Unconventional Superconductivity and Quantum Critical Point in $CeCoIn_5$

Roman Movshovich

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- Unconventional superconductivity from specific heat and thermal conductivity
- Pauli limiting in $CeCoIn_5$; d-wave superconductivity
- Phase diagram, first order SC transition, FFLO?
- Quantum Critical Point at H_{c2}: proximity to AFM? Sn and Cd doping studies.
- Pressure and Cd doping effects on QCP.

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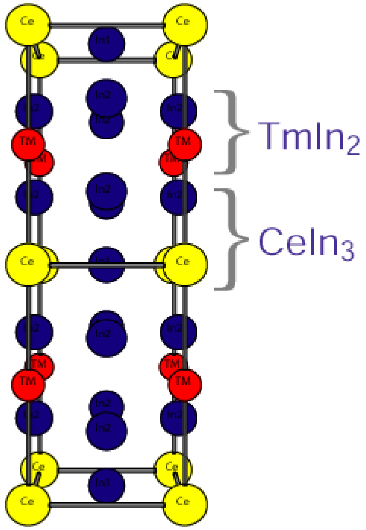
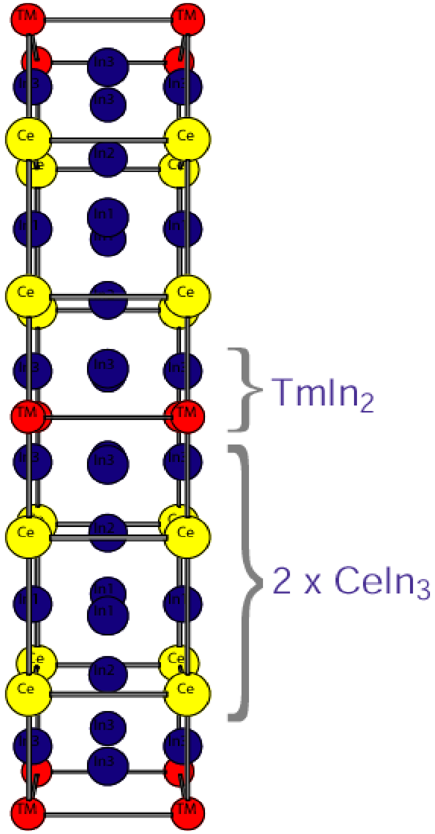
Crystal structures of the $Ce_nTm_mIn_{3n+2m}$ family

Tm = Rh,Co, or Ir

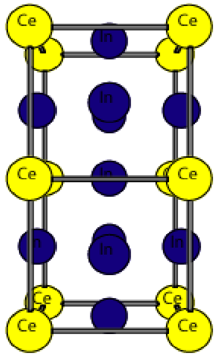
H ↑



$CeTmIn_5$



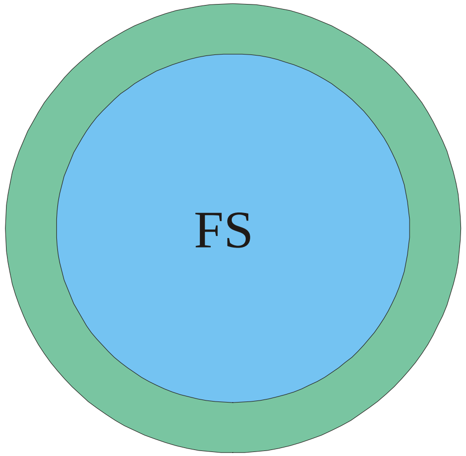
Ce_2TmIn_8



$CeIn_3$

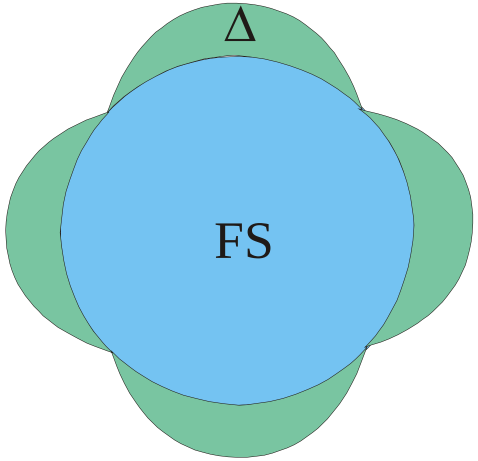
Superconductors,
T_c up to 2.3 K at
ambient pressure

T_c < 200 mK
P ~ 25 kbar



$C \propto \exp(-\Delta/T)$

$\kappa \propto \exp(-\Delta/T)$

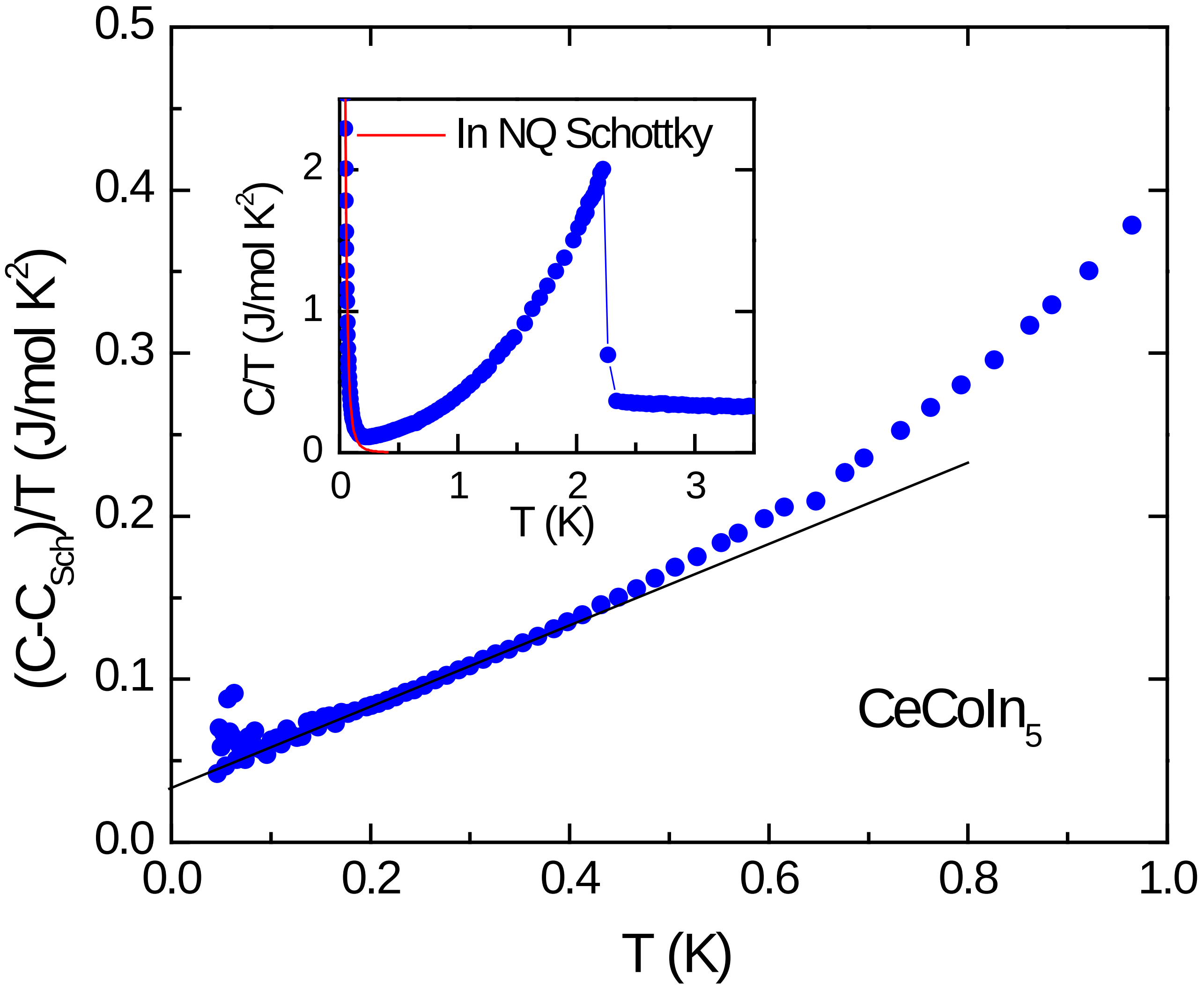


$C \propto T^2$

$\propto T$ in impurity
dominated region,
κ universal limit.

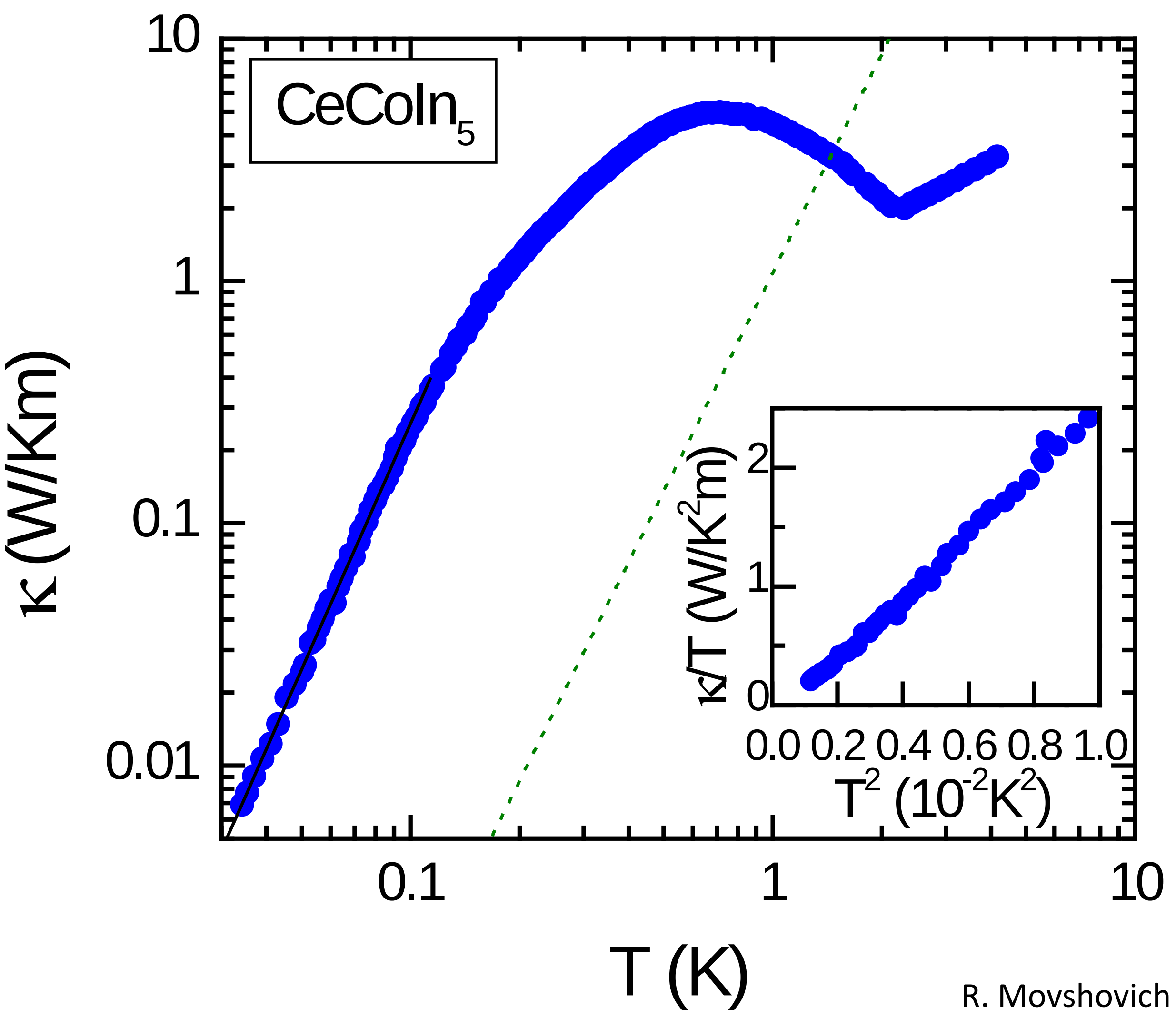
$\propto T^3$, clean limit

$C_{el} \approx aT + bT^2$ at low temperature $\Rightarrow$ lines of nodes in the energy gap

