PIER Graduate Week 2017

Nano-Optics of low dimensional semiconductor structures

Lecture 1:
Quantum Optics with Quantum Dots

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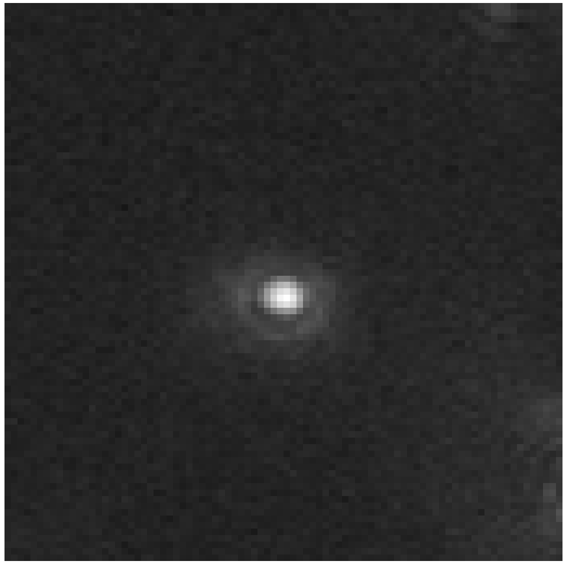
Quantum Photonics Group, ETH Zürich, Switzerland

Nano Optics

Explore the nano world with optical means.

Microscopy?

Limited by diffraction limit to the wavelength.
→ Not really "nano"



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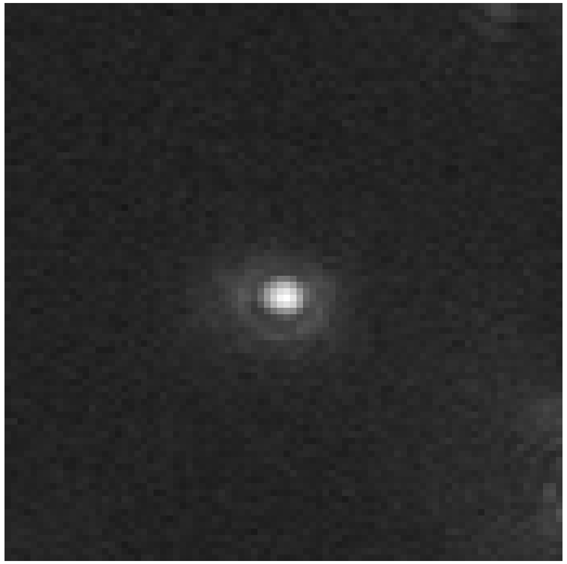

Microscopy beyond the diffraction limit:
- Electron microscopy, AFM, …
- Near field optics
- Super resolution microscopy
- …

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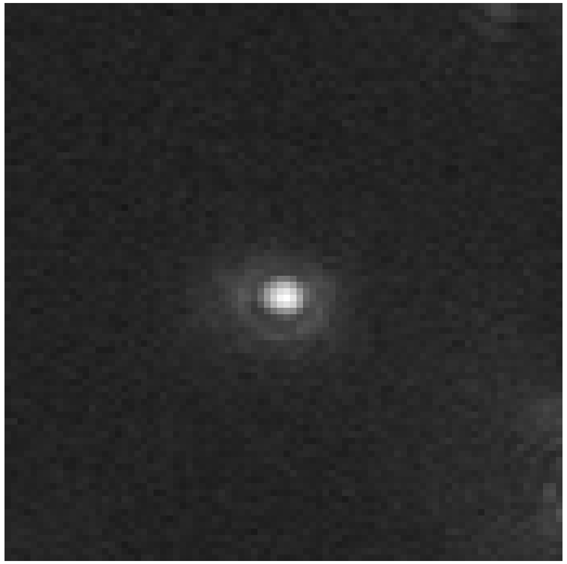

Microscopy beyond the diffraction limit:
- Electron microscopy, AFM, …
- Near field optics
- Super resolution microscopy
- …

Observe the structure of nanoscale objects

Why nano?

The physical properties of nano scale structures are governed by **quantum mechanics.**

We do not need to “see” the nano structure to explore its physical properites.
I.e. Quantum size effect.

N.C. Anheier, Nature 523, 39 (2015)

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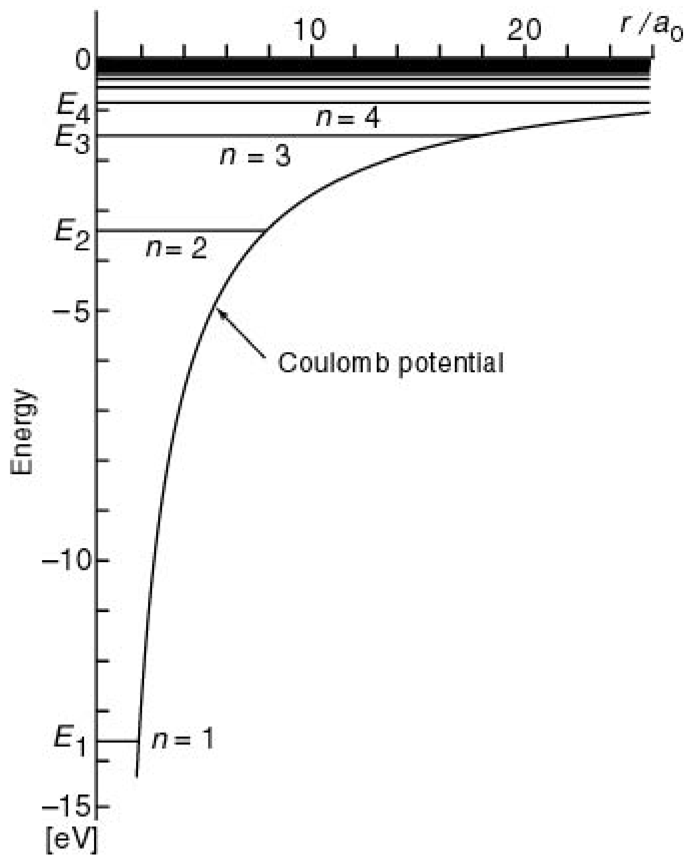
We do not need to “see” the nano structure to explore its physical properites.

Optically *create*, *manipulate* and *probe* quantum, states of light and matter:

- Explore and test quantum mechanics.
- Study interactions of light and matter.
- Observe new states of matter and explore their properties.

Quantum Systems

Hydrogen atom



Natural quantum system

But: Difficult to control and to couple

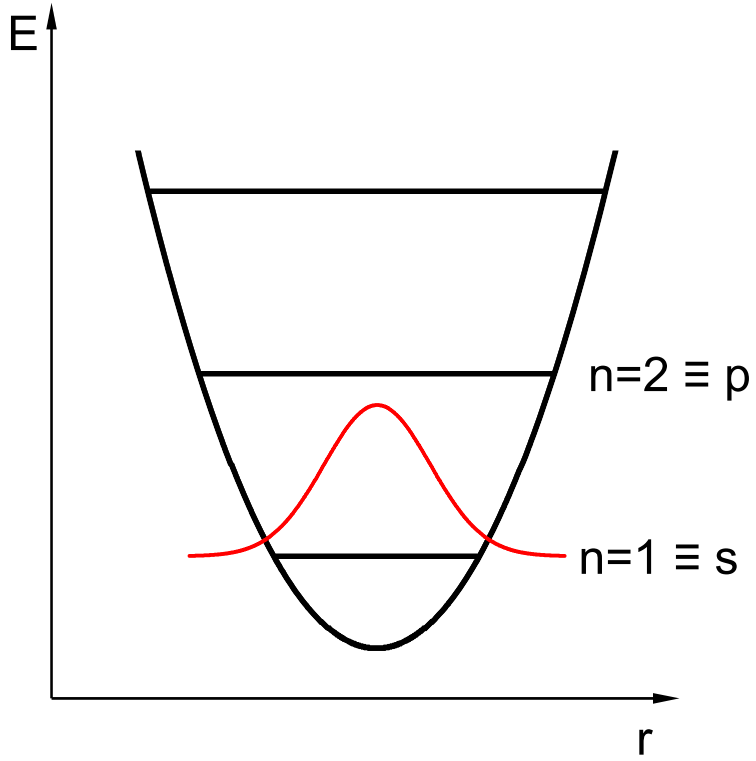
Nano technology:
Construct a quantum system with atom-like properties in a solid state environment: Quantum Dot

Requirement:
Energy level spacing larger than k_BT

www.kutl.kyushu-u.ac.jp

Quantum Dot on the Back of an Envelope

Quantum harmonic oscillator



Harmonic approximation:

Energy level separation $\Delta E = \hbar\omega$

s-state Electron wave function

$$\psi(r) = \frac{1}{\sqrt{\pi} l_e} \exp\left(-\frac{r^2}{2l_e^2}\right)$$

With the effective length

$$l_e = \sqrt{\frac{\hbar}{m^\star \omega}}$$

I.e.: In GaAs: $m^\star = 0.07 m_e$

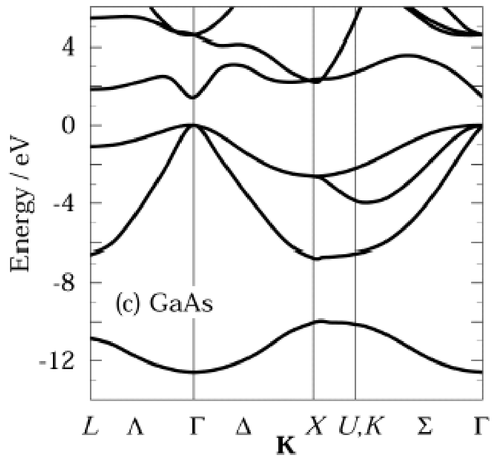
$$l_e = 10\mathrm{nm} \rightarrow T \lesssim 126\mathrm{K}$$

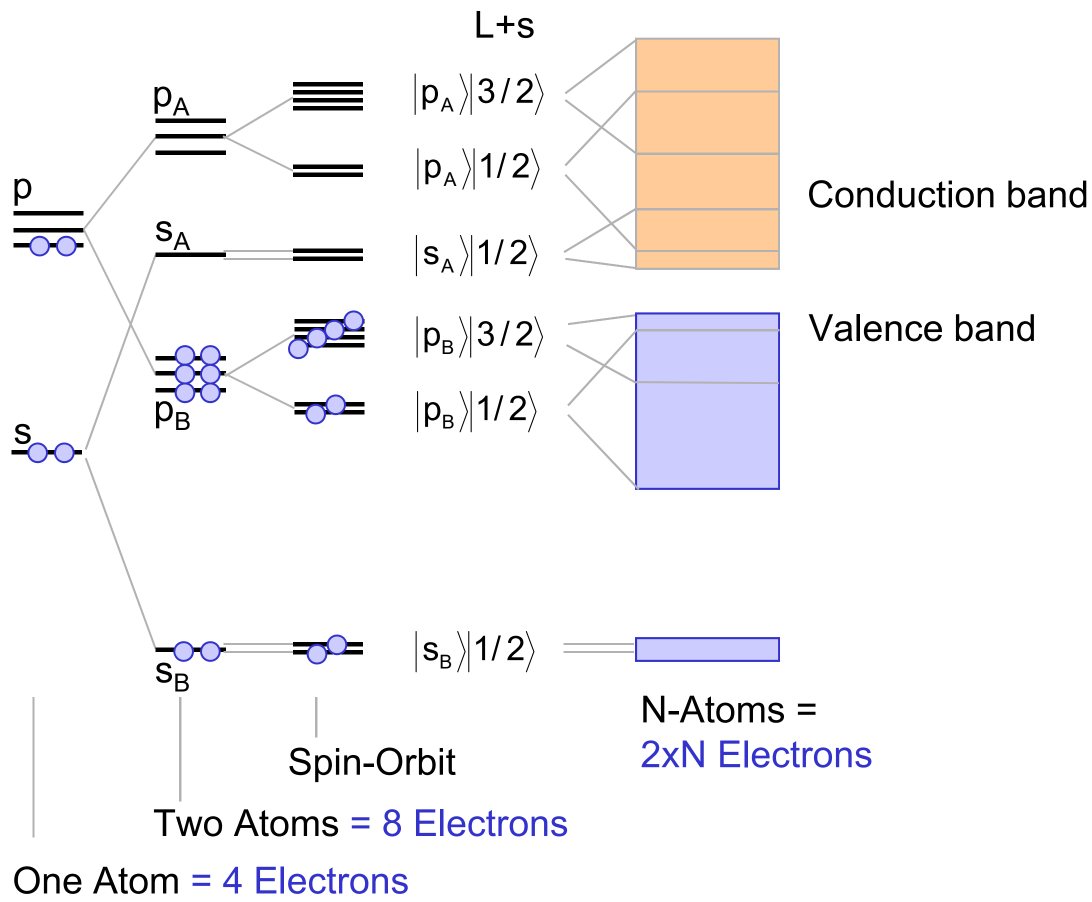
$$l_e = 100\mathrm{nm} \rightarrow T \lesssim 1.2\mathrm{K}$$

In reality temperatures must be smaller by approximately a factor of 10.

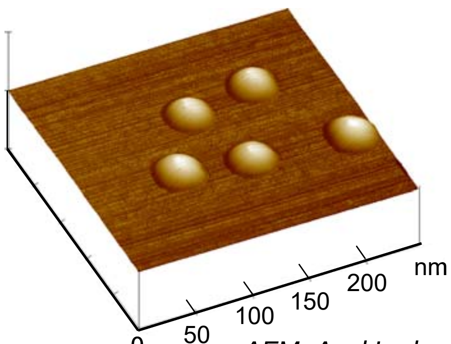
R. J. Warburton, PRB **58**, 16221 (1998)

Optically Active Quantum Dots – From Atoms to Bands

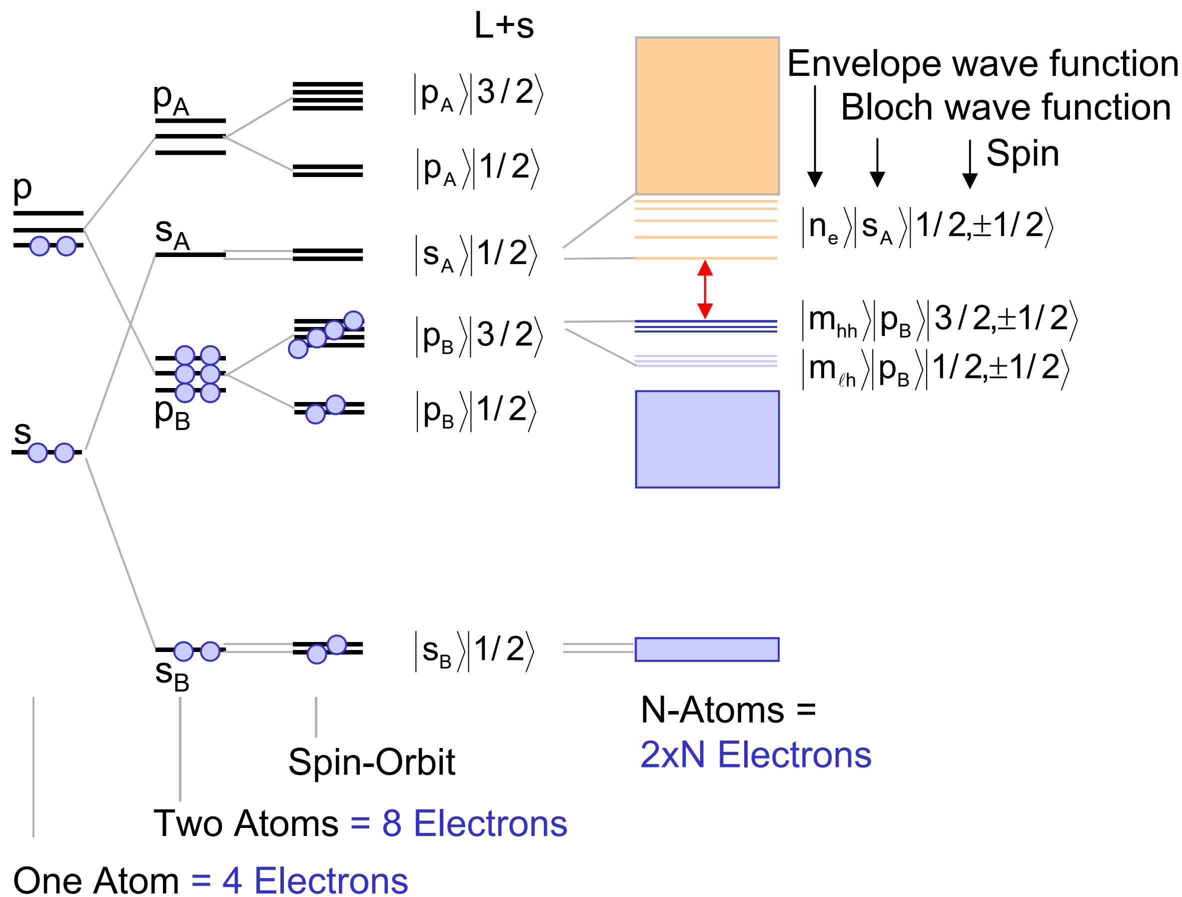




Optically Active Quantum Dots – From Bands to Discrete States

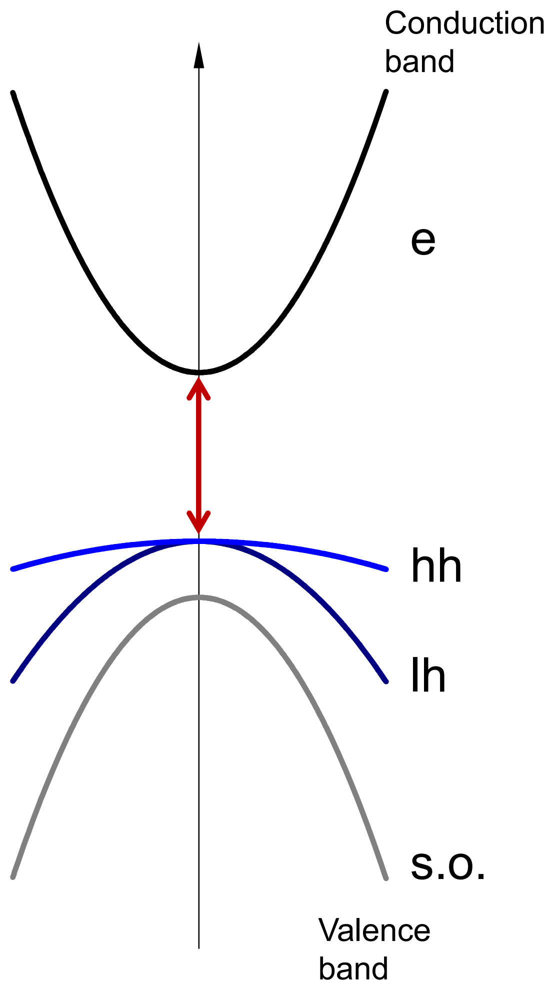


AFM: Axel Lorke



Quantized states for electrons due to nano structuring

Optical Selection Rules of Interband Transitions



$$W_{\mathrm{i}\to\mathrm{f}} = \frac{\pi}{2\hbar} \left|\langle i|H_{\mathrm{int}}|f\rangle\right|^2 \delta(E_{\mathrm{f}} - E_{\mathrm{i}} - \hbar\omega)$$

Dipole interaction Hamiltonian:

$$H_{\mathrm{int}} \sim \boldsymbol{\epsilon}\mathbf{p}$$

$\boldsymbol{\epsilon}$ ≡ Polarization

Wave function:

$$|\varphi\rangle = |\mathrm{Env}\rangle|\mathrm{Bloch}\rangle|\mathrm{Spin}\rangle$$

Only Bloch part of the wave function changes.

