Optical systems, entanglement and quantum quenches

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Outline

Lecture 1: Optical systems in mesoscopic physics:

- overview of quantum dots
- elementary optical measurements
- charge and spin control in quantum dots
- hyperfine interactions in a single dot: central spin problem
- Singlet-triplet states in coupled QDs
- quantum dots in cavities

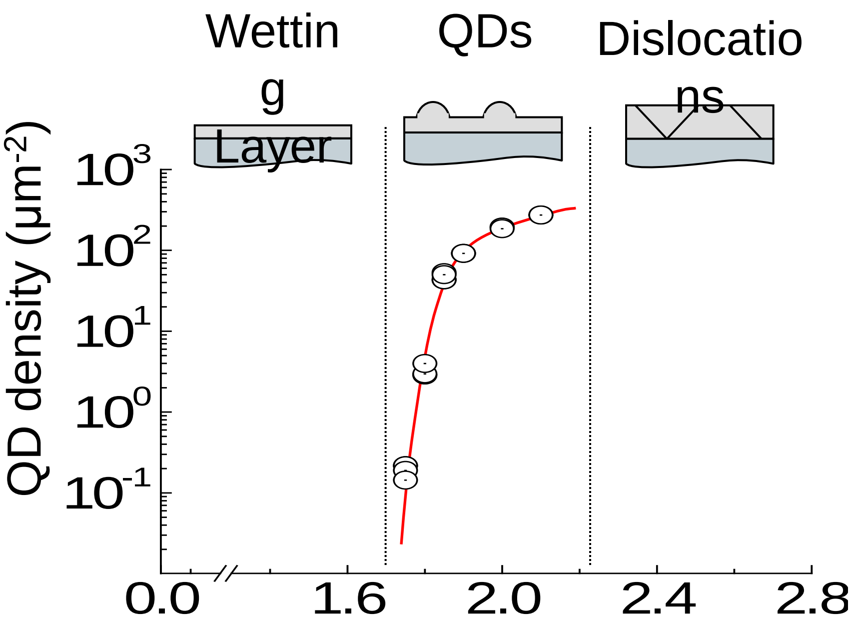
Lecture 2: Quantum quench of Kondo correlations

Wish list for optical investigation of mesoscopic physics

- Discrete optical excitations with natural linewidth Γ << energy scales of interest
- High radiative recombination efficiency to avoid heating
- Photon emission with wavelength $\lambda < 1\ \mu m$ to ensure single-photon counting using silicon detectors
- Strong correlations between electron spin and photon polarization (or energy) for spin manipulation

⇨ Satisfied by self-assembled InGaAs quantum dots – a.k.a. artificial atoms

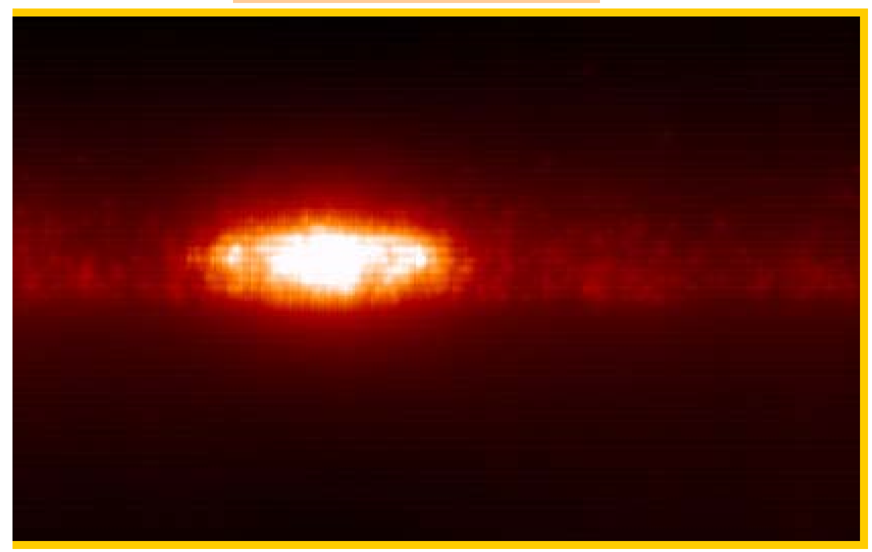
InGaAs Quantum Dots embedded in GaAs

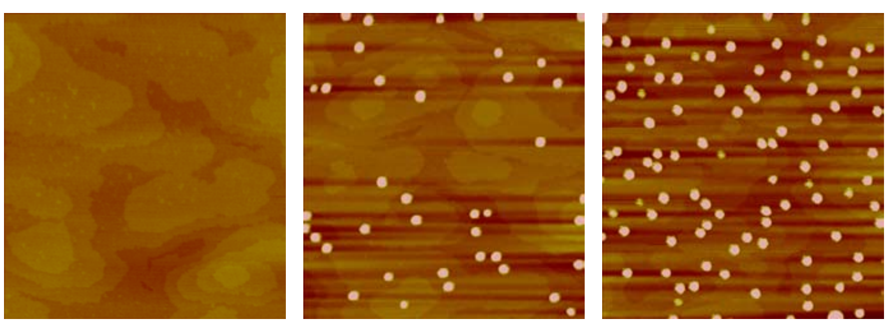


3-dimensional quantum confinement of electrons & holes

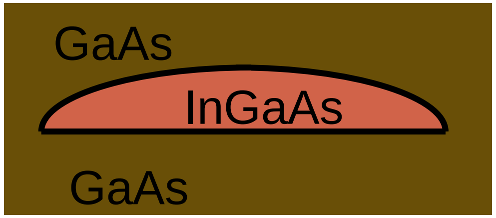
- Grown by molecular beam epitaxy (MBE)
- QDs are formed during the heteroepitaxy of lattice mismatched crystal layers

X-STM

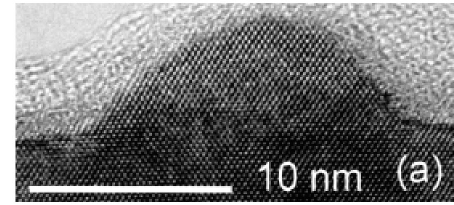


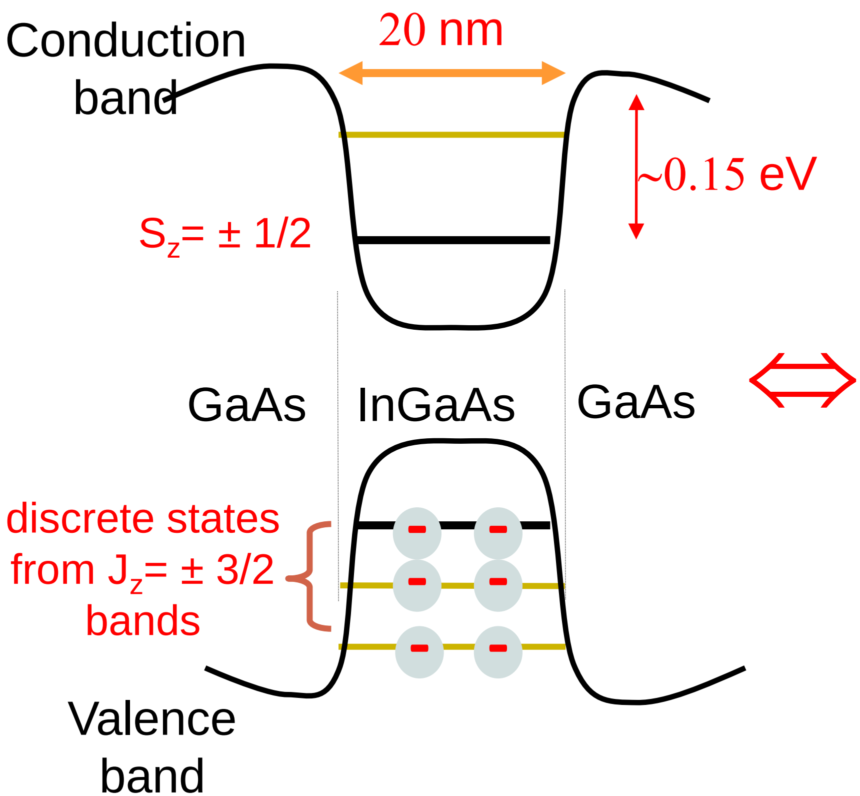


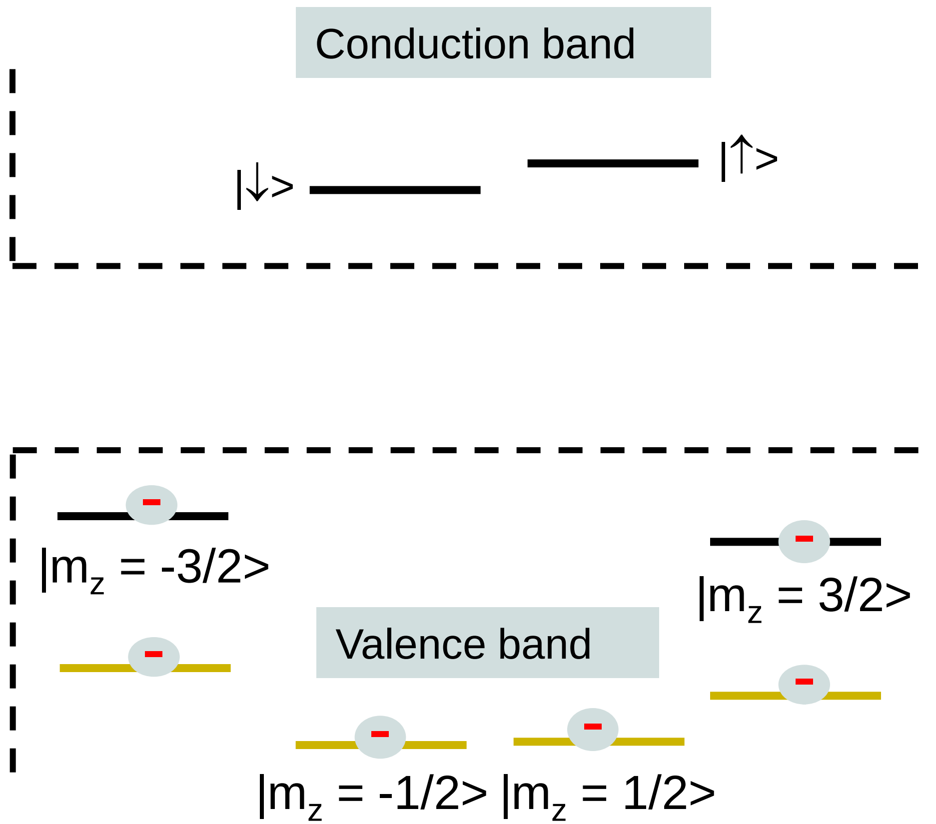
AFM



InGaAs Quantum dots (QD) embedded in GaAs



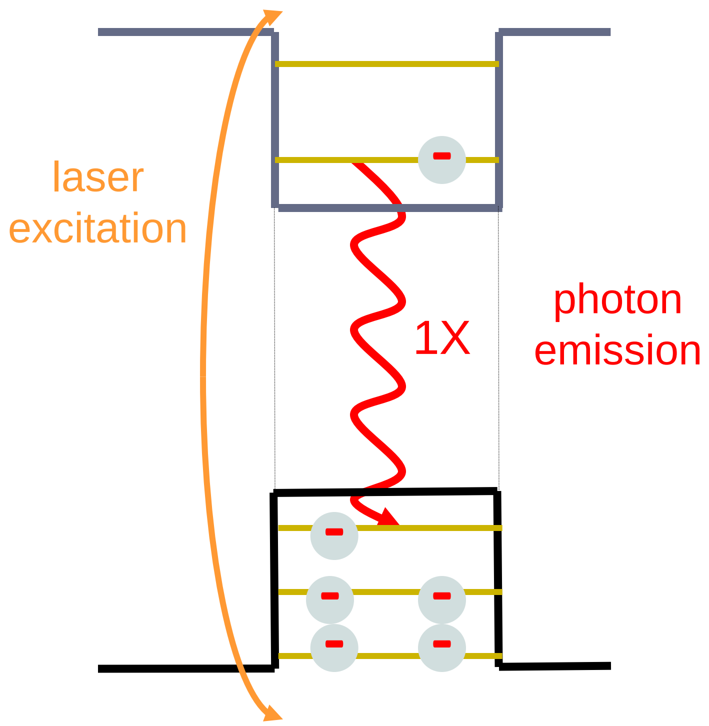


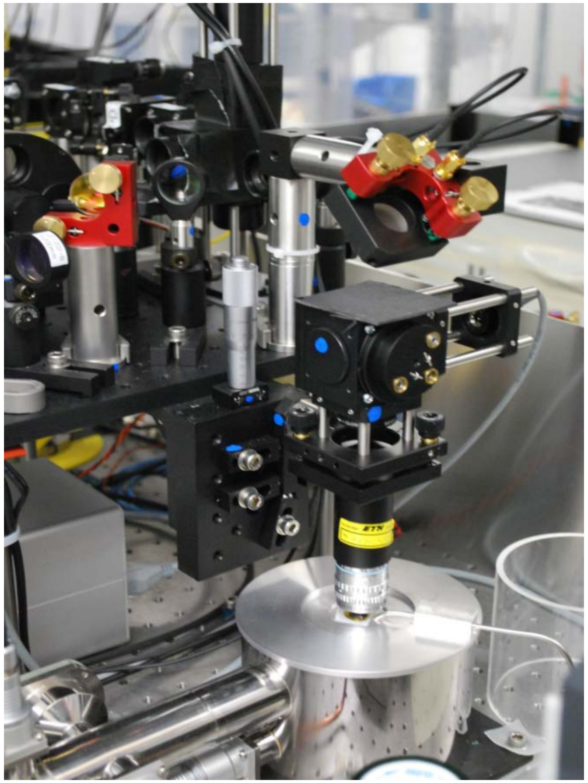


- Self-assembled QDs have discrete states for electrons & holes.
- Conduction band → anti-bonding s-orbitals; valence band → bonding p-orbitals.
- ~10^5 atoms (= nuclear spins) in each QD ⇒ a random magnetic field with $B_{rms} \approx 15$ mT

Optical measurements

- Photoluminescence (PL): we excite non-resonantly and monitor the characteristic emission lines/resonances of the QD





