Dipartimento di Fisica
Sapienza
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Nanophotonics

SHINING LIGHT ON SEMICONDUCTOR QUANTUM DOTS

...literally

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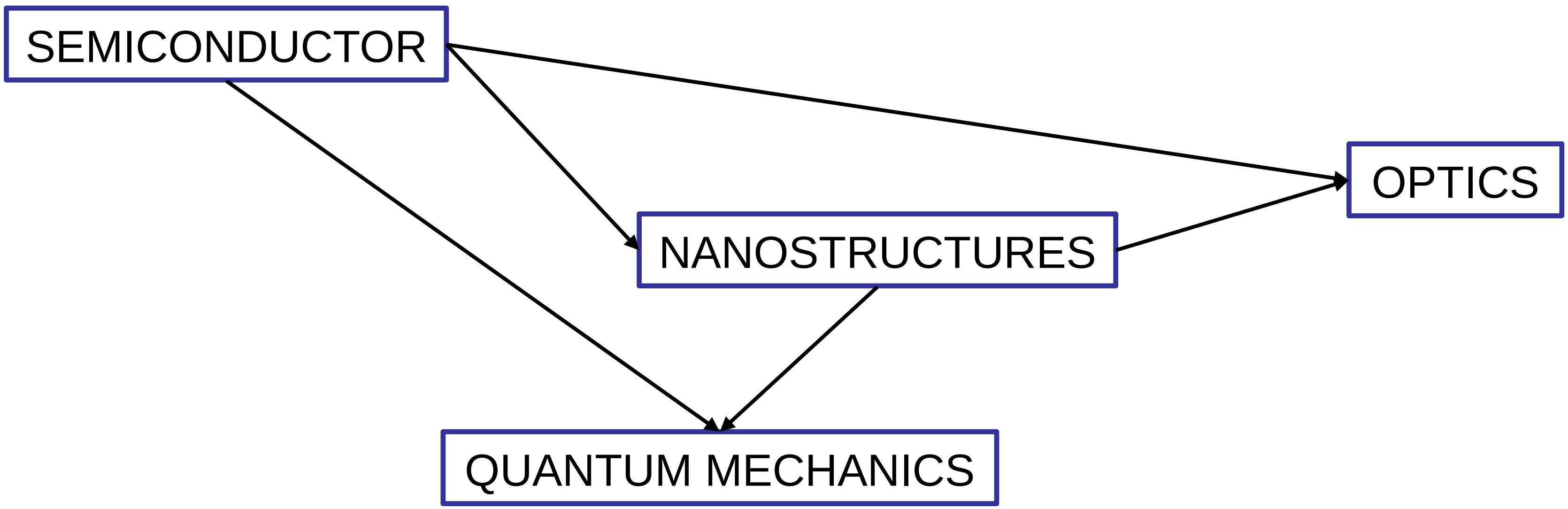
WHAT IS A QUANTUM DOT?

"Quantum dots (QDs) are semiconductor particles a few nanometres in size, having optical and electronic properties that differ from larger particles due to quantum mechanics."

From Wikipedia definition of "Quantum Dot"

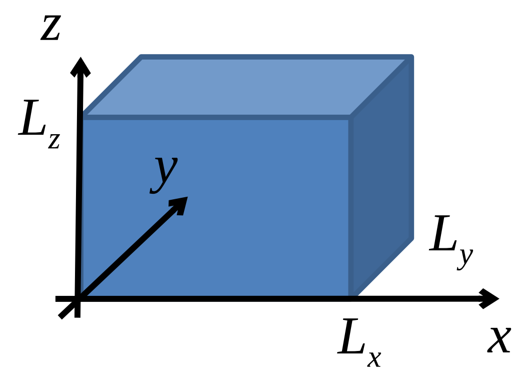


MODELING A QD

We must solve the Schrödinger equation for a QD potential V(**r**):

$$-\frac{\hbar^2}{2m}\nabla^2\psi(\mathbf{r}) + V(\mathbf{r})\psi(\mathbf{r}) = E\psi(\mathbf{r})$$

Simplest approximation:
The infinite quantum box
infinitely deep barriers ✉ ⇄ = 0 outside



$$V(x,y,z) = \begin{cases} 0 & \text{inside box} \\ \infty & \text{outside box} \end{cases}$$

$$\psi(x,y,z) = 2\sqrt{\frac{2}{L_x L_y L_z}}\sin\frac{\pi n_x}{L_x}x\,\sin\frac{\pi n_y}{L_y}y\,\sin\frac{\pi n_z}{L_z}z, \qquad n_x, n_y, n_z = 1,2,\ldots$$

$$E = \frac{\pi^2\hbar^2}{2m}\left[\left(\frac{n_x}{L_x}\right)^2 + \left(\frac{n_y}{L_y}\right)^2 + \left(\frac{n_z}{L_z}\right)^2\right]$$

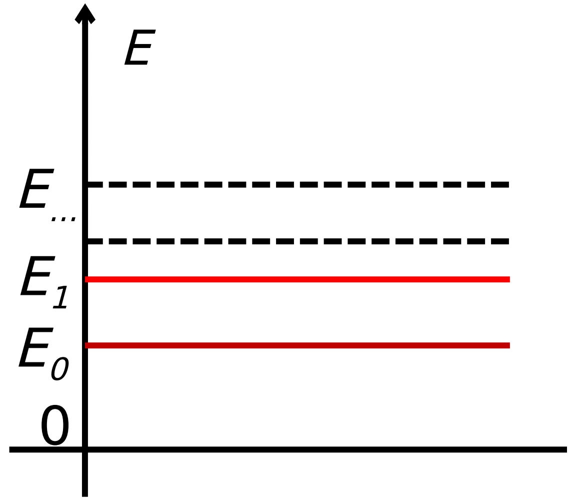
The infinite quantum box

When can a region of space be considered a QD?