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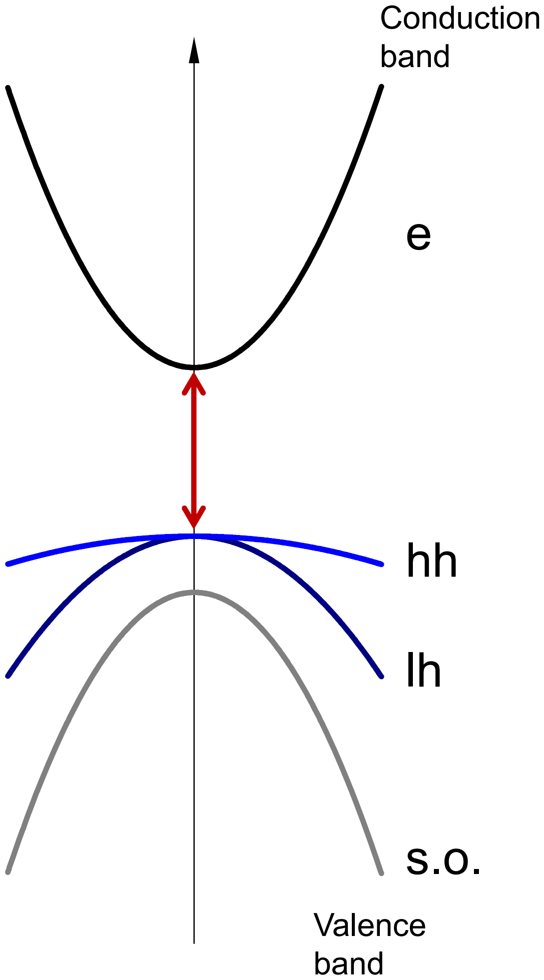

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Only Bloch part of the wave function changes.

i.e:
$$|\varphi_{\mathrm{e}}\rangle = |1/2,+1,2\rangle = |s\rangle|\uparrow\rangle$$
$$|\varphi_{\mathrm{hh}}\rangle = |3/2,+3/2\rangle = -\tfrac{1}{\sqrt{2}}\left(|x\rangle + \mathrm{i}|y\rangle\right)|\uparrow\rangle$$

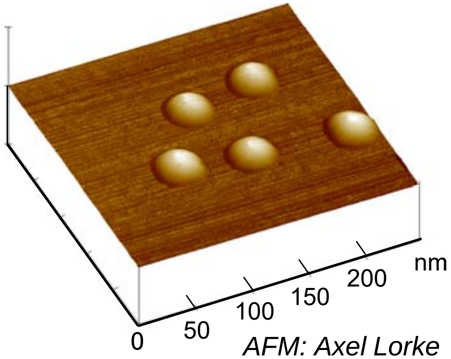
Matrix elements of dipole operator:

$$\langle x|p_x|s\rangle = \langle y|p_y|s\rangle = \langle z|p_z|s\rangle = \mathrm{i}p$$

$$\Longrightarrow \left|\langle x + \mathrm{i}y|\boxed{\frac{p_x - \mathrm{i}p_y}{\sqrt{2}}}|s\rangle\right|^2 = p^2$$

Only non zero matrix element for circular polarized light

Self-Assembled Quantum Dots - Crystal structure



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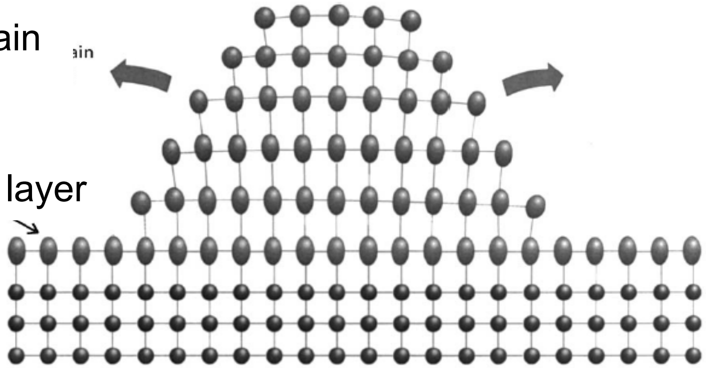
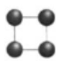
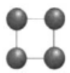


Stranski-Krastanov growth





K. Eberl et. al. Physica E 9 (2001) 164 -174

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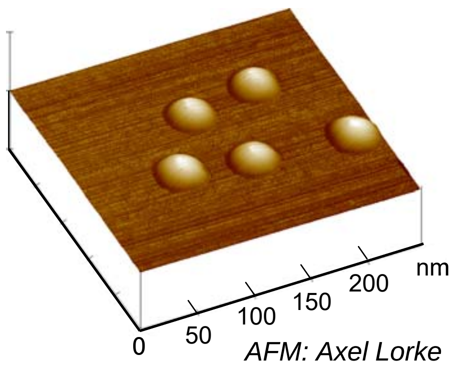
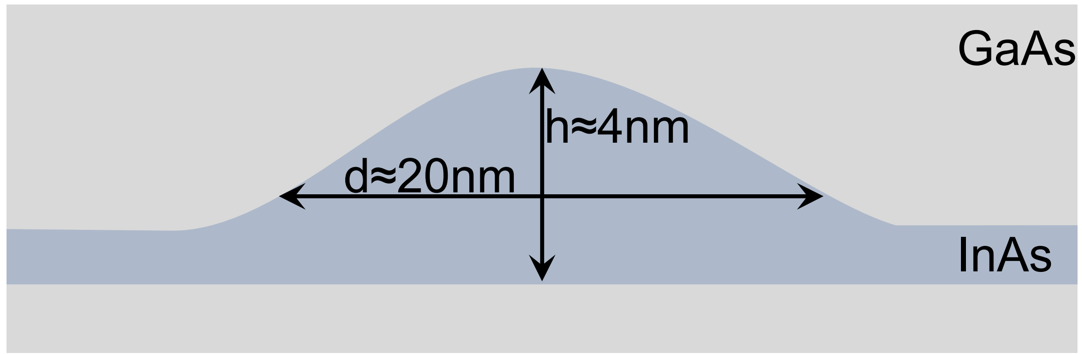
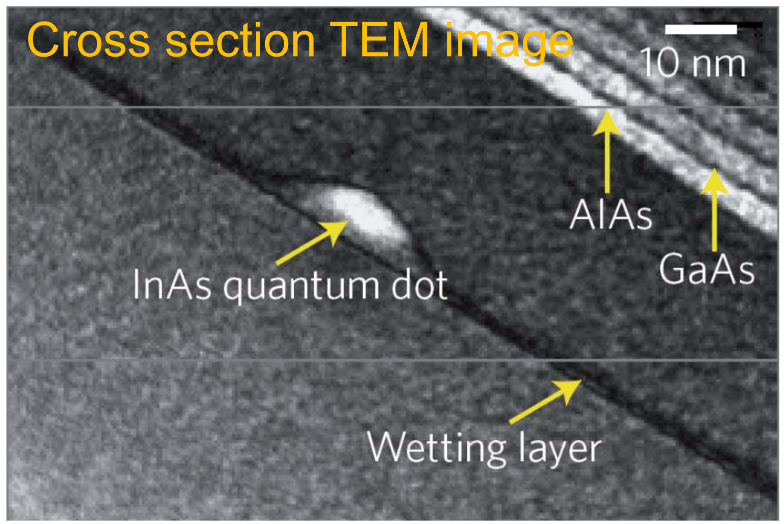


Self-assembled growth

⇒ Size and In distribution varies over QD ensemble

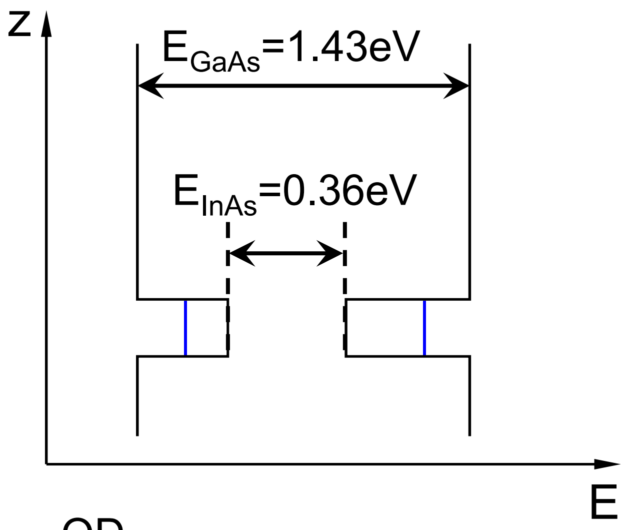




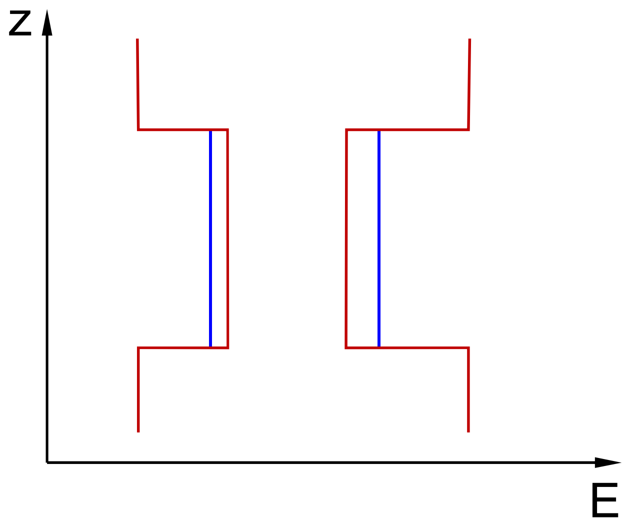
R.J. Warburton, Nat. Mat. **12**, 483 (2013)

Self-Assembled Quantum Dots - Potential Landscape

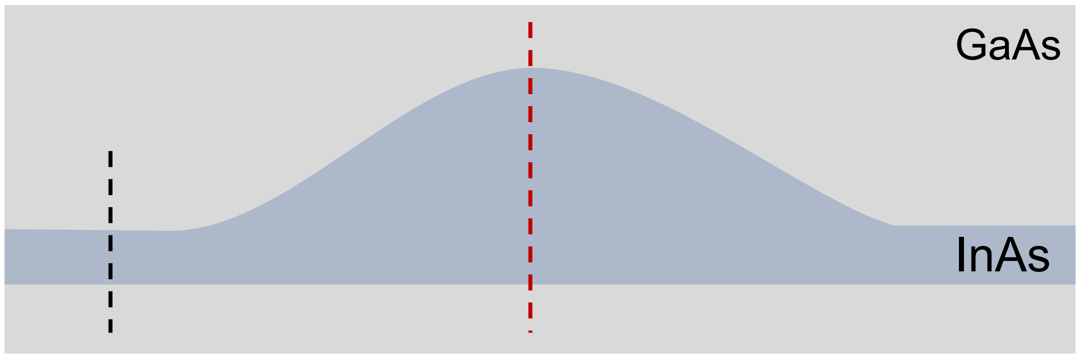
Wetting layer



QD



Approximation of QD potential by 2d-hamronic oscillator



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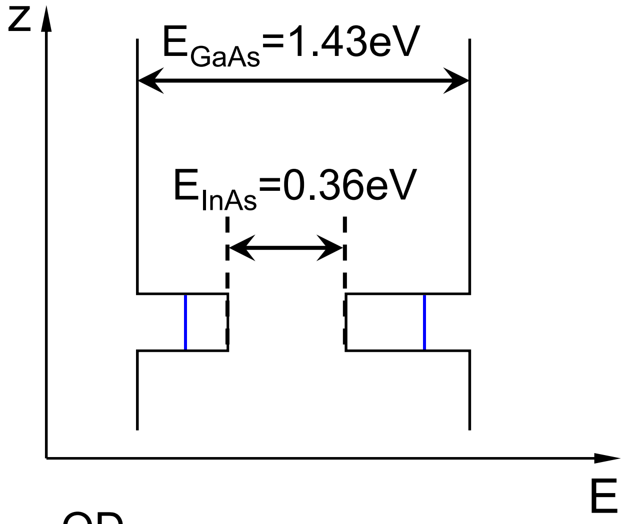
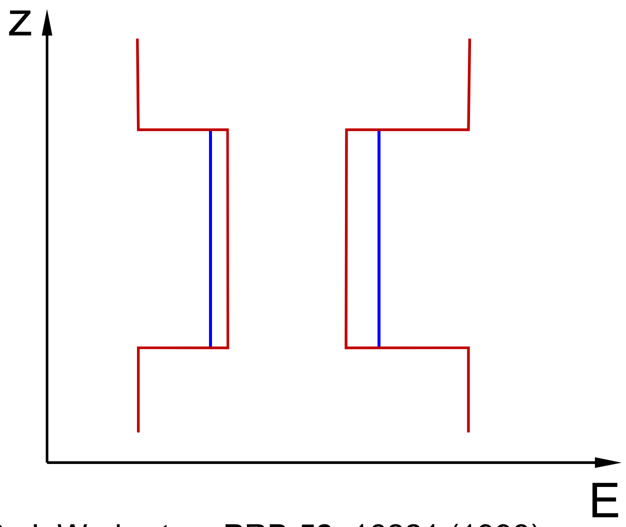


QD



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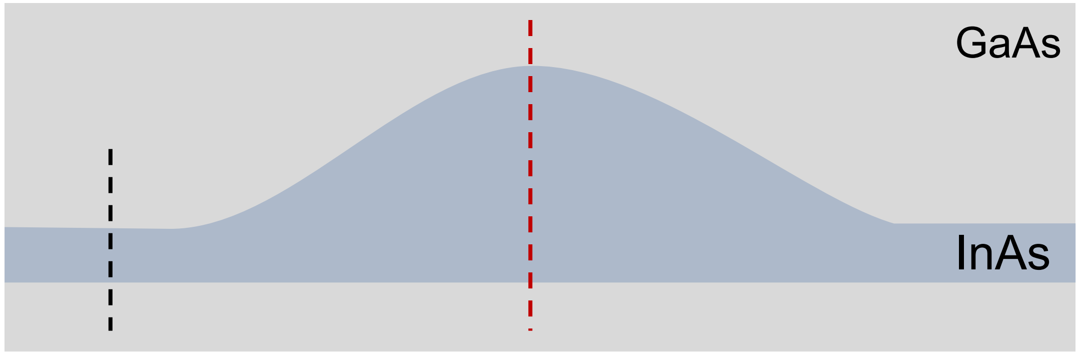
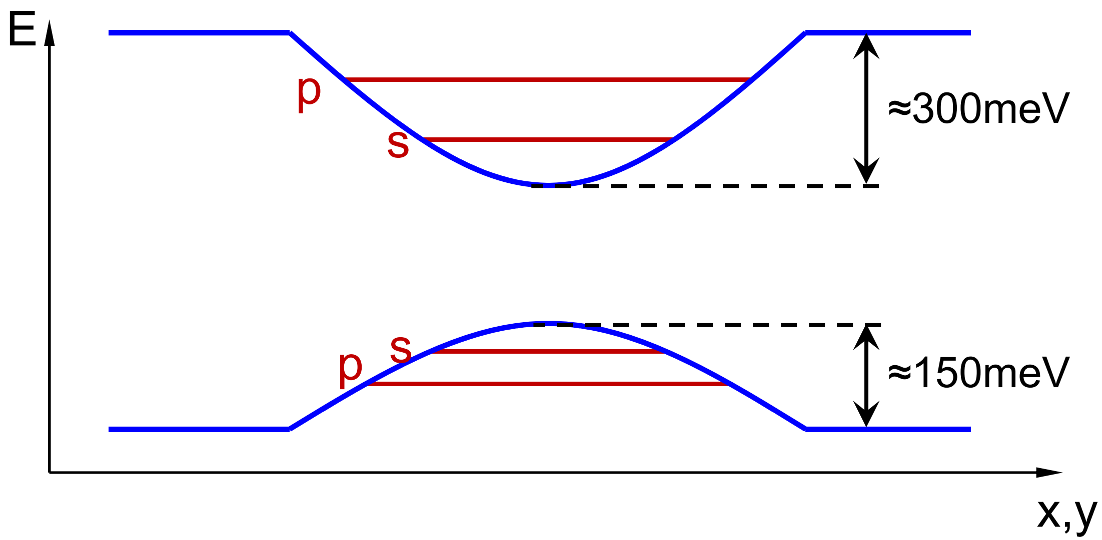


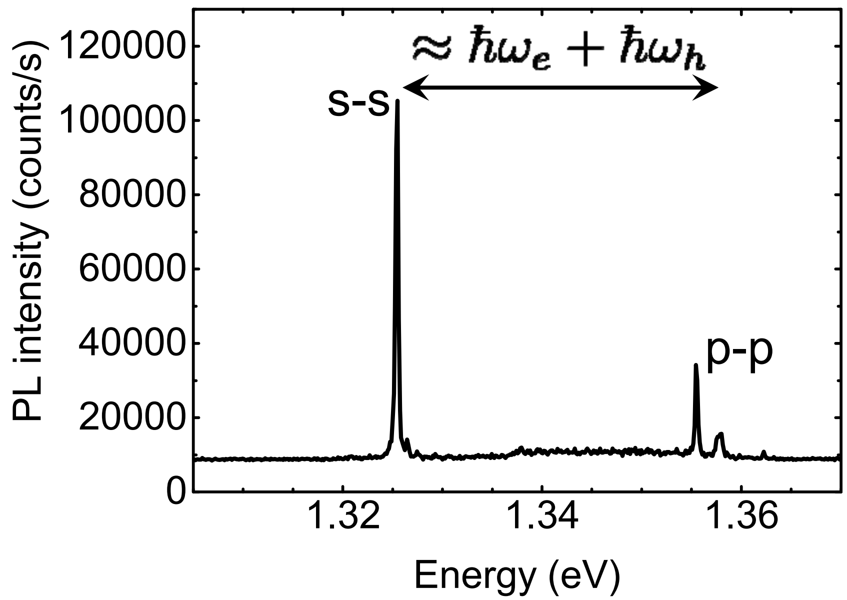


Self-Assembled Quantum Dots - Photoluminescence

- Non resonant excitation (i.e. λ_{exc}=850nm).
- Relaxation of electron and holes into the QD.
- Recombination of electrons and holes:

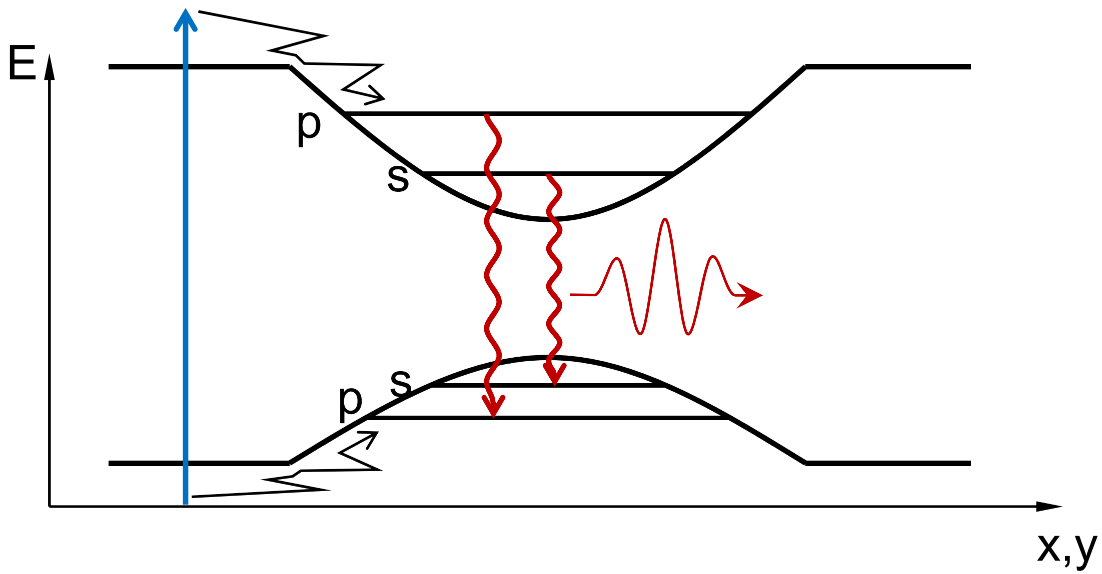
⇨ Photo emission.

Spectral laser filtering.



Quantization energy:

$$\hbar\omega_e + \hbar\omega_h \approx 30\mathrm{meV}$$



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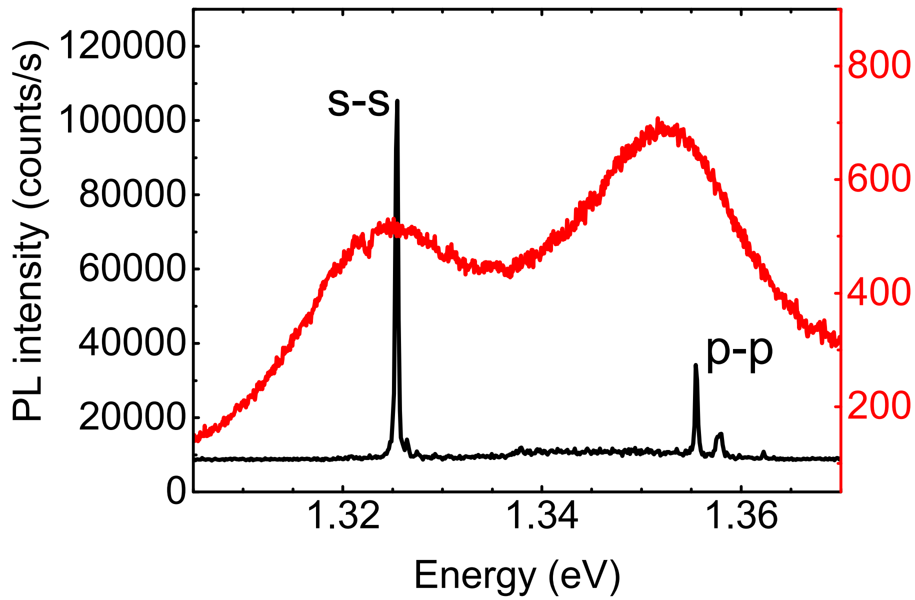


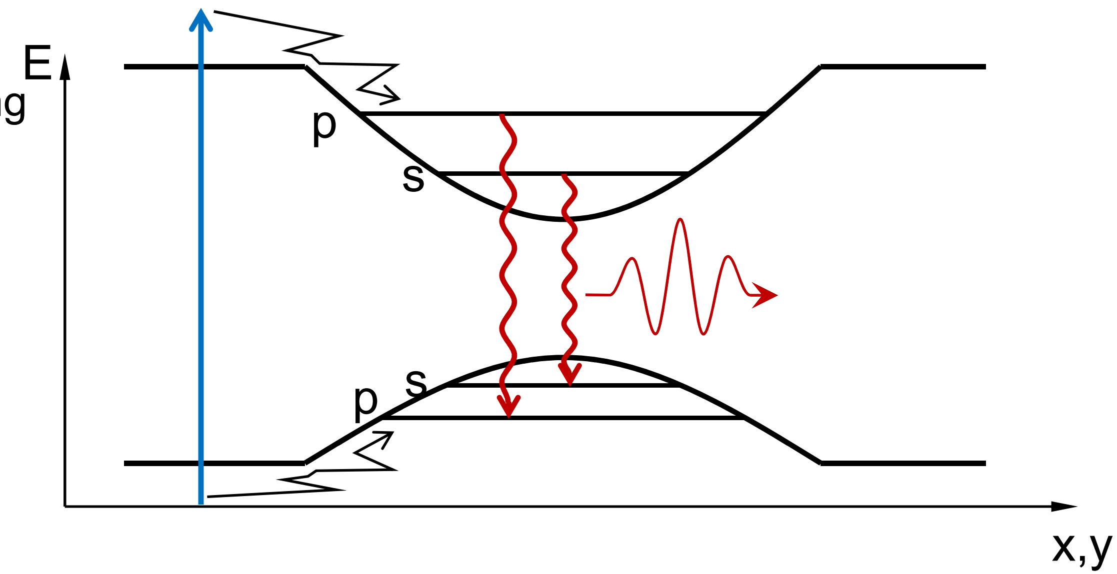
Size distribution over QD ensemble.

