Quantum optics in mesoscopic systems

Lecture I

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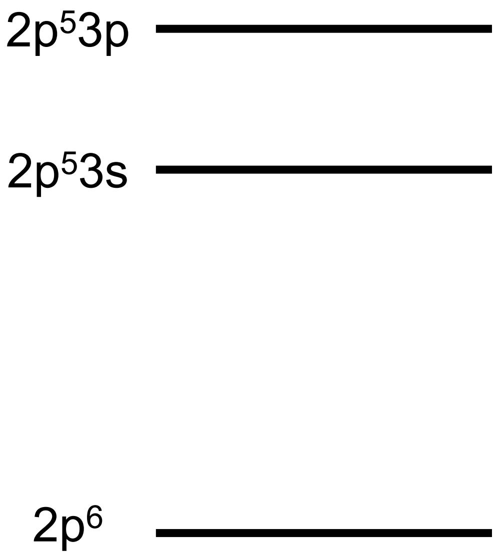
Outline

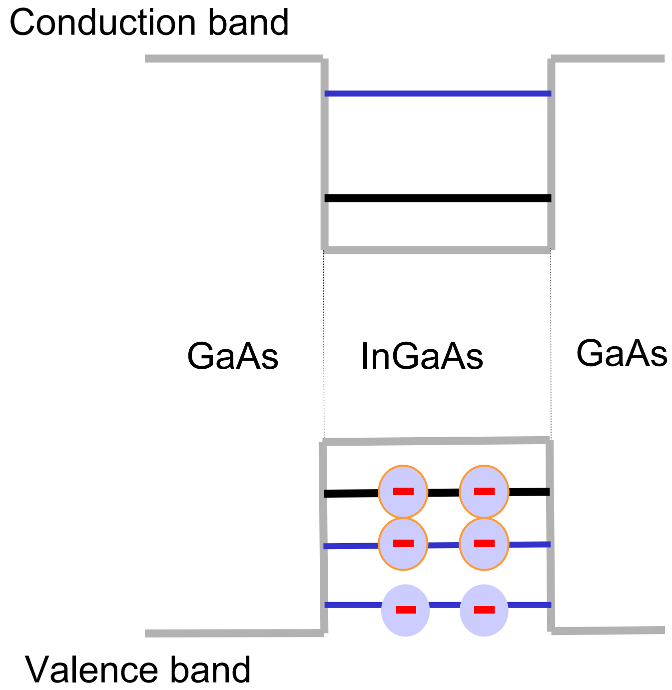
1) Brief overview of quantum dots – a.k.a. artificial atoms
2) Photon correlation measurements and single-photon sources
3) Cavity-QED with a single quantum dot

Optically active quantum dots (QD): Discrete anharmonic spectrum for optical excitations

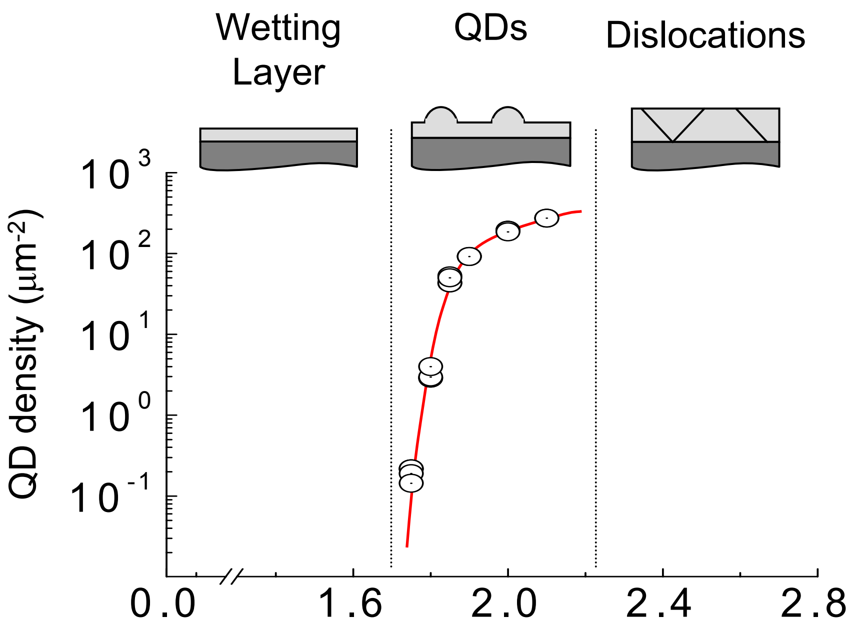
Goal: Confine both lowest energy electrons in conduction band and holes in valence band simultaneously.

Neon atom **Artificial atom**





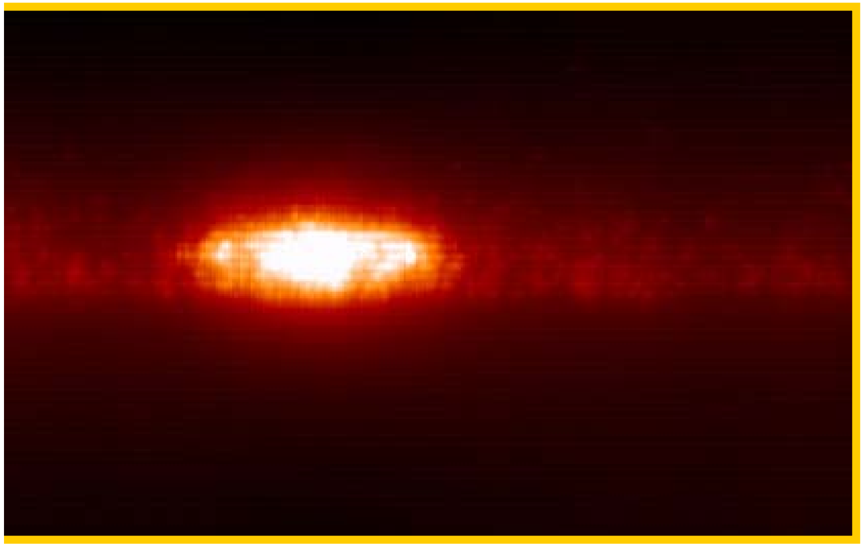
InAs/GaAs Self-Assembled Quantum Dots

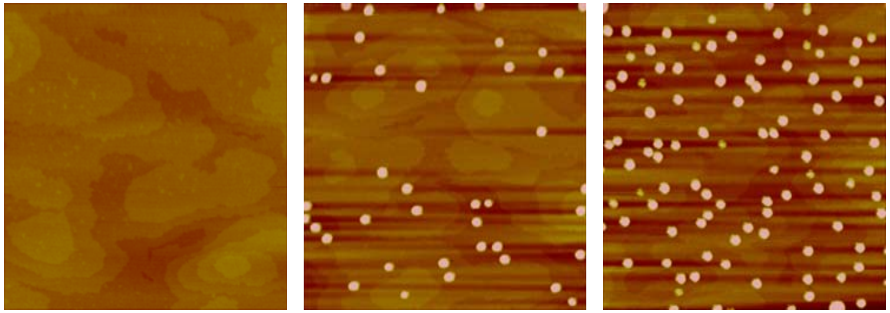


Self-assembled quantum dots confine both lowest energy electrons in conduction band and holes in valence band simultaneously.

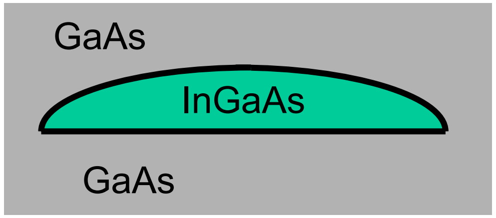
- **QDs are formed during the heteroepitaxy of lattice mismatched crystal layers**
- **Coherent mechanism of elastic relaxation**

