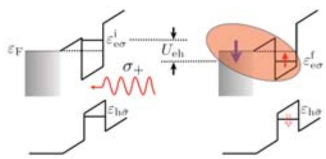
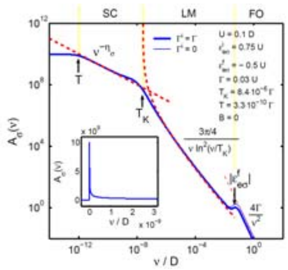
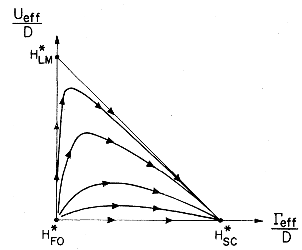
Quantum Quench of a Kondo-Exciton

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)







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

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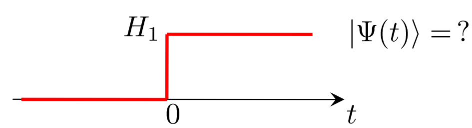
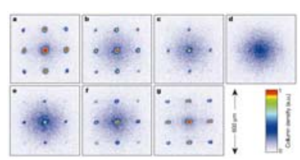
Transient Dynamics after Quantum Quench

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)

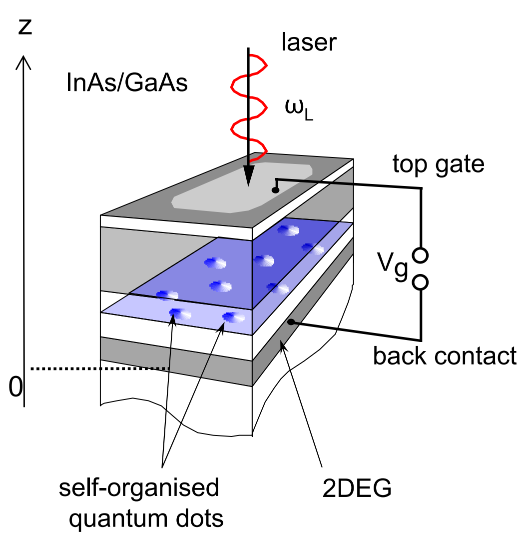
Old, well-known example:
X-Ray-Edge Singularity
(Mahan, PR ‘67)

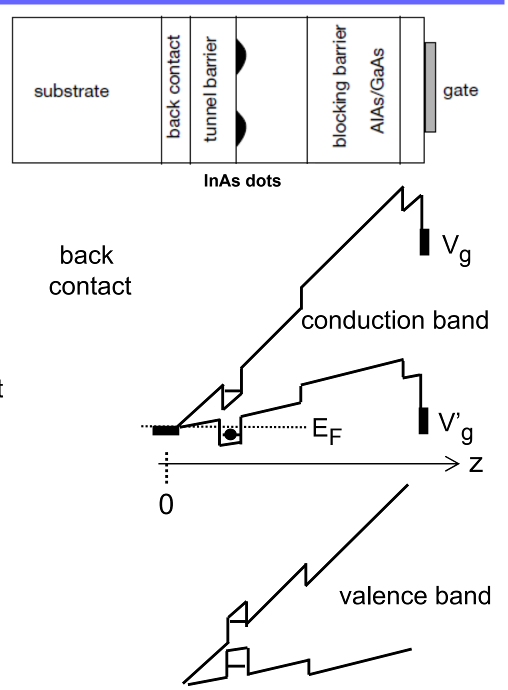
Exciton + Fermi-See:
Analogous to X-ray-edge problem
(Helmes, Sindel, Borda, von Delft, PRB ‘04)

Outline

- Experimental background
- Proposed experiment
- Transient dynamics of charge and spin
- Absorption spectrum at T=0
- Finite magnetic field B
- Finite temperature T
- Absorption threshold ω_{th}

