On-chip single photons using slow-light photonic crystal waveguides (L2)

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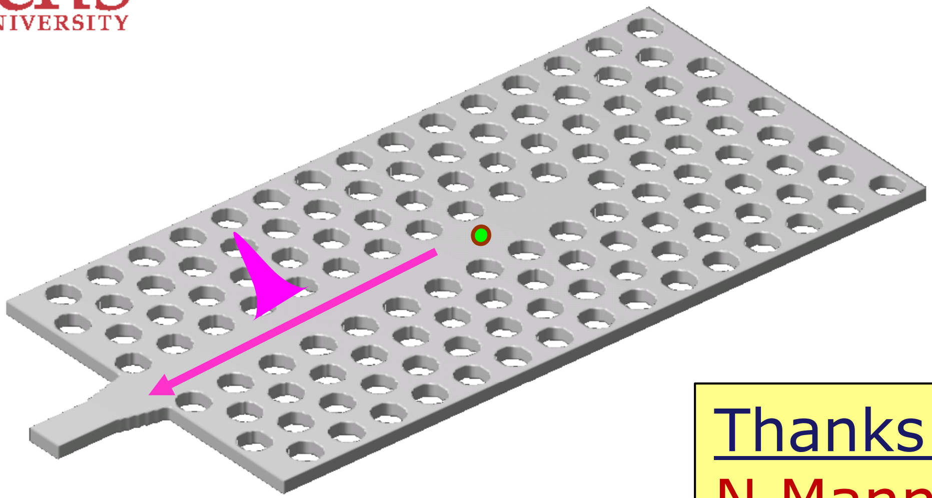
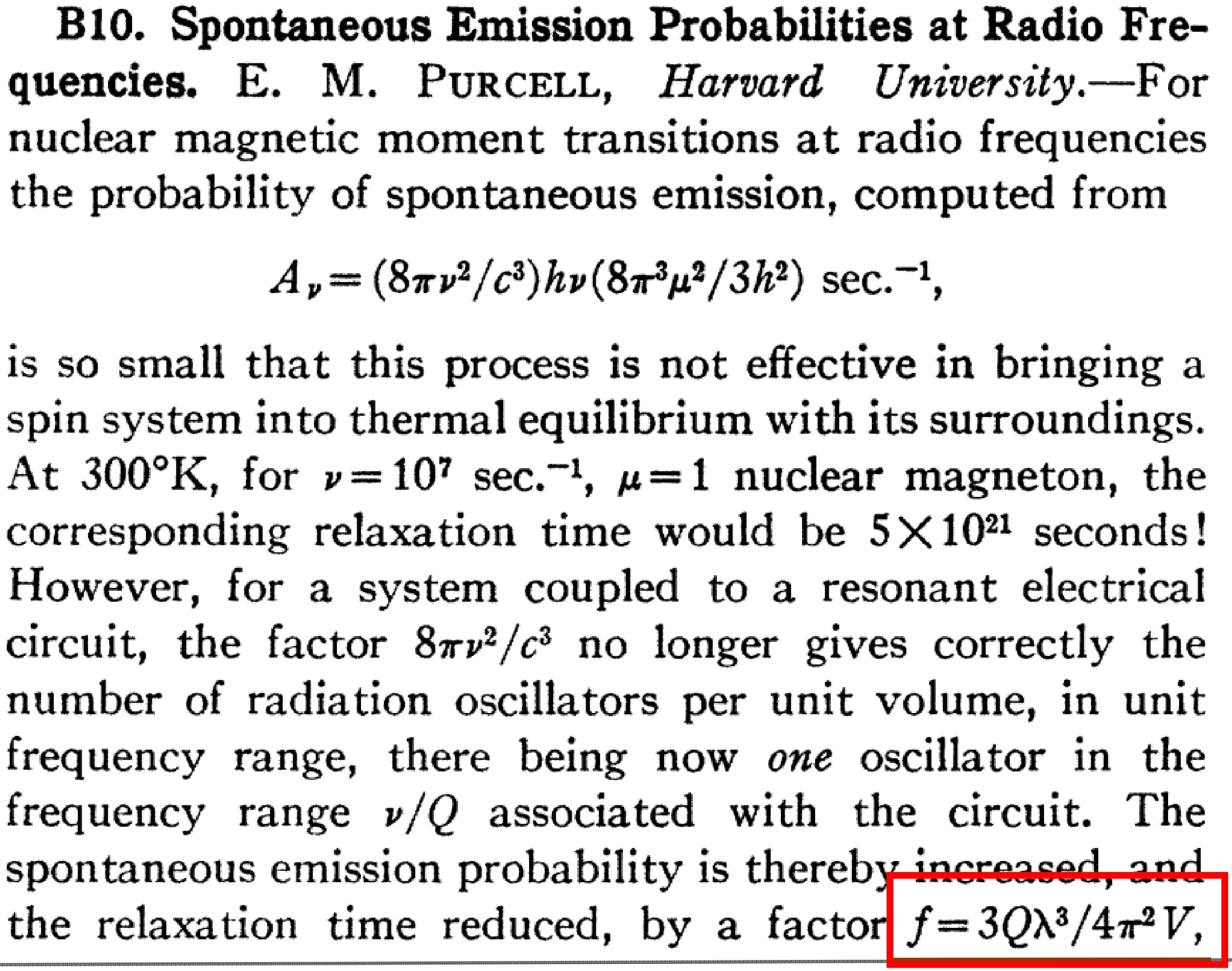


Thanks:
N Mann, V.S.C Manga Rao, P. Yao, NSERC/CFI

Outline – L2

- Fundamentals of on-chip single photon emitters using PC waveguides
- Role of disorder-induced scattering on density of states (DOS) and band structure
- Short waveguide designs and coupling to disorder-induced resonance modes

Purcell Effect (enhanced SE Factor)



B10. Spontaneous Emission Probabilities at Radio Frequencies. E. M. PURCELL, *Harvard University.*—For nuclear magnetic moment transitions at radio frequencies the probability of spontaneous emission, computed from

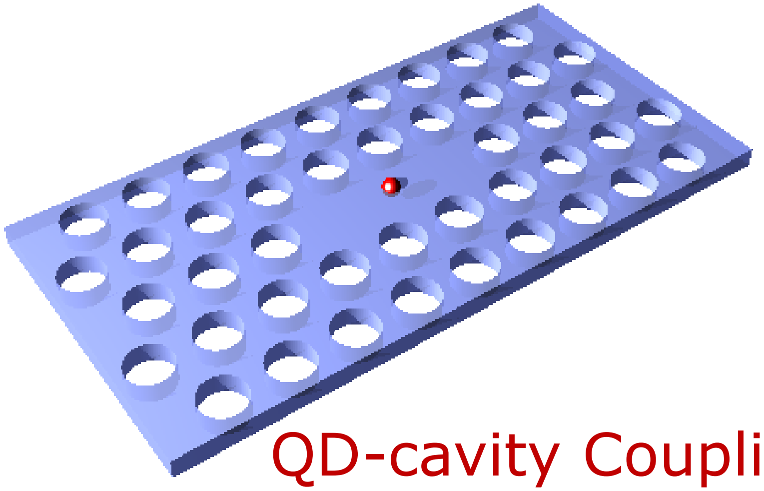
$$A_\nu = (8\pi\nu^2/c^3)h\nu(8\pi^3\mu^2/3h^2)\ \text{sec.}^{-1},$$

is so small that this process is not effective in bringing a spin system into thermal equilibrium with its surroundings. At 300°K, for $\nu = 10^7$ sec.$^{-1}$, $\mu = 1$ nuclear magneton, the corresponding relaxation time would be 5×10^{21} seconds! However, for a system coupled to a resonant electrical circuit, the factor $8\pi\nu^2/c^3$ no longer gives correctly the number of radiation oscillators per unit volume, in unit frequency range, there being now *one* oscillator in the frequency range ν/Q associated with the circuit. The spontaneous emission probability is thereby increased, and the relaxation time reduced, by a factor $\boxed{f = 3Q\lambda^3/4\pi^2 V,}$

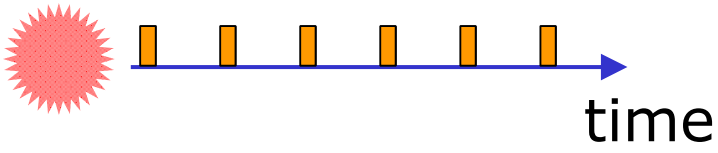
E. M. Purcell, Phys. Rev. 69, 681 (1946)

Non-Classical Light Sources

Quantum dots (QDs) in high Q/V cavities



Single photons



QD-cavity Coupling

$$g = \langle \hat{\mathbf{d}}.\hat{\mathbf{E}} \rangle \left(\propto \frac{d}{V_{\text{eff}}}\right)$$

e.g., with PC Cavities:

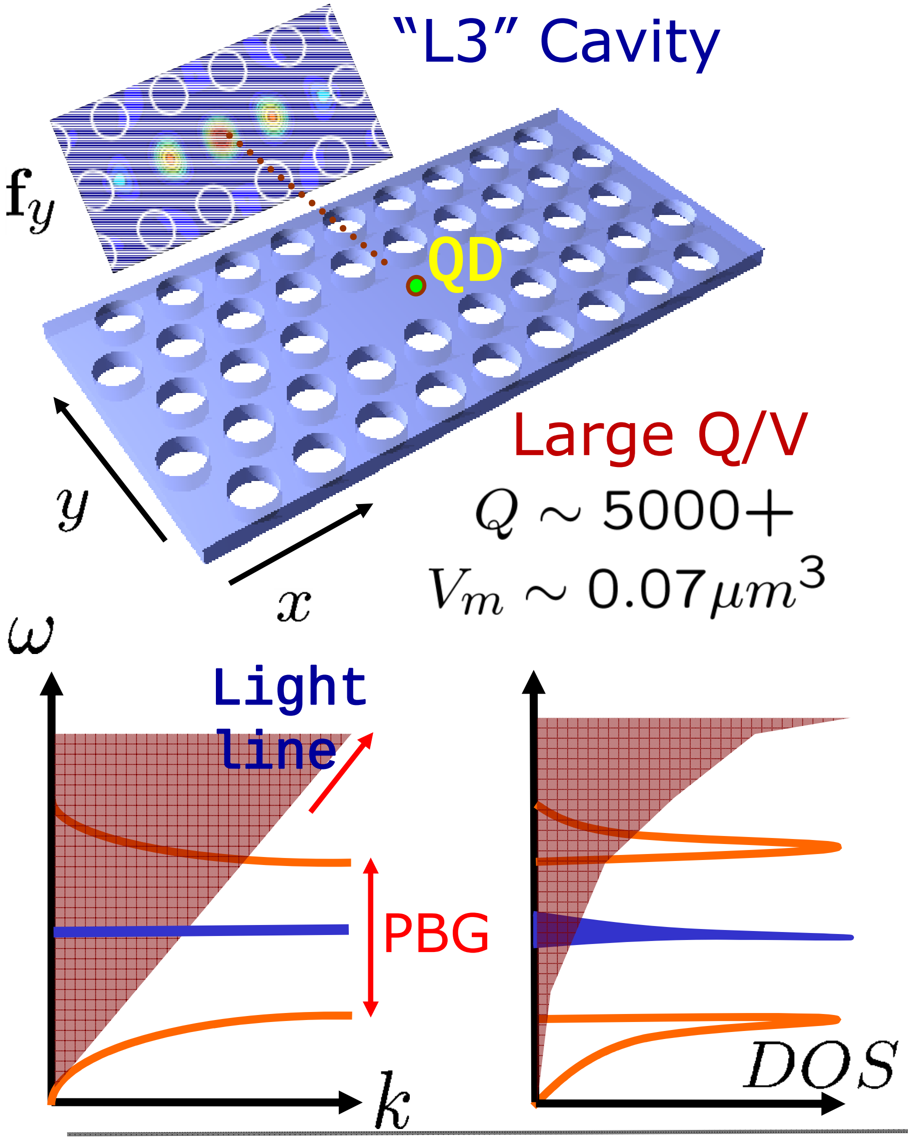
- Yoshie et al, Nature (2004)
- Englund et al, PRL (2005)