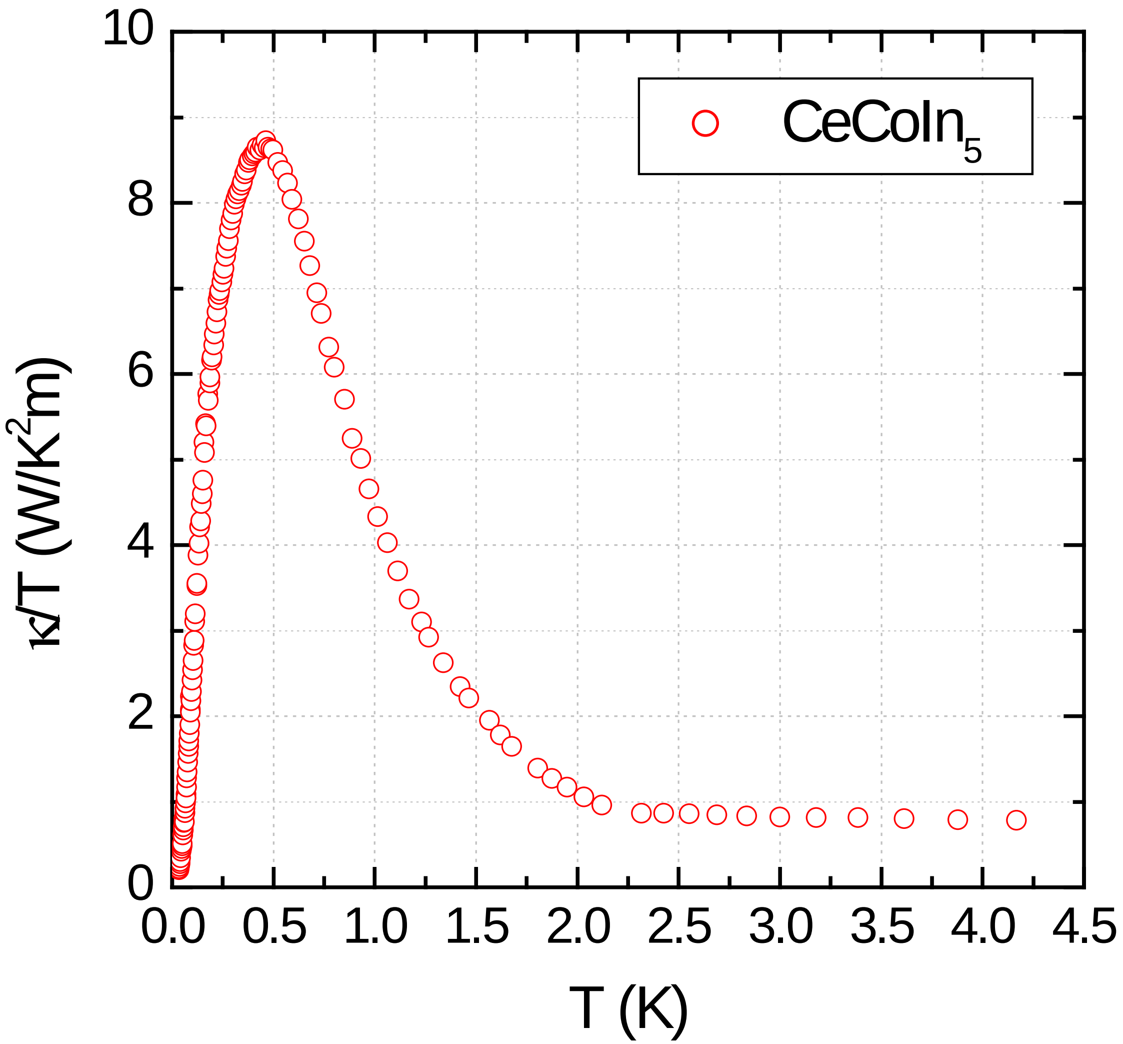


R. Movshovich *et al.,* PRL 86, 5152 (2001)

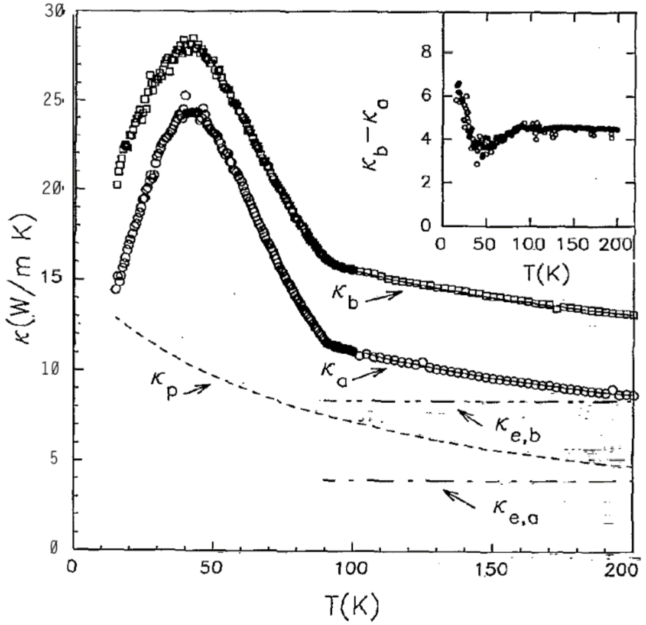
$\kappa \approx T^3$ at low temperature $\Rightarrow$ lines of nodes in the energy gap,
Impurity band width is less than 30 mK $\Rightarrow$ very clean material.



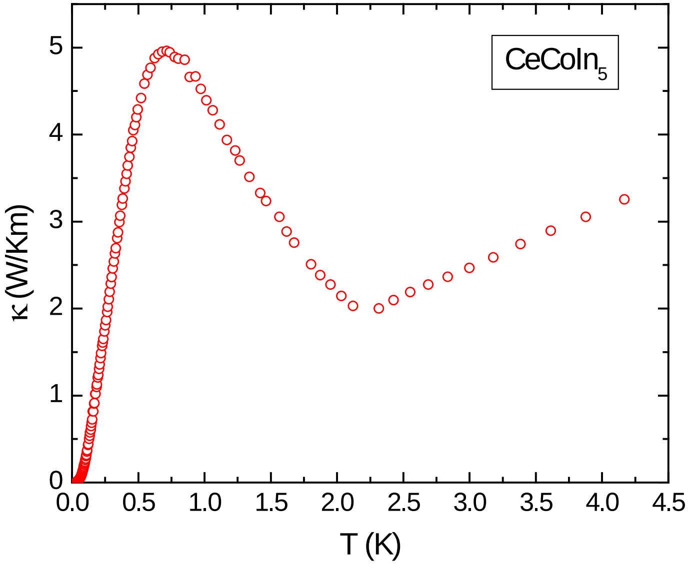
R. Movshovich *et al.,* PRL 86, 5152 (2001)



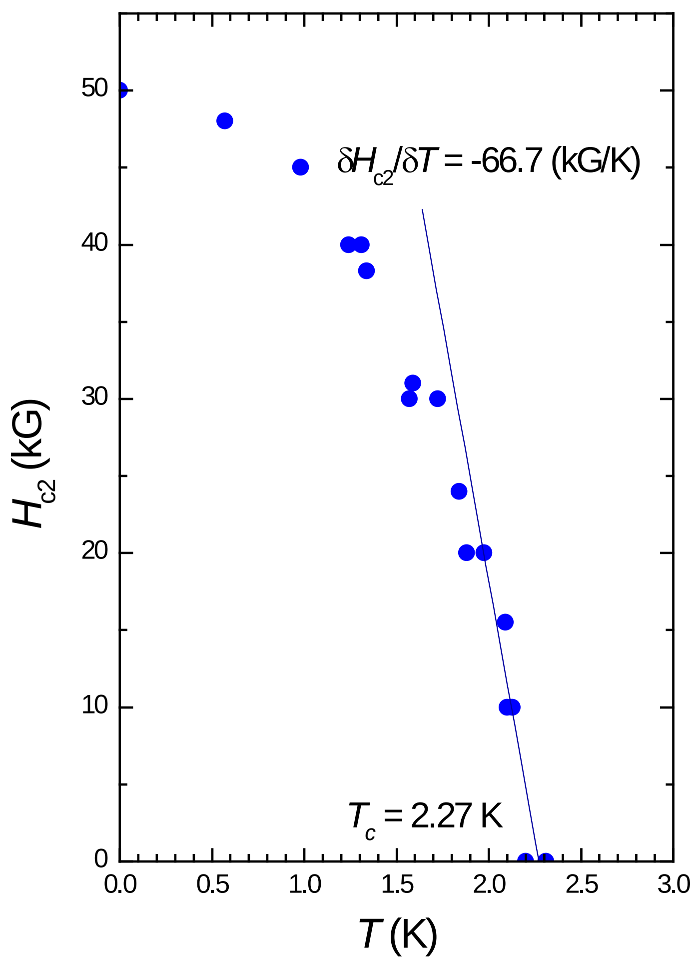
Order of magnitude rise in κ/T ⇒ qp mean free path of few μm.

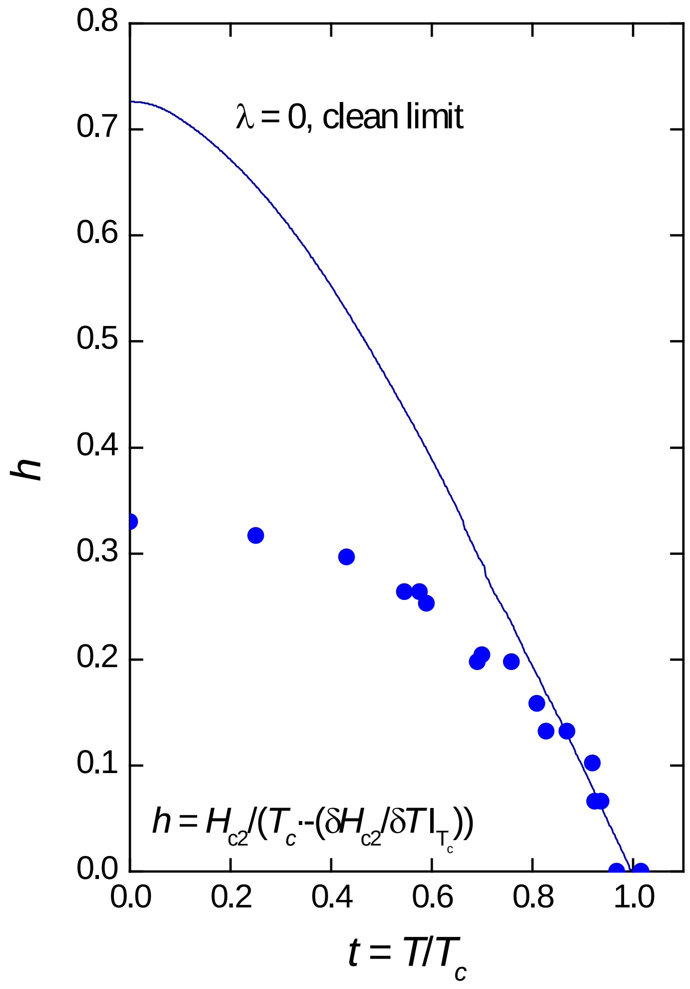


YBCO high temperature superconductor,
Yue *et al. PRL* **69,** 1431 (1992).



