

Night Thoughts on Superconducting Materials: What the Record Tells Us

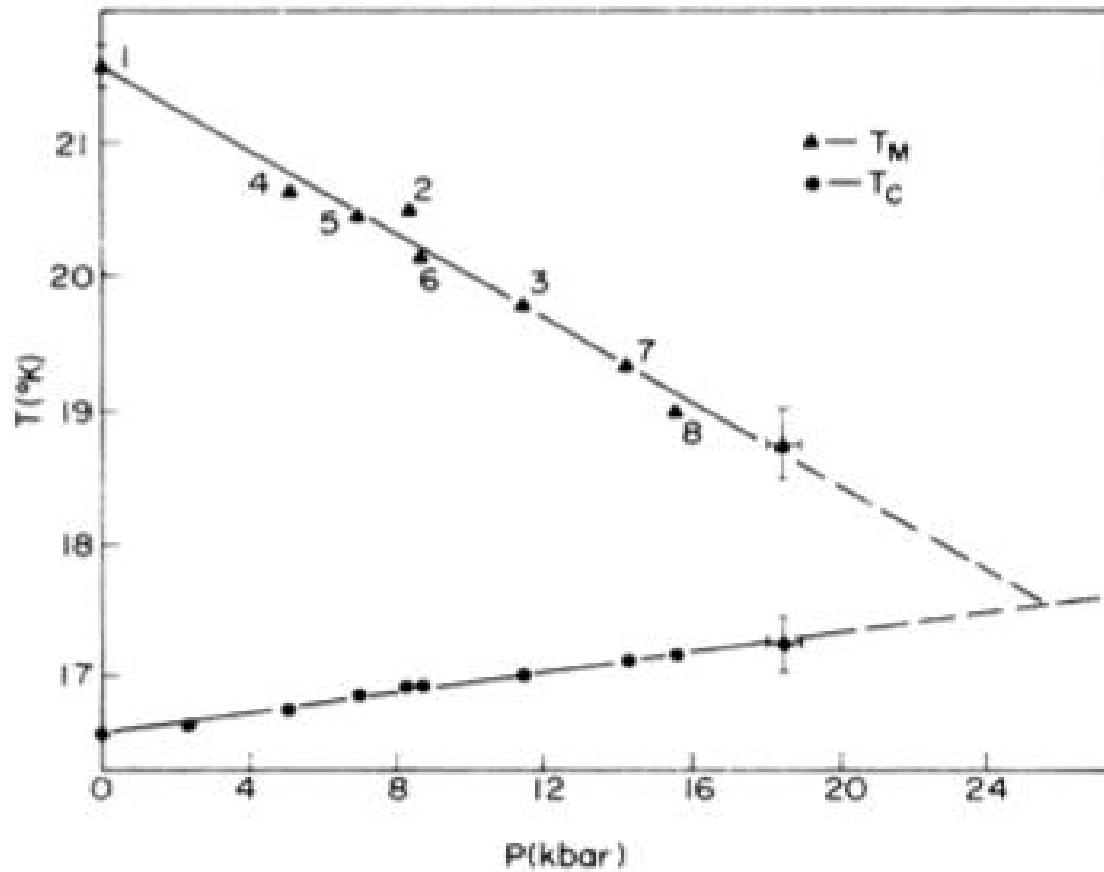
The Physics of Higher Temperature
Superconductivity
KITP June 16, 2009

Z. Fisk UC Irvine

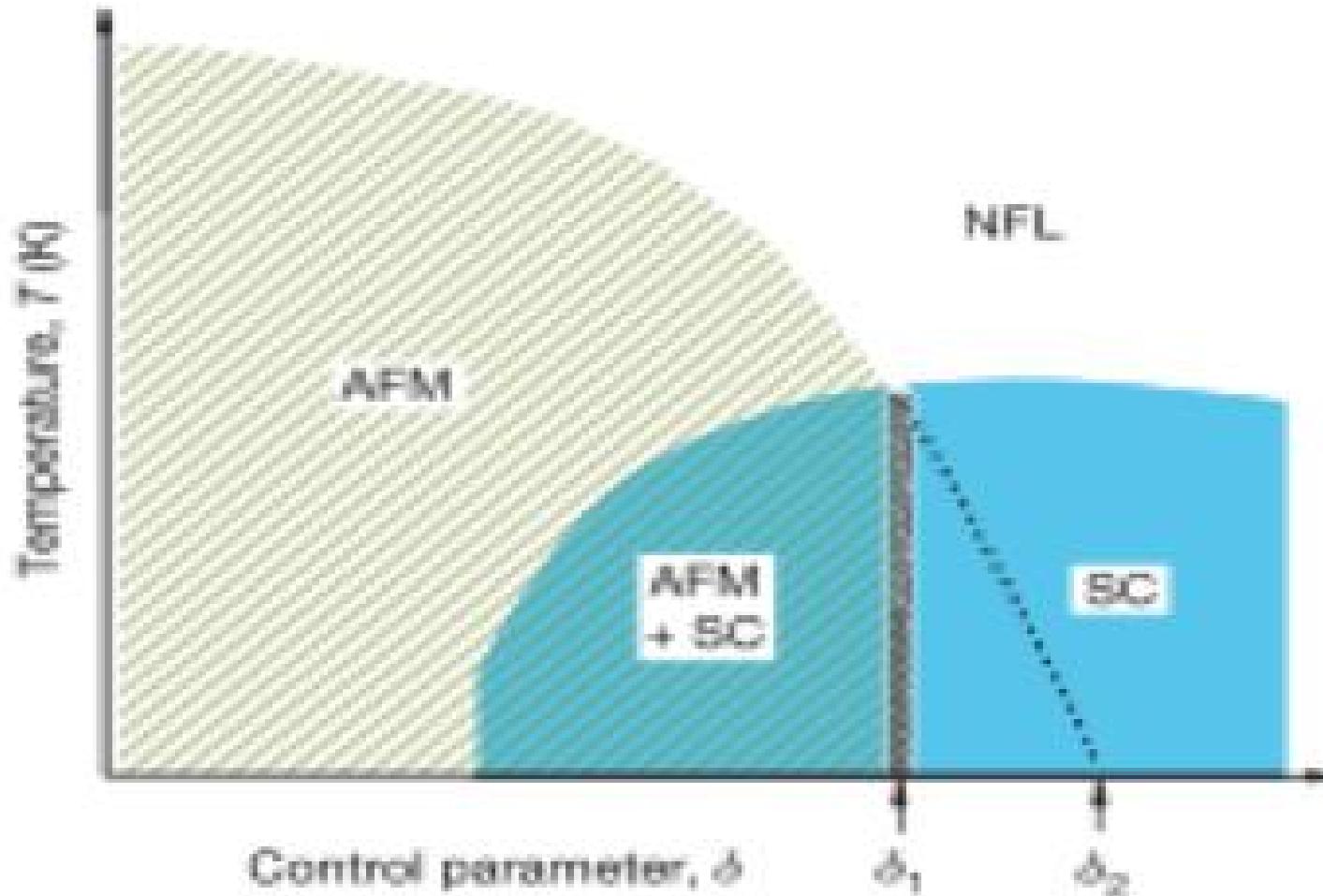
Maximizing T_c

- competing phase problem in:
 - (a) BCS superconductors
 - (b) heavy Fermions
 - (c) cuprates
- Zintl metals
- Energy scale in the Kondo lattice

