sections

Arcari, Sollner, Javadi, Hansen, Liu, Thyrrestrup, Lee, Song, Stobbe & Lodahl, arXiv:1402.2081.

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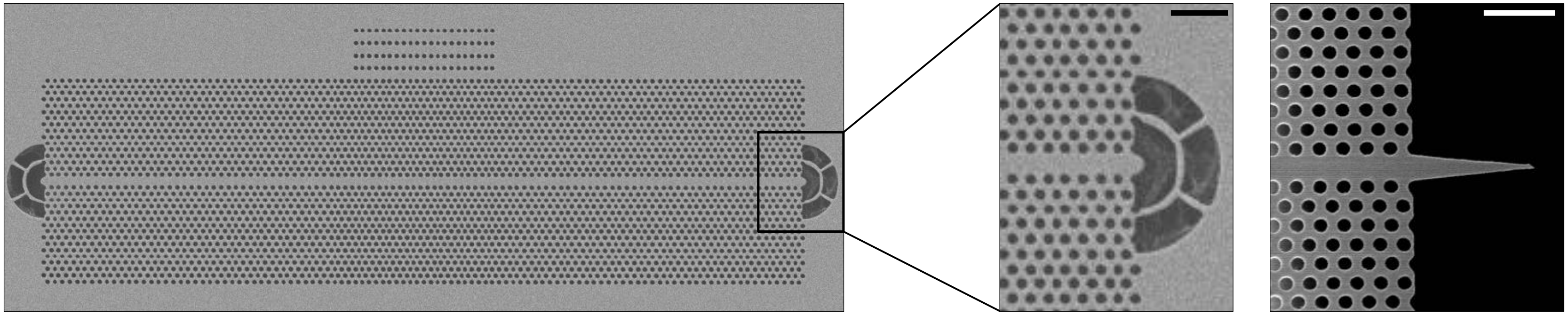
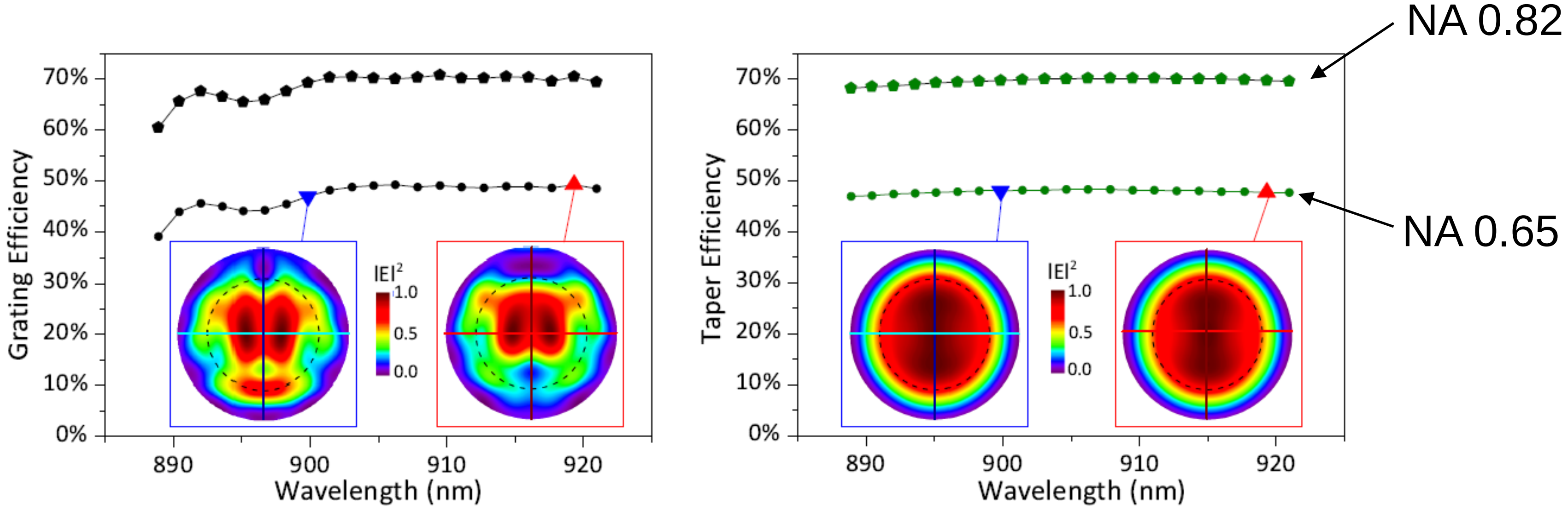
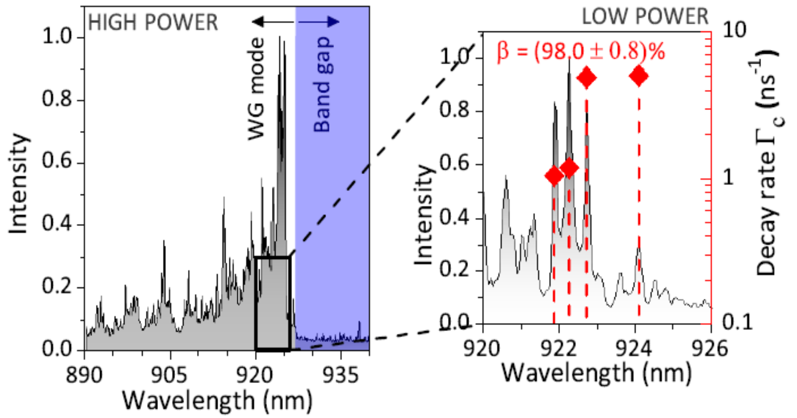
Outcoupling efficiency





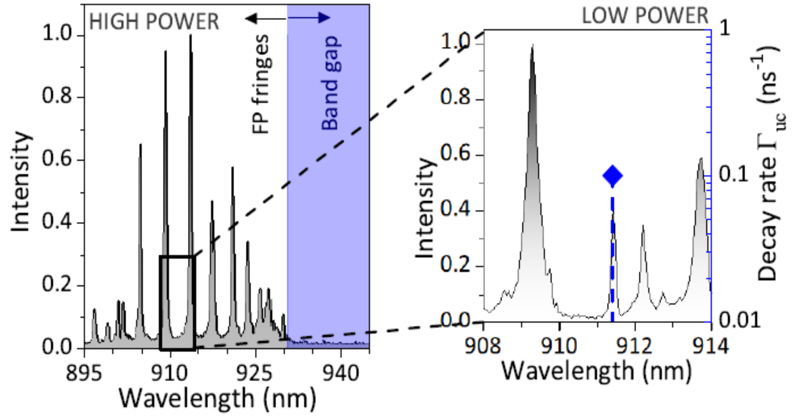
~ 70% out coupling efficiency
→ can be improved further by optimum design

Near-unity coupling efficiency



Efficiently coupled quantum dot in the slow-light regime of a waveguide:

$\gamma_{coup} = 5.0\ \mathrm{ns}^{-1}$



Weakly coupled quantum dot in between two Fabry-Perot resonances:

$\gamma_{un\text{-}coup} \leq 0.1\ \mathrm{ns}^{-1}$

Combining these measurements leads to: $\beta = 98.0 \pm 0.8\ \%$

Lund-Hansen, Stobbe, Julsgaard, Thyrrestrup, Sunner, Kamp, Forchel & Lodahl, Phys. Rev. Lett. 101, 113903 (2008).
Arcari, Sollner, Javadi, Hansen, Liu, Thyrrestrup, Lee, Song, Stobbe & Lodahl, arXiv:1402.2081.

