The Abdus Salam
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SMR.1766 - 3

Miniworkshop on
New States of Stable and Unstable Quantum Matter
(14 - 25 August 2006)

Possible FFLO inhomogeneous superconducting state in $CeCoIn_5$

Cigdem CAPAN
Louisiana State University
Department of Physics & Astronomy
202 Nicholson Hall
LA Baton Rouge, 70803-4001
U.S.A.

These are preliminary lecture notes, intended only for distribution to participants

"The human understanding is of its own nature prone to suppose the existence of more order and regularity in the world than it finds."
F.Bacon

Possible FFLO inhomogeneous superconducting state in $CeCoIn_5$

Cigdem CAPAN,
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Los Alamos NATIONAL LABORATORY

NHMFL FLORIDA STATE UNIVERSITY ★ UNIVERSITY of FLORIDA ★ LOS ALAMOS

Outline

1. Introduction to FFLO state,
2. The H-T phase diagram in $CeCoIn_5$
3. Experimental results suggesting an FFLO state in $CeCoIn_5$,
4. Perspective & Conclusion

Part 1:
Introduction to FFLO state

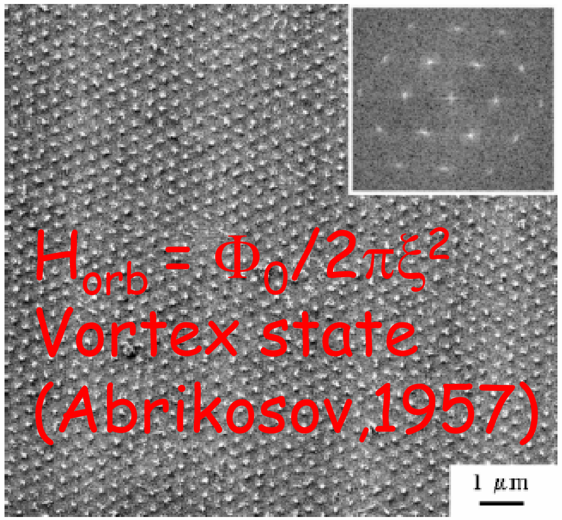
- What is FFLO state?
- Why is it inhomogeneous?

The superconducting state becomes inhomogeneous at high magnetic fields

Cooper pair $|\mathbf{k},\uparrow\rangle$ **ē** /\/\/\/\/\/\/\/\/\/\/ **ē** $|\mathbf{-k},\downarrow\rangle$

Pair breaking mechanisms at high magnetic fields:

"Orbital"



"Spin"

$H_P = \sqrt{2}\Delta/g.\mu_B$
A. Clogston, *PRL 9, 266 (1962)*

Superconductivity survives if:
- -spin triplet
- -FFLO

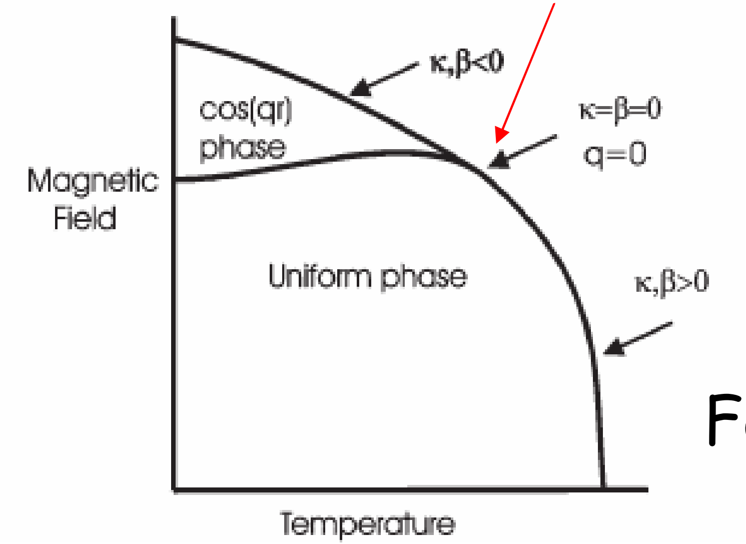
Fulde-Ferrell-Larkin-Ovchinnikov State

An inhomogeneous state is predicted in a spin-singlet superconductor when $g\mu_B H \geq \Delta$

A.I.Larkin & Y.N.Ovchinnikov, *JETP. 47, 1136 (1964)*

P.Fulde & R.A.Ferrell, *Phys. Rev. 135, A550 (1964)*

T*≈0.56Tc



Ginzburg-Landau free energy:

$$F = \alpha|\Delta|^2 + \beta|\Delta|^4 + \kappa|\nabla\Delta|^2 + \ldots + O(|\Delta|^6)$$

$\rightarrow$ non-uniform solution when $\kappa<0$

For s-wave, in clean limit: 1st order transition

A.I.Buzdin, H.Kachkachi *Phys. Lett. A 225, 341 (1997)*

D.F.Agterberg, K.Yang, *J. Phys.:Condens. Matt. 13, 9259 (2001)*

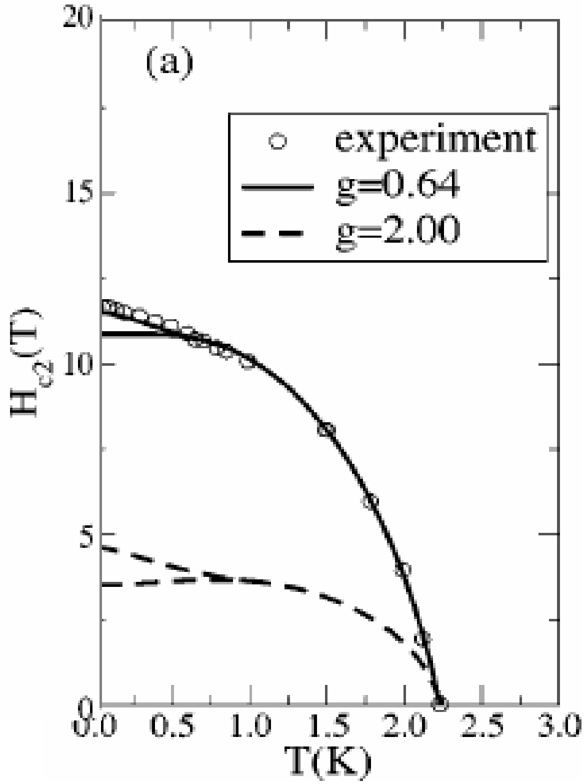
Maki Parameter: a useful criteria for the FFLO state

$$\alpha = \sqrt{2}\frac{H_{orb}}{H_P}$$

K.Maki, *Phys.Rev. 148, 362 (1966)*

FFLO state can exist if α > 1.8

Gruenberg & Gunther, *PRL 16, 996 (1966)*



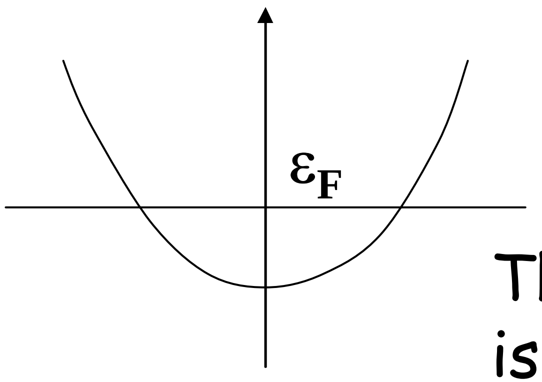
Estimated Maki Parameter for $CeCoIn_5$:

α=4.5	H $\perp$ c
3.6	H || c

Theoretical fit to H_{c2} shows that Pauli limiting is important for H$\perp$c only

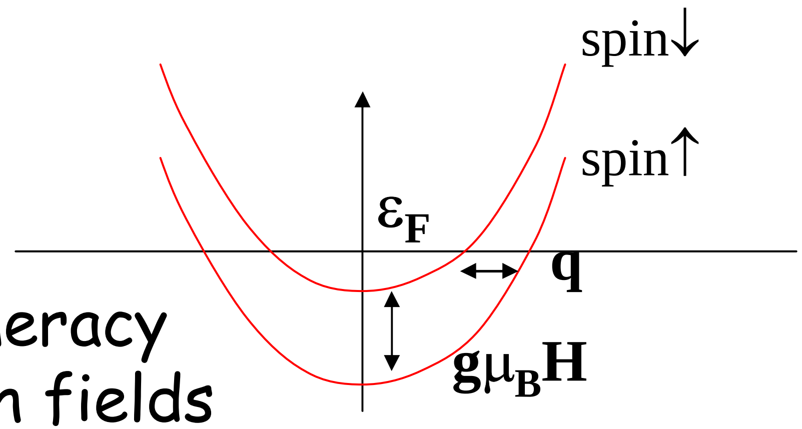
H.Won *et al. PRB 69, 180504 (2004)*

Origin of inhomogeneity in the FFLO state



H=0

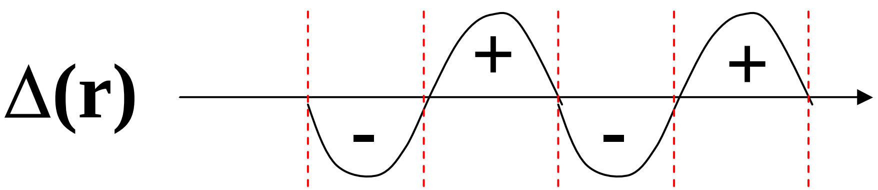
The spin degeneracy is lifted at high fields



H≠0

Cooper pairs acquire a finite momentum $\mathbf{q} \approx g\mu_B H/\hbar v_F$

H ⟶



$$\Delta(\mathbf{r}) = \Delta_0\, e^{i\mathbf{q}\cdot\mathbf{r}} \quad \text{(FF)}$$

$$\Delta(\mathbf{r}) = \Delta_0 \cos(\mathbf{q}\mathbf{r}) \quad \text{(LO)}$$

Nodal planes !

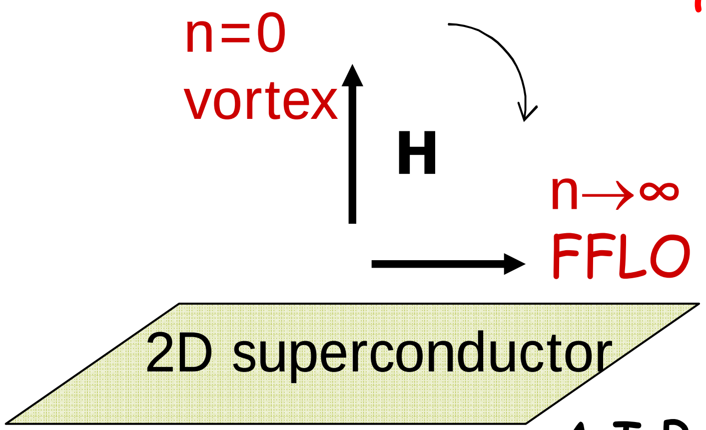
Structure of the vortex+FFLO state?

