# Introduction to Iron-Based Superconductors

David J. Singh
Oak Ridge National Laboratory

**Co-workers (Theory):**

M.H. Du (ORNL)
A. Subedi (ORNL)
L. Zhang (ORNL)
H. Takenaka (ORNL)
I.I. Mazin (NRL)
M.D. Johannes (NRL)

**Collaborations/Discussion:**

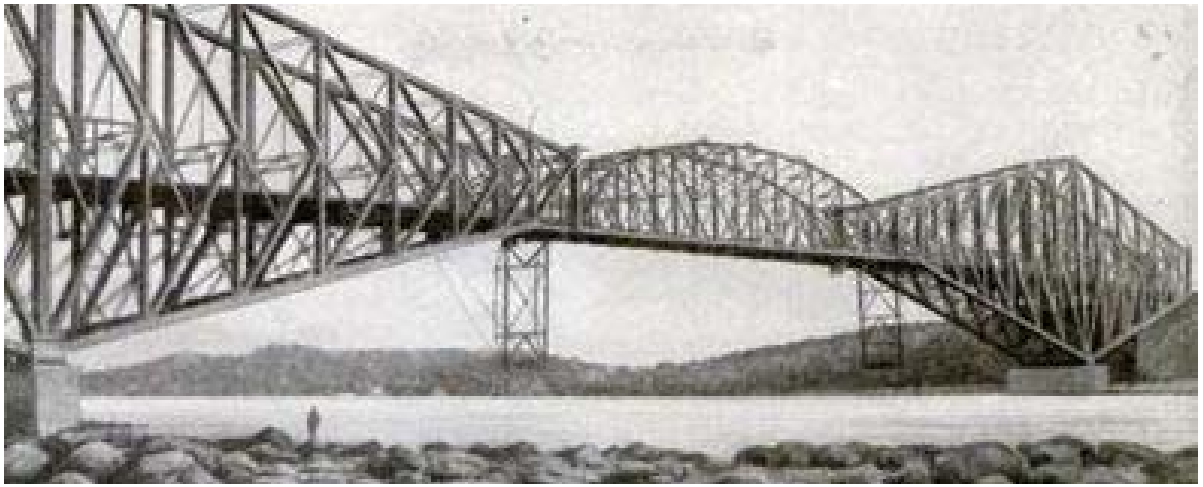
B.C. Sales, D. Mandrus,
A.S. Sefat, M. McGuire (ORNL)
Z.X. Shen, M. Yi, D. Lu (Stanford)
N. Mannella, T. Egami (U.T.)

Supported by DOE, Division of Materials Sciences and Engineering.

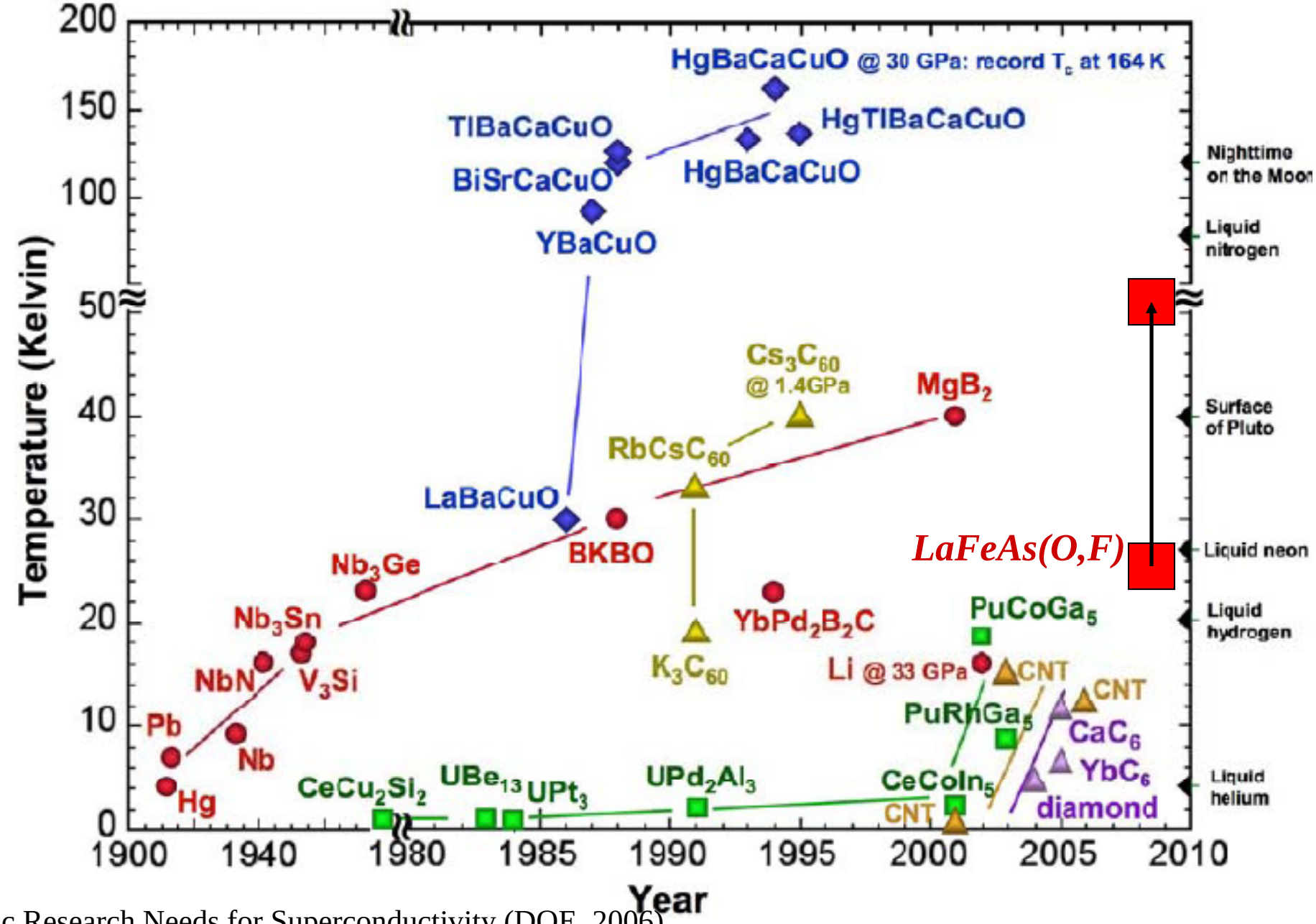
August 5, 2009

# Iron

The Iron Ring: Traditionally given to Canadian engineering graduates and worn by professional engineers.

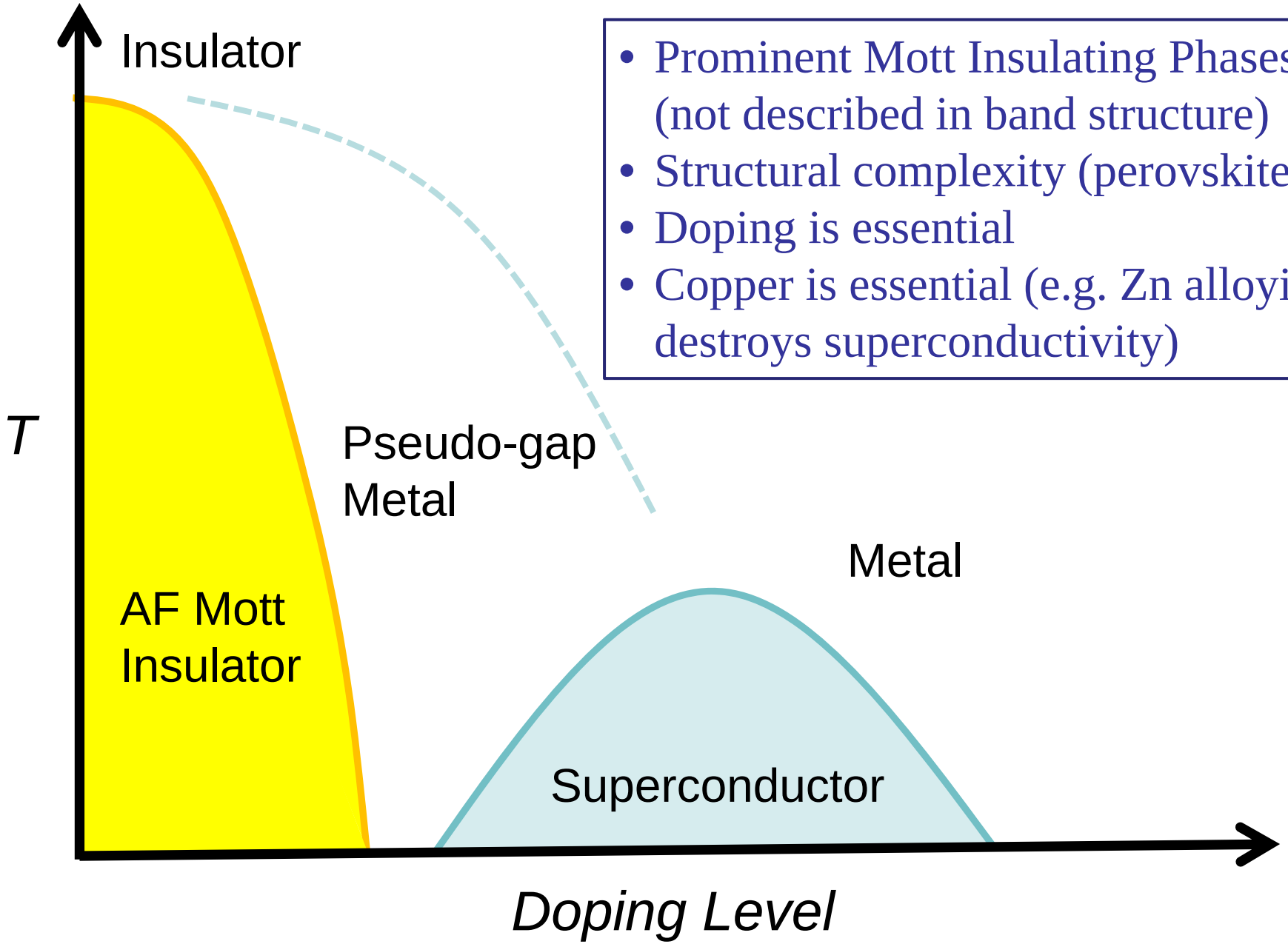


# Materials




Basic Research Needs for Superconductivity (DOE, 2006)

# A Brief Introduction to Cuprates




- Prominent Mott Insulating Phases (not described in band structure)
- Structural complexity (perovskite)
- Doping is essential
- Copper is essential (e.g. Zn alloying destroys superconductivity)

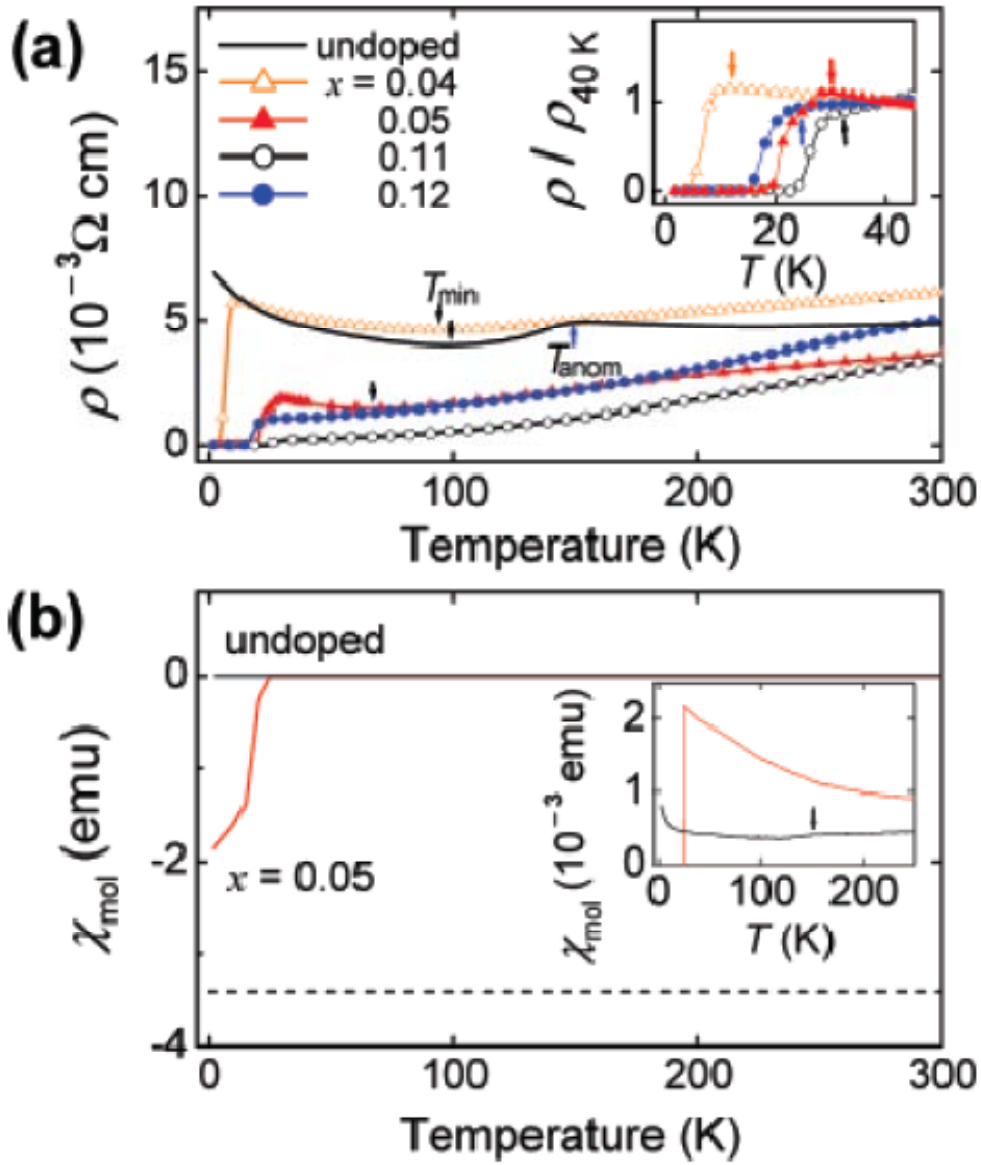
# Discovery of Superconductivity in Fe-As Compounds

Kamihara *et al.*, JACS, 2006

LaFePO, $T_c$ ~ 4K

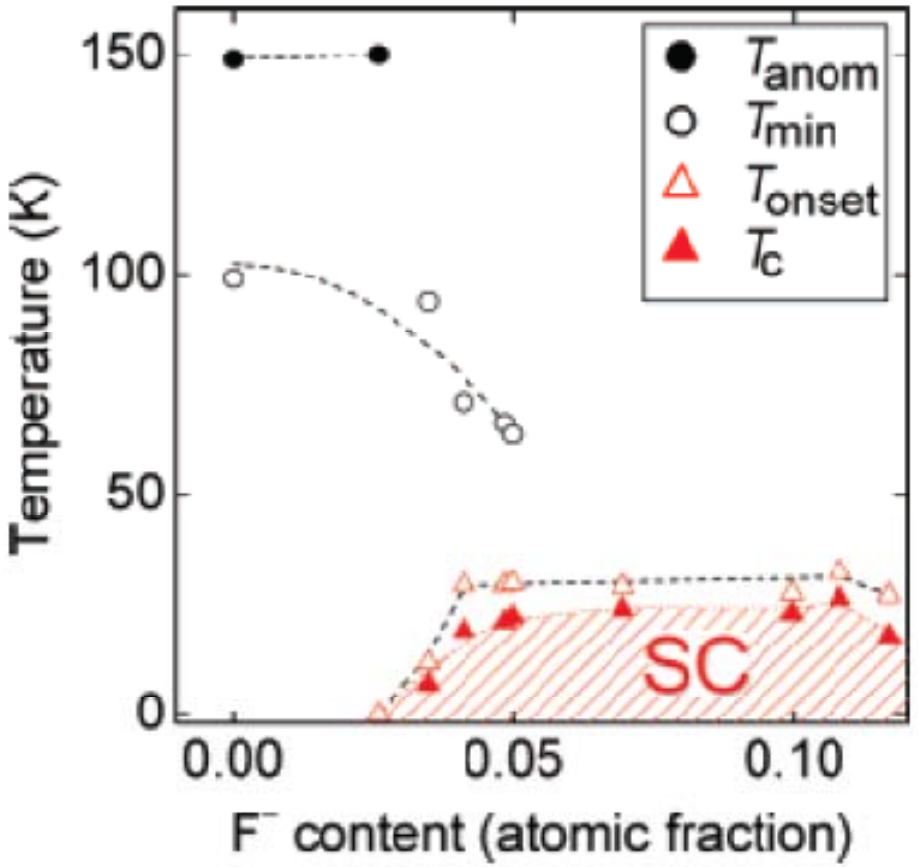
Kamihara, Watanabe and Hosono, JACS, Feb. 2008

$LaFeAsO_{1-x}F_x$ $T_c$=26K



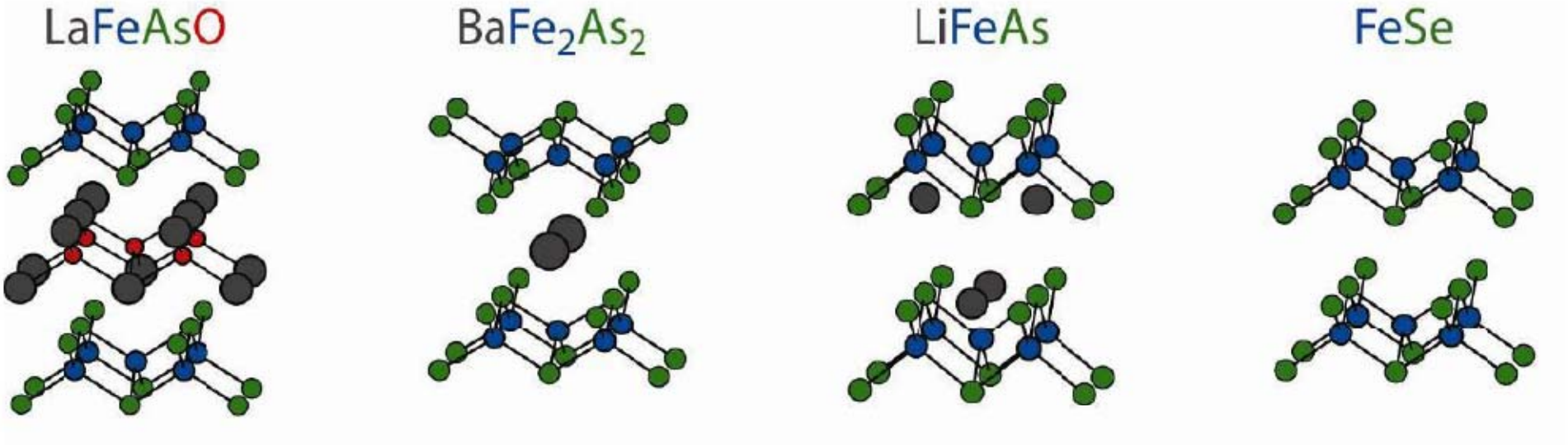
# Phase Diagram of LaFeAs(O,F)

Kamihara *et al.*




The undoped compound is now known to be an antiferromagnetic metal.

# Fe-based Superconducting Families

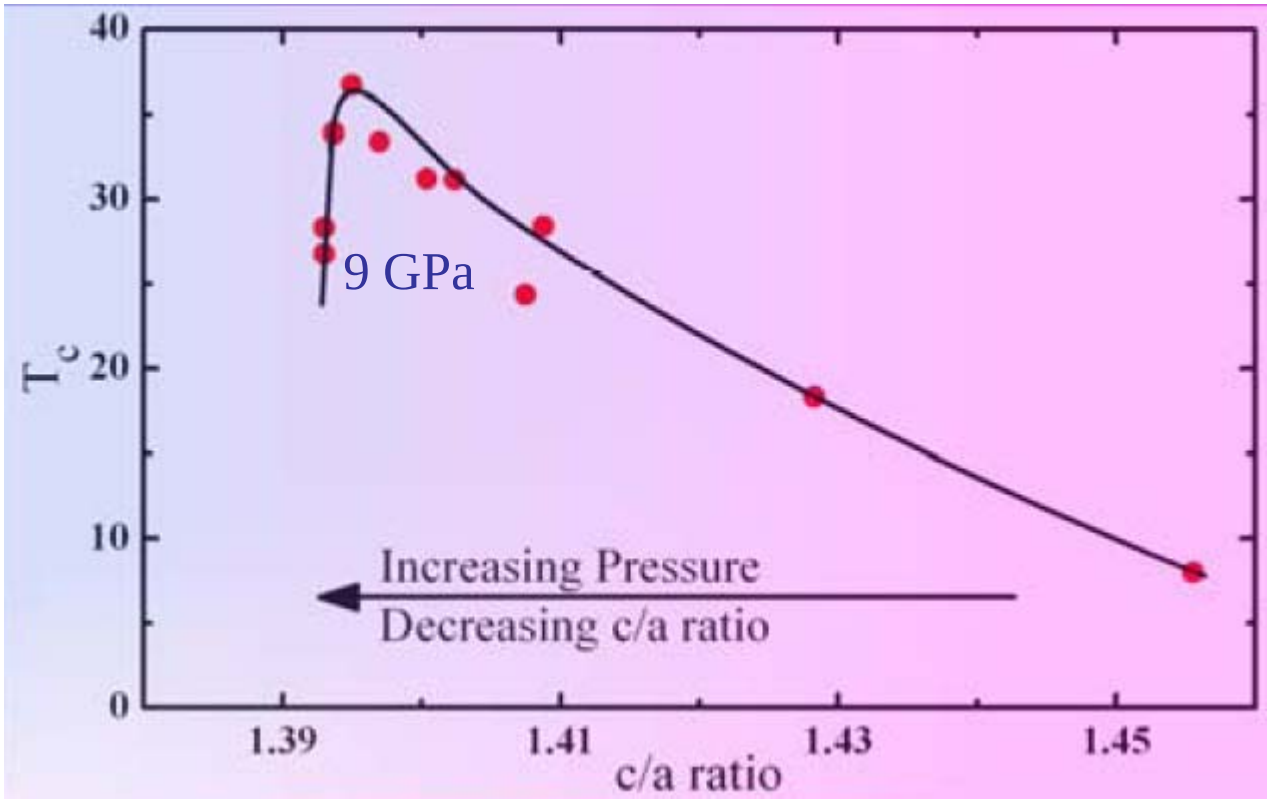



| $ZrSiCuAs$ | $ThCr_2Si_2$ | LiMnAs | PbO |
|---|---|---|---|
| *P4/nmm* | *I4/mmm* | *P4/nmm* | *P4/nmm* |
| ~55K | ~40K | ~20K | ~40K |

Superconductivity is robust. Occurs across a broad range of compositions, including replacement of As, and doping on the Fe site.