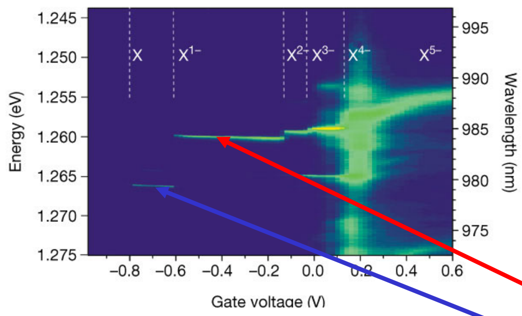
Experimental Setup

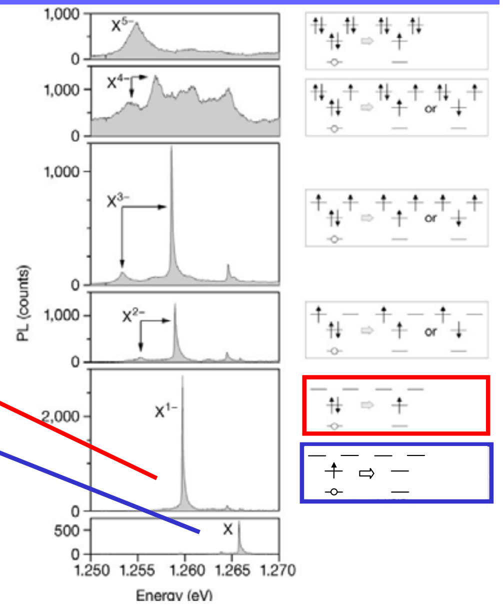




Optical Emission of Single (!) Quantum Dot

Warburton, Karrai *et al.*,
Nature **405**, 926 (2000):





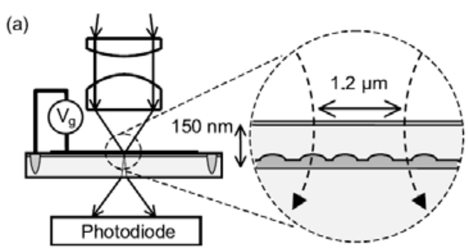
$E_{final} - E_{initial}$

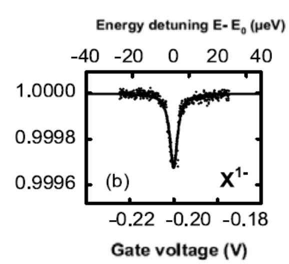
Discrete charge states tunable by back gate voltage

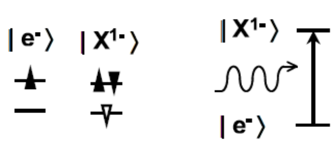
Optical Absorption for Single (!) Quantum Dot

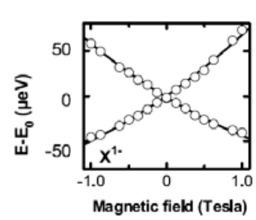
Högele *et al.*, PRL, 2004

T = 4.2 K





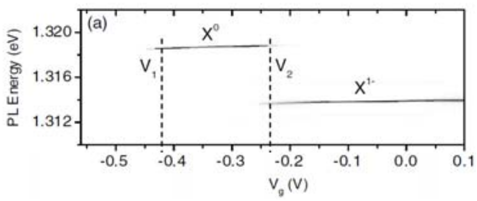


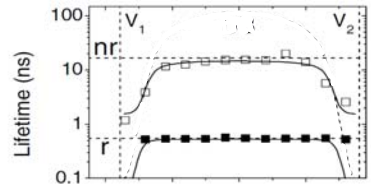


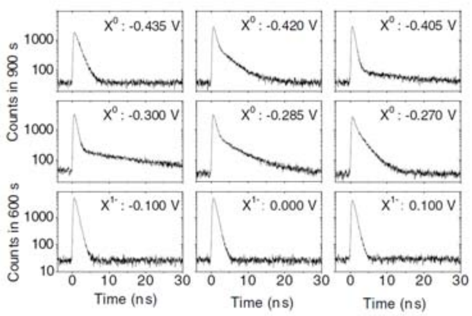
Transition energies tunable by magnetic field; optical polarization selects spin state

