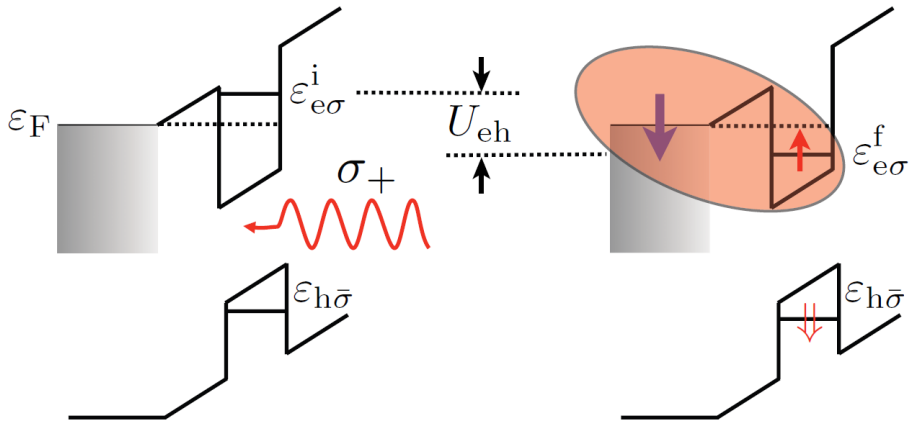
Theory of Kondo exciton: a quantum quench towards strong spin-reservoir correlations

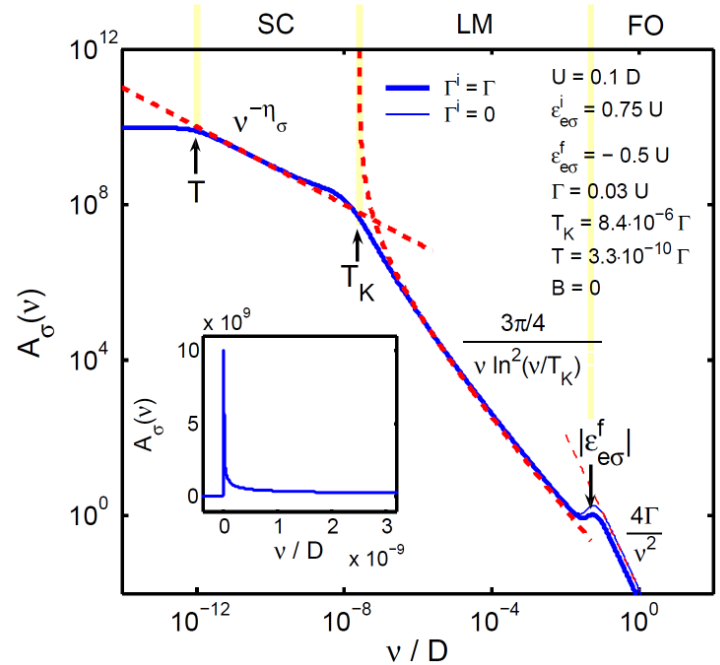
Hakan Tureci, Martin Claassen, Atac Imamoglu (ETH),

Markus Hanl, Andreas Weichselbaum, Theresa Hecht, Jan von Delft (LMU)

Bernd Braunecker (Basel), Sasha Govorov (Ohio), Leonid Glazman (Yale)

[arXiv:0907.3854]





What happens when an optical excitation is used to “switch on/off” Kondo correlations?

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SFB 631

Our first steps in this direction…

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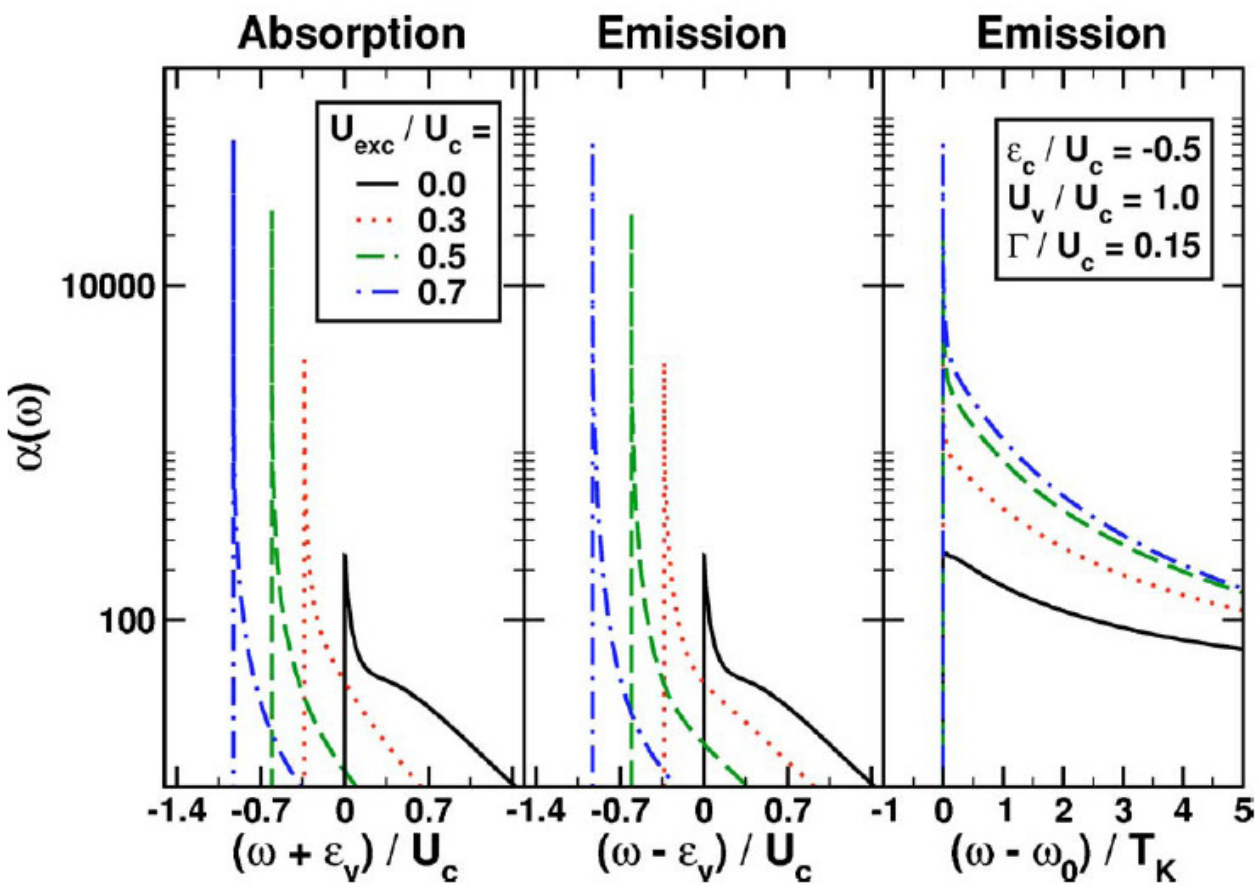
Absorption and emission in quantum dots: Fermi surface effects of Anderson excitons

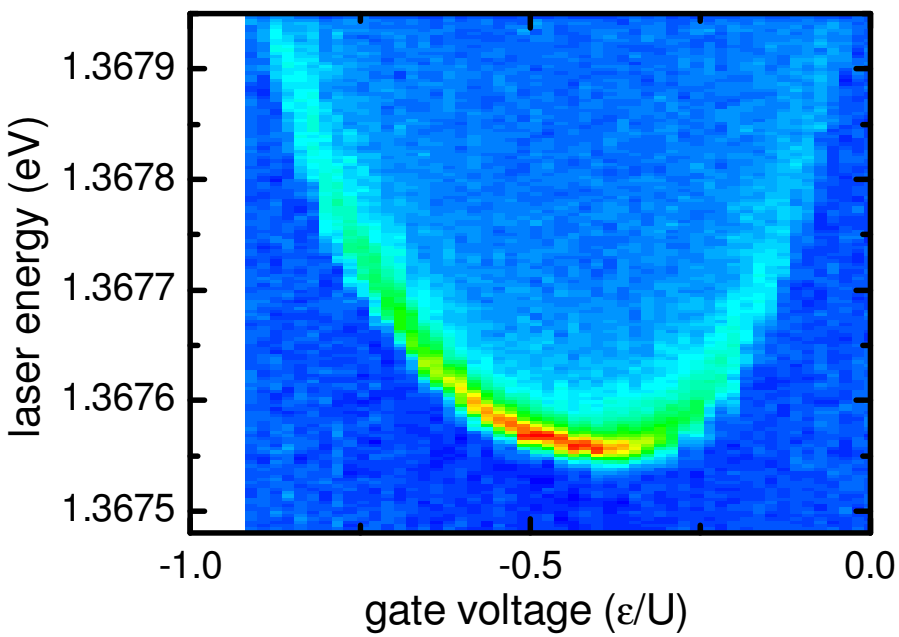
R. W. Helmes,[1] M. Sindel,[1] L. Borda,[1,2] and J. von Delft[1]

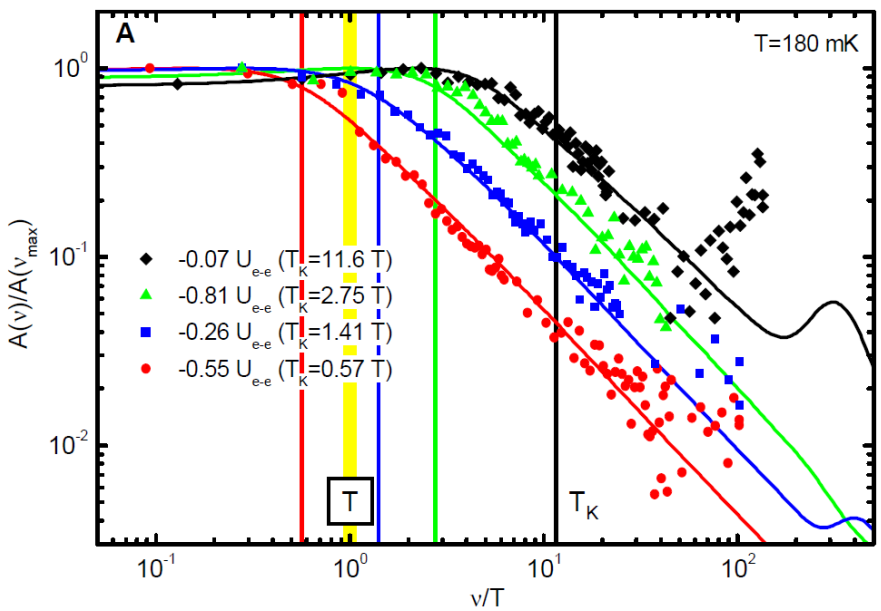


Experiment: Quantum quench of Kondo correlations in optical absorption

Christian Latta, F. Haupt, P. Fallahi, S. Faelt, Hakan Tureci, Atac Imamoglu (ETH),

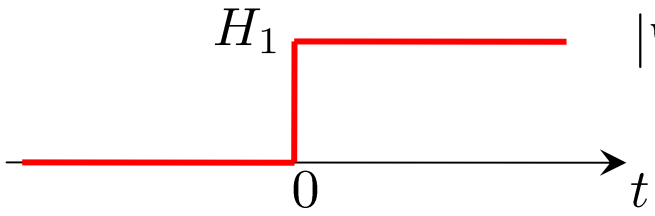
Markus Hanl, Andreas Weichselbaum, Jan von Delft (LMU), Leonid Glazman (Yale)





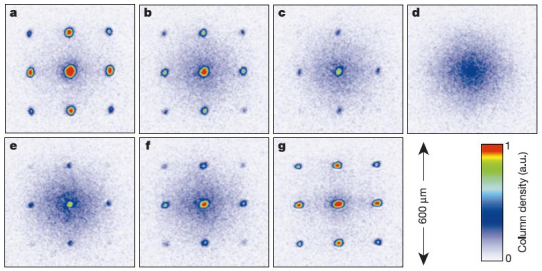
Transient Dynamics after Quantum Quench

Quantum dynamics after sudden change in Hamiltonian?



$$H(t) = H_0 + H_1\theta(t)$$

Modern Example:
"Collapse & Revival" of coherent matter waves of cold atoms.
(Greiner et al, Nature '02)



