Competition between Kondo effect and magnetic fluctuations in heavy fermion QCP

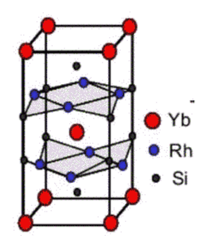
1. **What is the model ? Kondo lattice or valence fluctuations ?**
2. **What is critical and what is not ? how many universality classes?**
3. **Intinerant versus locally critical scenario.**
4. **Change of the Fermi surface volume? If yes, is it sharp ?**
5. **Is there a new excitation at the QCP ?**

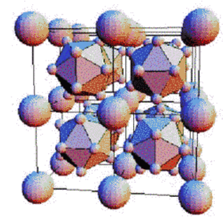
C. Pépin

(SPhT, Saclay)

Santa Barbara, Jan. 18th '05

$YbRh_2(Si_{1-x}Ge_x)_2$





UBe13 $\frac{m^*}{m} \approx 1000$

Indranil Paul (Saclay)
P.Coleman (Rutgers University)
J. Rech (Saclay + Rutgers)

Q.Si (Rice)
R. Ramazashvili (Argonne) J. Phys Cond Matt. 13. R723 (2001).

J. Custers, P. Gegenwart, C. Geibel, Nature 2003.
S. Paschen, H. Wilhelm, F. Steglich (Max Planck CPFG, Dresden)

A. Schröder (Kent State) G. Aeppli (U College London)
H. von Löhneysen (Karlsruhe) J. Sarrao (Los Alamos)

J-P. Paglione (Toronto) G. G. Lonzarich (Cambridge)

O. Parcollet (Saclay) A. Georges (Polytechnique)
A. Rosch (Karlsruhe) A. Chubukov (Madison)
M. Norman (Argonne) P. Sun (Rutgers)
G. Kotliar (Rutgers) D. Pines (Los Alamos)

Reviews

- C. Varma, Rev. Mod .Phys. **48**, 219 (1976)
- G.R. Stewart, Rev. Mod. Phys. **73**, 797 (2001)
- N. Mathur et al Nature **394**, 39 (1998).
- P. Coleman et al., J. Phys. Cond. Mat. **13**, R723 (2001).

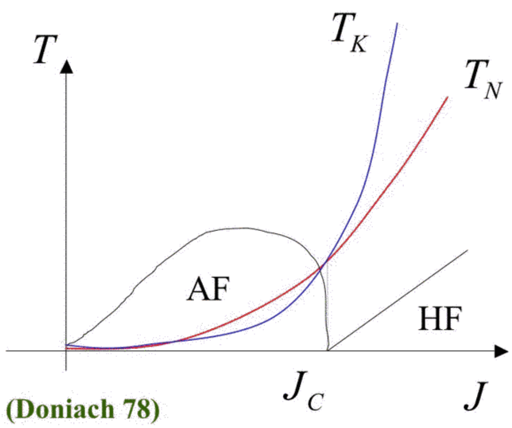
Experiments

- A. Schroder et al., Nature **407**, 351 (2000).
- J. Custers et al., Nature **424**, 524 (2003).
- H. von Lohneysen et al., Phys. Rev. Lett. **72**, 3262 (1994).
- O. Stockert et al., Phys. Rev. Lett. **80**, 5627 (1998).
- K. Ishida et al., Phys. Rev. Lett. **89**, 107202(2002).
- J. Sichelschmidt et al., Phys. Rev. Lett. **91**, 156401 (2003).
- R. Kuchler et al., Phys. Rev. Lett. **91**, 066405 (2003).
- G. Oomi et al., J. Phys. Soc. Jpn. **57**, 152 (1998).
- F. Steglich et al Phys. Rev. Lett. **43**, 1892 (1979).
- S. Kambe, J. Floquet and T.E. Hargreaves, J. Low Temp. Phys. **108**, 383 (1997).
- M.C. Aronson, Europhys. Lett. **46**, 245 (1997).
- S. Nakatsuji et al., Phys. Rev. Lett. **89**, 106402 (2002)
- S. L. Bud'ko, E. Morosan, and P. C. Canfield, Phys. Rev. B **69**, 014415 (2004).
- O.Trovarelli et al Phys. Rev. Lett. **85**, 626 (2000).
- P. Gegenwart et al Phys. Rev. Lett. **89**, 056402(2002).
- D. Jaccard and J. Flouquet, J. Mag. Mag. Matt. **47-48**, 45 (1985)
- N. Doiron-Leyraud et al., Nature **425**, 595 (2003).
- K. H. Kim et al., Phys. Rev. Lett. **91**, 256401 (2003).
- C. Petrovic et al., J. Phys. Condens. Matter **13**, L337 (2001)
- N. J. Curro et al., Phys. Rev. Lett. **90**, 227202 (2003).
- Y. Kawasaki et al., J. Phys. Soc. Japan **72**, 2308 (2003).
- J. Paglione et al., Phys. Rev. Lett. **91**, 246405 (2003).
- A. Bianchi et al., Phys. Rev. Lett. **91**, 257001 (2003).
- W. Higemoto et al., J. Phys. Soc. Japan **71**, 1023 (2002).
- B. Maple et al J. Low Temp. Phys. **99**, 223 (1995).
- R. Movschovich et Phys. Rev. Lett. **86**, 5152 (2001).
- M. Grosche *et al.*, J. Phys. Cond. Matt. **12** (2000), 533.
- S. R. Julian *et al.*, J. Phys. Cond. Matt. **8** (1996), 9675.
- S. Pashen *et al.*Nature **432**, 881 (2004).
- R. Bel, K. Behnia and H. Berger, Phys. Rev. Lett. **92**, 217002 (2004)
- P.Pedrazzini et al. E PhysJ B **38**,445 (2004)
- W. Bao et al, Phys. Rev.Lett. **91**, 127005 (2003).
- W. Knafo etal, JPCond Mat. **15**, 3741(2003)
- Saraki et al, Phys.Rev.B **64**,224417 (2001)
- Kawarasaki et al, Phys. Rev B **61**, 4167 (2000)

