Resistive anomaly at the Curie temperature in disordered itinerant ferromagnets

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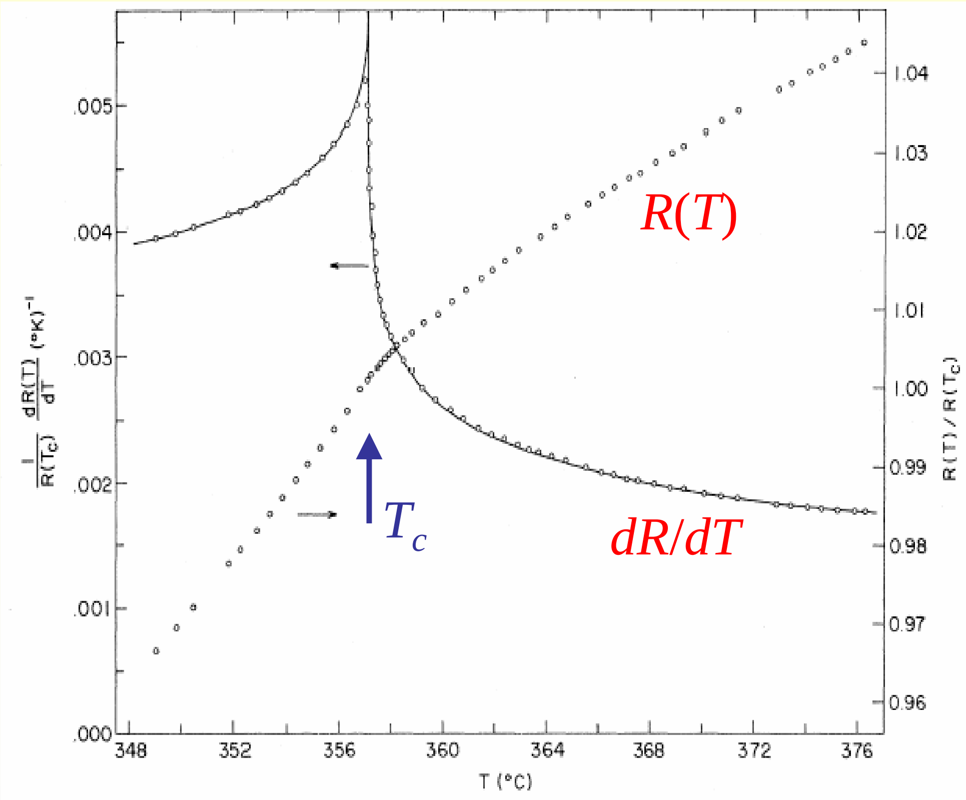
C.T., M.E.R. & F.v.O., PRL 94, 036602 (2005)

Resistive anomaly: Experiments

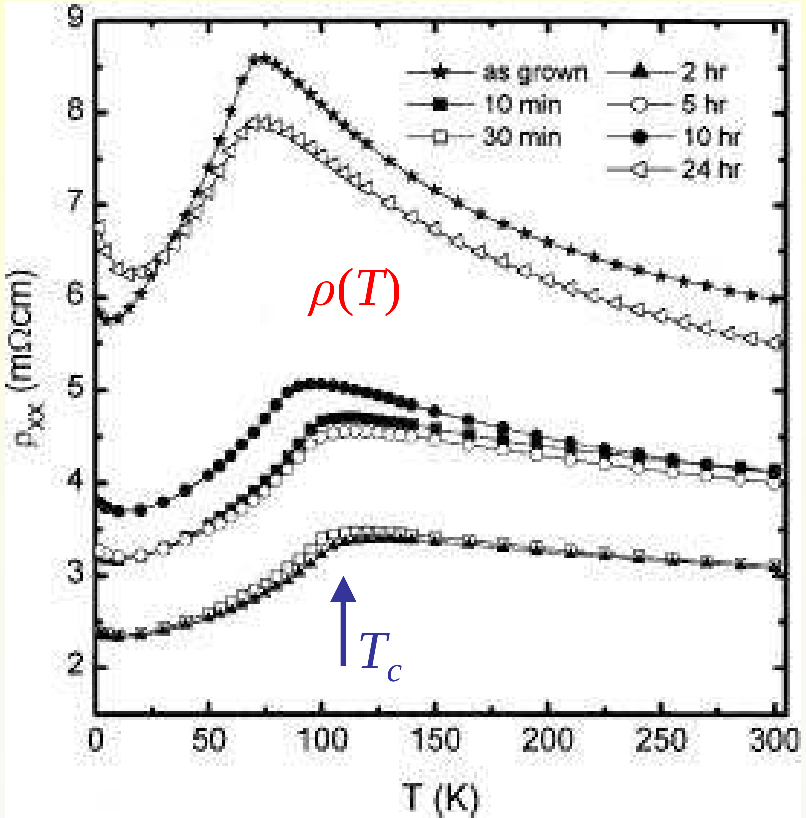
Zumsteg & Parks, PRL **24**, 520 (1970):

