Minicurso de Supercondutividade Experimental

IFGW Escola de Inverso 2015: Fenômenos emergentes em Magnetismo e Supercondutividade

Universidade de Campinas
Instituto de Física "Gleb Wataghin"
20-31 Julho 2015

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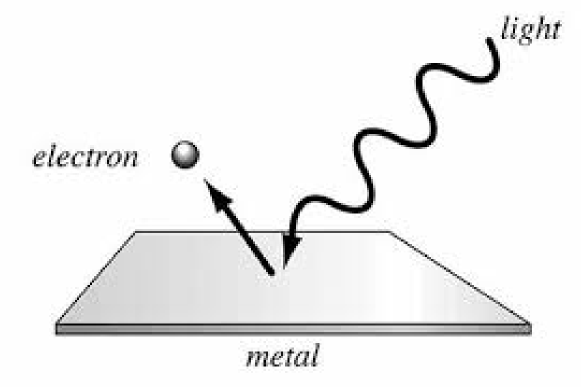
Photoemission Spectroscopy

Photoemission

Photoelectric effect: A metal can absorb a photon and eject an electron. If we can measure the KE of the ejected electron, then we can probe the density of states.

$$\hbar\omega = W + E_{\mathbf{k}} + \frac{1}{2}mv^2$$

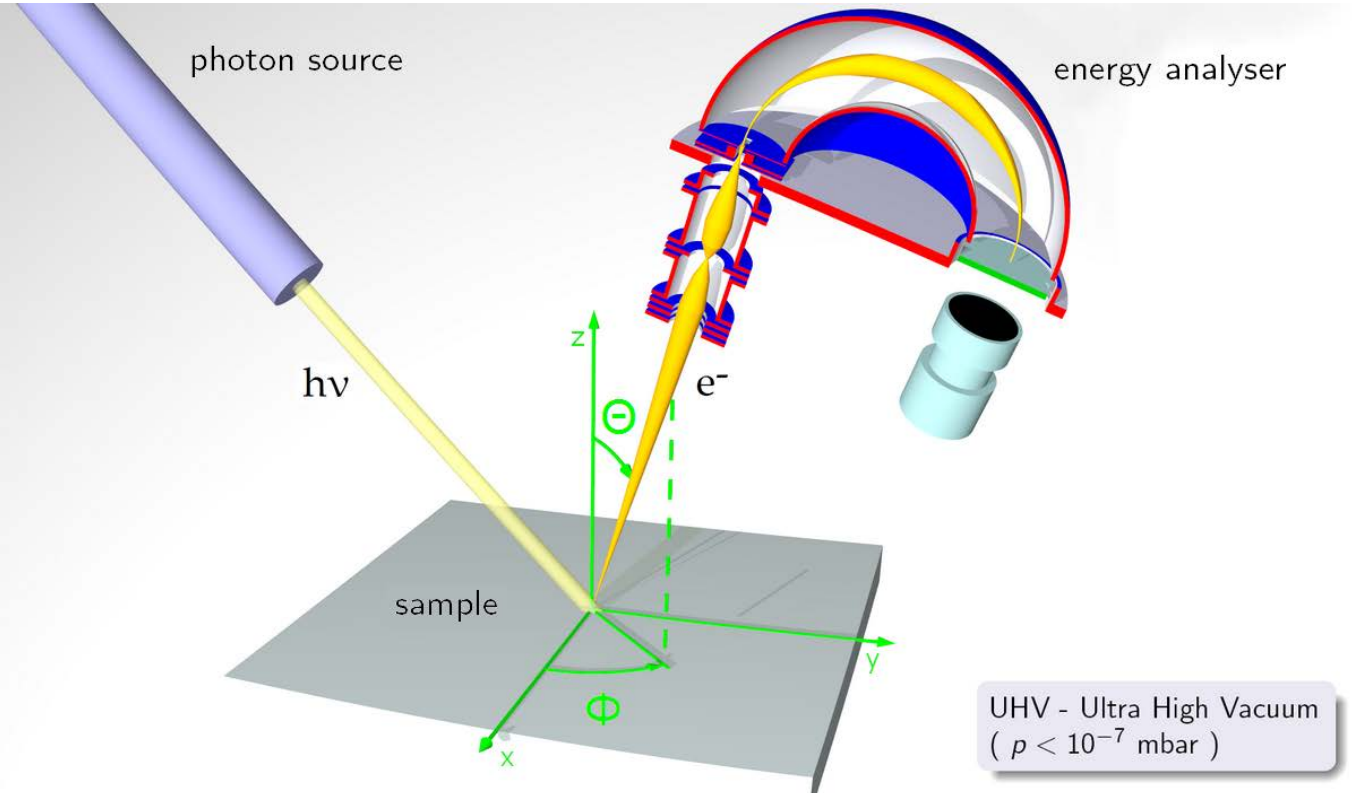


Can use this effect to probe the **energy gap**. However, this requires exceptionally high precision to measure energy gaps on the order of meV

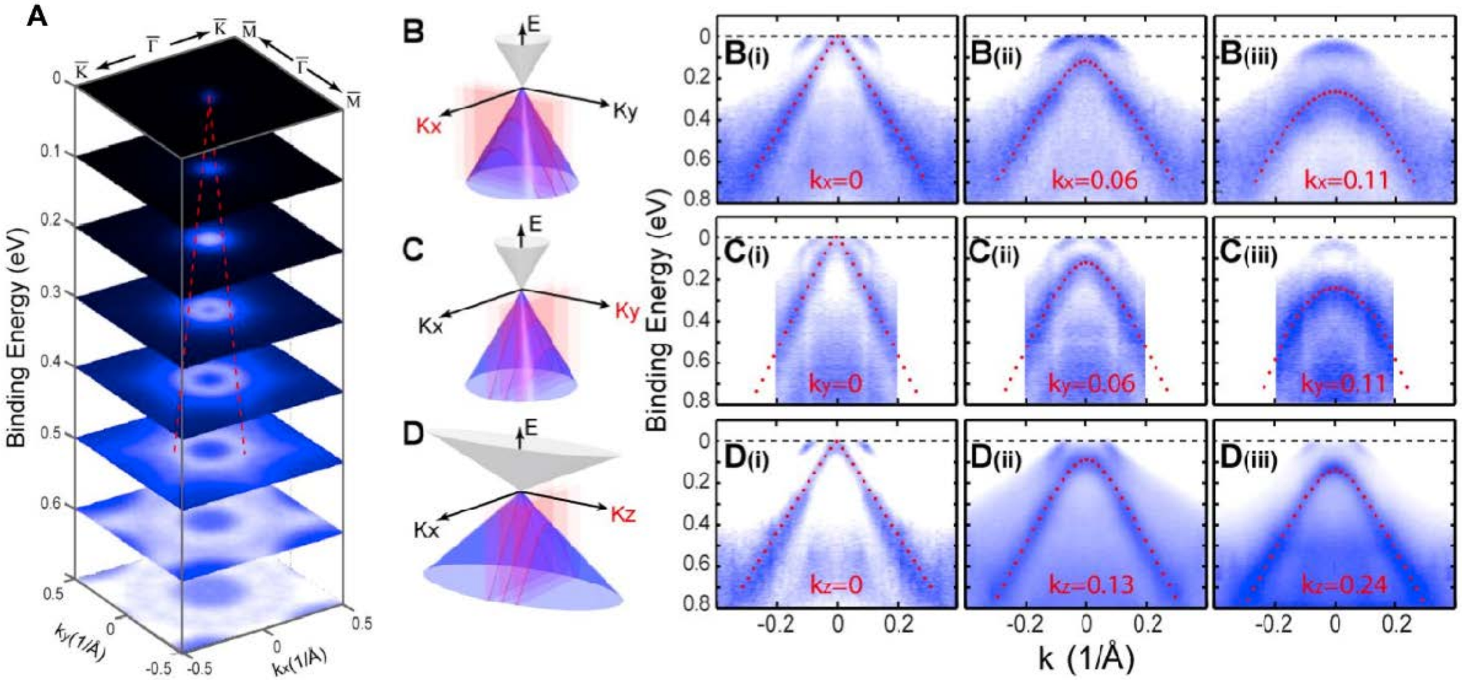
Photons are on the order of several eV

Angle Resolved Photoemission

If measure the momentum of the ejected photon, then can get the actual energy dispersion in the material. Modern synchrotrons and photoemission equipment can now directly probe the **k**-dependence of the energy gap!

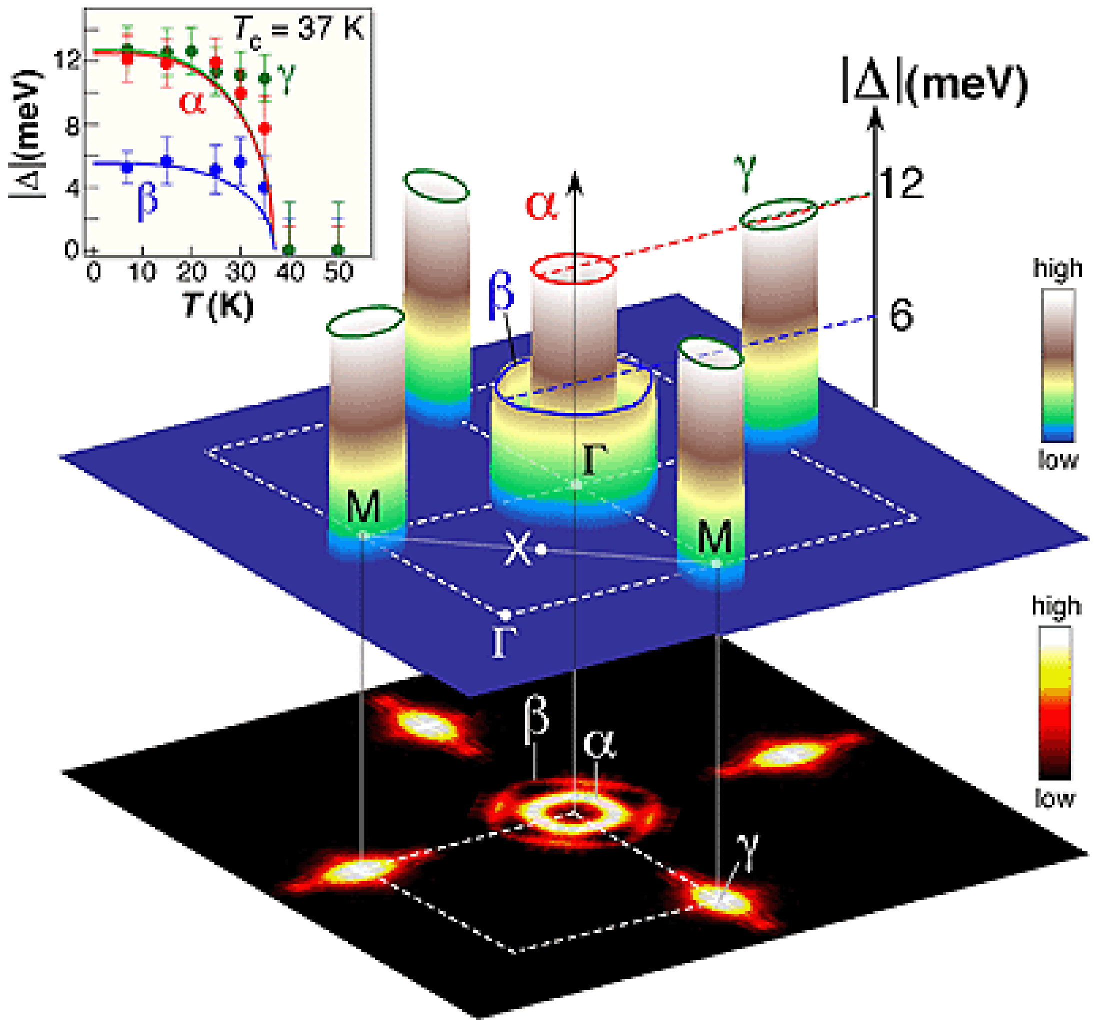


Dispersion



Na_3Bi (3D Dirac semi-metal); Liu et al, Science (2014)

