Kondo Enhanced Anderson Localization

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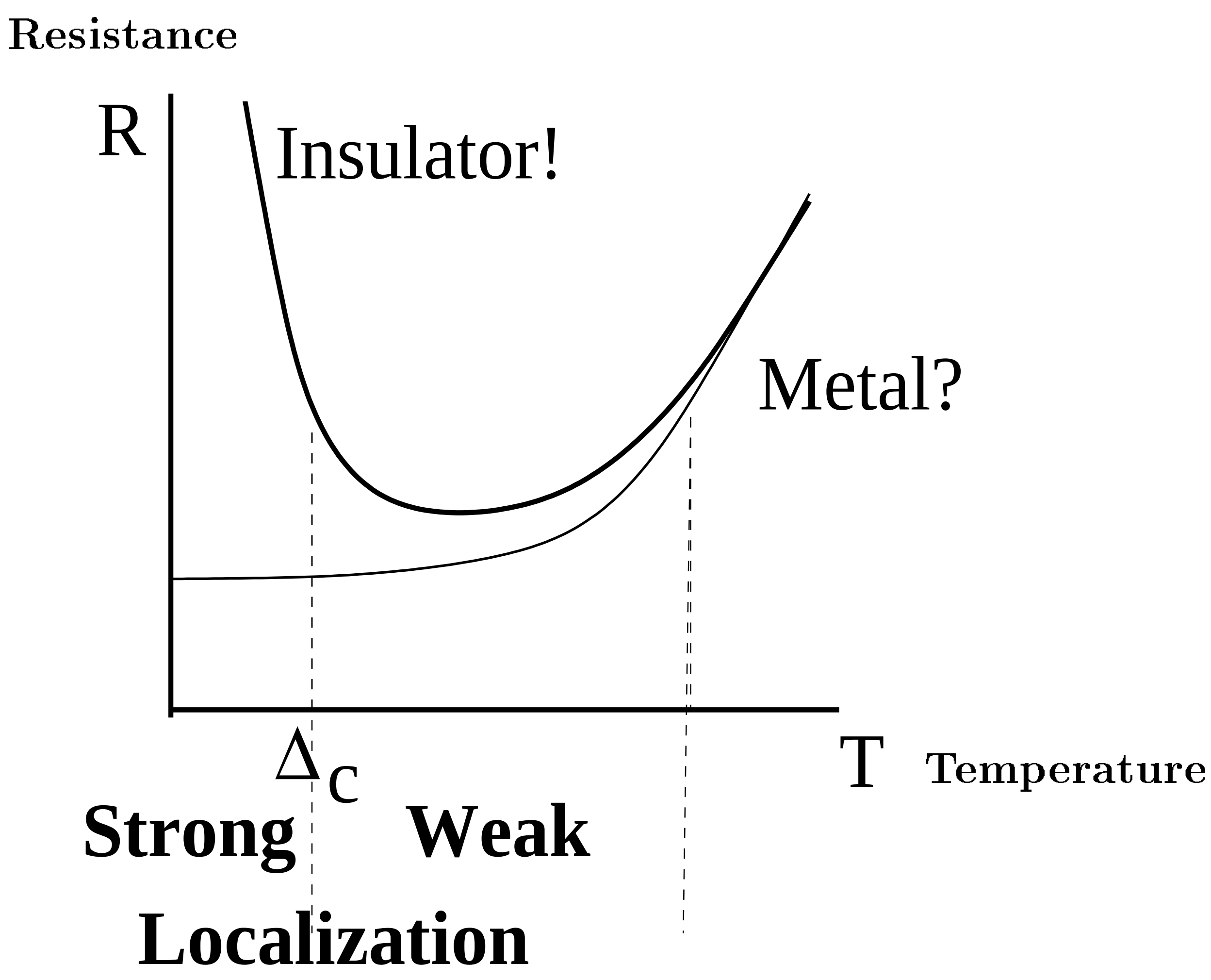
- **(Strong) Anderson Localization**
- **Magnetic Field and Symmetry Dependence of Strong Localization**
- **Kondo Renormalized Spin Scattering Rate**
- **Kondo Enhanced Anderson Localization**
- **Giant Parallel Magnetoresistance**



