Beyond Landau Fermi liquid and BCS superconductivity near quantum criticality

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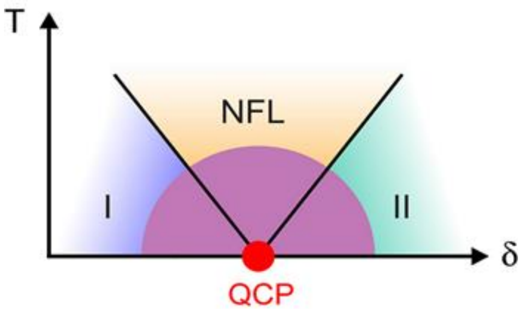


Karlsruhe Institute of Technology

Lecture 4
Examples of quantum critical *d*- and *f*-electron systems

Contents of Lecture 4

CePdAl – a partially frustrated heavy-fermion system

Approaching quantum criticality of CePdAl with Ni substitution

Frustrated Ce moments in CePdAl: a two-dimensional spin liquid?

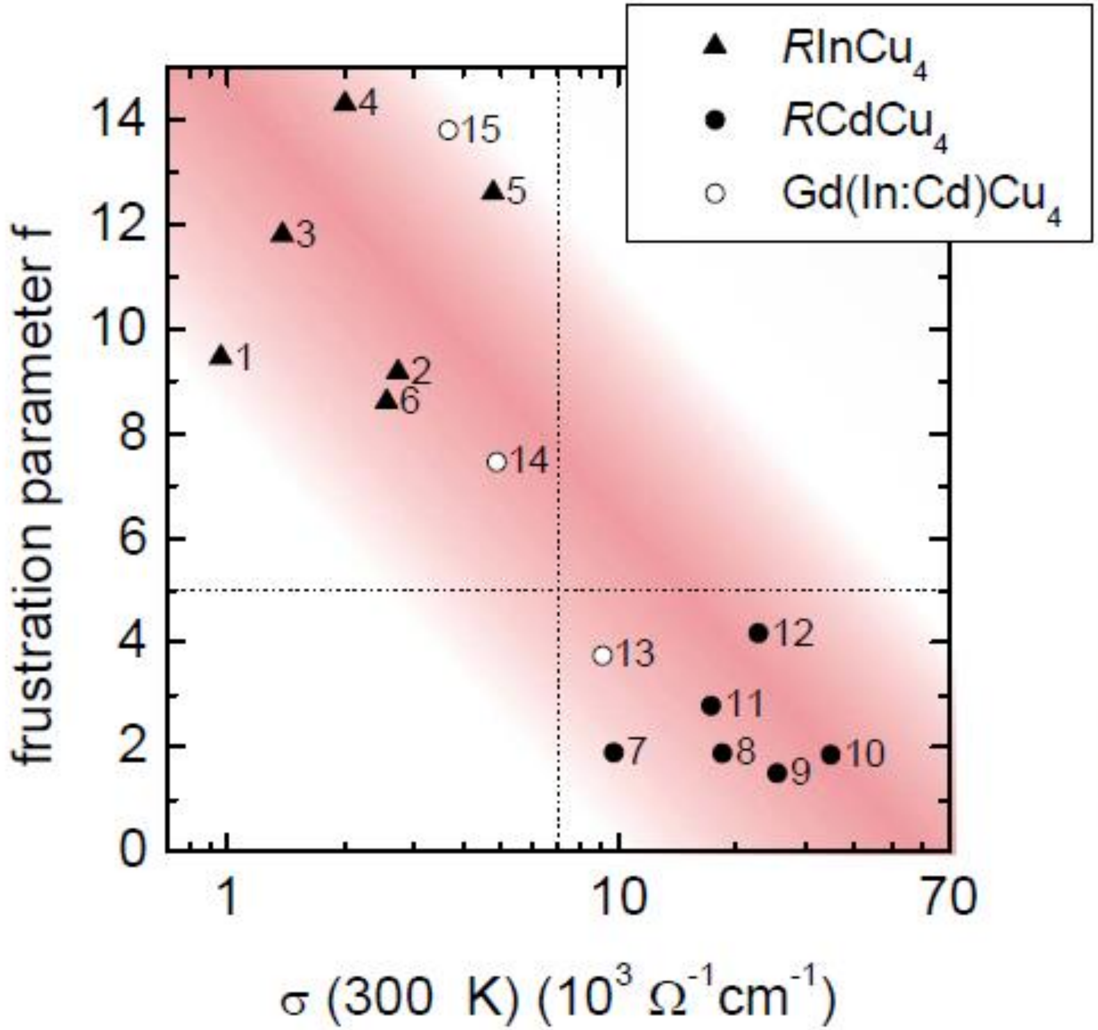
Classical and quantum phase transitions in the itinerant ferromagnet $Sr_{1-x}Ca_xRuO_3$

Evolution of critical expoenents in $Sr_{1-x}Ca_xRuO_3$ with x

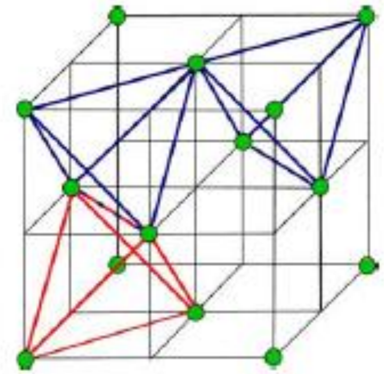
Unusually slow the quantum critical dynamics

CePdAl – a partially frustrated heavy-fermion system

Frustration and conductivity



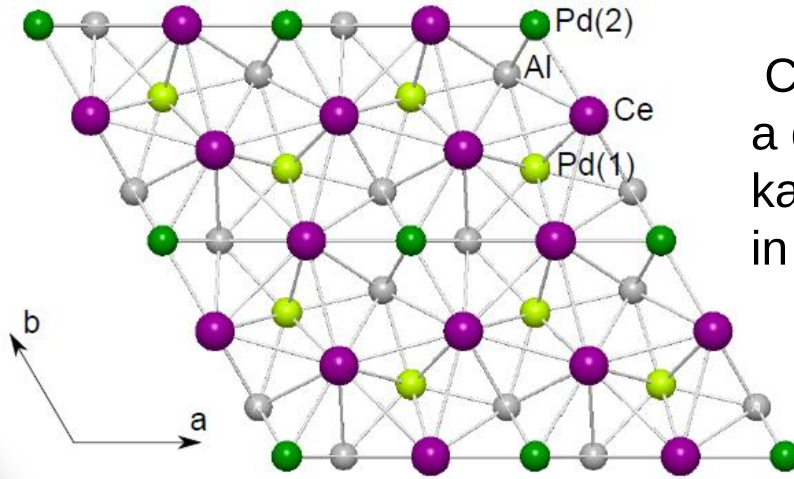
1: $GdInCu_4$
2: $TbInCu_4$
3: $DyInCu_4$
4: $HoInCu_4$
5: $ErInCu_4$
6: $TmInCu_4$
7: $GdCdCu_4$
8: $TbCdCu_4$
9: $DyCdCu_4$
10: $HoCdCu_4$
11: $ErCdCu_4$
12: $TmCdCu_4$
13: $GdIn_{0.25}Cd_{0.75}Cu_4$
14: $GdIn_{0.5}Cd_{0.5}Cu_4$
15: $GdIn_{0.75}Cd_{0.25}Cu_4$



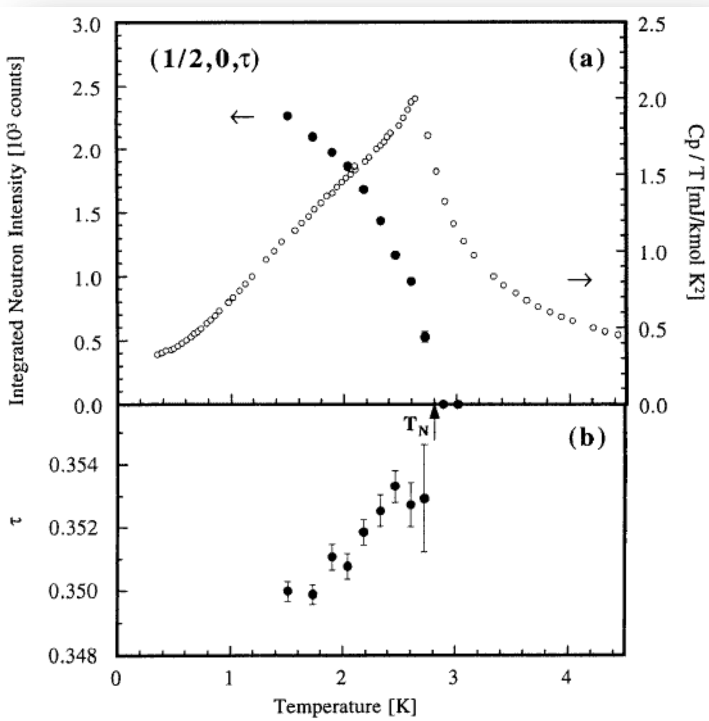
Frustration parameter $f = \Theta_{CW}/T_c$

V. Fritsch et al., PRB 72 (2006)

CePdAl – a partially frustrated Ce-based compound



Ce atoms form a distorted kagomé lattice in the *ab* plane

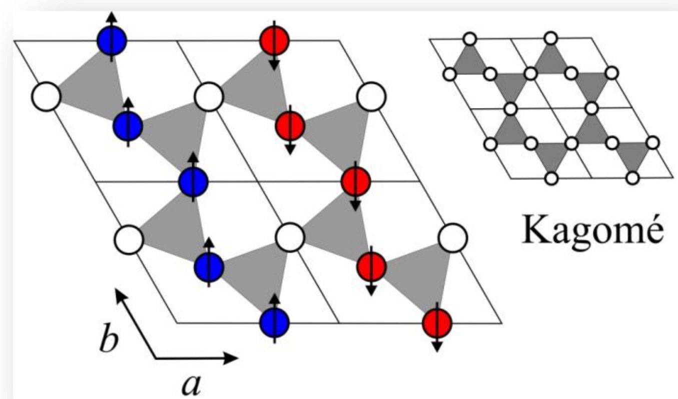


Magnetic structure

Magnetic order belowT_N = 2.7.K

Q = (½ 0 τ), τ ≈ 0.35

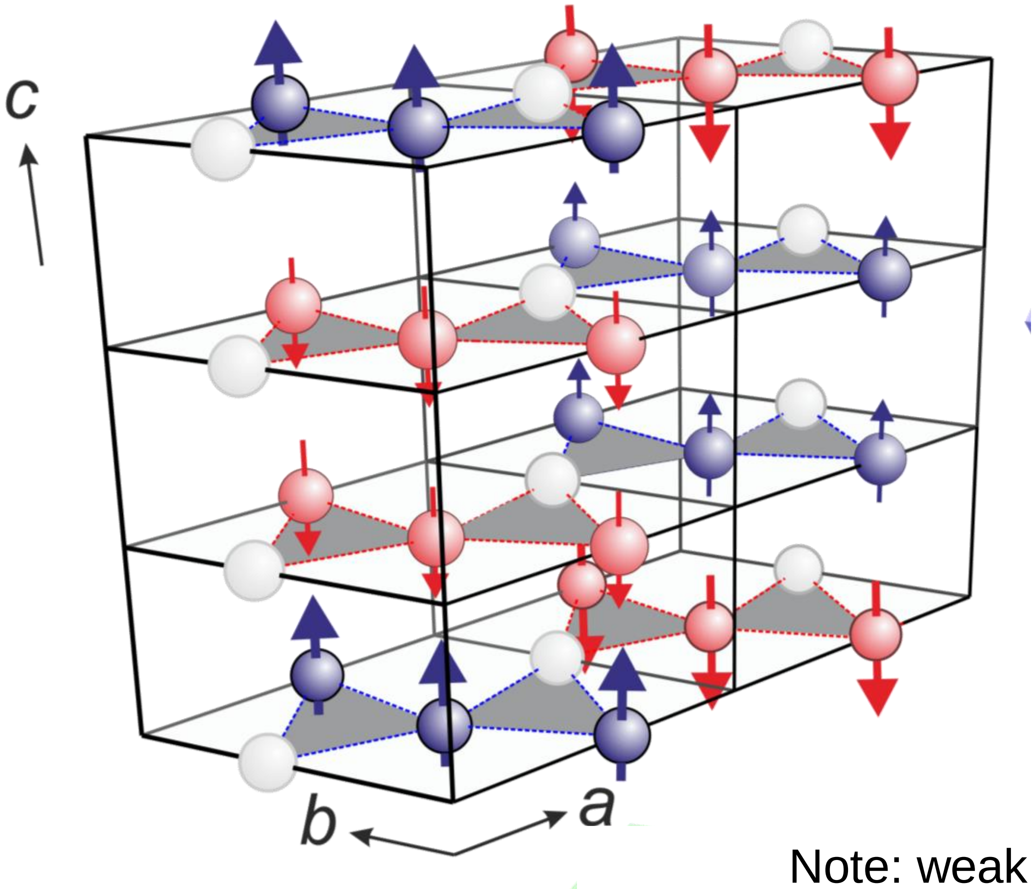
1/3 of Ce moments frustrated



*Kitazawa et al., Physica B **199&200**, 28, (1994)*
*Dönni et al., J: Phys.: Cond. Matt. **8**, 11213 (1996)*

Three-dimensional magnetic structure of CePdAl

Dönni et al.,
J. Phys.: Cond. Matt. ***8****, 11213 (1996)*



Magnetic ordering wector

Q = (½ 0 τ), $\tau \approx 0.35$

1/3 of Ce moments frustrated

μ(Ce1) = 1.58 μ_B

Note: weak *T*-dependent incommensuration neglected in the picture

Model of frustrated kagomé-like planes

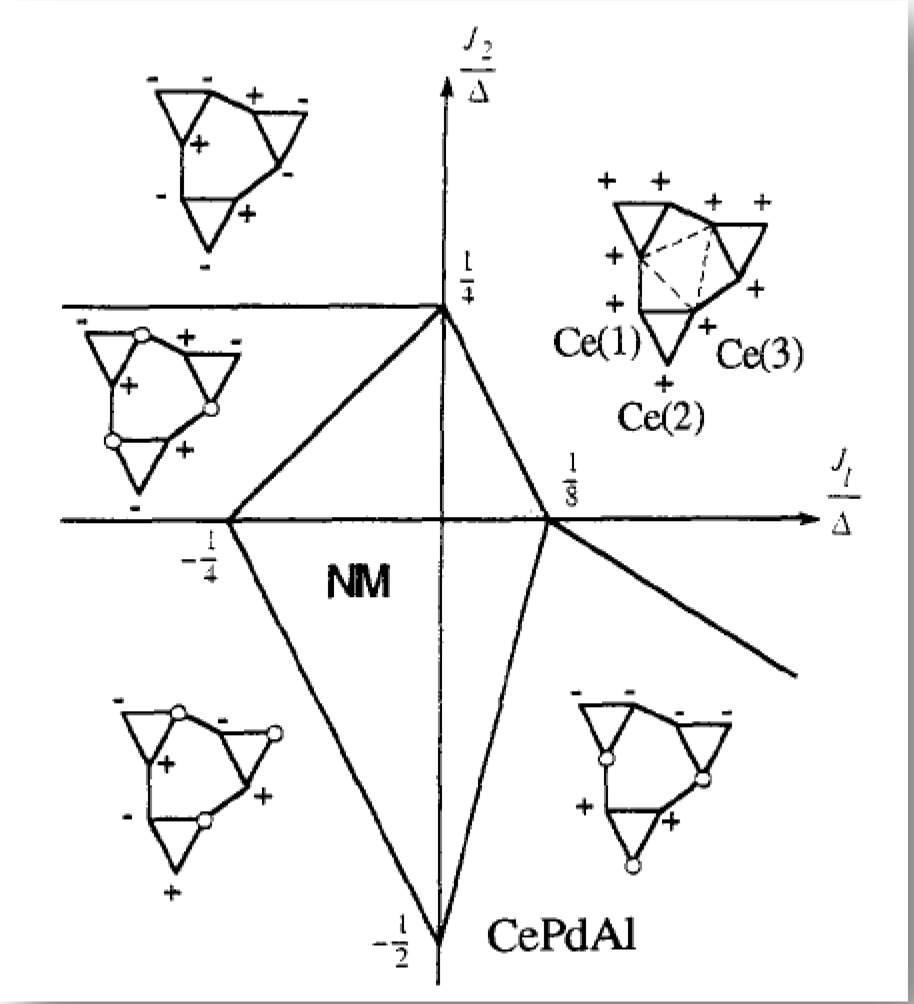
Nunez-Regueiro and Lacroix, Physica C 282-287, 1885 (1997)

nn interaction J_1 (FM) and nnn J_2 (AF) in the *ab* (kagome) planes, neglect of interplane coupling J_3

$$H = \sum_i \Delta_i(T)|\mu_i|^2 - \frac{1}{2}\sum_{i\neq j} J_{ij}\vec{\mu}_i\cdot\vec{\mu}_j$$

Kondo effect modelled by the energy difference $\Delta_i(T)$ between Ce nonmagnetic Kondo state $\mu_i = 0$ and magnetic state $\mu_i \neq 0$.