Energy Gap

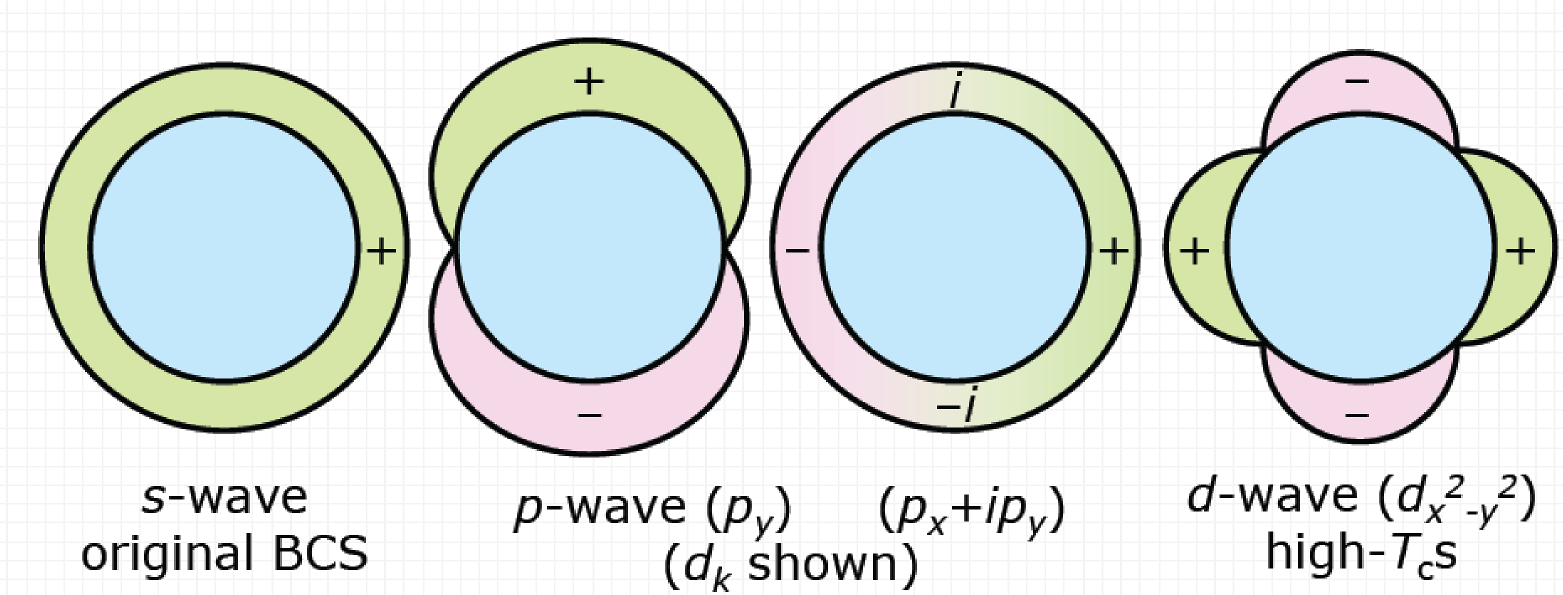


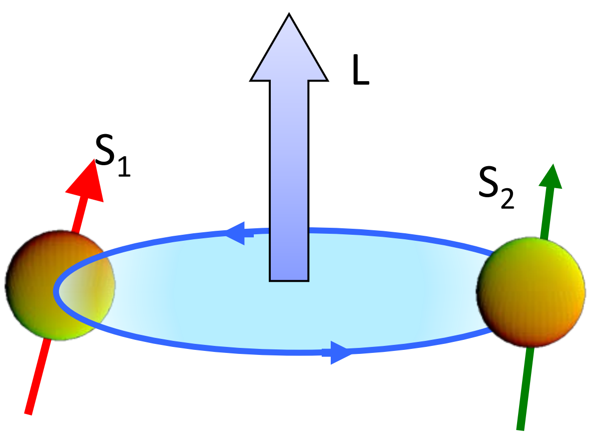
SC gap in k-space of $Ba(Fe,Co)_2As_2$

H. Ding (2008), Nature Phys.

Introduction to unconventional superconductivity

Unconventional Superconductivity

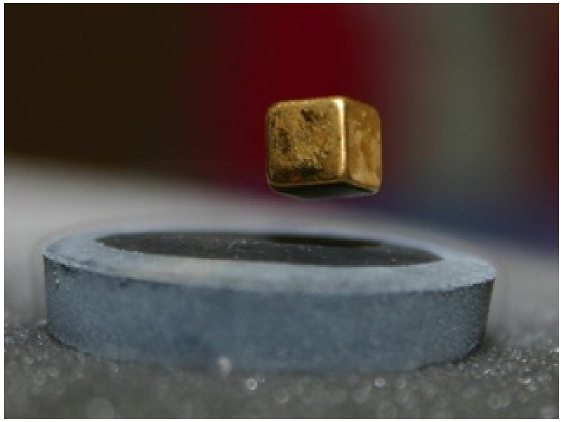


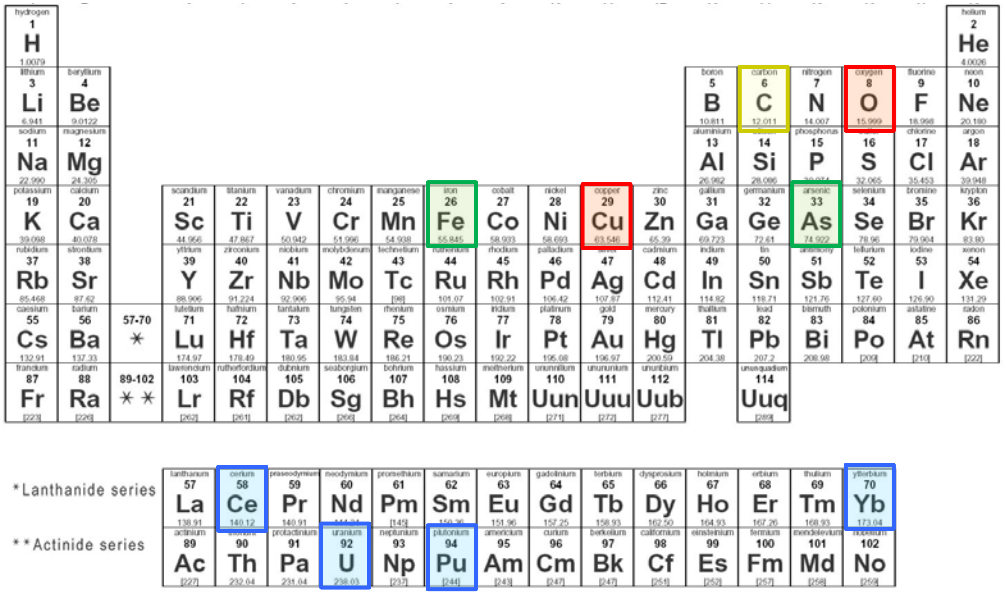


The angular momentum of the Cooper pairs may be non-zero. (L = 0,1,2,…) corresponding to s, p, d-wave pairing.

The **symmetry of the order parameter** is reflected in the k-dependence of the energy gap and in the spin of the pairs

Superconductor families





Unconventional superconductor families:

Heavy fermions	$T_c \sim 2$ K	1979
Organics	$T_c \sim 10$ K	1990
Cuprates	$T_c \sim 100$ K	1987
Iron Arsenides	$T_c \sim 40$ K	2008

Pairing symmetry

Cooper pairs: $$\Psi(\mathbf{r}_1,\mathbf{r}_2) = \underbrace{\chi(s_1,s_2)}_{\text{Spin part}}\,\underbrace{\phi(\mathbf{r}_1-\mathbf{r}_2)}_{\text{Spatial part}}$$

Ψ must be antisymmetrical under particle exchange

$$\chi(s_1,s_2) = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$$ Singlet (antisymmetrical)

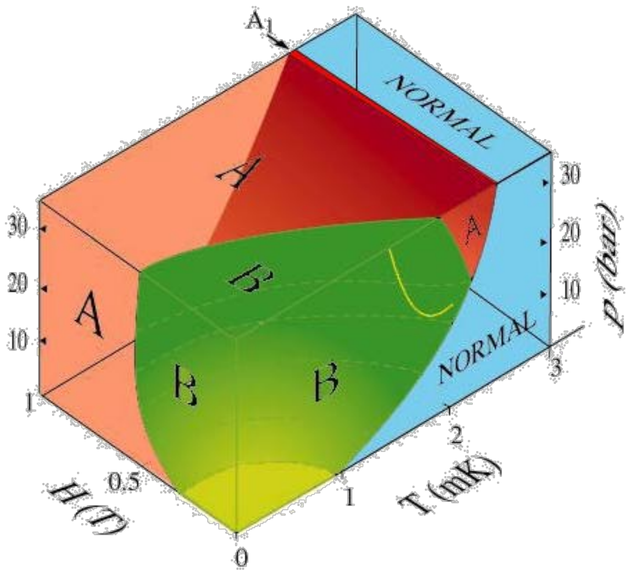
$$= \begin{cases} |\uparrow\uparrow\rangle \\ \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle) \\ |\downarrow\downarrow\rangle \end{cases}$$ Triplet (symmetrical)

$$\phi(\mathbf{r}_1-\mathbf{r}_2) = (-1)^L\phi(\mathbf{r}_2-\mathbf{r}_1)$$

L = 0, 2, 4, …   singlet pairing (s-, d-wave)

L = 1, 3, …   triplet pairing (p-wave)

Pairing Mechanism?



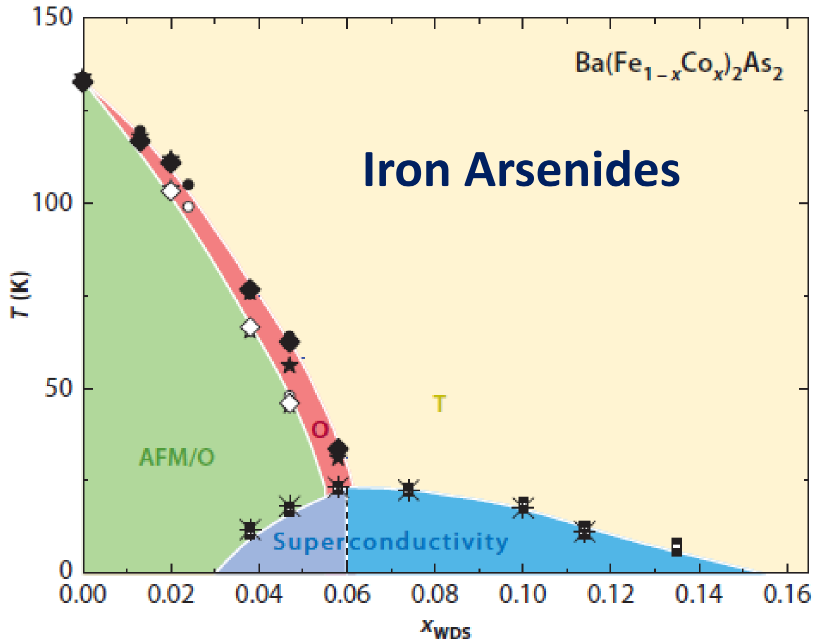
Superfluid He-3 is also a triplet p-wave condensate. The order parameter is no longer a scalar, and multiple types of symmetries are present.

In this case, the pairing arises not from the electron-phonon interaction, but rather the **spin-spin interaction** between the He-3 nuclei.

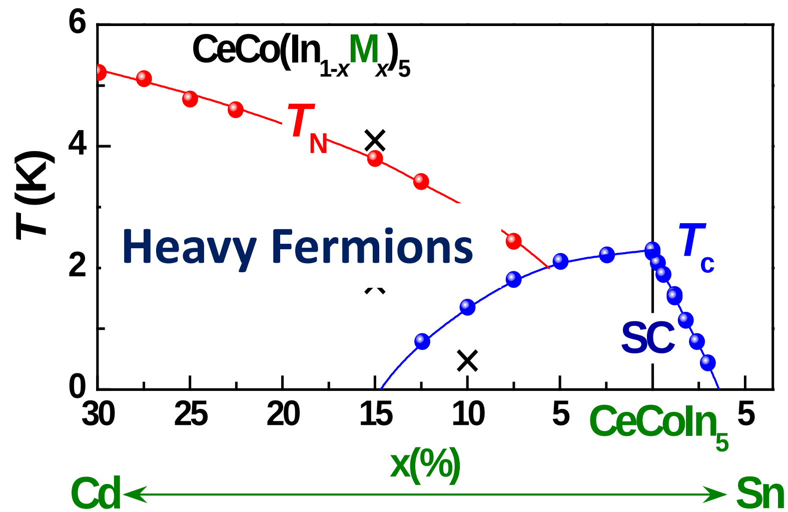
The pairing interaction in many of the unconventional superconductors is also believed to arise from spin-spin interactions.

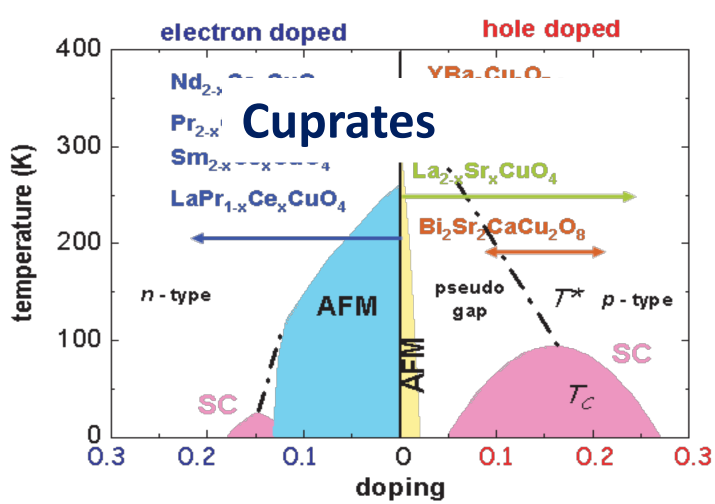
Superconductivity and Antiferromagnetism

Many superconductors appear to emerge at the “edge of antiferromagnetism” – this suggests that the coupling is magnetic in origin (spin-fluctuations).

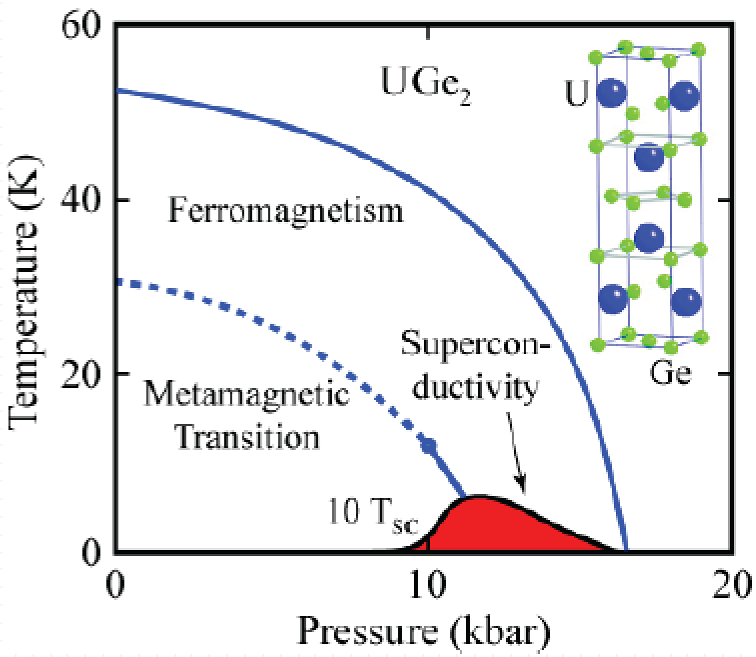


Electron doping





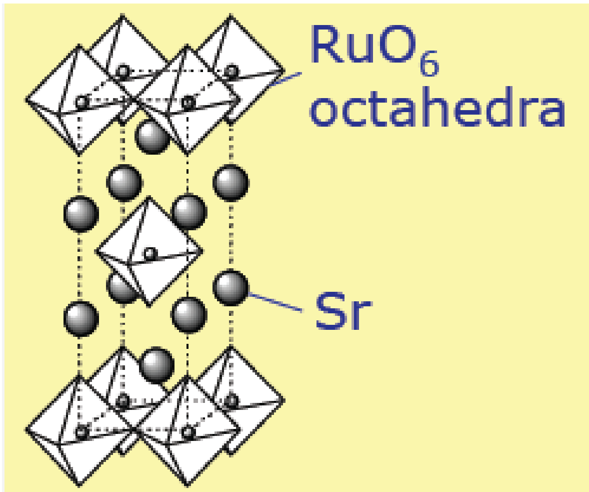
Triplet Pairing and Ferromagnetism

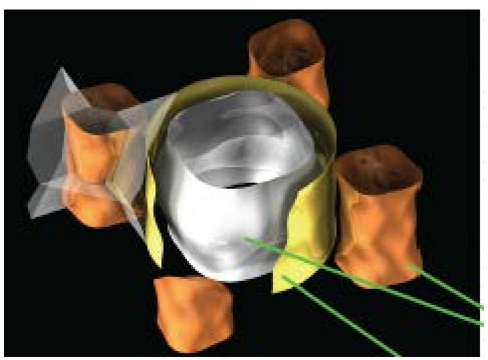


Superconductivity can sometimes emerge when a ferromagnetic transition is suppressed to zero at a quantum critical point. In this case, the superconductivity lives within the ferromagnetic phase. The ferromagnetism cannot coexist with singlets, therefore the Cooper pairs must be in a **triplet state** and the pairing must be **p-wave**.