Take into account orbital effects:

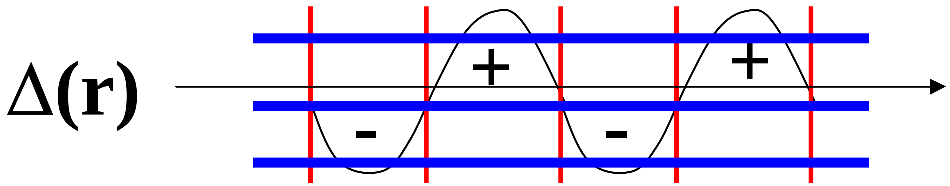
$\nabla\psi \rightarrow (\nabla - 2ieA/c)\psi$

$\Rightarrow$ minimize F with Landau level (LL) wavefunctions

Kinetic energy of the n^{th} LL: $|(2n+1)/\ell^2 - q^2|$



"modulated" vortex lattice in 3D (n=0, q≠0)



multiquanta vortices in 2D (n>0, q≠0)

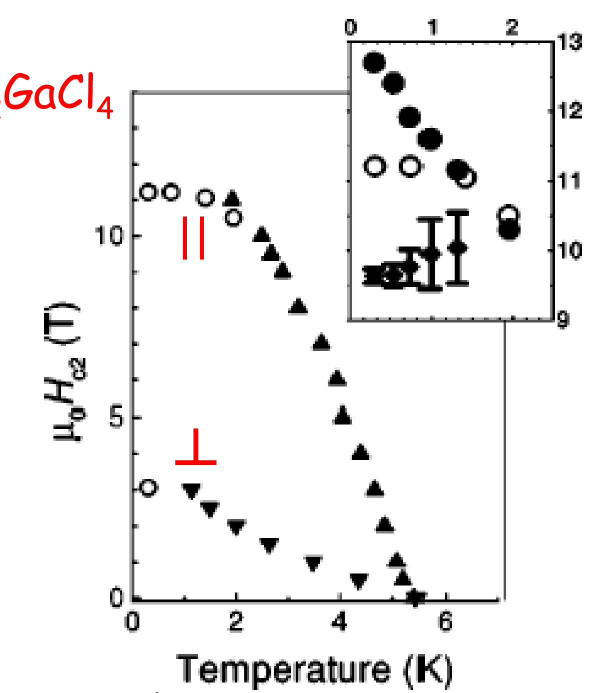
A.I.Buzdin, J.P.Brison *Phys. Lett. A 218, 359 (1996)*

Search for FFLO in unconventional superconductors

Pauli limit is rarely reached in conventional superconductors !

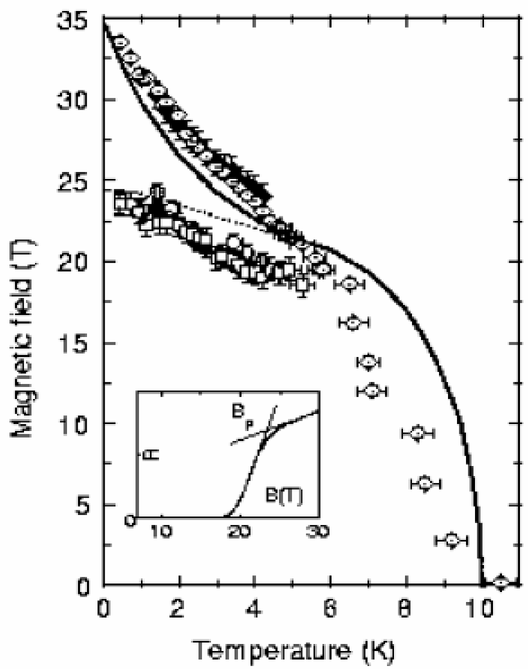
The low dimensionality + small coherence length in unconventional SC makes them potential candidates for FFLO

κ-$(BETS)_2GaCl_4$



M.A.Tanatar et al.,
Phys.Rev.B 66,134503 (2002)

κ-$(BEDT\text{-}TTF)_2Cu(NCS)_2$

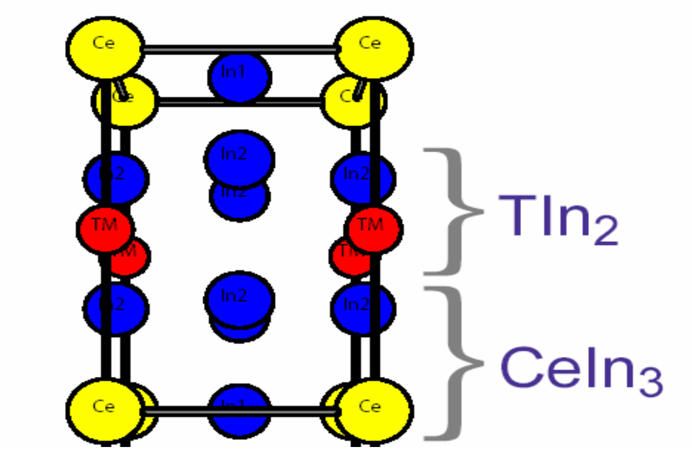


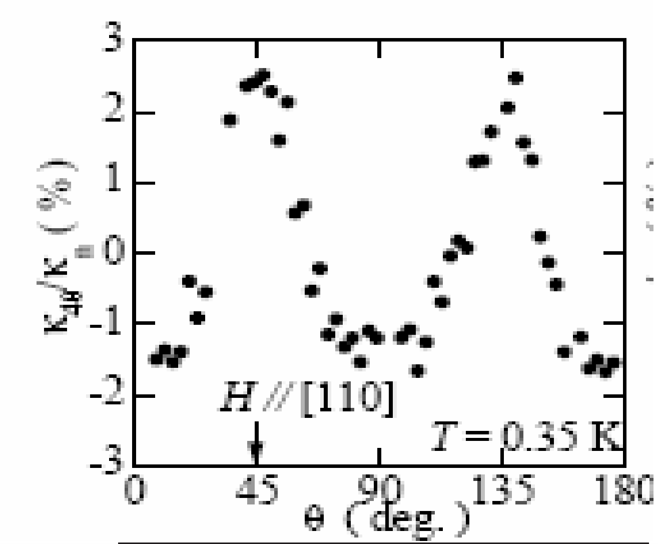
J.Singleton et al.,
J.Phys.:Condens.Matter 12, L641 (2000)

Part 2:
H-T phase diagram in $CeCoIn_5$

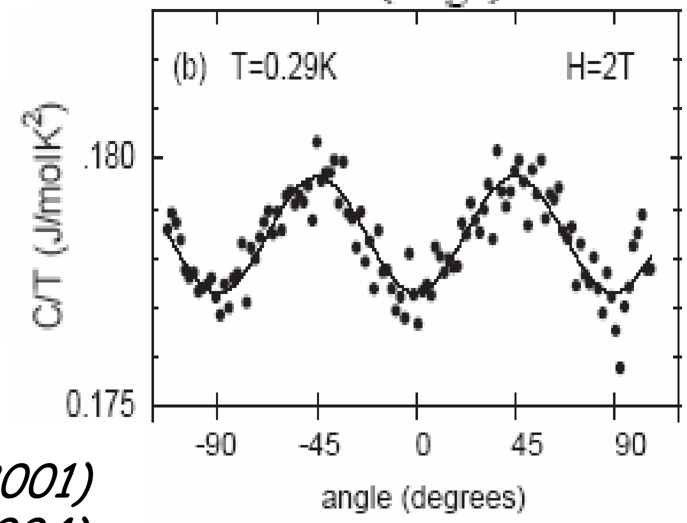
- Unconventional heavy fermion superconductivity in $CeCoIn_5$
- 1st order transition and the novel superconducting state at high fields
- Field-tuned quantum critical point near H_{c2}

$CeCoIn_5$: a heavy fermion superconductor





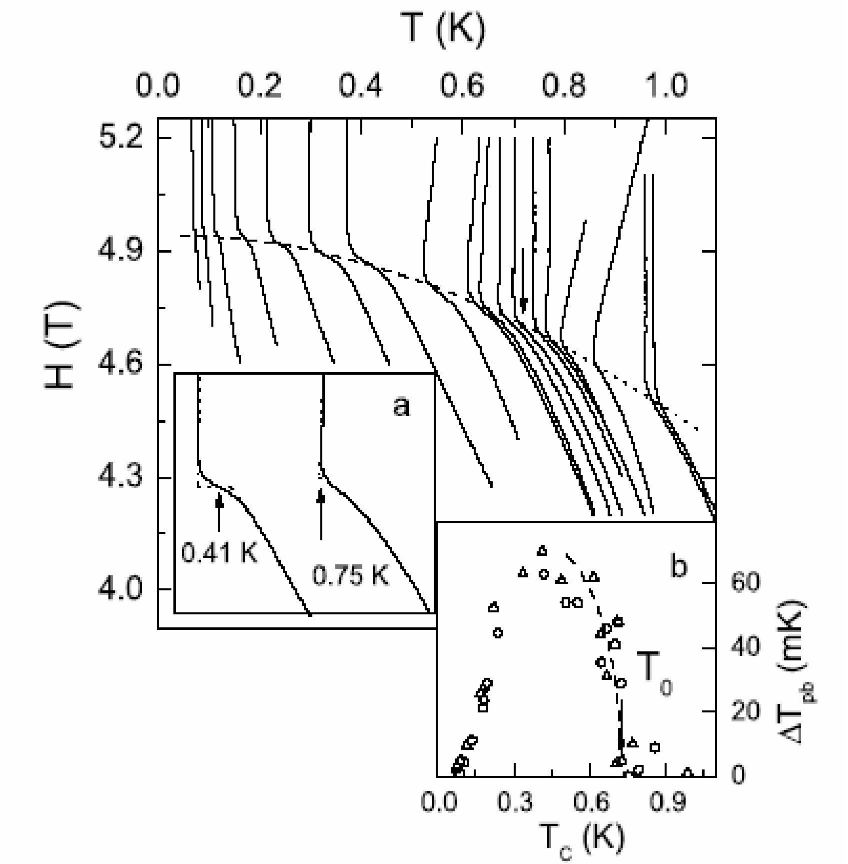
- Strong coupling ($\Delta C/C \approx 4.5\ k_BT_c$)
- Heavy fermion ($\gamma_0 \approx 0.3 JK^{-2}mol^{-1}$)
- clean limit ($\ell \geq 1\mu m$, $\rho_0 \leq 0.3\mu\Omega cm$)
- quasi-2D Fermi surface sheets
- d_{x2-y2} symmetry



K.Izawa et al., *Phys. Rev. Lett. 87, 057002 (2001)*
H.Aoki et al., *J.Phys:Condens.Matt 16, L13 (2004)*

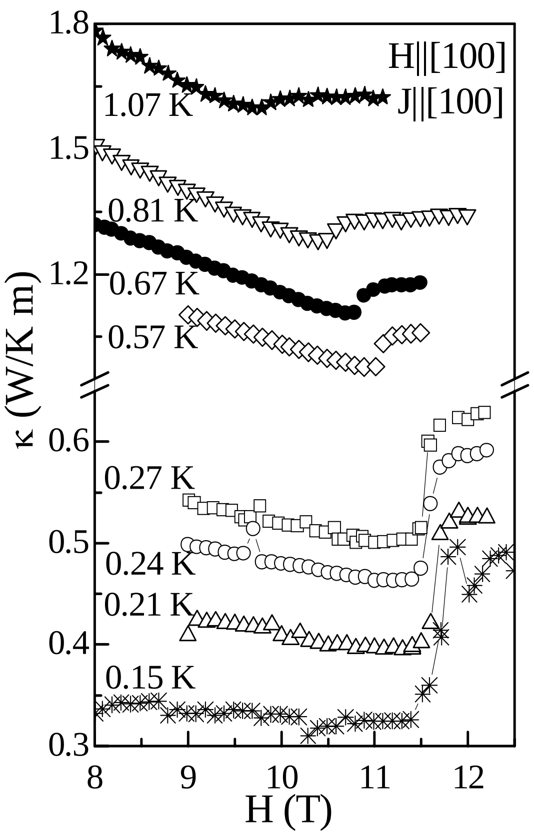
Step-like change at the superconducting transition

