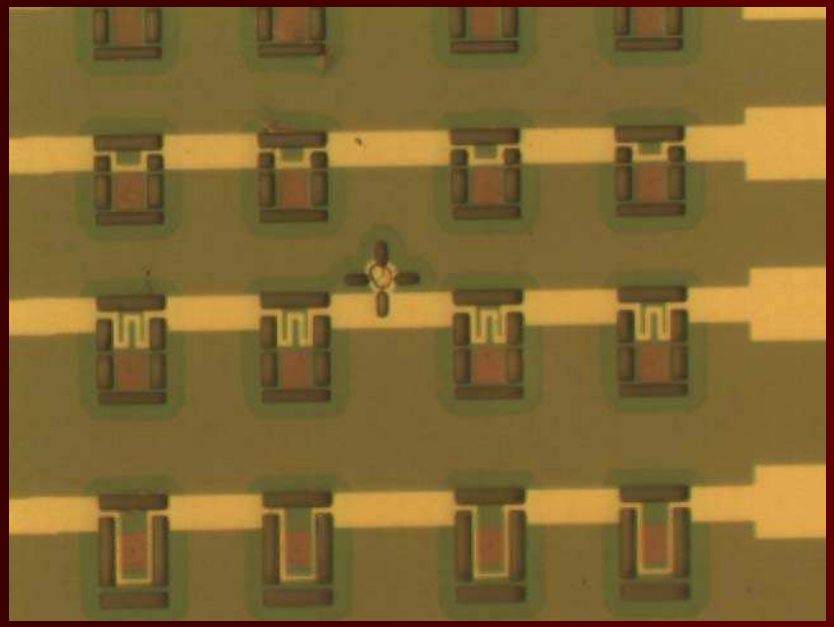
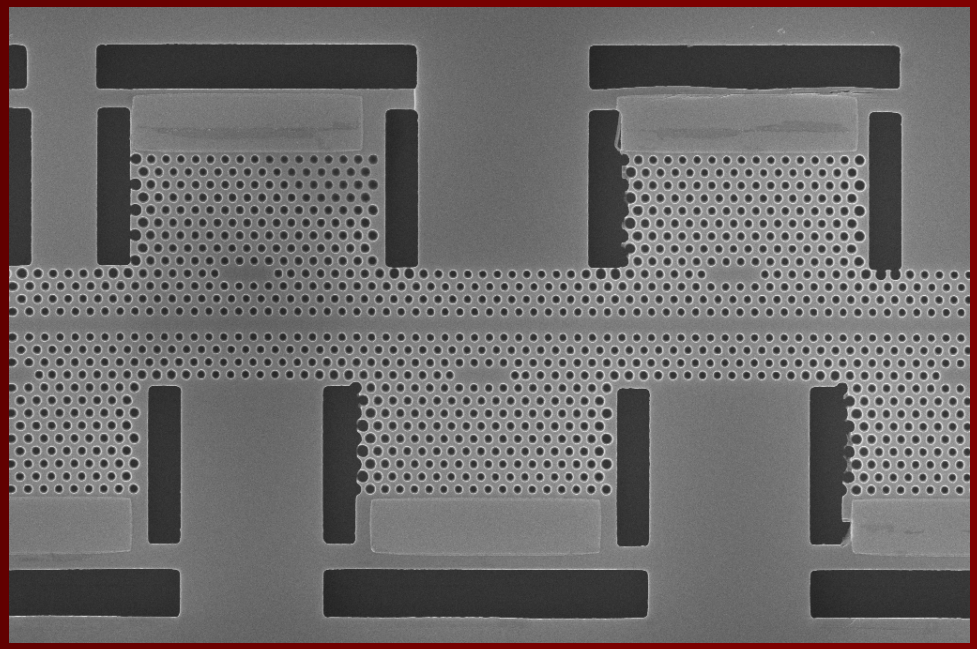
Quantum dots in photonic crystals: from quantum information processing to nonlinear optics at a single photon level

Jelena Vuckovic
Ginzton Laboratory, Stanford University, CA

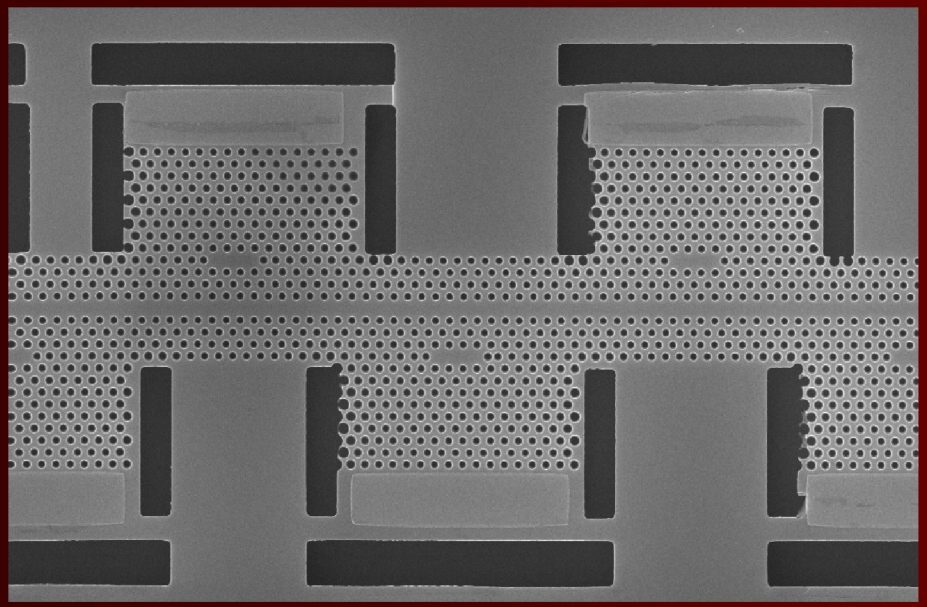


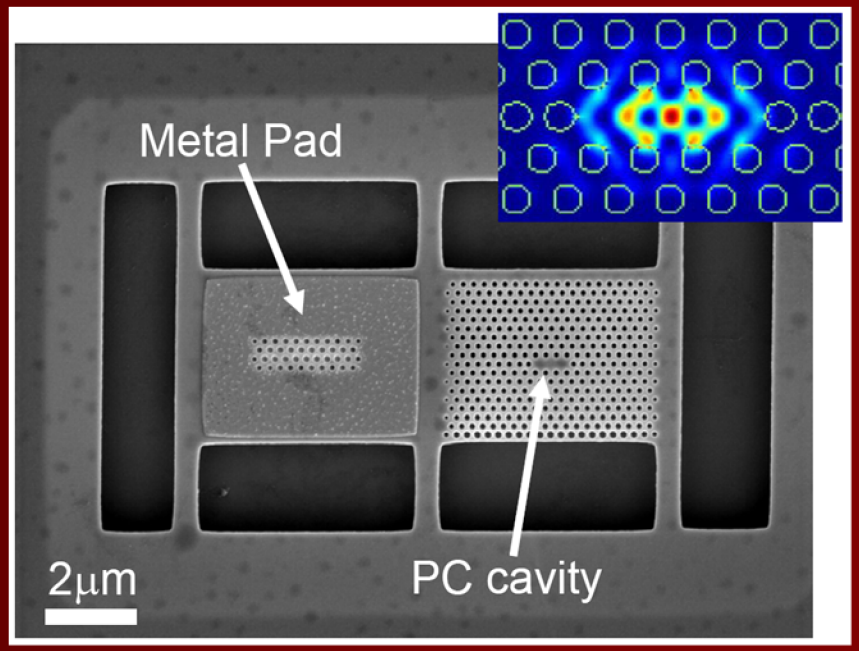


Stanford University

CQIQC III, Toronto, Aug. 2009

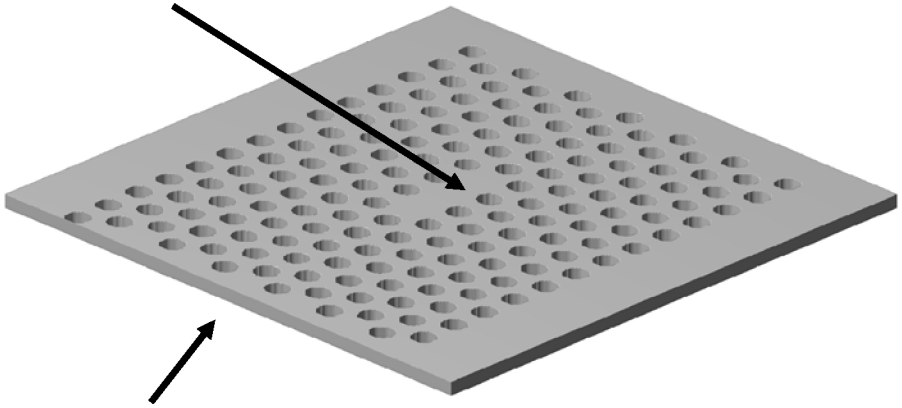
Platform: photonic crystal cavities with quantum dots



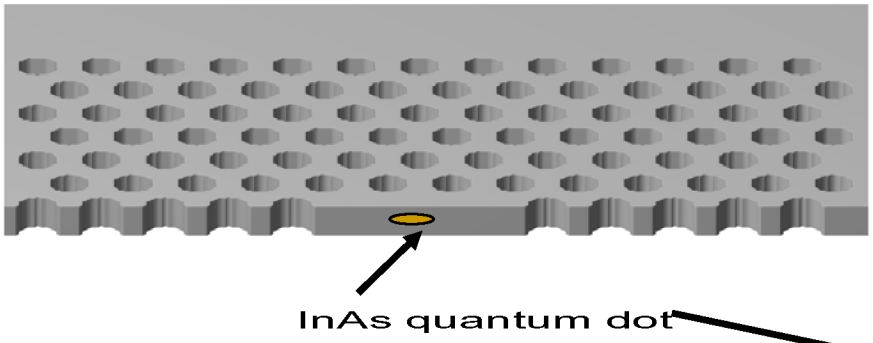


Photonic crystals and quantum dots

Photonic crystal cavity (resonator)

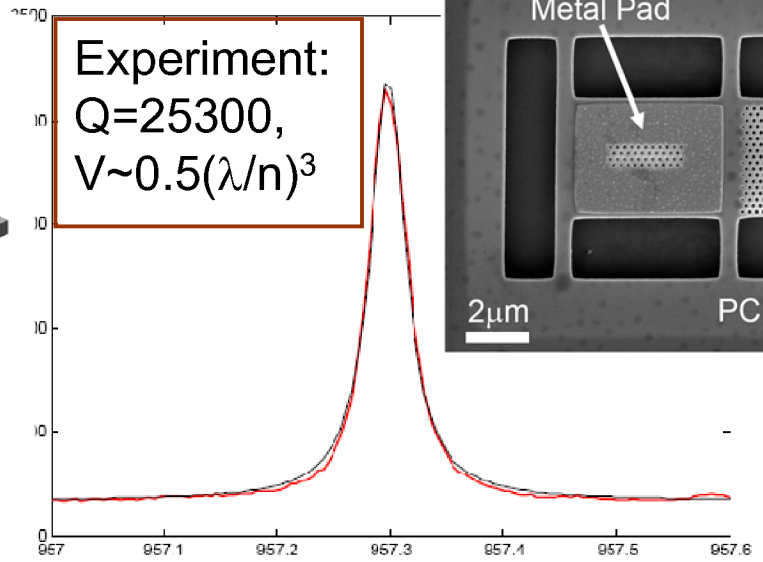


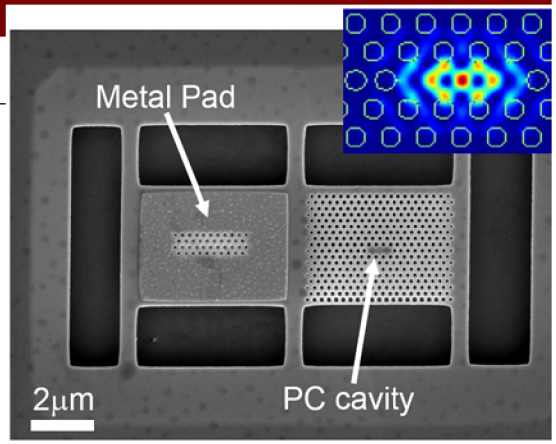
GaAs slab 170nm thick



Photonic crystals localize light into extremely small volumes $V<(\lambda/n)^3$ with high quality factors Q (long photon storage times)

