Unconventional Superconductivity and Nearby States in Correlated f-Electron Metals

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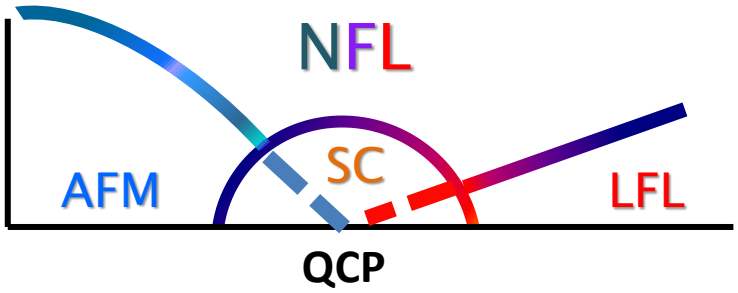
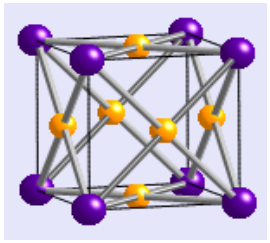
Outline:

- introduction
- $CePt_2In_7$ -- vis-à-vis $CeRhIn_5$
- U_2PtC_2 -- an old, new superconductor
- summary

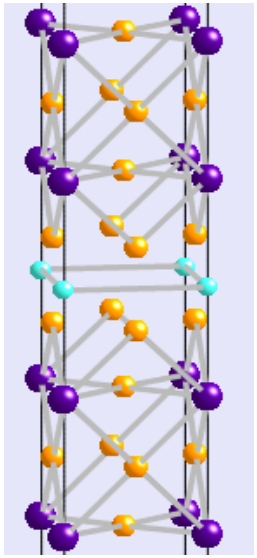


"Strong Correlations and Unconventional Superconductivity: Towards a Conceptual Framework", KITP, September, 2014

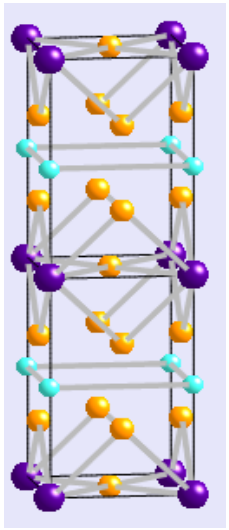
$CePt_2In_7$: a member of the $Ce_mM_nIn_{3m+2n}$ family



∞ layer
$CeIn_3$, T_c= 0.2K

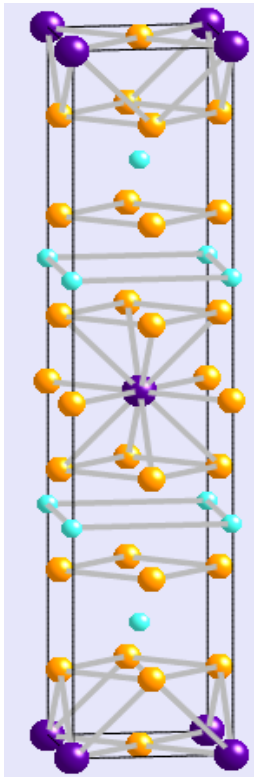


2-1-8
(2)$CeIn_3$+(1)MIn_2
$T_c \approx$ 1K



1-1-5
(1)$CeIn_3$+(1)MIn_2
$T_c \approx$ 2.3K

P4/mmm

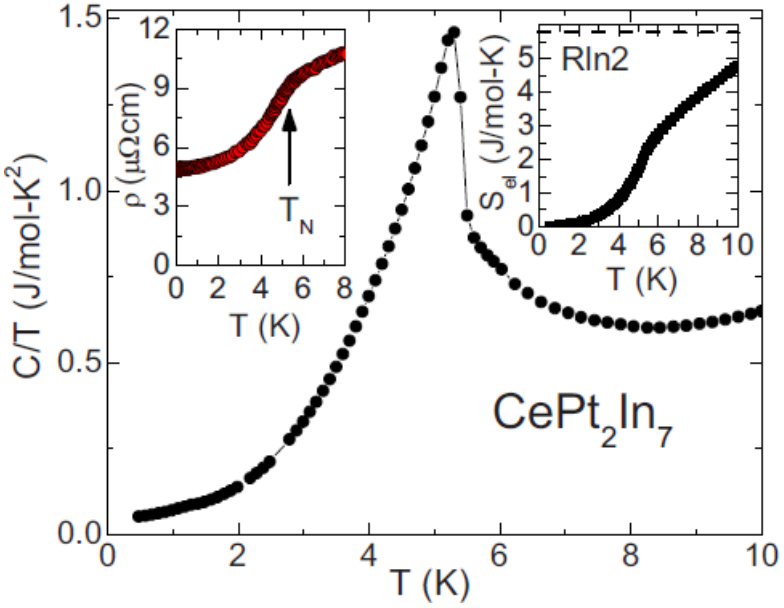


1-2-7
(1)$CeIn_3$+(2)MIn_2
$T_c \approx$ 2.2K

I4/mmm

- 3 layered variants of $Ce_mM_nIn_{3m+2n}$ with ground states highly tunable by pressure and M elements: Co, Rh, Ir, Pd, Pt
- $CePt_2In_7$ so far the only m=1, n=2 Ce member and in several respects similar to $CeRhIn_5$
- all strongly correlated, with superconductivity near an antiferromagnetic instability, and all with NFL states above T_c

