Neutron scattering study of iron based high T_c superconductors

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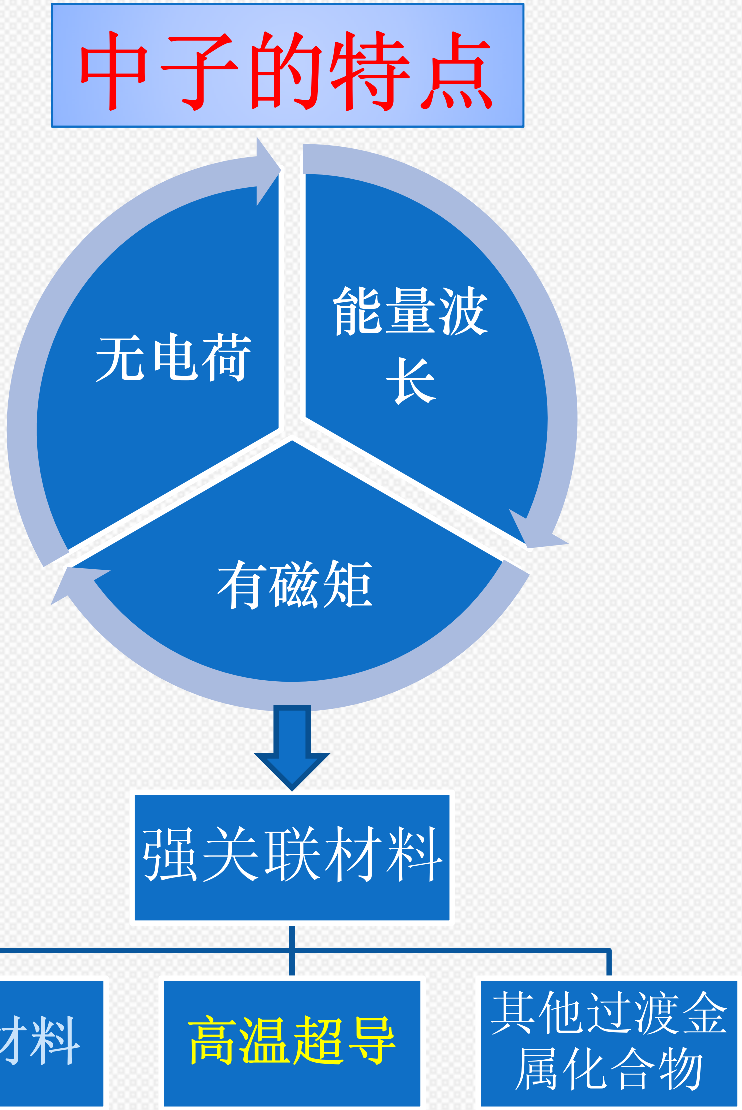
Outline

- ☐ Introduction of neutron scattering techniques
- ☐ Spin wave and magnetic exchange interactions in the parent compounds of iron based superconductors
- ☐ Spin excitations in iron based superconductors
- ☐ Summary

中子的特点和强关联电子体系



中子的特点

无电荷

能量波长

有磁矩

强关联材料

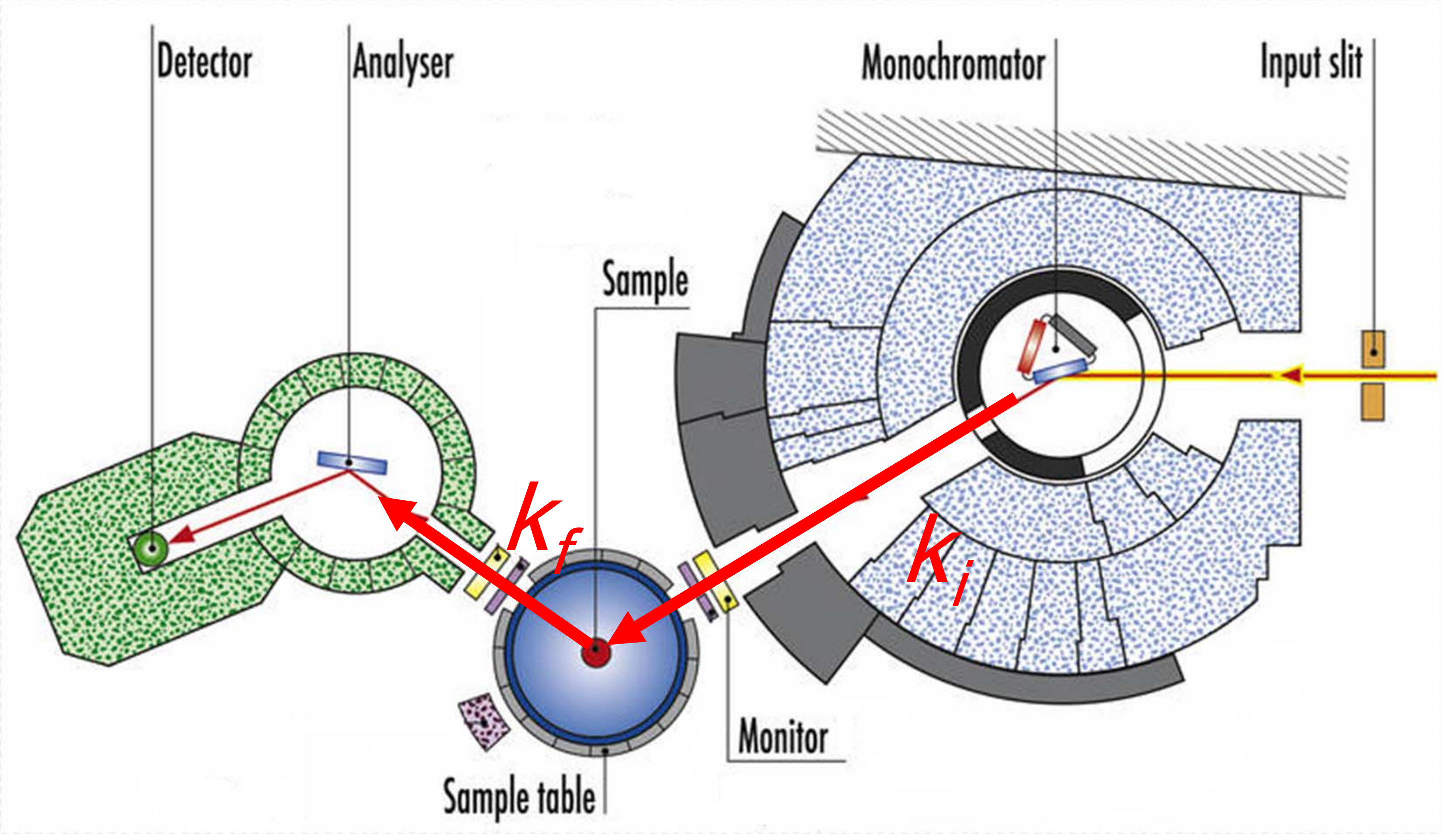
多铁材料

高温超导

其他过渡金属化合物

世界各地主要中子源分布

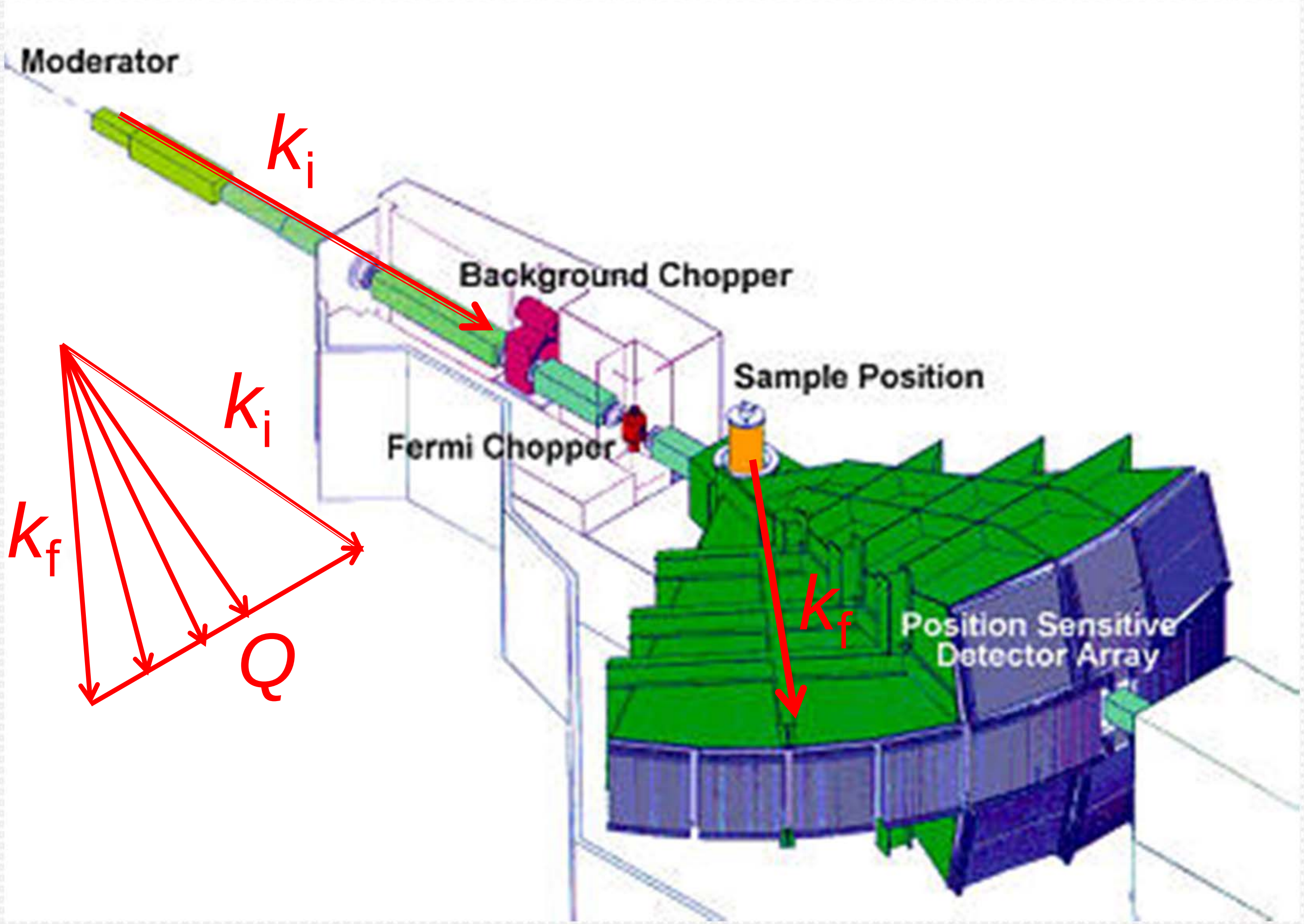
IN22 triple axis spectrometer, ILL, France

