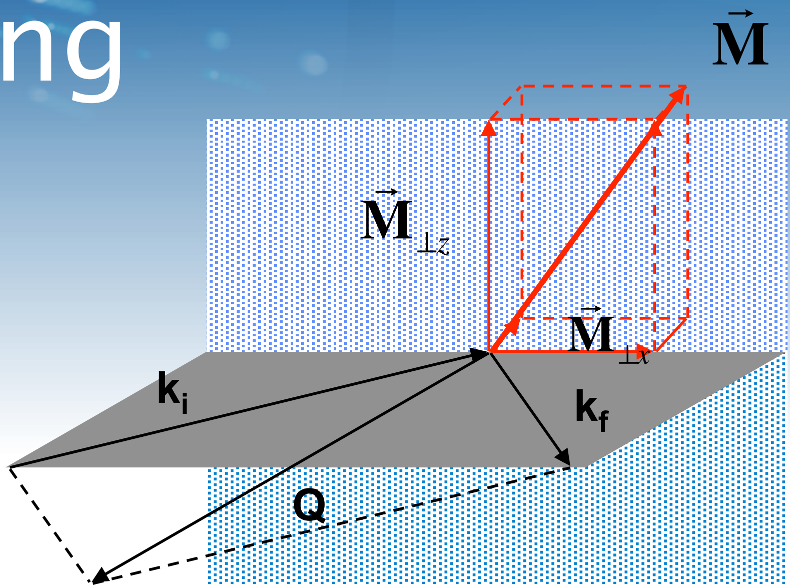
Polarized neutron spectroscopy of high-Tc superconductors.

Jiří Kulda Institut Laue-Langevin
Grenoble, France

Magnetic scattering



- only projection of **M⊥Q** contributes

$$\vec{M}_\perp\left(\vec{Q}\right) = \vec{e}_Q \times \vec{M}\left(\vec{Q}\right) \times \vec{e}_Q$$

$$\vec{M}\left(\vec{Q}\right) = \sum_j \vec{M}_j(Q)\exp\left(i\vec{Q}\vec{r}_j\right)\exp\left(-W_j\right)$$

"Moon's golden rule":

$\vec{M}_\perp \parallel \vec{\sigma}_n$	non spin-flip (NSF)	U^{++}, U^{--}
$\vec{M}_\perp \perp \vec{\sigma}_n$	spin-flip (SF)	U^{+-}, U^{-+}

Diagonal polarization analysis

- **Partial intensities (polarized beam):**

$$I_x^{NSF} \approx N^2 + \frac{1}{3} I_{SI} \qquad I_x^{SF} \approx M_{\perp y}^2 + M_{\perp z}^2 + \frac{2}{3} I_{SI}$$

$$I_y^{NSF} \approx \left(N + M_{\perp y}\right)^2 + \frac{1}{3} I_{SI} \qquad I_y^{SF} \approx M_{\perp z}^2 + \frac{2}{3} I_{SI}$$

$$I_z^{NSF} \approx \left(N + M_{\perp z}\right)^2 + \frac{1}{3} I_{SI} \qquad I_z^{SF} \approx M_{\perp y}^2 + \frac{2}{3} I_{SI}$$

- **Use difference signal to extract information:**

$$\chi_y'' \approx M_{\perp y}^2 \approx I_x^{SF} - I_y^{SF}$$

$$\chi_z'' \approx M_{\perp z}^2 \approx I_x^{SF} - I_z^{SF}$$

Superconductivity

Spin pairing:

s-wave pairing (S=0)

conventional superconductors – Nb, ...

d_{x2-y2}-wave pairing (S=0)

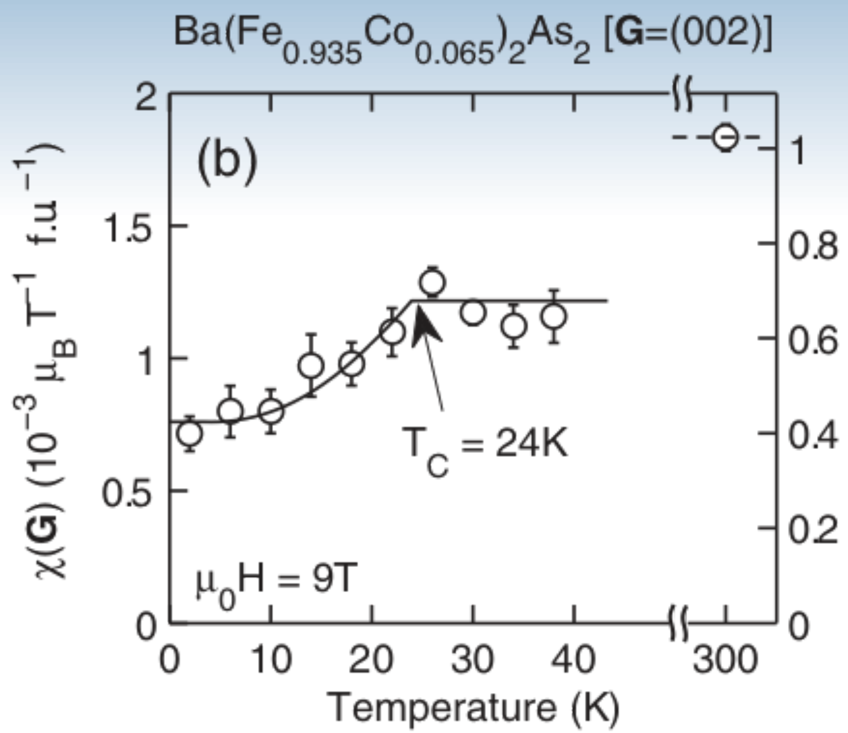
cuprates, Fe-based ....

d-wave pairing (S=1)

Sr_2RuO_4, UPt_3, UB_{13} ....

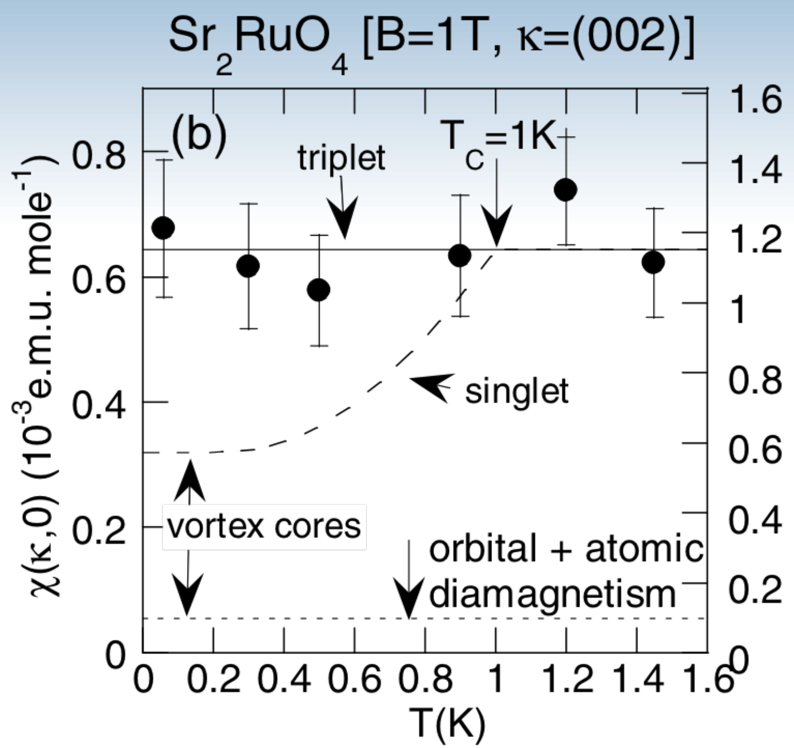
Spin pairing

S = 0



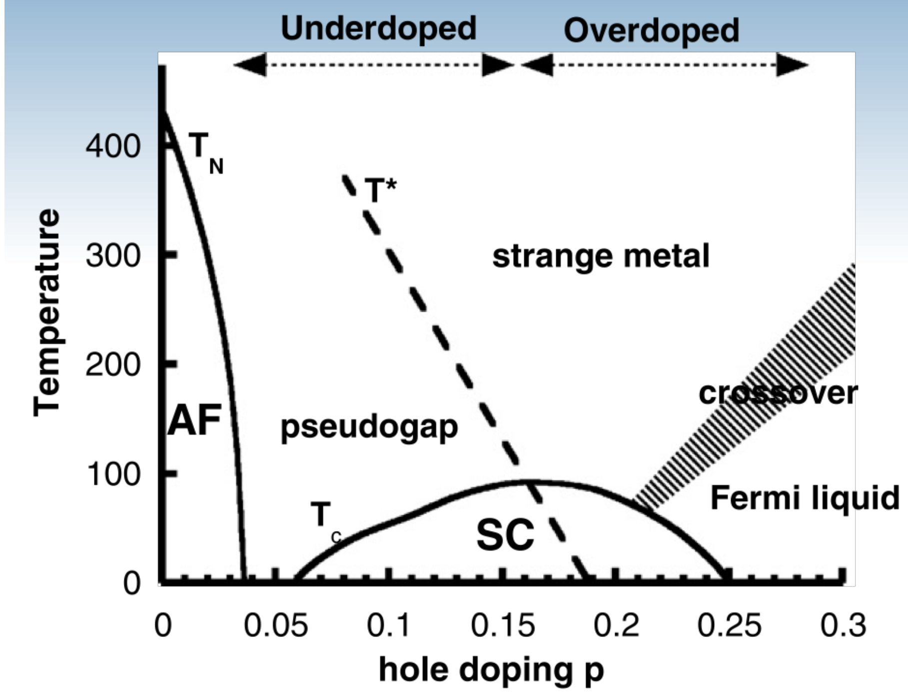
Lester, C. et al., Phys. Rev. B 81 (2010) 064505

S = 1



J.A. Duffy et al., PRL 85 (2000) 5413

Pseudogap phase



Experimental evidence:

- ARPES – q-dependent gap at $M = (\pi, 0)$
- Raman, STM, ...

