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Miniworkshop on Strong Correlations in Materials and Atom Traps

4 - 15 August 2008

Superconductivity, magnetism and criticality in the 115s.

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Superconductivity, magnetism and criticality in the 115s

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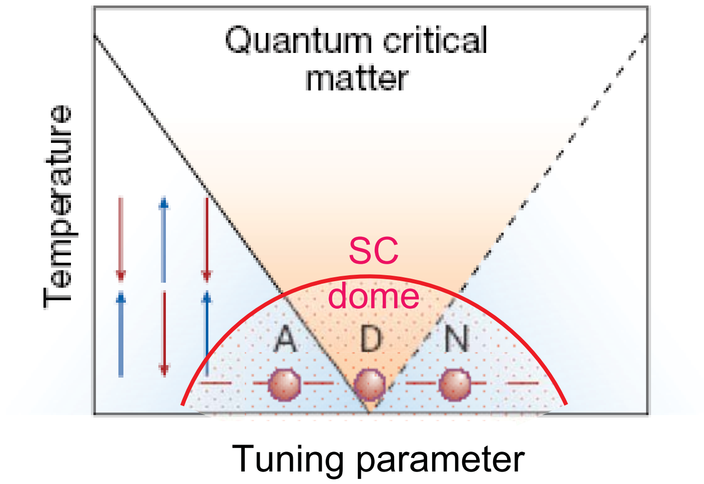
Outline:

- brief introduction
- interplay between unconventional superconductivity and magnetism in $CeRhIn_5$ – superconducting gap symmetry
- signatures for quantum criticality and implications – evidence for an unconventional form of criticality and its role in superconductivity
- summary and issues

special thanks to: A. Bianchi, N. J. Curro, Z. Fisk, R. Movshovich, M. Nicklas, J. L. Sarrao, V. A. Sidorov, O. Stockert, Y. Tokiwa and R. Urbano

the general problem



♦ zero-temperature transition between ordered (eg. antiferromagnetic) and disordered states; driven by quantum, not thermal, fluctuations

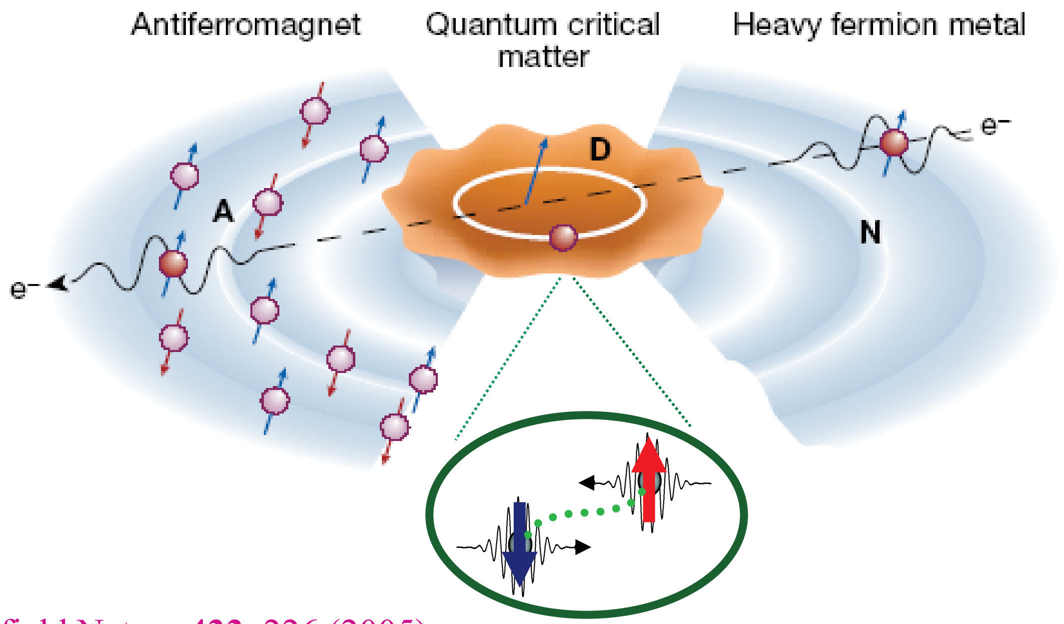
♦ a highly degenerate state susceptible to transformation into new electronic configurations, such as unconventional superconductivity, with critical fluctuations possibly providing a ‘glue’ that forms Cooper pairs (N. D. Mathur et al., Nature **394**, 39 (1998); P. Monthoux et al., Nature **450**, 1177 (2007) and references therein)

♦ questions:

-- Can magnetism and superconductivity coexist to the left of the QCP? If so, what is the nature of the superconductivity?

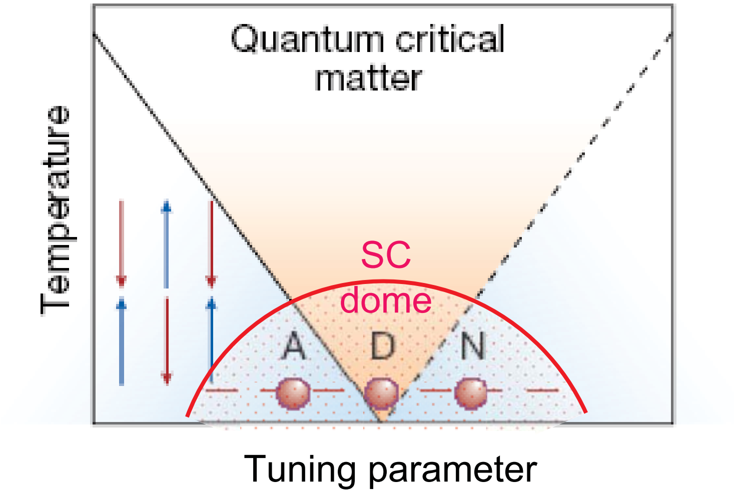
-- Can the QCP (‘D’) hidden by a dome of superconductivity be revealed by suppressing superconductivity?

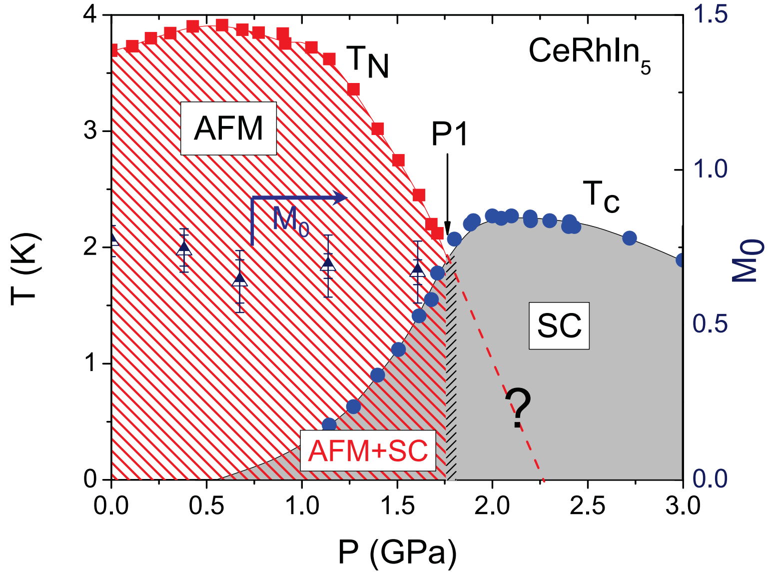
-- What is the nature of the quantum criticality? Does it provide glue?