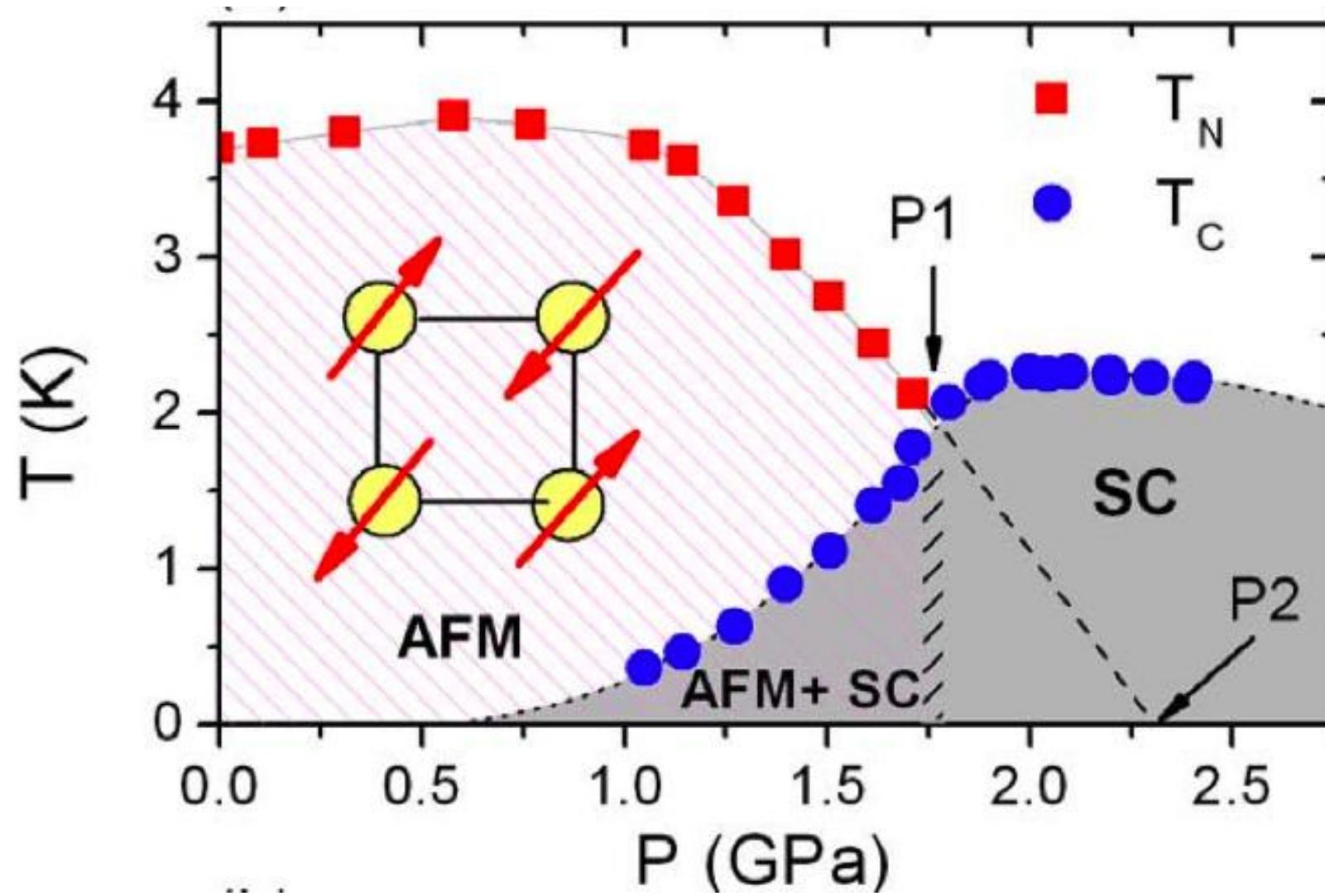
V_3Si : $T_{\text{Martensitic}} / T_c$



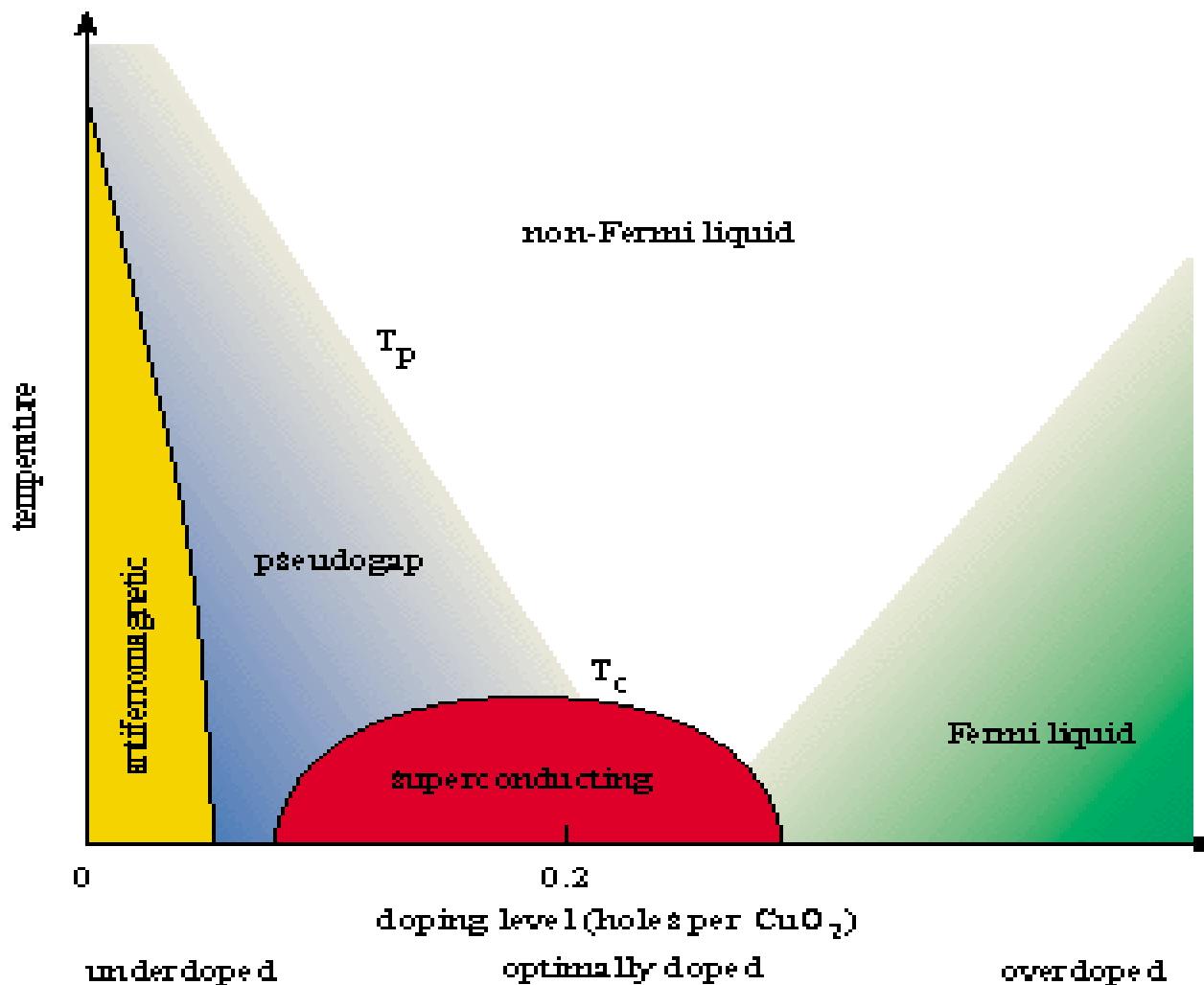
generic heavy Fermion phase diagram



Phase diagram of CeRhIn₅ (Park and Thompson)



generic cuprate phase diagram



Layered Systems

Zintl compounds:
metallic/ionic

Bonding dichotomy

Batlogg scenario

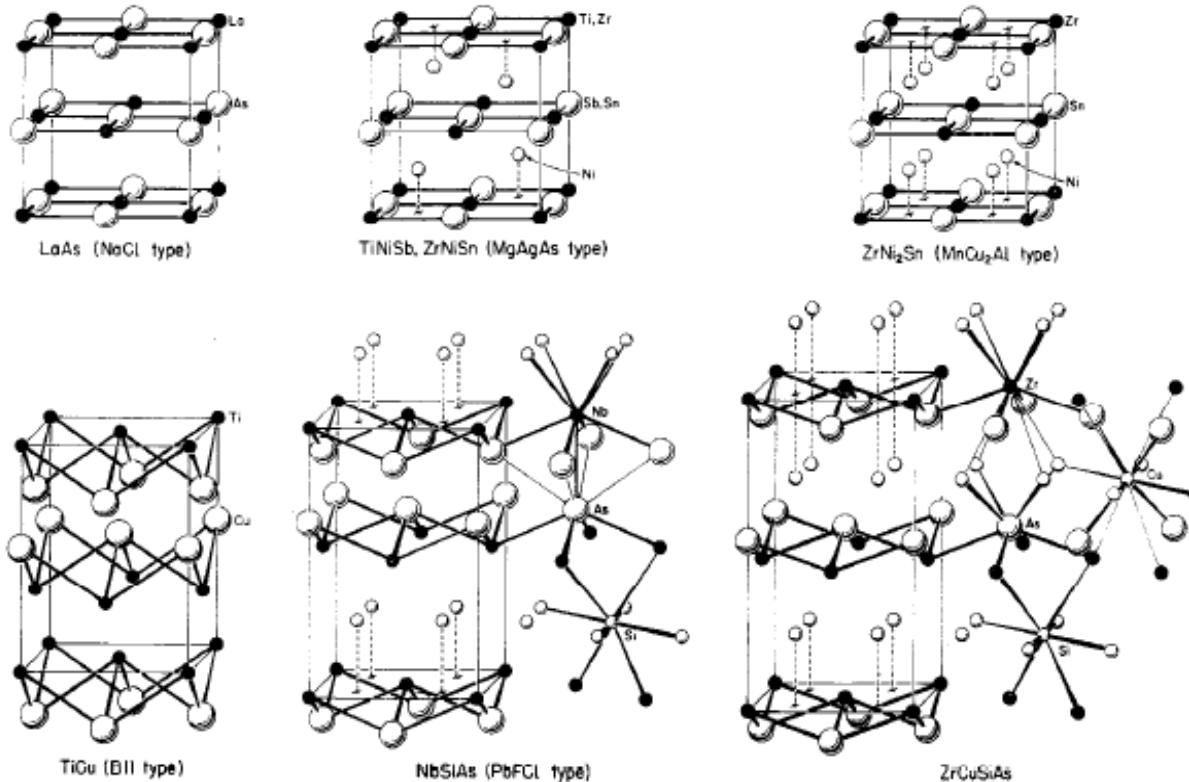


FIG. 1. Crystal structure and near neighbour environment of ZrCuSiAs as compared to the structures of related compounds. The unit cells outlined for ZrCuSiAs, NbSiAs, and TiCu are twice as large as the ones normally given for these structures in order to emphasize the correspondence with the related cubic compounds.