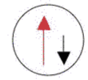
Theory

- S. Doniach, Physica, B**91**, 231 (1977).
- T. V. Ramakrishnan and K. Sur Phys. Rev. B **26**,1798-1811 (1982)
- J.A. Hertz, Phs. Rev. B **14**, 1165 (1976).
- A.J. Millis, Phys. Rev.B **48**, 7183 (1993).
- T. Moriya and T. Takimoto, J. Phys. Soc. Jpn. **64**, 960 (1995).
- Q. Si et al., Nature **413**, 804 (2001).
- A. Rosch et al., Phys. Rev. Lett. **79**, 159 (1997).
- L. Zhu et al., Phys. Rev. Lett. **91**, 066404 (2003).
- K. Miyake et al, Phys. Rev. B **34**, 6554 (1986).
- K. Miyake et al J. Phys. Soc. Jpn. **71**, 1007 (2002).
- Y. Onishi and K. Miyake, J. Phys. Soc. Jpn. **69**, 3955 (2000).
- S. Burdin, Phys. Rev B **66**, 04511 (2002)
- A. Rosch, Phys. Rev. B **64**, 174407 (2001).
- A. Rosch, Phys. Rev. Lett. **82** (1999) 4280.
- I. Paul et al, Phys. Rev. B **64**, 184414 (2001).
- T. Senthil *et al.*, Phys. Rev. Lett. **90**, 216403 (2003).
- V. R. Shaginyan, JETP Lett **79**, 286 (2004).
- P. Sun and G. Kotliar Phys. Rev B **66**, 85120 (2002)
- P. Sun and G. Kotliar, Phys. Rev. Lett. **91**, 37209 (2003).
- S. Nakatsuji , Phys. Rev. Lett. **92**, 16401 (2004).
- N. Curro et al, Phys. Rev. B 70, 235117 (2004).
- S. Pankov et al, Phys. Rev Lett (2003)
- C.Pepin cond-mat/ 0407155

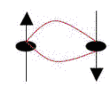
1. What is the model ? Kondo lattice or valence fluctuations ?



(Doniach 78)



$$T_K = \rho^{-1} Exp\left(\frac{-1}{\rho J}\right)$$



$$T_N = J^2 \rho$$

Kondo lattice model $H_{KL} = \sum_{k,\sigma} c^+_{k,\sigma} \varepsilon_k c_{k,\sigma} + J \sum_{i,\sigma,\sigma'} f^+_{i,\sigma} f_{i,\sigma'} c^+_{i,\sigma'} c_{i,\sigma}$

Yes, but... numerical values give $\boxed{J_C \rho = 1}$ **(Varma)**

meaning we would never see the HF phase !

Orbital degeneracy N doesn't cure the problem

(Ramakrishnan 78)

$$T_K = \rho^{-1} Exp\left(\frac{-1}{N\rho J}\right)$$

$$T_N = NJ^2 \rho$$

Ce : $4f^1$

S=1/2 L=3

Spin Orbit : J= |L-S|= 5/2

Yb : $4f^{13}$

S=1/2 L=3

S O : J= |L+S|= 7/2

U : $5f^2$

S=1 L=3+2

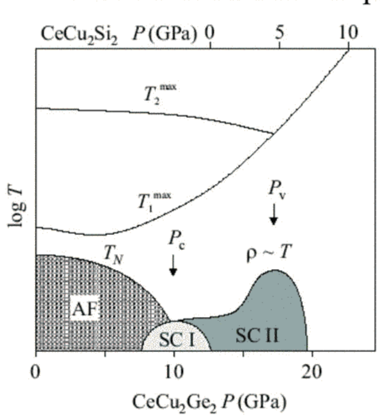
S O : J= |L-S|= 4

Crystal Electric Field effects split the big moments and compete with Hunds rules

- → Ferromagnetic flucutations
- → valence fluctuations
- → multiple stage screening ?

