Quantum optics using nanostructures: from many-body physics to quantum information processing

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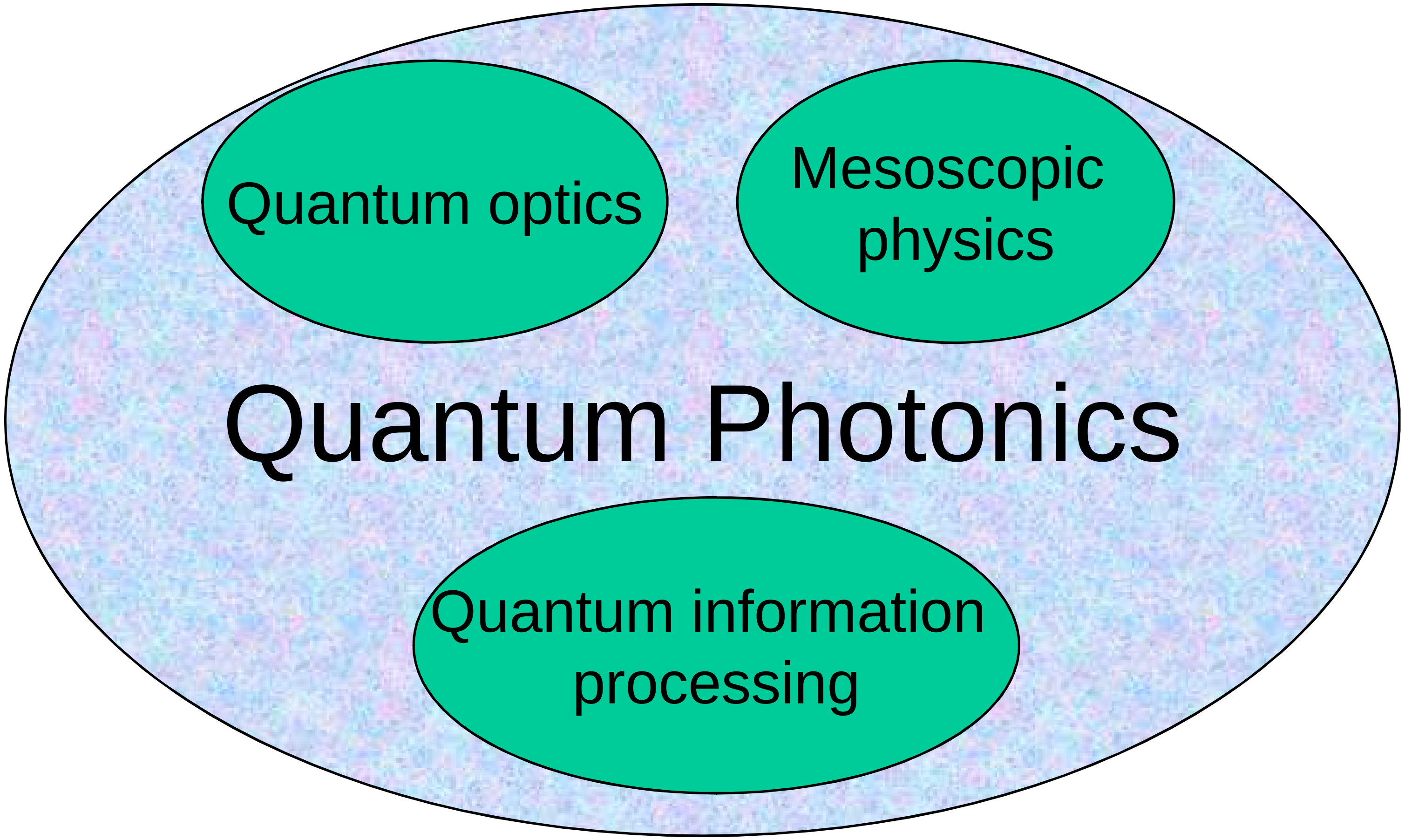
Outline

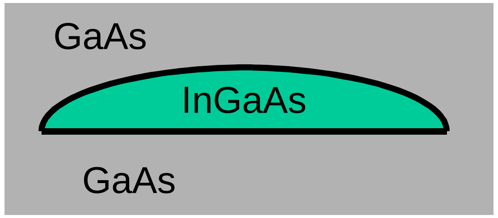
1) Brief overview of optically active quantum dots – a.k.a. artificial atoms
2) Dragging of quantum dot resonances: controlling nuclear spins



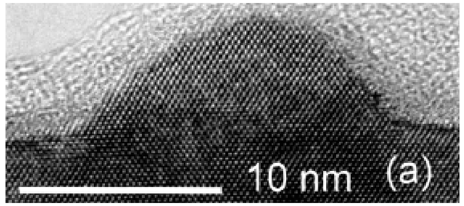
- Use novel properties of solid-state emitters to study quantum optical phenomena:
  - cavity-QED with ultra-small mode-volumes and fixed emitters
  - Nonclassical states of light; nonlinear optics at the single-photon level
- Use quantum optical techniques to study mesoscopic physics:
  - hyperfine interactions with quantum dot nuclear spin ensembles
  - photon correlation spectroscopy of carbon nanotubes
- Understand and suppress spin decoherence mechanisms; implement spin measurement, manipulation and entanglement; realize spin-polarization conversion

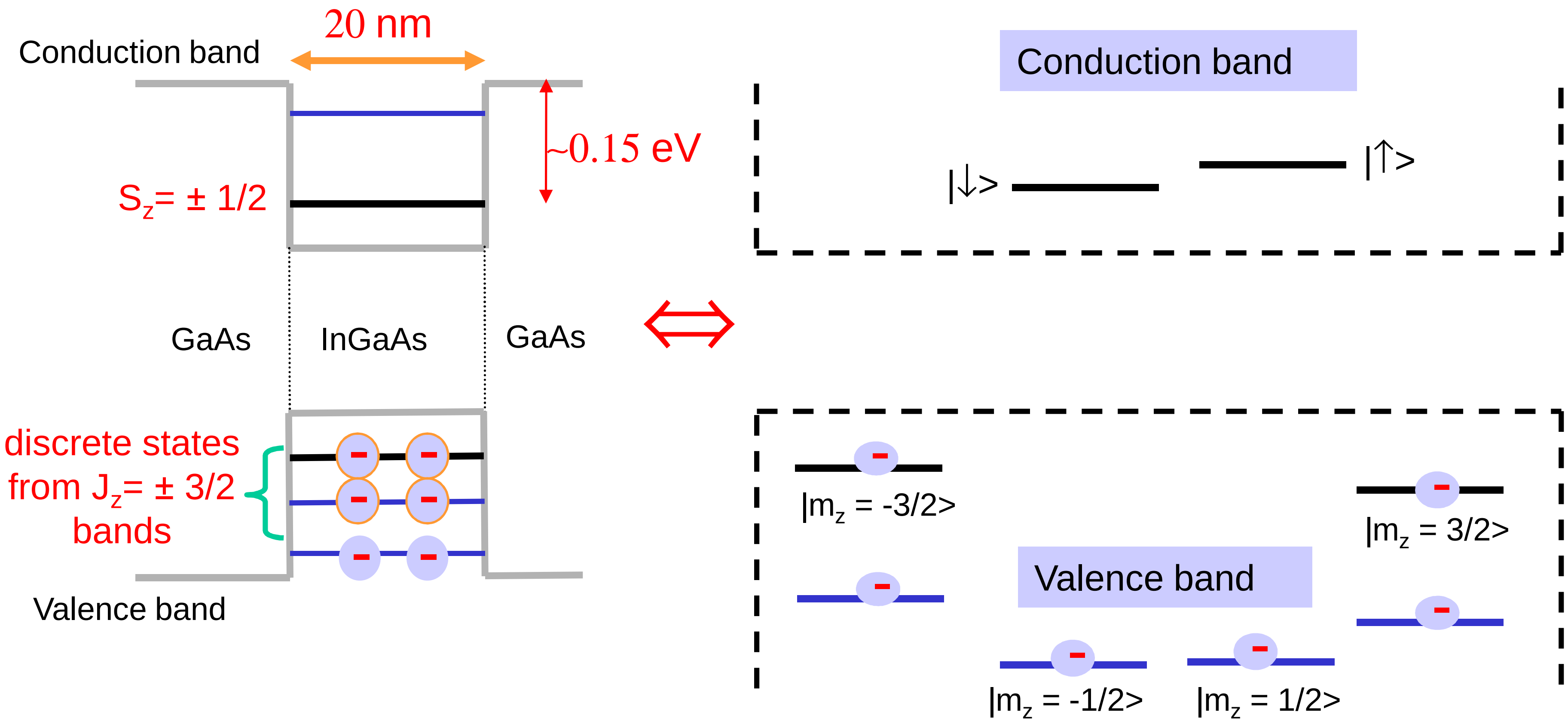
New angle: the use of quantum optical techniques for studying many-body effects

