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COLLEGE ON

PHYSICS OF NANO-DEVICES

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Quantum optics using quantum dots

Presented by:

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Quantum optics using quantum dots

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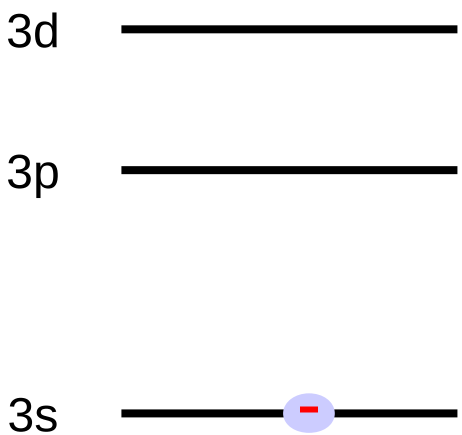
Outline

1) Brief overview of quantum dots – a.k.a. artificial atoms
2) Photon correlation measurements
3) Single photon sources

Atoms

- The allowed internal energy states (describing the relative motion of electrons with respect to a nucleus) form a discrete anharmonic set.
- Each discrete atomic orbital has a fine and hyperfine structure arising from the coupling of electronic spin to orbital angular momentum and electronic spin to nuclear spin, respectively.
- The eigenstates describing the center-of-mass motion of a free atom form a continuum; internal & external degrees of freedom could be coupled via light forces $\Rightarrow$ optical trapping.

<u>Ex</u>. sodium



Each atomic orbital consists of a number of discrete states:

<u>Ex</u>.: 3s $\Rightarrow$ 8 distinct eigenstates due to coupled electron (2) and nuclear (4) spin states.

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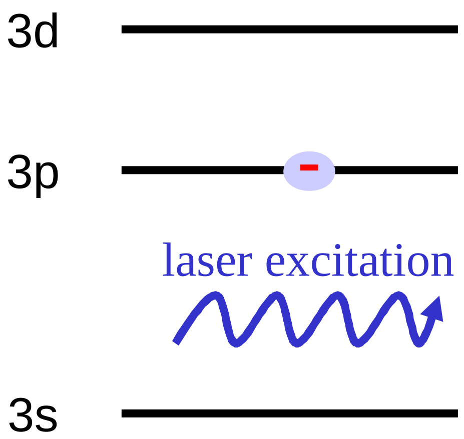

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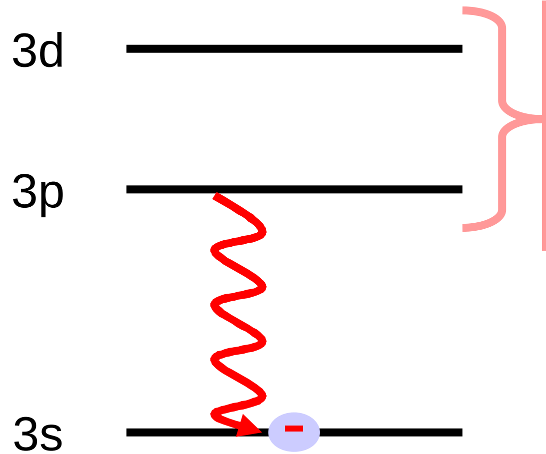
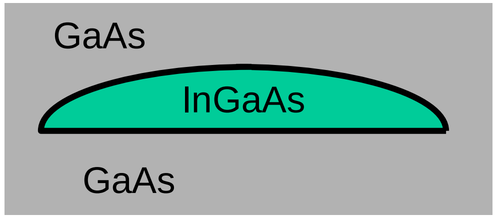
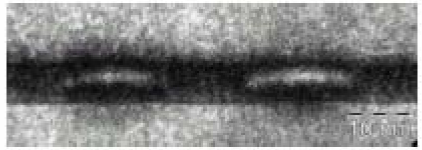
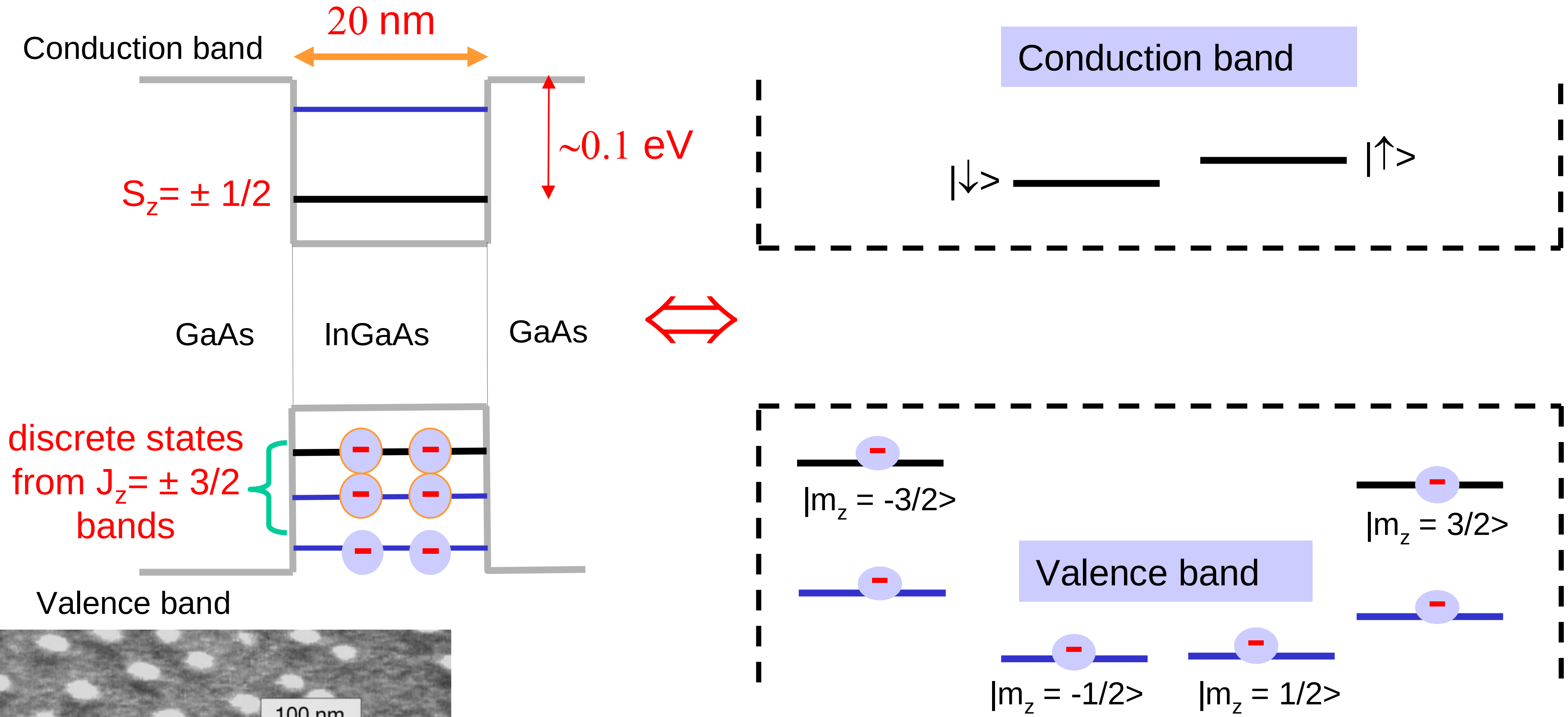


