Resonant optical manipulation of quantum dot dot electron and nuclear spins

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Outline

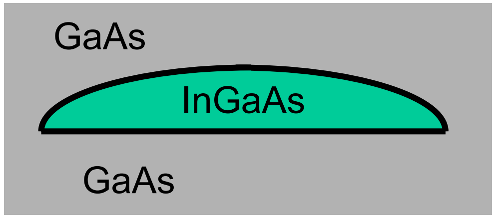
1) Optical pumping of quantum dot spins
2) Dragging of quantum dot resonances: controlling nuclear spins
3) Optical probe of the Kondo effect

Motivation to investigate quantum dot (QD) spin physics

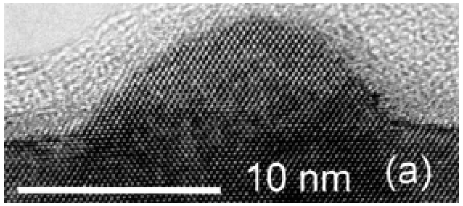
- QD spins may be used as qubits in quantum information processing schemes; optical manipulation of strongly confined spins could allow for fast manipulation using pulsed lasers, as well as realization of a spin-photon interface.

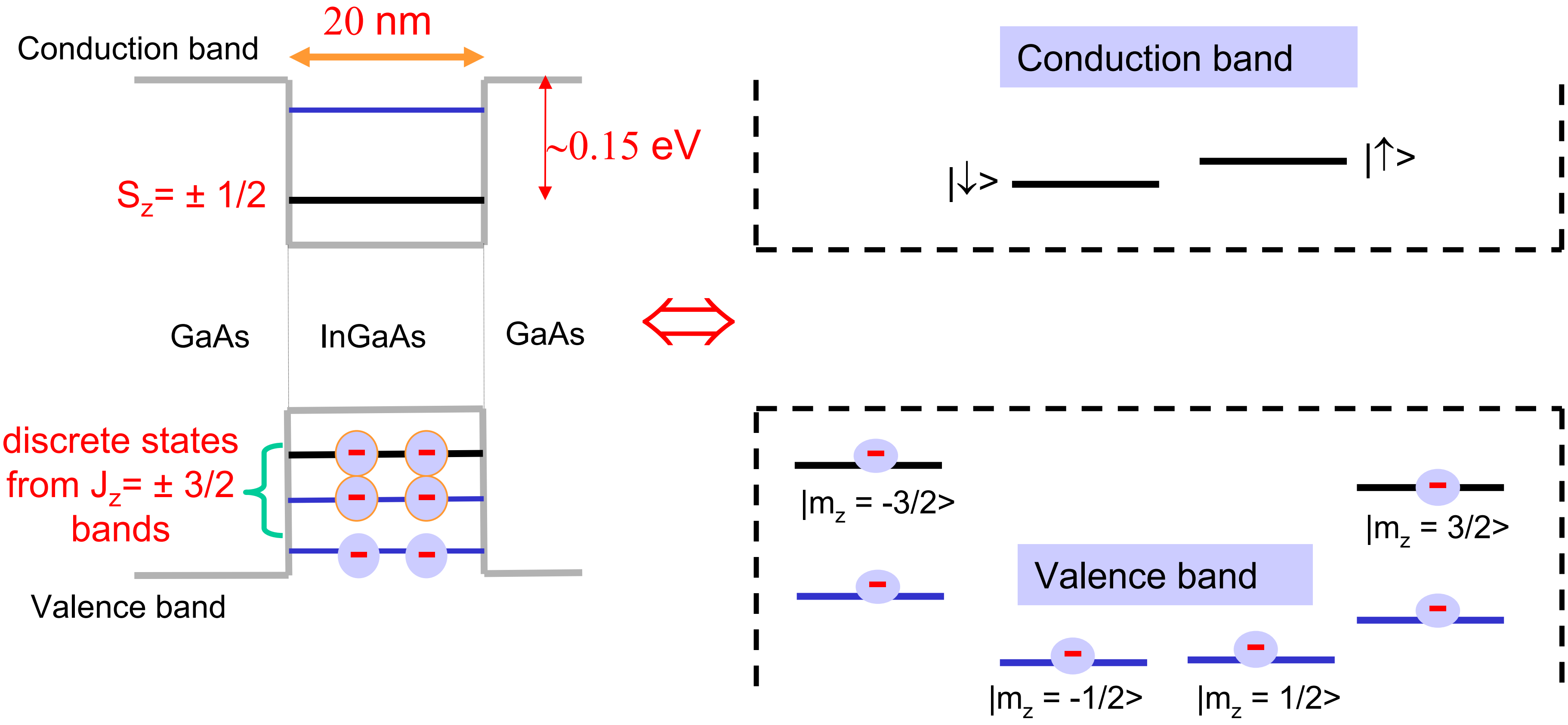
- Understanding (and suppressing) spin decoherence in QDs is a challenging mesoscopic physics problem

  - hyperfine interactions in QD nuclear spins
  - exchange interaction with a fermionic reservoir



InGaAs Quantum dots (QD) embedded in GaAs





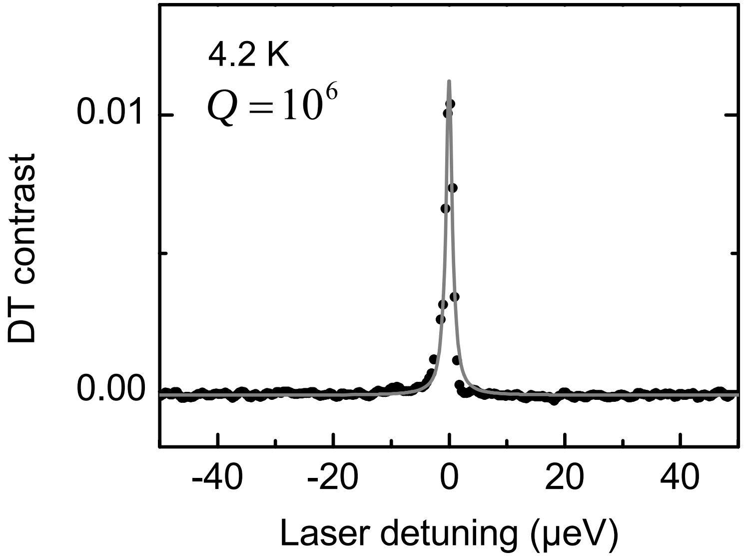
- Self-assembled QDs have discrete states for electrons & holes.
- Conduction band → anti-bonding s-orbitals; valence band → bonding p-orbitals.
- $\sim 10^5$ atoms (= nuclear spins) in each QD $\Rightarrow$ a random magnetic field with $B_{rms} \approx 15$ mT

Some key atom-like features of quantum dots

- Ultra-narrow lines in emission or absorption:

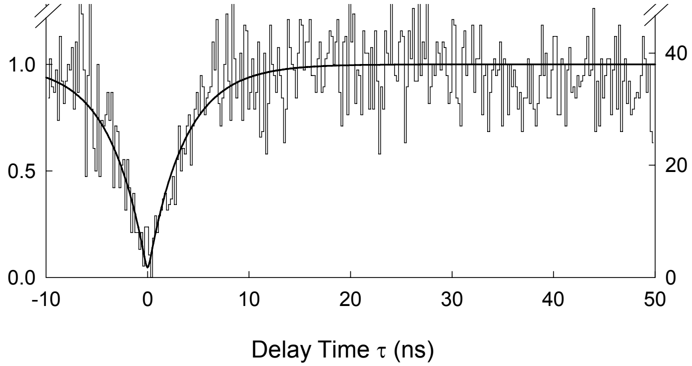
$\Gamma_{\text{spon}} = 0.7$ µeV $\Leftrightarrow 1$ nsec

The measured absorption width: 1.3 µeV



- Photon antibunching in photon correlation measurements:

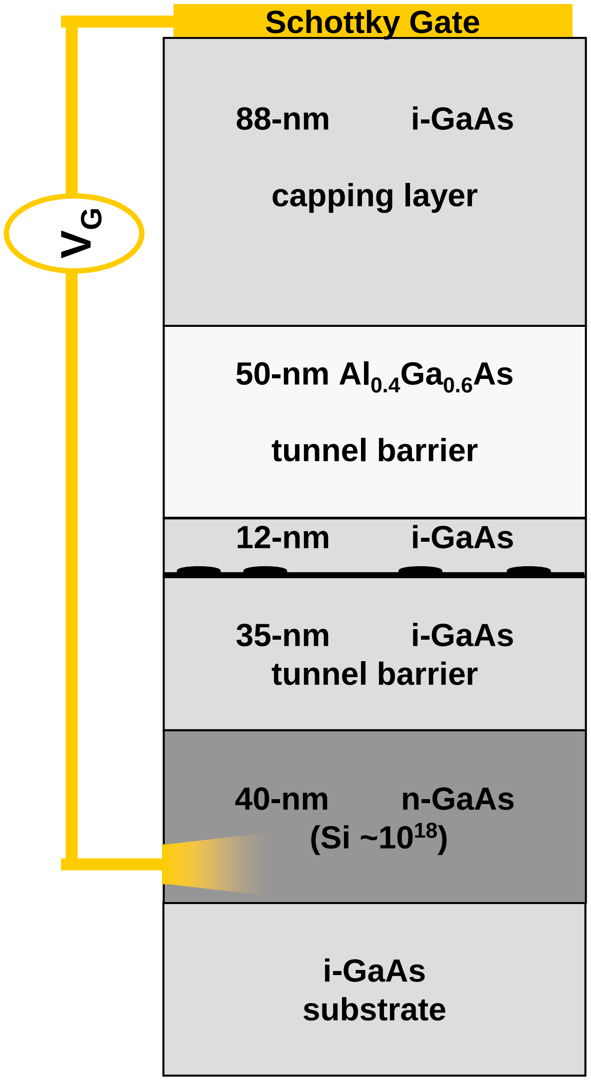
Strong photon antibunching proves that the luminescence originates predominantly from a single QD.