X-STM

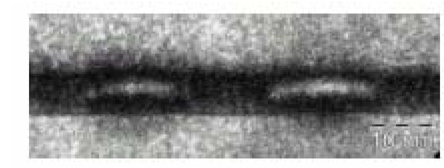


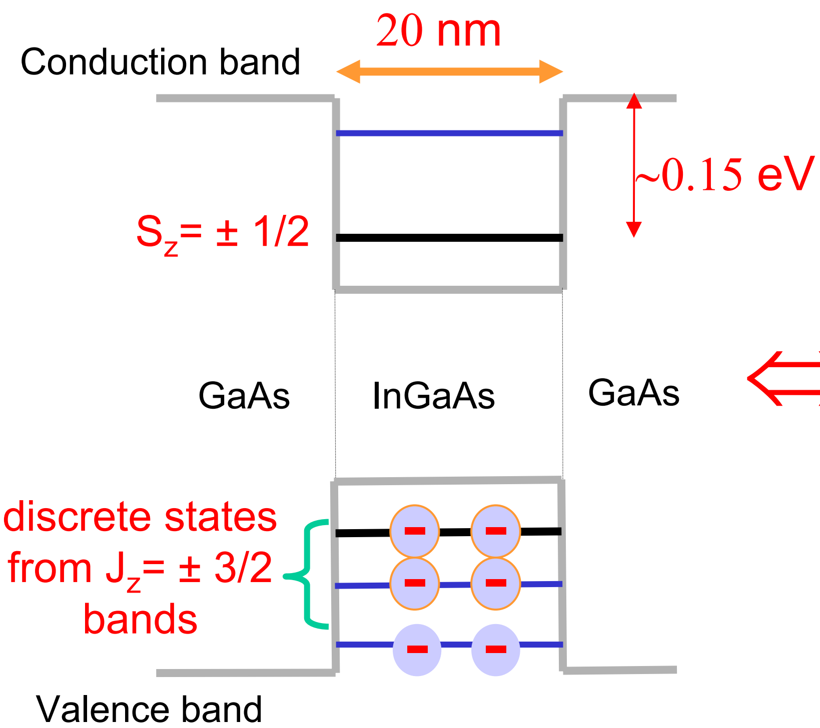


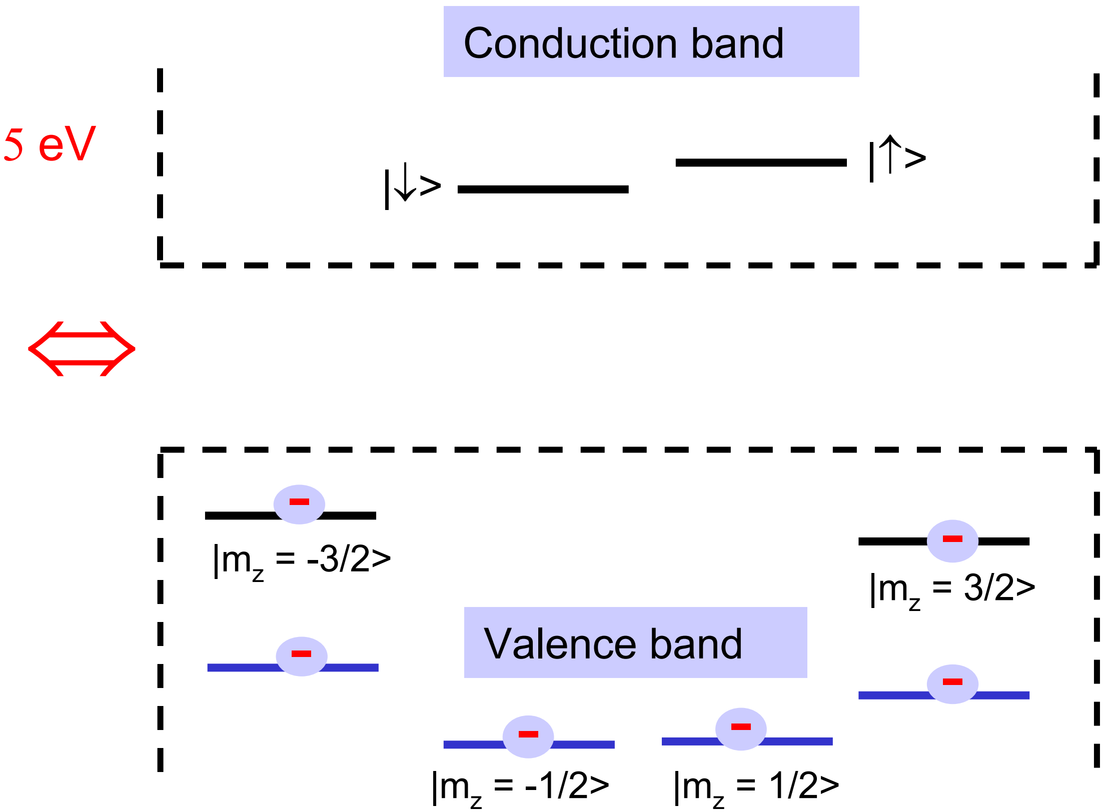
AFM



Quantum dots (QD)

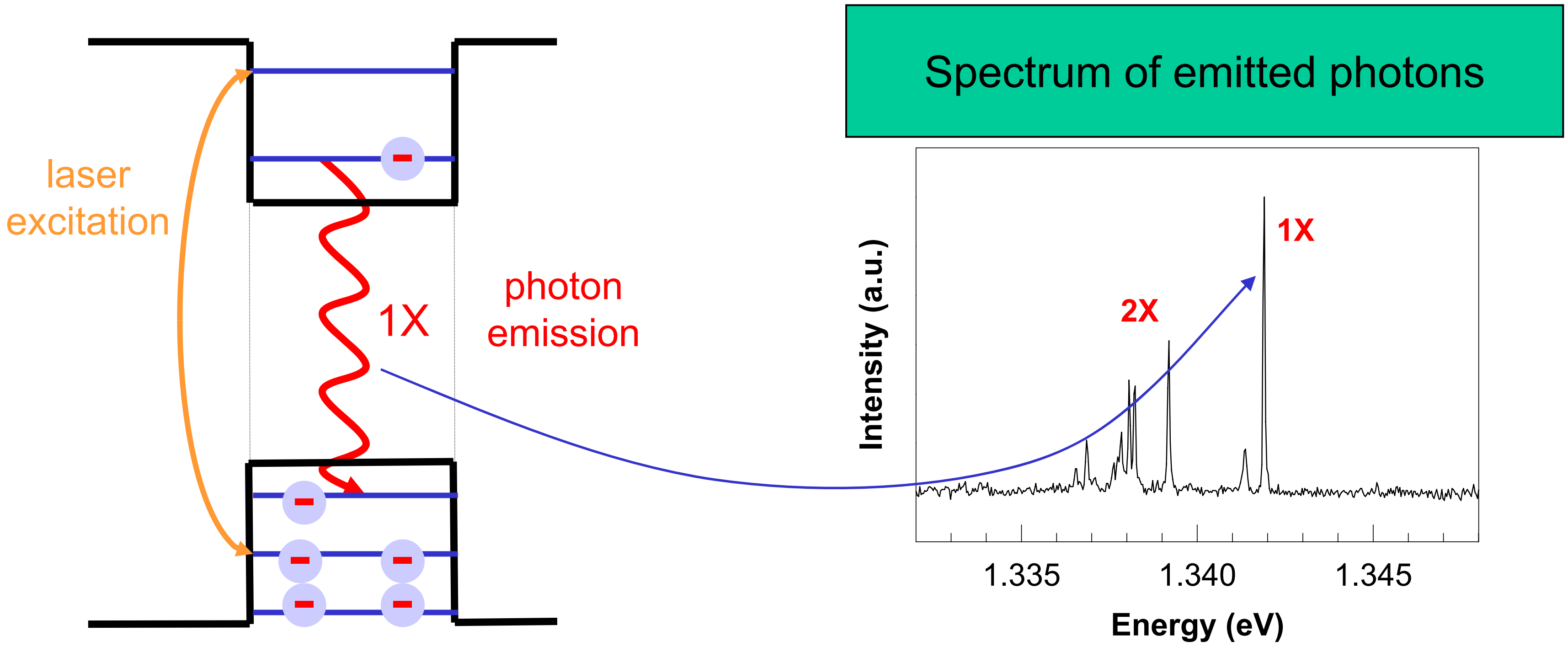






- Self-assembled QDs have discrete states for electrons & holes.
- QD location is fixed by growth.
- ~10^5 atoms (= nuclear spins) in each QD.

Photoluminescence (PL) from a single quantum dot

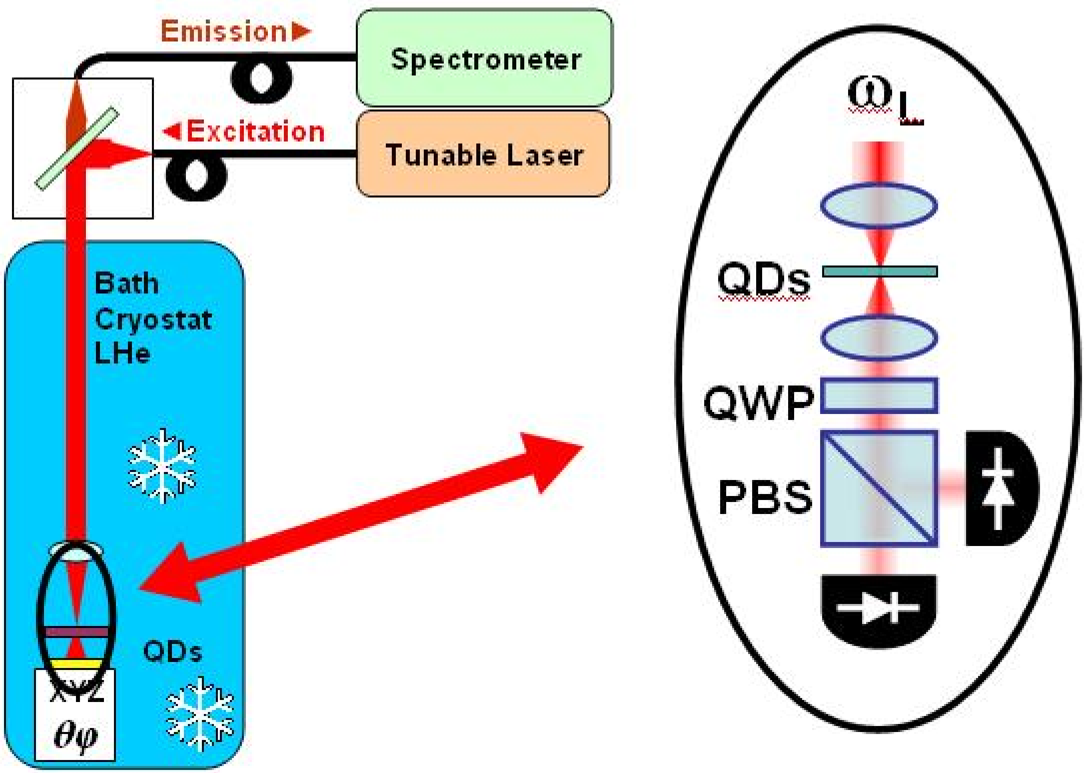


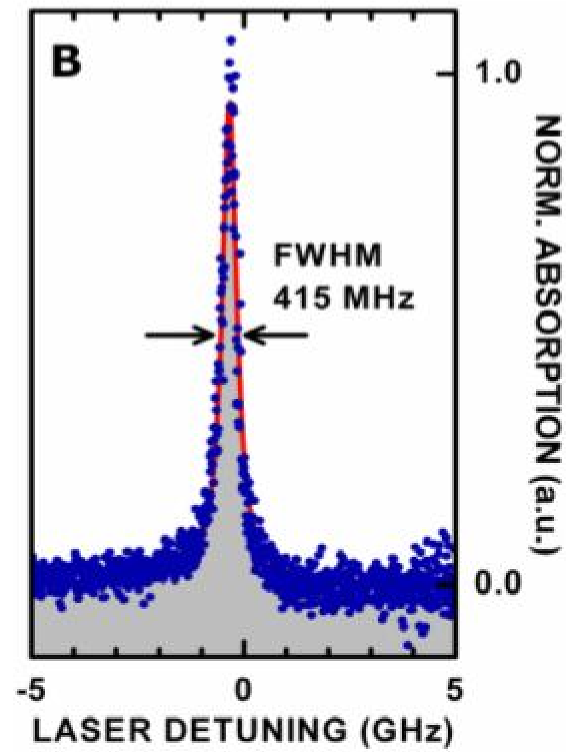
⇒ QDs typically exhibit several sharp emission lines – in part due to defects in the neighborhood that could charge/decharge during the excitation.