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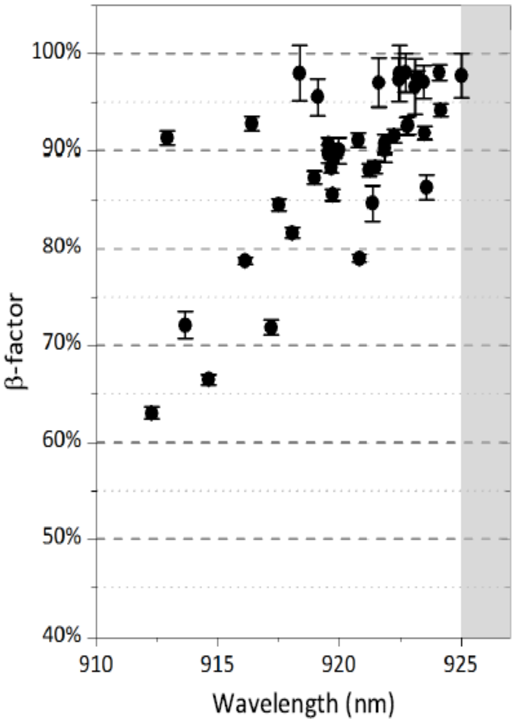
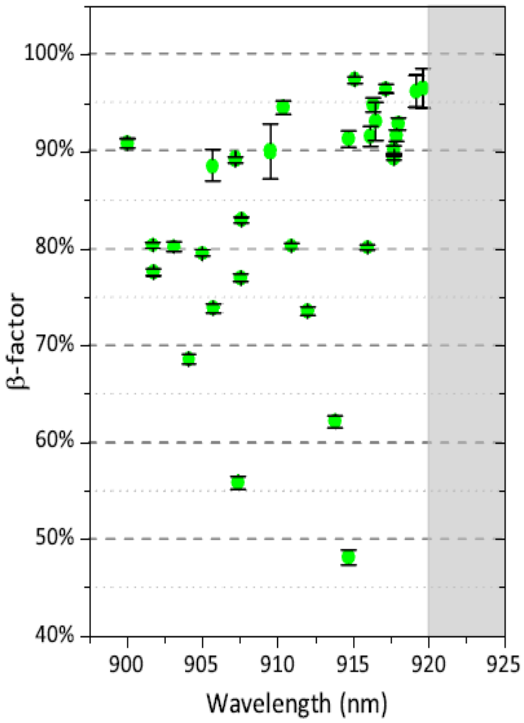
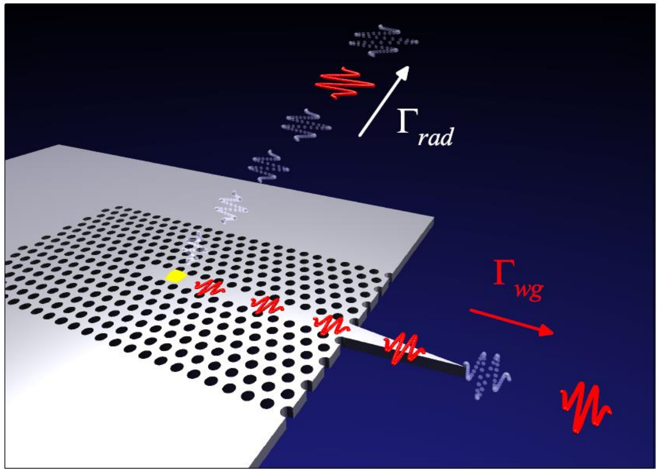
Statistics of β-factor measurements

Near unity β-factors are observed for many quantum dots over a wide spectral range







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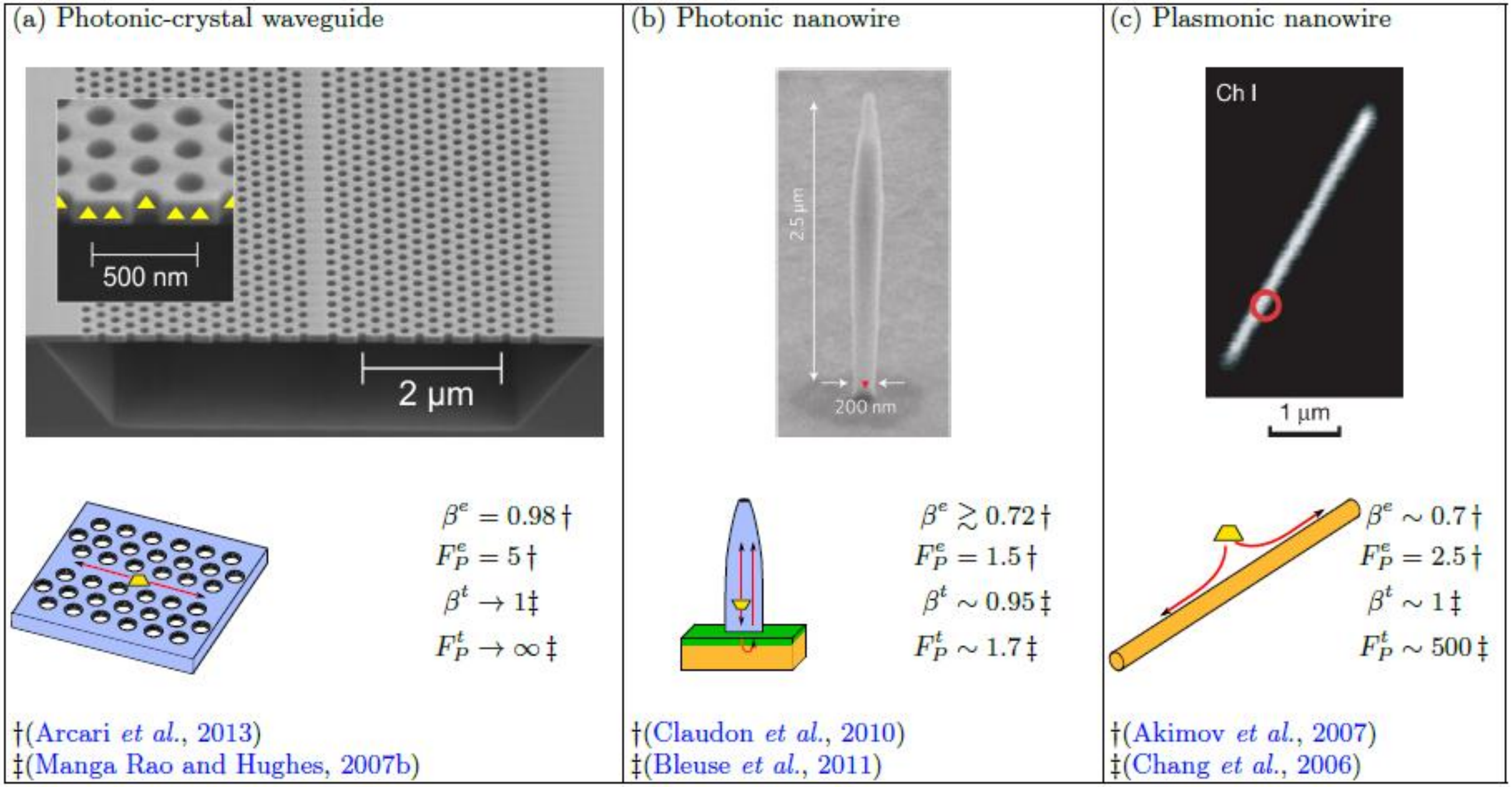
Arcari, Sollner, Javadi, Hansen, Liu, Thyrrestrup, Lee, Song, Stobbe & Lodahl, arXiv:1402.2081.

Comparison to other methods



(a) Photonic-crystal waveguide

$\beta^e = 0.98$ †
$F_P^e = 5$ †
$\beta^t \to 1$ ‡
$F_P^t \to \infty$ ‡

†(Arcari *et al.*, 2013)
‡(Manga Rao and Hughes, 2007b)

(b) Photonic nanowire

$\beta^e \gtrsim 0.72$ †
$F_P^e = 1.5$ †
$\beta^t \sim 0.95$ ‡
$F_P^t \sim 1.7$ ‡

†(Claudon *et al.*, 2010)
‡(Bleuse *et al.*, 2011)

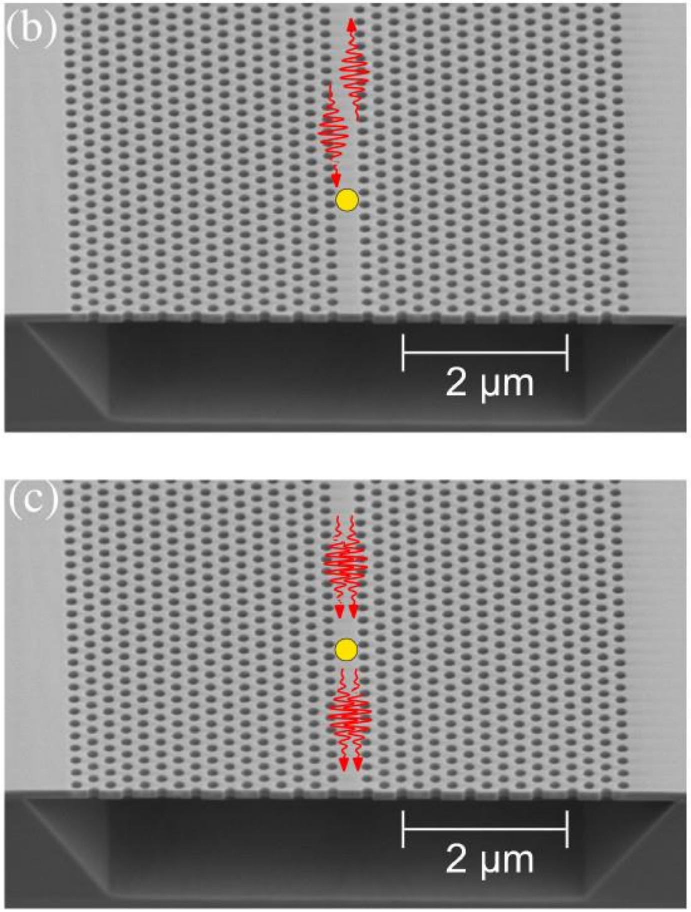
(c) Plasmonic nanowire

$\beta^e \sim 0.7$ †
$F_P^e = 2.5$ †
$\beta^t \sim 1$ ‡
$F_P^t \sim 500$ ‡

†(Akimov *et al.*, 2007)
‡(Chang *et al.*, 2006)

Lodahl, Mahmoodian & Stobbe, submitted to Rev. Mod. Phys. (2013). arXiv:1312.1079

Few-photon nonlinearity



Single quantum dot efficiently coupled to a photonic-crystal waveguide as a nonlinear medium.