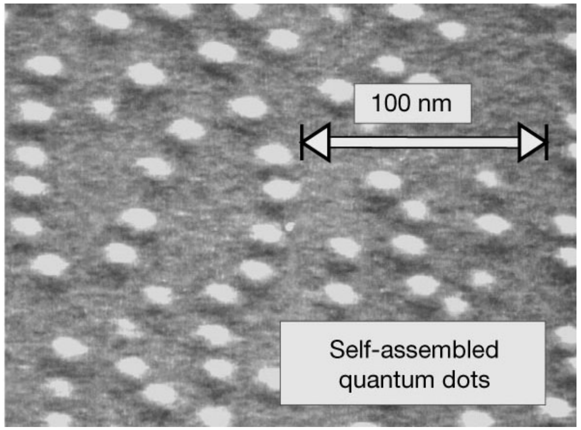
All excited states are broadened in energy due to spontaneous emission: the absorption/emission lineshape is a Lorentzian.



Quantum dots (QD)



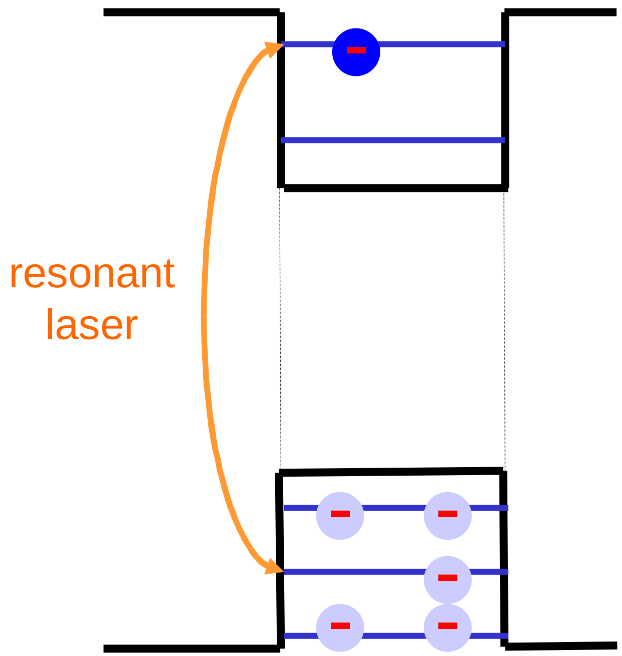




- QDs have discrete states for electrons & holes.
- QD location is fixed in a macroscopic crystal by growth.
- There are ~10^5 atoms in each QD.

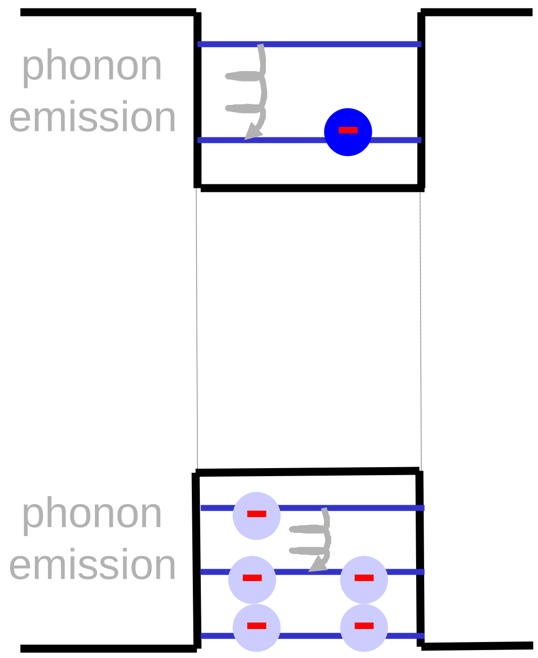
Light generation by a quantum dot

a) Optical excitation of an electron



Light generation by a quantum dot

b) Relaxation by phonon emission (~10 ps)



