The Physics of the Dense Kondo lattice

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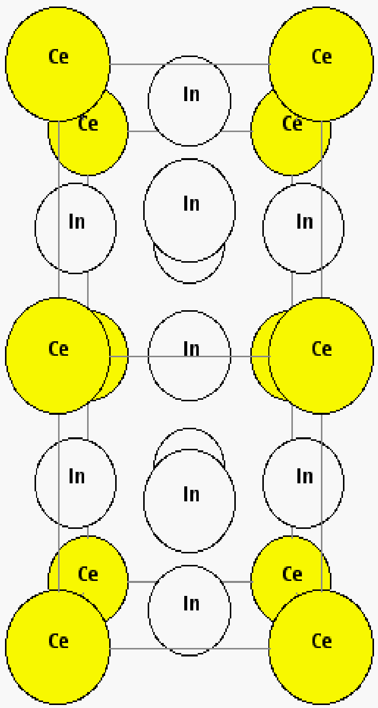
Outline

- evolution of coherent lattice with doping in $Ce_{1-x}La_xCoIn_5$
- comparison with $Yb_{1-x}Lu_xRh_2Si_2$
- scale for entropy development in these systems: T_K sets the lattice coherence scale
- using the sc condensation energy in $Ce_{1-x}La_xCoIn_5$ to show inhomogeneity of doped dense Kondo liquid
- evidence for intrinsic dilute gas of free Kondo centers in pure $CeCoIn_5$

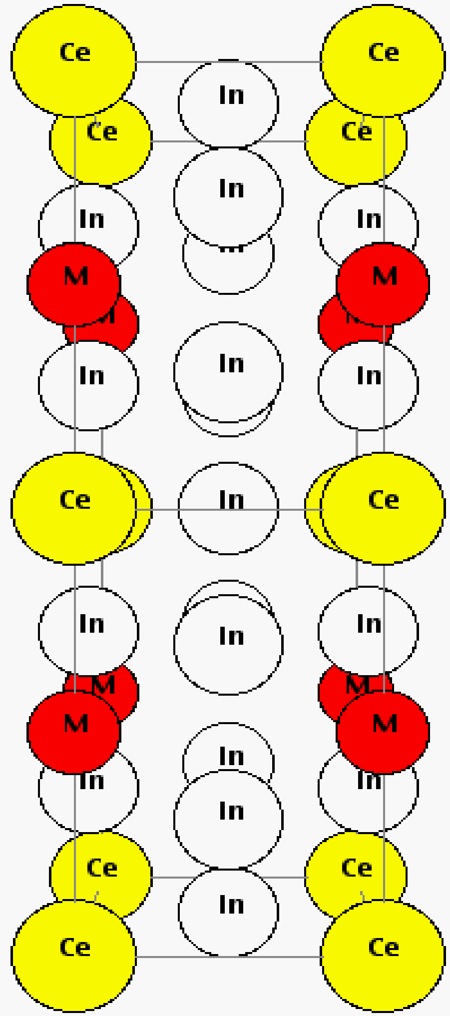
dilution studies of $CeCoIn_5$

Cross over from single ion Kondo to $C/T \alpha \ln(T/T^*)$ near 2D percolation threshold

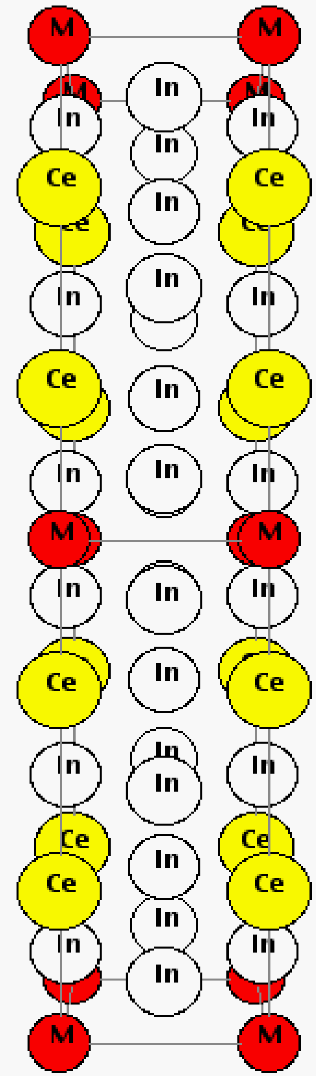
Crystal Structures



$CeIn_3$



$CeMIn_5$



Ce_2MIn_8

M = Co, Rh, Ir (isovalent)

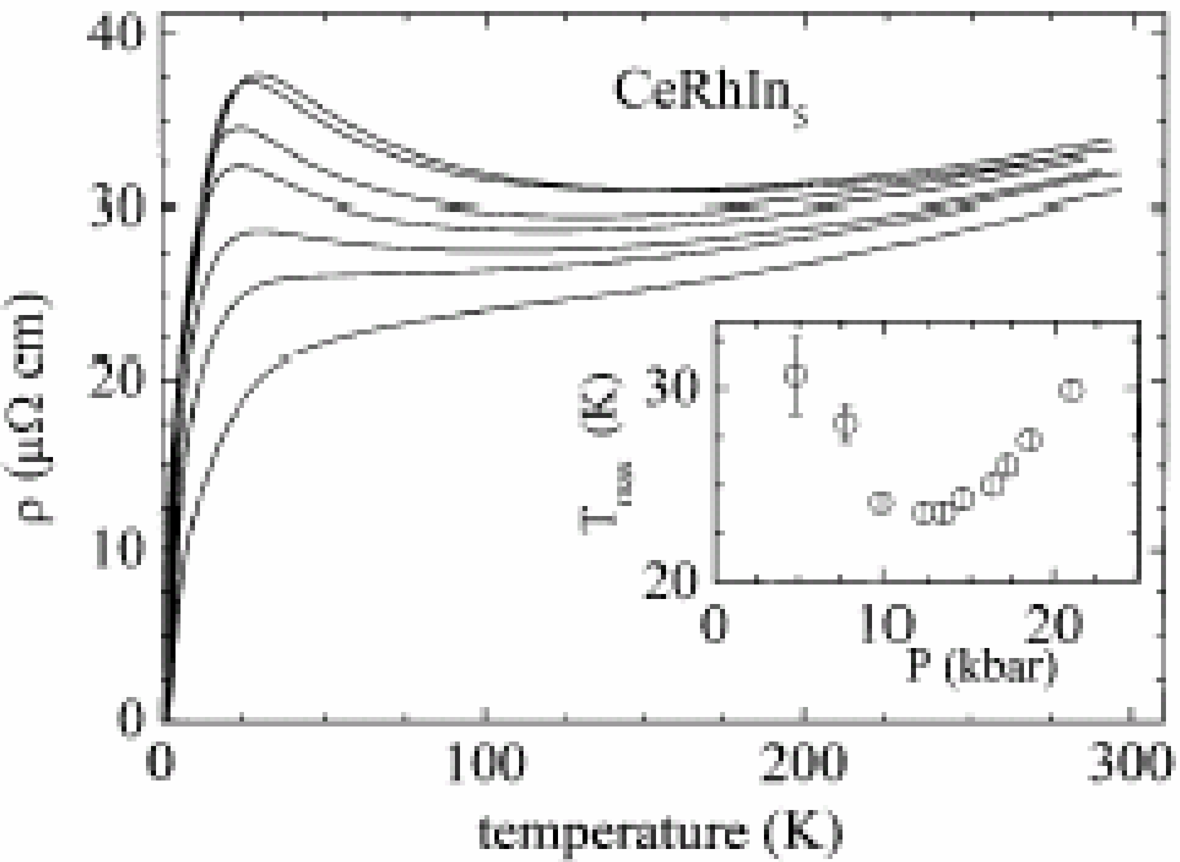
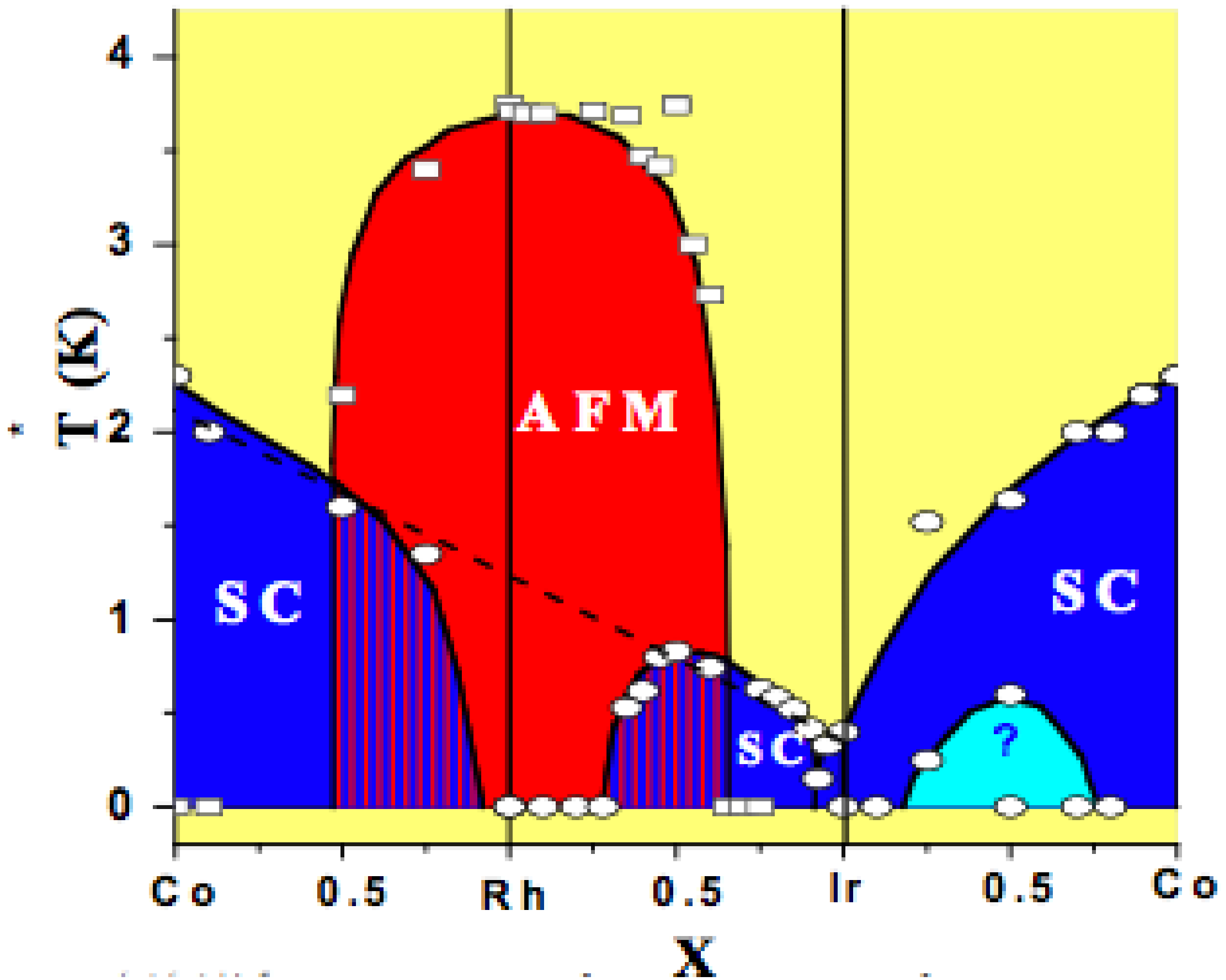
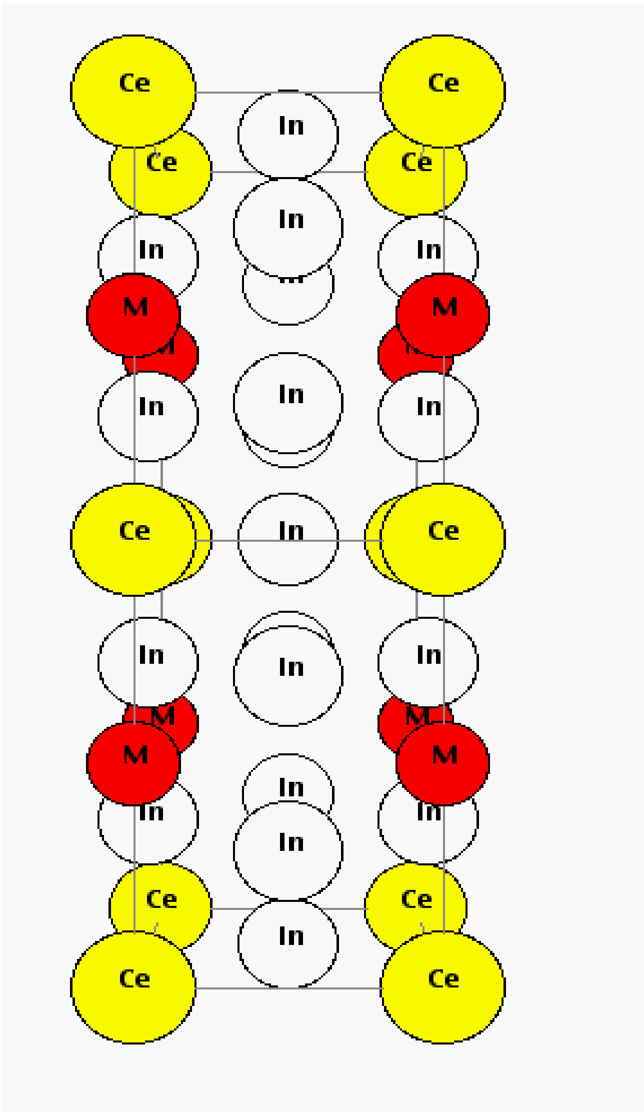


FIG. 2. Temperature dependence of the electrical resistivity of $CeRhIn_5$ at representative applied pressures. Data shown correspond to pressures of 0.001, 4.8, 7.9, 12.2, 14.5, 18.5, and 21.0 kbar and are associated, respectively, with curves of increasing resistivity at 50 K. The inset is a plot of the pressure dependence of the temperature T_{max} where the resistivity is a maximum.