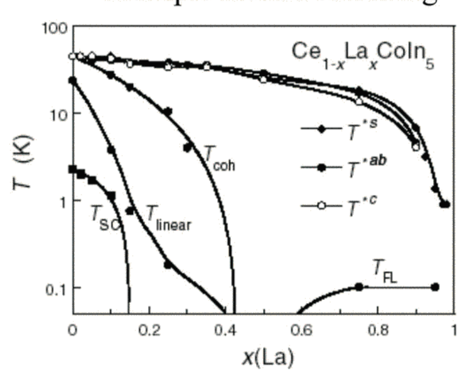
Miyake 99-04

Valence fluctuations at pc



Jaccard 03

Multiple Kondo screening



Nakatsuji 03

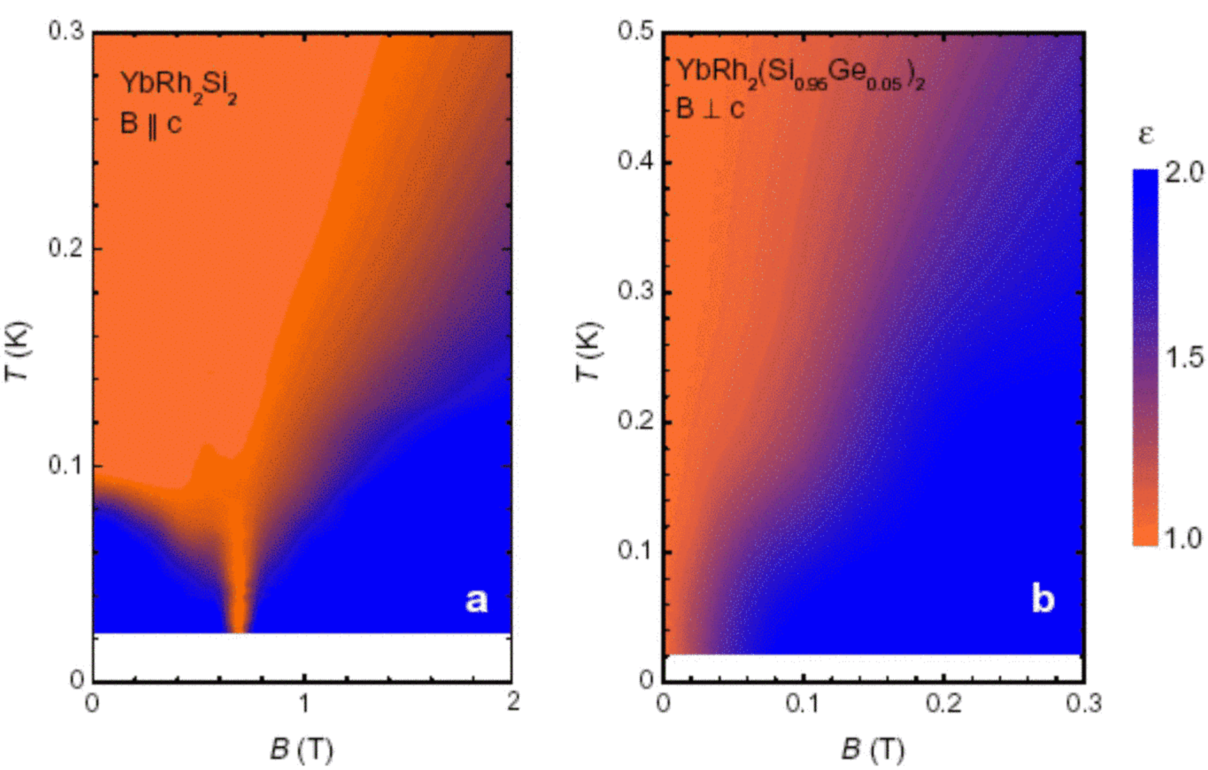
2. What is critical and what is not ?

Clear NFL in transport and specific heat: $YbRh_2(Si_{1-x}Ge_x)_2$, $CeCoIn_5$

3D Spin Density Wave ? Difficulties with logs. CDMFT gets logs in intermediate regimes aorund Tk (P.Sun '04): $Ce(Cu_{1-x}Au_x)_6$ … $YbAgGe$

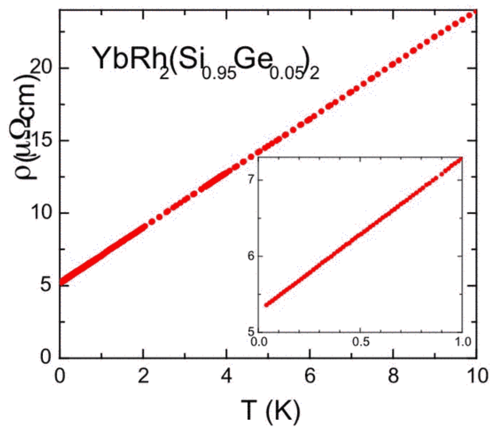
Is the anomaly due to a QCP ?: $CeIn_{3-x}Sn_x$ … $U_3Ni_3Sn_4$