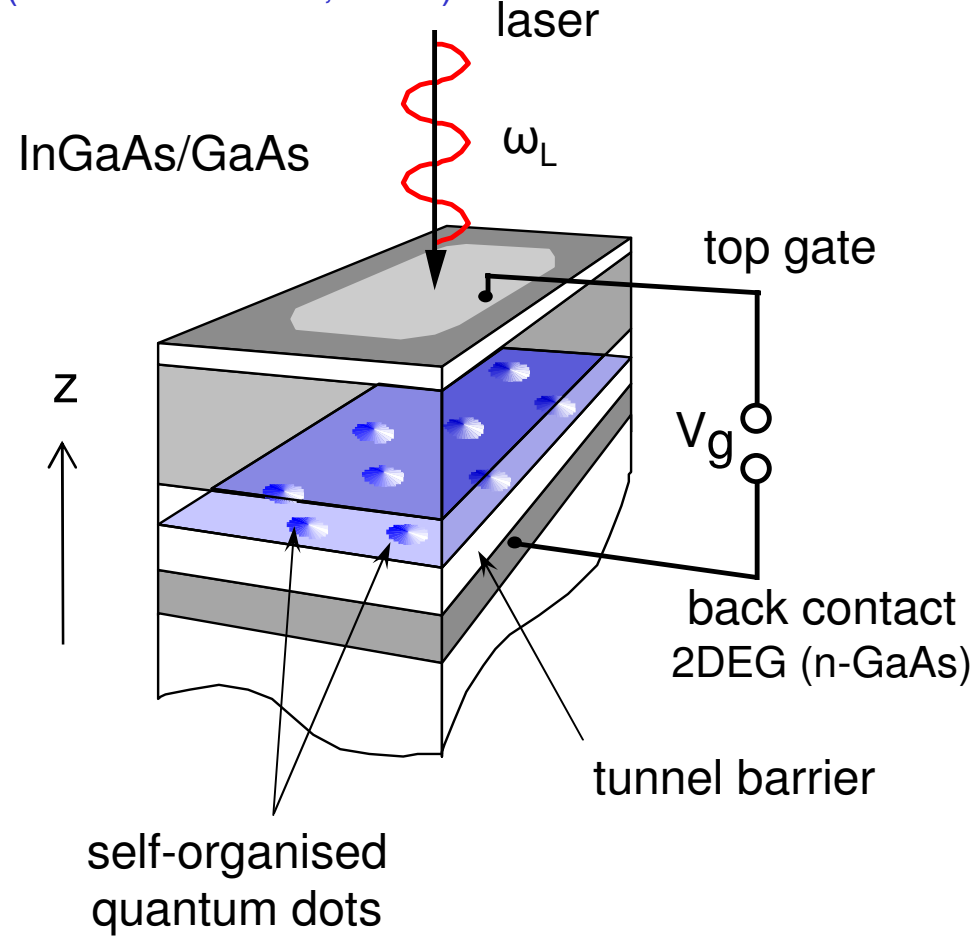
(B, V_g)

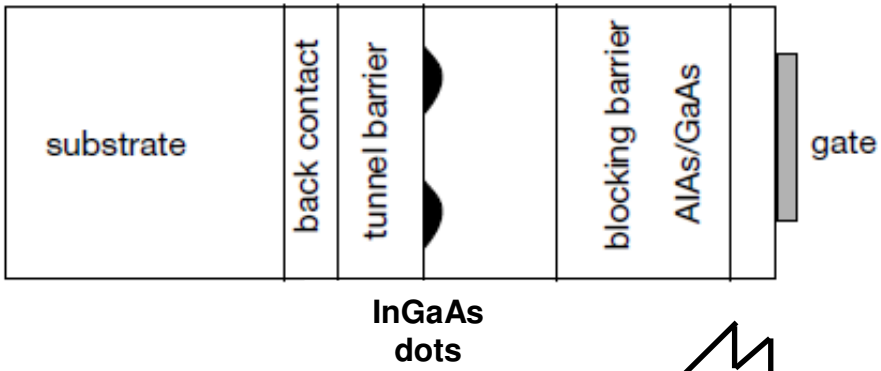
Old, well-known example:
X-Ray-Edge Singularity
(Mahan, PR '67)

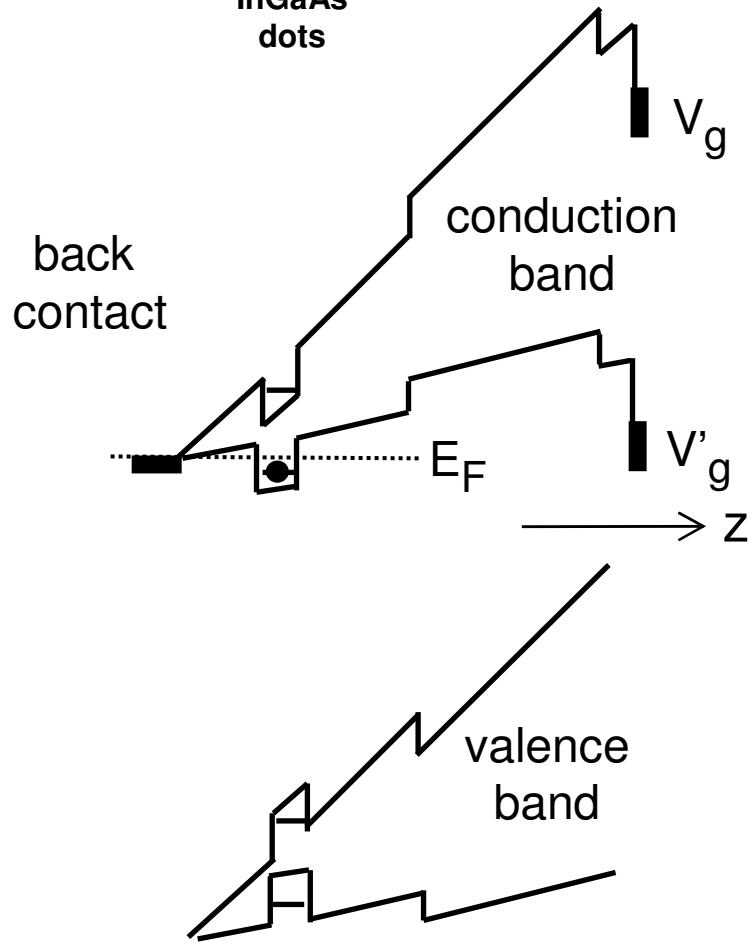
Exciton + Fermi-See:
Analogous to X-ray-edge problem
(Helmes, Sindel, Borda, von Delft, PRB '04)

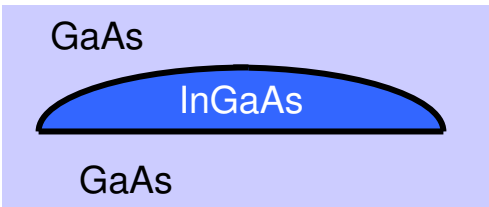
Experimental Setup

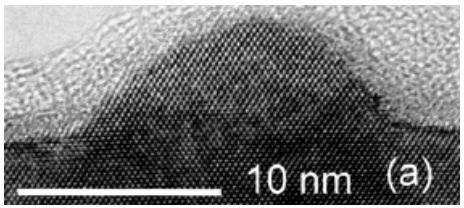
(Warburton et al., 2000)





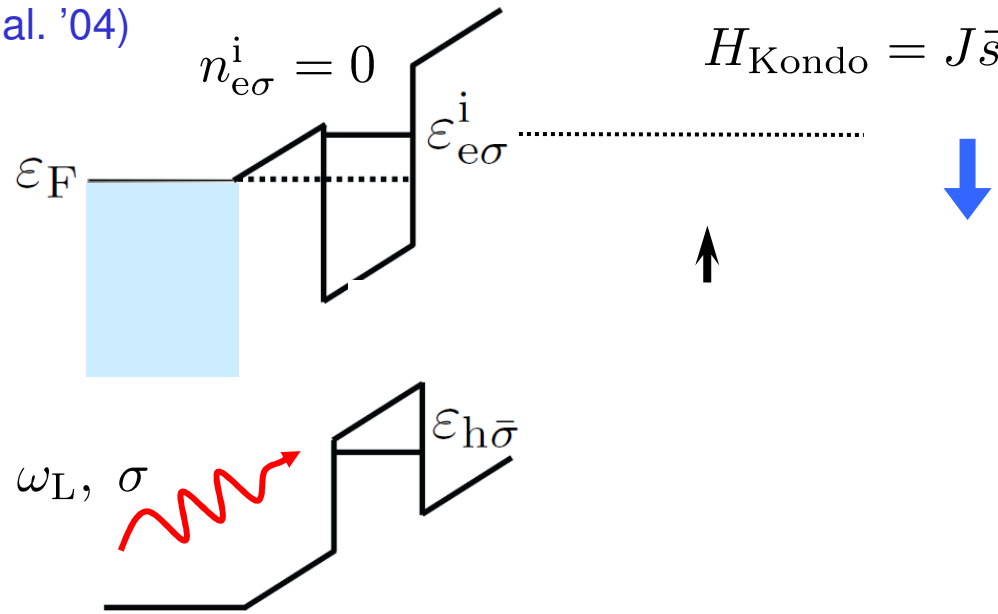






Proposed Experimental Setup: Absorption

(Helmes et al. '04)



initial

$$H_{\mathrm{Kondo}} = J\vec{s}_{\mathrm{FR}} \cdot \vec{S}_{\mathrm{dot}}$$

$$n^{\mathrm{f}}_{\mathrm{e}\sigma} \simeq 1$$

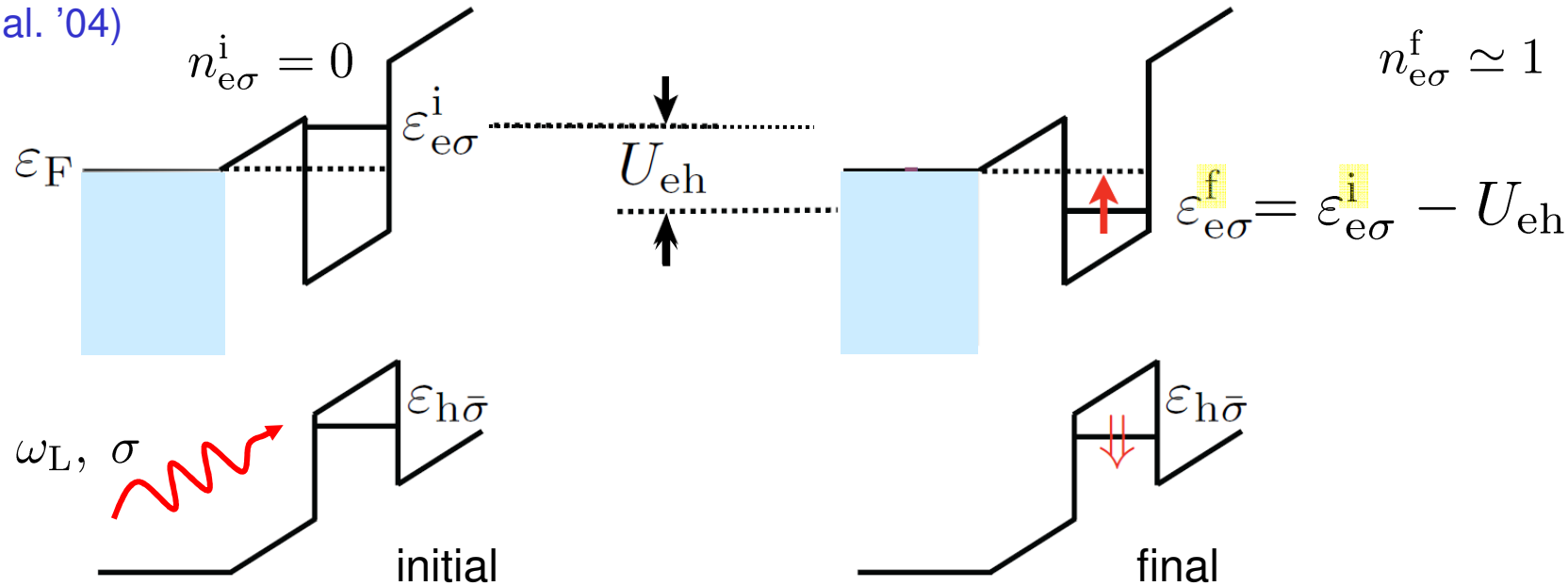
Optical absorption induces a quantum quench: $H^{\mathrm{initial}} \neq H^{\mathrm{final}}$

What is subsequent transient dynamics of dot + Fermi-sea ?

Transient dynamics after Kondo interaction is suddenly switched on ?

Hamiltonian

(Helmes et al. '04)



Anderson model (AM)

$$H^{\rm i/f} = H^{\rm i/f}_{\rm QD} + \sum_{k\sigma} \varepsilon_{k\sigma} c^\dagger_{k\sigma} c_{k\sigma} + \sqrt{\Gamma/\pi\rho} \sum_\sigma (e^\dagger_\sigma c_\sigma + {\rm h.c.})$$

$$H^{\rm i}_{\rm QD} = \sum_\sigma \varepsilon^{\rm i}_{{\rm e}\sigma} n_{{\rm e}\sigma} + U n_{{\rm e}\uparrow} n_{{\rm e}\downarrow}$$

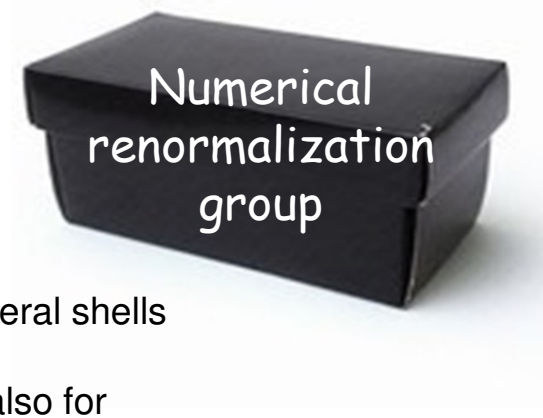
$$c_\sigma = \sum_k c_{k\sigma} = \psi_\sigma(0)$$

$$H^{\rm f}_{\rm QD} = \sum_\sigma \varepsilon^{\rm f}_{{\rm e}\sigma} n_{{\rm e}\sigma} + U n_{{\rm e}\uparrow} n_{{\rm e}\downarrow} + \varepsilon_{{\rm h}\bar\sigma}$$

SAM: $\varepsilon^{\rm f}_{{\rm e}\sigma} = -U/2;\ n^{\rm f}_{{\rm e}\sigma} = 1$

(symmetric Anderson model)

Dynamical correlation functions with Wilson's NRG



1989: Sakai, Shimizu, Kasuya / Costi, Hewson

1990: Yosida, Whitaker, Oliveira

1994: Costi, Hewson, Zlatic - Transport properties (resistivity)