$CePt_2In_7$ – basic properties

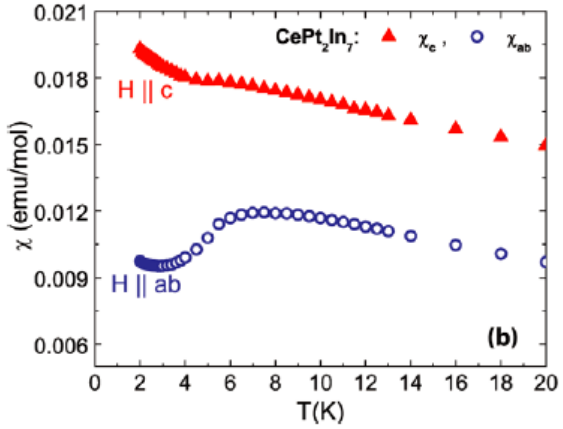


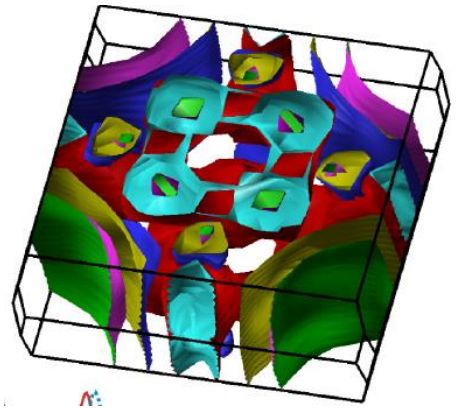
E. D. Bauer et al., PRB **81**, 180507 (2010)

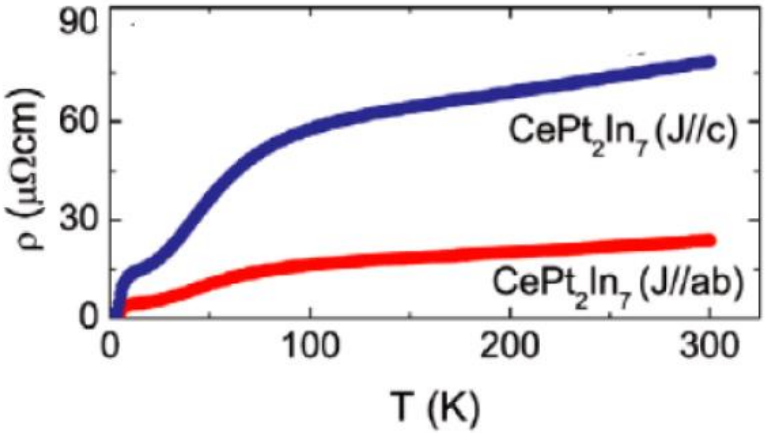
- antiferromagnetic order at 5.5K, above which estimate $\gamma \approx 350\text{-}400$ mJ/molK^2 and well below which $\gamma_0 \approx 50$ mJ/molK^2 $\Rightarrow$ typical of correlated Ce antiferromagnets

- entropy below $T_N \approx (0.3\text{-}.4)/ln2 \Rightarrow T_K \geq T_N$ and little, if any, participation of 4f electrons in the Fermi volume implied from SdH measurements
(M. Altarawneh et al. PRB **83**, 081103 (2011))

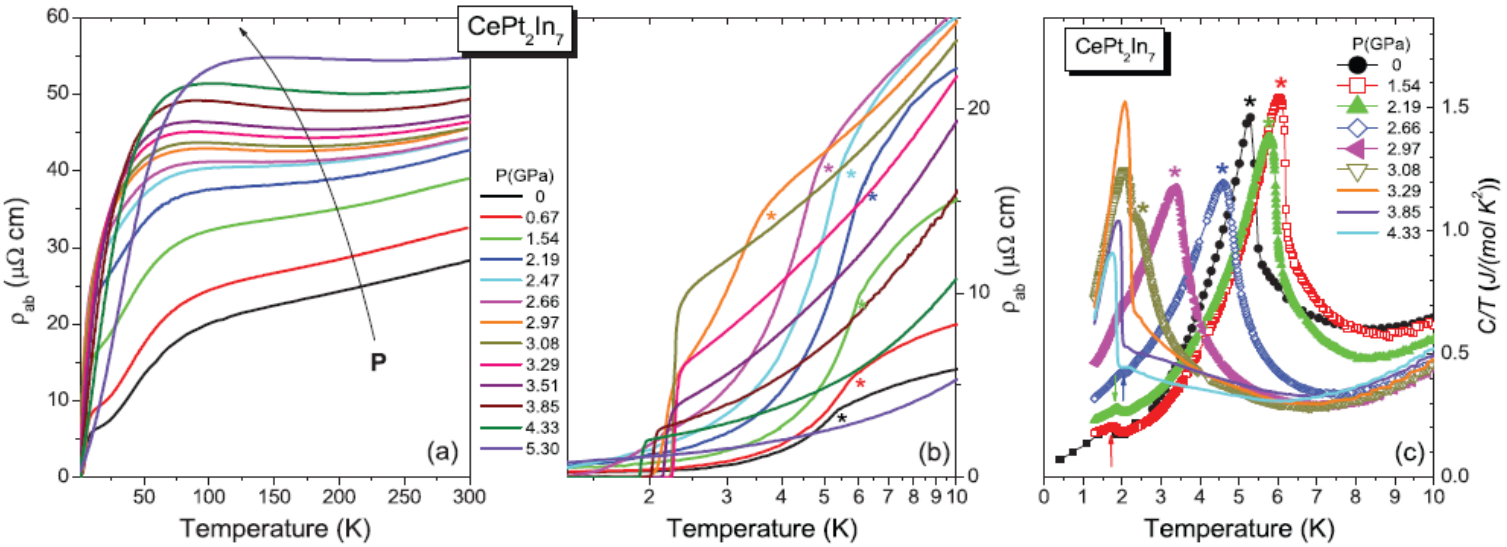
- modest anisotropy in χ(T) and ρ(T), consistent with measured and calculated FS topology







