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PHYSIQUE STATISTIQUE,
MAGNETISME ET
SUPRACONDUCTIVITE

Résonance de spin et ordre magnétique induit dans le supraconducteur non-conventionnel $CeCoIn_5$

Stéphane Raymond

UNIVERSITE JOSEPH FOURIER

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Outline

- Introduction

- Spin resonance under magnetic field : polarized neutron study

- Magnetic order stimulated by *d*-wave superconductivity

- Discussion and perspectives

Collaborators

PRL 109, 237210 (2012) PHYSICAL REVIEW LETTERS week ending 7 DECEMBER 2012

Evidence for Three Fluctuation Channels in the Spin Resonance of the Unconventional Superconductor $CeCoIn_5$

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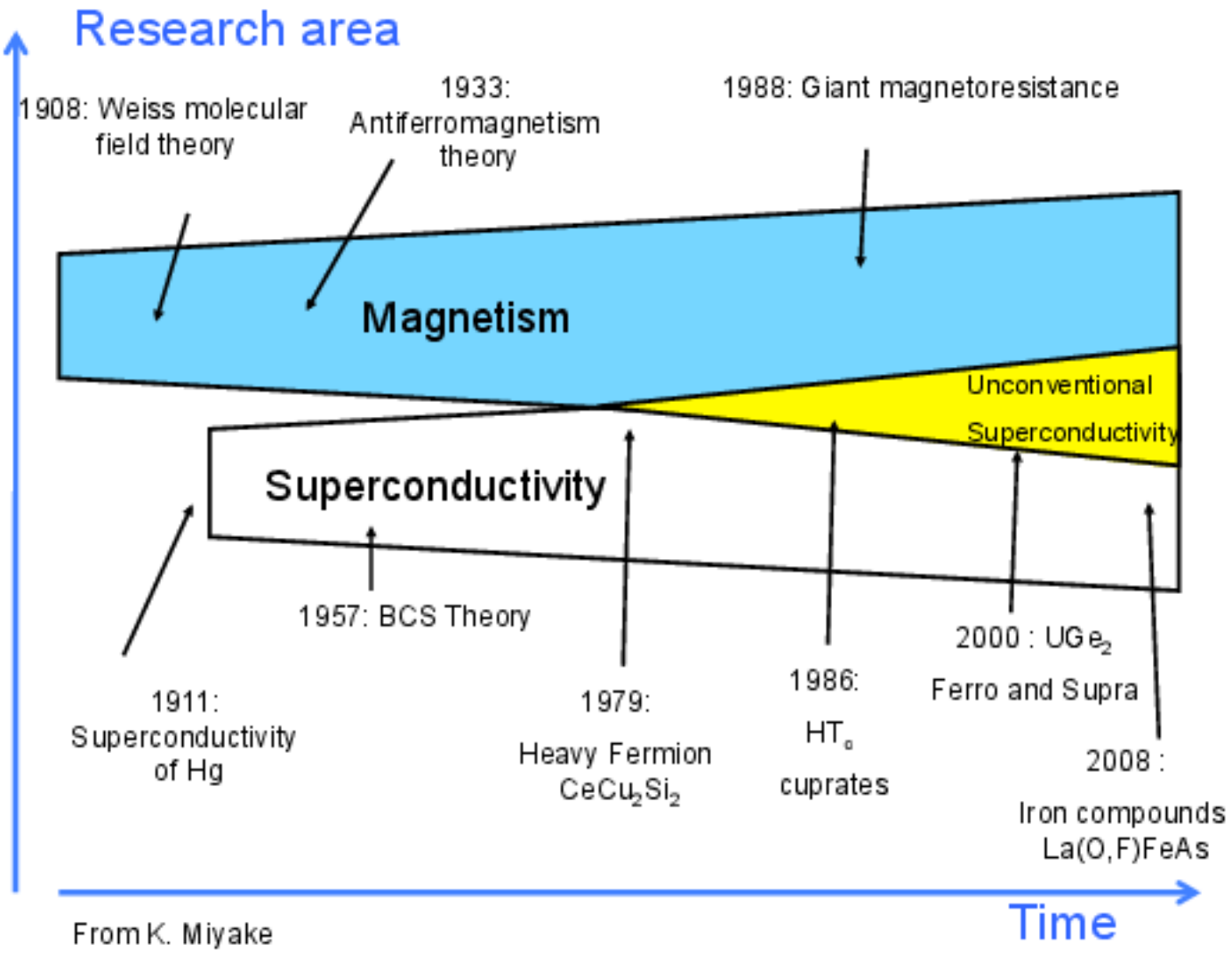
Magnetic order in $Ce_{0.95}Nd_{0.05}CoIn_5$: the Q-phase at zero magnetic field

S. Raymond, S. M. Ramos, D. Aoki, G. Knebel, V. Mineev and G. Lapertot[1]
[1]*SPSMS, UMR-E 9001, CEA-INAC/UJF-Grenoble 1, 38054 Grenoble, France*
(Dated: July 11, 2013)

To be published in J. Phys. Soc. Japan 83 (2014)

Magnetism and superconductivity



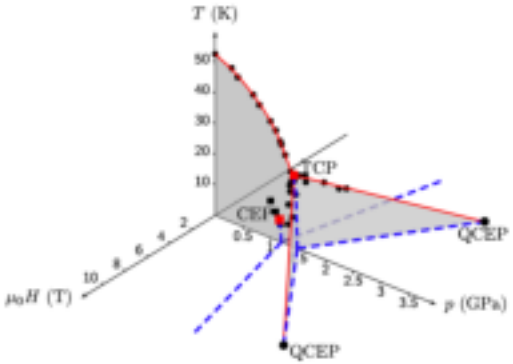
Heavy fermion systems

4*f* and 5*f* electron based systems with strong correlations -> large m*≈ 100-1000 me

-> solid state physics with small T_F ≈ 10-100K

Large effect of T, H, P, x -> New effects !