Pseudogap nature:

- *d*-wave gap precursor (incoherent short-range pairing) ?
- a competing state *behind* the superconductivity dome?

Spin fluctuations

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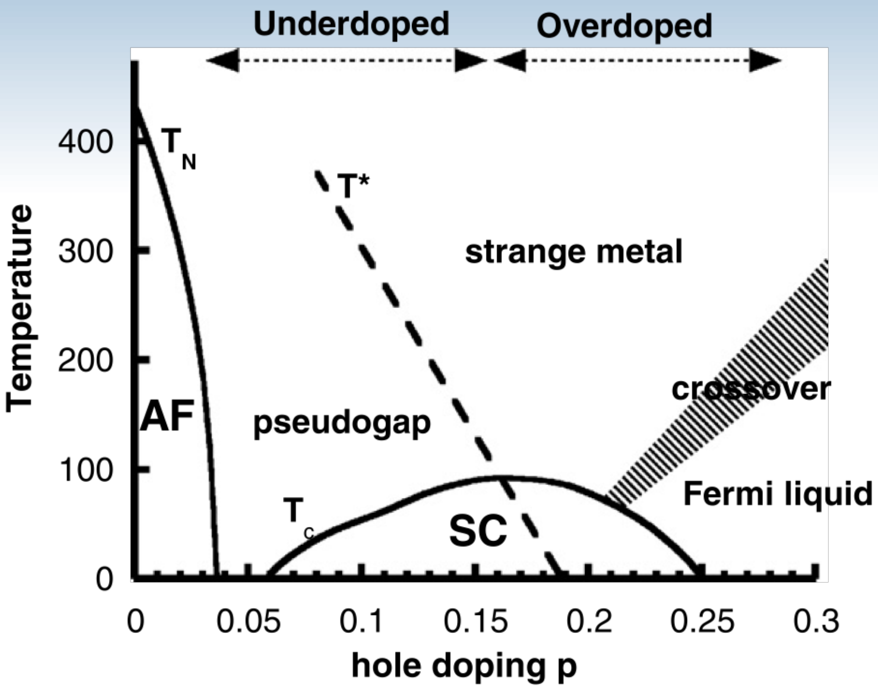
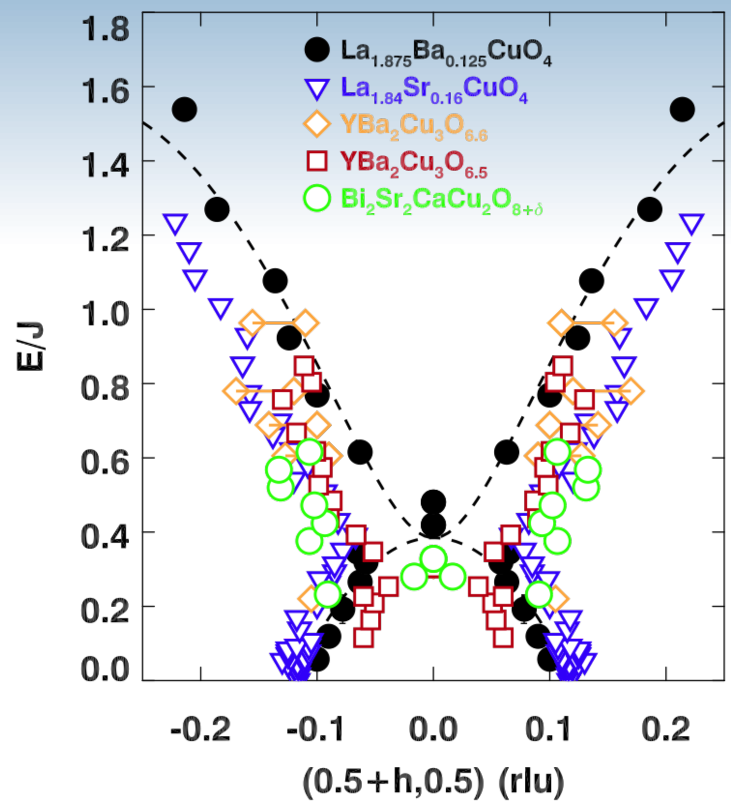
Cuprates

