Recent Developments in $CeMIn_5$ (M=Co, Ir, Rh)

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Outline

I. Basic Properties of $CeMIn_5$
- Structure
- Ground States
- d-wave superconductivity

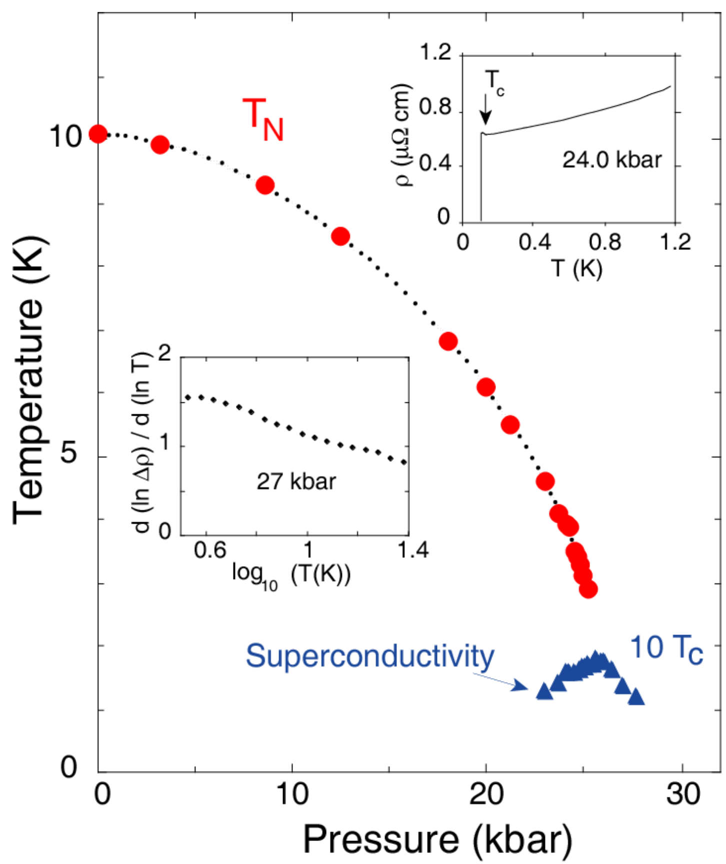
II. Phase Diagrams
- Doping & Pressure
- Ce_2RhIn_8
- H_c-T_c for $CeCoIn_5$

III. Issues & Questions

IV. Serendipitous Plutonium Superconductivity

Magnetically mediated superconductivity

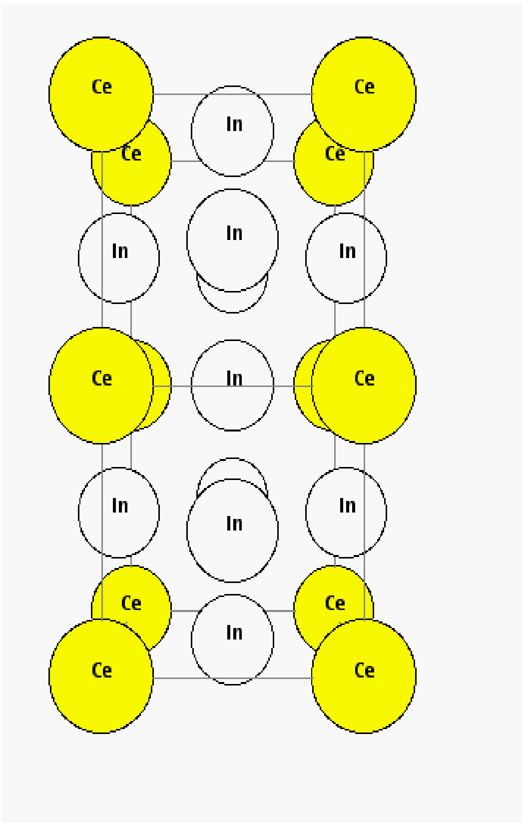
$CeIn_3$



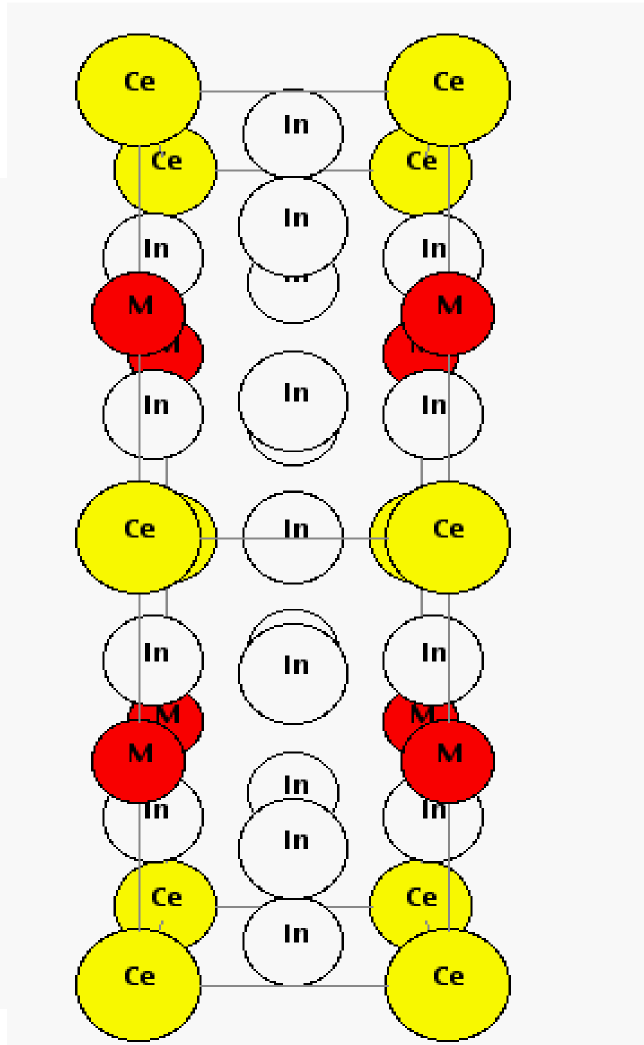
N.D. Mathur et al., Nature **394**, 39 (1998)

- Ambient pressure: antiferromagnet, T_N~10 K
- Non-Fermi liquid normal state near QCP
- T_c~ 200 mK at 25 kbar

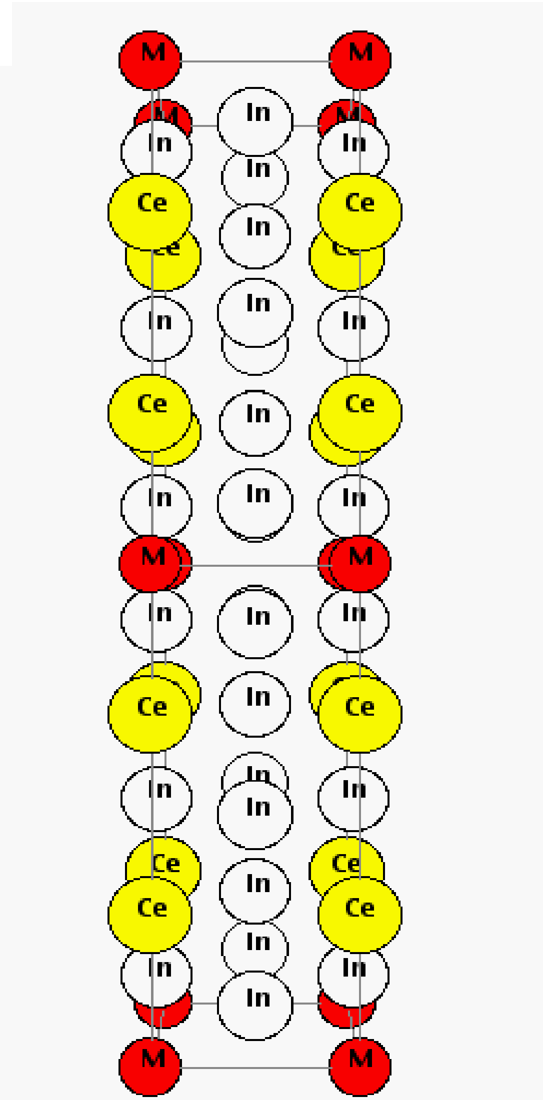
Crystal Structures



$CeIn_3$



$CeMIn_5$



Ce_2MIn_8

M = Co, Rh, Ir (isovalent)

Electronic structure

- Electronic anisotropy

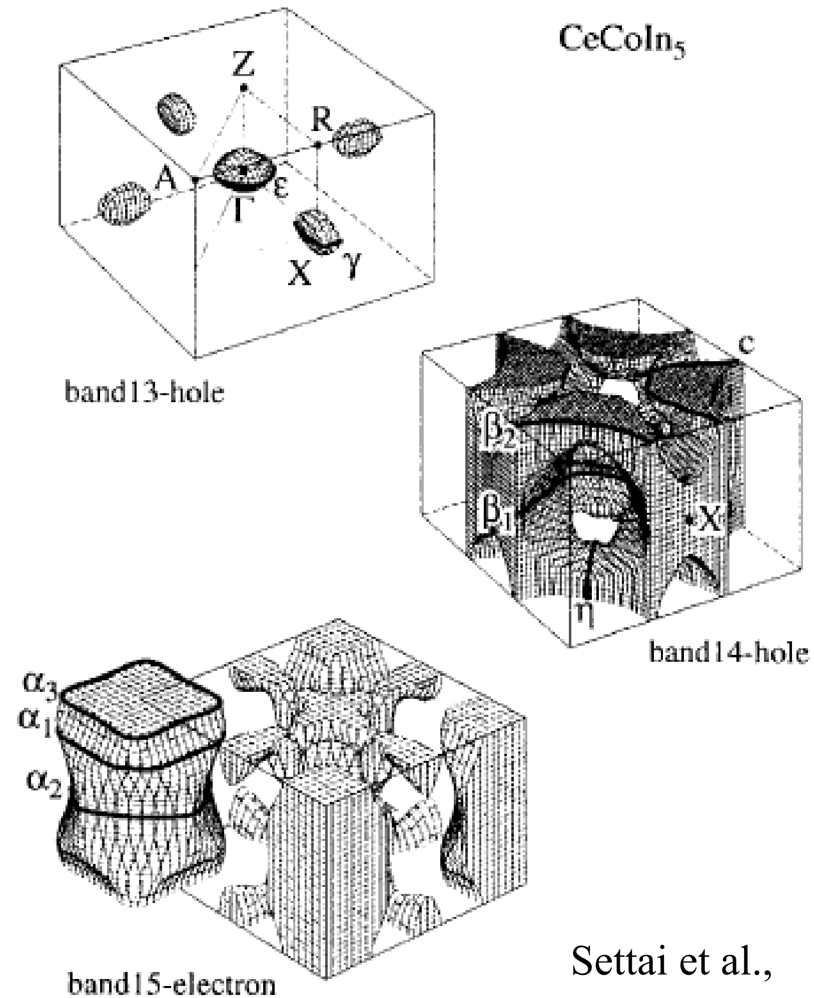
  $\rho_c/\rho_a \sim 1\text{-}3$

  $m^*_c/ m^*_a \sim 5\text{-}7$

- Calculated band structure in good agreement with dHvA

- Degree of warping in cylindrical sheet decreases Rh - Ir - Co
- (more quasi 2d)

- Effective mass of β orbits increases Rh - Ir - Co



LDA/GGA Fermi surfaces: CeMIn$_5$

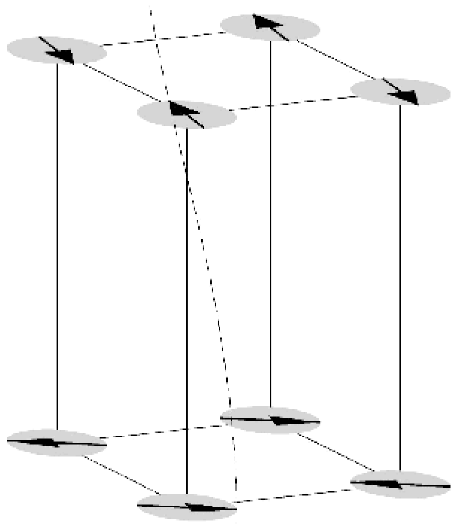
(Hall et al., Haga et al., Settai et al., Hall et al.)

Ambient-pressure $CeRhIn_5$:
a heavy Fermion antiferromagnet

T_N=3.8 K

γ~400 mJ/molK^2

Magnetic Structure



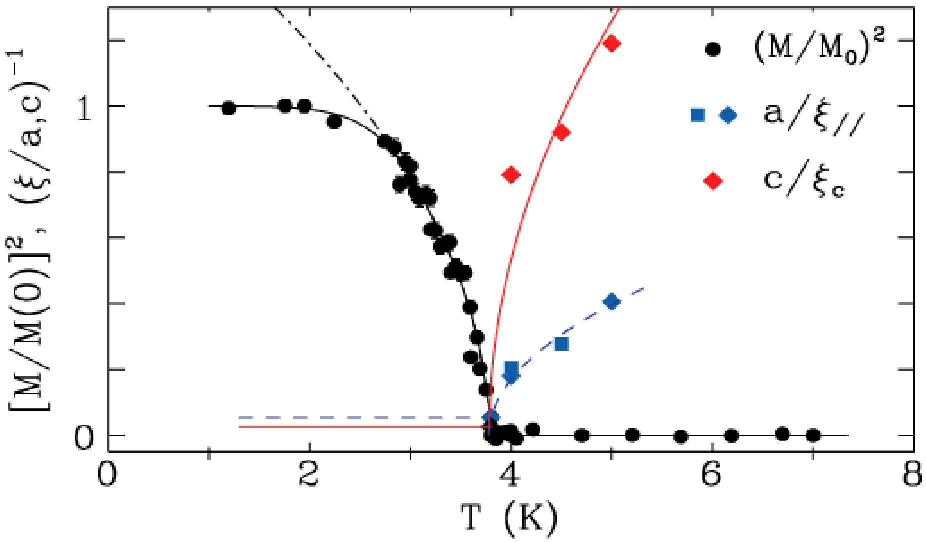
$M_{sublattice}=(1-T/T_N)^{0.25}$

$\mu_{ord}=0.37\ \mu_B$ /Ce (in plane)

107° spiral layer-to-layer

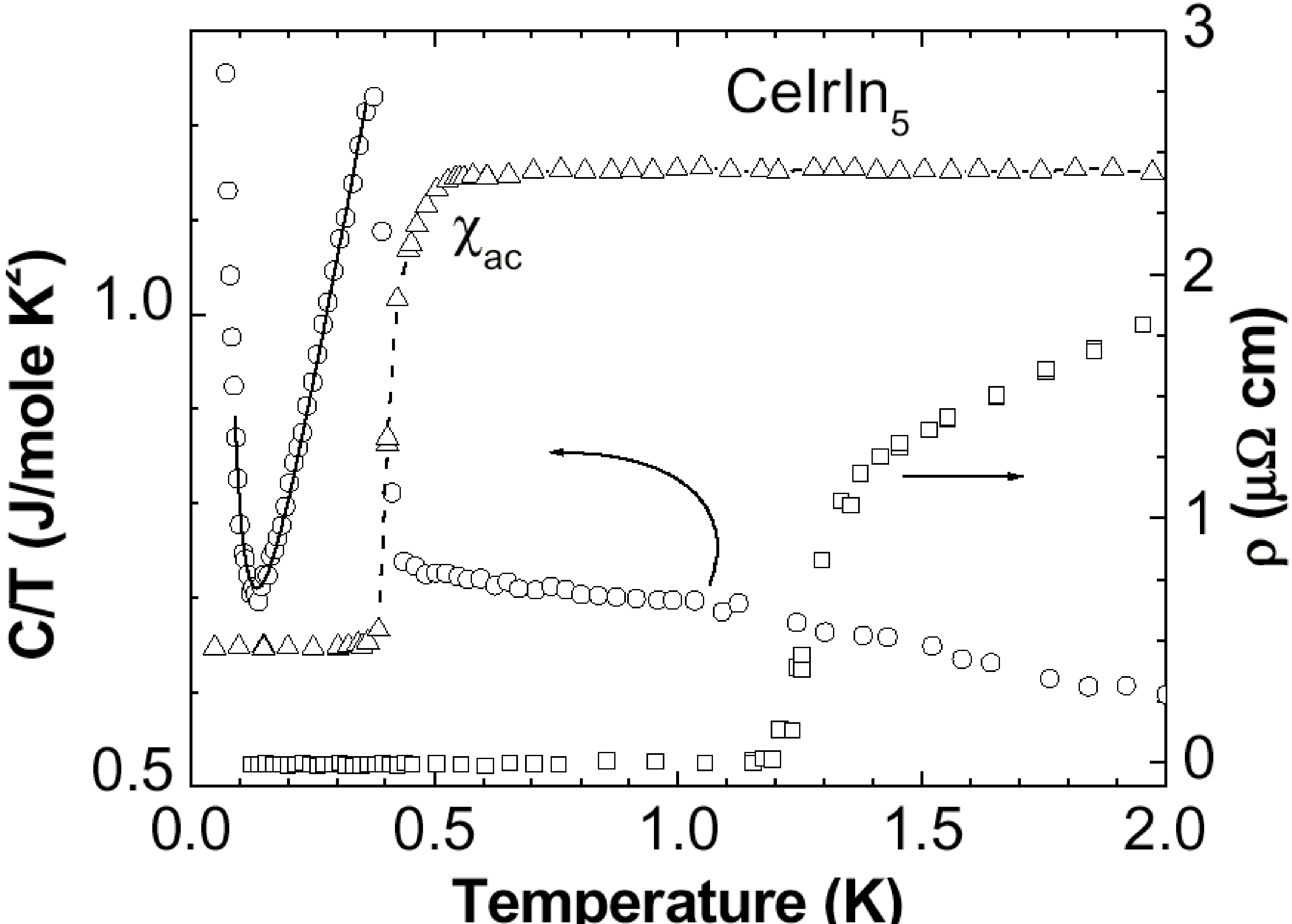
Curro et al., PRB 62, R6100 (2000)
Bao et al., PRB 62, R14621 (2000)

Spin fluctuations



Bao et al., PRB 65, 100505R (2002)

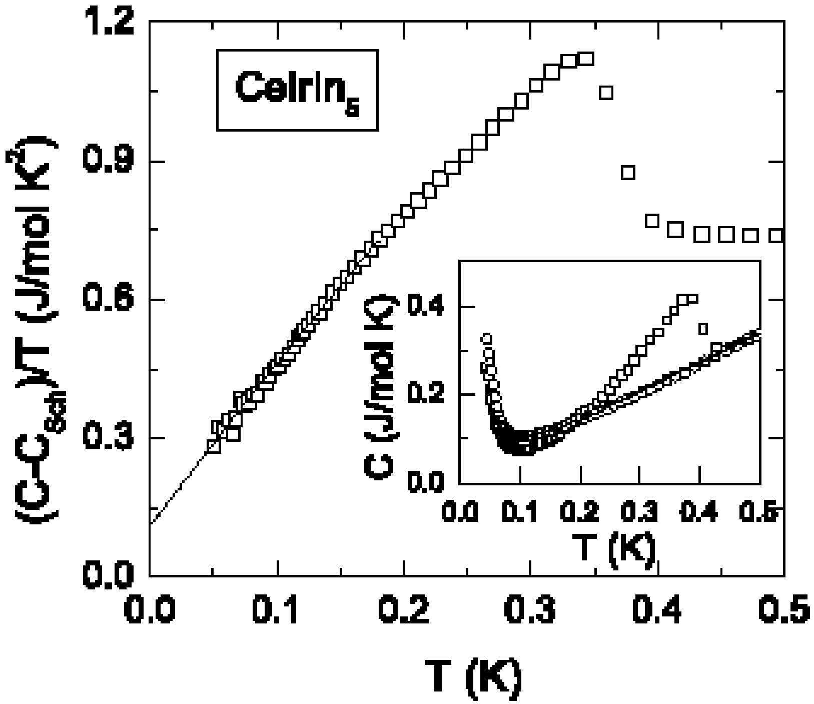
$CeIrIn_5$:
heavy Fermion superconductivity