Ni



Potashnik *et al.*, APL **79**, 1495 (2001):

(Ga,Mn)As



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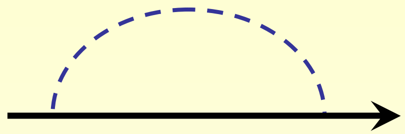
Resistive anomaly: Theory

(for paramagnetic regime, $T > T_c$)

de Gennes and Friedel, J. Phys. Chem. Solids **4**, 71 (1958):

- scattering from magnetic fluctuations
- close to T_c: critical slowing down $\longrightarrow$ static, elastic



$$\frac{1}{\tau_{qp}} = -2\,\mathrm{Im}\,\Sigma^R(\mathbf{k}_F, 0)$$

Approach equivalent to:

- perturbation theory, similar to inverse quasiparticle lifetime, but transport rate involves factor $1 - \cos\theta \propto q^2$
- anomaly from small momentum transfers q

$$\Delta\rho \sim \frac{1}{\tau_{\mathrm{trans}}} \propto \int_0^{2k_F} dq\, \frac{q^3}{t + q^2} \qquad t = \frac{T - T_c}{T_c} > 0$$

Ornstein/Zernicke

$\Rightarrow$ $\Delta\rho \propto t \ln t$ (sharp maximum)

Fisher and Langer, PRL **20**, 665 (1968):

disorder damping for large length scales $\leftrightarrow$ small q: electronic Green function decays exponentially on scale l (mean free path)

- no de Gennes-Friedel singularity from small q
- weak singularity from large $q \approx 2k_F$, have to go beyond Ornstein/Zernicke:

$$\Delta\rho \sim \frac{1}{\tau_{\text{trans}}} \propto \text{const} + t^{1-\alpha}$$

α: **small** anomalous specific-heat exponent

Equivalent to a Boltzmann equation approach, disorder and magnetic scattering treated on equal footing

Problem:

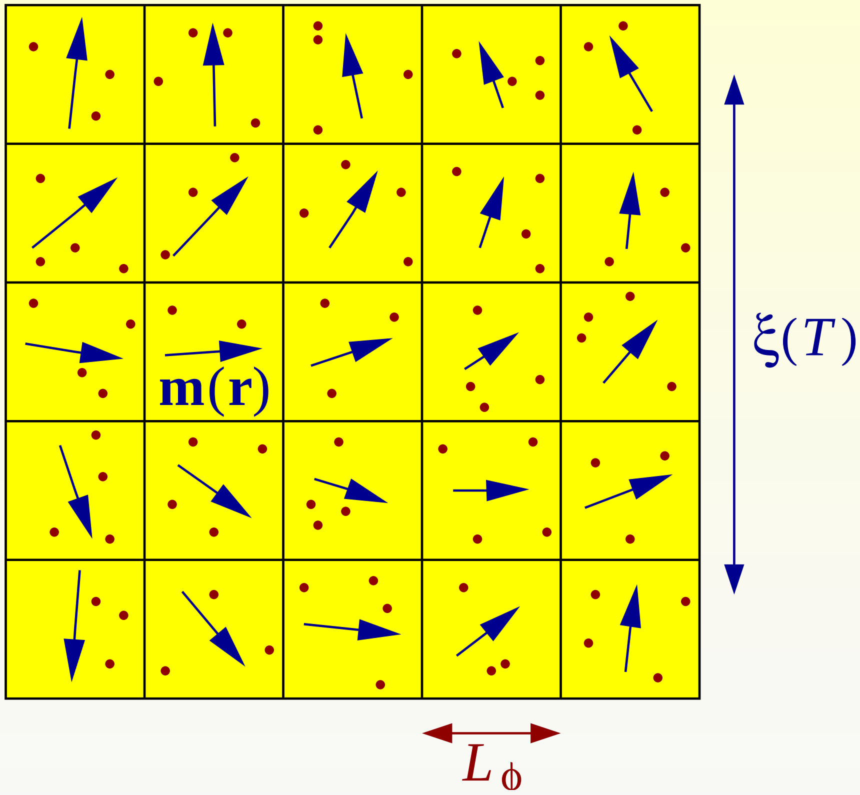
fails for magnetic correlation lengths $\xi(T) \gg l$ (mean free path),