AF and Superconductivity in $CeMIn_5$ systems



Heavy Fermion Superconductor CeCoIn▯



M = Co

- **Heavy Fermion Superconductor with $T_c \approx 2.3$ K**

  (C. Petrovic et al. J. Phys.: Condensed Matter **13**, L337 (2001).)

- **Quasi 2D electronic structure**

  (e.g. D. Hall et al., Phys. Rev. B **64**, 212508 (2001).)

- **Unconventional SC state**

  Line nodes, most likely $d(x^2 - y^2)$ symmetry

  (e.g. R. Movshovich et al., Phys. Rev. Lett. 86, 5152 (2001).
  Izawa et al., Phys. Rev. Lett. **87**, 057002 (2001))

- **Normal state**

  Non-Fermi-liquid behavior)

  $\Delta\rho \propto T$, $C_m/T \propto -\log T$

  probably due to strong AF fluctuations

  (e.g. V.A. Sidorov et al., cond-mat/0202251,
  Shishido et al., J. Phys. Soc. Jpn. **71**, 162 (2002).)

Theoretical expectations near 2D AF QCP,

$\Delta\rho \propto (T / T^{sf})$, $C_m/T \propto -\log (T / T^{sf})$

T^{sf}: a characteristic energy of spin-fluctuations

(e.g. T. Moriya and K. Ueda, Adv. Phys. **49**, 555 (2000).,
G. R. Stewart, Rev. Mod. Phys. **73**, 797 (2001).)

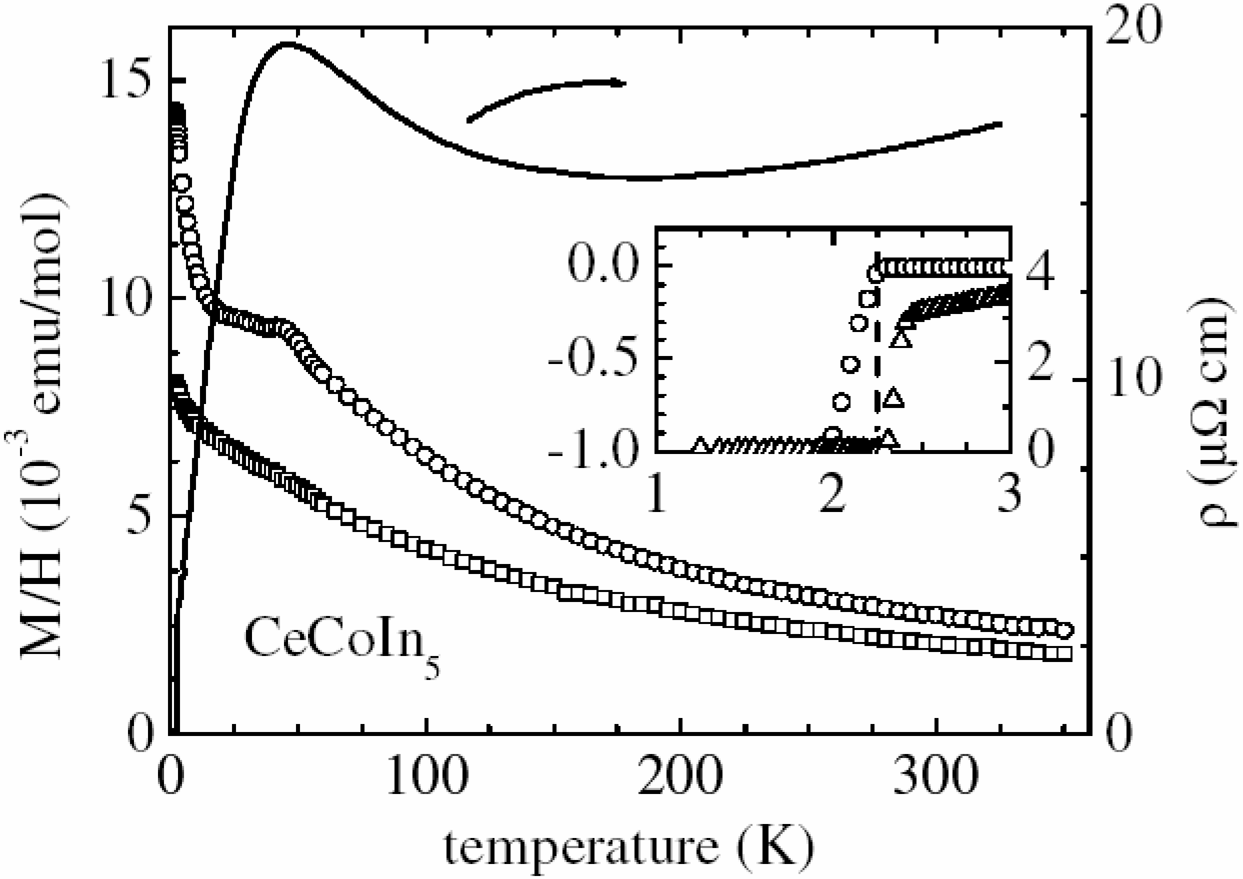


Figure 1. Magnetic susceptibility and electrical resistivity of $CeCoIn_5$. Susceptibility is measured in a 1 kOe field applied parallel (circles) or perpendicular (squares) to the *c*-axis of $CeCoIn_5$ using a SQUID magnetometer. The inset shows zero-field-cooled magnetic susceptibility (circles) as a fraction of $1/4\pi$ measured in 10 Oe and resistivity (triangles) in the vicinity of the superconducting transition.

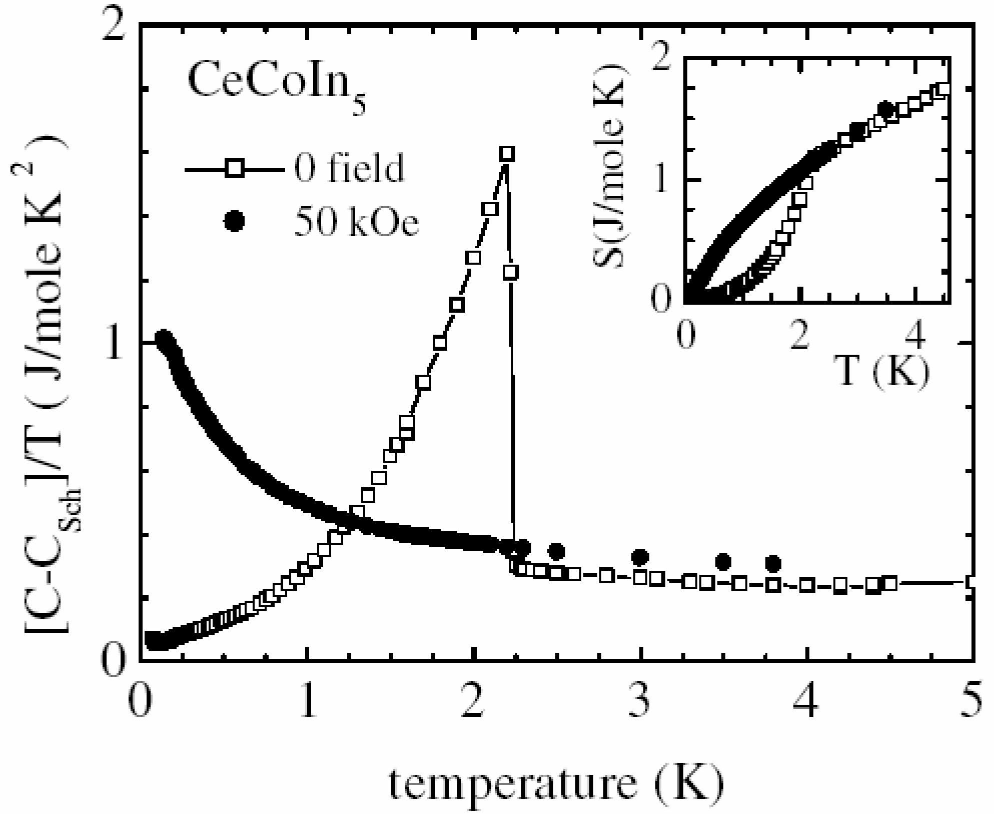
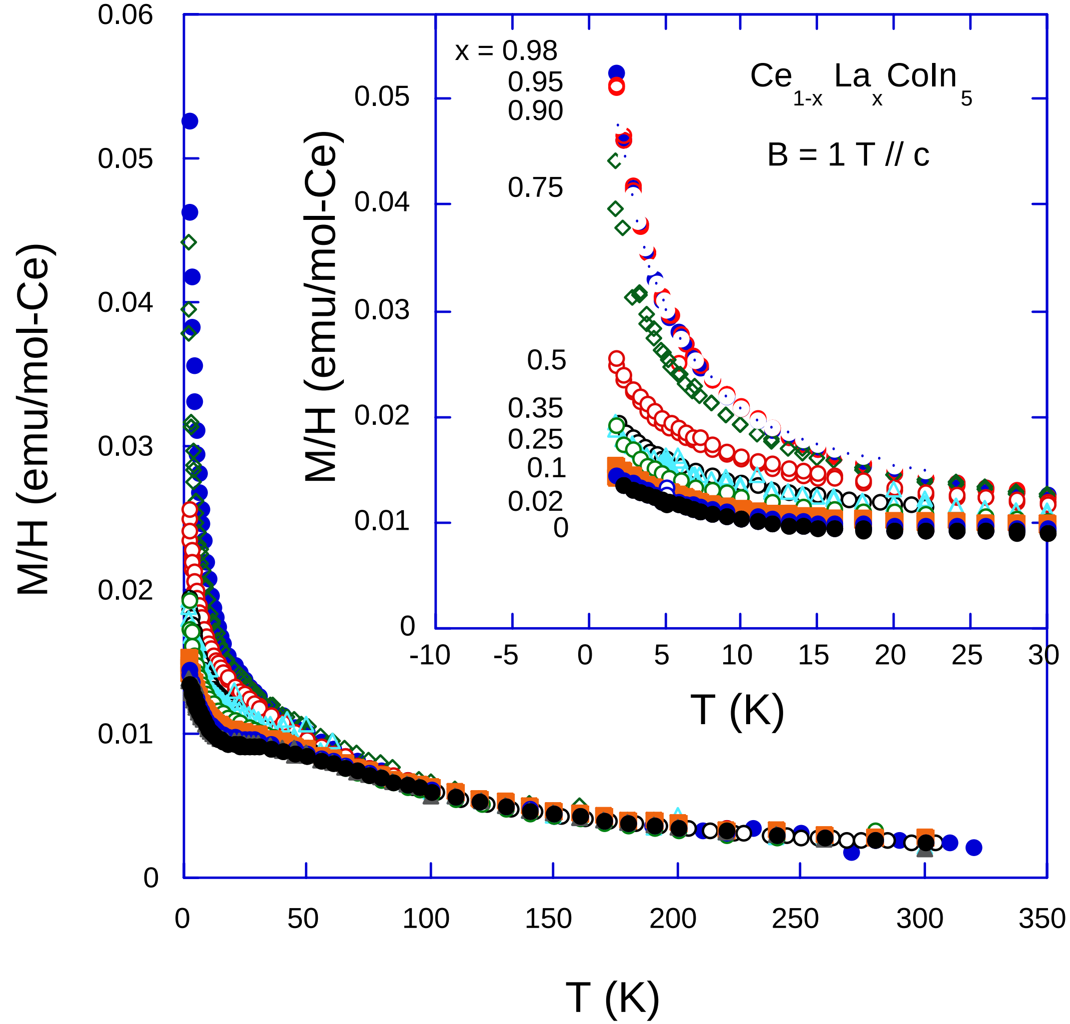


Figure 2. Specific heat divided by temperature versus temperature for $CeCoIn_5$. For both the zero-field (open squares) and 50 kOe (solid circles) data, a nuclear Schottky contribution, due to the large nuclear quadrupole moment of In, has been subtracted. The inset shows the entropy recovered as a function of temperature in the superconducting (open squares) and field-induced normal (solid circles) states.