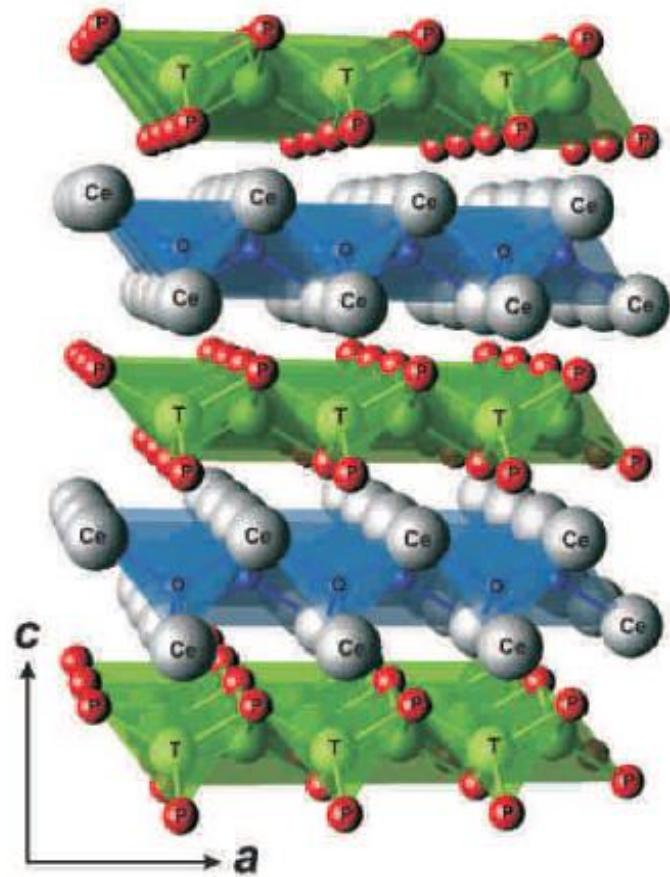


FIG. 1: (Color online) Tetragonal crystal structure ($P4/nmm$) of the CeTPO compound series, showing the alternating layers of TP_4 and OCe_4 tetrahedra.

heavy fermion
superconductivity
systematics of T^* : the
lattice coherence scale

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

relation between single
ion Kondo scale and
lattice T^*

Collaborators

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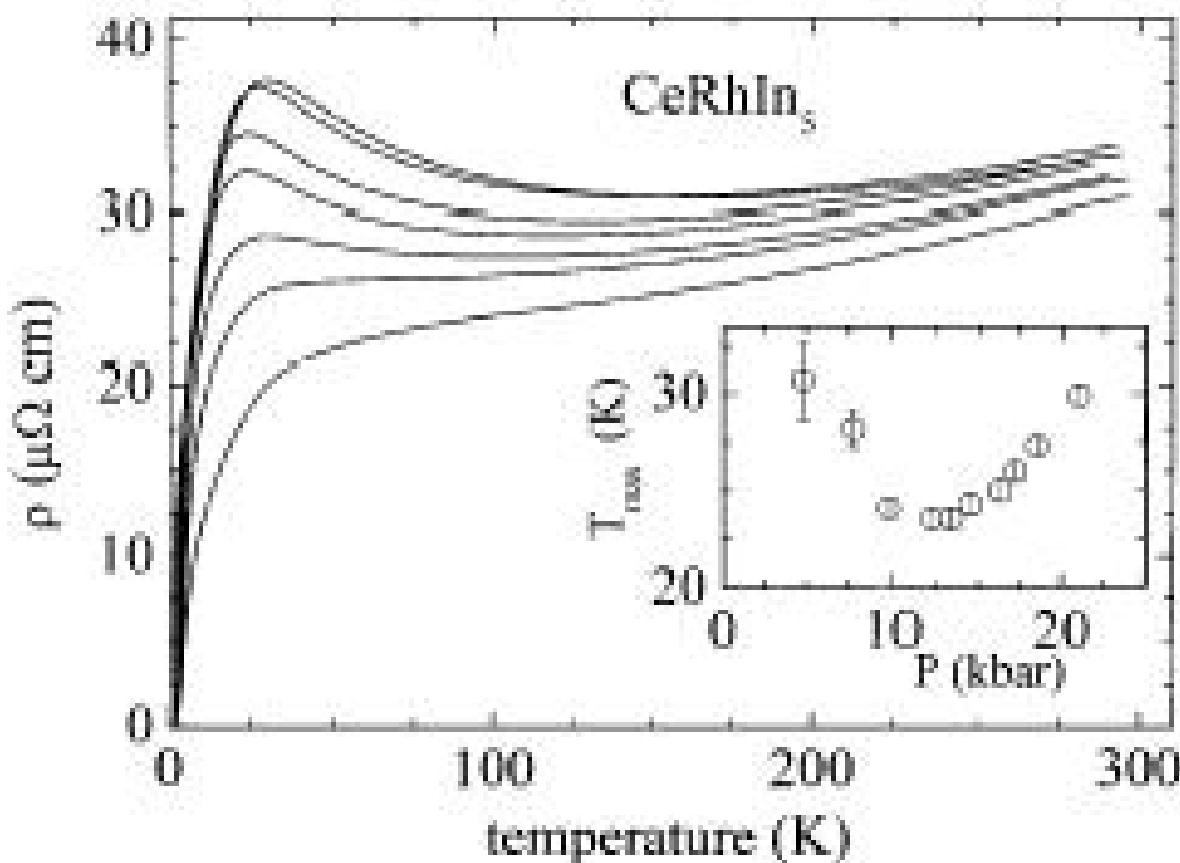


FIG. 2. Temperature dependence of the electrical resistivity of CeRhIn_5 at representative applied pressures. Data shown correspond to pressures of 0.001, 4.8, 7.9, 12.2, 14.5, 18.5, and 21.0 kbar and are associated, respectively, with curves of increasing resistivity at 50 K. The inset is a plot of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

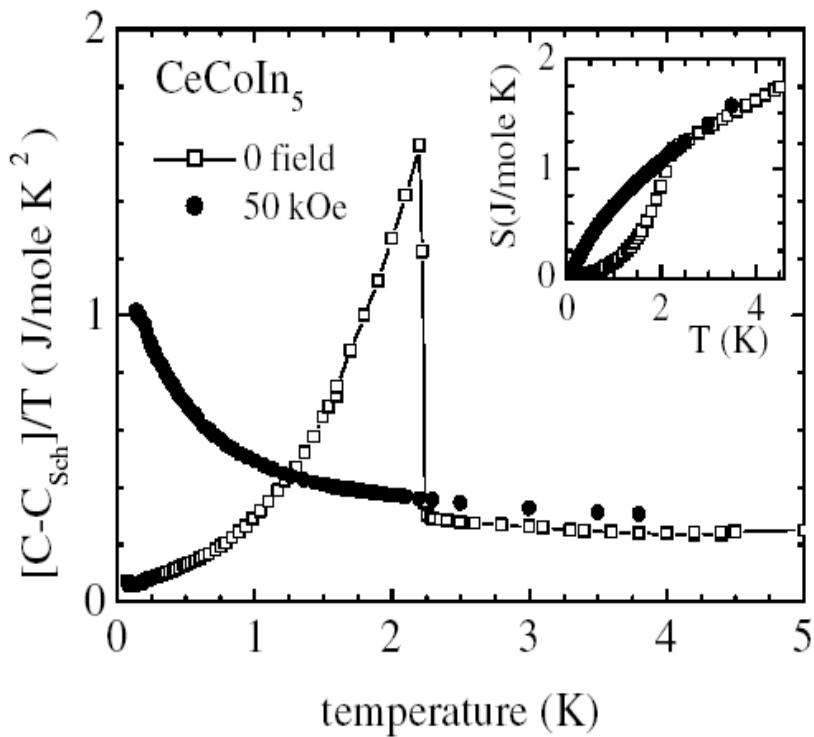


Figure 2. Specific heat divided by temperature versus temperature for CeCoIn_5 . For both the zero-field (open squares) and 50 kOe (solid circles) data, a nuclear Schottky contribution, due to the large nuclear quadrupole moment of In, has been subtracted. The inset shows the entropy recovered as a function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