⇨ Inhomogeneous broadening 10-20 meV.

⇨ Single QD spectroscopy.

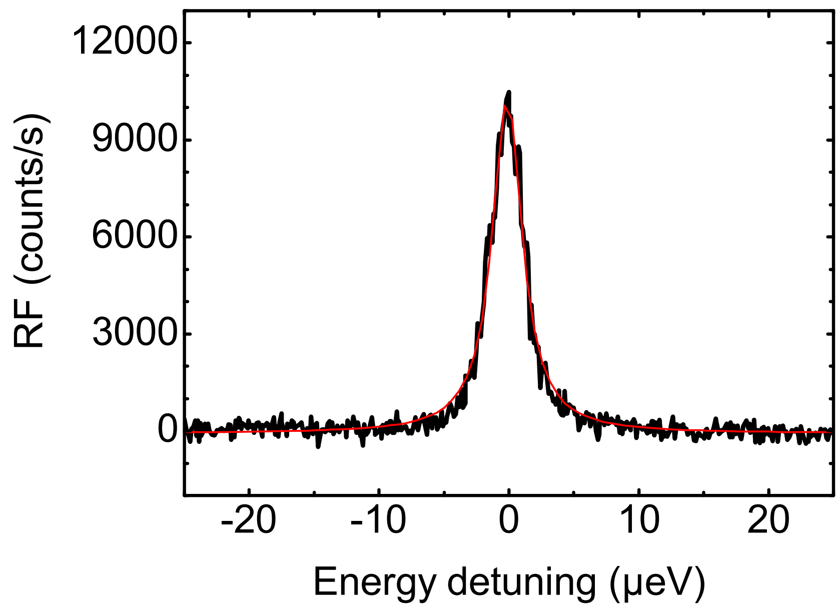
Non resonant excitation:

⇨ charge fluctuations incoherent spectroscopy



Self-Assembled Quantum Dots - Resonant Laser Spectroscopy

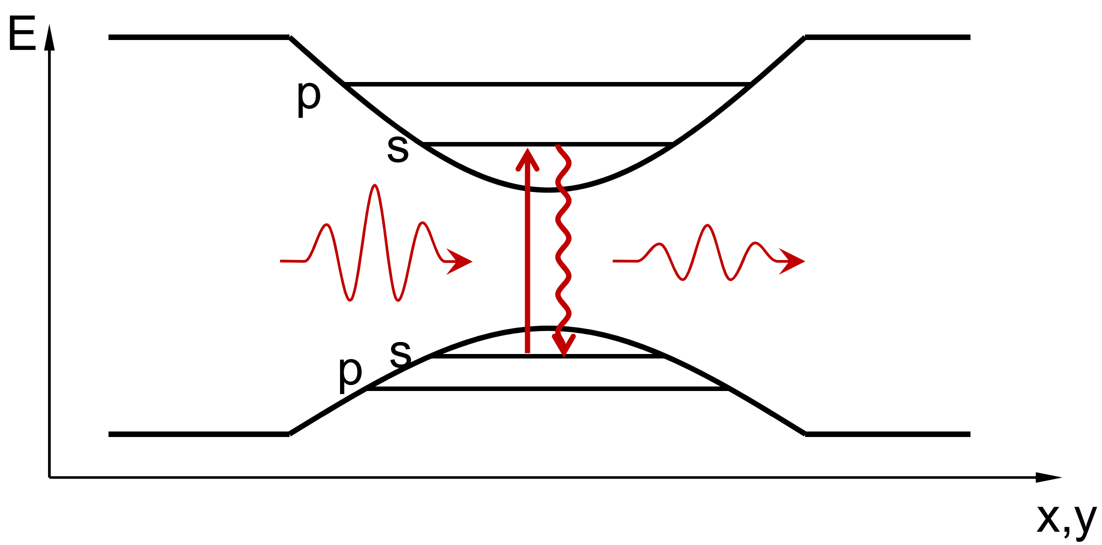
Excite exciton transition resonantly, measure scattered photons. (Laser suppression by polarization filtering)
⟹ Resonance fluorescence



Almost lifetime limited line width.
Here:

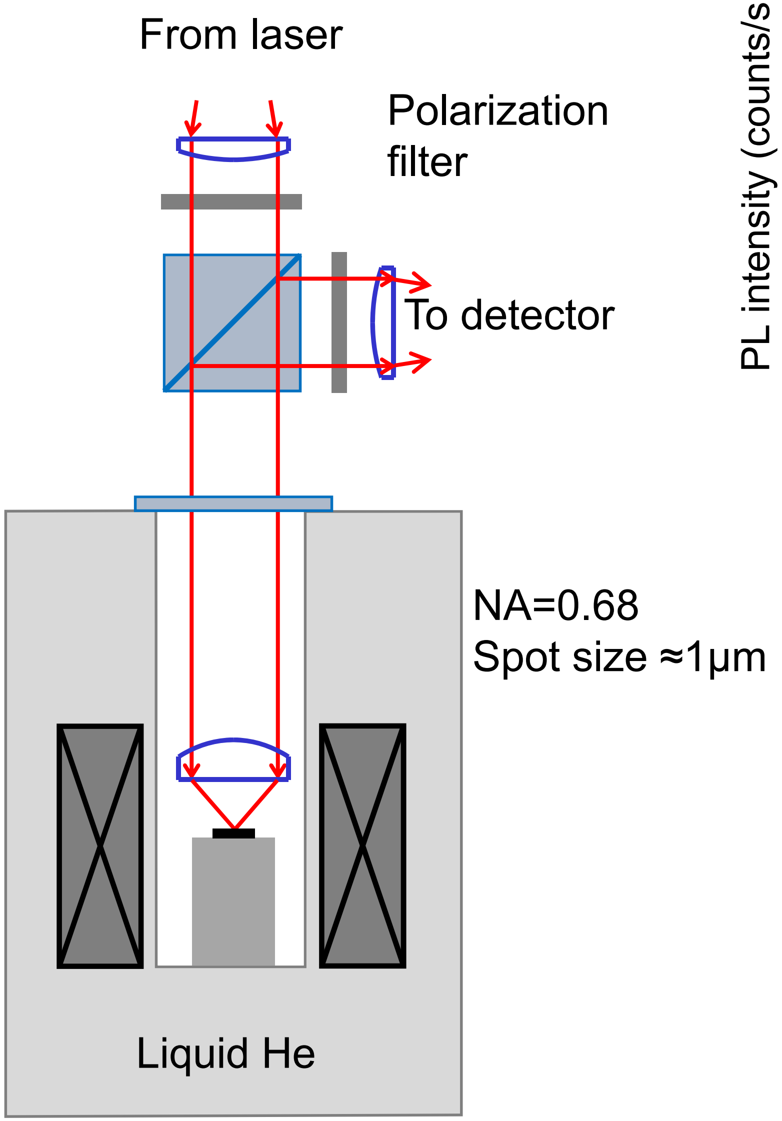
$$\mathrm{FWHM} = 2.8\mu e\mathrm{V}$$

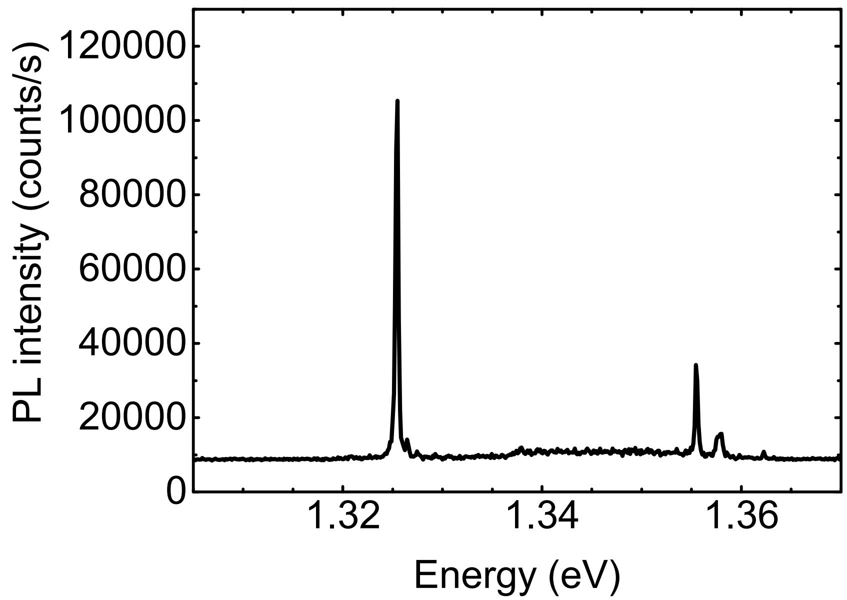
$$\Gamma = 1\mu e\mathrm{V} \quad \tau = 0.6\mathrm{ns}$$

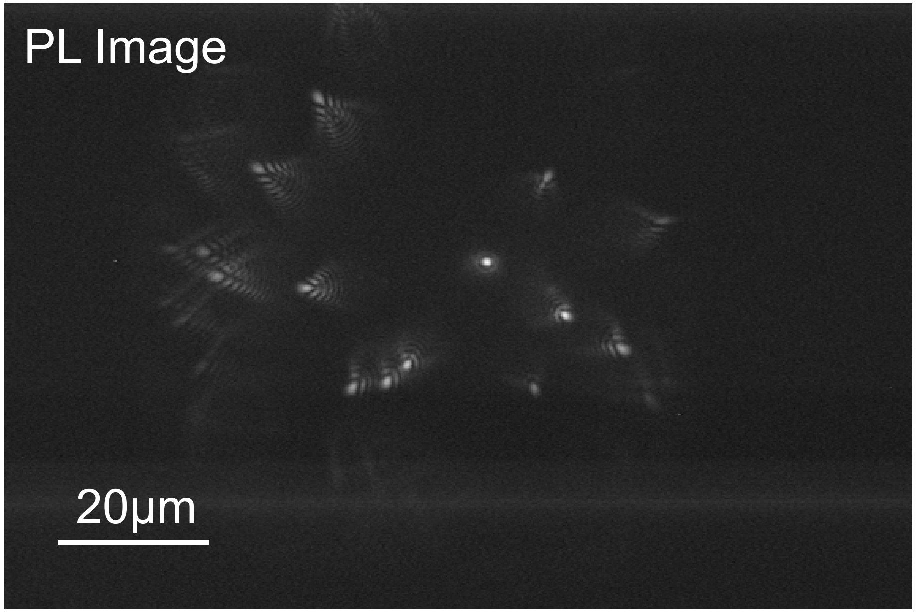


Atom like optical response
⟹ Artificial atom

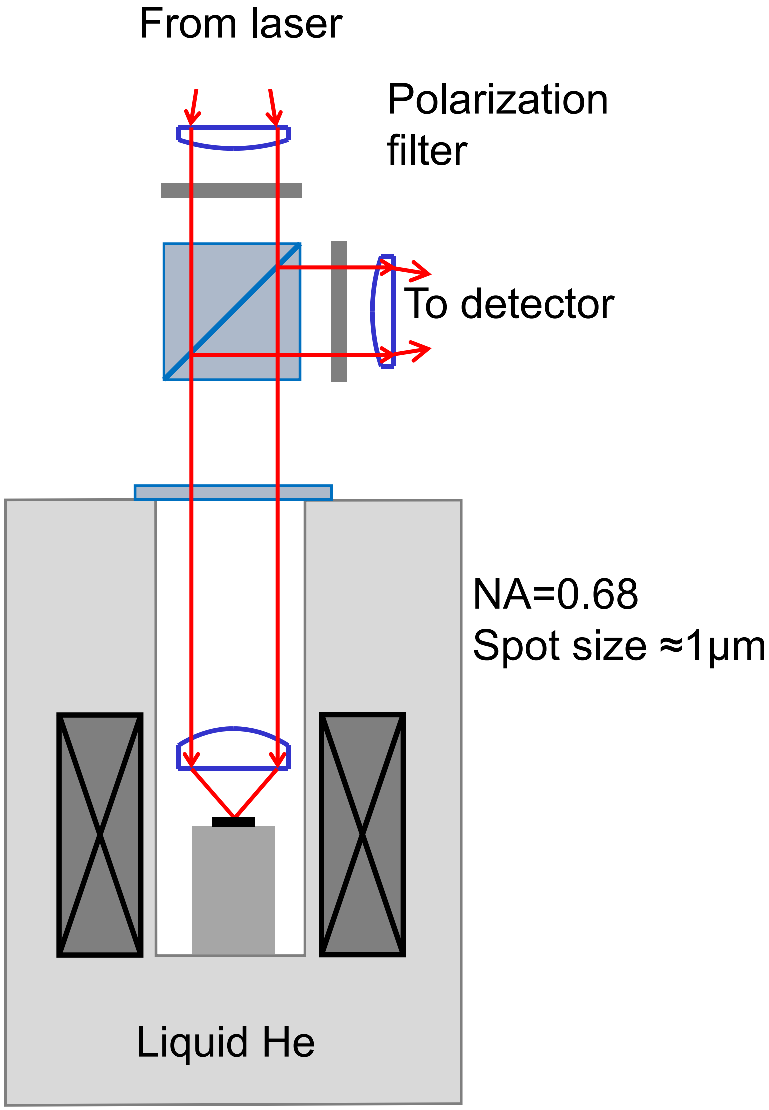
Self-Assembled Quantum Dots – Cryogenic Microscopy

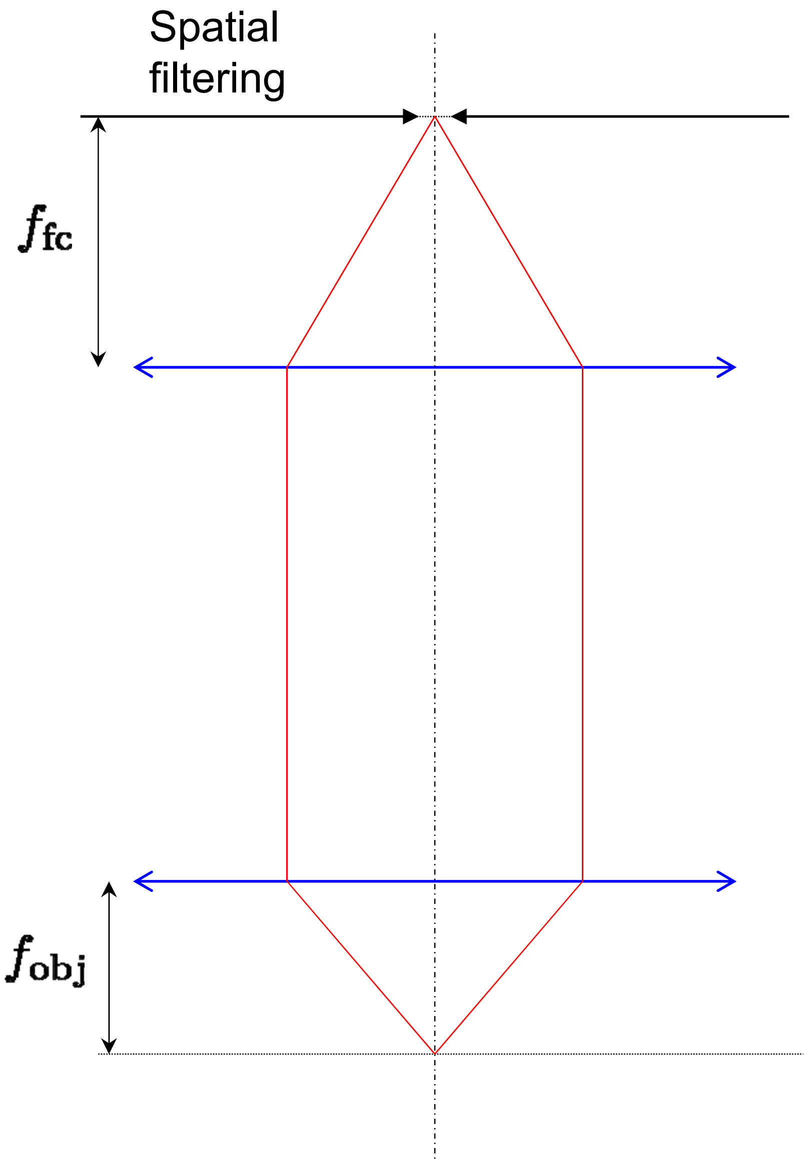






Confocal Microscopy





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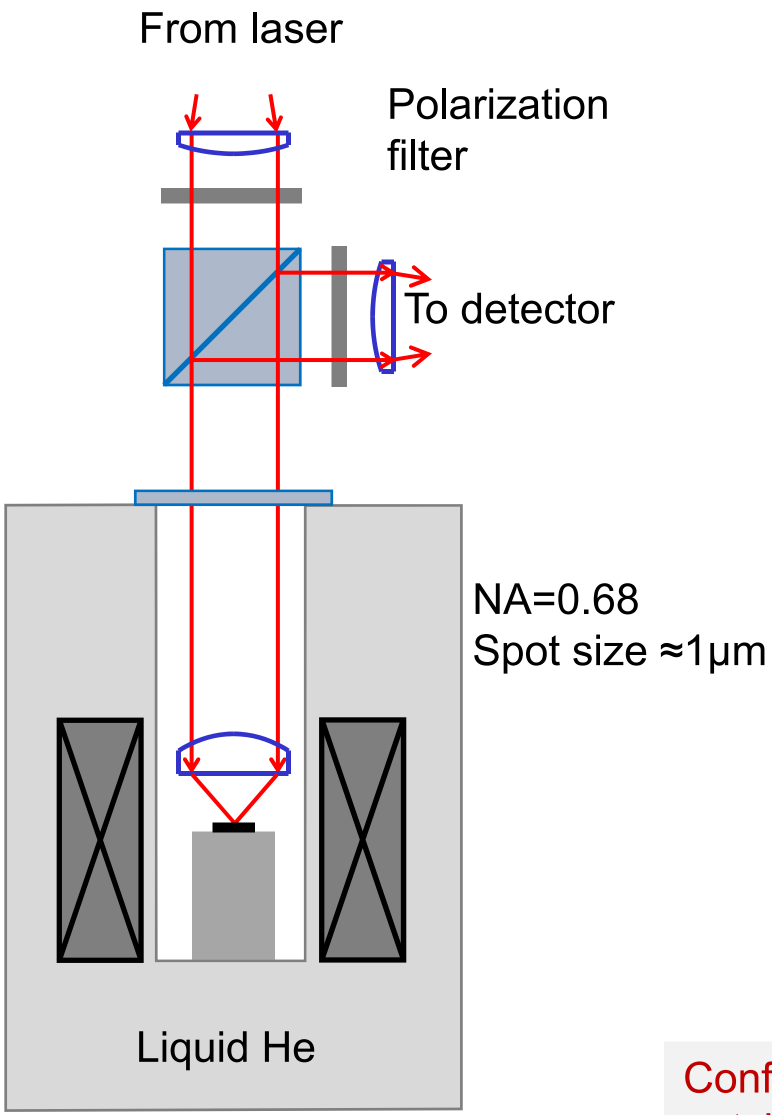
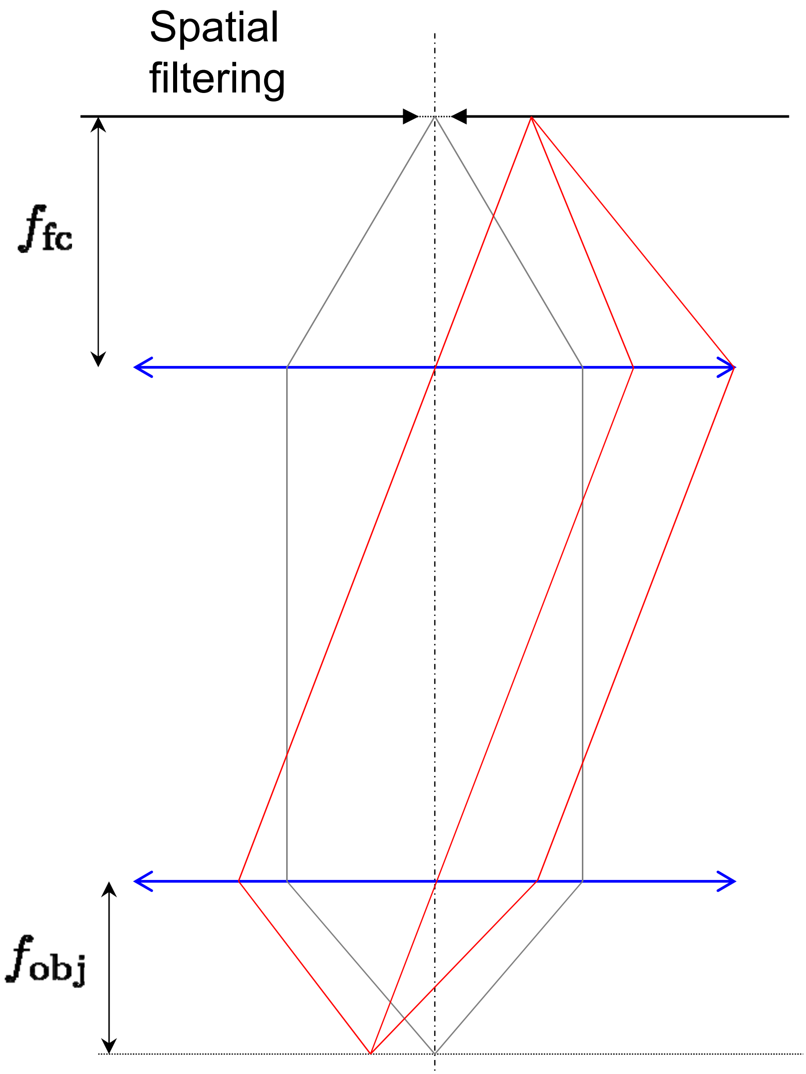
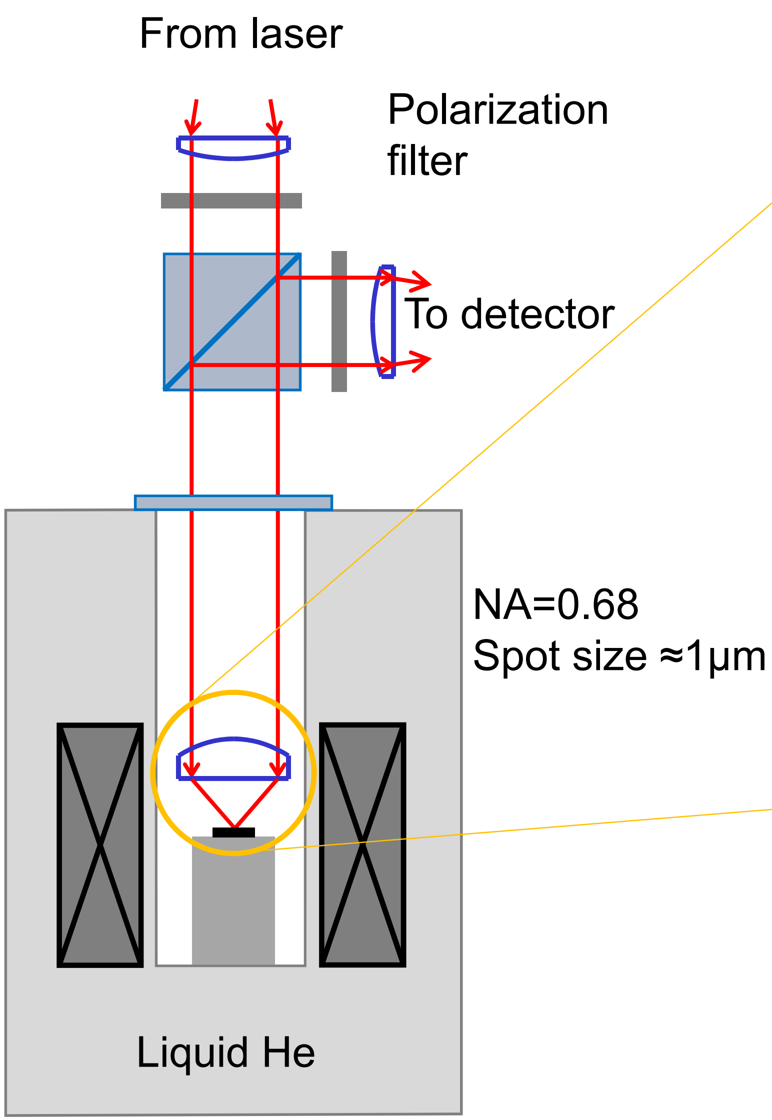
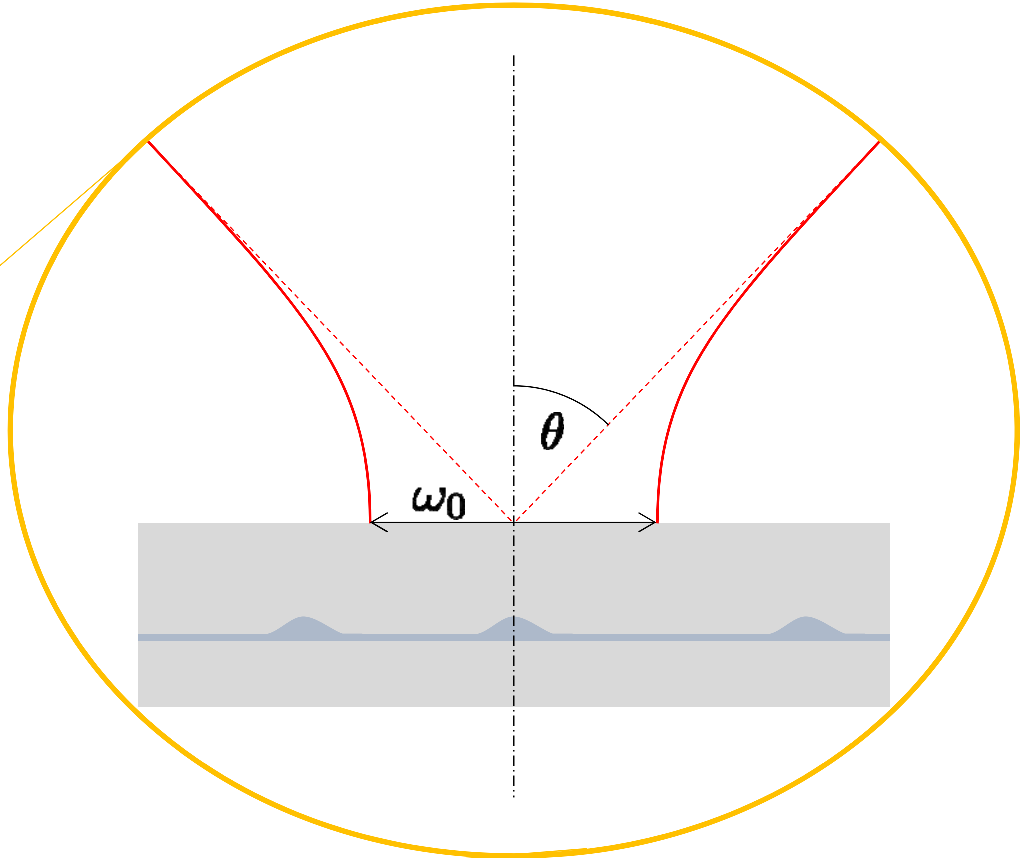