Systematic change in low *T* susceptibility

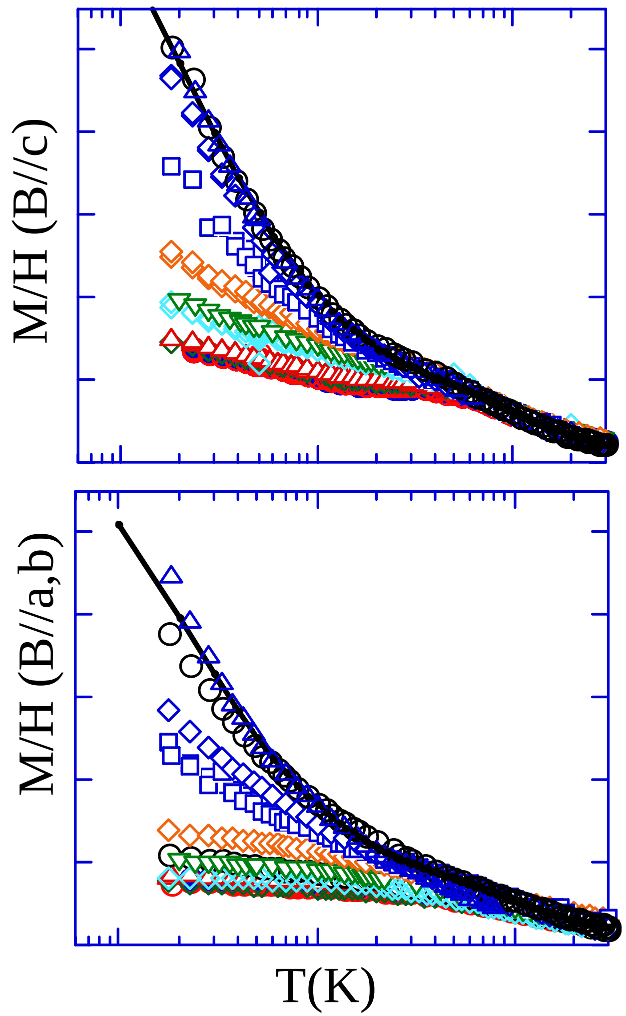


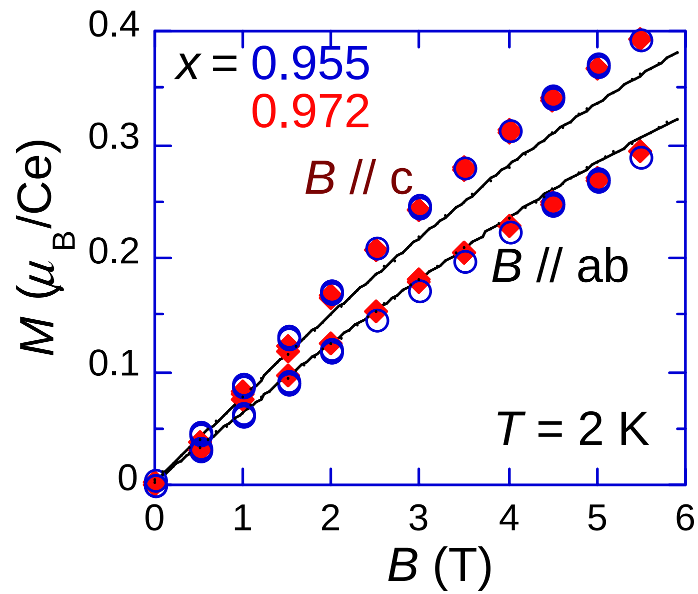
- Constant high temp. T_K
- Single impurity limit: x(La) > 0.95
- Systematic increase of *M/H* with La dilution at low temperatures

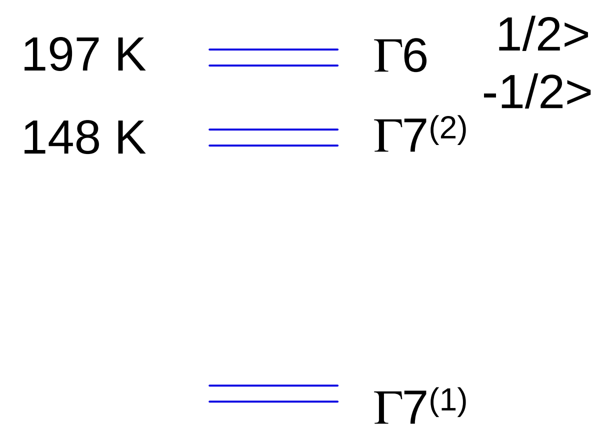
Possible origins:

1) Crystal field splitting
2) Kondo coupling T_K
3) Intersite coupling

Crystal field analyses for $Ce_{1-x}La_xCoIn_5$







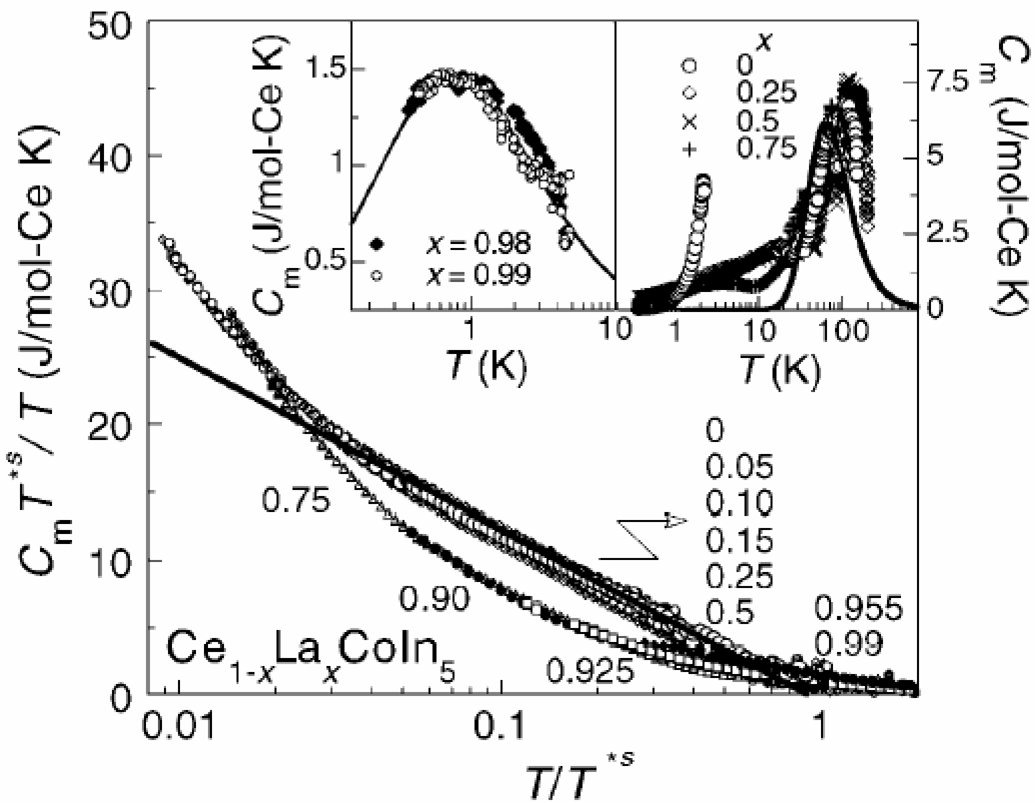


FIG. 3. C_m/T times T^{*s} vs T/T^{*s}. The solid line represents the $-\ln T$ fit. Left inset: T dependence of C_m for $x = 0.98$ and 0.99. The solid curve is the fit to the $S = 1/2$ Kondo impurity limit with $T_K = 1.7$ K. Right inset: T dependence of C_m. The solid curve is the fit based on our CEF scheme.

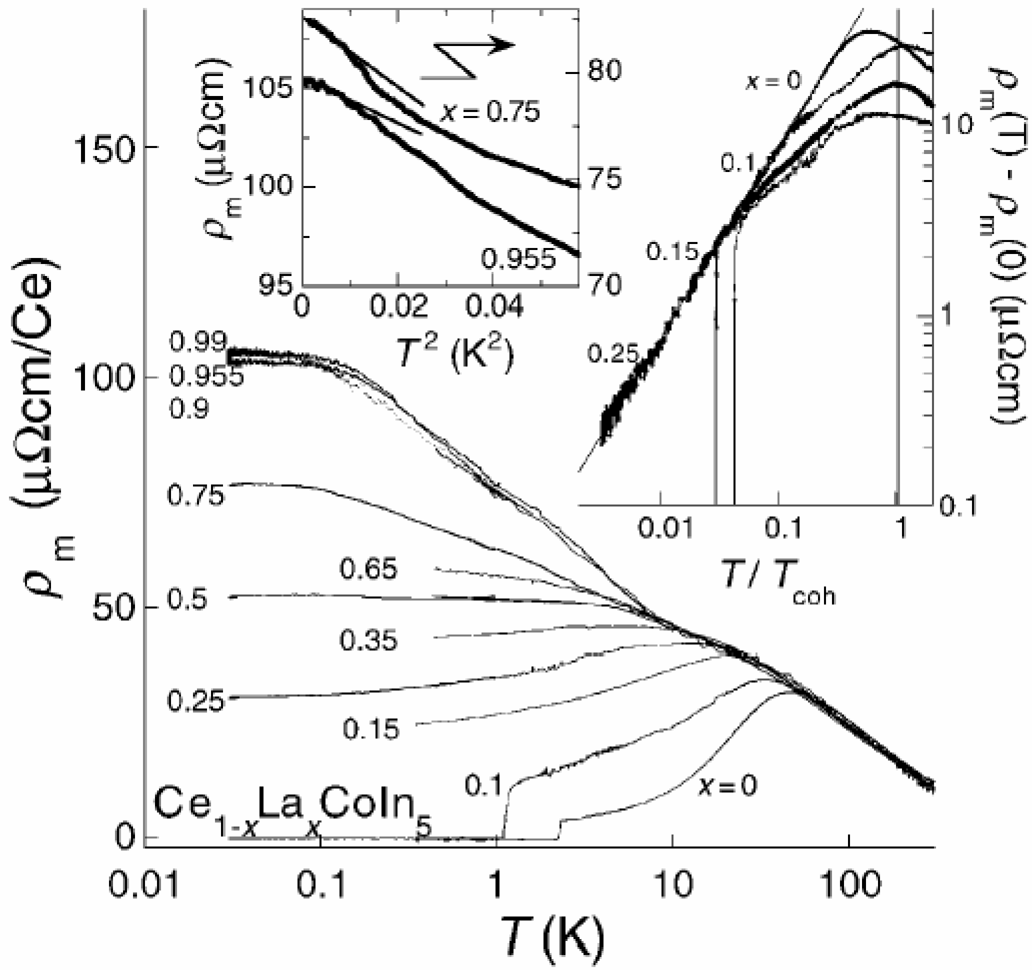
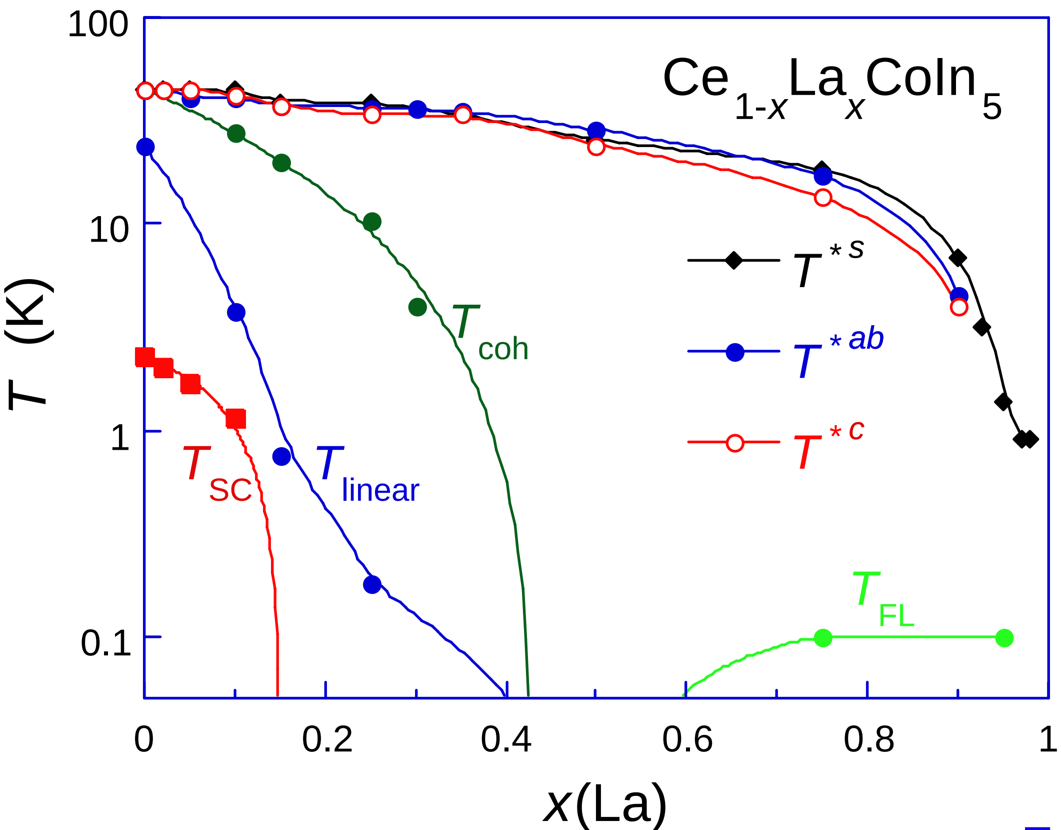


