Summary talk

— Experiments —

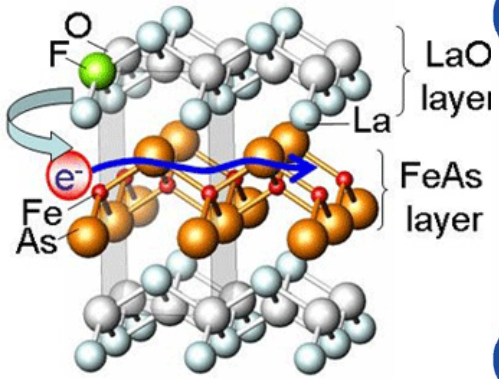
Yuji Matsuda

Department of Physics, Kyoto University

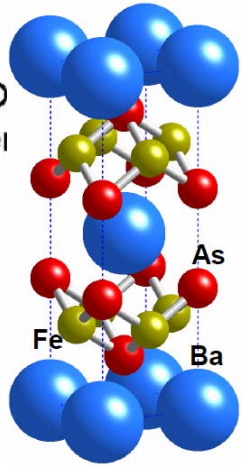
Kyoto, Japan

Fe-based high-T_c superconductors

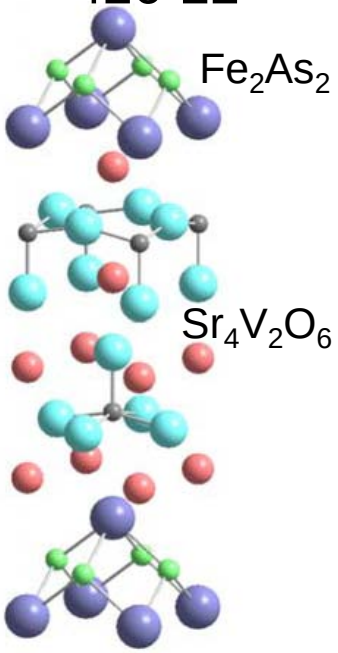
"1111"



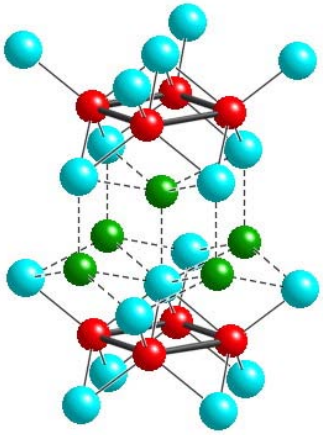
"122"



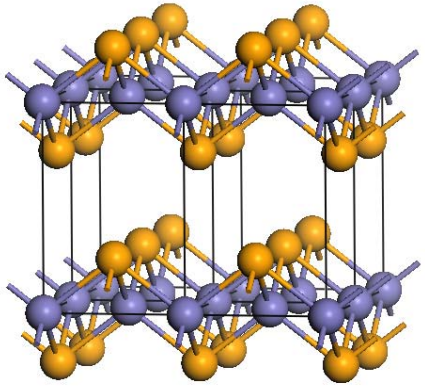
"426-22"



"111"

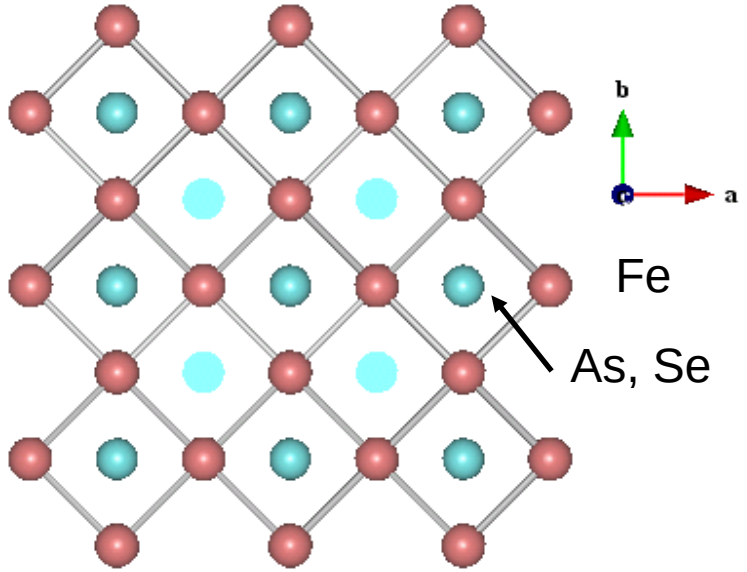


"11" (FeSe)

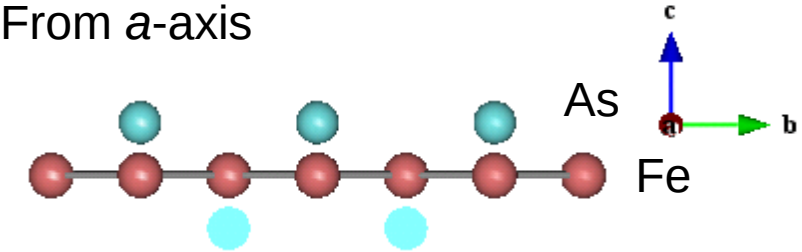


From *c*-axis

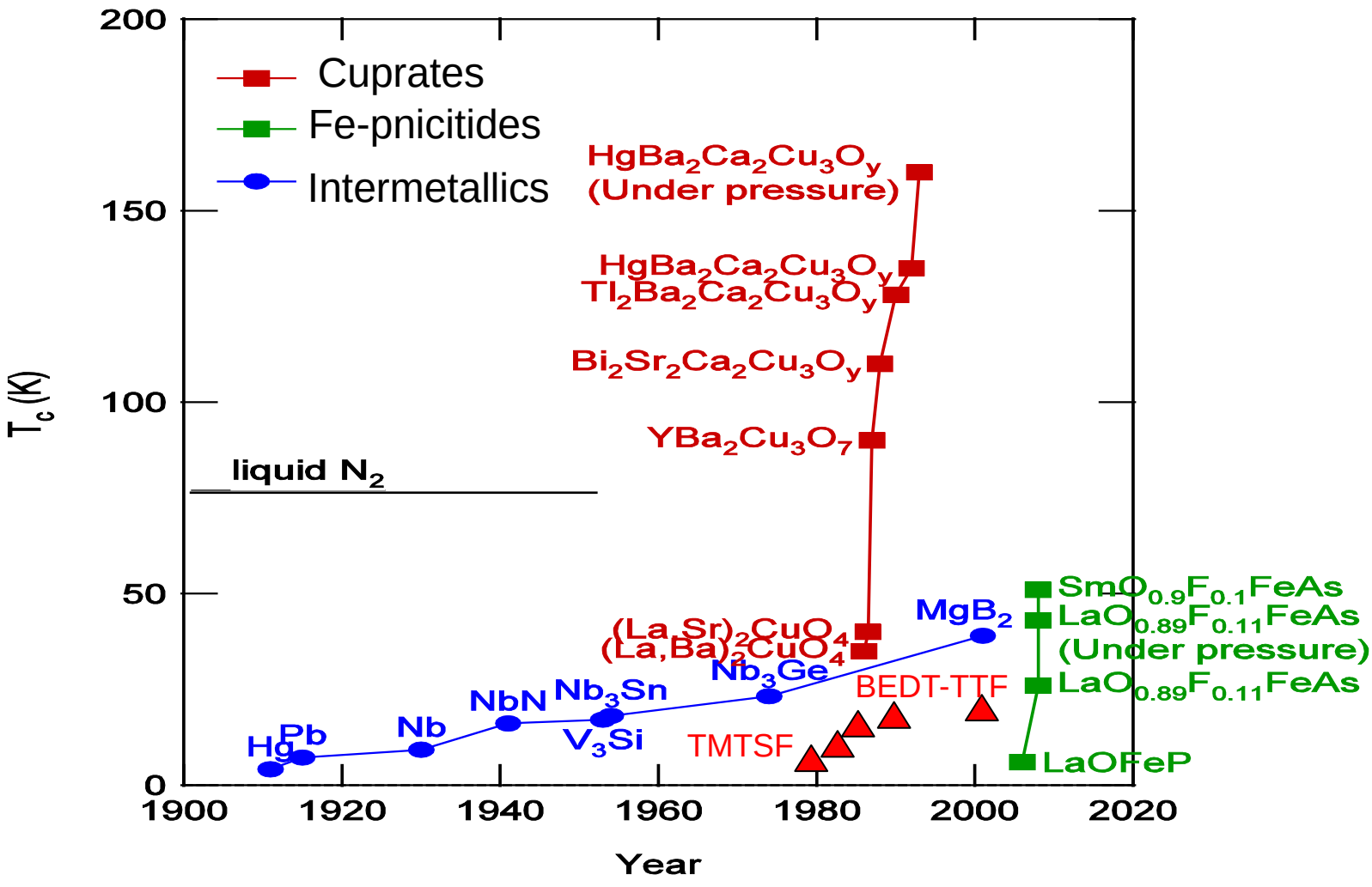
- 2D square lattice of Fe atom



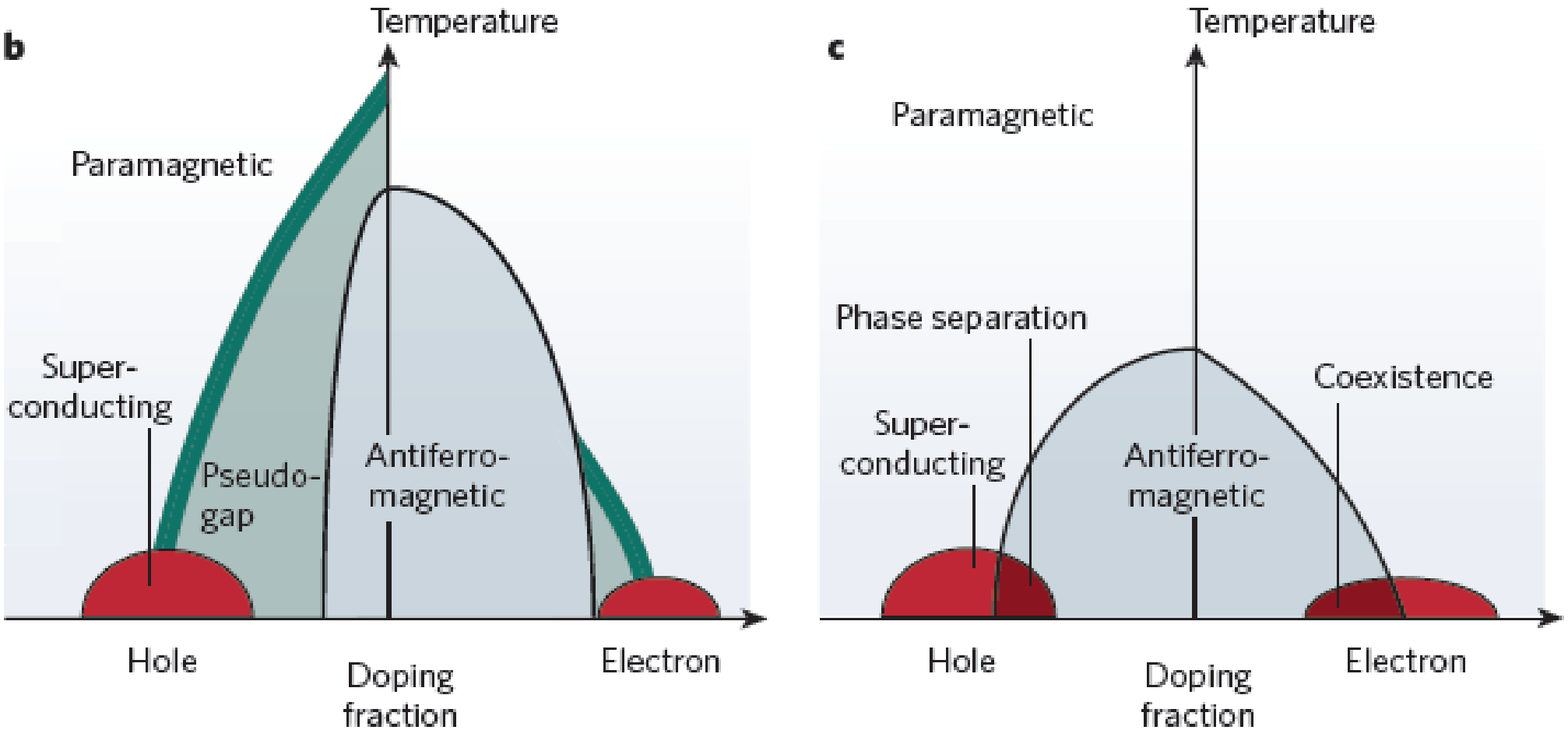
From *a*-axis



Y. Kamihara *et al., J. Am. Chem. Soc. 130, 3296 (2008).*


Cuprates
Fe-pnicitides
Intermetallics
HgBa2Ca2Cu3Oy
(Under pressure)
HgBa2Ca2Cu3Oy
Tl2Ba2Ca2Cu3Oy
Bi2Sr2Ca2Cu3Oy
YBa2Cu3O7
liquid N2
(La,Sr)2CuO4
(La,Ba)2CuO4
MgB2
Nb3Ge
BEDT-TTF
NbN
Nb3Sn
Nb
Hg
Pb
V3Si
TMTSF
SmO0.9F0.1FeAs
LaO0.89F0.11FeAs
(Under pressure)
LaO0.89F0.11FeAs
LaOFeP
Tc (K)
Year
200
150
100
50
0
1900
1920
1940
1960
1980
2000
2020

Phase diagrams of copper oxide and iron arsenide superconductors.



Mazin, Nature 464, 183 (2010).

1. Ordered state
    - Magnetism
    - Orbital physics

2. Electronic structure
    - Electron correlation and QCP
    - Nematicity

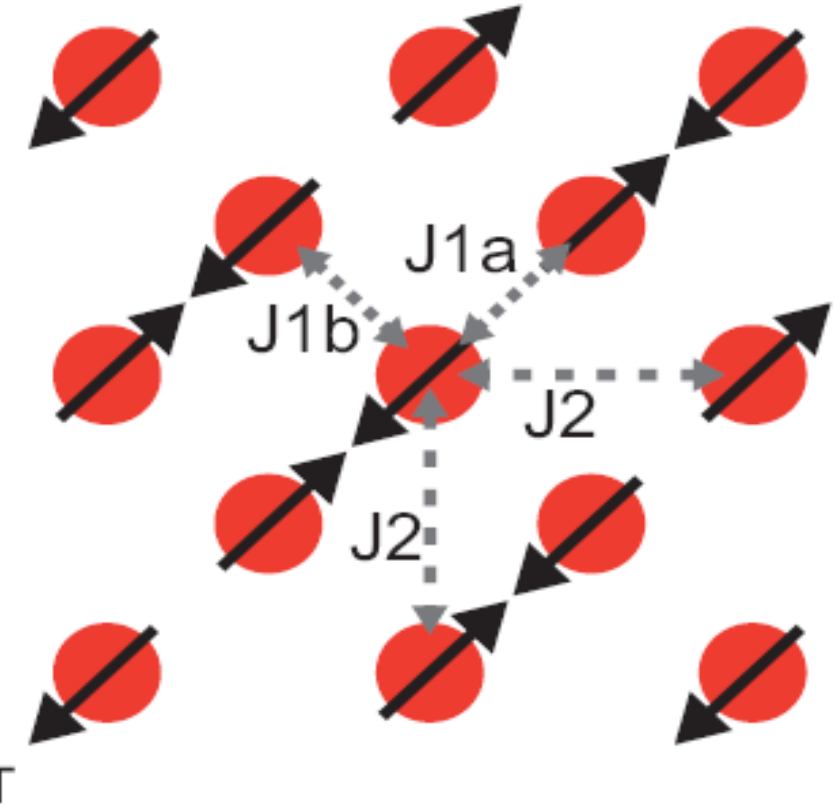
3. Superconducting state
    - Pairing symmetry
    - Pairing interaction

Magnetism

P. Dai (Neutron)
Y. Nakai (NMR)

Spin structures of Fe-based parent compounds

Ordered state (1111, 122,111)



Both itinerant and localized models can explain this collinear spin structure.

Itinerant

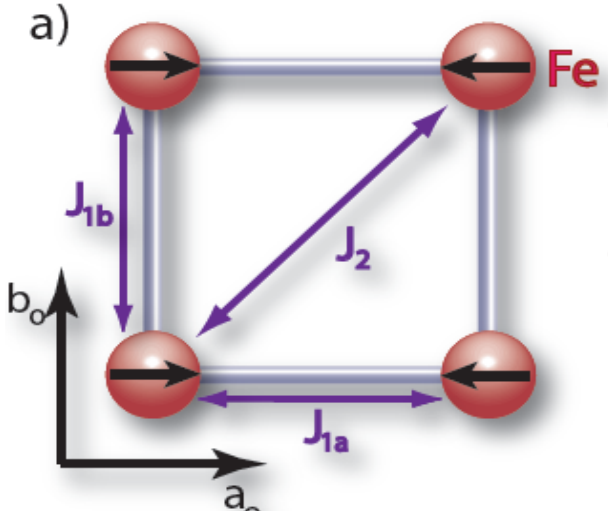
Nesting between electron and hole pockets

