Near Magnetic/Non-Magnetic Boundaries in $CeRhIn_5$

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with

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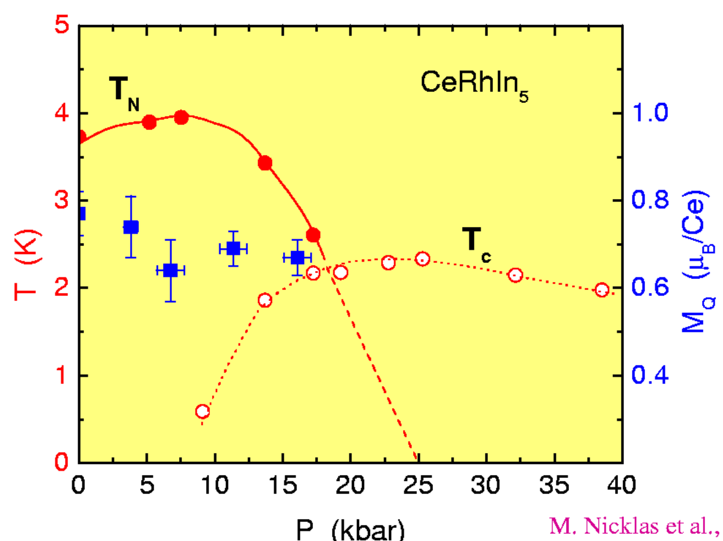
Outline:

- Introduction--the problem and the materials
- Magnetic/non-magnetic boundaries of $CeRhIn_5$
  - accessed by pressure
  - accessed by Sn substitutions
  - implications from comparisons to $CeCoIn_5$
- Perspective

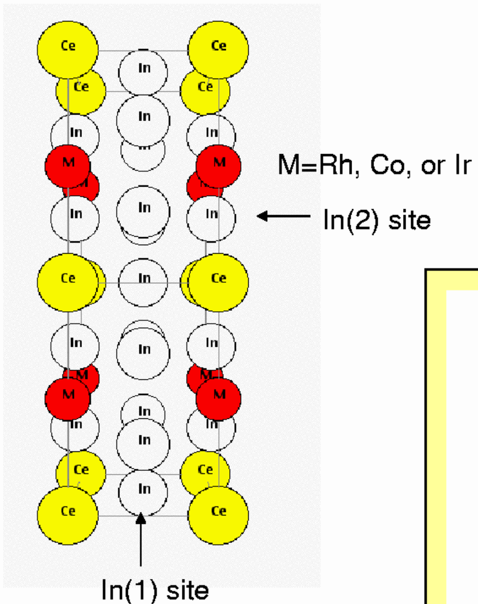
The problems



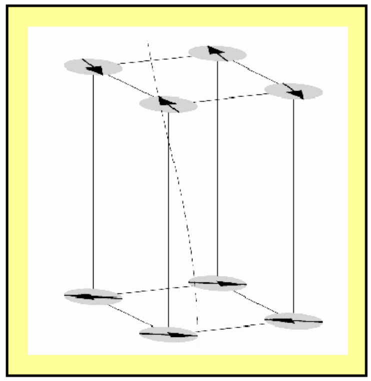
M. Nicklas et al., PRB **70**, 020505 (2004);
A. Llobet et al., PRB **69**, 024403 (2004)

- What happens to antiferromagnetism once T_c exceeds T_N?
- Does the 'hidden' AFM order terminate at a quantum-critical point at $P_c \approx 25$ kbar?
- If so, what is the nature of that criticality?
- Is $CeRhIn_5$ relevant to understanding the origin of quantum criticality in isostructural $CeCoIn_5$?

$CeRhIn_5$ and $CeCoIn_5$



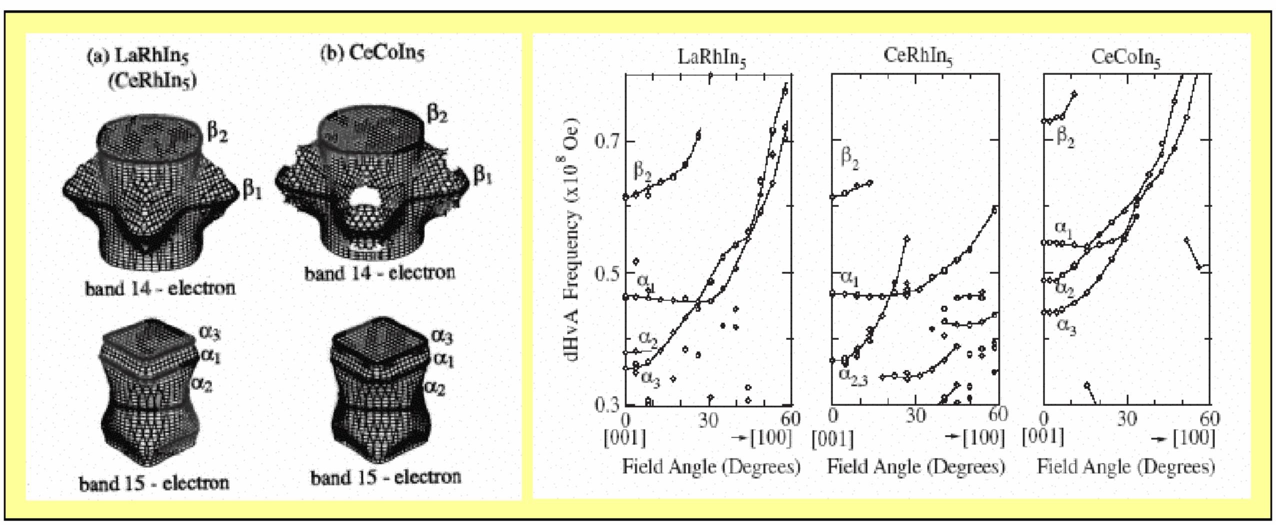
- $HoCoGa_5$ structure type: tetragonal with layers of $CeIn_3$ and MIn_2 stacked sequentially along c-axis
- heavy-fermion systems, with Sommerfeld coefficients $\gamma \approx 450$-1000 mJ/molK^2 $\Rightarrow$ quasiparticle effective mass $m^* \approx (50$- $100)m_e$
- $CeRhIn_5$-- antiferromagnetic with T_N=3.8 K



- ordered moment 0.79 μ_B (expect 0.84 μ_B for CEF doublet-local moment)
- incommensurate structure with Q = (½, ½, 0.297)

- $CeCoIn_5$– slightly smaller unit-cell volume than $CeRhIn_5$ (roughly equivalent to 16-kbar chemical pressure); unconventional superconductor with T_c=2.3K and signatures of quantum-critical behavior