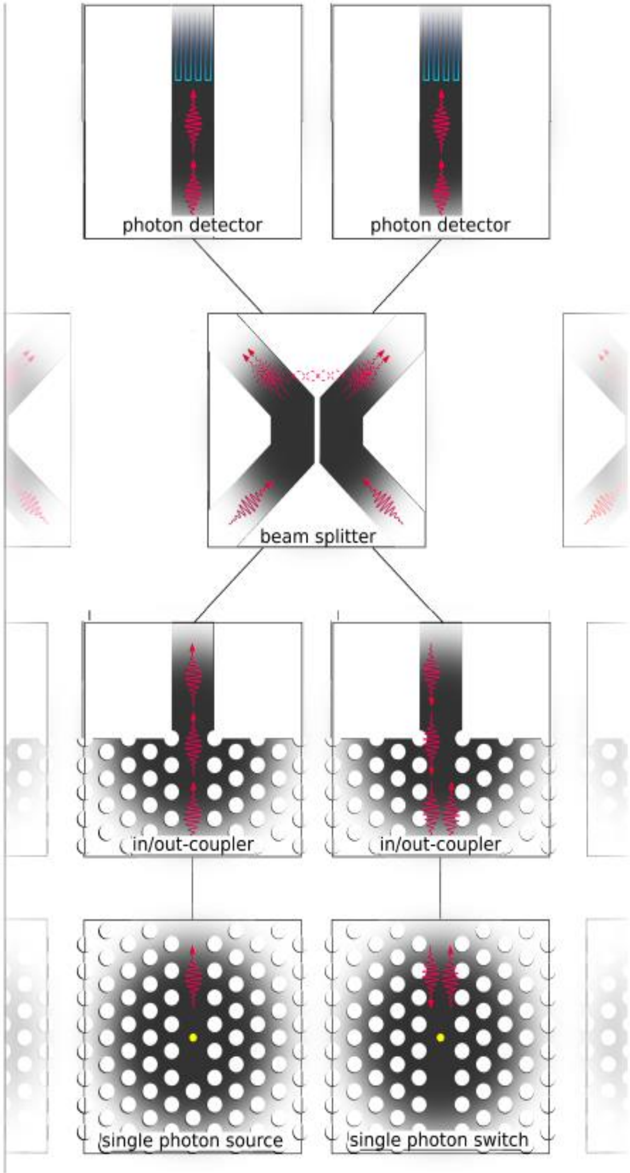
1-photon reflection coefficient:

$$R \approx \frac{1}{1+2\gamma_{\mathrm{dp}}/\gamma}\beta^2 \qquad \frac{\gamma_{\mathrm{dp}}}{\gamma} \approx 0.2$$

Applications:
Single-photon switch and quantum-phase gates

Madsen, Ates, Liu, Javadi, Albrecht, Yeo, Stobbe, &. Lodahl, arXiv:1402.6967
Lodahl, Mahmoodian & Stobbe, submitted to Rev. Mod. Phys. (2013). arXiv:1312.1079

Building blocks for integrated photonic circuits



On-chip single-photon detectors based on superconducting nanowires

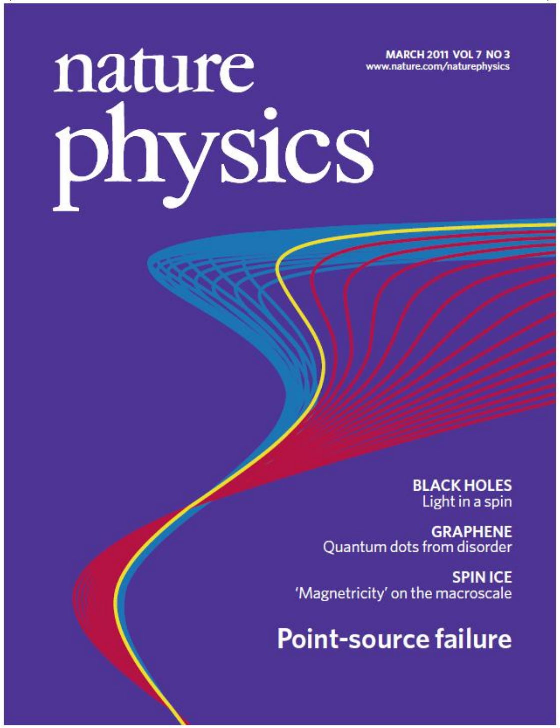
Photon circuits based on dielectric waveguides

Efficient coupling to dielectric waveguides for long-range propagation

Single-photon source and nonlinearity

Lodahl, Mahmoodian & Stobbe, submitted to Rev. Mod. Phys. (2013). arXiv:1312.1079

Mesoscopic Effects with Quantum Dots in Photonic Nanostructures



nature physics

MARCH 2011 VOL 7 NO 3
www.nature.com/naturephysics

BLACK HOLES
Light in a spin

GRAPHENE
Quantum dots from disorder

SPIN ICE
'Magnetricity' on the macroscale

Point-source failure

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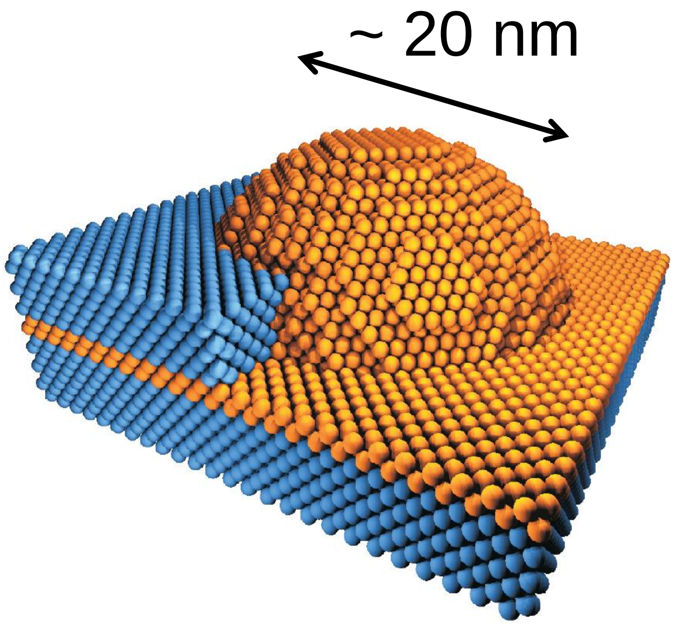
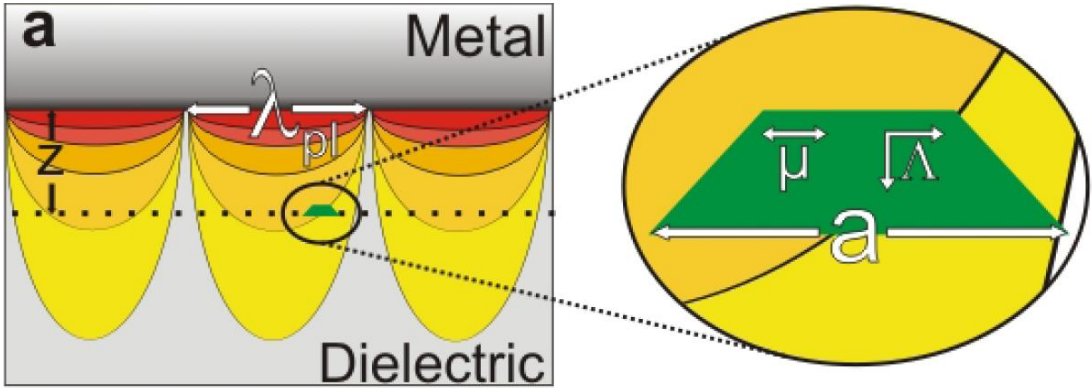
Break-down of dipole approximation for quantum dots coupled to plasmons

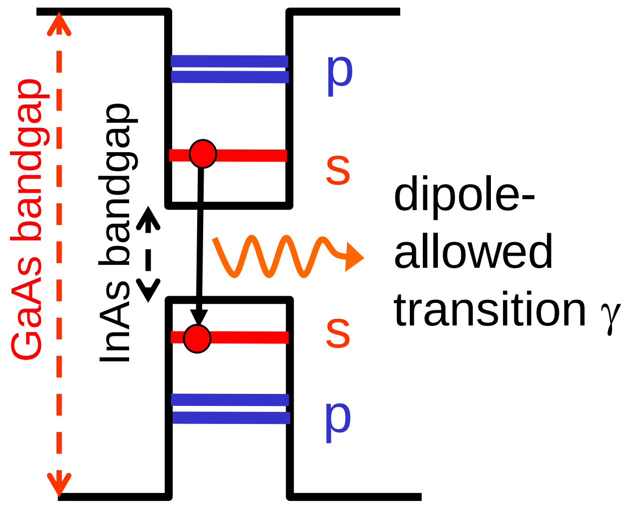
Mesoscopic dimensions of quantum dots
→ traditional point dipole description may not apply





Strong field gradients at metal interface due to coupling to surface plasmon polaritons