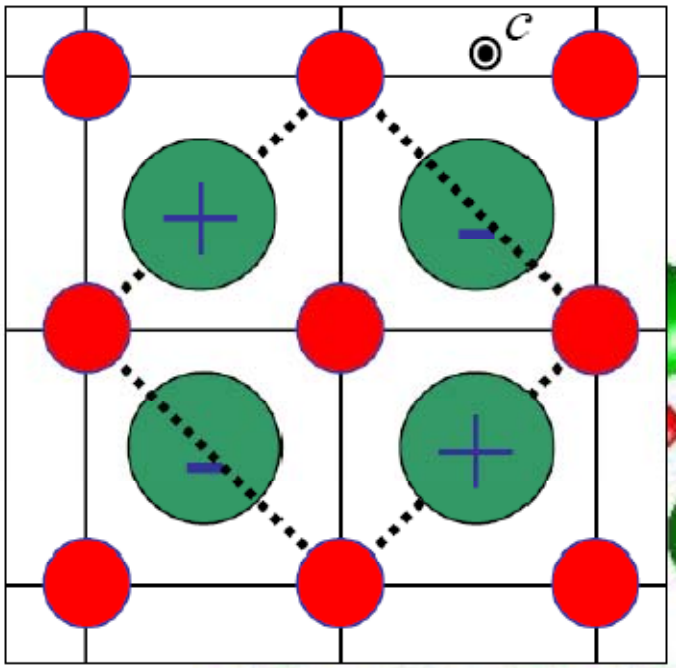
# Pressure Dependence in $Fe_{1+x}Se$

S. Medvedev et al. (cond-mat, 2009).



# FeSe - The “Simplest” Fe-Superconductor

- Simple tetragonal structure, four atoms per unit cell (Hagg and Kindstrom, Z. Phys. Chem. (1933).
  - Actual material is $Fe_{1+x}Se$, with extra Fe in holes of Se lattice.
  - LiFeAs is similar, but extra sites are filled with Li.



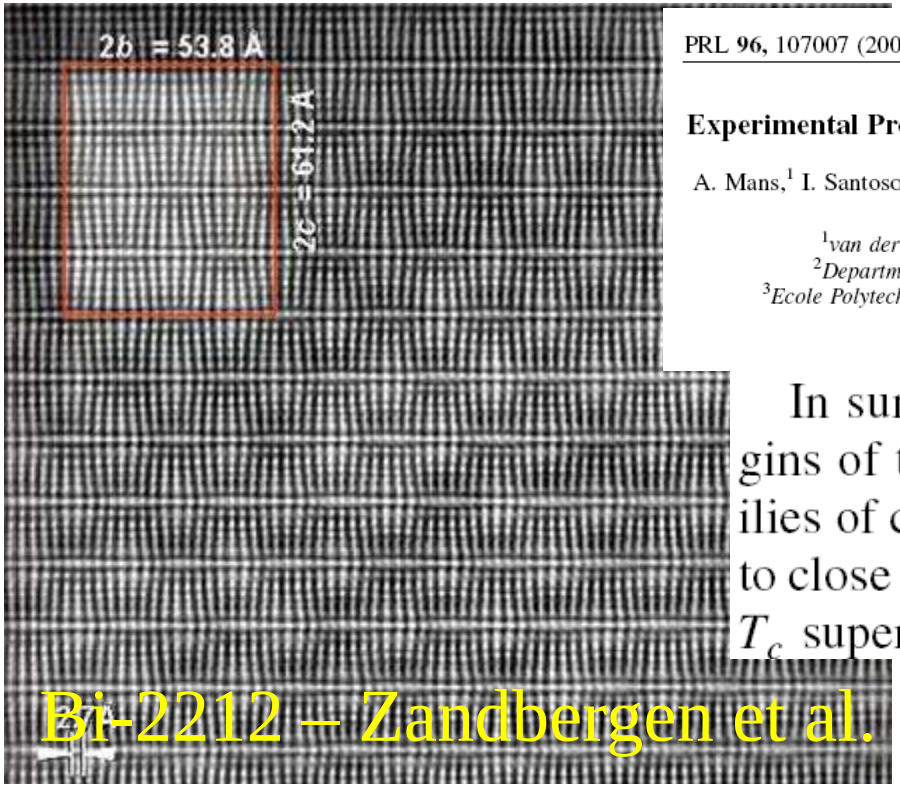




$d_{Fe\text{-}Fe}$= 2.66 Å

# A Word About Structure

- Large size of $As^{3-}$,$Se^{2-}$ relative to $Fe^{2+}$ leads to tetrahedral structures with anion contact (edge shared tetrahedra). Tendency to high symmetry, small unit cells without structural distortion.
- Cuprates, etc. are based on corner shared units, with resulting tendency to complex structure distortions. The interplay with properties greatly complicates the physics.




PRL 96, 107007 (2006) PHYSICAL REVIEW LETTERS week ending 17 MARCH 2006

**Experimental Proof of a Structural Origin for the Shadow Fermi Surface of $Bi_2Sr_2CaCu_2O_{8+\delta}$**

A. Mans,[1] I. Santoso,[1] Y. Huang,[1] W. K. Siu,[1] S. Tavaddod,[1] V. Arpiainen,[2] M. Lindroos,[2] H. Berger,[3] V. N. Strocov,[4] M. Shi,[4] L. Patthey,[4] and M. S. Golden[1]

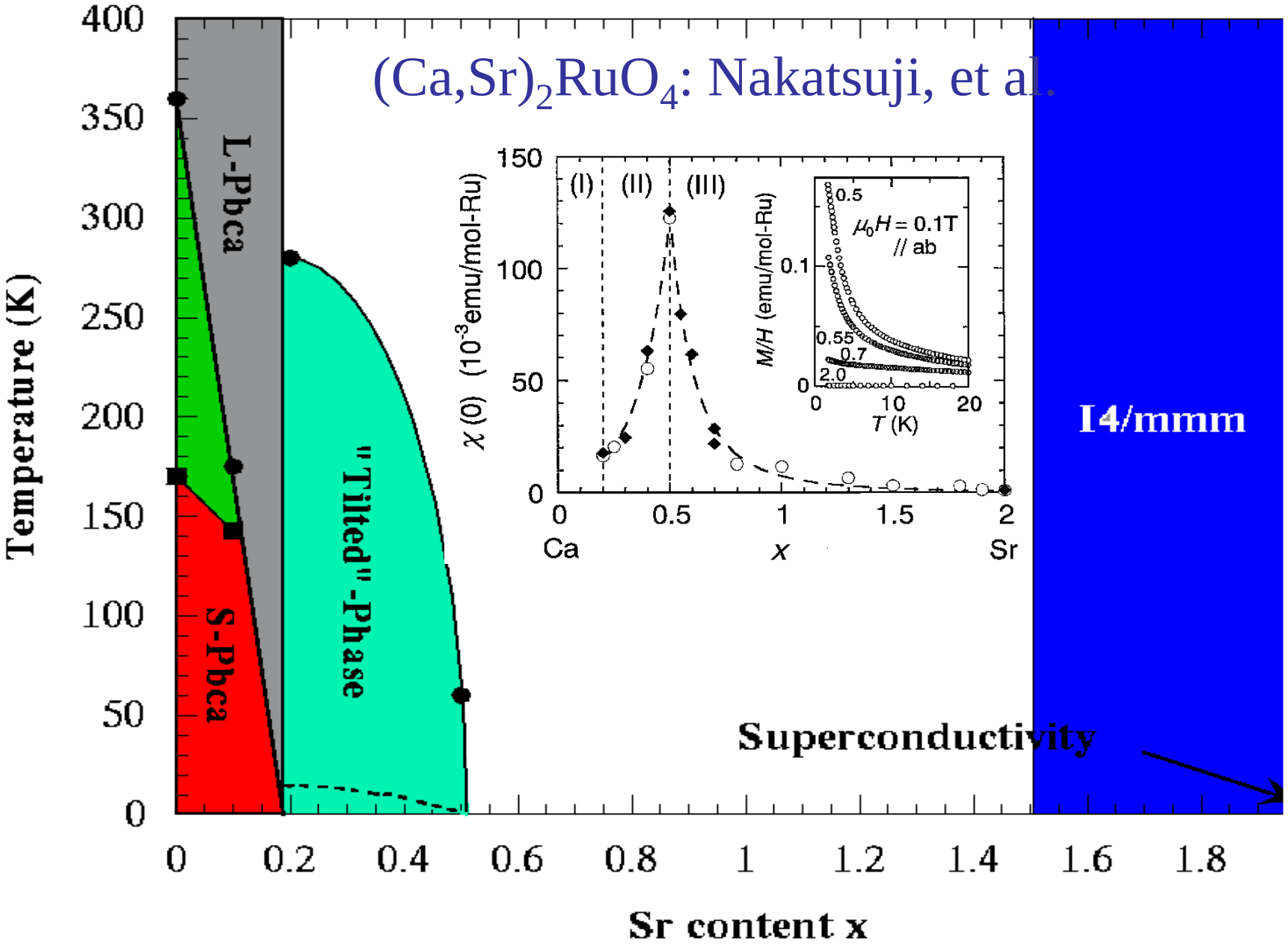
[1]*van der Waals-Zeeman Institute, University of Amsterdam, NL-1018XE Amsterdam, The Netherlands*
[2]*Department of Physics, Tampere University of Technology, PO Box 692, FIN-33101 Tampere, Finland*
[3]*Ecole Polytechnique Fédérale de Lausanne, Institut de Physique de la Matière Complexe EPFL Bt. PH CH-1015*
[4]*Swiss Light Source, Paul Scherrer Institute, CH-5232 Villigen, Switzerland*

(Received 3 August 2005; published 16 March 2006)

In summary, by proving the microscopic structural origins of the shadow bands in the Bi2212 and Bi2201 families of cuprate superconductors, we have finally been able to close this chapter in the rich and complex tale of the high $T_c$ superconductors.

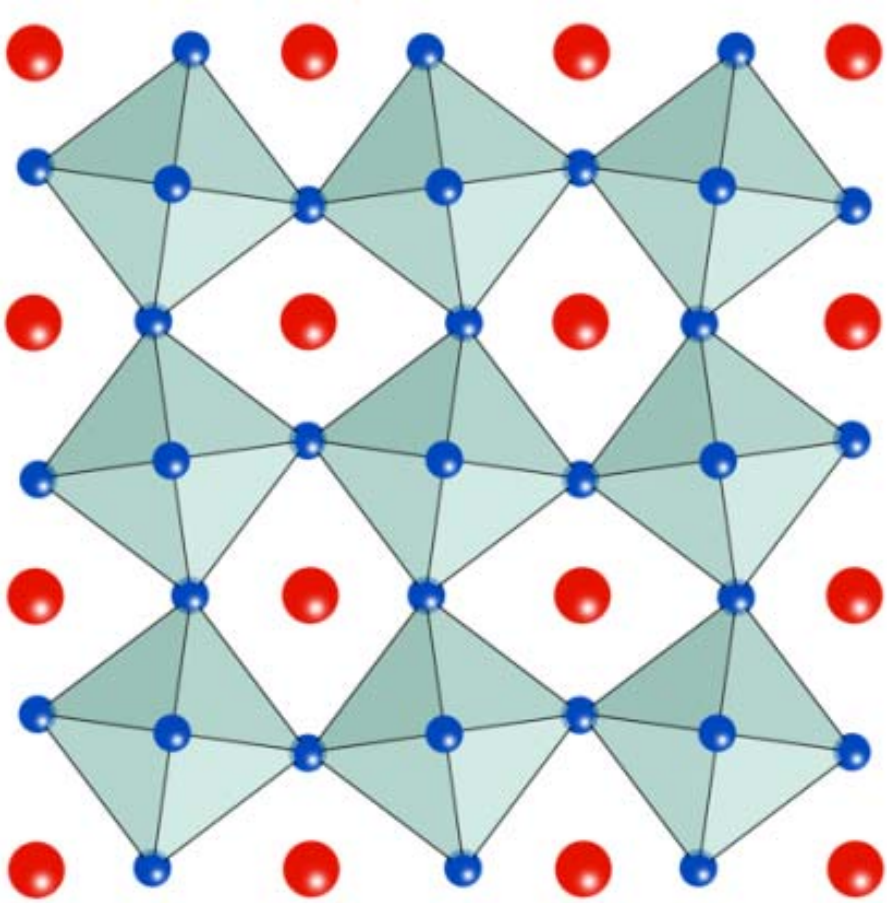
Bi-2212 – Zandbergen et al.

# A Word About Structure



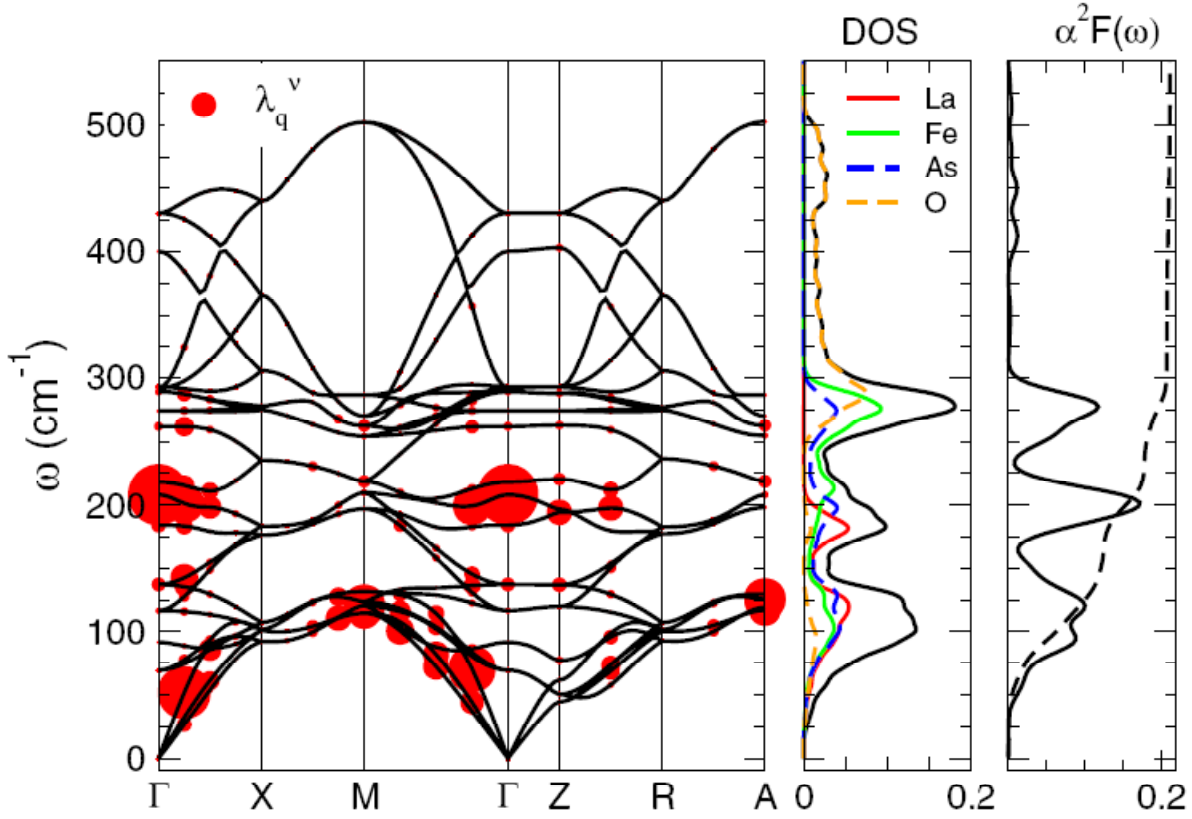
# Perovskite Tilt Modes

- Corner sharing polyhedra with even numbered rings.



# Phonons and Electron-Phonon Interaction

- First principles calculations allow direct calculation of pairing interaction, and almost first principles calculation of $T_c$.
- Calculations show weak coupling, no superconductivity ($\lambda_{ep}$~0.2).

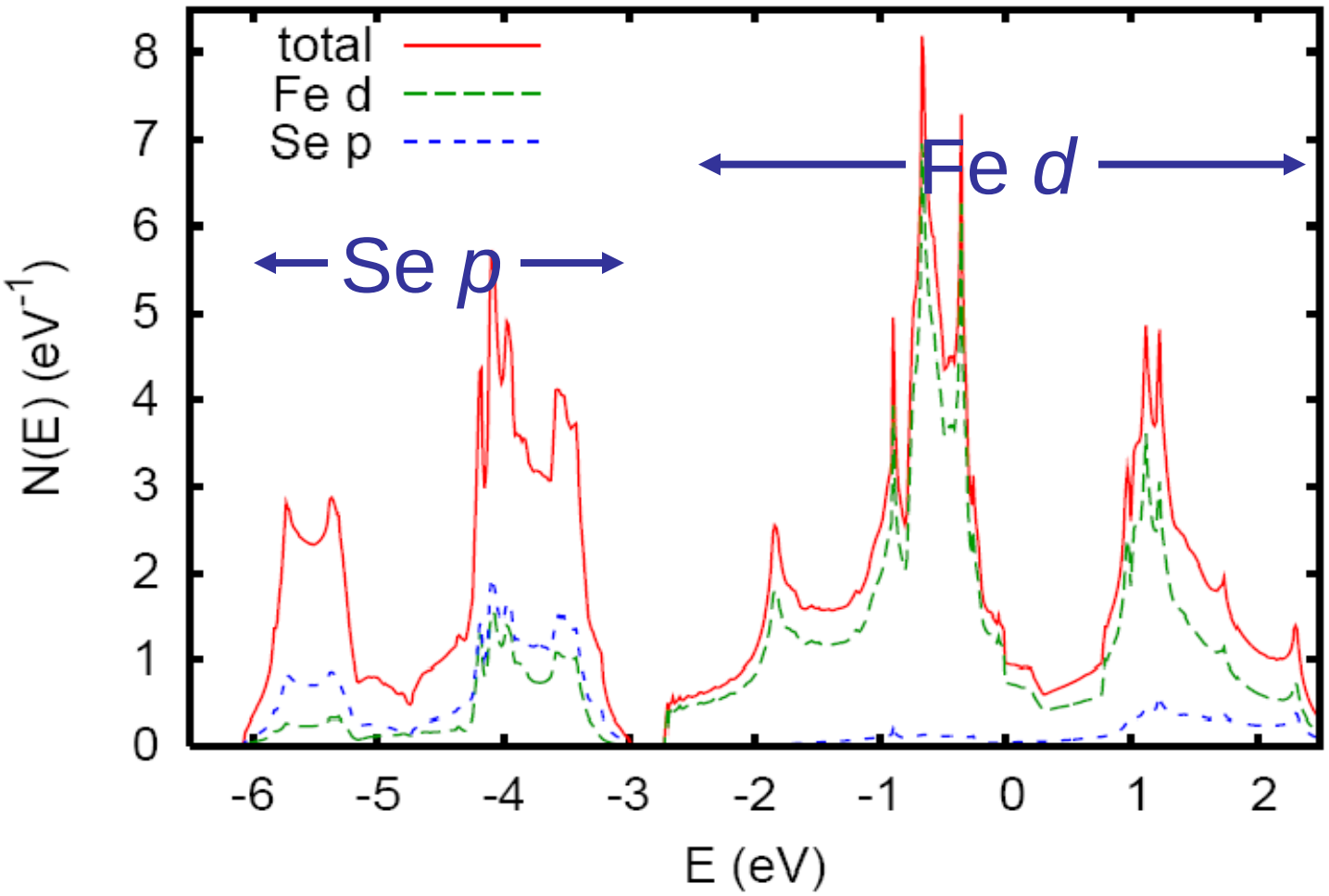



- Fe/As phonons are below 300 $cm^{-1}$.
- Corresponding Ni compounds, LaNiPO, LaNiAsO, $BaNi_2As_2$ ... are electron-phonon superconductors!
- Fe compounds are not electron-phonon superconductors.

Boeri, et al., PRL (2008); also Mazin, et al., PRL (2008).

# LDA Electronic Structure of FeSe

- A rather ionic material – $Fe^{2+}$ and $Se^{2-}$ with some hybridization, as in an oxide ➔ metallic sheets of $Fe^{2+}$ modified by interaction of anions.
- Pauling electronegativities: Fe = 1.83; Se = 2.55; As = 2.18.