- ^{4}He flow cryo @ 4K
- High NA objective
- Grating spectrometer

Optical measurements

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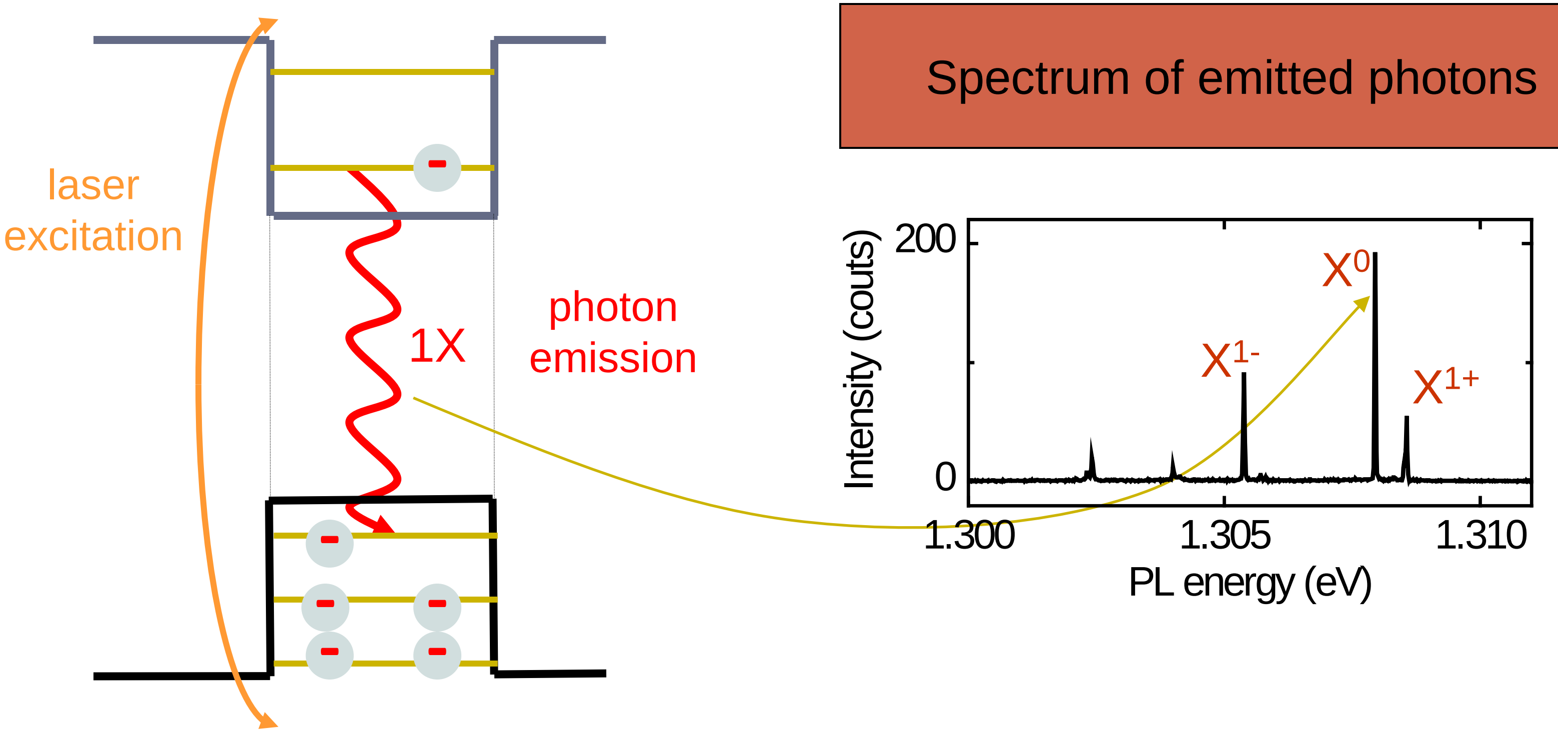
Spectrum of emitted photons



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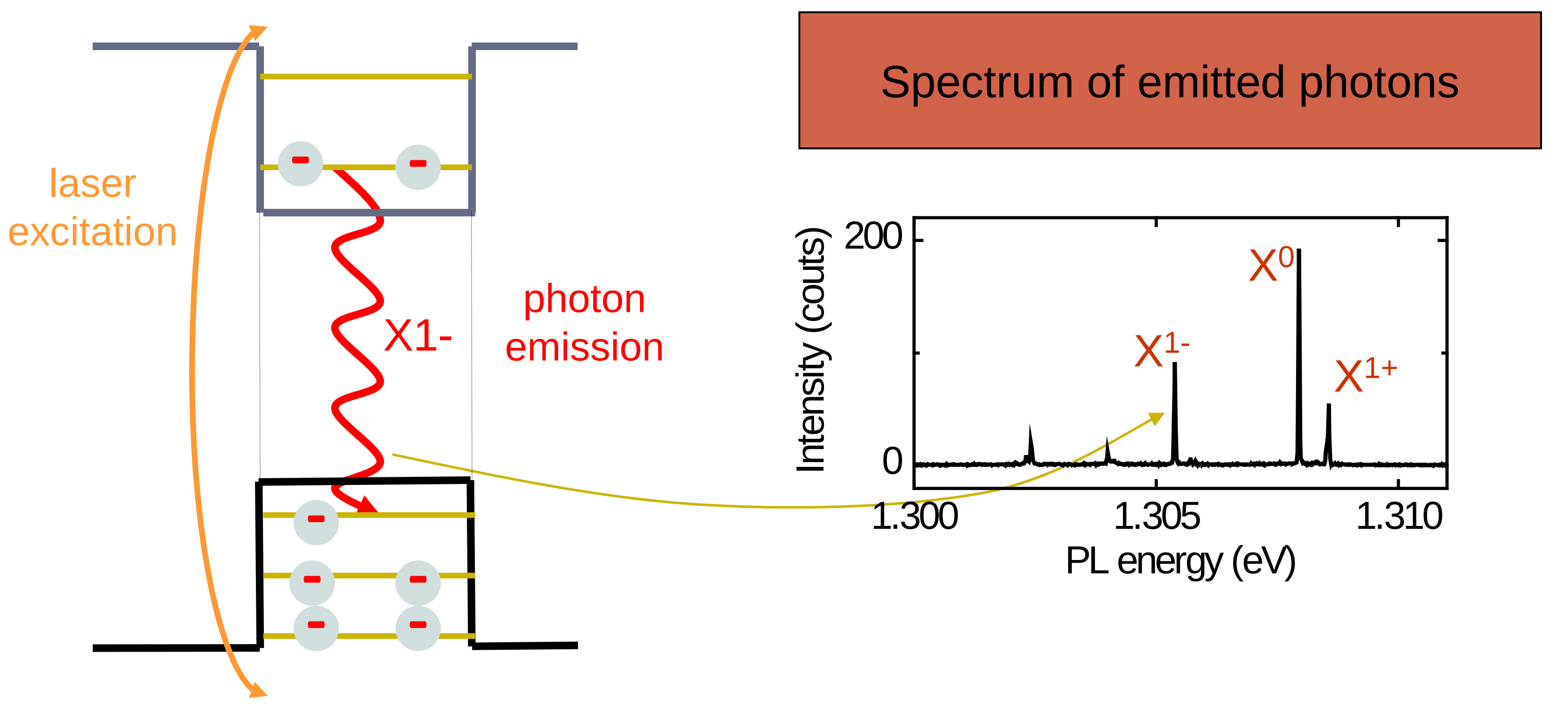
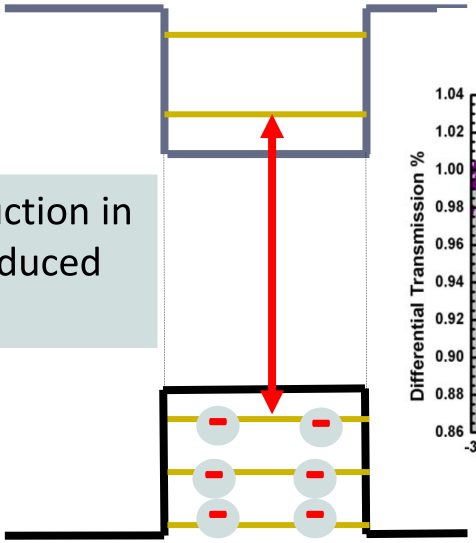
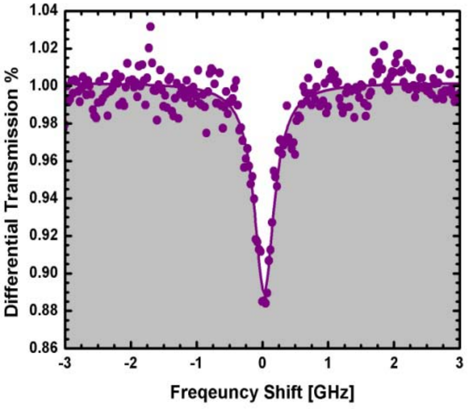


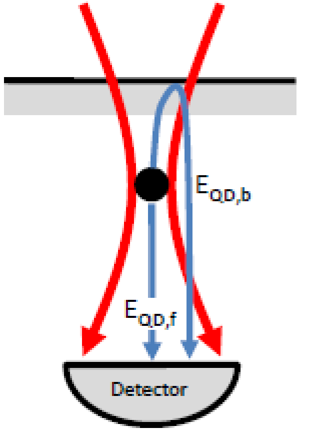
Optical measurements

- Photoluminescence (PL): we excite non-resonantly and monitor the characteristic emission lines/resonances of the QD
- Absorption measurement (DT): we tune the laser frequency across the resonance and monitor the transmitted field intensity
  - ⇨ An interference experiment since the total field is the superposition of the transmitted laser and the QD source field that spatially overlaps with the laser

Up to 12% reduction in transmission induced by a single QD







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  - ⇨ An interference experiment since the total field is the superposition of the transmitted laser and the QD source field that spatially overlaps with the laser
- <u>Resonance fluorescence</u> (RF): we park the laser on resonance with the QD transition and monitor the strength or the frequency dependence of the generated photons after eliminating background laser scattering by a polarizer.

<u>Note:</u> Photon correlation or time-resolved (pump-probe) measurements could be combined with any of these elementary measurement techniques.

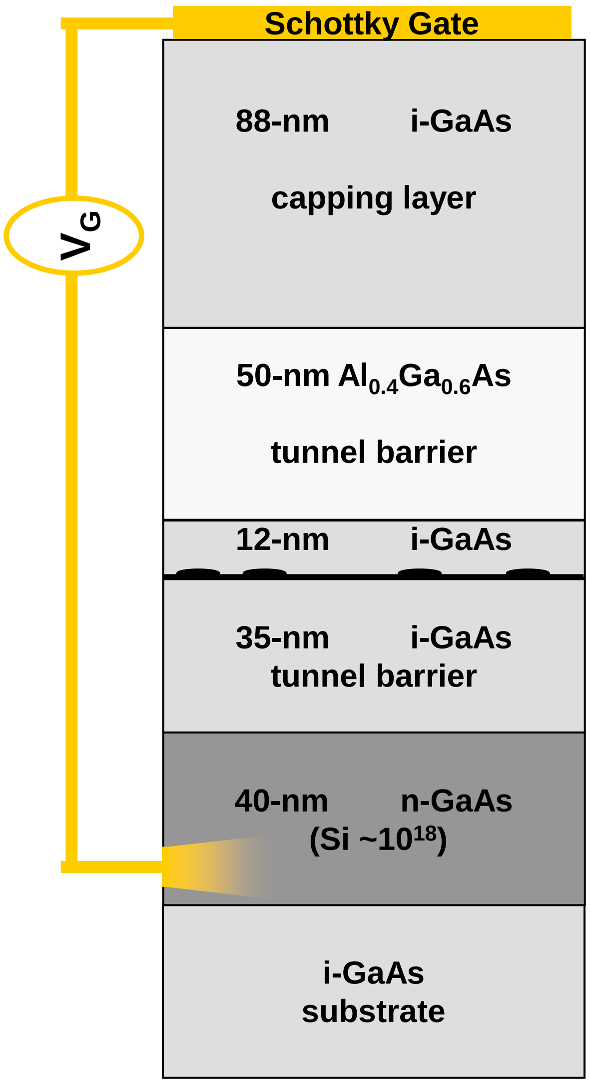
Quantum dot spin physics

To study spin physics, we need to fix the charging state of the QD such that even under resonant excitation there are no charge fluctuations.

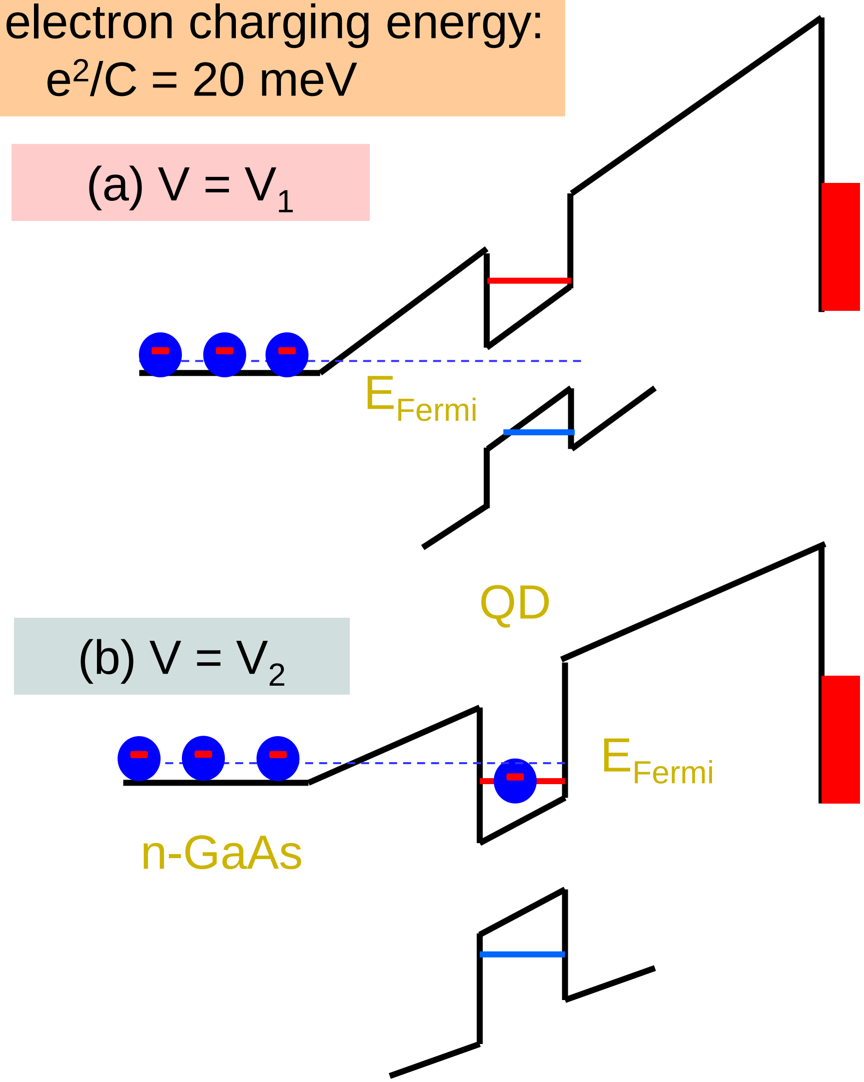
QD spins: controlled charging of a single QD

Quantum dot embedded between n-GaAs and a top gate.

