The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific
and Cultural Organization

International Atomic
Energy Agency

SMR.1766 - 10

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

Nicholas CURRO
Condensed Matter & Thermal Physics
MS K764
Los Alamos National Laboratory
Los Alamos, NM 87545
U.S.A.

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

Superconductivity at the Edge: The Strange Case of $CeCoIn_5$

Nicholas Curro (curro@lanl.gov)

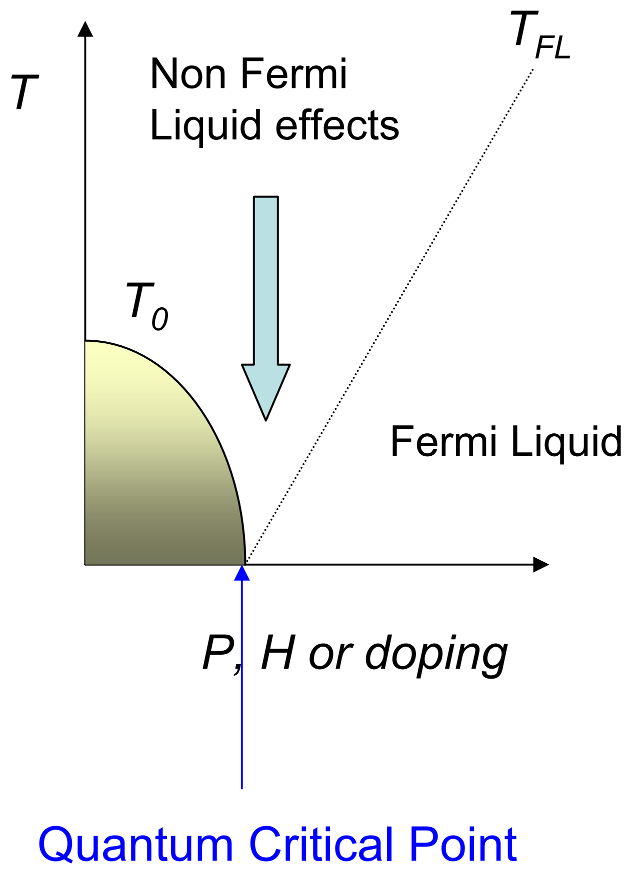
Condensed Matter and Thermal Physics
Los Alamos National Laboratory

Collaborators:

Ben-Li Young	*now at National Chiao Tung University, Taiwan*
Ricardo Urbano	LANL
Joe Thompson	LANL
John Sarrao	LANL
Matthias Graf	LANL Theory Division
Anton Vorontsov	LSU

Los Alamos NATIONAL LABORATORY EST.1943

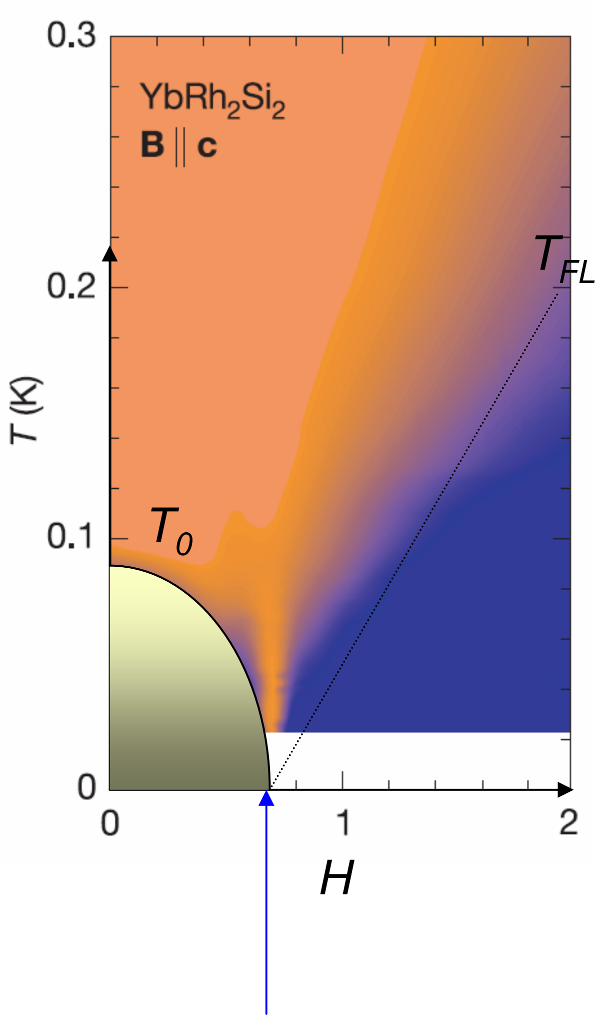
Phase Diagrams and QCPs



Long range ordered broken symmetry phase with transition temperature T_0

Typically can tune T_0 to $T=0$ with pressure, field or doping

Phase Diagrams and QCPs



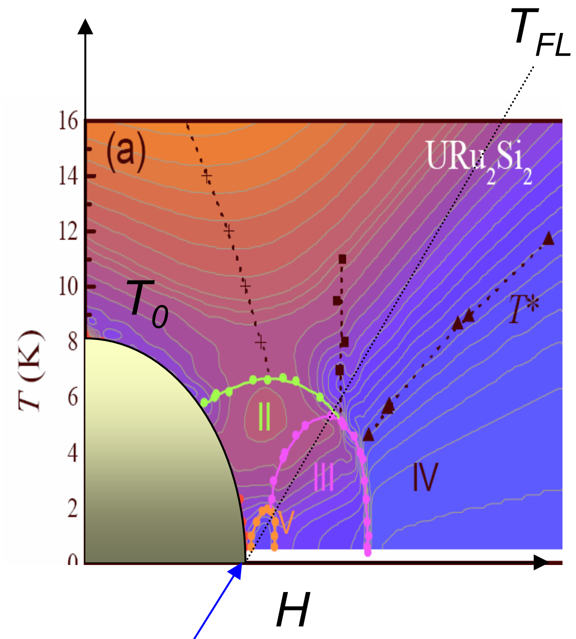
J. Custers, et al. Nature **424**, 524 (2003)

Quantum Critical Point

$YbRh_2Si_2$ is a classic example, which shows no evidence for a new phase in the vicinity of the QCP

Los Alamos
NATIONAL LABORATORY
EST.1943

Phase Diagrams and QCPs



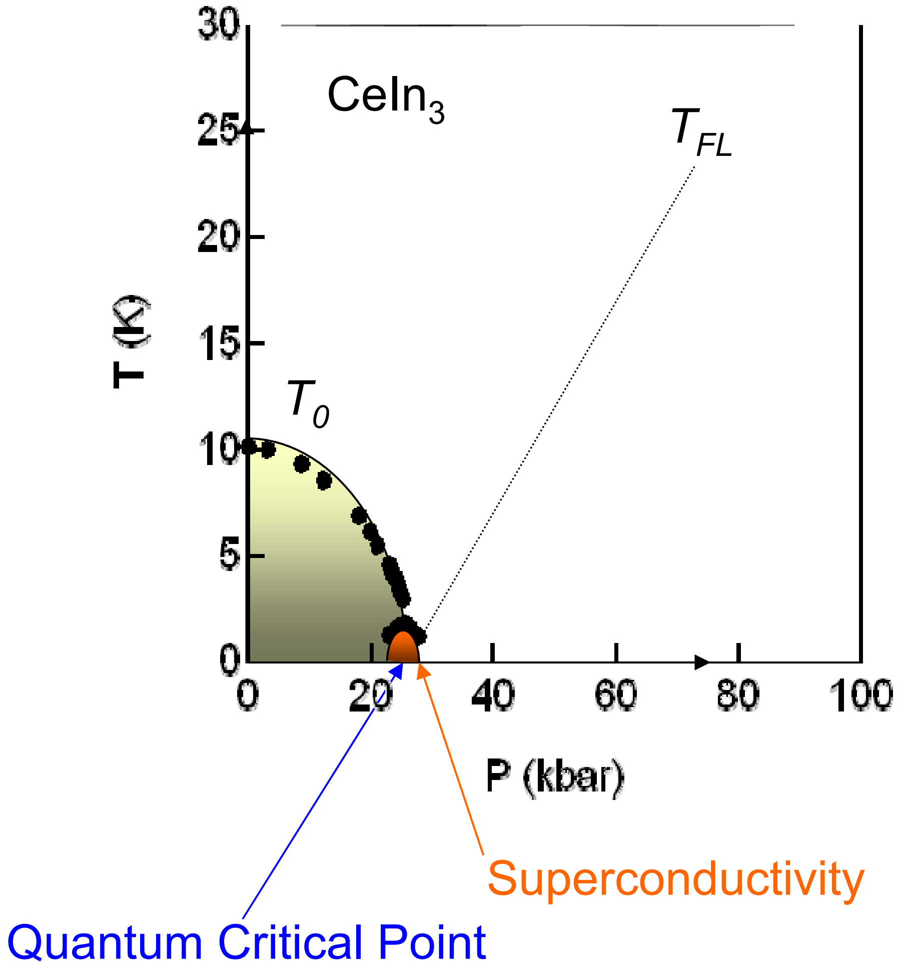
K. H. Kim, et al. Phys. Rev. Lett. 91, 256401 (2003)

URu_2Si_2 develops multiple phases

Also Strontium ruthenate

Quantum Critical Point

Phase Diagrams and QCPs

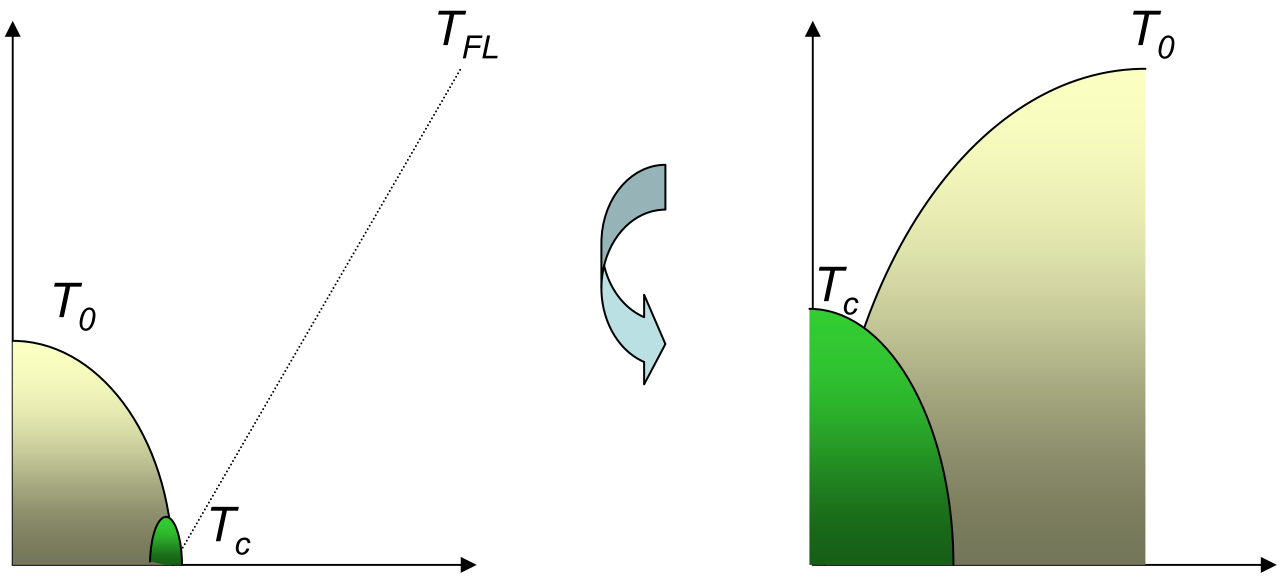


N. D. Mathur, et al. Nature **394**, 39 (1998)

$CeIn_3$, on the other hand, develops a new phase in the vicinity of the QCP

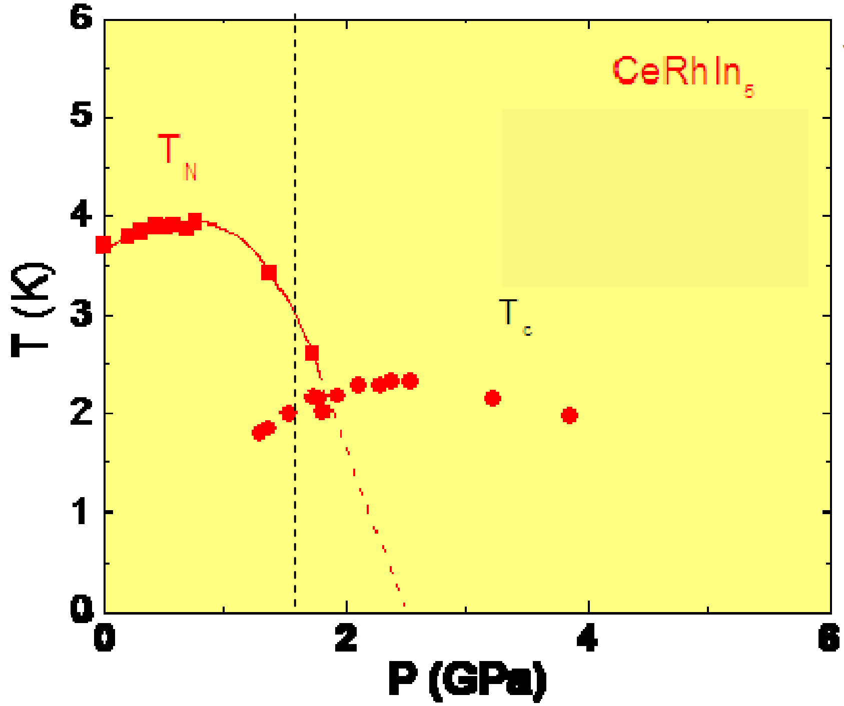
Emergence of a new phase near the QCP may be natural, since competing orders may become stabilized if long-range magnetic order cannot form

Another point of view

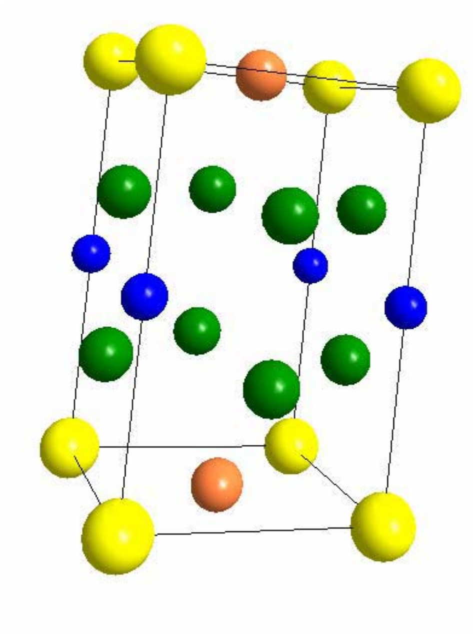


The heavy fermion superconductor $CeCoIn_5$ is an ideal case to investigate how *magnetism* emerges from *superconductivity*.