P. Coleman and A. Schofield Nature **433**, 226 (2005)

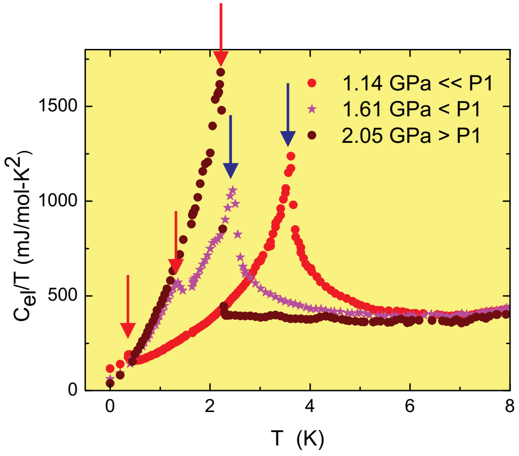
CeRhIn$_5$ as an example

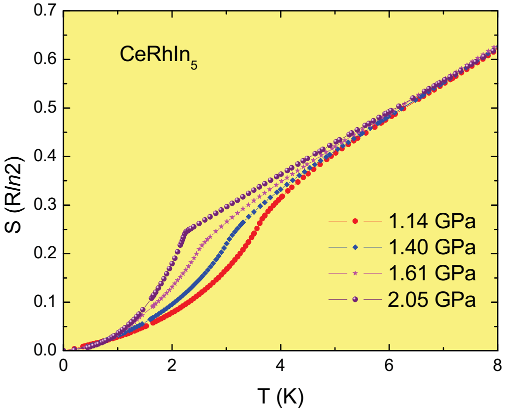




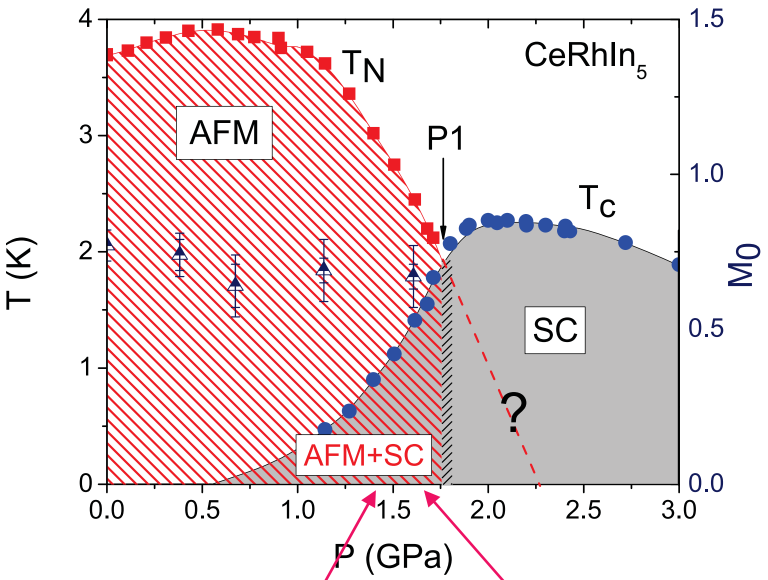
- phase diagram from *ac* specific heat; below ~ 8K, electronic entropy independent of ground state

- CeRhIn$_5$: antiferromagnetic member of the 115s that include the unconventional heavy-fermion superconductors CeCoIn$_5$ and CeIrIn$_5$
- exceptionally 'clean', with RRR ~ 500 and $\rho_0 \leq 100 n\Omega cm$
- antiferromagnetic with T_N=3.8 K, above which $\gamma \approx 450$ mJ/molK^2, and below which is an ordered moment M_0=0.79 μ_B, slightly reduced from 0.84 μ_B expected for a CEF doublet-local moment
- temperature-pressure phase diagram similar to generic example: region of superconductivity and magnetic order; no evidence for magnetism above P1 where T_N=T_c; maximum T_c where T_N extrapolates to T=0

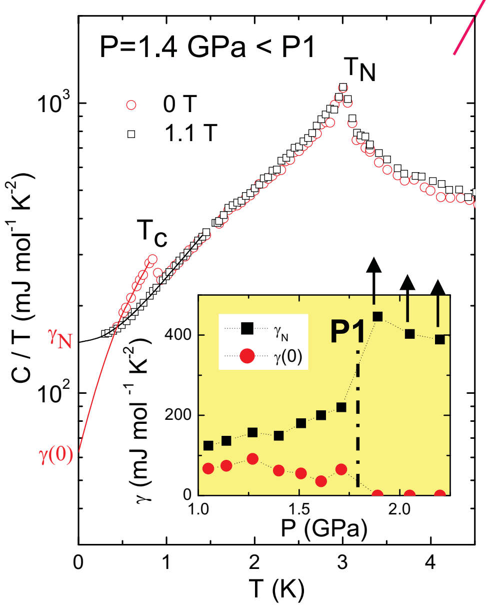




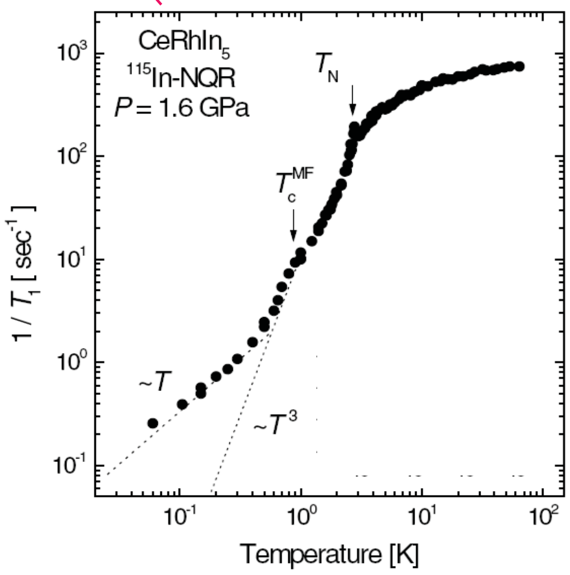
coexistence to the left of the QCP



- specific heat and $1/T_1$ ⇒ clear evidence that bulk SC and AFM coexist below P1
- T_1: microscopic coexistence; below T_c, $1/T_1 \propto T^3$, as expected for a gap with nodes; T-linear $1/T_1$ at the lowest temperatures – residual low-energy excitations reflected as well in finite $\gamma(0)$
- as P→P1, γ_N increases ⇒ itinerant charge carriers become more massive; above P1, $\gamma(0)$ becomes small and T-linear $1/T_1$ absent