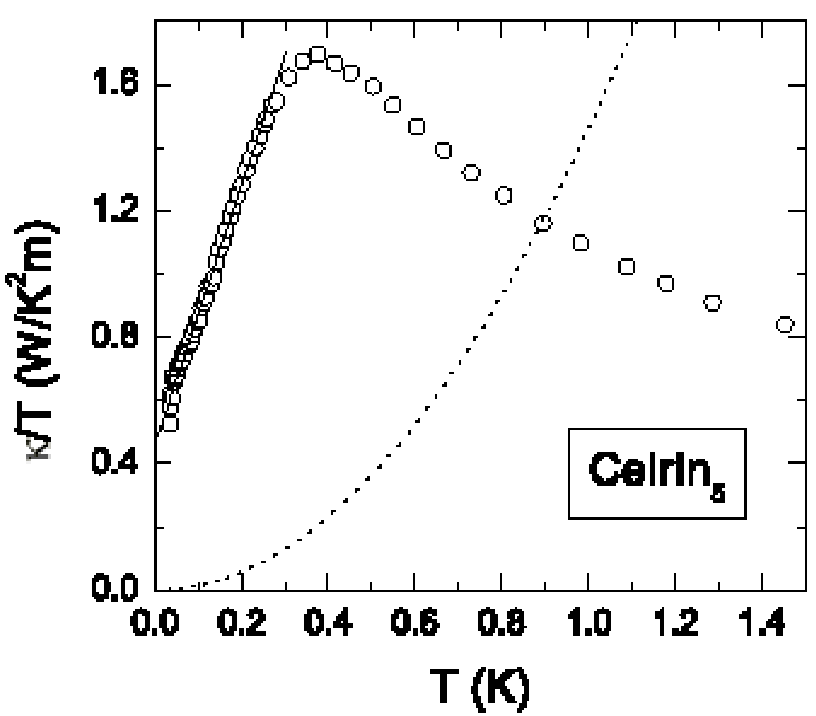


Petrovic et al. Europhys. Lett. 53 (2001) 354

Evidence for unconventional superconductivity in $CeIrIn_5$

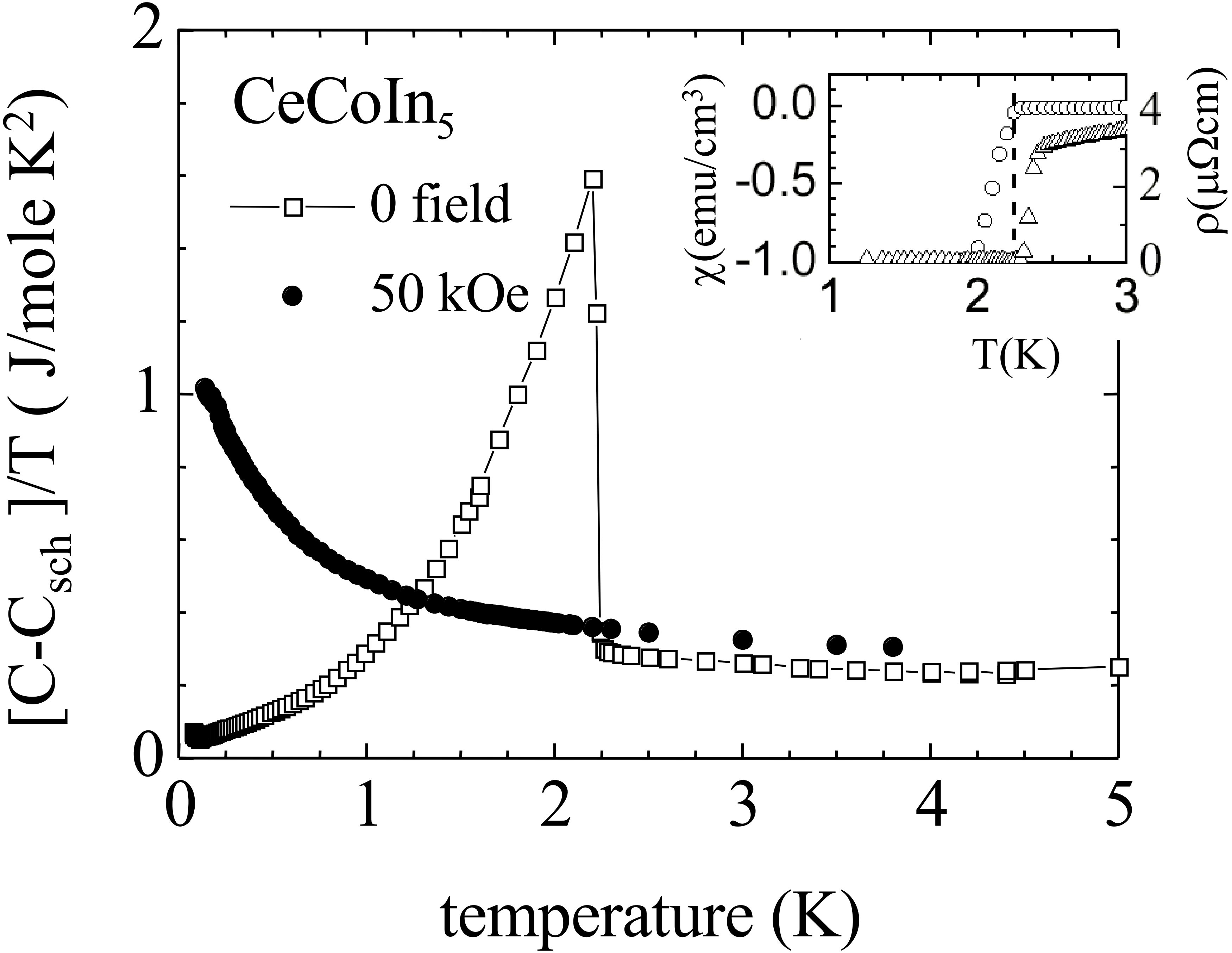
- Heat capacity and thermal conductivity power laws suggest lines of nodes
- Similar conclusions from $1/T_1$ (Kohori et al.; Zheng et al.)



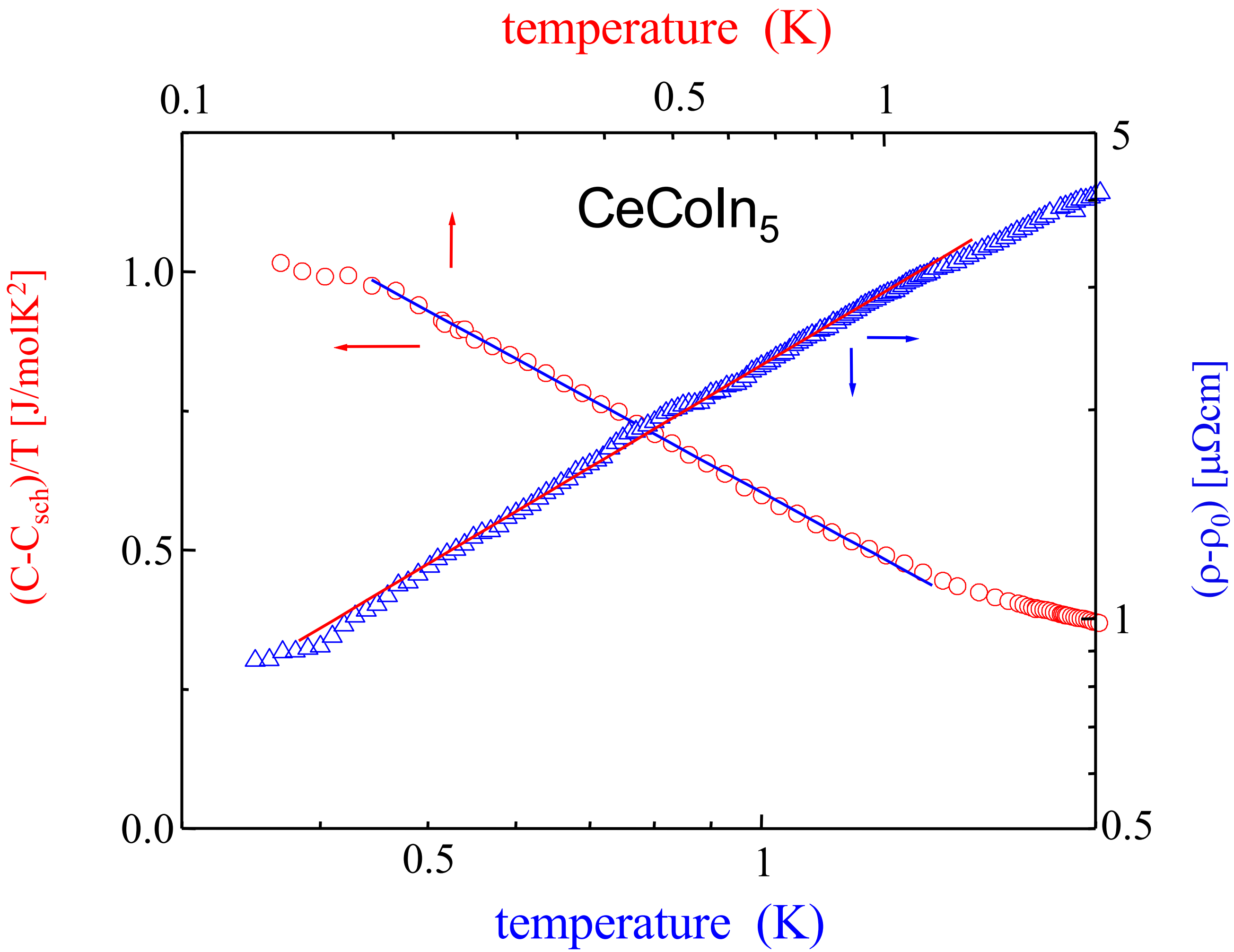


Petrovic et al. Europhys. Lett. 53 (2001) 354; R. Movshovich et al., PRL 86 (2001) 5152

C. Petrovic et al., J. Phys.: Cond Mat. 13 (2001) L337

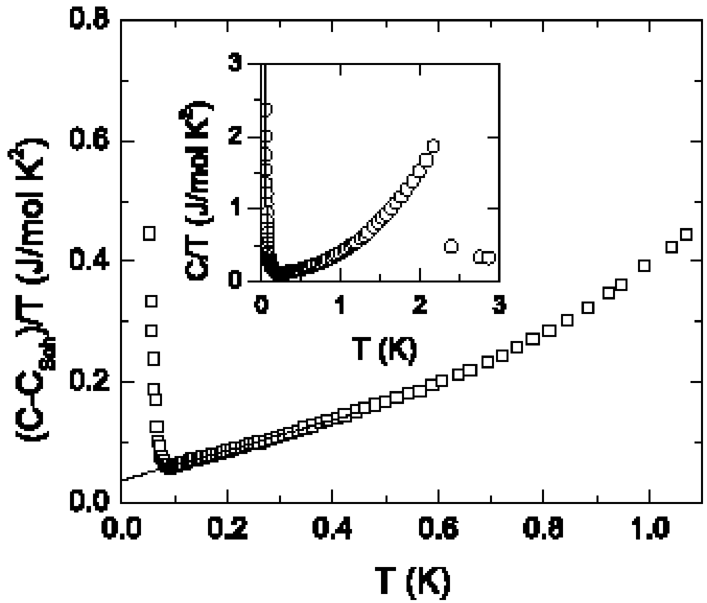


$CeCoIn_5$ field-induced normal state: Non-Fermi liquid behavior



- $\rho - \rho_0 \propto T^{0.95}$ for $0.3 < T < \sim 1.5$K
- $C/T \propto -\ln T$ for $T \leq 1$K

Evidence for unconventional superconductivity in $CeCoIn_5$



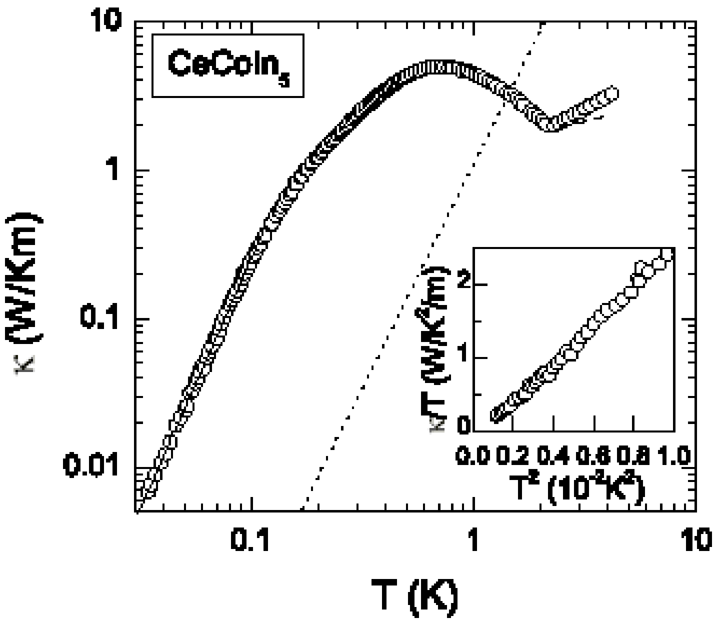
- Heat capacity and thermal conductivity power laws suggest lines of nodes

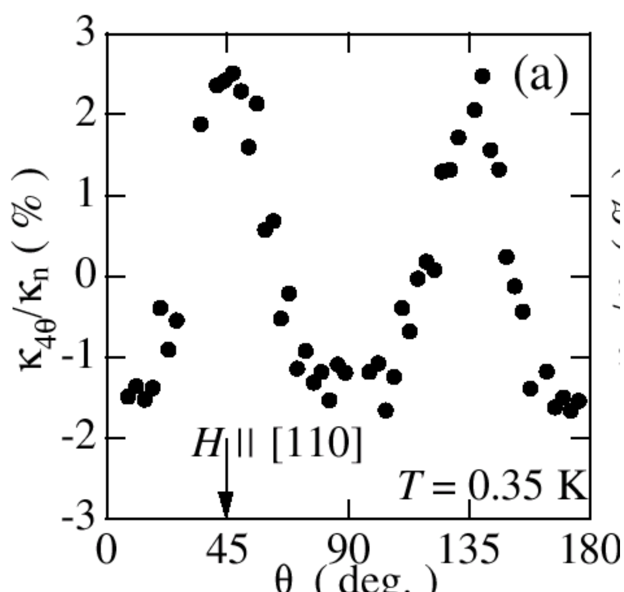
(Movshovich et al.)

- Similar conclusions from $1/T_1$

(Kohori et al.)

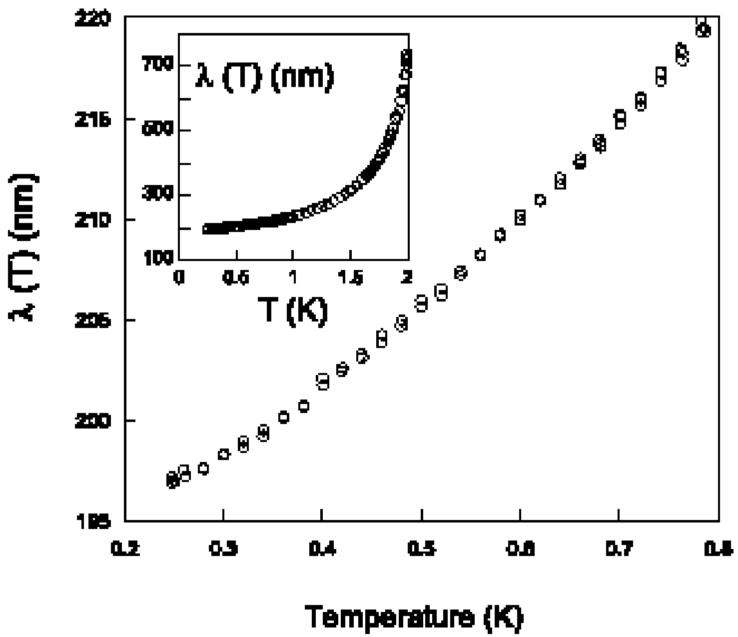
- All of the above identical to that observed in $CeIrIn_5$
- Knight shift implies spin singlet pairing



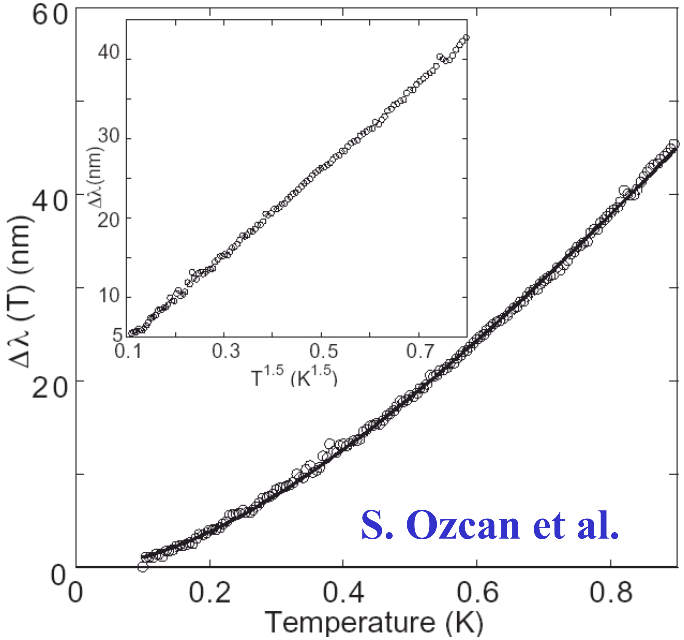


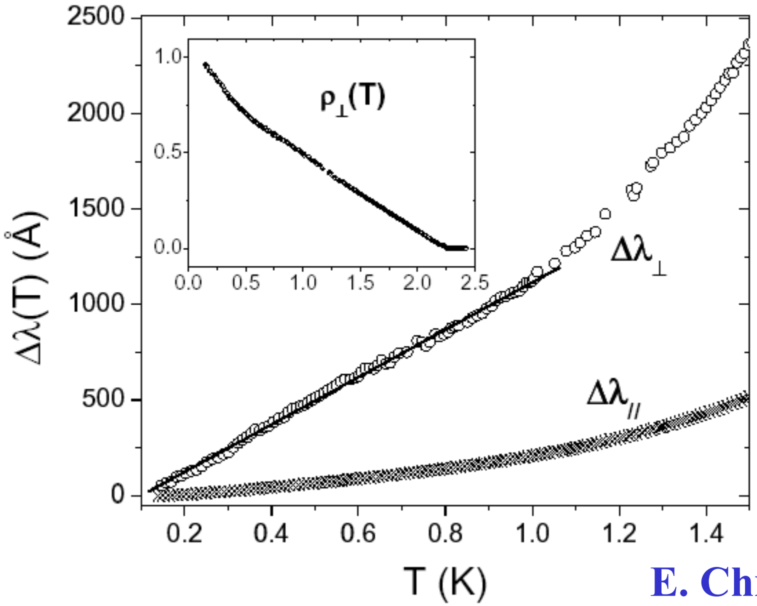
Izawa et al., PRL 87 (2001) 057002

d_{x2-y2} superconductivity in $CeCoIn_5$, however, penetration depth:



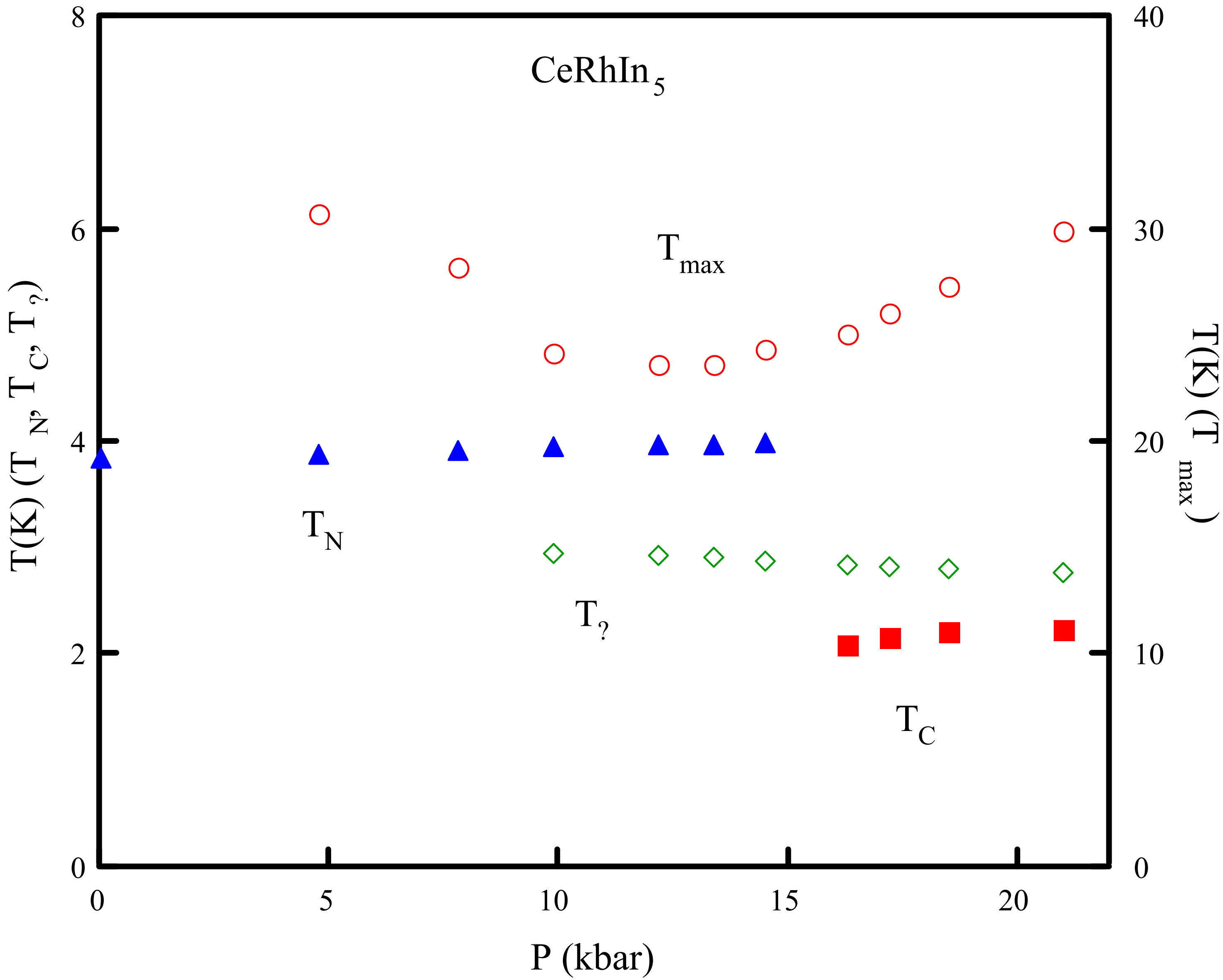
Ormeno et al., PRL 88 (2002) 047005





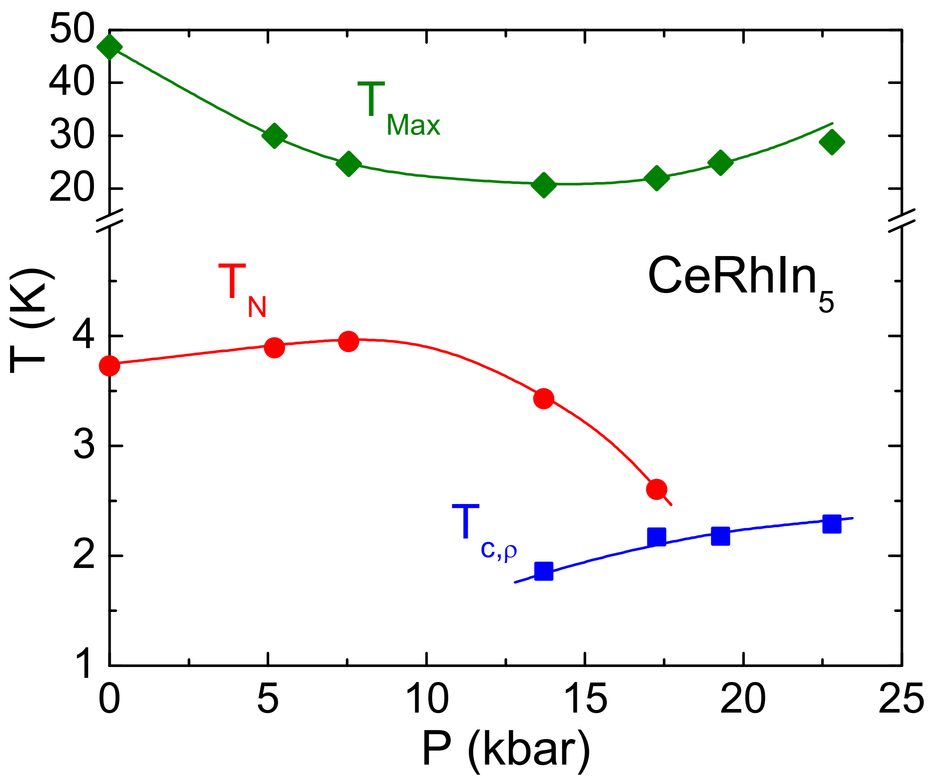
E. Chia et al.

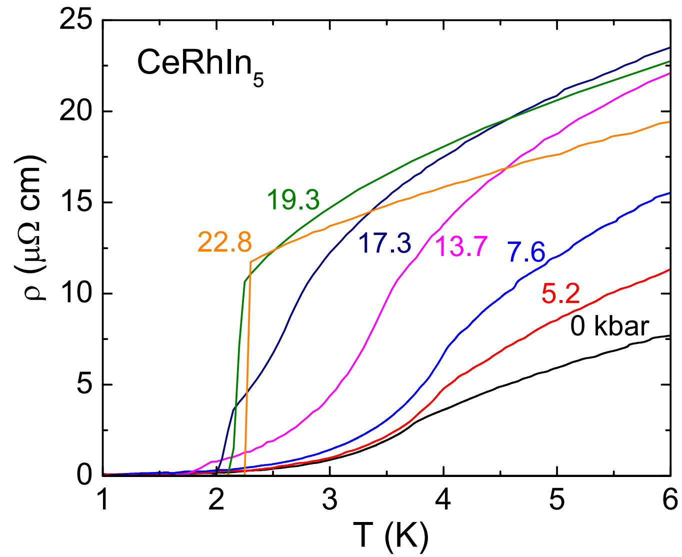
Pressure, doping, pressure & doping

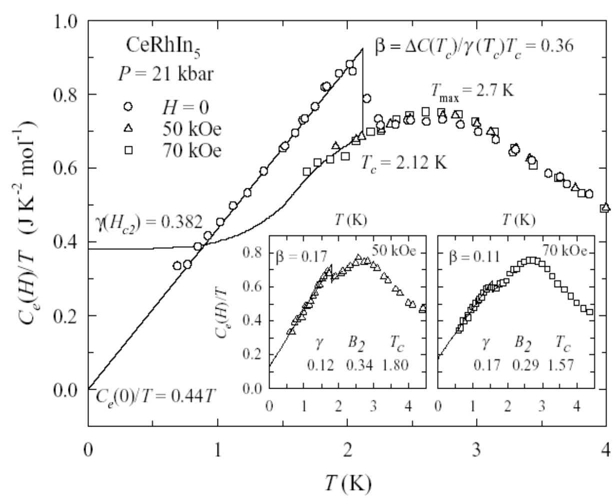


Hegger et al., PRL 84, 4986 (2000)

$CeRhIn_5$





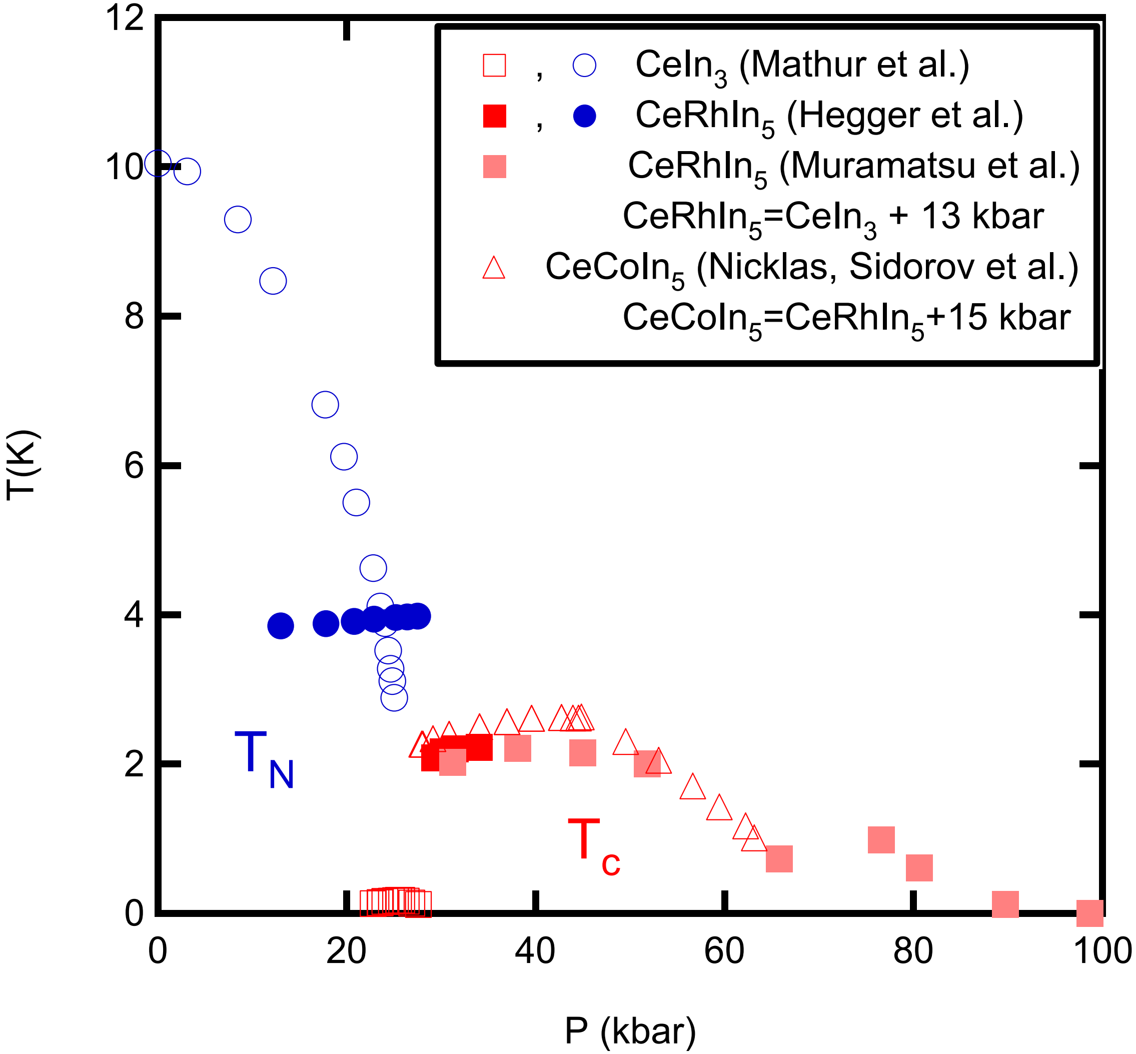


R.A. Fisher *et al.*, Phys. Rev. B **65**, 224509 (2002).

- Antiferromagnetic order at ambient pressure
- Pressure induced superconductivity
- Possible coexistence of superconductivity and antiferromagnetism

- unconventional superconductivity at 21 kbar

Generalized pressure phase diagram



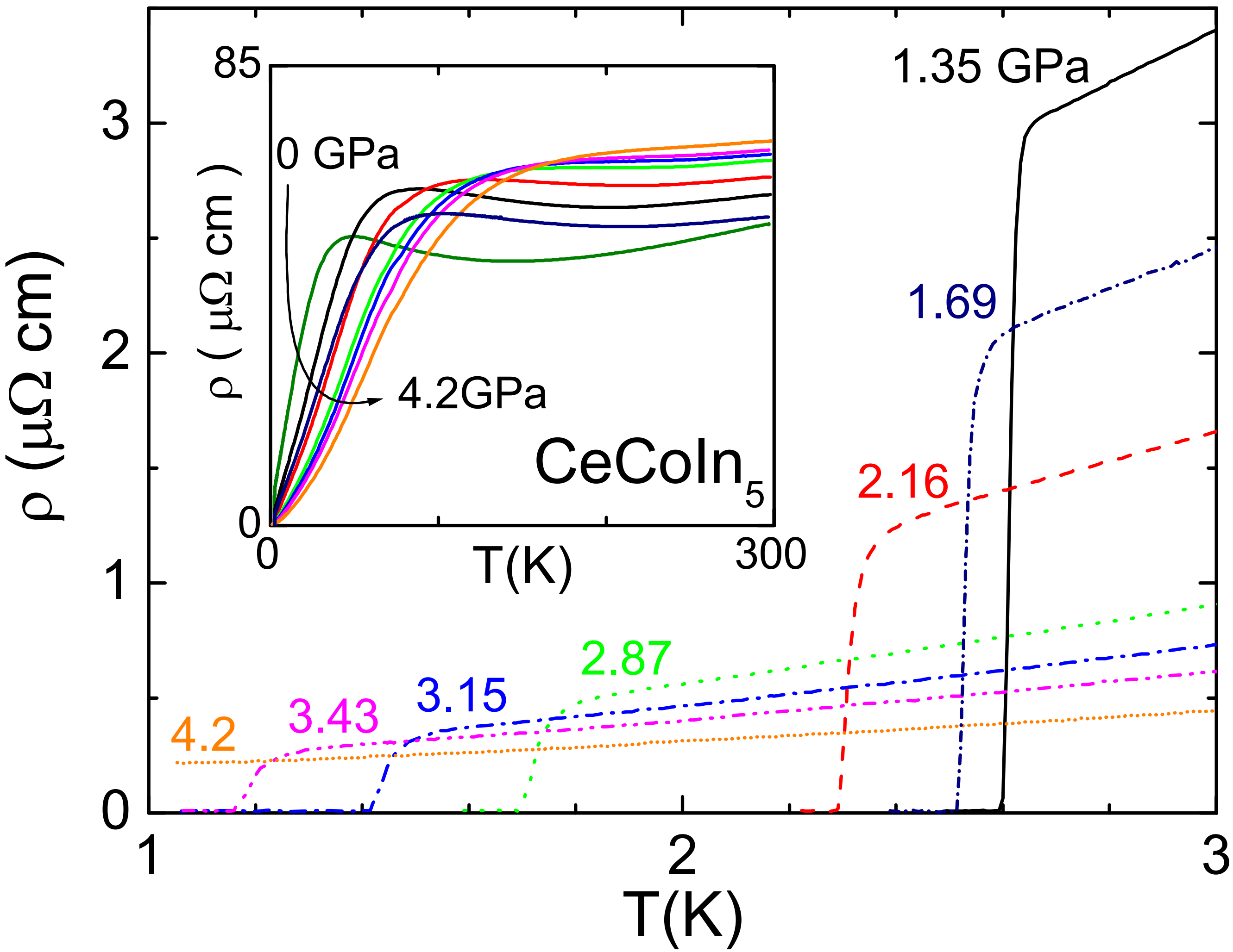
Using measures other than T_c,

"$CeRhIn_5 = CeIn_3 + 13$ kbar"

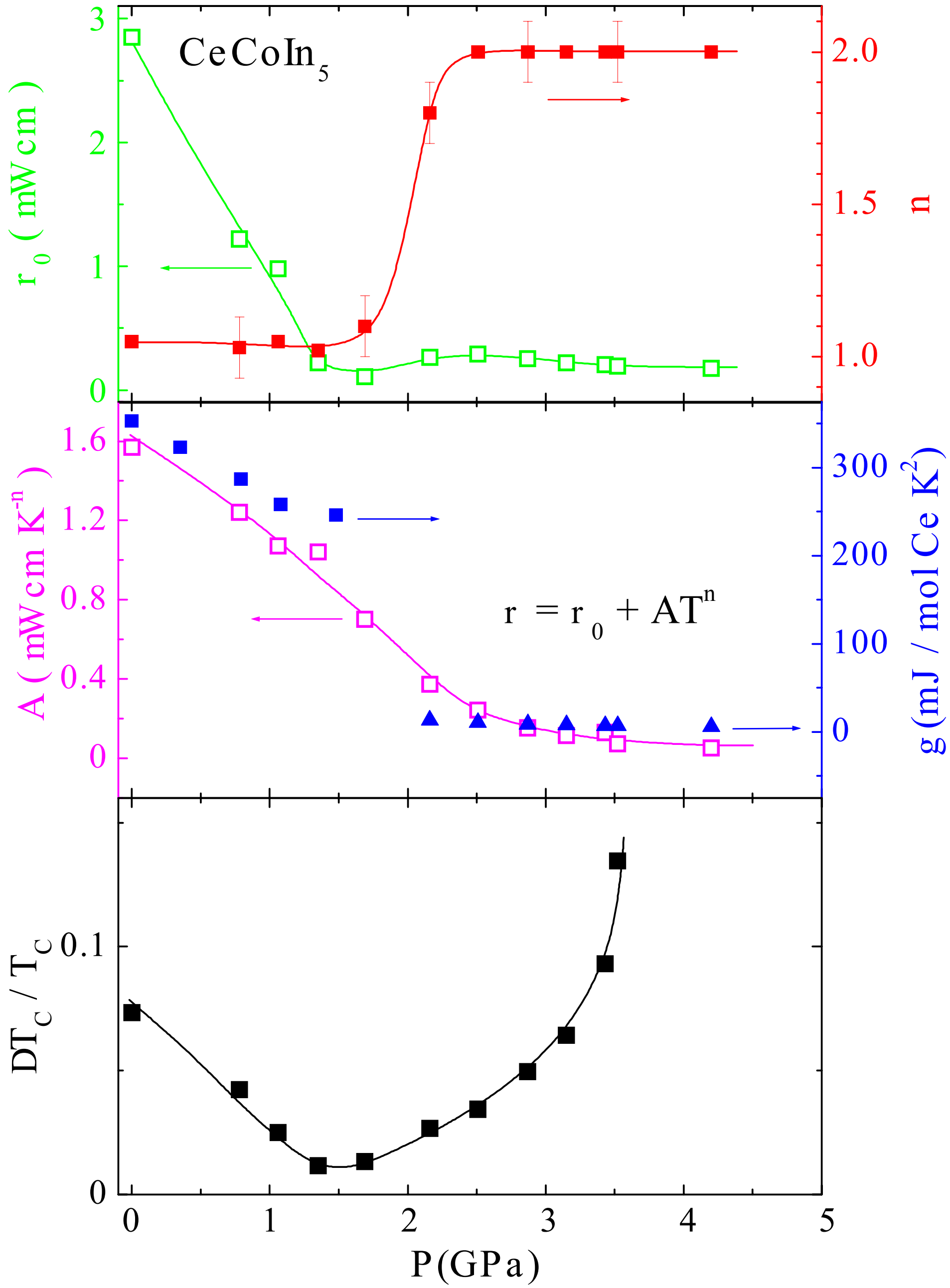
"$CeCoIn_5 = CeRhIn_5 + 15$ kbar"

Also, "superconducting dome" apparent at higher pressure:
$CeRhIn_5$ $P(T_c^{max}) \sim 30$ kbar
$CeCoIn_5$ $P(T_c^{max}) \sim 15$ kbar
(Onuki group, Osaka)