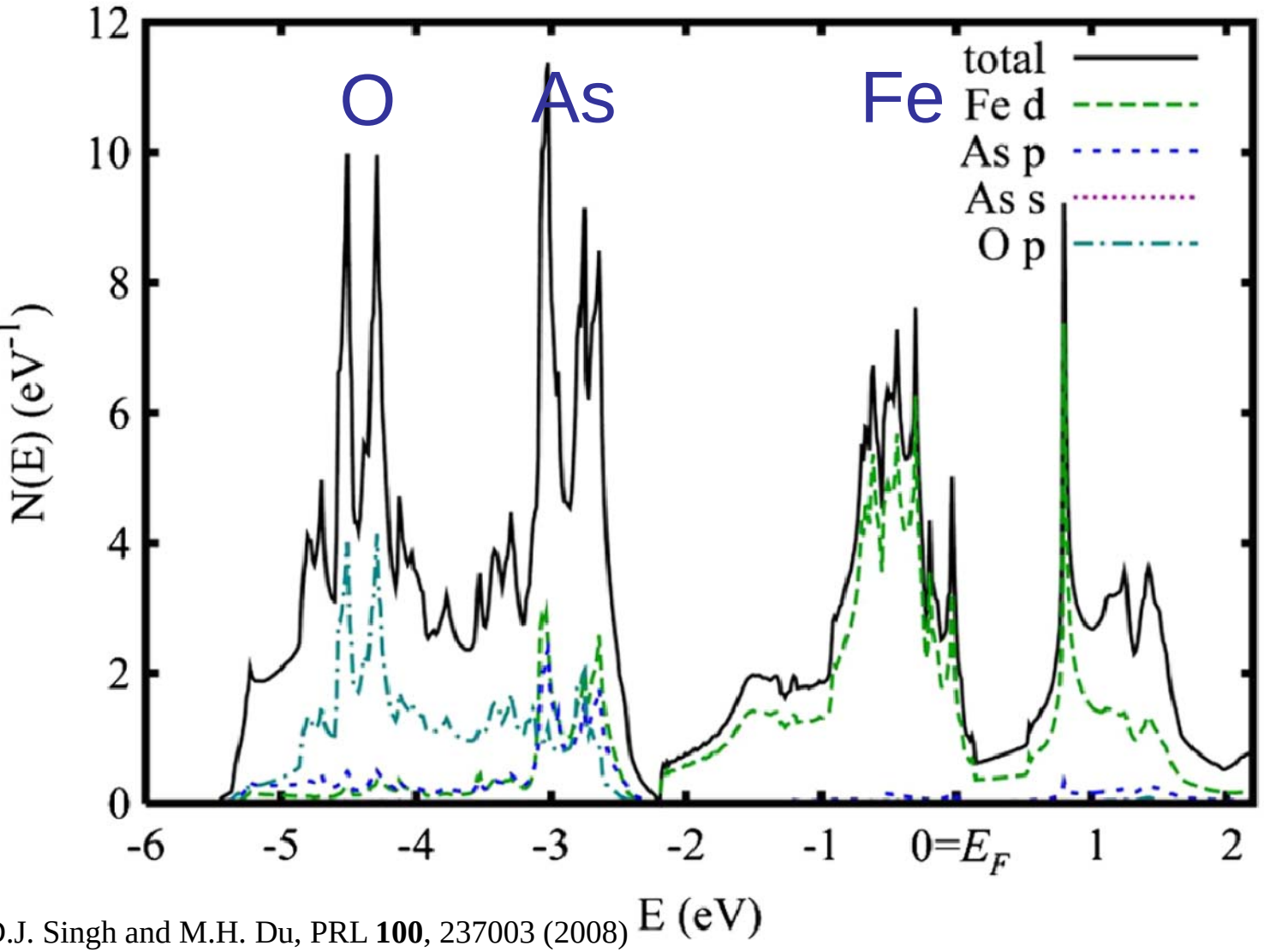



$Fe^{2+}$ ➔ $d^6$

$N(E_F)$ is at bottom of pseudogap.

# Arsenide Electronic Structure: LaFeAsO

- LaFeAsO: Rather ionic electronic structure: $O^{2-}$, $As^{3-}$, $La^{3+}$
- Bands near $E_F$ are derived from Fe with little As admixture




Metallic sheets of $Fe^{2+}$

$E_F$ is at the bottom edge of a pseudogap

High $N(E_F)$ ➔ near magnetism

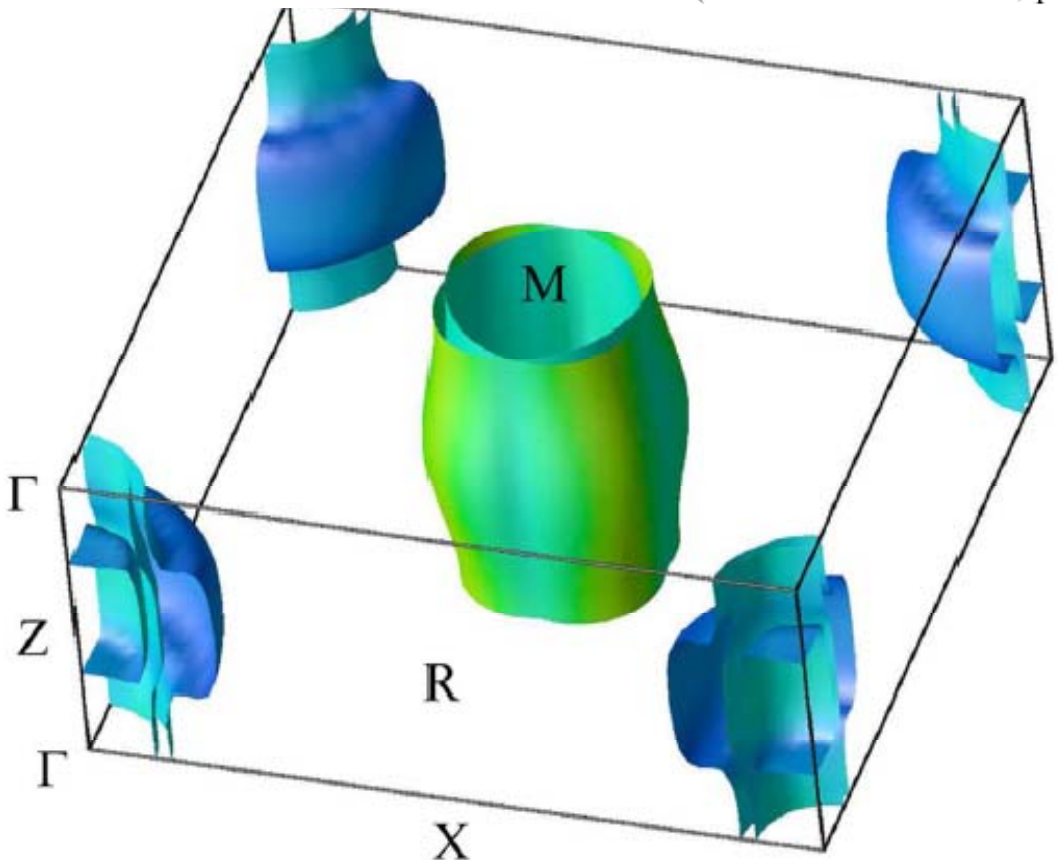
D.J. Singh and M.H. Du, PRL **100**, 237003 (2008)

# Density Functional Study of $LaFeAsO_{1-x}F_x$: A Low Carrier Density Superconductor Near Itinerant Magnetism

D. J. Singh and M.-H. Du

*Materials Science and Technology Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831-6114, USA*

(Received 4 March 2008; published 12 June 2008)




Fermi Surface of LaFeAsO

(not spin polarized)

Low carrier density:
$n_e = n_h = 0.13$ / Fe

Band anisotropy: $\langle v_x^2 \rangle / \langle v_z^2 \rangle \sim 15$ ➔
a modest value that is favorable for applications.

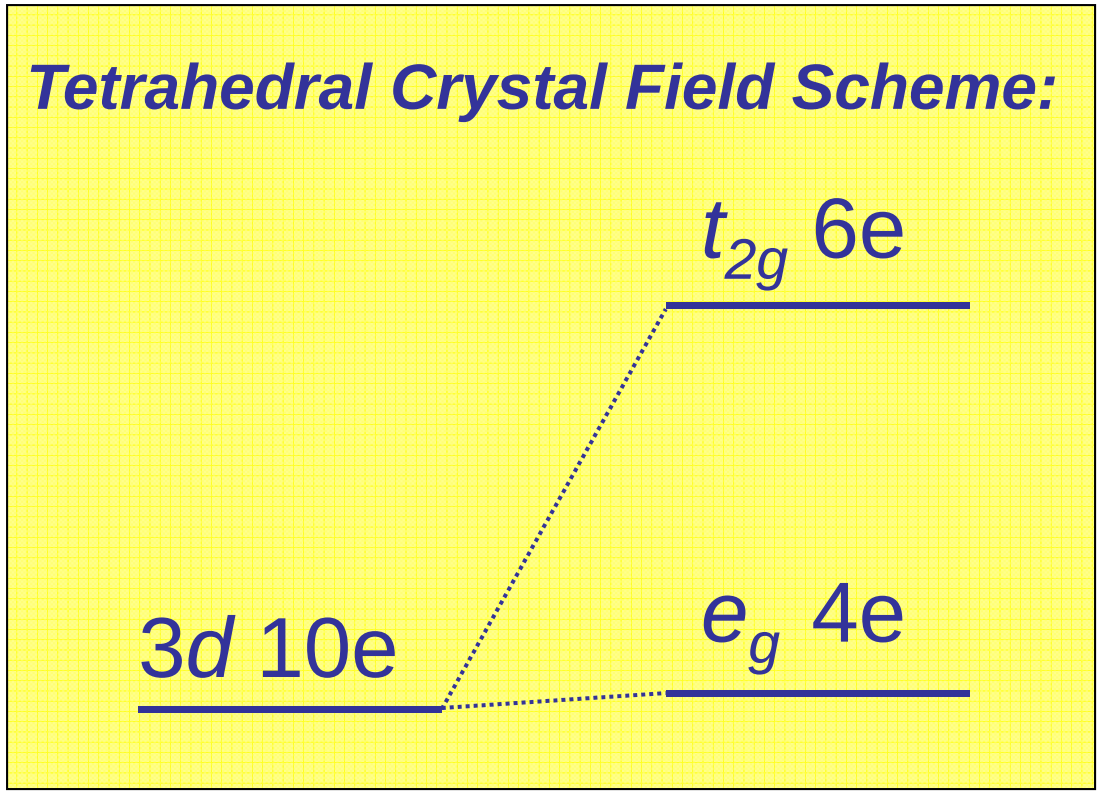
# Normal Metallic State

- Low carrier density semi-metal (dis-connected small Fermi surfaces).
- Less anisotropic than cuprates, even $YBa_2Cu_3O_7$.
- High $N(E_F)$.
  - Near itinerant magnetism in general.
  - Expect short coherence length relative to $T_c$.
  - Expect high superfluid density.
- Electron-Phonon interaction is weak ($\lambda \sim 0.2$, $T_c = 0$)

# Formation of Band Structure

- Bands from -2 eV to +2 eV are derived from $Fe^{2+}$ *d*-states.
- $Fe^{2+}$ has 6 *d*-electrons.

***Tetrahedral Crystal Field Scheme:***

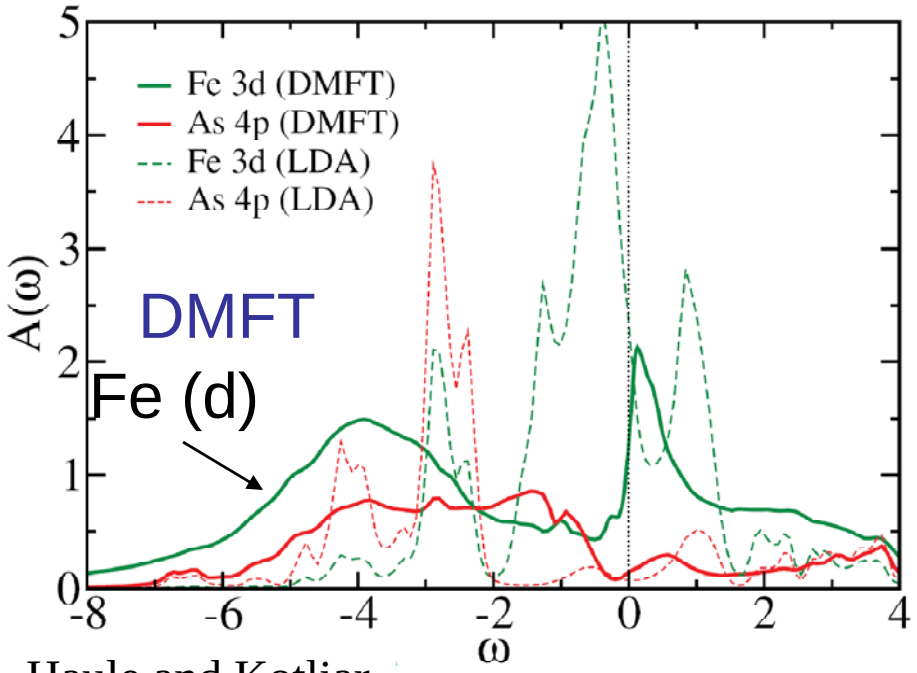



***Does not correspond to the calculated electronic structure.***

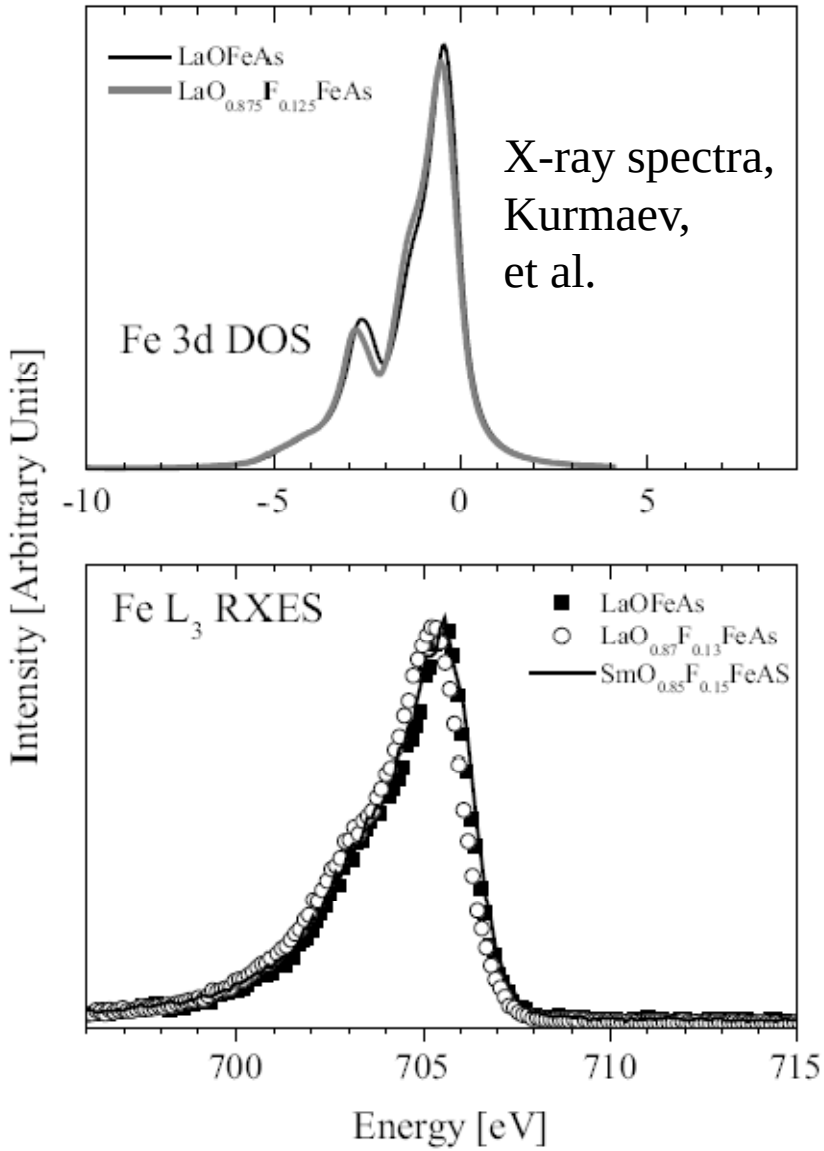
***Key is the short Fe-Fe bond length → direct Fe-Fe interactions.***

# Coulomb Correlations

- LDA and correlated approaches give different predictions.
- So far Hubbard bands are not seen; strong Fe d character is seen at Fermi edge.
- There is however a renormalization of ~2 in band width c.f. LDA.

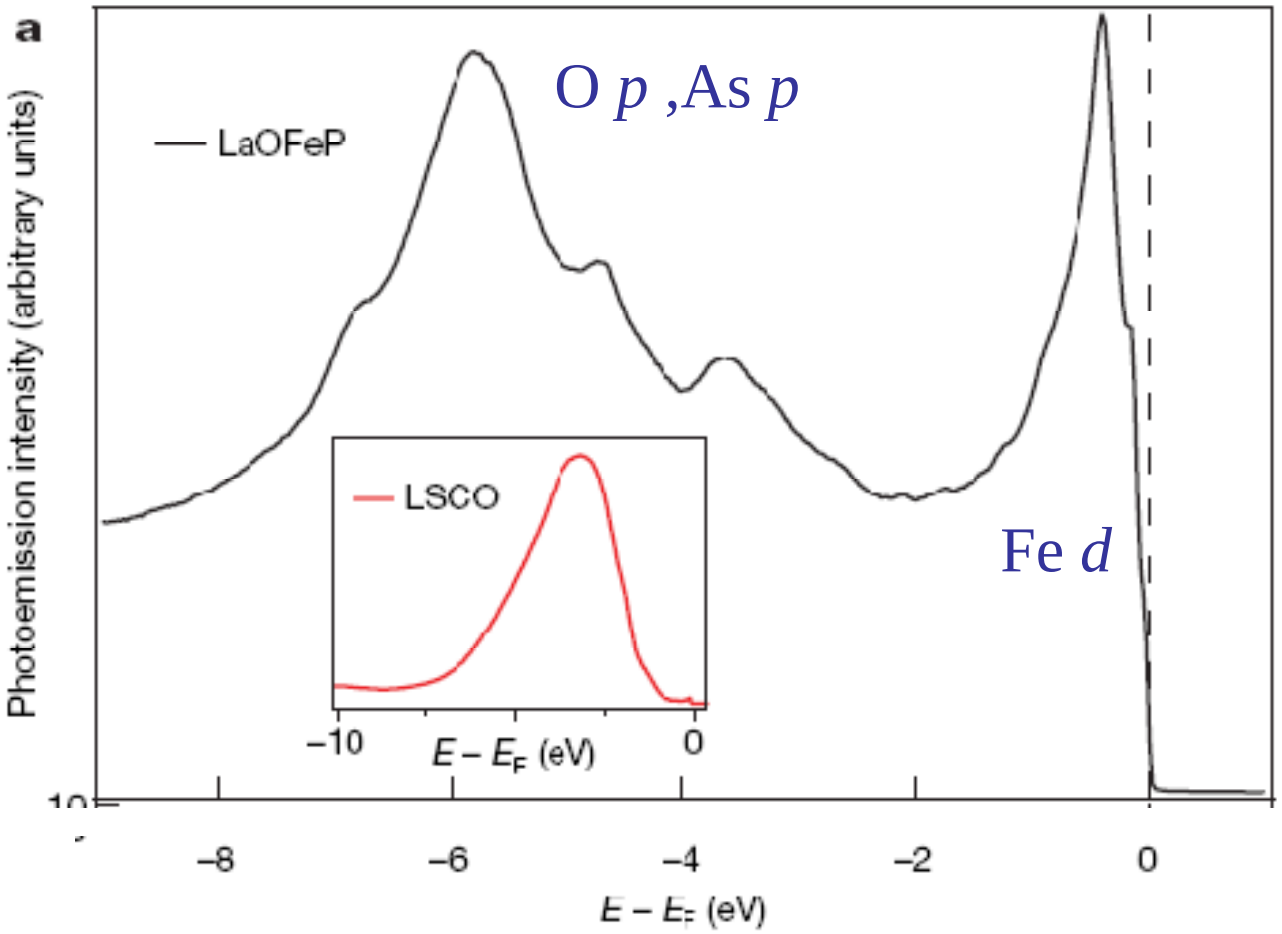



Haule and Kotliar



# Metallic Character

Photoemission: LaFePO (D.H. Lu et al.)



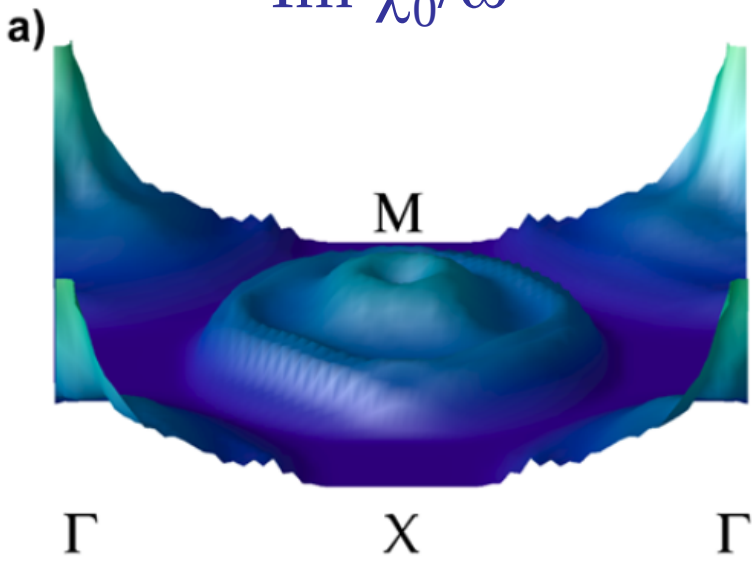

Very prominent Fermi edge (not like cuprates).