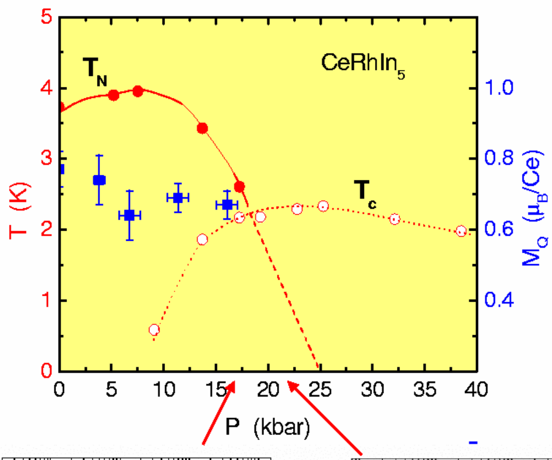
Fermi surfaces of $CeRhIn_5$ and $CeCoIn_5$

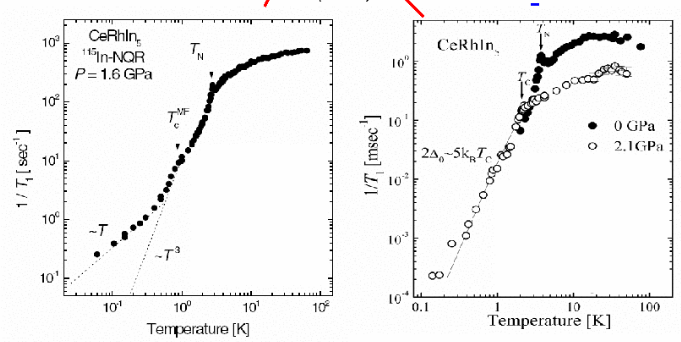


H. Shishido et al., J. Phys. Soc. Jpn. **71**, 162 (2002).

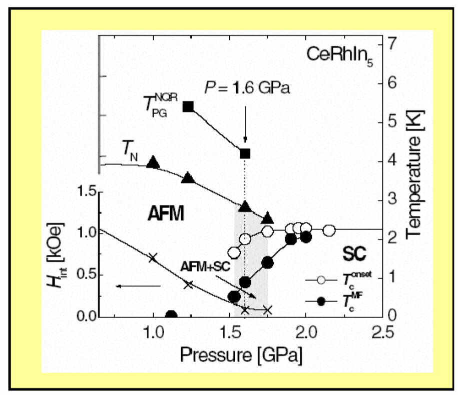
- quasi-2D Fermi surfaces (dominantly cylindrical), expected from layered crystal structure
- good agreement between experiment and band-structure calculations
- dHvA frequency: caliper of Fermi surface extremal cross-sections
- similar dHvA frequencies of $LaRhIn_5$ and $CeRhIn_5$ $\Rightarrow$ Ce's single 4f electron does not contribute to the Fermi surface, i.e., 4f electron is localized
- uniformly higher dHvA frequencies of $CeCoIn_5$ $\Rightarrow$ larger Fermi surface that accommodates ~90% of a band-like and ~ 10% of 'localized' 4f electron (Nakatsuji et al)

'Disappearance' of magnetism in $CeRhIn_5$: NMR



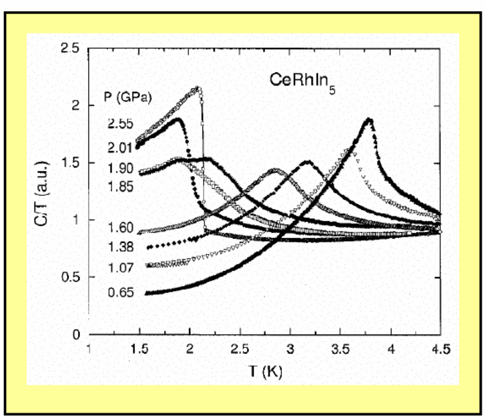


- coexistence of AFM and unconventional SC at 16 kbar from $1/T_1$ measurements on In(1)
- at 21 kbar, no evidence for AFM above 200 mK, but extrapolated $T_N(P)$ gives $T_N \approx 1K$ at this pressure
- NQR $\Rightarrow$ internal field $\rightarrow 0$ near 16-17 kbar; inconsistent with neutron experiments (A. Llobet et al., PRB **69**, 024403 (2004)); P-dependent hyperfine coupling?

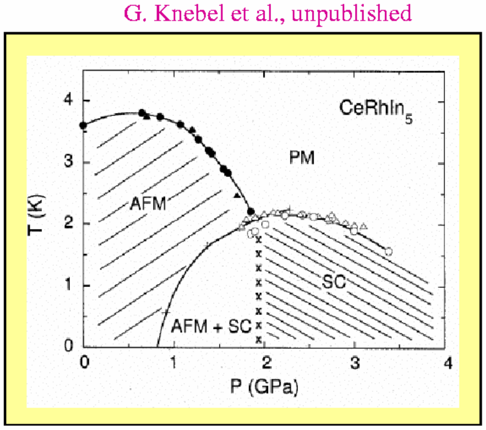


S. Kawasaki et al., PRL **91**, 137001 (2003); T. Mito et al., PRB **63**, 22507 (2001)

'Disappearance' of magnetism in $CeRhIn_5$: specific heat

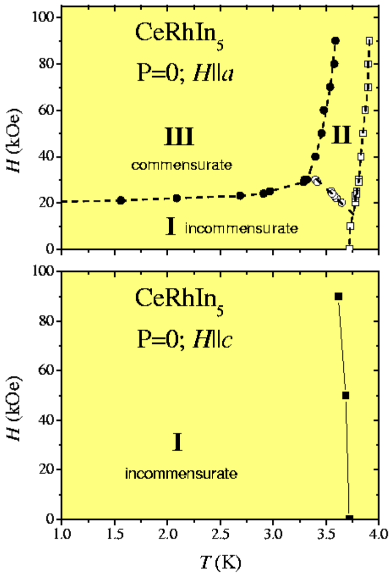


G. Knebel et al., unpublished



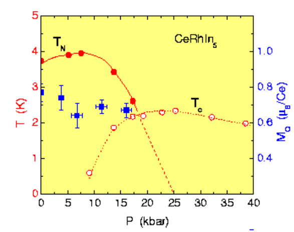
- *ac* specific heat-qualitatively consistent with earlier adiabatic measurements to 21 kbar (R. A. Fisher et al., PRB 65, 224509 (2002))
- T-P phase diagram from *ac* C_p: 1st order boundary between AFM+SC ($T_N>T_c$) and SC ($T_c>T_N$) regimes
- observed relationship between AFM and SC similar to other other systems, eg., $CePd_2Si_2$, $CeIn_3$, etc.
- Flouquet: 'to our knowledge there is no heavy-fermion compound where an antiferromagnetic phase appears after entrance into a superconducting state' (J. Flouquet, cond-mat/0501602; to be published in Progress in Low Temp. Phys.)
- What happens when SC is suppressed by a magnetic field??