Light generation by a quantum dot

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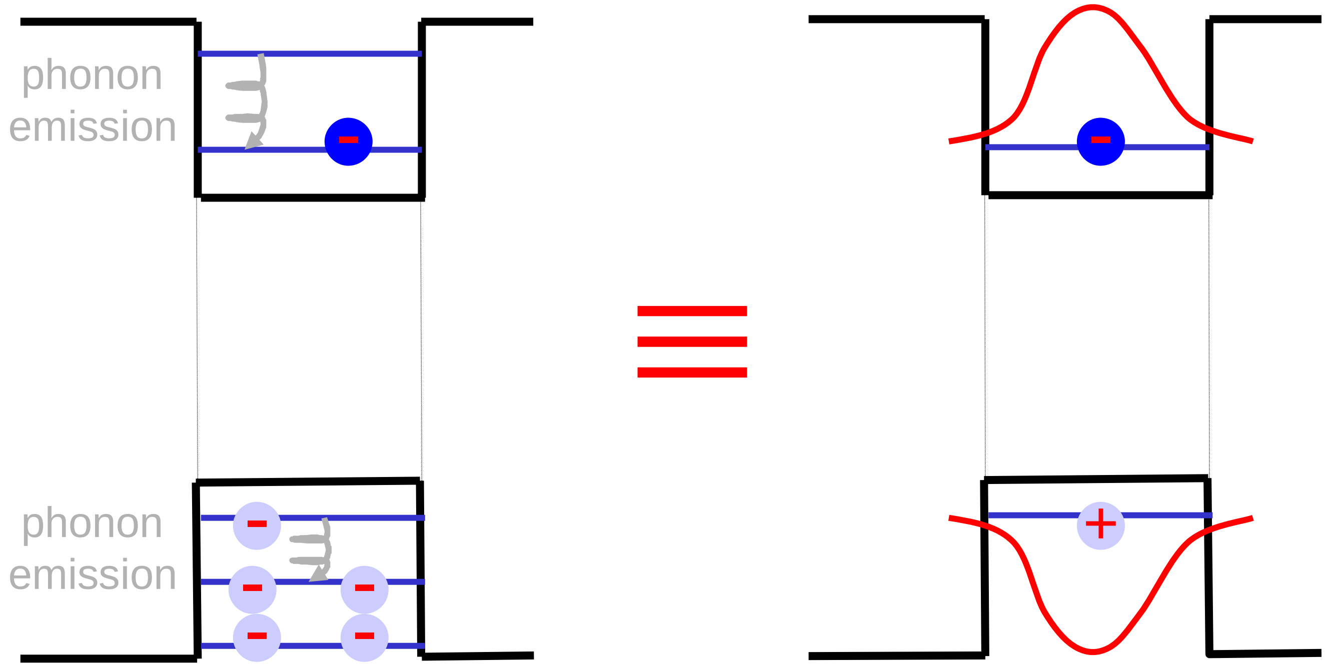
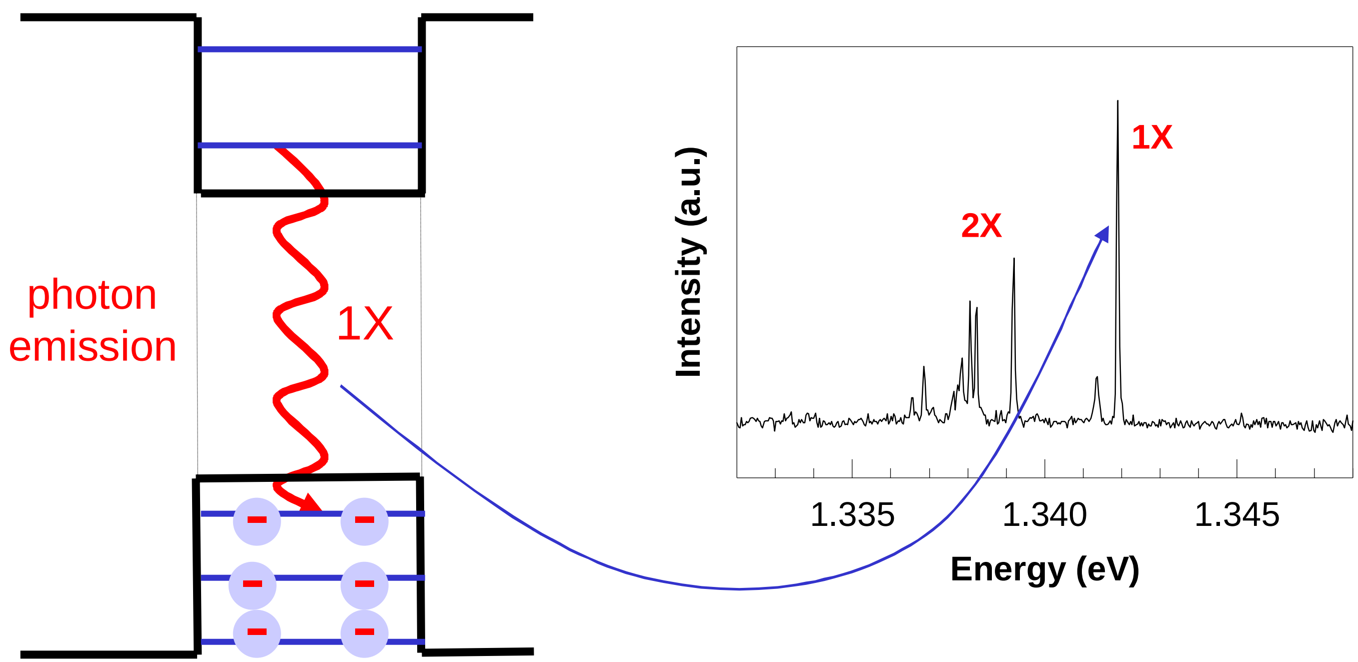


electron-hole pair = exciton

Light generation by a quantum dot

c) Emission of a photon (~1 ns)	Spectrum of emitted photons

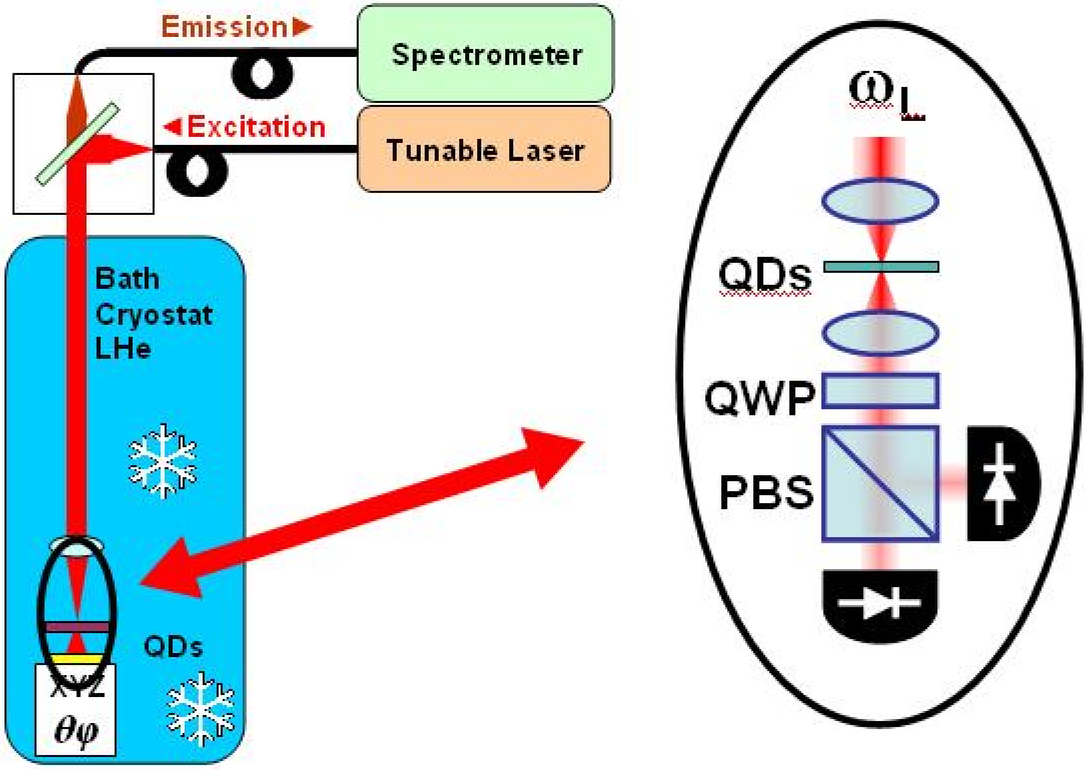


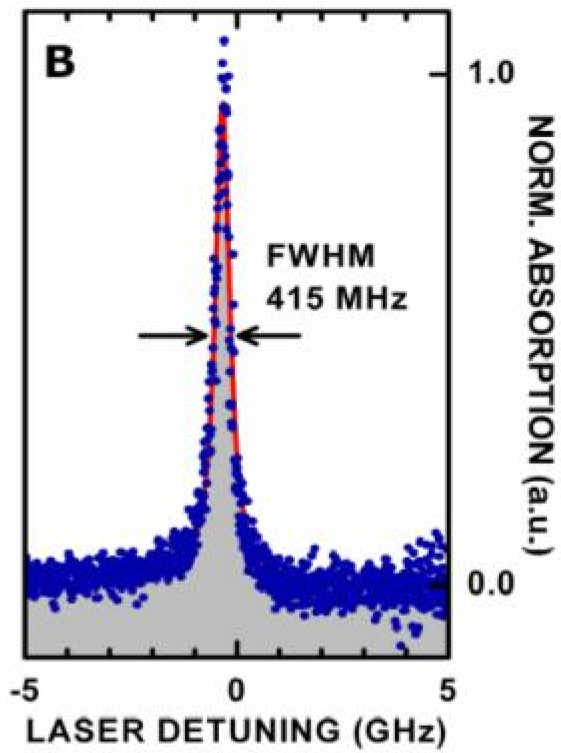
⇒ QDs typically exhibit several sharp emission lines

⇒ At low pump power, a single (exciton) line dominates the spectrum; the width of this line is resolution limited at ~ 30 μeV << kT ~ 300 μeV.

