Optical systems, entanglement and quantum quenches

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Part II: Quantum quench of Kondo correlations

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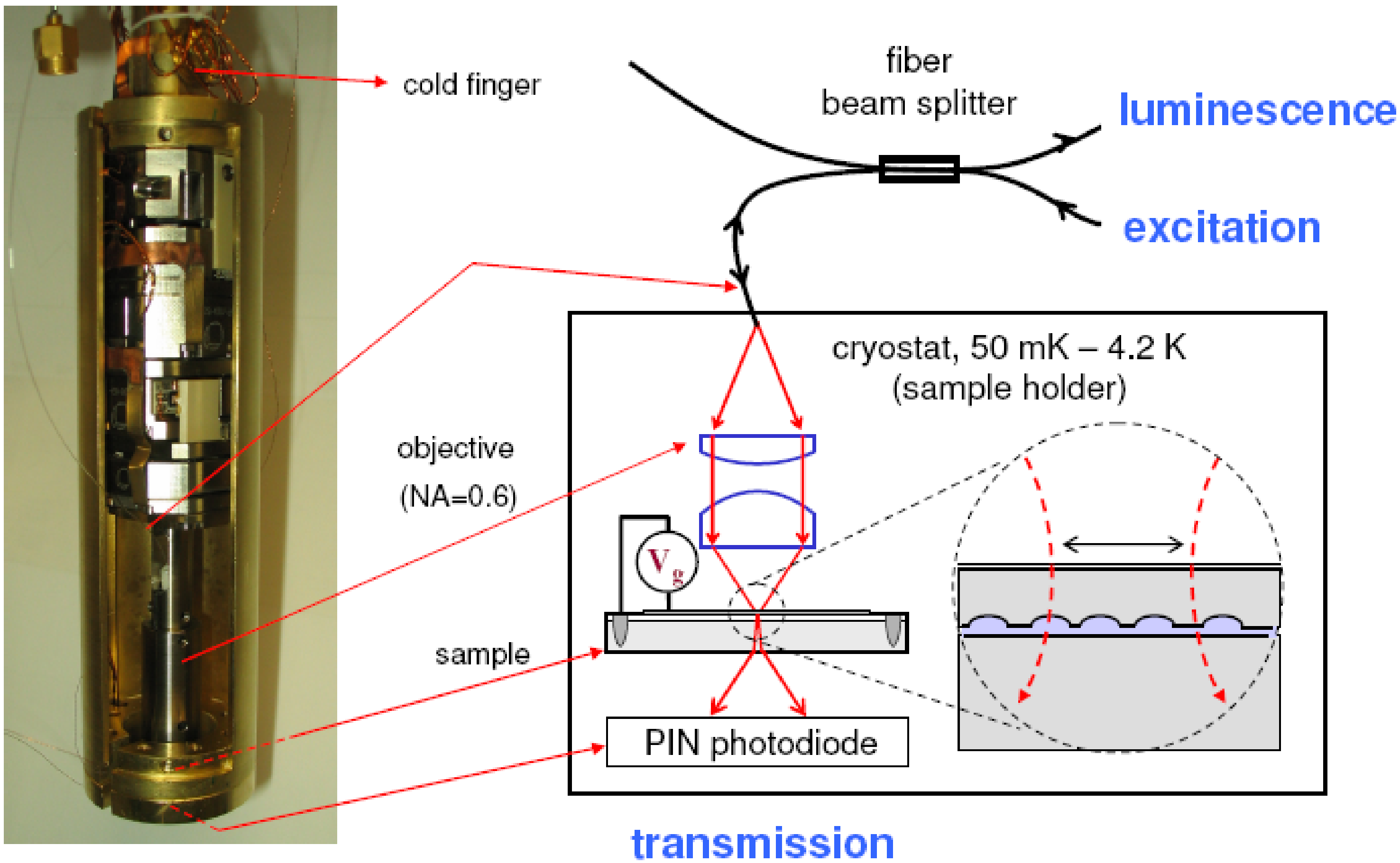
Confocal microscopy at low temperatures



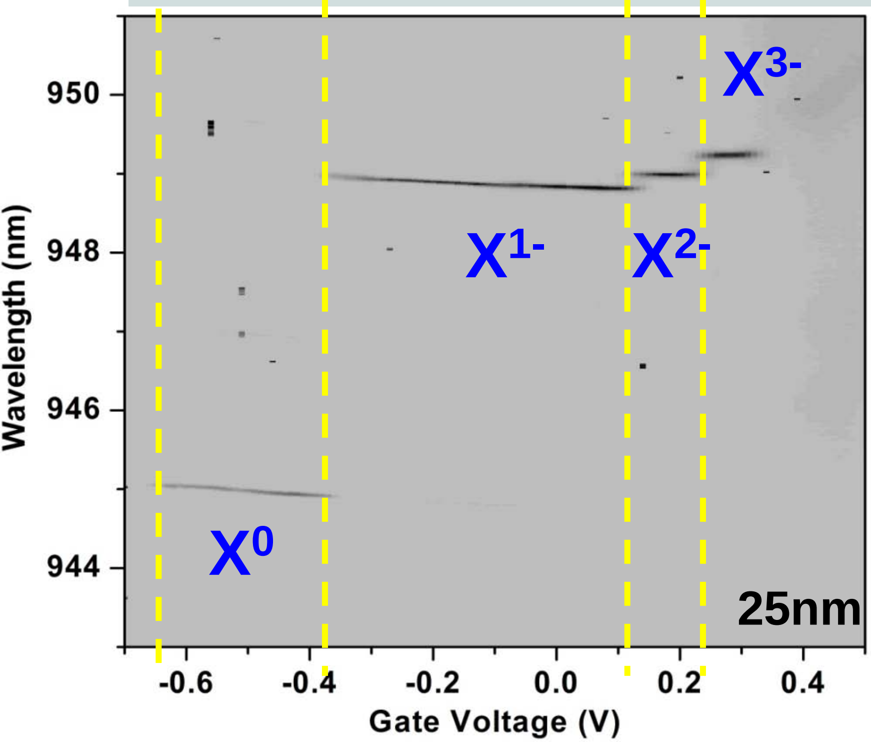
detected signal includes interference effect: $S(\nu) \sim \left[-i\chi(\nu)(1 + re^{i2\pi n(2L/\lambda)}\right]$

