Non-Ohmic dissipation in electronic Griffiths phases

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Ideal future postdoc!

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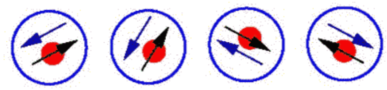
Disorder effects near QCP in correlated metals:

- Rare disorder configurations
- Localized low energy excitations: quantum Griffiths phases
- Deviations from Fermi liquid behavior?
- How different from "insulating" Griffiths phases?

Disorder-driven NFL behavior: Kondo alloys

- Local magnetic moments (rare-earth f-electrons) embedded in a sea of conduction electrons: UPt_3, $CeCu_6$, YbB_{12},...
  - Kondo effect: singlet formation



  - Fermi liquid behavior at low temperature

    $T < T^* \sim T_K = E_F \exp\{-1/\rho J_K\} \sim 10 - 100K$

    $\chi(T=0) = const.$, $\gamma(T=0) = const.$, $\rho(T) = \rho(0) + AT^2$,...
  - Small energy scale $\Rightarrow$ sensitive to perturbations: pressure, fields, disorder,...

Effects of disorder:

$UCu_{5-x}Pd_x$

$La_{1-x}Ce_xCu_{2.2}Si_2$

$M_{1-x}U_xPd_3$ (M=Y,Sc)

NOTE: α _ 1, ("weak" NFL)

$\gamma(T) \sim \ln(T_1/T)$ or $T^{\alpha-1}$

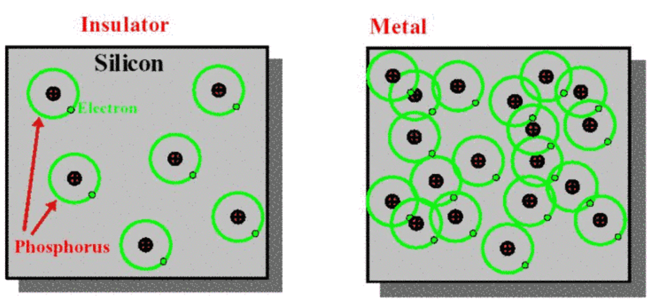
$\rho(T) \approx \rho(0) - AT$ decreases linearly

$\tau^{-1}(\omega) \approx \tau^{-1} - A\omega$

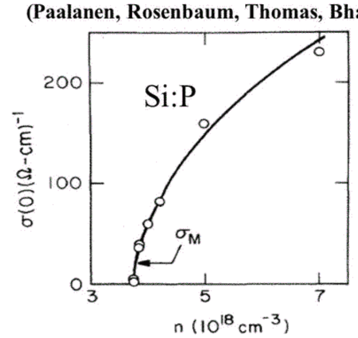
Further consistent anomalies in magnetoresistance, dynamic neutron scattering,...

Disorder-driven NFL behavior: doped semiconductors

Doped Semiconductors: Si:P (classic), FeSi:Al [doped Kondo insulator]



(Paalanen, Rosenbaum, Thomas, Bhatt; 1982)



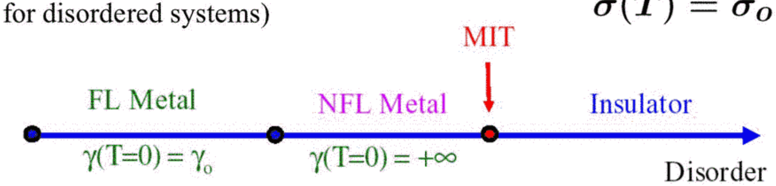
- **NFL "two-fluid" thermodynamics**

NOTE: α _ 0.3; ("strong" NFL!!!)

- **Conventional FL transport**
  (FL for disordered systems)

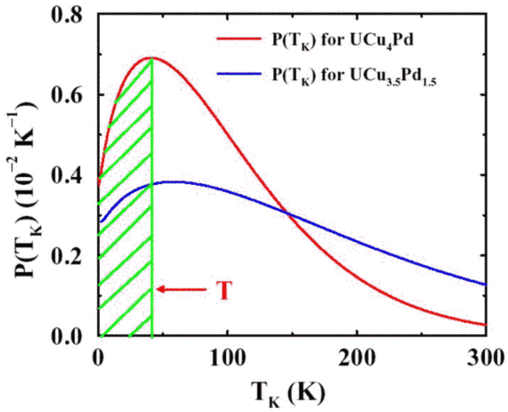
$$\gamma/\gamma_o = m^*/m^*_o + (T/T_o)^{\alpha-1}$$
$$\chi/\chi_o = m^*/m^*_o + \beta(T/T_o)^{\alpha-1}$$