How narrow are quantum dot exciton lines?

- The least perturbing measurement that can be done is a resonant absorption measurement





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

Photon correlation measurements

- 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 ($\tau=0$).

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

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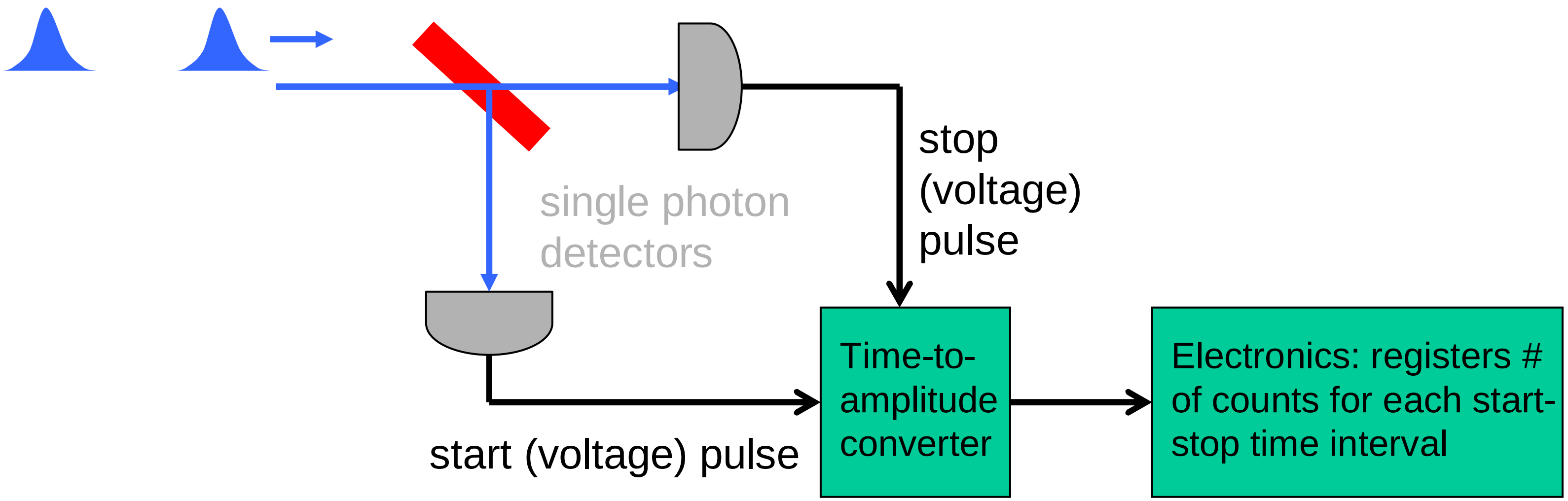
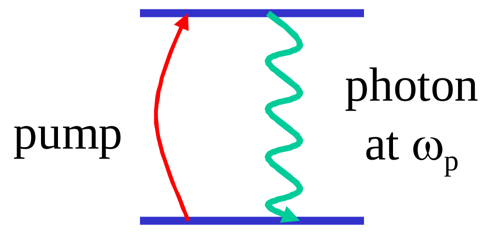
- Experimental set-up for photon correlation [$g^{(2)}(\tau)$] measurement:



Photon antibunching

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



• Assume that at $\tau=0$ 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

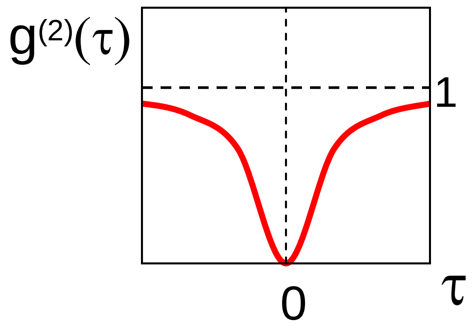
• If there are two or more 2-level emitters, detection of a photon at $\tau=0$ can not ensure that the system is in the ground state ($g^{(2)}(0) > 0.5$).

Signature of photon antibunching

- Intensity (photon) correlation function:

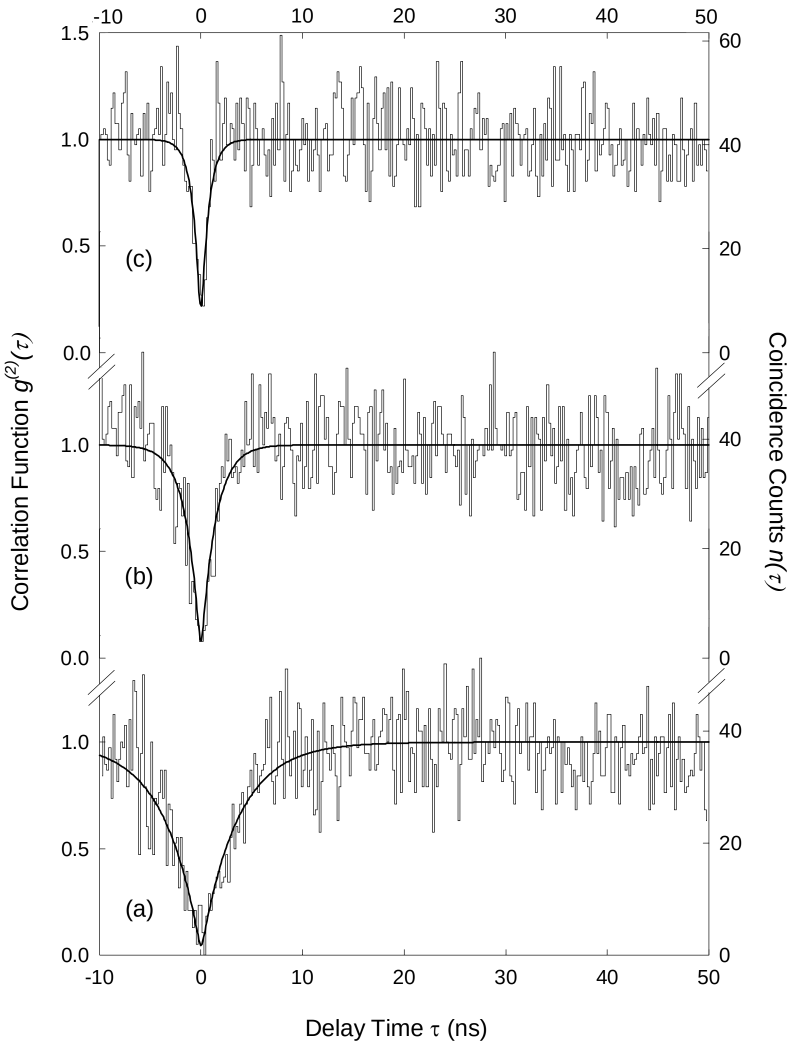
$$g^{(2)}(\tau) = \frac{\langle : I(t) I(t+\tau) : \rangle}{\langle I(t) \rangle^2}$$