The Ce-115 Phase Diagram

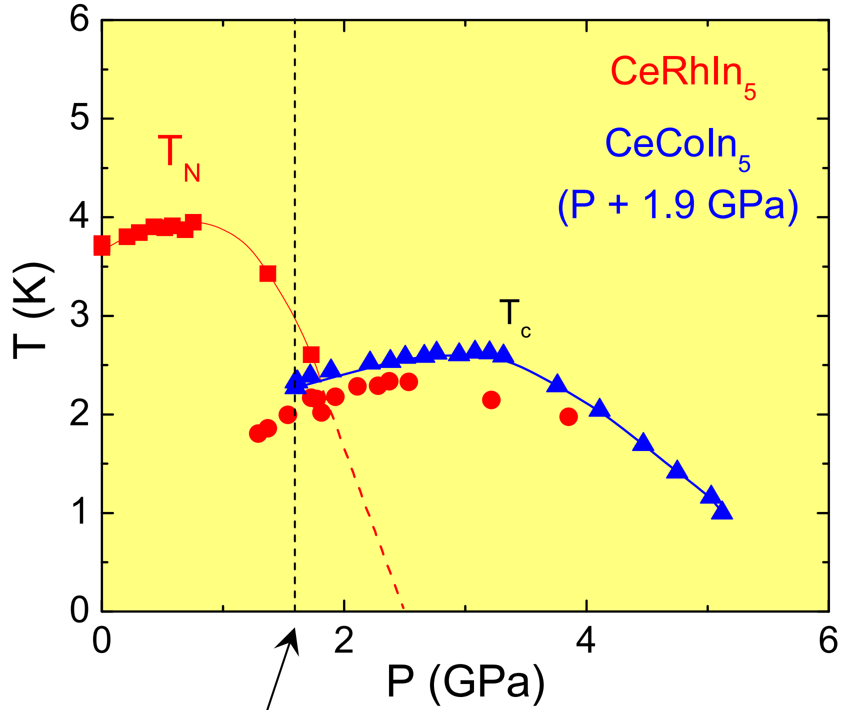


V. Sidorov, et al. Phys. Rev. Lett. 89, 157004 (2002)

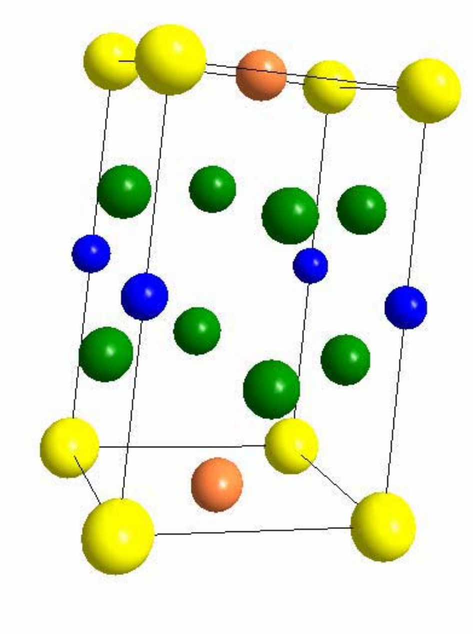


The $CeMIn_5$ materials, a 2D version of the $CeIn_3$ system, have enhanced T_c's

The Ce-115 Phase Diagram



V. Sidorov, et al. Phys. Rev. Lett. 89, 157004 (2002)

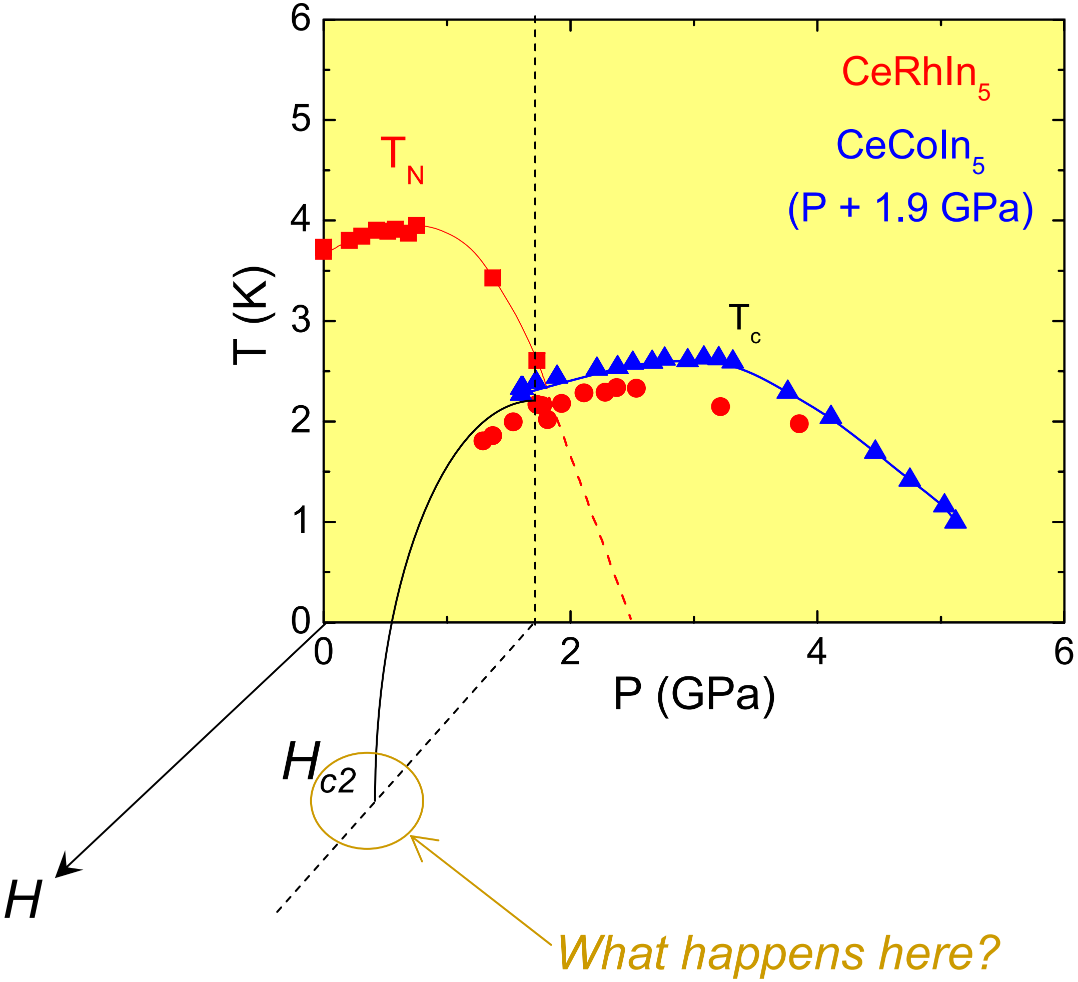


The $CeMIn_5$ materials, a 2D version of the $CeIn_3$ system, have enhanced T_c's

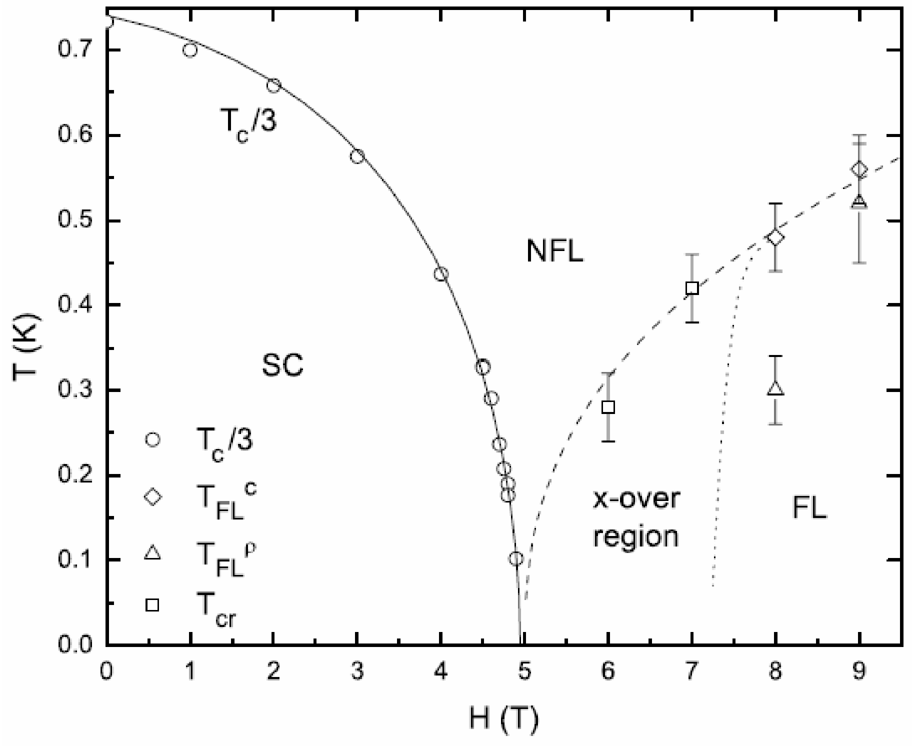
$CeCoIn_5$ at ambient pressure shows no Neél order

Los Alamos NATIONAL LABORATORY EST.1943

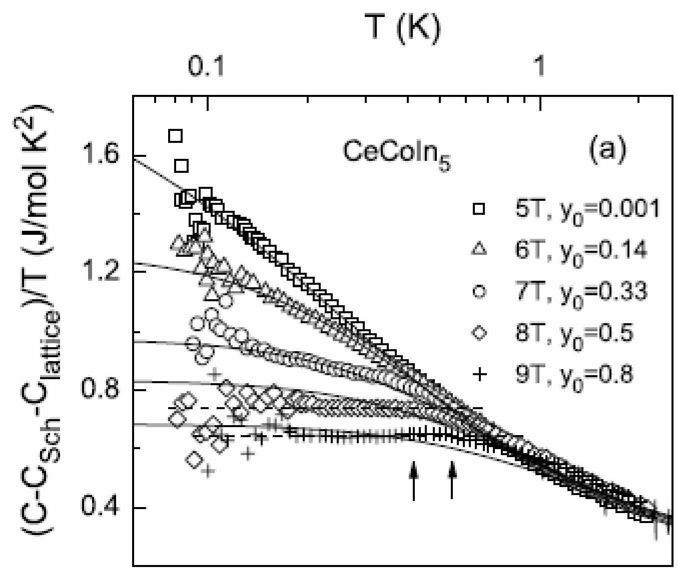
Magnetism in $CeCoIn_5$?



Quantum Critical Behavior in $CeCoIn_5$



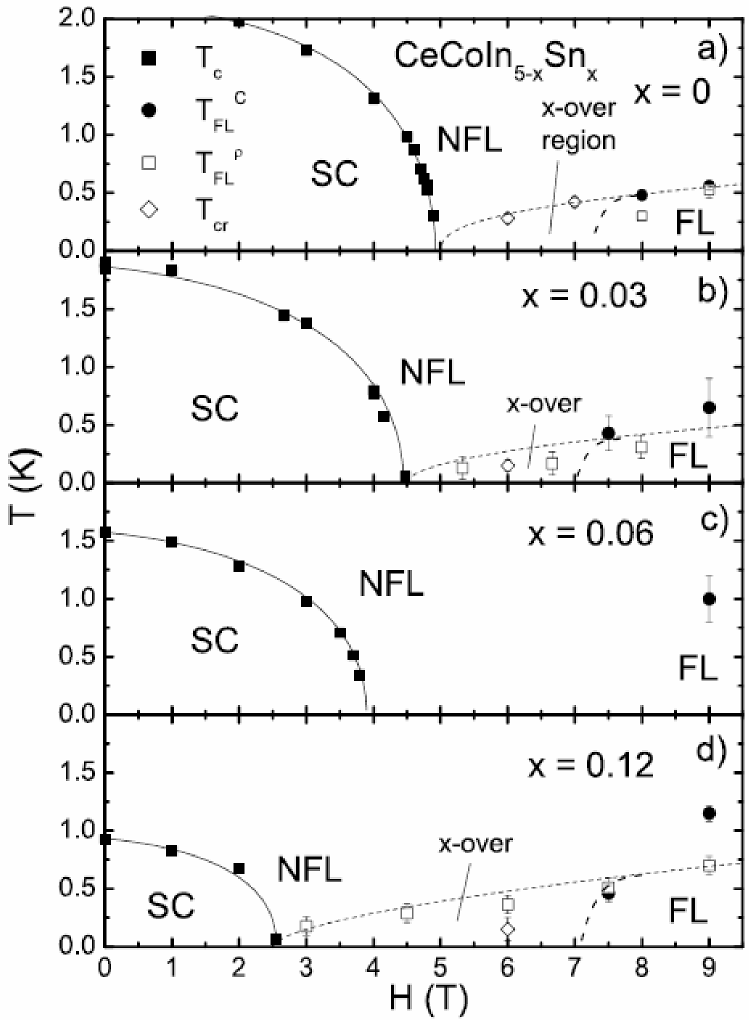
A. Bianchi, et al. Phys. Rev. Lett. **91**, 257001 (2003)



Resistivity and specific heat suggest a QCP close to H_{c2}

However, is the ordered state giving rise to the nFL behavior the superconductivity or an un-detected magnetic phase?