AF and Superconductivity in CeMIn₅ systems

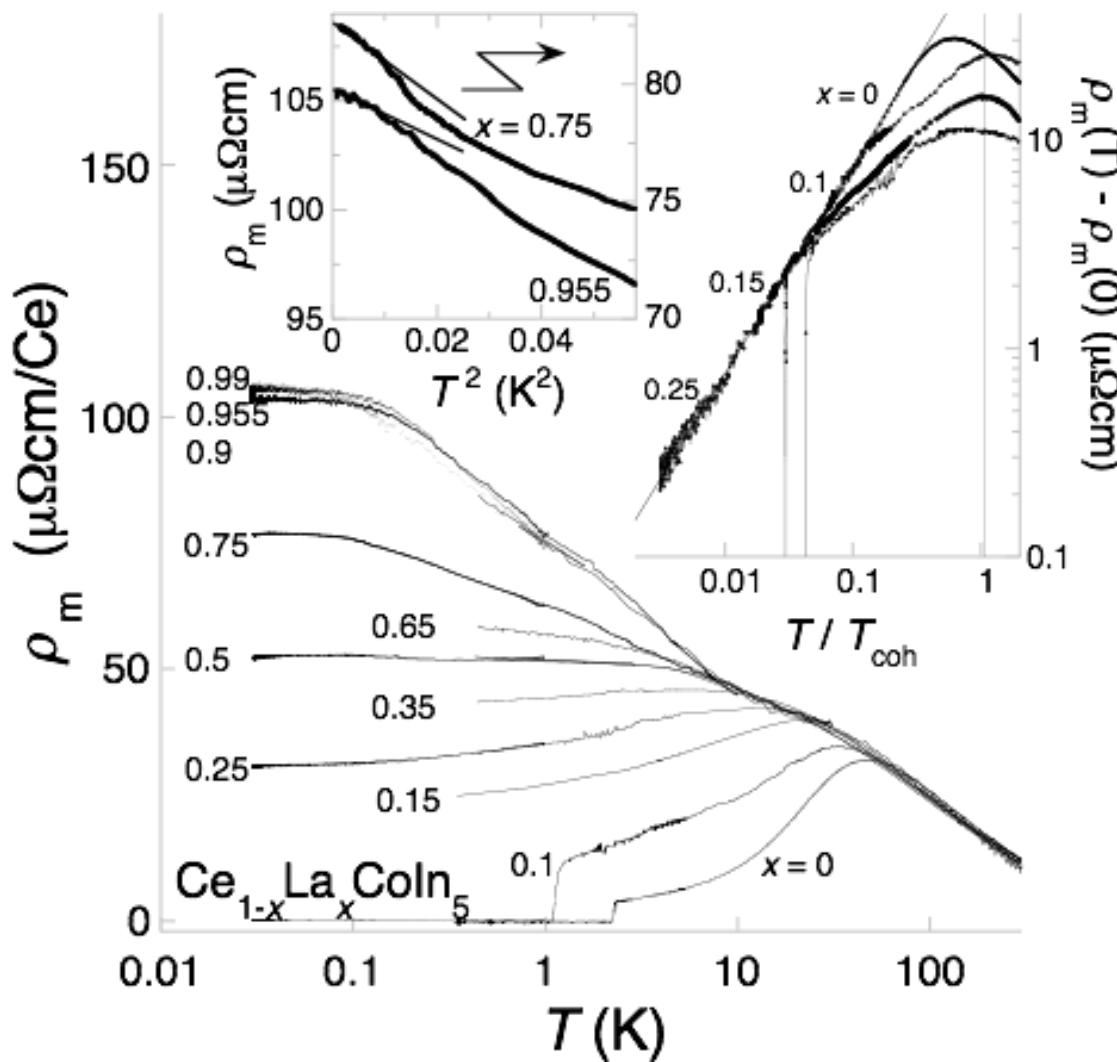
CeCoIn₅

CeRhIn₅

CeIrIn₅

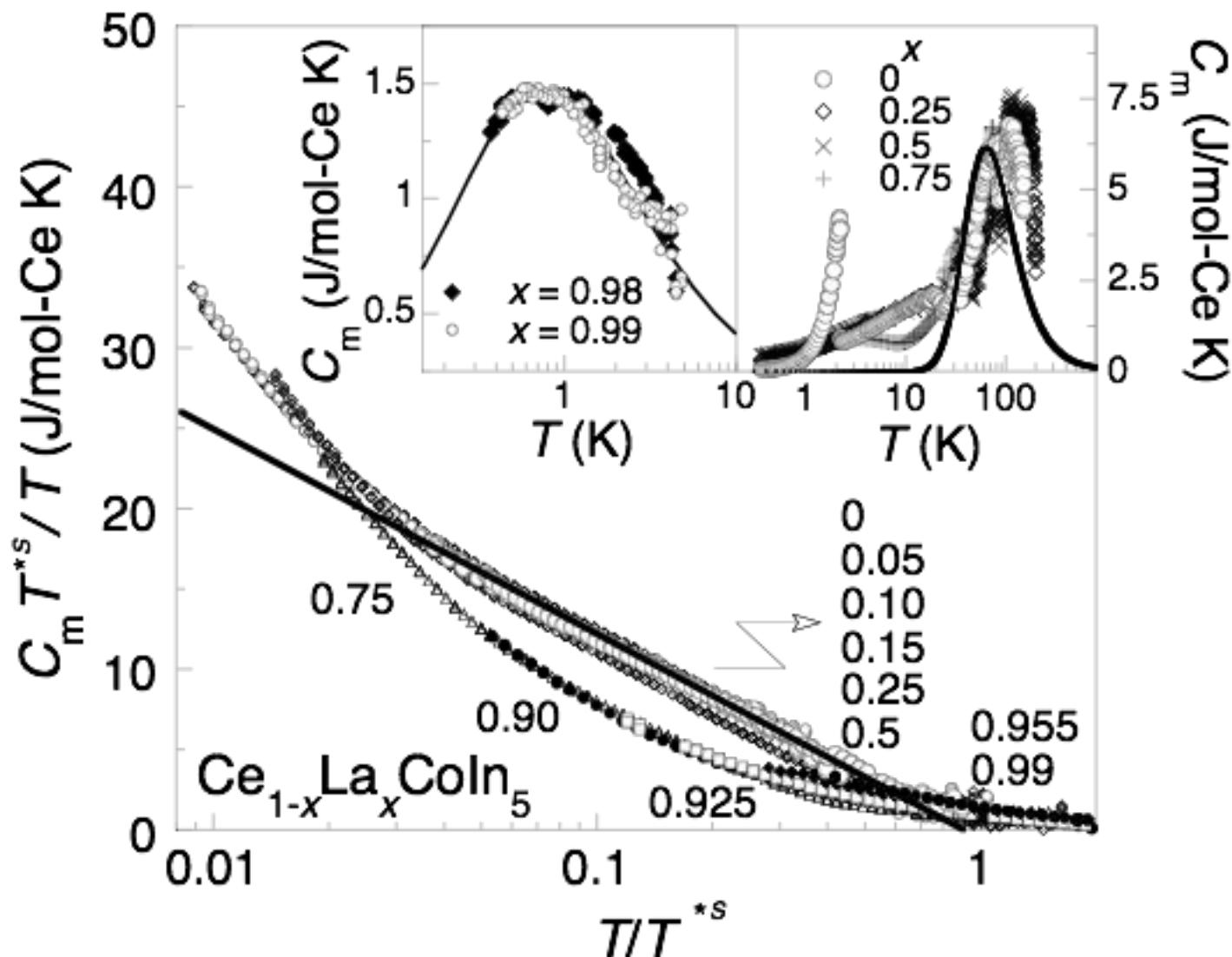
CeCoIn₅

Intersite coupling effects in a Kondo lattice – CeColn₅



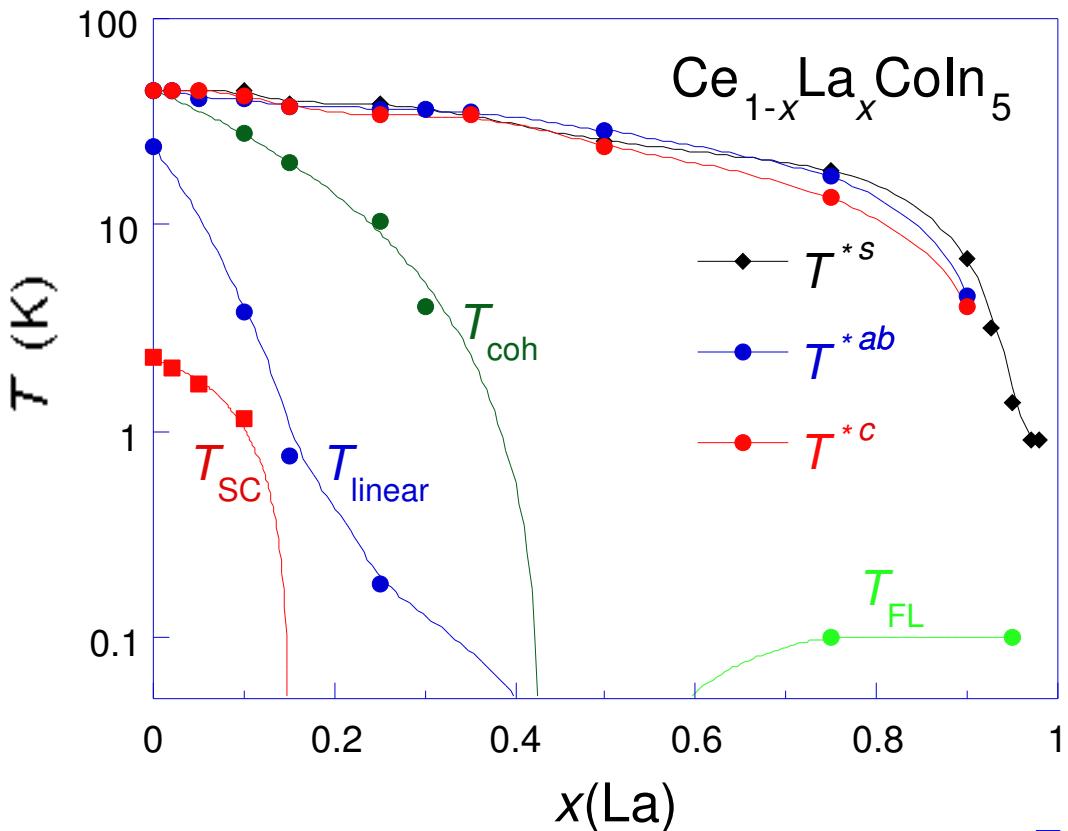
S. Nakasutji *et al.*, PRL 89, 106402 (2002).