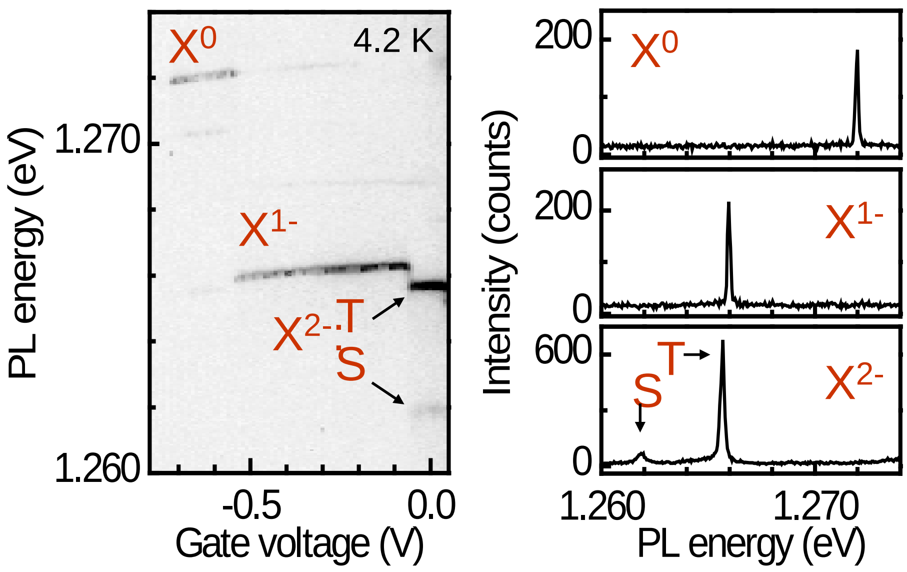
Coulomb blockade ensures that electrons are injected into the QD one at a time



Single electron charging energy:
$e^2/C = 20$ meV



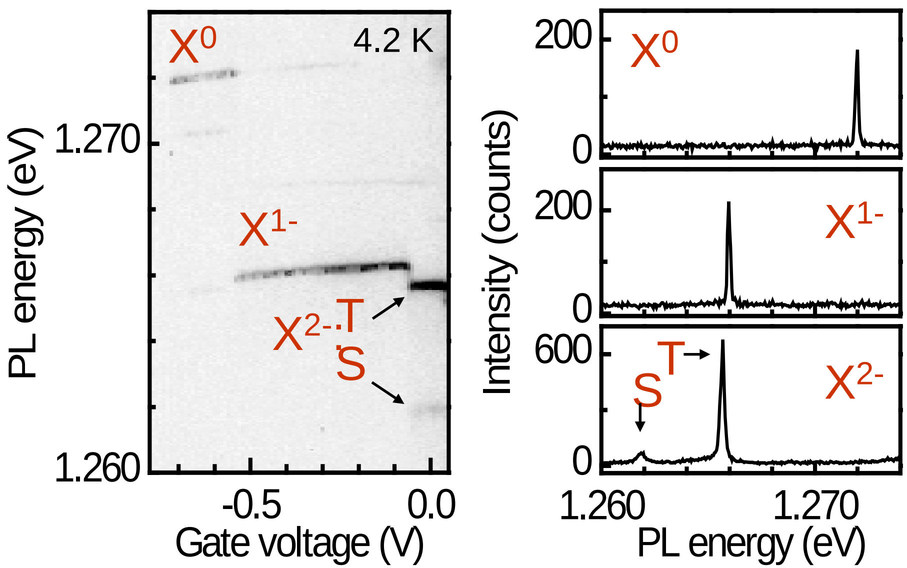
Voltage-controlled Photoluminescence



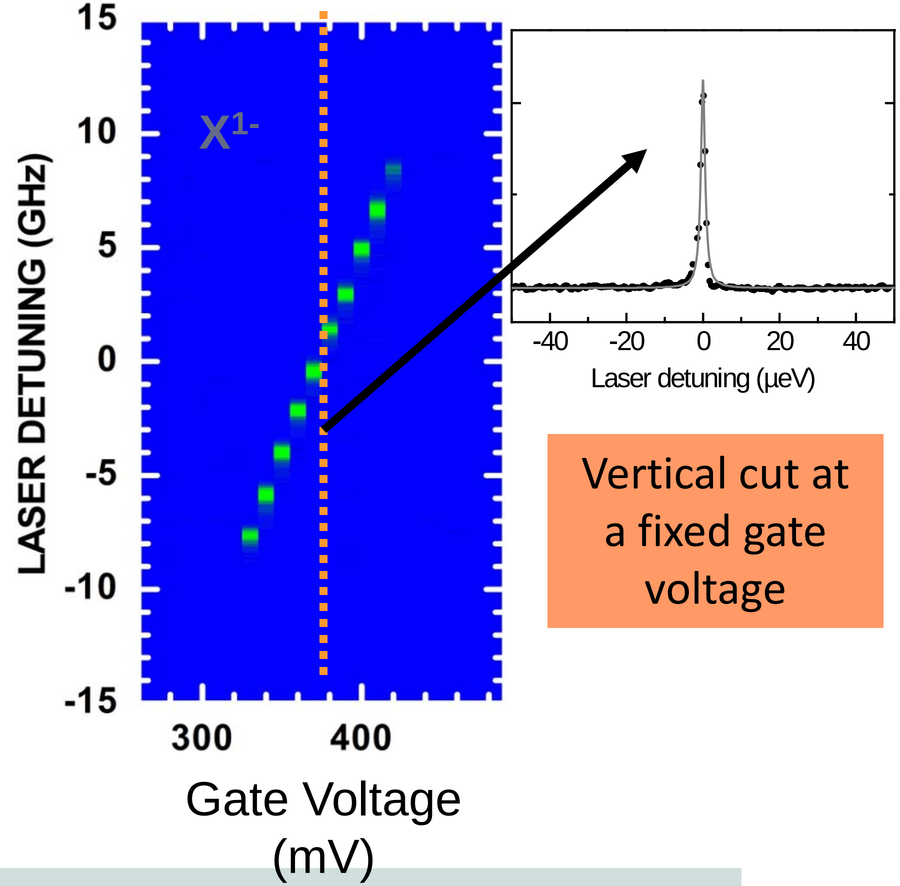
Quantum dot emission energy depends on the charge state due to Coulomb effects – "optical charge sensing."

X^0 and X^{1-} lines shift with applied voltage due to DC-Stark effect.

Voltage-controlled Photoluminescence



Voltage-controlled Absorption



Quantum dot emission energy depends on the charge state due to Coulomb effects – “optical charge sensing.”

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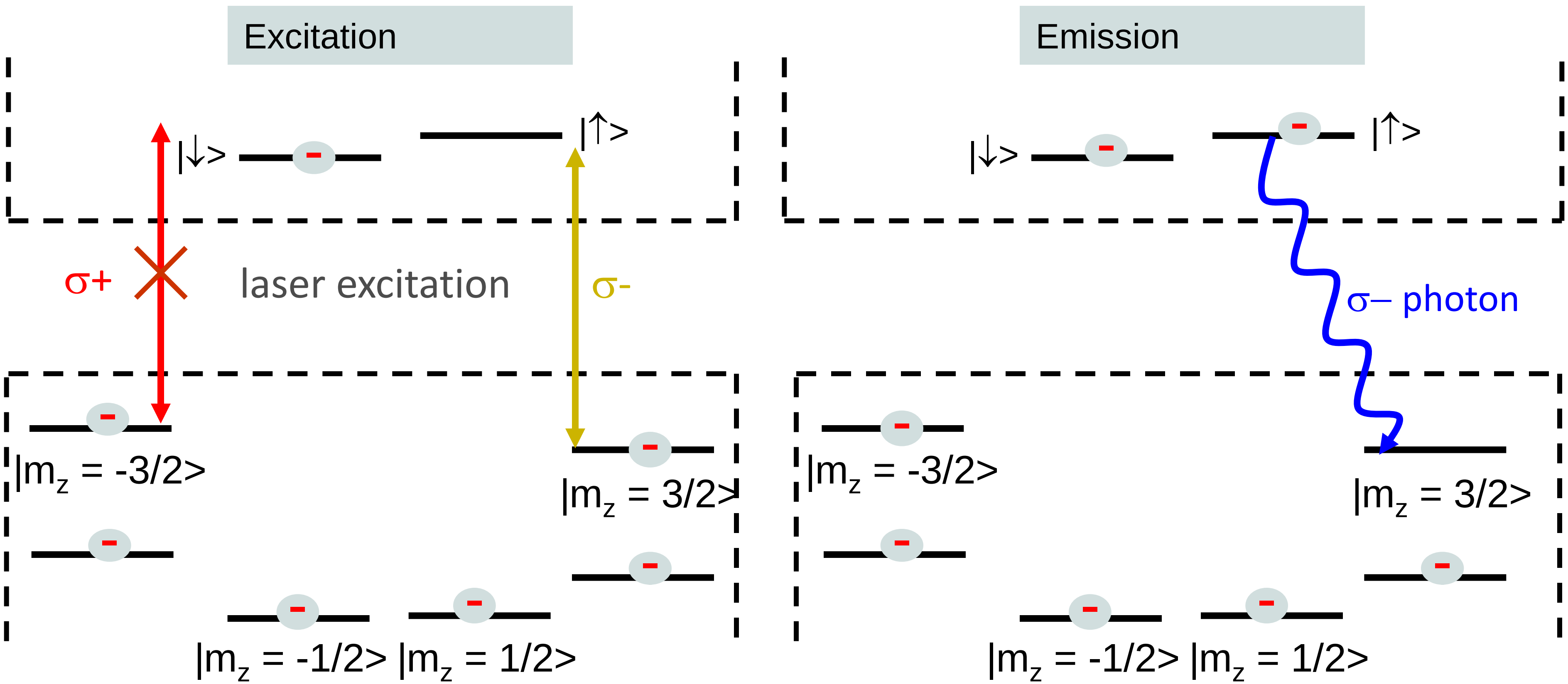
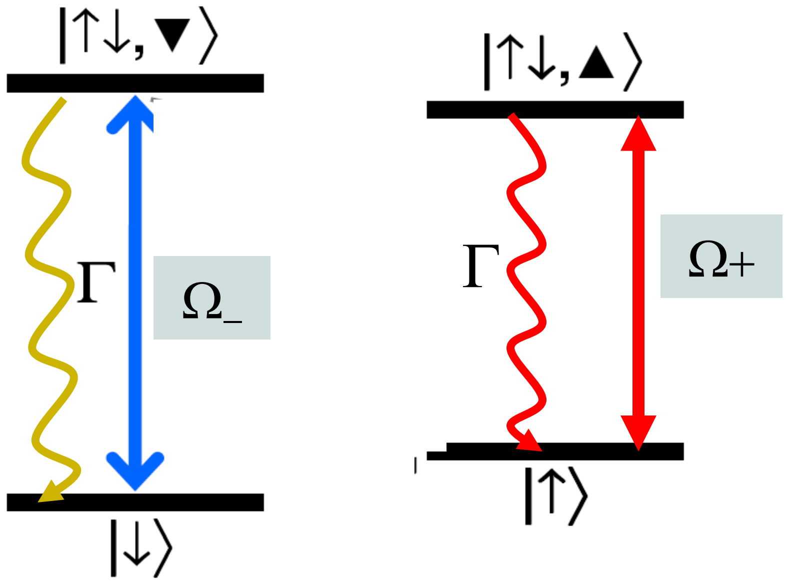
Charged QD X^{1-} (trion) absorption/emission



⇒ σ+ resonant absorption is Pauli-blocked

⇒The polarization of emitted photons is determined by the hole spin

Strong spin-polarization correlations



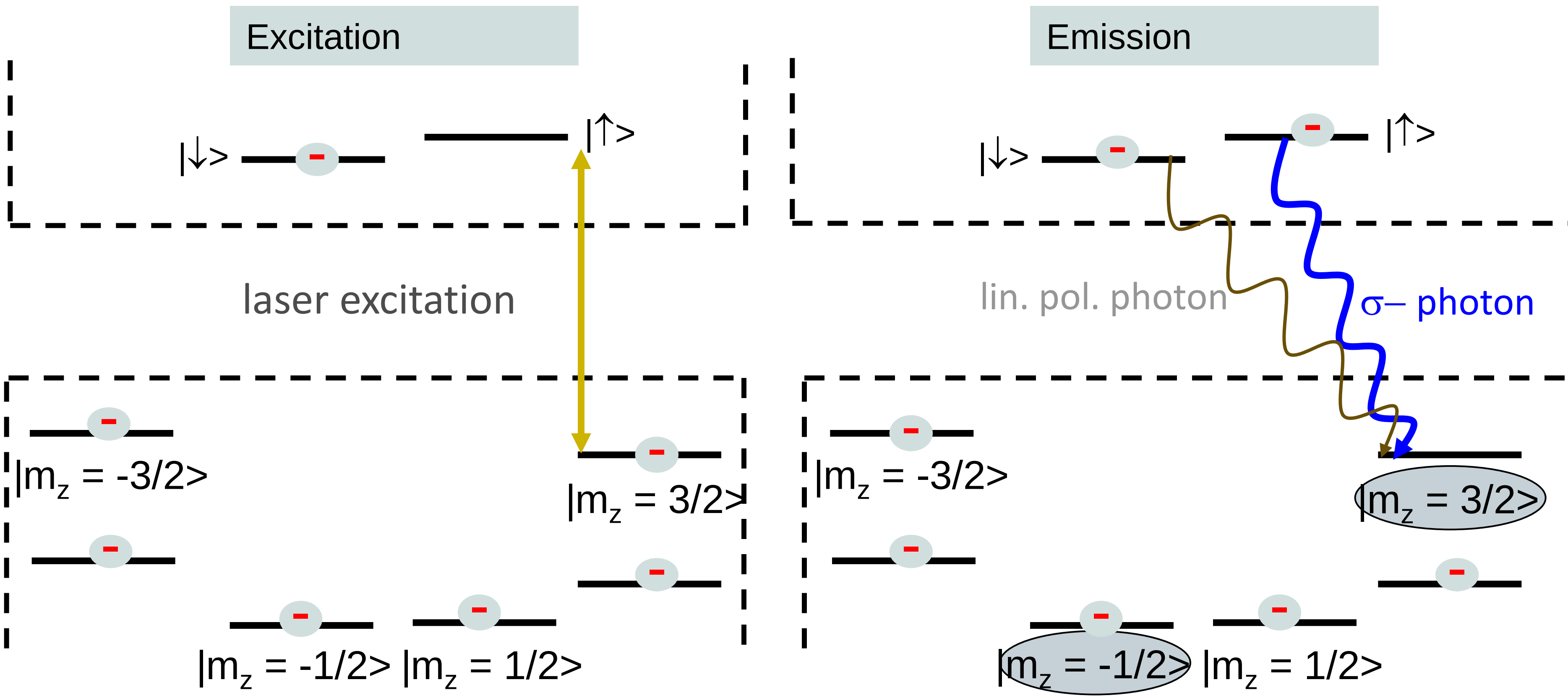
Γ: spontaneous emission rate

Ω: laser coupling (Rabi) frequency

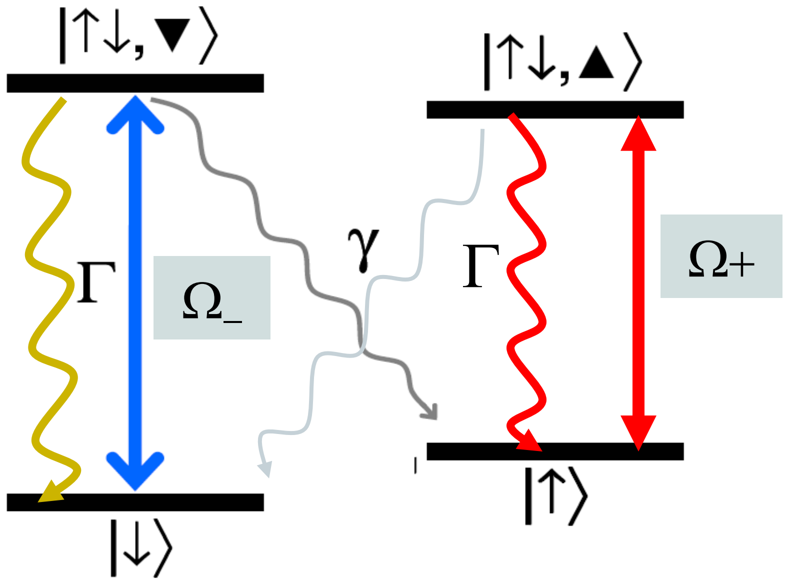
- QD with a spin-up (down) electron only absorbs and emits σ+ (σ-) photons – a recycling transition similar to that used in trapped ions.