scattered forward — scattered back & reflected

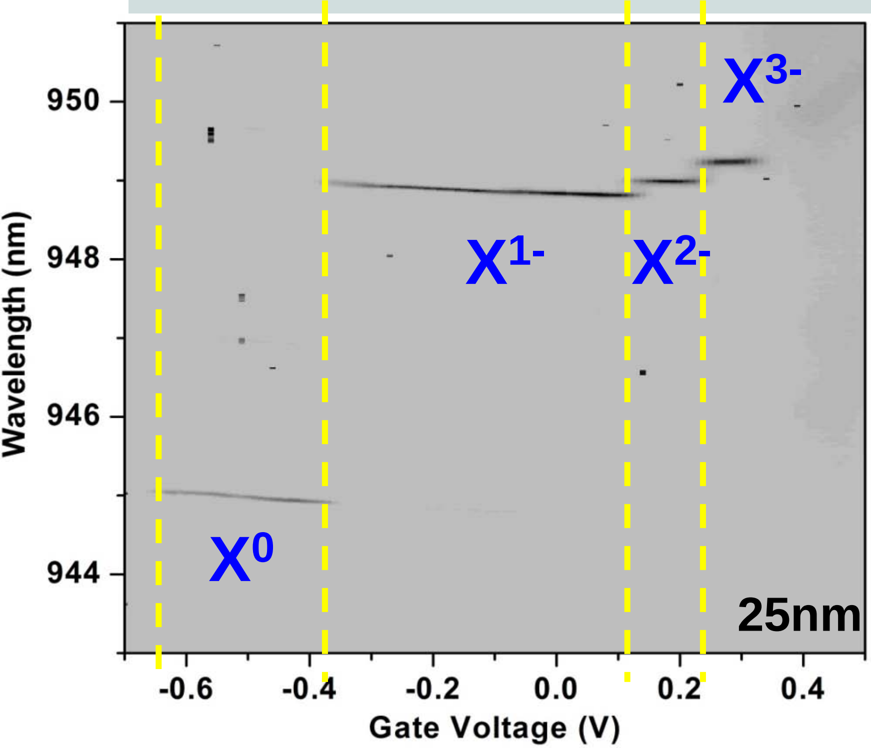
QD susceptibility: $\chi = \chi' + i\chi''$

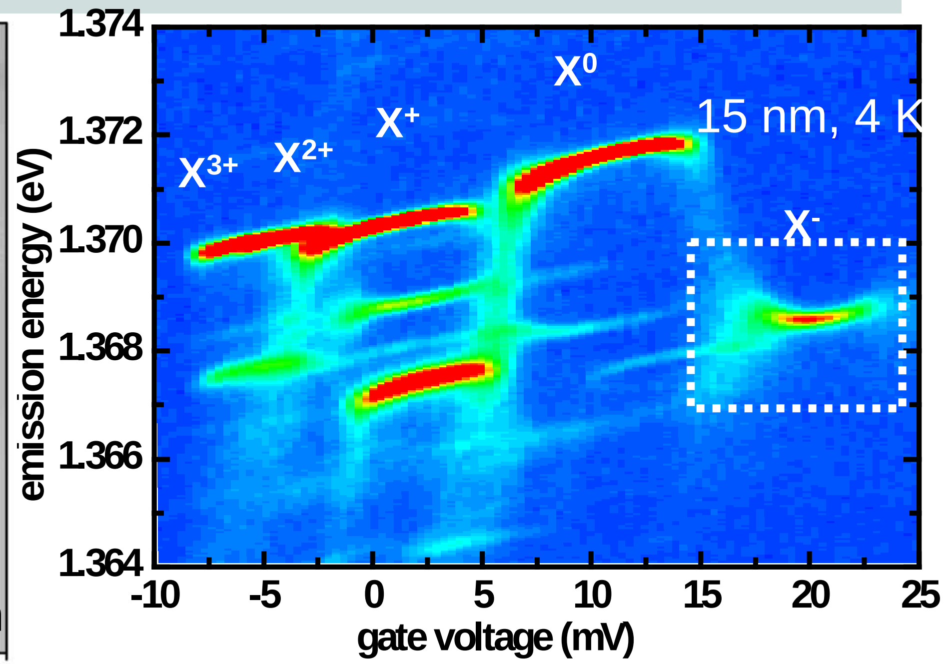
dispersive (χ'), absorptive ($i\chi''$)

Photoluminescence as a function of gate voltage reveals different charging states



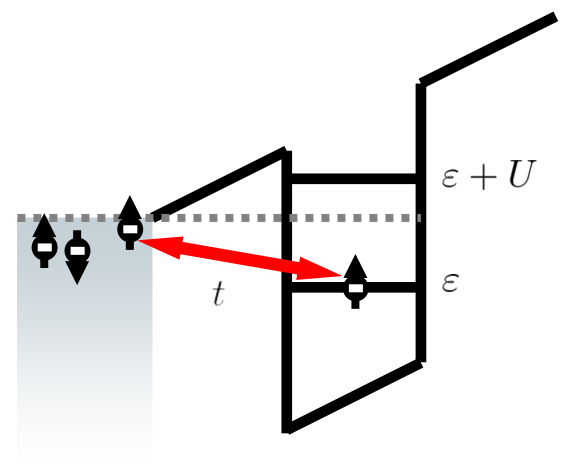
The influence on tunnel barrier width on QD photoluminescence