An elusive phase…

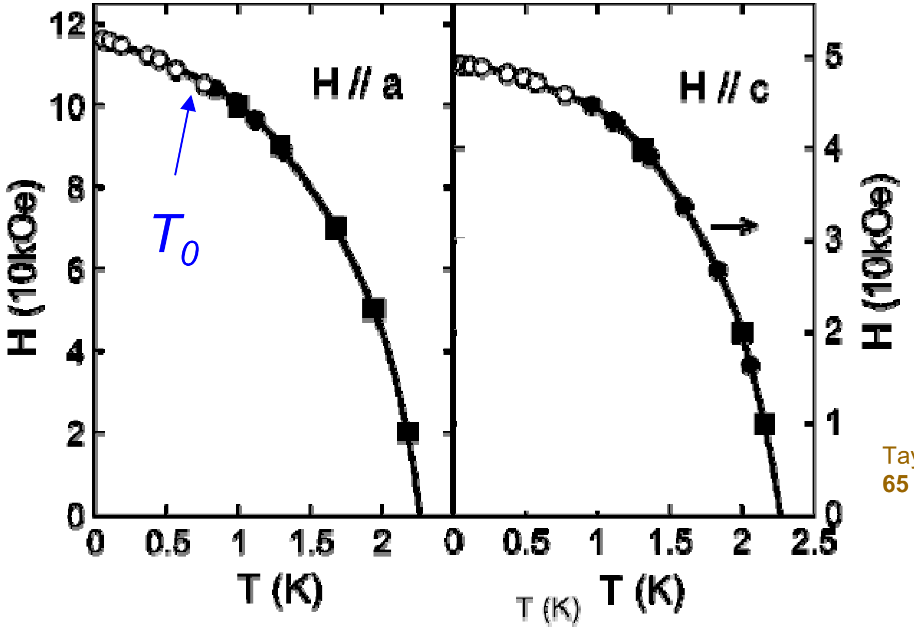


E. D. Bauer, et al. Phys. Rev. Lett. **94**, 47001 (2005)

Suppressing the superconductivity with Sn doping does not reveal a hidden magnetic phase

Suggests QCP tracks H_{c2}

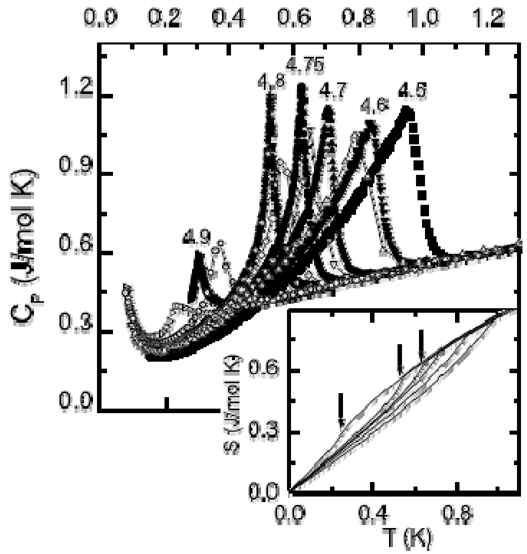
The unusual superconducting phase diagram

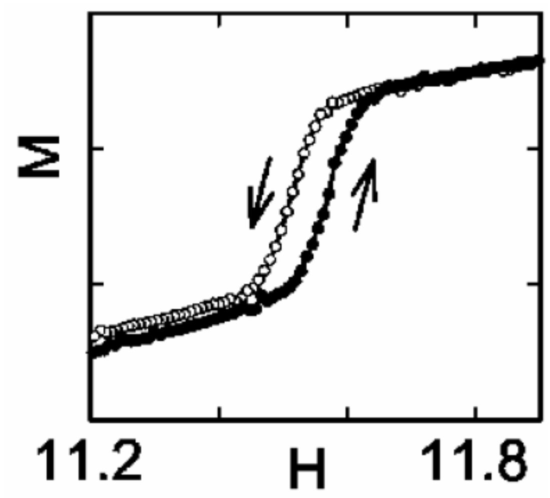


Specific heat and magnetization data show crossover from 2^{nd} to 1^{st} order transition for $T < T_0$

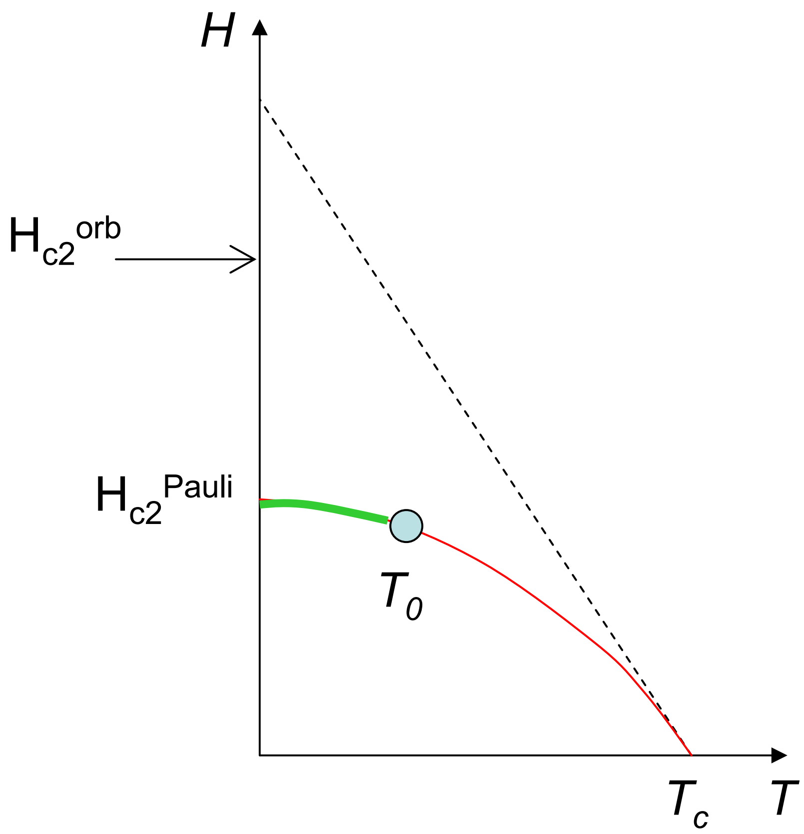
Tayama et al., PRB **65** 180504 (2002)

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





Orbital vs Pauli Limiting



$H_{c2}^{orb} = 0.7 dH_{c2}/dT_c\ T_c$
$H_{c2}^{Pauli} = \Delta_0/g\mu_B$

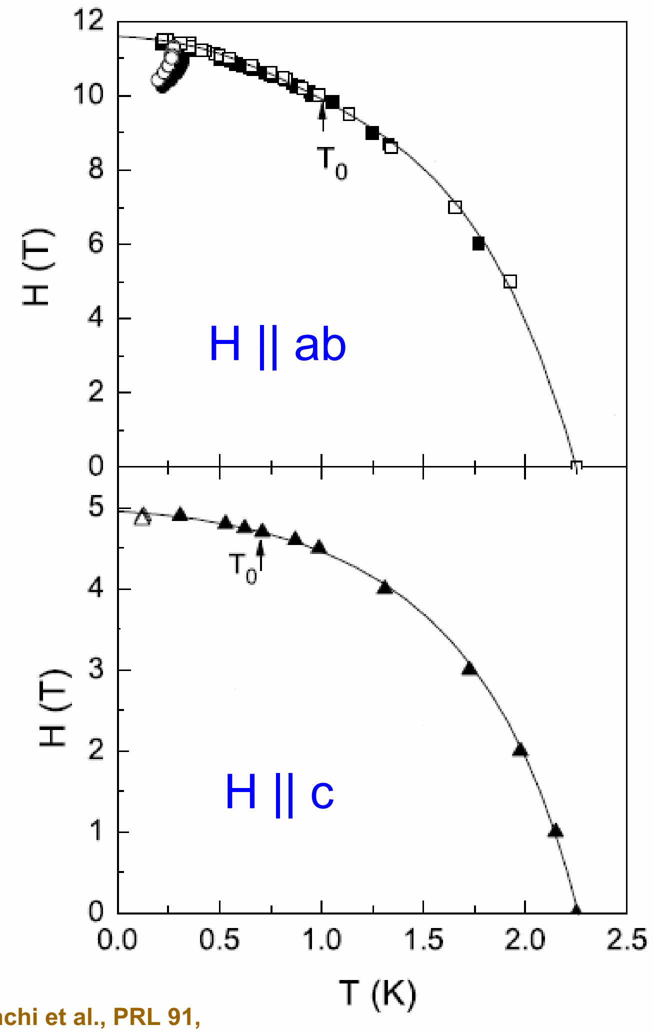
Can get first order transition when $\alpha = H_{c2}^{orb}/\ H_{c2}^{Pauli} > 1$

For $CeCoIn_5$, $\alpha \sim 3.6$

Agrees with theory (Maki) for $T_0(\alpha)$

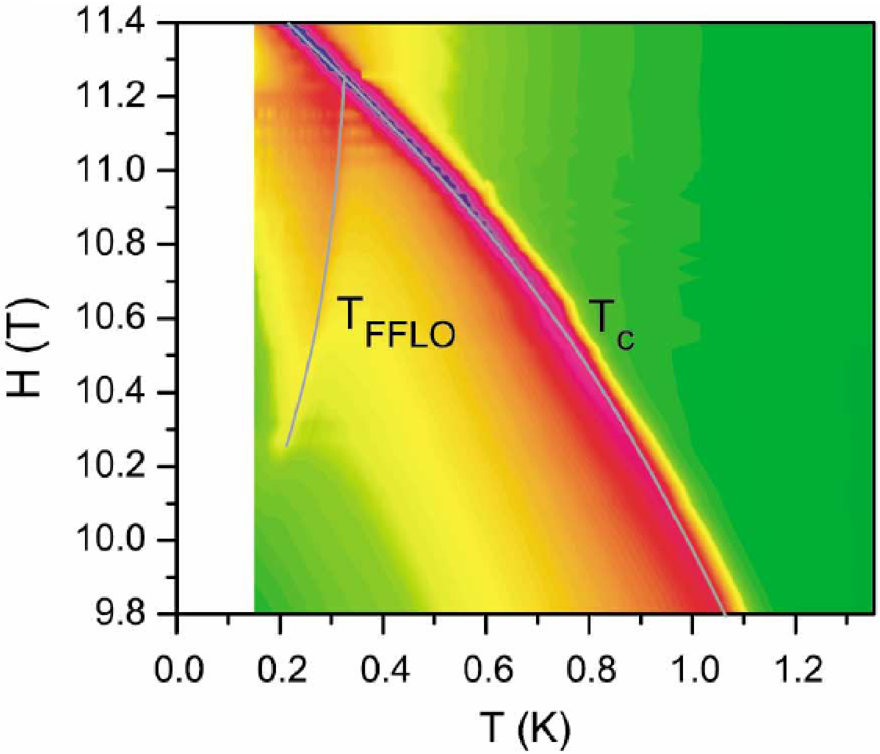
Important in superconductors with high spin susceptibility

The new phase



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

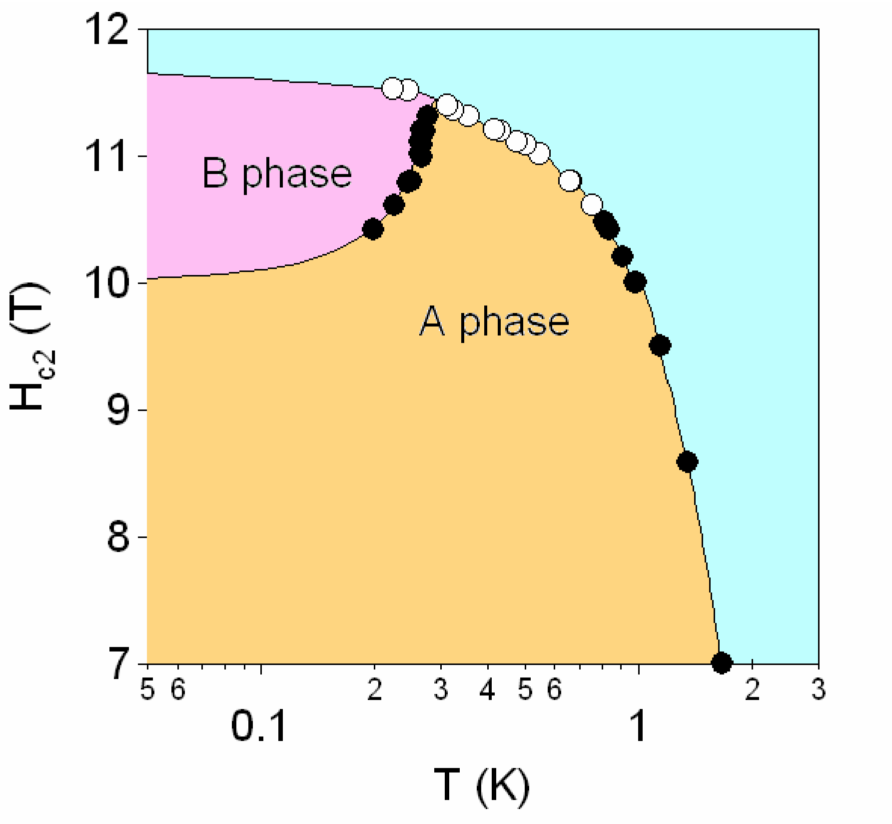
There is a clear second order phase transition at low T



What is the nature of this new phase?