Phase diagram



P. Bourges, Y. Sidis, C.R. Physique 12 (2011) 461

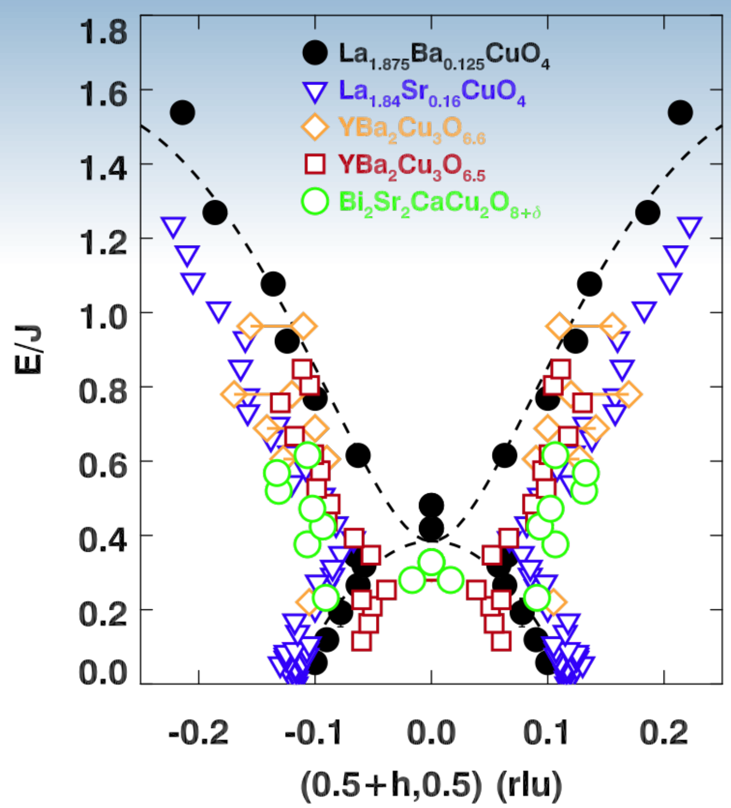
Hourglass dispersion



M. Matsuda *et al.*, J Phys Soc Japan **81**, 011007 (2012)

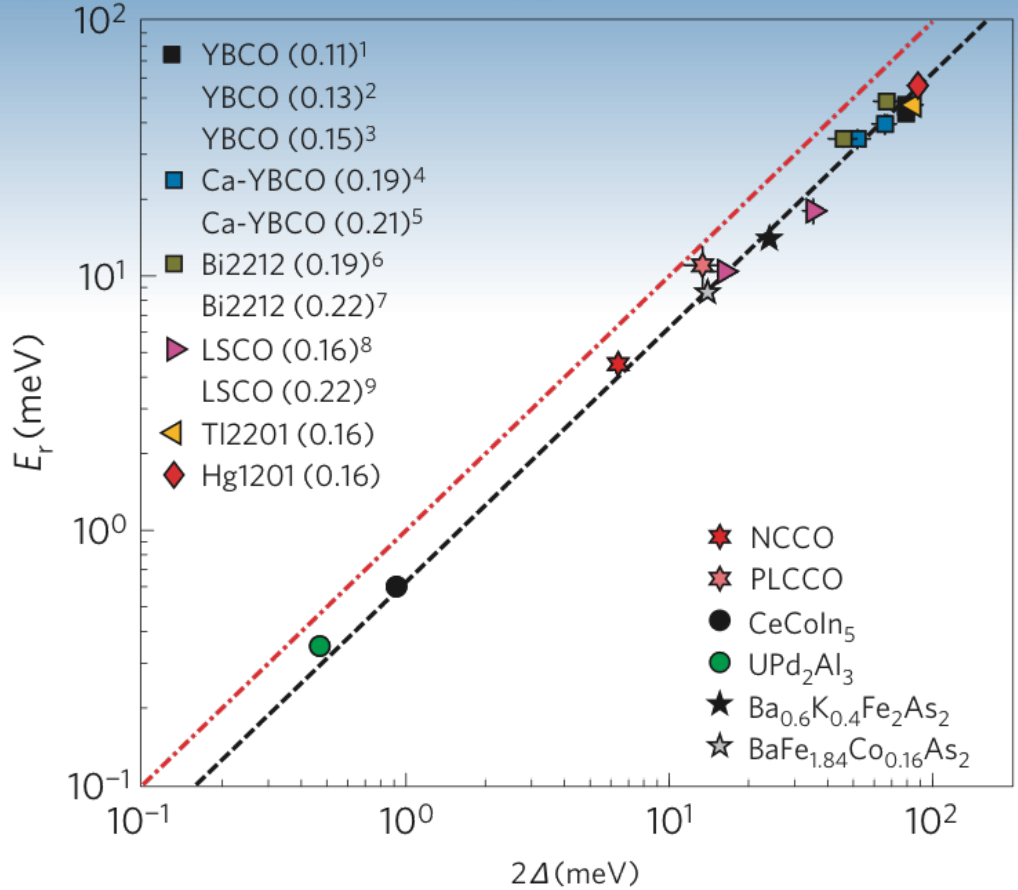
Resonance mode

Hourglass dispersion



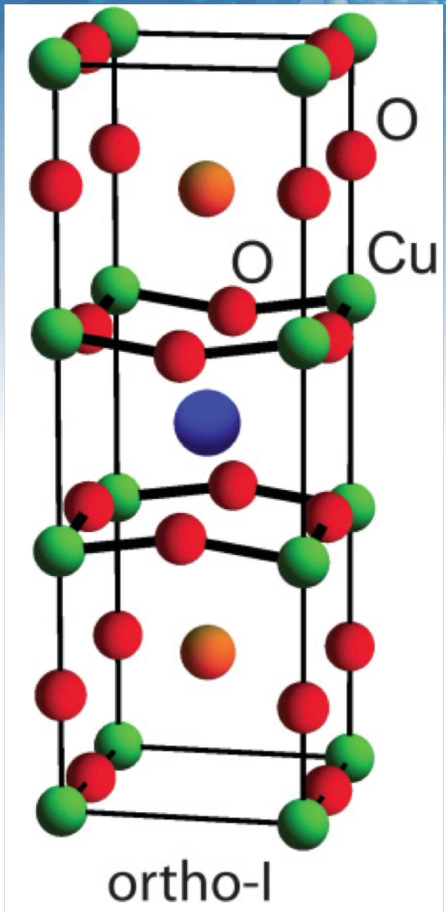
M. Matsuda *et al.*, J Phys Soc Japan **81**, 011007 (2012)

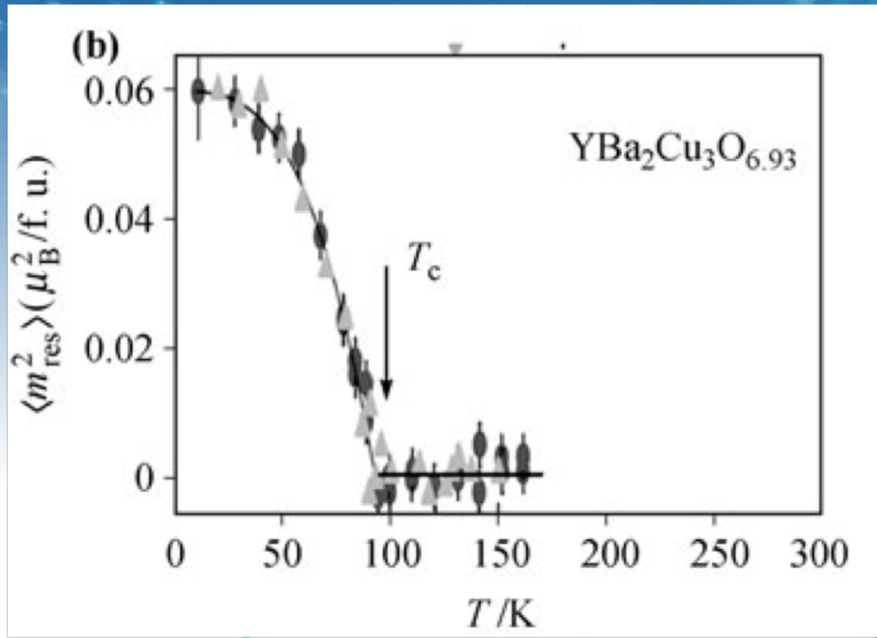
Resonance energy

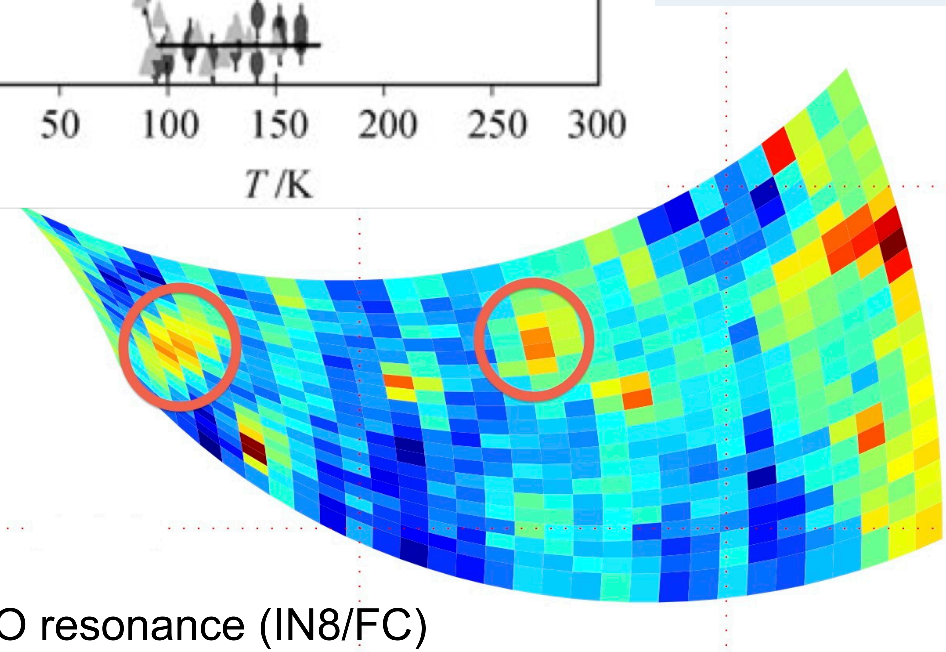


Yu, Li, Motoyama & Greven, nphys 1426 (2009)