Applications

- ♦ Quantum information processing
- ♦ Fundamental quantum optics

PC Cavities versus PC Waveguides

"L3" Cavity

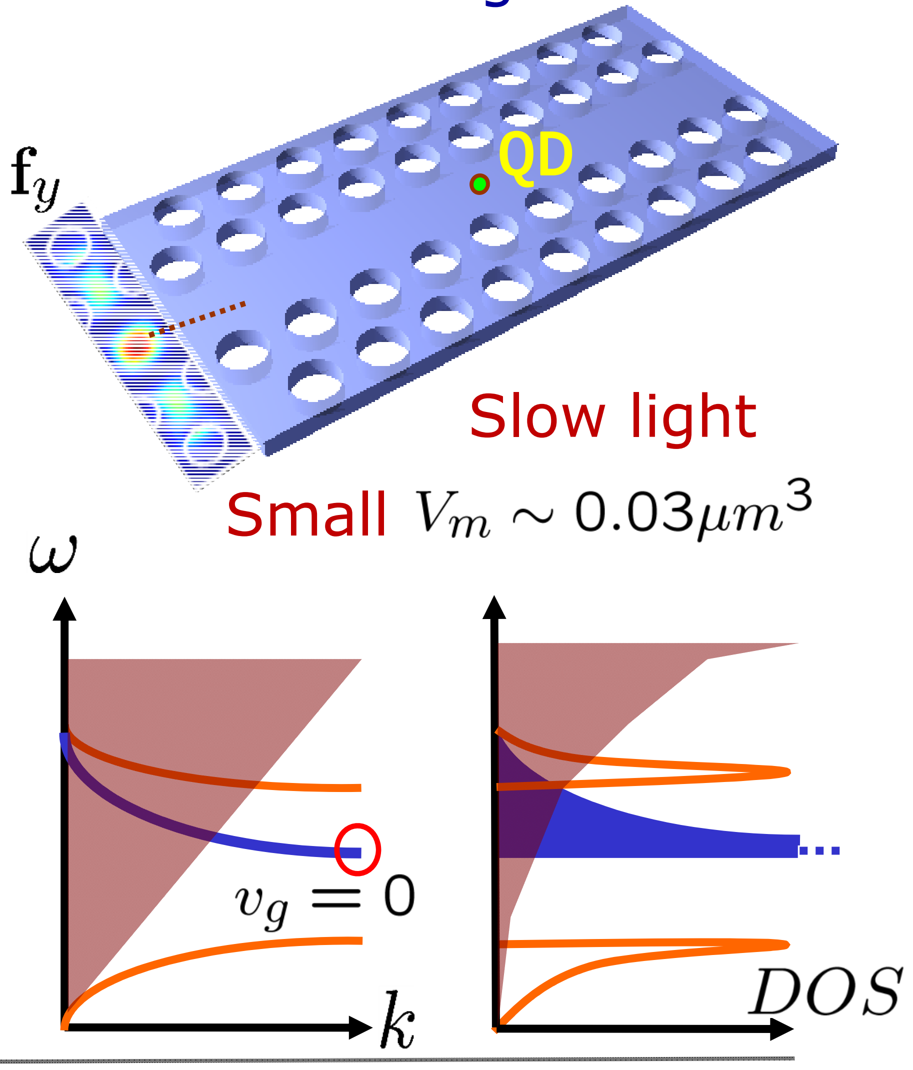


Large Q/V

$Q \sim 5000+$

$V_m \sim 0.07\mu m^3$

"W1" waveguide



Slow light

Small $V_m \sim 0.03\mu m^3$

Important Parameters for Single Photons

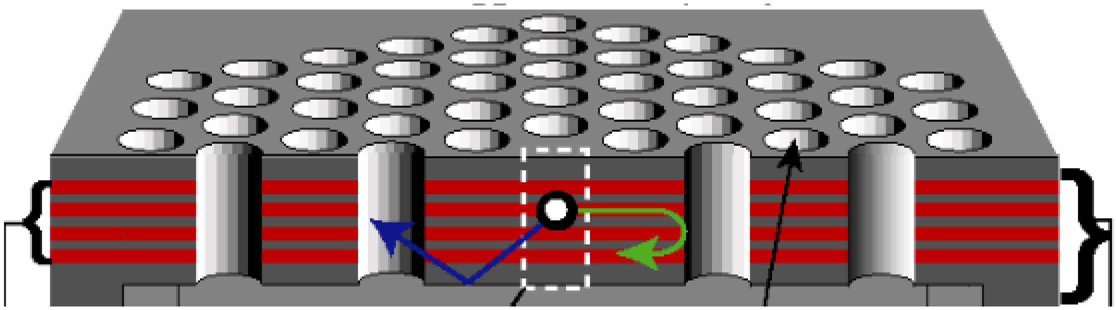
- Beta Factor – amount of spontaneous emission (SE) into a desired output mode

$$\boxed{\beta = \frac{\Gamma_{\text{bound}}}{\Gamma_{\text{bound}} + \Gamma_{\text{others}}}}$$

- Purcell factor – enhanced spontaneous emission factor relative to a homogeneous medium

$$\boxed{\text{PF}(\mathbf{r}) = \frac{\Gamma_{\text{bound}}}{\Gamma_{\text{hom}}} = \frac{\boldsymbol{d} \cdot \text{Im}[\mathbf{G}^{\text{PC}}(\mathbf{r}, \mathbf{r}; \omega)] \cdot \boldsymbol{d}}{\boldsymbol{d} \cdot \text{Im}[\mathbf{G}^{\text{hom}}(\mathbf{r}, \mathbf{r}; \omega)] \cdot \boldsymbol{d}}}$$

Single photon emission rate in any general medium (photonic reservoir)



$$\boxed{\Gamma_i(\mathbf{r},\omega) = \frac{\pi\omega\rho_i(\mathbf{r},\omega)d^2}{\varepsilon_0\hbar}}$$

QD dipole: $\mathbf{d} = \hat{i}d$

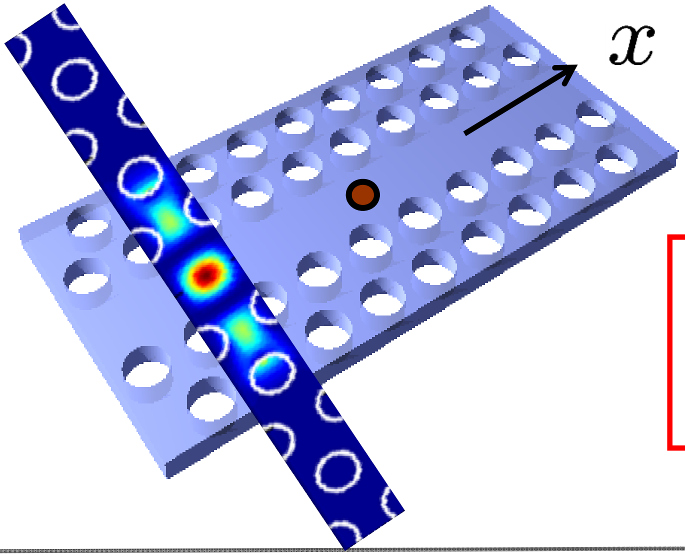
Projected LDOS using **G** defined in previous lecture:

$$\rho_i(\mathbf{r}) \propto \mathrm{Im}[\mathbf{G}_{ii}(\mathbf{r},\mathbf{r};\omega)]$$

LDOS for QD in a PC Waveguide

Using:

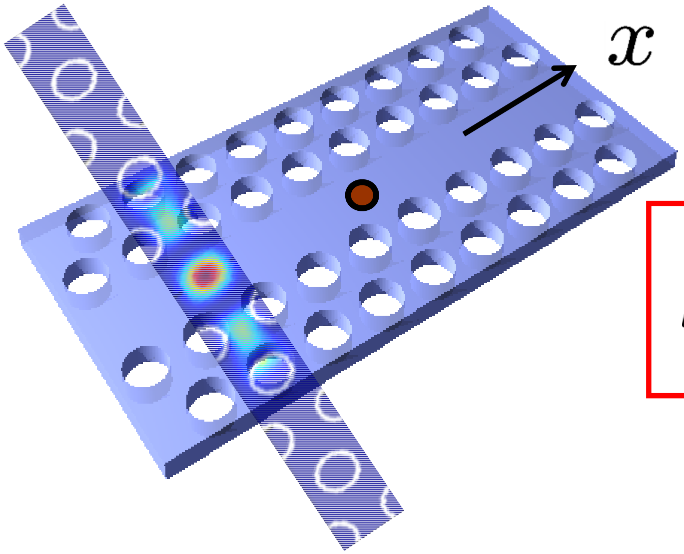
$$\mathbf{G}_{\text{bound}}(\mathbf{r},\mathbf{r}';\omega) = \frac{ia\omega}{2v_g}\Big[H(x-x')\,\mathbf{f}_{k_0}(\mathbf{r})\mathbf{f}^*_{k_0}(\mathbf{r}')e^{ik_0(x-x')} + H(x'-x)\,\mathbf{f}_{-k_0}(\mathbf{r})\mathbf{f}^*_{-k_0}(\mathbf{r}')e^{-ik_0(x-x')}\Big]$$



$$\int_{\text{cell}} d\mathbf{r}\,\varepsilon(\mathbf{r})|\mathbf{f}_k(\mathbf{r})|^2 = 1$$

$$\rho_\alpha(\mathbf{r},\omega) = \frac{a|\mathbf{f}_k(\mathbf{r})|^2}{\pi\varepsilon^{1/2}v_g(\omega)}$$

LDOS and Purcell factor at field antinode position



LDOS:

$$\boxed{\rho_\alpha(\mathbf{r}_a,\omega) = \frac{a}{V_{\text{eff}}\pi n_b^3 v_g(\omega)}}$$

Effective mode volume (per unit cell):

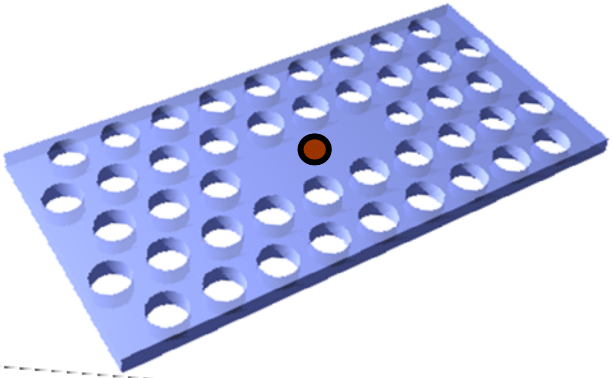
$$V_{\text{eff}} = \frac{1}{\varepsilon(\mathbf{r}_a)|\mathbf{f}_k(\mathbf{r}_a)|^2}$$

PF:

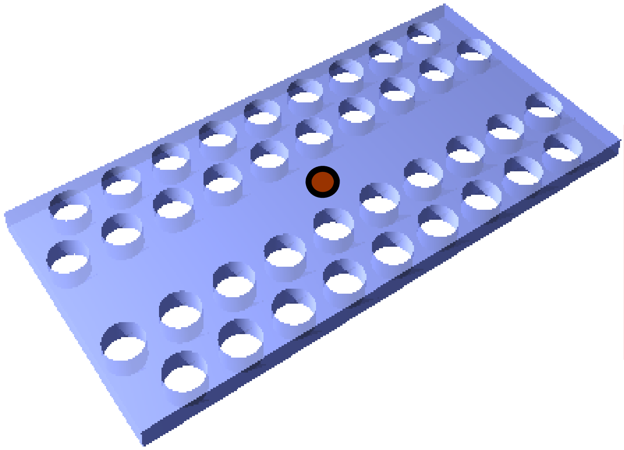
$$\boxed{\text{PF}(\mathbf{r}_a,\omega) = \frac{3\pi c^3 a}{V_{\text{eff}}\omega^2 n_b^3 v_g(\omega)}}$$