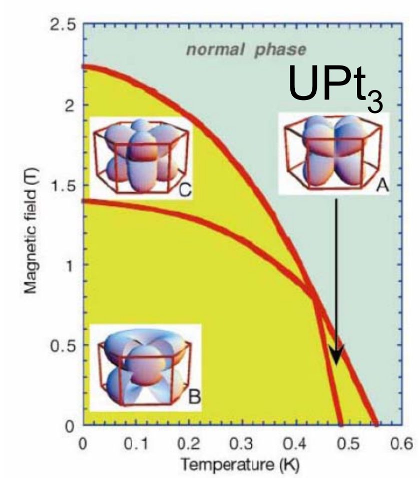
Los Alamos NATIONAL LABORATORY EST. 1943

Some possible interpretations



The B phase can be either

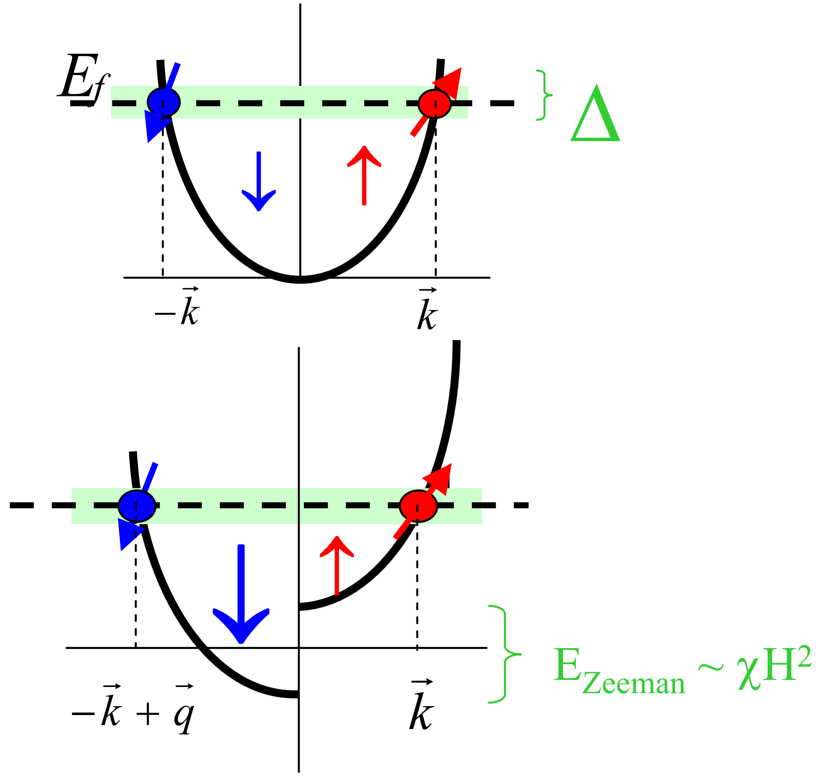
1. a different symmetry of the superconducting order parameter
2. an FFLO superconducting phase
3. a magnetically ordered phase

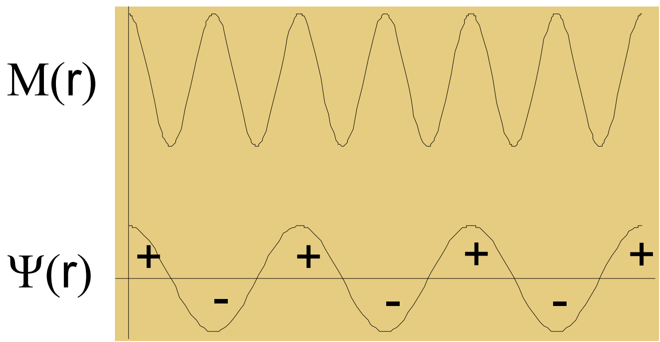


Presumably the A phase is simply the Abrikosov mixed phase…

Los Alamos NATIONAL LABORATORY EST.1943

FFLO Physics





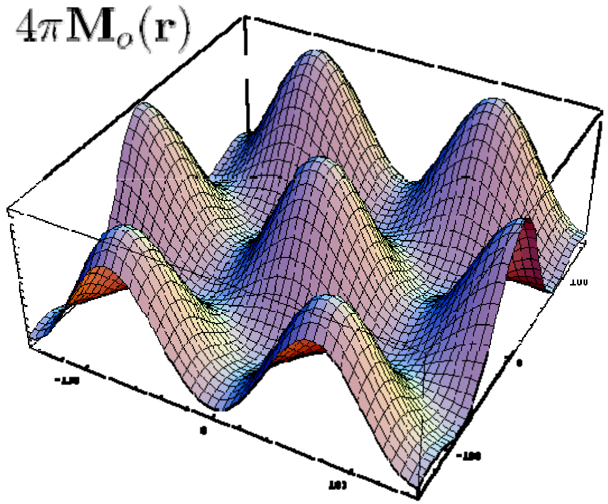
- *Unequal populations of spin up and spin down Fermi surfaces undergo pairing with non-zero center of mass momentum, hq*
- *Similar phenomena at work in cold fermi gases and possibly in neutron stars*
- *In superconductors, orbital currents screen fields, so H_{c2} is determined by a delicate balance between Pauli limiting and orbital limiting effects. This leads to a crossover to a first order transition across H_{c2}-T_c phase boundary*
- *FFLO phase: ψ and M modulated along field direction with length scale ~ ξ*

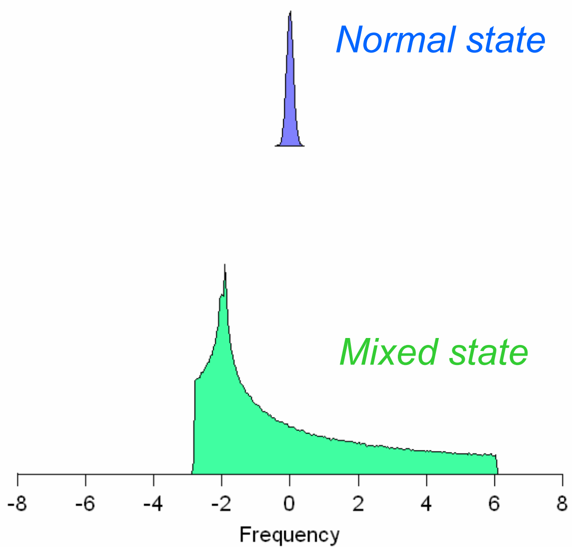
Los Alamos
NATIONAL LABORATORY
EST.1943

NMR in the superconducting state

Both spin and orbital parts of magnetization can affect the NMR response:

$$f(\mathbf{r}) = {}^{\eta}\gamma \left| \mathbf{H} + \underbrace{4\pi \mathbf{M}_o(\mathbf{r})}_{\text{Orbital currents}} + \underbrace{A\mathbf{M}_s(\mathbf{r})}_{\text{Spin polarization}} \right|$$

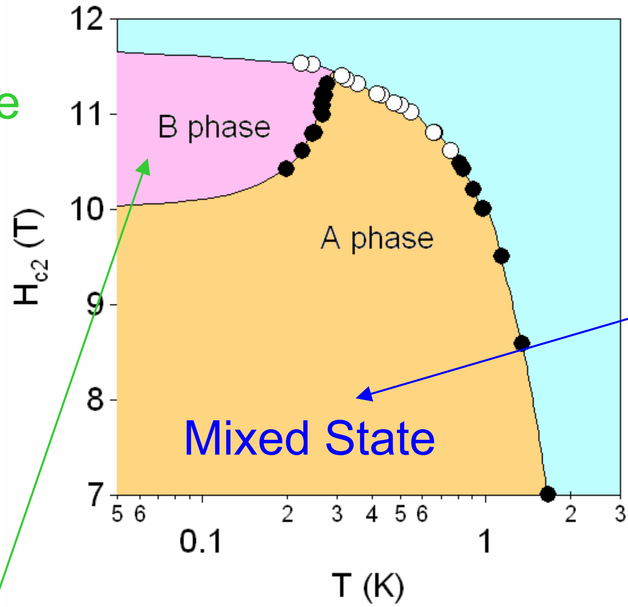


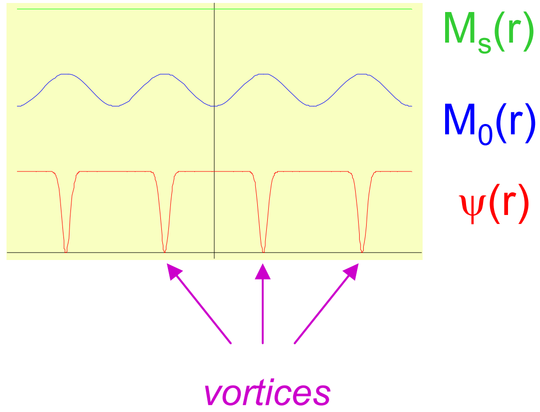


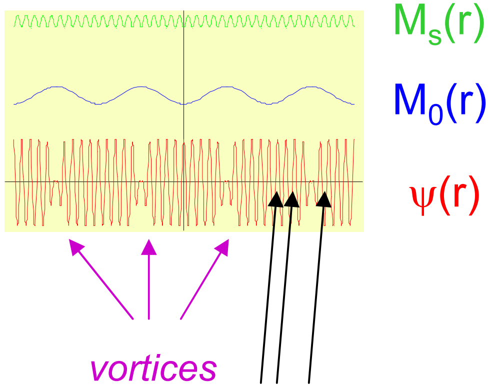
- Knight shift contributes to first moment of resonance
- Vortex lattice contributes to second moment

What can we expect to see with NMR?

Mixed State and FFLO





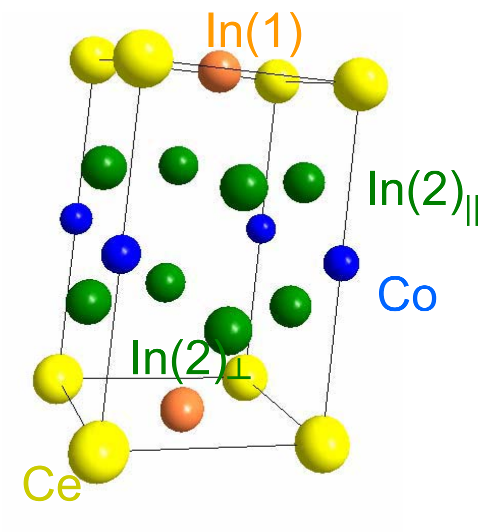


Nodal planes of FFLO phase

- *In the mixed state, expect broadening only from vortex lattice (orbital currents)*
- *In the FFLO phase, expect extra line broadening due to hyperfine fields from S(r)*
- *All modulations on length scale greater than or equal to the coherence length (~ 20-30Å)*

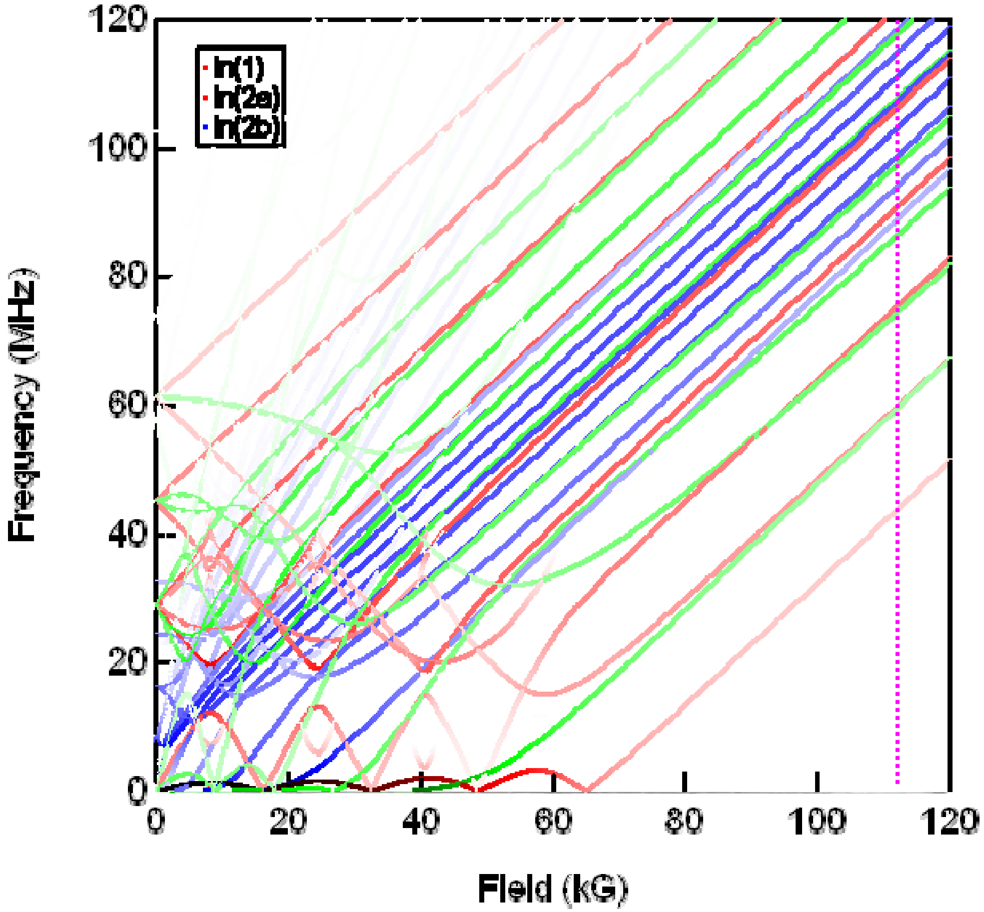
Los Alamos NATIONAL LABORATORY EST.1943

NMR in $CeCoIn_5$



•Four NMR sites: ^{115}In (I = 9/2) and ^{59}Co (I = 7/2)