Normal-state changes in $CeCoIn_5$ with pressure



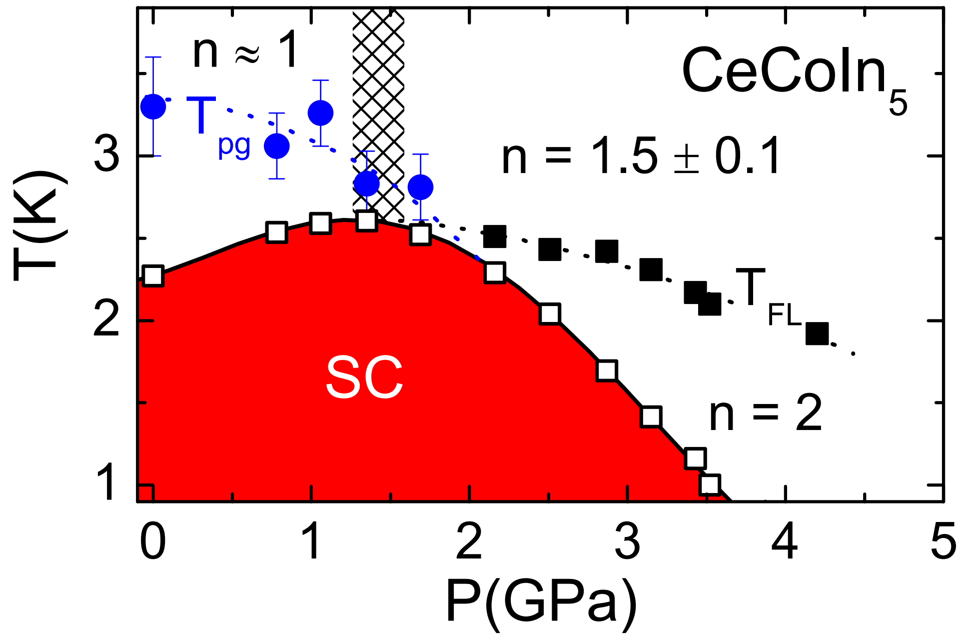
- overall pressure response typical of Ce-based heavy-fermion materials
- strong pressure-induced variations in T_c and $\rho(T \geq T_c)$



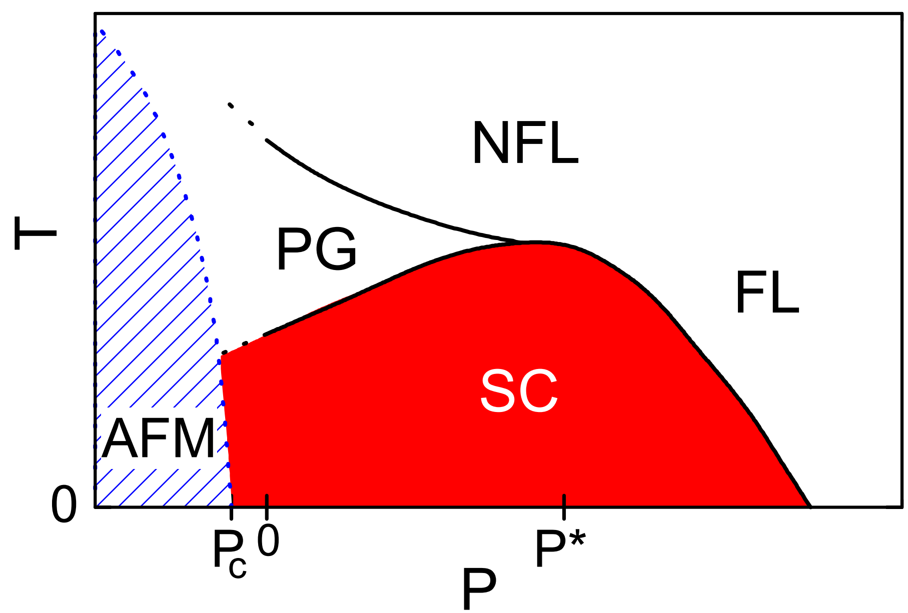
- pronounced crossover in transport and thermodynamic properties at P* ≈ 1.6 GPa
  - -- $\rho_0(P \geq P^*) \approx \rho_0(0)/10$
  - -- step-like increase in 'n'
  - -- large change in 'A' and step-like decrease in γ (directly measured at 3K for P ≤ 1.5 GPa and inferred from Kadowaki-Woods relation for P ≥ 2 GPa)

- minimum in $\Delta T_c/T_c$ (and ΔT_c) near P*
  - -- superconductivity singularly homogeneous near P*

T-P phase diagram in $CeCoIn5$ – pseudogap??



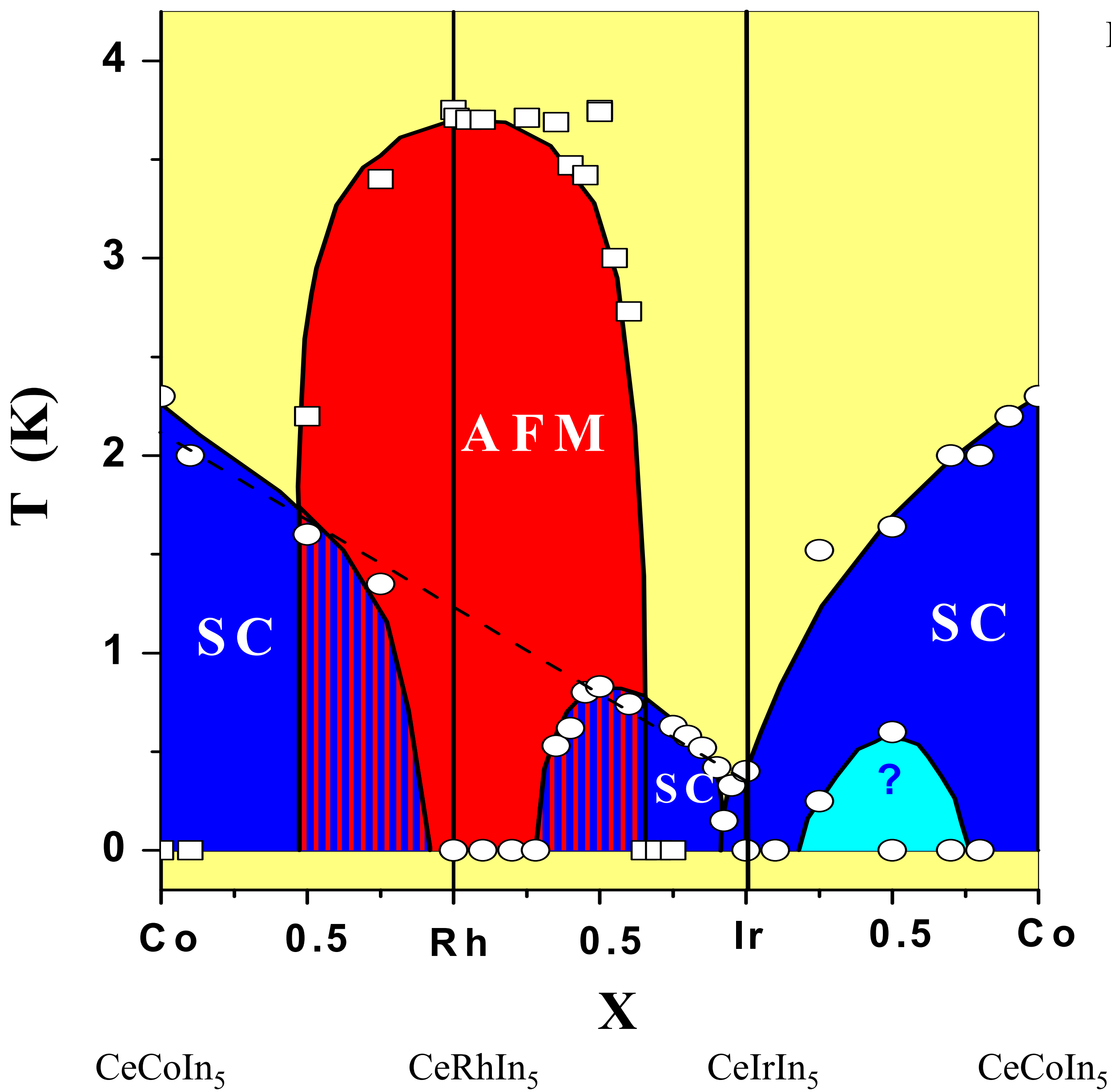
- ♦ $T_c(P)$ qualitatively similar to H. Shishido et al., JPSJ **71**, 162 (2002)
- ♦ n≈1 and $C/T \propto -\ln T$ for P≤1.6 GPa=P* suggests proximity to a QCP at P<0
- ♦ crossover from n ≈ 1 to 1.5 near P* ⇒ change from 2D- to 3D-like quantum fluctuations



- ♦ 1.7% smaller cell volume of $CeCoIn_5$ compared to $CeRhIn_5$ ⇒ $CeCoIn_5$ under effective chemical pressure
- ♦ suggest generic phase diagram that combines $CeRhIn_5$ and $CeCoIn_5$ and that is similar to cuprate T-x diagram
- ♦ is T_{pg} evidence for a pseudogap or ???

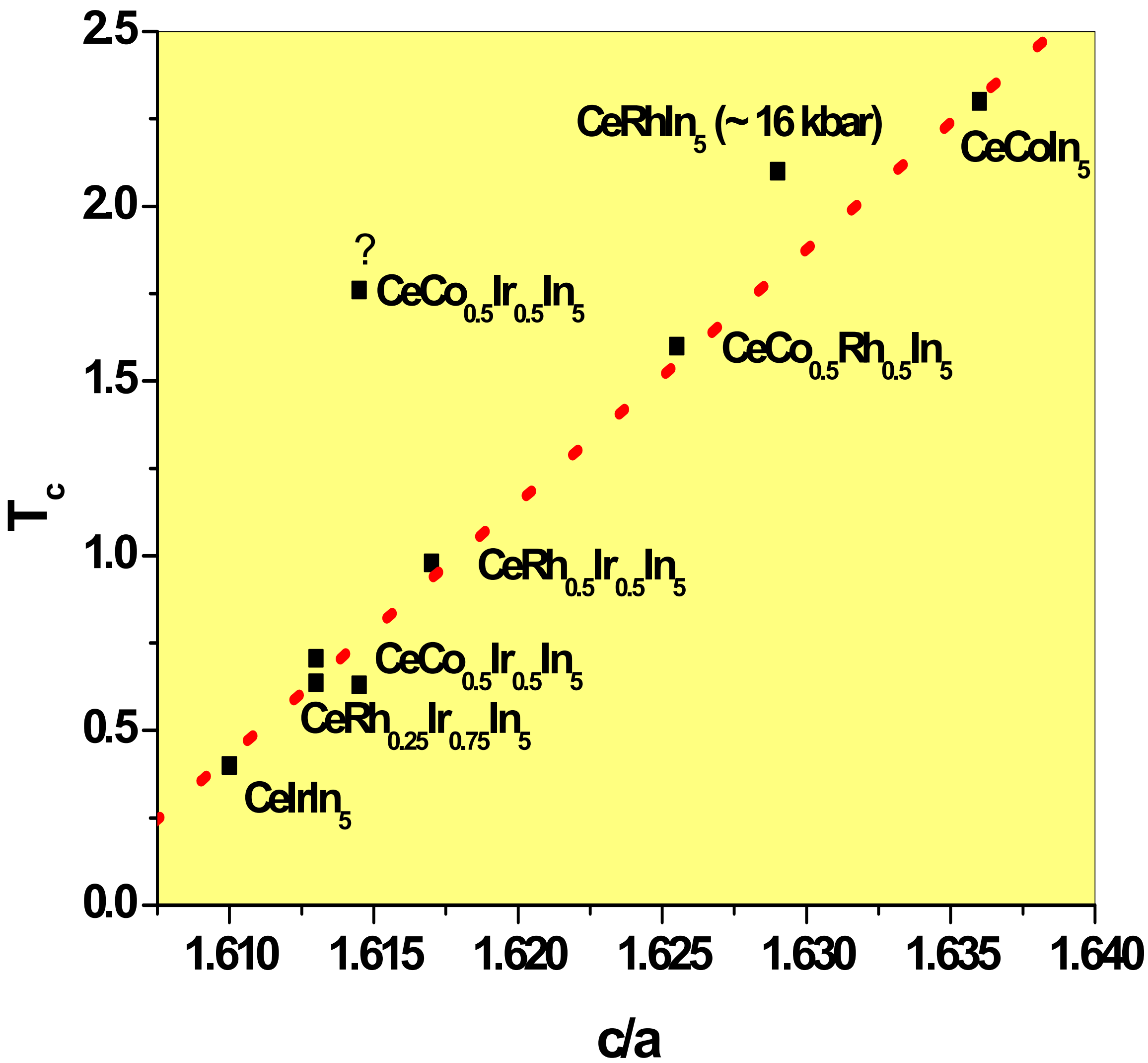
Generalized Doping-Temperature Phase Diagram

Pagliuso et al.

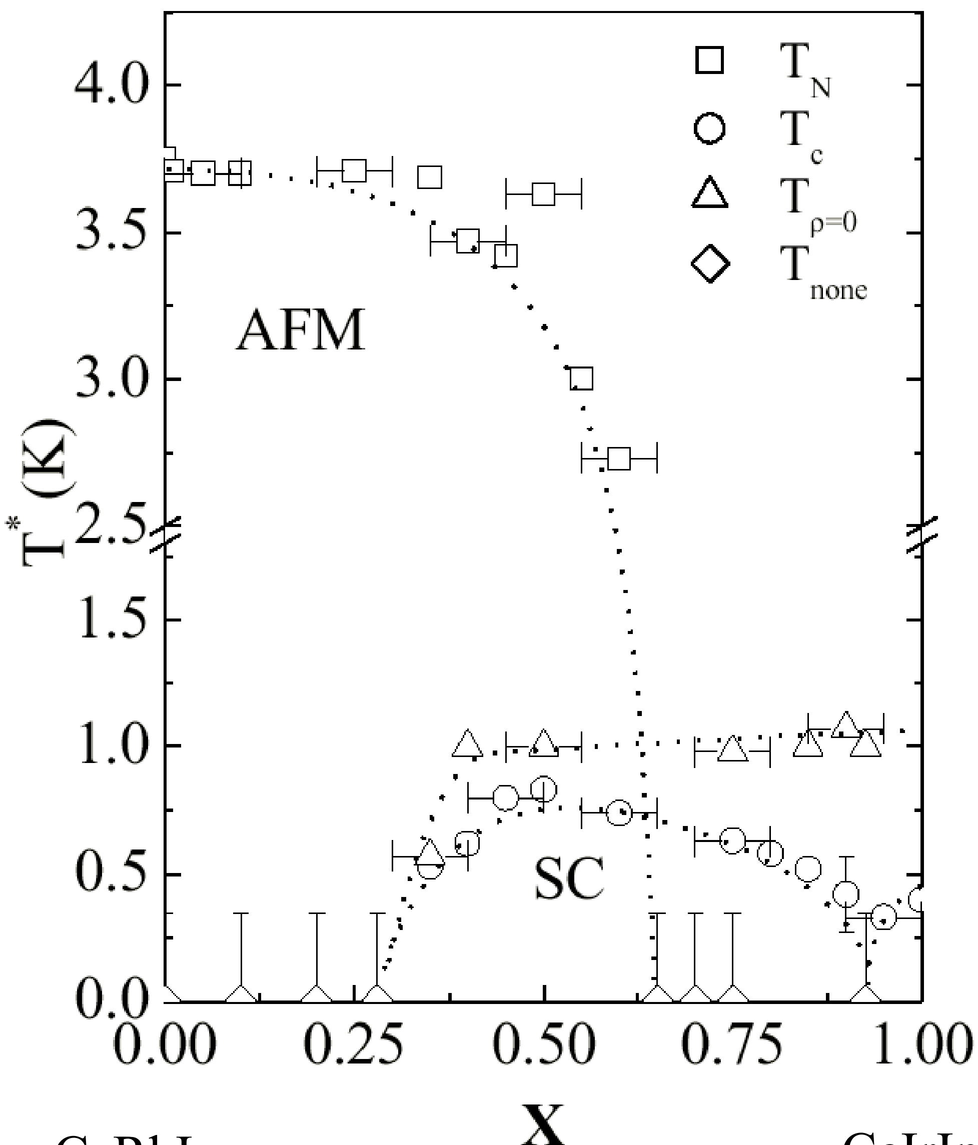


c/a as control parameter for T_c

Pagliuso et al.

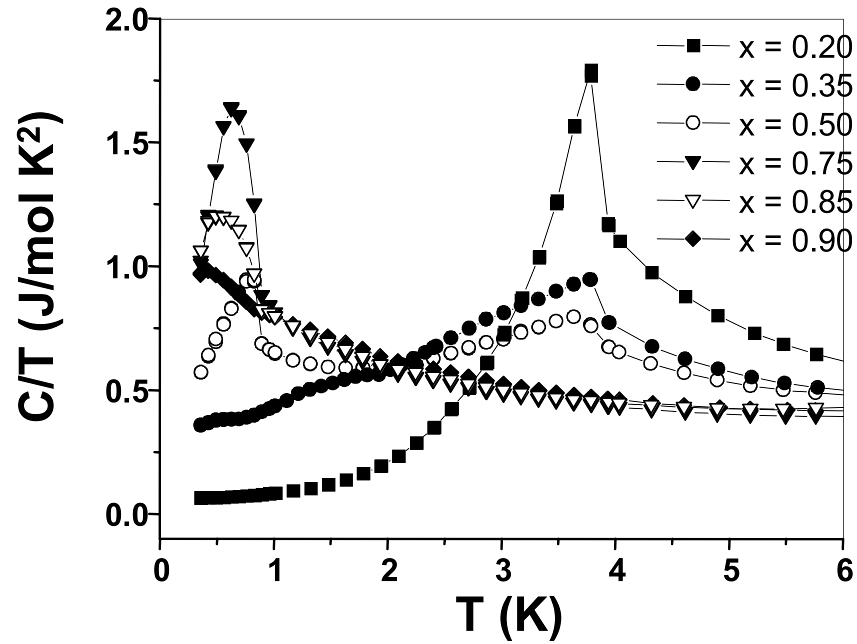


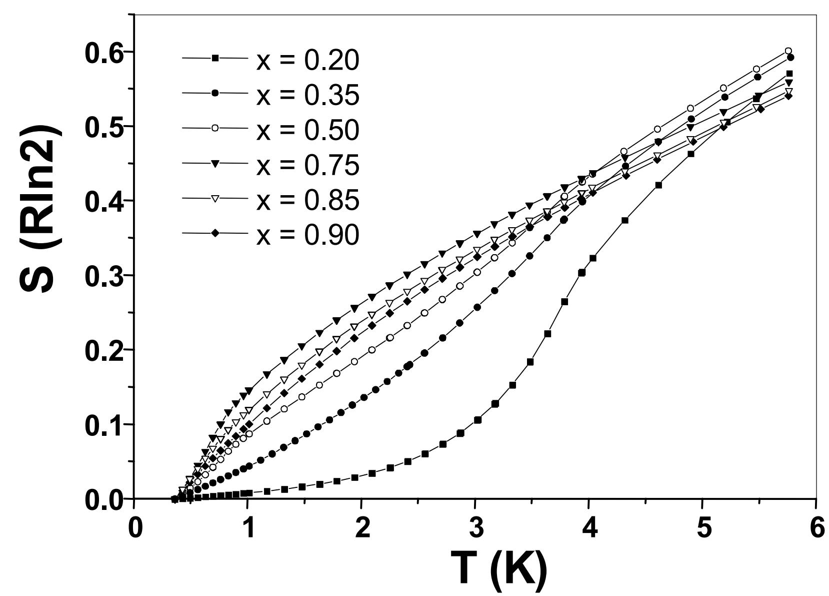
$CeRh_{1-x}Ir_xIn_5$: Coexistence of magnetism and superconductivity