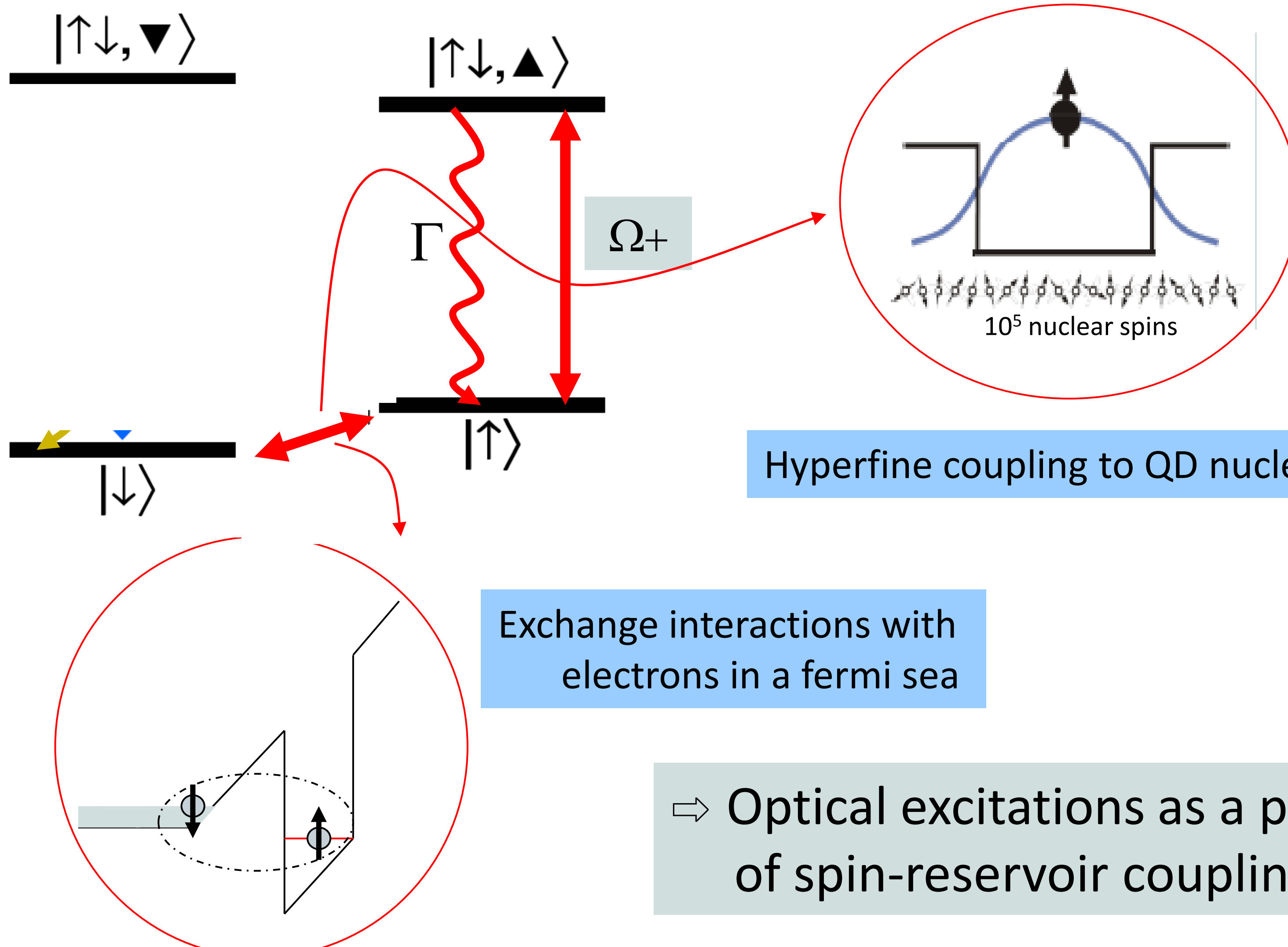
Signatures of strong tunnel coupling to fermionic reservoir (FR): Broad emission lines & spatially indirect transitions

- By adjusting the tunnel barrier we can suppress or enhance tunnel coupling to the reservoir.



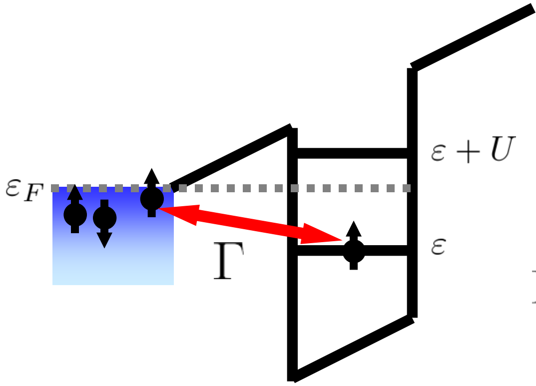
Optical probe of spin physics

In some cases decoherence can be more interesting than coherent dynamics



⇨ Optical excitations as a probe of spin-reservoir coupling

Single electron charged QD+Fermionic reservoir



An electron (magnetic impurity) in the proximity of a Fermi reservoir (FR) - Anderson Hamiltonian

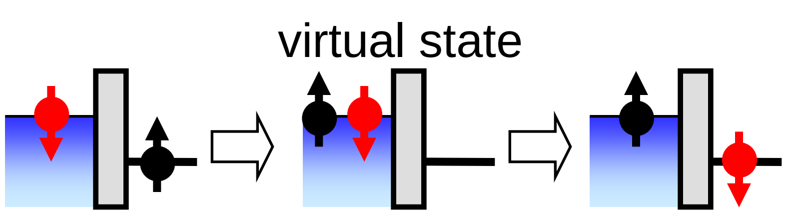
$$\hat{\mathrm{H}} = \sum_{k,\sigma} \varepsilon_{k,\sigma} \hat{\mathrm{c}}^{\dagger}_{k,\sigma} \hat{\mathrm{c}}_{k,\sigma} + \sum_{\sigma} \varepsilon_{\sigma} \hat{\mathrm{e}}^{\dagger}_{\sigma} \hat{\mathrm{e}}_{\sigma} + U \hat{\mathrm{n}}_{\uparrow} \hat{\mathrm{n}}_{\downarrow} + \Gamma \sum_{k,\sigma} \hat{\mathrm{c}}^{\dagger}_{k,\sigma} \hat{\mathrm{e}}_{\sigma} + \mathrm{h.c.}$$

Quantum dot electron in local moment regime : $\langle \hat{\mathrm{n}}_e \rangle = 1$
Coupling is reduced to an effective spin-spin interaction

$$\hat{\mathrm{H}}_{sd} = J \hat{\mathrm{S}}(0) \cdot \hat{\mathrm{s}}_e$$

Fermi sea electrons (→ $\hat{\mathrm{S}}(0)$) QD electron (→ $\hat{\mathrm{s}}_e$)