Modified excitation of plasmons



dipole-allowed transition γ

$$\hat{H}_I(\vec{r}) \propto \vec{\hat{p}} \cdot \vec{\hat{A}}(\vec{r})$$

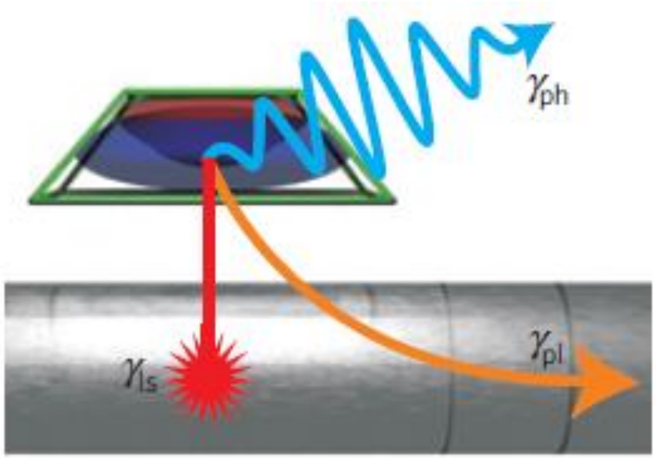
$$\hat{A}_j(\vec{r}) \approx \hat{A}_j(\vec{r}_0) + \sum_n (\vec{r} - \vec{r}_0)_n \left[\nabla_n \hat{A}_j\right]_{\vec{r}_0}$$

Rate of decay to plasmons

$$\gamma_{pl} = \gamma_{pd} + \xi_{me}$$

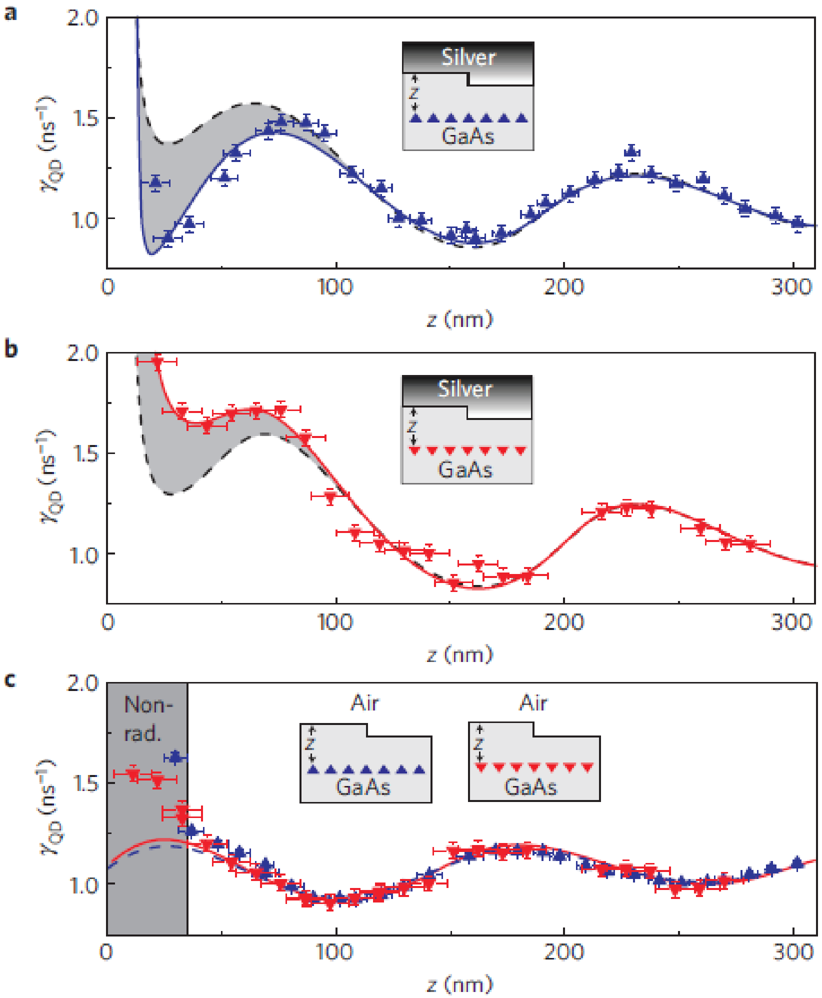
point dipole

mesoscopic
(i.e. magnetic dipole
and electric quadrupole)



Mesoscopic contribution can either add or subtract depending on geometry

Observation of break down of dipole approximation



Direct structure: suppressed excitation of plasmons

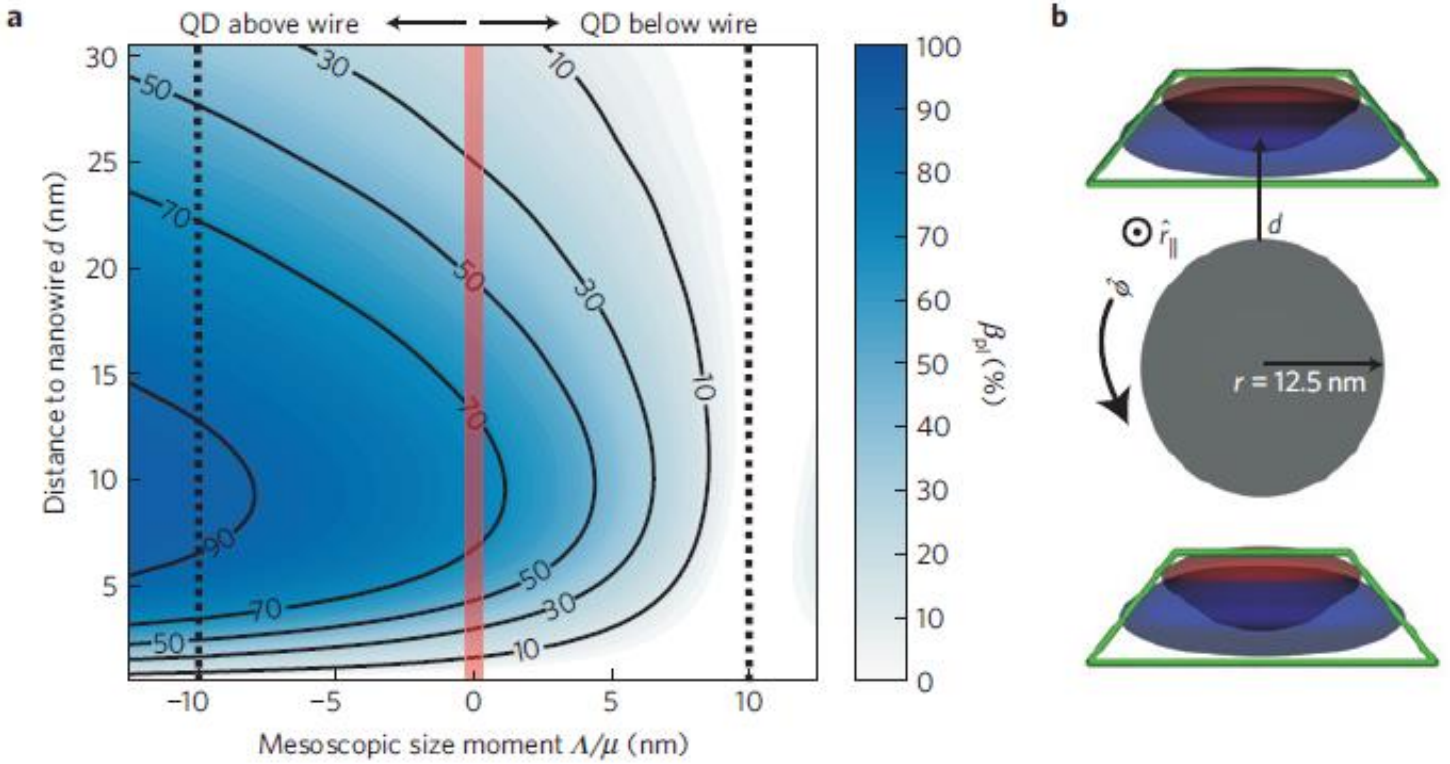
Inverted structure: enhanced excitation of plasmons

Reference measurement before metal depsition

Andersen, Stobbe, Sørensen & Lodahl, Nature Physics 7, 215 (2011)

Improving plasmon single-photon sources

Quantum dot coupled to a plasmon nanowire for efficient single-photon source



[Proposal of: Chang, Sørensen, Hemmer & Lukin, PRL 97 053002 (2006)]

Andersen, Stobbe, Sørensen & Lodahl, Nature Physics 7, 215 (2011)