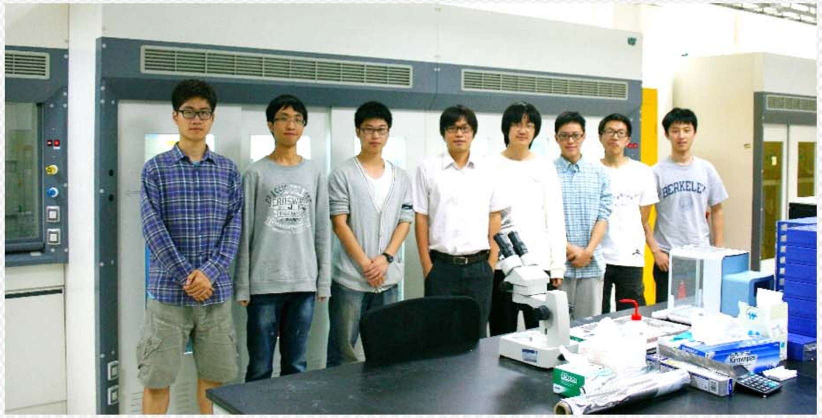


$\vec{Q} = \vec{k}_i - \vec{k}_f$ Momentum conservation

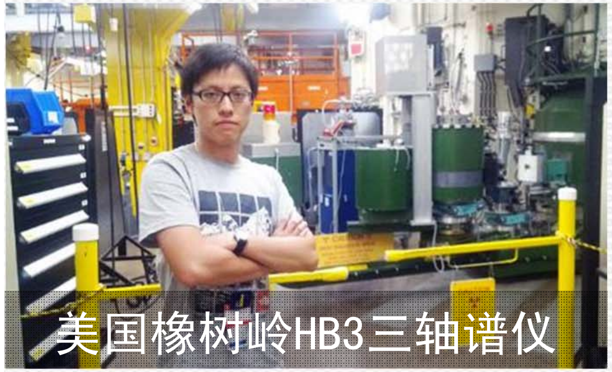
$\hbar\omega = E_i - E_f$ Energy conservation

Time of Flight Chopper Spectrometer, ISIS, U.K.





美国标准局博物馆



美国橡树岭HB3三轴谱仪

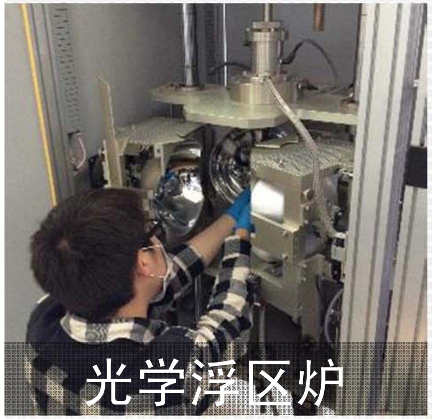
德国慕尼黑FRM-II中子源

华盛顿

美国橡树岭HB1三轴谱仪

FRM-II中子源

美国标准局



光学浮区炉

布里奇曼炉

$K_xFe_{2-y}Se_2$

$Ba(Fe_{1-x}Ru_x)_2As_2$

$Ba(Fe_{1-x}Mn_x)_2As_2$

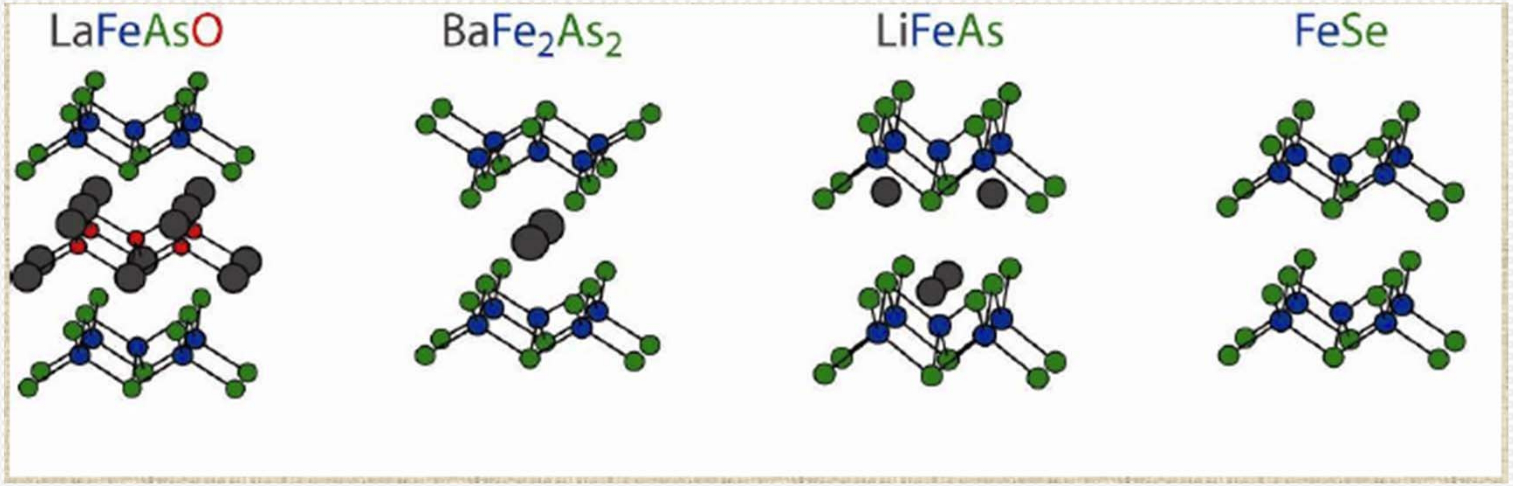
手套箱

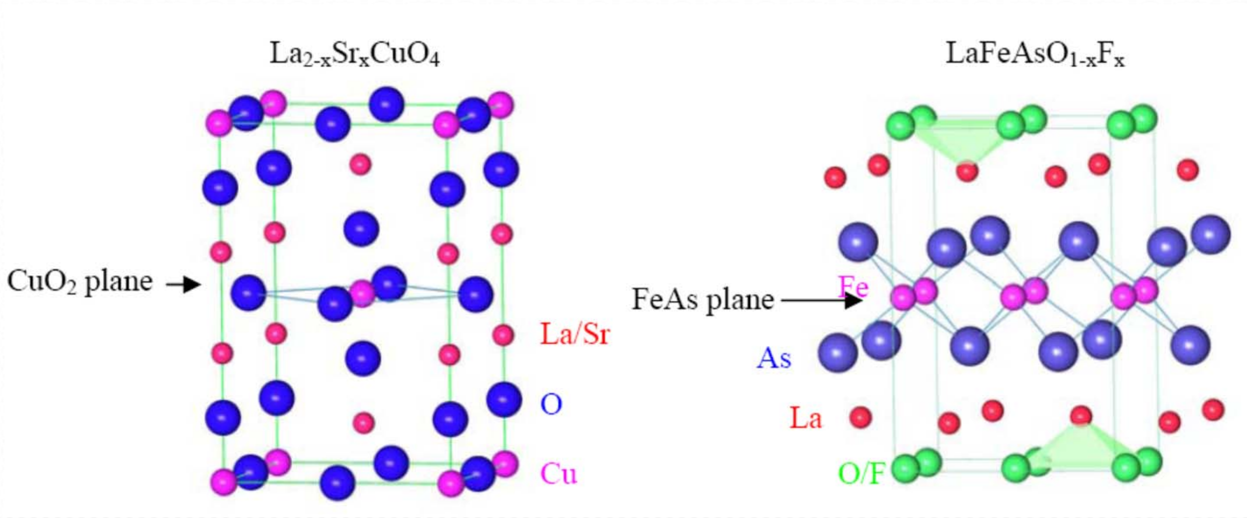
焊炬

电弧炉

实验室全景

Discovery of Iron-based high T_c Superconductors



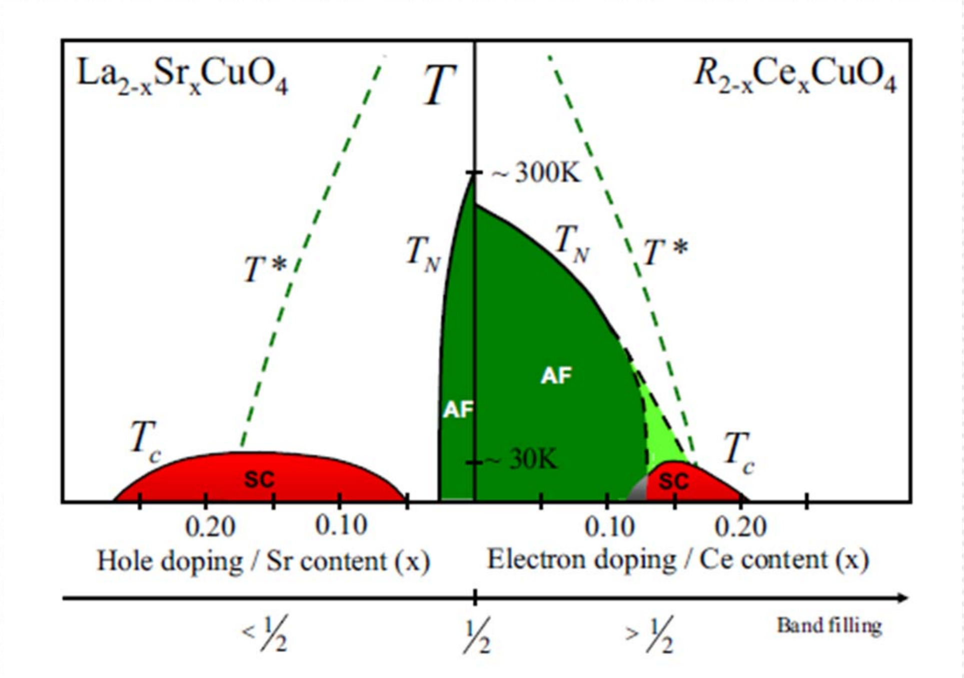


What are universal ?