Spin exchange



$J > 0$ (anti - ferromagnetic)

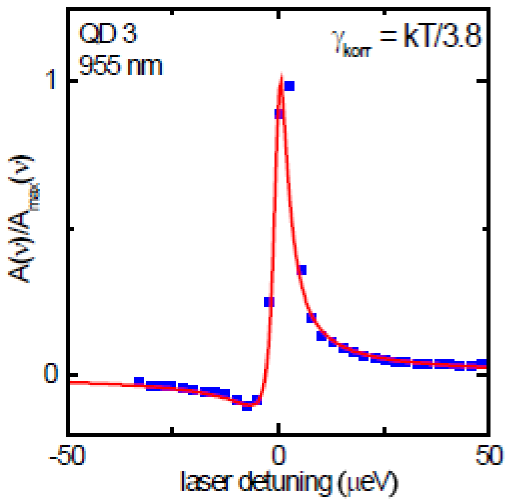
Can we learn something new about Kondo effect using optical absorption ?

- Competition between exchange coupling (leading to Kondo screening cloud) and Zeeman interaction should yield reduced magnetization: strong spin-polarization correlations allows us to measure magnetization from the area under the absorption curve.

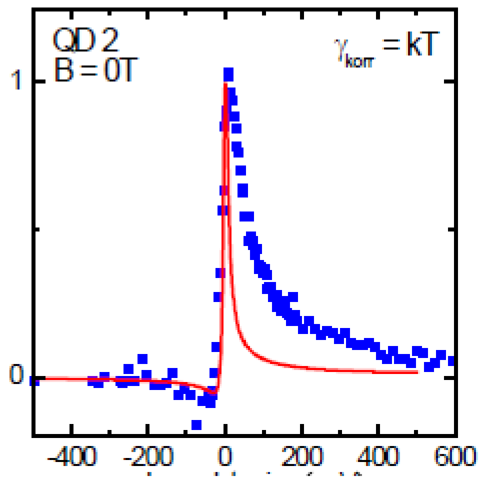
- The quench of Kondo correlations upon optical excitation (trion formation) modify the lineshape, leading to power-law tails.

Absorption lineshapes of a single electron charged QD

Weakly coupled QD



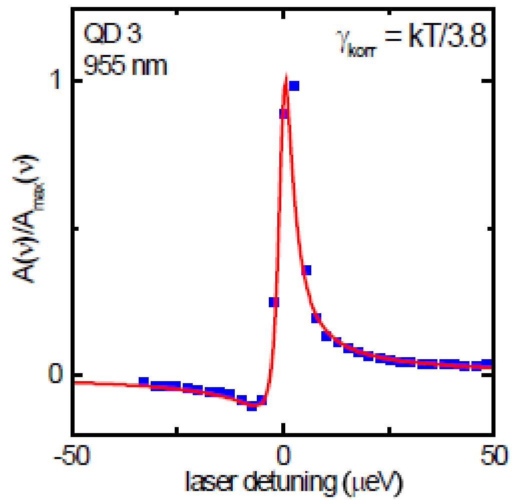
Strongly coupled QD



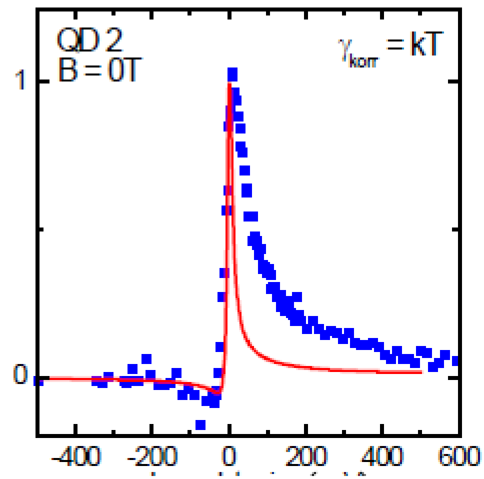
- The asymmetry in the lineshape is partly due to an optical interference effect
- Impossible to fit the strongly coupled QD with a perturbative lineshape