Magnetism in $CeRhIn_5$: low pressure specific heat and resistivity in a magnetic field

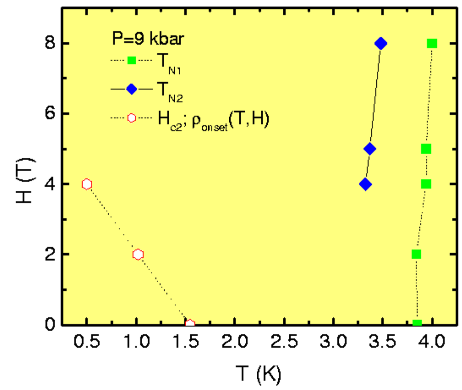


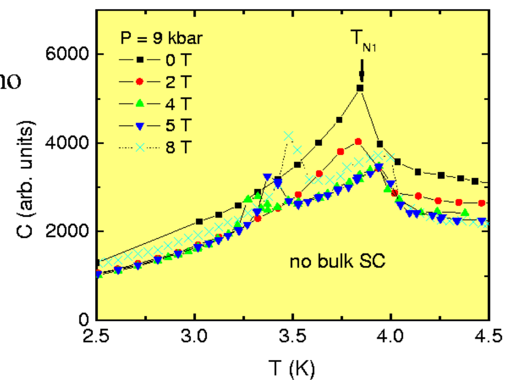
A. Cornelius et al., PRB **64**, 144411 (2002); A. Llobet et al., unpublished

- ♦ magnetic H-T phase diagrams essentially identical at P=0 and P= 9 kbar (determined by isomagnetic temperature sweeps in *ac* specific heat for H//a-b plane); consistent with neutron diffraction
- ♦ resistive onset of incomplete SC transition at 9 kbar--no bulk SC above 0.5 K

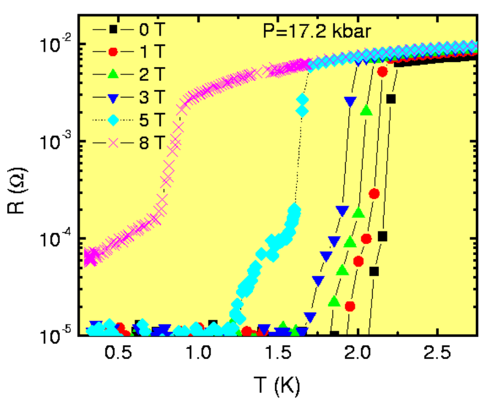


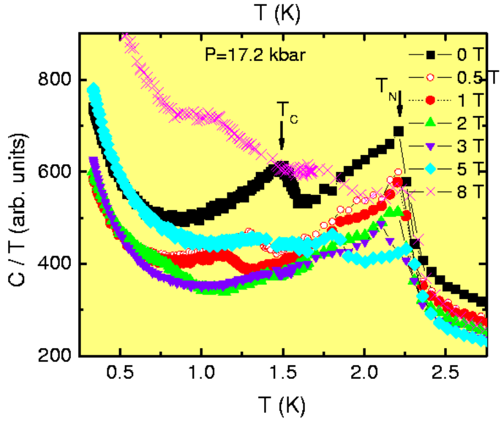
T. Park et al., unpublished



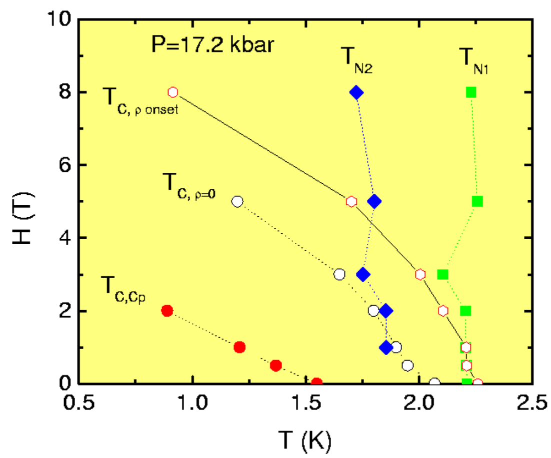


Magnetism on the border of superconductivity in $CeRhIn_5$



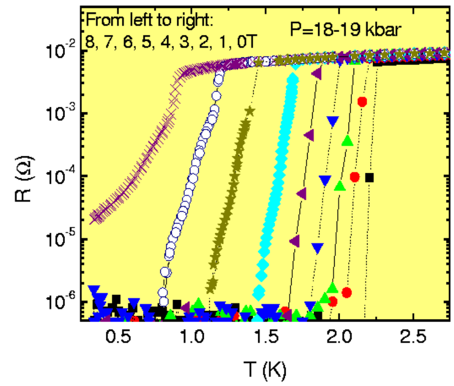


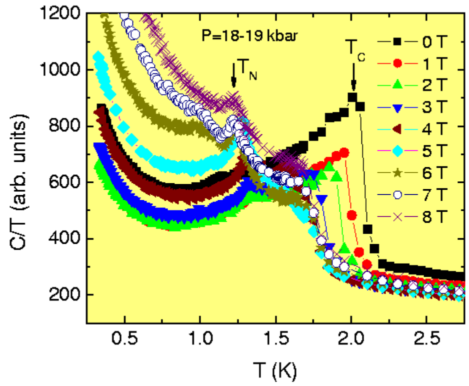
T. Park et al., unpublished

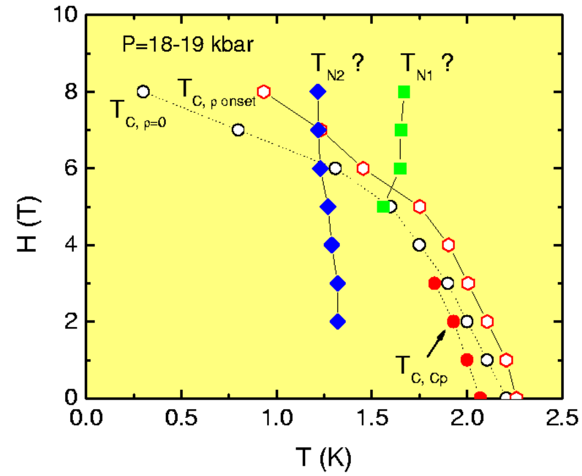


- ♦ at H=0, T_{N1} and $T_{c,\rho\ onset}$ nearly coincident and at $T>>T_{c,CP}$
- ♦ T_{N1} and T_{N2} evolve with H as at lower P, but $T_{N2}< T_{c,\rho\ onset}$
- ♦ resistive transition sharp at low field but develops pronounced structure with increasing H; appears $\rho\neq0$ at 8T
- ♦ evidence for phase separation or ??