1. Magnetocaloric effect:

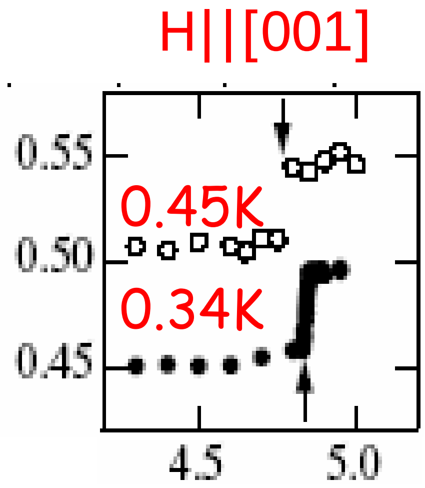


A.Bianchi et al. PRL 89, 137002 (2002)

2. Thermal conductivity:



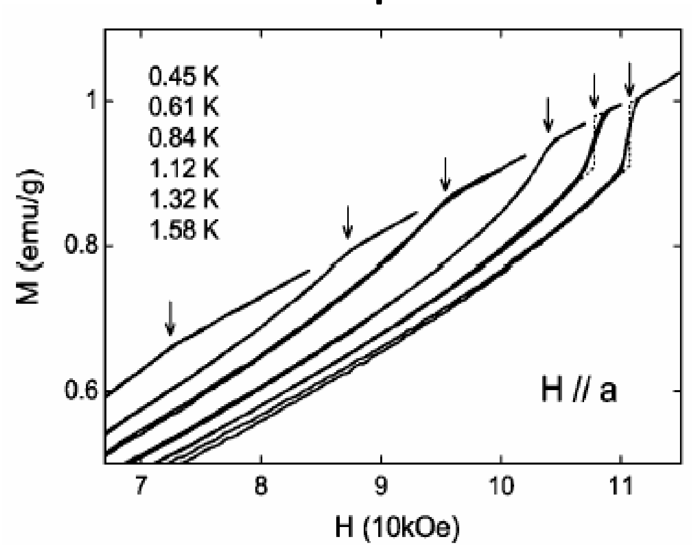
C.Capan et al. PRB 70, 134513 (2004)

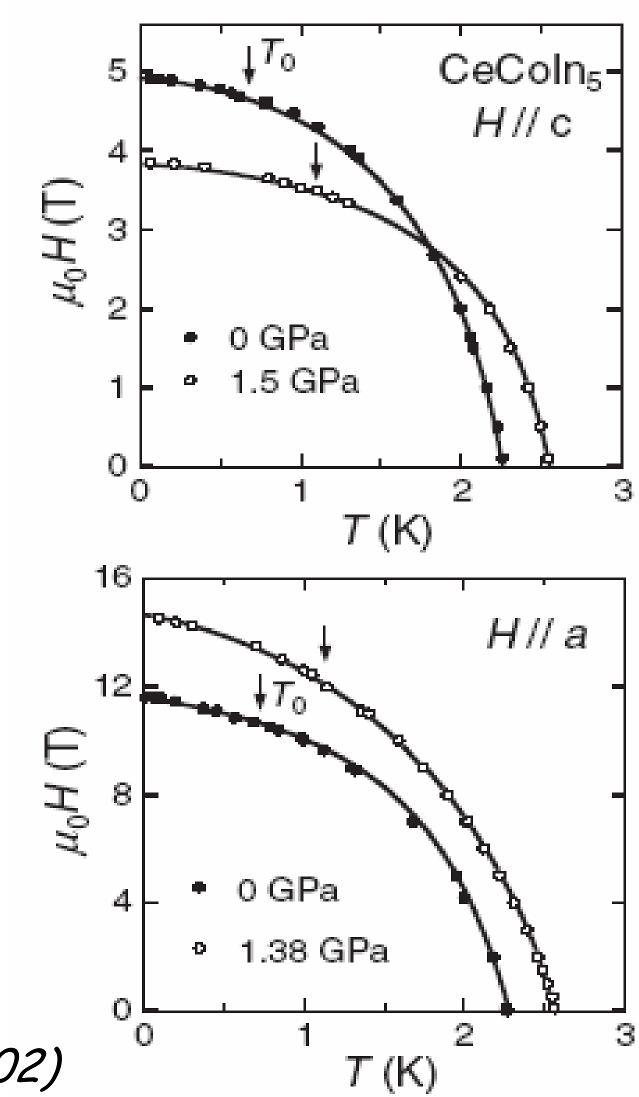


K.Izawa *et al.*
PRL 87,057002 (2001)

First order superconducting transition in $CeCoIn_5$

- Observed for both H || [100] ($T<T_0\approx1K$) and H || [001] ($T<T_0\approx0.7K$)
- 1st order transition persists and T_0 increases under pressure



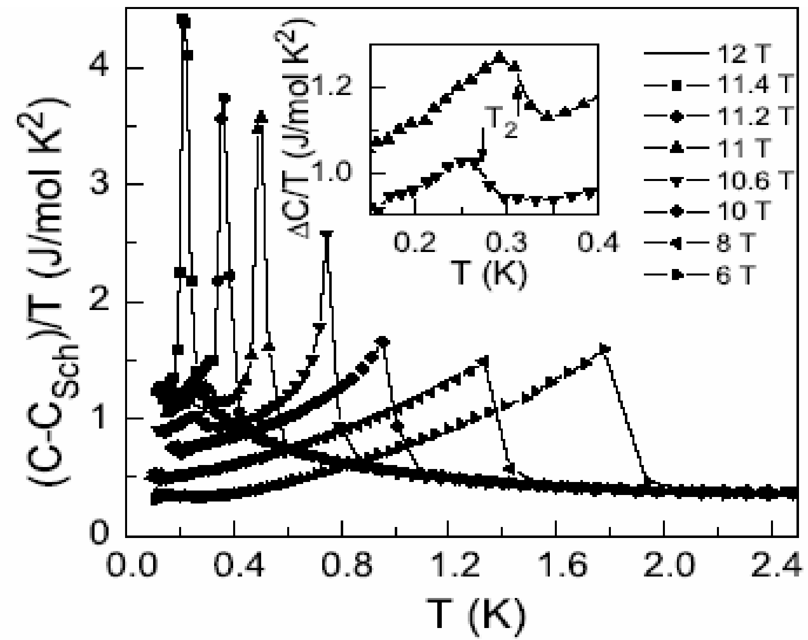


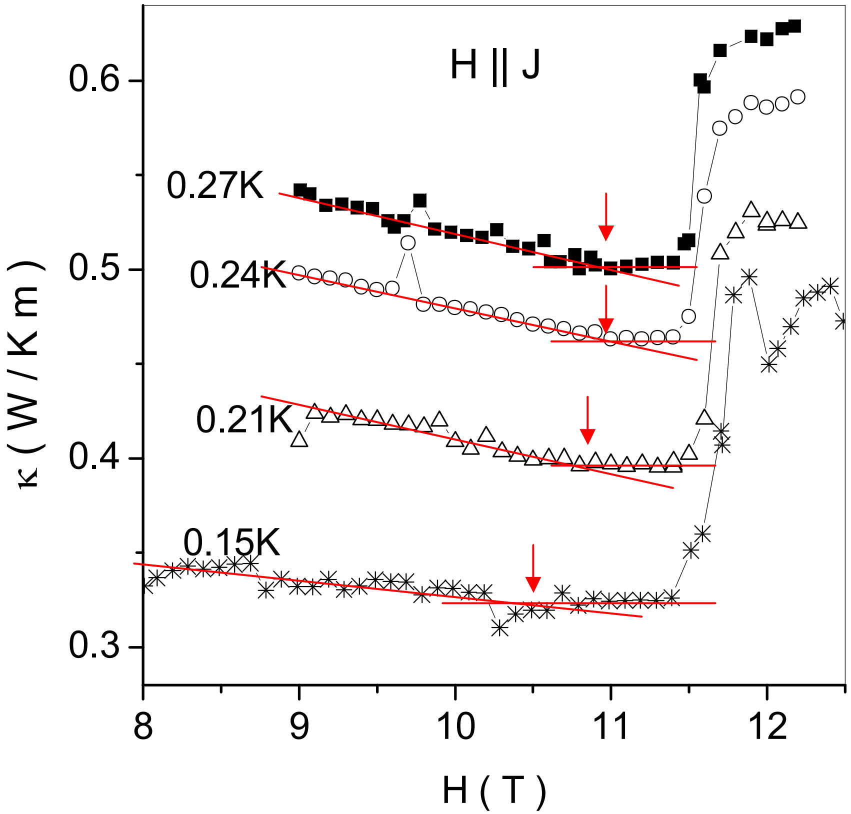
T.Tayama *et al. PRB 65, 180405 (2002)*
T.Tayama *et al. JPSJ 74, 1115 (2005)*
See also T.P.Murphy et al. PRB 65, 100514 (2002)

Novel superconducting state at high fields

Additional transition line within the superconducting state:

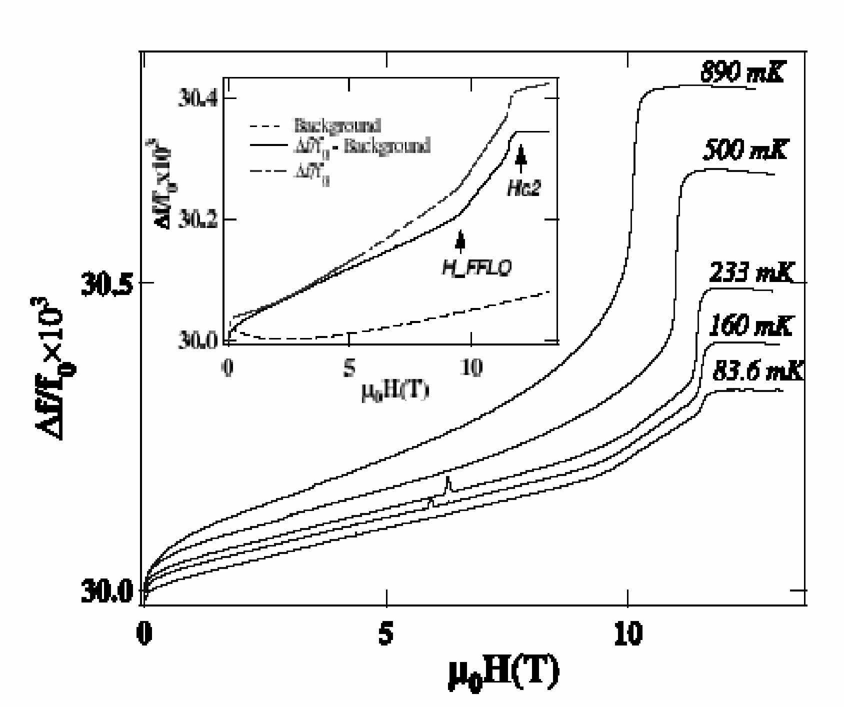
- Second anomaly in specific heat
- Kink in thermal conductivity κ(H)

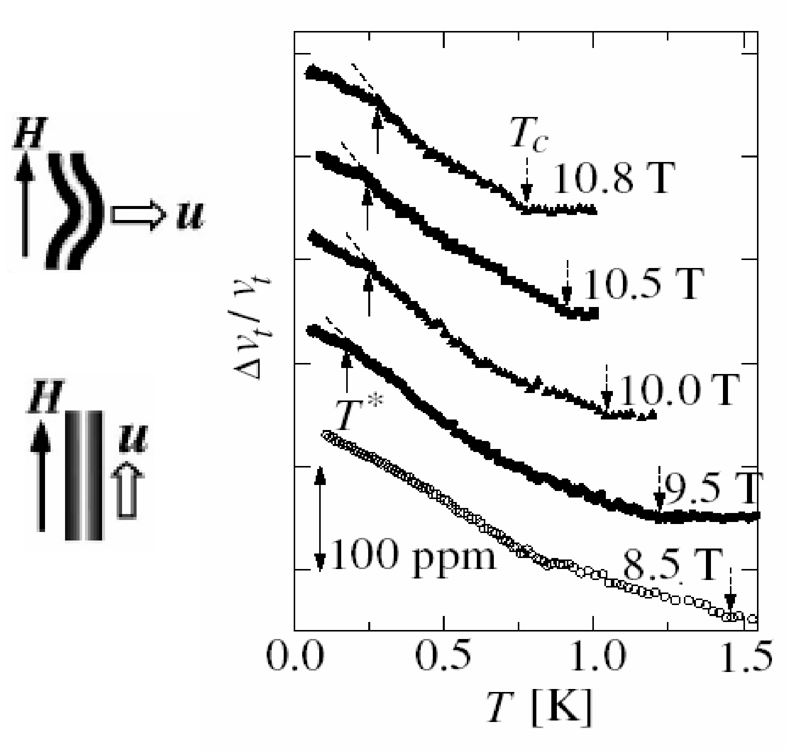




A.Bianchi et al. PRL 91, 187004 (2003)
C.Capan et al. PRB 70, 134513 (2004)
See also H.A.Radovan et al. Nature 425, 51 (2003)