Manga Rao and Hughes, PRB 75, 205437 (2007)

Simple Cavity PF versus Waveguide PF

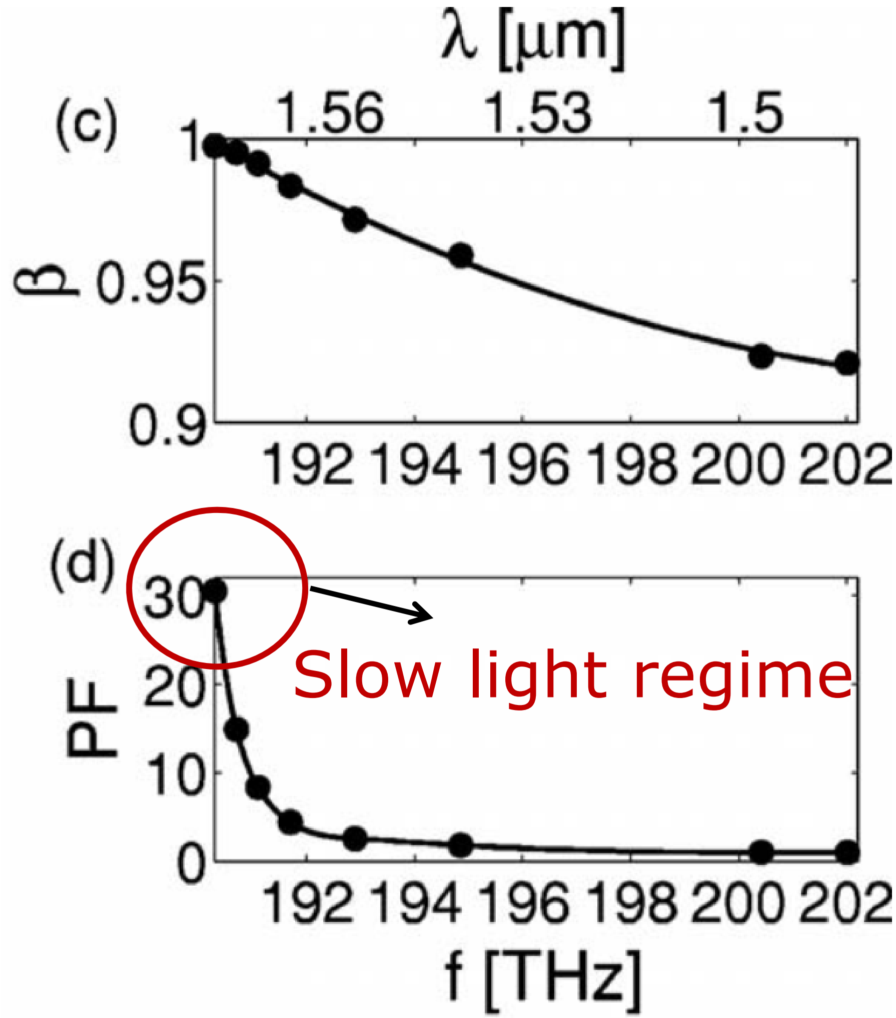


$$\mathrm{PF}^{\mathrm{cav}}(\mathbf{r}_a,\omega_c) = \frac{3}{4\pi^2}\left(\frac{\lambda_0}{n_b}\right)^3 \frac{Q}{V_{\mathrm{eff}}}$$



$$\mathrm{PF}^{\mathrm{wg}}(\mathbf{r}_a,\omega_c) = \frac{3}{4\pi^2}\left(\frac{\lambda_0}{n_b}\right)^3 \frac{\omega a/v_g(\omega)}{V_{\mathrm{eff}}}$$

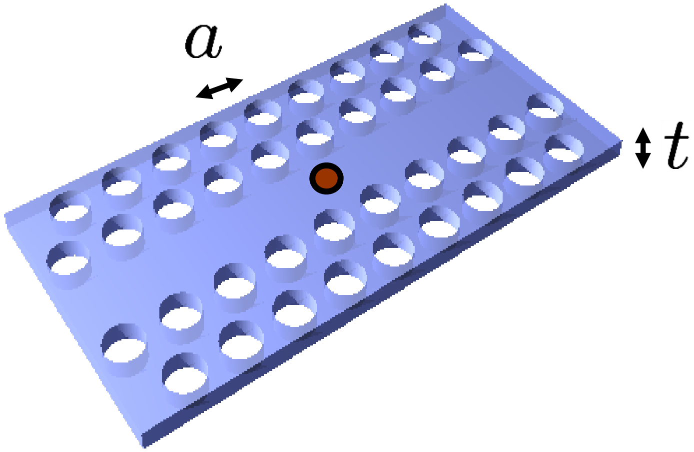
Purcell Factor and Beta Factor vs Frequency



Slow light regime

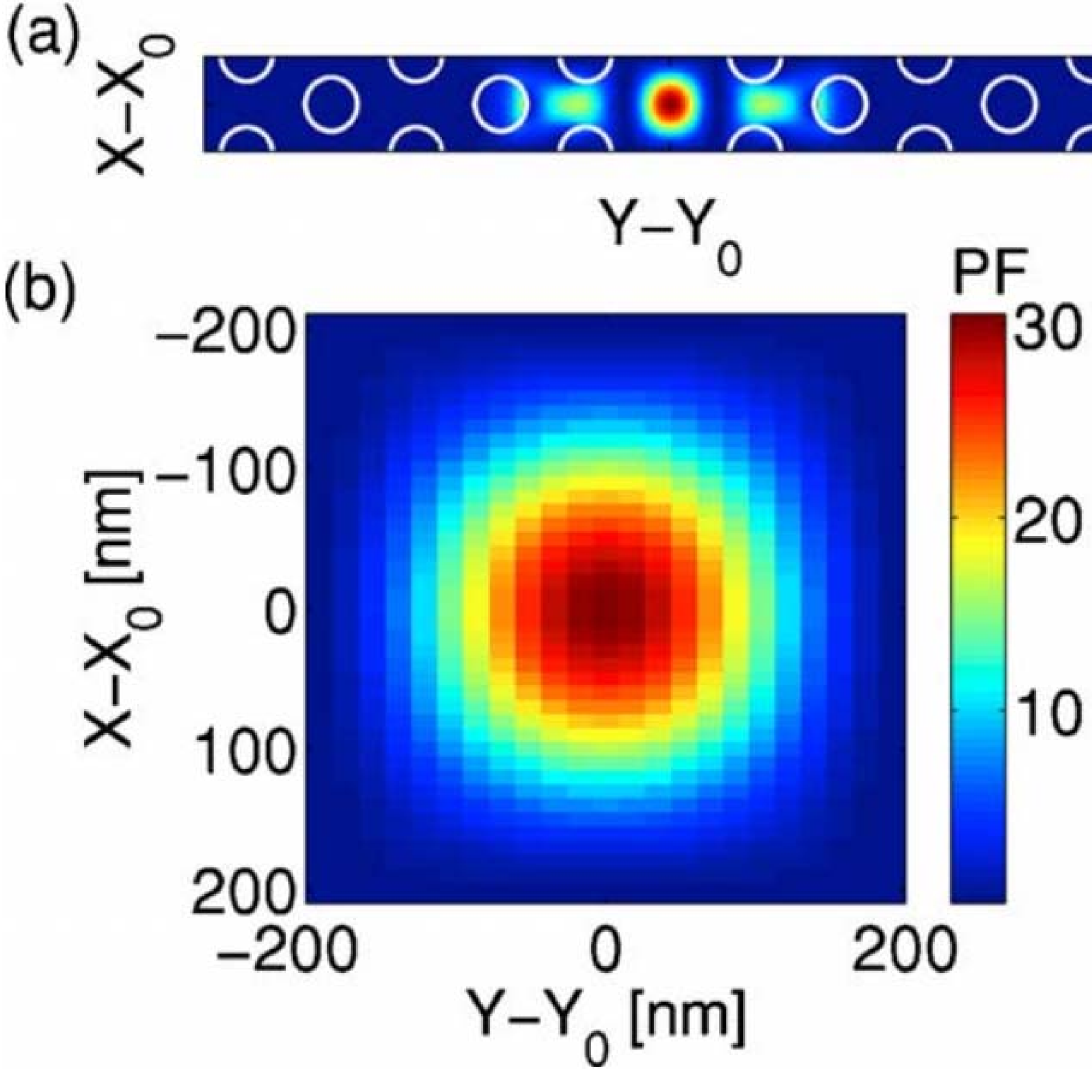
$a = 420\,\mathrm{nm}$

$t = 0.5\,a$



Manga Rao and Hughes, PRB 75, 205437 (2007)

Example PF vs QD Position (slab center)

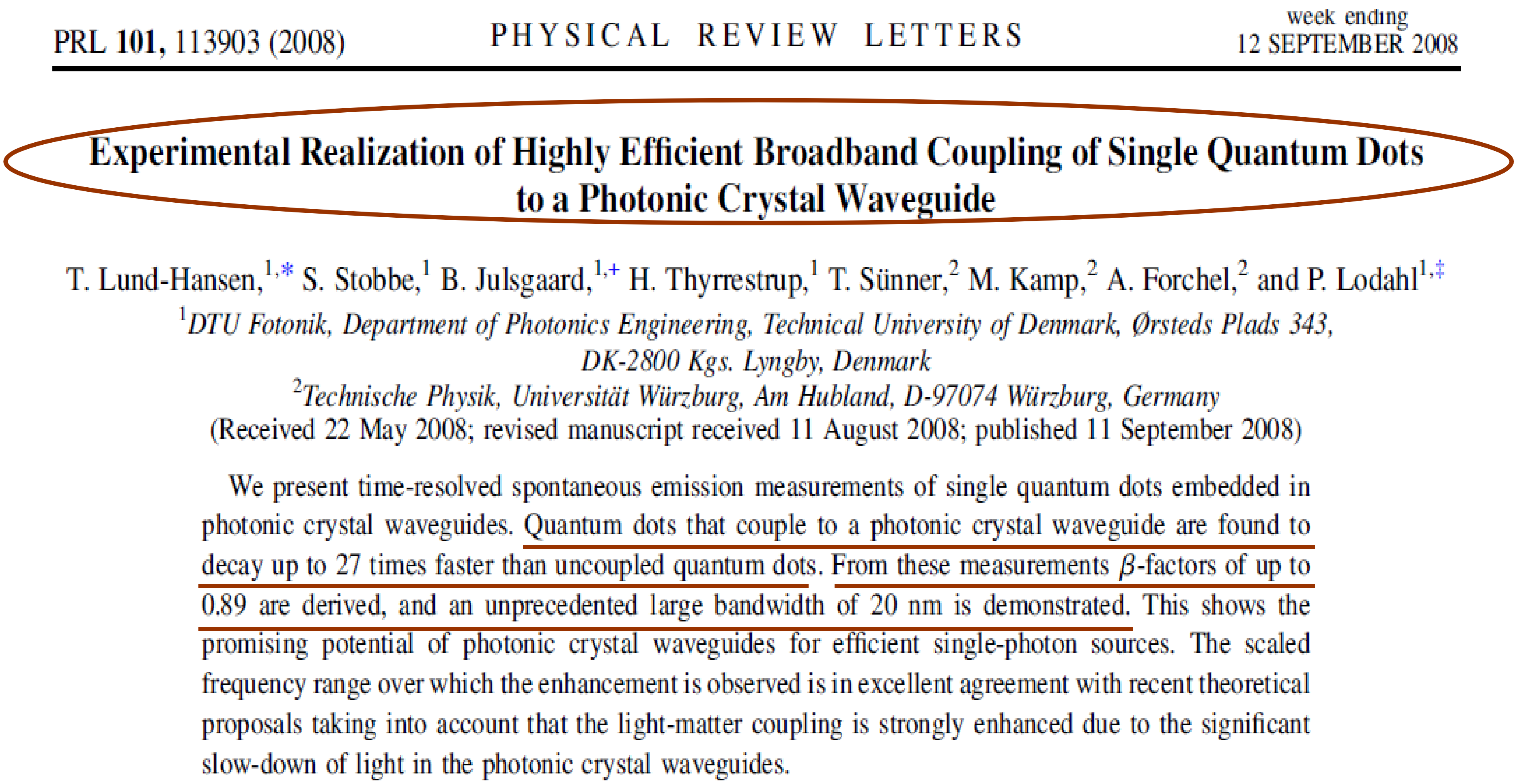


$$v_g \sim c/100$$

$$V_{\mathrm{eff}} = (300\,\mathrm{nm})^3$$

Manga Rao and Hughes, PRB 75, 205437 (2007)