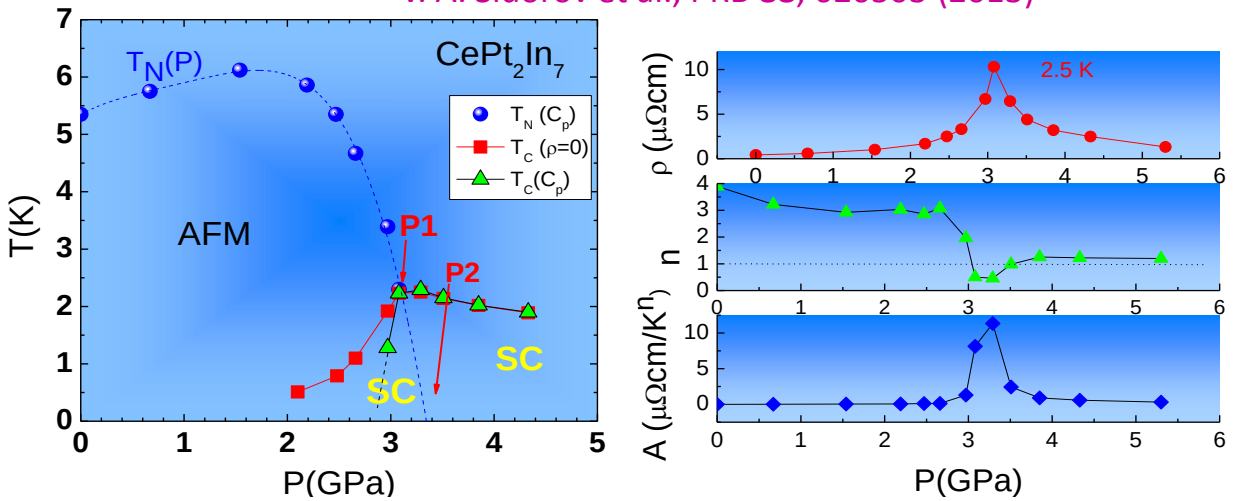
$CePt_2In_7$ response to pressure

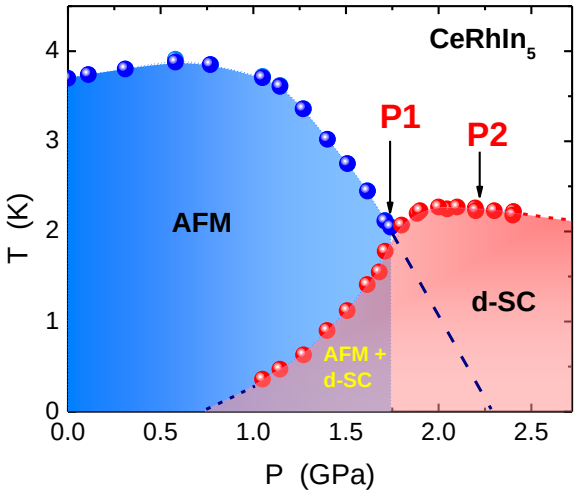


♦ pressure-induced superconductivity with T-P phase diagram similar to $CeRhIn_5$, including similar T_c's but a narrower P-range of coexisting AFM and SC; resistive evidence for critical scattering when P1 < P < P2

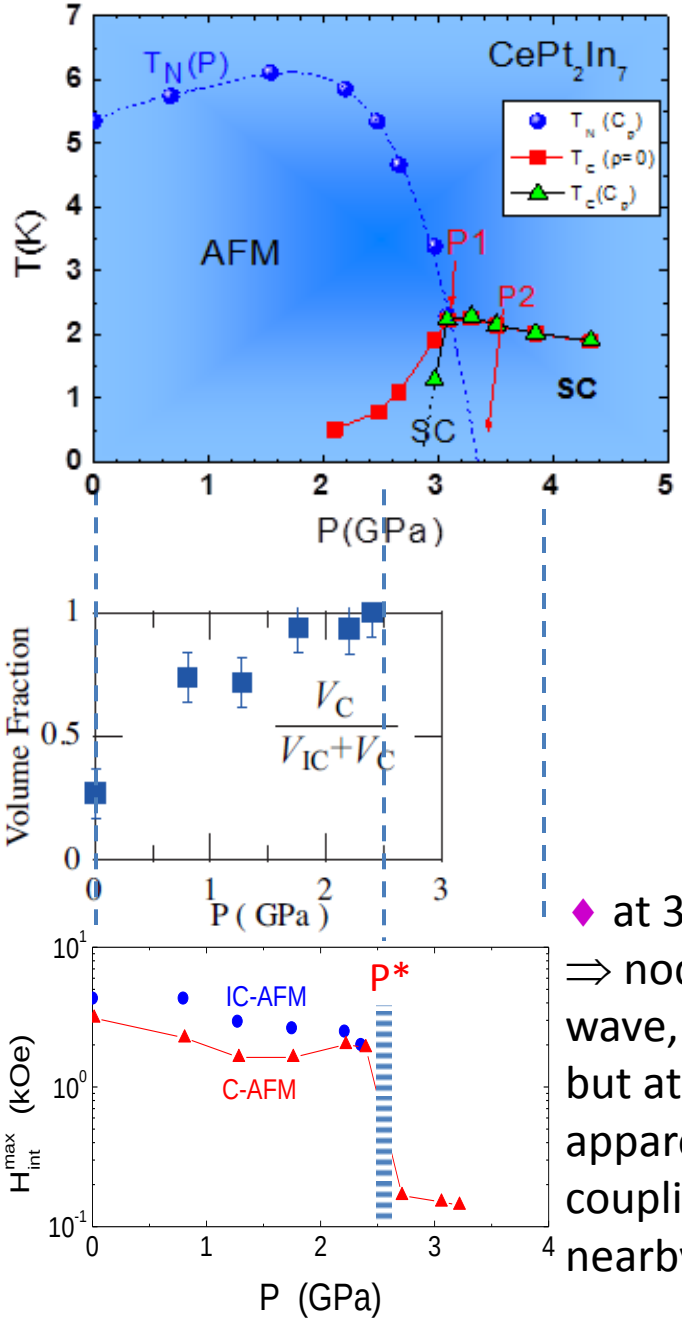
Park et al., Nature **440**, 65 (2006)