Mean-field phase diagram



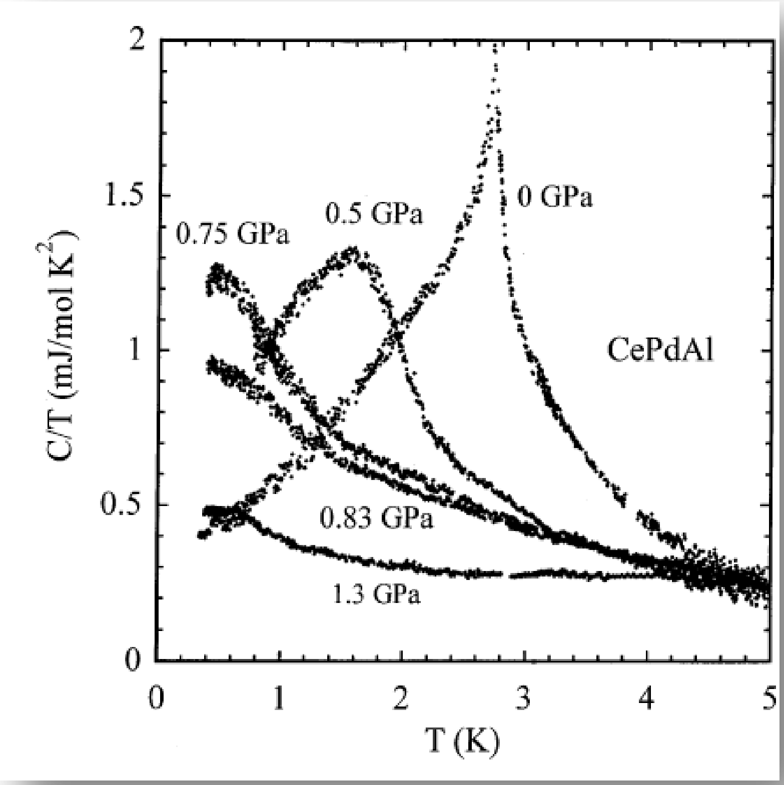
confirmed by variational MC

*Motome et al., PRL **105**, 036403*

coupling between planes neglected!

Approaching quantum criticality of CePdAl with Ni substitution

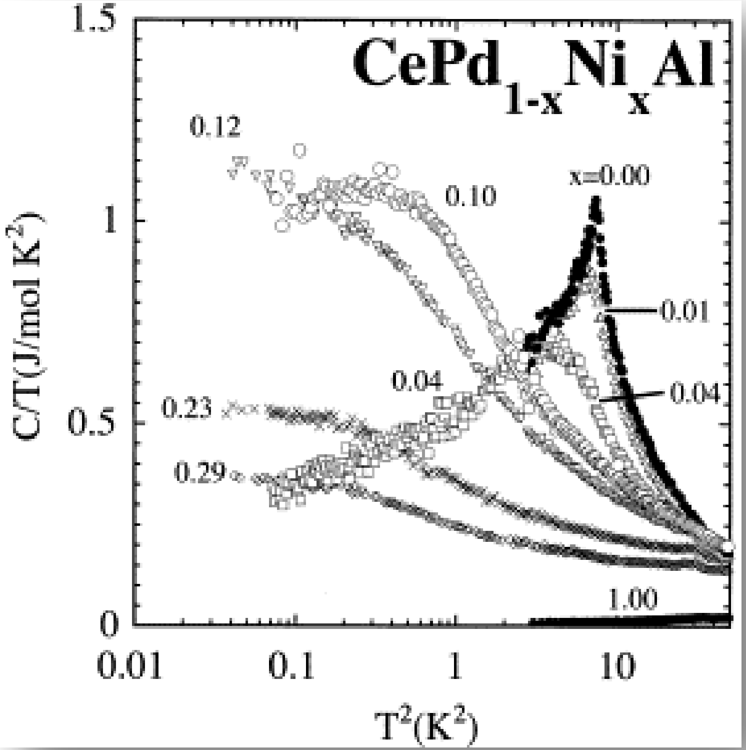
CePdAl – a partially frustrated Ce-based compound



Suppression of T_N by hydrostatic pressure …

Goto et al., J. Phys. Chem: Sol. ***63****, 1159 (2001)*

…

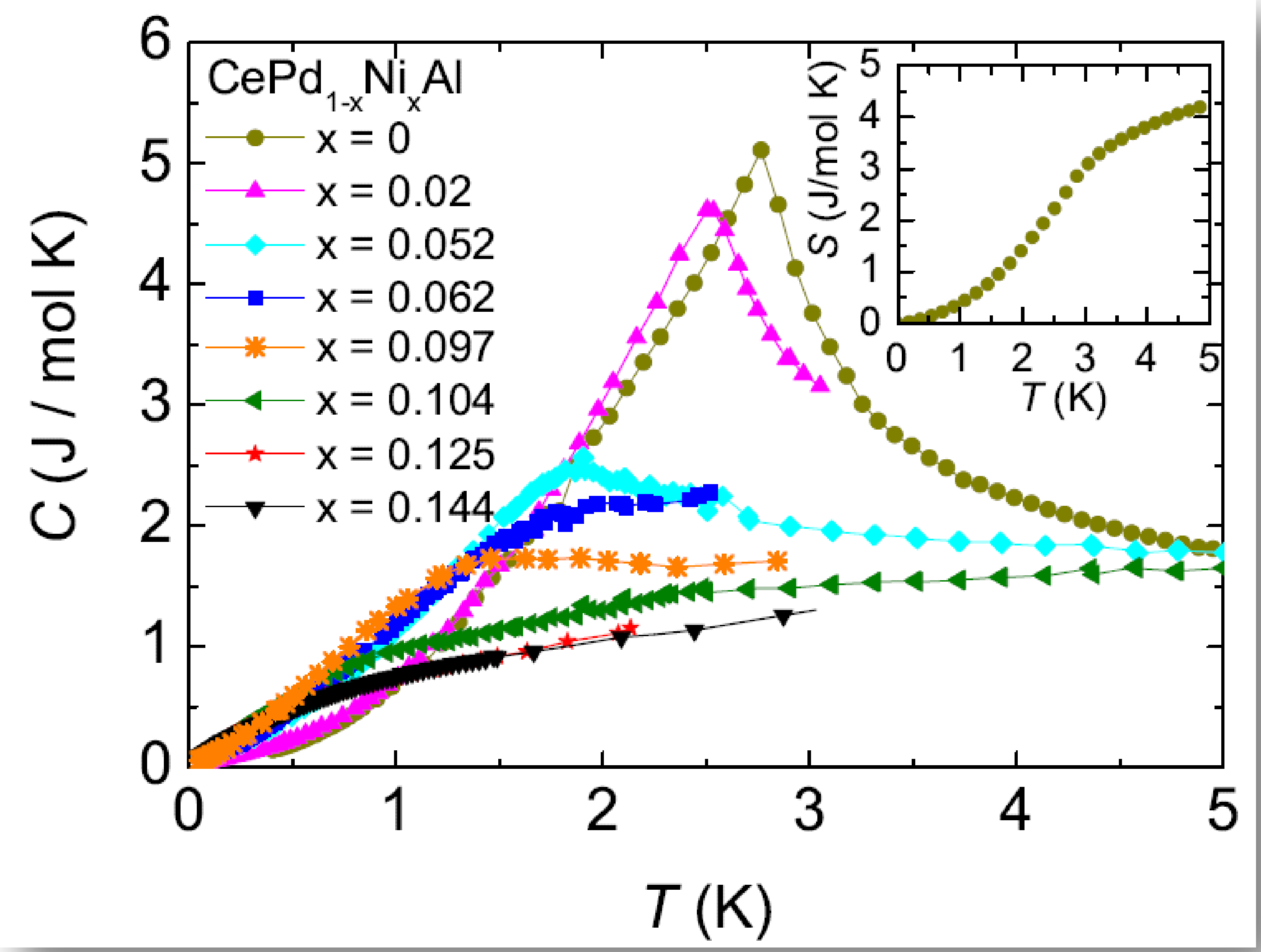


… or by isoelectronic Ni doping

Isikawa et al., Physica B ***281&282****, 36 (2000)*
Bagrets, Fritsch et al., unpublished

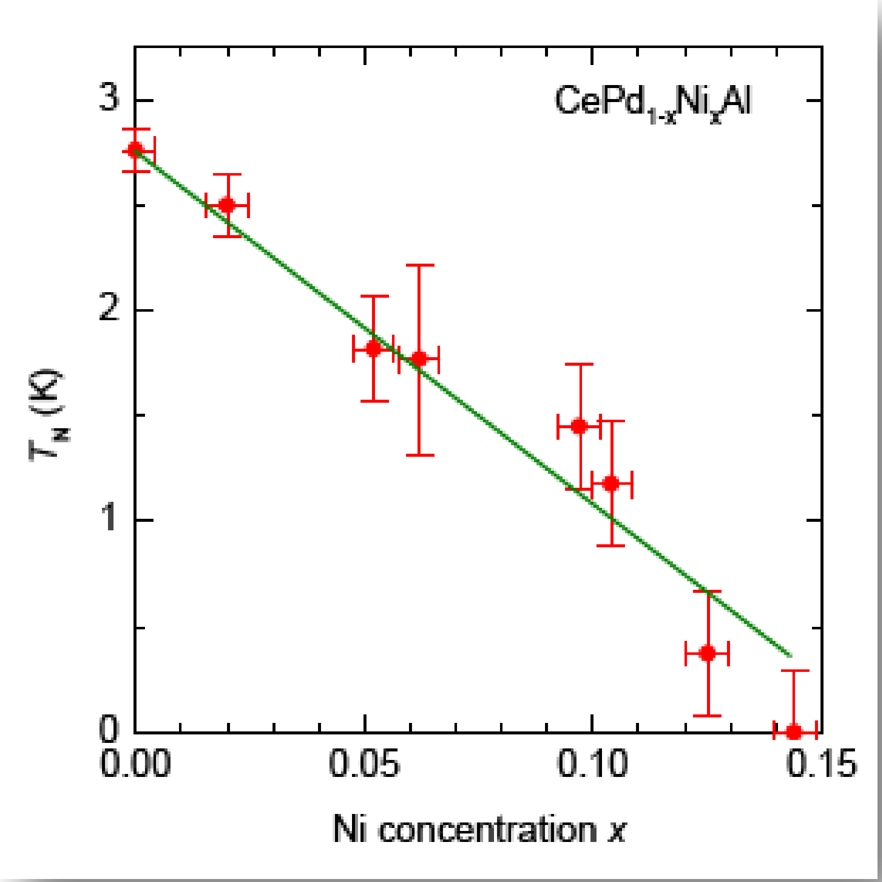
Quantum critical point?

Specific heat of $CePd_{1-x}Ni_xAl$ polycrystals



Specific-heat anomaly at T_N broadens and is completely suppressed around $x = 0.14$

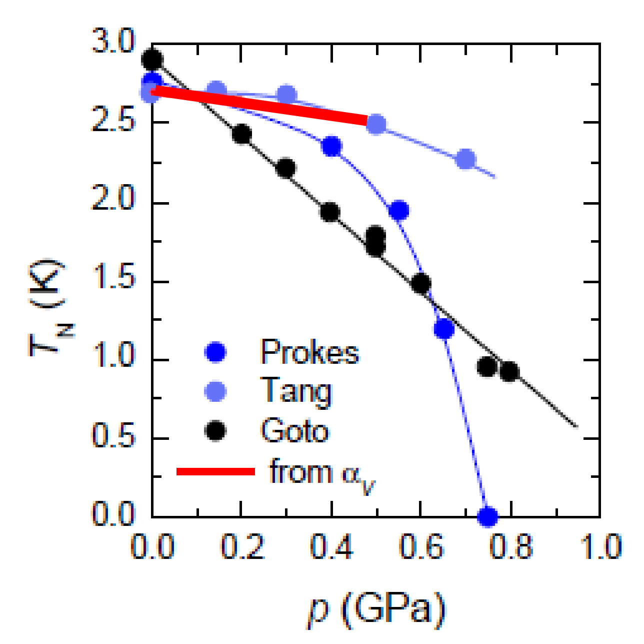
$T_N(x)$ of $CePd_{1-x}Ni_xAl$ polycrystals



V. Fritsch et al., unpublished

Comparison of pressure and Ni substitution: $T_N(V(x))$ and $T_N(V(p))$? Experimental $T_N(p)$ data differ strongly!

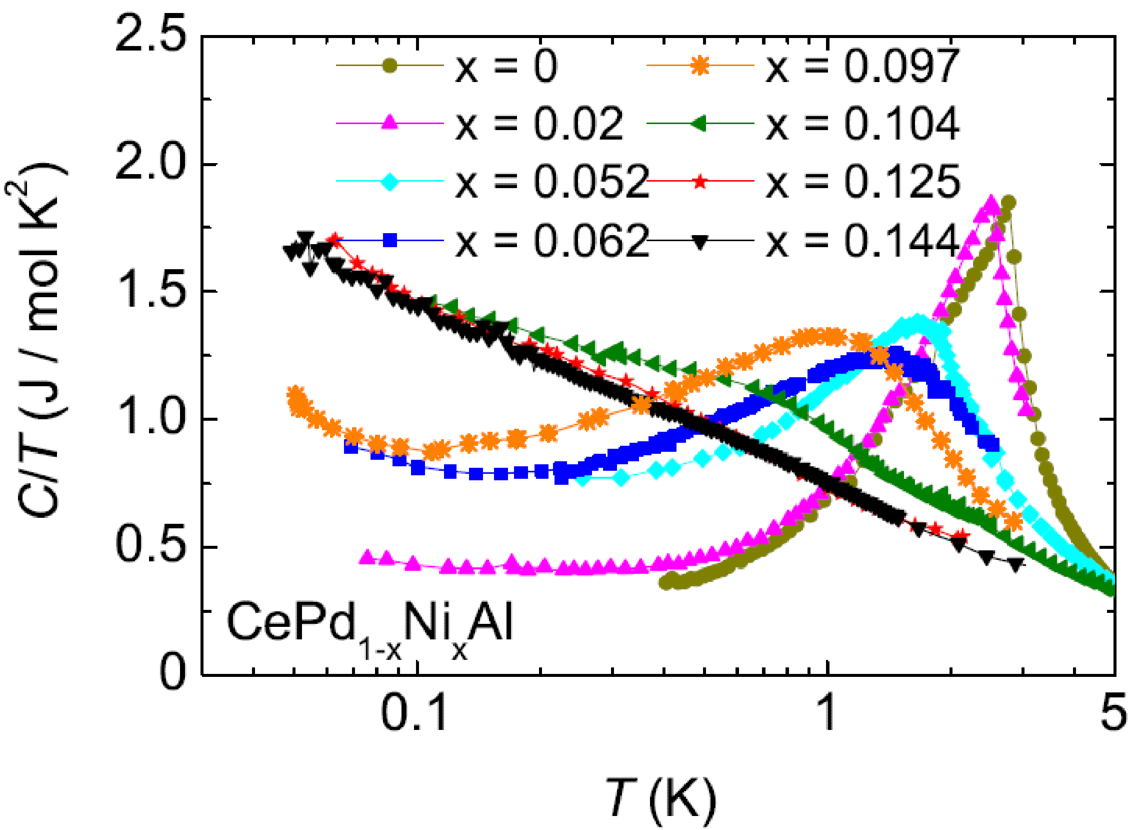
Likely reason: non-hydrasticity of *p*. Thermal expansion: $\alpha \parallel c < 0$, $\alpha \perp c > 0$ $\rightarrow dT_N/dp_a > 0$ and $dT_N/dp_c < 0$.