Fe d bands are narrower (by ~2) compared to LDA.

# LaFeAs(O,F) Lindhard Function

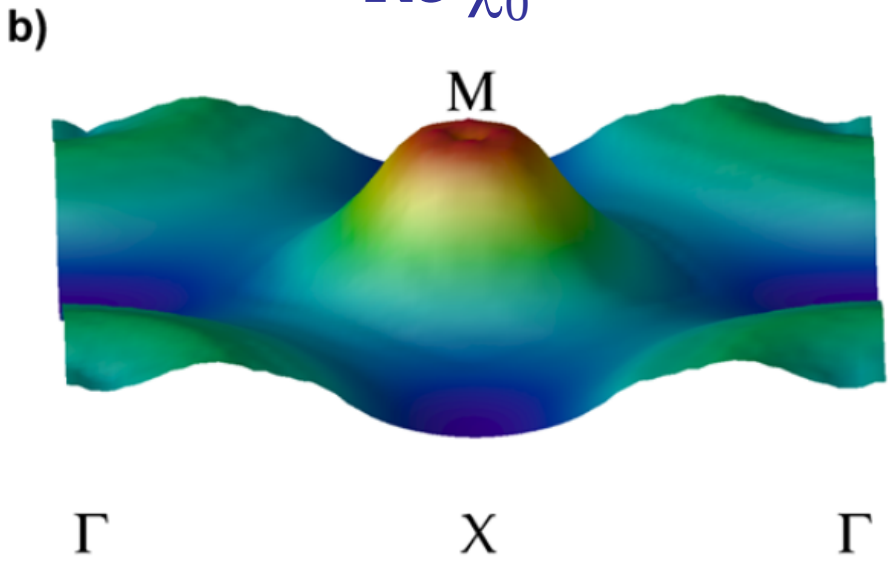
- Neglecting Matrix Elements:

Im $\chi_0/\omega$




Scattering, Transport

Re $\chi_0$




Magnetism, Superconductivity

***Note the pronounced peak at the zone corner.***

I.I. Mazin, D.J. Singh, M.D. Johannes and M.H. Du, PRL **101**, 057003 (2008)

# Spin Fluctuations and Superconductivity

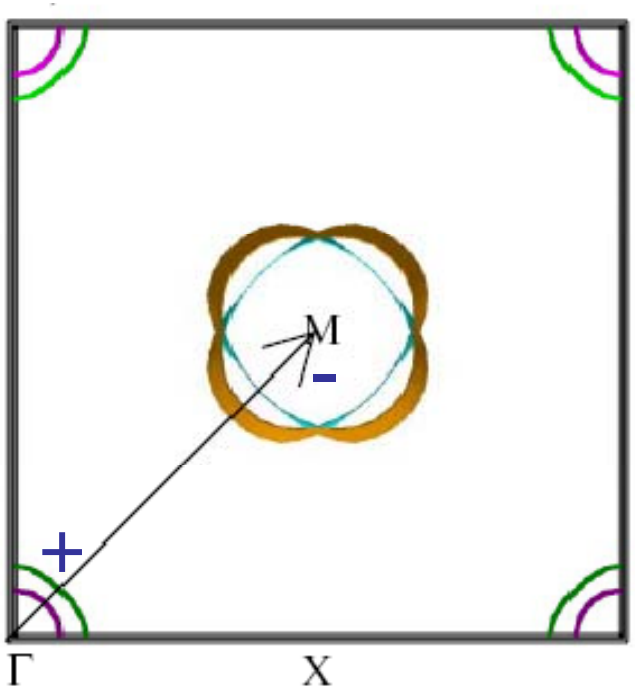
One way to proceed (weak coupling):

- Calculate matrix elements $V_{\mathbf{k},\mathbf{k}'}$, for a set of **k**,**k**' on the FS.
- Set-up gap equation -- diagonalize V.

*Berk-Schrieffer-Fay-Appel weak coupling theory, 1966-1980*:

Singlet:

$$V(\mathbf{q}) = - \frac{I^2(q)\chi_0(\mathbf{q})}{1 - I^2(\mathbf{q})\chi_0^2(\mathbf{q})}$$



Electron doped LaFeAsO

In a singlet channel there is a minus sign for spin fluctuations (repulsive), which then favors opposite order parameters on the electron and hole sheets ➔ s +/- state.

Note prior work, Aronov & Sonin (1972); Kuroki and Arita (2001)

Does not have an obvious strongly q-dependent interaction for nodes in a FS.

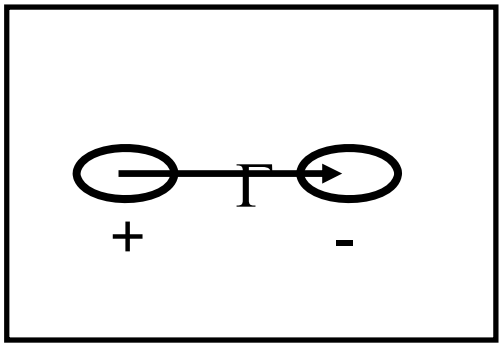
I.I. Mazin, D.J. Singh, M.D. Johannes and M.H. Du, PRL **101**, 057003 (2008)

# Spin Fluctuation Driven $s_{+/-}$ Properties

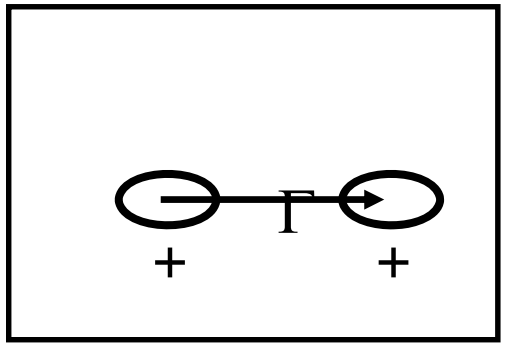
- Two gap.
- SDW and superconductivity are driven by the same interaction and compete for the same electrons.
- Simplest form is nodeless, but this is not essential.
- Robust against low *q* scattering (Co, Ni doping)
- No corner junction shifts (*s*-wave symmetry)
- Coherence factors depend on q. Reduced Hebel-Slichter peak in NMR relaxation rate.
- Resonance peak in neutron scattering.

# Small Fermi Surfaces in General

- Does superconductivity arise in general if one has small Fermi surfaces with nesting driven spin fluctuations? – Answer seems to be no.




*p-wave state (triplet)*: spin-fluctuation pairing interaction has + sign ➔ Pair breaking for the state shown.




*s-wave state (singlet)*: spin-fluctuation pairing interaction has – sign ➔Pair breaking for the state shown.

e.g. small pockets on $Na_xCoO_2$ (Johannes et al., 2004).

In such cases, look for chemistry with strong electron phonon and low Stoner parameter, to obtain Kohn anomaly and e-p superconductivity or maybe strange states, e.g. odd frequency.

nature Vol 456|18/25 December 2008|doi:10.1038/nature07625

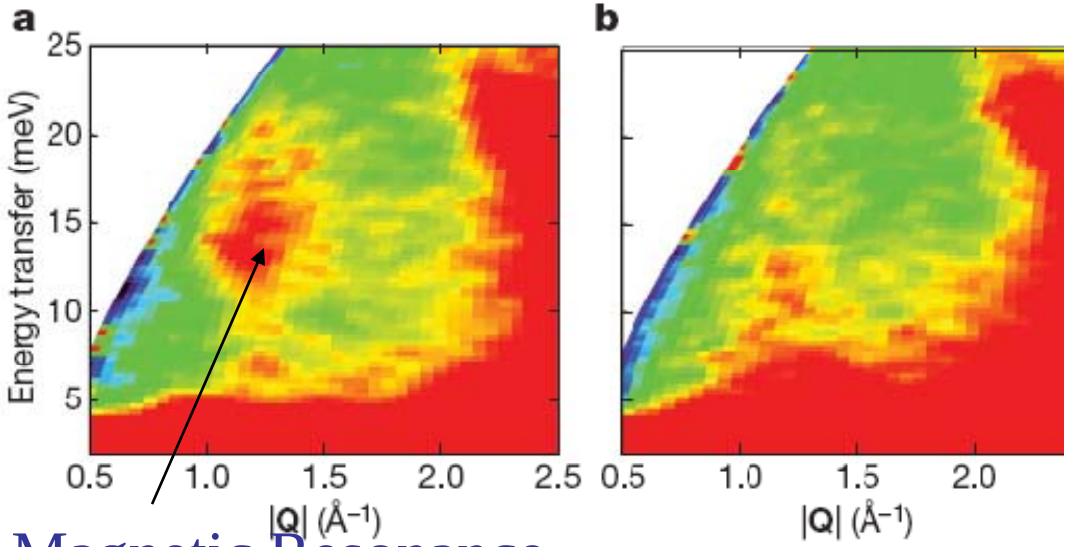
LETTERS

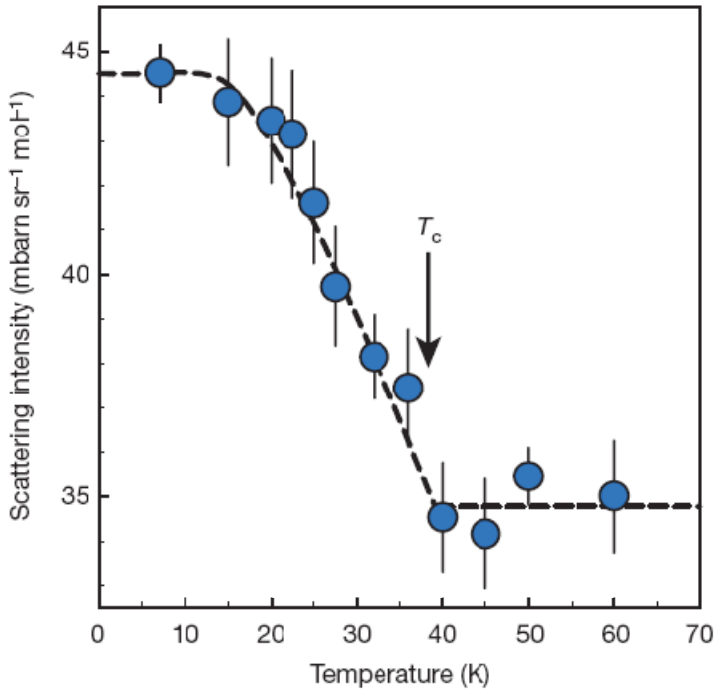
# Unconventional superconductivity in $Ba_{0.6}K_{0.4}Fe_2As_2$ from inelastic neutron scattering

A. D. Christianson[1], E. A. Goremychkin[2,3], R. Osborn[2], S. Rosenkranz[2], M. D. Lumsden[1], C. D. Malliakas[2,4], I. S. Todorov[2], H. Claus[2], D. Y. Chung[2], M. G. Kanatzidis[2,4], R. I. Bewley[3] & T. Guidi[3]

*T*=7K

*T*=50K



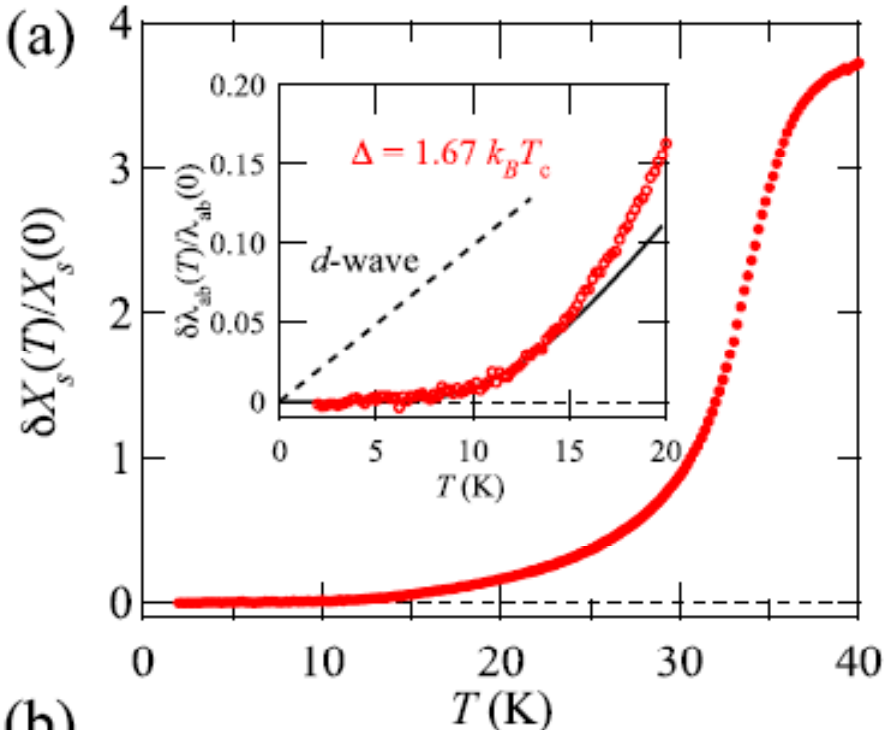

Magnetic Resonance

Sign changing gap with q corresponding to $(\pi,\pi)$

# Gap Structure

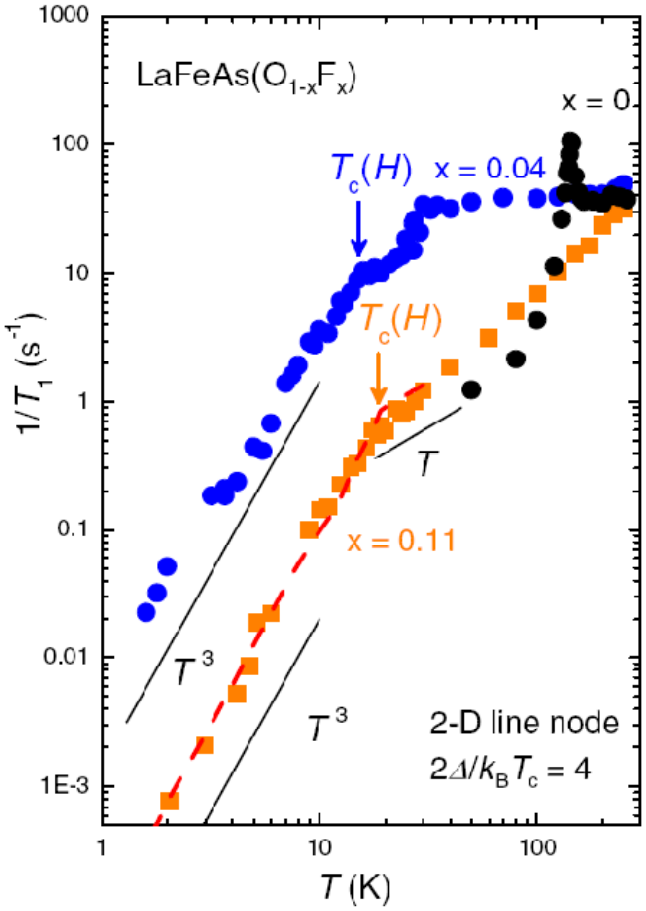
**Fully Gapped**: Andreev reflection, ARPES penetration depth (oxy-arsenides), tunneling.

**Power Law (e.g. Line Nodes)**:




BCS $\dfrac{\delta\lambda_{ab}(T)}{\lambda_{ab}(0)} \approx \sqrt{\dfrac{\pi\Delta}{2k_BT}}\exp\left(-\dfrac{\Delta}{k_BT}\right)$

Microwave penetration depth, $PrFeAsO_{1-x}$
K. Hashimoto, et al., PRL (2009).

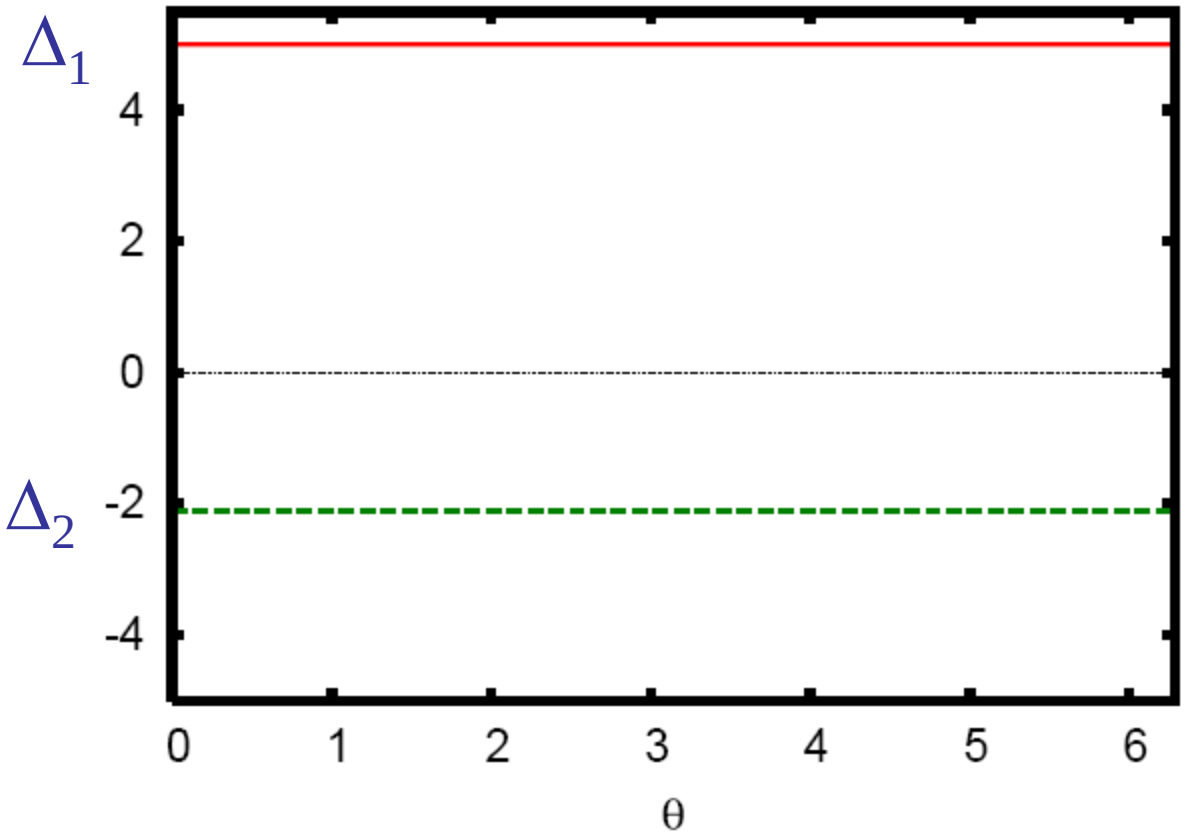



NMR, LaFeAs(O,F)
Y. Nakai, et al., JPSJ (2008).

# Gap Structure

If some compounds have a clean gap and others have nodes, does this mean that there are two competing (different) superconducting states, such as s+/- and something else?

s+/-



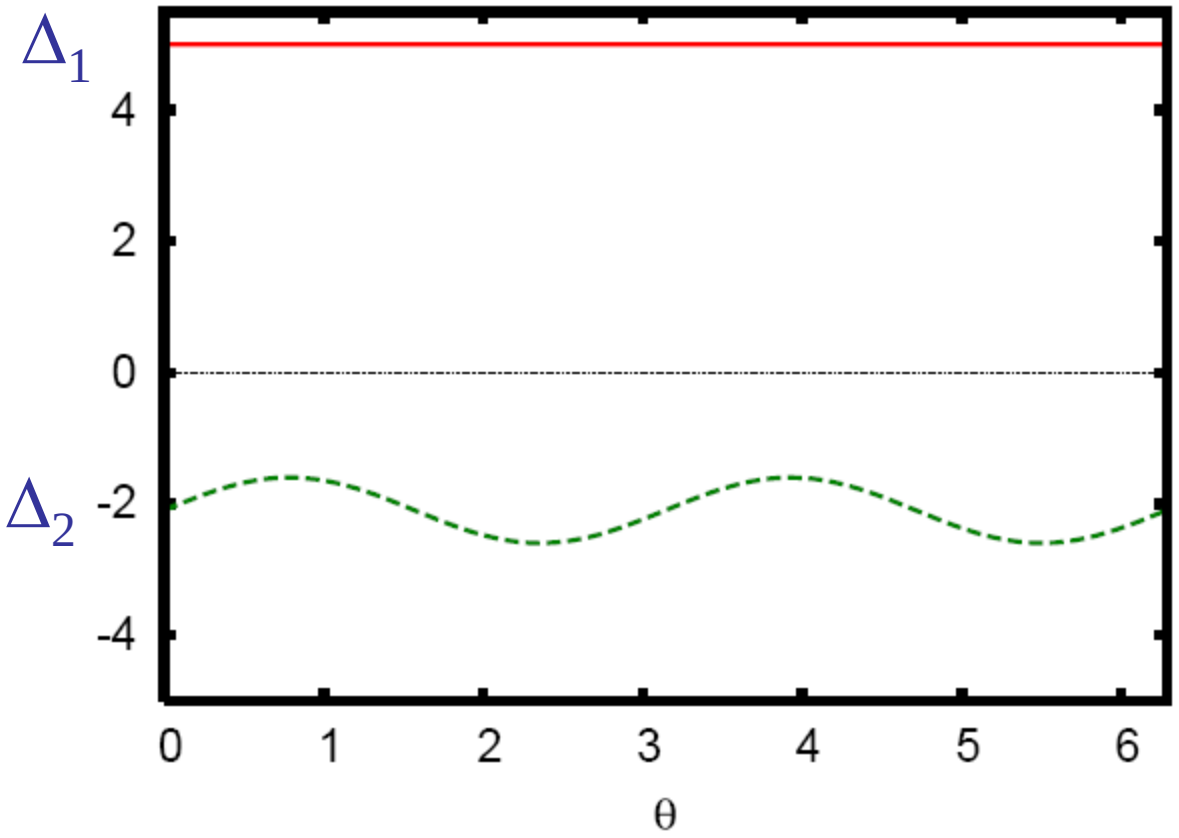

Competing State

?

