Title: Non-Metallic Resistivity in Strongly Correlated Metals

Date: Apr 24, 2008 04:30 PM

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Abstract: There are a few examples in the literature of metals that, in the T ïƒ 0 K limit, show a resistivity that rises with decreasing temperature without any sign of either saturation or a gap. Well known cases include underdoped cuprates in high magnetic fields and some doped uranium heavy fermion compounds. I will review these and some less-well-known cases, before describing the behaviour of FeCrAs [1], in which we find a continuously rising resistivity from 900 K down to below 50 mK, with a brief interruption due to an antiferromagnetic transition at about 100 K. Down to at least 50 mK the resistivity is nearly linear in temperature, but with a negative coefficient. We speculate that this behaviour may be connected to fluctuations of frustrated iron â€œtrimersâ€• that do not order magnetically. 1. W. Wu, A. McCollam, P.M.C. Rourke, D. Rancourt, I. Swainson and S.R. Julian, in preparation.

Non-metallic resistivity in strongly correlated electron systems

Stephen Julian
University of Toronto

- Non-fermi-liquid behaviour in
  - $YUPd_3$, $UCu_{5-x}Pd_x$, and other heavy fermions
  - Frustrated spin system $PrIr_2O_7$
- Non-metallic resisitivity and other properties of FeCrAs
  - Underscreened Kondo model?

Collaborators: W. Wu, A. McCollam, D. Rancourt, I. Swainston

Non-Fermi-liquid transport

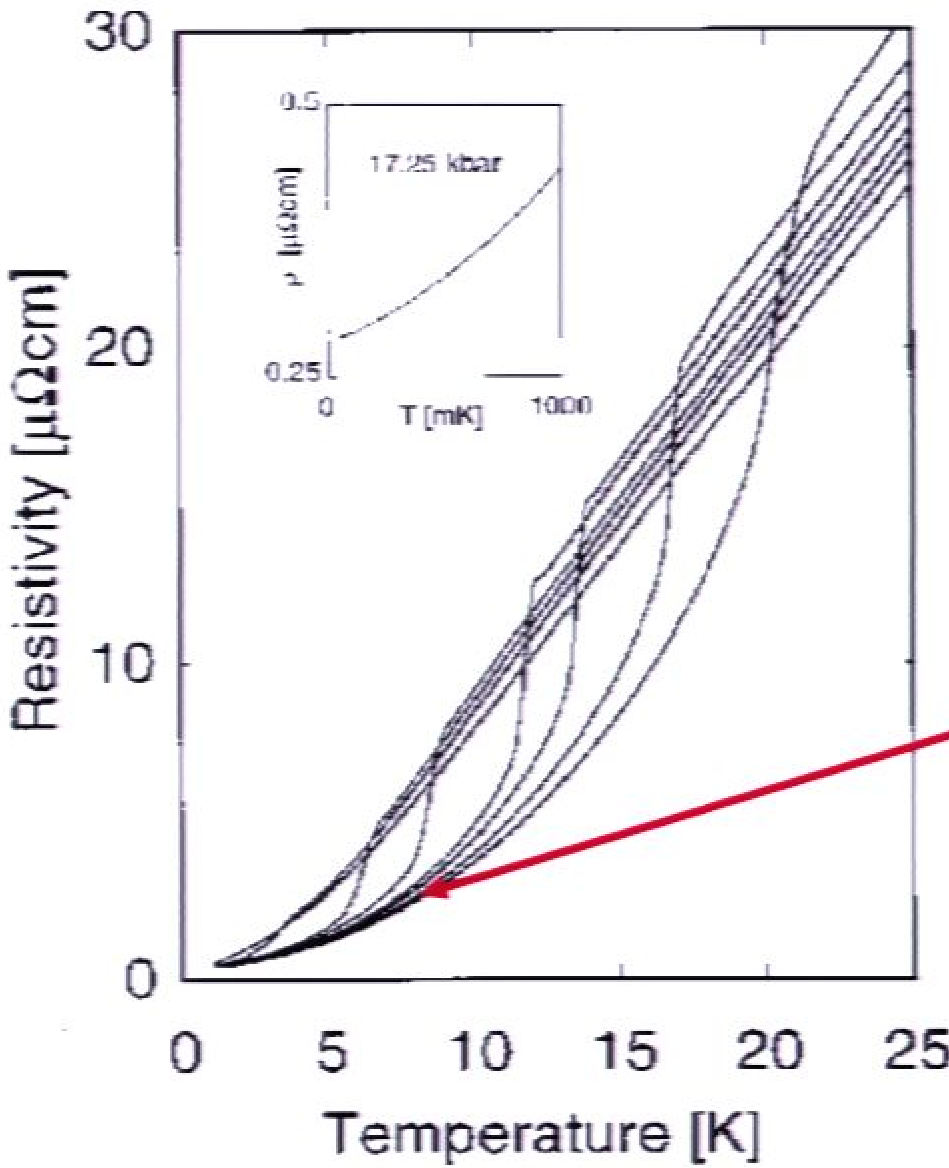
$$\rho = \rho_0 + AT^{\alpha}$$

$\alpha < 2$

Non-Fermi-liquid transport

$$\rho = \rho_0 + AT^{\alpha}$$

α **< 2**



T^2

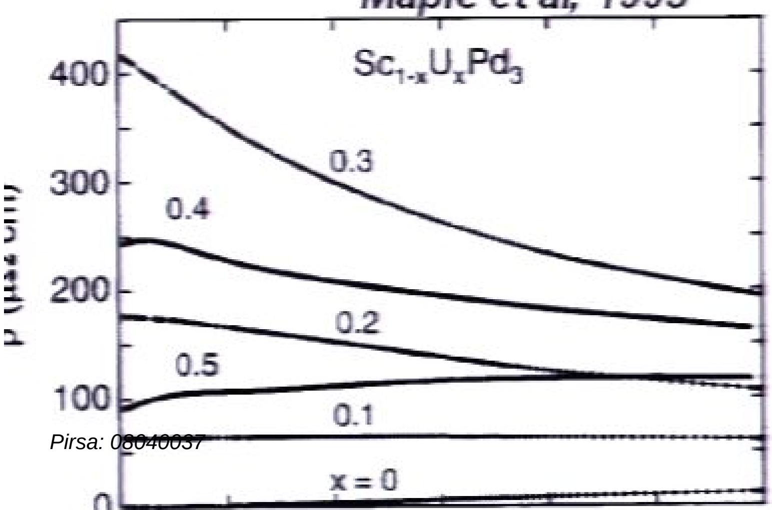
Non-Fermi-liquid transport

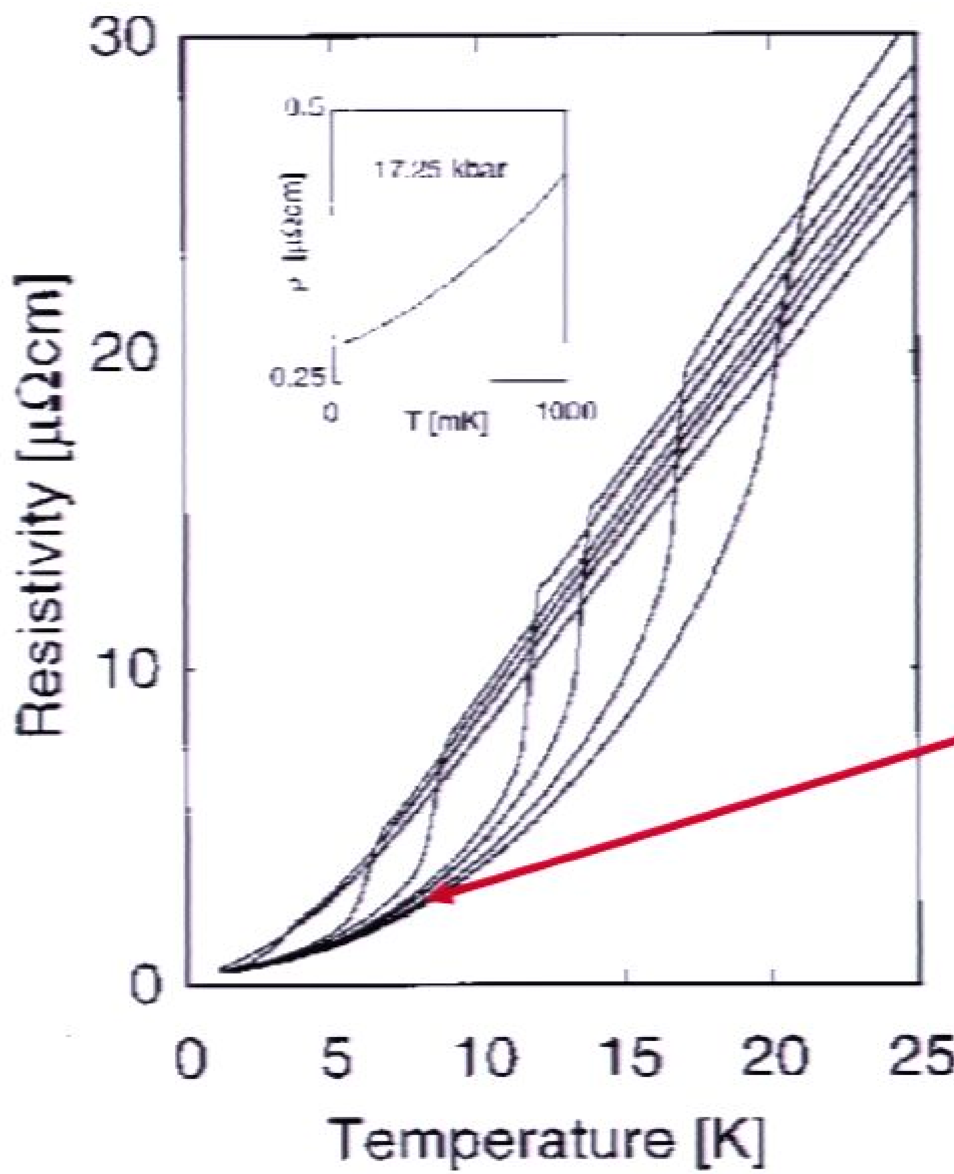
$$\rho = \rho_0 + AT^{\alpha}$$

$\alpha < 2$

$A < 0$

Maple et al, 1995



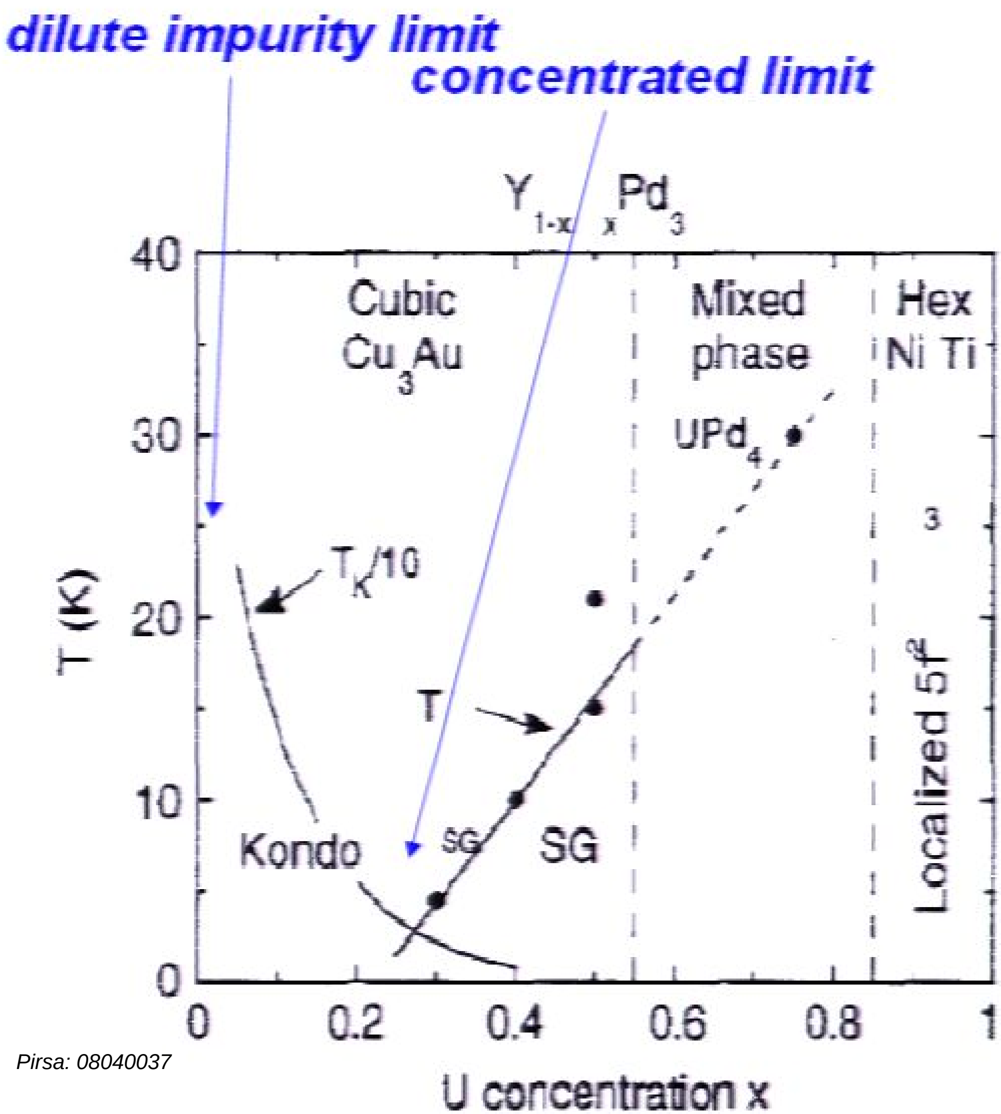


T^2

non-Fermi-liquid systems with $d\rho/dT < 0$ in the T -> 0K limit

- There are not many
- Roughly they can be divided into concentrated and dilute impurity limit systems.

$M_{1-x}U_xPd_3$ (M=Y,Sc)



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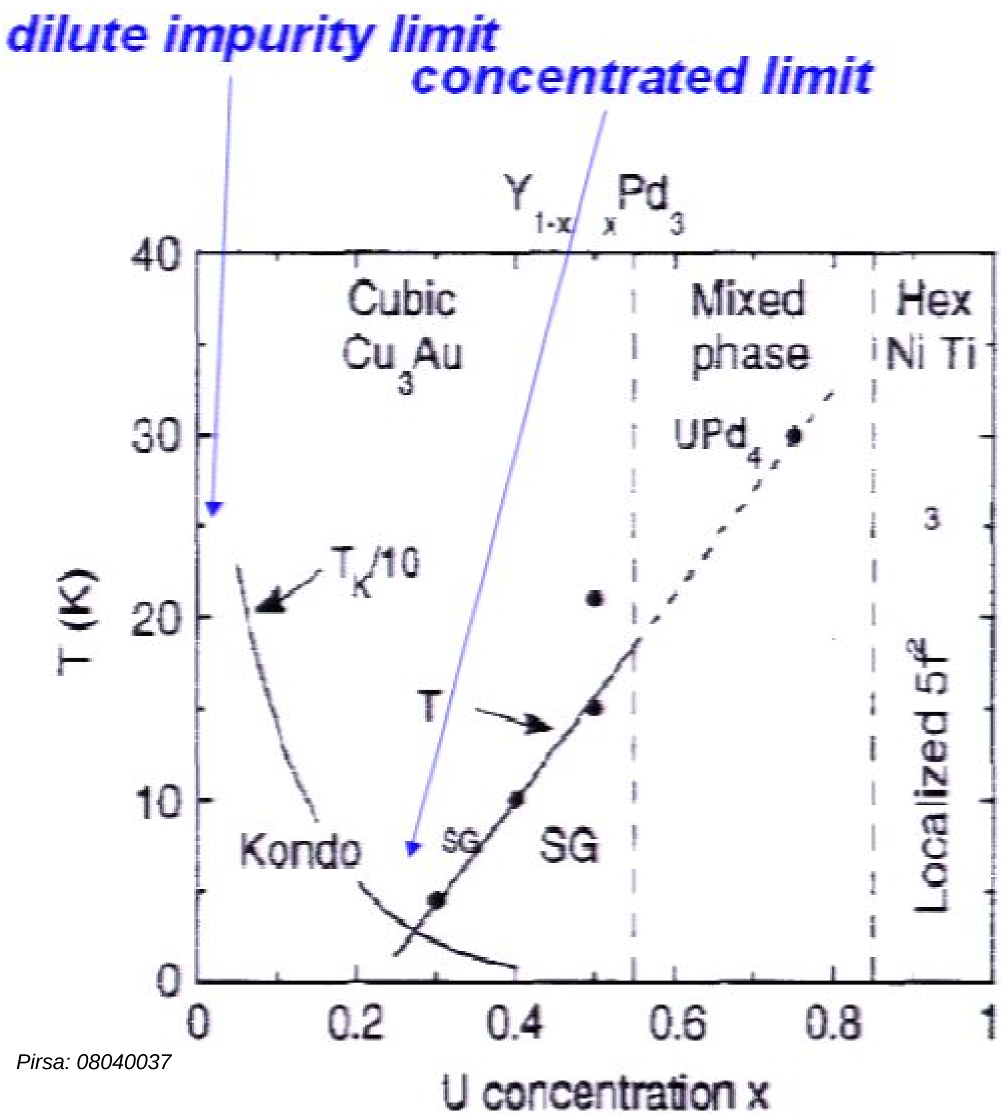
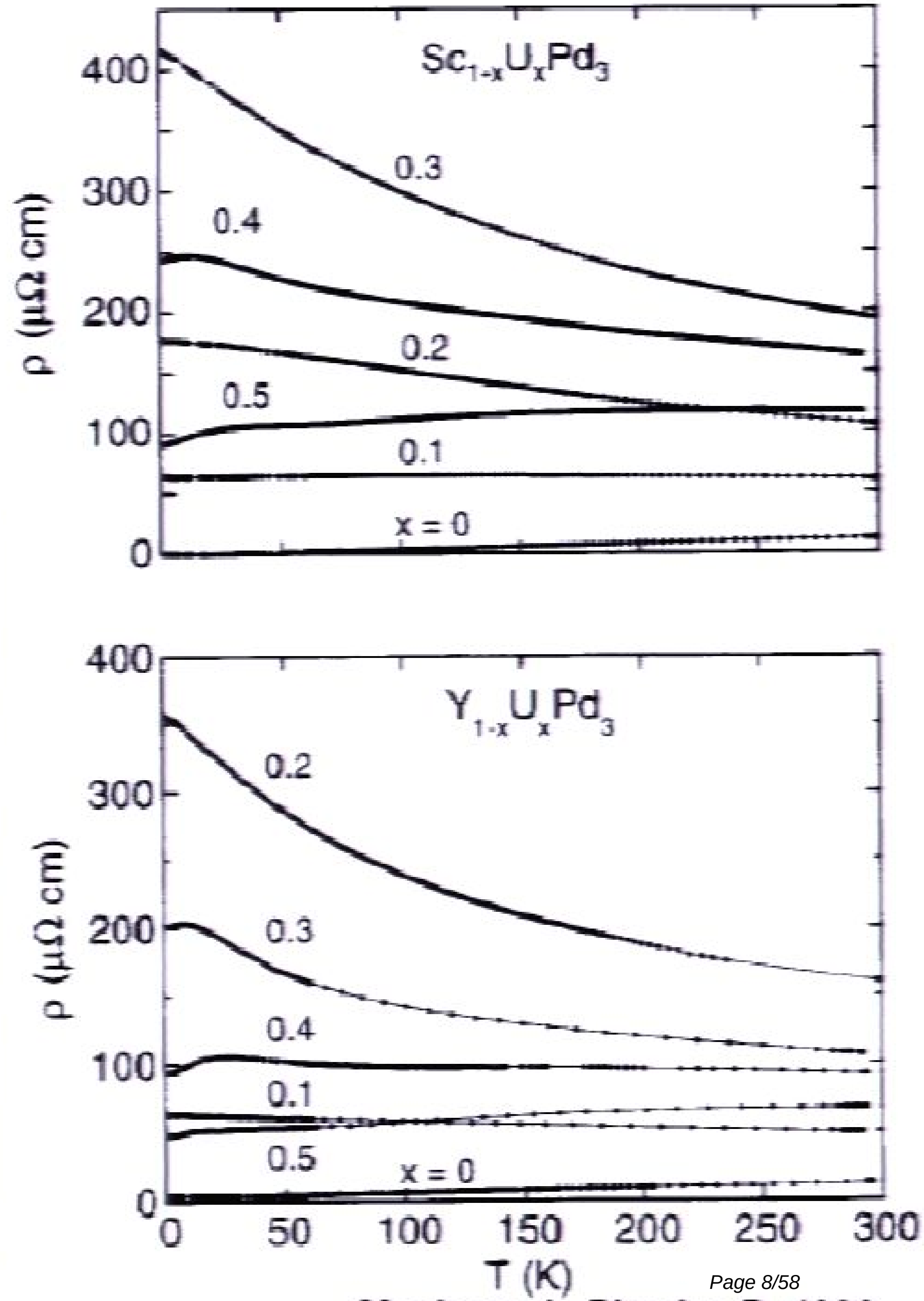
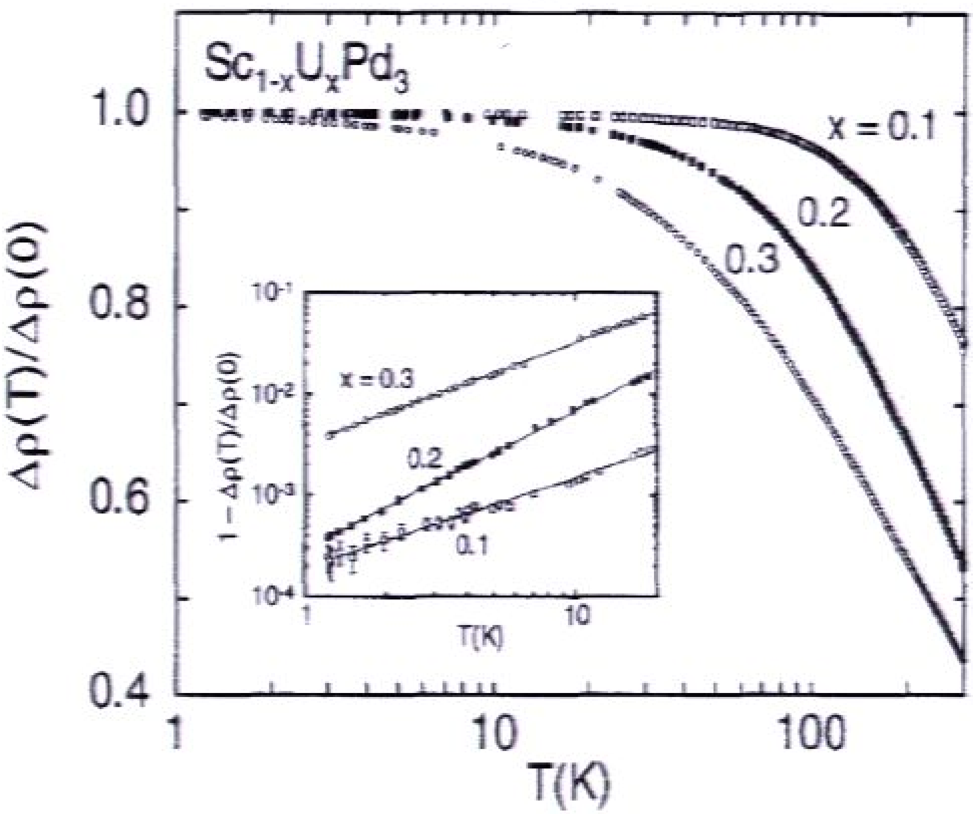




Maple et al., Physica B, 1996.