First Exp. Report: Coupling QDs to PC Guides



PRL **101,** 113903 (2008) PHYSICAL REVIEW LETTERS week ending 12 SEPTEMBER 2008

Experimental Realization of Highly Efficient Broadband Coupling of Single Quantum Dots to a Photonic Crystal Waveguide

T. Lund-Hansen,[1,*] S. Stobbe,[1] B. Julsgaard,[1,+] H. Thyrrestrup,[1] T. Sünner,[2] M. Kamp,[2] A. Forchel,[2] and P. Lodahl[1,‡]

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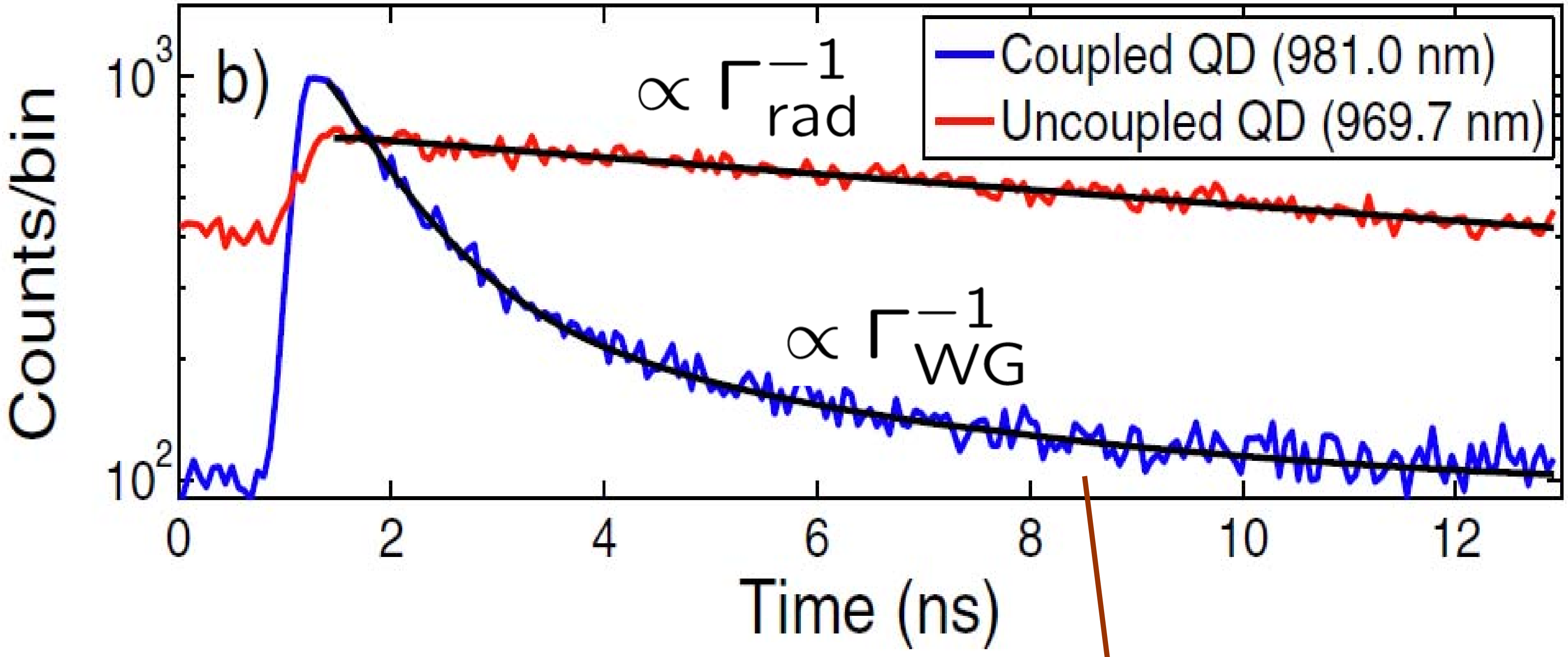
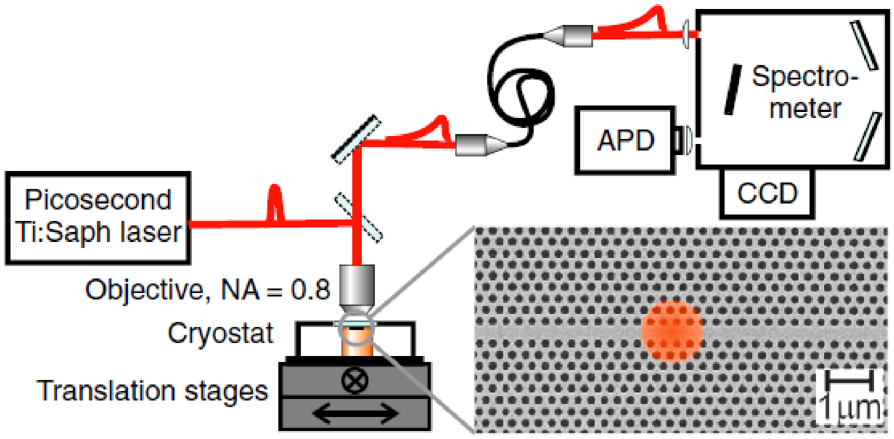
We present time-resolved spontaneous emission measurements of single quantum dots embedded in photonic crystal waveguides. Quantum dots that couple to a photonic crystal waveguide are found to decay up to 27 times faster than uncoupled quantum dots. From these measurements β-factors of up to 0.89 are derived, and an unprecedented large bandwidth of 20 nm is demonstrated. This shows the promising potential of photonic crystal waveguides for efficient single-photon sources. The scaled frequency range over which the enhancement is observed is in excellent agreement with recent theoretical proposals taking into account that the light-matter coupling is strongly enhanced due to the significant slow-down of light in the photonic crystal waveguides.

Lund-Hanson et al. PRL 101,113903 (2008)

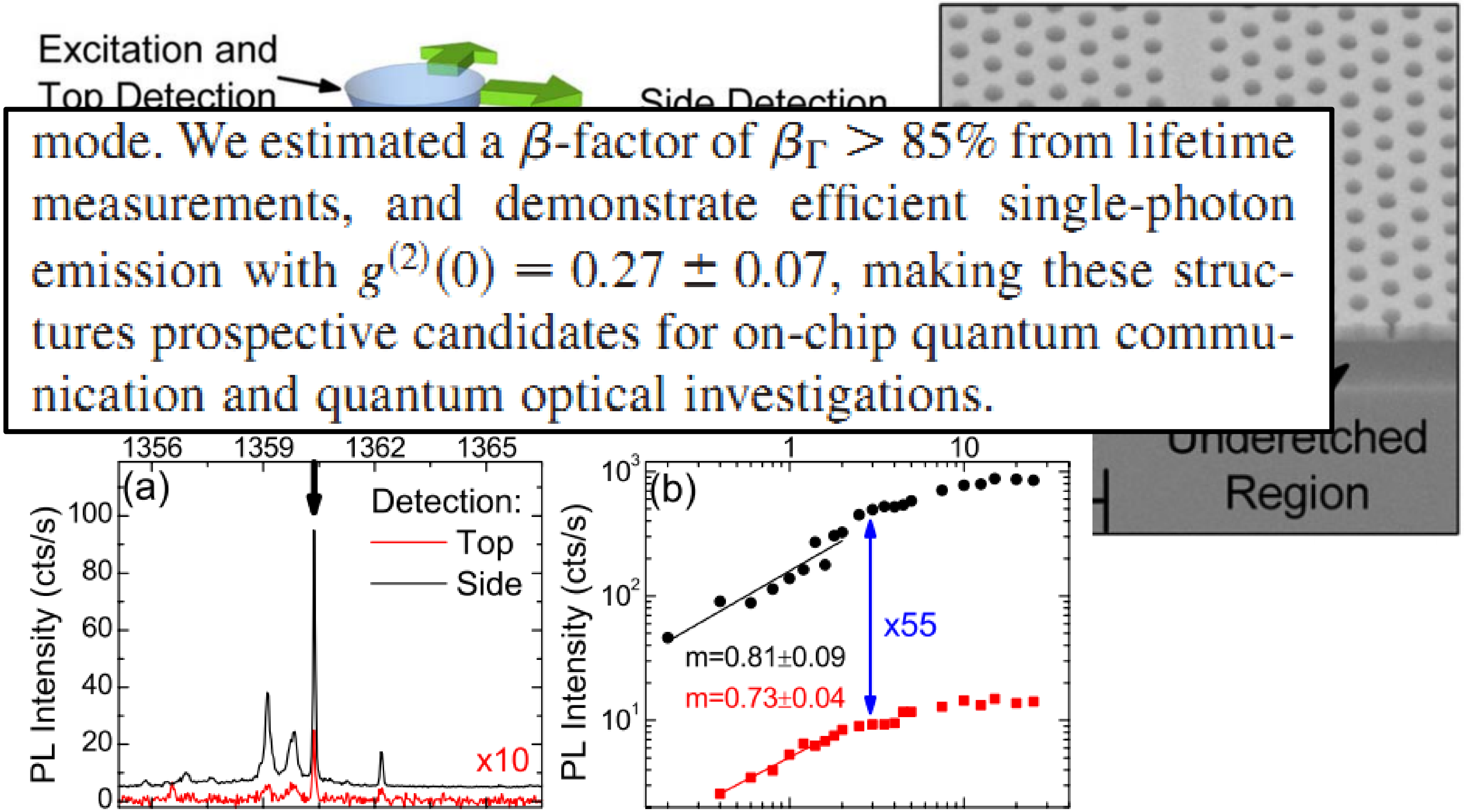




Coupled to waveguide mode, then QD has a much faster photon decay

Recent example with top/side detection

Laucht et al. PRX 2 011014 (2012)