Best fit with linear T_N dependence on *x*, compatible with 2D HMM scenario, deviation for $x \rightarrow x_c$ (“order by disorder“?)

Approaching quantum criticality of CePdAl by Ni substitution

Specific heat



V. Fritsch et al., PRB 2014

$T_N \to 0$ for $x \approx 0.14$

$C/T \sim -\log(T/T_0)$

2D quantum criticality or novel QCP?

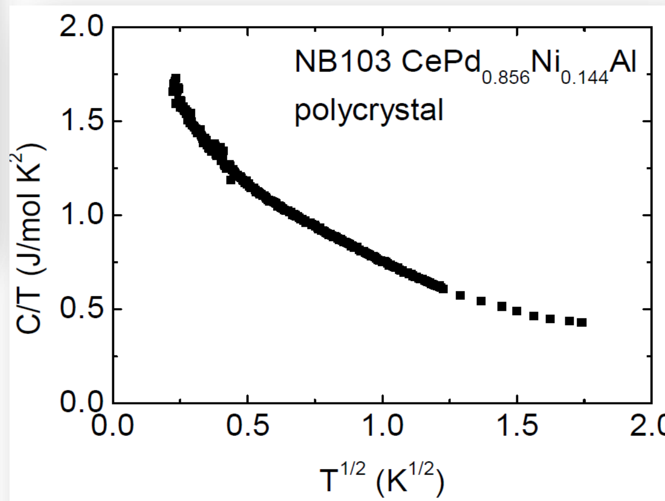
cf. $\rho(T)$ of CePdAl

at p = 1 – 1.2 GPa:

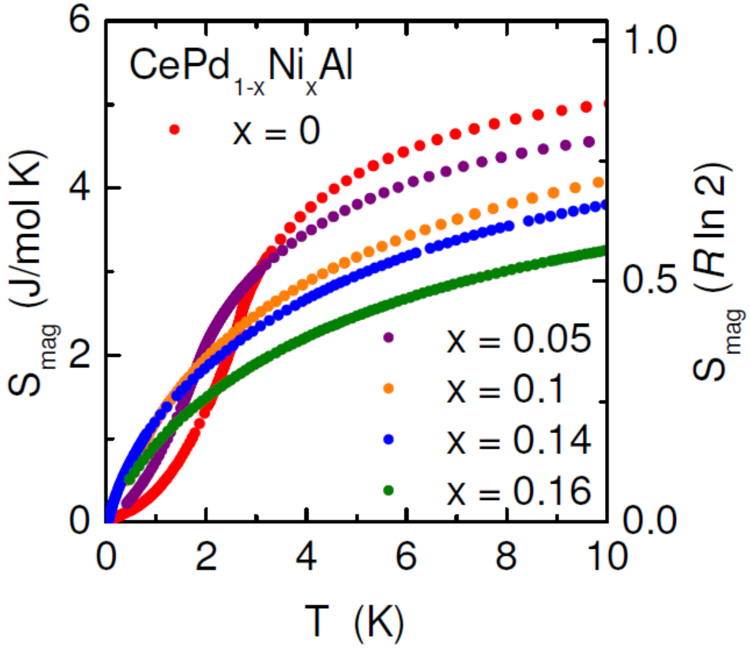
$\rho(T) \sim \rho_0 + AT^n$

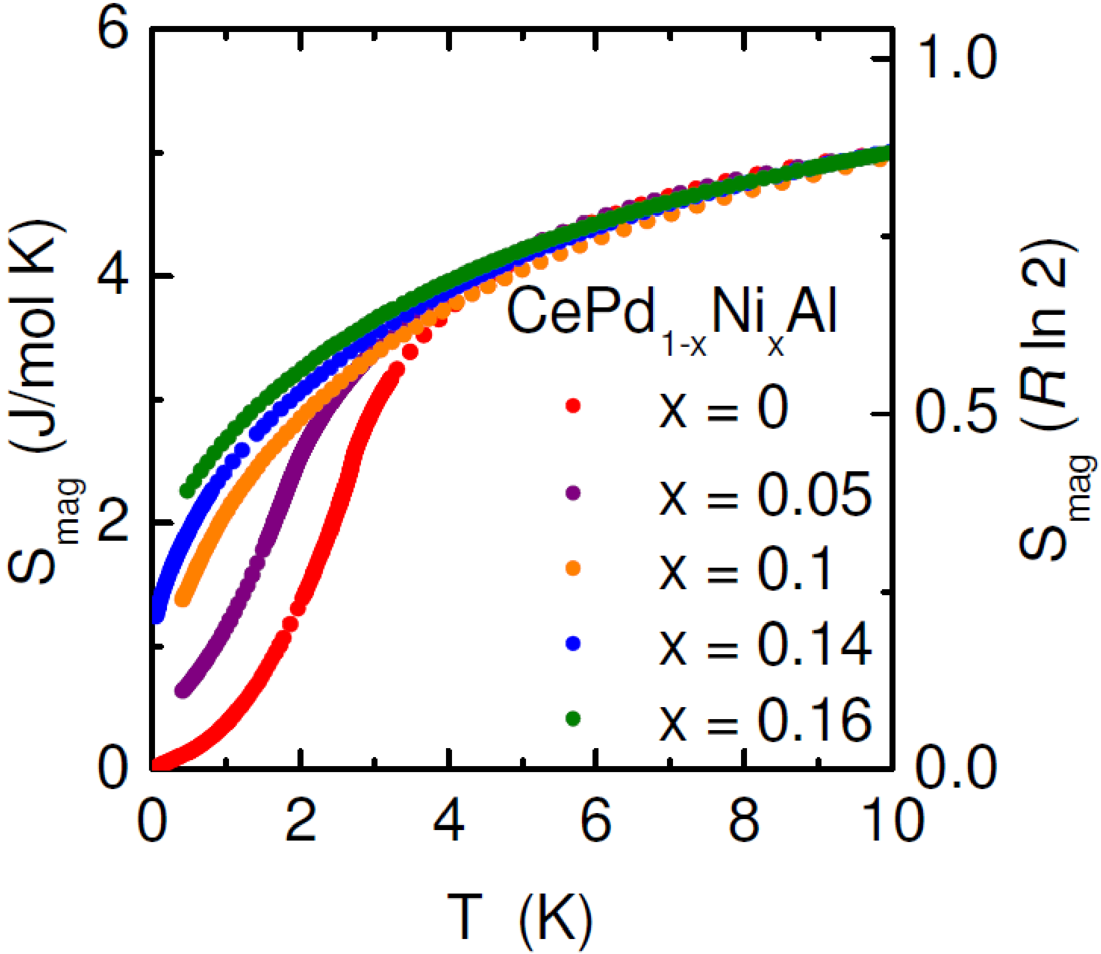
Goto et al., J. Phys. Chem. Sol. ***63****, 1159 (2002)*

Data do not follow →
$C/T \sim 1 - \sqrt{T}$ (3D QCP)

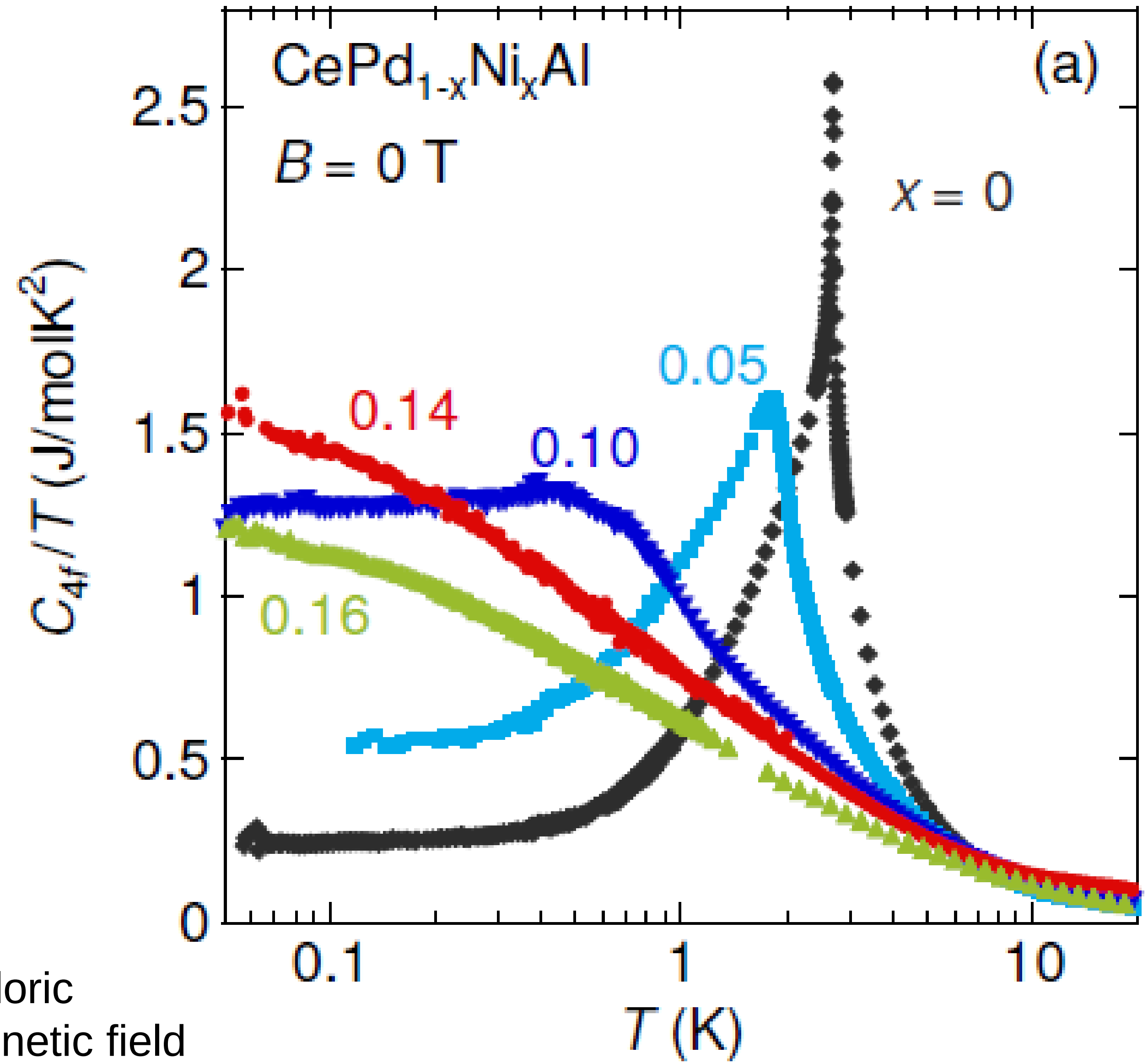


Entropy of $CePd_{1-x}Ni_xAl$



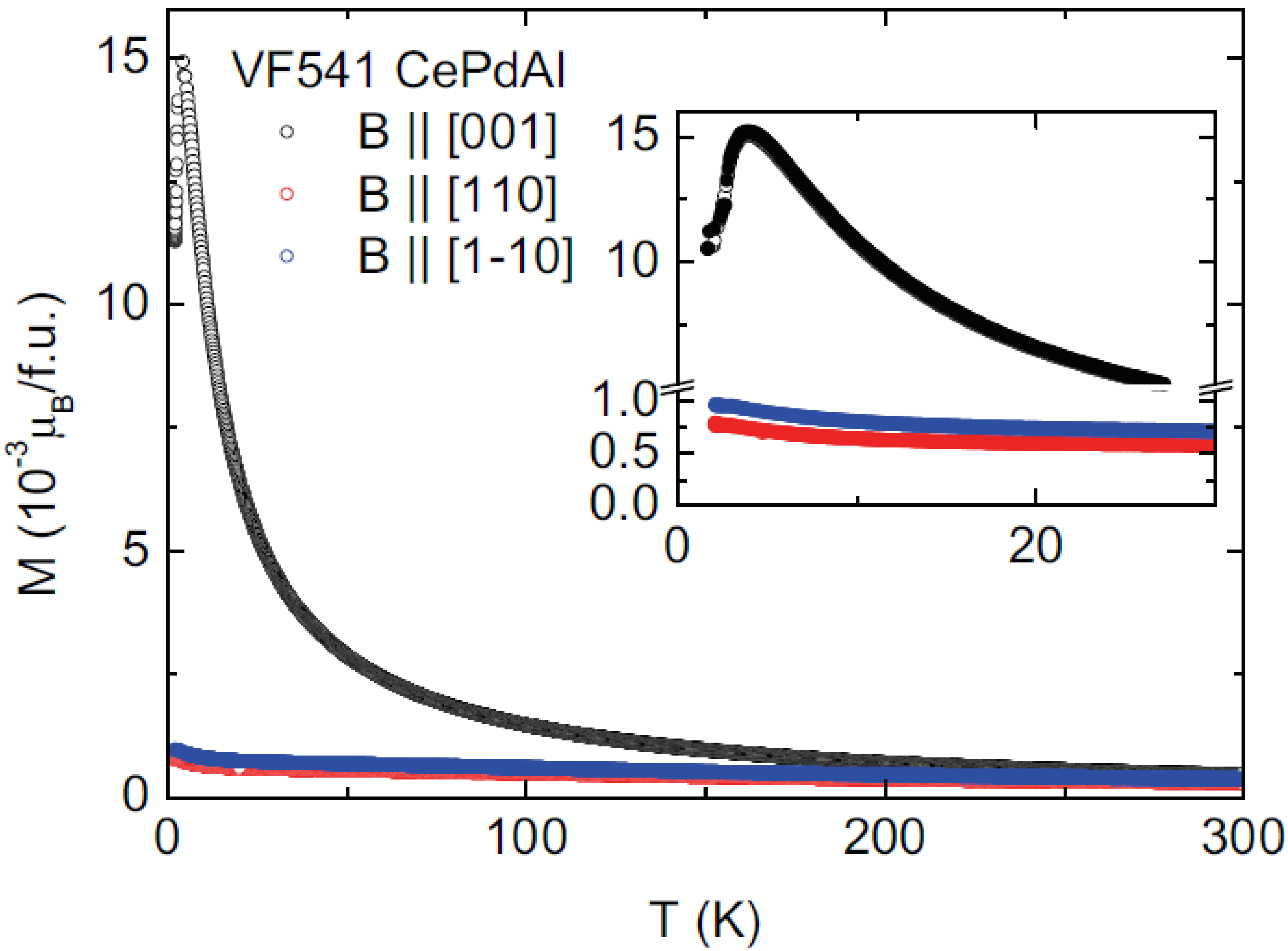


First experiments on $CePd_{1-x}Ni_xAl$ single crystals



Planned: magnetocaloric mesurements in magnetic field

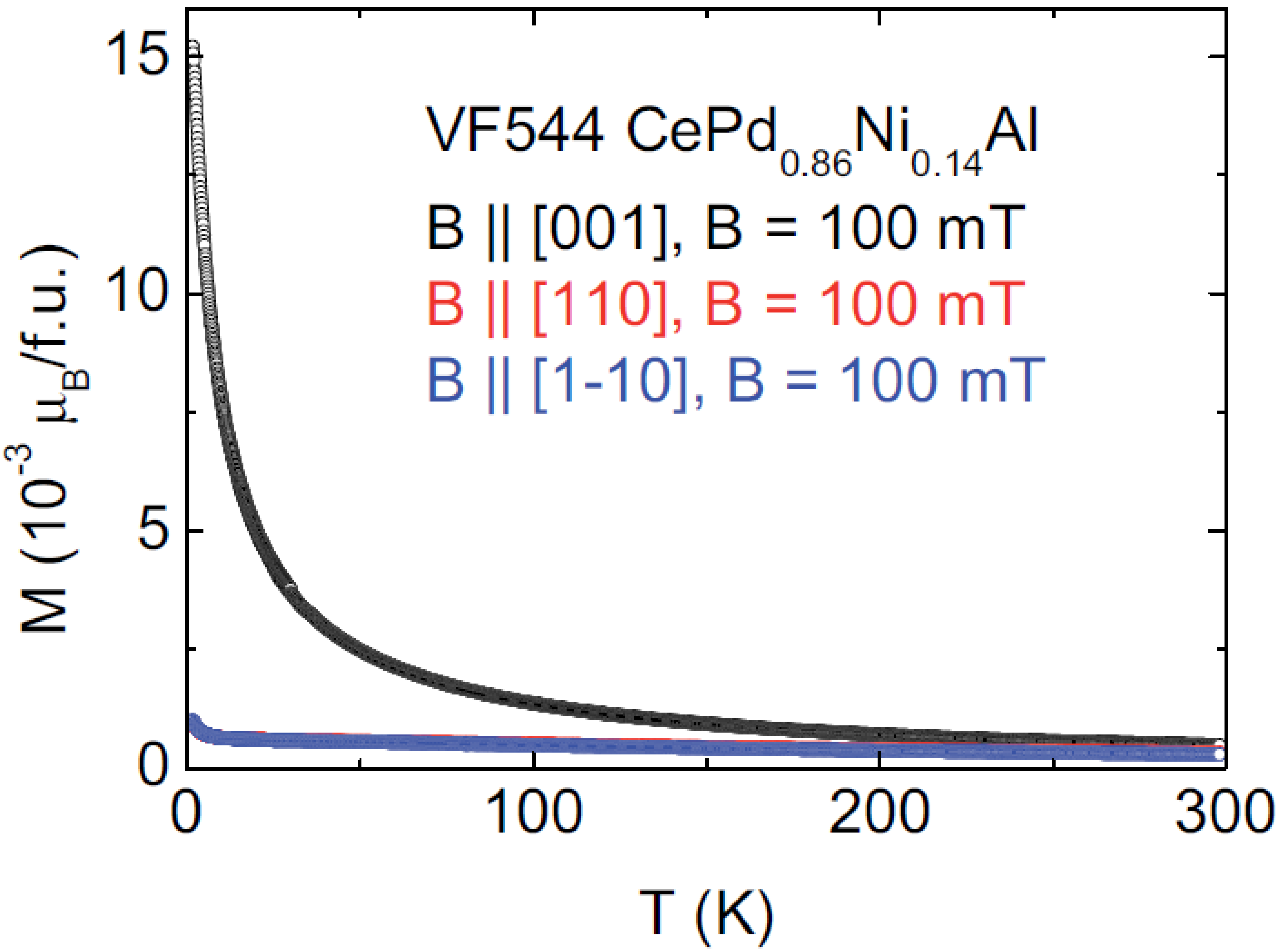
Magnetic susceptibility of a CePdAl single crystal