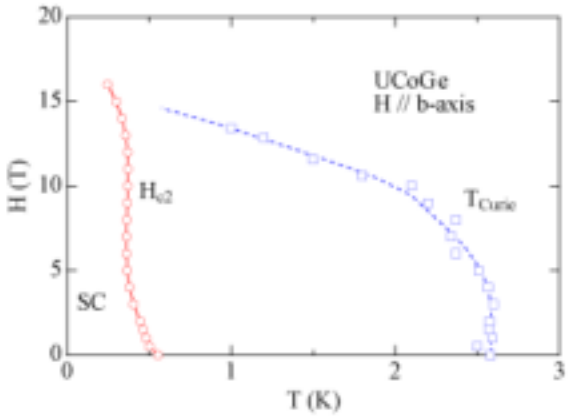
Quantum criticality



Tricritial point in itinerant FM

UGe_2 Taufour (2010)

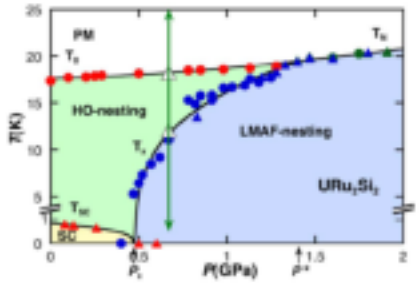
Unconventional SC



Ferro supra

UCoGe Aoki (2009)

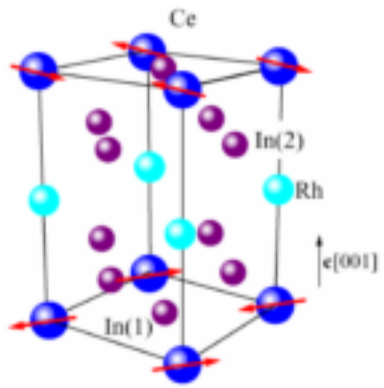
Multipolar order



URu_2Si_2

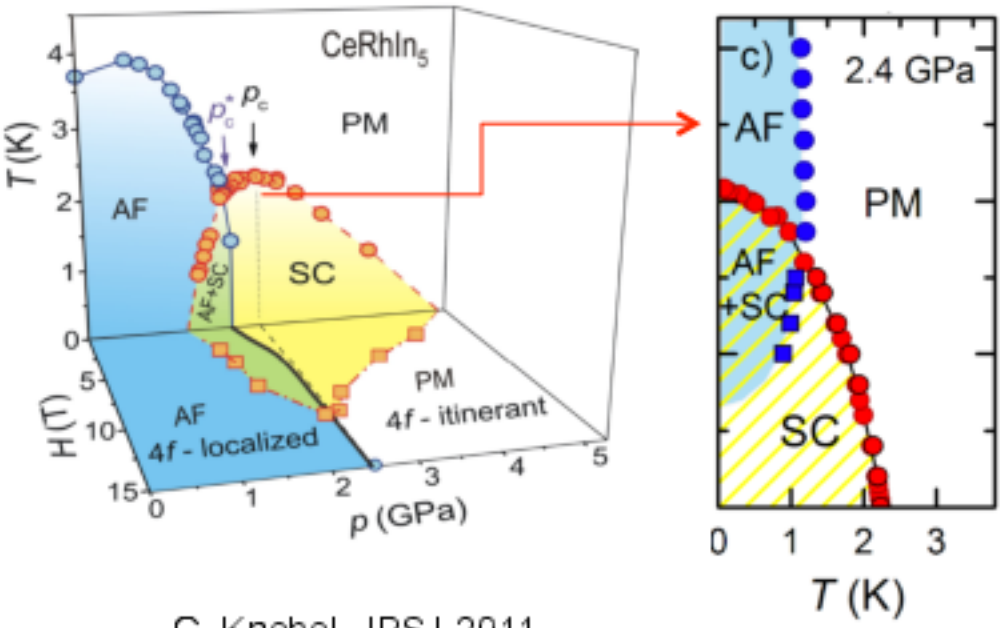
OP = dotriacontapole ?

$J_xJ_yJ_z(J_x^2-J_y^2)$



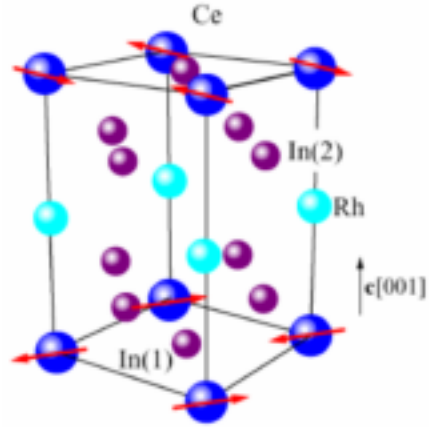
Ce 1-1-5 compounds realize unique case of $T_N \approx T_C$

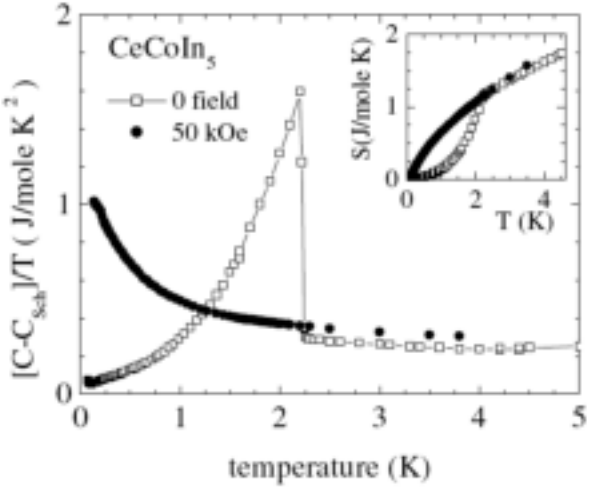
interplay AFM / SC can be tuned by P, H, x



G. Knebel, JPSJ 2011

heavy fermion superconductor with highest transition temperature T_c = 2.3 K
in absence of SC : γ ≈ 1000 mJ /molK^2