Metal turns to Insulator for $d \leq 2$

at temperature $T \ll \Delta_c$

Δ_c = Activation energy of insulator

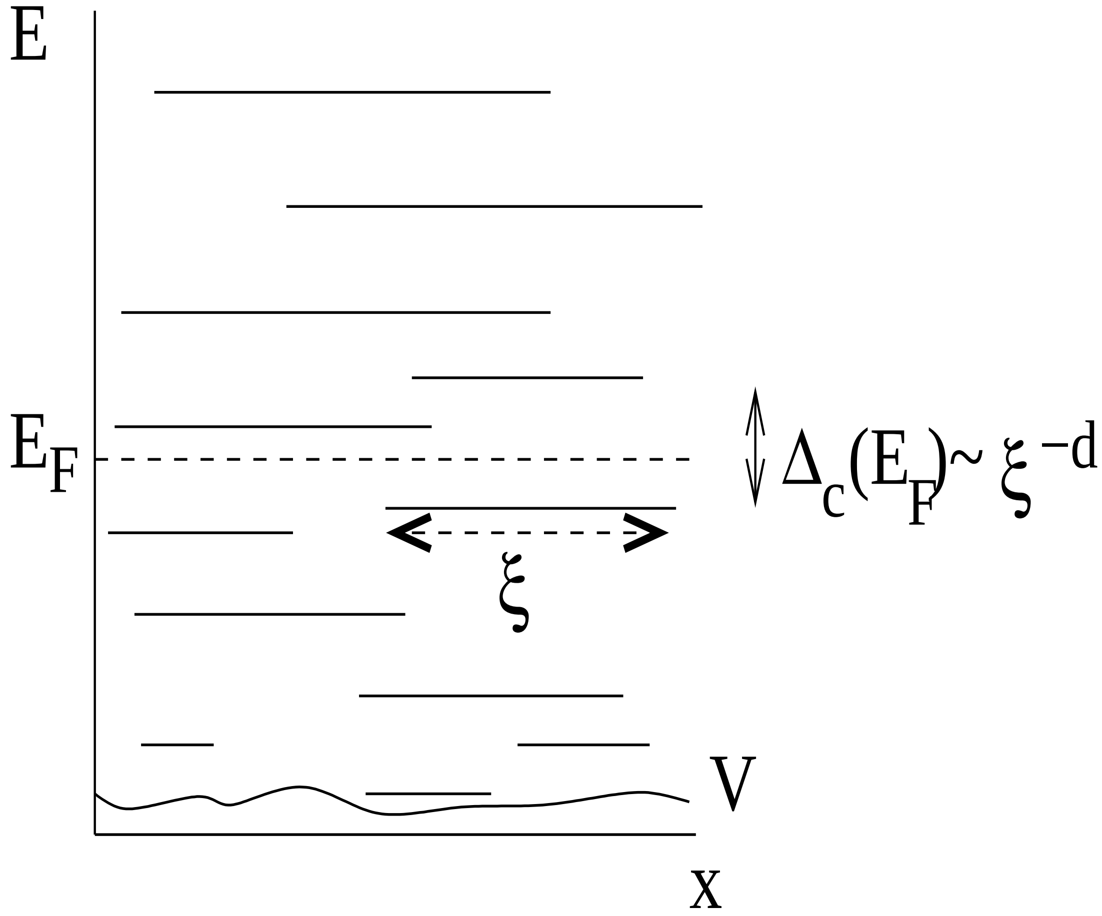
Even at weak disorder

$$g = k_{\mathrm{F}} l > 1$$

l = **elastic mean free path**

when classically Metal

Quantum Mechanical Localization:



$$(H_0 + V)\psi = E\psi$$

At $T < \Delta_c$: Strong quantum mechanical Localization in $d \leq 2$ for arbitrarily small disorder potential V. When $T > \Delta_c$: Only Weak localization corrections to resistance.

Magnetic Field and Symmetry Dependence of Strong Localization

Magnetic field breaks Time Reversal Symmetry

$\Rightarrow$ localization length ξ becomes larger:

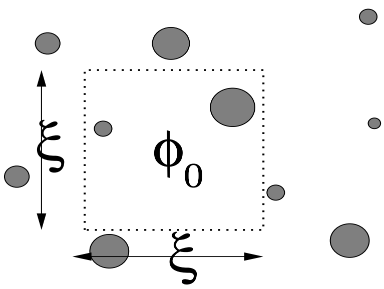
In 2D ($\xi < W$) Exponential enhancement of ξ:

Orthogonal: $\xi = (g/k_F)\exp(\pi g/2)$

$\Downarrow$

Unitary: $\xi = (g/k_F)\exp(\frac{1}{4}\pi^2 g^2)$

for $B\xi^2 > \phi_0$



Wegner '79, Hikami '80

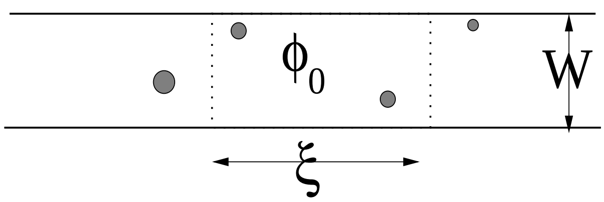
In 1 D ($\xi > W$) Doubling of ξ :

Orthogonal: $\xi = \frac{1}{2}gW$

$\Downarrow$

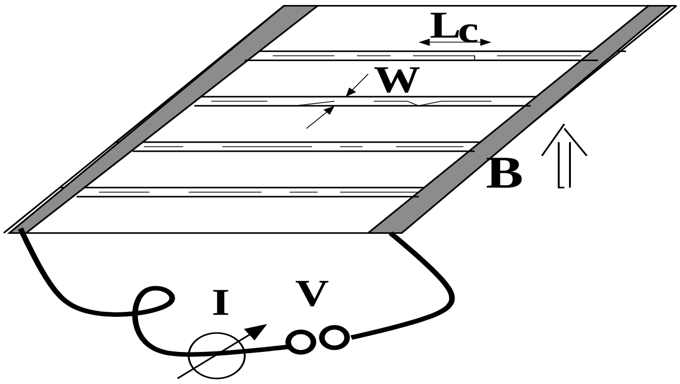
Unitary: $\xi = gW$

for $B\xi W > \phi_0$



Efetov, Larkin '83; Dorokhov '83

Experimental Observation of Strong Quantum Localization in Low-Mobility Quantum Wires



Electrons

- **Tunnel**

$\sim \exp(-L/\xi)$

or

- **Hop activatedly**

$\sim \exp(-\Delta_c/T)$

$\rightarrow$ **Mott variable range hopping (VRH)**

$$\boxed{R(T) = R_0 \exp[(\gamma(\Delta_c/T)^{1/2}]}$$

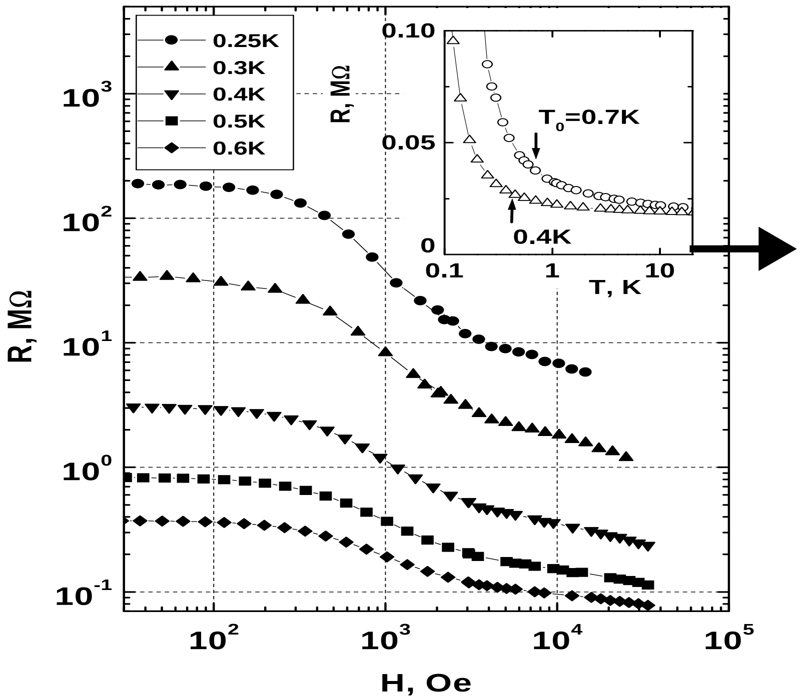
For $\xi > W$ (= Quasi–1–D) activated Resistance

$$\boxed{R \sim R_0 \exp(\Delta_c/2T)}$$

for $T_1 = \frac{\Delta_c}{2\ln(L/L_c)} < T < \Delta_c$

(Kurkijarvi ’73, P. A Lee ’84; Raikh, Ruzin, ’89)