Absorption lineshapes of a single electron charged QD

Weakly coupled QD



Strongly coupled QD



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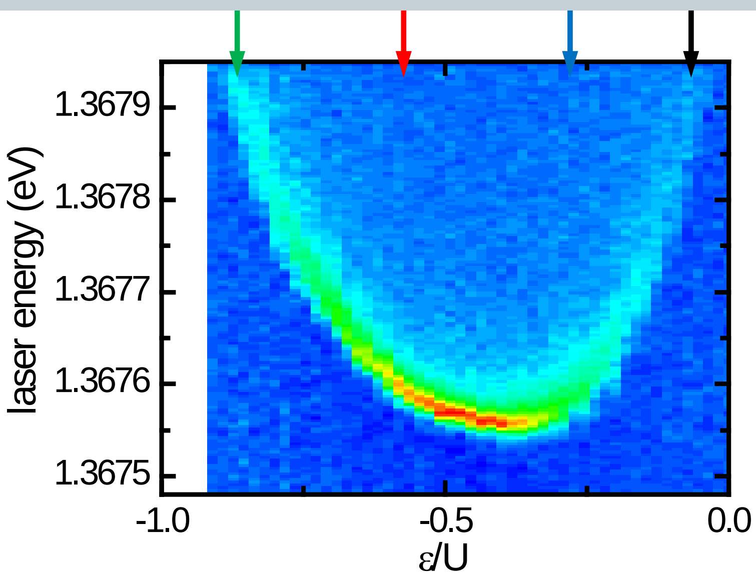
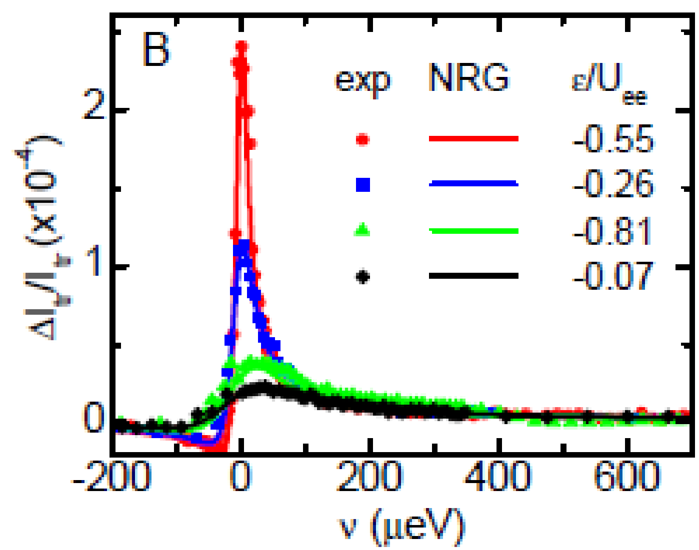
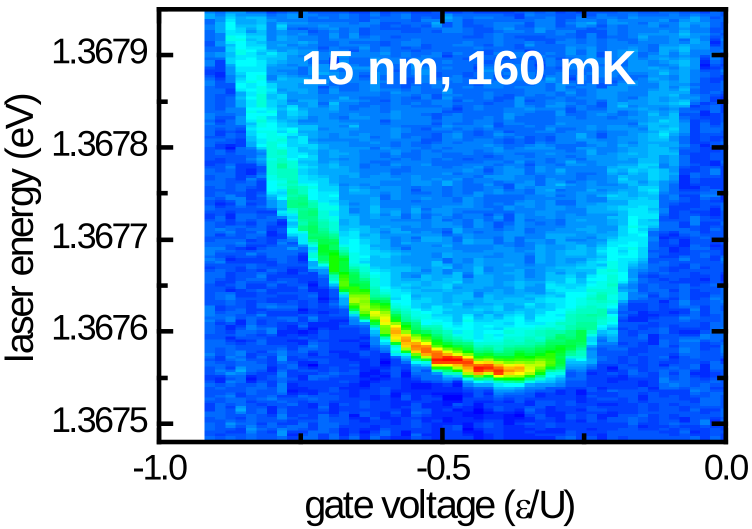
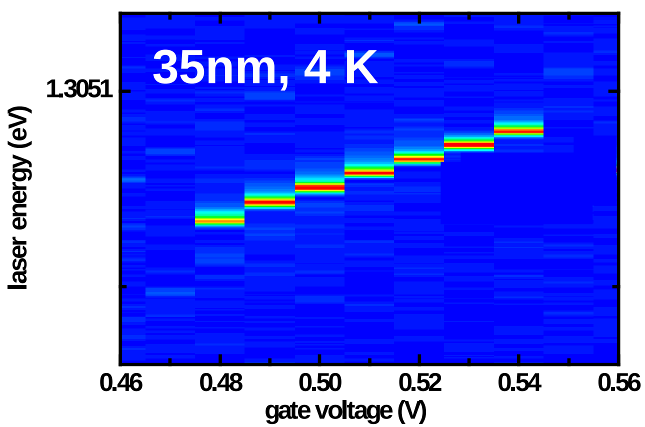
The lineshape depends strongly on gate voltage & hence the Kondo temperature:





The influence on tunnel barrier width on a negatively charged QD absorption

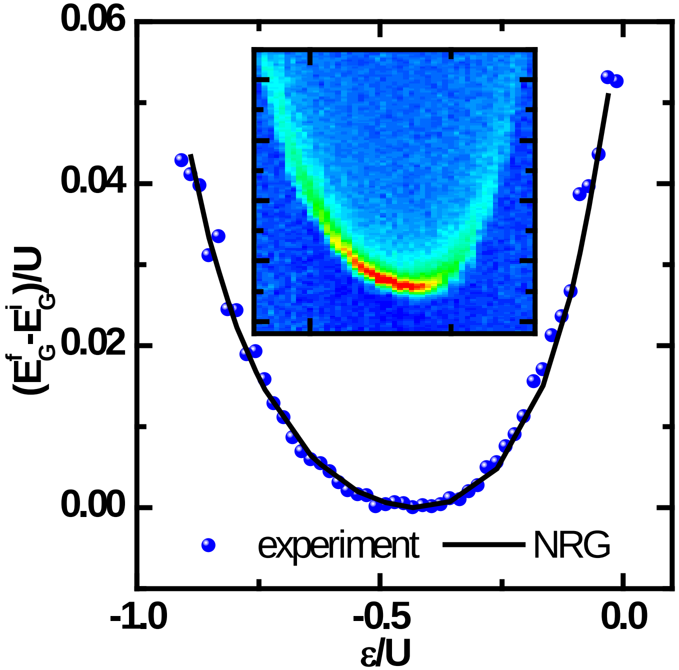


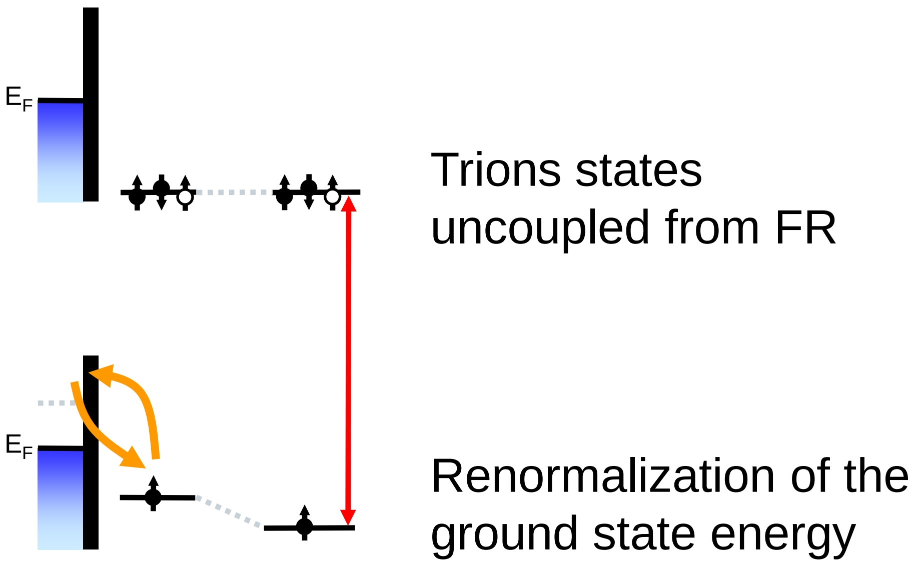


Signatures of strong tunnel/exchange coupling:

- Asymmetric broadening at the edges
- Lamb-shift of the ground-state

The influence on tunnel barrier width on a negatively charged QD absorption





From fit (NRG):

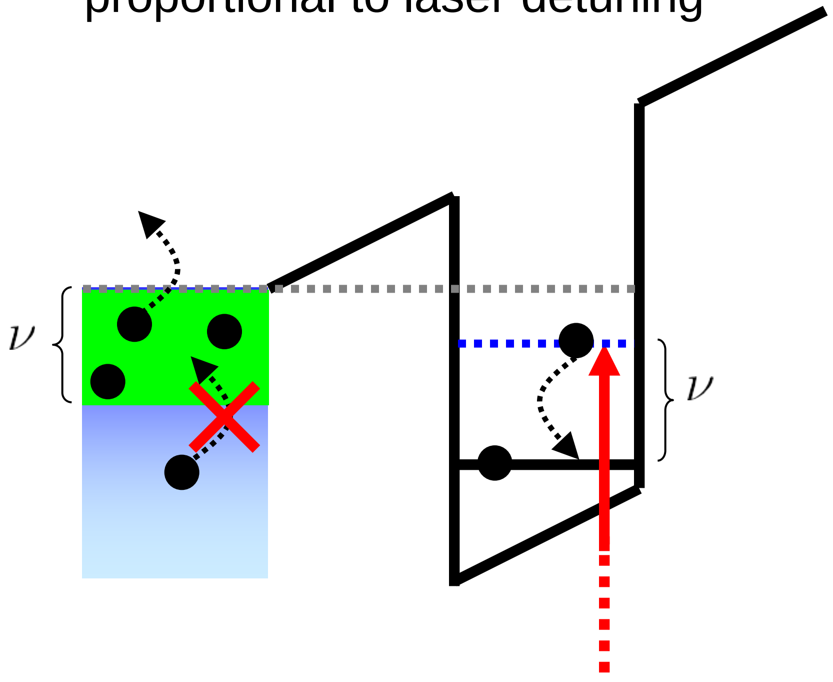
$$U_{e-e} = 7.5\text{meV}$$
$$\Gamma = 0.7\text{meV}$$
$$D = 3.5\text{meV}$$

Signatures of strong tunnel/exchange coupling:

- Asymmetric broadening at the edges
- Lamb-shift of the ground-state

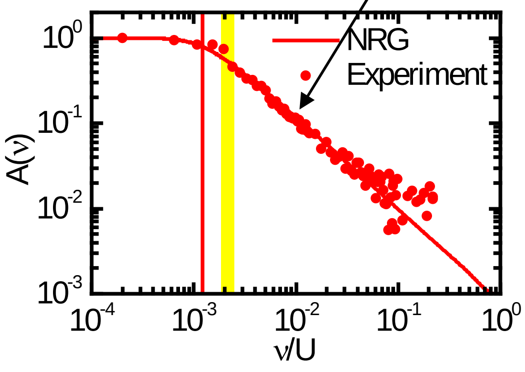
Perturbative regime: $\nu > T_K$

2D DOS: Bandwidth of states D in the Fermi sea which contribute is proportional to laser detuning



Blue laser detuning

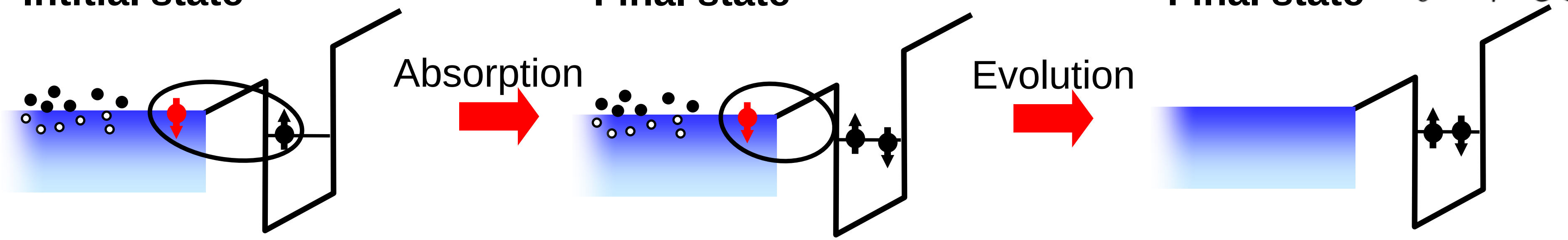
$$A(\nu) \propto \frac{1}{\nu^2} \cdot \nu = \frac{1}{\nu^1}$$



Red detuning: exponential tails which allow us to determine the electron temperature

Kondo strong coupling regime: $\nu < T_K$

Intitial state **Final state** **Final state** $t \to \infty$



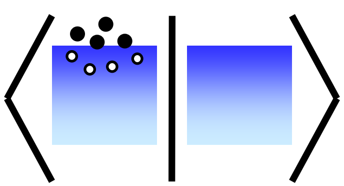
$|\psi_i\rangle = |\psi_{Kondo}\rangle$

$|\Psi(0)\rangle = \hat{e}^\dagger_\sigma \hat{h}^\dagger_{\bar{\sigma}} |\psi_{Kondo}\rangle$

(Hole: only spectator)

$$|\Psi(\infty)\rangle = \hat{e}^\dagger_\uparrow \hat{e}^\dagger_\downarrow \hat{h}^\dagger_{\bar{\sigma}} \prod_{k \leq k_F} \hat{c}^\dagger_{k,\sigma} \hat{c}^\dagger_{k,-\sigma} |\text{vac}\rangle$$

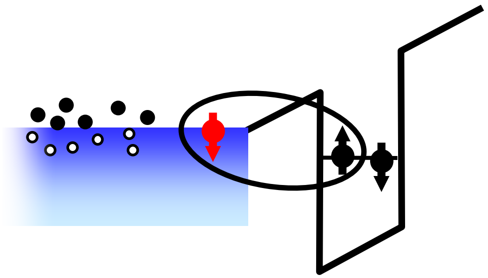
- Absorption process „turns off“ the interactions $\hat{H}_i \neq \hat{H}_f$
- Fermionic reservoir (FR) strongly modiefied: part of the system
- Initial and final state FR are orthogonal

