Exotic Quantum Criticality in Kondo Lattices

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Outline:

1. Quantum critical heavy fermions:
   - Fermi-surface evolution
   - Anomalous dynamics
2. Destruction of Kondo effect: EDMFT
3. Beyond the microscopics

KITP, June 30, 2004

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F. Steglich	**P. Coleman**	

- **Kondo lattices:**

$$\mathcal{H} = \sum_{ij,a} I_{ij}^a \, S_i^a \, S_j^a + \sum_{ij,\sigma} t_{ij} \, \mathbf{c}_{i\sigma}^\dagger \, \mathbf{c}_{j\sigma} + \sum_{i,a} J_K^a \, S_i^a \, s_{c,i}^a$$

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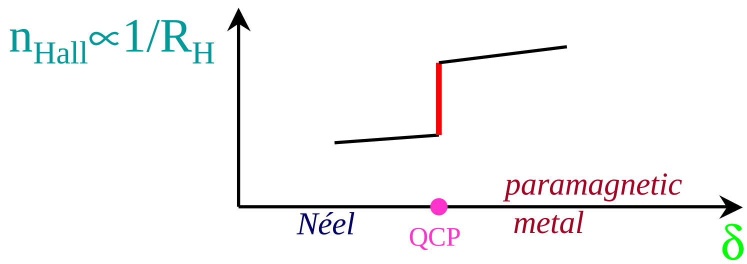
- **Heavy fermions near a magnetic QCP:**
  - $YbRh_2Si_2$ (critical Bab=60mT, Bc=0.7T)
    tetragonal; easy-plane anisotropy (Mab:Mc≈100:1 at low T); $T_K^0 \approx$ 20 K
  - $Ce(Cu_{1-x}Au_x)_6$ (critical x ≈0.017)
    nearly orthorhombic; Ising-anisotropy (Mc:Ma:Mb ≈10:2:1); $T_K^0 \approx$ 6 K
  - Phases: AF metal; paramagnetic metal

Hall Effect in $YbRh_2Si_2$

- **The Hall number has a sharp jump @ QCP in the $T = 0$ limit (by extrapolation):**



- **Suggesting a sudden collapse and reconstruction of the Fermi surface at the QCP**

S. Paschen et al., preprint '04

Dynamics of the quantum critical $CeCu_{5.9}Au_{0.1}$

- **Frequency and temperature dependences of the dynamical spin susceptibility:**
  - **an anomalous exponent $\alpha < 1$**
  - **ω/T scaling**

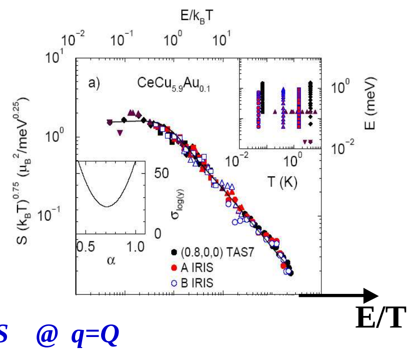
  implying non-Gaussian fixed point

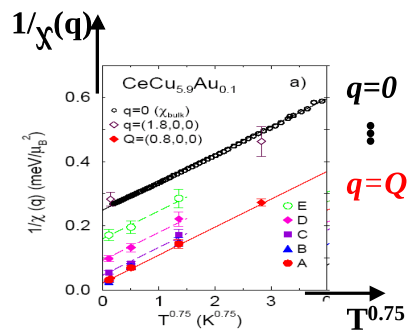
- **The anomalous exponent α is seen essentially `everywhere' in the momentum space**