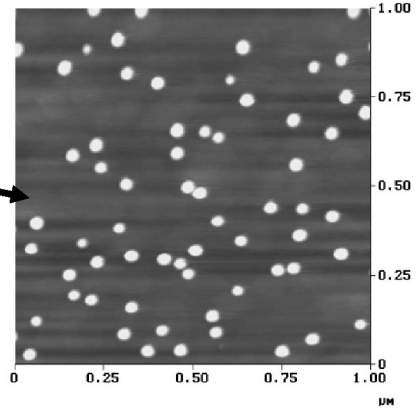
Cavity spectrum





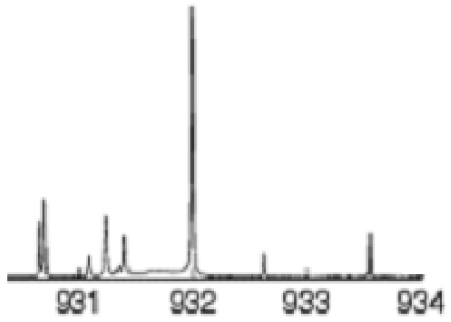
SEM image of a cavity

AFM image of quantum dots

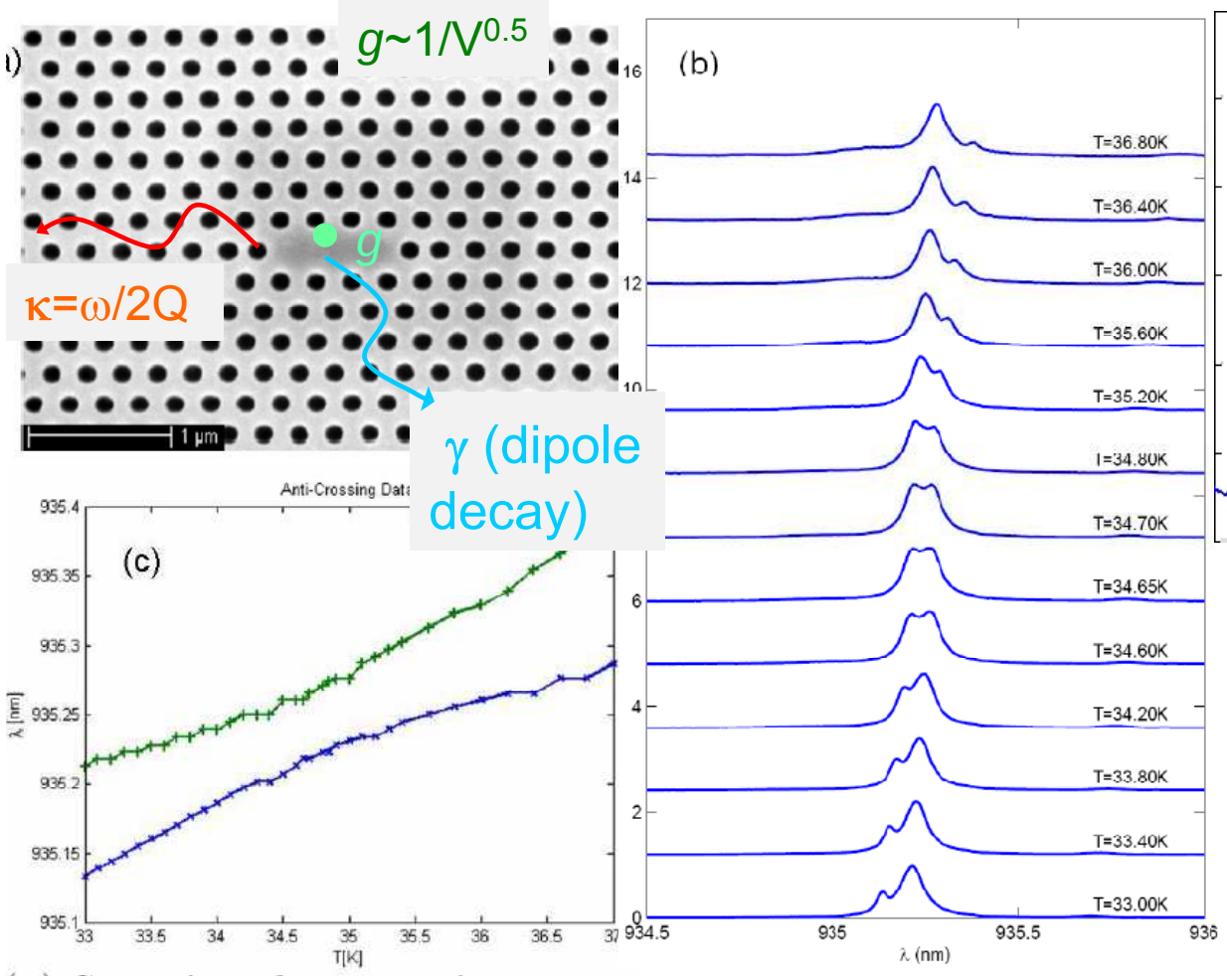


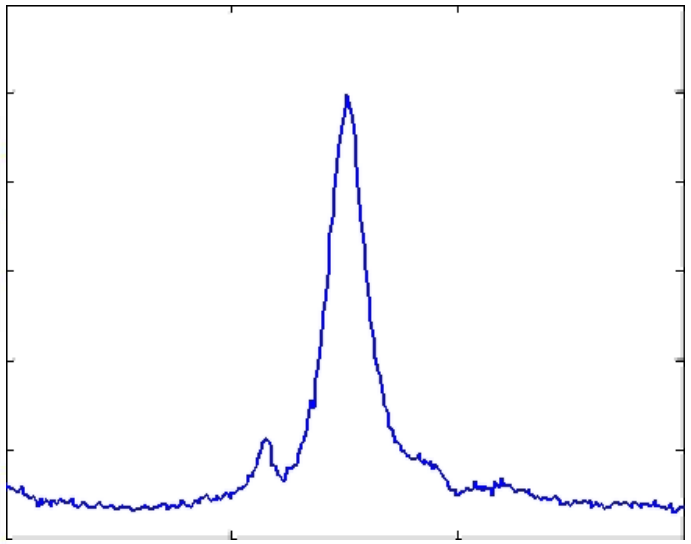
Pierre Petroff, UCSB

Quantum dot spectrum



QD-Photonic crystal cavity in the strong coupling regime



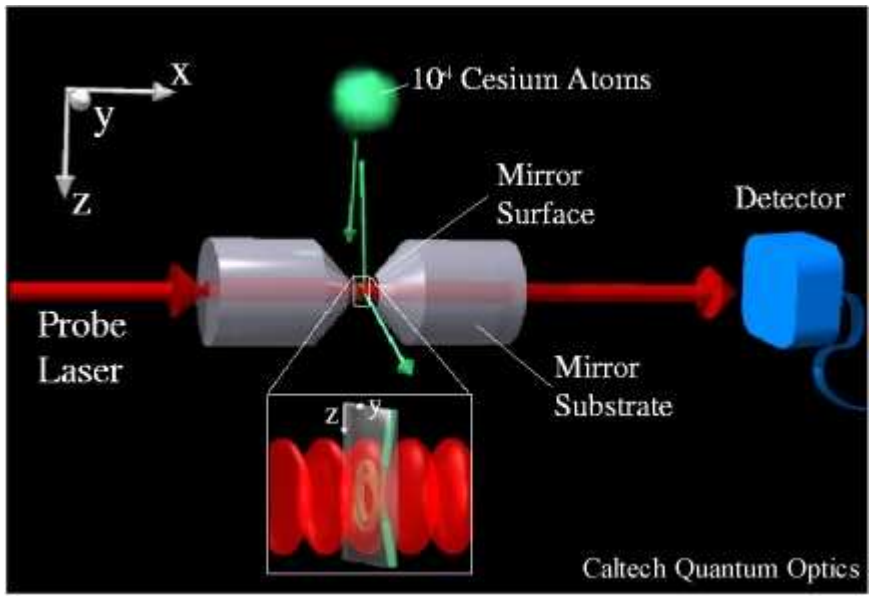


- coupling strength: g/2π=8-25GHz => 0.05-0.2nm splitting
- γ/2π=0.1GHz
- cavity field decay: κ/2π=8-16GHz => 0.05-0.1nm linewidth (Q>10000)

Also demonstrated in PL by:Gibbs-Khithrova-Scherer; Imamoglu-Hu;Forchel-Yamamoto; Gerard-Bloch

Solid-state cavity QED platform

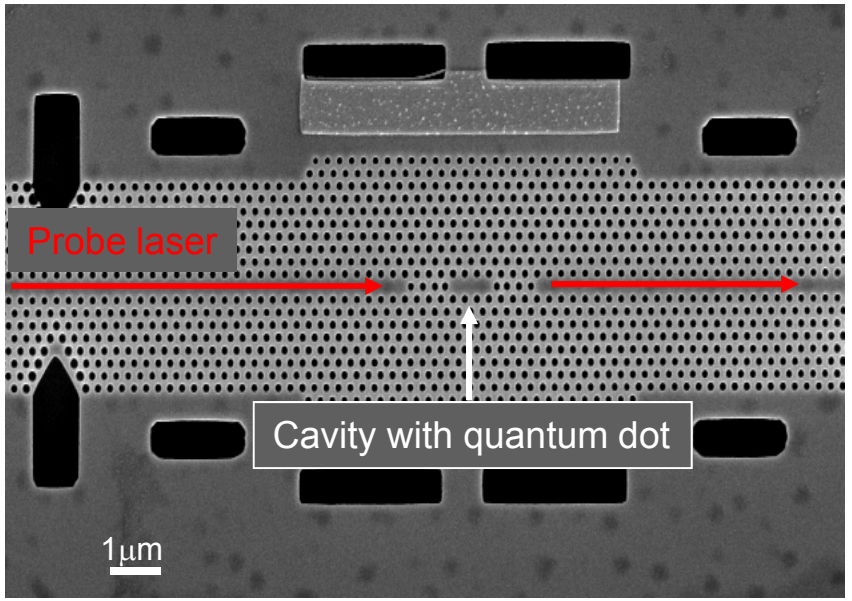
Atomic physics



- Macroscopic scale
- MHz speed
- Complex
- Atom trapping

J. Kimble group, http://www.its.caltech.edu/~qoptics/

Solid State

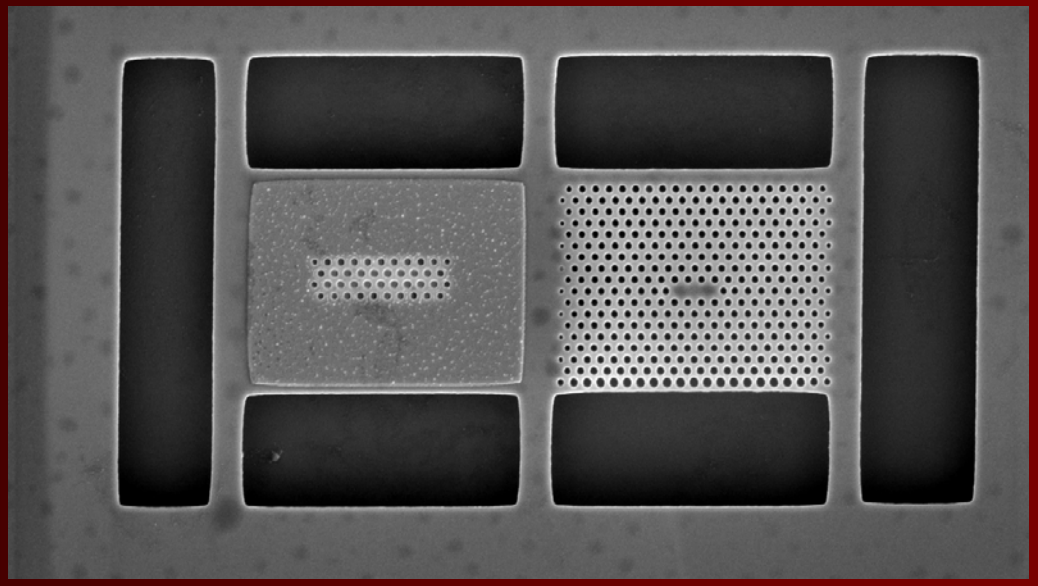


- Nano - scale
- GHz speed
- On chip
- No atom trapping

Outline

1. Local tuning techniques for PCs and QDs
2. QD-PC cavity based quantum information processing & single photon nonlinear optics
    1. Controlling cavity reflectivity with a single quantum dot
    2. Controlled amplitude and phase shifts with a single quantum dot
    3. Fast electro-optical switching with a quantum dot with sub-fJ energies
    4. Coherent generation of nonclassical light on a chip via photon-induced tunneling and blockade
3. Conclusions & present/future work

Local quantum dot and cavity tuning on photonic crystal chips



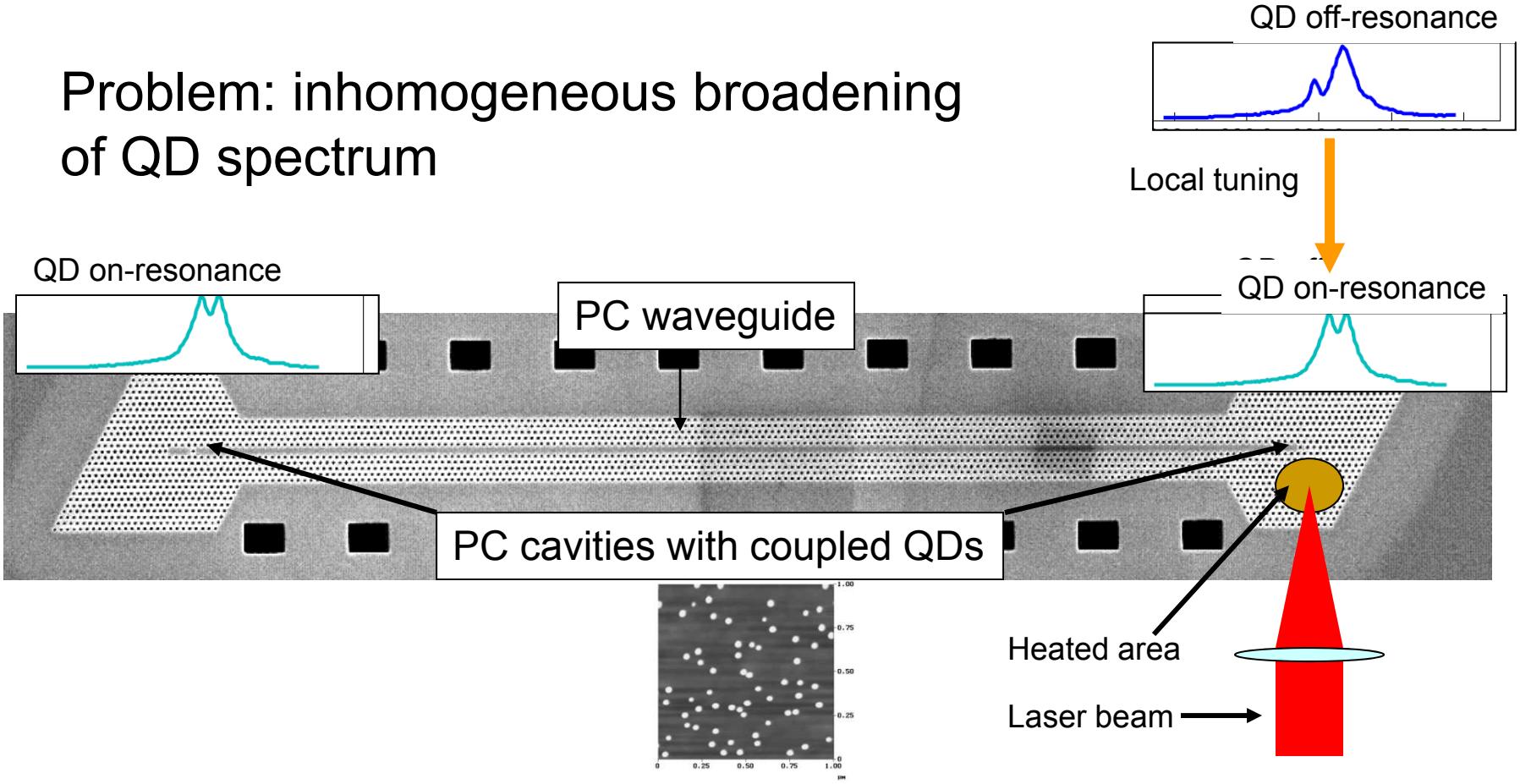
Andrei Faraon, Dirk Englund, Ilya Fushman, Nick Stoltz, Pierre Petroff, Jelena Vuckovic, Applied Physics Letters 90, 213110 (2008)

Andrei Faraon, Dirk Englund, Douglas Bulla, Barry Luther-Davies, Benjamin Eggleton, Nick Stoltz, Pierre Petroff, Jelena Vuckovic, Applied Physics Letters 92, 043123 (2008)

Andrei Faraon and Jelena Vuckovic, Applied Physics Letters 95, 043102 (2009)

QD-Photonic Crystal Quantum Networks

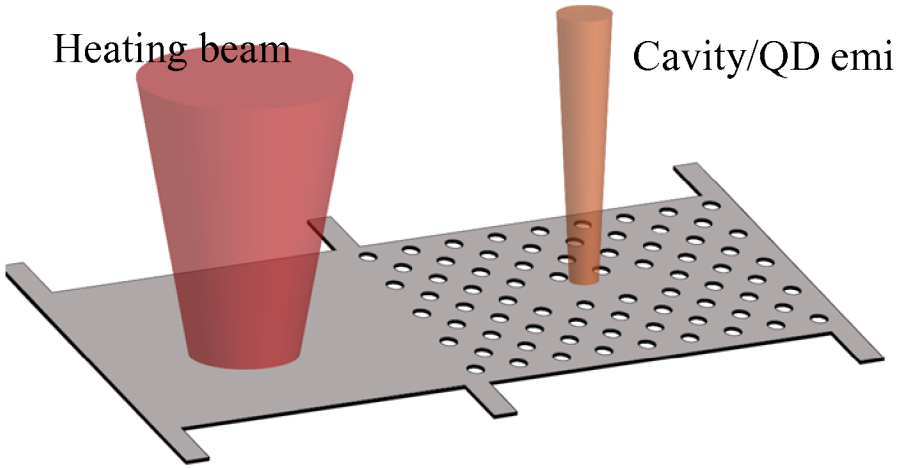
- Problem: inhomogeneous broadening of QD spectrum

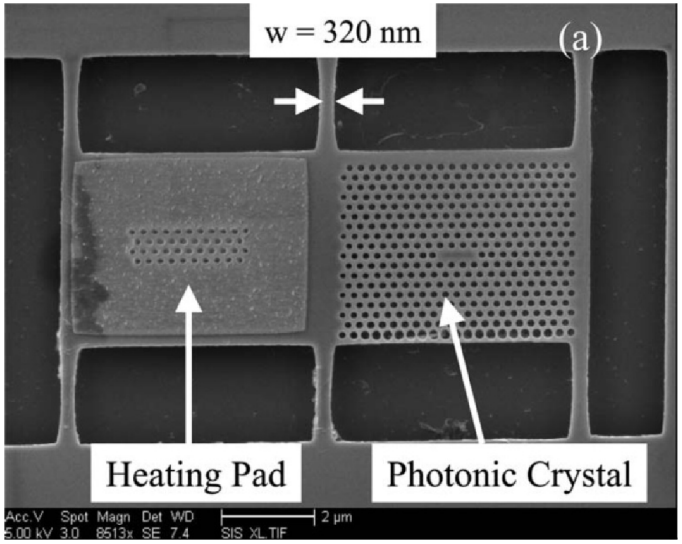


- How to independently tune QDs into resonance with PC cavities?