Compound	$H_c/P_c/x_c$	$\frac{C_v}{T} \to \infty$?	$\rho \sim T^a$	Reference
$YbRh_2(Si_{1-x}Ge_x)_2$	$x_c = 0.05$ $H_c^{\|\|c} = 0.66T$ $H_c^{\perp c} = 0.06T$	$T^{-0.34}$	T	Steglich
$CeCoIn_5$	$H_c = 5T$	$T^{-\alpha}$	T	Moschovich and others
$Ce(Cu_{1-x}Au_x)_6$	$x_c = 0.016$	$Log\left(\frac{T_o}{T}\right)$	T	Schroeder
$CeCu_{6-x}Ag_x$	$x_c = 0.2$	$Log\left(\frac{T_o}{T}\right)$	$T^{1.1}$	Heuser, Stewart
$CeNi_2Ge_2$	$P_c = 0$	$Log\left(\frac{T_o}{T}\right)$	$T^{1.4}$	Grosche, Gegenwart Julian, Lonzarich
U_2Pt_2In	$P_c = 0$	$Log\left(\frac{T_o}{T}\right)$	T	Devisser
$CeCu_2Si_2$	$Pc = 0$	$Log\left(\frac{T_o}{T}\right)$	$T^{1.5}$	Steglich and others
$YbAgGe$	$H = 4T$	$Log\left(\frac{T_o}{T}\right)$	T	Canfield
$CeIn_{3-x}Sn_x$	$p_c = 26kbar$	?	$T^{1.6}$	Mathur
U_2Pd_2In	$P_c < 0$	?	T	Devisser
$CePd_2Si_2$	$P_c > 0$	?	$T^{1.2}$	Grosche
$CeRhIn_5$	$P_c \sim 1.6GPa$	?	T	Moschovich, Sarrao
$CeIn_3$	$P_c > 0$	?	$T^{1.5}$	Grosche
$Ce_{1-x}La_xRu_2Si_2$	$x_c = 0.1$	no	?	Flouquet
$U_3Ni_3Sn_4$	$P_c > 0$	no	?	Devisser

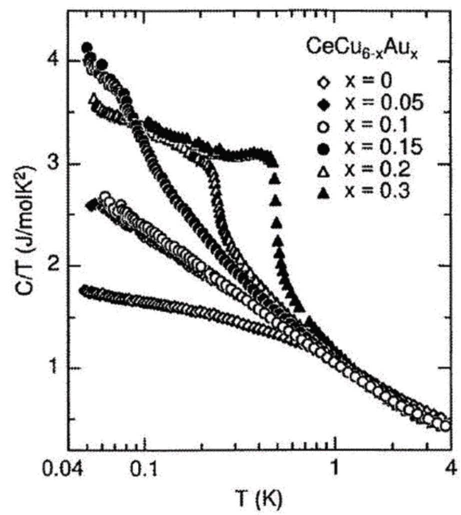


Custers et al (CP), Nature 2003

Criterium for criticality →
- lowest energy scale
- driven away from it by x, p, H
- trust for an exponent: at least 2 to 3 decades of E



Custers et al (2002).



H. Von Lohneyson (1996)

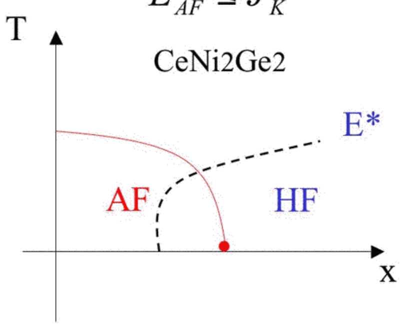
Several possible Quantum Critical Points

Deep in the AF phase, Kondo screening incomplete.
Deep in the HF phase, Kondo screening complete.
Is the Kondo screening drinving the transition ?