V. A. Sidorov et al., PRB **88**, 020503 (2013)





magnetism and criticality in $CePt_2In_7$

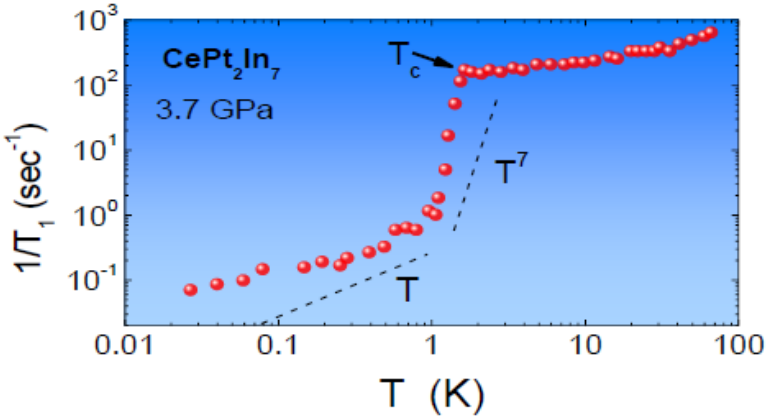


♦ complex magnetic order: commensurate AFM just below T_N followed at lower temperatures by coexisting incommensurate order; volume fraction of commensurate order ≈ 100% at P*~2.4 GPa <P1 (H. Sakai et al., PRB **83**, 140408 (2011))

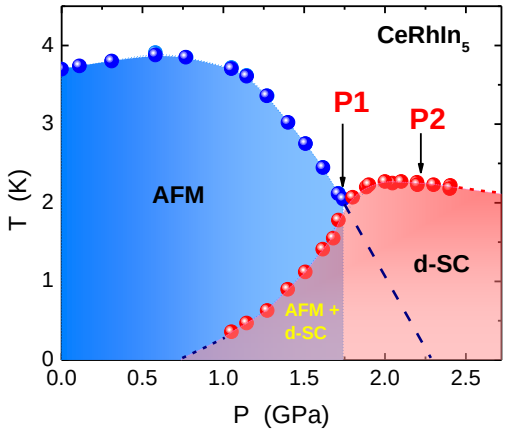
♦ internal field produced by magnetic order collapses by over an order of magnitude at P* (< P1< P2) where ν_Q also increases sharply ⇒ a 4f-localized/delocalized transition *in the ordered state* and approximately coincident with the emergence of bulk superconductivity (H. Sakai et al., Phys. Rev. Lett. **112**, 206401 (2014)); *expect change in Fermi volume at P**

♦ maximum T_c near P1 = 3.07 GPa, not at the extrapolated (SDW??) critical point P2

♦ at 3.1 GPa, $1/T_1 \propto T^3$ ⇒ nodal, possibly d-wave, superconductivity, but at 3.7 GPa > P2, apparently 1st order ⇒ coupling of SC to a new nearby state?



