Open Issues in "115" Materials: Tuning Unconventional Superconductors

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Outline

I. Tuning T_c – anisotropy and T_{sf}

II. Field-tuned/"Hidden" QCPs: Sn-doping in $CeCoIn_5$

III. Multiple superconducting states: $Ce(Rh,Ir)In_5$ and P

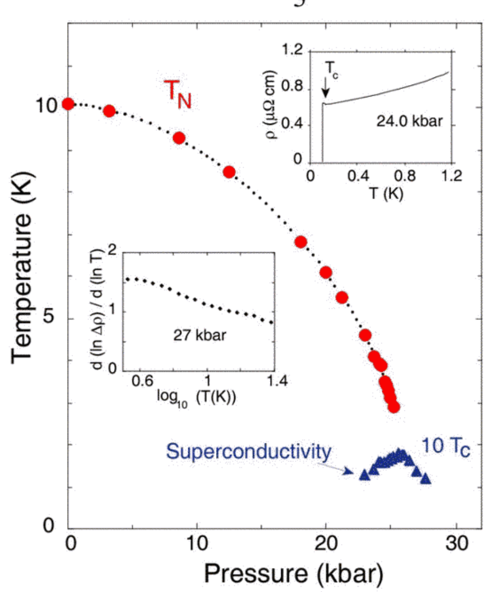
IV. Fermi surfaces and two-fluid models

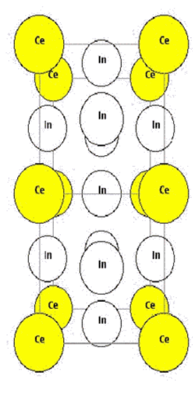
Intro/Tuning T_c – anisotropy and T_{sf}

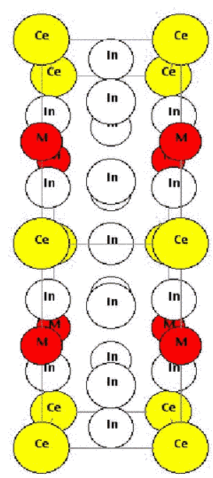
(How is T_c related to QCP(s)?)
(Why do certain crystal structures 'like' to superconduct)

Tuning $CeIn_3$

$CeIn_3$







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

$1/T_1$(P): (Kawasaki et al., PRB 66(2002) 054521)

$CeMIn_5$, $PuMGa_5$

$CeCoIn_5$, T_c=2.3 K

$PuCoGa_5$, T_c=18.5 K

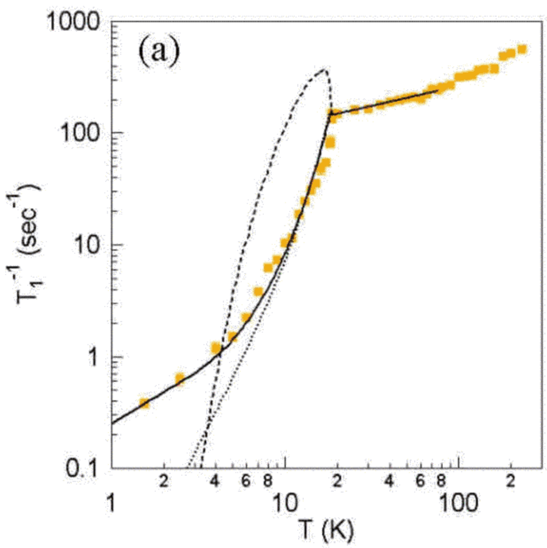
Ce → Pu, dilution, "tetragonal"-ness

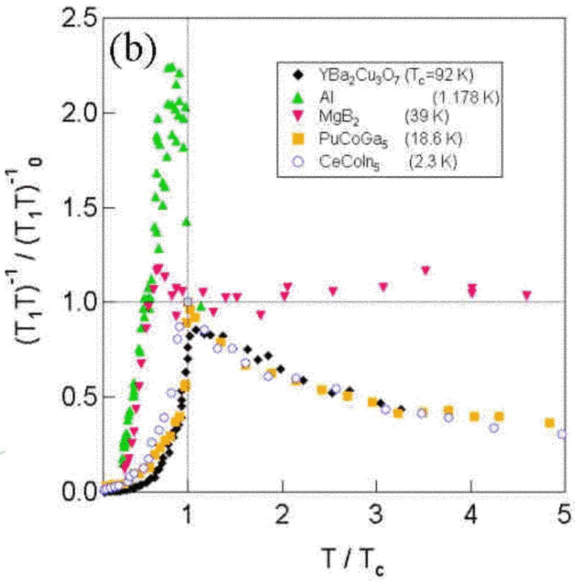
M: Rh ←→ Ir ←→ Co (isovalent)

