Spin-Polarized Tunneling Microscopy and the Kondo Effect

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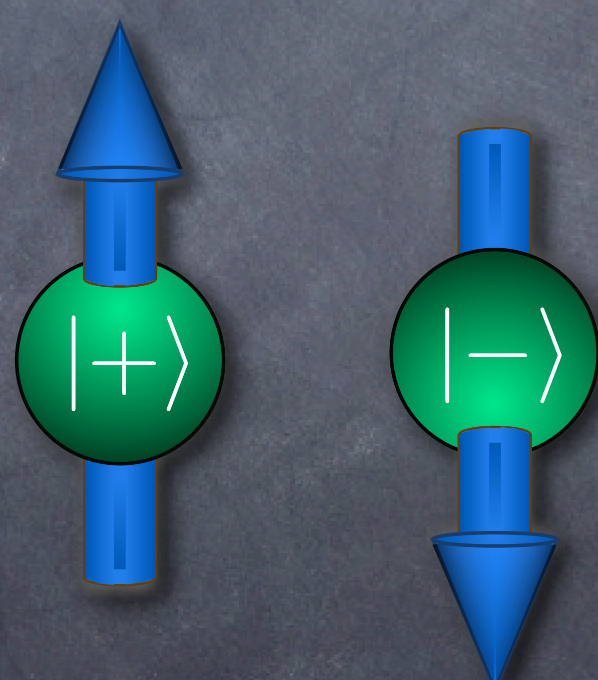
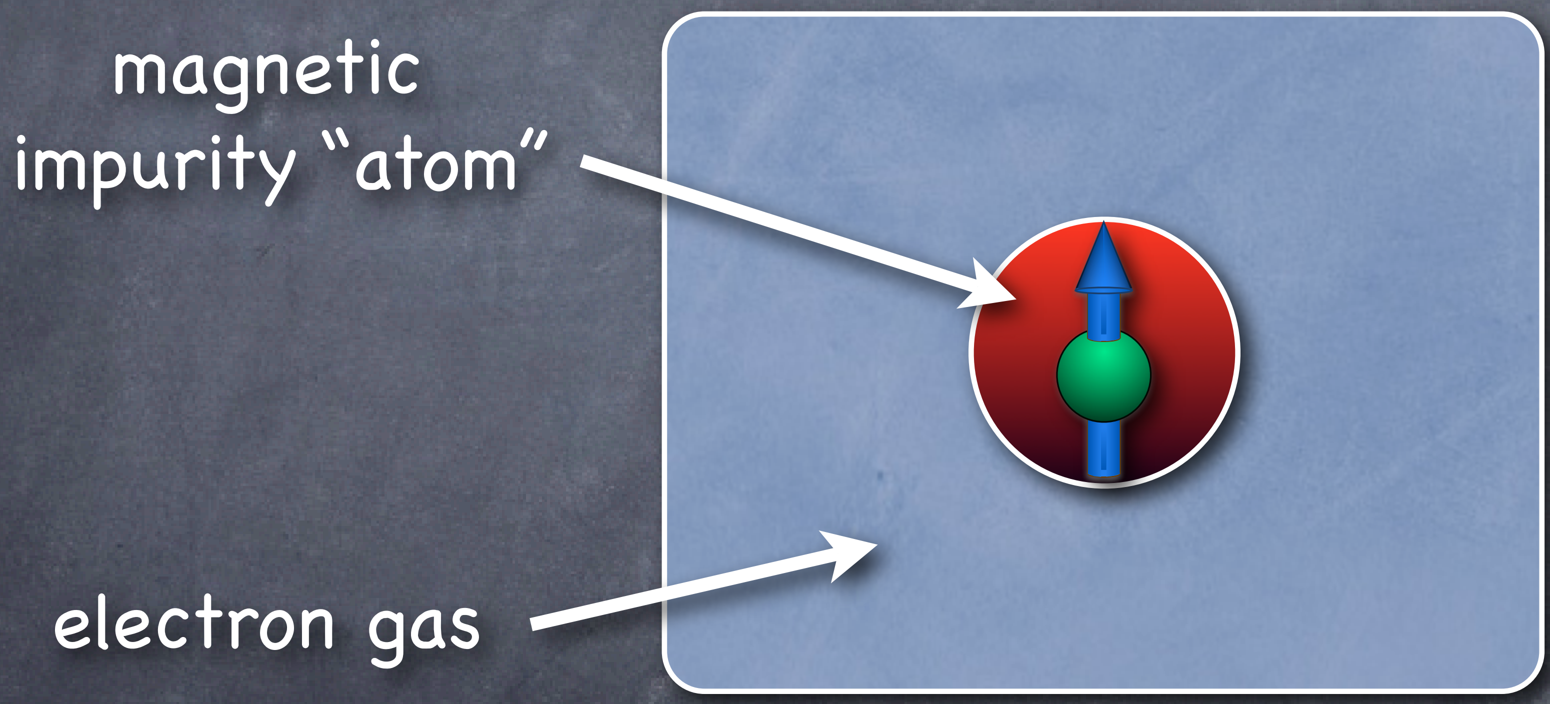
Acknowledgments

- Stefan Kettemann (Hamburg)
- Andrey Zhuravlev (Hamburg/Ekaterinbrug, Russia)
- Alexander Lichtenstein (Hamburg)

- Overview of the Kondo Effect
- Kondo Systems: Quantum Dots and STM
- Spin-Polarzied STM and the Kondo effect



Kondo Effect



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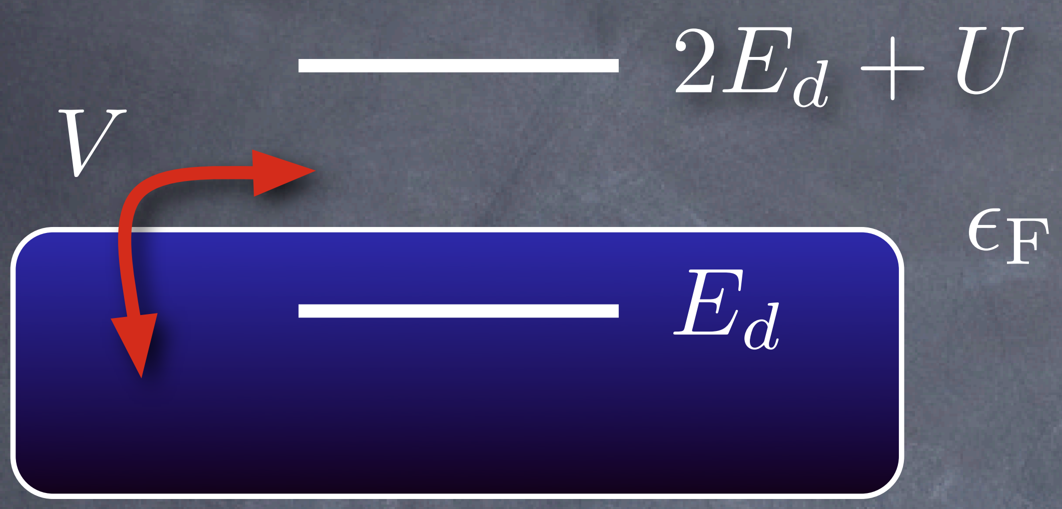
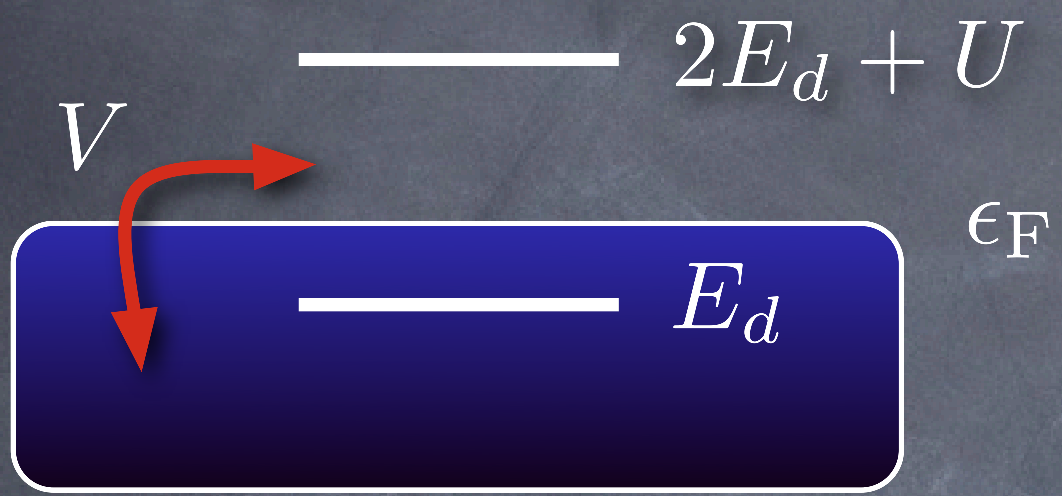


(Anderson model)

Kondo Effect



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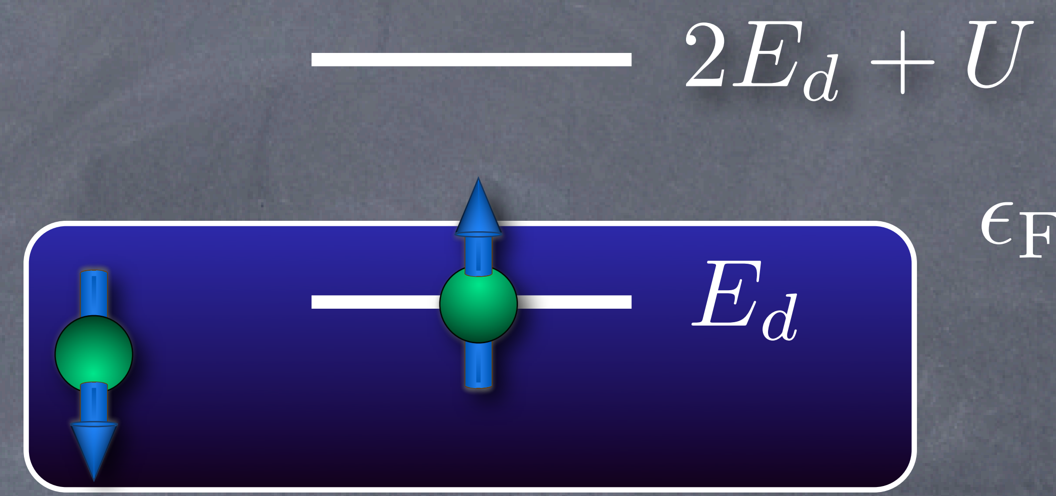

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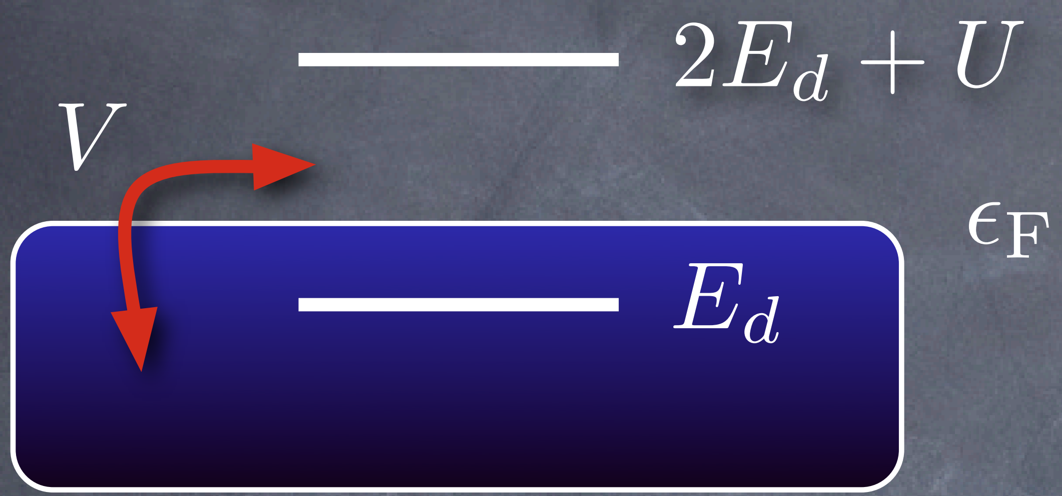

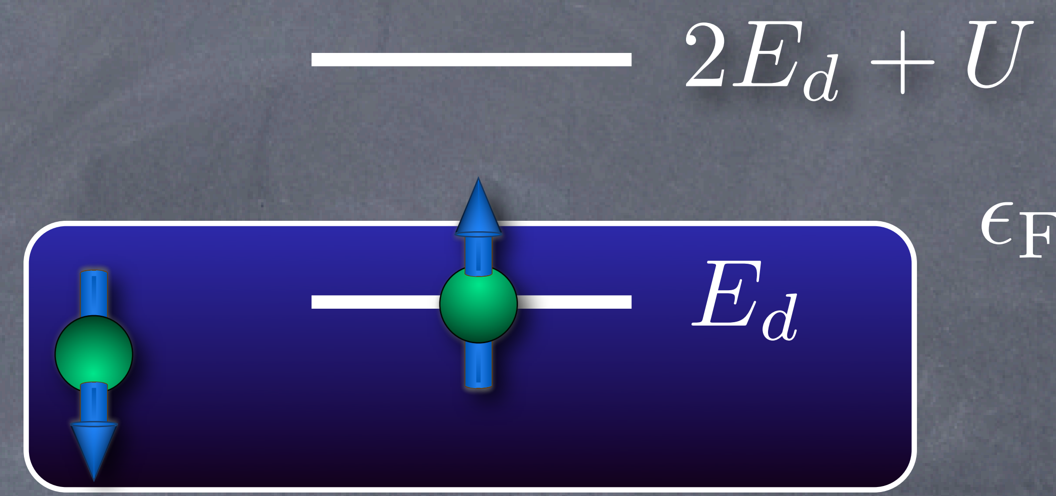

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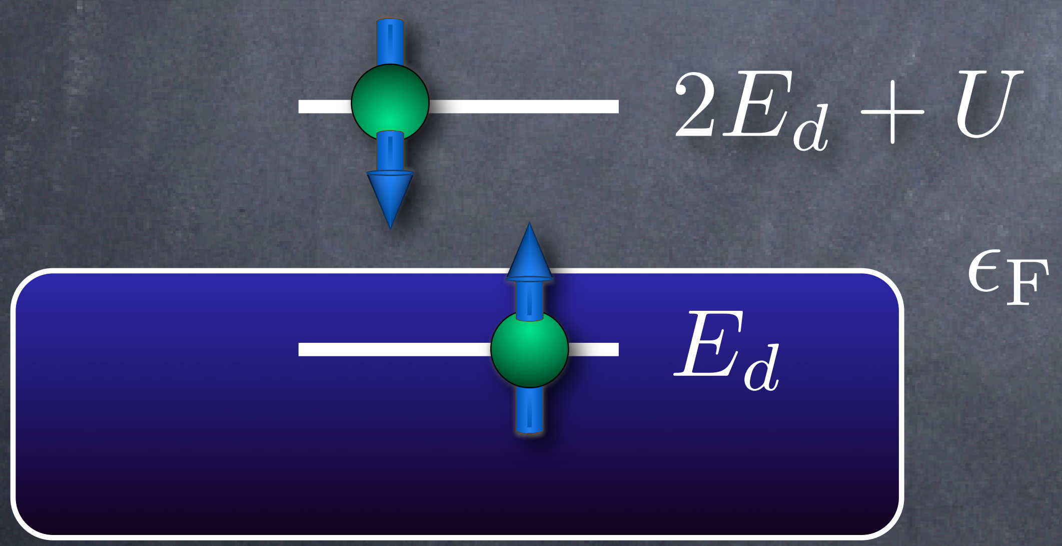