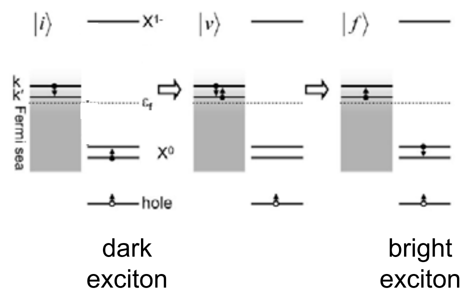
Hybridization of Dot with Fermi Sea (2DEG)

Smith et al, PRL'05









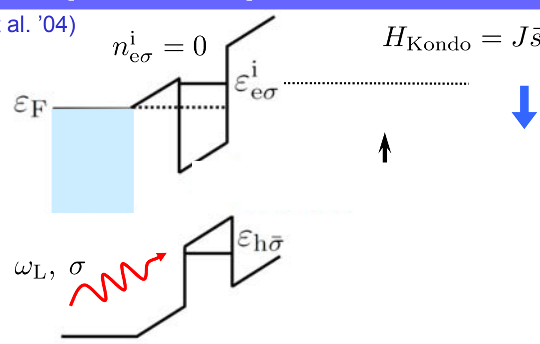
Hybridization with 2DEG can be strong, causing spin-flip dynamics for electron-levels

Further signatures for hybridization: Karrai et al, Nature '04 ; Dalgorno et al., PRL'08

Proposed Experimental Setup: Absorption

(Helmes et al. '04)

$n^{\mathrm{i}}_{\mathrm{e}\sigma} = 0$ $\qquad H_{\mathrm{Kondo}} = J\vec{s}_{\mathrm{FR}} \cdot \vec{S}_{\mathrm{dot}}$ $\qquad n^{\mathrm{f}}_{\mathrm{e}\sigma} \simeq 1$



initial

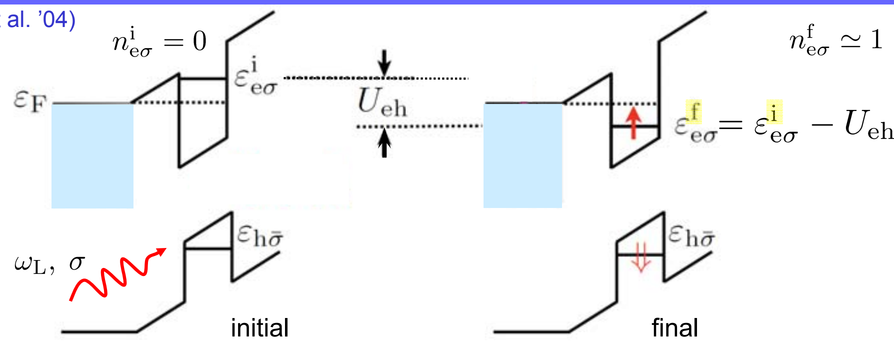
Optical absorption induces a quantum quench: $H^{\mathrm{initial}} \neq H^{\mathrm{final}}$

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)

Proposed Parameters

~~$\Gamma_{\rm eh} < J_{\rm eh}$~~ $\ll T_{\rm K}, T, B \ll \Gamma \ll U, U_{\rm eh} \ll D \ll \varepsilon_{{\rm h}\bar{\sigma}}$

Electron-hole recombination rate: $\Gamma_{\rm eh} \approx 1\mu$eV

Electron-hole exchange: $J_{\rm eh} \approx 200\mu$eV$\simeq$ 2K

Decay width to reservoir: $\Gamma \approx$ 1-10meV

Coulomb charging energy: $U \approx$ 15-20 meV

Electron-hole binding energy: $U_{\rm eh} \approx$ 20-25 meV

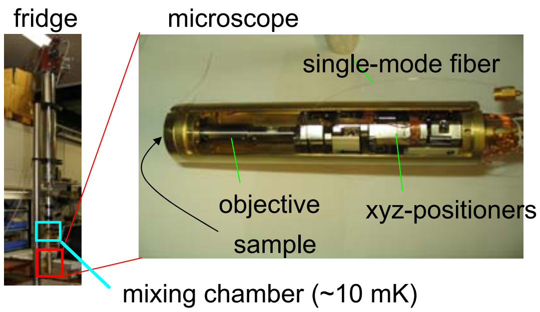
Reservoir bandwidth: $D = 1/(2\rho) \approx$ 30 meV