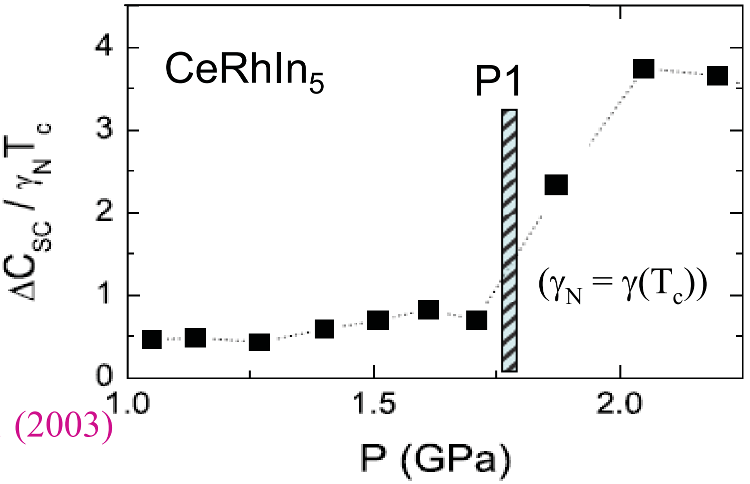


T. Park et al., PNAS **105**, 6825 (2008)

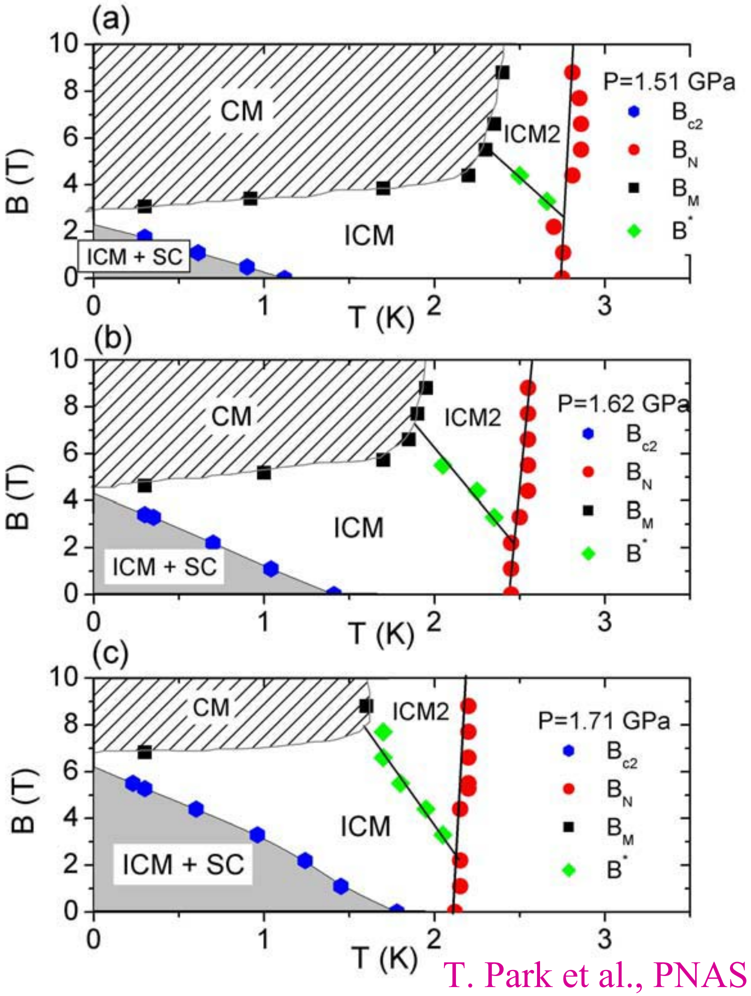


S. Kawasaki et al., PRL **91**, 137001 (2003)

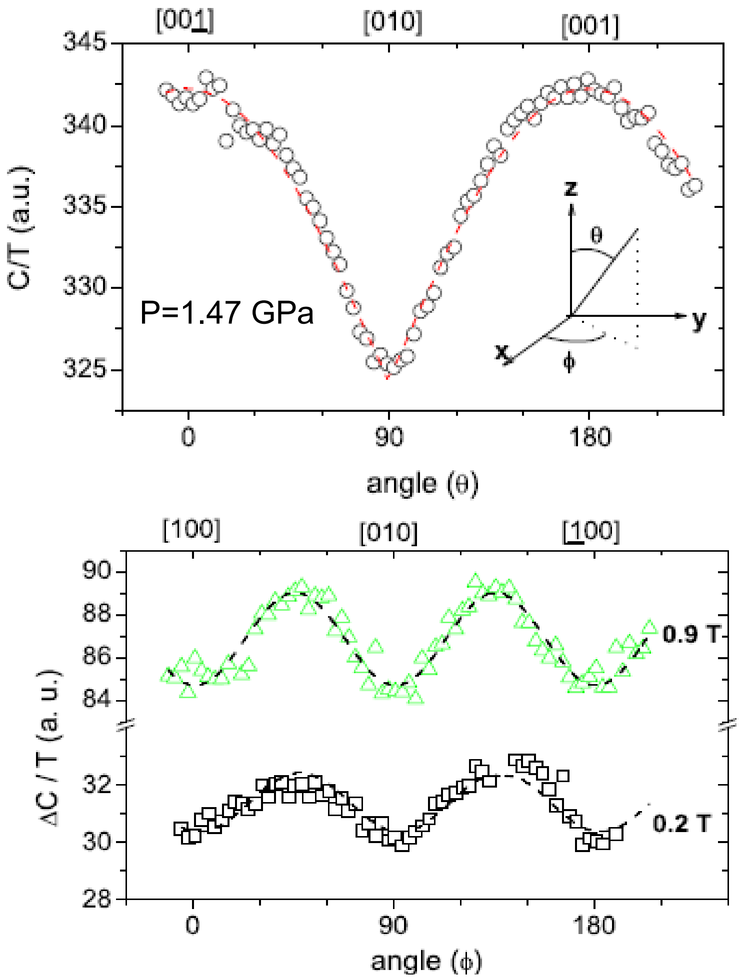
- below P1, $\Delta C/\gamma_N T_c$ ~ const ⇒ SC from heavy itinerant component reflected in γ_N