Type 1

$E_{AF} \leq J_K$

CeNi2Ge2

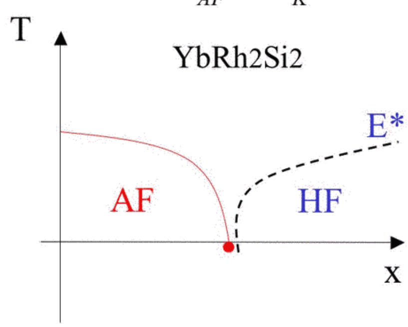


SDW scenario:
big Fermi surface at the QCP

Type 2

$E_{AF} \geq J_K$

YbRh2Si2

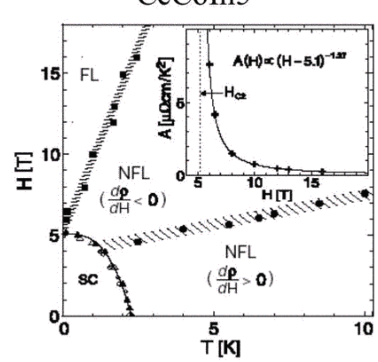


QCP with fractionalization

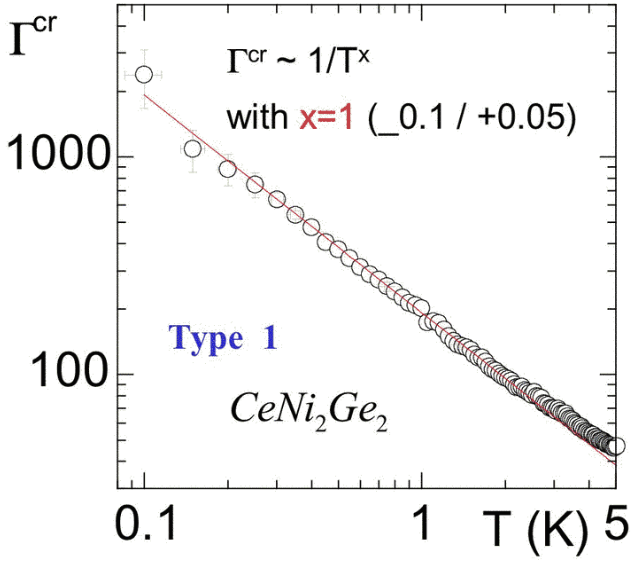
Type 3

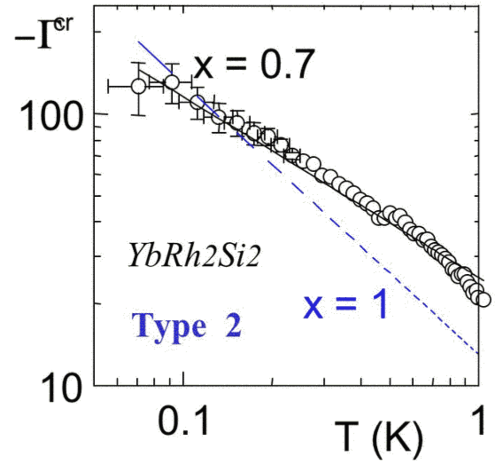
$H \approx T_K$

CeCoIn5



Paglione '03





Zhu et al '02
Küchler et al '02

Grüneisen parameter

$$\Gamma \propto \frac{\partial \log E^*}{\partial r}$$

$$\Gamma \approx T^{-1/\nu z}$$

Hertz-Millis

$\nu = 1/2$

$z = 2$

$r \approx \omega$

$\Gamma \approx T^{-1}$

C.Pepin 2004

$\nu = 1/2$

$z = 3$

$r \approx \omega^{2/3}$

$\Gamma \approx T^{-2/3}$

3. Itinerant versus localy critical scenarios

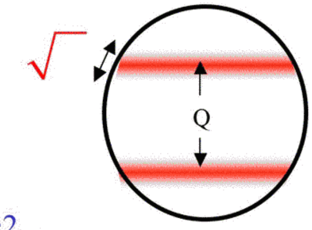
Relevance of Moriya-Hertz-Millis type scenarios

$$\frac{m}{m^*} \approx 1 - \frac{\partial \Sigma}{\partial \omega} \propto \ln(\Gamma / T)$$

•3D Spin Density Wave

$\Delta\rho \approx T^{3/2}$

$\gamma \approx cst - \sqrt{T}$



Rosch, '98

Type 1 CeNi2Ge2 ...

•2D Spin Density Wave into 3D metal

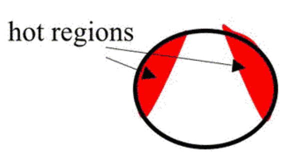
Rosch ('98), Georges, Kotliar, Paul ('03)

$\Delta\rho \approx T$

$\gamma \approx \log\left(\frac{T_0}{T}\right)$

Type 2 CeCu6Au, or CeCu6Ag ...

No anomalous exponent
in spin susceptibility



``Chubukov+Abanov 2003'' type effect in D=2 has been missed ?