CeRhIn$_5$

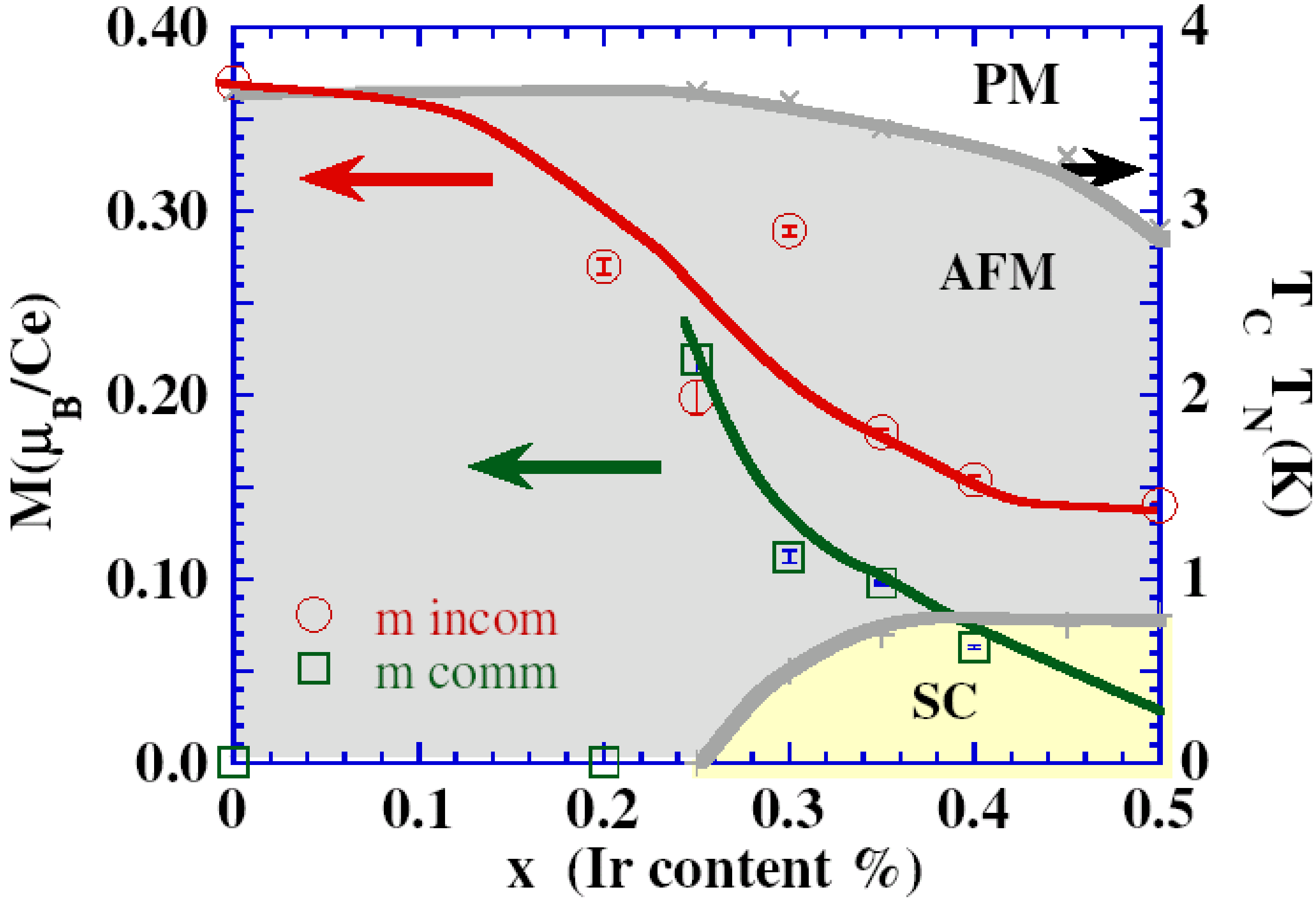
CeIrIn$_5$





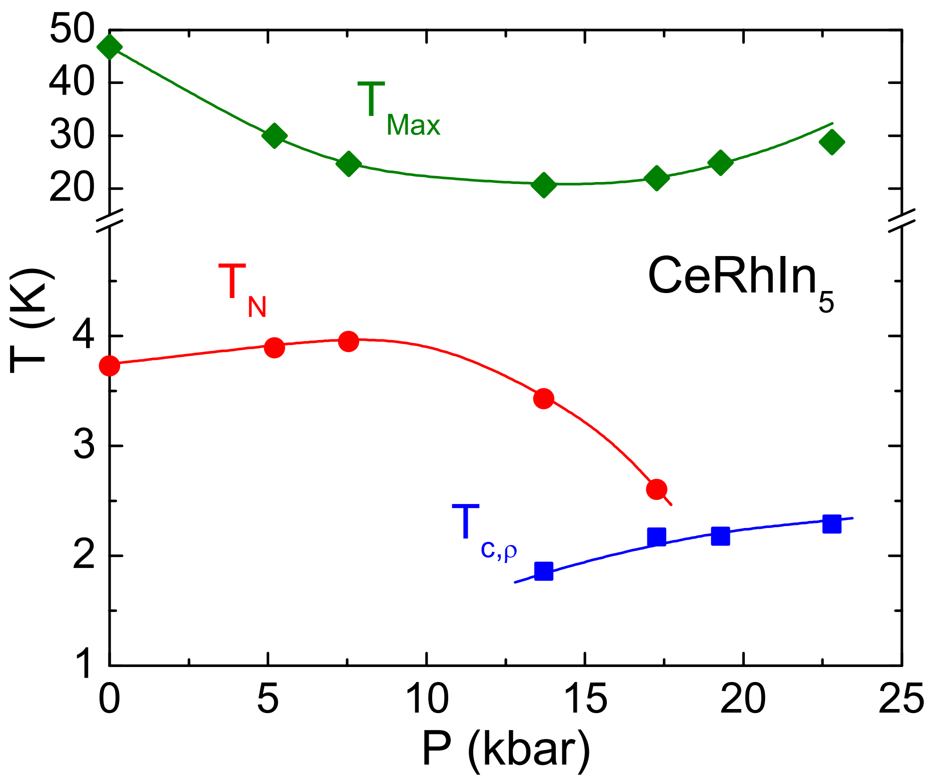
P.G. Pagliuso et al. PRB 64 (2001) 100503

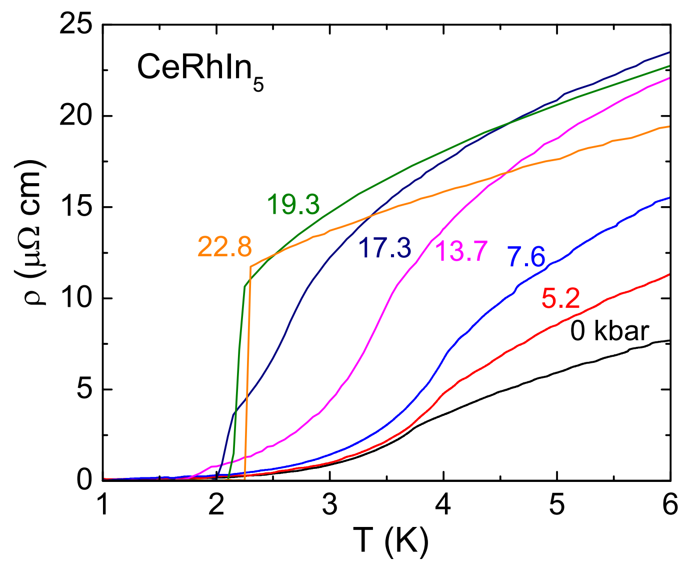
$CeRh_{1-x}Ir_xIn_5$: Evolution of the Magnetic Structure

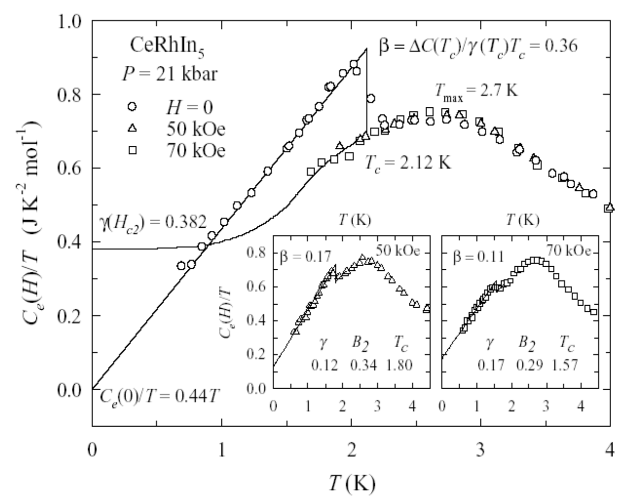


- Commensurate component appears near the onset of superconductivity.

$CeRhIn_5$







- Antiferromagnetic order at ambient pressure
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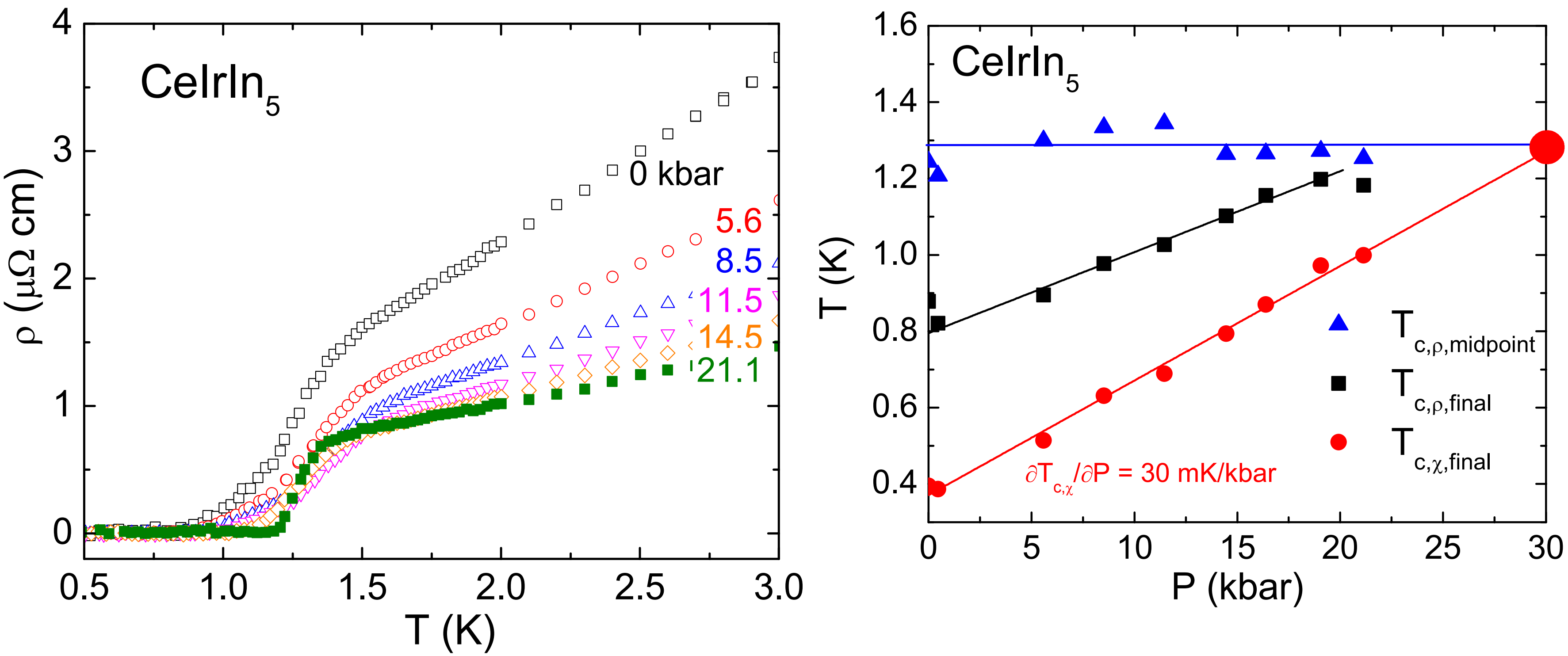
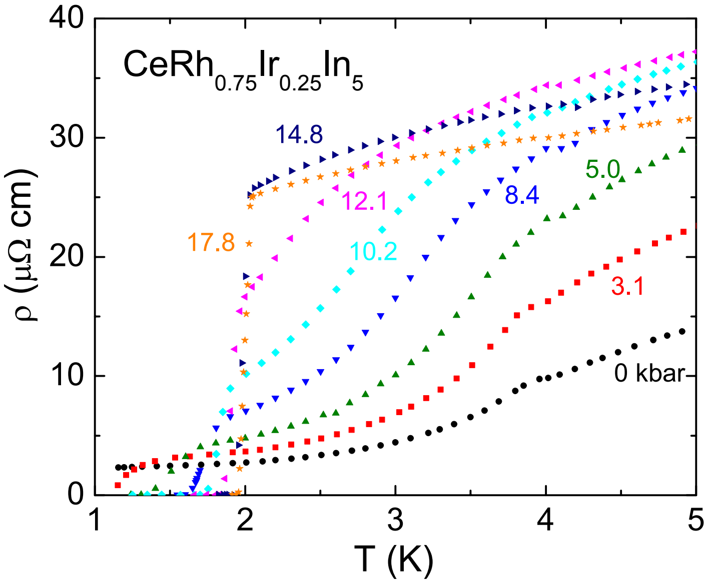
R.A. Fisher *et al.*, Phys. Rev. B **65**, 224509 (2002).

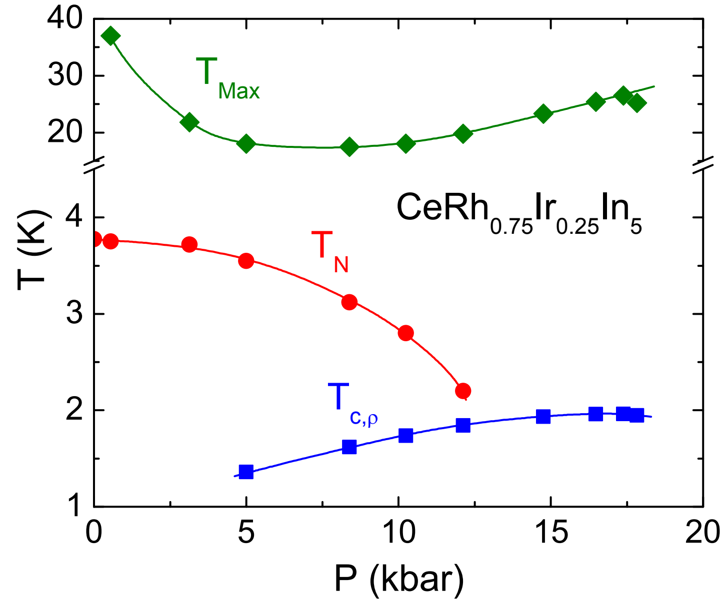
$CeIrIn_5$

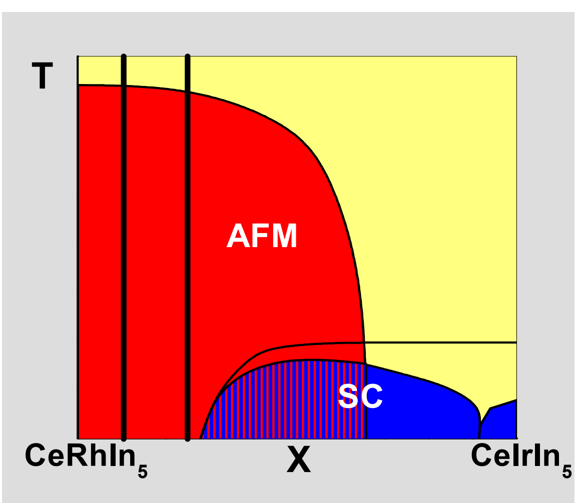


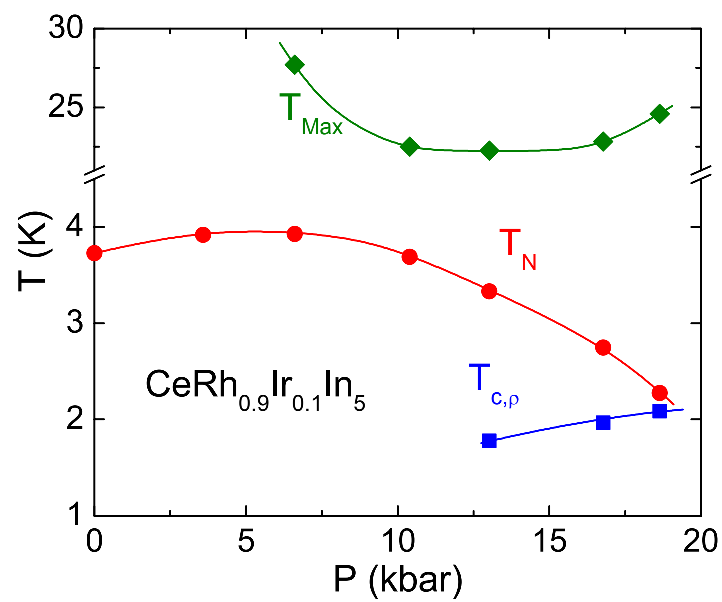
- High sensitivity of the bulk and zero resistivity transition to pressure
- Transition is sharpening with increasing pressure
- Bulk and resistive transition extrapolate to same T_c at 30 kbar