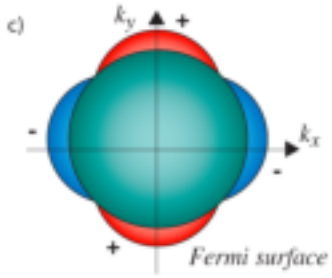


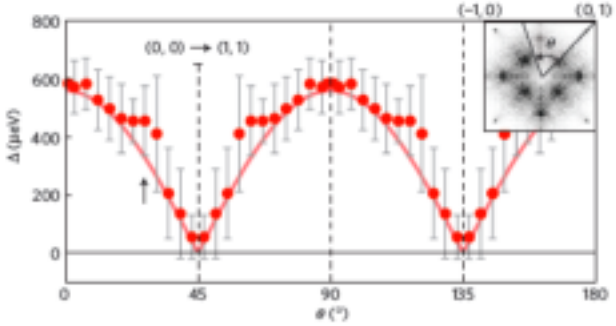


C. Petrovic, 2001

d-wave symmetry of superconducting gap

SC gap d_{x2-y2}





STS

M.P. Allan , 2013

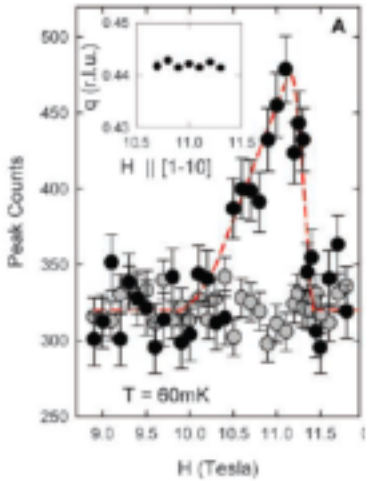
B. Z. Zhou, 2013

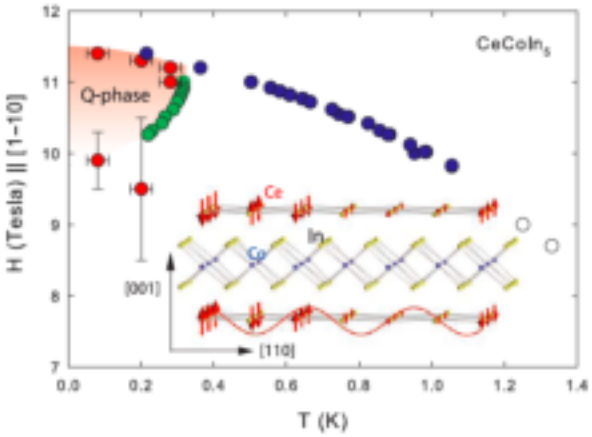
$CeCoIn_5$: magnetic field effects

-

Antiferromagnetic order induced by magnetic field (applied in plane)

incommensurate magnetic ordering k=(0.44, 0.44, 0.5) and m//c





Kenzelmann, Science 2008

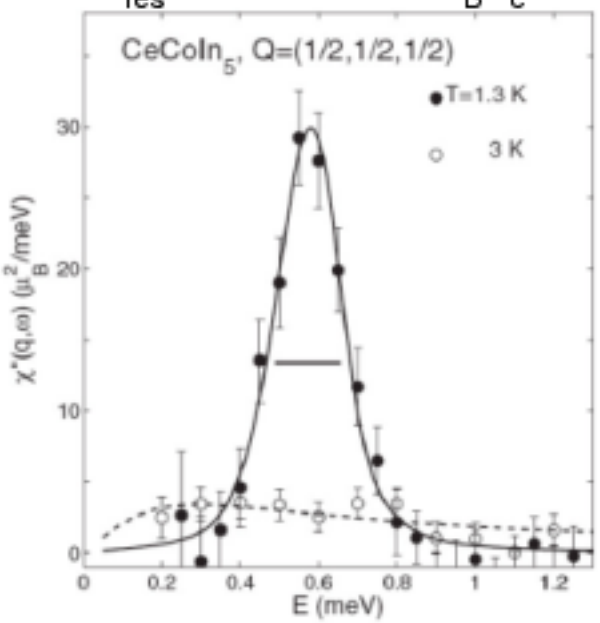
disappears at H_{c2} : cooperative effect between magnetism and SC

Spin resonance in $CeCoIn_5$

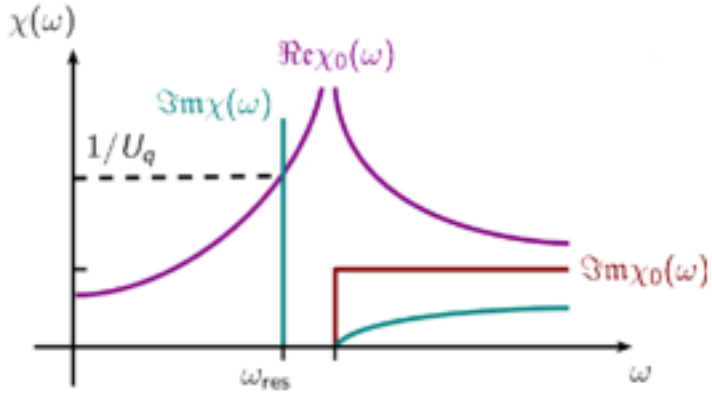
Inelastic Neutron Scattering experiment :

well defined magnetic excitation appearing below T_c at wave-vector (1/2, 1/2, 1/2)

$\Omega_{res} = 0.6\ meV \approx 3k_BT_c$



C. Stock et al., PRL 100 (2008) 087001



1) Susceptibility in SC phase, coherence factor :

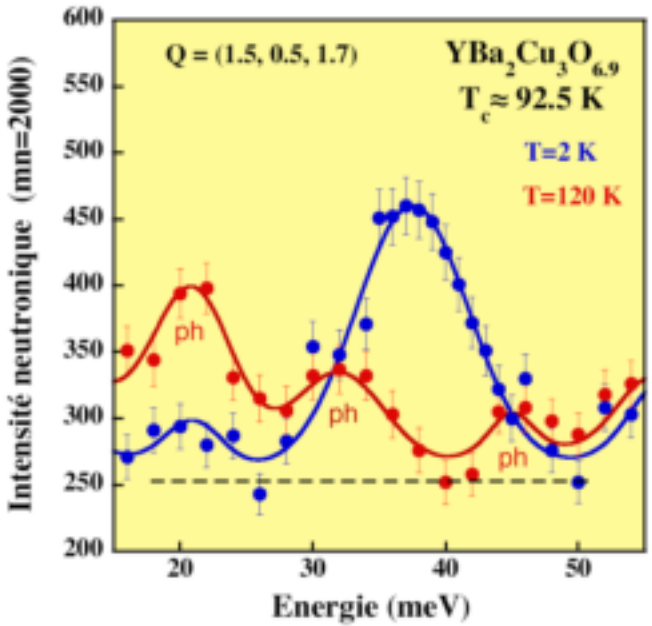
$$\chi_0(q,\omega) = -\frac{1}{(g\mu_B)^2}\lim_{\delta\to 0}\sum_k \frac{1}{2}\left[1-\frac{\tilde{\xi}(k+q)\tilde{\xi}(k)+|\Delta(k+q)\Delta(k)|}{E(k+q)E(k)}\right]\frac{f(k+q)-f(k)}{\hbar\omega-\left[E(k+q)-E(k)\right]-i\delta}$$