In: Sn, …

bi-layer materials A_2MX_8

$PuCoGa_5$: T_1 data



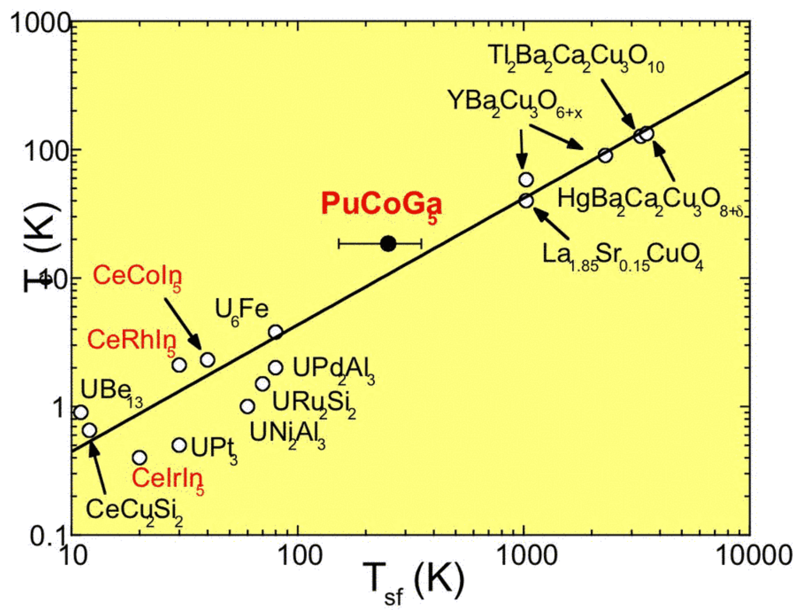


- No coherence peak
- T^3 power law suggests nodal superconductor
- Probably d-wave (low-T cp ~ T^2)

Normal-state T_1 scales with T_{sf}

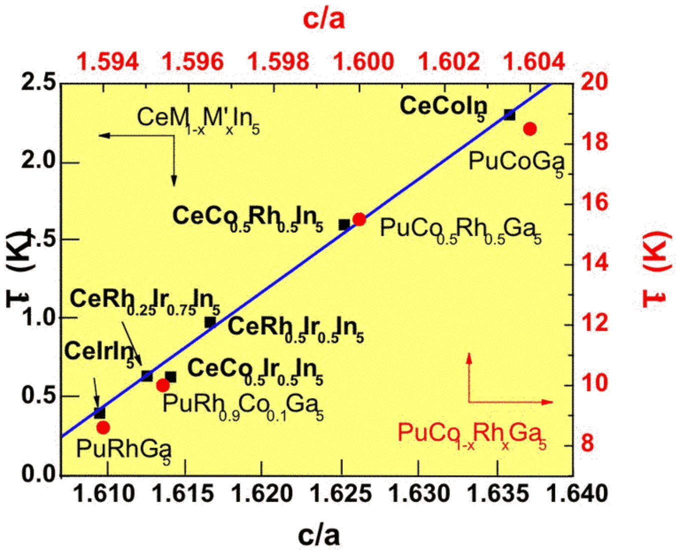
Curro et al. (2004)

$PuCoGa_5$: T_c and T_{sf}



$T_c \propto T_{sf}$ reflects energy spread of Q-dependent spin fluctuations (estimated from C/T for f-electron materials and from T-linear resistivity of cuprates--Moriya and Ueda)

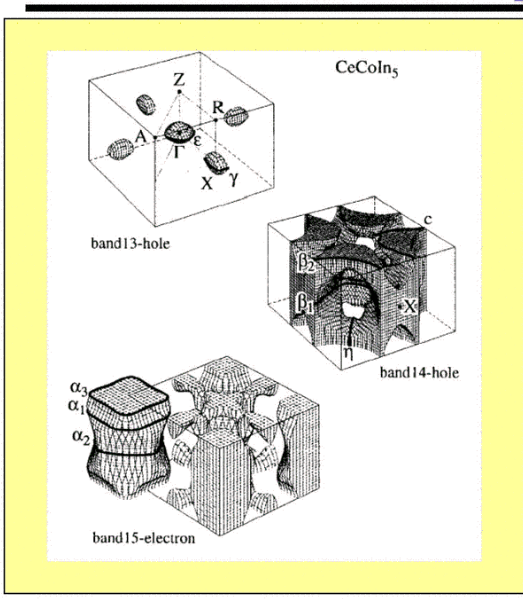
T_c and c/a



- $CeMIn_5$ and $PuMGa_5$ isostructural but with order of magnitude higher T_c in Pu-materials
- $d\ln T_c/d(c/a) \approx 100$ in both; predicts $PuIrGa_5$ not superconducting and it is not
- common underlying physics?
- origin of $T_c \propto c/a$ correlation in both 4f and 5f homologs?

E.D. Bauer et al., PRL 93 (2004) 147005

Electronic Anisotropy: Quasi-2D Fermi Surface



R. Settai et al., JPCM **13**, L627 (2001)

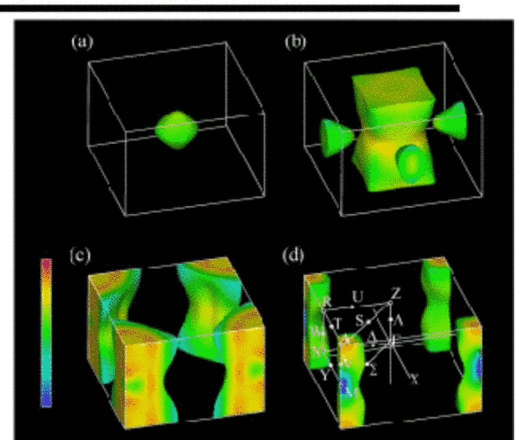


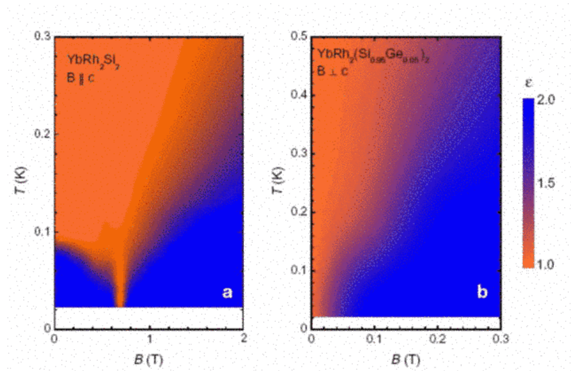
Fig. 2 T. Maehira et al.