What are material dependent?

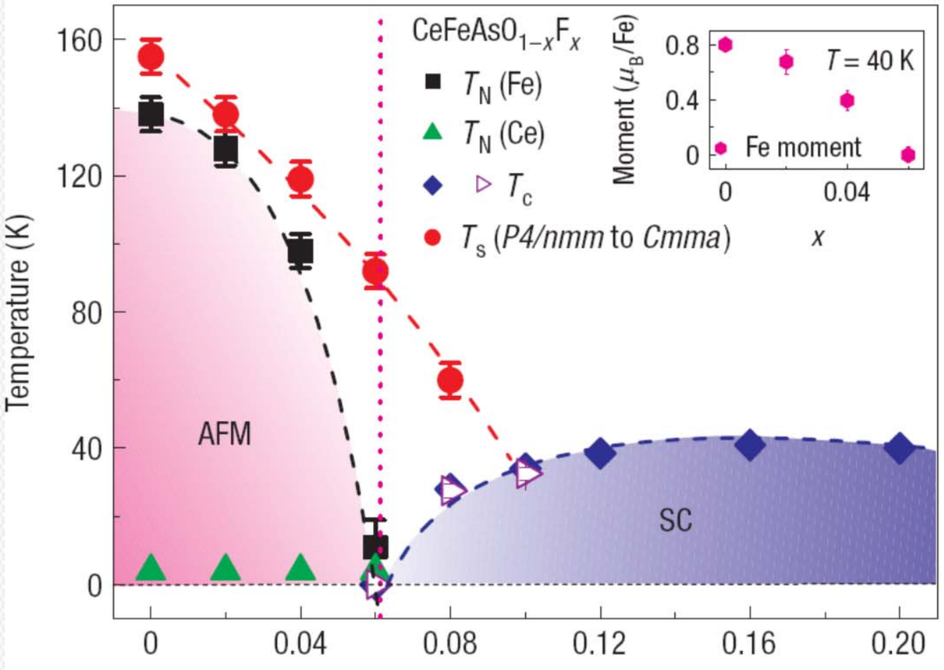
Antiferromagnetism & superconductivity

Cuprates



N. P. Armitage *et al.,* Rev. Mod. Phys 82 2421 (2010)

Fe pnictides



J. Zhao et al., Nature Materials 7 953 (2008)

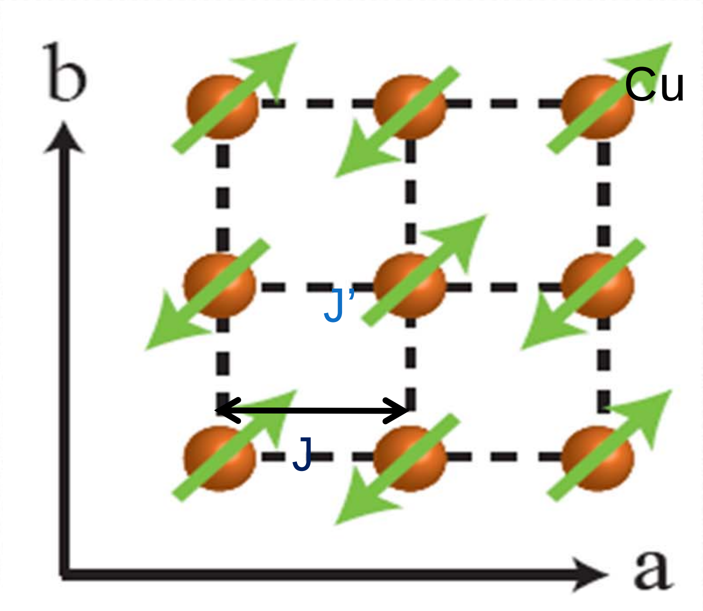
Parent compound: antiferromagnetic Insulators

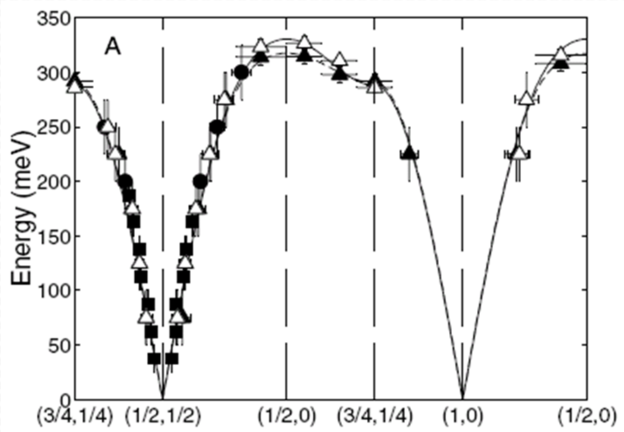
Fe pnictides: antiferromagnetic Semi-metals

Antiferromagnetism is universal !

Spin waves in the parent compounds of Cuprates

La_2CuO_4



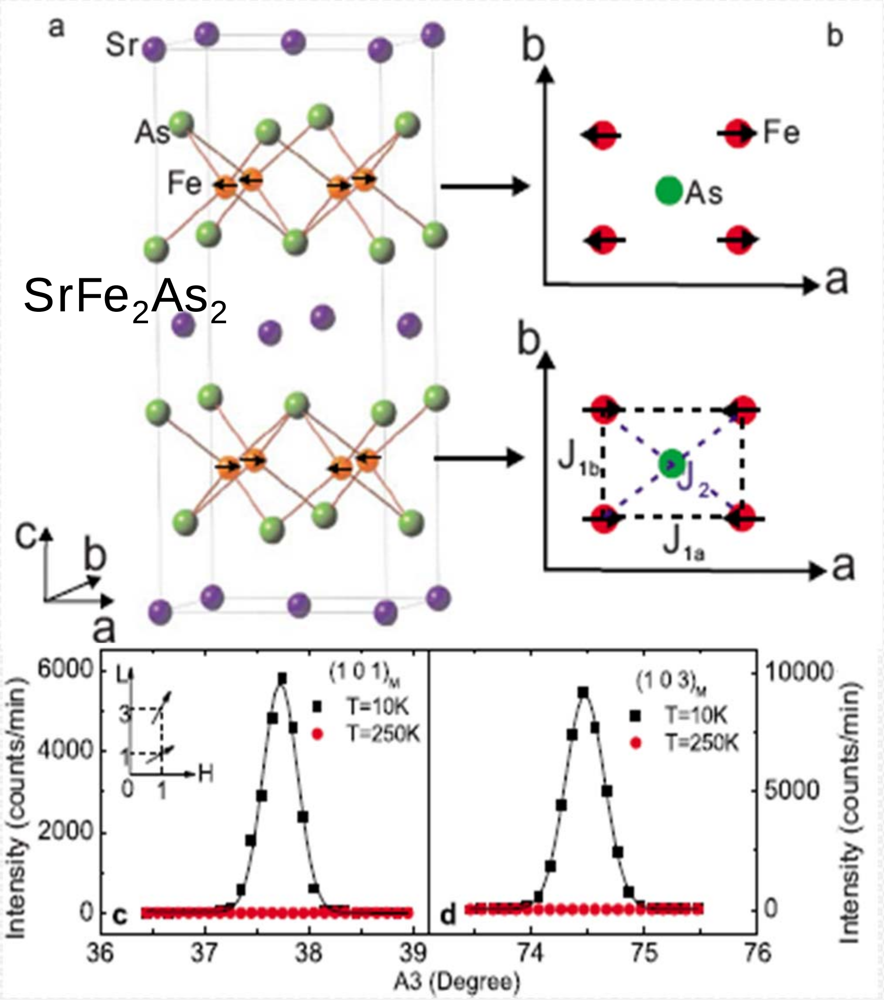


$$H = \sum_{<ij>} J_{ij}\, \vec{S}_i \cdot \vec{S}_j$$

J = 112 meV, J'= -11 meV

Coldea et al. PRL 86 5377 (2001)

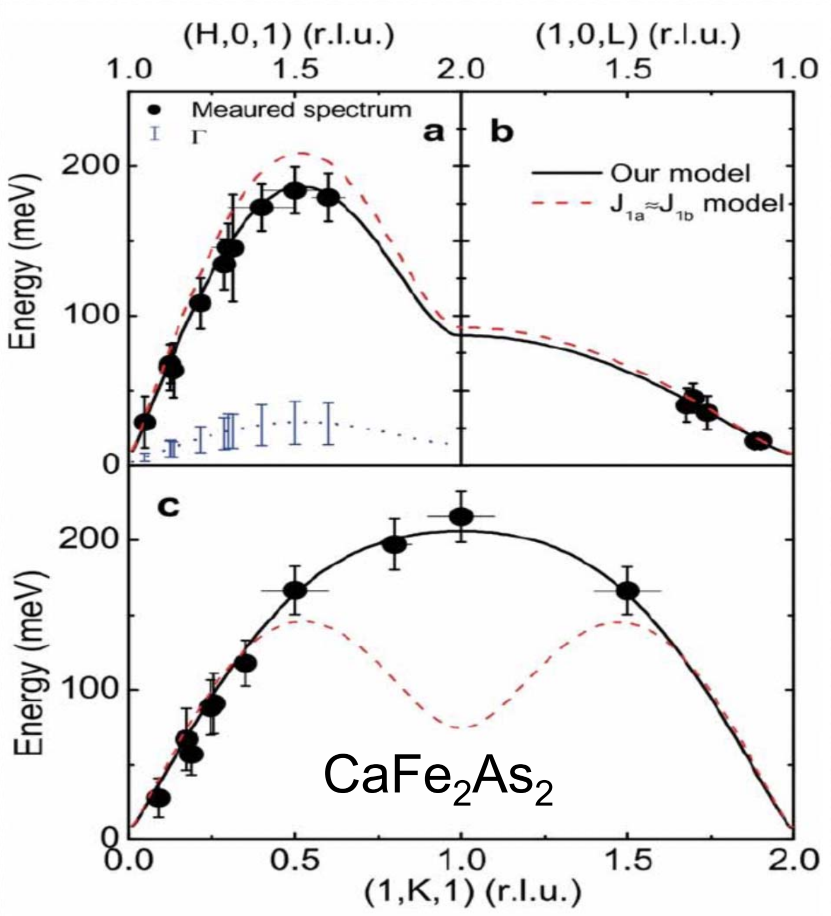
Magnetic structures of Fe pnictide parent compounds