2) Interaction -> collective mode below the gap

$$\chi_{RPA} = \frac{\chi_0}{1-U_q\chi_0}$$

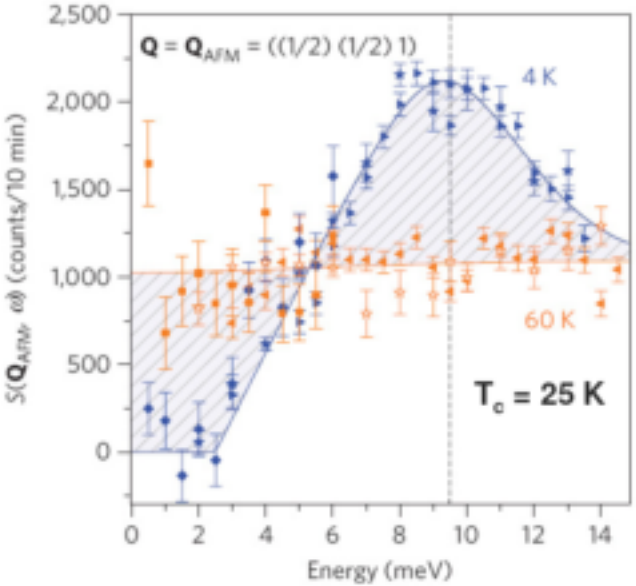
Spin resonance in other unconventional SC

Discovered in $YBa_2Cu_3O_{6+x}$
by J. Rossat-Mignod et al. (1991)



L.-P. Regnault, unpublished

Fe superconductor
$BaFe_{1.85}Co_{0.15}As_2$



D. Inosov et al., Nature Physics 6 (2010) 178

- resonance appears below T_c
- at the wave-vector k for which $\Delta(Q+k) = -\Delta(Q)$
- with the energy $\Omega_{res} \approx 0.6\ \Delta$

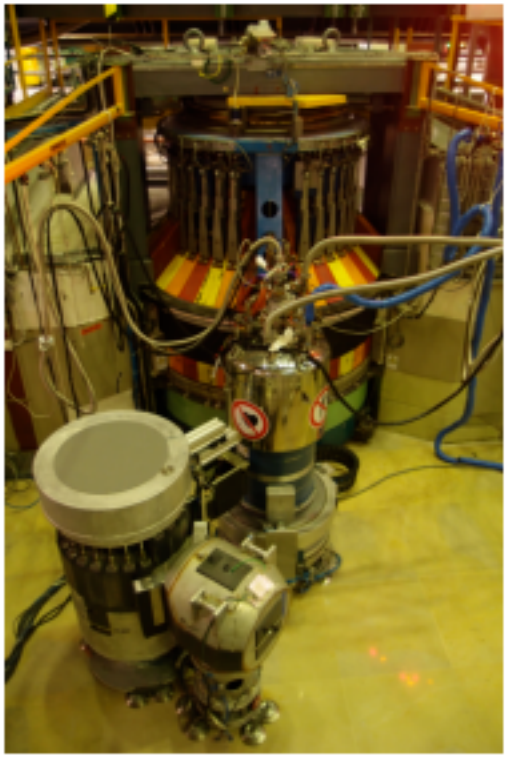
Resonance in $CeCoIn_5$

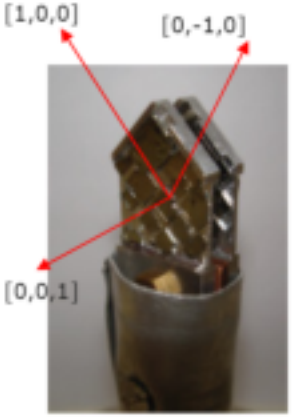
-Study as a function of H : 1 - relation with field induced AF ?

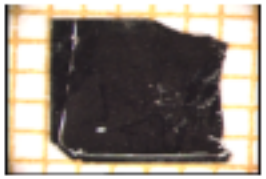
2 - lifting of degeneracy ?

-> insight into nature of this excitation and on superconductivity

Cold neutron TAS IN14 and IN12 (ILL, Grenoble)







Thickness 0.1 mm

Typical assembly of ≈ 50 samples

Total volume ≈ 100 mm^3

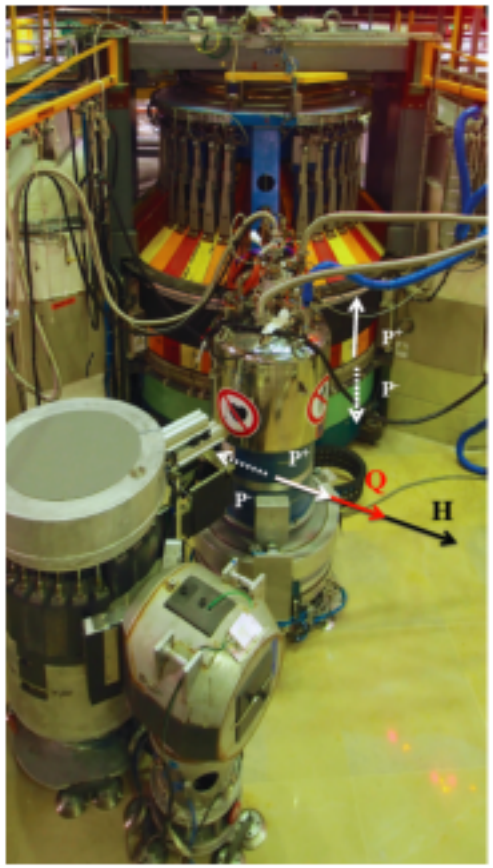
Mosaicity ≈ 1 degree

Flux method : G. Lapertot

$CeCoIn_5$ under H : polarized INS

Polarized neutron scattering in horizontal magnetic field (H // Q // P_0)

Initial beam is polarized (P_0) and the final polarization is not analyzed



$$\frac{d^2\sigma}{d\Omega d\omega} = < \boldsymbol{M}_{\perp \boldsymbol{Q}} . \boldsymbol{M}^{\dagger}_{\perp \boldsymbol{Q}} >_E - i P_0 < \boldsymbol{M}_{\perp \boldsymbol{Q}} \times \boldsymbol{M}^{\dagger}_{\perp \boldsymbol{Q}} >_E$$

↓ Usual correlation function → F

↓ Chiral contribution → G_{ch}

We measure $F \pm P_0 G_{ch}$

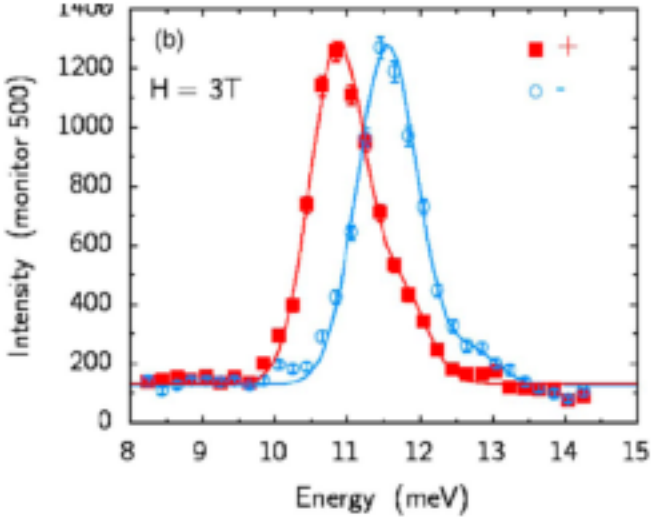
1- information of degeneracy of excitation