T. Maehira et al., PRL 90 (2003) 207007;
I. Opahle and P. M. Oppeneer, PRL 90 (2003) 157001

- similar quasi-2D Fermi surfaces in $CeCoIn_5$ and $PuCoGa_5$ -- calculated assuming f-electrons are itinerant
- Fermi-surface topology and large effective electron masses confirmed by dHvA in $CeCoIn_5$
- substantial 4f character at E_F in $CeCoIn_5$ due to strong Kondo coupling between 4f and ligand electrons
- 5f configuration in $PuCoGa_5$?

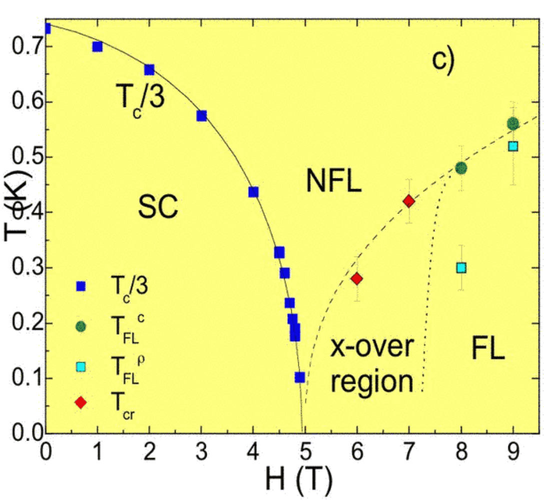
Field-induced/“Hidden” QCPs: Sn-doping in $CeCoIn_5$

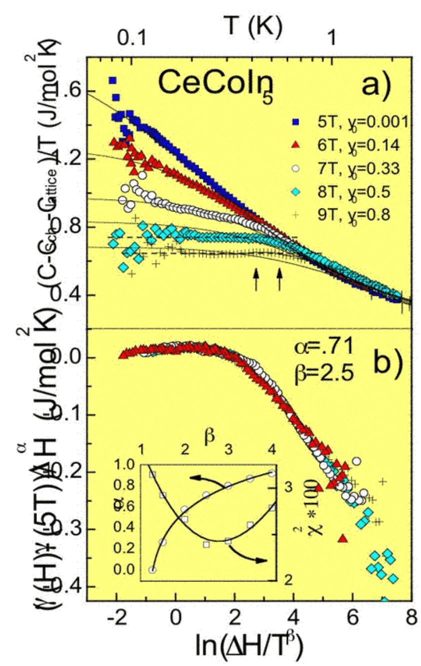
(a la $YbRh_2Si_2$)



Custers et al (CP), Nature 2003

Field Tuning in $CeCoIn_5$



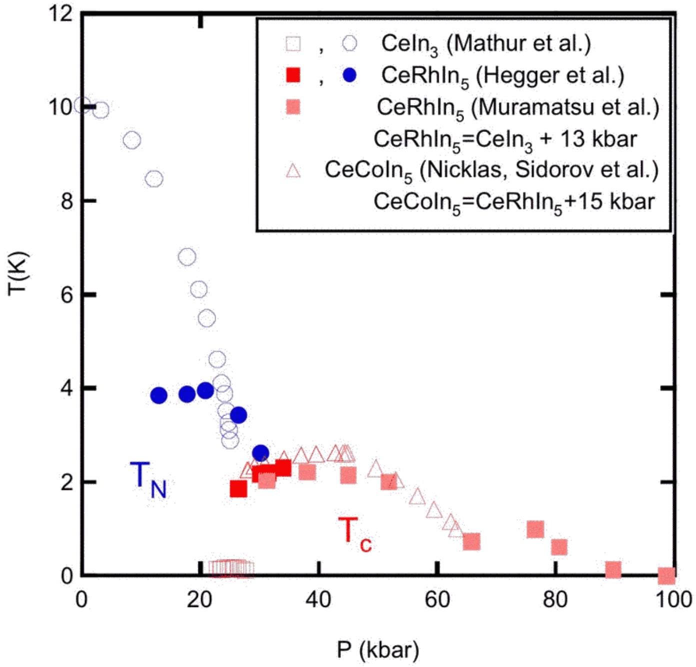


♦ Moriya-type scaling analysis of C(H)/T for H ≥H_{c2} ⇒ $CeCoIn_5$ just beyond an AFM QCP, with the quantum-critical field H_c =5 T and $H_{c2}(0)$= 4.95 T, but no other evidence for AFM order

♦ possible origin of ‘hidden’ AFM in $CeCoIn_5$ suggested from combined T-P diagram for $CeRhIn_5$ and $CeCoIn_5$: $CeCoIn_5$ at P=0 ≈ $CeRhIn_5$ at 16 kbar