1999: Bulla, Hewson, Pruschke - Patching rules for combining data from several shells

2000: Hofstetter - DM-NRG (accurate ground state needed also for high-frequency information)

2004: Helmes, Sindel, Borda von Delft - Absorption/emission spectra after quantum quench

2005: Anders & Schiller - Complete Fock space basis for t-NRG

2005: Verstraete, Weichselbaum, Schollwöck, von Delft, Cirac - Relation between NRG & DMRG via MPS

2007: Peters, Anders, Pruschke - Sum-rule-conserving spectral functions (single-shell DM)

2007: Weichselbaum & von Delft - First truly "clean" algorithm for spectral functions at finite temperatures (full multi-shell DM)

2008: Weichselbaum, Verstraete Schollwöck, von Delft, Cirac -Non-logarithmic discretization for split Kondo resonance

2008: Toth, Moca, Legeza, Zarand - Flexible NRG code with non-Abelian symmetries

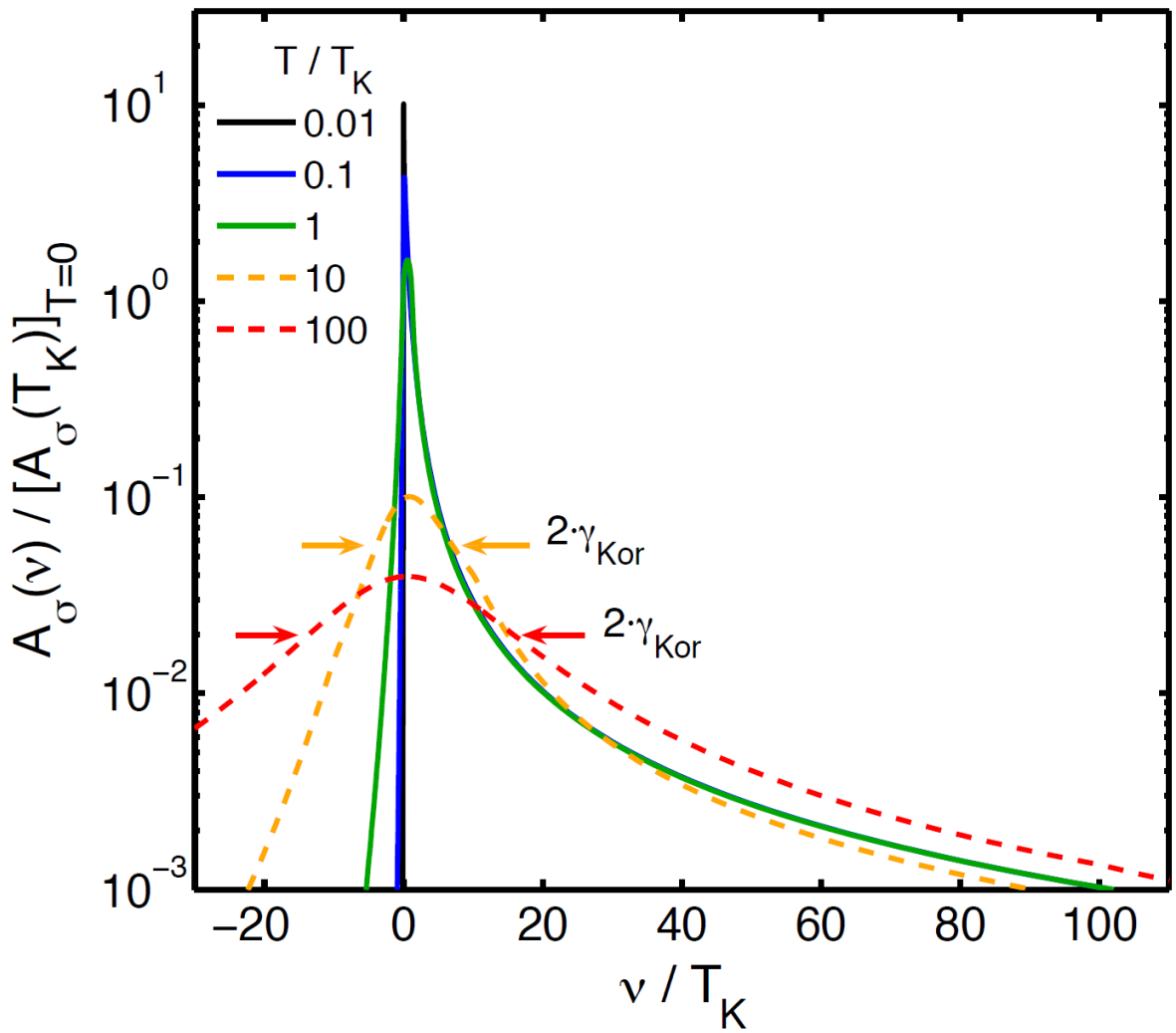
2009: Anders - Nonequilbrium correlators via scattering state NRG

Absorption Lineshape (log-linear) [SAM]

$$A_\sigma(\nu) \quad = \quad 2\pi \sum_{\alpha\beta} \rho^{\rm i}_\alpha \left| {}_{\rm f}\langle\beta|e^\dagger_\sigma|\alpha\rangle_{\rm i}\right|^2 \delta(\nu + \omega_{\rm th} - E^{\rm f}_\beta + E^{\rm i}_\alpha)$$

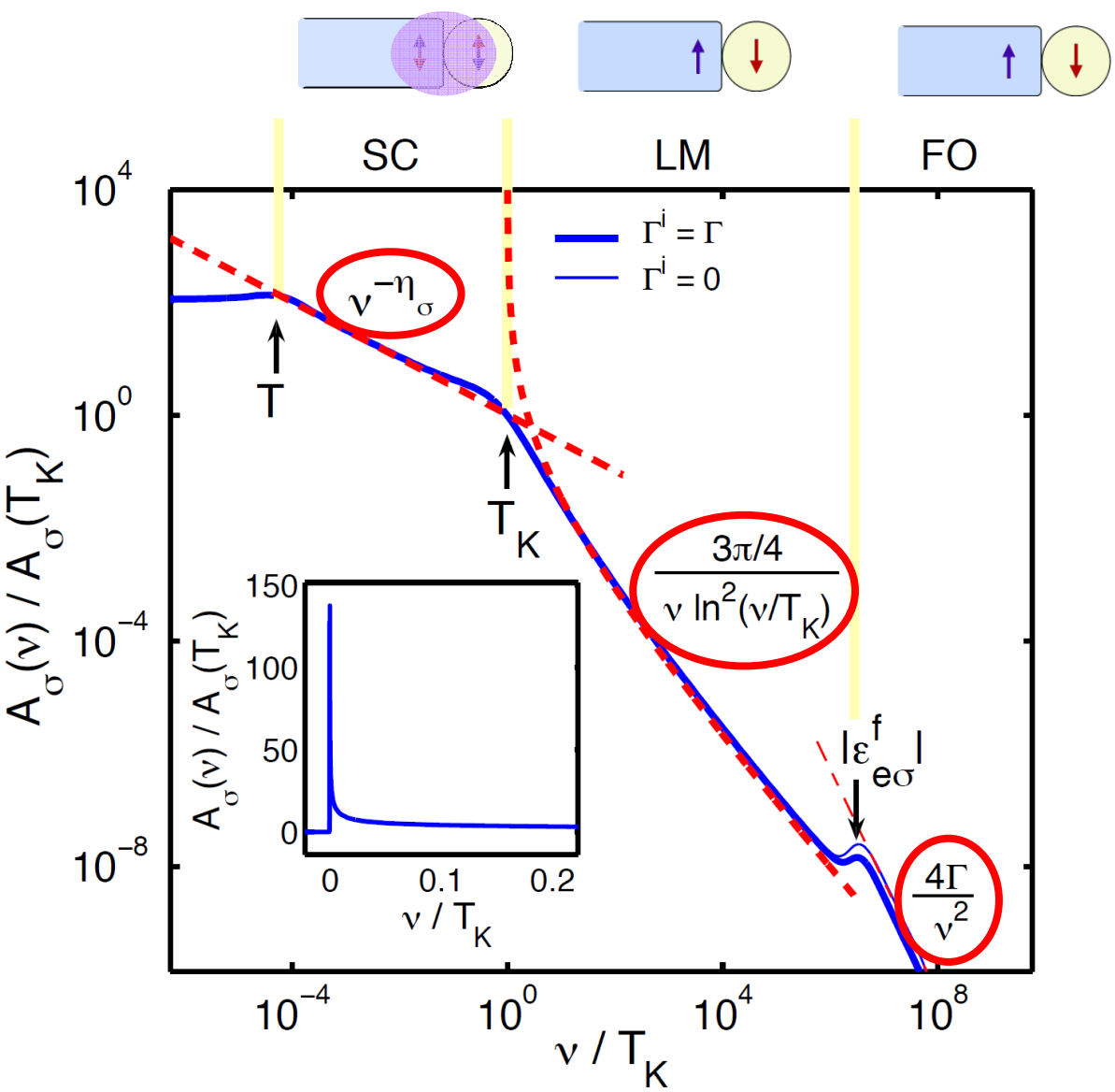
Properties of lineshape:

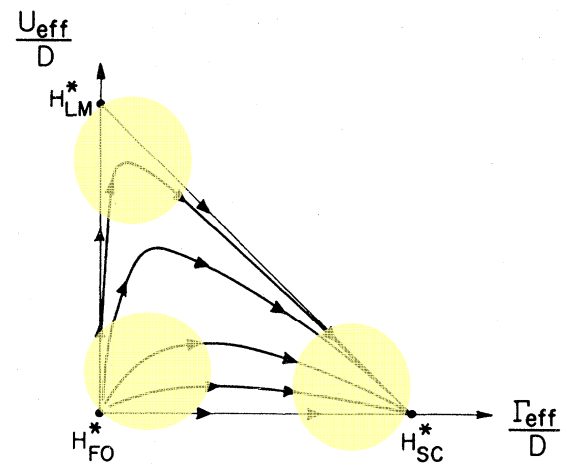
- depends on initial <u>and</u> final eigenstates
- is roughly symmetric at large T
- as T decreases, lineshape develops asymmetric threshold behavior
- and peak becomes narrower and sharper
- for T→0, lineshape shows power-law singularity

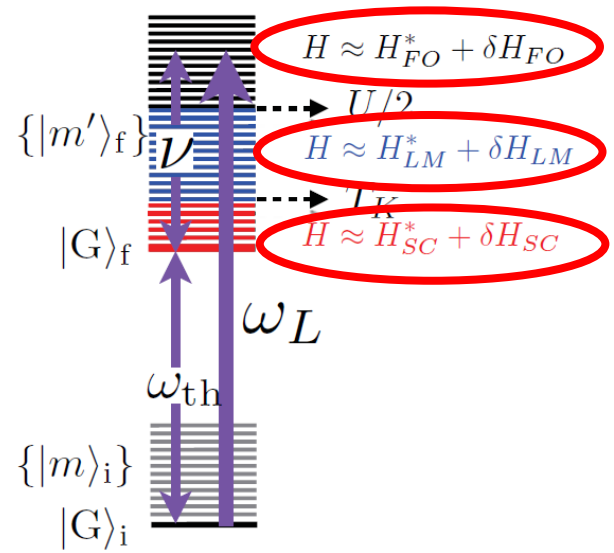


Absorption Lineshape (log-log): T = 0 [SAM]

$$A_\sigma(\nu) = 2\pi \sum_\beta \left| {}_{\mathrm{f}}\langle\beta|e^\dagger_\sigma|\mathrm{G}\rangle_{\mathrm{i}} \right|^2 \delta(\nu + \omega_{\mathrm{th}} - E^{\mathrm{f}}_\beta + E^{\mathrm{i}}_{\mathrm{G}})$$



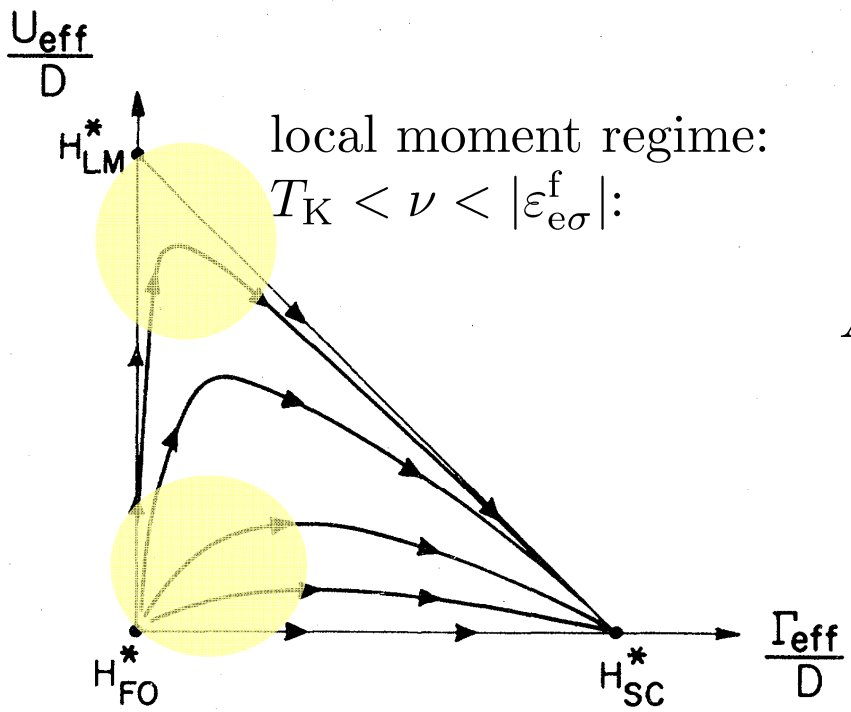




FPPT: Fixed-Point Perturbation Theory (FO, LM)

$$A_\sigma(\nu) = -2\mathrm{Im}\left[{}_{\mathrm{i}}\langle \mathrm{G}|e_\sigma \frac{1}{\nu + i0^+ - H^{\mathrm{f}} + E^{\mathrm{i}}_{\mathrm{G}}} e^\dagger_\sigma|\mathrm{G}\rangle_{\mathrm{i}}\right]$$

near fixed point: $H^{\mathrm{f}} = H^* + H'$, expand in H'