Emergence of magnetism in $CeRhIn_5$ at $T<T_c$



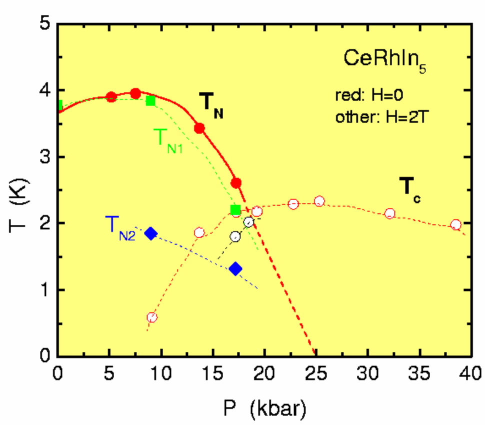




T. Park et al., unpublished

- $T_{c,\rho\ onset}$, $T_{c,\rho=0}$, and $T_{c,CP}$ nearly coincident ⇒ homogeneity, but resistive transition develops structure with increasing H, as at 17.2 kbar
- *magnetism ‘hidden’ at H=0 and revealed in a field*
- T_{N2}? clearly coexists with bulk superconductivity, and no significant change in T_c or T_{N2}? when they cross
- for H≥10-11T, only magnetism as T→0

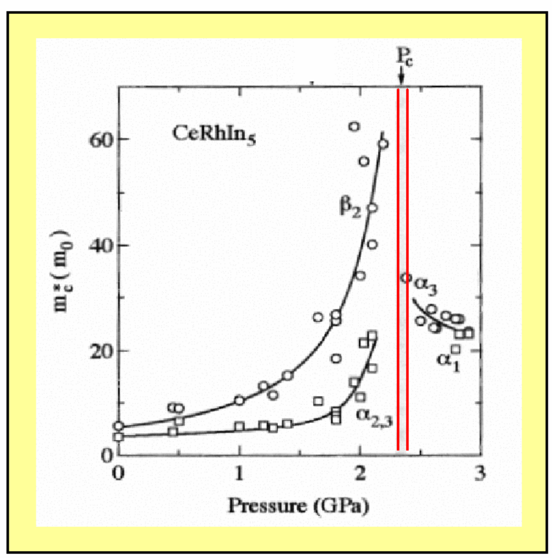
T-P phase diagram at H=0 and 2T and evidence for criticality



T. Park et al., unpublished

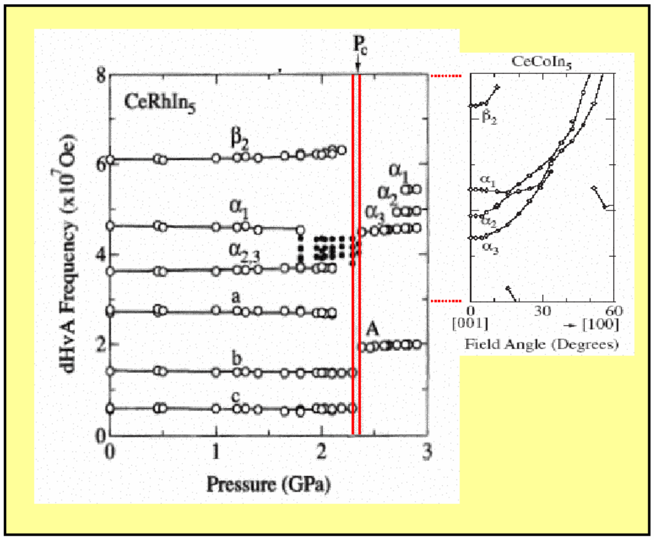
- clearly more work to be done; nevertheless, initial experiments establish that (1) magnetism does not ‘disappear’ once $T_c>T_N$ and (2) there is a plausible mechanism for an antiferromagnetic quantum-critical point near 25 kbar.

Y. Onuki et al., unpublished



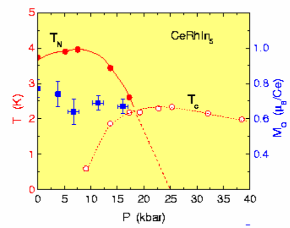
- Earlier dHvA measurements to 21 kbar (H. Shishido et al., PRB 66, 214510 (2002)) suggested approach to a QCP but a QCP of what?
- new measures of m* to 30 kbar, combined now with evidence for magnetism below T_c ⇒ rather convincing evidence for an antiferromagnetic quantum-phase transition near 24 kbar

Fermi-surface volume change at P_c



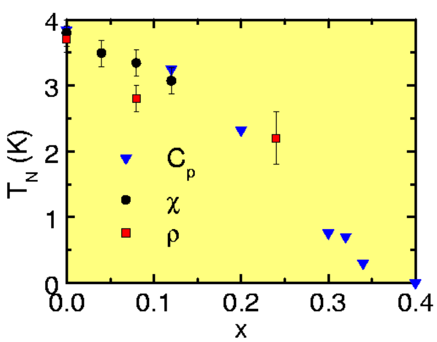
Y. Onuki et al., unpublished

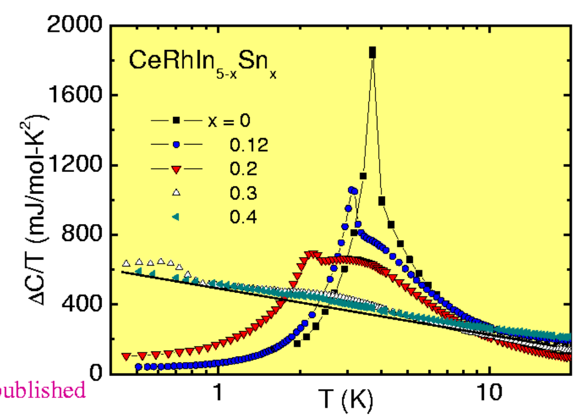
- ♦ main dHvA frequencies (Fermi surface volume) essentially unchanged for P < 23.5 kbar ⇒ f-electron remains localized
- ♦ new, unexplained, branches in a limited P interval, 18 < P < 23.5 kbar
- ♦ above 24 kbar, qualitative change in dHvA spectrum, particularly emergence of new α_i and A branches



- ♦ frequencies of α_i branches above 24 kbar essentially identical to those of $CeCoIn_5$ at P=0 ⇒ f-localized to f-delocalized transition in a very narrow P interval at P_c
- ♦ abrupt change in Fermi surface volume and smoothly varying m* above and below P_c
- ♦ not expected for a conventional SDW QCP; appropriate theoretical description?? Coleman? Pepin? Si? Norman? Others?
- ♦ related to quantum-critical behaviors in $CeRhIn_{5-x}Sn_x$ and $CeCoIn_5$?