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

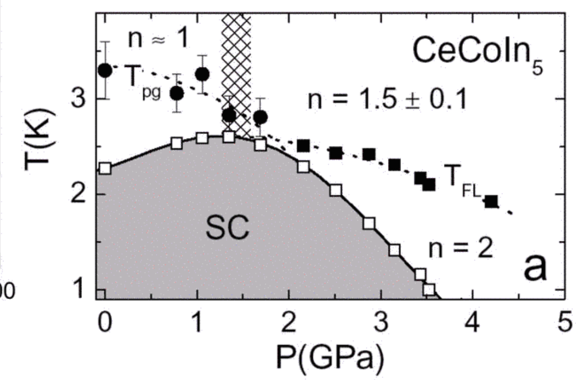
Generalized pressure phase diagram



Using measures other than T_c,

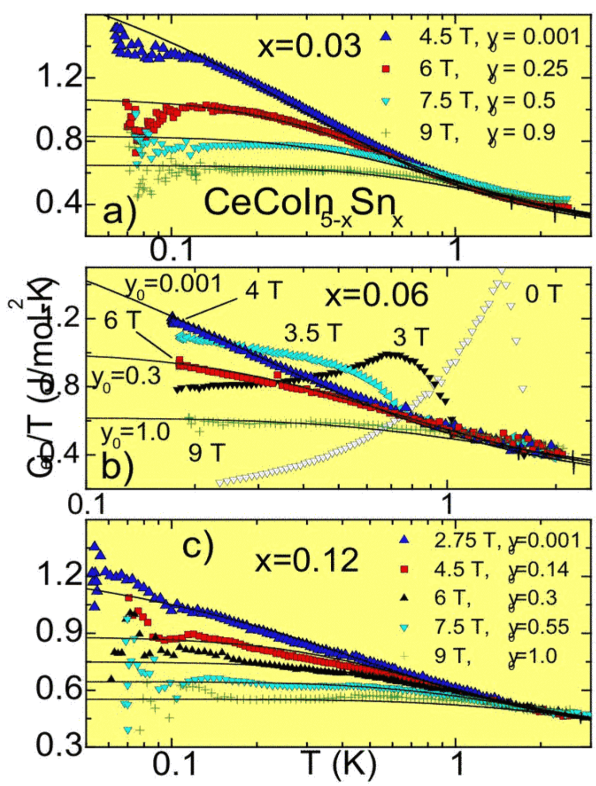
"$CeRhIn_5$=$CeIn_3$+13 kbar"

"$CeCoIn_5$=$CeRhIn_5$+15 kbar"



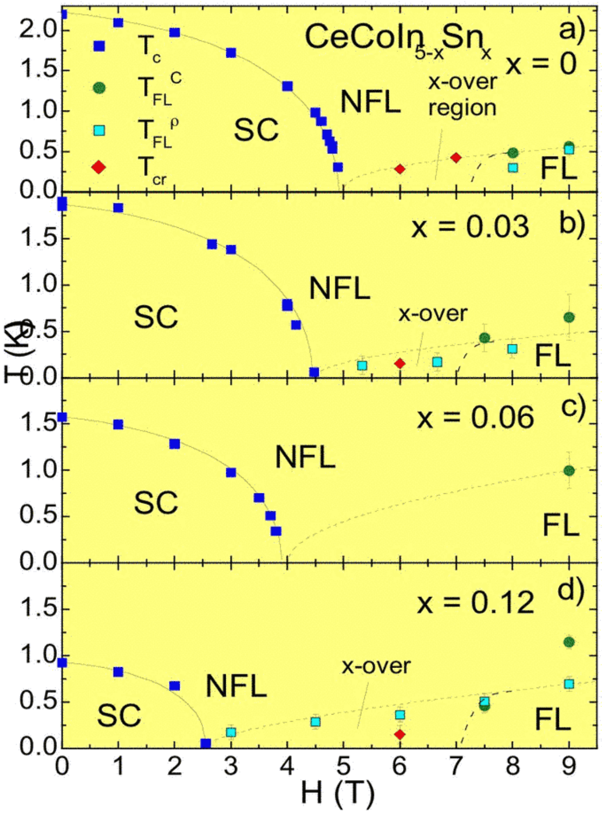
Sidorov et al., PRL 89(2002) 157004

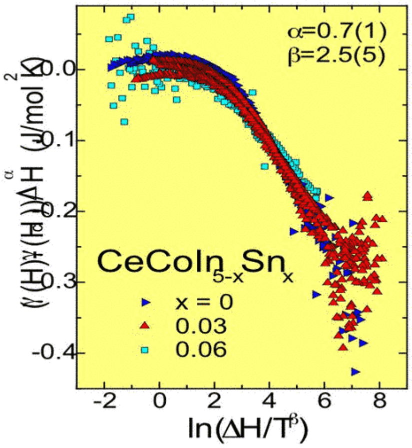
Effect of Sn doping on 'hidden' AFM in $CeCoIn_5$



- for $CeCoIn_{5-x}Sn_x$, dT_c/dx = -0.6K/at.%Sn, with $x_c \approx 0.18$
- logarithmic T-dependence below ~1 K down to the lowest temperature at the upper critical field H_{c2} (=4.5 T, 4 T, 2.75 T for x=0.03, 0.06, 0.12, respectively) for all Sn concentrations.
  - ⇨ **Magnetic field for quantum criticality H_c and H_{c2} closely related**
- for H> H_{c2}, C_{el}/T tends toward saturation with crossover region; Fermi-liquid behavior observed for H>8 T for all x.
- fits to Moriya spin fluctuation model, with y_0 parameterizing the distance from the QCP, further support near equality of H_c and H_{c2}

"Negative Pressure" in $CeCoIn_5$: Sn doping



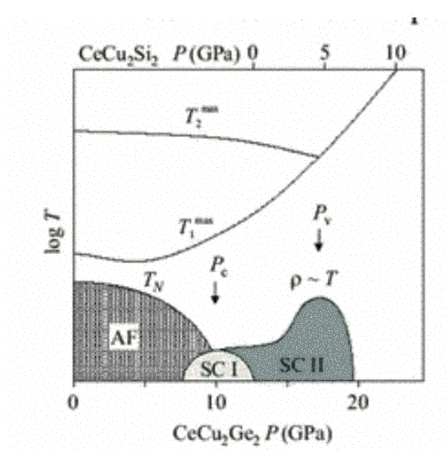


Bauer et al., to appear in PRL (2005)