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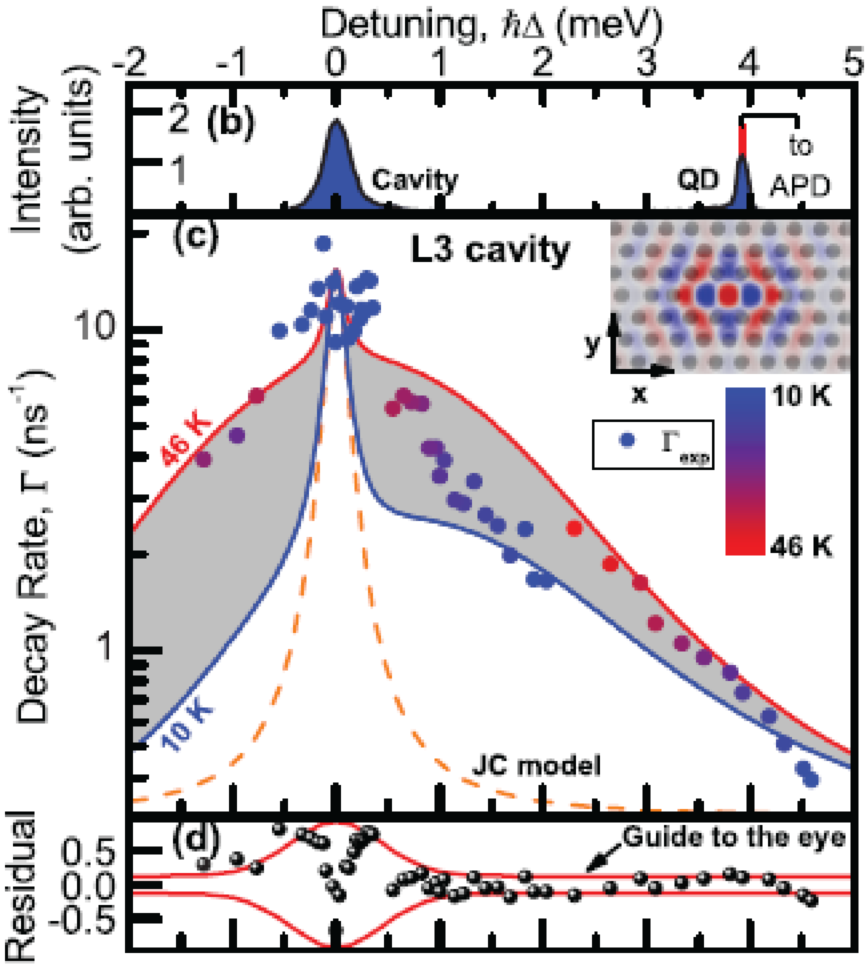
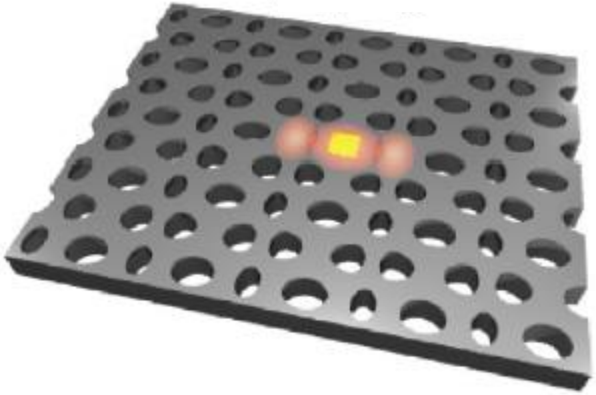
Phonon-assisted Purcell enhancement in a photonic-crystal cavity





Wide bandwidth of Purcell enhancement due to coupling to phonons

Theory: **Kaer, Nielsen, Lodahl, Jauho & Mørk, Phys. Rev. Lett. 104, 157401 (2010).**
Kaer, Nielsen, Lodahl, Jauho & Mørk, Phys. Rev. B 86, 085302 (2012).

Exp: **Madsen, Kaer, Kreiner-Møller, Stobbe, Nysteen, Mørk, and Lodahl, Phys. Rev. B 88, 045316 (2013).**

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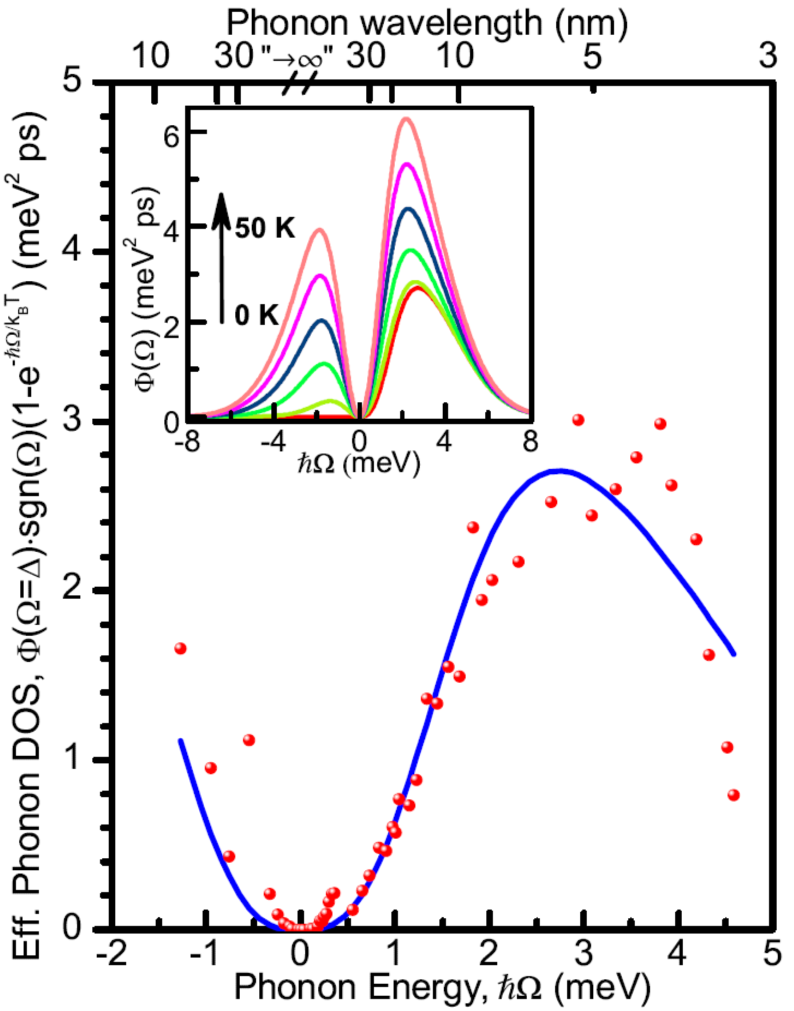
The effective phonon density of states



Effective phonon density of states can be extracted from the QD decay rate:

$$\boxed{\Gamma} = \gamma + 2g^2 \frac{\gamma_{\mathrm{tot}}}{\gamma_{\mathrm{tot}}^2 + \Delta^2}\left[1 + \frac{1}{\hbar^2 \gamma_{\mathrm{tot}}} \boxed{\Phi(\Omega = \Delta)}\right]$$

Probe intrinsic QD phonon dephasing process by cavity QED

Theory: **Kaer, Nielsen, Lodahl, Jauho & Mørk, Phys. Rev. Lett. 104, 157401 (2010).**
Kaer, Nielsen, Lodahl, Jauho & Mørk, Phys. Rev. B 86, 085302 (2012).

Exp: **Madsen, Kaer, Kreiner-Møller, Stobbe, Nysteen, Mørk, and Lodahl, Phys. Rev. B 88, 045316 (2013).**

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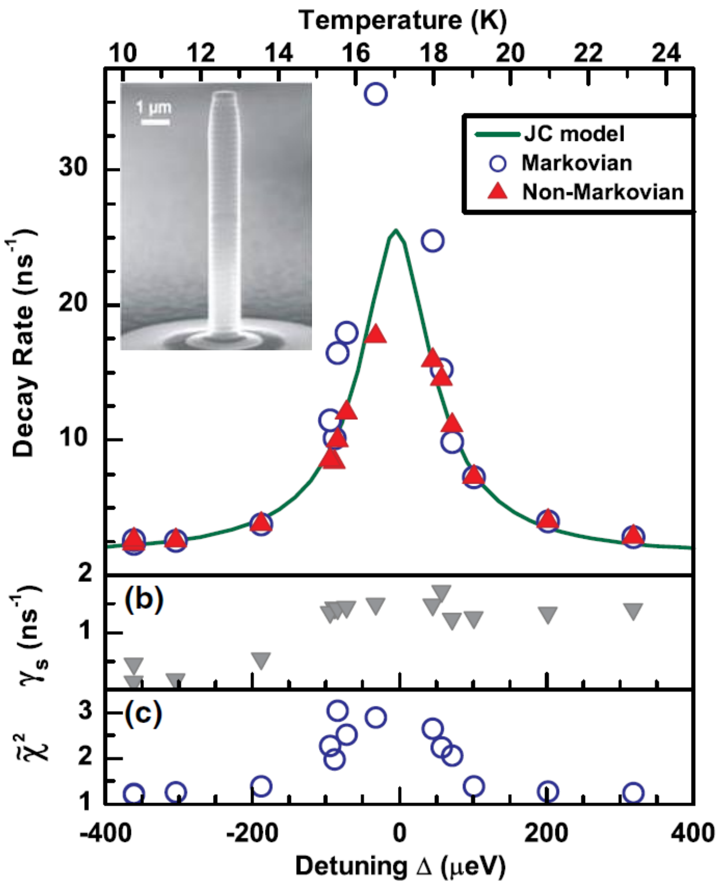
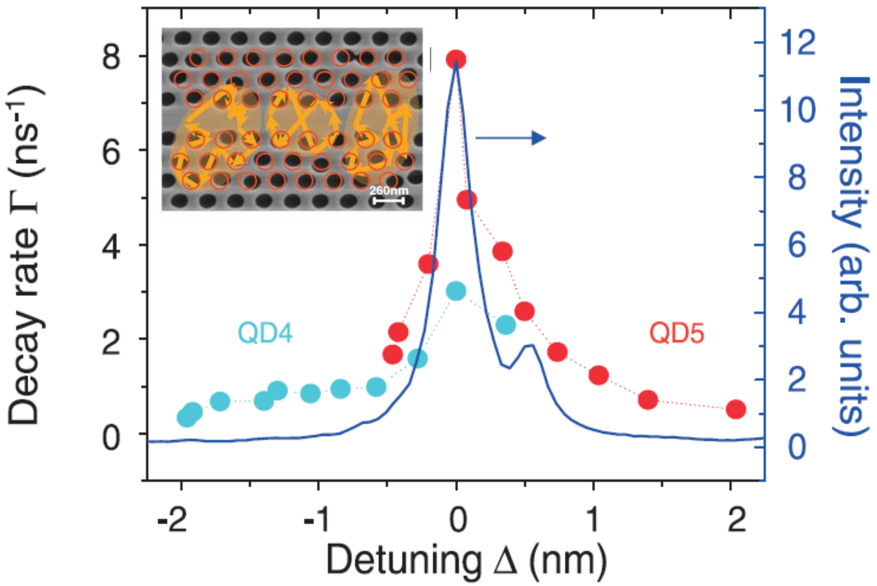
Purcell effect in other cavities