FIG. 1. Magnetic in-plane resistivity ρ_m for various x of $Ce_{1-x}La_xCoIn_5$. Right inset: The log-log plot for the inelastic part of ρ_m vs T/T_{coh}; the solid line is the T linear fit and the vertical lines mark the onset of superconductivity. Left inset: ρ_m vs T^2 for the incoherent regime.

Energy scale diagram of $Ce_{1-x}La_xCoIn_5$



1) T^{*ab}, T^{*c}, T^{*s} are essentially identical.

2) T^* originates from the single-ion T_K at $x \to 1$ limit.

3) The systematic increase should arise from intersite correlation.
$T_{coh} \to T^*$ at $x \to 0$ limit.

4) Change in the ground state properties at around $x = 0.5$.

Evolution of intersite AF fluctuations similar to RVB with energy scale of T^* and correlation length of several *a*

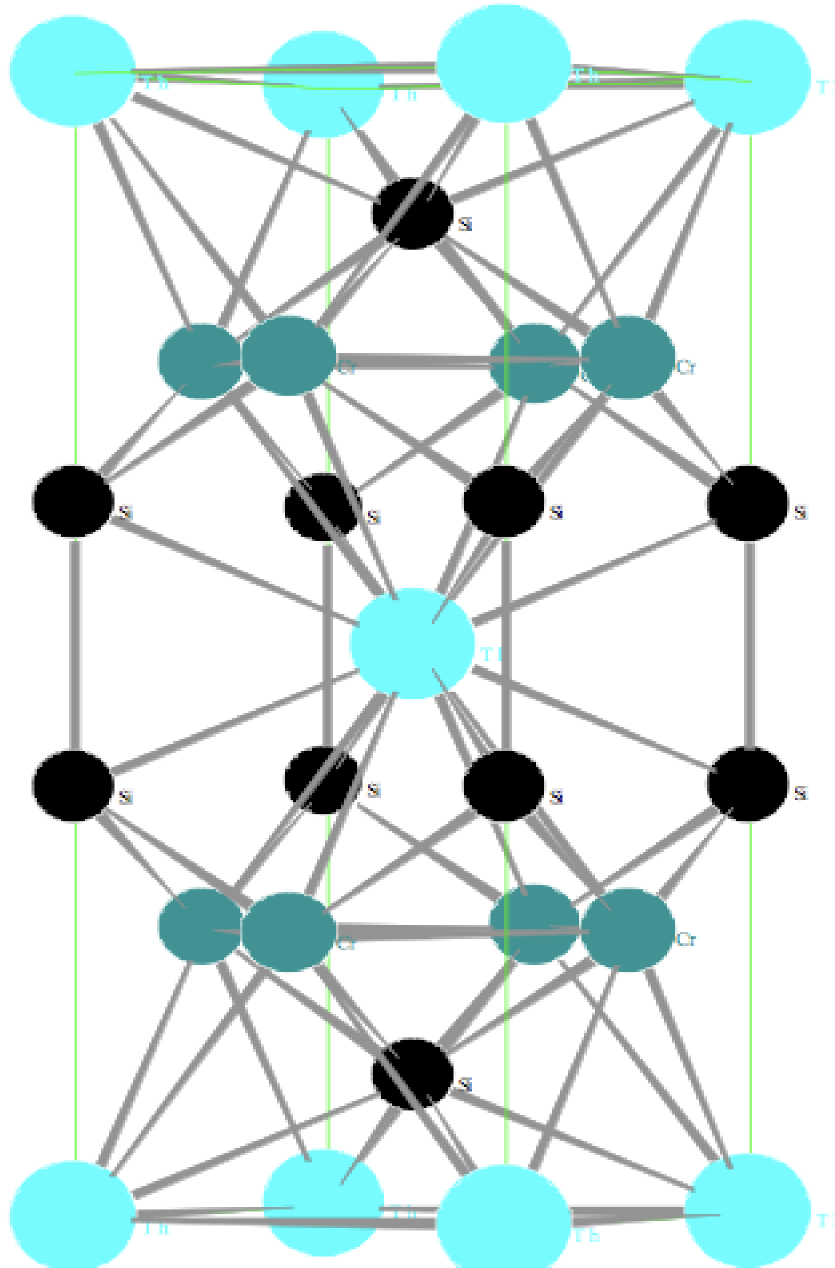
Basis of our analysis: $T_K \ll T^*$ (intersite) $\ll \Delta$(crystal field)