$\Rightarrow$ **Activation gap** $\Delta_c(B)$



Circle: $B = 0$

Triangle: $B = 17kG$

width $W = .05\mu$

length $L = 100\mu$

mean free path $l = .02\mu$

$g = k_{\rm F} l \approx 3$

mobility $\mu = 1000 cm^2/Vs$

(Khavin, et al. PRL 81, 1066 (1998), PRB 58, 8009 (1998) , also: J. Pichard, M. Sanquer, et al. PRL 65, 1812 (1990))

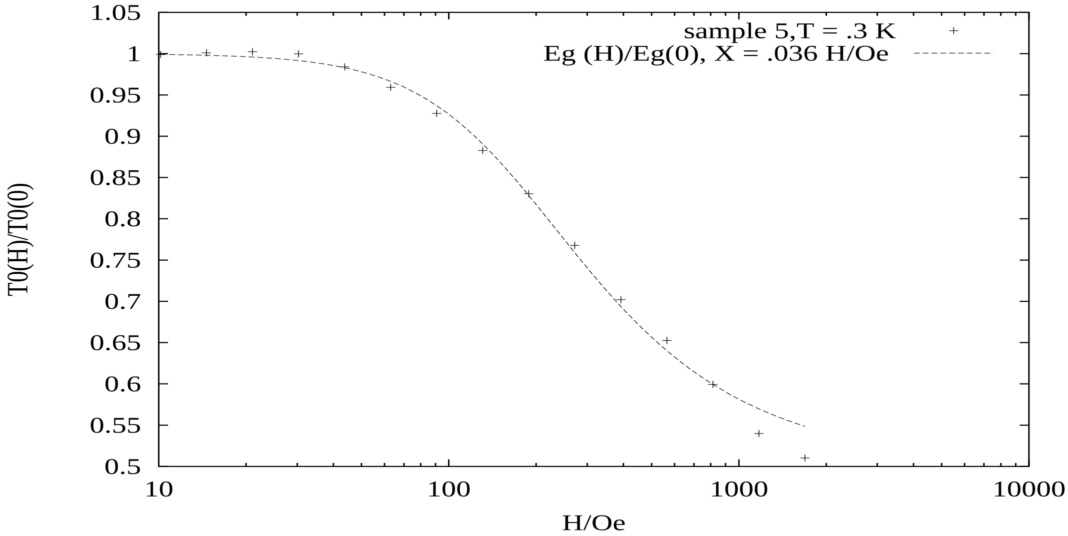
$\Rightarrow$ Magnetic field dependent Activation Gap $k_{\rm B} T_0 = \Delta_c = (\nu_2 W \xi)^{-1}$

$\Rightarrow$ Magnetic field dependent Localization Length

$\xi(B)$

from Exponentially Large Negative Magneto-resistance

Magnetic field dependent gap of compact field theory E_g in comparison with experimental activation energy Δ_c



$X = 2\pi\phi/\phi_0$, $\phi = \mu_0 H\xi W/\sqrt{12}$ = **Magnetic Flux through Area of Localized State.**

$$E_G(X) = 4(2 + \sqrt{49 + X^2} - \sqrt{25 + X^2})/\xi.$$

= Energy gap of Compact Nonlinear Sigma–model

$$F[Q] = \frac{1}{16}\xi \int_0^L \mathbf{d}x\mathbf{Tr}\left[(\nabla_x Q(x))^2 - X^2[Q,\tau_3]^2\right]$$

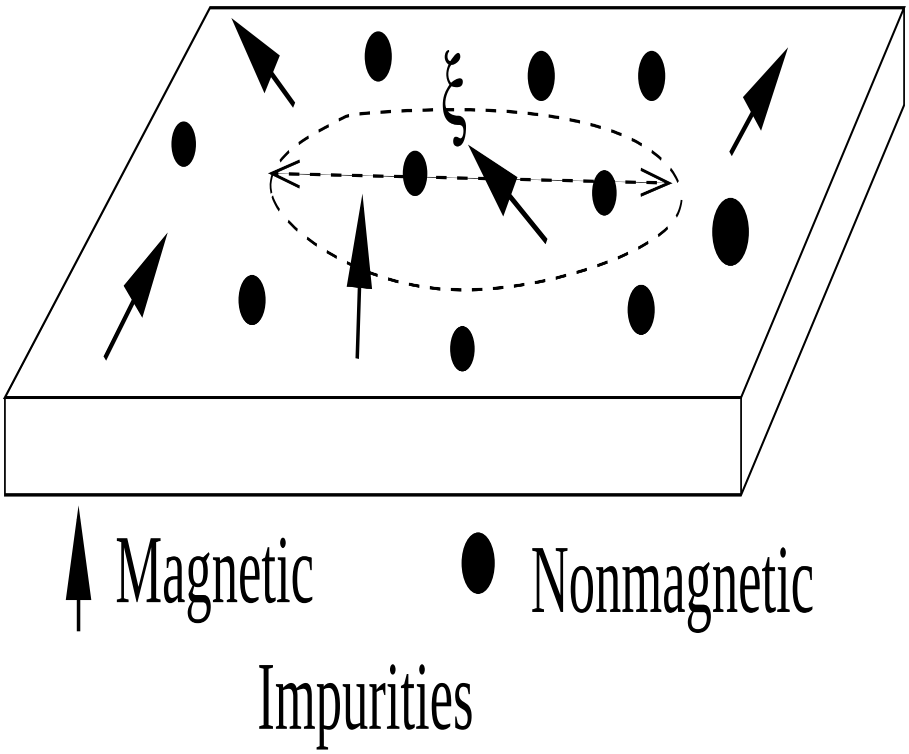
where $\xi = gW$**, and** Q **are compact symmetry dependent matrices with** $Q^2 = 1$**.**

proportional to the Activation energy $T_0(H)/T_0(0) \sim 1/\xi(H)$

S.Kettemann, PRB Rapid Communications 62, 1382 (2000);