Logarithmic Sommerfeld coefficient in a Kondo lattice – CeColn₅



S. Nakatsuji *et al.*, PRL 89, 106402 (2002).

Energy scale diagram of $\text{Ce}_{1-x}\text{La}_x\text{CoIn}_5$



- 1) T^{*ab} , T^c , T^s are essentially identical.
- 2) T originates from the single-ion T_K at $x \rightarrow 1$ limit.
- 3) The systematic increase should arise from intersite correlation.
 $T_{\text{coh}} \rightarrow T$ at $x \rightarrow 0$ 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

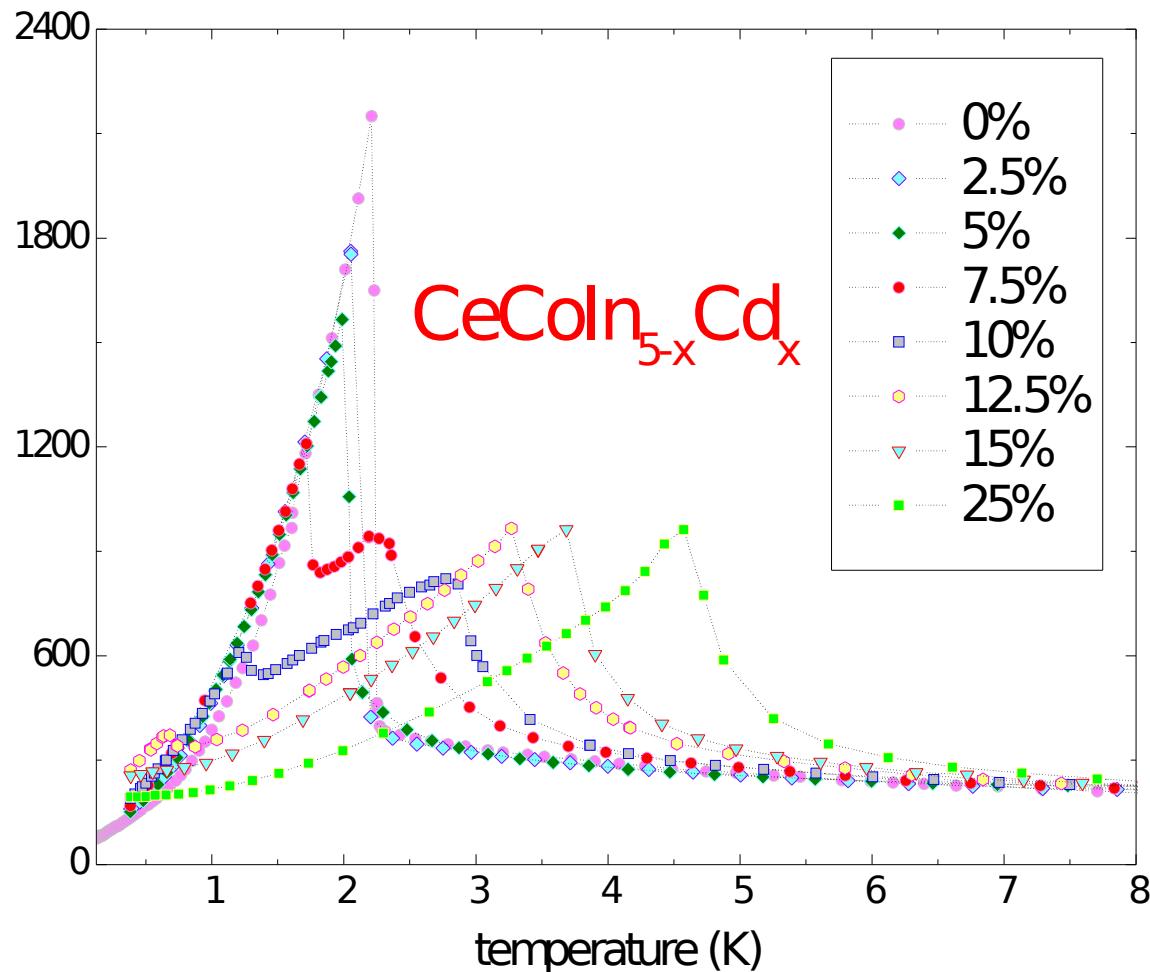


Fig. 1 | Specific heat divided by temperature as a function of temperature for $\text{CeCoIn}_{5-x}\text{Cd}_x$ at fixed Cd concentrations and zero applied field. The coexistence between superconductivity and antiferromagnetism is seen for $x = 7.5\%$, 10% , 12.5% Cd. Data was taken with a commercially available Physical Property Measurement System (PPMS).

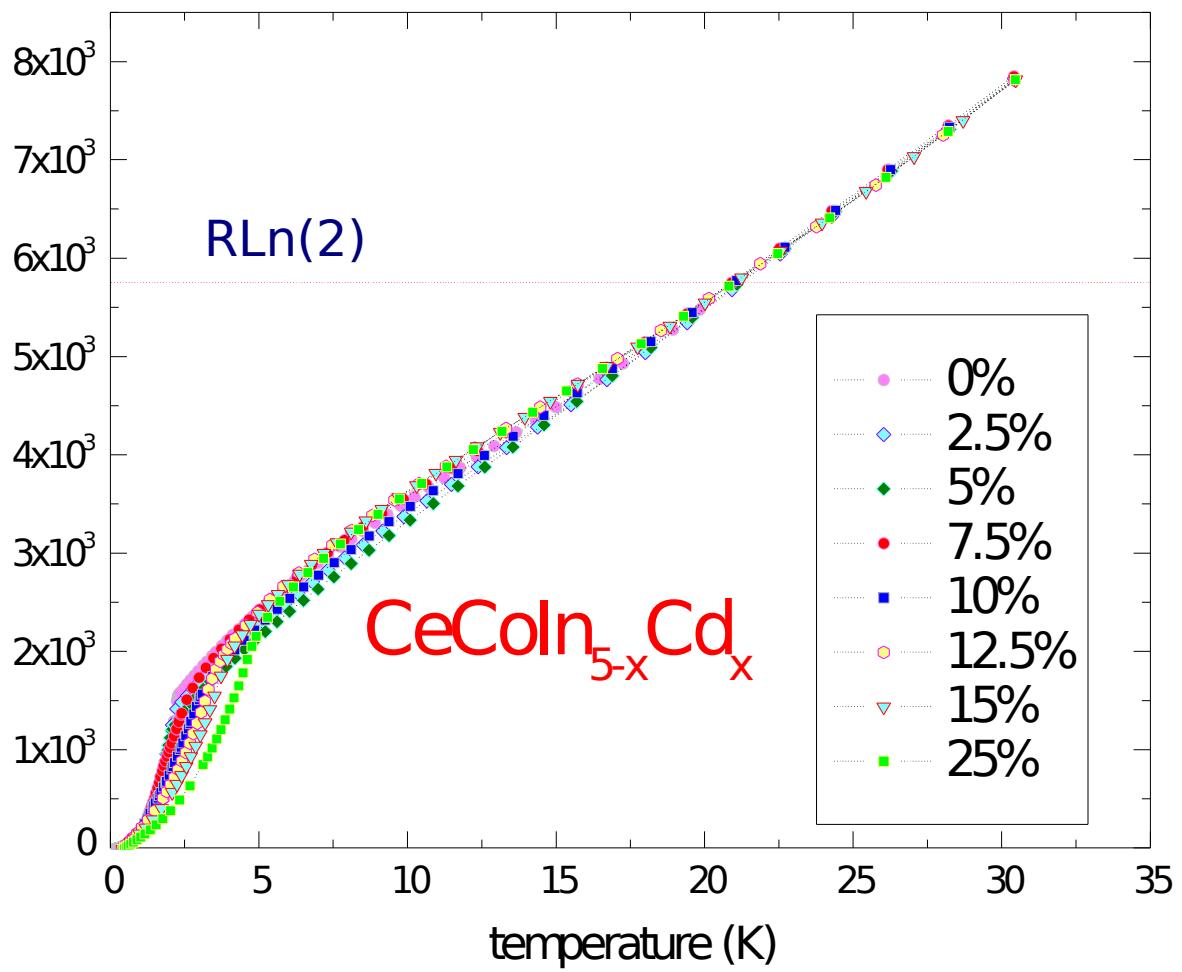


Fig. 2 | Entropy as a function of temperature of $CeCoIn_{5-x}Cd_x$ at fixed Cd concentrations and zero applied field. $RLn(2)$ is recovered above $\sim 20K$ for all x . Data was taken with a commercially available Physical Property Measurement System (PPMS).