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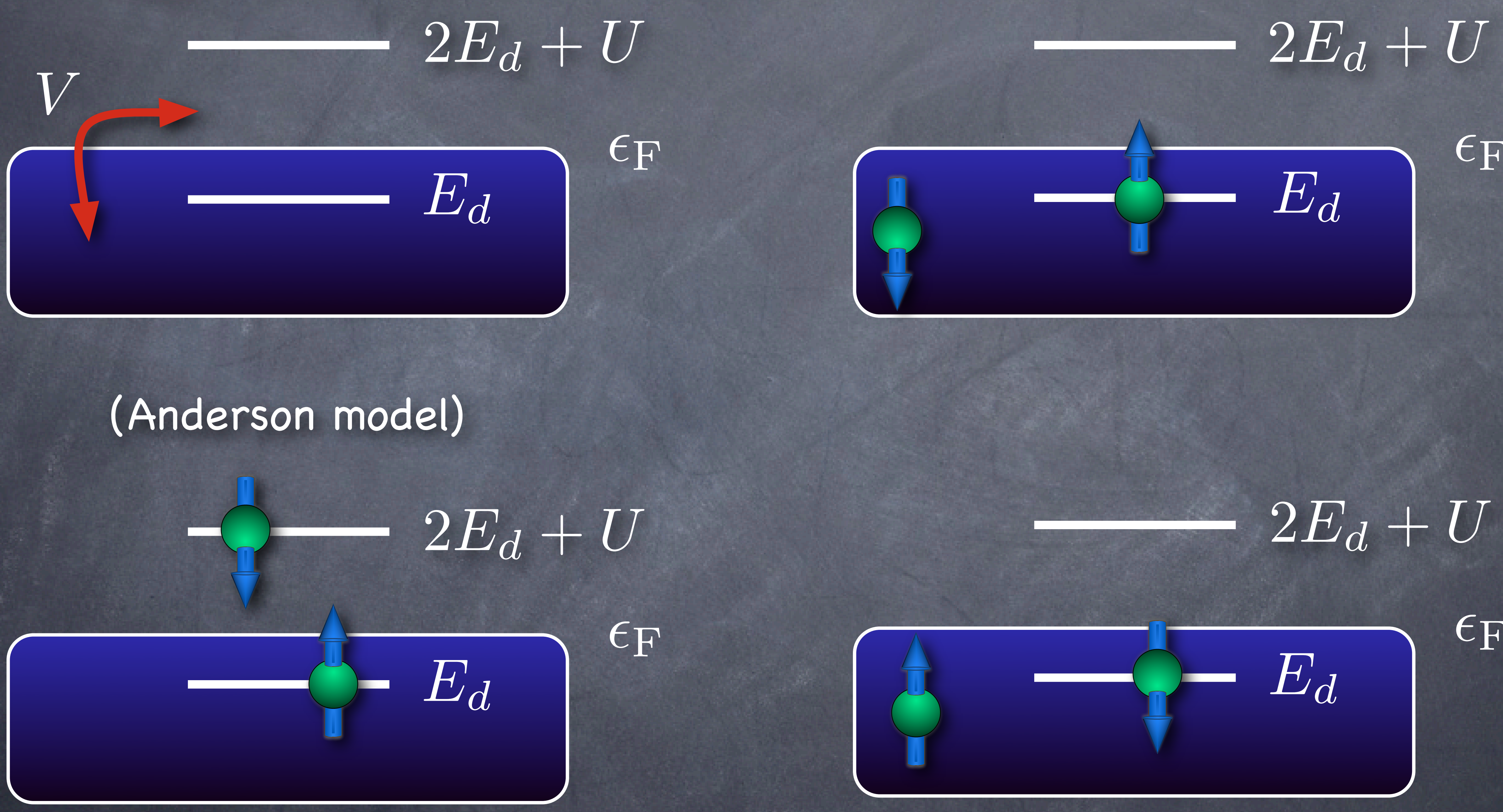
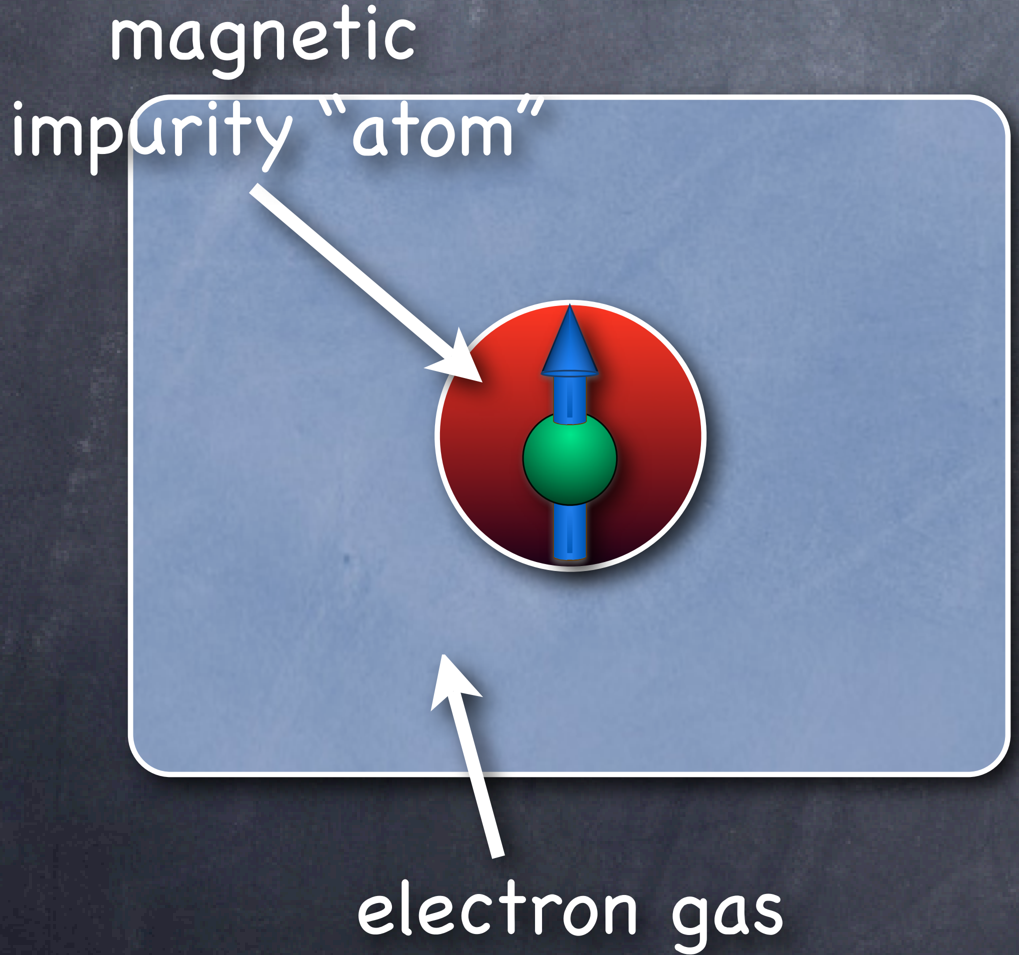


Kondo Effect

$$H_{\text{And}} = \underbrace{\sum_{k,\sigma} \epsilon_k c^\dagger_{k\sigma} c_{k\sigma}}_{\text{electron gas}} + \underbrace{E_d \sum_{\sigma} d^\dagger_\sigma d_\sigma + U \hat{n}_\uparrow \hat{n}_\downarrow}_{\text{impurity}} + \underbrace{\sum_{k,\sigma} V_{kd} c^\dagger_{k\sigma} d_\sigma + \text{H.c.}}_{\text{hopping}}$$



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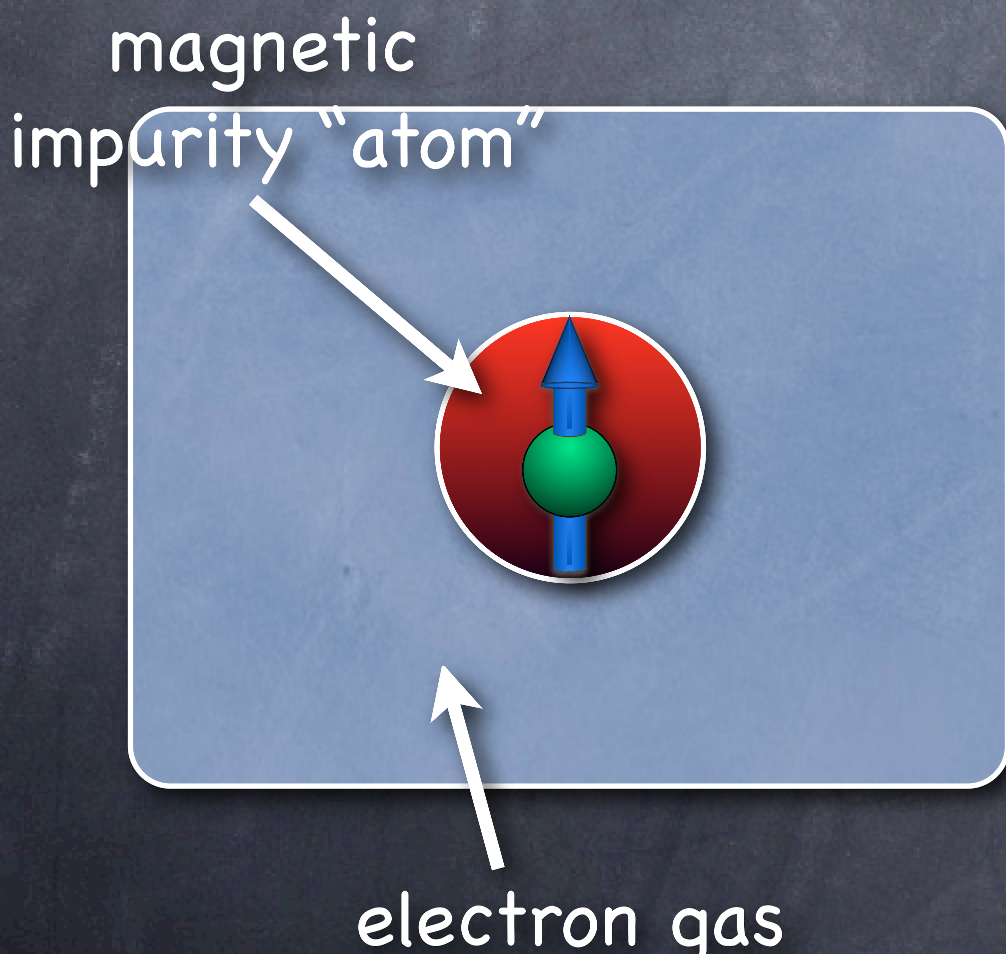

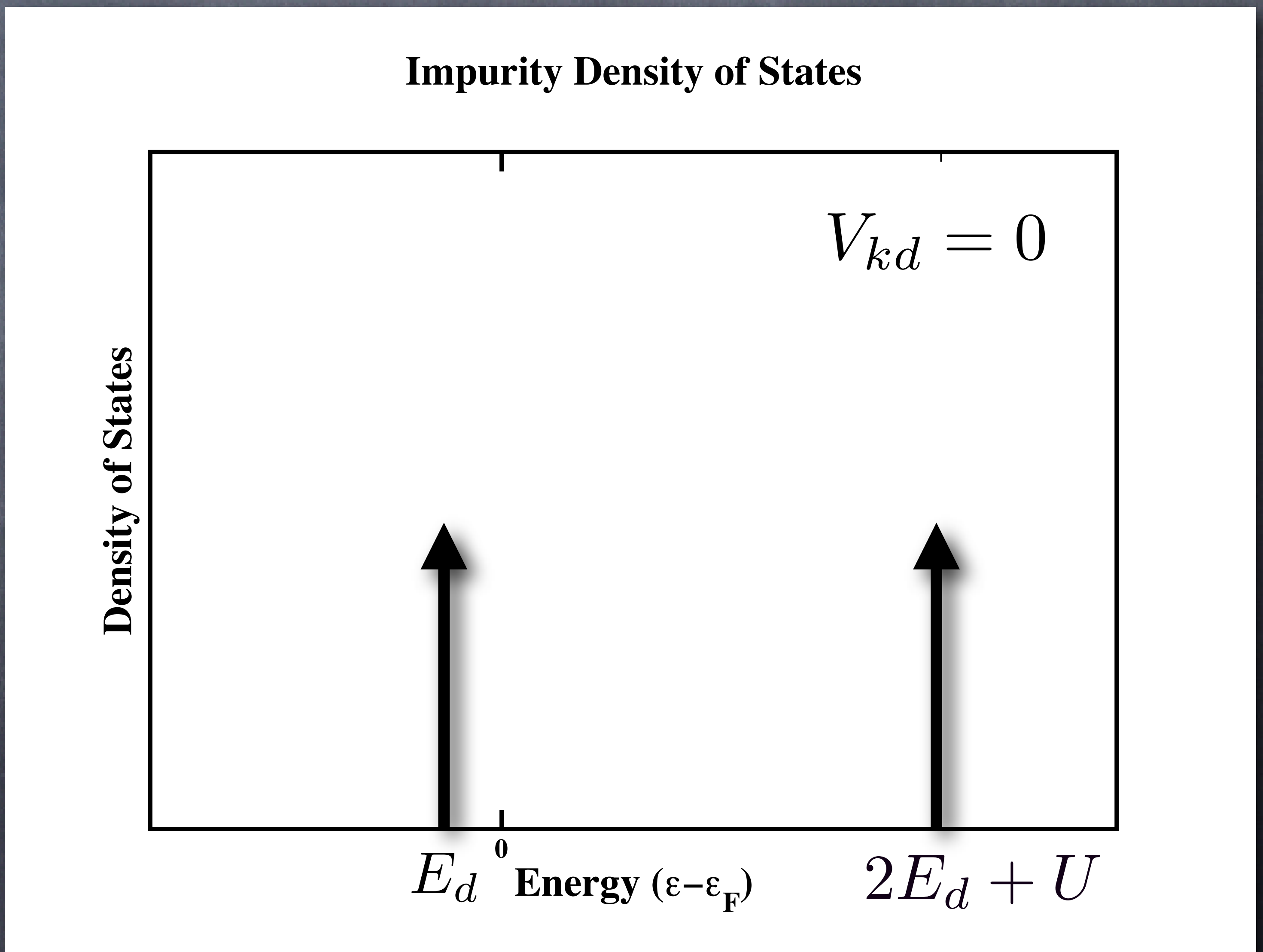

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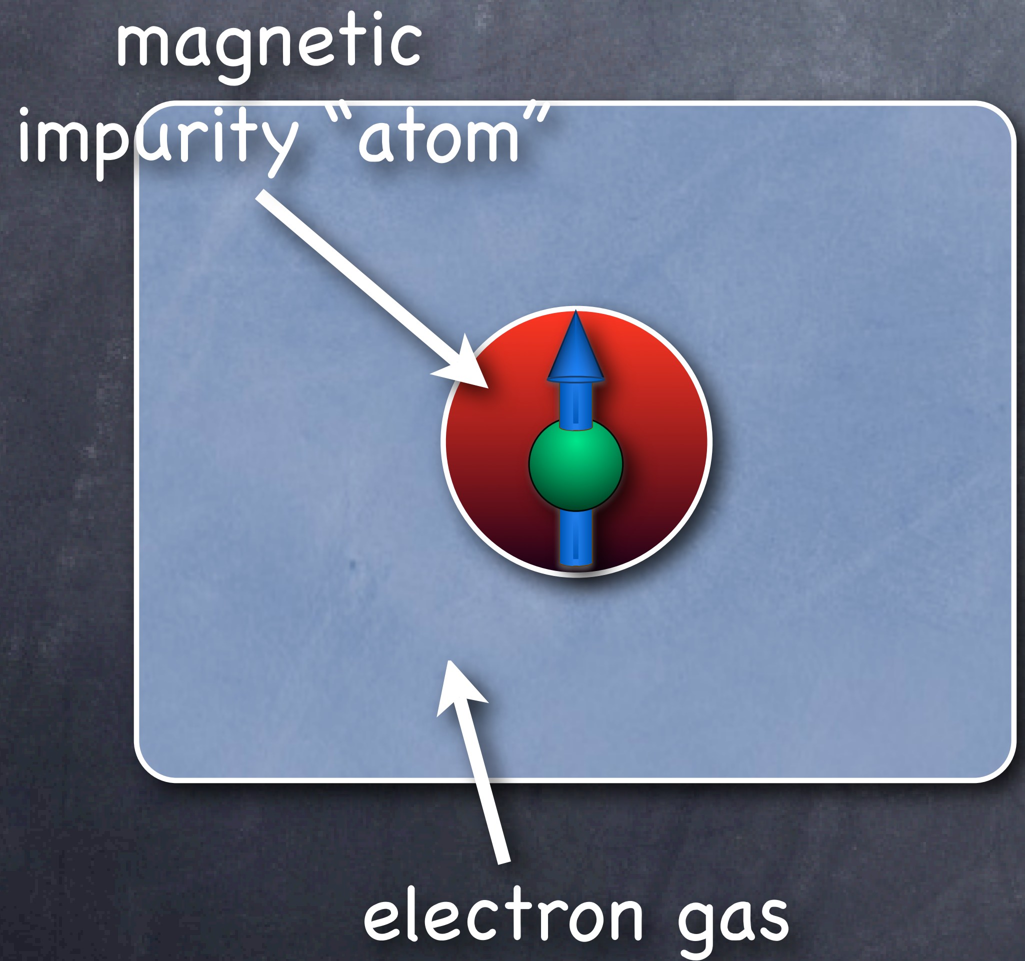
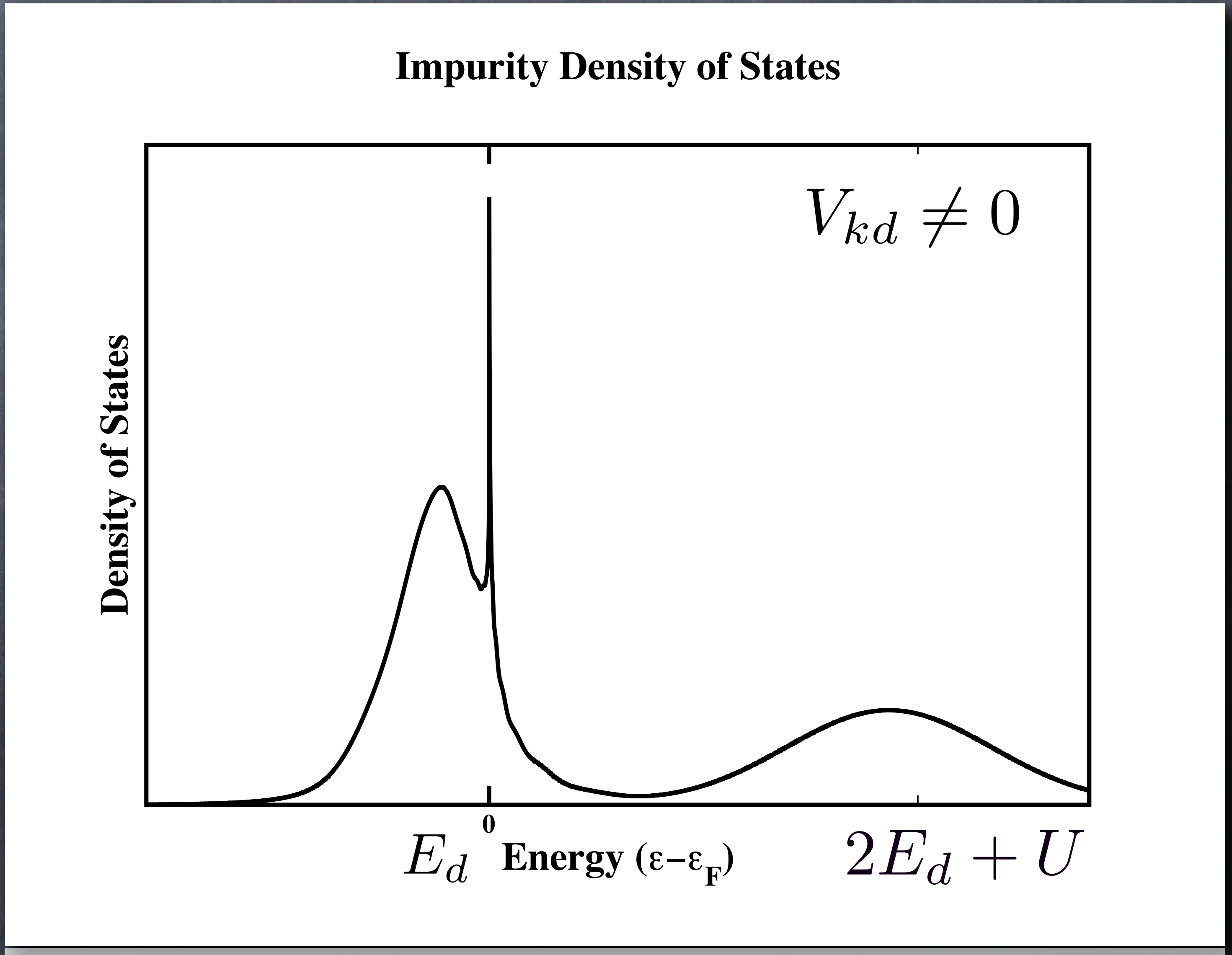
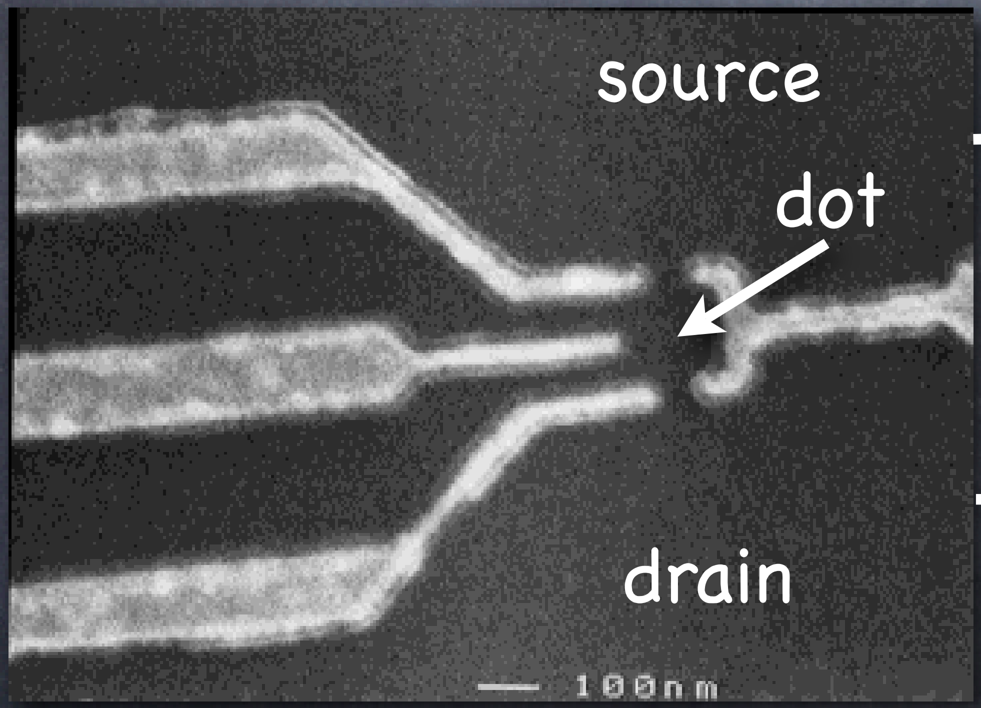
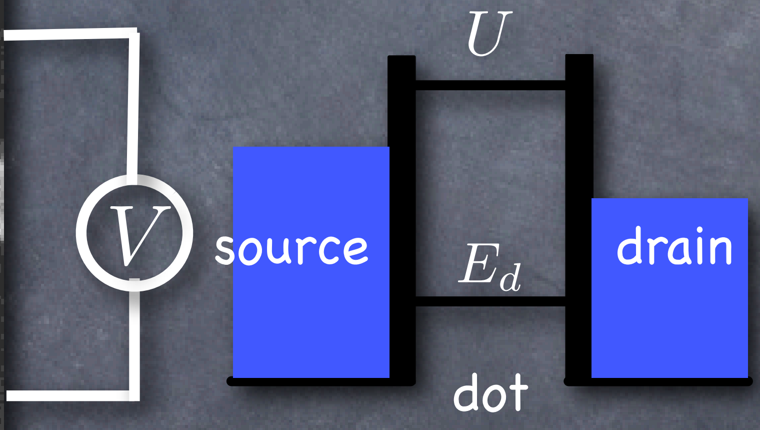