Evidence of Kondo and non-Fermi-liquid physics:



- ***Log(T/T$_o$) resistivity at high T***
- ***Linear resistivity at low T***

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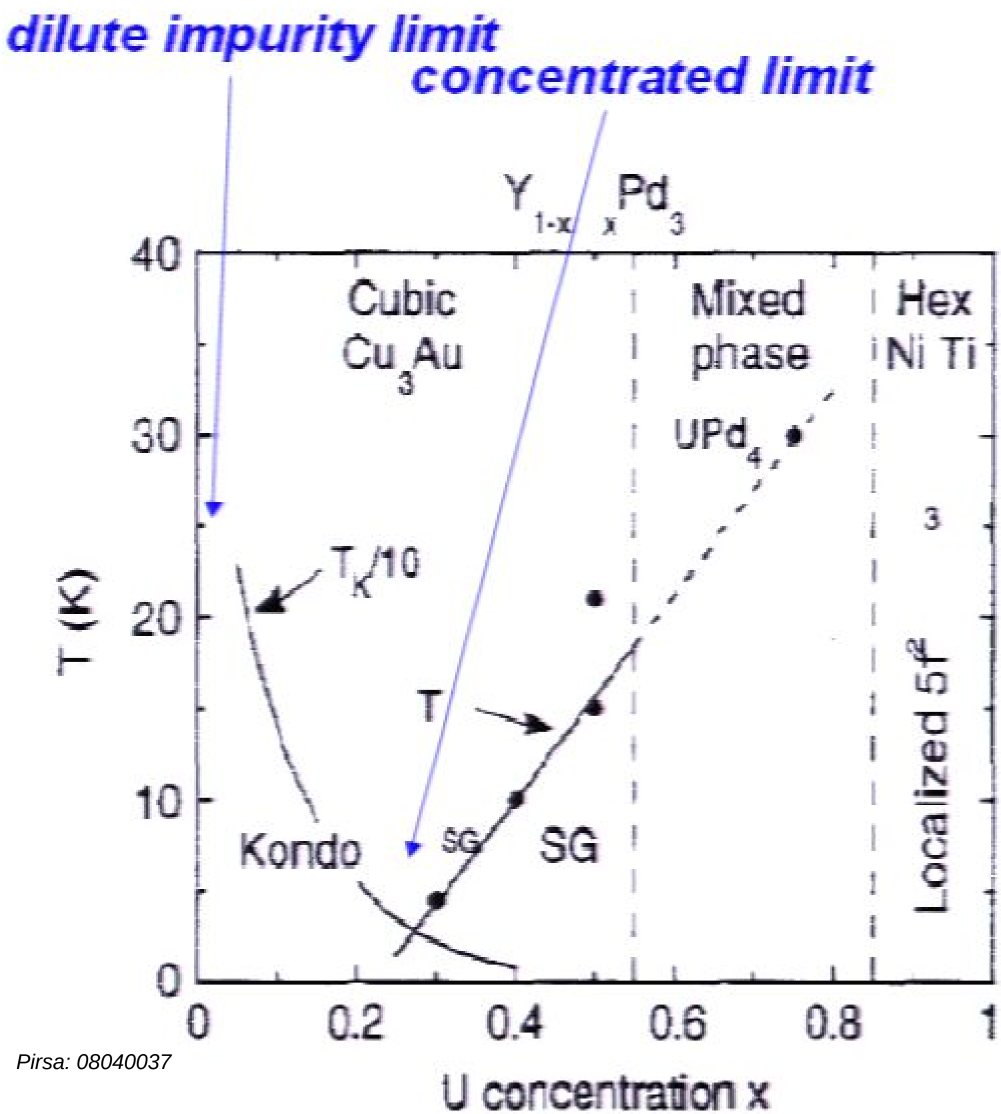

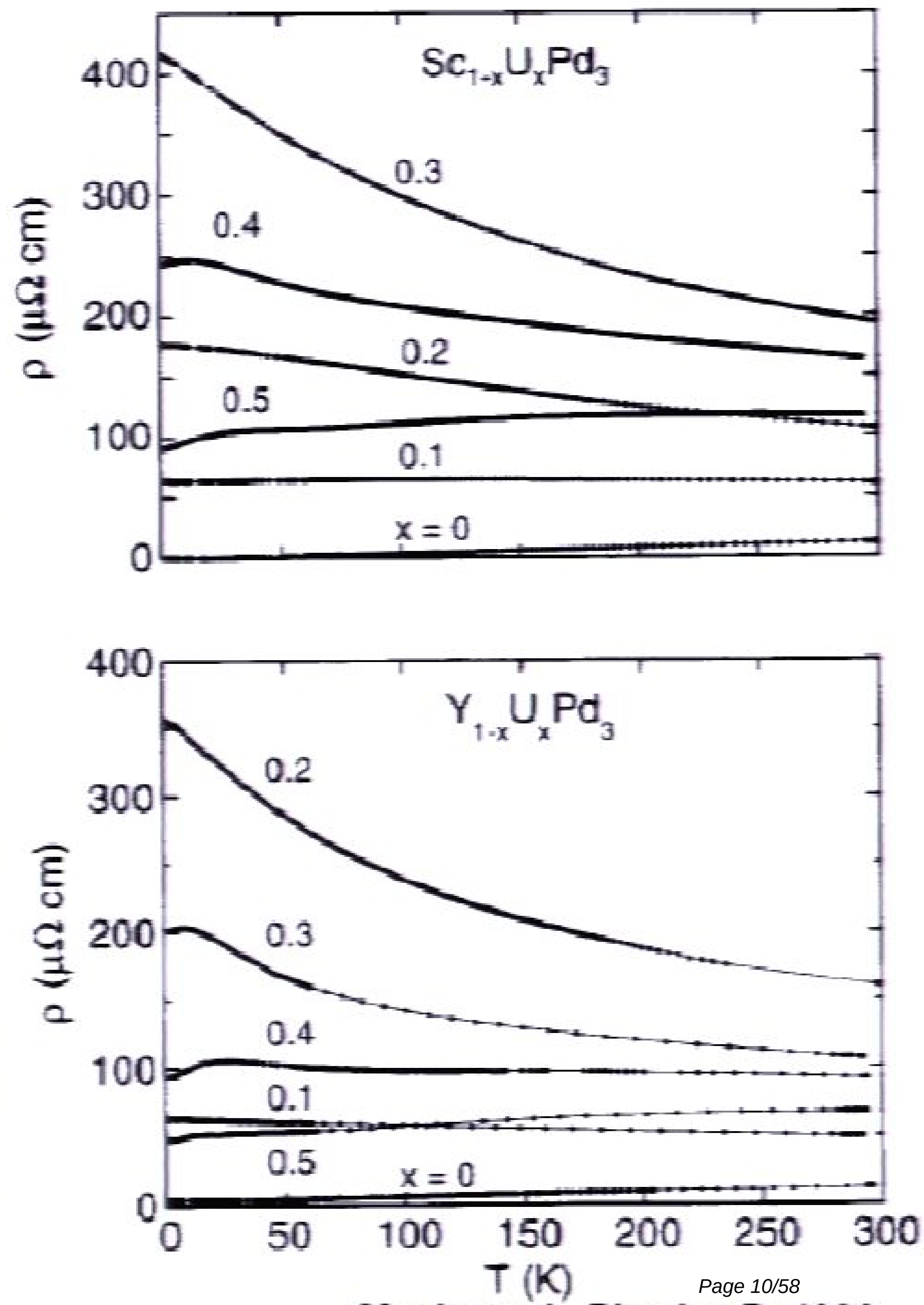

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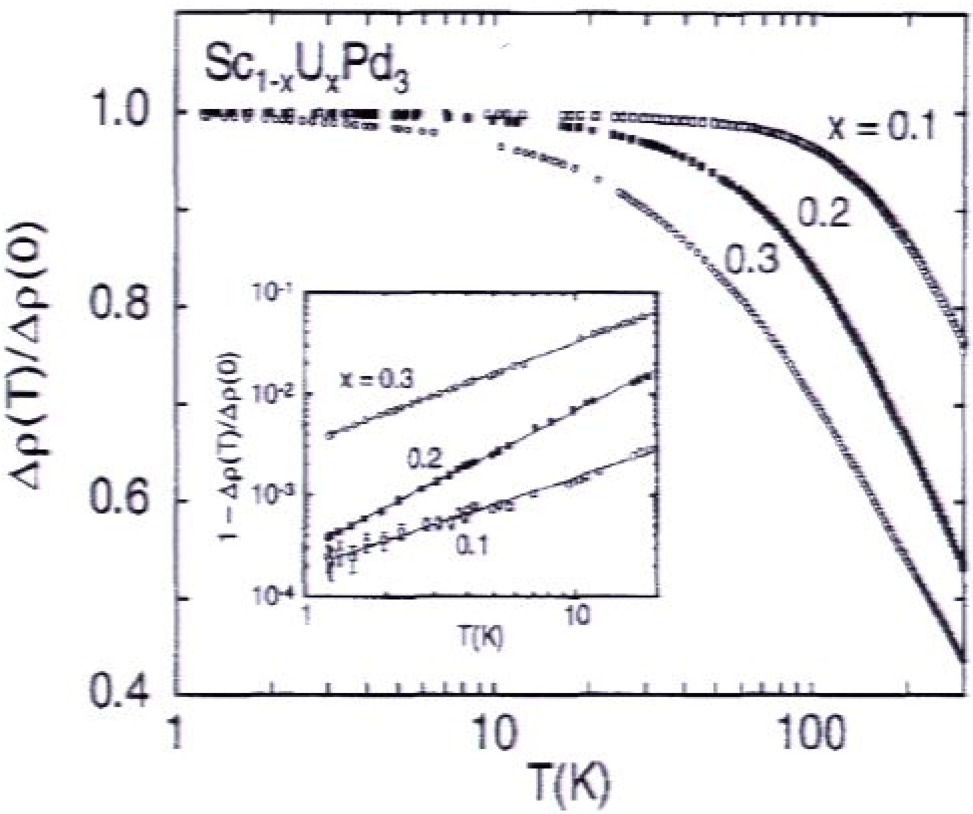
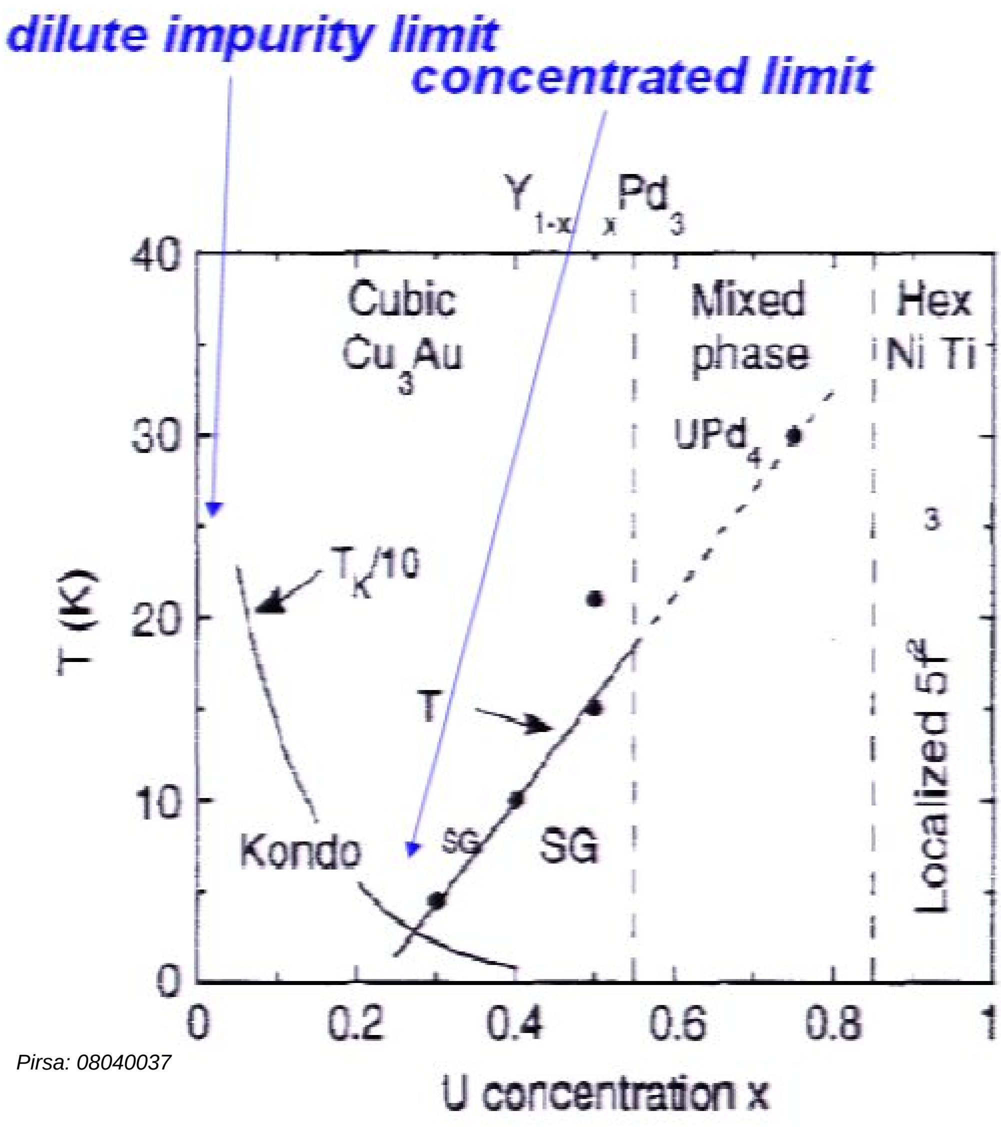
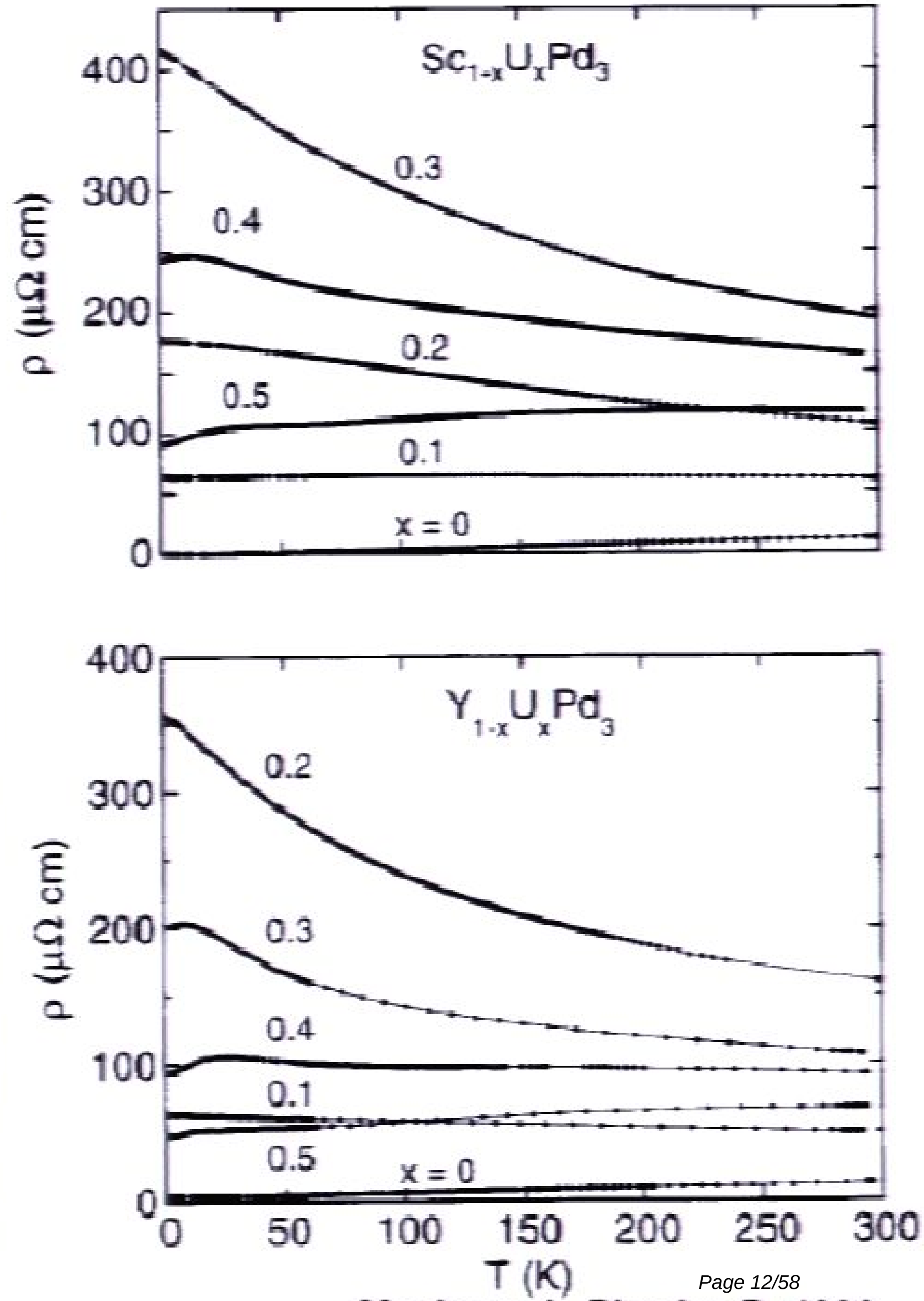


- *Log(T/T_o) resistivity at high T*
- *Linear resistivity at low T*

$M_{1-x}U_xPd_3$ (M=Y,Sc)





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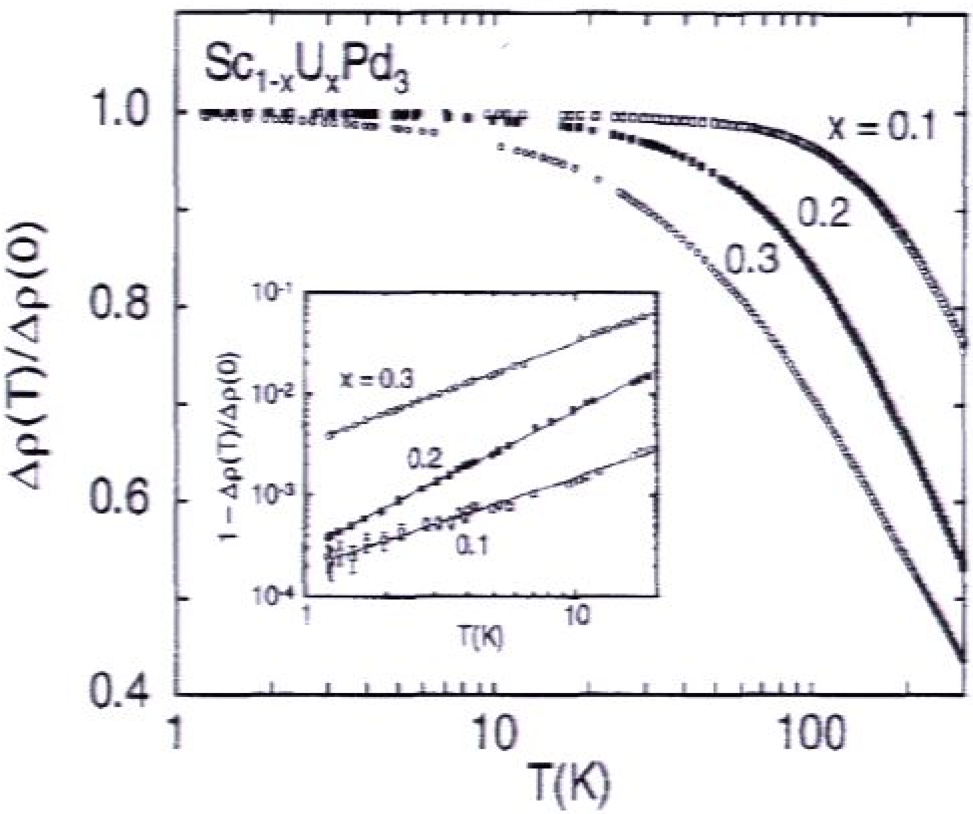
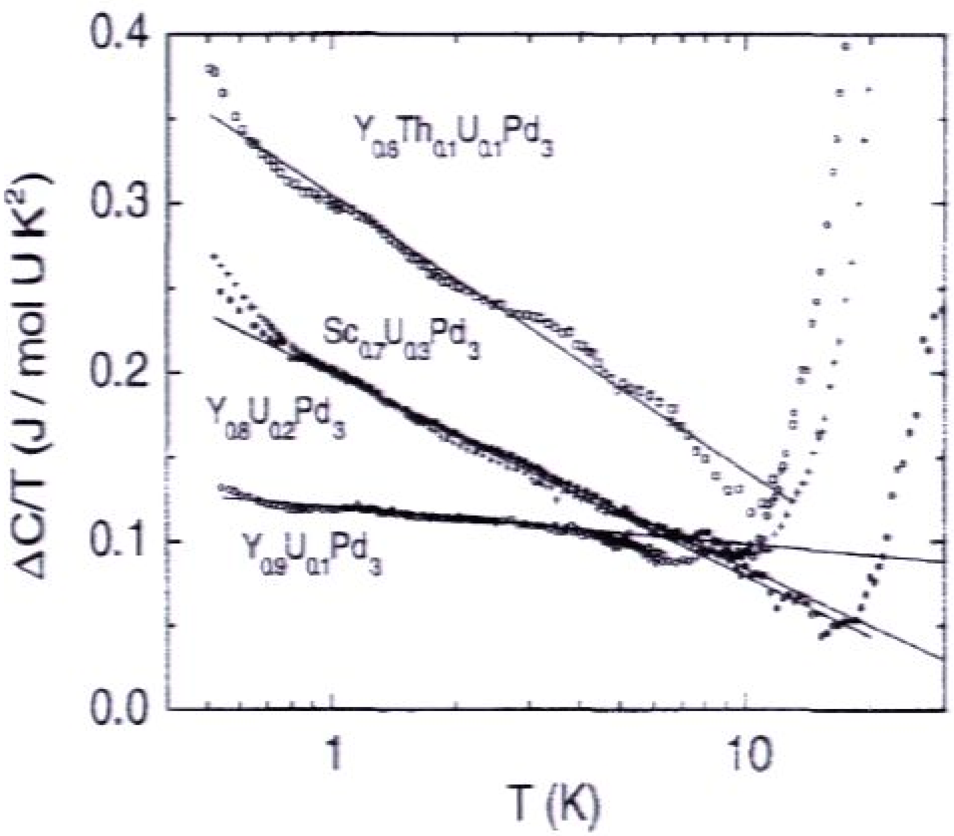