 ≈ 0

Anderson orthogonality catastrophe (AOC)

Anderson orthogonality catastrophe:

Consequence of quantum quench of Kondo correlations

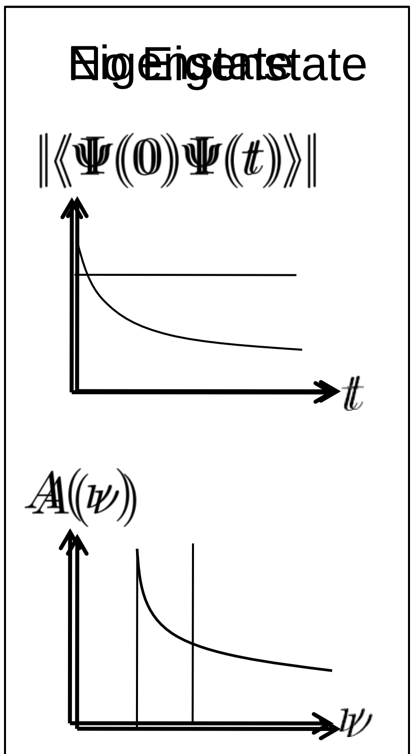


$$A_\sigma(\nu) = 2\pi \sum_{mm'} \rho^{\mathrm{i}}_{\mathrm{m}} |{}_{\mathrm{f}}\langle \mathrm{m}'|e^\dagger_\sigma|m\rangle_{\mathrm{i}}|^2 \delta(\omega_{\mathrm{L}} - E^{\mathrm{f}}_{\mathrm{m}'} + E^{\mathrm{i}}_{\mathrm{m}})$$

After absorption, system is not in an Eigenstate of $\hat{H}_f$

$$|\Psi(0)\rangle = \hat{e}^\dagger_\sigma |\psi_{Kondo}\rangle$$

$$|\Psi(t)\rangle = e^{i\hat{H}_f t} \hat{e}^\dagger_\sigma |\psi_{Kondo}\rangle$$



Absorption spectrum can be rewritten as:

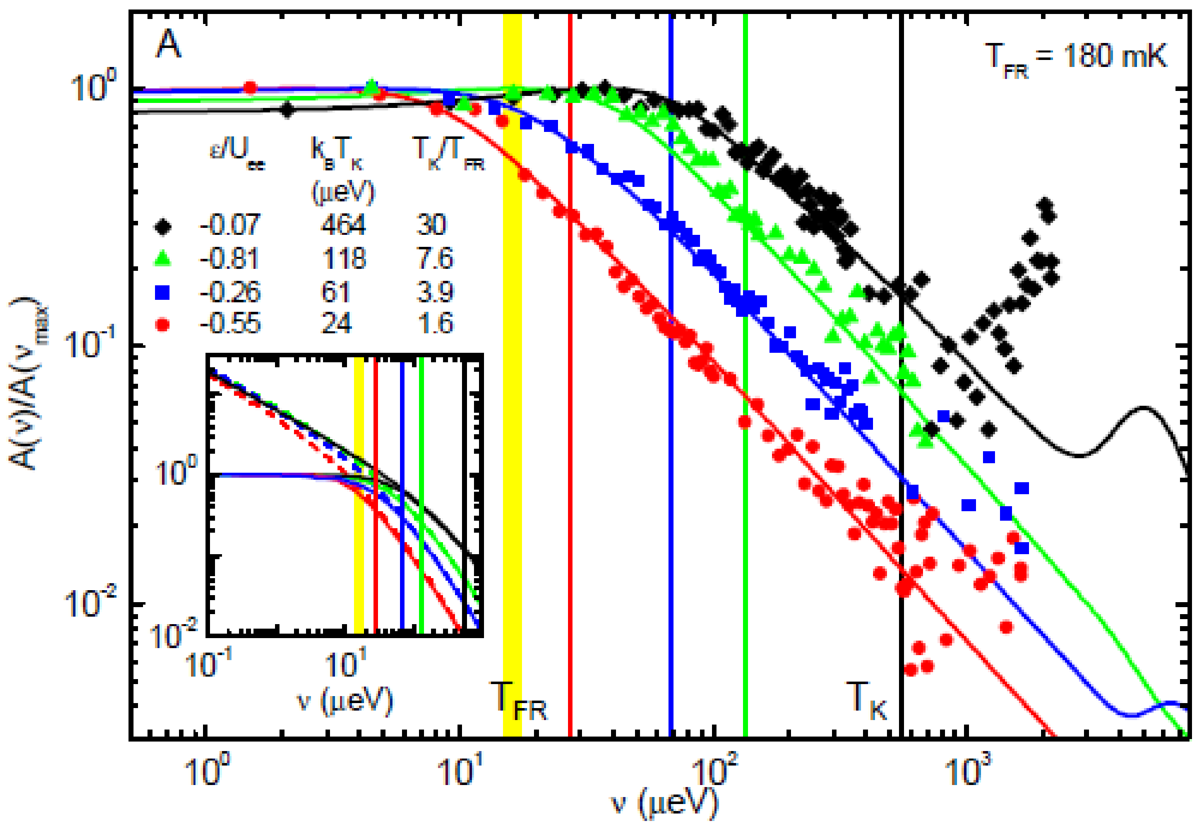
$$A(\nu) = -2\mathrm{Im}\mathcal{F}_\nu\{\langle\Psi(0)\Psi(t)\rangle\}$$