S. K., R. Mazzarello, Phys. Rev. B **65** *085318 (2002)*

Anderson Localization in the Presence of Magnetic Impurities



Crossover to Unitary Localization when

$$\boxed{\xi^2 > D\tau_s}$$

D **diffusion constant**

Strong localization governed by magnetic scattering rate $1/\tau_s$ from magnetic impurities

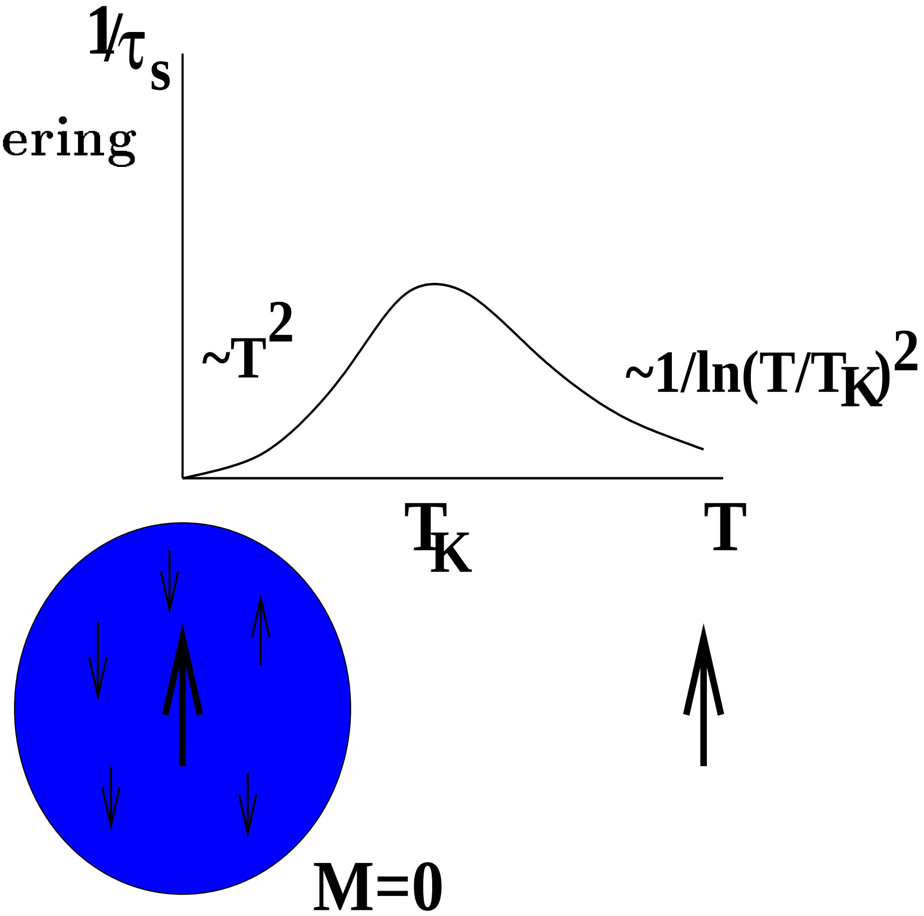
Lee; Hikami, Larkin, Nagaoka (1980)

Kondo Effect: Spin–Scattering rate $1/\tau_s$ dependends on temperature

Impurity–Spin screened by conduction electrons in Kondo Cloud for $T \ll T_K$.

Spin–Scattering Rate

Kondo–Cloud forms Kondo–singlet



- **Fermi Liquid for $T \gg T_K$**

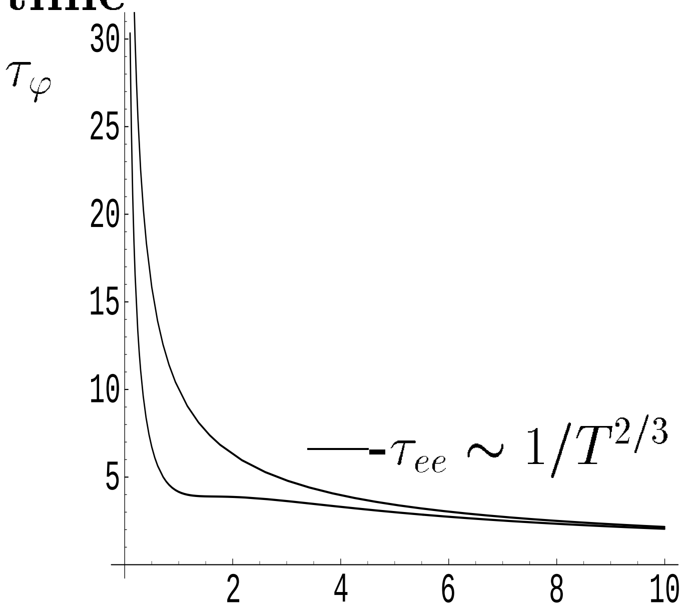
$1/\tau_s$: *Mueller-Hartmann, Zittartz '71* .

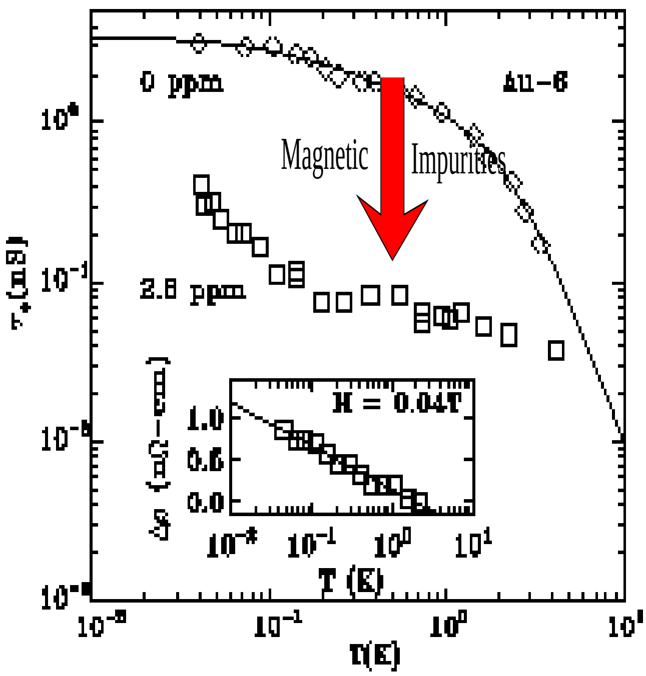
- **Strongly Correlated for $T \approx T_K$ (Kondo).**
- **Fermi Liquid for $T \ll T_K$ (Nozieres '74).**

Kondo Effect on Spin Scattering rate seen in temperature dependence of total dephasing time as obtained from weak localization:

$$\tau_\varphi = \left(\frac{1}{\tau_{ee}} + \frac{2}{\tau_s}\right)^{-1}$$

Dephasing time





T/T_K

Bergmann et al. PRL '84, '87; van Hasendonck et al. PRL '87, Mohanty et al. PRL '97; Schopfer et al. 2002

But: What happens with Strong Localization?