- $Log(T/T_o)$ *resistivity at high T*
- *Linear resistivity at low T*

Non-Fermi-liquid thermodynamic properties



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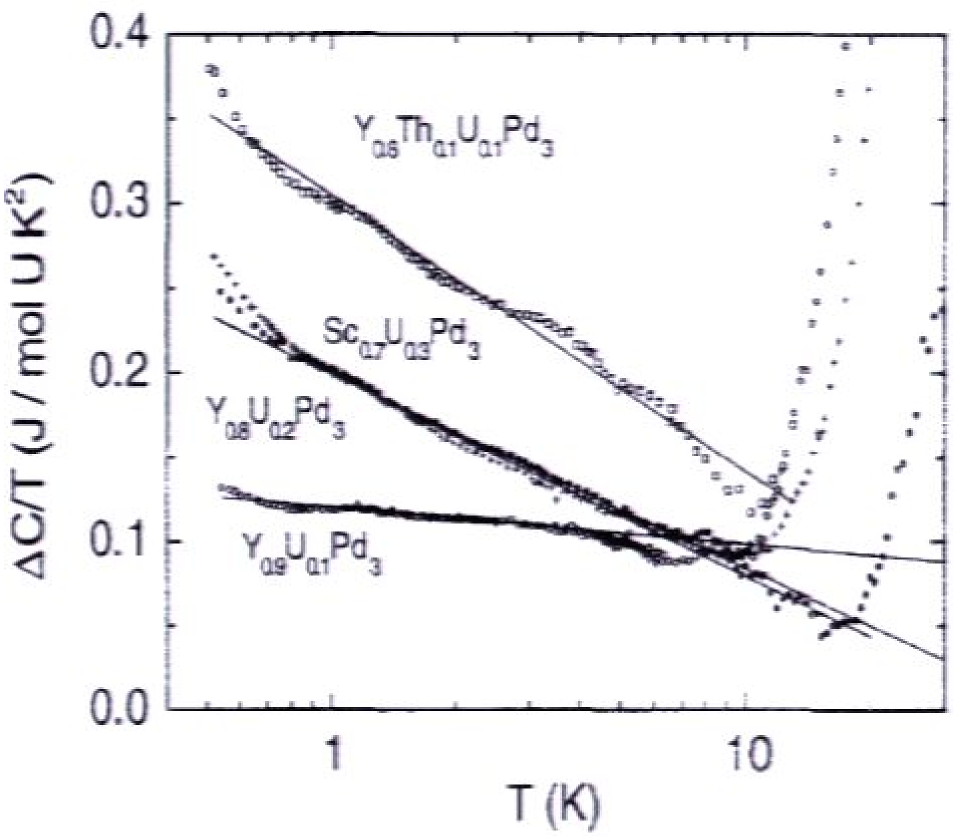
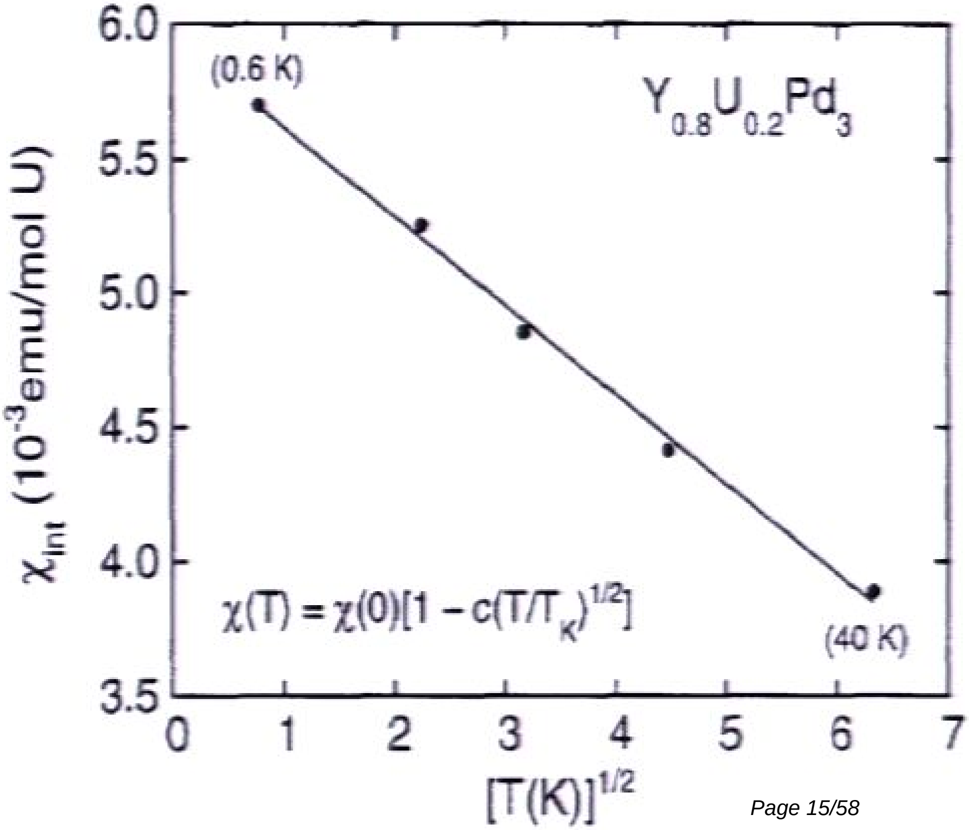
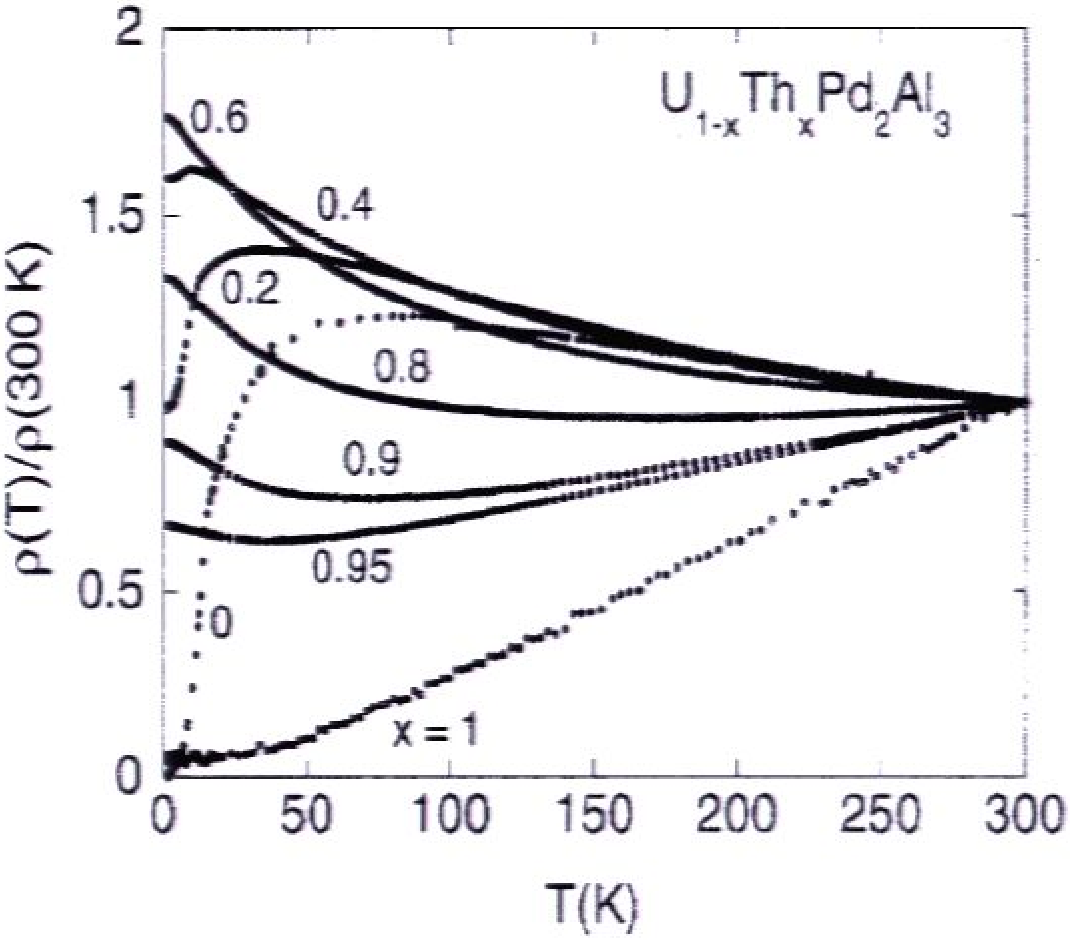
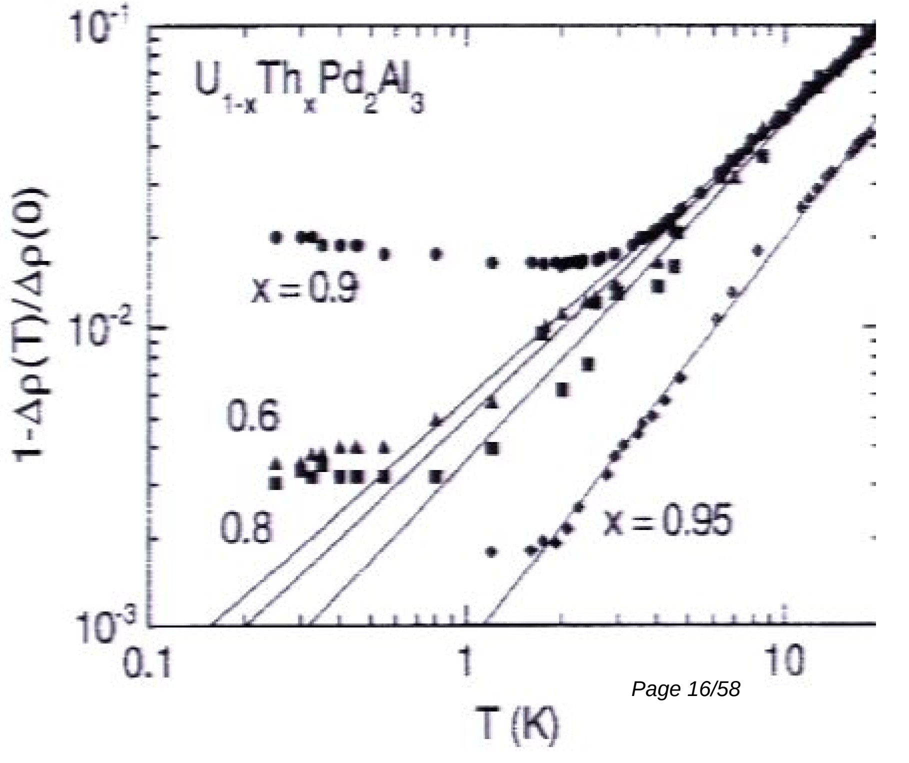


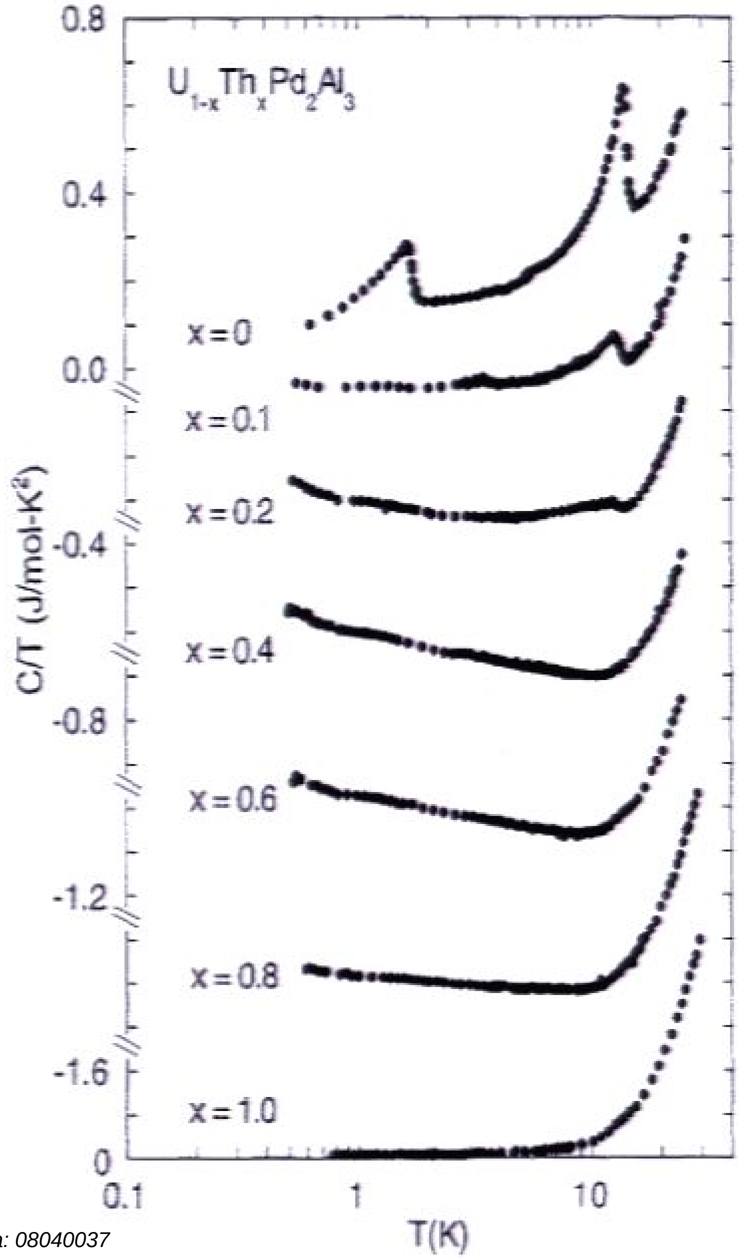


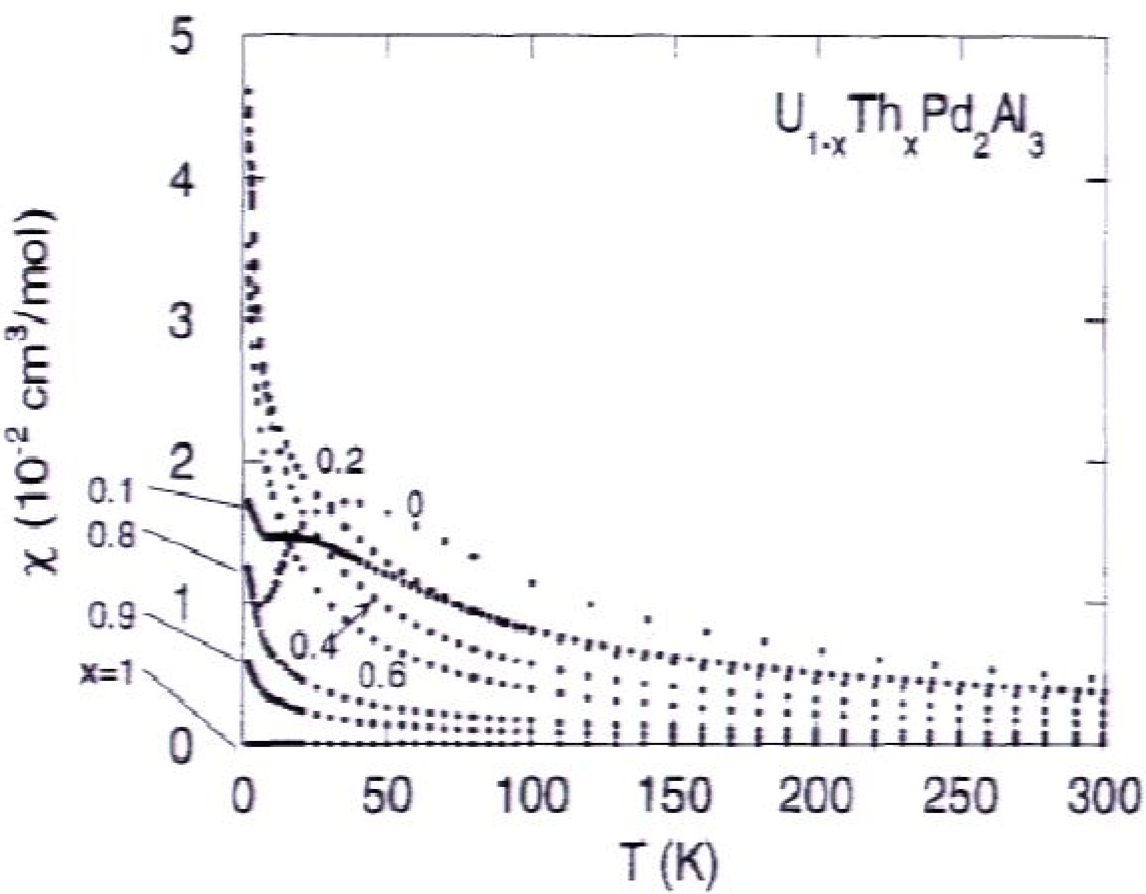
$U_{1-x}Th_xPd_2Al_3$





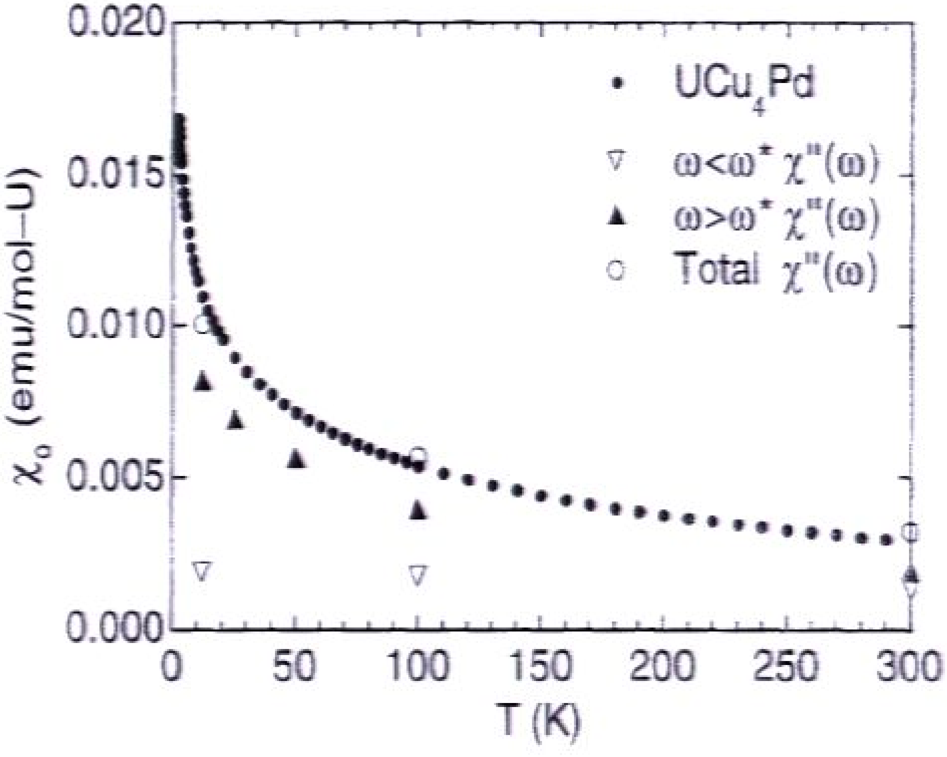
NFL thermodynamic properties





$UCu_{5-x}Pd_x$

- UCu5 has T_N = 15 K, T_K = 100 K
- $UCu_{3.5}Pd_{1.5}$ and UCu_4Pd have no long range order, and show the same NFL behaviour as $Y_{1-x}U_xPd_3$



Overview of NFL properties

Table 2. Examples of f-electron systems which exhibit characteristic non Fermi liquid behavior in the low temperature electrical resistivity $\rho(T) \sim 1 - aT/T_0$, specific heat $C(T)/T \sim (-1/T_0)\ln(T/bT_0)$, and magnetic susceptibility $\chi(T) \sim 1 - c(T/T_0)^{1/2}$.

System	ρ	C/T	χ	T_0^* (K)
$La_{0.9}Ce_{0.1}Cu_2Si_2$	yes	yes	—	9
$M_{1-x}U_xPd_3$ (M = Sc, Y)	yes	yes	yes	40-220
$UCu_{3.5}Pd_{1.5}$	yes	yes	yes	28
$U_{1-x}Th_xPd_2Al_3$	yes	yes	yes	20
$M_{0.1}U_{0.9}Ni_2Al_3$ (M = Pr, Th)	—	yes	yes	200
$Ce_{1-x}Th_xRhSb$	—	yes	—	33
$Th_{1-x}U_xRu_2Si_2$	(a<0)	yes	$-\ln(T/bT_K)$	11
$U_{0.9}Th_{0.1}Be_{13}$	(a<0)	yes	yes	8
$CeCu_{5.9}Au_{0.1}$	(a<0)	yes	yes	3.5

*Deduced from the slope $A = d(C/T)/d\ln T$ of the logarithmic divergence in the specific heat: $T_0 = -0.251R/A$

Maple et al. JLTP 1995

Summary:

- These doped systems, both dilute and concentrated show:

$$\rho(T) = \rho_0 - AT^1$$

$$\chi(T) = \chi_o(1 - c\sqrt{T / T_K})$$

$$C(T)/T = -\ln(T / T_K)$$

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$$\rho(T) = \rho_0 - AT^1$$

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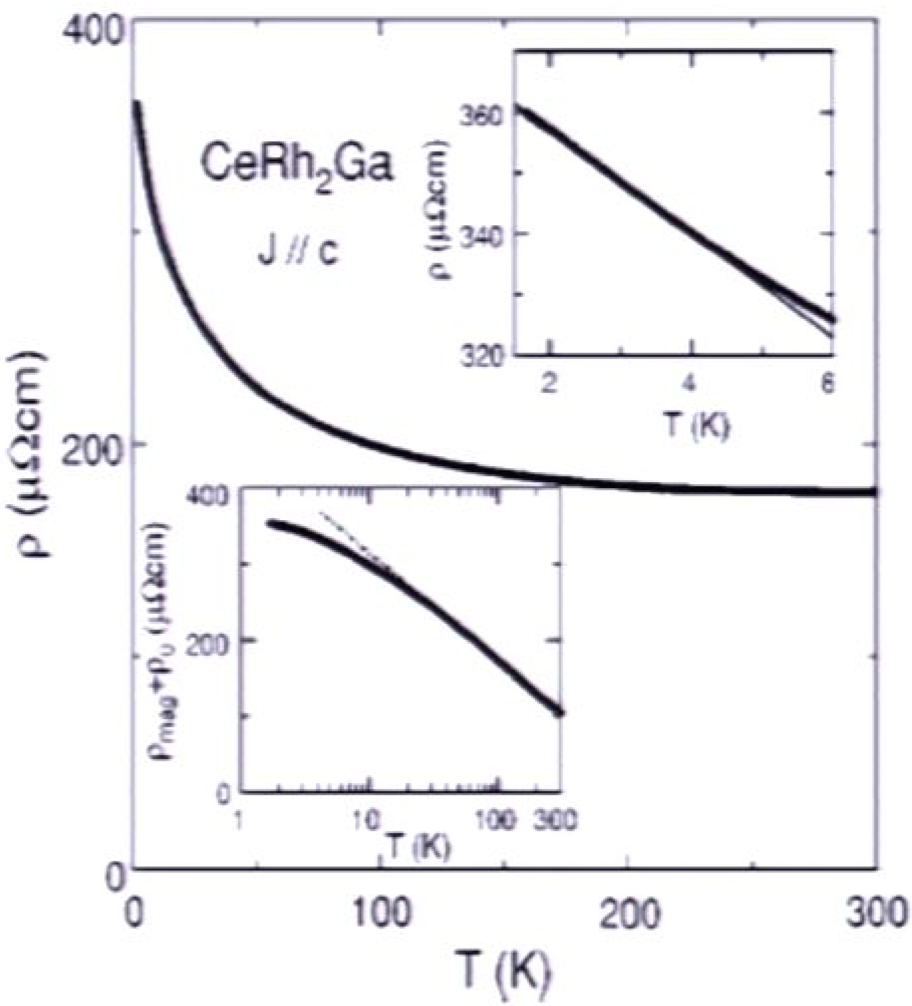
$$C(T)/T = -\ln(T / T_K)$$

(note that it is difficult to establish these asymptotic behaviours very precisely)

Role of disorder in concentrated systems?

- Until recently, all of the concentrated NFL "non-metallic" systems had high levels of disorder (this may still be true)
- A long-standing model has been Griffiths phase physics (Castro-Neto; Sachdev; Millis, Morr and Schmalian)
- Even stoichiometric materials are interpreted this way:

$CeRh_2Ge$



Hexagonal crystal structure.
Considerable site disorder.

Chen et al., PRB 2004.

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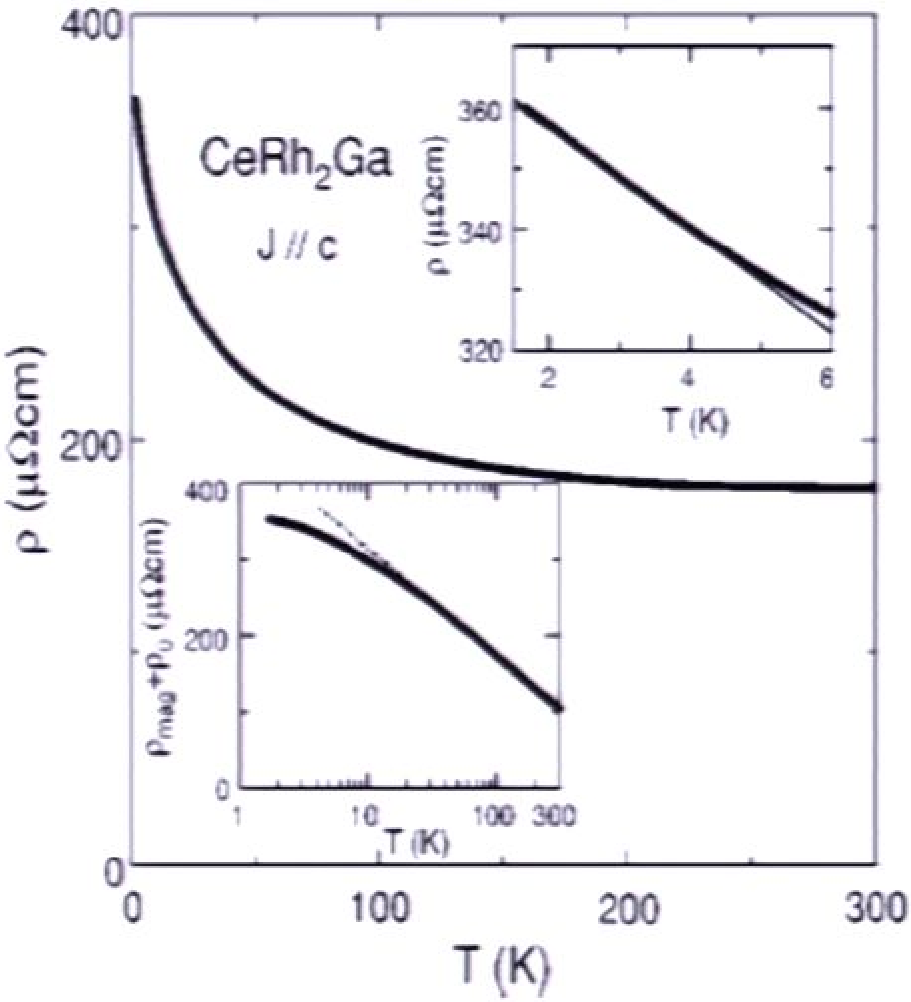