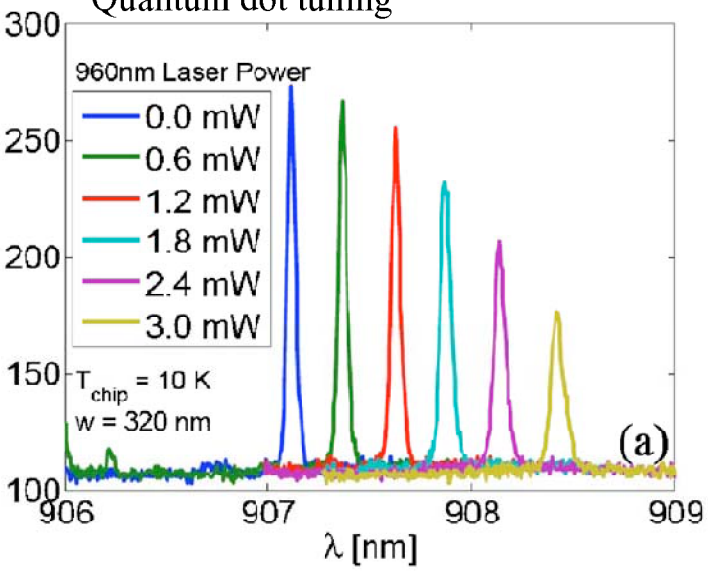
Faraon et al, Applied Physics Letters 90, 213110 (2008)

Local temperature tuning

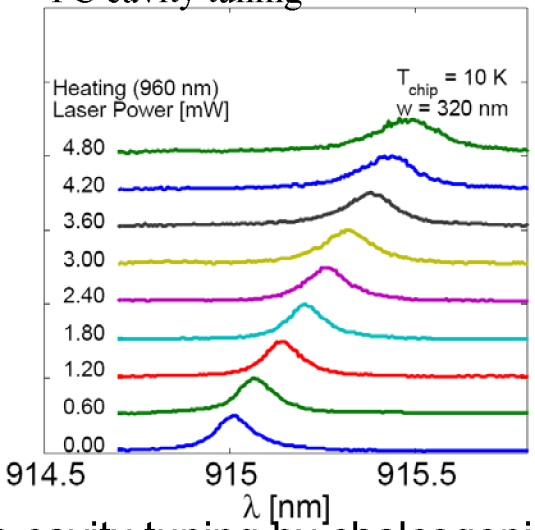




Quantum dot tuning

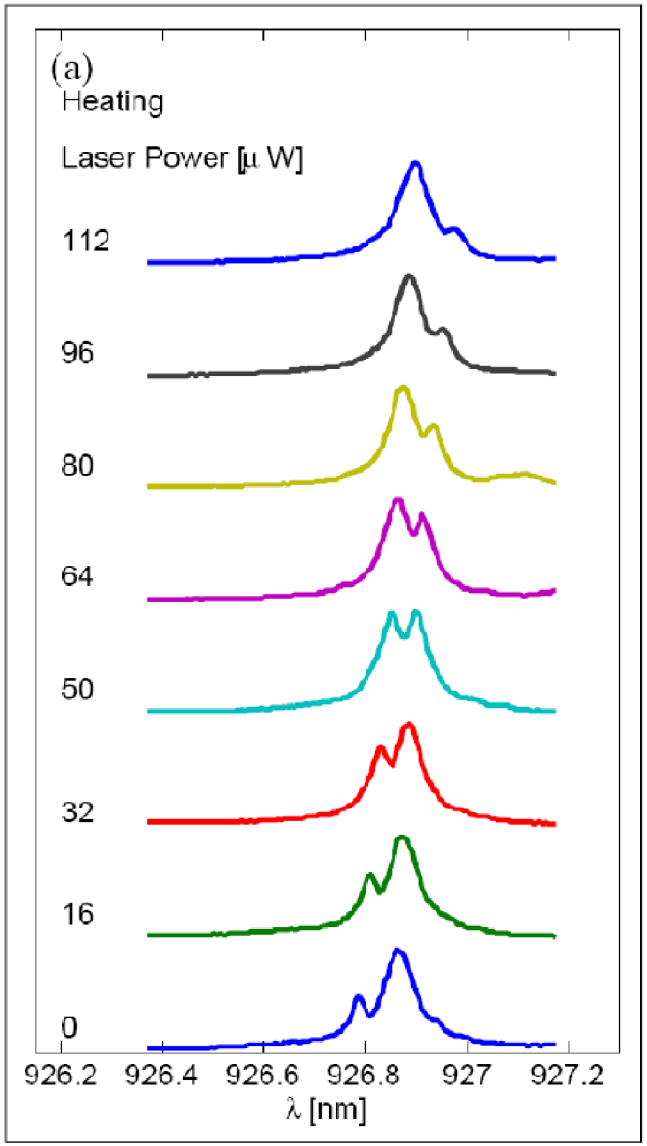


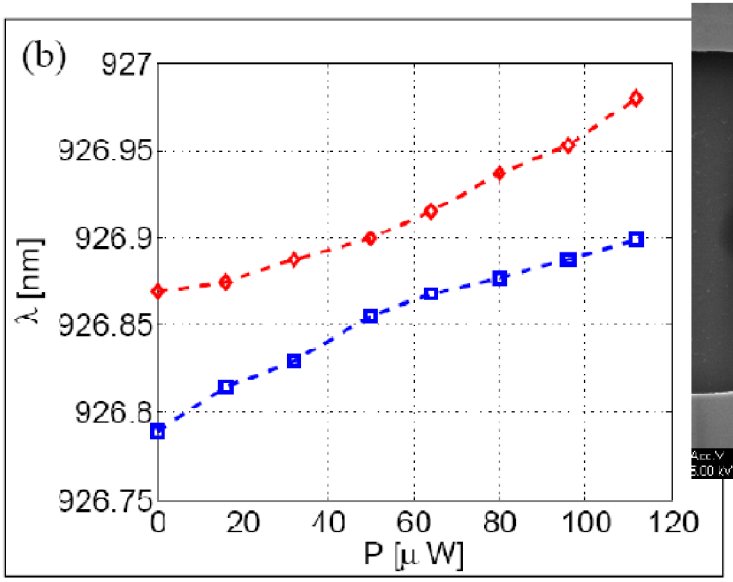
PC cavity tuning

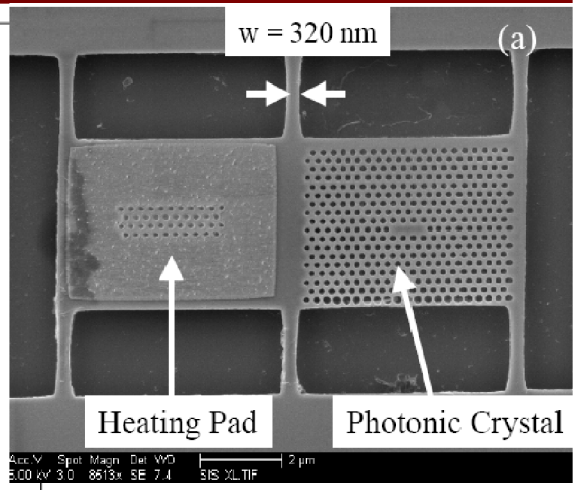


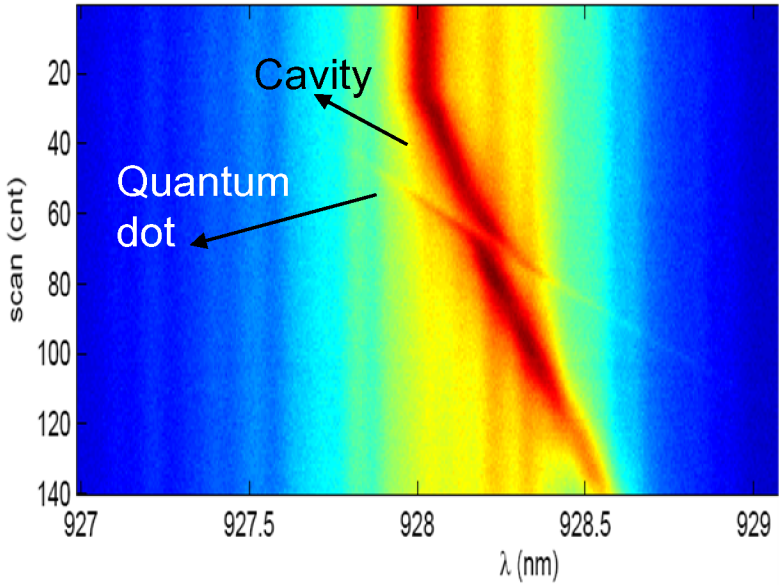
Selective cavity tuning by chalcogenides:
Applied Physics Letters 92, 043123 (2008)

QD tuning into strong coupling with cavity



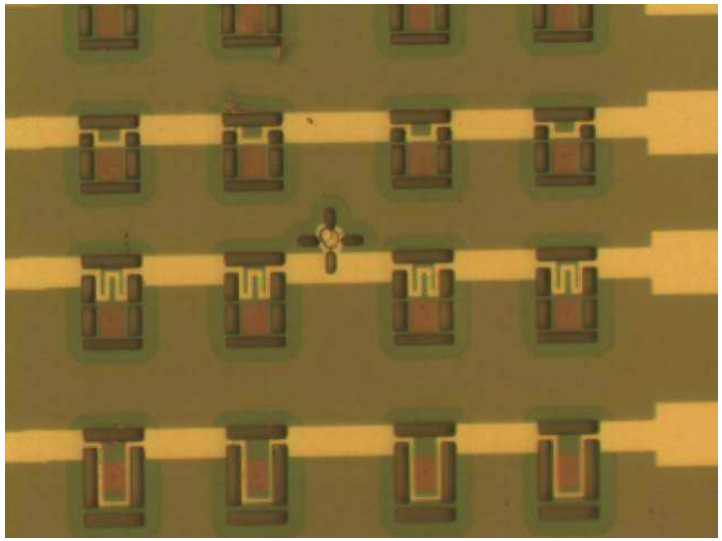


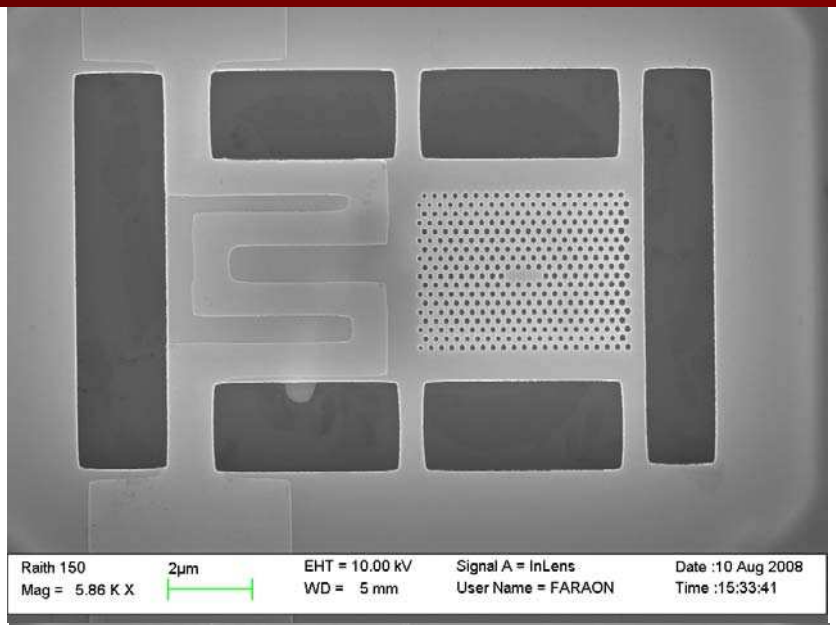




QD can be selectively tuned both into the weak or strong coupling with PC cavity

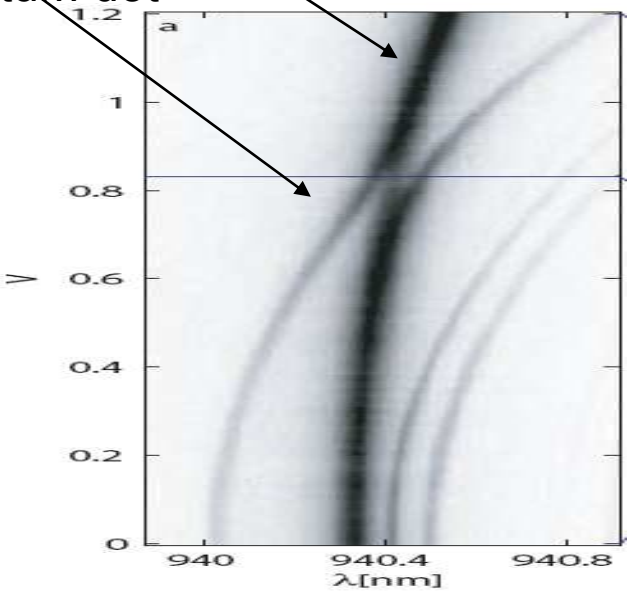
Ohmic heaters



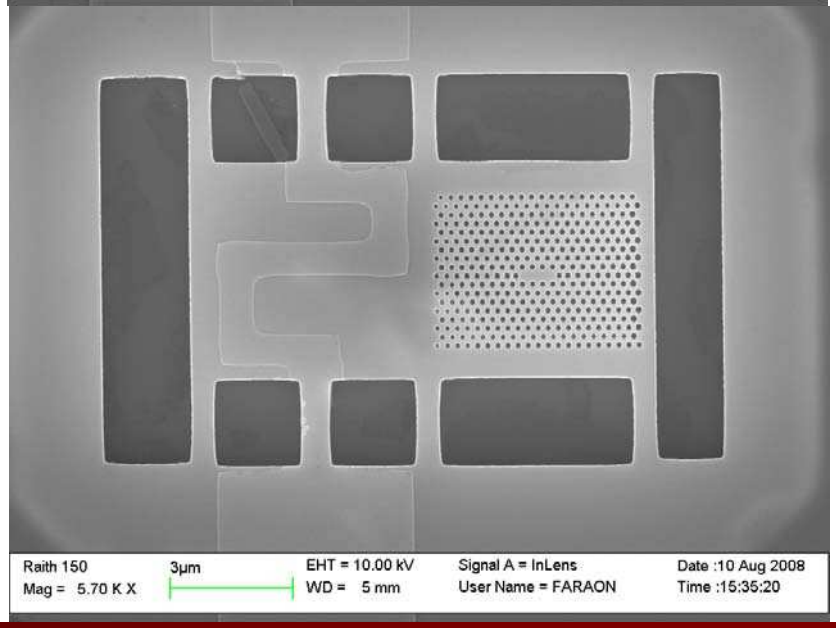


Cavity

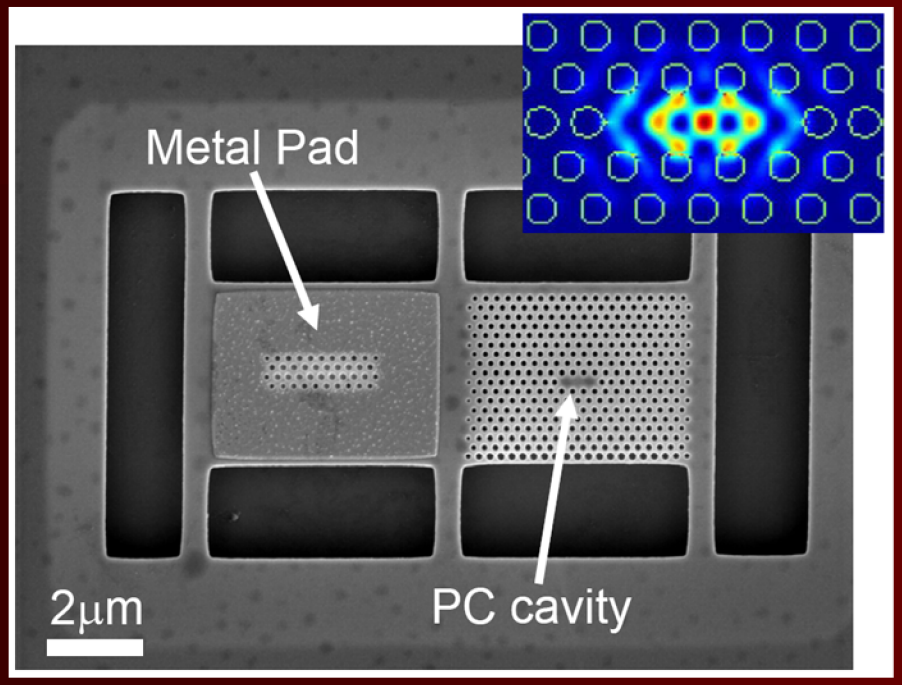
Quantum dot

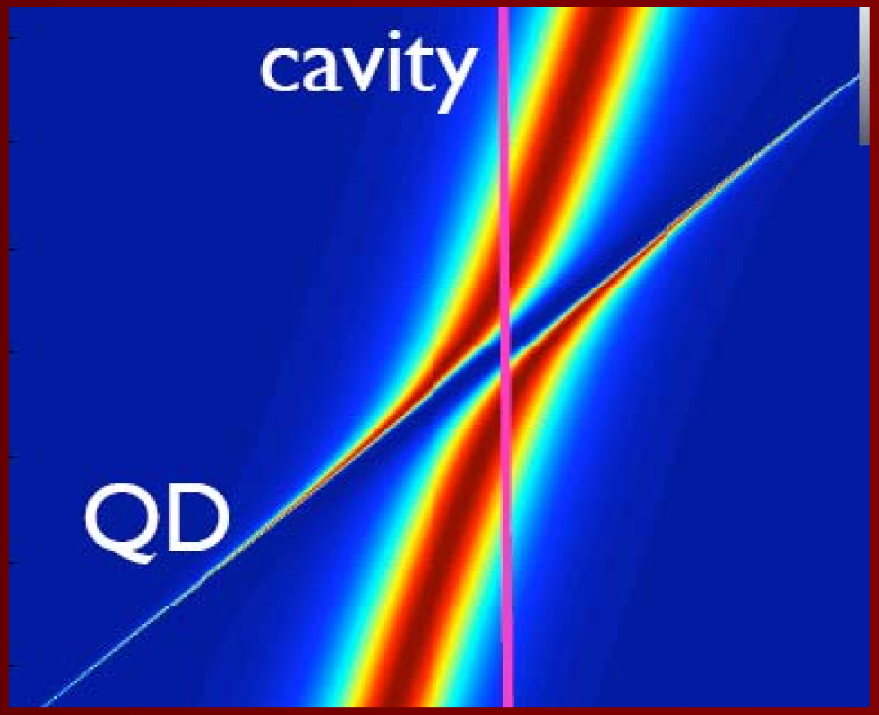


10kHz tuning speed



Coherent probing of the strongly coupled QD-PC cavity: controlling cavity reflectivity with a single quantum dot