CeCoIn5 – upper critical field for *H* II c





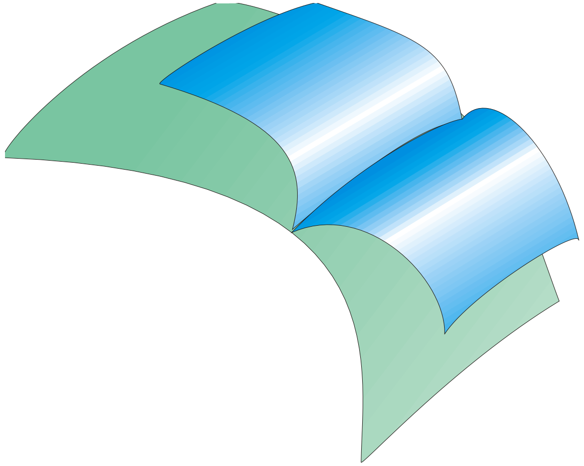
E. Helfand and N.R. Werthamer Phys.Rev. **147** 313 (1967)

Symmetry of the order parameter of CeCoIn$_5$

Pauli limiting ⇒ ↑↓

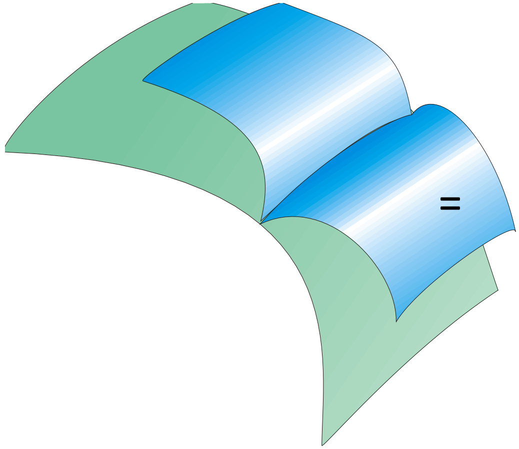
Specific heat

Thermal conductivity ⇒



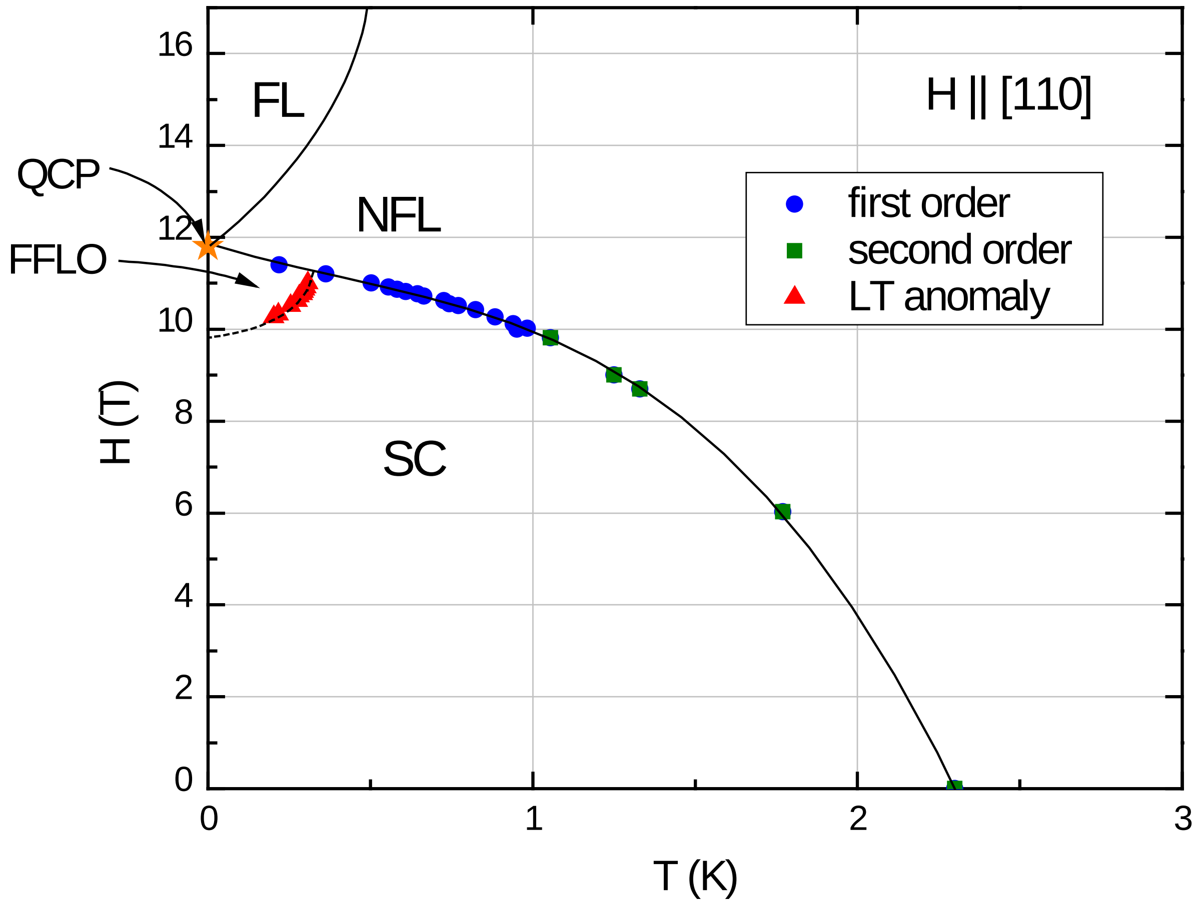
NQR

↑↓ +



= *d-wave*

H-T phase diagram of $CeCoIn_5$



Complex phase diagram :

1. coinciding QCP and H_{c2}
2. superconducting transition itself changes from second to first order
3. a new phase in the High Field-Low Temperature HFLT corner of SC phase.

Q's:

- origin of QCP?
- HFLT - possibly FFLO?
- relation between HFLT and QCP and its underlying magnetism?

SC is suppressed at H_{c2}= 4.95 T, H || c

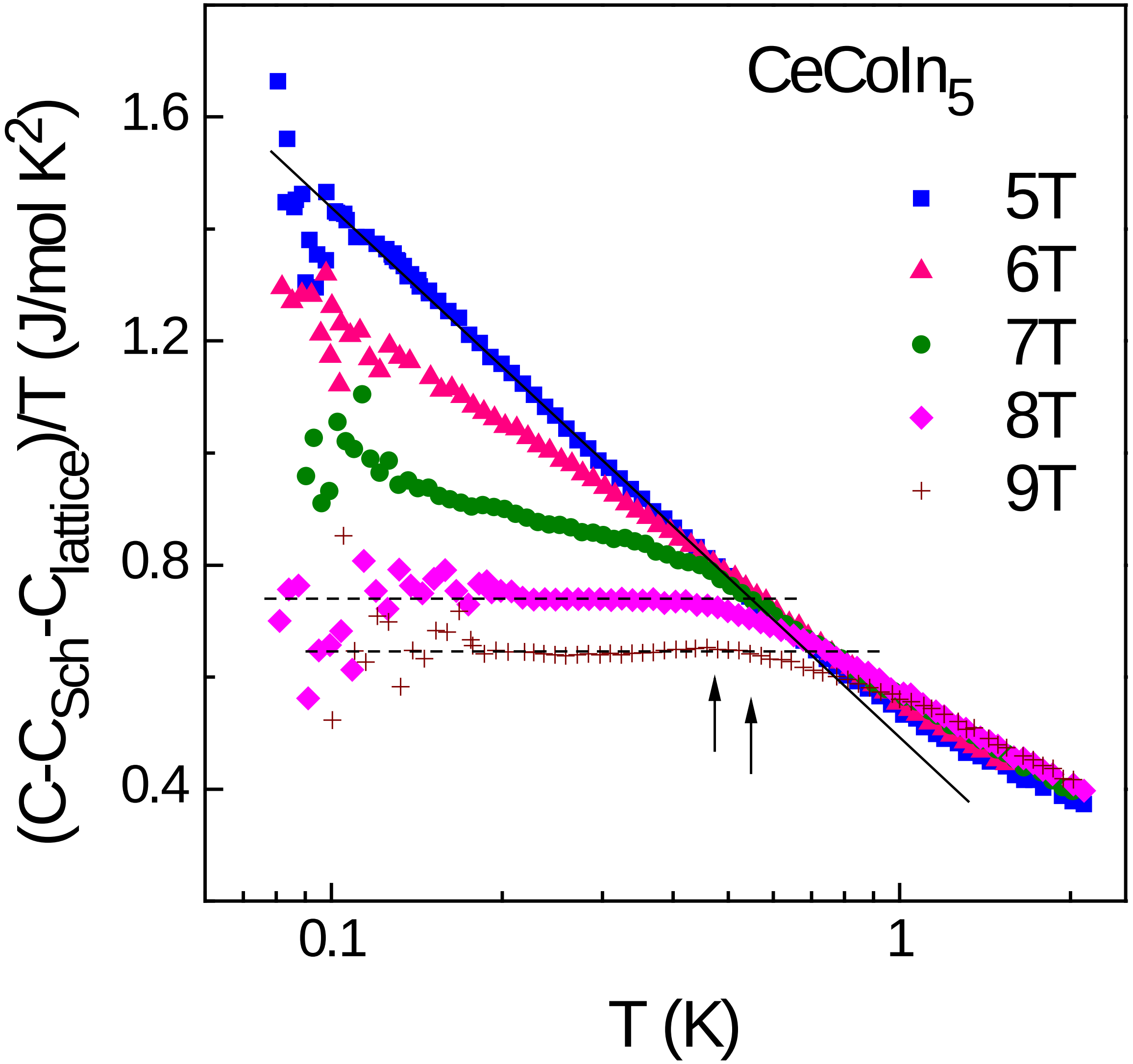
At *5 T γ ≈ -log (T) over almost a decade.*

Above 8 T Fermi liquid region of γ = const. develops at low temps.

For intermediate fields, FL region is not reached, γ peals off the -log (T) curve at higher T for higher H.

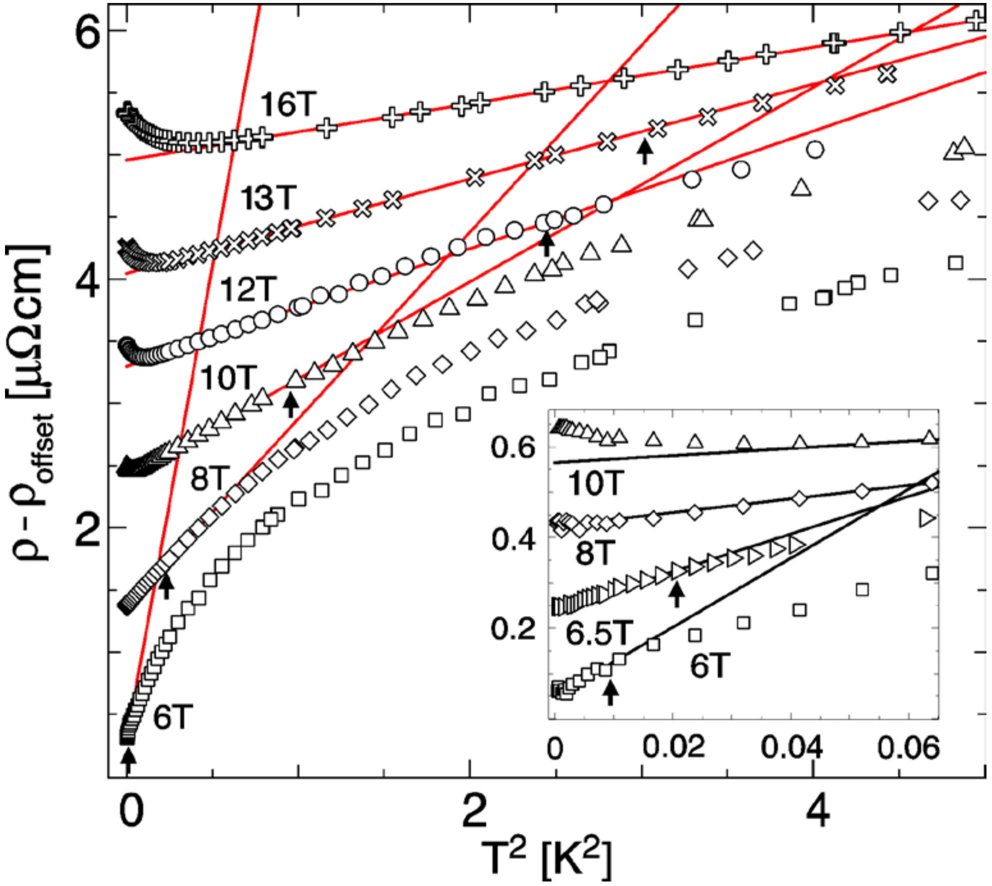
Q: 1) is there a magnetic QCP?