$YBa_2Cu_3O_{6.9}$



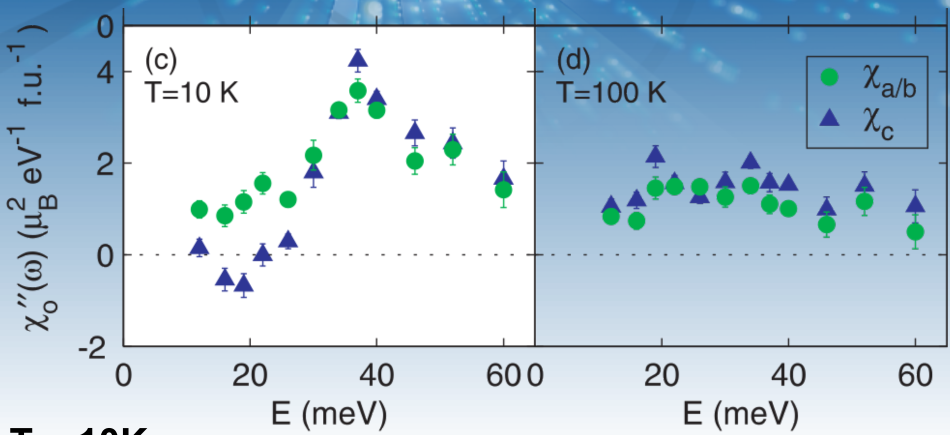




$YBa_2Cu_3O_{6.9}$
T_c = 93.0(2) K

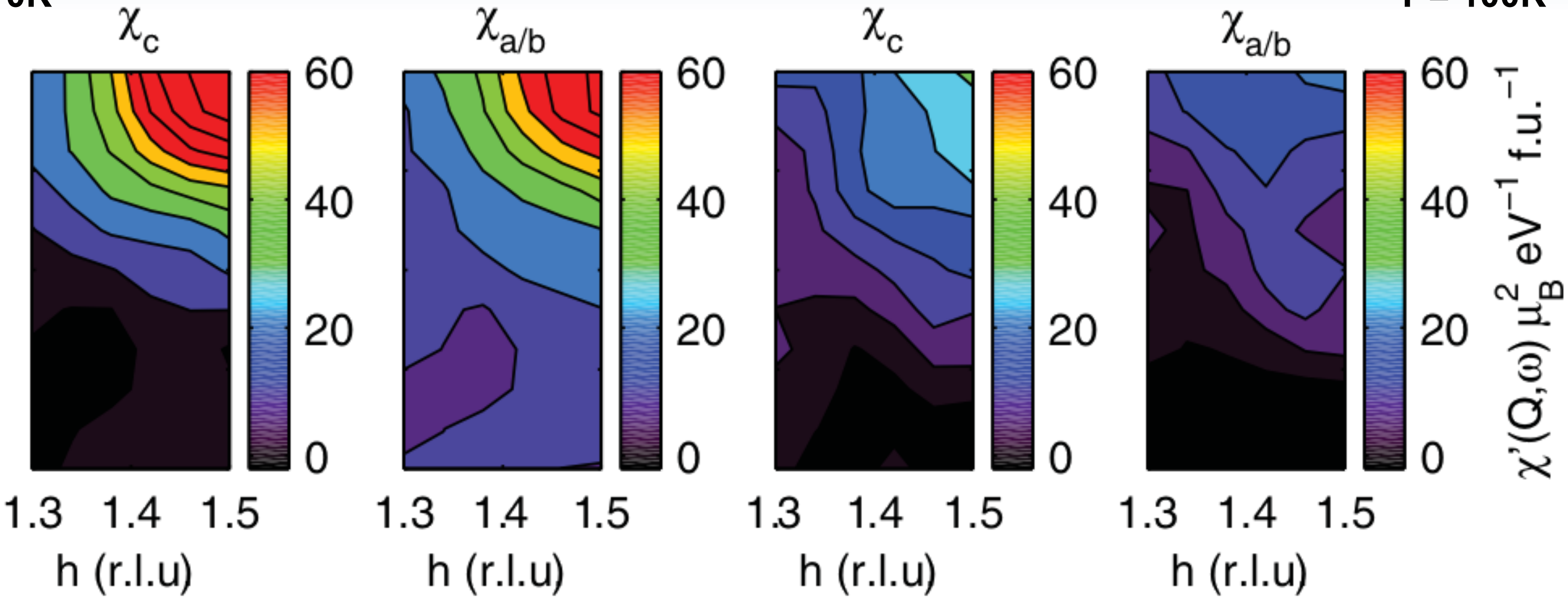
YBCO resonance (IN8/FC)
T = 10K, ΔE = 40 meV