- 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/cm^2

$g^2(0)$=0.1

τ = 750 ps

55 W/cm^2

$g^2(0)$=0.0

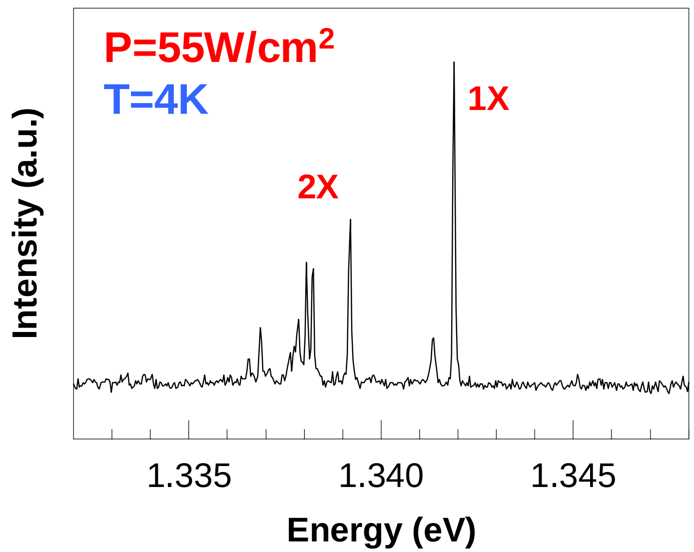
τ = 1.4 ns

15 W/cm^2

$g^2(0)$=0.0

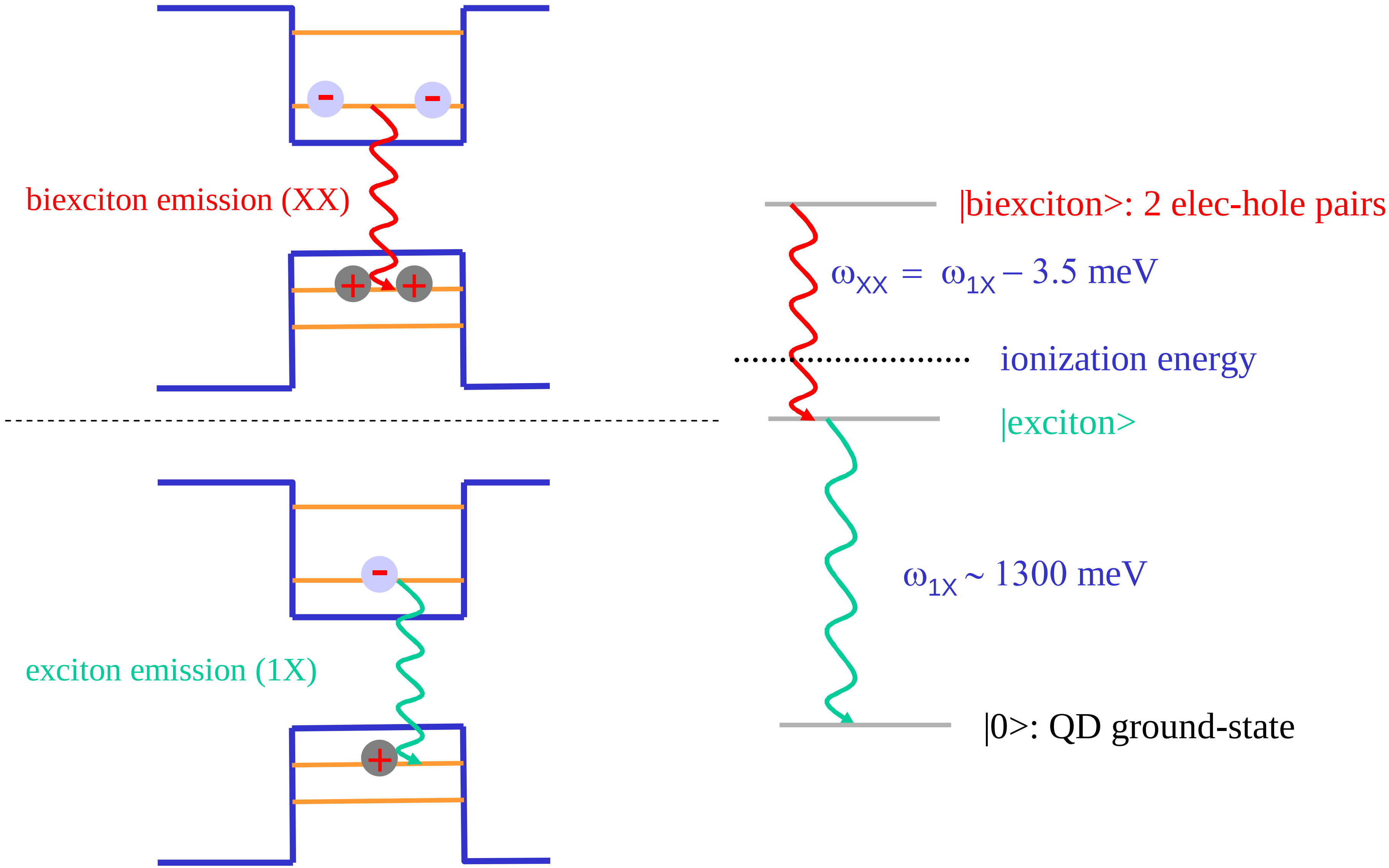
τ = 3.6 ns

PL spectrum



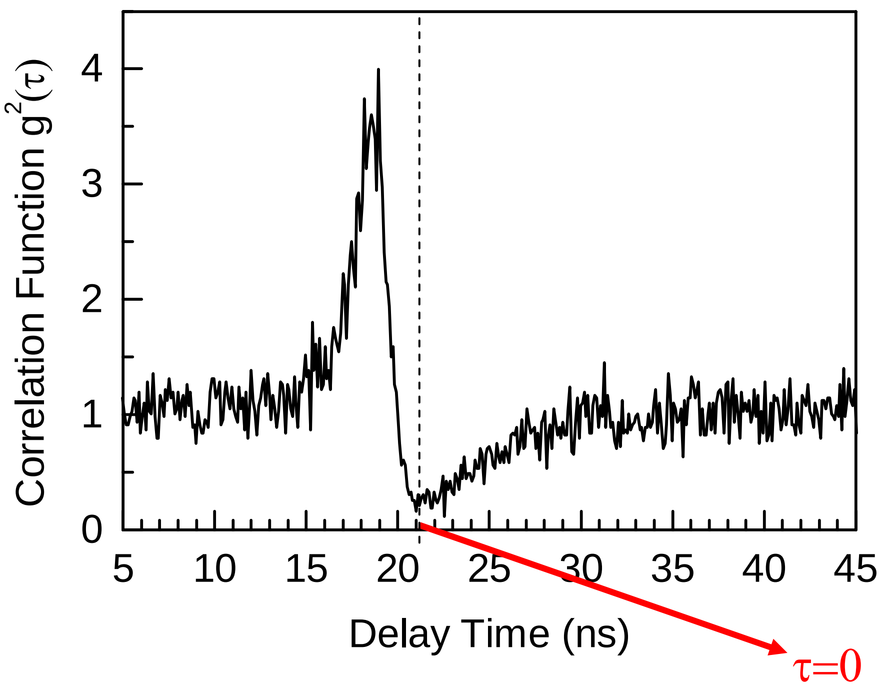
⇨ Proof of atom-like behaviour

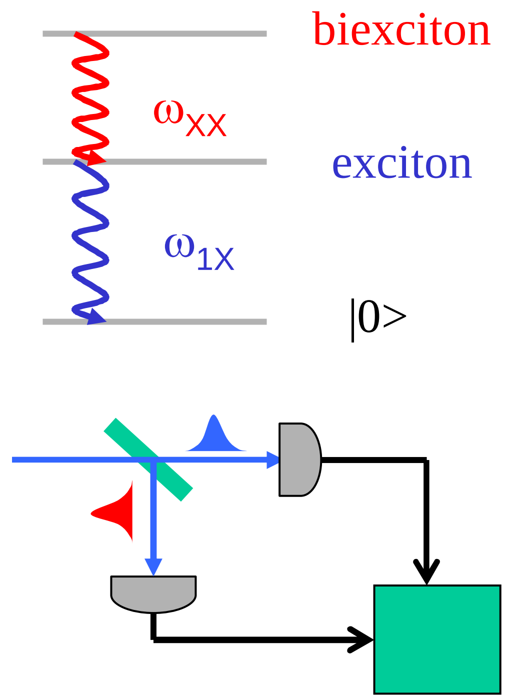
Higher-order optical excitations in a quantum dot



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***

Why quantum dots?

- 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.

- A single confined electron interacts weakly with ~ 10^5 nuclei; the nature of hyperfine interactions is completely different.
  - novel non-Markovian decoherence mechanism for electron spin
  - single electron controls an isolated mesoscopic (nuclear) spin ensemble.
- Interactions between electrons and lattice vibrations:
  - may enable optical manipulation of nano-mechanical systems.
- Kondo-type many-body effects between QD electron spin and the spins of a nearby electron reservoir (n-type region).

Single Photon Sources

A regulated sequence of optical pulses that contain one-and-only-one photon

$\Rightarrow$ Why are we interested in single-photon sources?

i) **Quantum communication**:

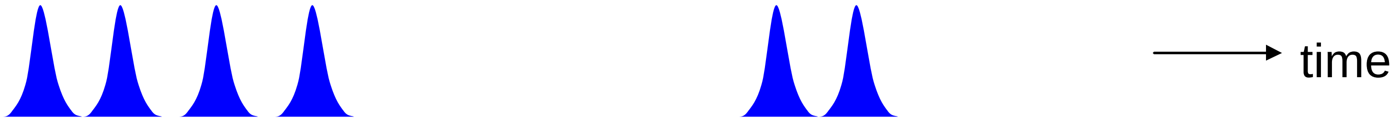
- key distibution in quantum cryptography

- quantum teleportation: transmission of quantum information without transmitting the physical qubit (which remains in an unknown state)

i) **Quantum computation**: single photons + linear optical elements + photo-detection can eliminate the need for photon-photon interactions.