2- information on polarization of excitation

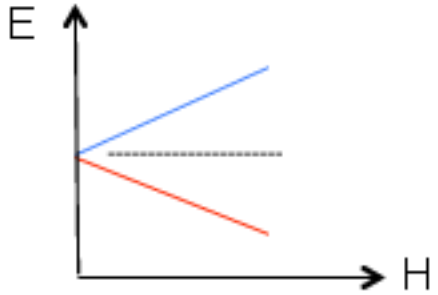
Demonstrative experiment

Example spin chain / ladder $Sr_{14}Cu_{24}O_{41}$ under H (Lorenzo et al., PRB 75 (2007) 054418)

Singlet – Triplet energy gap splitted by the magnetic field

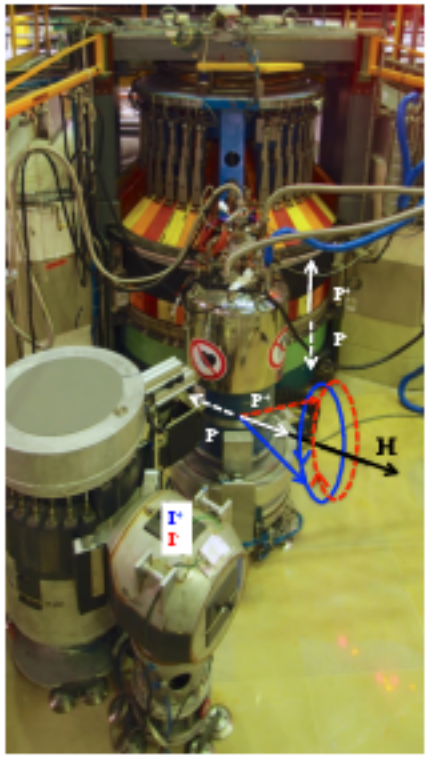


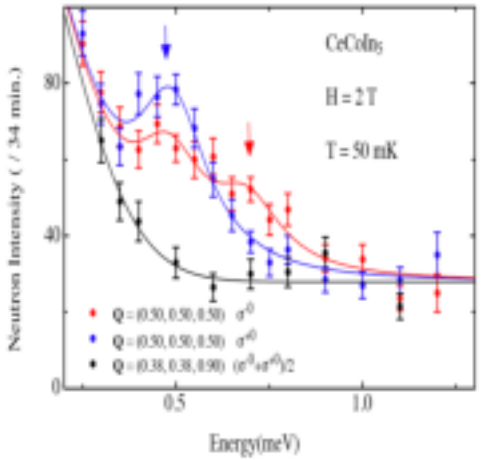
Different precession handedness selected by neutron polarisation

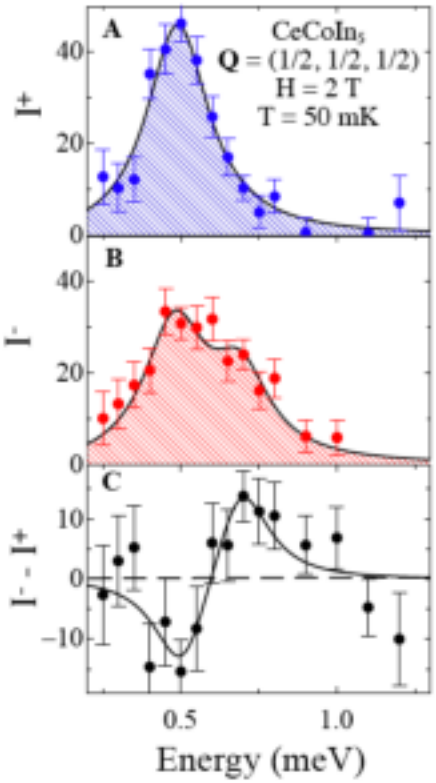


-> resolution of a small splitting

$CeCoIn_5$ under H : polarized INS







I-I+ is symmetric around Ω(H=0) : Zeeman splitting under H

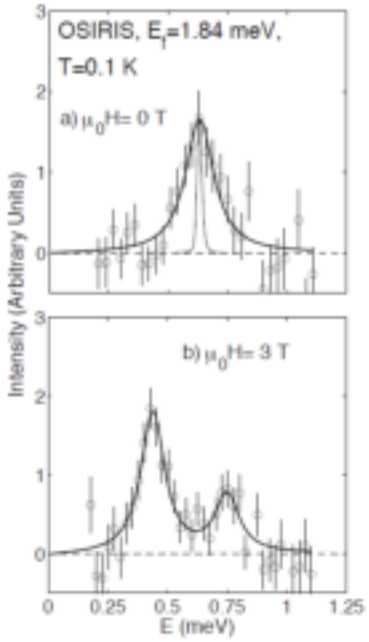
Polarization of fluctuations is more complicated than a simple spin precession around H

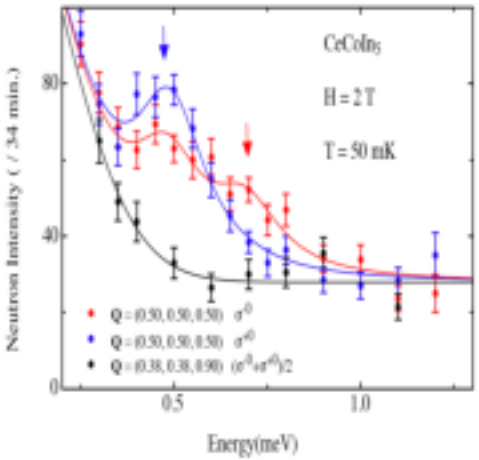
Zeeman splitting not so trivial for superconducting resonance : at least a doublet.