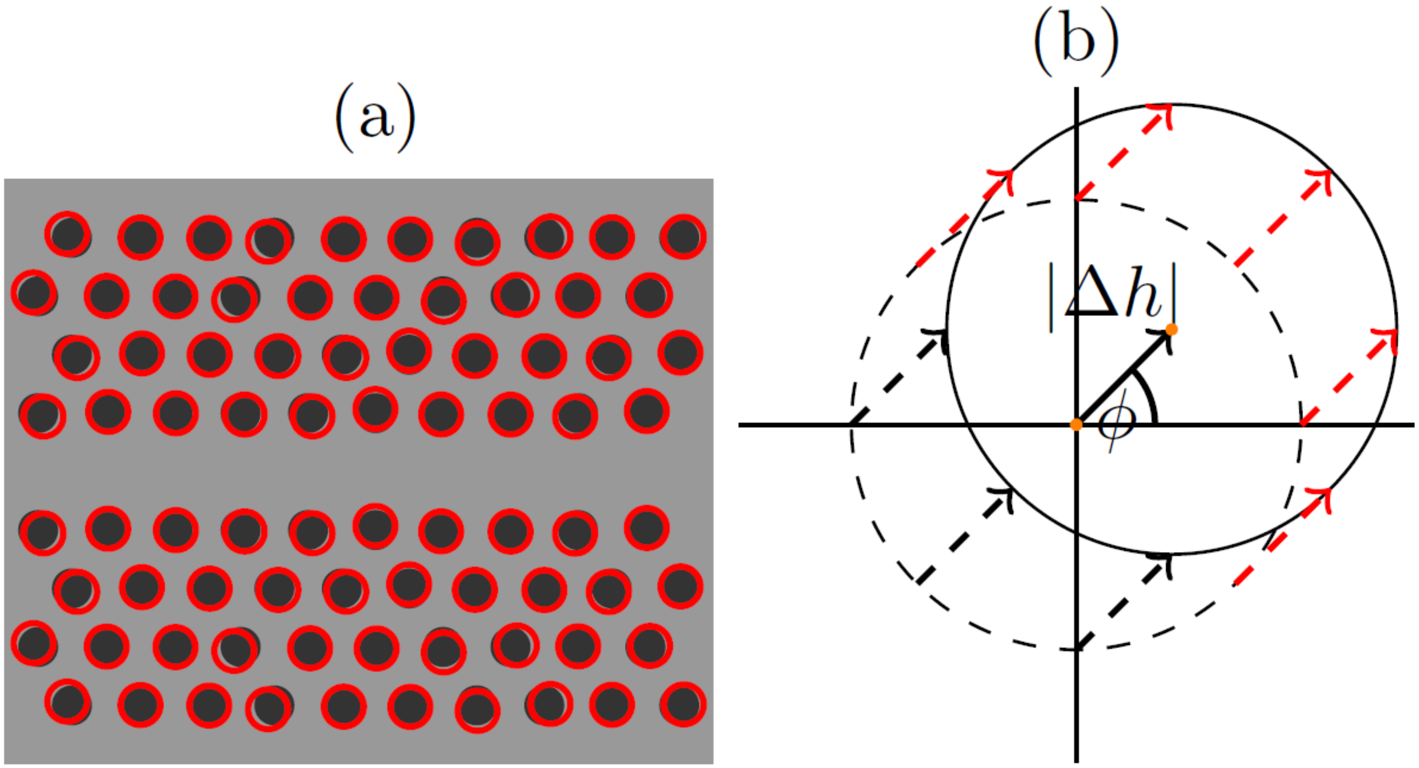


mode. We estimated a β-factor of $\beta_\Gamma > 85\%$ from lifetime measurements, and demonstrate efficient single-photon emission with $g^{(2)}(0) = 0.27 \pm 0.07$, making these structures prospective candidates for on-chip quantum communication and quantum optical investigations.

Outline

- Fundamentals of on-chip single photon emitters using PC waveguides
- **Role of disorder-induced scattering on density of states (DOS) and band structure**
- Short waveguide designs and coupling to disorder-induced resonance modes

Role of disorder on density of states (DOS) and band structure



With this type of external hole fluctuation, disorder parameters can be increased systematically

N. Mann, SH, P. Lodahl group, unpublished

Basic theory of disorder-induced resonance shifts

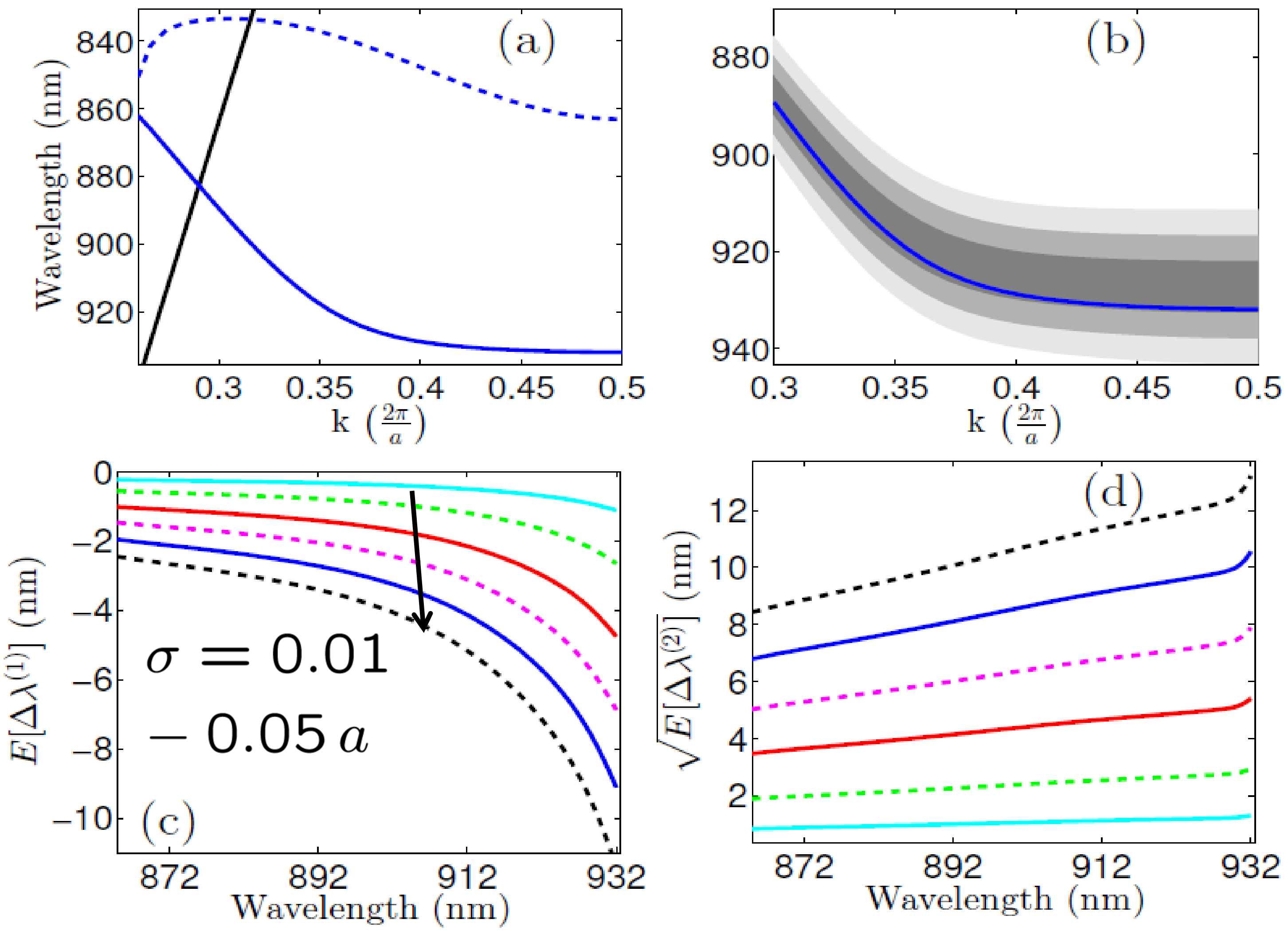
First-order resonance shifts (**P** from disorder):

$$\mathbb{E}\left[\Delta\omega^{(1)}\right] = -\frac{\omega_0}{2}\int_{\text{cell}} \mathbb{E}\left[\mathbf{E}^*(\mathbf{r})\cdot\mathbf{P}(\mathbf{r})\right] d\mathbf{r},$$

Second-order resonance shifts:

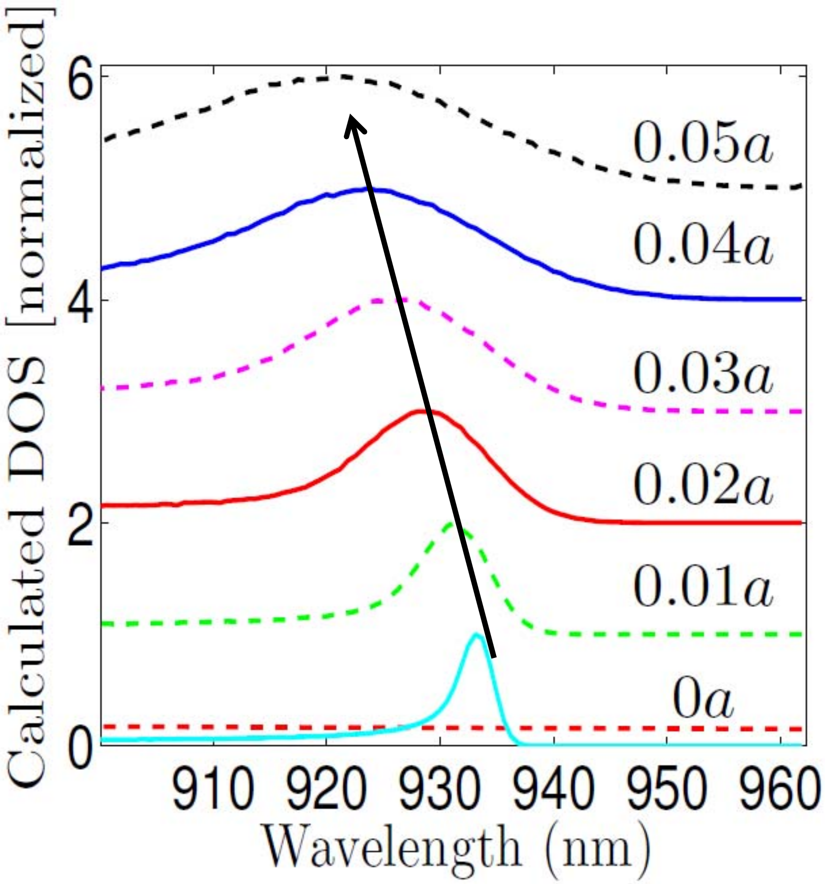
$$\mathbb{E}\left[\Delta\omega^{(2)}\right] =$$
$$\frac{\omega_0^2}{4}\iint \mathbb{E}\left[\mathbf{E}^*(\mathbf{r})\cdot\mathbf{P}(\mathbf{r})\,\mathbf{E}^*(\mathbf{r}')\cdot\mathbf{P}(\mathbf{r}')\right] d\mathbf{r}d\mathbf{r}'.$$

Impact of disorder on band structure

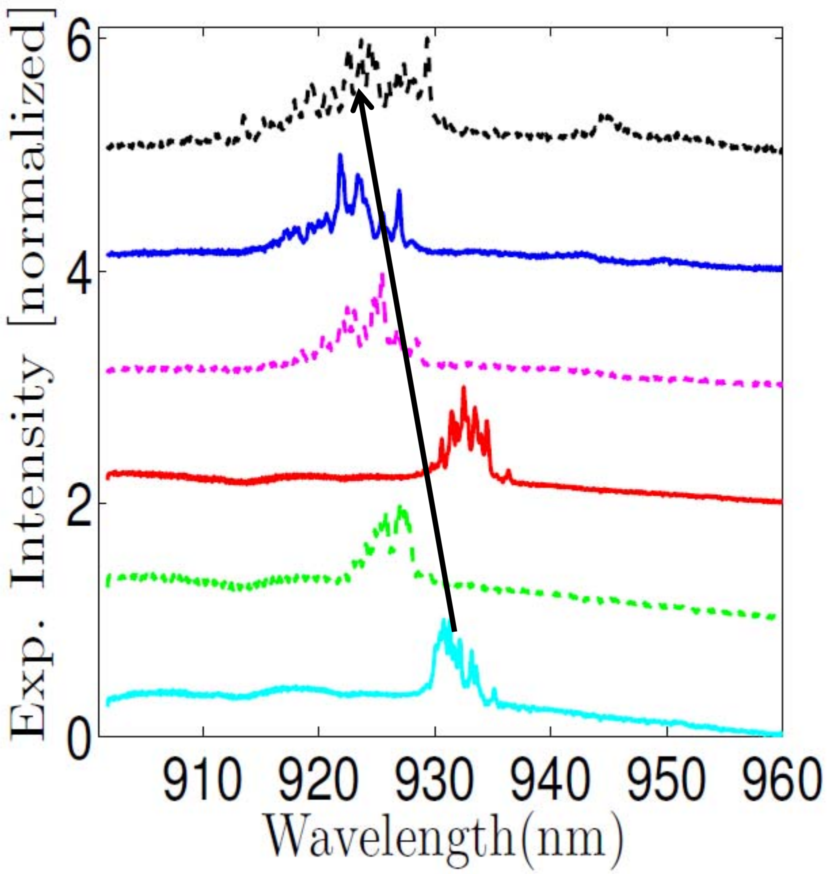


Theory and experiment – DOS average versus increasing disorder

Theory:

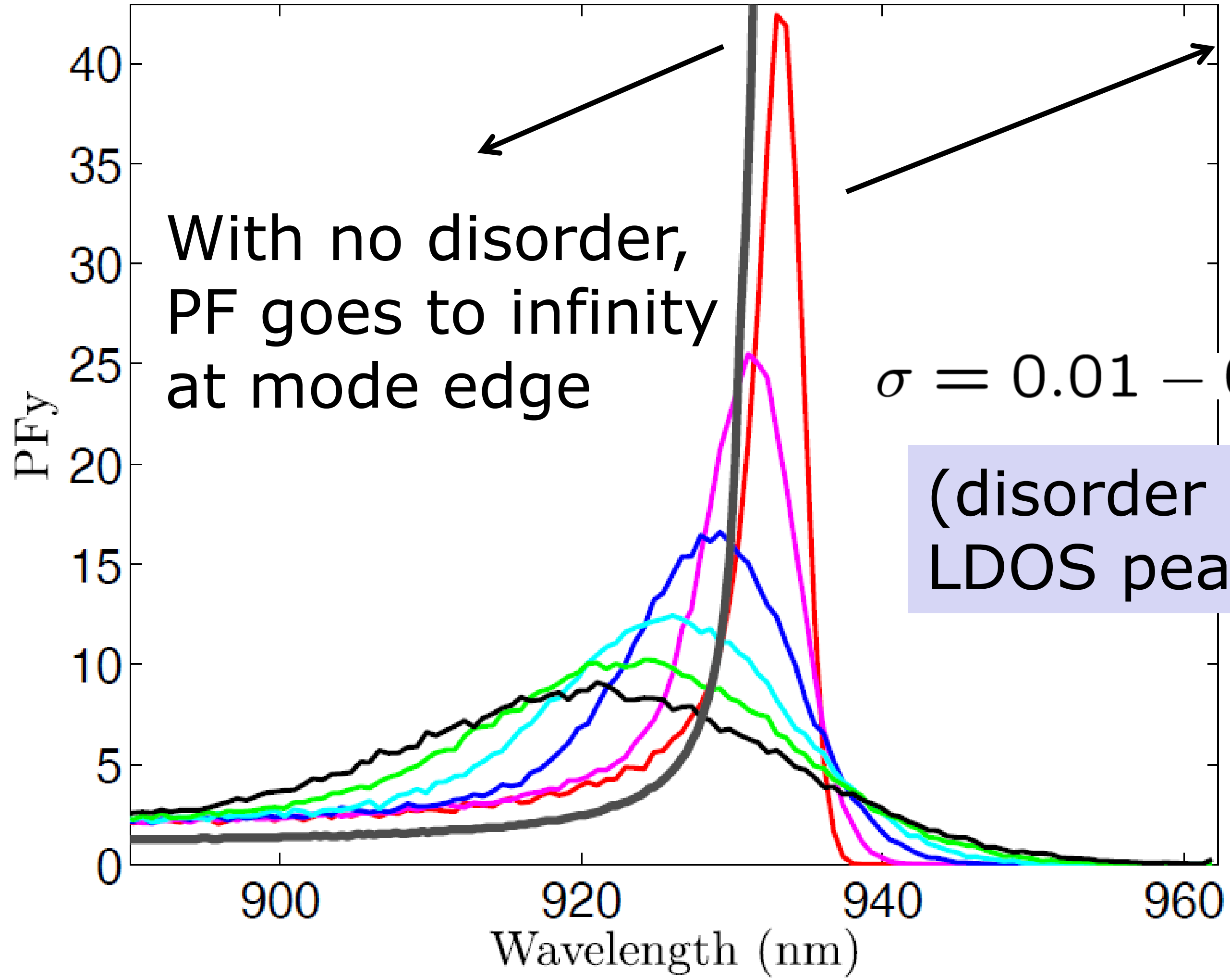


Experiments (GaAs):



N. Mann, SH, P. Lodahl group, unpublished

Impact on Purcell Factor



Intrinsic disorder

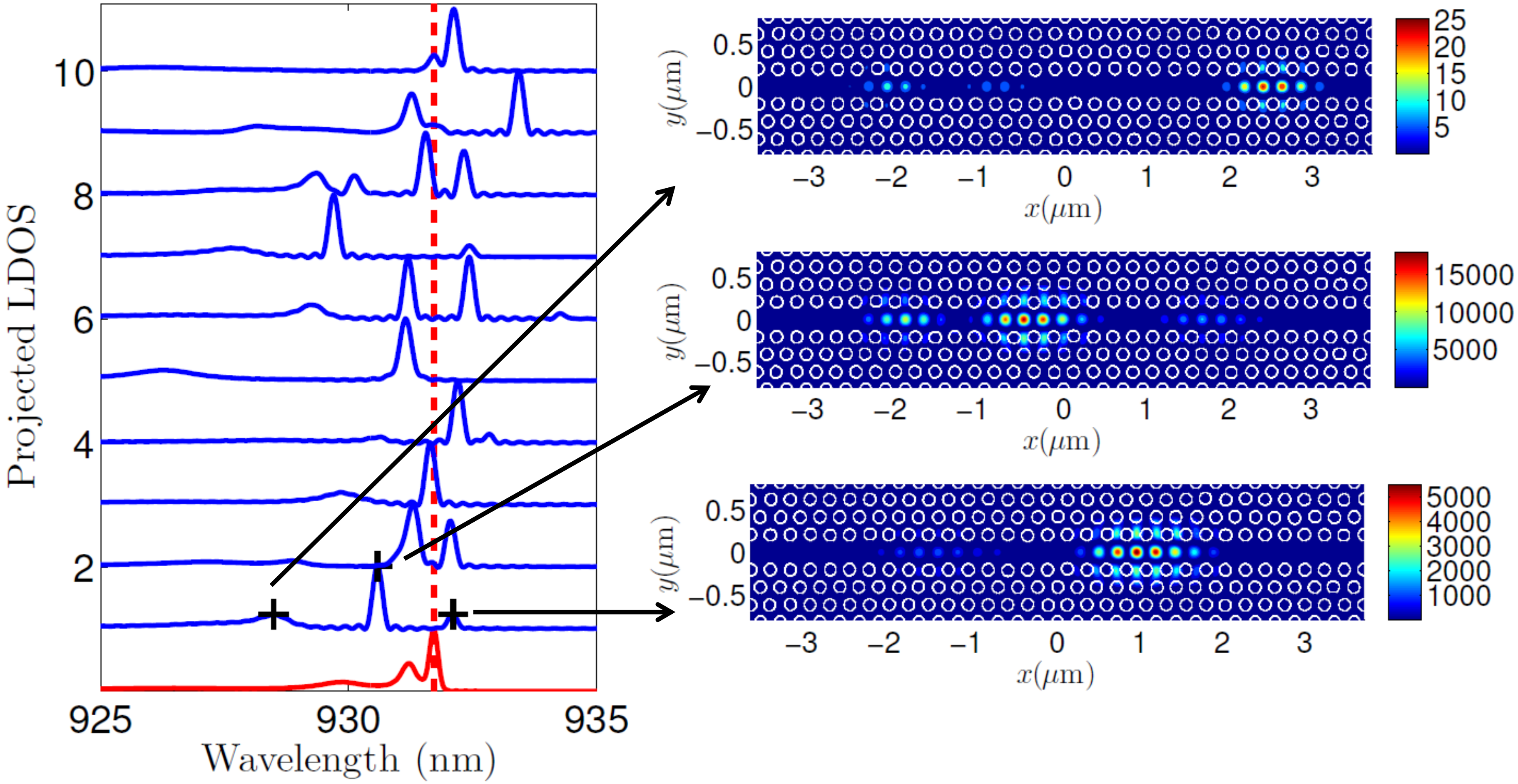
With no disorder, PF goes to infinity at mode edge

$\sigma = 0.01 - 0.05\,a$

(disorder limits LDOS peak)

Disorder-Induced Resonances

10 instances using 3D FDTD (37 unit cells):



Full 3D Maxwell solution of a disordered *instance*

Impact from disorder-induced scattering on waveguide cavity-QED

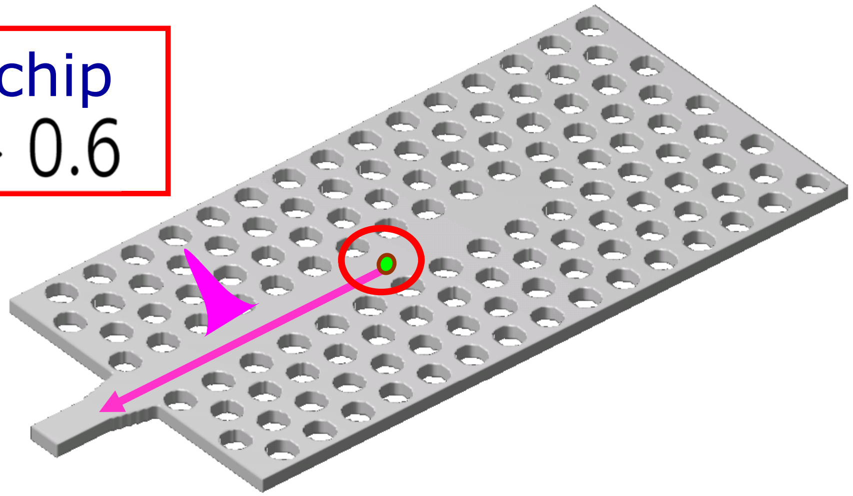
- Long waveguides have large losses with slow-light modes, causing spatial regions of disorder-induced light localization.
- This also limits the minimum group velocity that can be measured and used from the ideal band structure picture.
- Hoiwever, one can still exploit the modes, by: using shorter guides, or coupling to the disordered-induced resonances.