  ⇨ Spin measurement and spin-photon entanglement

Charged QD X^{1-} (trion) absorption/emission
Heavy-light hole mixing



Spins weakly coupled via Raman transitions



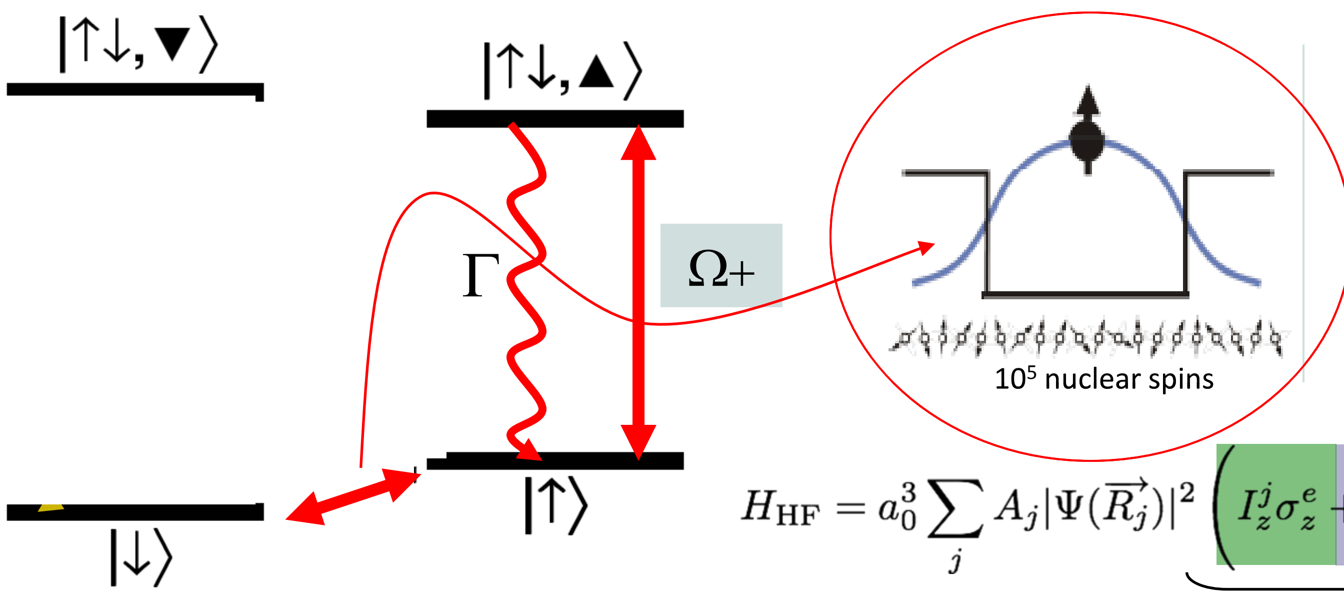
Γ: spontaneous emission rate

Ω: laser coupling (Rabi) frequency

γ: spin-flip spontaneous emission

- The spin-flip Raman scattering rate γ is ~10^{-3} times weaker than Rayleigh scattering rate for B≥1 Tesla
- For short times ($t < \gamma^{-1}$): spin measurement
  For long times ($t > \gamma^{-1}$): spin pumping into | ↓> (provided only $\Omega_+ \neq 0$)

Spin decoherence due to hyperfine coupling



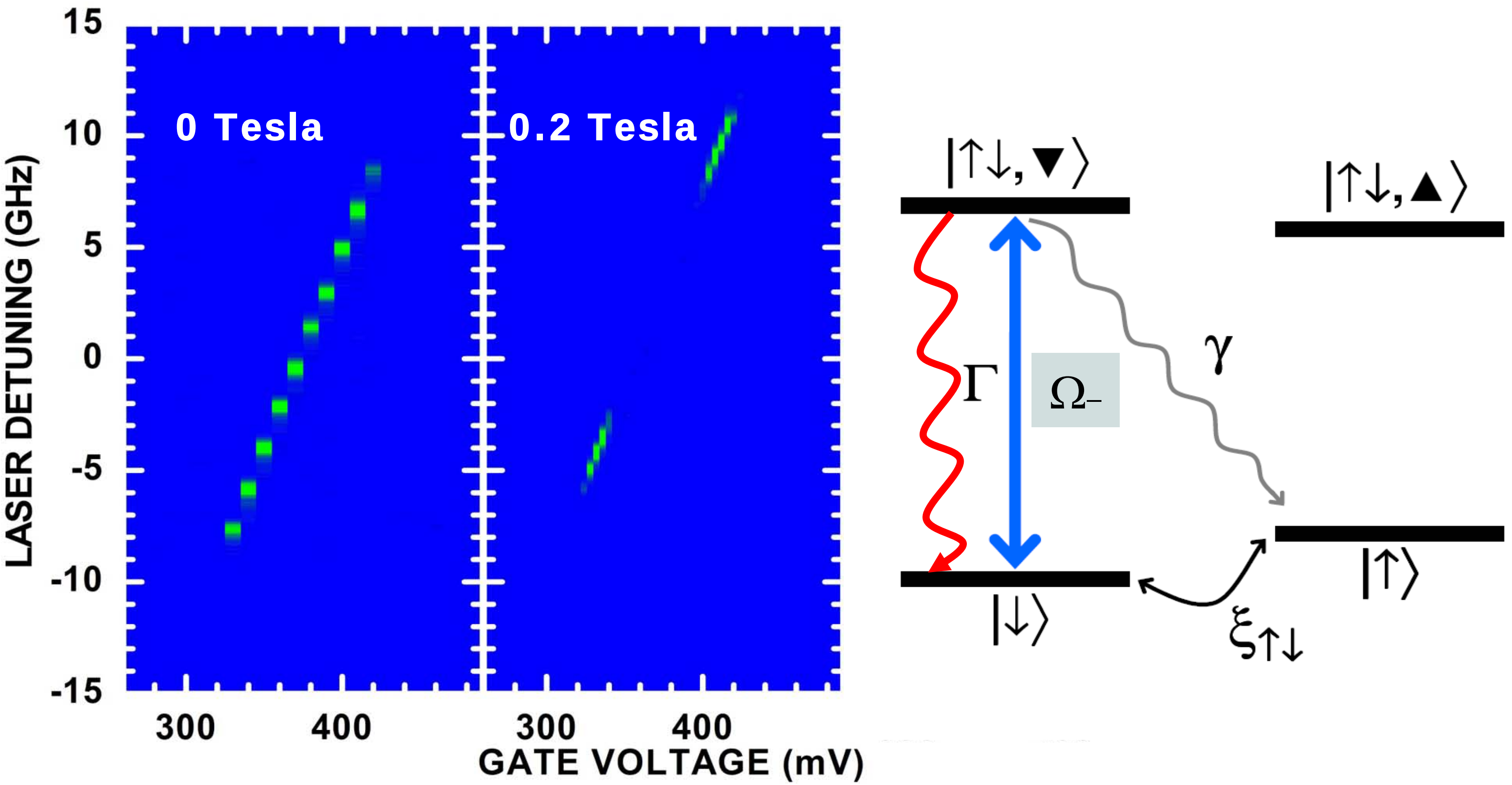
$$H_{\mathrm{HF}} = a_0^3 \sum_j A_j |\Psi(\overrightarrow{R_j})|^2 \underbrace{\left(I_z^j \sigma_z^e + \frac{I_+^j \sigma_-^e + I_-^j \sigma_+^e}{2} \right)}_{\overrightarrow{I^j} \cdot \overrightarrow{\sigma^e}}$$

- Transverse (flip-flop) component causes simultaneous electron-nuclei spin flip events; however these processes do not conserve energy and are suppressed in the presence of an external magnetic field.

- Longitudinal component gives rise to a quasi-static effective magnetic Overhauser (Knight) field seen by the electron (nuclei)

⇨ fluctuations in the Overhauser field lead to electron spin decoherence

Spin pumping in a single-electron charged QD



⇒ For B > 15 mT, the applied resonant σ– laser leads to very efficient spin pumping (exceeding 99%) due to suppression of hyperfine flip-flop events

⇒ Initialization of a spin qubit (or erasure of an ancilla) in > 10nsec time-scale

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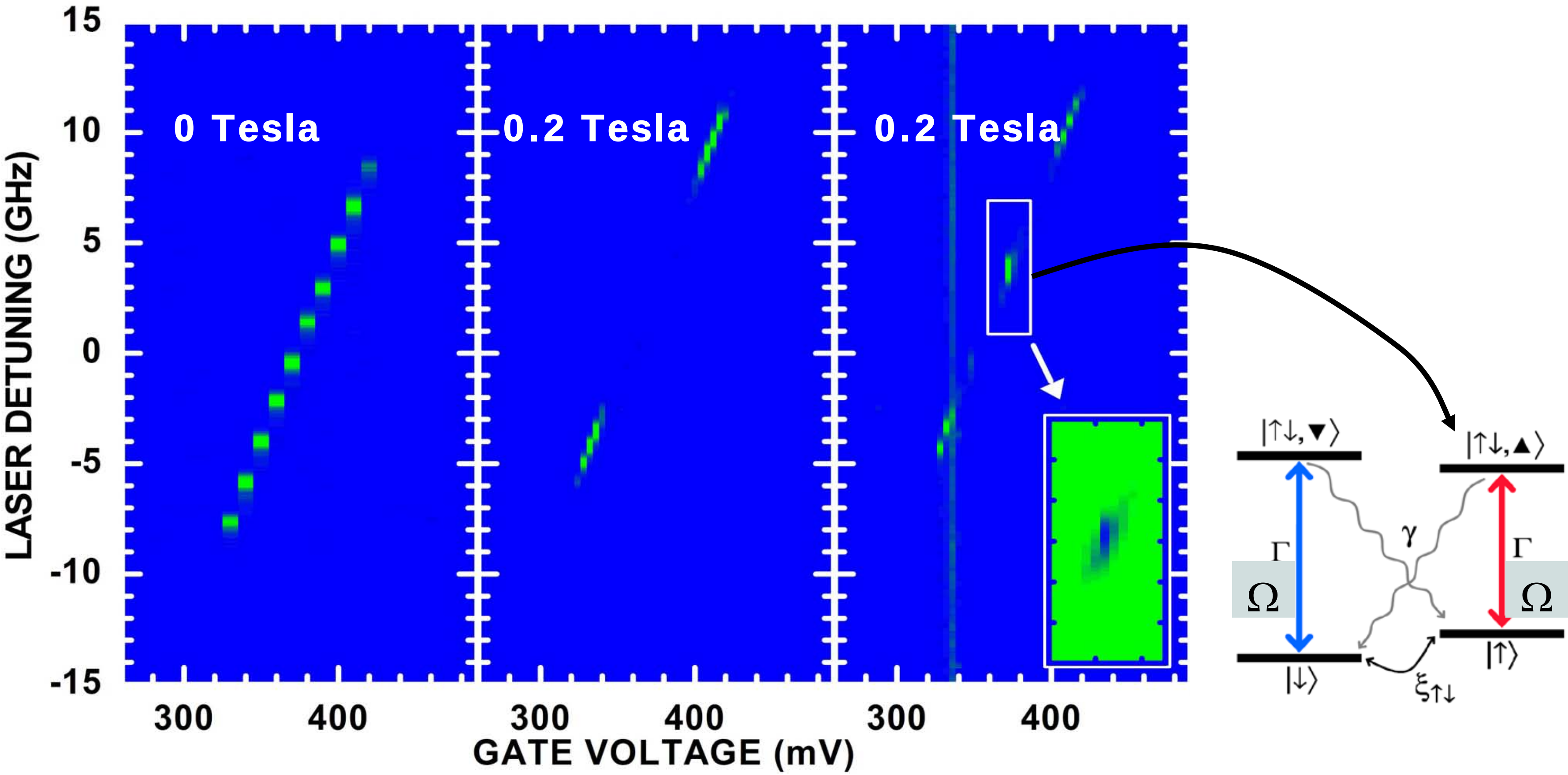