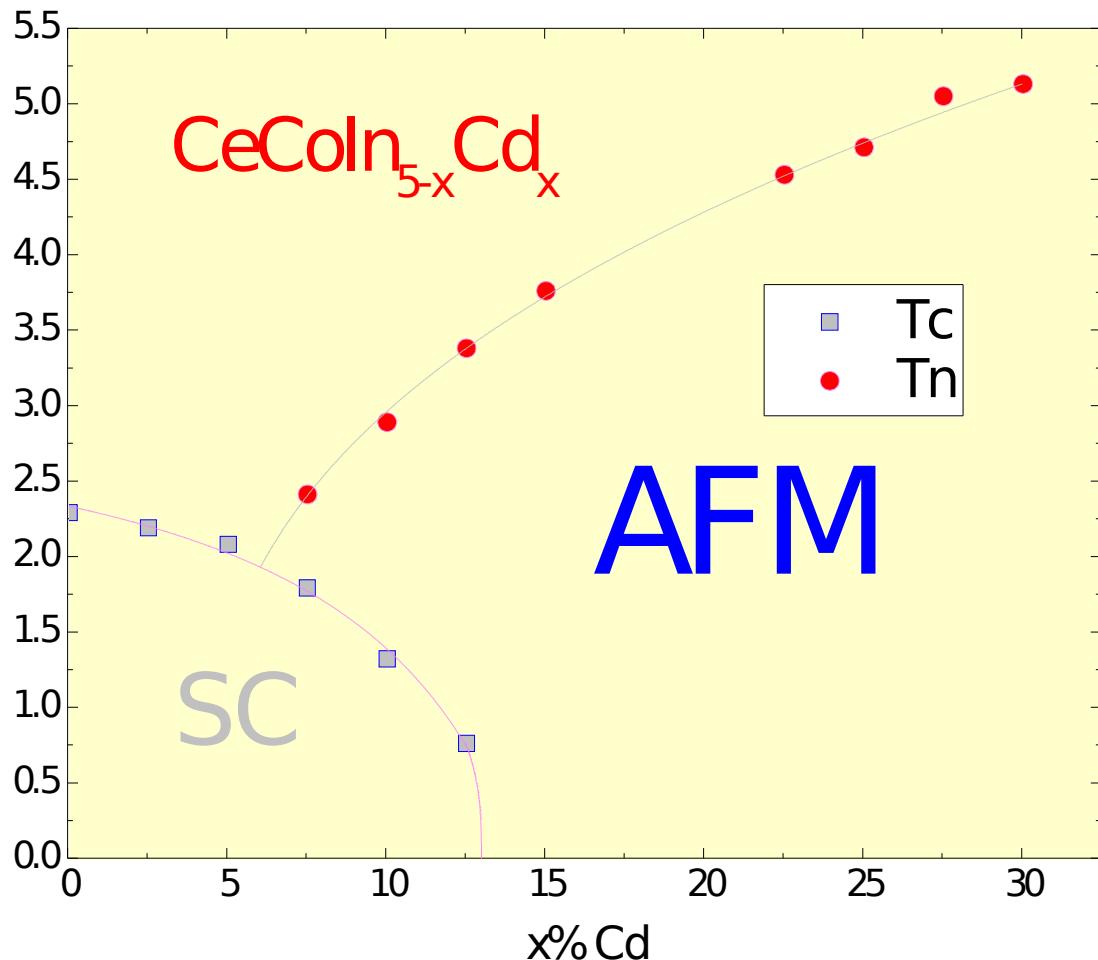
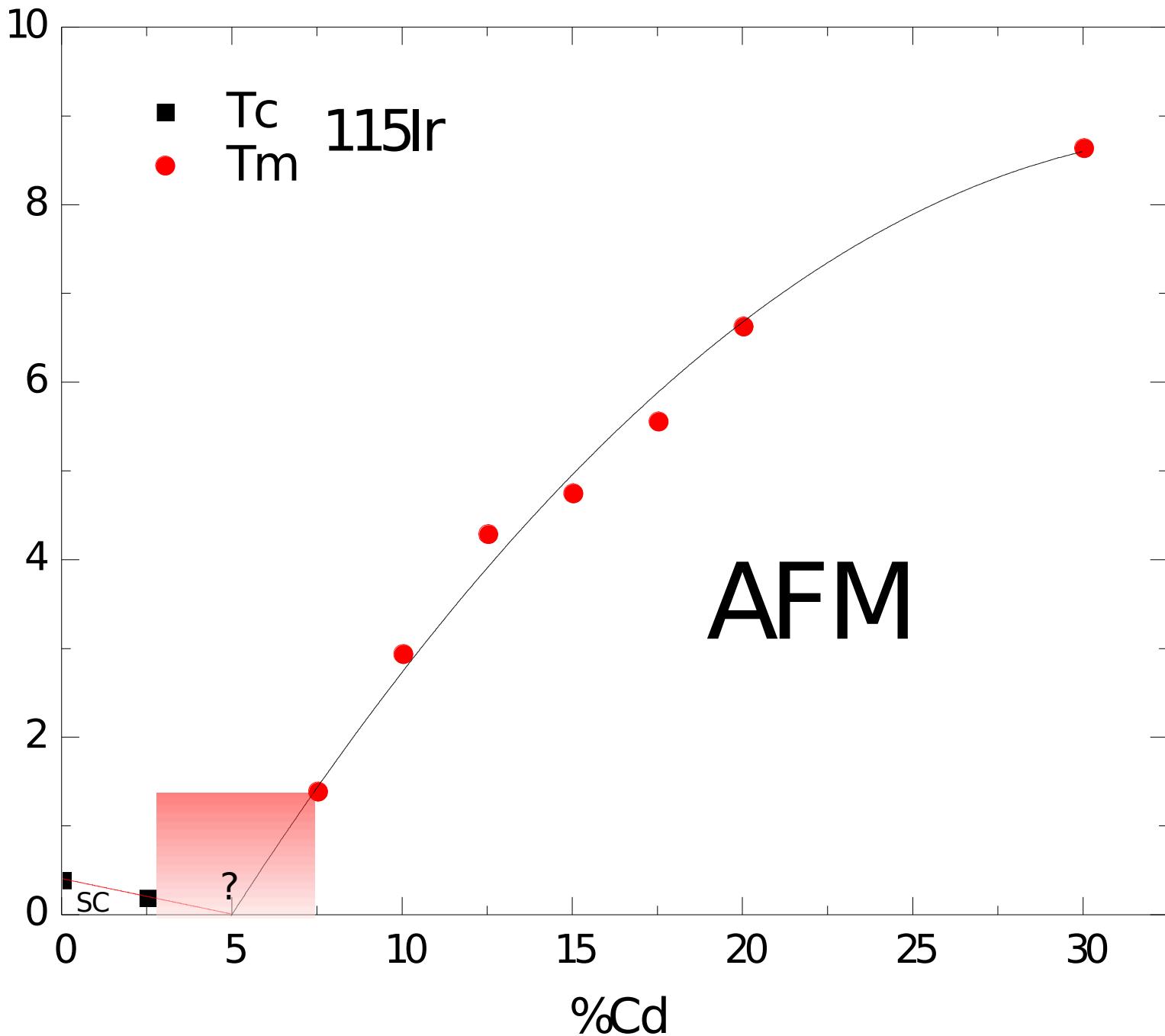
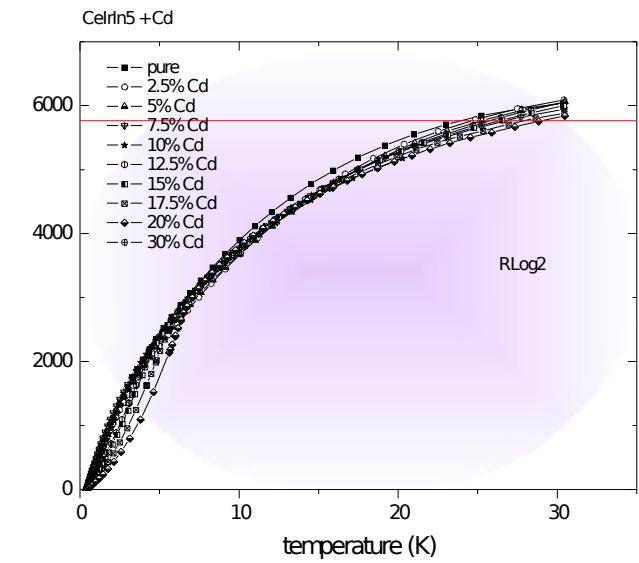
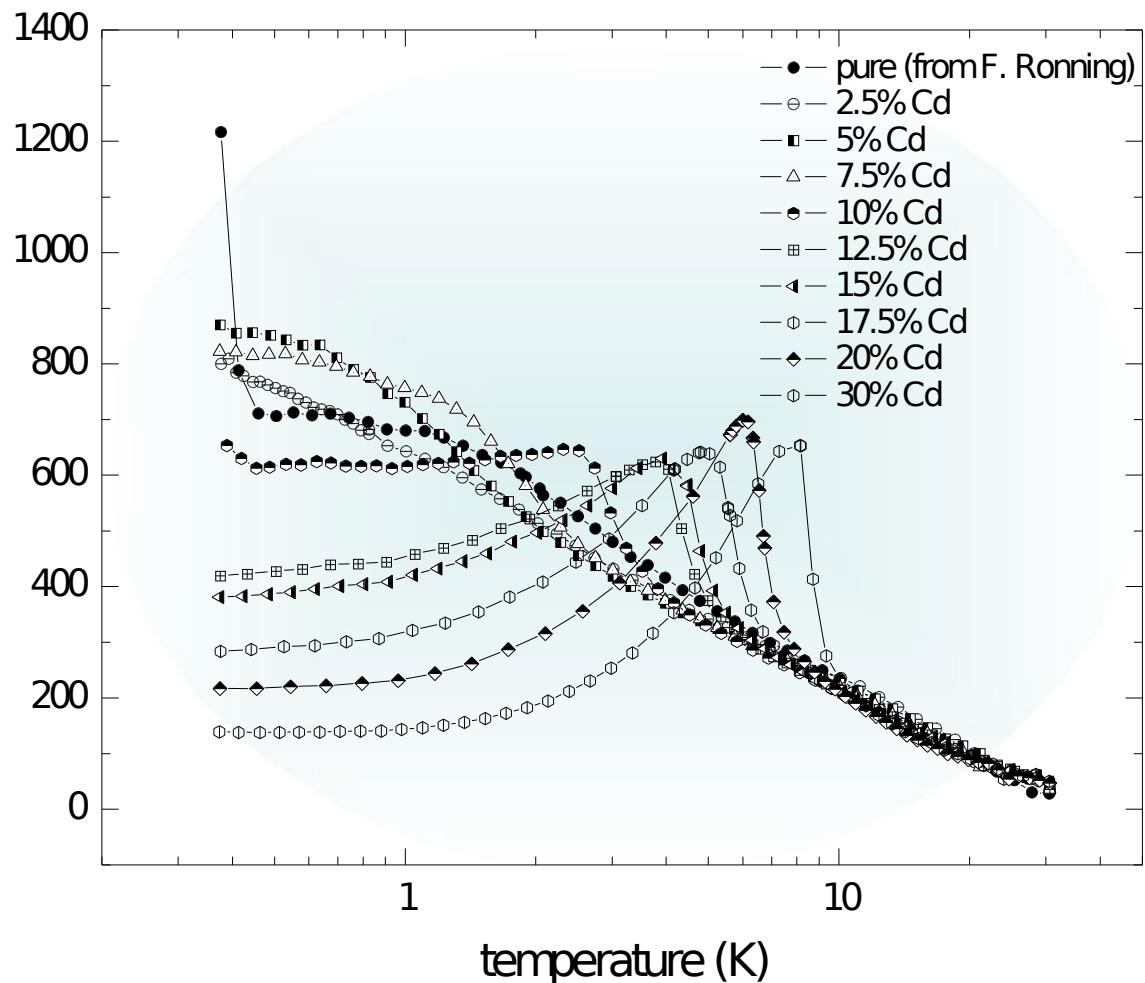