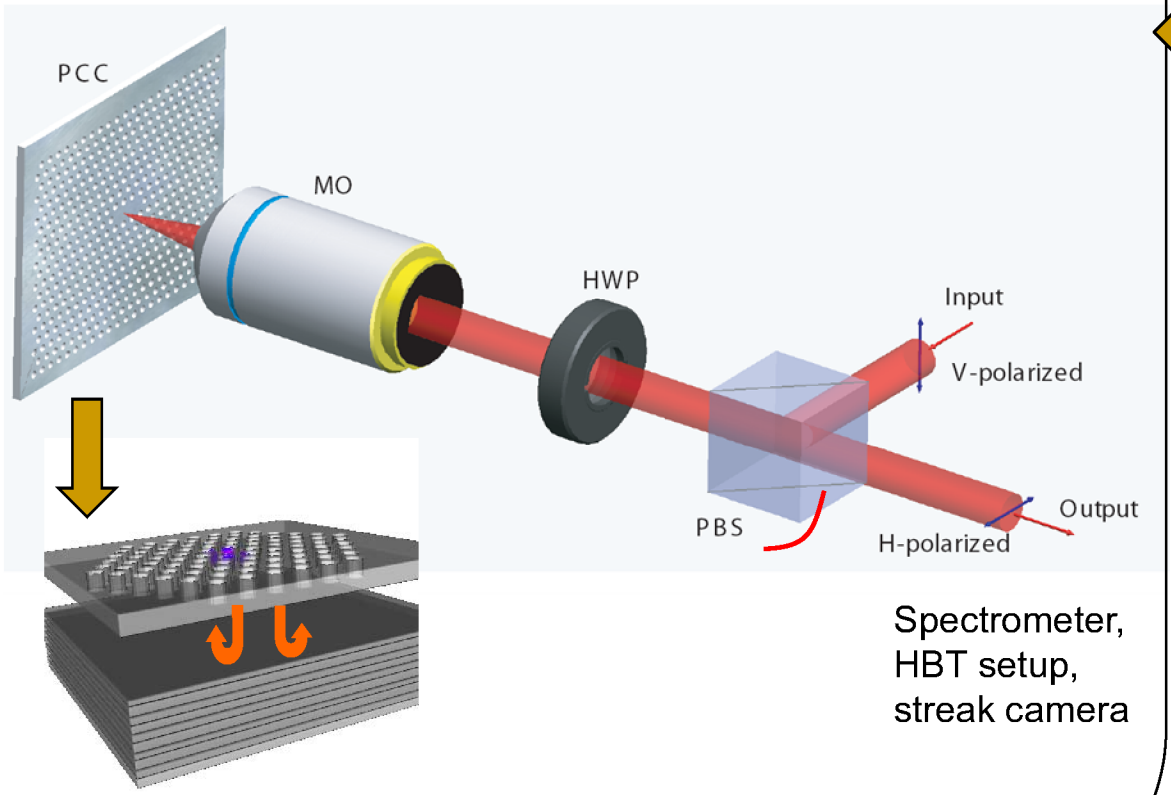




Dirk Englund, Andrei Faraon, Ilya Fushman, Nick Stoltz, Pierre Petroff, Jelena Vuckovic
Nature **450**, 857-861 (6 December 2007)

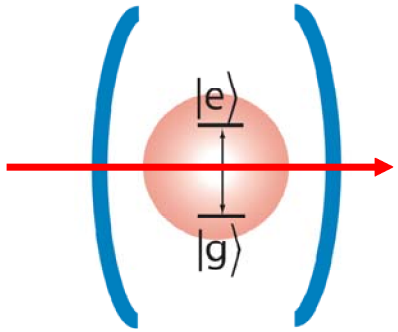
Coherent probing of a strongly coupled QD-cavity

Cross-polarized reflectivity

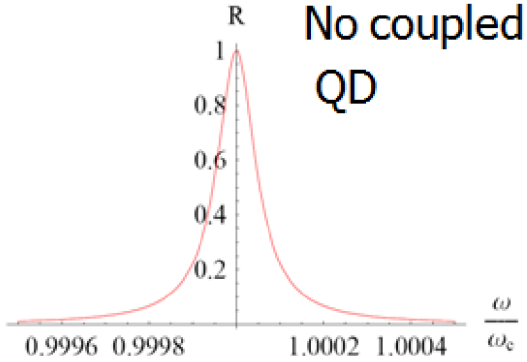


Spectrometer,
HBT setup,
streak camera

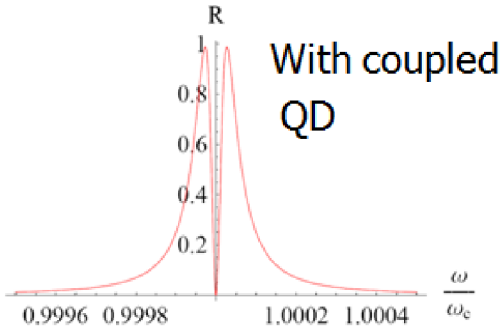
Transmission



No coupled QD



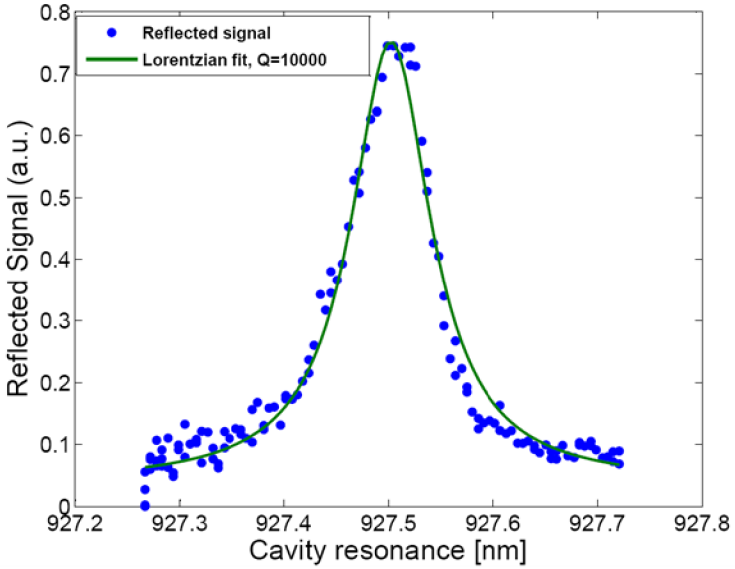
With coupled QD



Nature **450**, 857-861 (2007)

Single QD controlled cavity reflectivity

Empty cavity



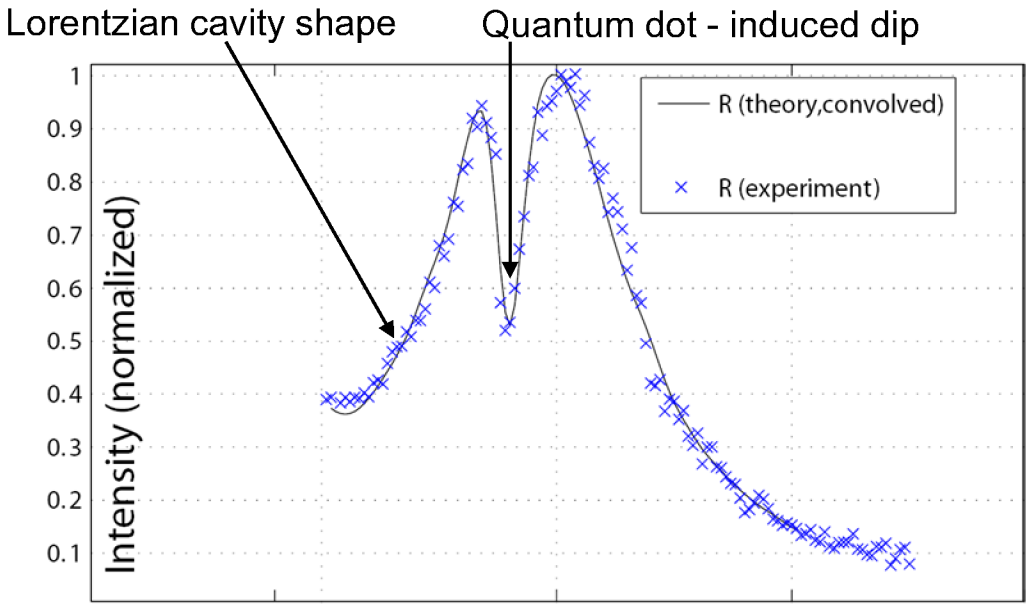
$$|1-t|^2 \propto R(\omega) \propto \left| \frac{\kappa}{i(\omega_c - \omega) + \kappa + \frac{g^2}{i(\omega_d - \omega) + \gamma}} \right|^2$$

$\omega_c =$ cavity resonance; $\kappa =$ cavity loss;

$\omega_d =$ dipole resonance; $g =$ coupling strength

$\gamma =$ dipole decay rate

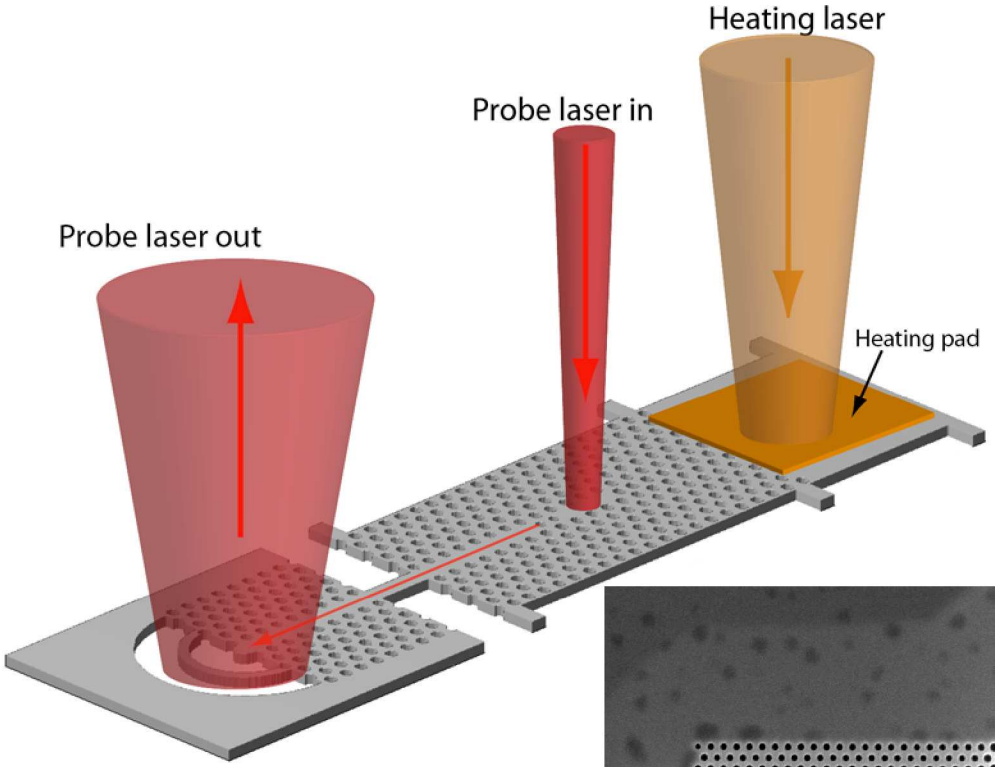
Cavity with a strongly coupled QD

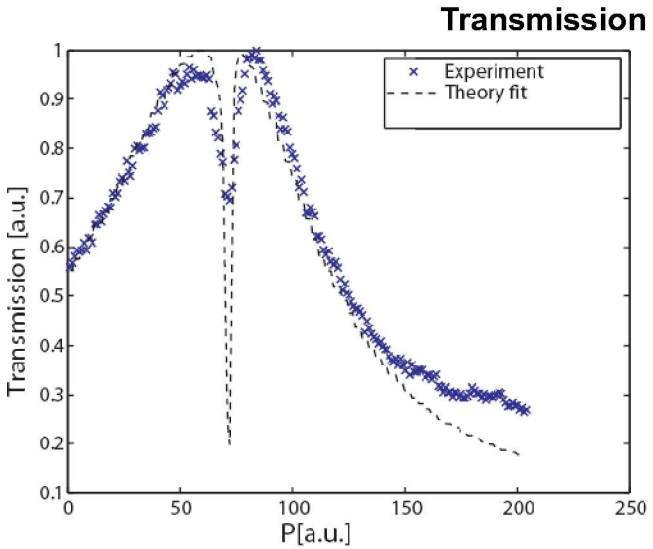


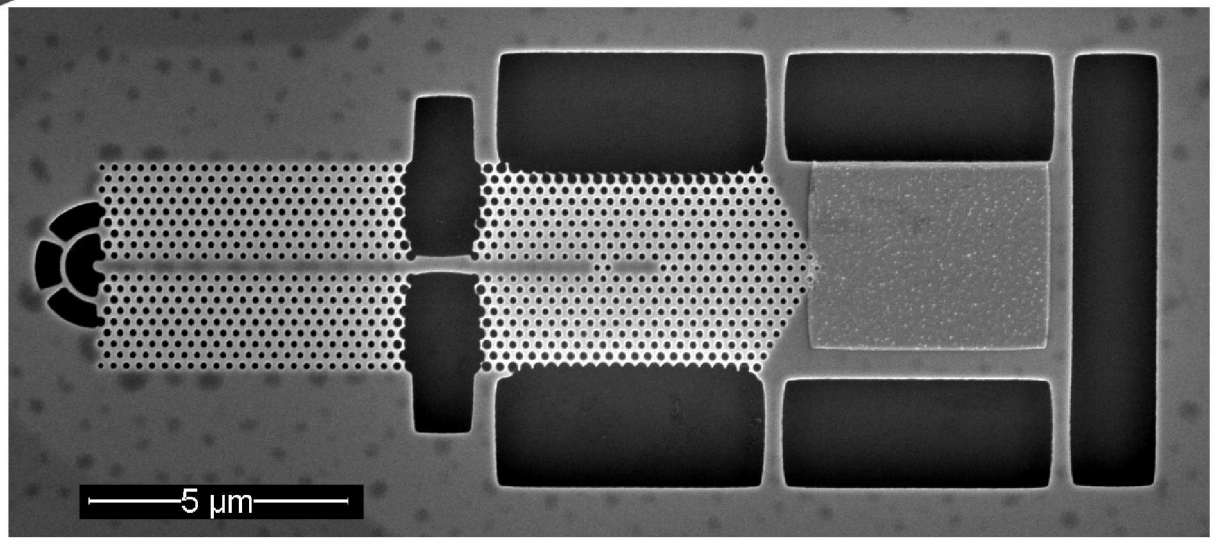
Heating laser power [a.u. – linear scale]

Nature **450**, 857-861 (2007)