Micropillar cavity



Madsen, Ates, Lund-Hansen, Loffler, Reitzenstein, Forchel, and Lodahl, Phys. Rev. Lett. 106, 233601 (2011).

Anderson-localized cavity



Sapienza, Thyrrestrup, Stobbe, Garcia, Smolka & Lodahl, Science 327, 1352 (2010).

Figure-of-merit for broadband Purcell: g^2/γ

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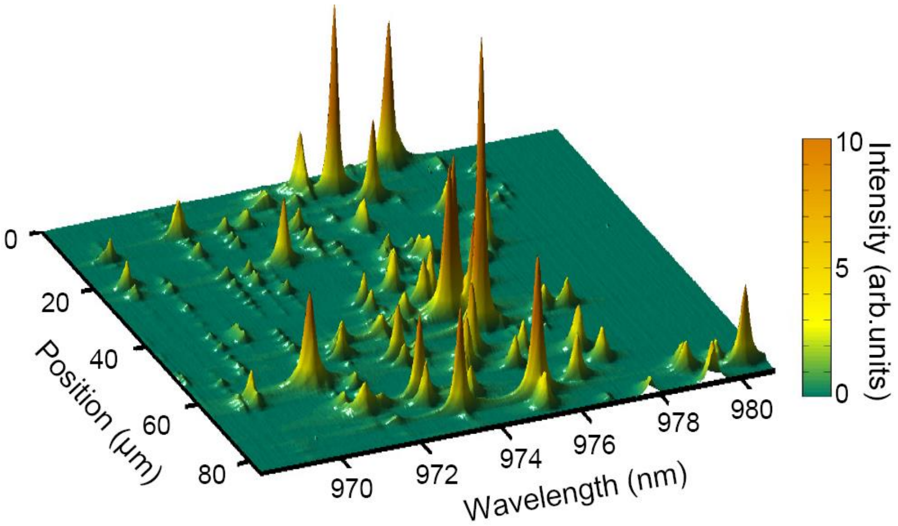
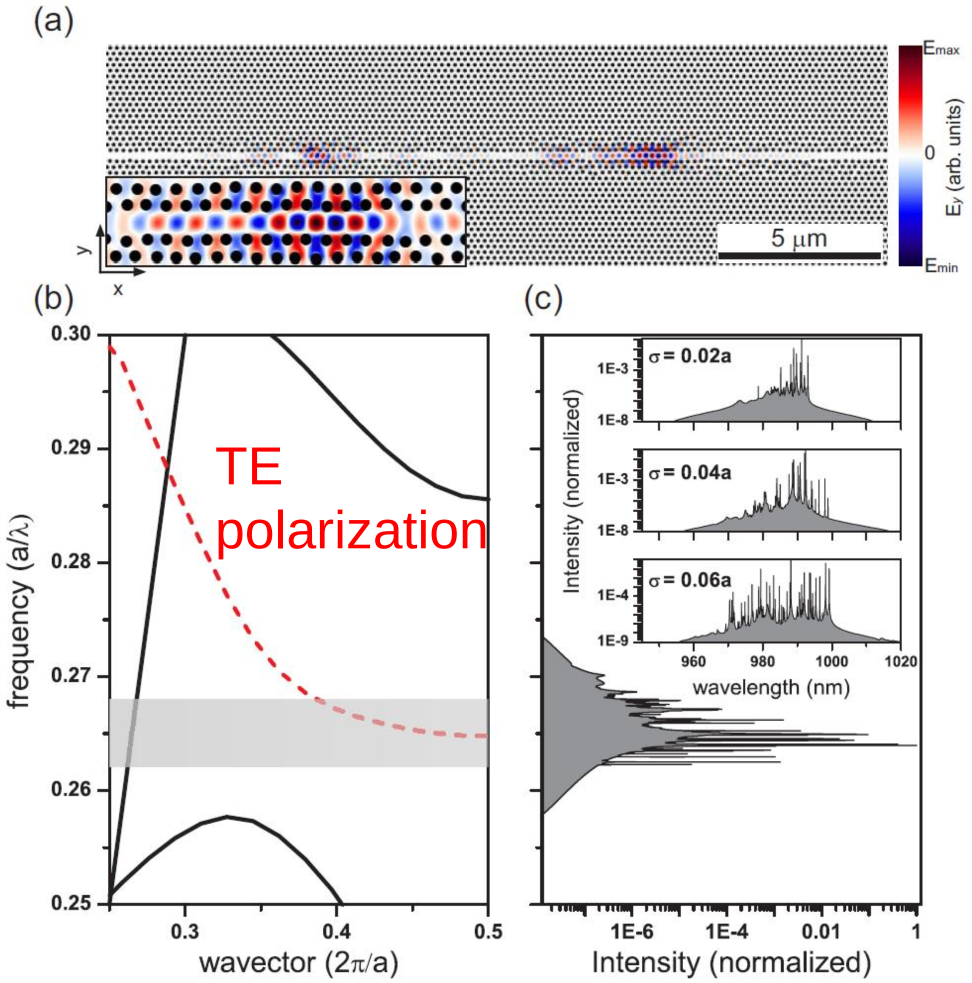
Anderson Localization in Disordered Photonic Crystals



Formation of 1D Anderson-localized modes



Disorder breaks up Bloch modes leading to localized states in the slow-light regime

Garcia, Javadi, Thyrrestrup & Lodahl, Appl. Phys. Lett. 102, 031101 (2013).

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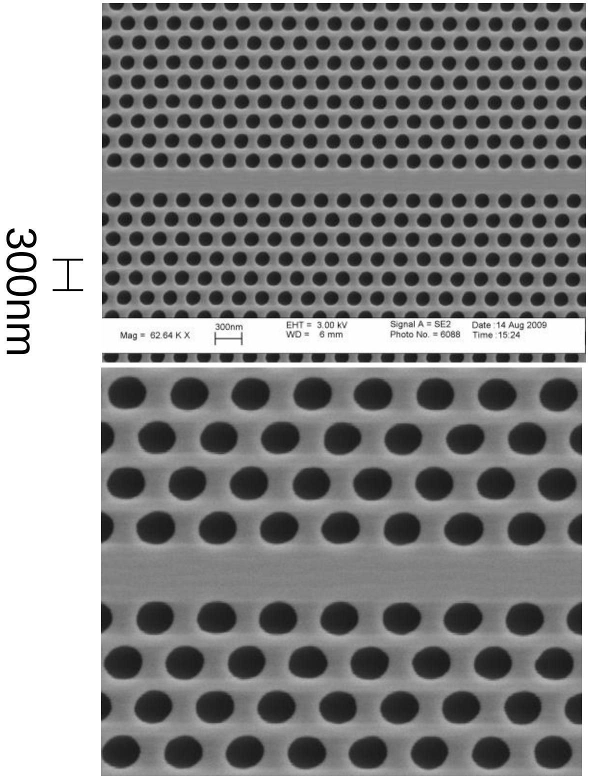
Adding disorder to photonic-crystal waveguides