⇒ At low pump power, a single (exciton) line dominates the spectrum; the width of this line is resolution limited at ~ 8 GHz << kT ~ 80 GHz.

How narrow are quantum dot exciton lines?

- Resonant absorption measurements reveal QD linewidths under minimal excitation/disturbance:





$\Rightarrow$ Observed absorption linewidth is 1.5 μev ~ 1.5 Γ_{spon}

Photon correlation measurements

- Intensity (photon) correlation function:

$$g^{(2)}(\tau) = \frac{\langle : I(t) I(t+\tau) : \rangle}{\langle I(t) \rangle^2}$$

$\rightarrow$ gives the likelihood of a second photon detection event at time t+τ, given an initial one at time t (τ=0).

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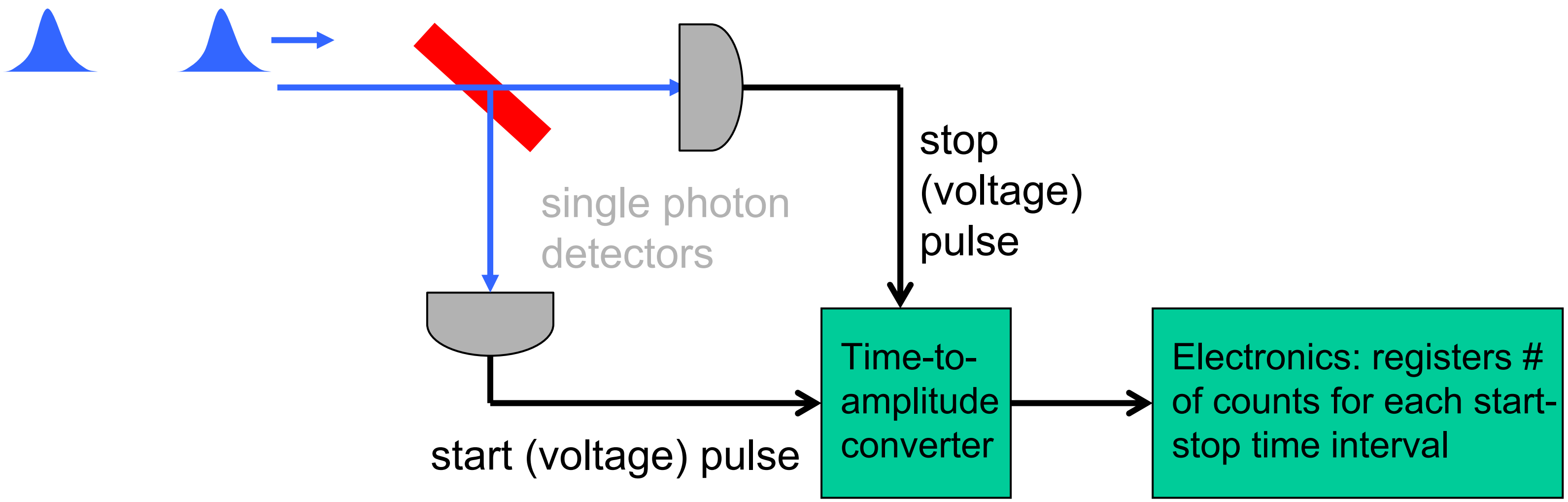
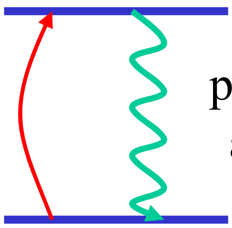
- Experimental set-up for photon correlation [$g^{(2)}(\tau)$] measurement:



Photon antibunching

• Intensity correlation ($g^{(2)}(\tau)$) of light generated by a single two-level (anharmonic) emitter.



• Assume that at τ=0 a photon is detected:

$\rightarrow$ We know that the system is necessarily in the ground state |g>

$\rightarrow$ Emission of another photon at $\tau=0+\varepsilon$ is impossible.

$\Rightarrow$ Photon antibunching: $g^{(2)}(0) = 0$.

• $g^{(2)}(\tau)$ recovers its steady-state value in a timescale given by the spontaneous emission time.

nonclassical light

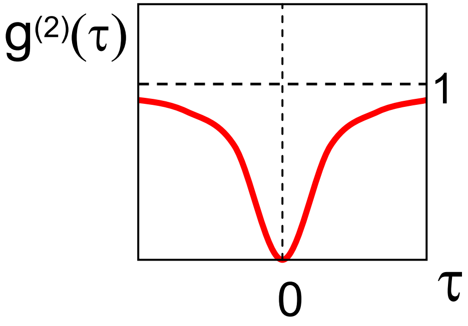
- Proof of anharmonic nature of optical excitations
- If there are two or more 2-level emitters, detection of a photon at τ=0 can not ensure that the system is in the ground state ($g^{(2)}(0)$ >0.5).

Signature of photon antibunching

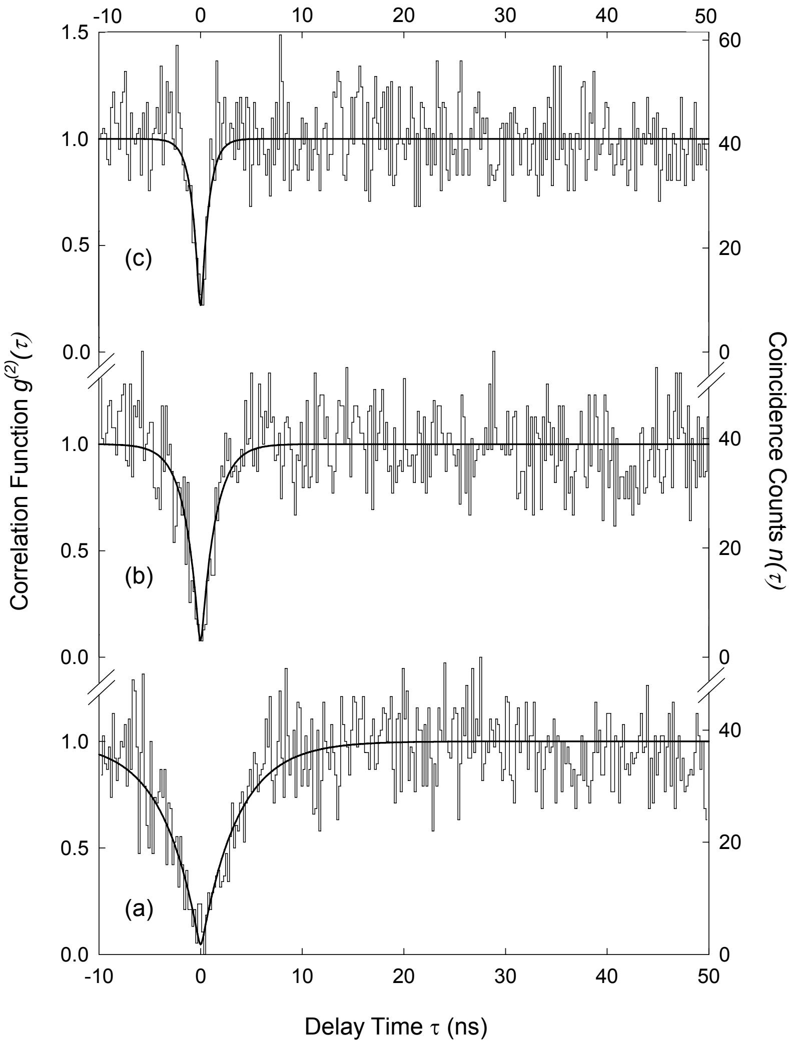
- Intensity (photon) correlation function:

$$g^{(2)}(\tau) = \frac{\langle : I(t) I(t+\tau) : \rangle}{\langle I(t) \rangle^2}$$

- Single quantum emitter (i.e. an atom) driven by a cw laser field exhibits photon antibunching.



Photon antibunching from a Single Quantum Dot



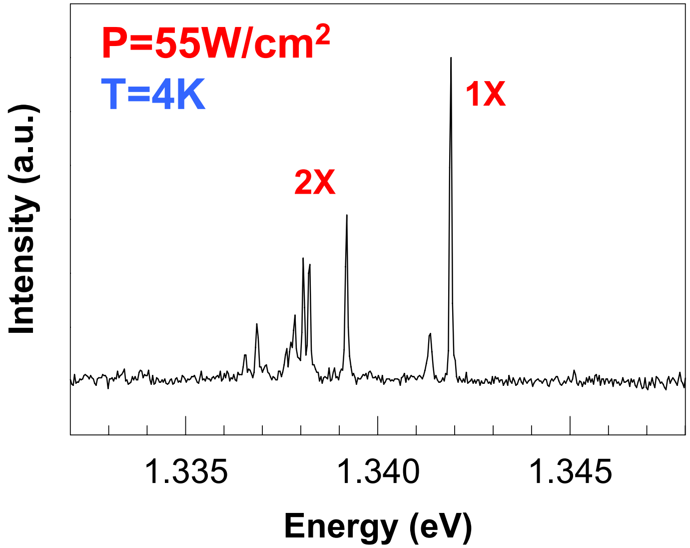
(continuous-wave excitation)