Confocal imaging – suppression of emission from outside the focal volume

Diffraction Limited Microscopy





Diffraction limited spot:

Spot size $\omega_0 = \frac{2\lambda}{\pi \mathrm{NA}}$

$$\lambda \approx 950\mathrm{nm}$$

$$\Longrightarrow \omega_0 \approx 1\mu\mathrm{m}$$

Photon Extraction from a QD

Extraction of photons:

Acceptance angle of objective:

$$\mathrm{NA} = n \sin(\theta) = 0.68$$
$$\theta = 43^\circ$$

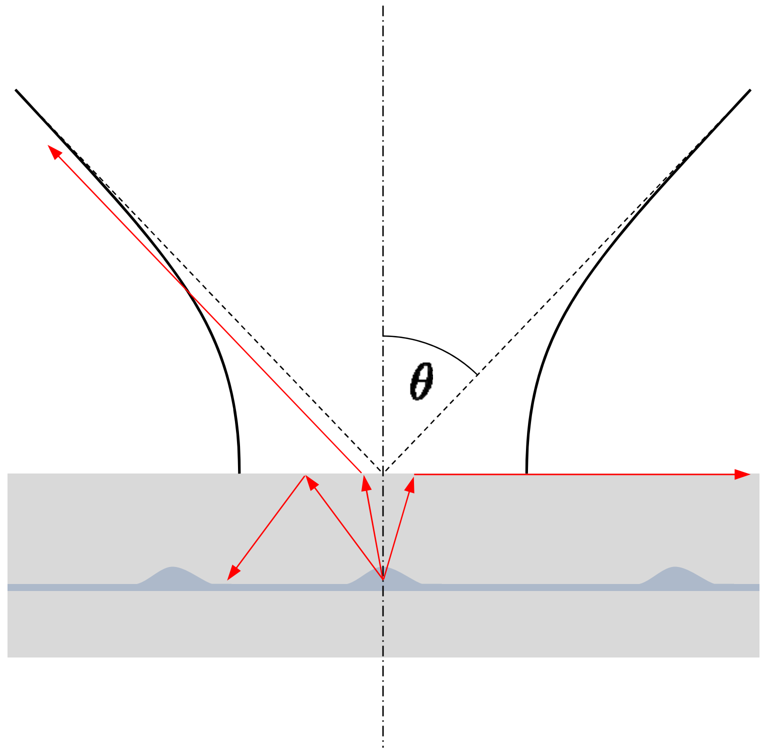
QD embedded in high refractive index GaAs:

$$n_{\mathrm{GaAs}} = 3.4$$

Angle of total internal reflection:

$$\alpha_{\mathrm{tot}} = 17^\circ$$

$$\alpha_{\mathrm{max}} = 11^\circ$$



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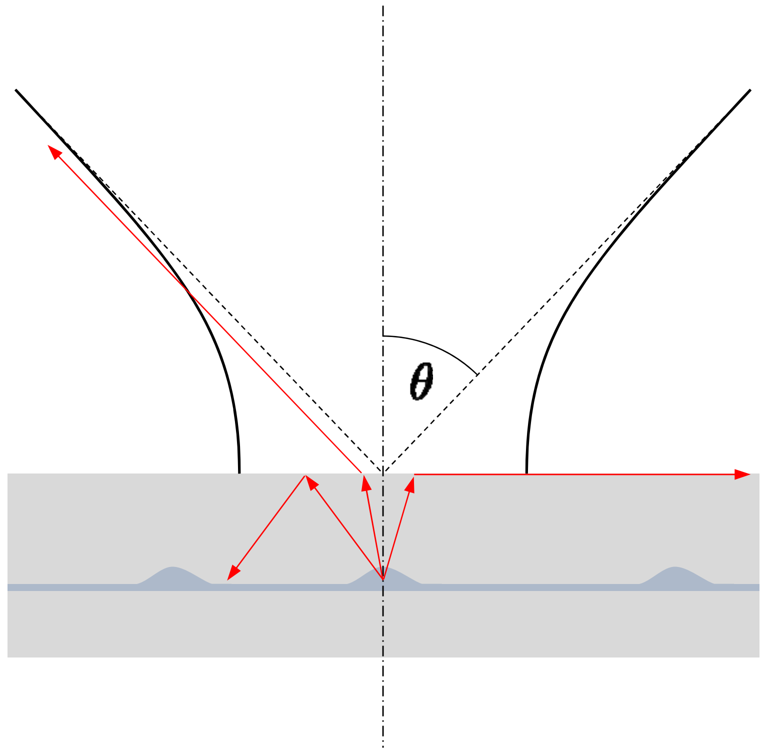


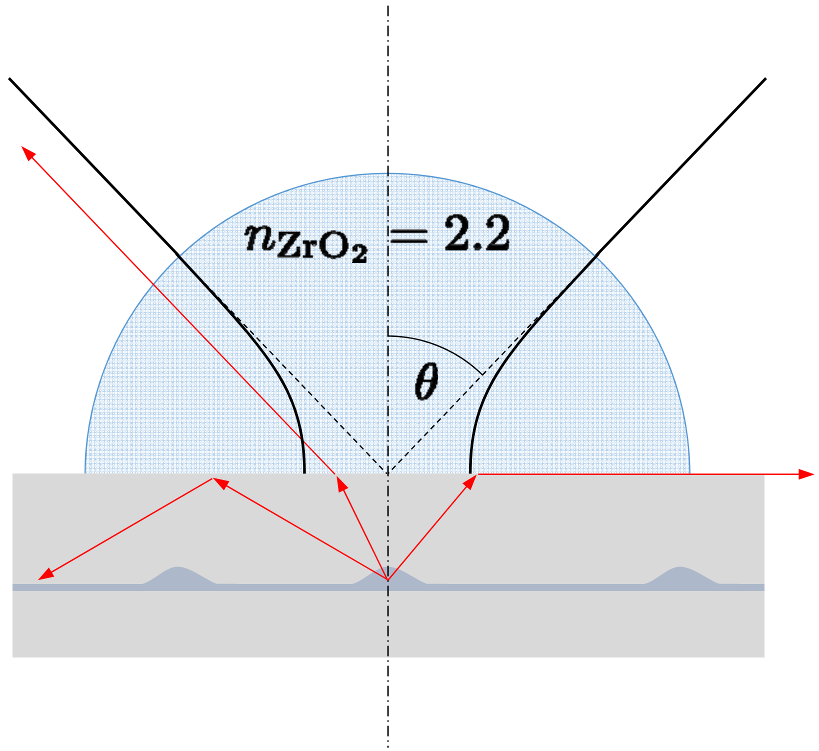
Photon Extraction from a QD

Extraction of photons with SIL:

$$\mathrm{NA} = n\sin(\theta) = 1.5$$

$$\alpha_{\mathbf{max}} = 26°$$

Light extracted from the sample passes perpendicular through the surface of the SIL



Increase NA of the objective with solid immersion lens

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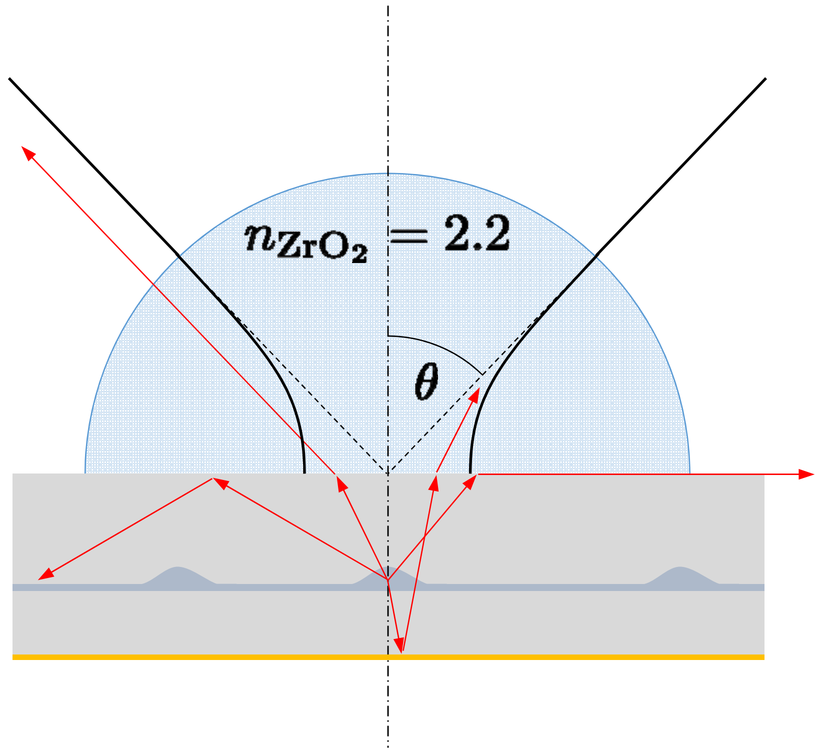
Enhance extraction efficiency by adding mirror behind QD



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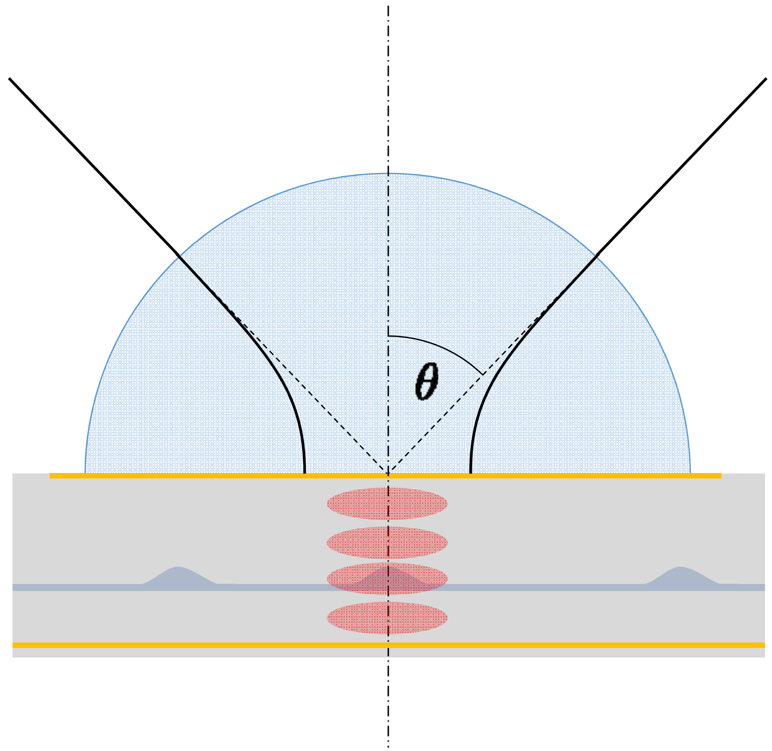
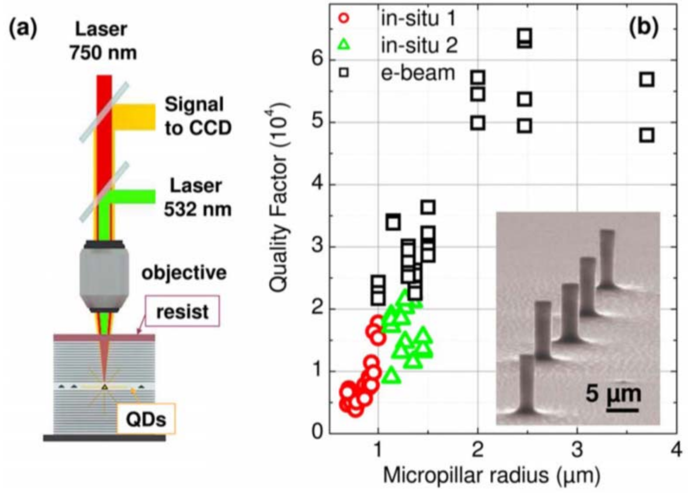


Enhance extraction efficiency by adding mirror behind QD

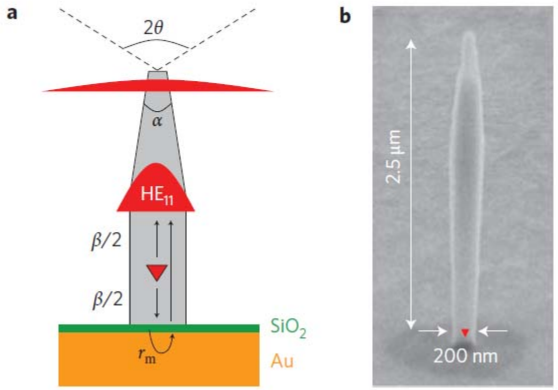
Enhance light matter coupling by embedding the QD into a cavity

With optimal coupling the collection efficiency can reach more than 10%

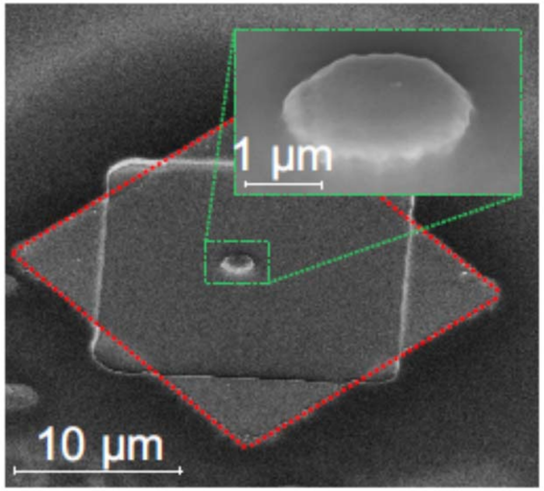
High Photon Extraction Efficiency from QDs



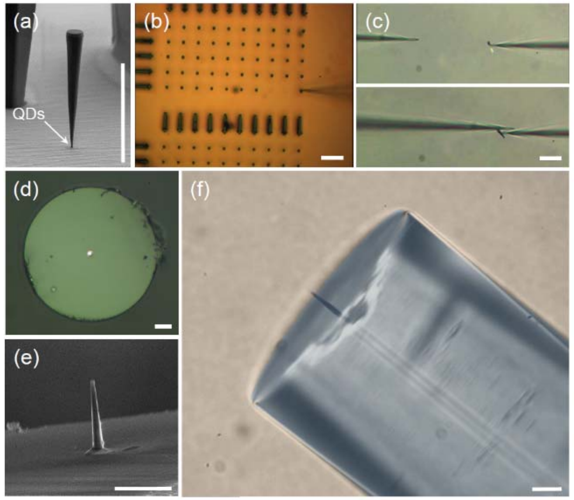
Collection efficiency >90%
A. Dousse, APL (2009).



Collection efficiency of 72%.
J. Claudon, et al., Nature Photonics (2010).

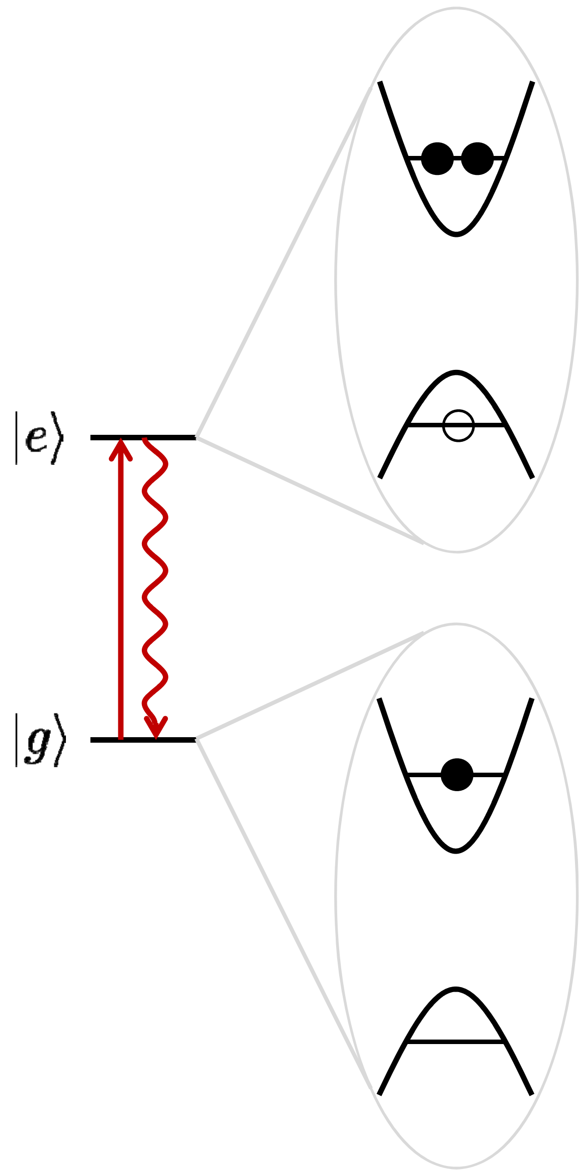


Collection efficiency 21%
A. Kaganskiy, ArXiv 1708.03512 (2017).