magnetization variations are explored by diffusive carriers

Beyond the Boltzmann approach:

(1) Description of transport on large length scales
$r \gg L_\phi$ (phase coherence length):

3D resistor network



- magnetization ~ constant in cells
- conductivity of network:

$$\sigma_{\text{eff}} = \langle\sigma\rangle - \frac{\langle\delta\sigma(\mathbf{r})^2\rangle}{3\langle\sigma\rangle}$$

$$\delta\sigma(\mathbf{r}) = \delta g(\mathbf{r}, E_F, \mathbf{m}(\mathbf{r}))/L_\phi$$

- spatial average
- large system:
  equivalent to average over
  - quenched disorder
  - magnetization (thermal)

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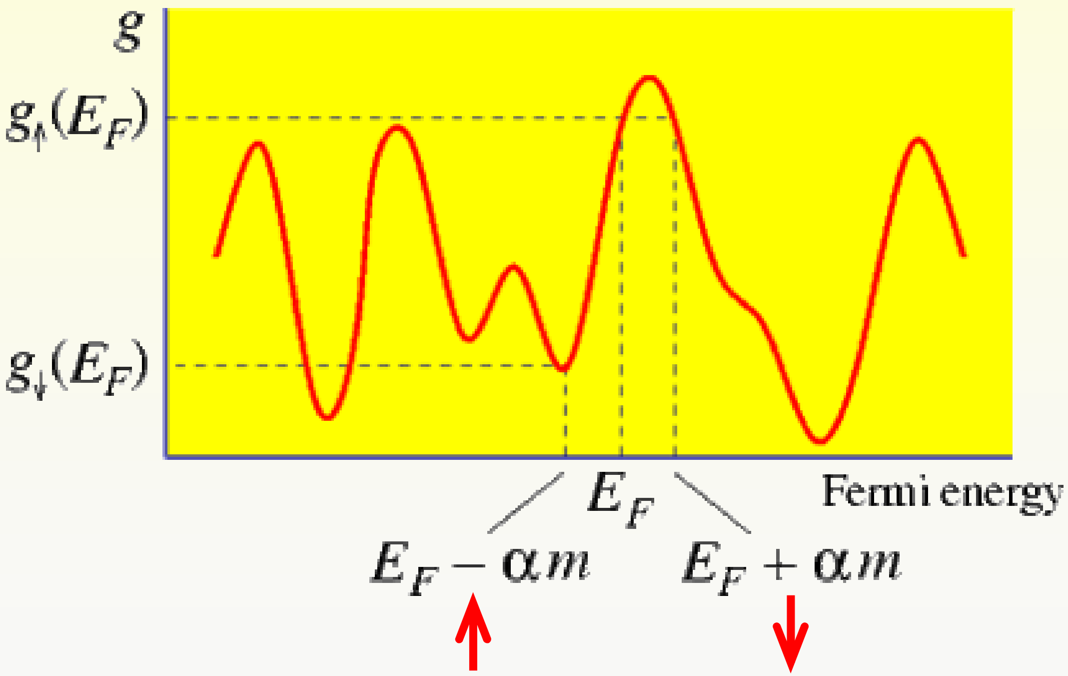
(2) Two spin subbands: ↑,↓

$$\langle \delta g^2 \rangle = \underbrace{\langle \delta g_\uparrow \delta g_\uparrow \rangle}_{\text{UCF}} + \langle \delta g_\uparrow \delta g_\downarrow \rangle + \langle \delta g_\downarrow \delta g_\uparrow \rangle + \underbrace{\langle \delta g_\downarrow \delta g_\downarrow \rangle}_{\text{UCF}}$$