Kondo: power-law singularity

$A(\nu) \propto 1/\nu^\eta$ with $\eta = 0.5$

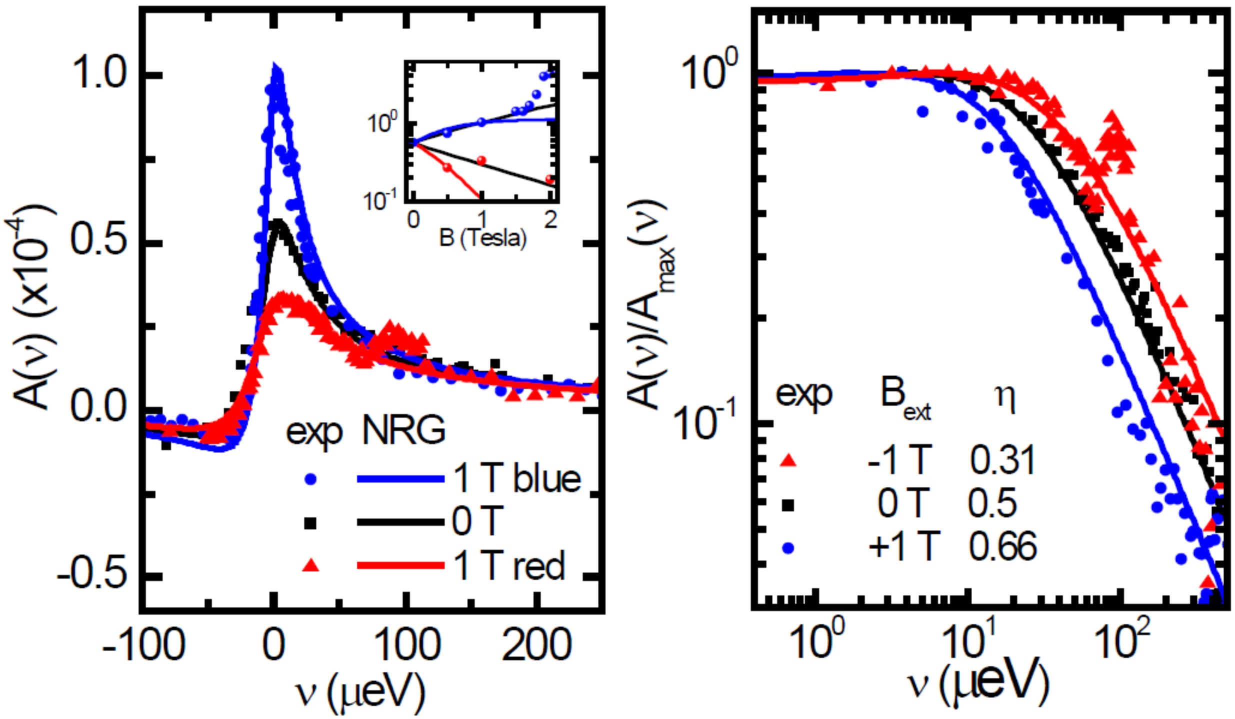
η related to the phase shifts in the Fermi sea and could be determined using the (generalized) Hopfield rule

Experimental signatures of Kondo correlations: remarkable agreement with the theory



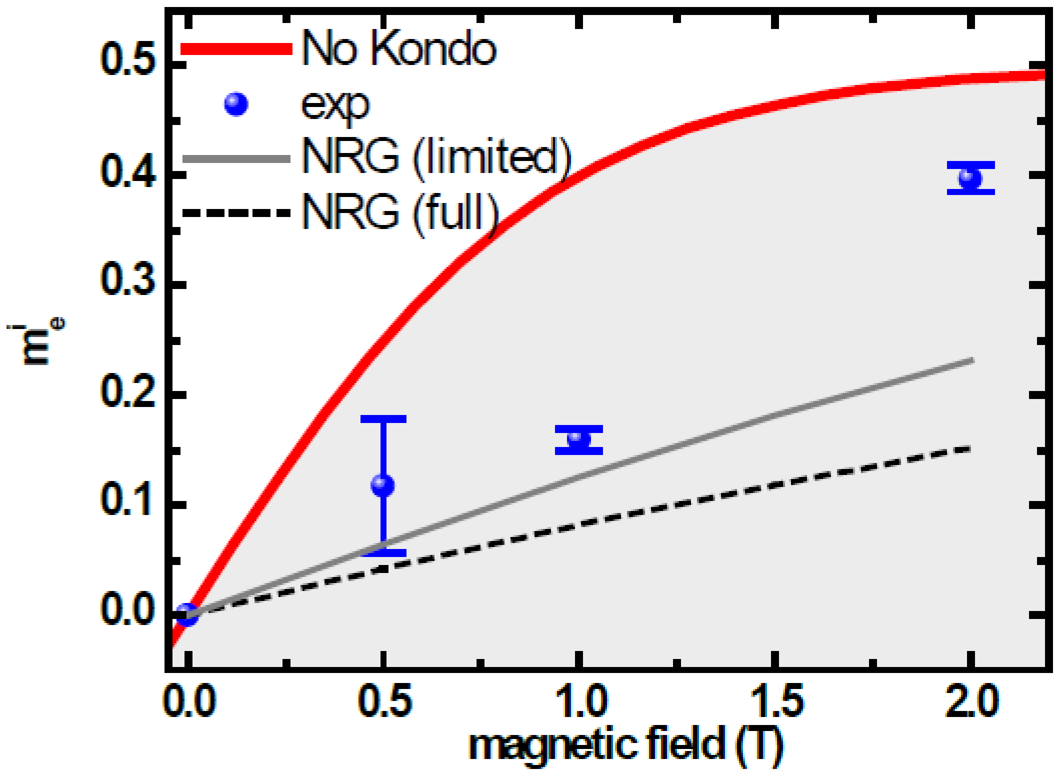
- Power-law tails for $\nu < T_K$ are smeared out by finite electron temperature!

How to determine the power law exponents?



- By adjusting the (circular) polarization of the laser, we could address transitions from spin up (blue) or down (red) initial states.
- The lineshapes are sensitive to the magnetic-field-tunable power-law exponents.

Suppression of magnetization



- The area under the absorption lineshapes reveal that the magnetization of the QD is suppressed.

Summary and Outlook

- Optical measurements allowed us to obtain signatures of quantum quench of Kondo correlations for the first time
- The Anderson orthogonality catastrophe induced power law exponents can be tuned by changing the magnetic field
- Use QD nuclear spin relaxation to monitor Kondo correlations
- Photon correlations can be used to monitor time-evolution following the quench.