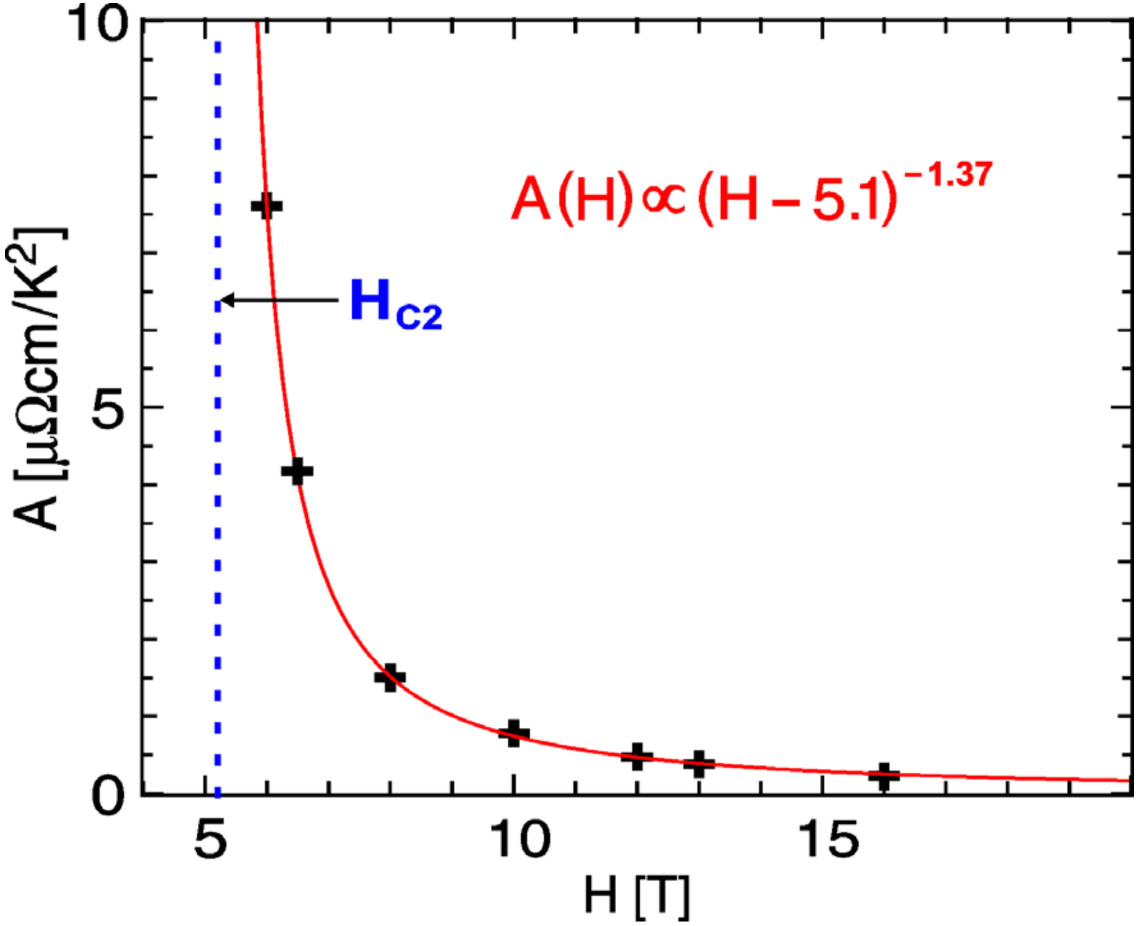
2) can we identify critical field?



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

Evidence for a Field-tuned QCP in $CeCoIn_5$ for H // [001] from resistivity





J. Paglione, *et al*, PRL **91**, 246405 (2003).

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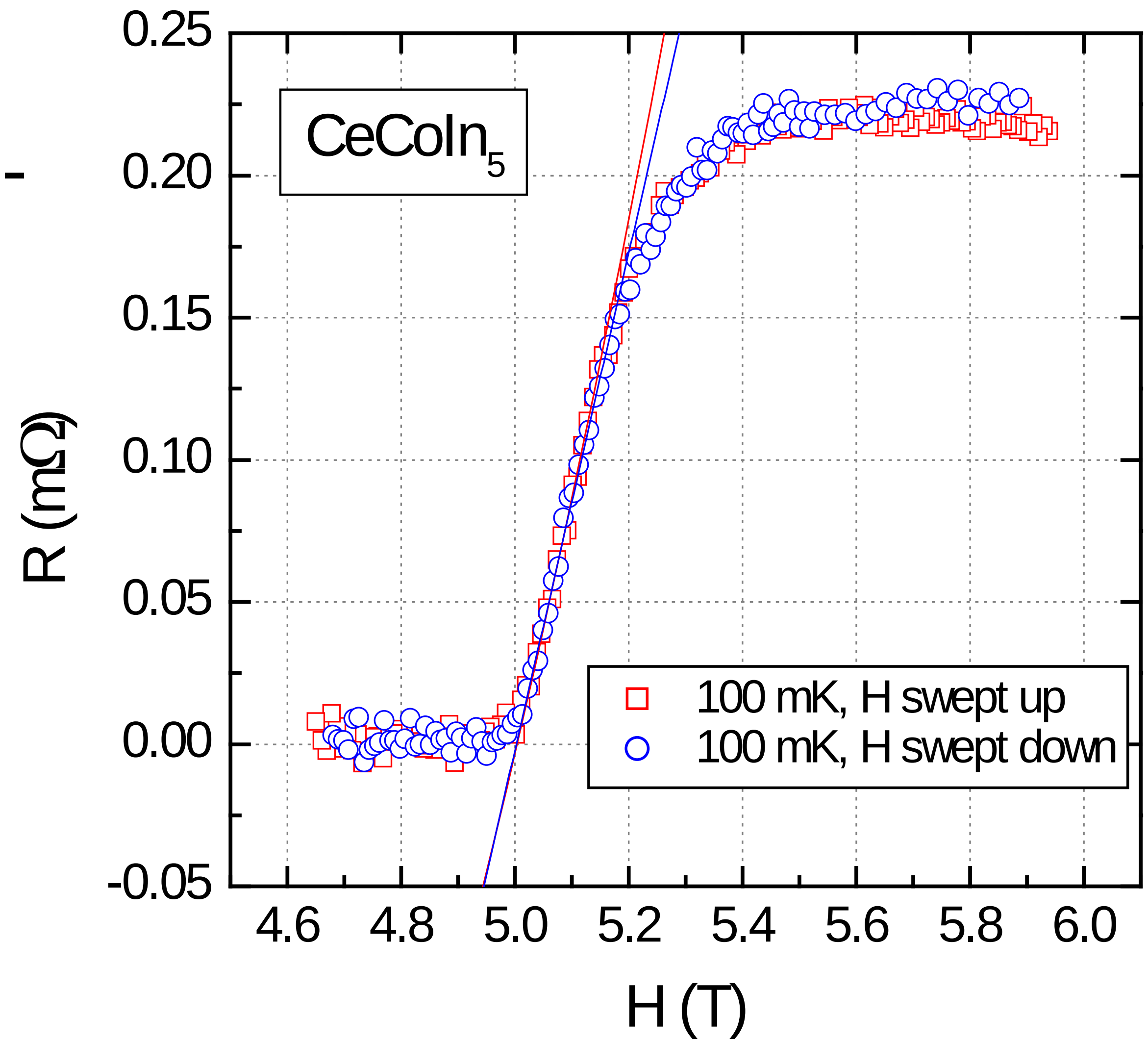
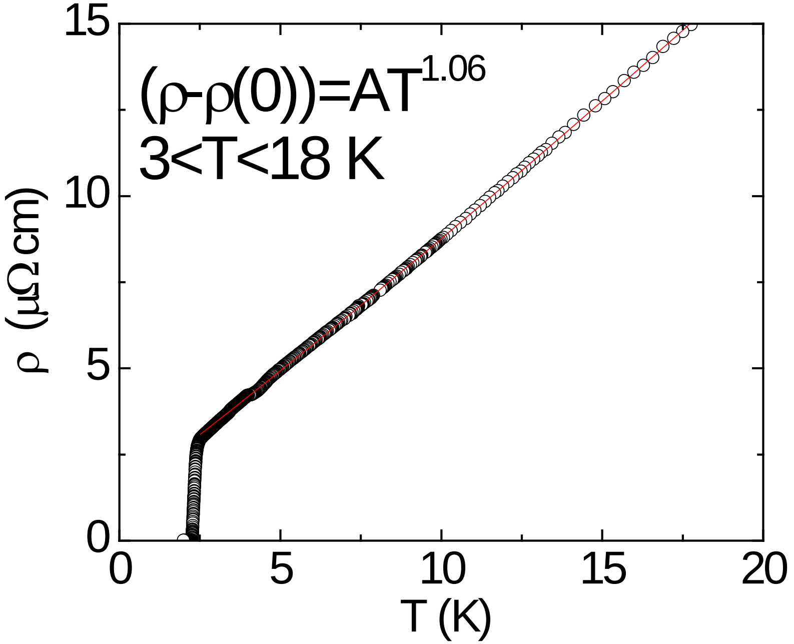
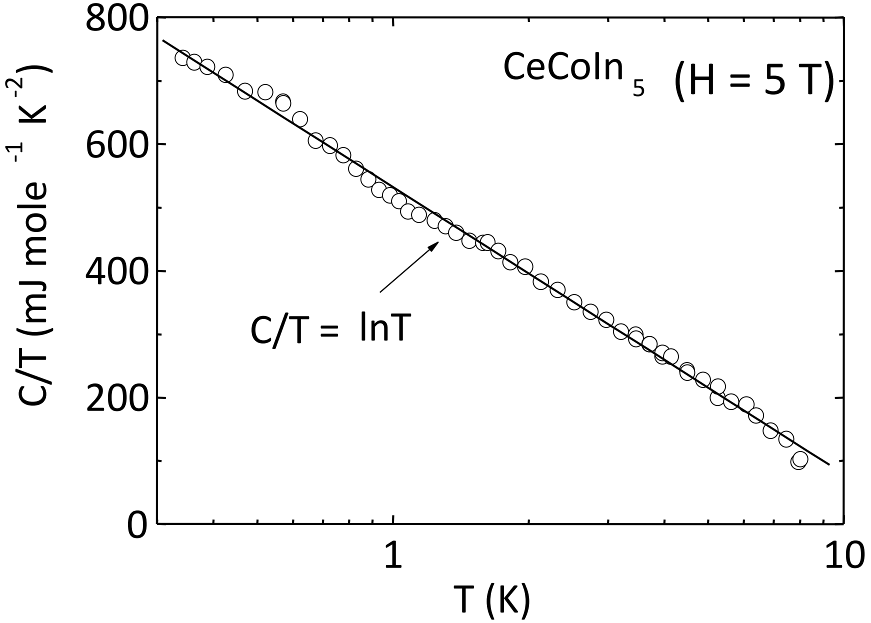
Resistivity for H||[001]

Transition is rather wide-Puzzle.



Non-Fermi Liquid Behavior in $CeCoIn_5$





FL: $\rho \sim \rho_{res} + AT^2$

NFL: $\rho \sim \rho_{res} + AT^{\alpha}$

FL: $C/T \equiv \gamma \sim$ const.

NFL: $C/T \equiv \gamma \sim \ln(T)$

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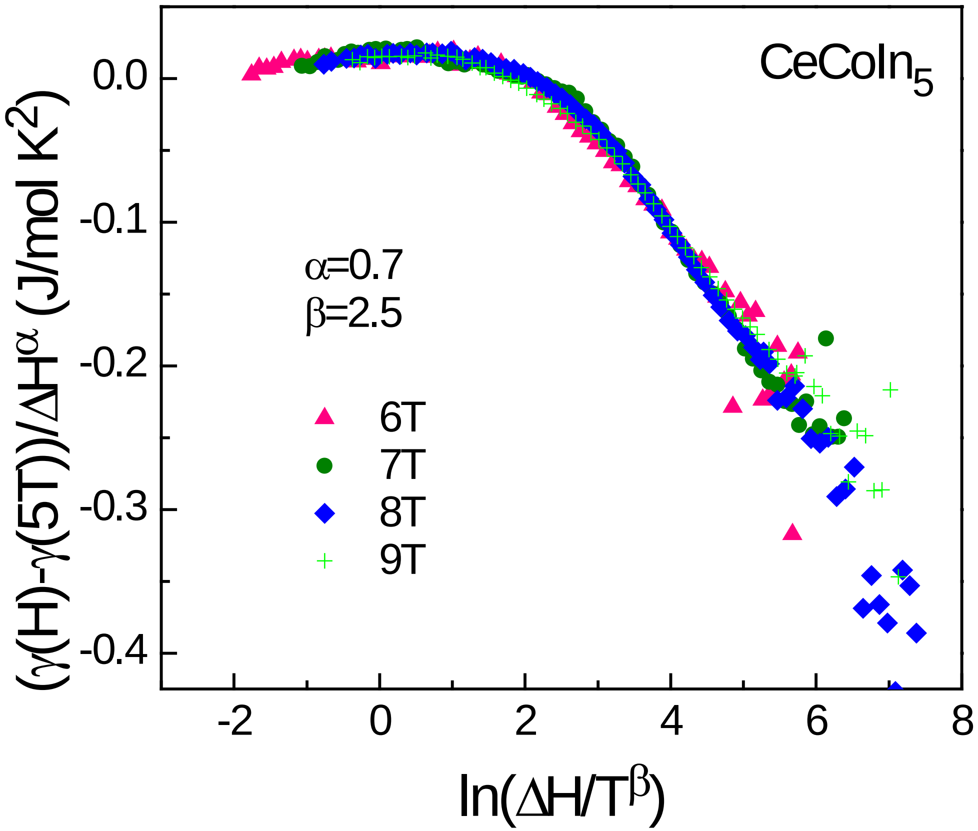
C. Petrovic, *et al*, J. Phys. Cond. Mat. **13**, L337 (2001).