$YBa_2Cu_3O_{6.9}$



resonance
ΔE = 40 meV
isotropic polarisation

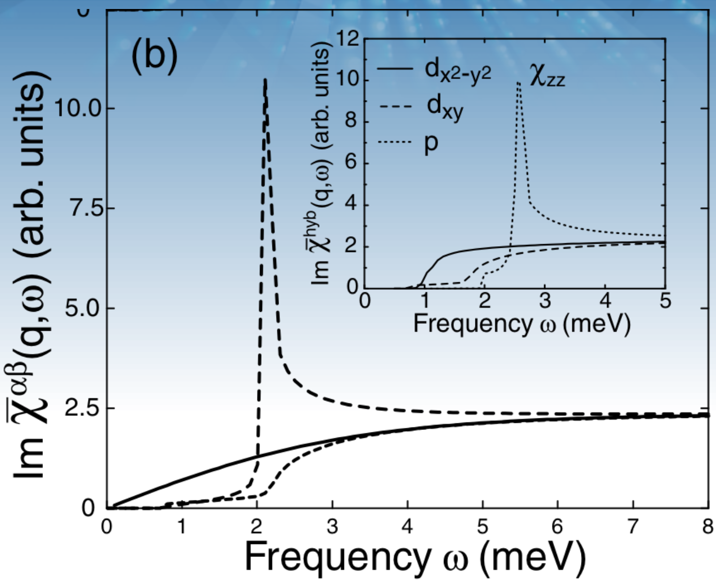
T = 10K **T = 100K**

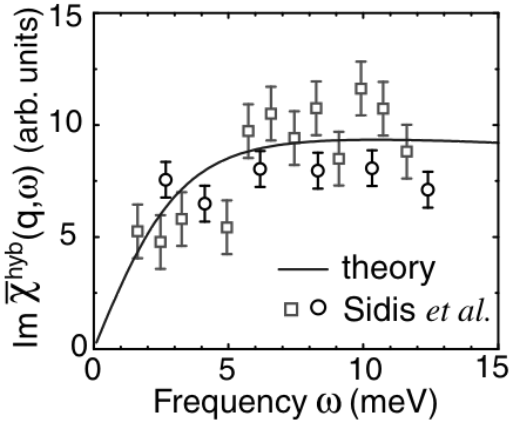


N. Headings et al., Phys. Rev. B 84 (2011) 104513

Sr_2RuO_4

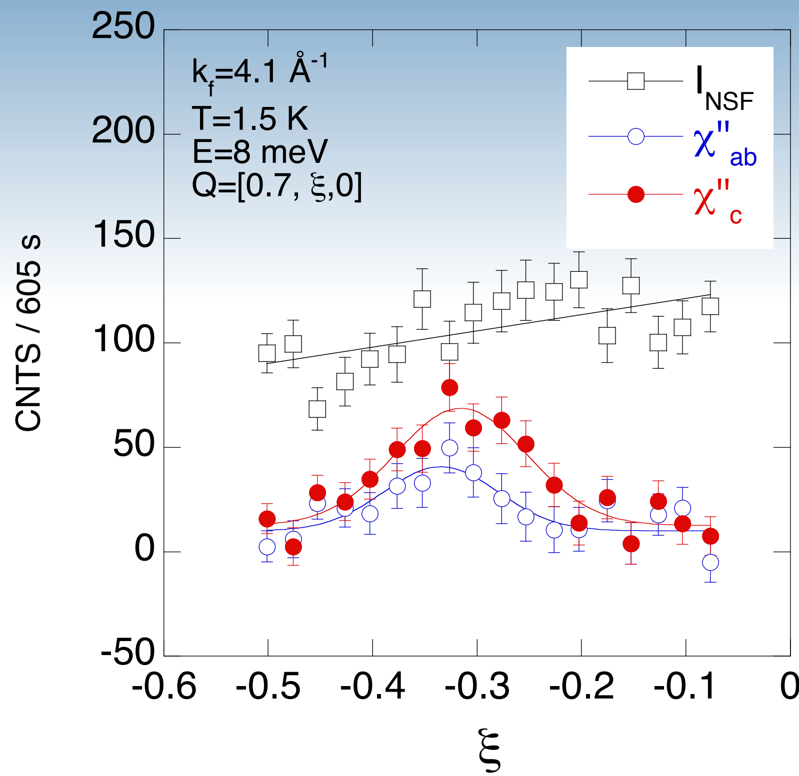
theory





Morr et al., Phys. Rev. Lett. 86 (2001) 5978

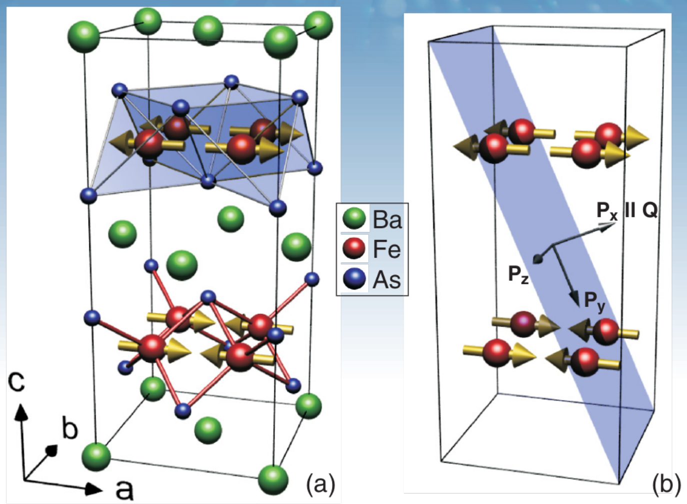
IN20 PA data

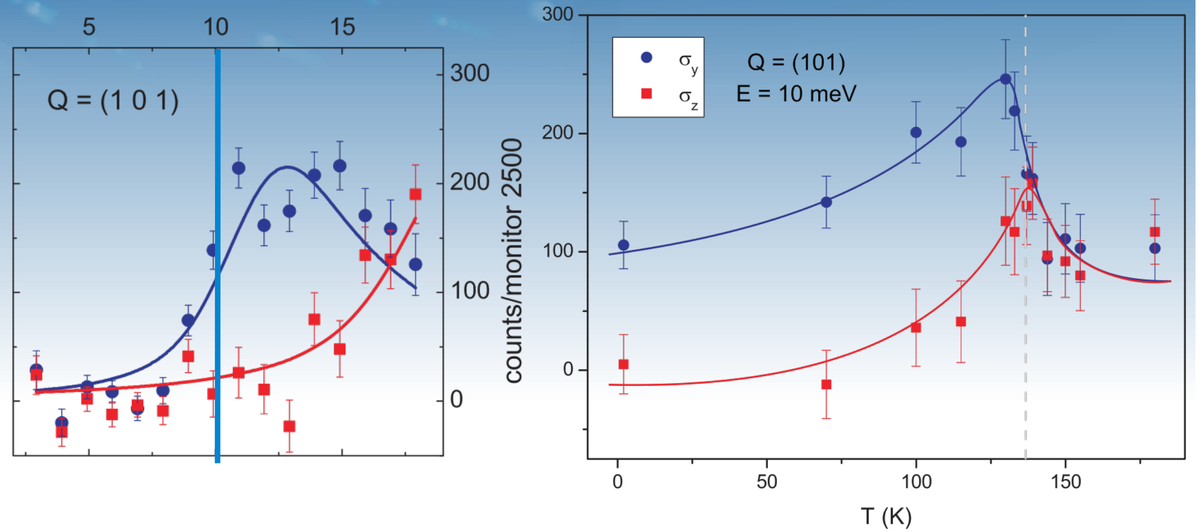


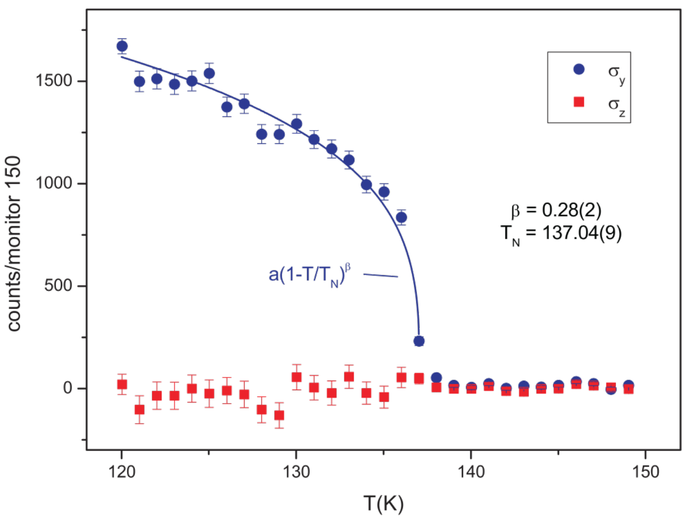
M. Braden et al., Phys. Rev. Lett. 92 (2004) 097402

Anisotropy in 122 Pnictides

$BaFe_2As_2$







- non-SC parent compound
- AF order below 137K
- large single-ion anisotropy
- SC by electron/hole doping

N. Qureshi et al., Phys. Rev. B86, (2012) 060410(R)

Anisotropy in 122 Pnictides

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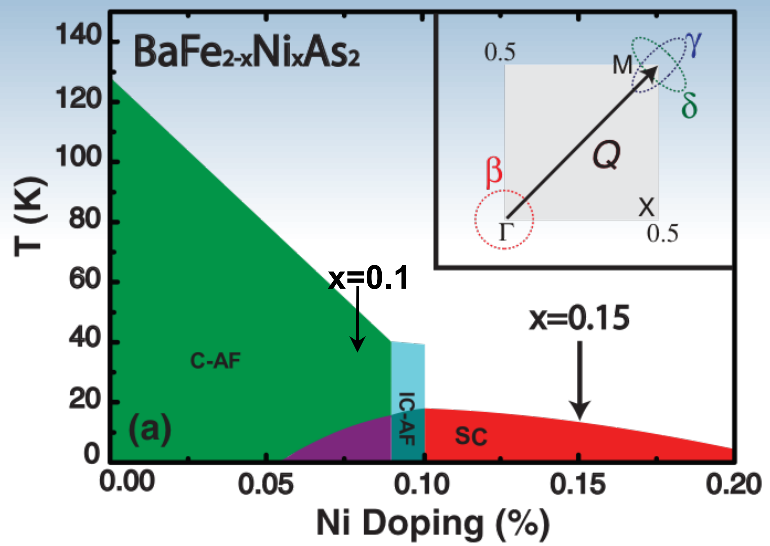
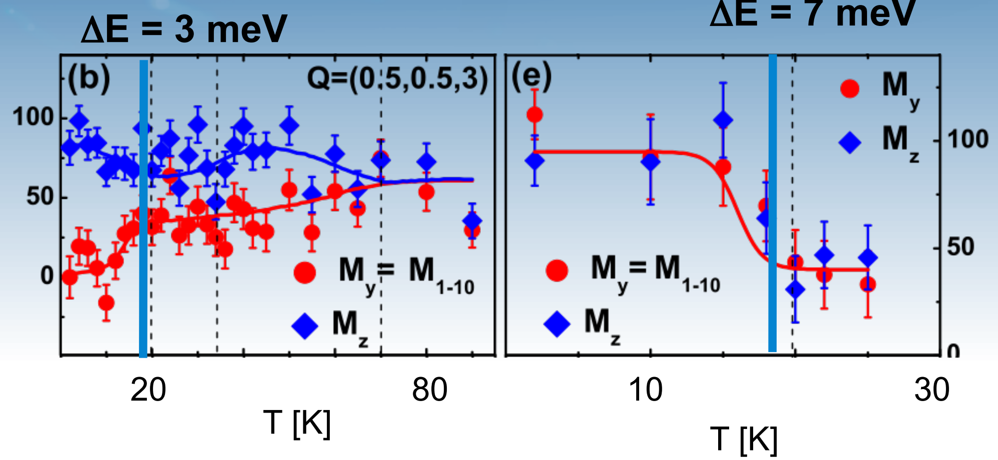
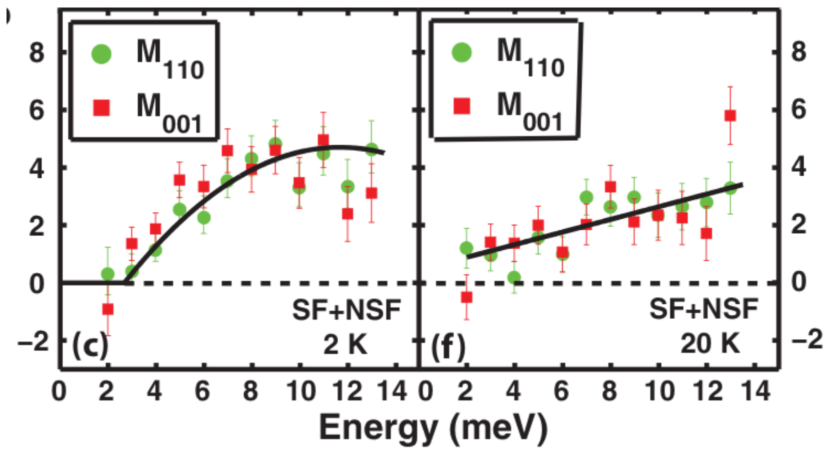
$BaFe_2As_2$ electron doped