$$\sigma(T) = \sigma_o + m\sqrt{T}$$

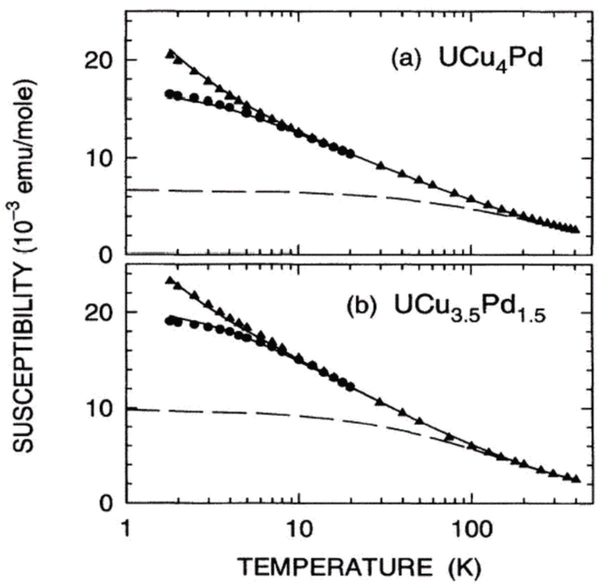


Phenomenological Kondo-Disorder Model (DKM)

(Bhatt & Fisher, 1992; Bernal et al., 1995; Miranda, et al., 1996)



Broad distribution of Kondo temperatures,
Due to random environment (random J-s)
$P(T_K)$ fitted for susceptibility



$$\chi(T) \sim \int_0^{\Lambda} \frac{dT_K P(T_K)}{T + T_K}$$

Marginal behavior:

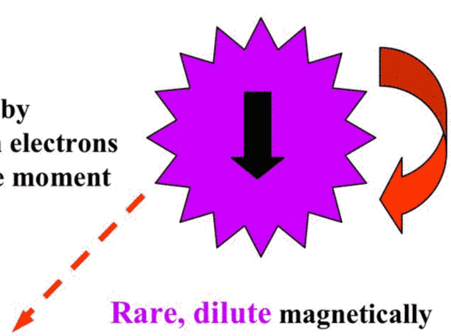
$$P(T_K = 0) = const.$$

Magnetic Griffiths phase (MGP) scenario

(Castro-Neto & Jones, 1998, 2000)

- **Idea:** proximity to a **magnetically ordered** phase+**disorder**
- **Clusters (droplets) form even before global ordering**
- **Numerical evidence of this in insulating random magnets** *(Huse, Bhatt, et al.)*
- **Metallic host: quantum tunneling of clusters (cluster Kondo effect)**
- **Distribution of clusters sizes ⇨ distribution of tunneling rates "T_K"**

Scattering by conduction electrons can flip the moment



Rare, dilute magnetically ordered cluster

- **Phenomenology IDENTICAL as in the Kondo disorder model** *(only thermodynamics explored)*
- $P(T_K) \sim (T_K)^{\alpha-1}$; $\chi(T) \sim (T)^{\alpha-1}$
- **Non-universal exponent α**

Disorder-driven NFL - open questions:

- Microscopic model?
- Universality: why is NFL so common?
- Vicinity of QCP: which one?
- Is it OK to consider rare events as "independent"?
- Role of long-ranged RKKY in metallic NFL?

(*Why "strong" NFL for Si:P, "weak" for $UCu_{5-x}Pd_x$?*)

Localization-induced electronic Griffiths phase

(Miranda & Dobrosavljevic, PRL 86, 264 (2001))

The physical picture

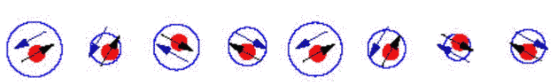
- Localization effects: approach to disorder-driven MIT (Note: a *non-magnetic* quantum critical point)

  $\Rightarrow$ local DOS fluctuations $\rho(\varepsilon, x) \sim |\Psi_E(x)|^2$

  $\Rightarrow$ broad distribution of $T_K(x) = D \exp\{-1/\rho(x) J_K\}$

  (Dobrosavljevic, Kirkpatrick, Kotliar, 1992)

