Iron-Age Superconductors

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Physics 1, 21 (2008)

Saas-Fee, Jan. 10, 2011

Iron-Based Layered Superconductor La[$O_{1-x}F_x$]FeAs ($x = 0.05-0.12$) with $T_c = 26$ K

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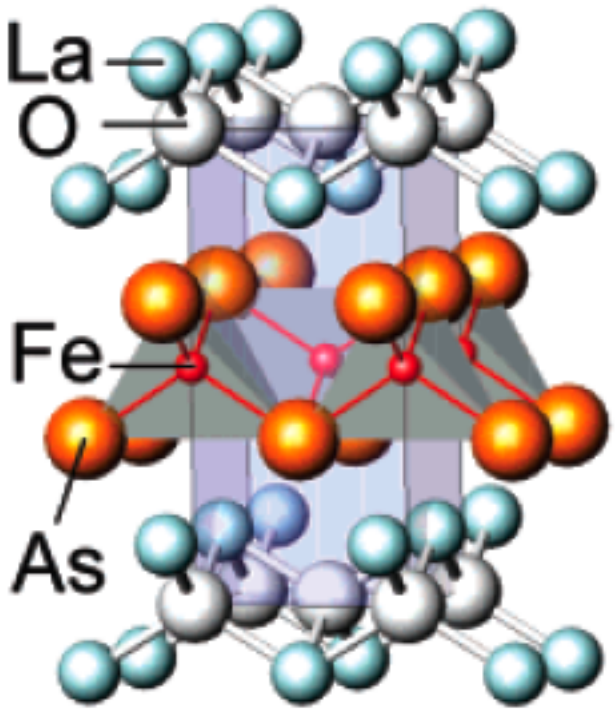
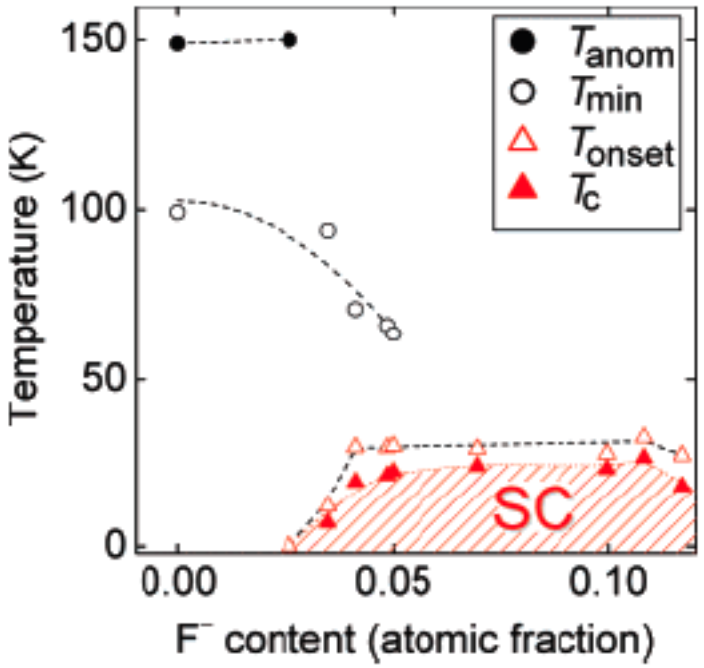
Received January 9, 2008; E-mail: hosono@msl.titech.ac.jp

1111

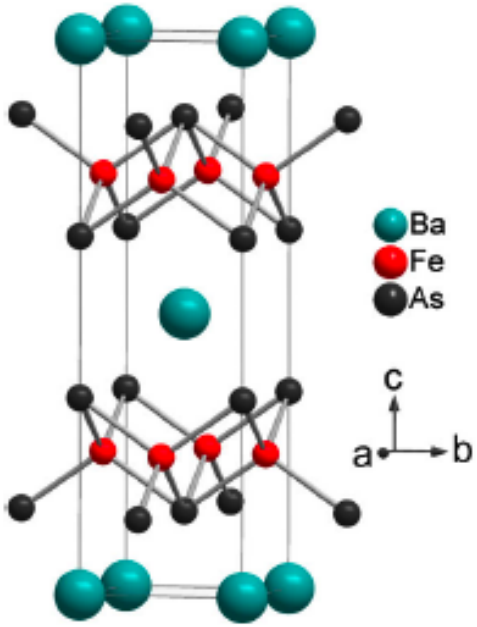




JACS 130, 3296 (2008)

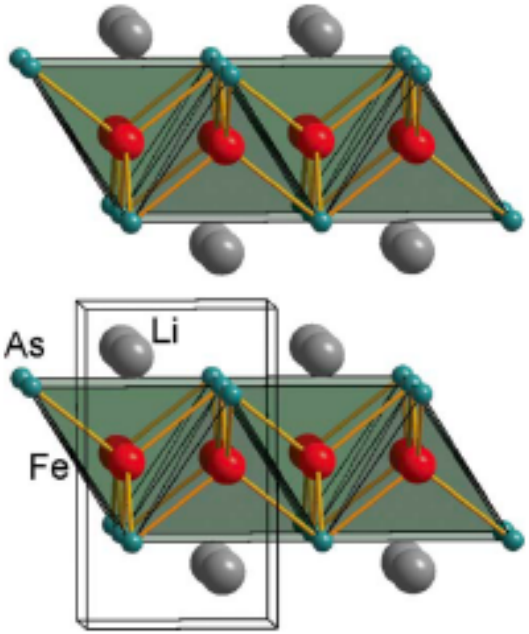
There are a number of different crystal structures

122



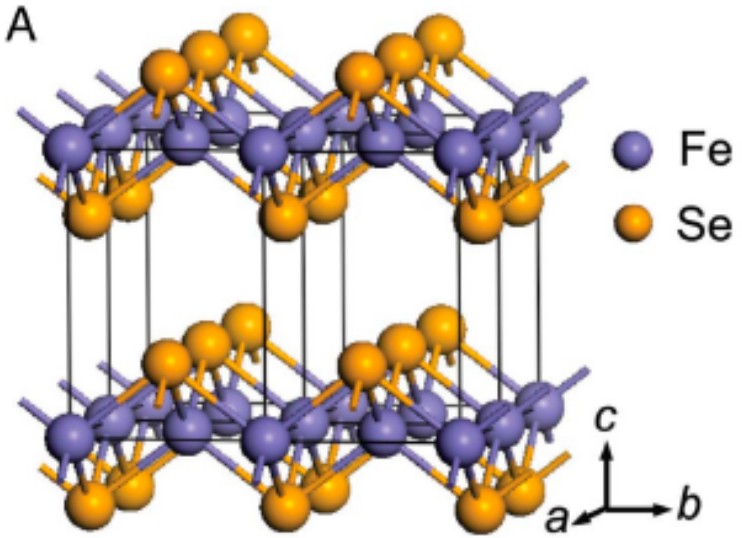
Rotter *et al.*
PRL 101, 107016 (2008)

111



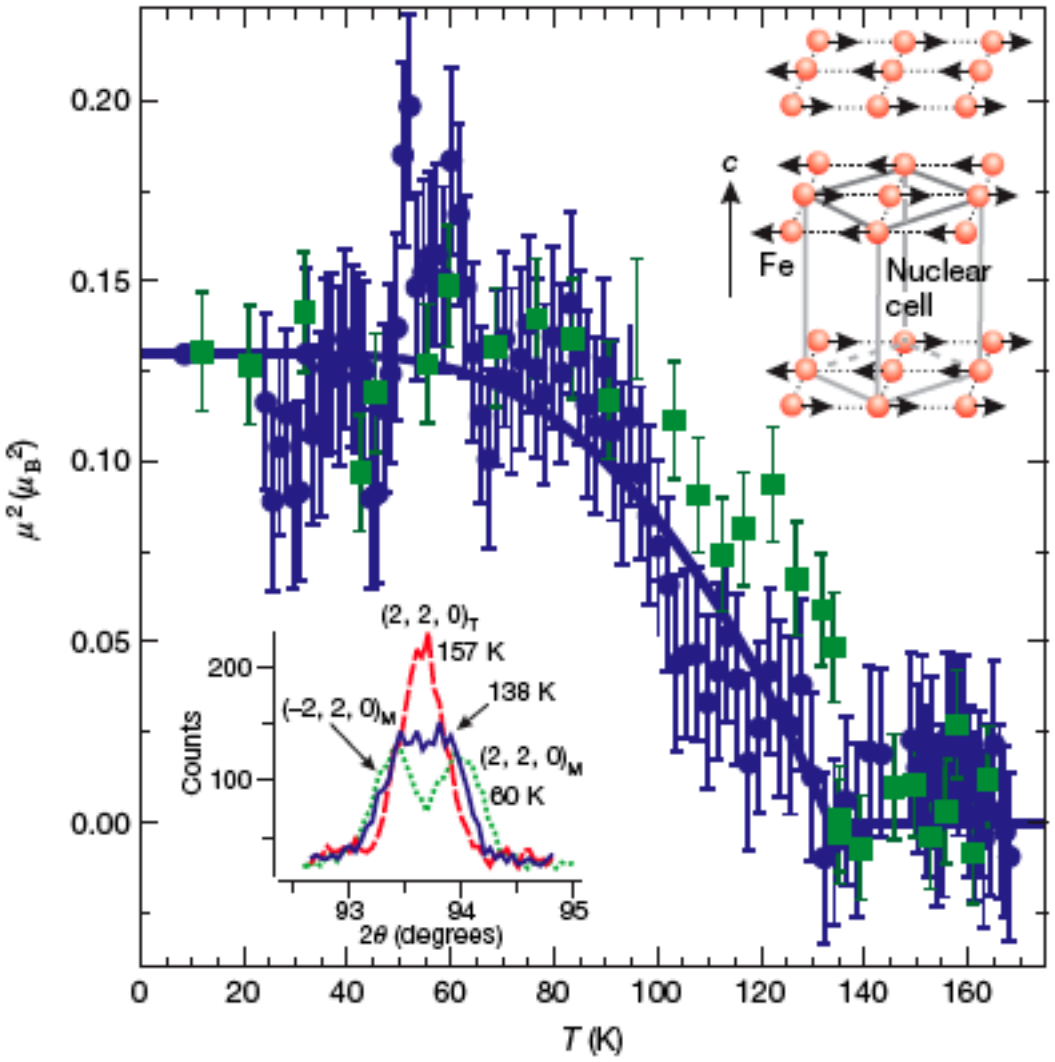
Tapp *et al.*
PRB 78, 060505 (2008)

11



Hsu *et al.*
PNAS 105, 14262 (2008)

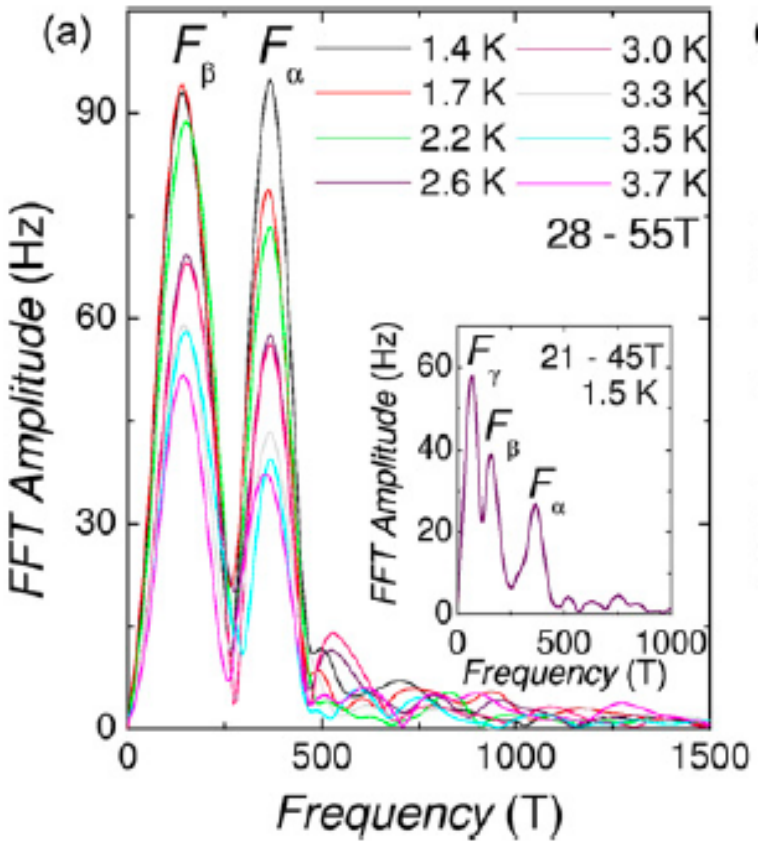
The Undoped Material is an Antiferromagnet (just like the cuprates)

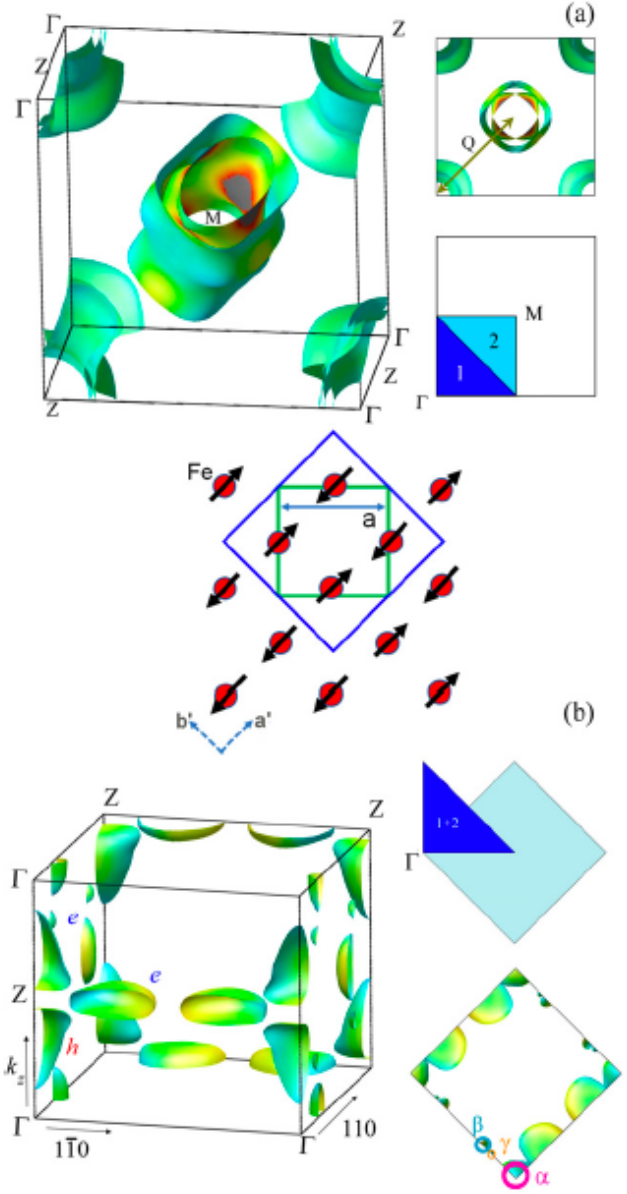


de la Cruz *et al.*, Nature 453, 899 (2008)

But it is a Metal (unlike the cuprates)

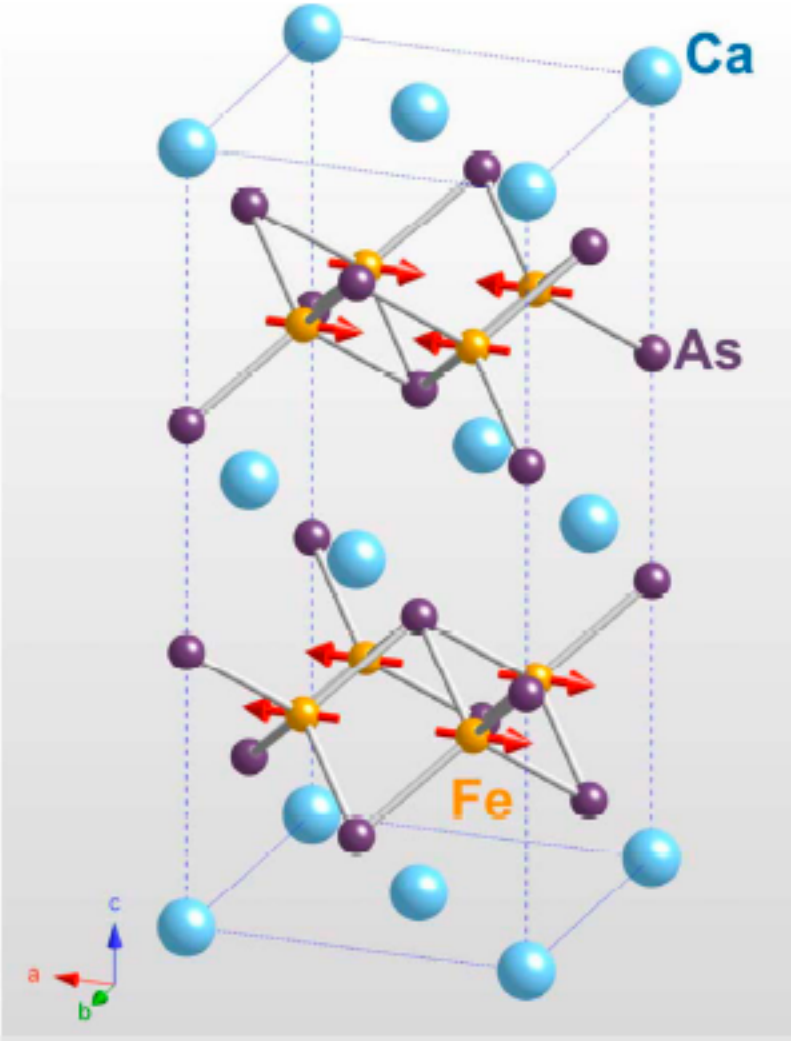
quantum oscillations in Sr-122

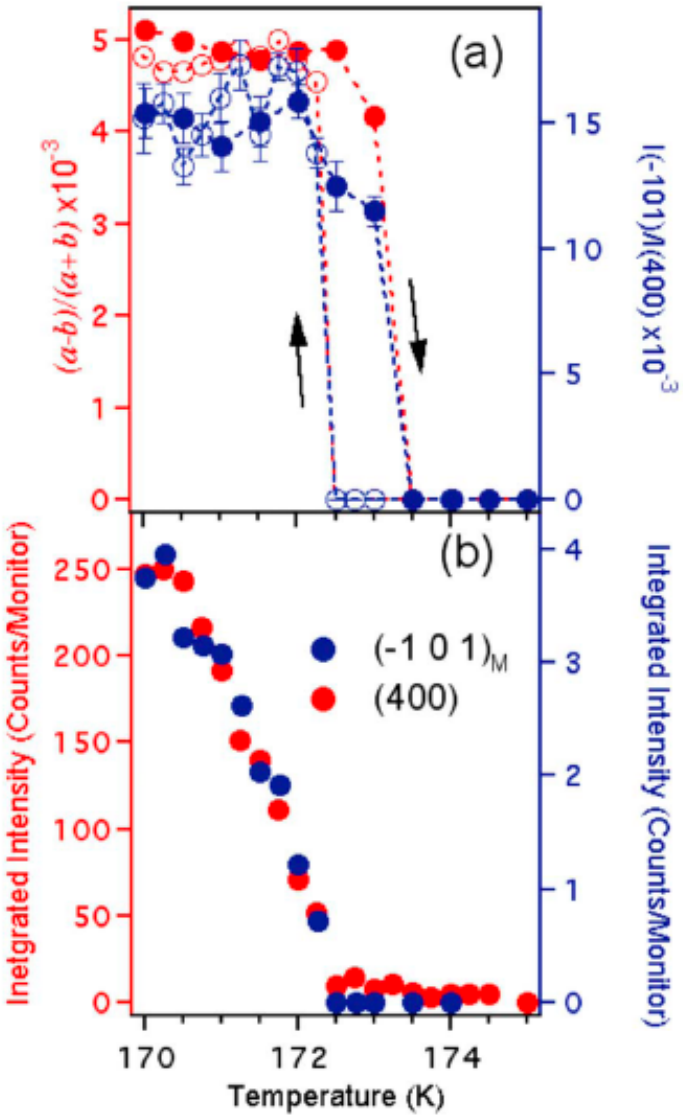




Sebastian *et al*., JPCM 20, 422203 (2008)

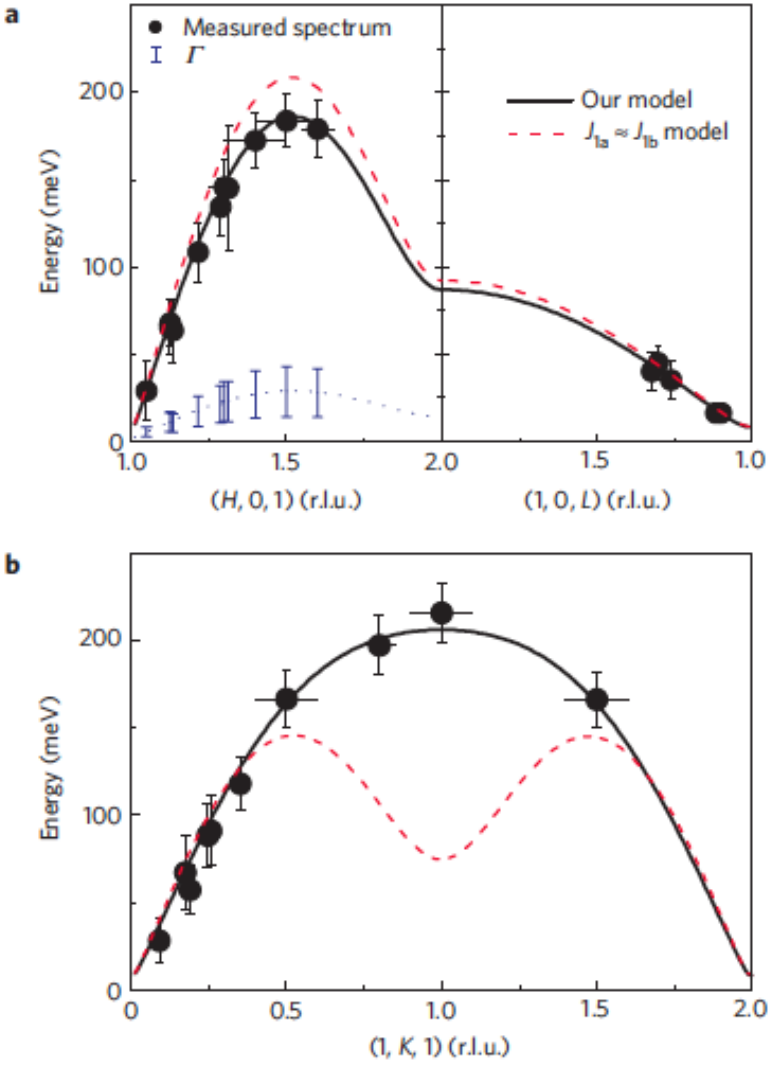
Magnetic and Structural Transitions are Tied Together