Outline

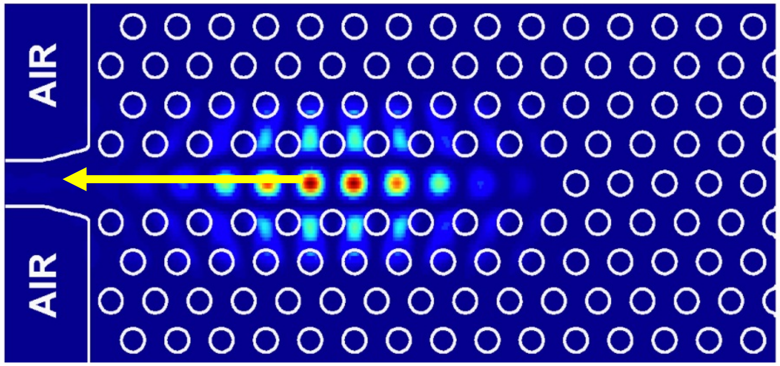
- Fundamentals of on-chip single photon emitters using PC waveguides
- Role of disorder-induced scattering on density of states (DOS) and band structure
- **Short waveguide designs and coupling to disorder-induced resonance modes**

Single Photon Gun in a finite-size PC waveguide

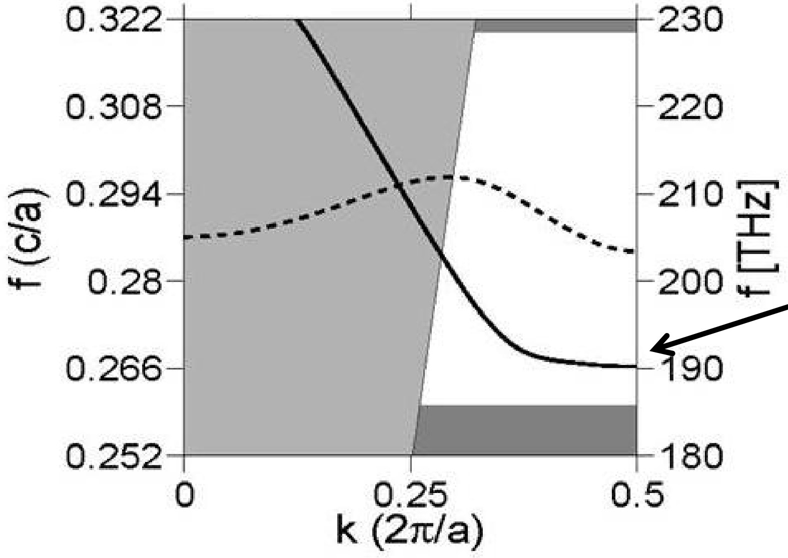
On-chip
$\beta > 0.6$



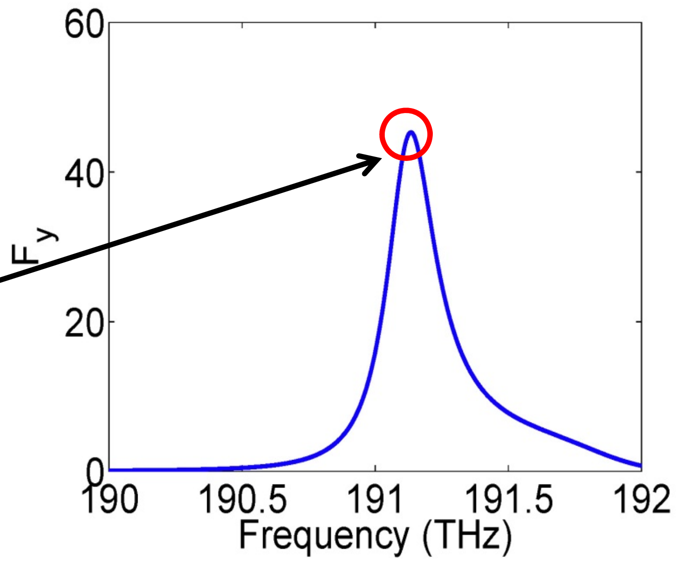
E-field at slab center



PC guide band structure

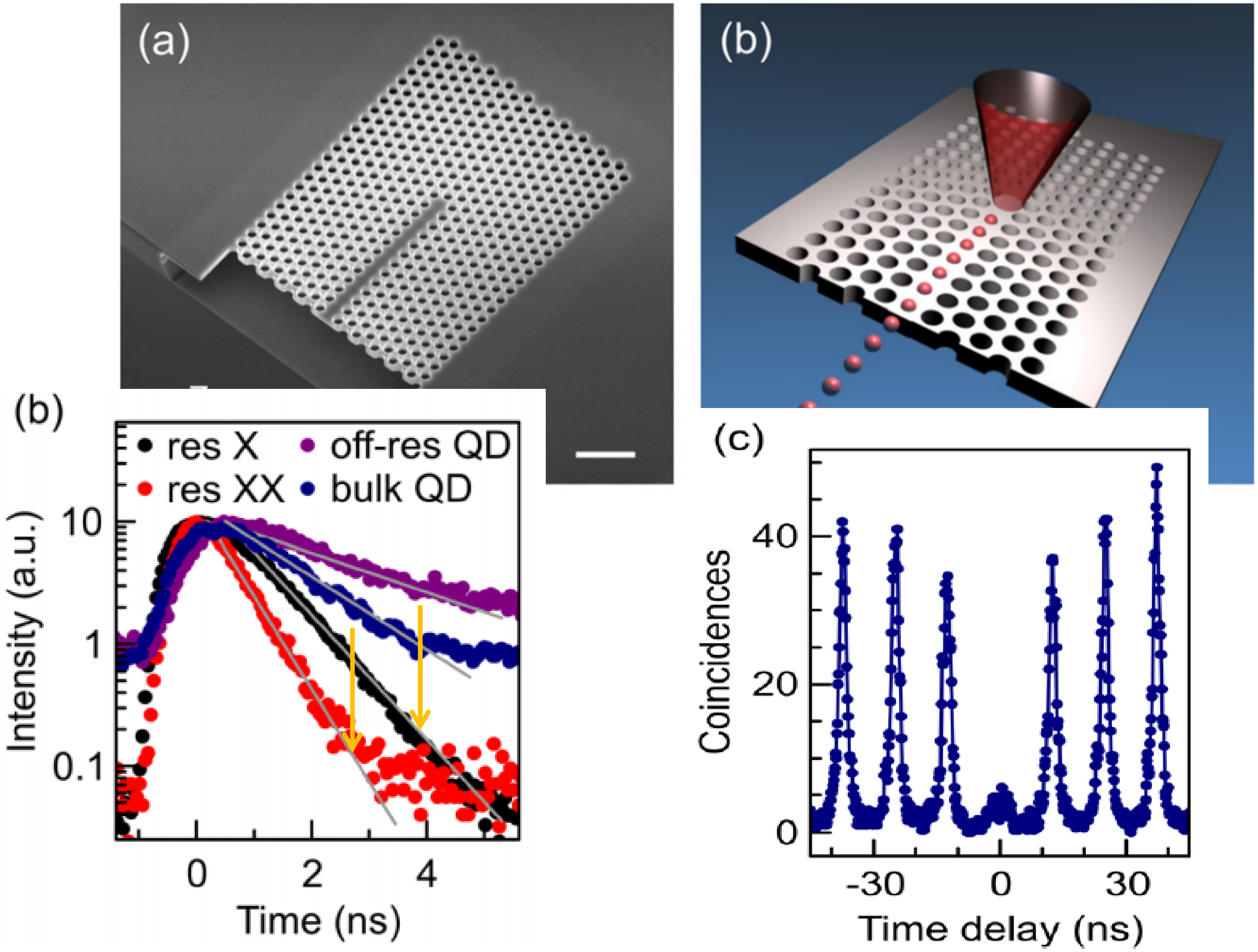


Purcell Effect

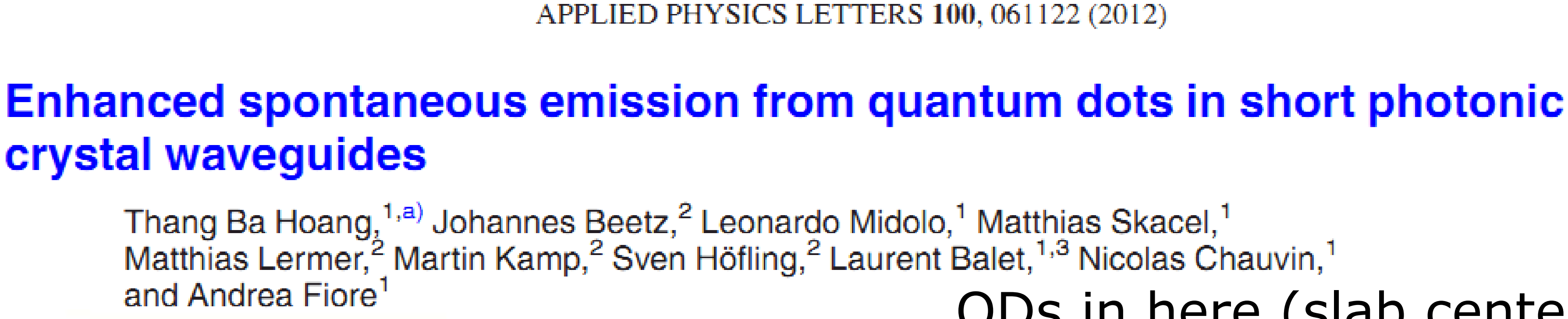


V. Manga Rao and SH,PRL 99, 193901 (2007)

Schagmann et al, APL <u>99</u>, 261108 (2011)



Recent QD example with short guide

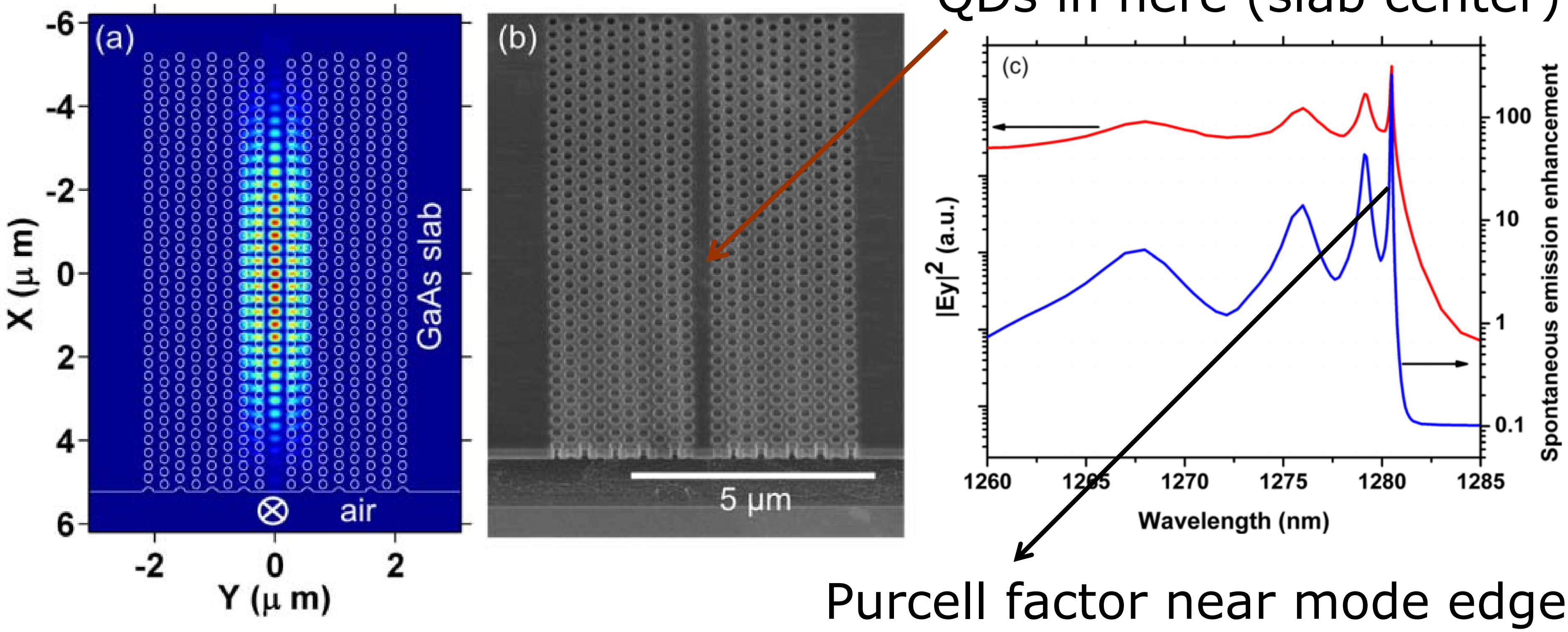


APPLIED PHYSICS LETTERS **100**, 061122 (2012)

Enhanced spontaneous emission from quantum dots in short photonic crystal waveguides