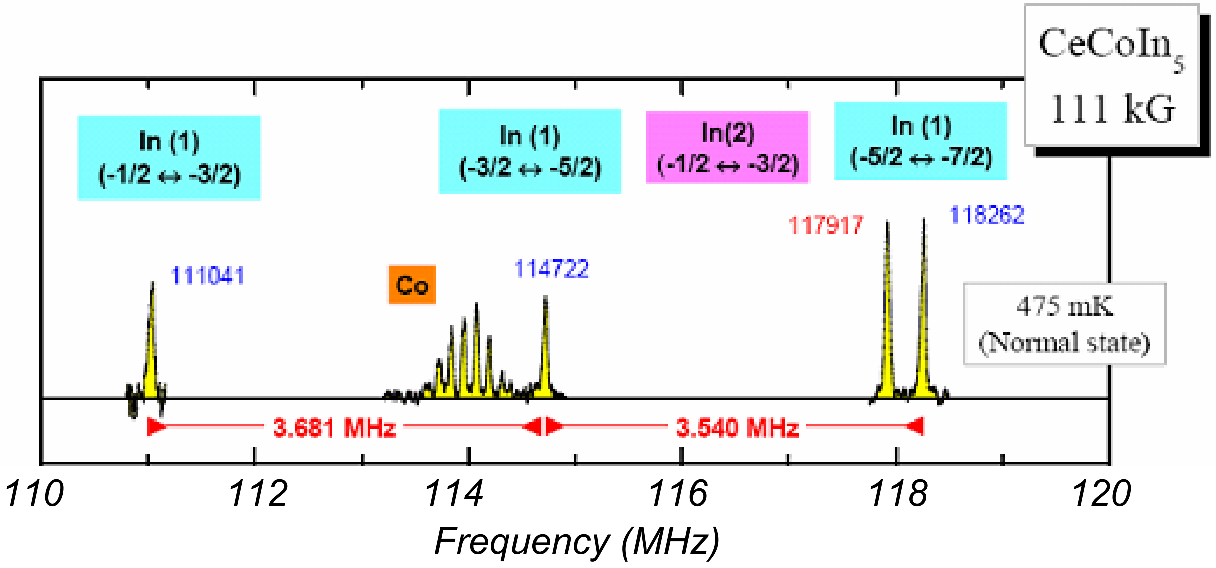
Several different satellite transitions for each In site



$$\hat{\mathcal{H}}_{\rm nuc} = \hat{\mathcal{H}}_{\rm Z} + \hat{\mathcal{H}}_{\rm Q}$$

$$\hat{\mathcal{H}}_Q = \frac{h\nu_{cc}}{6}\left[(3\hat{I}_c^2 - \hat{I}^2) + \frac{\nu_{aa}-\nu_{bb}}{\nu_{cc}}(\hat{I}_a^2 - \hat{I}_b^2)\right]$$

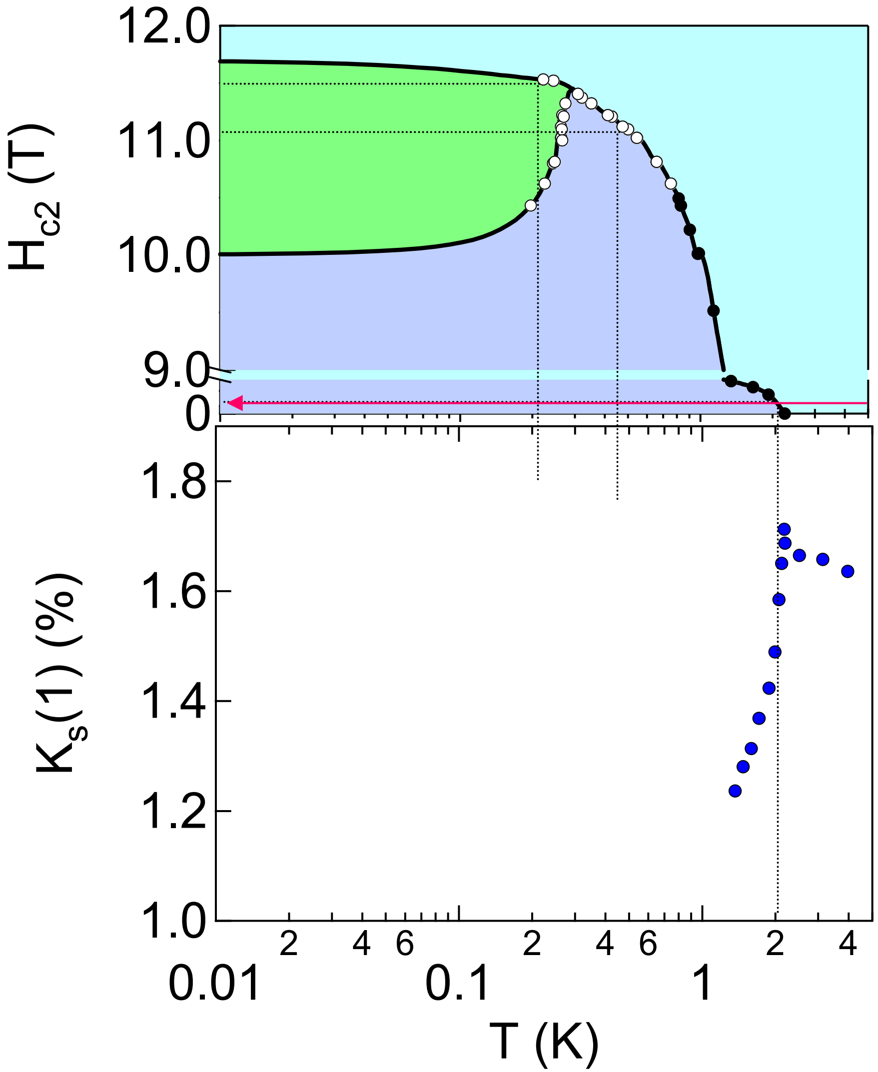
Spectra

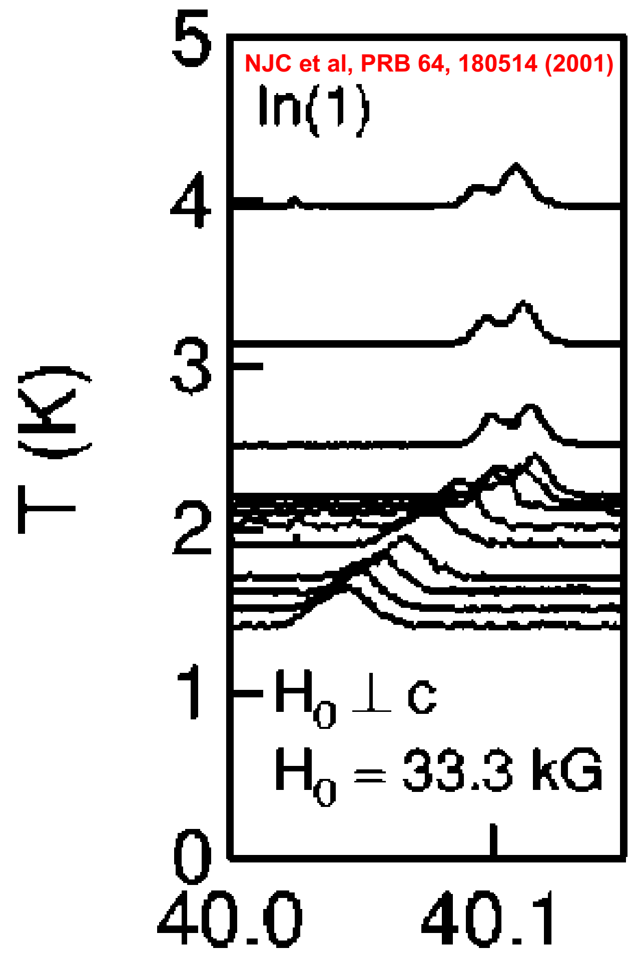


NMR in dilution refrigerator, in low homogeneity magnet – intrinsic linewidth ~ 20 Oe, but excellent SNR

Can measure response in A and B phases at several different satellites and nuclear sites!