$CeRh_{0.75}Ir_{0.25}In_5$ - $CeRh_{0.9}Ir_{0.1}In_5$

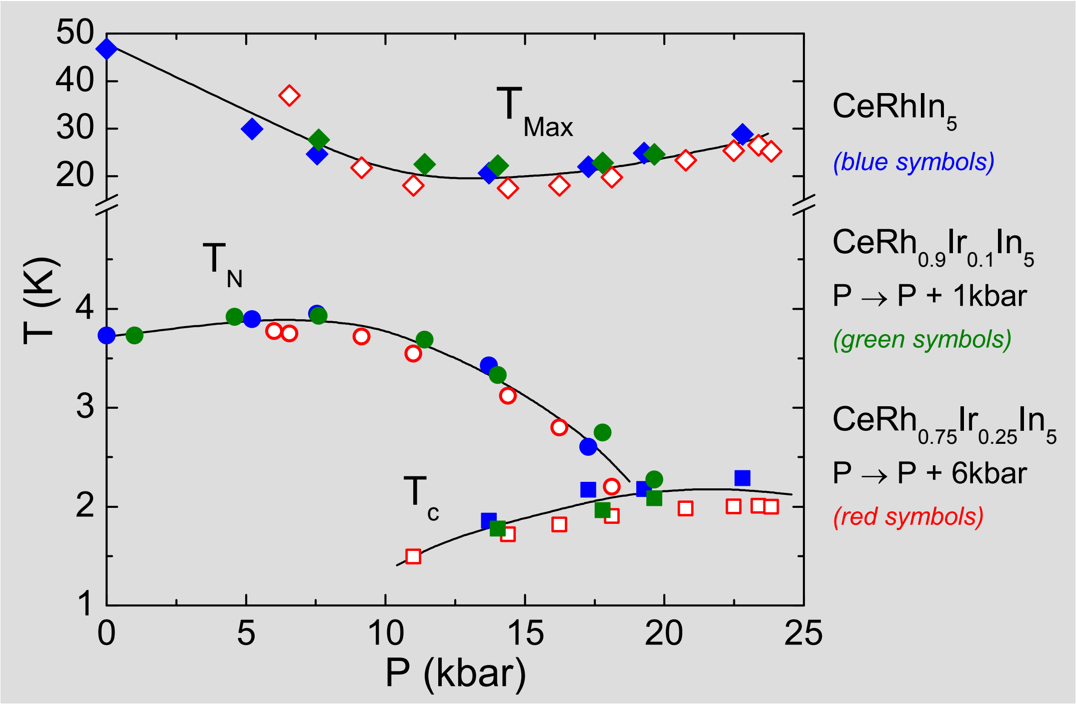


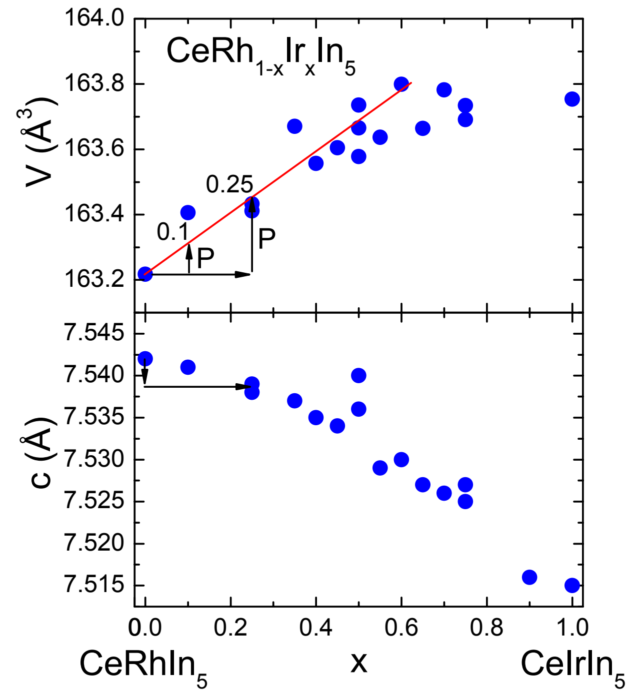


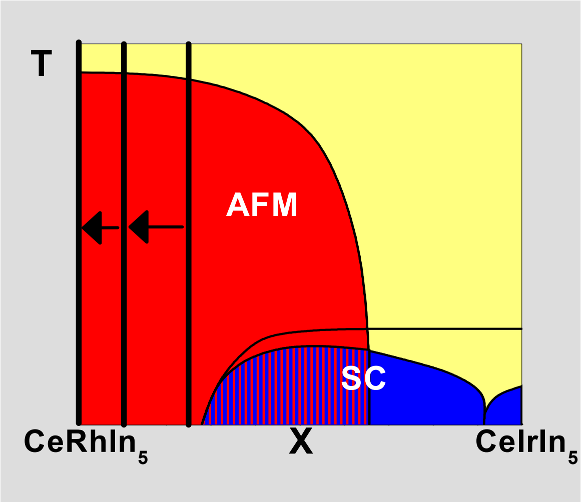




$CeRh_{1-x}Ir_xIn_5$ - Control Parameter

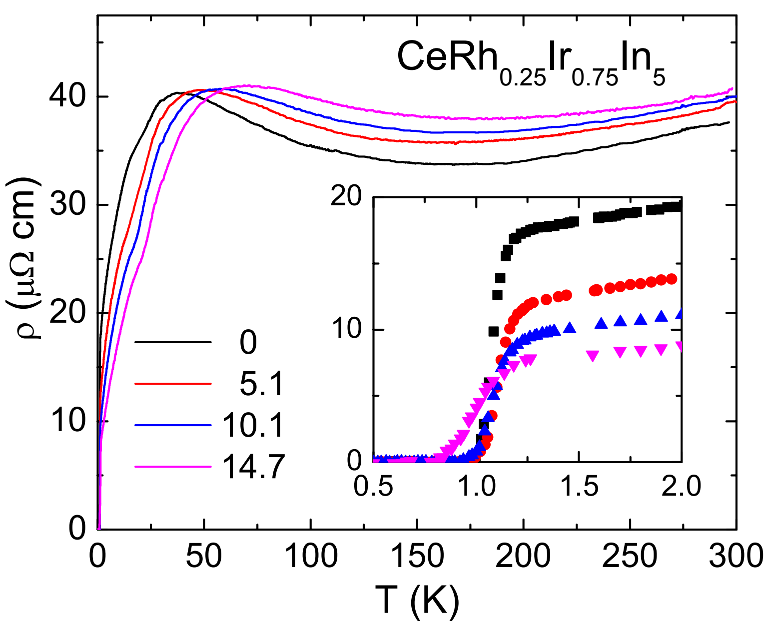


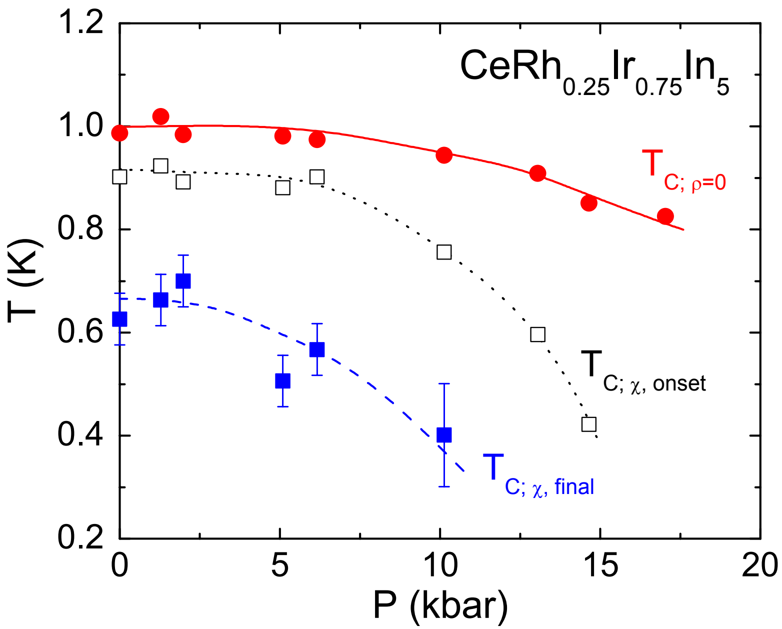


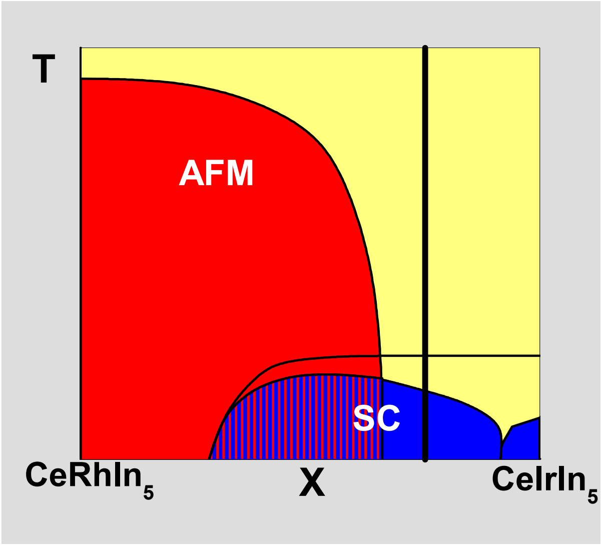


- Not just a volume effect
- Ce-(Rh,Ir) hybridization determines magnetic and superconducting properties?

$CeRh_{0.25}Ir_{0.75}In_5$



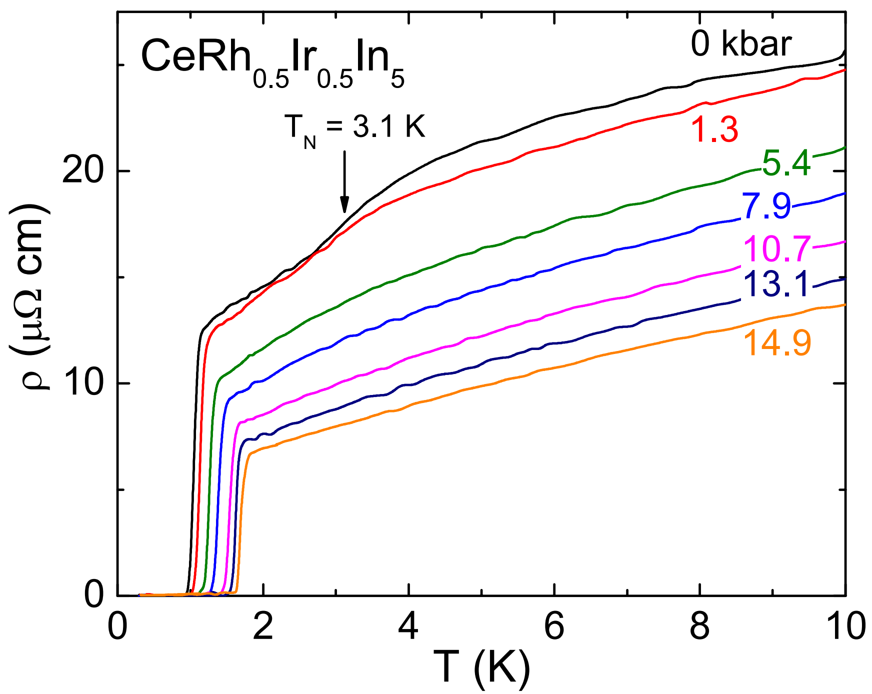


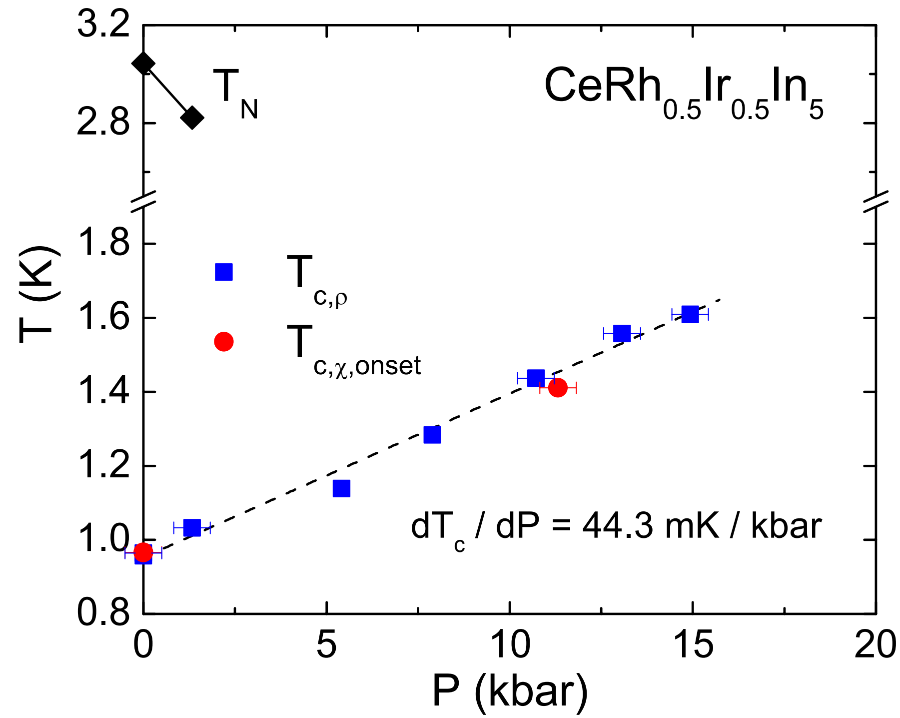


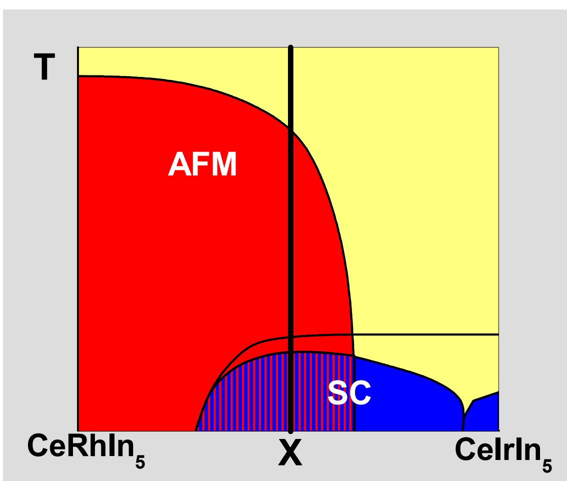
- Transition broadening with pressure
- T_c decreasing with pressure
- Bulk transition and resistive transition not at the same temperature

- $\partial\rho(T_c^+)/\partial P < 0$

$CeRh_{0.5}Ir_{0.5}In_5$



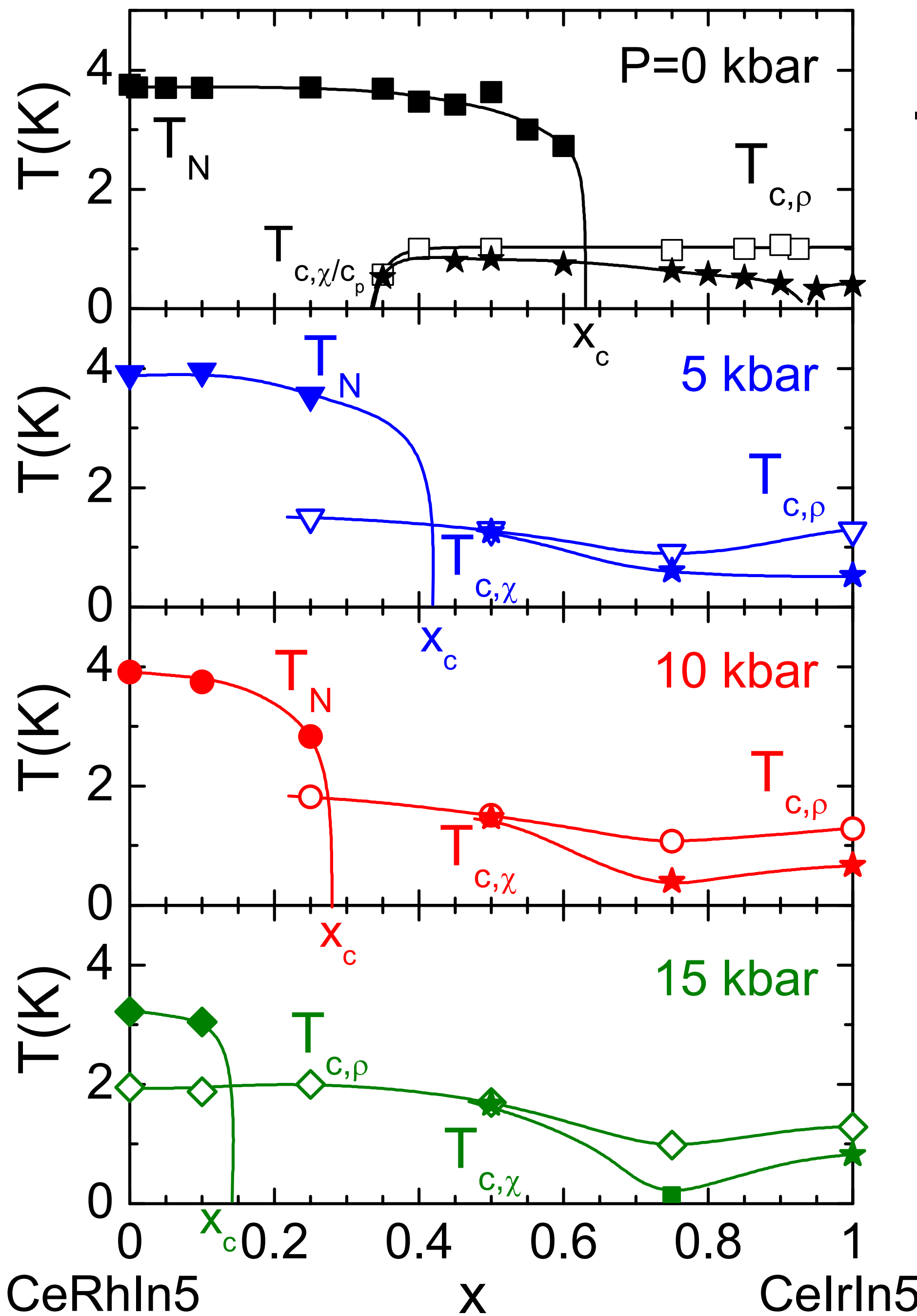




- $T_N = 3.1$ K at ambient pressure
- T_c increasing linearly
- $T_{c,\rho} = T_{c,\chi}$

- $\partial\rho(T_c^+)/\partial P \approx 0$ for $P \leq 1.3$ kbar
- $\partial\rho(T_c^+)/\partial P < 0$ for $P > 1.3$ kbar