105 W/cm²
$g^2(0)=0.1$
τ = 750 ps

55 W/cm²
$g^2(0)=0.0$
τ = 1.4 ns

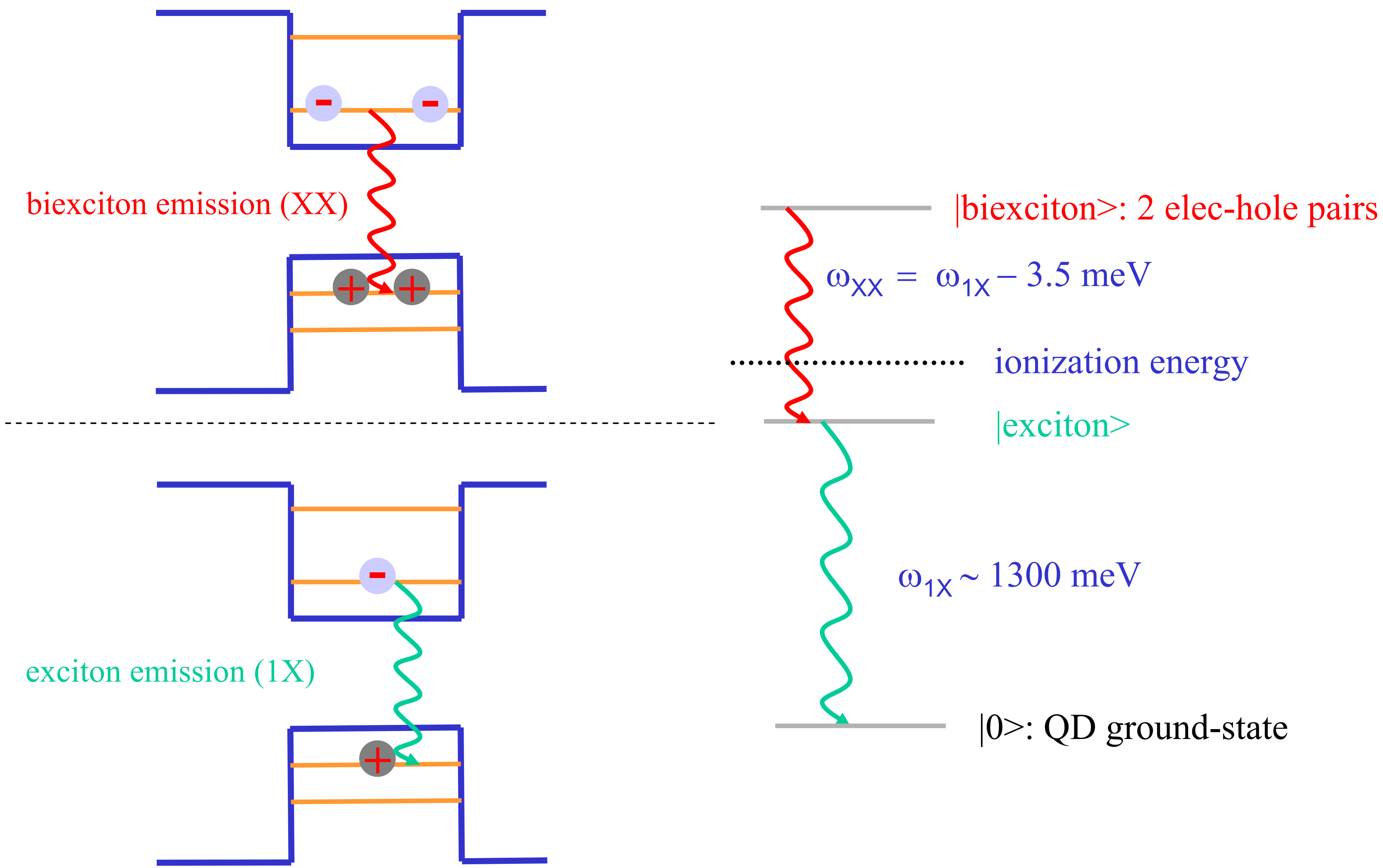
15 W/cm²
$g^2(0)=0.0$
τ = 3.6 ns

PL spectrum



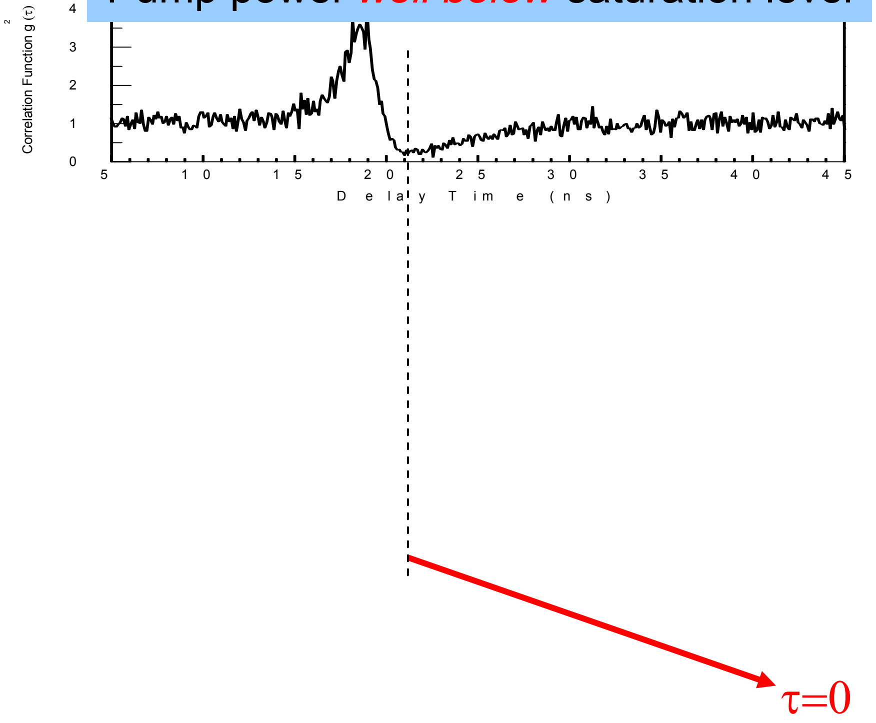
⇨ Proof of atom-like behaviour

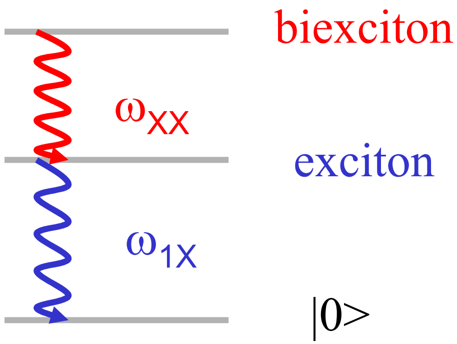
Higher-order optical excitations in a quantum dot

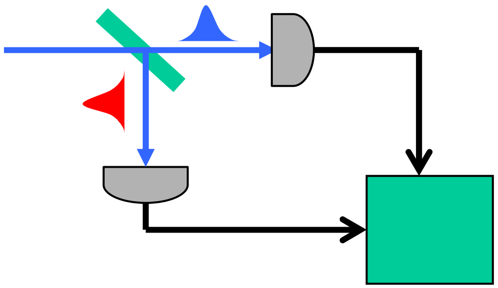


Exciton/biexciton (X1/XX) cross-correlation

Pump power *well below* saturation level







⇨At low excitation regime (average number of excitons < 1):

When a biexciton is observed, the QD projected is onto X1 state; as a result observation of an X1 photon becomes more likely than it is on average ⇒ ***bunching***

⇨Photons emitted in a biexciton cascade are polarization-entangled

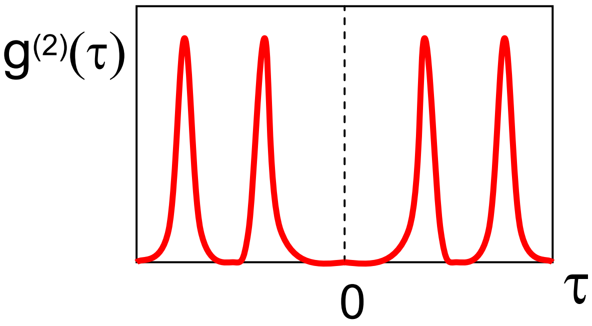
Signature of a single-photon source

- Intensity (photon) correlation function:

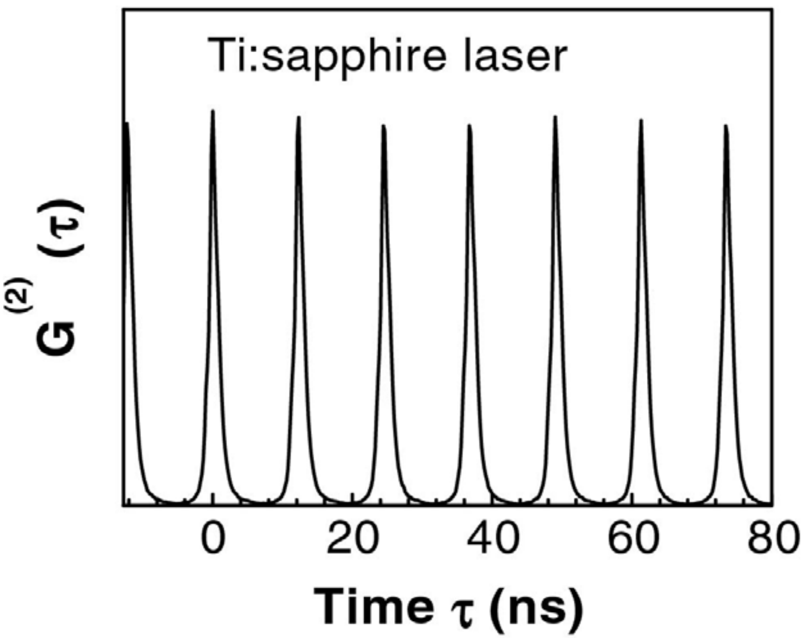
  $\rightarrow$ gives the likelihood of a second photon detection event at time t+τ, given an initial one at time t (τ=0).

$$g^{(2)}(\tau) = \frac{\langle : I(t) I(t+\tau) : \rangle}{\langle I(t) \rangle^2}$$

- <u>Triggered single photon source</u>: absence of a peak at τ=0 indicates that none of the pulses contain more than 1 photon.