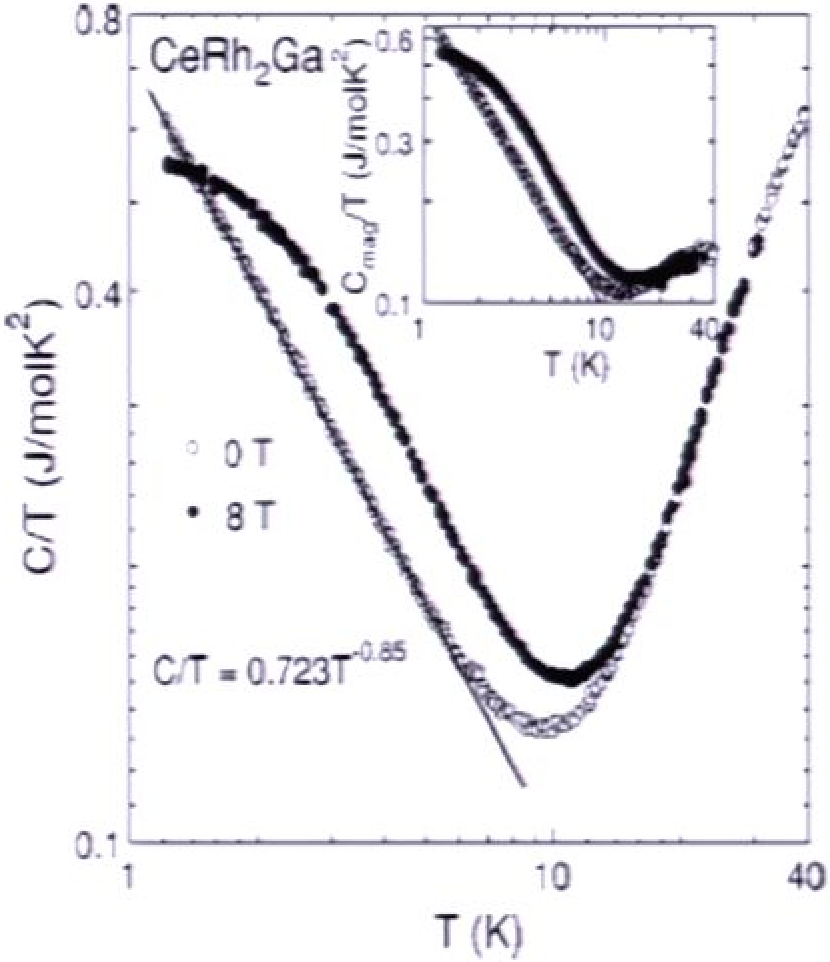

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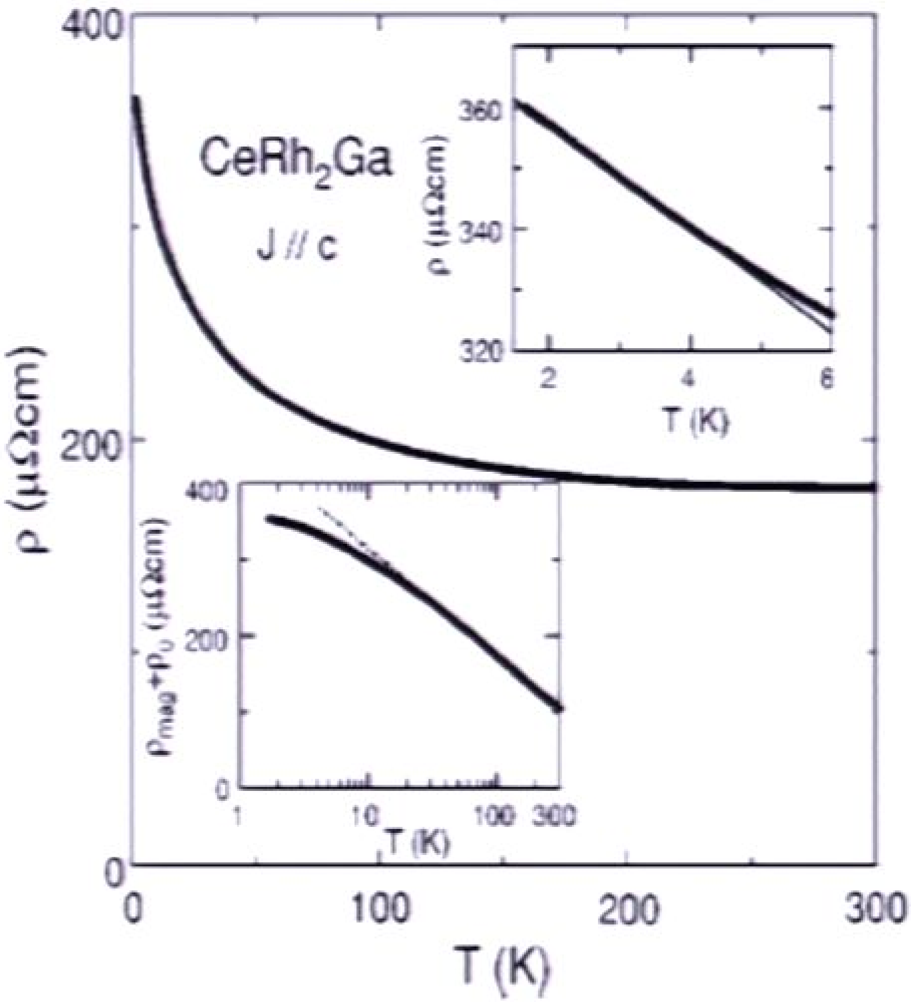

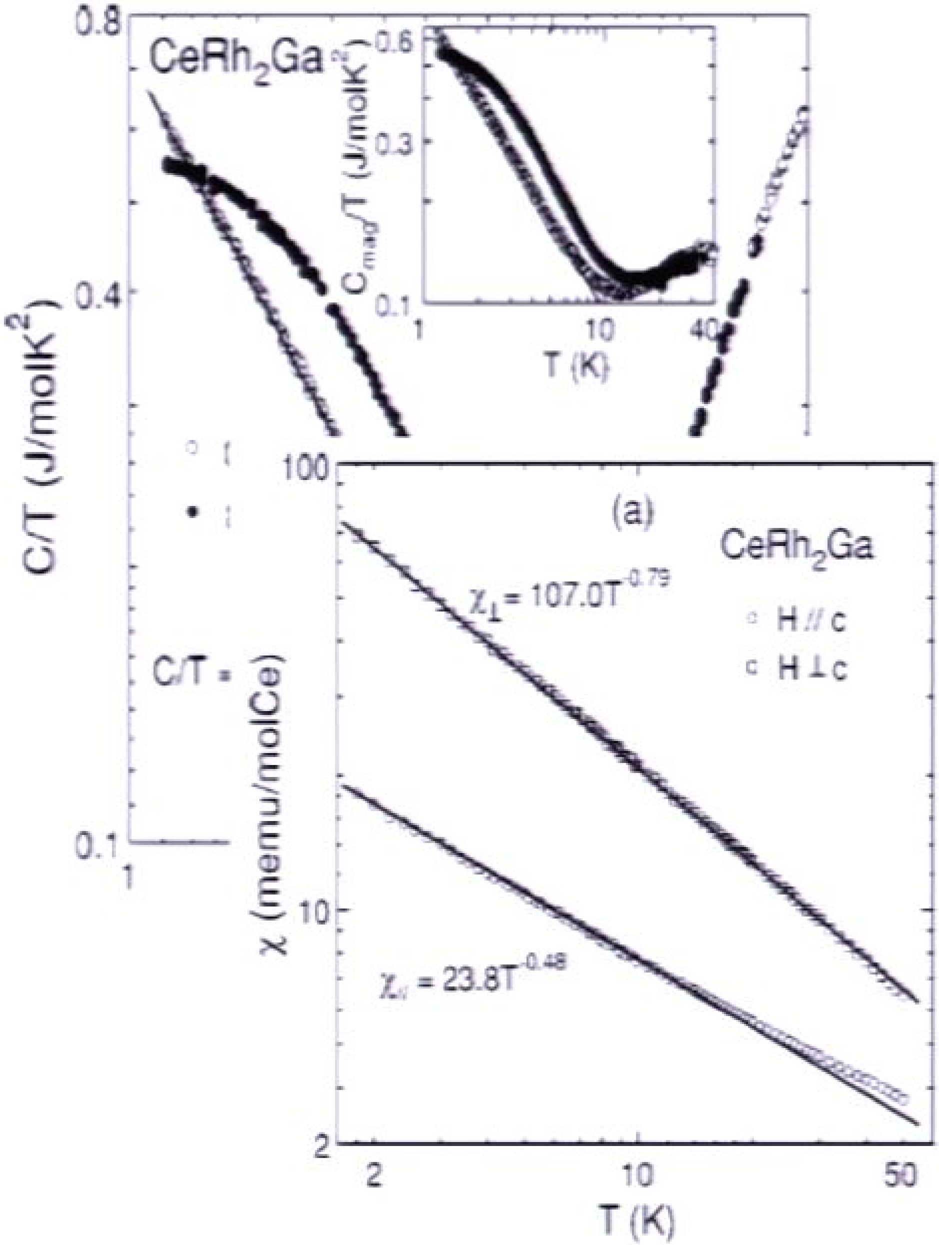

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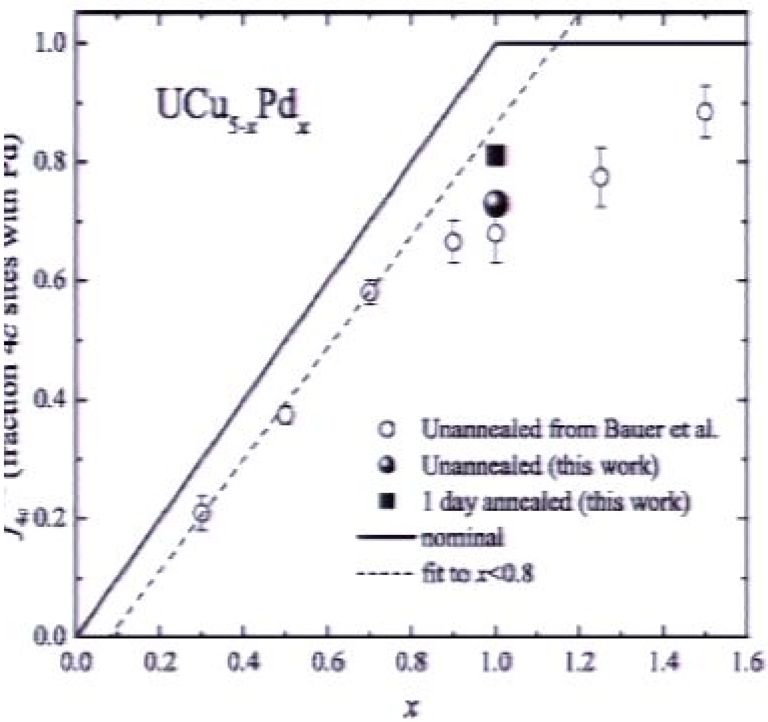
Disorder effects in concentrated systems



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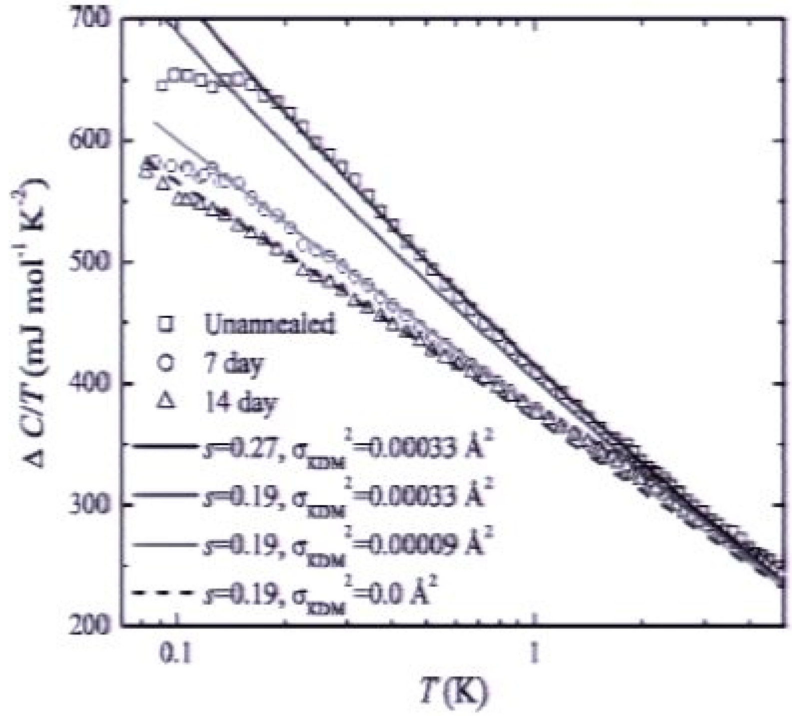

Effect of annealing on UCu_4Pd.

Otop et al, PRB 2008.

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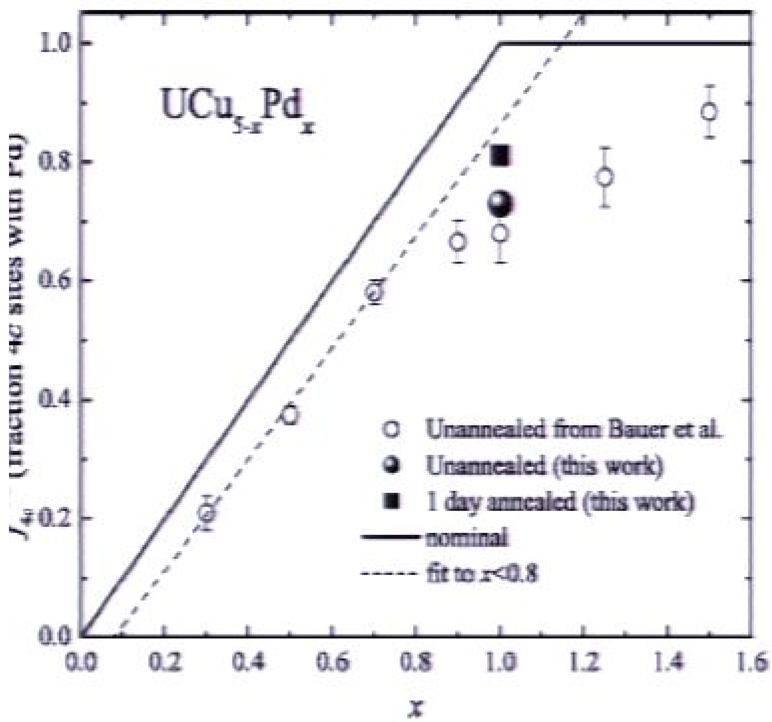

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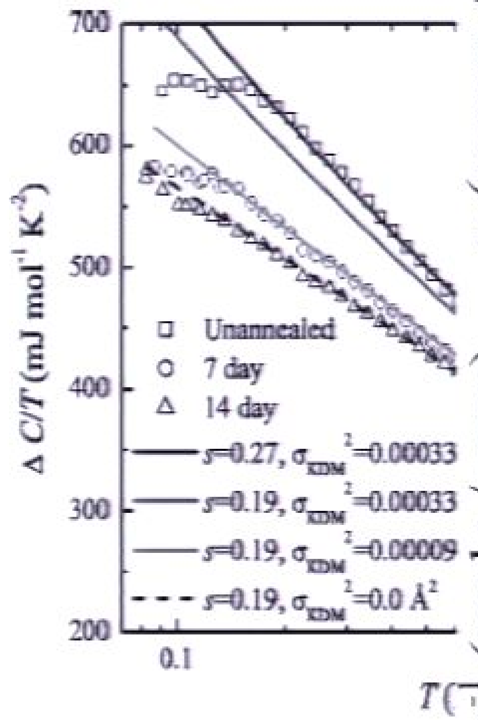

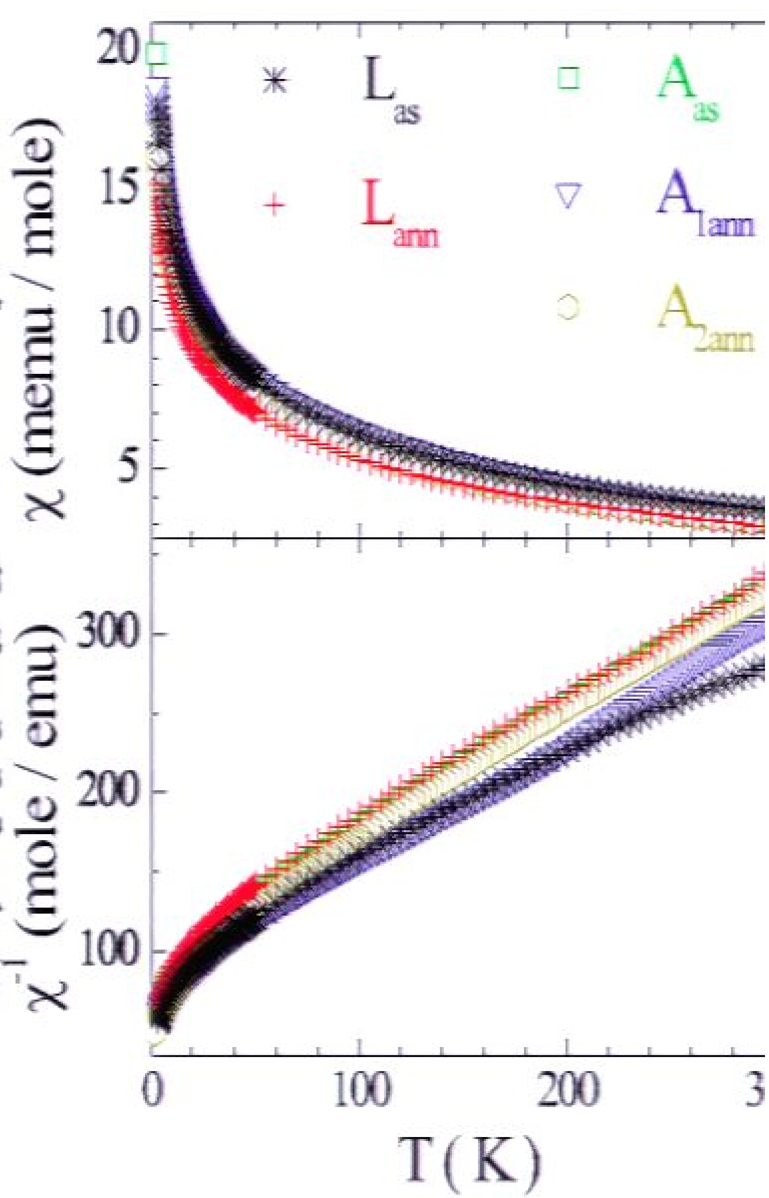

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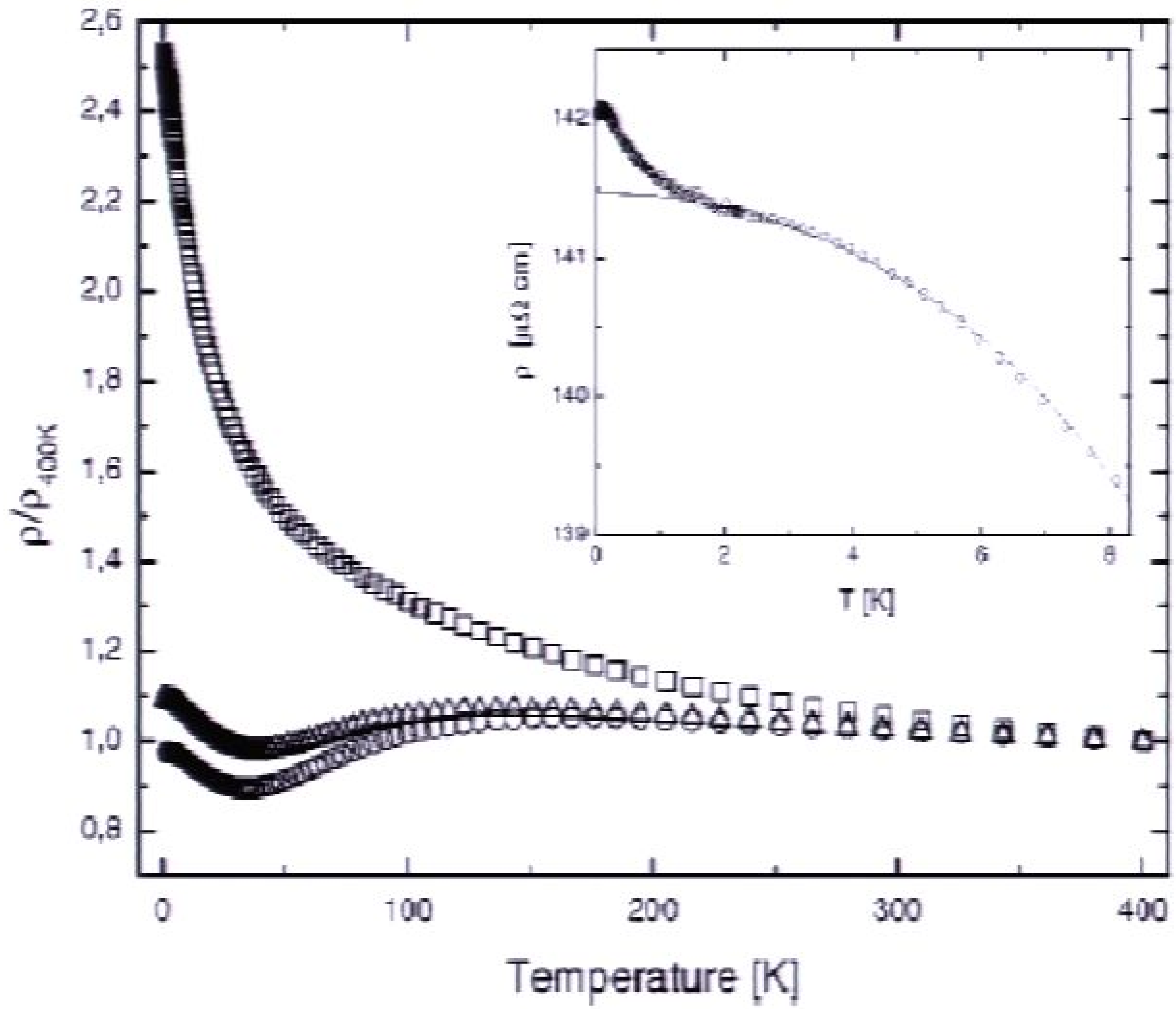
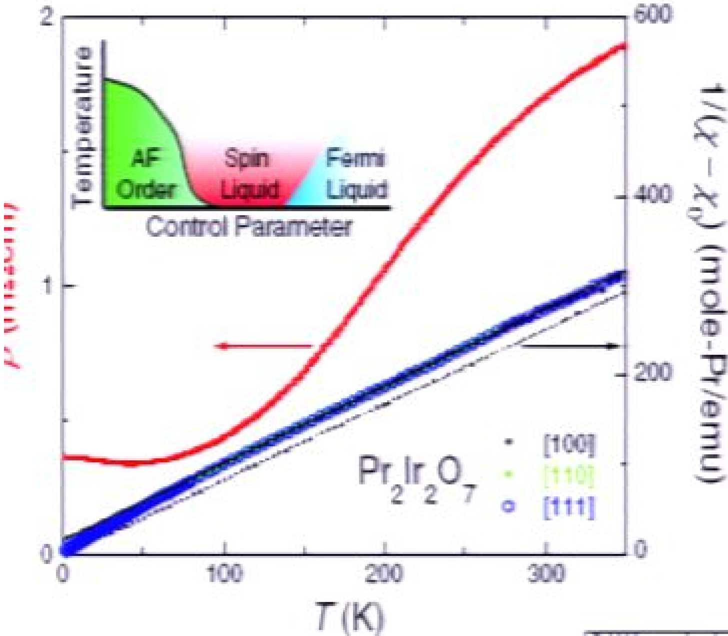
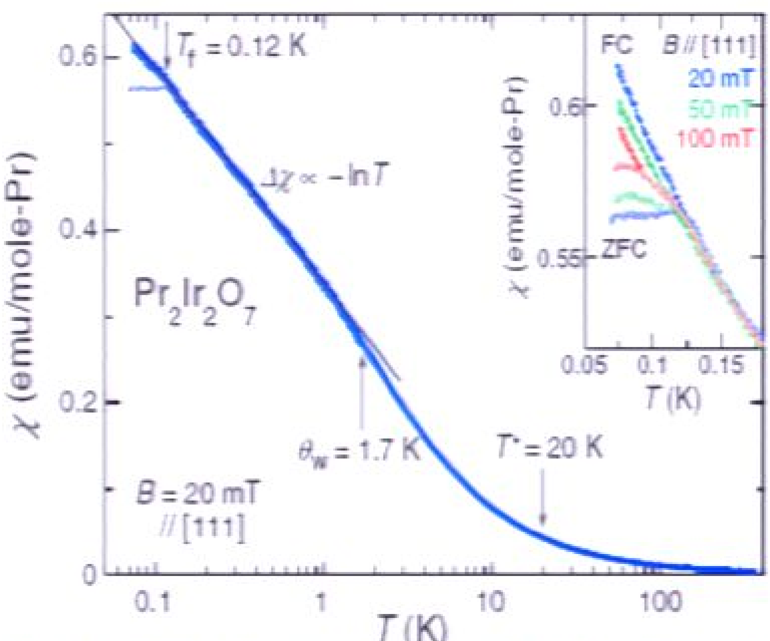
UCu$_4$Pd: effect of annealing on ρ vs T

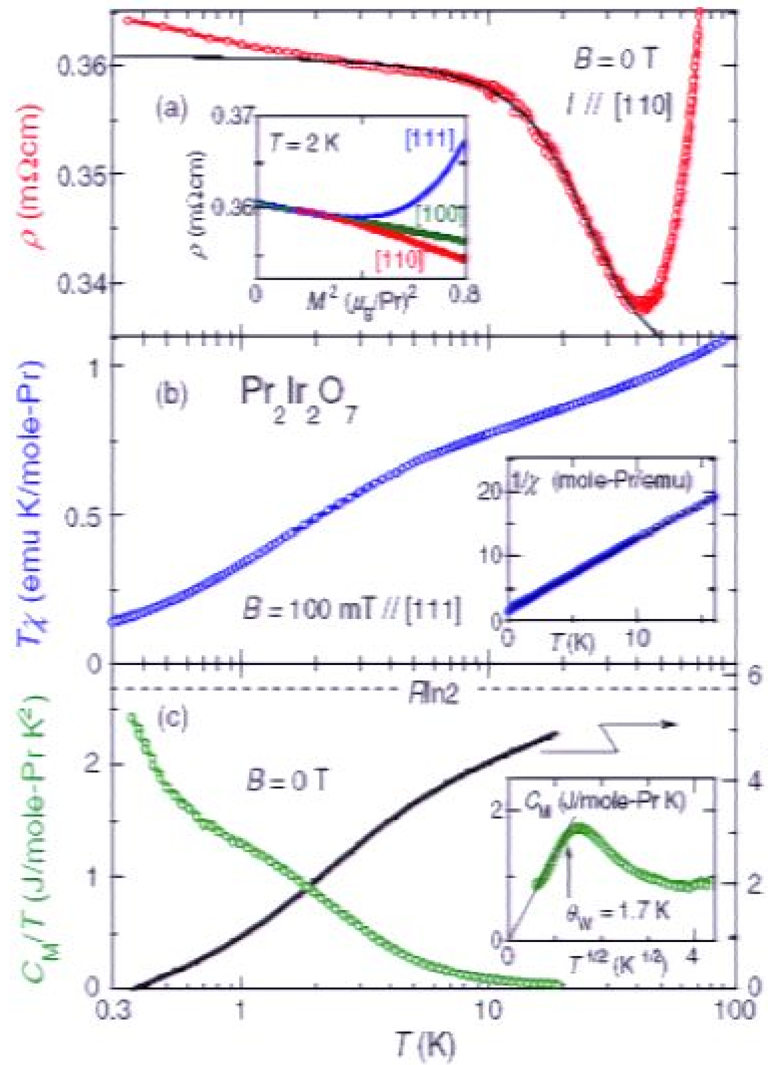


Weber et al., PRB, 2001.