nature of AFM and SC in coexistence phase



T. Park et al., PNAS **105**, 6825 (2008)

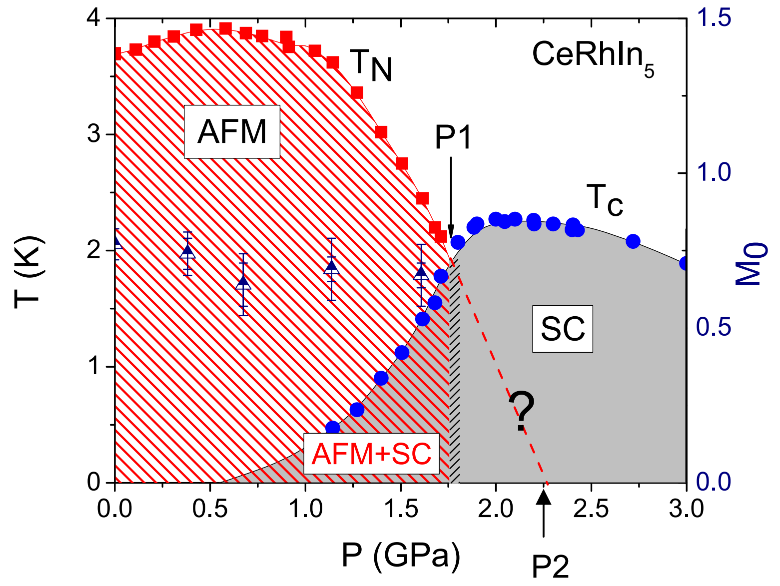


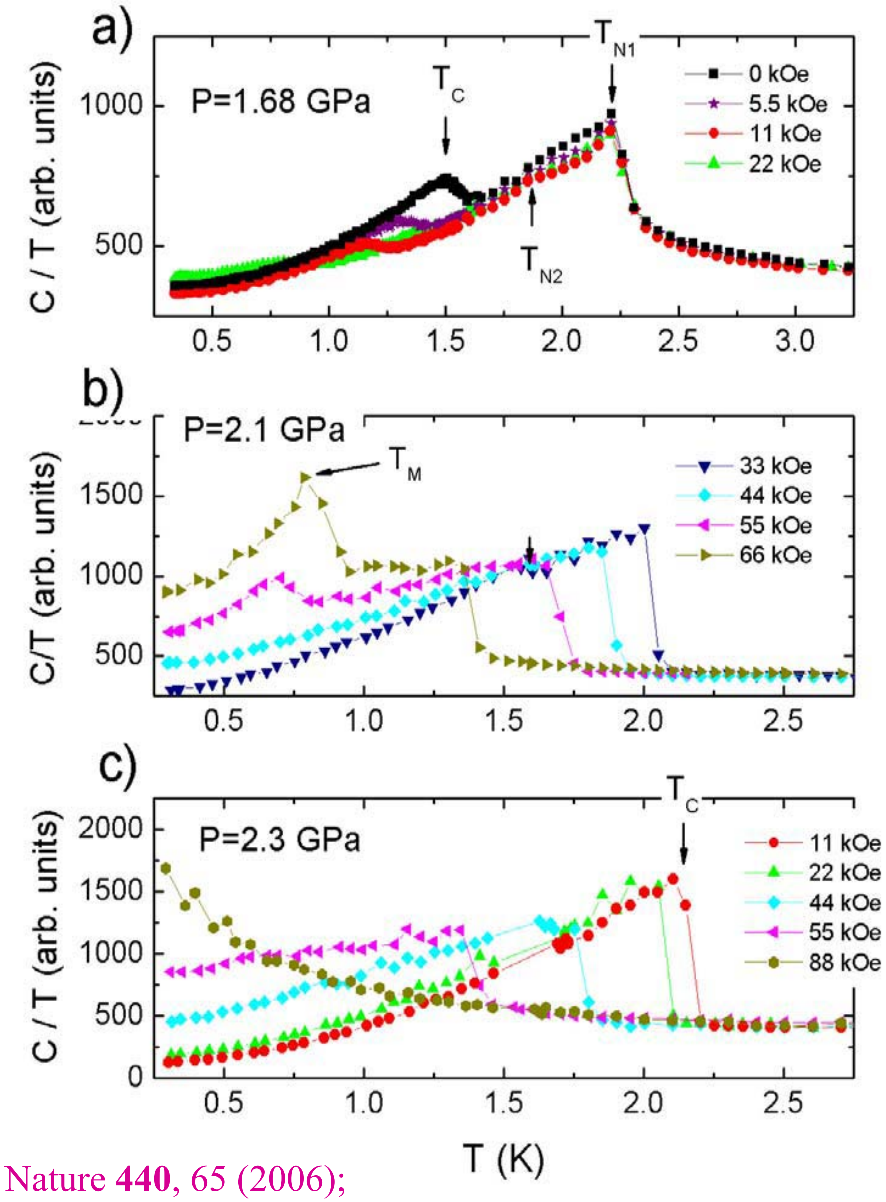
T. Park et al., arXiv:0806.3308

- except for pressure-induced superconductivity, H-T phase diagram unchanged for 0 < P < P1; combined with only small decrease in ordered magnetic moment ⇒ 4f electrons remain dominantly ‘localized’ but also participate in SC

- 2-fold modulation in polar sweep ⇒ anisotropy reflected in H_{c2}; 4-fold in-plane modulation with minima along [100] ⇒ d_{xy} line nodes along c-axis; no evidence for exotic nodal structure, eg. due to magnetic order

emergence of magnetic order above P1



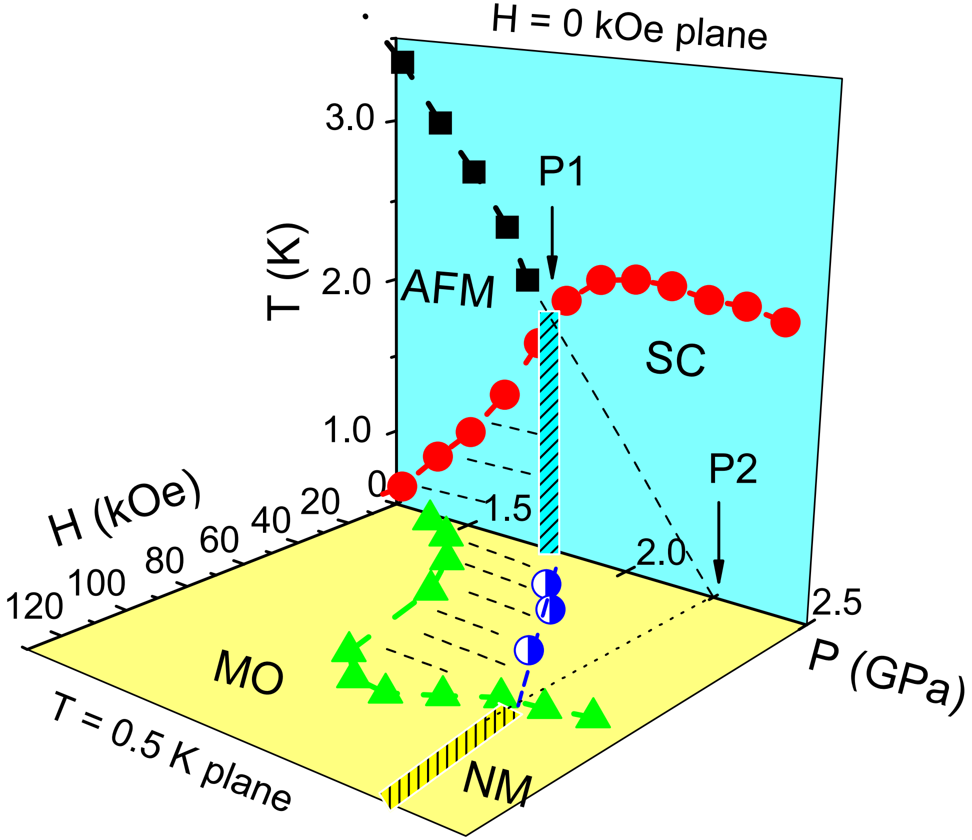


◆ at 2.1 GPa, where only superconductivity in $H=0$, magnetism 'hidden' by superconductivity emerges in the superconducting state when $H \geq 55$ kOe; T_N weakly increasing with H, as at $P<P1$ and $S(T_N) \propto H \propto$ areal density of vortices; similar results at P=1.8 and 1.9 GPa

◆ no evidence for field-induced magnetism at 2.3 GPa; once superconductivity suppressed, C/T diverges as $T \to 0$