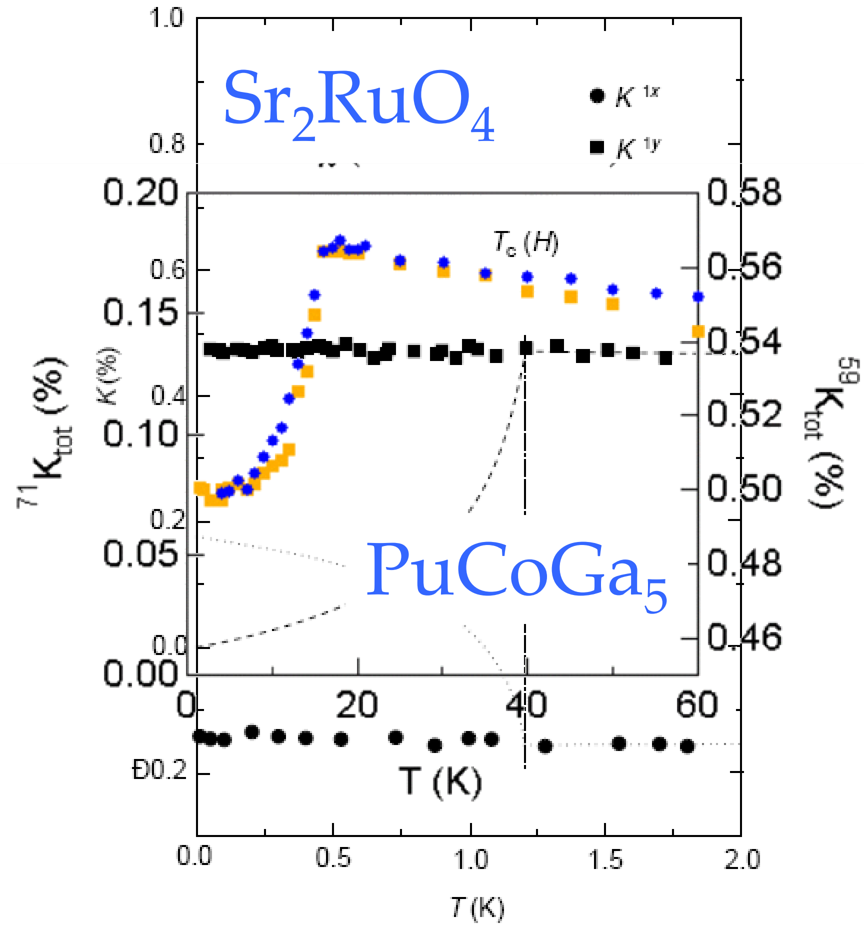
This is still an active area of research and the pairing nature in these systems is not well understood.

Triplet Pairing





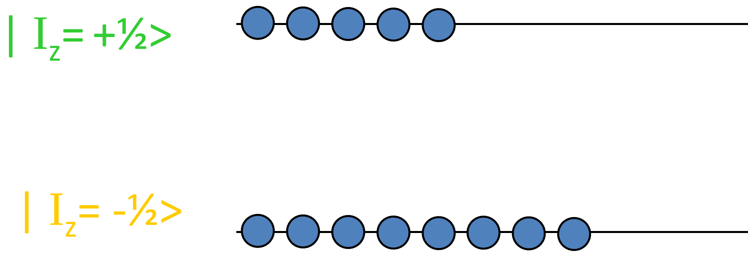
Fermi surface



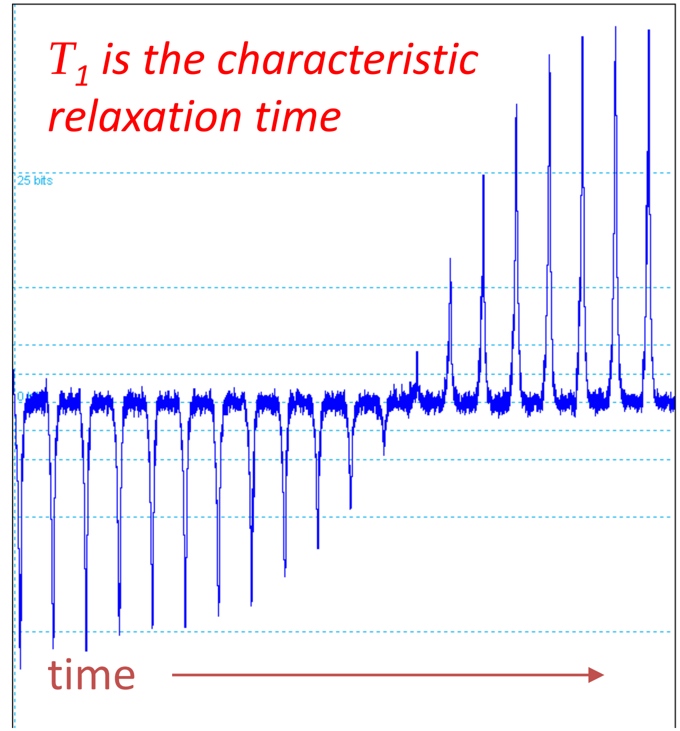
Knight shift in the superconducting state indicates that χ_{spin} remains finite – p or f-wave pairing

NMR in unconventional superconductors

Nuclear Spin Dynamics



By applying rf pulses, we can perturb the equilibrium Boltzmann distribution, and then watch as the system relaxes to a finite spin temperature

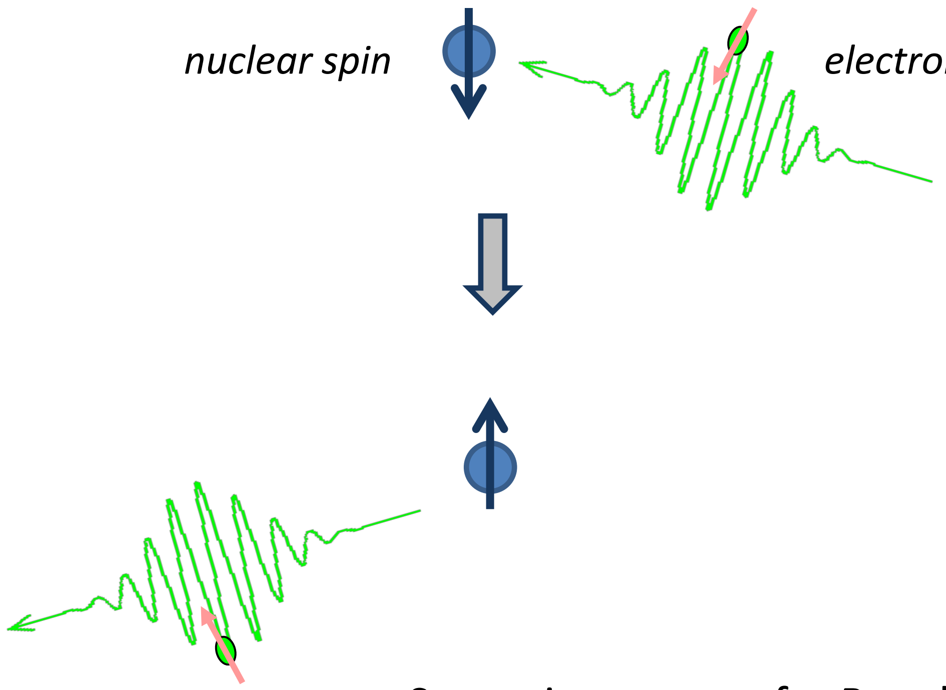


$$M(t) \sim 1 - e^{-t/T_1}$$

$$(T_1T)^{-1} \sim \lim_{\omega \to 0} \frac{\chi''(\mathbf{q},\omega)}{\omega}$$

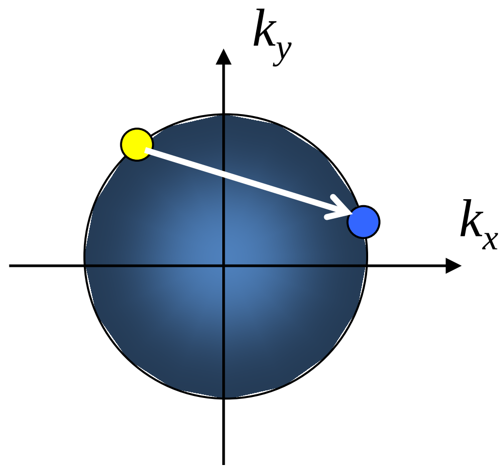
Hyperfine Interactions in Metals

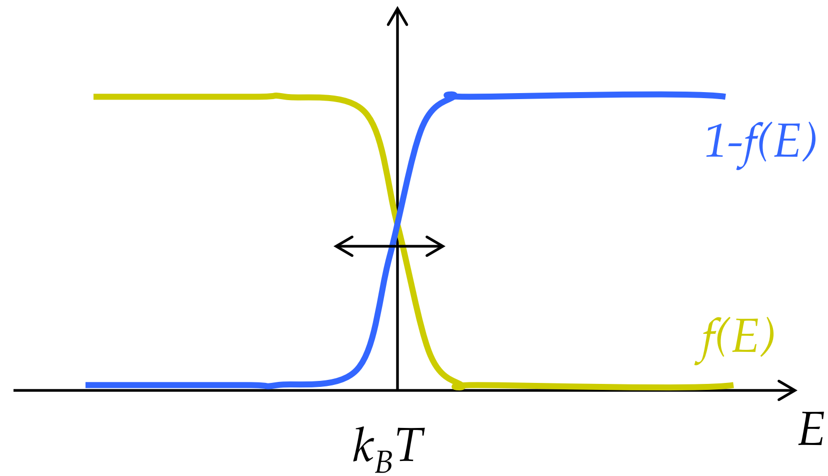
Nuclear spins relax by spin-flip scattering from electrons:



Scattering process for Bogoliubons requires taking into account the **coherent superposition** of spin-up and spin-down electrons!

Spin Lattice Relaxation



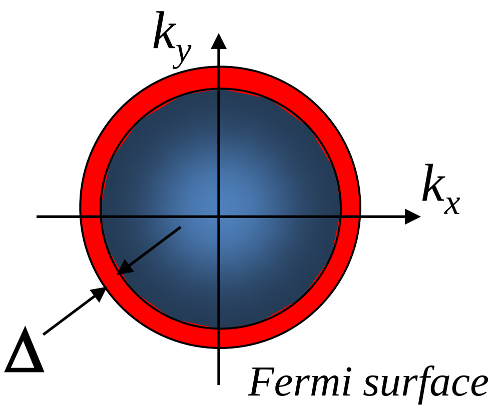


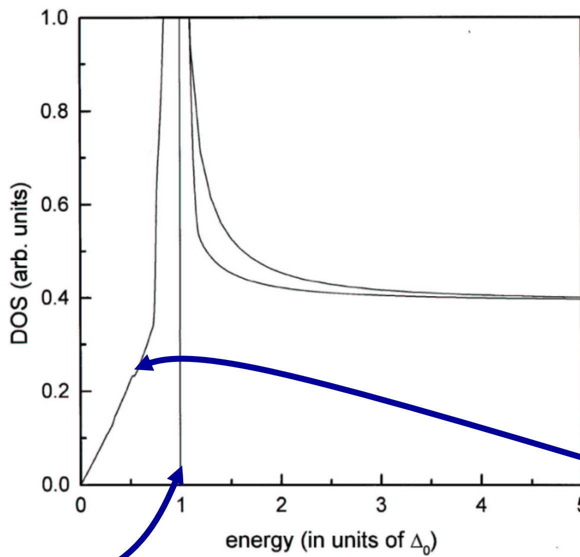
$$\begin{aligned}\frac{1}{T_1} &\propto A^2 \int \overbrace{N(E_F + g\mu_N H) f(E_F + g\mu_N H)}^{\text{Initial state}} \overbrace{N(E_F - g\mu_N H)(1 - f(E_F - g\mu_N H))}^{\text{Final state}} dE \\ &\propto A^2 N^2(E_F) \int f(E_F)(1 - f(E_F)) dE \\ &\propto A^2 N^2(E_F) k_B T\end{aligned}$$

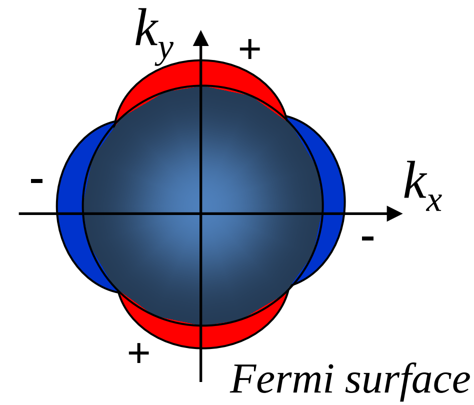
In metals, $T_1 T \sim N^2(E_F)$; a sensitive probe of the spin-flip scattering by electrons at the Fermi surface. (Korringa relaxation)

Gap Function

The fundamental parameter of a superconductor is the gap $\Delta(\mathbf{k})$







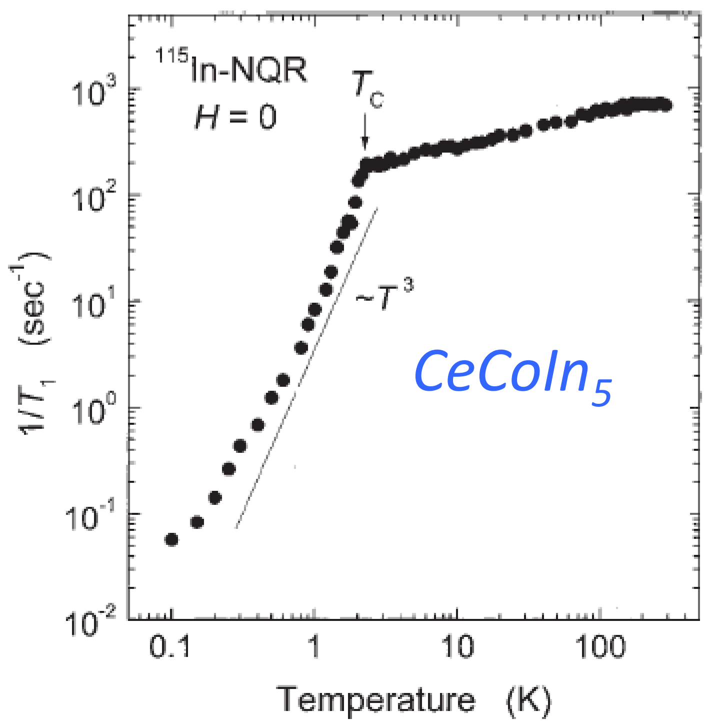
s-wave: isotropic gap

$T_1^{-1} \sim e^{-\Delta/k_B T}$

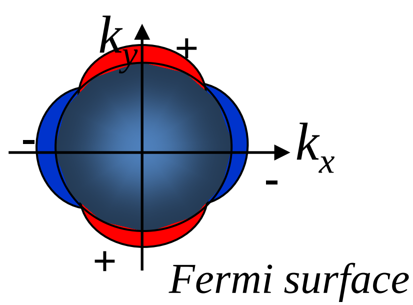
d-wave: nodes in k-space where gap vanishes