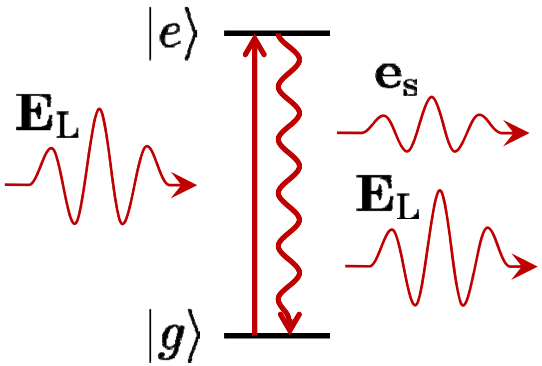


D. Cadeddu et al., Appl. Phys. Lett. 108, 011112 (2016).

Resonant Laser Spectroscopy



Interferometric Rayleigh scattering



Scattering response of the QD (weak excitation):

$$\mathbf{e_s} = \mathbf{E}_\mathrm{L}\sigma\frac{\delta\gamma + \mathrm{i}\gamma^2}{\delta^2+\gamma^2}$$

Scattering cross section σ
Laser detuning δ
Radiative damping rate $\gamma = \frac{\Gamma}{2}$

Coherently and incoherently scattered light:

$$\mathbf{e_s} = \mathbf{e_{coh}} + \mathbf{e_{incoh}}$$

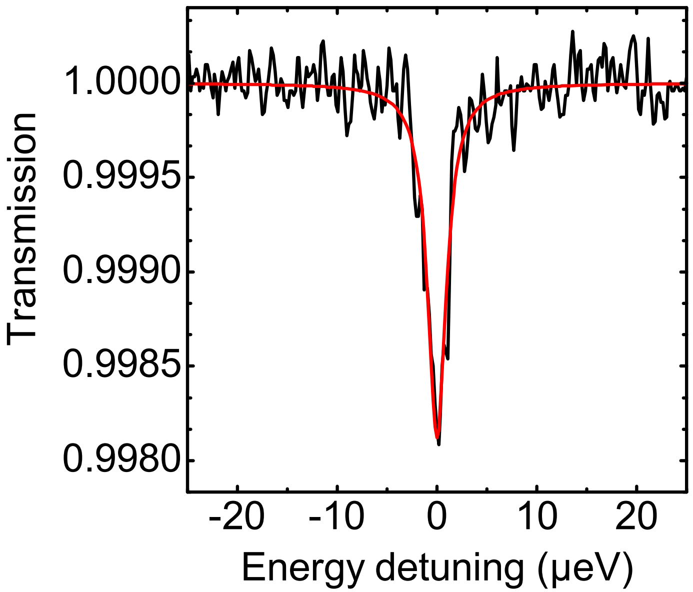
Coherently scattered light can interfere with laser light:

$$\Delta T = |\mathbf{E}_\mathrm{L}|^2 + 2\mathbf{e}_\mathrm{coh}\mathbf{E}_\mathrm{L} + |\mathbf{e}_\mathrm{coh}|^2$$

Transmission contrast:

$$\frac{\Delta T}{T} \approx 2\mathbf{e}_\mathrm{coh}\mathbf{E}_\mathrm{L} \sim \sigma\frac{\gamma^2}{\delta^2+\gamma^2}$$

Interferometric Rayleigh scattering



$\mathrm{FWHM} = 2.3\mu eV$

$\mathrm{contrast} = 0.2\%$

Scattering response of the QD (weak excitation):

$$\mathbf{e_s} = \mathbf{E}_\mathrm{L}\sigma\frac{\delta\gamma + i\gamma^2}{\delta^2+\gamma^2}$$

Scattering cross section σ

Laser detuning δ

Radiative damping rate $\gamma = \frac{\Gamma}{2}$

Coherently and incoherently scattered light:

$$\mathbf{e_s} = \mathbf{e_{coh}} + \mathbf{e_{incoh}}$$

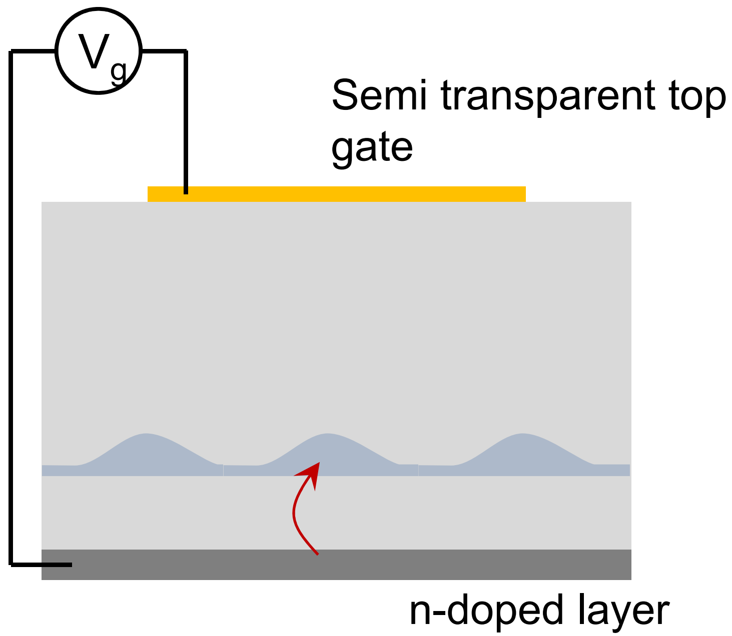
Coherently scattered light can interfere with laser light:

$$\Delta T = |\mathbf{E_L}|^2 + 2\mathbf{e}_\mathrm{coh}\mathbf{E_L} + |\mathbf{e}_\mathrm{coh}|^2$$

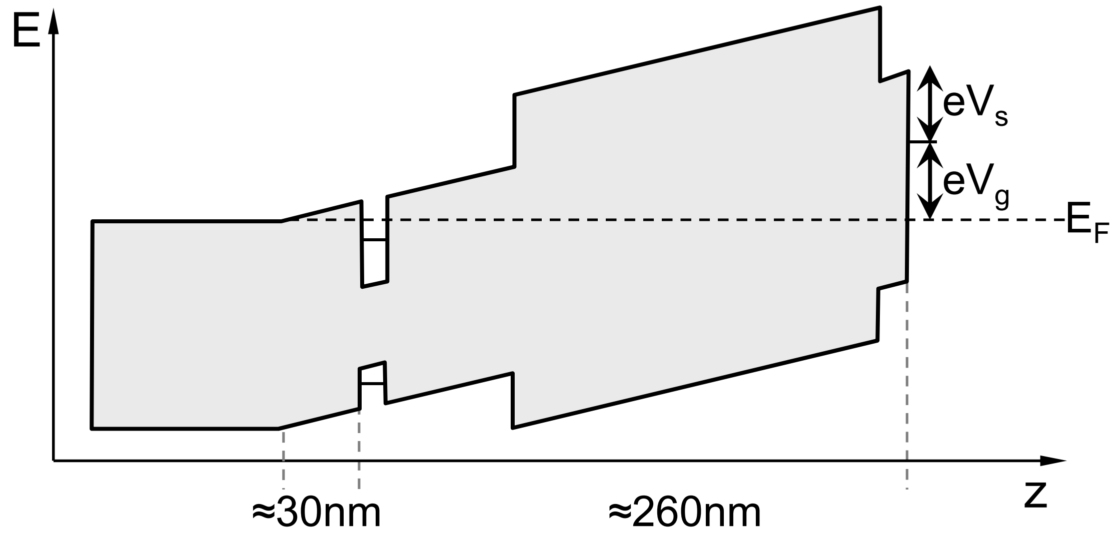
Transmission contrast:

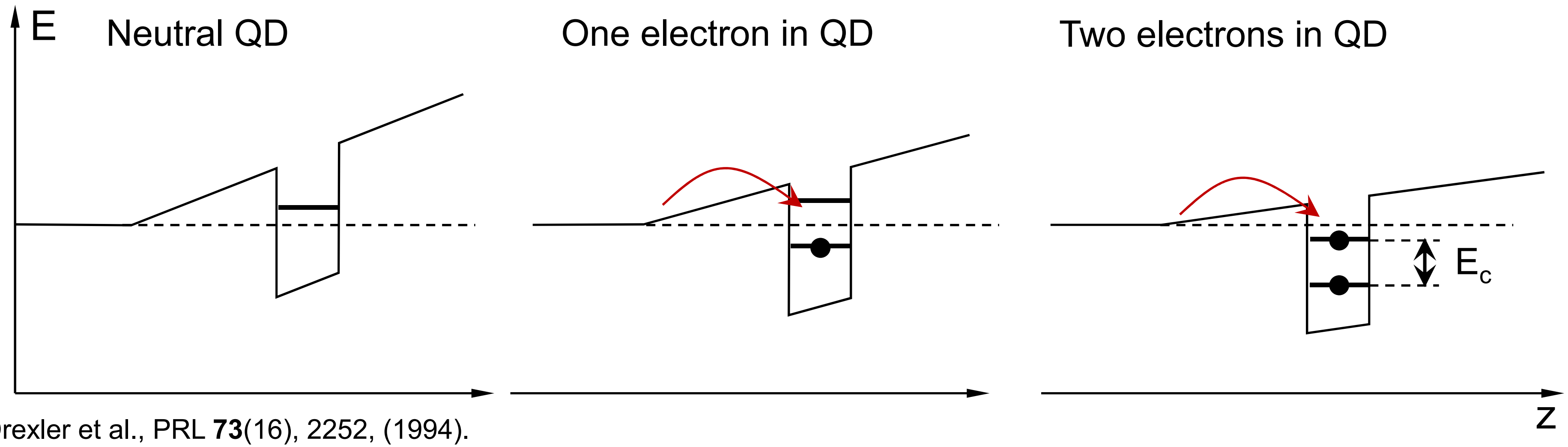
$$\frac{\Delta T}{T} \approx 2\mathbf{e}_\mathrm{coh}\mathbf{E_L} \sim \sigma\frac{\gamma^2}{\delta^2+\gamma^2}$$

Self-Assembled Quantum Dots - Charge tunable Quantum Dots



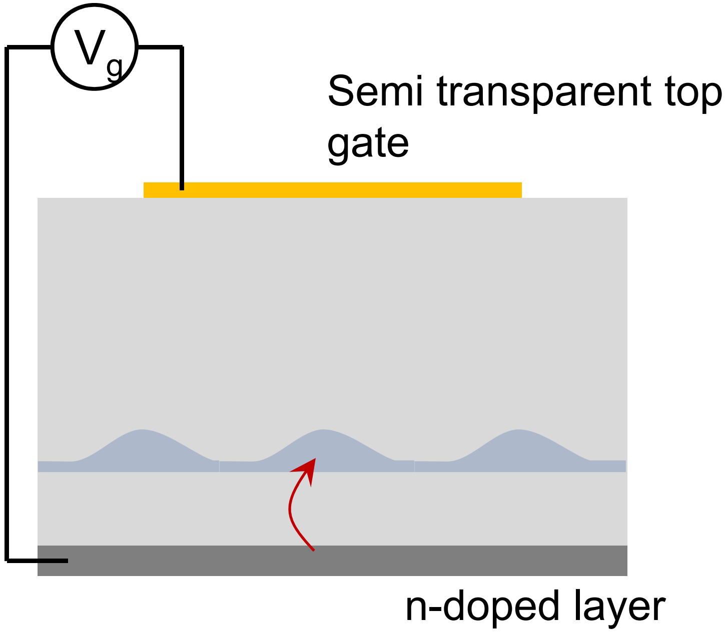
QD layer embedded in field effect structure
⇨ apply electric field in growth direction.



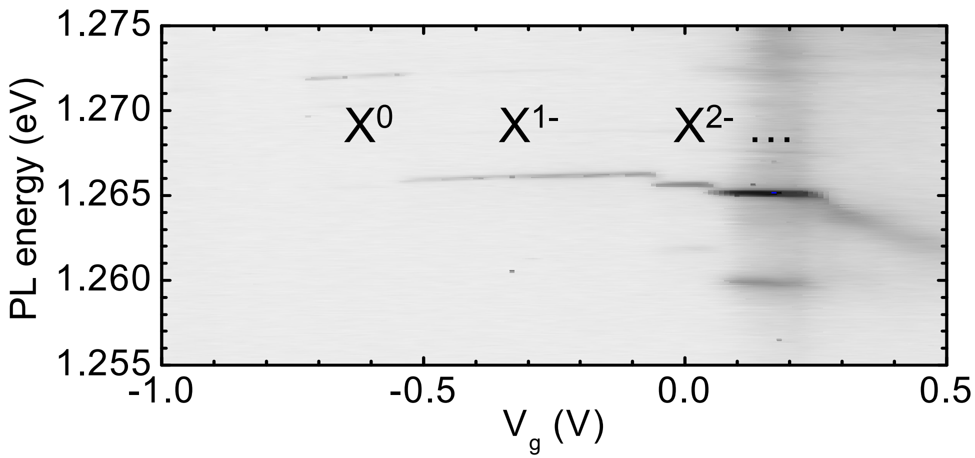


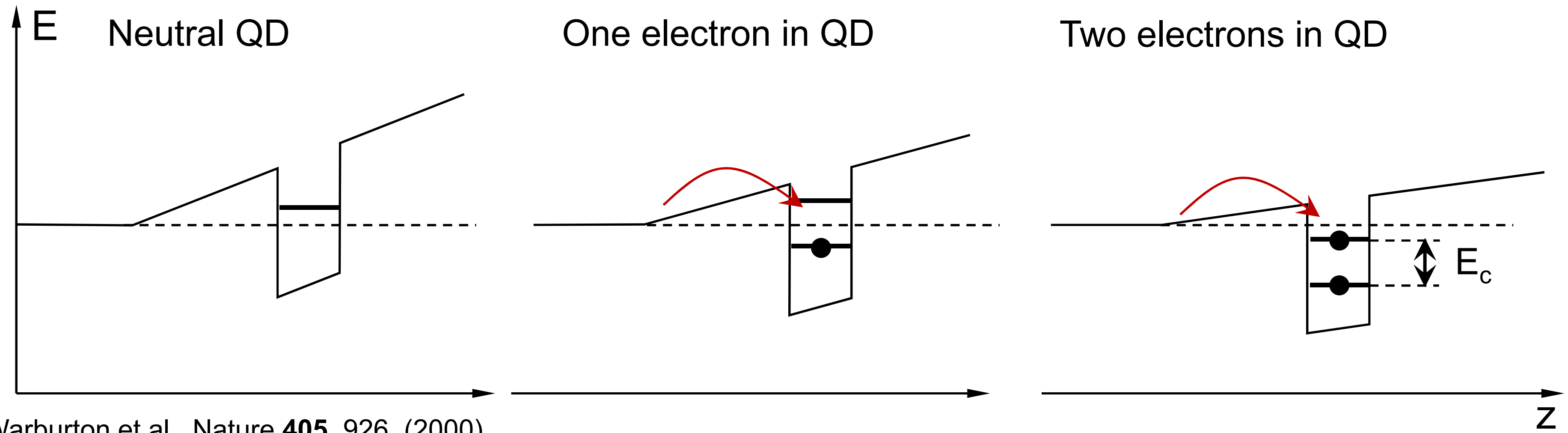
Drexler et al., PRL **73**(16), 2252, (1994).

Self-Assembled Quantum Dots - Charge tunable Quantum Dots



Charge of QD changes exciton energy
⟹ map out charge state by PL.

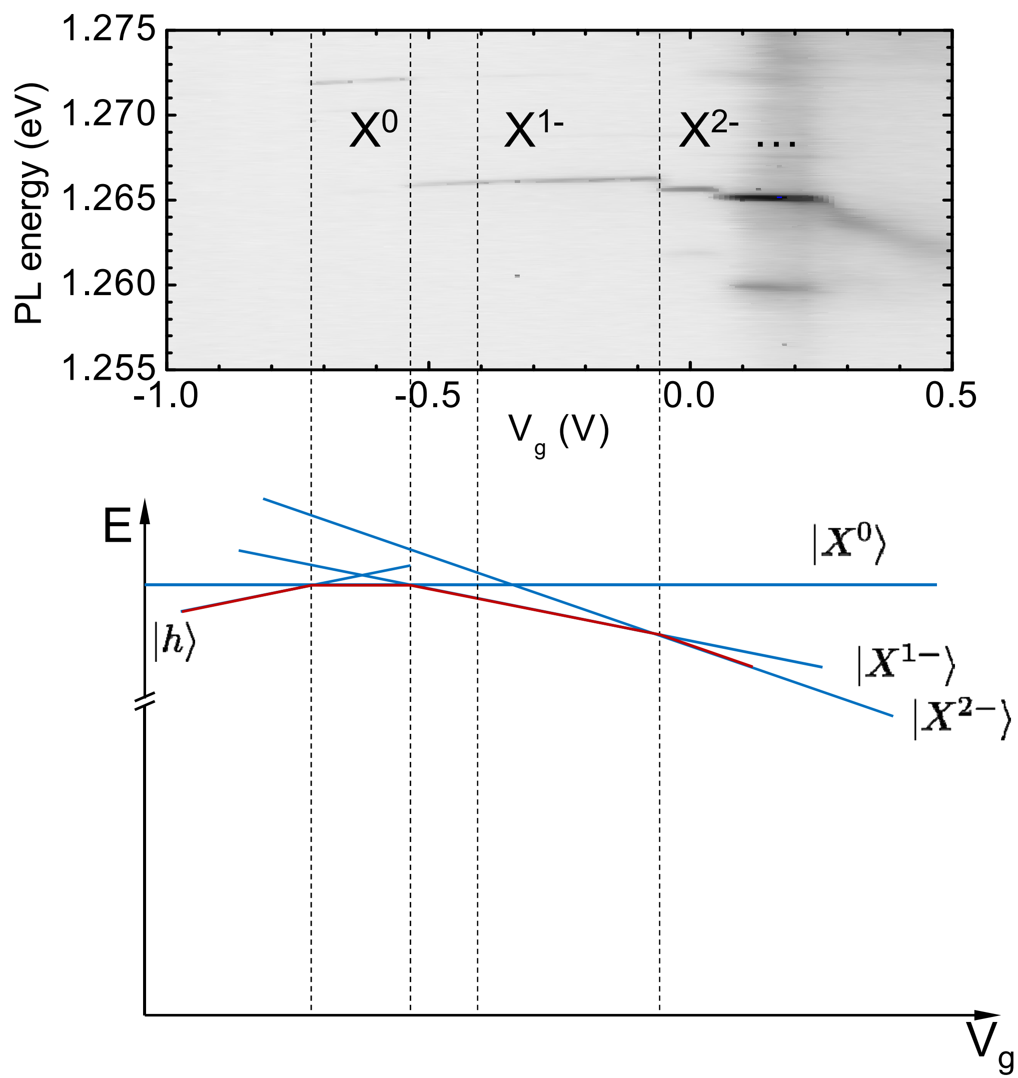




Warburton et al., Nature **405**, 926, (2000).

Self-Assembled Quantum Dots - Coulomb Interactions

Charge of QD changes exciton energy
⟹ map out charge state by PL.



Self-Assembled Quantum Dots - Coulomb Interactions

Typical Coulomb energies:

$$E^{\mathrm{ee}} = 23\mathrm{me}V$$
$$E^{\mathrm{eh}} = 29\mathrm{me}V$$

Typical ionization energy:

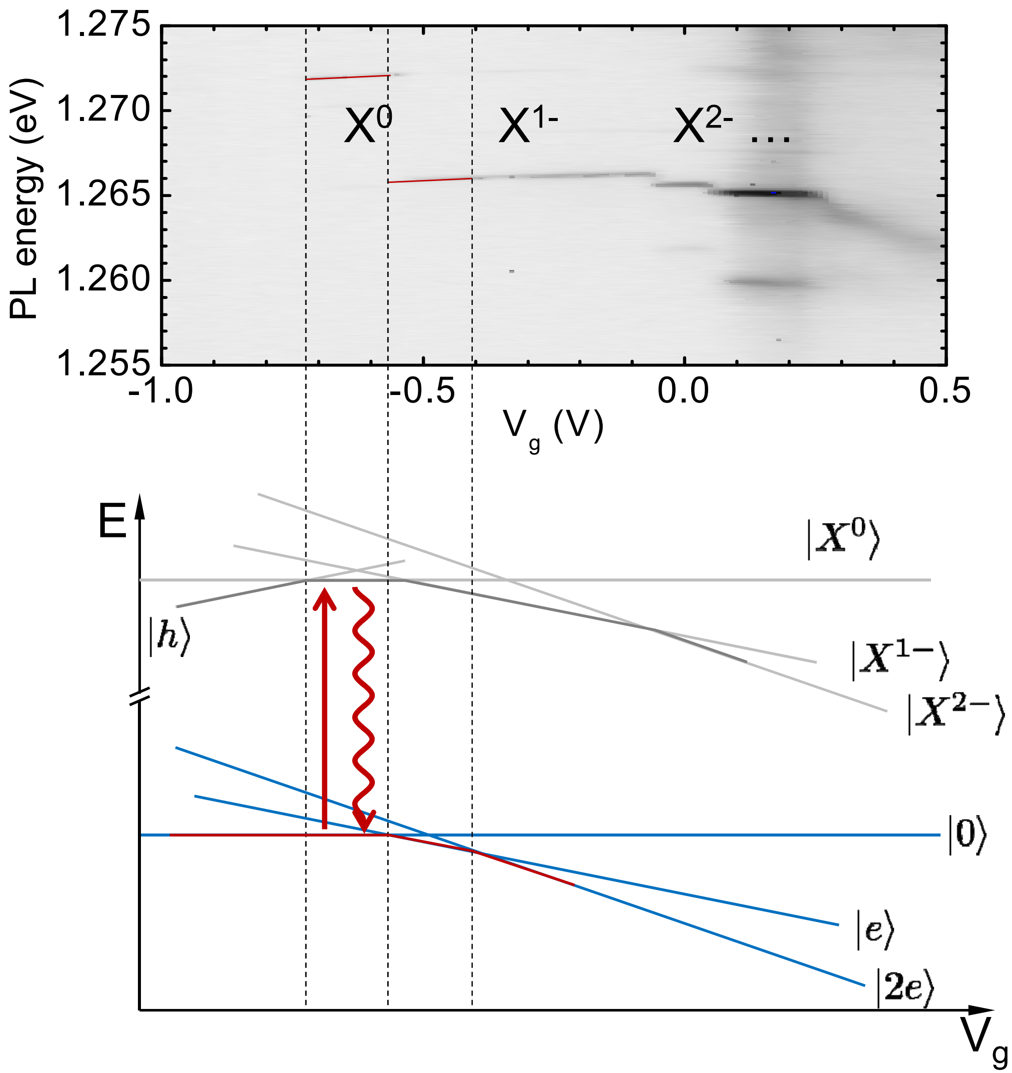
$$E_{\mathrm{C}} = 134\mathrm{me}V$$

Length of X^{1-} Plateau:

- RF $\Longrightarrow$ charging energy,
- PL $\Longrightarrow$ quantization energy.