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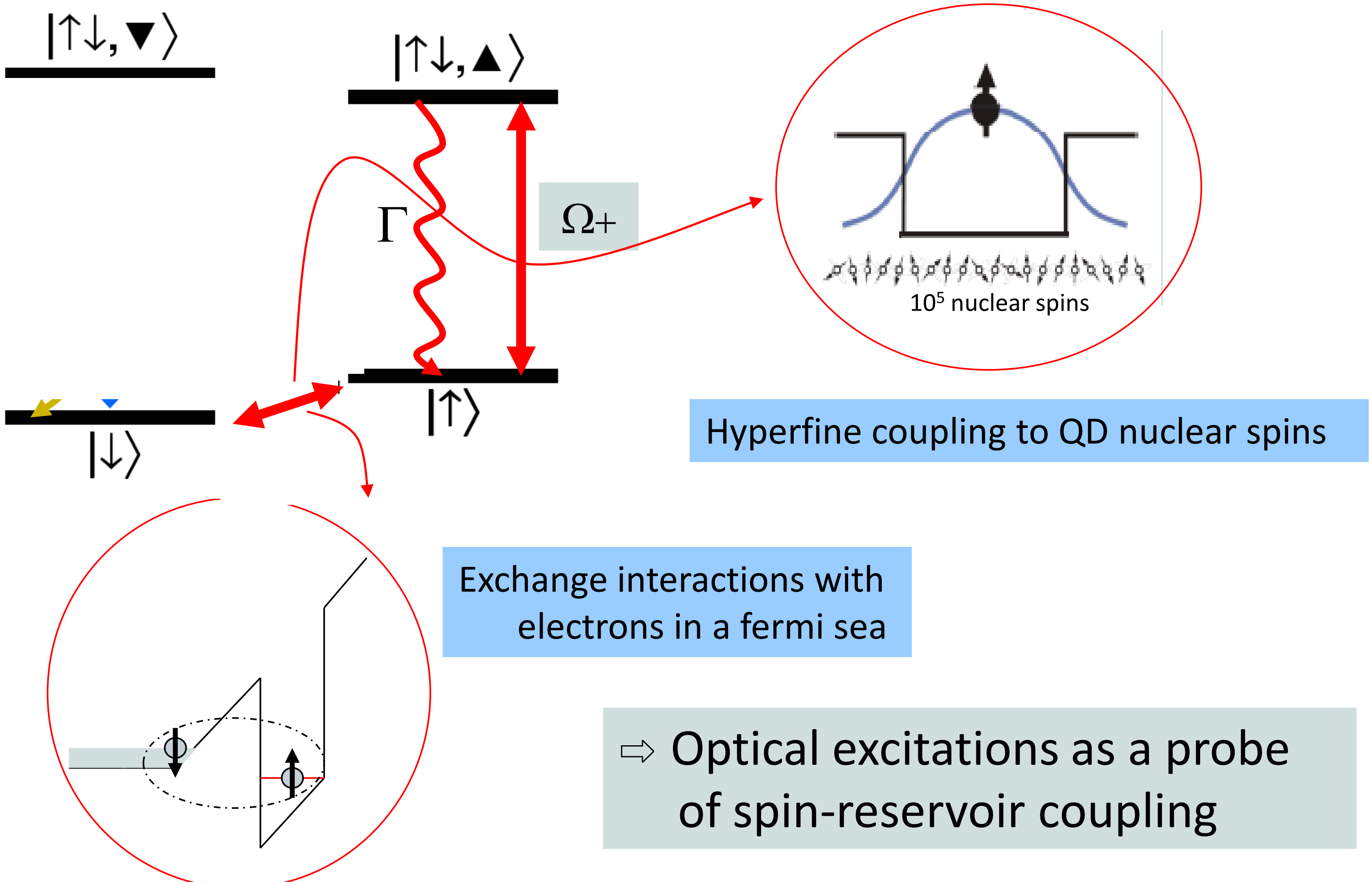
⇒ Initialization of a spin qubit (or erasure of an ancilla) in > 10nsec time-scale

⇒ Spin pumping does not take place at the edges of the absorption plateau?

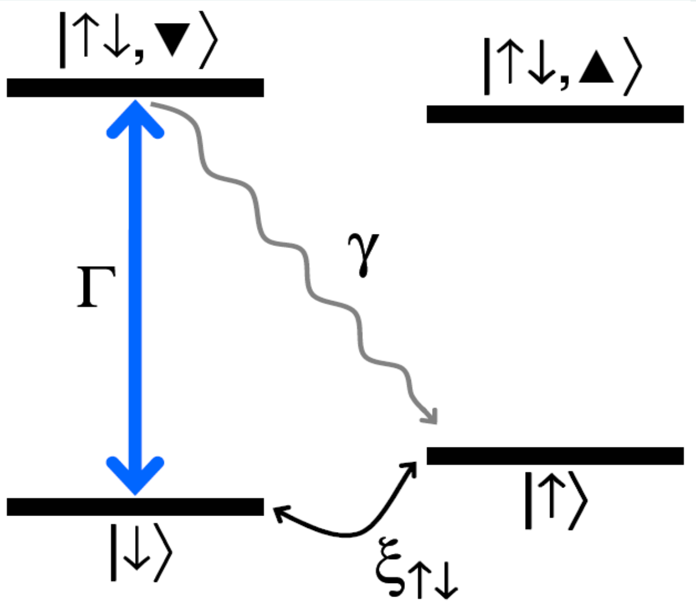
Summary: Optical probe of spin physics

In some cases decoherence can be more interesting than coherent dynamics



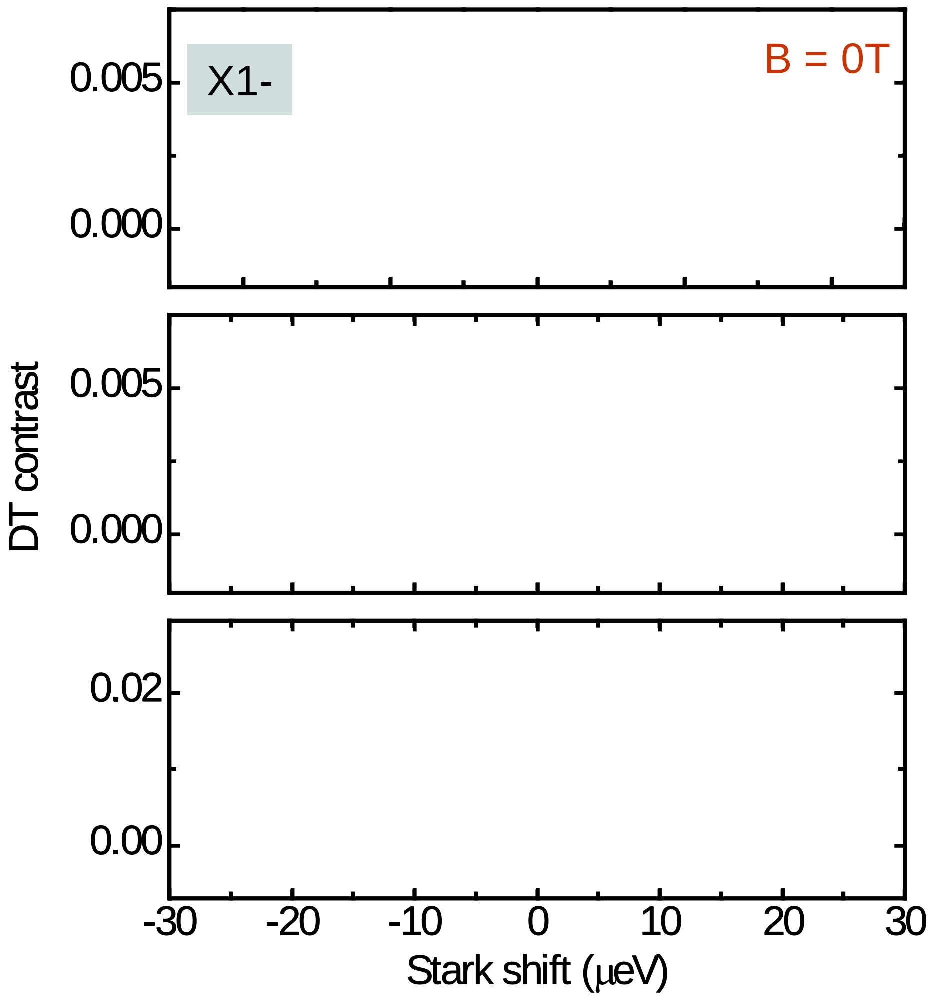
⇨ Optical excitations as a probe of spin-reservoir coupling

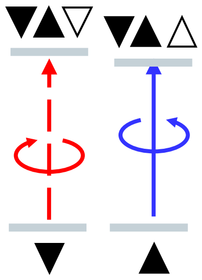
Optical manipulation of nuclear spins



- The diagonal spontaneous emission with rate γ occurs thanks to simultaneous photon emission and an electron-nuclear flip-flop process
- Flipping nuclear spins always in the same (spin-down) direction leads to a red shift of the driven trion resonance, providing a feedback to the electron.

Breakdown of an isolated two-level system description of a QD trion resonance under high magnetic fields





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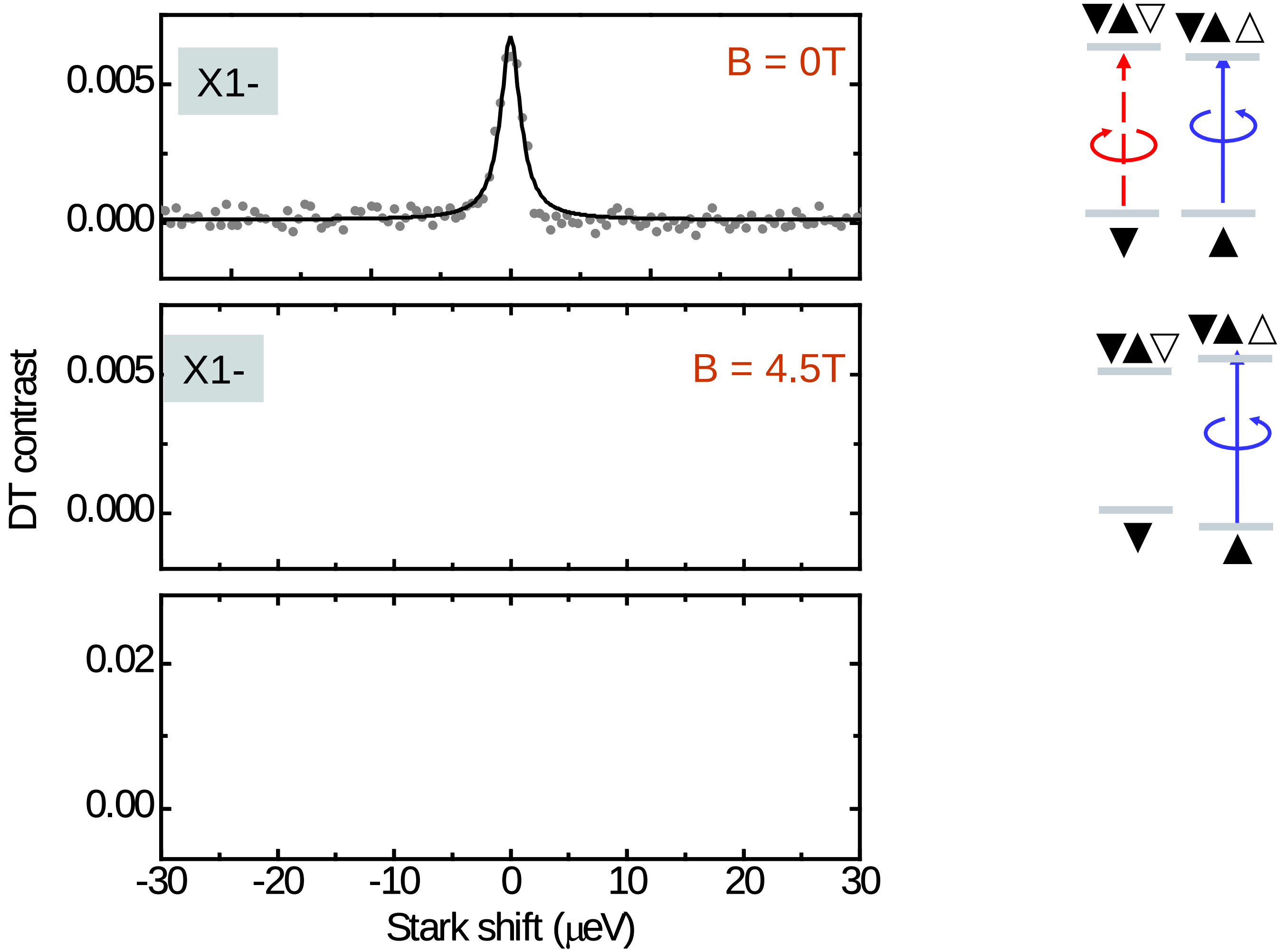

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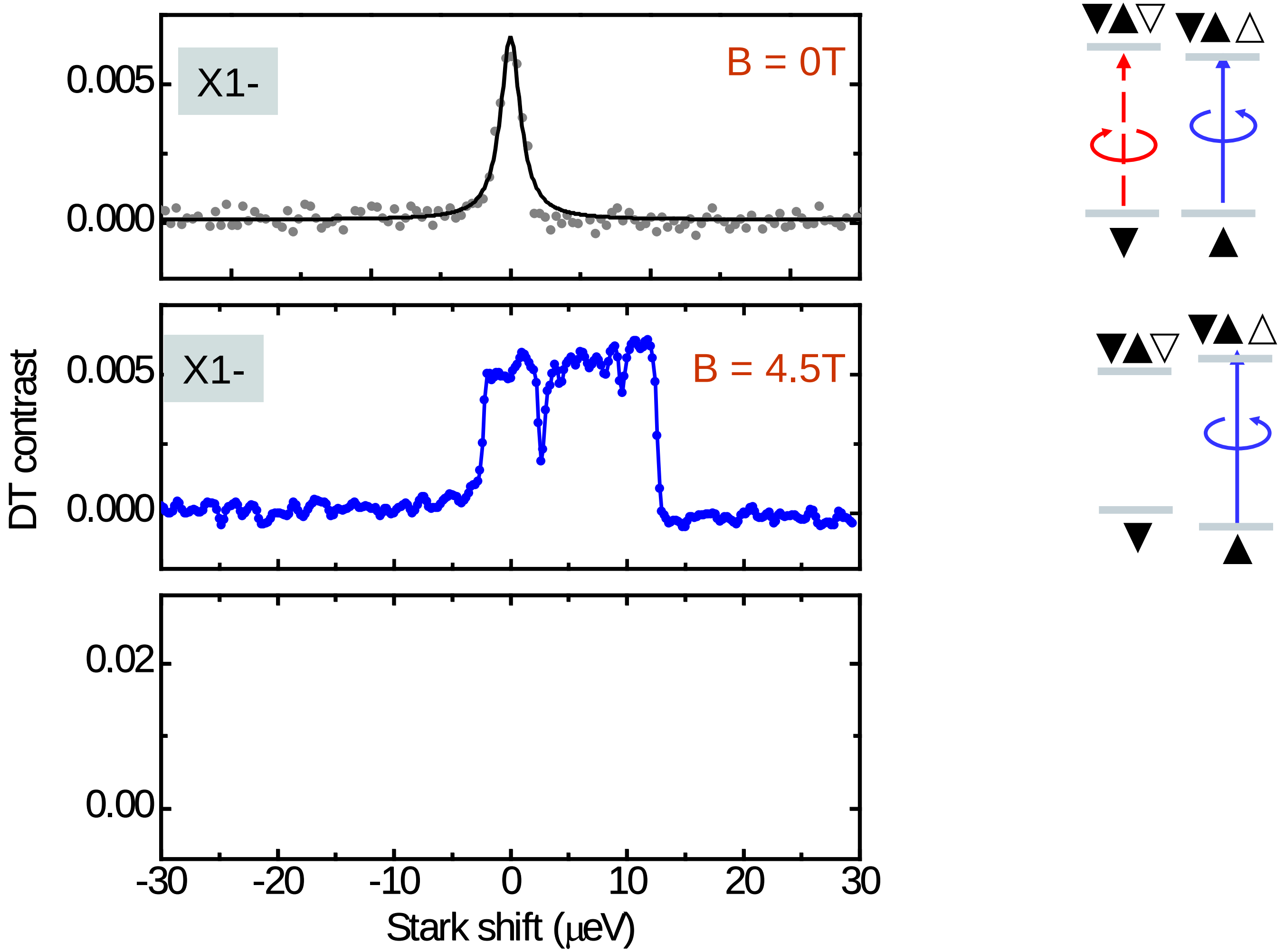