- Kondo disorder $\Rightarrow$ extra scattering for conduction electrons

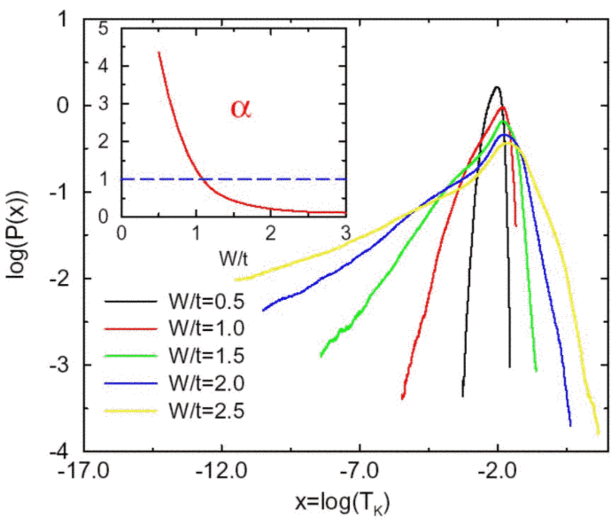
   $\Rightarrow$ more localization

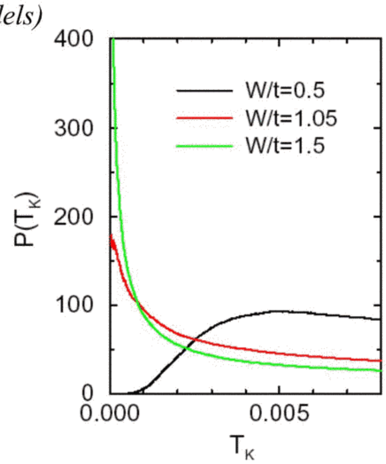
- Nonlocal feedback effect $\Rightarrow$ UNIVERSALITY
- Implementation: "Statistical" DMFT approach *(Dobrosavljevic & Kotliar, 1997)*

Results: Transition to NFL Behavior

*(for Anderson lattice **and** Hubbard models)*

- Weak disorder: log-normal, universal $P(T_K)$ (same results for various forms of disorder)
- At $W > W_c/t \approx 1$, NFL phase, $P(T_K)$ singular
- "Critical" behavior just as for a Griffiths phase





– Near $W \approx W_c$ a long tail develops: $P(T_K) \sim (T_K)^{\alpha-1}$

– $\alpha = \alpha(W)$ varies with W

– This is not a phase transition

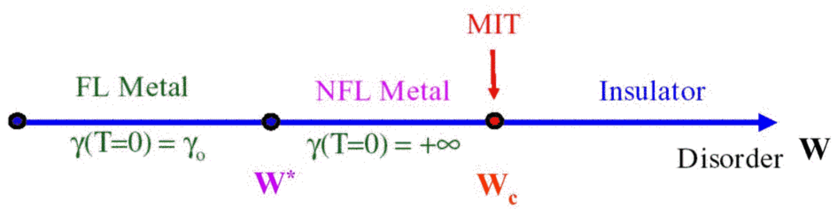
– Susceptibility at $T = 0$ then is: $\chi(T=0) \sim \int dT_K P(T_K)/T_K \sim$ $\sim T^{-(1-\alpha)}$ singular at $W > W_c$

Electronic Griffiths phase & metal-insulator transition (MIT)

(Tanaskovic, Dobrosavljevic, Miranda; PRB 70, 205108 (2004))

EGP sets in for W > $W^* = (\pi t^2 \rho_{av} J_K)^{1/2}$

MIT at W = $W_c \sim E_F$



Does EGP always come BEFORE the MIT? YES!

DMFT (no localization): $\Delta" \rightarrow \pi t^2 \langle \rho(\varepsilon_i) \rangle_\varepsilon = \pi t^2 \rho_{av}$

statDMFT (with localization): $\Delta" \rightarrow \pi t^2 \exp\{\ln \langle \rho(\varepsilon_i) \rangle_\varepsilon\} = \pi t^2 \rho_{typ} \sim (W_c - W)^\beta$

$$W^* \approx W_c - W_c (W_c^2/\pi t^2 C J_K)^{1/\beta} < W_c$$

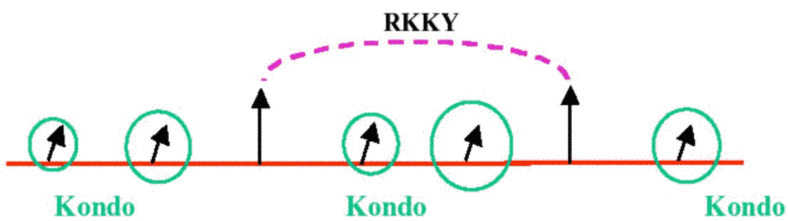
Analytical approach: "TMT"

What's missing from the statDMFT picture of the EGP?