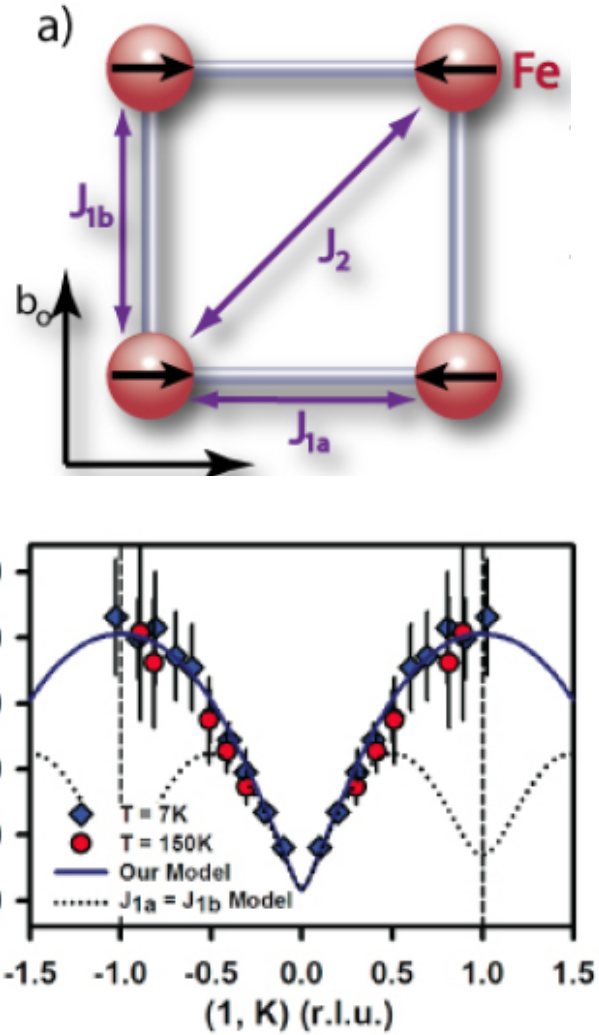


Goldman *et al.*, PRB 78, 100506 (2008)

Anisotropic Spin Exchange (Ca-122)

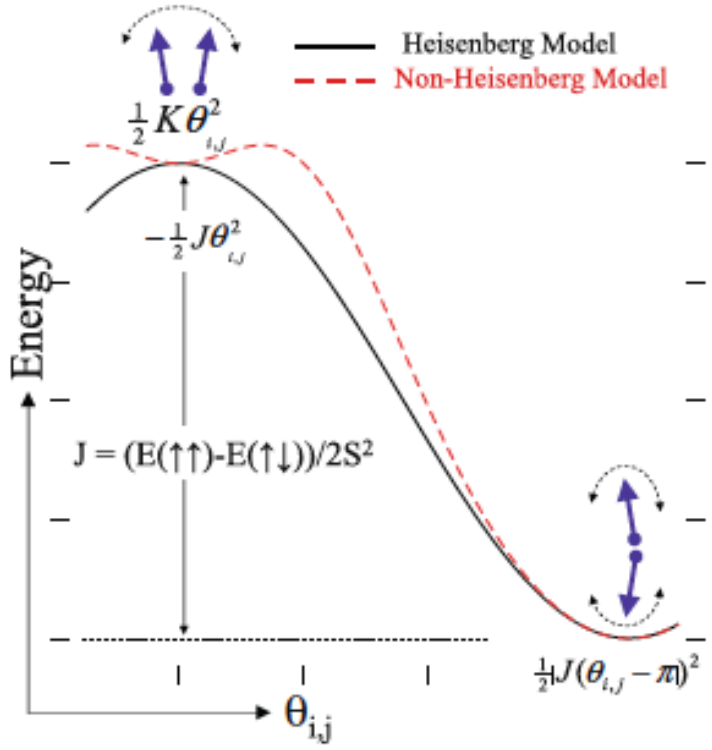


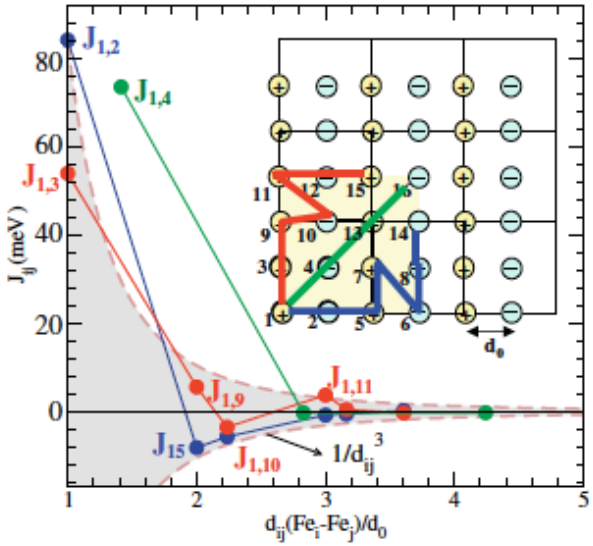
Zhao *et al.*, Nat. Phys. 5, 555 (2009)



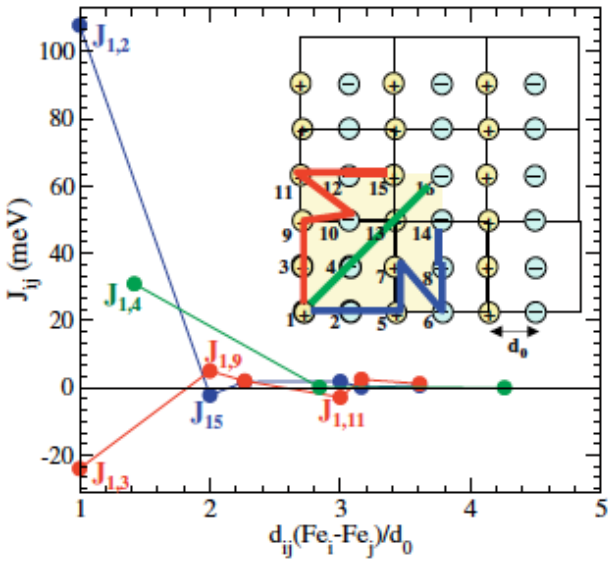
Harriger *et al.*, arXiv:1011.3771

Anisotropic Spin Exchange (theory)





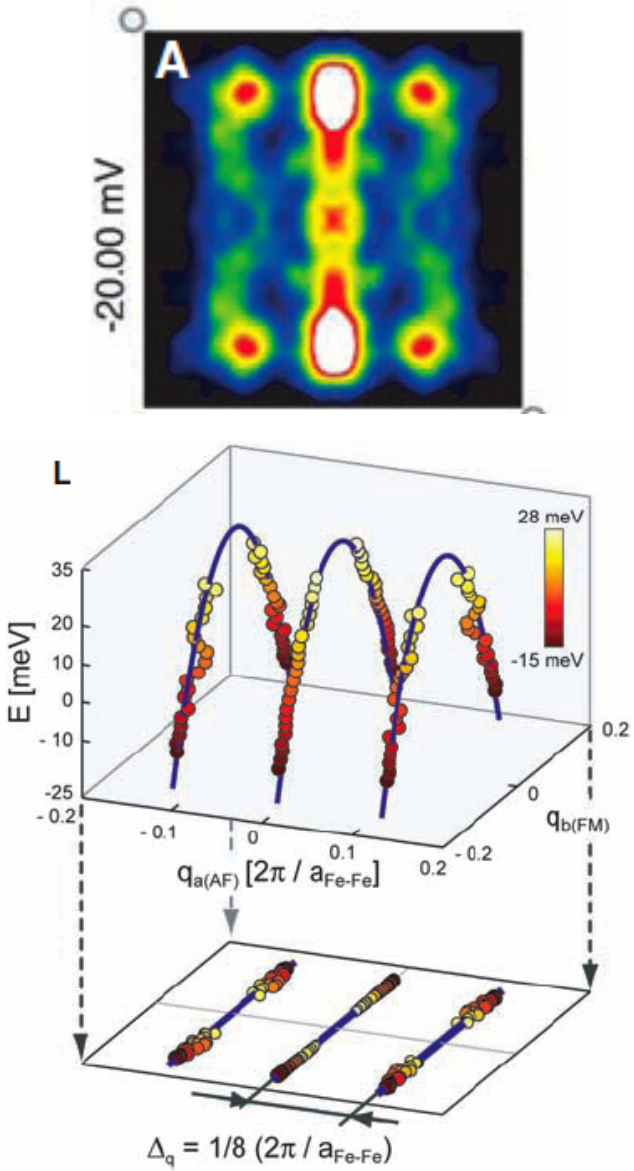
spin flip

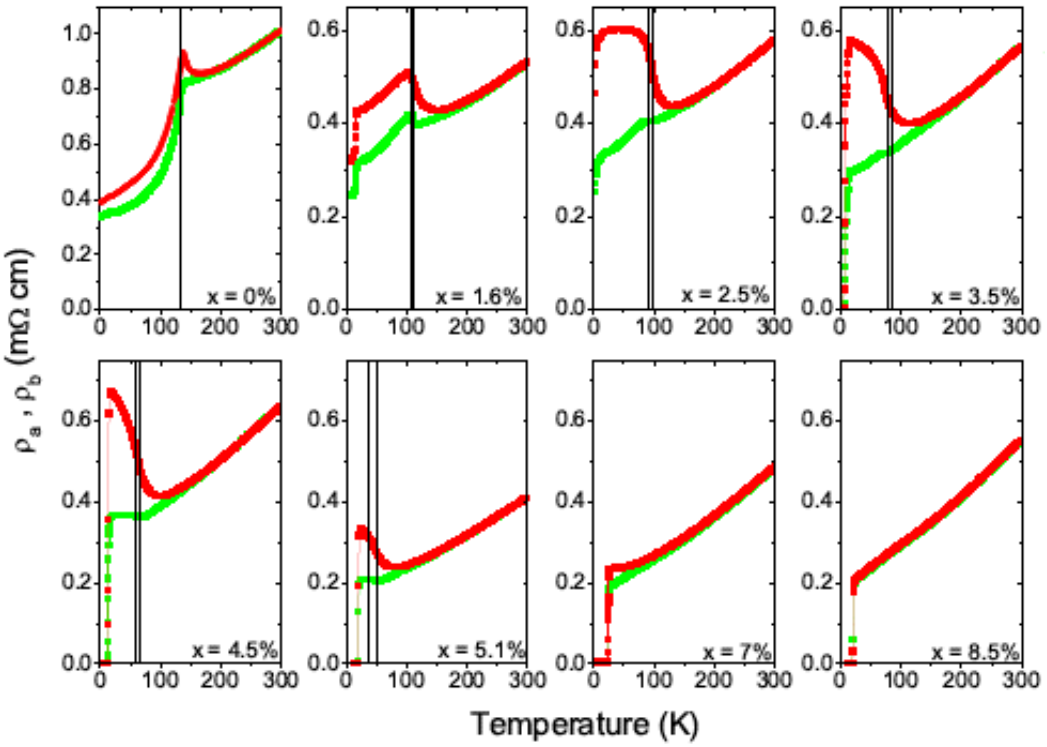


linear response

Yildirim, Physica C 469, 425 (2009)

Nematic Order in 122 (STM & transport)

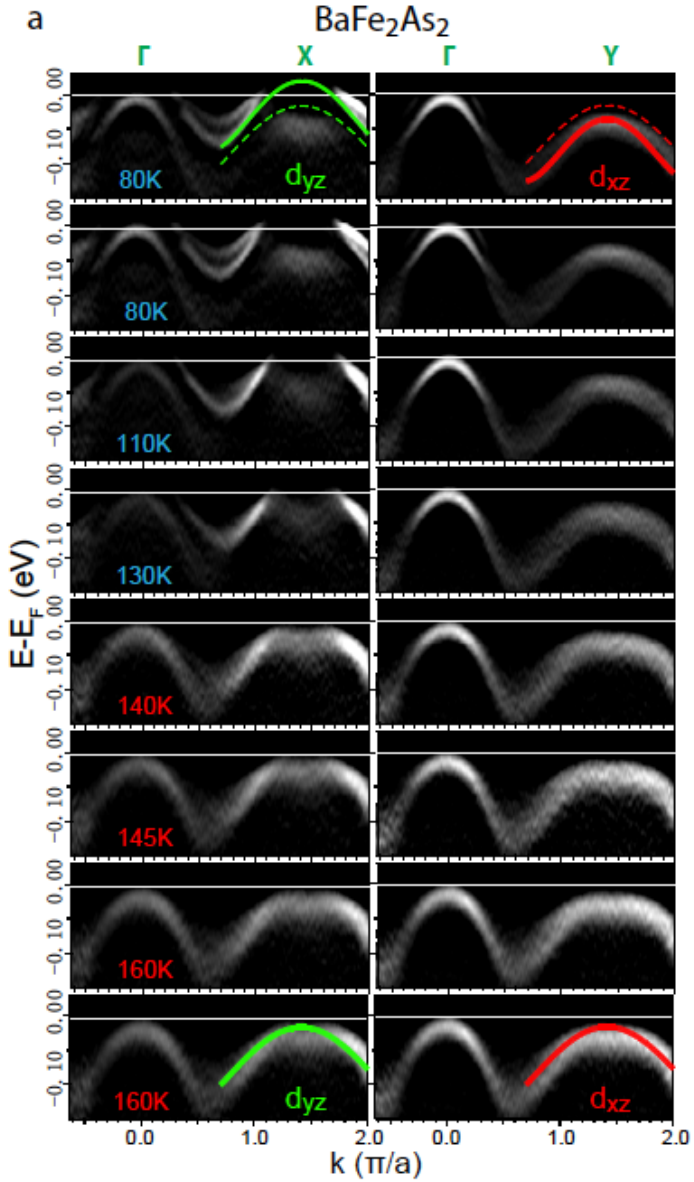




Chu *et al.*, Science 329, 824 (2010)

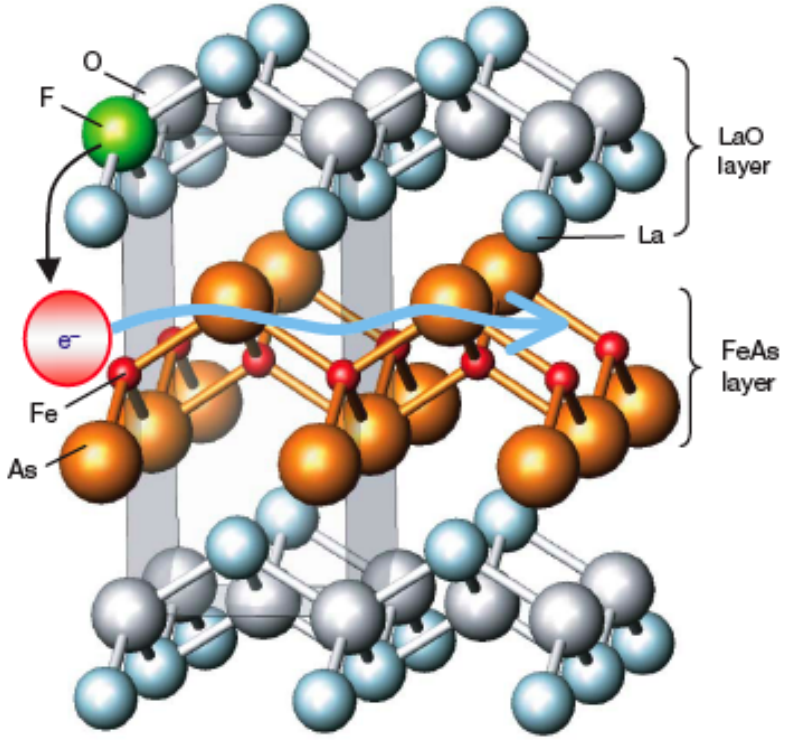
Chuang *et al.*, Science 327, 181 (2010)

Nematic Order in 122 (ARPES)

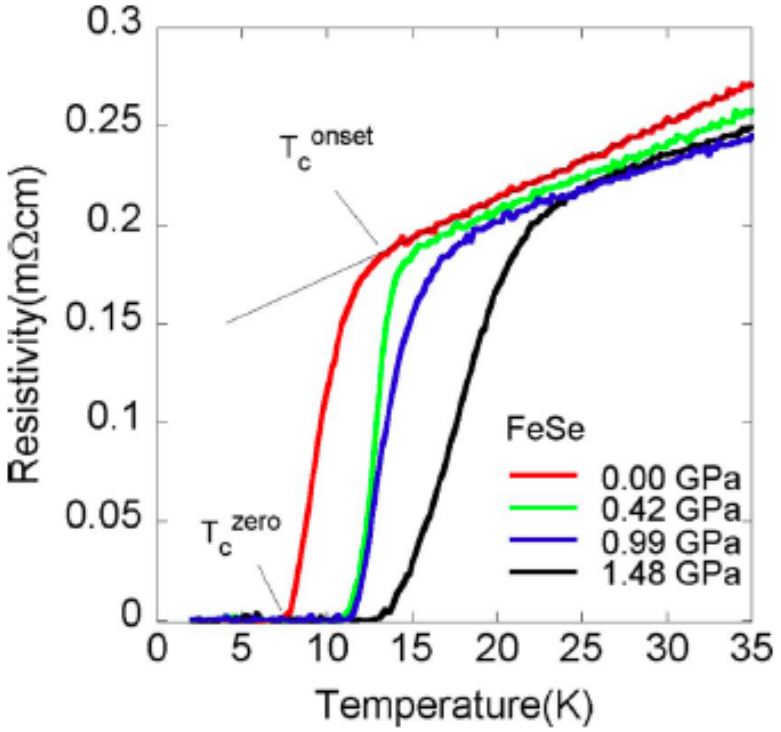


Yi *et al*., arXiv:1011.0050

Superconductivity can be induced by Doping or Pressure

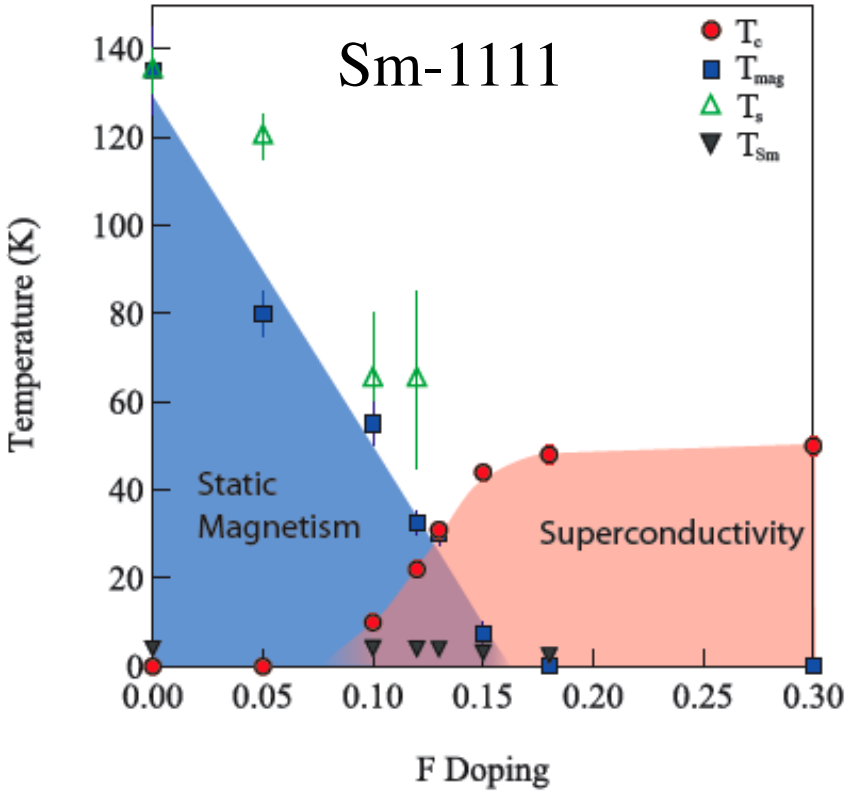


Takahashi *et al.*,
Nature 453, 376 (2008)

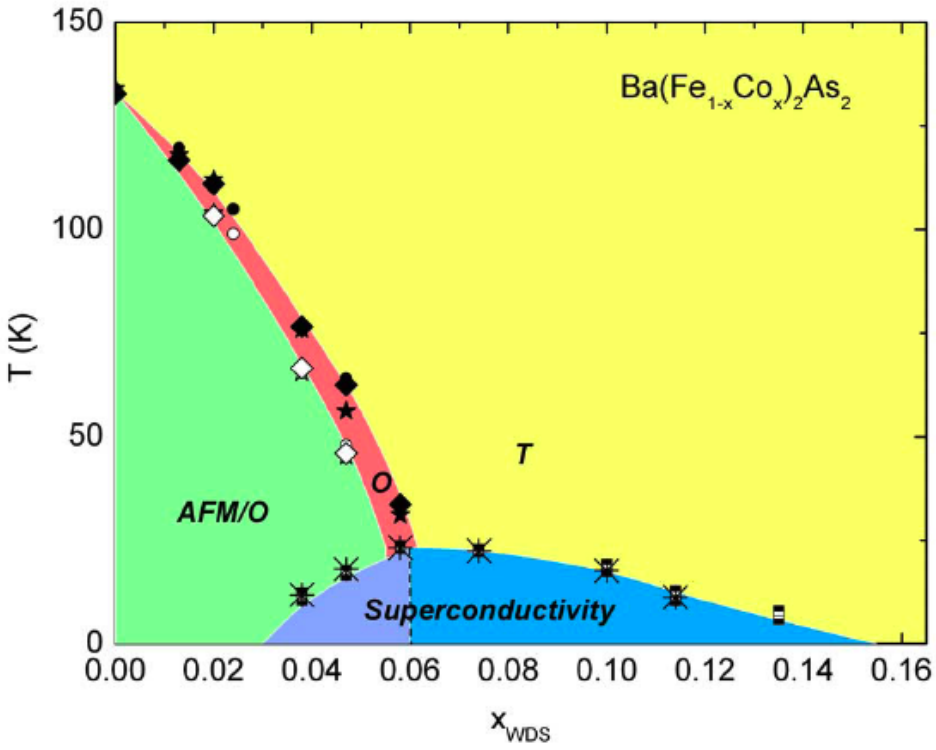


Mizuguchi *et al.*,
APL 93, 152505 (2008)