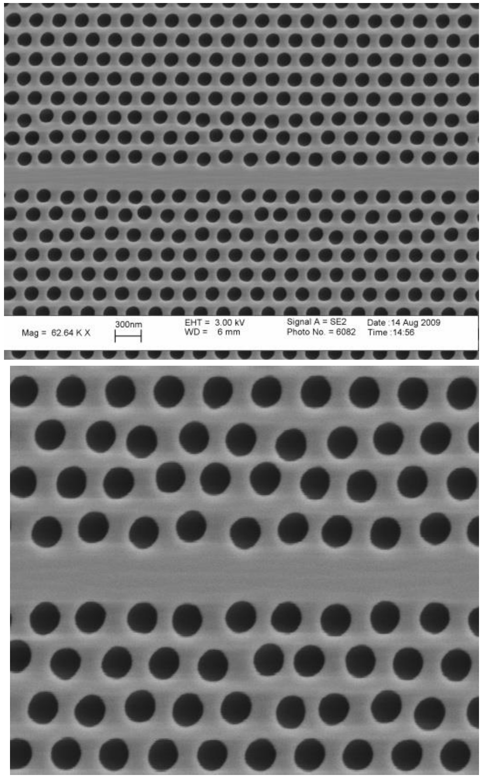
Random disorder on position of holes

Standard deviations in percentage of the lattice constant

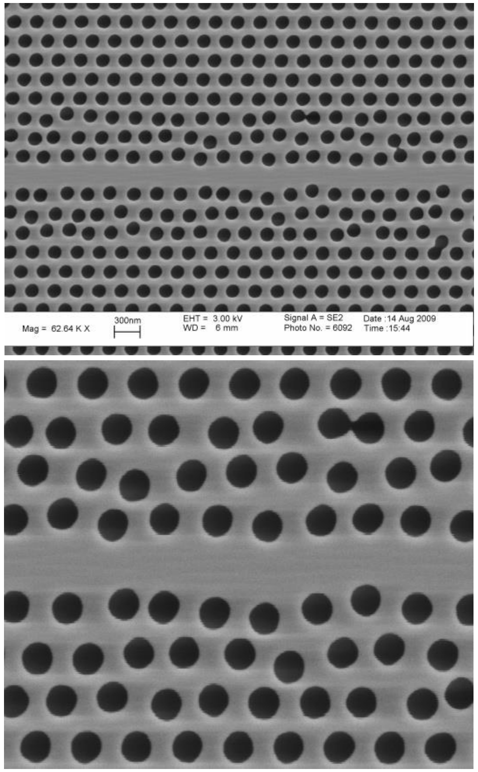
δ=0%



δ= 6%



δ= 12%



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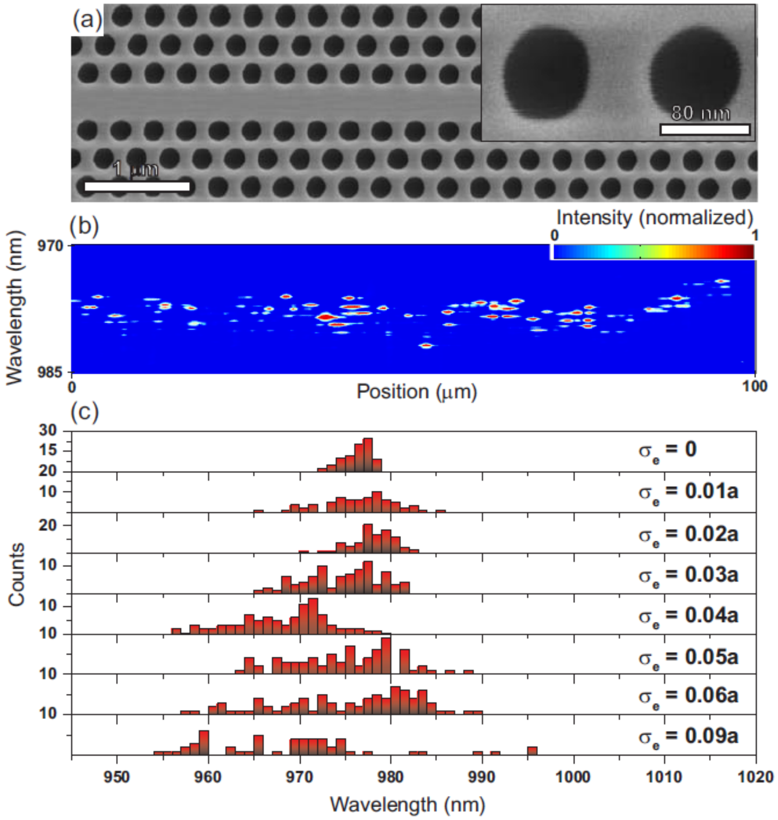
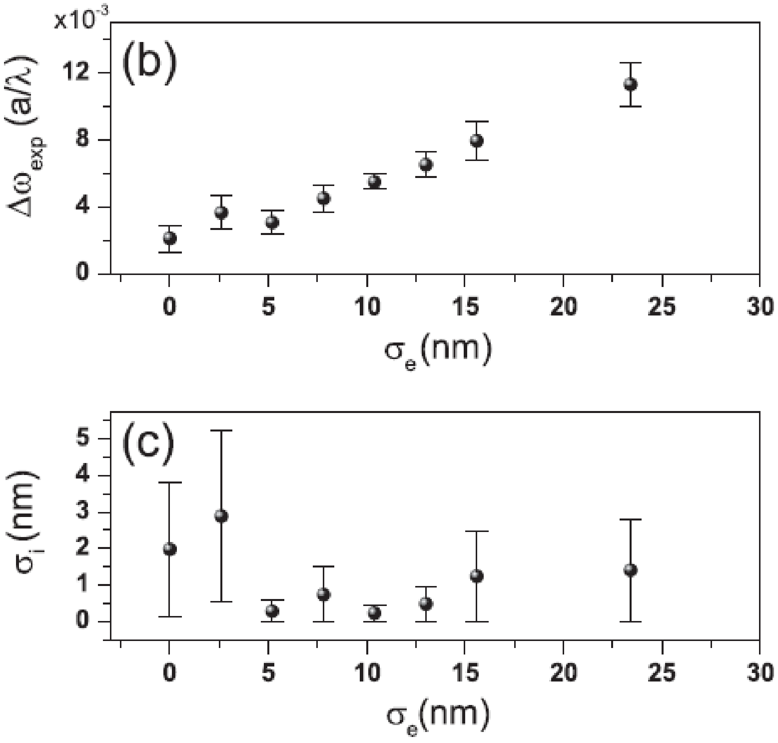
Quantifying Intrinsic Disorder

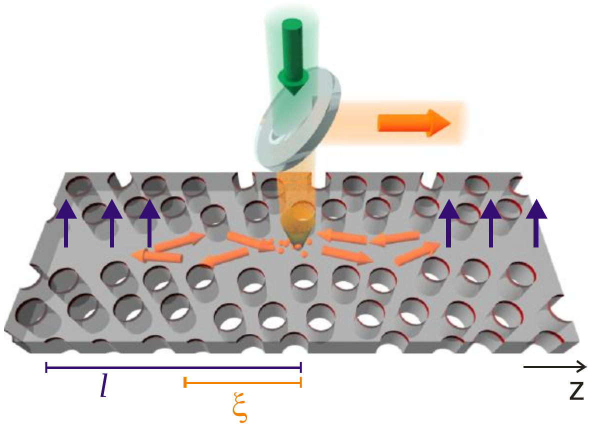
Intrinsic disorder (σ_i) can be measured from the width of the region of localized modes





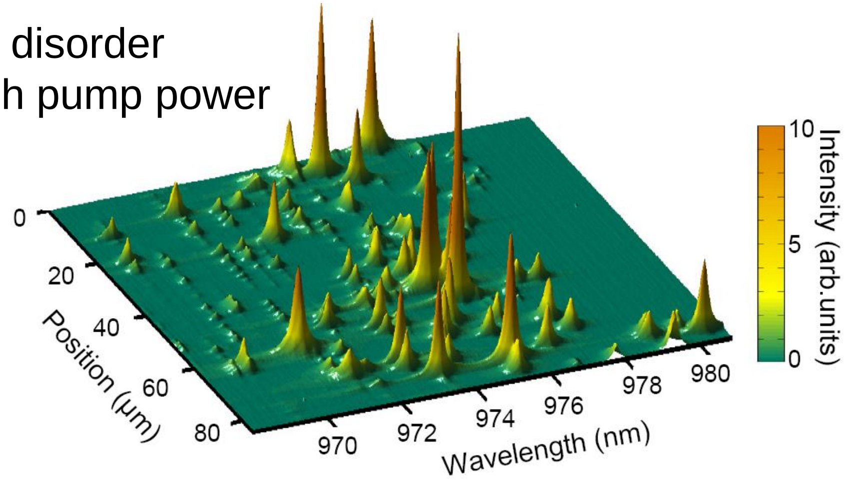
Garcia, Javadi, Thyrrestrup & Lodahl, Appl. Phys. Lett. 102, 031101 (2013).

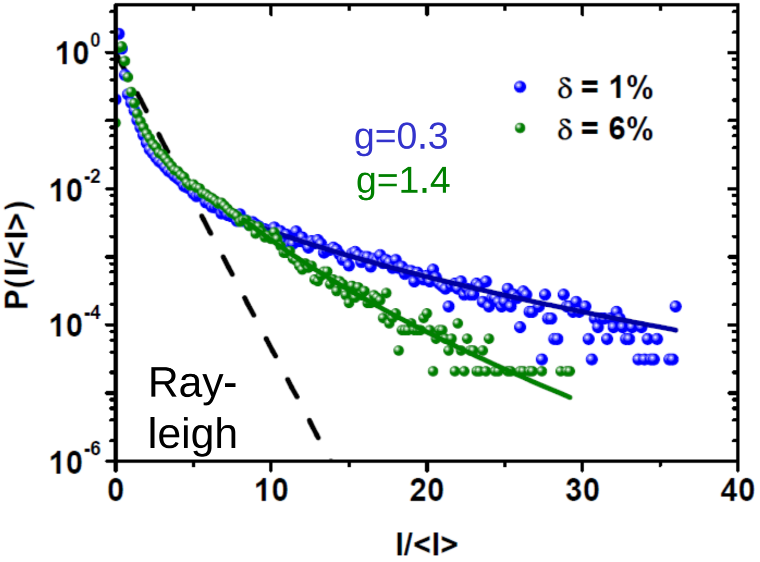
Observation of Anderson-localized modes



Quantum dot spectra recorded when scanning along waveguide

3% disorder
High pump power





Sapienza, Thyrrestrup, Stobbe, Garcia, Smolka & Lodahl, Science 327, 1352 (2010).