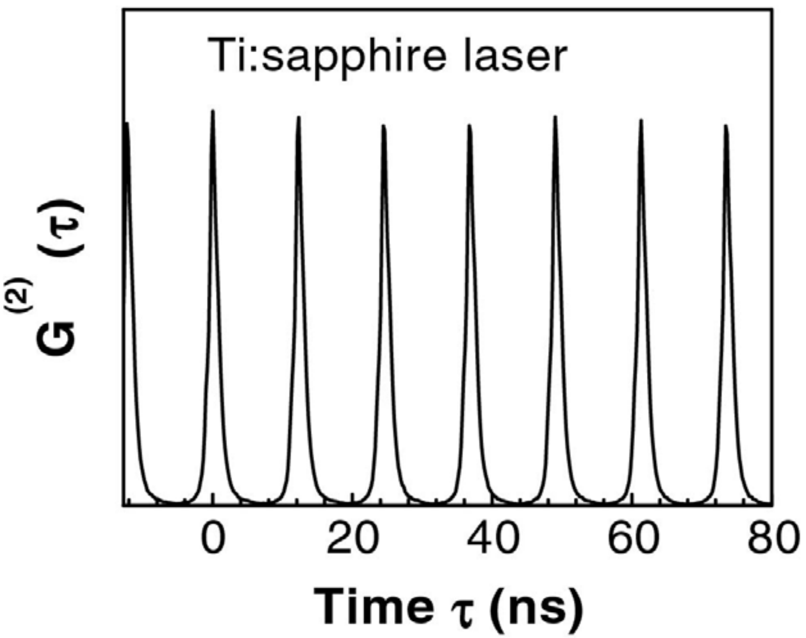


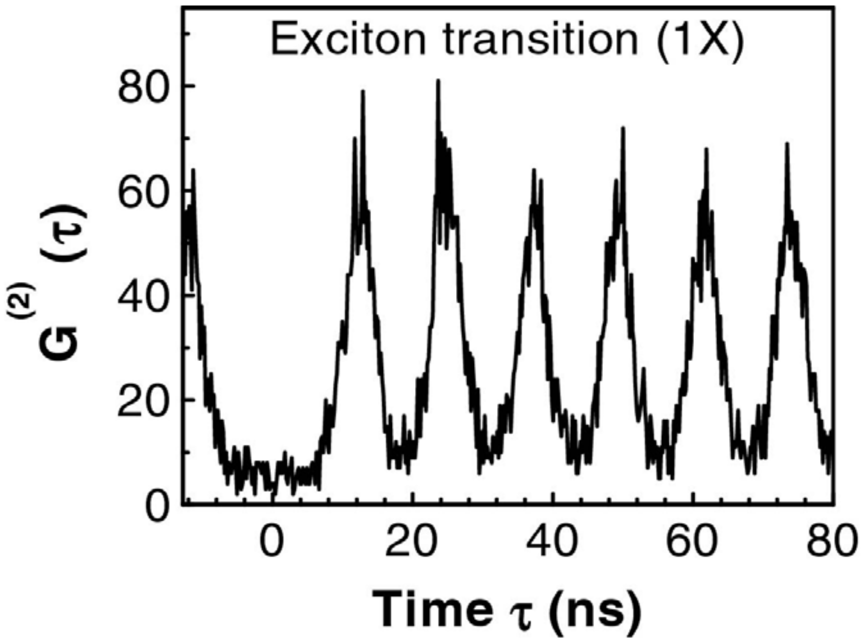
Single QD driven by a pulsed laser



➔ all peaks in $G^{(2)}(\tau)$ have the same intensity, including the one at $\tau=0$
➔ pulsed coherent light

Photon correlation of a single-photon source

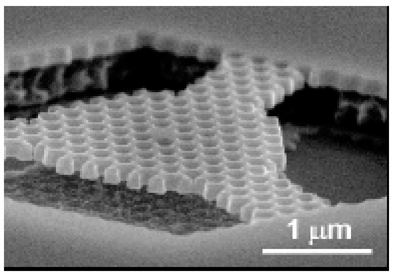




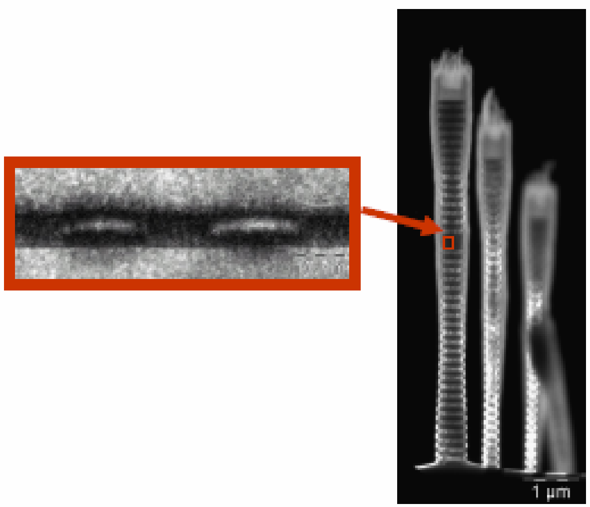
➔ all peaks in $G^{(2)}(\tau)$ have the same intensity, including the one at $\tau=0$
➔ pulsed coherent light

➔ the peak at $\tau=0$ disappears.
➔ single photon turnstile device with at most one photon per pulse

Single-photon sources: state-of-the-art
(I. Robert-Phillip and co-workers, LPN Paris)

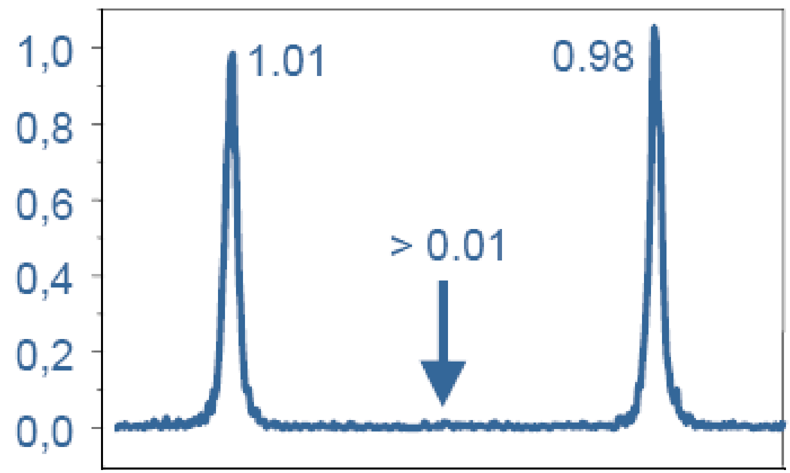


PC cavity enables large cavity-QD coupling



Micropillar cavity allows for well-collimated output: efficiency ~10%

Photon correlation measurements under pulsed excitation



Probability that any given pulse contains 2 or more photons is 1%

Why is it interesting to couple QDs to cavities?

- Near-unity collection efficiency of single photon sources
- Strong interactions between single photons mediated by a QD
- Cavity-mediated coupling between distant spins

Cavity Quantum Electrodynamics (cavity-QED)

- Single two-level (anharmonic) emitter coupled to a single cavity mode is described by the Jaynes-Cummings (JC) Hamiltonian

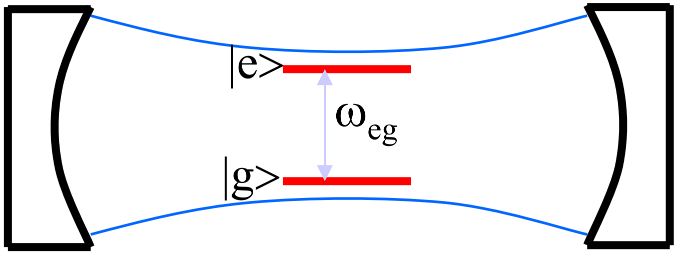
$$H_{JC} = \hbar\omega_{eg}\sigma_{ee} + \hbar\omega_c a_c^+ a_c + \hbar g_c(\sigma_{eg} a_c + a_c^+ \sigma_{ge})$$

An exactly solvable model

- ω_{eg} : emitter frequency
- ω_c : cavity frequency
- g_c : cavity-emitter coupling strength

In all optical realizations:

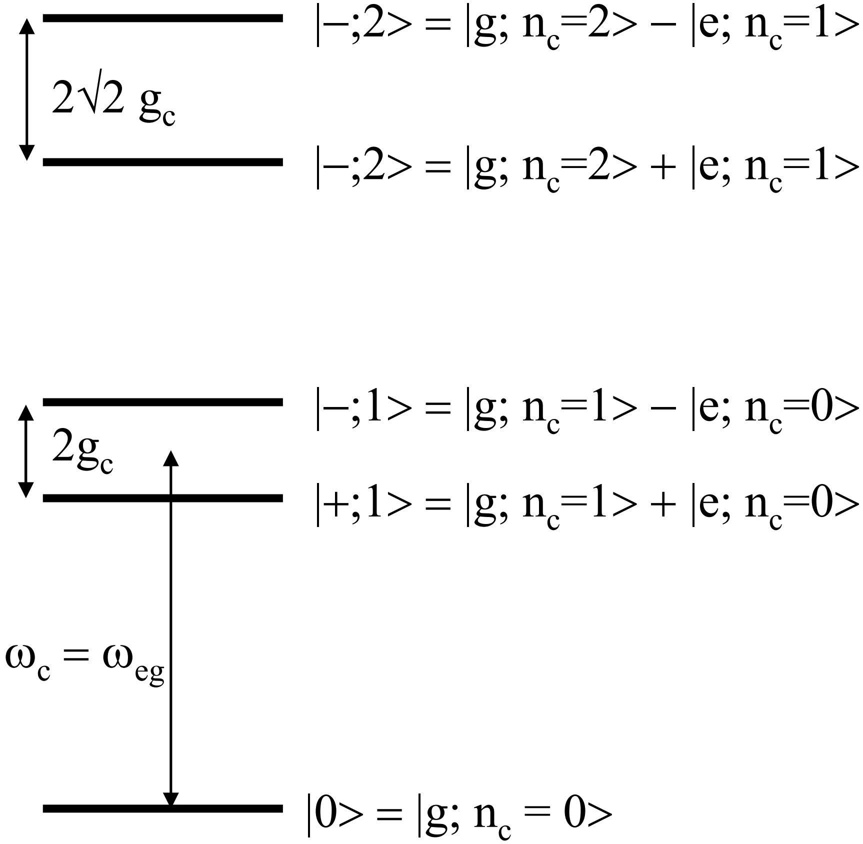
g_c	$<<$	ω_c	$\approx$	ω_{eg}
10^{10}		10^{15}		10^{15}



For electric-dipole coupling:

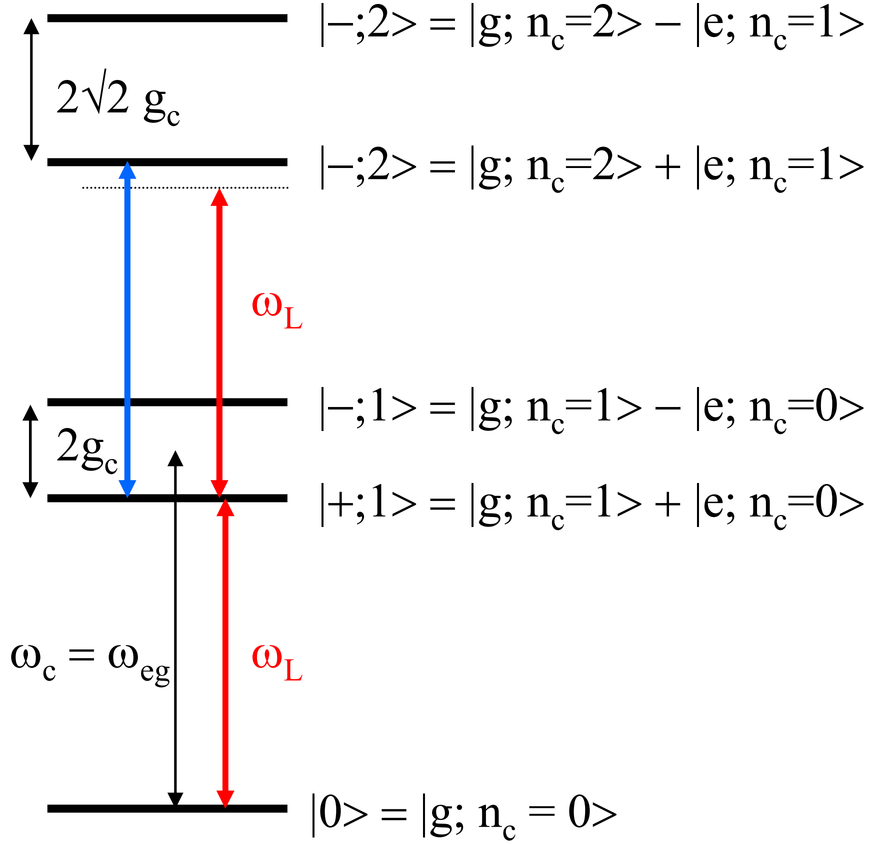
$$\hbar g_c = \left(\frac{\hbar\omega}{2\varepsilon_0 \varepsilon V}\right)^{1/2} e \langle e| \boldsymbol{\varepsilon}.\mathbf{r} |g\rangle$$

Eigenstates of the JC Hamiltonian



- The eigenstates of the coupled system are entangled emitter-cavity states
- The spectrum is anharmonic: the nonlinearity of the two-level emitter ensures that the coupled system is also anharmonic.

Eigenstates of the JC Hamiltonian



- The eigenstates of the coupled system are entangled emitter-cavity states
- The spectrum is anharmonic: the nonlinearity of the two-level emitter ensures that the coupled system is also anharmonic.

Ex: A laser (ω_L) that is resonant with the |0>-|+;1> transition will be off-resonant with all other transitions; the emitter-cavity molecule may act as a two-level system.

$\Rightarrow$ Single photon blockade!

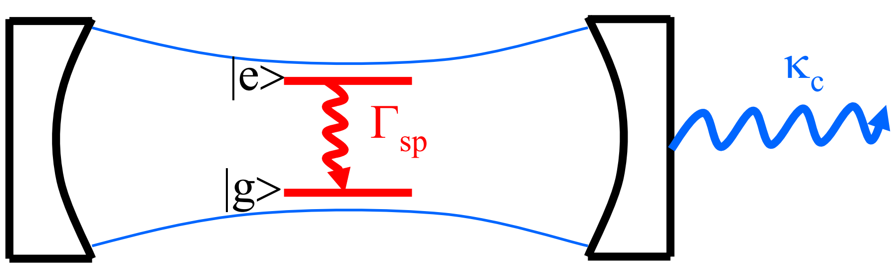
Dissipative cavity-emitter coupling: an open quantum system

- Single two-level (anharmonic) emitter coupled to a single cavity mode is described by the non-Hermitian JC Hamiltonian

$$\tilde{H}_{JC} = \hbar\omega_{eg}\sigma_{ee} + \hbar\omega_c a_c^+ a_c + \hbar g_c(\sigma_{eg}a_c + a_c^+\sigma_{ge})$$
$$-i\frac{\hbar}{2}\Gamma_{sp}\sigma_{ee} - i\frac{\hbar}{2}\kappa_c a_c^+ a_c$$

+ noise terms describing quantum jumps associated with spontaneous emission and cavity decay processes.

≡ description using a markovian master equation



<u>Purcell regime</u>: $g_c^2 >> \kappa_c \Gamma_{sp}$

<u>Strong coupling</u>: $g_c > \frac{\Gamma_{sp}}{4}, \frac{\kappa_c}{4}$

Quantum dots as two-level emitters in cavity-QED

- Quantum dots do not have random thermal motion and they can easily be integrated in nano-scale cavities.
- Just like atoms, quantum dots have nearly spontaneous emission broadened emission lines.
- Exciton transition oscillator (dipole) strength ranges from 10 to 100 (depending on the QD type) due to a collective enhancement effect.

- QDs nucleate in random locations during molecular beam epitaxy growth;
- The size and hence the emission energy of each QD is different; the standard deviation in emission energy is ~50 meV.

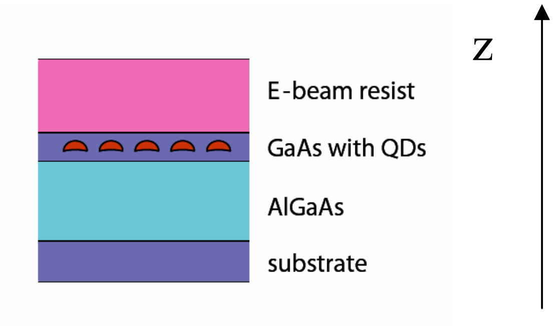
$\Rightarrow$ **Obtaining spatial and spectral overlap between the QD and the cavity electric field is a major challenge.**

Light confinement in photonic crystals

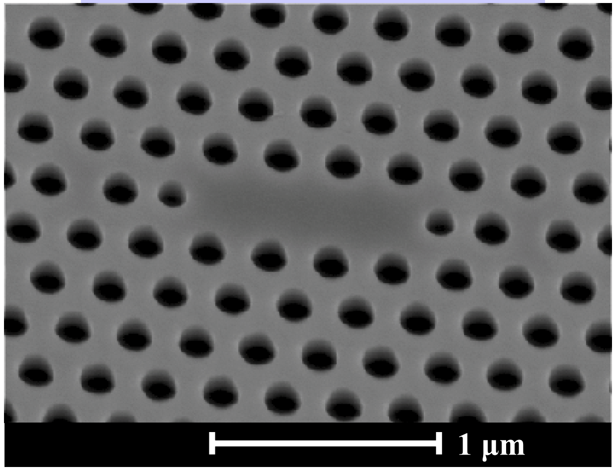
- A photonic crystal (PC) has a periodic modulation in dielectric constant and modifies the dispersion relation of electromagnetic fields to yield allowed energy bands for light propagation. For certain crystal structures there are band-gaps: light with frequency falling within these band-gaps cannot propagate in PCs.
- A defect that disrupts the periodicity in a PC confines light fields (at certain frequencies) around that defect, allowing for optical confinement on length scales ~ wavelength.
- A two dimensional (2D) PC membrane/slab defect can confine light in all three dimensions: the confinement in the third dimension is achieved thanks to total internal reflection between the high index membrane and the surrounding low-index (air) region.

Note: Total internal reflection and mirrors based on periodic modulation of index-of-refraction are key ingredients in all solid-state nano-cavities.

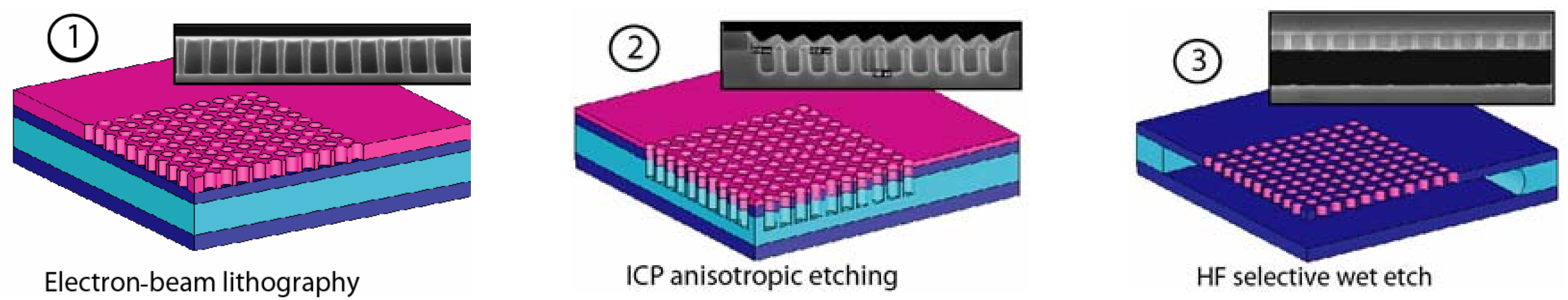
Photonic crystal fabrication



L3 defect cavity



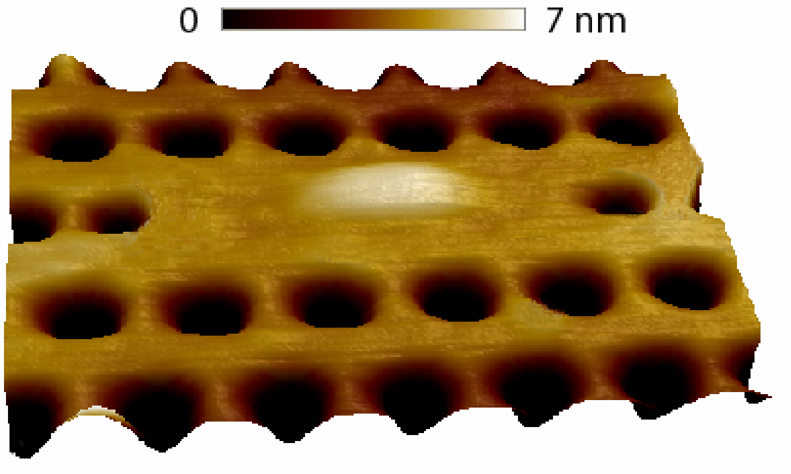
$Q \approx 2\times10^4$, $V_{eff} \approx 0.7\ (\lambda/n)^3$