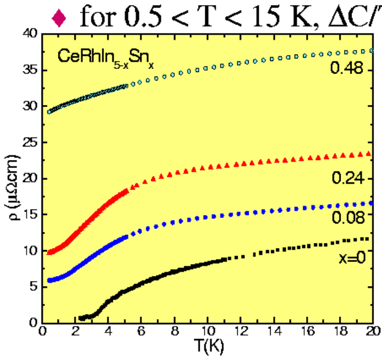
Accessing the magnetic/non-magnetic boundary with Sn



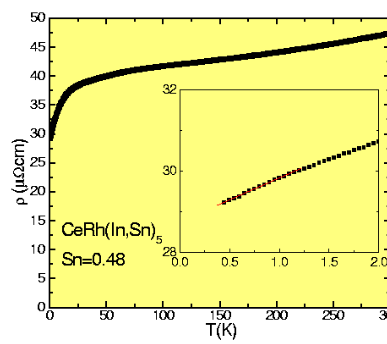


E. D. Bauer, F. Ronning et al., unpublished

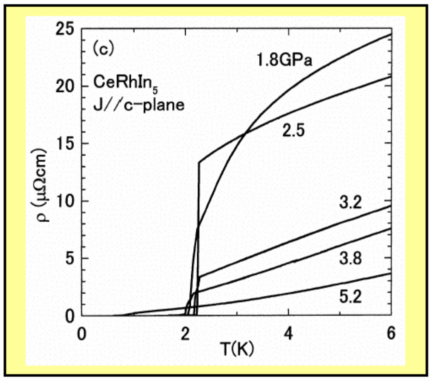
- ♦ $T_N \rightarrow 0$ at $x_c \approx 0.35$ in $CeRhIn_{5-x}Sn_x$, i.e., about 7% of all In's replaced by Sn but probably a greater fraction of In(1)'s (as found in $CeCoIn_{5-x}Sn_x$)
- ♦ for $0.5 < T < 15$ K, $\Delta C/T \sim -\ln T$ for x=0.4



- ♦ substantial increase in residual resistivity and possible T-linear $\rho(T)$ for x = 0.48

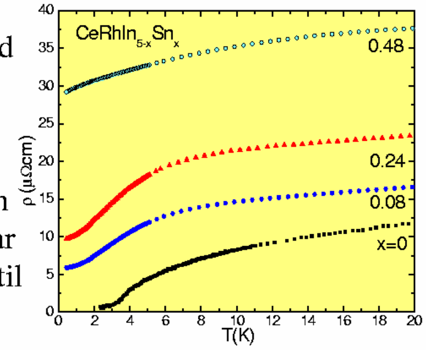


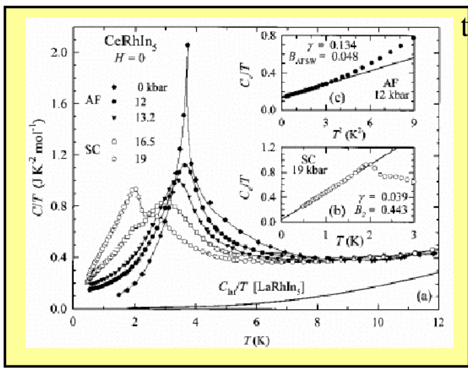
Pressure versus Sn-doping $CeRhIn_5$



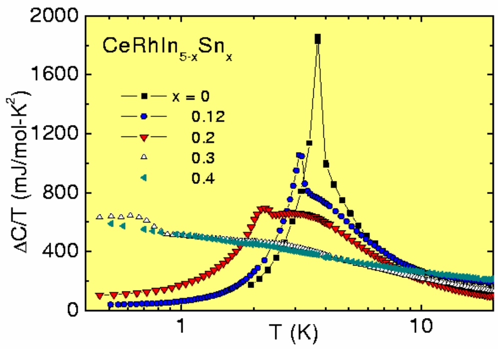
T. Muramatsu et al., JPSJ **70**, 3362 (2001).

- aside from unavoidable frozen disorder in Sn-doped and SC in pure $CeRhIn_5$, qualitatively similar evolutions in ρ(T) and C/T
- pronounced maximum in $\rho(T_c,P)$ near P_c, but T-linear ρ for P>> P_c and T^2 not until P> 80 kbar—extended regime of NFL behavior characteristic of localized/delocalized QP transition?

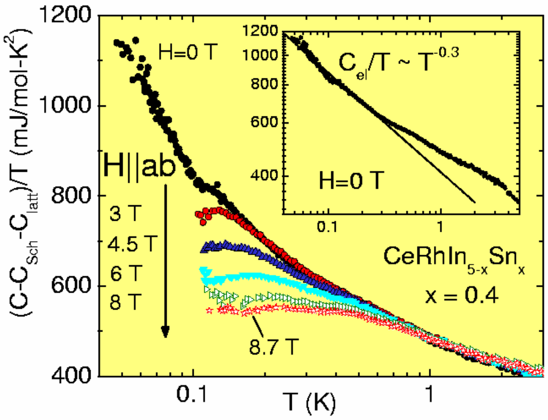




R. A. Fisher et al., PRB 65, 224509 (2002)

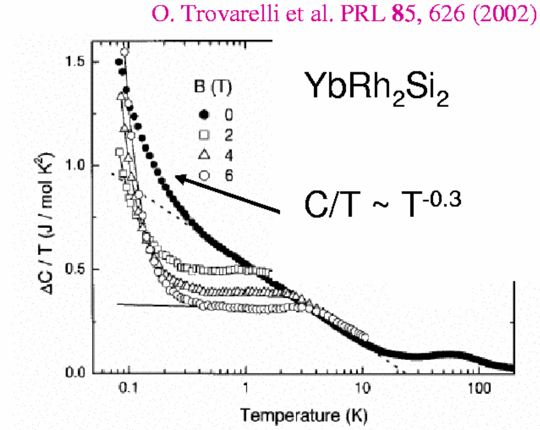


Localized/delocalized QPT in $CeRh_{5-x}Sn_x$ and $YbRh_2Si_2$?



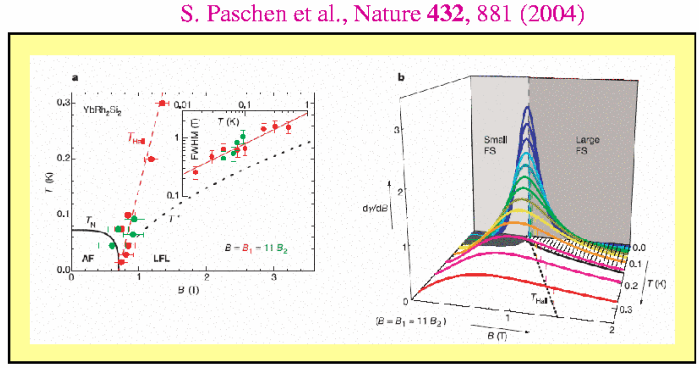
E. D. Bauer, F. Ronning et al., unpublished

O. Trovarelli et al. PRL **85**, 626 (2002)



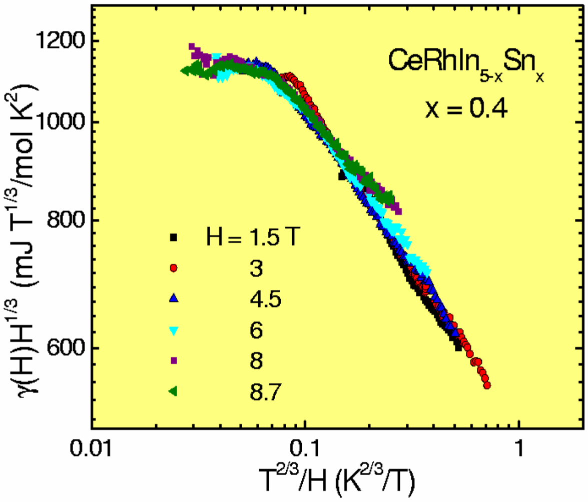
- possible localized/delocalized H-induced QPT in $YbRh_2Si_2$ implied by Hall effect
- unusual $T^{-0.3}$ divergence in C/T below –lnT regime in both $YbRh_2Si_2$ and $CeRh_{5-x}Sn_x$
- similar physics?