Kondo Effect: Quantum Dots

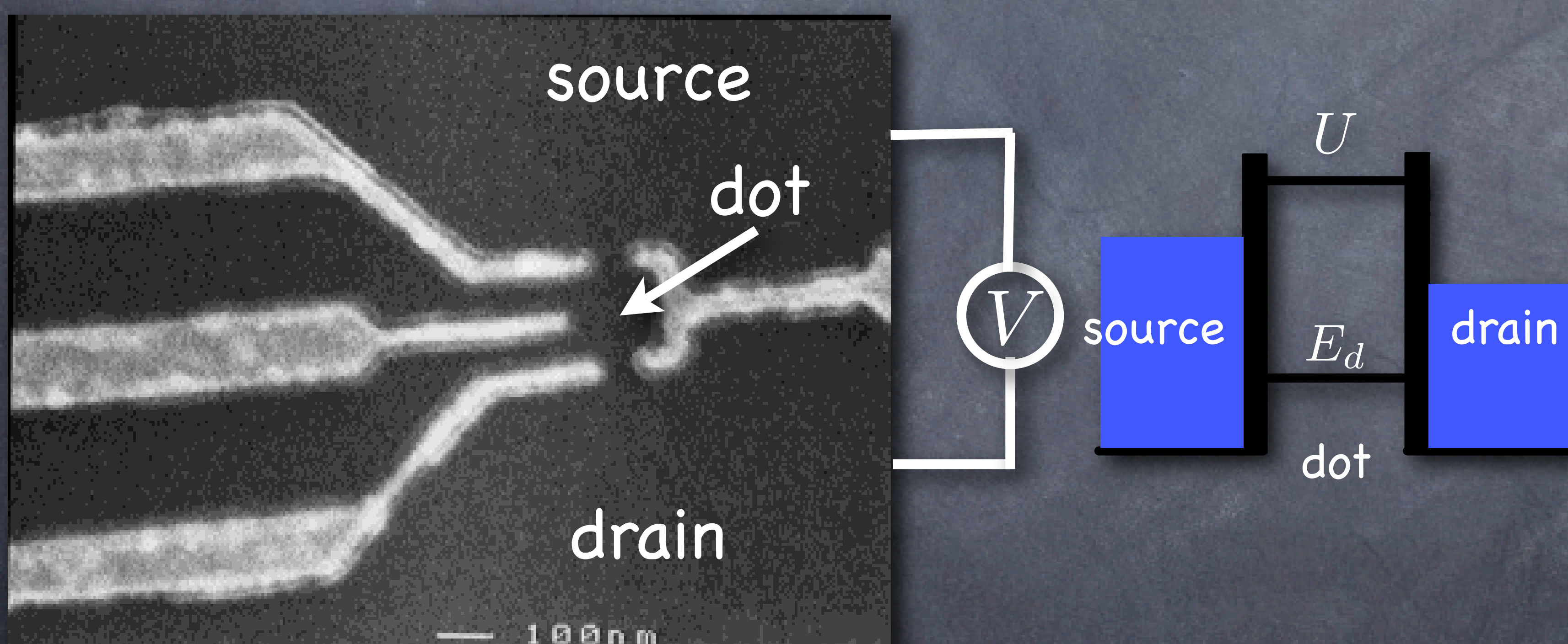




D. Goldhaber-Gordon
Nature **39**, (1998)

Kondo Effect: Quantum Dots

$$H = \underbrace{\sum_{\alpha\in \mathrm{L,R}} \sum_{k,\sigma} \epsilon_k c^\dagger_{\alpha k\sigma} c_{\alpha k\sigma}}_{\text{Leads}} + \underbrace{E_d \sum_\sigma d^\dagger_\sigma d_\sigma + U\hat{n}_\uparrow \hat{n}_\downarrow}_{\text{dot}} + \underbrace{\sum_{\alpha\in \mathrm{L,R}} \sum_{k,\sigma} V_{\alpha k d} c^\dagger_{\alpha k\sigma} d_\sigma + \mathrm{H.c.}}_{\text{tunneling}}$$



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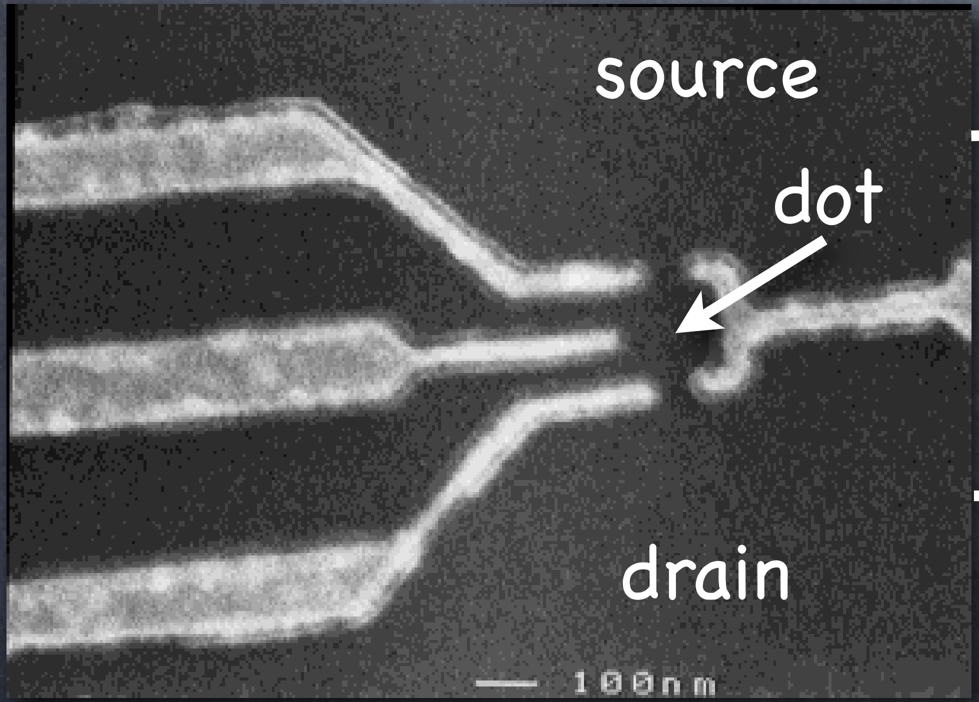

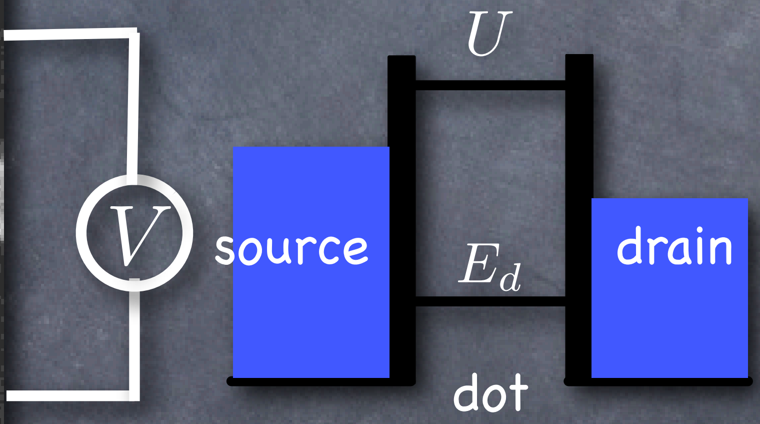

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$$\frac{dI}{dV} \propto \rho_{\mathrm{dot}}(\omega)$$

$\rho_{\mathrm{dot}}(\omega)$= density of states

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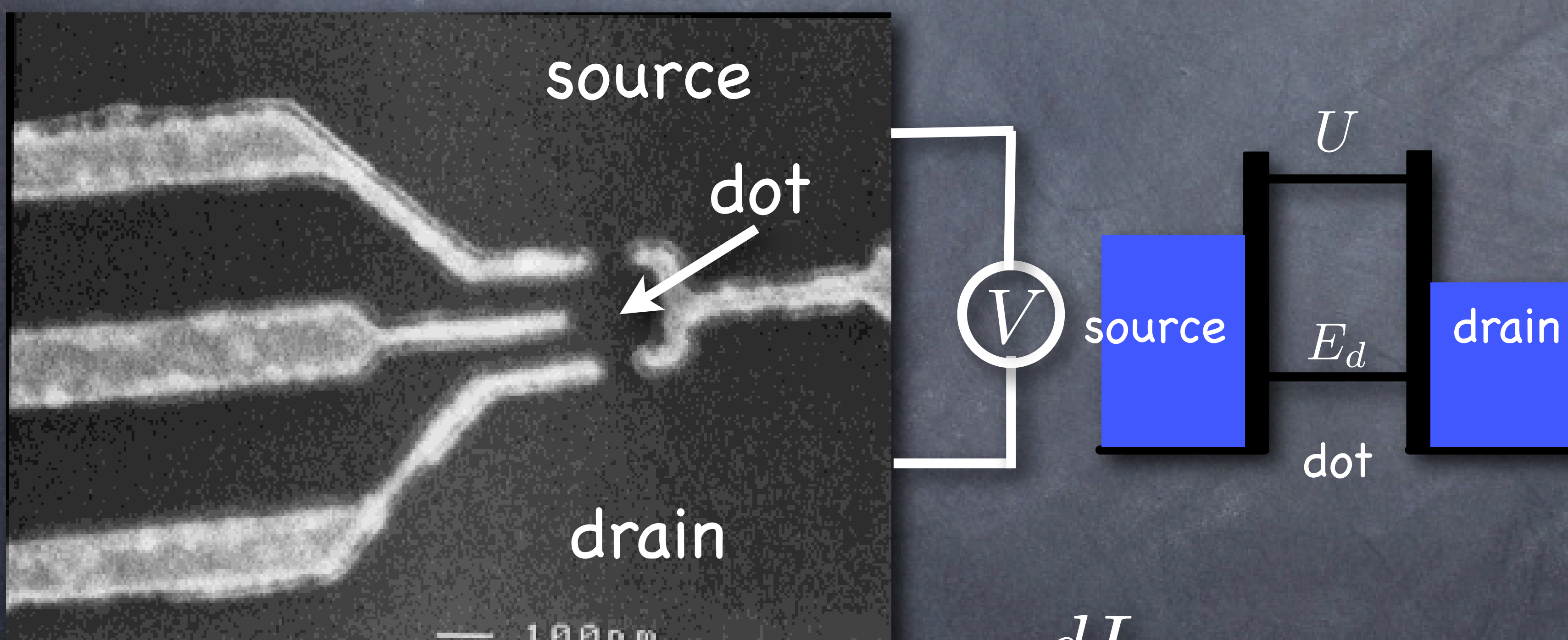