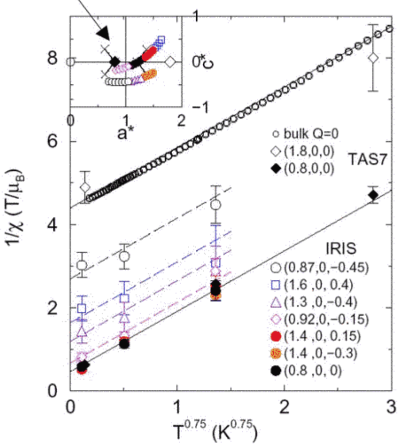
Gruneisen ratio $\Gamma \approx -Log(T)$

Kuchler 03

- Hint for a local excitation at the QCP

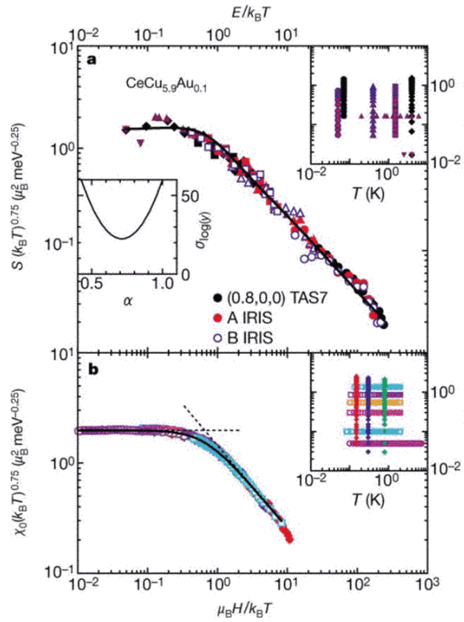
Anomalous exponent + ``local'' scaling
B/T scaling at the QCP: for any point
in the Brillouin Zone

Quasi 2D-spectrum



$CeCu_{6-x}Au_x$ (x=0.1)

Schroeder et al, Nature 407,351 (2000).

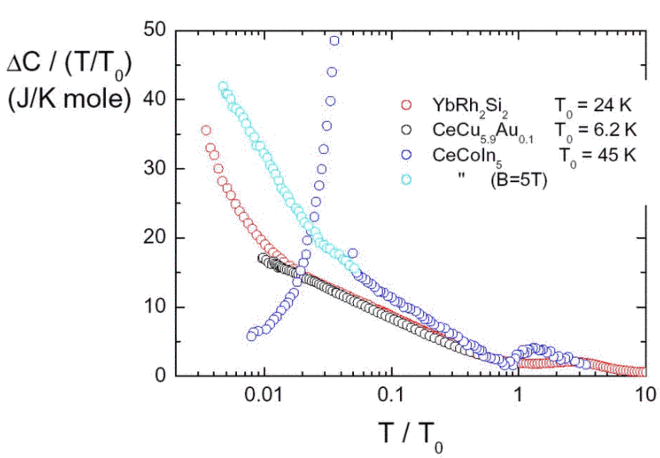


Critical specific heat:

$$\gamma(T) = \frac{C}{T} \approx T^{-\alpha}, 0 < \alpha < 1$$

No residual entropy: No free spin

Gegenwart, Lohneysen, Moschovich



$$F \approx d\omega d^d k$$

bosons → $F \approx \Delta\omega(\Delta q)^d$ → $\gamma(T) \approx T^{\frac{d-z}{z}}$

fermions → $F \approx \Delta\omega\Sigma(\omega)\Delta k_H$ → $\gamma(T) \approx T^{\frac{1-z_f+\alpha z_f}{z_f}}$

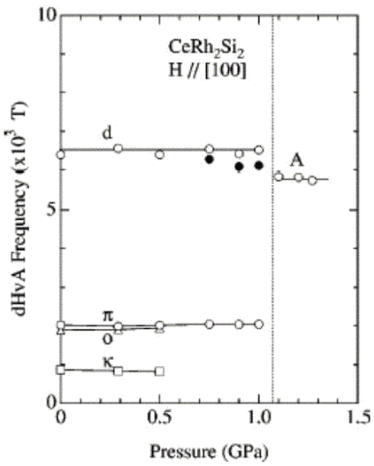
α width of hot spots

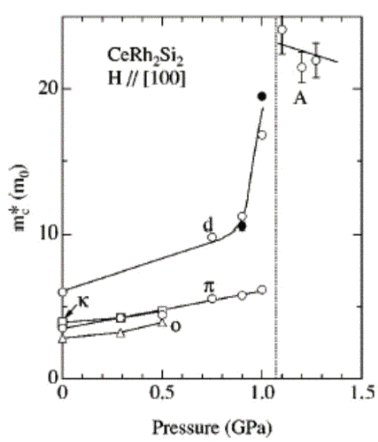
Two choices :

1. damping increases : z ↗
2. system more local : d ↘

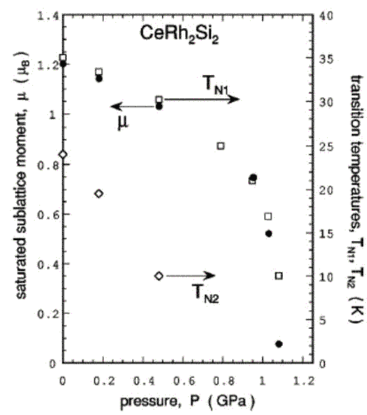
4. Change in the Fermi surface volume at the QCP ? If yes, is it sharp ?