Hole creation energy: $\varepsilon_{{\rm h}\bar{\sigma}} \approx$ 1.3 eV

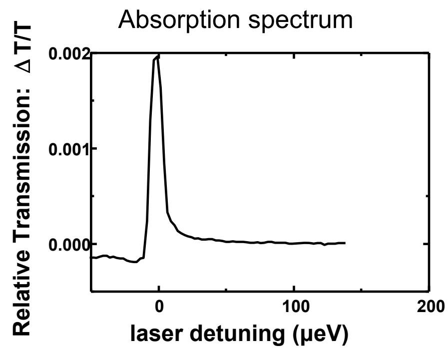
Electron g-factor: $g_{\rm e} \approx -$0.6-0.7

Hole g-factor: $g_{\rm h} \approx$ 1.1-1.2

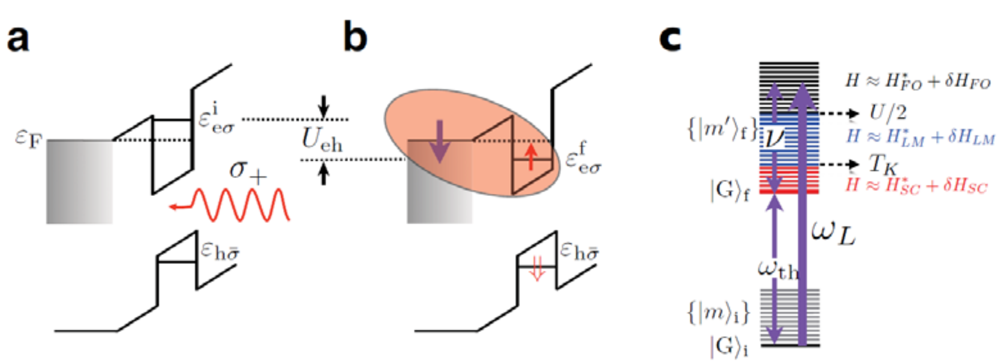
Experimental Parameters (Imamoglu, ETH Zürich)



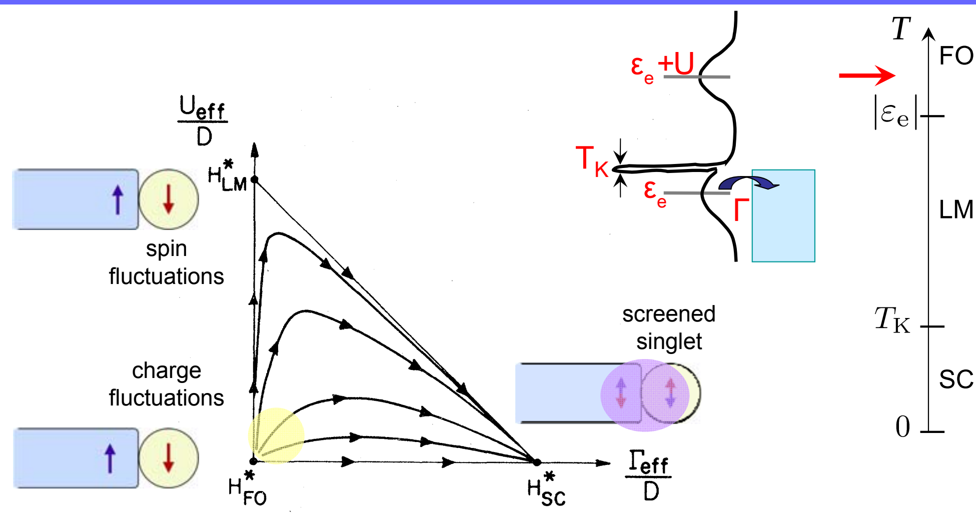
Base temperature:	50 mK
Spectral resultion	100 mK
Dot-Fermi-sea coupling:	10 – 100 K
Charging energy:	150 – 250 K
Magnetic field:	6 Tesla