Dynamical and Static Susceptibilities in $CeCu_{5.9}Au_{0.1}$

- E/T scaling
- Fractional exponent α=0.75

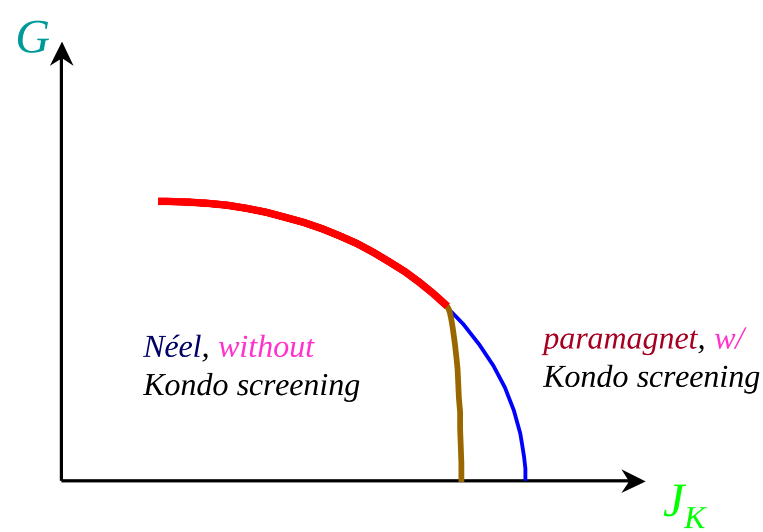
- α=0.75 `everywhere' in **q**.



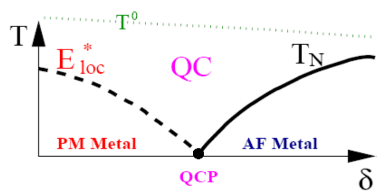


INS @ q=Q ***INS and M/H***

A. Schröder et al., Nature '00; PRL '98; O. Stockert, H. v. Löhneysen, A. Rosch, N. Pyka, & M. Loewenhaupt, PRL '98



Local Quantum Critical Point



Destruction of Kondo effect ($E_{loc}^* \rightarrow 0$) at the QCP

- **Local susceptibility also diverges:** $\chi_{\rm loc}(\omega) = \frac{1}{2..}\ln\frac{..}{-i\omega}$ **wher e**
- **"spin self-energy" has anomalous exponent**

$M(\omega) \sim I_Q + A(-i\omega)^{\alpha}$ **where** $\alpha = \frac{1}{2\rho_I(I_Q)..}$

QS, S. Rabello, K. Ingersent, & J. L. Smith, Nature 413, 804 (2001)

Extended-DMFT* of Kondo Lattice

(* Smith & QS; Chitra & Kotliar; Sengupta & Georges)

- **Mapping to a Bose-Fermi Kondo model:**

$$\mathcal{H}_{\rm eff} = J_K\, \mathbf{S}\cdot\mathbf{s}_c + \sum_{p,\sigma} E_p\, c^{\dagger}_{p\sigma} c_{p\sigma} + g\,\mathbf{S}\cdot\sum_p\left(\vec{\phi}_p + \vec{\phi}^{\dagger}_{-p}\right) + \sum_p w_p\, \vec{\phi}^{\dagger}_p\cdot\vec{\phi}_p$$

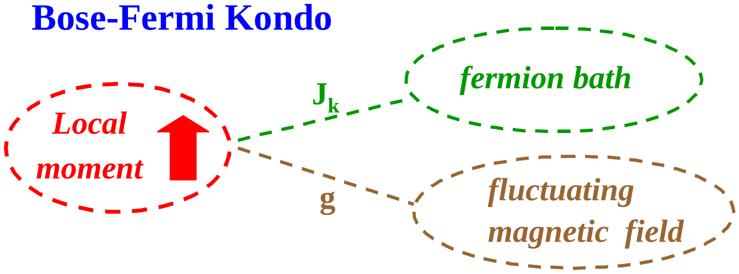
+ self-consistency conditions

- **The effective impurity problem determines**
  - **Electron self-energy $\Sigma(\omega)$**
  - **"spin self-energy" $M(\omega)$**
- **Dynamical spin susceptibility:** $\chi(\mathbf{q},\omega) = \frac{1}{M(\omega) + I_{\mathbf{q}}}$