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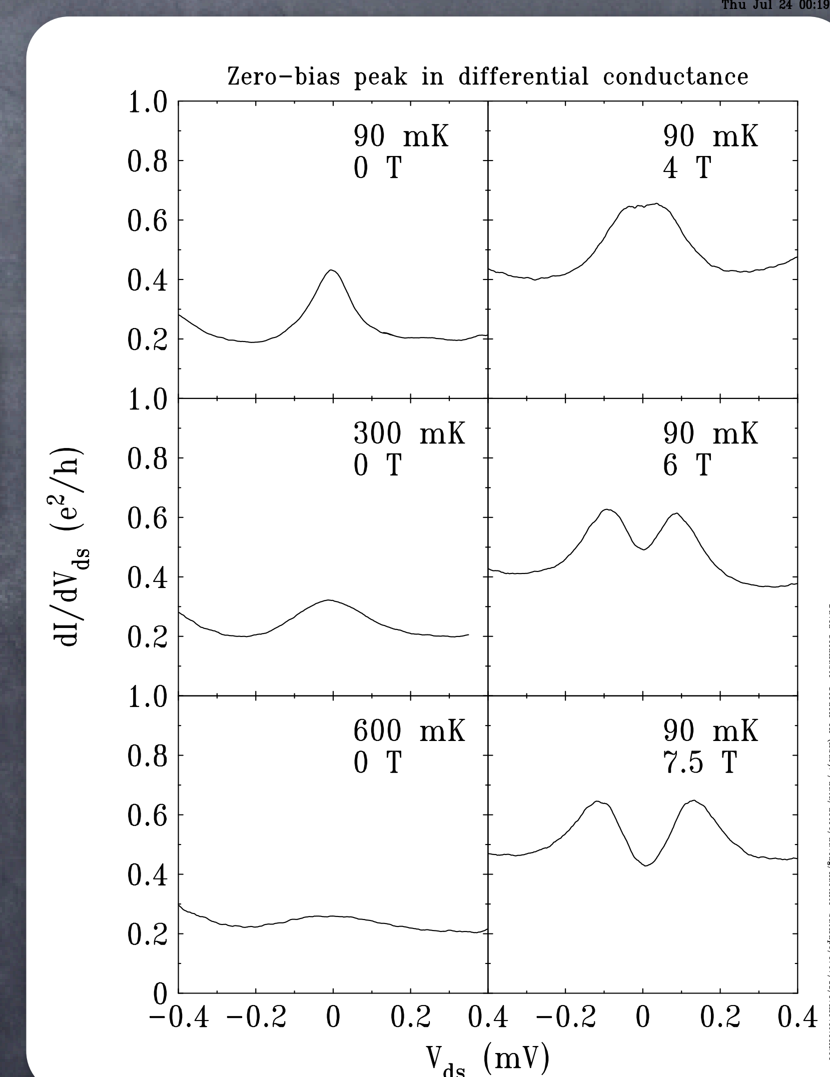
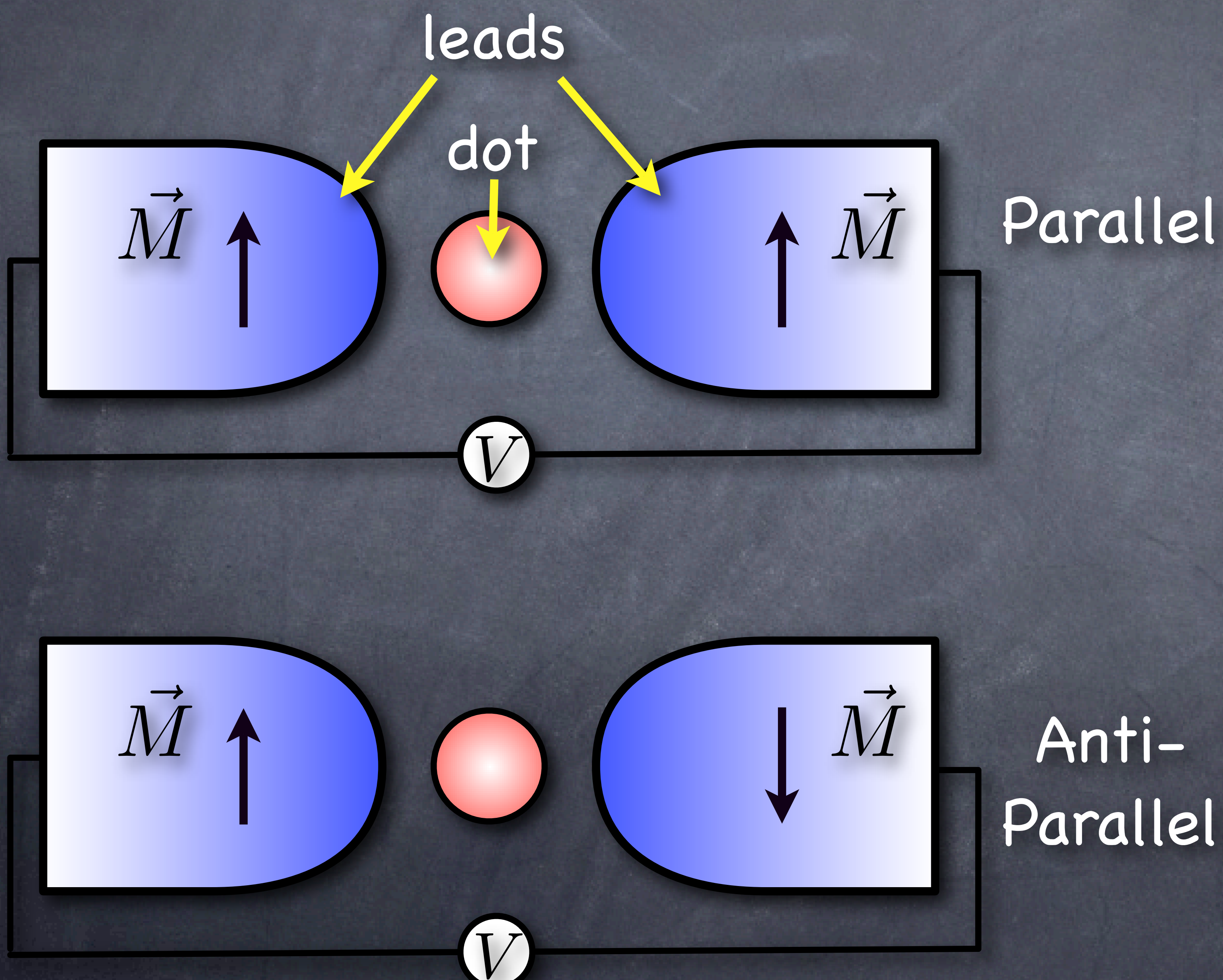


Kondo Effect in the Presence of Ferromagnetism



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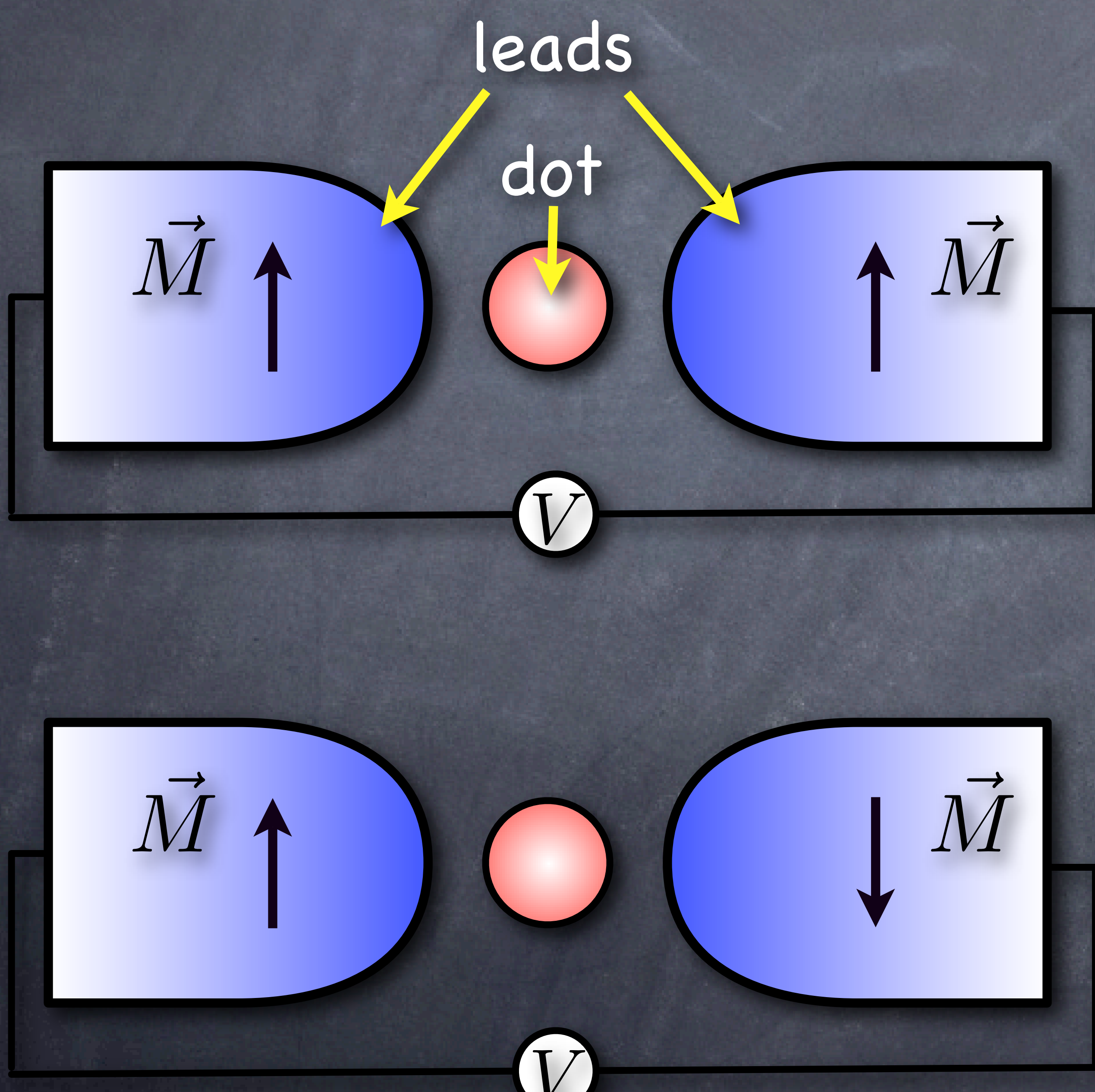
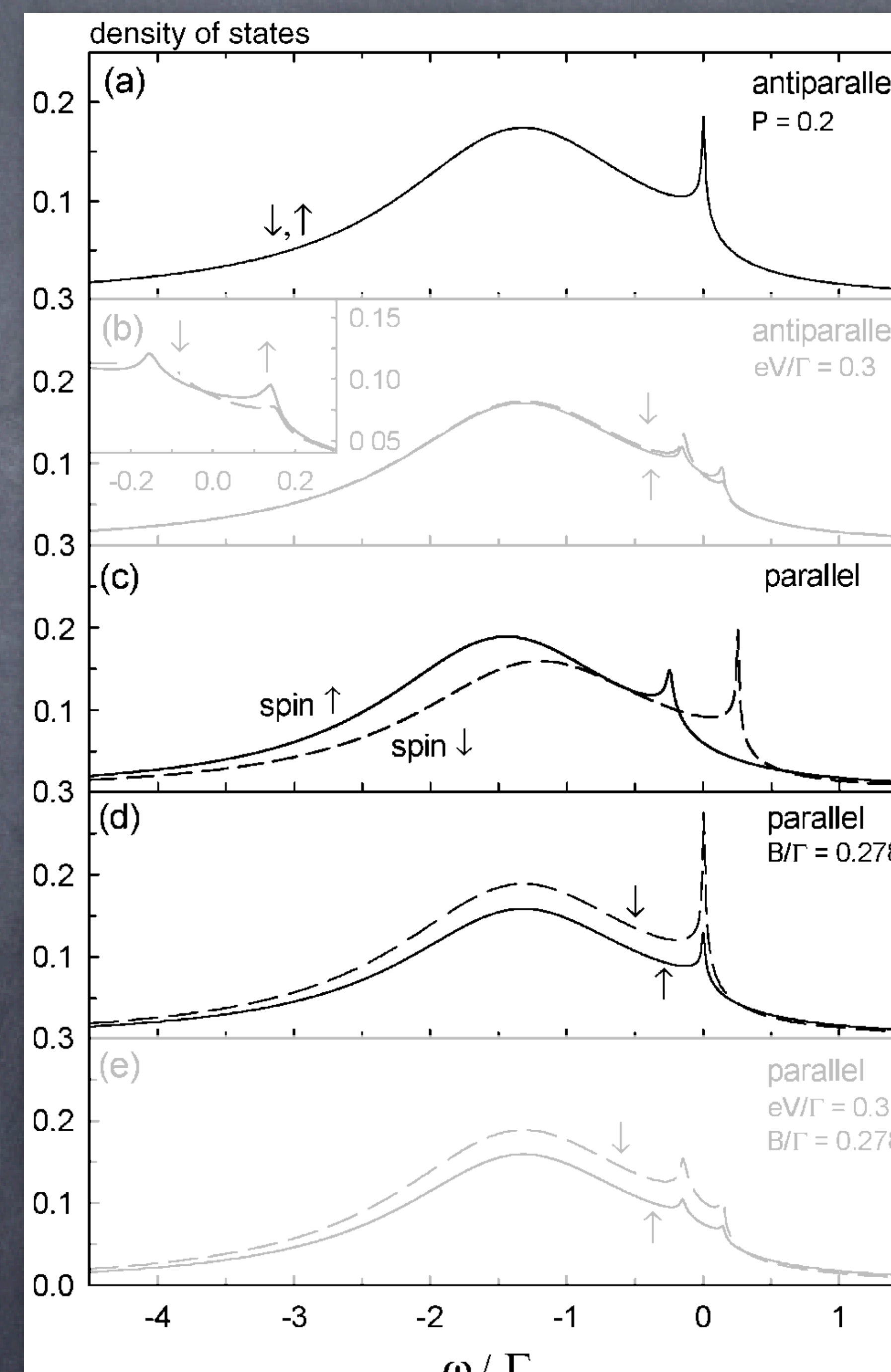


$E_d^{\uparrow} \neq E_d^{\downarrow}$

Parallel

$E_d^{\uparrow} = E_d^{\downarrow}$

Anti-Parallel



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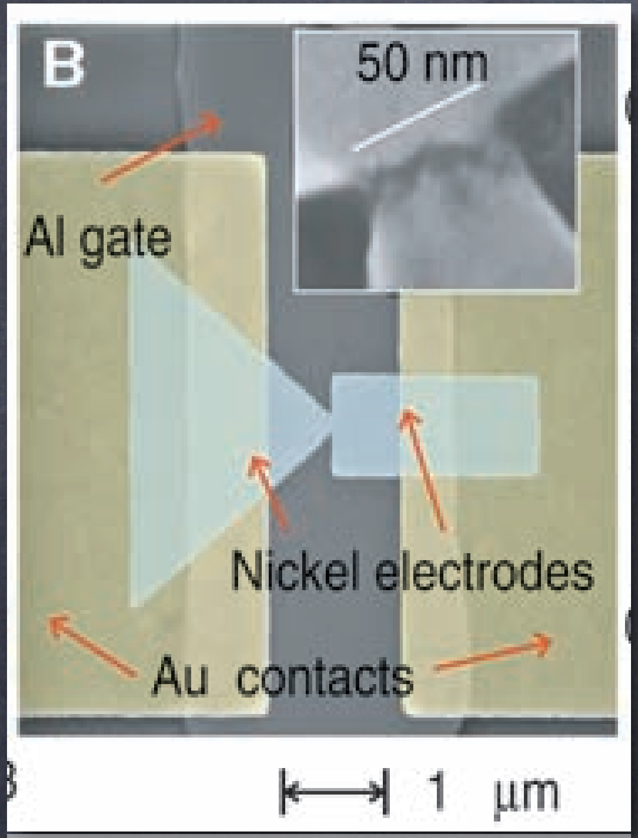
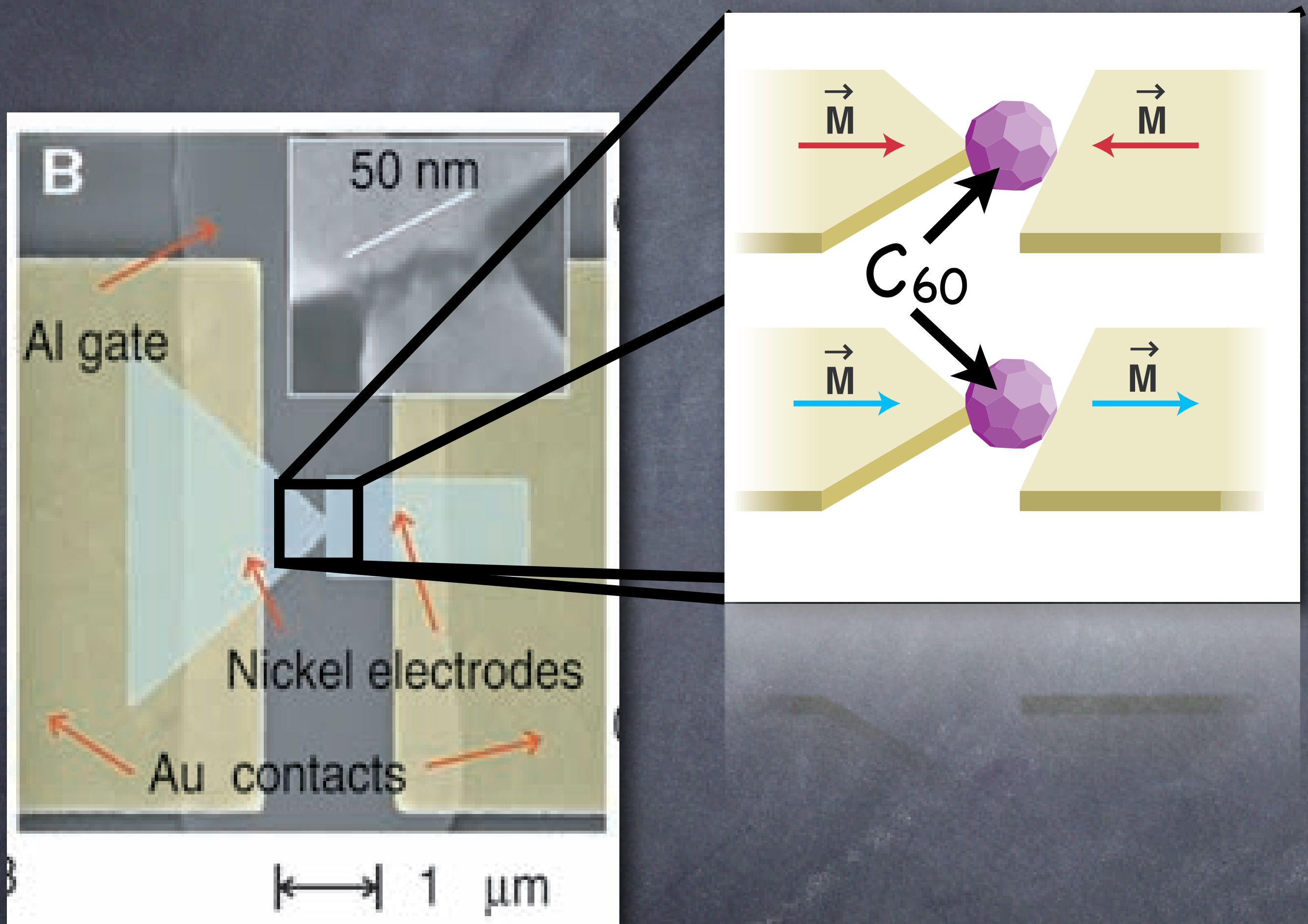