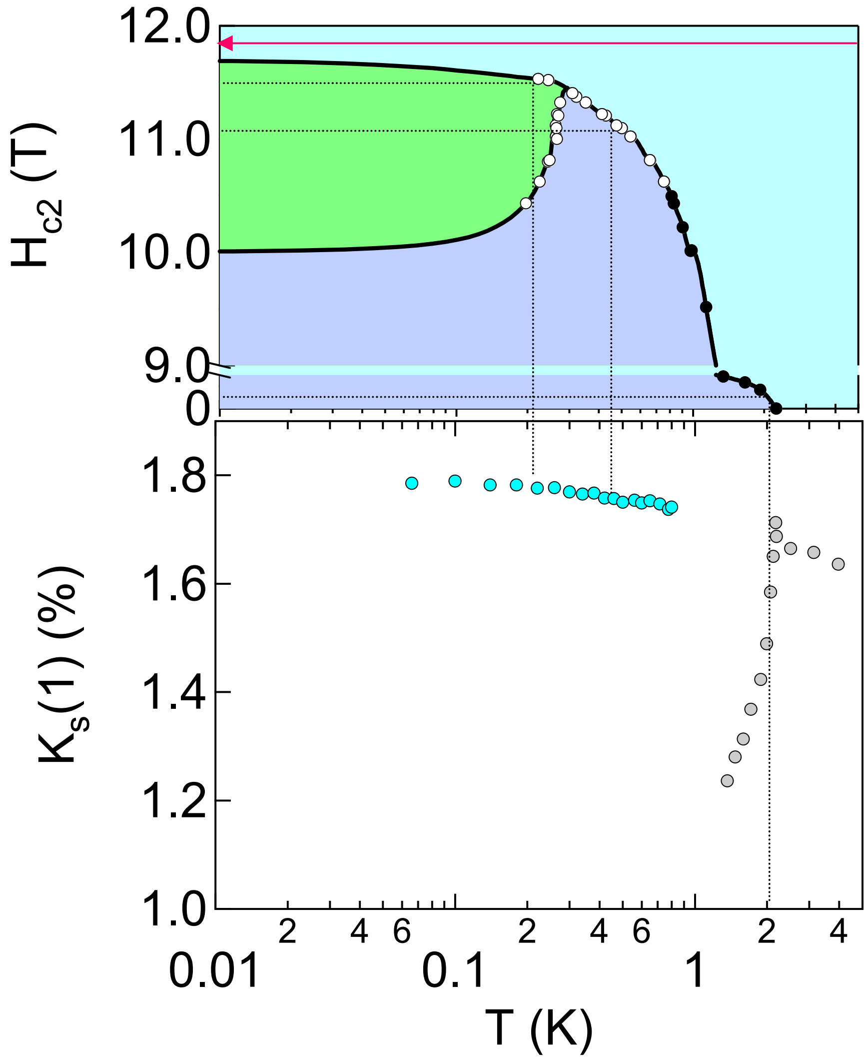
Low field Knight shift

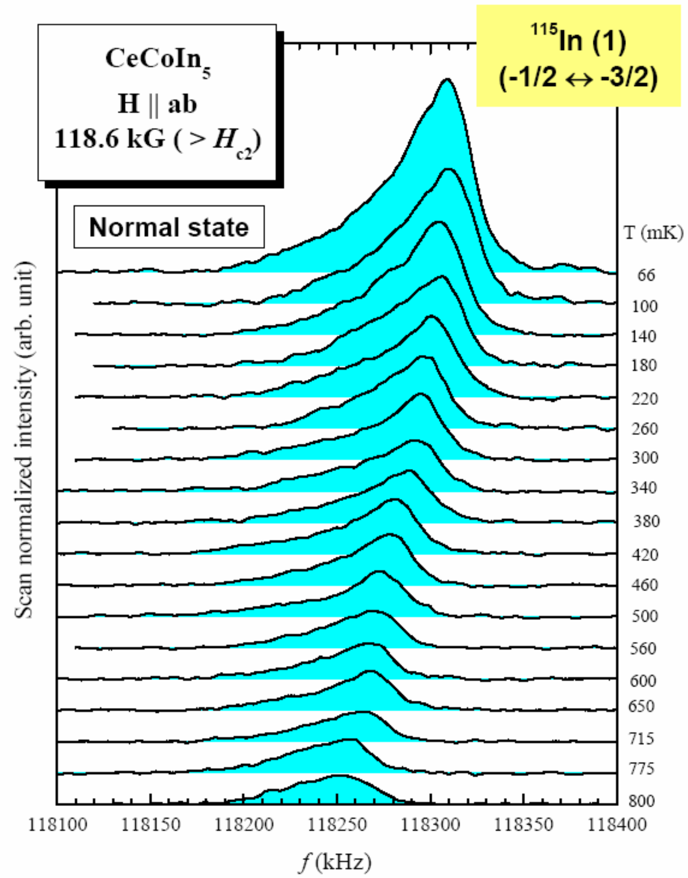




Typical behavior for a spin singlet superconductor in low fields

Normal state susceptibility

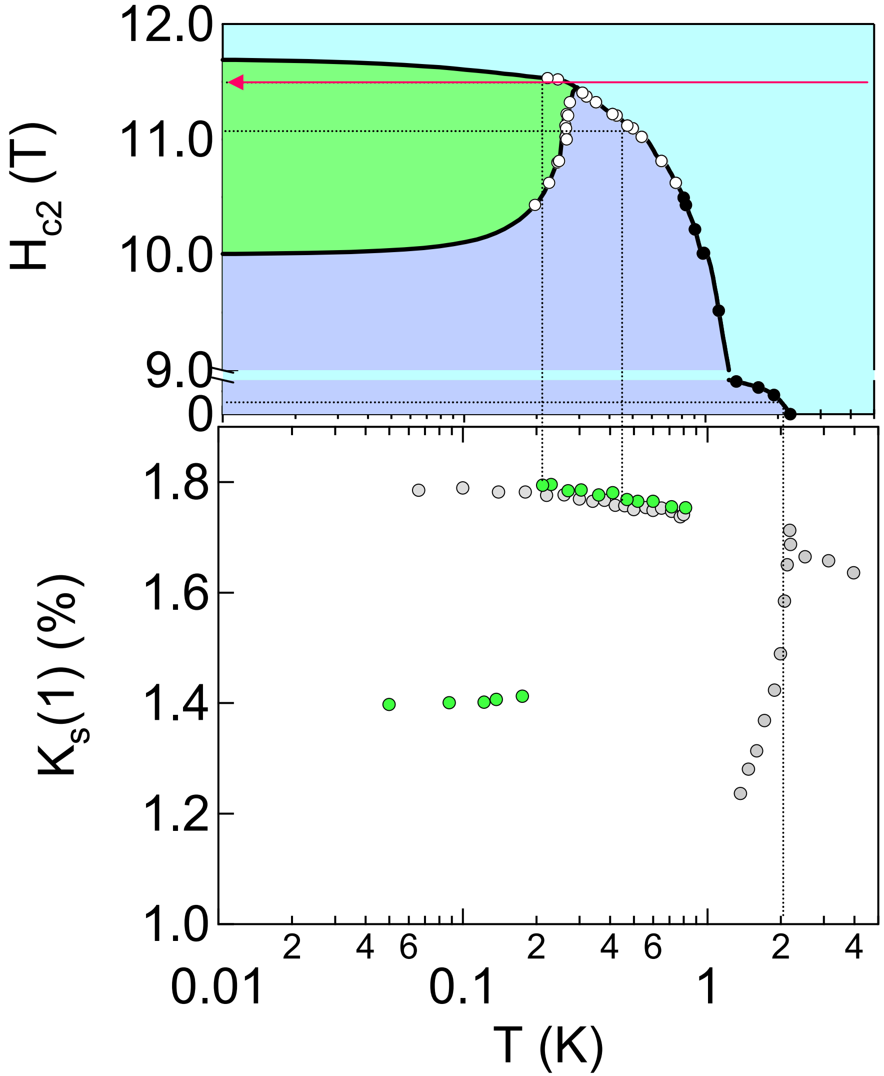


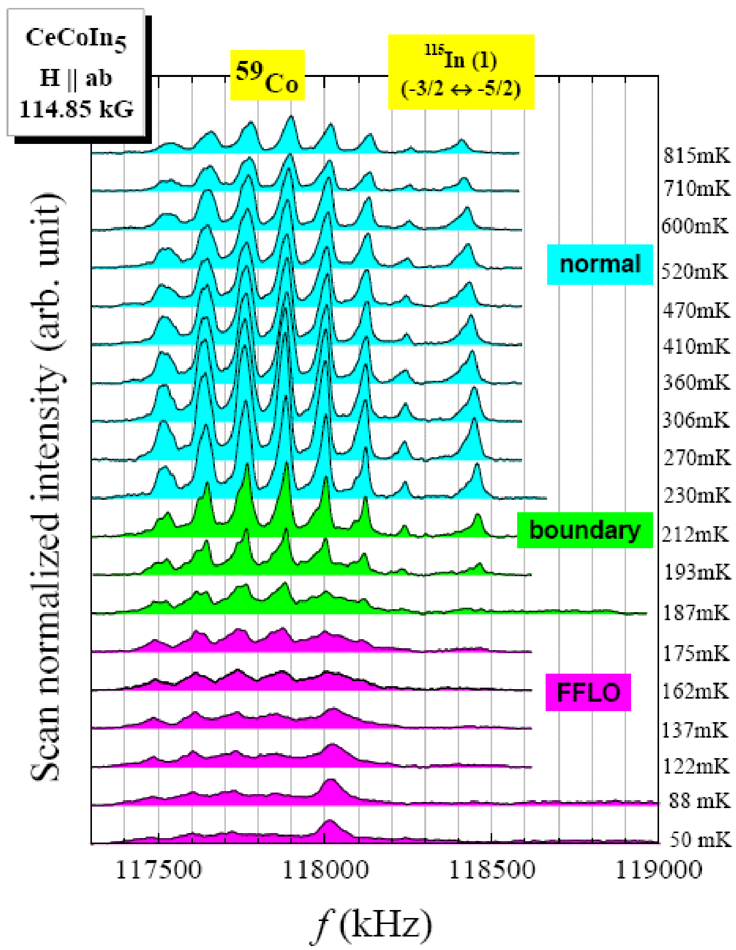


Knight shift tracks bulk susceptibility, no unusual broadening of spectra down to 60mK

Los Alamos NATIONAL LABORATORY EST.1943

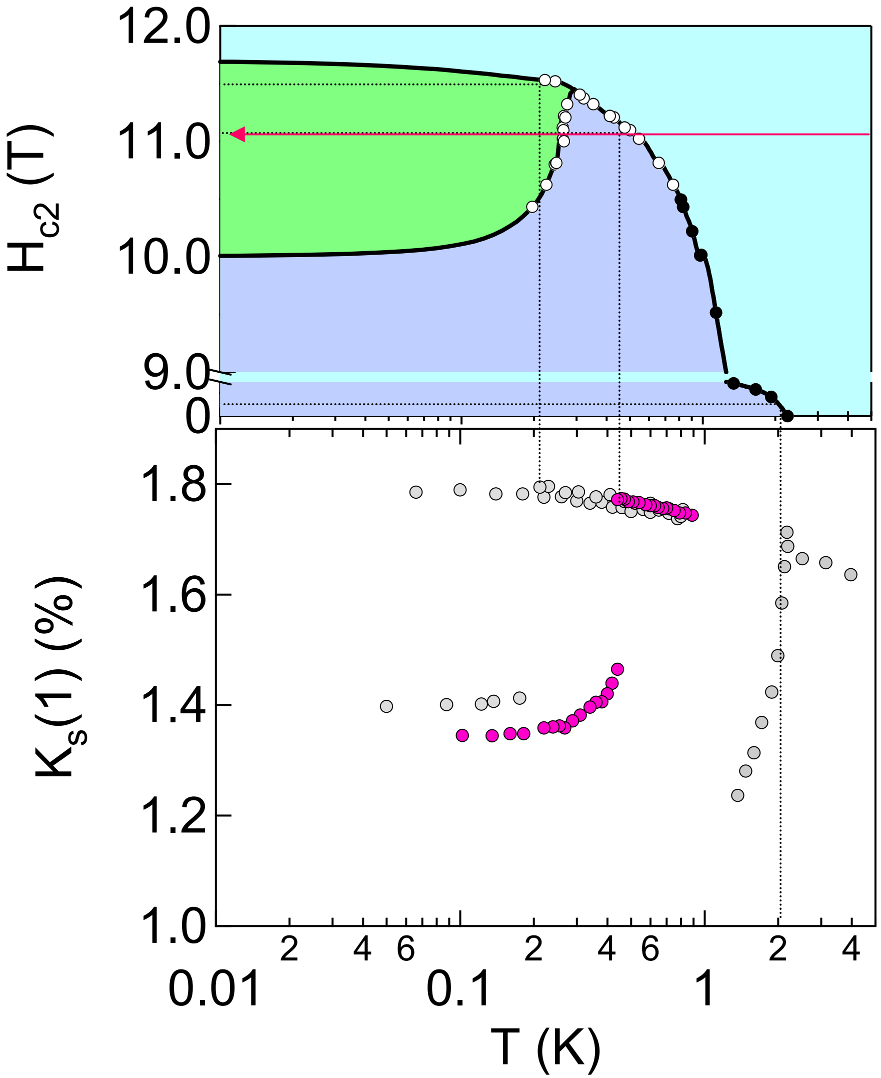
Normal to B phase

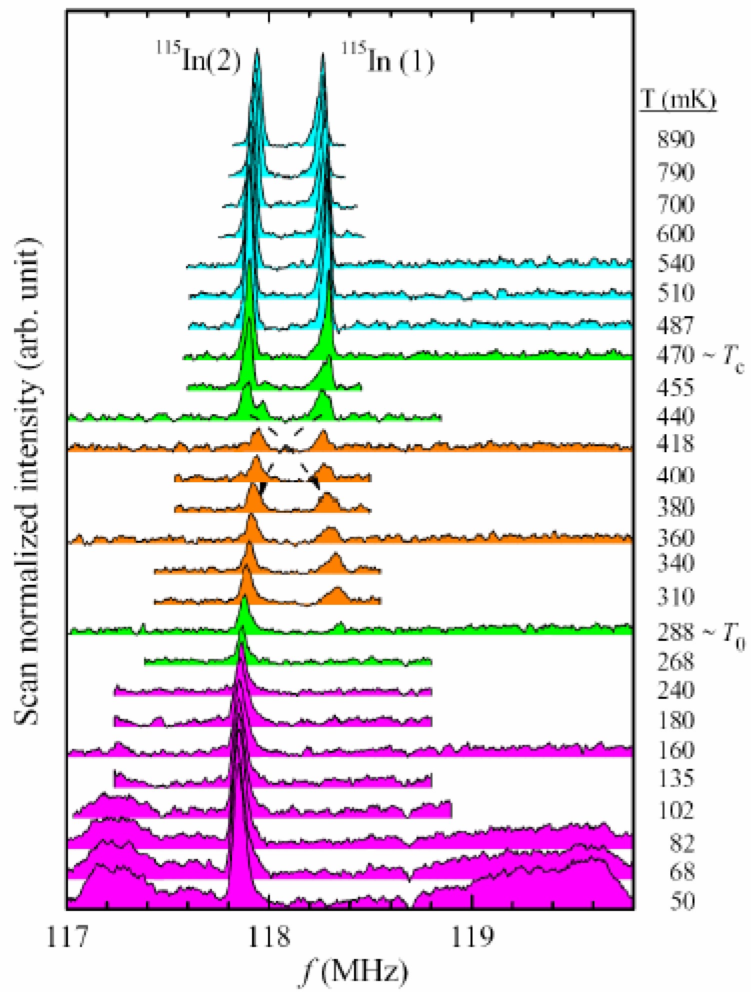




- *Dramatic change in spectra at first order transition*
- *Significant broadening in SC state*