Coexistence of superconductivity & magnetism

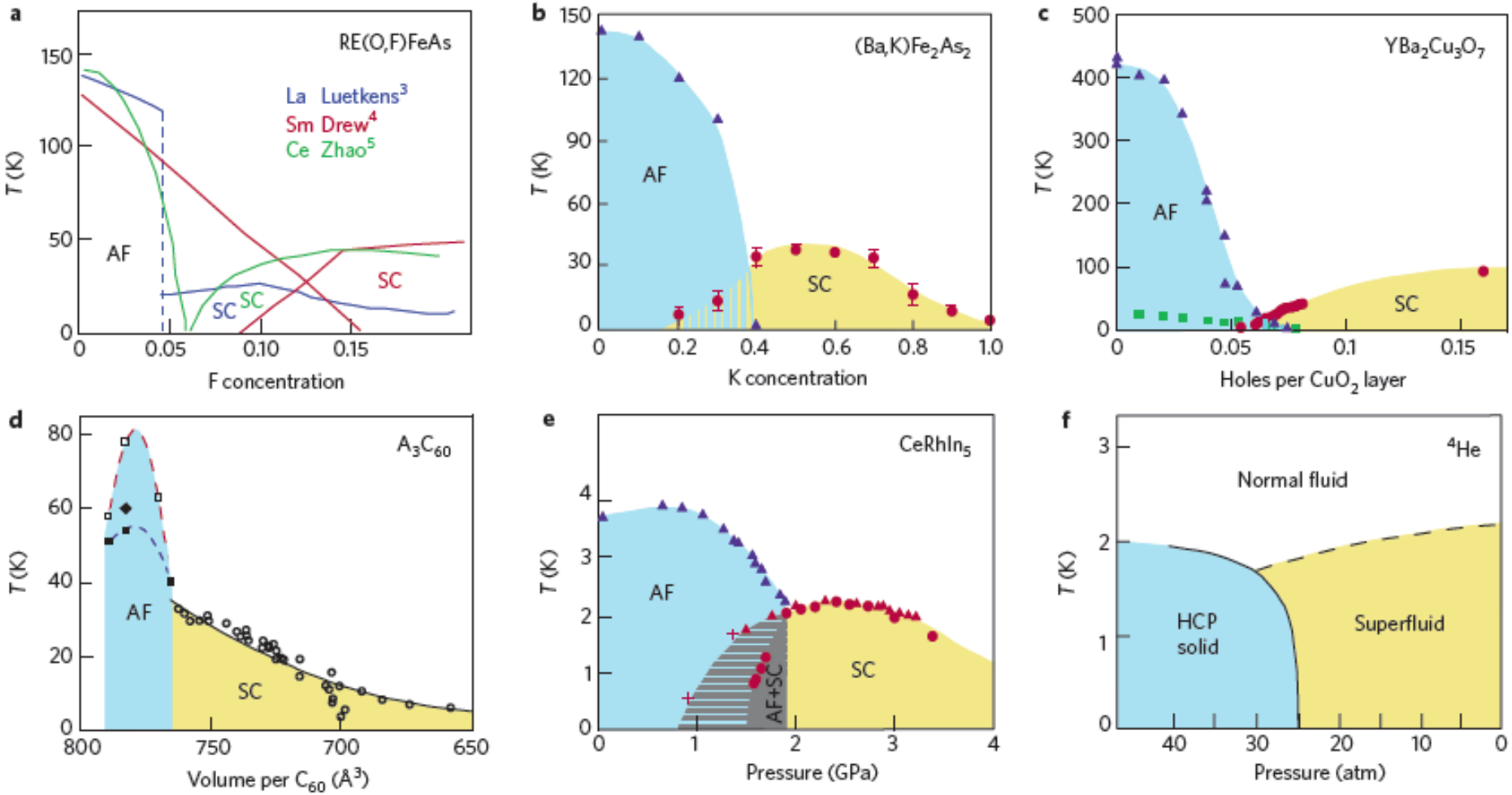


Drew *et al*., Nat. Matls. 8, 310 (2009)



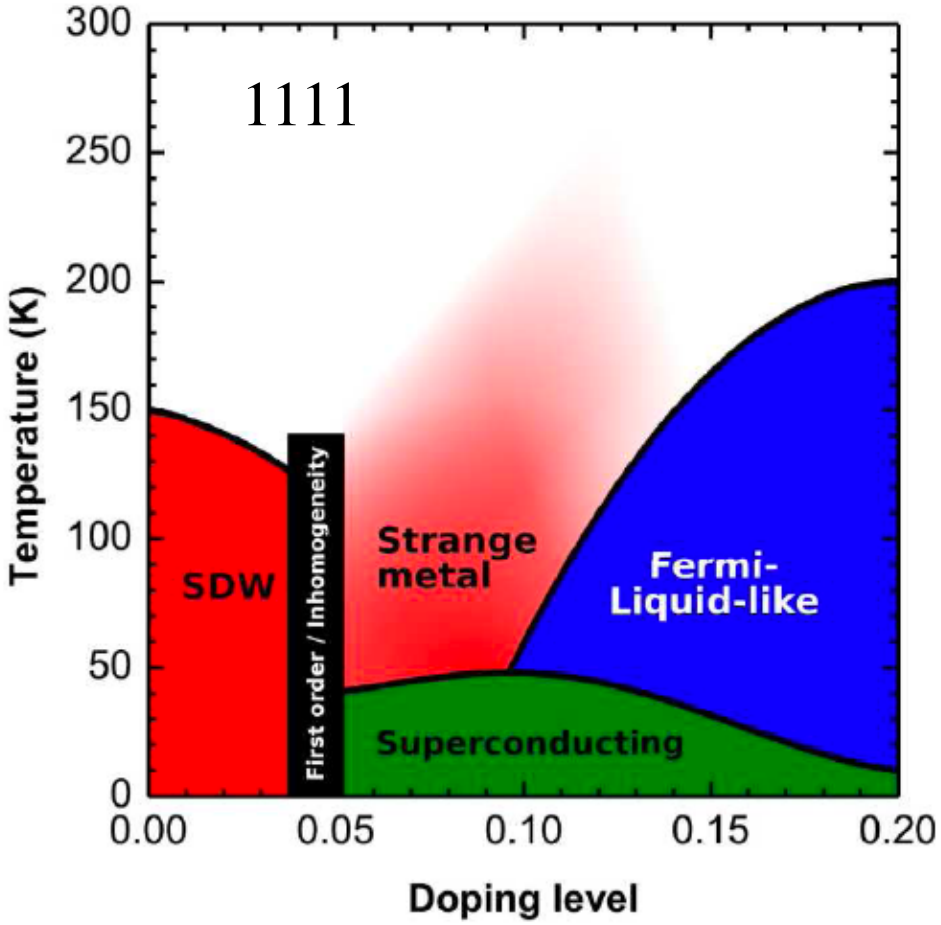
Canfield & Bud'ko, Ann. Rev. Condens. Matter Phys. 1, 27 (2010)

Similarity of Phase Diagrams



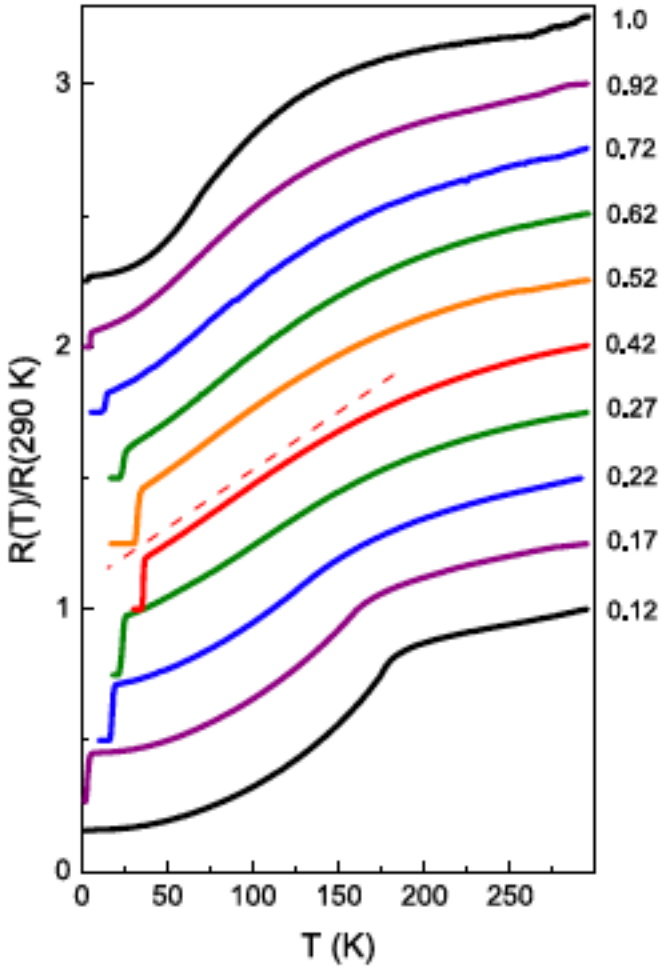
Uemura, Nat. Matls. 8, 253 (2009)

Phase Diagram - Cuprates in Disguise?

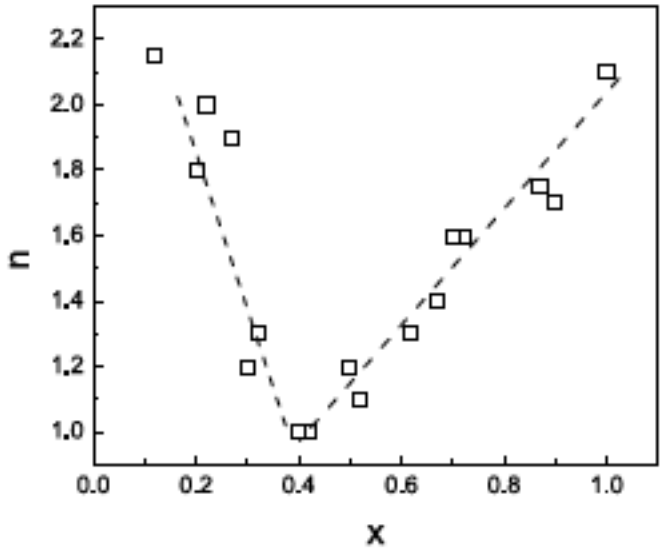


Hess *et al.*, EPL 87, 17005 (2009)

Quantum Criticality? (K-doped 122)

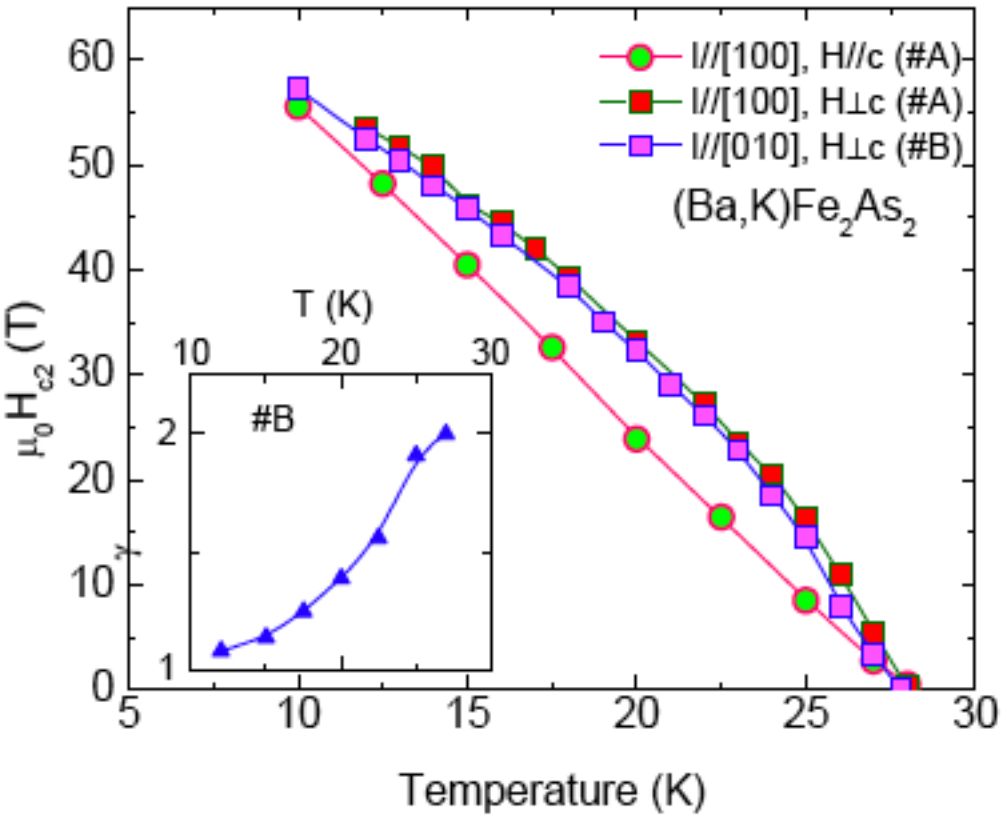


$\rho - \rho_0 \sim T^n$



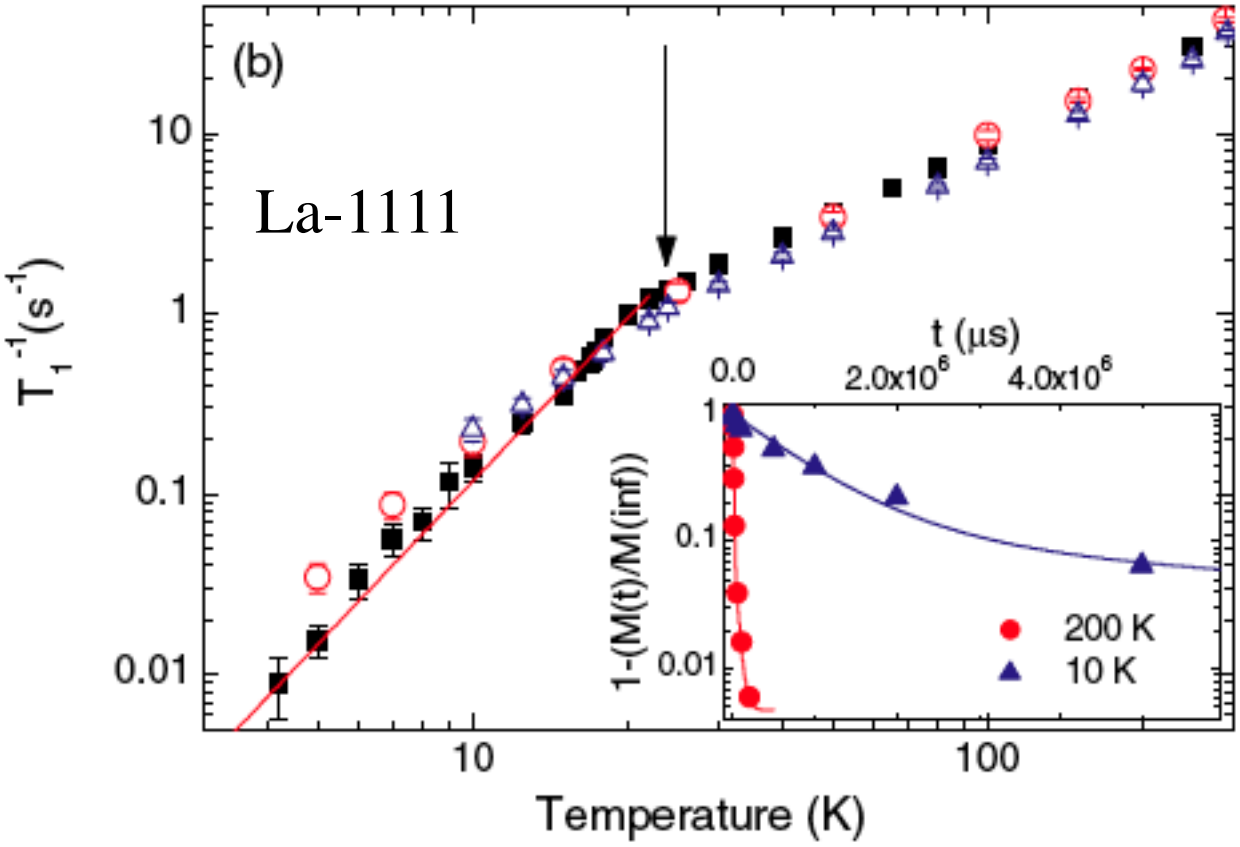
Gooch *et al.*, PRB 79, 104504 (2009)

Weak Anisotropy of H_{c2}



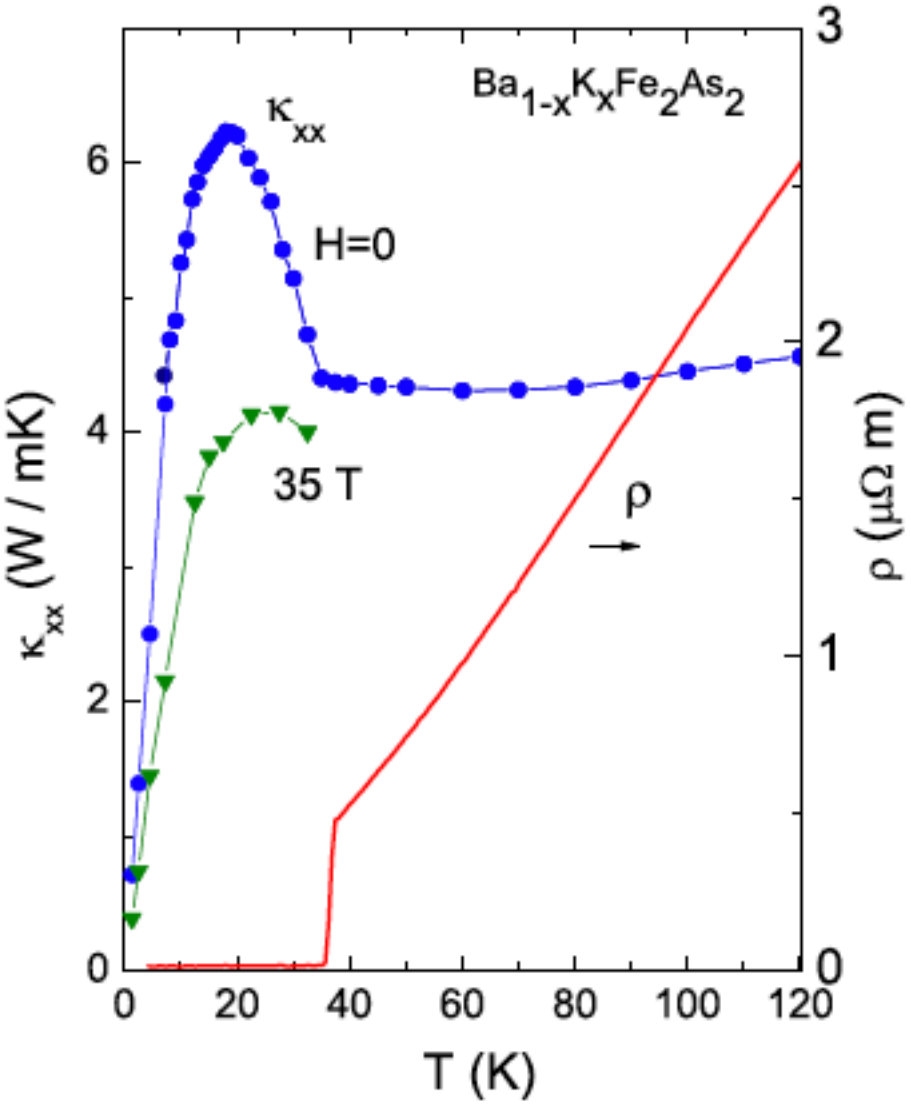
Yuan *et al*., Nature 457, 565 (2009)

T^3 NMR relaxation rate



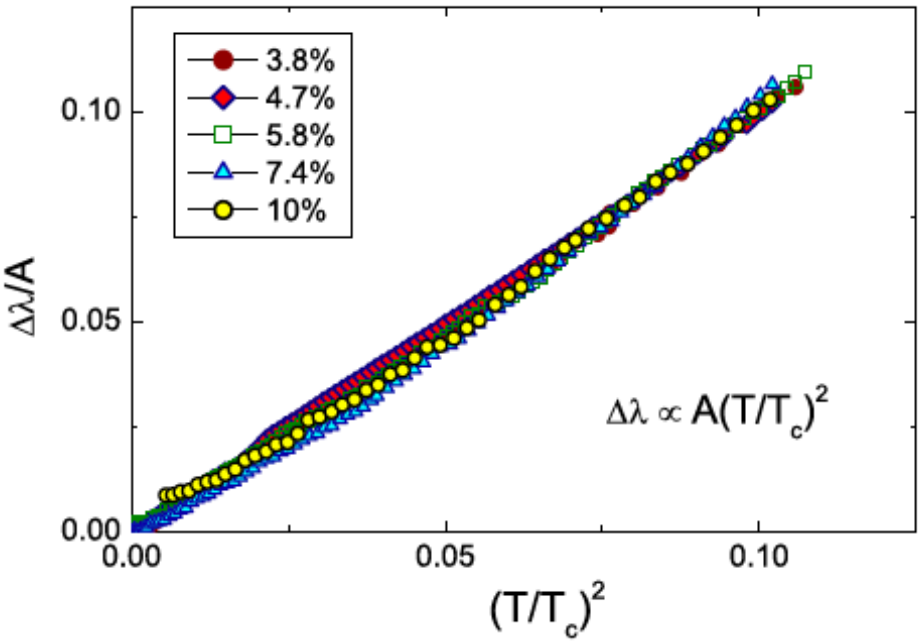
Grafe *et al.*, PRL 101, 047003 (2008)

Thermal conductivity similar to cuprates

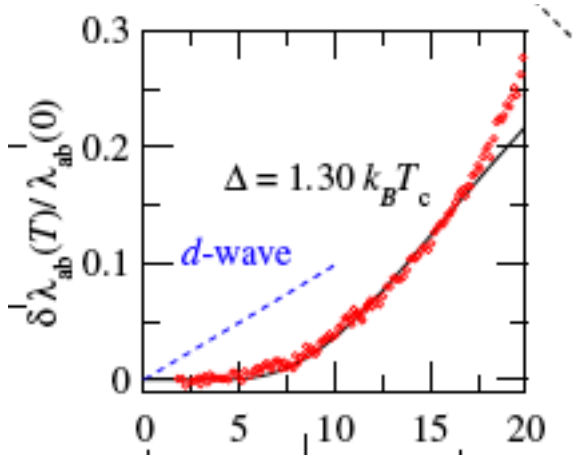


Checkelsky *et al.*, arXiv:0811.4668

Penetration Depth, T^2 versus exponential



Co-doped 122

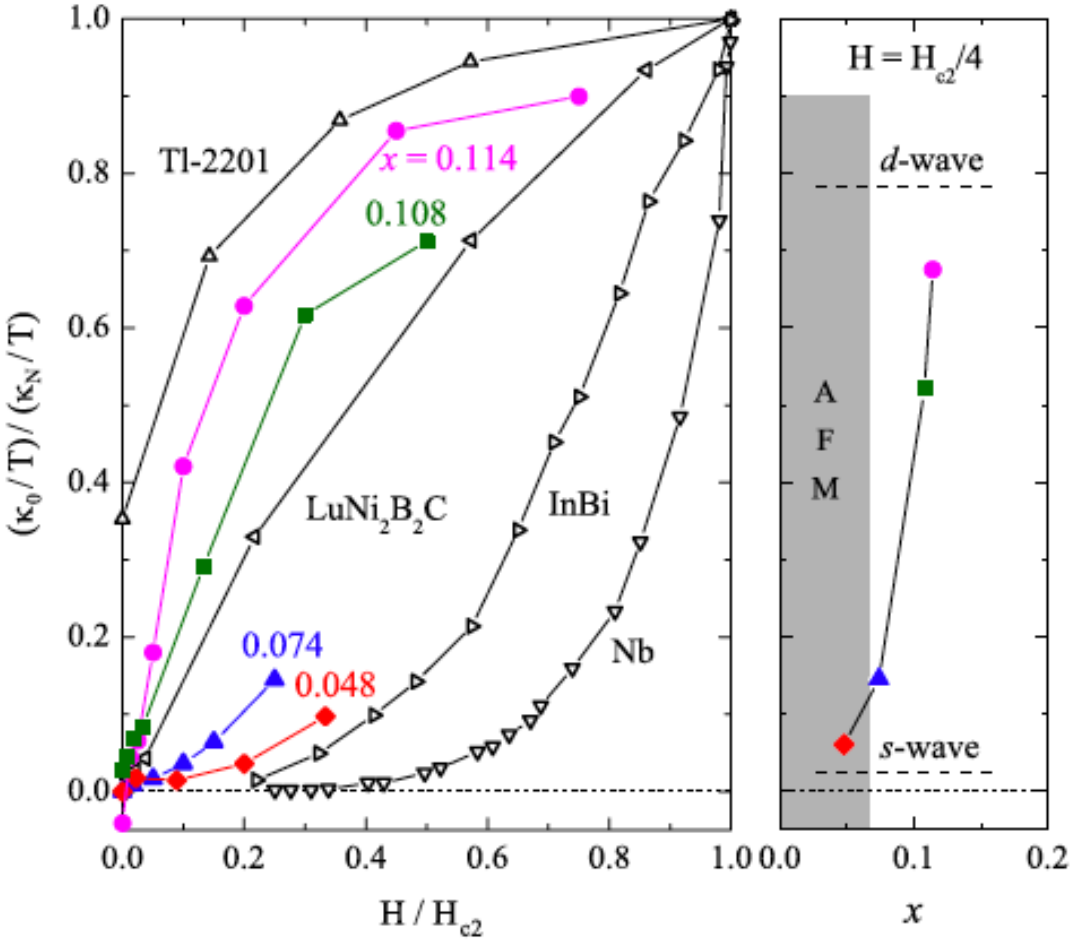


K-doped 122

Gordon *et al.*, PRB 79, 100506 (2009)