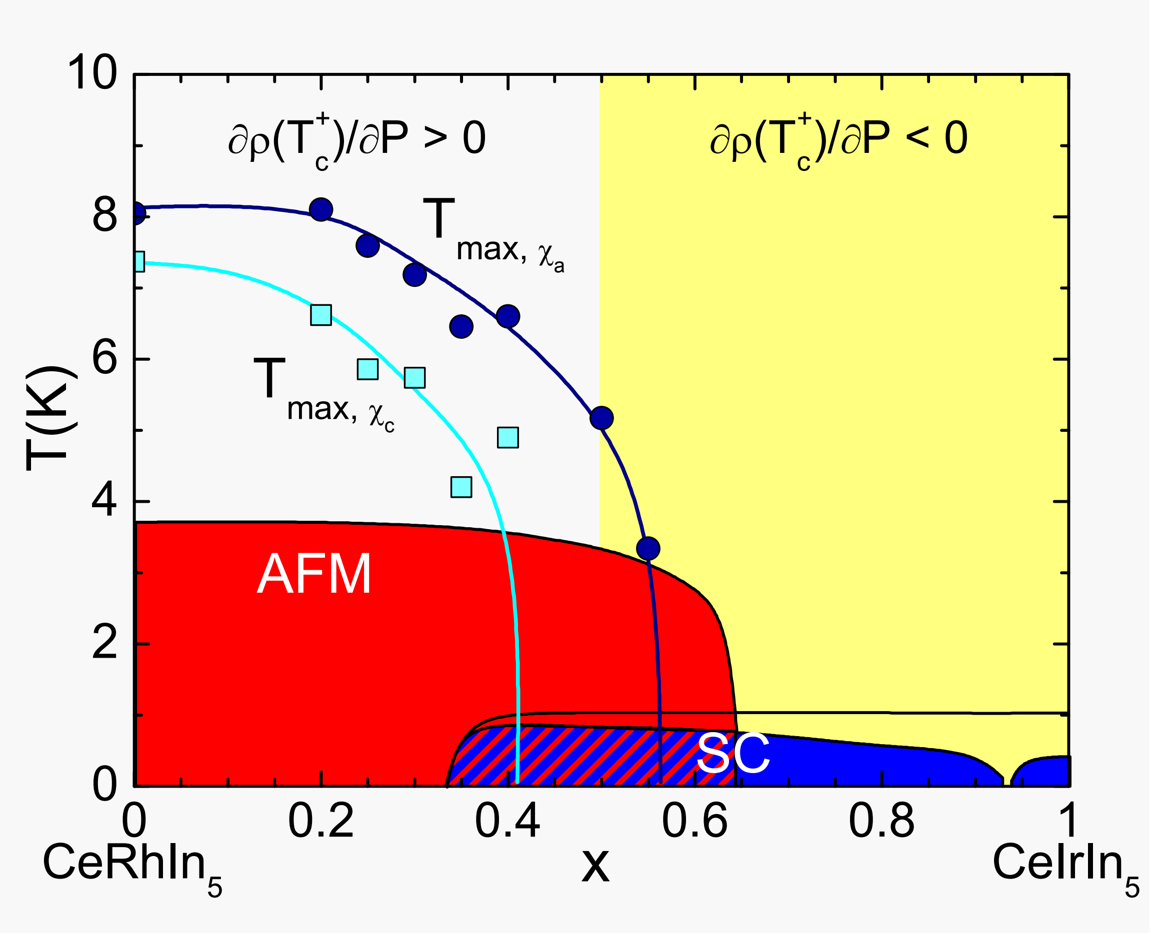
$CeRh_{1-x}Ir_xIn_5$



- AFM suppressed with pressure
- x_c moves to smaller x with pressure

- Minimum in bulk T_c moves to lower x with pressure ⇒ more than pair breaking

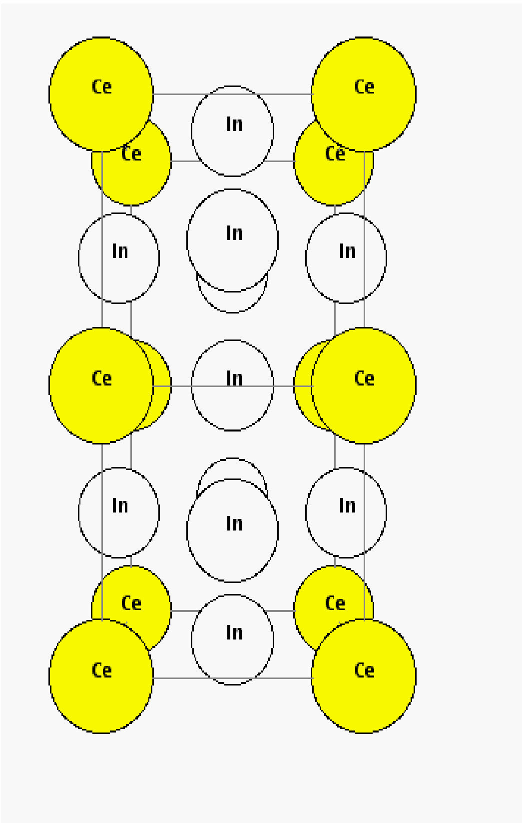
$CeRh_{1-x}Ir_xIn_5$



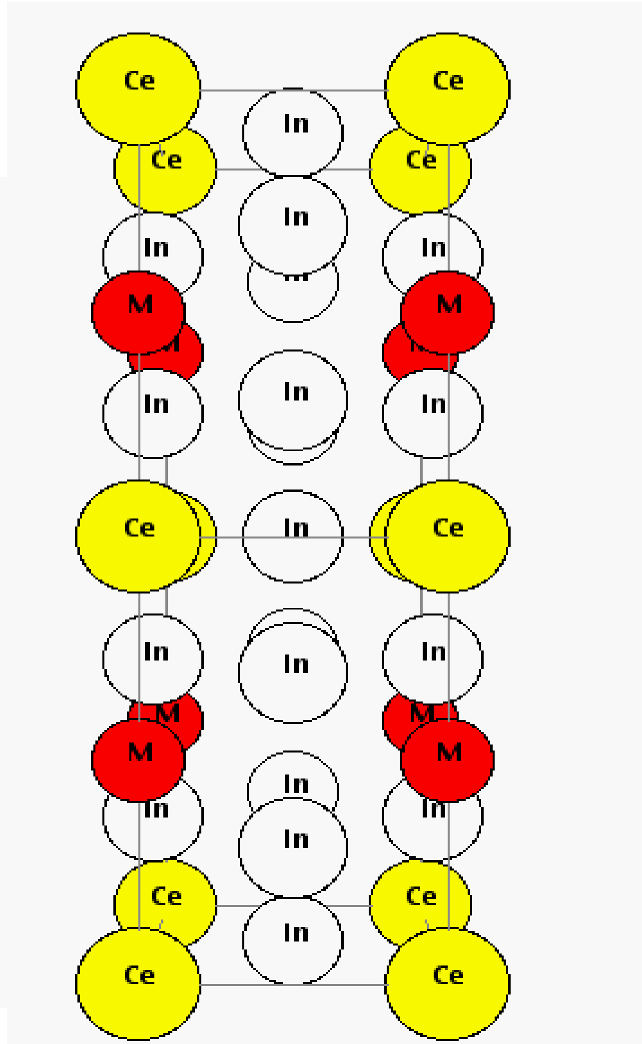
- Qualitatively two regions x < 0.5 and x > 0.5 reflect different q and ω dependence of χ(q,ω)

M. Nicklas et al.

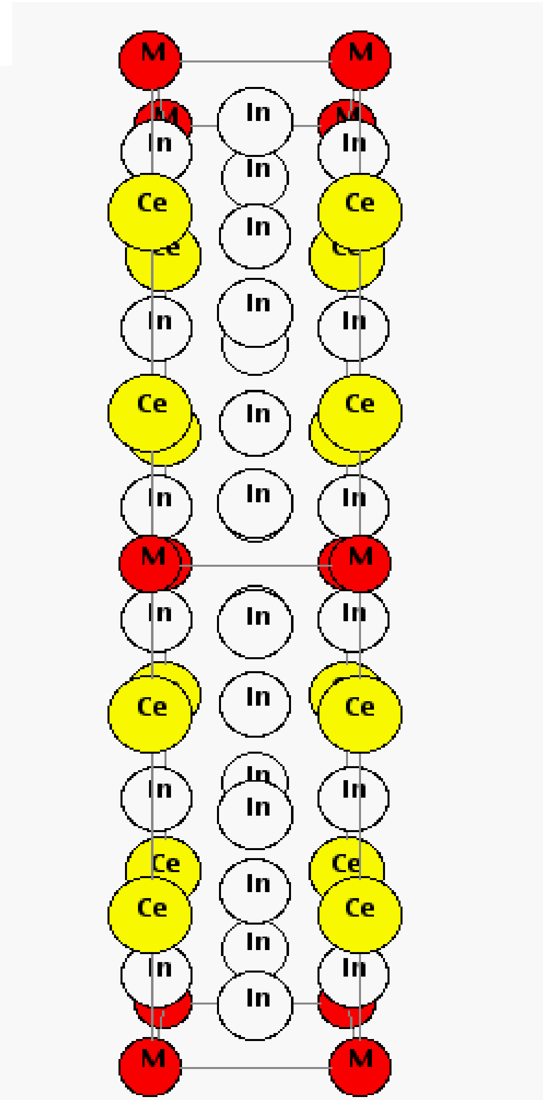
Crystal Structures



$CeIn_3$

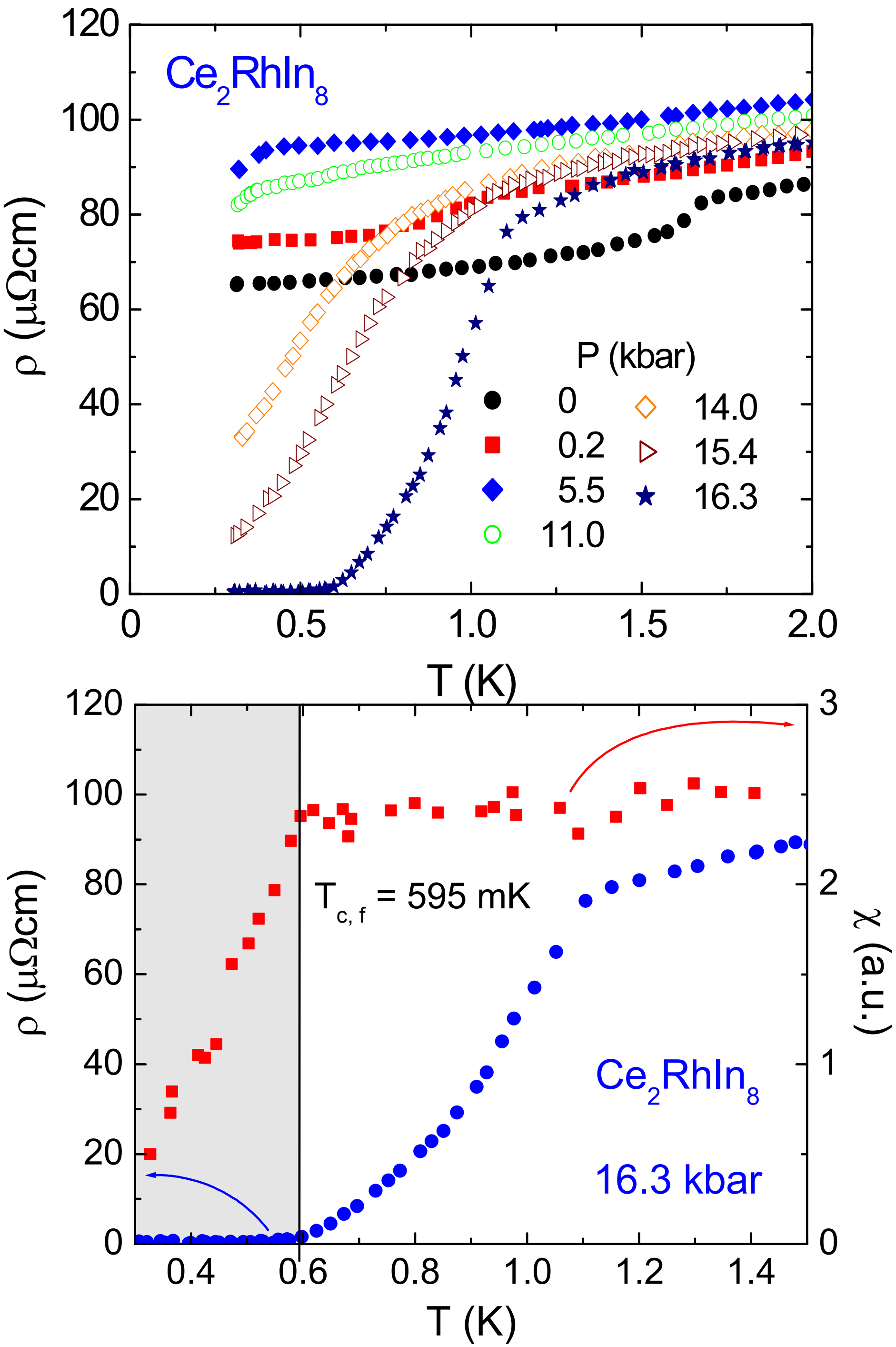


$CeMIn_5$



Ce_2MIn_8

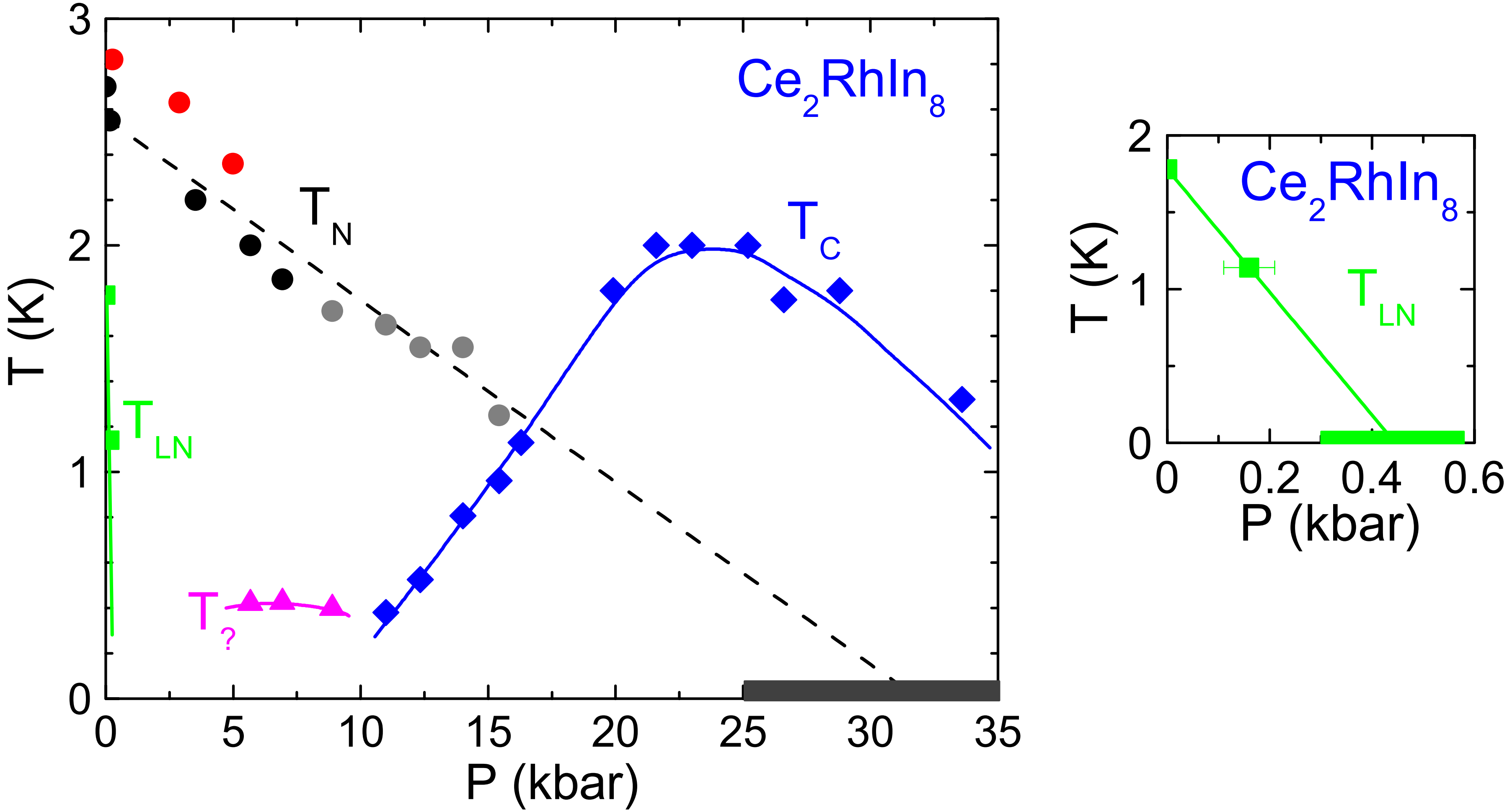
M = Co, Rh, Ir (isovalent)



Pressure induced superconductivity in Ce_2RhIn_8

- zero-resistivity state at 16.3 kbar below T_c = 600 mK (T_c of $CeRhIn_5$ at 16 kbar ≈ 2 K)
- diamagnetic response below 600 mK ⇒ bulk superconductivity
- superconductivity from a highly resistive state

T-P Phase Diagram for Ce_2RhIn_8

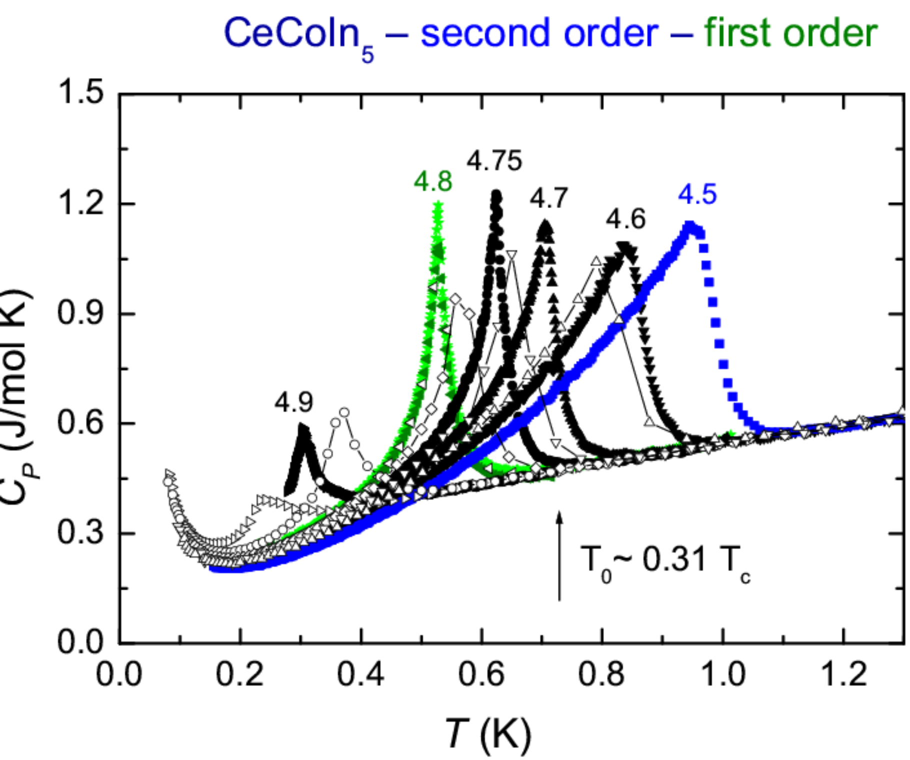


- $\partial T_N/\partial P \approx$ -82 mK/kbar, similar to initial slope of -60 mK/kbar in $CeIn_3$ but distinct from $T_c(P)$ in $CeRhIn_5$
- $CeIn_3$-like magnetism and $CeRhIn_5$-like superconductivity
- coexistence of superconductivity and magnetism?

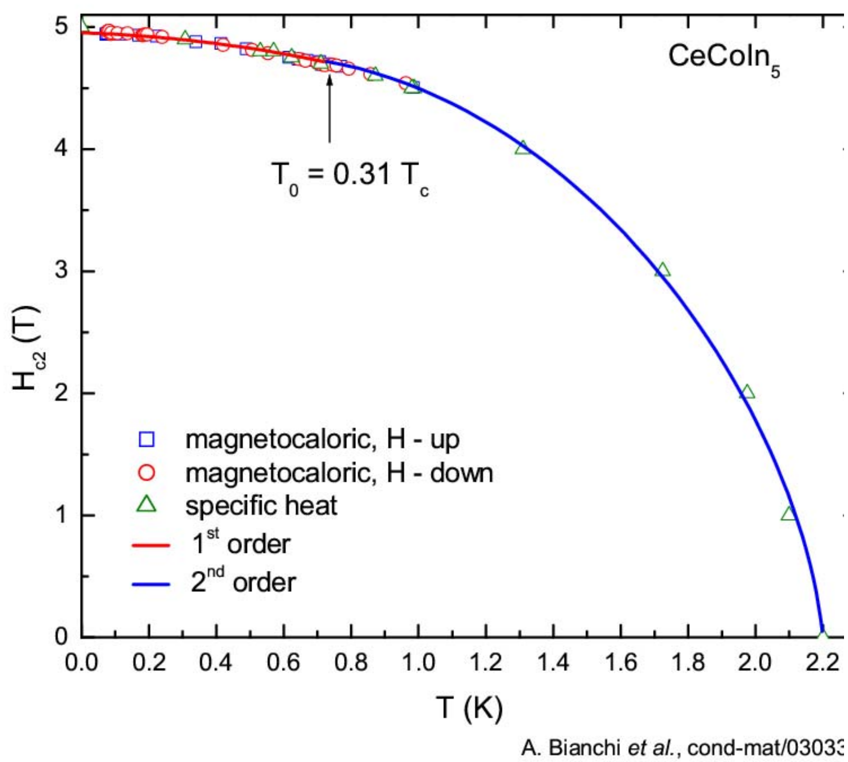
M. Nicklas et al.