A highly pure concentrated system: $PrIr_2O_7$







Nakatsuji et al., PRL 2006, geometrically frustrated (pyrochlore) lattice

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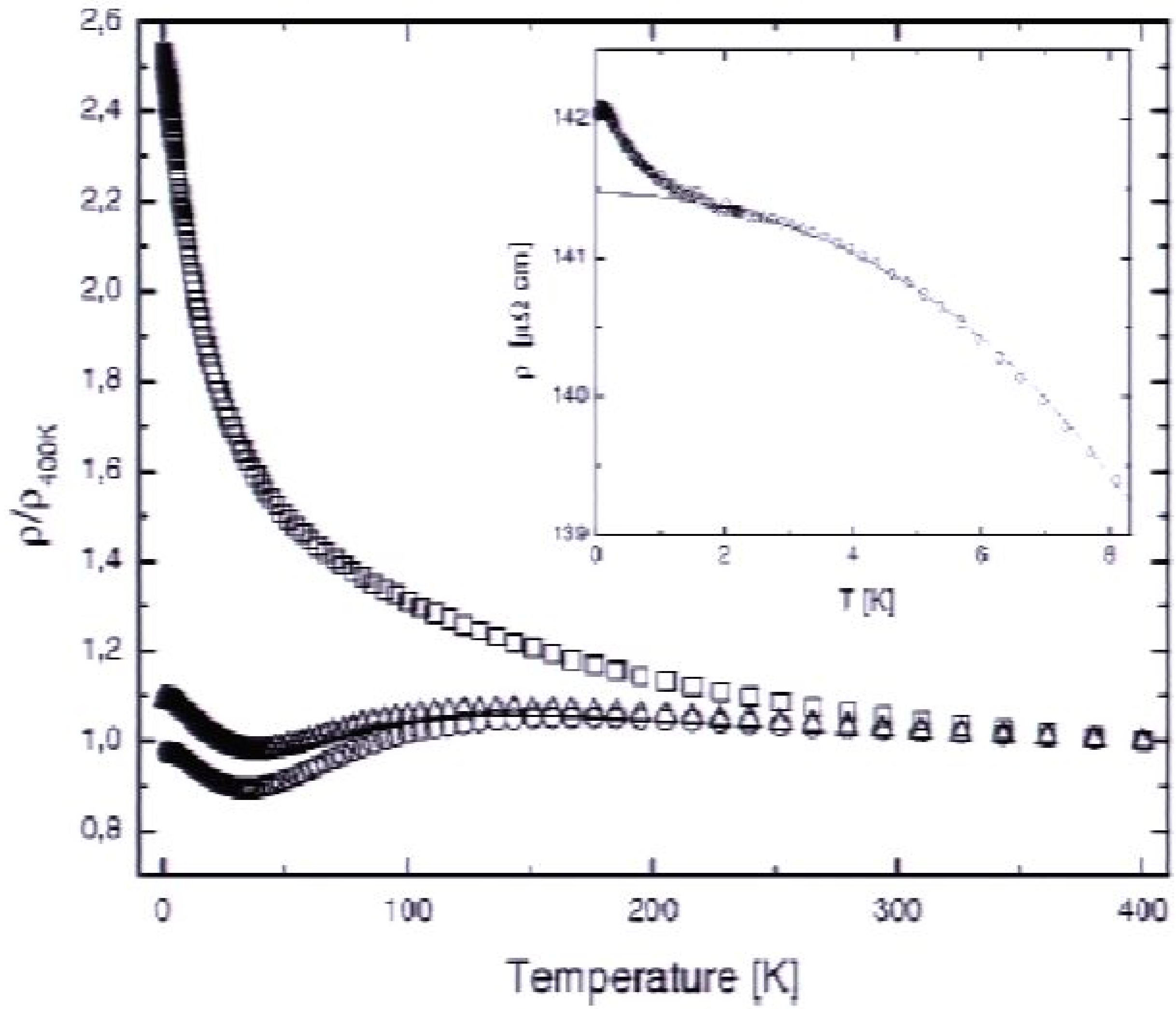

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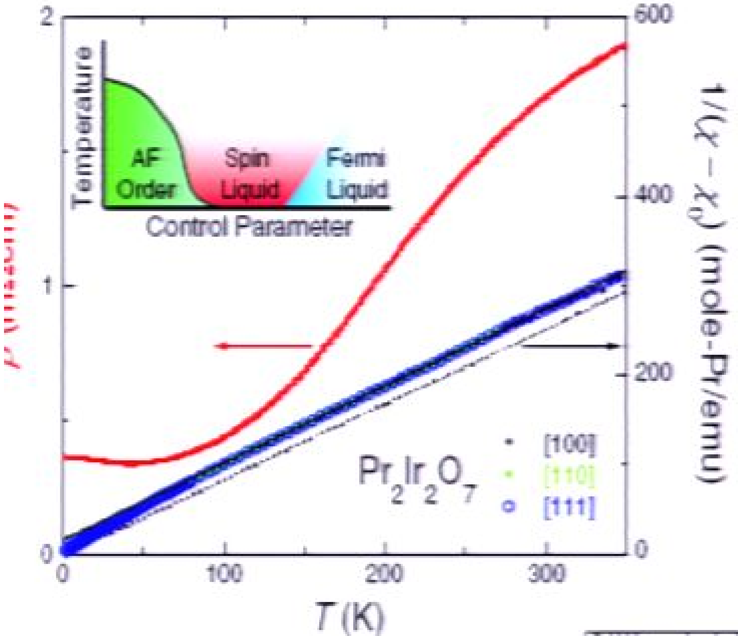

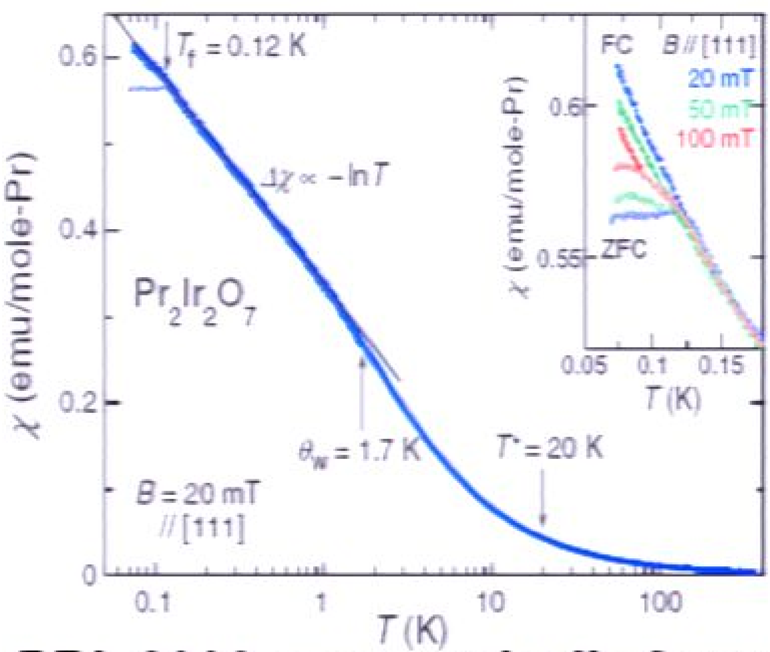

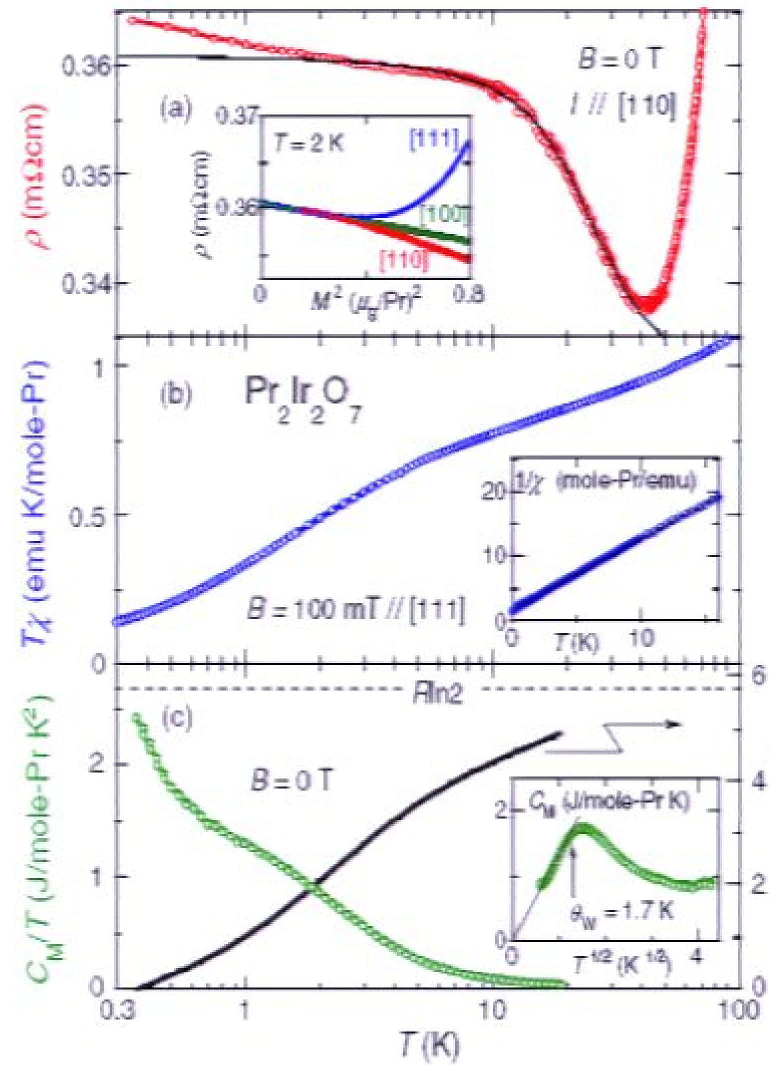

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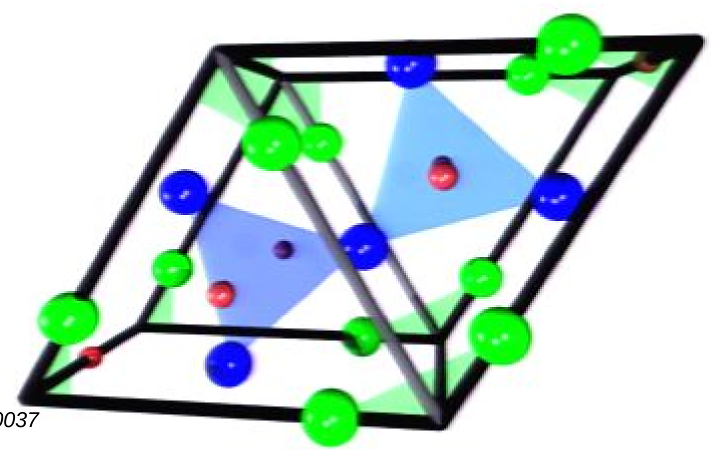
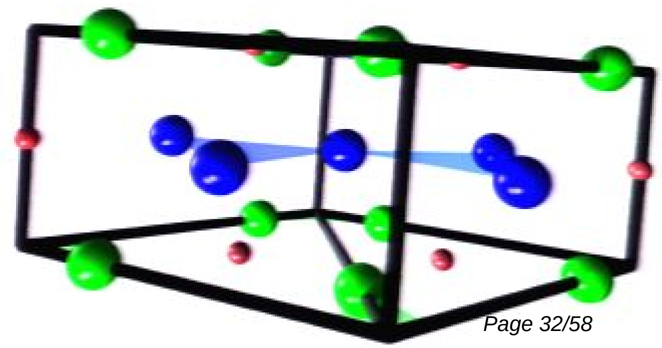
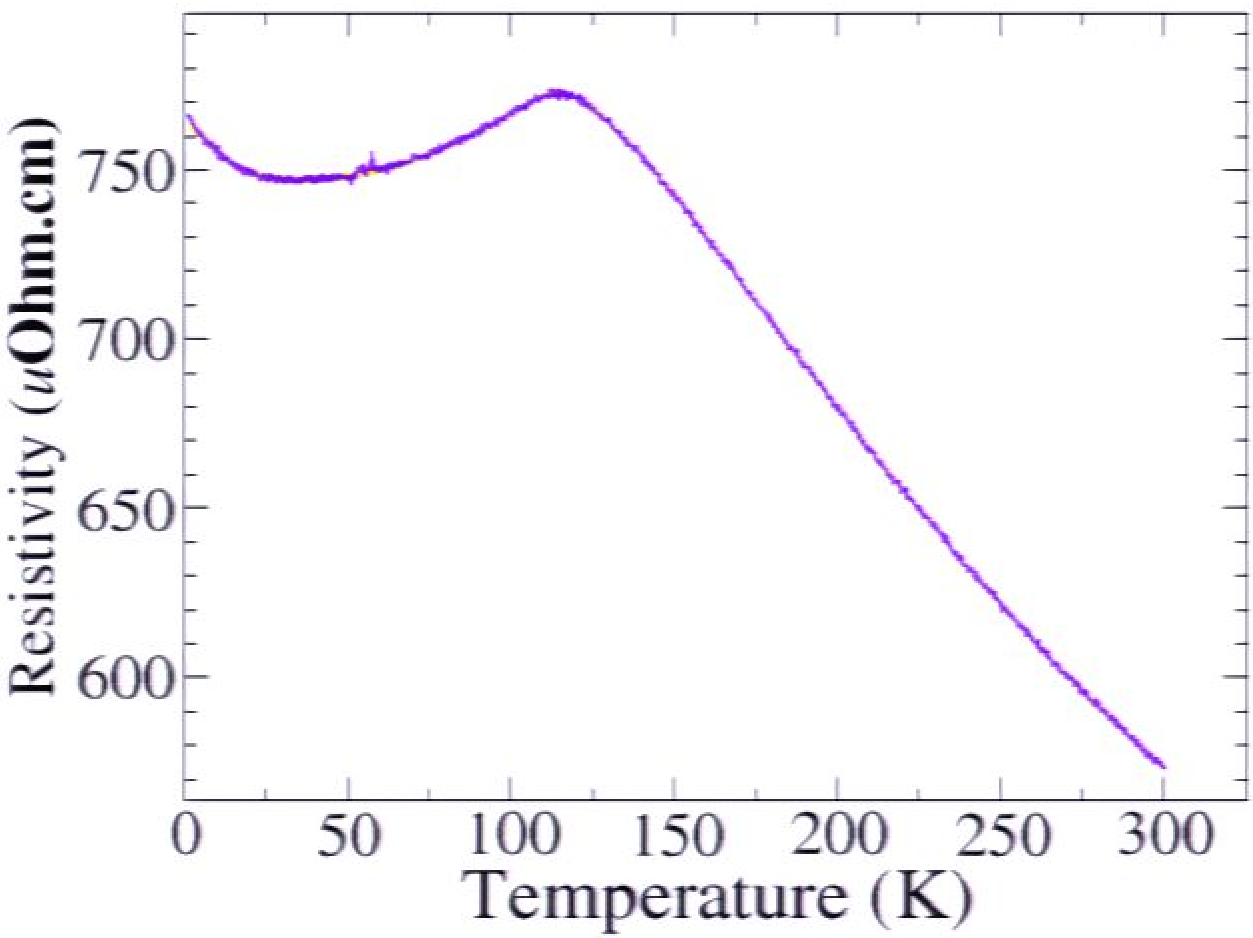
FeCrAs: background

- FeCrAs is a hexagonal (Fe_2P) member of a large ternary monopnictide family
- Most members are tetragonal, and order antiferromagnetically above room temperature
- Early (unpublished) Mossbauer work suggested no magnetic order down to 4.2K in FeCrAs





Resistivity of polycrystalline FeCrAs (magnetic sample)



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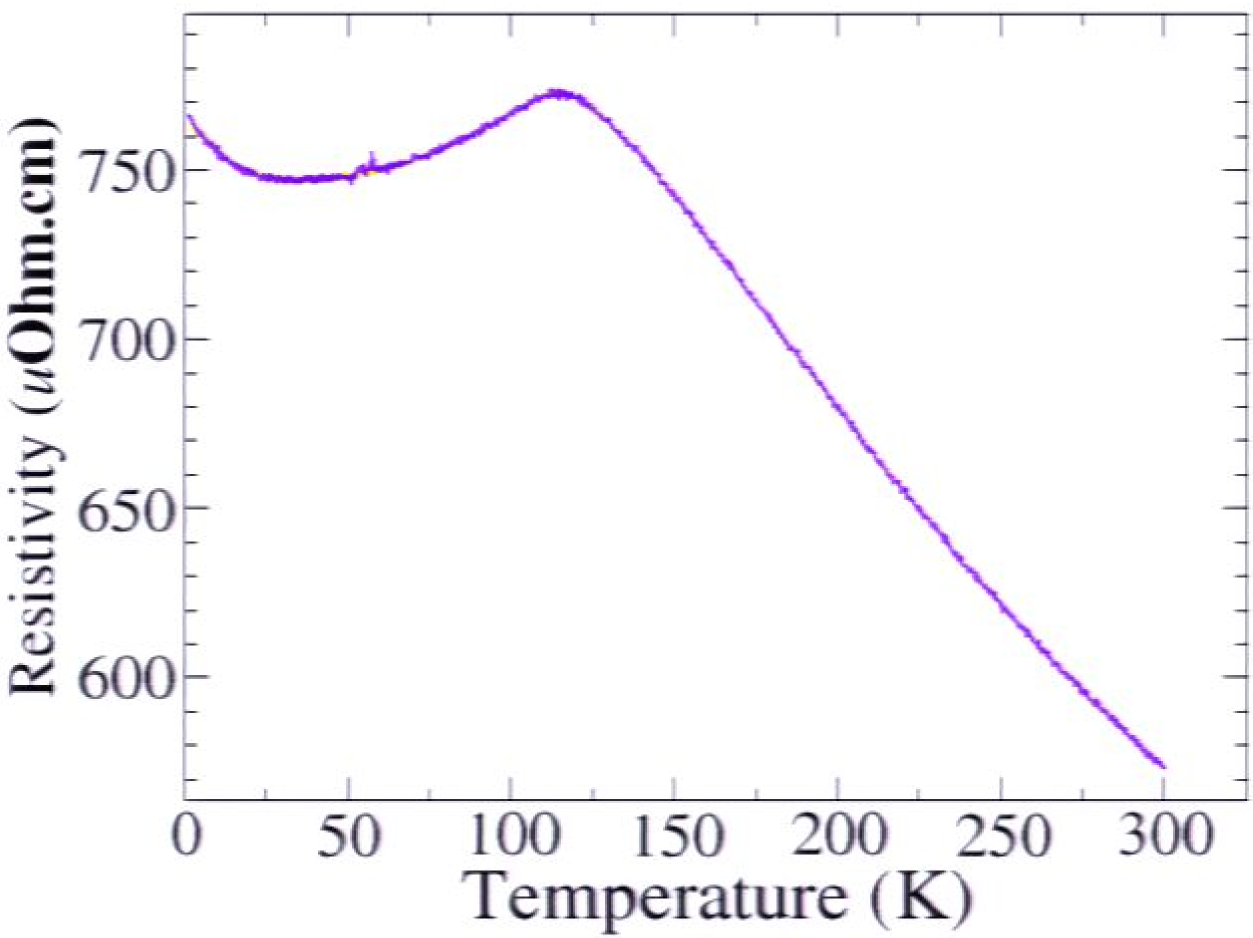
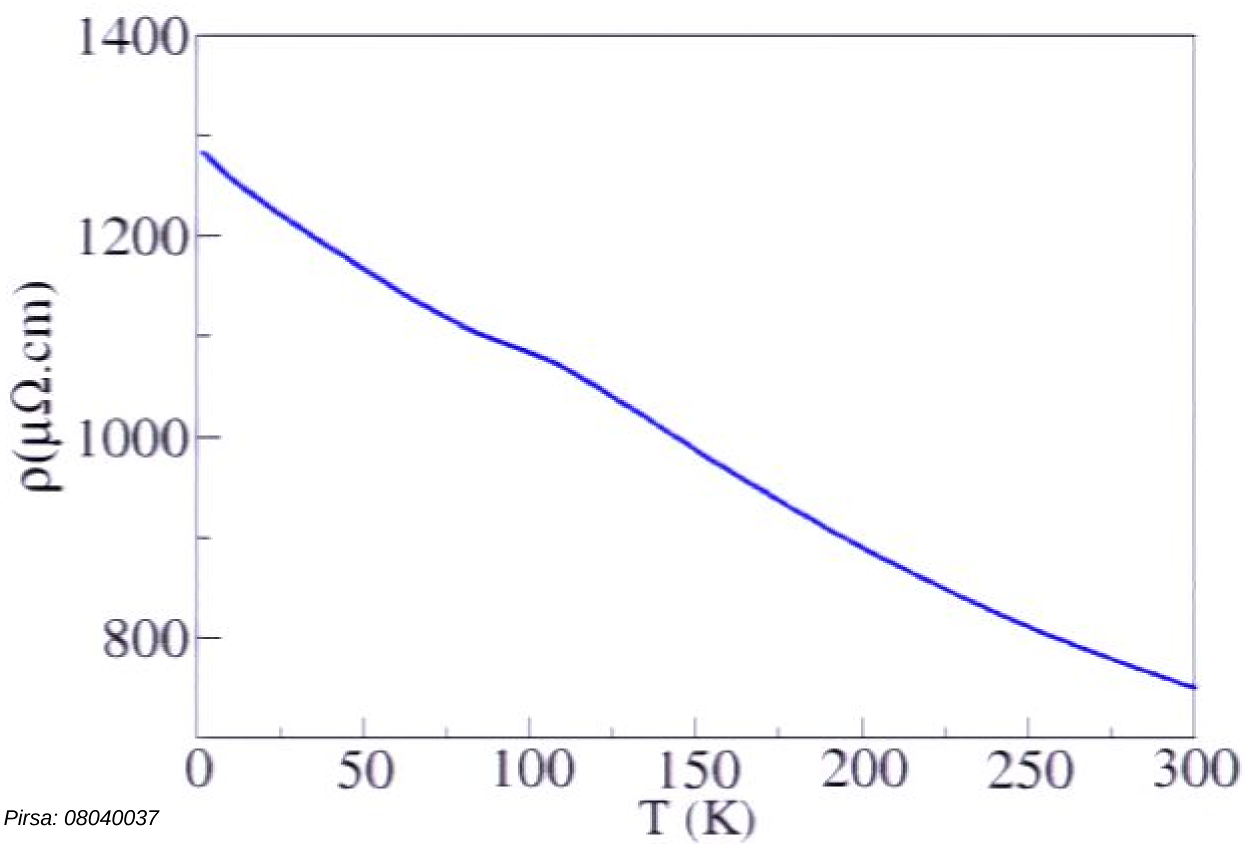