$CeCoIn_5$ under H : polarized INS

Result consistent with previous unpolarized neutron experiment (peak position, global intensities)

C. Stock et al., PRL 109 (2012) 167207





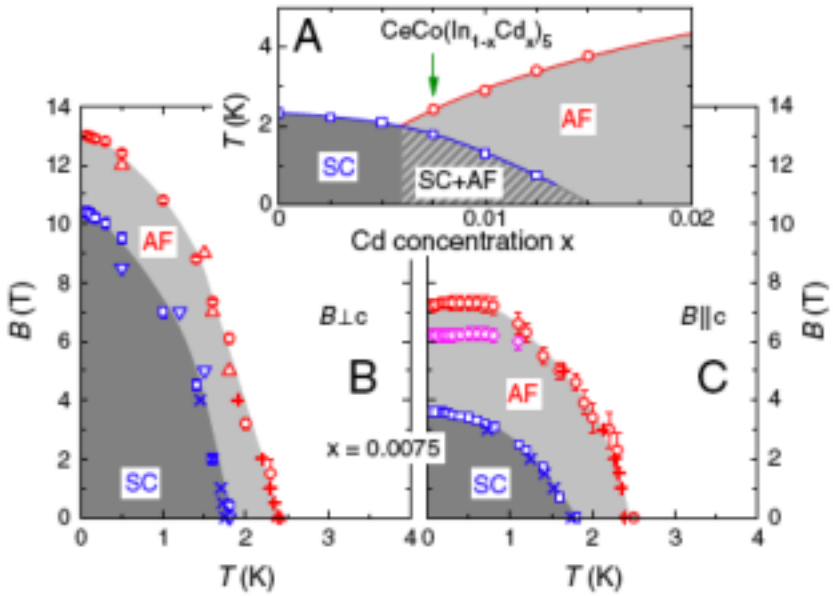
New information : complex polarization pattern

Need to understand this complexity : - role of crystal field anisotropy (here H // [1,1,1])
- role of electronic continuum above resonance under H

Chemical subsitution on $CeCoIn_5$

$CeCoIn_5$ is very close to quantum critical point

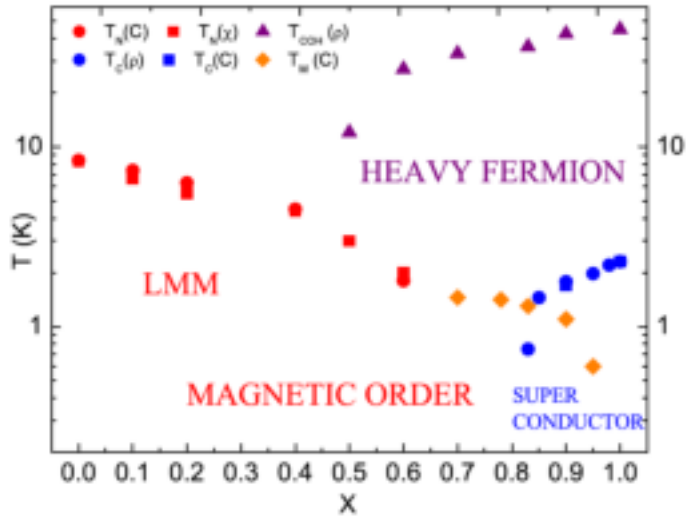
- Non Fermi liquid behaviour in bulk measurments
- Magnetic ordering for low substitution.
- $T_N > T_C$; commensurate **k**=(1/2, 1/2, 1/2)



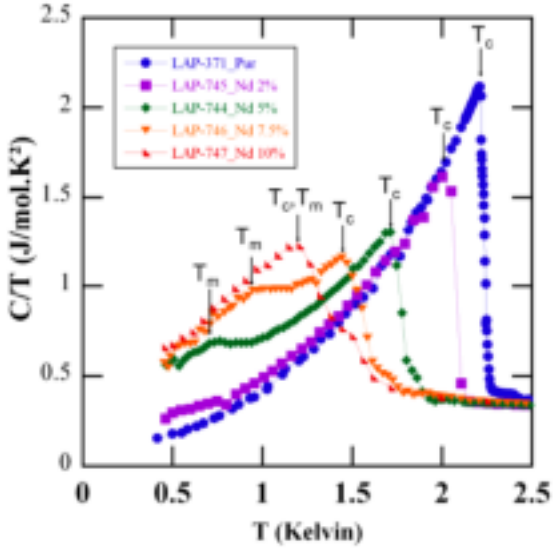
Nair, PNAS 2010

$Ce_{1-x}Nd_xCoIn_5$

Nd substitution : rare experimental case with $T_N < T_c$

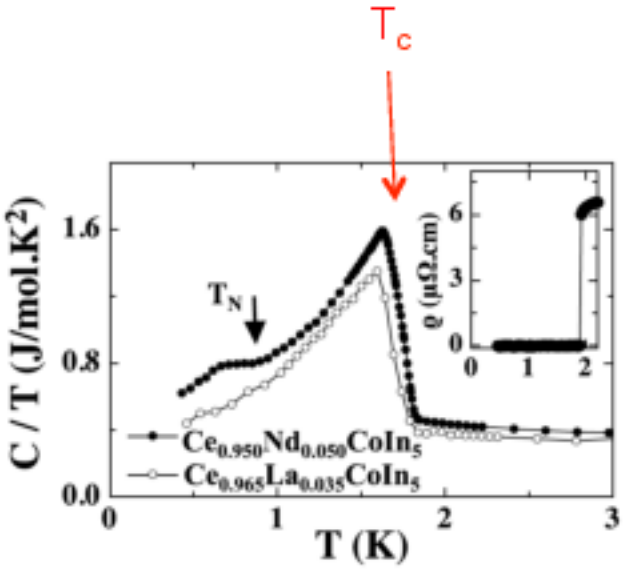


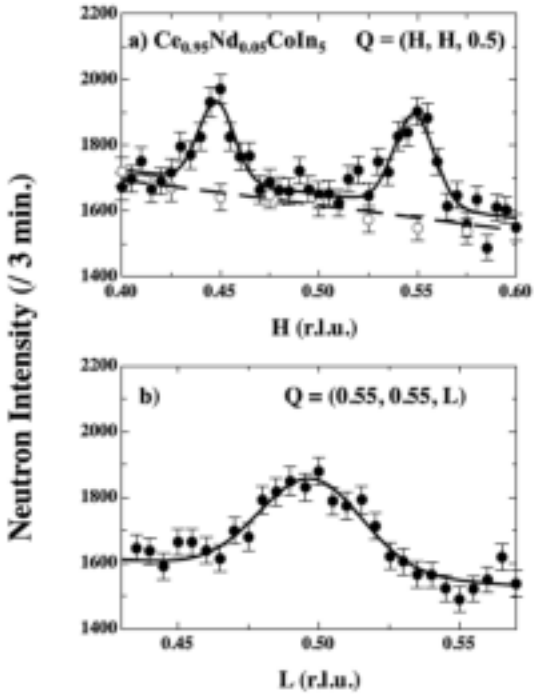
Hu, PRB 2008

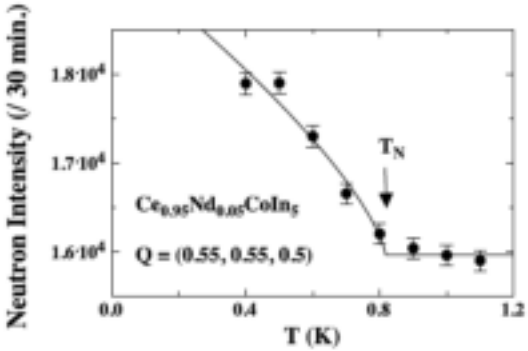


Panarin (PhD)