$CeRhIn_5$: similar but different

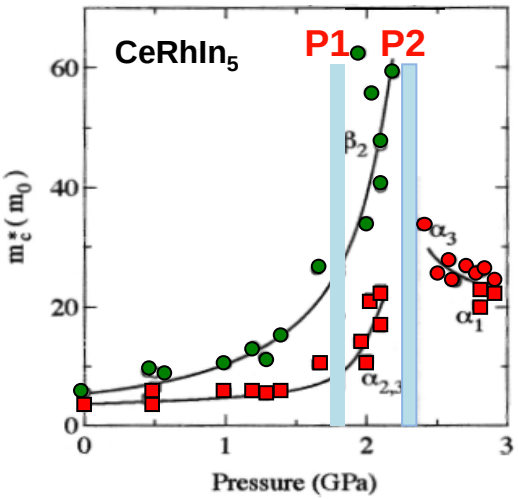


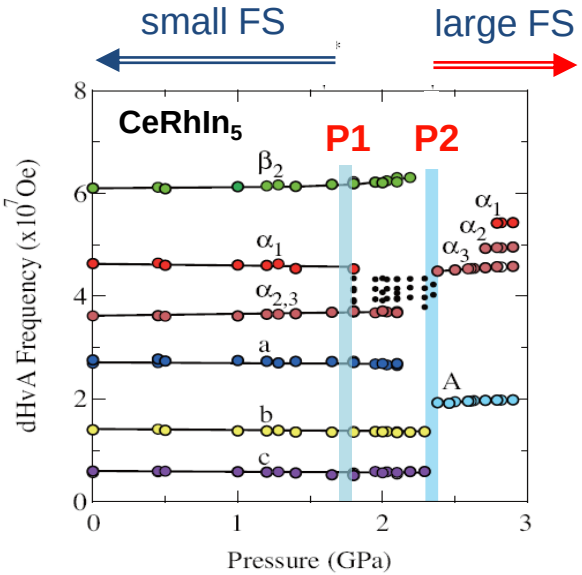
♦ maximum T_c at P2 where P,H-dependent specific heat and resistivity measurements find a QCP (T. Park et al., Nature **440**, 65 (2006); G. Knebel et al., PRB **74**, 020501 (2006))

♦ as expected, diverging high field m* at P2 from dHvA *BUT* accompanied by a jump in dHvA frequencies at P2 (H. Shishido et al., JPSJ **74**, 1103 (2005))

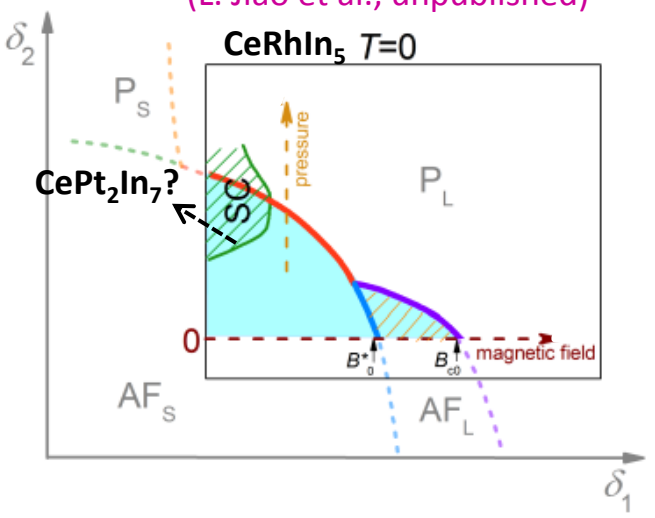
♦ consistent with an unconventional QCP (Kondo breakdown) where a 4f-localized /delocalized transition is coincident with a T=0 magnetic transition, unlike $CePt_2In_7$

♦ P- and H-dependent responses appear to map onto 'global' phase diagram of unconventional criticality (Q. Si, Physica B 27, 378 (2006); P. Coleman et al, JLTP 161, 182 (2010)); $CePt_2In_7$?

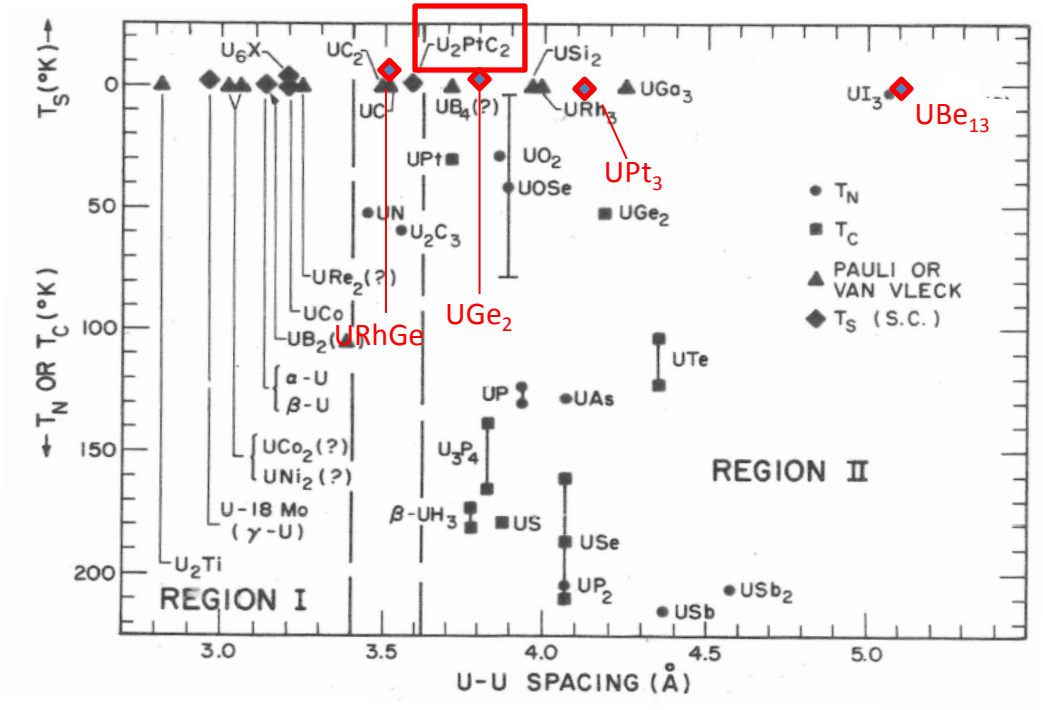




(L. Jiao et al., unpublished)