Extended-DMFT of Kondo Lattice

Kondo Lattice

Bose-Fermi Kondo



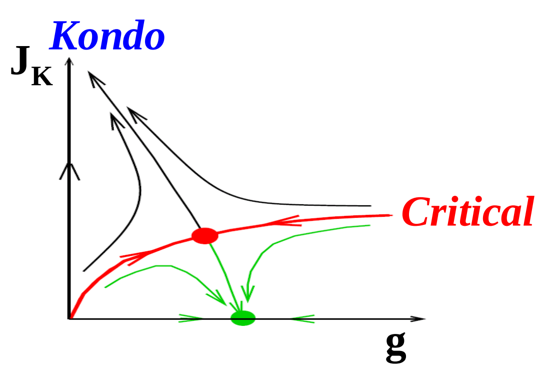
+ self-consistency

Cf. QS, S. Rabello, K. Ingersent and J.L.Smith, Phys. Rev. B '03 for details

ε(≡ 1- λ) expansion of Bose-Fermi Kondo model:

$\sum_p \delta(\omega \quad w_p)$

$\sim \omega$



Order ε: *J. L. Smith & QS '97; A. M. Sengupta '97*

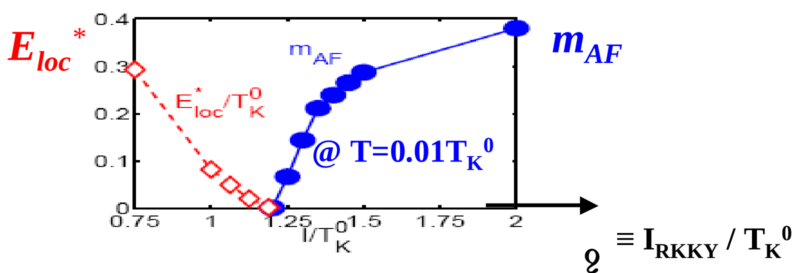
Higher orders in ε and the effect of spin anisotropies:
L.Zhu & QS '02; G. Zarand & E. Demler '02

$J_K = 0$: *S. Sachdev & J. Ye '93 (large N); M. Vojta, C. Buragohain, & S. Sachdev '00*

Kondo lattice with Ising anisotropy

EDMFT of $\mathcal{H} = \mathcal{H}_0(c) + \sum_i J_K \mathbf{S}_i \cdot \mathbf{s}_{c,i} + \sum_{ij} I_{ij} S_i^z S_j^z$

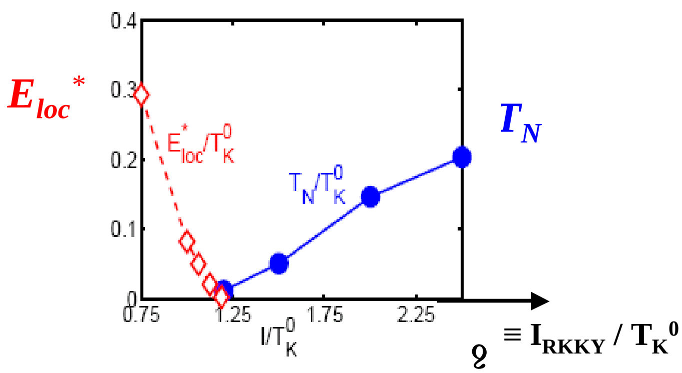
(Quantum Monte Carlo algorithm of Grempel and Rozenberg '99)



- **m_{AF} → 0: continuous AF transition**
- **E_{loc}^* → 0: destruction of Kondo resonances**

J.-X. Zhu, D. Grempel, & QS, Phys.Rev.Lett. '03

Kondo lattice with Ising anisotropy (cont'd)