# Gap Structure

If some compounds have a clean gap and others have nodes, does this mean that there are two competing (different) superconducting states, such as s+/- and something else?

s+/-



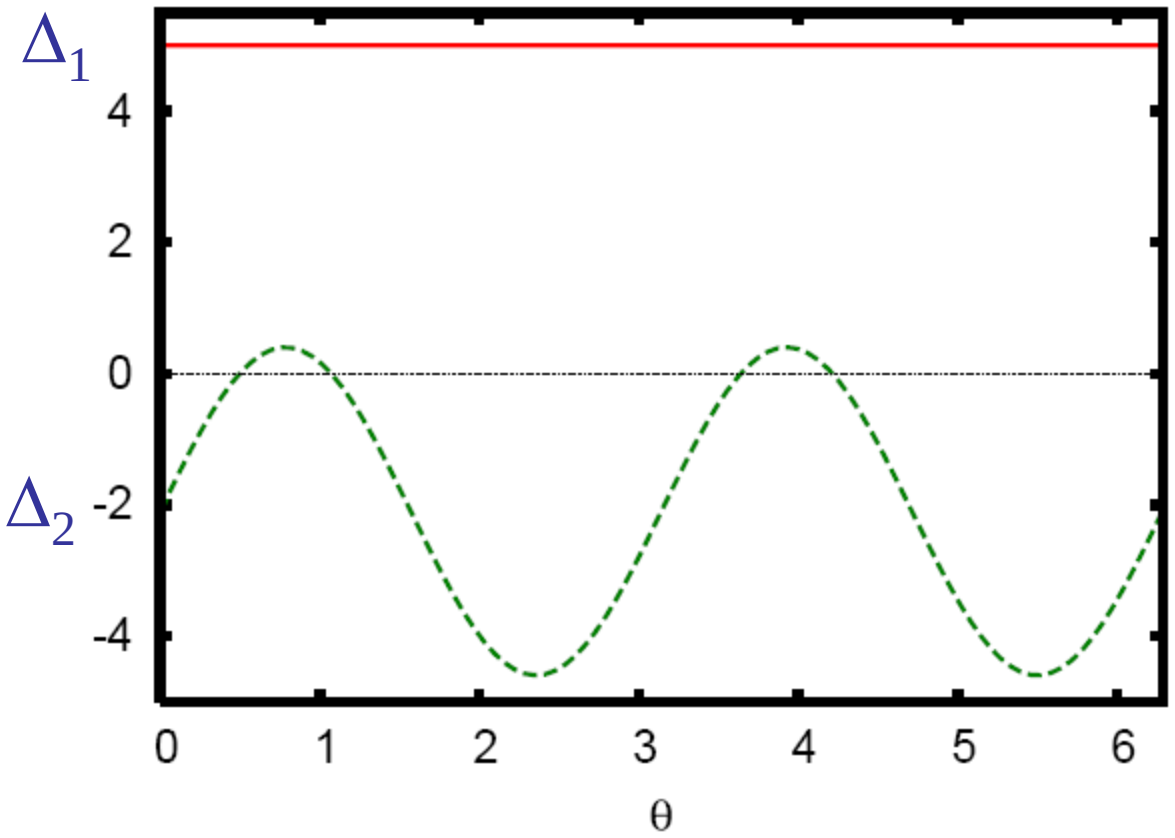

Competing State

?

# Gap Structure

If some compounds have a clean gap and others have nodes, does this mean that there are two competing (different) superconducting states, such as s+/- and something else?

s+/-



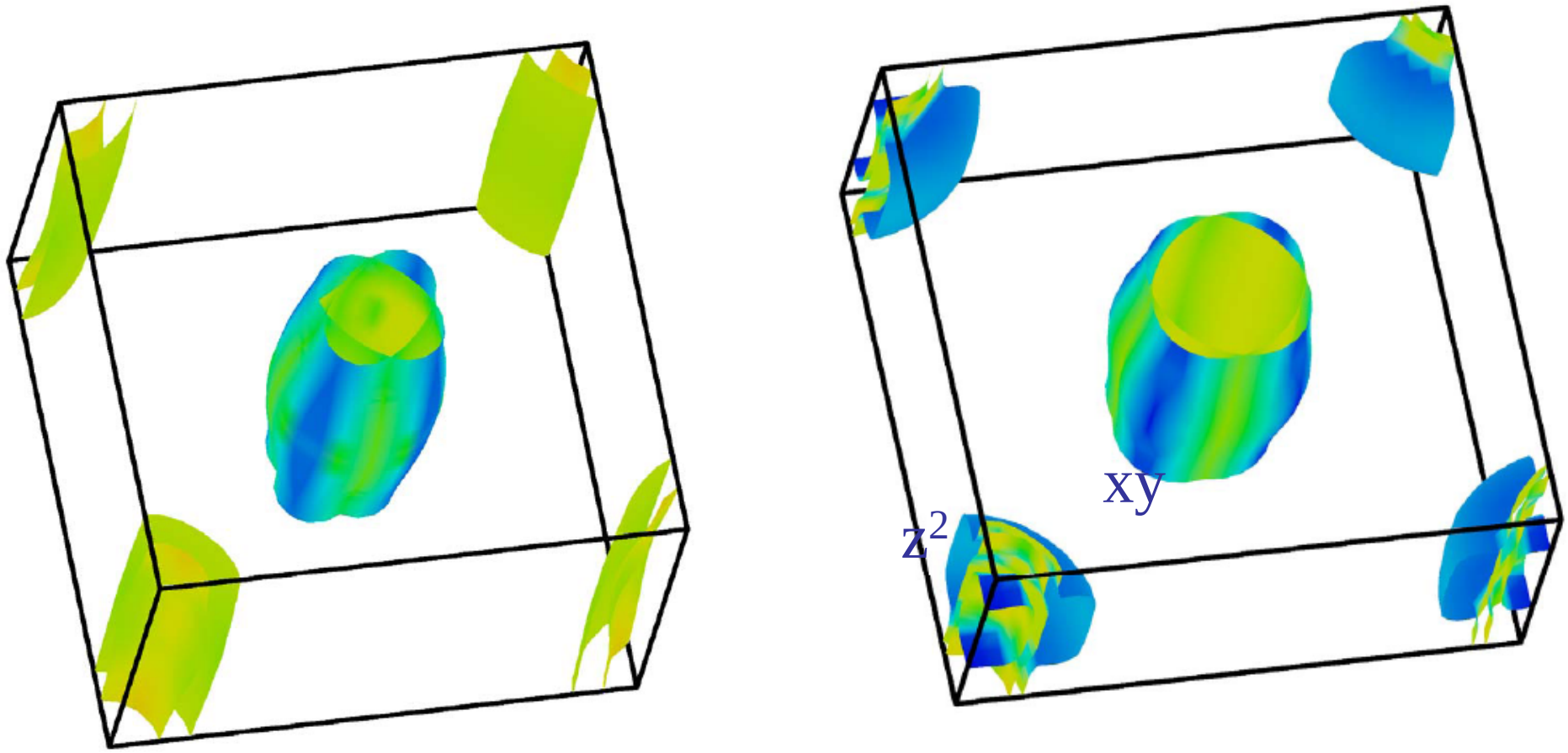

Why should this happen?

# Fermi Surface Structure

Fermi surface shaded by d *xz*/*yz* character

FeSe

LaFeAsO




Lobes of the electron sheets are not as nested as the inner parts due to matrix element

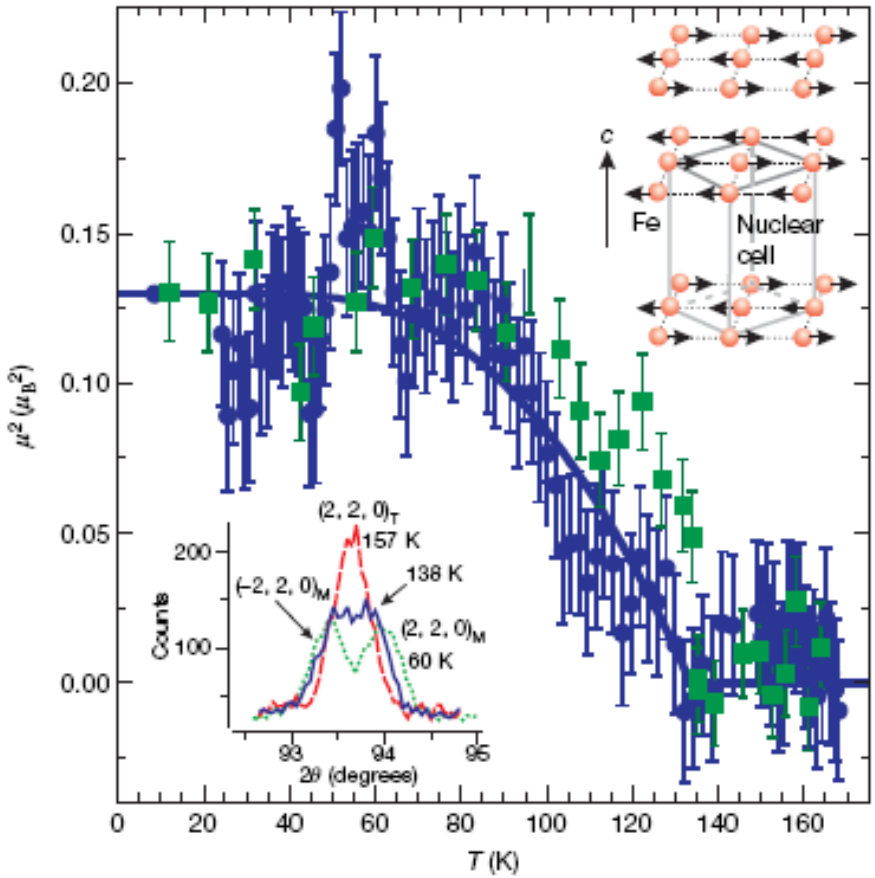
# Neutron Scattering – Magnetism & Structure

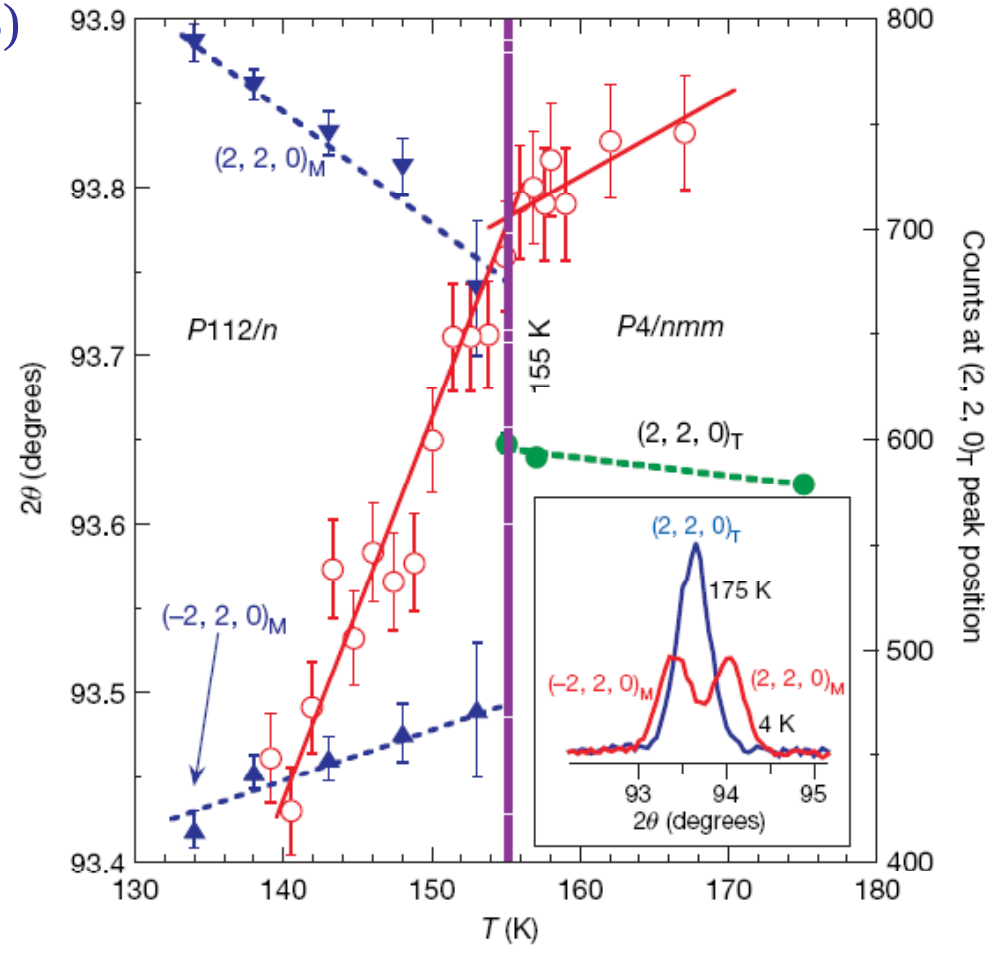
**LaFeAsO:**

Ordered $m$(Fe) = 0.36 $\mu_B$

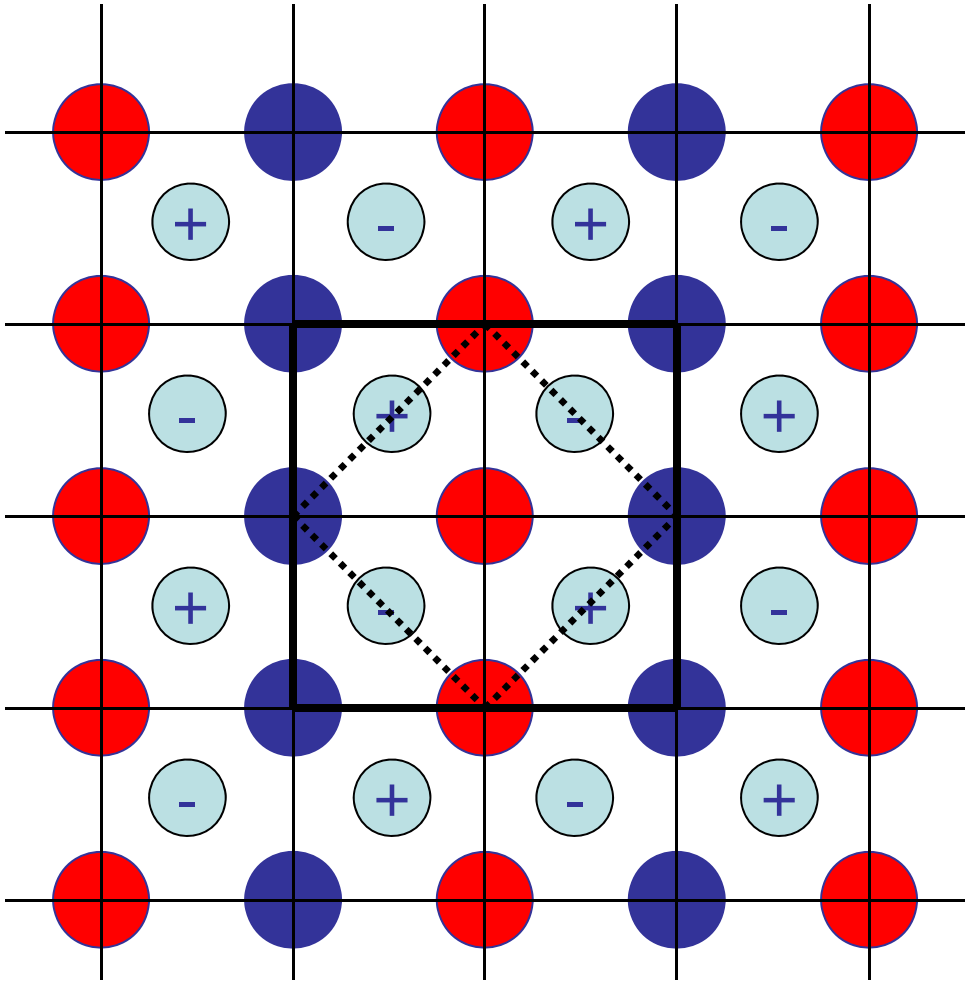
(other compounds so far are between 0.3 and 1 $\mu_B$)