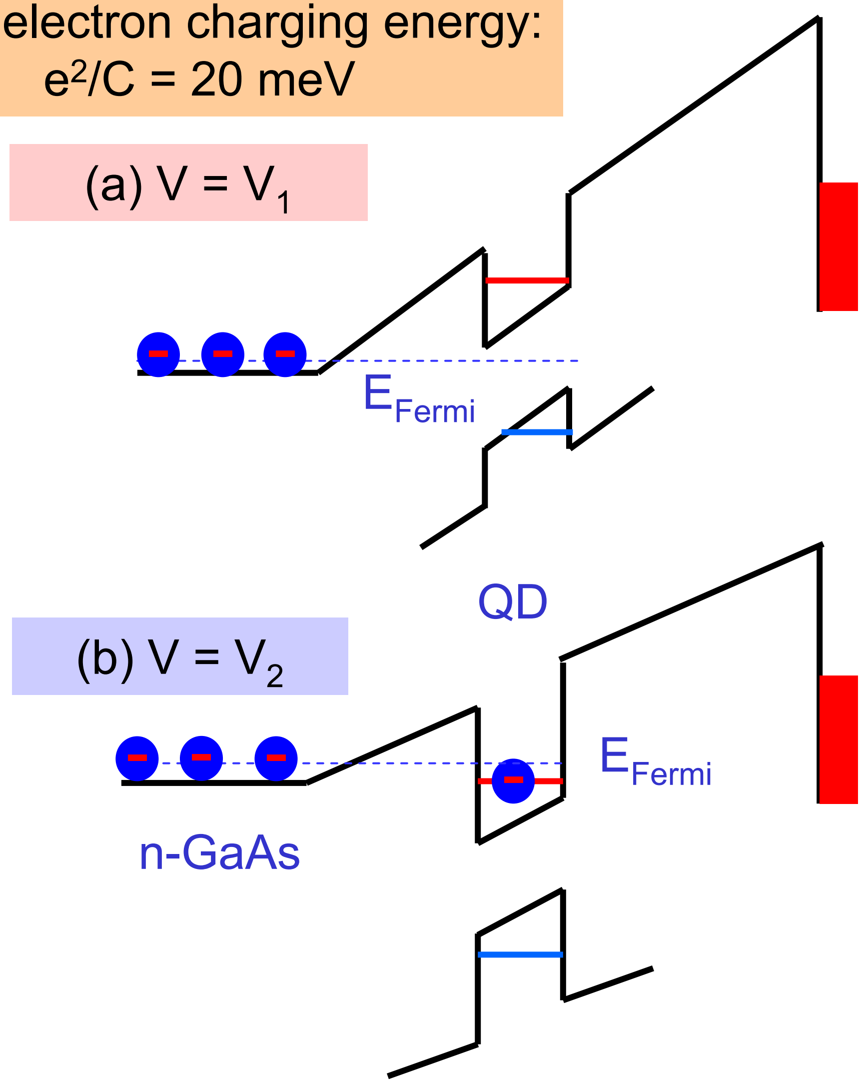
QD spins: controlled charging of a single QD

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

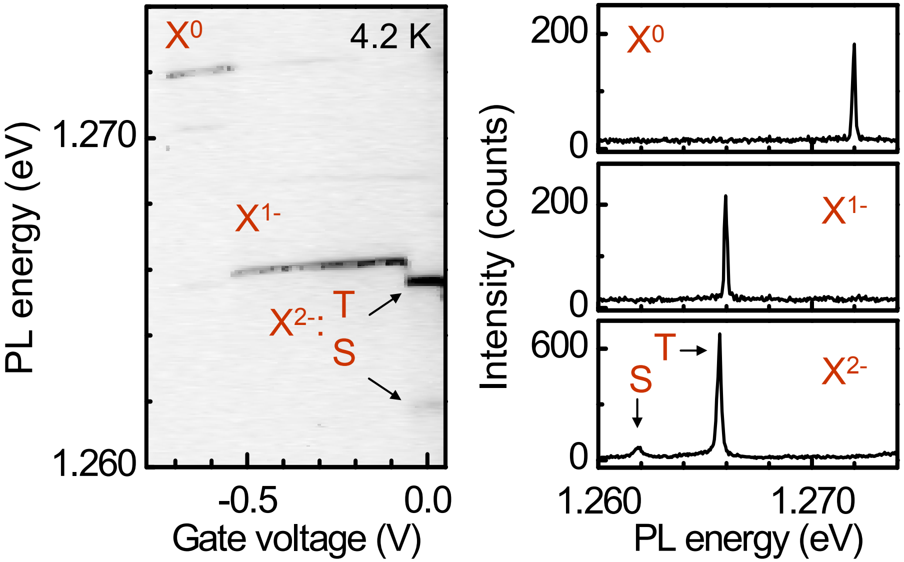
Coulomb blockade ensures that electrons are injected into the QD one at a time



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



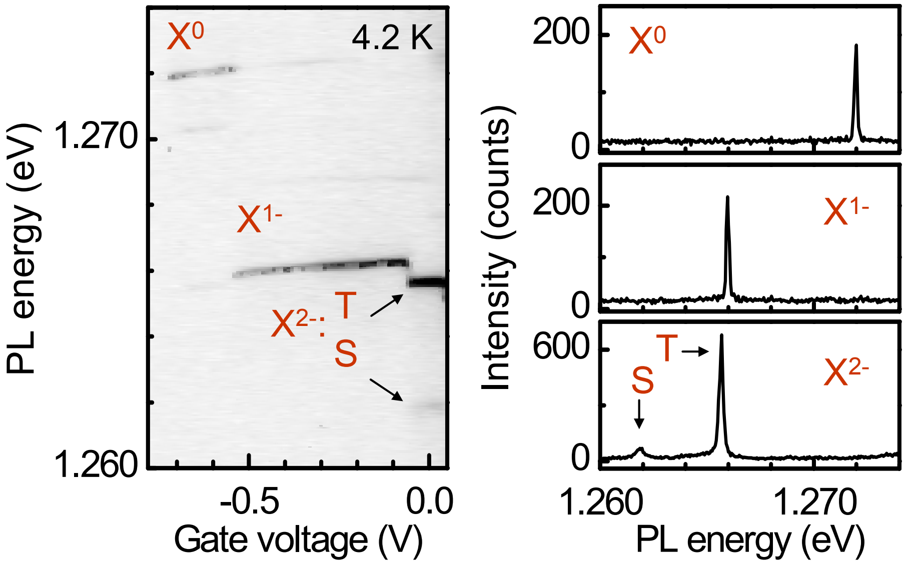
Voltage-controlled Photoluminescence



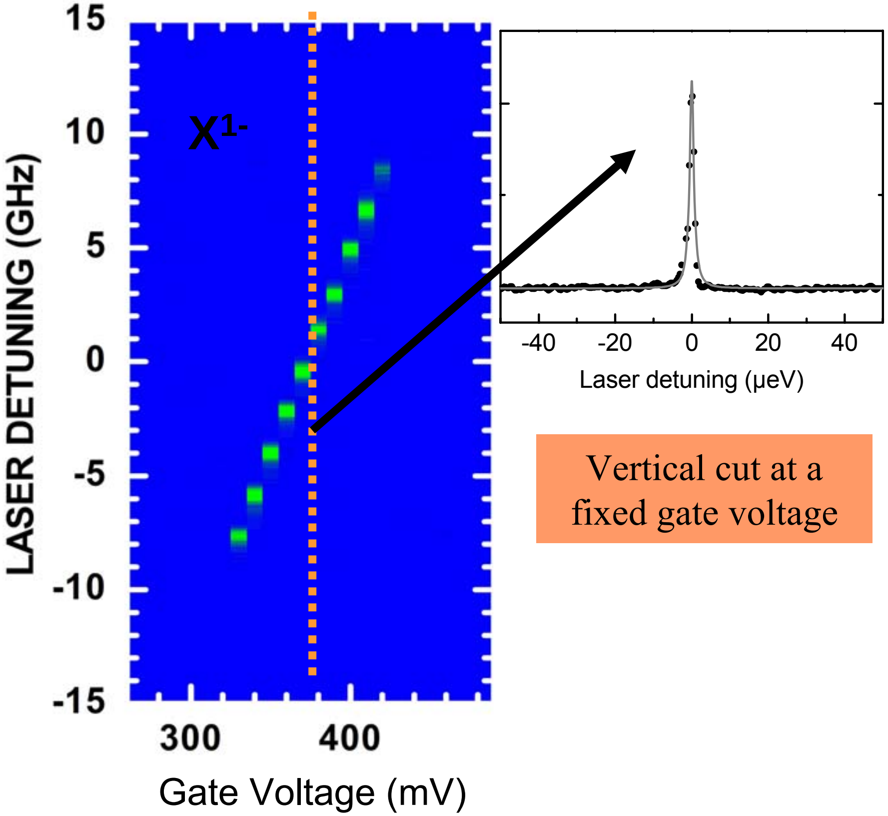
Quantum dot emission energy depends on the charge state due to Coulomb effects – "optical charge sensing."

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

Voltage-controlled Photoluminescence



Voltage-controlled Absorption

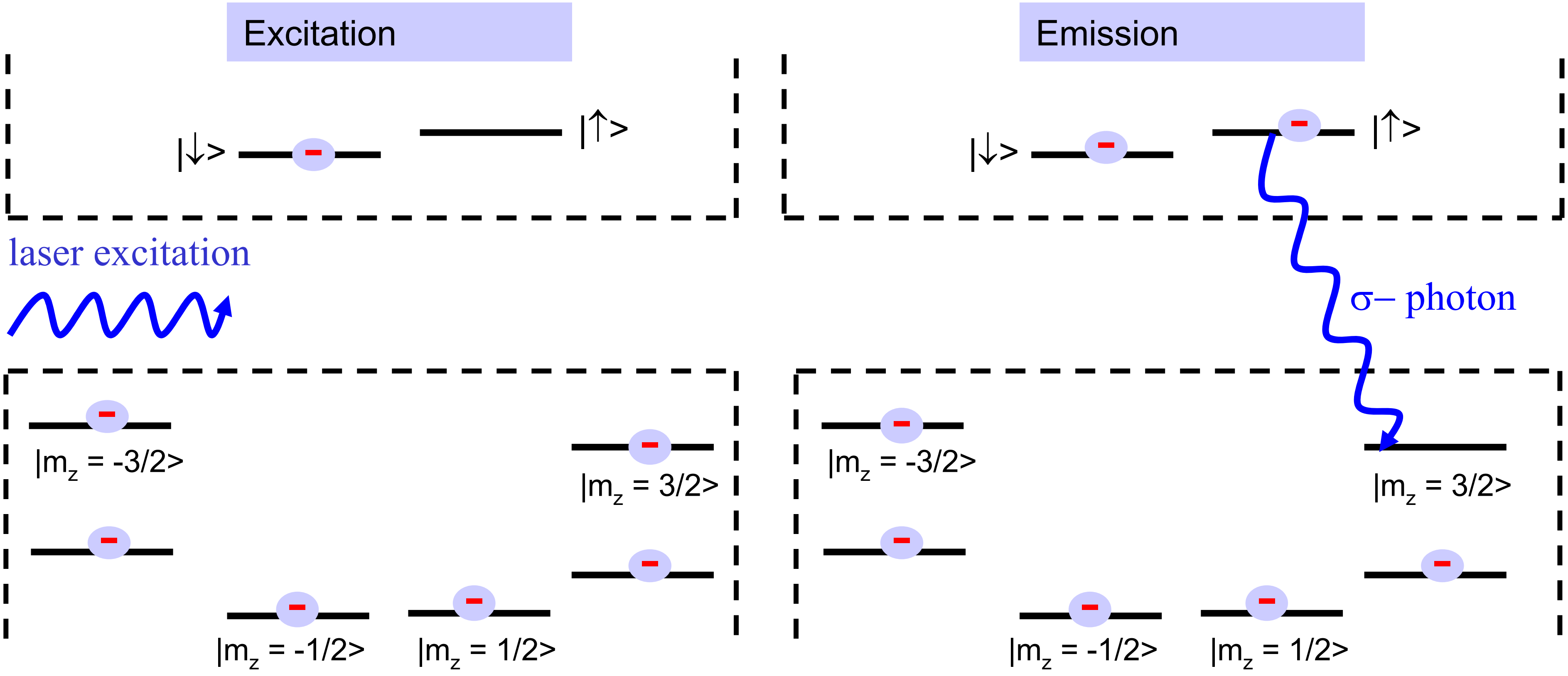


Vertical cut at a fixed gate voltage

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.