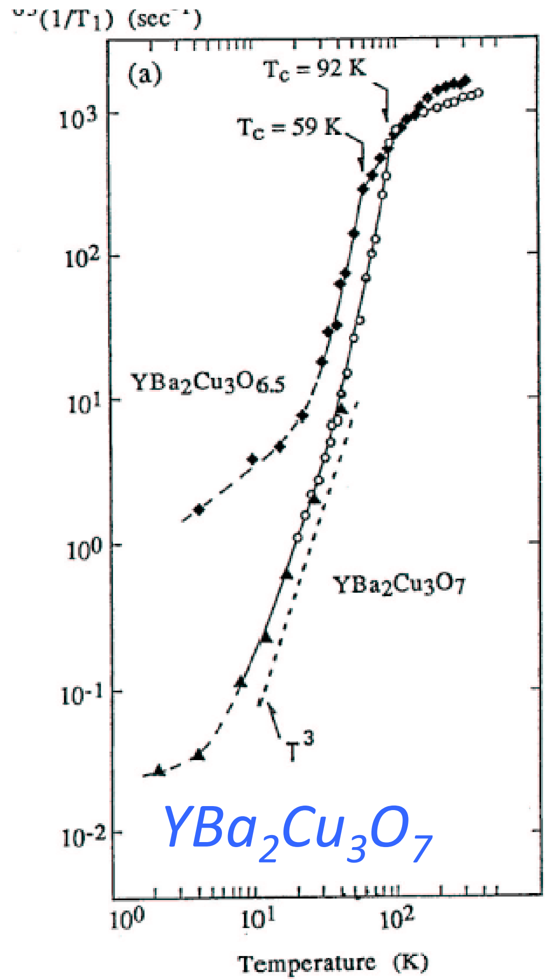
$T_1^{-1} \sim T^3$

Spin lattice relaxation – unconventional pairing

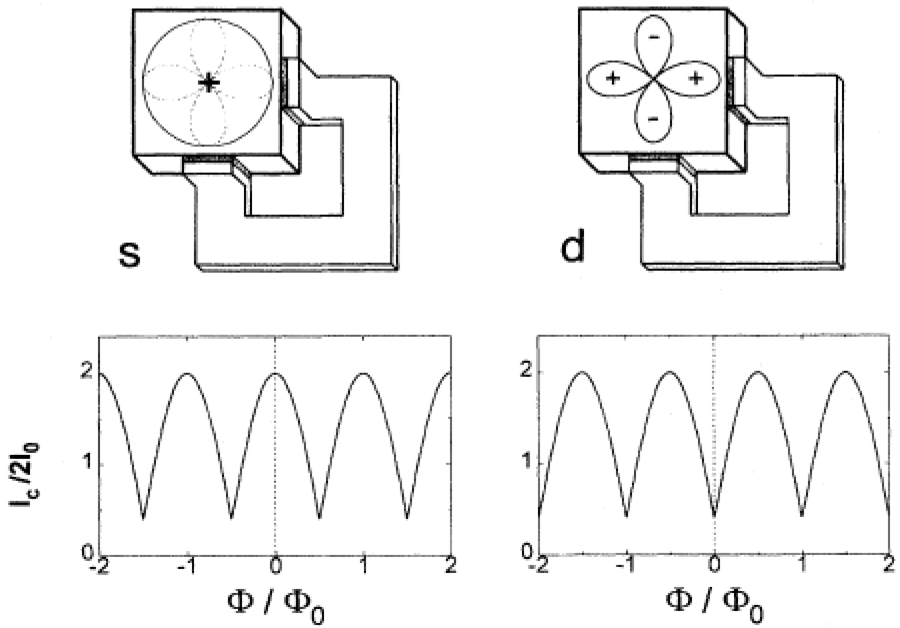


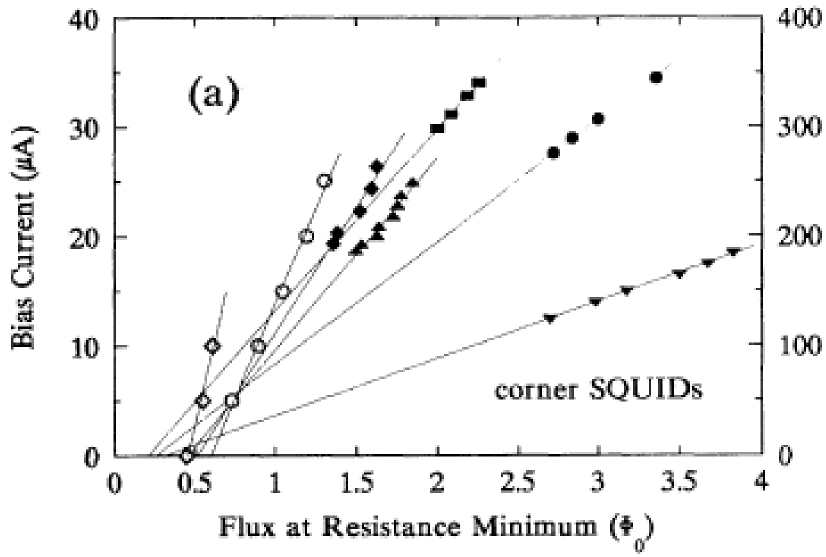
In the presence of line nodes, $1/T_1 \sim T^3$





Measuring the Phase





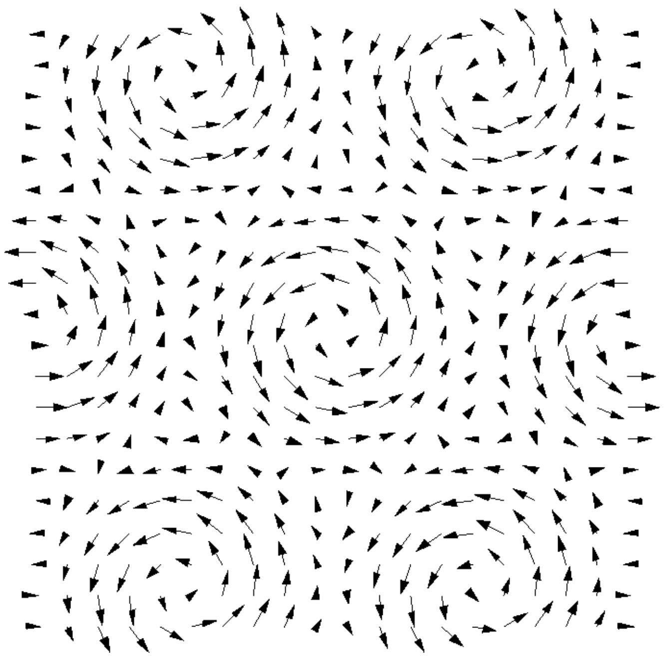
Josephson Pi Junction – change of phase of the d-wave order parameter gives rise to a 180 degree shift of the SQUID response.

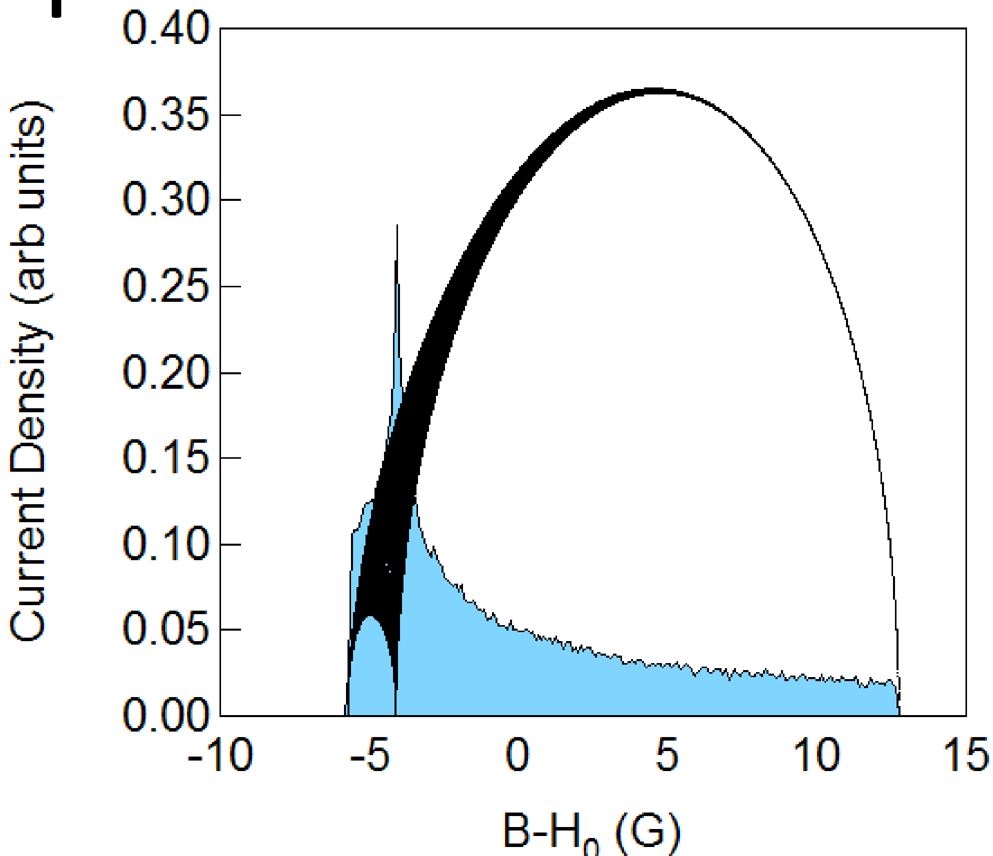
First direct confirmation of d-wave phase change in YBCO

Corner dc SQUID

Van Harlingen et al., PRL (1993)

Doppler shift

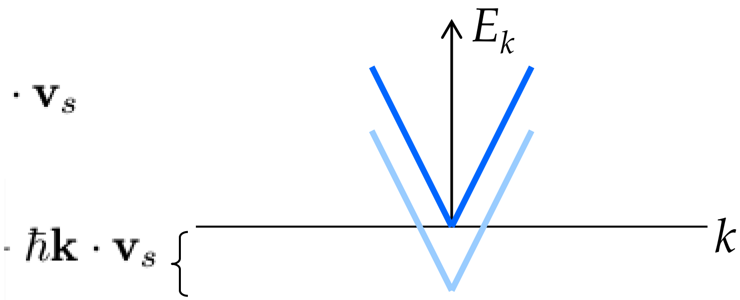




G. Volovik

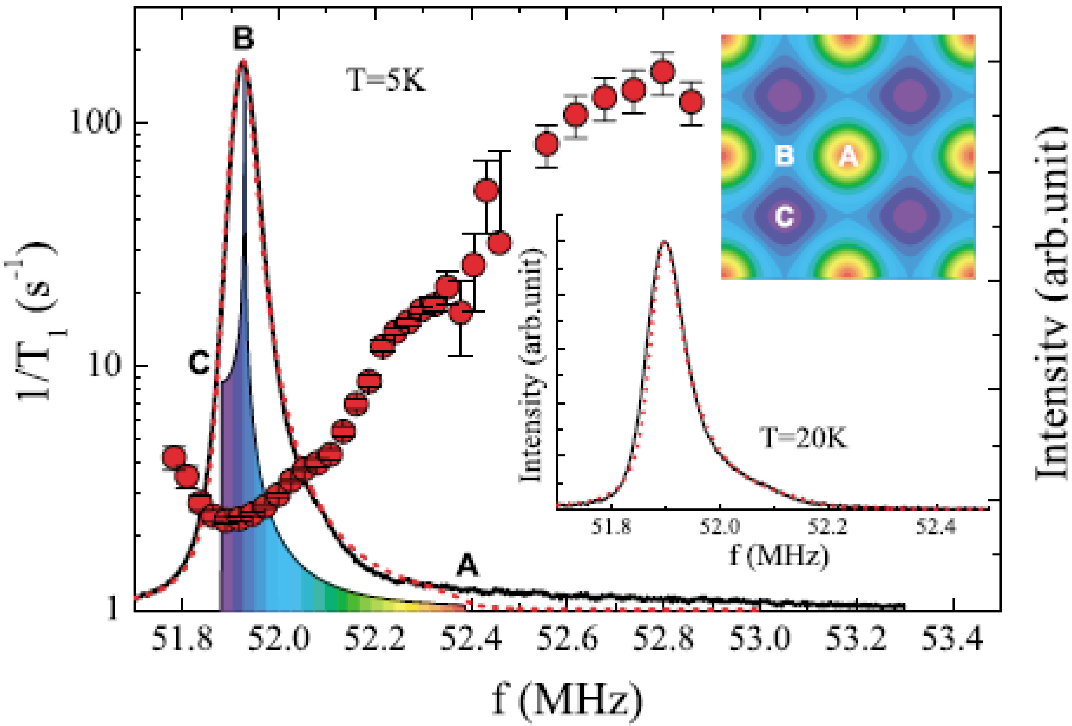
$$E_{\mathbf{k}} = \sqrt{\epsilon_{\mathbf{k}}^2 + \Delta_{\mathbf{k}}^2} + \hbar\mathbf{k}\cdot\mathbf{v}_s$$

$1/T_{1local} \sim N^2(0) \sim v_s^2$



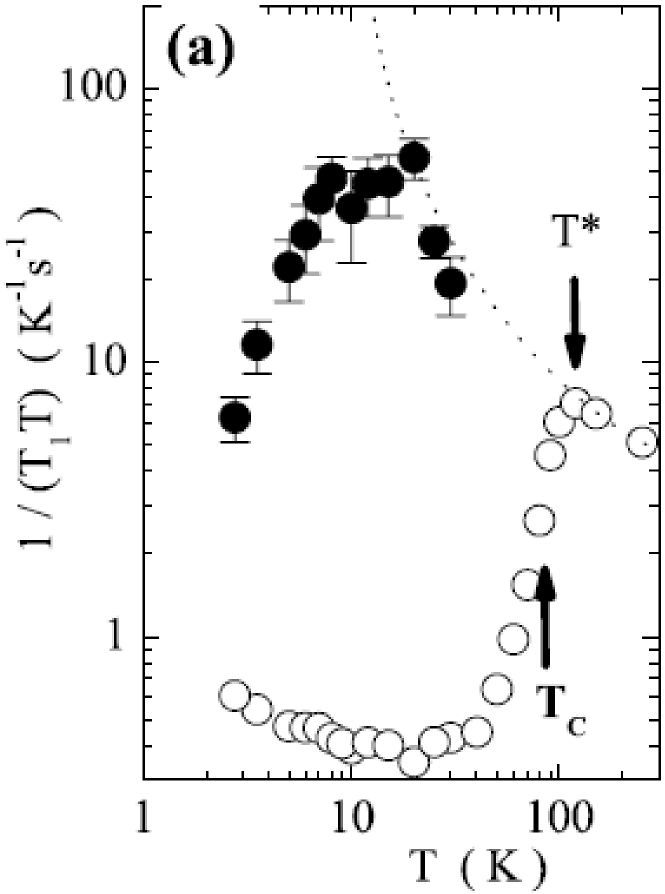
T_1 in vortex lattice

$Tl_2BaCu_2O_6$



$YBa_2Cu_3O_7$ - Curro and Slichter (2000)
$YBa_2Cu_3O_7$ - Mitrovic and Halperin (2001)
$Tl_2BaCu_2O_6$ - Kumagai (2003)

T_1 in vortex cores



Very different temperature dependence of T_1 in vortex cores versus outside the cores