Fig. 3 | $T_{c,n}$ as a function of Cd concentration in zero applied field for $\text{CeCoIn}_{5-x}\text{Cd}_x$, where $T_{c,n}$ is the superconducting and Neel temperature, respectively.

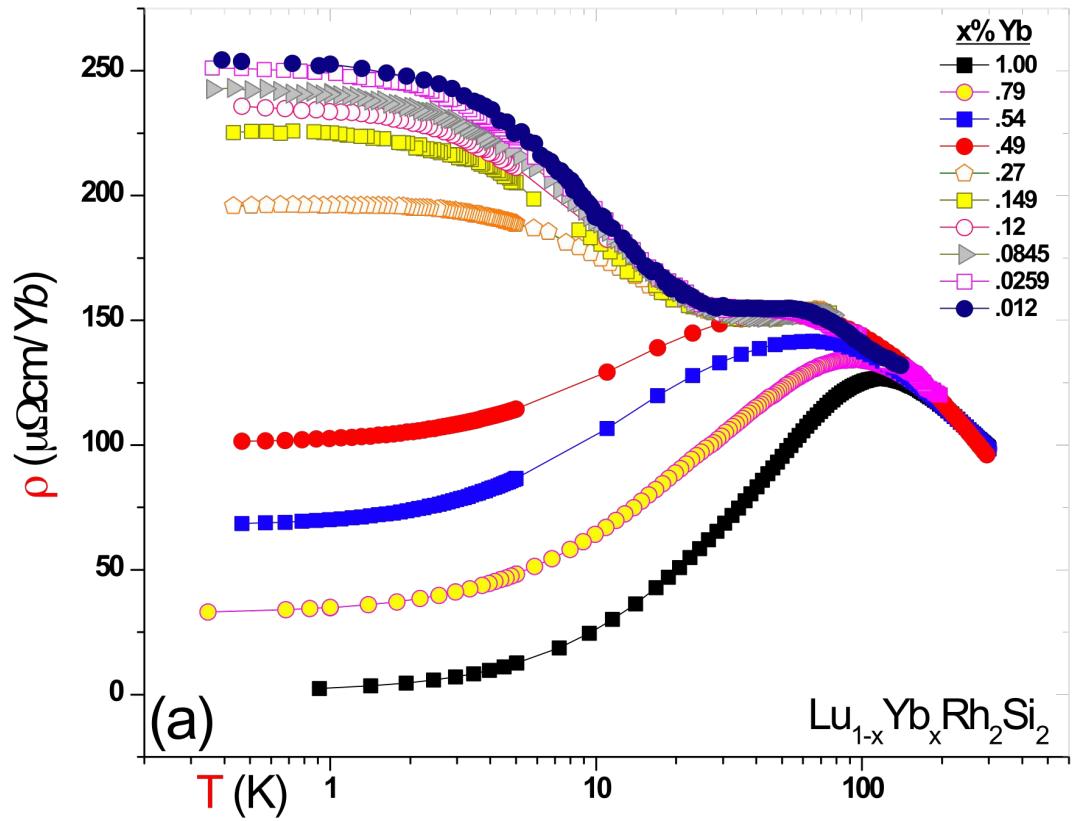


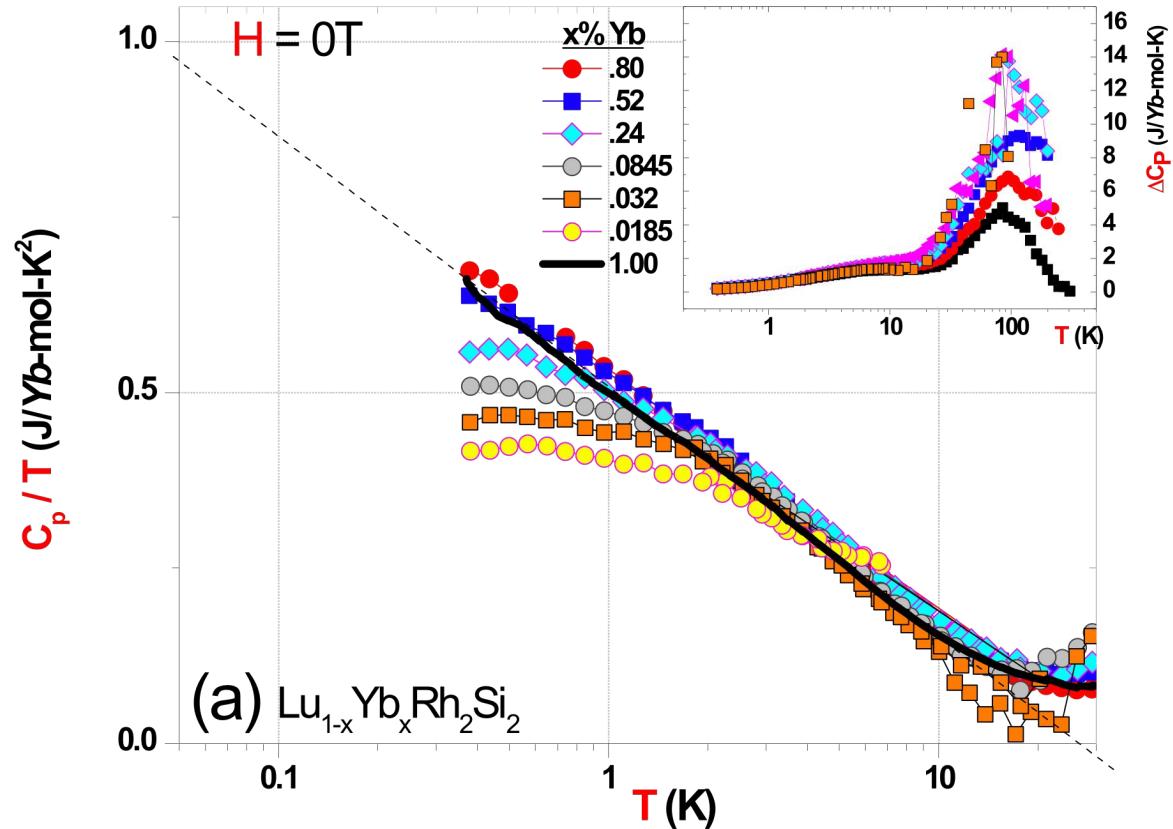
Heat Capacity

CeIr($\text{In}_{1-x}\text{Cd}_x$)₅

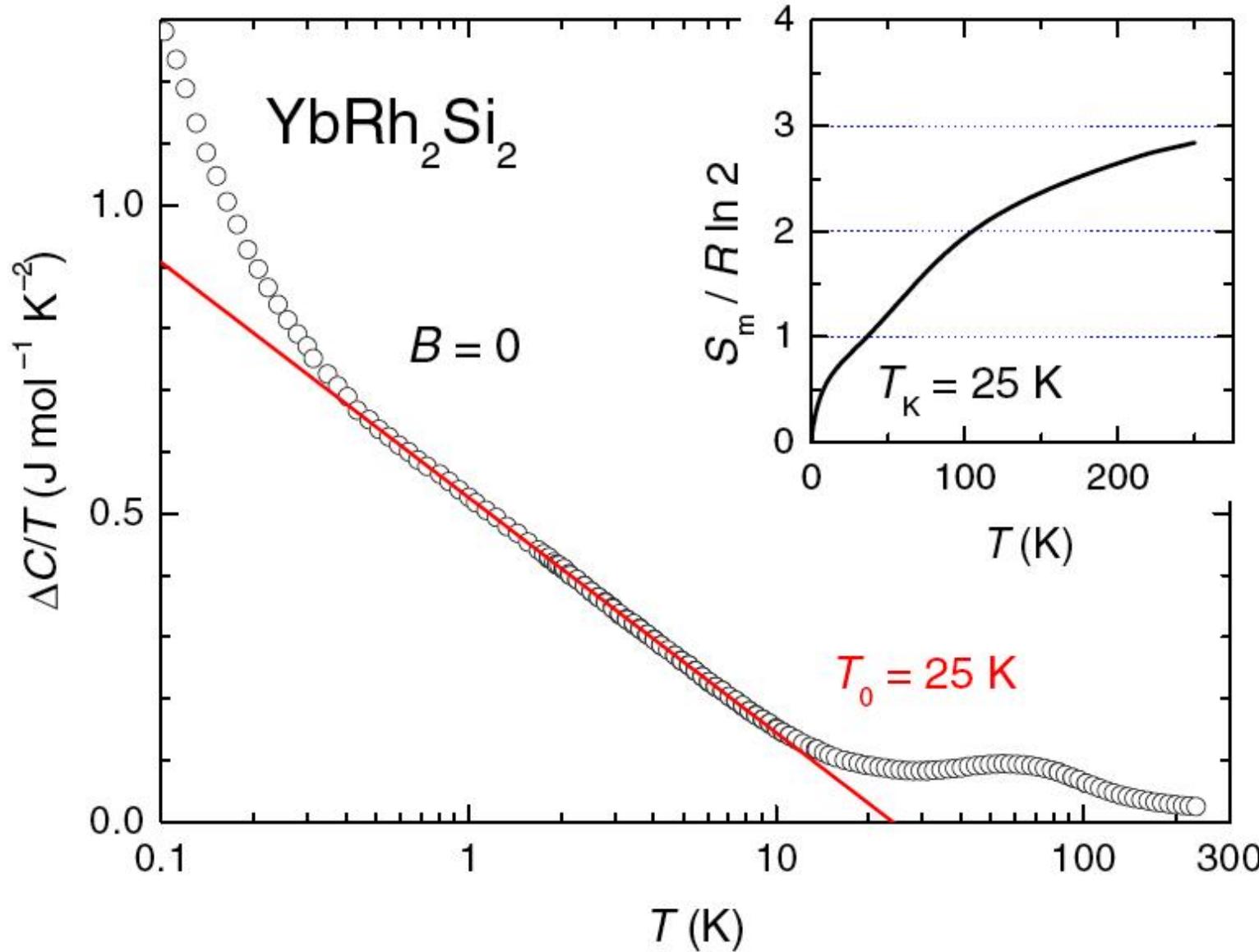


- $C/T \sim -\log T$ at 2.5% down to lowest T before SC sets in at $\sim 0.2\text{K}$.

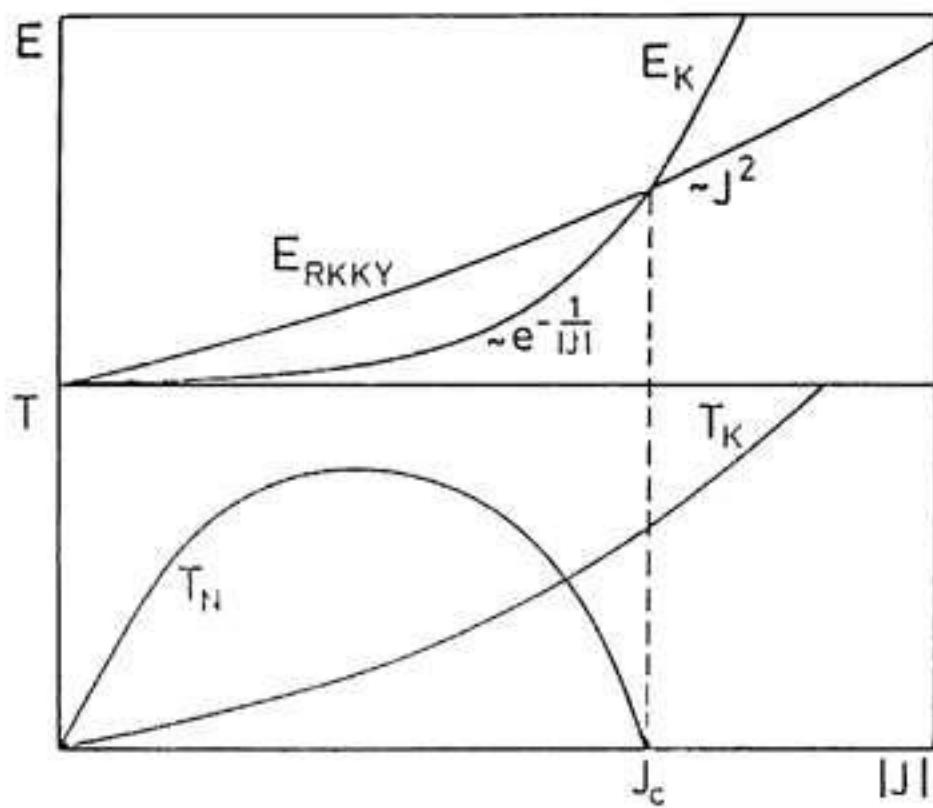




Sommerfeld coefficient – Kondo lattice?



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