- Strongly correlated photons in an array of driven-dissipative cavities: fermionization of photons
- Optical signatures of the Kondo effect: what does absorption lineshape of a single confined electron tell us about many-body correlations in an electron gas
- Experimental study of dissipative quantum phase transition in the sub-Ohmic spin-boson model
- An isolated ensemble of 10^5 nuclear spins: using photons to study the central spin problem

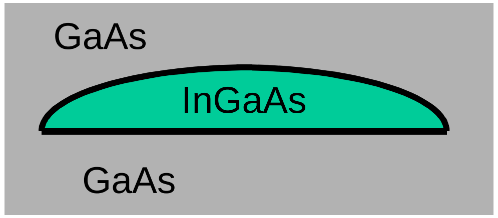


Quantum dots (QD)





- 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



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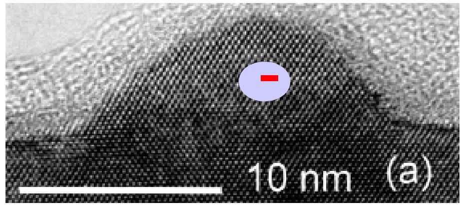

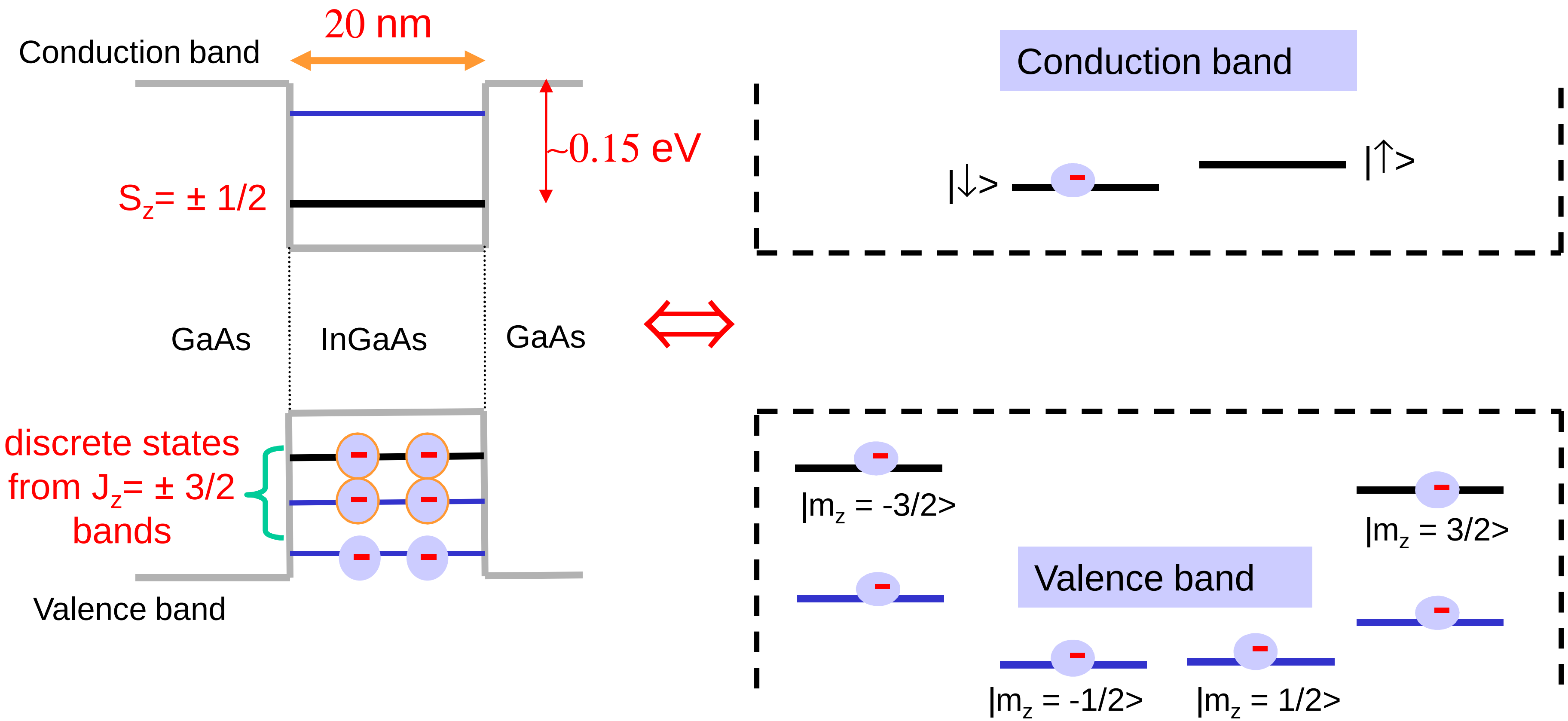

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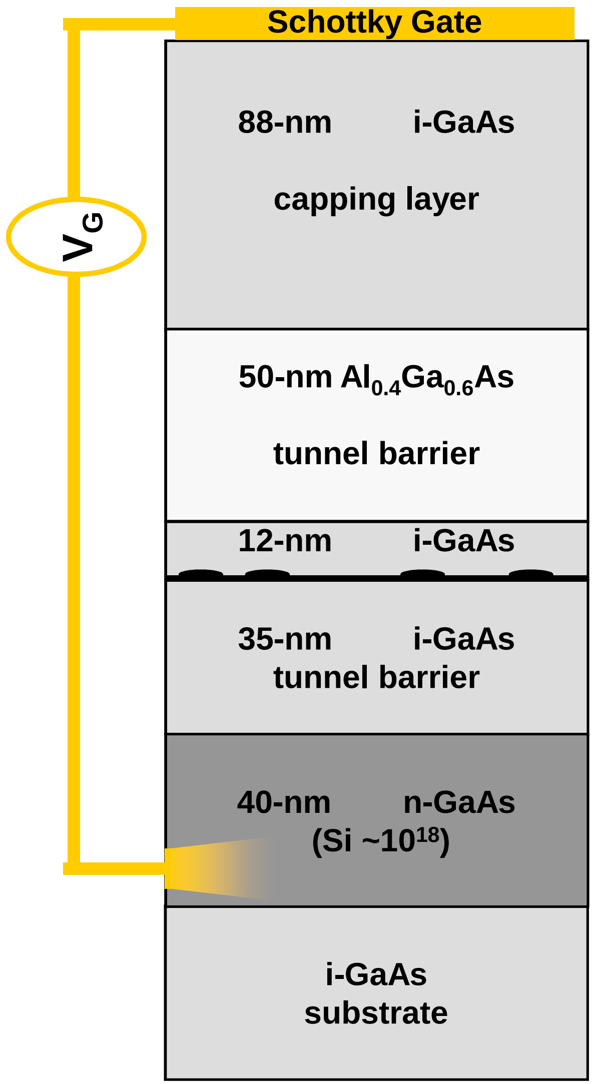
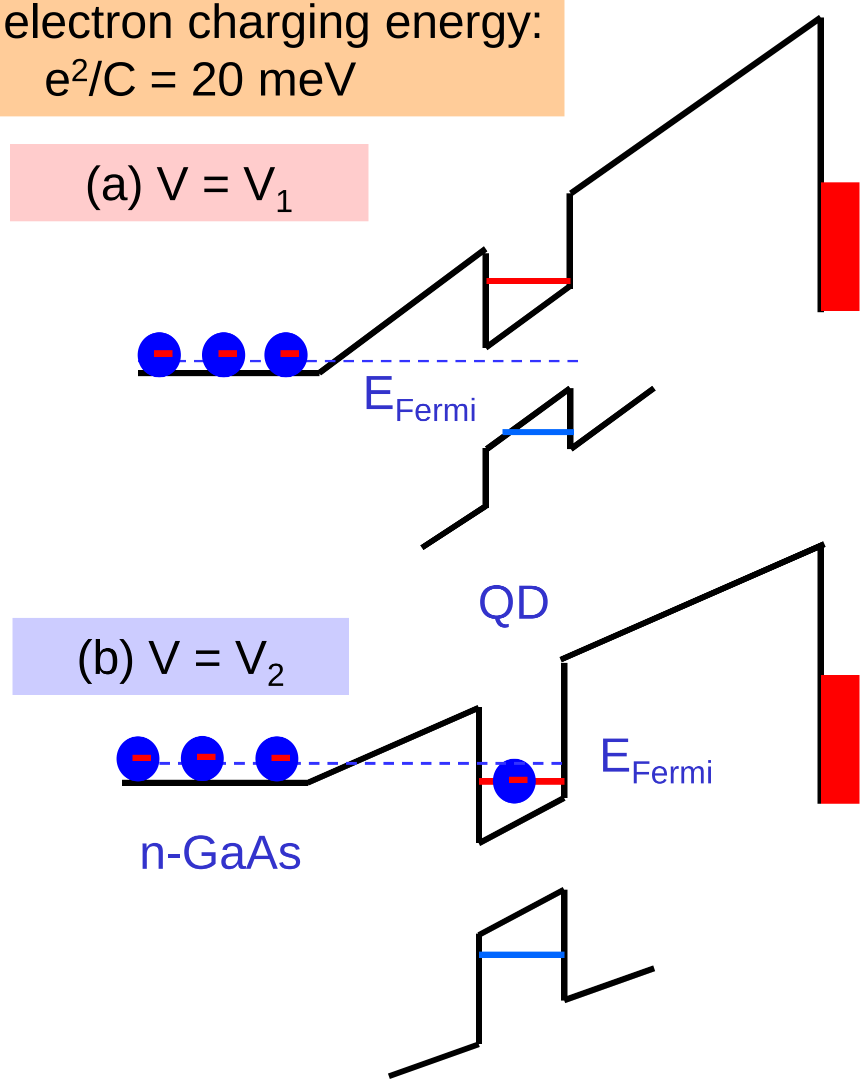
QD spins: controlled charging of a single QD

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

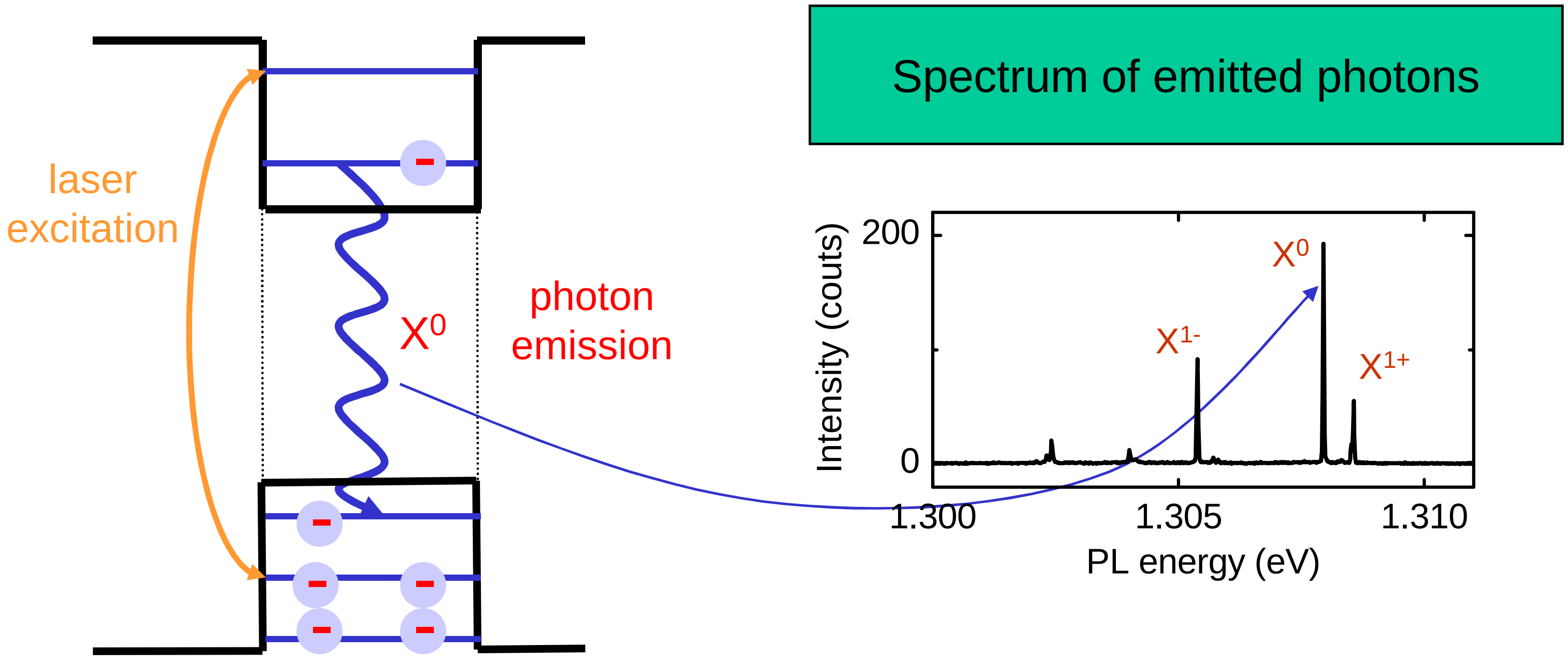
Coulomb blockade ensures that electrons are injected into the QD one at a time



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



Photoluminescence (PL) from a single quantum dot



⇒ QDs typically exhibit several sharp emission lines – in part due to charging of the QD with an excess electron or hole 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.