For $CeCoIn_{5-x}Sn_x$, $dT_c/dx = -0.6$K/at.%Sn, Sn preferentially on In(1) site

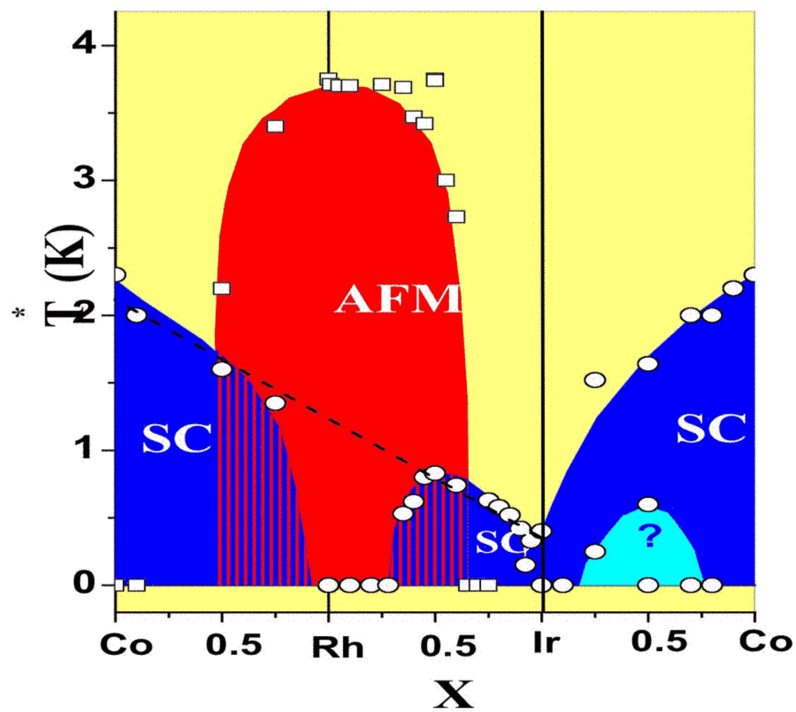
Collapse of Moriya-type scaling onto a common curve for x=0, 0.03 and 0.06
⇒AFM QCP tracks $H_{c2}(x)$ or SC QCP ??

Multiple superconducting states: $Ce(Rh,Ir)In_5$ and P



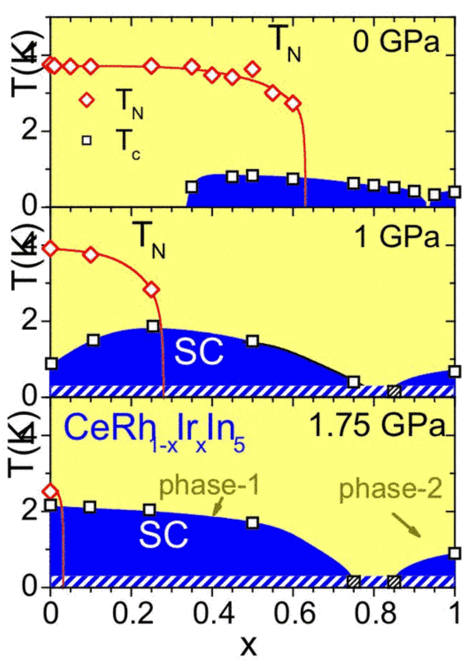
Jaccard 03

Generalized x,T Phase Diagrams



$CeCoIn_5$ $CeRhIn_5$ $CeIrIn_5$ $CeCoIn_5$

Joint Doping-Pressure Phase Diagram

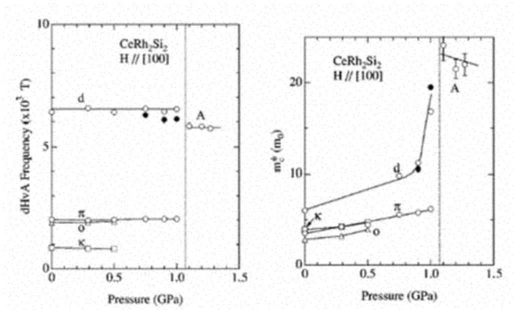


$CeRhIn_5$ $CeIrIn_5$

Nicklas et al. PRB 70 (2004) 020505(R)

- Further evidence for robustness of superconductivity
- Apparently, two characteristic T_cs: ~ 2 K and ~ 1K
- Perhaps, analogous to spin fluctuations and charge fluctuations as in e.g., $CeCu_2(Si,Ge)_2$
- See also $CeRhIn_5$ (P) vs $CeIrIn_5$ (P)