T. Park et al., Nature **440**, 65 (2006);
G. Knebel et al., PRB **74**, 020501 (2006)

T–P–H phase diagram of $CeRhIn_5$

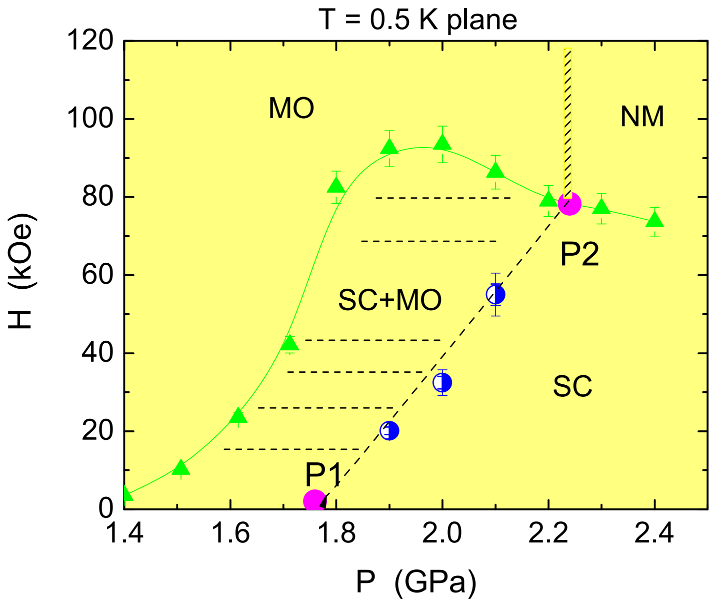


T. Park et al., Nature **440**, 65 (2006)

- H=0 plane, as before; representative H-P plane at T=0.5K

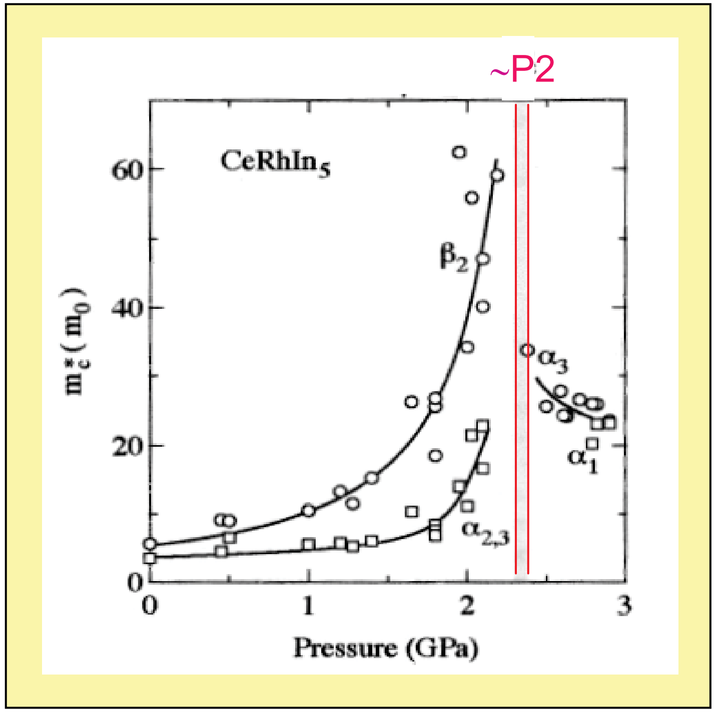
- line of field-induced, second-order magnetic transitions connecting P1 and P2 inside the SC state; line separates a phase of coexisting magnetic order (MO) and superconductivity (SC) from a purely unconventional superconducting state

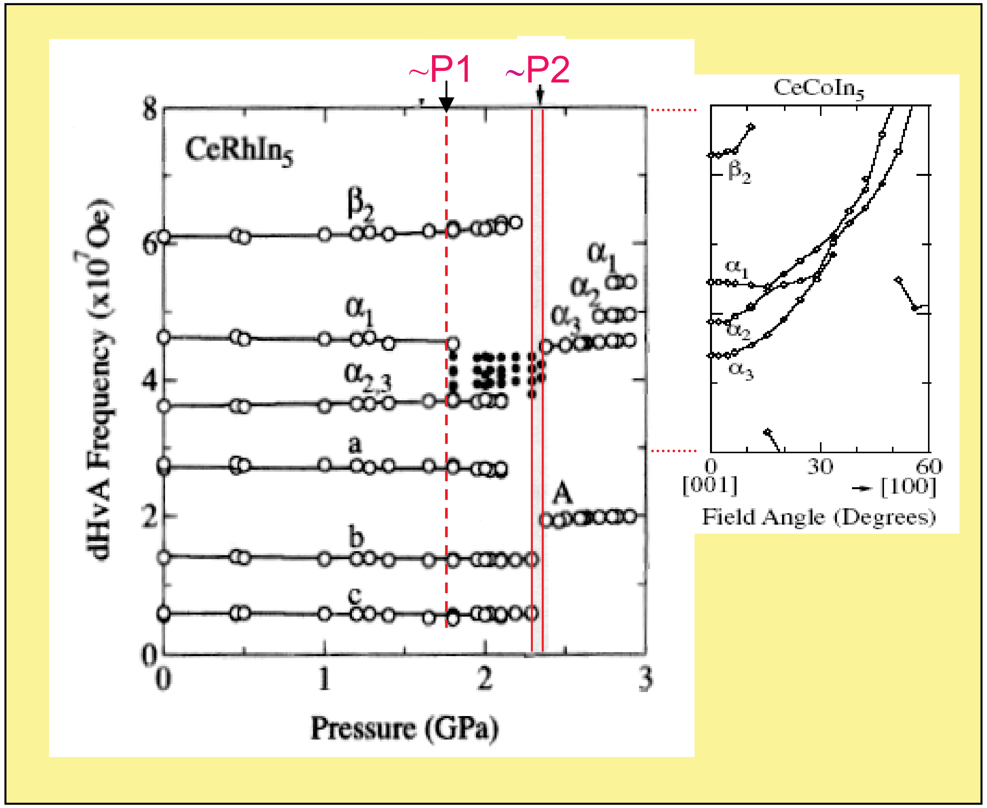
- if similar at T=0, have a line of field-induced magnetic quantum criticality
- anticipated theoretically by Demler et al. (E. Demler et al., PRL **87**, 067202 (2001)) in the context of cuprates, where hole doping, instead of pressure, is the tuning parameter



relationship to deHaas-vanAlphen results

◆ divergence of cyclotron mass m* near 2.35 GPa ≈ P2, where $C/T \propto m^*$ also diverges





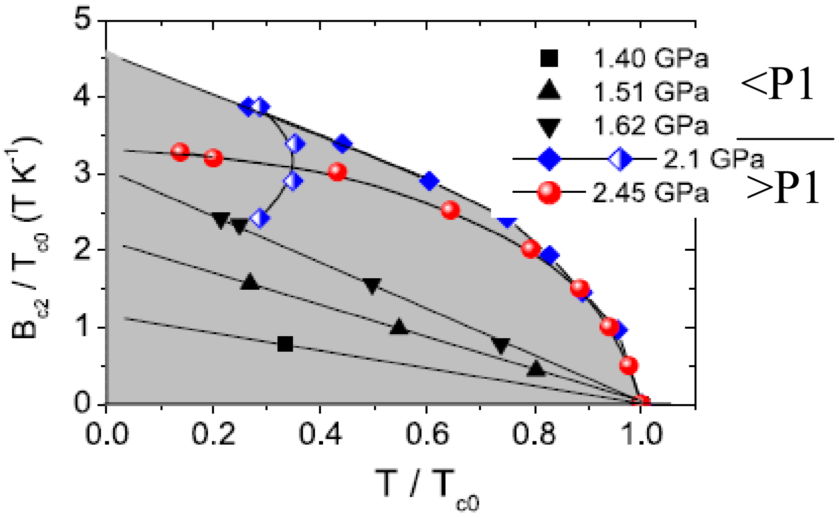
H. Shishido et al., JPSJ **74**, 1103 (2005)

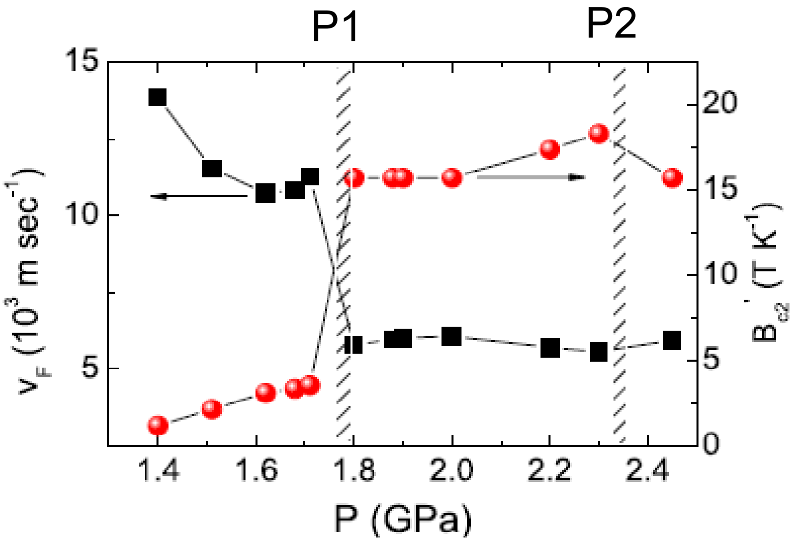
◆ main dHvA frequencies (Fermi surface volume) essentially unchanged for P < 2.3 GPa ⇒ f-electron remains localized; but also new branches in interval ~ P1 < P < ~ P2

◆ above 2.4 GPa, qualitative change in dHvA spectrum; frequencies of α_i branches for P > P2 essentially identical to those of CeCoIn$_5$ at P=0 in which 4f electrons contribute to FS ⇒ f-‘localized’ to f-‘delocalized’ (small-to-large Fermi volume) transition in a narrow P interval