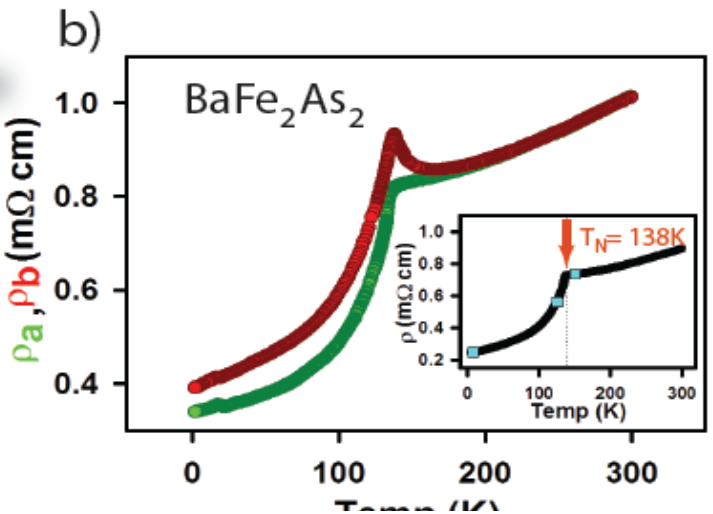
Localized

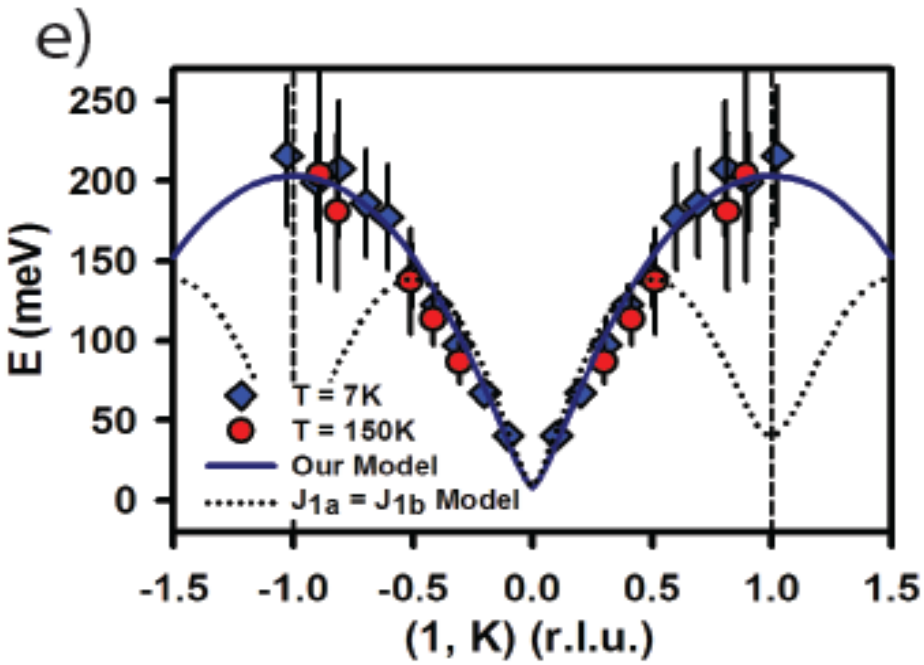
Frustration disappears below T_S

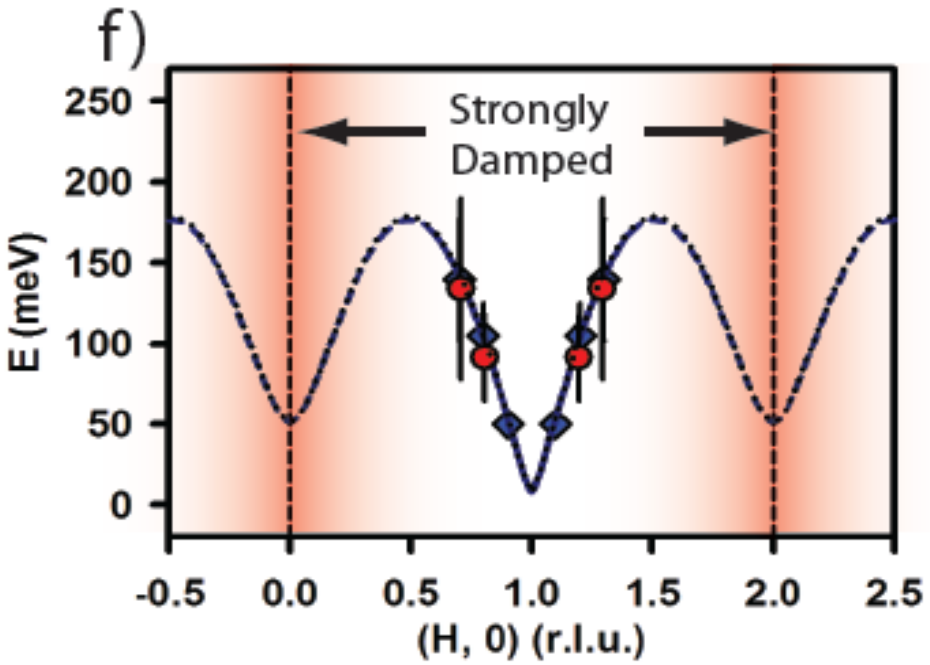
Wave vector dependence of spin-waves in $BaFe_2As_2$

P. Dai





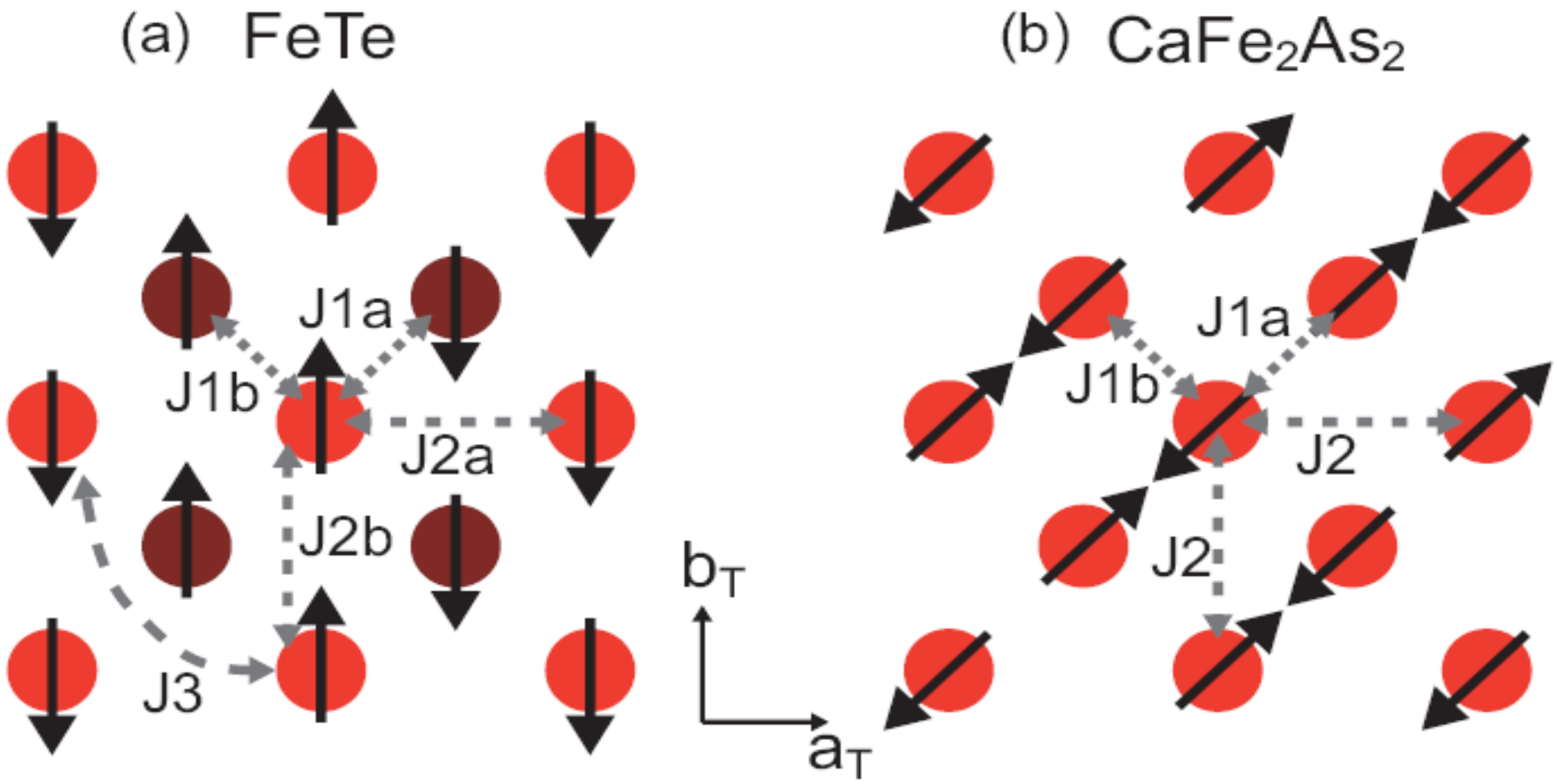




SJ1a = 49 *SJ1b* = -5.7 *SJ2* = 19 *SJc* = 5.3 meV

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

Spin structures of Fe-based parent compounds



FeTe

11

Bi-collinear spin structure

CaFe2As2

122

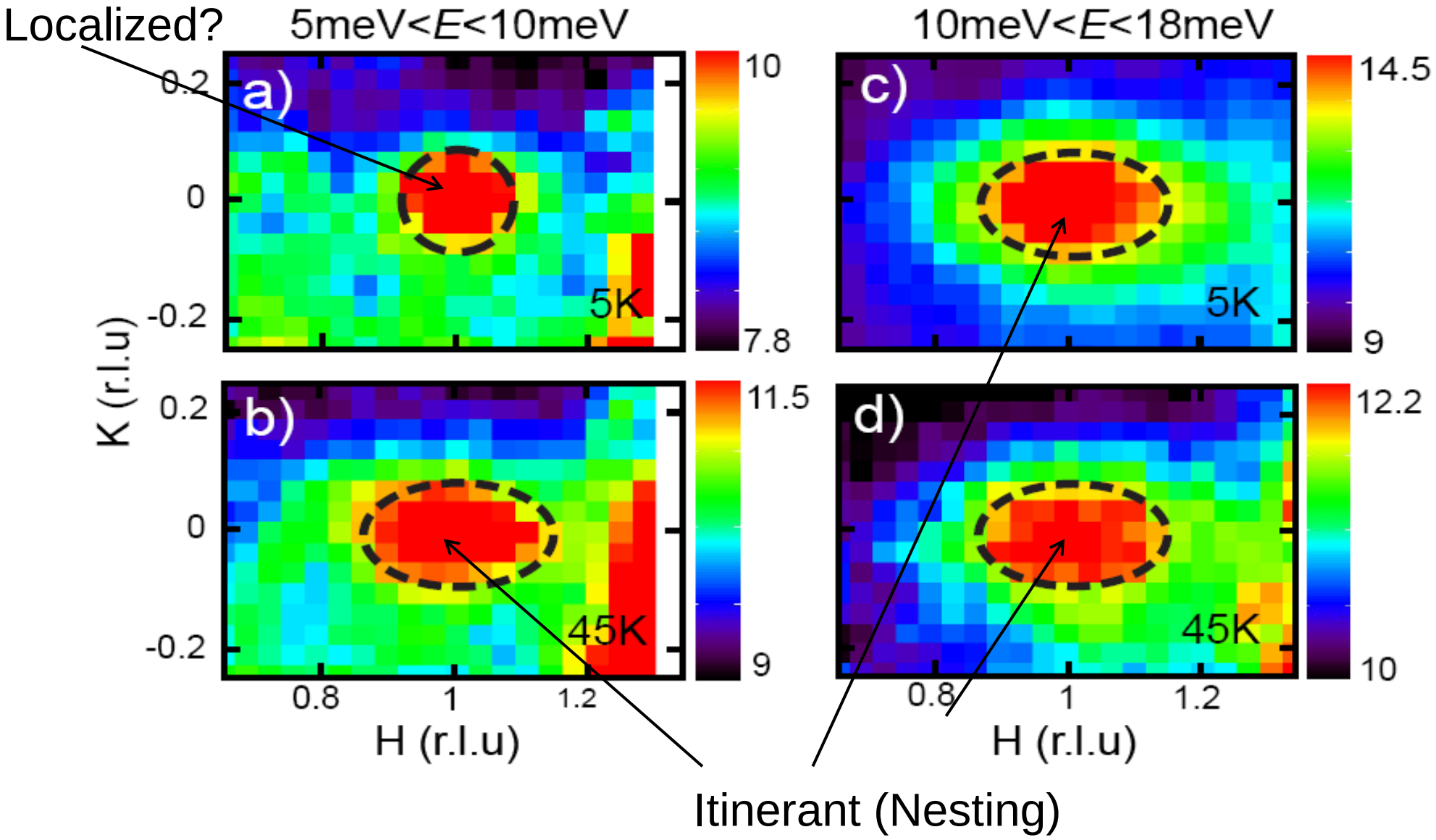
Collinear spin structure

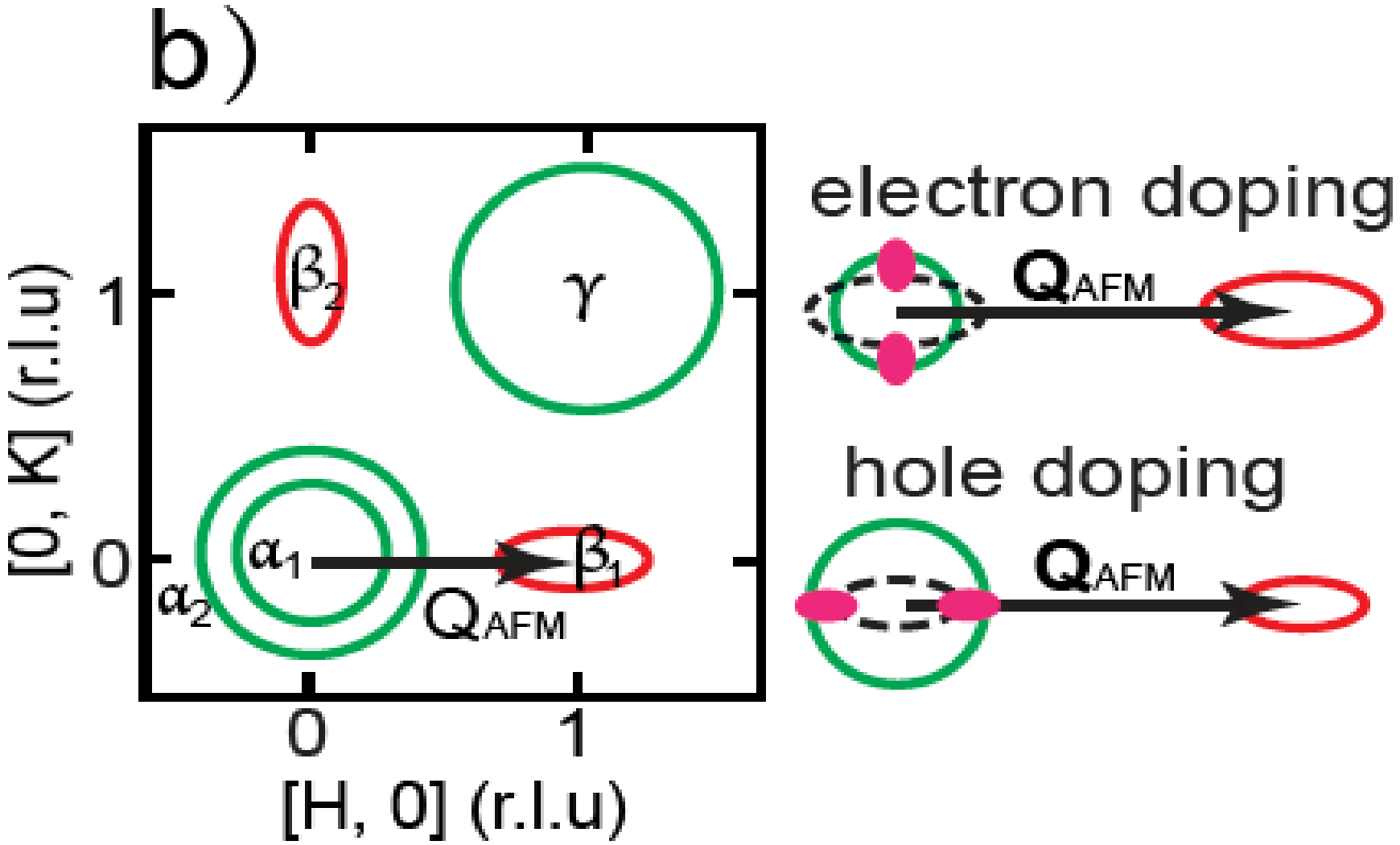
Cannot be explained by intinerant model?

Low energy spin excitation $Ba_{0.6}K_{0.4}Fe_2As_2$

P. Dai

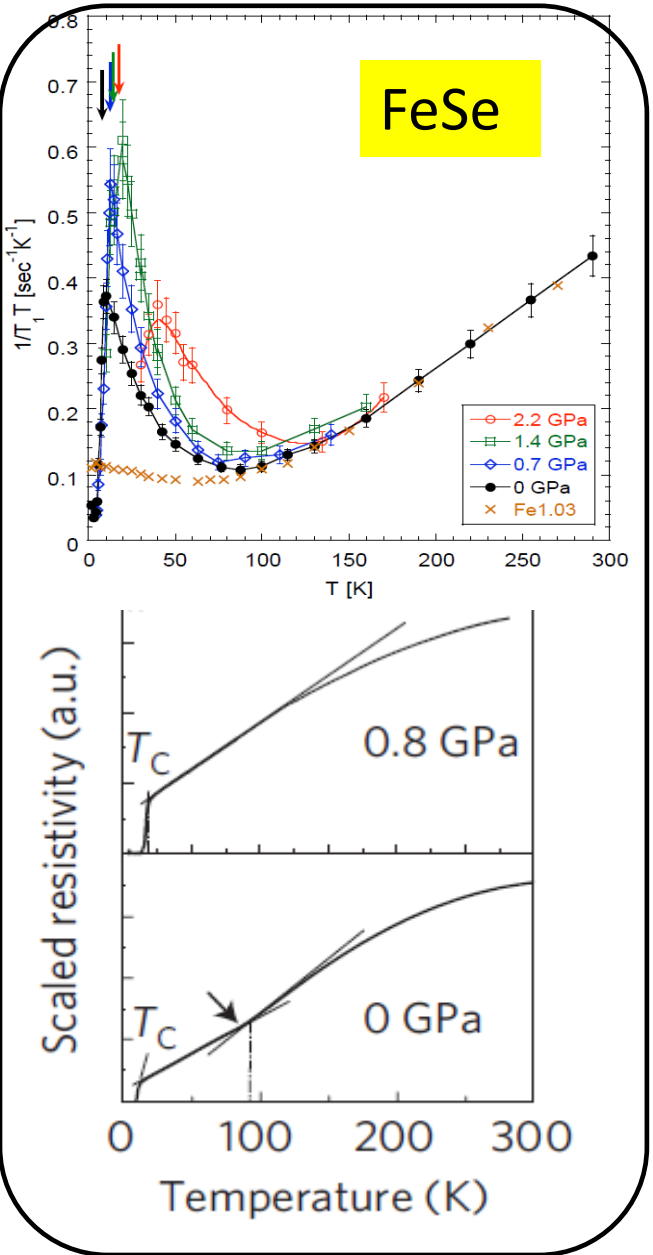
Temperature dependence of the neutron spin resonance and low-energy excitations