We can ask that:

$$1) E_0 > 3K_B T \quad \& \quad 2) E_1 - E_0 > 3K_B T$$

$$\rightarrow \; L_x < \frac{\pi\hbar}{\sqrt{2mK_B T}}$$



1) ✉ ground state energy is larger than the „thermal energy“. The system behaves differently from a „bulk“ box at the temperature T.
2) implies that <u>all</u> dimensions are „small enough“. If a particle is put in the ground state, it will stay there with high probability (the thermal energy is barely sufficient to promote it to the first excited state).

$$L_z < L_y < L_x \rightarrow \; E_0 = \frac{\pi^2\hbar^2}{2m}\left[\frac{1}{L_x^2} + \frac{1}{L_y^2} + \frac{1}{L_z^2}\right], \quad E_1 = \frac{\pi^2\hbar^2}{2m}\left[\frac{4}{L_x^2} + \frac{1}{L_y^2} + \frac{1}{L_z^2}\right]$$

$$\rightarrow \; E_1 - E_0 = 3\frac{\pi^2\hbar^2}{2mL_x^2}$$

The infinite quantum box

When can a region of space be considered a QD?

Let's put numbers:

$$m = \alpha\, m_0, \quad m_0 \text{ free electron mass}$$

$$E_0 = \frac{\pi^2 \hbar^2}{2m}\left[\frac{1}{L_x^2} + \frac{1}{L_y^2} + \frac{1}{L_z^2}\right] \approx \frac{376\, meV}{\alpha}\left[\frac{1}{L_x^2} + \frac{1}{L_y^2} + \frac{1}{L_z^2}\right][nm^{-2}]$$

$$L_x < \frac{\pi\hbar}{\sqrt{2mK_BT}} \approx \frac{19\, nm}{\sqrt{\alpha\, K_BT[meV]}} \approx \frac{3.8\, nm}{\sqrt{\alpha}}$$

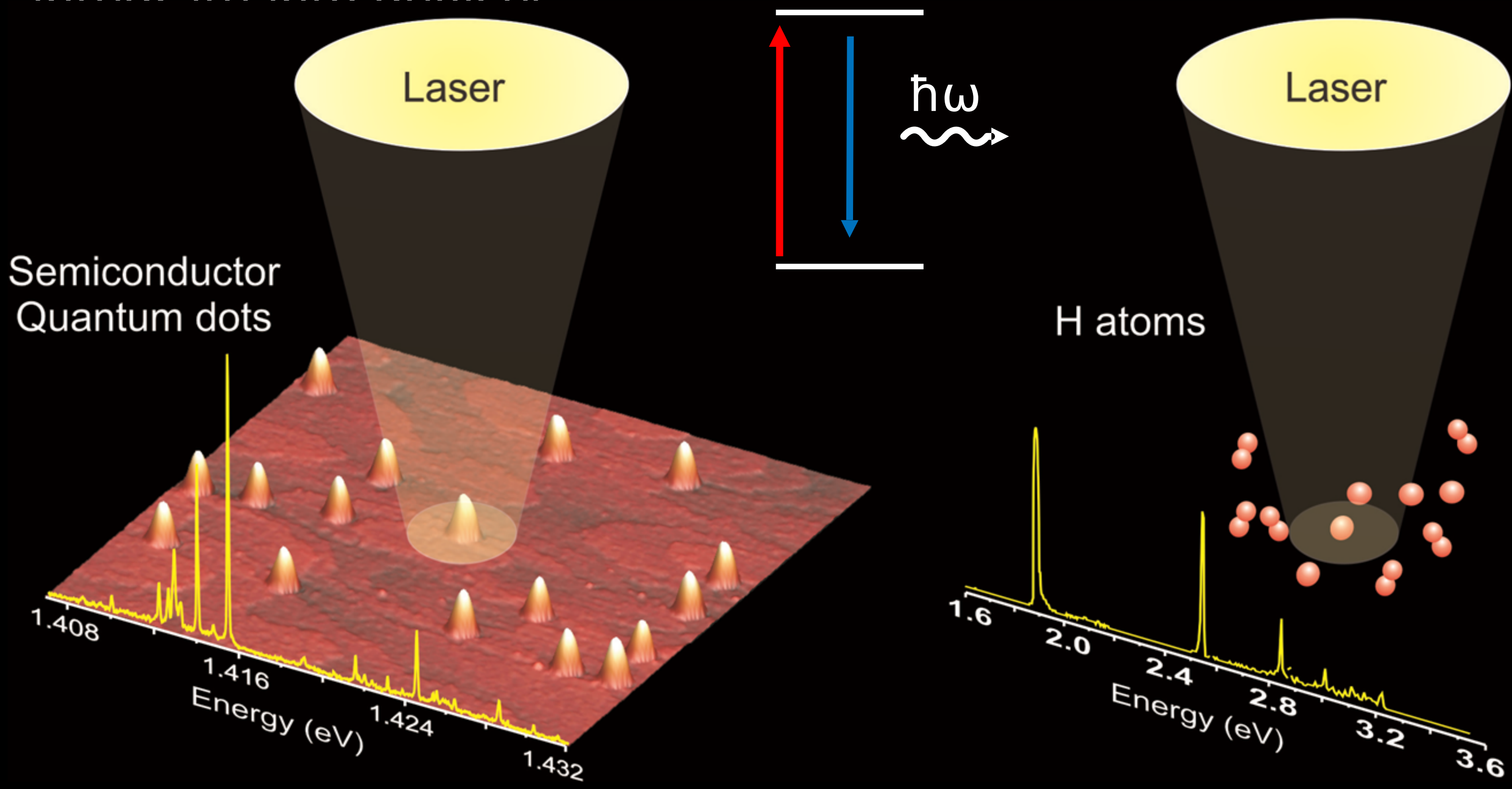
At room temperature

If we would be able to confine an electron in vacuum, the box should be smaller than about 5 nm. In a semiconductor we can approximate electrons and holes as free carriers with an effective mass *m*, which is usually smaller than m_0 (➔<1).

✉ The QD must have sizes of some nanometer! Nanostructures are required to „see“ quantum effects (at least at room temperature).