Kondo effect in Quantum Insulator: magnetic + non-magnetic Disorder

Kondo Hamiltonian, or s–d exchange model plus disorder

$$\hat{H} = \sum_{\mathbf{k},\alpha=\pm} \frac{\mathbf{k}^2}{2m} c^+_{\mathbf{k},\alpha} c_{\mathbf{k},\alpha} + \sum_{\mathbf{k},\mathbf{k}',\alpha=\pm} V(\mathbf{k},\mathbf{k}') c^+_{\mathbf{k},\alpha} c_{\mathbf{k}',\alpha}$$
$$+ \sum_{\mathbf{k},\mathbf{k}'} J(\mathbf{k},\mathbf{k}')[S^+ c^+_{\mathbf{k},-} c_{\mathbf{k}',+} + S^- c^+_{\mathbf{k},+} c_{\mathbf{k}',-}$$
$$+ S_z (c^+_{\mathbf{k},+} c_{\mathbf{k}',+} - c^+_{\mathbf{k},-} c_{\mathbf{k}',-})].$$

J = AF exchange coupling

Kondo problem has exact solution without electrostatic disorder potential $V(\mathbf{x}) = 0$.

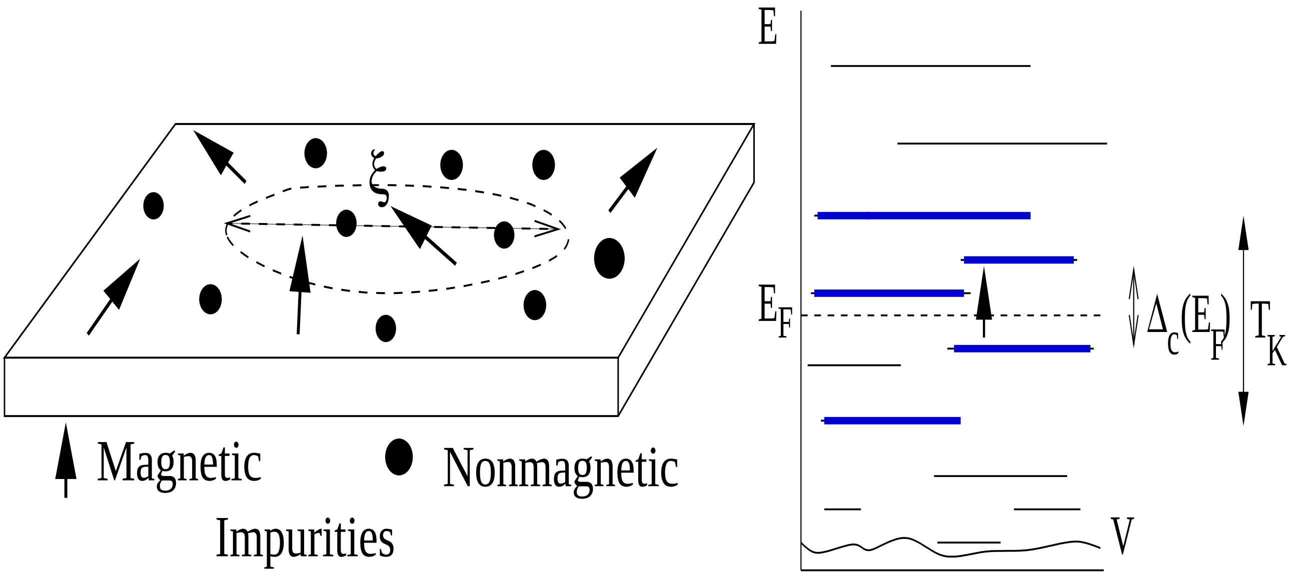
(*Wiegman, Tsvelik 1981, Andrei 1981*)

But what if $V(\mathbf{x}) \neq 0$?

Non-perturbative Treatment?

Very Complex Many-Body Problem!

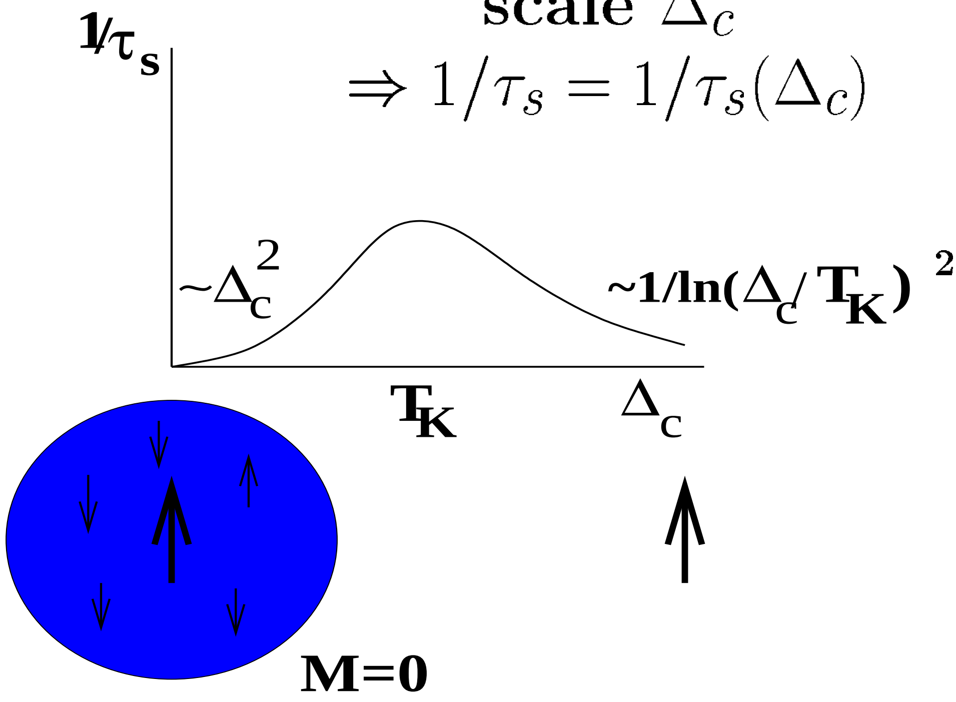
Kondo effect
in the Anderson Insulator Box