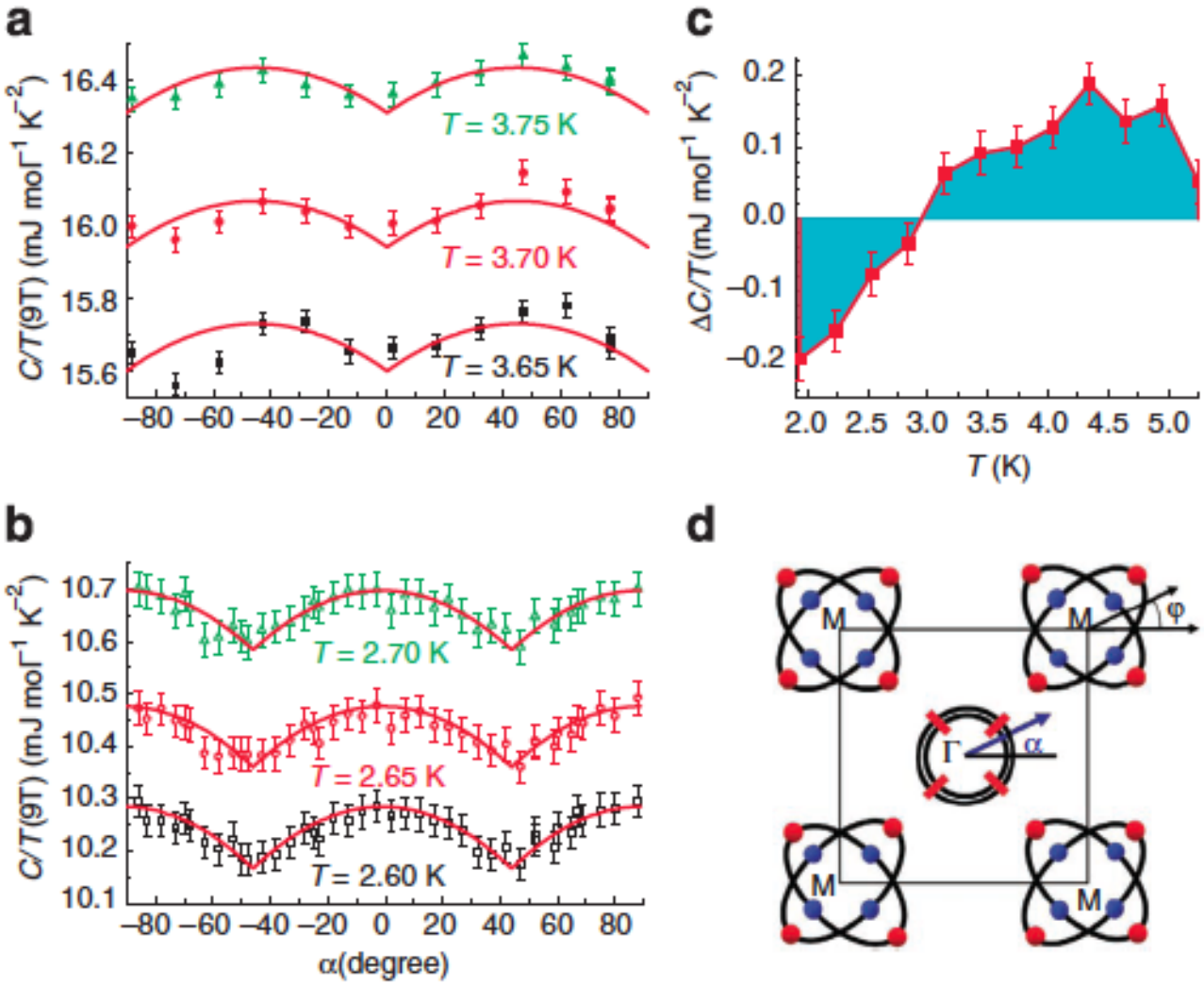
Hashimoto *et al.*, PRL 102, 207001 (2009)

Field Dependence of Thermal Conductivity
(Co-doped 122)



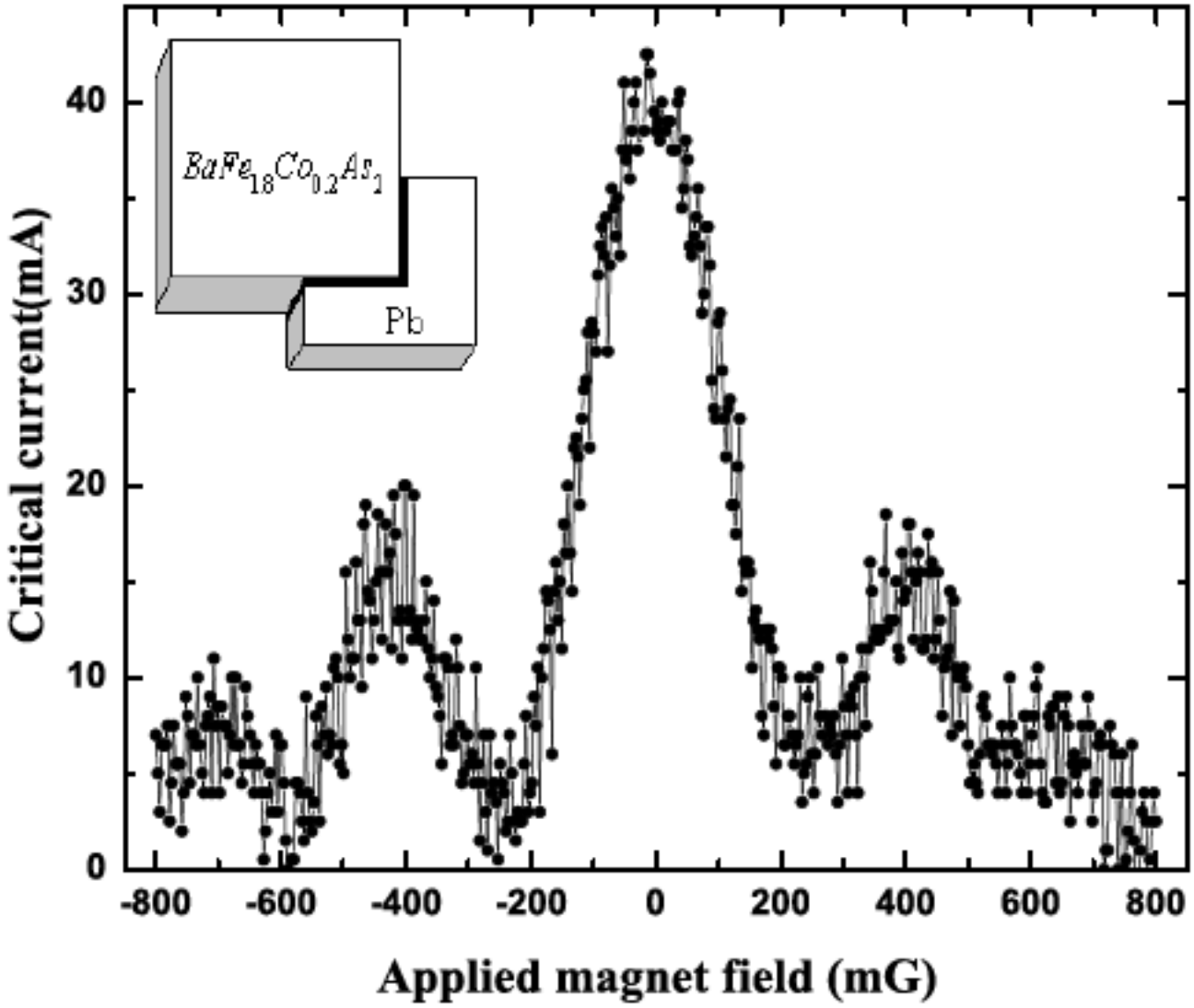
Tanatar *et al*., PRL 104, 067002 (2010)

Field Angular Dependence of Specific Heat
(FeSe-Te)



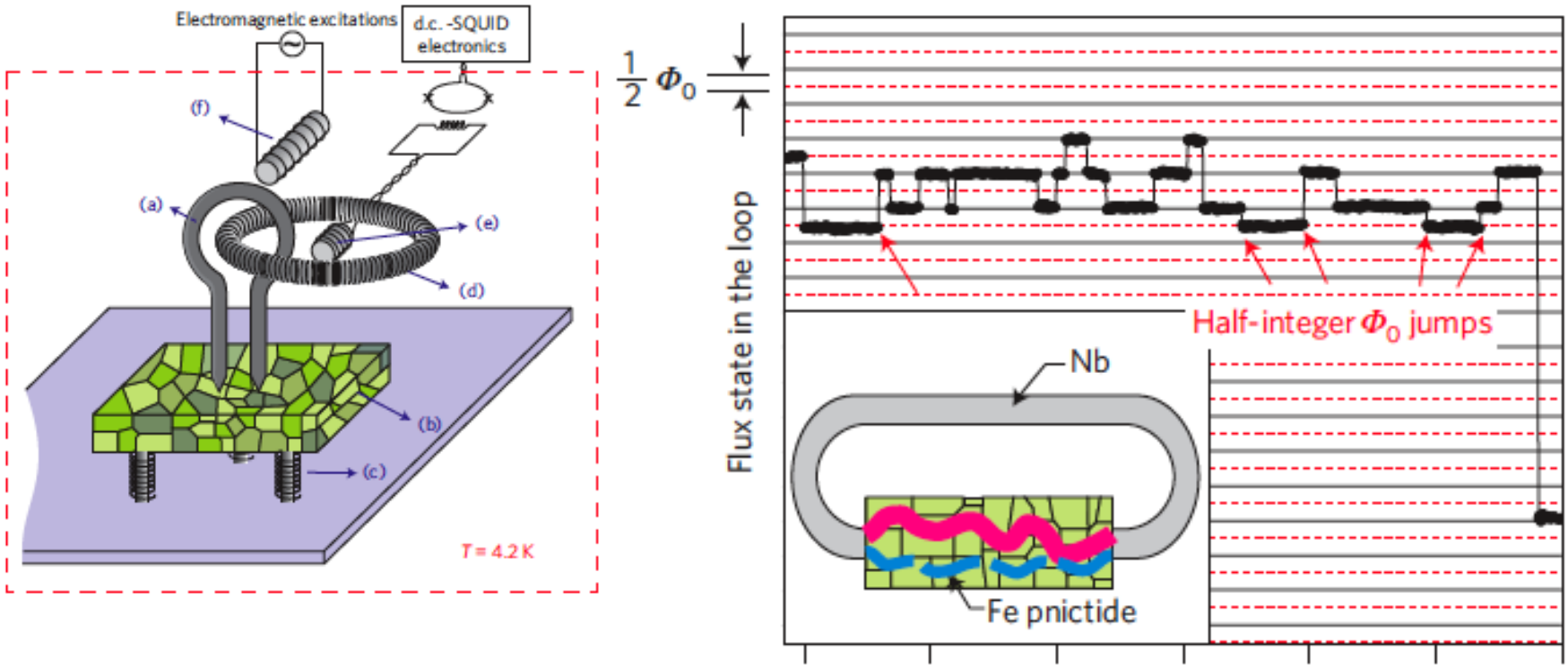
Zeng *et al*., Nature Comm. 1, 112 (2010)

No Phase Shift in Corner Junctions



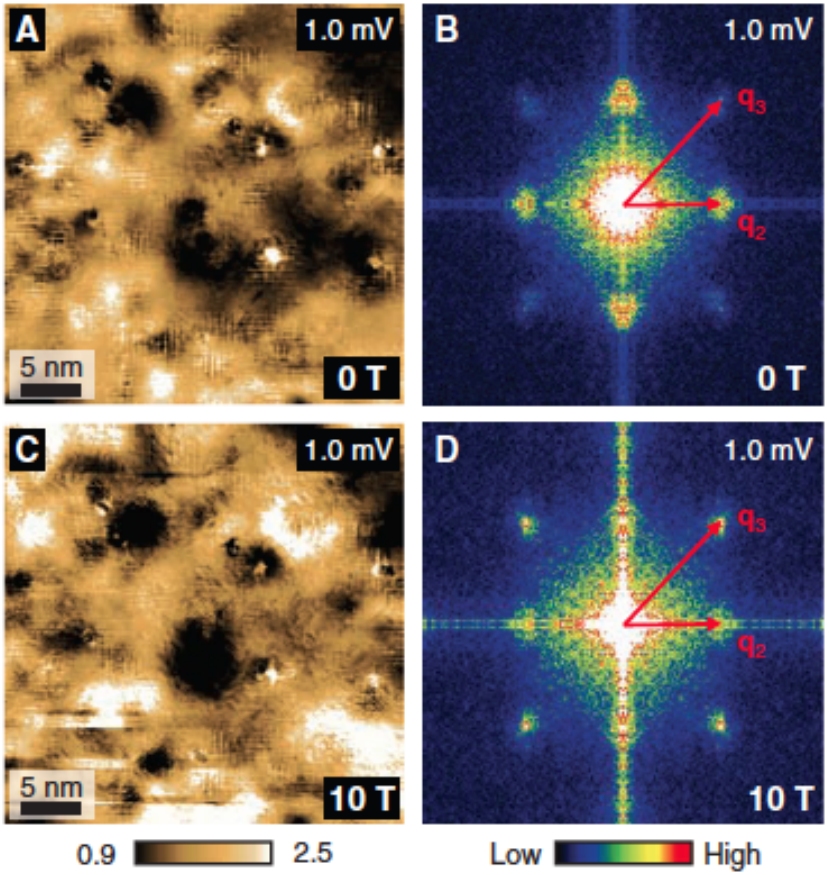
Zhou *et al*., arXiv:0812.3295

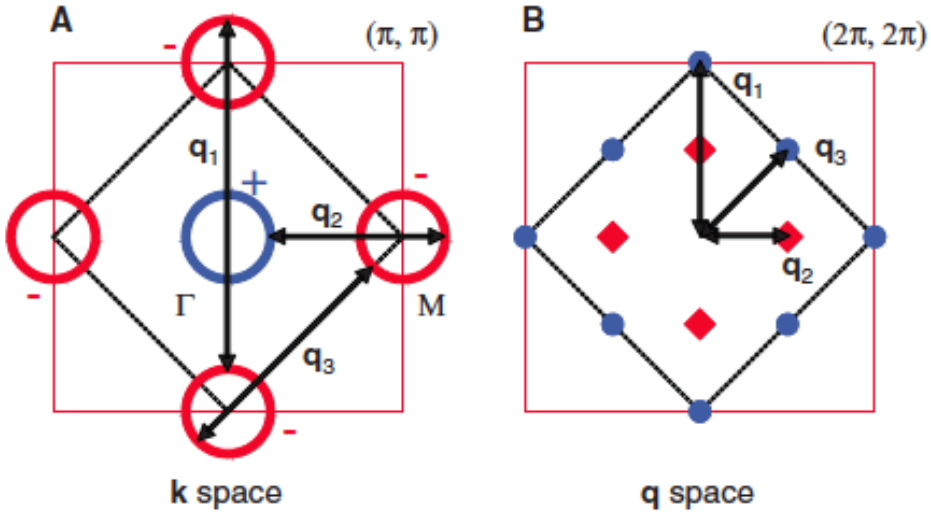
Half Flux Quantum Vortices (Nd-1111)

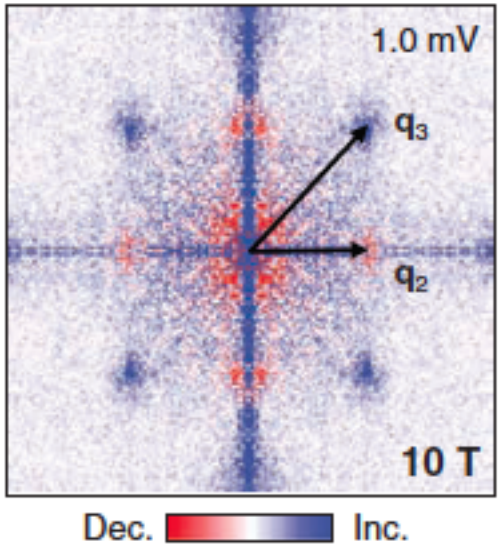


Chen *et al.*, Nat. Phys. 6, 260 (2010)

Quantum Interference in FT-STM (FeSe-Te)

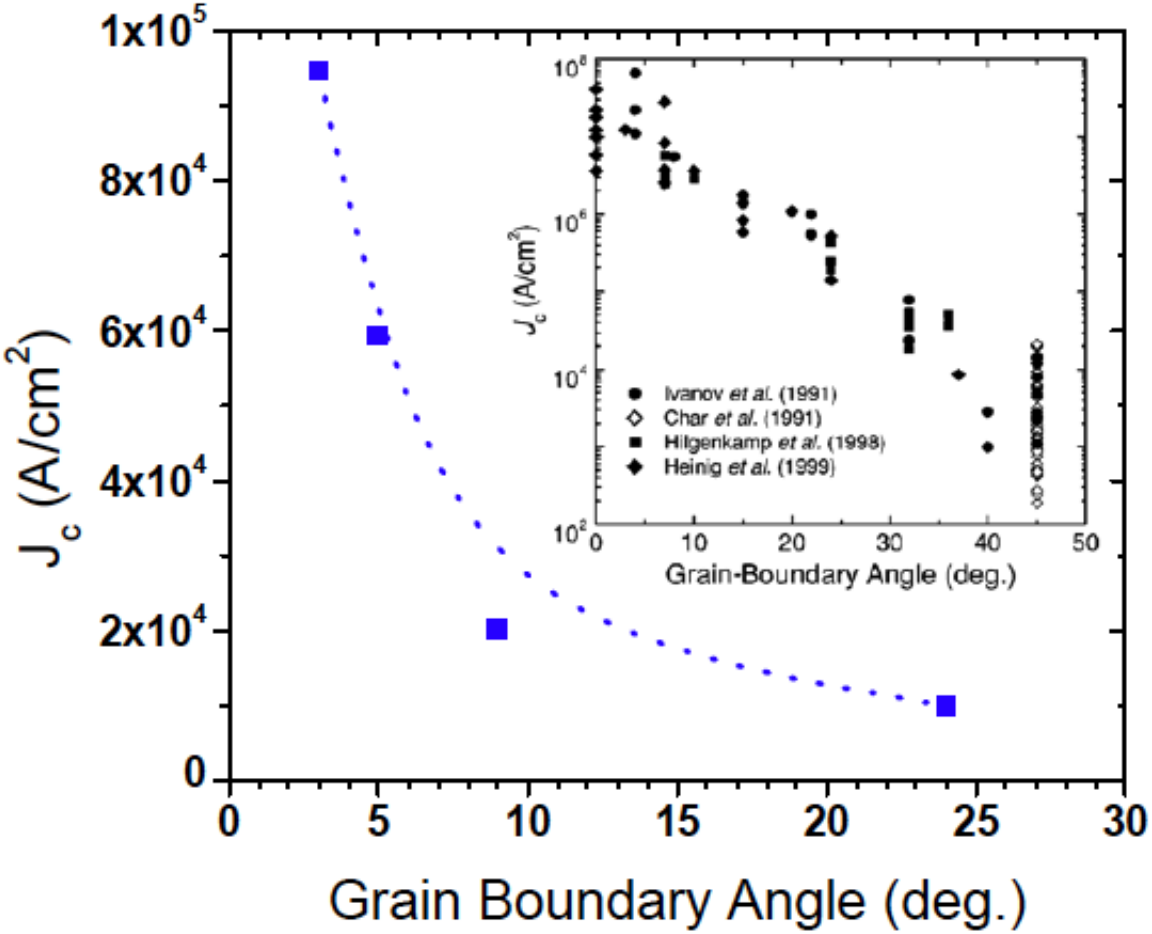






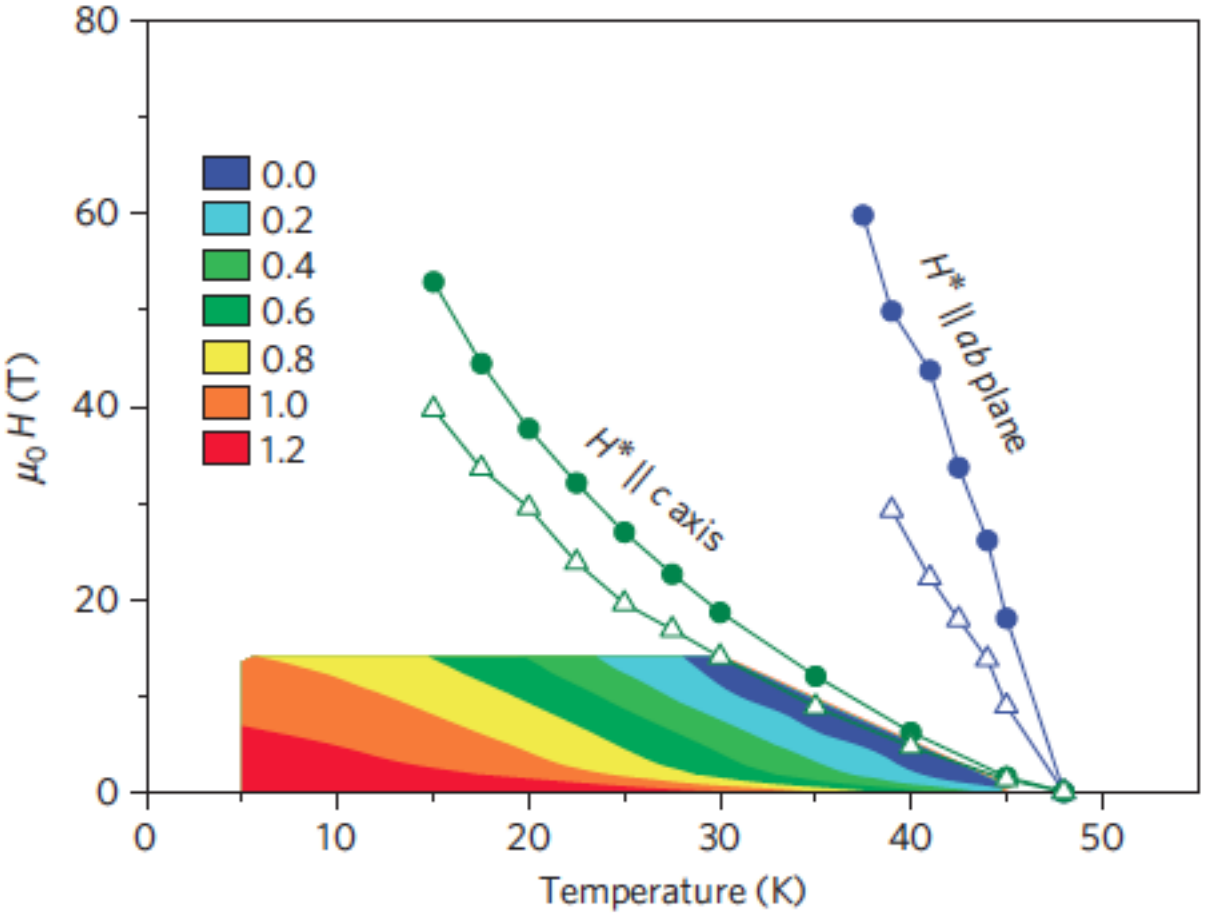
Hanaguri *et al.*, Science 328, 474 (2010)