(Remember: Coulomb diamonds in transport spectroscopy)

Charge of QD changes exciton energy
$\Longrightarrow$ map out charge state by PL.



Seidl et al., PRB **72**, 195339, (2005).

Self-Assembled Quantum Dots – Quantum Confined Stark Effect

Exciton energy in electric field:

$$E_{\mathbf{X}}(F) = E_0 + p_{\mathbf{z}}F + \beta F^2$$

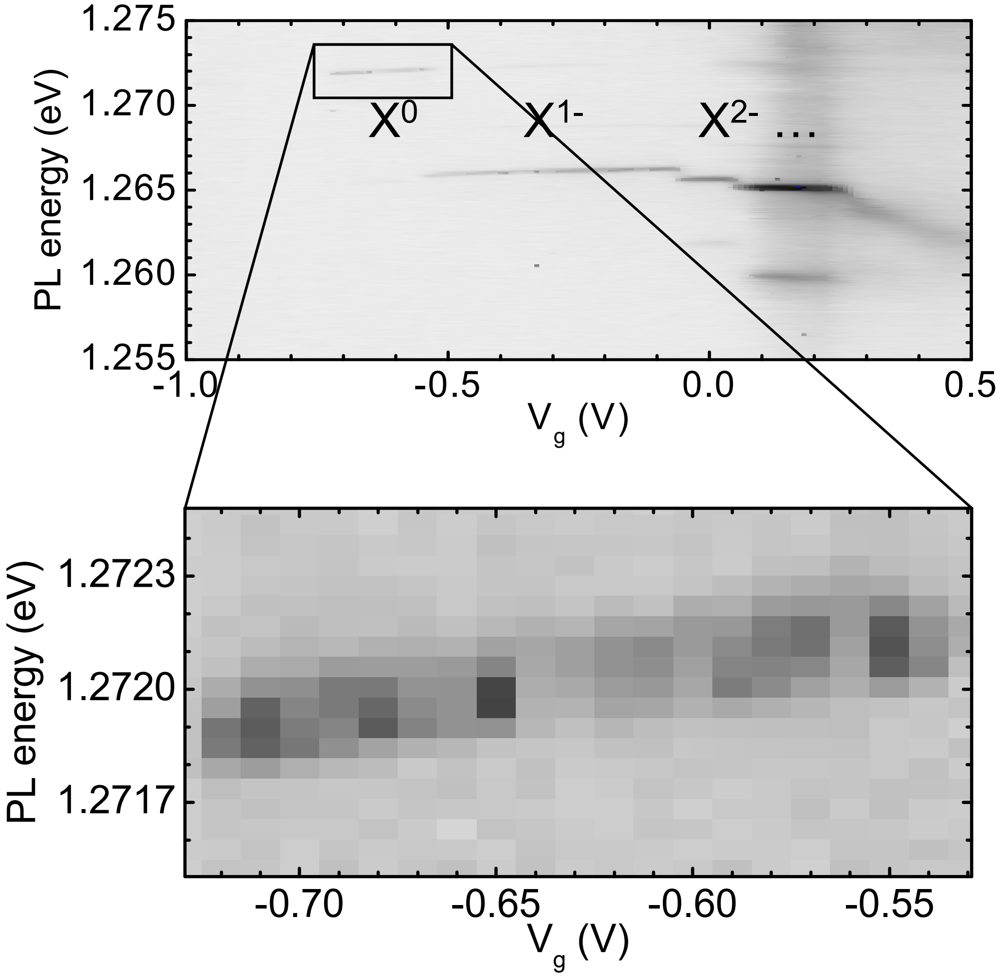
Exciton dipole moment

$$\frac{p_{\mathbf{z}}}{e} \approx 0.1\mathrm{nm}$$

Polarizability

$$\frac{\beta}{e} \approx -40\mathrm{nm}^2/\mathrm{V}$$

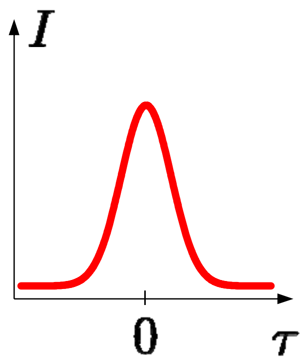
Exciton energy can be controlled via applied gate voltage

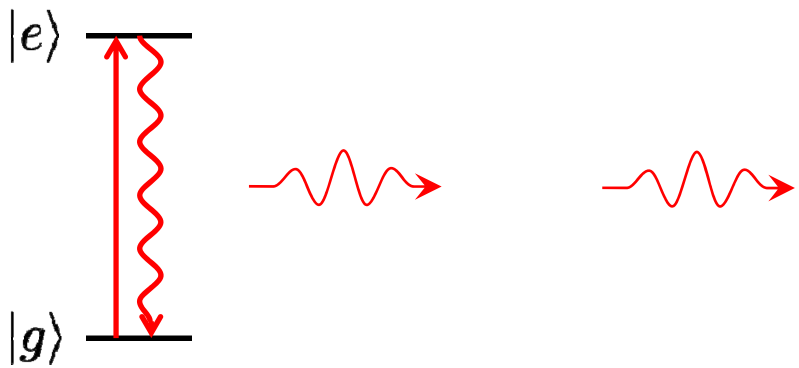


Finley, et al., PRB **70**, 201308 (2004)

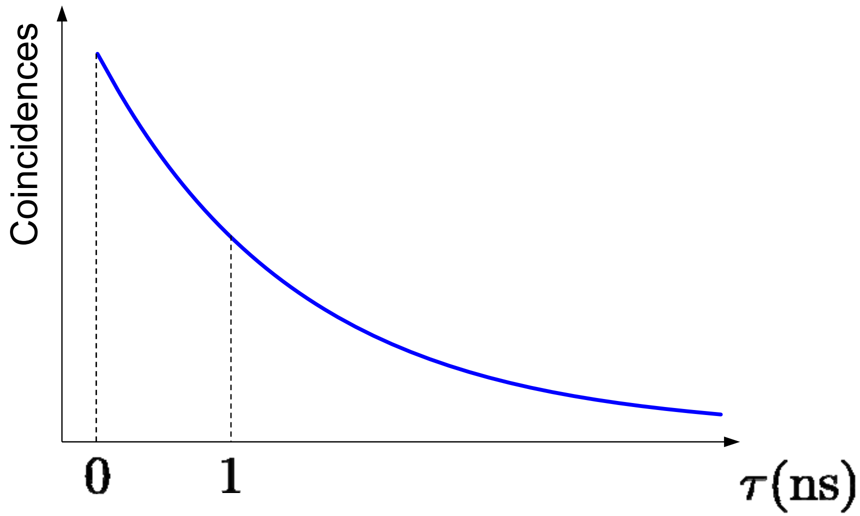
QD as a Single Photon Emitter

Short laser pulse (ps) → Record time between laser pulse and photon detection event



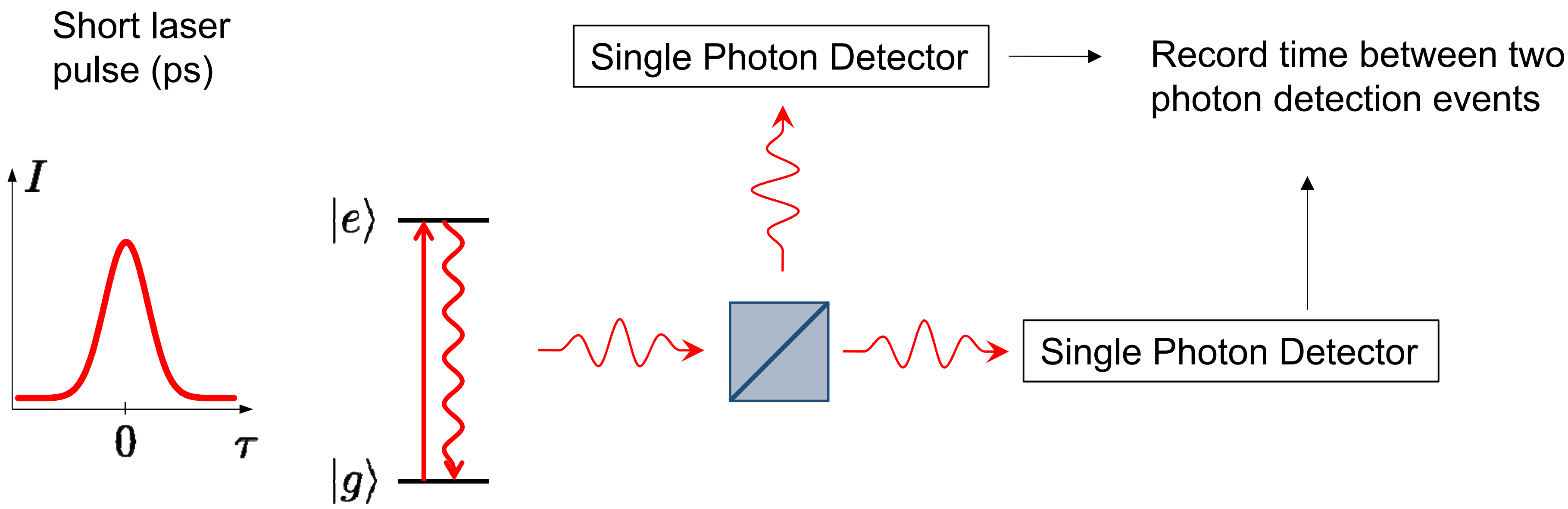


Single Photon Detector



Radiative lifetime of a QD exciton ≈1ns

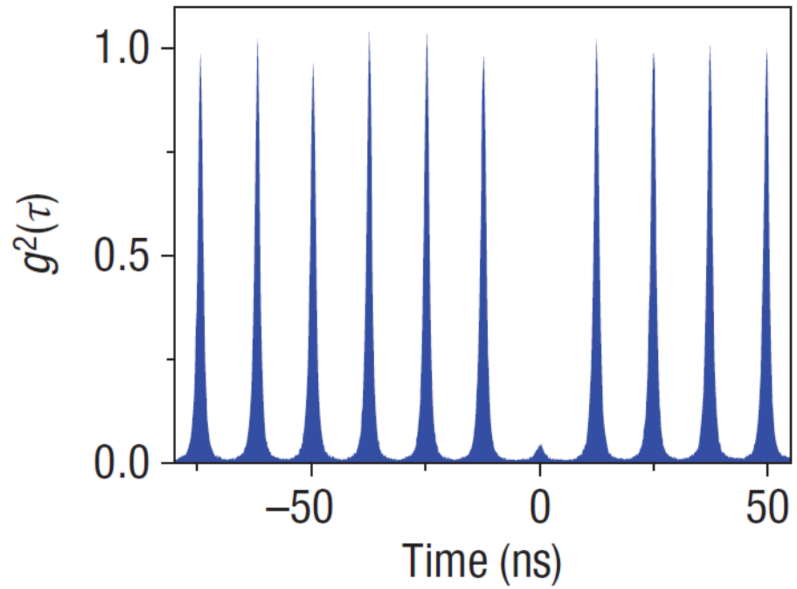
QD as a Single Photon Emitter



Hanbury Brown and Twiss experiment:
Measure second order correlation function:

$$g^{(2)}(\tau) = \frac{\langle I(\tau) I(0) \rangle}{\langle I(\tau) \rangle \langle I(0) \rangle}$$

Quantum dot is a (perfect) single photon emitter



S. Strauff, et al., Nat. Phot. **27**, 704 (2007)

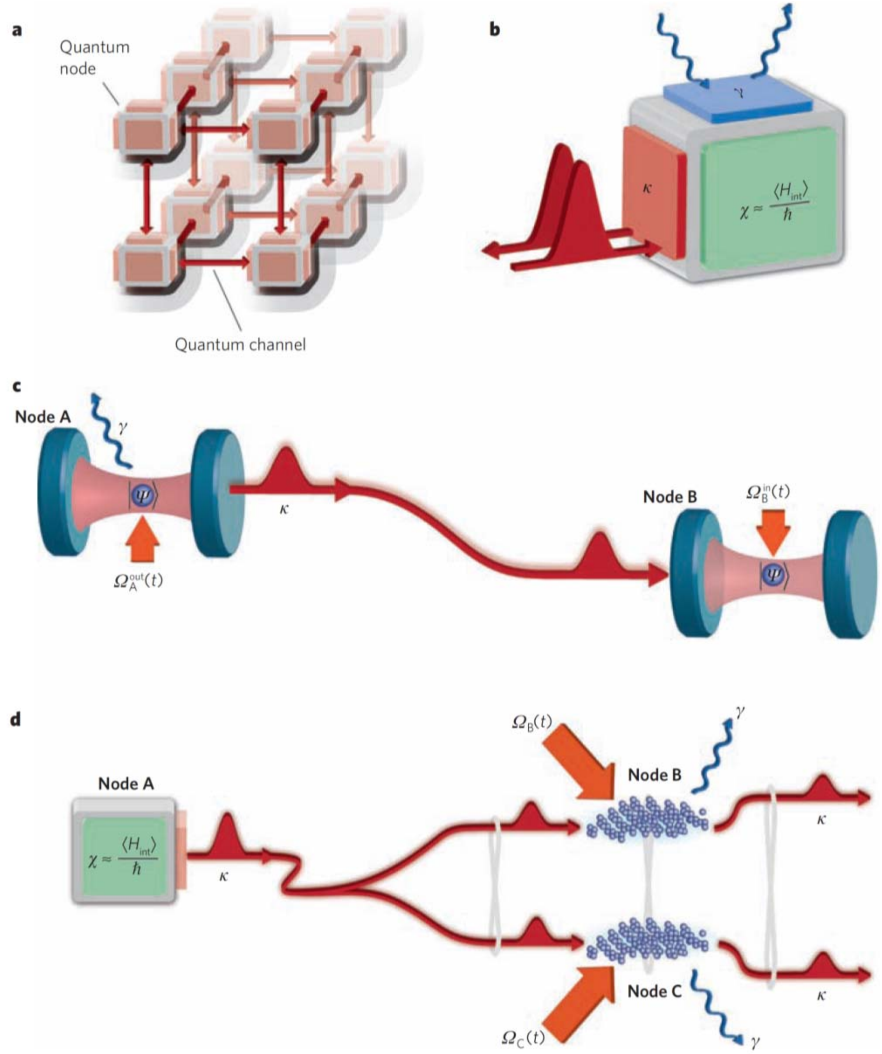
Towards a Quantum Network

Vision:

Quantum information and communication

Requires:

- Quantum nodes (Qubits)
- Quantum channels:
  - Quantum state transfer
  - Entanglement distribution



Quantum dots as toy model to explore these tasks

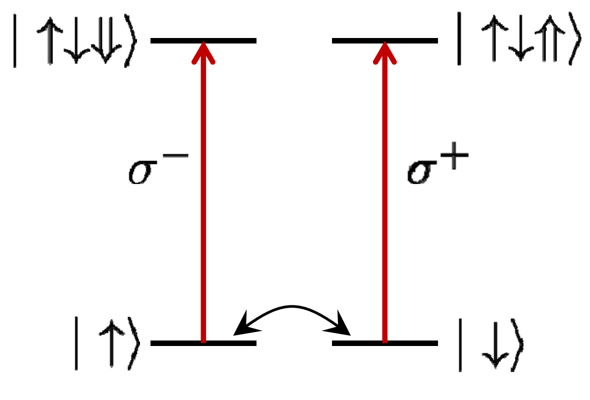
Node: Quantum dot
Qubit: Electron (or hole) spin in a QD
Quantum channel: Photon

*H. J. Kimble, Nature **453**, 1023-1030 (2008).*

Spin Qubit

Single electron in a QD:

- Degenerate spin states
- Fast spin decay and decoherence



S. Seidl PRB **72**, 195339, (2005).

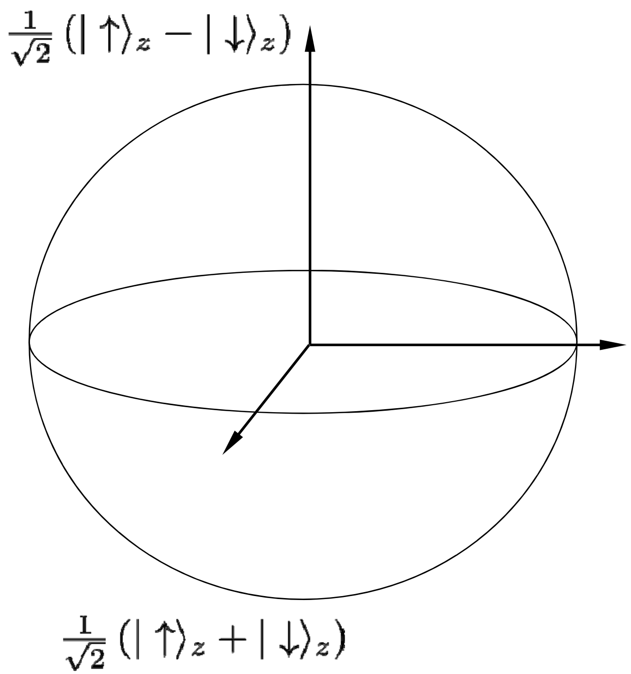
Spin Qubit

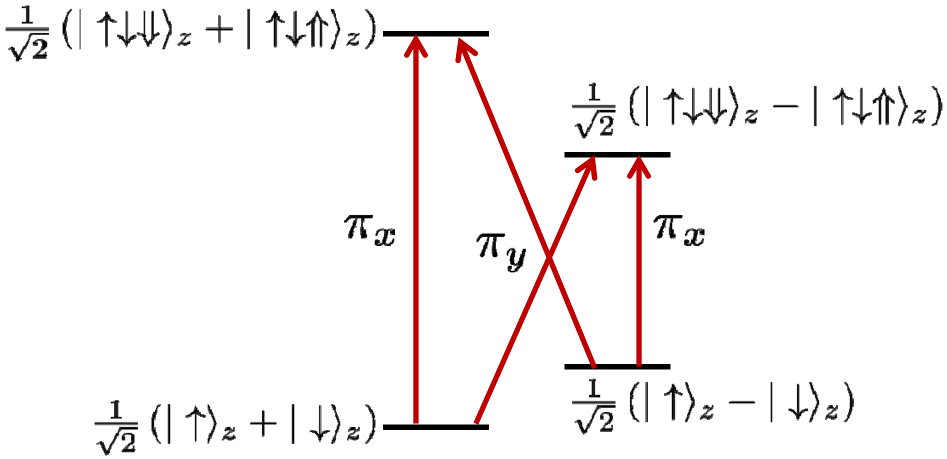
Single electron in a QD:

- Degenerate spin states
- Fast spin decay and decoherence

⇨ Apply external magnetic field (i.e. in the QD plane)

⇨ All optical transitions allowed





Represent electron spin state on Bloch sphere

M. Kroner PRB **78**, 075429, (2008).

Spin Qubit

Single electron in a QD:

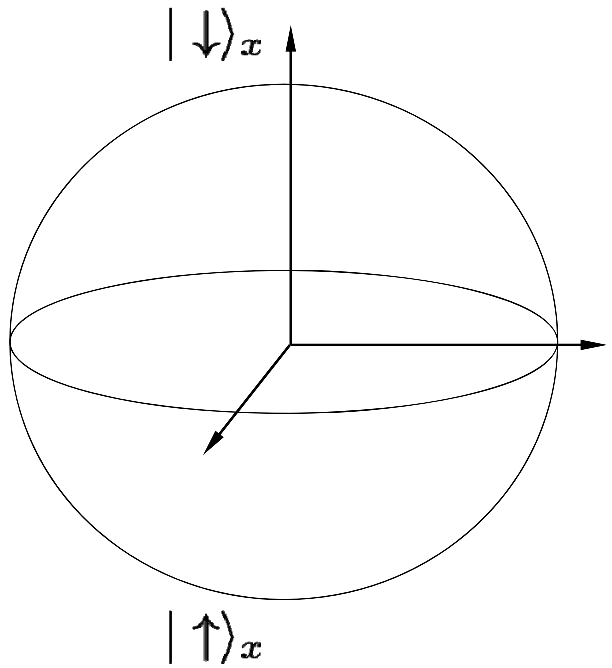
- Degenerate spin states
- Fast spin decay and decoherence