S. Paschen et al., Nature **432**, 881 (2004)

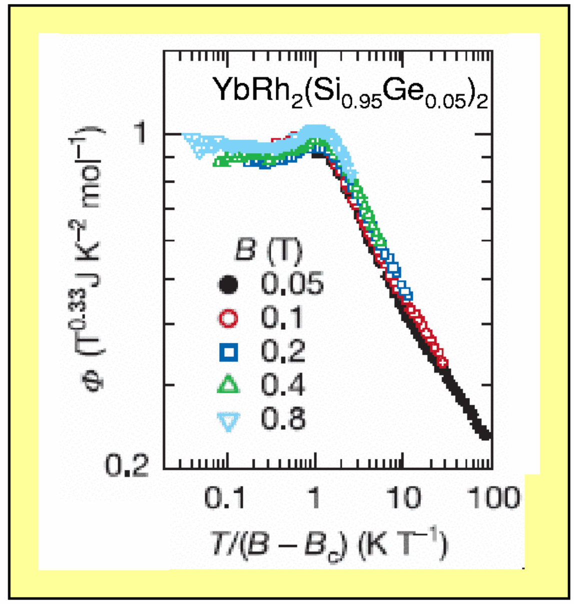


Similar scaling forms in $CeRh_{5-x}Sn_x$ and $YbRh_2Si_2$

E. D. Bauer et al., unpublished



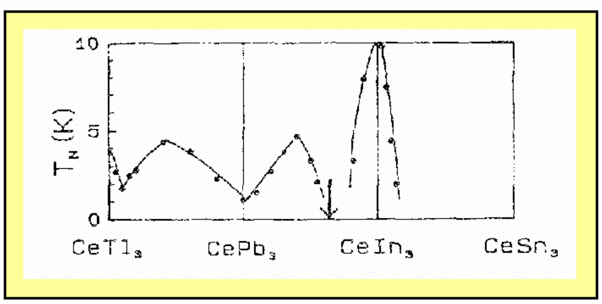
J. Custers et al., Nature **424**, 524 (2003)

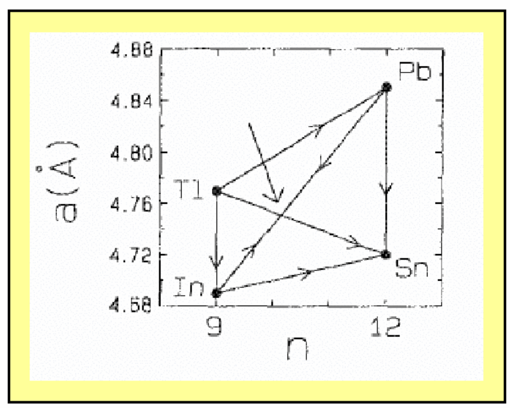


- near x_c, scaling form of γ (T, H) similar to that found in $YbRh_2(Si_{.95}Ge_{.05})_2$ where $\Phi = \gamma H^{1/3}$ and B_c=0 in Sn-doped $CeRhIn_5$
- difference : characteristic scale governing cross-over from NFL to Fermi-liquid behavior in Yb122, $T_o \propto (B-B_c)$ but in Ce115, $T_o \propto B^{3/2}$

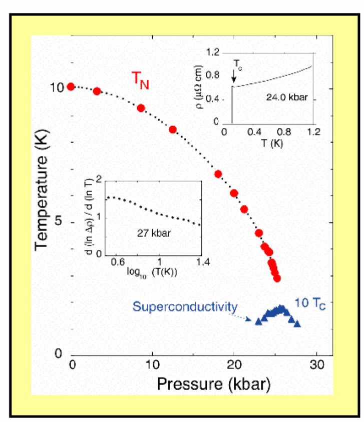
What is Sn doing?: $CeIn_3$

S. Rahman et al., JAP **67**, 5209 (1990)





- structural building block of $CeMIn_5$ with commensurate AFM order (μ_0=0.5 μ_B)
- $P_c \approx$ 25 kbar, essentially identical to P_c of $CeRhIn_5$
- T_N from 10 K to 0 at $x_c \approx 0.65$ in $CeIn_{3-x}Sn_x$ (J. Custers et al, Acta Phys. Polonica **34**, 379 (2003)) vs. (T_N=3.8 K and $x_c \approx$ 0.35 for $CeRhIn_{5-x}Sn_x$)
- Sn substitution not a volume effect: vol.⇑, T_N⇓
- stronger hybridization + increase in conduction electron count tends to force Ce^{3+} to Ce^{4+}, i.e., localized 4f to delocalized 4f; same tendency with P

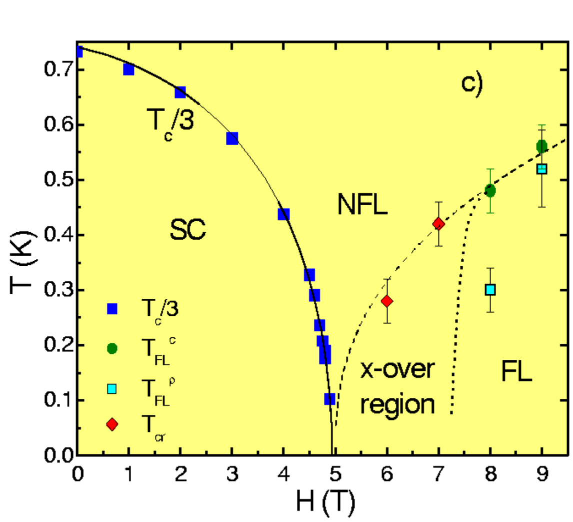


N.D. Mathur et al., Nature **394**, 39 (1998)