Lineshape probes different fixed points



Anderson Model



$$H_{FO} = \sum_{k\sigma} \varepsilon_{k\sigma} c^\dagger_{k\sigma} c_{k\sigma}$$

$$+ \sum_\sigma \varepsilon_{e\sigma} n_{e\sigma} + U n_{e\uparrow} n_{e\downarrow} + \sqrt{\frac{\Gamma}{\pi\rho}} \sum_\sigma (e^\dagger_\sigma c_{k\sigma} + \text{h.c.}) \qquad T_K = \sqrt{\frac{\Gamma U}{2}} e^{-\frac{\pi|\varepsilon^f_e(\varepsilon^f_e + U)|}{(2U\Gamma)}}$$

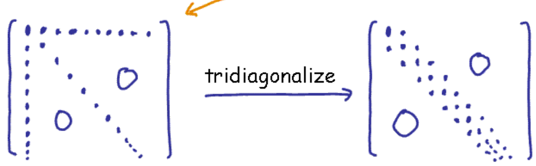
(Anderson)

Numerical Renormalization Group (NRG)

Mapping to "Wilson chain" (Wilson '75)

$$H = H_0(d^\dagger_\sigma, d_\sigma) + \sum_{k\sigma} \varepsilon_k c^\dagger_{k\sigma} c_{k\sigma} + \Big(v \sum_\sigma \sum_k c^\dagger_{k\sigma} d_\sigma + h.c.\Big) \qquad (1)$$

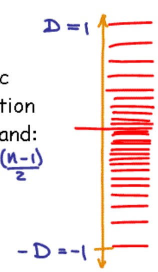
($d_\sigma = f_{0\sigma}$; $\sum_k c^\dagger_{k\sigma} \to f_{1\sigma}$)



logarithmic discretization of cond. band:

$\omega_n = \Lambda^{-\frac{(n-1)}{2}}$

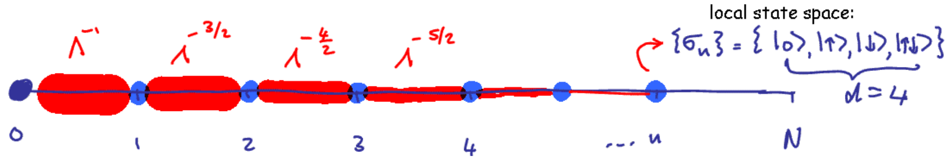
$\Lambda > 1$



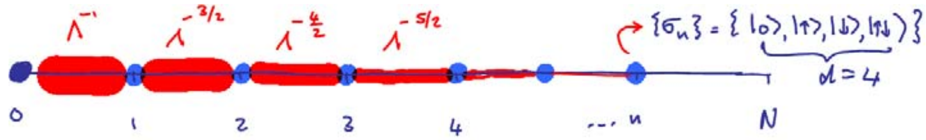
Wilson chain:

$$H = \lim_{N\to\infty} H_N = H_0(f^\dagger_0, f_0) + \sum_{n=1}^{N\to\infty} \lambda_n (f^\dagger_n f_{n-1} + h.c.) \qquad (2)$$

$\lambda_n \simeq \Lambda^{-n/2}$

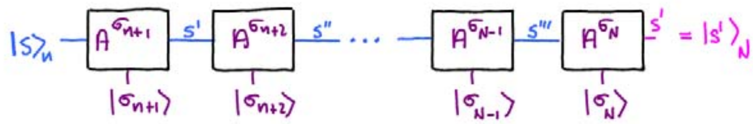


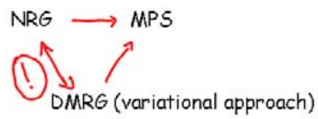
NRG - Matrix-Produkt-Zustände - DMRG



NRG yields MPS: $\sum_{s\,\sigma_{n+1}} |s\rangle_n\, |\sigma_{n+1}\rangle |\sigma_{n+2}\rangle \ldots |\sigma_{N-1}\rangle |\sigma_N\rangle \left[A^{\sigma_{n+1}} A^{\sigma_{n+2}} \ldots A^{\sigma_{N-1}} A^{\sigma_N}\right]_{ss'} = |s'\rangle_N$