Single crystal FeCrAs: In-plane resistivity and magnetoresistance



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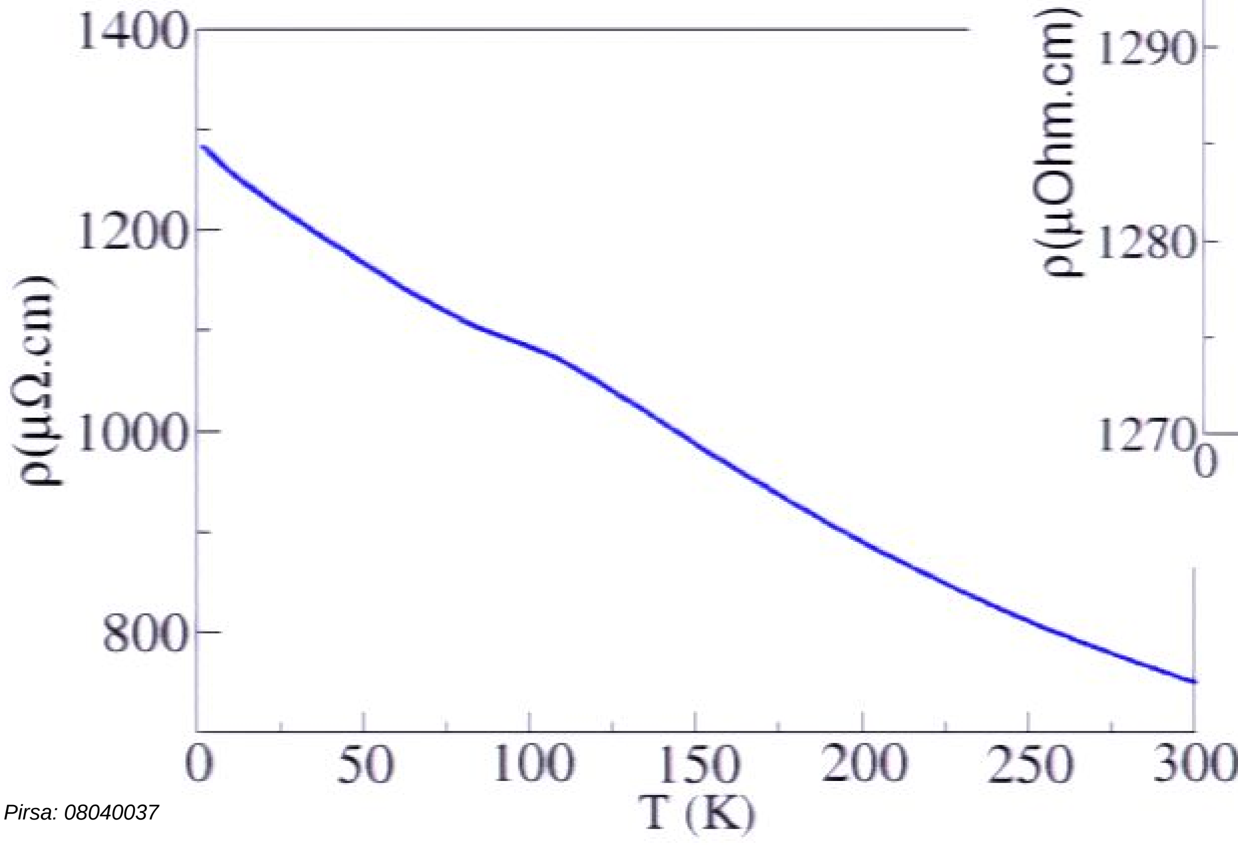
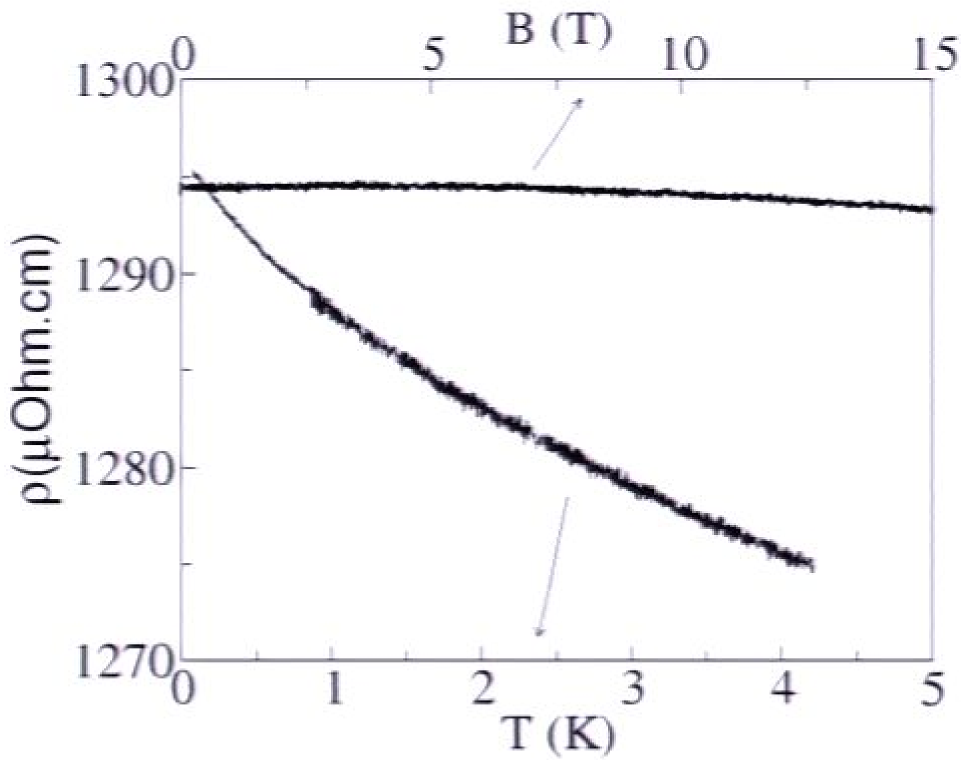
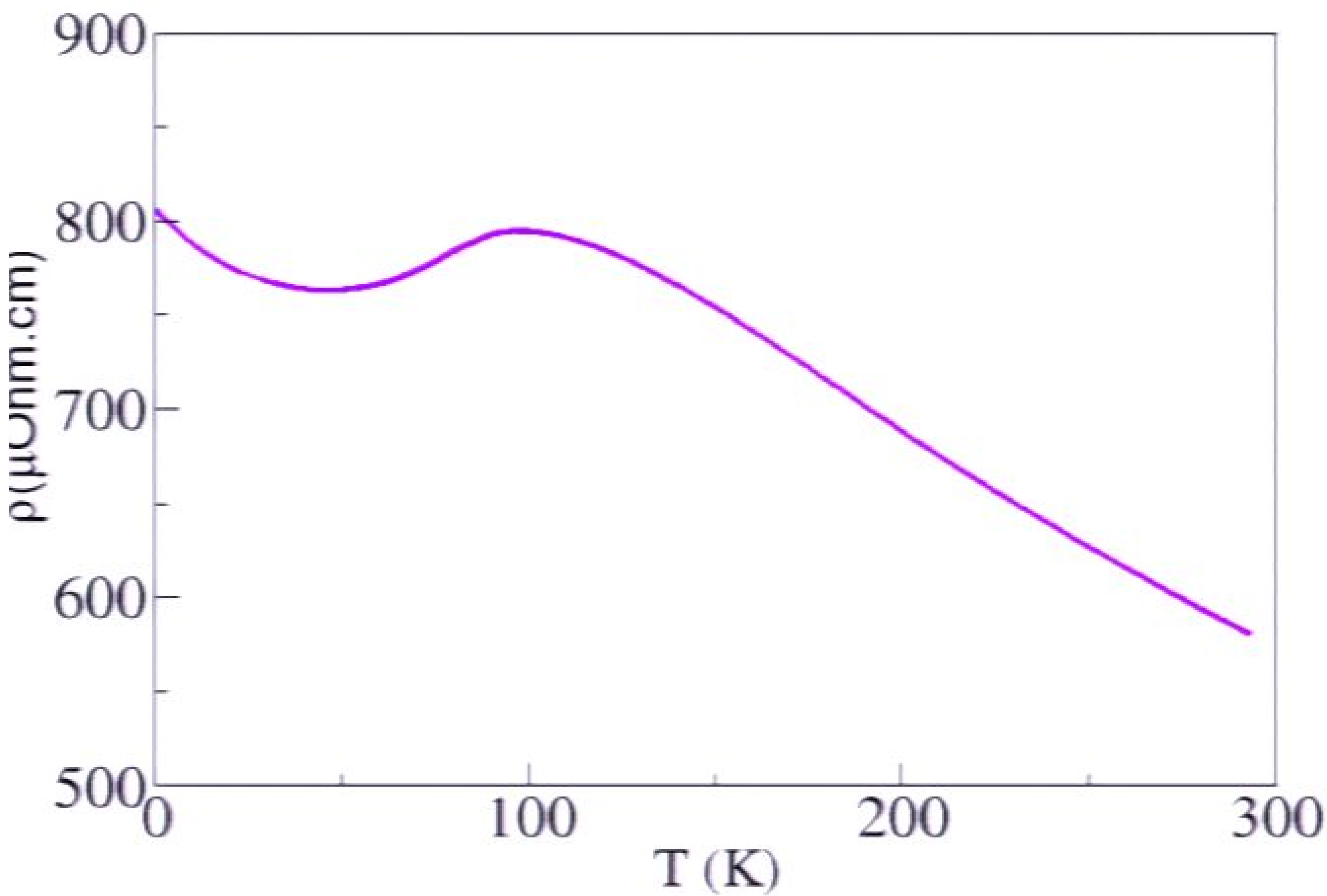




Out-of-plane non-magnetic single crystal



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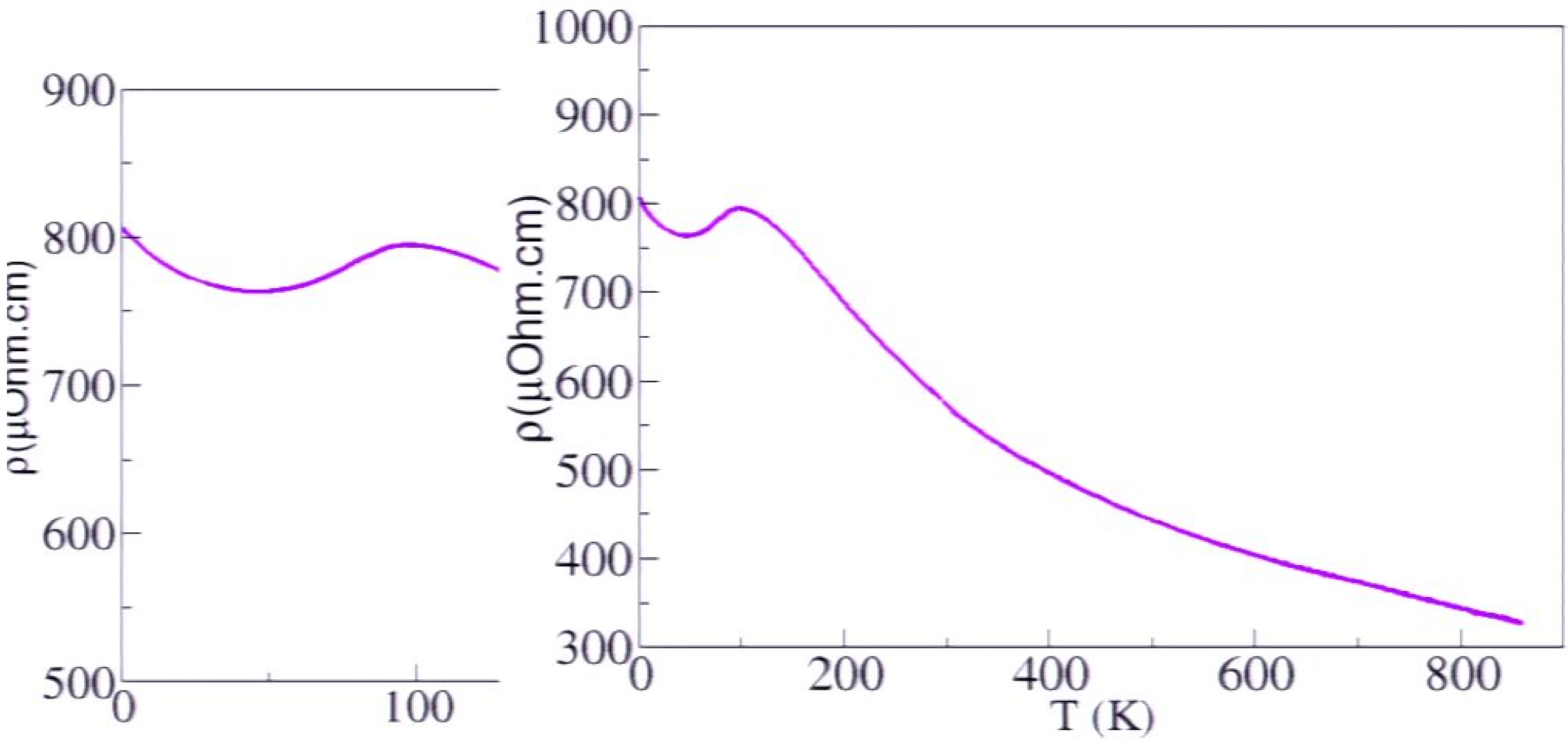
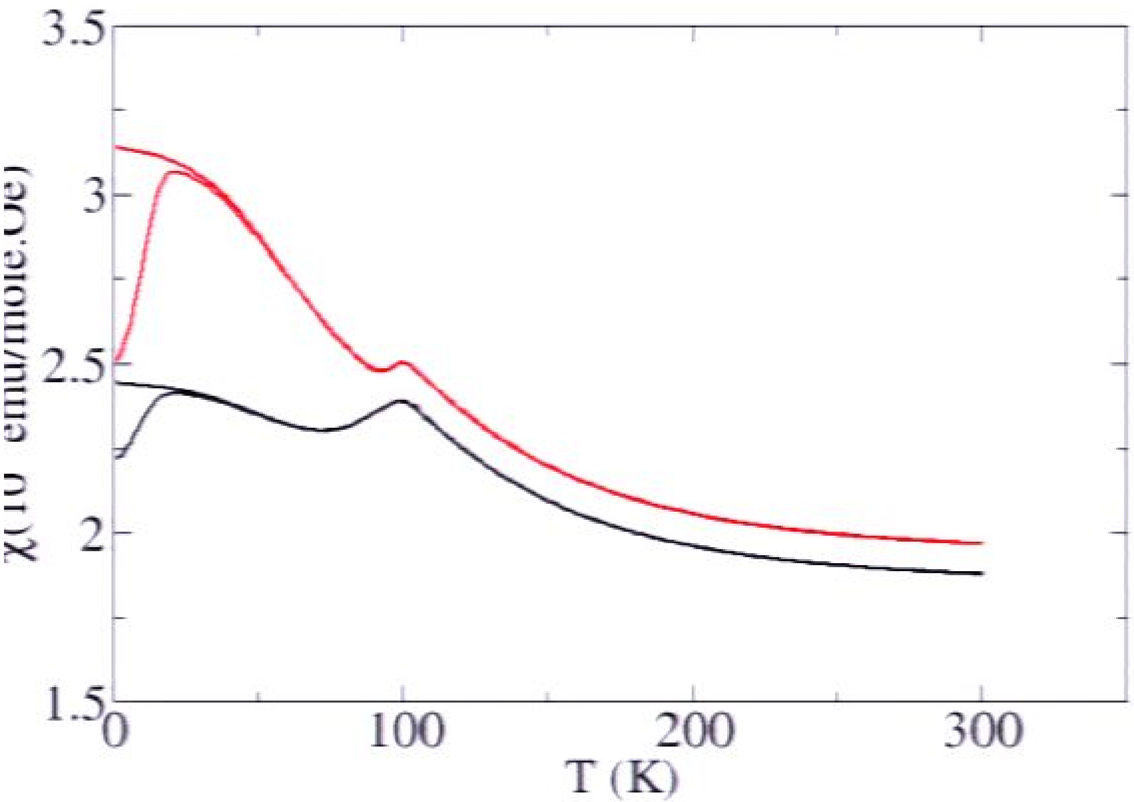


Magnetic susceptibility: non-magnetic sample



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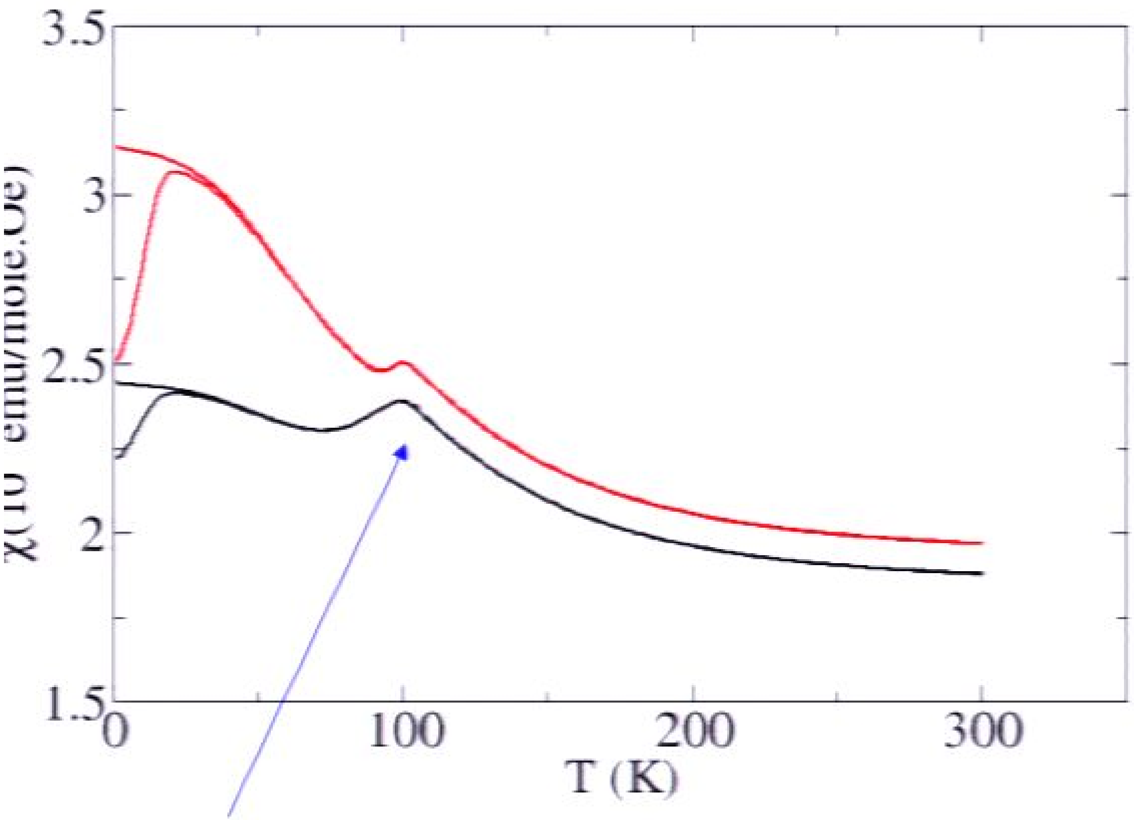

Powder neutron diffraction reveals that this is an antiferromagnetic transition

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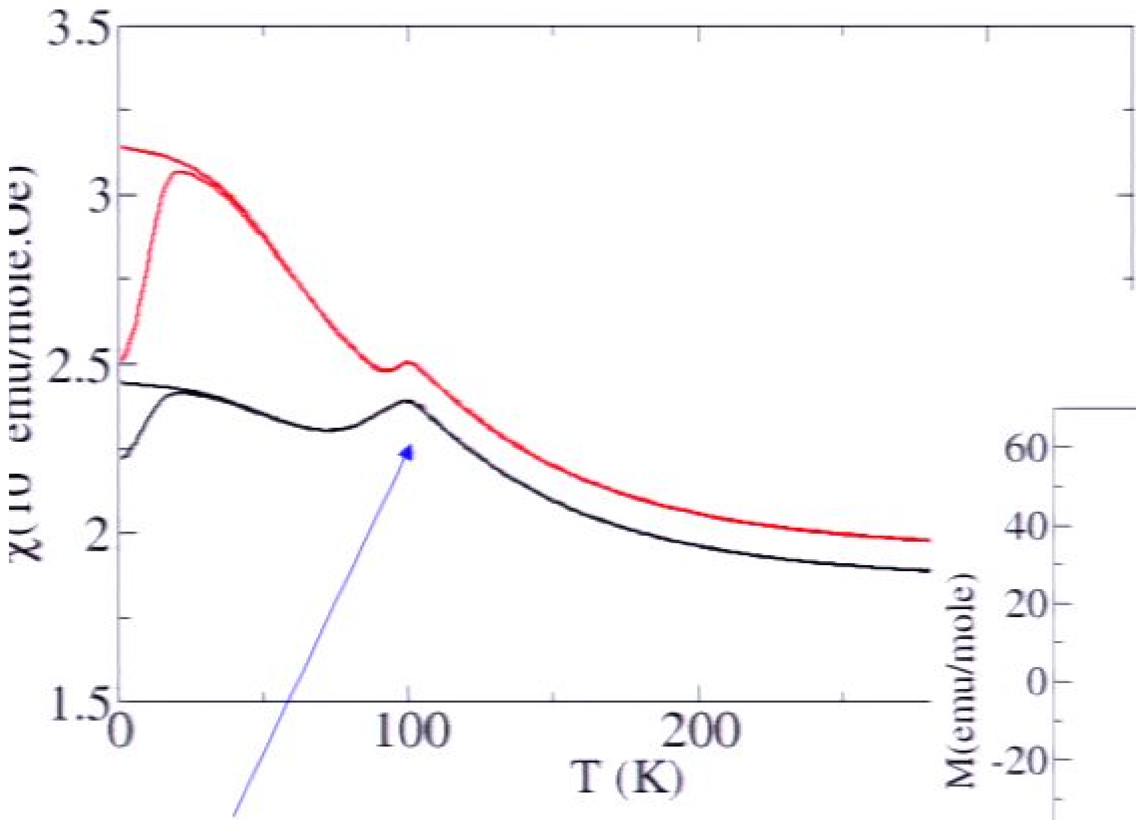

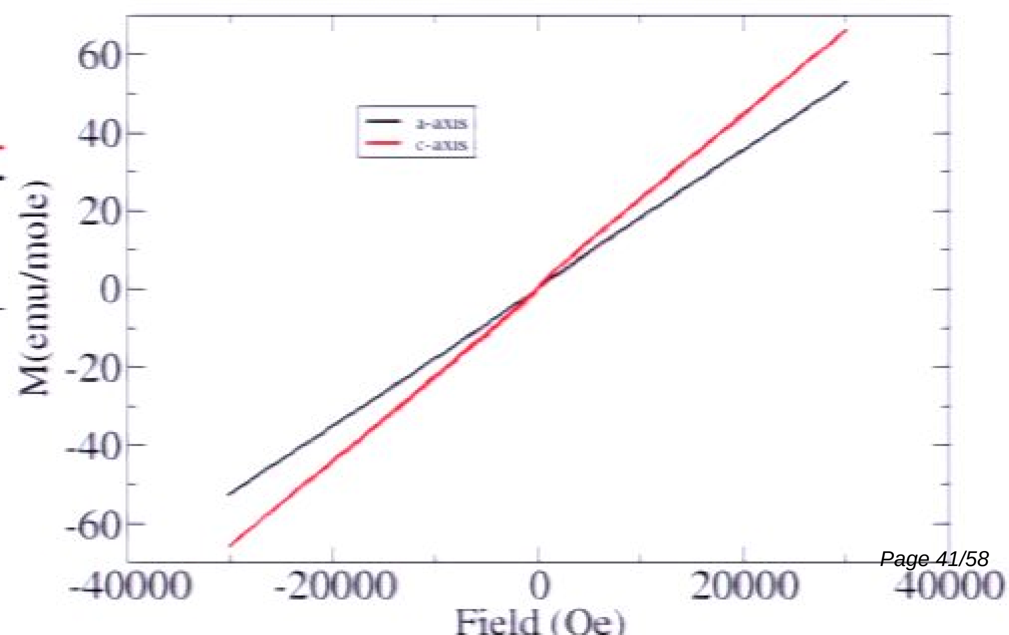

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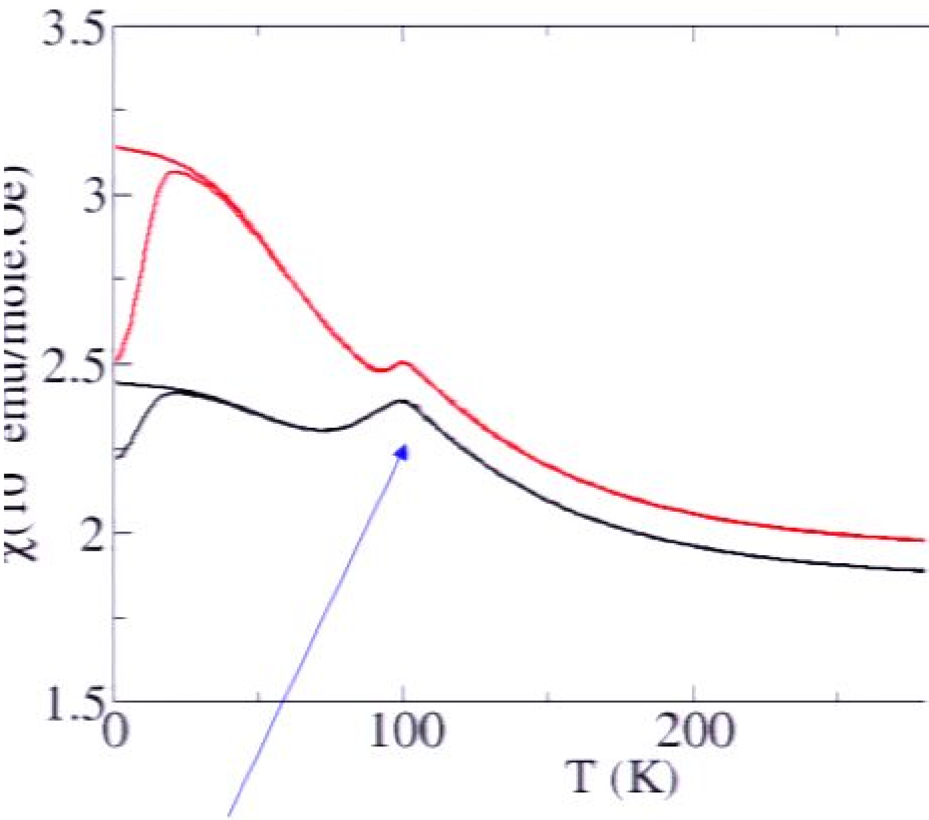