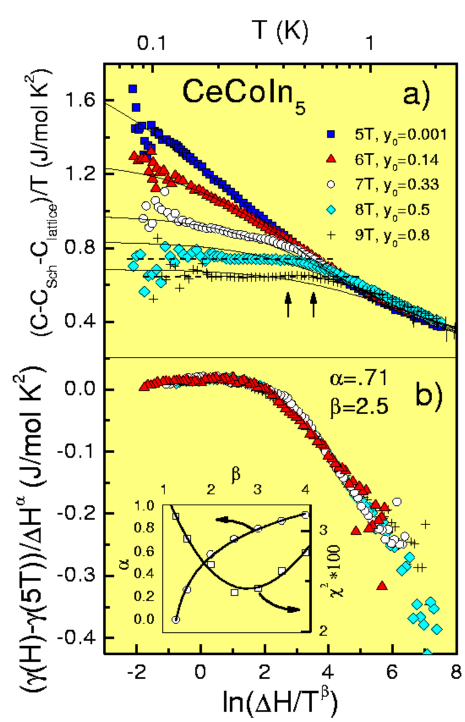
Quick summary

- Magnetism emerges below T_c in $CeRhIn_5$, providing a plausible rationale for the origin of a QCP near P_c =24-25 kbar.
- QCP is not conventional (SDW-like) but is associated with a small-to-large Fermi-surface volume change (localized/delocalized 4f).
- Evidence for NFL behavior in $\rho(T)$ extending well above P_c
- QCP also accessed by Sn doping, with similarities between C/T of $CeRhIn_{5-xc}Sn_{xc}$ and $YbRh_2Si_2$, which has a small-to-large Fermi-surface type QCP
- Are these critical behaviors in pressurized and Sn-doped $CeRhIn_5$ relevant to $CeCoIn_5$ and vice versa?

Criticality in $CeCoIn_5$

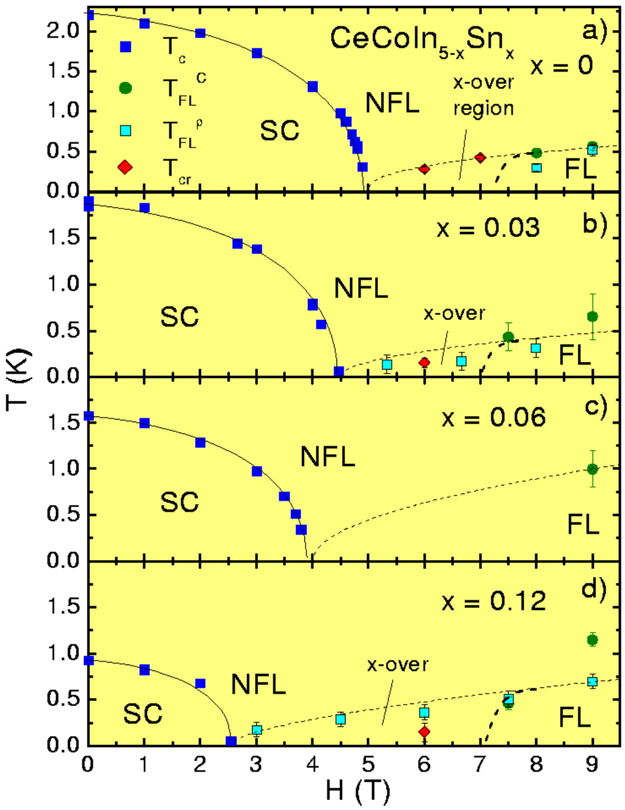


A. Bianchi et al., PRL **91,** 257001(2003)



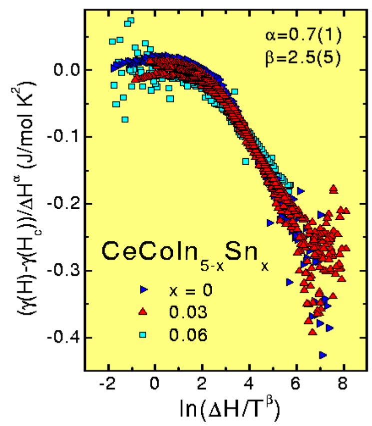
- $C/T \propto -\ln T$ and $\rho(T) \propto T$ at H=0 and $T \geq T_c$
- Moriya-type scaling analysis of C(H)/T for $H \geq H_{c2}$ $\Rightarrow$ $CeCoIn_5$ just beyond an AFM QCP, with the quantum-critical field H_c =5 T and $H_{c2}(0)$= 4.95 T, but no evidence for AFM order at H=0 or H>0
- quantum criticality associated with hidden/avoided antiferromagnetism or superconductivity?

'Avoided AFM' or superconducting criticality in $CeCoIn_5$?



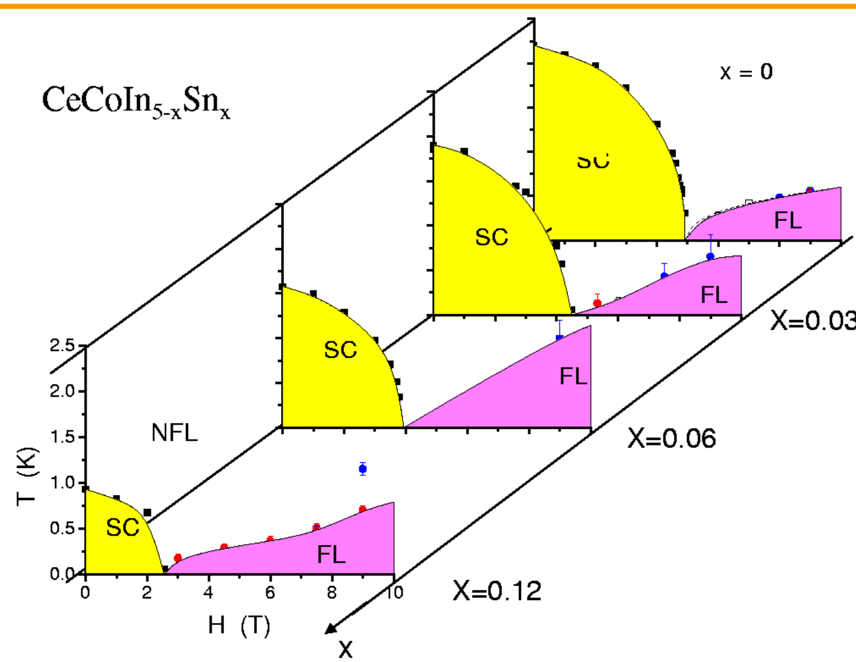
E. D. Bauer et al., PRL **94**, 047001 (2005)

- for $CeCoIn_{5-x}In_x$, $dT_c/dx = -0.6$K/at.%Sn, with $x_c \approx 0.18$ (Sn dominantly on In(1) site)
- maximum divergence (~ -lnT) of C/T very near H_{c2} and recovery of Fermi-liquid behavior for $H>>H_{c2}$, as in $CeCoIn_5$



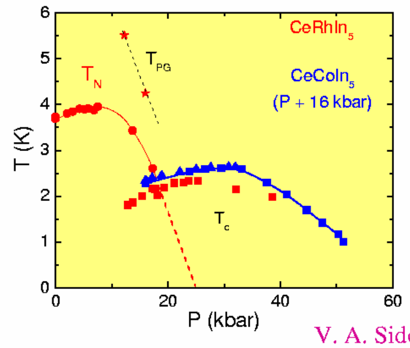
- collapse of Moriya-type scaling onto a common curve for x=0, 0.03 and 0.06 ⇒ critical behavior tracks $H_{c2}(x)$ but is this all?