U_2PtC_2



H. H. Hill, Plutonium 1970 and Other Actinides, p.2 (1970)

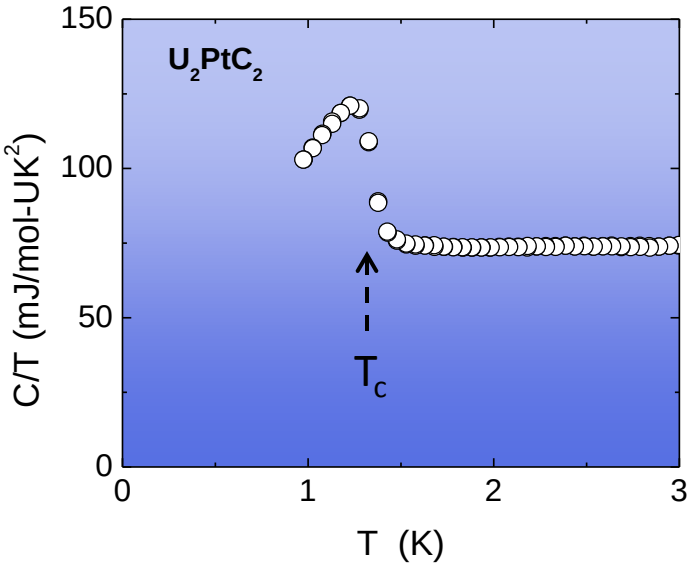
♦ superconductivity in U_2PtC_2 known already in 1969 (B. T. Matthias et al., PNAS **64**, 459 (1969)) – long before UPt_3 and UBe_{13} and other U-based heavy-fermion superconductors

♦ in part instrumental in defining the 'Hill plot' which argued superconductivity at small U-U spacing and magnetic order at U-U > 3.6 Å

♦ virtually unexplored, except briefly by Meissner et al. (G. P. Meissner et al., PRL **53**, 1829 (1984)) and a few others

♦ subsequent discoveries of correlated ferromagnetic superconductors UGe_2 and URhGe with U-U spacing bracketing U_2PtC_2 ⇒ revisit this old superconductor

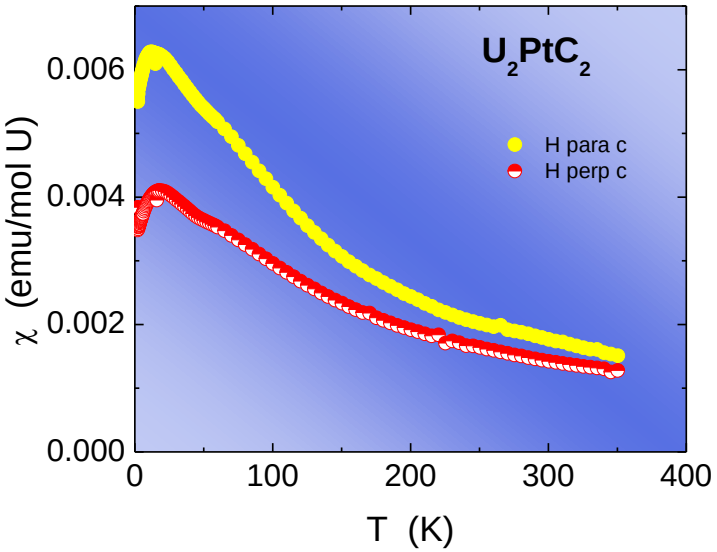
modestly correlated and anisotropic

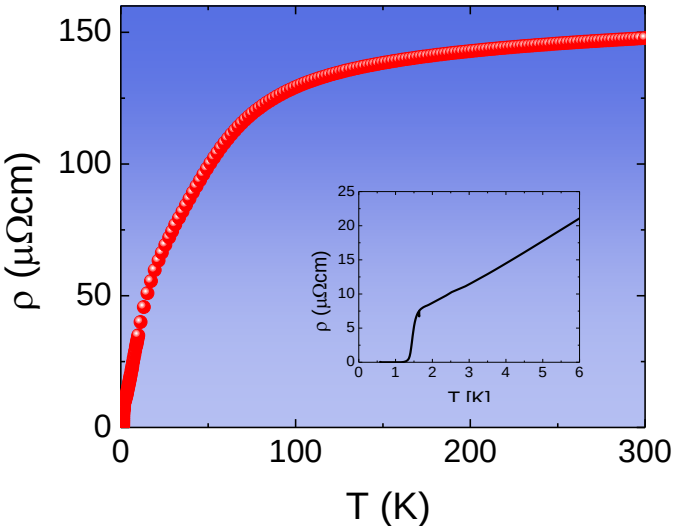


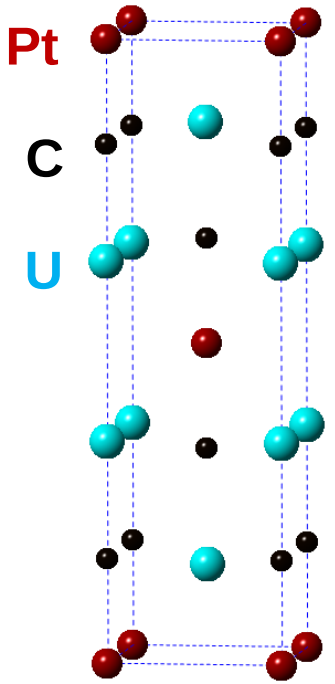
♦ nicely Fermi-liquid-like with γ = 75 mJ/mol-UK^2 above T_c= 1.47 K

♦ difficult to prepare—no crystals – but aligned powder with $\chi_c > \chi_a$ and RRR > 25