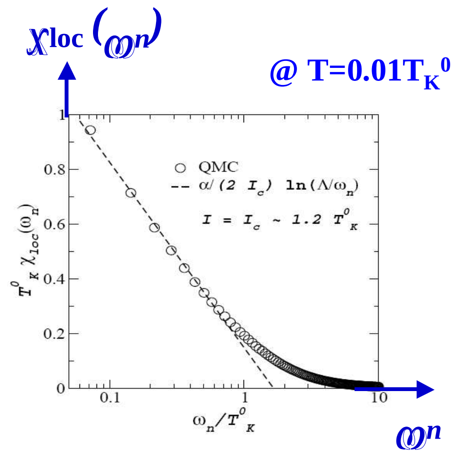


The destruction of Kondo resonances (E_{loc}^* → 0)
meets with the vanishing of the Néel temperature

Quantum Critical Dynamics

- **Local spin susceptibility at $I \approx I_c \approx 1.2\, T^0_K$:**

$$\chi_{loc}(\omega_n) = \frac{1}{2\alpha}\ln\frac{\Lambda}{|\omega_n|}$$

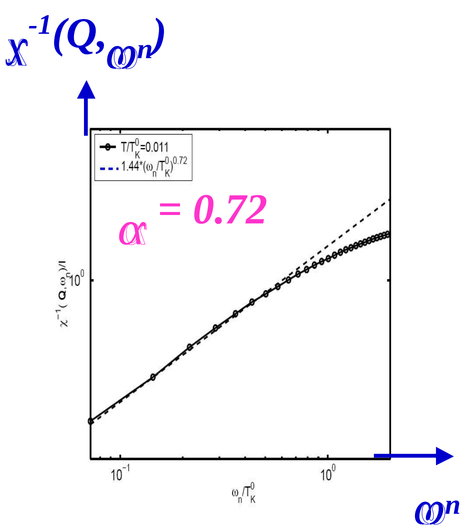


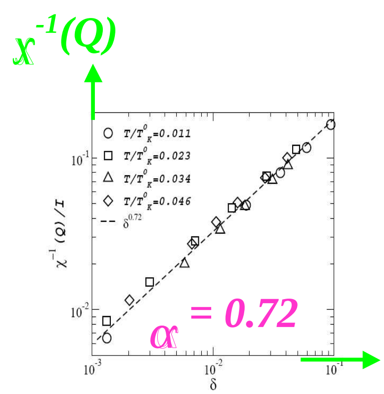
- **Calculated $\alpha \approx 0.7$**

D. Grempel and QS, Phys. Rev. Lett. '03

Fractional exponent in the dynamics

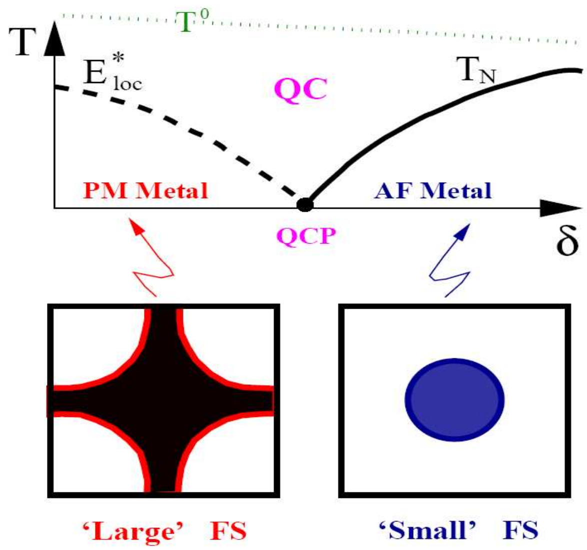
- **Inverse peak susceptibility at $I \approx I_c$**