1 K　　50 K　　200 K

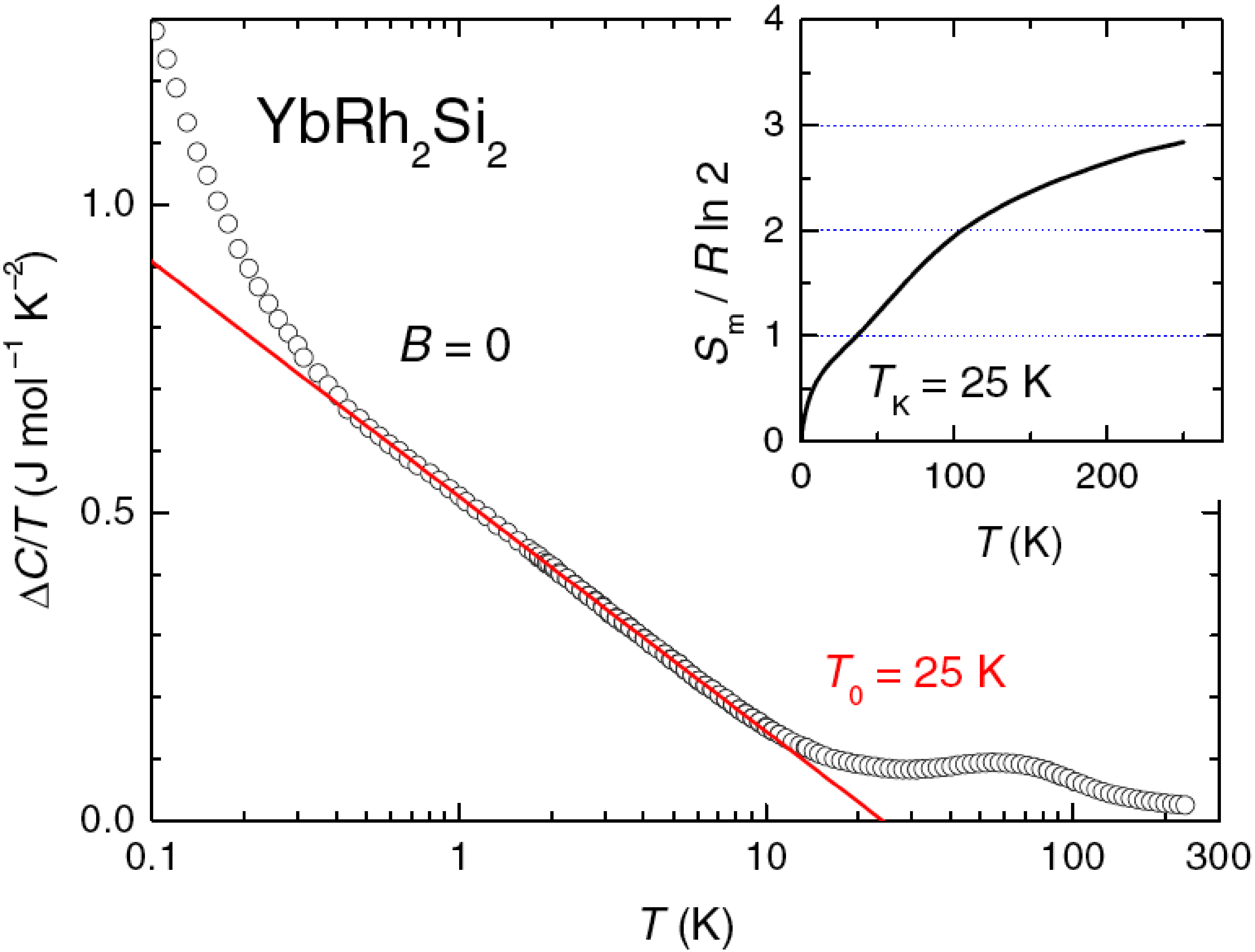
dilution in $YbRh_2Si_2$

same trends as seen in $CeCoIn_5$

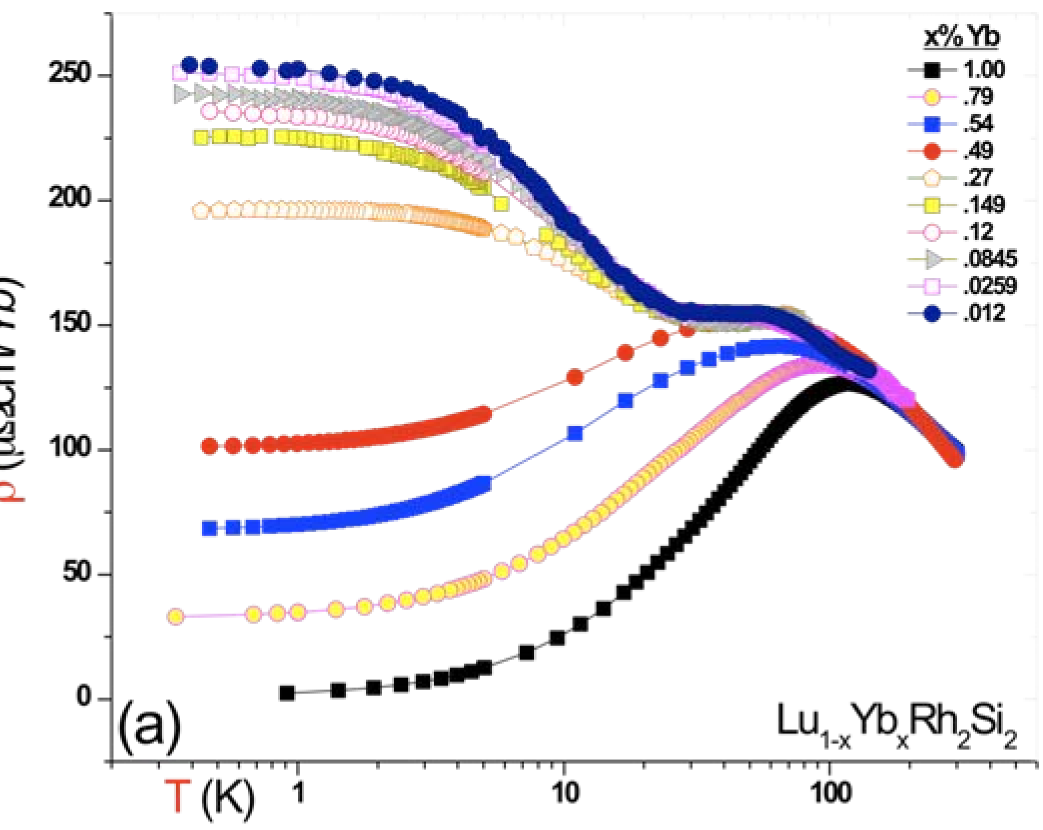
ThCr$_2$Si$_2$ Prototype Structure



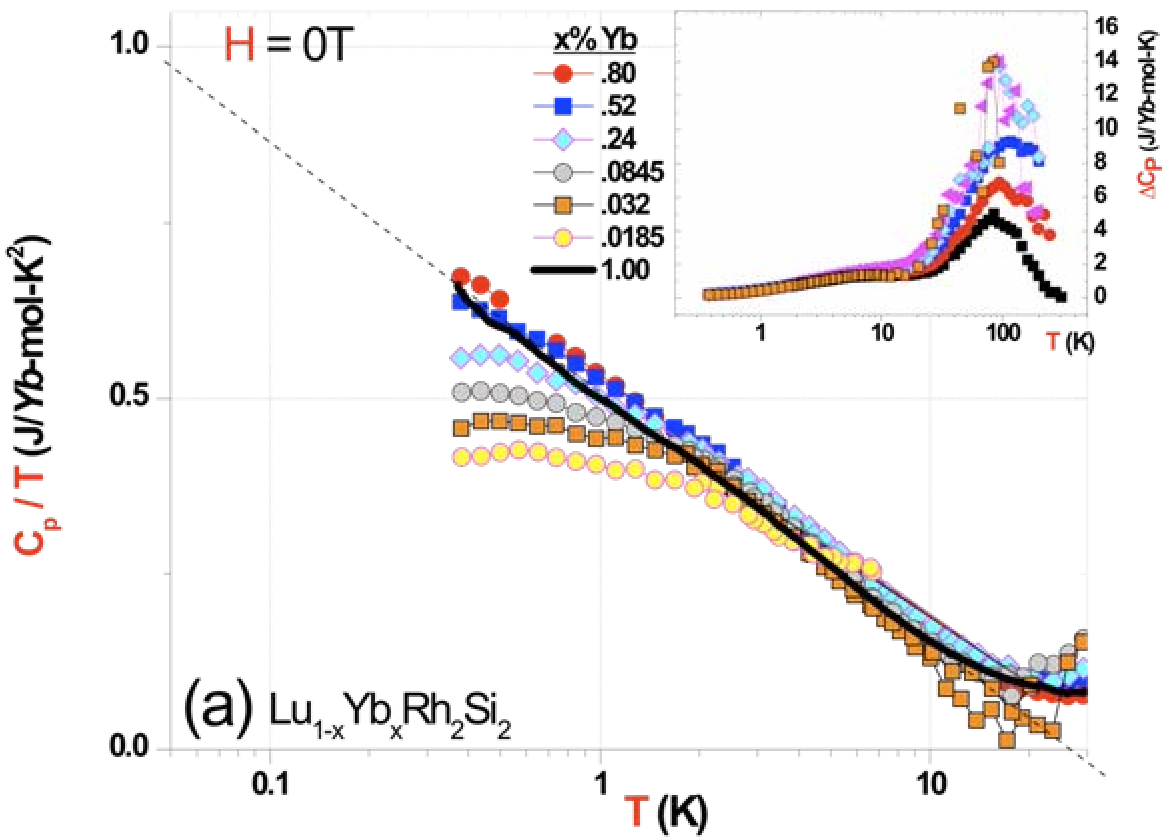
Sommerfeld coefficient – Kondo lattice?



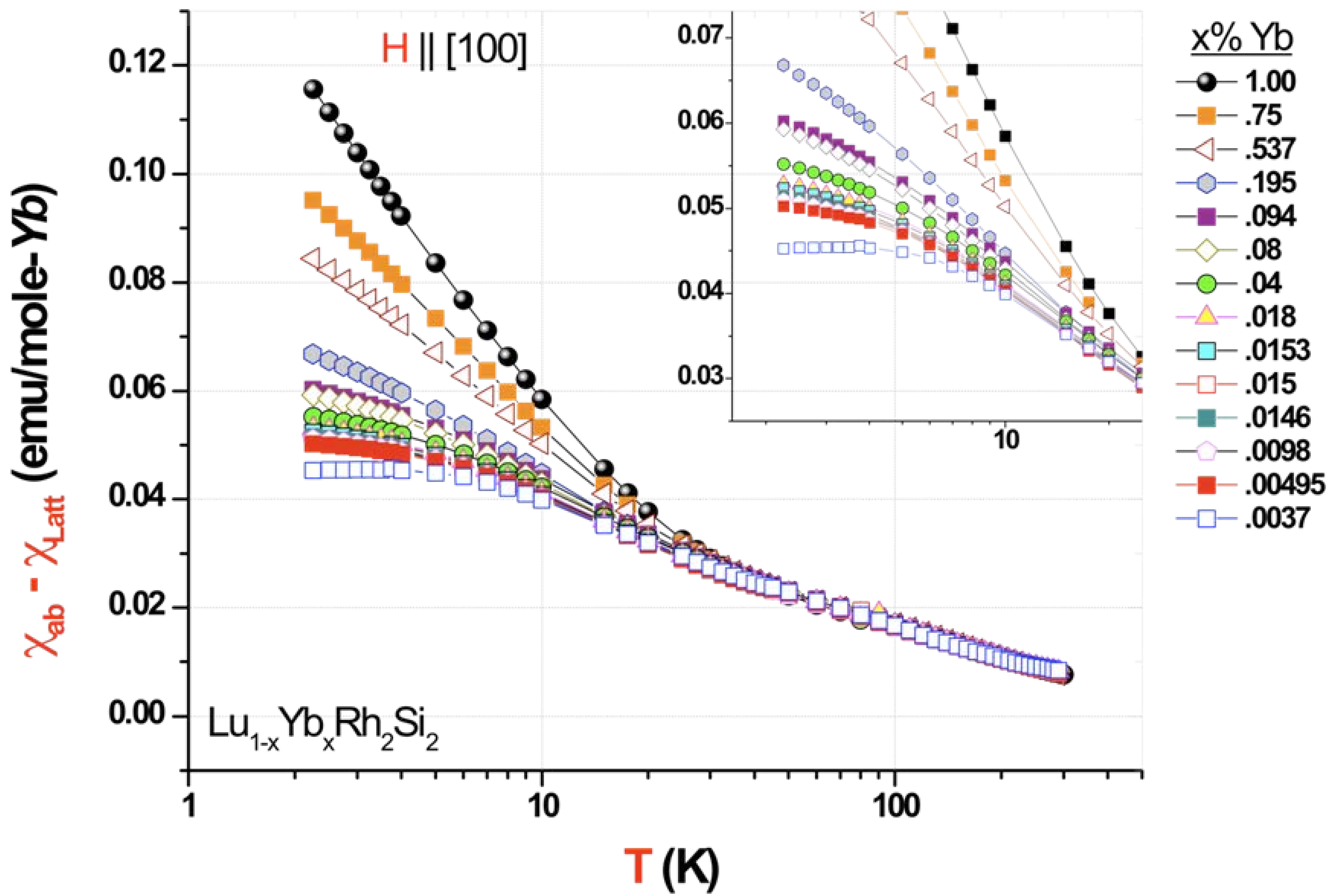
P. Gegenwart *et al.*, New J. Phys. **8**, 171 (2006).



x% Yb
1.00
.79
.54
.49
.27
.149
.12
.0845
.0259
.012
250
200
150
100
50
0
ρ (μΩcm/Yb)
(a)
$Lu_{1-x}Yb_xRh_2Si_2$
T (K)
1
10
100


H = 0T
x% Yb
.80
.52
.24
.0845
.032
.0185
1.00
C_p / T (J/Yb-mol-K^2)
T (K)
ΔC_P (J/Yb-mol-K)
T (K)
(a) $Lu_{1-x}Yb_xRh_2Si_2$
1.0
0.5
0.0
0.1
1
10
100
16
14
12
10
8
6
4
2
0

more than 1 plate/mass



Entropy development in quantum critical regime

$C/T \propto \ln T$

Typically: $C/T = (R\ln 2/T^*)\ln(T^*/T)$

and $S(T^*) = R\ln 2$

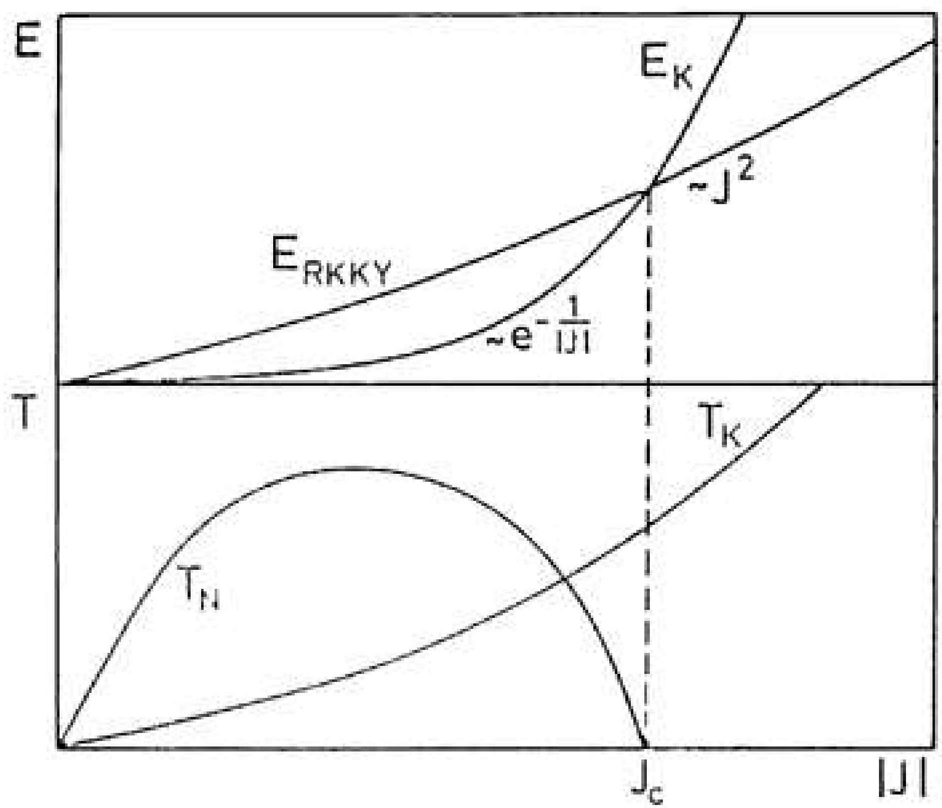
T* sets the scale for heavy Fermion physics

For heavy Fermion superconductors:

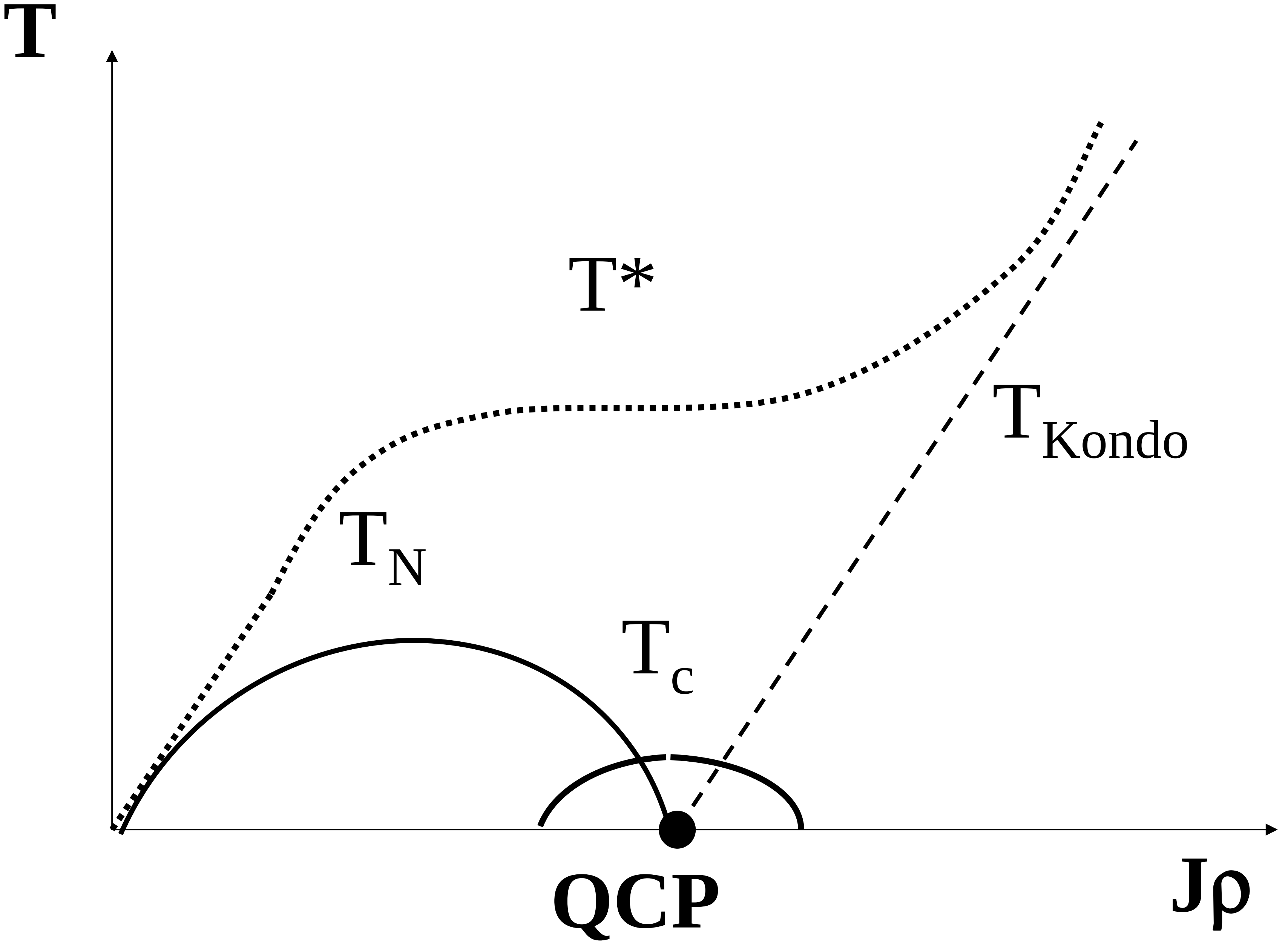
$S(T_c)$ ~ 10-20% Rln2 $\leftrightarrow$ T_c/T^* ~ 1/20

Source of coherence scale in dense Kondo lattice

Kondo coupling parameter (ρJ) determines both T_K and T^*



top - Dependences of the characteristic energies connected to the Kondo effect and the RKKY interactions as function of the coupling constant J.
below - Connected "phase diagram".



T
T*
T_{Kondo}
T_N
T_c
QCP
Jρ

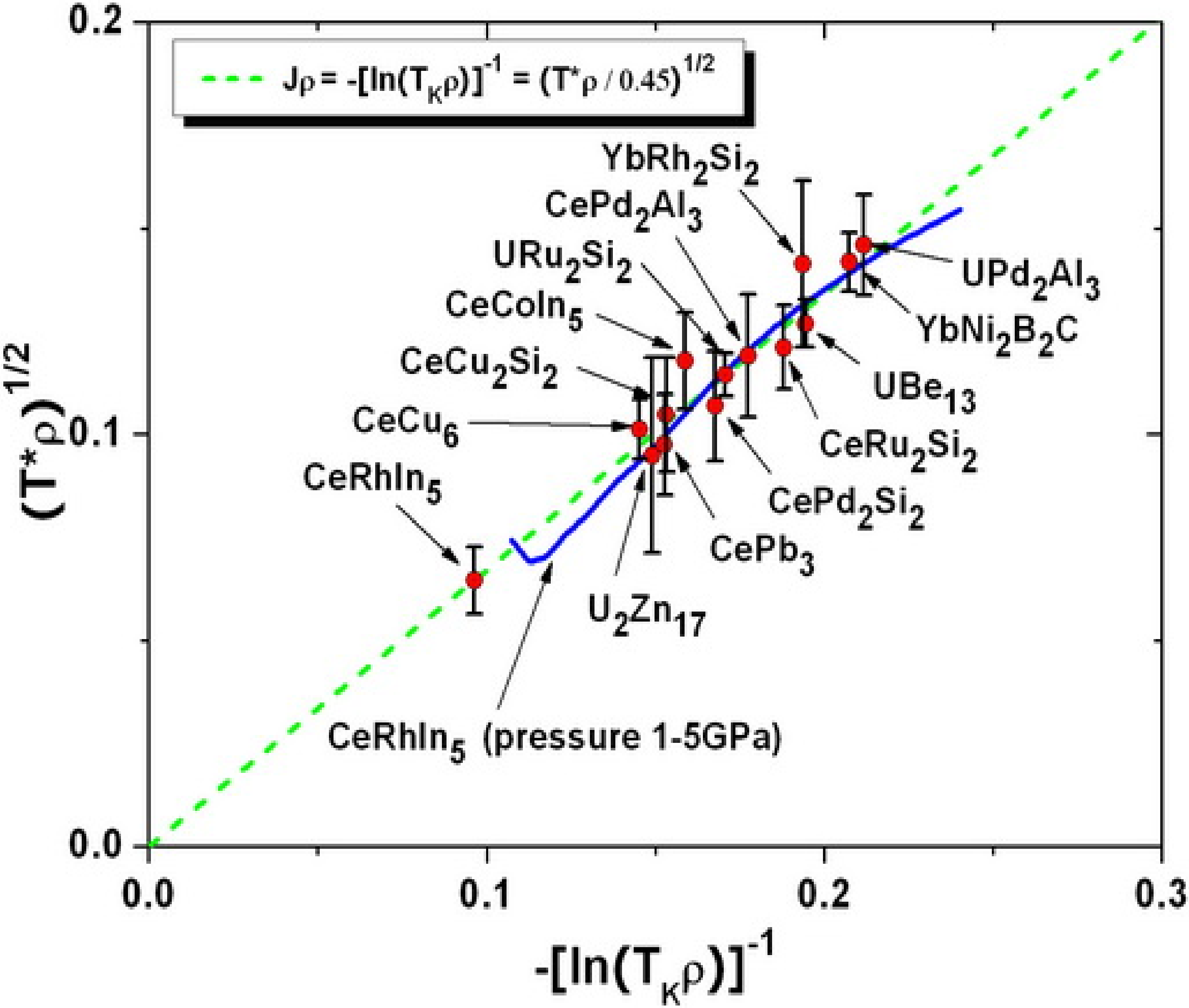
Kondo scale: $T_K = \rho^{-1} e^{-1/J\rho}$

RKKY scale: $T^* = cJ^2 \rho$

$$J\rho = -1/\ln(T_K \rho) = \sqrt{(c^{-1} T^* \rho)}$$

Table I. Experimental T^*, T_K and γ for a variety of Kondo lattice compounds.

Compound	T^* (K)	T_K (K)	γ (mJ/mol K^2)	$J\rho$	c	Reference
$CeRhIn_5$	20	0.15	5.7	0.10	0.45	5,7,(H.L.)
$CeCu_6$	35	3.5	8	0.15	0.49	8,9
U_2Zn_{17}	20	2.7	12.3	0.15	0.41	10,11,12
$CeCu_2Si_2$	75	10	4	0.15	0.47	5,13,14
$CePb_3$	20	3	13	0.15	0.41	15,16
$CeCoIn_5$	50	6.6	7.6	0.16	0.55	3,5,6
$CePd_2Si_2$	40	9	7.8	0.17	0.41	17,18
URu_2Si_2	55	12	6.5	0.17	0.45	5,19,20
$CePd_2Al_3$	40	10	9.7	0.18	0.45	21,22,23
$CeRu_2Si_2$	60	20	6.68	0.19	0.42	24,25
UBe_{13}	55	20	8	0.19	0.43	26,27
$YbRh_2Si_2$	70	20	7.8	0.19	0.53	(Z.F.)
$YbNi_2B_2C$	50	20	11	0.21	0.47	28
UPd_2Al_3	60	25	9.7	0.21	0.48	23,29



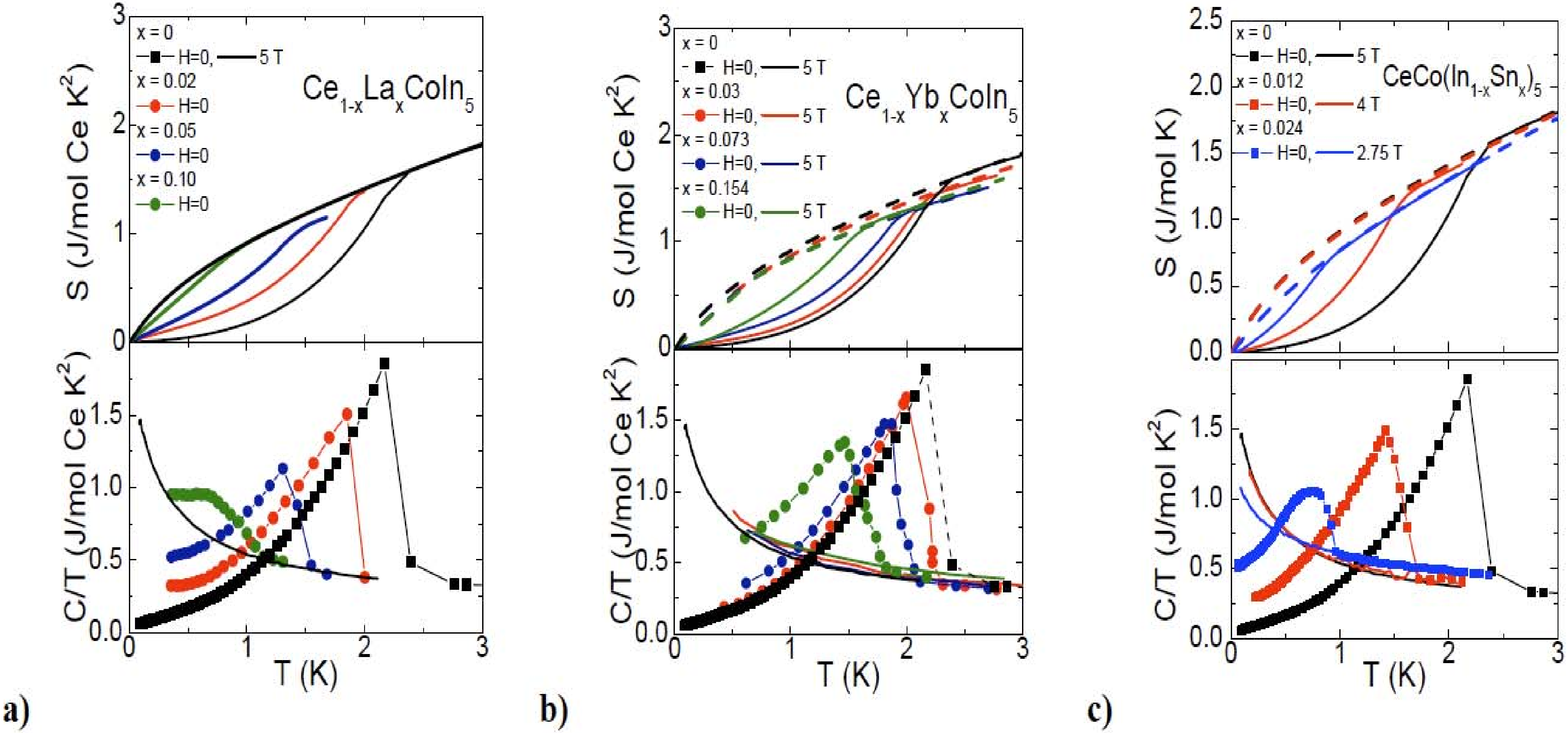
$J\rho = -[\ln(T_K\rho)]^{-1} = (T^*\rho / 0.45)^{1/2}$
$YbRh_2Si_2$
$CePd_2Al_3$
URu_2Si_2
$CeCoIn_5$
$CeCu_2Si_2$
$CeCu_6$
$CeRhIn_5$
UPd_2Al_3
$YbNi_2B_2C$
UBe_{13}
$CeRu_2Si_2$
$CePd_2Si_2$
$CePb_3$
U_2Zn_{17}
$CeRhIn_5$ (pressure 1-5GPa)
$(T^*\rho)^{1/2}$
$-[\ln(T_K\rho)]^{-1}$
0.0
0.1
0.2
0.3