♦ first hint of something interesting: Wilson ratio $\mathcal{R} \approx$ 4.5 and $H_{c2}(0)$ =8-10T >> Clogston field $\approx$ 2.7T $\Rightarrow$ ferromagnetic correlations

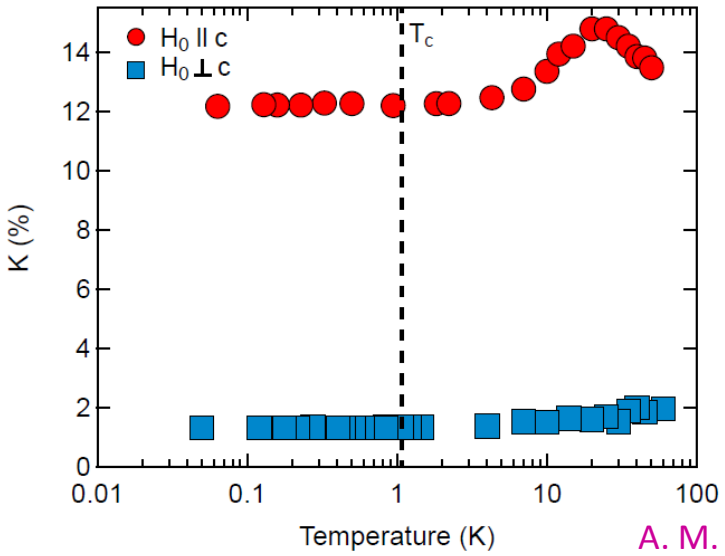


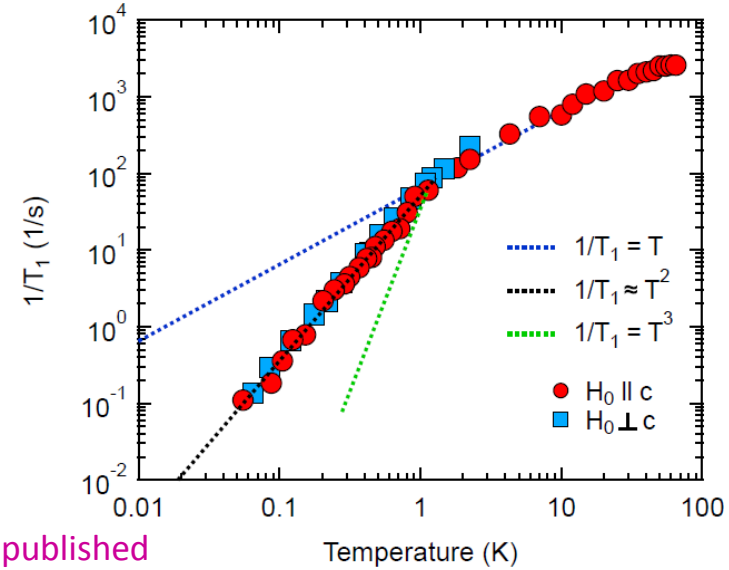




BCC with a=3.52 Å and c=12.54 Å

evidence for unconventional superconductivity

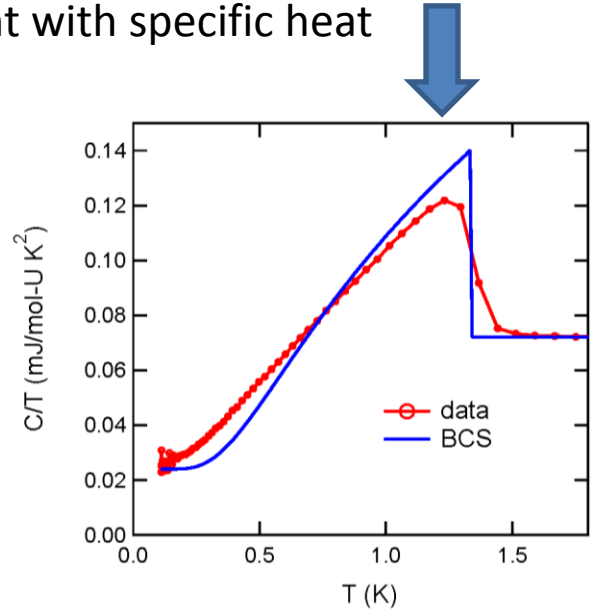




A. M. Mounce et al., unpublished

♦ no Knight shift in ^{195}Pt NMR below T_c; for singlet pairing estimate K ~ several %, well outside resolution of ~0.2% ⇒ equal spin pairing

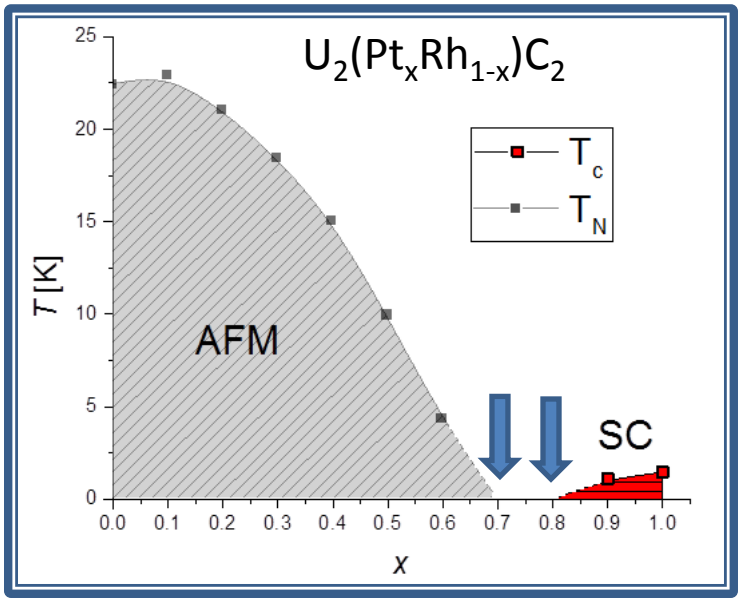
♦ unusual $1/T_1 \propto T^2$ over 10^3 change in $1/T_1$ below T_c ⇒ not fully gapped, consistent with specific heat