Strong Ising-like anisotropy due to single-ion crystal-field effects

Isikawa et al., J. Phys. Soc. Jpn. ***65,*** *Suppl. B, 117 (1996)*

Magnetic susceptibility of $CePd_{1-x}Ni_xAl$ with x = 0.14

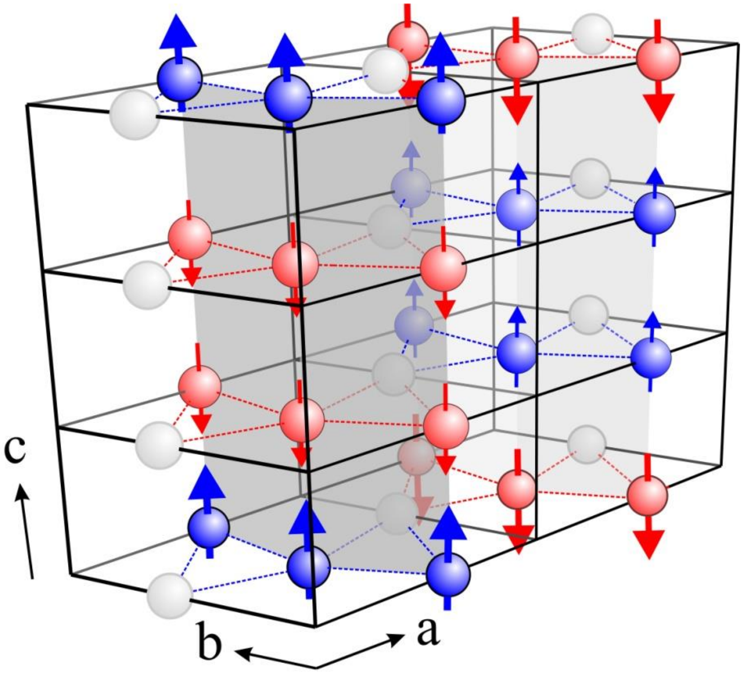


Ising-like anisotropy survives

AF order and 2D quantum criticality in $CePd_{1-x}Ni_xAl$?

Interpretation within the Hertz-Millis-Moriya model:
candidate for planes with 2D fluctuations?

planes perpendicular *ab*



AF planes separated
by frustrated moments

Proposition needs to be checked
by inelastic neutron scattering

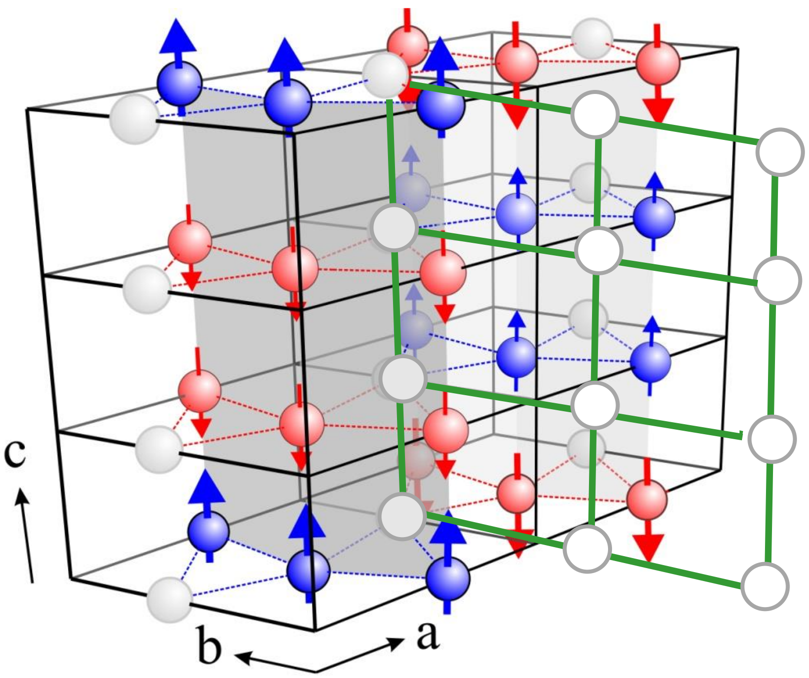
In this scenario, frustrated moments
play a key role and provide
a rationale for 2D fluctuations

However, frustrated moments
may lead to additional fluctuations
not contained in the HMM model

Frustrated Ce moments in CePdAl: a two-dimensional spin liquid?

Spin liquid in CePdAl?

planes ⊥ *ab*



AF planes separated
by frustrated moments

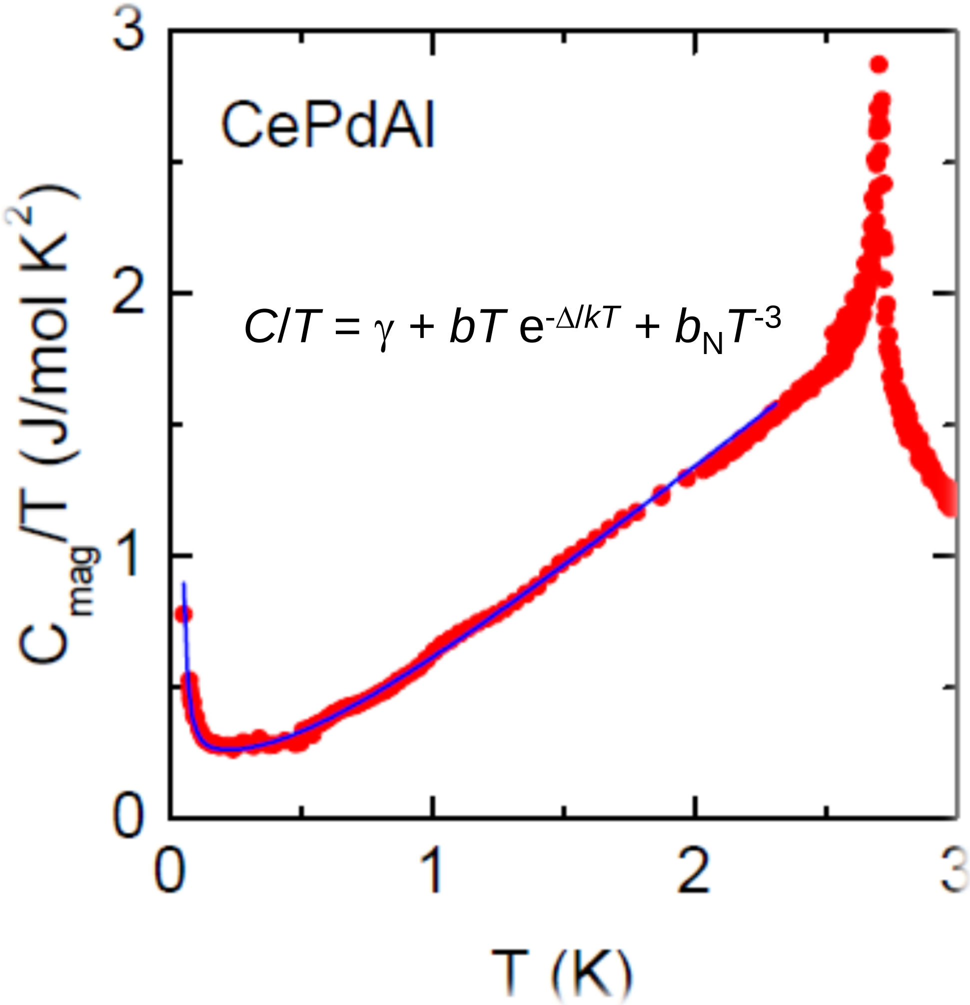
Frustrated planes between AF planes form a rectangular 2D lattice:

2D Ising spin liquid?

^{27}Al NMR measurements down to 30 mK: dynamics of frustrated moments prevails down to very low T, with $T_1^{-1} \sim T$

*Oyamada et al., Phys. Rev. B **77**, 064432 (2008).*

Specific heat of CePdAl at low temperature



Several unusual features

large γT term

$\gamma \sim 0.8$ J/mole$_{Ce\text{-}no}$K^2

T^2 term ~ T^2 setting in at 0.5 K

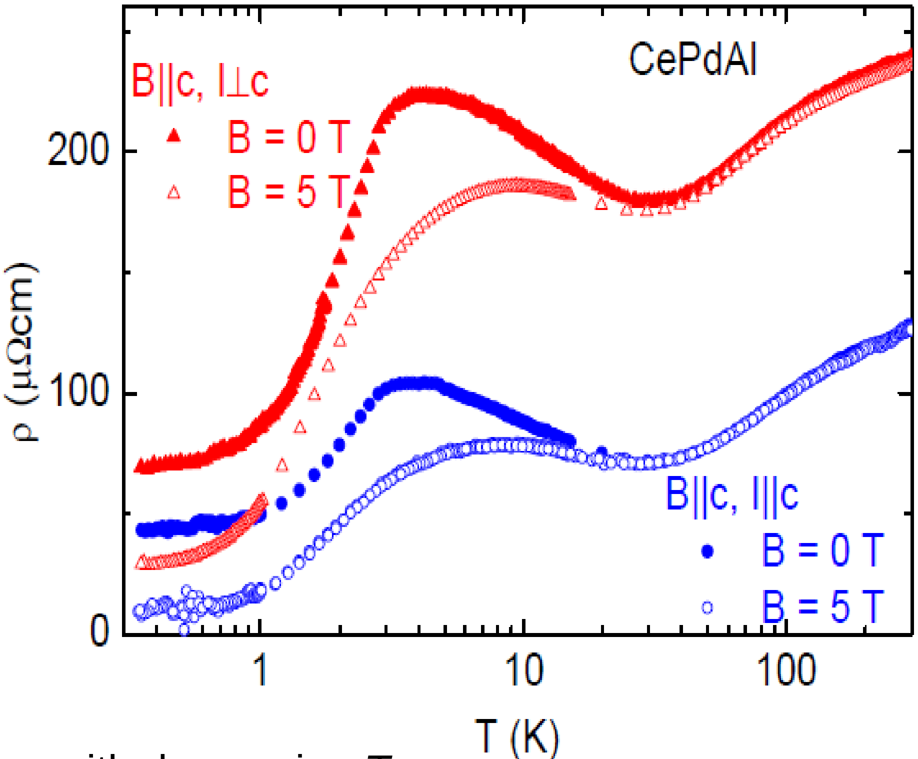
excitation gap: $\Delta / k_B \approx 0.9$ K

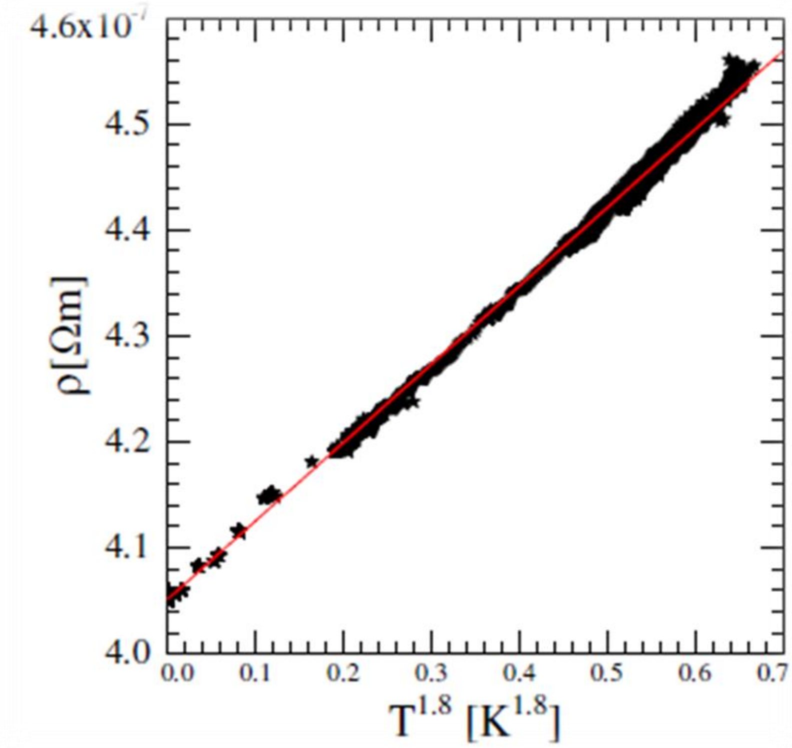
2D spin waves in AF planes

T^{-2} contribution at low T presumably

due to nuclear hyperfine splitting

Electrical resistivity of CePdAl single crystals





with decreasing *T*:

- Kondo increase
- coherence maximum
- drop to ρ_0

strong decrease of the residual resistivity ρ_0 in magnetic field above B_c:

$\Delta\rho_0/\rho_0$ strongest for ρ II c

at lowest temperature: $\rho(T) = \rho_0 + AT^{1.8}$.

- no indication of Kondo effect by non-ordered frustrated Ce moments
- assuming T^2 resistivity:

  $A/\gamma^2 \sim 13\ a_{KW}$

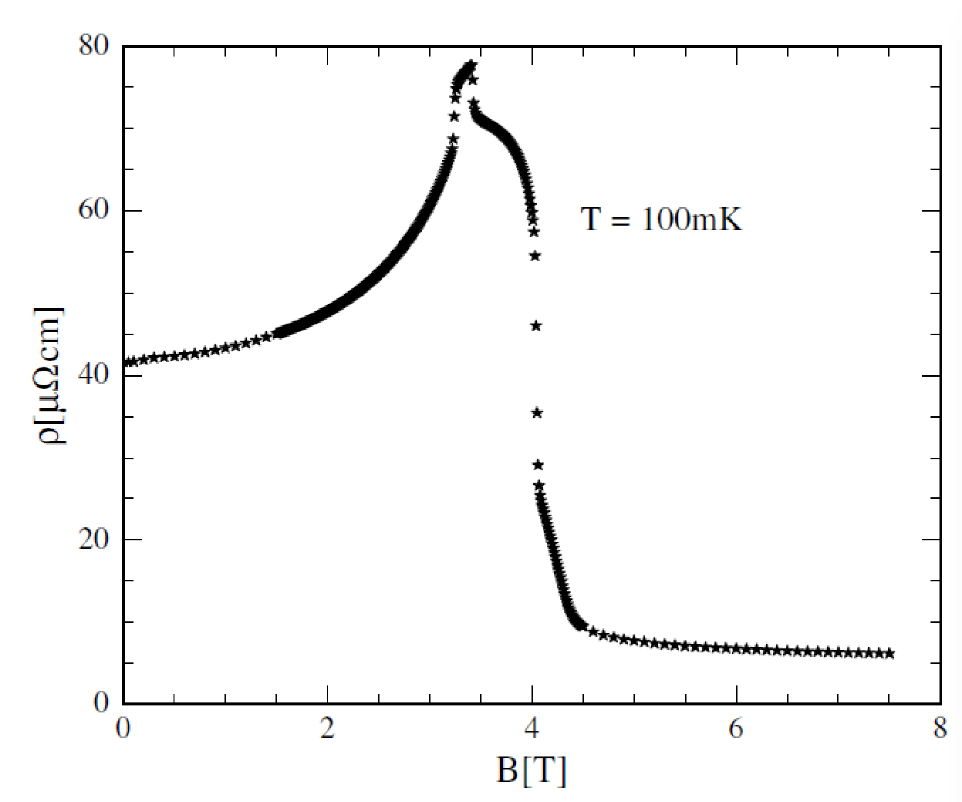
  Spinon excitations?