Electronic inhomogeneity in doped dense Kondo lattice

normalized condensation energy in doped heavy Fermion superconductors shows linear decrease with doping

Electronic inhomogeneity in doped dense Kondo lattice

normalized condensation energy
in doped heavy Fermion
superconductors shows linear
decrease with doping



a)
Ce1-xLaxCoIn5
x = 0
H=0, 5 T
x = 0.02
H=0
x = 0.05
H=0
x = 0.10
H=0
S (J/mol Ce K2)
C/T (J/mol Ce K2)
T (K)
b)
Ce1-xYbxCoIn5
x = 0
H=0, 5 T
x = 0.03
H=0, 5 T
x = 0.073
H=0, 5 T
x = 0.154
H=0, 5 T
S (J/mol Ce K2)
C/T (J/mol Ce K2)
T (K)
c)
CeCo(In1-xSnx)5
x = 0
H=0, 5 T
x = 0.012
H=0, 4 T
x = 0.024
H=0, 2.75 T
S (J/mol K)
C/T (J/mol K2)
T (K)

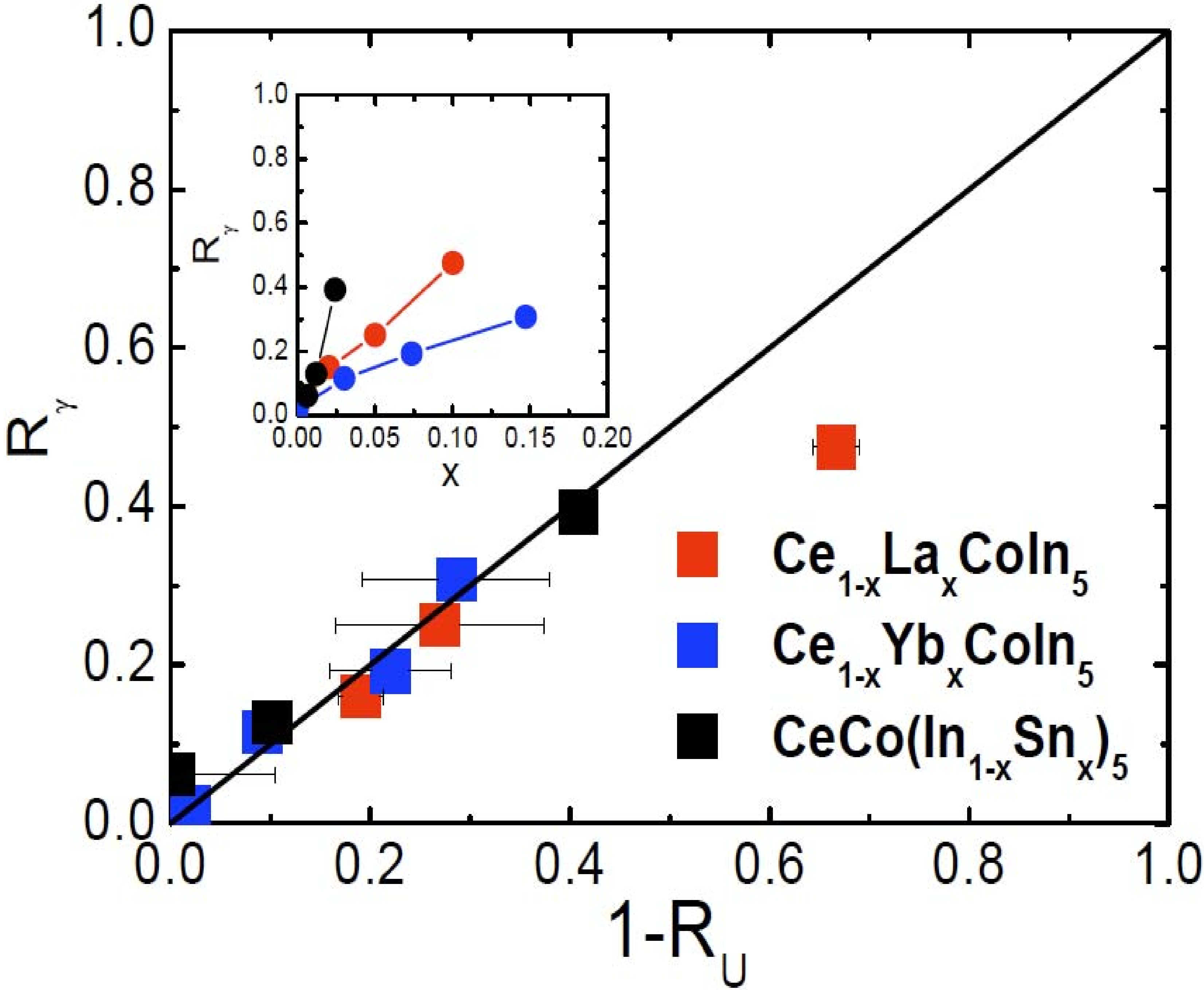
Superconducting condensation energy

$$U_{sc} = \int(S_N - S_{sc})dT$$

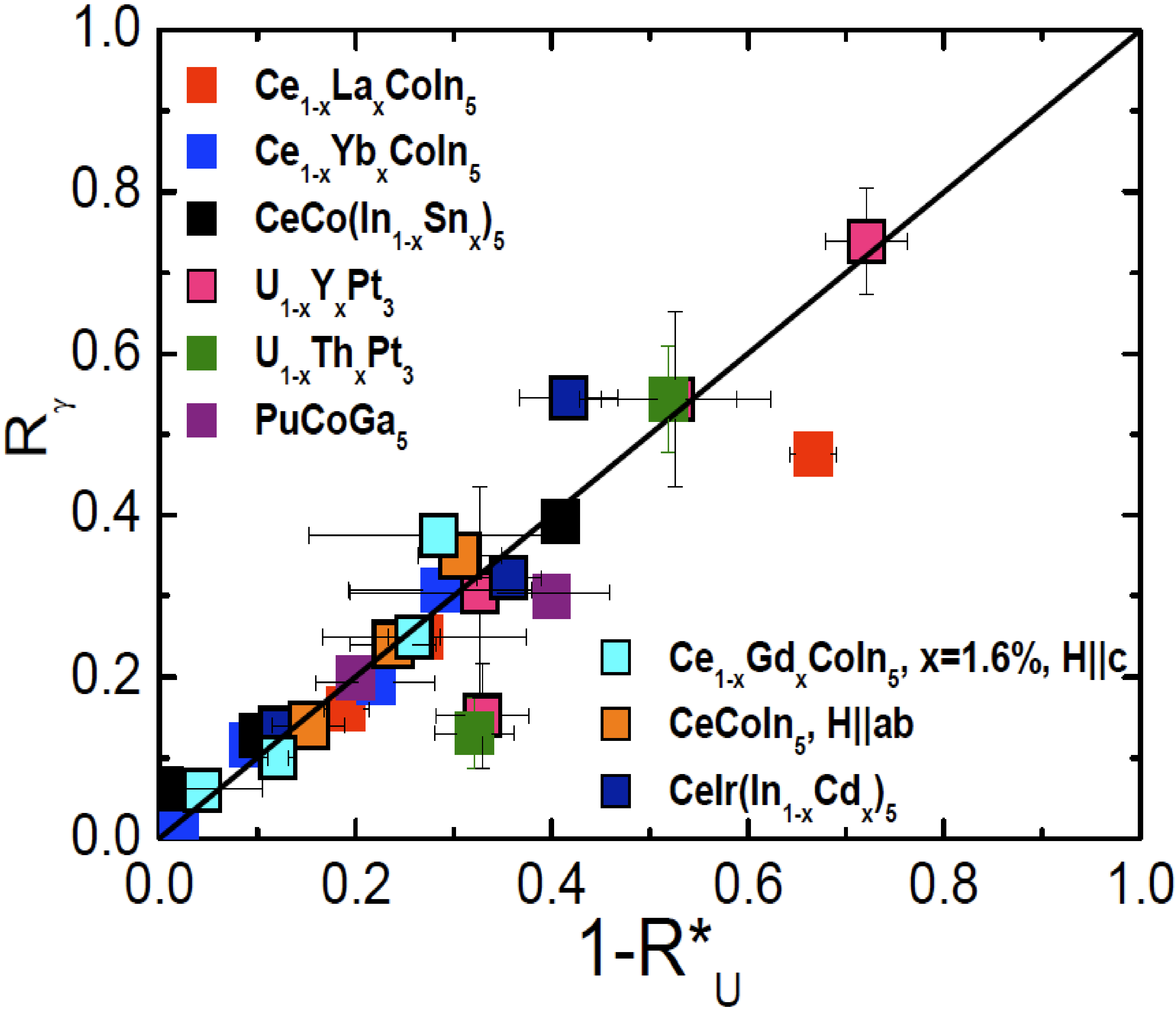
expect $U_{sc} \propto T_c^2$

$$R_U = [U_{sc}(x)/T_c^2(x)]/[U_{sc}(0)/T_c^2(0)]$$

$$R_\gamma = \gamma_0/\gamma_N$$



1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0
R_γ
$1-R_U$
$Ce_{1-x}La_xCoIn_5$
$Ce_{1-x}Yb_xCoIn_5$
$CeCo(In_{1-x}Sn_x)_5$
0.00
0.05
0.10
0.15
0.20
x

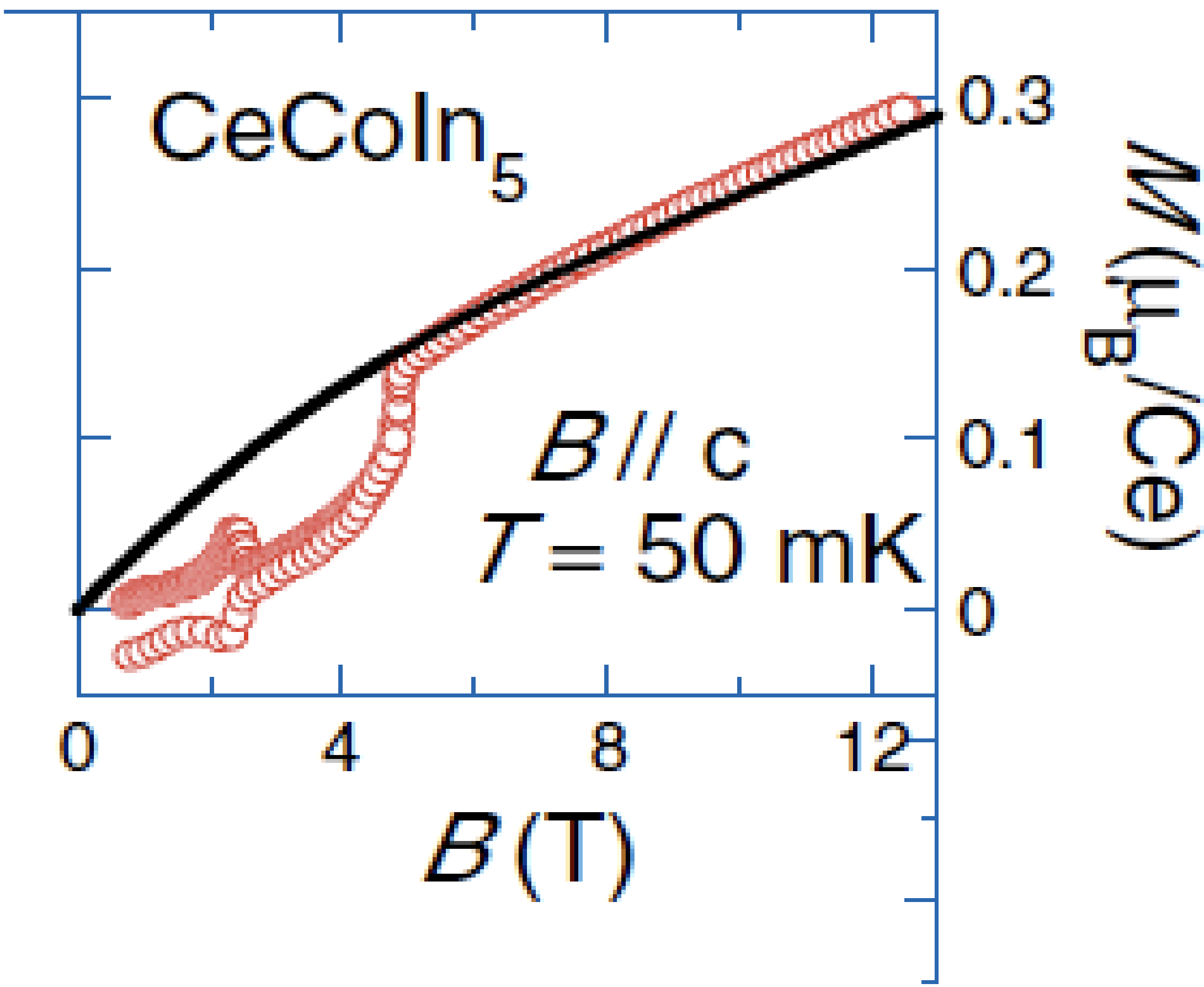


1.0
0.8
0.6
0.4
0.2
0.0
R γ
Ce1-xLaxCoIn5
Ce1-xYbxCoIn5
CeCo(In1-xSnx)5
U1-xYxPt3
U1-xThxPt3
PuCoGa5
Ce1-xGdxCoIn5, x=1.6%, H||c
CeCoIn5, H||ab
CeIr(In1-xCdx)5
0.0
0.2
0.4
0.6
0.8
1.0
1-R*U