Critical current versus grain boundary angle (Co-doped 122)



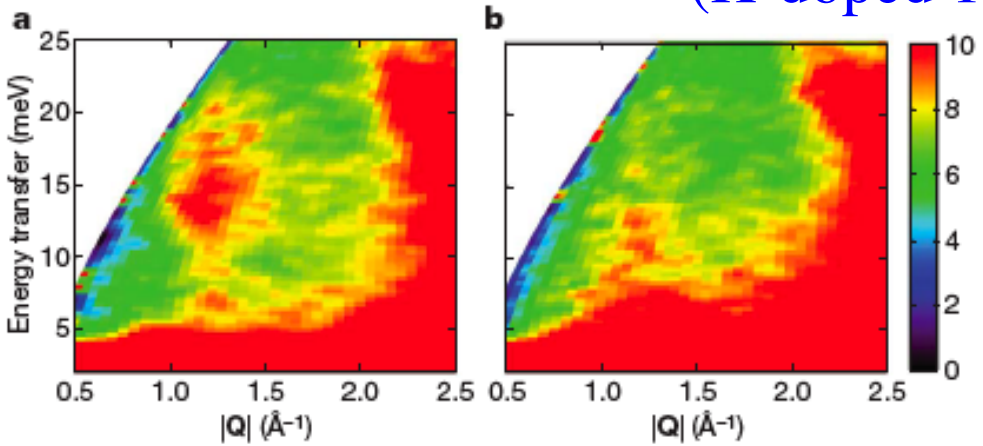
Lee *et al*., APL 95, 212505 (2009)

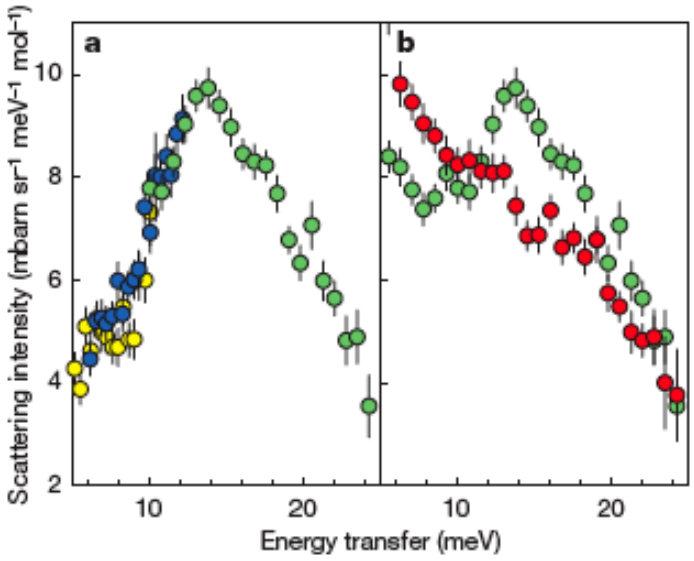
Critical current versus magnetic field
(F-doped Sm-1111)

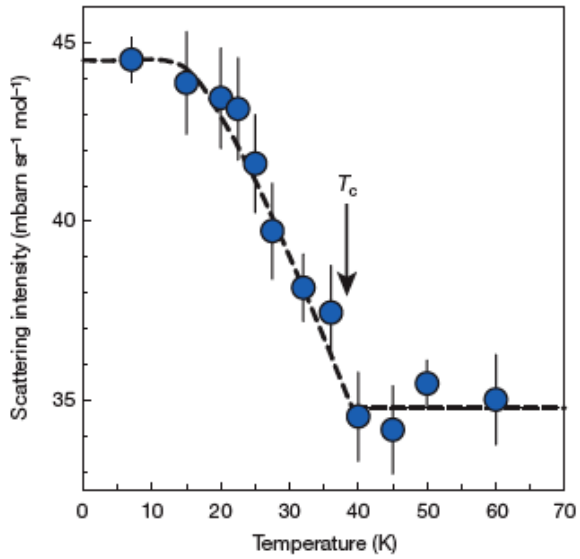


Moll *et al.*, Nat. Matls. 9, 628 (2010)

Spin Resonance Mode in Superconducting Phase
(K-doped 122)



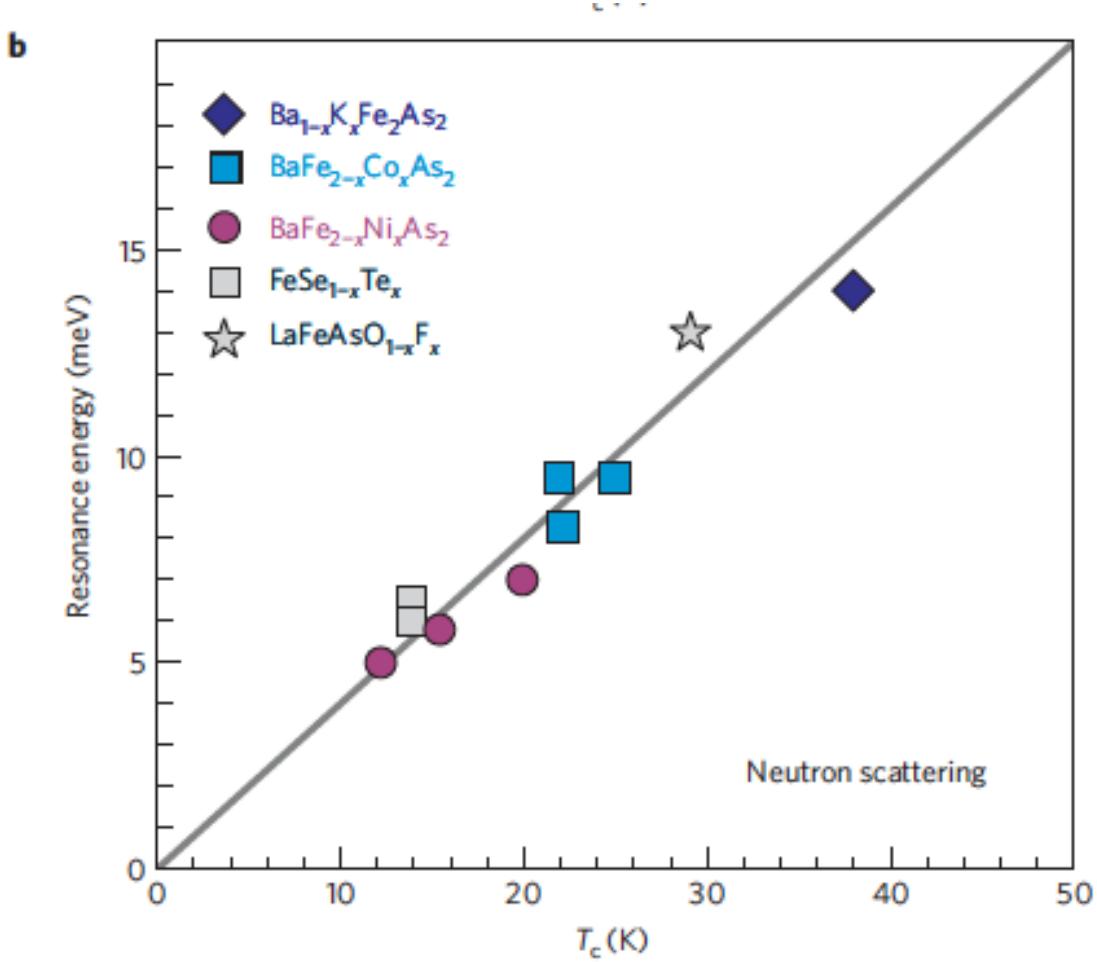




$$\Delta_k = -\Delta_{k+Q}$$

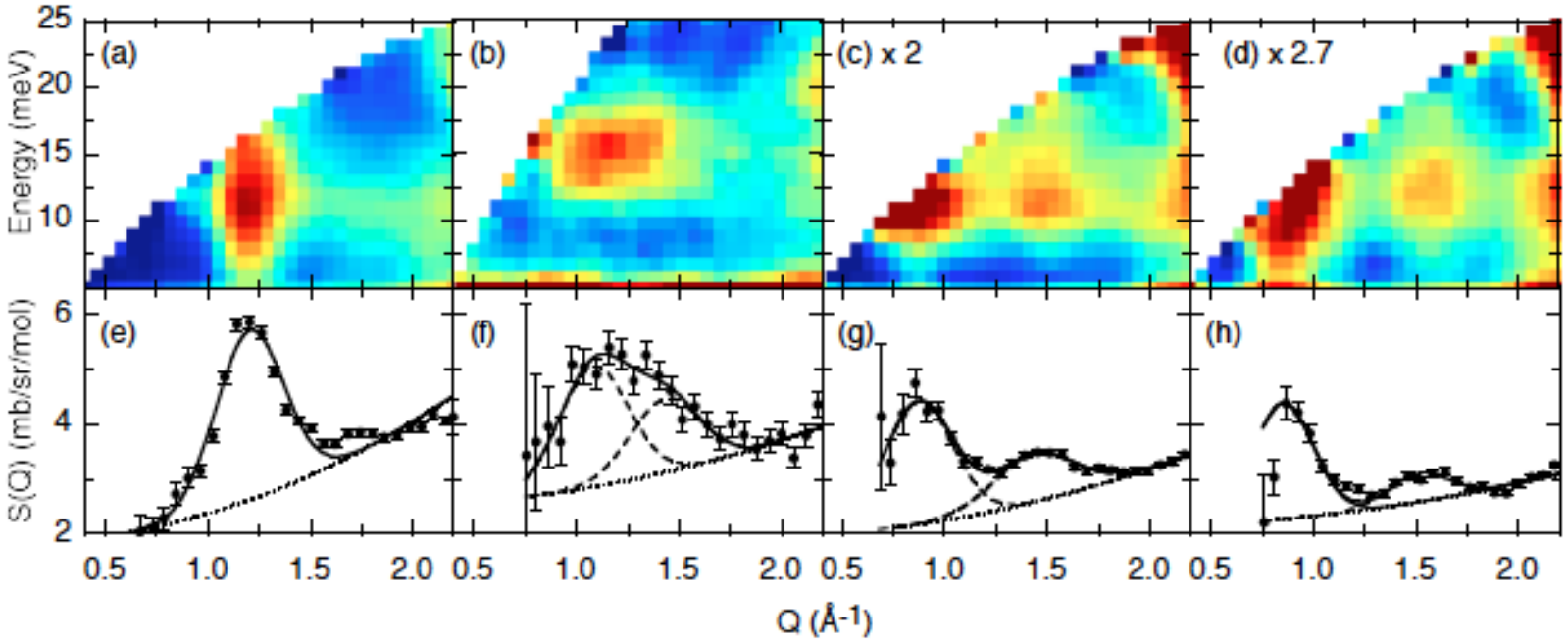
Christianson *et al.*, Nature 456, 930 (2008)

Scaling of Resonance Energy with Gap



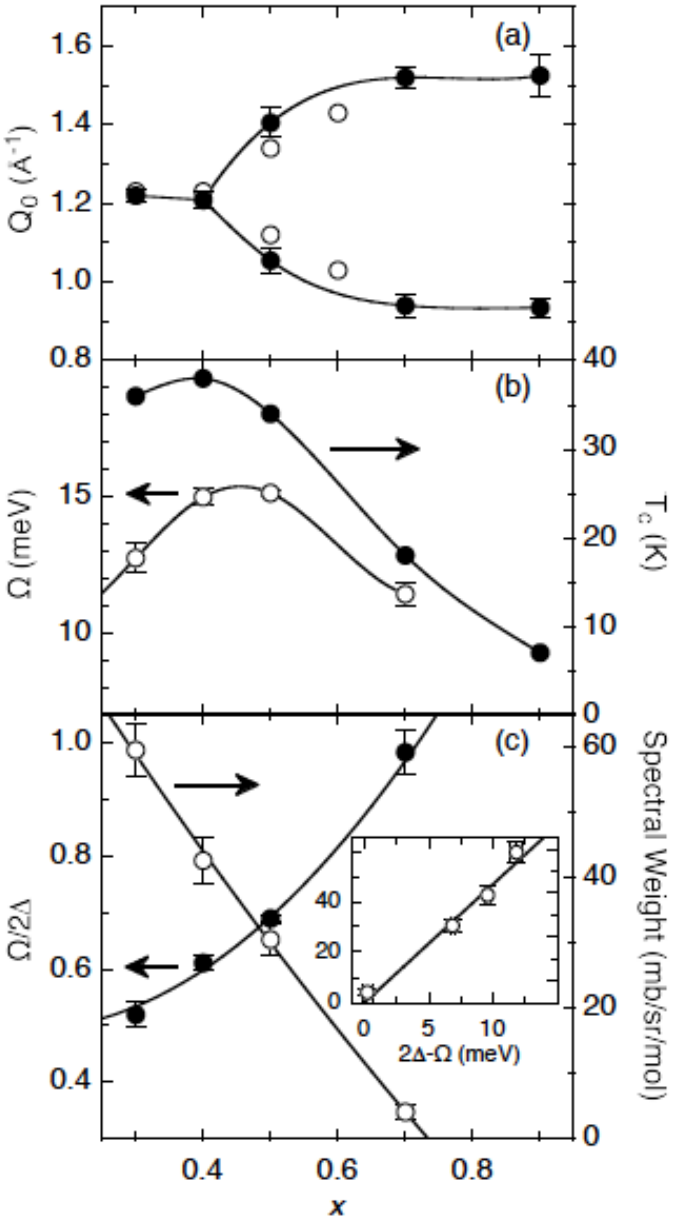
Paglione & Greene, Nat. Phys. 6, 645 (2010)

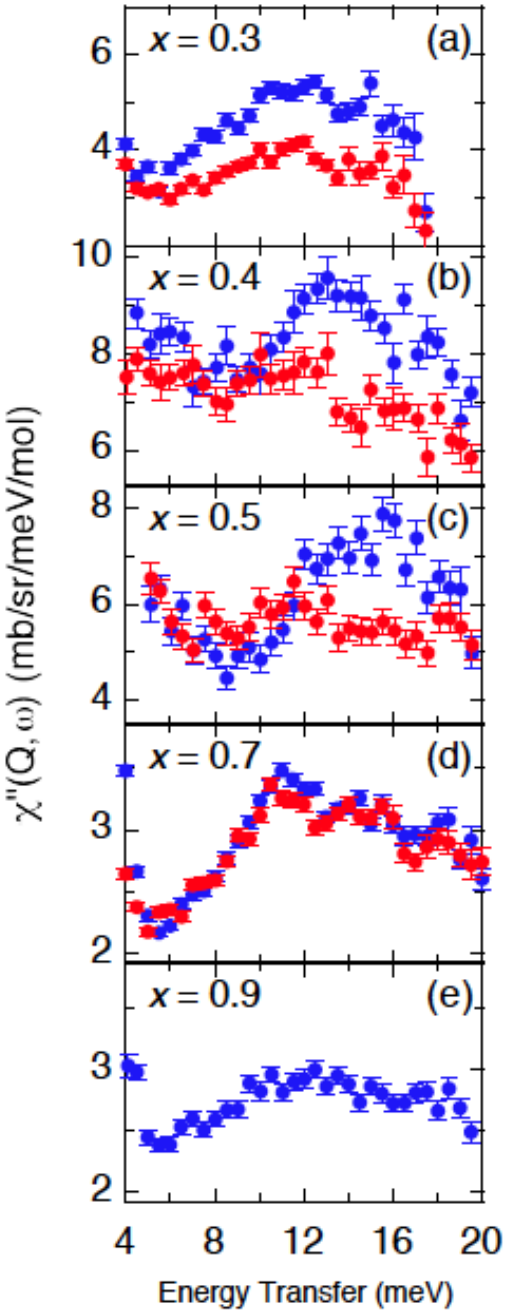
Doping Dependence of Spin Resonance Mode (K doped Ba122)



x=0.3 x=0.5 x=0.7 x=0.9

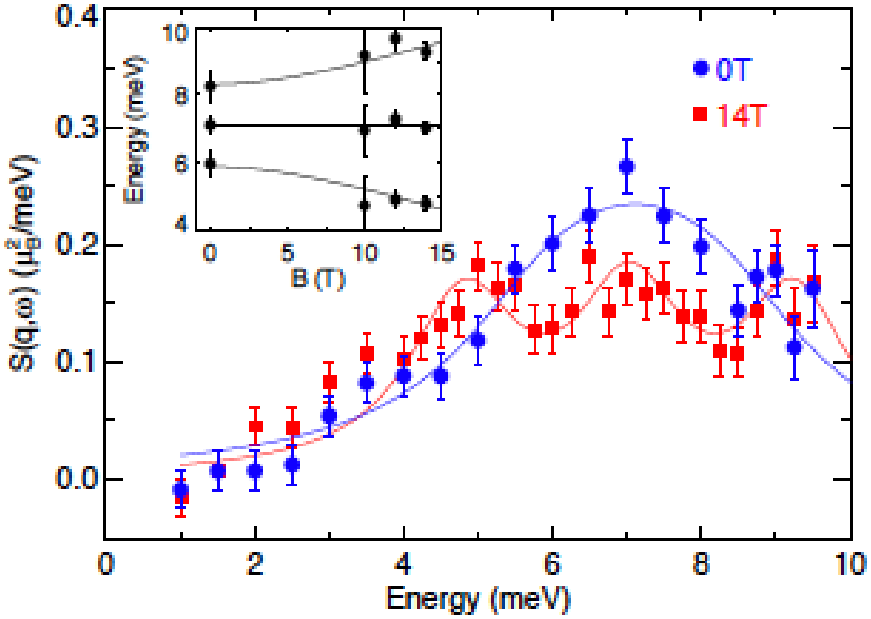
Castellan *et al*., unpublished



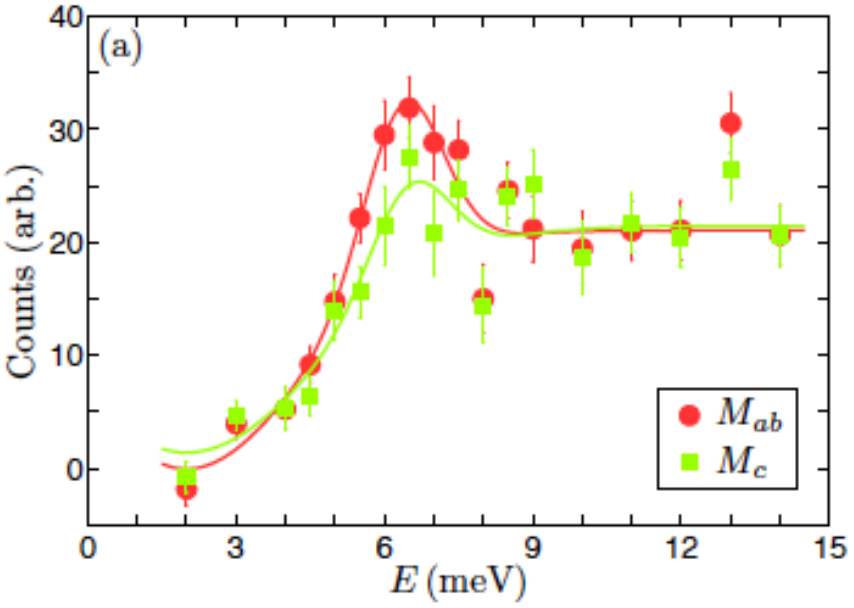


Castellan *et al*., unpublished

Is it a Triplet (FeSe-Te)?



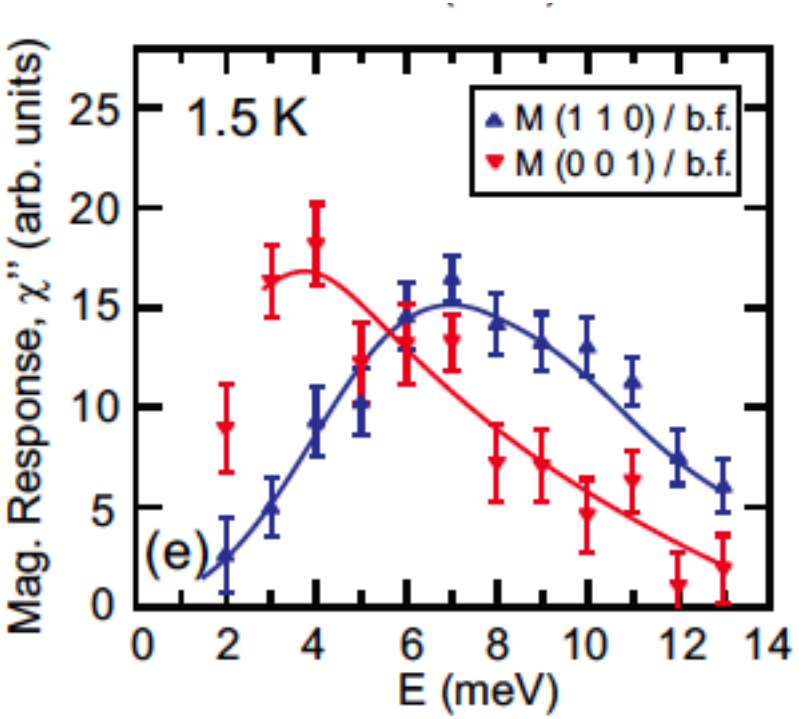
Bao *et al*., arXiv:1002.1617

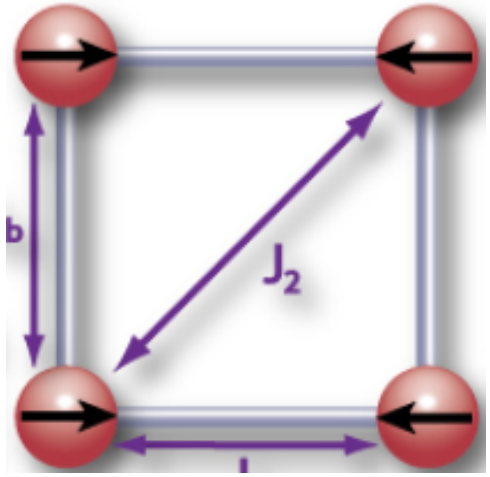


Babkevich *et al*., arXiv:1010.6204

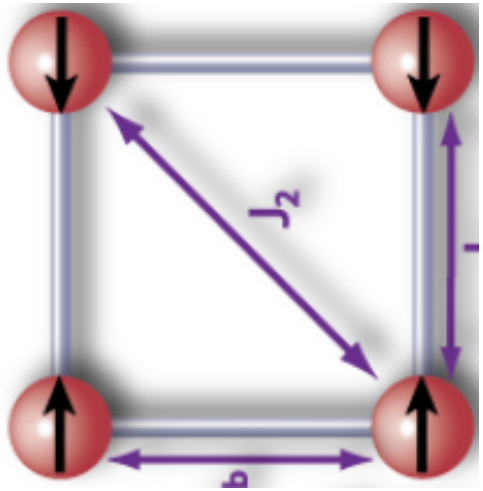
Is it a Doublet (S_c=±1)?