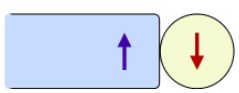
local moment regime:
$T_{\mathrm{K}} < \nu < |\varepsilon^{\mathrm{f}}_{\mathrm{e}\sigma}|$:

$$H^*_{\mathrm{LM}} = \sum_{k\sigma} \varepsilon_{k\sigma} c^\dagger_{k\sigma} c_{k\sigma}\,, \quad H'_{\mathrm{LM}} \frac{J}{\rho} \vec{s}_{\mathrm{e}} \cdot \vec{s}_{\mathrm{c}}$$

$$A^{\mathrm{LM}}_\sigma(\nu) = \frac{3\pi}{4} \frac{J^2(\nu)}{\nu}$$

$$J(\nu) = \frac{1}{\ln(\nu/T_{\mathrm{K}})} \quad \text{(rescaled coupling)}$$

free-orbital regime:
$|\varepsilon^{\mathrm{f}}_{\mathrm{e}\sigma}| < \nu$:

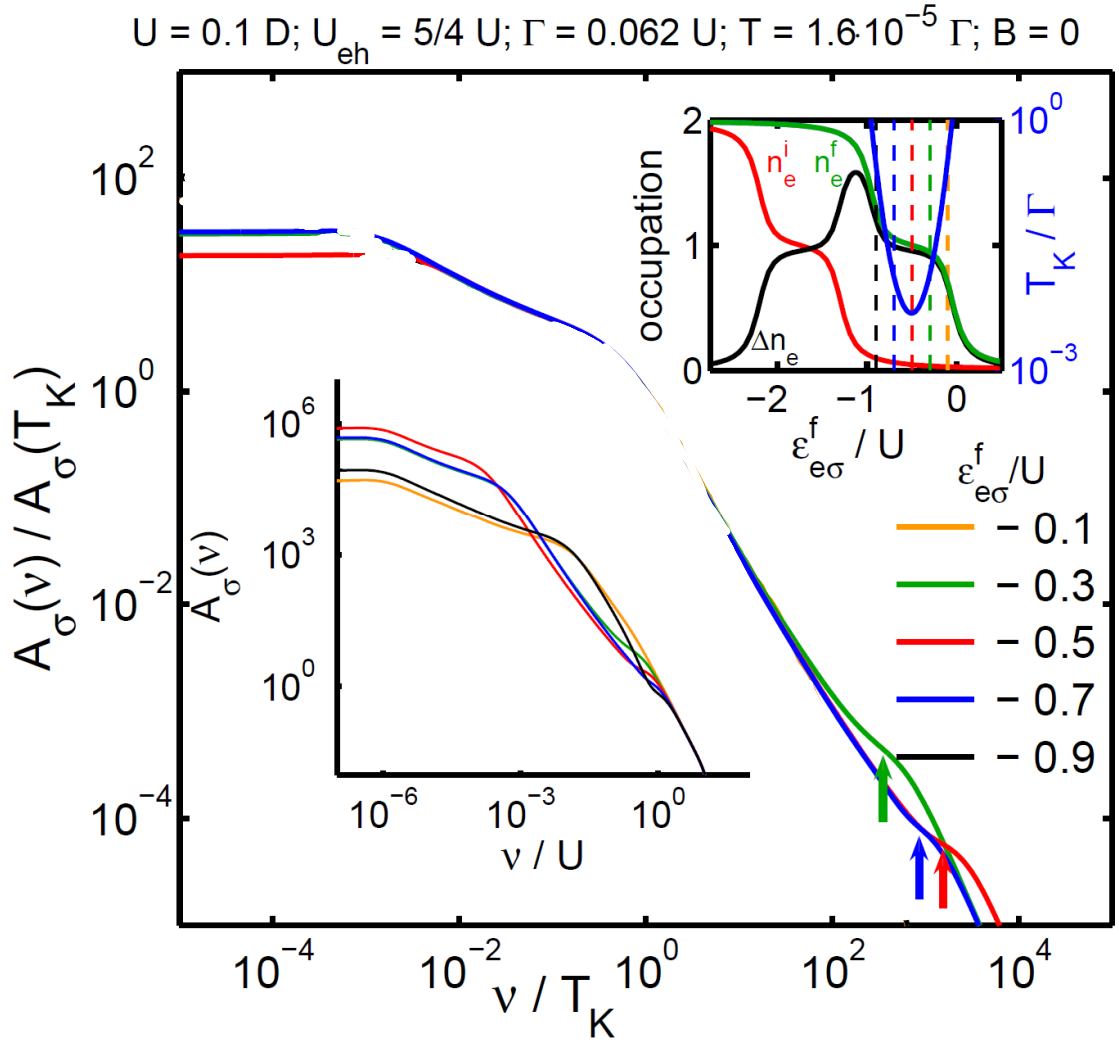


$$H^*_{\mathrm{FO}} = H^{\mathrm{f}}_{\mathrm{QD}}\,, \quad H'_{\mathrm{FO}} = \sqrt{\frac{\Gamma}{\pi\rho}} \sum_\sigma (e^\dagger_\sigma c_\sigma + \mathrm{h.c.})$$

$$A^{\mathrm{FO}}_\sigma(\nu) = \frac{4\Gamma}{\nu^2} \theta(\nu - |\varepsilon^{\mathrm{f}}_{\mathrm{e}\sigma}|)$$

Scaling Collaps (asymmetric AM)

$$T_{\mathrm{K}} = \sqrt{\frac{\Gamma U}{2}} e^{-\frac{\pi |\varepsilon_{\mathrm{e}}^{\mathrm{f}} (\varepsilon_{\mathrm{e}}^{\mathrm{f}} + U)|}{(2U\Gamma)}}$$



Arrows: $\varepsilon_{\mathrm{e}\sigma}^{\mathrm{f}}/T_{\mathrm{K}}$

Strong-Coupling Regime ($T \ll \nu \ll T_K$)

$$H_{\rm SC} = \sum_{k\sigma} \tilde{\varepsilon}_{k\sigma} \tilde{c}^\dagger_{k\sigma} \tilde{c}_{k\sigma}$$

Use analogy to x-ray edge problem: (Mahan '67)

$$A_\uparrow(\nu) = -2{\rm Im}\mathcal{G}^\uparrow_{\rm ee}(\nu) \quad \sim \quad \nu^{-\eta_\uparrow}$$

$$\mathcal{G}^\uparrow_{\rm ee}(t) \sim \langle \psi_{\rm i}(0^+)|\psi_{\rm i}(t)\rangle \sim t^{-\eta'},$$

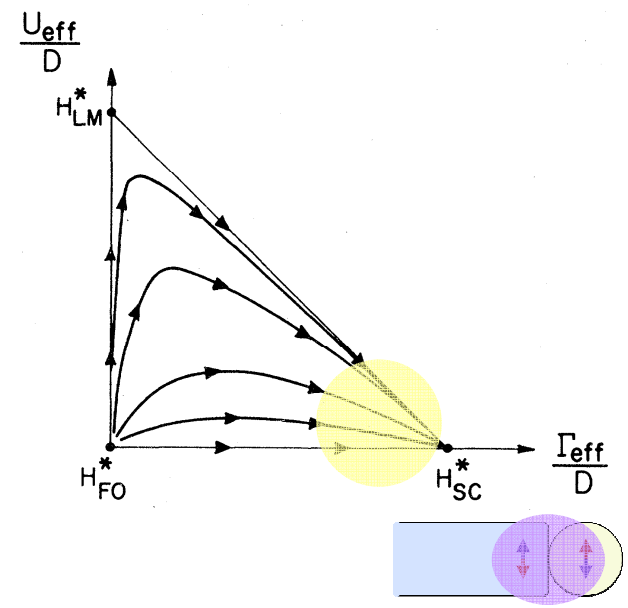
$$|\psi_{\rm i}(0^+)\rangle = e^\dagger_\uparrow |{\rm G}\rangle_{\rm i}, \qquad |\langle \psi_{\rm i}(0^+)|\psi_{\rm i}(\infty)\rangle|^2 \sim N^{-\eta'}$$

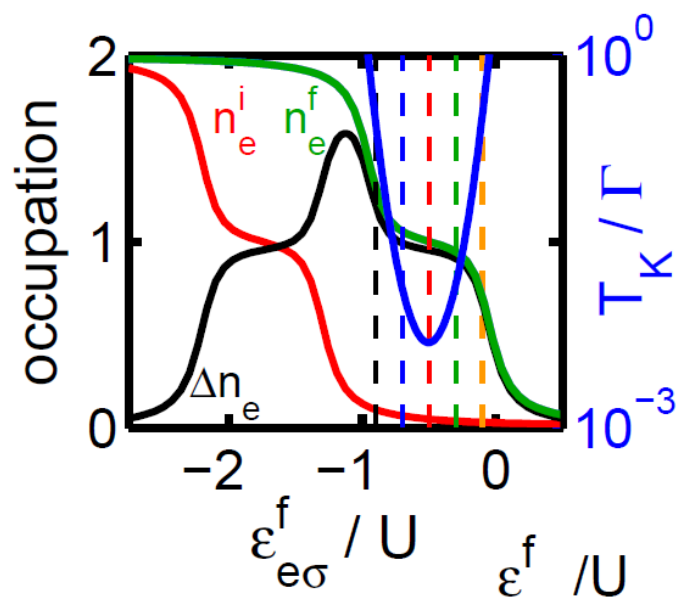
Anderson orthogonality

$$\eta_\uparrow = 1 - \sum_\sigma (\Delta n'_{{\rm e}\sigma})^2$$

(Friedel, '56, Nozieres, '69, Hopfield '69)

$$\Delta n'_{{\rm e}\sigma} = \langle n_{{\rm e}\sigma}\rangle_\infty - \langle n_{{\rm e}\sigma}\rangle_{0+} = \underbrace{\langle n_{{\rm e}\sigma}\rangle_{\rm f} - \langle n_{{\rm e}\sigma}\rangle_{\rm i}}_{\text{change in local charge}} - \delta_{\sigma\uparrow}$$

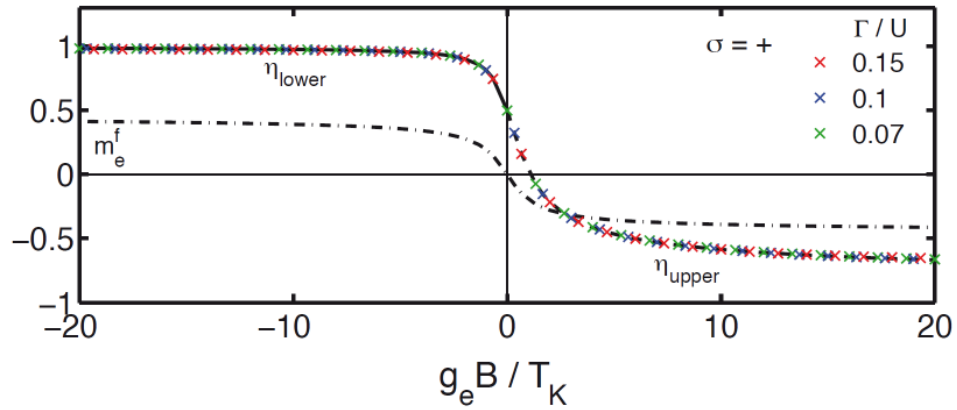




Absorption line shape: B-dependence (SAM)