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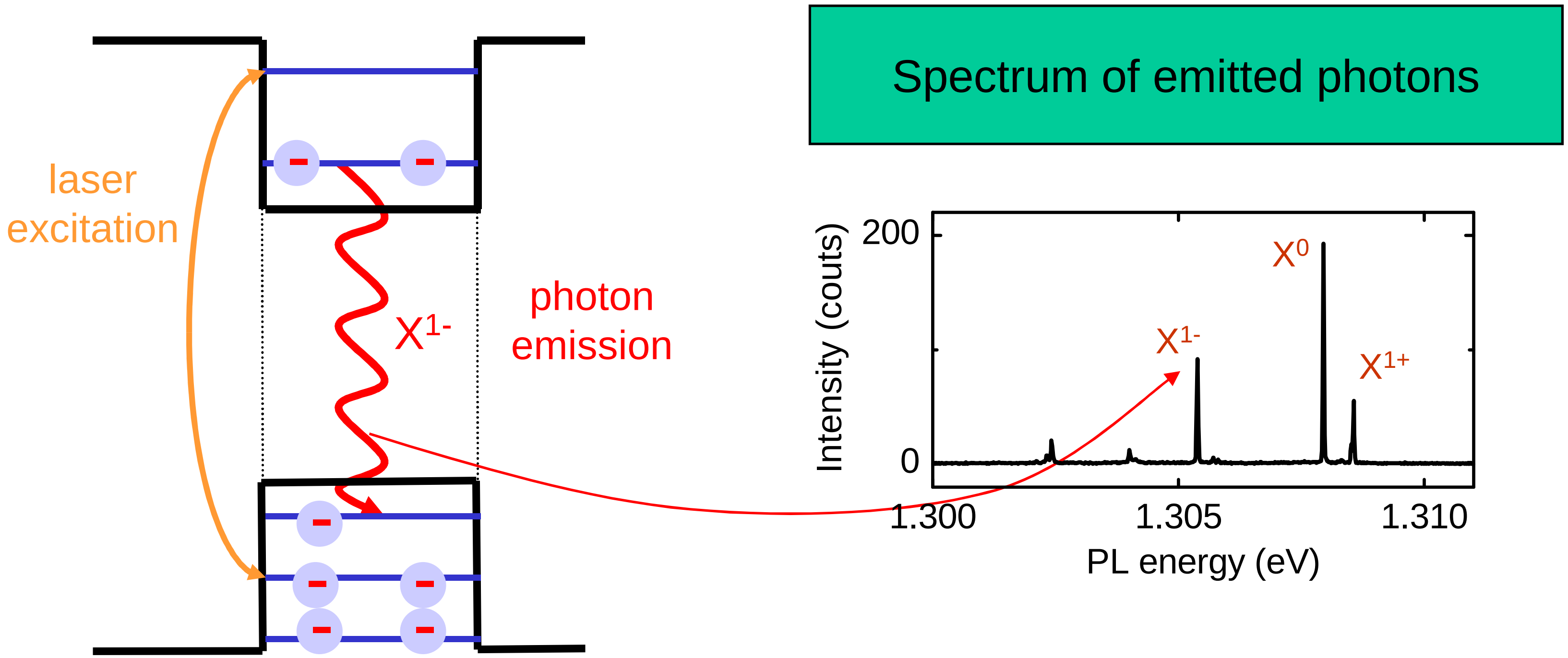

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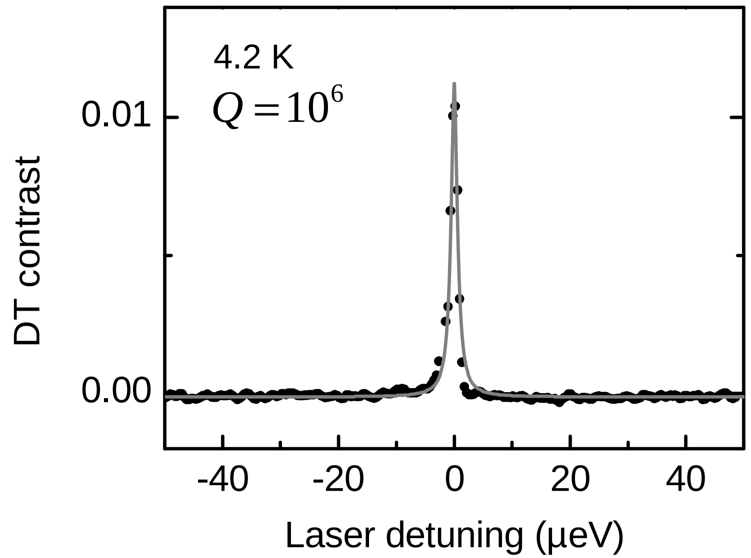
Some key atom-like features of quantum dots

- Ultra-narrow lines in emission or absorption:

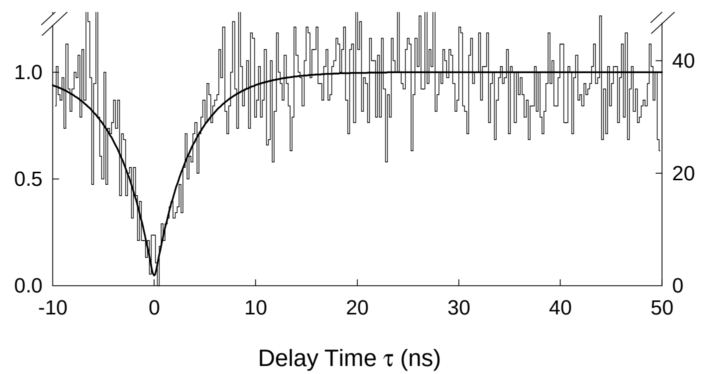
  $\Gamma_{\text{spon}} = 0.7$ µeV $\Leftrightarrow 1$ nsec

  The measured
  absorption width: 1.3 µeV

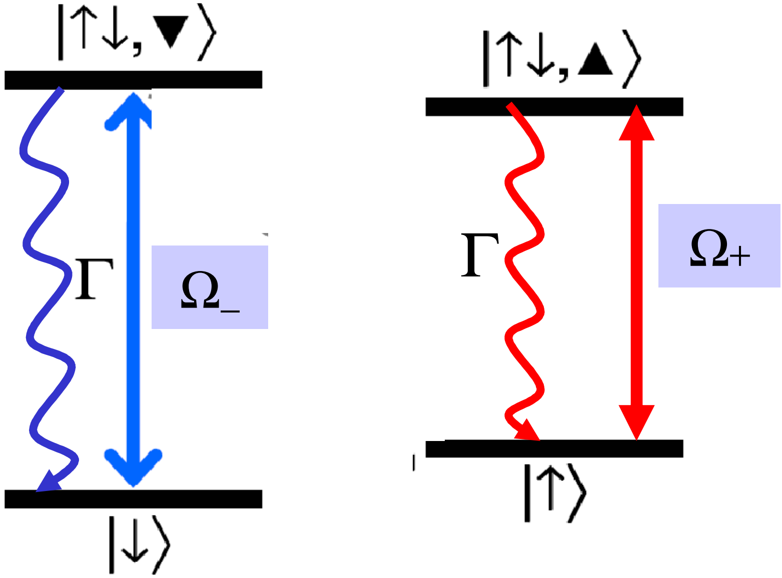


- Photon antibunching in photon correlation measurements:

  Strong photon antibunching proves that the luminescence originates predominantly from a single QD.



Strong spin-polarization correlations in a single-electron charged quantum dot

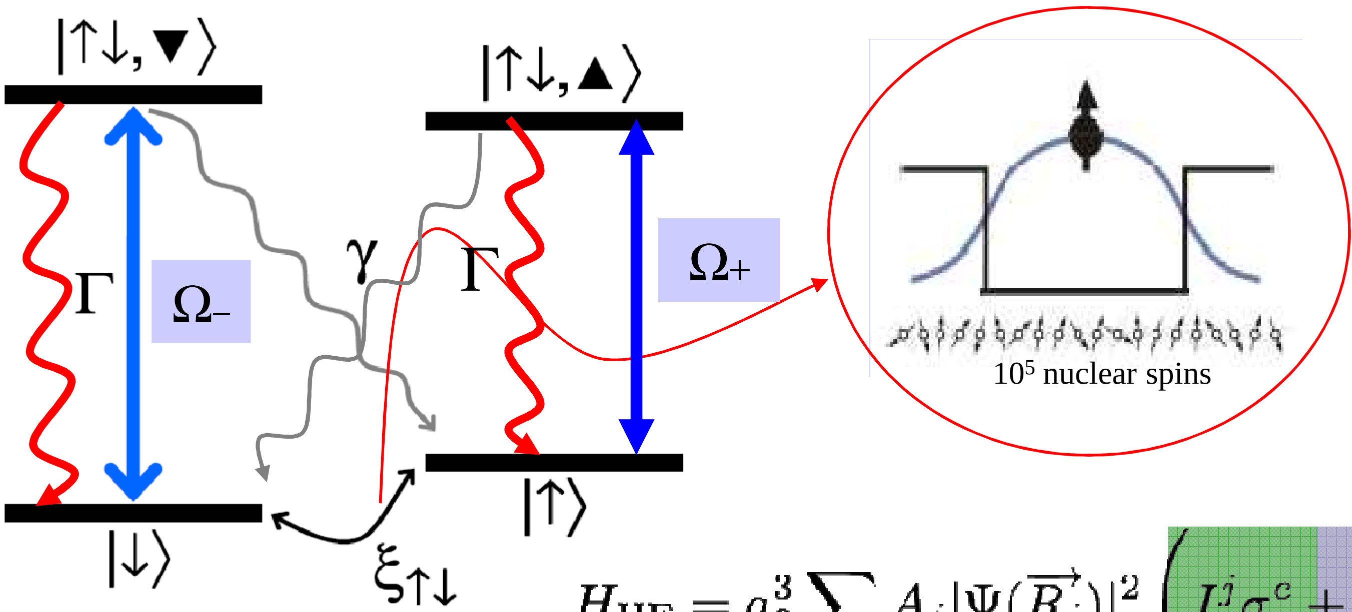


Γ: spontaneous emission rate ~ 10^9 s^{-1}

Ω: laser coupling (Rabi) frequency

- QD with a spin-up (down) electron only absorbs and emits σ+ (σ-) photons.
- A strong detuned σ+ laser field generates an ac-Stark field only for the spin-up state – an effective magnetic field.