Graphical representation:





(density matrix renormalization group, White 1992)

So, variationally minimize energy:

$$\frac{\partial}{\partial A^n}\, {}_{MPS}\langle\psi|H|\psi\rangle_{MPS} = 0$$

$\forall\, n$; sweep !!

t-DMRG: $|\psi(t+\Delta t)\rangle = e^{-iH\Delta t}|\psi(t)\rangle$

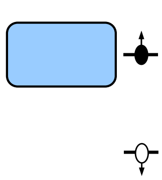
Transient Relaxation

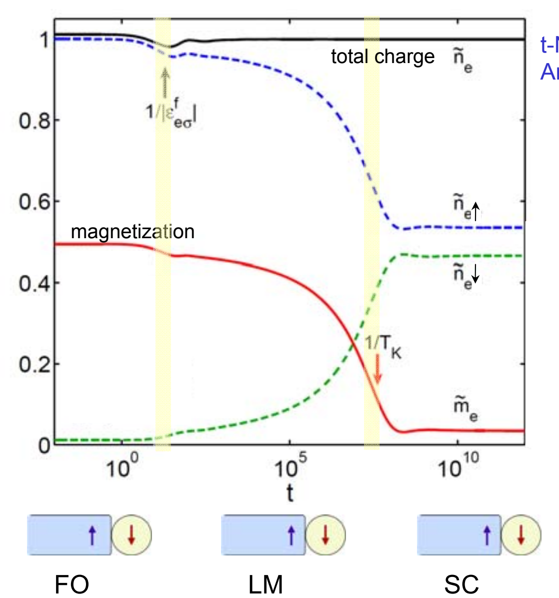
$$\widetilde{B}(t) = \mathrm{Tr}(e^{-iH^f}\hat{\rho}^f_p e^{iH^f t}\hat{B})$$

$$\hat{\rho}^f_p = \frac{|e_\sigma\rangle\langle 0|\hat{\rho}^i|0\rangle\langle e_\sigma|}{1 - n^i_{e\sigma}}$$

$$\widetilde{n}_{e\sigma}(0^+) = 1$$

t = 0⁺

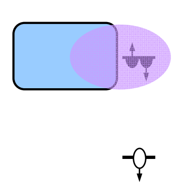




t-NRG: Anders, Schiller '05

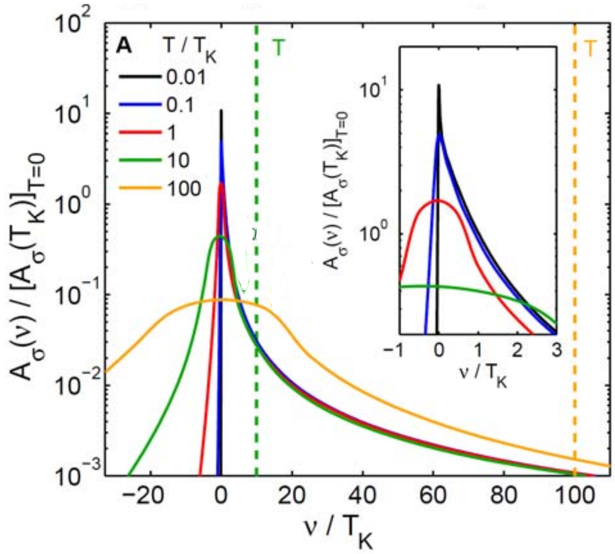
nonzero final magnetizaton is finite-size effect

t = ∞



Absorption Lineshape (SAM)