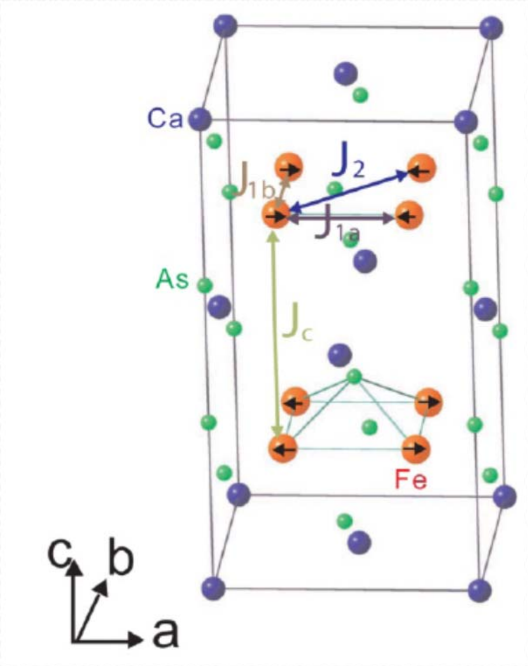


$SrFe_2As_2$

Zhao et al. Phys. Rev. B 78, 140504 R (2008)

Anisotropic magnetic exchange interactions in $CaFe_2As_2$





$J_{1a}=49.9\pm9.9$ meV $J_{1b}=-5.7\pm4.5$meV

$J_2=18.9\pm3.4$ meV $J_c=5.3\pm1.3$ meV

J. Zhao et al., Nature Physics 5, 555 (2009)

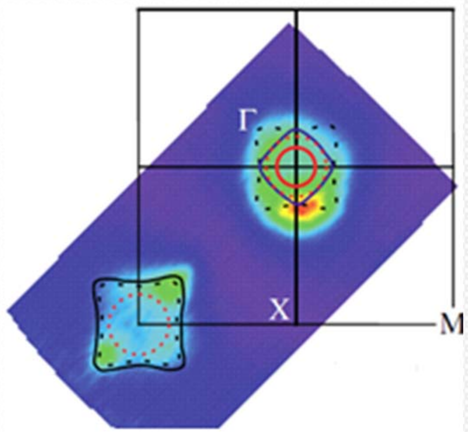
磁相互作用各项异性理论解释

1. Orbital ordering
2. Nematic ordering
3. Biquadratic interactions
4. Fermi Surface nesting
5. Combination of local moments and itinerant electrons

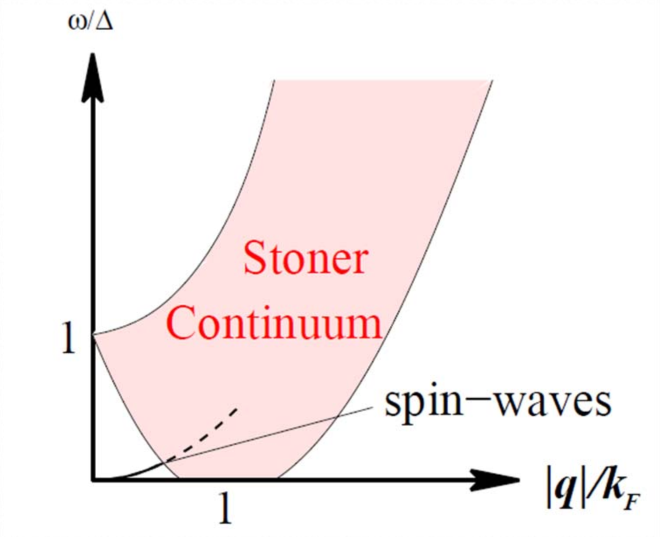
……

巡游磁性（费米面嵌套）

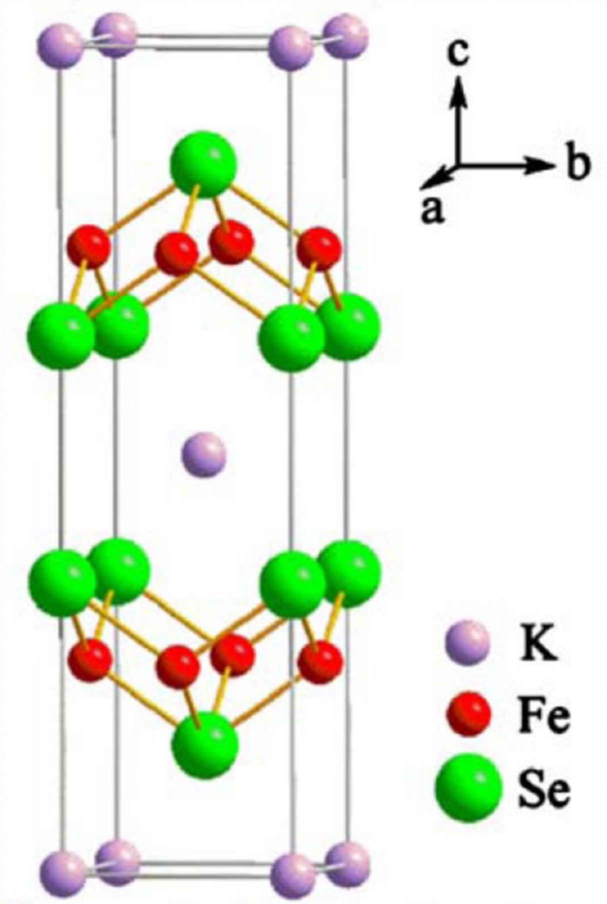
$BaFe_2As_2$

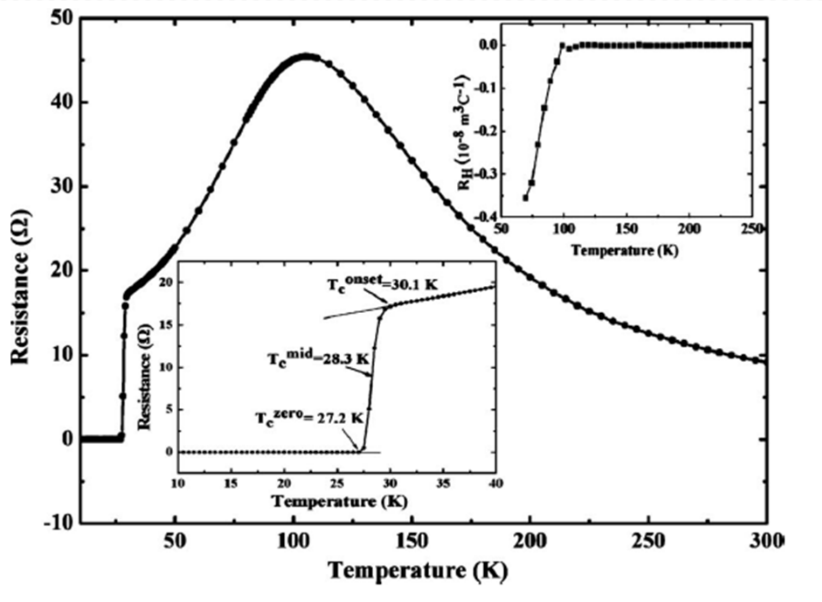


L. X. Yang et al. PRL 102 107002 (2009)



Discovery of $K_{0.8}Fe_{1.7}Se_2$ (T_c= 32 K)