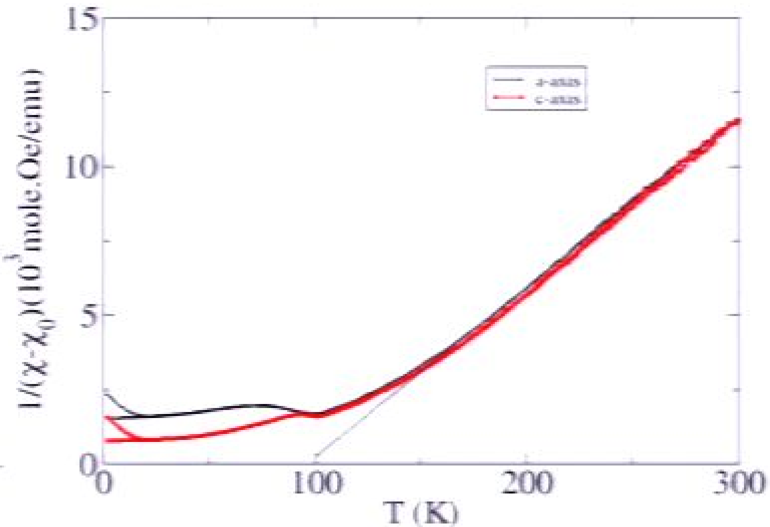

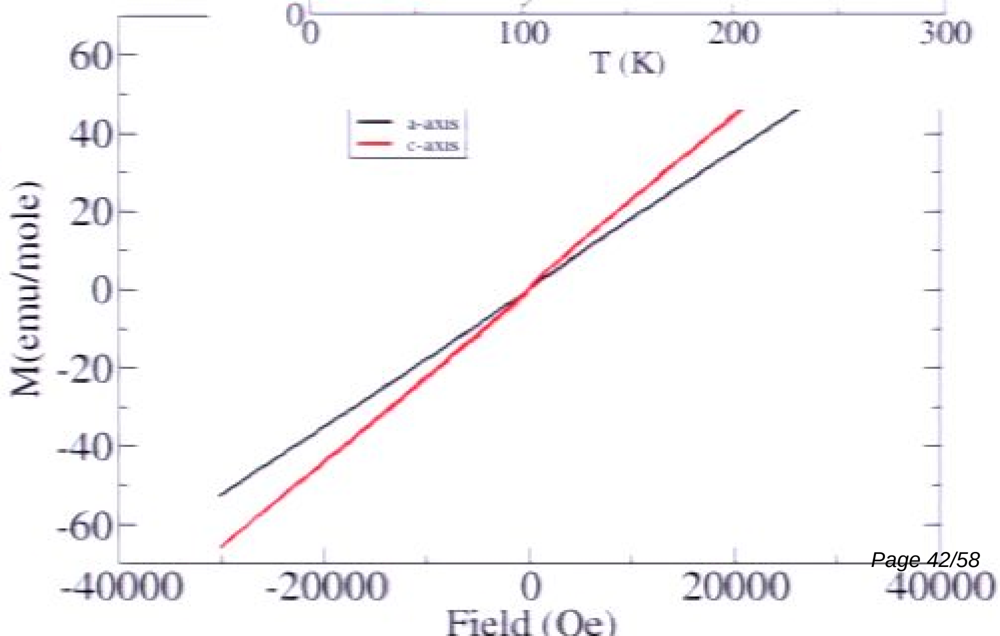

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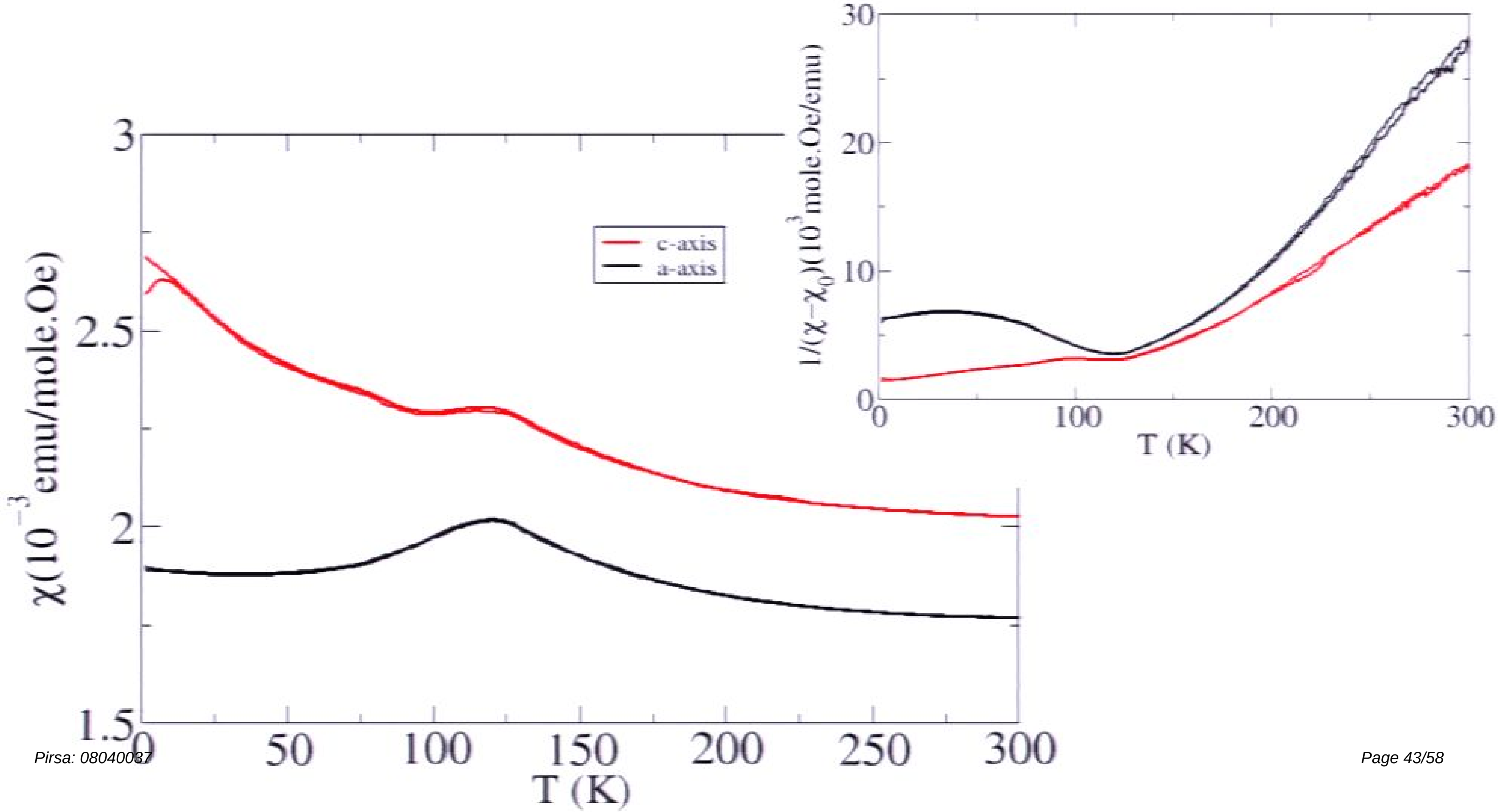
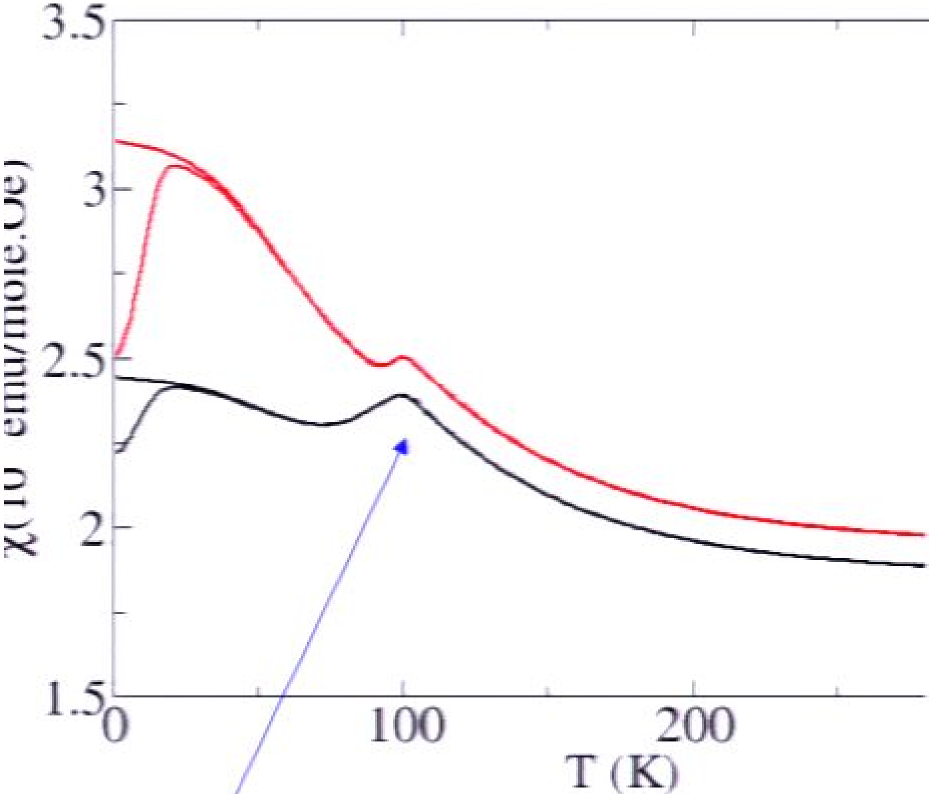
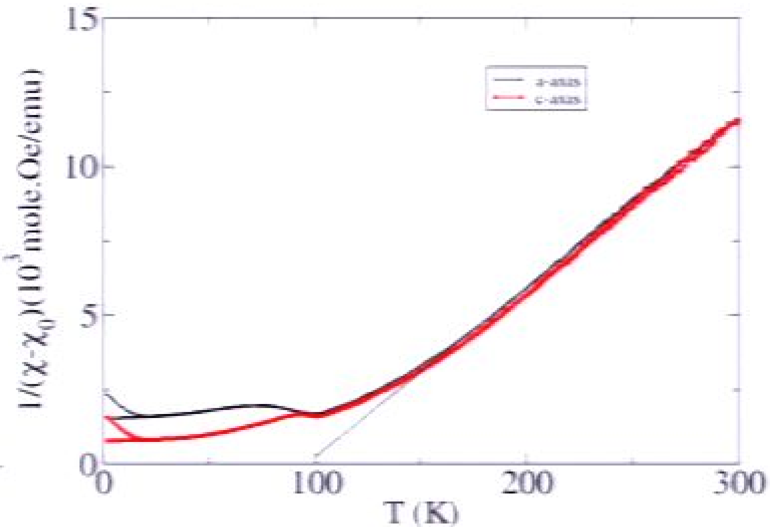
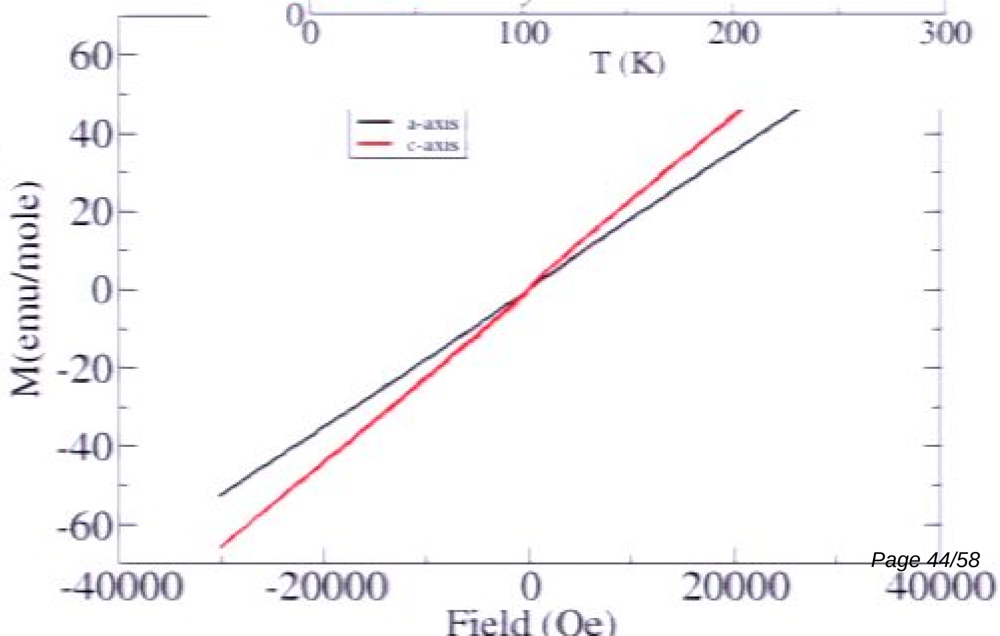
Non-magnetic annealed sample



Magnetic susceptibility: non-magnetic sample

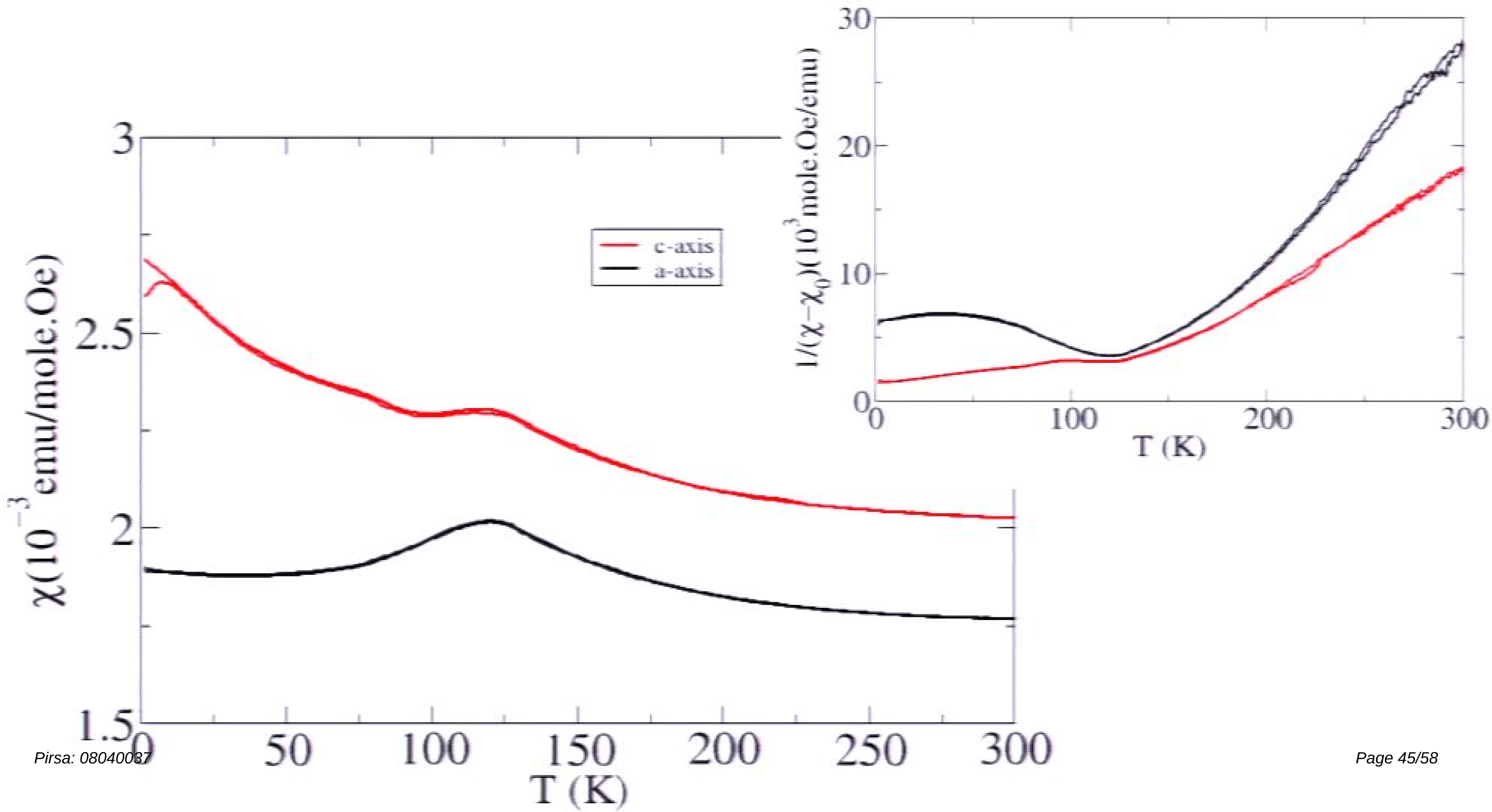




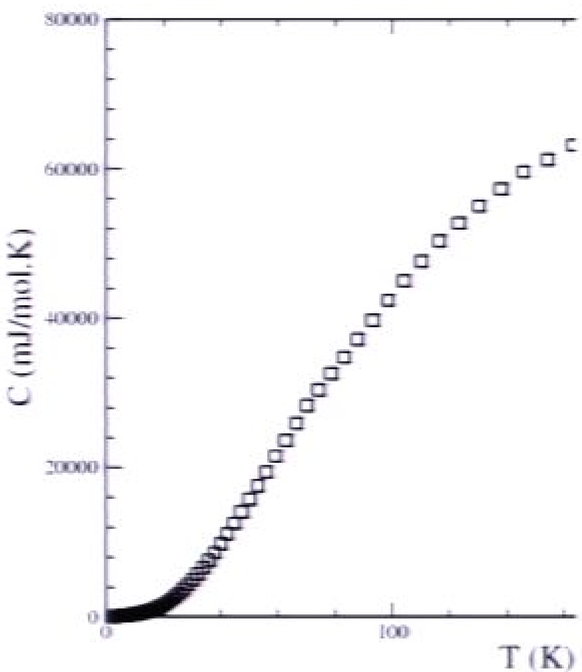


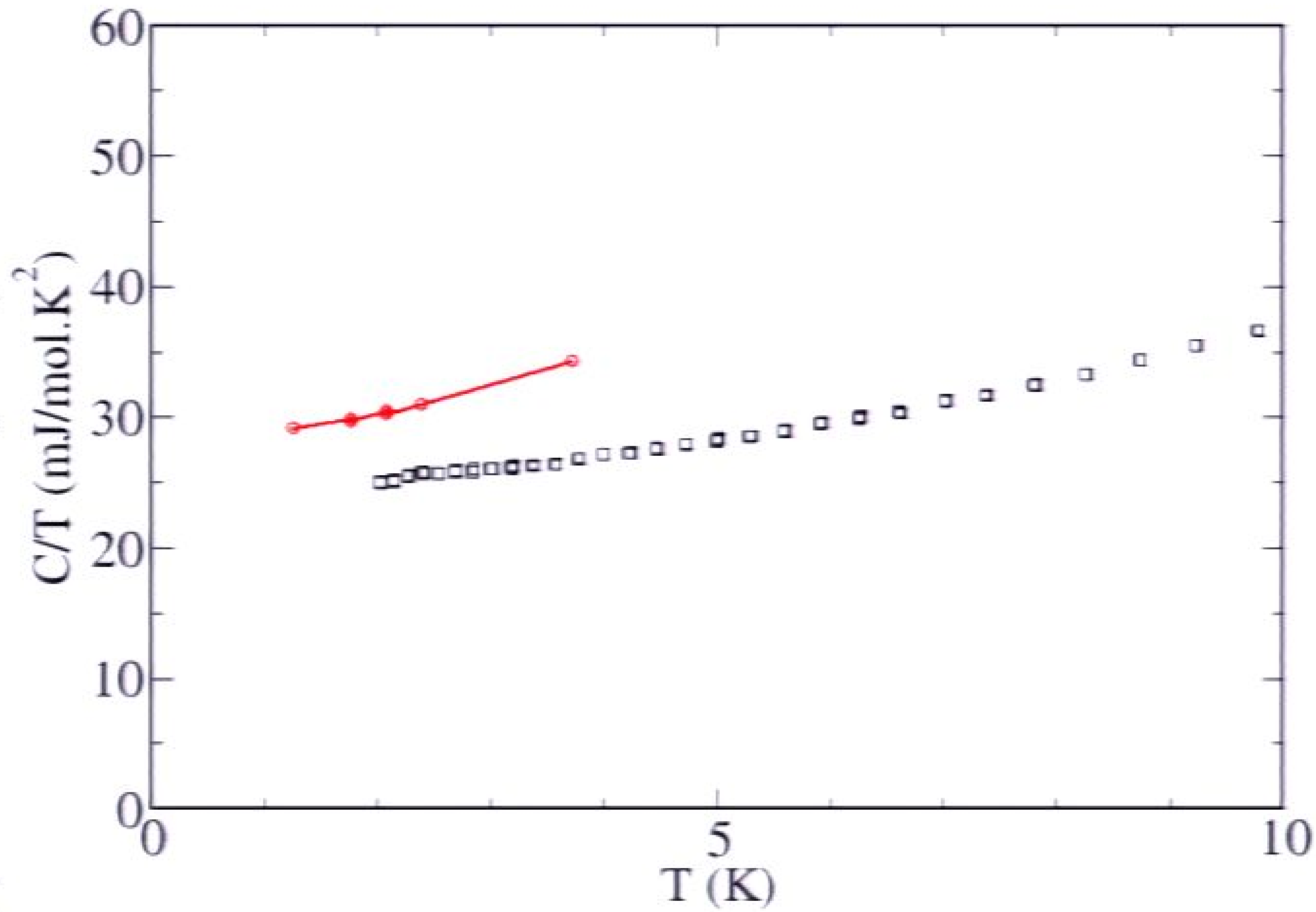
Powder neutron diffraction reveals that this is an antiferromagnetic transition