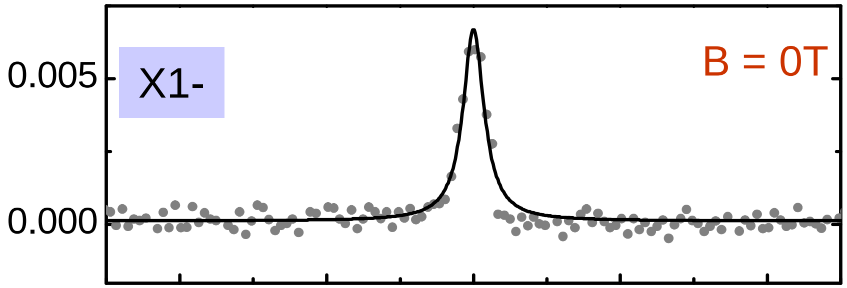
Trion transitions in a charged QD

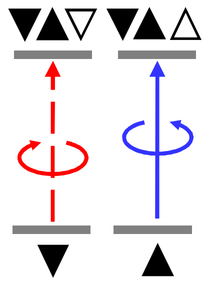


$$H_{\mathrm{HF}} = a_0^3 \sum_j A_j |\Psi(\vec{R}_j)|^2 \underbrace{\left(I_z^j \sigma_z^e + \frac{I_+^j \sigma_-^e + I_-^j \sigma_+^e}{2} \right)}_{\vec{I^j} \cdot \vec{\sigma^e}}$$

- Longitudinal component gives rise to a quasi-static effective magnetic Overhauser (Knight) field seen by the electron (nuclei)
- Transverse (flip-flop) component causes simultaneous electron-nuclei spin flip events

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





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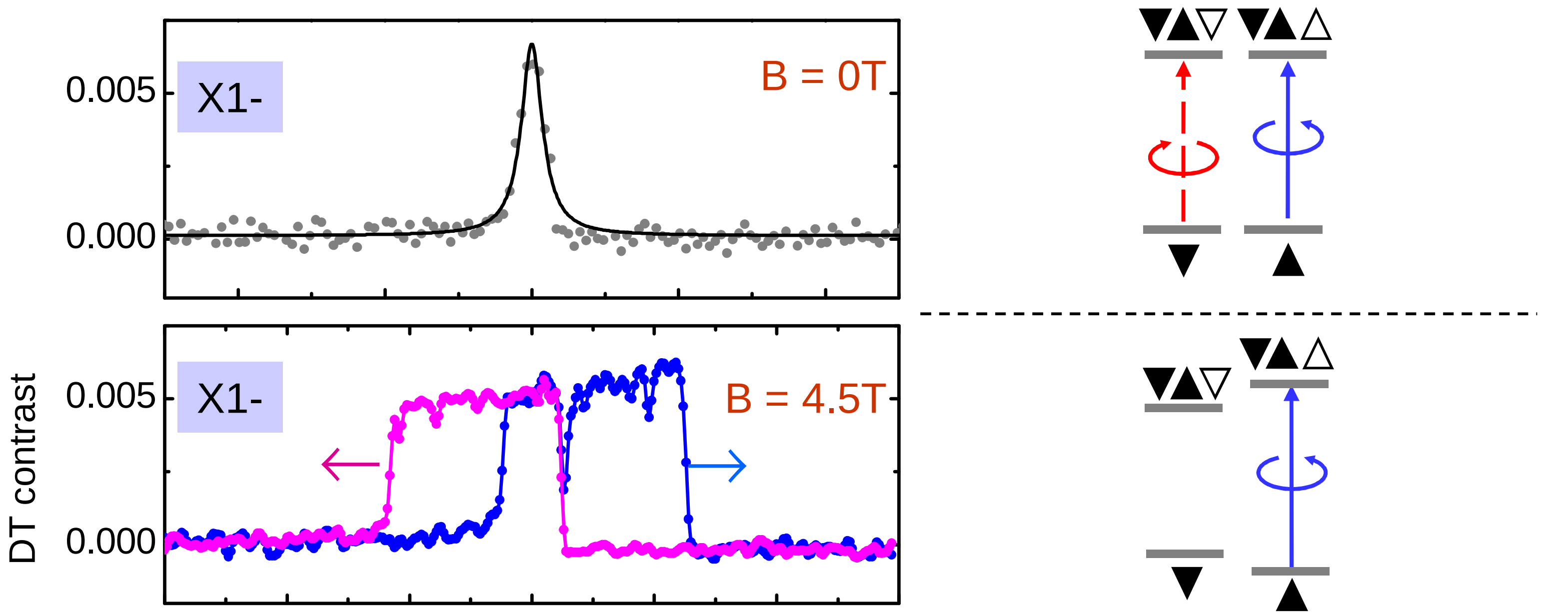