ARTIFICIAL ATOMS

- Quantum dots feature discrete states (as atoms) ✉ “artificial atoms”
- They don’t move around (solid state) ✉ easier to study and integrate into devices

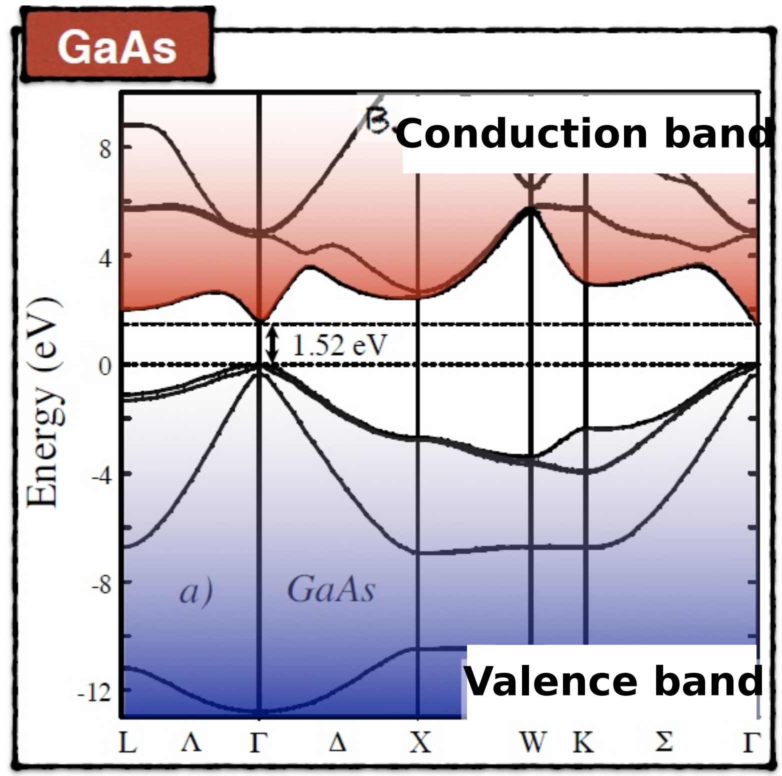


- Discrete energy levels ✉ single photons emission (Pauli exclusion principle)
- Emission on demand ✉ fast excitation and emission times

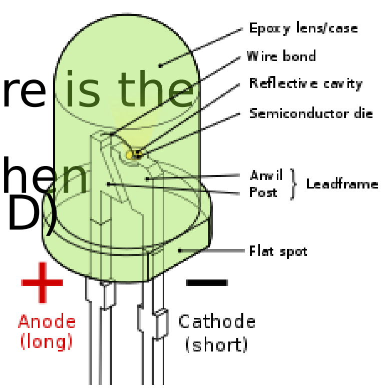
HOW CAN WE FABRICATE “QUANTUM BOXES”?

SEMICONDUCTORS

- Semiconductors are crystalline solids with a band gap (≈eV), between conduction and valence band
- At T=0 K, all electrons are in the valence band
- Semiconductors are interesting for many purposes: diodes, transistors, etc.
- One interesting feature is the ability to emit light when stimulated

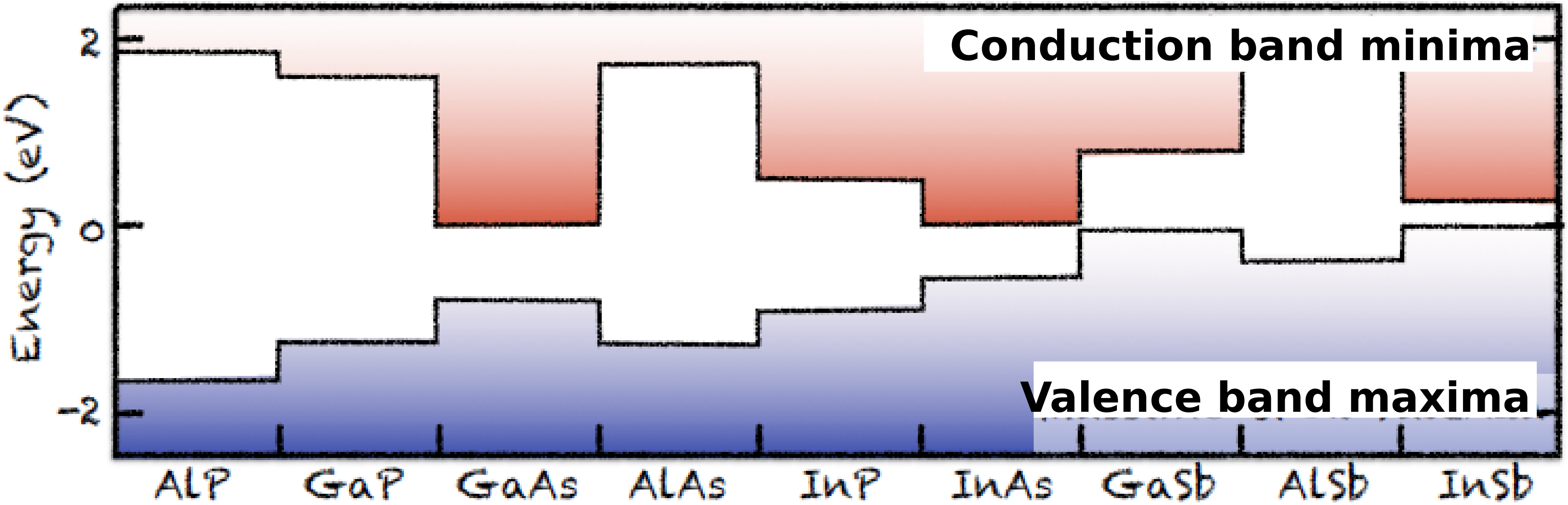


Light Emitting Diode (L.E.D)