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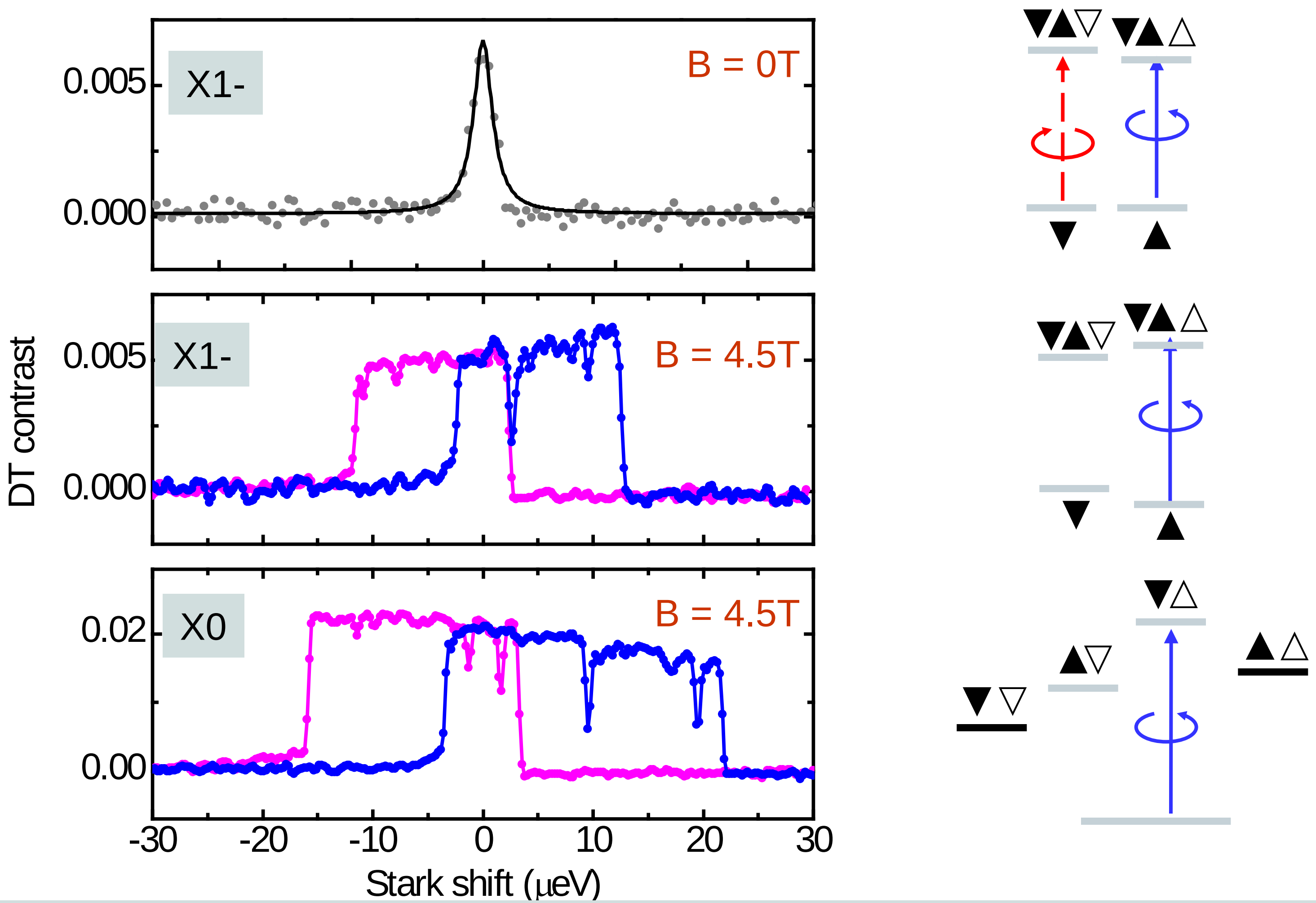


⇨ Coupled electron-nuclear spin dynamics ensures „digital optical response“

Dragging and nuclear spin polarization

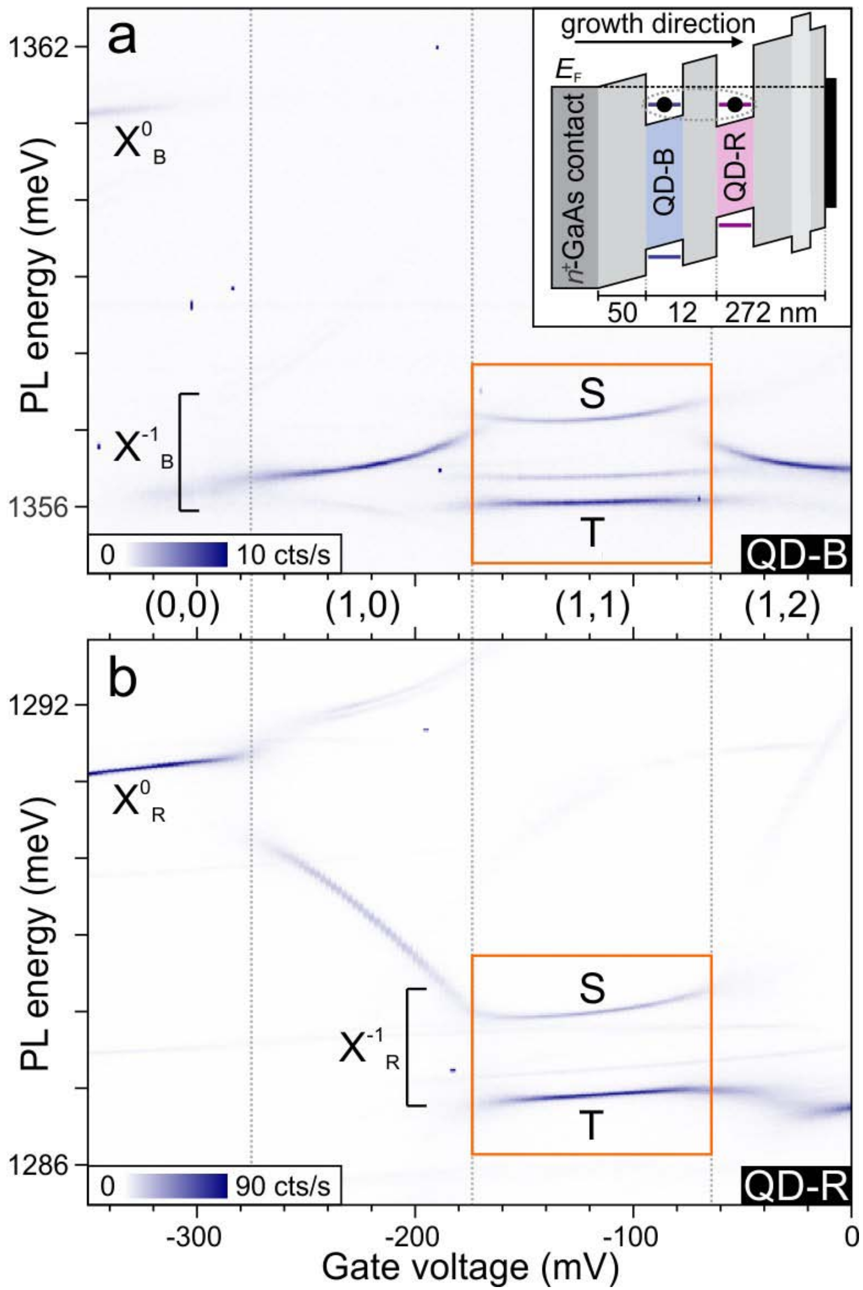
- The experiments suggest that for B > 1 Tesla, nuclear spins polarize in a way to ensure that the QD resonance remains locked to the applied laser field

⇨ How could nuclear spins polarize in both directions?

⇨ Why is absorption strength fixed to its maximum value?

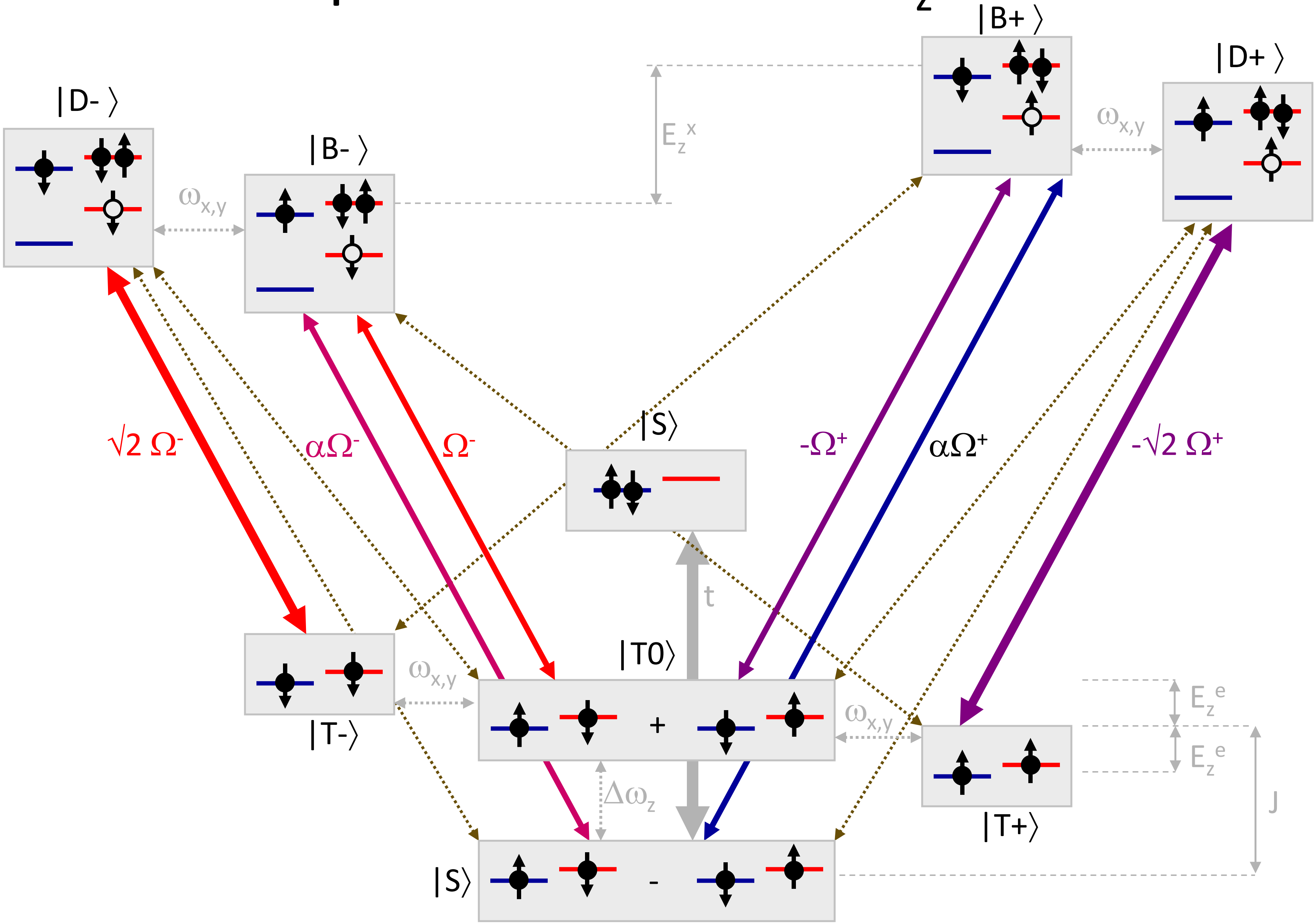
⇨ Why are the trion and neutral excitons behaving similarly?

Tunnel coupled quantum dot pair

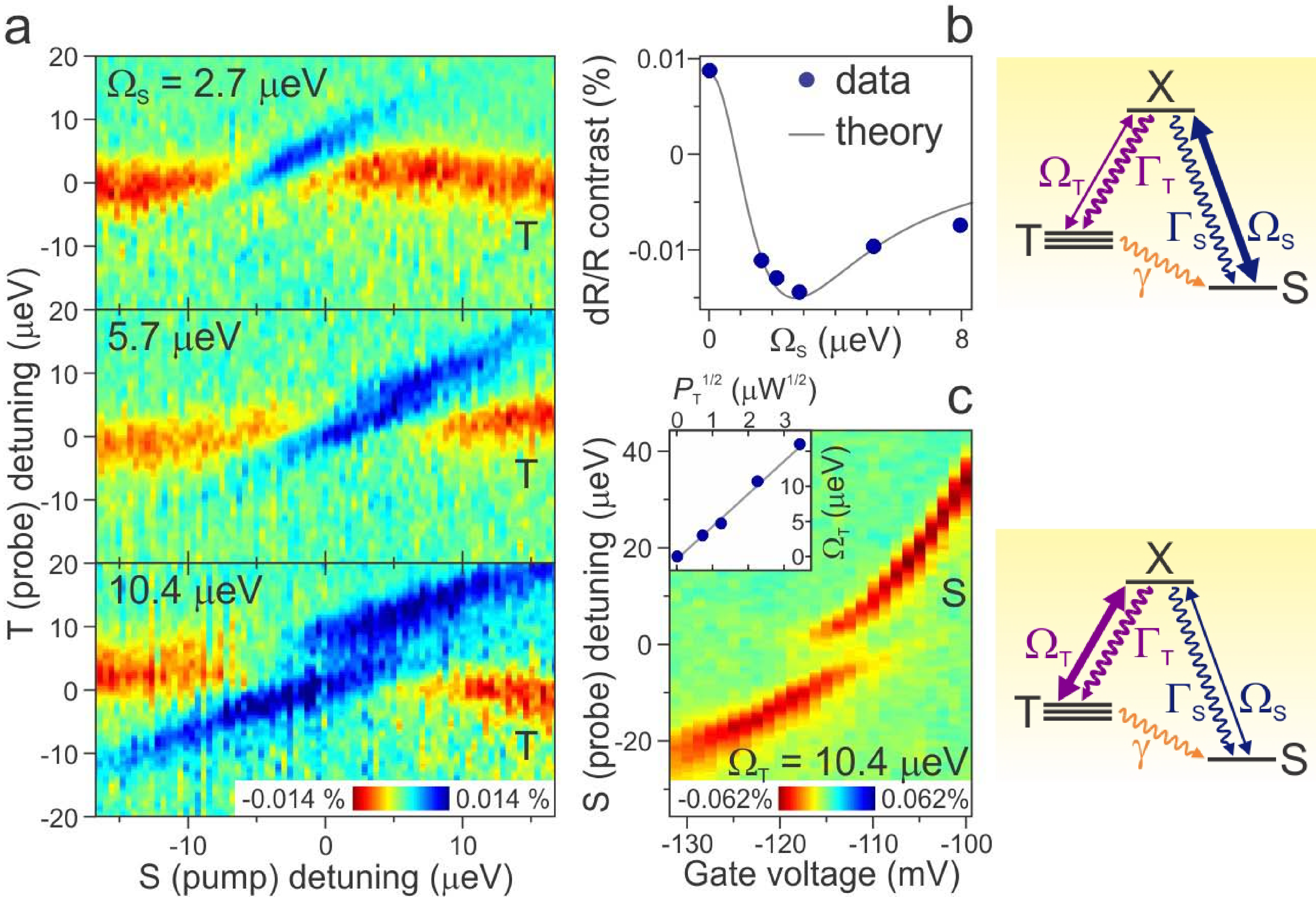


- Reaching (1,1) regime requires accurate control of QD thickness (=emission wavelength)
- Bottom dot (QD-B) ~50 nm more blueshifted than top dot (QD-R)
- Thin tunnel barrier (12 nm) allows strong electron tunneling
- Thick spacer layer (50 nm) allows weak coupling to back contact
- Fill CQD with electrons one by one
- Analyze PL to determine charging sequence
- Electron tunneling ~1.4 meV
- ST splitting ~1.1 meV