The second transition is also observed with various other techniques





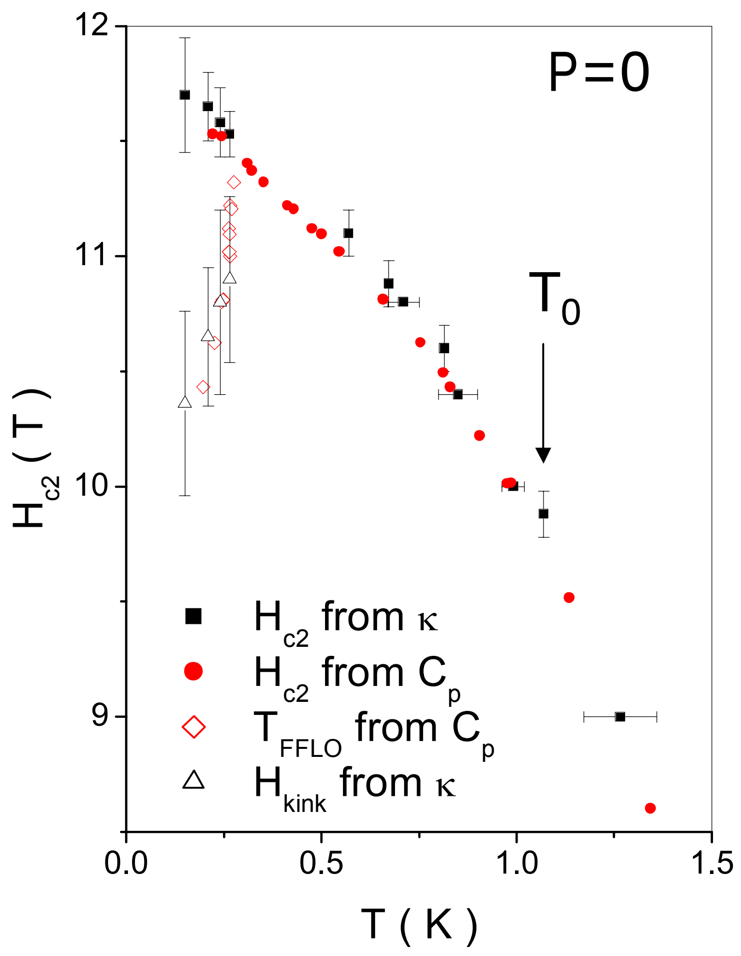
Kink in the penetration depth λ (=inverse superfluid density)

C.Martin *et al. PRB 71, 020503 (2005)*

Kink in the ultrasound attenuation (transverse sound velocity)

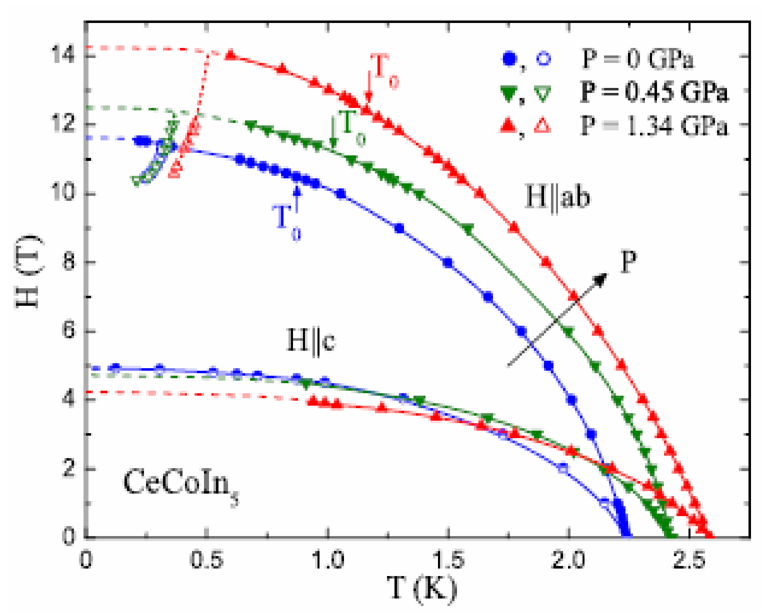
T.Watanabe *et al. PRB 70, 020506 (2004)*

H-T phase diagram of $CeCoIn_5$



→ Consistent with a mean field phase diagram obtained in a GL model of a 2D d-wave superconductor

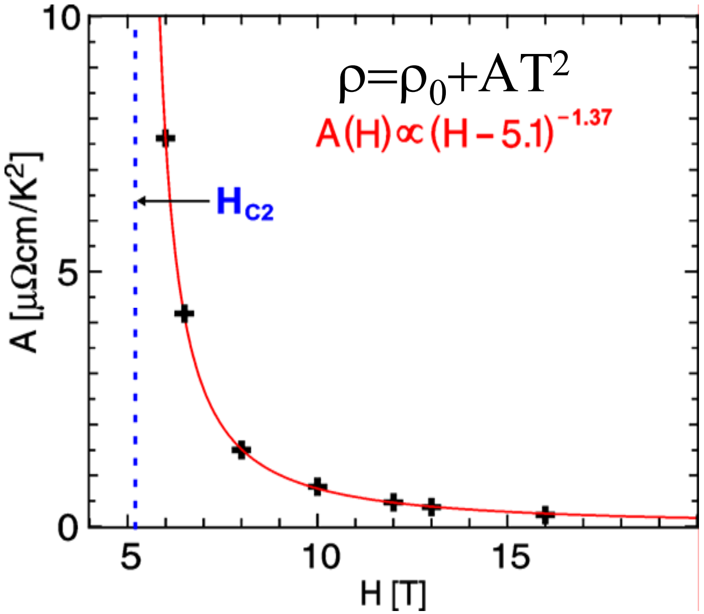
R.Ikeda et al. *PRB 68, 184510 (2003)*



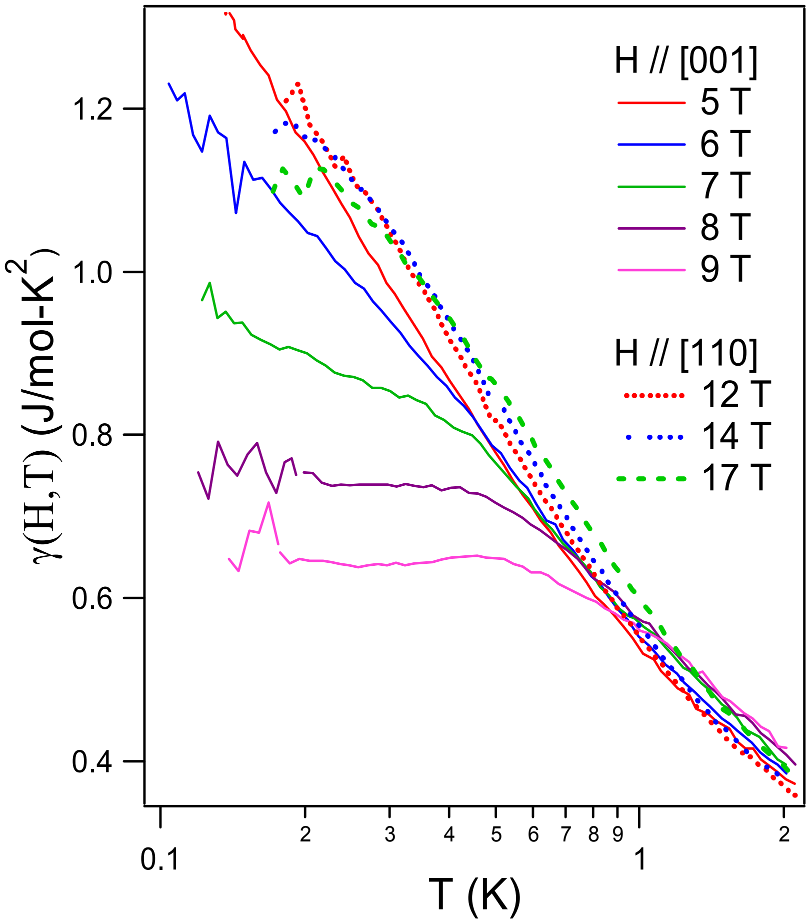
C.F.Miclea et al. *PRL 96, 117001 (2006)*

Field tuned quantum critical point in $CeCoIn_5$

Strong deviation from Fermi Liquid behavior in resistivity and specific heat close to H_{c2}