Field-induced phases in CePdAl close to the critical field

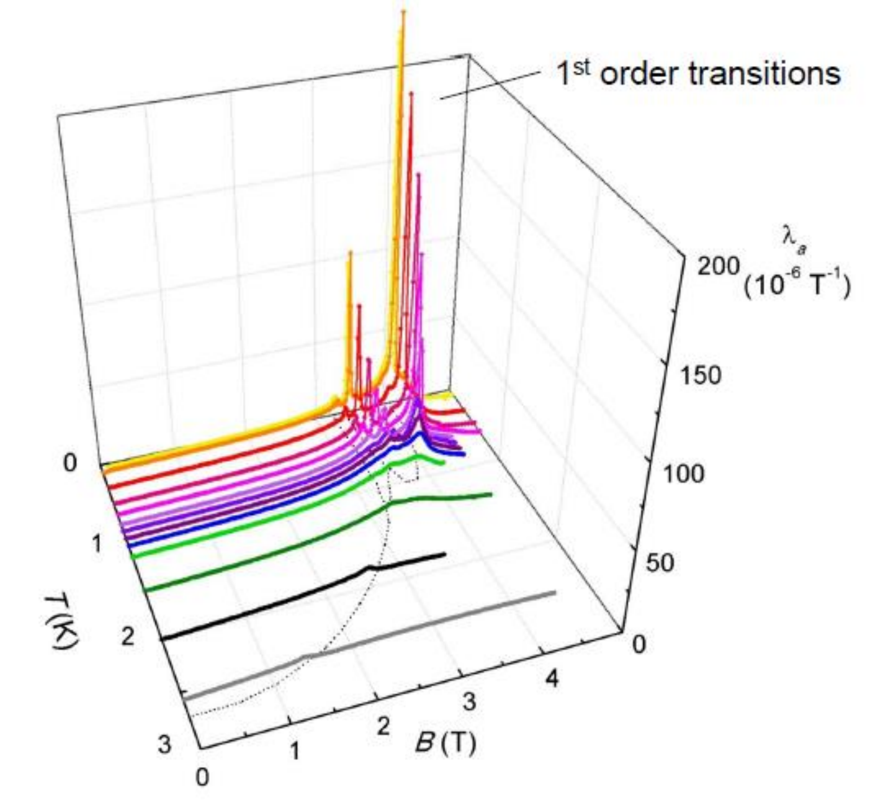
Features in magnetizattion *M*(*B*) and resistivitiy ρ(*T*) are suggestive of first-order transitions

T. Goto et al., J. Phys. Chem. Sol. 63, 1159 (2002)

Resistivity at 100 mK



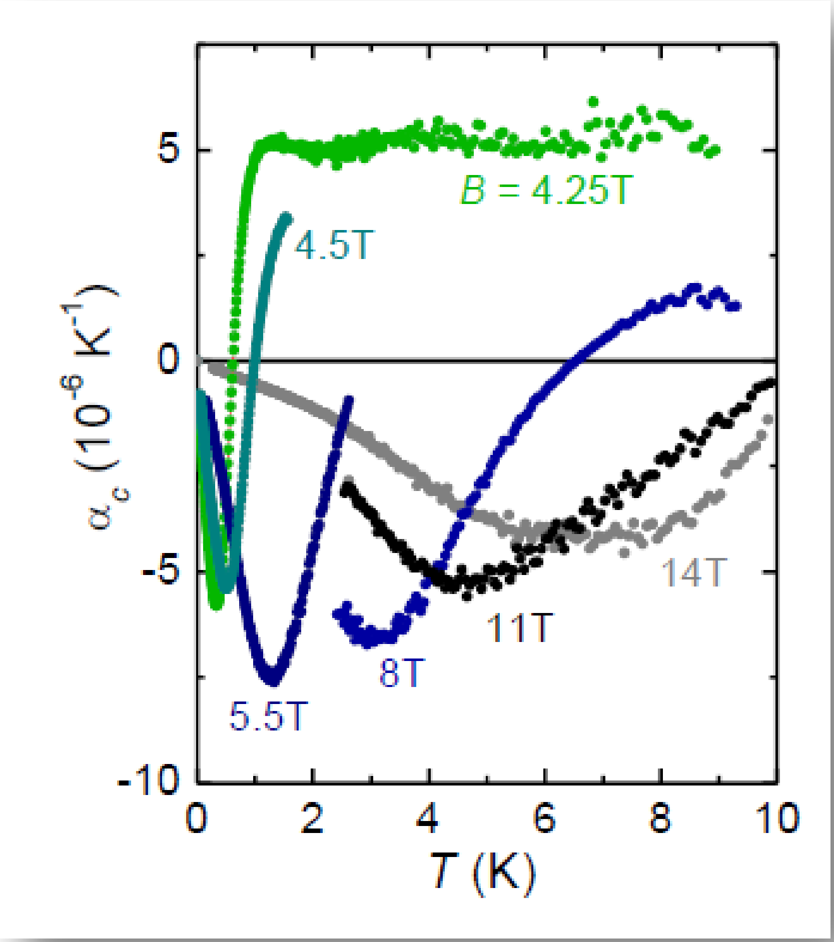
Magnetostriction

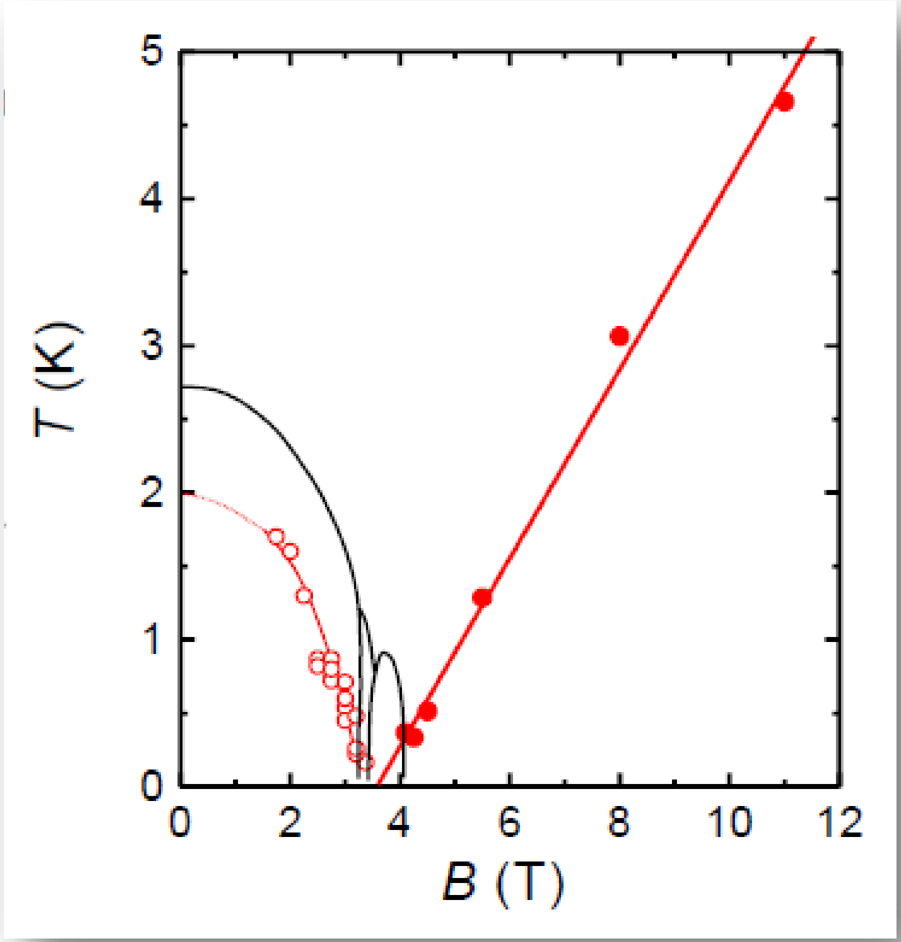


C. Taubenheim et al.

K.Grube et al.

High-field thermal expansion of CePdAl

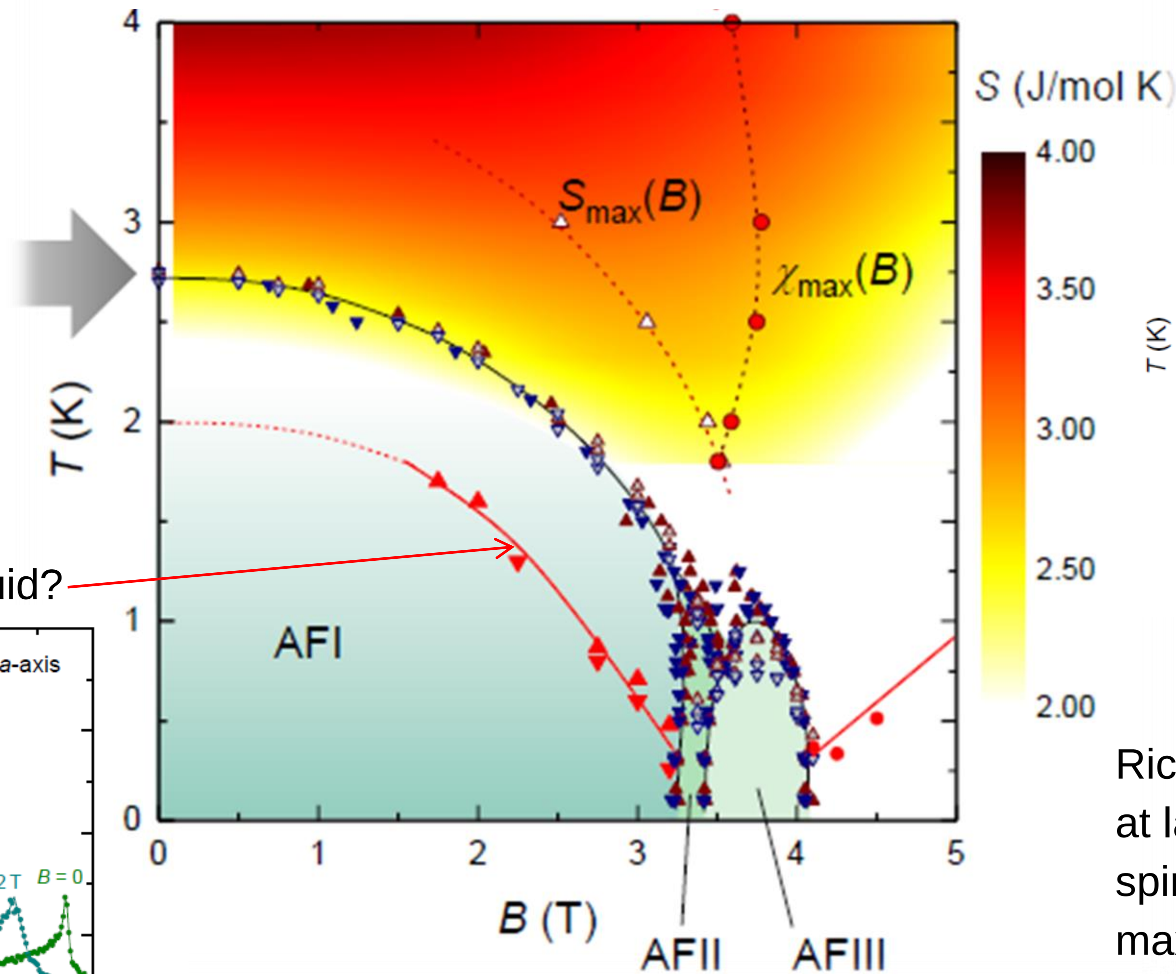




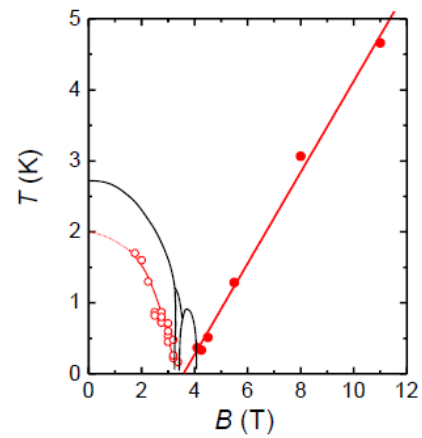
Extrema in α_c above B_c: due to Zeeman splitting of the lowest CEF doublet?

$k_B T_{max} \sim g\,\mu\,(B - B_c)$

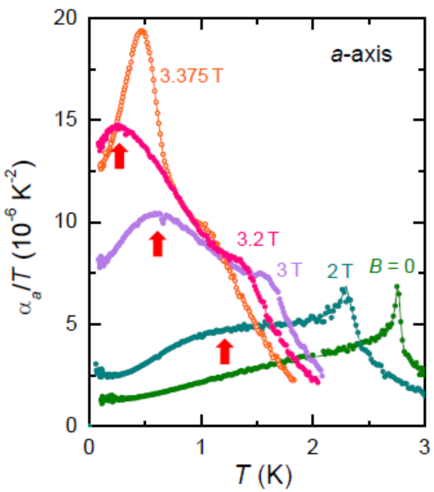
Magnetic phase diagram of CePdAl from thermal expansion and magnetostriction



High-field Schottky anomaly due to Zeeman splitting



Crossover to spin-liquid?