'Cone' of superconductivity embedded in NFL space



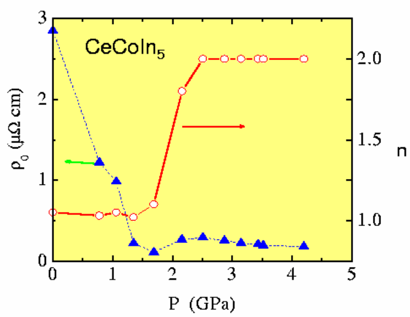
- huge T-H-x space filled with critical fluctuations in which is embedded a cone of superconductivity bounded by T_c, H_{c2} and $x_c(H=0)=0.18$
- not superconducting quantum criticality but what??

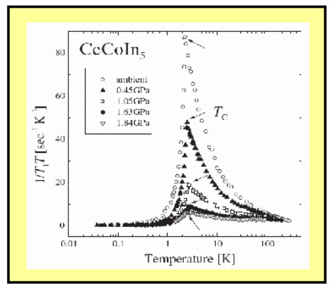
Relationship of $CeRhIn_5$ and $CeCoIn_5$

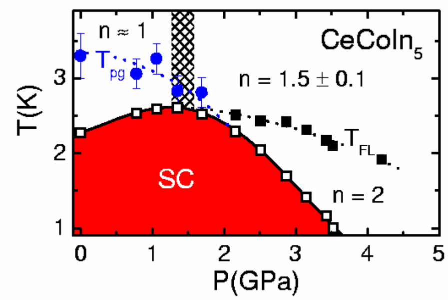


- smaller cell volume of $CeCoIn_5 \Rightarrow$ +16 kbar chemical pressure relative to $CeRhIn_5$
- similar T-P diagram for $CeRhIn_5$ and T-(P+16 kbar) diagram for $CeCoIn_5$
- 16 kbar chemical pressure- a simple estimate; dHvA on $CeRhIn_5$ and $CeCoIn_5$ more consistent with $CeCoIn_5$ near the localized/delocalized border of $CeRhIn_5$ (P_c ~24 kbar)

V. A. Sidorov et al., PRL **89**, 157004 (2002)

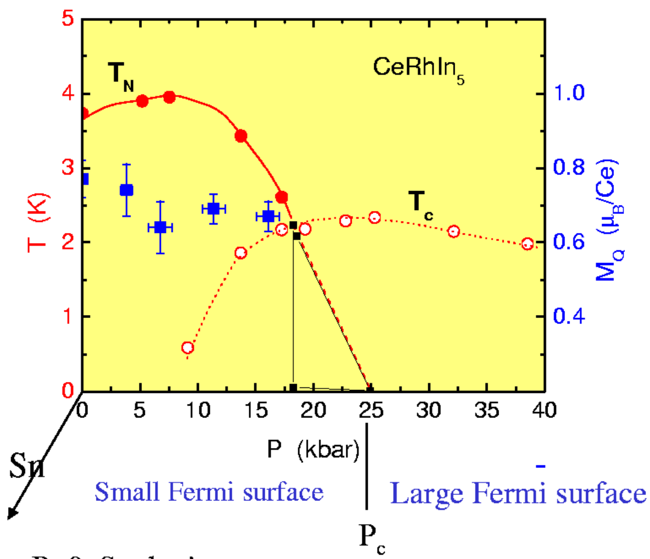


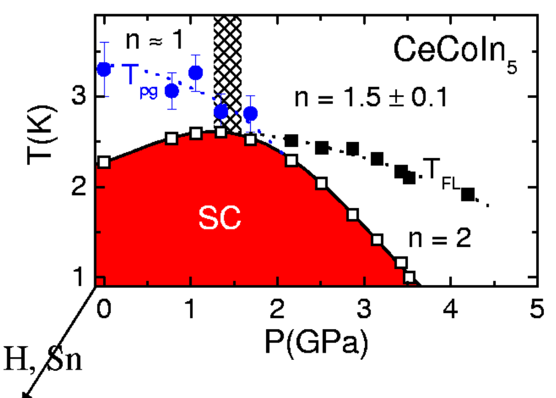




- persistence of NFL behaviors in $CeCoIn_5$ beyond its putative QCP near P=0, as with pressurized $CeRhIn_5$ and Sn-doped $CeCoIn_5$, without a detectable change in Fermi-surface volume to 30 kbar (H. Shishido et al., JPCM **15**, L499 (2003)); recovery of Fermi-liquid-like $1/T_1T$ (M. Yashima et al. JPSJ **73**, 2073 (2004)) and T^2 ρ(T) at P ≥ 20 kbar

Summary relationships of $CeRhIn_5$ and $CeCoIn_5$





- P=0, Sn doping: H-T scaling similar to $YbRh_2Si_2$
- triangle of hidden magnetism revealed in magnetic field (like $CeCu_2Si_2$?)

- P=0: like $CeRhIn_5$ at $P \geq P_c$; large Fermi surface with partially unscreened moments
- Moriya-like scaling (itinerant magnetism) with H for $CeCoIn_5$ and for Sn doped
- residual resistivity 'collapse' for P= 15-20 kbar; marks appearance of fully coherent Kondo lattice?

Speculative perspective

- by some mechanism, local moment magnetism hidden below T_c in $CeRhIn_5$ for $P < 24$ kbar and revealed with applied magnetic field

- for $P > P_c$ 24 kbar, $CeRhIn_5 \approx CeCoIn_5$, which has extended ranges of NFL behavior as a function of tuning parameters P or x and partially unscreened local moment

- localized/delocalized transition incomplete at P_c (not fully coherent Kondo lattice); large Fermi surface contains fractionally unscreened 4f moment above P_c, as it does in $CeCoIn_5$ above T_c at P=0, x=0 *a la* Nakatsuji, Pines and Fisk two-fluid picture (S. Nakatsuji et al., PRL **92**, 016401 (2004))?

- mechanism stabilizing the NFL regime: like local moments, superconductivity also ‘protects’ fractionally unscreened local moments, which are ubiquitous in heavy-fermion systems (N. J. Curro et al. PRB **70**, 235117 (2004)), and that produce NFL-like excitations in the heavy-fermion state??

- parametric extent of NFL regime a function of how effective hybridization (P or x) is in eventually producing fully coherent Kondo lattice state with maximally large Fermi surface?

- generic behavior, e.g. also $YbRh_2Si_2$ and $YbCuIn_4$, or specific to Ce115’s?