Fermi surfaces and two-fluid models



Evolution of Fermi Surface

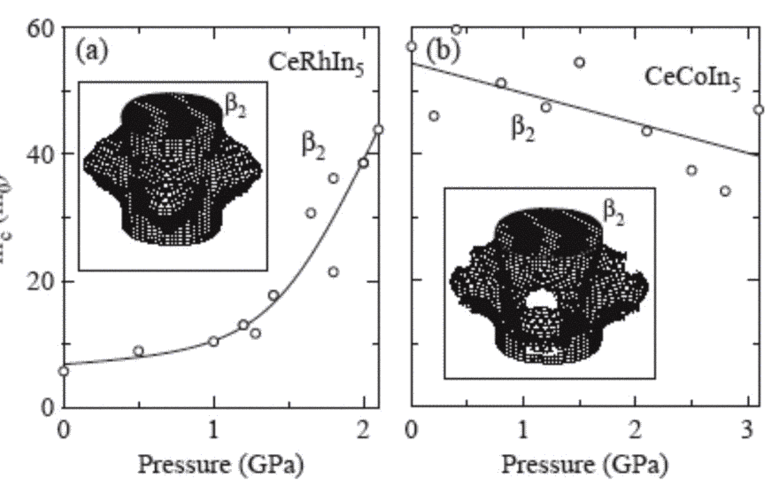
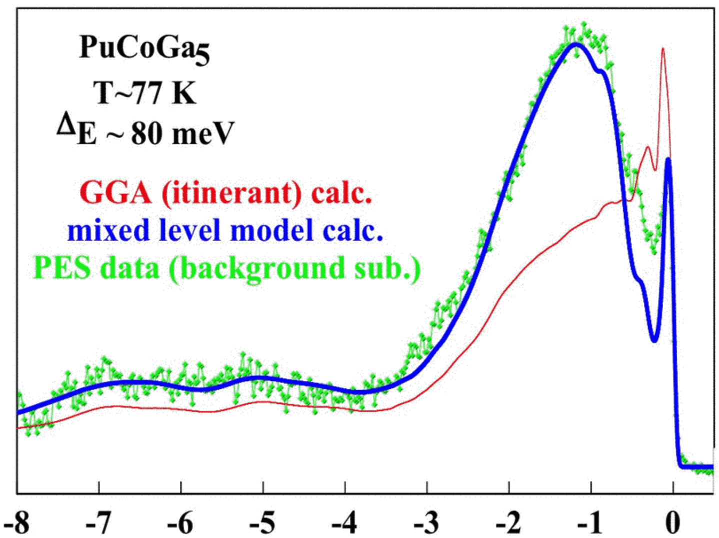


Fig. 2. Pressure dependence of cyclotron mass of branch β_2 in (a) $CeRhIn_5$ and (b) $CeCoIn_5$.The inset shows the Fermi surface corresponding branch β_2.

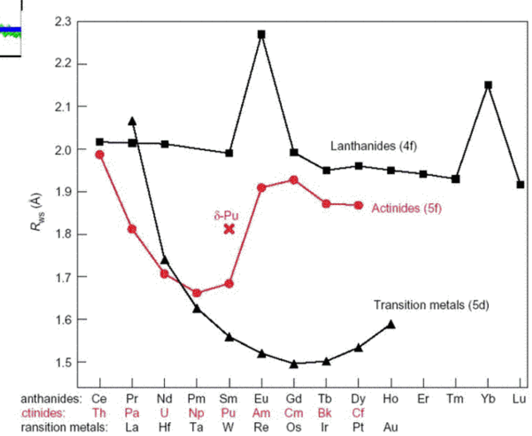
Shishido et al., JMMM 272 (04) 225

$PuCoGa_5$ Photoemission: partial localization



- Partially localized f manifold ("mixed level model") qualitatively better than fully itinerant treatment ("GGA")

Joyce et al., PRL 91 (2003) 176401



Summary

A growing number of well-posed experimental issues ripe for theoretical understanding

I. Tuning T_c – anisotropy and T_{sf}

II. Field-tuned/"Hidden" QCPs: Sn-doping in $CeCoIn_5$

III. Multiple superconducting states: $Ce(Rh,Ir)In_5$ and P

IV. Fermi surfaces and two-fluid models

Synthesis & Characterization
E.D. Bauer - LANL
P.G. Pagliuso - LANL
N.O. Moreno - LANL
E.G. Moshopoulou - LANL
C. Petrovic - FSU & LANL
S. Nakatsuji - FSU
Z. Fisk - FSU & LANL
J.L. Sarrao - LANL

Thermodynamic & Transport Properties
H. Hegger - LANL
M. Jaime - LANL
A. Bianchi - LANL
A. Malinowski - LANL
M. Nicklas - LANL
M.F. Hundley - LANL
R. Movshovich - LANL
J.D. Thompson - LANL

P. Gegenwart - Dresden
G. Sparn - Dresden

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

Magnetic Spectroscopies
N. Curro - LANL

Y. Kitaoka – Osaka
G-q Zheng - Osaka

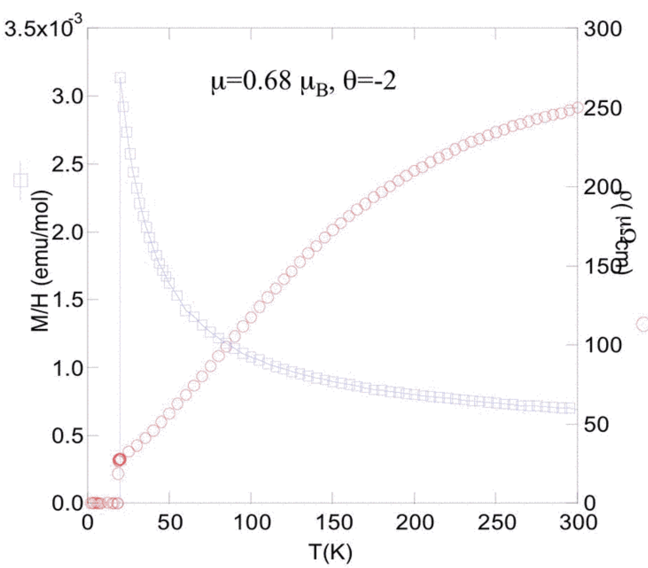
R.H. Heffner - LANL
A. Christianson - LANL
A. Llobet Megias - LANL
W. Bao - LANL
G. Aeppli - NEC