Kondo impurity communicates with finite number of Electron States

For $T < \Delta_c = 1/\nu\xi^2$: Kondo Renormalization stopped by energy scale Δ_c

$$\Rightarrow 1/\tau_s = 1/\tau_s(\Delta_c)$$

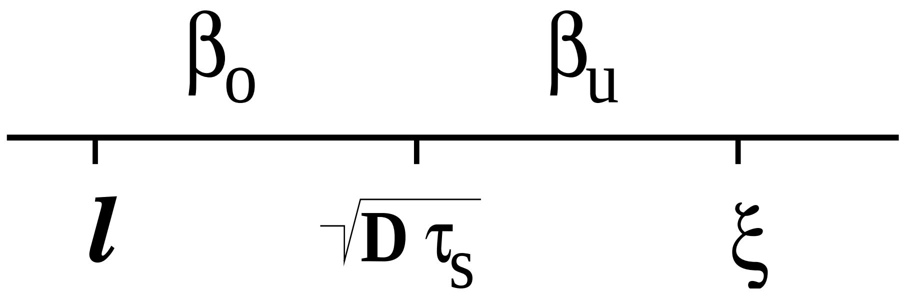


$\Rightarrow 1/\tau_s(\xi)$ **depends on localization length** ξ**!**

But: localization length ξ **depends itself on** $1/\tau_s$**!**

$\Rightarrow$ **Self consistent equation** $\xi(\tau_s)$**.**

Find $\xi(\tau_s)$ **from Integration of beta function** $\beta(g) = \frac{d \ln g}{d \ln L}$**:**



Approximate $\beta(\tau_s)$**:**

$\beta_O = -\frac{2}{\pi g}$ **for** $l < L < \sqrt{D\tau_s}$

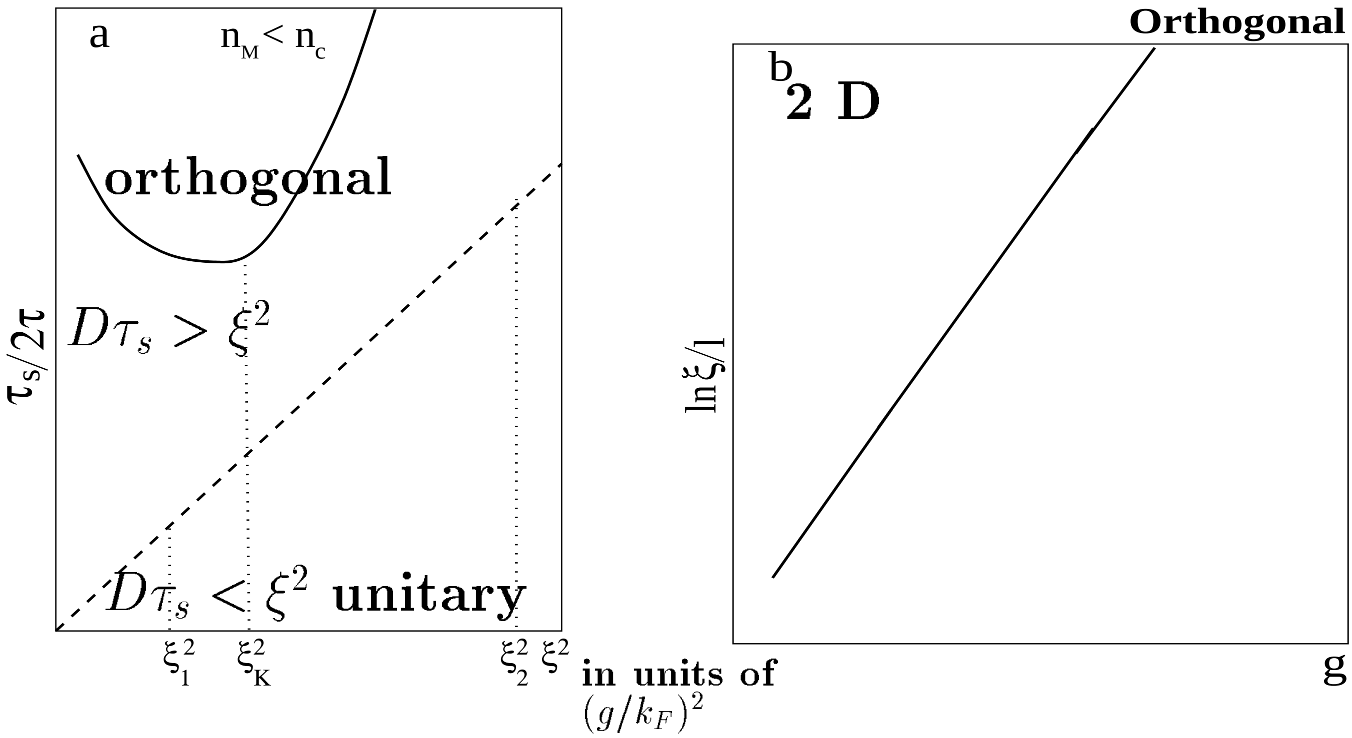
$\beta_U = -\frac{1}{2\pi g^2}$ **for** $\sqrt{D\tau_s} < L < \xi$**.**