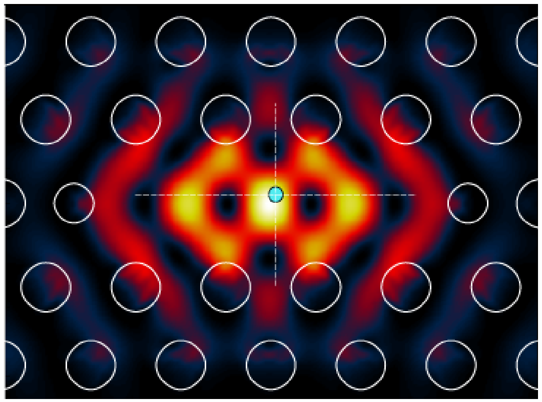


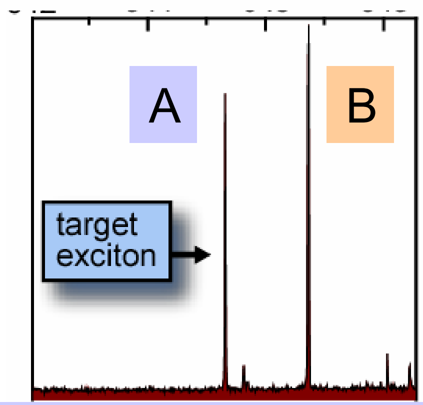
Best Q ~ Finesse value = 1,200,000 with $V_{eff} \approx (\lambda/n)^3$ (Noda)

A single quantum dot in an L3 cavity

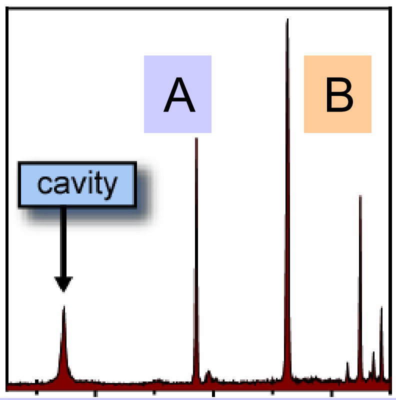
<u>Strategy</u>: first identify the QD location and emission energy; then fabricate the cavity







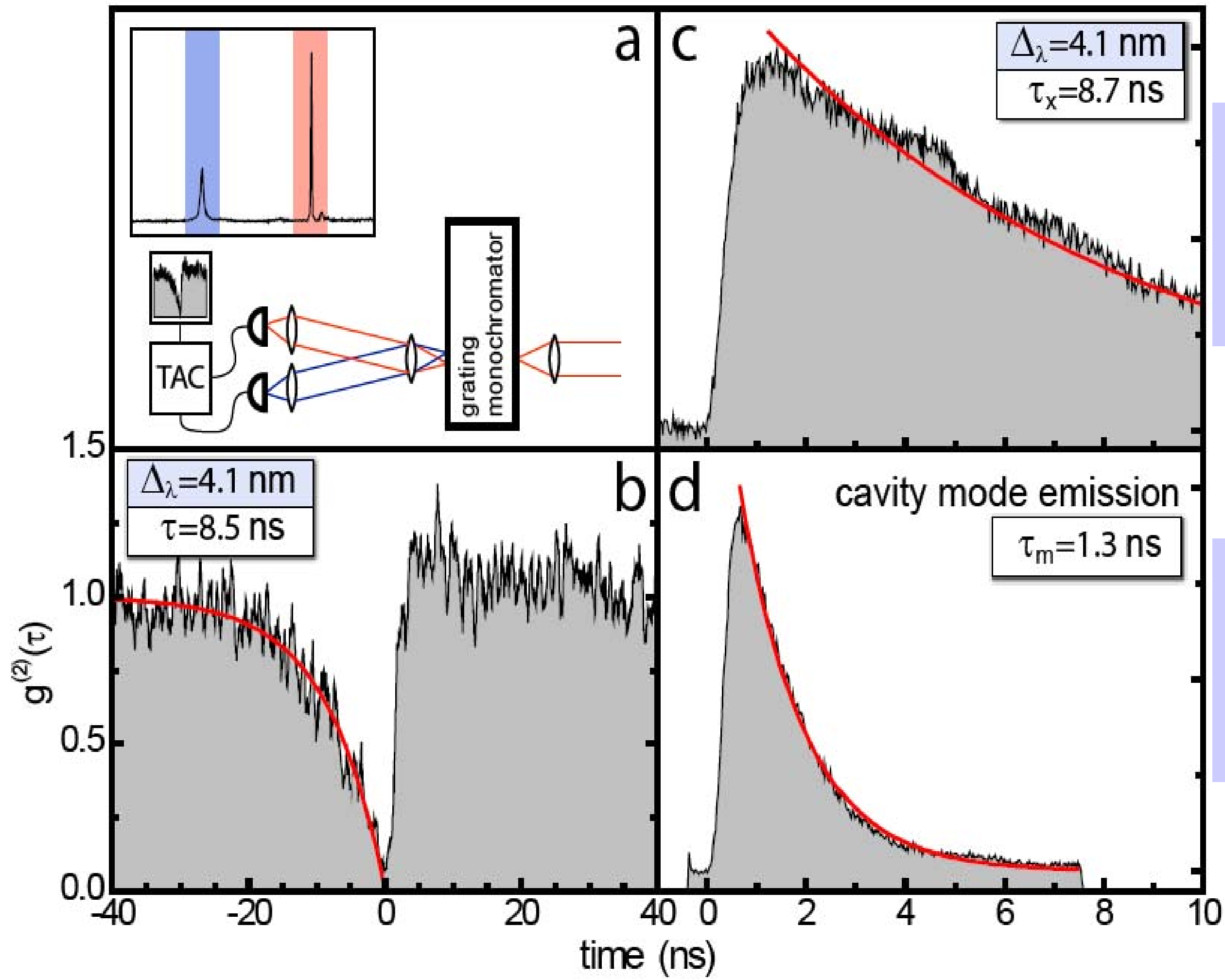
QD PL before PC fabrication



QD PL after PC fabrication

- We observe emission at cavity resonance (following QD excitation) even when the cavity is detuned by 4 nm (1.5 THz) !
- Control experiments with cavities containing no QDs (confirmed by AFM) or a QD positioned at the intra-cavity field-node yield no cavity emission.

Nonresonant coupling of the nano-cavity mode to the QD

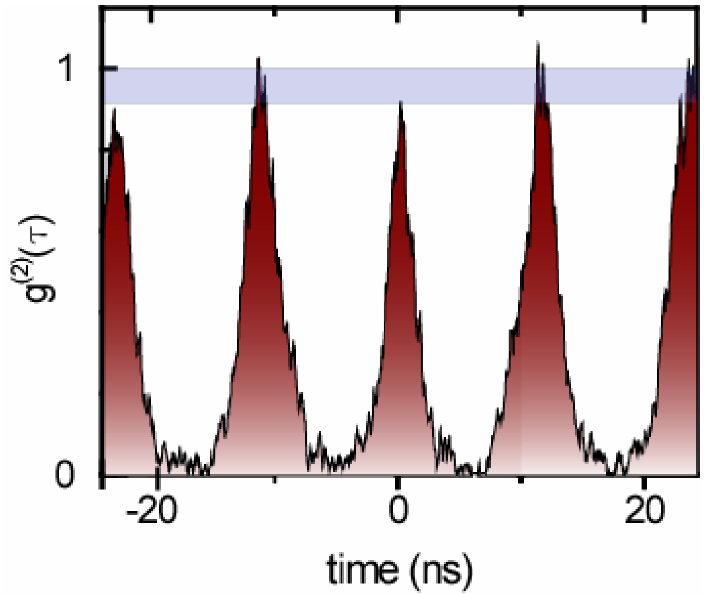


Off-resonance QD lifetime is prolonged by a factor of 10 due to photonic band-gap

Cavity emission lifetime is determined by the pump duration (cavity lifetime ~10 ps)

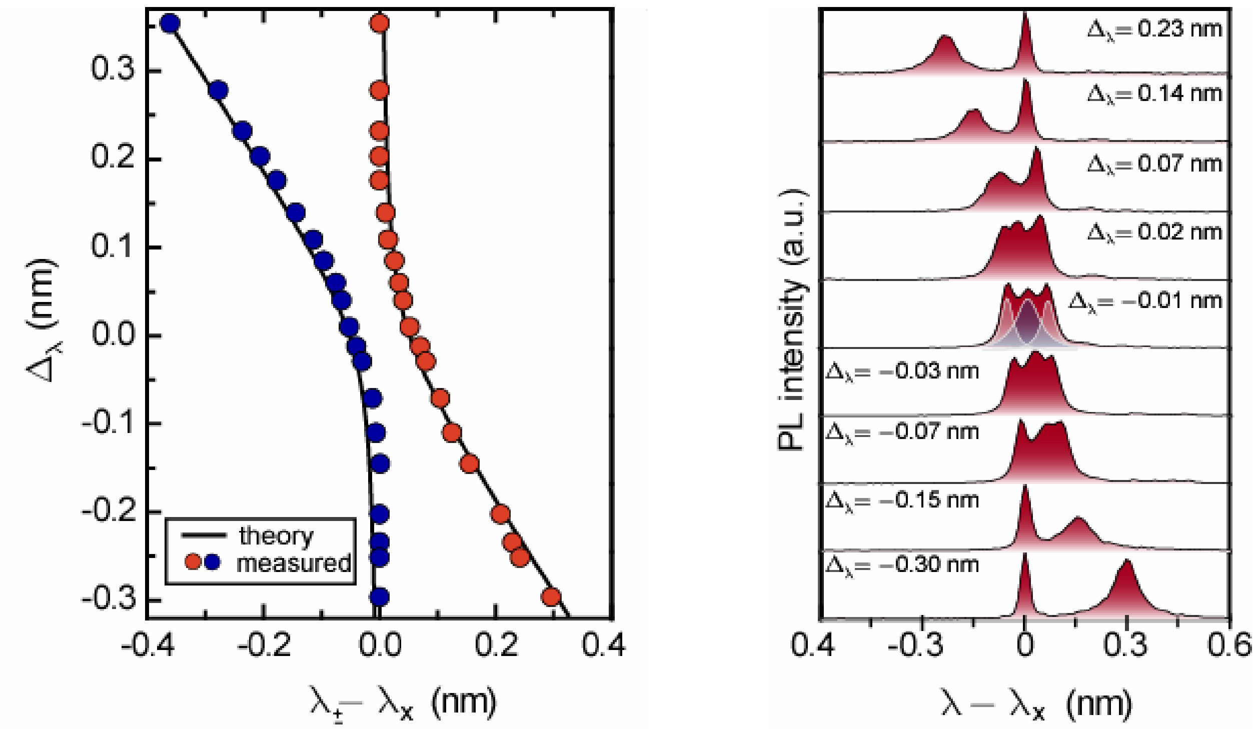
Strong photon antibunching in cross-correlation proves that the QD and cavity emission are quantum correlated.