x = 0.10 T_c = 19.8 K



x = 0.15 T_c = 14 K



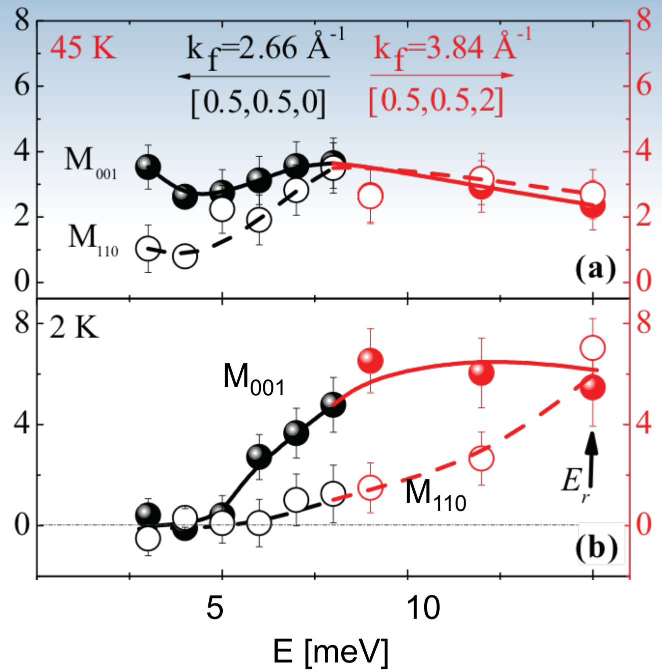
Anisotropy disappears with e⁻-doping

M. Liu et al., Phys. Rev. B85 (2012) 214516
H. Luo et al., Phys. Rev. Lett. 111 (2013) 107006

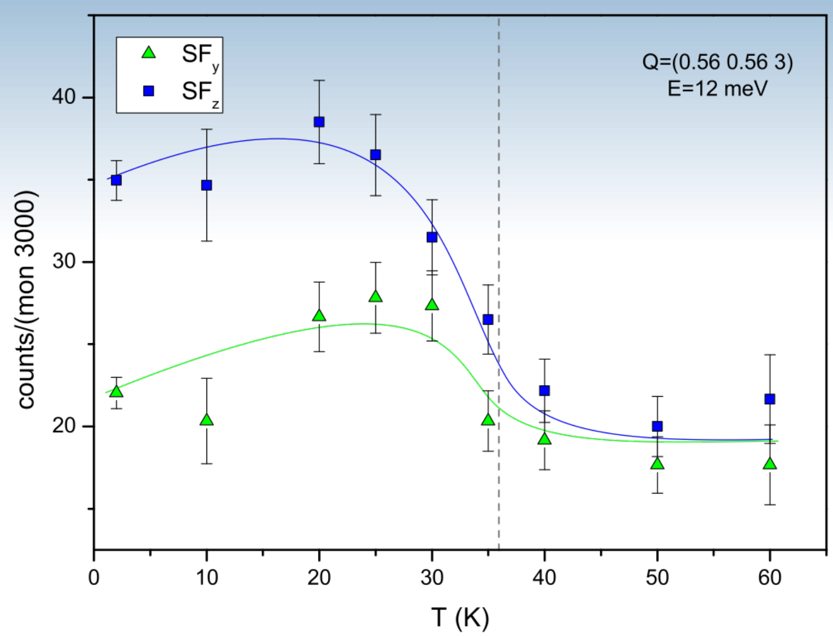
Anisotropy in 122 Pnictides

$Ba_{1-x}K_xFe_2As_2$ hole doped

x = 0.33 (optimum) Tc = 38 K



x = 0.5 (overdoped) T_c = 36 K

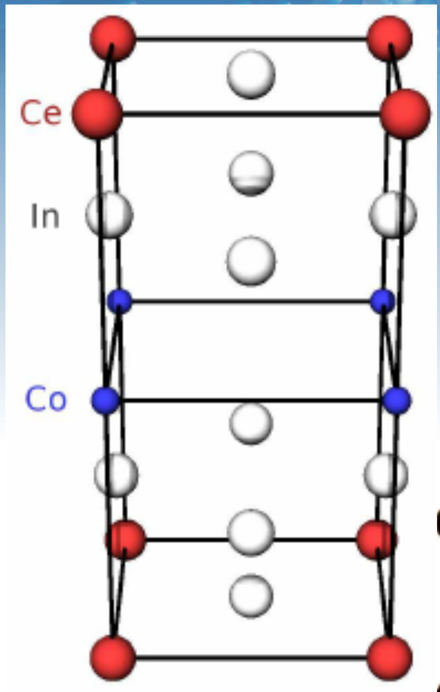


C. Zhang et al., Phys. Rev. B87 (2013) 081101(R)
N. Qureshi et al., Phys. Rev. B90, (2014) 100502(R)

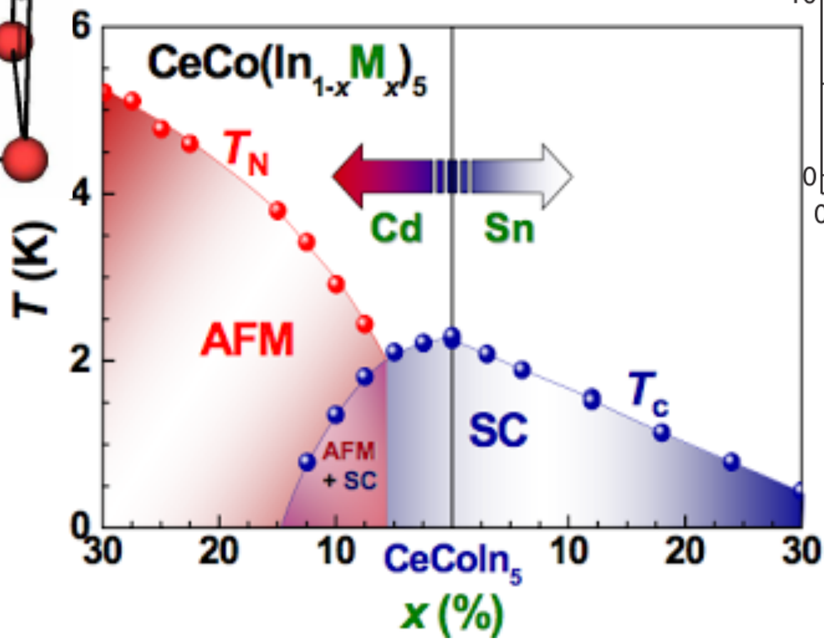
Anisotropy persists with hole-doping!

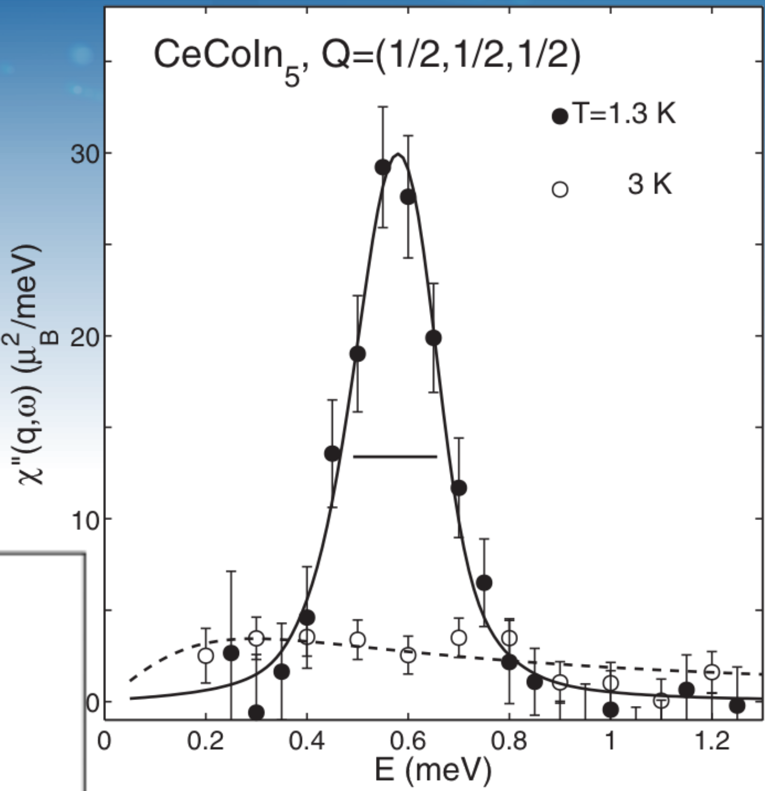
chemistry difference between Ni and K?

$CeCoIn_5$



T_c = 2.3 K

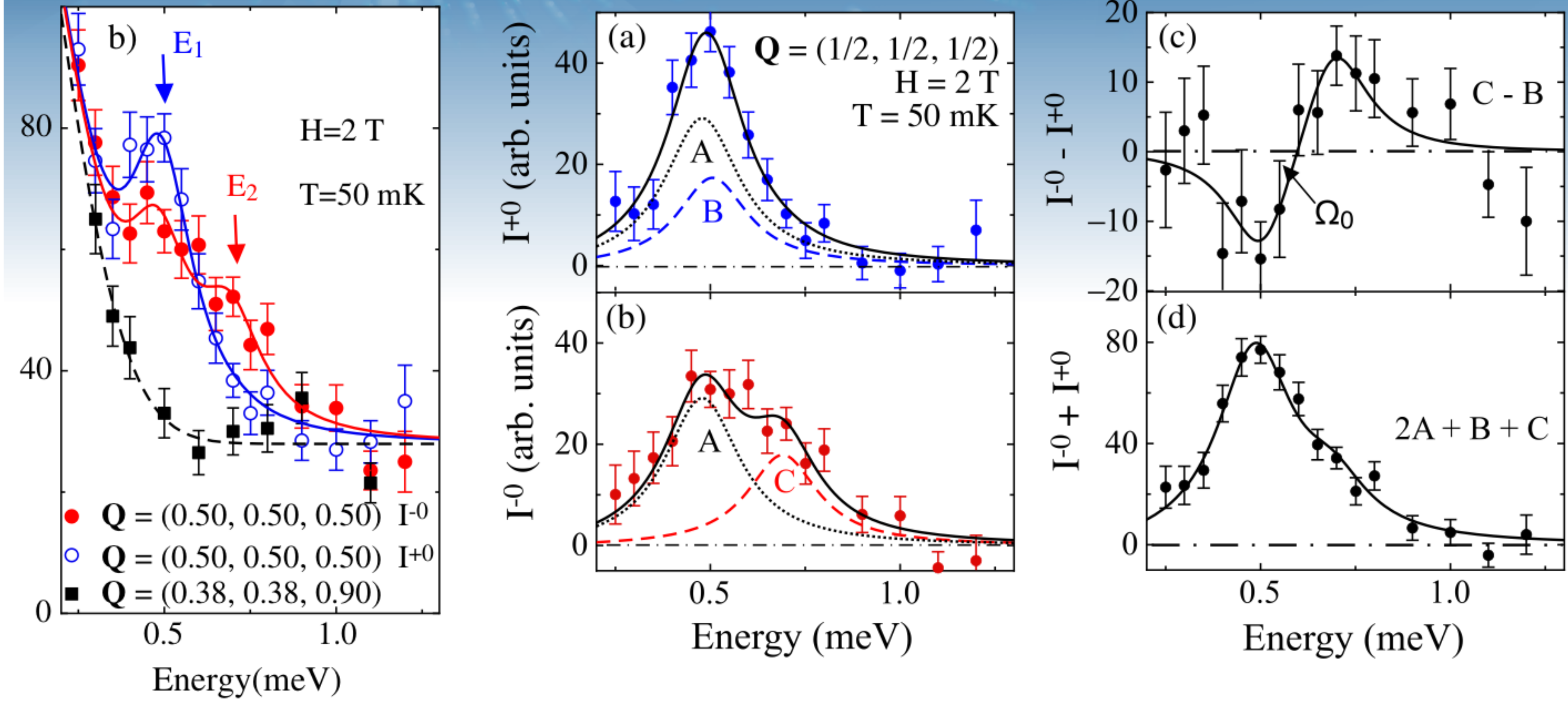




resonance
("background" subtracted)