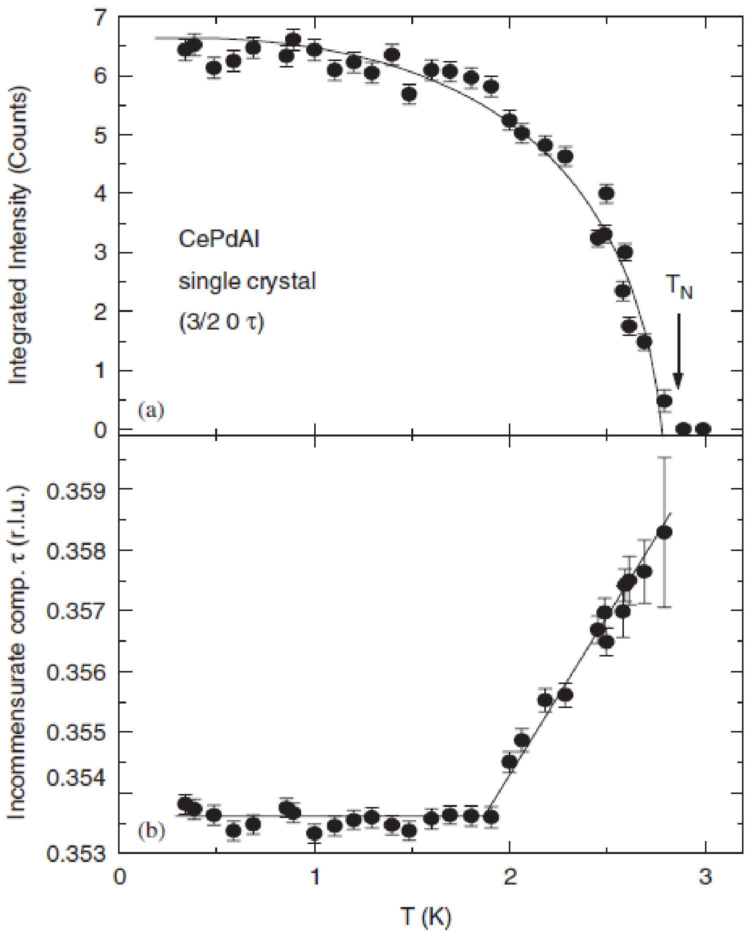


Rich phase diagram at large B and low T: spin liquid freezes out, maximum of $S(B,T = \text{const})$

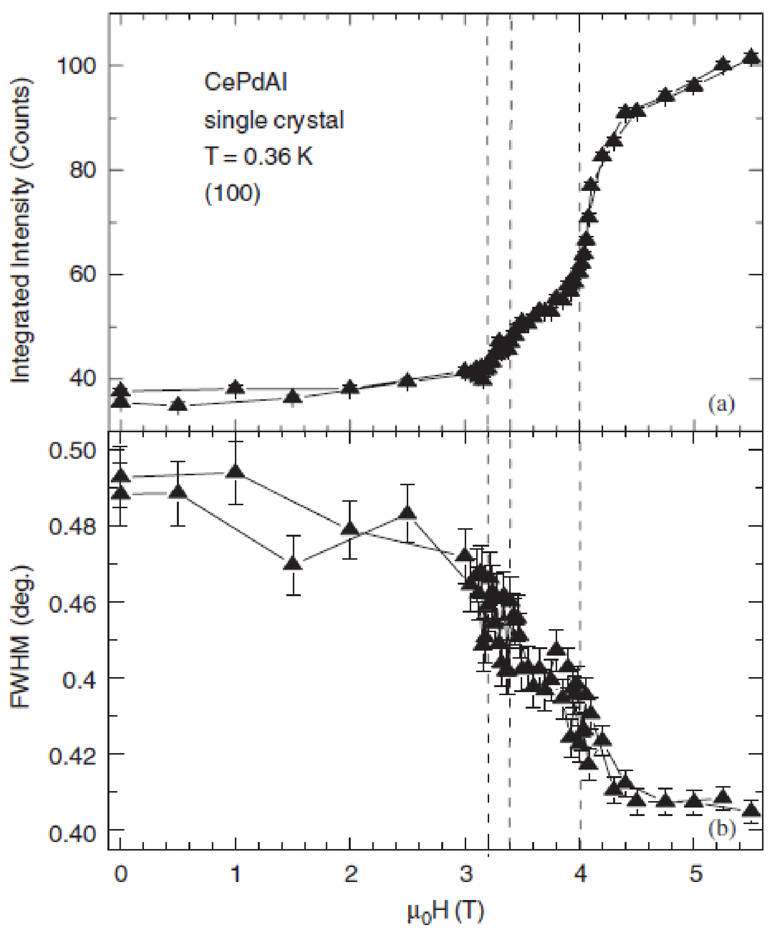
K. Grube et al., unpublished

Towards a (*B*,*T*) phase diagram from elastic neutron scattering

Lock-in of the *c* component τ of the magnetic propagation vector at 1.9 K: relation to feature in $\alpha_a(T)$?



Evolution of ferromagnetic component with magnetic field



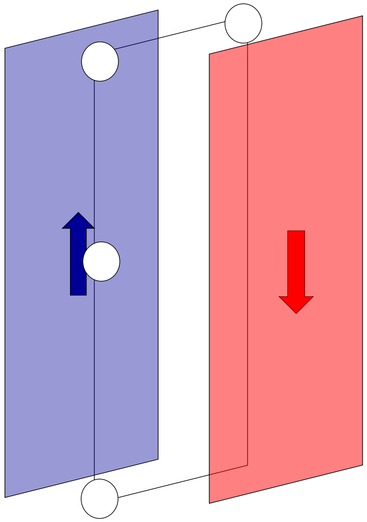
*K. Prokes et al., Physica B **385-386**, 359 (2006)*

Fate of the Kondo effect in the presence of frustration?

If we now naively generalize this single-impurity model to the lattice, we will find that the $T=0$ ground state always has Kondo screening. It is only upon including frustrating intermoment exchange interactions—equivalent to having "dispersing" spinons—that it is possible to break down Kondo screening and reach a state in which the slave boson is not condensed.

*Senthil, Vojta, Sachdev, PRB **69**, 135111 (2004)*

(1)



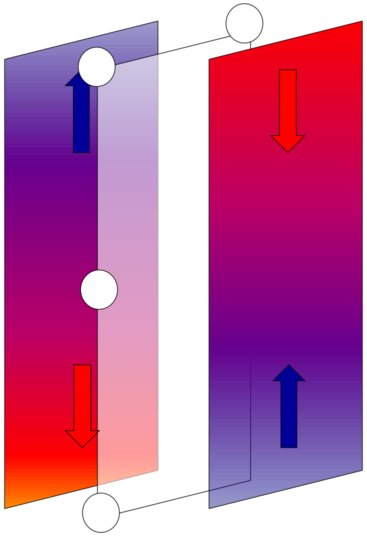
A pedestrian's approach to the problem

(1) 2D rectangular Kondo lattice exposed to frustrating molecular field within an *ab* layer?

(2) Include staggered magnetization.

(3) Additional complication: $6s^2 5d^1$ electrons.

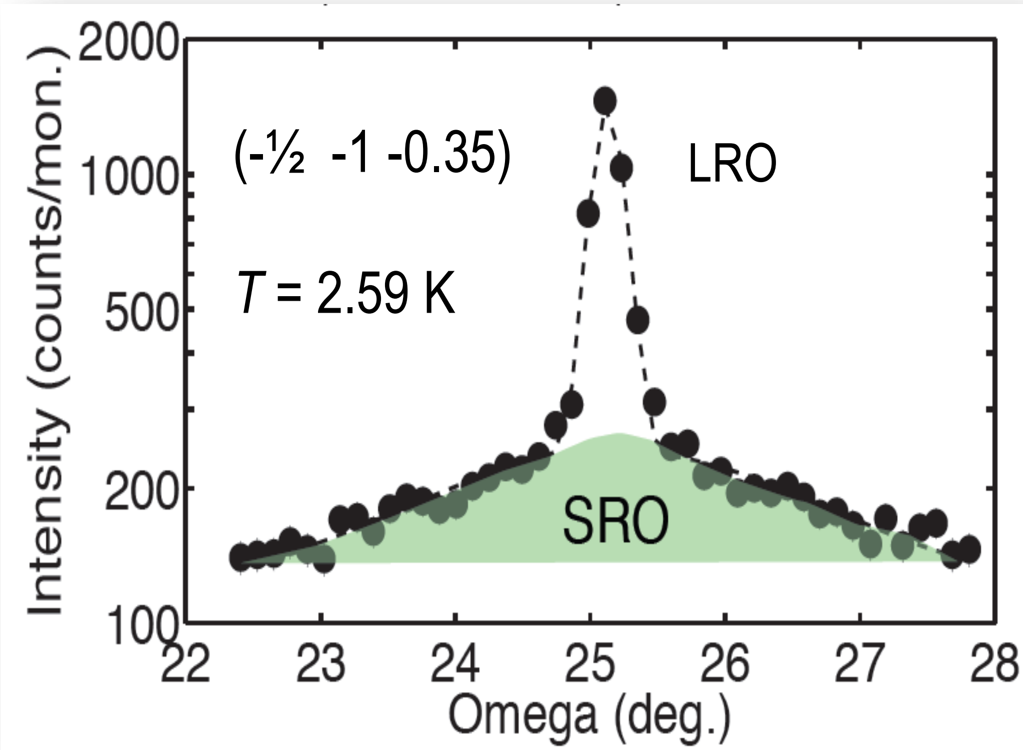
(2)

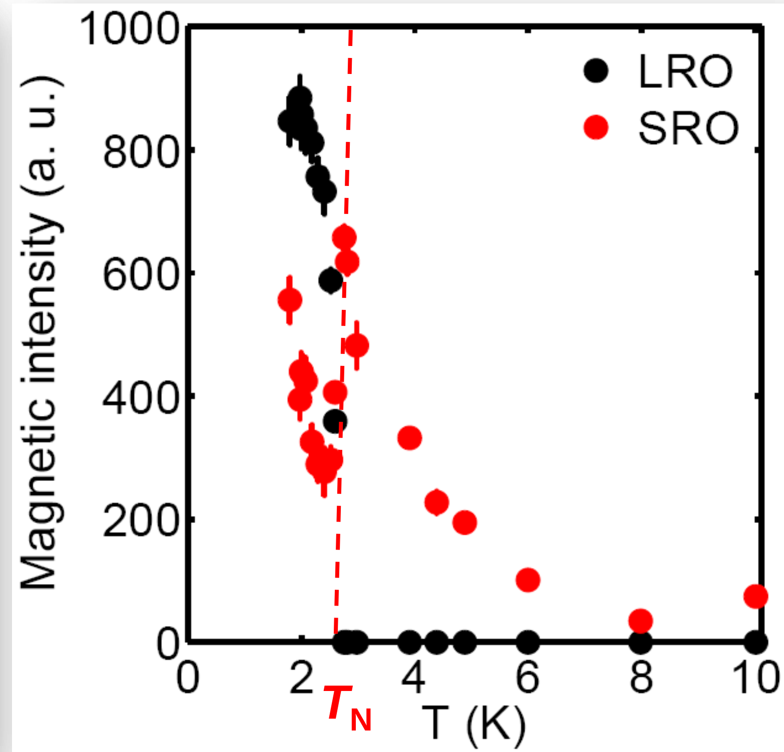


Long-range and short-range magnetic order in CePdAl

D20 ILL

O. Stockert et al., unpublished





LRO/SRO intensity ratio of 2/1 below T_N:

compatible with short-range (dynamic?) order of frustrated moments

→ rationale for quasi-2D fluctuations

cf. NMR measurements *Oyamada et al., Phys. Rev. B 77, 064432 (2008).*

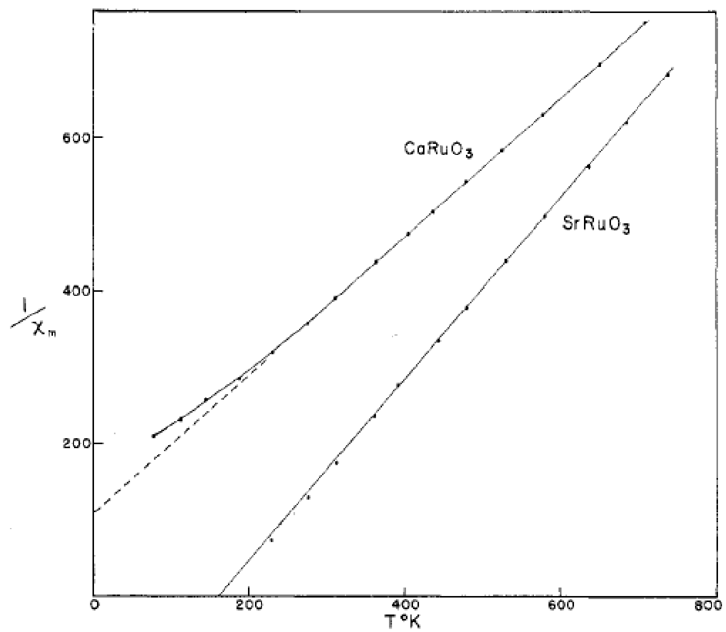
Classical and quantum phase transitions in the itinerant ferromagnet $Sr_{1-x}Ca_xRuO_3$

A brief history of $Sr_{1-x}Ca_xRuO_3$

$SrRuO_3$ is the $n = \infty$ member of the Ruddleston-Popper series $Sr_{n+1}Ru_nO_{3n+1}$
Most prominent are the n =1 and n = 2 materials

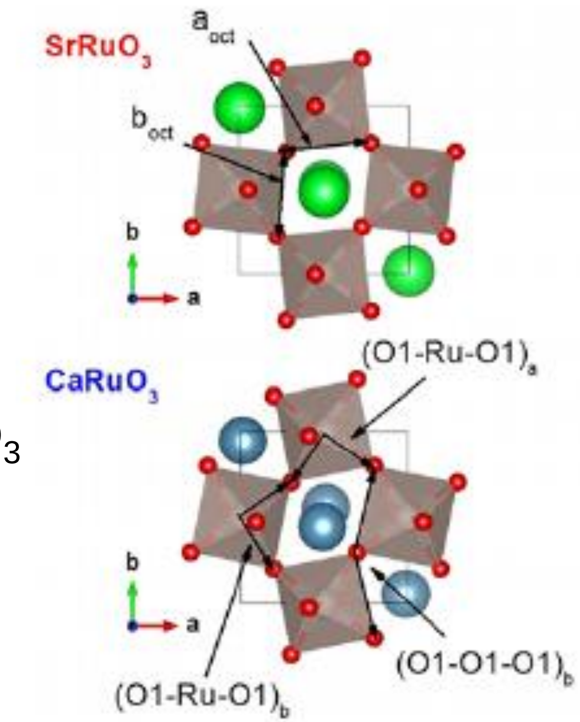
Sr_2RuO_4 odd-parity superconductor
$Sr_3Ru_2O_7$ anomalous quantum criticality

Discovery of ferromagnetism



A. Callaghan et al., Inorg. Chem. ***5****, 1572 (1966)*

Structural differences between $SrRuO_3$ and $CaRuO_3$

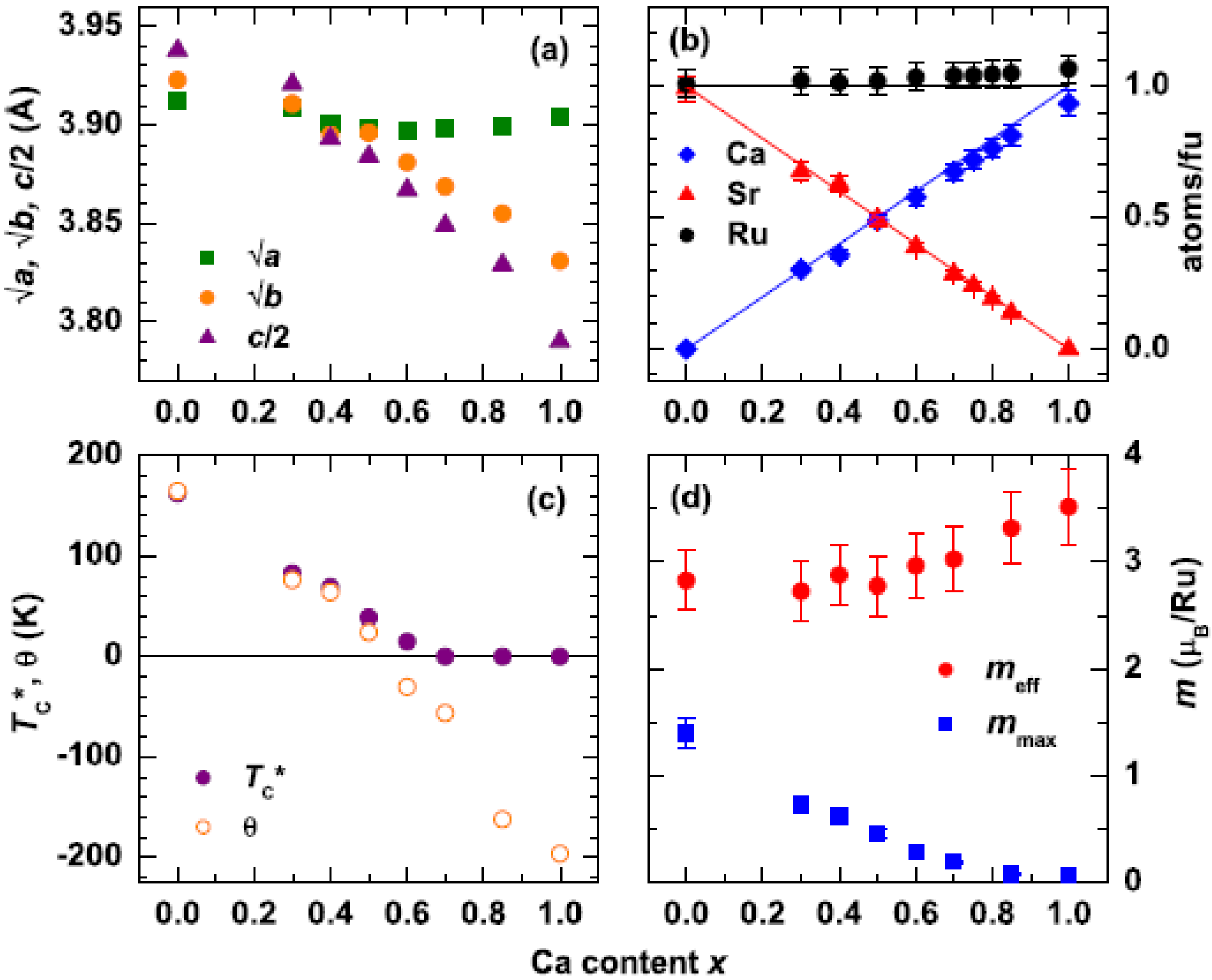


S. Lee et al., J. Phys. Cond. Matt. ***25****, 465601 (2013)*

Structural and magnetic data of $Sr_{1-x}Ca_xRuO_3$

Polycristalline samples:

- Sintering of $SrCO_3$, $CaCo_3$, and RuO_2 powders
- Calcination at 900°C, 10 h
- Milling and pelleting and sintering at 1370°C, 30 h



*D. Fuchs et al., PRB **89**, 147405 (2014)*

Evolution of critical expoenents in $Sr_{1-x}Ca_xRuO_3$ with *x*

Critical exponents: single crystals vs. polycristals

Two cases

(1) Magnetic easy axis varies on a length scale < ξ: random anisotropy changes the universality class of the transition

(2) Crystallites (~ several µm) >> ξ: individual crystallites obey scaling relations. Each crystallite is exposed to an effective field

$$H_{\text{eff}} = H \times f(\theta, \varphi)$$

leading to a magnetization density $M(\theta, \varphi)$.