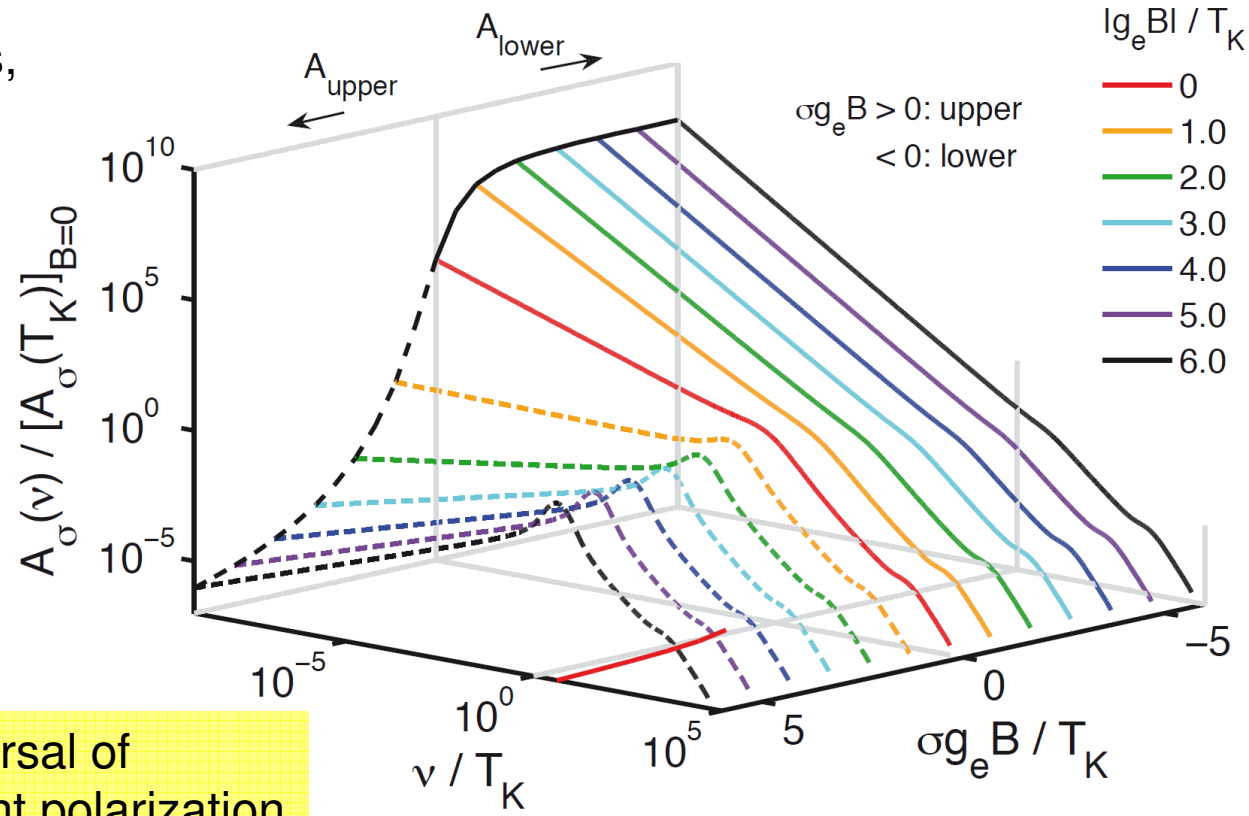
$$A_{\uparrow}(\nu) \sim \nu^{-\eta_{\uparrow}}$$

$$\eta_{\uparrow} = 1 - (n_{\uparrow \mathrm{f}} - 1)^2 - (n_{\downarrow \mathrm{f}})^2$$



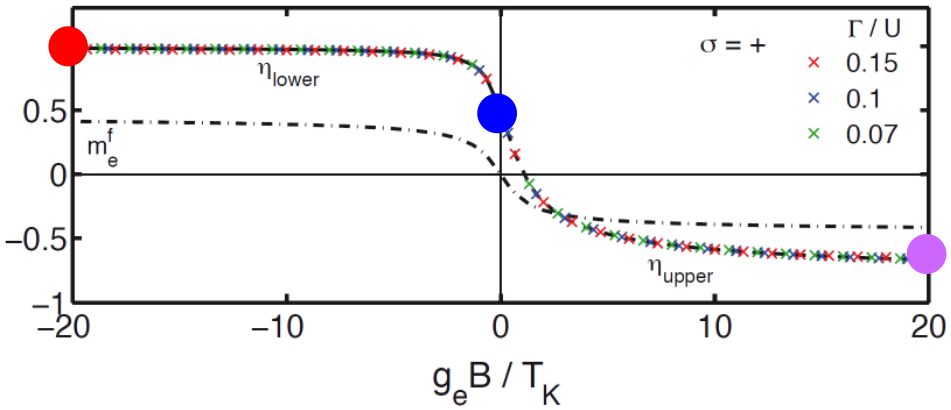
A_{lower} : divergence is strengthened

A_{upper} : divergence disappears, peak shifts to $\nu = |g_e B|$



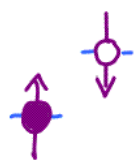
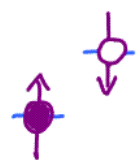
Strong asymmetry under reversal of magnetic field for fixed incident polarization

Tunable Anderson Orthogonality



$$A_\uparrow(\nu) \sim \nu^{-\eta_\uparrow}$$

$$\eta_\uparrow = 1 - \underbrace{\left[(n_{\uparrow \mathrm{f}} - 1)^2 + (n_{\downarrow \mathrm{f}})^2\right]}_{\text{from Anderson orthogonality}}$$

	$\lvert\psi\rangle_{0^+}$	$\lvert\psi\rangle_{\infty}$	$n_{\uparrow f}$	$n_{\downarrow f}$	$\eta_\uparrow$	orthogonality
$B \ll -T_K$, $\uparrow$ = lower			1	0	1	none
						intermediate
						maximal

Main predictions

Absorption spectrum maps out physics of different fixed points

In local moment regime (T < ν < Tk):

- $A(\nu) \sim \dfrac{1}{\nu \ln^2(\nu / T_K)}$

- ν/Tk scaling

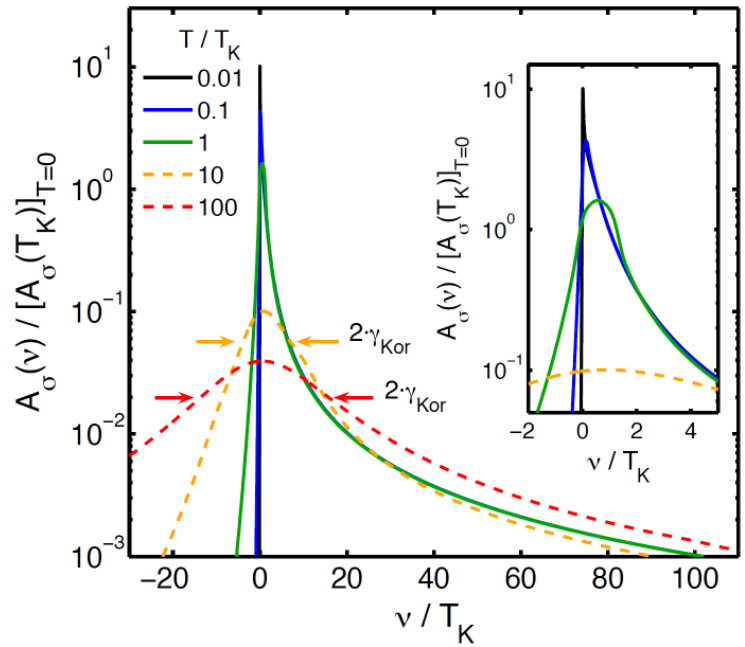
In strong-coupling regime (T < v < Tk):

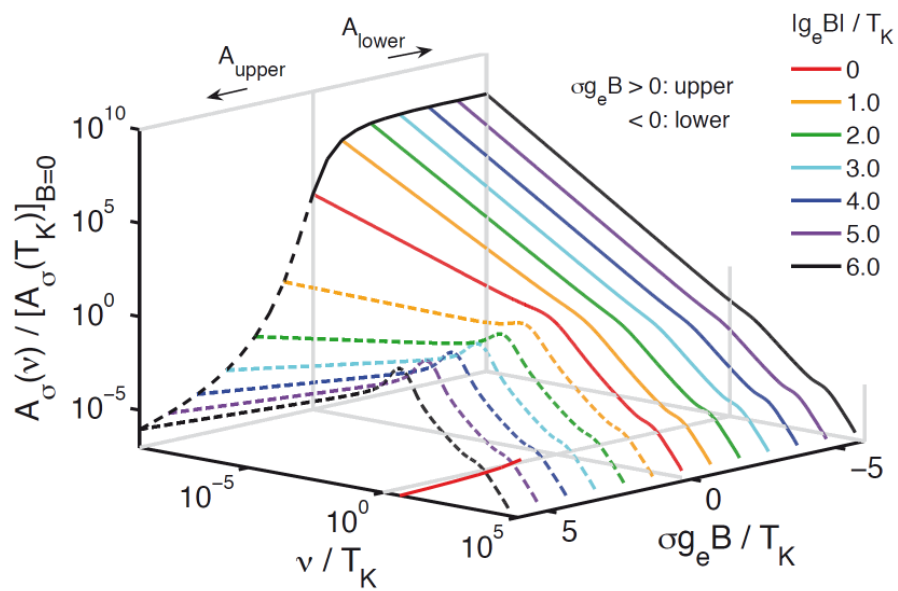
For T/Tk → 0: Powerlaw divergence

$$A(\nu) \sim \nu^{-\eta}$$

Anderson/Mahan-exponents are
- tunable;
- have universal values for SAM in the limit of small or large magnetic fields

Lineshape is B-asymmetric





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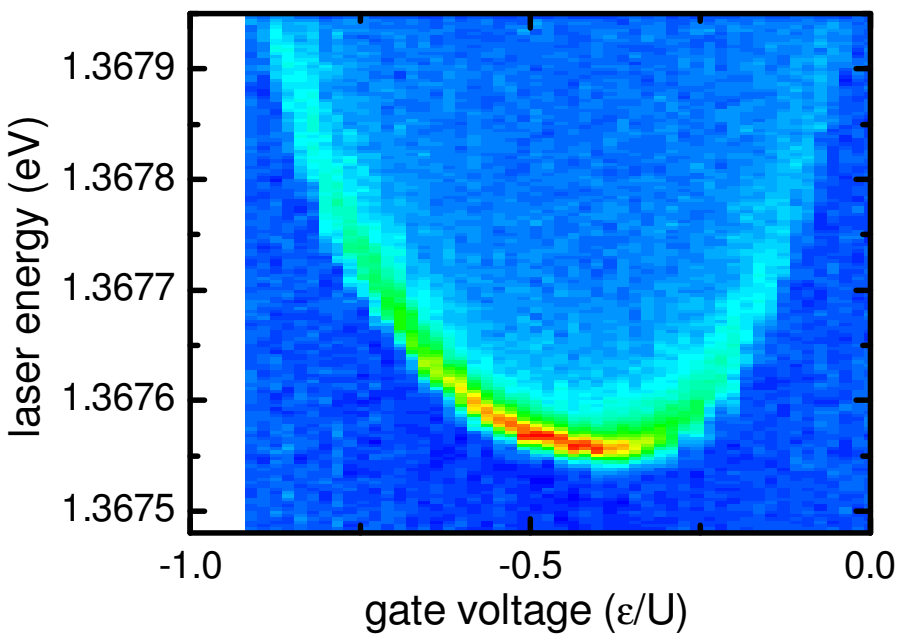
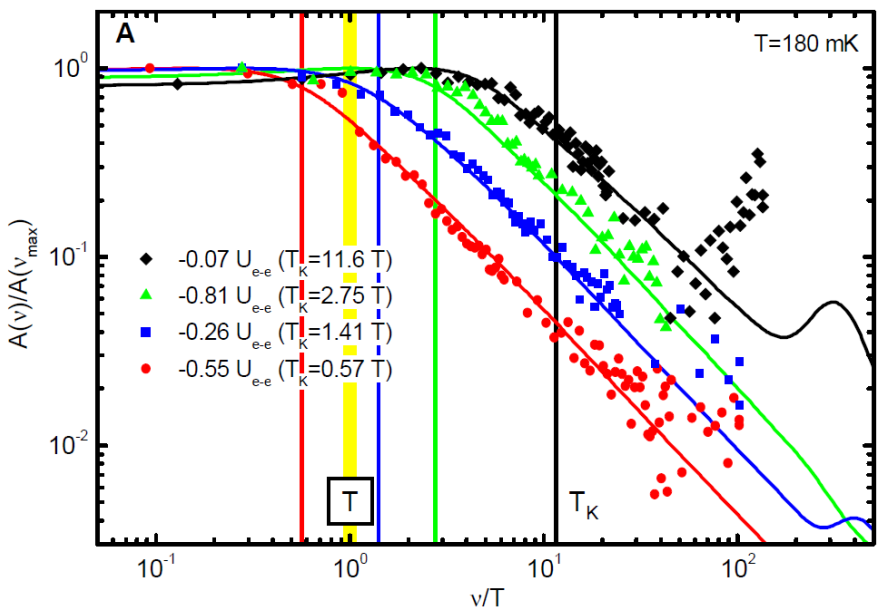
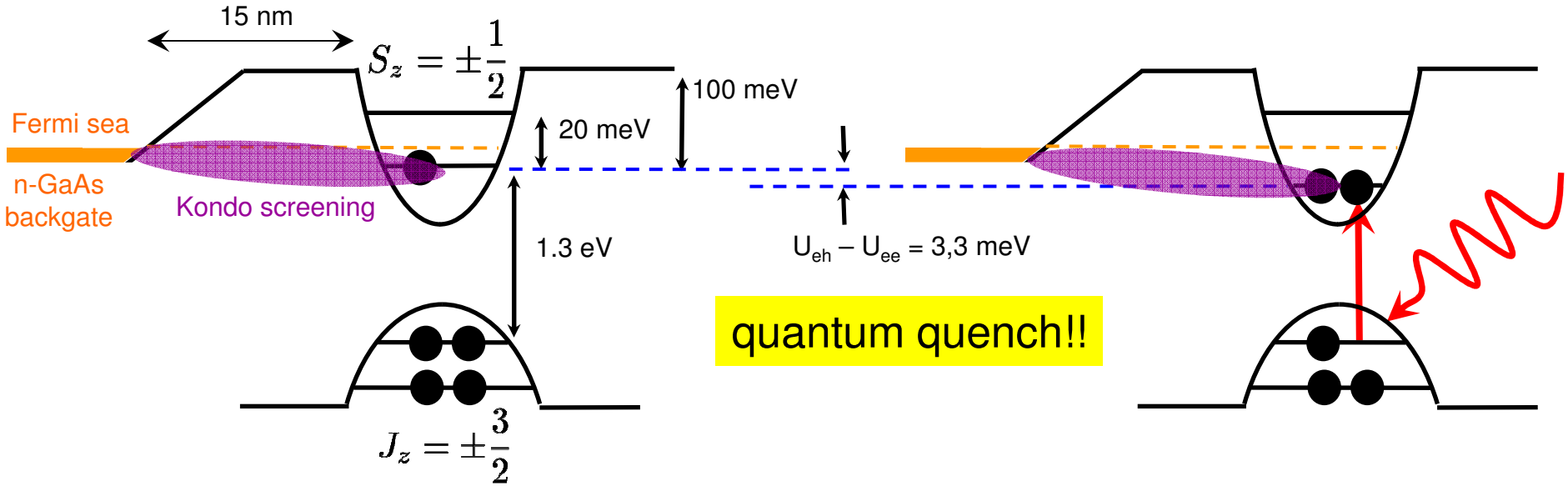


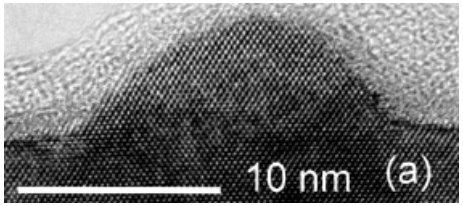


Thanks to Atac Imamoglu for supplying some slides !

