Kaleidoscope of Heavy Electrons: Superconductivity, Magnetism, Quantum Critical Points

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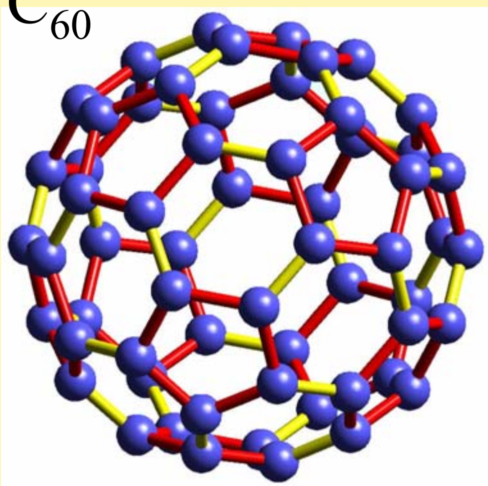
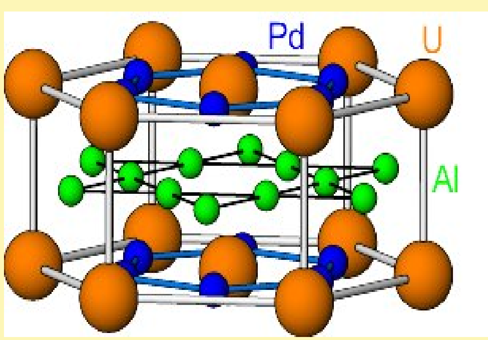
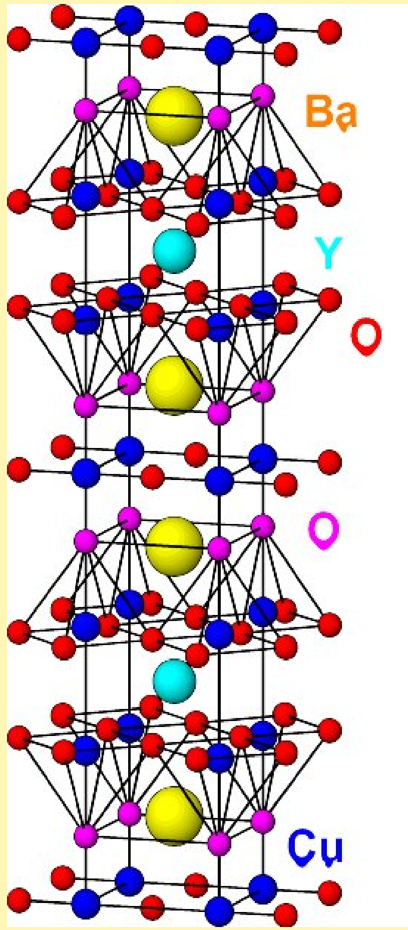
Crystal structures and phenomena

C_{60}





UPd_2Al_3



$YBa_2Cu_3O_7$

ferroelectricity	
charge density wave	
quantum Hall effect	1985, 98
conductivity in polymers	2000 (C)
superfluidity	1996, 2003
superconductivity (SC)	1913, 72, 73, 2003
high-T_c SC in cuprates	1987
colossal magnetoresistance	
heavy fermions	
quantum phase transitions	

Outline

- Heavy-fermion (HF) metals
- Superconductivity
- Quantum criticality
- Outlook

Superconductivity in $CeCu_2Si_2$

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Superconductivity in the Presence of Strong Pauli Paramagnetism: $CeCu_2Si_2$

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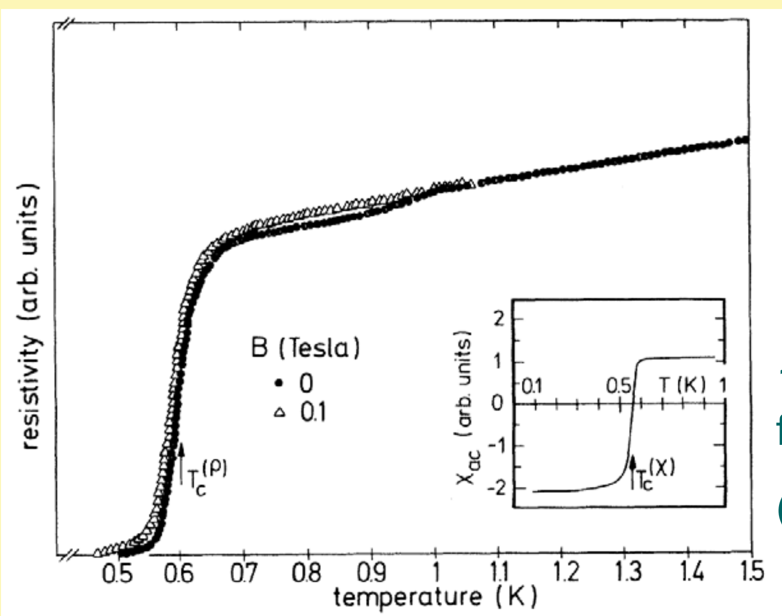
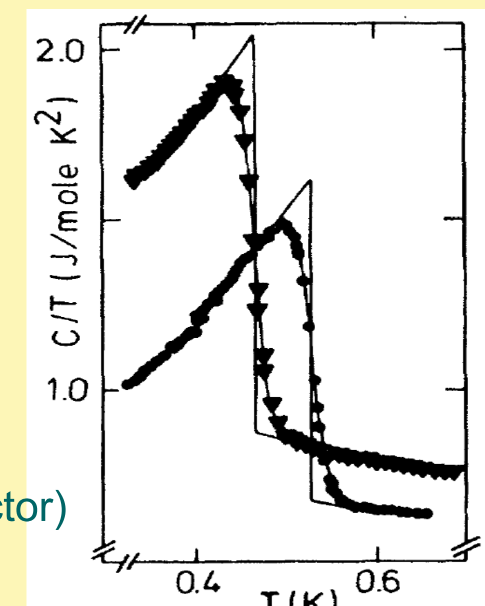
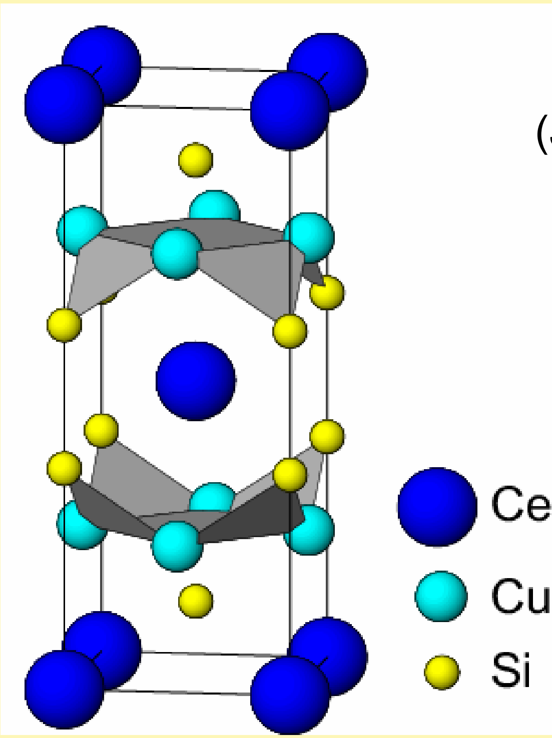


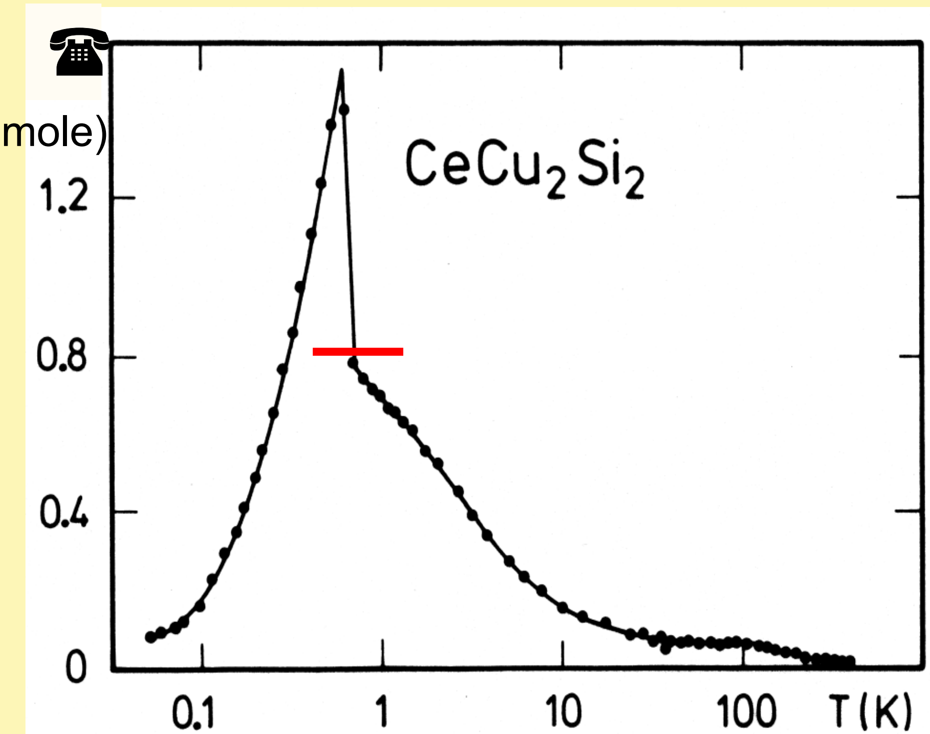
100 at% Ce^{3+} ions **necessary** for superconductivity

($LaCu_2Si_2$ is not a superconductor)



Superconductivity of Heavy Fermions





☎ ~ m*

$T_K \approx 15$ K

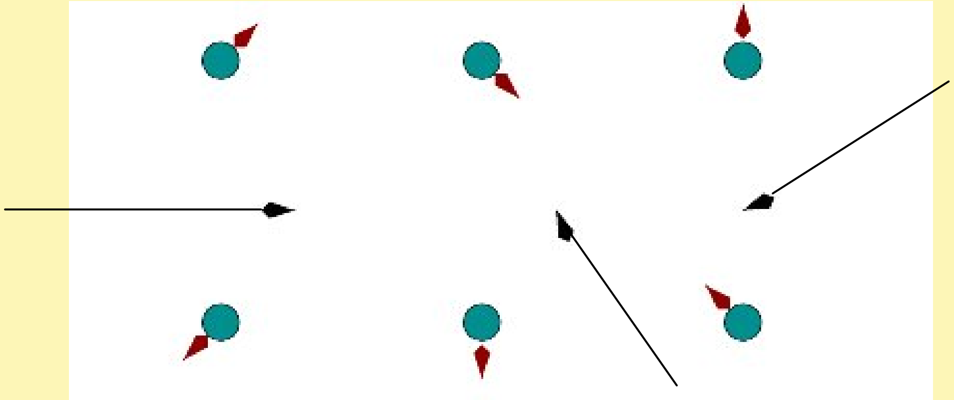
- **Normal state**
  ($B_{c2} \approx 3$ Tesla)
  ☎ → 1 J/K²mole (Cu: 0.7 · 10^{-3} J/K²mole)
  Heavy Electrons
  ("Heavy Fermions")

- **Superconducting phase transition**
  (B = 0)
  $\Delta C/T_c \approx$ ☎(T_c)
  Cooper pairs formed by "Heavy Fermions"
  Anisotropic order parameter

Heavy-Fermion metals

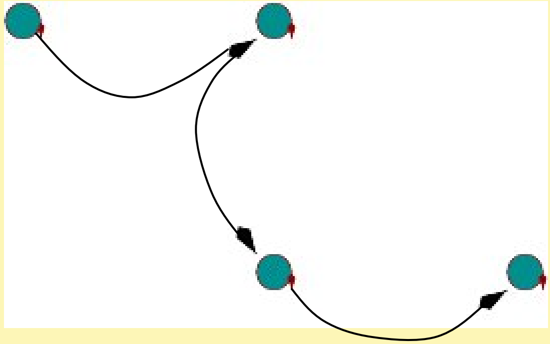
$T \gg T_K$ (10 ... 100 K)