Averaging over crystallites with $p(\theta, \varphi)$ gives the total magnetization density

$$M = \int \sin\theta d\theta d\varphi p(\theta,\varphi) M(\theta,\varphi) = t^{\beta} \tilde{\phi}(H/t^{\beta\delta}),$$

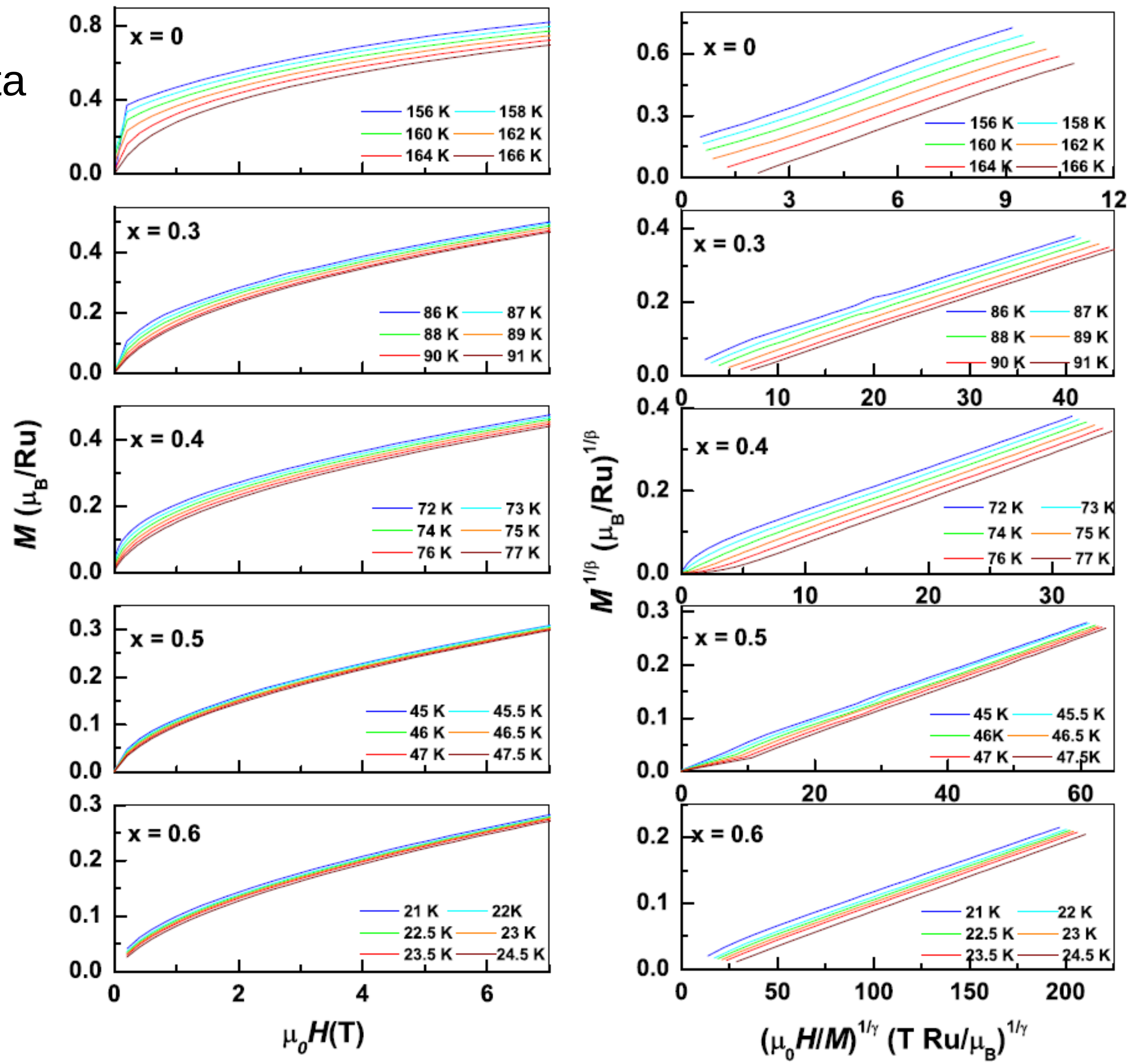
where

$$\tilde{\phi}(x) = \int \sin\theta d\theta d\varphi p(\theta,\varphi) \phi(f(\theta,\varphi),x).$$

This is the same scaling form with modified scaling function (except for pathological $p(\theta, \varphi)$ distributions). In particular, the limits for small and large arguments, corresponding to Arrott-Noakes plots, are the same.

Magnetization of ferromagnetic $Sr_{1-x}Ca_xRuO_3$

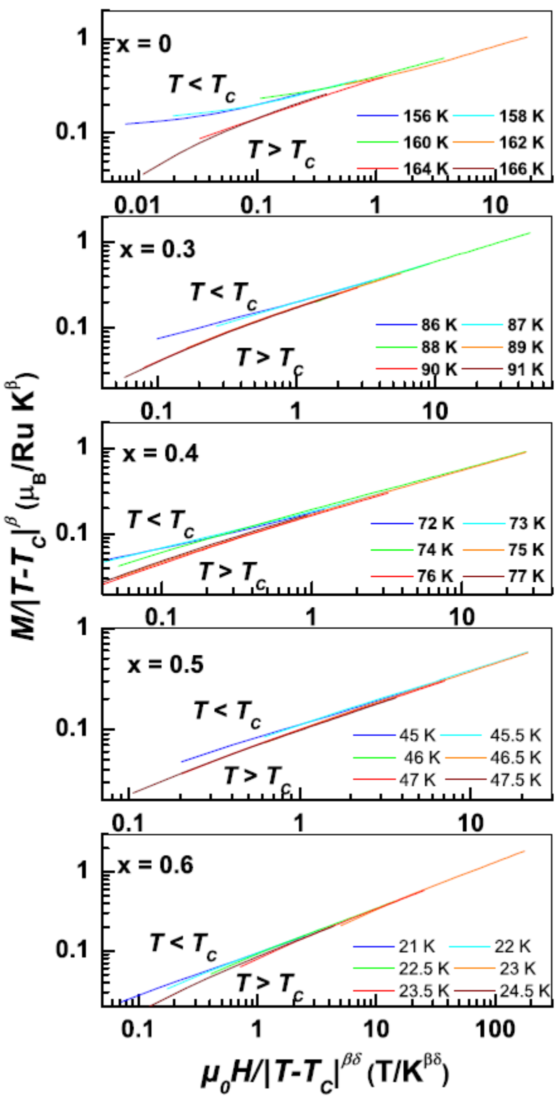
M(*H*) data



Determination of critical exponents β and γ from modified Arrott plots

D. Fuchs et al., PRB ***89****, 147405 (2014)*

Scaling analysis of the finite-T transitions in $Sr_{1-x}Ca_xRuO_3$



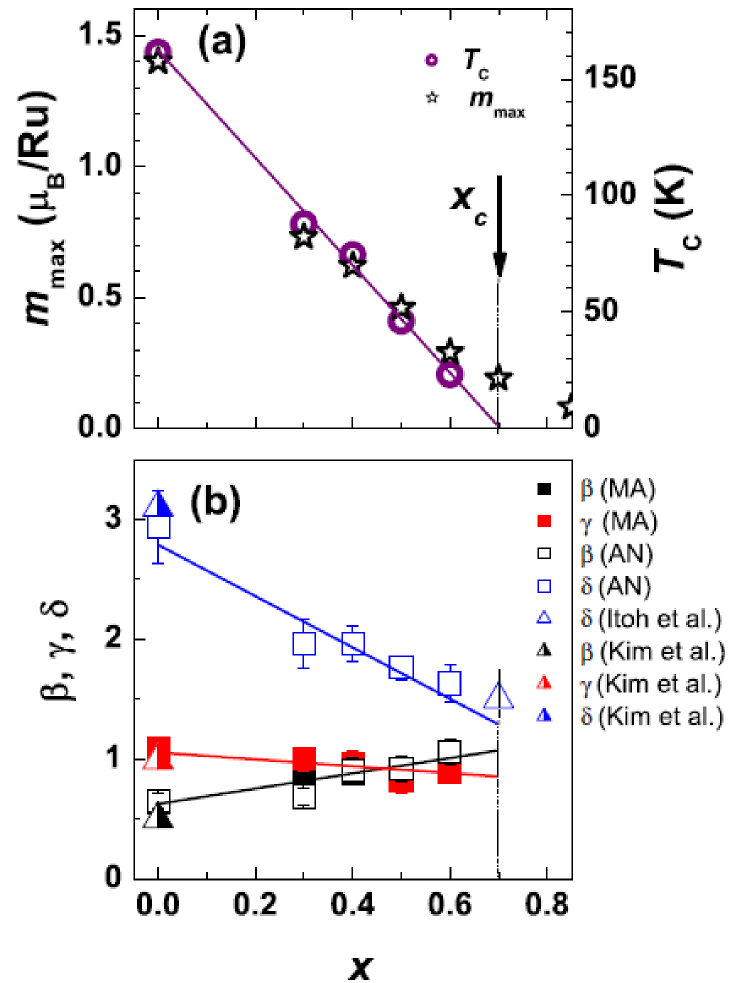
$$M(t,H) = t^{\beta}\phi(H/t^{\beta\delta})$$

$x = 0$
$\beta \approx 0.5, \gamma \approx 1,\ \delta \approx 3$

$x > 0$
continuous change of β, γ, and δ

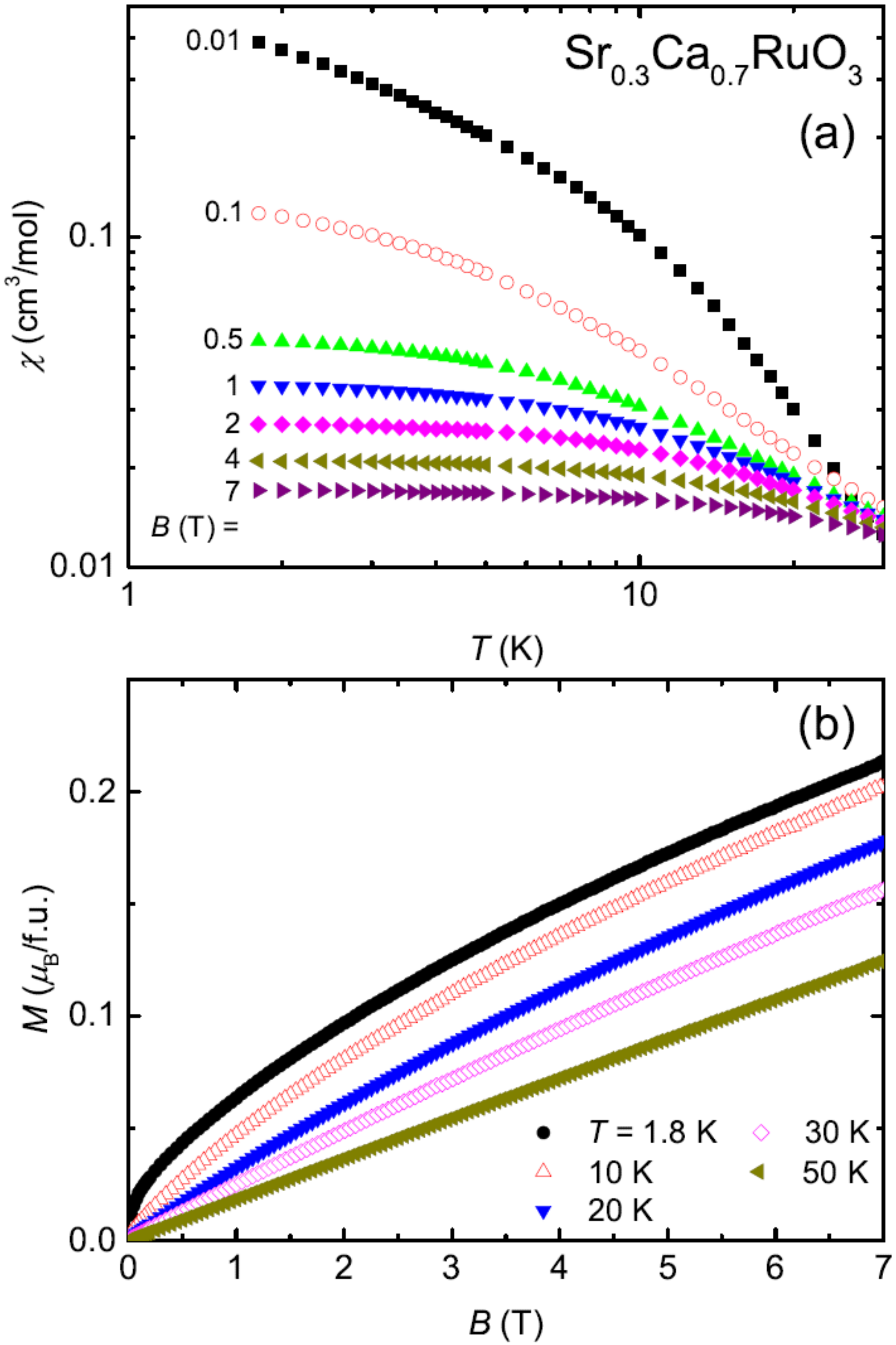
Widom relation
$\gamma/\beta = \delta - 1$
approximately obeyed for all $x \leq 0.6$

*D. Fuchs et al., PRB **89**, 147405 (2014)*



Unusually slow quantum critical dynamics

Magnetization and susceptibility of $Sr_{0.3}Ca_{0.7}RuO_3$



..C.-L. Huang et al., Nature Conm. 2015

Scaling relations near a quantum critical point

Scaling law of the free energy at a QCP

$$\mathcal{F}(T,B) = b^{-(d+z)}\mathcal{F}(b^z T, b^y B),$$

yields for the magnetization

$$M(T,B) = -\frac{\partial \mathcal{F}}{\partial B} = b^{y-(d+z)} M(b^z T, b^y B).$$

Setting the scale factor $b^z T = 1$, or $b^y B = 1$ for $T \to 0$ gives

$$M(T,B) = T^{\frac{d+z-y}{z}} \Phi(\frac{B}{T^{y/z}}), \text{ or } \quad M(B) \propto B^{\frac{d+z-y}{y}} \propto B^{1/\delta}$$