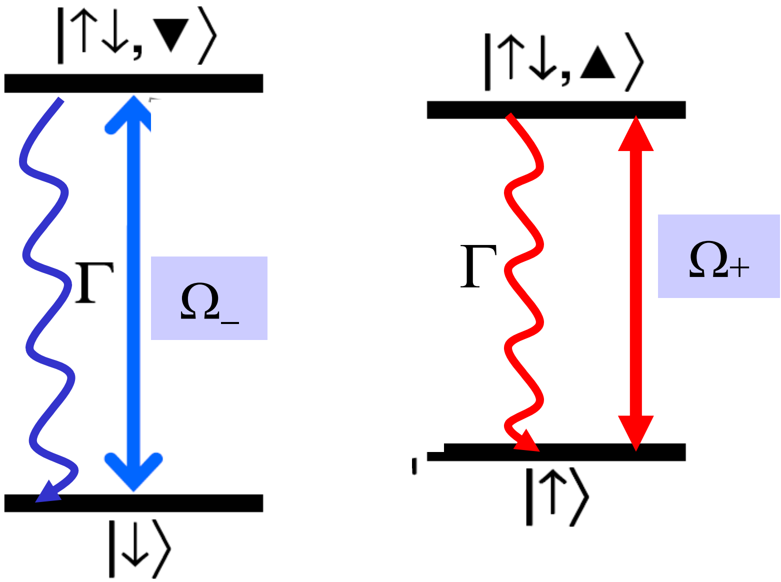
Charged QD X^{1-} (trion) absorption/emission



⇒ 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

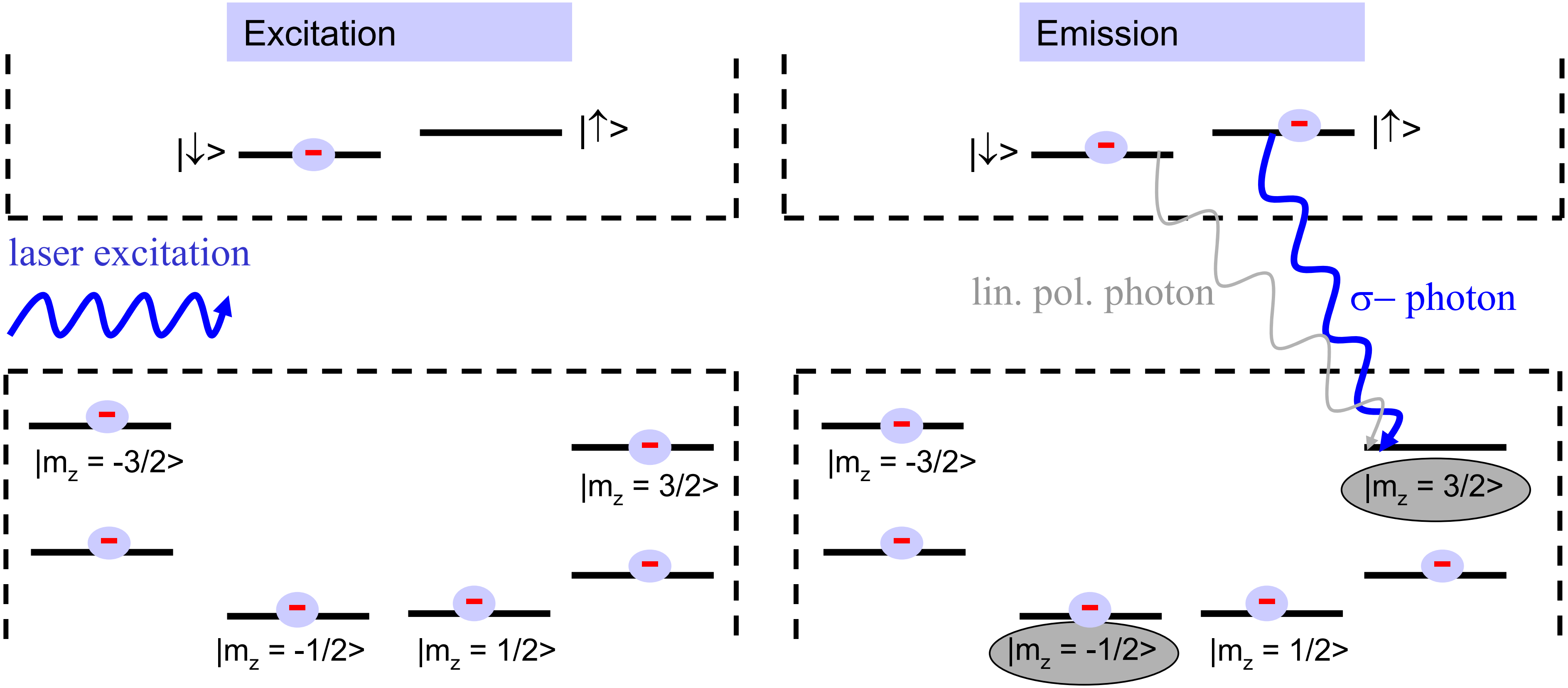
Ω: laser coupling (Rabi) frequency

- QD with a spin-up (down) electron only absorbs and emits σ+ (σ-) photons – a recycling transition.

  ⇨ Spin measurement and spin-photon entanglement

- A strong detuned σ+ laser field generates an ac-Stark field only for the spin-up state – an effective magnetic field.

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



Excitation

|↓>

|↑>

laser excitation

$|m_z = -3/2\rangle$

$|m_z = 3/2\rangle$

$|m_z = -1/2\rangle$

$|m_z = 1/2\rangle$

Emission

|↓>

|↑>

lin. pol. photon

σ– photon

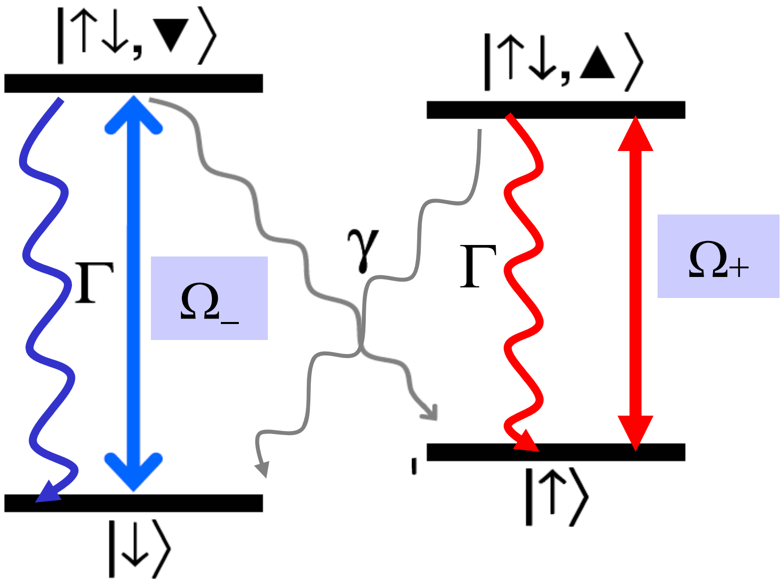
$|m_z = -3/2\rangle$

$|m_z = 3/2\rangle$

$|m_z = -1/2\rangle$

$|m_z = 1/2\rangle$

Strong spin-polarization correlations



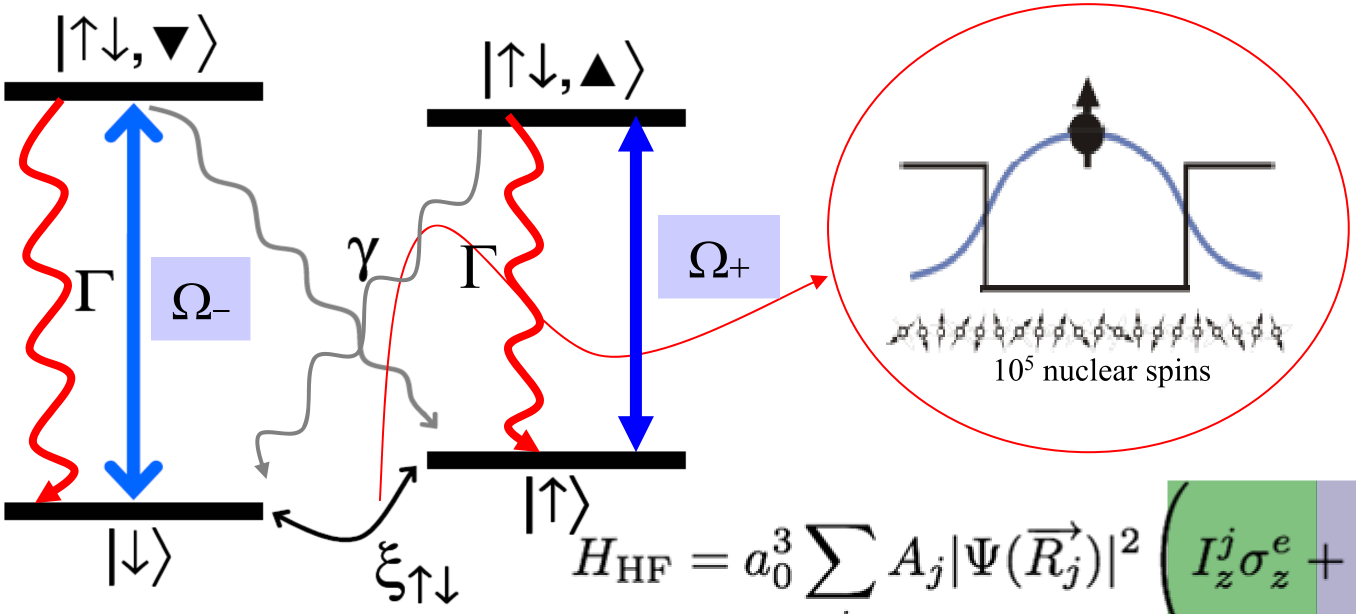
Γ: spontaneous emission rate

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 $B \geq 1$ 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