H-T phase diagram for $CeCoIn_5$: 1st-order superconducting transition

H || [001]



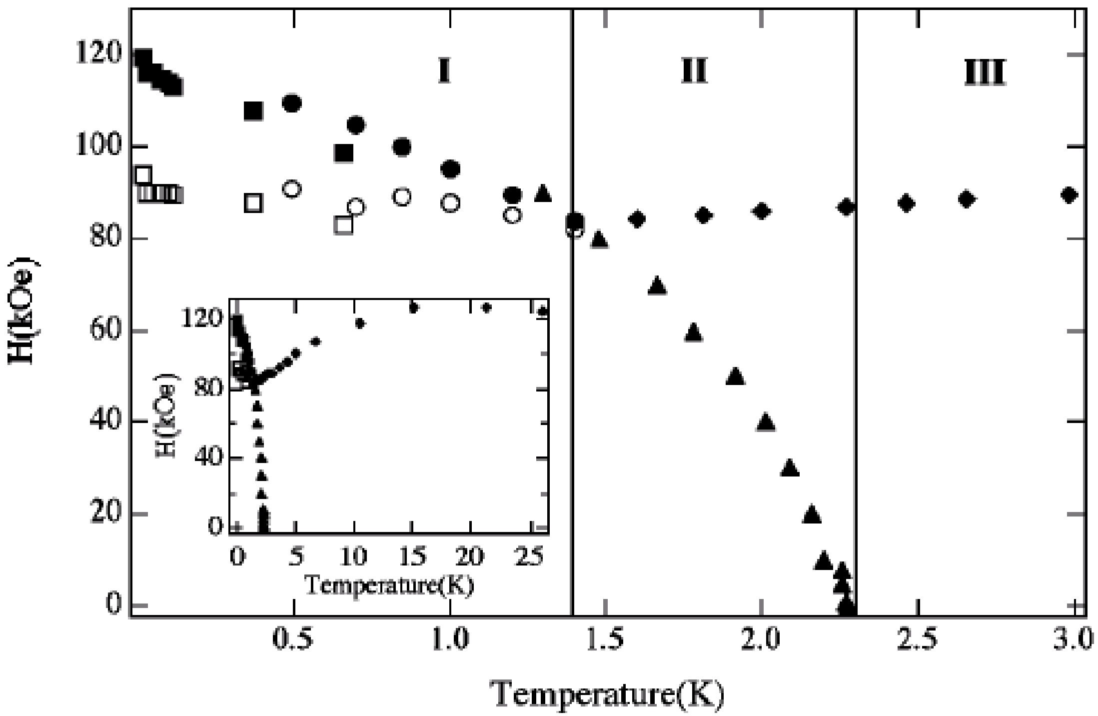
A. Bianchi *et al.*, cond-mat/0203310
R. Movshovich *et al.*, proceedings of SCES'01
APS March 2002: B12.006, R. Movshovich



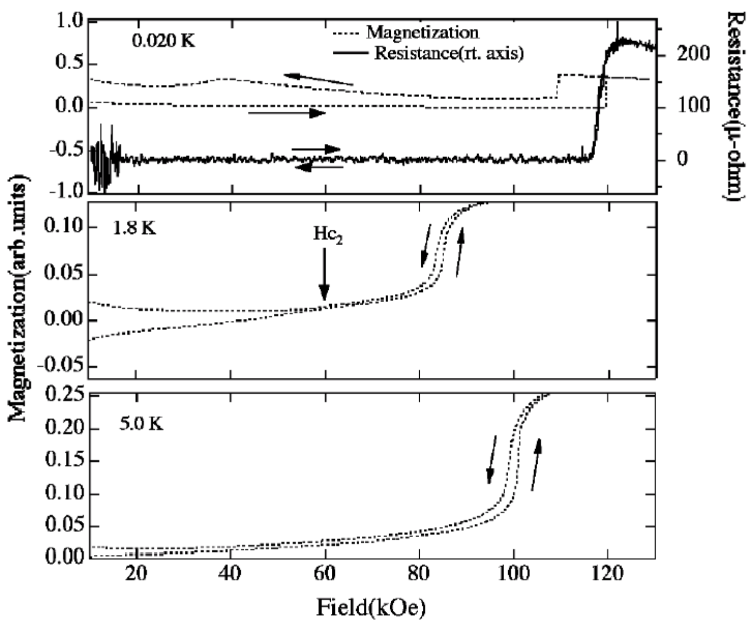
Similar evidence:
Thermal expansion
Thermal conductivity (Izawa, Matsuda, et al.)

Evidence for FFLO in $CeCoIn_5$

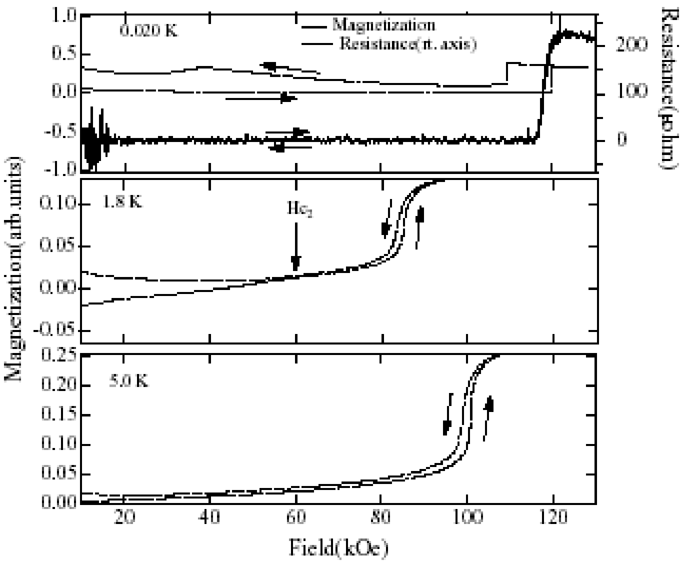
(Murphy et al.)

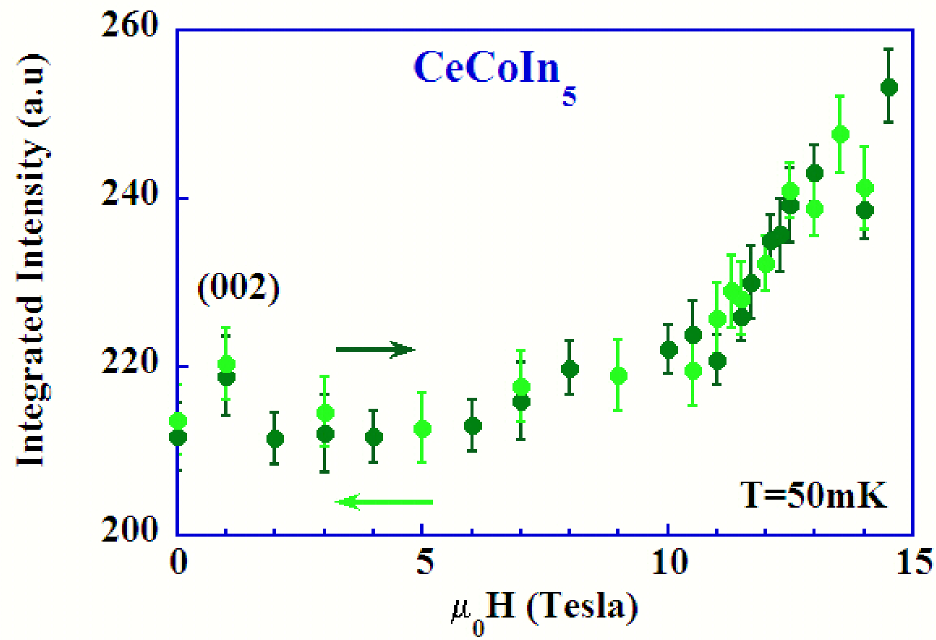


- $Hc_2(110)$ >> Pauli limit at low T
- Low-T high-field transitions suggestive of FFLO state
- Observation of normal-state metamagnetic transition

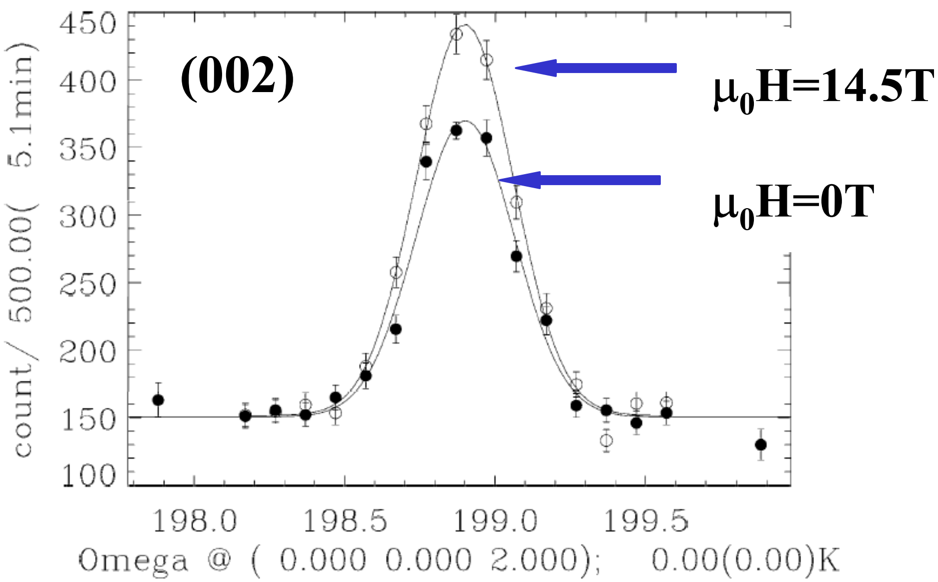


Neutron study on the magnetic field induced FM in $CeCoIn_5$

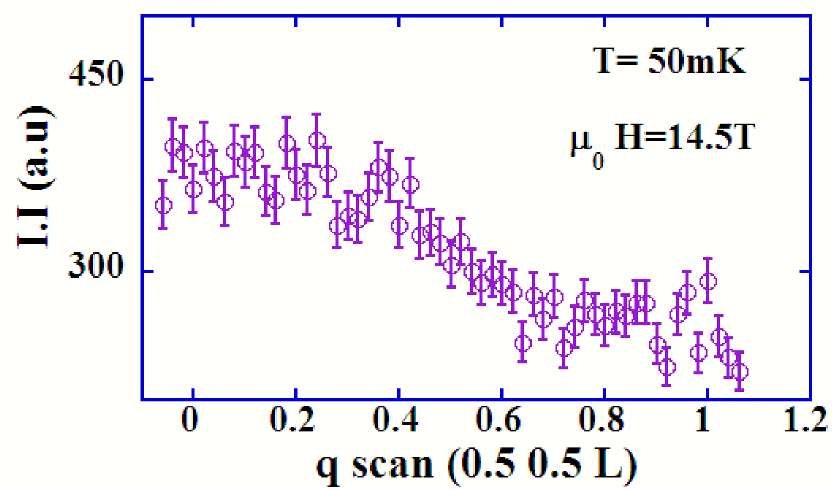




FM contribution



No evidence of AFM



A. Llobet, W. Bao et al.

Summary

- Certain crystal structures 'like' to superconduct

  Approaching $ThCr_2Si_2$ for heavy fermion superconductivity

- Evident similarity to cuprate phase diagram

  Strong evidence for d-wave superconductivity
  What is the generalized control parameter?
  Layering relevant, but not strongly anisotropic materials

- A rich testing ground for many correlated electron phenomena

  Existence of quantum critical point(s)
  Non-fermi liquid superconductivity
  First-order superconducting transition

Issues & Questions

- How many quantum critical points in the generalized phase diagram?

    What is the control parameter?

    Emerging complexity…

- What is the nature of the spin fluctuations that apparently give rise to superconductivity?

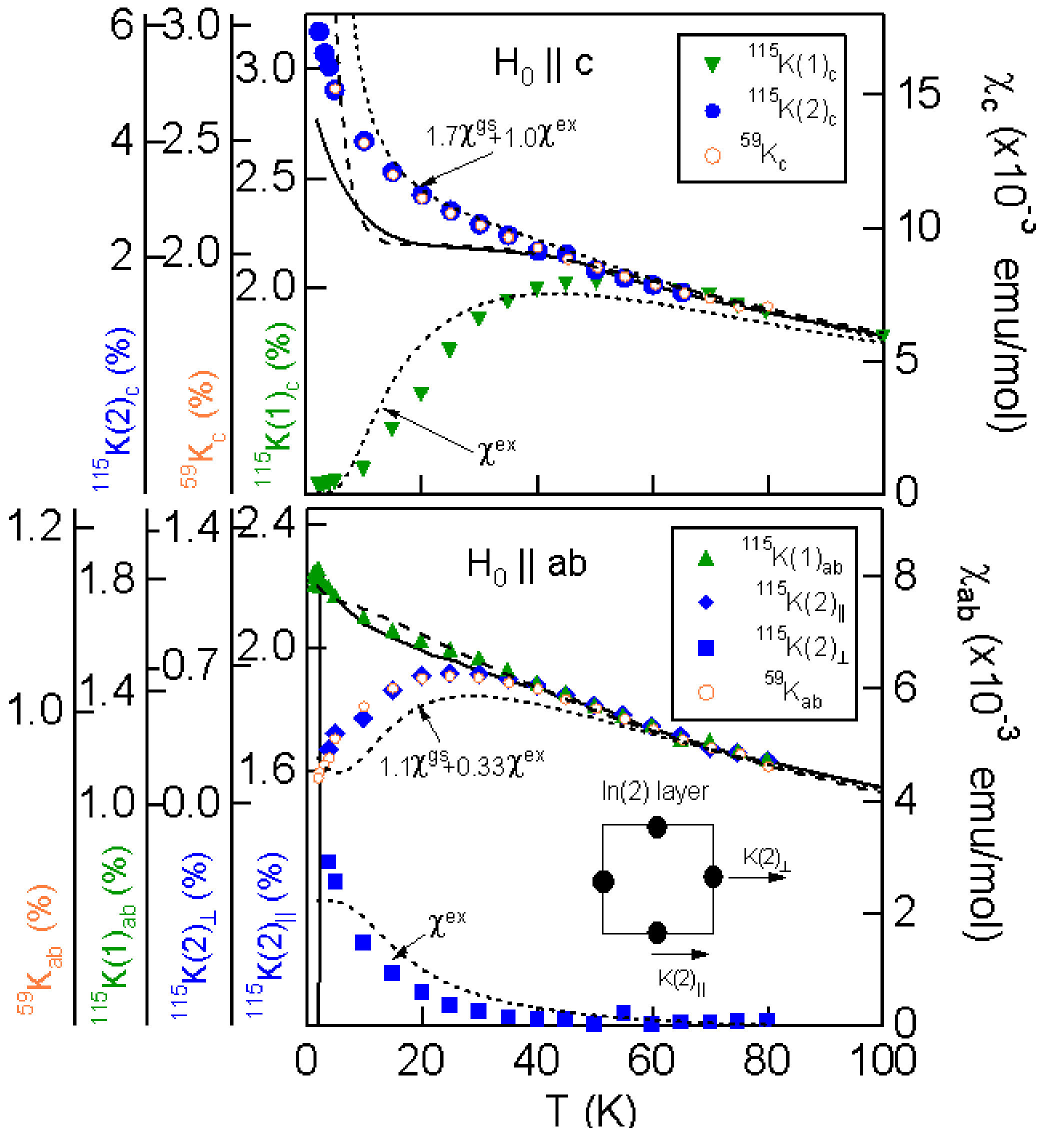
- Are the f-electrons localized or itinerant?

    dilution studies

        dHvA on $Ce_{1-x}La_xRhIn_5$ shows no change in FS volume

    importance of crystal fields

Role of crystal fields in $CeMIn_5$



CeCoIn$_5$: Curro et al.

•Anomalous shape of magnetic susceptibility (and thermal expansion) of $CeRhIn_5$ and $CeIrIn_5$ can be fit by accounting for crystal field effects

(Takeuchi et al.)

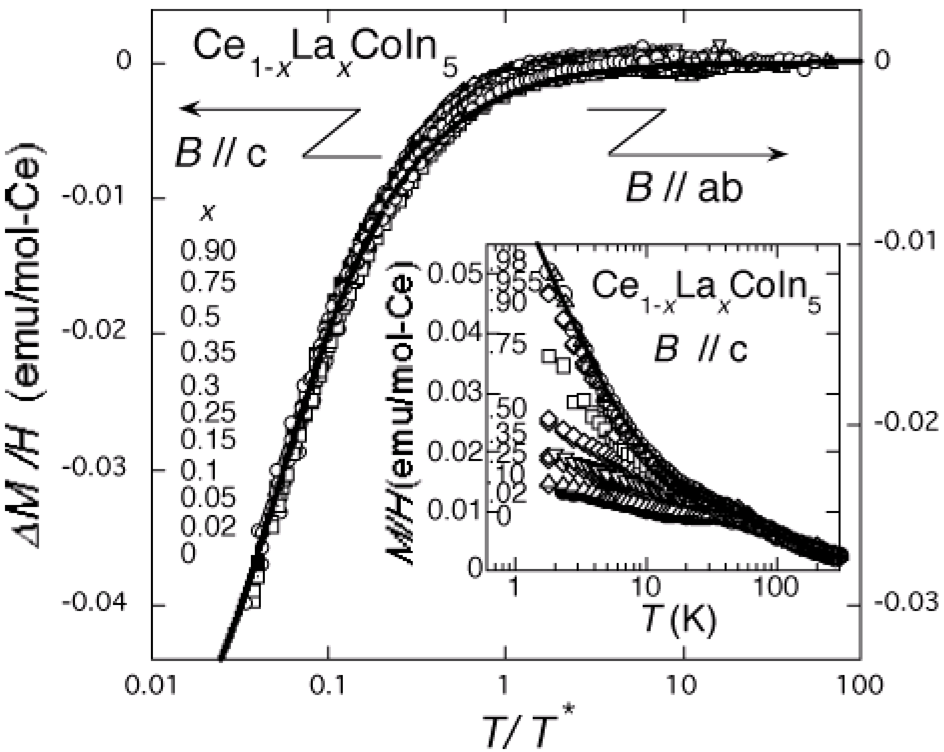
•Site-specific Knight shifts and bulk susceptibility in $CeCoIn_5$ can be similarly fit.

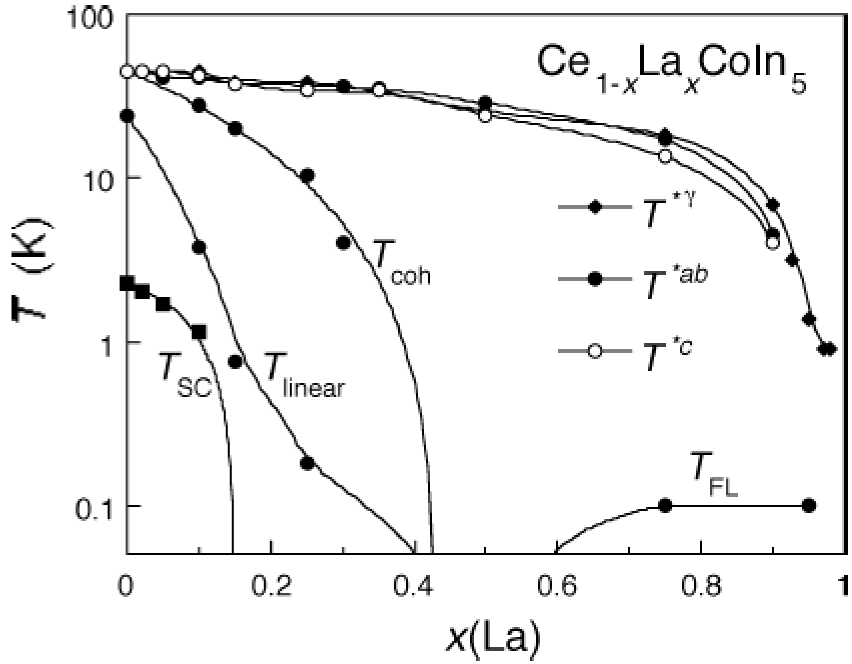
(Curro et al.)

•Similar behavior to $CeCu_2Si_2$ and $CeNi_2Ge_2$

Role of orbital fluctuations for unconventional superconductivity (Hotta et al.)

An alternative view: intersite coupling effects in $CeCoIn_5$





S. Nakatsuji,et al.

Synthesis & Characterization

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E.G. Moshopoulou - LANL
C. Petrovic - FSU & LANL
S. Nakatsuji - FSU
Z. Fisk - FSU & LANL
J.L. Sarrao - LANL

Thermodynamic & Transport Properties

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M. Jaime - LANL
A. Bianchi - LANL
A. Malinowski - LANL
M. Nicklas - LANL
M.F. Hundley - LANL
R. Movshovich - LANL
J.D. Thompson - LANL

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G. Sparn - Dresden

G.R. Stewart - Gainesville
N. Phillips - Berkeley

Magnetic Spectroscopies

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B. Simovic - LANL
P.C. Hammel - LANL

R.H. Heffner - LANL
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Theoretical Support

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D. Pines - LANL