Ni-doped Ba122





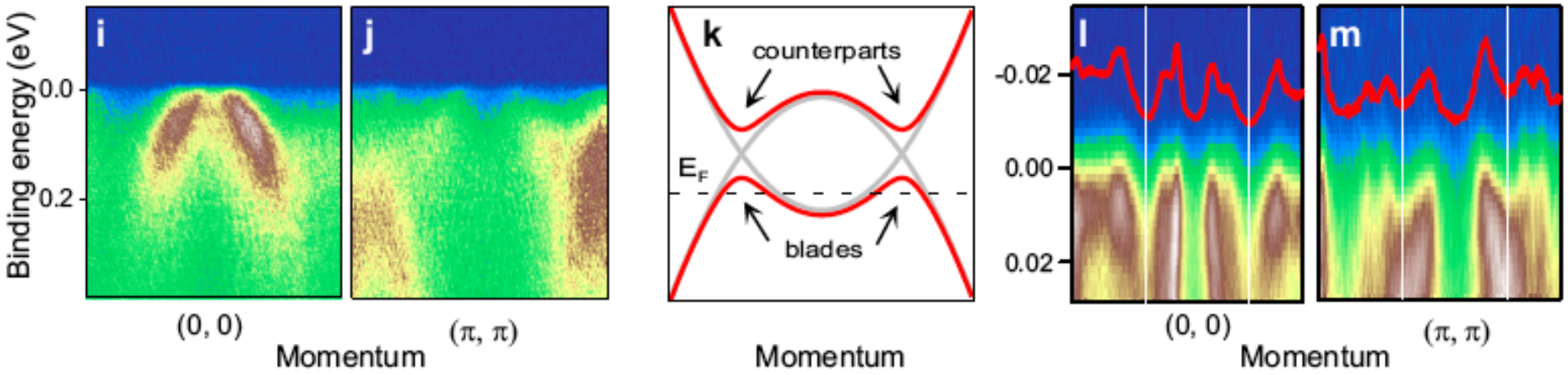
S_a=0



S_b=0

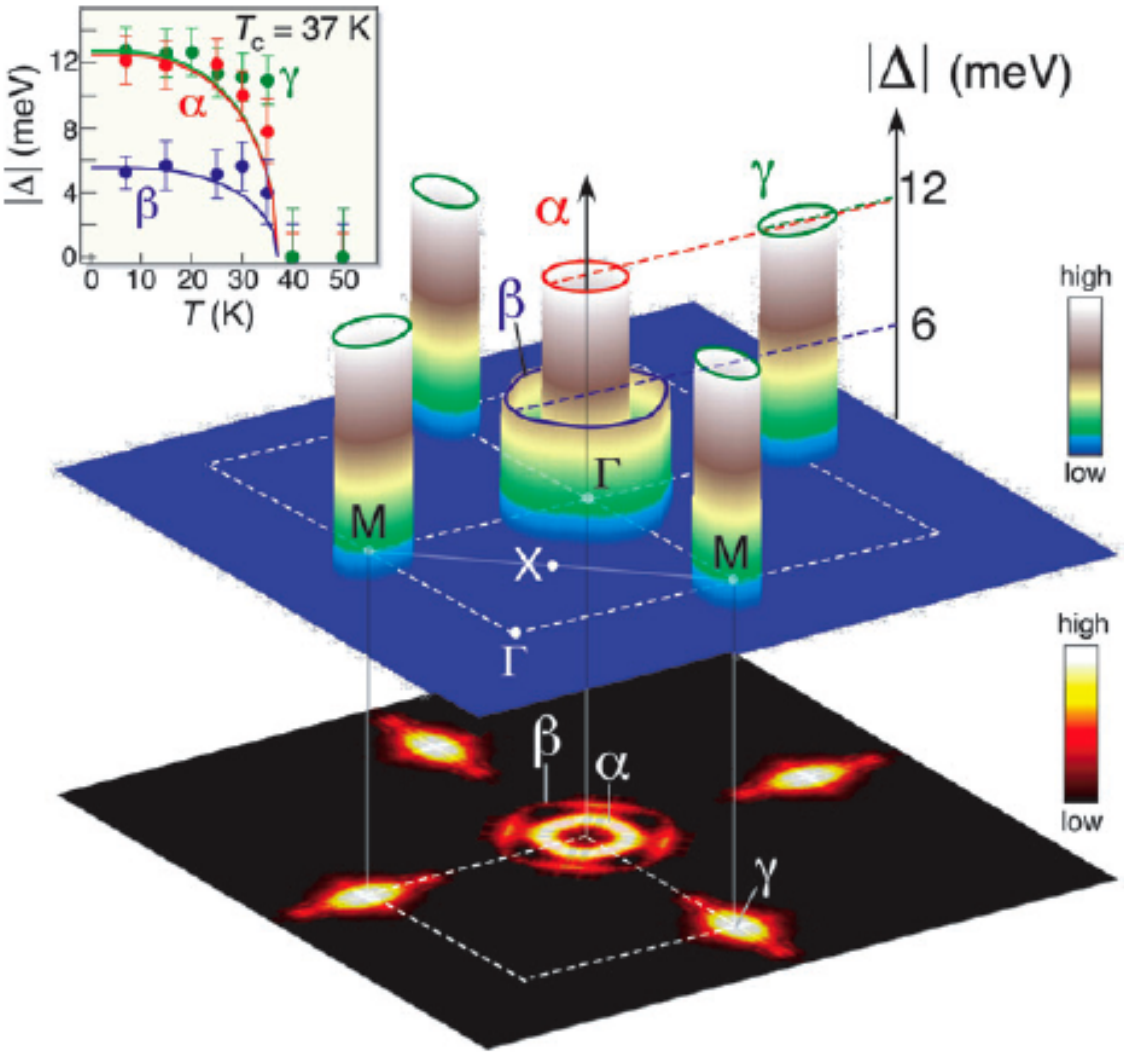
Lipscombe *et al*., PRB 82, 064515 (2010)

(π, π)-electronic order in iron arsenide superconductors



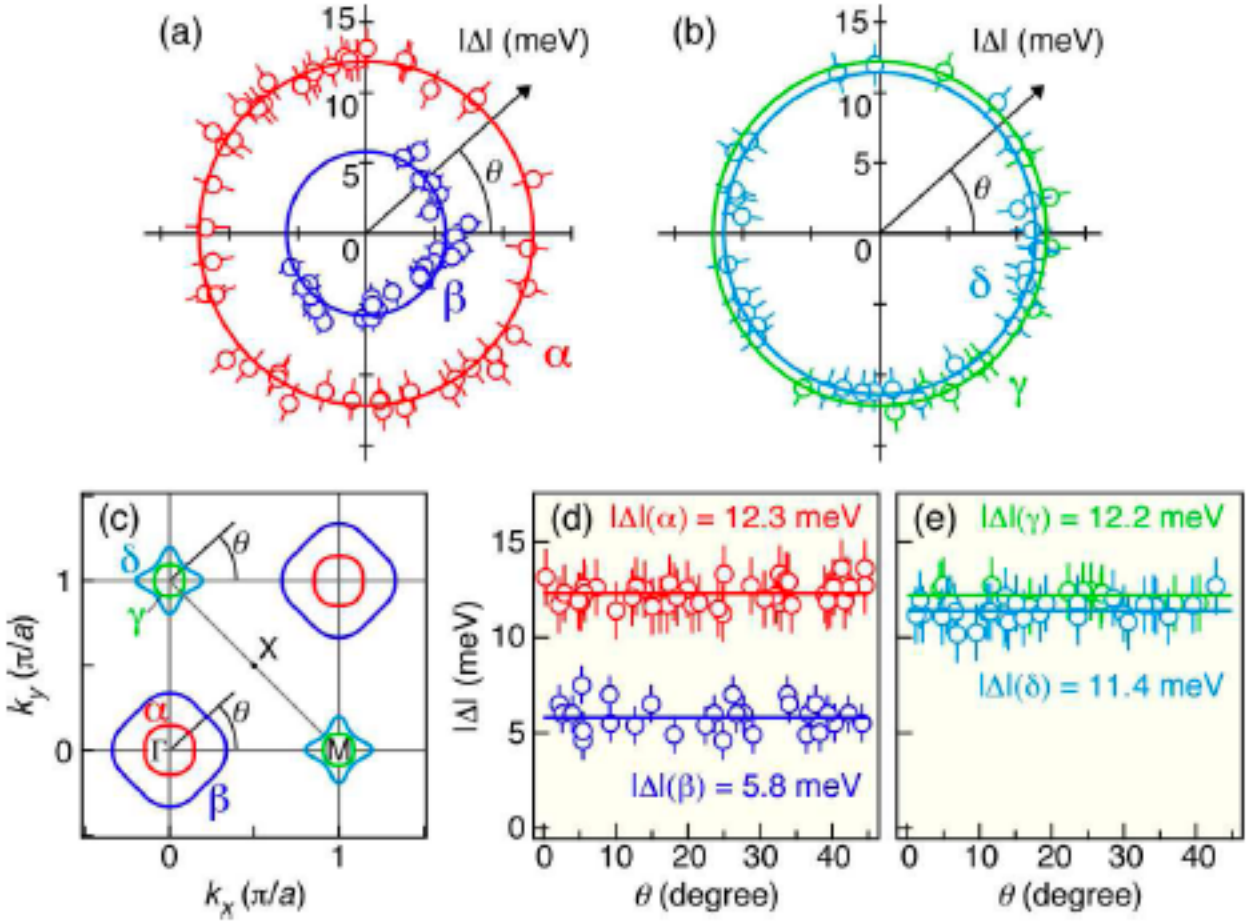
Zabolotnyy *et al*., Nature 457, 569 (2009)

Energy Gaps from ARPES (K-doped 122)



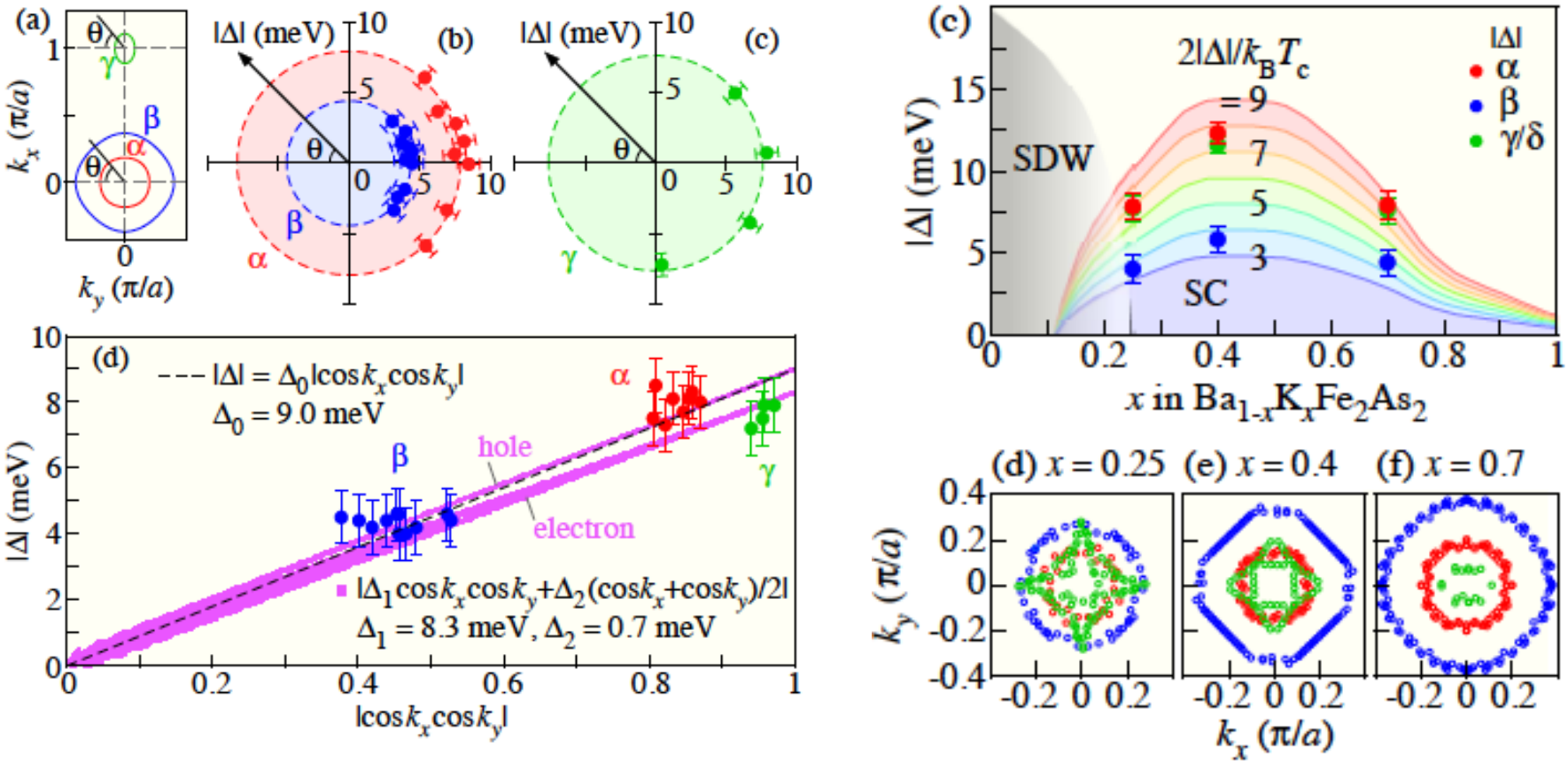
Ding *et al.*, EPL 83, 47001 (2008)

Energy Gaps from ARPES (K-doped 122)



Nakayama *et al*., EPL 85, 67002 (2009)

Energy Gaps from ARPES (K-doped 122)



Nakayama *et al.*, arXiv:1009.4236

ARPES Doping Dependence - Nesting and T_c

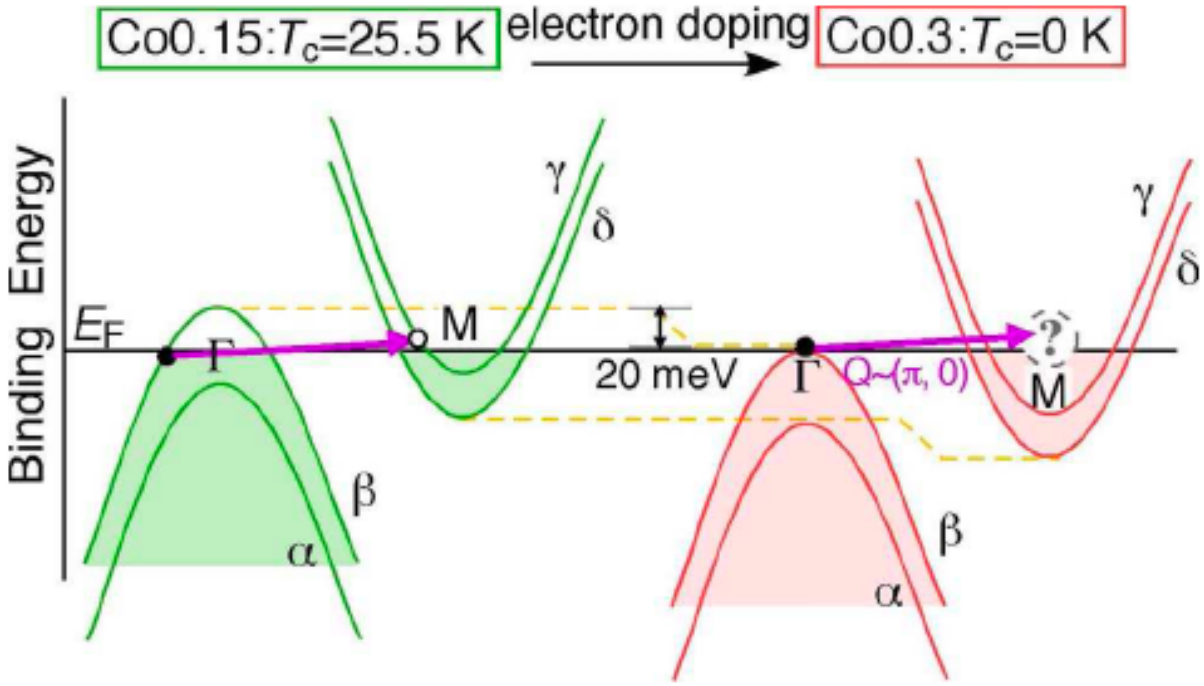
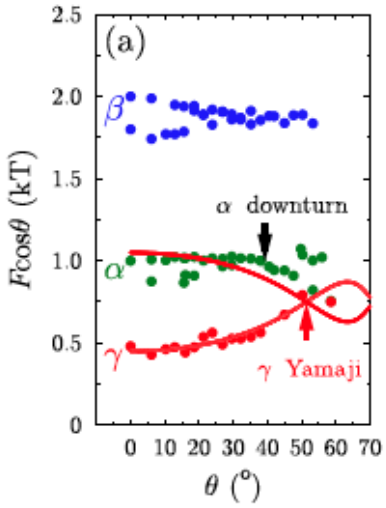
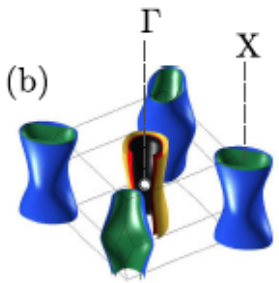


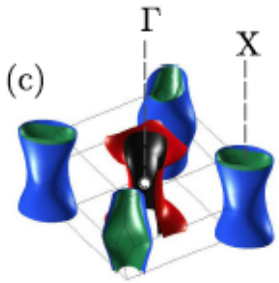
FIG. 4: Comparison of energy bands between the Co0.15 and Co0.3 samples. The interband scattering is dramatically suppressed in the non-SC Co0.3 sample since the holelike α and β bands at the Γ point are basically occupied.

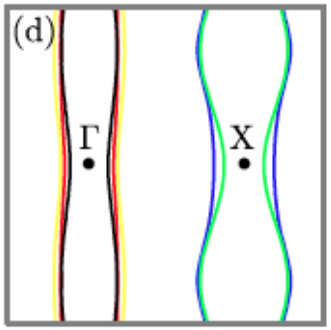
Sekiba *et al.*, New J Phys 11, 025020 (2009)

dHvA Doping Dependence - Nesting and T_c

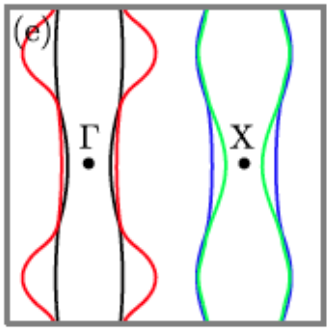




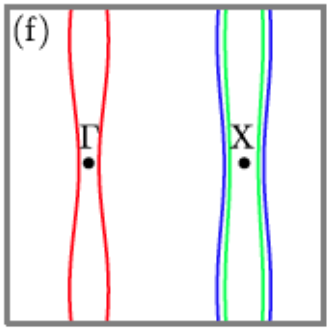




$BaFe_2As_2$



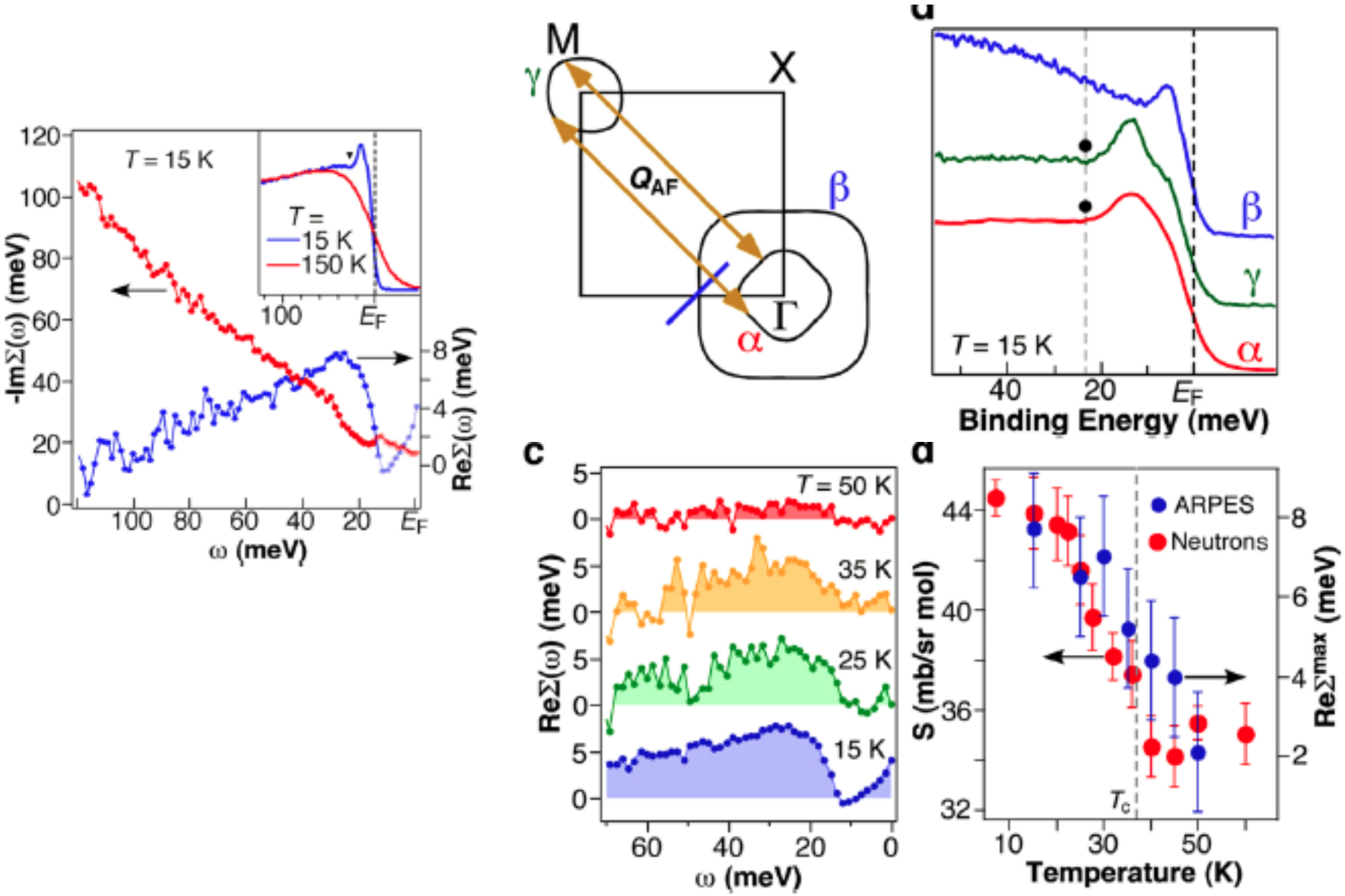
$BaFe_2P_2$



$BaFe_2As_2$ - shifted

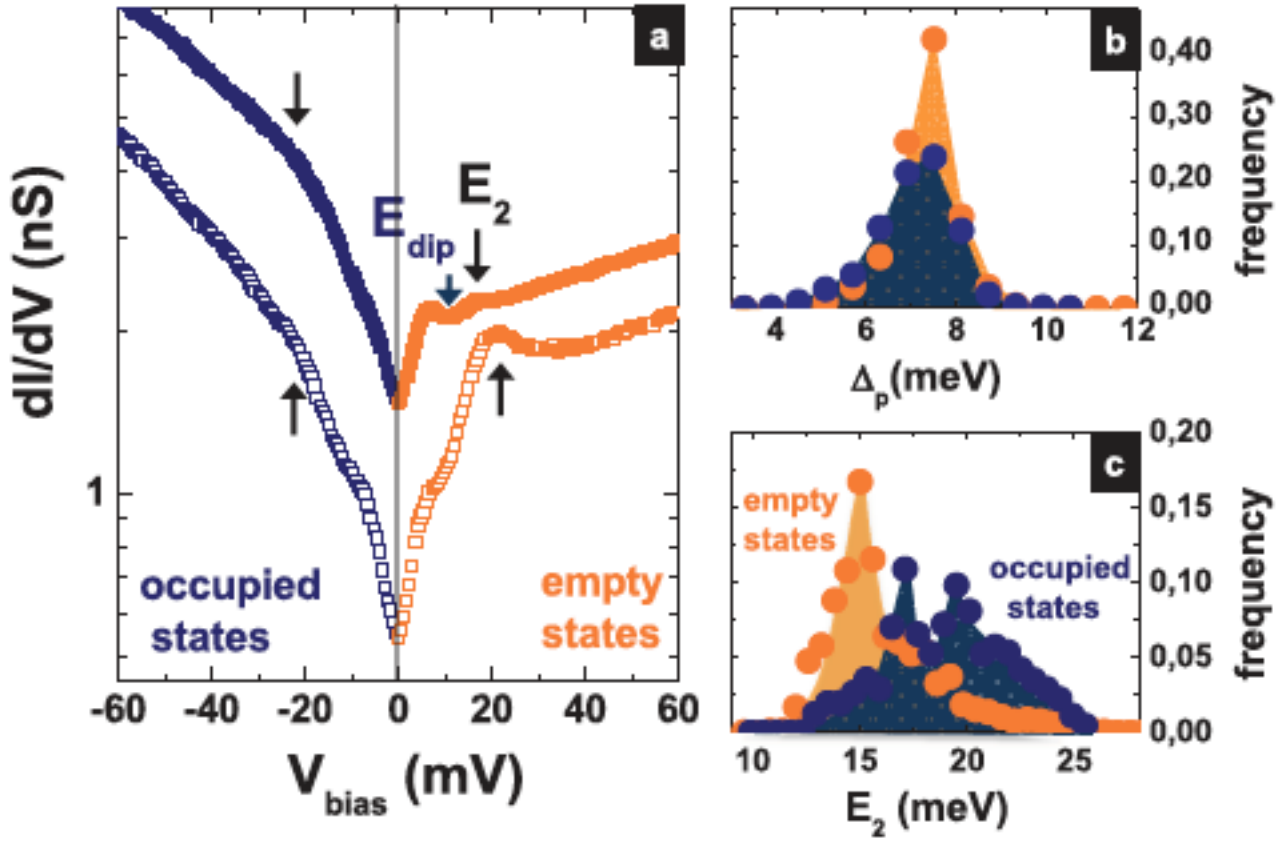
Analytis *et al.*, PRL 105, 207004 (2010)