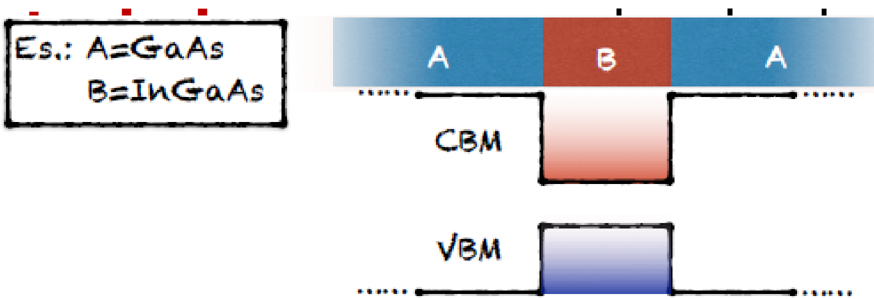


SEMICONDUCTORS

Alignment of band gaps between different semiconductors



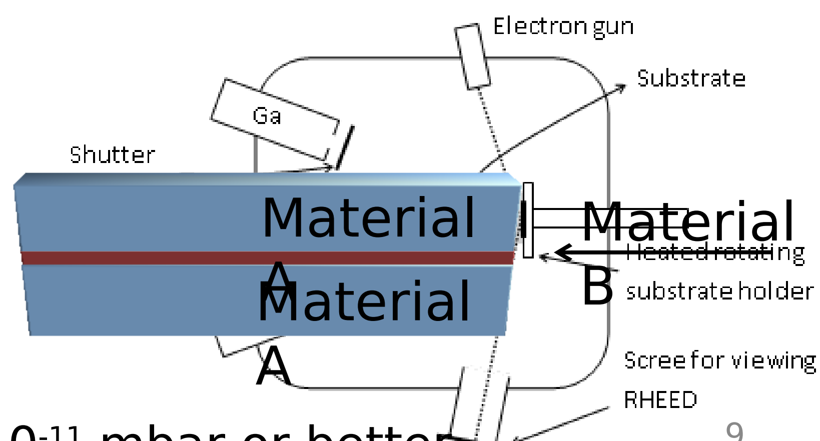
With **epitaxial growth**



am ow ith ons (<

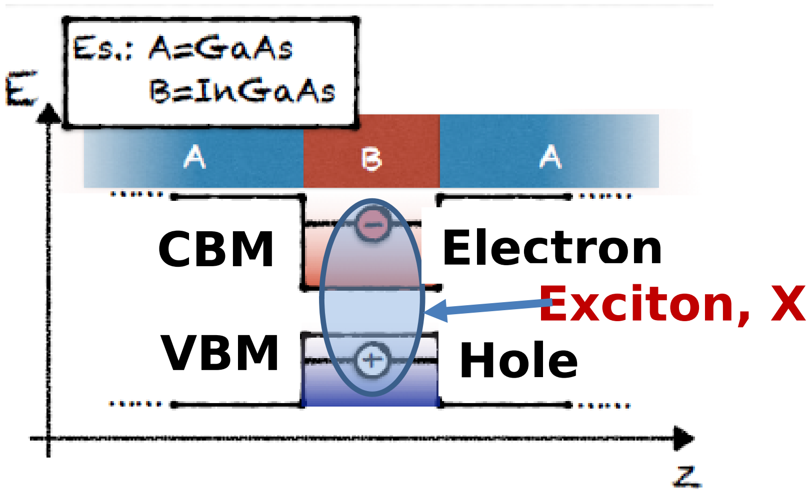
single atomic plane)

Type I band alignment



$P=10^{-11}$ mbar or better

QUANTUM WELLS



We have thus realized a “quantum well” that can confine electrons and holes in one dimension (confinement along z).

ybrid band diagram (band edges vs. positon)
alid under “**effective-mass approximation**”

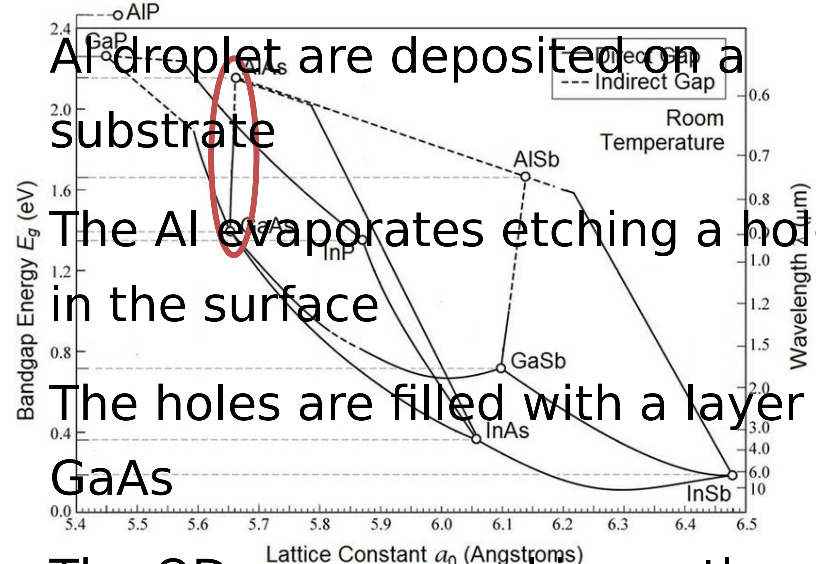
Excitons: **Bound state** between electron and hole.
Quantum confinement become visible when thickness is of the order of the **exciton Bohr radius** (roughly 10 nm for III-V semiconductors).

…. BUT HOW DO WE MAKE A QUANTUM BOX ?

DROPLET ETCHING / EPITAXY QUANTUM DOTS

One example to create quantum boxes is the so called droplet etching technique.

Using two materials that have a very similar lattice constant (GaAs/AlGaAs) one can create stress-free heterostructures:

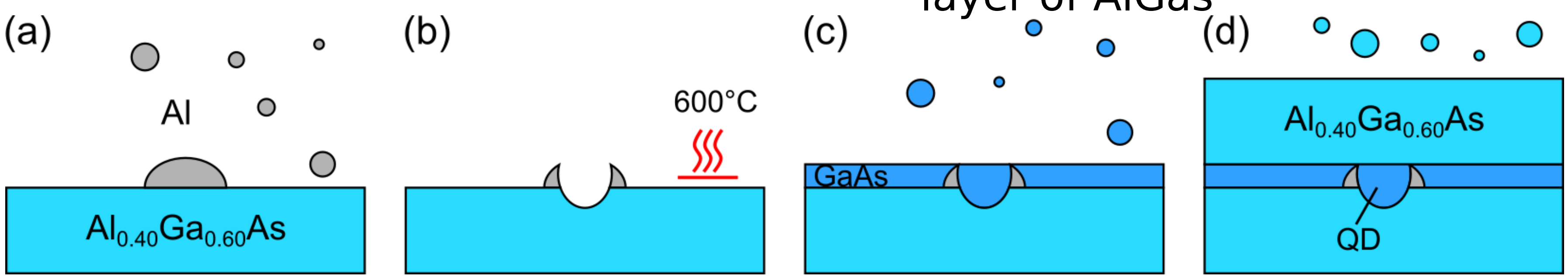


a) Al droplet are deposited on a substrate

b) The Al evaporates etching a hole in the surface

c) The holes are filled with a layer of GaAs

d) The QDs are capped in another layer of AlGas

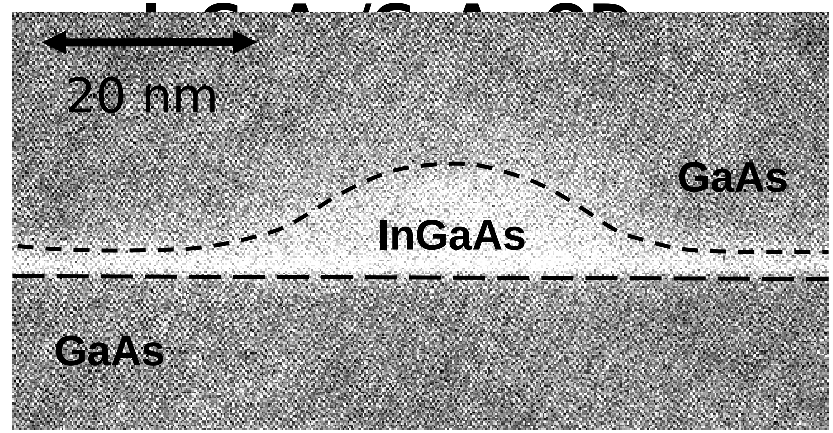


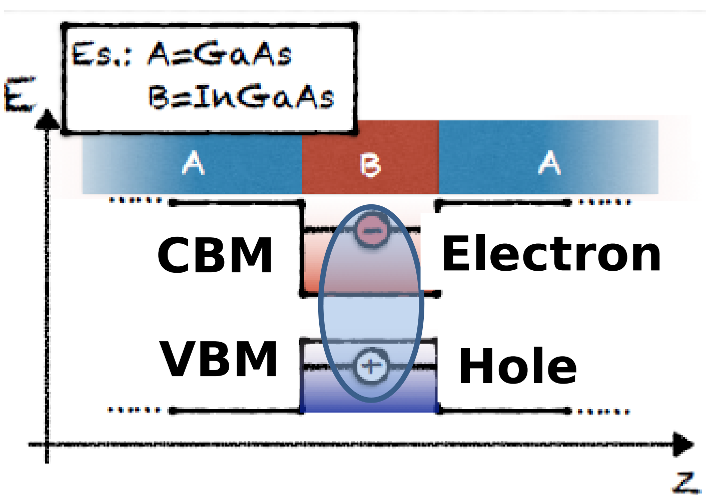
Substrate: single crystal with clean surface
Environment: for MBE ultra-high vacuum ($p \sim 10^{-13}$ bar)