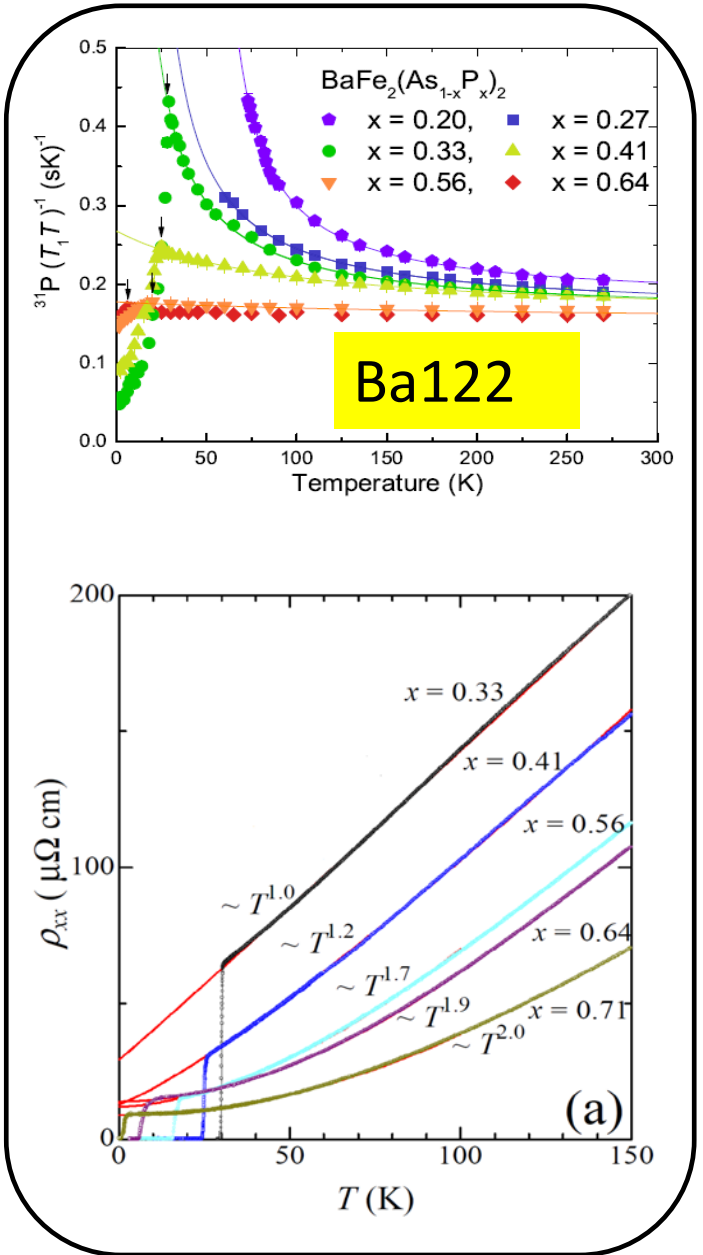


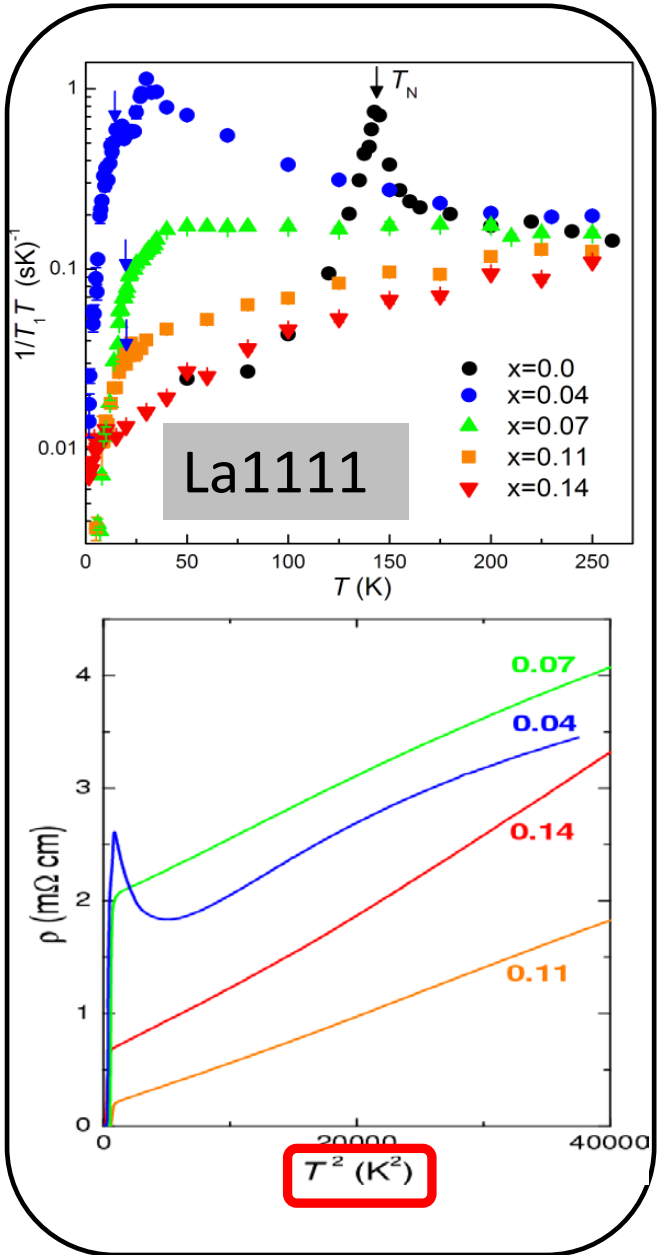

b)
β2
γ
α1
β1
α2
QAFM
1
0
0
1
[0, K] (r.l.u)
[H, 0] (r.l.u)
electron doping
QAFM
hole doping
QAFM

NMR: Ba122 & FeSe & La1111

Y. Nakai



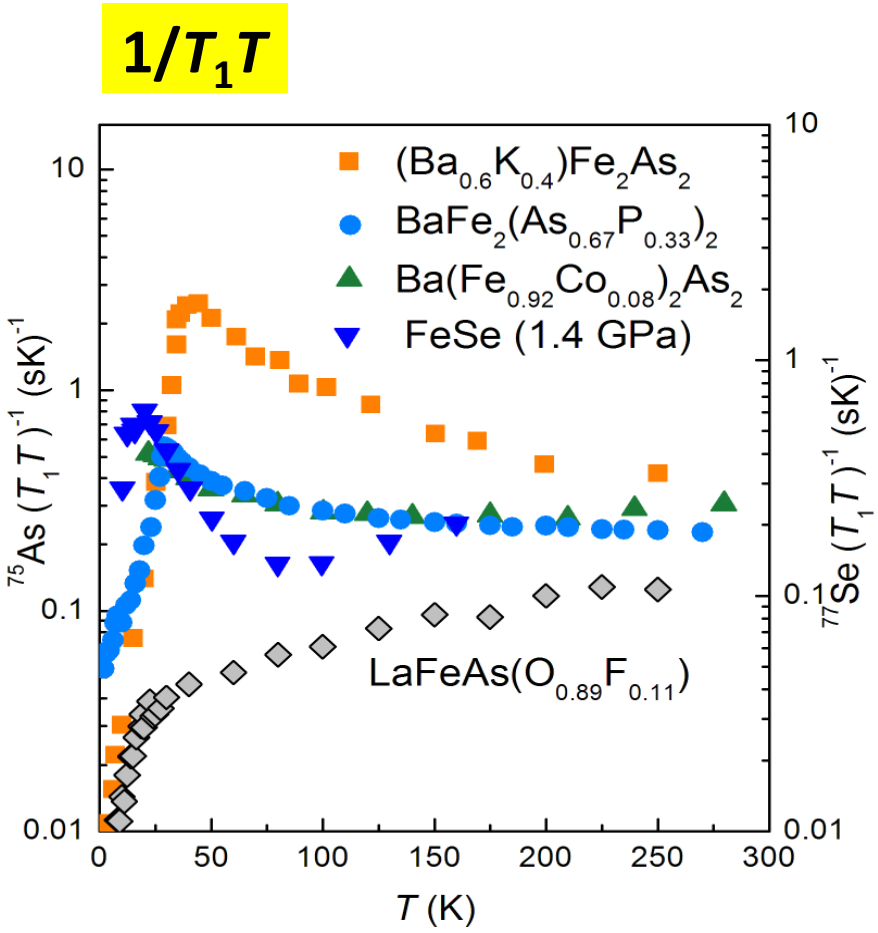




Low-energy AF fluctuations & superconductivity

Y. Nakai

- Development of AF fluctuations at low T is observed in optimal Ba122 & FeSe superconductors.
- In contrast, enhancement of AF fluctuations is not observed in optimal LaFeAs(O,F).



Relationship between AF spin fluctuations ana superconductivity appears different between in Ba122, FeSe and LaFeAs(O,F).

questions

Magnetism; Itinerant or localized?

Magnitude of localized moment (too small)

Bicollinear spin structure of FeTe

Why are the low energy spin fluctuations small in 1111 system with highest T_c?

Orbital physics

Orbital ordering

Lifting of the degeneracy between *xz* and *yz* orbitals

Nematicity

P. Dai (neutron),

I.Fisher (Transport ARPES)

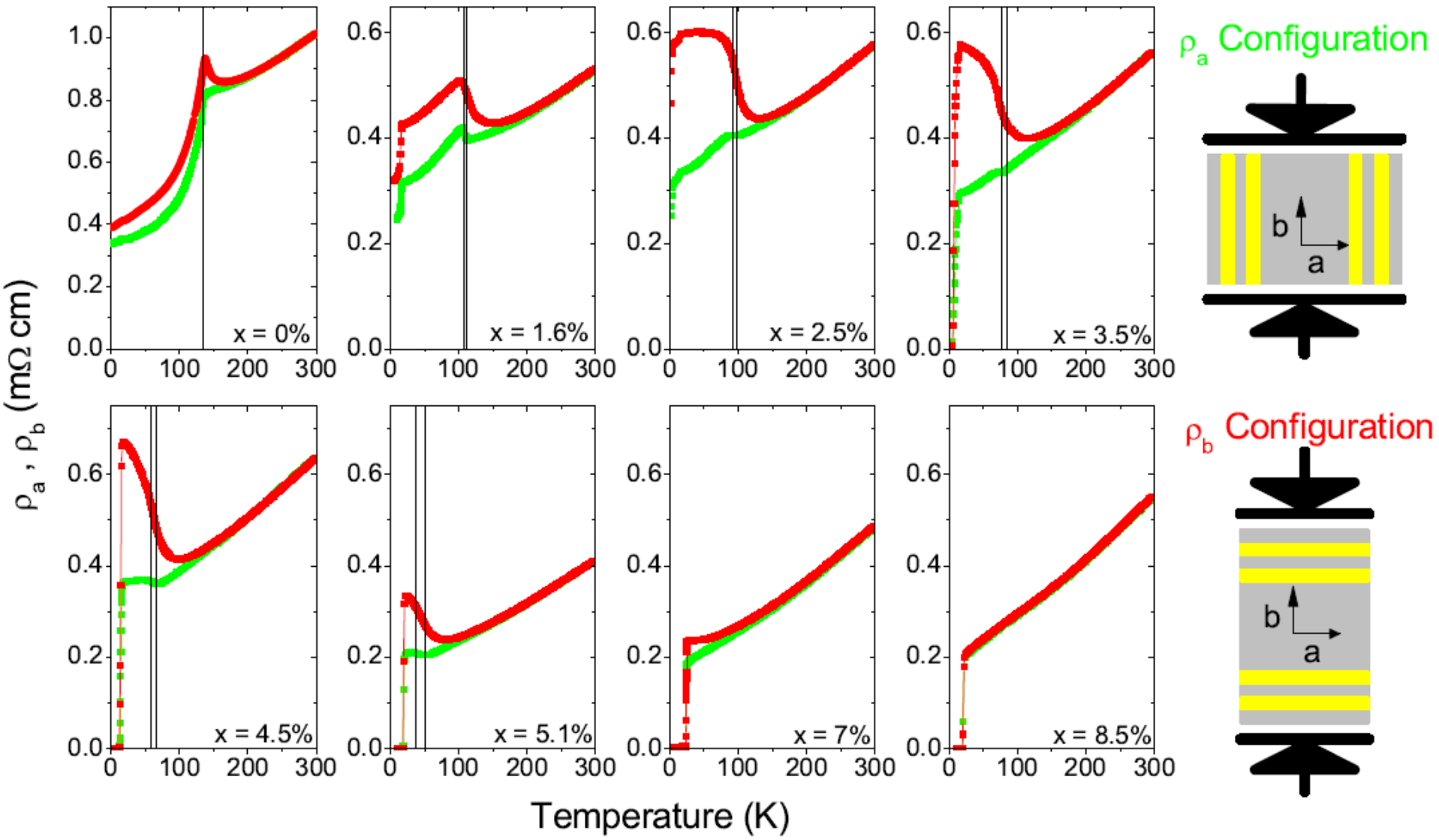
L. Degiorgi (Optical conductivity)

Y. Matsuda (Torque)

R. Porozorov (Transport)

I. Fisher

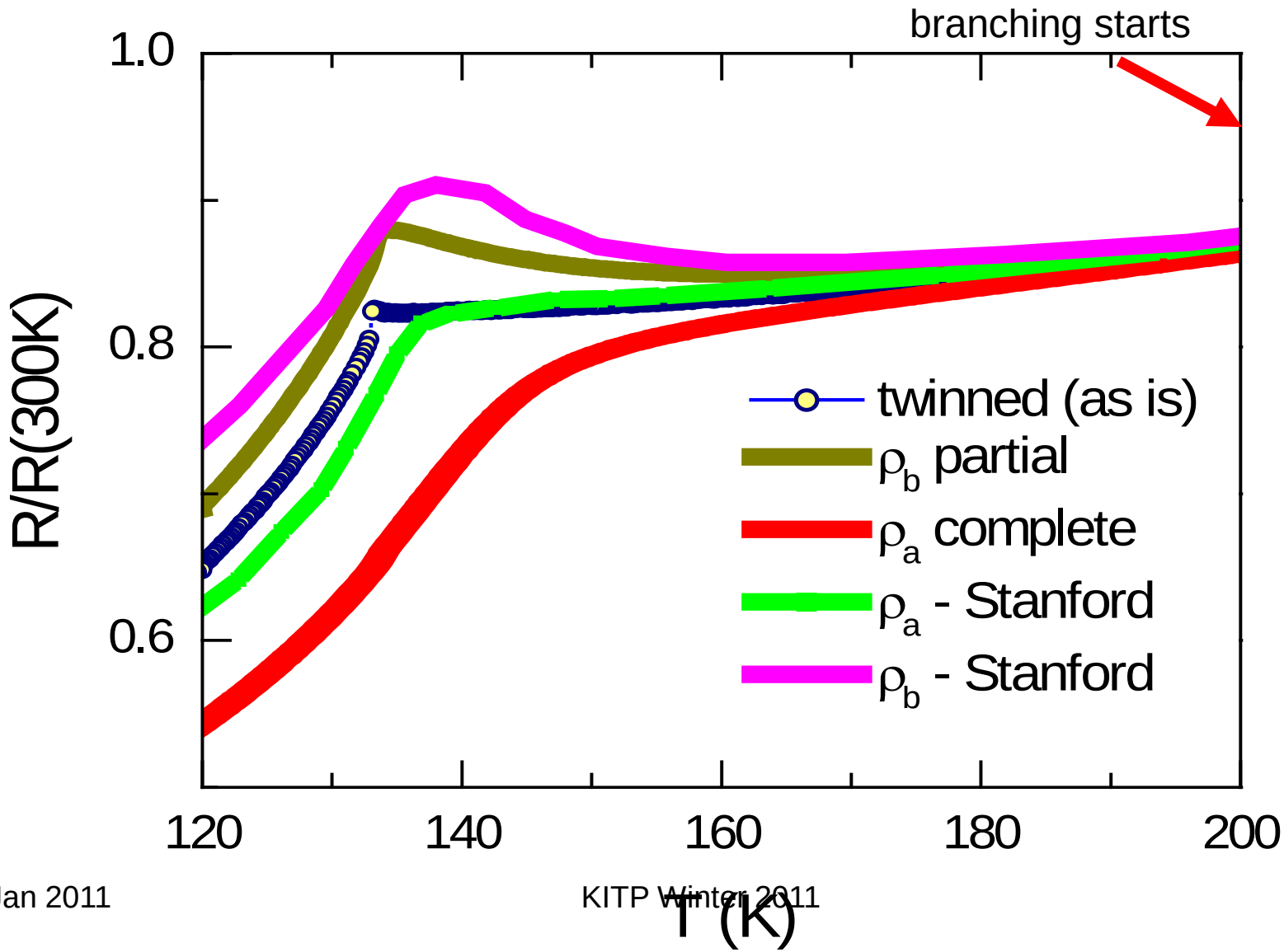
$Ba(Fe_{1-x}Co_x)_2As_2$ (detwinned by uniaxial pressure)



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

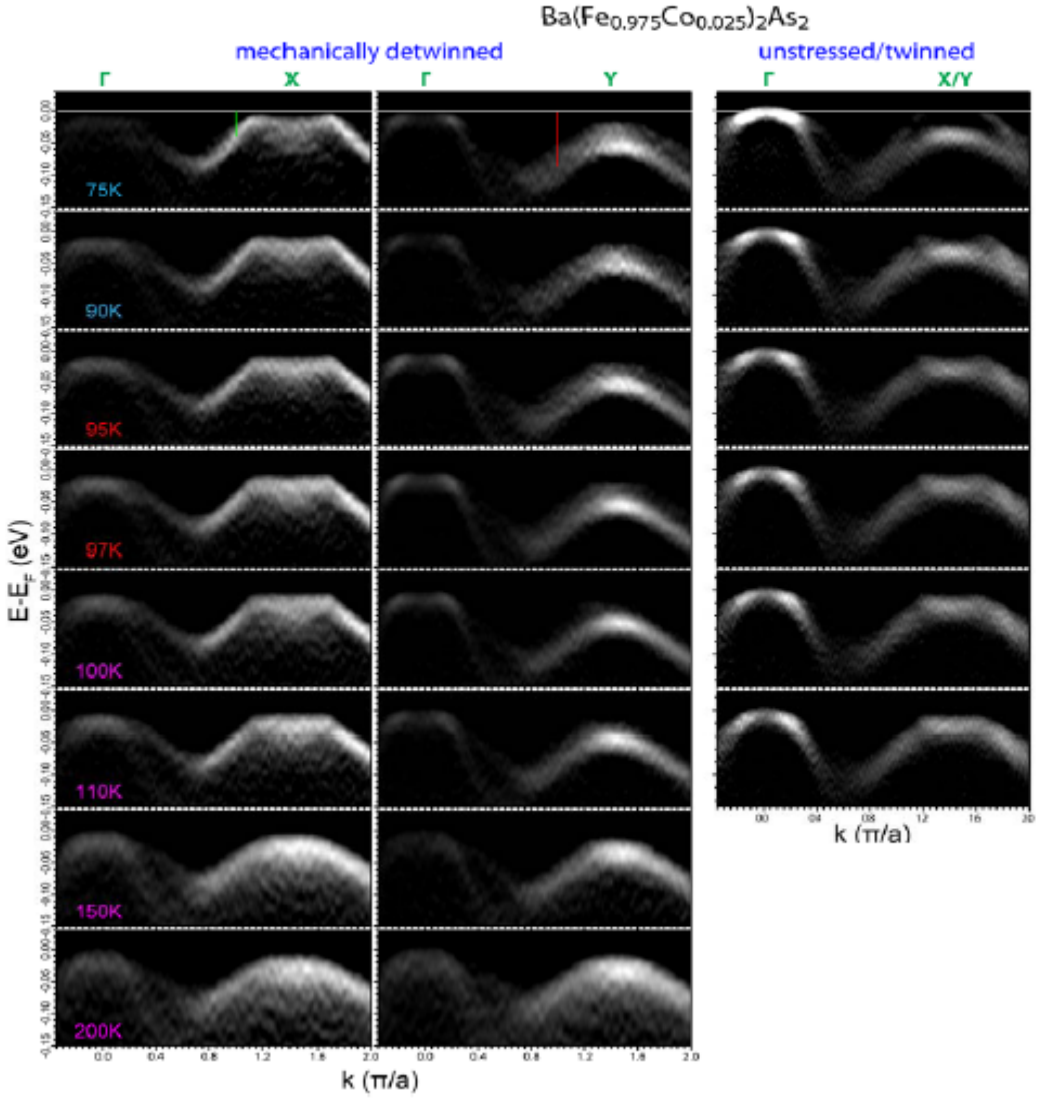
Ba122 – anisotropy in both ORT & TET!