Neutron diffraction results (IN12)



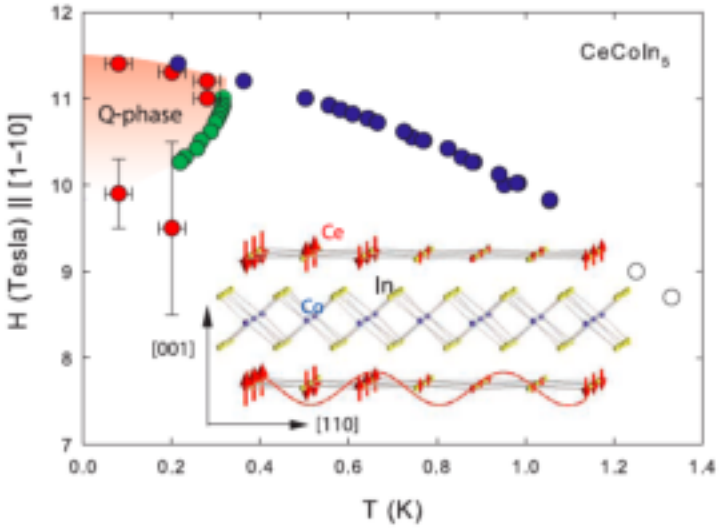




Incommensurate order with **k**=(0.45, 0.45, 0.5) is found !! M ≈ 0.1 μ_B

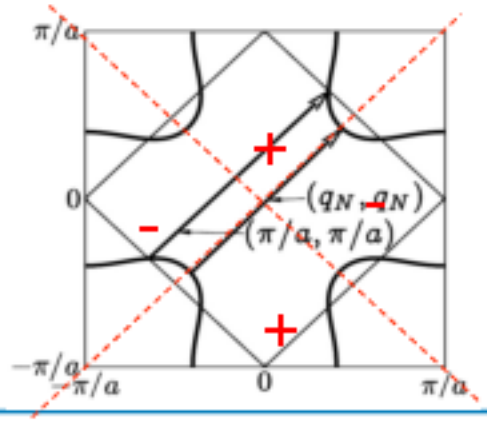
Important remark : for isotropic SC, magnetic order is not possible below T_c

Up to now, this incommensurate order was found only under H (in $CeCoIn_5$)



Proposed theoretical models

- multicomponent order parameter
(SDW and SC with q≠0 : FFLO, PDW, π-triplet)
(Yanase 2011, Aperis 2010, Agterberg 200
- role of the vortex lattice (Sukuki 2011)
- importance of Pauli limited superconductivity
(Ikeda 2010)
- spin-exciton condensation (Michal 2011)
- enhancement of nesting by superconductivity
(Kato 2011)



Without H (« no escape »), possible scenario is

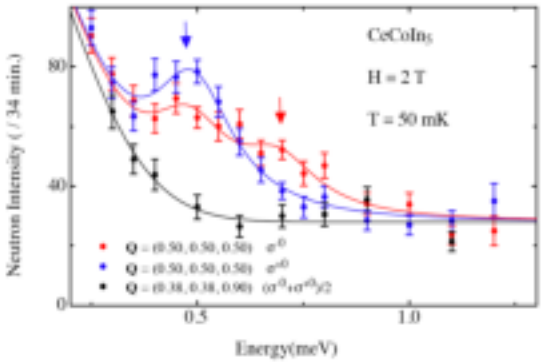
Enhancement of nesting condition by d-wave SC

Discussion and perspectives

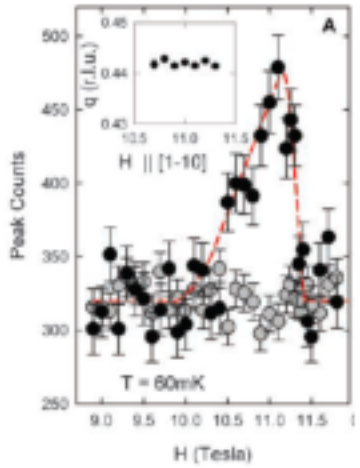
Spin resonance

Magnetic ordering

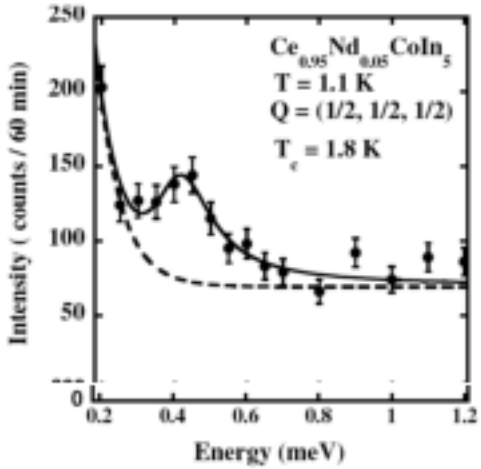
$CeCoIn_5$ under H



?

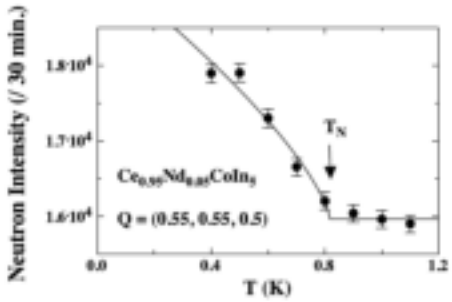


$CeCoIn_5$, 5% Nd



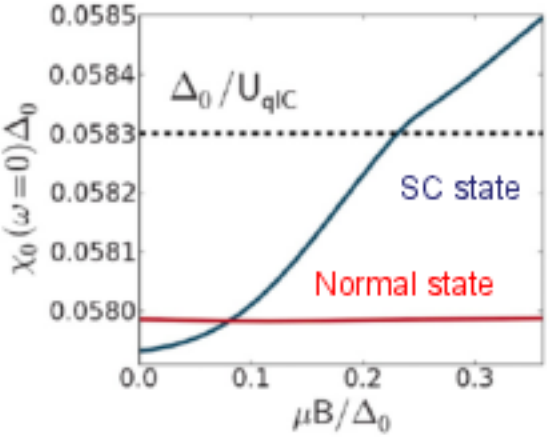
$T > T_N$

?