Normal to A to B phase



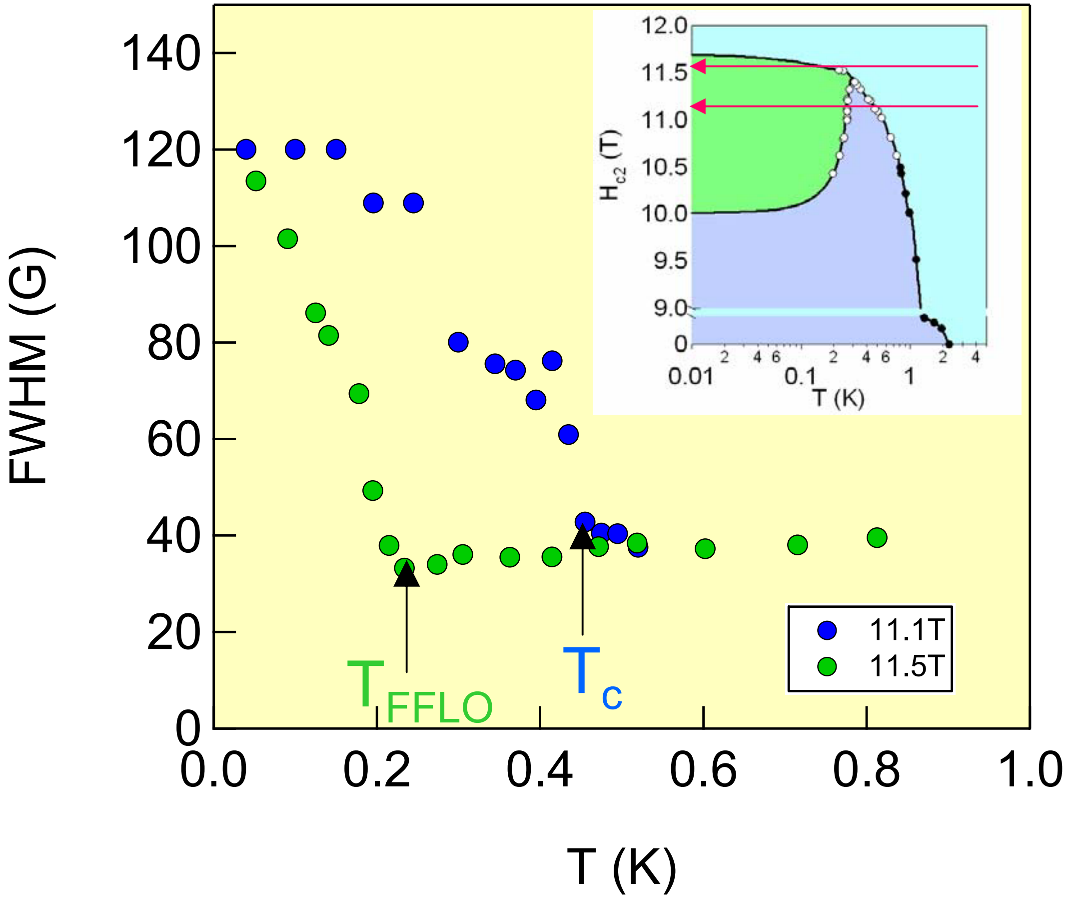


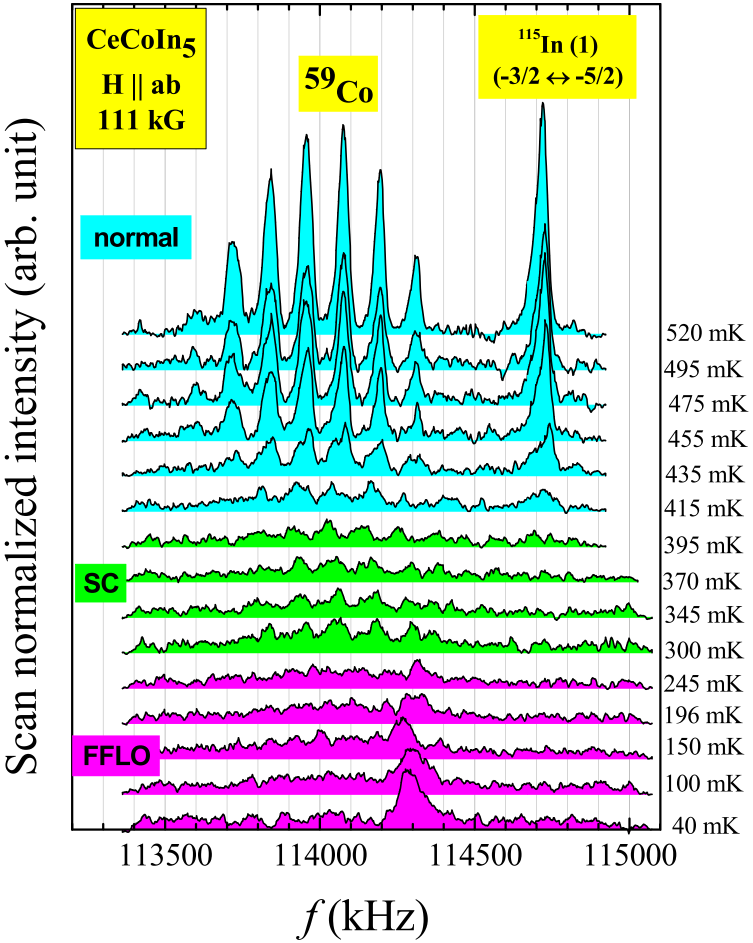
Knight shift discontinuous at T_c

No obvious changes to In(1) below T_{FFLO}

Los Alamos
NATIONAL LABORATORY
EST.1943

Co spectra



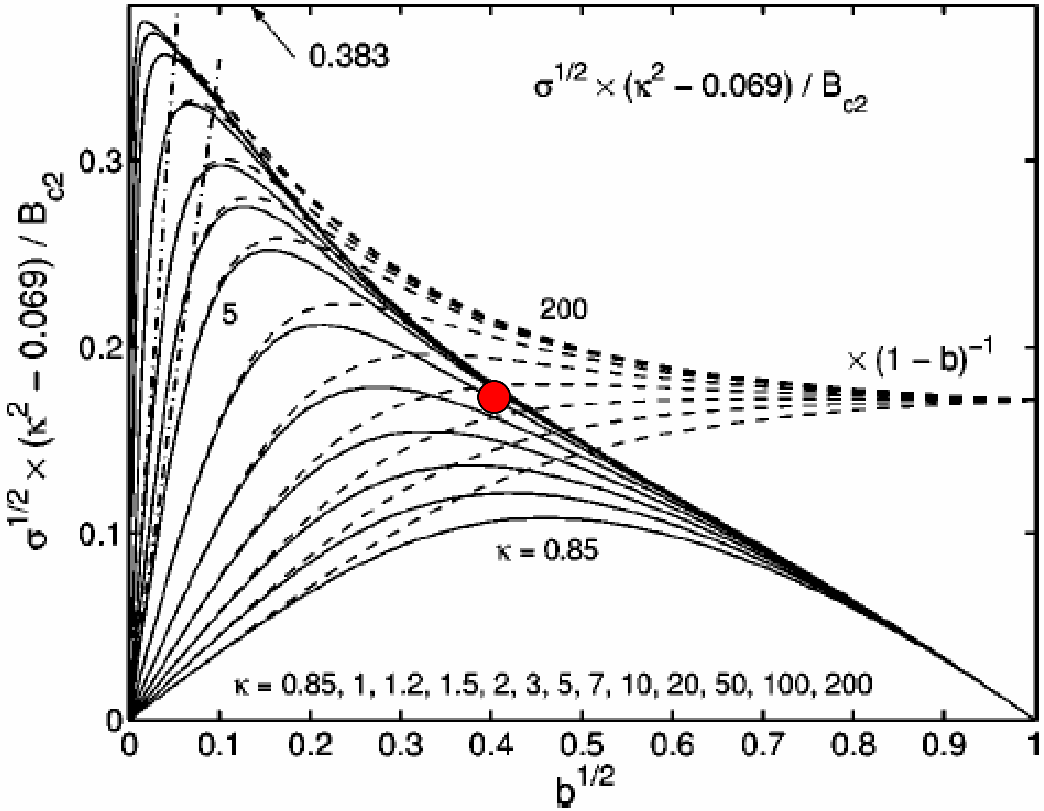


Significant broadening is larger than expected for vortex lattice (London equations) for H ~ H_{c2}

Why does broadening turn on at T_c, not at T_{FFLO}?

Los Alamos NATIONAL LABORATORY EST.1943

Vortex lattice broadening



H. Brandt, PRB **68**, 054506 (2003)

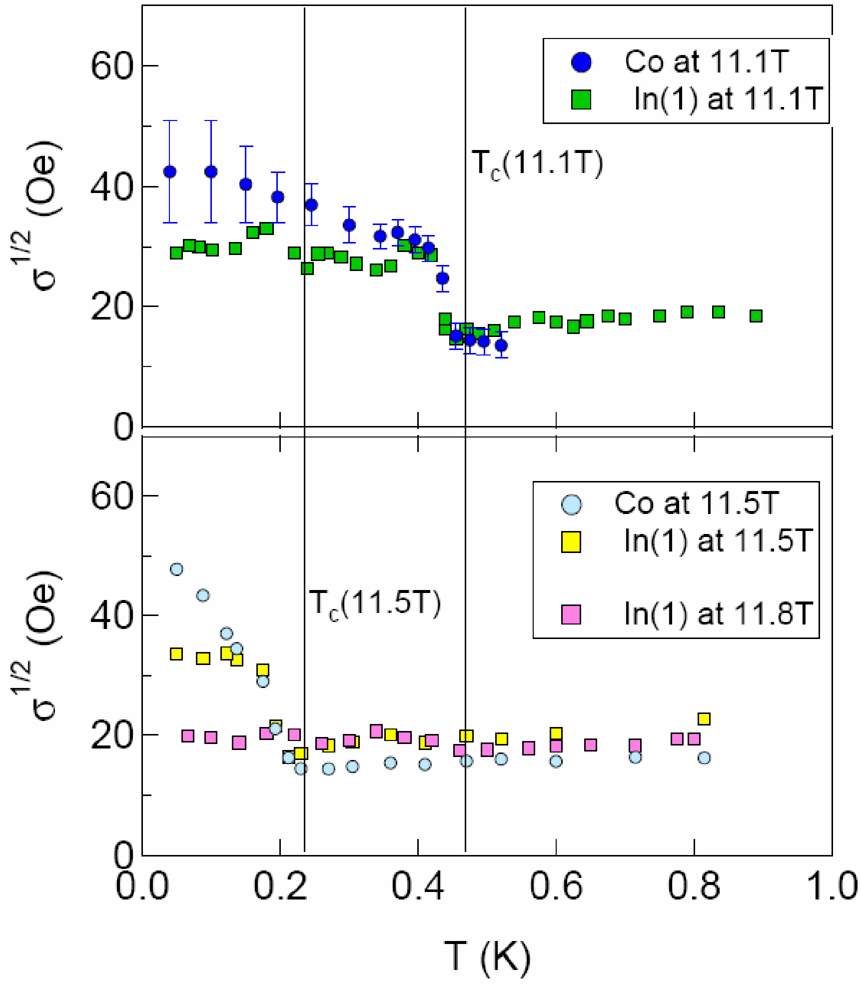
Detailed calculations by Brandt for second moment of vortex lattice as function of field

Assume B_{c2} ~ 35-40T is the orbital limiting field!

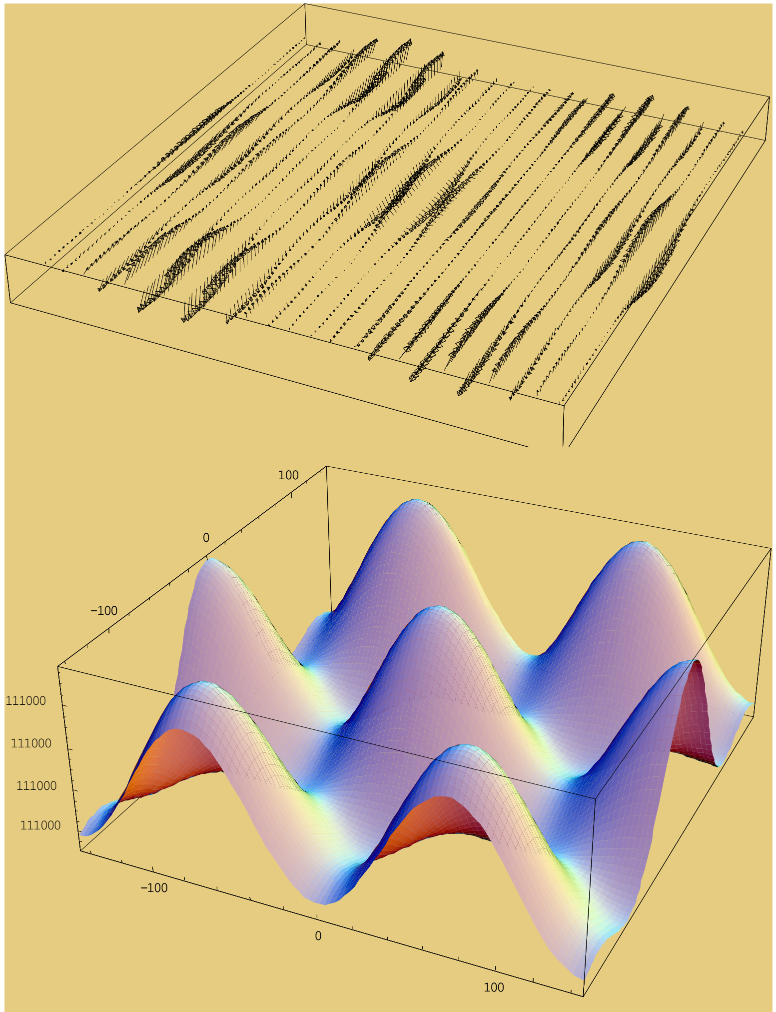
κ ~ 50-60 for $CeCoIn_5$

Linewidths at In(1) and Co

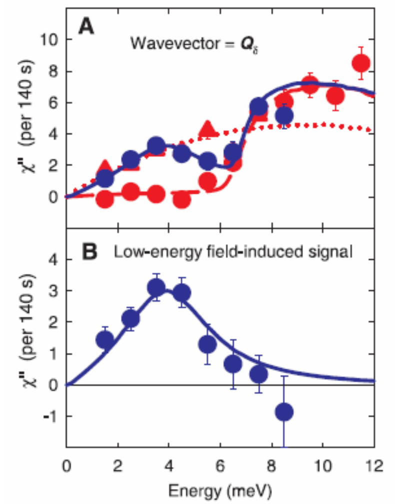
- *Magnetic broadening at T_c, not at T_{FFLO}*
- *Expected vortex lattice broadening ~ 2-12 Oe*
- *Different broadening at In(1) and Co – not expected for any modulation associated with superconductivity (coherence length >> unit cell)*
- *Broadening must be due to hyperfine fields, hence spin (not orbital) magnetization*



A possible interpretation



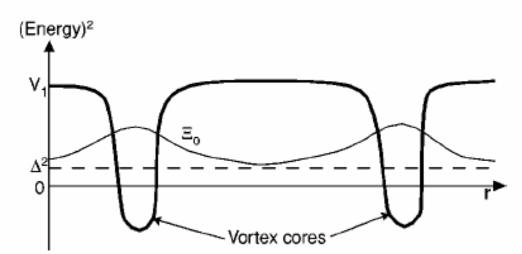
$$f(\mathbf{r}) = {}^{\eta}\gamma |\mathbf{H} + 4\pi \mathbf{M}_o(\mathbf{r}) + A\mathbf{M}_s(\mathbf{r})|$$



Spins in the Vortices of a High-Temperature Superconductor

B. Lake,[1] G. Aeppli,[2,3*] K. N. Clausen,[3] D. F. McMorrow,[3] K. Lefmann,[3] N. E. Hussey,[4,5†] N. Mangkorntong,[4] M. Nohara,[4] H. Takagi,[4] T. E. Mason,[1] A. Schröder[6]

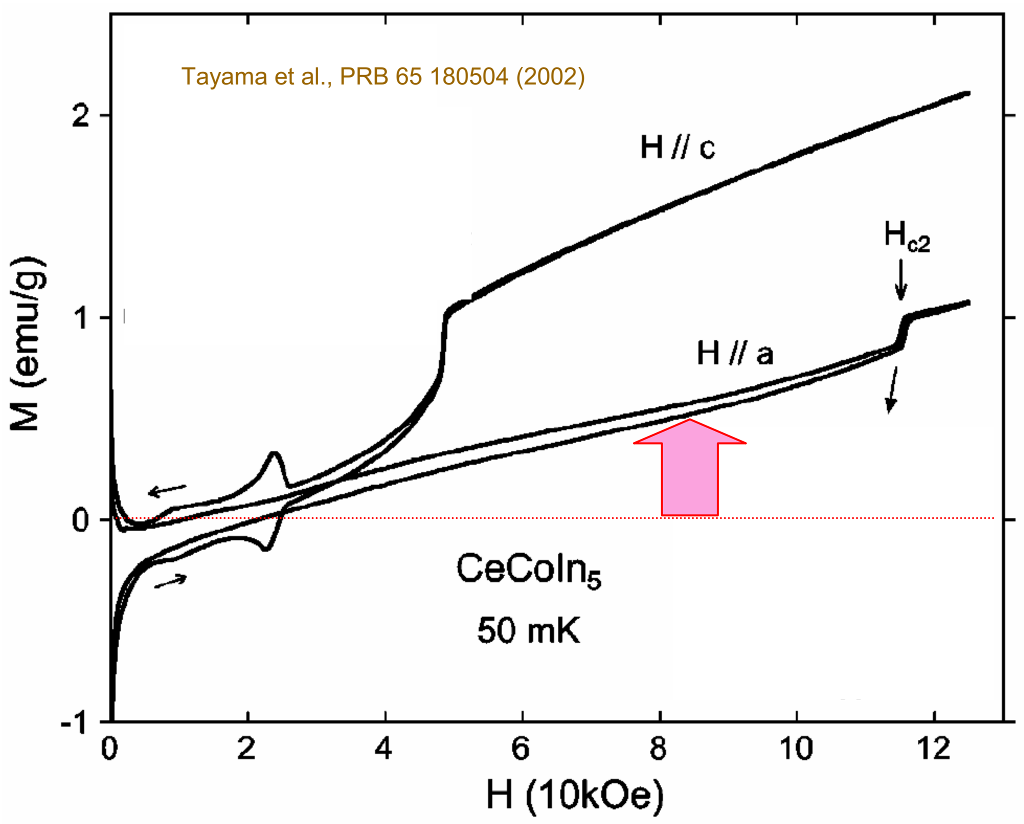
Neutron scattering evidence for polarized vortex cores in $La_{2-x}Sr_xCuO_4$



Demler et al., PRB 66 094501 (2002)

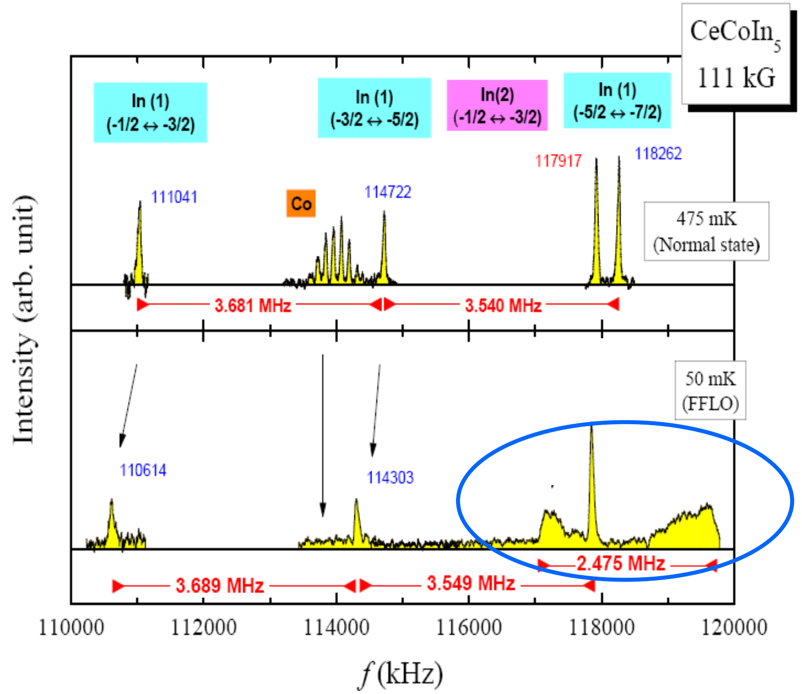
Los Alamos NATIONAL LABORATORY EST. 1943