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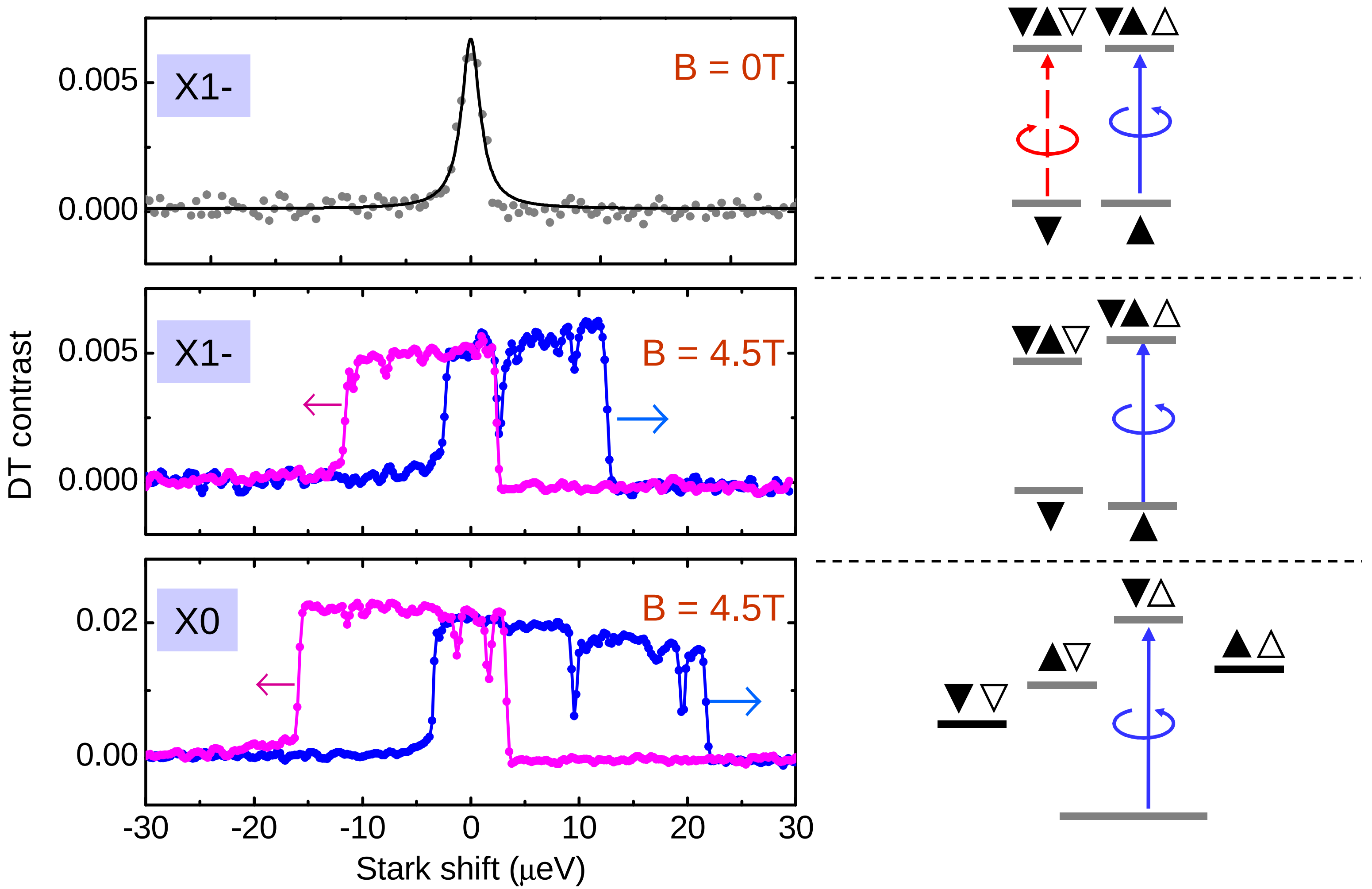
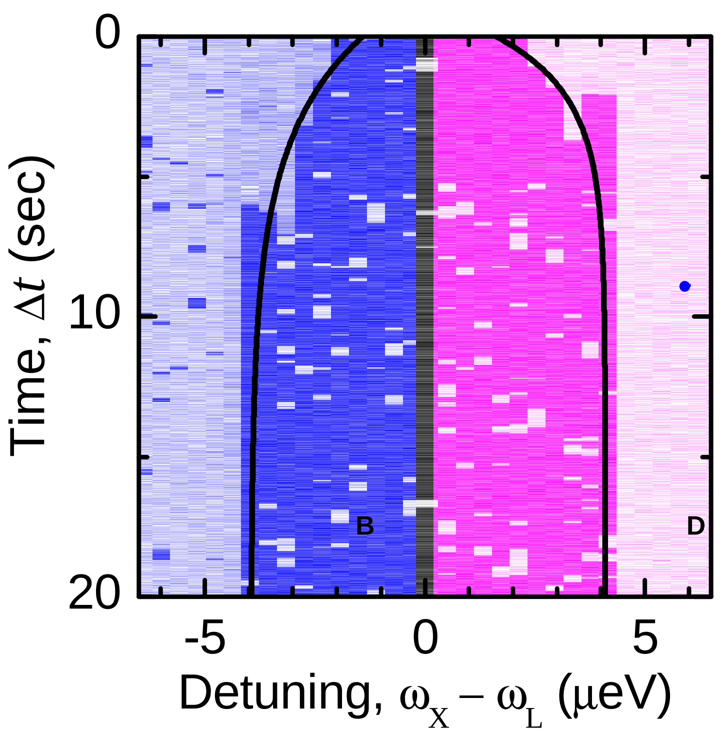
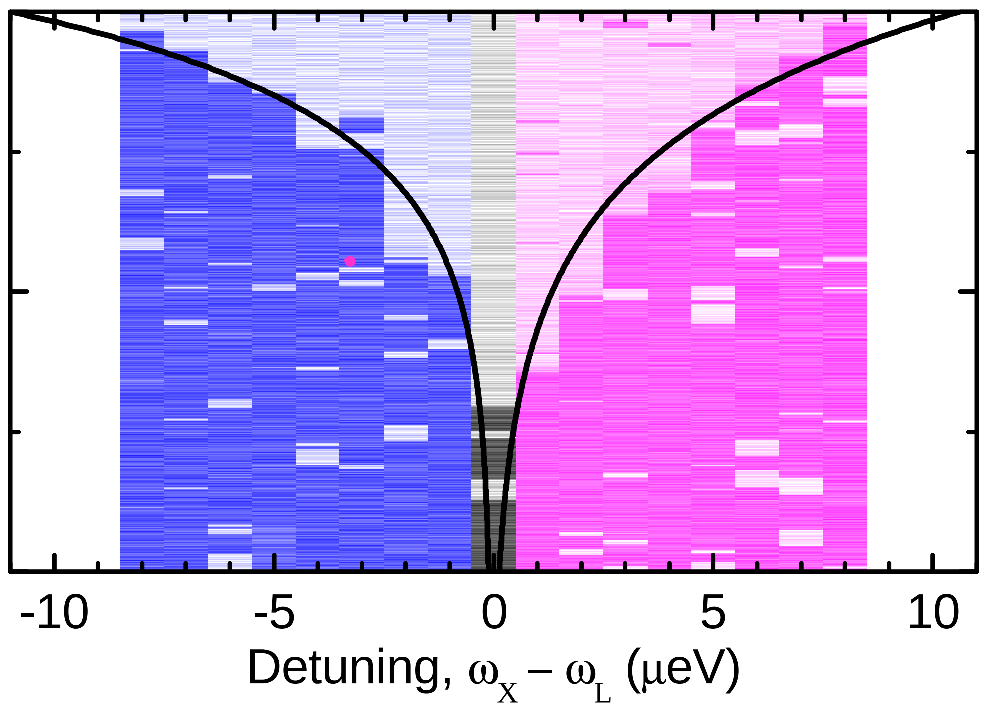


Locking of the QD trion resonance to a laser field

Erase the memory by waiting, then tune the laser near resonance and monitor the time-scale over which the QD self-tunes

Drag the trion either to the blue or the red side of the bare resonance, abruptly change the laser frequency and monitor the time-scale over which full absorption recovers





X^{1-} decay time scale: seconds

X^{0} decay time scale: hours

Dragging and nuclear spin polarization

- The experiments suggest that for B > 2 Tesla, nuclear spins polarize in a way to ensure that the QD resonance remains locked to the applied laser frequency

- Strong exchange coupling to a Fermi sea leads to enhanced nuclear spin decay and a disapearance of dragging/locking

⇨ How could nuclear spins polarize in both directions?

⇨ Why is absorption strength fixed to its maximum value?