Hall effect: Heavily electron doped

J. Guo et al., PRB 82 180520 (2010)

ARPES measurements on $K_{0.8}Fe_{1.7}Se_2$

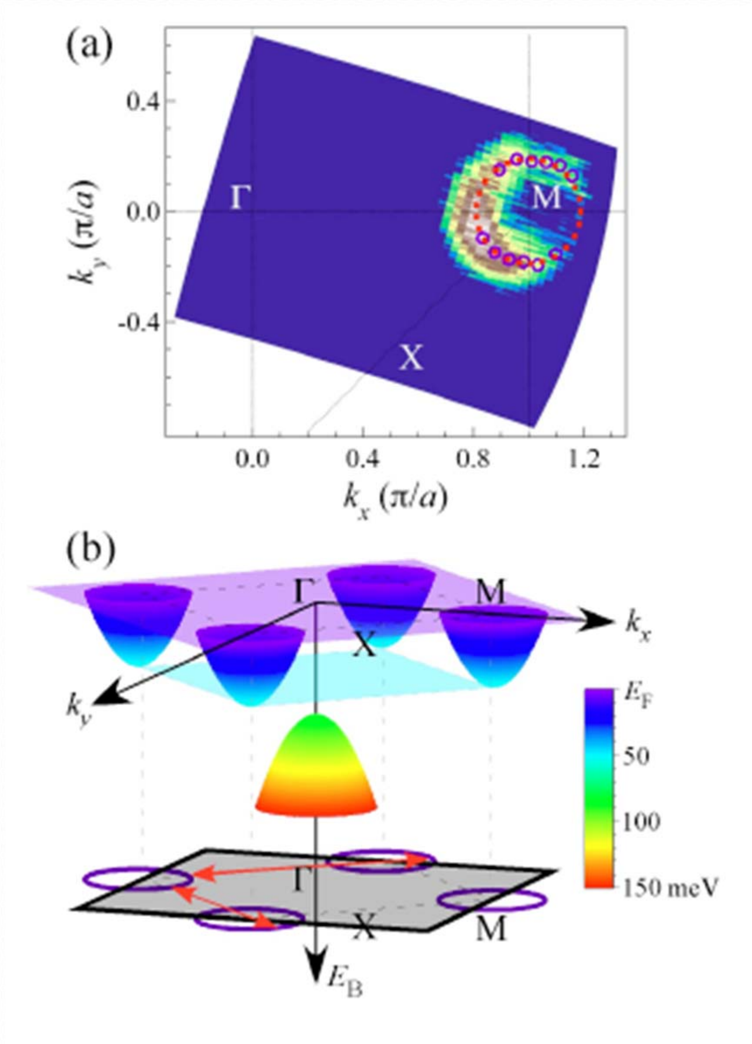
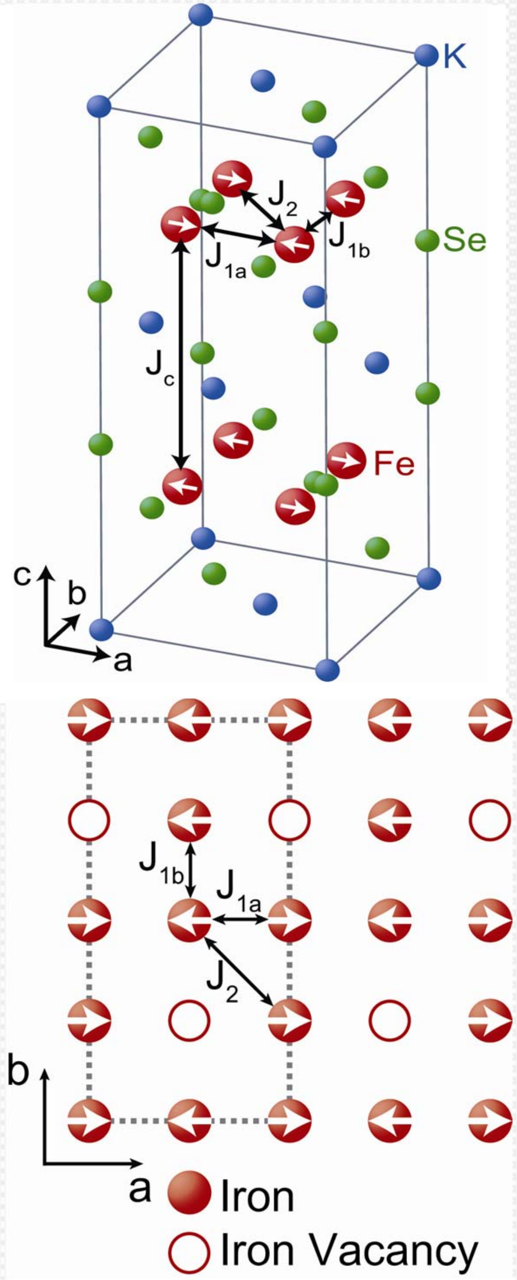
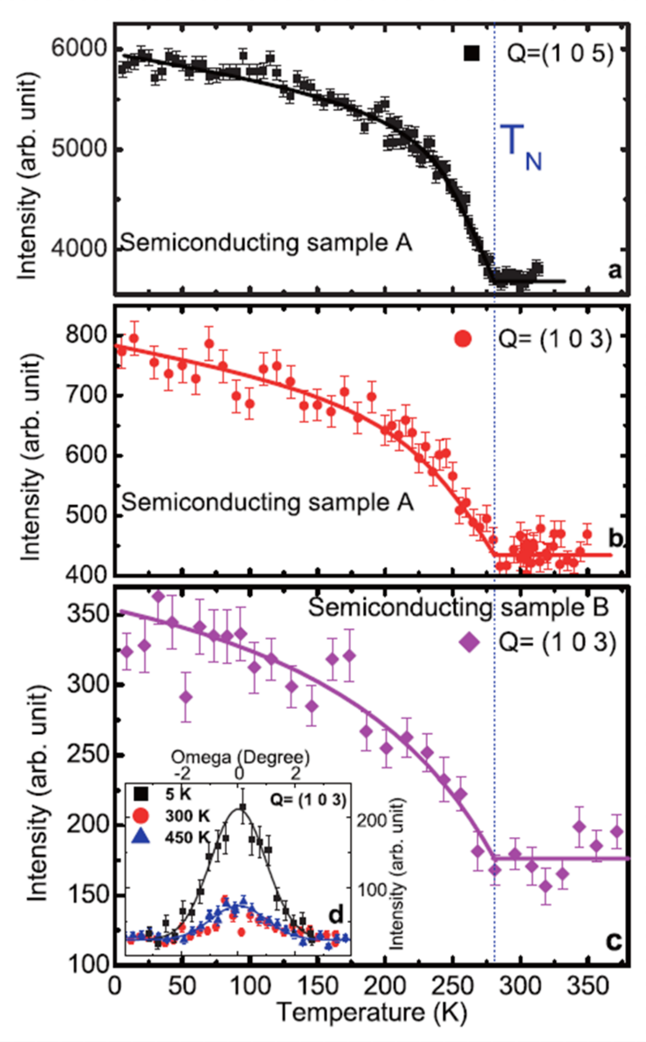


Fig. 4

T. Qian et al., *Phys.Rev. Lett*. 106, 187001 (2011)
Y. Zhang, *et al. Nature Materials* **10** 273-277 (2011).
D. X. Mou, *et al. Phys. Rev. Lett.* **106** 107001 (2011).

Magnetic and crystal structures of semiconducting $K_{0.85}Fe_{1.54}Se_2$

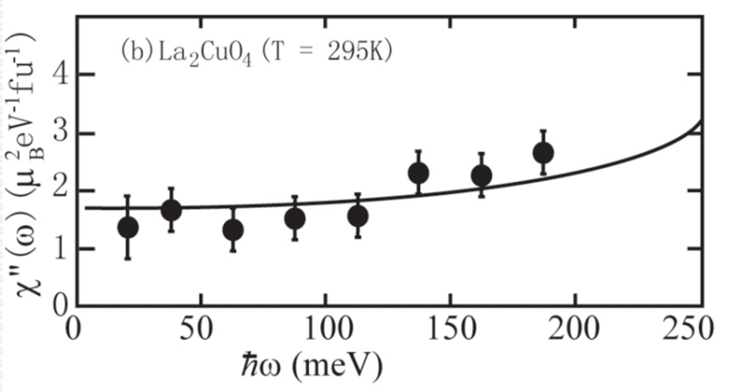


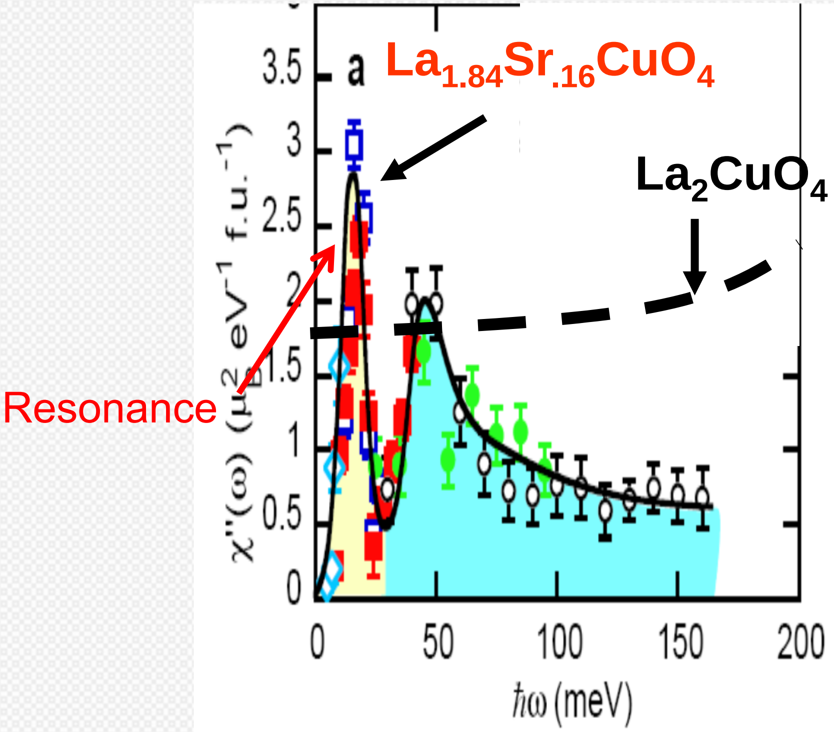


J. Zhao et al., *Phys. Rev. Lett.* 109, 267003 (2012)

What about superconductors ?

Spin excitations in cuprate superconductors





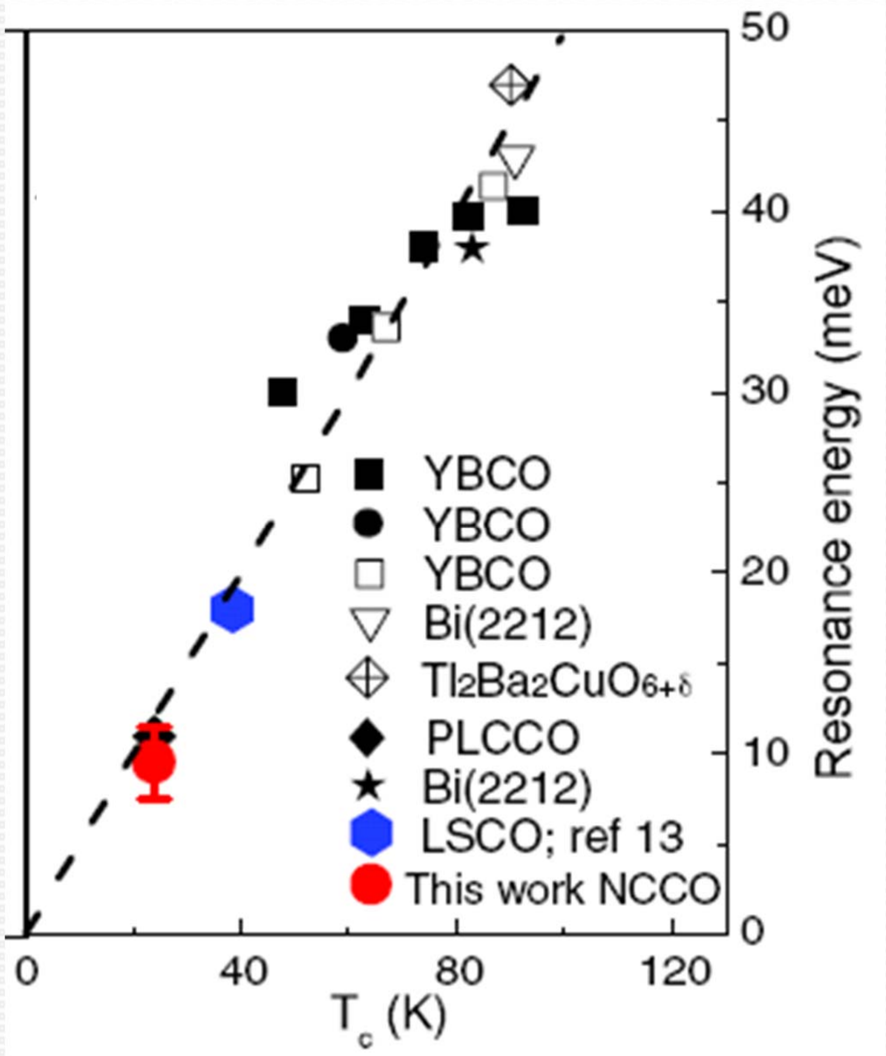
B. Vignolle et al. Nature Physics 3 163 (2007)
S. M. Hayden et al, Phys. Rev. Lett. 76 1344 (1996).