$v_F \approx 10^6 \frac{m}{s}$



$T \ll T_K$: Heavy electrons ("composite fermions")

$v_F^* \approx 10^3 \frac{m}{s}$



→ $m^* \approx 1000\, m_{el}$: "strongly correlated electron system"

Groundstate properties

- Heavy Landau Fermi liquid (LFL) : $CeCu_6$
- Non-Fermi liquid (NFL) : $YbRh_2Si_2$
- Magnetic order : $NpBe_{13}$
- Superconductivity : UPd_2Al_3

Heavy-Fermion Superconductors

Ce-based

	T_c(K)	
$CeCu_2Si_2$	0.7	('79 DA/K)
[p = 2.9 GPa:	2.3	('84 GE/GR)]
$CeNi_2Ge_2$	0.2	('97 DA, '98 CA/GR)
$CeIrIn_5$	0.4	('00 LANL)
$CeCoIn_5$	2.3	('00 LANL)
Ce_2CoIn_8	0.4	('02 NA)
$CePt_3Si$	0.7	('03 VI)

p > 0

$CeCu_2Ge_2$	0.6	('92 GE)
$CeRh_2Si_2$	0.4	('95 LANL)
$CePd_2Si_2$	0.4	('94 CA)
$CeIn_3$	0.2	('98 CA)
$CeRhIn_5$	2.1	('00 LANL)
Ce_2RhIn_8	1.1	('03 LANL)

U-based

	T_c(K)	
UBe_{13}	0.9	('83 Z/LANL)
UPt_3	0.5	('84 LANL)
URu_2Si_2	1.4	('84 K)
UNi_2Al_3	1.2	('91 DA)
UPd_2Al_3	2.0	('91 DA)

Pr-based

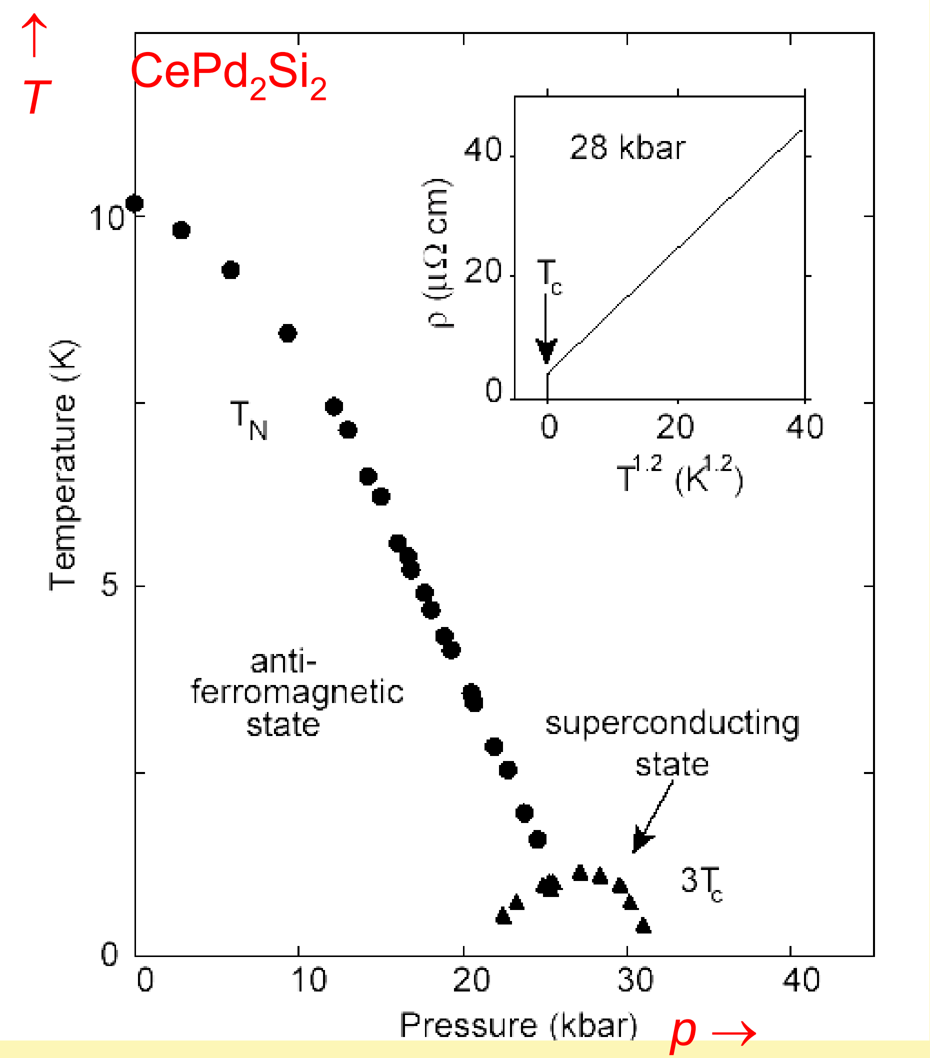
$PrOs_4Sb_{12}$	1.85	('01 UCSD)

Pu-based

$PuCoGa_5$	18.5	('02 LANL)
$PuRhGa_5$	8.7	('03 KA)

Non-Fermi-Liquid Superconductor: $CePd_2Si_2$

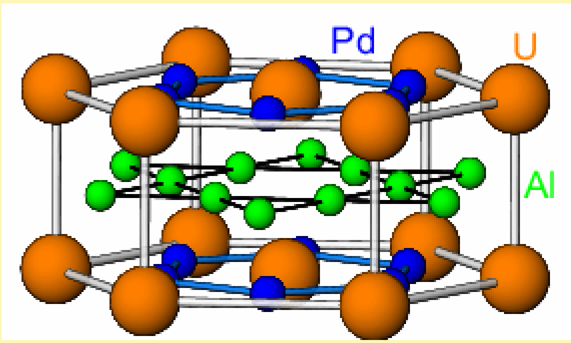
[N.D. Mathur et al., Nature **394**, 39 (1998)]

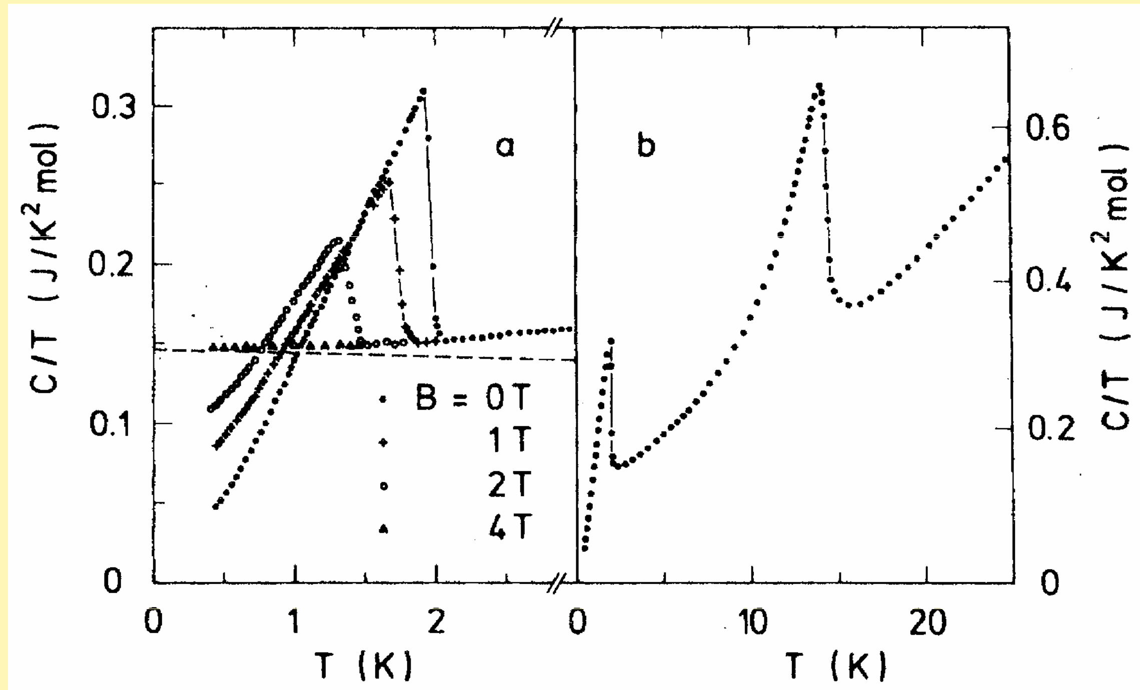


- AF QCP at p_c = 28 kbar
- T_c = 0.4 K at $p=p_c$
- NFL normal state
- SC mediated by strong spin-fluctuations ?

Magnetic Cooper pairing in UPd_2Al_3

C. Geibel et. al., 1991





T_{magn}	$\approx$	14 K
μ_s	$\approx$	0.85 μ_B
γ	$\approx$	140 mJ/K^2mol
T_c	$\approx$	2 K
$2\Delta_0/k_BT_c$	$\approx$	6 (Kyougaku et al., 1993)

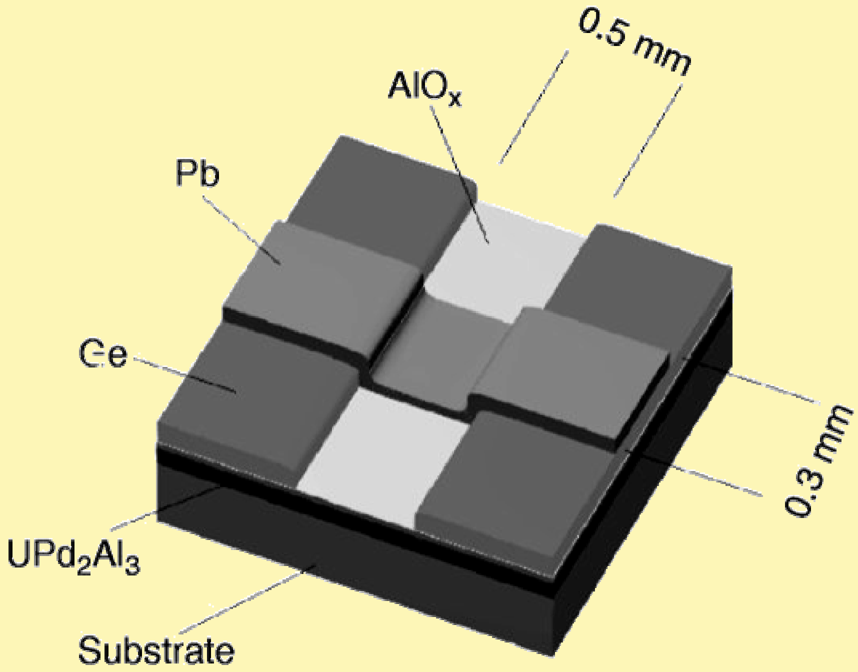
U^{3+} $(5f^3)$

- **Two more localized ("core") electrons:** magnetism
- **one less localized ("heavy" itinerant) electron:**
  - heavy LFL state ($T_c < T < T_N$)
  - heavy-fermion SC ($T < T_c$)