- **Disorder-dependent "Griffiths" exponent $\alpha(W)$** [$\chi(T) \sim T^{\alpha-1}$]

- **Experiments:** **Kondo alloys**, e.g. $UCu_{5-x}Pd_x$ $\alpha \sim 1$ (*marginal for ALL samples*)
  (in contrast to doped semiconductors, e.g. Si:P $\alpha \sim 0.3$*)*

Physical picture: **importance of RKKY interactions for $T_K < J_{RKKY}$**

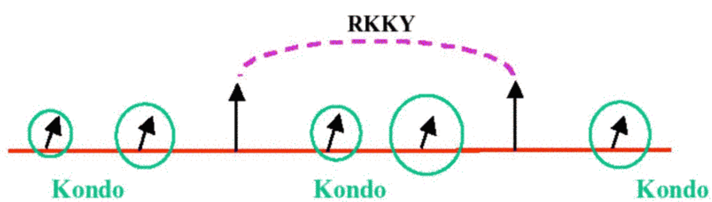


Spin-Glass ordering of Kondo-unscreened spins?
[experiments by D. MacLaughlin, PRL 2001; quantum spin-glass dynamics at $T < 1K$]

Kondo + RKKY, analytical theory?

DMFT "effective model" of EGP +RKKY interactions

(Tanaskovic, Dobrosavljevic, Miranda; cond-mat/0412100)



- **RKKY interactions between (distant) low-T_K (unscreened) spins:**
  oscillatory with distance ⇒ random in magnitude and sign

- **Expect quantum spin-glass (SG) dynamics at low T**

- **Mode-coupling (DMFT) theory for RKKY interactions:**

$$S_{\rm eff}^{(j)} = S_{\rm toy}^{(j)} + S_{RKKY}; \quad S_{RKKY} = g \int d\tau d\tau' \vec{\sigma}_f(\tau) \chi(\tau - \tau') \vec{\sigma}_f(\tau')$$

spin operator of the f-electron

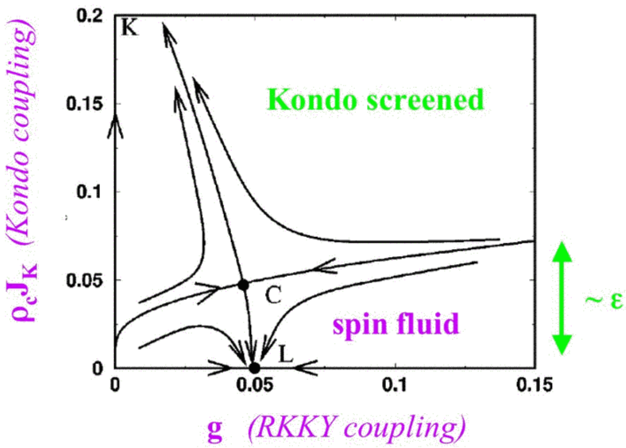
- **Self-consistency:** $\chi(\tau - \tau') = \overline{\langle \vec{\sigma}_f(\tau) \vec{\sigma}_f(\tau') \rangle}$

- **Local action: "Bose-Fermi (BF) Kondo model"**
- *(E-DMFT; A. Sengupta, Q. Si,..)*

Decoupling of spins and two-fluid behavior

(paramagnetic solution)

- **BF model has a phase transition for a sub-Ohmic dissipative bath ($\varepsilon > 0$)**



- **EGP model: distribution of Kondo Couplings all the way to zero!**
- **A finite fraction of spins fall on each side of the critical line**
- **Kondo effect destroyed by dissipation on a finite fraction of spins**
- **Decoupled spins J_K flows to zero; they form a spin fluid (Sachdev-Ye)** *(frustrated insulating magnet)*

Griffiths phase: destruction of the Kondo effect

- **How RKKY affect the Kondo effect for low T_K spins (stability of the EGP)?**
- **Examine small g-limit**