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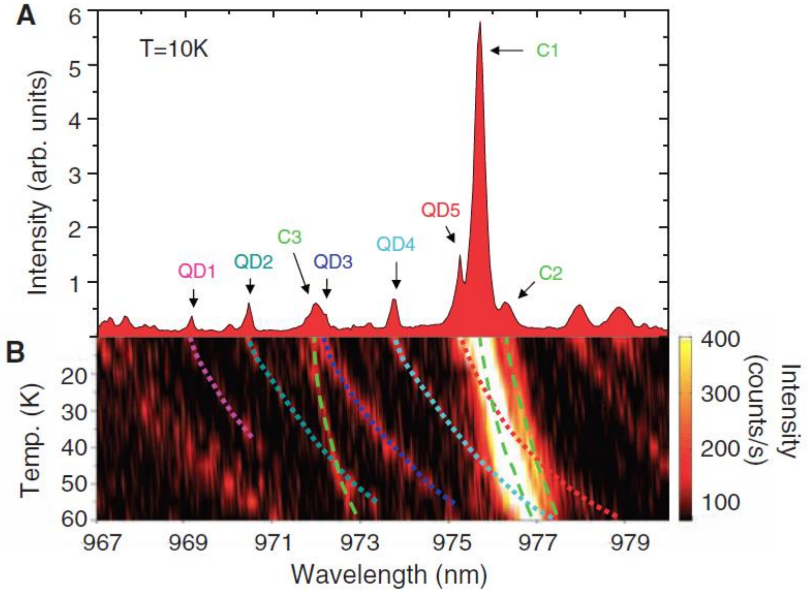
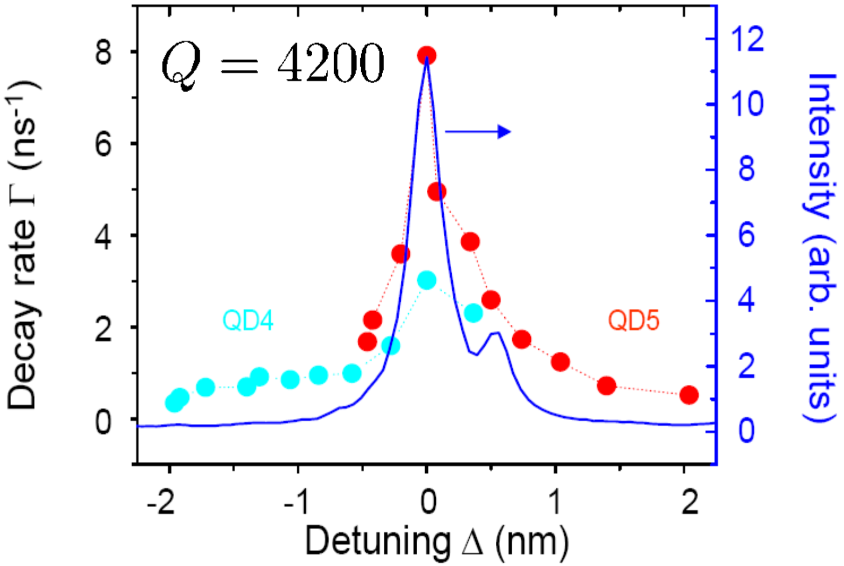
Cavity QED with Anderson-localized modes

Low excitation power: single quantum dot lines are revealed





x15 enhancement of emission rate
→ 94% efficient channeling of photons into cavity

Sapienza, Thyrrestrup, Stobbe, Garcia, Smolka & Lodahl, Science 327, 1352 (2010).

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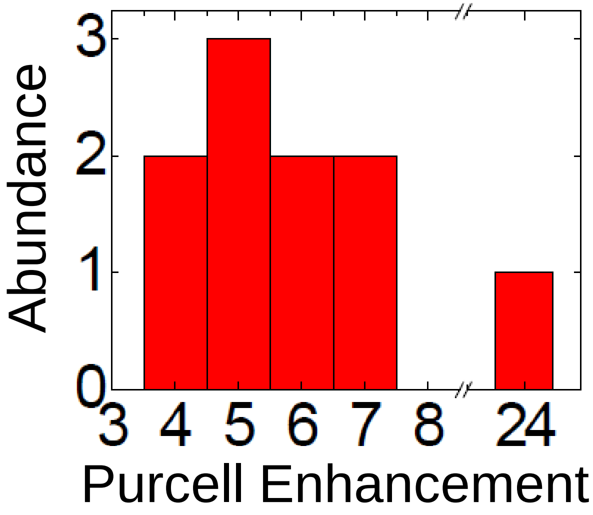
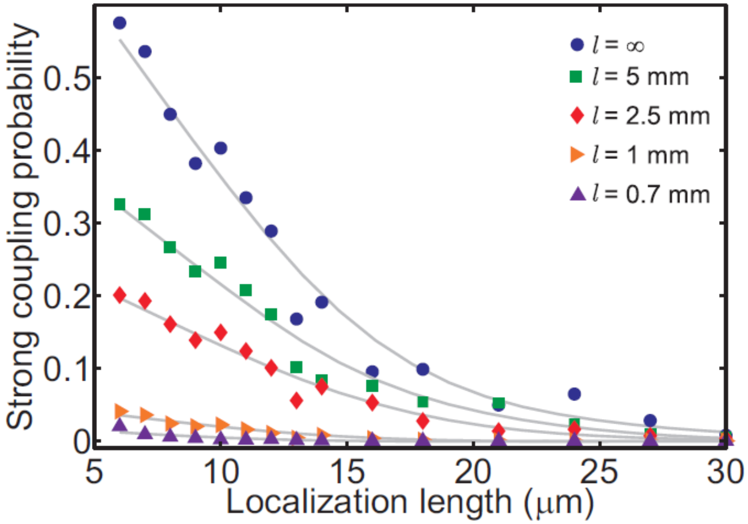
Statistics of Purcell enhancement and strong-coupling probability



Recorded statistics of Purcell enhancement (high Purcell factor tail of distribution)

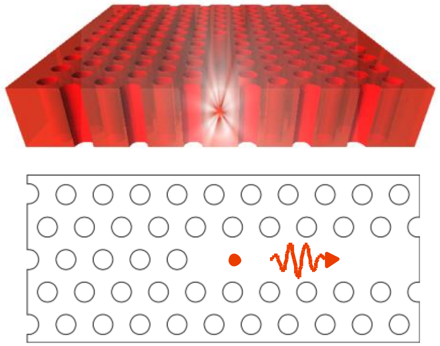


The probability of observing strong coupling of a randomly positioned quantum dot for realistic values of localization and loss lengths

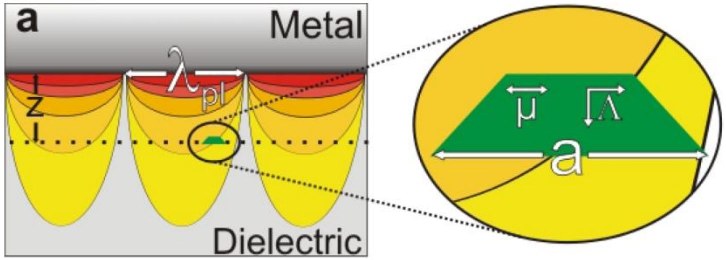
Sapienza, Thyrrestrup, Stobbe, Garcia, Smolka & Lodahl, Science 327, 1352 (2010).
Thyrrestrup, Smolka, Sapienza & Lodahl, Phys. Rev. Lett. 108, 113901 (2012).

Conclusions

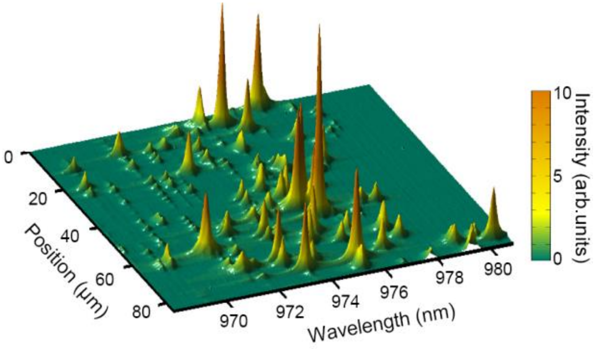
- Photonic crystals enable spontaneous emission control and enhancement of the interaction between a single photon and a single quantum dot



- Solid-state emitters behave fundamentally different than atomic emitters



- Disorder leads to new physics: formation of Anderson-localized modes enabling cavity QED



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(KIST, Korea)

Recent review on quantum nanophotonics with quantum dot light sources:
Lodahl, Mahmoodian & Stobbe, submitted to Rev. Mod. Phys. (2013). arXiv:1312.1079

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