Correlation function $\langle \delta g_\uparrow \delta g_\downarrow \rangle$:

spin ↑,↓ carriers have different Fermi energies but see same disorder

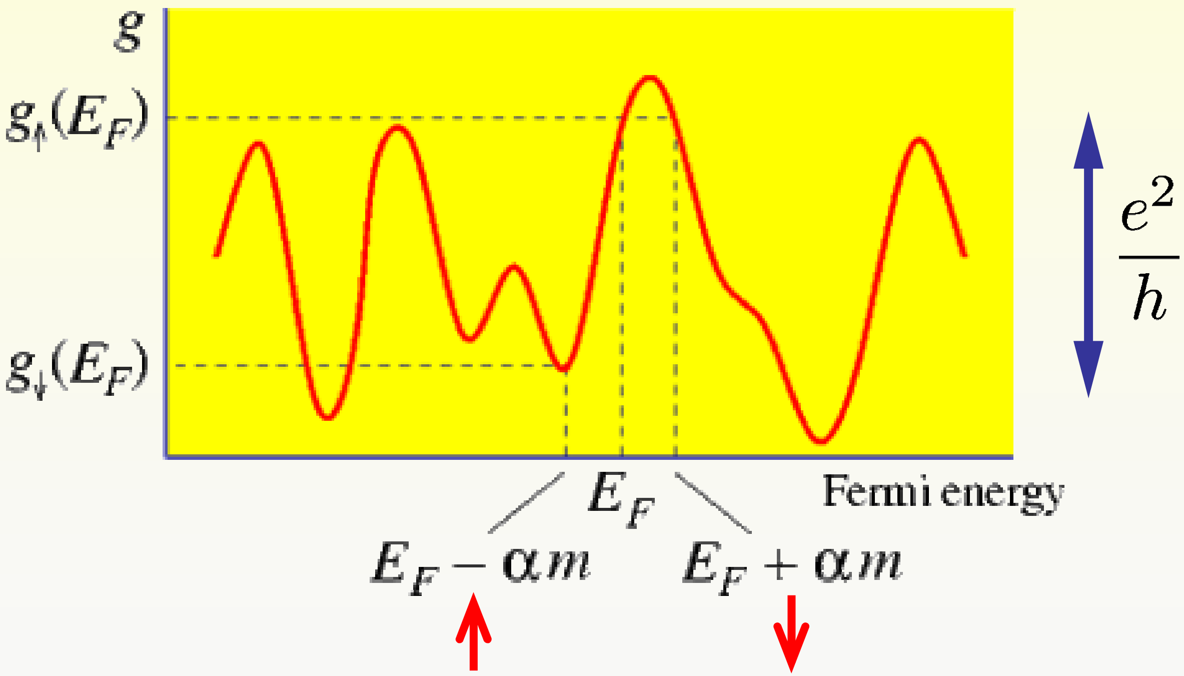


$\frac{e^2}{h}$ universal conductance fluctuations (UCF)

$\langle \delta g_\uparrow \delta g_\downarrow \rangle$ is a scaling function of x = eff. Zeeman energy $\times$ diffusion time
(Stone 1985, Altshuler 1985, Lee and Stone 1985)

$$\langle \delta g_\uparrow \delta g_\downarrow \rangle \propto \begin{cases} 1 - C_1 x^2 & \text{for } x \ll 1 \\ C_2 x^{-1/2} & \text{for } x \gg 1 \end{cases}$$

(correlations decrease with increasing Zeeman energy)



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(3) With spin-orbit coupling (realistic case):

$\langle \delta g^2 \rangle$ is a scaling function $H(y)$ of y = eff. Zeeman energy $\times$ spin-orbit time, increases by factor of 2 in strong eff. Zeeman field

(4) Typical magnetization:

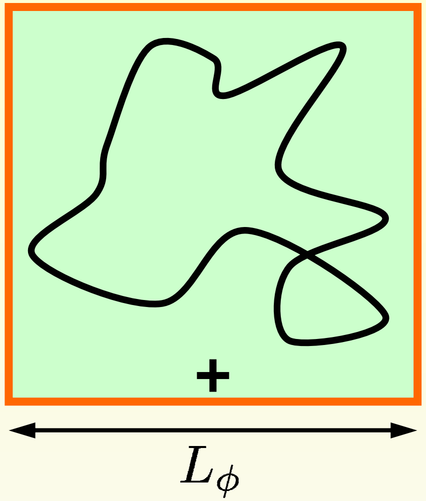
assuming Gaussian fluctuations: $$m = \sqrt{\langle m^2 \rangle} \propto \left[\int_{q<1/L_\phi} \frac{d^3 q}{t + q^2 a^2} \right]^{1/2}$$

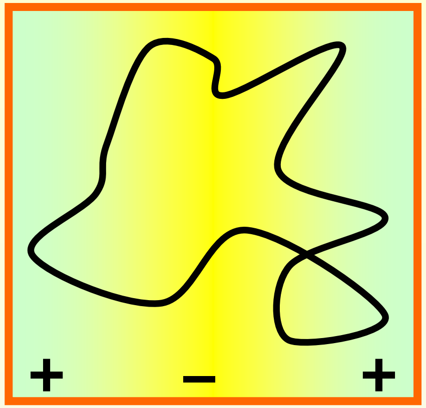
coarse-grained – why?

$$m = \sqrt{\langle m^2 \rangle} \propto \left[\int_{q<1/L_\phi} \frac{d^3q}{t + q^2 a^2} \right]^{1/2}$$

why coarse-grained?

$q < 1/L_\phi$





$q > 1/L_\phi$

phase factors partially cancel, higher order corrections

for $\xi \gg L_\phi$: $\quad m \propto 1 - \frac{\pi L_\phi}{4\xi}$ with $\quad \xi = \frac{a}{\sqrt{t}}$

$$\rho_{\text{eff}} = \frac{1}{\sigma_{\text{eff}}} \cong \rho_0 + \text{const} \times \left[H(y_0) - H'(y_0)\, y_0 \, \frac{\pi L_\phi}{4\xi(T)} \right]$$

scaling function

Result for Gaussian fluctuations:

$$\Delta\rho \propto -\frac{1}{\xi(T)} \propto -\sqrt{t}$$

Beyond Gaussian fluctuations:

$$\Delta\rho \propto -t^{\nu(1+\eta)}$$

stronger singularity…

…than in Fisher/Langer and de Gennes/Friedel theories

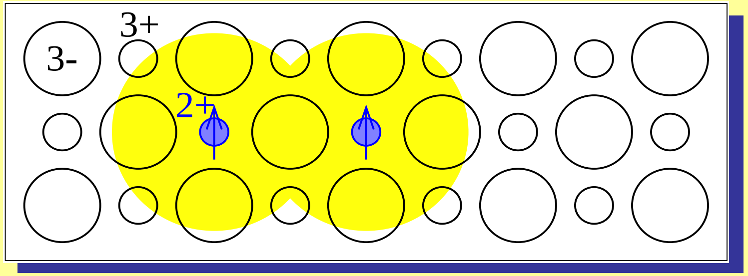
Condition:

Transport is disorder-dominated around T_c (low T_c, strong disorder)

Diluted magnetic semiconductors?

specifically Mn-doped III-V compounds (GaAs, InAs, InSb,…)

Mn^{2+} replaces 3+ cation, introduces a hole and a local spin 5/2



- strong Coulomb disorder
- T_c can be low (InSb)

Theory predicts maximum of ρ at T_c

Critical behavior sits on top of high, broad peak (de Gennes/Friedel) due to strong spin scattering

Conclusions

If $\rho(T)$ close to T_c is dominated by disorder, not phonons:

- much stronger singularity then found in clean ferromagnets
- possible applications to bad metallic ferromagnets and diluted magnetic semiconductors

C.T., M.E. Raikh, and F. von Oppen, PRL **94**, 036602 (2005)