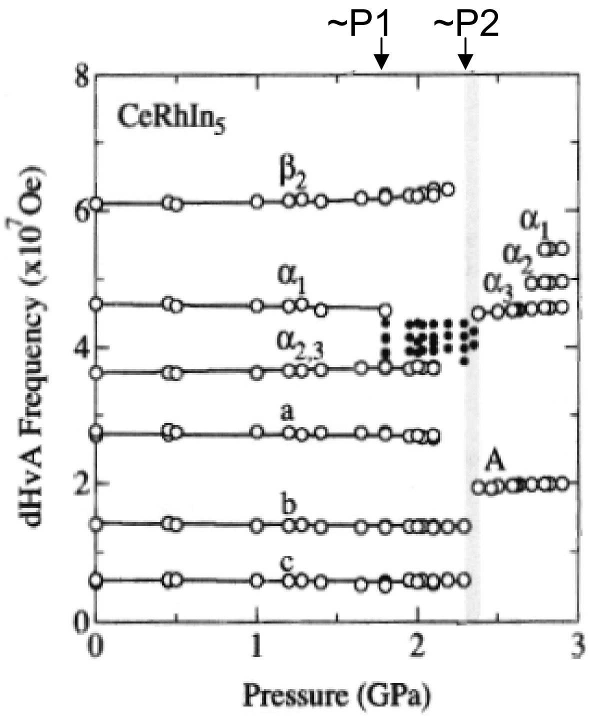
◆ not a conventional quantum phase transition; what happens at P1?

connecting P1 and P2





T. Park et al., PNAS **105**, 6825 (2008)



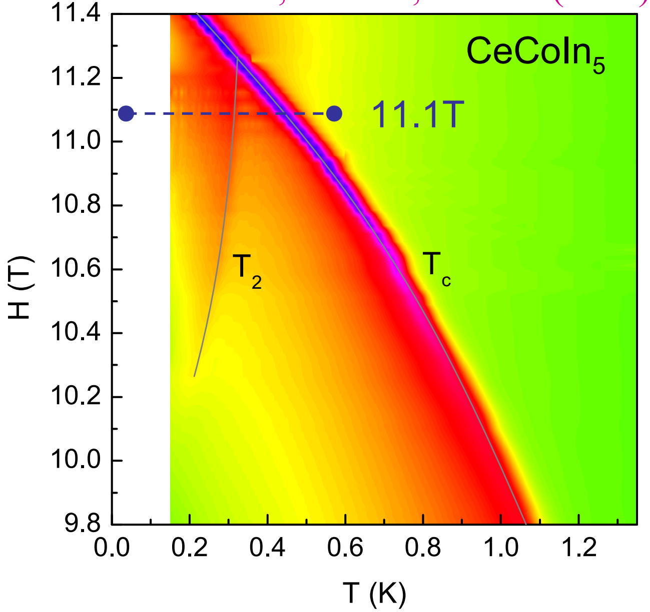
- from slope of B_{c2} (T) near T_c, $(1/B_{c2}')^{1/2} \propto v_F \propto 1/m^*$
- m^* ($\sim \gamma_N$) increasingly heavy as P approaches P1 but jumps by ~ 2x upon crossing P1, not seen in high field dHvA
- diverging high field m^* at P2 from dHvA and jump in zero-field m^* at P1; consistent with T-P-H phase diagram – line of field-induced quantum criticality accompanied by Fermi-surface reconstruction

aside: relation to CeCoIn$_5$

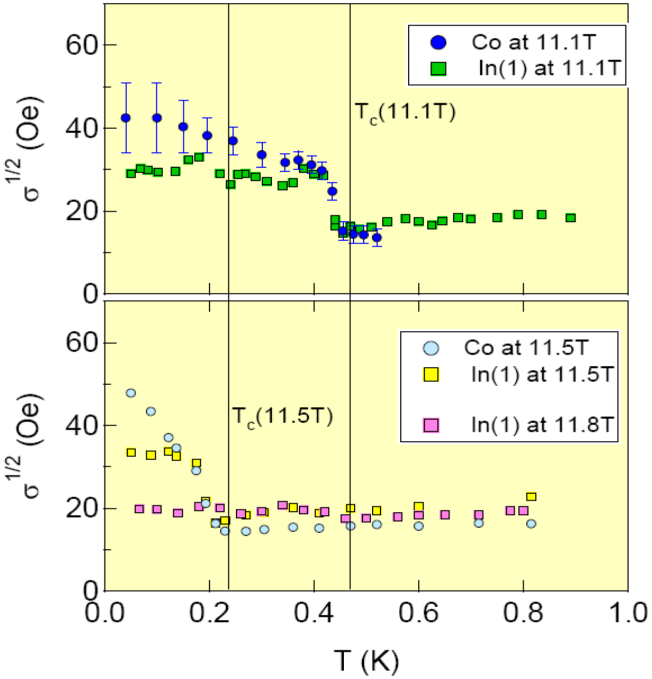
◆ CeCoIn$_5$: upper critical field boundary 1st order in the low-T, high-H limit ⇒ Pauli limited and a phase inside the vortex state that may be FFLO now also shown to be magnetic from NMR and neutrons

◆ CeRhIn$_5$: H_{c2} boundary also 1st order near P2 and field-induced magnetism in low-T, high-H phase for P just less than P2

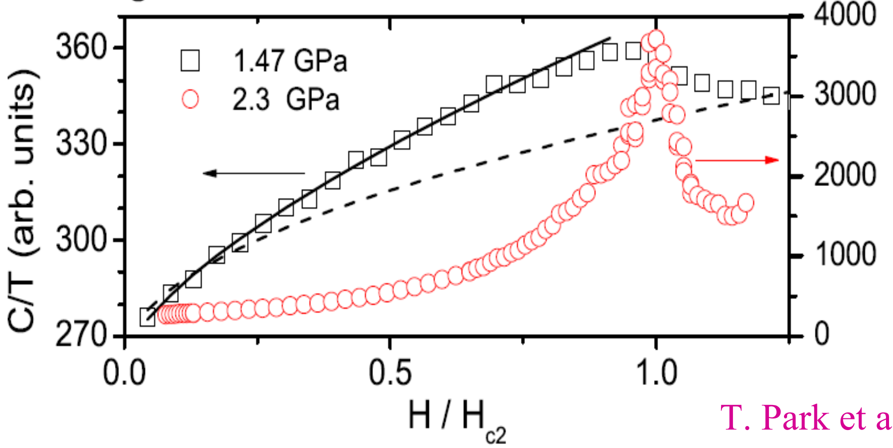
A. Bianchi et al., PRL **91**, 187004 (2003)



◆ both quantum critical, similar dHvA frequencies, and coexisting SC and H-induced magnetism



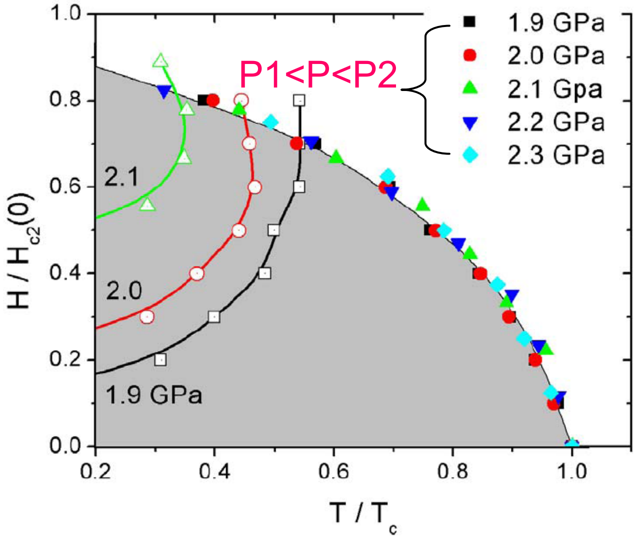
B.-L. Young et al., PRL **98**, 036402 (2007)