Scaling of γ as a function of H/T^{β} is a signature of critical behavior with field as a tuning parameter.

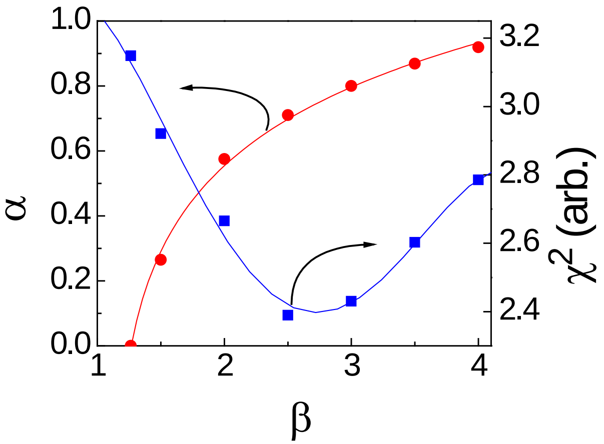
Scaling function:
$\Delta\gamma = \Delta H^{\alpha} \ln(\Delta H/T^{\beta})$

$\alpha = 0.7$ and $\beta = 2.5$ give the lowest standard deviation χ^2

NFL behavior of specific heat is due to magnetically tuned QCP.

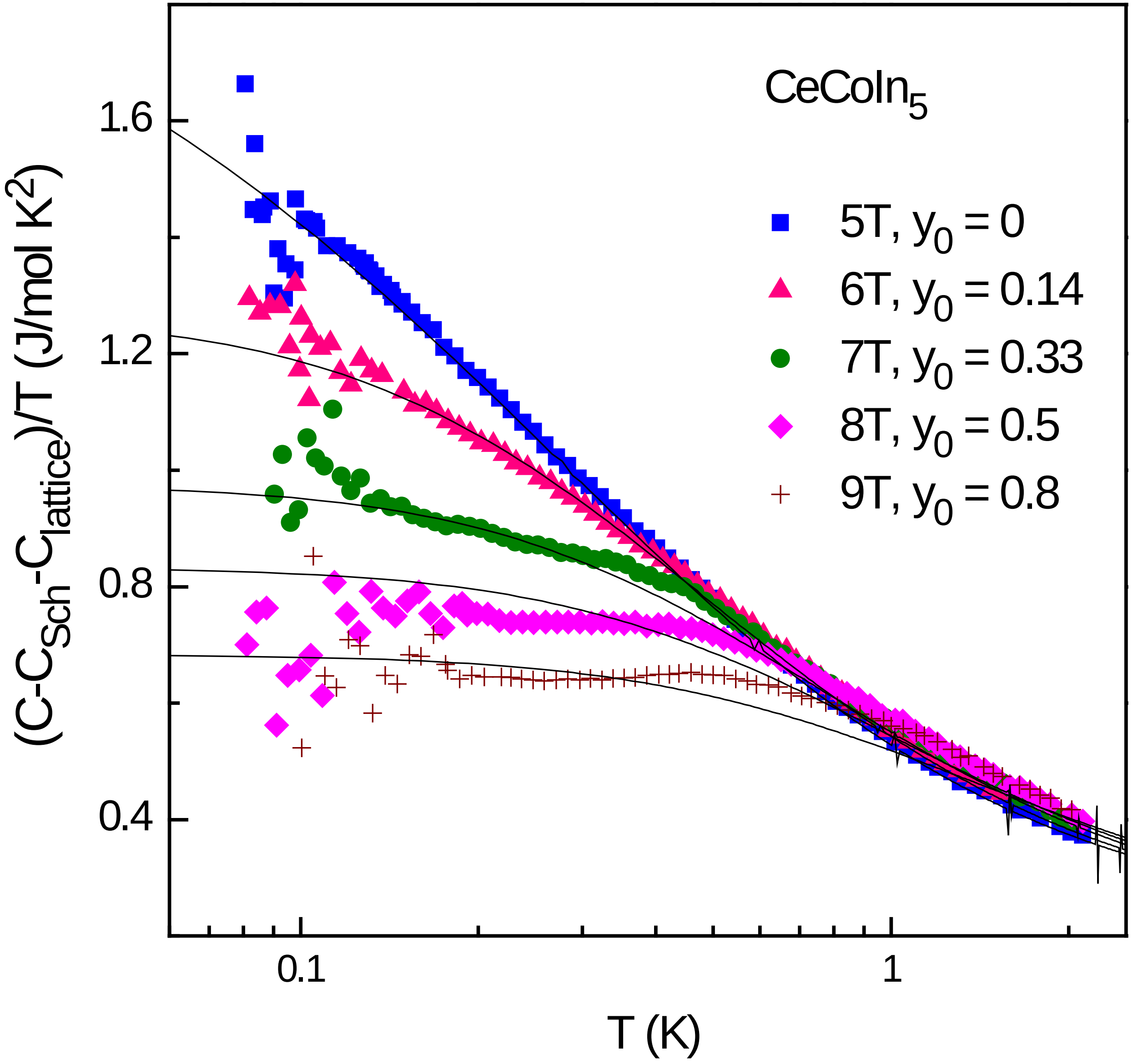


Quality of the scaling fits is not overly sensitive to choices of α & β
$\beta > 2$ may indicate presence of 3D fluctuations.



Fits with Moriya spin fluctuations theory near a AF QCP;
y_0 parameterizes the distance from the QCP in the tuning parameter.

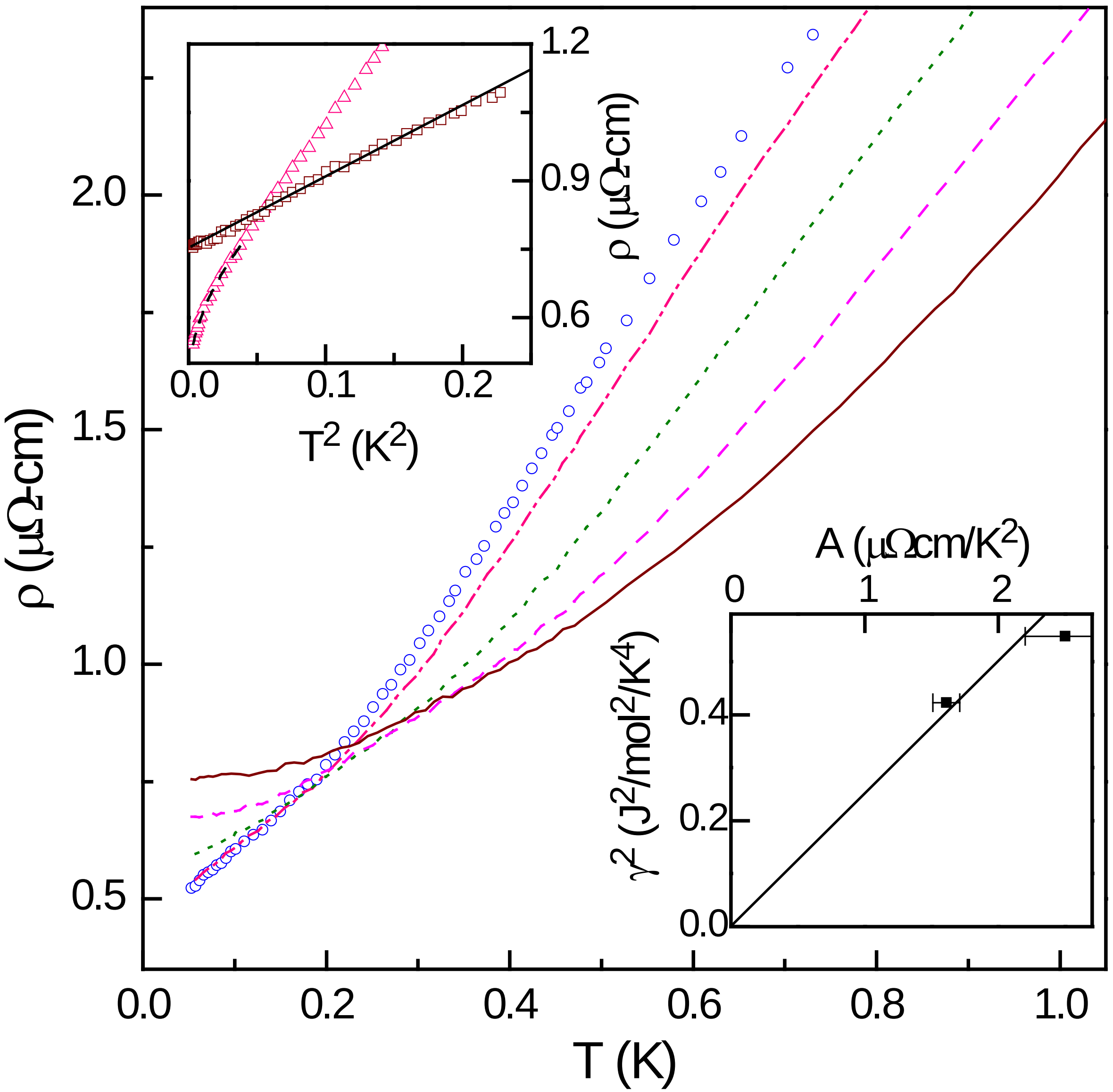
Good quality of the theoretical fits to the data is consistent with AF origin of the QCP in $CeCoIn_5$.



Resistivity

There is a close correlation between ρ and C:

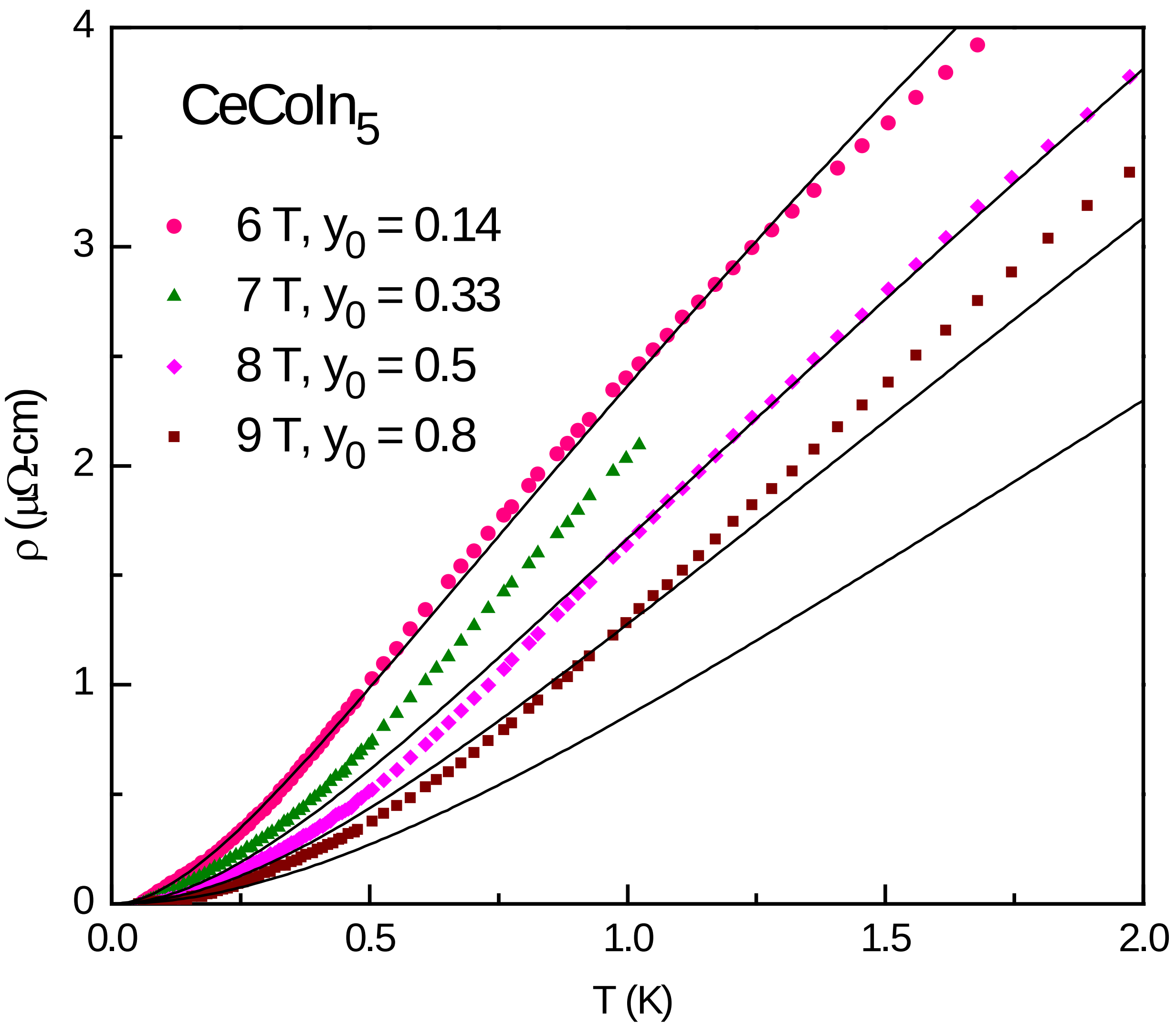
1. FL behavior for H≥8 T
2. Kadowaki-Woods is obeyed within a factor of three.
3. NFL at H ≤ 7 T
4. T-linear behavior at 6 T



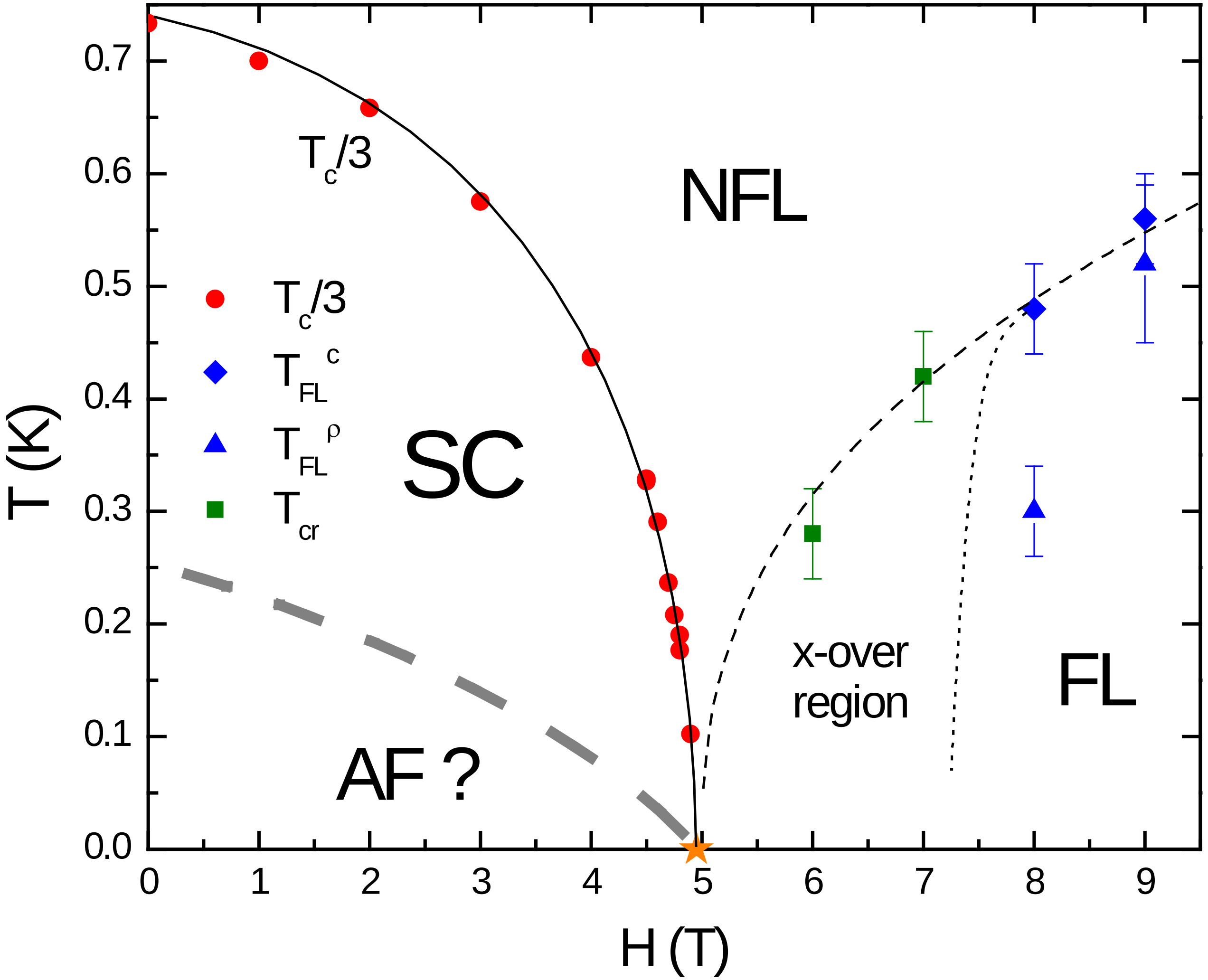
Resistivity

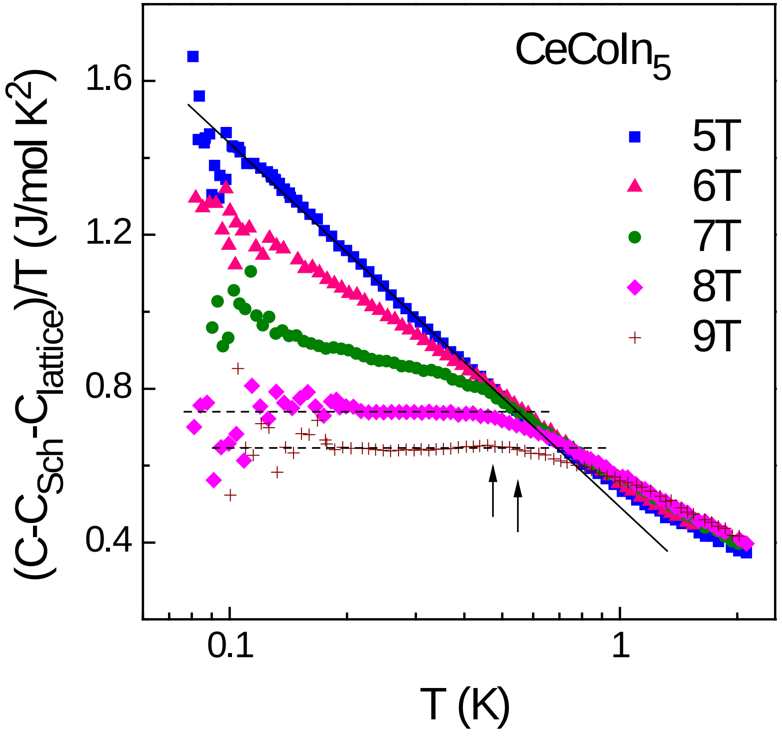
Fits of resistivity data with theory of spin-fluctuations near antiferromagnetic QCP (Moriya et al.) reproduce the overall shape of the data.

1. Single overall scale factor
2. Same values of the y_0 parameter as used for specific heat.
3. Fits miss the higher temperature resistance, perhaps due to variations in magnetic field



QCP in CeCoIn$_5$: Avoided AFM order scenario.