Integrated structures

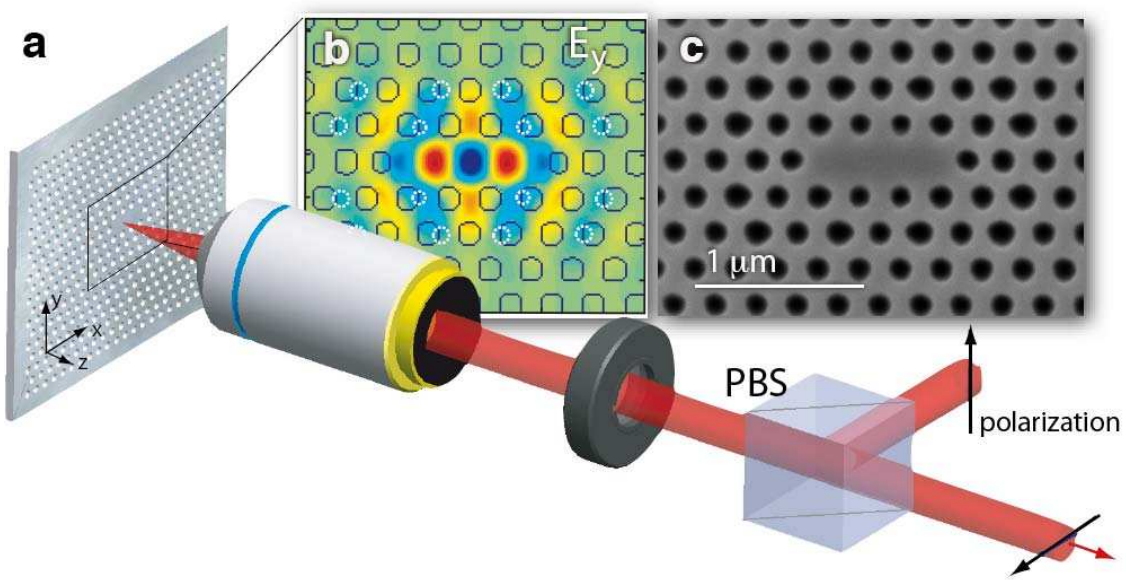


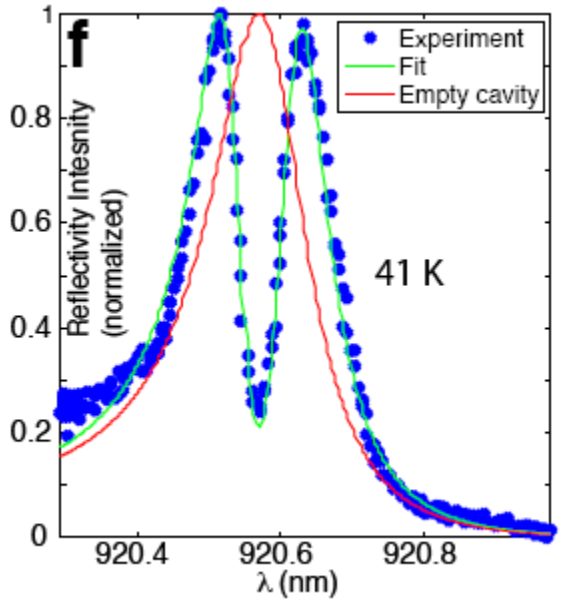


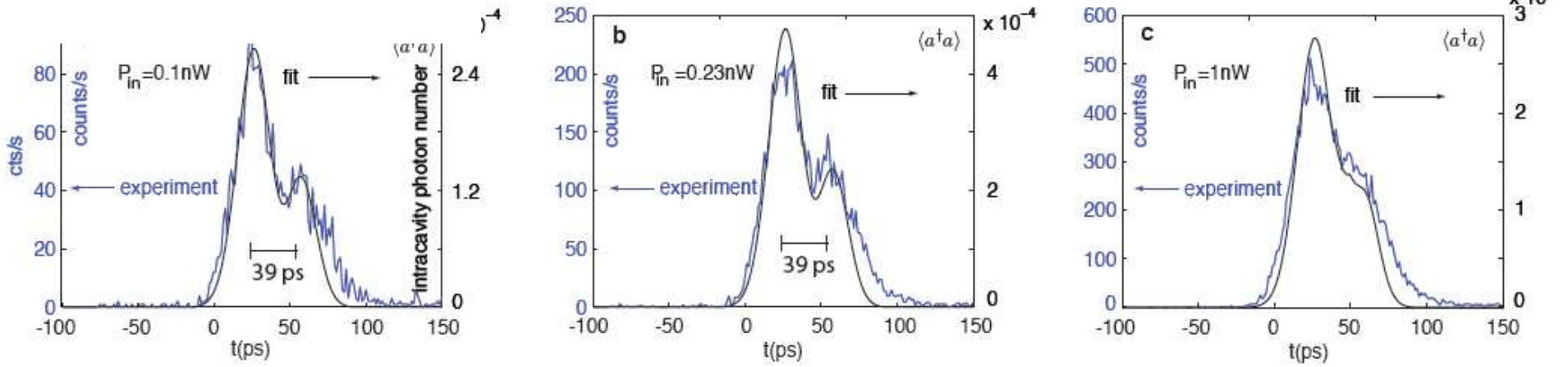


Faraon et. al., *Optics Express, Vol. 16, No. 16, pp 12154, 2008*

Rabi oscillation in time domain



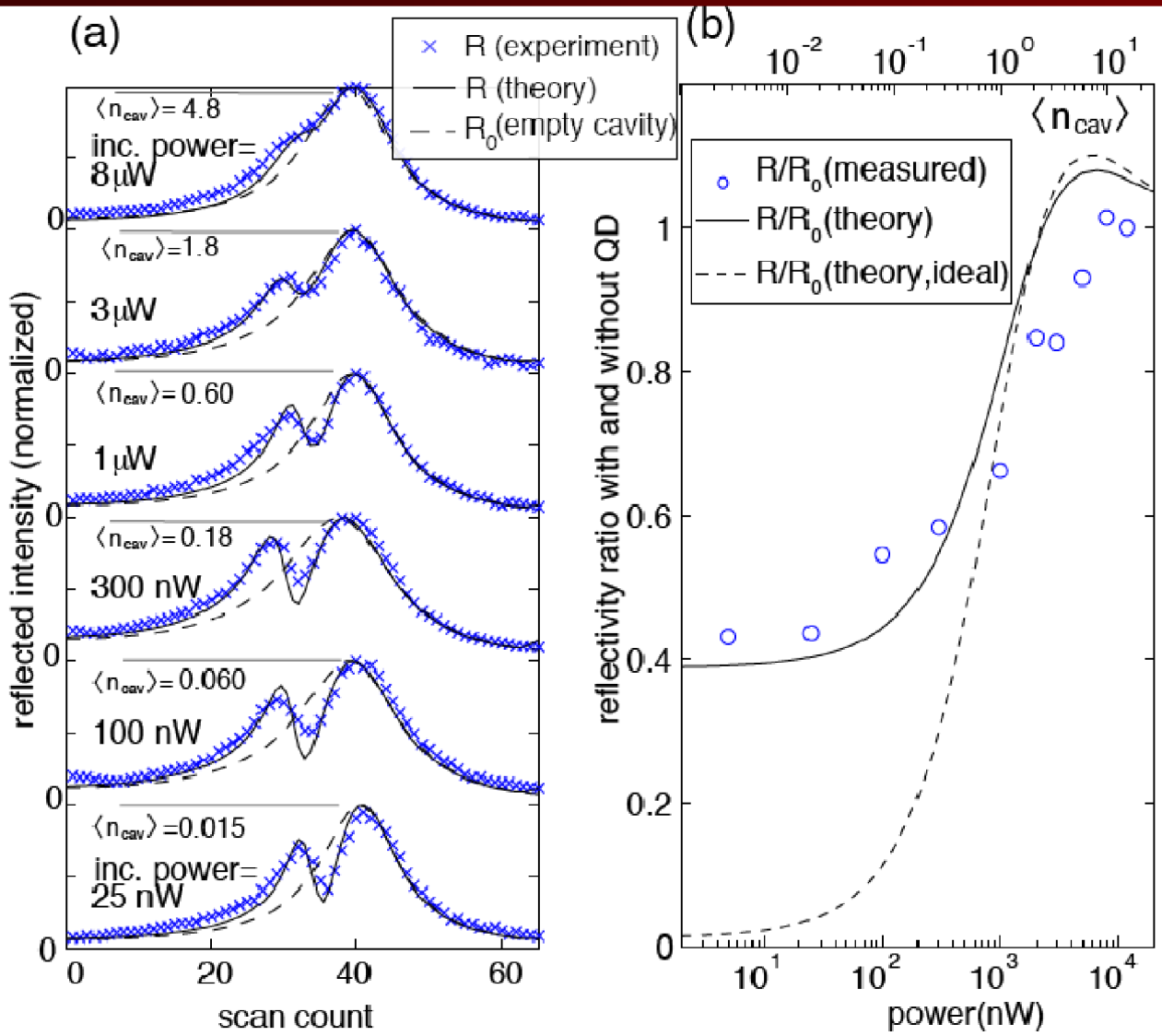




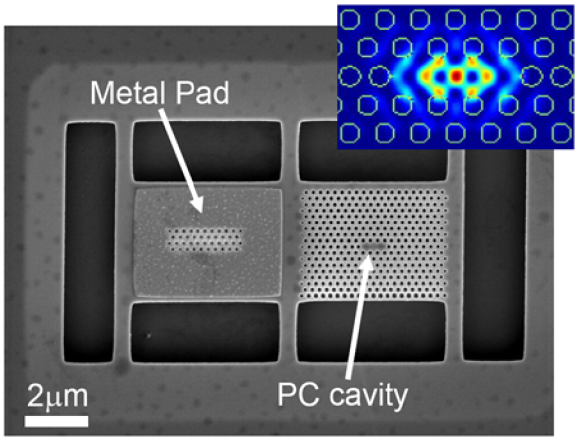
Time resolved reflectivity measurement at different probe powers
Rabi oscillation period T=39ps=2π/g (g/ 2π =25GHz)

Englund et al, (arXiv:0902.2428)

Giant optical nonlinearity – single photon switching of cavity reflectivity



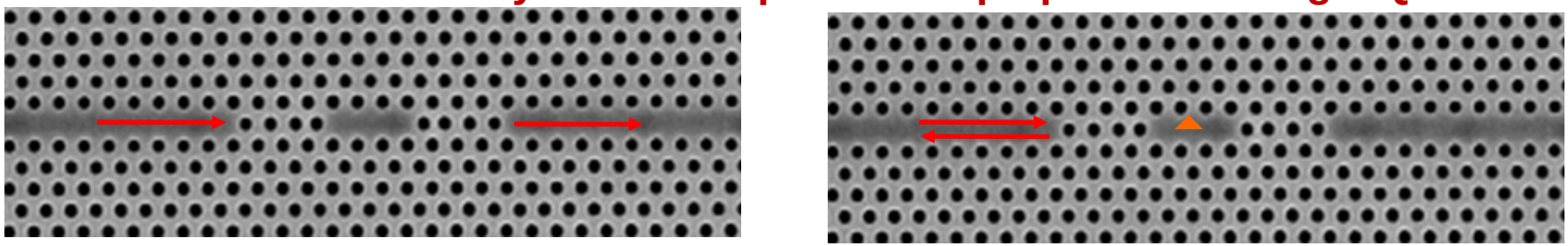
Saturation power inside the cavity = 20nW (n_{cav}~0.5)



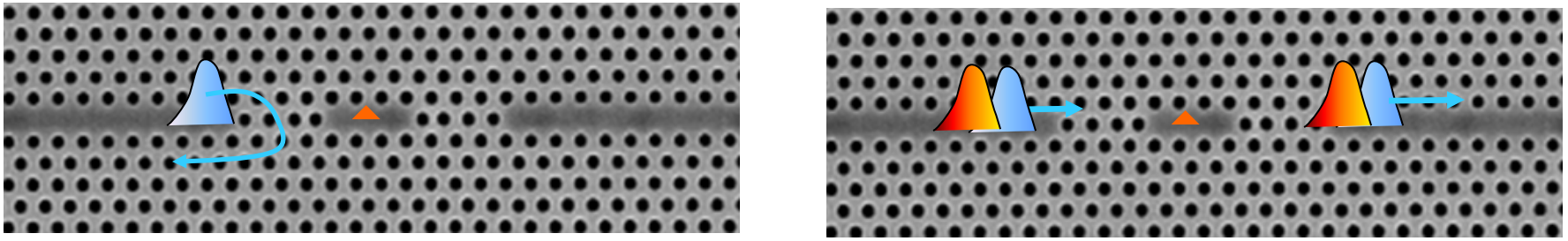
Nature **450**, 857-861 (2007)

Interesting things we can do with this system

Switch the cavity from transparent to opaque with a single QD



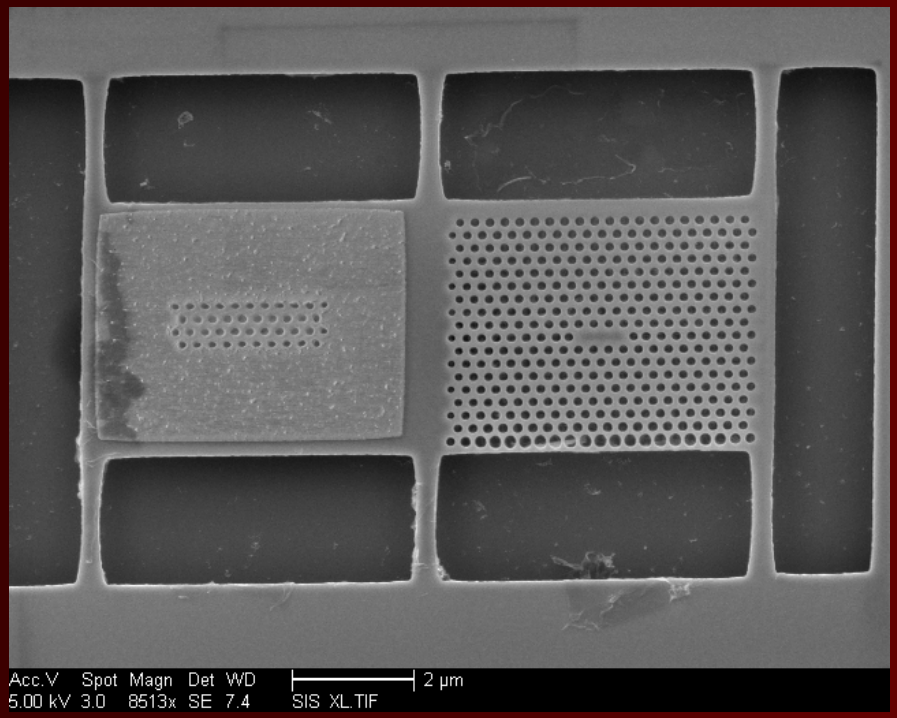
Optical switch controlled at a single photon level

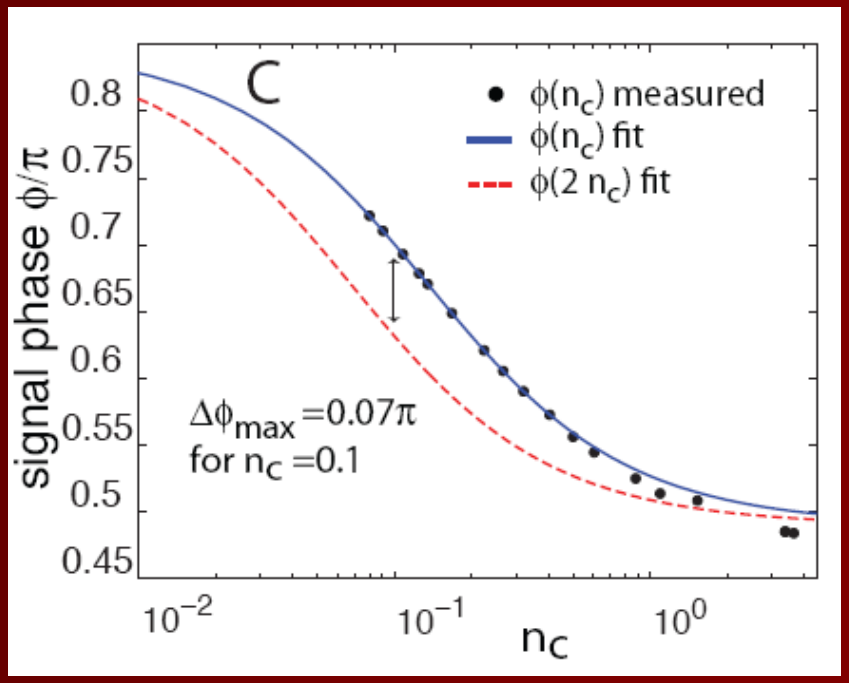


- **Building optical switches, modulators, and logic controlled with ~10nW powers (aJ energies) and at the speed of 100GHz and beyond (state of the art today: >10μW, 20GHz)**

- **Quantum gates (for long distance quantum communication and computing)**

Controlled amplitude and phase shifts with a single QD Fast electro-optical switching with a quantum dot and with sub-fJ control energies

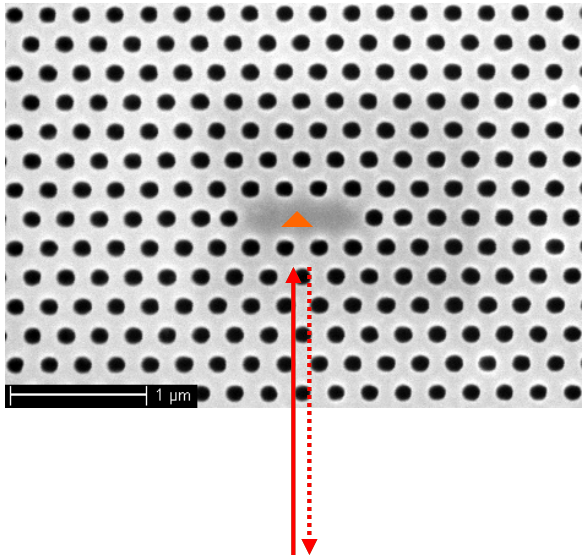




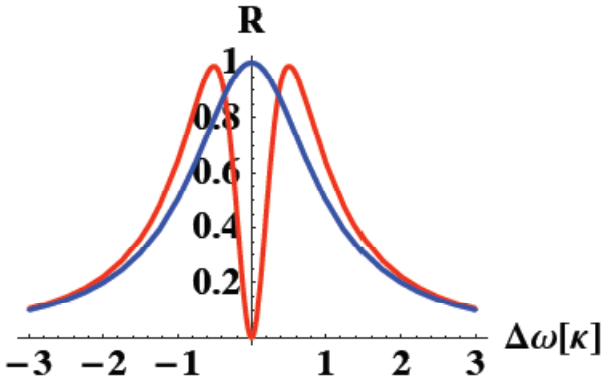
Ilya Fushman, Dirk Englund, Andrei Faraon, Nick Stoltz, Pierre Petroff, Jelena Vuckovic, *Science*, vol. 320, number 5877, pp. 769-772 (May 2008)

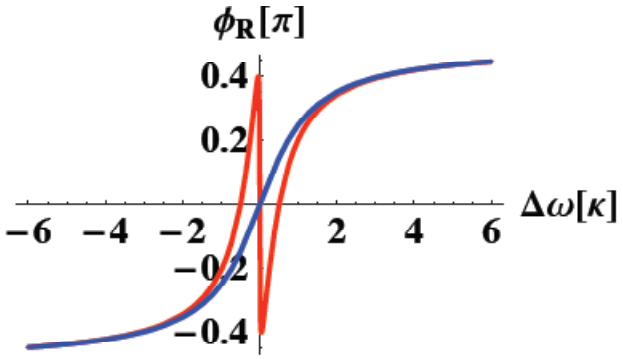
A. Faraon, A. Majumdar, H. Kim, P. Petroff & J. Vuckovic, *Phys. Rev. Letters* (2009)

Quantum dot-photonic crystal cavity QED: amplitude and phase of the reflected signal