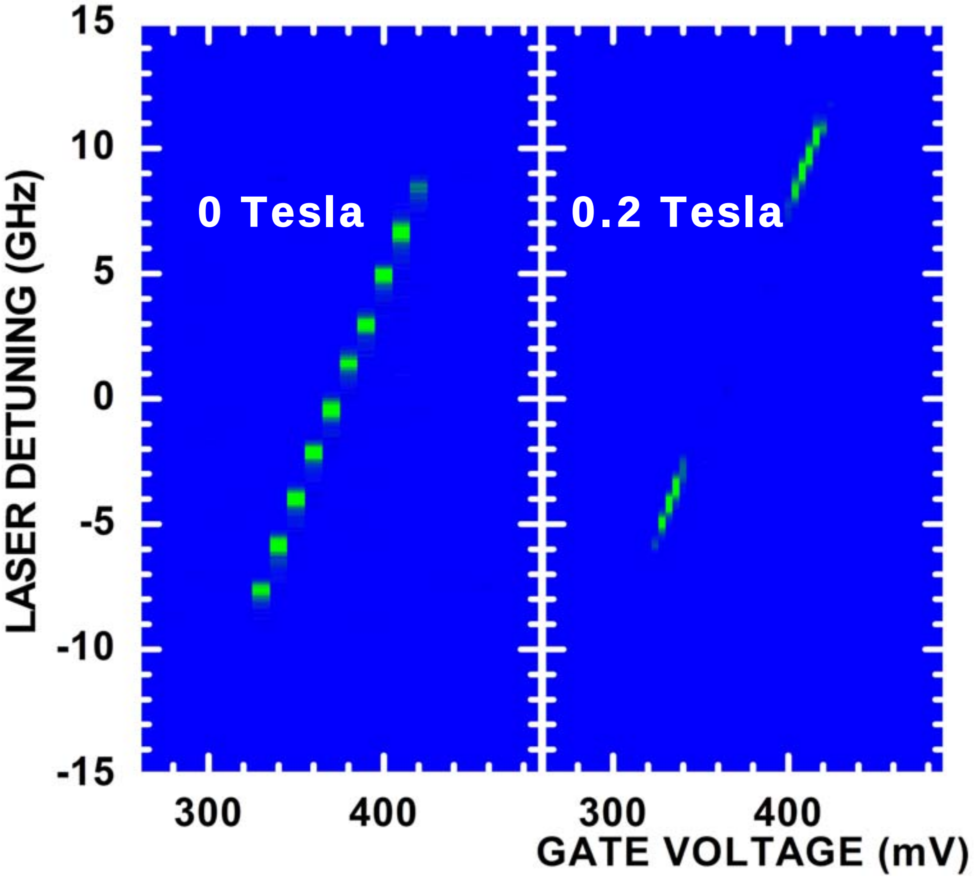
$$H_{\rm HF} = a_0^3 \sum_j A_j |\Psi(\vec{R_j})|^2 \underbrace{\left(I_z^j\sigma_z^e + \frac{I_+^j\sigma_-^e + I_-^j\sigma_+^e}{2}\right)}_{\vec{I^j}\cdot\vec{\sigma^e}}$$

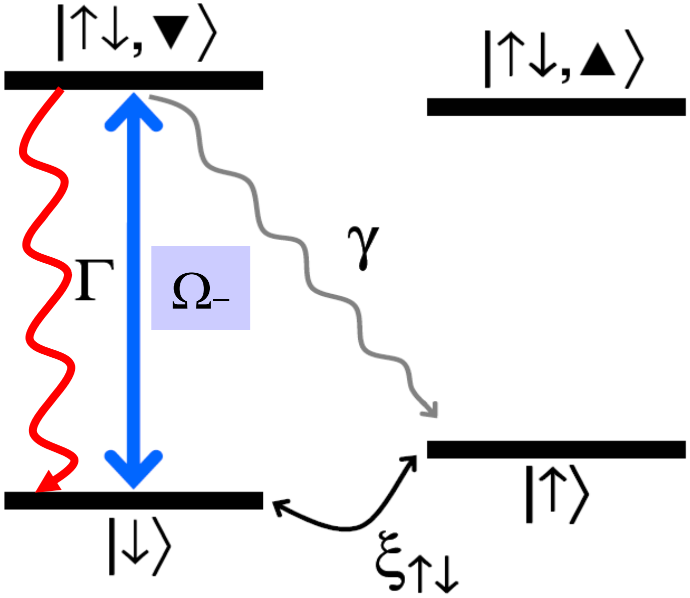
- Longitudinal component gives rise to a quasi-static effective magnetic Overhauser (Knight) field seen by the electron (nuclei)

  ⇨ Overhauser field determines the effective optical detuning

- Transverse (flip-flop) component causes simultaneous electron-nuclei spin flip events – important when electron spin splitting is zero?

Spin pumping in a single-electron charged QD



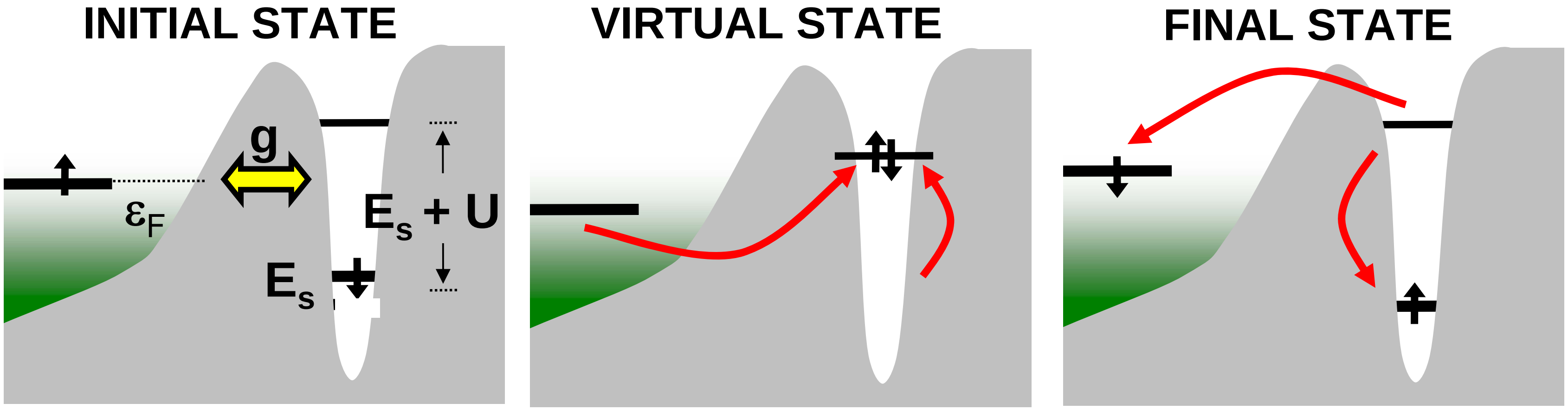


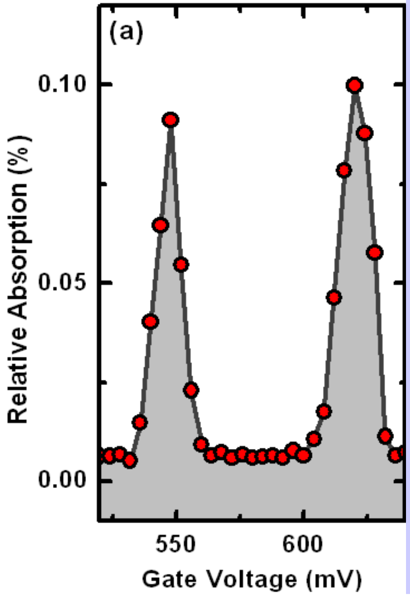
⇒ For B > 15 mT, the applied resonant $\sigma-$ laser leads to very efficient spin pumping (exceeding 99%) due to suppression of hyperfine flip-flop events

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

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

Exchange interactions with the Fermi-sea induce spin-flip co-tunneling (Korringa relaxation)

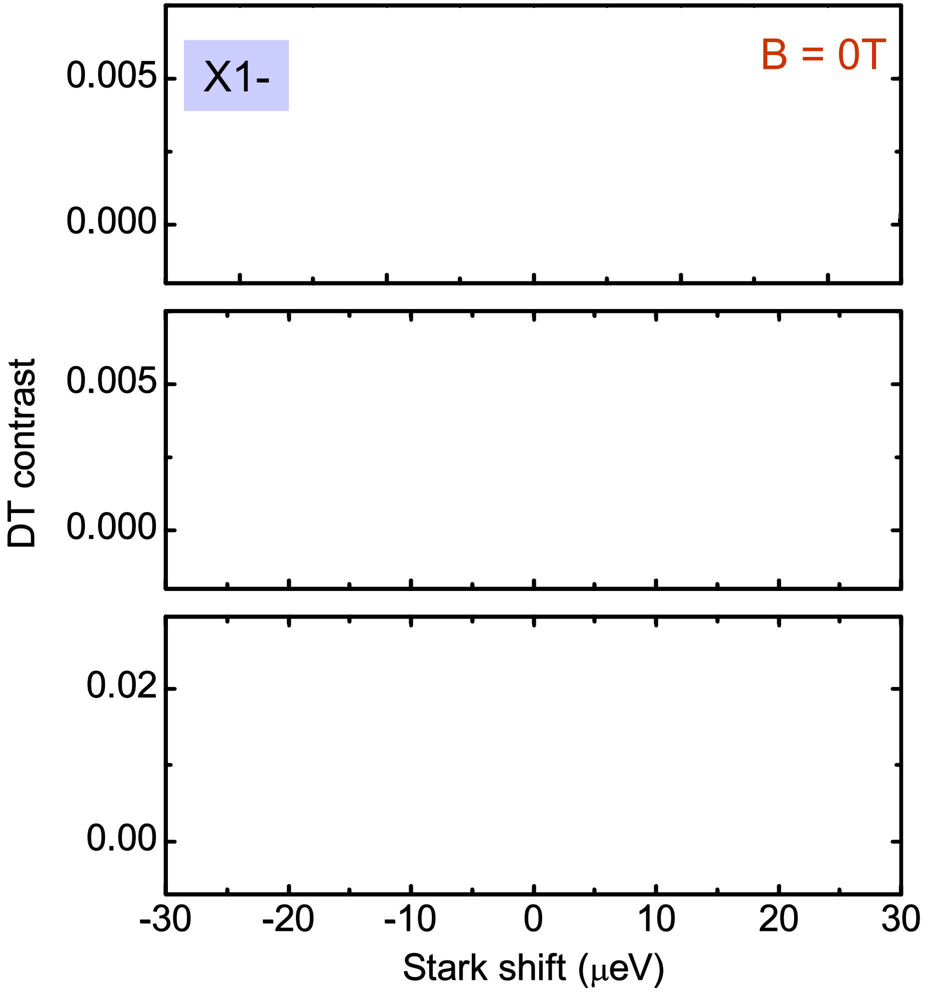


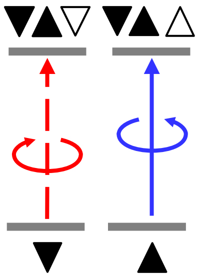


- Co-tunneling is enhanced at the edges of the absorption plateau where the intermediate state energy ~ initial (= final) state energy

- Co-tunneling rate changes by more than 5-orders-of-magnitude from the plateau edge to the center

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





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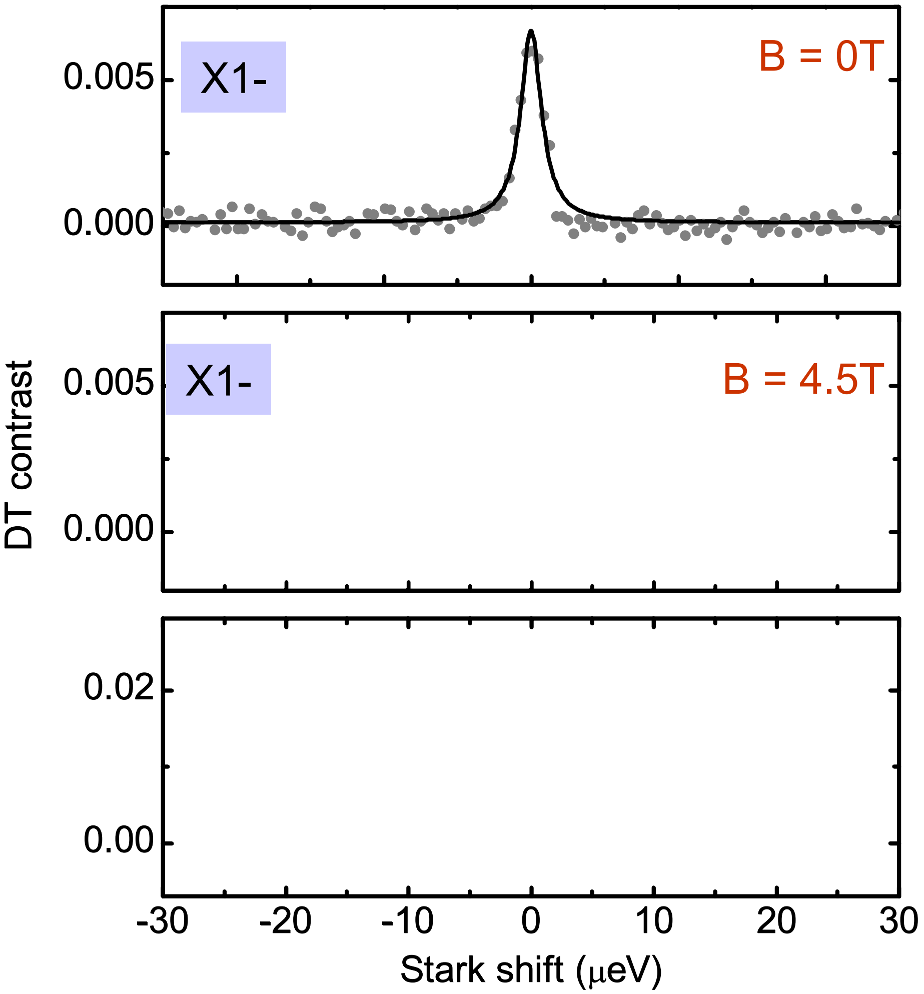