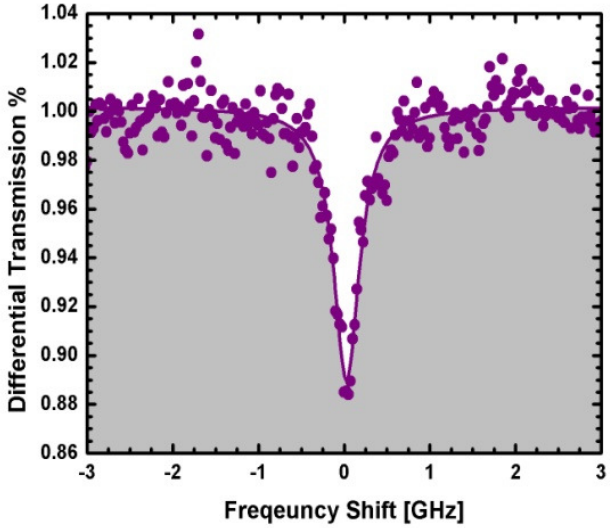
Optical absorption: X^{1-} transition



GaAs **InAs** **GaAs**

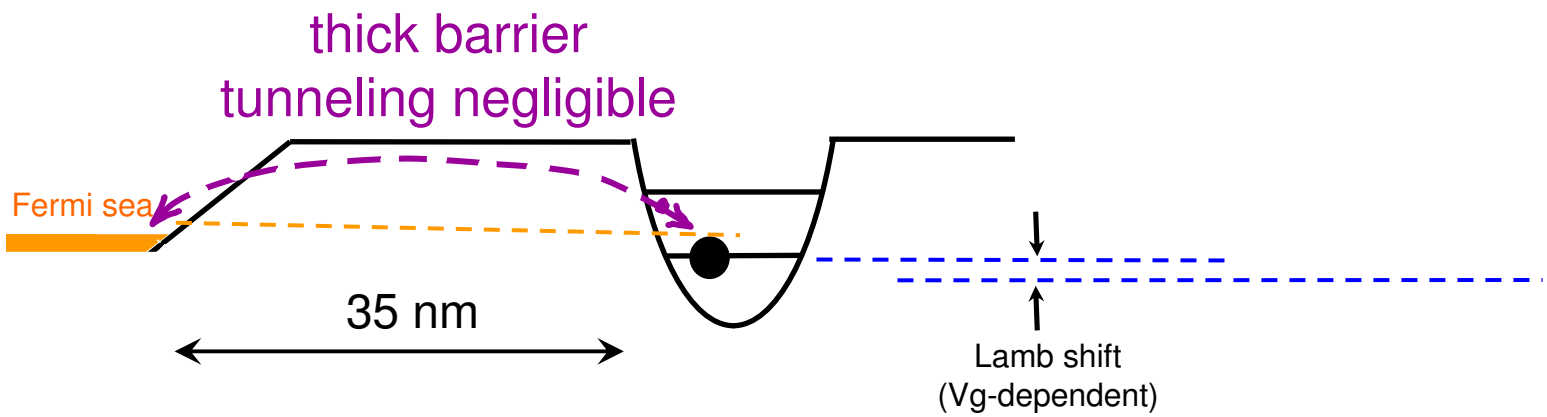


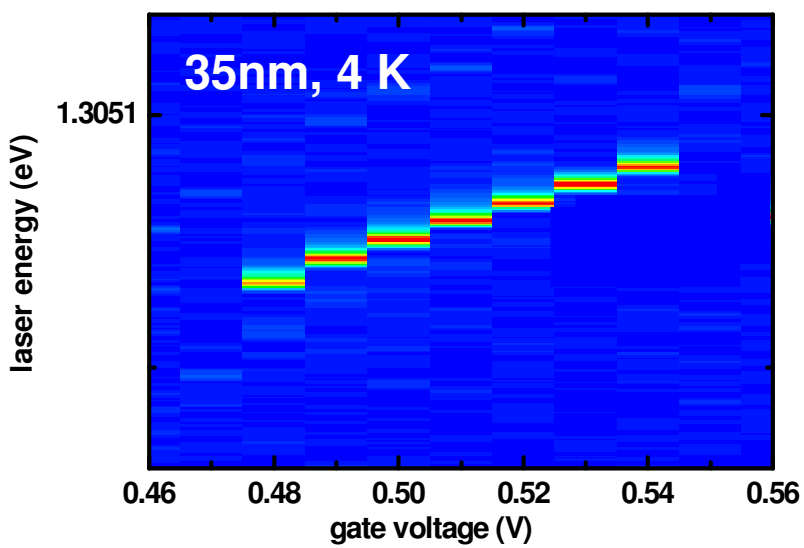
InGaAs Quantum dots (QD) embedded in GaAs



tune laser frequency across resonance, monitor transmitted field intensity

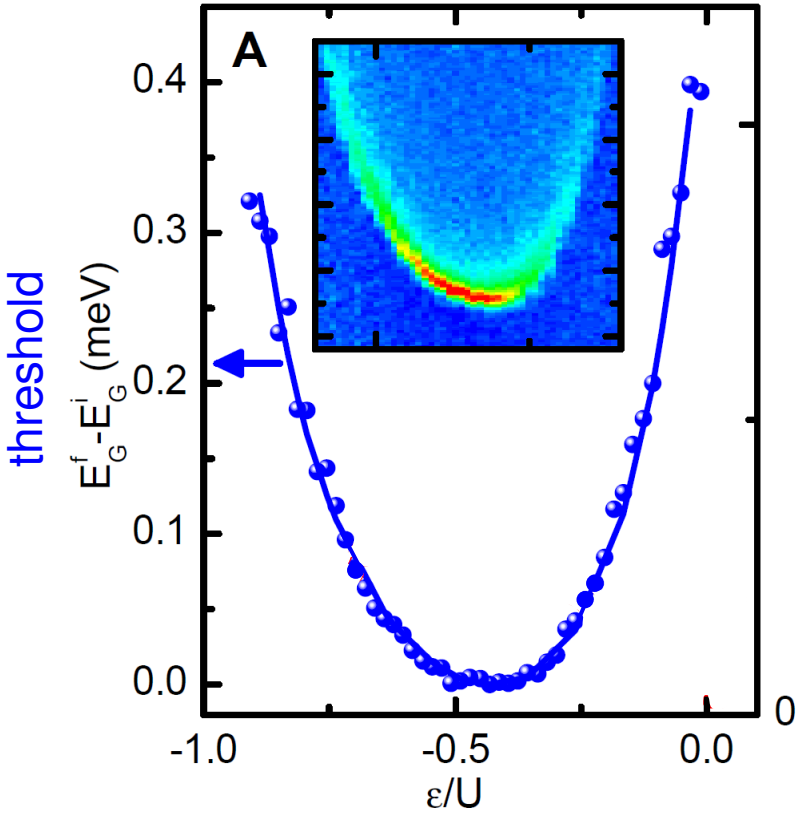
Influence on tunnel barrier width on X- absorption

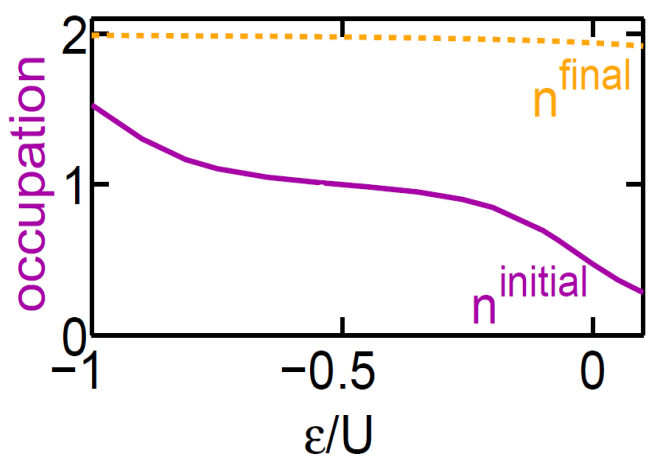




linear dc-Stark shift

Fixing model parameters by fitting NRG to data





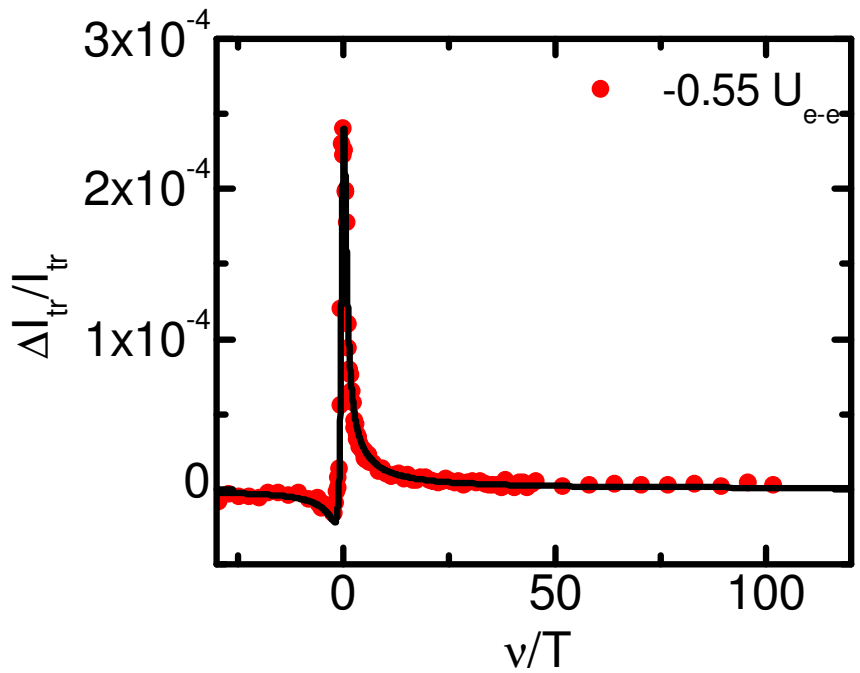
From fit to NRG for threshold:

$U_{e\text{-}h}$ = 11 meV

$U_{e-e} = 7.5\text{meV}$

$\Gamma = 0.7\text{meV}$

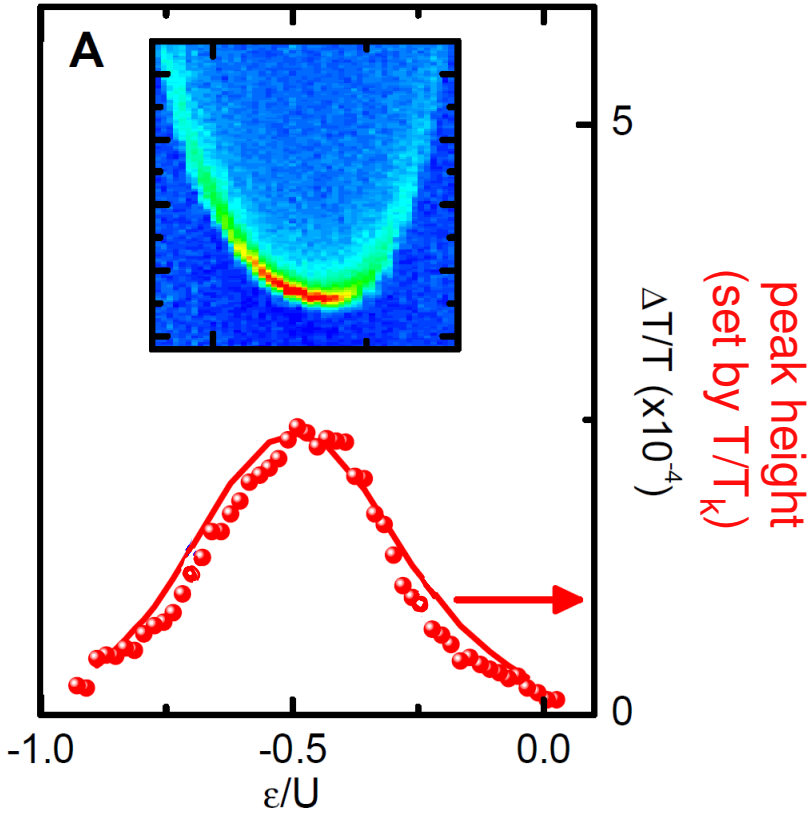
$D = 3.5\text{meV}$

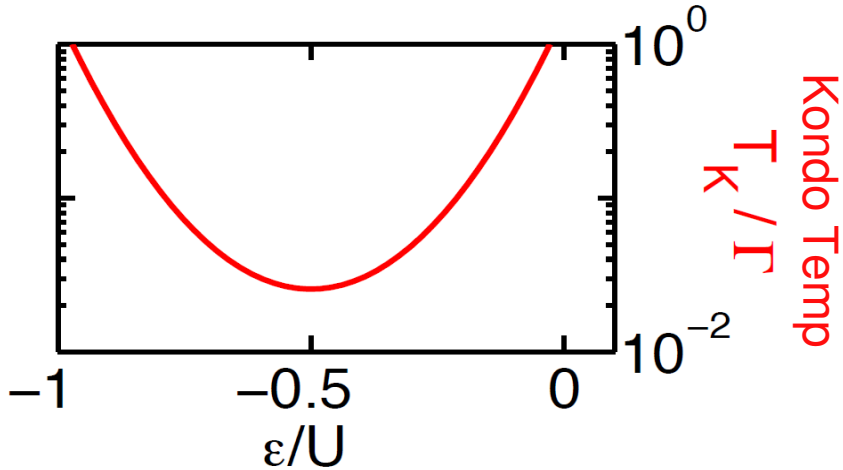


From fit to NRG for $\nu/T < 0$:

T = 180 mK

Fixing model parameters by fitting NRG to data





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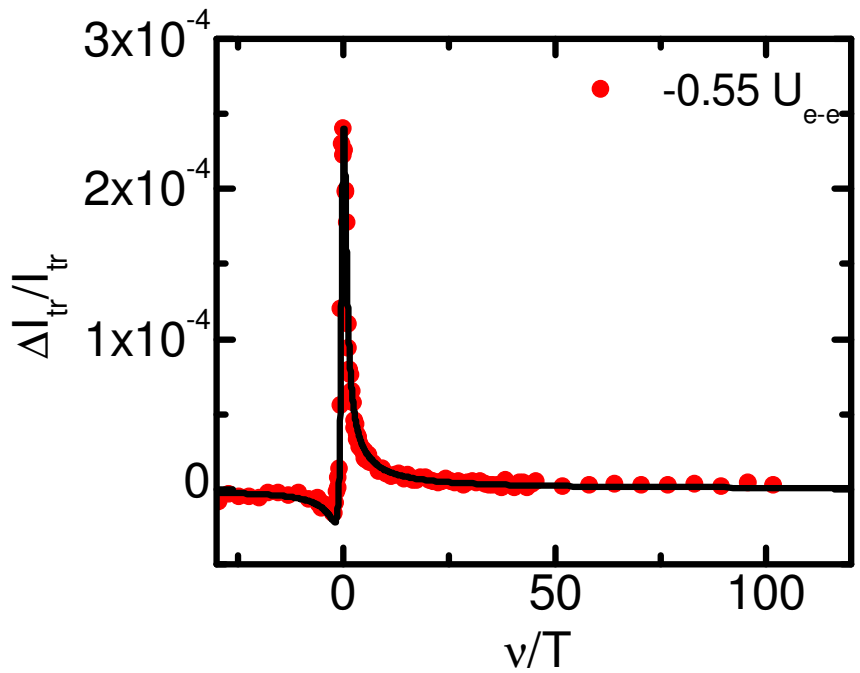

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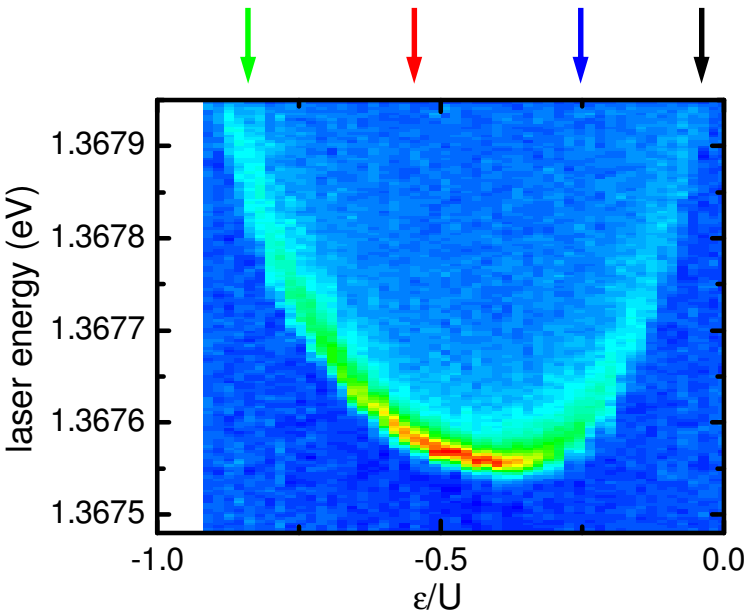
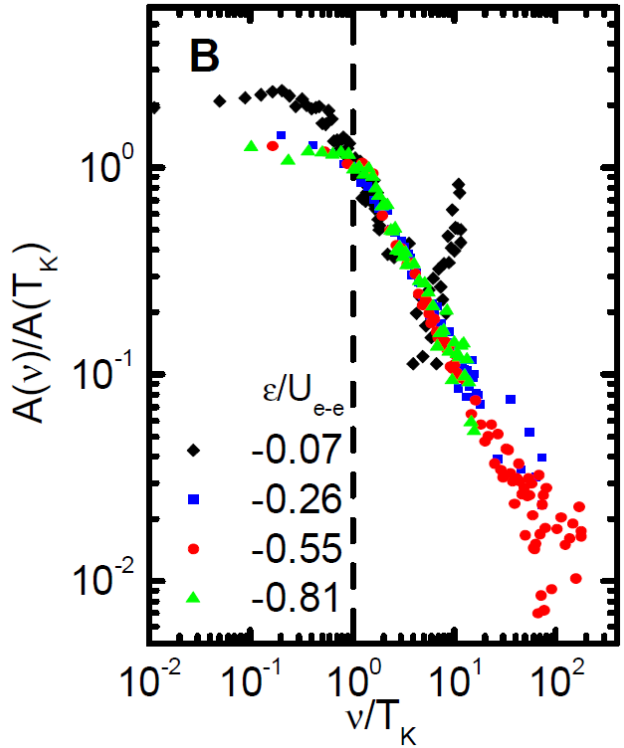
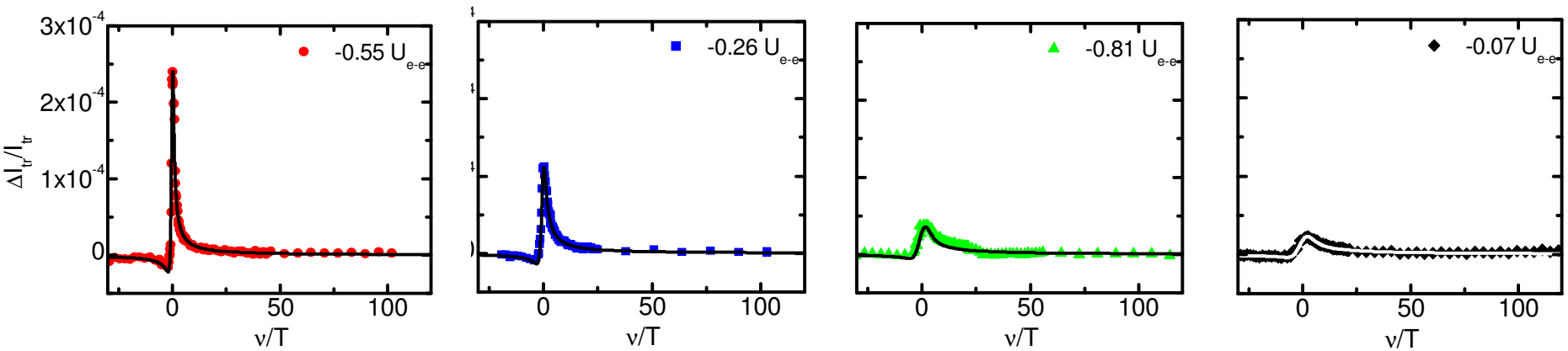
Anatomy of the line shapes



scaling collapse: signature of local moment regime!

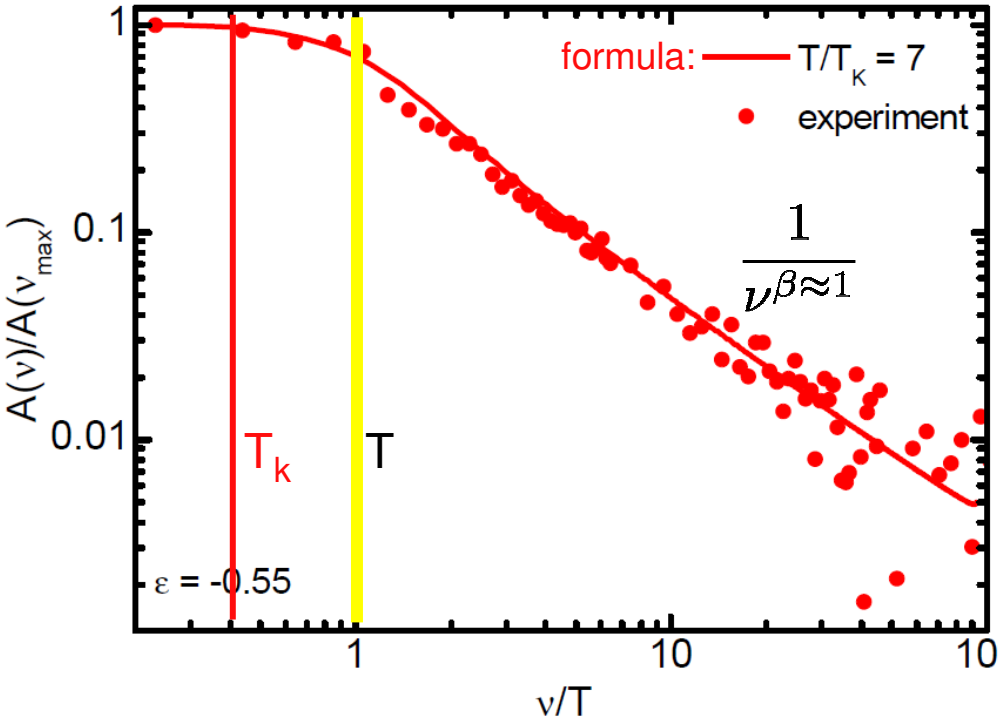


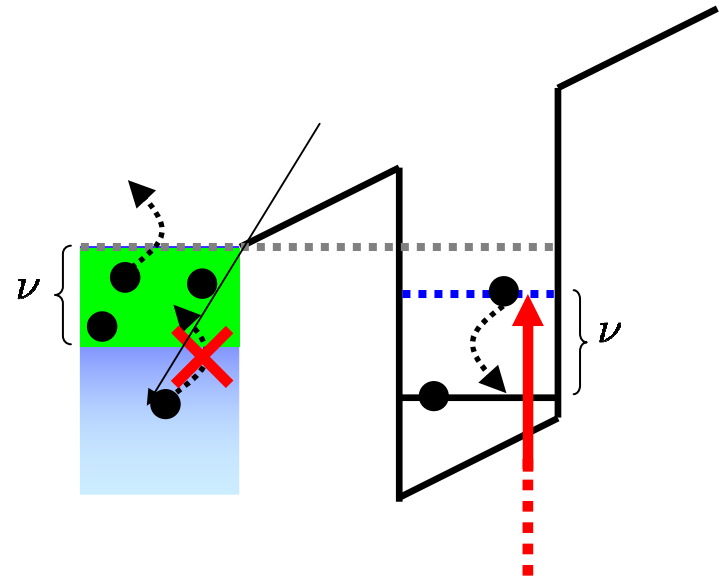
center → edge



NRG line shapes are no fits!

Local moment regime: T > T_K





$$A_\sigma(\nu) = \frac{3\pi}{4}\frac{\nu/T}{1-\mathrm{e}^{-\nu/\mathrm{T}}}\frac{\gamma_{\mathrm{Kor}(\nu,\mathrm{T})}/\pi}{\nu^2+\gamma^2_{\mathrm{Kor}}(\nu,T)}$$

Korringa relaxation rate:

$$\gamma_{\mathrm{Kor}}(\nu,T) = \pi T/\ln^2[\max(|\nu|,\mathrm{T})/\mathrm{T_K}]$$

$0 < \nu < T$ Lorentzian, of width γ_{Kor}

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

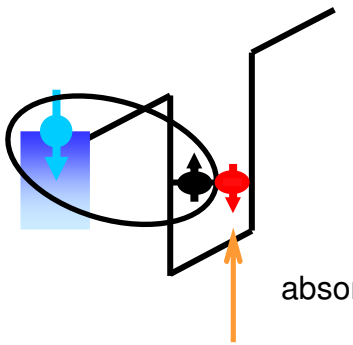
absorption, assisted by generation of e-h pair in the FR

Non-perturbative regime: $T < \nu < T_K$

Anderson orthogonality catastrophe (AOC)

$$\left|\psi_i(t=0)\right\rangle = d^\dagger \left|FR_i\right\rangle$$

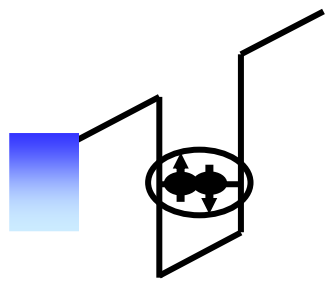
Intitial state just after absorption: Kondo singlet + single electron