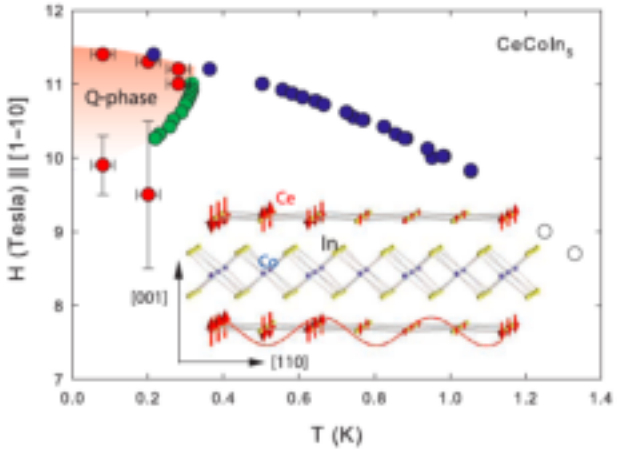


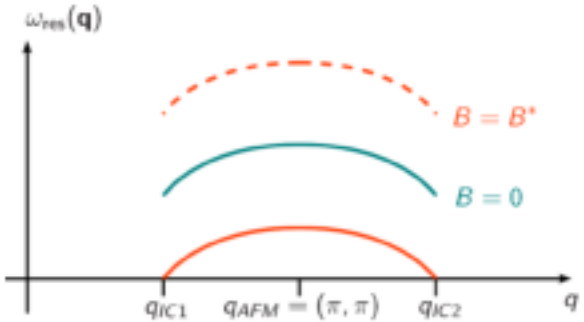
$CeCoIn_5$ under H : soft mode theory

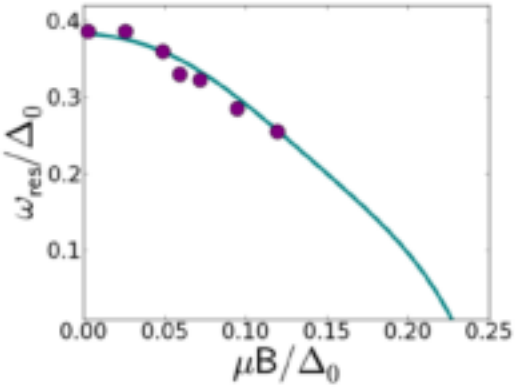
Magnetic correlations enhanced due to d_{x2-y2} SC



Excitation : soft mode leading to high magnetic field induced AF phase (here Ising)





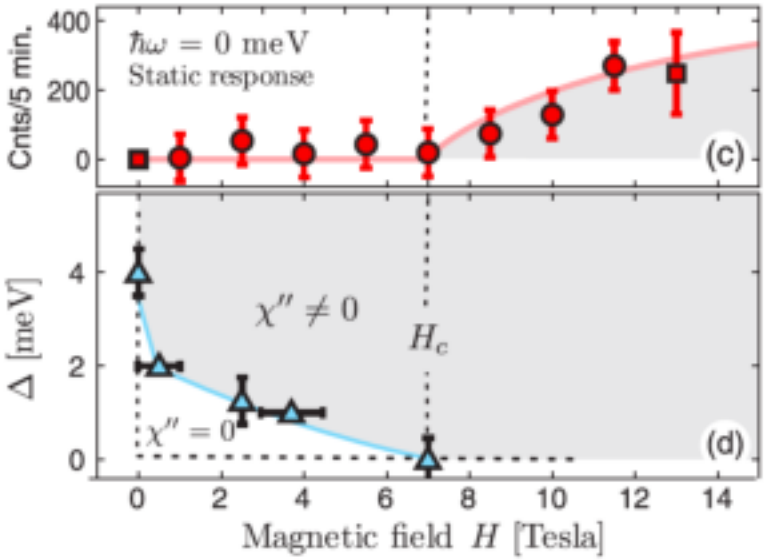


V. Michal and V. Mineev, PRB 84 (2011) 052508

V. Michal, proceedings SCES 2011

$CeCoIn_5$ under H : soft mode theory

Such scenario may occur in $La_{1.855}Sr_{0.145}CuO_4$



J. Chang et al., Phys. Rev. Lett. 102 (2009) 177006

Does magnetism exist above H_{c2} ?

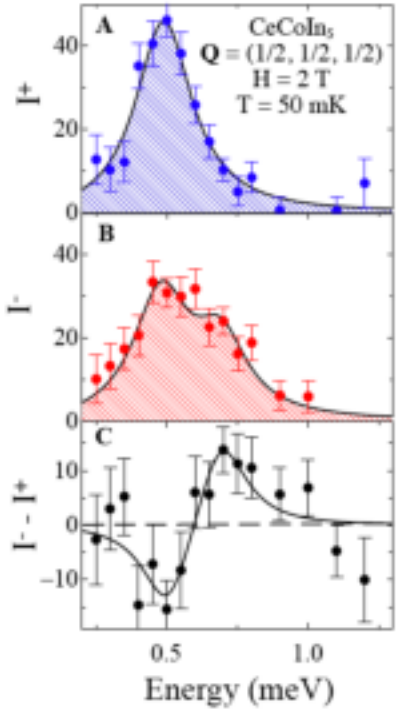
$CeCoIn_5$ and HF with low energy scales are better suited to study these effects.

Conclusion

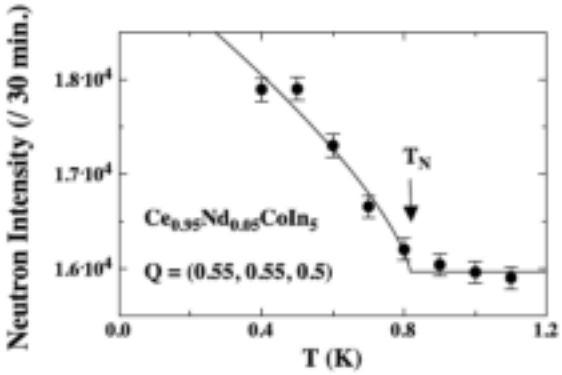
Polarized neutron experiment under H

Reveals new features of spin resonance

At least 2 modes ……



Magnetic order inside SC phase



-> question of mechanism

d-wave SC stimulated ?

Relationship between excitation and magnetic order to be addressed

Many microscopic data to help understanding unconventional superconductivity …