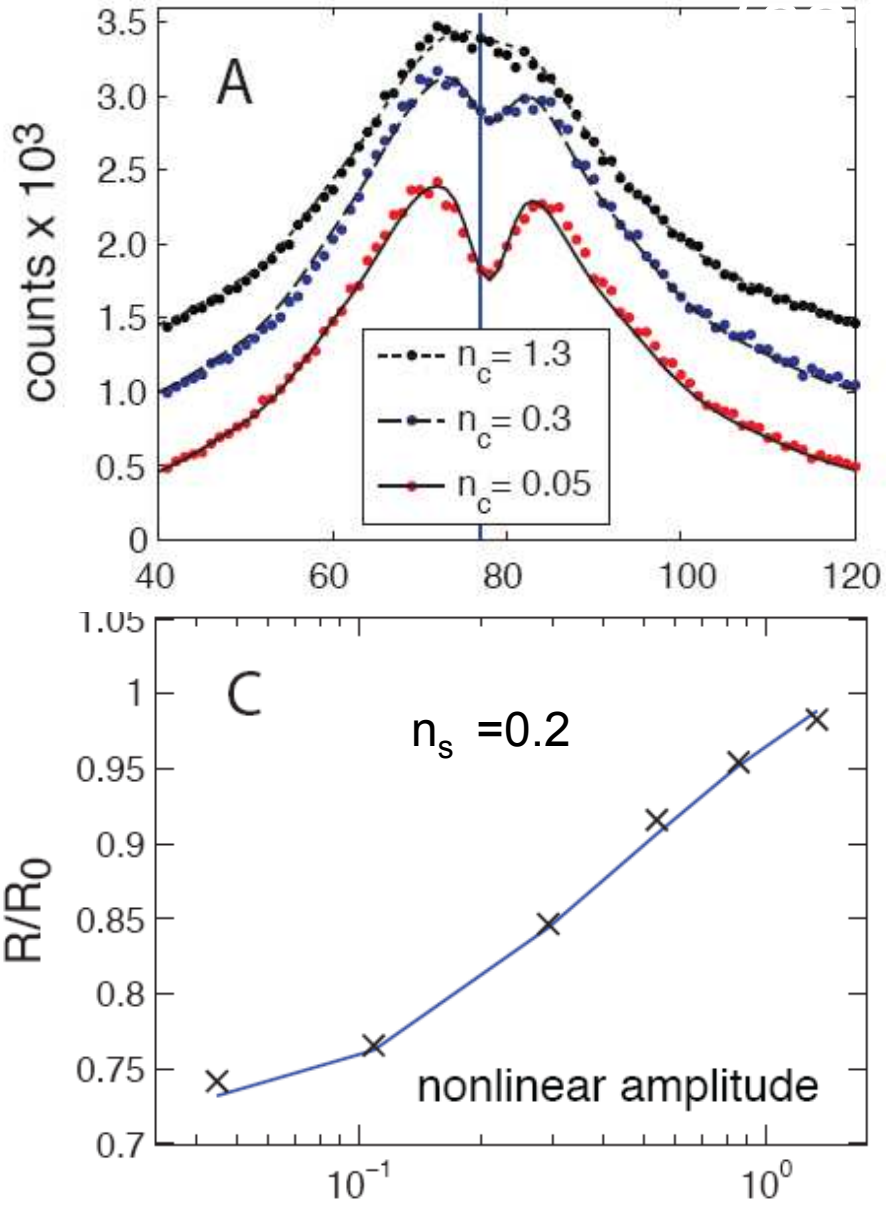


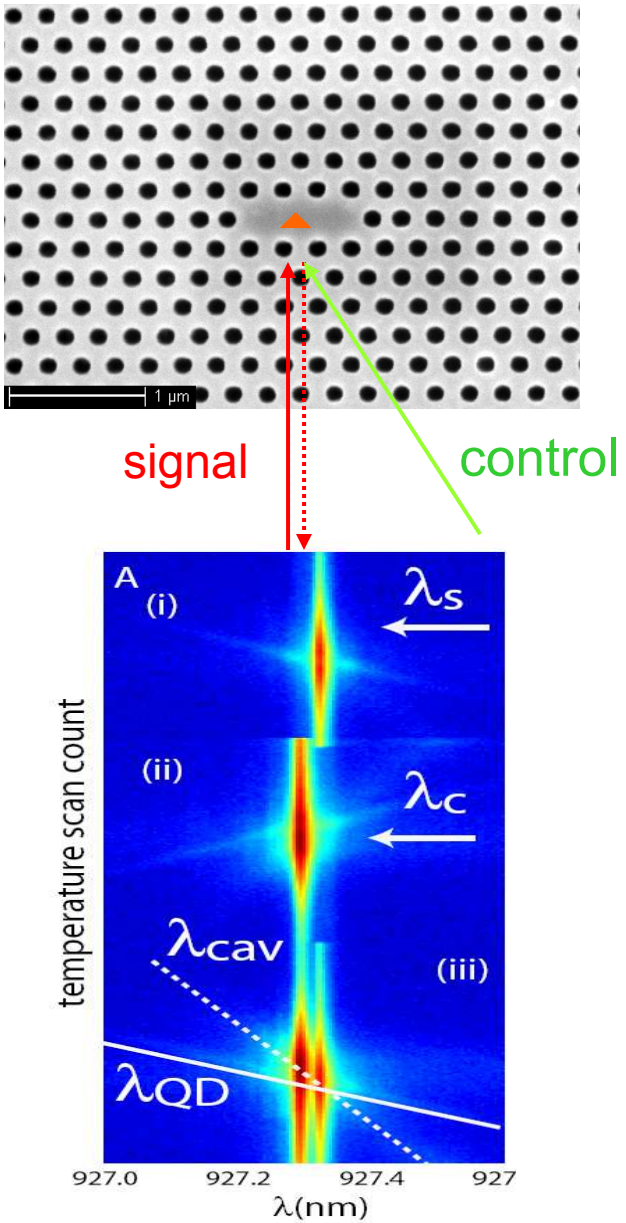
Blue - no QD or in saturation





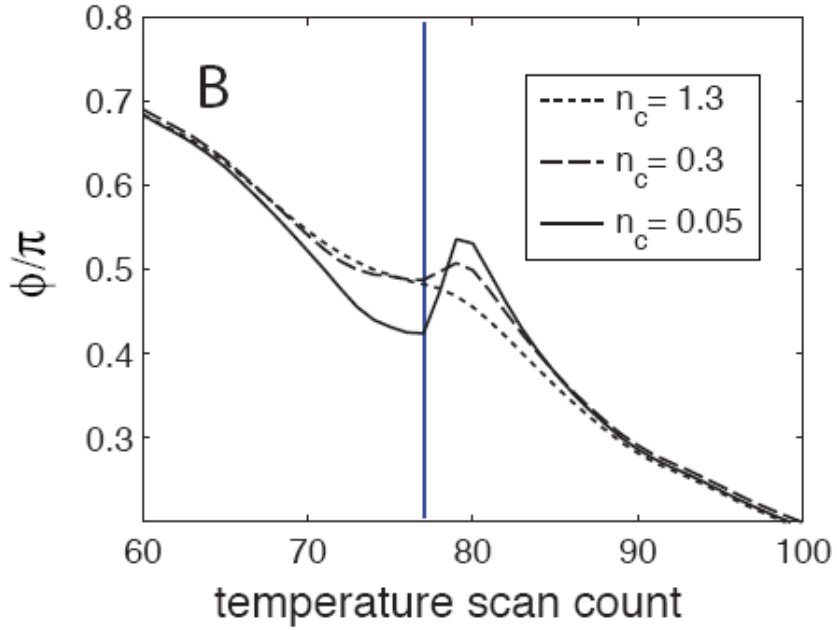
Controlled amplitude shift ($\lambda_{signal} \neq \lambda_{control}$)

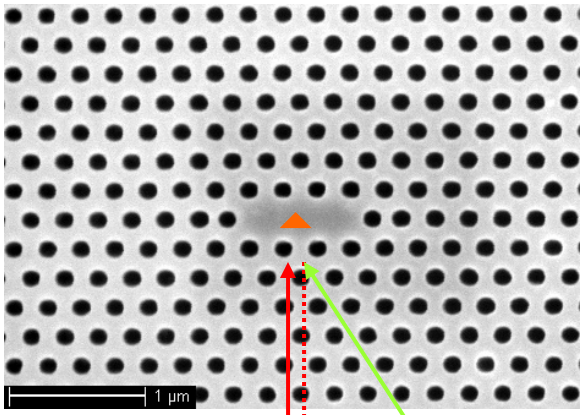


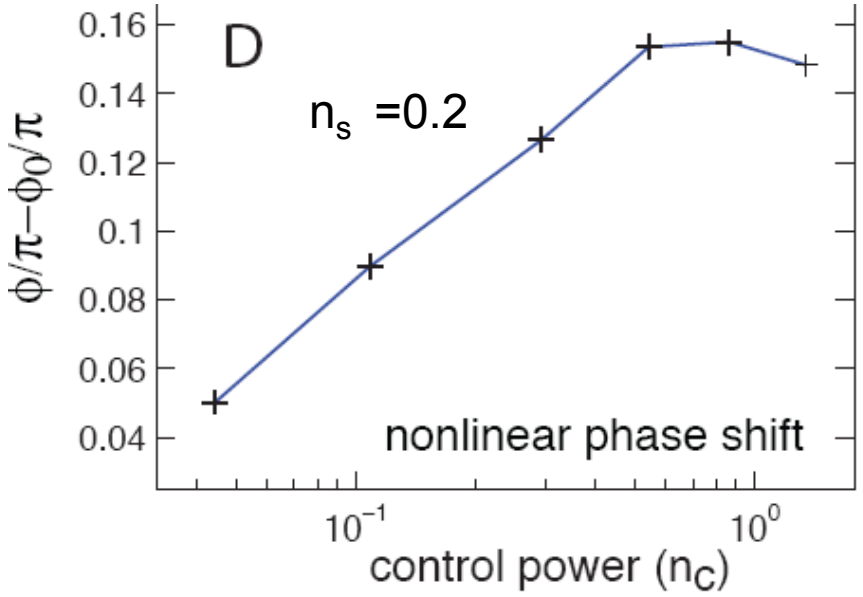


Science **320**, pp. 769-772 (2008)

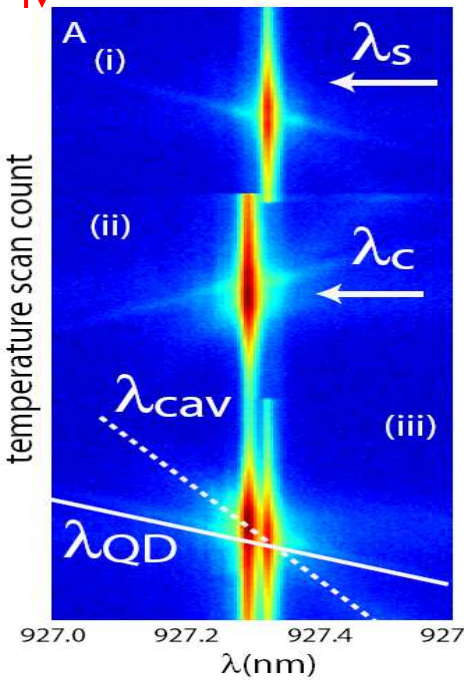
Controlled phase shift ($\lambda_{signal} \neq \lambda_{control}$)



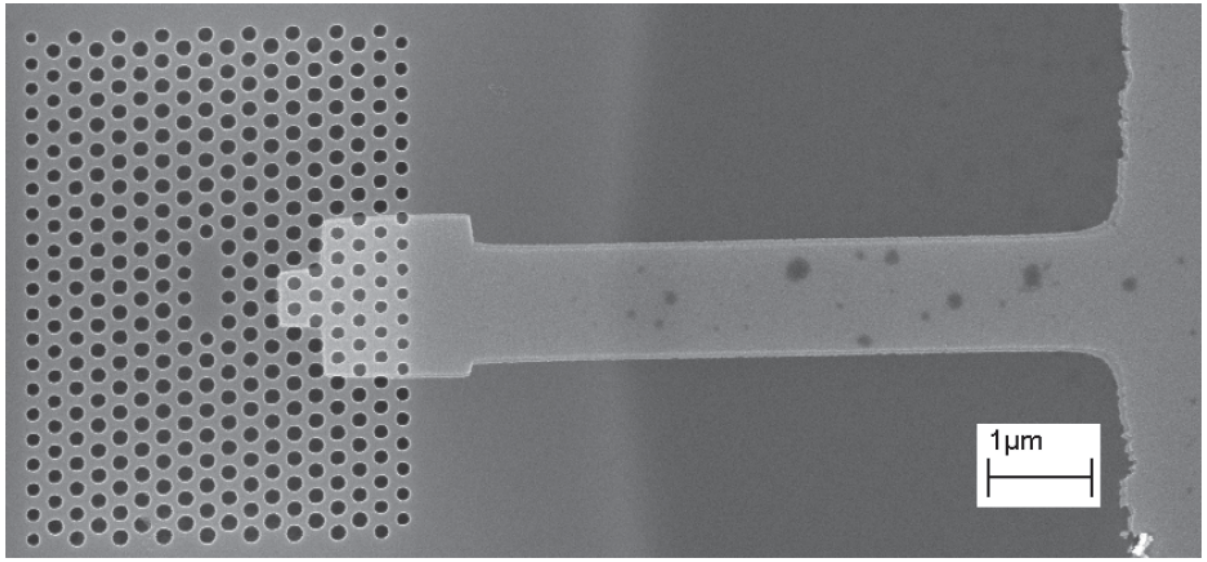


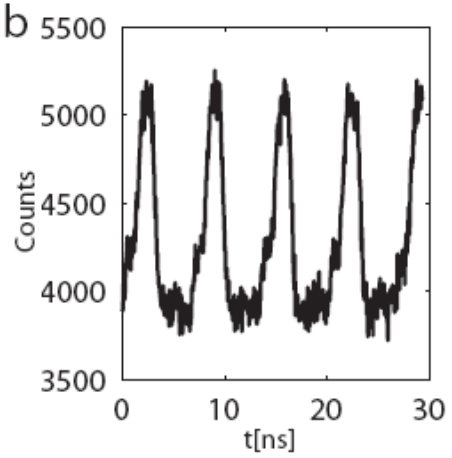


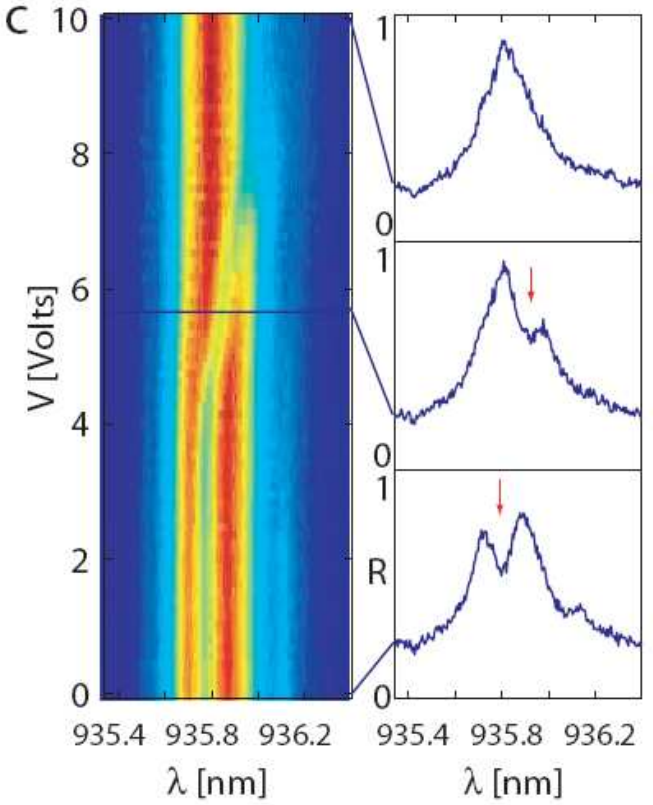
Up to π/4
shift for complete
QD saturation



Electro-optic switching with a quantum dot strongly coupled to a nanocavity



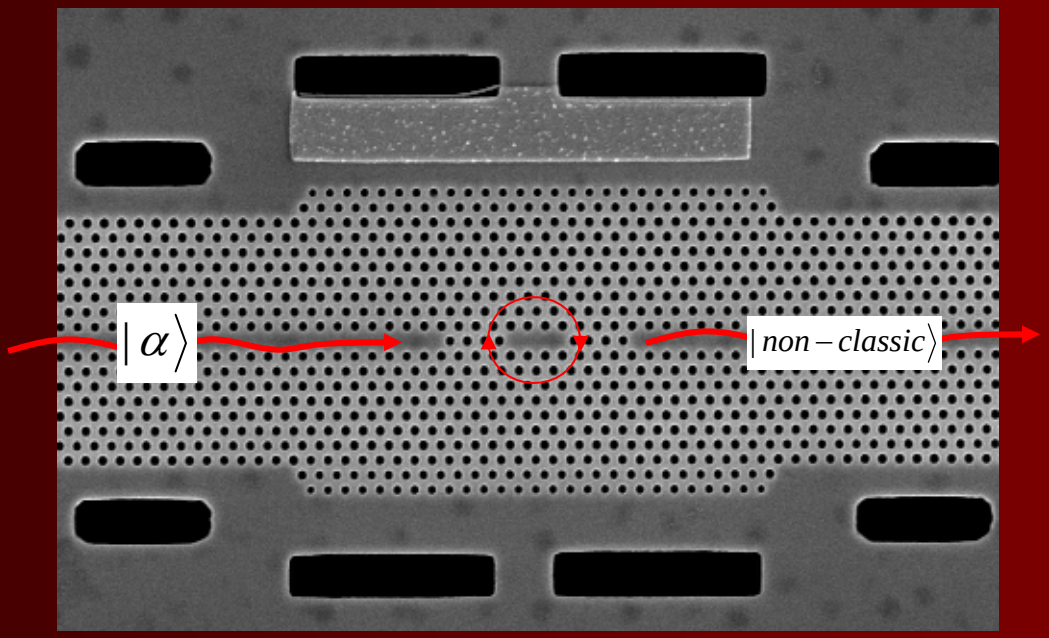




- <fJ/operation (0.1aJ possible)
- ~10GHz speed (currently 150MHz because of RC constant)