Resonance is a universal feature in cuprates

- ❑ Found in different classes of materials, both electron and hole-doped cuprates.

- ❑ Intensity increases like an order parameter below T_c.

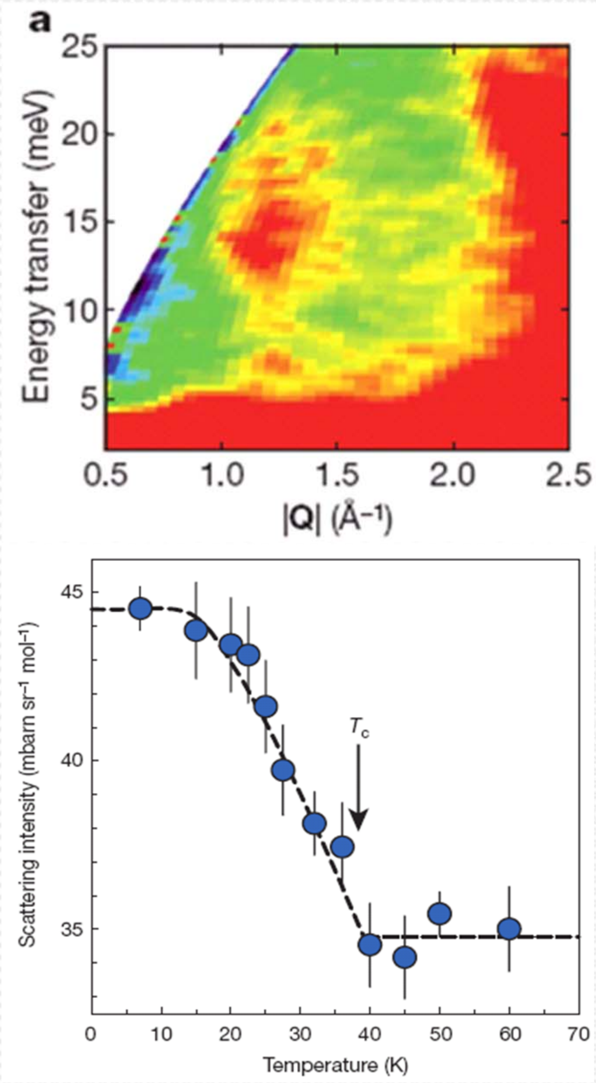
- ❑ **The energy of the mode scales with T_c.**



J. Zhao *et al.*, Phys. Rev. Lett. 99, 017001 (2007).

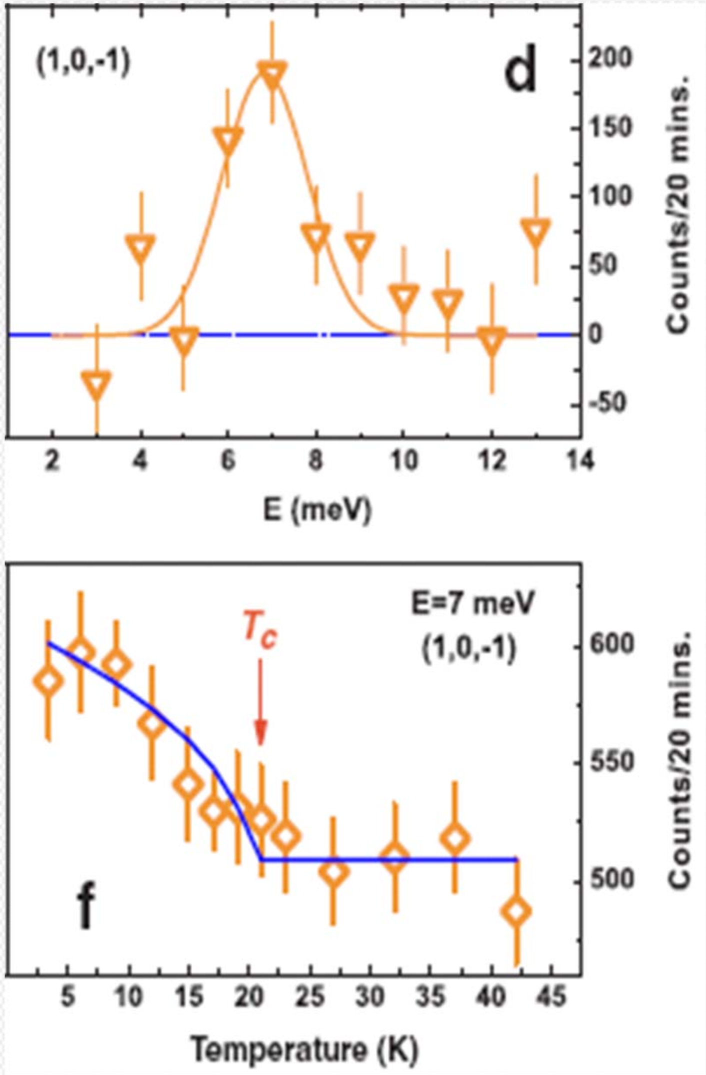
Neutron resonance in Fe pnictides

(Ba,K)Fe_2As_2 (T_c=38K)



A. D. Christianson *et al.*,
Nature 456, 930 (2008).

$BaFe_{1.9}Ni_{0.1}As_2$ (T_c=20 K)

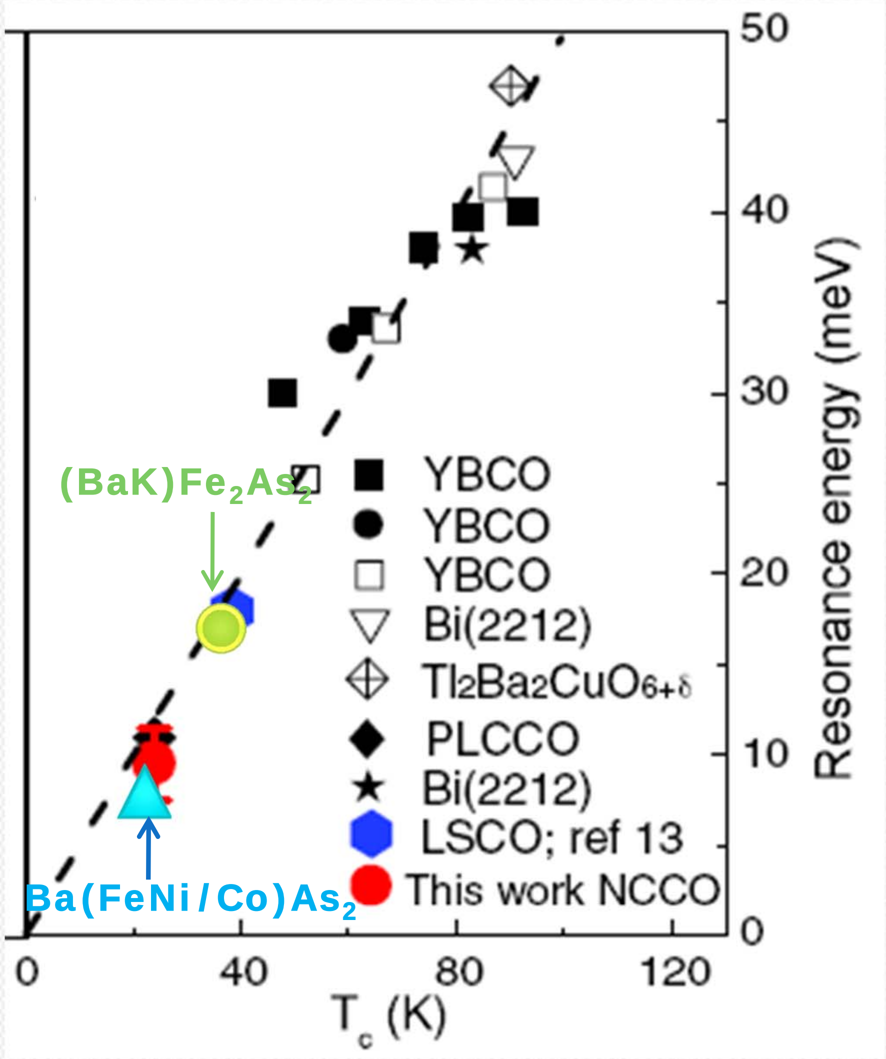


S. Chi *et al.*,
Phys. Rev. Lett. 102, 107006 (2009).

Resonance is a universal feature for high T_c superconductors

Resonance energies in Fe pnictides also scale with T_c

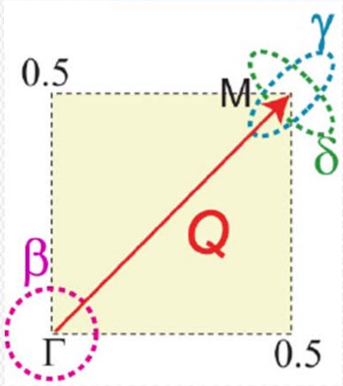
Resonance is universal !