$\delta(T, I_c) \propto T$; $\delta(T = 0) \propto (I_c - I)$

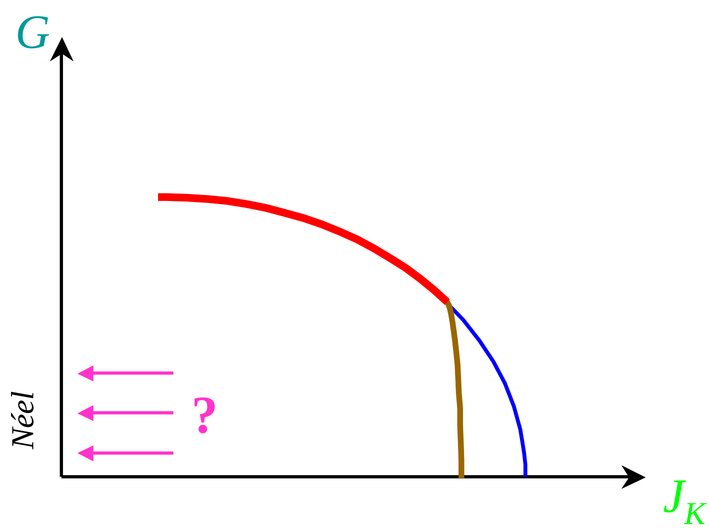
Fermi Surface Evolution



In what sense is the QCP local?

- **Localization of f-electrons**
  - m* → ∞ over the entire Fermi surface as $\varrho \to \varrho^{QCP}$
  - Reconstruction of the Fermi surface across ϱ^{QCP}
- **Anomalous spin dynamics everywhere in q.**
- **Destruction of Kondo effect** ➡
  - Non-Fermi liquid excitations part of the quantum-critical spectrum.

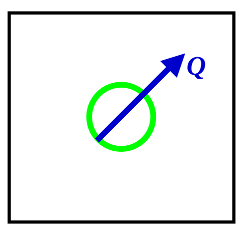
- **What happens beyond EDMFT?**



- ***Ising case:*** Kondo coupling to fermions irrelevant
- ***Heisenberg case:***

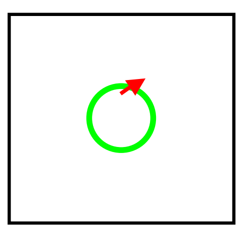
$$\mathbf{S}(\mathbf{x},\tau) \sim \mathbf{m} + \mathbf{n}\, e^{i\mathbf{Q}\cdot\mathbf{x}}$$

  - Coupling of fermions to *n* irrelevant:



  - Coupling of fermions to *m*:

$$\sum_a \gamma^a \int d\mathbf{x}\, d\tau\; m^a(\mathbf{x},\tau)\, m_c^a(\mathbf{x},\tau)$$



Related problem in 1D:

$$\beta(y_\perp) = \left(1 - \frac{K_\tau}{2} - \frac{1}{2K_\tau}\right) y_\perp + u K_\tau y_z y_\perp$$

$$\beta(y_z) = u K_\tau^2 y_\perp^2$$

$$\beta(K_\tau) = \left(1 - K_\tau^2\right) y_\perp^2$$

where $u = \sqrt{2\pi} v_s / (v_s + v_\tau)$

E. Pivovarov, & QS, Phys.Rev. B '04;
O. Zachar, & A. M. Tsvelik, PRB '01;
A. E. Sikkema, I. Affleck, & S. R. White, PRL '97;
O. Zachar, S. A. Kivelson, & V. J. Emery, PRL '96

SUMMARY

- **Two types of quantum critical metals**
  - T=0 SDW transition (Gaussian)
  - Locally quantum-critical: destruction of Kondo effect exactly at the magnetic QCP (interacting)
- **Microscopic (EDMFT) results of Kondo lattice models**
- **Evidence from Hall effect, inelastic neutron scattering, NMR, and Grüneisen ratio**
- **Beyond microscopics**
- **Relevance to other strongly correlated metals?**