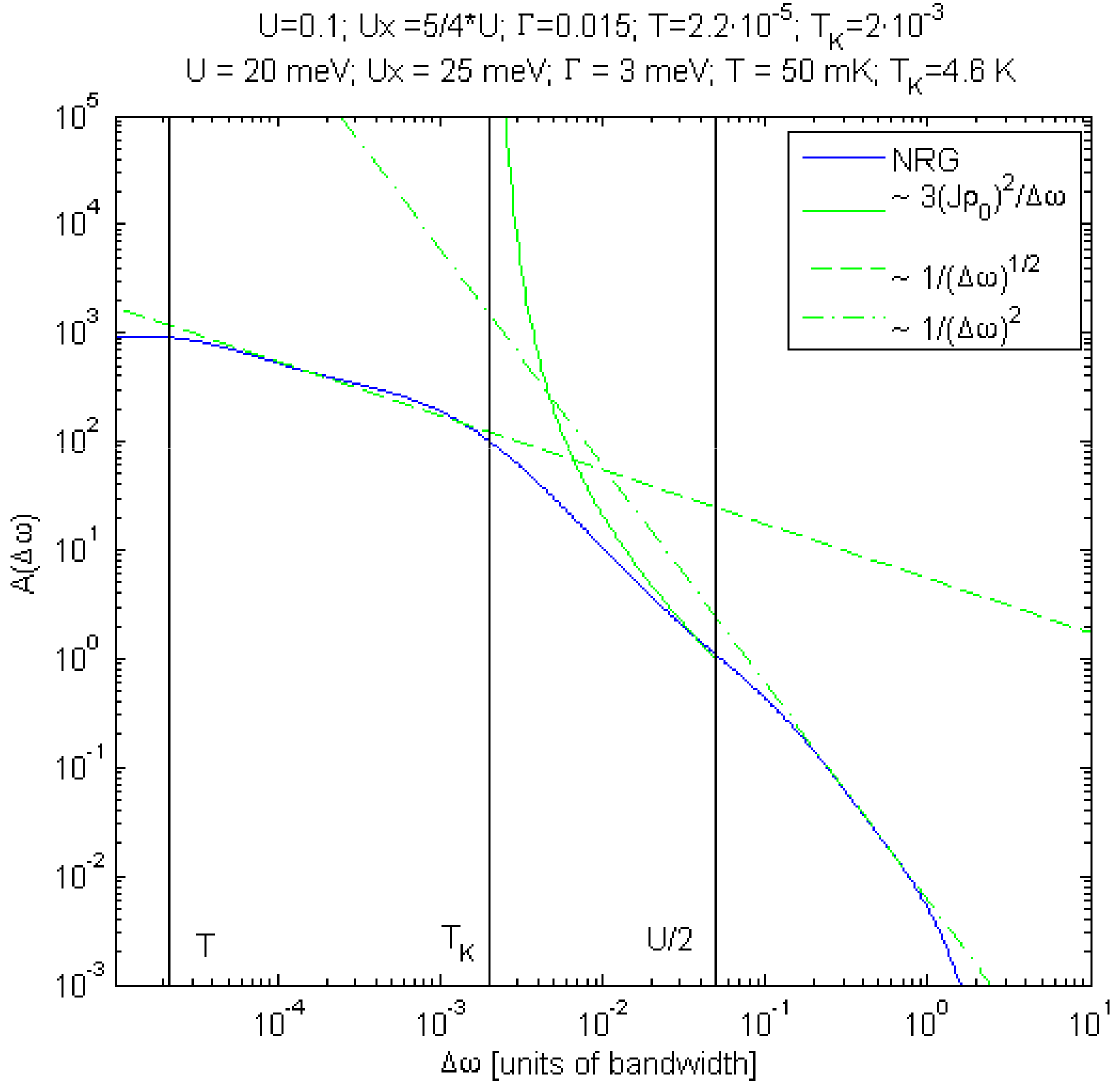
⇨ Why are the trion and neutral excitons behaving similarly?

Implications of dragging

- Numerical results as well as indirect experimental evidence suggests a suppression of Overhauser field variance ↔ $T_2^* = T_2$
  ⇨ Spin coherence without spin echo

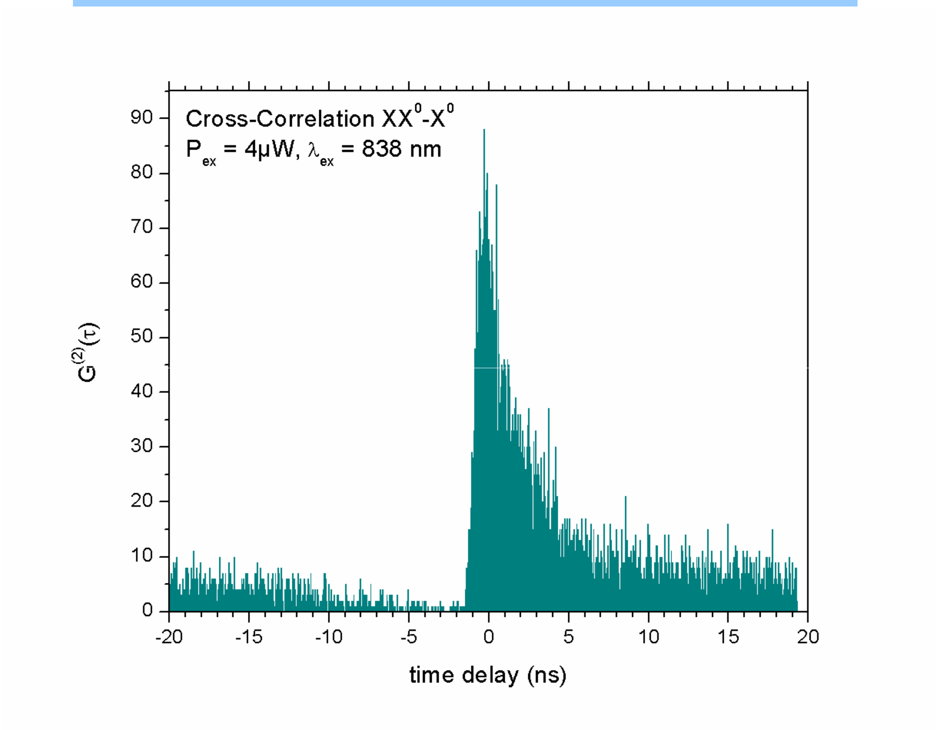
- Tuning electron g-factors by a laser field such that we have identical spins
  ⇨ Experiments such as probabilistic entanglement of distant spins become accessible

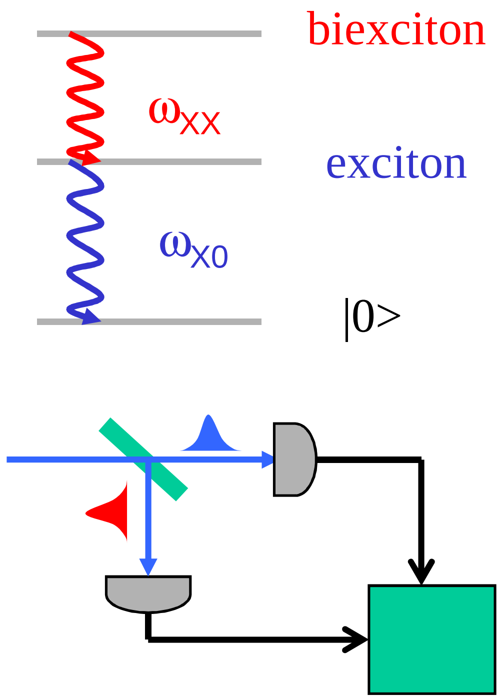
QD absorption in the presence of strong exchange coupling to a 2DEG