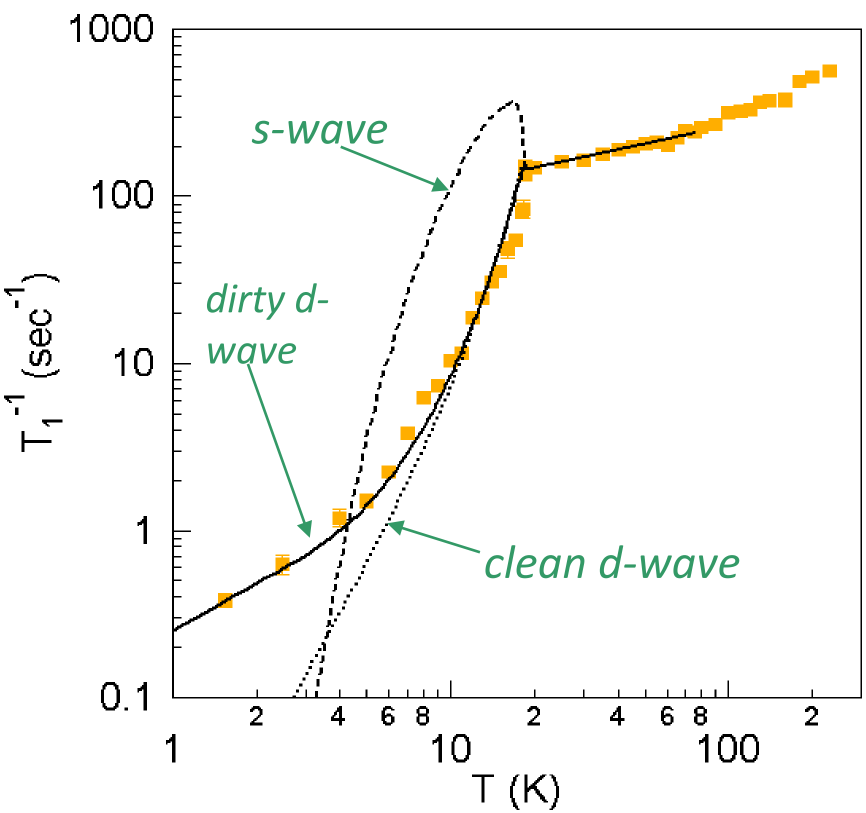
Suggestive of other relaxation mechanisms in core

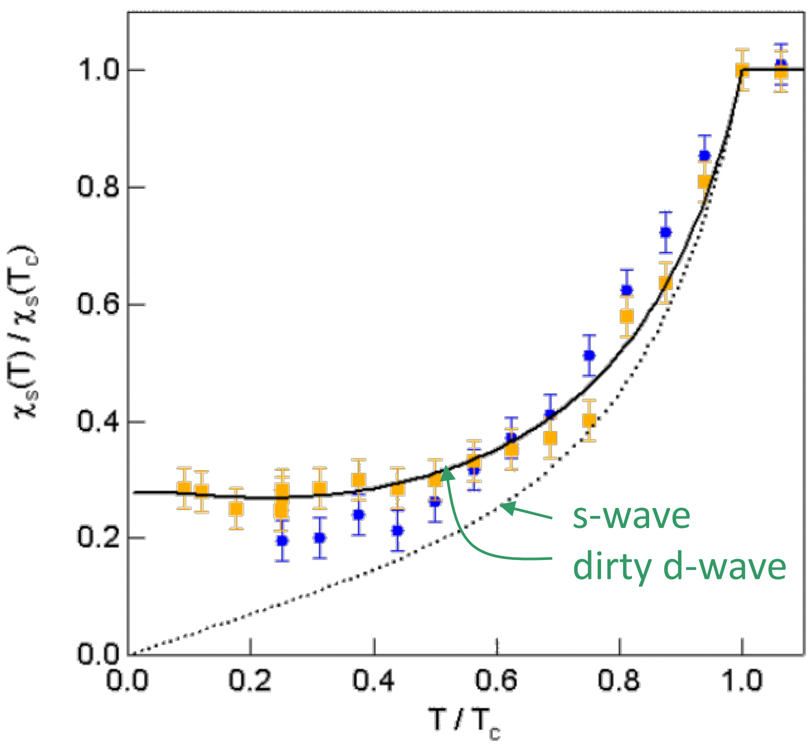
Localized states?

Antiferromagnetism?

Vortex lattice vibrations?

Effect of Impurities



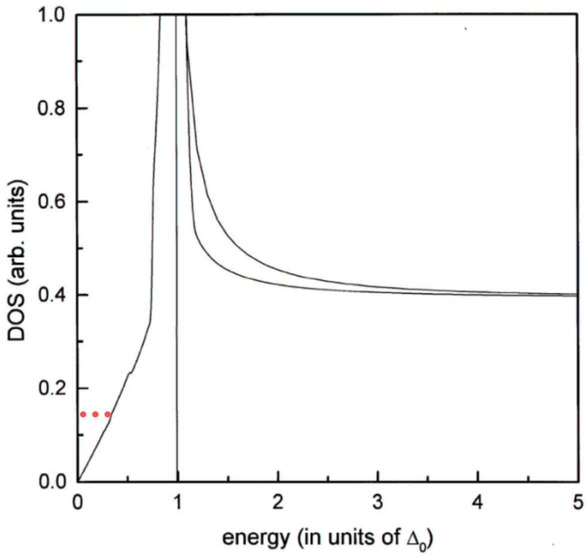


$PuCoGa_5$ (T_c = 18.5K) is a d-wave superconductor

Self-irradiation strongly affects low temperature properties

$1/T_1 \sim T$, $\chi_s (T=0) > 0$

Pair Breaking and Aging



- T_c is reduced with age because of impurity scattering
- Impurity scattering rate Γ probably arises from Frenkel pairs (0.086 displacements per month per Pu atom)* (potential/magnetic scattering center)
- NMR measurements: $d\Gamma/dt$ ~ 0.25K/month
- Abrikosov-Gor'kov:

$$\Delta T_c = \pi/4\ \Delta\Gamma \sim 0.2\text{K/month}$$

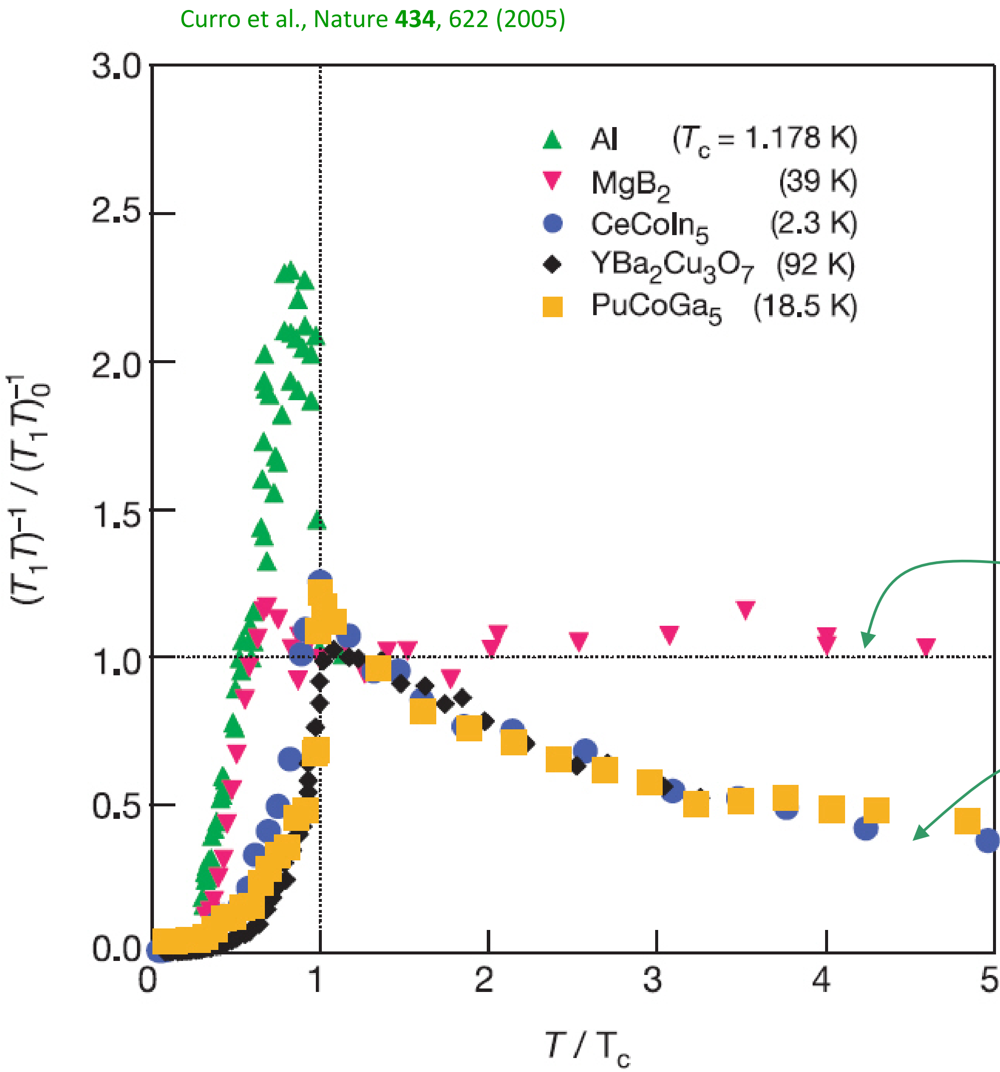
- Estimate T_{c0} ~ 19.1K for pristine, defect free $PuCoGa_5$

Y. Bang, et al., PRB **69**, 014505 (2004)

N. J. Curro et al., Nature (2005)

**In 10 years, each Pu atom will be displaced once*

Comparing HF and High-T_c Superconductivity



T_1T scales with T/T_c :

Suggests AF fluctuations are responsible for d-wave SC

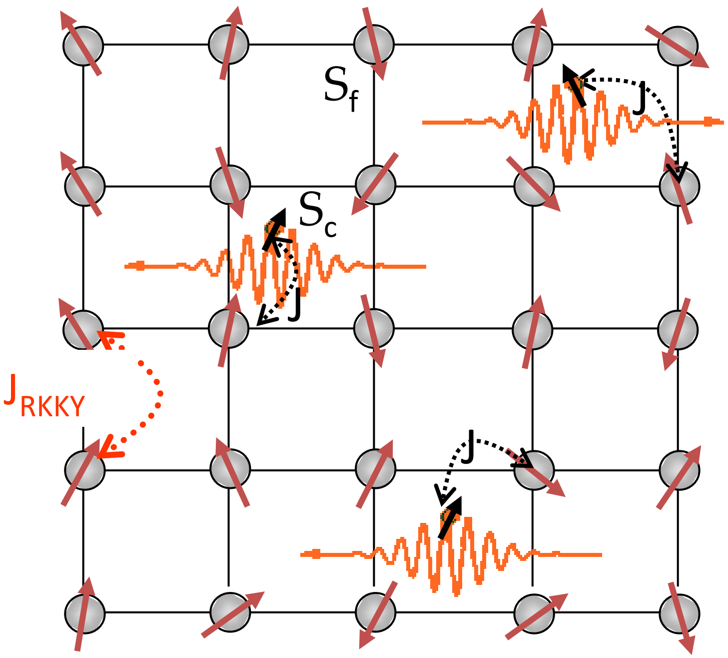
•s-wave: T_1T ~ constant (Fermi liquid)

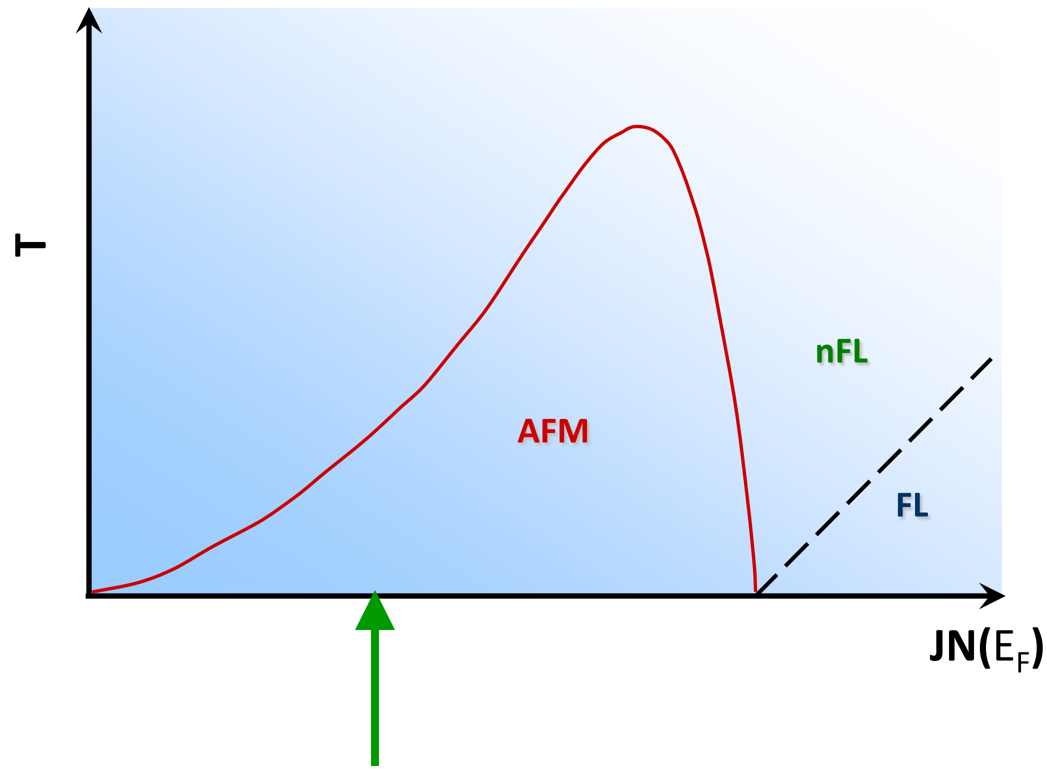
•d-wave: $T_1T \sim 1/\xi \sim (T + T_0)^\beta$ (Antiferromagnetic fluctuations)

Unconventional Scaling

For all the known d-wave superconductors, T_c scales roughly with T_0 ~ J, the characteristic spin fluctuation temperature