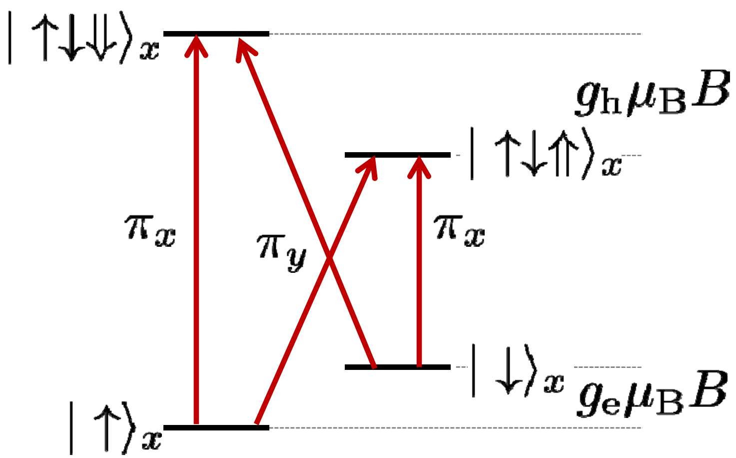
⇨ Apply external magnetic field (i.e. in the QD plane)

⇨ All optical transitions allowed

Eigenstates split by Zeeman energy

Represent electron spin state on Bloch sphere

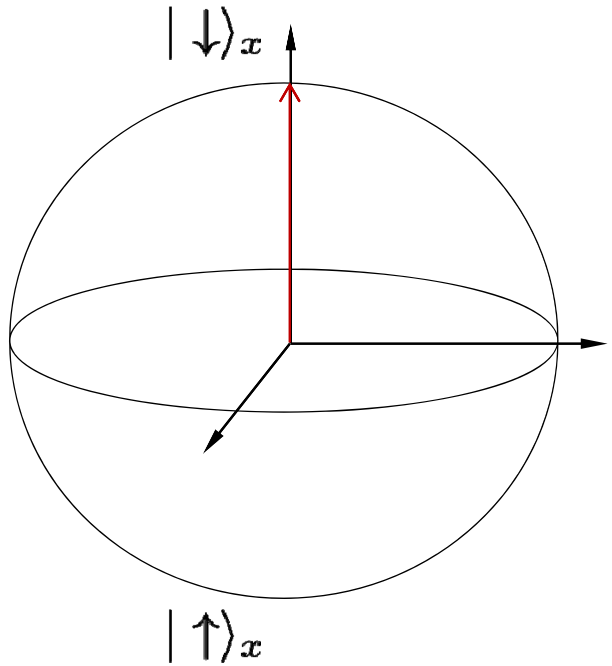


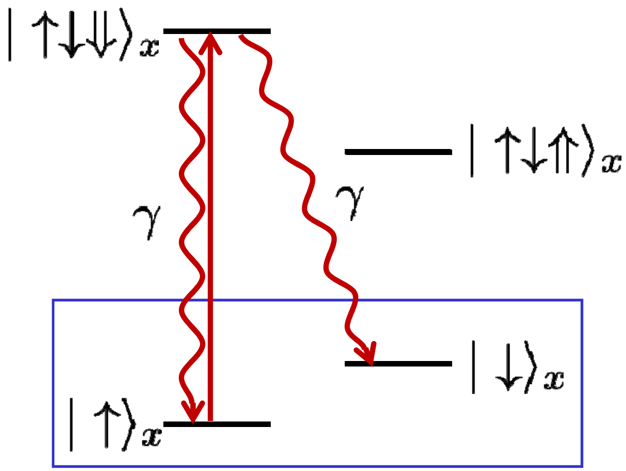


M. Kroner PRB **78**, 075429, (2008).

Electron Spin Initialization

Spin initialization and measurement by resonant pumping.



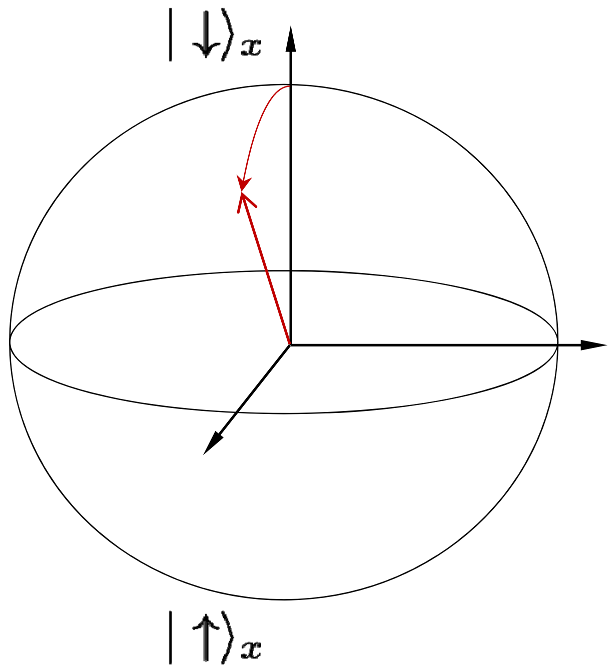


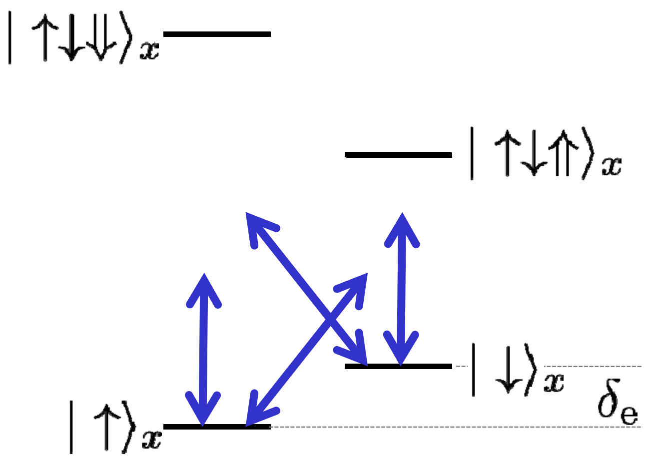
X. Xu PRL **99**, 097401, (2007).

Coherent Spin Rotation

All optical spin rotation:

Send short, detuned, circular polarized laser pulse.





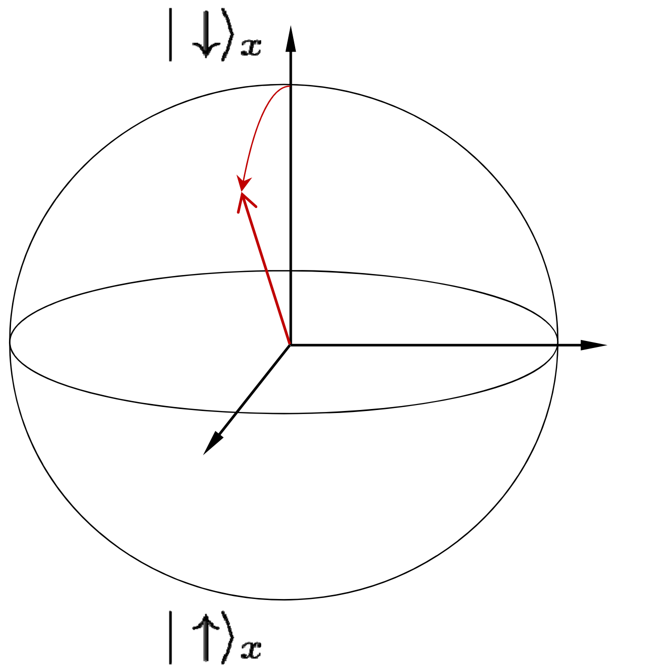
D. Press Nature **456**, 218, (2008).

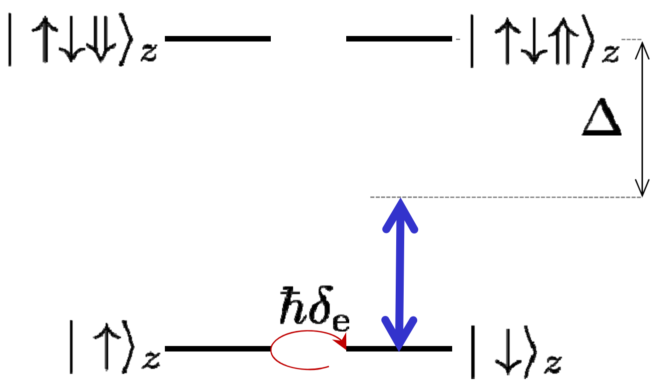
Coherent Spin Rotation

All optical spin rotation:

Send short, detuned, circular polarized laser pulse.

In z-basis:
Laser leads to ac-Stark shift.





D. Press Nature **456**, 218, (2008).

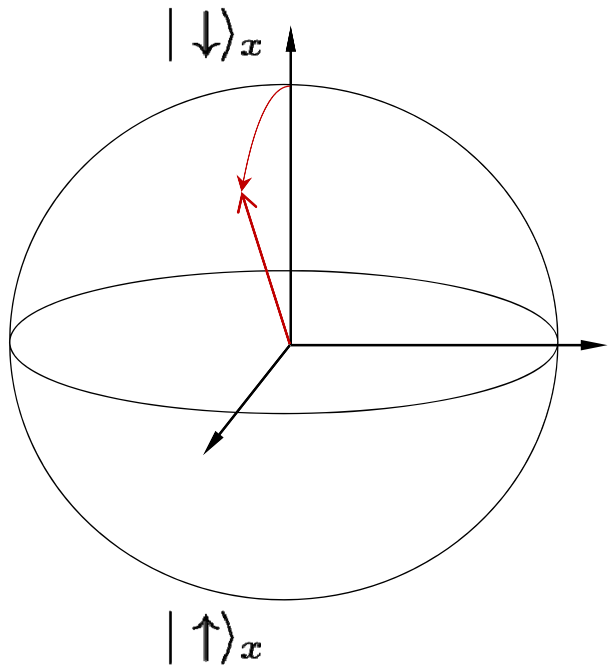
Coherent Spin Rotation

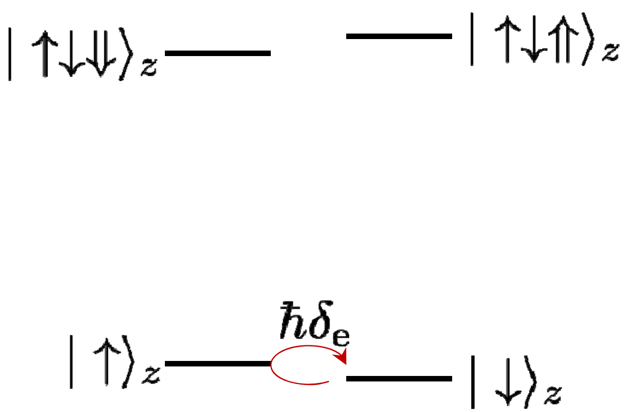
All optical spin rotation:

Send short, detuned, circular polarized laser pulse.

In z-basis:
Laser leads to ac-Stark shift.
$\Longrightarrow$ Effective magnetic field in z-direction.

$\Longrightarrow$ Spin rotation around x-axis.





D. Press Nature **456**, 218, (2008).

Self-Assembled Quantum Dots – Coherent Spin Rotation

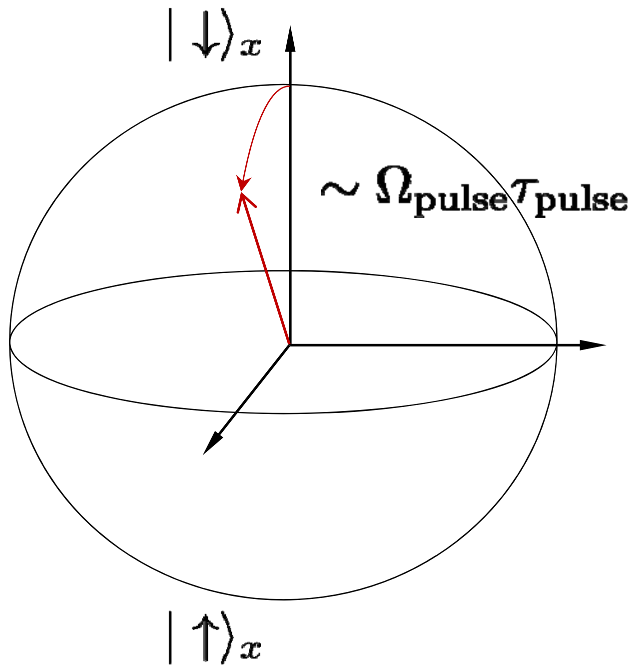
All optical spin rotation:

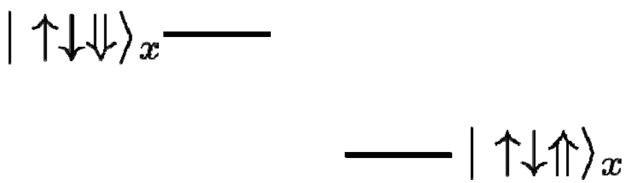
Send short, detuned, circular polarized laser pulse.

In z-basis:
Laser leads to ac-Stark shift.
⟹ Effective magnetic field in z-direction.

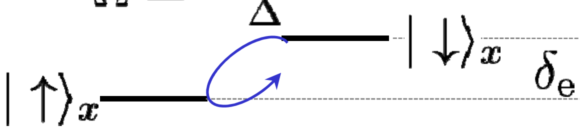
⟹ Spin rotation around x-axis.

Rotation angle depends on pulse shape.
(i.e. pulse power, pulse duration)



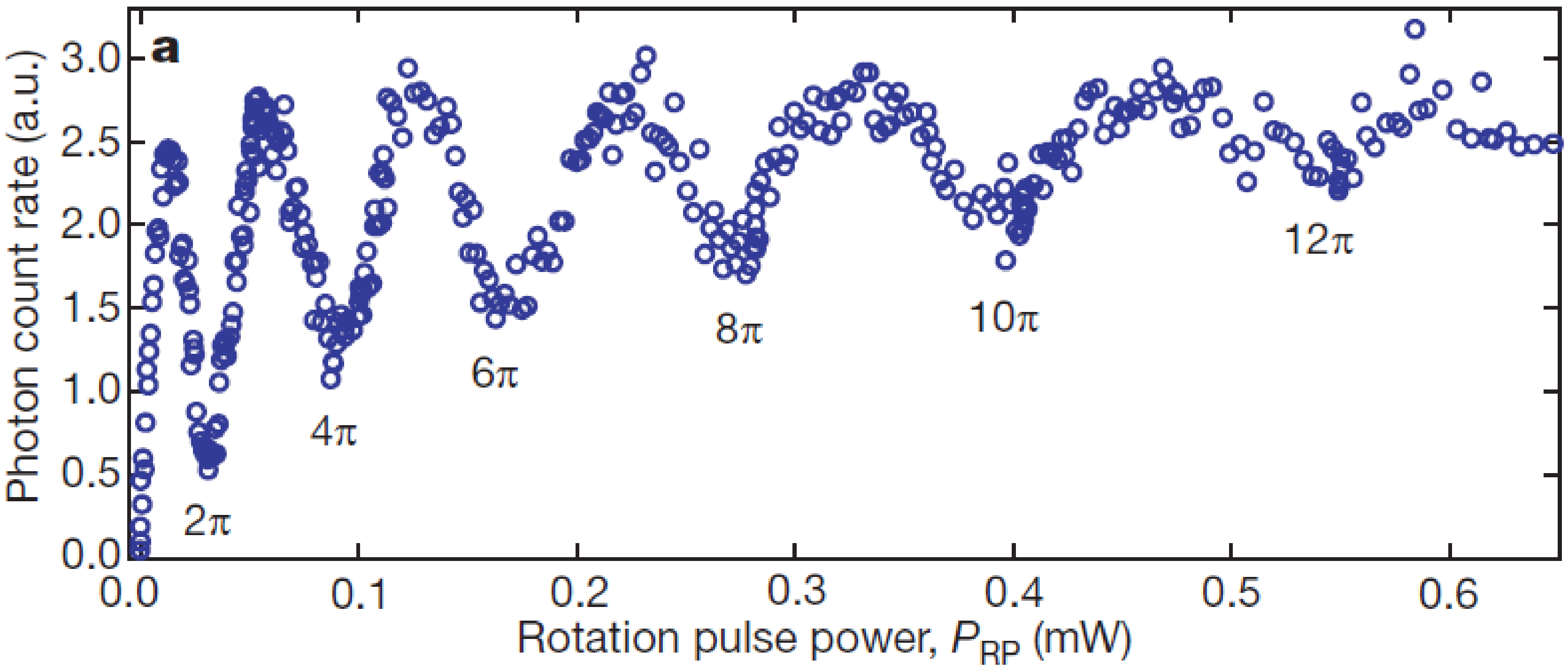


$$\Omega = \frac{\Omega^2_{\mathrm{pulse}}}{\Delta}$$



D. Press Nature **456**, 218, (2008).

Self-Assembled Quantum Dots – Coherent Spin Rotation



Rotation angle depends on pulse shape.
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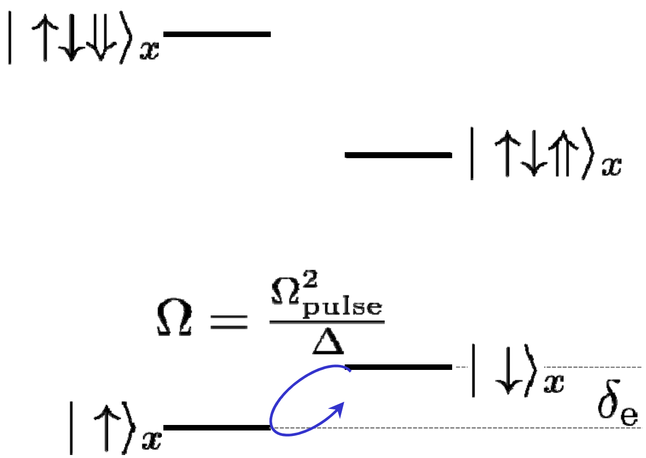


Rabi oscillations

D. Press Nature **456**, 218, (2008).

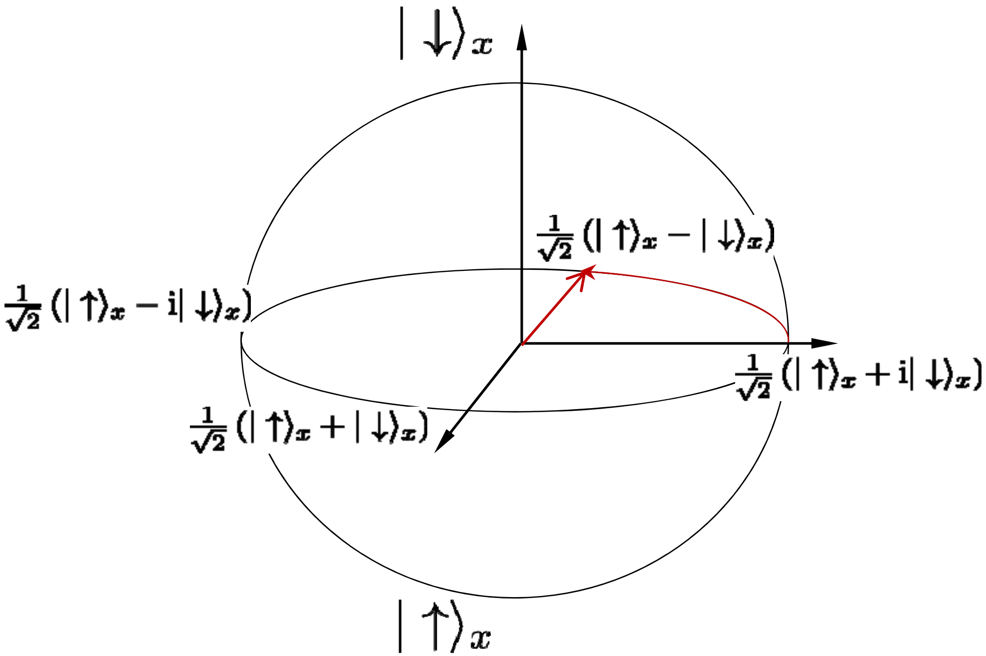
Coherent Spin Rotation

Equator:

Not eigenstates of the system
⟹ Larmor precession

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left(|\uparrow\rangle_x + e^{i\phi}|\downarrow\rangle_x\right)$$

$$\phi = -\omega t$$



Larmor frequency: $\omega = g\mu_B B/\hbar$

Rabi oscillations and Larmor precession:

⟹ Complete coherent control

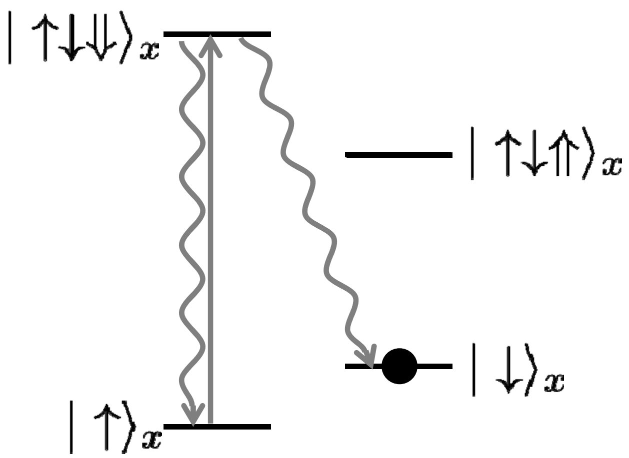
D. Press Nature Phot. **4**, 367, (2010).

Spin-Photon Entanglement

Spin qubit with optical control and readout:

⟹ Spin photon entanglement

- Initialize into state $|\downarrow\rangle_x$



W.B. Gao Nature **491**, 426, (2012).