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



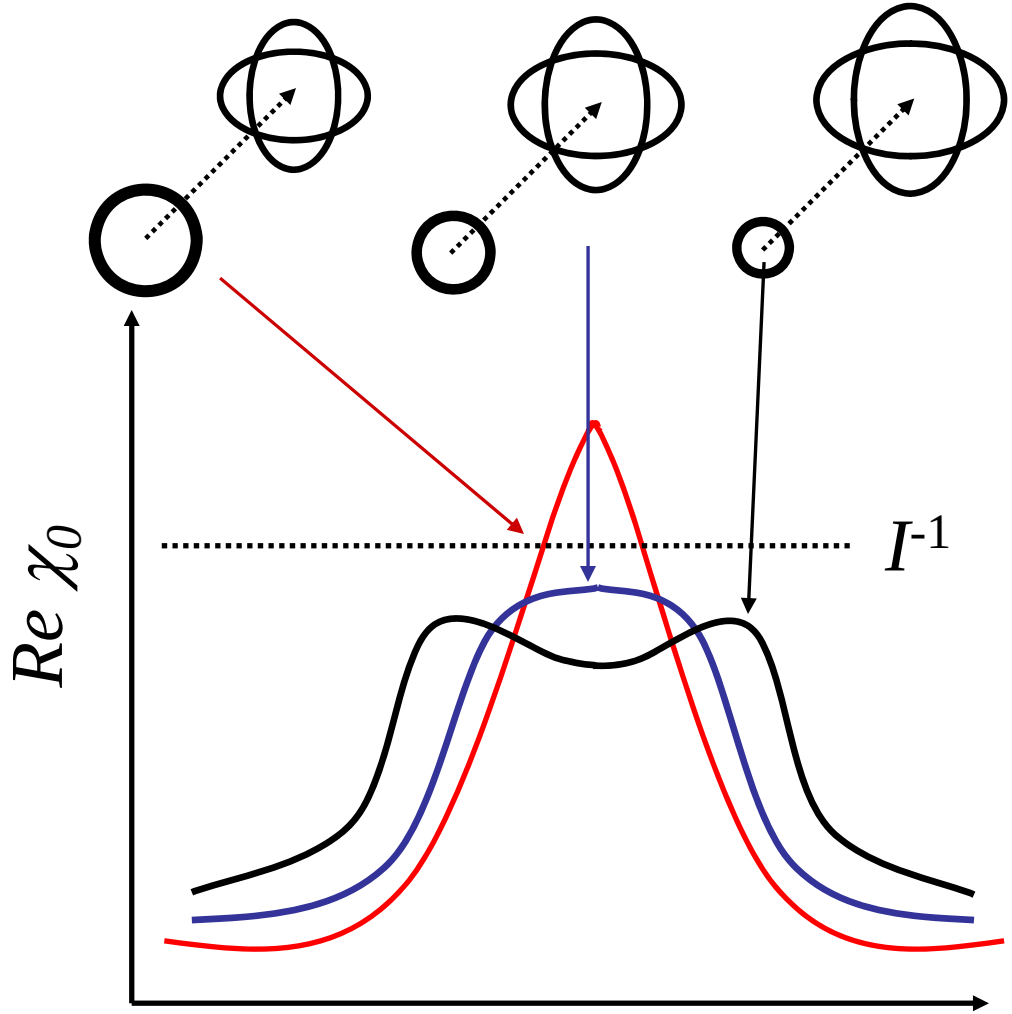



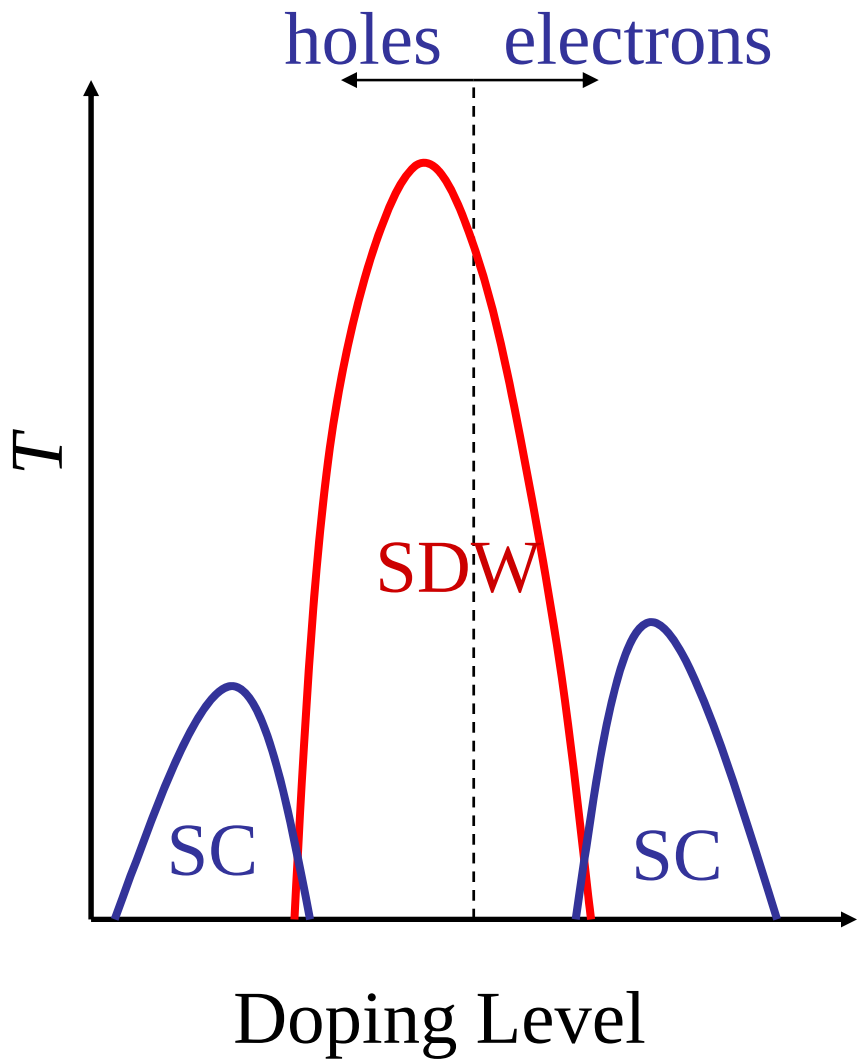
# In-plane SDW structure




1 D Chains of parallel spin Fe atoms.

# Nesting, Doping and the Lindhard Function

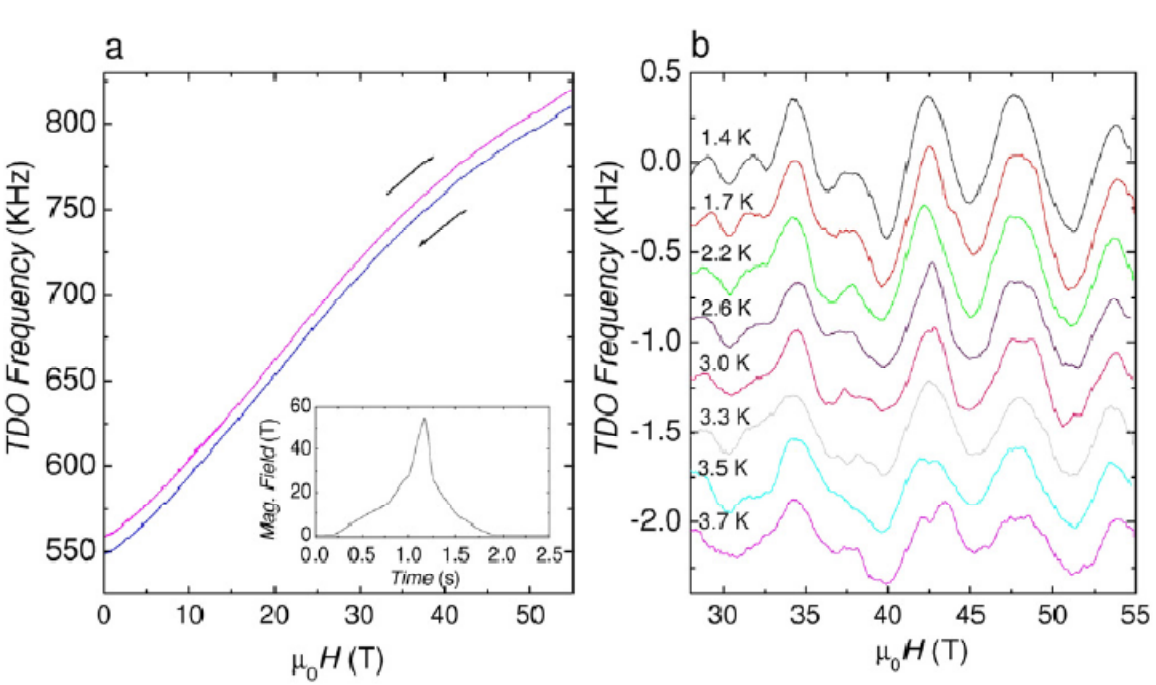


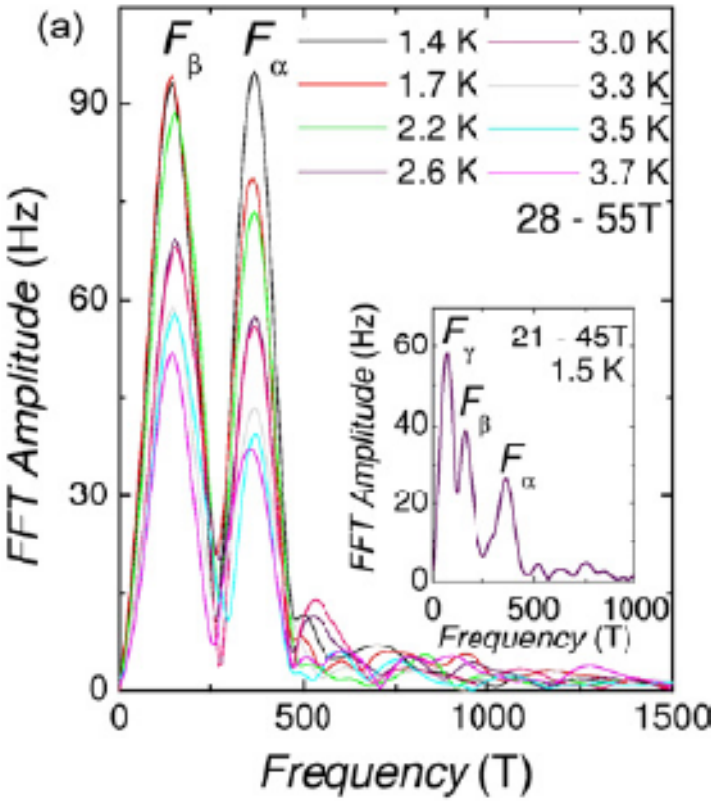




***Could we realize disorder induced superconductivity?***

# Metallic SDW State

$SrFe_2As_2$ (Sebastian *et al.*)



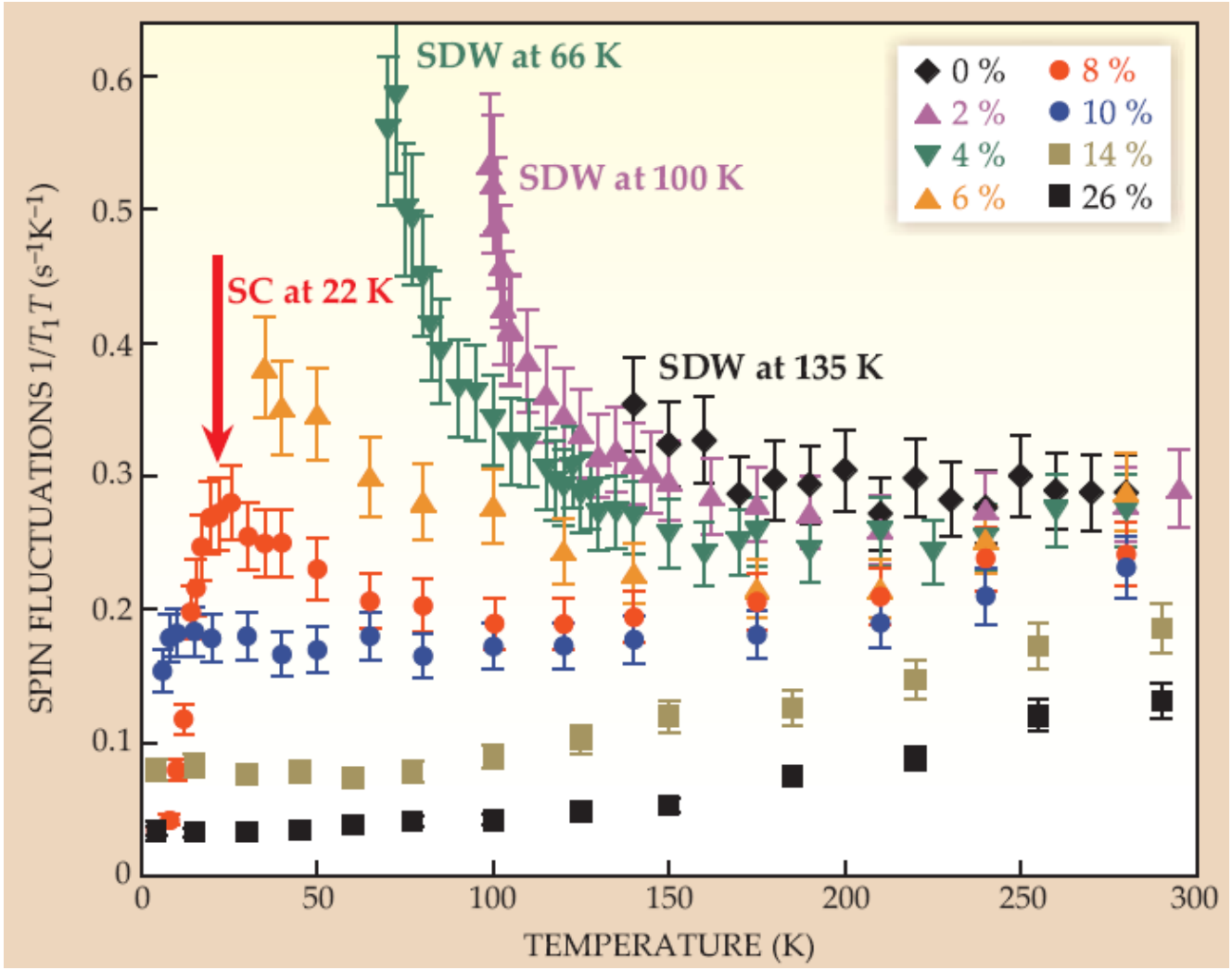




Shubnikov – de Hass measured by tunnel diode method.

SDW state has quantum oscillations reflecting a Fermi surface and is therefore a metal.

# NMR: Connection of SDW and SC States

$1/T_1T$ shows strong spin fluctuations (constant for ordinary F.L.)




Ning, et al., JPSJ **78**, 013711 (2009) – $Ba(Fe,Co)_2As_2$.

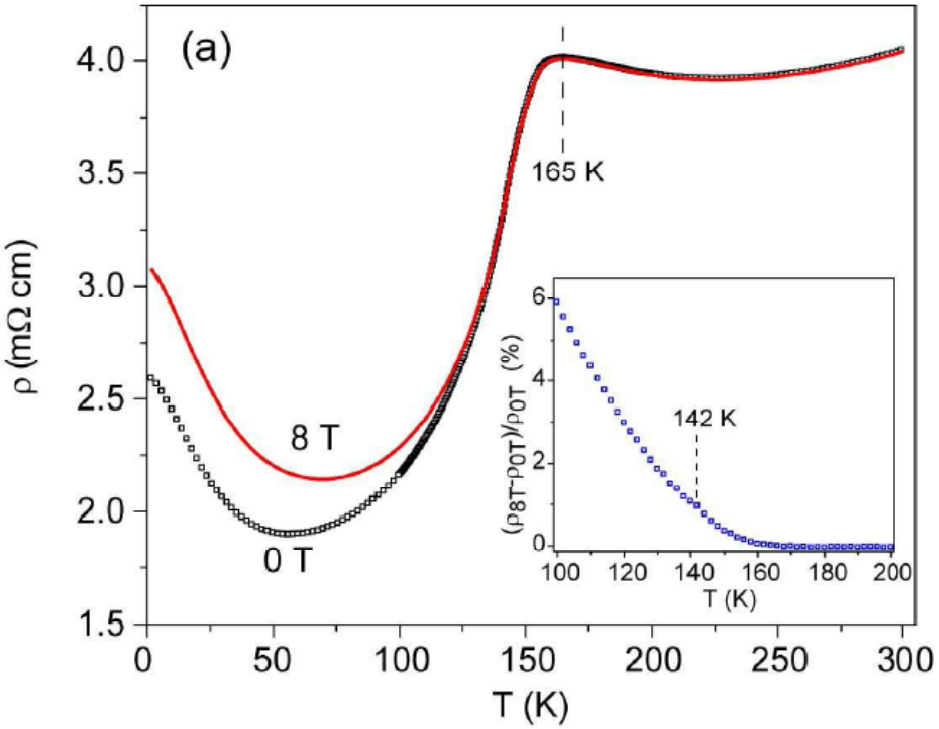
# Implications for Models

- Models reduce the degrees of freedom in order to extract and understand the important physics. They must retain fidelity to the important aspects of the physical system to be relevant.
- The FeSC are NOT near Mott insulators in any normal sense – a Mott insulating state is not produced by doping, alloying, pressure, magnetic field or other small or even large experimentally realizable perturbations.
- Models “near” a Mott insulator (small parameter changes produce a Mott state) need improvement.

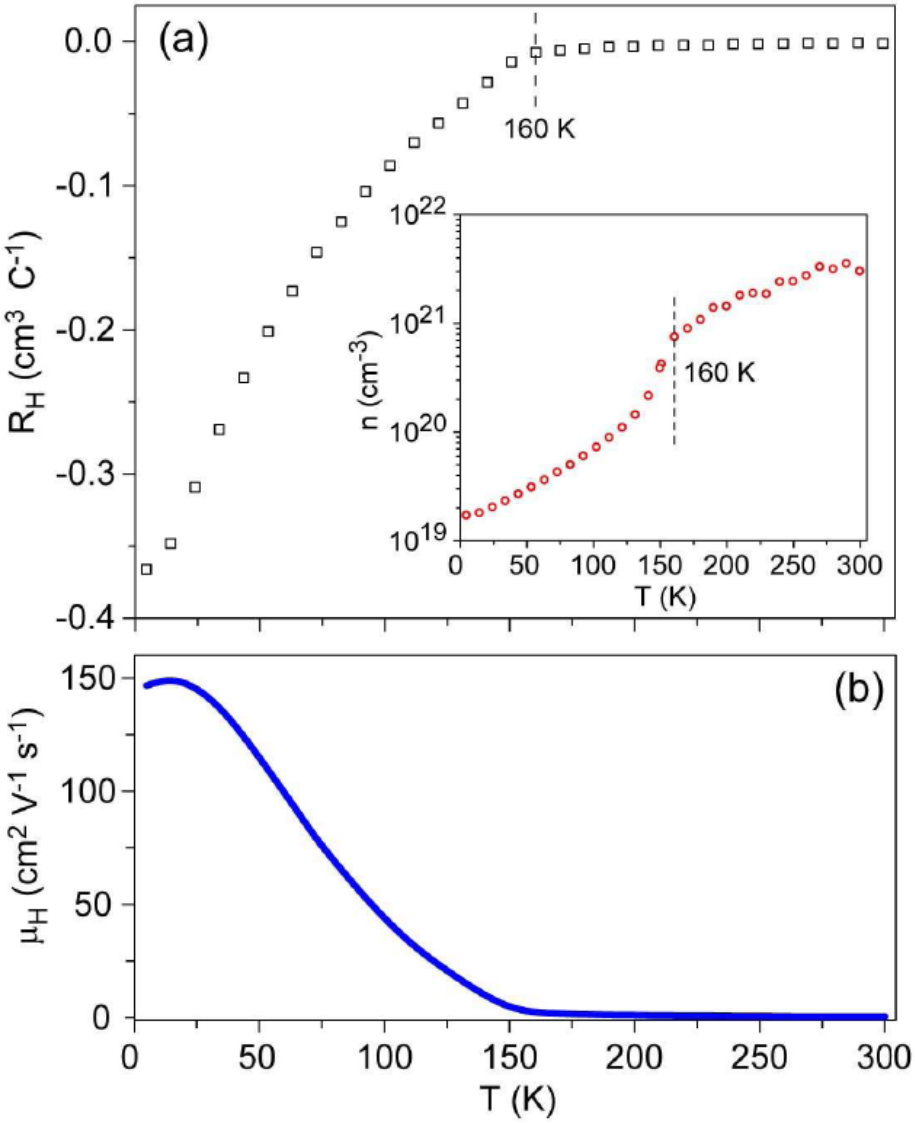
# Resistivity in LaFeAsO

McGuire *et al.* (cond-mat):

Resistivity:




Hall:

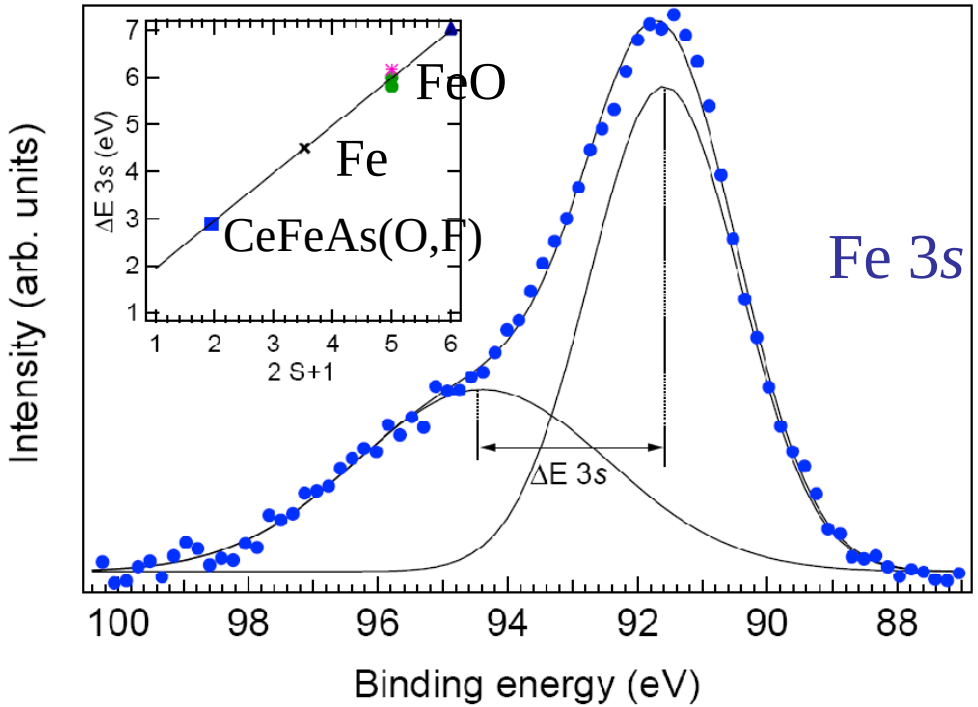



Evidence of strong interplay of magnetic ordering and Fermi surface.

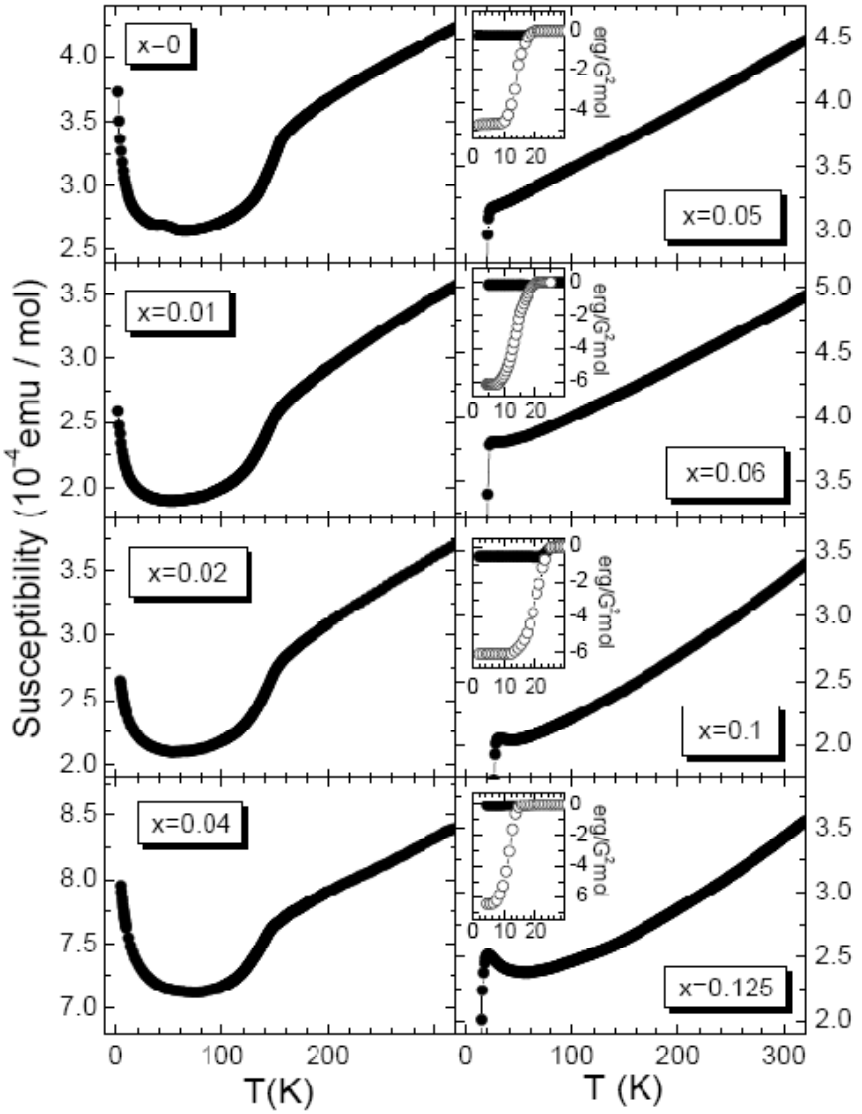
Evidence of spin fluctuations.