Integration from shortest length scale l **to localization length** ξ **yields:**

$$\boxed{\ln\left(\frac{\xi}{l}\right) = \frac{1}{2}\ln\left(\frac{\tau_s}{\tau}\right) + \left[\pi g - \ln\left(\frac{\tau_s}{\tau}\right)\right]^2}$$

compare: Imry, Lerner 1995

Kondo enhanced Localization at small concentration of magnetic impurities

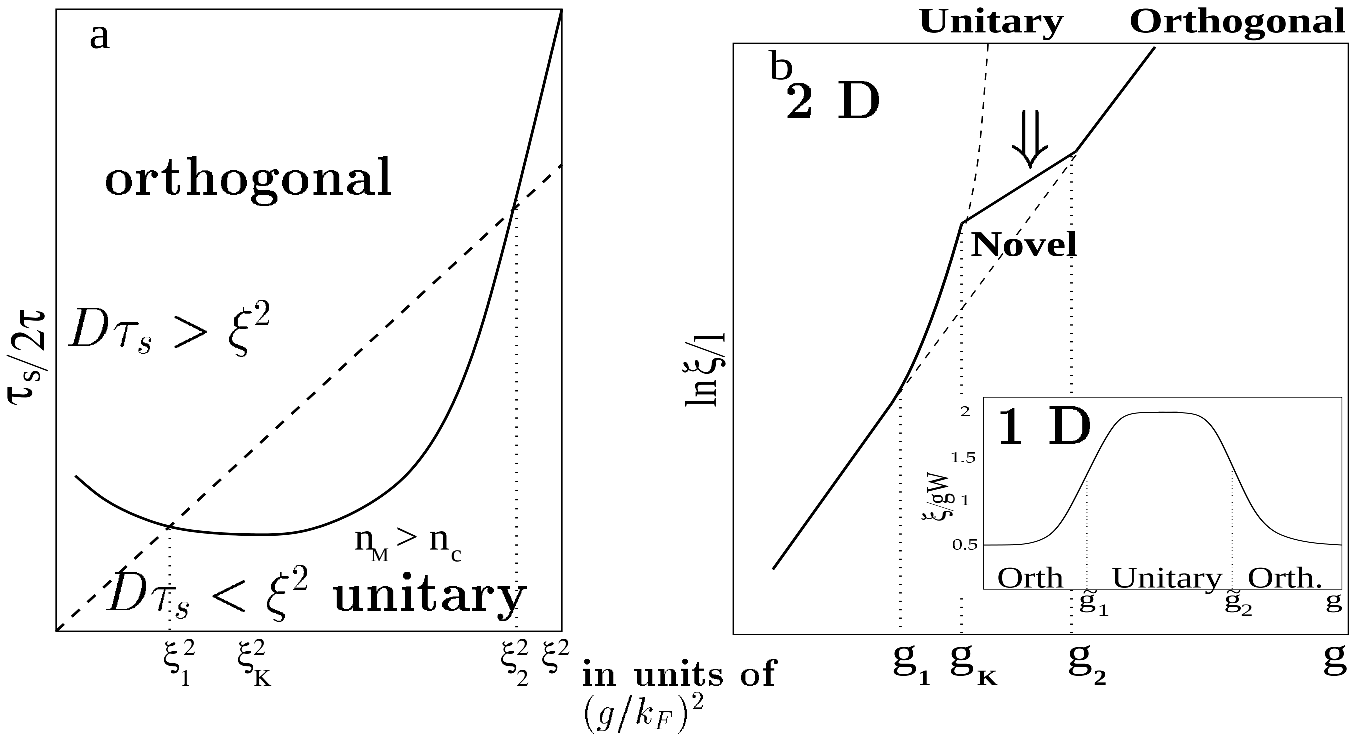


Localization remains orthogonal when concentration of magnetic impurities

$$n_M < n_c = \frac{n_e}{\pi}\left(\frac{T_K}{E_F}\right)\ln\left(\frac{E_F}{T_K}\right)$$

S. Kettemann, M. Raikh, cond-mat/0209309 (2002)

Kondo enhanced Localization at Large concentration of magnetic impurities



Novel regime of Localization: $\xi \sim \exp(\frac{\pi}{4}g)$,
when concentration of magnetic impurities

$$n_M > n_c = \frac{n_e}{\pi}\left(\frac{T_K}{E_F}\right)\ln\left(\frac{E_F}{T_K}\right)$$

Due to Interplay of

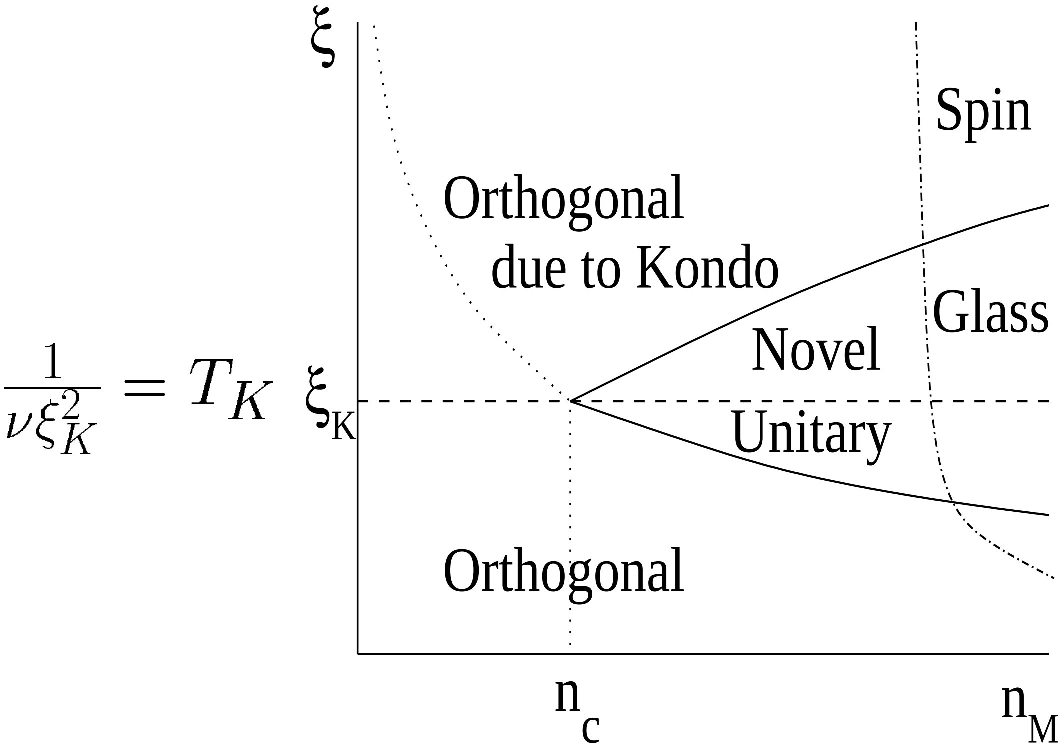
Hubbard Interaction

(→ RKKY exchange J and Kondo Temperature $T_K = E_F \exp(1/(\nu J))$)

and Quantum Interference (→ Δ_c)