Atomic Force Microscopy (AFM) Of InGaAs/GaAs QDs on SURFACE

scale 1400x700x12 nm^3

Cross-sectional Transmission Electron Microscopy (TEM) of



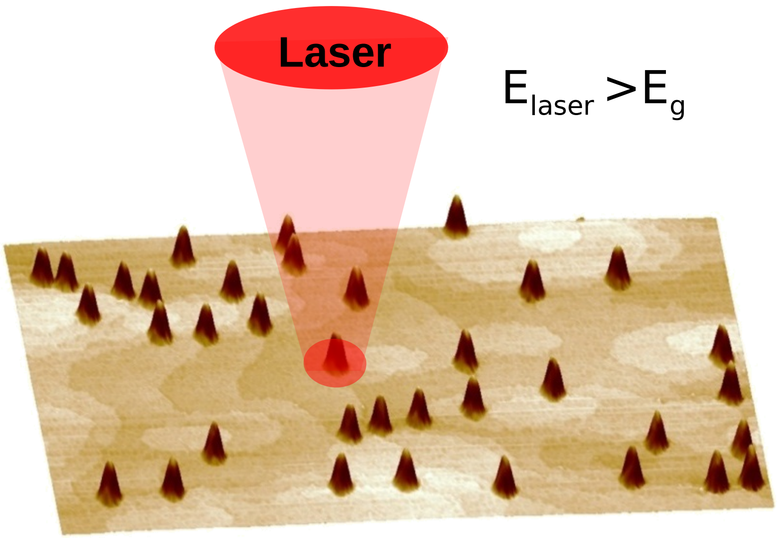


Electrons and holes are confined in <u>all spatial directions</u>

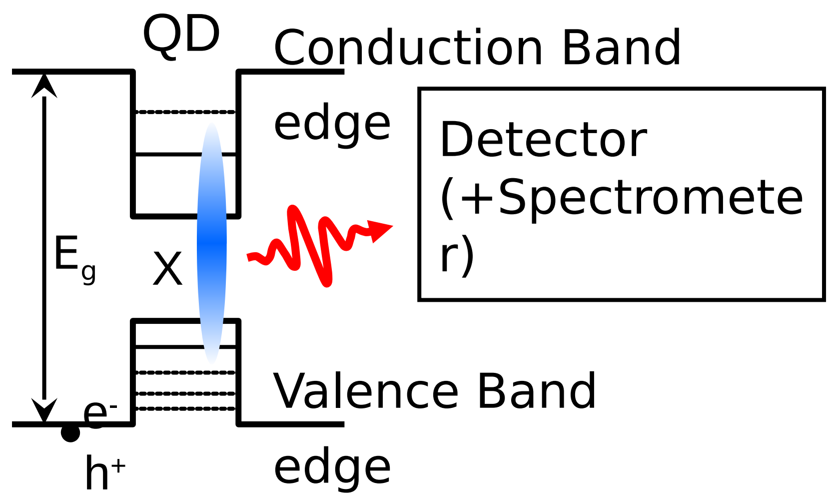
QD: A solid-state quantum box

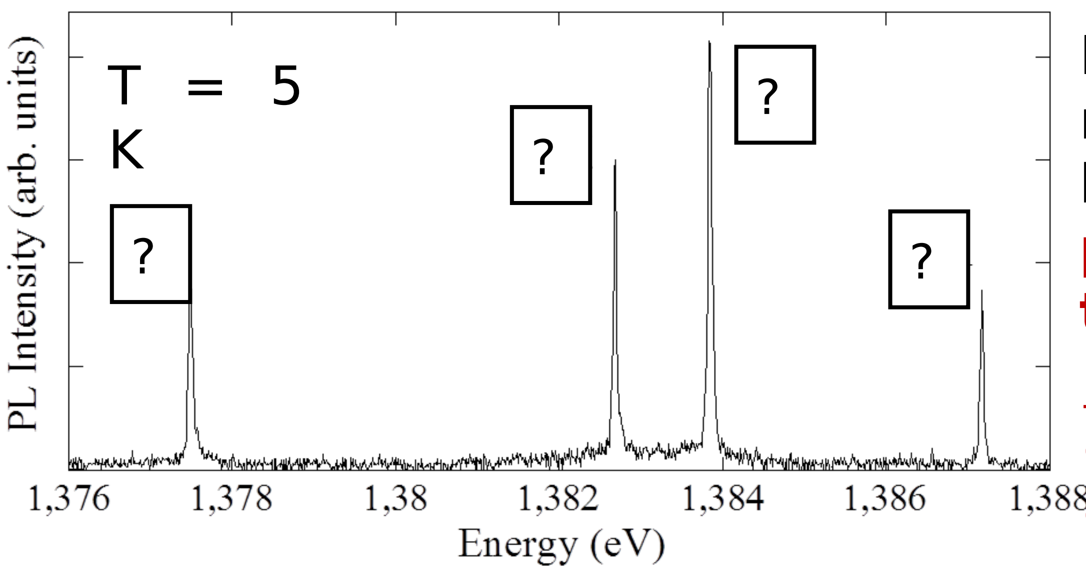
SHINING LIGHT ON QUANTUM DOTS

PHOTOLUMINESCENCE SPECTROSCOPY



scale 1400x700x12 nm³



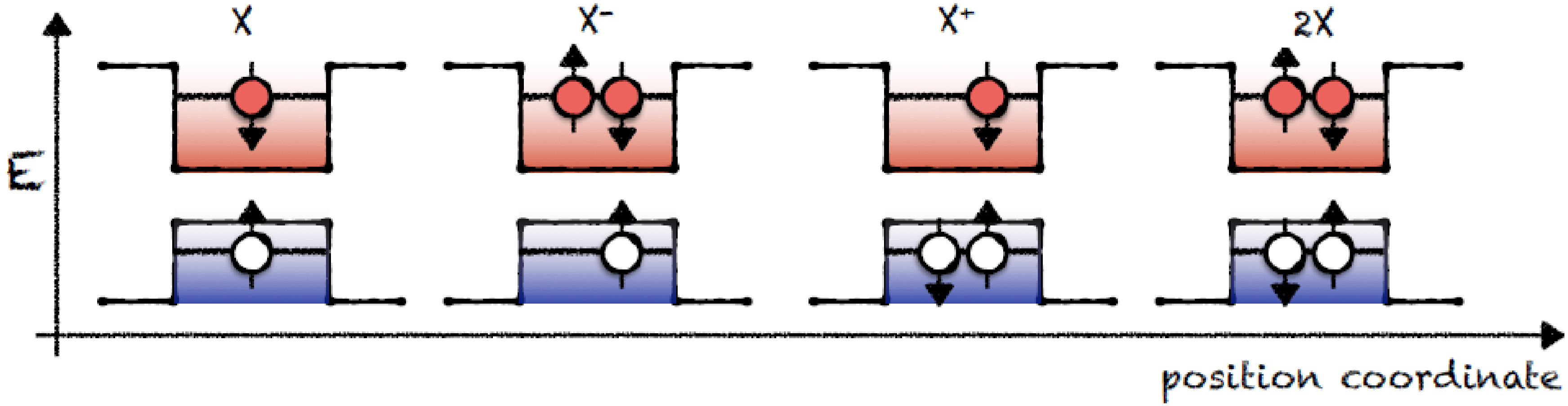


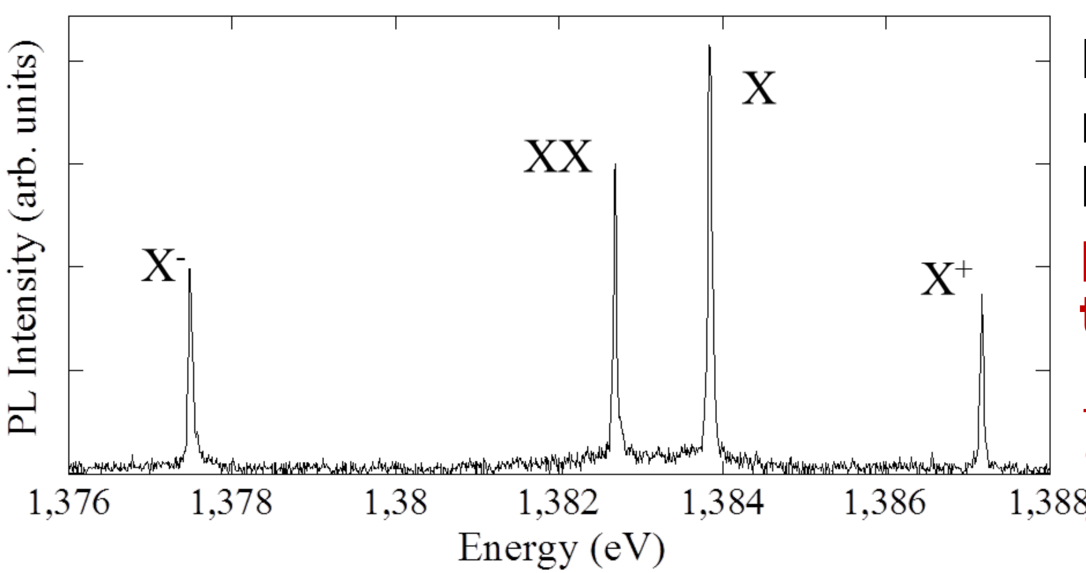
Typical spectrum of an InGaAs/GaAs QD (~2-5 nm height, 10-20 nm base length) at **low power** and **low temperature**

Important: transitions occur at different energies

What are these lines ???