Mode coupling from ARPES (K-doped 122)



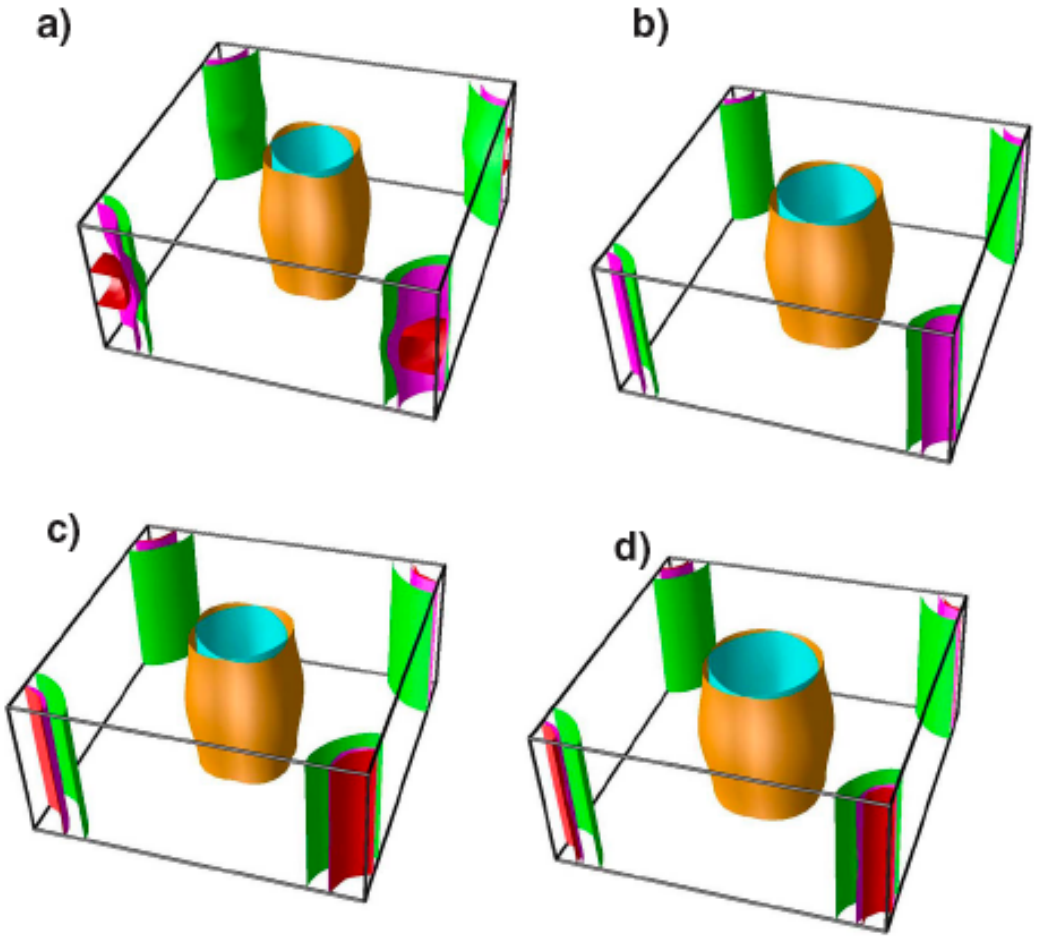
Richard *et al.*, PRL 102, 047003 (2009)

Mode coupling from STM (F-doped 1111)



Fasano *et al*., PRL 105, 167005 (2010)

LDA Fermi Surface (1111)



x=0 x=0.1

Mazin *et al.*, PRB 78, 085104 (2008)

LDA Fermi surface (111)

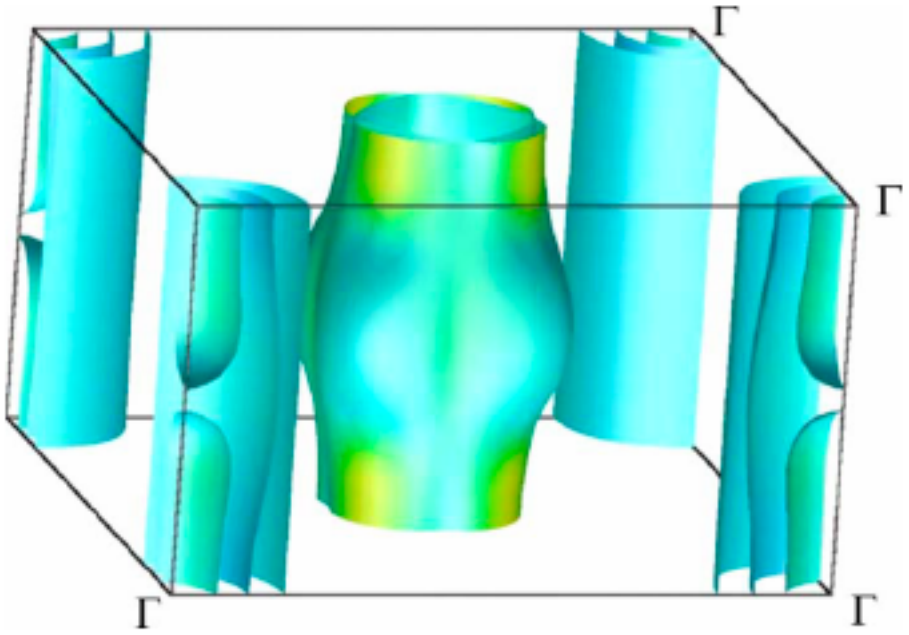
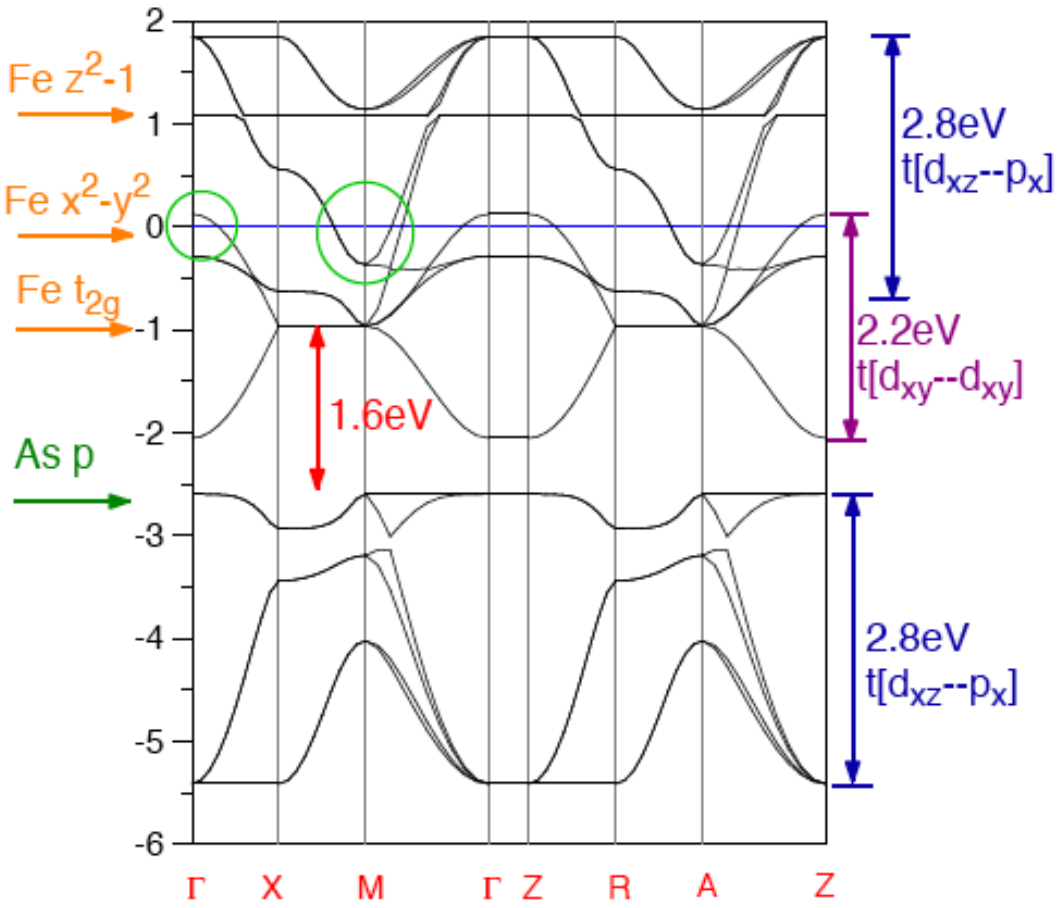


FIG. 7. (Color online) LDA Fermi surface of LiFeAs for the LDA internal coordinates, shaded by band velocity.

Singh, PRB 78, 094511 (2008)

LDA - all 5 iron d levels involved

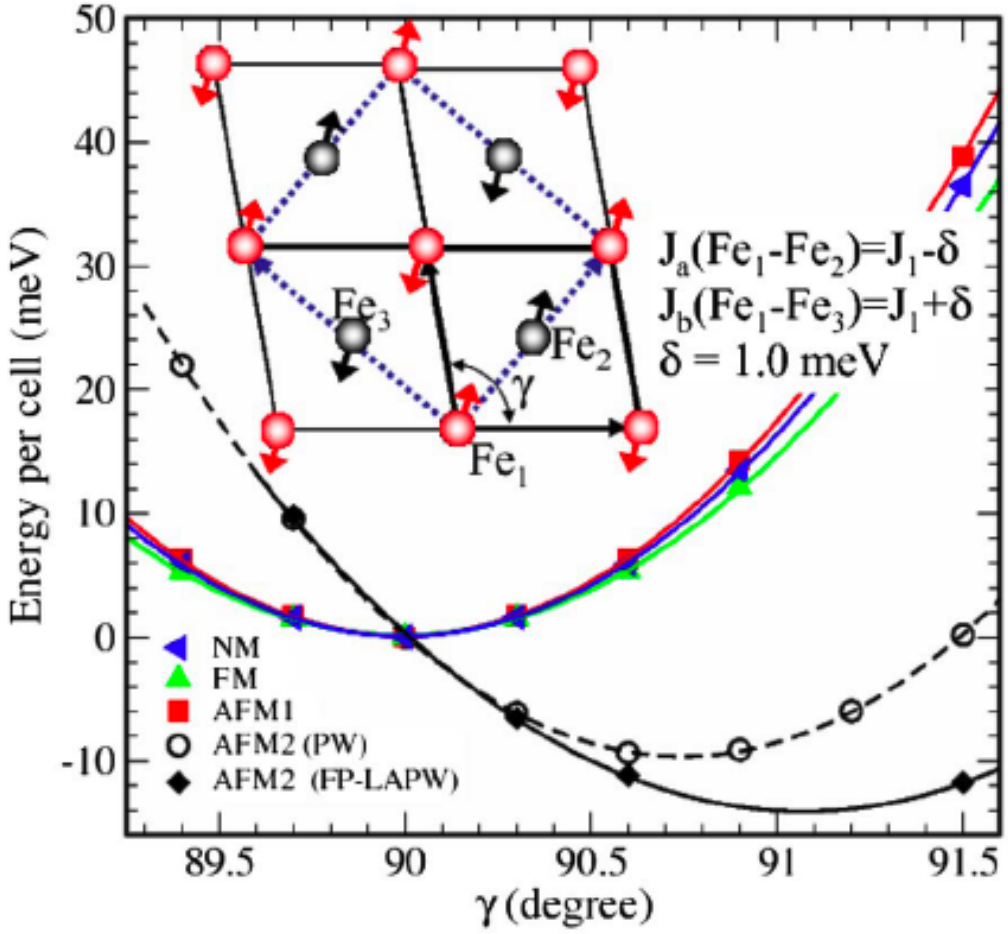


System	Moment
LaFeAsO	1.69
CeFeAsO	1.79
PrFeAsO	1.76
NdFeAsO	1.49
$CaFe_2As_2$	1.51
$SrFe_2As_2$	1.69
$BaFe_2As_2$	1.68
KFe_2As_2	1.58
LiFeAs	1.69

LDA tends to overestimate the size of the AF moments

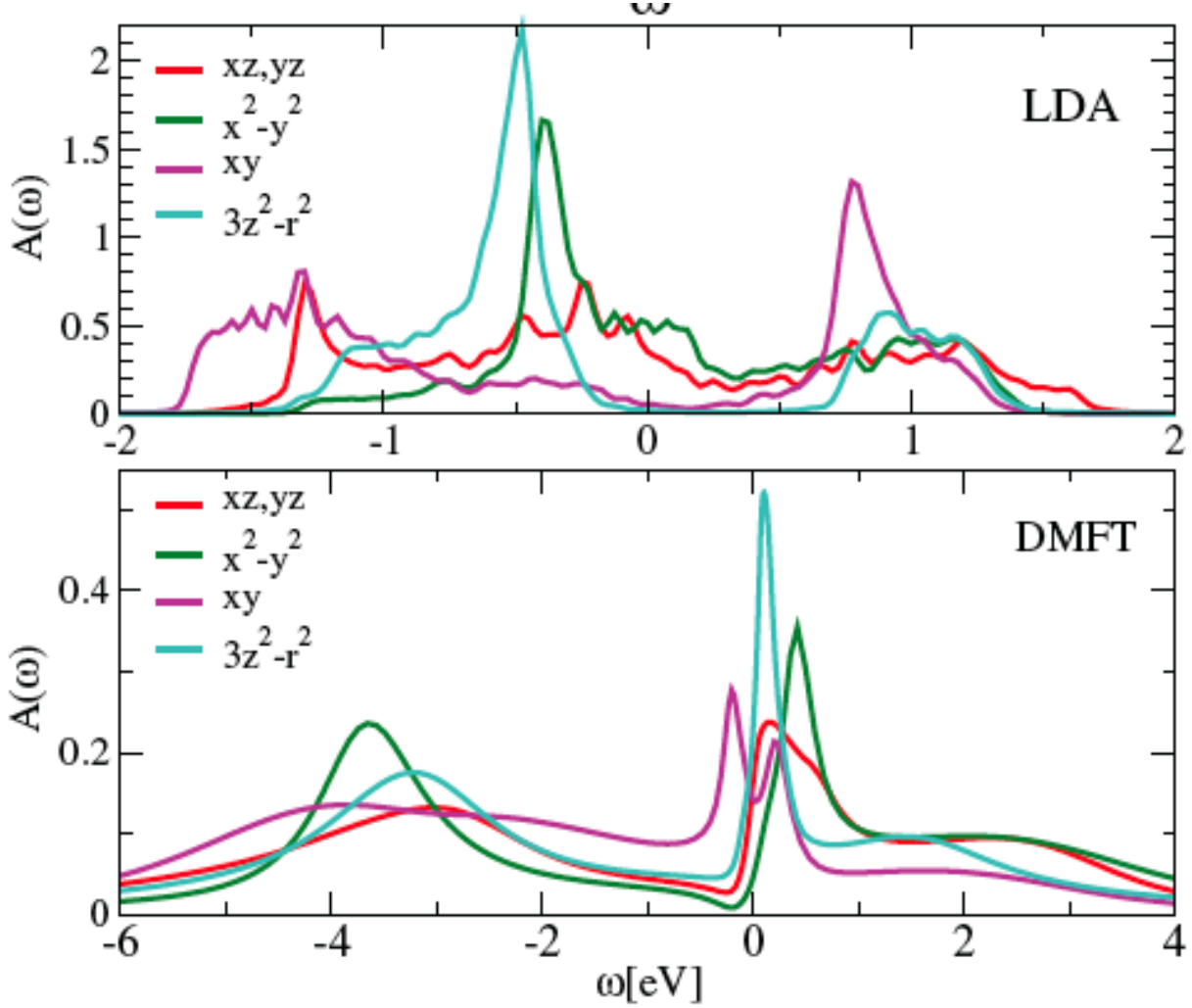
Han *et al.*, PRL 102, 107003 (2009)

LDA - Magnetism and Structure



Yildirim, PRL 101, 057010 (2008)

Dynamical Mean Field Theory



Haule, Shim, Kotliar, PRL 100, 226402 (2008)

Effective Coulomb U

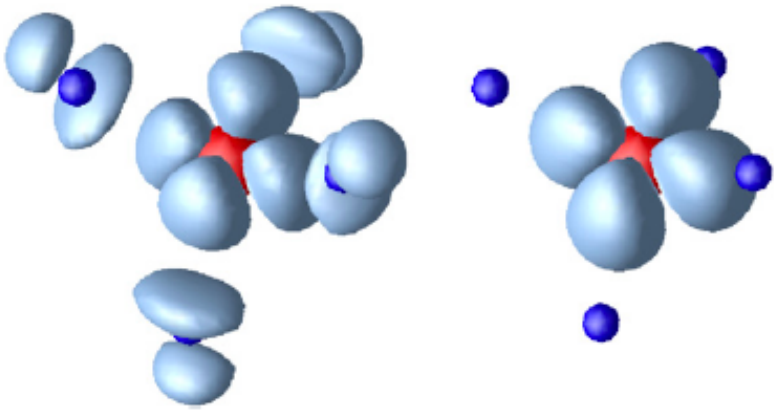


Table 1. The constrained DFT calculated values of average Coulomb interaction $\bar{U}$ and Hund's exchange J (eV) parameters for d-symmetry Wannier functions computed with two different sets of bands and orbitals.

DFT method	Restricted to Fe-3d bands	Full bands set
TB-LMTO-ASA	$\bar{U} = 0.49$, $J = 0.51$	$\bar{U} = 3.10$, $J = 0.81$
PWSCF	$\bar{U} = 0.59$, $J = 0.53$	$\bar{U} = 4.00$, $J = 1.02$

extended (left panel). It has a significant weight on neighboring

Anisomov *et al.*, JPCM 21, 075602 (2009)

Is $LaFeAsO_{1-x}F_x$ an Electron-Phonon Superconductor?

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[1]*Max-Planck-Institut für Festkörperforschung, Heisenbergstraße 1, D-70569 Stuttgart, Germany*
[2]*Faculty of Science and Technology and MESA+ Institute for Nanotechnology, University of Twente, 7500 AE Enschede, The Netherlands*

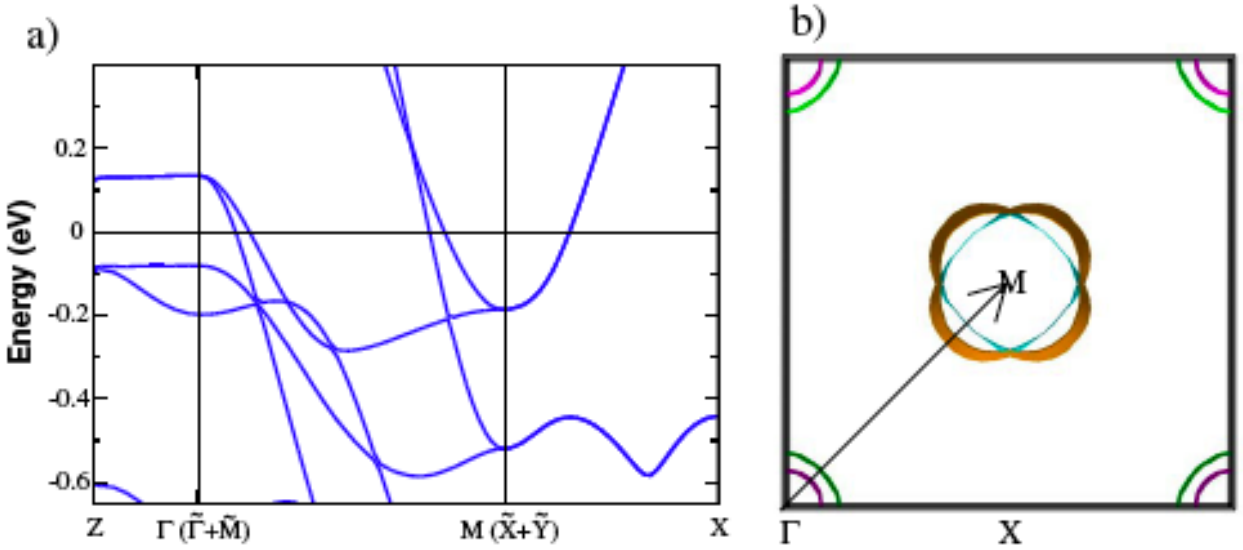
(Received 18 March 2008; published 8 July 2008)

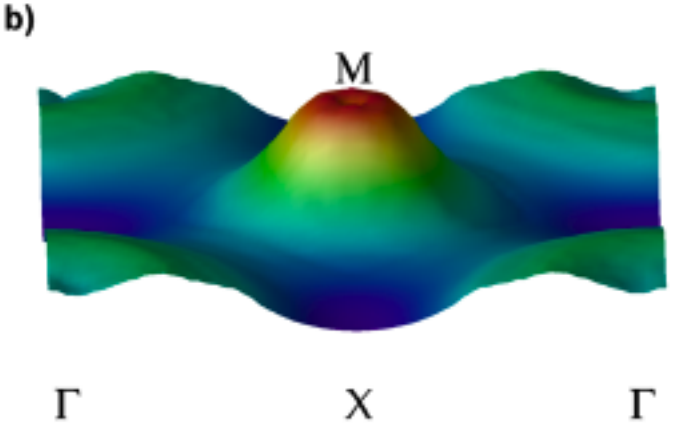
In this Letter, we calculate the electron-phonon coupling of the newly discovered superconductor $LaFeAsO_{1-x}F_x$ using linear response. For pure LaFeAsO, the calculated electron-phonon coupling constant $\lambda = 0.21$ and logarithmic-averaged frequency $\omega_{\ln} = 206$ K give a maximum T_c of 0.8 K, using the standard Migdal-Eliashberg theory. For the F-doped compounds, we predict even smaller coupling constants. To reproduce the experimental T_c, a 5–6 times larger coupling constant would be needed. Our results indicate that electron-phonon coupling is not sufficient to explain superconductivity in the whole family of Fe-As-based superconductors, probably due to the importance of strong-correlation effects.