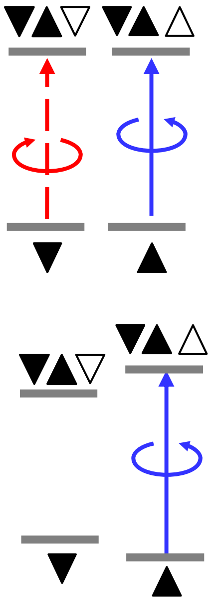

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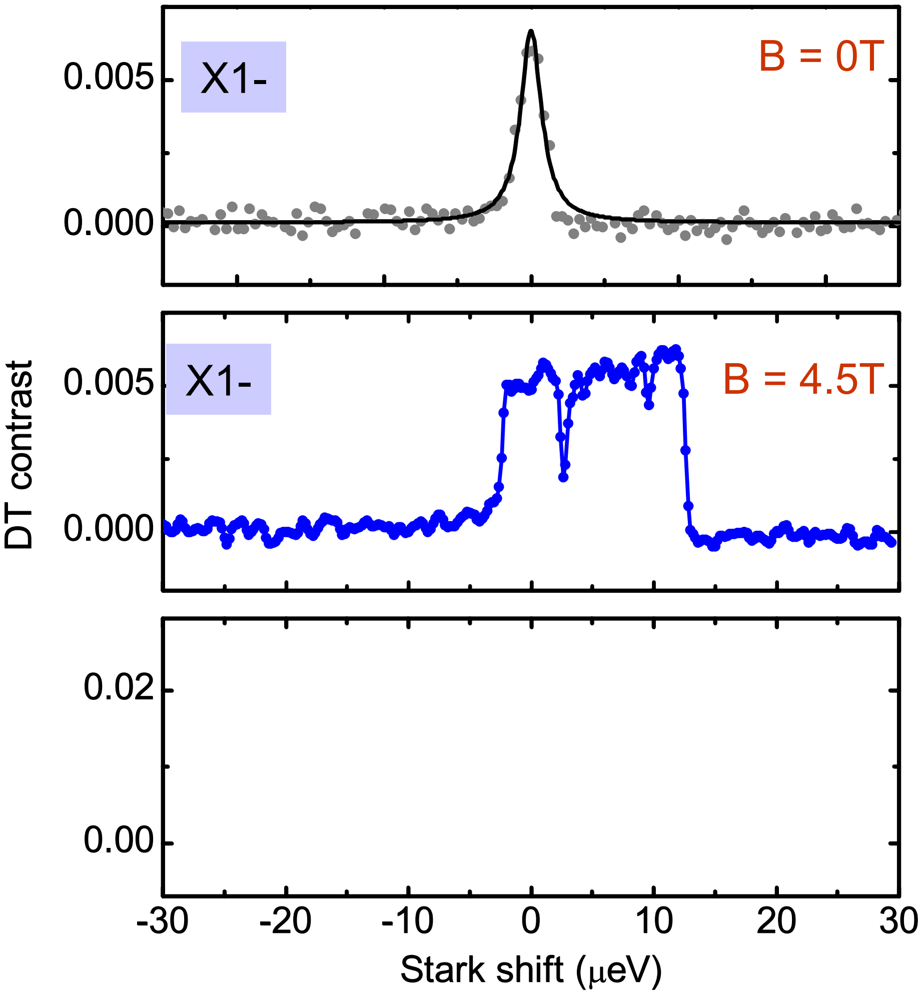

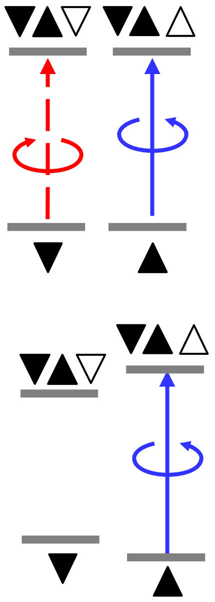

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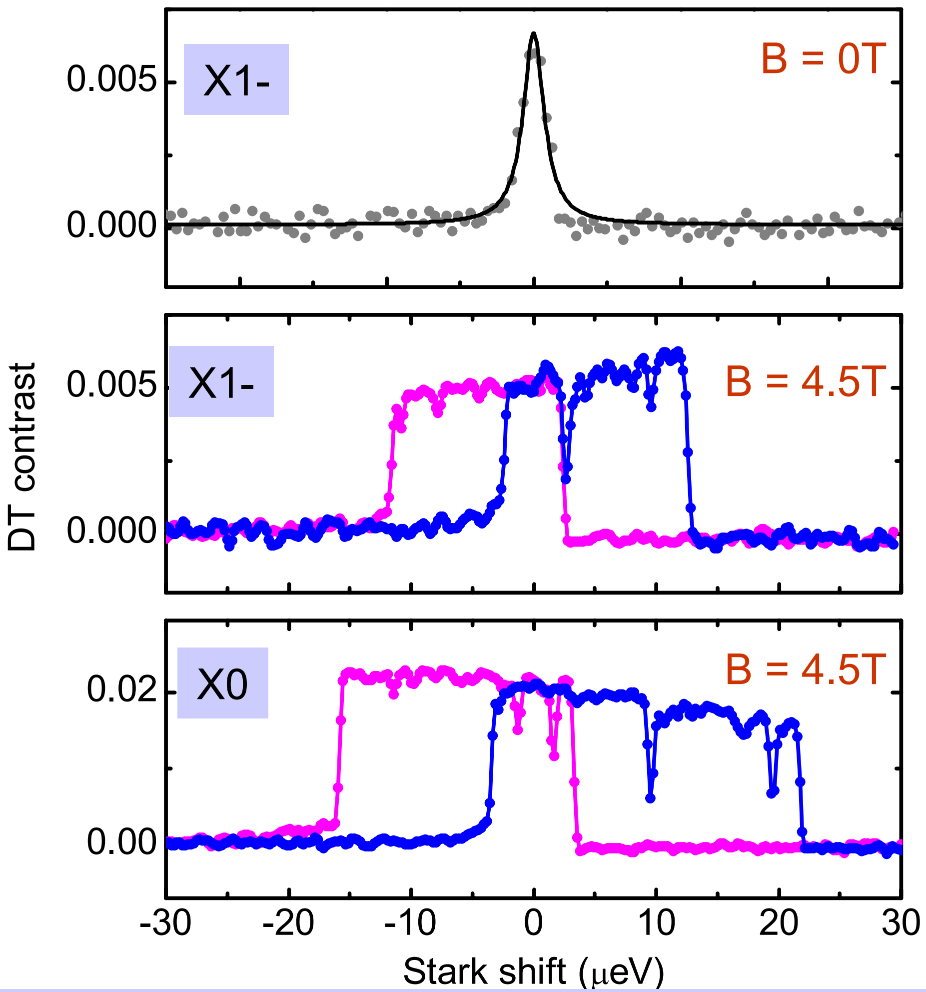
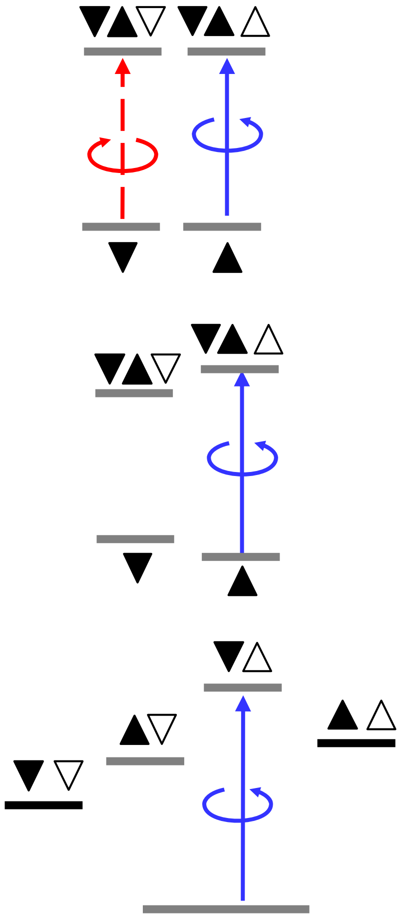
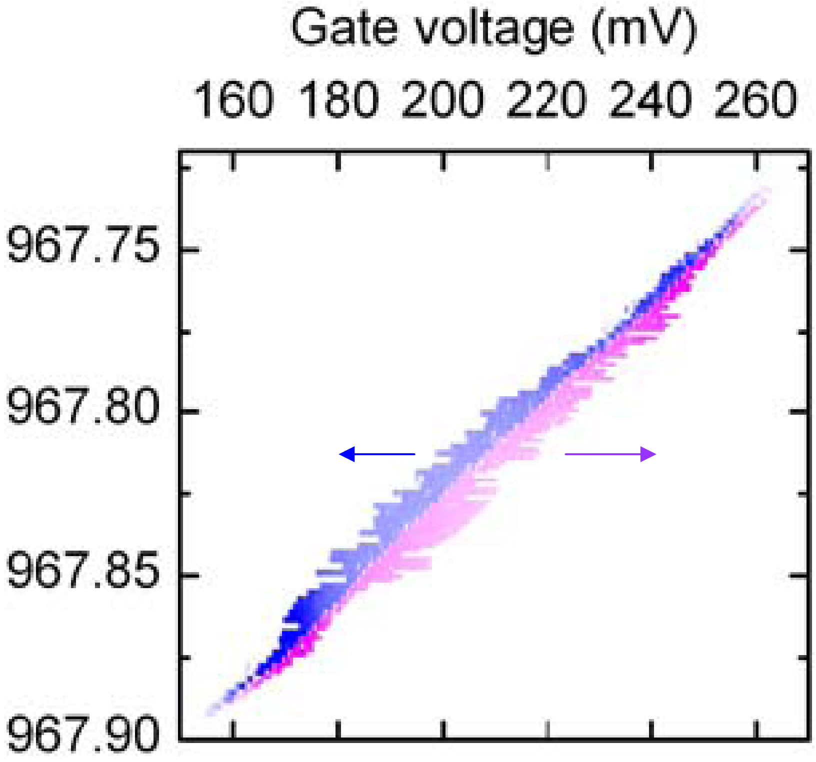