FEW PARTICLE STATES

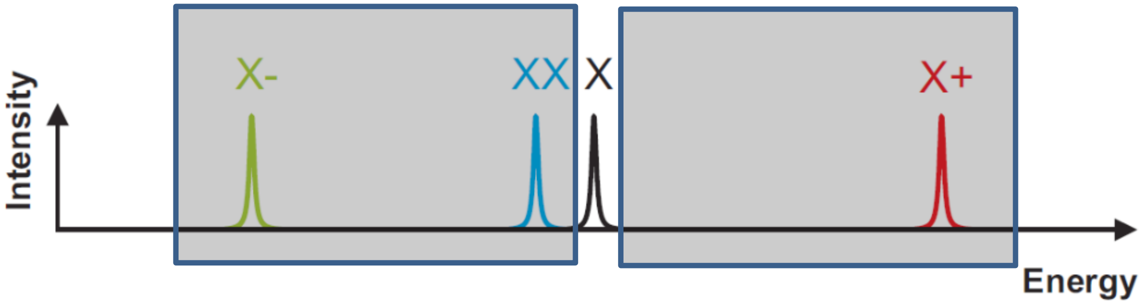


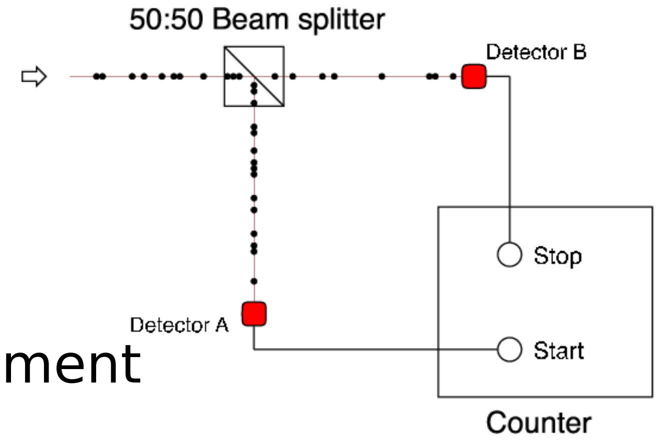


Typical spectrum of an InGaAs/GaAs QD (~2-5 nm height, 10-20 nm base length) at **low power** and **low temperature**

<u>Important</u>: transitions occur at different energies

PHOTON ANTIBUNCHING



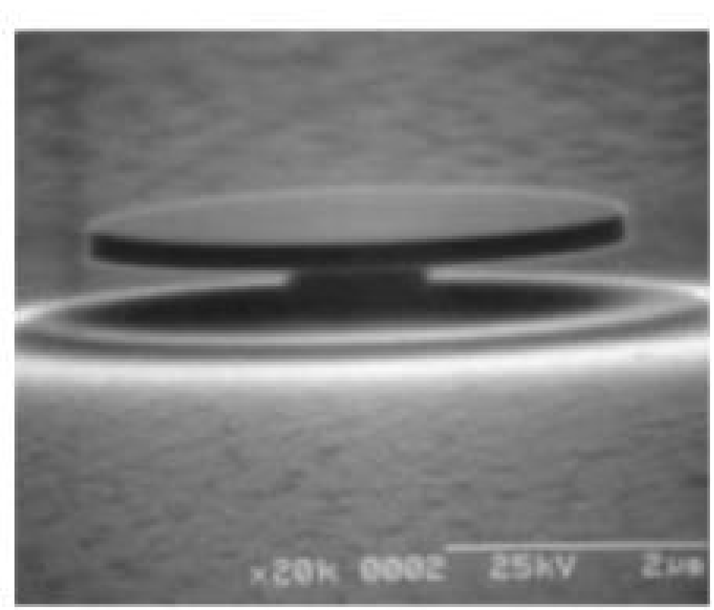


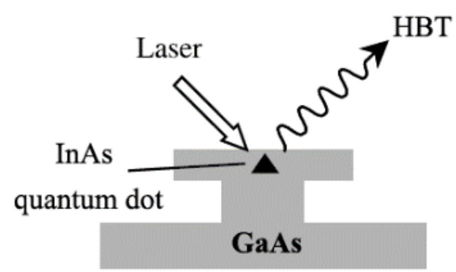
y the X is selected to perform the HBT experiment

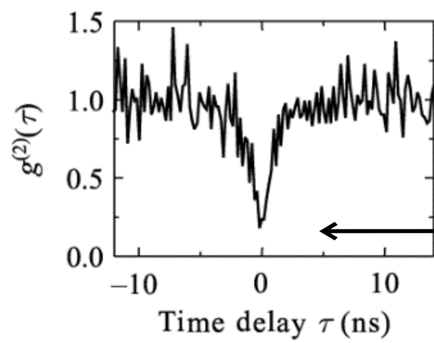
Filtering is important!

First observation of photon antibunching with QDs

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





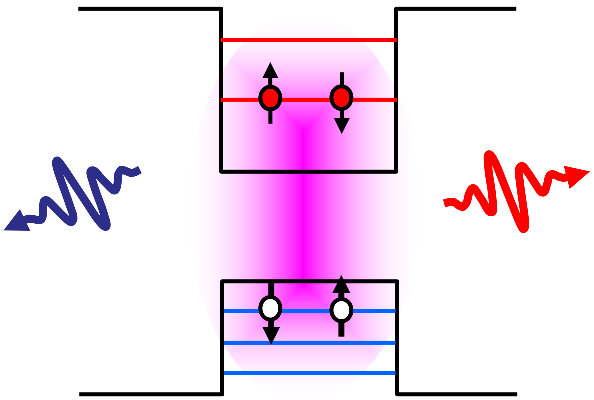


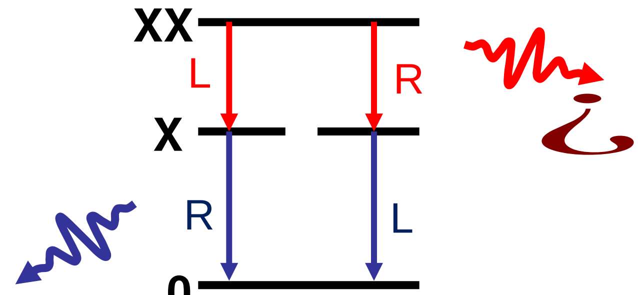
$$g^{(2)}(0) < 1$$

Non-classical light

Not exactly zero because of the experimental temporal resolution

ENTANGLED PHOTONS GENERATION





XX→X→0 cascade
Exciton state:
2 radiative decay paths possible

2 states
First , then polarized photon

or vice versa

Biexciton XX:

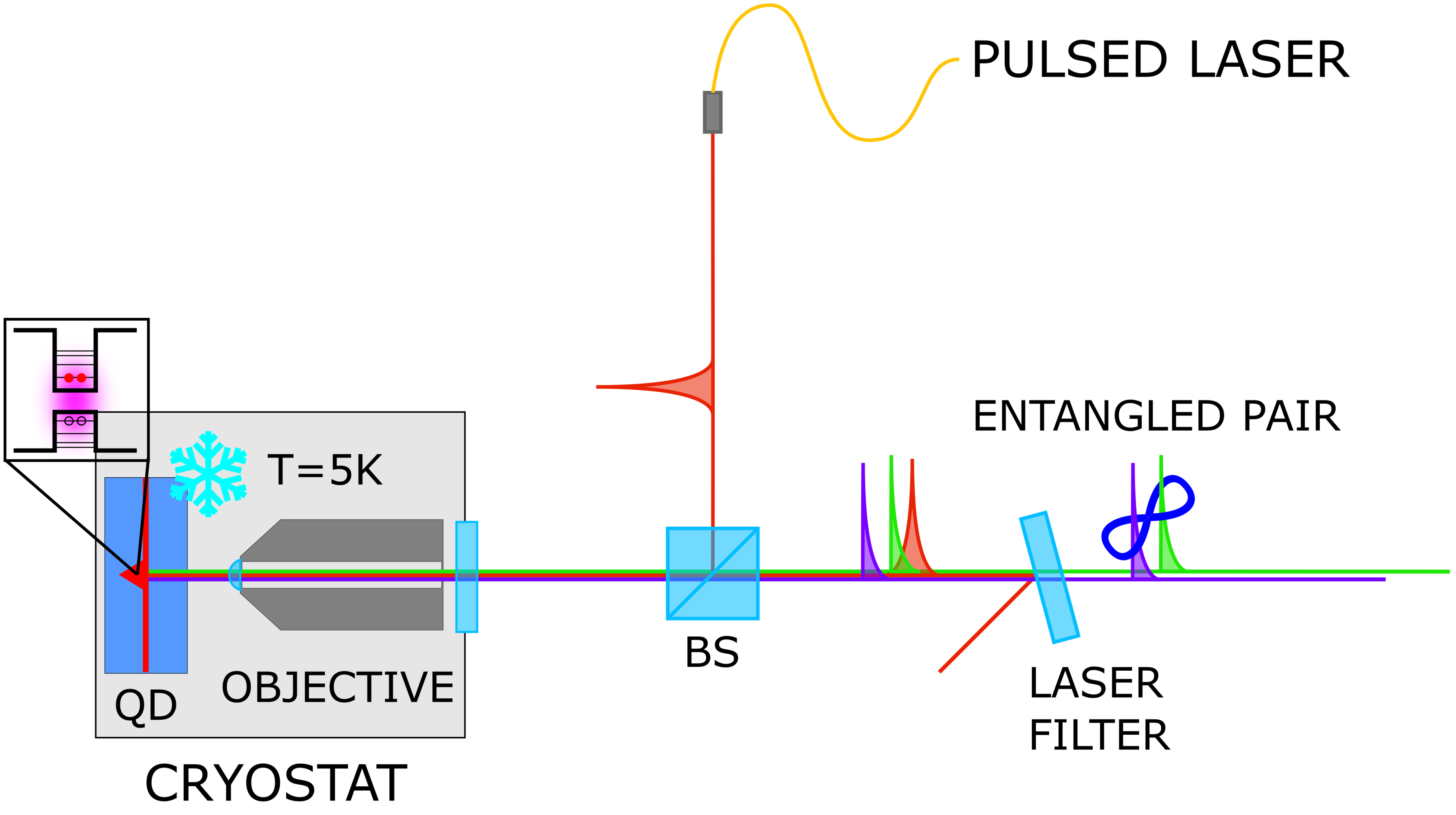
- 2 e^- excited to CB leave 2 h^+ in VB.
- 2 photon cascade from radiative recombination

If paths are indistinguishable

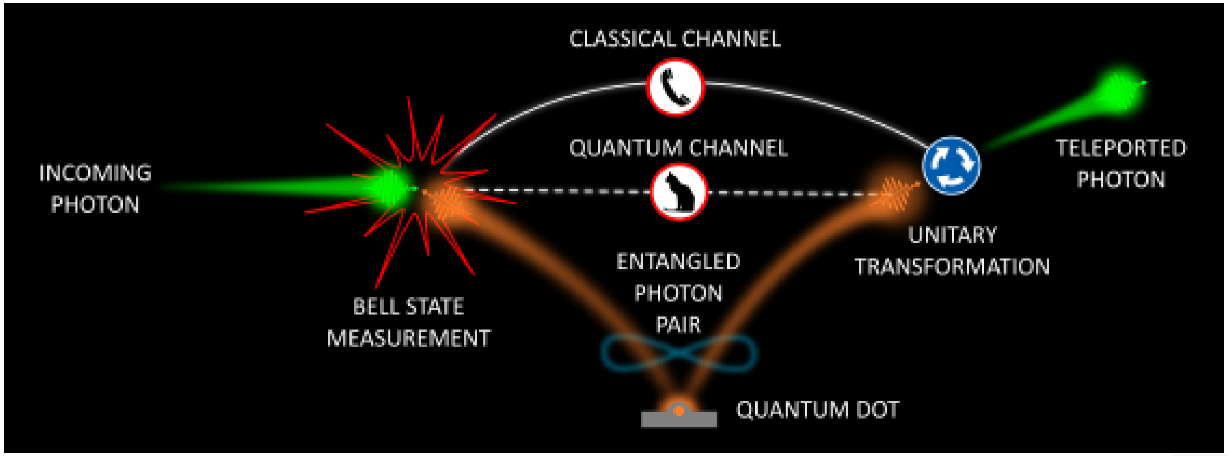
The state is entangled

O. Benson *et al.,* Phys. Rev. Lett. **84**, 2513 (2000)
N. Akopian *et al.,* Phys. Rev. Lett. **96**, 130501 (2006)

EXPERIMENTAL SETUP



EXPERIMENTS WITH QDS



Quantum teleportation & Entanglement swapping

Science Advances
12, 1255 (2018)
Phys. Rev. Lett.
123, 160501 (2019)

Daylight Quantum key distribution
To be published

Quantum key distribution
Science Advances
7, eabe6379 (2021)

(in collaboration with Prof. Sciarrino's group)

We recently implemented Daylight Quantum Key Distribution: 4 days of uninterrupted key exchange