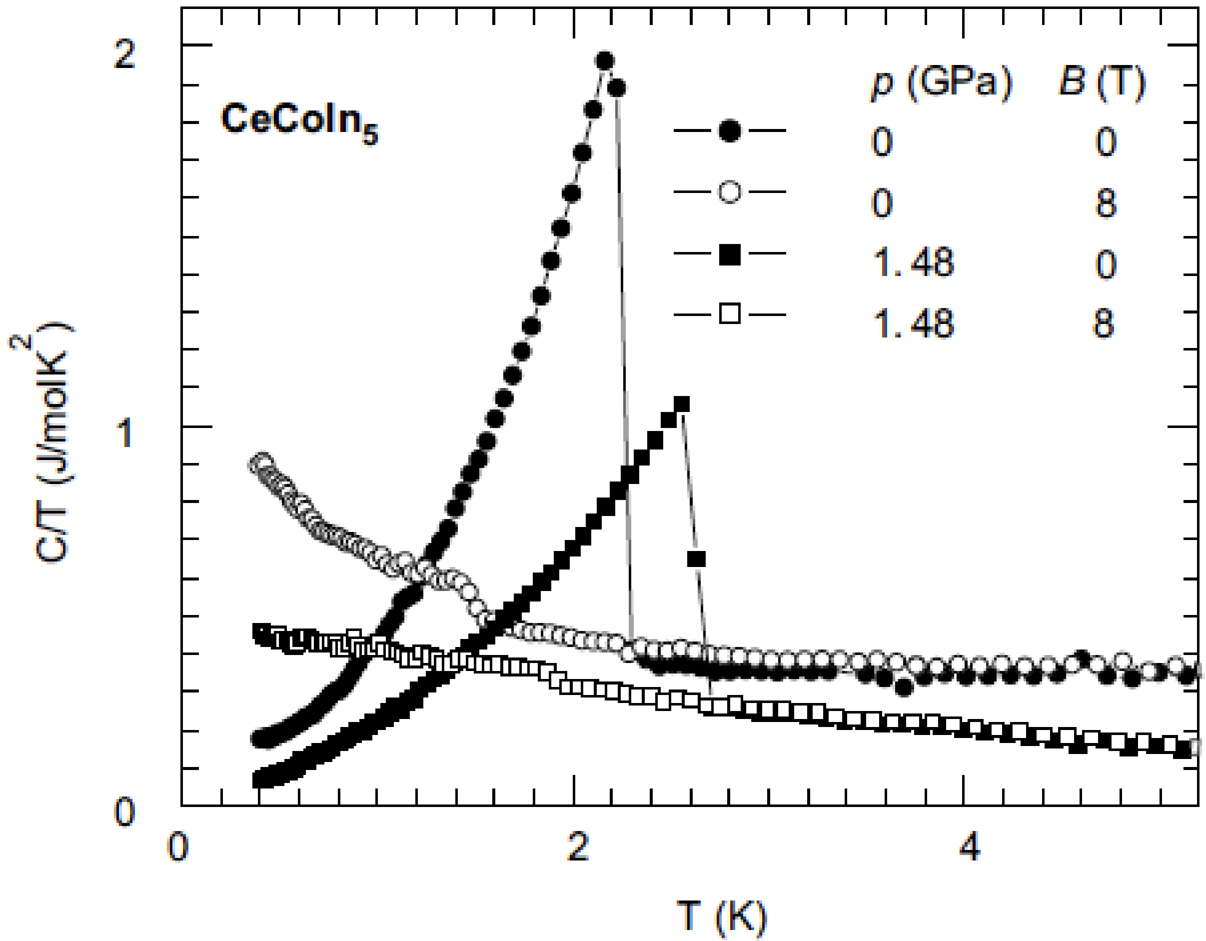
intrinsic Kondo impurities in pure $CeCoIn_5$

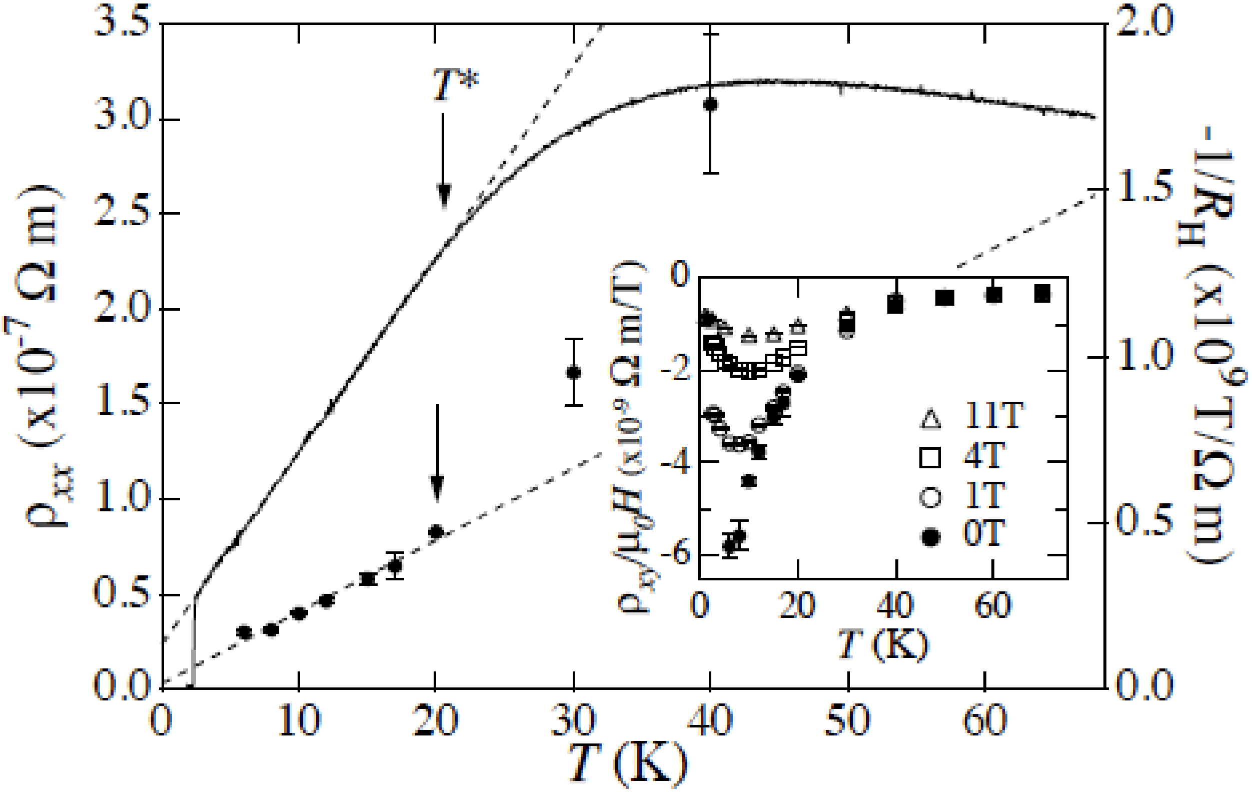
low T properties consistent with

~ 10% free Kondo centers

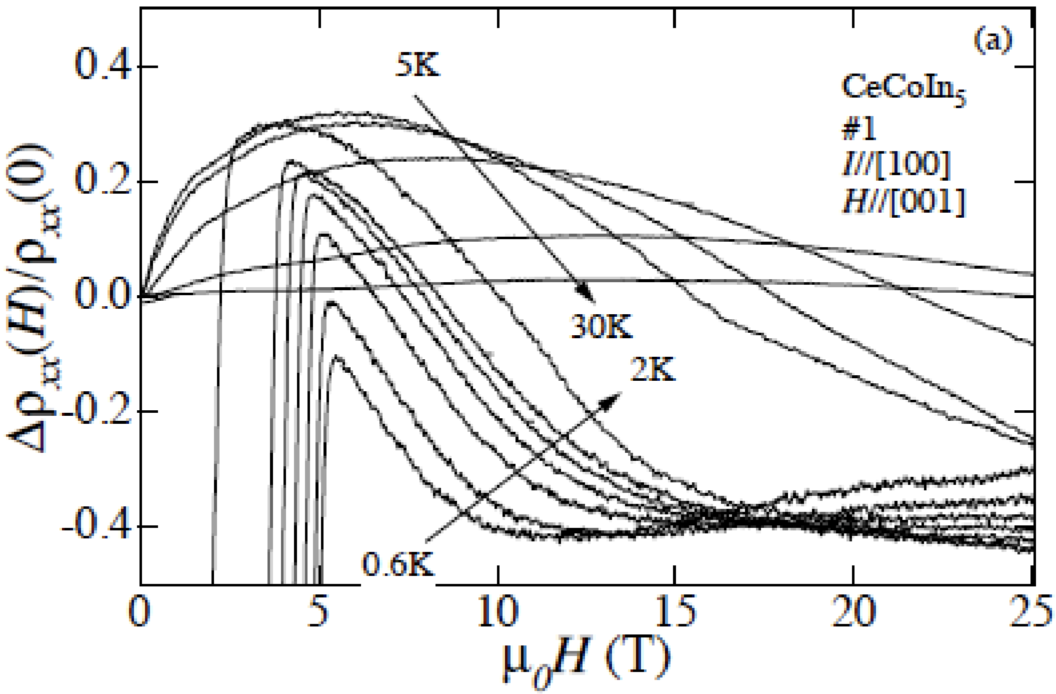


CeCoIn5
B // c
T = 50 mK
0
4
8
12
B (T)
0.3
0.2
0.1
0
M (μB/Ce)


CeCoIn$_5$
p (GPa)
B (T)
0
0
0
8
1. 48
0
1. 48
8
C/T (J/molK^2)
T (K)
2
1
0
0
2
4



3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
ρ_{xx} (x10^{-7} Ω m)
2.0
1.5
1.0
0.5
0.0
$-1/R_H$ (x10^9 T/Ω m)
0
10
20
30
40
50
60
T (K)
T^*
0
-2
-4
-6
$\rho_{xy}/\mu_0 H$ (x10^{-9} Ω m/T)
0
20
40
60
T (K)
11T
4T
1T
0T


(a)
CeCoIn$_5$
#1
I//[100]
H//[001]
5K
30K
2K
0.6K
0.4
0.2
0.0
-0.2
-0.4
$\Delta\rho_{xx}(H)/\rho_{xx}(0)$
0
5
10
15
20
25
$\mu_0 H$ (T)

conclusions

- dense Kondo lattice scale set by Kondo single ion scale
- Kondo liquid state disrupted by percolative non-Kondo component
- similarity between doped dense Kondo and cuprate superconductors: Swiss cheese
- residual Kondo gas in stoichiometric systems