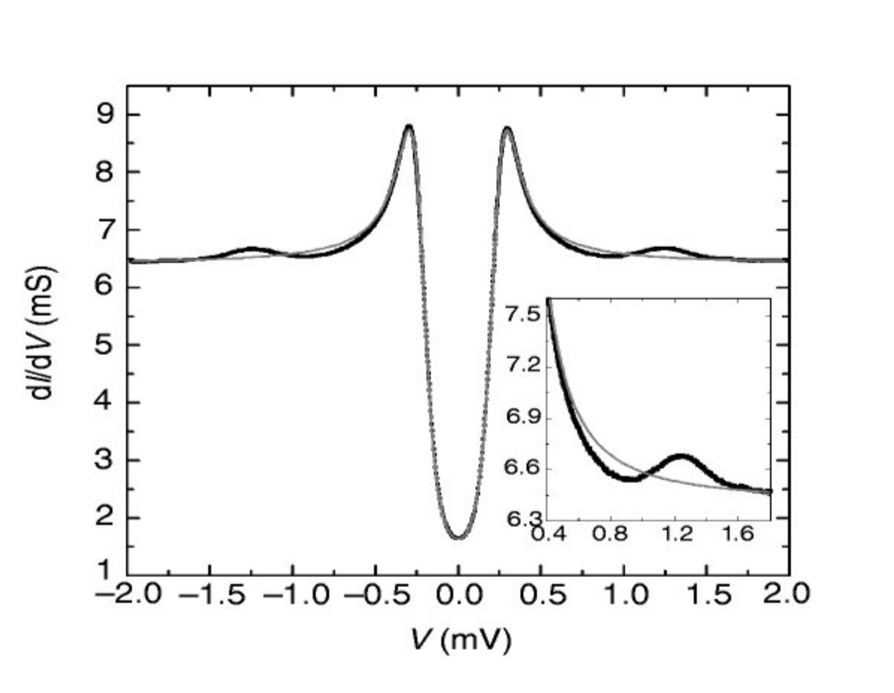
  coexisting with local AF

Quasiparticle tunneling

[M. Jourdan et. al., Nature **398,** 47 (1999)]



tunnel diode UPd_2Al_3 - AlO_x - Pb
(Pb normal conducting : B = 0.3 T)

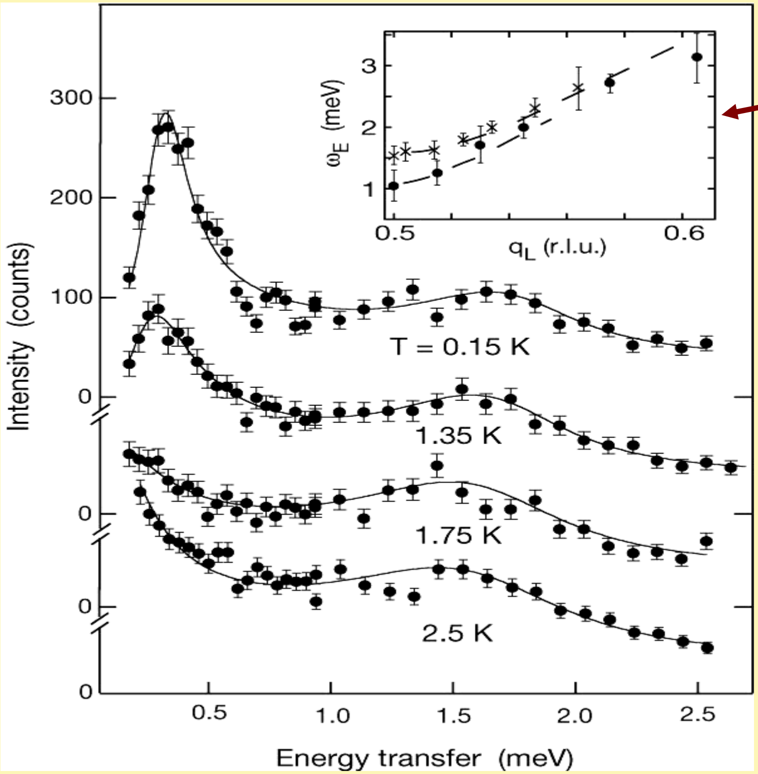


dI/dV

(T = 0.15 K)

Inelastic neutron scattering

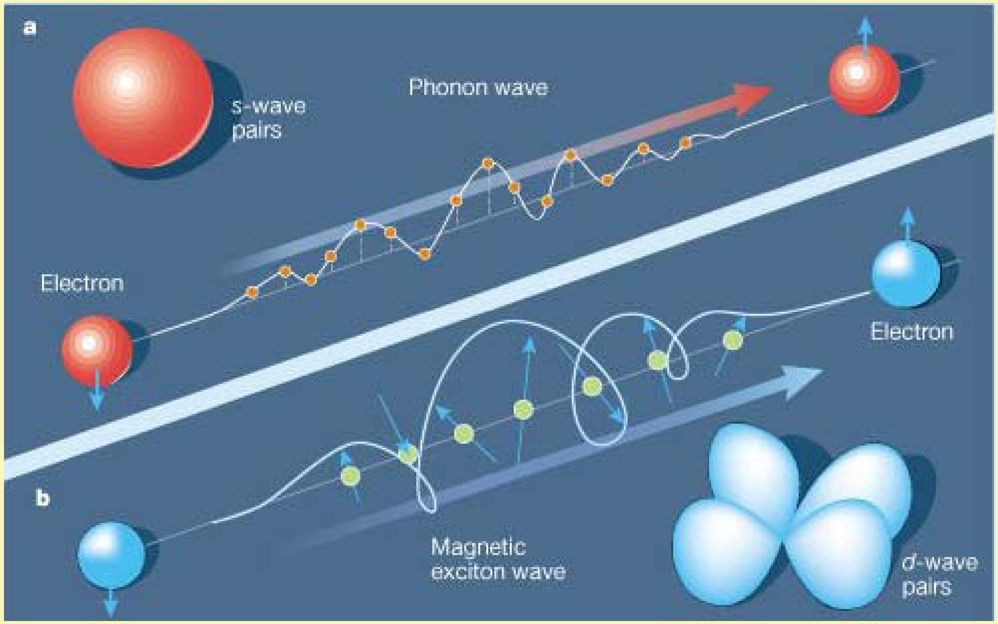
[N.K. Sato et al., Nature **410**, 340 (2001)]



acoustic magnon ("magnetic exciton")

$\vec{Q} = \vec{Q_0} = (0, 0, 1/2)$

$T_c = 1.8$ K

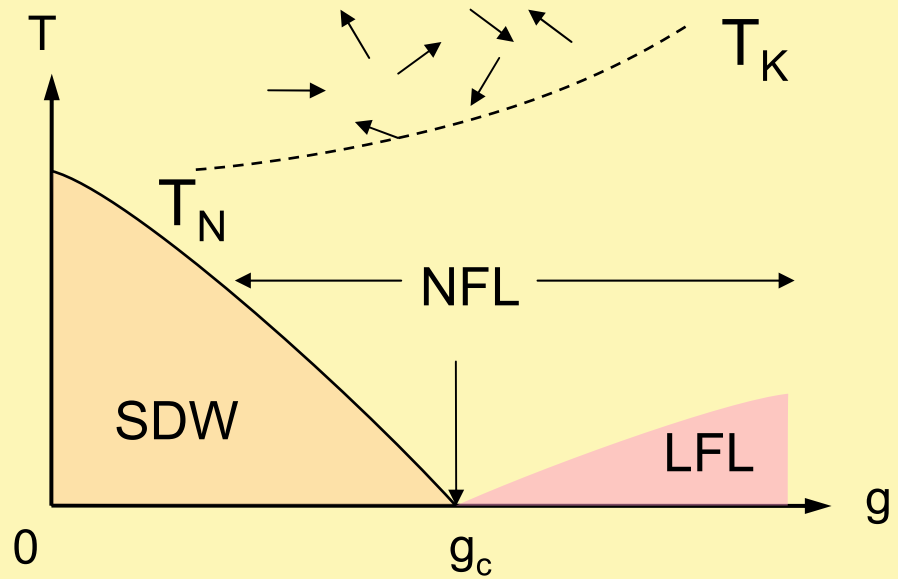


Cooper pairs formed by heavy electrons ("itinerant" 5f electrons)

superconducting glue provided by magnetic excitons in the system of "localized" 5f electrons

Itinerant (SDW) scenario

Moriya, Hertz, Millis, Continentino, Lonzarich, …



$T < T_K$

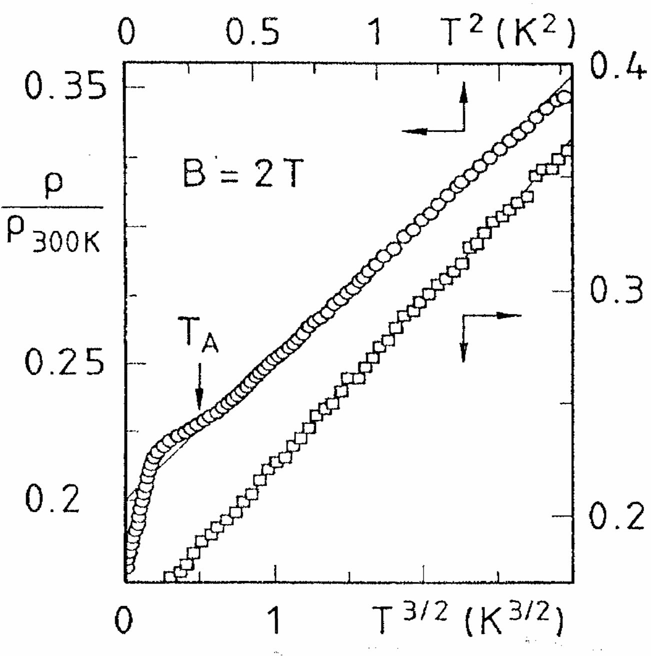
- local moments screened
- heavy QPs formed ("itinerant f-electrons")
- weak coupling: SDW phase
- QPs scattered off critical spin fluctuations

NFL

- in wide regions of phase diagram (T, $|g-g_c|$)
- thermal excitation of quantum critical modes
- coupling of statics and dynamics: $\tau_c \sim \xi^z$ (AF: $z = 2$); $d_{eff} = d + z$

$CeCu_2Si_2$: "A-S" transition at $p < 0.7$ GPa

[G. Sparn et al., Rev. High Press. Sci. Technol. **7**, 431 (1998)]

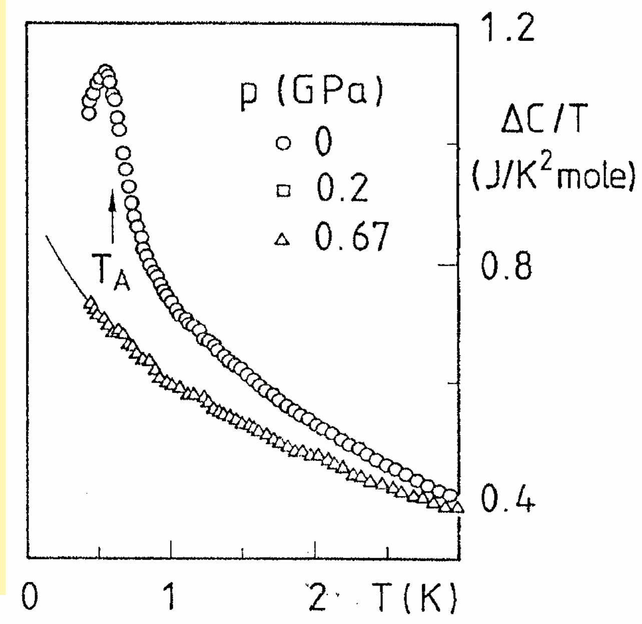


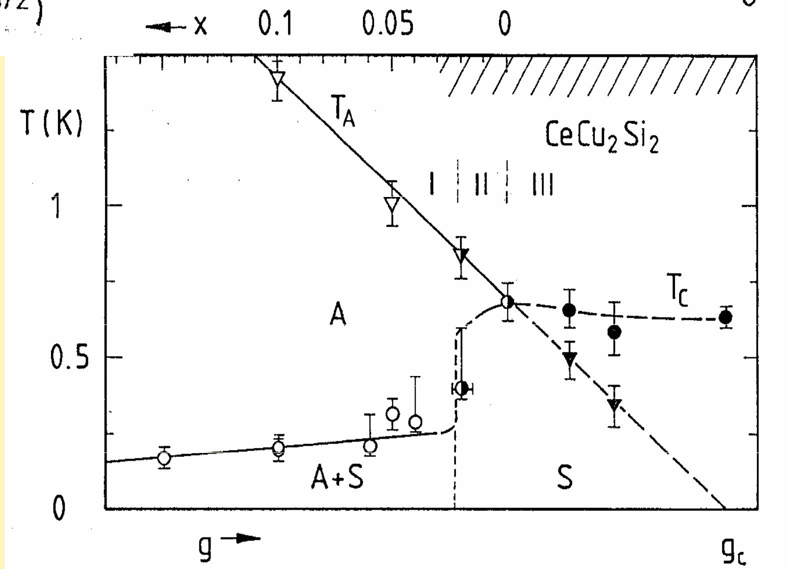
$p > p_c$:

$\Delta\rho = \alpha T^{1.5}$

$\gamma = \gamma_0 - \beta T^{0.5}$

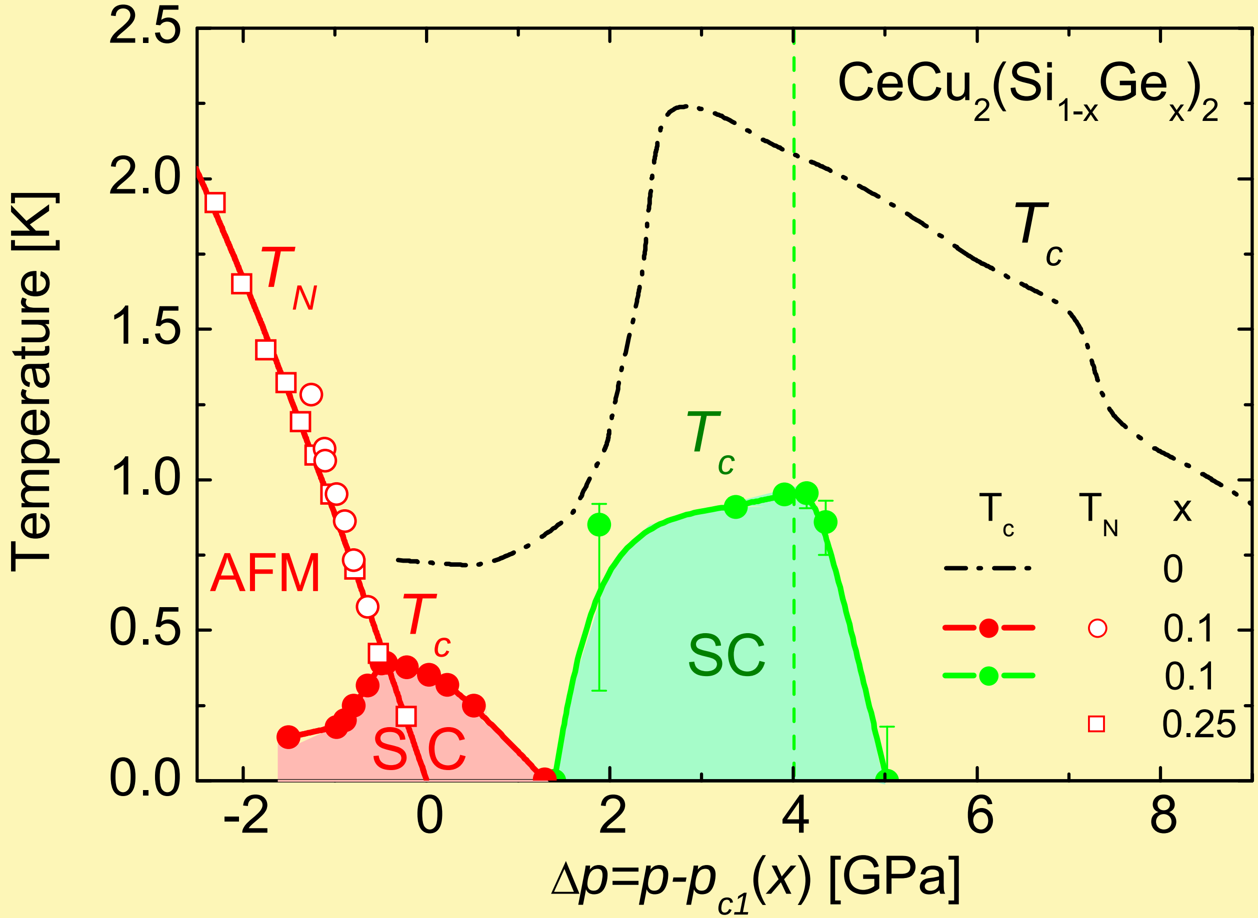
(3D-SDW scenario)





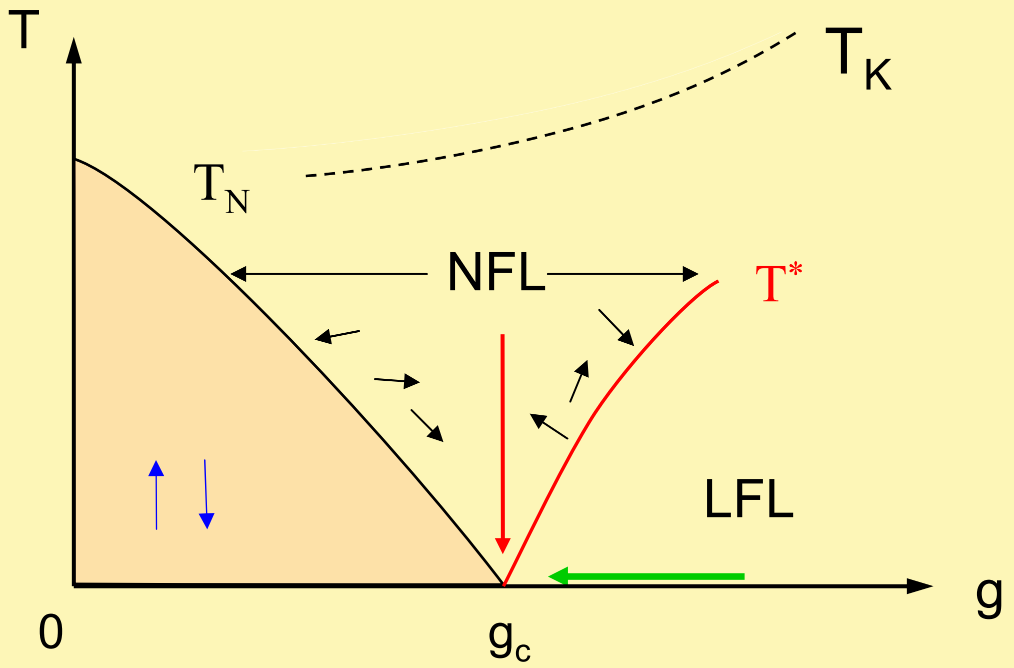
Observation of two distinct superconducting phases in $CeCu_2Si_2$

[H. Q. Yuan et al., Science **302**, 2104 (2003)]



Locally critical (local moment) scenario

Schröder,
Coleman,
Si,
Pépin,
Ingersent,
Ramazashvili



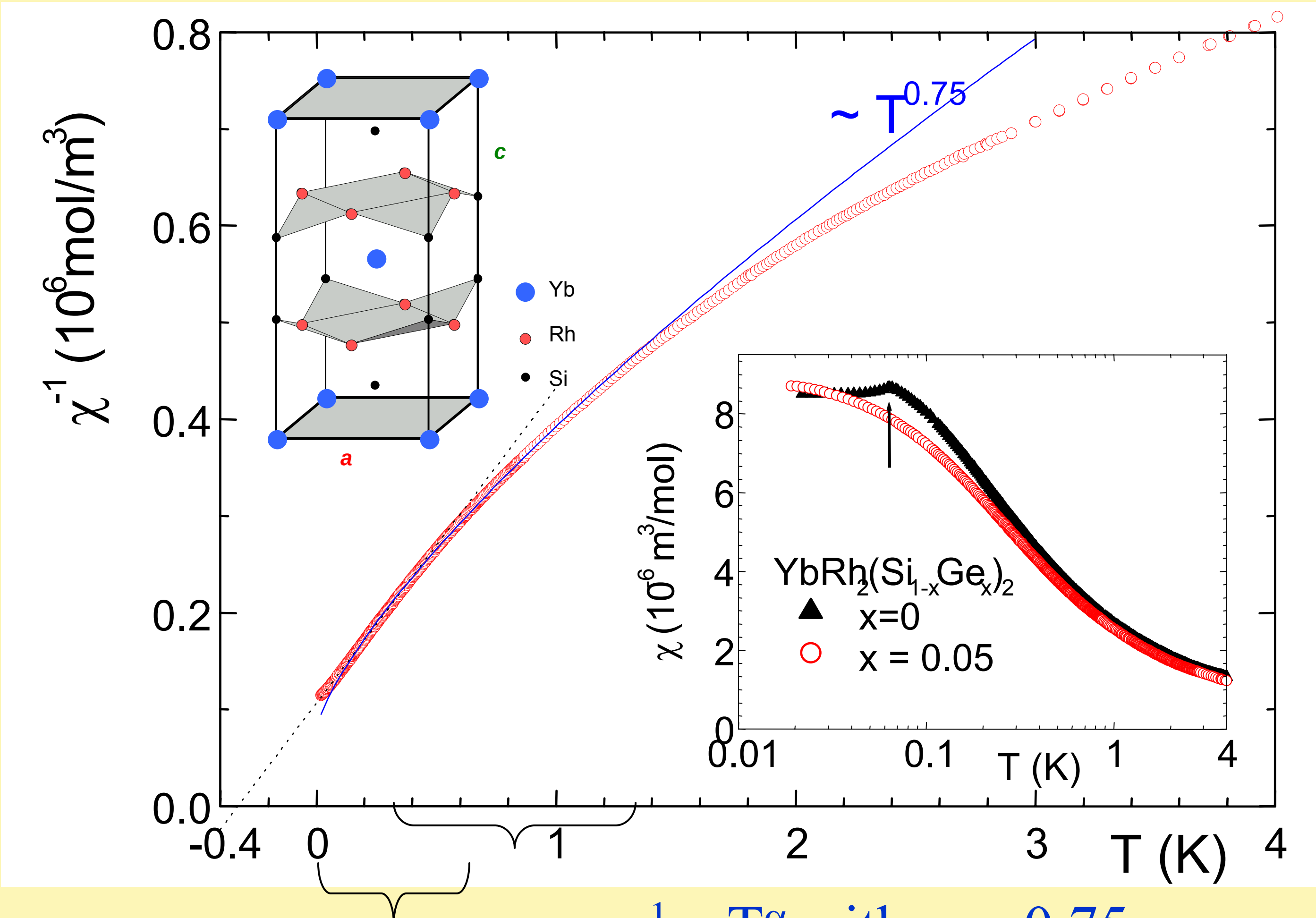
- Two QCPs coinciding: AFM - PM; LFL - NFL
- New quantum criticality dominating: **local** spin fluctuations
- At QCP: Kondo resonance not fully developed
- NFL: fluctuations between small and large Fermi surface

experimental techniques: T-dependence (at $g = g_c$)

g (p or B) -dependence (at T = 0)

$YbRh_2(Si_{0.95}Ge_{0.05})_2$

[P. Gegenwart et al., Acta Pol. Phys. B **34**, 323 (2003)]