Deutsche Forschungsgemeinschaft DFG

DAAD Deutscher Akademischer Austausch Dienst German Academic Exchange Service

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$$\rho_{\text{eff}} = \text{const} + \frac{4\rho_0^3}{3L_\phi^2}\left\langle \delta g(\mathbf{r}, E_F + \alpha m)\, \delta g(\mathbf{r}, E_F - \alpha m)\right\rangle$$

(3) correlator: scaling function
(Stone, Altshuler, Lee)

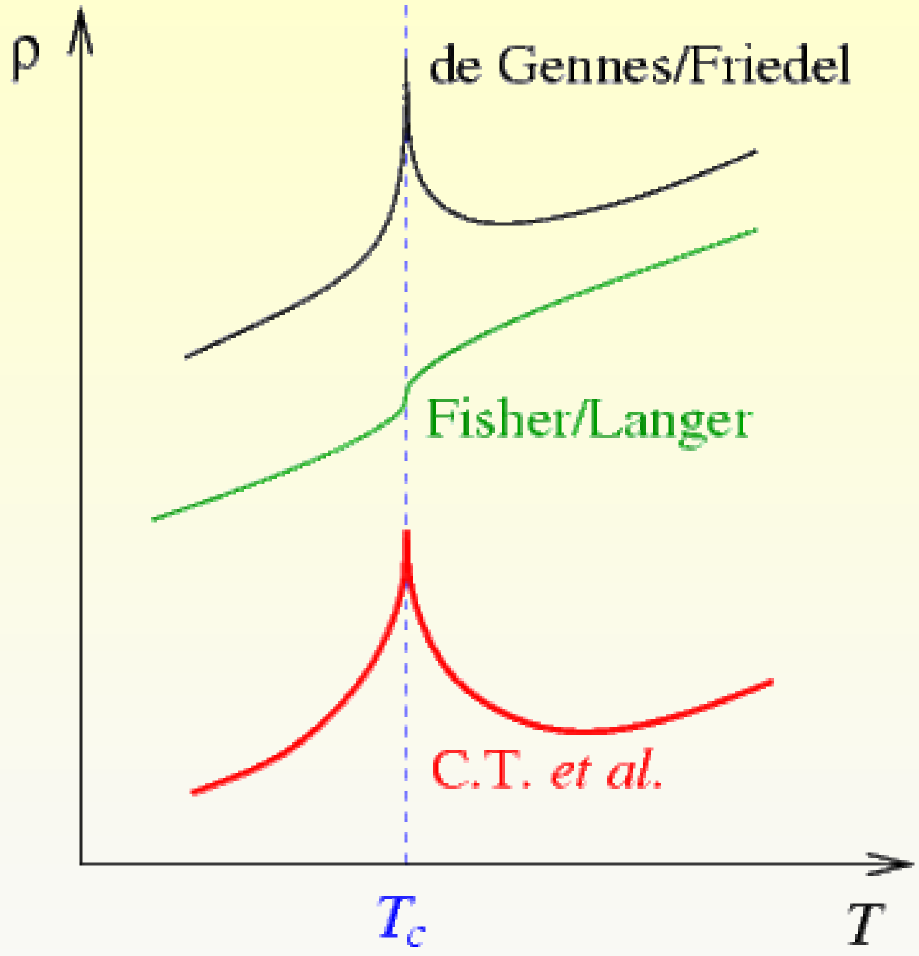
(4) assume Gaussian fluctuations:

$$\Delta\rho_{\text{eff}} \sim -\sqrt{t} \qquad t = (T - T_c)/T_c$$

in general: $\Delta\rho_{\text{eff}} \sim -t^{\nu(1+\eta)}$

→ stronger singularity

...if ρ is disorder-dominated at T_c



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Ferromagnetic phase:

- $\langle\sigma\rangle$ obtains magnetization dependence, expect $\Delta\langle\sigma\rangle \propto \langle m\rangle^2$: harmless
- contribution from $\langle g_\uparrow g_\downarrow\rangle$:
  - average magnetization $\langle m\rangle$ gives $\Delta\rho \propto H(y)$ with $y \propto \langle m\rangle$: harmless
  - fluctuations give same power as in the paramagnetic phase as long as $\langle m^2\rangle \gg \langle m\rangle^2$