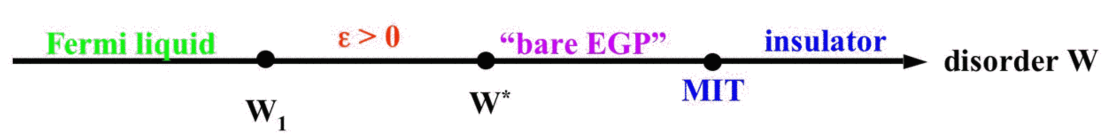
$$\chi(\tau-\tau') \rightarrow \chi_o(\tau-\tau') = \chi(g=0, \tau-\tau')$$

[examine BF model in bath of the "bare" (toy model) theory]

$$\chi^o(i\omega_n) = \int_0^\Lambda dT_K^o P(T_K^o) \frac{1}{i\omega_n + T_K^o} \sim \chi(0) - C(i\omega_n)^{1-\epsilon}$$

Exponent $\varepsilon = 2 - \alpha > 0$ for $W > W_1 = (\pi t^2 \rho_{av} J_K/2)^{1/2} < W^*$

NOTE: $\varepsilon > 0$ leads to sub-Ohmic (strong) dissipation, phase transition in BF model



Self-consistent marginal FL solution

average over sites

- Impose self-consistency condition $\chi(\tau - \tau') = \overline{\langle \vec{\sigma}_f(\tau)\vec{\sigma}_f(\tau') \rangle}$
- Self-consistent solution ε=1 *(RG and large N results)*
- Leading contribution from decoupled spins (spin-fluid)

  $\chi(T) \sim \ln(T_o/T)$

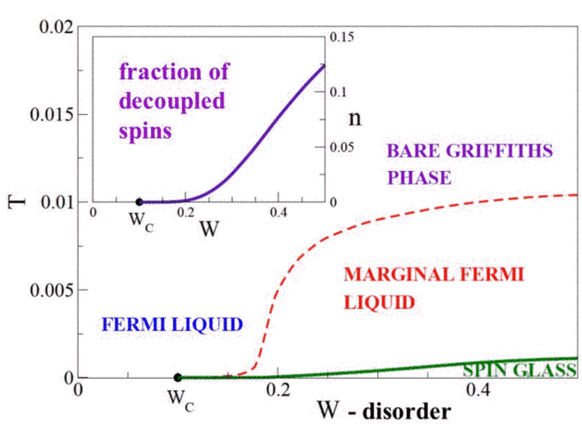
- Corresponds to renormalized Griffiths exponent $\alpha_R = 1$ for any $W > W_1$ (marginal Fermi liquid)
- Renormalized, universal distribution of Kondo temperatures *(for the spins that remain Kondo-screened)*

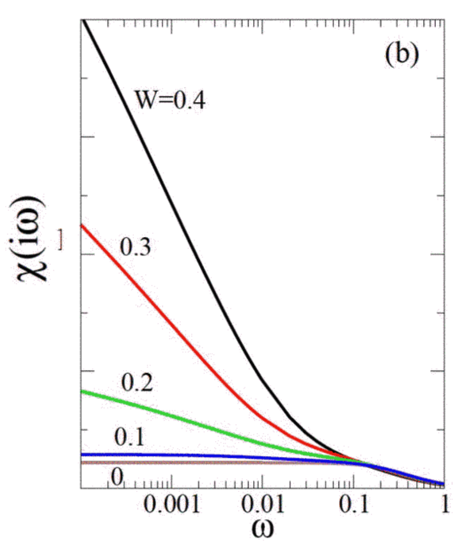
  $P_R(T_K) \sim (T_K)^{-1/2}$ *(one loop RG result)*

- Spin-fluid as quantum critical dynamics as precursor of the SG phase

Spin-glass (SG) instability of the EGP

- SG instability criterion: $\chi(T)\, J_{RKKY} = 1$
- $\chi(T) \sim \ln(T_o/T)$ for spin fluid (decoupled spins)
- Finite (very low!!) temperature SG instability as soon as spins decouple
- Quantitative (numerical) results: large N





Summary and Open Questions:

- Universal emergence of Electronic Griffiths Phase (EGP)
  (*but non-universal - tunable - Griffiths exponent*)
- EGP + RKKY interactions: non-Ohmic dissipation
- Destruction of Kondo effect on low-T_K spins, two-fluid behavior
- Low temperature spin-glass instability as generic property of Griffiths phases
- UNIVERSAL marginal Fermi liquid behavior
- Similar effect of RKKY on magnetic (cluster) Griffiths phases
  (*non-Ohmic dissipation, two-fluid behavior:* cond-mat/0408336)

- Limitation of mode-coupling theory for decoupled spins?
  (local singlets; localization for the collective mode????)