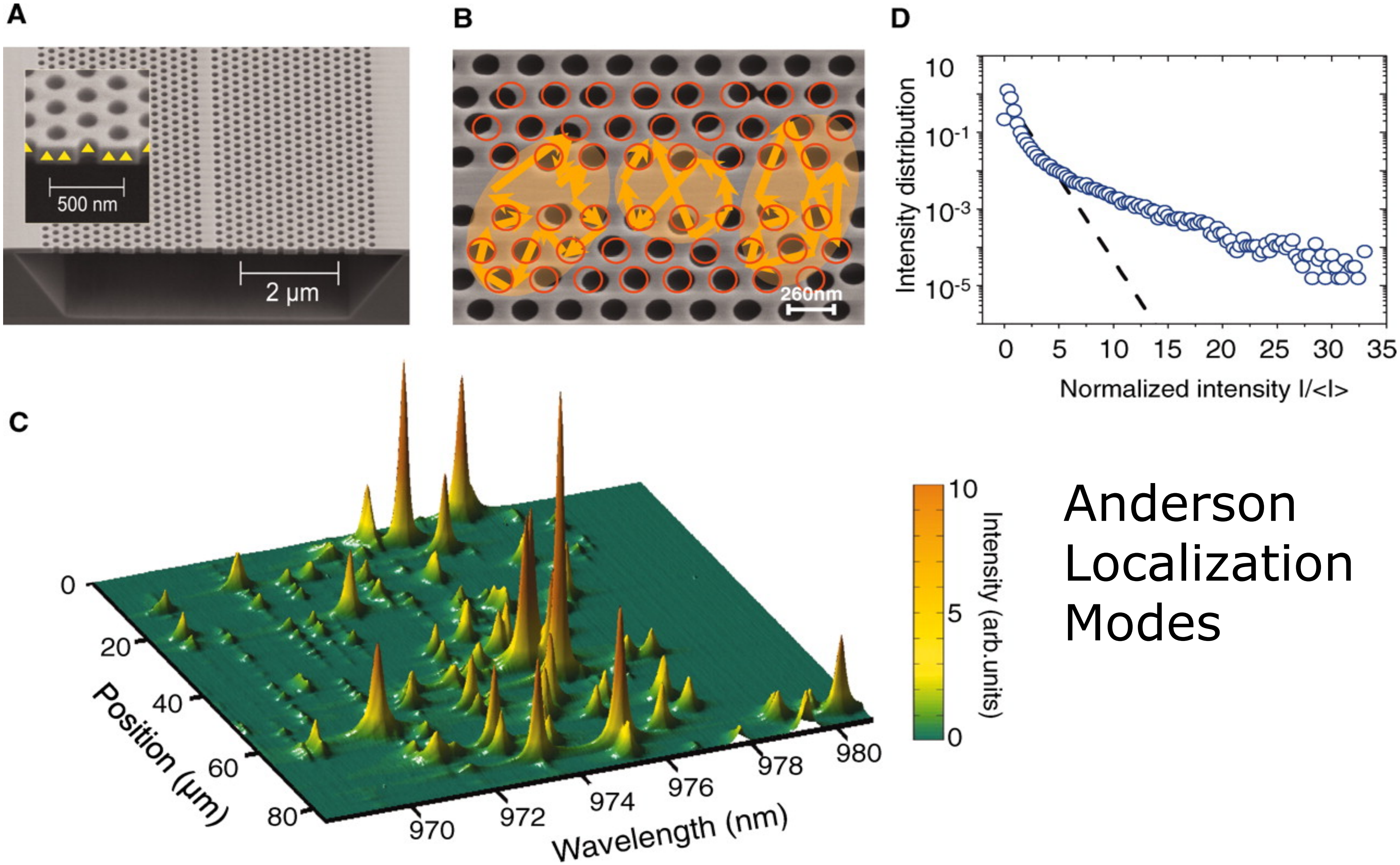
Thang Ba Hoang,[1,a)] Johannes Beetz,[2] Leonardo Midolo,[1] Matthias Skacel,[1]
Matthias Lermer,[2] Martin Kamp,[2] Sven Höfling,[2] Laurent Balet,[1,3] Nicolas Chauvin,[1]
and Andrea Fiore[1]

QDs in here (slab center)



Purcell factor near mode edge

Exploiting deliberate disorder with QDs

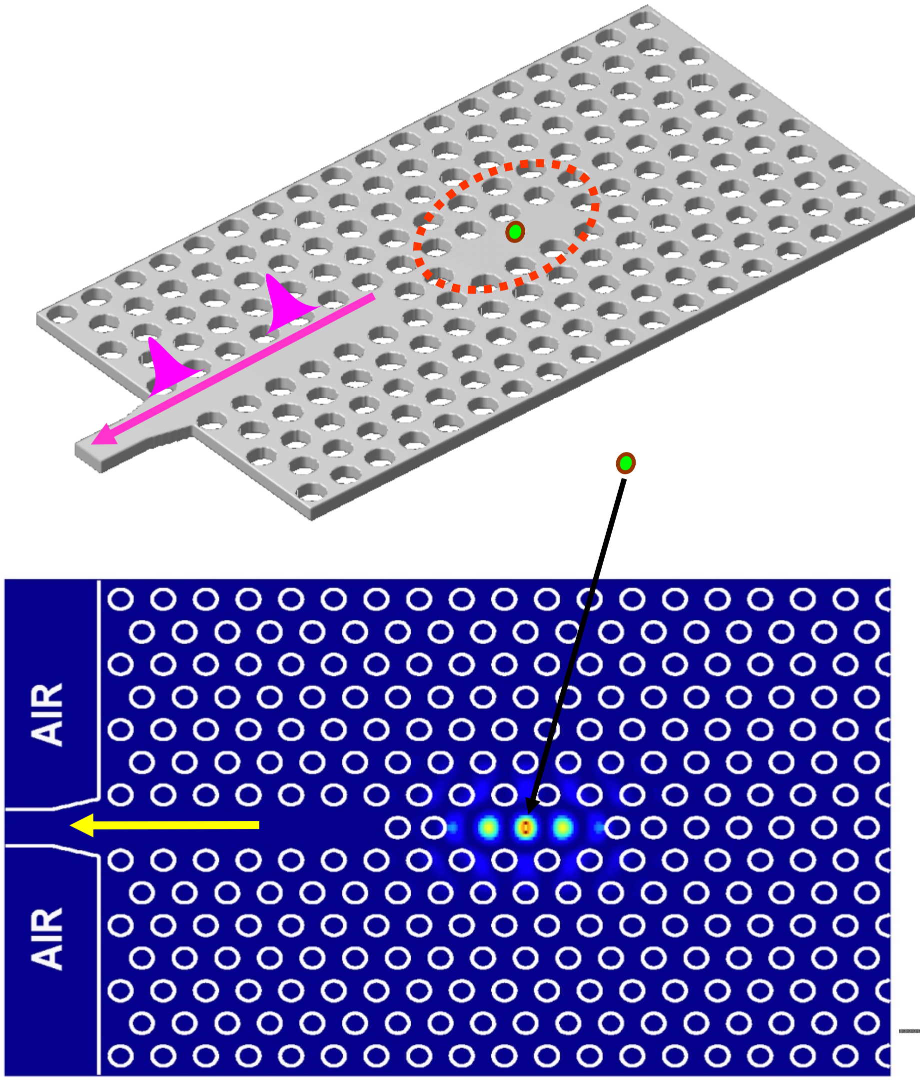


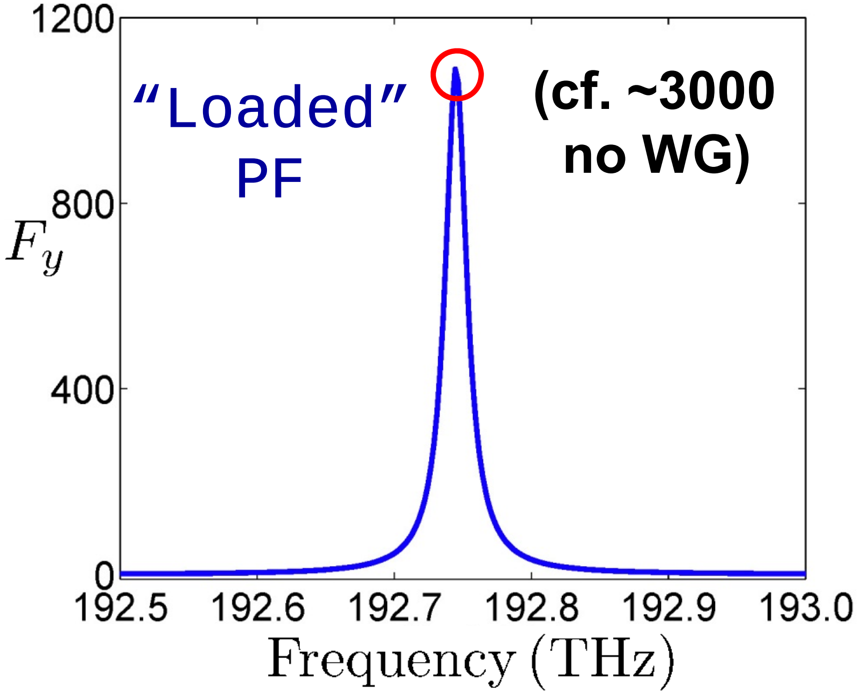
Anderson Localization Modes

Sapienza et al, Science (2010)

Integration with cavities also possible

P. Yao and SH, PRB 2010

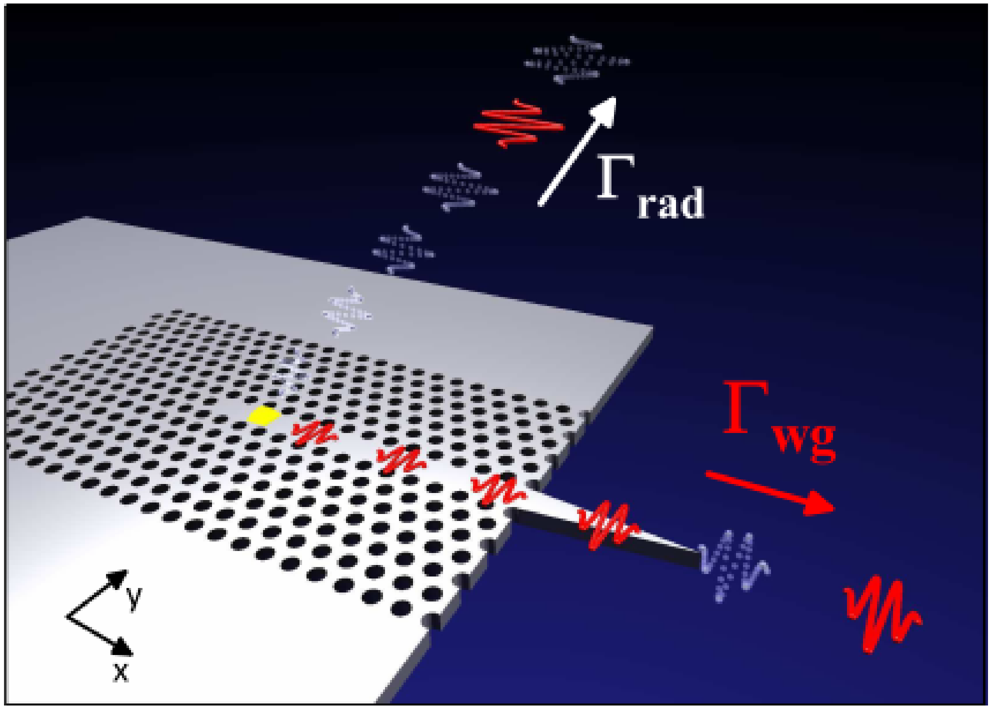




$$\beta > 0.8$$

$$PF \sim 1000$$

Very recent paper on the arXiv server



Source: http://arxiv.org/abs/1402.2081

“Near-unity coupling efficiency of a quantum emitter to a photonic-crystal waveguide”
(Submitted on 10 Feb 2014)

Summary

- PC waveguides show great promise as a platform technology for chip-based quantum light sources
- Intrinsic disorder limits the enhanced emission factors, but disorder (possibly deliberate) can also be used to enhance coupling to quantum dot emitters.
- Large beta factor is robust (i.e., the probability of being emitted into the desired output mode): broadband (5-10 THz is typical for a slow-light waveguide mode).
- These important parameters can (again!) be calculated using intuitive Bloch mode Green functions and rigorous dipole solutions for the structure.