Spin-Photon Entanglement

Spin qubit with optical control and readout:

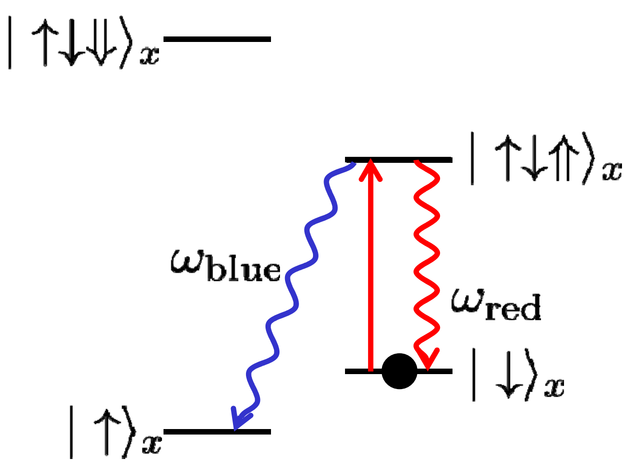
$\Longrightarrow$ Spin photon entanglement

- Initialize into state $|\downarrow\rangle_x$
- Resonant laser pulse creates population of state $|\uparrow\downarrow\Uparrow\rangle_x$

$\Longrightarrow$ Decay with equal probability into $|\uparrow\rangle_x$ or $|\downarrow\rangle_x$
By emitting either a "red" or "blue" photon.

Spin photon entangled state:

$$\boxed{|\Psi\rangle = \frac{1}{\sqrt{2}}\left(|\downarrow\rangle_x|\omega_{\mathbf{red}}, H\rangle + \mathbf{i}|\uparrow\rangle_x|\omega_{\mathbf{blue}}, V\rangle\right)}$$



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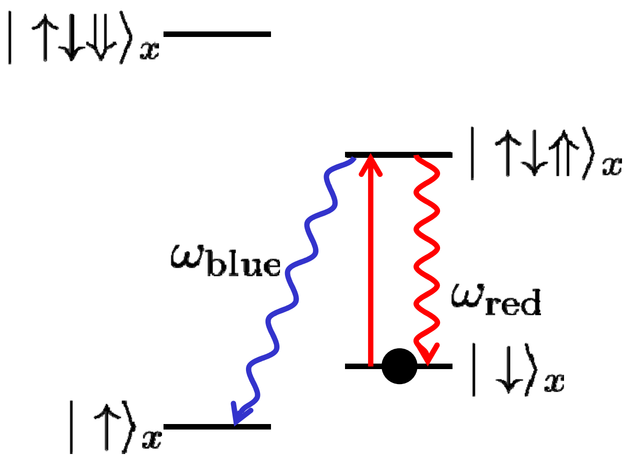
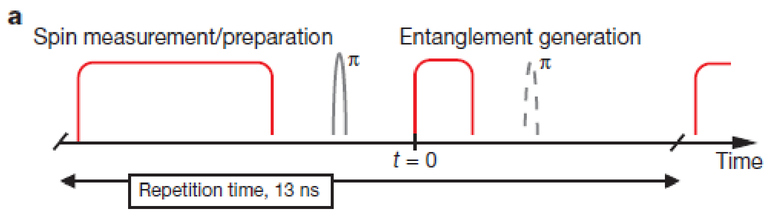
- Measure photon and spin state



W.B. Gao Nature **491**, 426, (2012).

Spin-Photon Entanglement

Spin qubit with optical control and readout:



⟹ Spin photon entanglement

- Initialize into state $|\downarrow\rangle_x$
- Resonant laser pulse creates population of state $|\uparrow\downarrow\Uparrow\rangle_x$

⟹ Decay with equal probability into $|\uparrow\rangle_x$ or $|\downarrow\rangle_x$
By emitting either a "red" or "blue" photon.

Spin photon entangled state:

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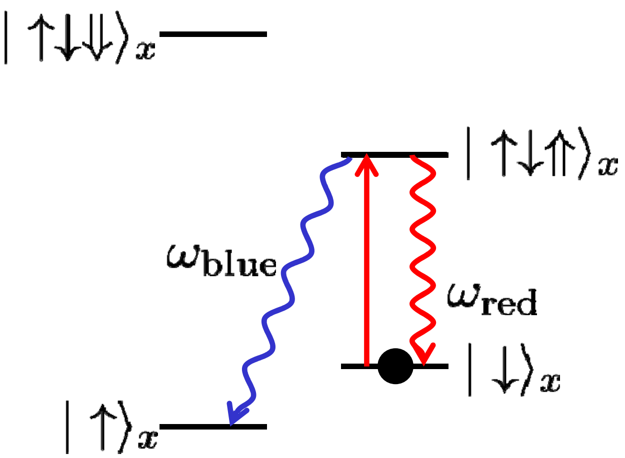


- Measure photon and spin state

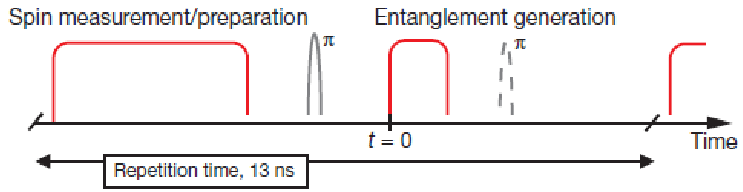
Low detection probability of the photon (~0.1%)
⟹ Heralded spin photon entanglement

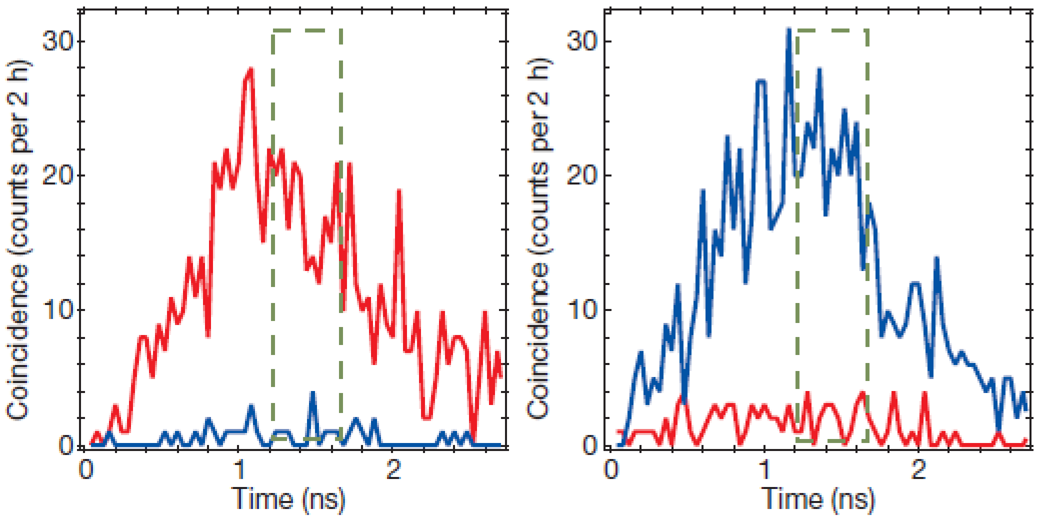
W.B. Gao Nature **491**, 426, (2012).

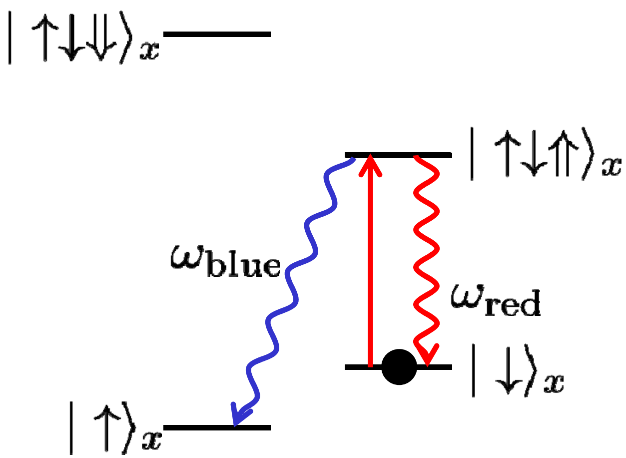
Spin-Photon Entanglement

Classical correlations between spin and photon:

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left(|\downarrow\rangle_x|\omega_{\mathrm{red}}, H\rangle e^{-i\omega t} + \mathrm{i}|\uparrow\rangle_x|\omega_{\mathrm{blue}}, V\rangle\right)$$







Number of red and blue photons for $|\downarrow\rangle_x$

Number of red and blue photons for $|\uparrow\rangle_x$ (after π-pulse)

Classical correlation fidelity: 0.87

W.B. Gao Nature **491**, 426, (2012).

Spin-Photon Entanglement

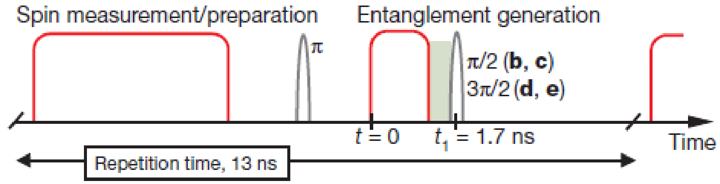
Quantum correlations between spin and photon:

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left(|\downarrow\rangle_x|\omega_{\mathbf{red}}, H\rangle e^{-\mathrm{i}\omega t} + \mathrm{i}|\uparrow\rangle_x|\omega_{\mathbf{blue}}, V\rangle\right)$$

Project spin onto equator of the Bloch sphere

⟹ Spin precesses with Larmor frequency ω

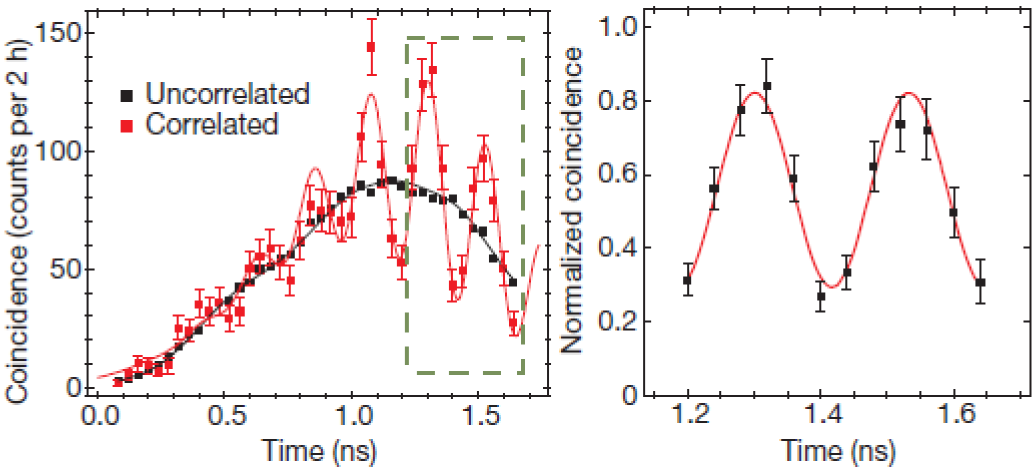
$$|\tilde{\Psi}\rangle = \frac{1}{\sqrt{2}}\left(|\downarrow\rangle_x|\omega_{\mathbf{red}}, H\rangle e^{-\mathrm{i}\omega(t_1-t_g)} + \mathrm{i}|\uparrow\rangle_x|\omega_{\mathbf{blue}}, V\rangle\right)$$



$$t_g = t_d - L/c$$

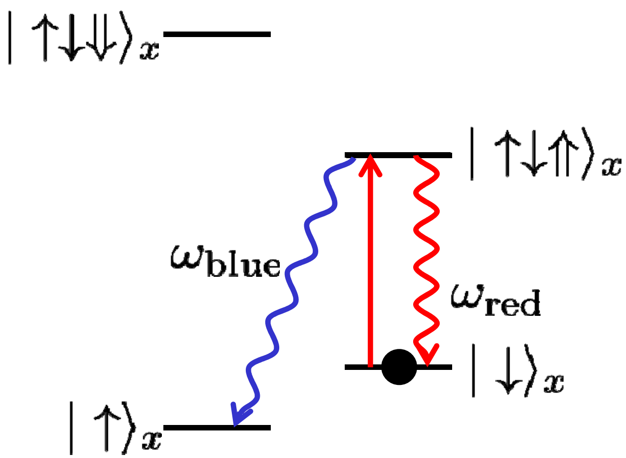
Time between photon detection and emission

⟹ Oscillations of coincidence



Quantum correlation fidelity: 0.46

(limited by T_2^*)



W.B. Gao Nature **491**, 426, (2012).

Spin-Spin Entanglement

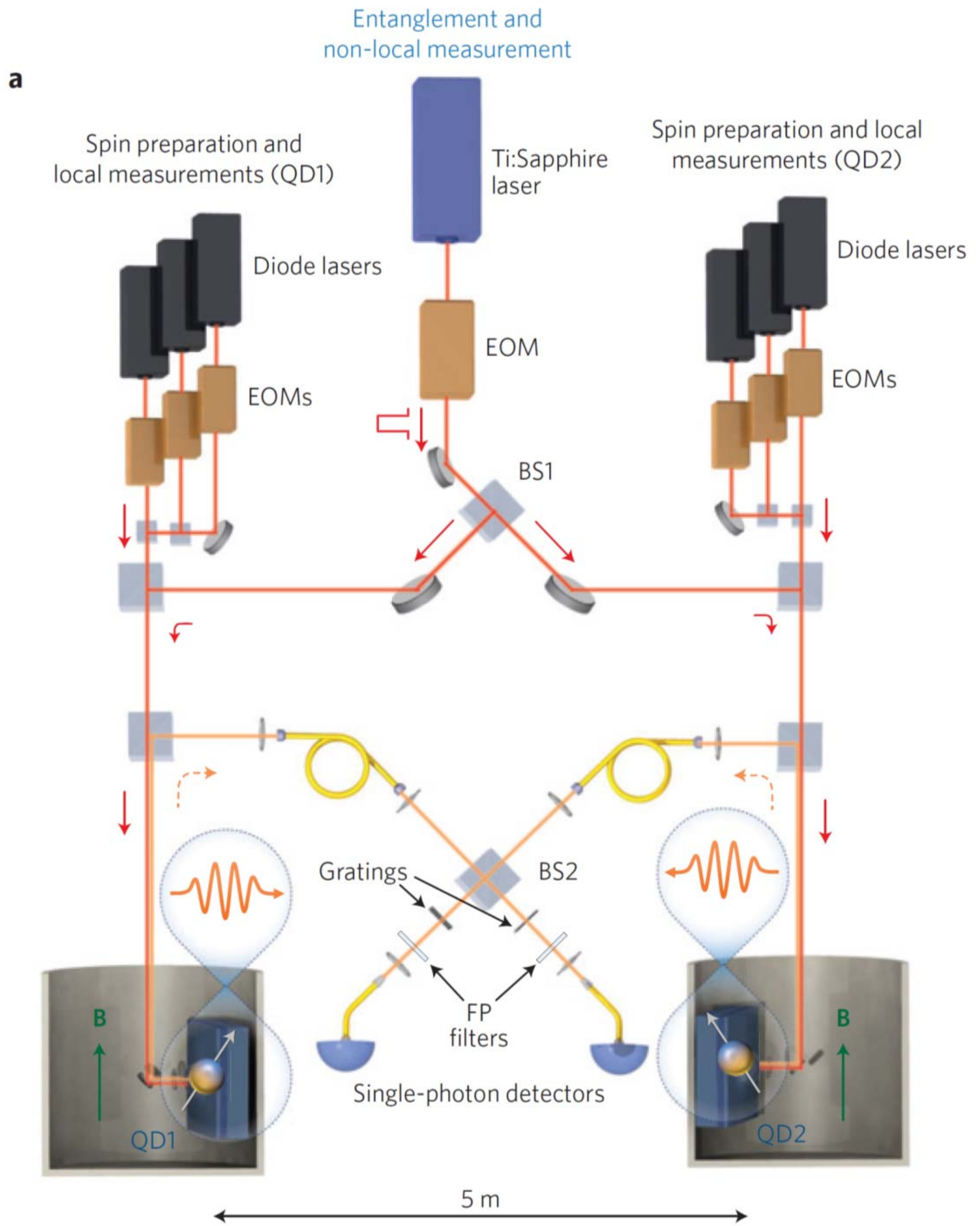
Entanglement of two distant (hole) spins:

Two identical QDs each holding one hole.

⟹ Generate an entangled photon-hole pair in each QD

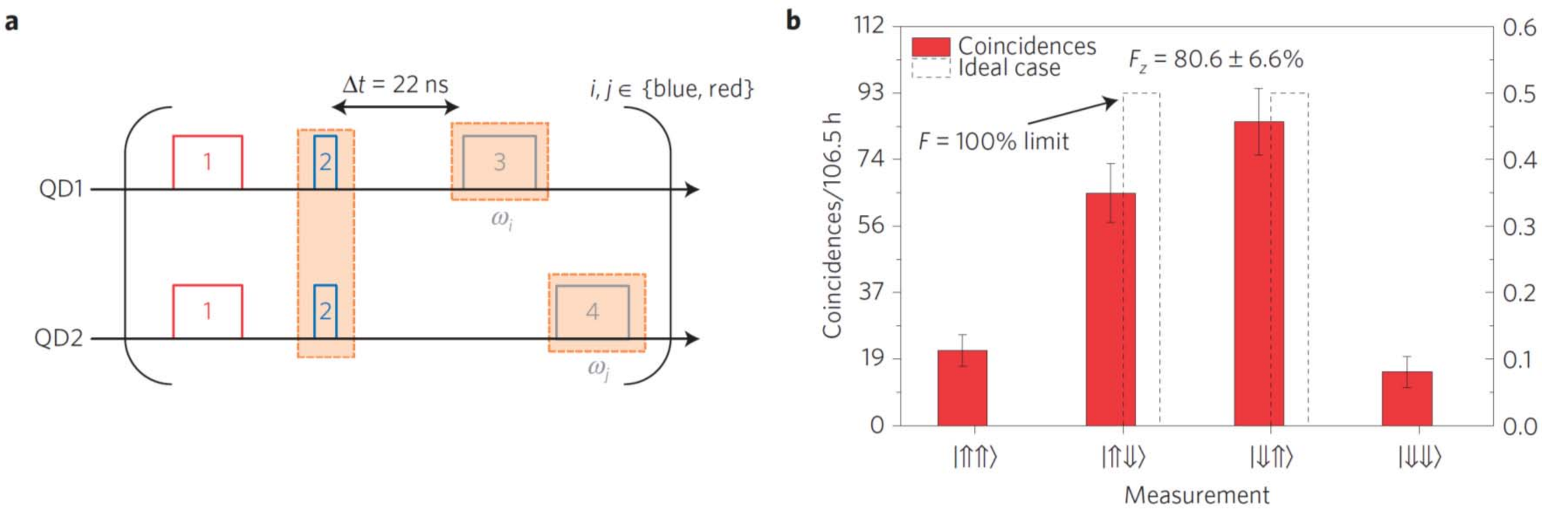
⟹ Entangle the two photons

⟹ Entanglement of the two hole spins.



A. Delteil Nat. Phys. **12**, 2187, (2016).

Spin-Spin Entanglement



Measure classical correlations between the two hole spins:

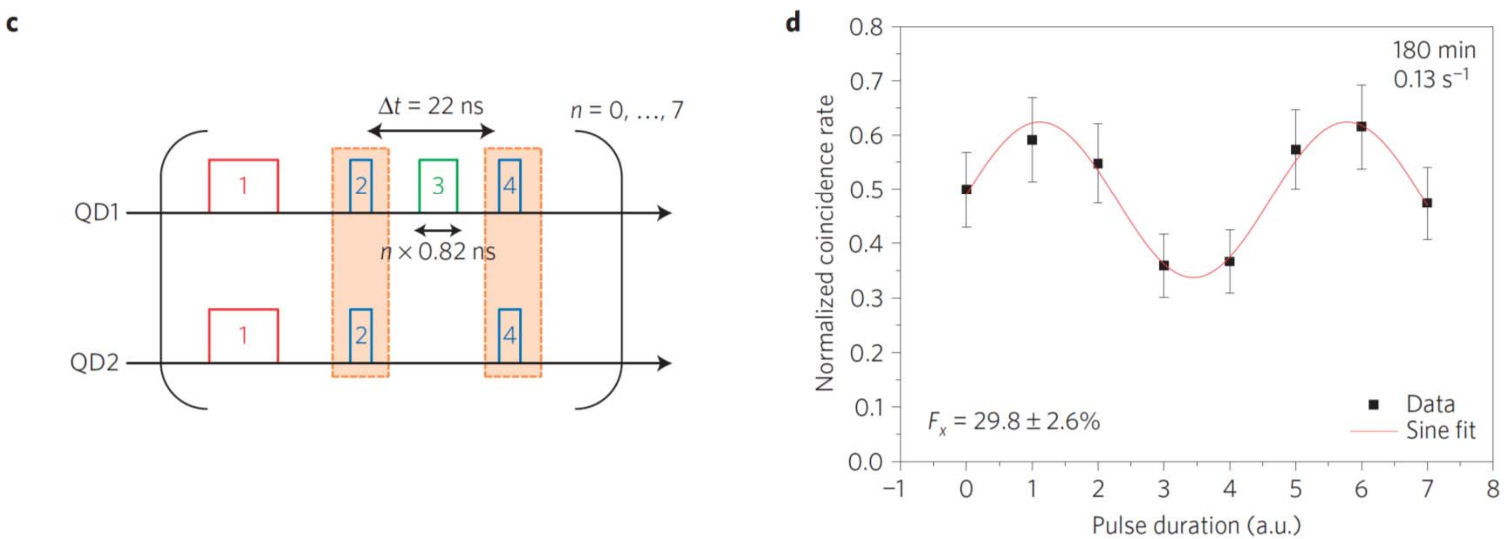
1: Spin initialization
2: Entanglement generation
3: Spin measurement in QD1
4: Spin measurement in QD2
(in the x-basis)

A. Delteil Nat. Phys. **12**, 2187, (2016).

Spin-Spin Entanglement

Measure quantum correlations between the two hole spins:

1: Spin initialization
2: Entanglement generation
3: Phase shift on spin in QD 1
4: Spin measurement in QD1 and QD2
(in the x-basis)



A. Delteil Nat. Phys. **12**, 2187, (2016).