A. N. Pasupathy Science **306** (2004)

Kondo Effect in the Presence of Ferromagnetism



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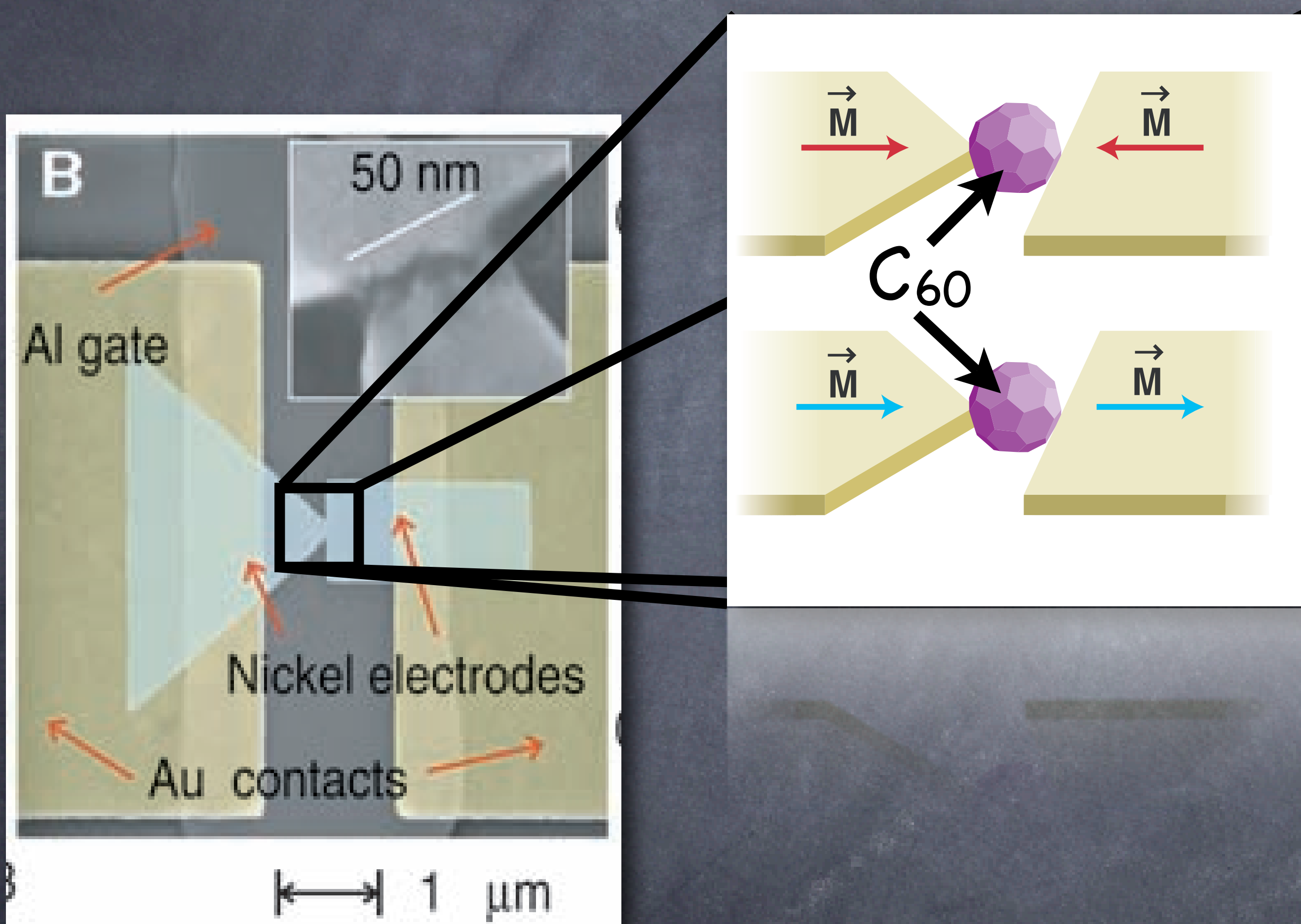
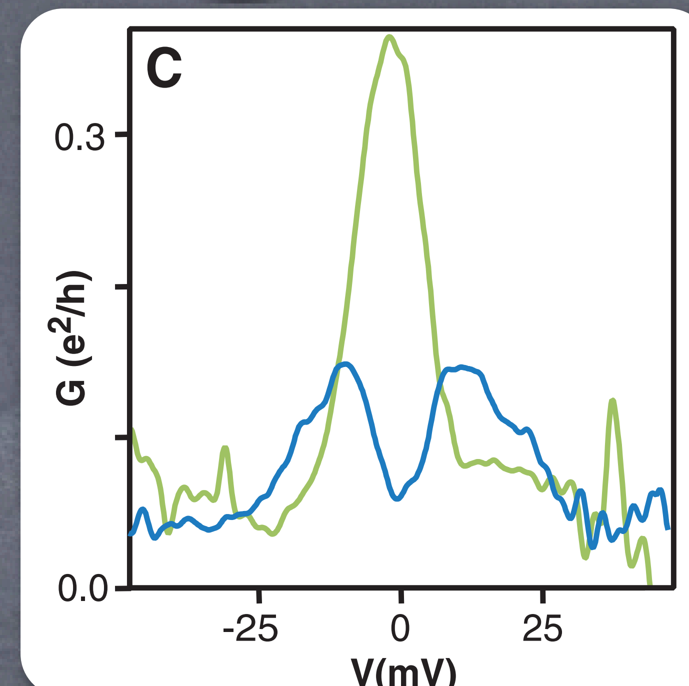
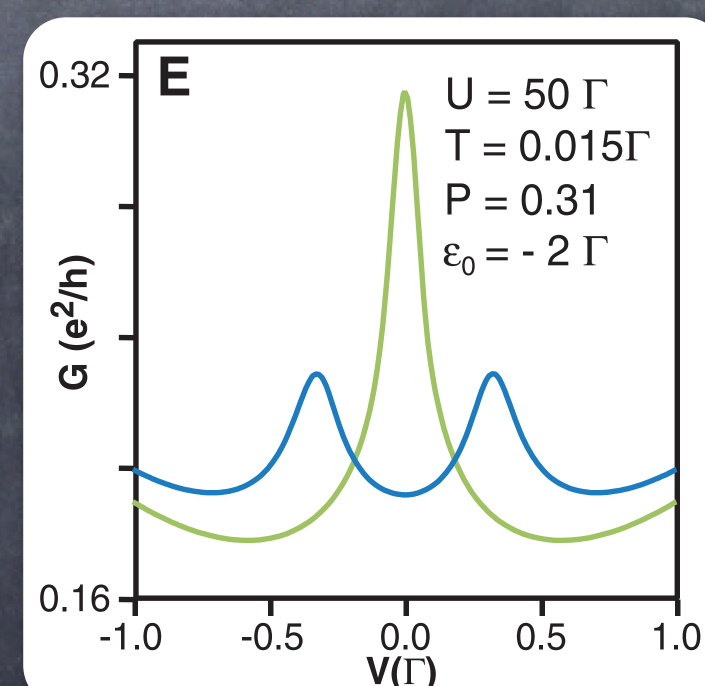
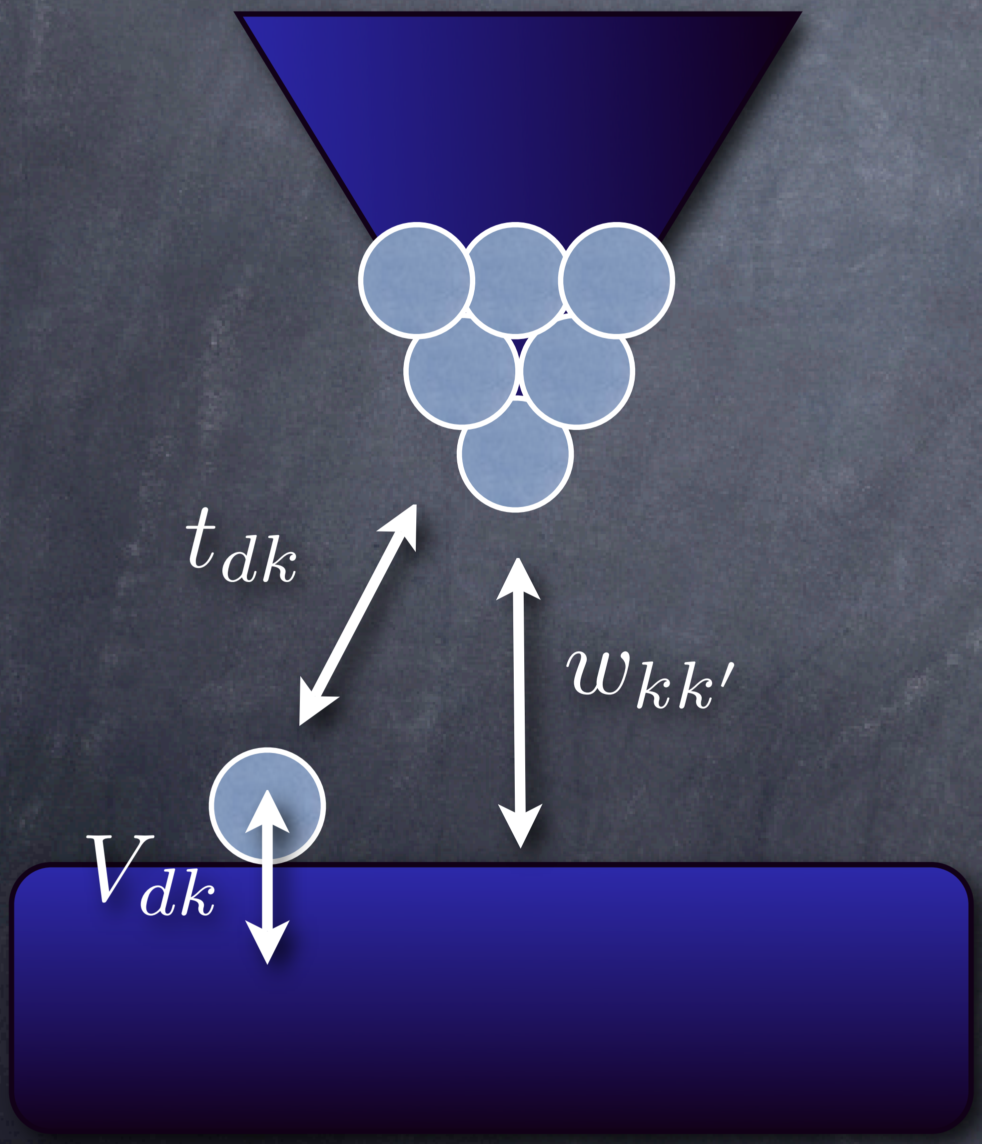






A. N. Pasupathy Science **306** (2004)

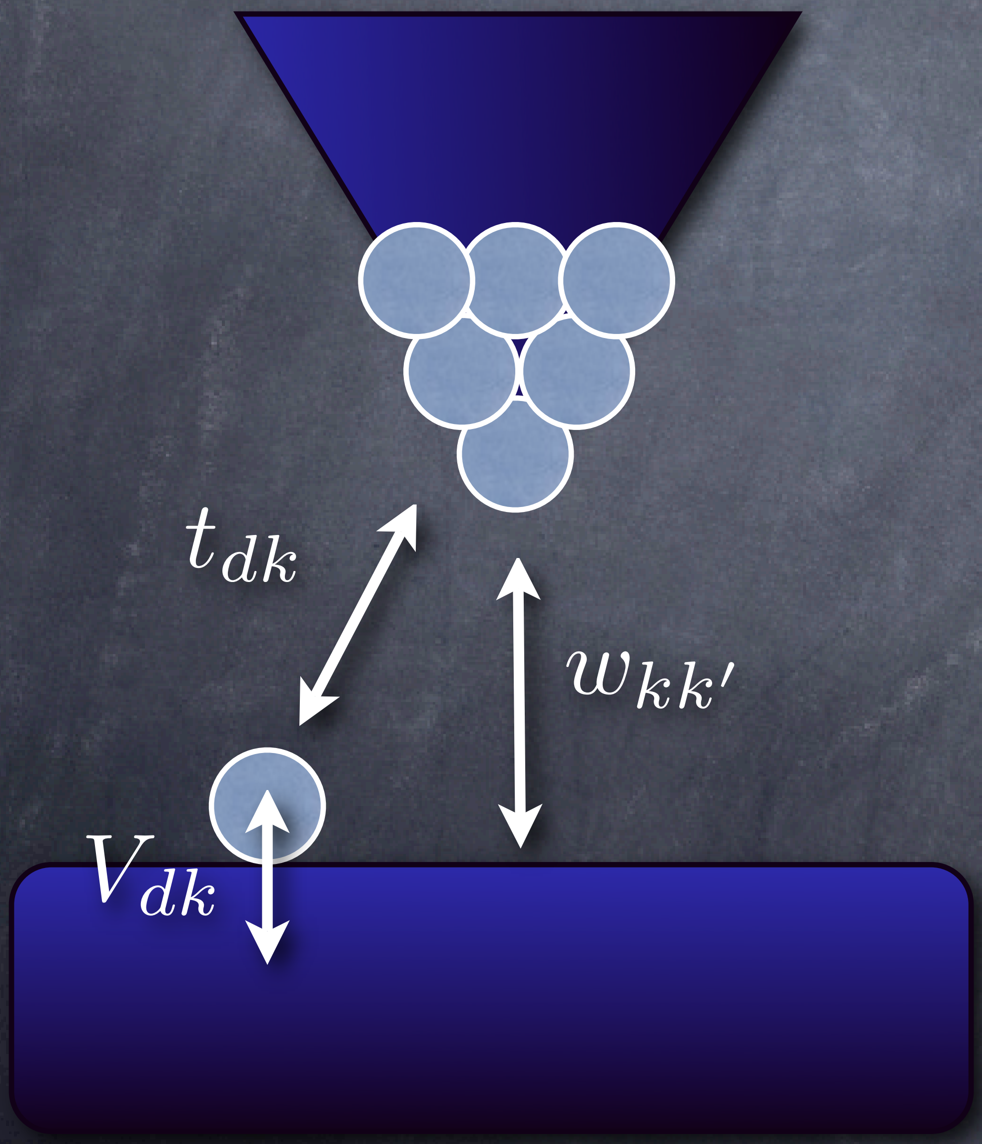
Kondo Effect: STM



Kondo Effect: STM

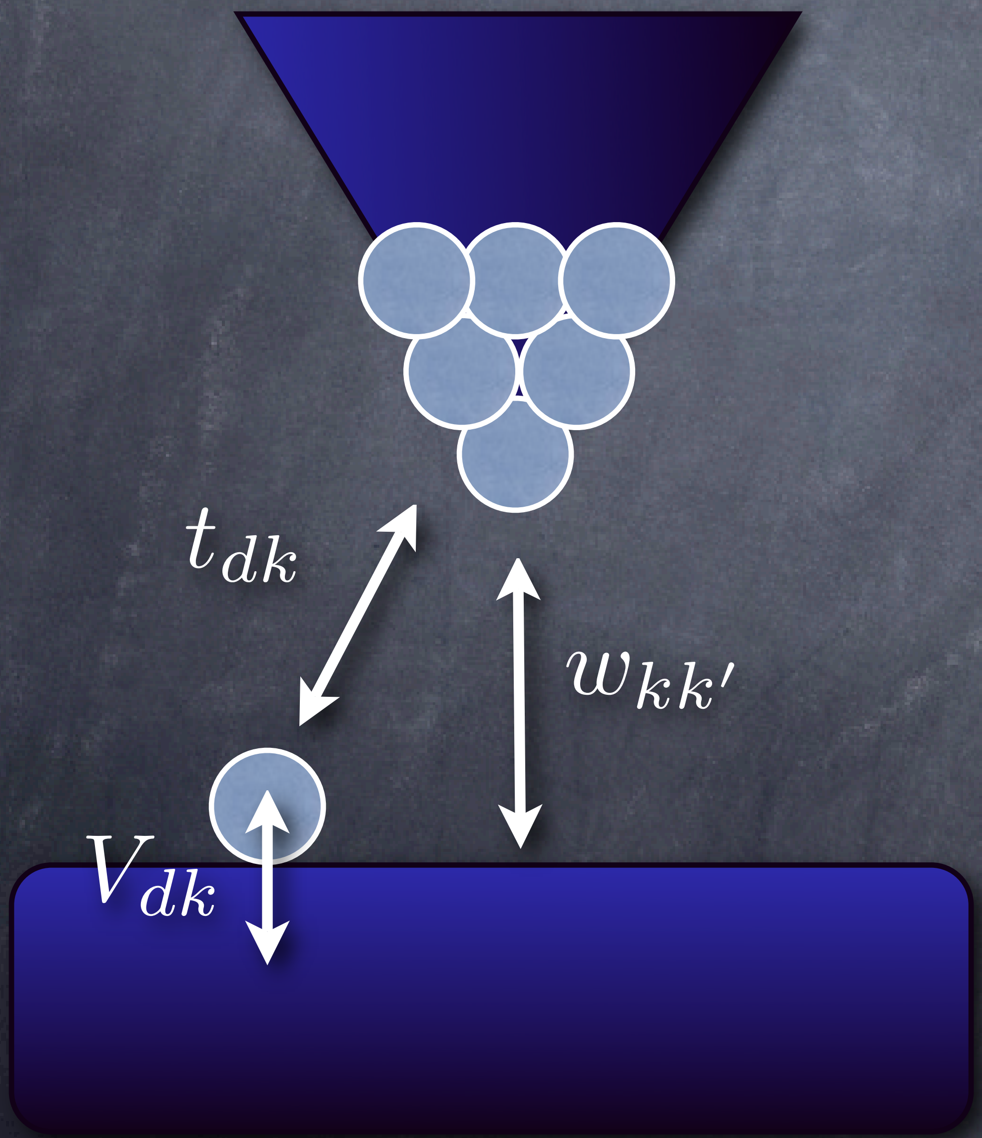
$$H = \sum_{k\sigma} \epsilon_k c^\dagger_{k\sigma} c_{k\sigma} + \sum_{k\sigma} \epsilon_k a^\dagger_{k\sigma} a_{k\sigma} + E_d \sum_{\sigma} d^\dagger_\sigma d_\sigma + U \hat{n}_\uparrow \hat{n}_\downarrow + \sum_{k\sigma} V_{kd} c^\dagger_{k\sigma} d_\sigma + \mathrm{H.c}$$

$$+ \sum_{k\sigma} t_{kd} a^\dagger_{k\sigma} d_\sigma + \mathrm{H.c} + \sum_{k,k',\sigma} w_{kk'} c^\dagger_{k\sigma} a_{k'\sigma} + \mathrm{H.c}$$