Non-magnetic annealed sample

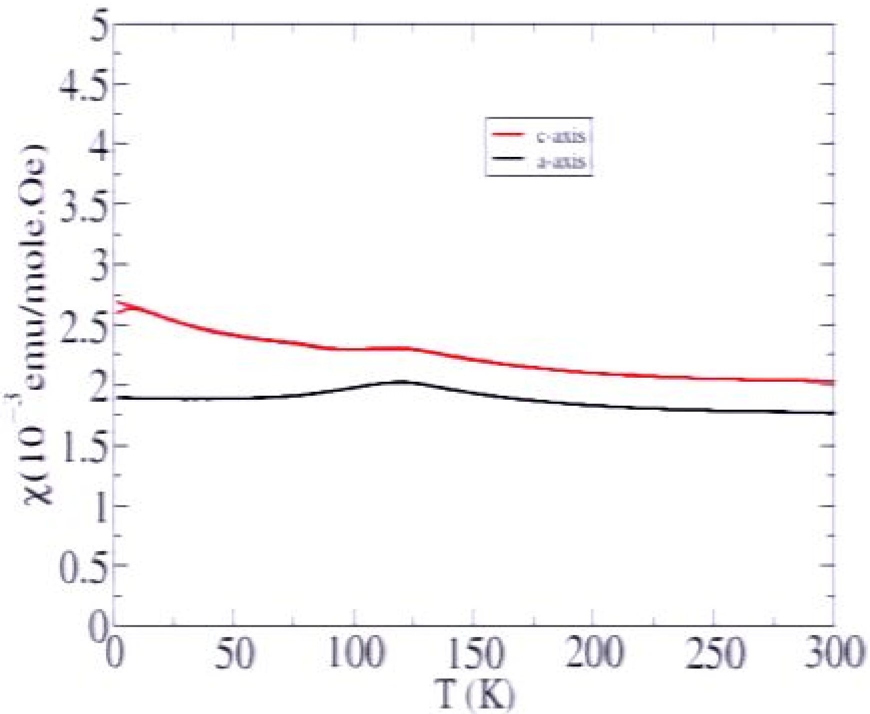


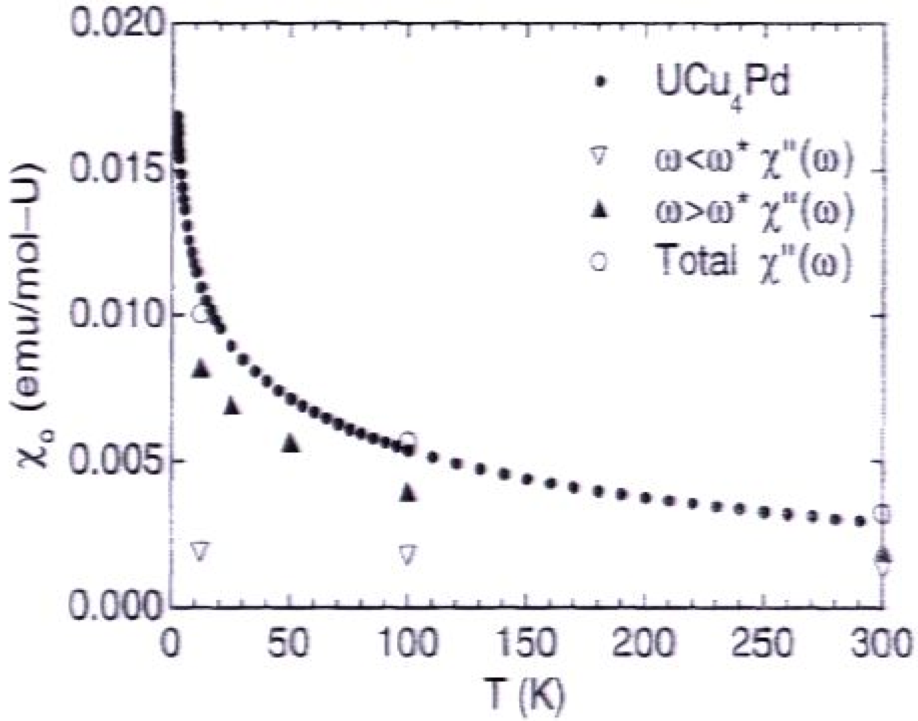
Specific heat



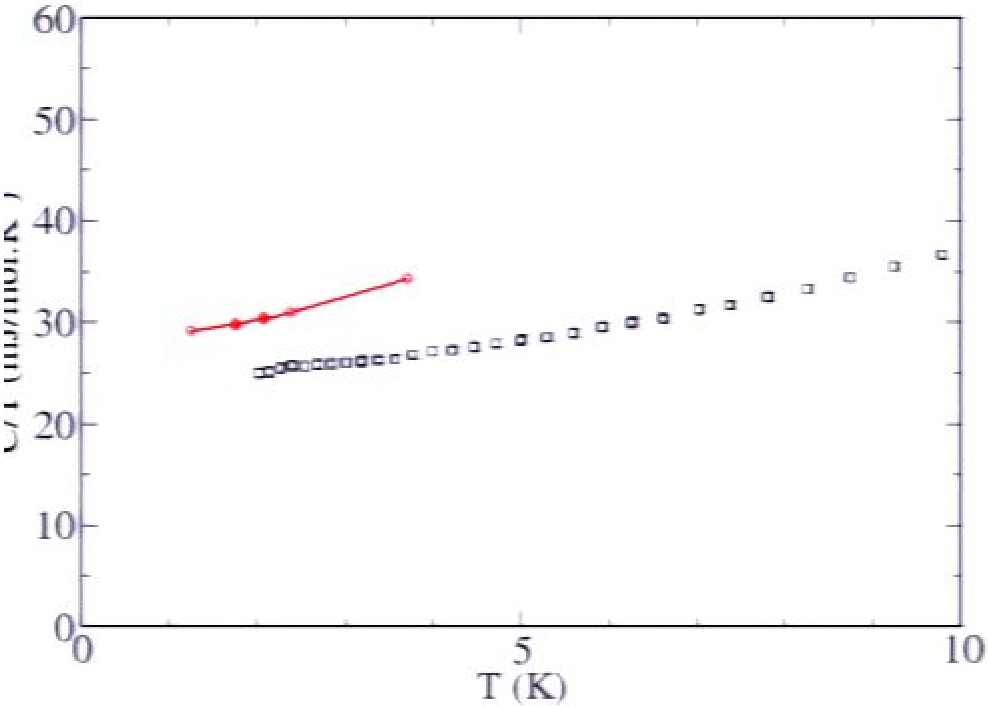


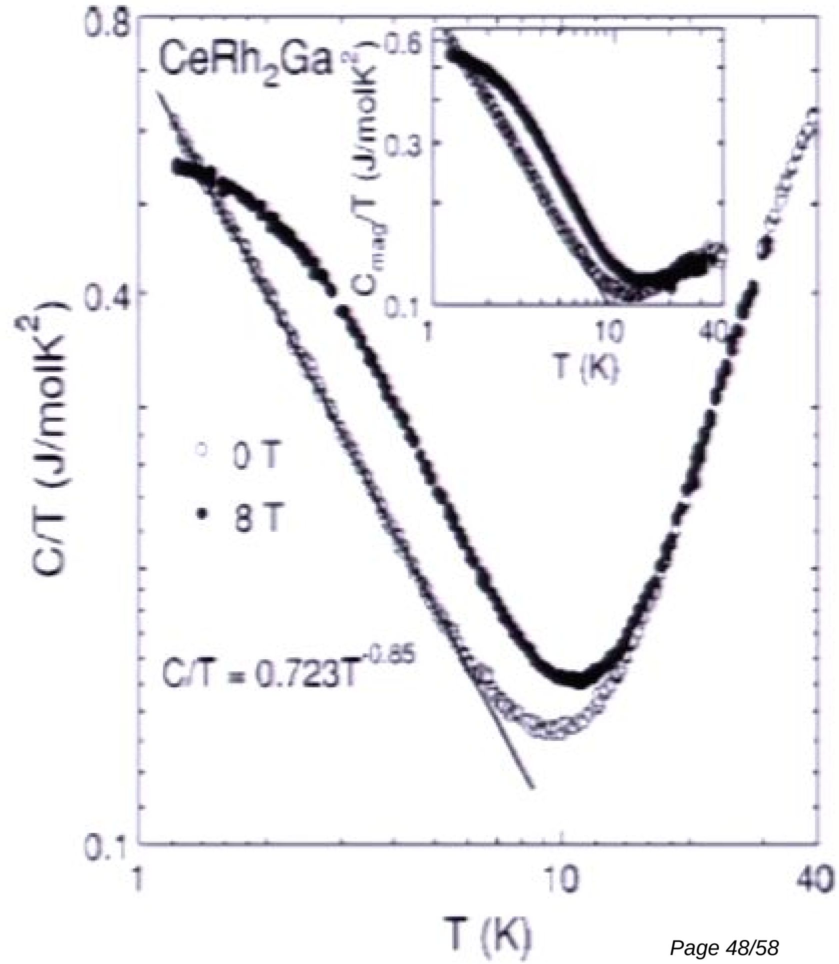
Comparison of susceptibility with doped systems:





Comparison of specific heat with doped systems:

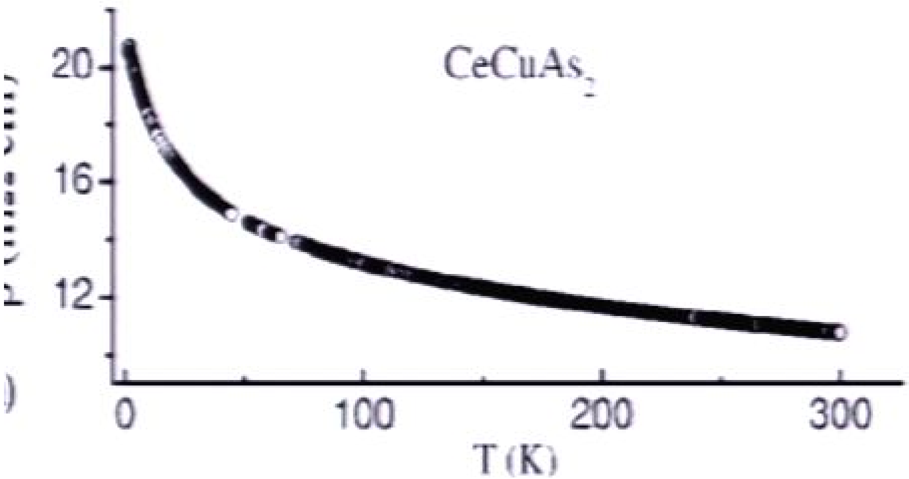


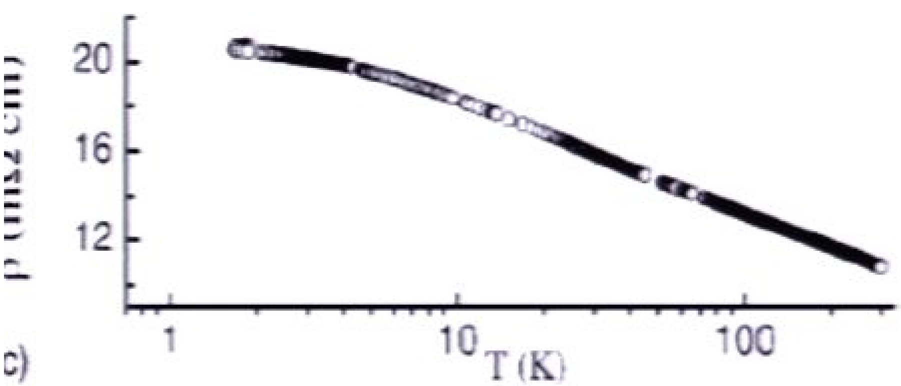


Summary:

- Neutron scattering and magnetic susceptibility agree, there is an antiferromagnetic transition above 100K
- The ordered moment on the iron site is very small (from Mossbauer spectroscopy)
- The magnetic susceptibility is large, and not strongly dependent on temperature
- The anomalous behaviour of resistivity is field independent, and not strongly dependent on annealing or other treatment of the crystal
- The specific heat is roughly linear in T at low temperature, and not strongly enhanced.

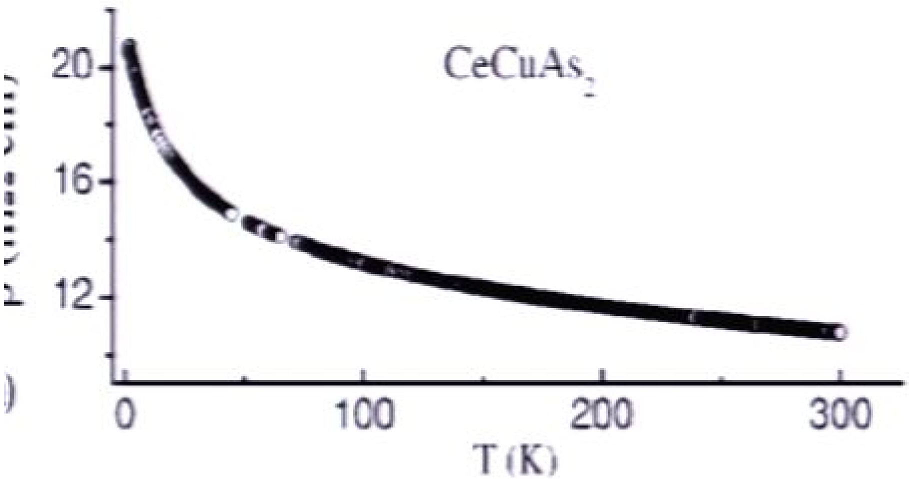
$CeCuAs_2$

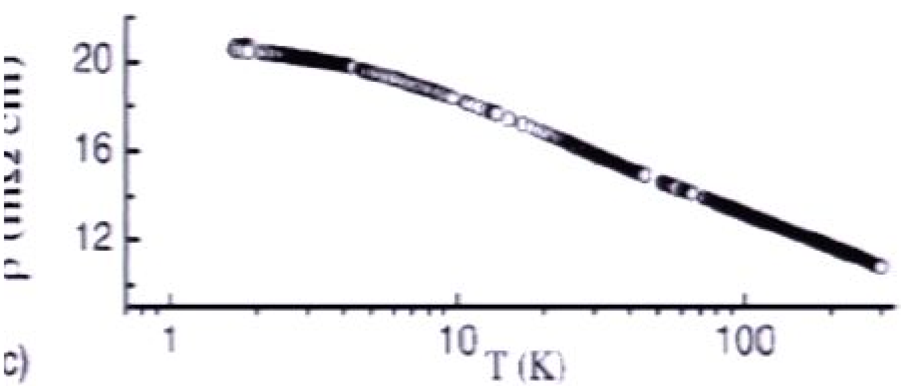


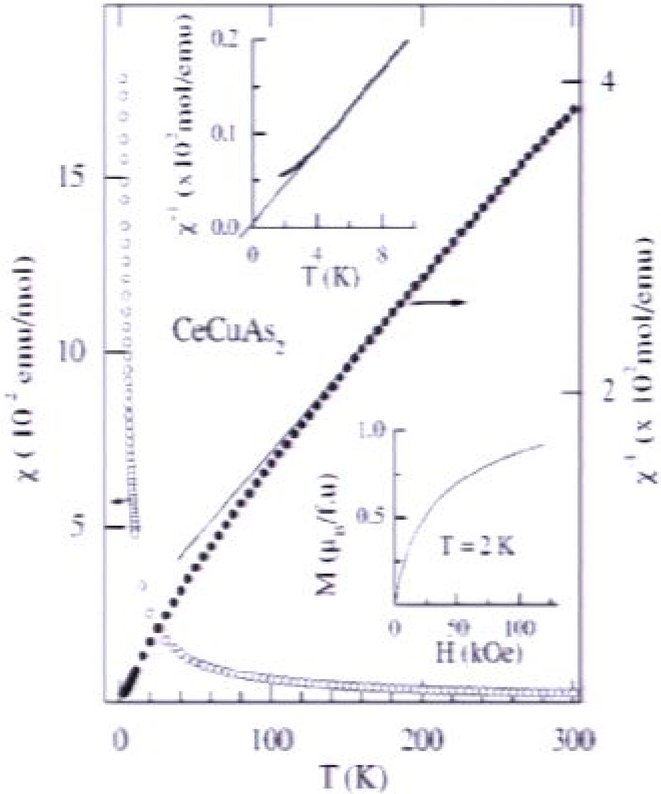


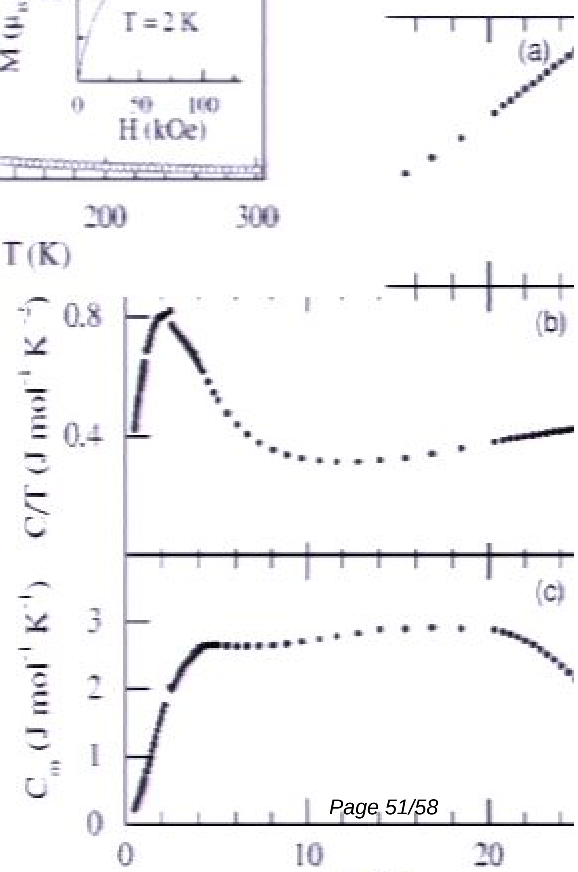
 Sengupta et al., PRB 70, 2004.

$CeCuAs_2$









Sengupta et al., PRB 70, 2004.

- FeCrAs seems to show quite different thermodynamic behaviour from previously discovered “non-metallic strongly correlated electron systems”
  - Constant C(T)/T as opposed to ln(T/T_0)
  - Slowly rising χ(T) as opposed to steep rise.

Is the physics different?

A possible theoretical model: underscreened Kondo lattice

- Andrei and Orignac, PRB 2000: 1d chain electrons plus spin S>1.
  - A chiral non-Fermi-liquid
  - (Generalized Wess-Zumino-Novikov-Witten model)
  - Strong tendency to antiferromagnetism.

$$\chi(T) = (2S-1)/2\pi v$$

$$C(T)/T = const.$$

(But Coleman and Pepin (2003) predict ln divergence in C(T) in 3d.)

Details:

$$H_{\rm el} = H_\rho + H_\sigma . \quad (2)$$

$$H_\rho = \int dx \frac{v_F}{2\pi}[(\pi\Pi_\rho)^2 + (\partial_x\phi_\rho)^2].$$

$$H_\sigma = \frac{2\pi v_F}{3}\int dx(\vec{J}_R\cdot\vec{J}_R + \vec{J}_L\cdot\vec{J}_L). \quad (3)$$

where the canonically conjugate fields Π_ρ, ϕ_ρ describe the charge excitations, and the non-Abelian $SU(2)_1$ currents $\vec{J}_{R,L}$ describe the electron-spin excitations. The local moments are described in the low-energy regime by the Hamiltonian

$$H_{\rm mom} = \frac{2\pi v_s}{2(1+S)}\int dx(\vec{S}_R\cdot\vec{S}_R + \vec{S}_L\cdot\vec{S}_L), \quad (4)$$

where $\vec{S}_{R,L}$ are $SU(2)_{2S}$ WZNW currents. The Kondo interaction λ_K at incommensurate filling becomes

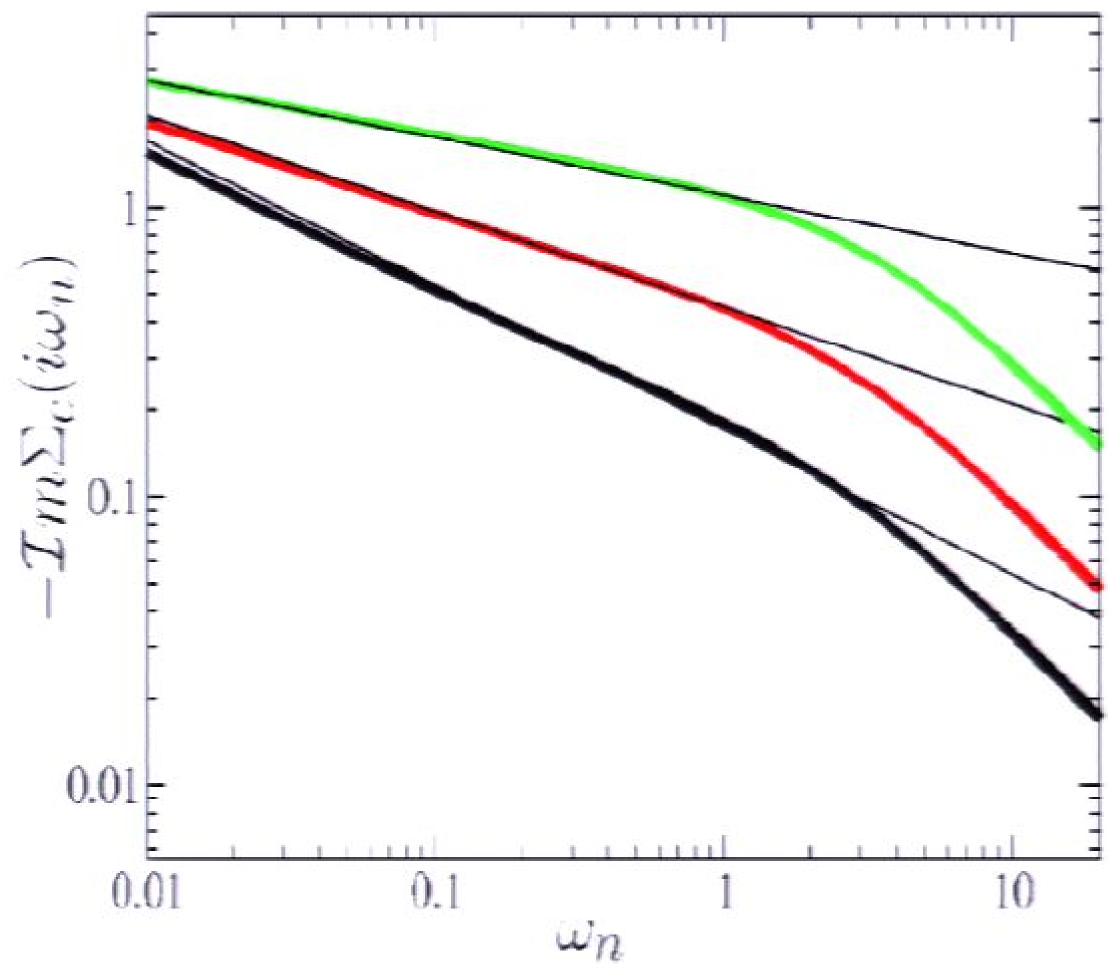
$$\lambda_K a\int dx(\vec{J}_R + \vec{J}_L)\cdot(\vec{S}_L + \vec{S}_R)(x) \quad (5)$$

Underscreened Kondo Lattice: 1/N calculation

Insulating pseudogap regime in place of usual renomalized metal, preventing the buildup of coherence over the lattice.

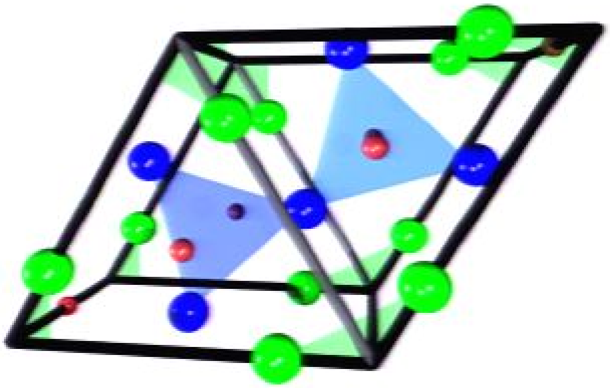
The underscreened Kondo lattice has a pseudogap density of states above the ordering temperature of the moments.

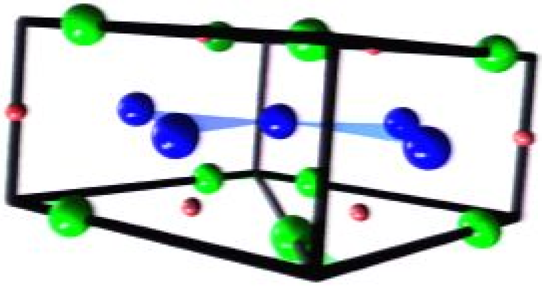
Predict power-law resistivity increasing with decreasing T.

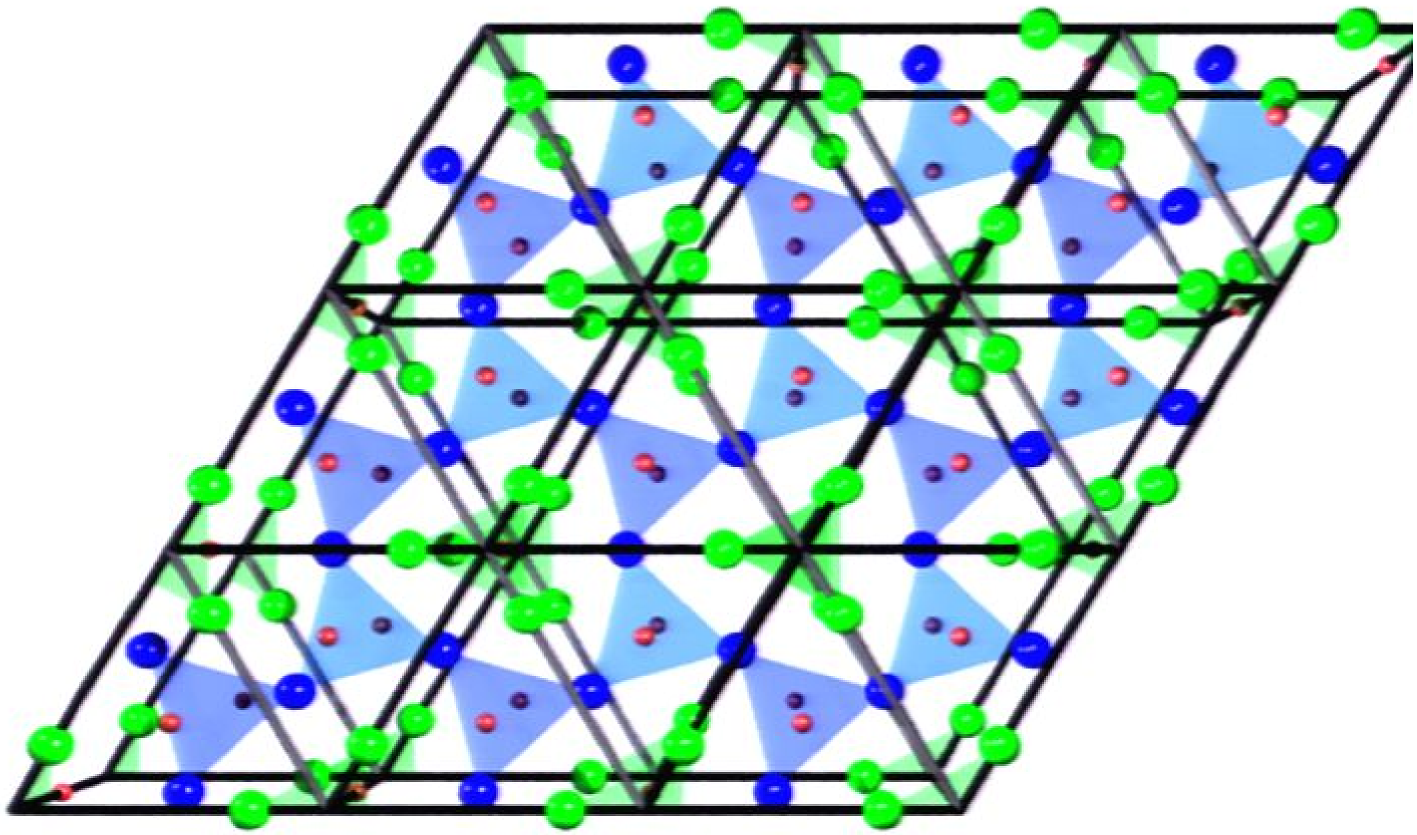


S. Florens, PRB, 2004.

Crystal structure FeCrAs







Summary:

- FeCrAs shows a robust “non-metallic” low temperature resistivity
- Specific heat and magnetic susceptibility are enhanced, but not anomalous compared to previously discovered “non-metallic” concentrated Kondo systems
- Is this evidence of a new kind of behaviour?

Crystal structure FeCrAs