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".

Appearance of a new order



Entropy development in quantum critical regime

$$C/T \propto$$

$$\ln T$$

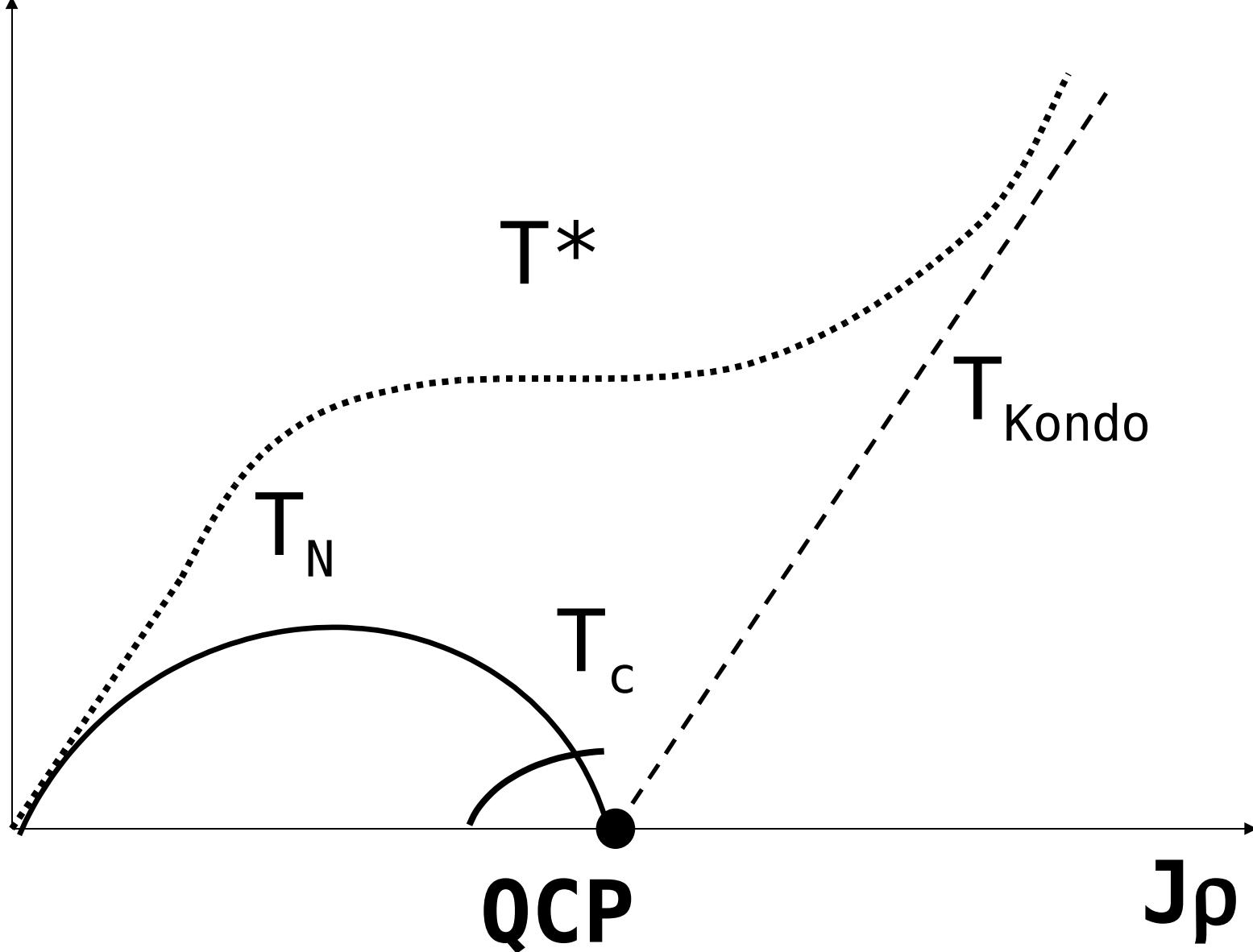
Typically: $C/T = (R\ln 2/T^*) \ln(T^*/T)$

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

T^* sets the scale for heavy Fermion physics

For heavy Fermion superconductors:

$$S(T) \approx 10\text{-}20\% R\ln 2 \Leftrightarrow$$



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

$$\text{RKKY scale: } T^* = c J^2 \rho$$

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