Kondo Effect: STM

$$\frac{dI}{d(eV)} \propto |w|^2\rho_{\mathrm{sub}}(\omega) + |t|^2\rho_d(\omega) - \frac{1}{\pi}\mathrm{Im}\left\{2twVG_0^{\mathrm{R}}(\omega)G^d(\omega)\right\}$$



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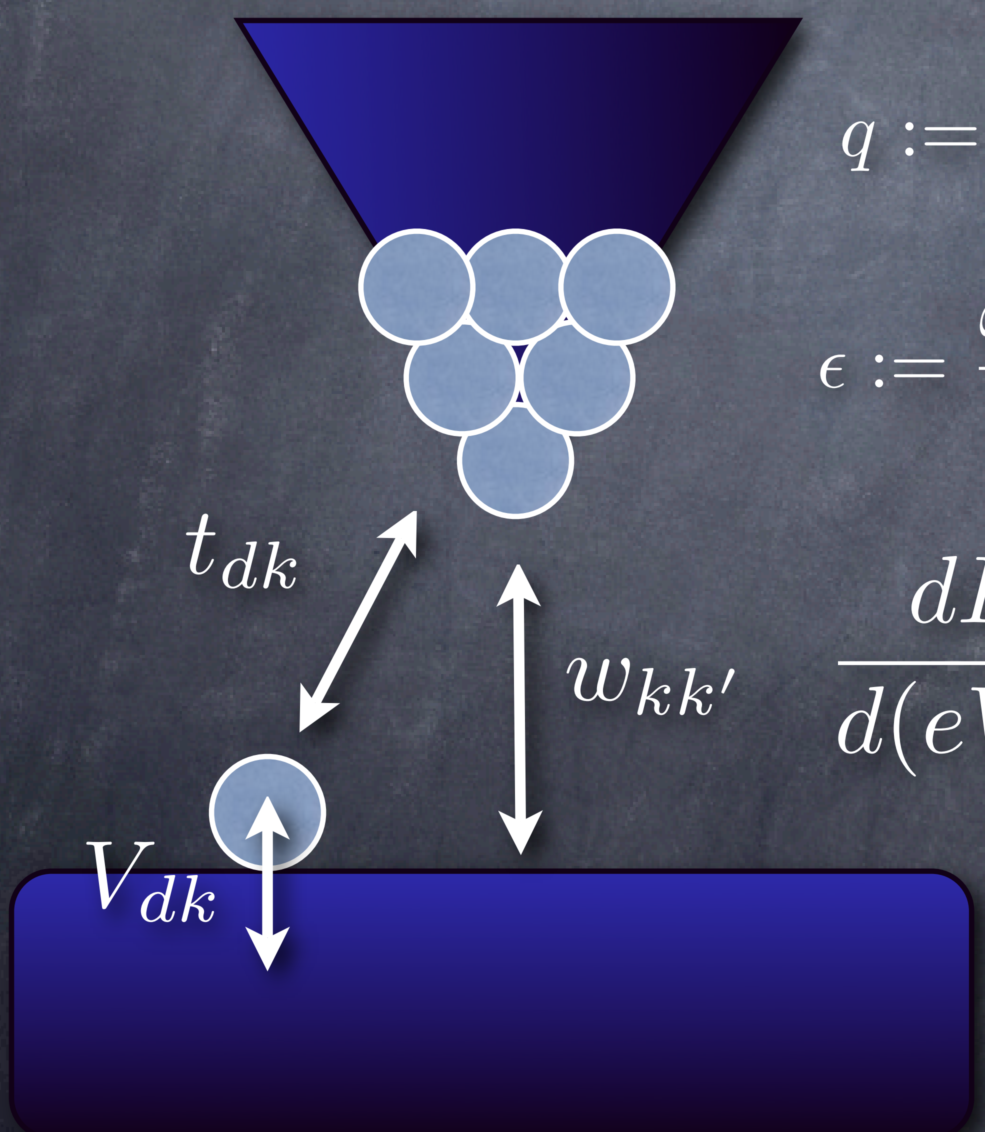

$$q := \frac{t + wV\mathrm{Re}\left[G_0(\omega)\right]}{\pi w V \rho_{\mathrm{sub}}(\omega)}$$

$$\epsilon := \frac{\omega - E_d - \mathrm{Re}[\Sigma_d(\omega)]}{\mathrm{Im}[\Sigma_d(\omega)]}$$

$$\frac{dI}{d(eV)} \sim \frac{(q+\epsilon)^2}{1+\epsilon^2}$$

Fano line-shape

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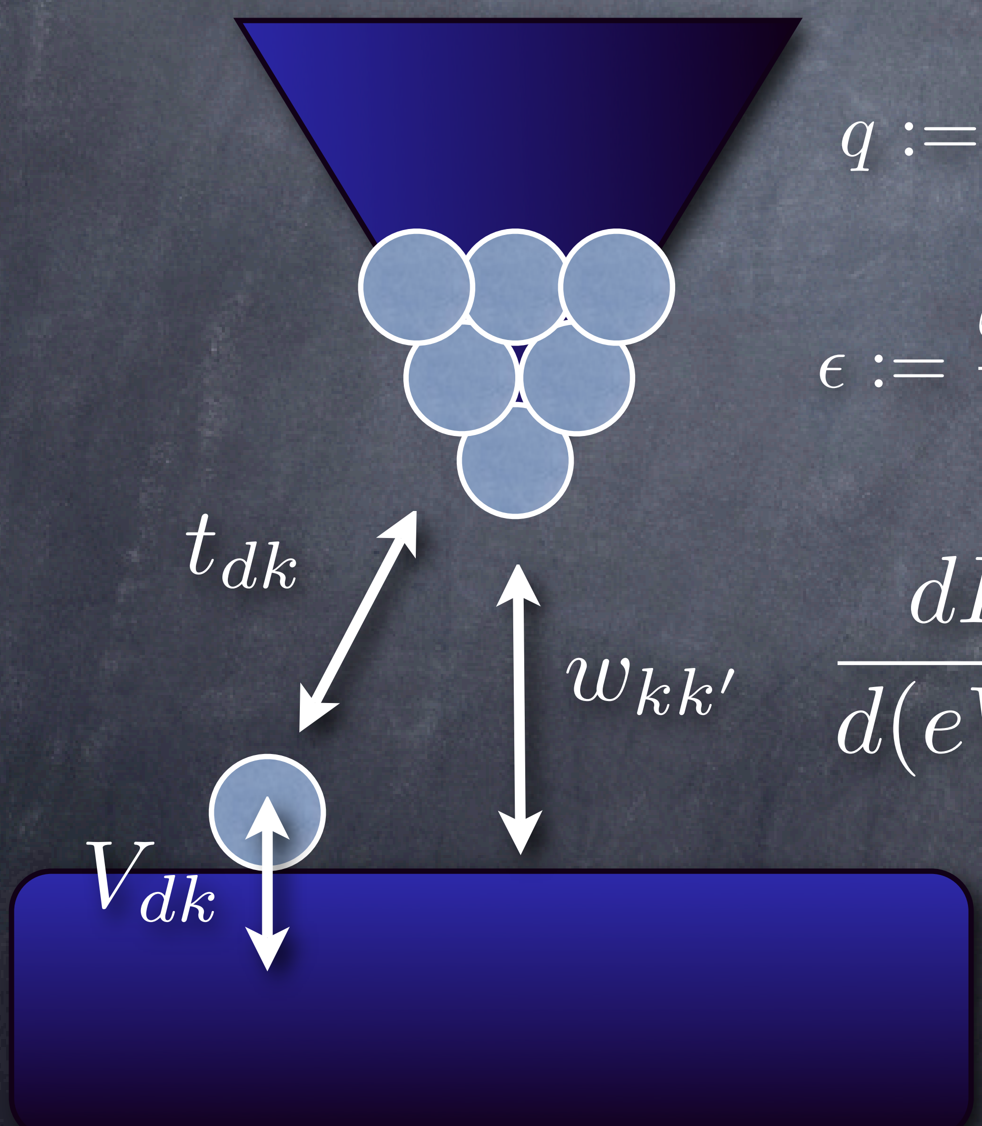

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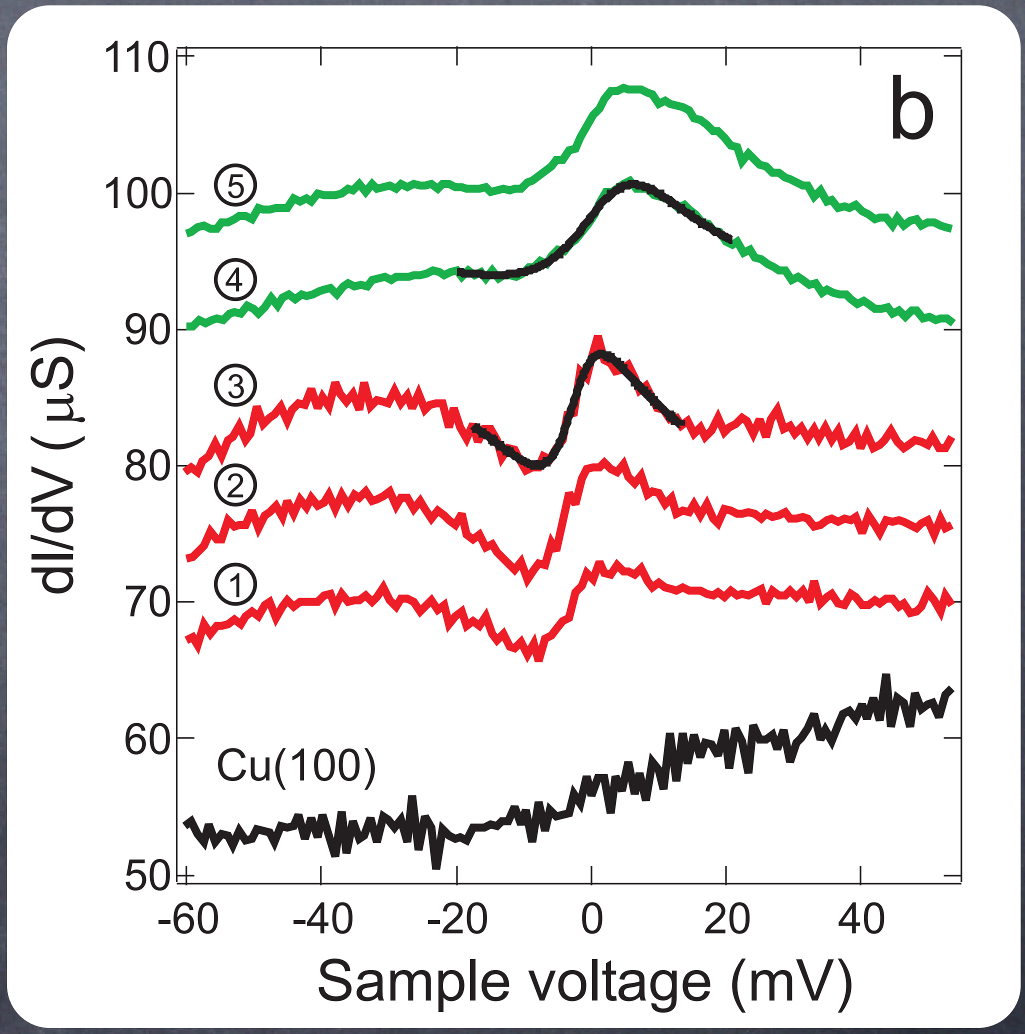
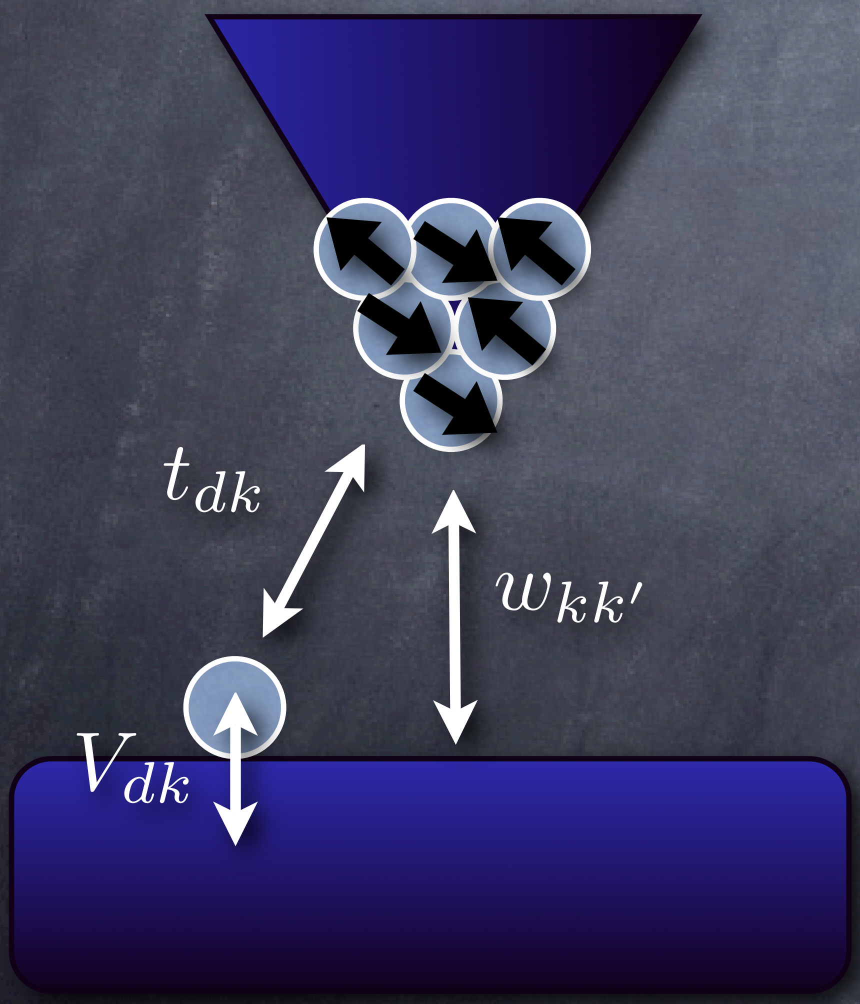


N. Néel PRL **98** (2007)

Kondo Effect: SP-STM



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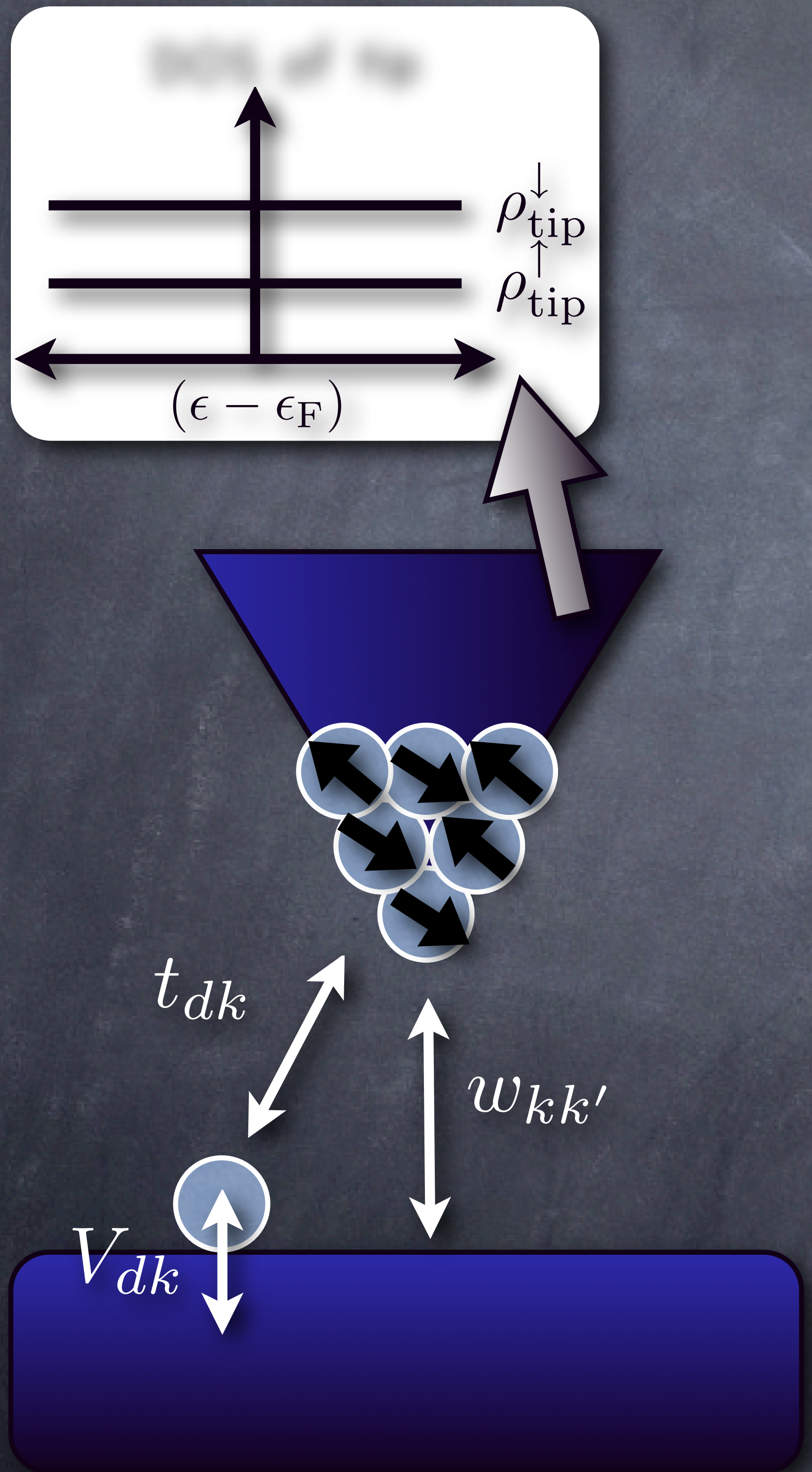