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

$CeCoIn_5$

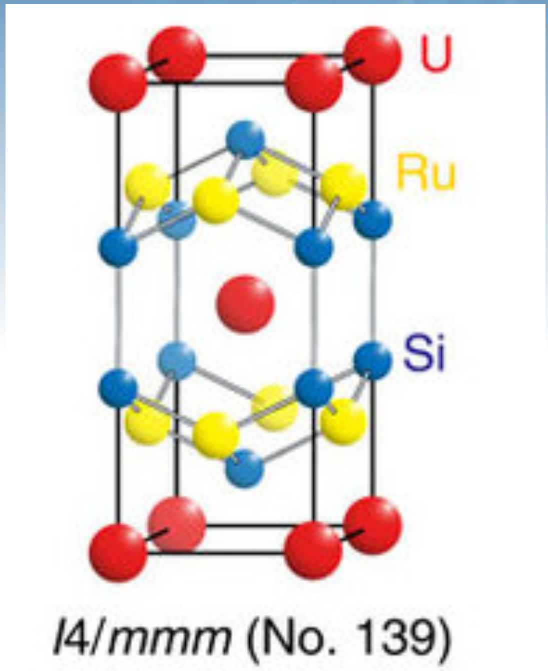


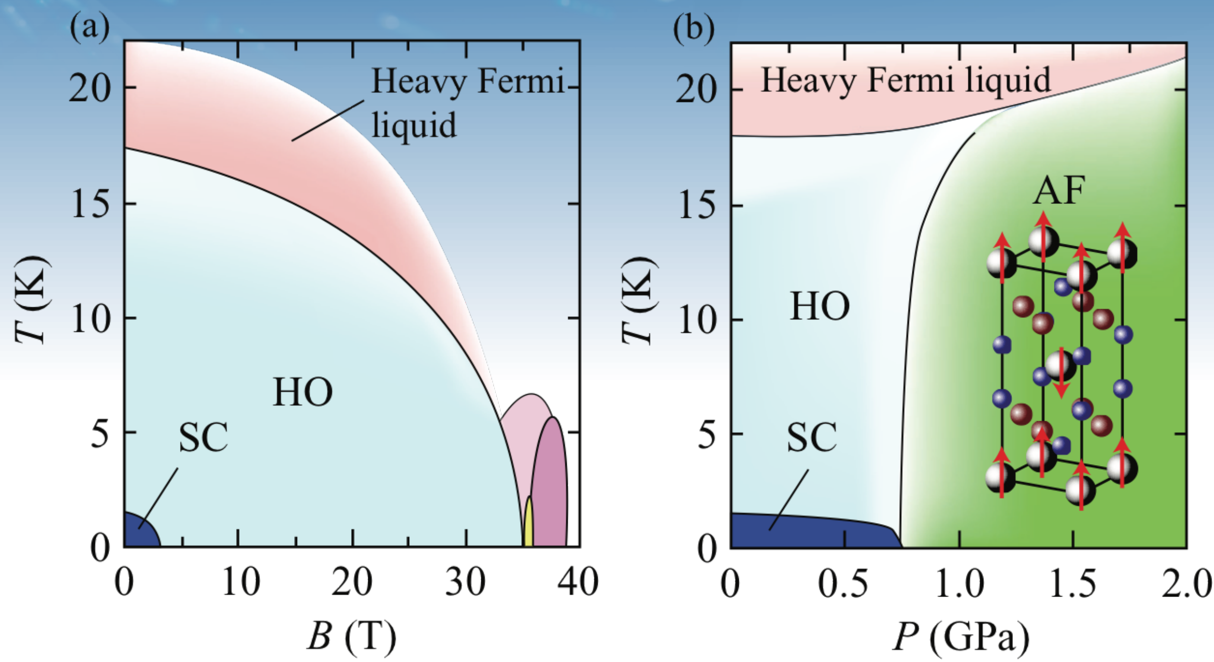
B || [0.5 0.5 0.5]

"chiral" component (B,C)!

S. Raymond et al., PRL 109 (2012) 237210

URu_2Si_2



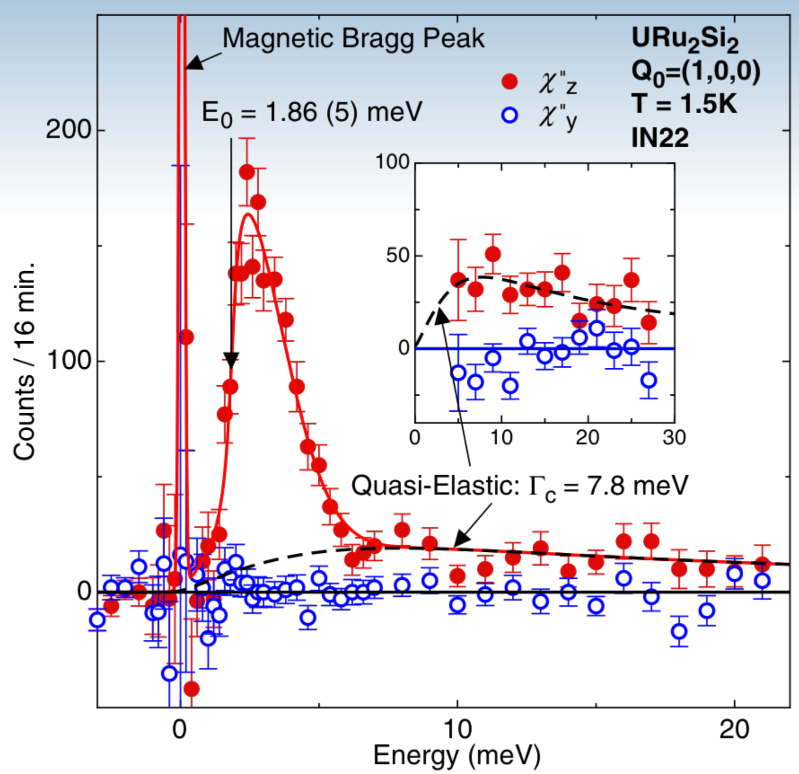


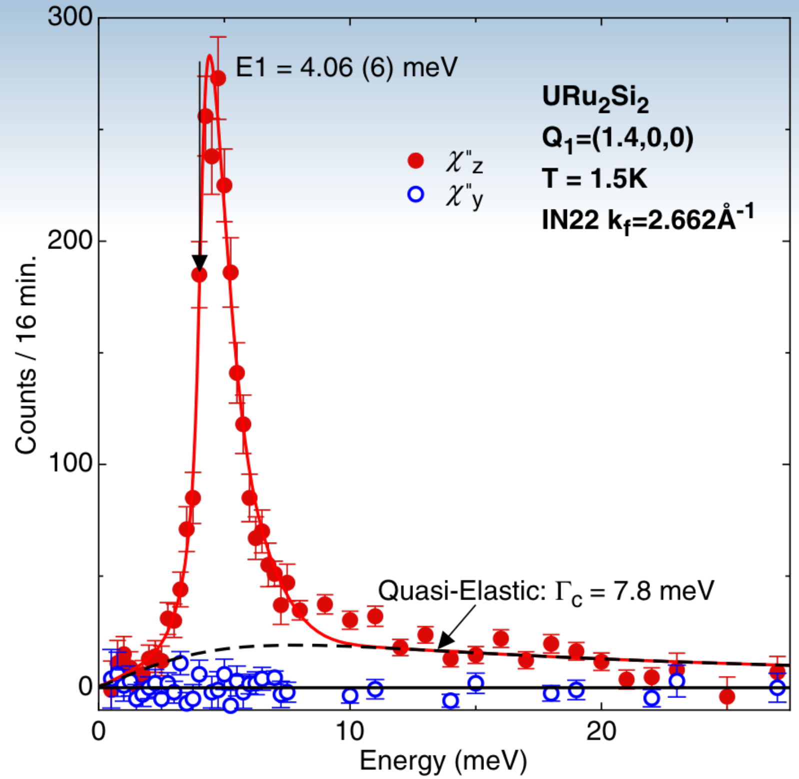
$T_c \approx 1.5$ K

- hidden order (HO) phase T < 17.5 K and B < 36T
- two resonances
  - Q_0 = (1 0 0) disappears in favour of AF order
  - Q_1 = (1.4 0 0) persistent
  - both strongly anisotropic