Latta *et al.*, Nature Physics (2009)

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

Dependence of resonance dragging on the co-tunneling rate

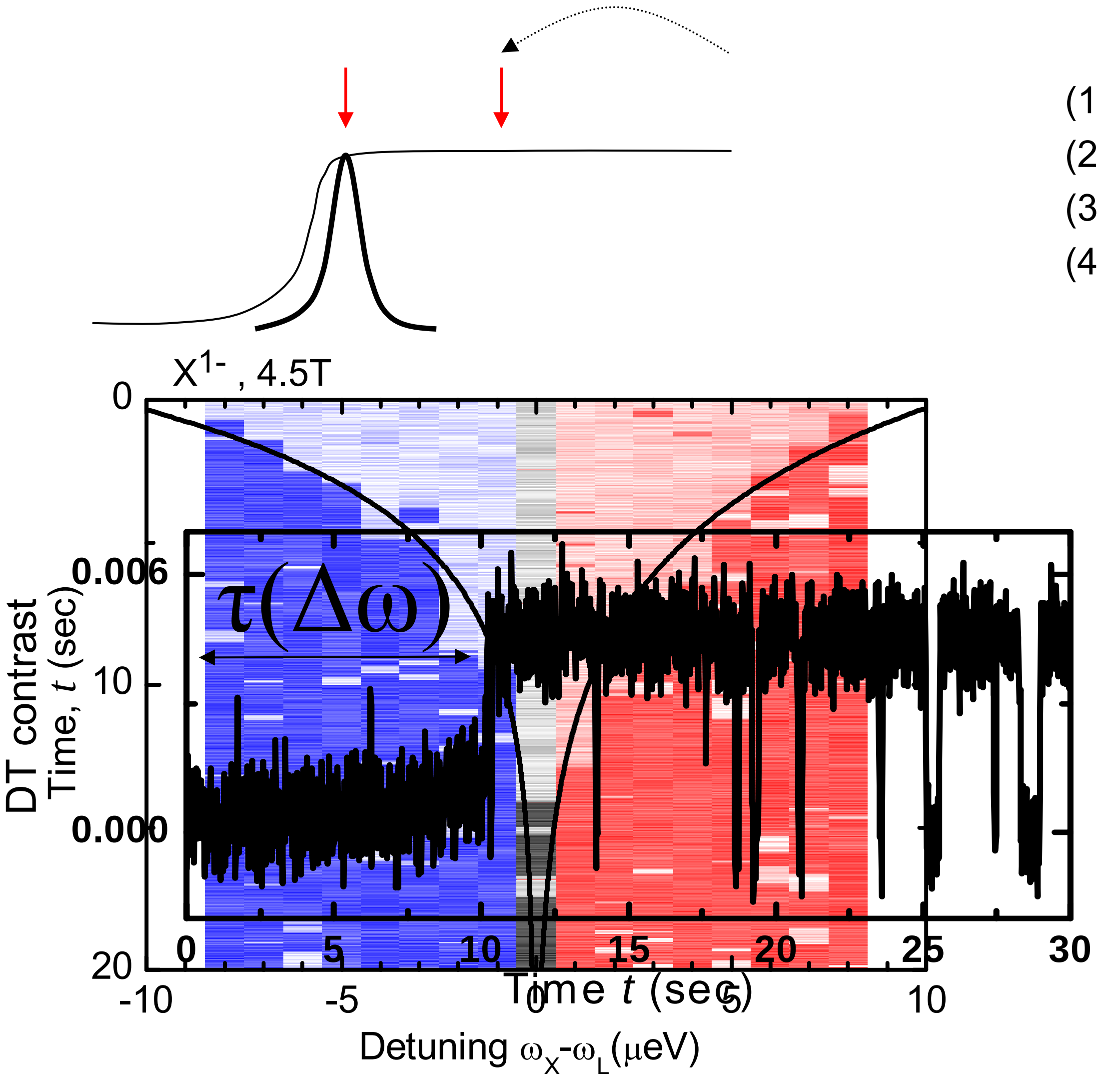


Dragging dissapears at the edges of the absorption plateau where the exchange coupling to the Fermi sea is stronger.

⇨ Faster nuclear spin decay?

Decay of nuclear spin polarization

In the center of charge stability plateau



(1) Depolarize
(2) Buildup of polarization (dragging)
(3) Change detuning condition
(4) Recovery of the full absorption strength

$$\left.\begin{array}{l}\tau_{\mathrm{d,blue}} = 3.7 \pm 0.7\ \mathrm{s} \\ \tau_{\mathrm{d,red}} = 4.9 \pm 0.9\ \mathrm{s}\end{array}\right\} \tau_{\mathrm{d}} \approx 4\ \mathrm{s}$$

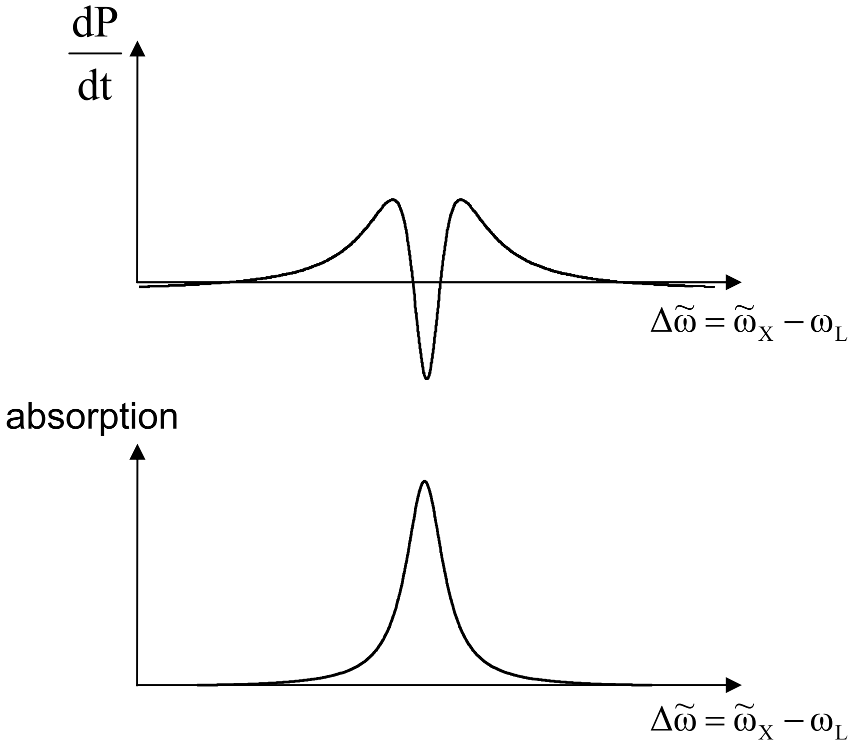
If we eject the electron out of the QD immediately after changing the laser wavelength, then we never recover absorption: τ_n > hours

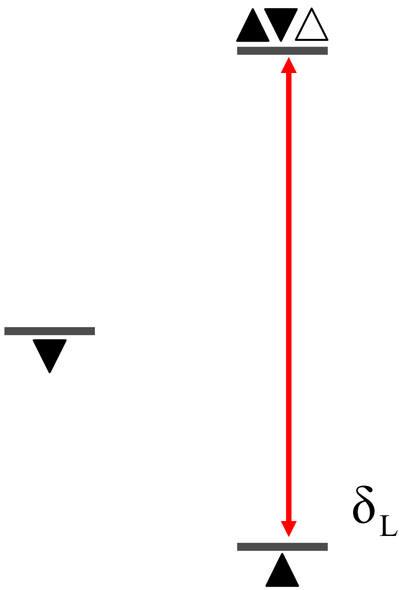
Maletinsky *et al.*, PRL (2008)
Maletinsky *et al.*, Nature Physics (2009)

Locking of optical transitions by nuclear spins

In steady-state, the coupled electron-nuclear spin system seeks the effective detuning for which the net polarization rate = 0

⇨ Interplay of mechanisms polarizing nuclear spins in opposite directions





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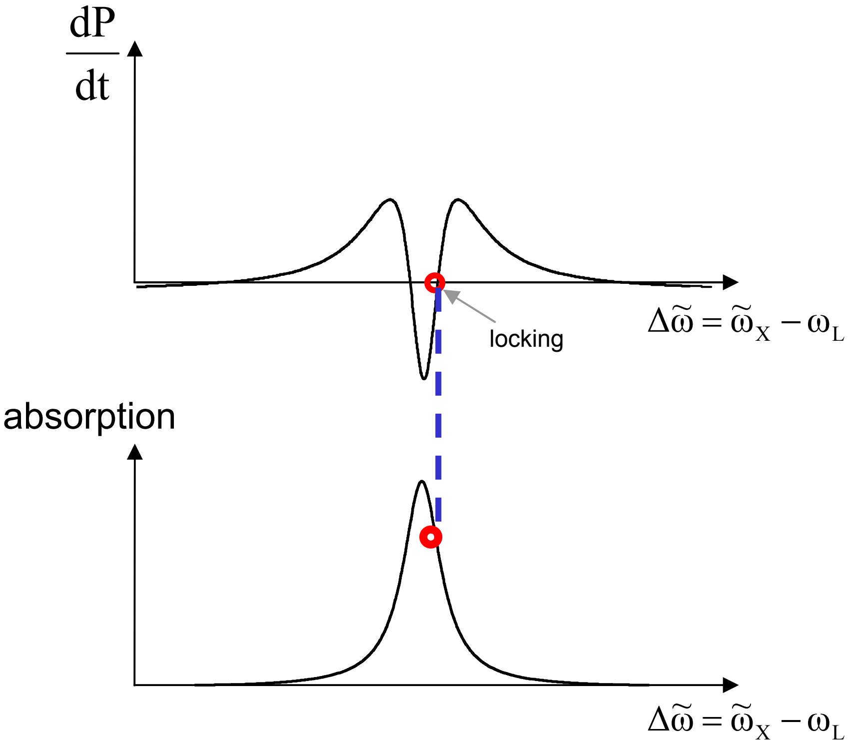