R. Porozorov

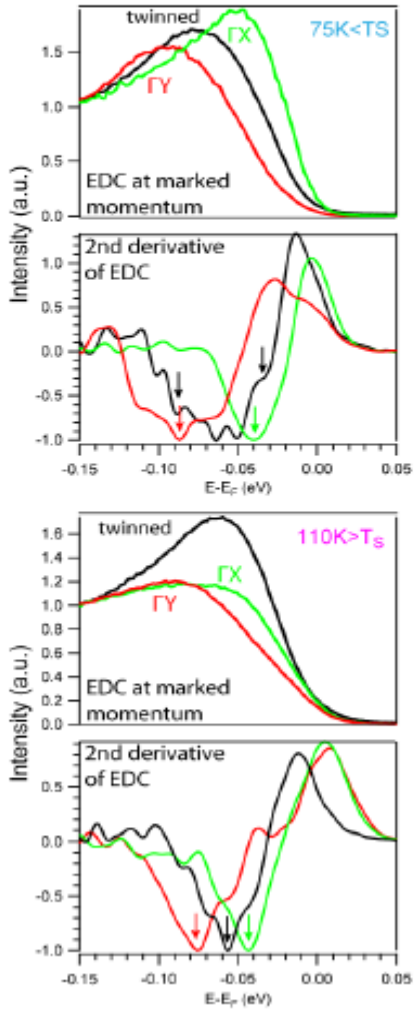


Comparison of stressed and unstressed crystals

M. Yi, D-H. Lu, Z.X. Shen et al arXiv:1011.0050



T_N = 94.5 K T_s = 99 K

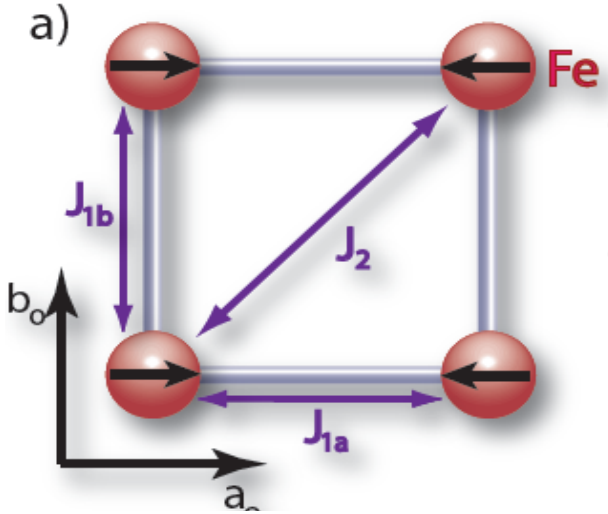


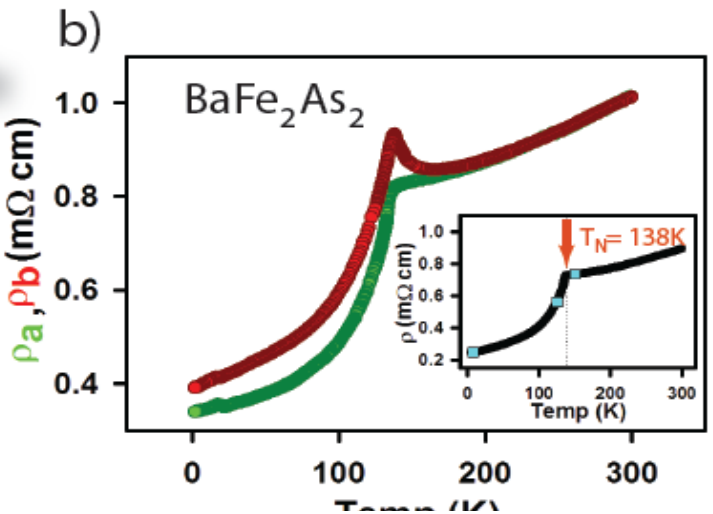
Energy Distribution Curve

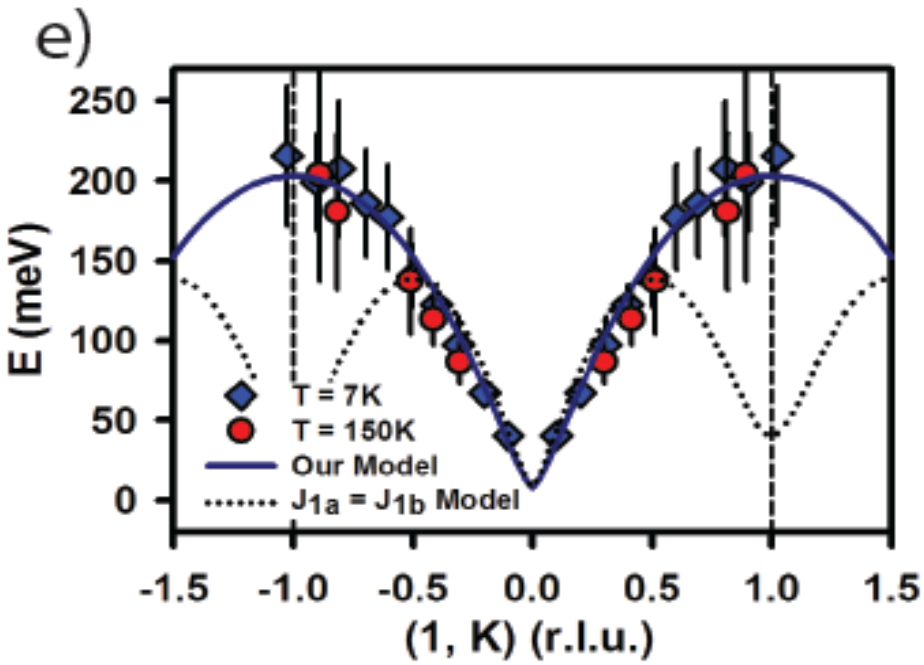
Nematic :static in detwinned crystal
fluctuation in twinned crystal

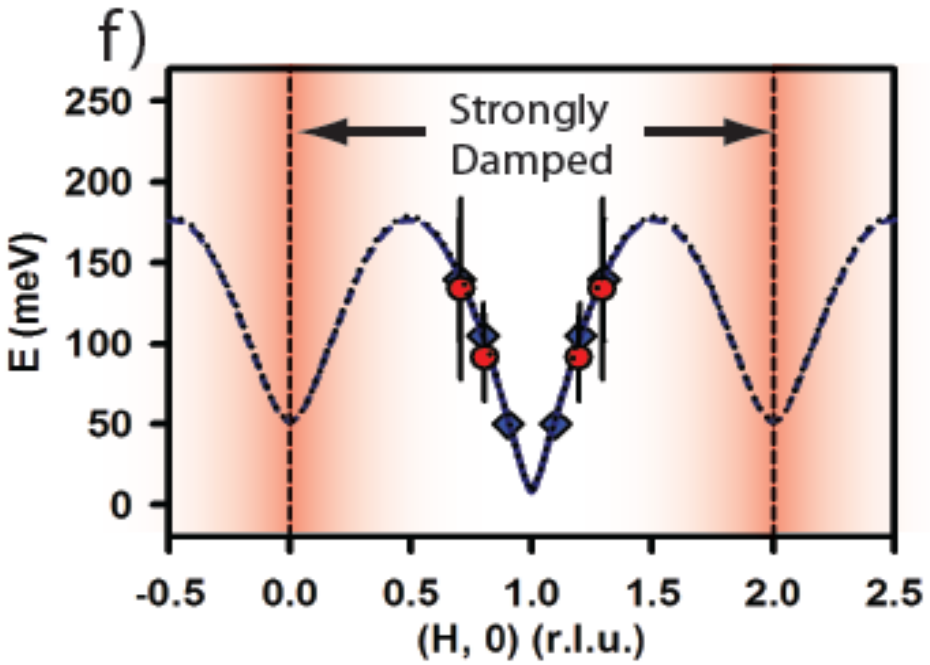
Wave vector dependence of spin-waves in $BaFe_2As_2$

P. Dai









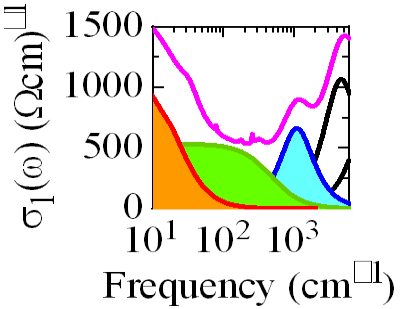
SJ1a = 49 *SJ1b* = -5.7 *SJ2* = 19 *SJc* = 5.3 meV

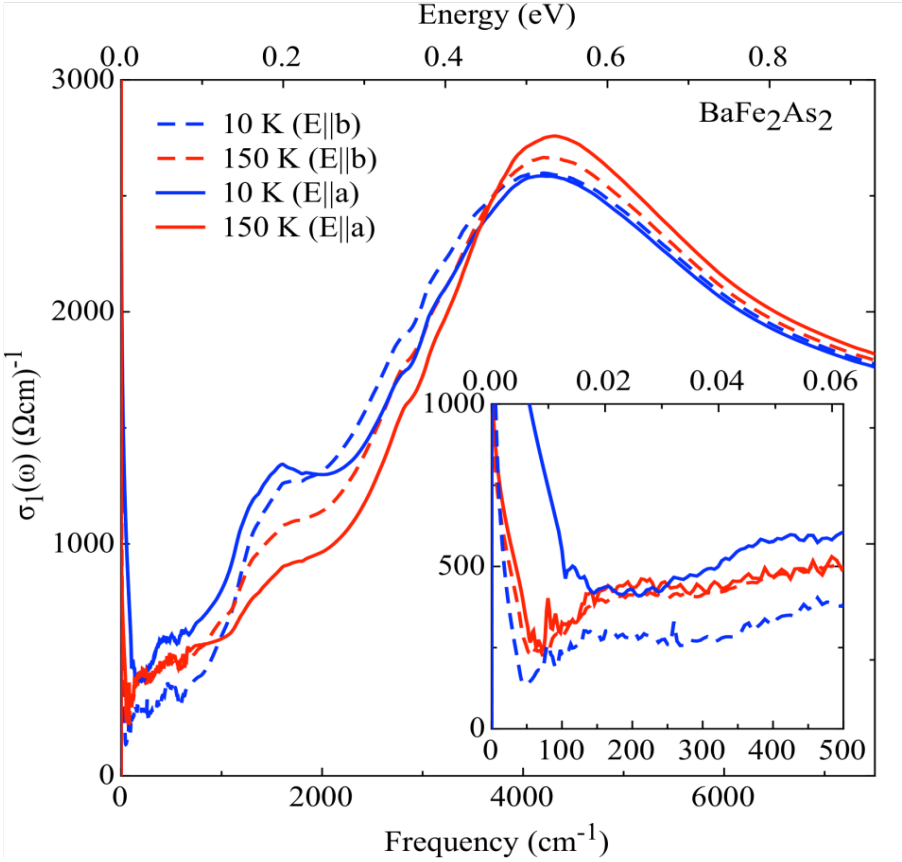
Jun Zhao *et al.,* Nature Physics 5, 555 (2009).

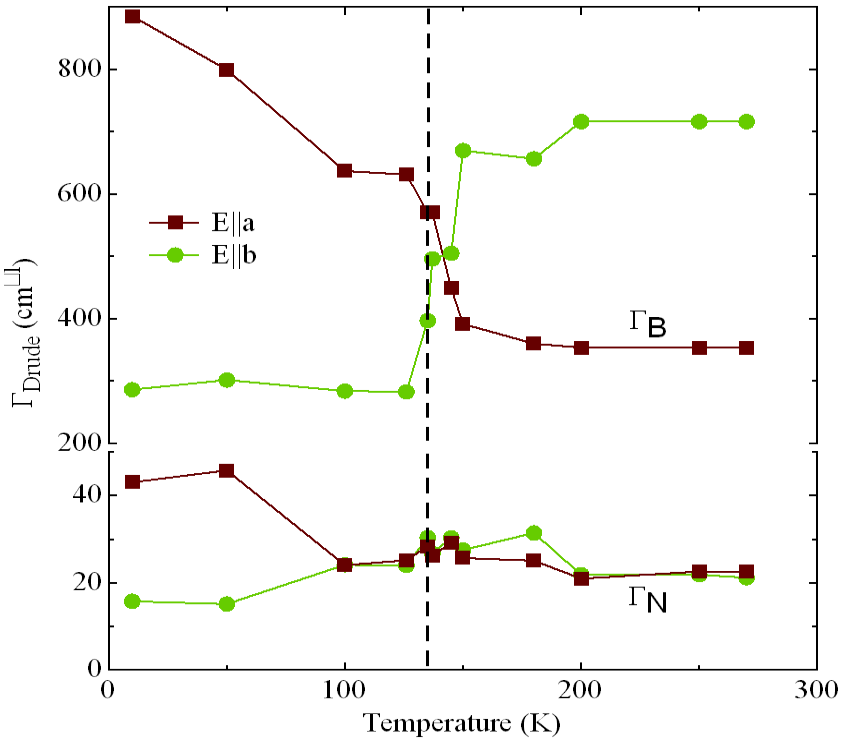
Nematicity observed by optical conductivity

$Ba(Fe_{1-x}Co_x)_2As_2$ detwinned

L. Degiorgi

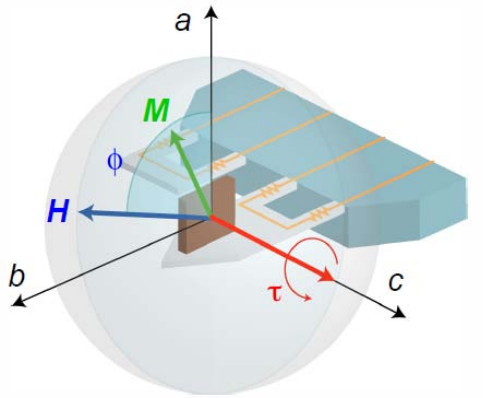






Nematicity observed in torque measurements (no uniaxial stress)

Y. Matsuda



2-fold symmetry begins to grow at $T < 150$ K.

→Broken Rotational Symmetry
above the Tetra.-Ortho. Structural Transition.

Thermodynamic Evidence for
“Nematic Order Transition”

Questions

Orbital ordering?

How is it related with structural transition, SDW and nematicity?

Nematicity

Static or fluctuation above T_s?

Origin; Orbital? Spin?

Electron correlation effect

1111

122

111

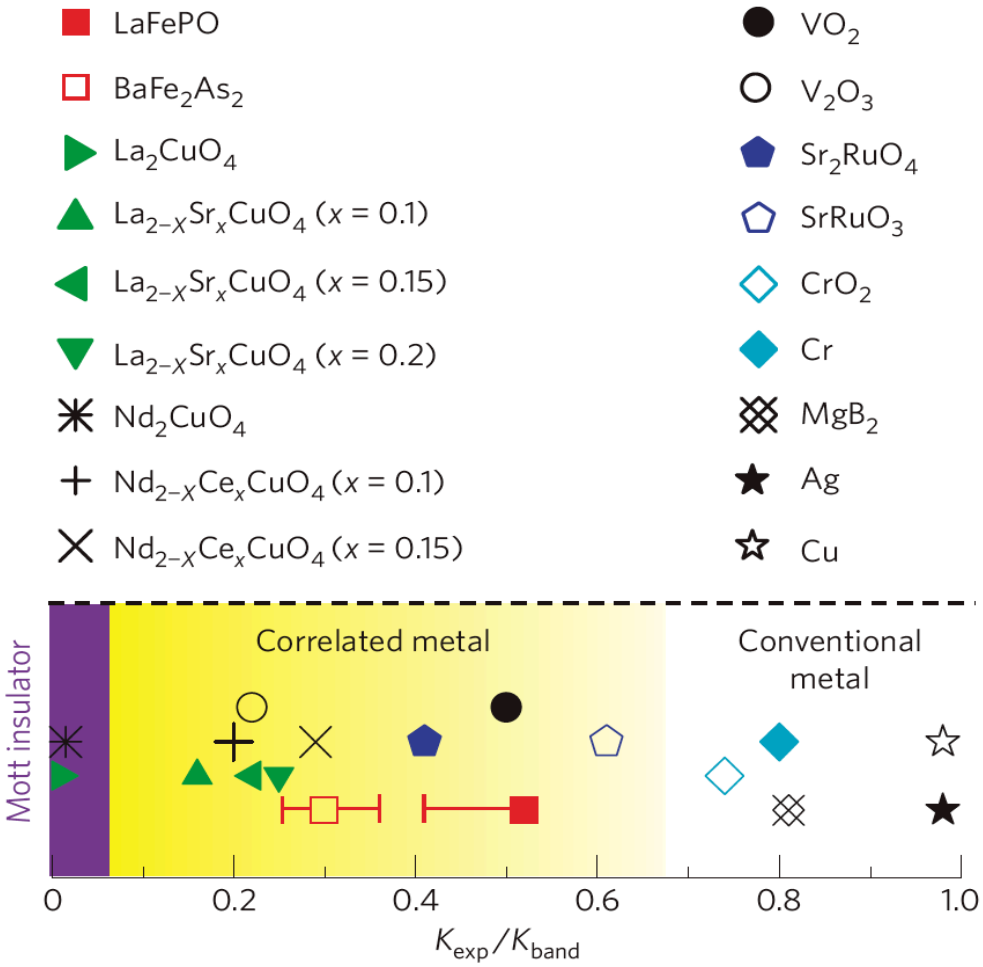
11

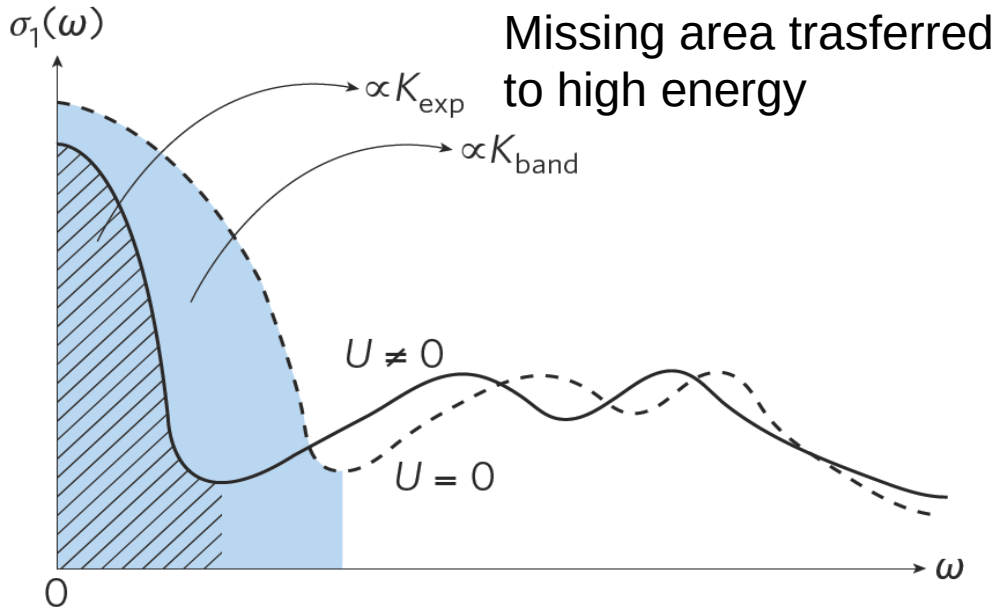
strong

Optical conductivity
D.Basov,
L. Degiorgi
Quantum oscillation
A. Coldea
Y. Matsuda
ARPES
H.Ding
Specific heat
H.H. Wen
NMR
Y. Nakai

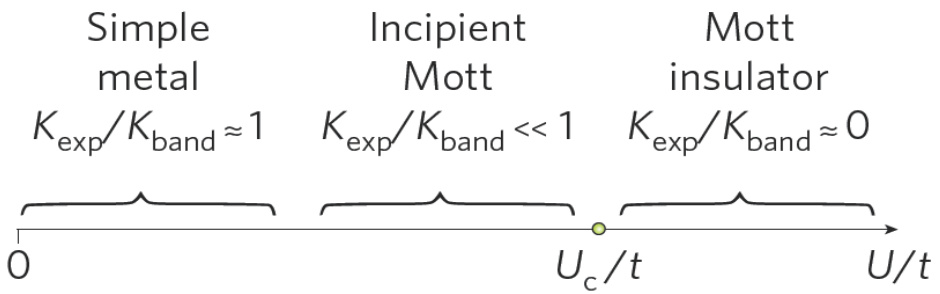
How Strong Are Electronic Correlations in Iron-Pnictides?