Optical transitions at $B_z > 0$



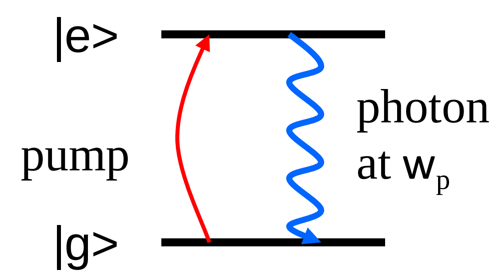
Raman gain in transition between entangled-states



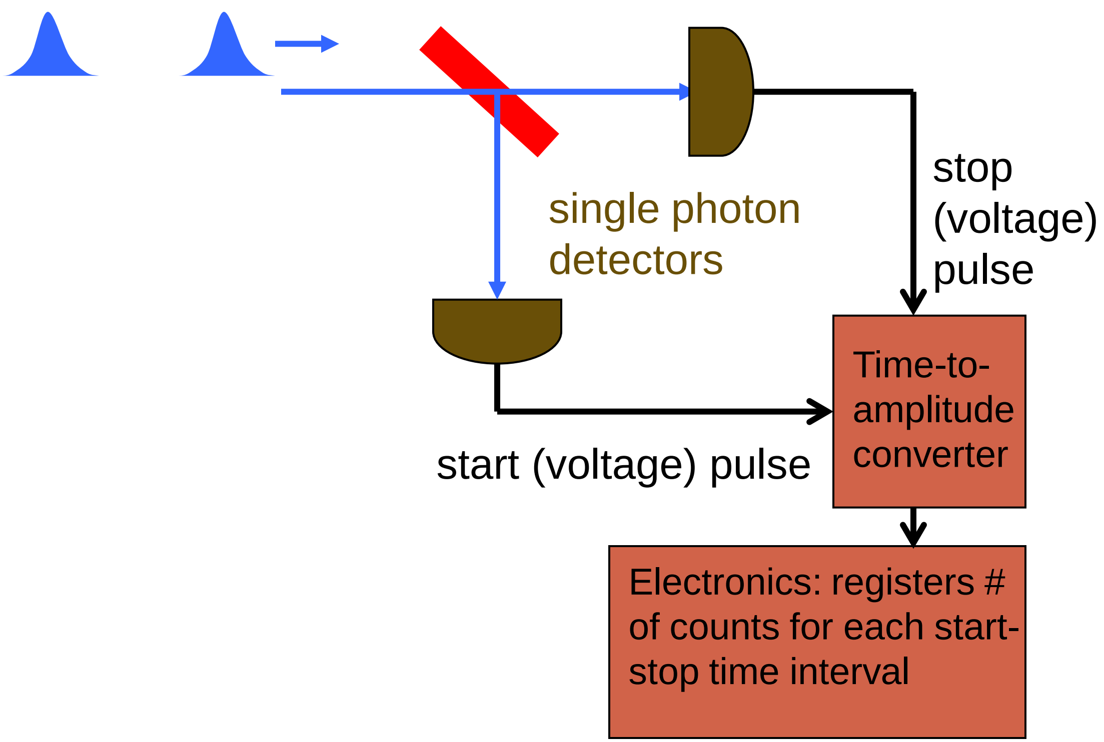
Photon correlation measurements and photon antibunching

- 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+t, given an initial one at time t (t=0).



- Experimental set-up for $g^{(2)}(t)$ measurement:



Detection of the first photon at t=0 tells us that the emitter is now in state |g>; emission of a second photon at t=0+e is impossible.

$\Rightarrow$ Photon antibunching

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

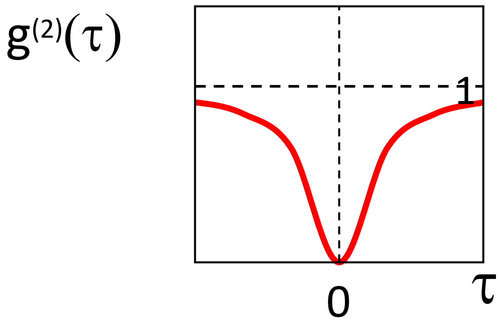
$\Rightarrow$ Only true if we have emission from a single emitter.

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 driven by a <u>cw laser field</u> exhibits photon antibunching.



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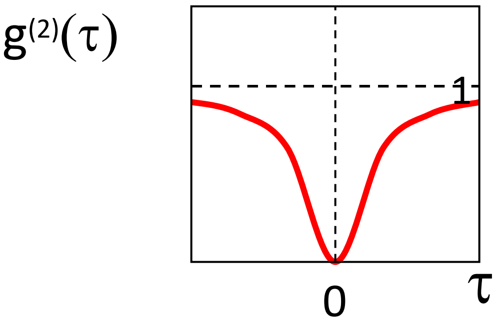
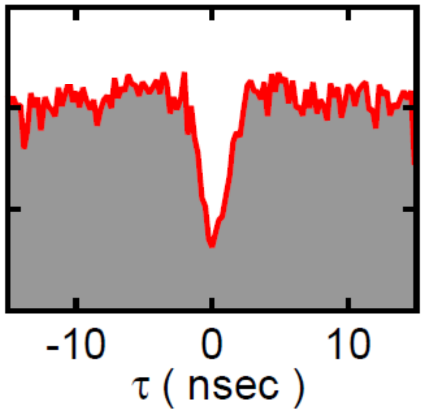


- Photon correlation experiments on a single quantum dot
  - A single photon source?



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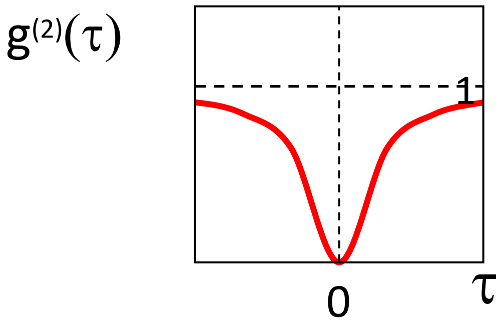
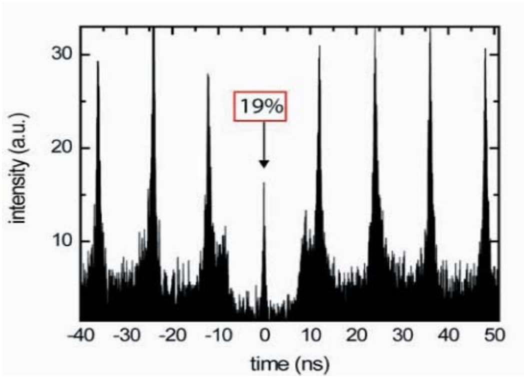
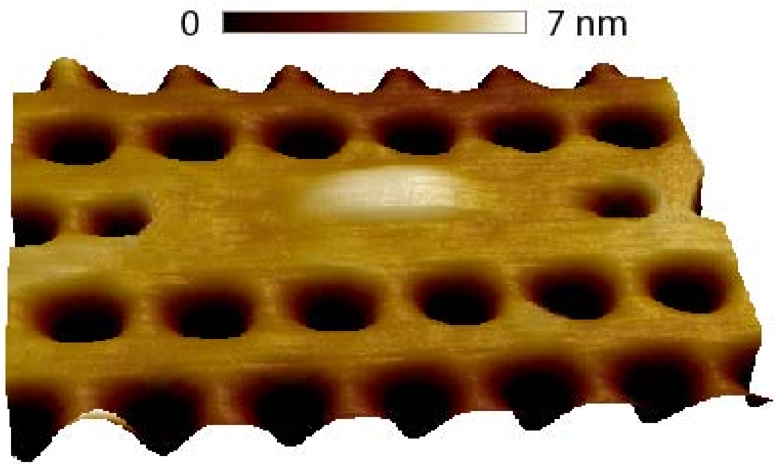


• Single quantum emitter driven by a pulsed laser field with repetition rate 1/T realizes a single-photon source:

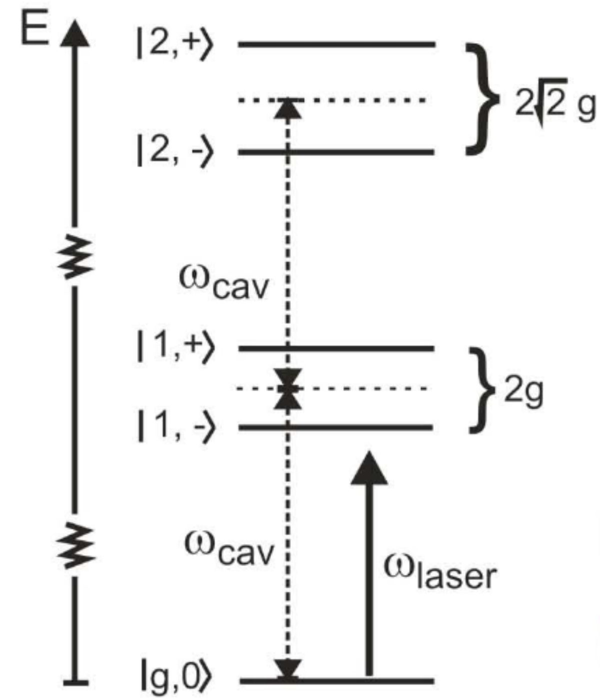
→ the area of the τ=0 peak, normalized to the area of the successive peaks, gives the likelihood of 2-photon emission.



Resonant excitation of a strongly coupled quantum dot nanocavity system

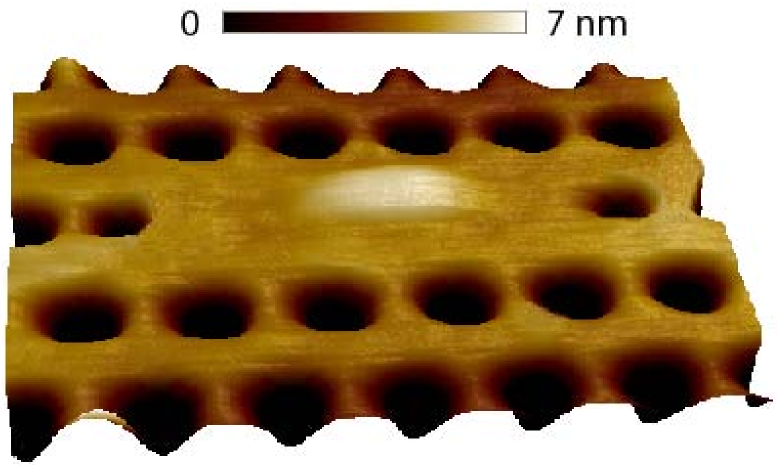


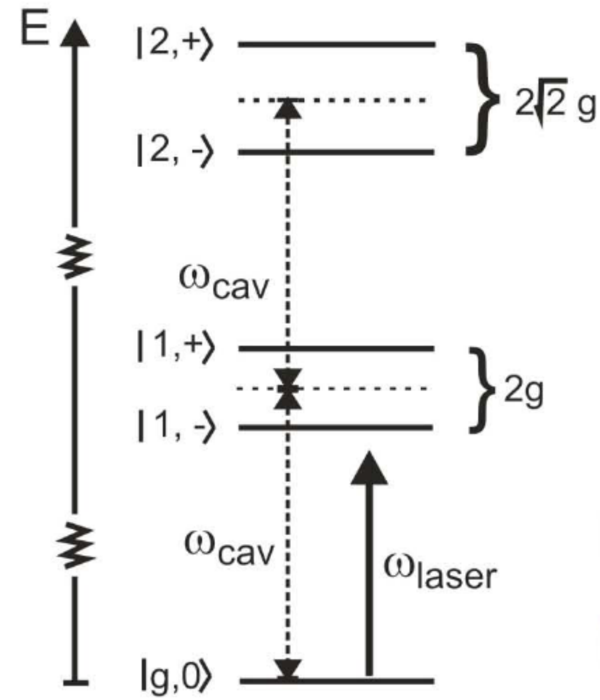
Single quantum dot („white hill“) embedded in a photonic crystal cavity

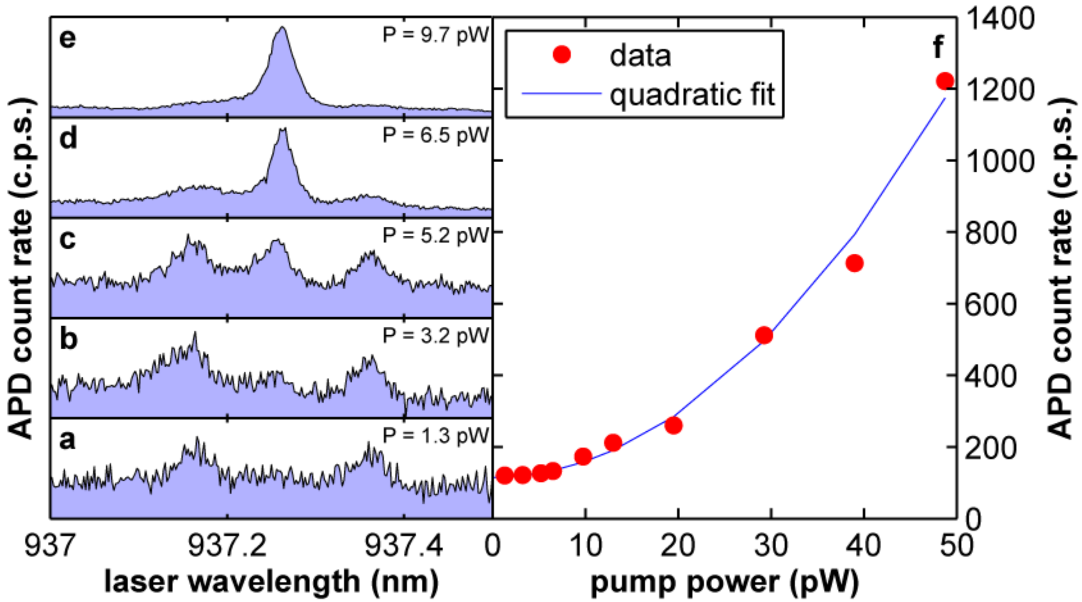


Jaynes-Cummings Model: Anharmonic energy levels for photon-emitter molecules

Resonant excitation of a strongly coupled quantum dot nanocavity system

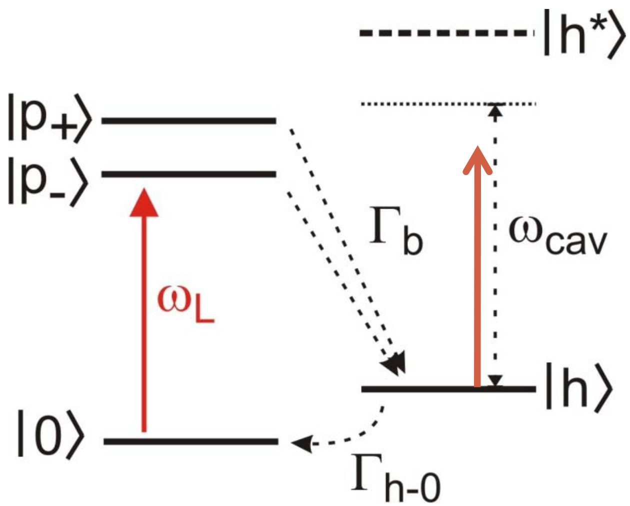






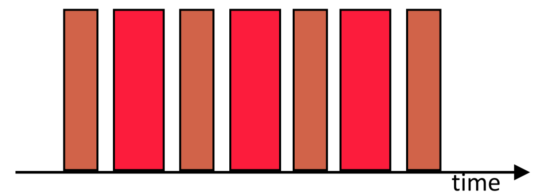
Upon resonant excitation with mean intracavity photon number n_c<0.01, the polaritons (|1,+> & |1,->) disappear from the spectrum and we only observe bare cavity scattering.