$\chi^{-1} \sim T^{\alpha}$ with $\alpha \approx 0.75$

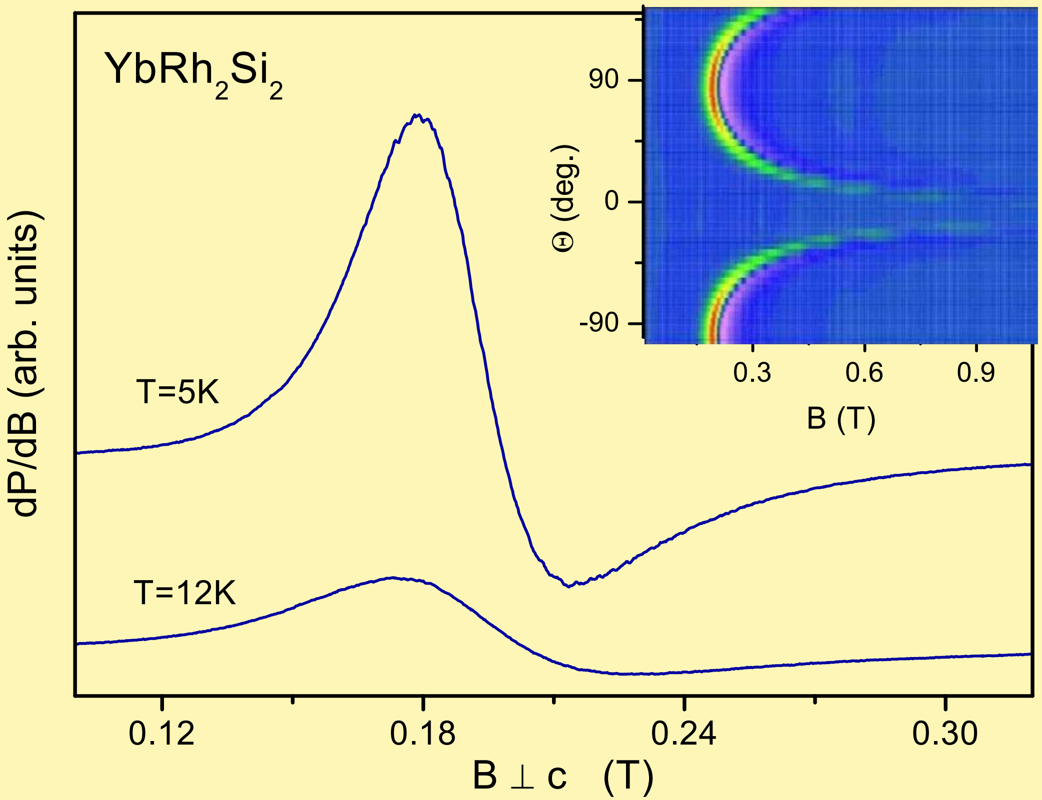
$\chi = C/(T-\theta)$

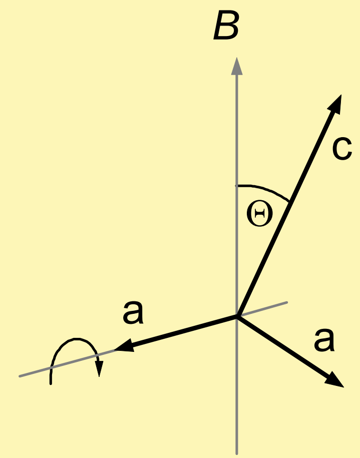
$\theta = -\,0.3$ K

$C \rightarrow \mu_{para} = 1.4\ \mu_B/Yb^{3+}$

Yb^{3+} ESR in $YbRh_2Si_2$

[J.Sichelschmidt et al., PRL **91**, 156401 (2003)]





$g_{\perp} = 3.561 \pm 0.006$

$g_{\parallel} = 0.17 \pm 0.07$

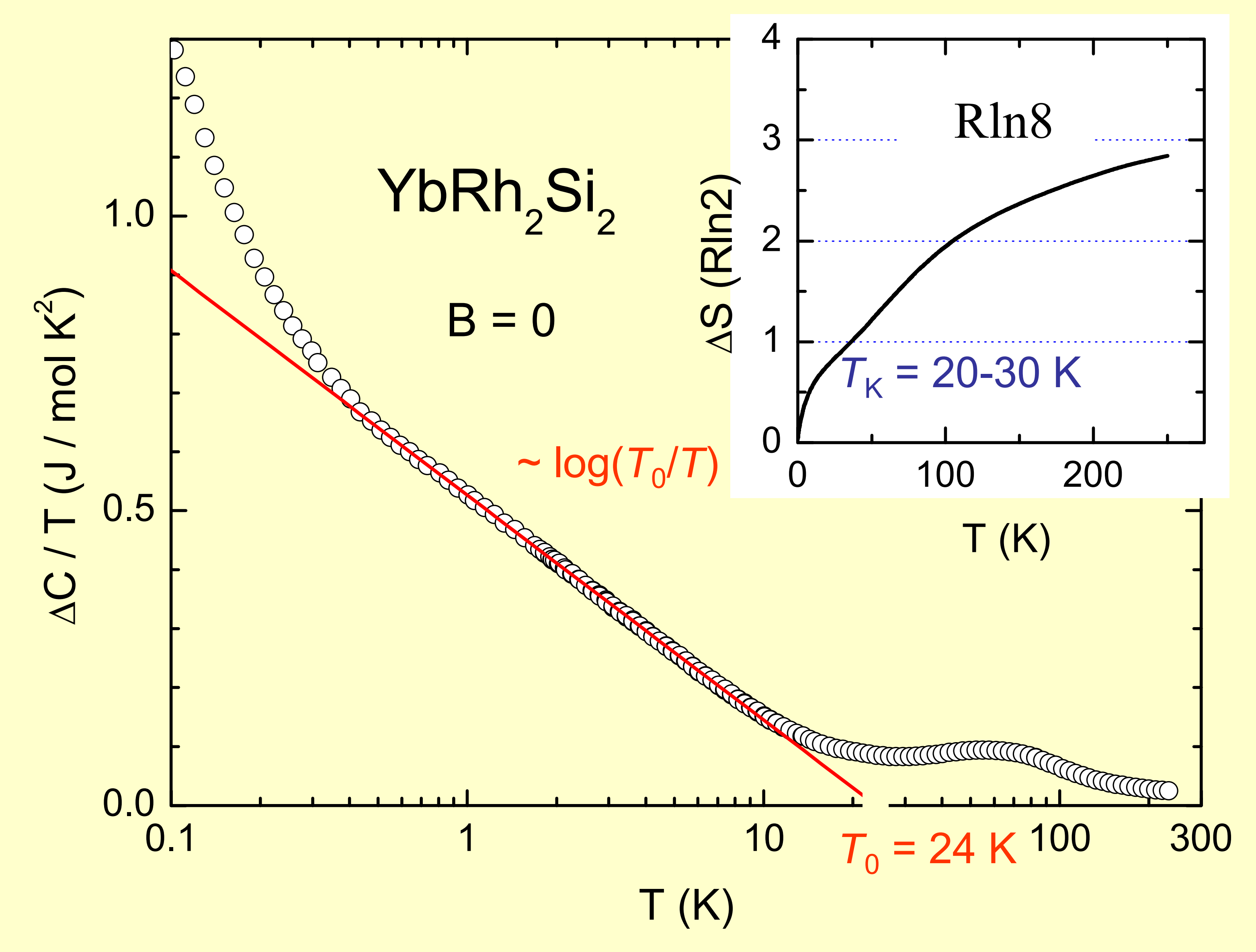
linewidth $\Delta B_{exp} = 0.02T << \Delta B_K = k_B T_K/\mu_B = 37$ T ($T_K = 25$ K)