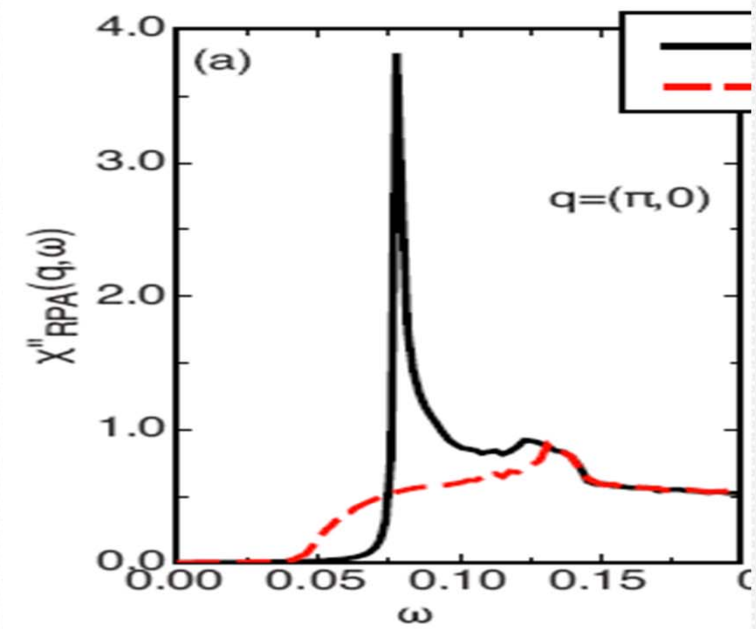


J. Zhao *et al.*, Phys. Rev. Lett. 99, 017001 (2007).

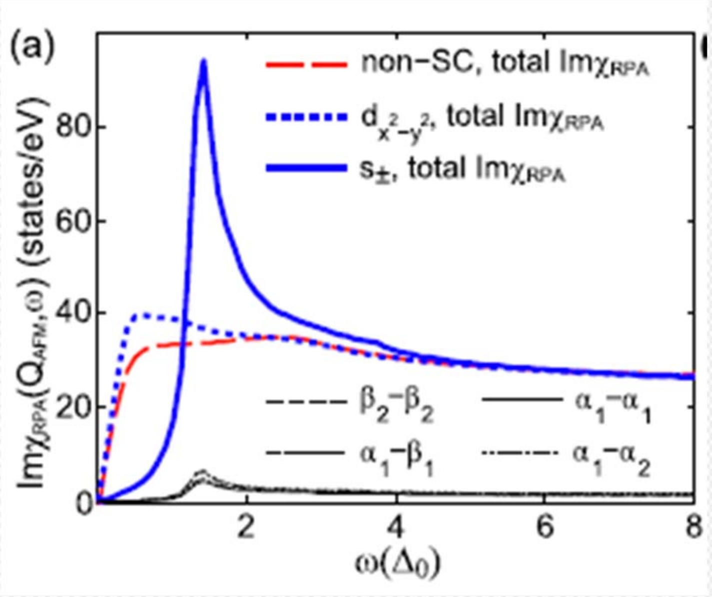
Theoretical model for resonance: collective spin-1 excitation

Sign-reversed s wave gap in Fe pnictides





Maier et al., Phys. Rev. B (2008)

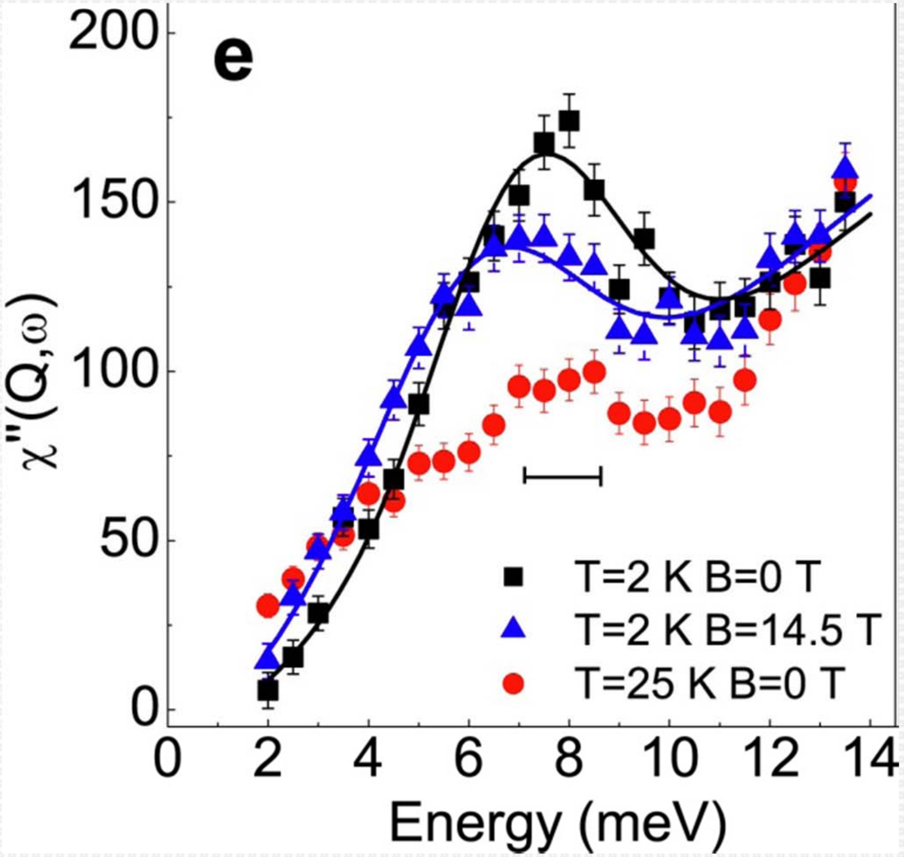


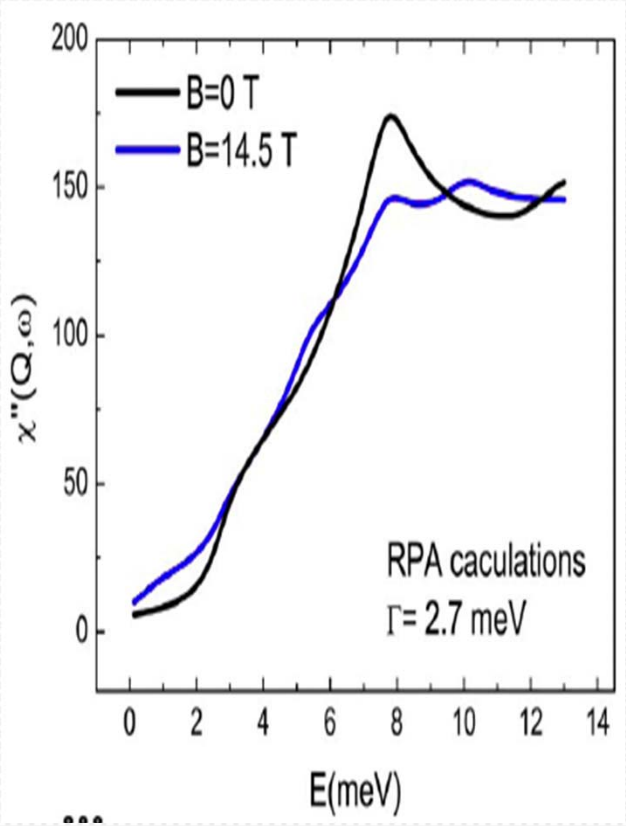
Korshunov et al., Phys. Rev. B (2008)

$$E_r \leq |\Delta_{(K)}| + |\Delta_{(K+Q)}|$$

Field effect on the dynamic susceptibility

$BaFe_{1.9}Ni_{0.1}As_2$ (T_c=20 K)