The correlation length exponent ν can be obtained by determining the magnetization as function of $r = x_c - x$ because $\xi \sim |r|^{-\nu}$:

$$M(r) = r^{\nu(d+z-y)} M(r=0) \sim |r|^{\beta}$$

Hence $\beta = \nu(d+z-y)$. With δ we obtain

$$y = \delta\beta/\nu.$$

The critical part of the specific heat scales as

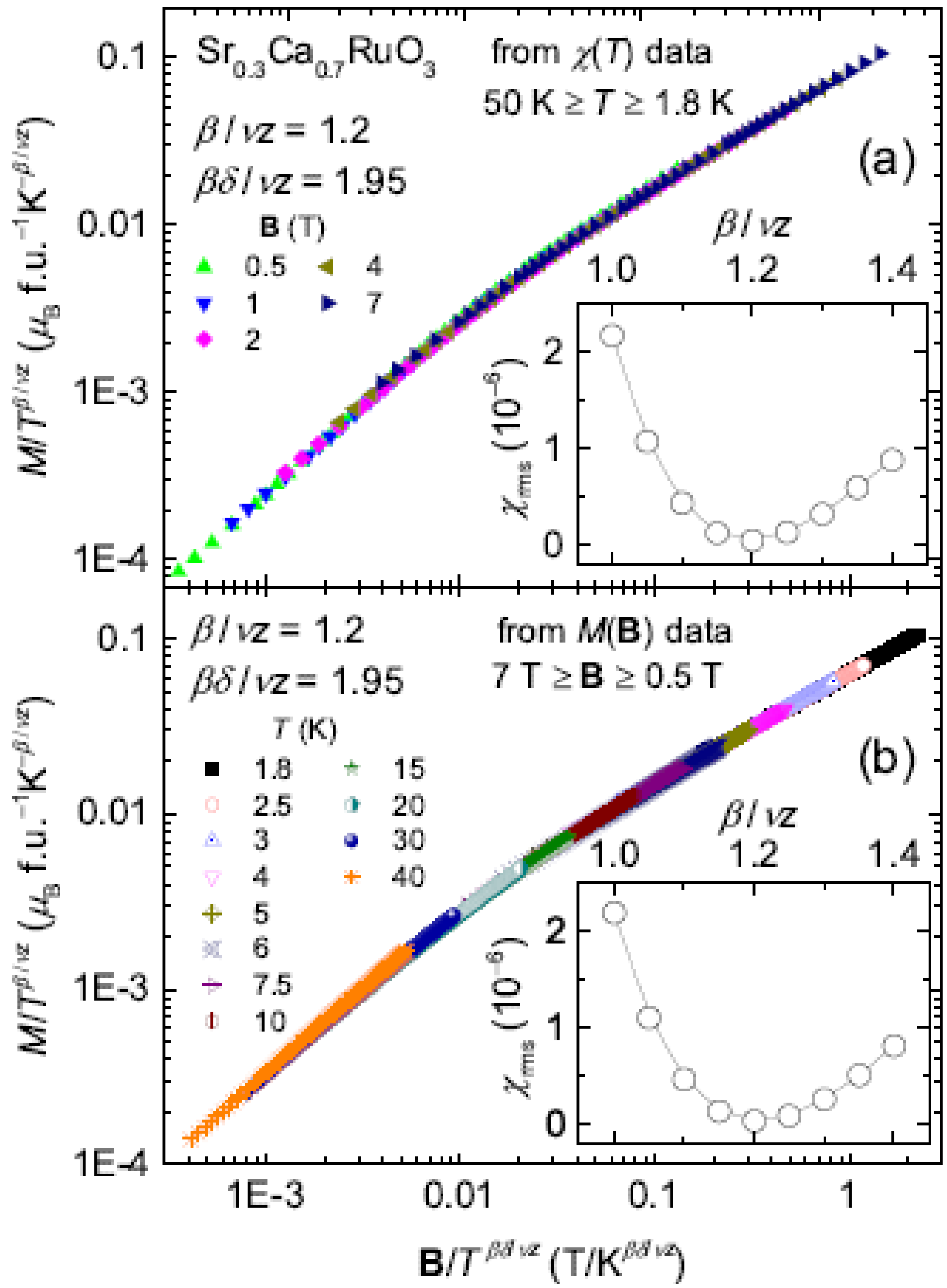
$$C_{cr}(T,B) = T^{\frac{d}{z}} \Psi\left(B/T^{\frac{\beta\delta}{\nu z}}\right).$$

Scaling of the susceptibility and magnetization

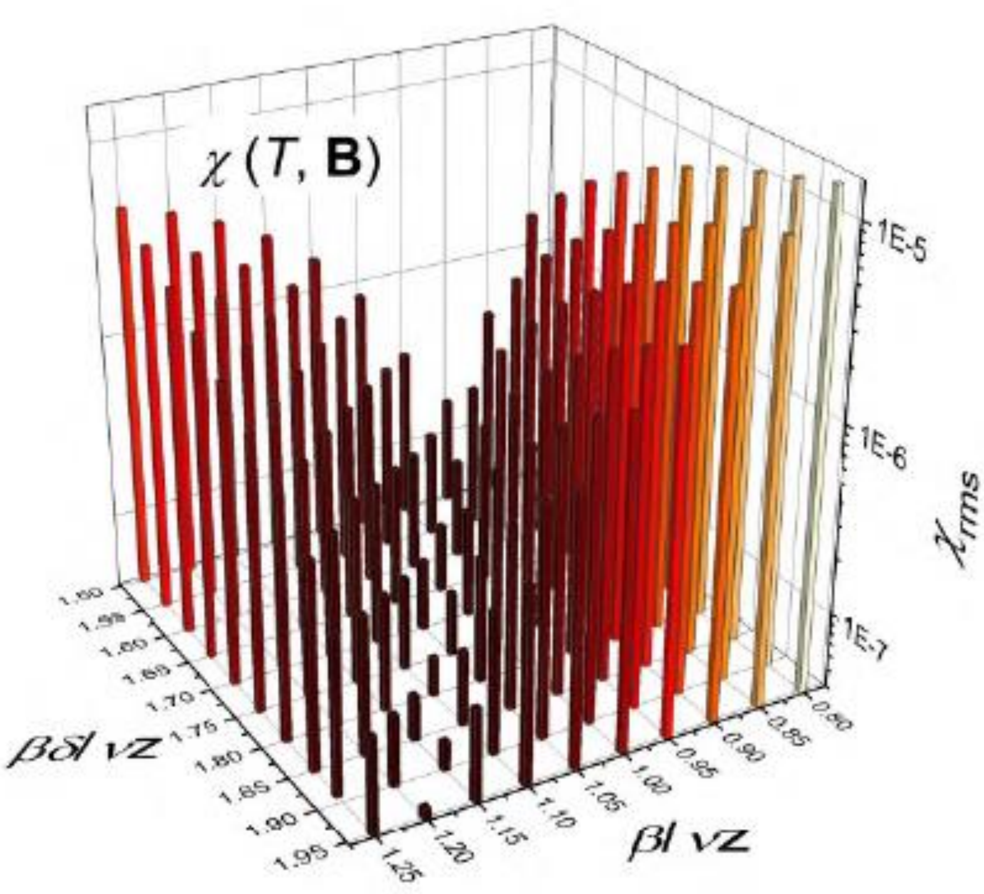
best data collapse observed with exponents

$$\frac{\beta}{\nu z} \approx 1, \ \frac{\delta\beta}{\nu z} \approx 1.7$$

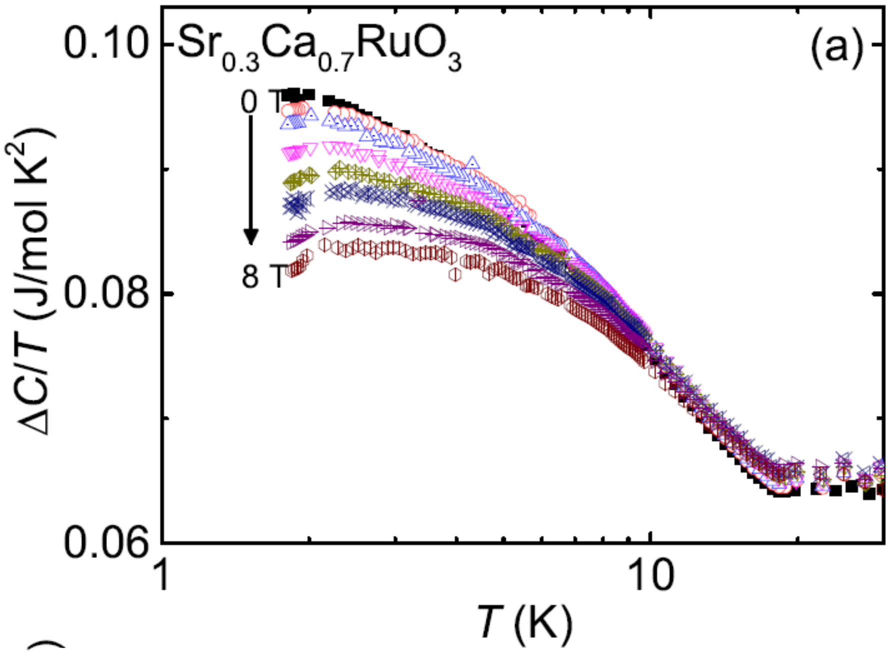
for both $\chi(T,B)$ and $M(T,B)$.



Determining the least-squares fit



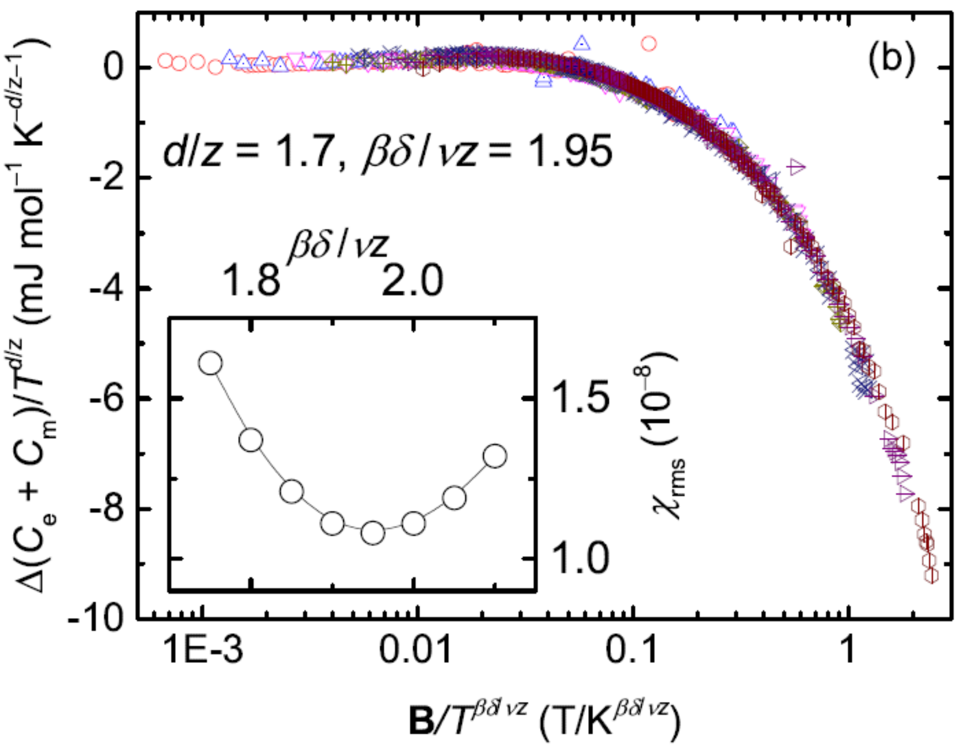
Scaling of the field dependence of the specific heat



$\Delta C(B,T) - \Delta C(0,T)$
(phonon contribution subtracted)

best data collapse observed with $\frac{\delta\beta}{\nu z} \approx 1.7$

in agreement with $\chi(T,B)$ and $M(T,B)$



Strikingly, $d/z = 1.7$ yields with $d = 3$:

$z \approx 1.8$,

much smaller

than in typical ferromagnets

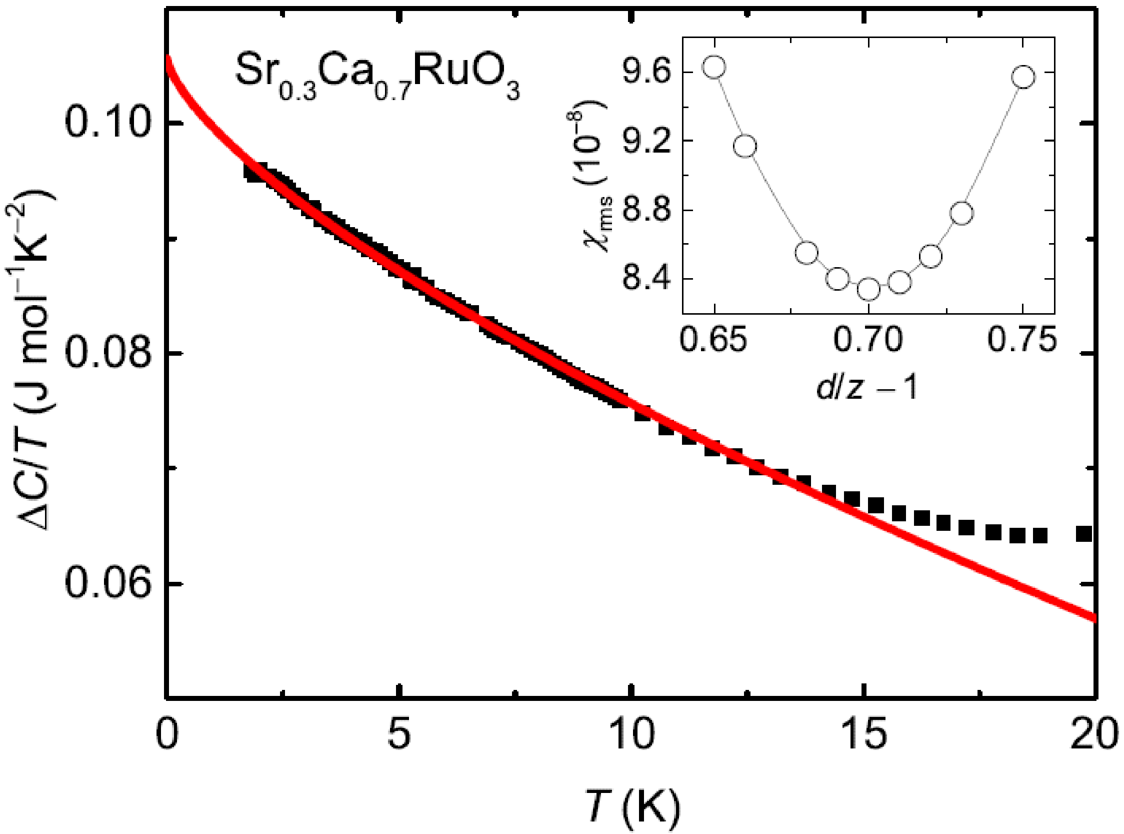
Zero-field specific heat of $Sr_{0.3}Ca_{0.7}RuO_3$

Consequence of $d > z \approx 1.8$: critical contribution subleading to electronic contribution, resulting in a finite $\Delta C/T$ at $T = 0$

Power-law dependence

$\Delta C/T \sim -T^{0.7}$

in perfect agreement with $d/z - 1 = 0.7$



Qualitative discussion on the anomalous dynamic exponent *z* in $Sr_{0.3}Ca_{0.7}RuO_3$

Original prediction by Hertz 1976

$z = 3$ for a clean ferrromagnet

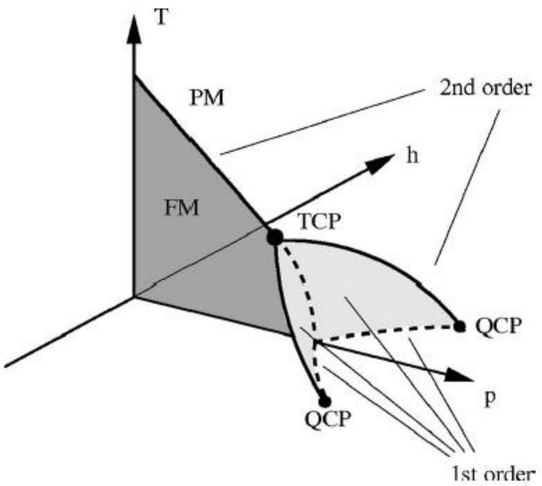
$z = 4$ for a disordered ferromagnet

Generally, disorder tends to enhance z

Complication because additional dynamics of fermions

might lead to a first-order transition

Belitz and Kirkpatrick



Alternative scenario Griffiths phase in ferromagnet

example $Ni_{1-x}V_x$

Ubaid-Kassis et al., PRL 104, 066402 (20910)

Strong coupling between critical fluctuations and incoherent quasiparticles:

local fluctuations may lead to a local gap in the Stoner continuum,

leading to less damping of fluctuations, i. e., smaller z