Exciton/biexciton (X1/XX) cross-correlation

Pump power *well below* saturation level



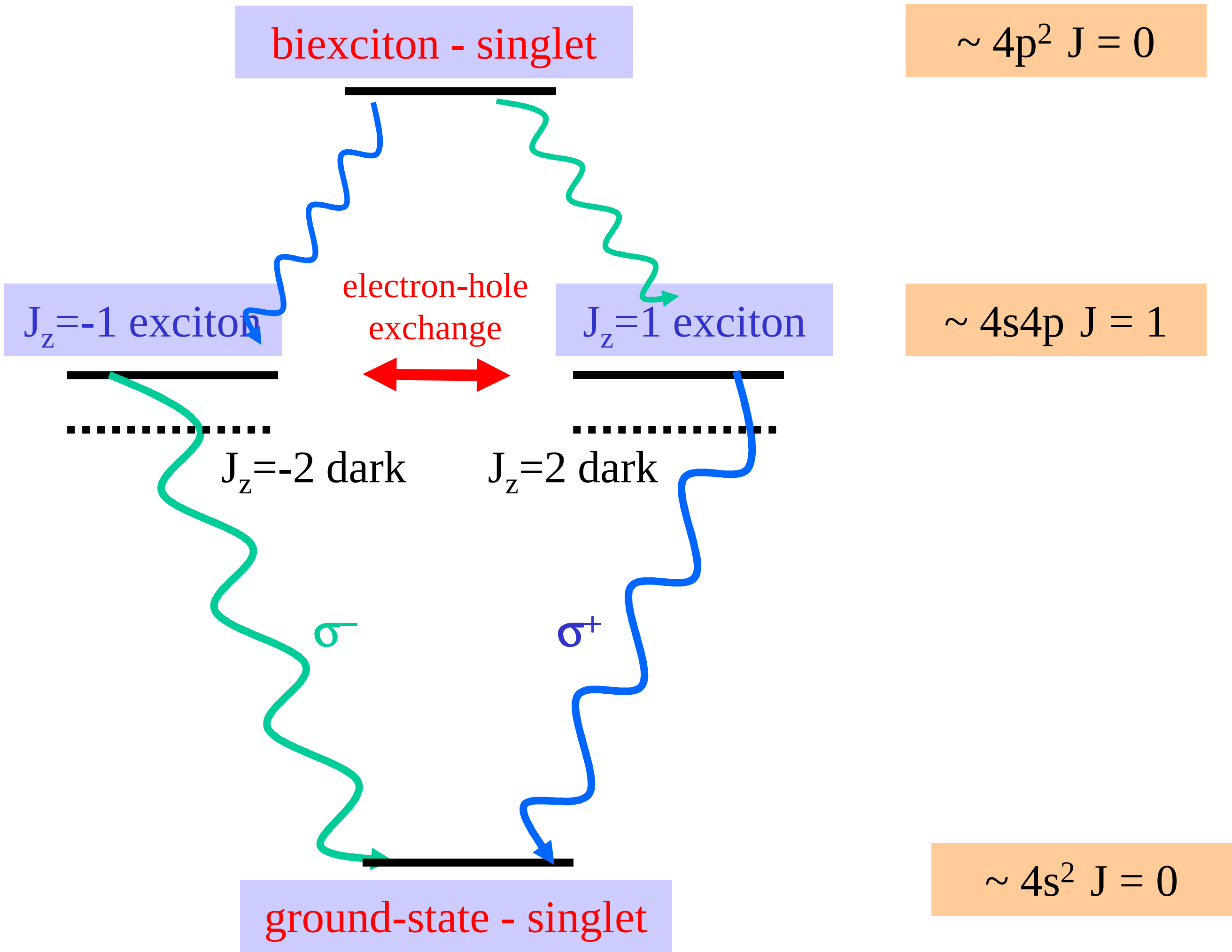


⇨At low excitation regime (average number of excitons < 1):

When a biexciton is observed, the QD projected is onto X0 state; as a result observation of an X0 photon becomes more likely than it is on average ⇒ ***bunching***

⇨Photons emitted in a biexciton cascade are polarization-entangled

Elementary excitations of a neutral QD



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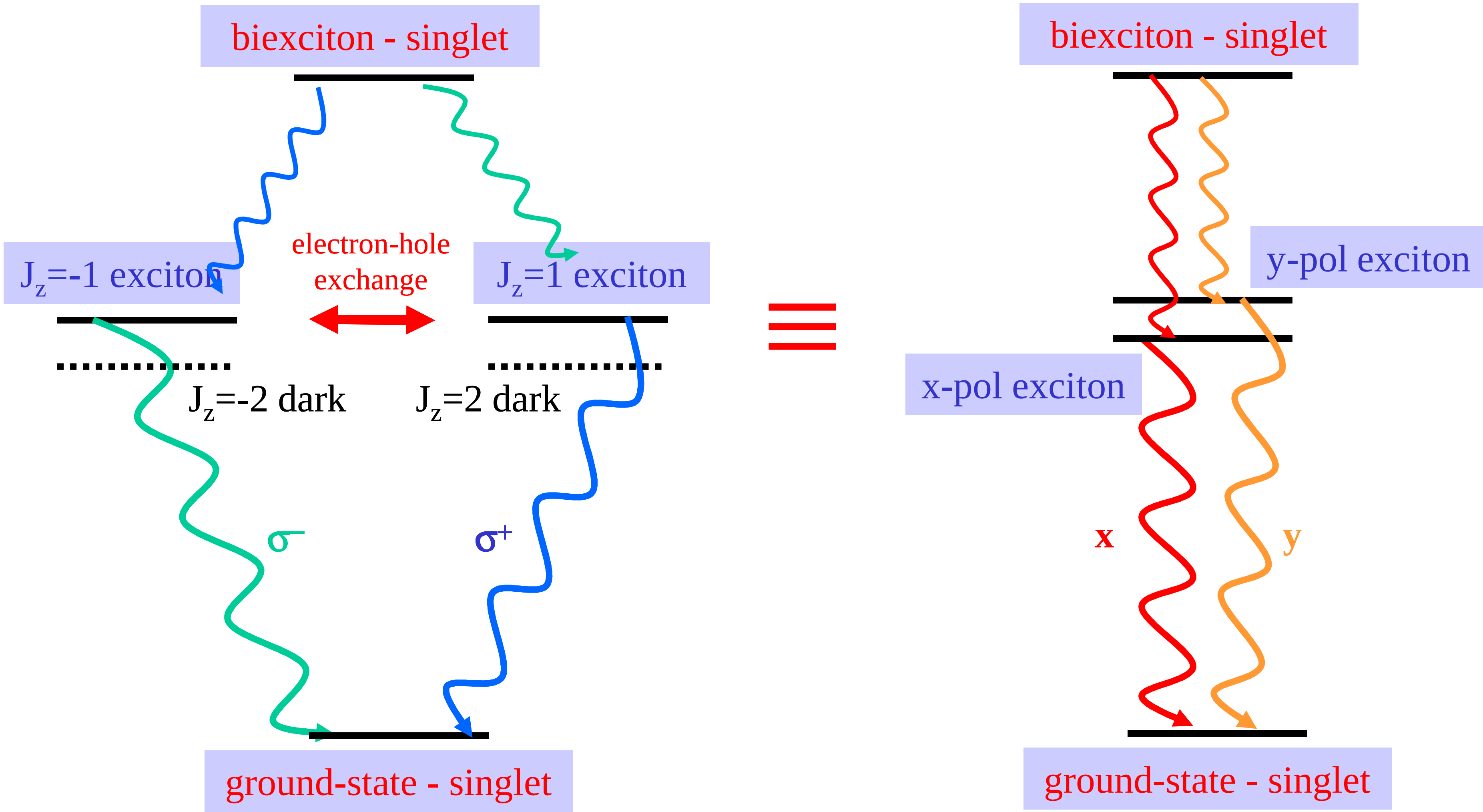
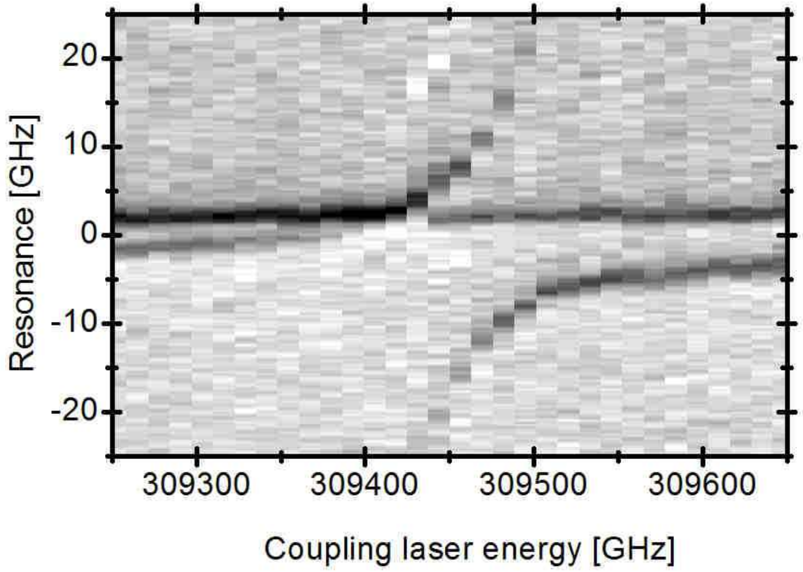


⇒ Polarization entaglement of photons emitted in biexciton cascade is difficult to observe

Cancellation of exchange splitting

Absorption of 45º-polarized probe laser



• Ac-Stark effect can be used to cancel the exchange splitting of exciton lines

• Polarization/photon-energy correlations in biexciton cascade can be erased

$\Rightarrow$ Deterministic generation of polarization-entagled photons

• Effective optically induced magnetic fields that can be turned on/off in sub-psec timescales (Awschalom and co-workers)