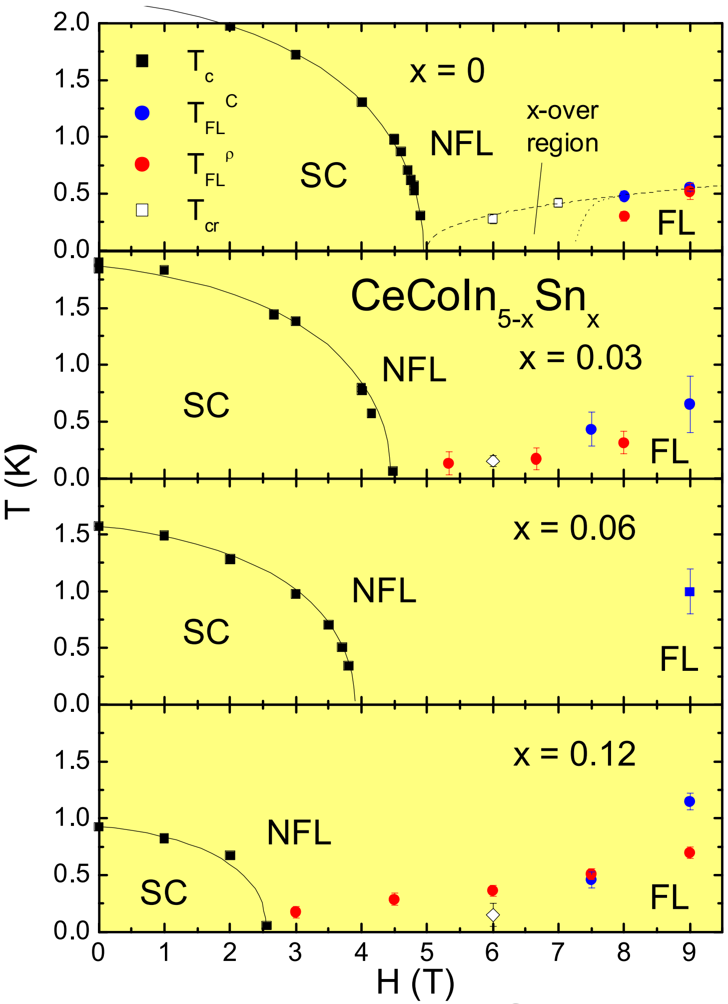


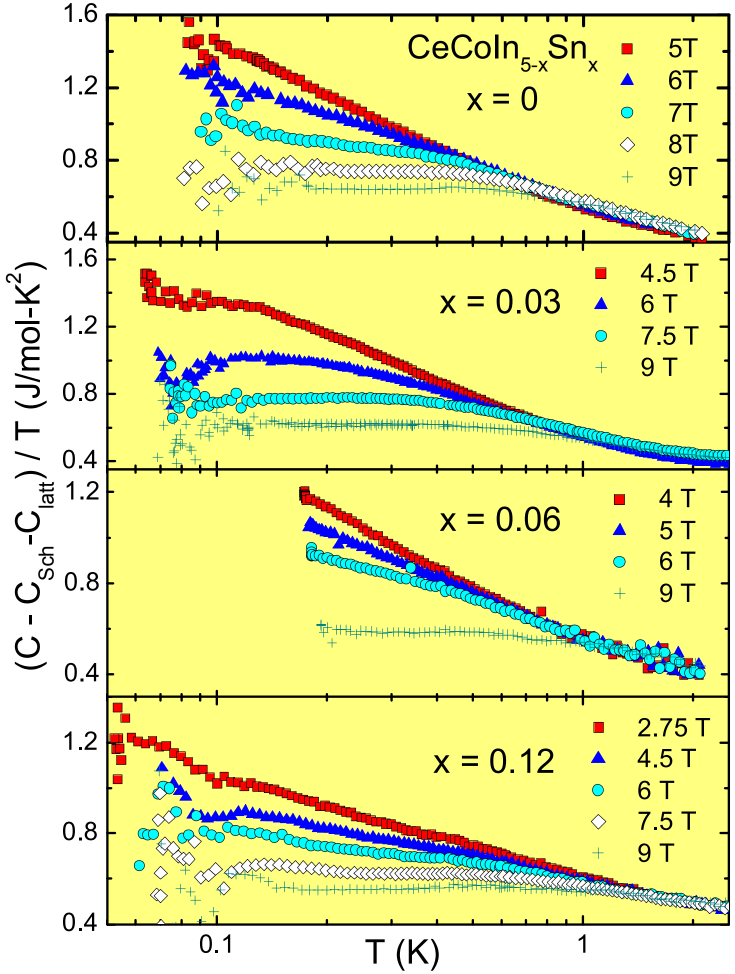
J. Paglione *et al*,
PRL 91, 246405 (2003)



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

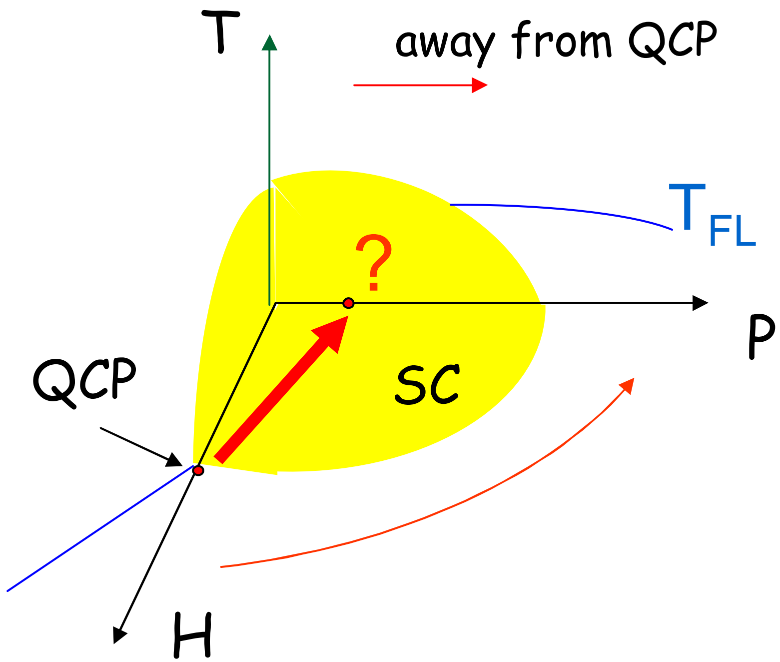
QCP coincides with H_{c2} in $CeCo(In,Sn)_5$

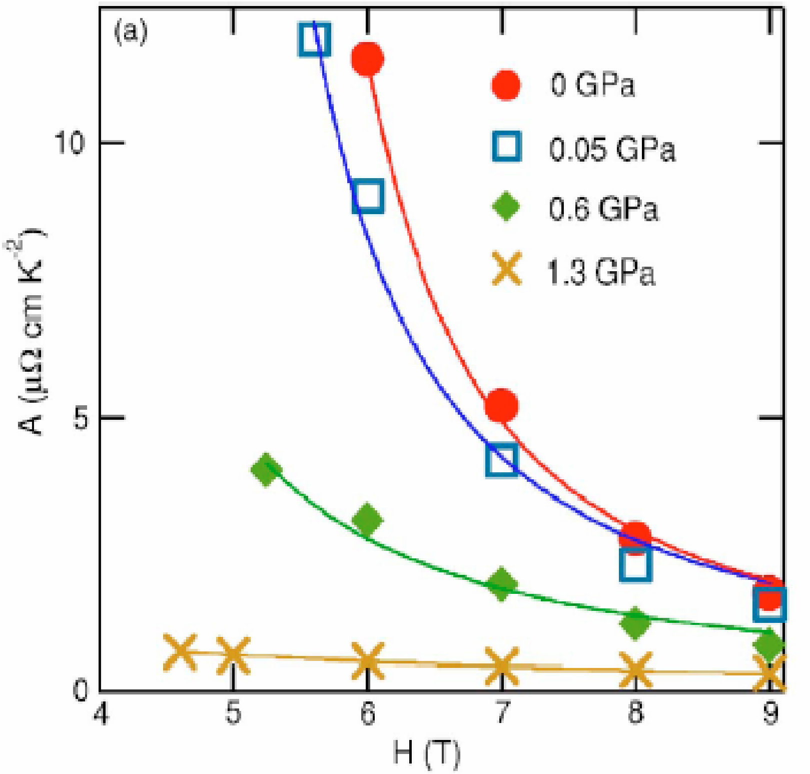




E.D.Bauer *et al. PRL 94, 047001 (2005)*

The quantum critical behavior is suppressed with pressure





With increasing pressure, H_{QCP} is suppressed much faster than H_{c2}

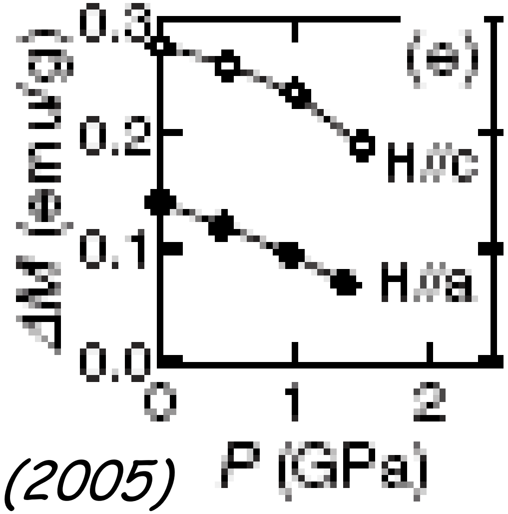
⇒ The origin of QCP in $CeCoIn_5$ is not superconductivity

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

Is there a connection between the QCP and the novel high field state?

- The origin of QCP is unlikely related to the FFLO state !

(see pressure + Sn-doping results)



- Effect of strong AF spin fluctuations:

-On the 1st order transition?

-On vortex cores?

-On nodal planes?

T.Tayama *et al. JPSJ 74, 1115 (2005)*

- Enhanced X_{spin} leads to a reduced phase space available for FFLO

A.B.Vorontsov, M.J.Graf *cond-mat/0606572*

$\rightarrow$ consistent with the observed pressure dependence of T_{FFLO}

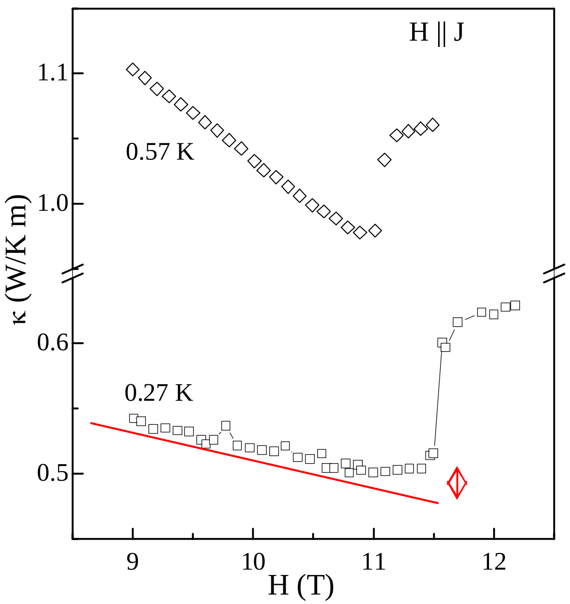
Part 3:
Existing evidence for FFLO in $CeCoIn_5$

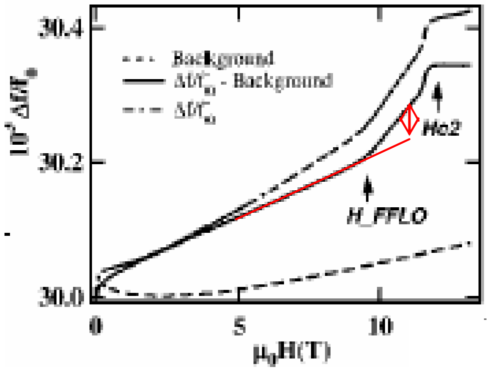
- Enhanced QP density in the high field state
- Probing the nodal planes with the anisotropy of thermal conductivity

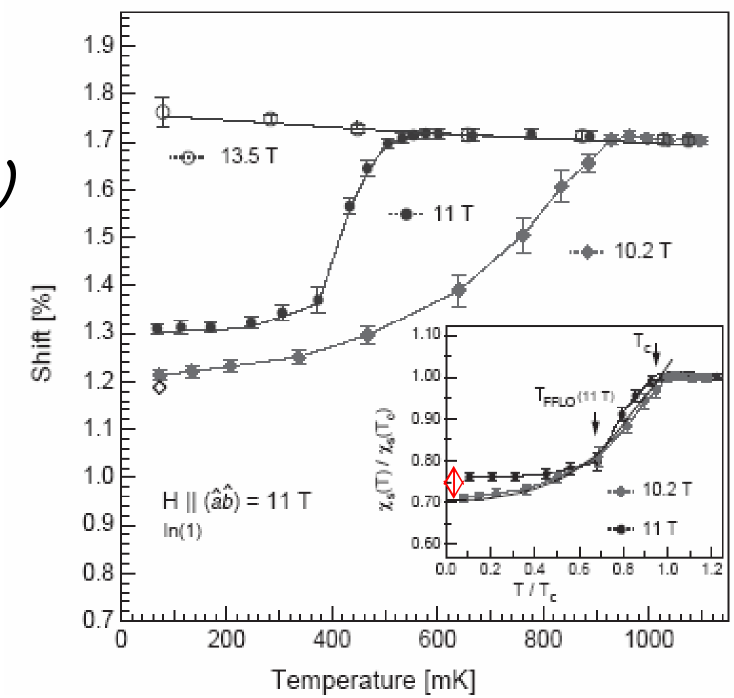
Enhanced QP density in the high field state:

✓Superfluid density decreases faster
C.Martin *et al. PRB 71, 020503 (2005)*

✓Thermal conductivity is enhanced
C.Capan *et al. PRB 71, 020503 (2005)*

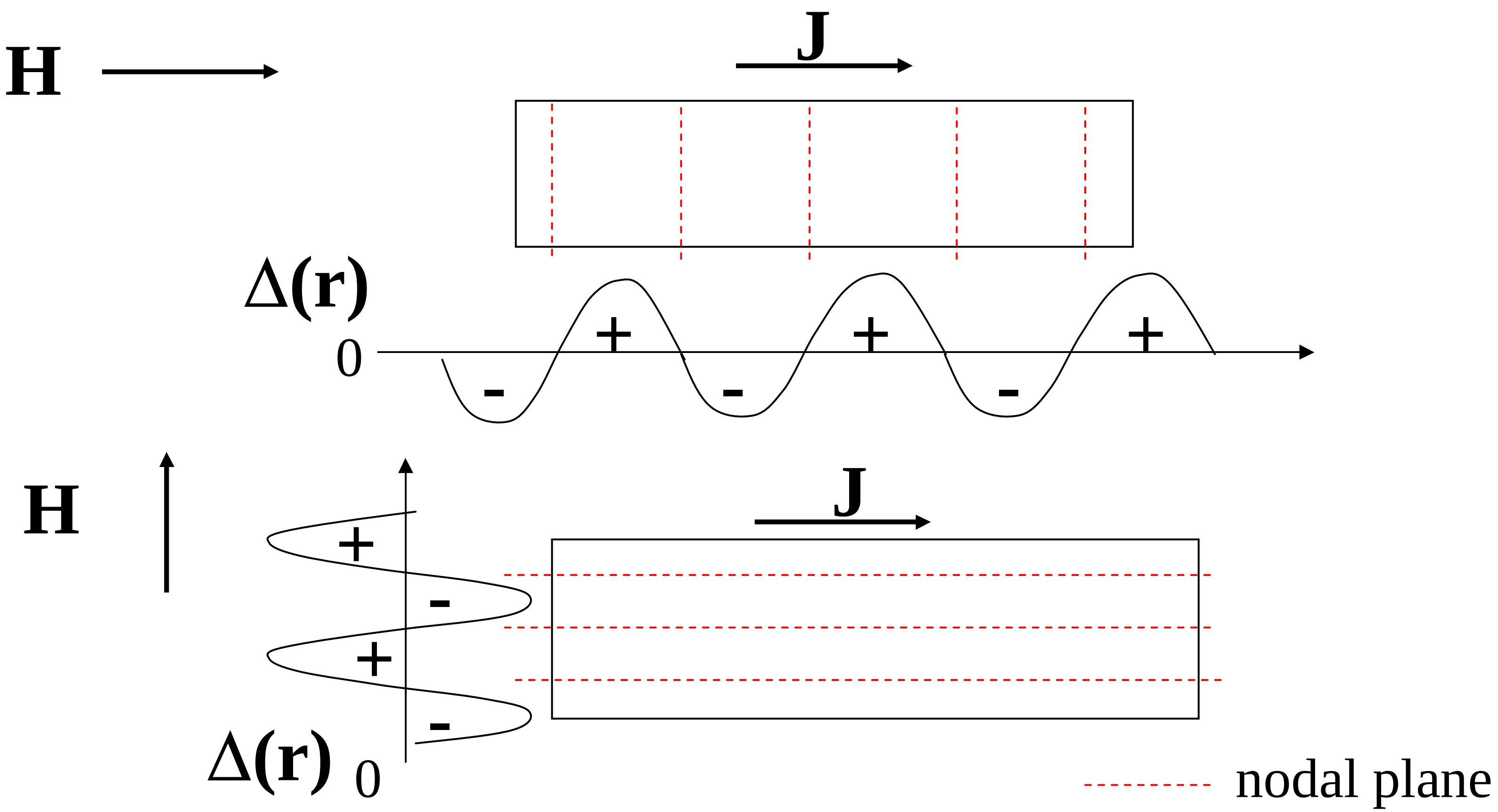






✓X_{spin} is enhanced
V.Mitrovic *et al. cond-mat/0605305*

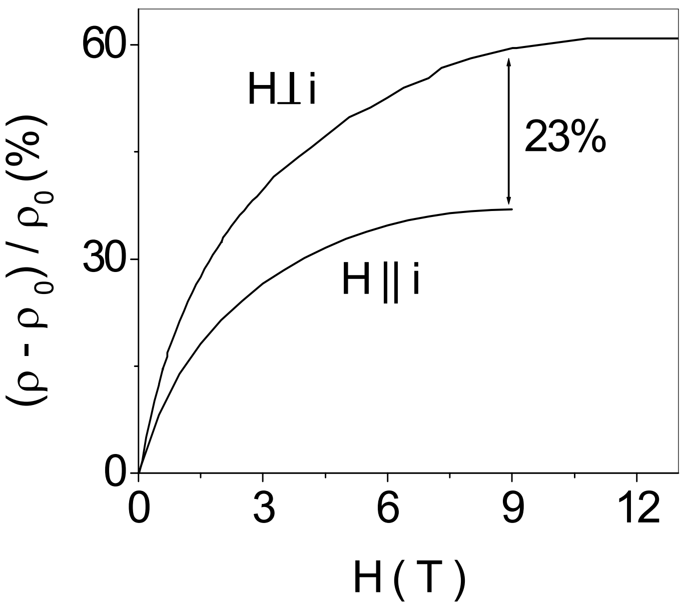
Probing the nodal planes with thermal conductivity



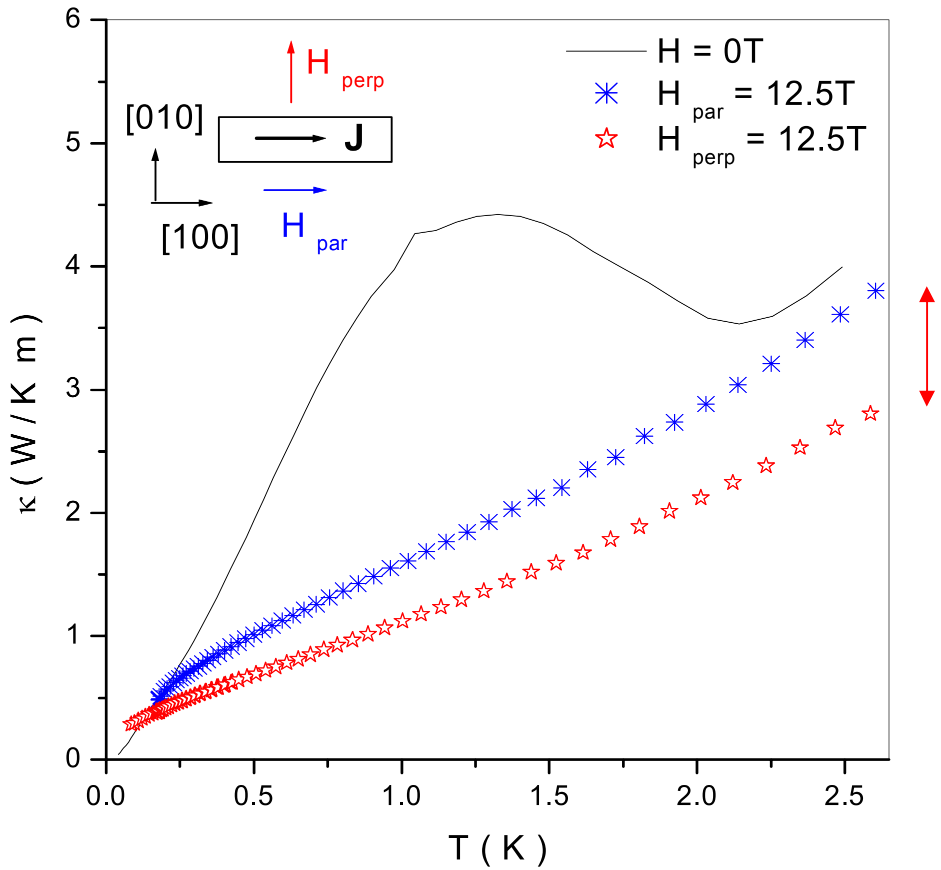
One would expect an enhanced QP density for H⊥J ⇒

$\kappa_{H\perp J} > \kappa_{H||J}$

The anisotropy of κ in the normal state is well understood:



Magnetoresistance at T=2.5K



The anisotropy of thermal conductivity in the normal state is due to the Lorentz force on electrons.

The anisotropy of κ in the mixed state is opposite to what we expected for nodal planes:

We expected:

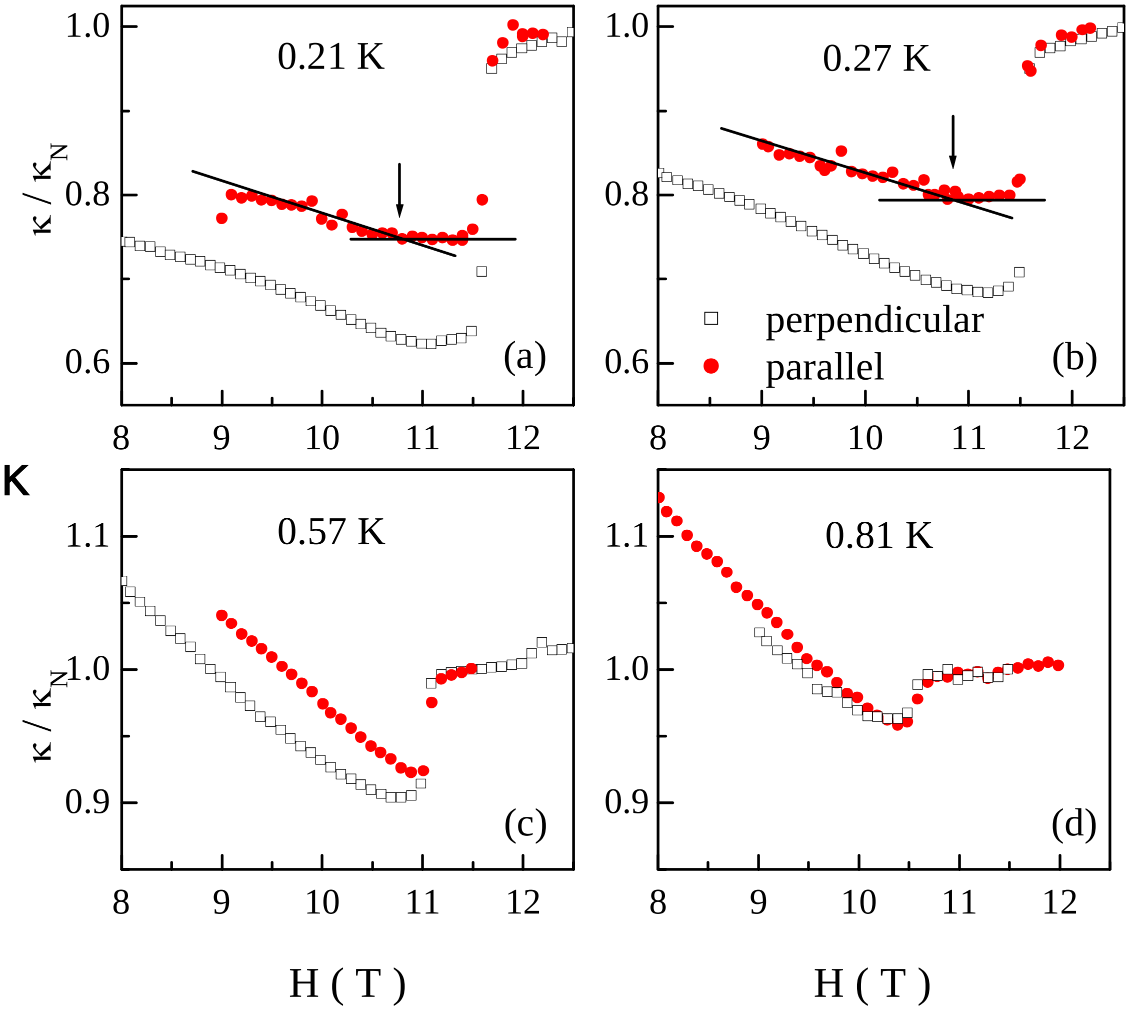
$\kappa_{H\perp J} > \kappa_{H||J}$

We observe:

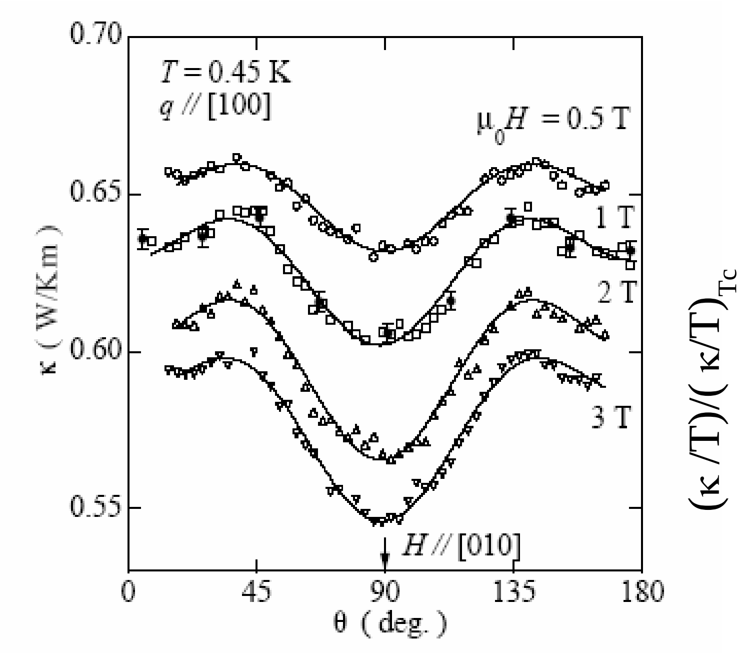
$\kappa_{H\perp J} < \kappa_{H||J}$

Close to H_{c2}, the anisotropy of κ should be small since vortices overlap strongly.

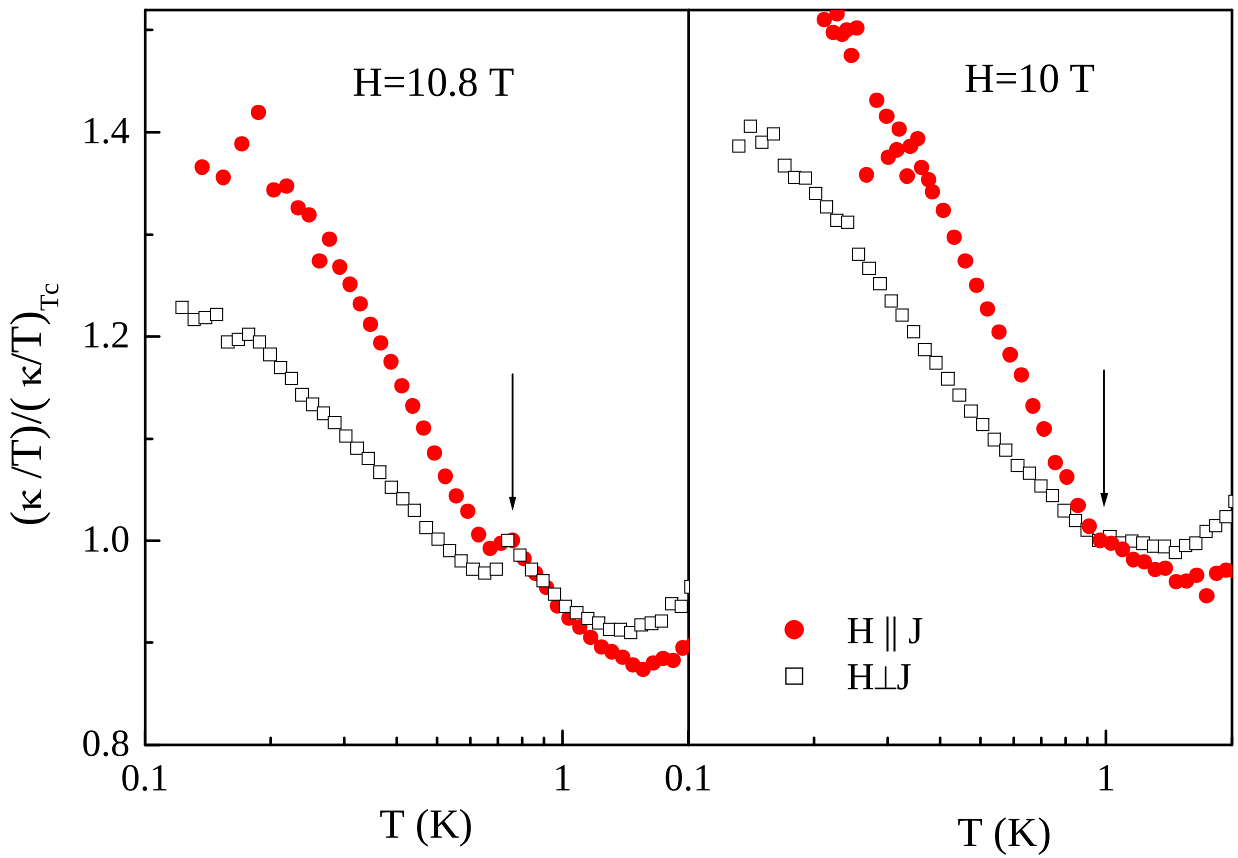
In $CeCoIn_5$, we found a large anisotropy at low temperatures!



The anisotropy of κ in the mixed state increases upon cooling:

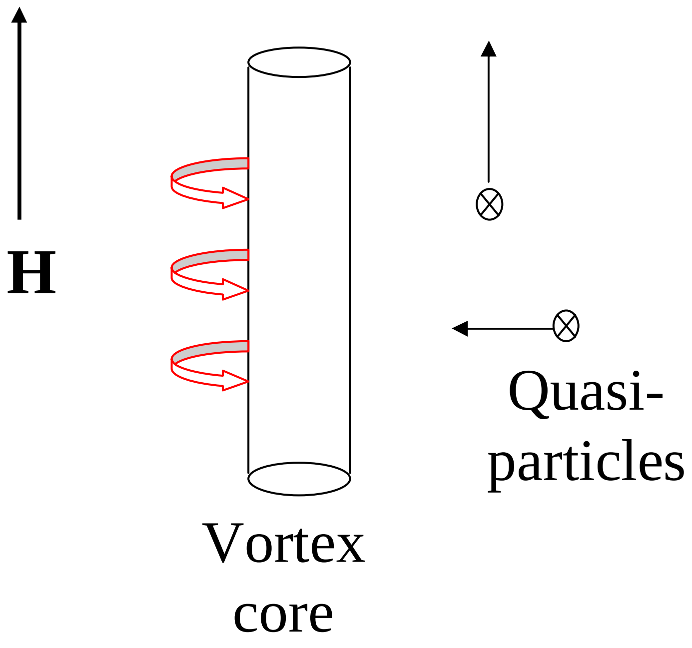


K.Izawa et al.,
PRL 87, 057002 (2001)



- κ/T is reminiscent of C/T divergence close to H_{c2},
- Sign of anisotropy consistent with previous report at lower fields.

Expected anisotropy of κ in the mixed state:



•**At low temperature:**
Larger density of quasiparticles excited for H⊥v (Volovik effect)

$\kappa_{H\perp J} > \kappa_{H\|J}$

•**At high temperature:**
Vortices scatter quasiparticles with H⊥v preferentially

$\kappa_{H\perp J} < \kappa_{H\|J}$

- s-wave : reversal of the 0-90° anisotropy of κ upon cooling
  K.Maki, *Phys.Rev. 158, 397 (1967)*
- d-wave : similar result + nodal quasiparticles
  A.Vorontsov, I.Vekhter, *Phys. Rev. Lett. 96, 237001 (2006)*

Possible reasons for the observed anisotropy

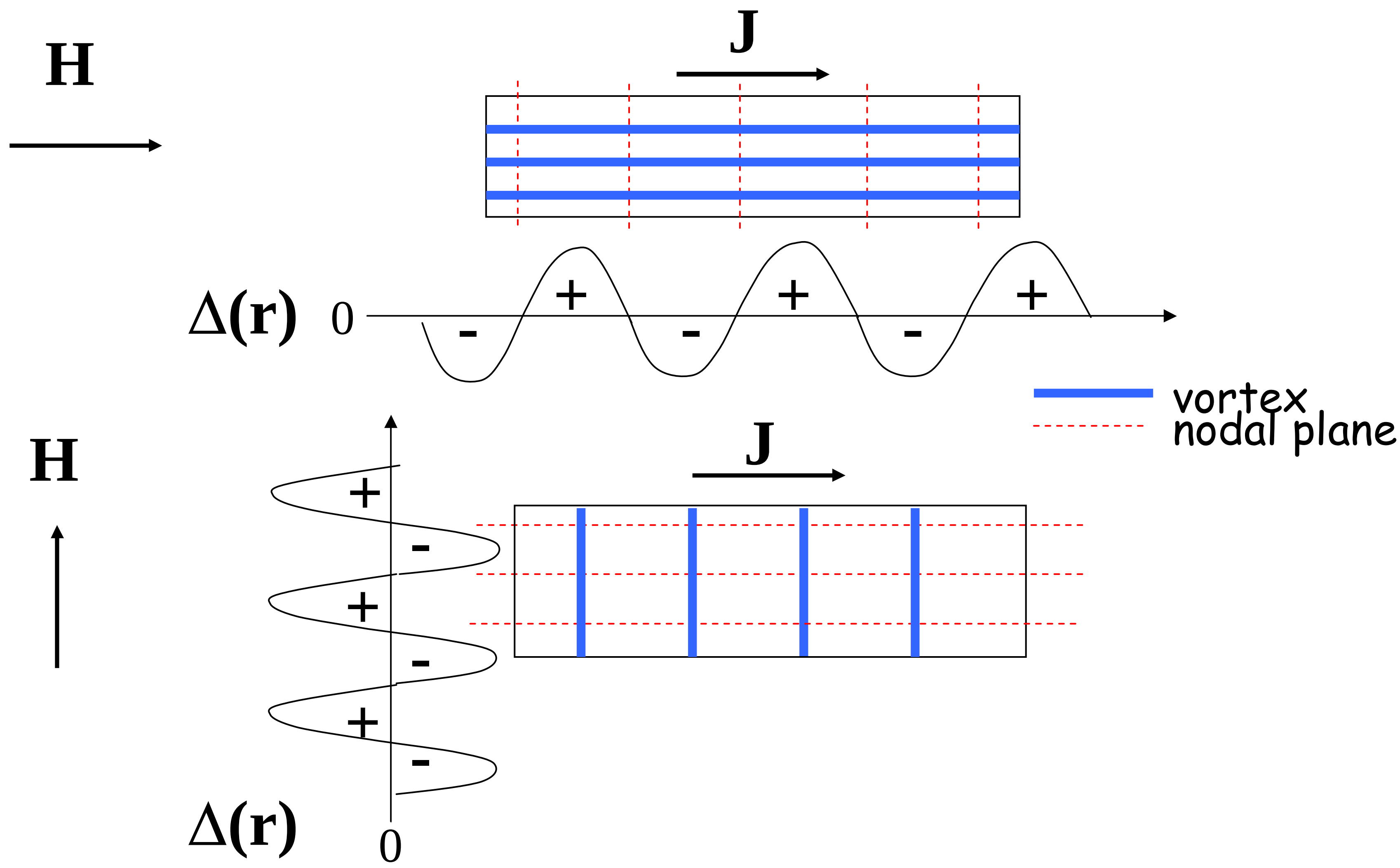
$$\kappa\,(\mathbf{H} \parallel \mathbf{J}) > \kappa\,(\mathbf{H} \perp \mathbf{J})$$

- Vortex contribution dominates over the nodal planes?