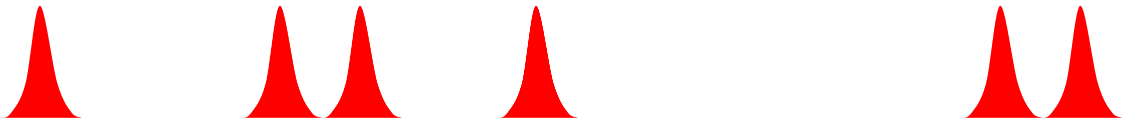
Typical light fields as a stream of photons

• thermal light
(light bulb)



⇒ Photons are bunched together giving rise to large (super Poissonian) fluctuations in detected energy per unit time.

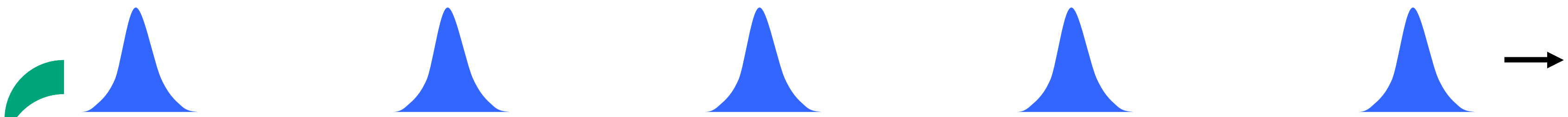
• coherent light
(laser)



⇒Photons are completely uncorrelated, giving rise to Poissonian photon detection events (shot noise in photo-current) – i.e. $\Delta n^2 = \langle n \rangle$.

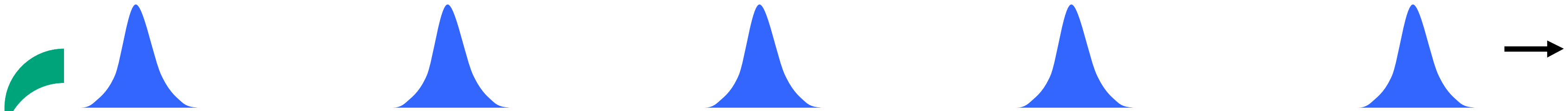
⇒Both thermal and coherent light correlations can be explained using <u>classical Maxwell's equations</u>.

Single Photon Sources



A regulated sequence of optical pulses that contain one-and-only-one photon

Single Photon Sources



A regulated sequence of optical pulses that contain one-and-only-one photon

⇒ How can we generate single photon pulses?

- An attenuated laser with average photon number per pulse <n> = 1 is <u>not</u> a single-photon source, since standard deviation $\Delta n = 1$.

- Photons generated by a <u>single quantum dot</u> driven by a periodic pump (i.e. laser or electrical current) realise a single photon source:

  <u>Proposal</u>: A. Imamoglu and Y. Yamamoto, Phys. Rev. Lett. **72**, 210 (1994)

  <u>Experiments</u>: P. Michler *et al*., Science **290**, 2282 (2000)
  Z. Yuan *et al*., Science **295**, 102 (2002)
  C. Santori *et al*., Nature **419**, 584 (2002)

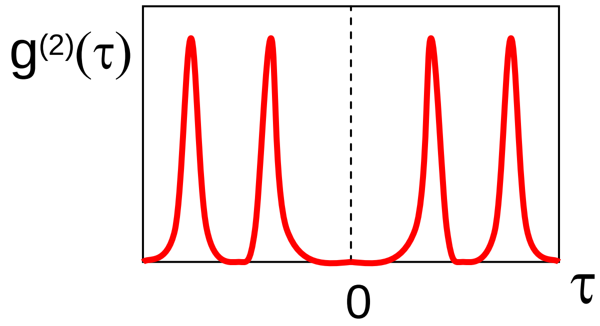
Signature of a single-photon source

- Intensity (photon) correlation function:

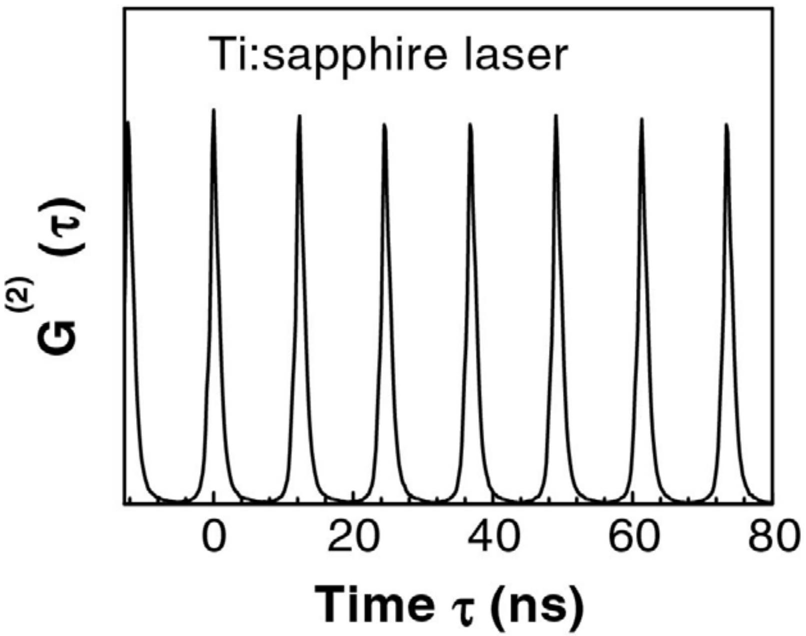
$$g^{(2)}(\tau) = \frac{\langle : I(t) I(t+\tau) : \rangle}{\langle I(t) \rangle^2}$$

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

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



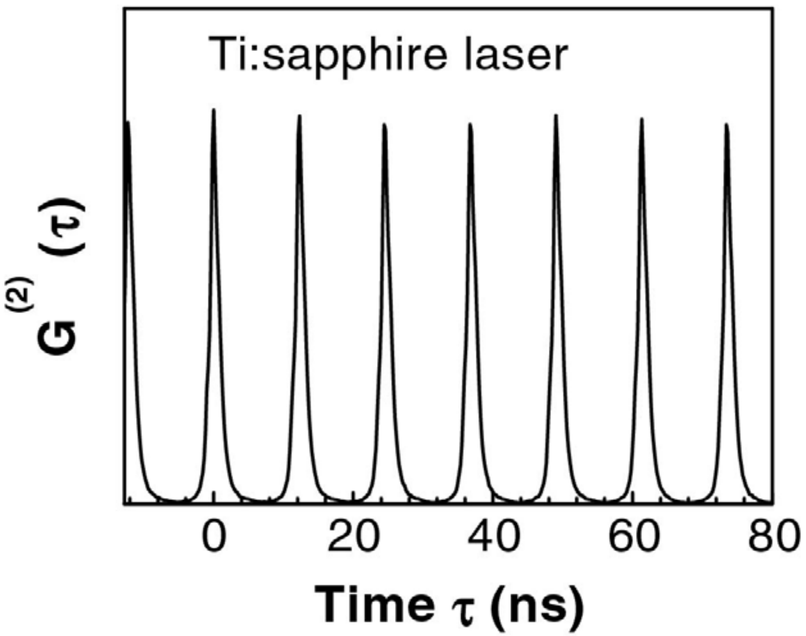
Single QD driven by a pulsed laser

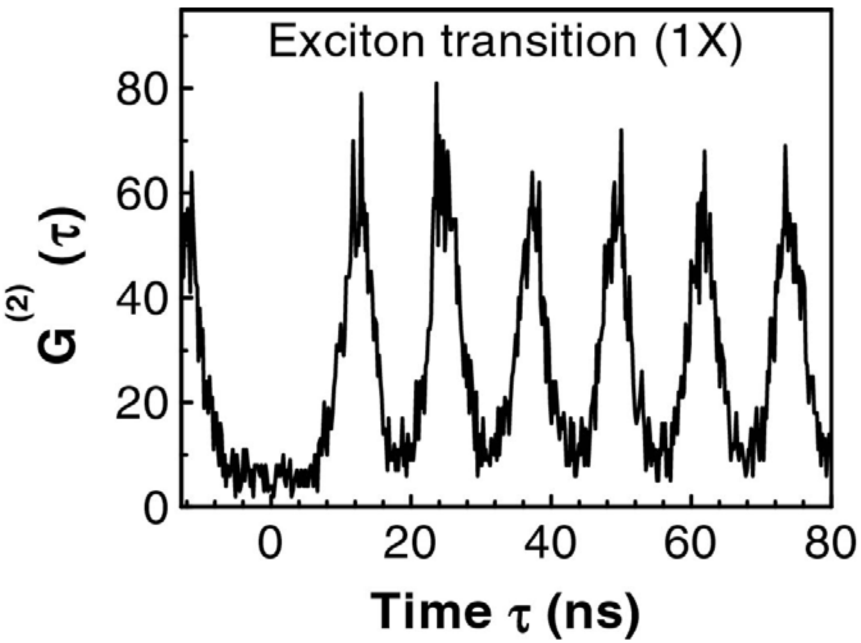


➔ all peaks in $G^{(2)}(\tau)$ have the same intensity, including the one at $\tau=0$

➔ pulsed coherent light

Photon correlation of a single-photon source





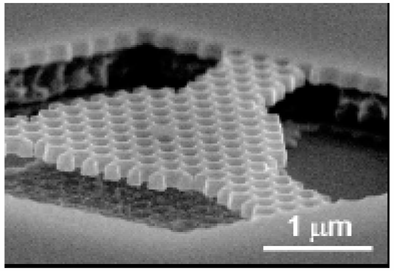
➔ all peaks in $G^{(2)}(\tau)$ have the same intensity, including the one at τ=0
➔ pulsed coherent light

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

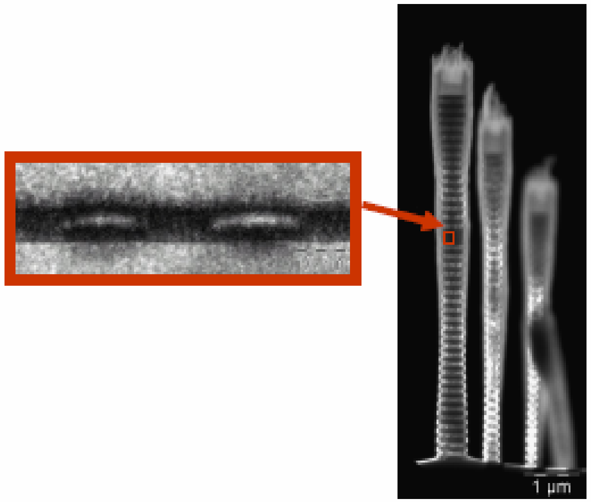
[P. Michler et al., Science **290**, 2282 (2000)]

Single-photon sources: state-of-the-art

(I. Robert-Phillip and co-workers, LPN Paris)