The Kondo lattice





Localized f-spins

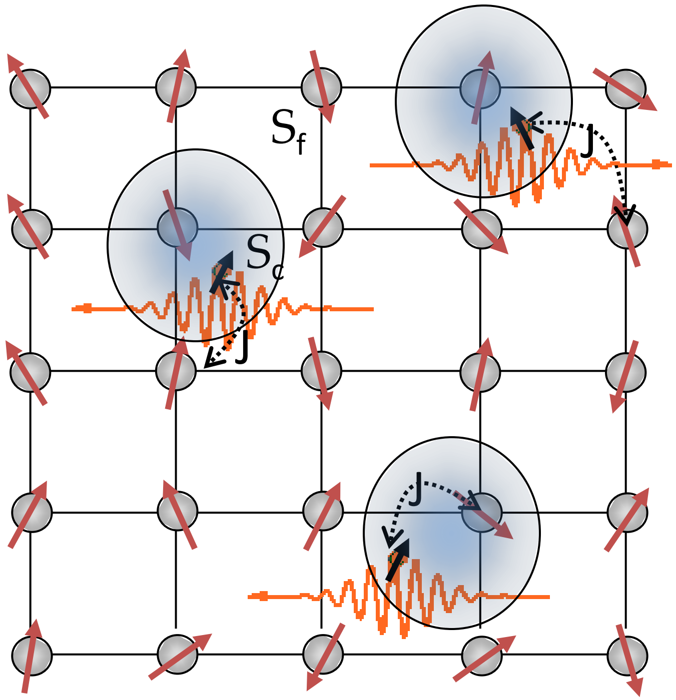
Delocalized conduction electrons

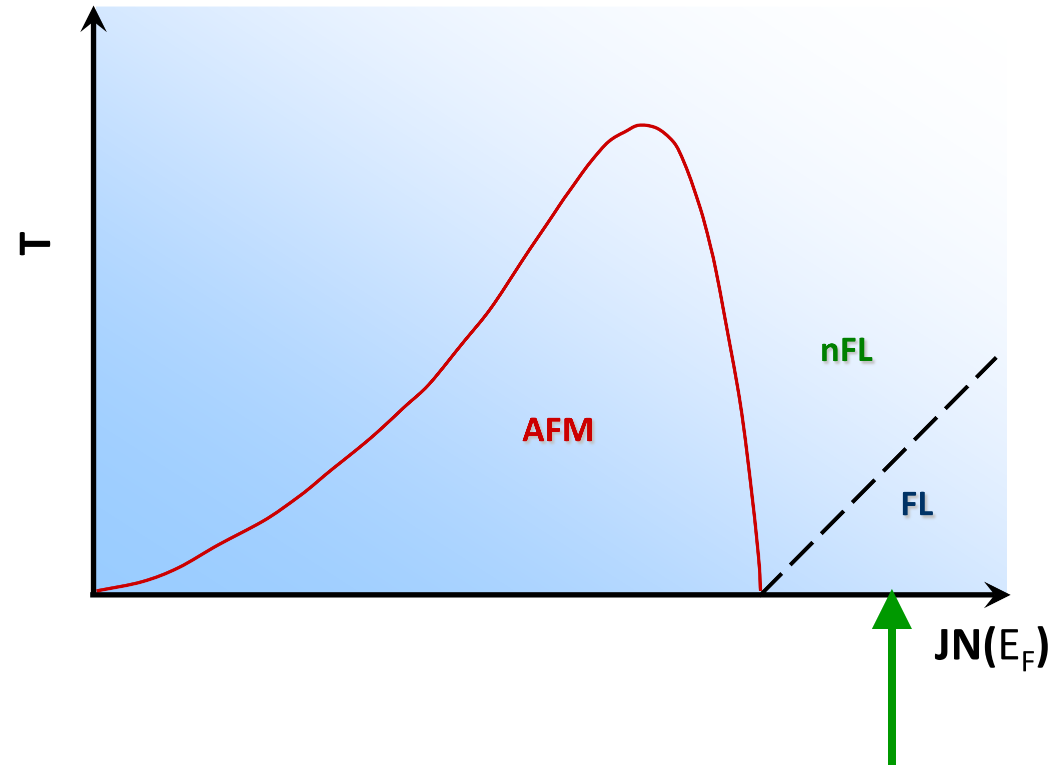
$JN(E_F) < 1$

ordered local moments

S. Doniach, Valence Instabilities and Related Narrow Band Phenomena, p. 169 (Plenum, 1977},

The Kondo lattice





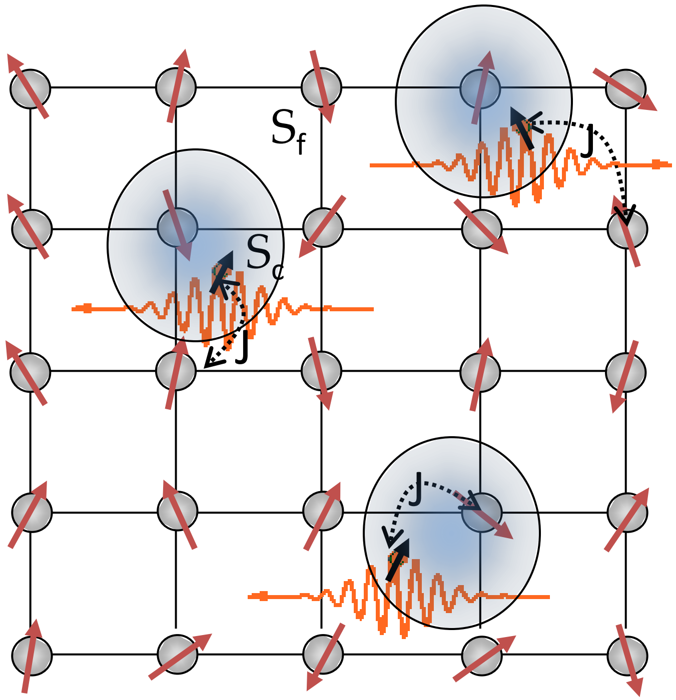
Localized f-spins

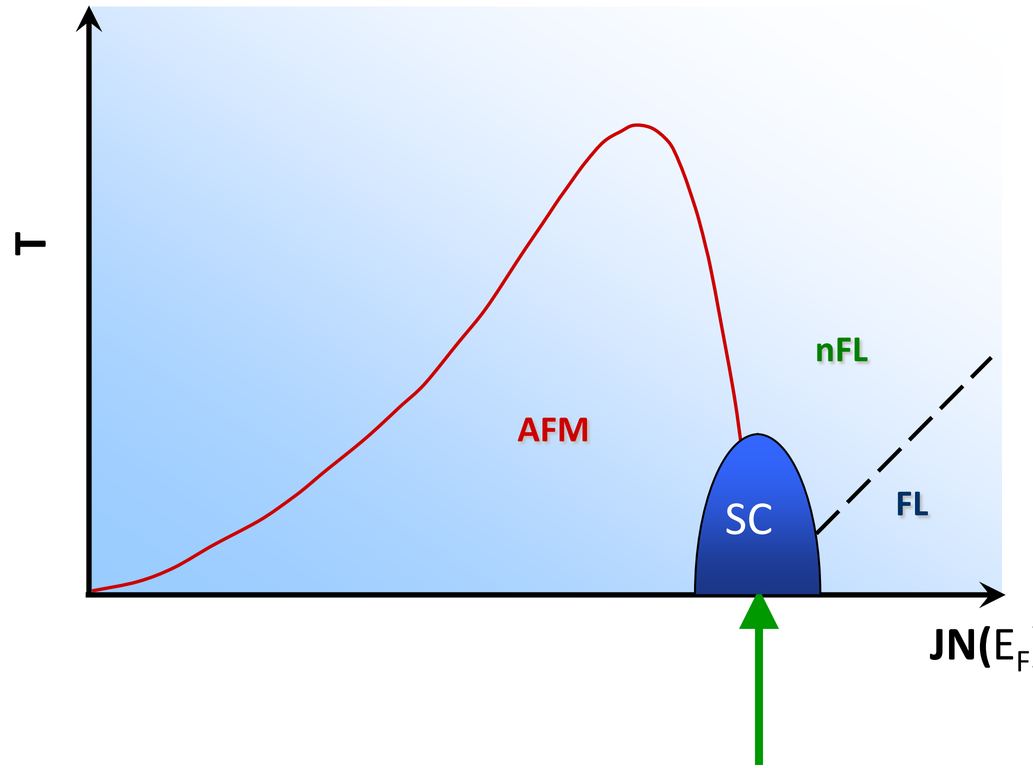
Delocalized conduction electrons

JN(E$_F$) > 1

spin singlets – no long range order

The Kondo lattice





Localized f-spins

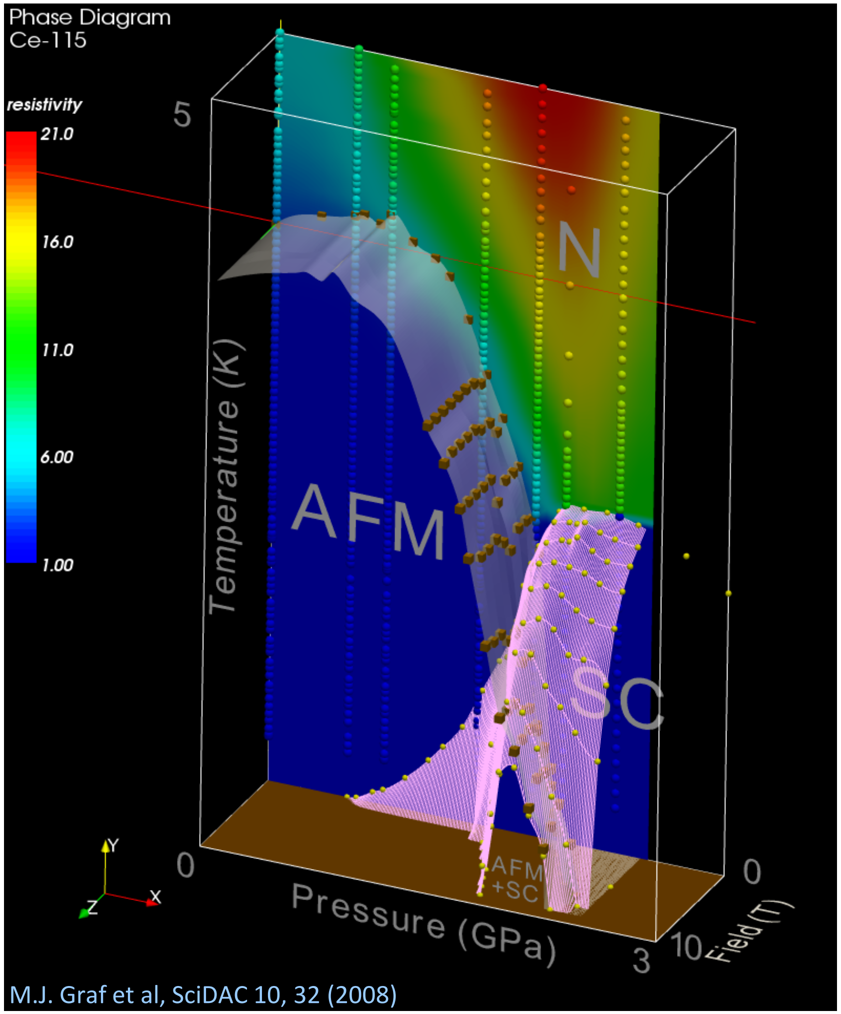
Delocalized conduction electrons

Competition between RKKY and Kondo interactions

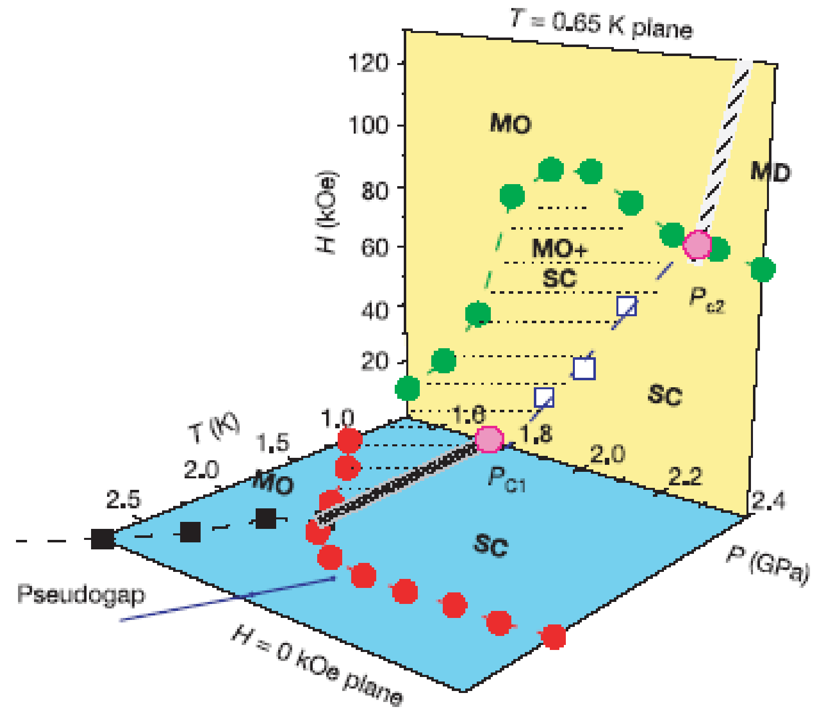
$JN(E_F) \sim 1$

quantum phase transition

$CeRhIn_5$ Phase Diagram



T. Park et al. Nature (2006, 2008)



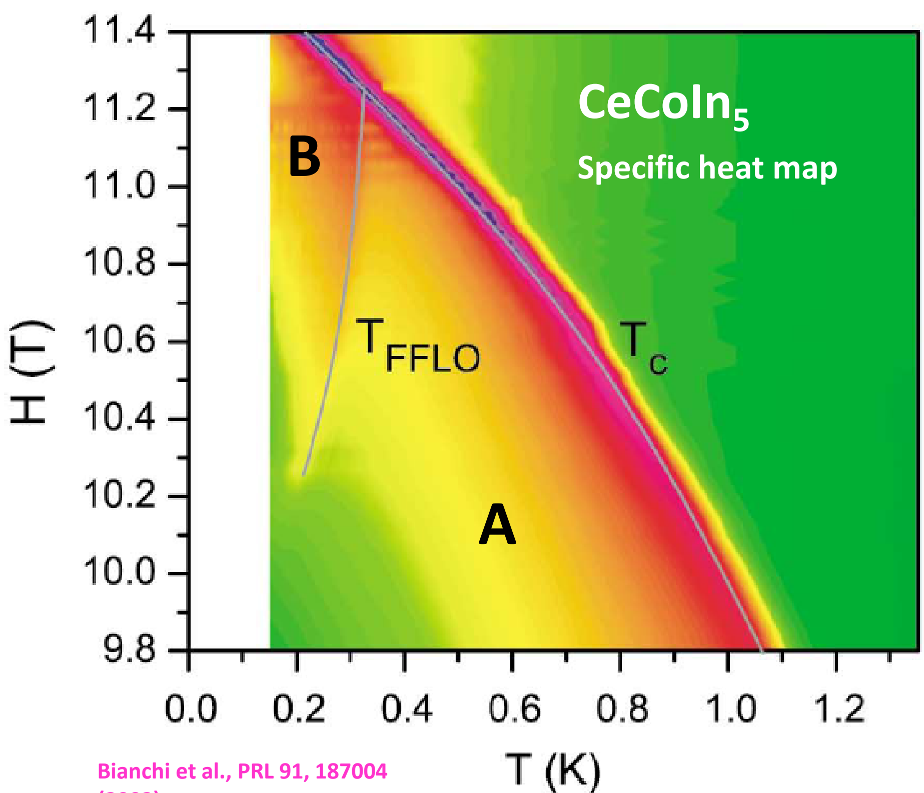
Field induced magnetism for 1.7 GPa < P < 2.3 GPa

A new phase

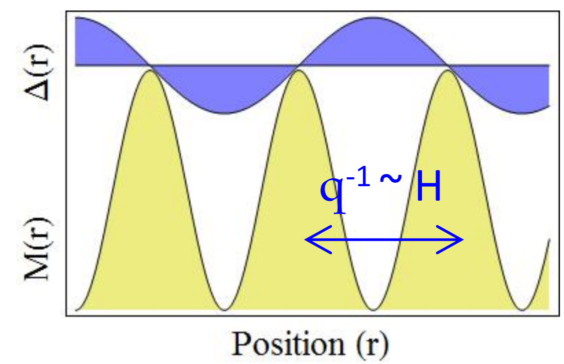
VOLUME 91, NUMBER 18 PHYSICAL REVIEW LETTERS week ending 31 OCTOBER 2003