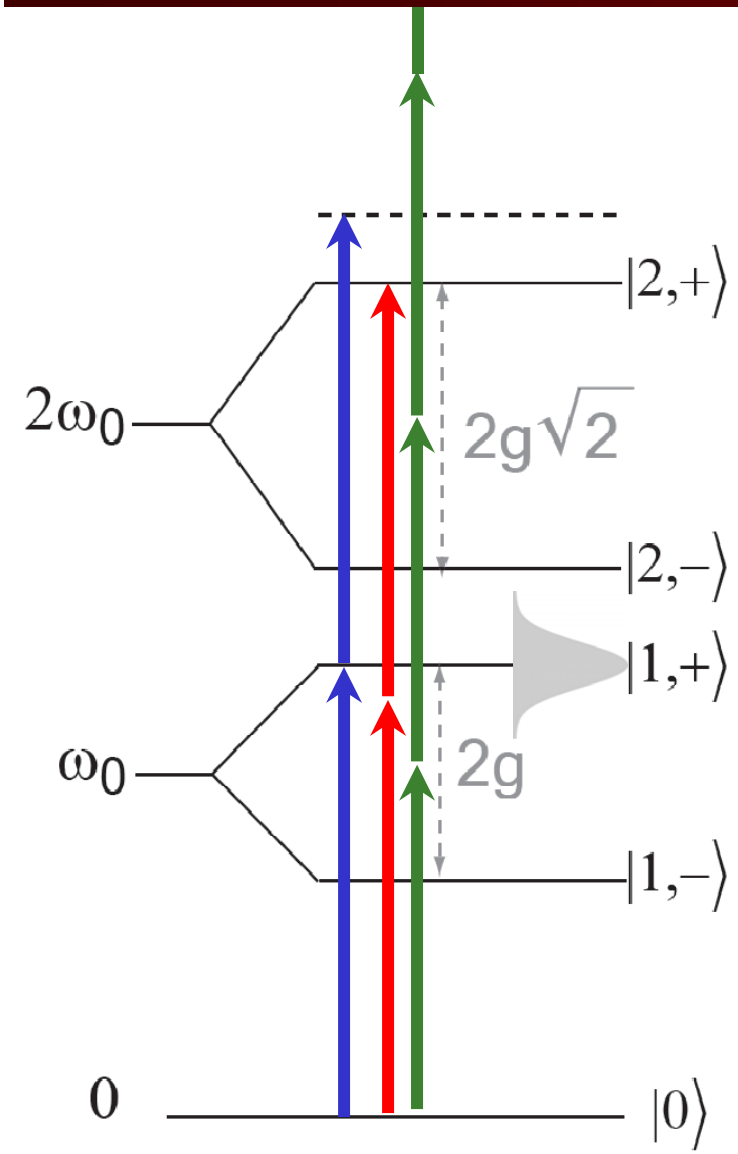
A. Faraon, A. Majumdar, H. Kim, P. Petroff & J. Vuckovic, PRL (2009)

Solid state cavity QED based quantum info. processing: Coherent generation of nonclassical light on a chip via photon-induced tunneling and blockade

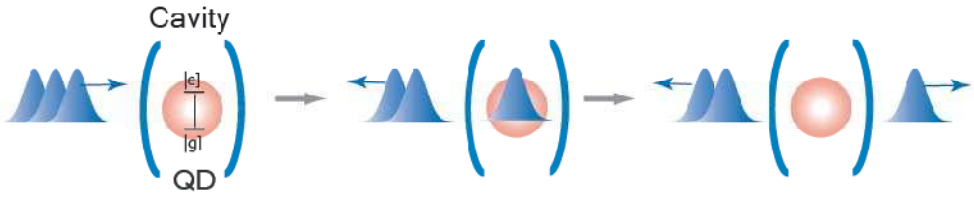


Andrei Faraon, Ilya Fushman, Dirk Englund, Nick Stoltz, Pierre Petroff, Jelena Vuckovic
Nature Physics, Vol. 4, pp. 859-863 (2008)

Nonlinear Optics at Single Photon Level

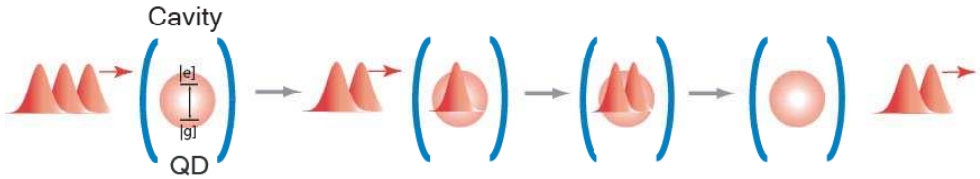


Photon Blockade

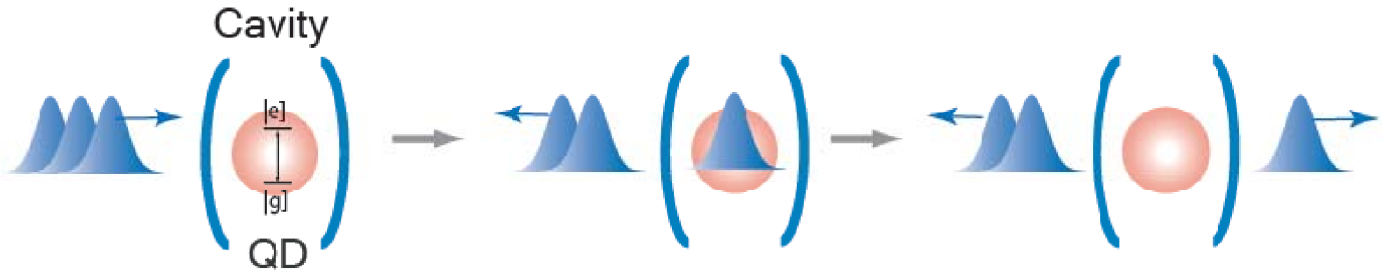


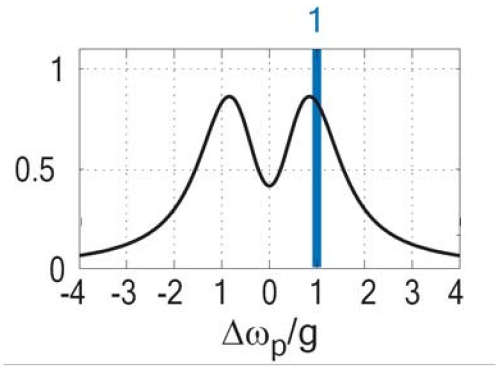
Proposal: Imamoglu et al, PRL, 1999
Birnbaum et al, Science, 2005