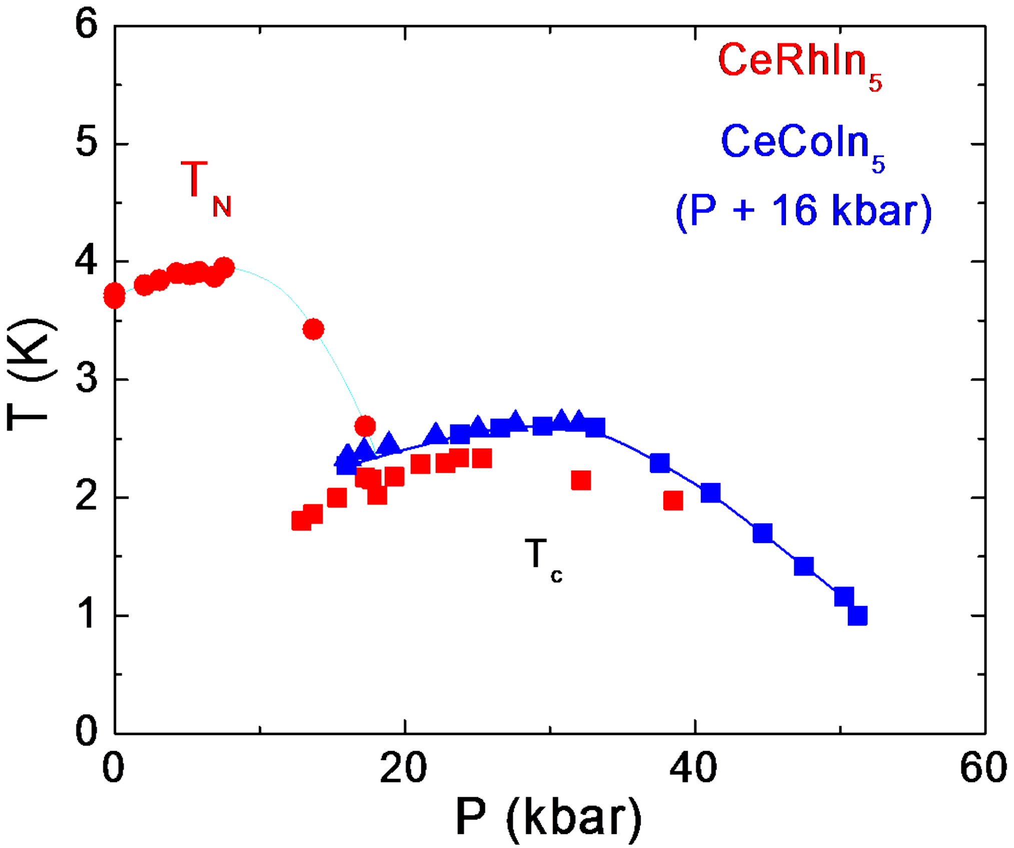




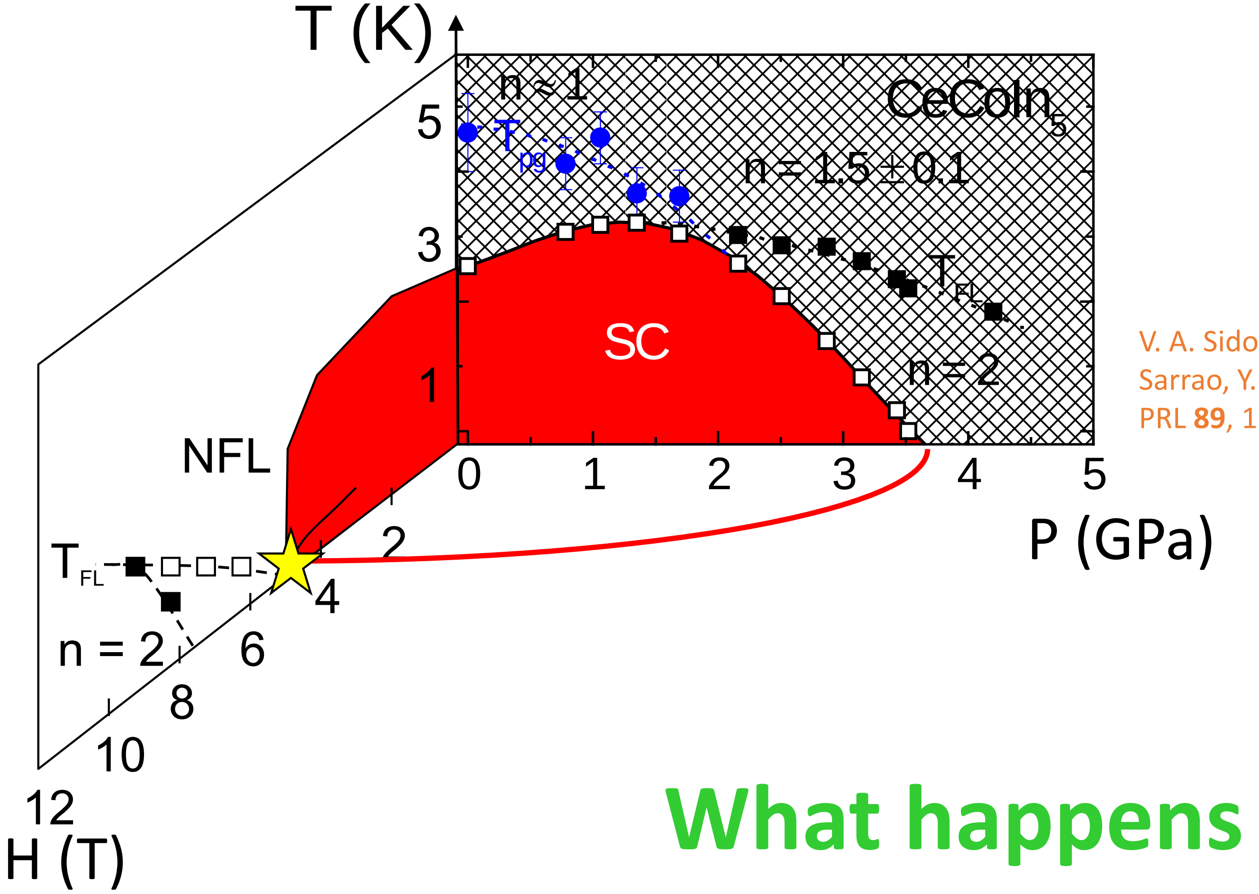
Postulated that the QCP (manifested itself via divergence in C/T at H_{c2}) is due to the underlying AFM transition in CeCoIn$_5$ that is superseded by SC. Need to suppress SC to reveal AFM ground state responsible for the QCP.

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

Additional evidence for AF origin of the QCP behavior: Superconductivity in $CeCoIn_5$ is very similar to that of the ambient pressure antiferromagnet $CeRhIn_5$.



M. Nicklas *et al. J. Phys. :Condens. Matter* **13,** L905 (2001);
V. A. Sidorov *et al.* "Superconductivity and Quantum Criticality in $CeCoIn_5$", *Phys. Rev. Lett.* **89**, 157004 (2002)



V. A. Sidorov, M. Nicklas, P. G. Pagliuso, J. L. Sarrao, Y. Bang, A. V. Balatsky, J. D. Thompson, PRL **89**, 157004 (2002).

What happens to H_{QCP} with pressure?

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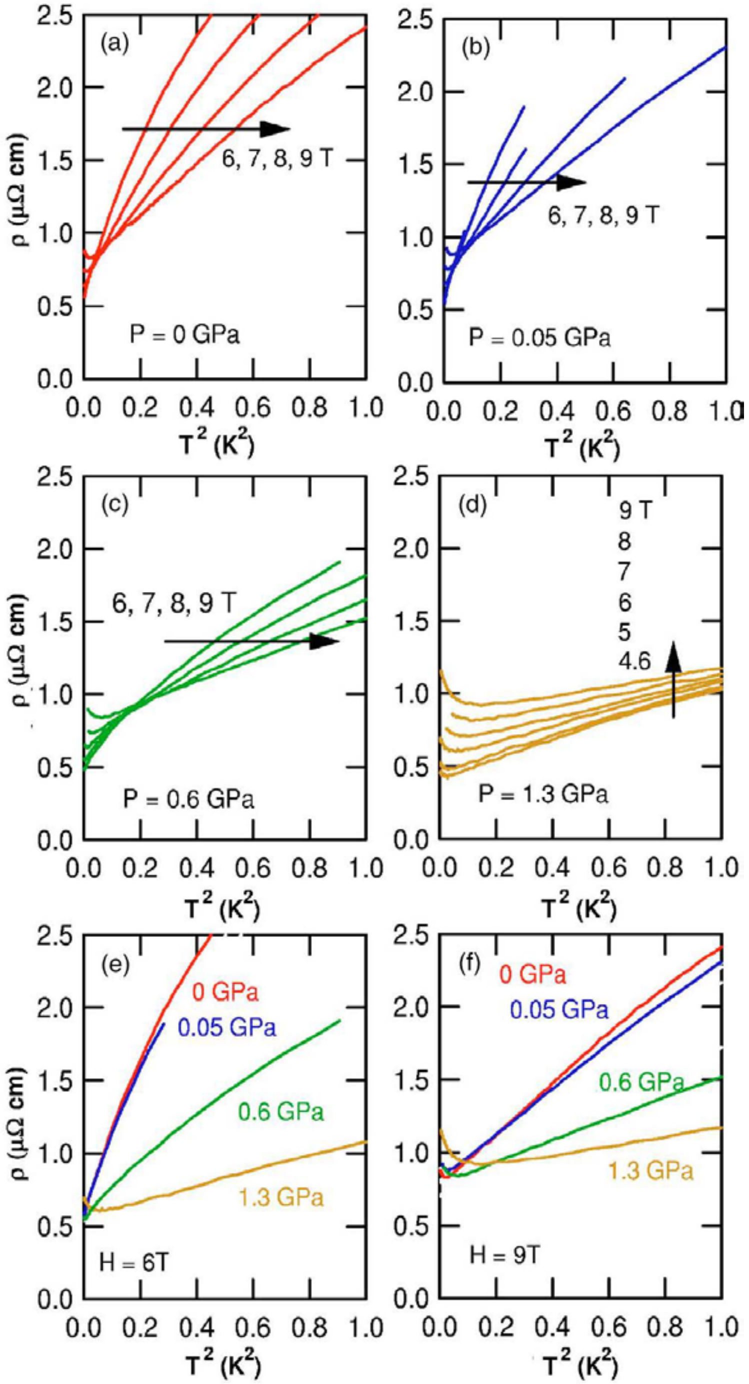
Resistivity under pressure and in magnetic field:

$\rho \propto \rho_0 + AT^2$

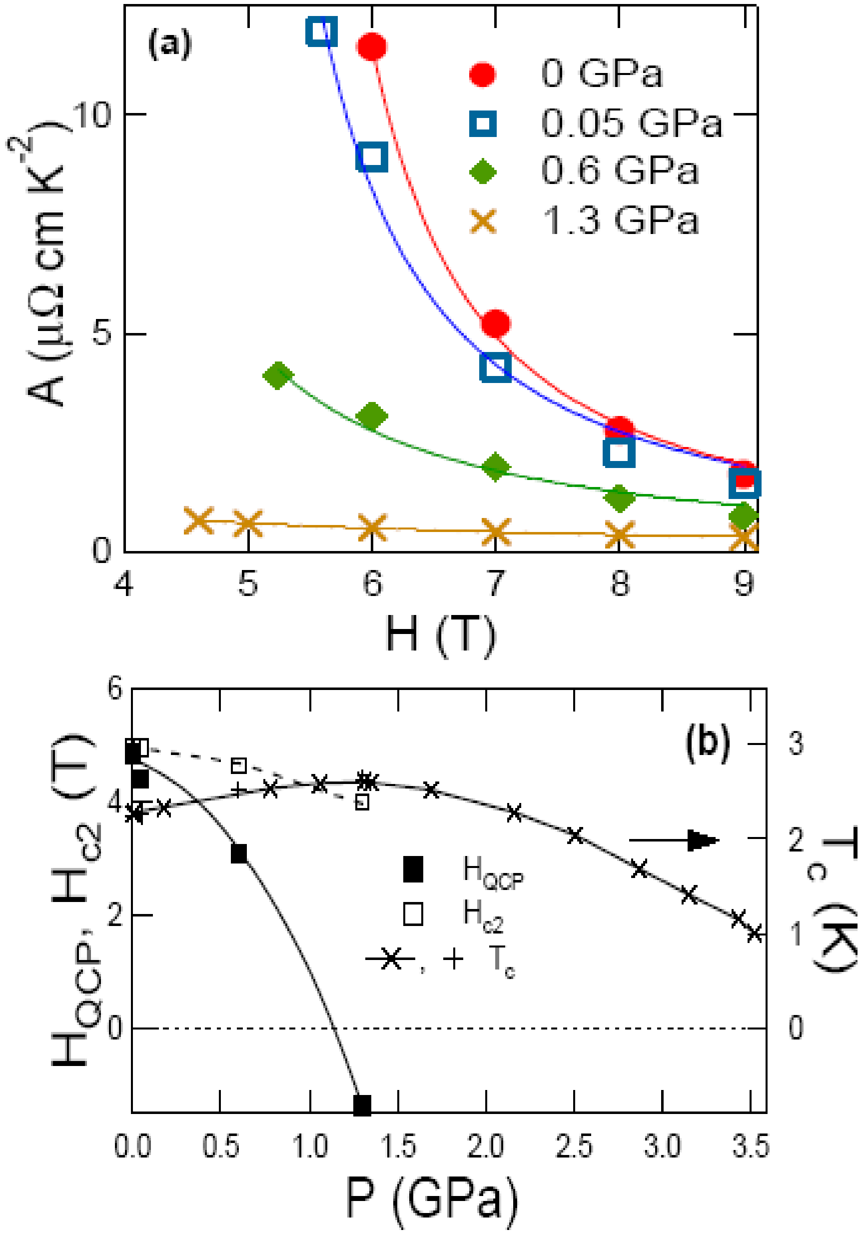
Pressure suppresses overall values of A. What does it do to its divergence? Does it move H_{QCP}?



F. Ronning, PRB **73**, 064519 (2006)

$$A = A_0\,(H - H_{QCP})^{\alpha}$$

$$\alpha = 1.37$$



F. Ronning, PRB **73**, 064519 (2006)

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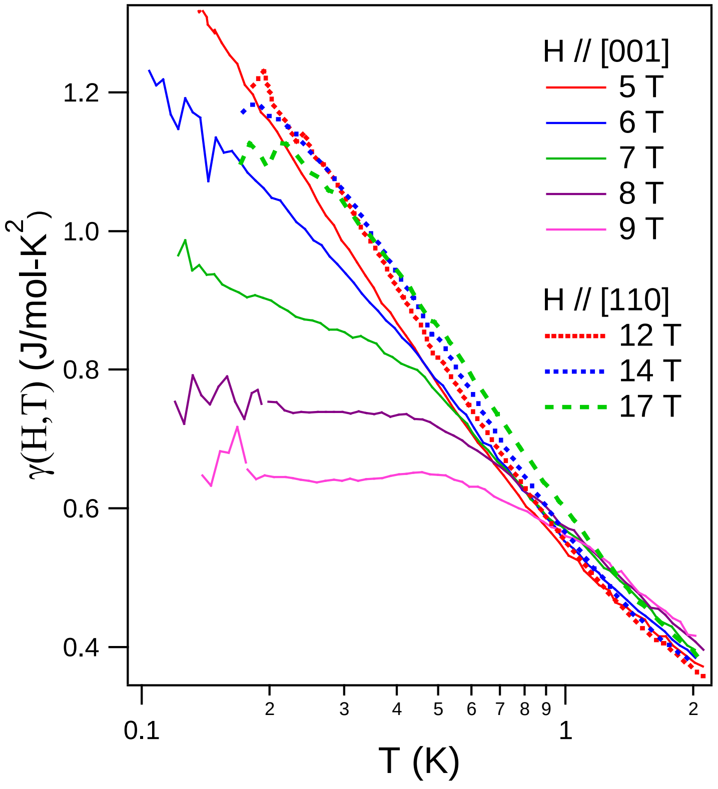
Phase Diagram of CeCo(In,Sn)$_5$