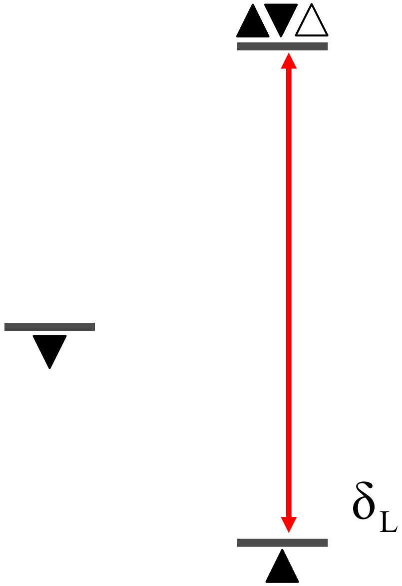

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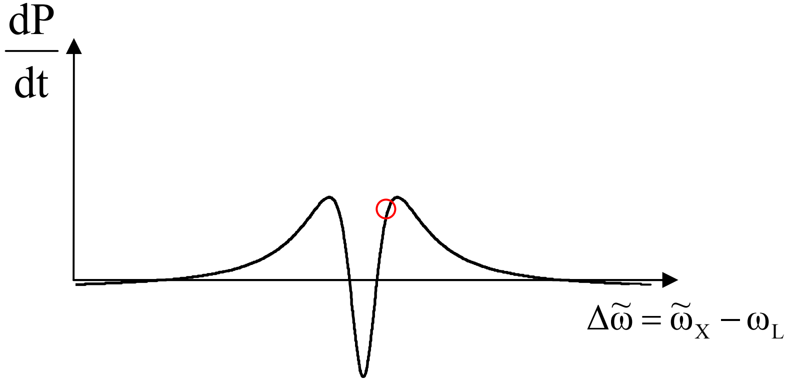
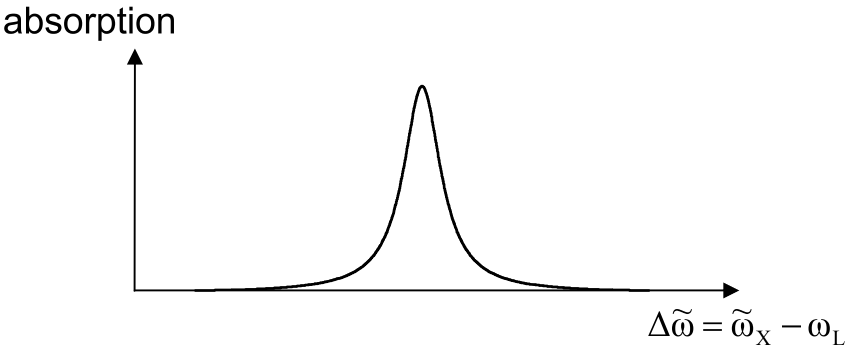
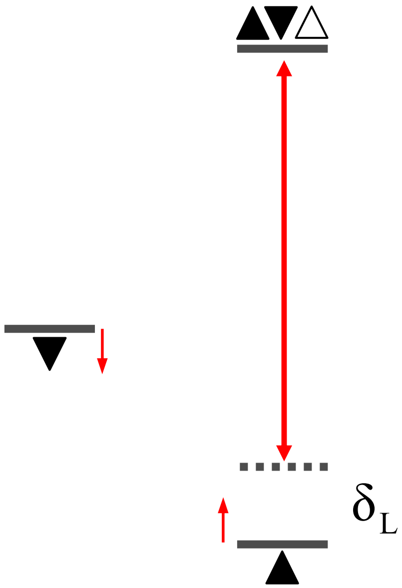






Bi-directional nuclear spin polarization

- Tuning the laser to the red of the resonance ($\delta_L>0$), temporarily leads to $dP/dt > 0$; nuclear spins polarize in the +z direction until $dP/dt = 0$ is once again reached

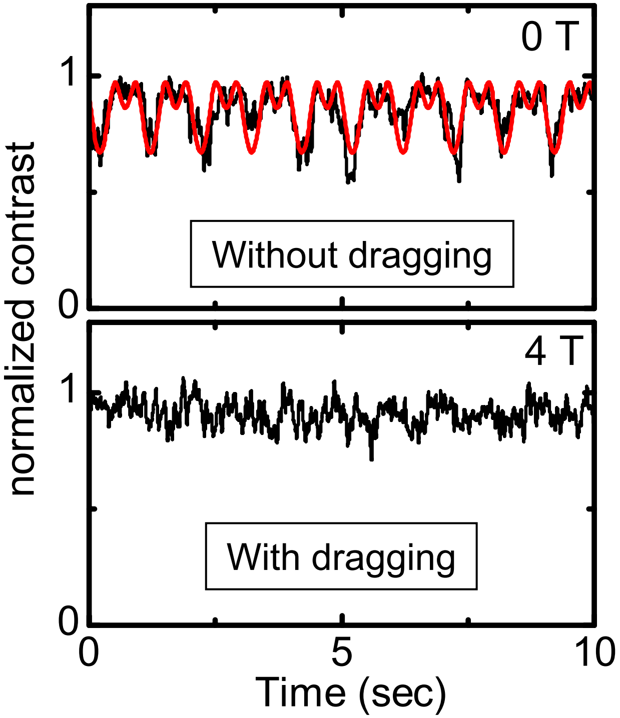
- Conversely, tuning the laser to the blue side ($\delta_L<0$), leads to $dP/dt < 0$; nuclear spins then polarize in the –z direction to reach the stable point.

- This interplay is to first oder independent of whether the nuclear spins are initially polarized in one or the other direction

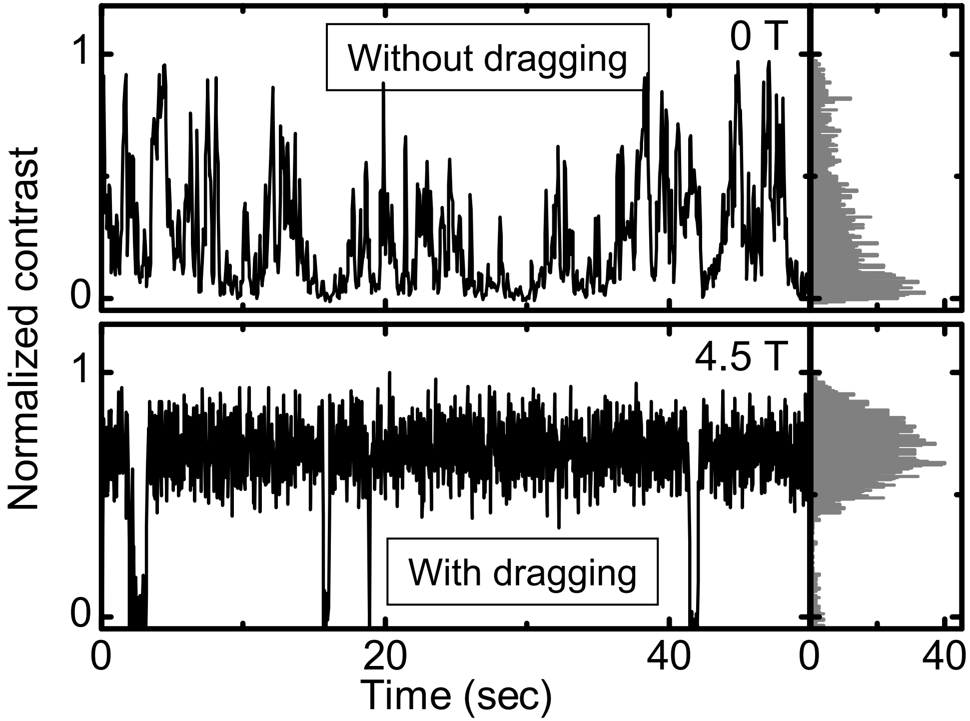
Suppression of fluctuations in transition energy

Externally induced fluctuations:

(Gate voltage modulation)

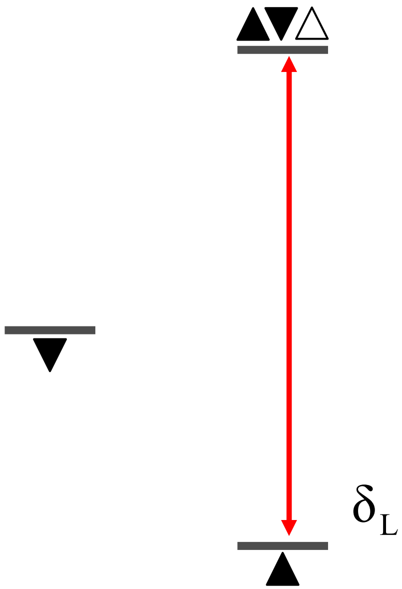


Intrinsic fluctuations



Control of QD nuclear spins

- The Overhauser field ($=\sum A_j I_z^j$) determines the effective optical detuning and hence the absorption strength W_{abs} of the trion transition.
- Conversely, by measuring W_{abs} we determine the magnitude of the Overhauser field.
- Locking of the optical trion resonance by nuclear spins at the same time allows us to set the mean magnitude of the Overhauser field and suppress ist fluctuations.
- CPT/EIT schemes should yield much higher sensitivity in measurement/locking of the Overhauser field.



$$W_{abs} = \frac{\Omega_L^2 \Gamma}{\Delta\tilde{\omega}^2 + \Gamma^2}$$

$$\Delta\tilde{\omega} = \tilde{\omega}_X - \omega_L$$ ⇨ Determined by the Overhauser field

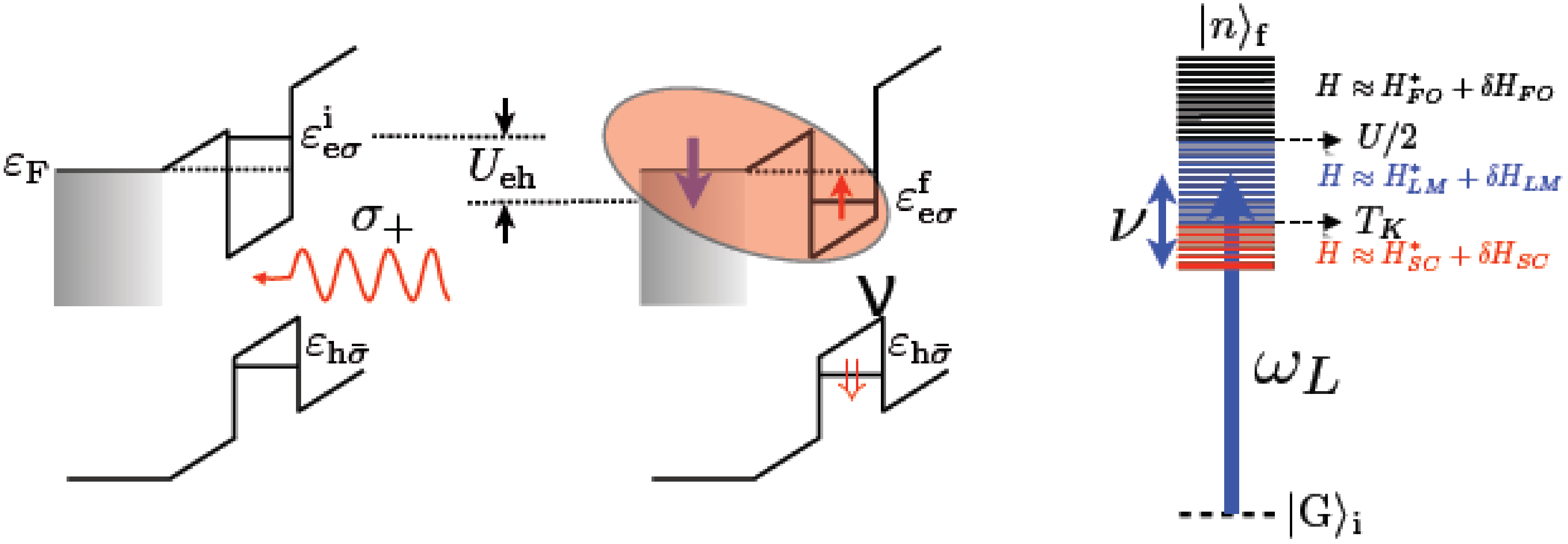
Open questions

- Why is dragging in both directions so similar?
- What is the nature of laser enhanced dephasing/decay processes that lead to Overhauser process?
- Why does the theoretical model fail to describe the abrupt turn on of absorption?
- What are the limits of Overhauser field variance narrowing that could be obtained?
- Does dragging also prolong the actual T_2 time of the electron spin?