Dimitri Basov





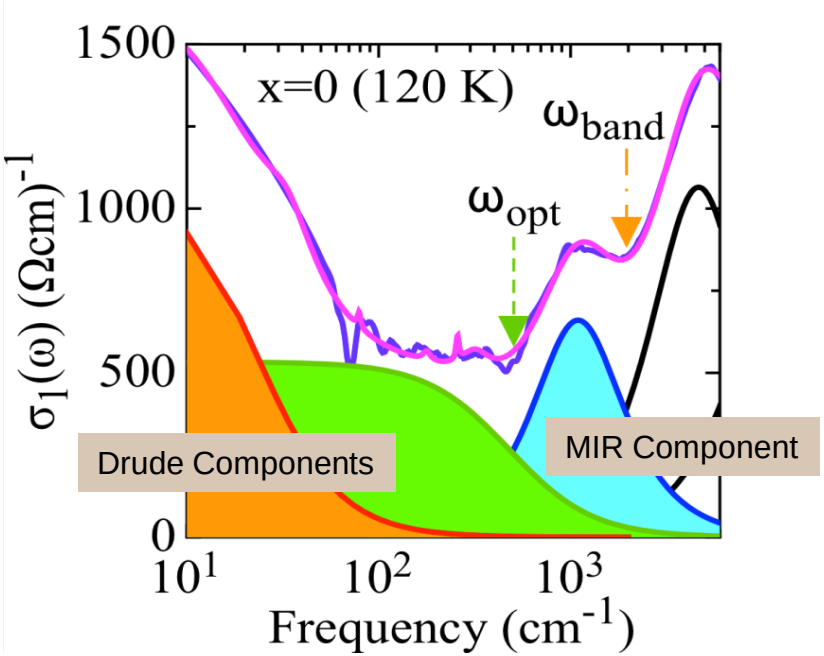
Missing area trasferred to high energy



$$K_{exp}(\omega_c) = \frac{\hbar c_0}{e^2} \int_0^{\omega_c} \frac{2\hbar}{\pi} \sigma_1(\omega) d\omega$$

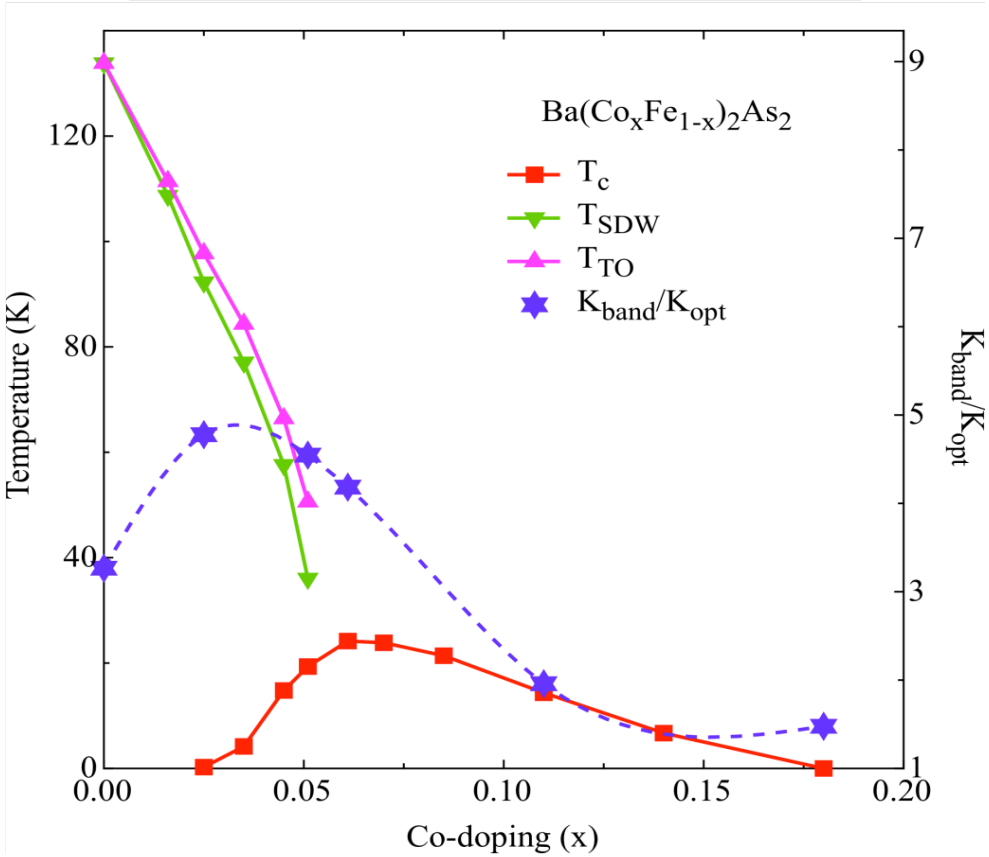
Electronic Correlations and Phase Diagram in $Ba(Fe_{1-x}Co_x)_2As_2$

L. Degiorgi



$$\frac{K_{opt}}{K_{band}} = \frac{\omega_p^2}{\omega_p^2 + \left(\omega_p^{MIR}\right)^2} = \frac{\int_0^{\omega_{opt}} \sigma_1(\omega) d\omega}{\int_0^{\omega_{band}} \sigma_1(\omega) d\omega}$$

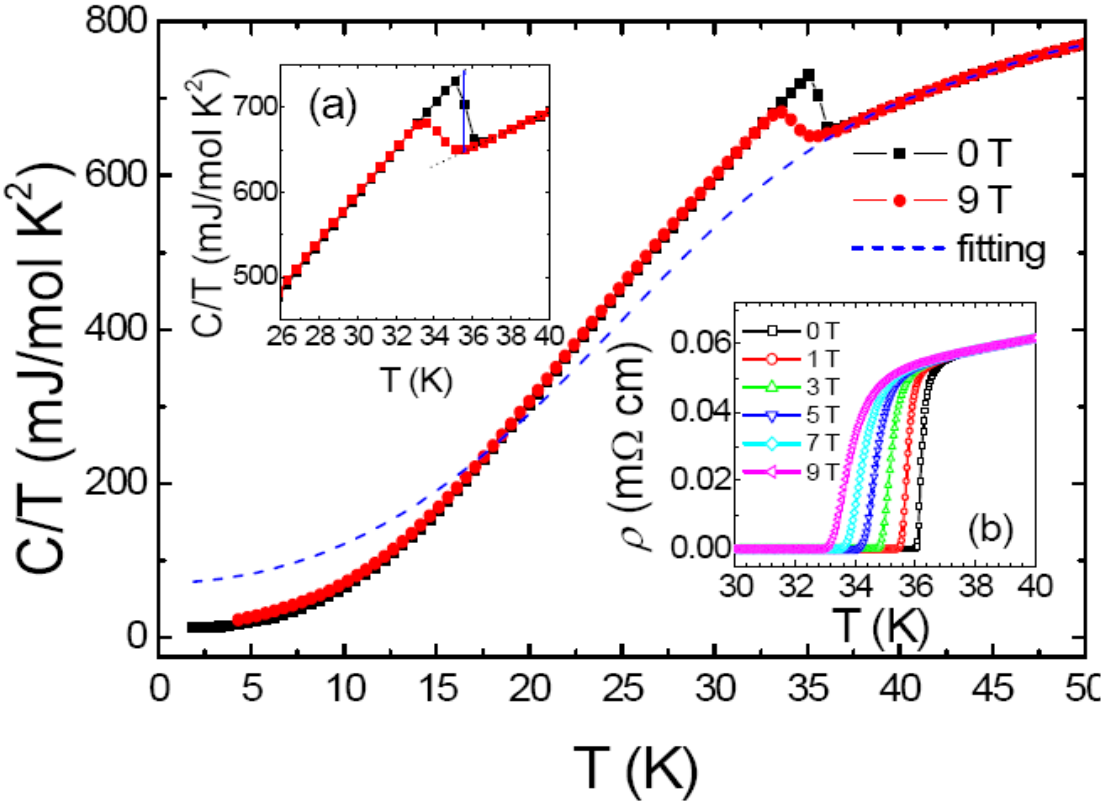
Strength of Electronic Correlation



Specific heat in $Ba_{1-x}K_xFe_2As_2$

Strong renormalization of the electron mass

H.H.Wen



$$\Delta C/T\,|_{T_c} = 98-102 mJ/molK^2$$

$$\frac{\Delta C}{\gamma_n T_c} = 1.43$$ Weak coupling

$$\frac{\Delta C}{\gamma_n T_c} \approx 2$$ Strong coupling

$$\gamma_n \geq 50 mJ/molK^2$$

$$\gamma_n = \frac{2\pi^2}{3} N(E_F) k_B^2 (1+\lambda),$$

Extremely strong mass enhancement!

Consistent with ARPES data

H. Ding et al., arXiv:0812.0534

Gang Mu et al., Phys. Rev. B79, 174501 (2009)

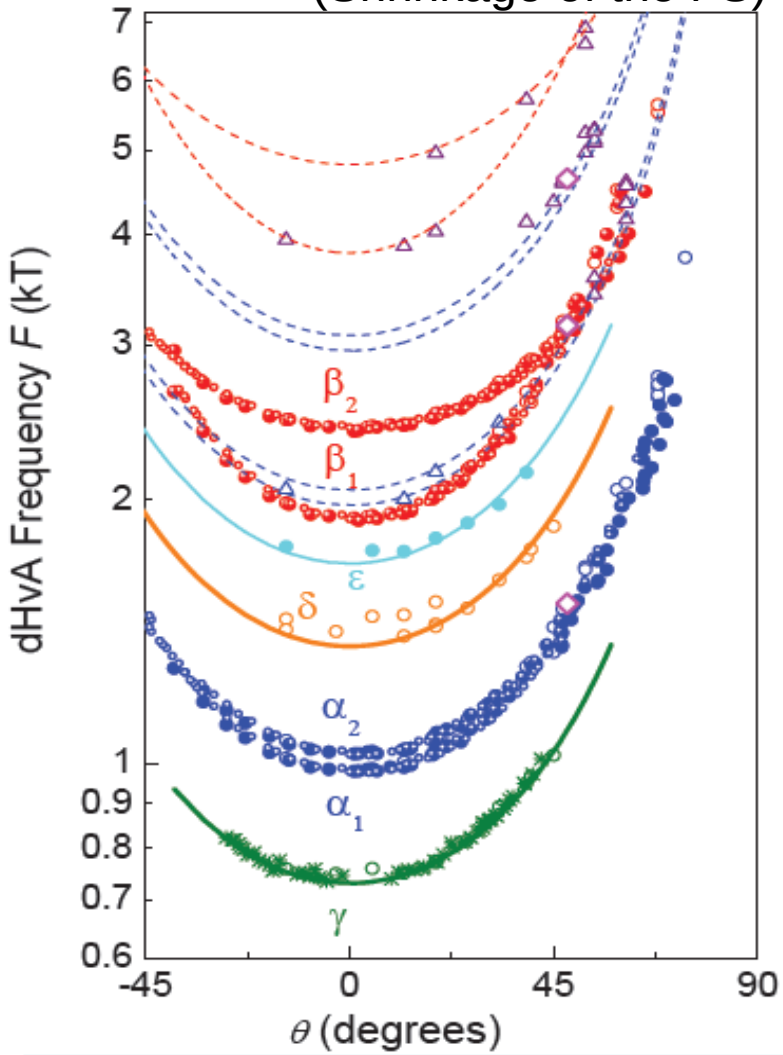
Heavily hole doped KFe_2As_2 γ~100 mJ/K²mol

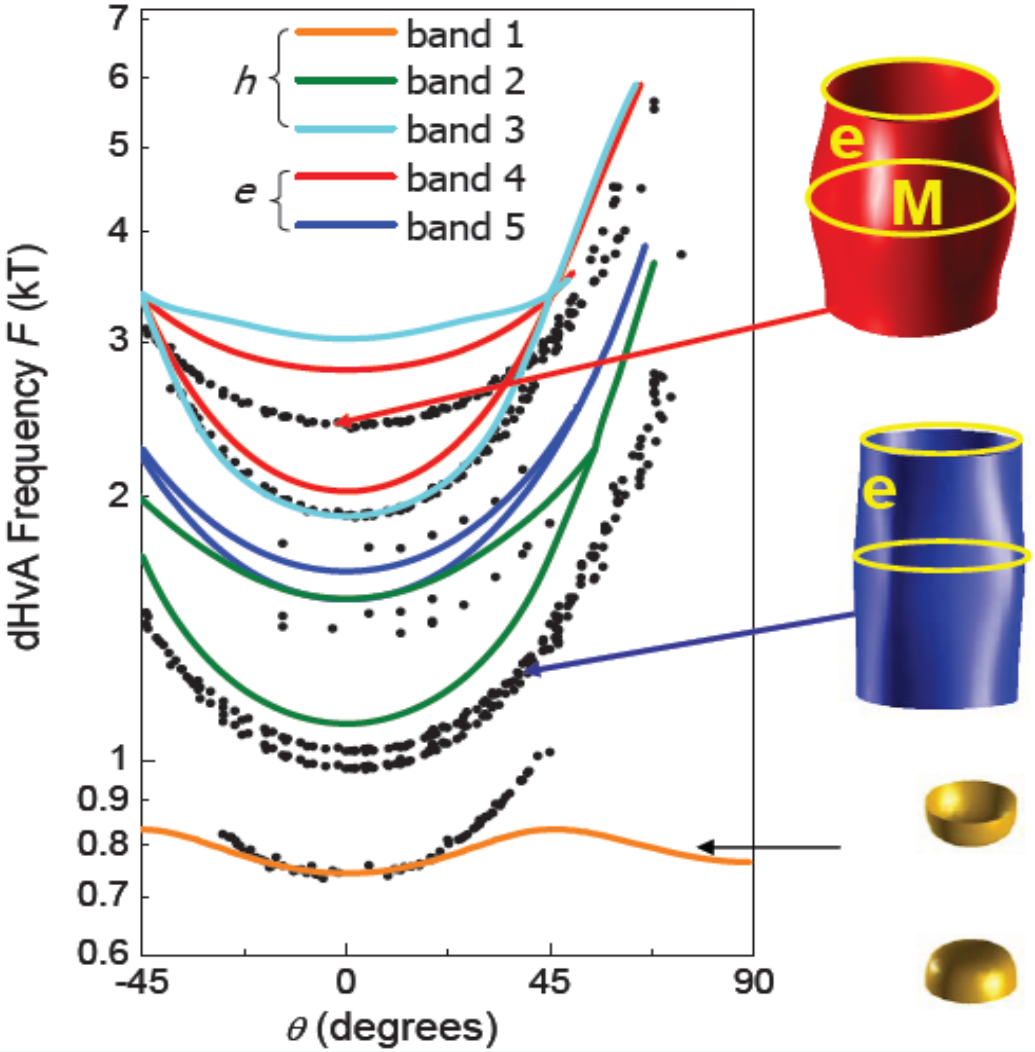
dHvA data versus band structure calculations

LaFePO

(Shrinkage of the FS)

A. Coldea



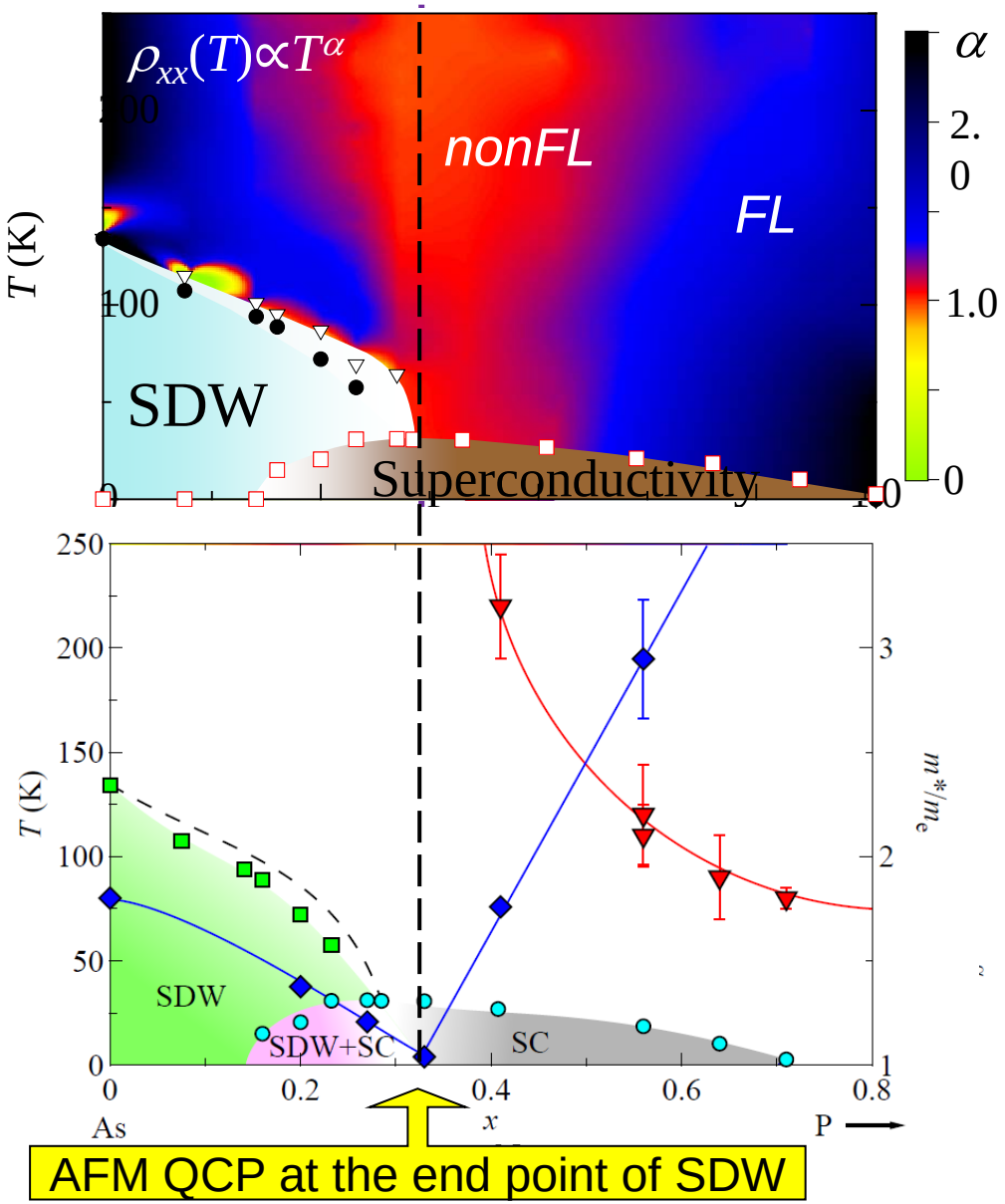


- electronic branches show similar dispersion to the experimental α and β pockets;
- no experimental branch matches the weak dispersion due to the 3D hole pocket;