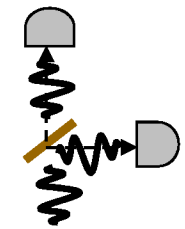
Photon-induced tunneling



Photon Blockade

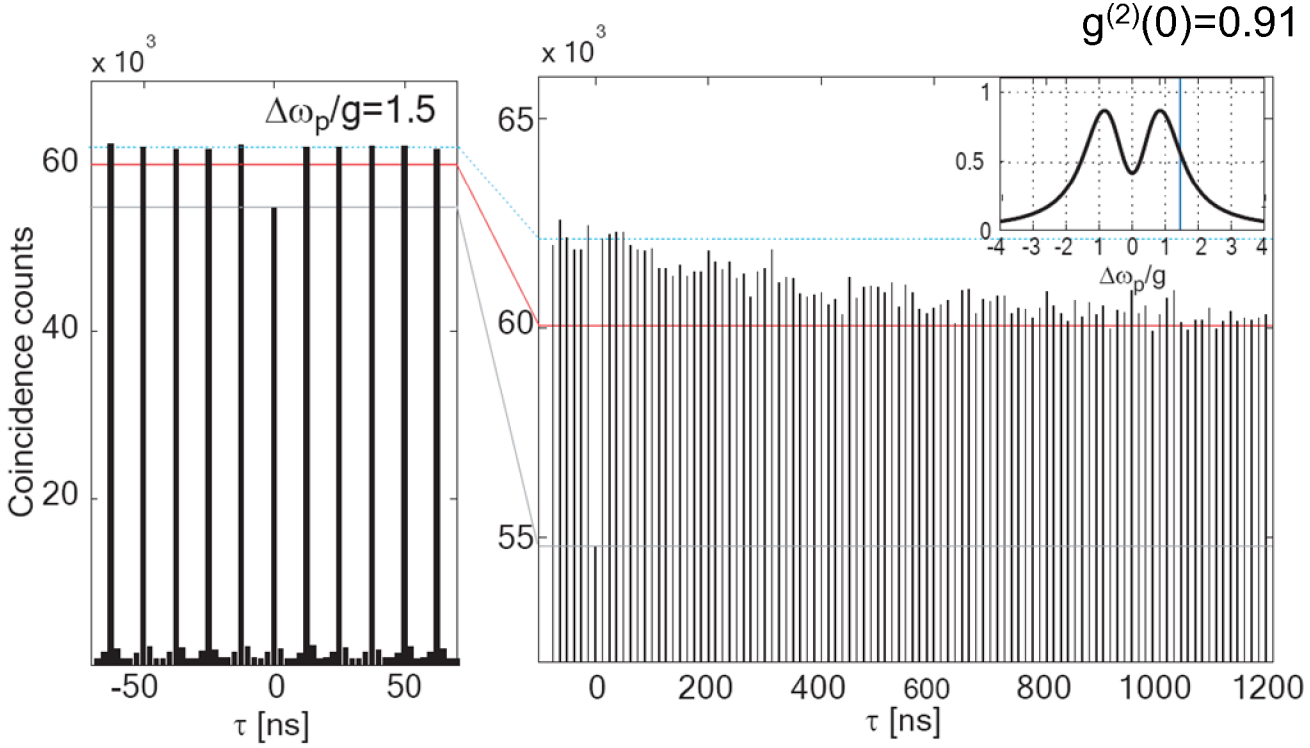




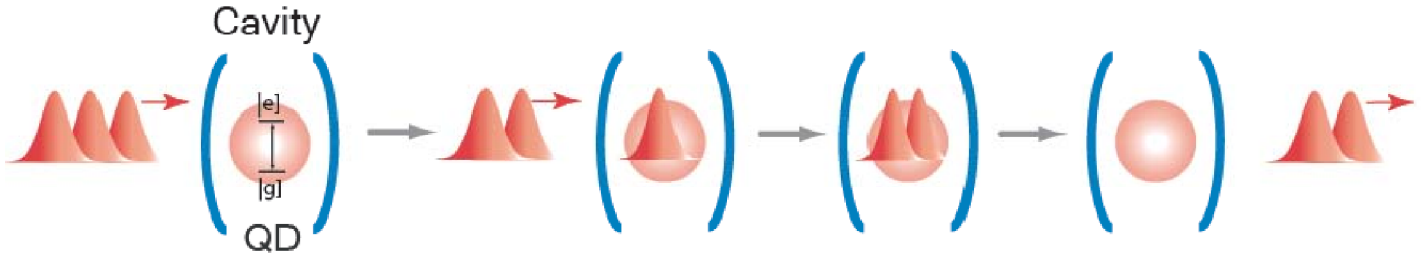


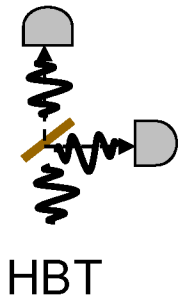
HBT

$g^{(2)}(0)=0.91$

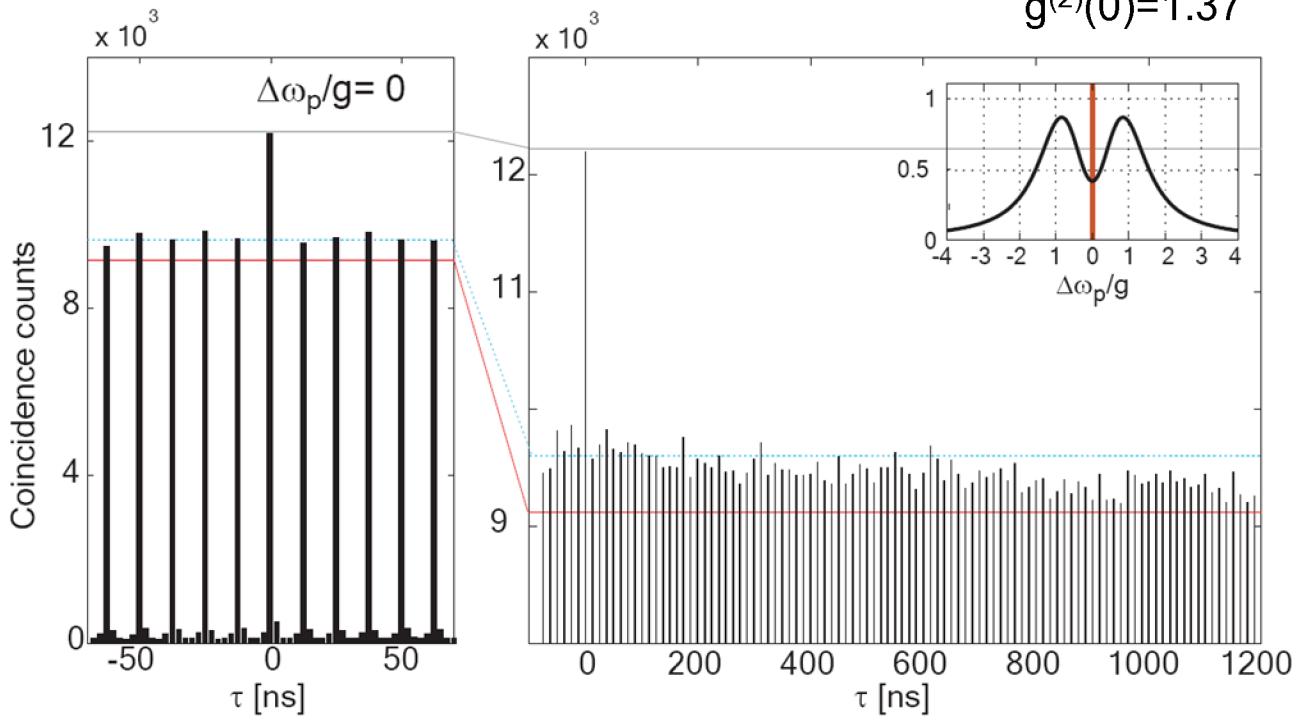


Photon-Induced Tunneling

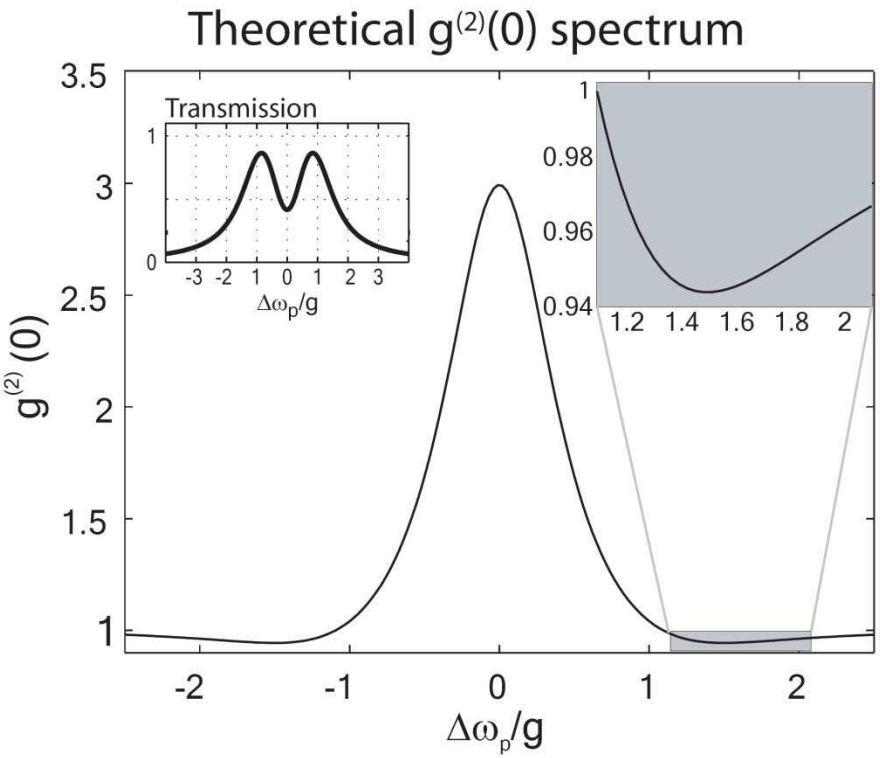


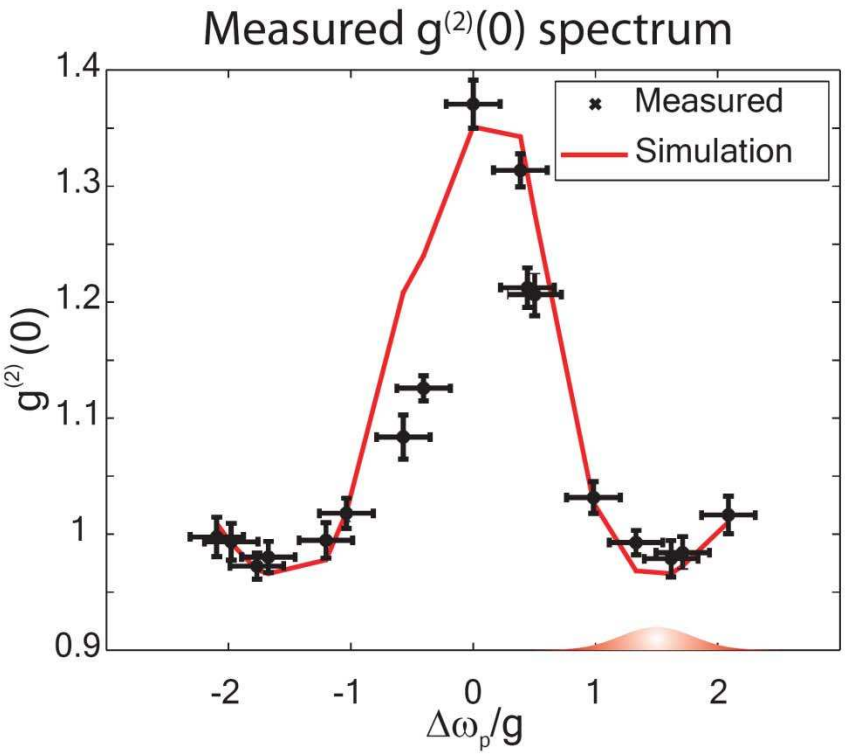


$g^{(2)}(0)=1.37$



Mapping the $g^{(2)}$ spectrum

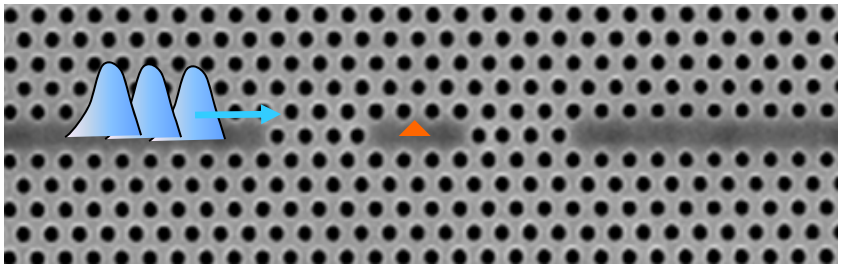


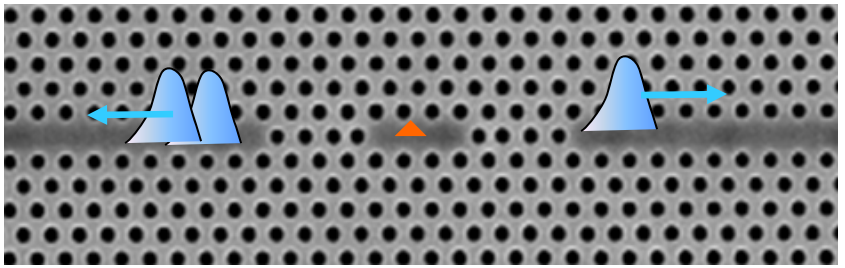


-Transition from photon blockade to photon induced tunneling observed when changing laser detuning

Interesting things we can do with this system

Photon blockade (only one photon at a time can tunnel through the cavity)

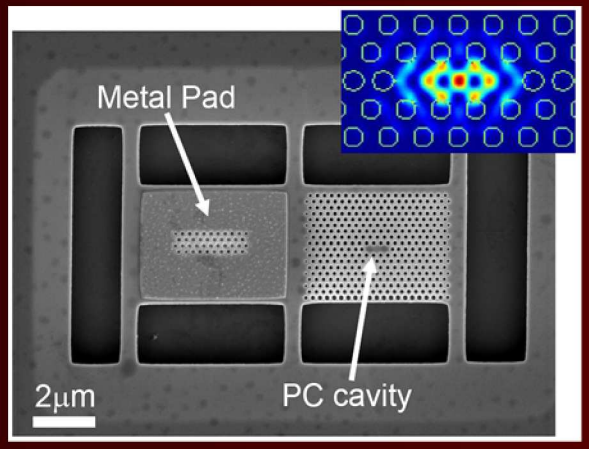


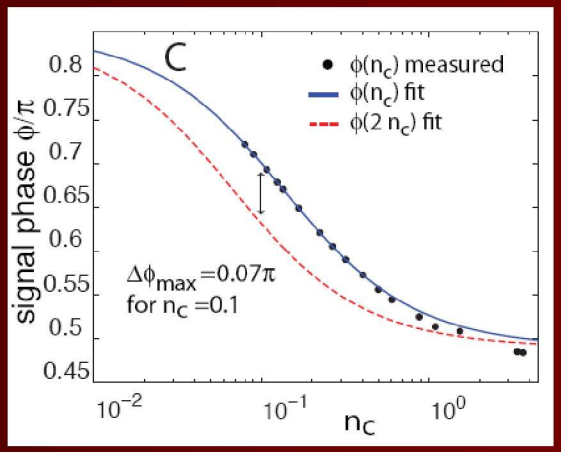


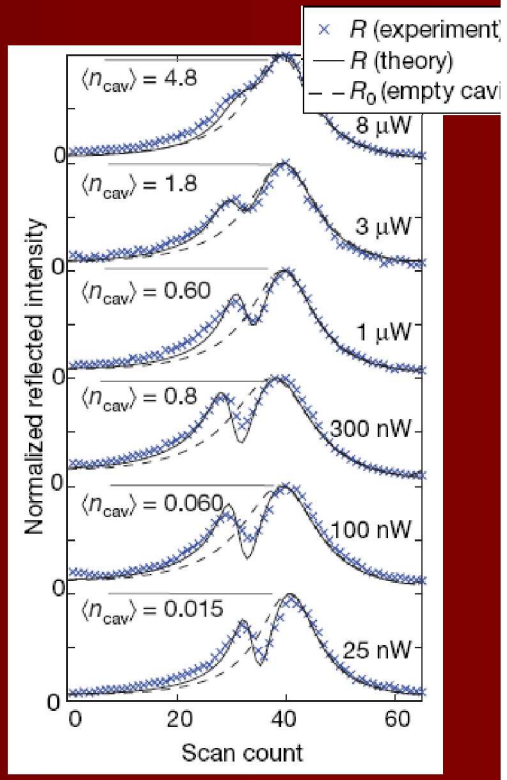
- Generation of nonclassical states of light
- Single photon switches
- Single photon source

Summary

QD-PC cavity QED system (locally tunable)

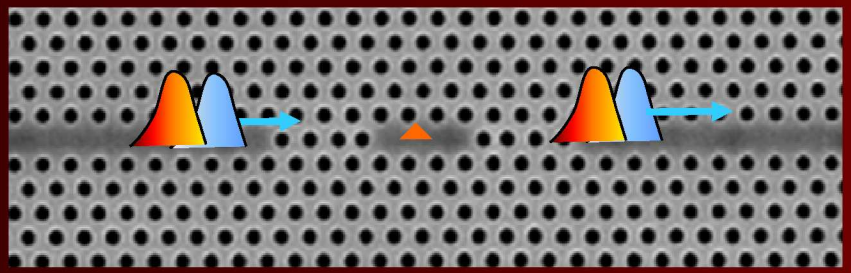


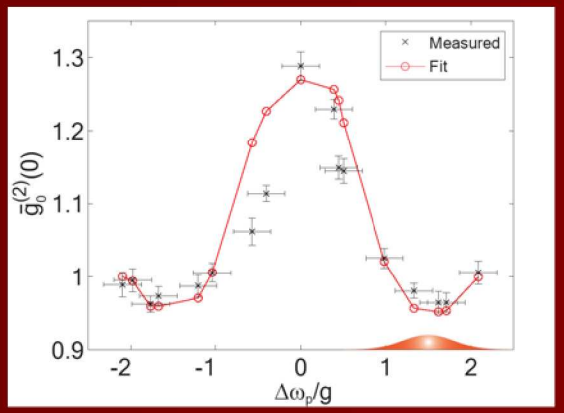




Reflectivity amplitude and phase control at a single photon level – cavity QED based quantum info. processing

Optical and electro-optical switching with aJ-fJ control



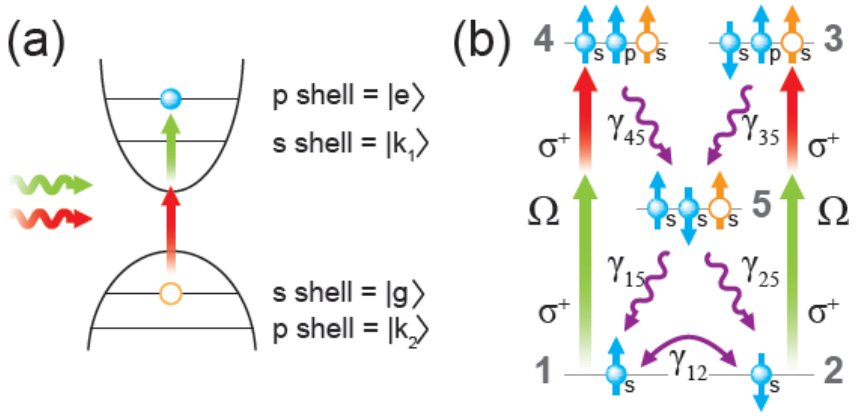


Photon blockade and nonclassical light generation

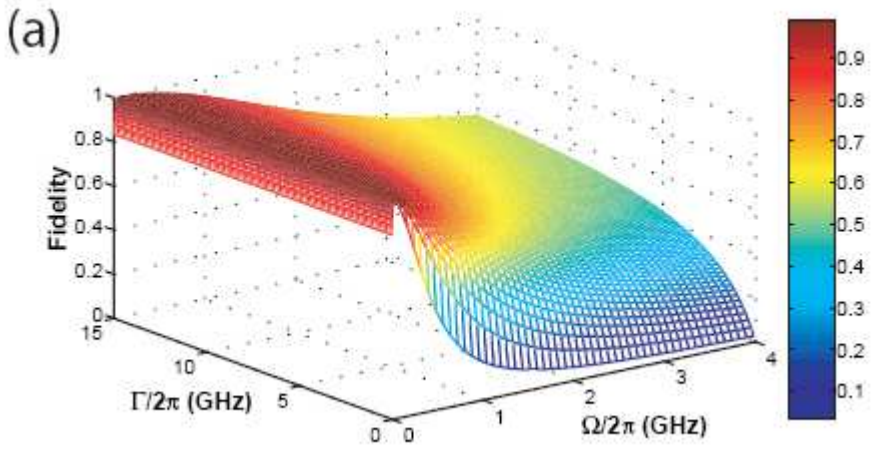
Stanford University

What's next?

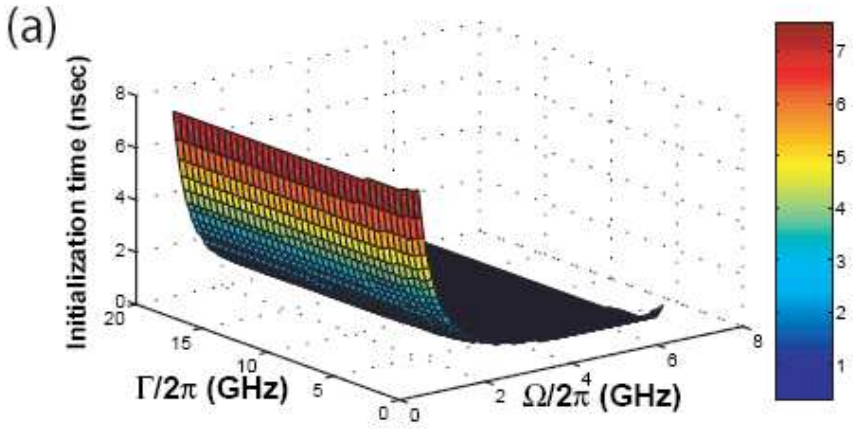
- Coherent mapping between a photon state and a quantum dot spin state in a cavity
- Quantum dot spin initialization without a cavity (Voigt geometry: Press et al, Nature 2007; Xu et al, PRL 2007; Faraday geometry: Atature et al, Science 2006)



- Quantum dot spin initialization with weak magnetic field (<0.2T); speed up to 1.3GHz; fidelity up to 99.7% (Majumdar, Lin et al, arXiv:0907.3187)

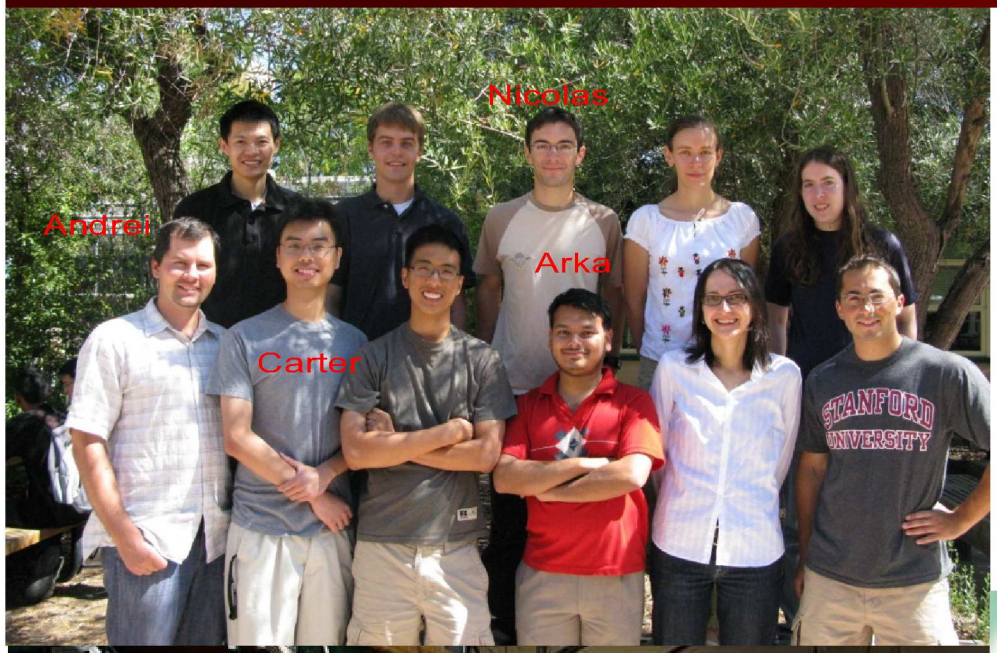


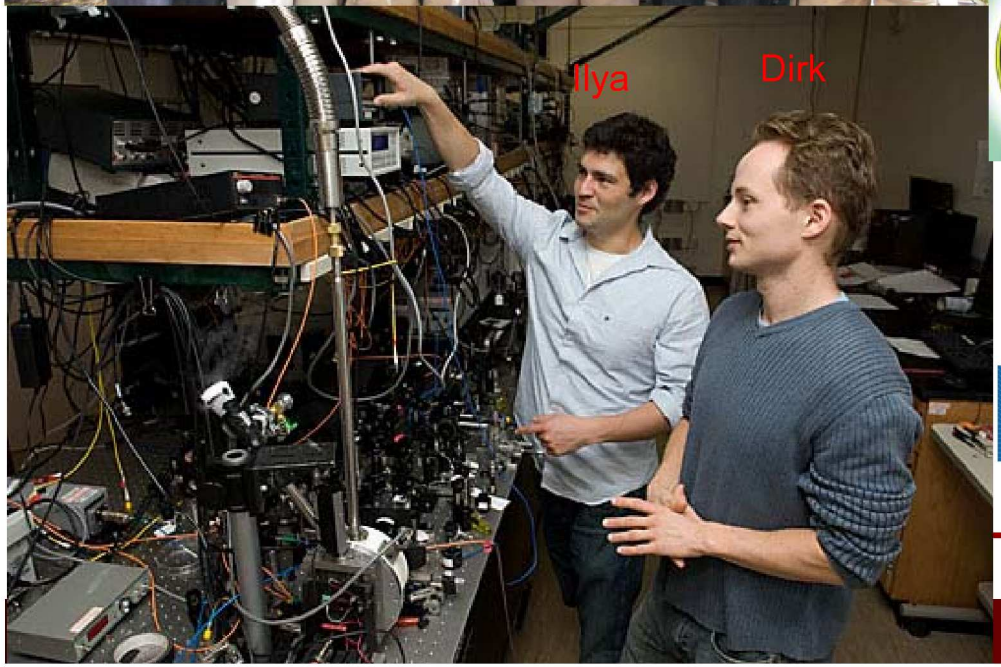
Γ- spontaneous emission rate



Ω - effective Rabi frequency for two-photon process

Acknowledgements





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Office of Naval Research

National Science Foundation
WHERE DISCOVERIES BEGIN