Coupling of a QD to a Fermionic Reservoir: Anderson Model

An InGaAs QD that is separated from a 2DEG by a small tunnel barrier

Before absorption **After absorption** **Eigenstates**

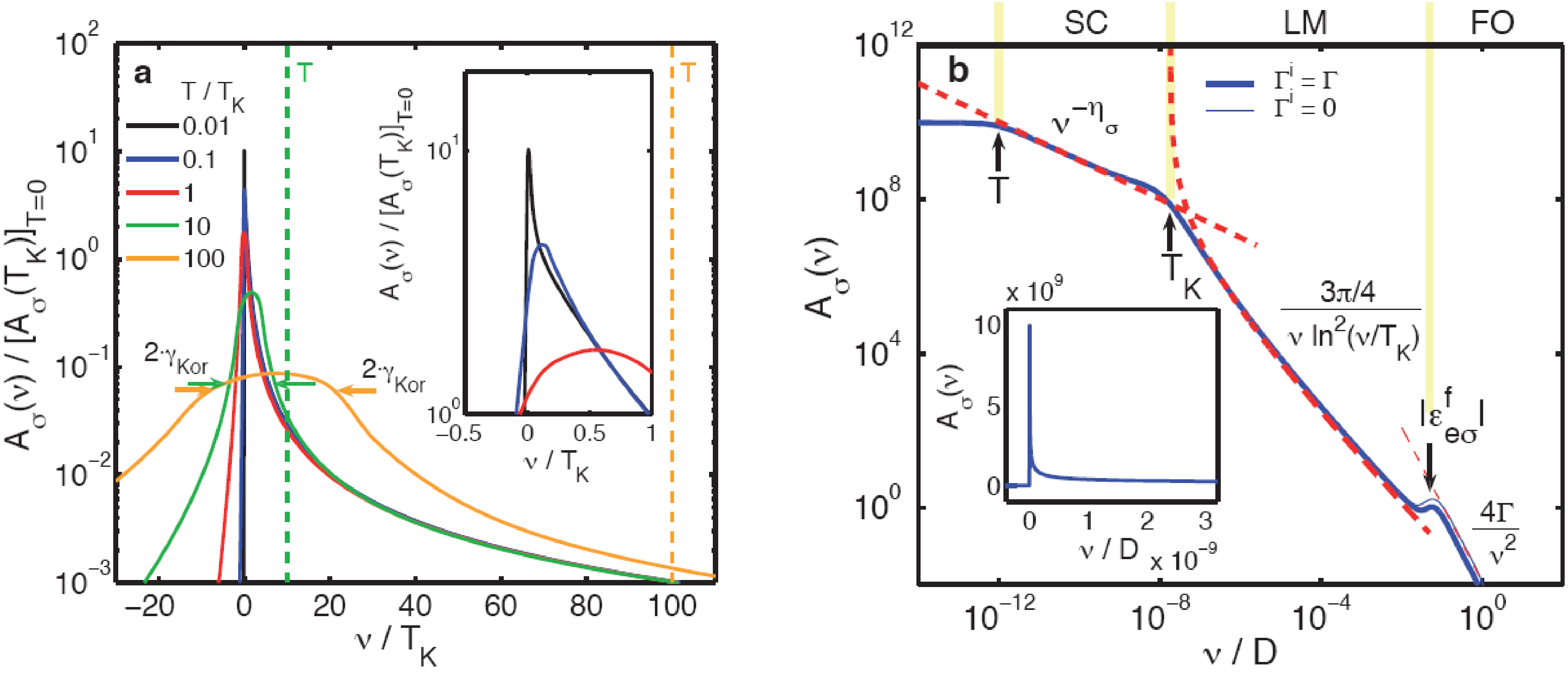


Absorption spectrum of a cw laser probes the many-body spectrum

(with H. Tureci, J. von Delft, L. Glazman)

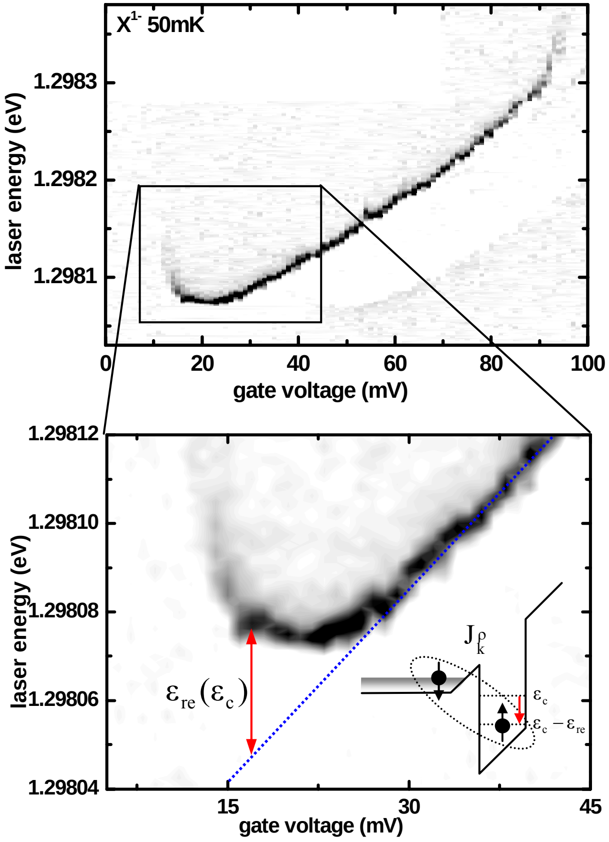
Conditional resonant absorption of two coupled QDs

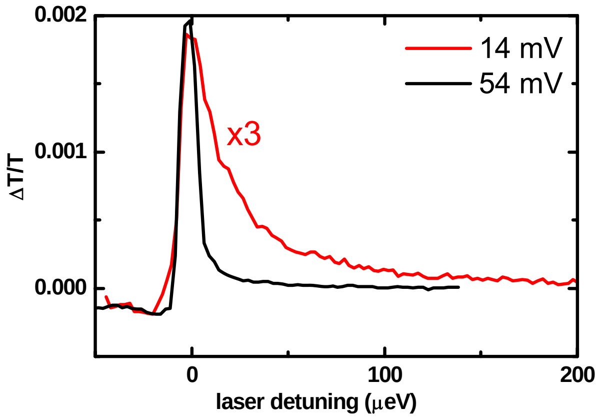
Absorption spectrum is highly asymmetric for ν > T with a power-law singularity at ν = 0



The exact NRG calculated spectrum is well described by different power-law tails

Absorption of a single-electron charged QD with a small tunnel barrier to a 3D electron gas at 50 mK





- At the edge of the plateau where exchange coupling is strong, the QD electron state sees a „lamb shift“

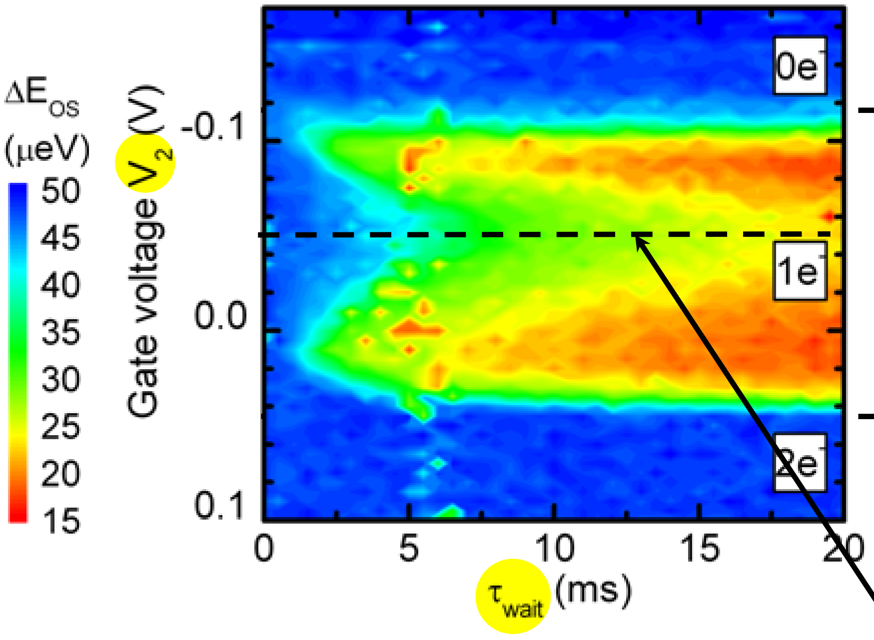
- The line broadening is highly asymmetric with a 1/ν blue-tail BUT the data also exhibits Fano type interference

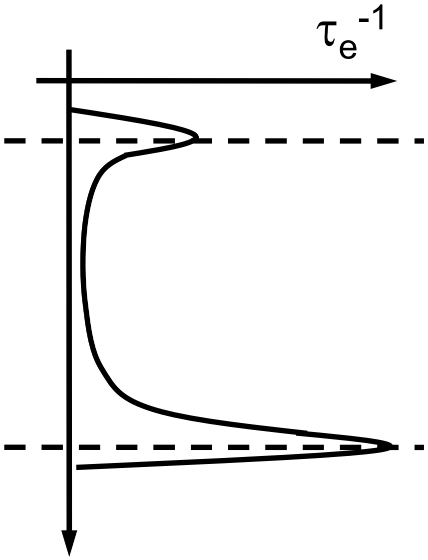
What‘s next?

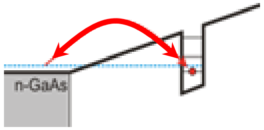
- Anistropic Kondo using heavy-holes coupled to a 2D hole-gas: mapping to ohmic spin-boson model
- Nonlinear Kondo: interplay between nonperturbative Rabi coupling and exchange
- Coherent spin manipulation by coupling to a fermionic reservoir

DNSP decay due to co-tunneling

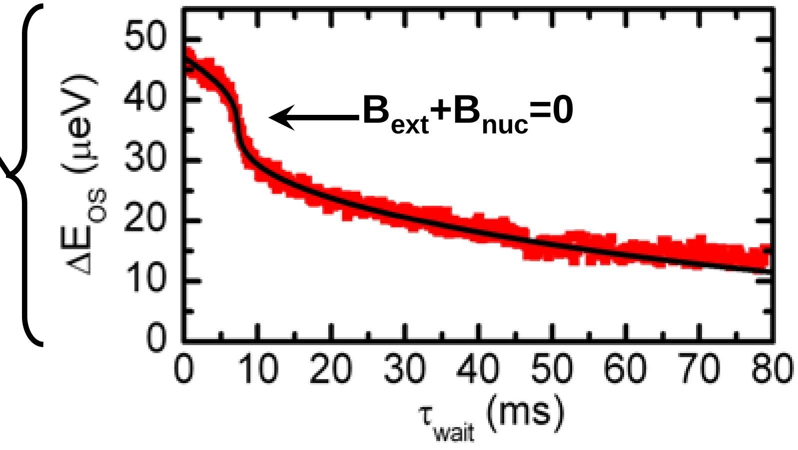
B_{ext}=1T, σ^+ exc.







Electron co-tunneling rate depends strongly on gate voltage!



Smith *et al.*, PRL, **94**, 197402 (2005)