If one believe the Kondo screening is un-complete in the AF phase,
the system must experience a change of the number of carriers at the QCP, evolving
for small FS in the AF phase to large FS in the heavy electron phase.



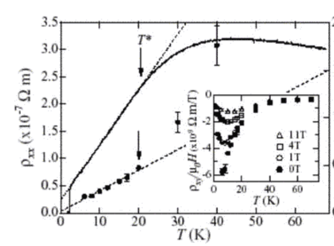


Onuki (2001)

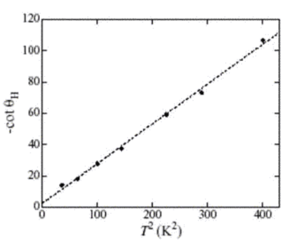


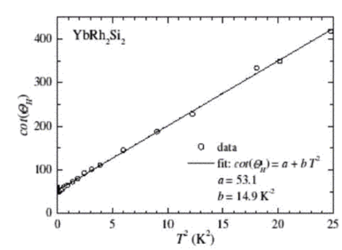
Kawaraski (2001)

Hall constant measurements

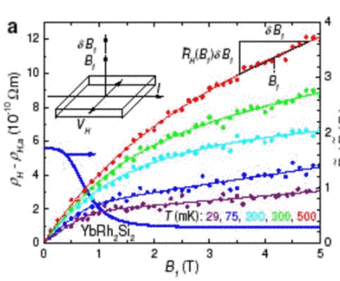


Matsuda 2002, CeCoIn5

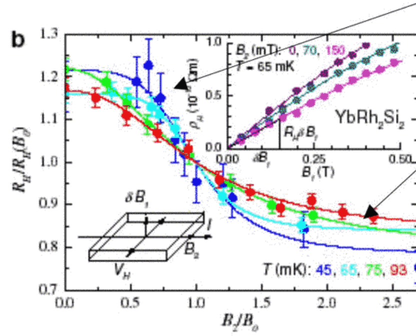




Pashen 2002, YbRh2Si2



Pashen 2004

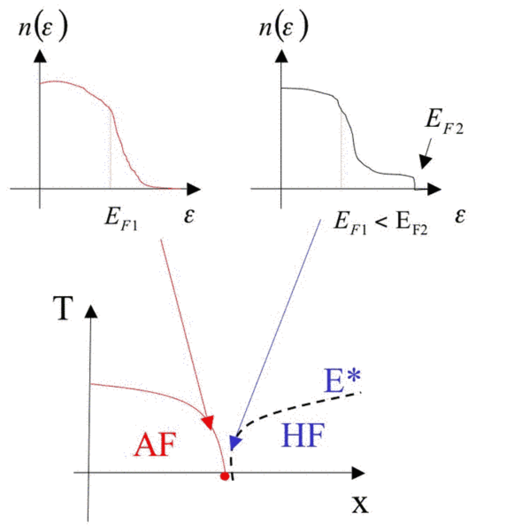


Is it a sharp change at the QCP ?

Different views

Smooth evolution of the number of carriers around the QCP

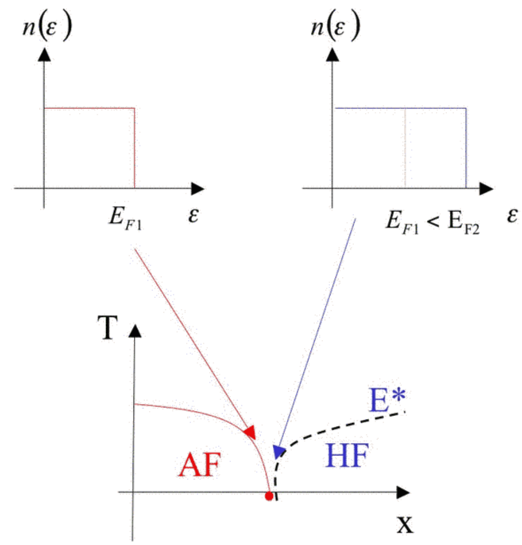
C. Pepin, (2004)



Damped new fermionic excitation at T=0

Sharp ``jump'' of the number of carriers at the QCP

Si, Coleman (2004)



Fully local excitation at T=0, but whole volume of FS is hot

4. Is there a new excitation at the QCP ? Beyond HMM scenarios

- Local QCP (**Q. Si et al. 2002**): local excitation at the QCP $\chi_{loc} \approx Log(T)$ but $\chi(Q,\omega) \approx \omega^{-0.7}$ Sharp FS volume transition. No uptrun in C/T.