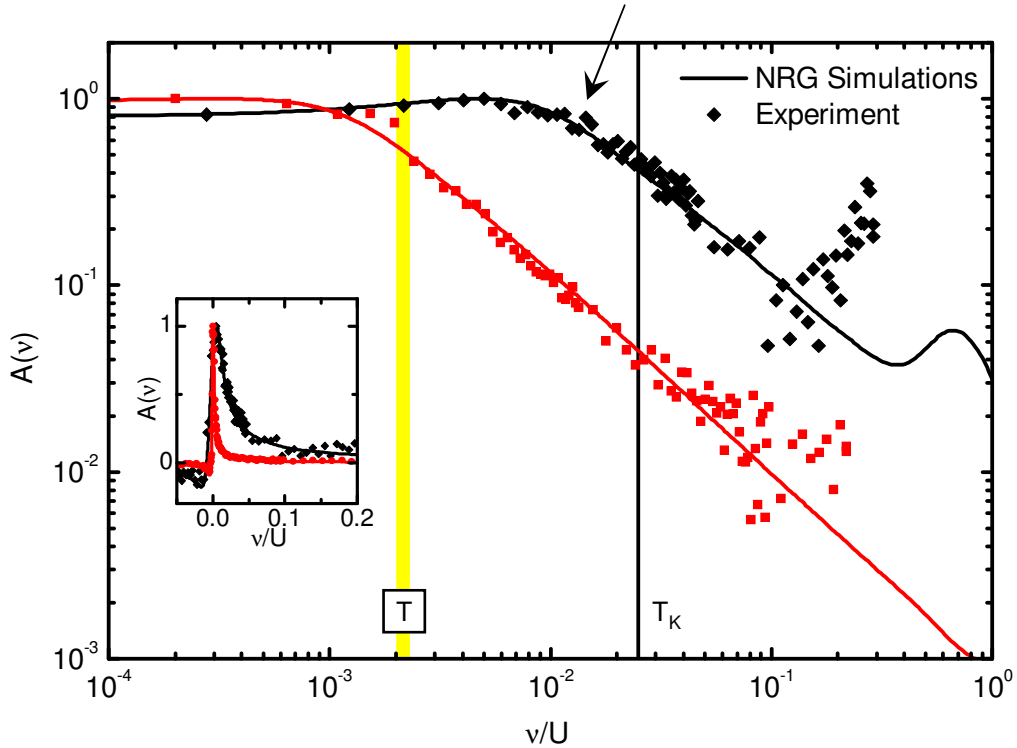
time evolution:

$$\left|\psi_i(t\to\infty)\right\rangle$$

Final state in long-time limit: singlet on dot



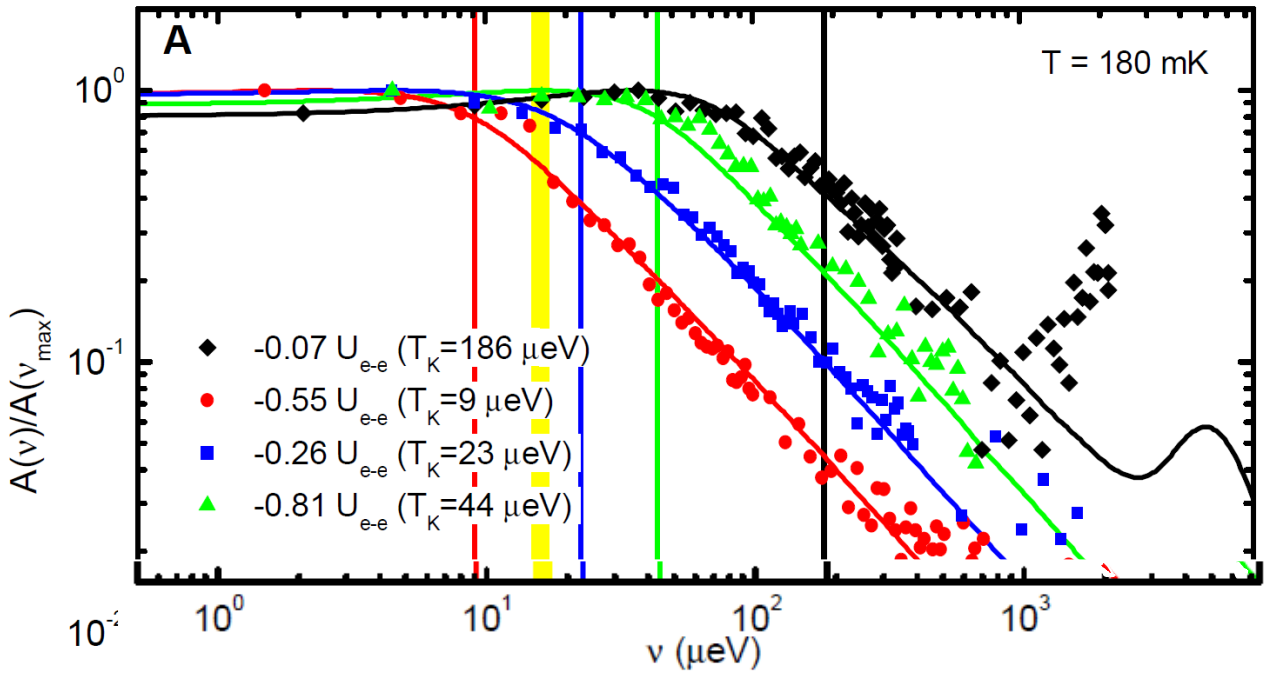
no clear power law below Tk…



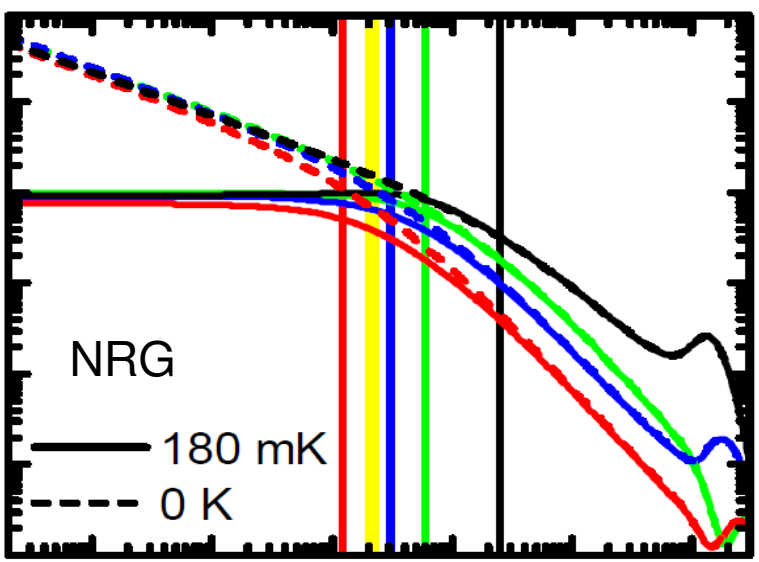
Initial state just after absorption and final state in long-time limit are orthogonal:

$$\left\langle\psi_i(t=0)\middle|\psi_i(t\to\infty)\right\rangle = 0 \qquad A(\nu)\sim\nu^{-\eta} \qquad \eta\in[0,1/2]$$

Power laws are hidden by finite temperature

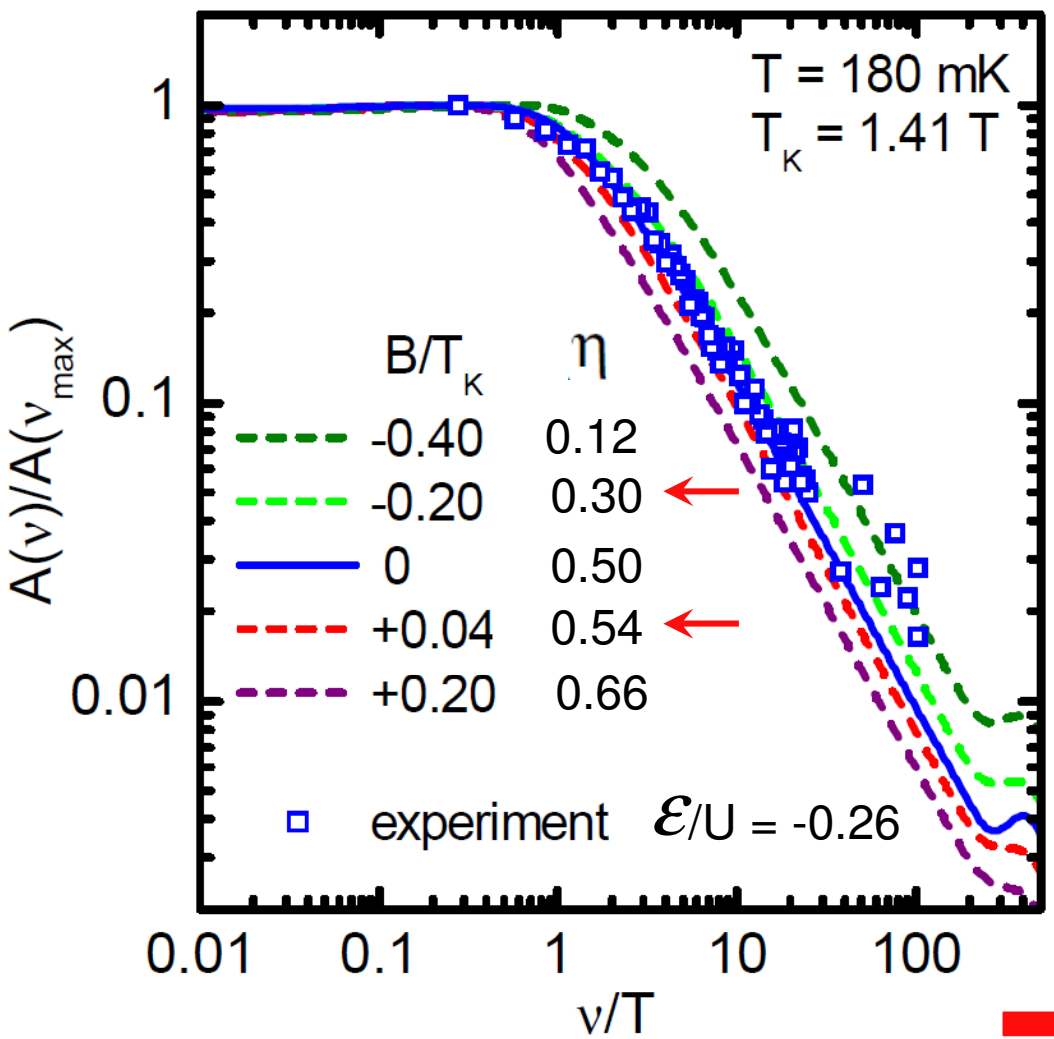


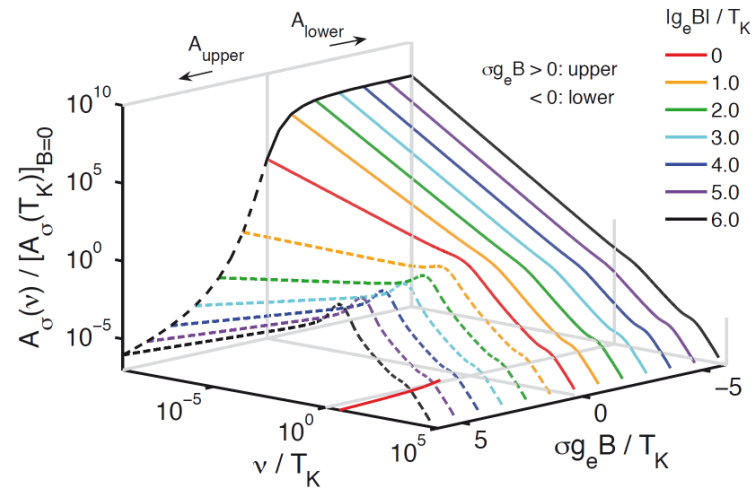
finite temperature



zero temperature

(Theory): Tuning exponent by magnetic field





Expected for B=0: $\eta = 1/2$

Experimental "error bars": $\eta \in (0.30, 0.54)$

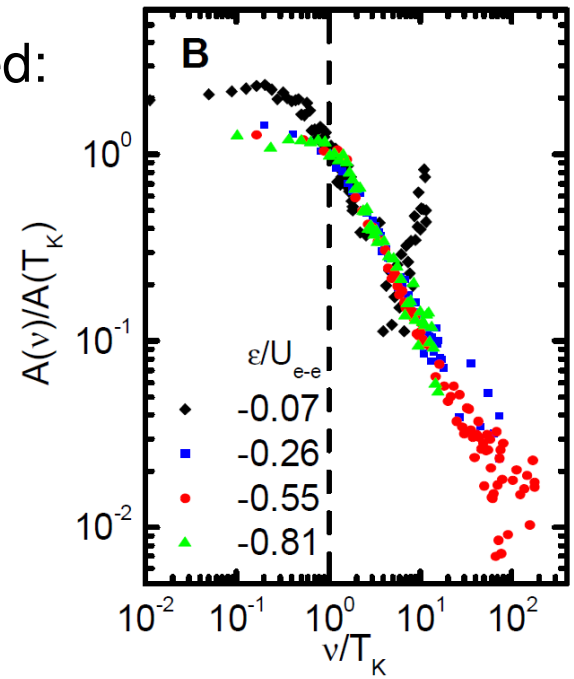
For comparison: in local moment regime: $\eta = 1$

strong-coupling behavior has been observed!

Applying B-field in experiment would demonstrate <u>TUNABLE</u> Anderson orthogonality !

Main experimental results

Optical signatures of Kondo effect have been observed:



Local moment regime:

Scaling collapse, $1/\nu$ power law

Strong-coupling regime:

Finite temperature hides $\nu^{-\eta}$ behavior,

but theoretical B-tuning suggests

$\eta \simeq 1/2$ has been observed

NRG reproduces data very well !