PRL 101, 026403 (2008)

Unconventional Superconductivity with a Sign Reversal in the Order Parameter of $LaFeAsO_{1-x}F_x$

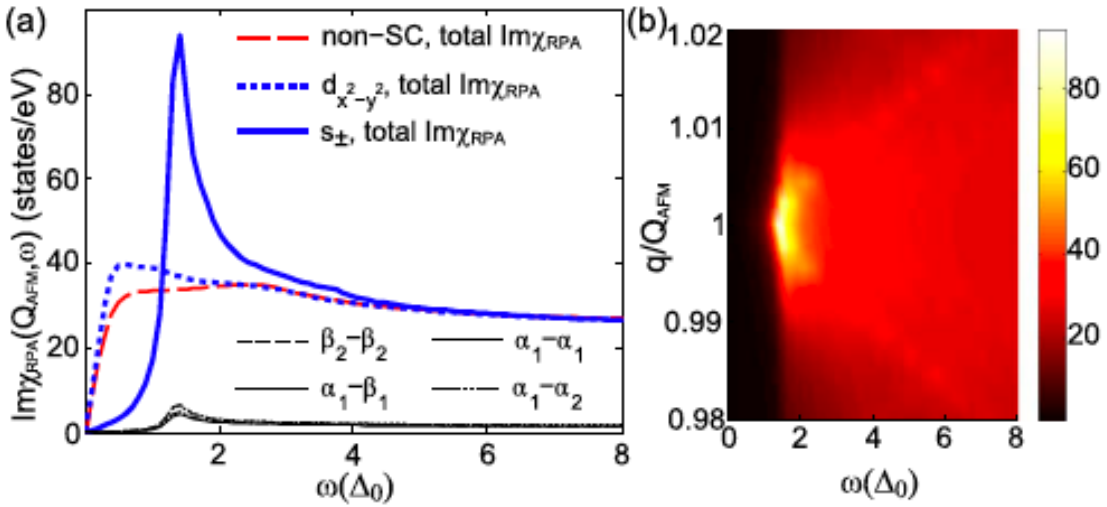
I. I. Mazin,[1] D. J. Singh,[2] M. D. Johannes,[1] and M. H. Du[2]





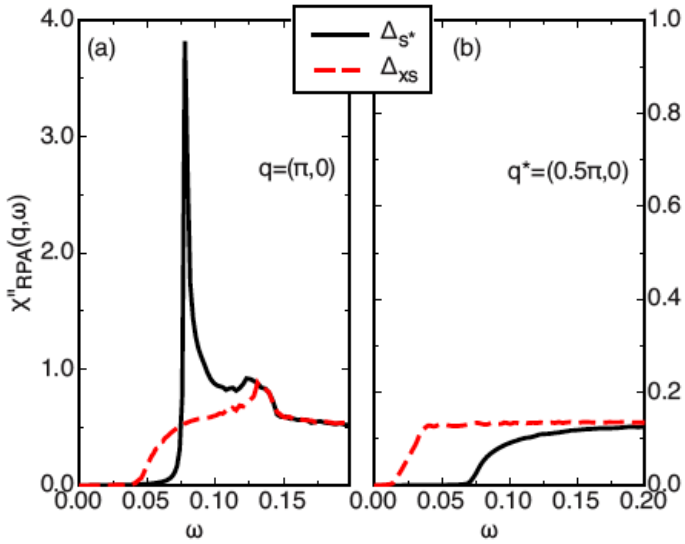
PRL 101, 057003 (2008)

Spin resonance for $s_{\pm}$ state



Korshunov and Eremin
PRB 78, 140509 (2008)

Maier and Scalapino
PRB 78, 020514 (2008)



Dirty $s_{\pm}$ state?

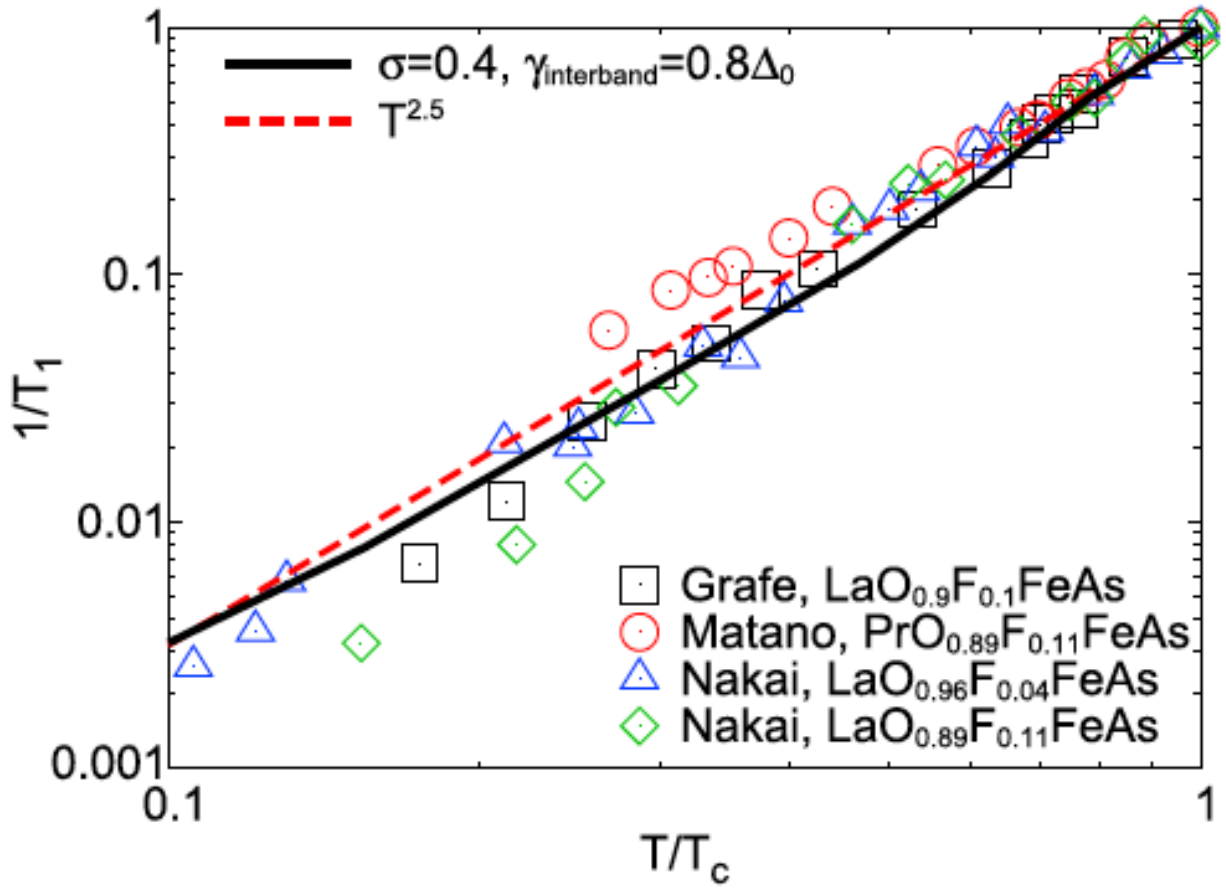
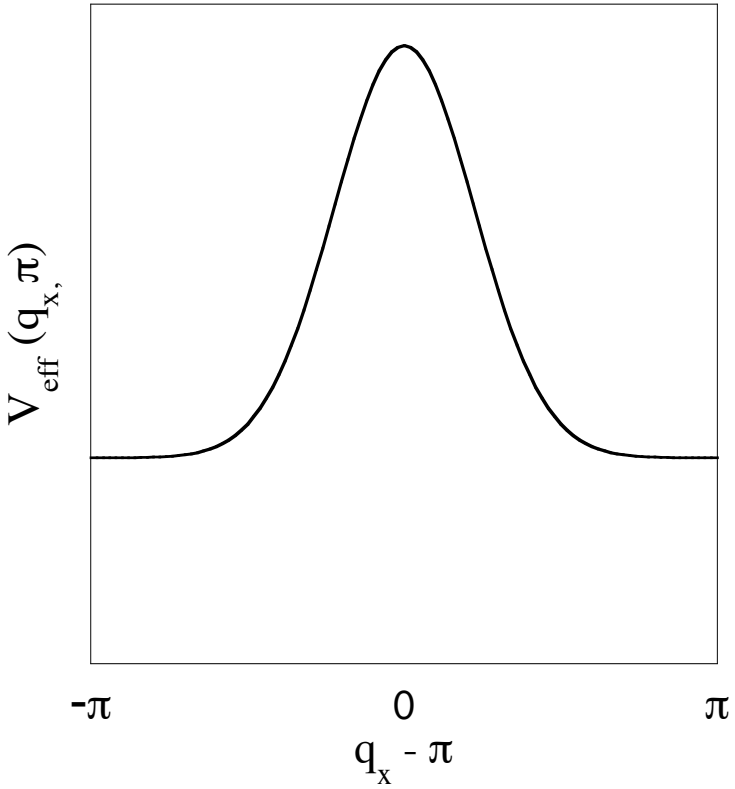


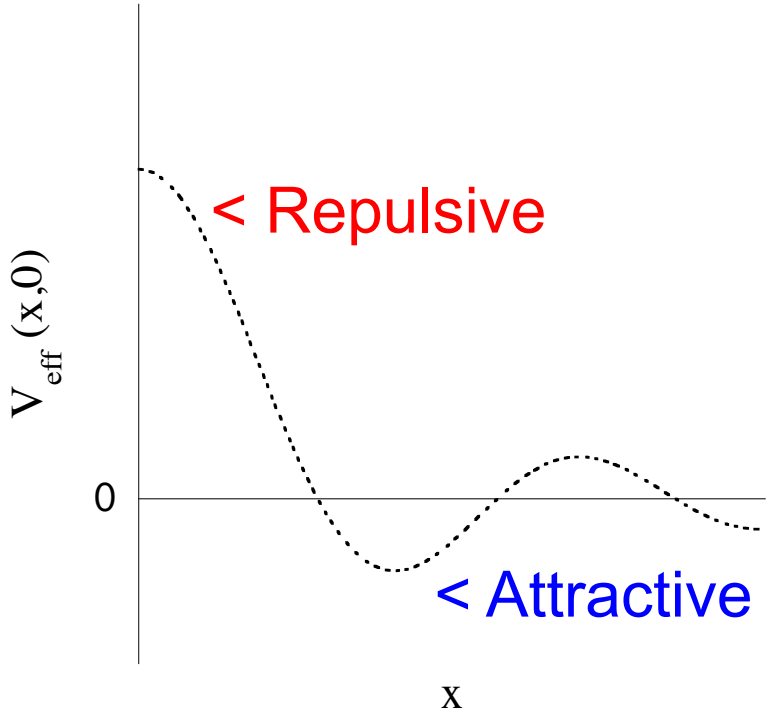
FIG. 4. (Color online) Calculated spin-lattice relaxation rate for the $s_{\pm}$ superconducting state together with experimental $1/T_1$ data from several groups, as indicated. $T^{2.5}$ trend is also shown.

Parker *et al.*, PRB 78, 134524 (2008)

Antiferromagnetic spin fluctuations can lead to pairing (an e^- with up spin wants its neighbors to have down spins)

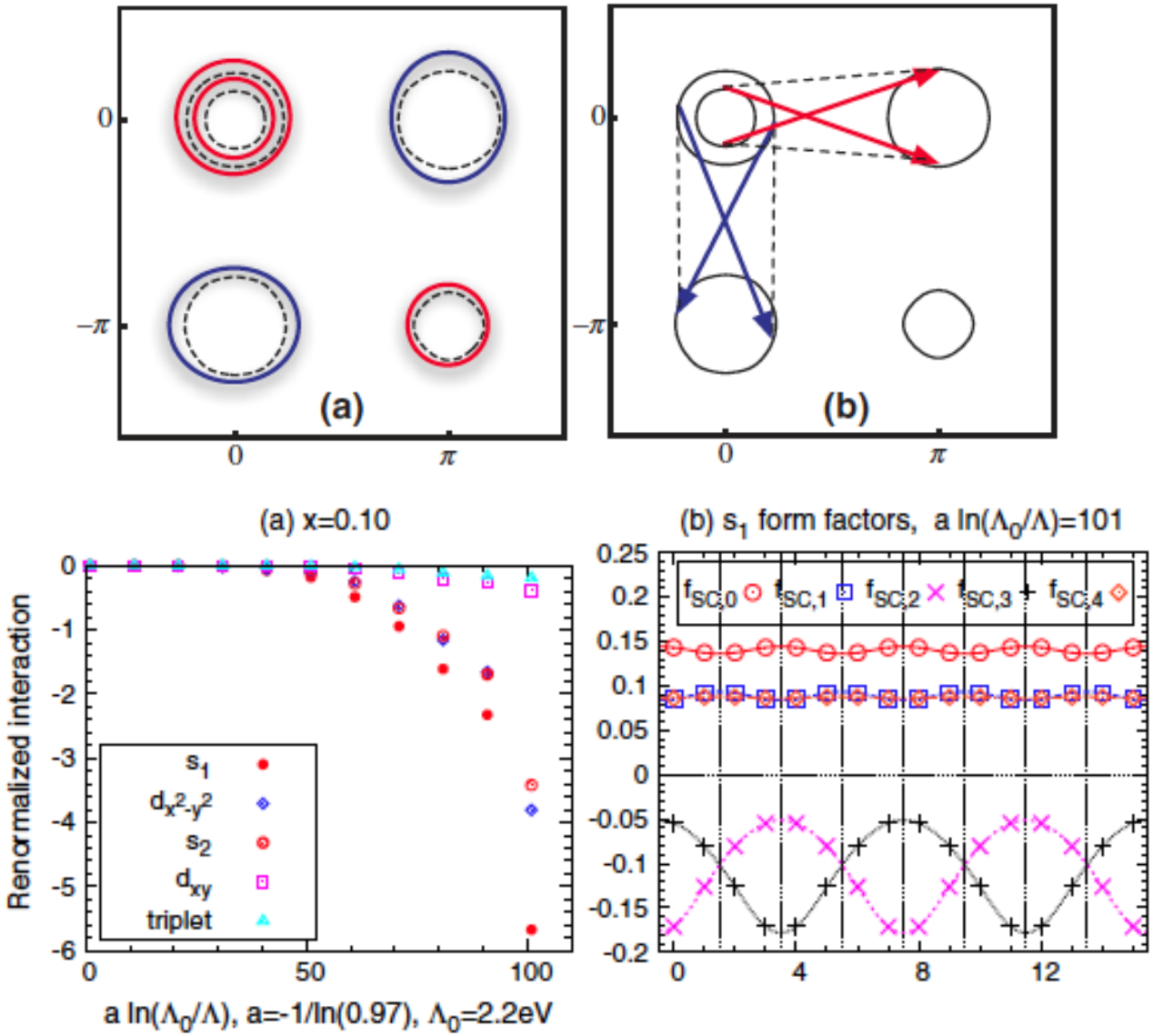
Heavy Fermions - Varma (1986), Scalapino (1986)
High T_c - Scalapino (1987), Pines (1991)





single band - d-wave
two band - $s_{\pm}$

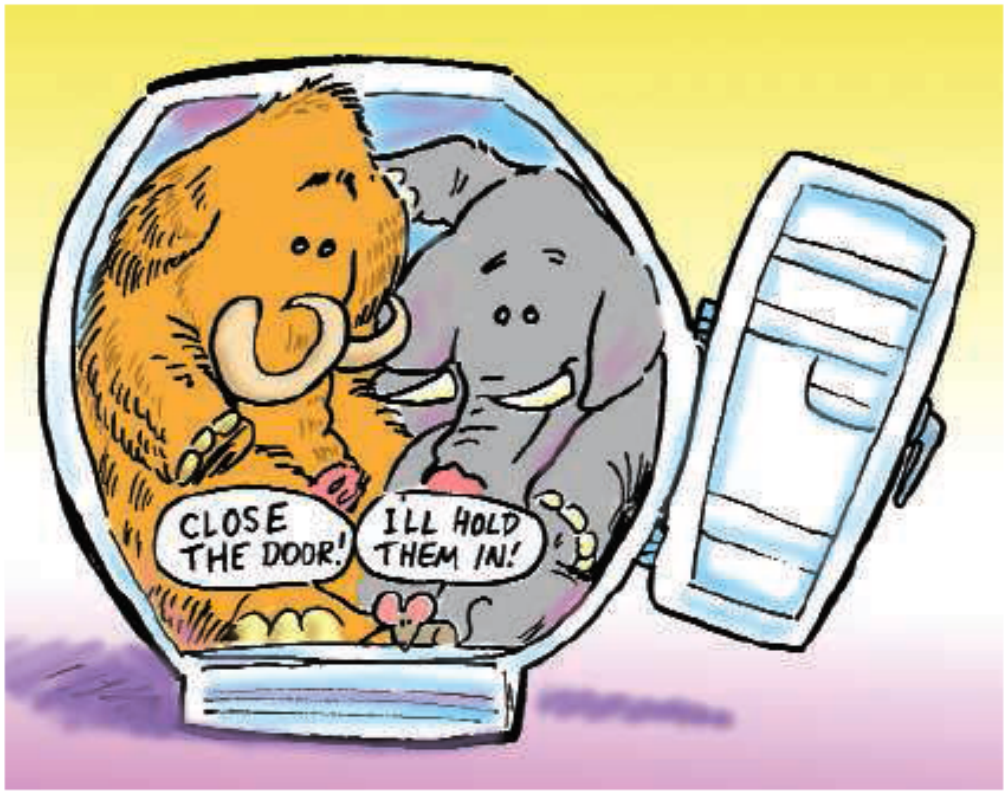
Functional RG, etc., show $s_{\pm}$ state to be the preferred solution



Wang *et al.*, PRL 102, 047005 (2009)

Is There Glue in Cuprate Superconductors?

Philip W. Anderson

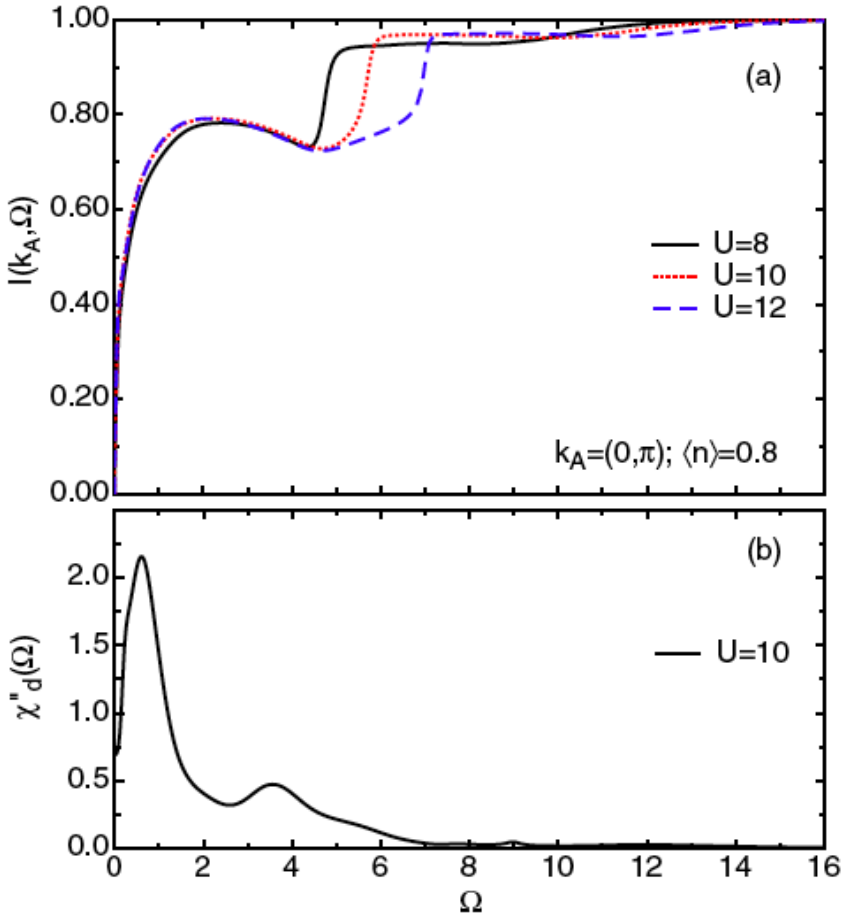


"We have a mammoth and an elephant in our refrigerator—do we care much if there is also a mouse?"

Science 317, 705 (2007)

Dynamics of the Pairing Interaction in the Hubbard and *t*-*J* Models of High-Temperature Superconductors

T. A. Maier,[1,*] D. Poilblanc,[2,†] and D. J. Scalapino[3,‡]



PRL 100, 237001 (2008)

So

The real question
(according to some!)
is not

Are the Pnictides like the Cuprates?

but rather

Are the Cuprates like the Pnictides?

Ironing Out Consensus on the Iron-Based Superconductors

Adrian Cho
Science 327, 1320 (2010)

"Here we are at 2 years and you're asking, 'Are we there yet, Daddy?' Come on!" (Paul Canfield)

"The system could be on the verge of the Mott [insulator] transition." (Qimiao Si)

"The problem has a chance to be solved, and it's a matter of refining existing theoretical tools" (Andrey Chubukov)

"The parent compound is not a metallic vegetable." (Seamus Davis)

"If you're interaction has the wrong sign you can reverse it by making your order parameters have opposite signs. It's a little bit mathematical." (Igor Mazin)

"To take [them] as giving you information about the cuprates is to try to reconstruct the human figure from a cubist painting." (Phil Anderson)

"The iron-based superconductors liberate us from the belief that the Mott physics is essential for high-temperature superconductivity, which is what has kept us stuck for such a long time." (Dung-Hai Lee)