# Strong Spin Fluctuations in Normal State

- Transport data.
- Susceptibility - $\chi(T)$.
- Spectroscopy.
- Scattering.
- Overly magnetic in LDA.
- Precursor structural transition.




Bondino et al. (2008); c.f. $NbFe_2$

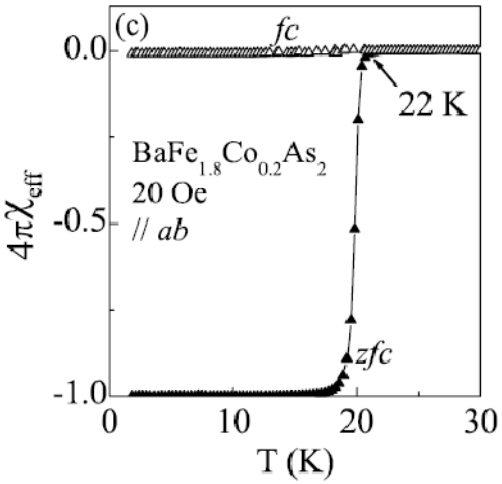


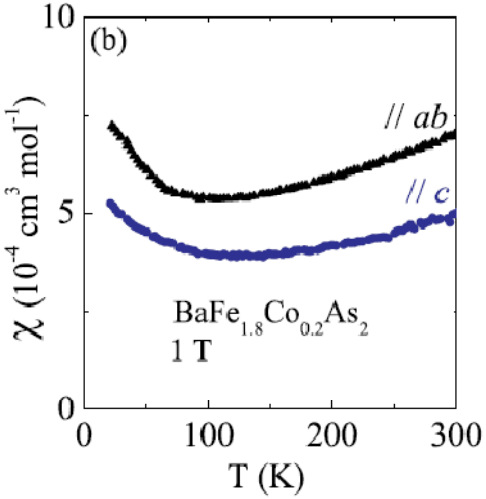

R. Klingeler et al., cond-mat

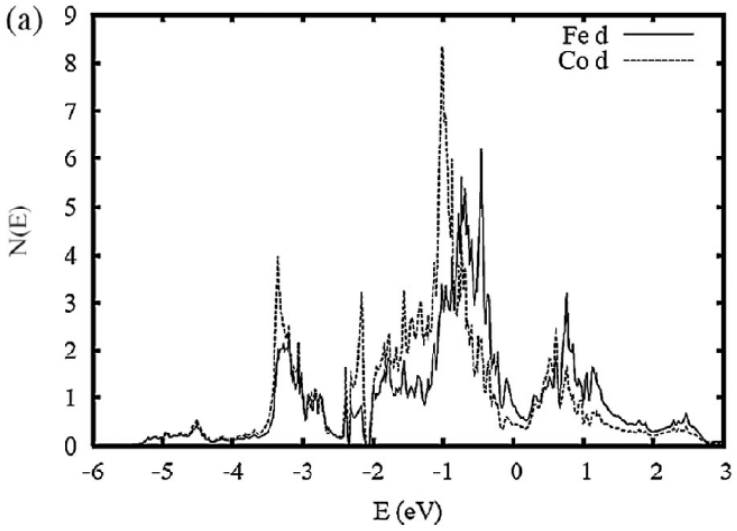
$LaFeAsO_{1-x}F_x$

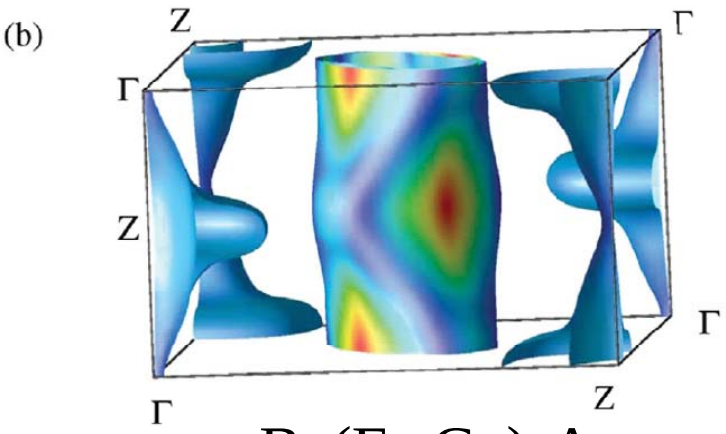
# Superconductivity in Metal Doped Materials

- Superconductivity requires destruction of SDW by doping.
- Remarkably, doping with Co or Ni works (*c.f.* cuprates).




$Ba(Fe,Co)_2As_2$

A.S. Sefat, et al., PRL (2008).

Calculations show that alloy behaves very much in a rigid band sense.

Fe-Co-Ni behave very similarly apart from electron count.

Mn and Cr show strong spin dependent hybridization (different).

***Is iron essential?***

JOURNAL OF SOLID STATE CHEMISTRY 56, 278–287 (1985)

# The $ThCr_2Si_2$ Structure Type

## The Most Populous of All Crystal Structure Types—the Tetragonal $BaAl_4$ Structure

W. B. PEARSON

*Departments of Physics and of Chemistry, University of Waterloo, Waterloo, Ontario, Canada, N2L 3G1*

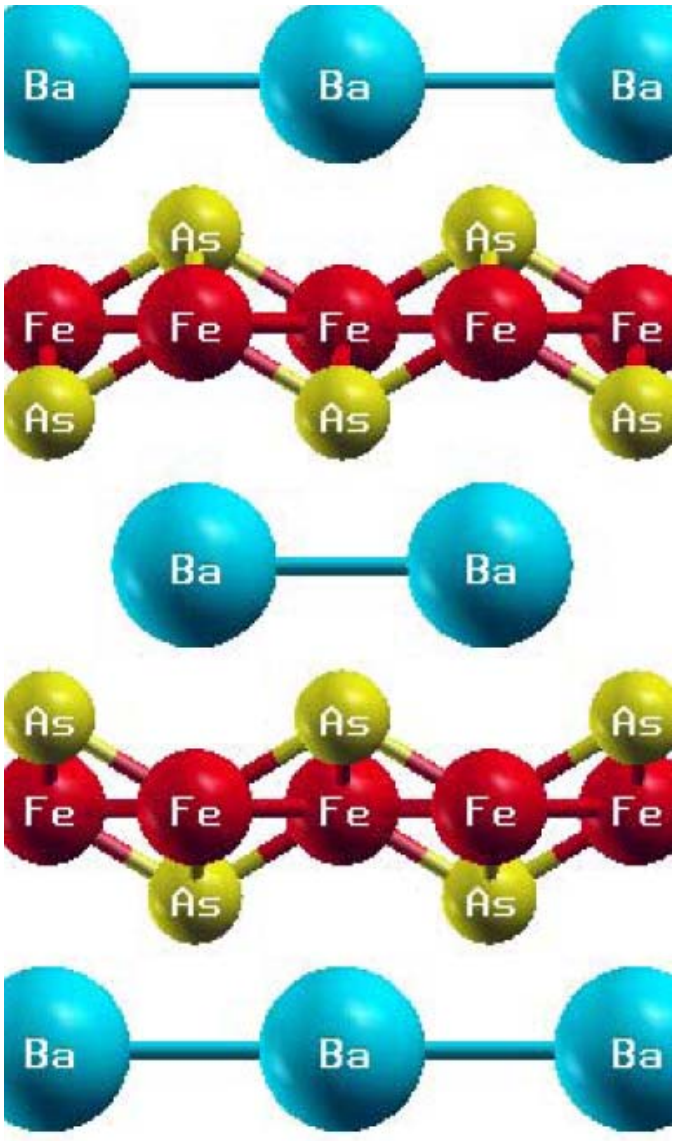
Pearson data-base now has 2,000+ $ThCr_2Si_2$ entries

Received April 9, 1984; in revised form August 3, 1984

The $BaAl_4$ ($ThCr_2Si_2$) *tI*10 structure, $MN_2X_2$, is not only the most populous of all known structure types, being adopted by some 400 phases, but is representative of a new group of metallurgically

**Examples**: $BaZn_2P_2$, $BaFe_2As_2$, $BiN_2Th_2$, $CaAl_2Ga_2$ , $SrCd_2Ga_2$ …

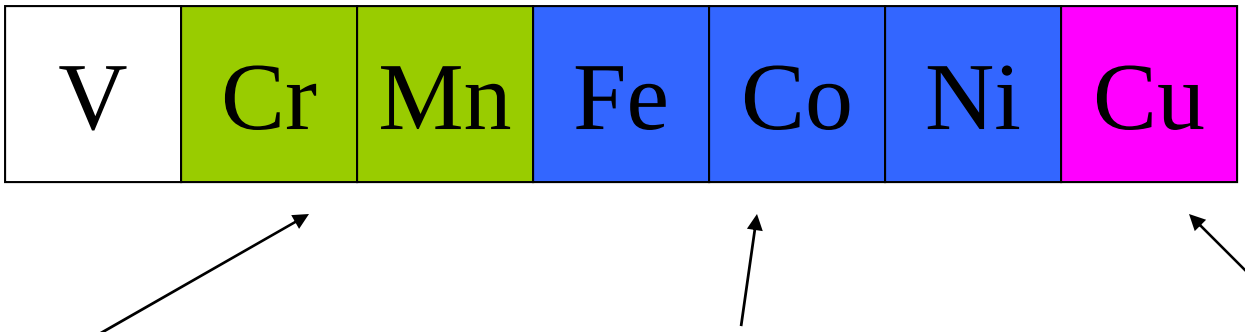
# The $ThCr_2Si_2$ Structure Type




Stabilized by different types of bonding: ionic, M-X bonding, M-M bonding, X-X bonding, A-X --- can tune to crossovers.

Interplay between magnetism and bonding in Fe compounds, e.g. collapsed phase of $CaFe_2As_2$ (Yildirim)

# $ThCr_2Si_2$ Structure $DT_2As_2$




Strong spin dependent *T*-As hybridization, G-type AF with high $T_N$.
$BaCr_2As_2$ is itinerant metal. $BaMn_2As_2$ is a semiconductor.

Metallic $M^{2+}$ sheets. As is anionic. *M* can be alloyed.
Fe: SDW and superconductivity.
Co: Near FM
Ni: electron-phonon superconductor.

$BaCu_2As_2$ has Cu $d^{10}$ with As-As and Cu-As sp bonding.

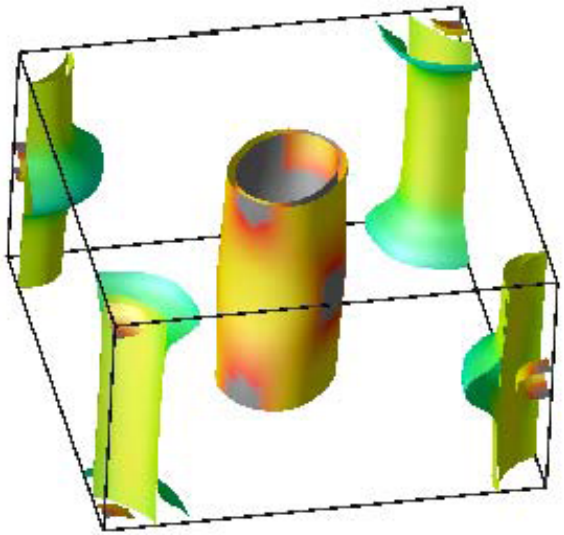
***Chemistry of chalcogenides may be expected to differ.***

# Is Iron Essential for Iron-Based Superconductivity?

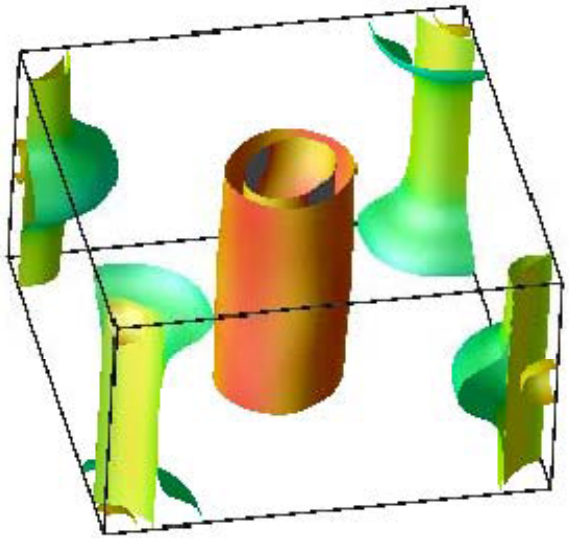
$KRu_2As_2$; $KFe_2As_2$; $KCo_2As_2$: Can we do something with the alloys?

$KFeCoAs_2 \approx BaFe_2As_2$

$KFeCoAs_2$

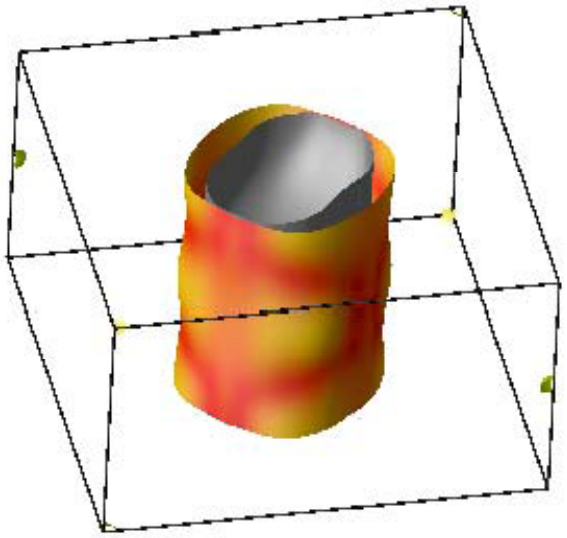


Virtual Crystal



Ordered Cell

$KFe_{0.5}Co_{1.5}As_2$ (overdoped)

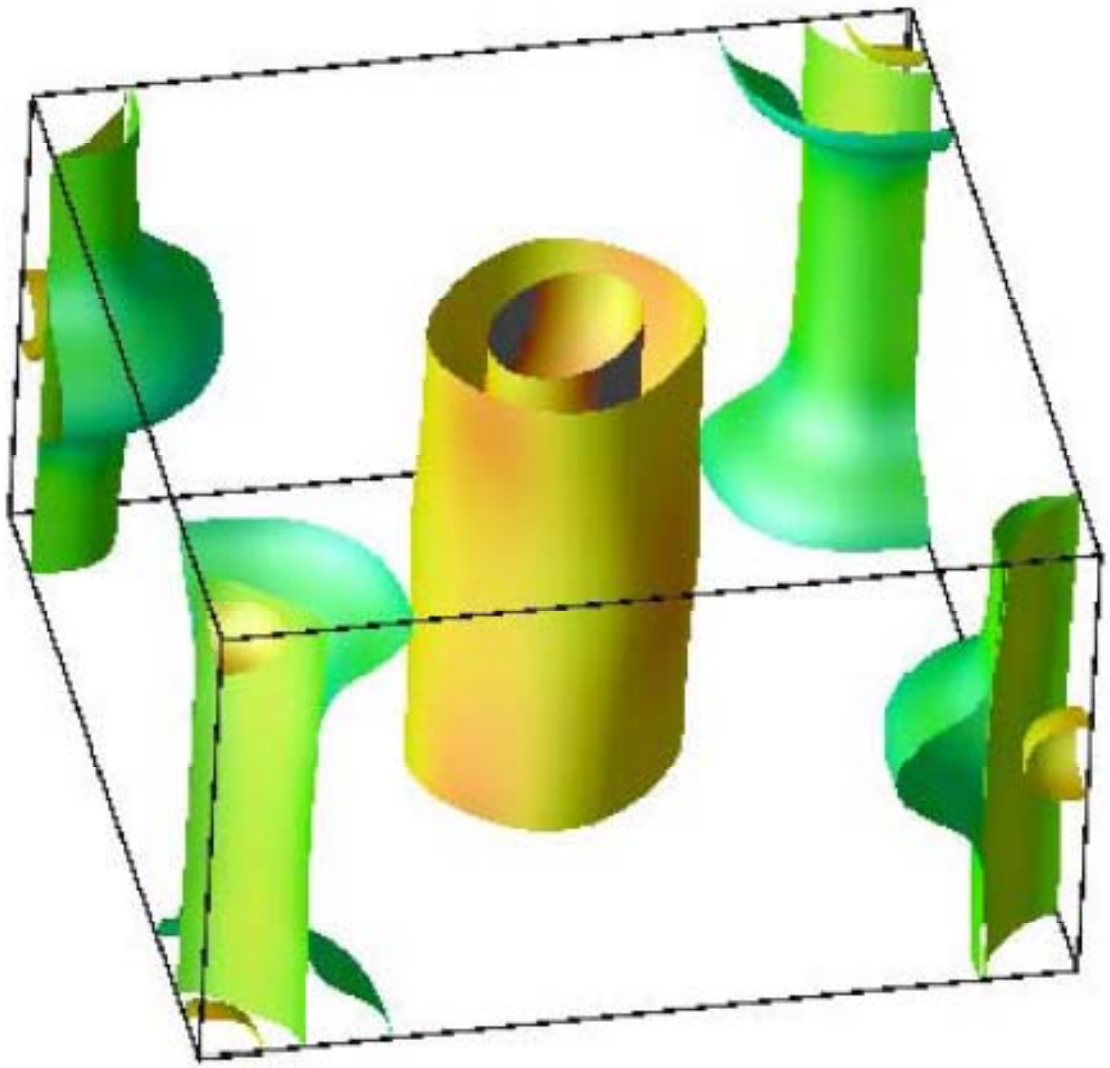


Virtual Crystal

Coherent alloy: Look for superconductivity in $KFe_{1-x}Co_{1+x}As_2$ (Fe-poor)

Also, similar results, but less magnetic for $KRu_{1-x}Co_{1+x}As_2$, but significantly less magnetic (Fe-free).

# Fermi Surface of Ordered $KRuCoAs_2$



Do not find SDW magnetic order at this composition.

Will it appear as Ru concentration is reduced.

Will superconductivity appear?

$$\chi(\mathbf{q}) = \frac{\chi_0(\mathbf{q})}{1 - \chi_0(\mathbf{q}) I(\mathbf{q})}$$

Ru lowers average Stoner parameter $I(\mathbf{q})$ both because it is 4*d* and because of Ru *d* – As *p* hybridization.

# Neutron Scattering – Structure Details

## LaFeAsO (Tetragonal → Orth/Mono):

**Table 2 | Properties of LaOFeAs at 4 K**

a, Refined structure parameters

| Atom | Site | x | y | z | B (Å²) |
|---|---|---|---|---|---|
| La | 2e | ¼ | ¼ | 0.1426(3) | 0.54(6) |
| Fe | 2f | ¾ | ¼ | 0.5006(12) | 0.16(4) |
| As | 2e | ¼ | ¼ | 0.6499(4) | 0.23(7) |
| O | 2f | ¾ | ¼ | −0.0057(17) | 0.69(7) |

$z_{As}$(4K) = 1.308 Å

$z_{As}$(175K)=1.317 Å

## $LaFeAsO_{0.92}F_{0.08}$ (Tetragonal):

**Table 3 | Properties of $LaO_{0.92}F_{0.08}FeAs$ at 10 K (first line), 35 K (second line) and 175 K (third line)**

a, Refined structure parameters

| Atom | Site | x | y | z | B (Å²) |
|---|---|---|---|---|---|
| La | 2c | ¼ | ¼ | 0.1448(3) | 0.40(5) |
| | | ¼ | ¼ | 0.1458(3) | 0.50(5) |
| | | ¼ | ¼ | 0.1446(3) | 0.73(5) |
| Fe | 2b | ¾ | ¼ | ½ | 0.32(4) |
| | | ¾ | ¼ | ½ | 0.41(4) |
| | | ¾ | ¼ | ½ | 0.65(4) |
| As | 2c | ¼ | ¼ | 0.6521(4) | 0.41(7) |
| | | ¼ | ¼ | 0.6515(4) | 0.40(6) |
| | | ¼ | ¼ | 0.6527(4) | 0.69(7) |
| O/F | 2a | ¾ | ¼ | 0 | 0.53(6) |
| | | ¾ | ¼ | 0 | 0.62(6) |
| | | ¾ | ¼ | 0 | 0.71(6) |

$z_{As}$(10K) = 1.323 Å

$z_{As}$(175K)=1.331 Å

Non-magnetic LDA calc. (LaFeAsO – Tetragonal)

$z_{As}$(LDA) = 1.159 Å

***A huge difference!***

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

# Structure and Magnetism

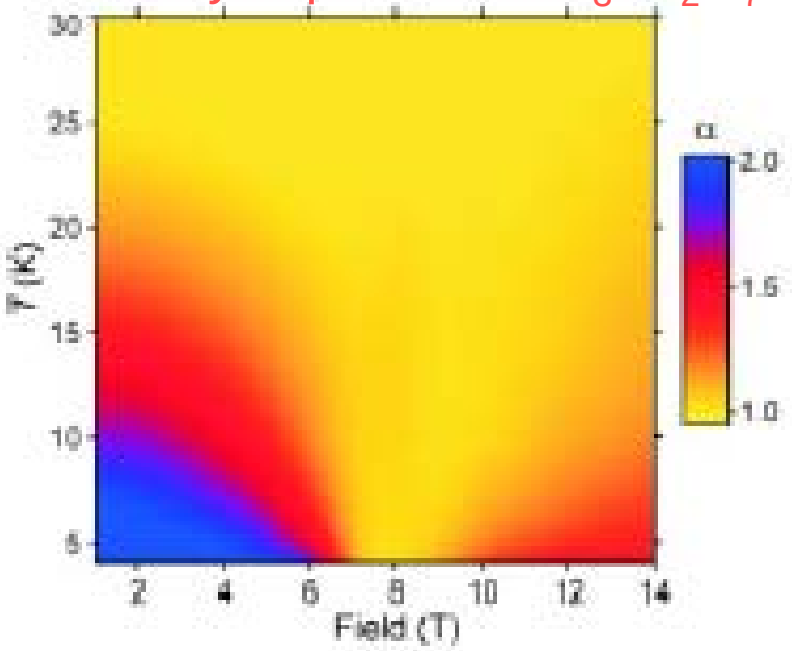
- As height is too low by ~0.1 Å in non-magnetic LSDA calculations.
- SDW is too robust compared to experiment.
- Using GGA and including magnetism one can obtain much better As height. In that case magnetism is extremely robust ($m \sim 2\mu_B$) contrary to experiment.
- Discrepancy in As height persists in the paramagnetic (superconducting) doped phases.
- There is a strong isotope effect both on $T_c$ and on $T_{SDW}$ (Liu *et al.*, cond-mat, 2008).
- We take this as an indication of very strong non-trivial spin-fluctuations.