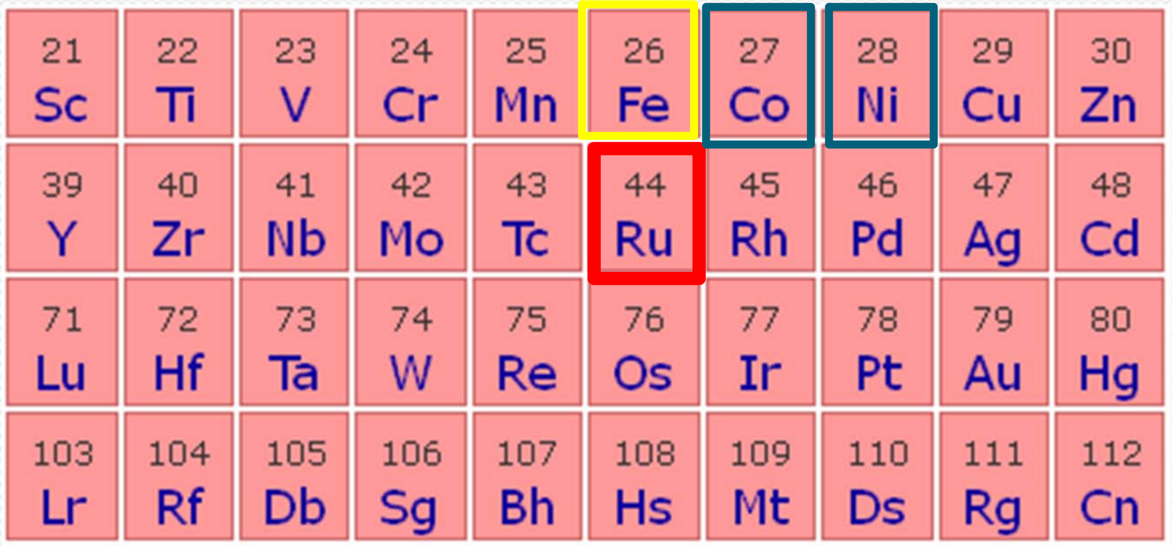




J. Zhao et al., Phys. Rev. B 81, 180505(R) (2010)

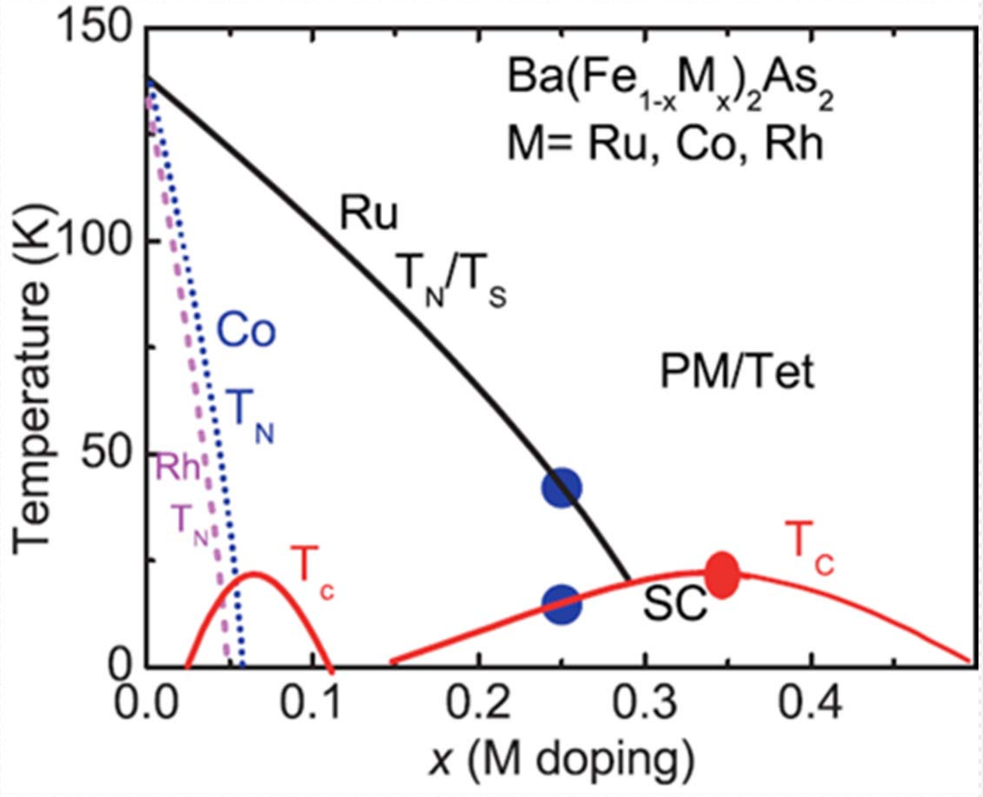
$$\Delta E = \pm g\mu_B B \cdot S \approx \pm 1.7 meV$$

Isovalent Doping effect



21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn
39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd
71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg
103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn

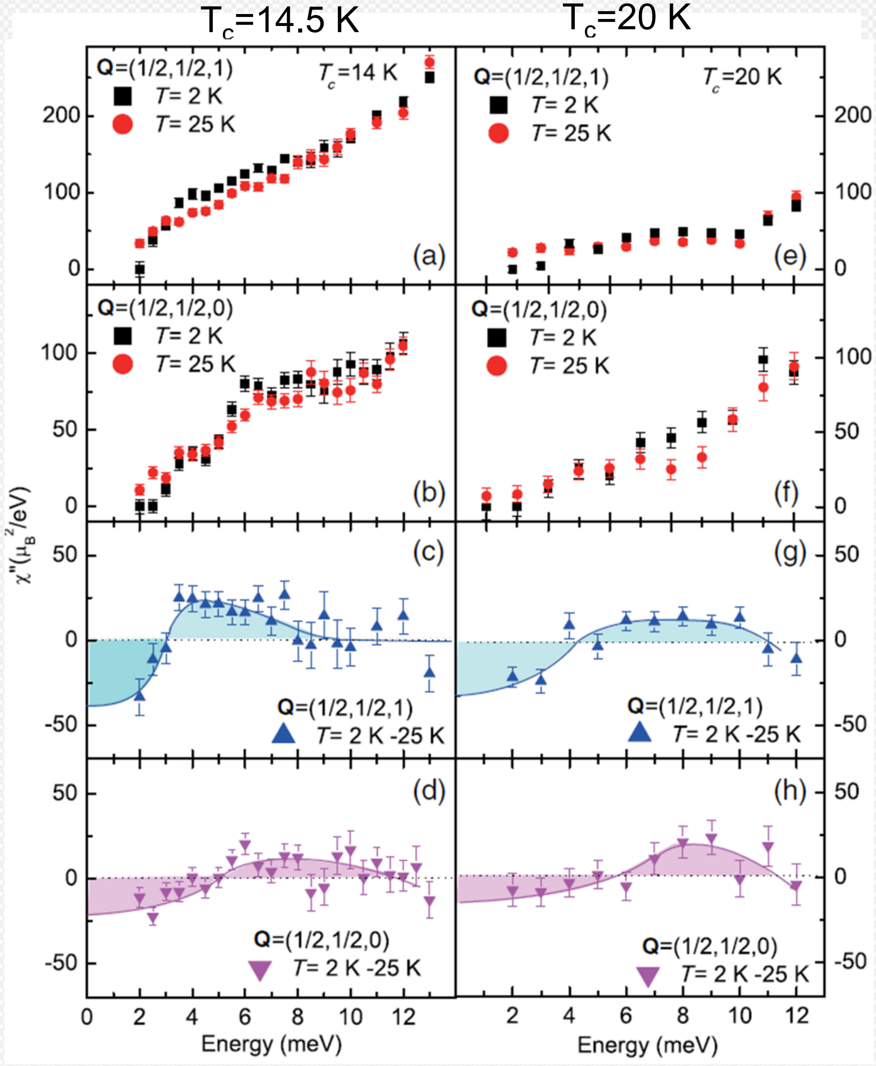
Phase diagrams of isovalent doped iron based superconductors



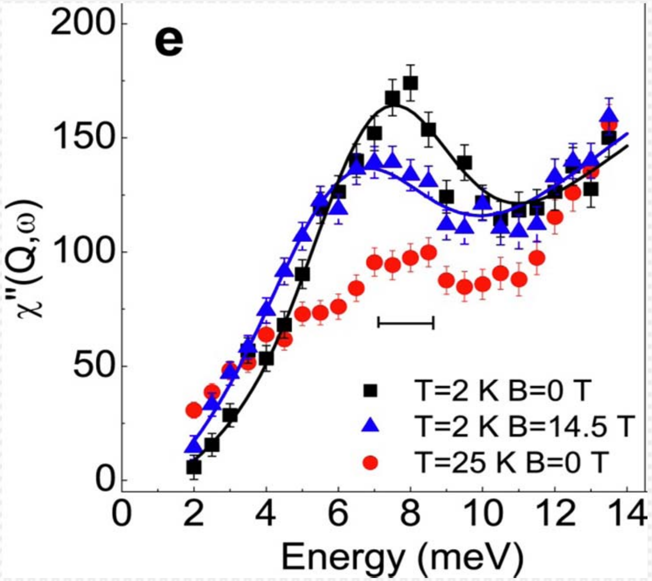
Damped resonance mode in $Ba(Fe_{1-x}Ru_x)_2As_2$

$Ba(Fe_{1-x}Ru_x)_2As_2$

T_c=14.5 K T_c=20 K



$BaFe_{1.9}Ni_{0.1}As_2$ (T_c=20 K)



J. Zhao et al., Phys. Rev. Lett. 110,147003 (2013)

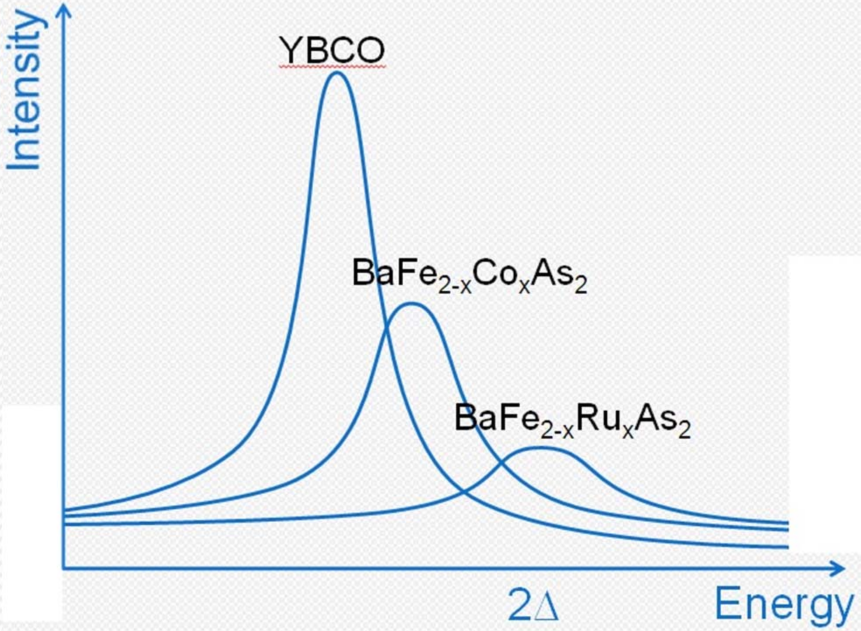
Effect of electron correlation on the resonance intensity

21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn
39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd
71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg
103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn

Strong

Correlation

Weak



Summary

- The iron-based superconductors exhibit a similar phase diagram to those of the cuprates.
- In the parent compounds of iron-based superconductors, the Fe spin dynamics provide needed high energy scale (~200 meV) for the pairing.
- All parent compounds display a stripe AFM order with large in plane anisotropy of the exchange coupling constants; such stripe AFM order is driven by exchange interactions between local moments and does not necessarily only appear under Fermi surface nesting.
- Low energy spin excitations of iron-based superconductors are dominated by a resonance mode.
- No Zeeman splitting observed for the resonance mode.
- The resonance energy is proportional to the superconducting gap.
- Resonance is damped when electron correlations are weakened. Resonance may not be the only ingredient for pairing.

Acknowledgements

Fudan University

Yao Shen, Qisi Wang, Yiqing Hao, Yu Feng

UC Berkeley

Robert Birgeneau, Dung-Hai Lee

Edith Bourret-Courchesne

University of Tennessee & Oak Ridge National Laboratory

Pengcheng Dai Group

HFIR and SNS of ORNL

Huibo Cao, D. L. Abernathy

NIST Center for Neutron Research

J. Lynn, Q. Huang , Y. Zhao,
W. Ratcliff, Y. Chen, M. A. Green

ISIS, Rutherford-Appleton Lab U.K.

D. T. Adroja, R. Bewley

ILL, Grenoble, France

L.P. Regnualt, P. Steffens, A. Hiess

Purdue University & IOP

Jiangping Hu, Daoxin Yao, Chen Fang

Renmin University

Zhongyi Lu, Miao Gao

Institute of Physics, Chinese Academy of Sciences

Z.X. Zhao, F, Zhou, Z. Li,
N. L. Wang, G. F. Chen, J. L. Luo

University of Science of Technology of China

X. H. Chen, X. F. Wang, G. Wu