URu_2Si_2

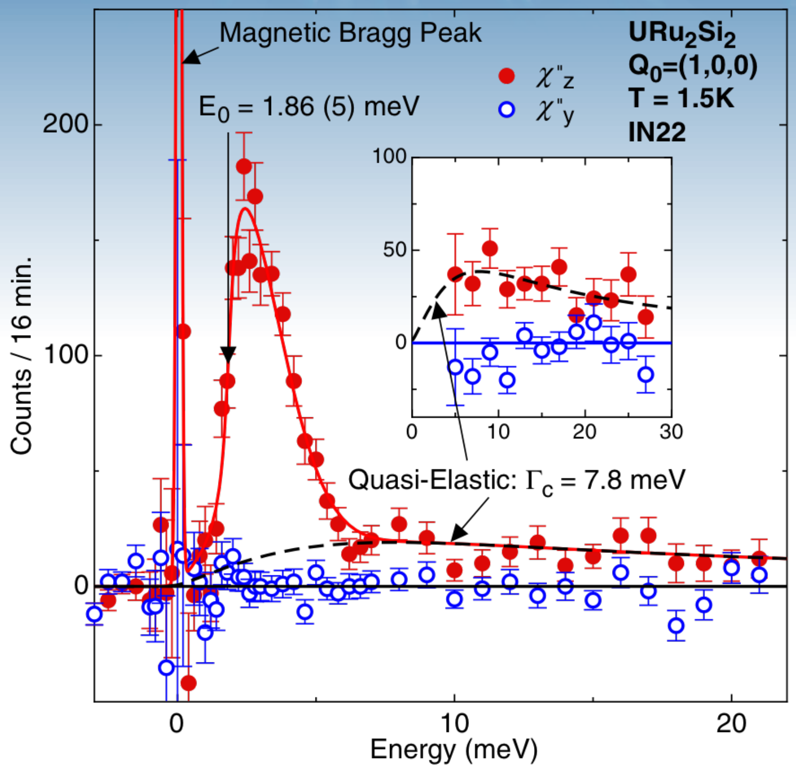
longitudinal ***z* || *c***
transversal ***y* || *b***

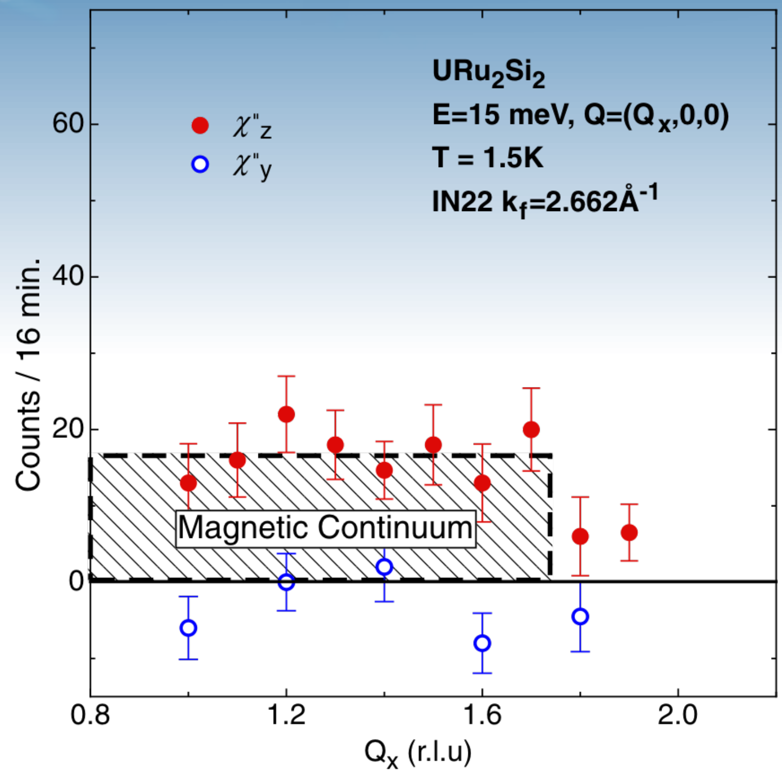




fingerprint of the HO phase

URu_2Si_2

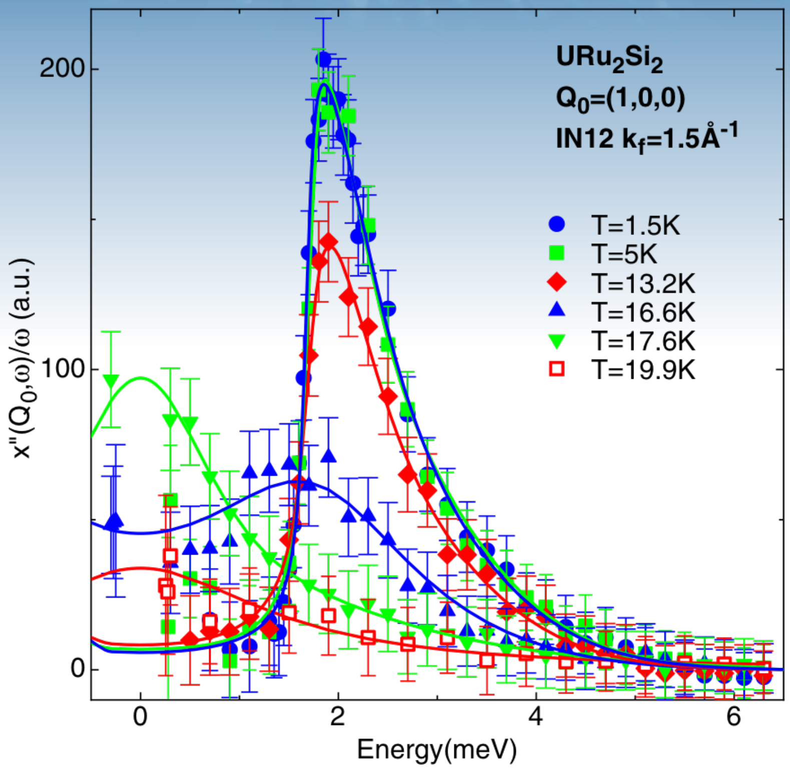


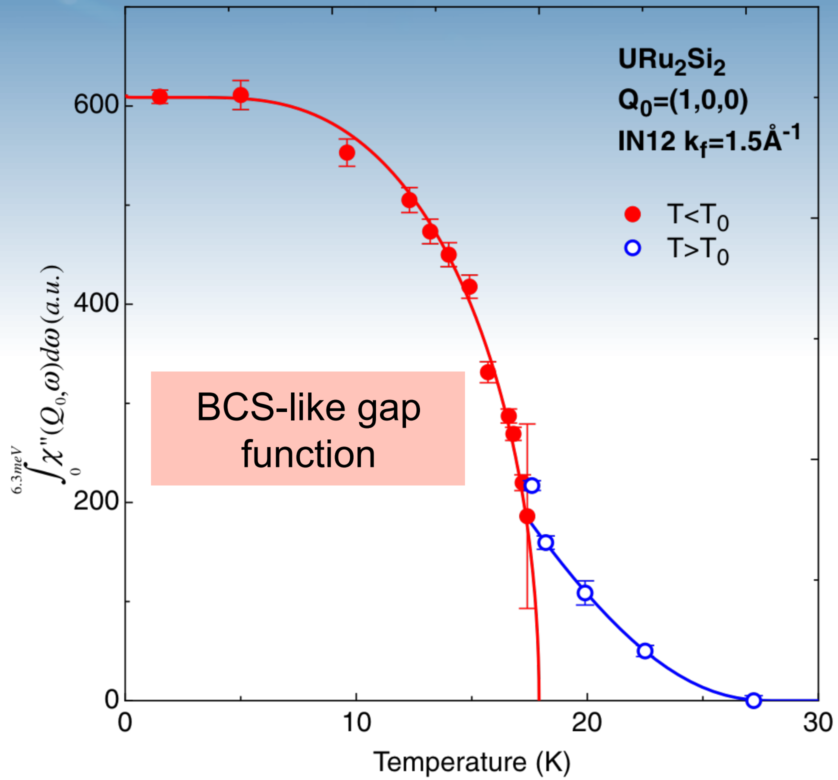


longitudinal ***z* || *c***

transversal ***y* || *b***

URu_2Si_2





imaginary part of dynamical susceptibility w/o continuum

Summary

Resonance peak polarization :

- all degrees of anisotropy
- no clear relation to the pairing mechanism
- possibly closer relation to parent compound magnetism

"While there is no consensus on the origin of such an excitation and its relevance to the pairing mechanism, it provides important information about the superconducting state."

Need for

- ***more polarized experiments***
- ***high quality & well characterized samples***
- ***more theory & new ideas***