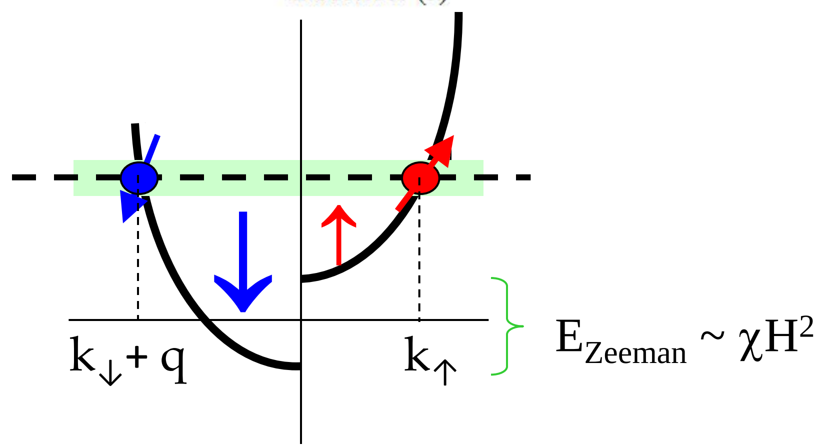
Possible Fulde-Ferrell-Larkin-Ovchinnikov Superconducting State in $CeCoIn_5$

A. Bianchi,[1] R. Movshovich,[1] C. Capan,[1] P. G. Pagliuso,[2] and J. L. Sarrao[1]
[1]*Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*
[2]*Instituto de Física "Gleb Wathagin," UNICAMP, 13083-970 Campinas, Brazil*

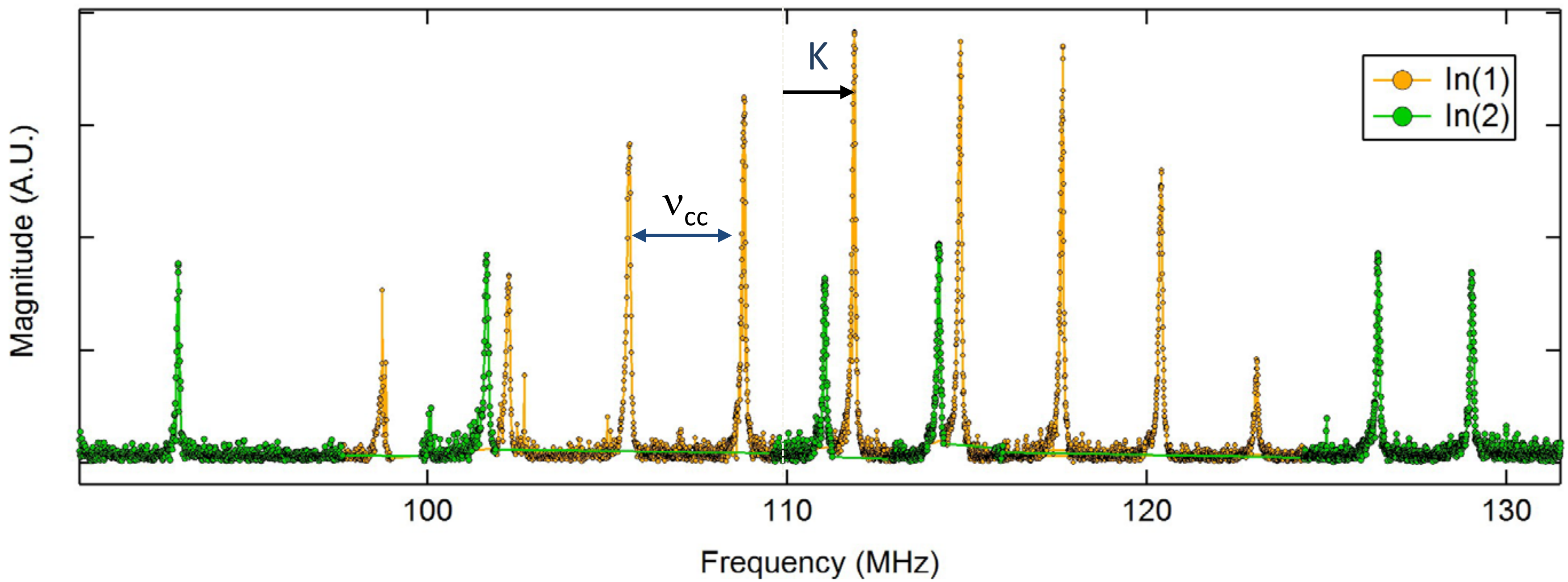


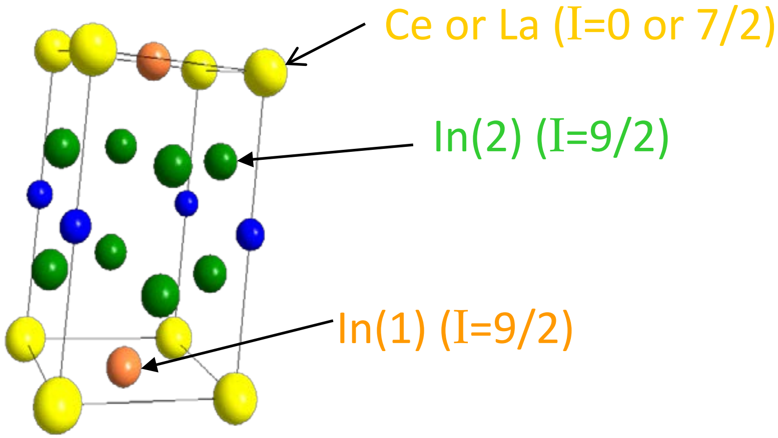
Bianchi et al., PRL 91, 187004 (2003)





NMR in $CeMIn_5$

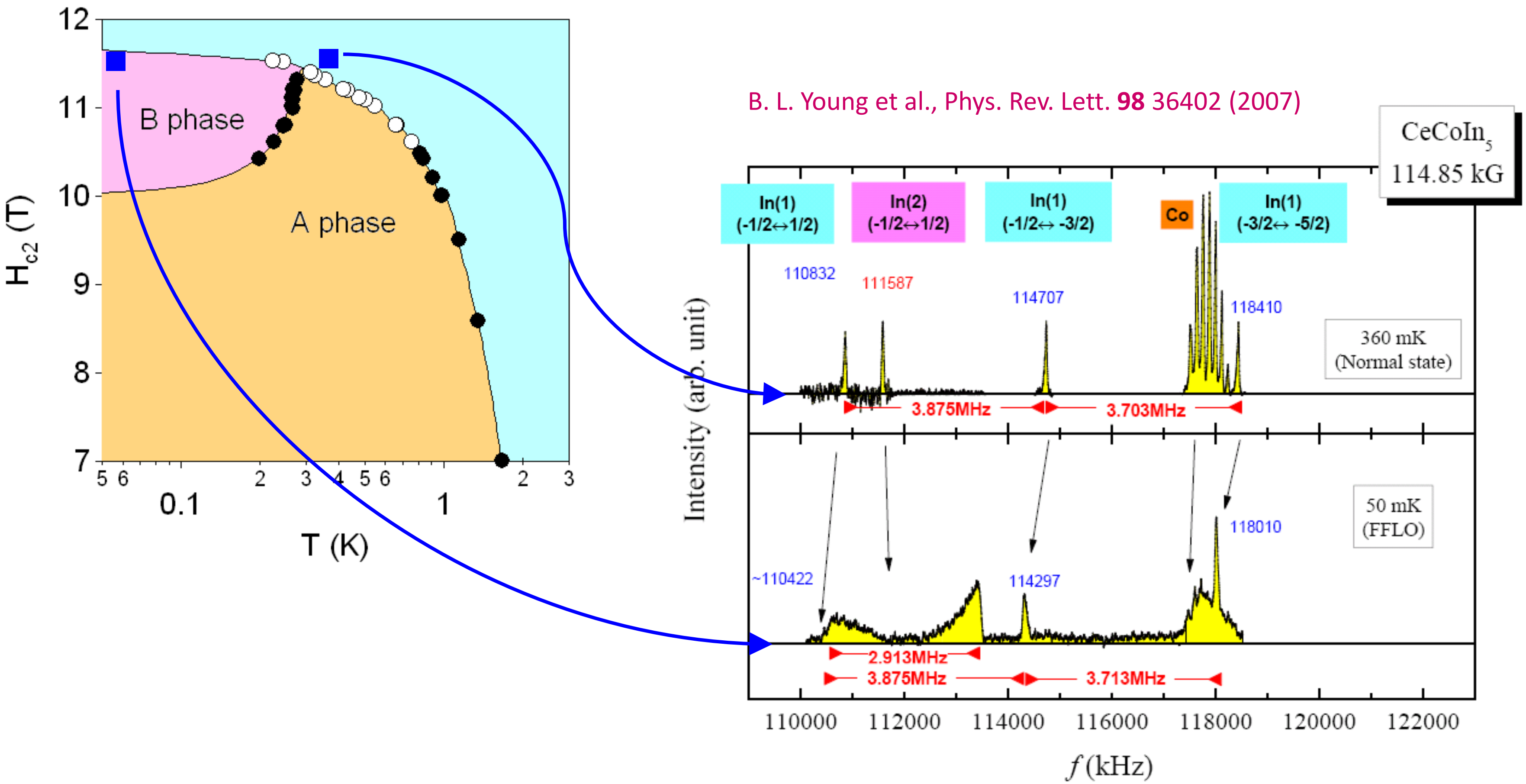




Splitting controlled by EFG

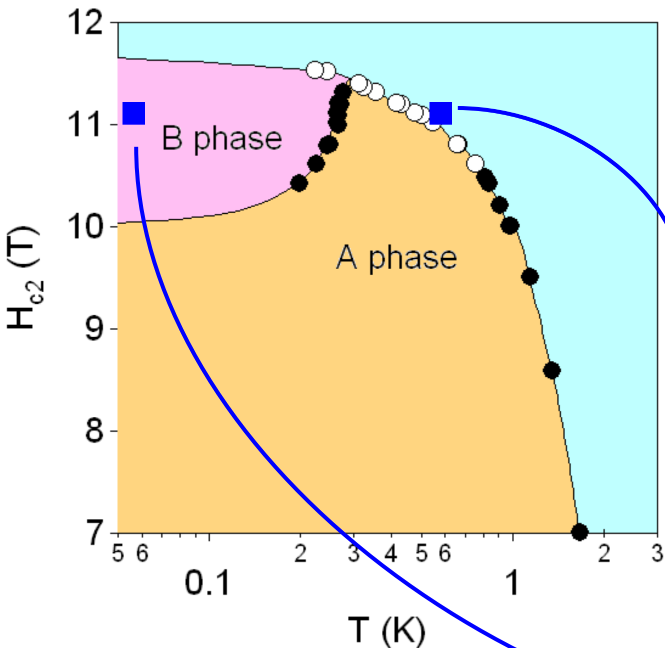
Relative frequency controlled by Knight shift

NMR Spectra I

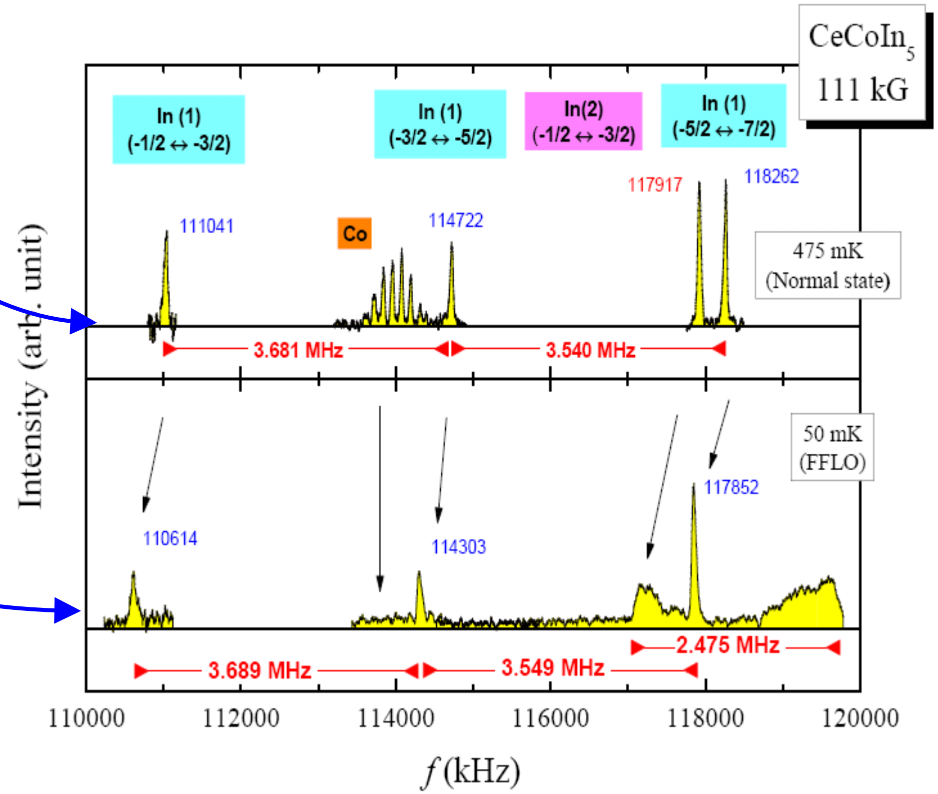


- In(1) shifts to lower frequencies (Knight shift)
- Co broadens slightly
- In(2) broadens by > 2MHz