# Quantum Critical Points and the LDA

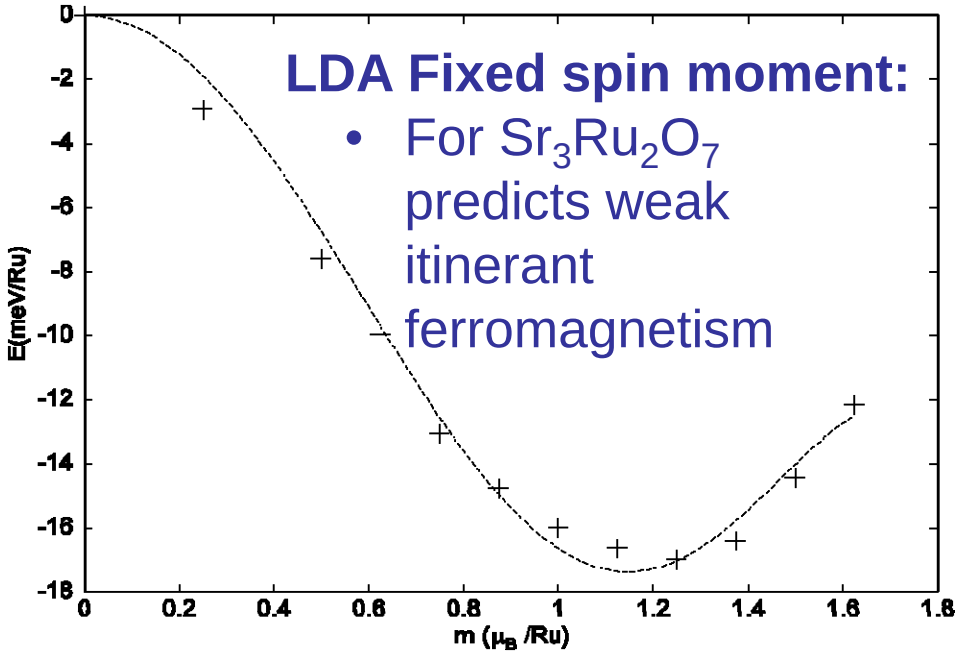
**Density Functional Theory**: LDA & GGA are widely used for first principles calculations but have problems:

- Mott-Hubbard: Well known poor treatment of on-site Coulomb correlations.
- Based on uniform electron gas. Give mean field treatment of magnetism: Fluctuations missing.

Resistivity exponent in $Sr_3Ru_2O_7$




Grigera *et al.*, Science (2001).




**LDA overestimate of ferromagnetic tendency is a signature of quantum critical fluctuations – neglected fluctuations suppress magnetism**

# Some Metals Where the LSDA Overestimates Ferromagnetism

**Class 1**: Ferromagnets where the LDA overestimates the magnetization.

| | m (LDA, $\mu_B$/f.u.) | m (expt., $\mu_B$/f.u.) |
|---|---|---|
| $ZrZn_2$ | 0.72 | 0.17 |
| $Ni_3Al$ | 0.71 | 0.23 |
| $Sc_3In$ | 1.05 | 0.20 |

**Class 2**: Paramagnets where the LDA predicts ferromagnetism

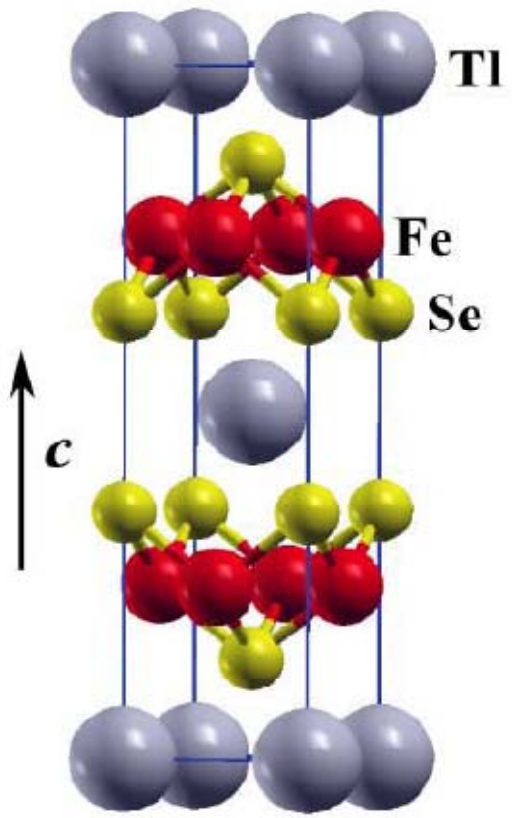
| | m (LDA, $\mu_B$/f.u.) | m (expt., $\mu_B$/f.u.) |
|---|---|---|
| FeAl | 0.80 | 0.0 |
| $Ni_3Ga$ | 0.79 | 0.0 |
| $Sr_3Ru_2O_7$ | 0.9 | 0.0 |
| $Na_xCoO_2$ | 0.50 | 0.0 |

**Class 3**: Paramagnets where the LDA overestimates the susceptibility.

| | $\chi$ (LDA, $10^{-4}$ emu/mol) | $\chi$ (expt., $10^{-4}$ emu/mol) |
|---|---|---|
| Pd | 11.6 | 6.8 |

# Properties of the Over-Doped Side: $TlFe_2Se_2$

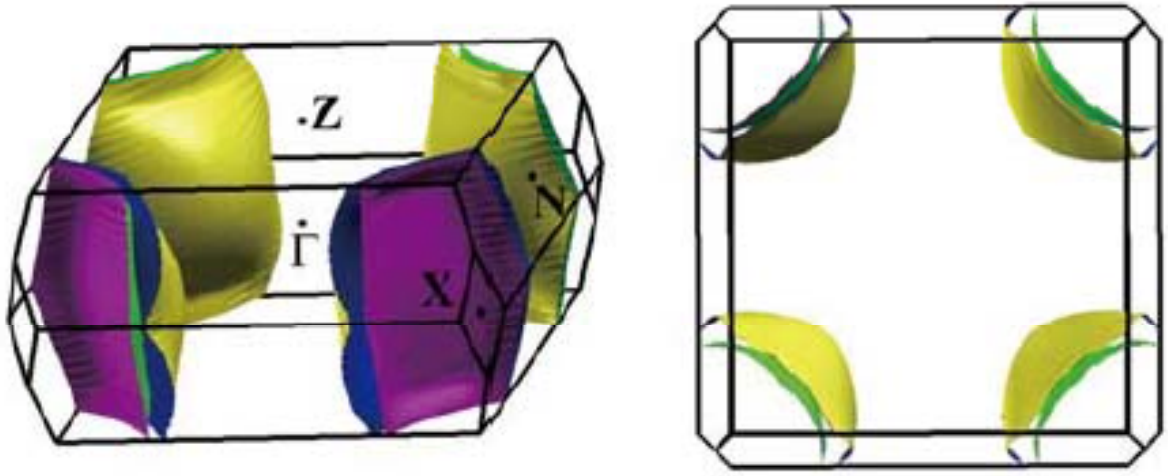
Haggstrom, 1986




Antiferromagnetic with $T_N$ ~ 450 K. Unknown order.

First Principles Results (GGA):

- Electronic structure is very similar to FeSC, but with higher electron count (0.5 e/Fe).
- Strong instability against nearest neighbor AFM (78 meV/Fe) and weaker instability against FM (44 meV/Fe). No instability for SDW type chain order → itinerant n.n. AFM

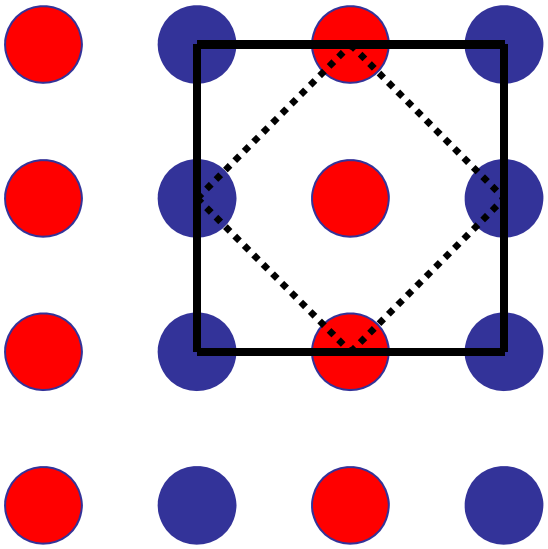



Non spin polarized Fermi surface

# Competing Magnetic States

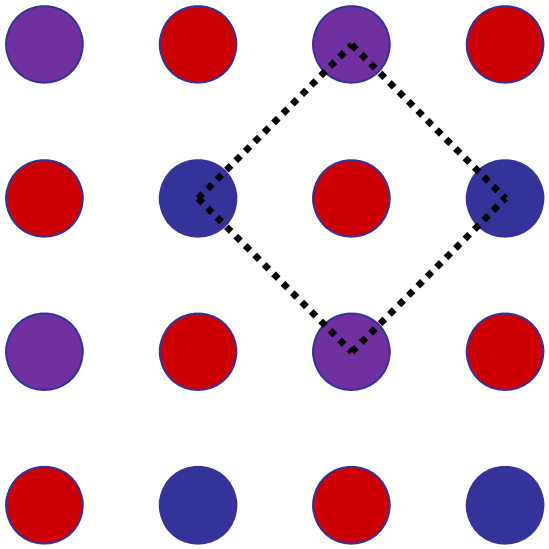
Competition between different magnetic states provides phase space for fluctuations and works against ordering.

SDW - c(2x2)



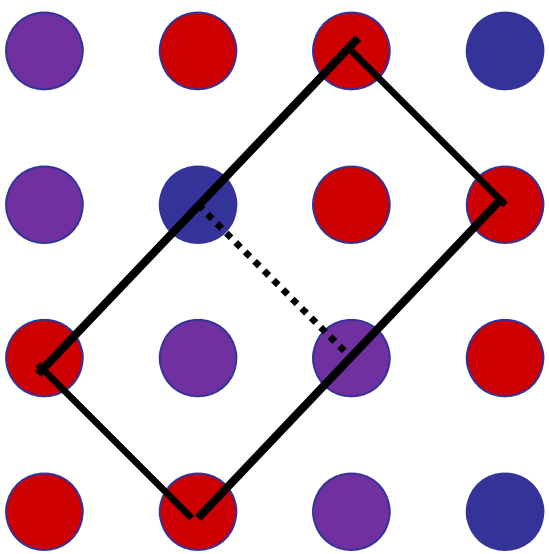
LaFeAsO

N.N (1x1)



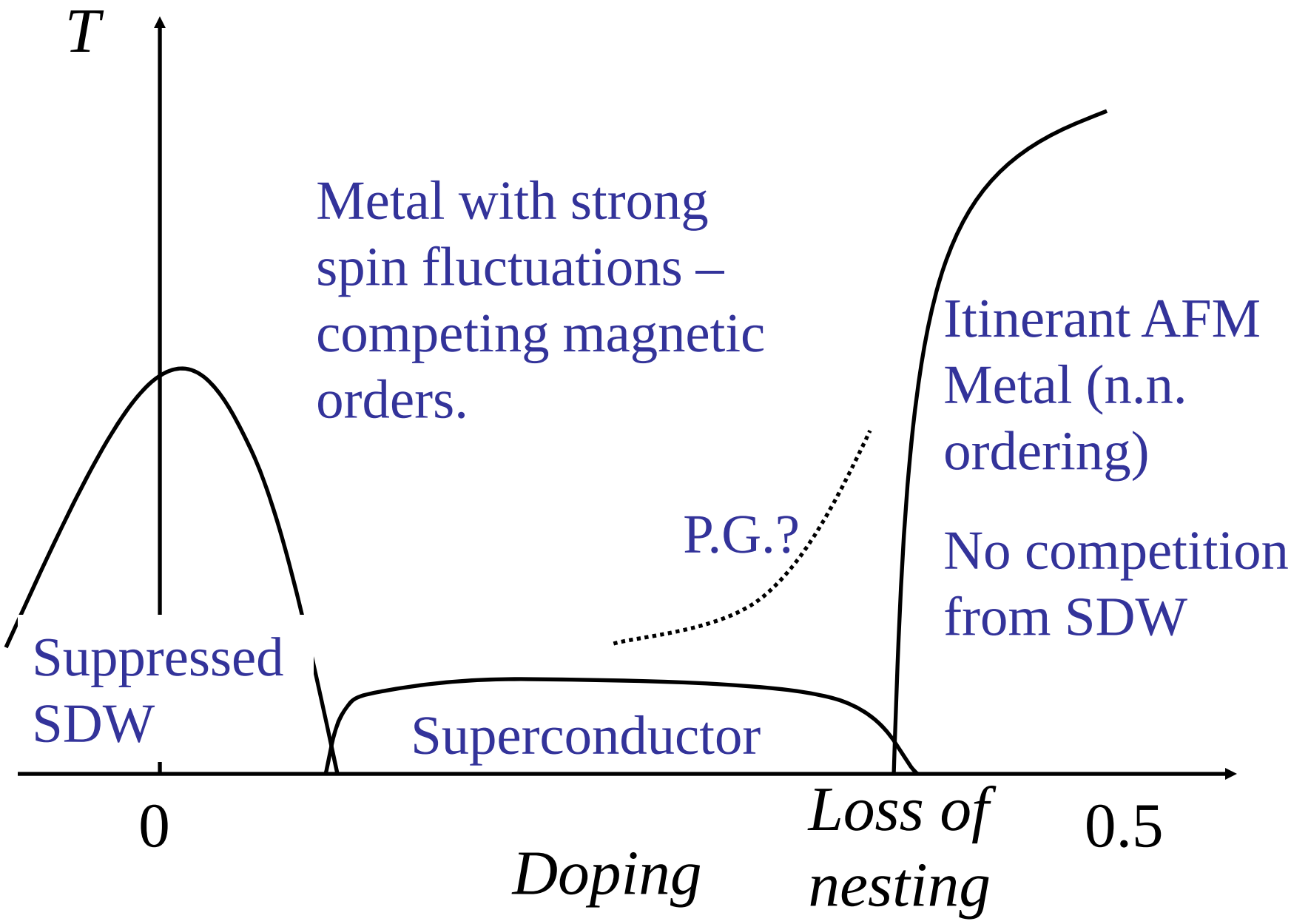
$TlFe_2Se_2$

(2x1)



$Fe_{1+x}Te$

# Possible Electron Doped Phase Diagram



# Hund's Coupling

- Hund's coupling in 3d ions is strong (Stoner $I$~0.8 eV)
- Spin-fluctuations are then expected to couple to electronic states in the *d*-band going up to high energy (i.e. the *d*-band width) – may be observable in spectroscopy. Drude weight seems reduced in optics.

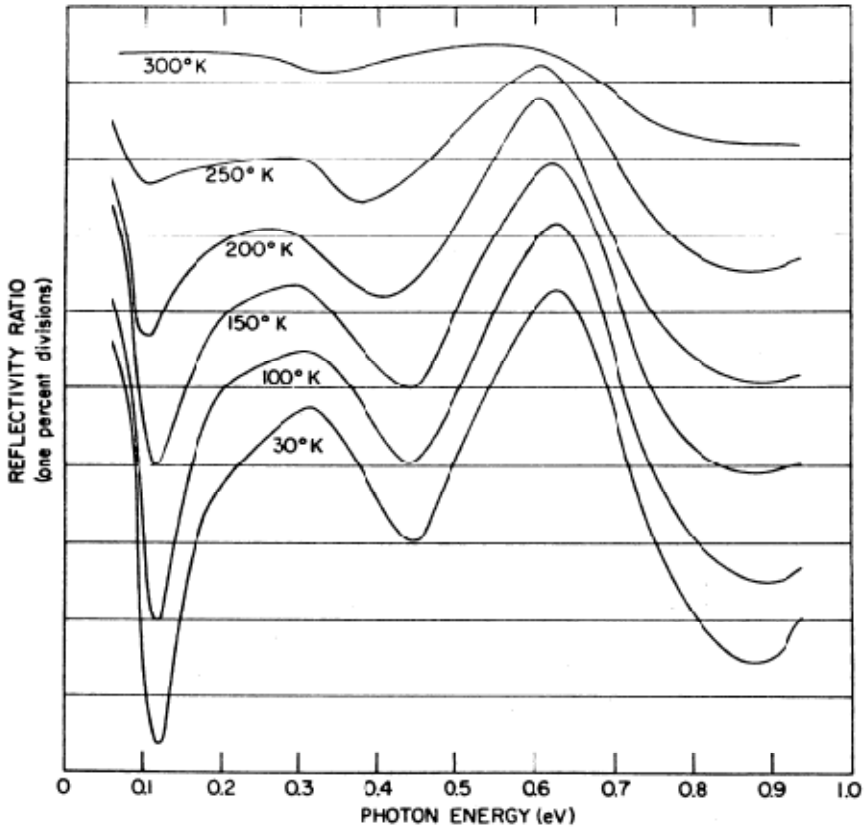
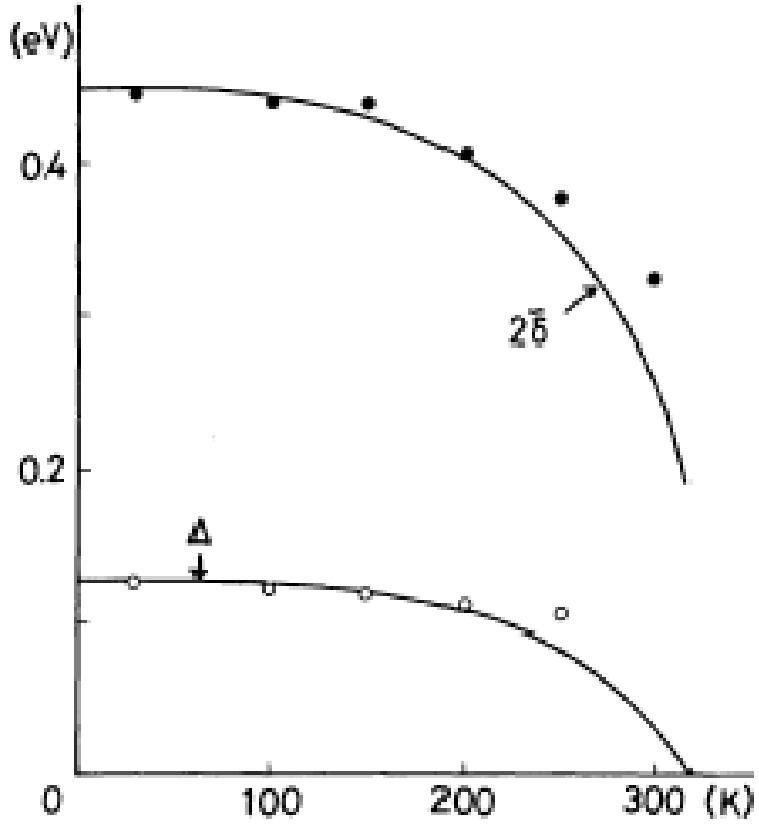



Fig. 3. The temperature dependent reflectivity of chromium normalized to $T=400$ K.

Cr metal: Machida et al., JPSJ (1984).



# Comparison with Cuprates

| | Cuprates | Fe-As |
|---|---|---|
| Magnetic & superconducting phases | Yes, magnetic phase insulating above & below $T_{N.}$ (Mott insulator) | Yes. Magnetic phase is metallic. Above $T_N$ is is similar to the metal in the superconducting phase. |
| Electronic structure | Moderate $N(E_F)$, large FS at least for optimal doped | High $N(E_F)$, small disconnected FS |
| Doping | Essential. | Destruction of SDW is enough. |
| Magnetic character | Local moment | Strong coupled, apparently itinerant. |
| Correlations | Strong. Mott-Hubbard type (e.g. p.e. satellites) | Possibly substantial but different e.g. spin fluctuations. Not Mott-Hubbard type. |
| Superconductivity | *d*-wave. Nodes. One band. Highly anisotropic | Nodeless (*s* +/- ?). Two band. Less anisotropic (material dependent). |
| Structure | Oxides, corner shared octahedra -- complex | Simpler – tetragonal / orthorhombic, small unit cells. |