Spin polarization in vortex cores



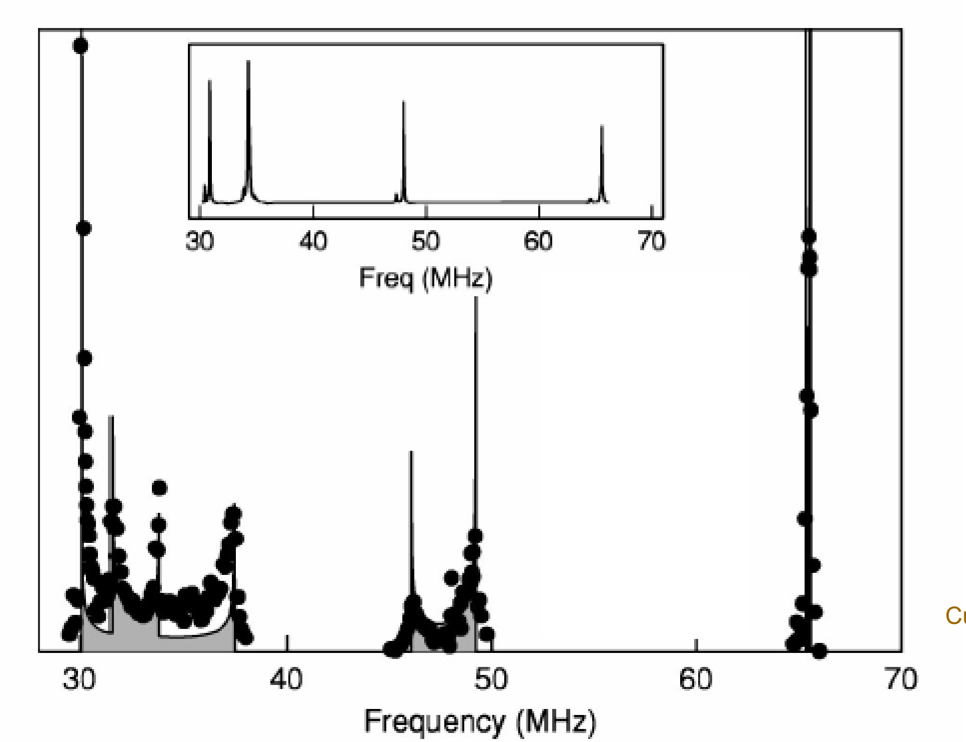
- *Magnetization curves at constant $T<T_c$ show positive magnetization in superconducting (mixed) state.*
- *Probably cause is from paramagnetic normal cores*
- *The core spin magnetization will affect the nuclear hyperfine field, and will be different at each site*

In(2) response in B phase



- *In(2) sees a broad, incommensurate distribution of fields in B phase*
- *Distribution of hyperfine fields / complex magnetic structure?*
- *Field distribution at In(1), In(2) and Co are different – NOT expected for FFLO, where modulation of spin density and orbital magnetization are on length scale ~ coherence length*

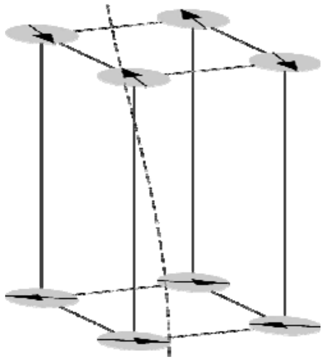
Incommensurate magnetism in $CeRhIn_5$



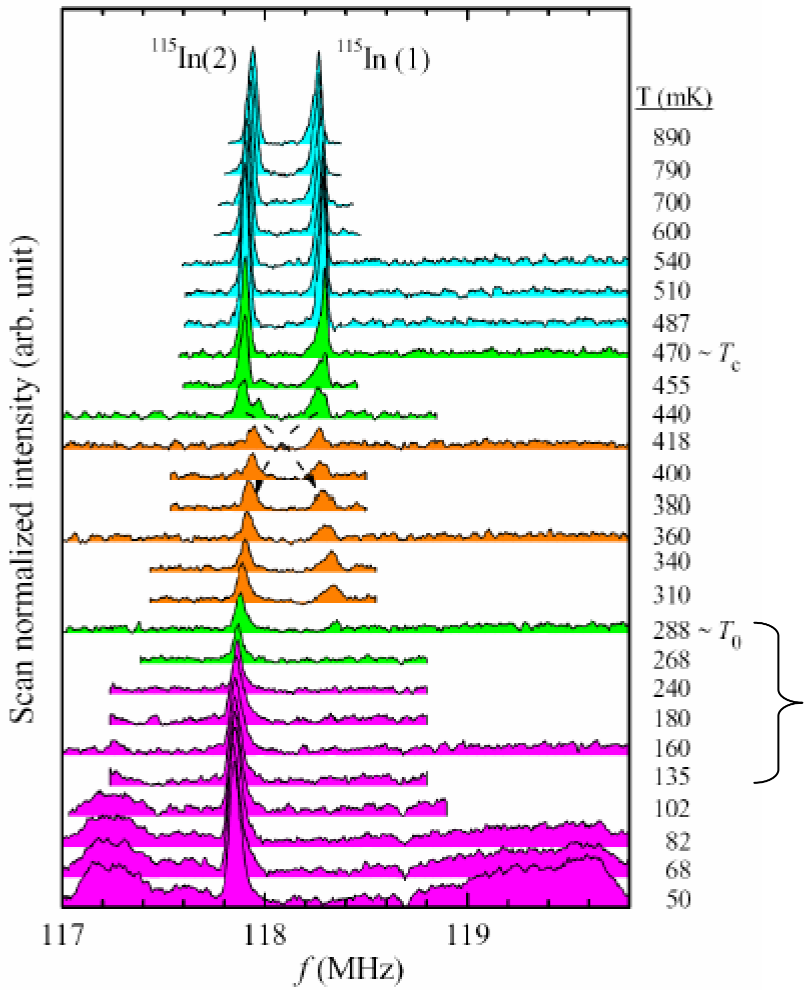
The In(2) site in the spiral antiferromagnet shows broad peak, similar to that observed in $CeCoIn_5$

The In(1) remains sharp

Curro et al., PRB 62 6100 (2000)

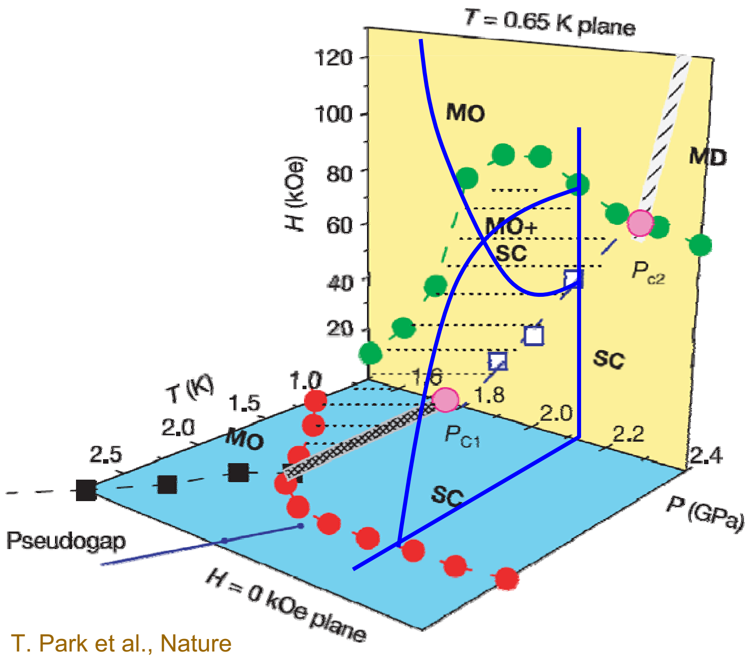


Slow dynamics



In(2) has large hyperfine field, and is wiped out by T2 effects – motional narrowing

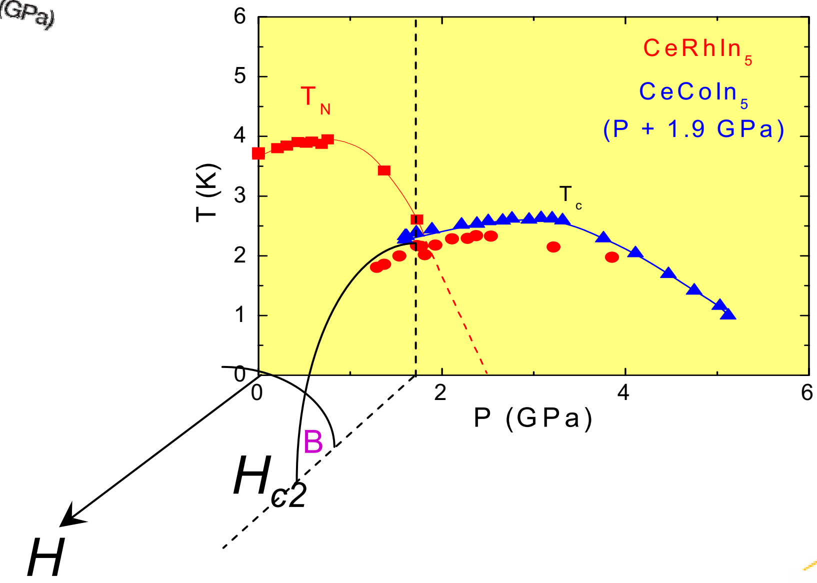
Field-Induced Magnetism



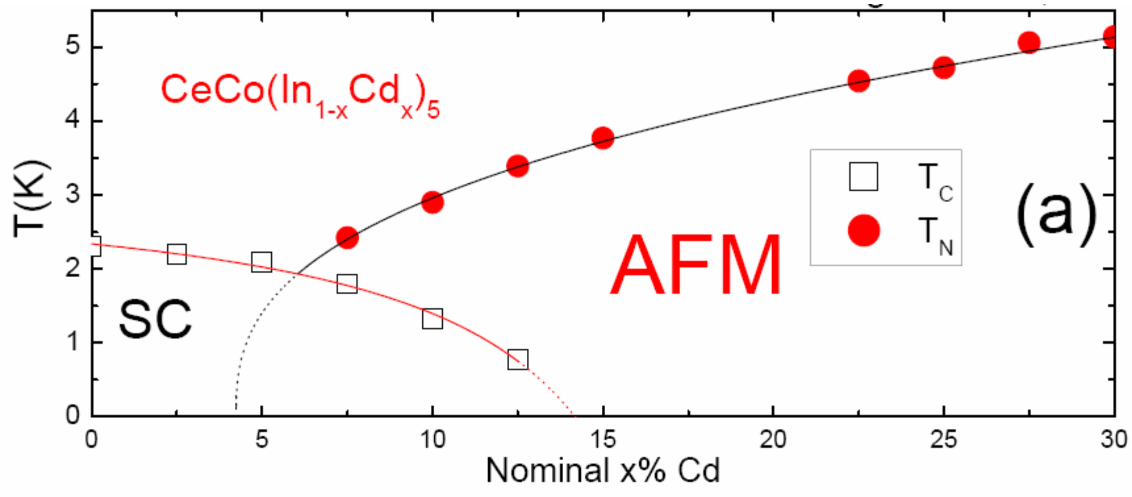
T. Park et al., Nature
440 65 (2006)

$CeRhIn_5$ shows field induced magnetism in superconducting state

Possibly the "FFLO" phase in $CeCoIn_5$ is a field-induced magnetic state that is stabilized by the d-wave superconductivity, where the magnetism in the vortex cores becomes correlated between vortices

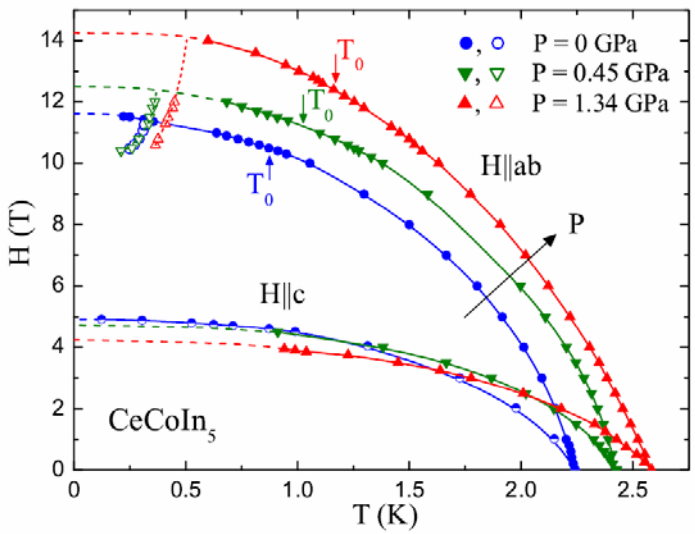


$CeCoIn_5$ at the edge of magnetism



Pham et al., PRL (2006)

Cd doping induced magnetism in $CeCoIn_5$



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

Pressure appears to stabilize the B phase

Summary

A phase: •*Clear evidence of first order transition*

•*Anomalously large magnetic broadening*

•*Suggests polarized spins in the vortex cores*

B-phase: •*Response within unit cell very different*

•*strongly suggestive of long range magnetic ordering of local moments*

•*A change of symmetry or a pure FFLO phase cannot explain these results*

•*Possibly a magnetic phase, or one that coexists with the FFLO*

•*Magnetism stabilized by superconductivity?*

See cond-mat/0604080

Los Alamos NATIONAL LABORATORY EST.1943