NMR Spectra II

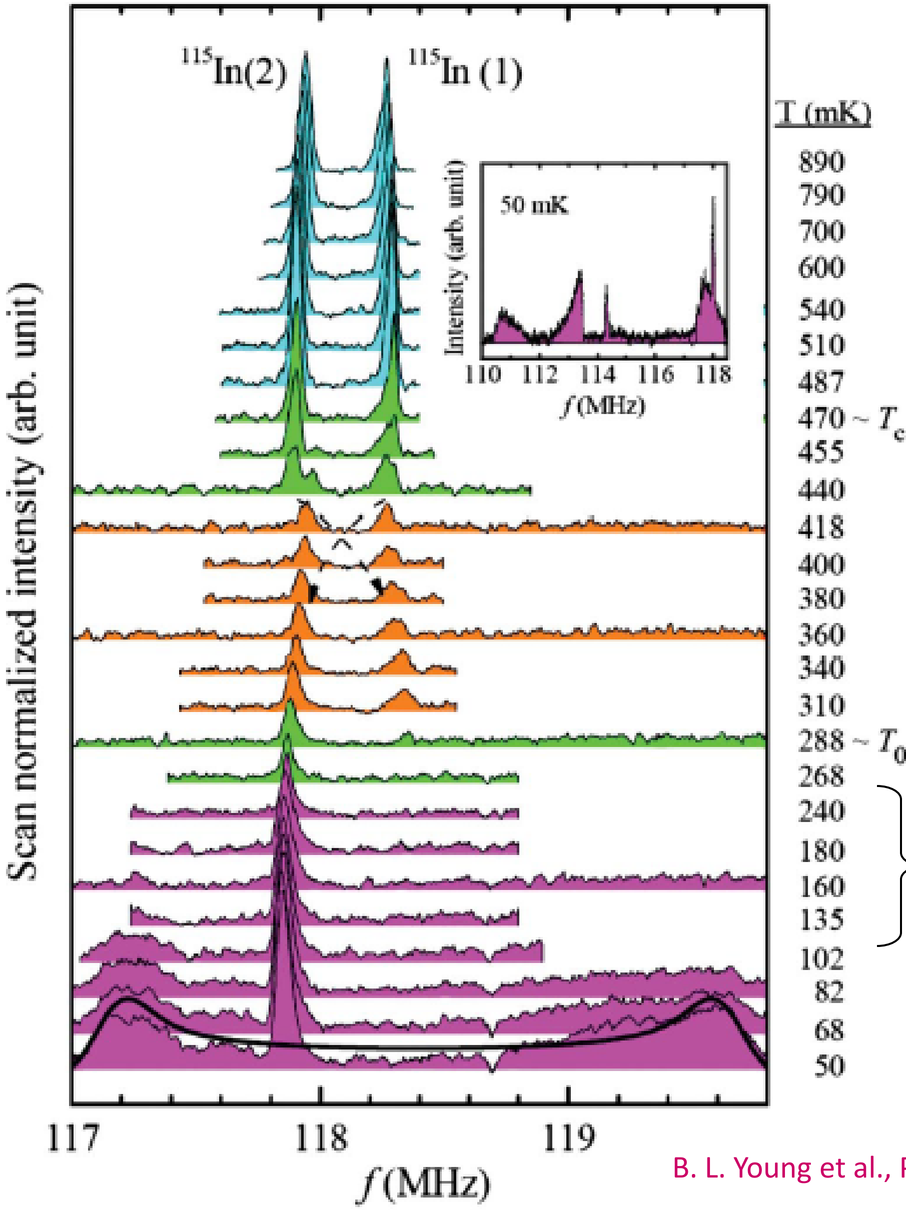


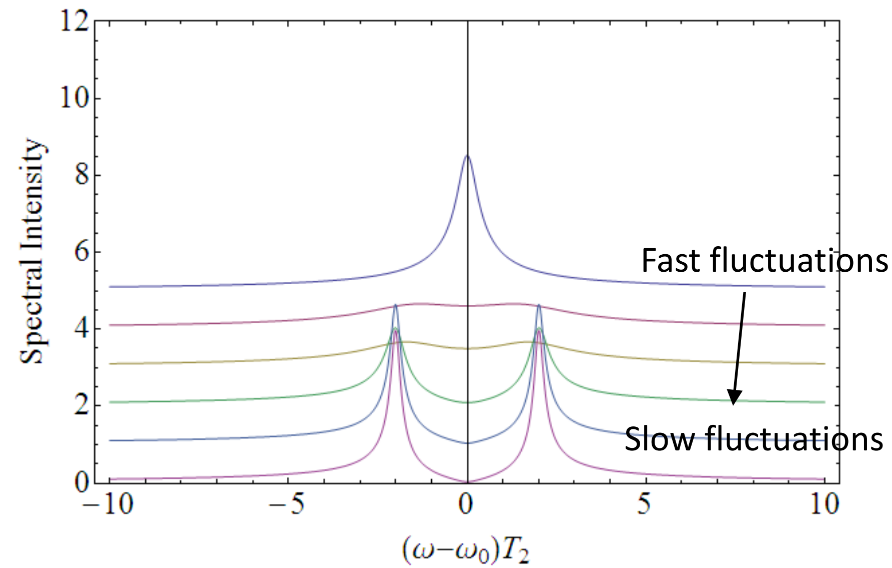
B. L. Young et al., Phys. Rev. Lett. **98** 36402 (2007)



- In(2) sees a broad, incommensurate distribution of fields in B phase
- λ_{FFLO} ~ 10 ξ >> a (34 nm >> 0.46 nm)
- **Local moment magnetism?**

Temperature Dependence

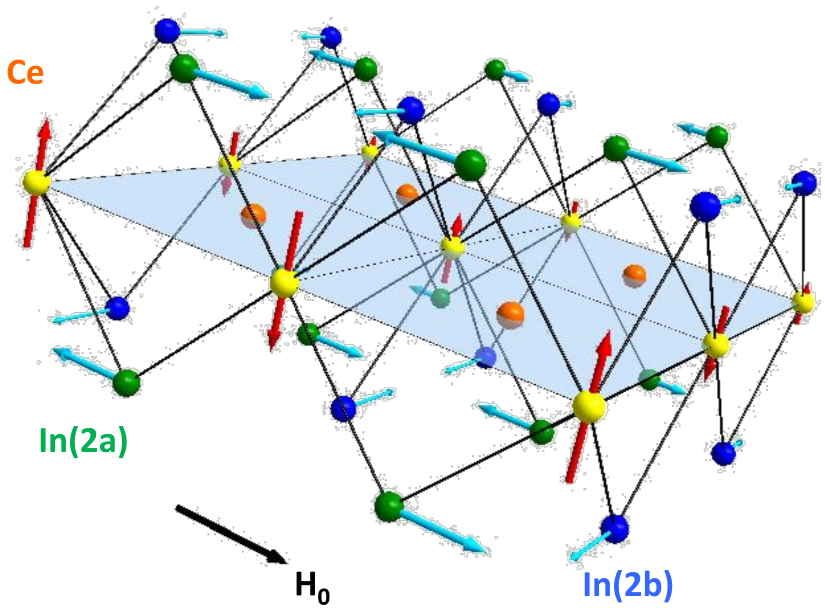




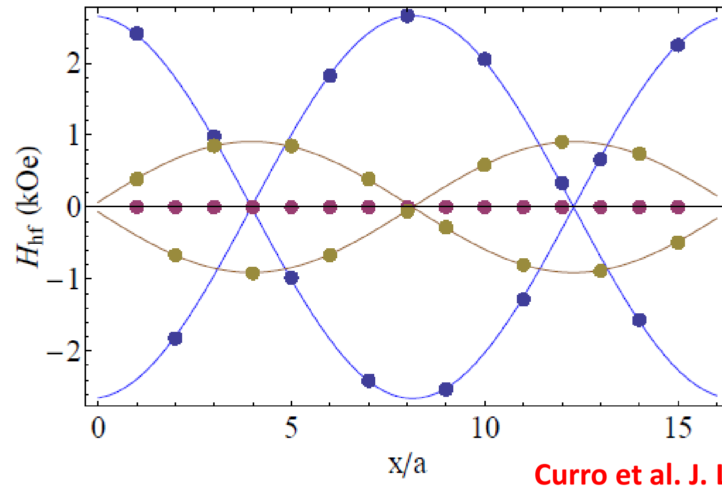
In(2) has large hyperfine field, and is wiped out by T2 effects – motional narrowing

B. L. Young et al., Phys. Rev. Lett. **98** 36402 (2007)

Possible magnetic NMR structures

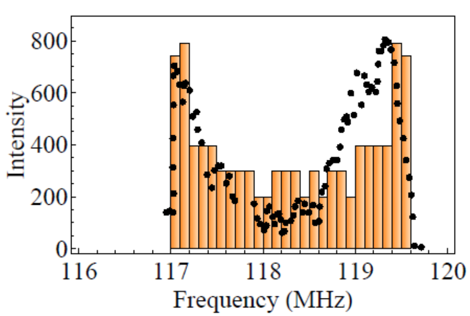


Hyperfine fields at In(2a) and In(2b) sites:

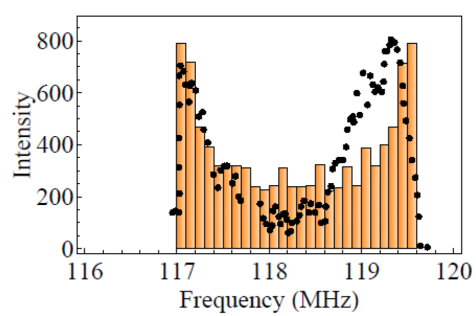


Curro et al. J. Low T Phys. (2009)

$\mu_{Ce} \sim 0.07\mu_B$



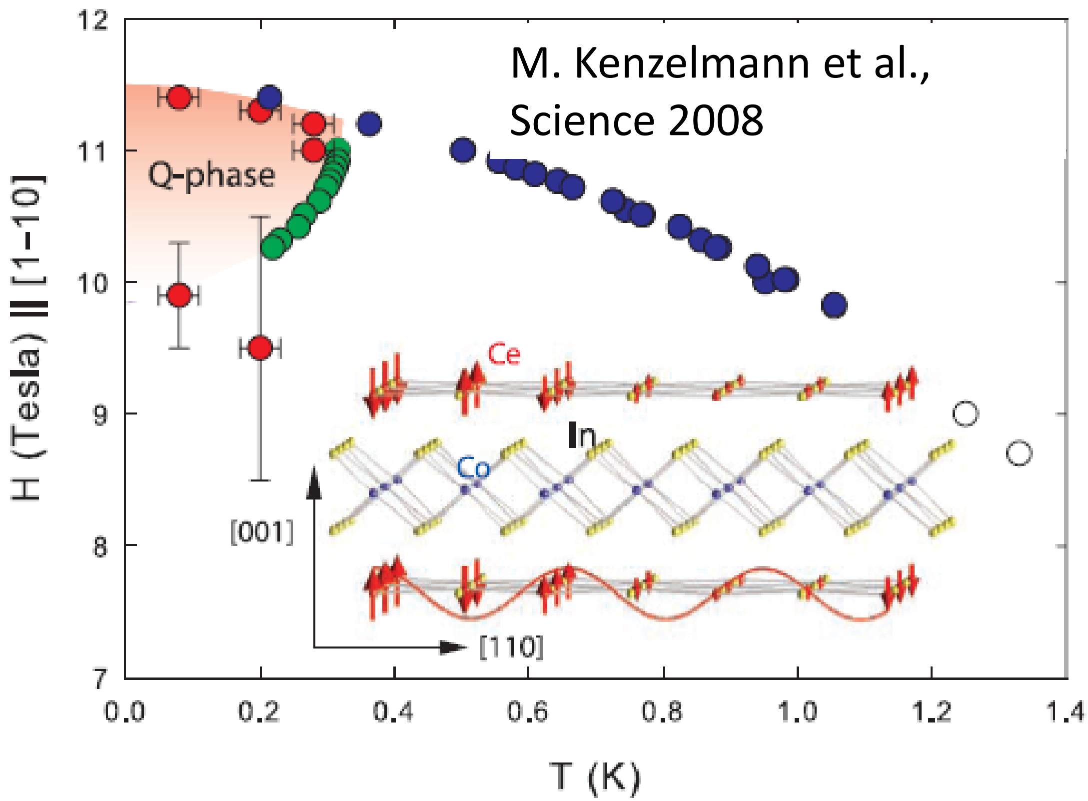
Q_i || [010]

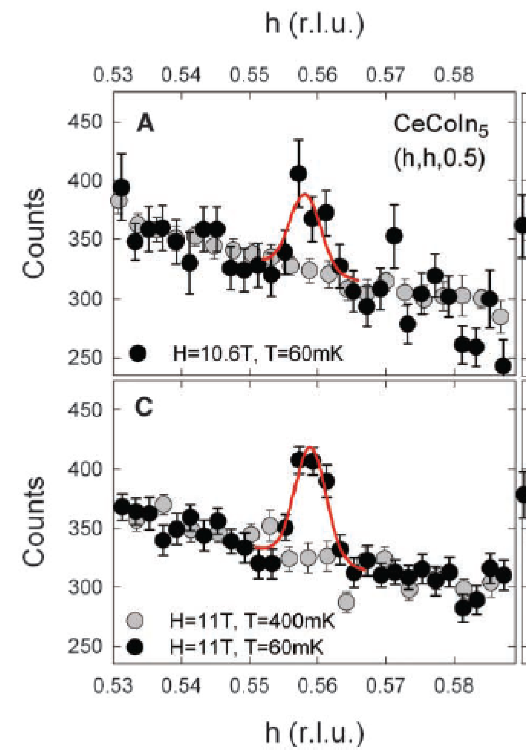


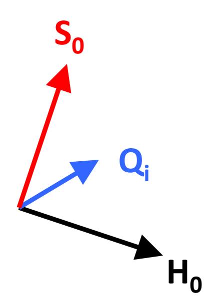
Q_i || [110]

Not an FFLO phase but rather an incommensurate antiferromagnet!

Magnetic neutron diffraction



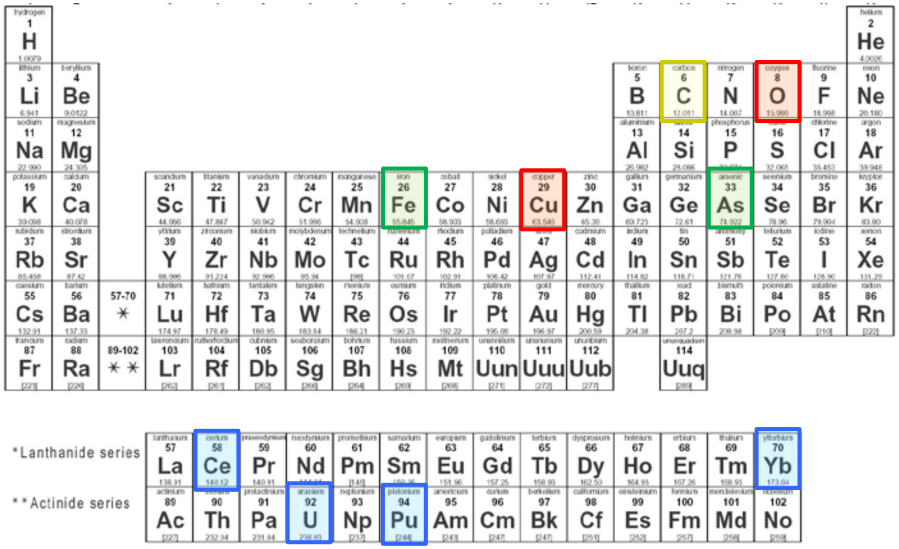


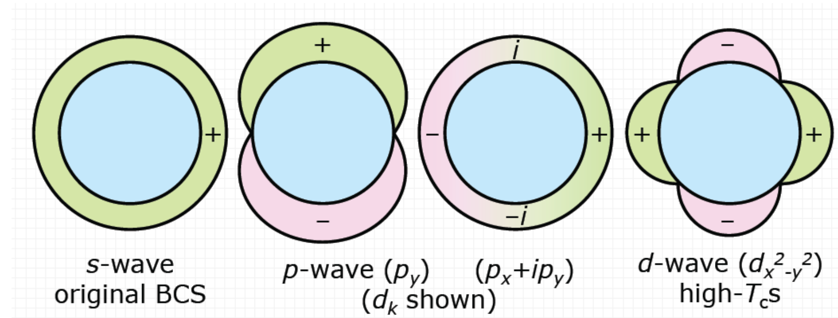


Neutron
Scattering
confirms
NMR

Field $\mathbf{H_0}$ || [1-10]
Ce moment **S** || [001]
Wavevector **Q** || [111]

Future Prospects and Open Questions





- *Very rich physics associated with unconventional superconductors, with many different variations*
- *Towards room temperature?*
- *Understanding the "Normal State"*
- *There is no "magic" technique – best approach is a suite of different techniques*