No shrinkage of the FS in collapsed tetragonal $CaFe_2As_2$

Quantum Criticality

Mainly $BaFe_2(As,P)_2$



At a critical doping value x_c=0.33 close to the end point of SDW

T_c becomes maximun

Hallmark of non-Fermi in the transport coefficients

Y. Matsuda

Strong enhancement of effective mass m^* (dHvA and ARPES) as x is tuned towards x_c=0.33

A. Coldia

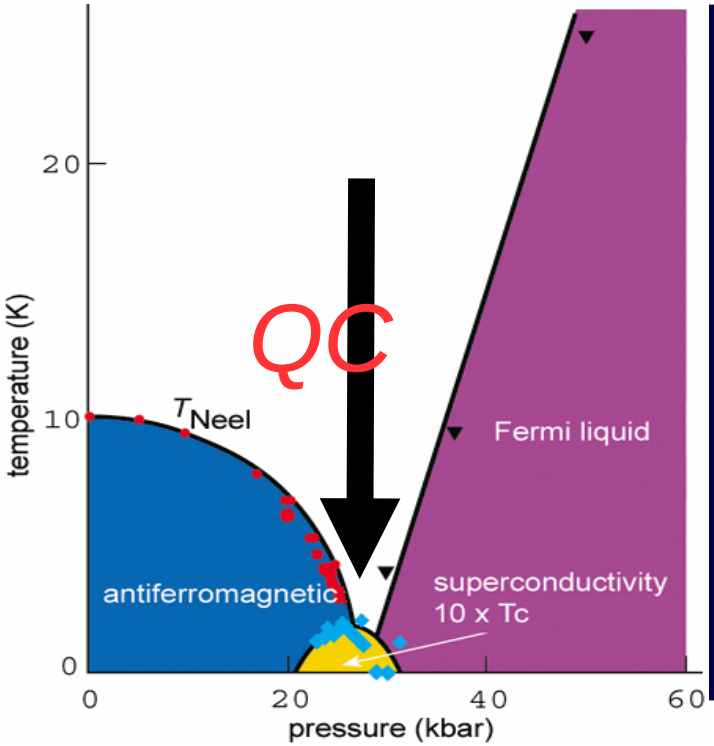
Weiss temperature θ (NMR) goes to zer

Y. Nakai

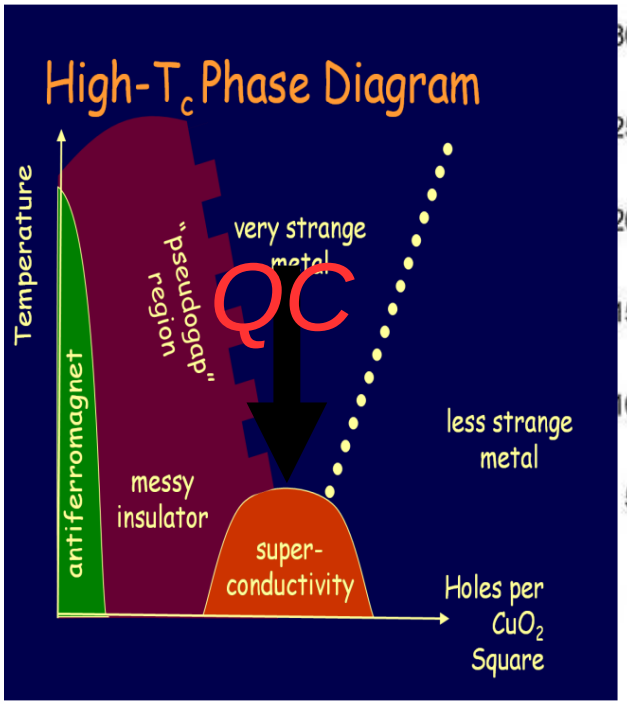
Non-Fermi liquid properties, magnetic fluctuations, electron correlations and superconductivity are intimately linked.

Questions

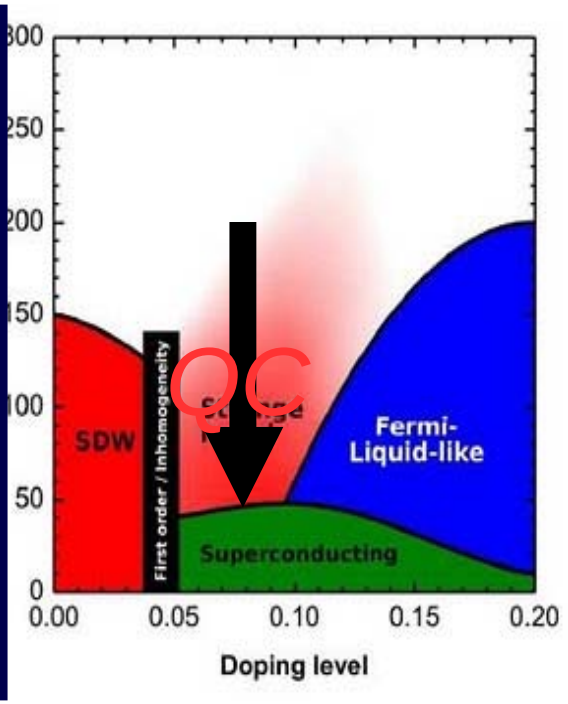
Weak coupling or strong coupling?
Is QCP common feature in pnictide?



Heavy fermions



Cuprates



Pnictides

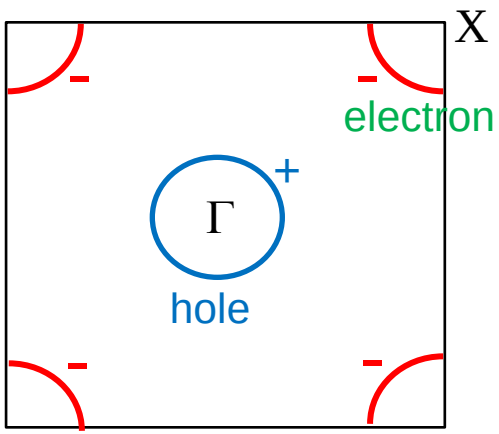
Superconducting gap structure

R. Porozorov (penetration depth)
K. Moler (penetration depth)
Y. Matsuda (penetration depth, thermal conductivity, NMR)
T. Hanaguri (STM)
H. Ding (ARPES)
H.H.Wen (specific heat, Andreev reflection, STM)

2D

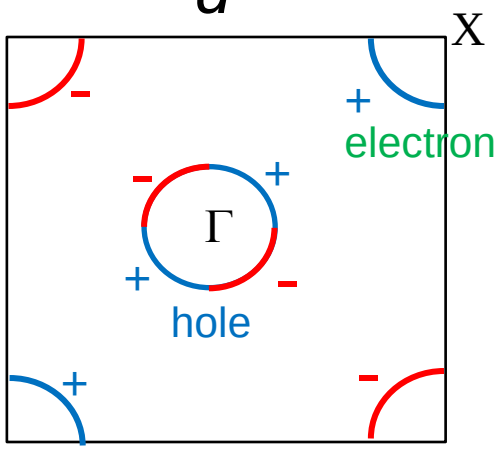
Nodeless

$s_{\pm}$

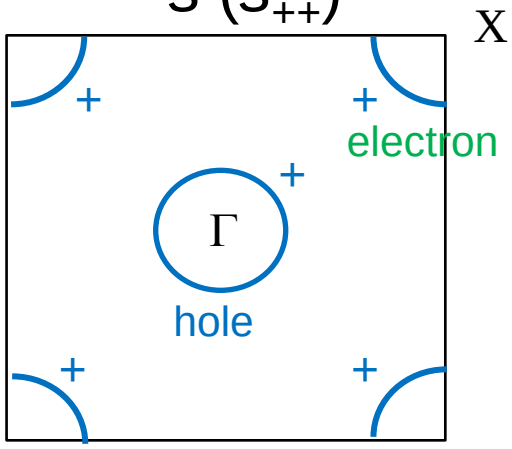


Nodal

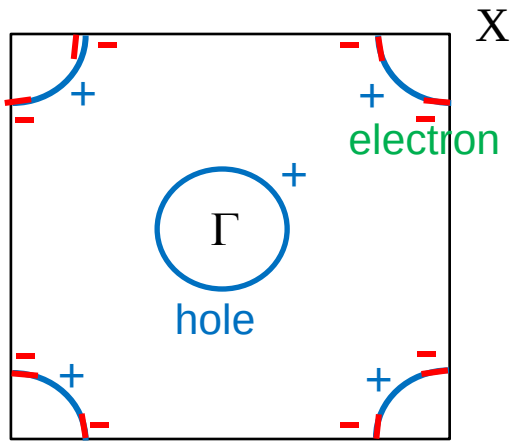
d



s (s_{++})

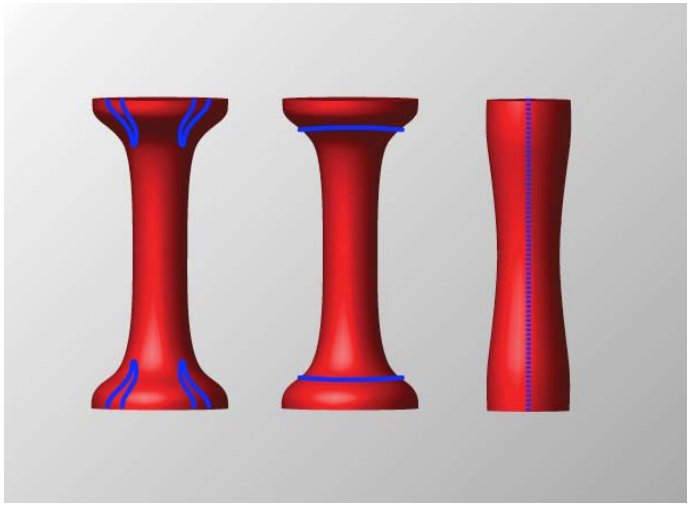


nodal s

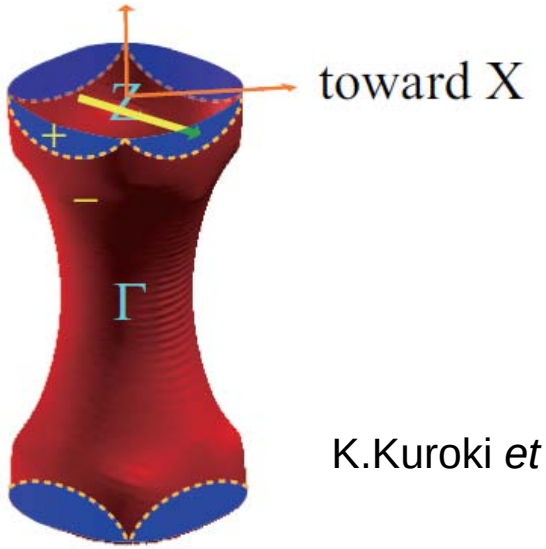


Possible gap functions (3D)

Node in the hole band



P.J. Hirschfeld and D.J. Scalapino, Physics **3**, 64 (2010)



K.Kuroki *et al.* arXiv:1010.3542

Node in the electron band

I.I. Mazin *et al.*, PRB (10)

SC gap structure

Fully gapped or nodal?

Fully gapped superconductivity

1111(As)

λ,κ R. Porozorov, Y. Matsuda

122 $(Ba,K)Fe_2As_2$ optimally doped region

122 $Ba(Fe,Co)Fe_2As_2$ optimally doped region

λ,κ R. Porozorov, K. Moler, Y. Matsuda

ARPES H. Ding

111 LiFeAs, NaFeAs

λ R. Porozorov

ARPES H.Ding

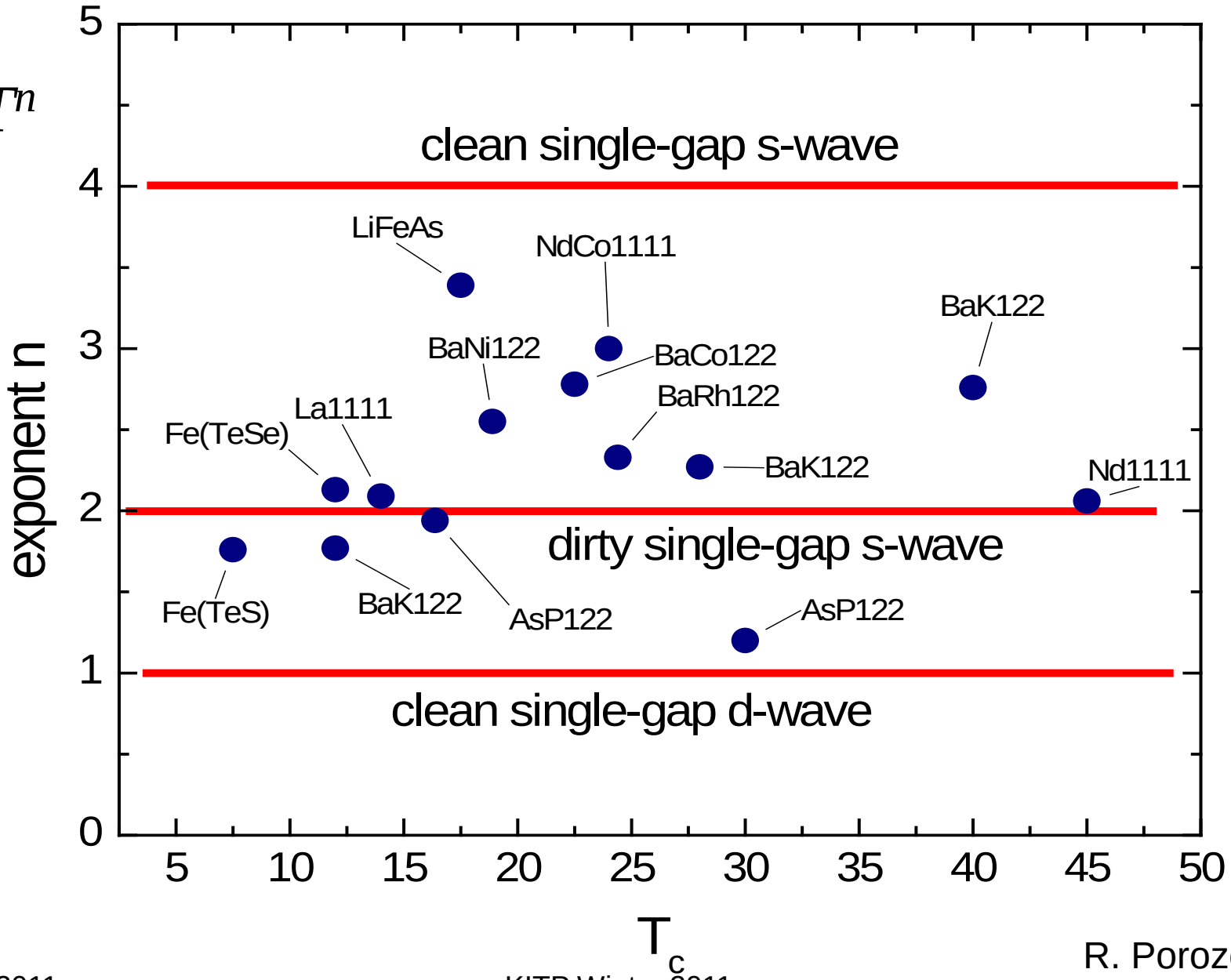
STM T.Hanaguri

11 Fe(SeTe)

ARPES (Isotropic) H.Ding

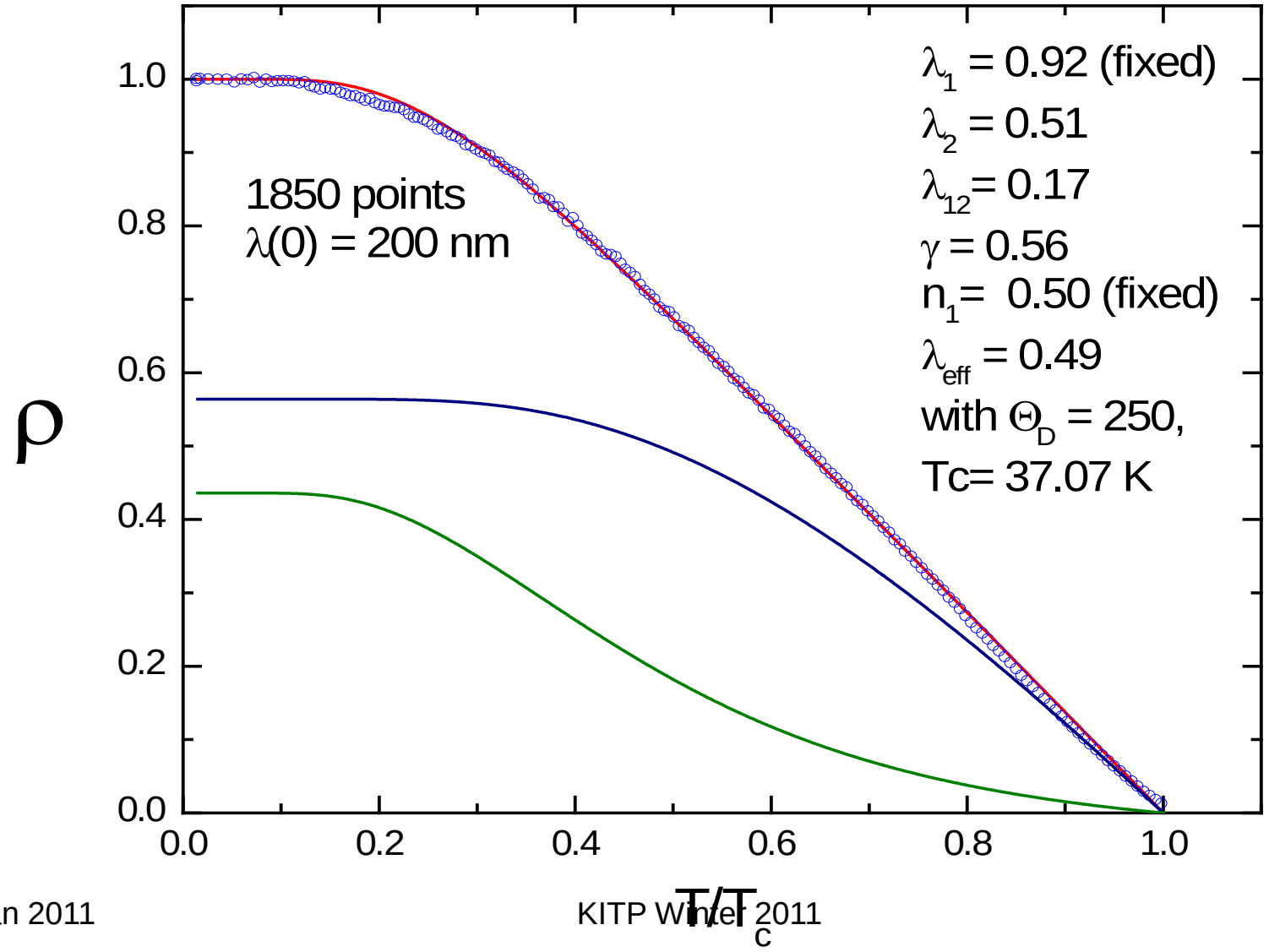
Angle resolved specific heat (Anisotropic) H.H. Wen