Photon (auto)correlation of (detuned) cavity emission



⇒ Essentially Poissonian photon statistics despite the fact that cross-correlation with the exciton emission shows strong photon antibunching!

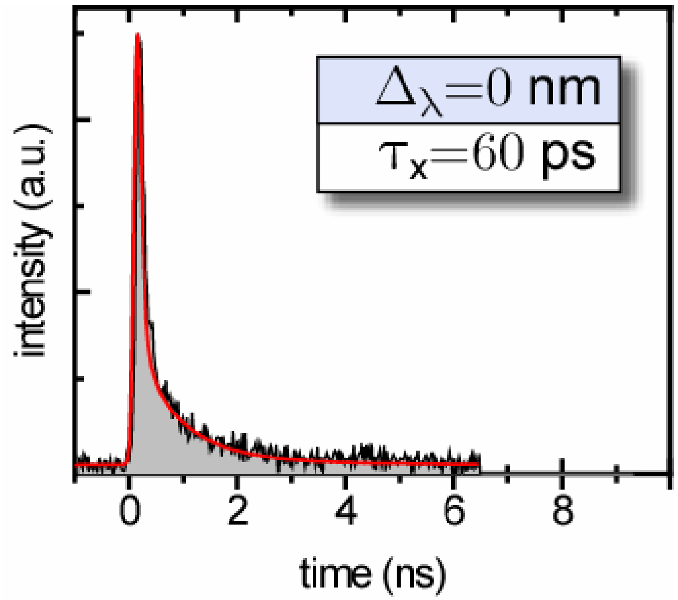
Observation of deterministic strong-coupling



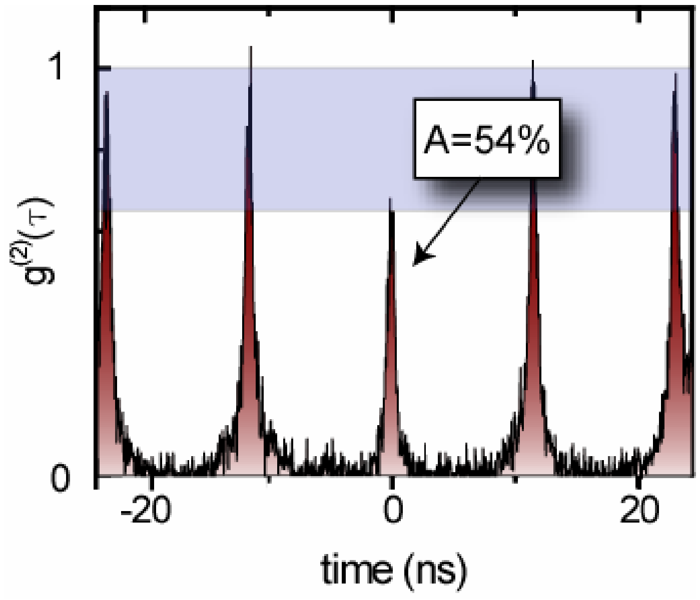
• Cavity tuning by waiting: the spectrum depicted above is aquired in ~30 hours, allowing us to carry out photon correlation and lifetime measurements at any given detuning.

• The center-peak on resonance is induced by cavity emission occuring when the QD is detuned due to defect-charging (and is emitting at the B-resonance).

Quantum correlations in the strong coupling regime

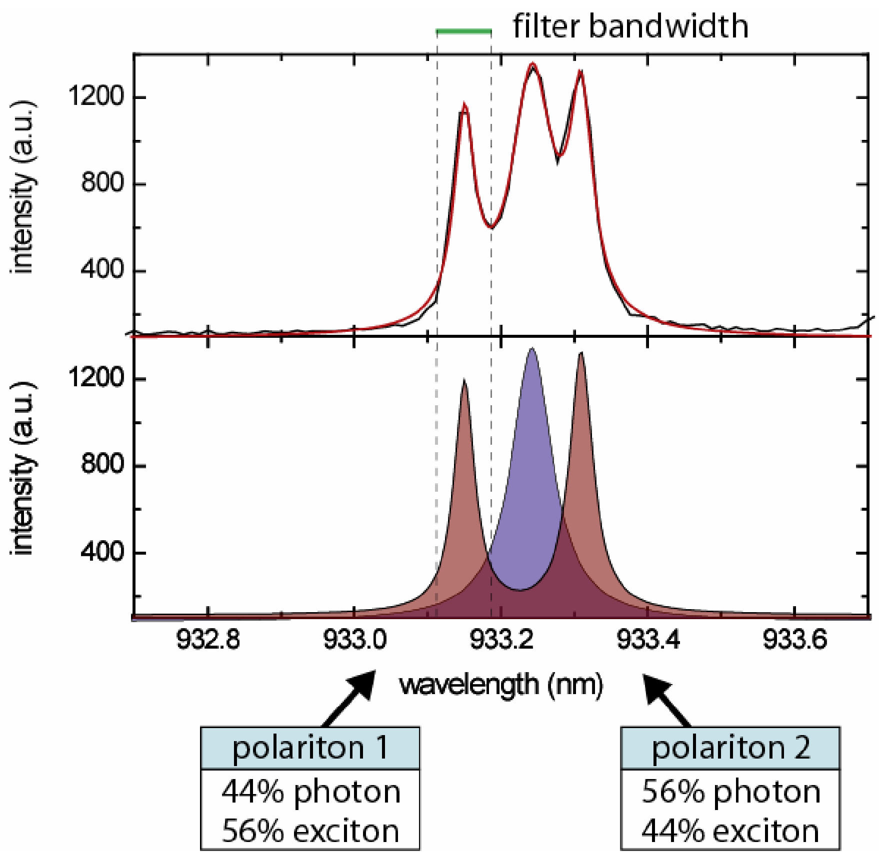


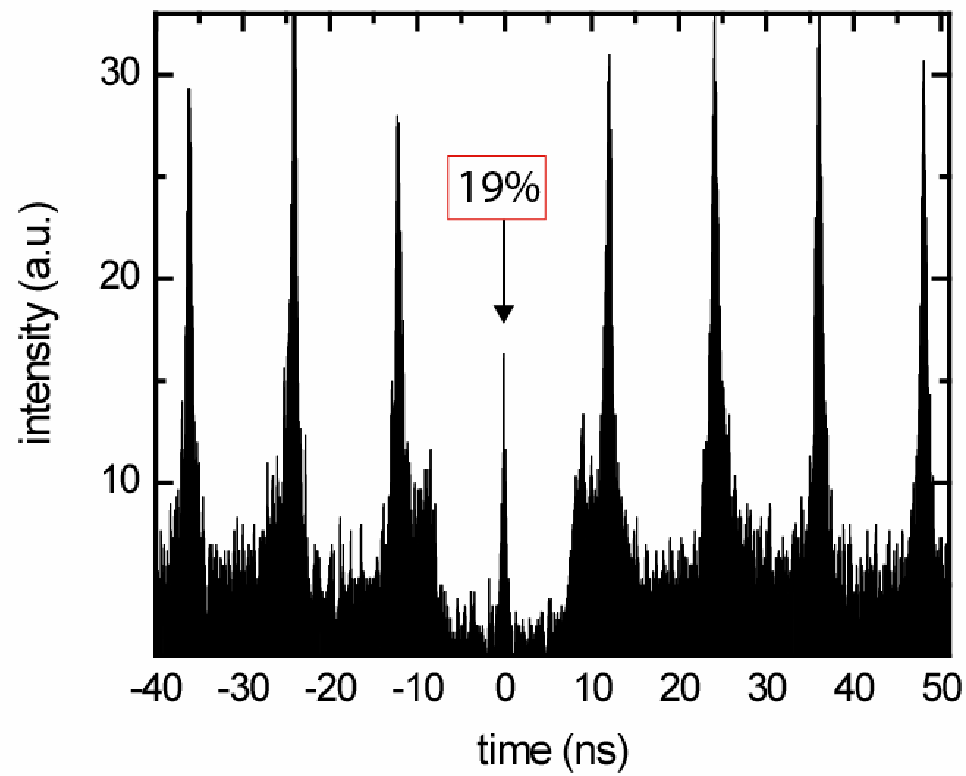
Emission lifetime is reduced by a factor of 120 on resonance



The combined PL from the 3 emission peaks on resonance exhibit photon antibunching.

Photon correlation from a single cavity-polariton peak
(data from another device exhibiting 25 GHz vacuum Rabi coupling)





⇒ Proof of the quantum nature of strongly coupled system

⇒ First step towards photon blockade

Comments/open questions

- It is possible to couple nano-cavities via waveguides defined as 1D defects in the PC (Vuckovic)
- High cavity collection efficiency to a high NA objective can be attained using proper cavity design or by using tapered-fiber coupling.
- It is possible to fine-tune cavity resonance using nano-technology (AFM oxidation, digital etching, N or Xe condensation).
- How does the cavity mode, detuned from the QD resonances by as much as 15 nm, fluoresce upon QD excitation?
- Why does the detuned cavity emission have Poissonian statistics while exhibiting strong quantum correlations with the exciton emission?