Why do the polaritons disappear?



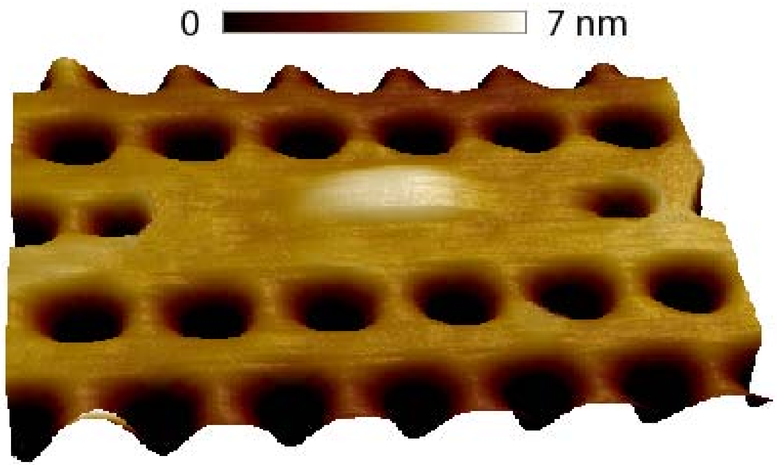
Use laser @ 857nm as repump to repopulate |0>!

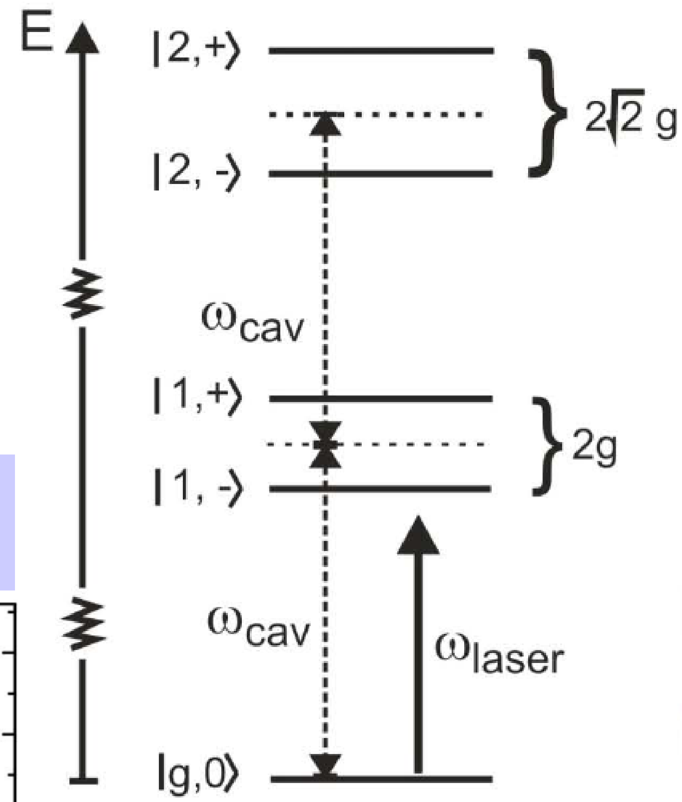
pump/probe scheme



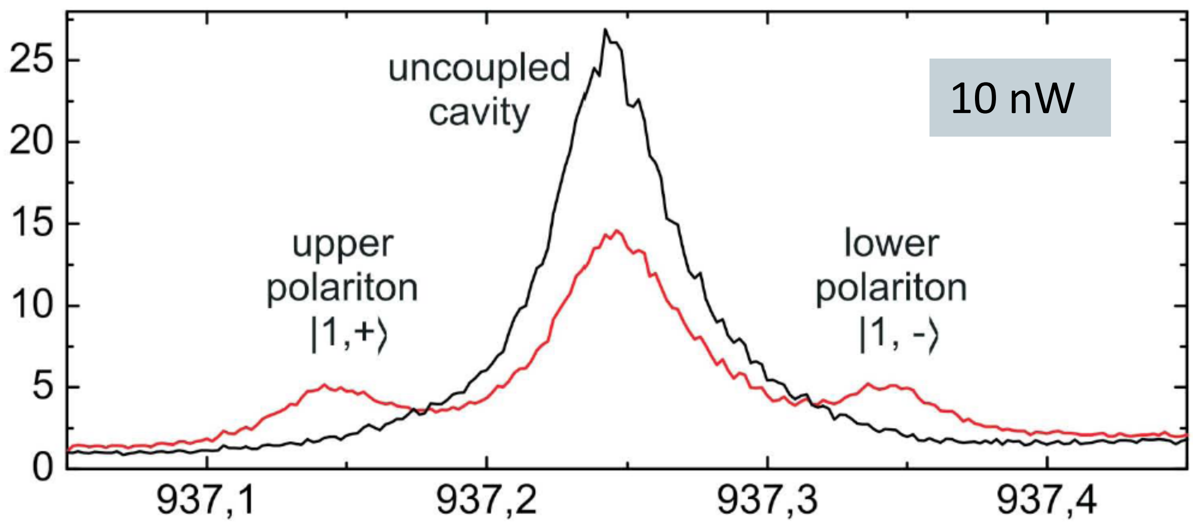
- After ~10^5 photon scattering events, the QD is shelved in a metastable state |h>; the cavity is off resonance with QD transition and the laser probes the bare cavity resonance
- Pump/probe ensures that 40% of the time the QD is in the state |0>.

Resonant excitation of a strongly coupled quantum dot nanocavity system with re-pump

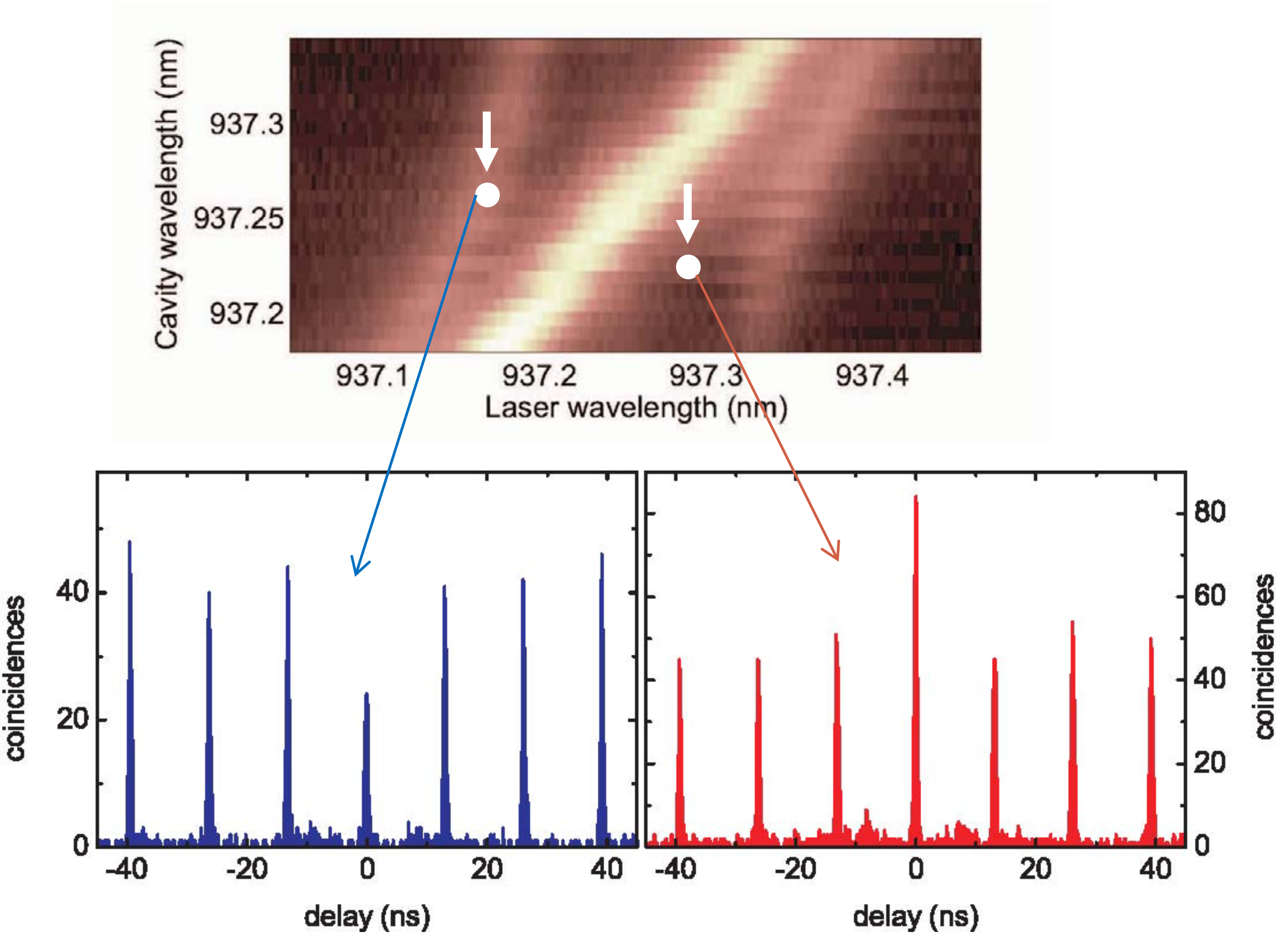


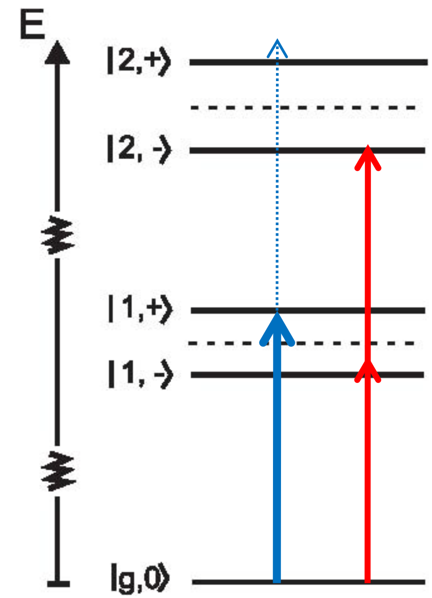


The re-pump laser restores the QD to its neutral ground state with a success probability of 0.5.



Photon correlations under resonant pulsed laser excitation





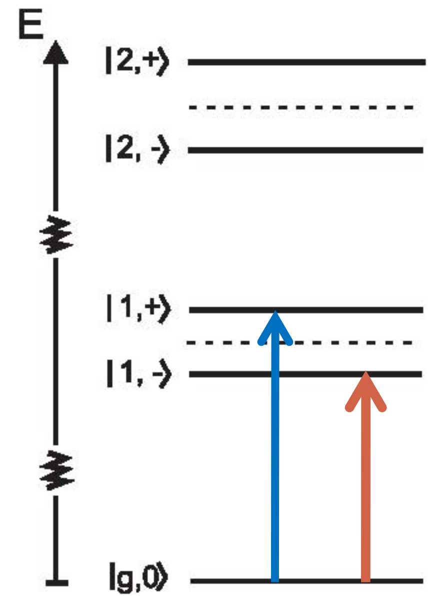
Photon blockade when the laser is resonant with the lower or upper polariton

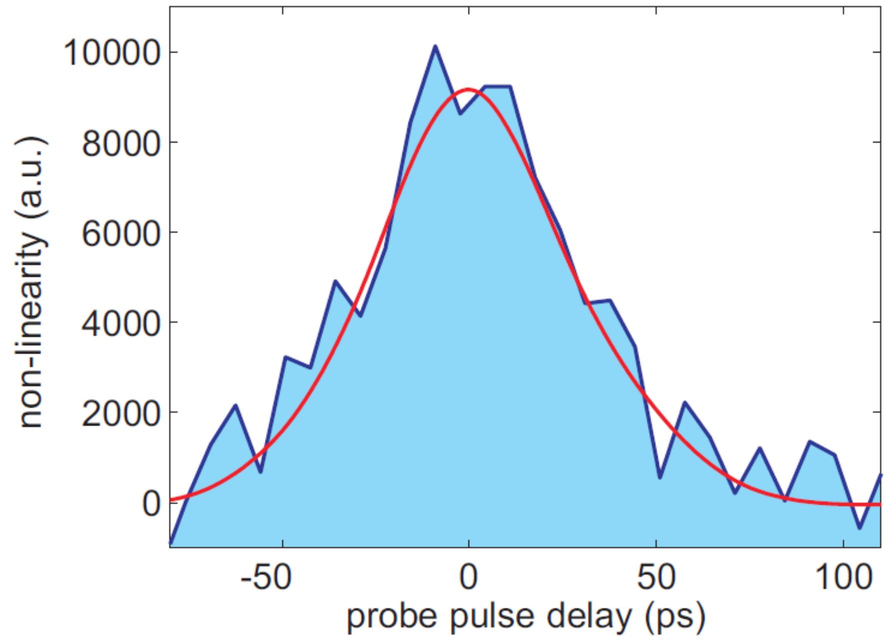
Photon bunching when the laser is two-photon resonant with the second manifold eigenstates

Single photon autocorrelator using QD cavity-QED

If we apply a laser pulse with a known duration on the red polariton transition, we will modify the reflection of a single photon pulse on the blue polariton transition provided that the two fields are overlapping in time:

→ Application of single-photon nonlinearity





Red curve: pulse shape from independent streak-camera measurements

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