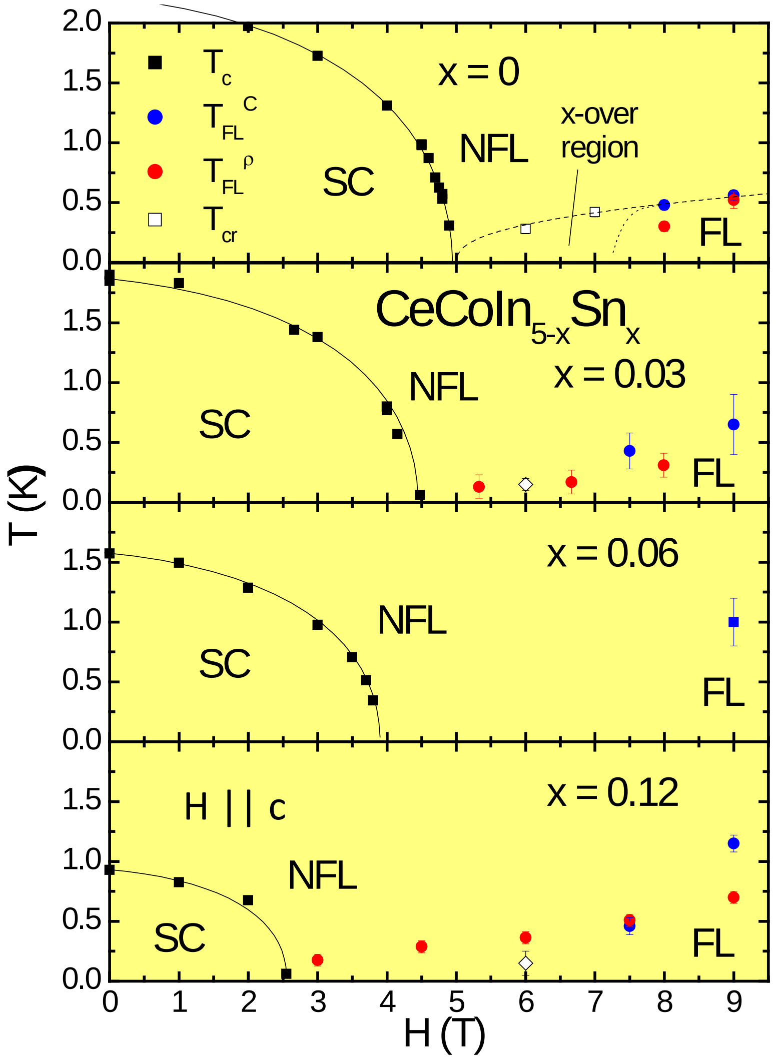


H // c

H_{c2} ~ 5T

H // ab

H_{c2} ~ 12T



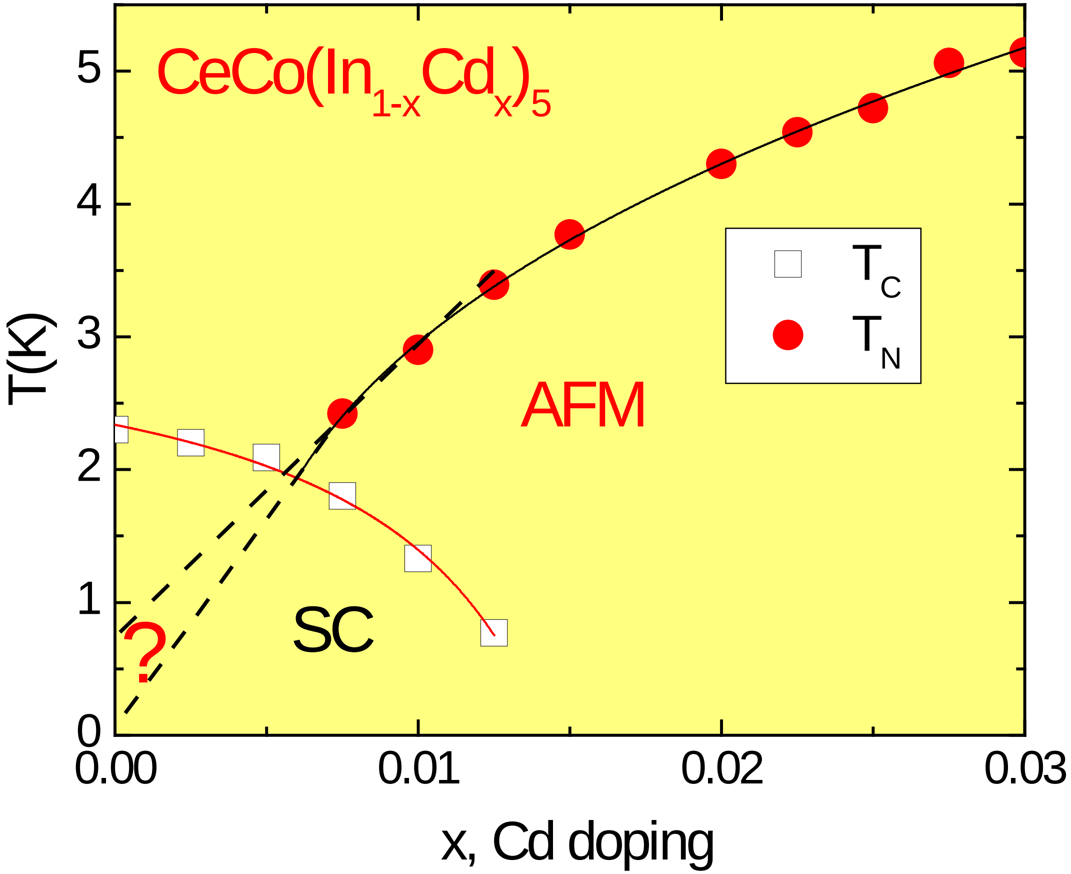
- **γ(H_{c2}) ∝ ln(T) implies a H_{QCP} ~ H_{c2} for both field orientation; also corroborated by resistivity.**
- **The anisotropy of the specific heat does not match the anisotropy of the critical fields.**

F. Ronning, *et al*, PRB.

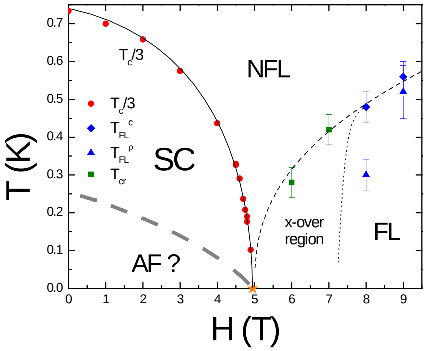
E.D. Bauer, *et al*, PRL **94**, 047001 (2005).

The Quantum Critical Point is tied to the superconducting H_{c2} with Sn doping and field orientation! Not likely a coincidence.

Doping studies of the QCP in CeCoIn$_5$



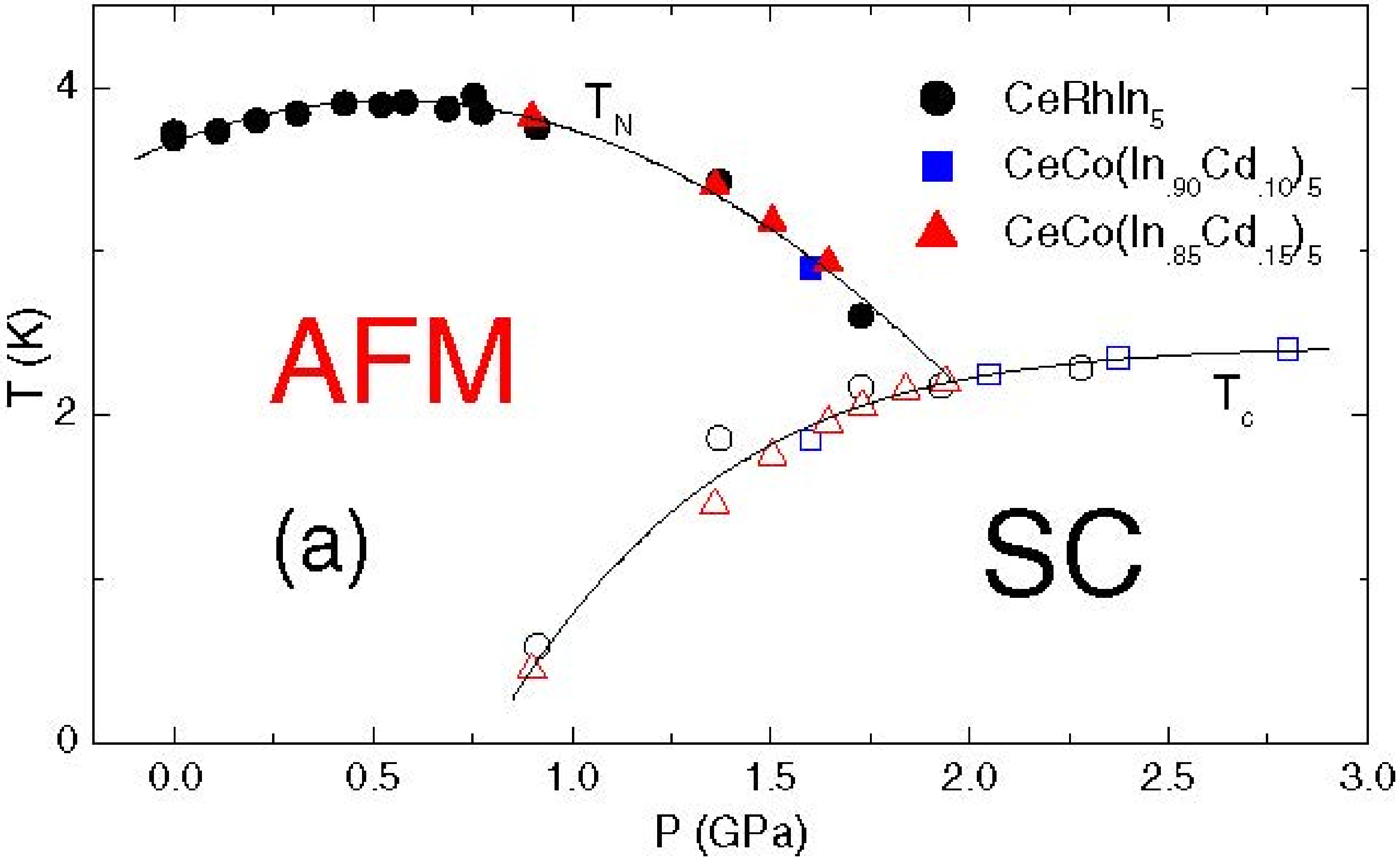
L. Pham *et al.*, PRL 97, 056404 (2006)



Small Cd doping indeed stabilizes an AFM state and suppresses SC state. Extrapolation of T_N to x = 0 may have positive T-axis intercept.

Q: Is there a possible connection between AFM and HFLT (FFLO?) state?

Effect of Cd doping is reversed with pressure, we use this fact to look for an answer.



Pressure dependence of the Neel T_N and superconducting transition temperature T_c for $CeRhIn_5$ (black circles) and $CeCoIn_{1-x}Cd_{x5}$ at nominal x 0.10 (blue squares) and 0.15 (red triangles). With $CeRhIn_5$ as the reference, a rigid shift of nominal x=0.15 data by 0.9 GPa and of nominal x=0.10 data by an additional 0.7 GPa (i.e., a total shift of 1.6 GPa relative to $CeRhIn_5$) superimposes all three sets of data.

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

•Cd doping appears to be a powerful tool in probing similarities and differences between $CeCoIn_5$ and $CeRhIn_{5.}$

• Small Cd doping does not appear to push $CeCoIn_5$ into the regime of field induced magnetic order, similar to $CeRhIn_5$.

Conclusions:

$CeCoIn_5$ is a d-wave superconductor in a clean limit.

There is a magnetically tuned QCP in $CeCoIn_5$ in the vicinity of $H_{c2} = 5$ T.
Evidence:

1. Scaling of specific heat with H/T^{β}
2. Spin-fluctuations near AF QCP theory of Moriya et al. explains with reasonable consistency both specific heat and resistivity.
3. Pressure studies separate H_{c2} and QCP $\Rightarrow$ QCP is not due to superconductivity
4. Cd doping stabilizes AFM phase, interpolation to Cd doing x=0 may lead to avoided AFM state.

$\Rightarrow$ The most likely origin of the QCP is an avoided AF order.