intensity $I \sim \chi(\omega = 0, \mathbf{q} = 0)$

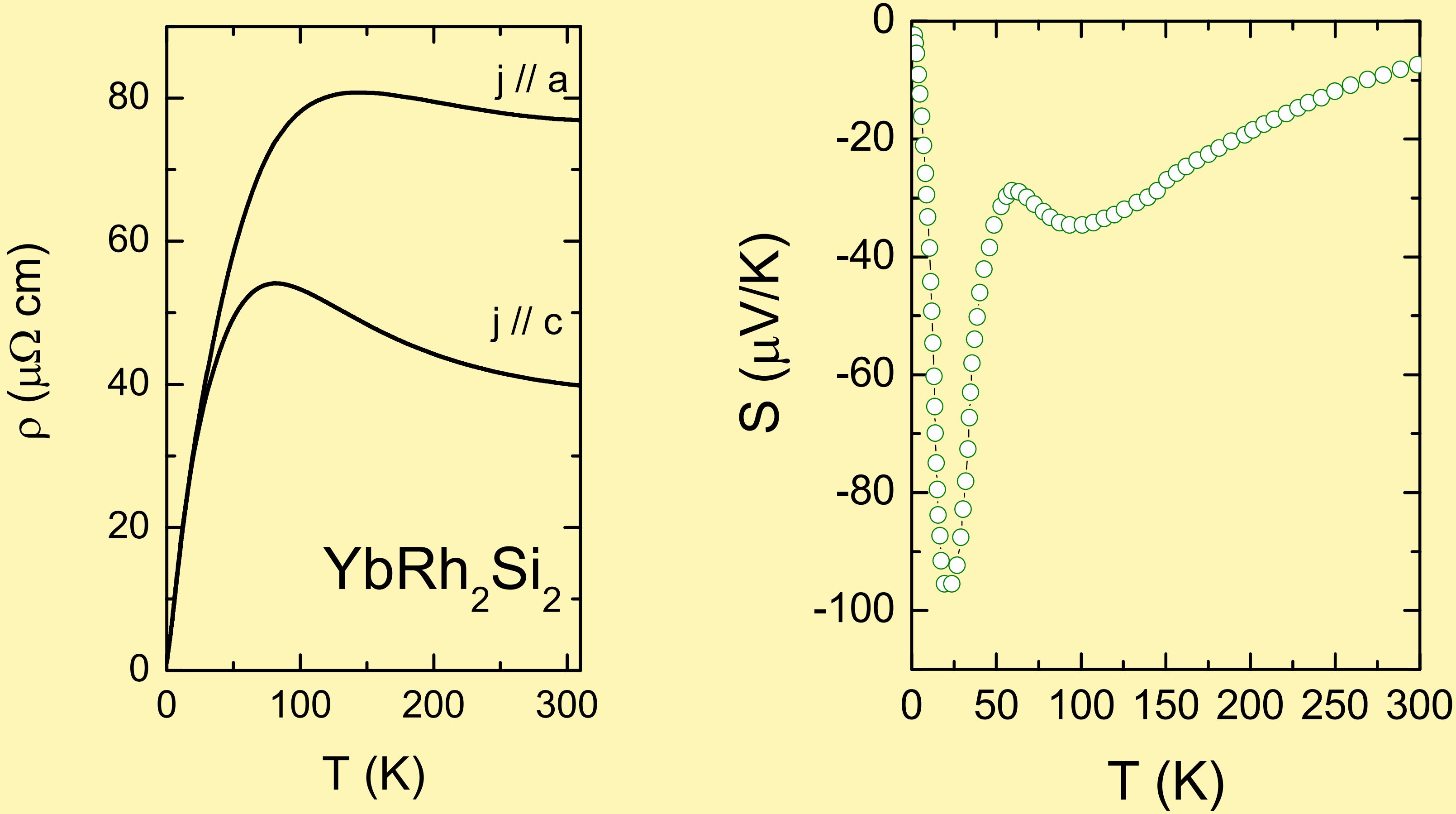
anisotropy

large local Yb^{3+} moments exist **well below** $T_K = 25$ K

Kondo temperature T_K from thermodynamics

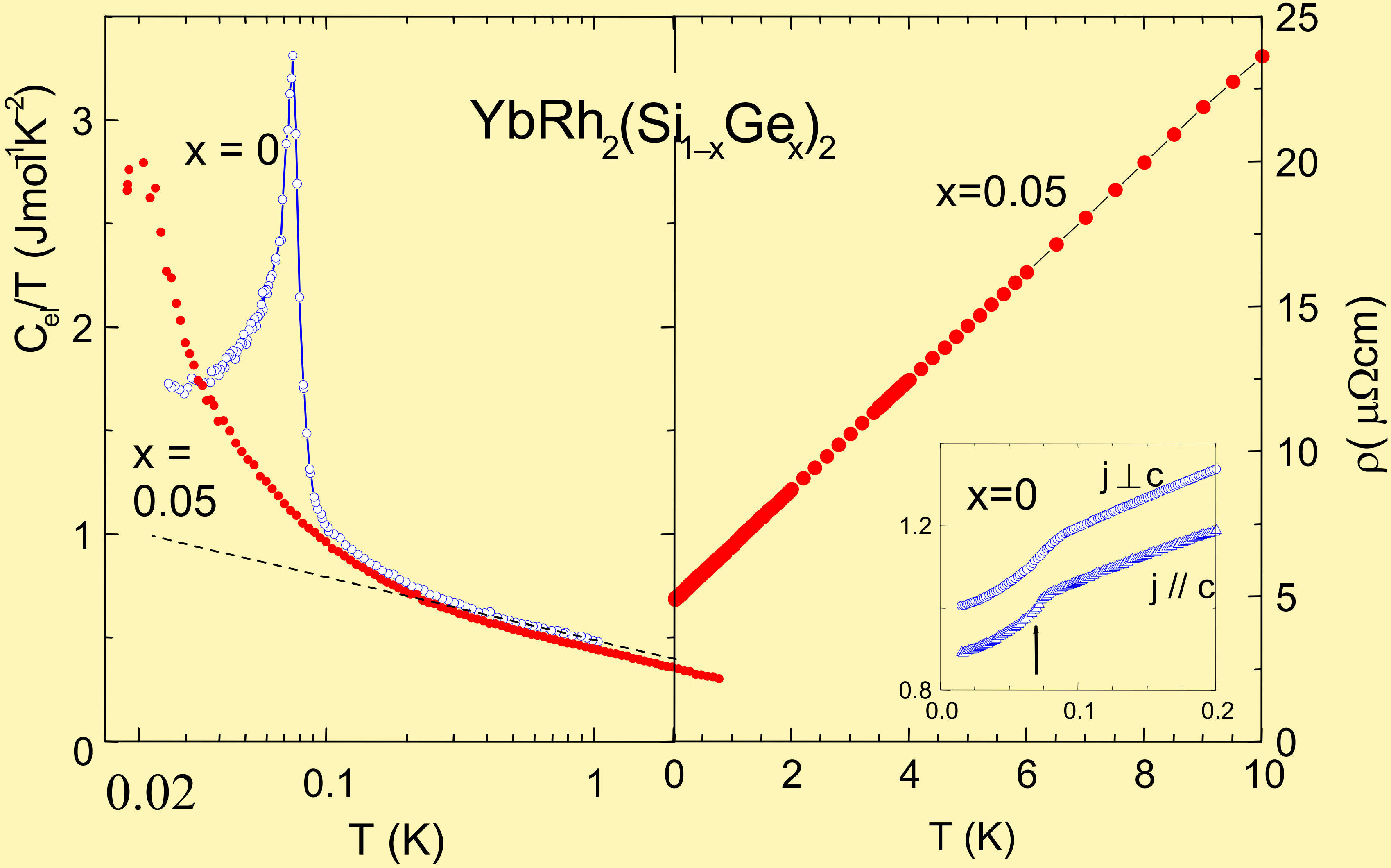


Kondo temperature T_K from transport

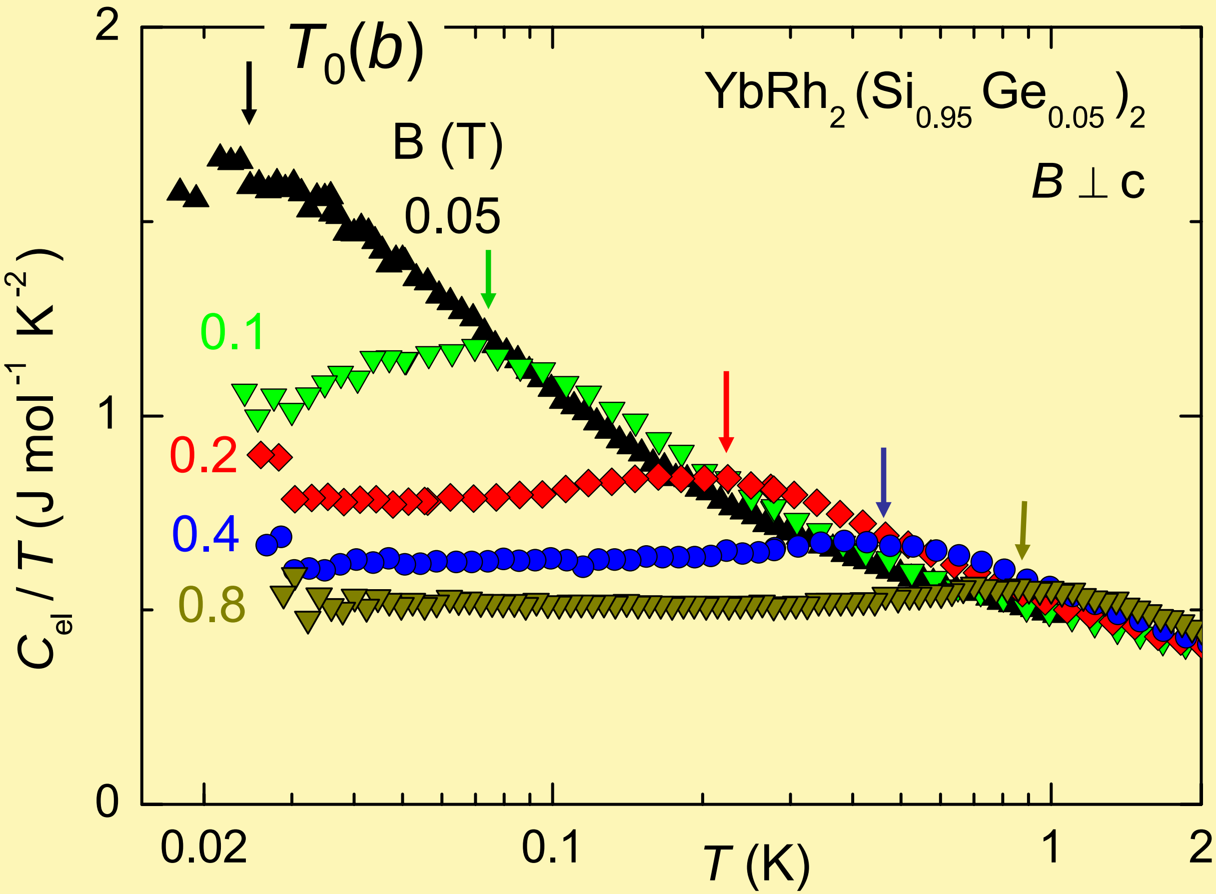


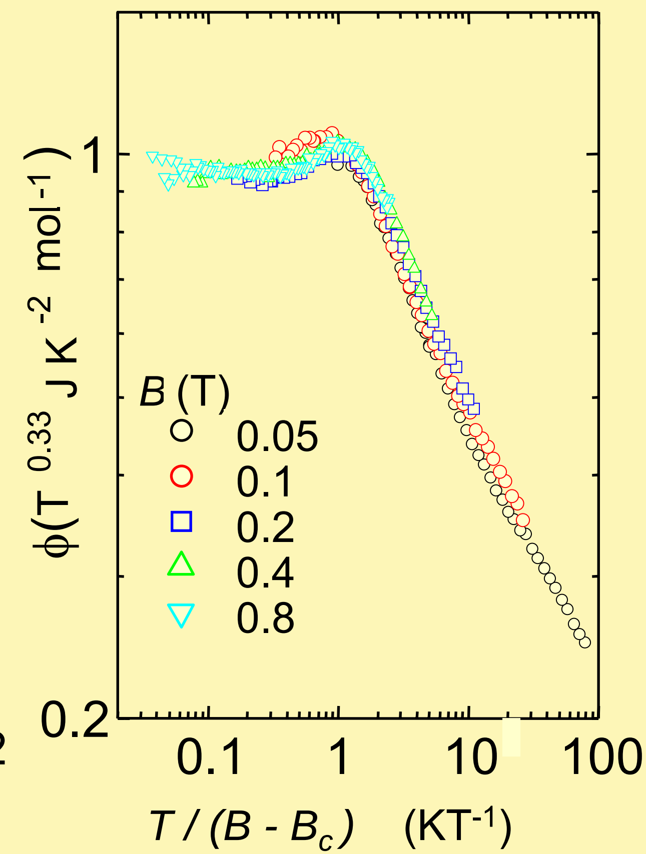
Disparity between C_{el}/T and ρ in $YbRh_2Si_2$

[J. Custers et. al., Nature **524**, 424 (2003)]



Scaling behavior in $C_{el}(T,b)/T$; $b = B - B_c$



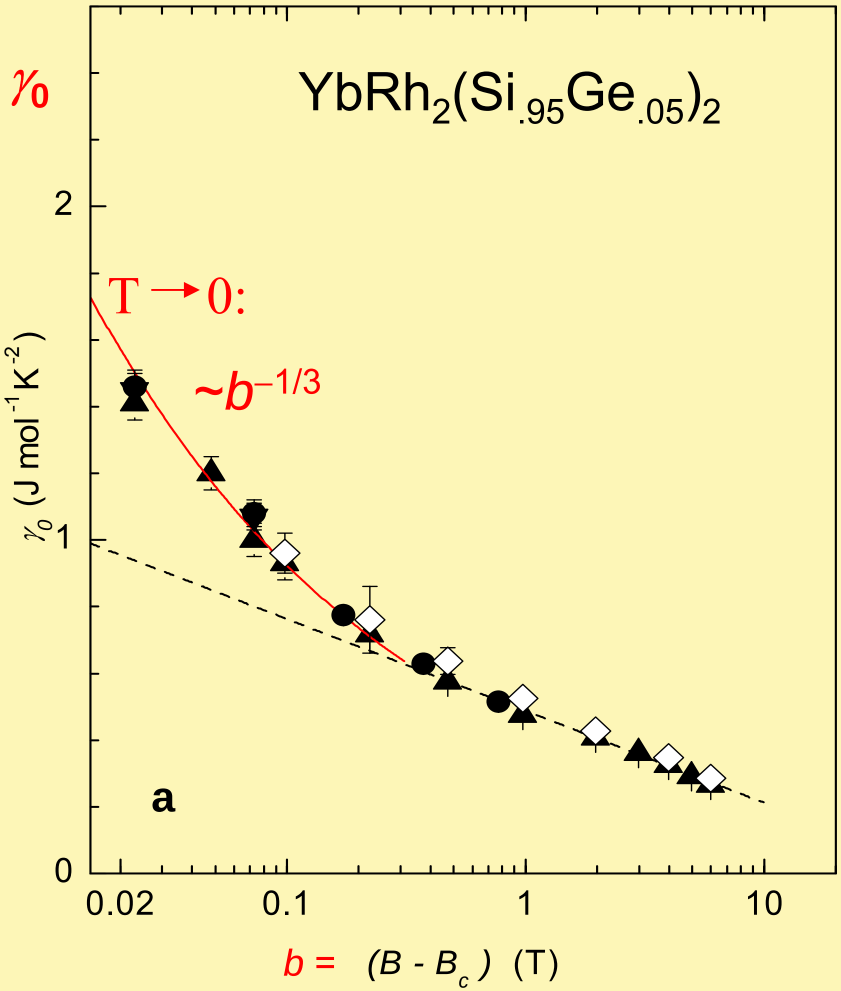


Characteristic energy scale $T_0(b) \sim b$ vanishes at QCP

$\Rightarrow T/T_0$ scaling for $\Phi(T,b)$ with $\Phi(T,b) = b^{1/3} \cdot C(T,b)/T$

$\Rightarrow S(T,b)=b^{2/3}\,S(T/T_0) \rightarrow 0$ at QCP $\Rightarrow$ no residual entropy at QCP

Field dependence of $\gamma_0(b)$, $b \perp c$ (B_c = 0.027 T)