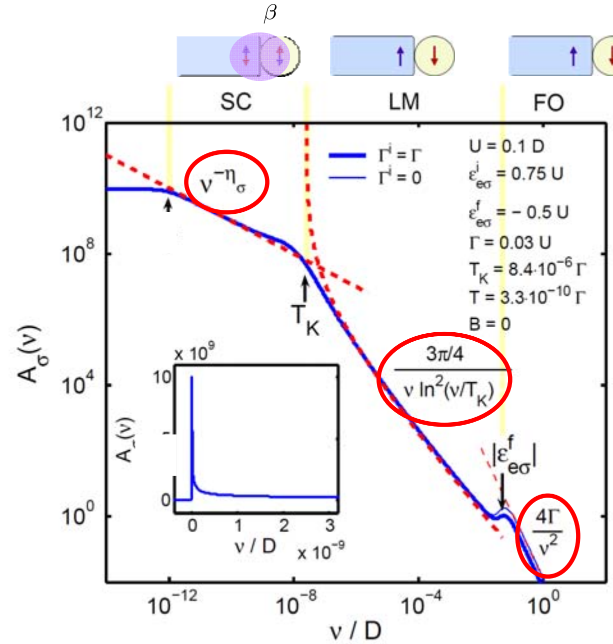
$$A_\sigma(\nu) = 2\pi \sum_{\alpha\beta} \rho^{\rm i}_\alpha \left| {}_{\rm f}\langle\beta|e^\dagger_\sigma|\alpha\rangle_{\rm i}\right|^2 \delta(\nu + \omega_{\rm th} - E^{\rm f}_\beta + E^{\rm i}_\alpha)$$

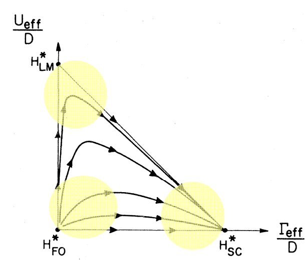


Absorption Lineshape: T = 0 (SAM)

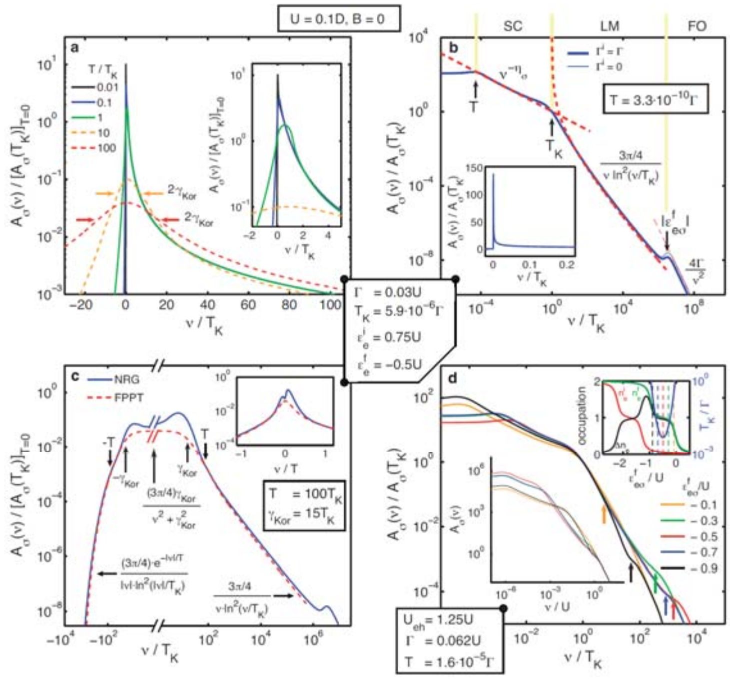
$$A_\sigma(\nu) = 2\pi \sum_{\beta} \left| {}_{\rm f}\langle\beta|e^\dagger_\sigma|{\rm G}\rangle_{\rm i}\right|^2 \delta(\nu + \omega_{\rm th} - E^{\rm f}_\beta + E^{\rm i}_{\rm G})$$

Helmes et al, '04





Spectral function: T- dependence



Spectral function: B- dependence