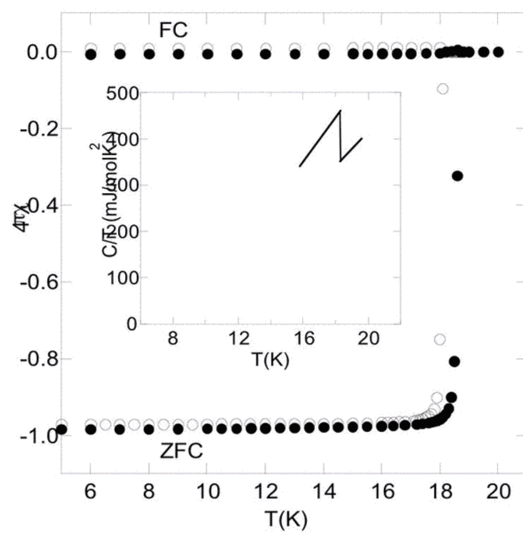
Electronic Structure
A.L. Cornelius - UNLV
D. Hall - NHMFL
T.P. Murphy - NHMFL
E.C. Palm - NHMFL
S.W. Tozer - NHMFL
R.G. Goodrich - LSU
J.J. Joyce - LANL
J.M. Wills - LANL

Theoretical Support
A.V. Balatsky – LANL
Y. Bang – LANL
P. Monthoux - Cambridge
G.G. Lonzarich - Cambridge
D. Pines - LANL

Plutonium
L.A. Morales - LANL
B.L. Scott - LANL
F. Wastin - Karlsruhe
J. Rebizant - Karlsruhe
P. Boulet - Karlsruhe
E.Colineau - Karlsruhe
G.H. Lander – Karlsruhe

Properties of $PuCoGa_5$

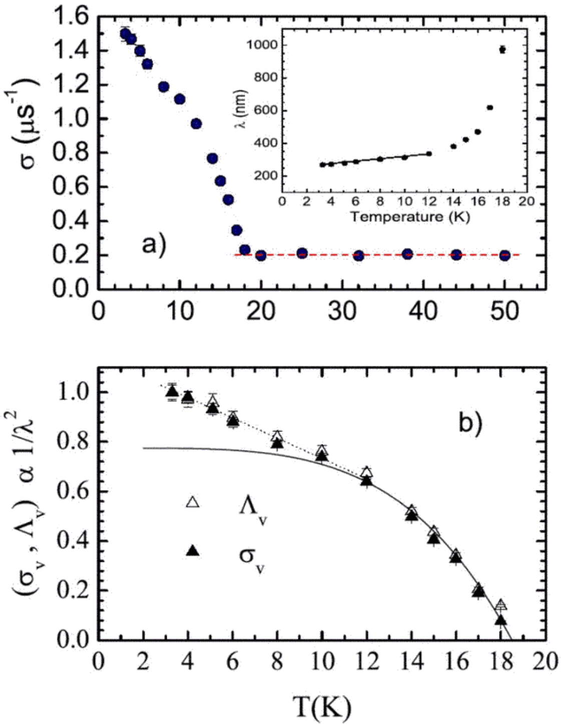




$PuRhGa_5$ has ~ identical normal state properties to its lower T_c of ~ 9K

J.L. Sarrao, et al., Nature 420 (2002) 297

μSR studies of $PuCoGa_5$



No evidence for low-T magnetic order

No time-reversal symmetry breaking
→ singlet SC

Well below Tc,

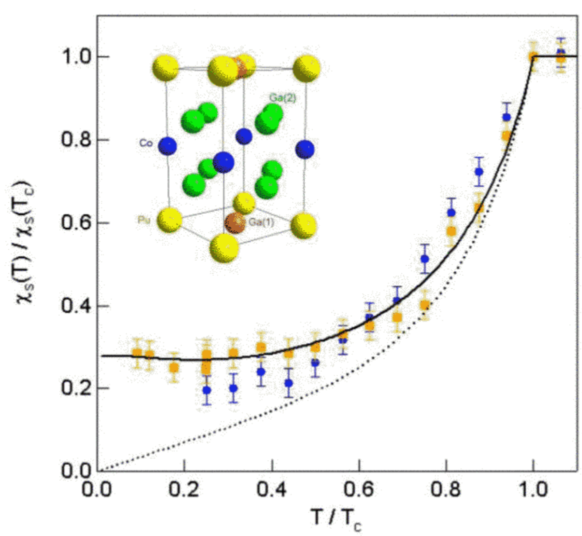
•Penetration depth linear in T

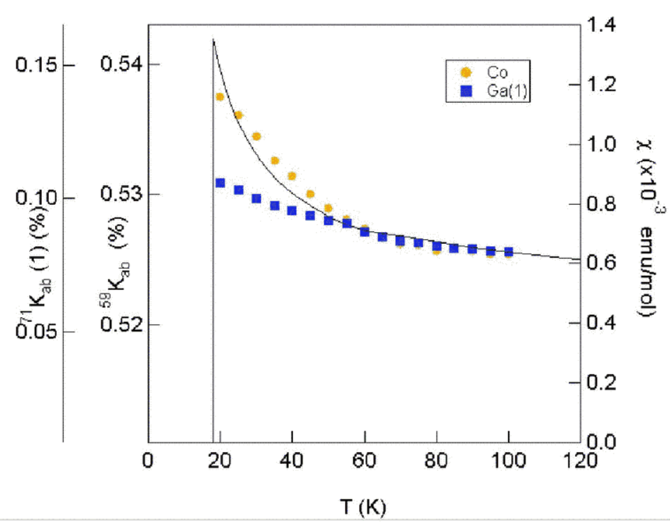
•Increasing relaxation rate

→ d-wave SC

G.D. Morris et al., submitted to PRL (2004)