S. Kettemann, M. Raikh, cond-mat/0209309 (2002)

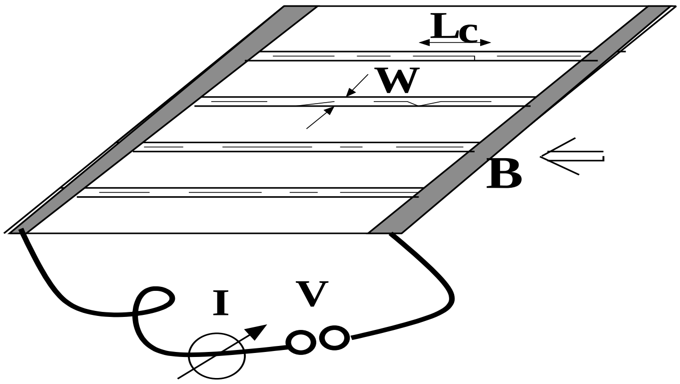
Phase Diagram of Localization in the presence of Kondo Impurities



- $n_M < n_c$: **orthogonal localization for all conductances** g
- $n_M > n_c$: **Unitary and novel localization exists**
- **Kondo Spins are frozen, when RKKY exchange interaction** $\sim E_F/\ln^2(E_F/T_K)\, r^2$ **between magnetic impurities at distance** r **exceeds** $T_K \Rightarrow$ **Spin Glass Phase.**

Giant Parallel Magnetoresistance

For $0K < k_{\rm B}T < \Delta_{\rm C}$, Electrons



- **Tunnel**

$\sim \exp(-L/\xi)$

or

- **Hop activatedly**

$\sim \exp(-\Delta_c/T)$

$\rightarrow$ Mott variable range hopping (VRH)

$$\boxed{R(T) = R_0 \exp[(\gamma(\Delta_c/T)^{1/2}]}$$

For quasi-1-D, $\xi > W$: $\Delta_c = 1/\xi(\tau_s)W\nu$. Localization affected by small parallel magnetic field $g_s B \sim \Delta_c$!

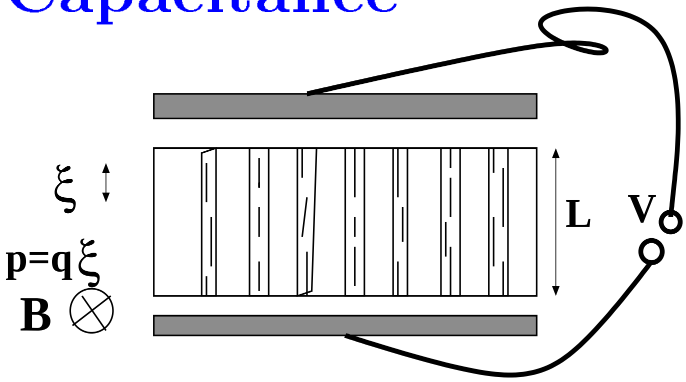
Choose small width W, dirty metal (small g) with large Kondo Temperature T_K.

Possible Candidate: doped $In_2O_{3-x} : Au$

$$T_K = .7K$$

Ovadyahu PRB 63 (2001)

- Capacitance



Dipole moment $p = q\xi$

Crossection S

- Metal: Conduction electrons screen electrical fields $\rightarrow$ dielectrical function diverges:

$\epsilon(q \Rightarrow 0, \omega = 0) \sim q^{-2} \sim L^2$

- Insulator: localized electrons yield Dipole moment $p = qL_{\mathrm{C}}$ for $\Delta_c > T$. $\Rightarrow$

$$\boxed{\epsilon(q \rightarrow 0, \omega = 0) \sim e^2 \nu L_{\mathrm{C}}^2.}$$

Efetov, Larkin (1983), Lee, Ramakrishnan (1987).

$\Rightarrow$ **Kondo-reduced-Capacitance**

$$\boxed{C(1/\tau_s) = \epsilon_0 \epsilon(\xi) S/L \sim \xi^2(1/\tau_s)},$$

Allows direct measurement of localization length ξ.

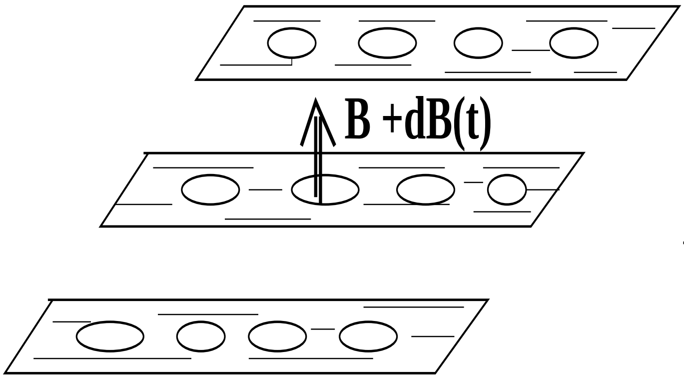
- **Landau–Diamagnetism** $\omega_c \tau \ll 1$

$$\boxed{\chi_L = -n_e \frac{e^2}{K_d \pi^2 m^*} \lambda_F^2} \quad (K_3 = 16,\ K_2 = 12).$$

Insensitive to Localisation since $\xi > \lambda_F$!

Compare with Langevin-diamagnetism,

$$\chi_{Dia} = -Z n_A \frac{e^2}{6 m_e} < r^2 > .$$



Diffusive Antidot lattice or mesoscopic rings with cicumference L_R and diffusive width W

Interplay between Quantum localization and mesoscopic Persistent Currents

Surprise: Large Persistent Diamagnetism due to Localization (non dissipative)!

$$\boxed{\chi \sim \chi_L \frac{L_R^2}{W^2} \gg \chi_L .}$$

in Magnetic field $B + \delta B(t)$, Frequency $1/\nu S L < \omega < \Delta_c$, $T < \Delta_c$ *(S. Kettemann, K. B. Efetov, PRL '95)*

Conclusions

- **Nonperturbative Theory of Anderson Localization with Kondo Impurities**
- **Localization remains orthogonal for small** $n_M < n_c$
- **Reentrant behaviour of localization for** $n_M > n_c$
- **Novel Localization (neither unitary nor orthogonal) for** $\Delta_c < T_K$
- **Giant Parallel Magnetoresistance: Parallel Magnetic field controls Kondo enhanced Localization.**