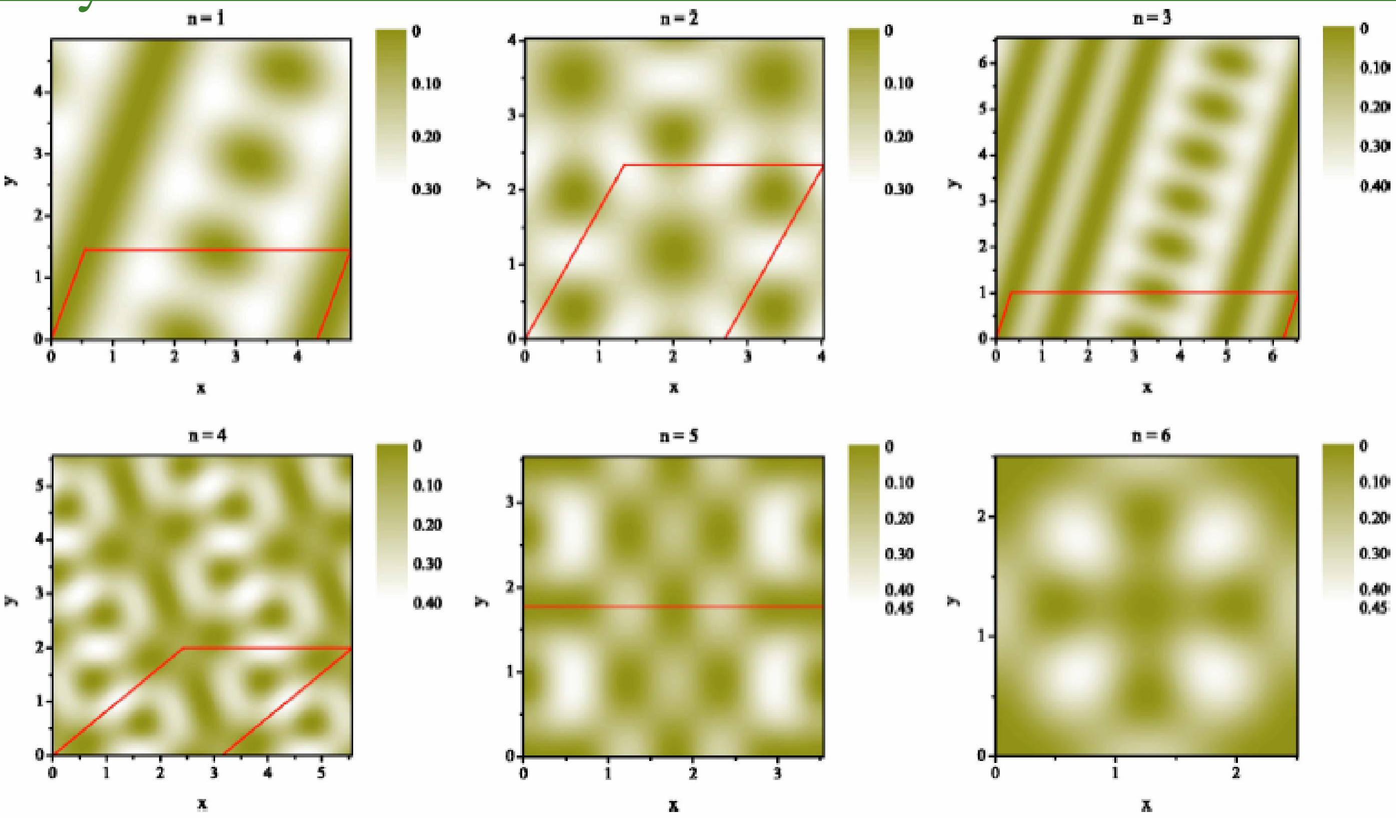
  → QP density in vortex core > in nodal plane
  → Scattering by vortices > by nodal planes

- The spatial structure of FFLO state in presence of vortices may not involve nodal planes!

Vortex vs FFLO contribution to the anisotropy of κ



Interplay between FFLO and vortex structures



- The real space profile of Δ is not universal

  U.Klein, D.Rainer, H.Shimahara, *J.Low Temp. Phys. 118, 91 (2000)*

- Near T_0 the profile of Δ is determined by n (LL index) and the vortex lattice structure K. Yang, A.H. MacDonald, *PRB 70, 094512 (2004)*

Conclusion

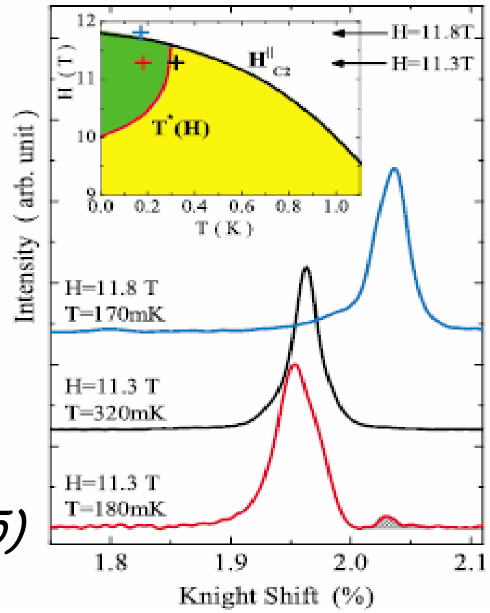
- Experimental H-T Phase diagram of $CeCoIn_5$ with H in-plane:
  - 1^{st} order superconducting transition below T*=1K
  - 2^{nd} order transition between vortex state-FFLO below T_{FFLO}=0.3K
  - Field tuned QCP near H_{c2} for both H||[001] and [100] at ambient pressure

- The anisotropy of thermal conductivity can be used to probe nodal planes in the high field superconducting state: we found an anisotropy opposite in sign to what is expected from nodal planes.

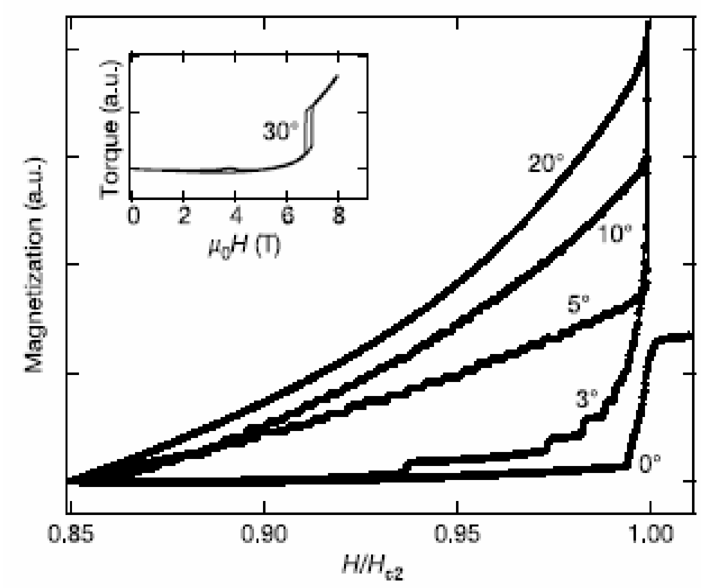
Need for more theoretical + experimental work !

Controversies about FFLO in $CeCoIn_5$:

- Is there a second transition line for H||[001]?
- Are there nodal planes in the high field state?
- Are the magnetization steps evidence for multiquanta vortices?



K.Kakuyanagi et al.,
PRL 94, 047602 (2005)



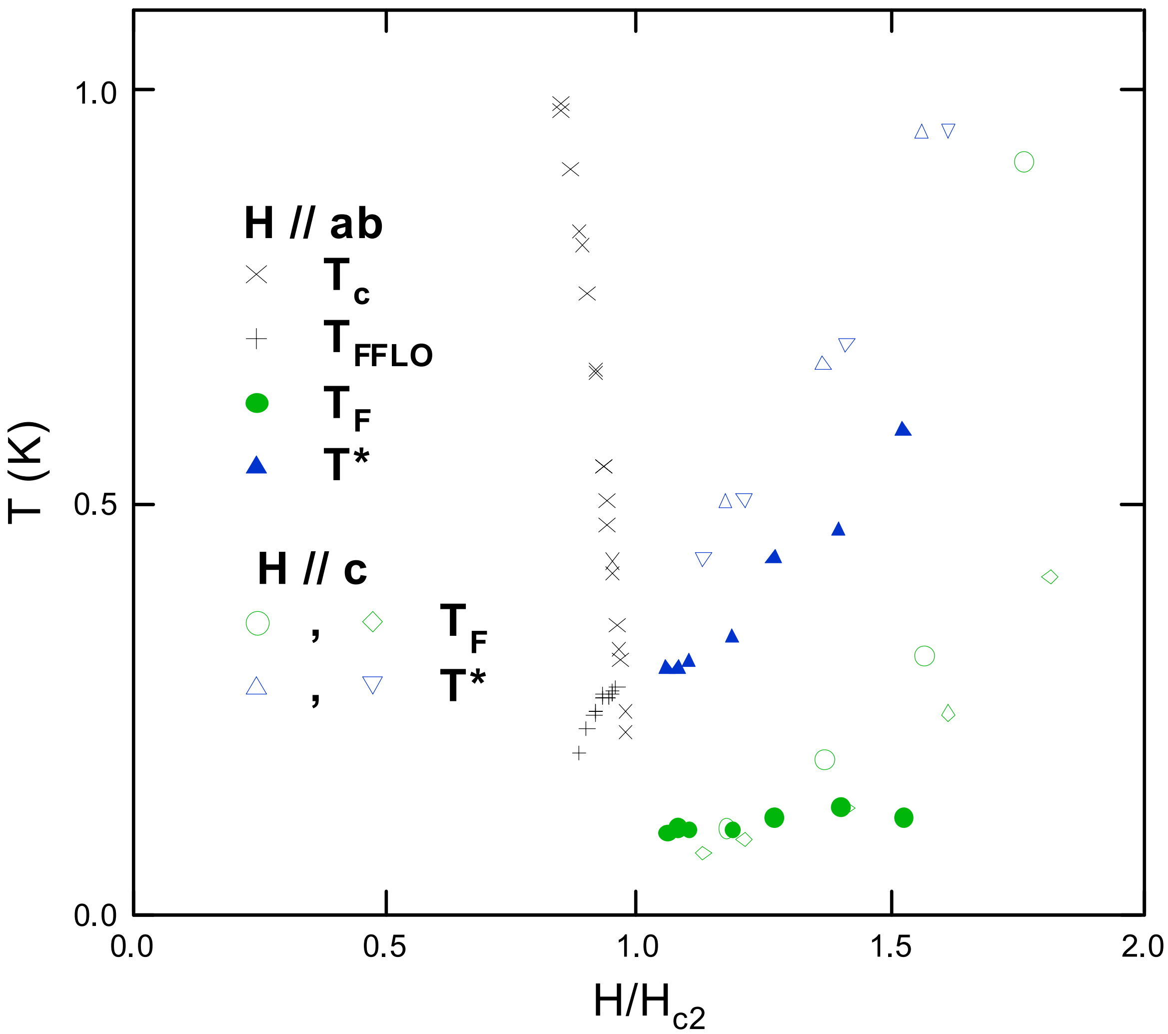
H.A. Radovan et al. *Nature 425, 51 (2003)*
See also R. Movshovich Nature 427, 802 (2004)

acknowledgements

A.D.Bianchi,
F.Ronning,
R.Movshovich,
A.Malinowski,
M.F.Hundley,
A.D.Christianson,
A.Lacerda,
E.D.Bauer,
P.G.Pagliuso,
J.L.Sarrao,
J.D.Thompson

Thank you!

Supplemental slide : H-T phase diagram from resistivity



Supplemental slide: Resistivity under pressure for H||[001]