$\Delta\lambda \sim T^n$



BaK122

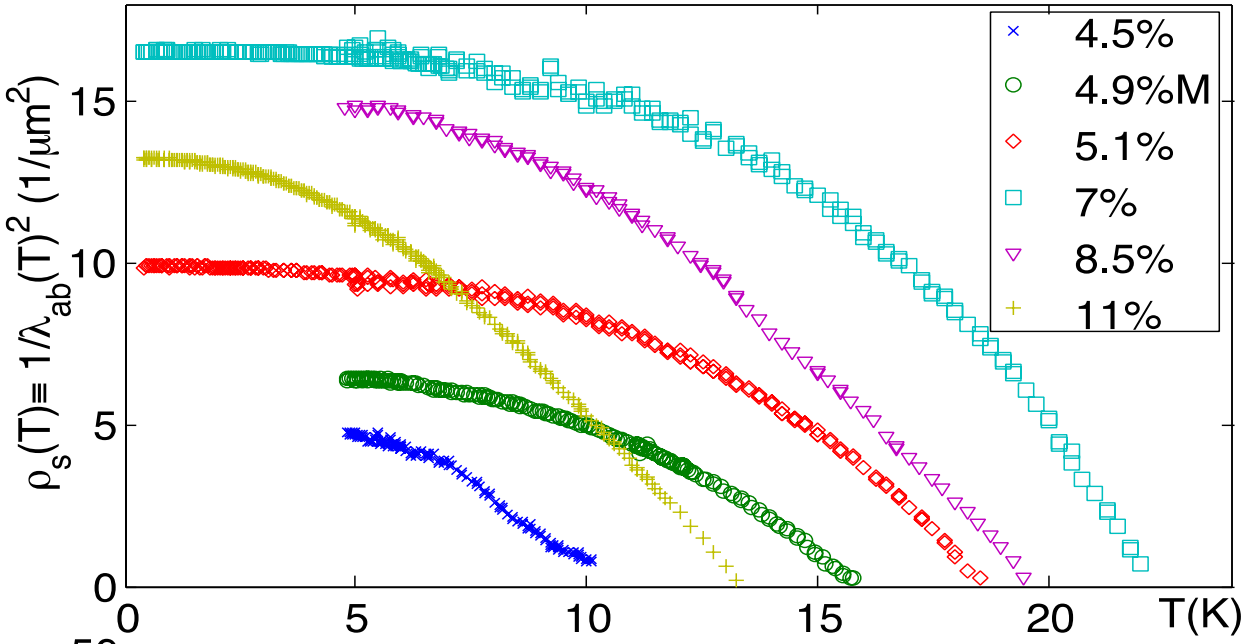
R. Porozorov

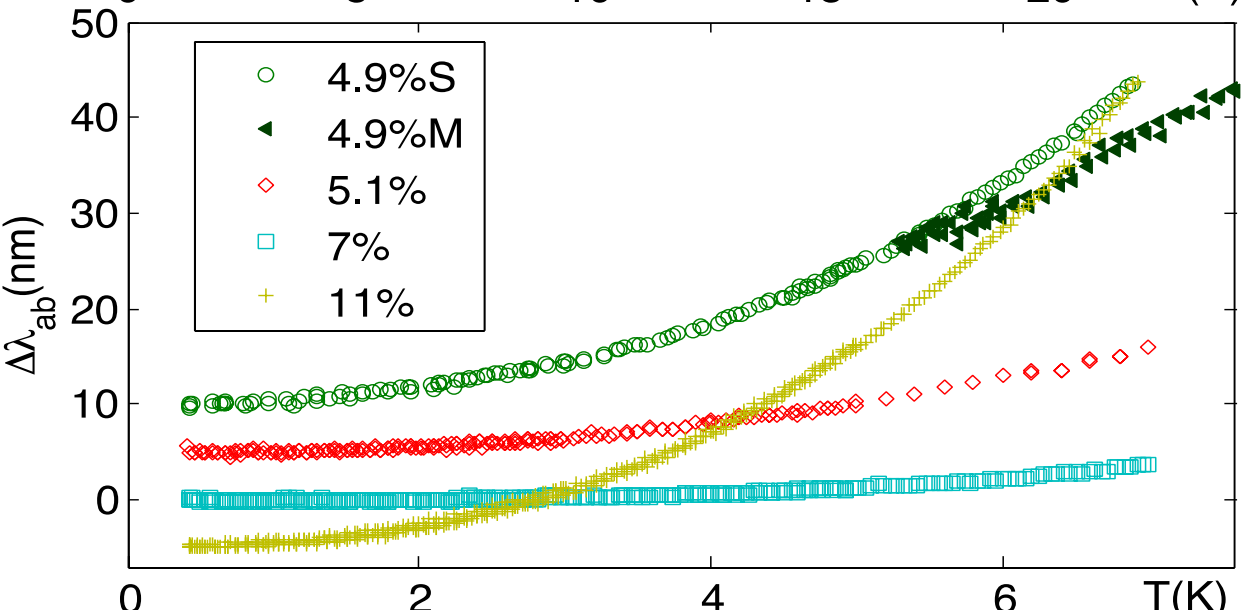


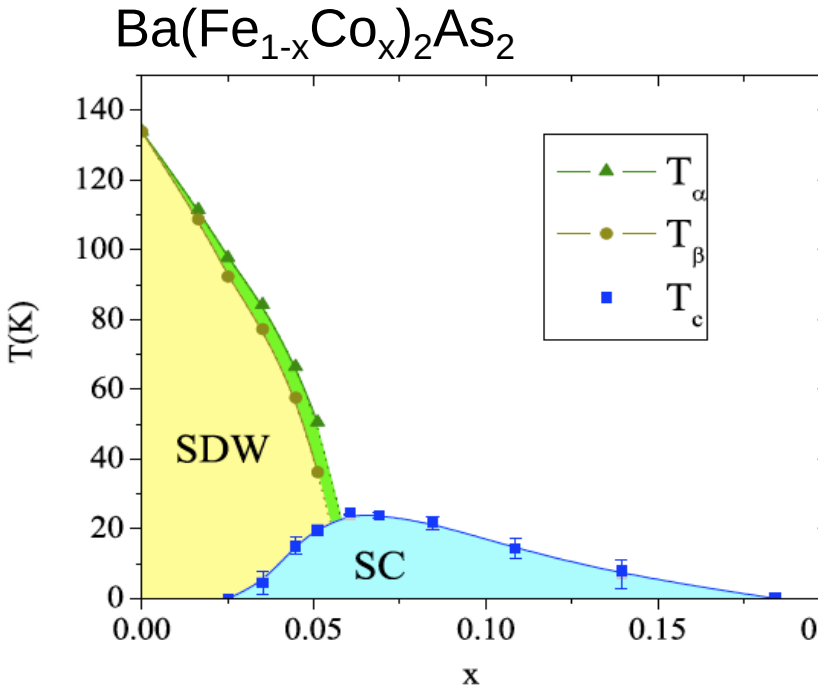
Scanning SQUID Microscopy

K.Moler

Systematic evolution of $\rho_s(T)$







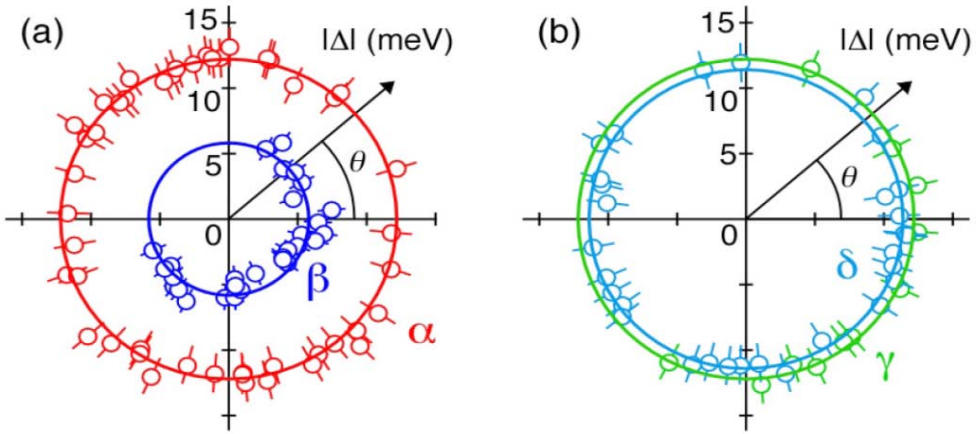
Full single gap behavior at optimal doping

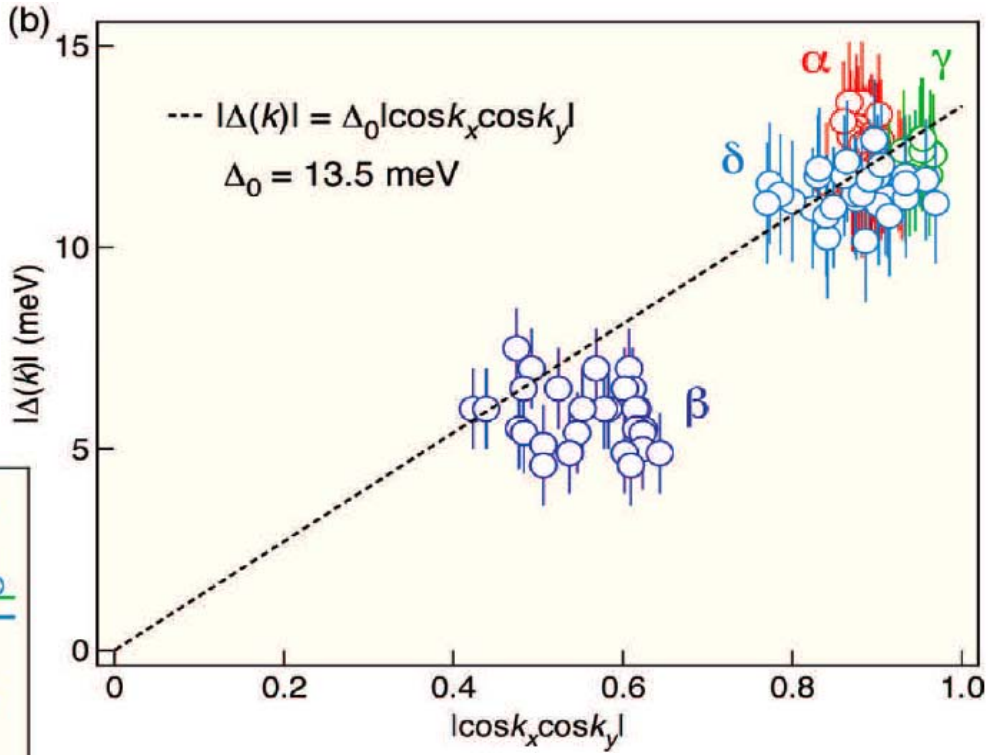
Two different gaps, or a power law, away from optimal doping

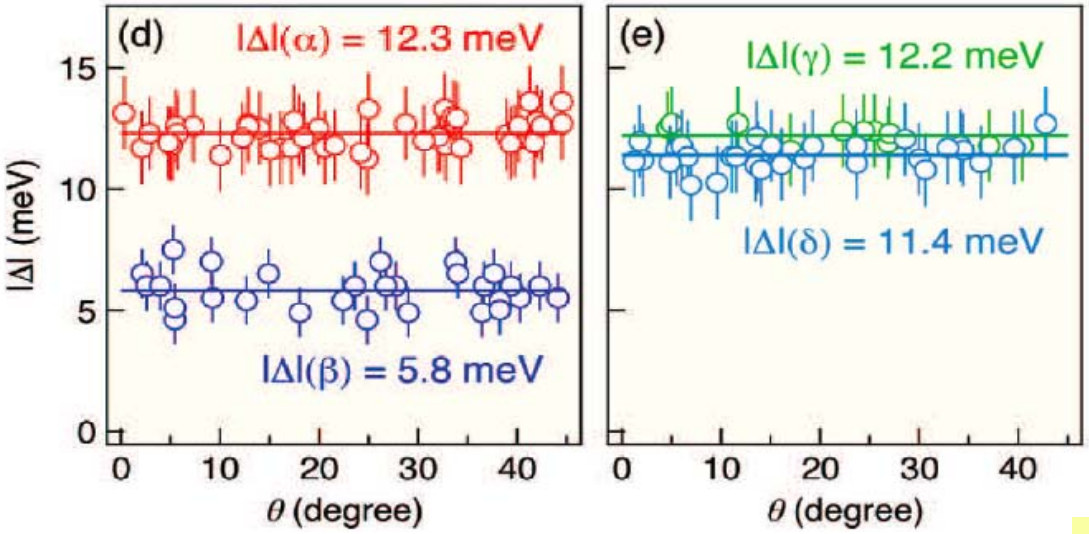
Momentum dependence of SC gaps

Optimally doped $(BaK)Fe_2As_2$

Hong Ding







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

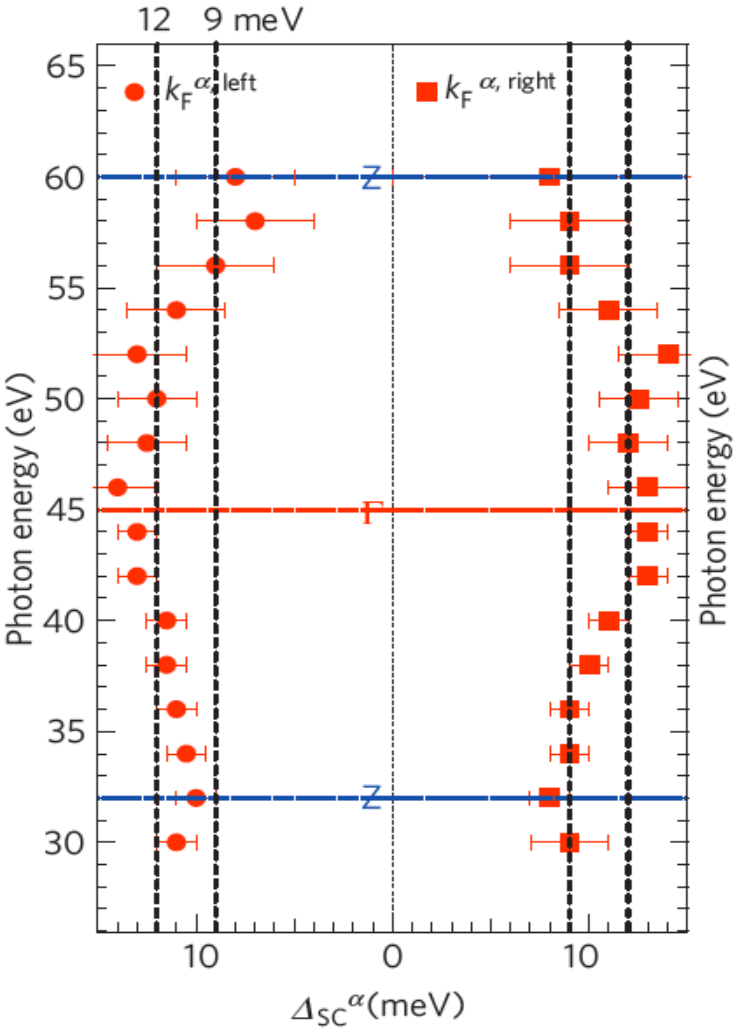
k_z dependence of SC gaps

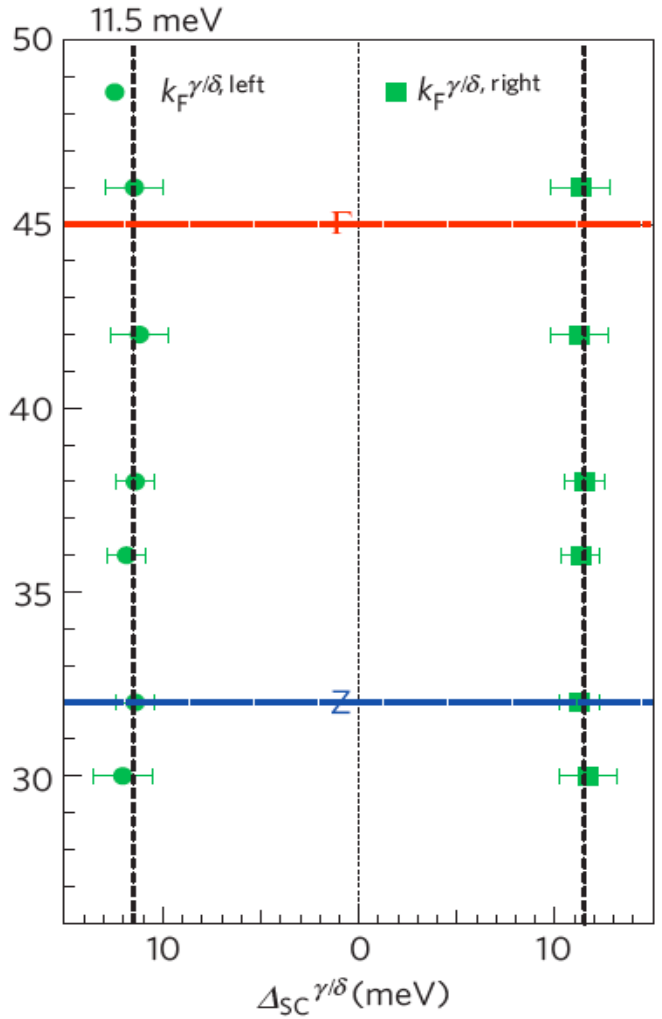
Optimally doped $(BaK)Fe_2As_2$

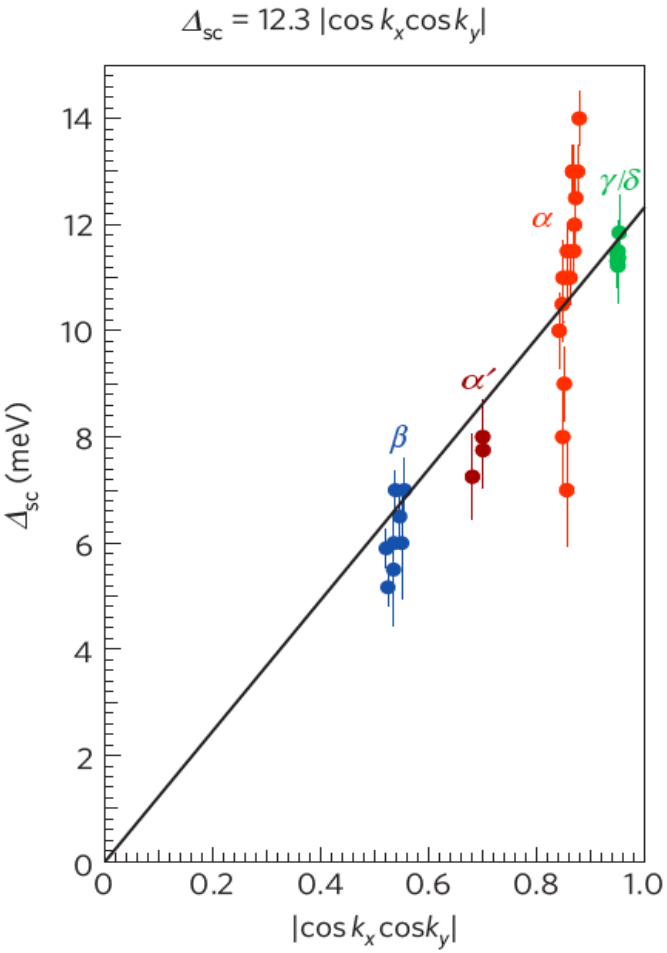
H. Ding

Δ on smaller hole FS

Δ on electron FS







$Ba(Fe,Co)_2As_2$

$(Ba,K)Fe_2As_2$

In both systems, SC gap becomes anisotropic with doping

λ, κ	R. Porozorov
C	H.H.Wen

Increasing anisotropy has not been reported by ARPES

Difference between bulk and surface probe?