♦ further evidence for ferromagnetic correlations:

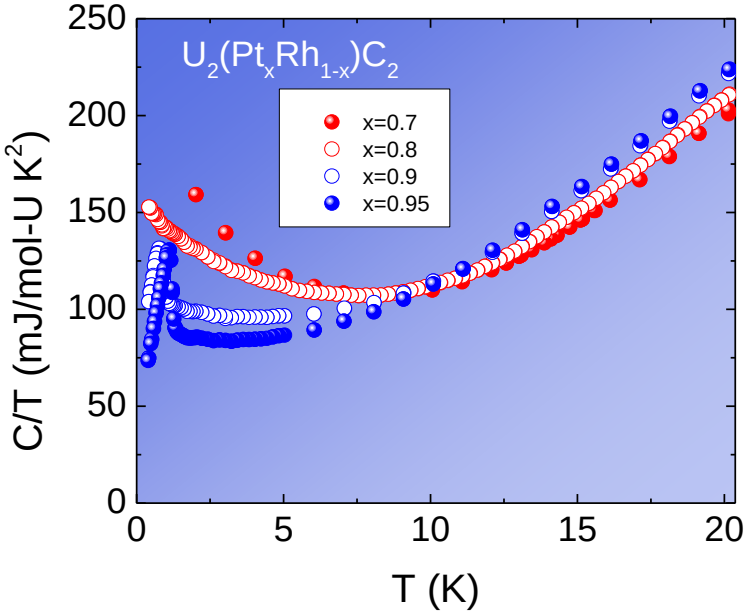
- $T_1TK^2 = S/K(\alpha)$, where S is Korringa constant and $K(\alpha)$ is an enhancement factor [K=1 for non-interacting electrons, >1 for antiferromagnetic exchange and <1 for ferromagnetic exchange]
- find K=0.03, comparable to nearly ferromagnetic $TiBe_2$ (K=0.032)

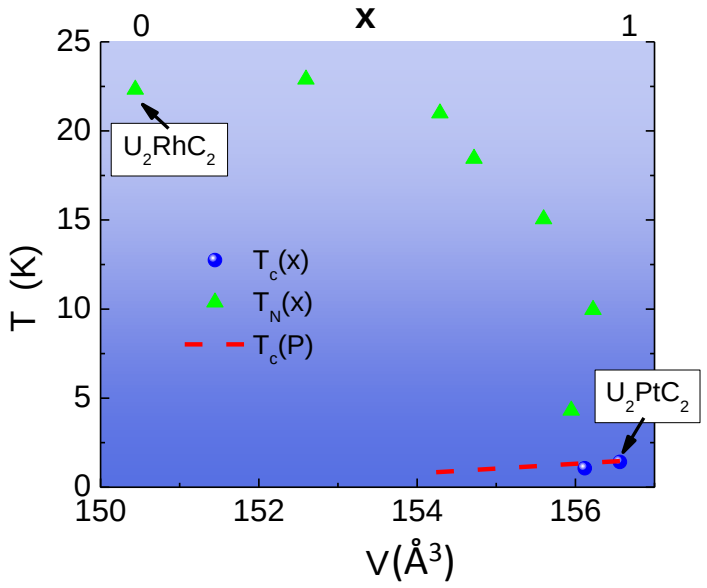
nearby magnetic order?



N. Wakeham et al., unpublished

- Rh substitution for Pt: suppresses superconductivity and induces AFM (but also removes one d-electron/Rh)
- near x=0.7, where $T_N \rightarrow 0$, strongest divergence in C/T and still pronounced upturn at x=0.8 $\Rightarrow$ antiferromagnetic fluctuations detrimental to U_2PtC_2 superconductivity?
- probable spin-triplet SC relatively robust against impurities, but suppression of SC more rapid with doping than with applied pressure
- perhaps nearby ferromagnetic order if cell volume of U_2PtC_2 expanded?





summary

♦ unconventional superconductivity in correlated Ce-based compounds commonly found near an antiferromagnetic QCP – $CePt_2In_7$ another example, but more complex/interesting

- field-induced small-to-large Fermi volume change at P=0
- collapse of ordered moment in its H=0 AFM state and coincident with onset of bulk SC at P*
- evidence for quantum critical behavior at $P > P^*$ where $T_N(P) \rightarrow 0$
- qualitatively similar but quantitatively different than $CeRhIn_5$

♦ possibility that T=0 P,H phase diagrams of $CePt_2In_7$ and $CeRhIn_5$ map onto 'global' phase diagram predicted for unconventional (Kondo-breakdown) quantum criticality and that superconductivity should be considered part of the diagram (J. K. Pixley et al., arXiv:1308.0839)

♦ evidence from $H_{c2}(0)$, Wilson ratio, Knight shift and T_1 that U_2PtC_2 is a nodal, spin-triplet superconductor near a ferromagnetic instability but its nearby ferromagnetic state not found yet

♦ if spin-triplet, superconductivity somewhat surprisingly robust against disorder