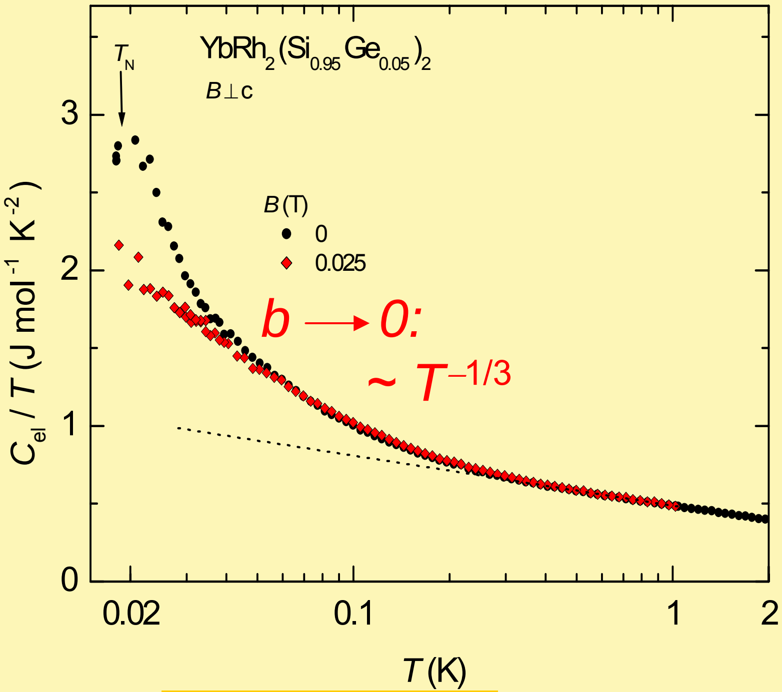


γ ~ (-log b) for $b \geq 0.3$ T

$b^{-1/3}$ ($b \to 0$)

⇒ contradiction to 2D-SDW scenario

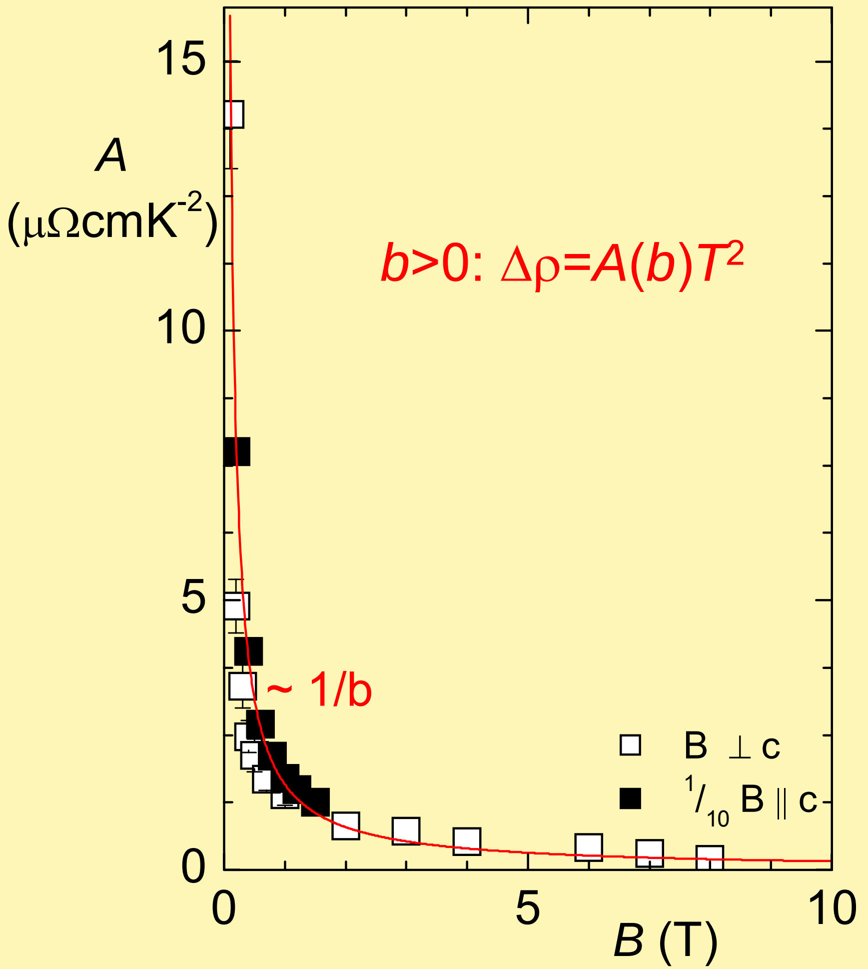
⇒ b-dependence at T=0 similar to T-dependence at b=0

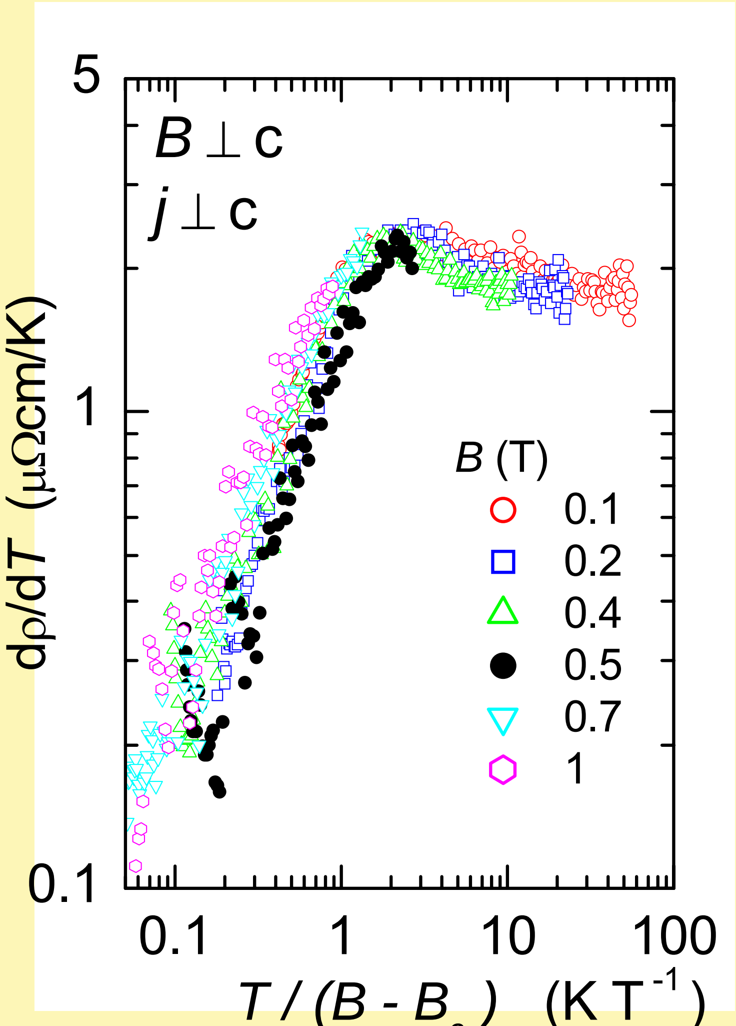


Similar: $$\frac{T^2}{\Delta\rho} = A^{-1} \sim$$

T ($b \to 0$)
b ($T \to 0$)

Scaling behavior in $\rho(T,b)$, $b = B - B_c$





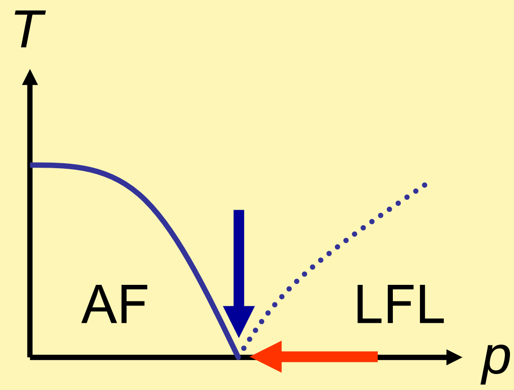
Grüneisen ratio

[R. Küchler et al., PRL **91**, 066405 (2003)]

Specific heat: $C/T \sim \partial S/ \partial T$

Thermal expansion: $\beta \sim (- \partial S/ \partial p)$

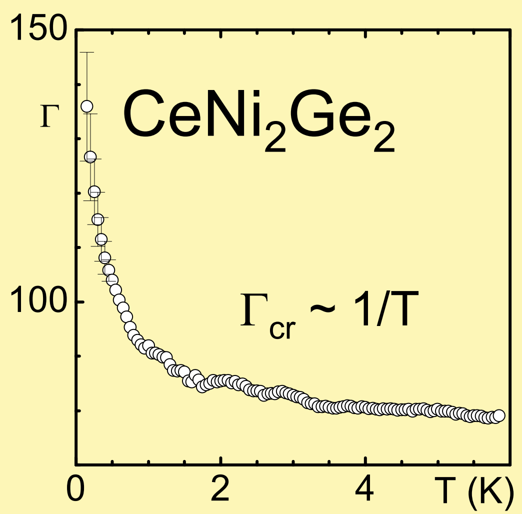
$(\beta = 1/V\ dV/dT)$



L. Zhu, M. Garst, A. Rosch, Q. Si, PRL **91**, 066404 (2003):

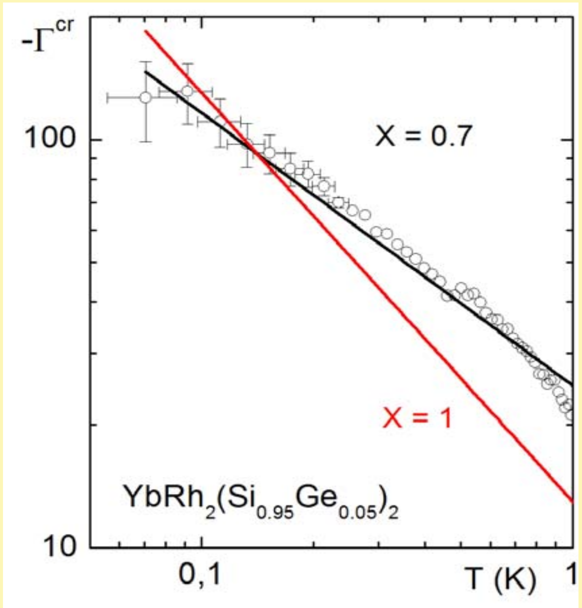
Grüneisen ratio $\Gamma_{cr} = \beta_{cr}/C_{cr}$ diverges at any QCP, $\Gamma_{cr} \sim T^{-x}$

Critical exponent x ⟶ nature of QCP



x = 1:

3D-SDW scenario



Outlook

Importance of local f-degrees of freedom, e.g.,

UPd_2Al_3 - Cooper pairing via (propagating) local 5f-excitation

$YbRh_2$(<u>Si</u>, Ge)$_2$ - suggestive of local QCP

- non-Kondo-screened fluctuating Yb^{3+} moments
- break-up of heavy ("composite") quasiparticles
- fractional exponent for Grüneisen ratio

- **no** superconductor

However:

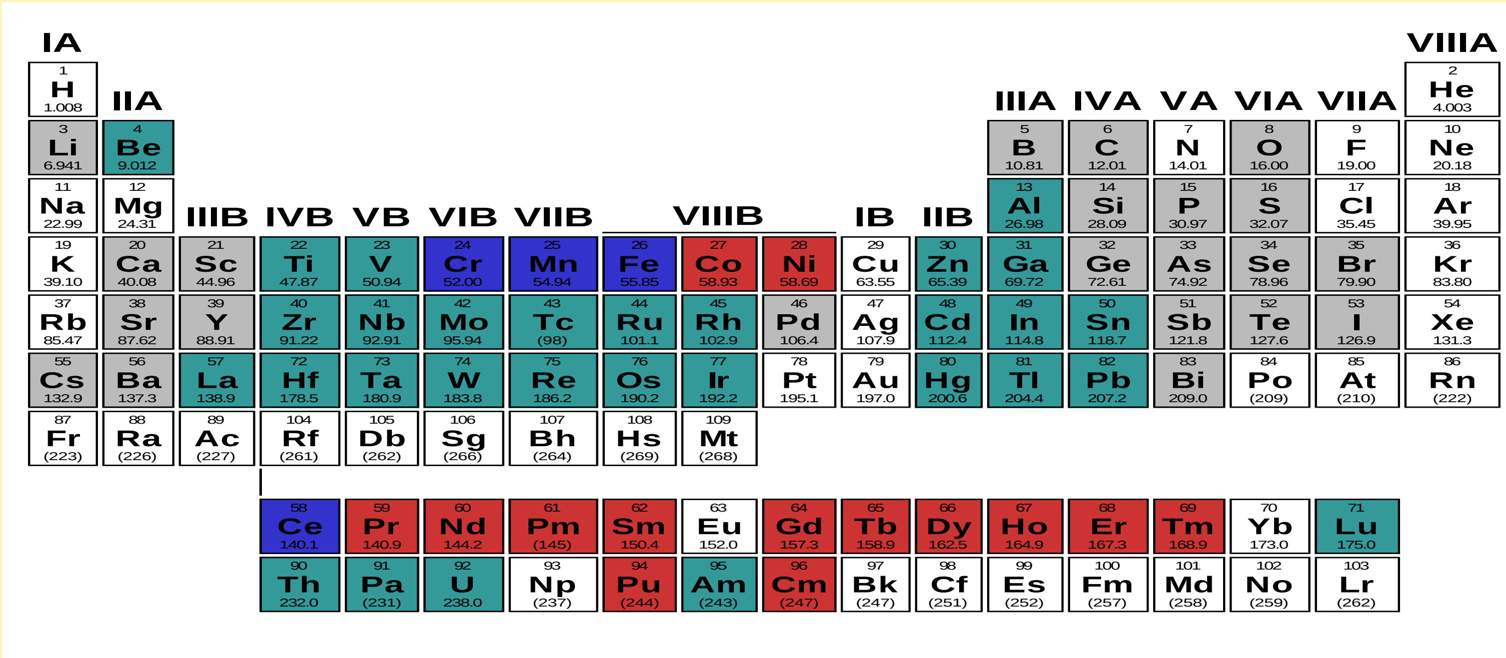
$CeCu_2Si_2$ - compatible with (3D) SDW scenario, superconductors

$CeNi_2Ge_2$

⋮

→ Is local QCP **unfavorable** for superconductivity?

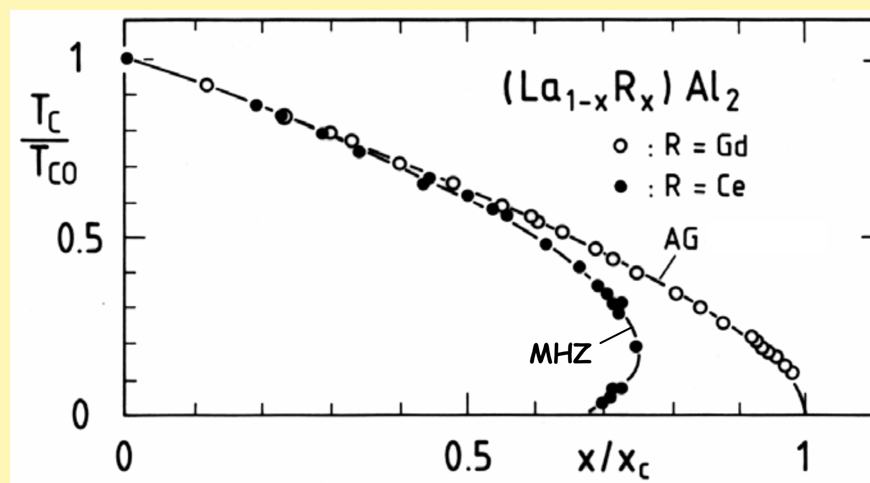
Superconductivity vs. magnetism



- **Pairbreaking by magnetic impurities (x_c < 1 at%)**

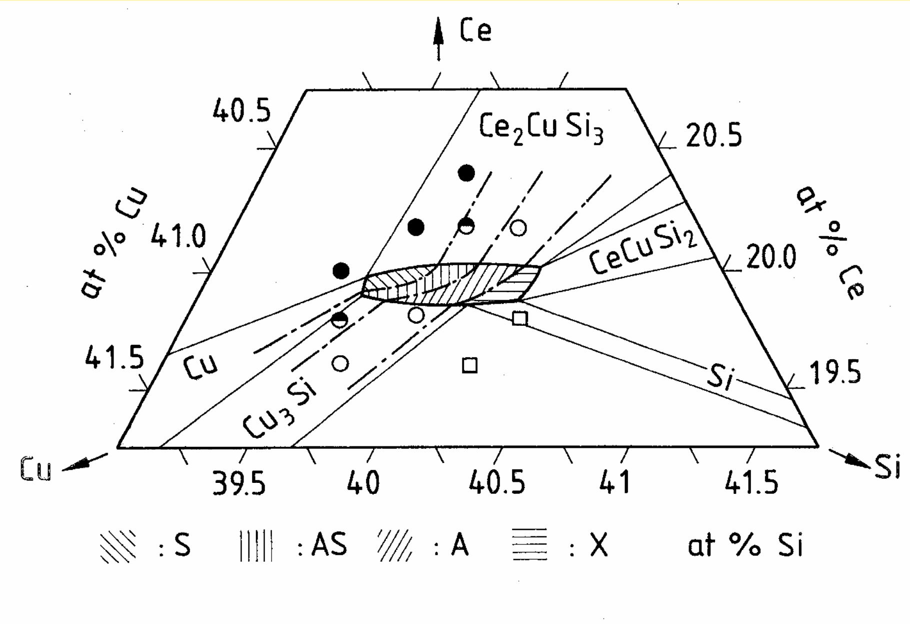
LaAl$_2$ T_{Co} = 3.3 K
Gd-doping: x_c = 0.6 at%
Ce-doping: x_c = 0.9 at%
T_K = 0.5 K

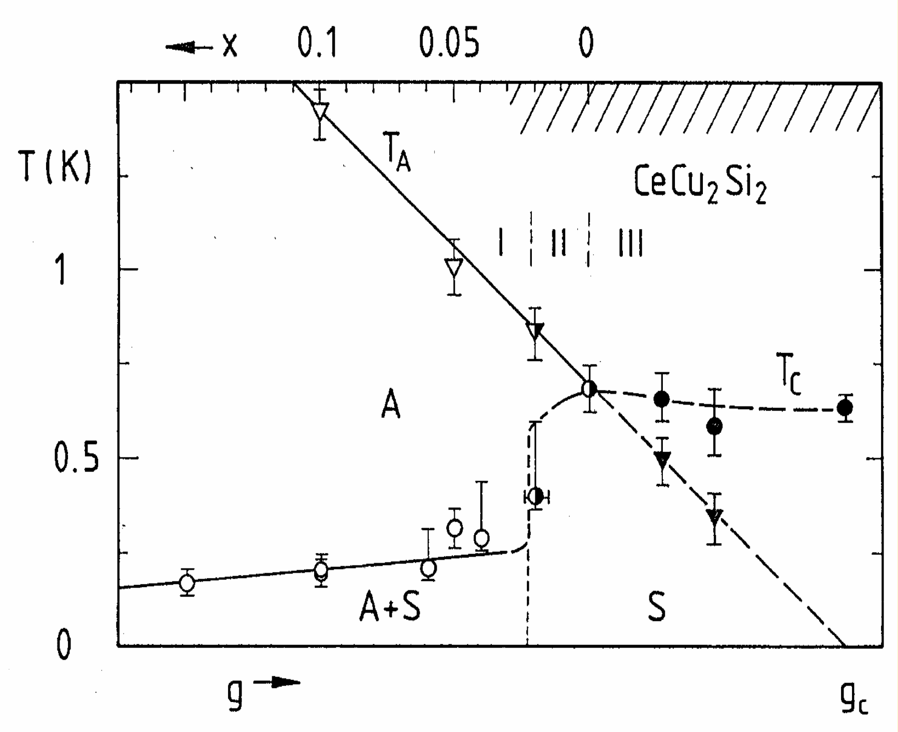
(Riblet, Winzer 1971)



$CeCu_2Si_2$: Phase diagrams

chemical (C. Geibel et al., 1995)

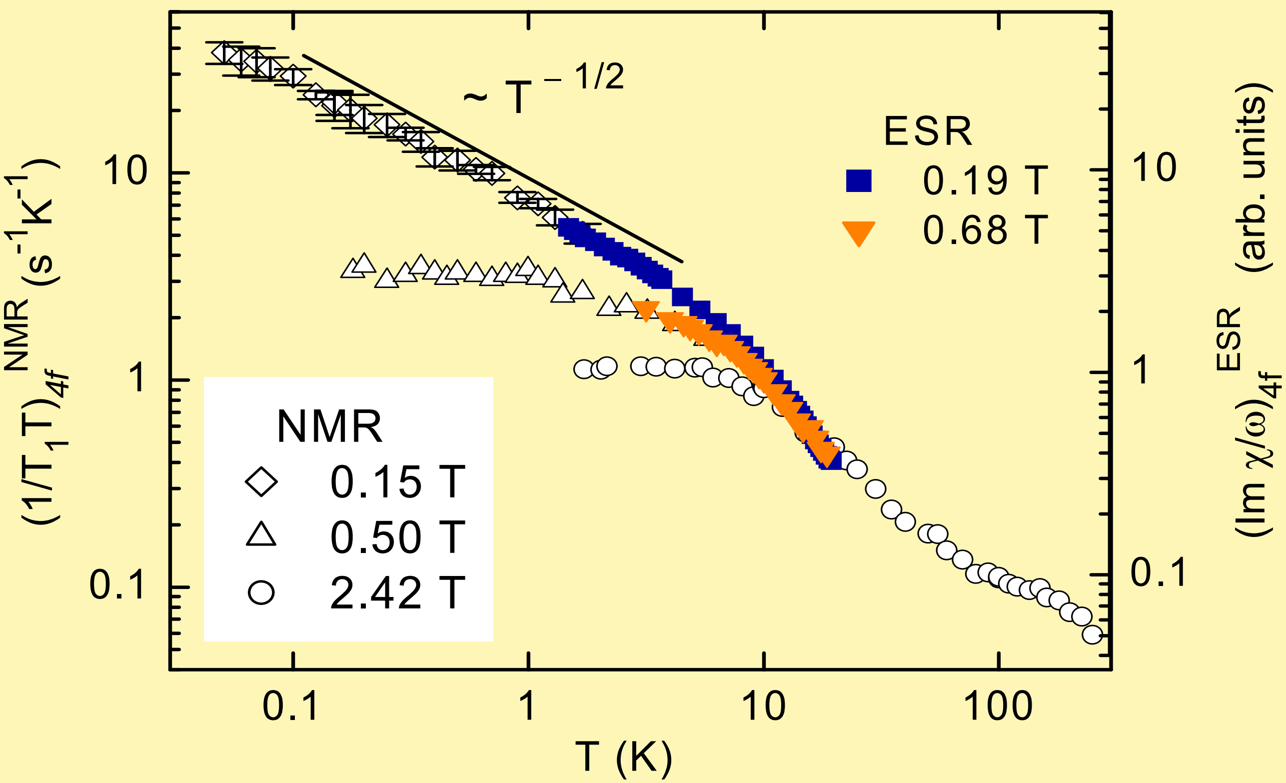




physical (P. Gegenwart et al., 1998)

^{29}Si NMR

[K. Ishida et al., PRL **89,** 107202 (2002)]



- B > B_c : LFL state below T*(B)
- $\left\{ \begin{array}{l} B \to B_c^+ \\ T \to 0 \end{array} \right\}$ $(1/T_1T)_{4f} \propto T^{-1/2}$