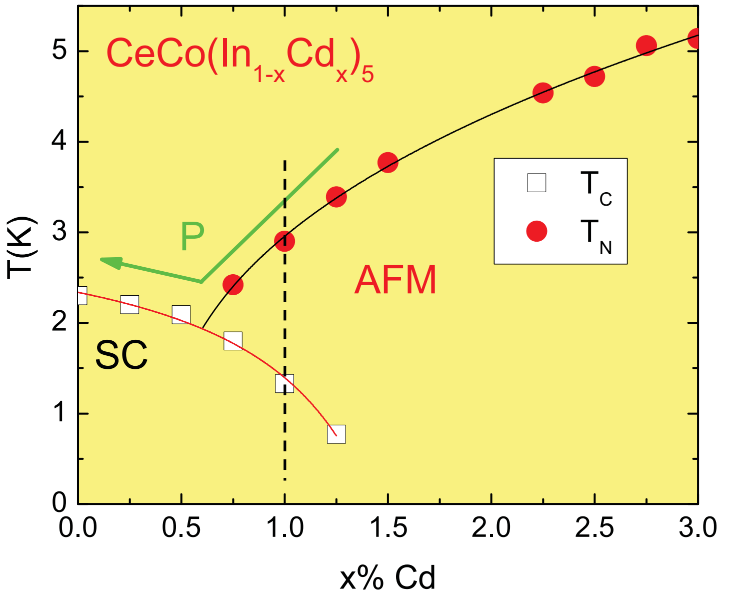
◆ CeCoIn$_5$ at P=0 ≈ CeRhIn$_5$ at P > P2

CeRhIn$_5$

T. Park et al., arXiv:0806.3308

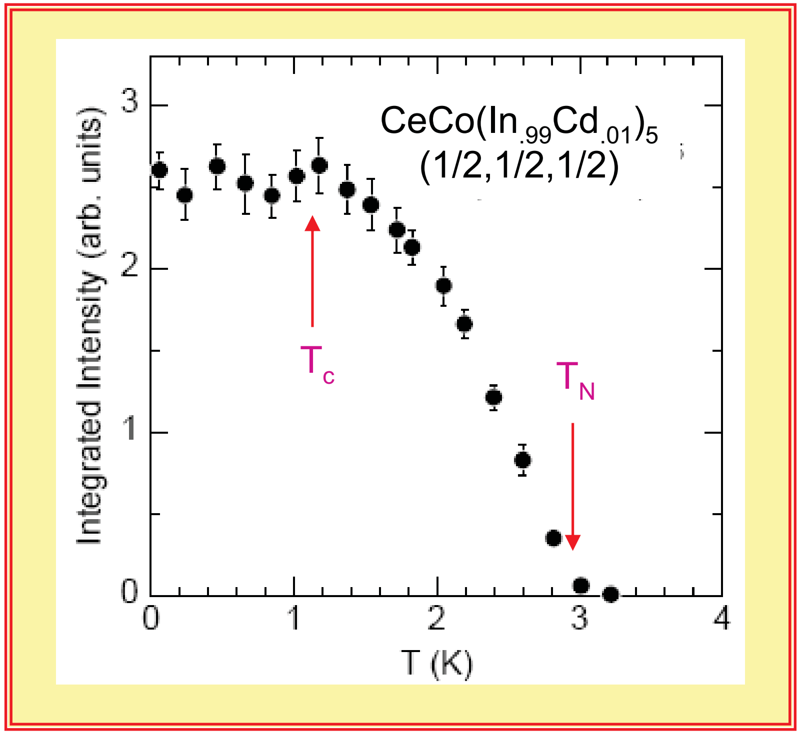


inferences from Cd-doped CeCoIn$_5$



L.Pham et al., PRL **97**, 056404 (2006)

◆ magnetism explicitly present for H=0 with small (~1%) Cd substitution for In; region of microscopic coexistence (NMR: R. R. Urbano et al., Phys. Rev. Lett. **99**, 146402 (2007)) of large-moment AFM (neutrons: M. Nicklas et al., PRB **76**, 052401(2007)) and SC; same conclusion from neutron diffraction on x=0.75%



M. Nicklas et al., PRB **76**, 052401(2007)

◆ abrupt halt to AFM order parameter development at $T_c \Rightarrow$ coupling of SC and AFM; what happens to magnetic degrees of freedom? some evidence, though not straightforward to separate from effects of disorder, that $\gamma(0)$ increases in the coexistence phase where $1/T_1 \propto T$ also appears at $T \ll T_c$

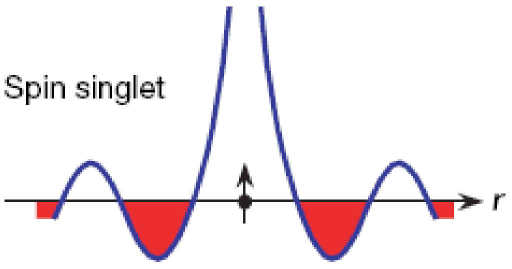
◆ if similar in CeRhIn$_5$'s coexistence regime, possible source of finite $\gamma(0)$ and T-linear $1/T_1$

no theory but a framework for non-phononic 'glue'

◆ consider a quasiparticle with spin **s** coupled to an effective field proportional to some spin density or magnetization **m**(**r**,t); then the interaction of the quasiparticle with the field is –**s•**[g**m**(**r**,t)]

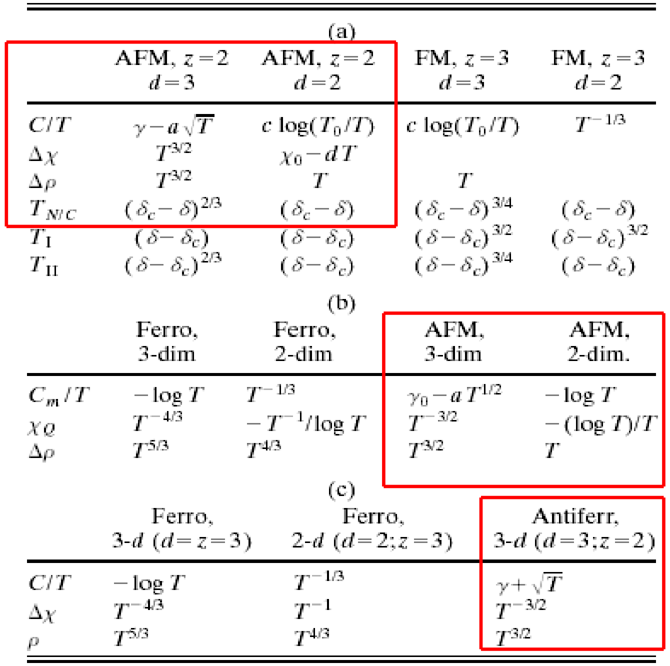
◆ in linear response **m**(**r**,t)=g**s**'χ(**r**,t), so the induced interaction V= -**s•s**'g^2χ(**r**,t)

◆ near an antiferromagnetic instability, χ(**r**,t) a maximum at **r**=0 but also oscillates in space with a period comparable to lattice spacing; for opposite spins, i.e. net S=0 (spin singlet), V repulsive at origin but attractive at **r** > 0, and by Pauli, must have even L, eg. L=2 ⇒ <u>d-wave</u>



Border of antiferromagnetism

P. Monthoux et al., Nature **450**, 1177 (2007) and references therein



(a)