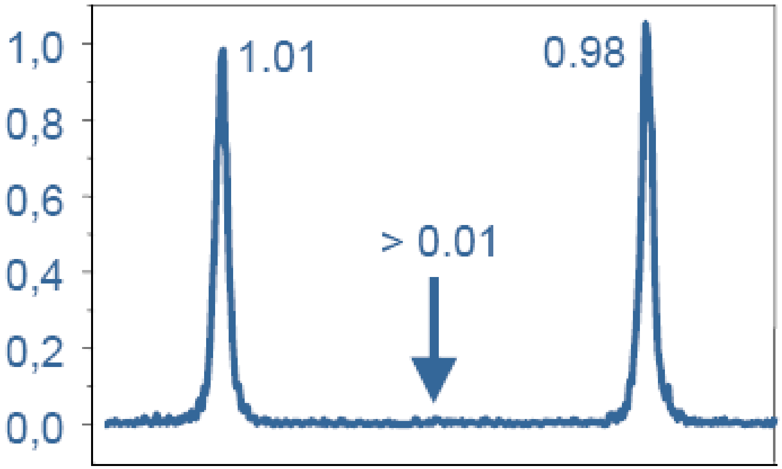


PC cavity enables large cavity-QD coupling



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

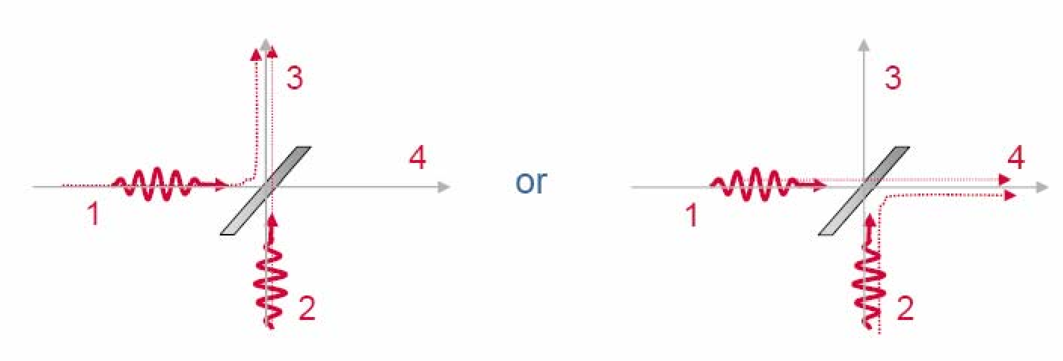
Photon correlation measurements under pulsed excitation

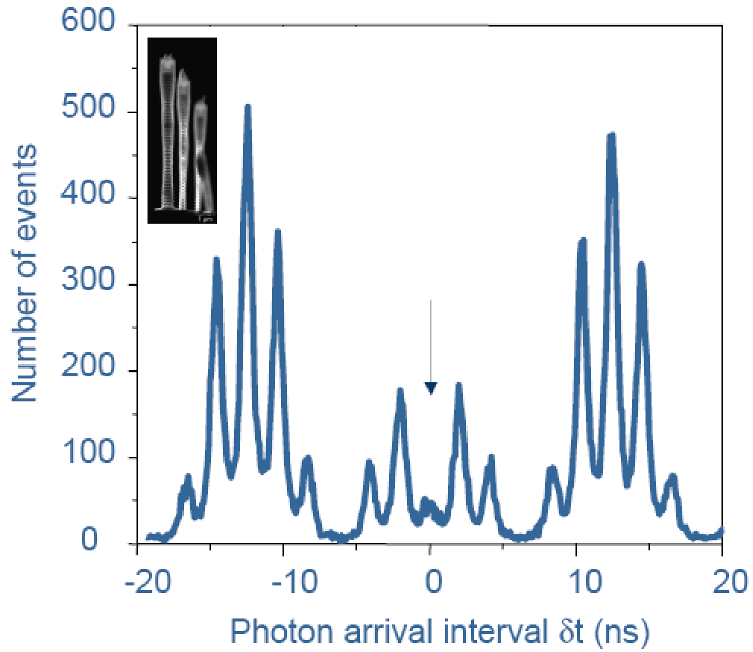


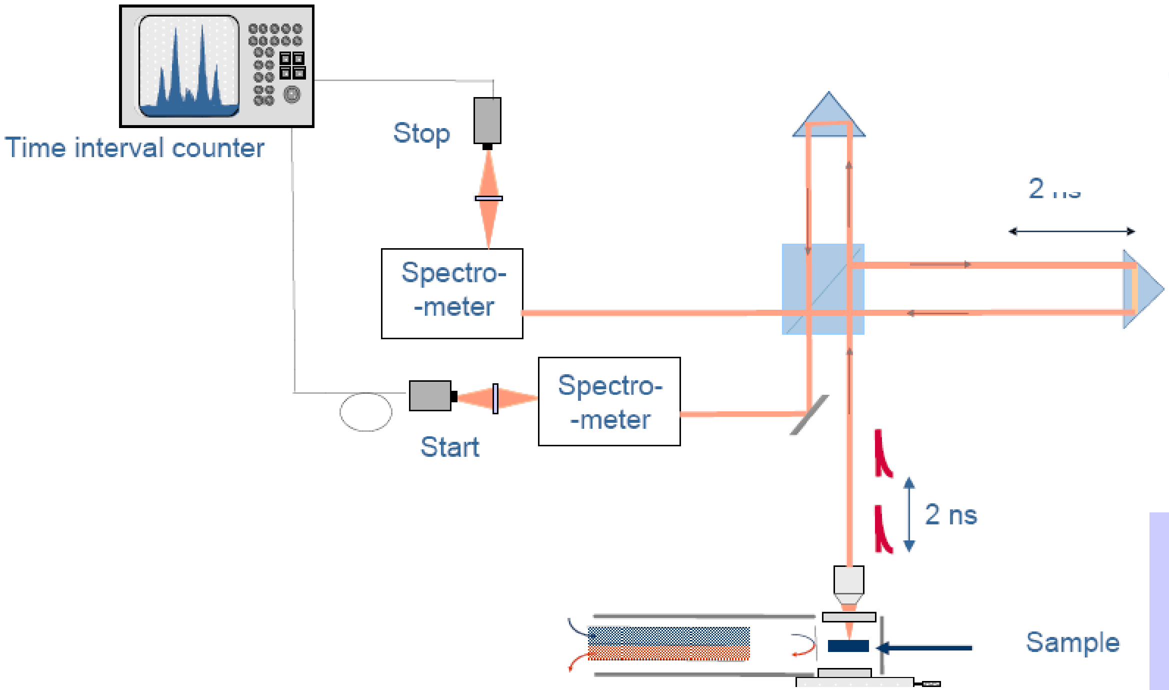
Probability that any given pulse contains 2 or more photons is 1%

Indistinguishable photons from a QD

(I. Robert-Phillip and co-workers, LPN Paris)







Degree of indistinguishability between successive photons: 75%

Key element in linear optics quantum information processing schemes

Future challenges

- Enhancing the efficiency of the single photon sources using cavities
- Generating indistinguishable photons from different quantum dots
- A quantum memory for the single photons