- CDMFT approach (**P. Sun et al**) : Phase diagram for HF systems. Ferromagnetic contribution appears. Questioning anomalous exponent of the locally QC scenario (Georges, Kotliar, Florens, Pankov)

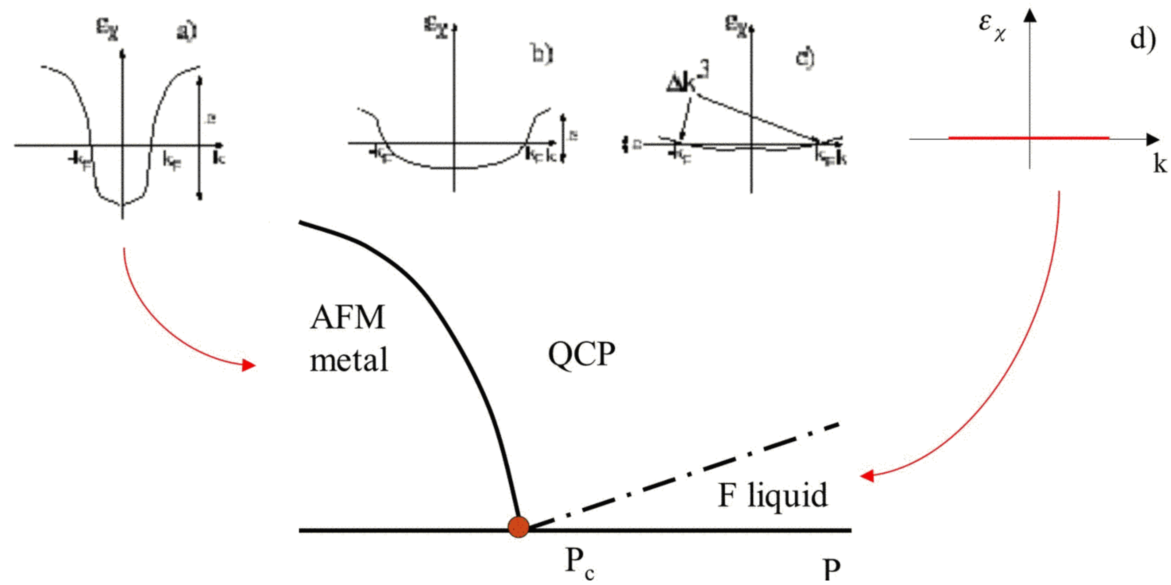
- Fractionalization (**Senthil et al**) : new excitation of bosonic nature at the QCP. Electron fractionalizes into a fermionic spinon and a bosonica guage field. New phase called FL*. Can this approach account for any observable quantity in any compound ?

- Two fluids (**Pines et al**): notion of unscreened spin.Works for describing data in CeCoIn5. One fluid is Fermi liquid, the other one unscreened spin. Does unscreen spin survives till very low temperature and is it critical in that sense ?

- Flat bands (**Shaginyan, 2003**) : idea of a ``flat band'' of conduction electrons at the QCP. No fractionalization of the electron.

- Spin and charge separation (**P. Coleman 2001**): spin and charge decouple or fractionalize at the QCP.

- Fermionic fractionalization (**C. Pepin 2004**) Electron fractionalizes into a bosonic spinon and fermionic gauge field χ. The gauge field is damped and massless at the QCP. Accounts for transport and thermodynamic critical exponents in Yb Rh2 Si2

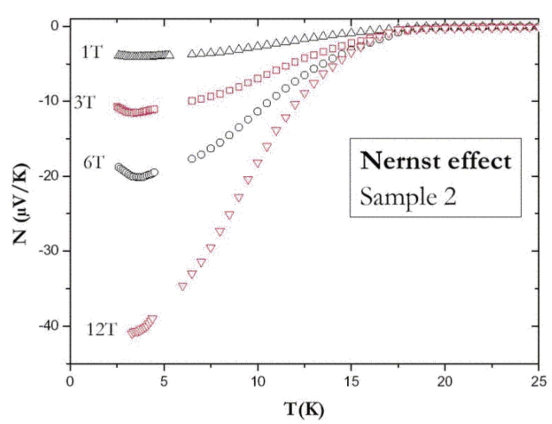


New mysteries

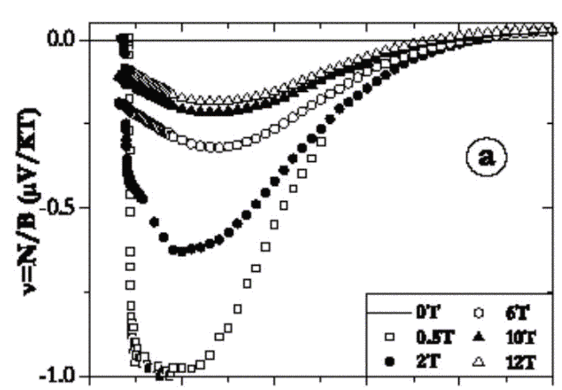
Huge Nernst effect observed in CeCoIn5, and URh2Si2. Same magnitude as in high Tc compounds (Ong) but opposite sign with respect to superconducting Nernst.

URu2Si2

Compound with TN = 16 K Tk ~ 1 K.



CeCoIn5



Bel, Behnia 03