	AFM, $z=2$ $d=3$	AFM, $z=2$ $d=2$	FM, $z=3$ $d=3$	FM, $z=3$ $d=2$
C/T	$\gamma-a\sqrt{T}$	$c\log(T_0/T)$	$c\log(T_0/T)$	$T^{-1/3}$
$\Delta\chi$	$T^{3/2}$	χ_0-dT		
$\Delta\rho$	$T^{3/2}$	T	T	
$T_{N/C}$	$(\delta_c-\delta)^{2/3}$	$(\delta_c-\delta)$	$(\delta_c-\delta)^{3/4}$	$(\delta_c-\delta)$
T_{I}	$(\delta-\delta_c)$	$(\delta-\delta_c)$	$(\delta-\delta_c)^{3/2}$	$(\delta-\delta_c)^{3/2}$
T_{II}	$(\delta-\delta_c)^{2/3}$	$(\delta-\delta_c)$	$(\delta-\delta_c)^{3/4}$	$(\delta-\delta_c)$

} Hertz/Millis

(b)

	Ferro, 3-dim	Ferro, 2-dim	AFM, 3-dim	AFM, 2-dim.
C_m/T	$-\log T$	$T^{-1/3}$	$\gamma_0-aT^{1/2}$	$-\log T$
χ_Q	$T^{-4/3}$	$-T^{-1}/\log T$	$T^{-3/2}$	$-(\log T)/T$
$\Delta\rho$	$T^{5/3}$	$T^{4/3}$	$T^{3/2}$	T

} Moriya

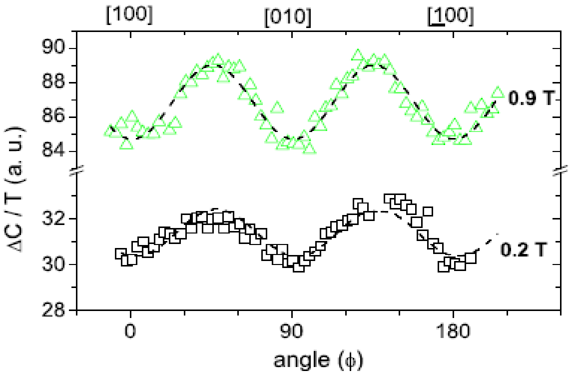
(c)

	Ferro, 3-d ($d=z=3$)	Ferro, 2-d ($d=2;z=3$)	Antiferr, 3-d ($d=3;z=2$)
C/T	$-\log T$	$T^{-1/3}$	$\gamma+\sqrt{T}$
$\Delta\chi$	$T^{-4/3}$	T^{-1}	$T^{-3/2}$
ρ	$T^{5/3}$	$T^{4/3}$	$T^{3/2}$

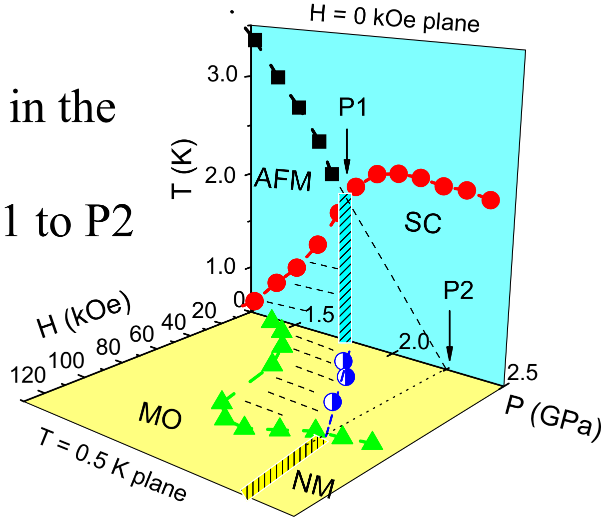
} Lonzarich

◆ as $T_N \to 0$, magnetic excitations become quantum critical ⇒ magnetic susceptibility singular at **Q**, possibly favorable for enhancing the induced attractive interaction, and leads to power-law forms of physical properties but no jump in Fermi volume

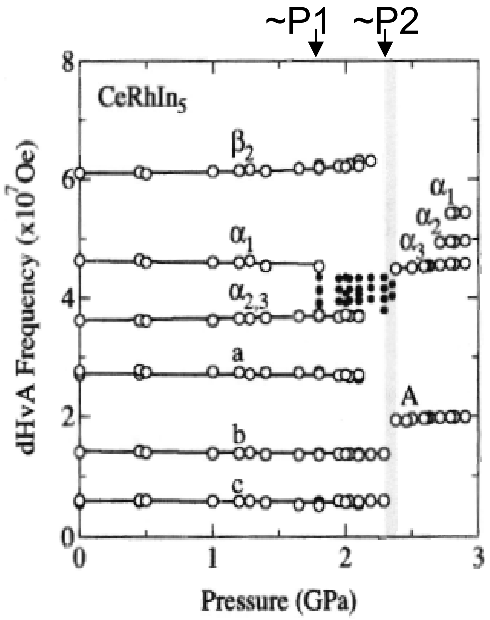
CeRhIn$_5$ summary



- field-induced magnetism in the SC state, with H-induced criticality extending from P1 to P2



- unconventional SC coexisting with AFM



- FS reconstruction at P1 and P2, with apparent jump in FS volume at P2

- sublinear resistivity and strong isotropic scattering emerging from P2 where T_c is a maximum, unexpected within conventional models of SDW-type of criticality

issues

(1) in coexistence phase below P1, f-electron basically localized (dHvA, M_0, H-T-P diagram, very low impurity T_K), yet ΔC at $T_c \Rightarrow$ bulk SC from heavy electrons – *how does the f-electron 'partition' itself between these two roles?* k-dependent, eg orbitally selective, hybridization? *Is the development of the ordered moment arrested at* T_c, *as in Cd-doped* $CeCoIn_5$, *and what is the role of the non-ordered magnetic component?* transfer of spectral weight?

(2) Fermi surface topology change at P1, where AFM disappears, and at P2, where m* diverges in high fields with apparent increase in Fermi volume ⇒ not obviously anticipated in conventional models of magnetic quantum criticality – *is Fermi surface reconstruction a signature of quantum criticality?* Perhaps, but counterexample in $CeRh_{1-x}Co_xIn_5$ (S. K. Goh et al., arXiv: 0803.4424) where reconstruction coincides with onset of SC and not $T_N \rightarrow 0$; *if a form of criticality, what is its nature?*

(3) line of field-induced magnetic transitions at $T \rightarrow 0$, with P1 apparent zero-field limit and P2 the high field limit – *what is the nature of the induced magnetism?* A continuation of the ambient pressure local moment type or an instability of the Fermi surface? Don't know! Analogies to $CeCoIn_5$ – maybe SDW-like or to Cd-doped $CeCoIn_5$—maybe local moment type, but nFL behavior dominated by P2

(4) O*rigin of the nFL state?* Resistivity exponent not within any framework of 3D criticality, though sublinear exponent above ~ 0.1K (~T-linear below) also found in purest $YbRh_2Si_2$ (P. Gegenwart et al. Nature Phys. **4**, 186 (2008)) that is believed to be locally critical; maybe just not low enough T in $CeRhIn_5$ to find T-linear?

issues (cont.)

(4) (cont.) large decrease in resistivity anisotropy in nFL regime, comparable to that near room temp. ⇒ involvement of entire Fermi surface; together with FS surface change at P2 ⇒ some form of unconventional criticality that involves fermionic and well as bosonic degrees of freedom, possibly of the local or Kondo-breakdown/selective Mott type? (T. Senthil et al; P. Coleman et al., J. Phys. Condens. Mat. **13**, R723 (2001); Q. Si et al., Nature **413**, 804 (2001); C. Pepin, PRL **94**, 066402 (2005); I. Paul et al., PRL **98**, 026402 (2007); C. Pepin, PRL **98**, 206401 (2007)); need theoretical predictions for comparison to experiment

(5) striking increase in scattering centered on P2 where T_c is a maximum ⇒ *fluctuations of the critical state a source of pairing glue?* If unconventional criticality ⇒ fluctuations in charge and spin channels, but which channels or channel dominate(s) the pairing interaction is an open question