$PuCoGa_5$: Knight shift data (single crystal)

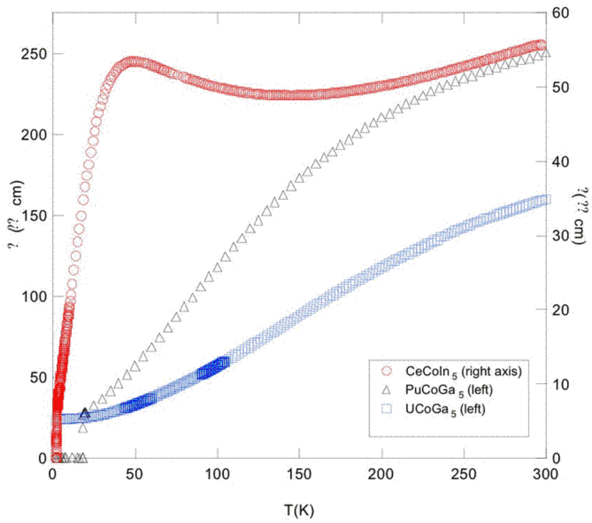


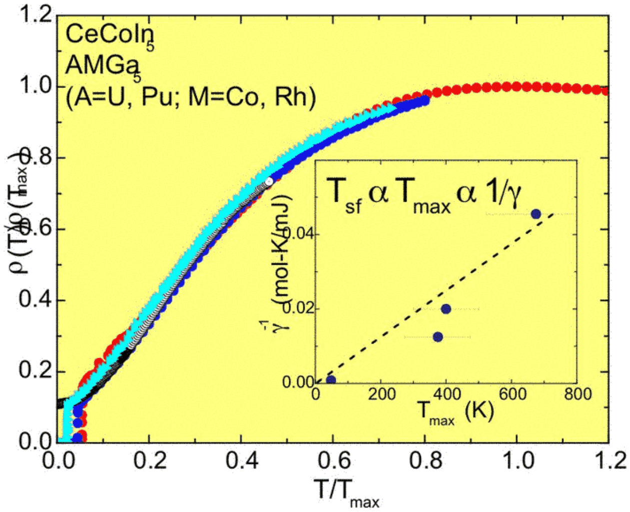


- Knight shifts of ^{59}Co and ^{71}Ga vanish below T_c: singlet pairing
- Normal state Knight shift reminiscent of $CeCoIn_5$

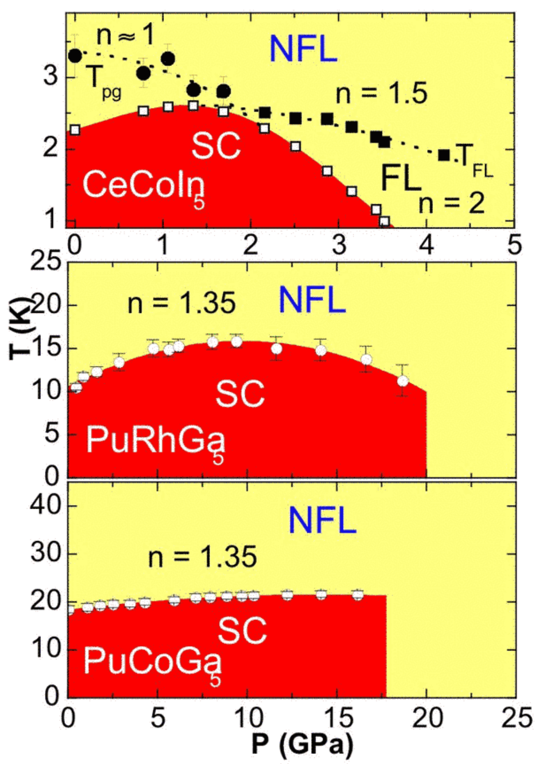
Curro et al. (2004)

Trends in 115: Evolution of T_{sf}

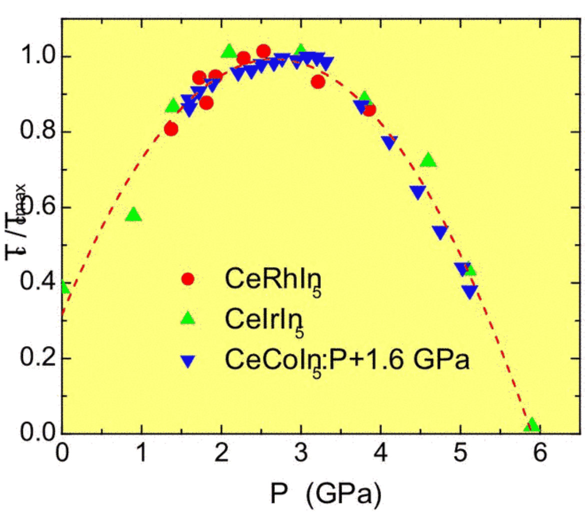




$PuMGa_5$ and $CeMIn_5$: Tc(P)



Qualitatively similar behavior of T_c(P), but no obvious scaling behavior



Despite apparent differences between $CeCoIn_5$ and $CeIrIn_5$, universal behavior of T_c(P)