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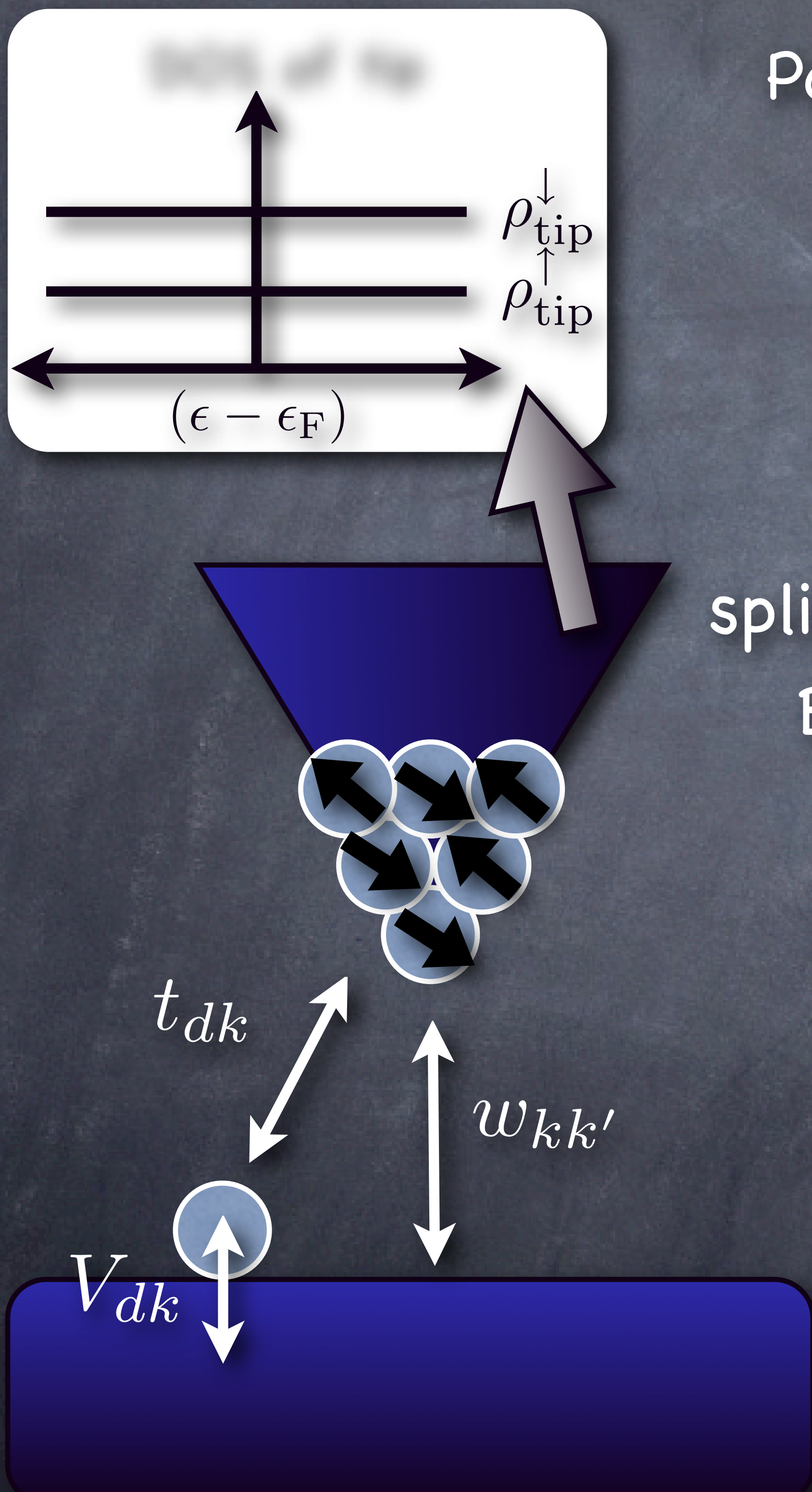


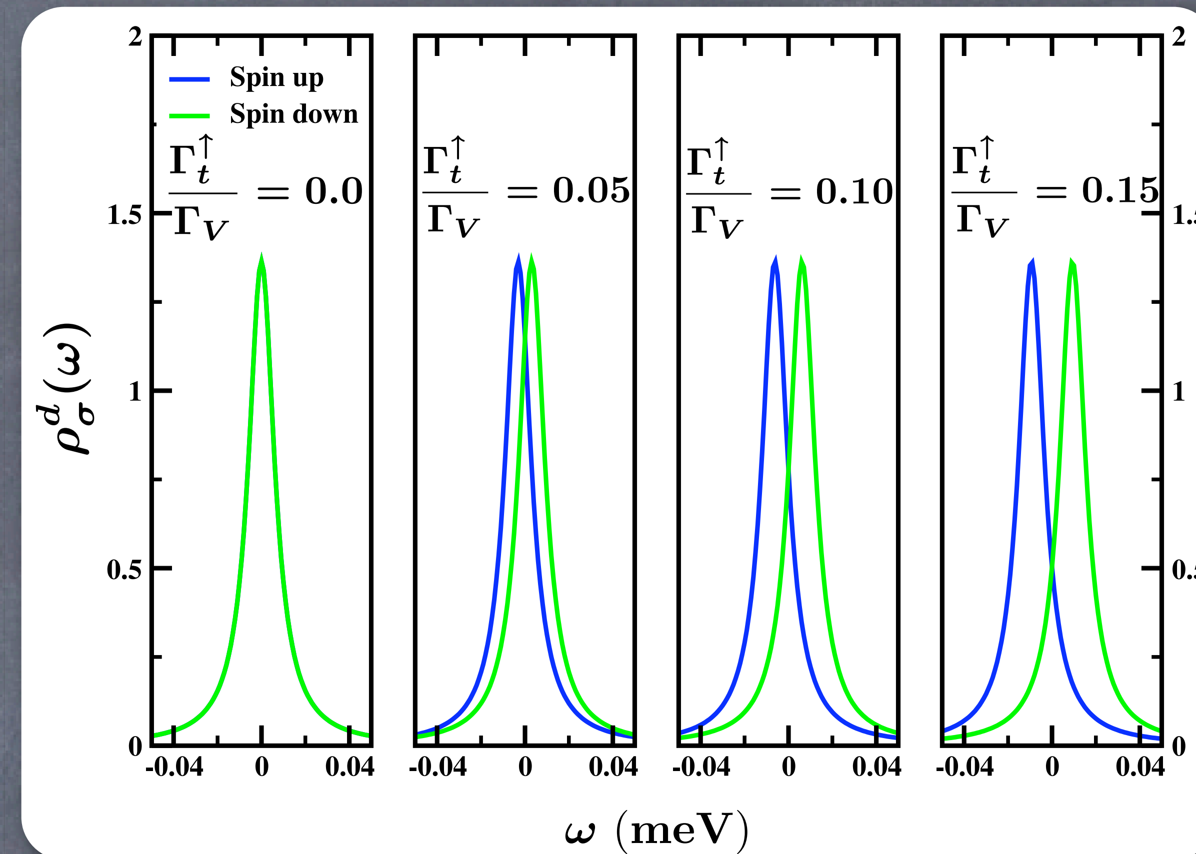
Pol.= 33% spin up

$$\Gamma_V = \pi |V|^2 \rho_{\rm sub}$$
$$\Gamma_t^{\uparrow} = \pi |t|^2 \rho_{\rm tip}^{\uparrow}$$

$$\Gamma_V \approx .2eV$$

splitting $\sim$ few meV

$B_{\rm eff}$ = 60-70 T



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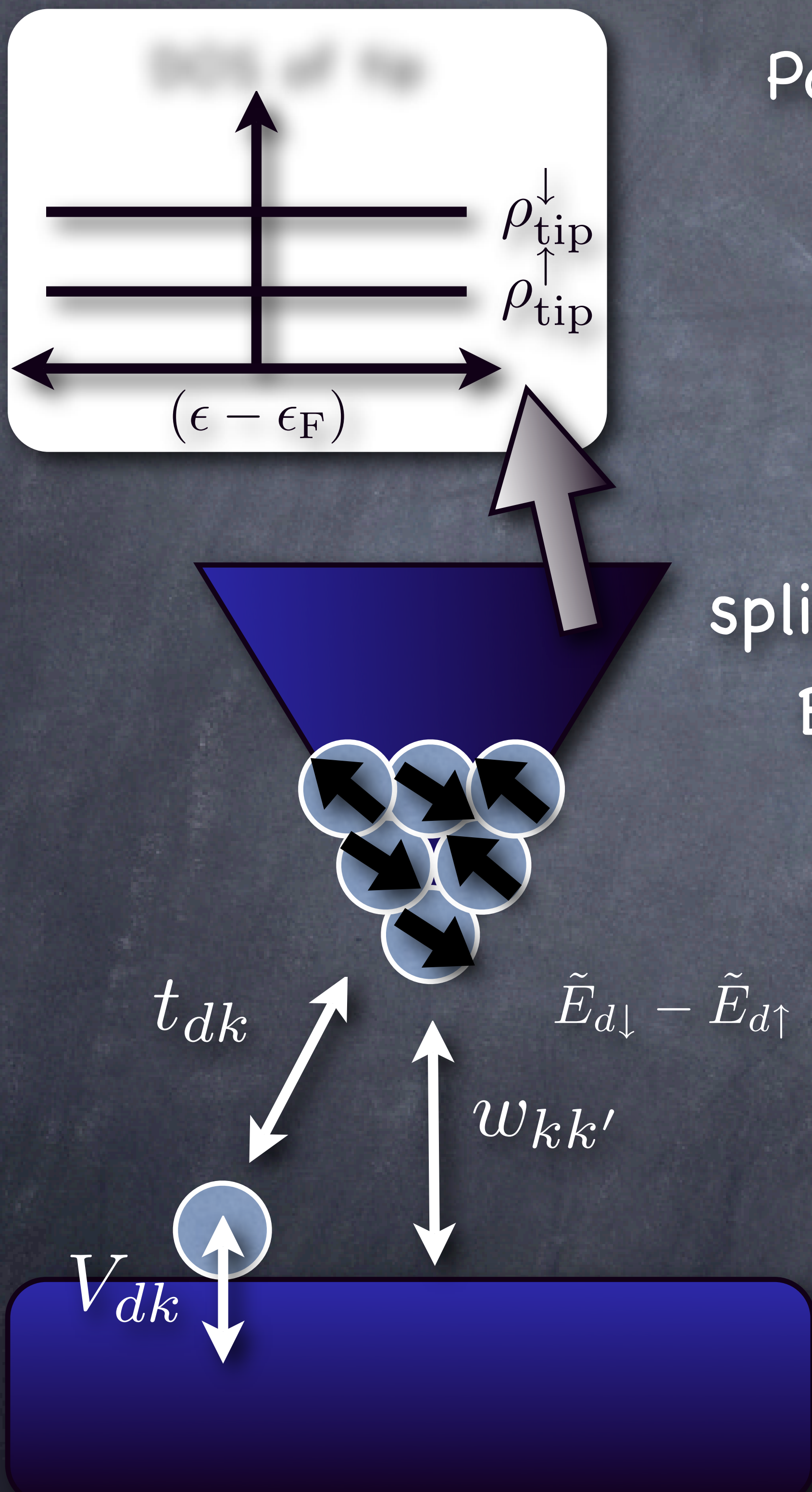

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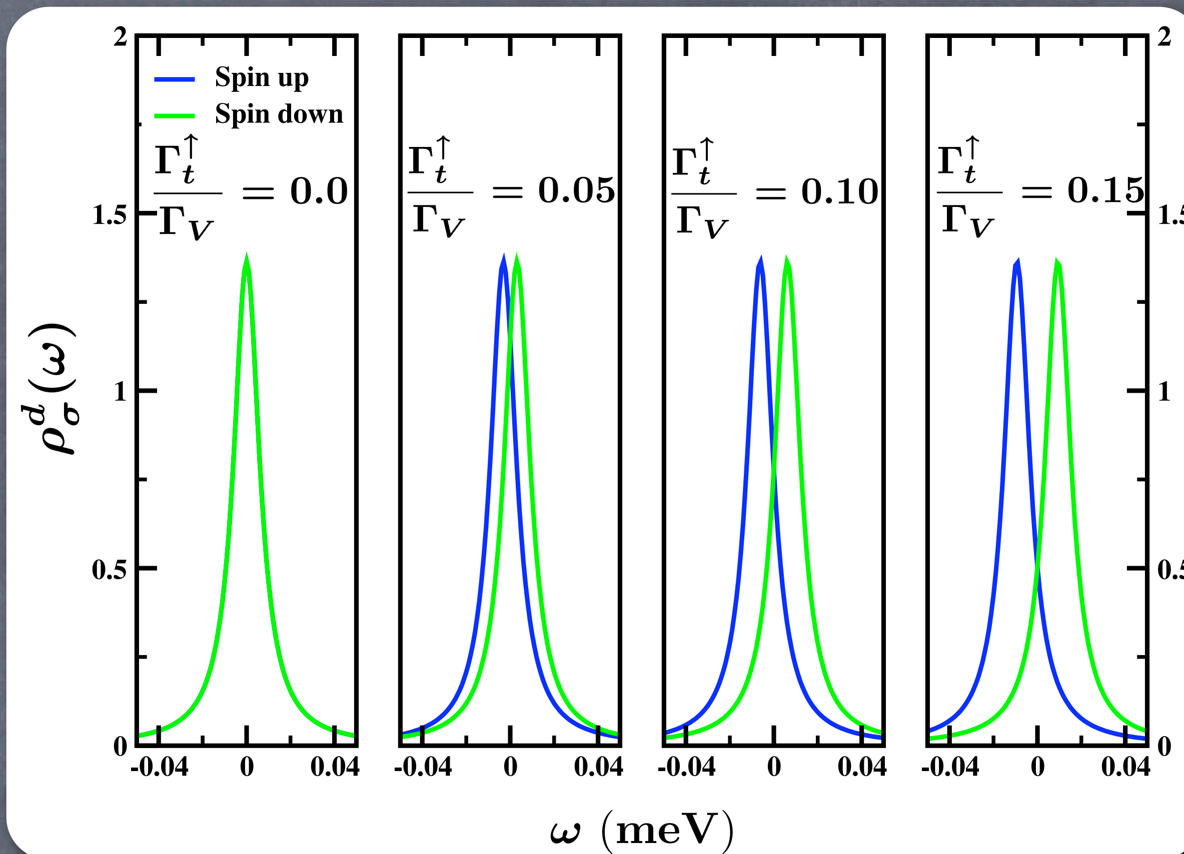
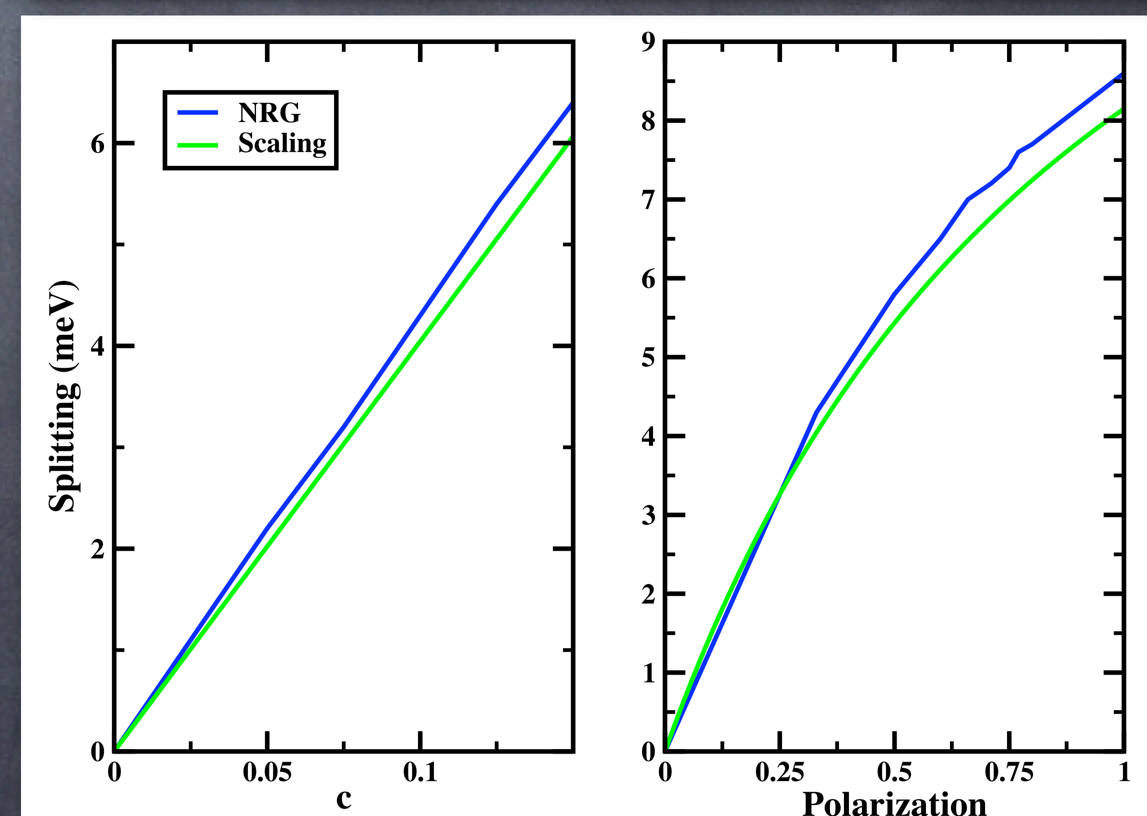
$$\tilde{E}_{d\downarrow} - \tilde{E}_{d\uparrow} \approx \frac{2\Gamma_V}{\pi} c \left(\frac{P_t}{1+P_t} \right) \ln \frac{D_0}{U}$$

$$(c = \Gamma_t^{\uparrow} / \Gamma_V)$$





Results:

Conductance

Pol.= 33% spin up

$$\Gamma_V = \pi |V|^2 \rho_{\rm sub}$$

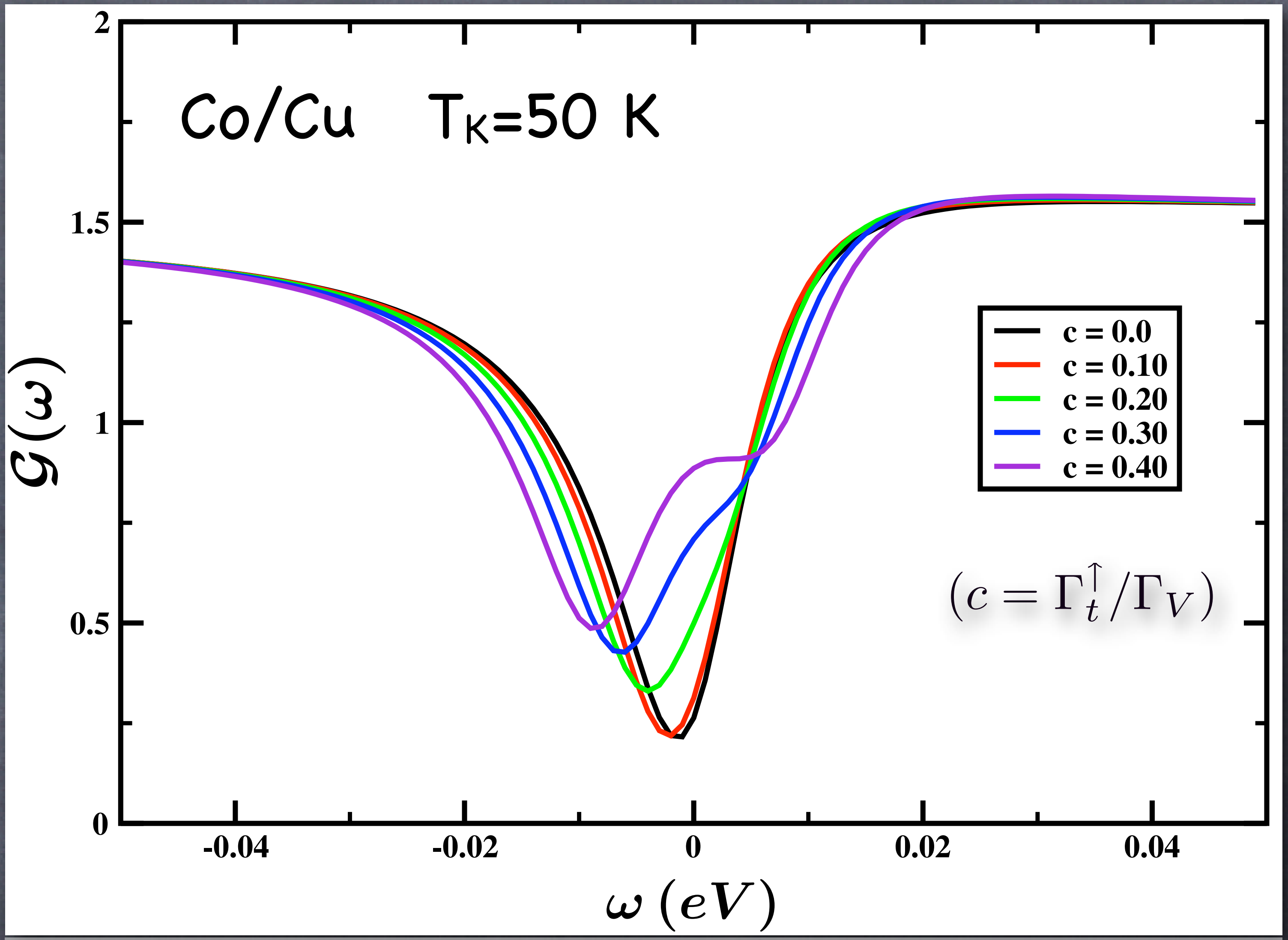
$$\Gamma_t^{\uparrow} = \pi |t|^2 \rho_{\rm tip}^{\uparrow}$$

$$\frac{dI}{d(eV)} \sim \sum_{\sigma} \frac{(q+\epsilon_\sigma)^2}{1+\epsilon_\sigma^2}$$

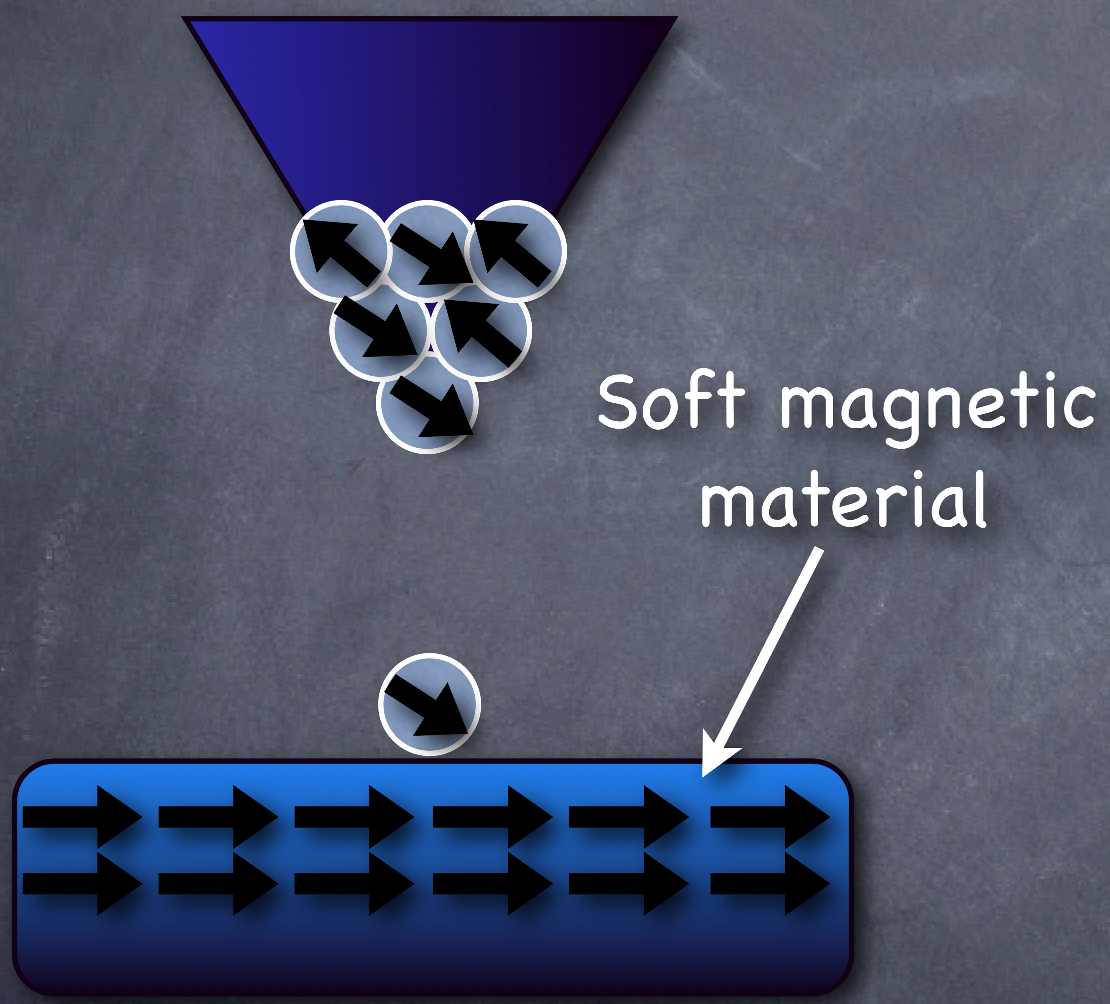
fixed $q = .6$

$$q := \frac{t + wV\mathrm{Re}\left[G_0(\omega)\right]}{\pi w V \rho_{\rm sub}(\omega)}$$

$$\epsilon_\sigma := \frac{\omega - E_d - \mathrm{Re}[\Sigma_d^\sigma(\omega)]}{\mathrm{Im}[\Sigma_d^\sigma(\omega)]}$$



Future Experiments?



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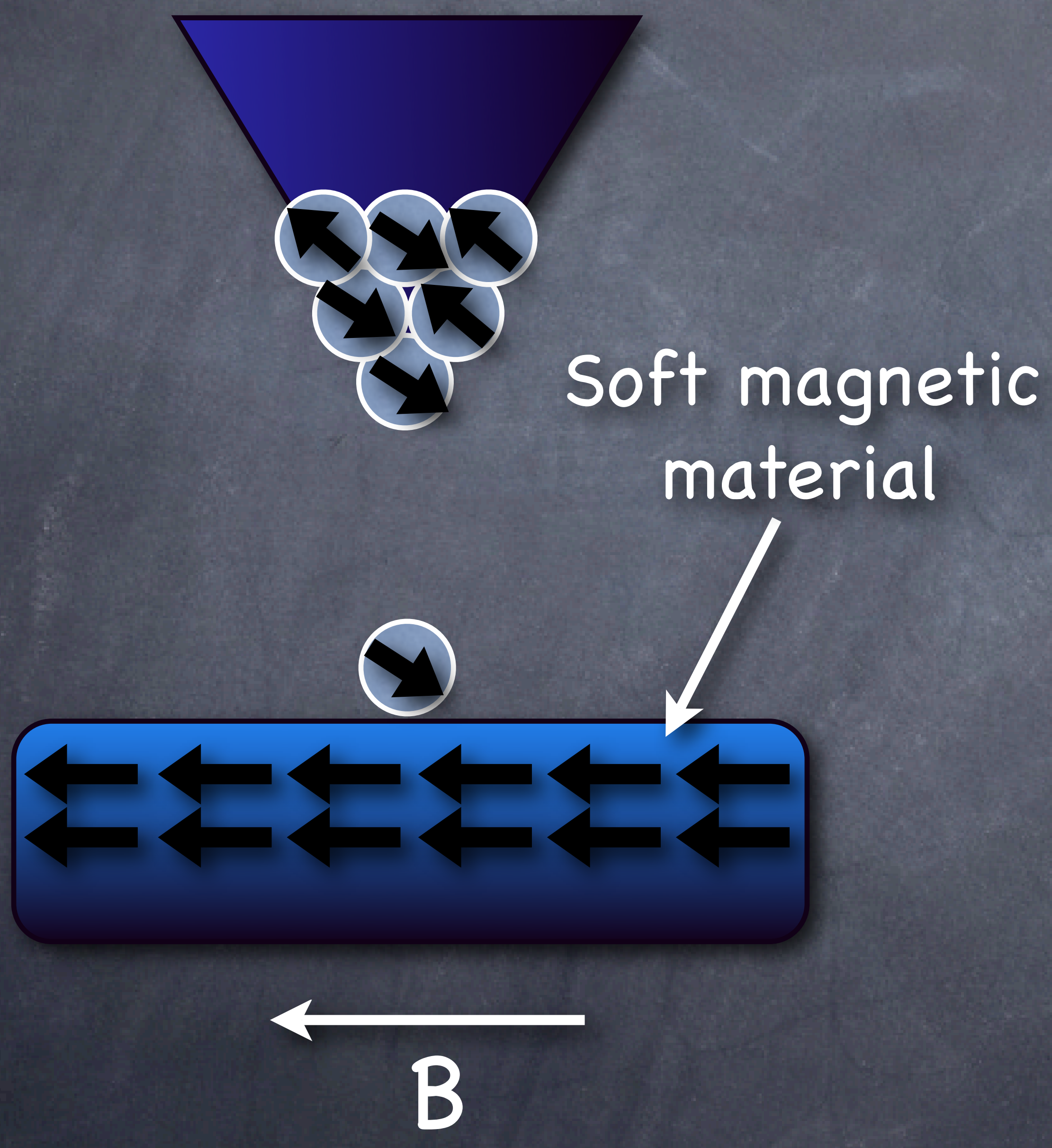

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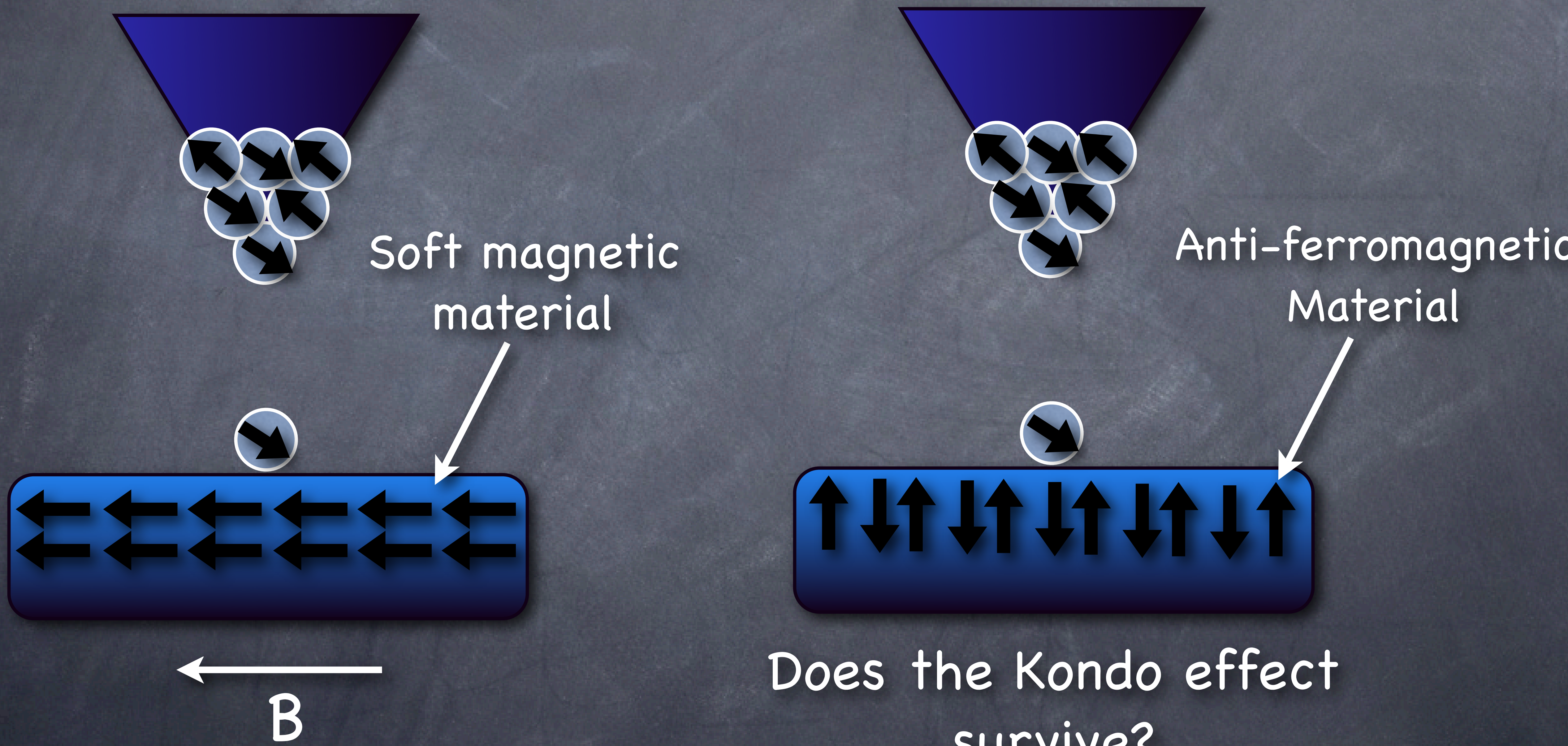

Does the Kondo effect
survive?

Summary

- SP-STM breaks the spin symmetry of a Kondo system (similar to applied magnetic field)
- Leads to splitting of Kondo peak (spin up/down)
- Which in turn splits the Fano resonance of the conductance
- Reference: Phys. Rev. B 76, 100408(R) (2007)

Thank you.