nature COMMUNICATIONS

OPEN

ARTICLE

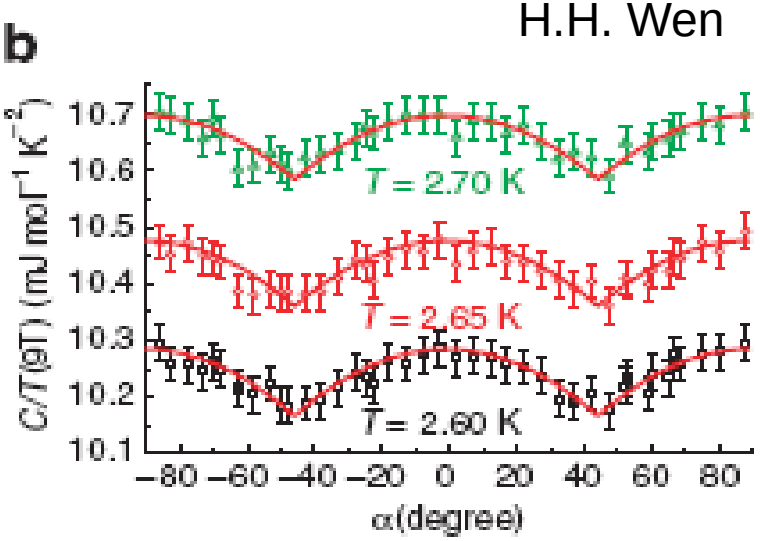
Received 6 Apr 2010 | Accepted 18 Oct 2010 | Published 16 Nov 2010

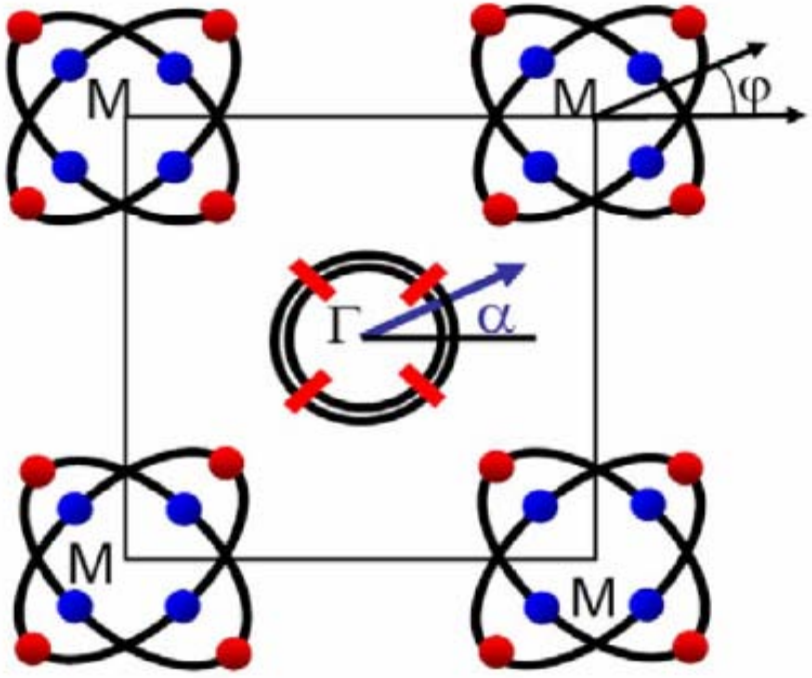
DOI: 10.1038/ncomms1115

Anisotropic structure of the order parameter in $FeSe_{0.45}Te_{0.55}$ revealed by angle-resolved specific heat

B. Zeng[1], G. Mu[1], H.Q. Luo[1], T. Xiang[1], I.I. Mazin[2], H. Yang[1,3], L. Shan[1], C. Ren[1], P.C. Dai[1,4,5] & H.-H. Wen[1,3]

H.H. Wen





- Vertical d-wave nodes on the hole pockets: unlikely
- Extended s-wave: accidental minimum of gaps on M-FS are possible

B. Zeng ……HHW.
Nature Comm. 1, 157 (2010)

Nodal gap structure

1. LaFePO (T_c=7 K)

Scanning SQUID Microscopy

K. Moler

2. KBa_2As_2 (T_c=3K)

κ, λ

No electron Fermi surface

Heavy electron mass (γ=100mJ/K^{2}mol)

3. $BaFe_2(As,P)_2$ (T_c=31K)

κ, λ, T_1 Y. Matsuda

Isovalent doping

4. Heavily overdoped $Ba(Fe,Co)_2As_2$

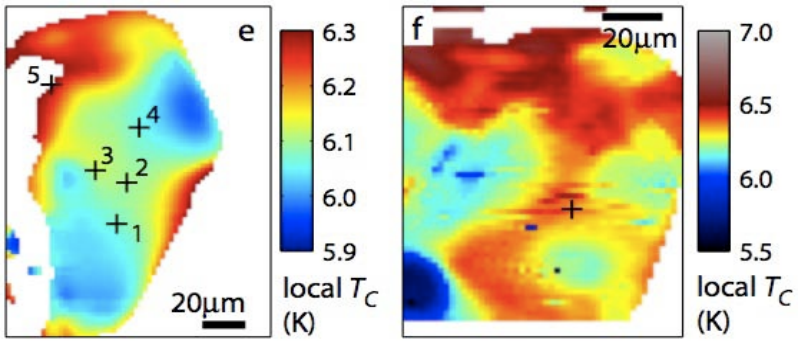
κ_c, λ_c

R. Polozorov

$\Delta\lambda(T)$ of LaFePO: linear, with a slope of 143±15 Å/K

K. Moler

1. measurement points:



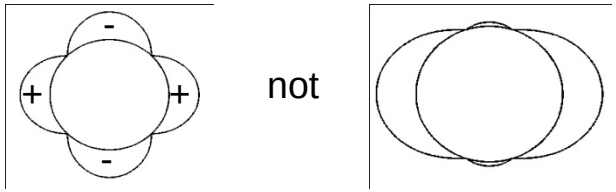
2. $d\lambda/dT$ over $0.7<T<1.6$ K:

sample #1: 1. 146
2. 139
3. 136
4. 150

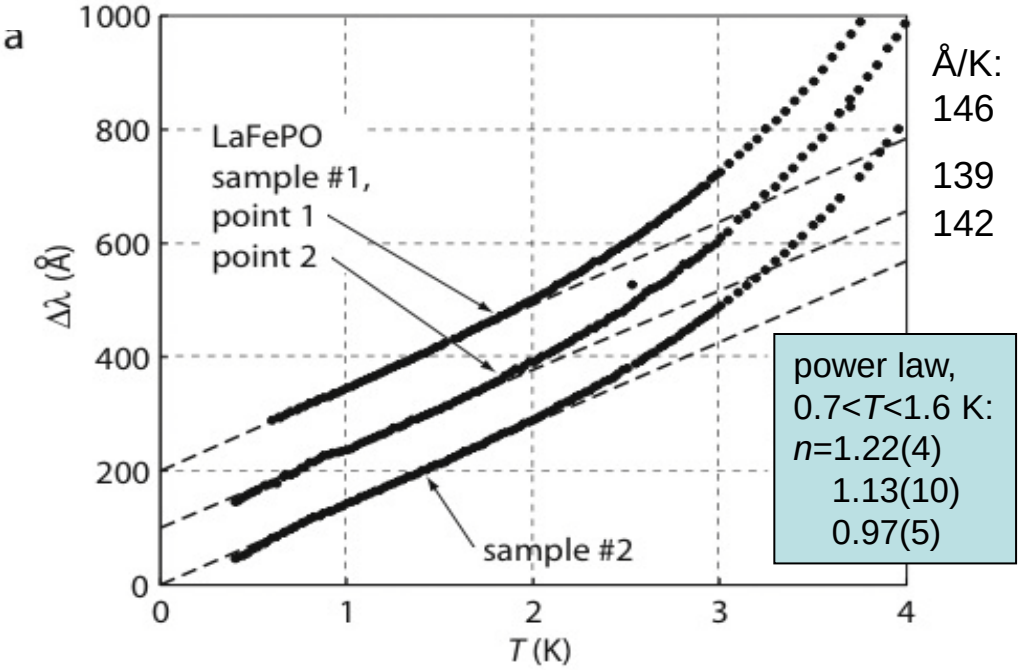
sample #2: 1. 142 Å/K

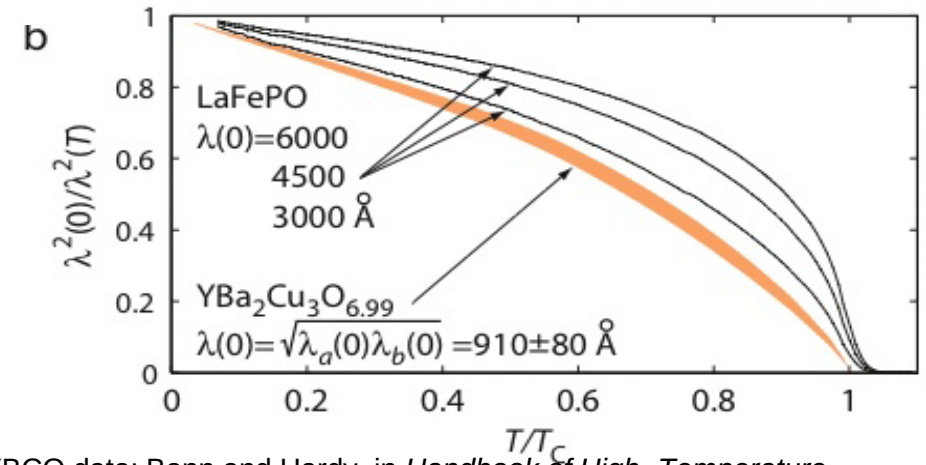
$d\lambda/dT$ of LaFePO at T-->0: 143±15 Å/K
(including systematic errors)

3. nodes are well-formed.



4. ρ_s rises sharply just below T_C.



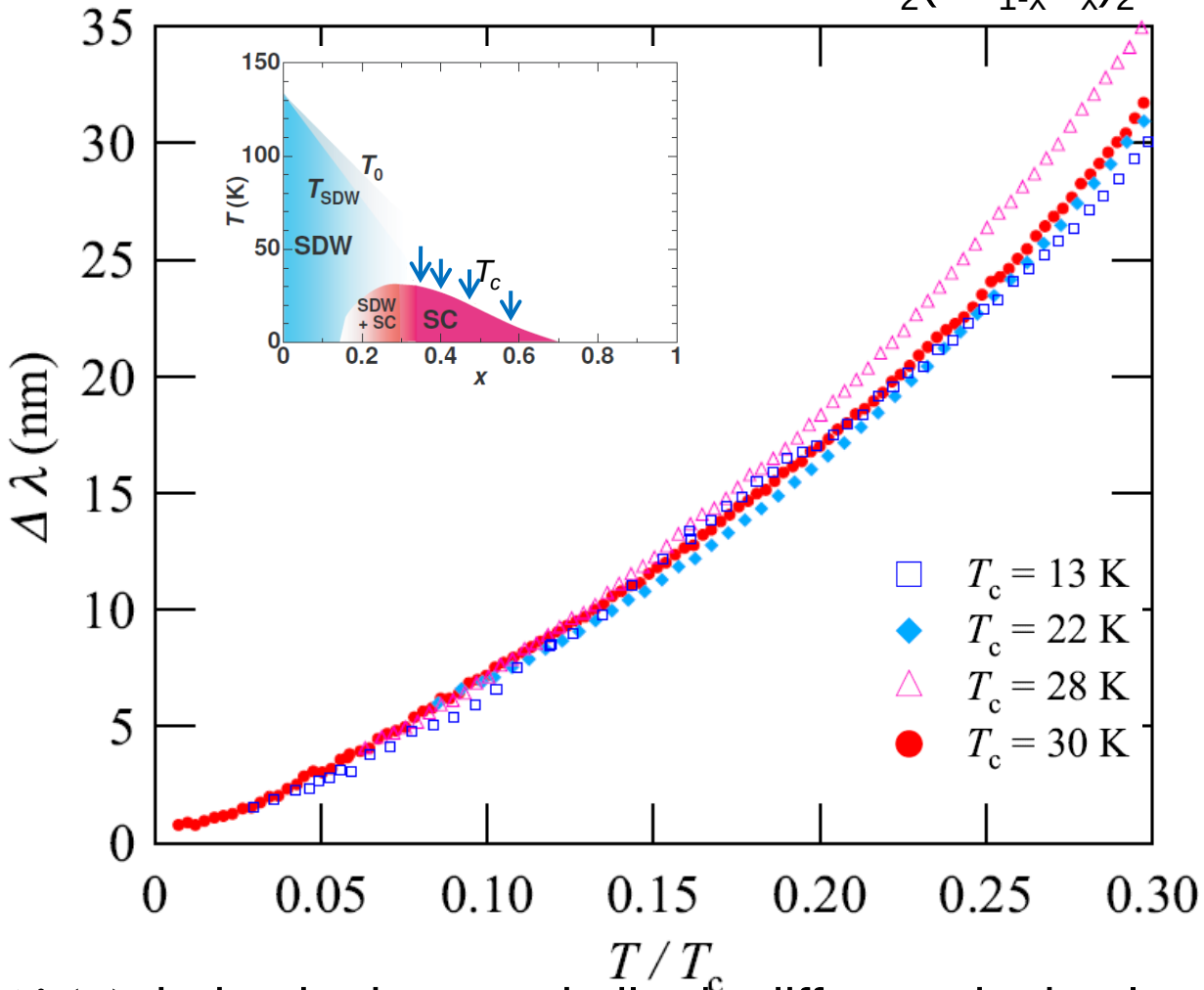


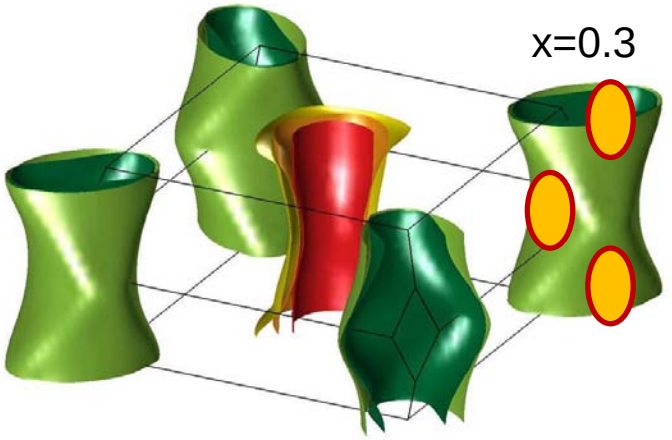
(YBCO data: Bonn and Hardy, in *Handbook of High- Temperature Superconductivity*, and Pereg-Barnea *et al*, PRB **69** (2004) 184513.)

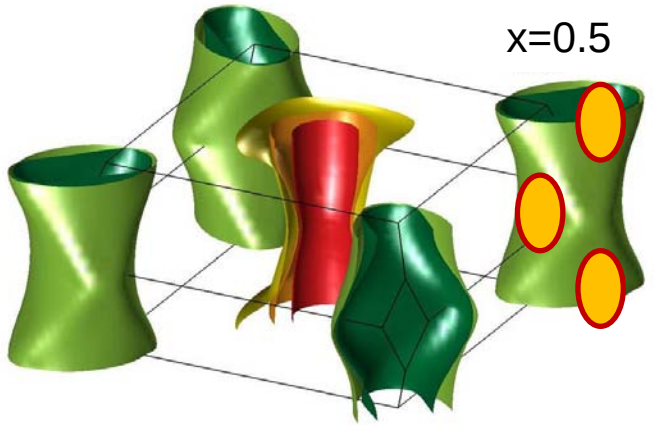
Nodes in the electron sheet

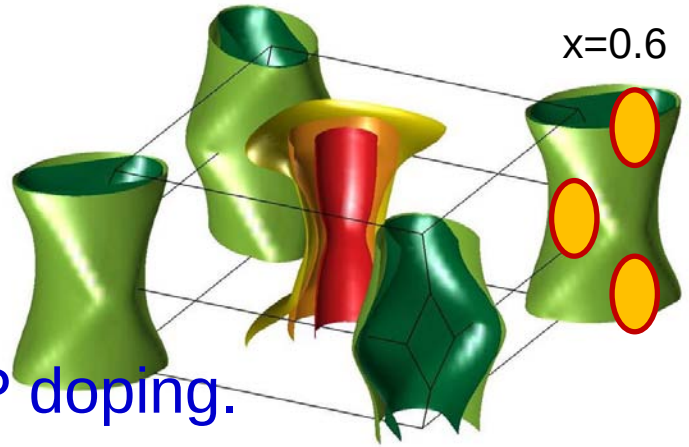
Y.Matsuda

$BaFe_2(As_{1-x}P_x)_2$









$\Delta\lambda(T)$ behavior is very similar in different doping levels

$$\Delta\lambda \sim N_0(\hat{k}_n)\frac{T}{T_c}$$

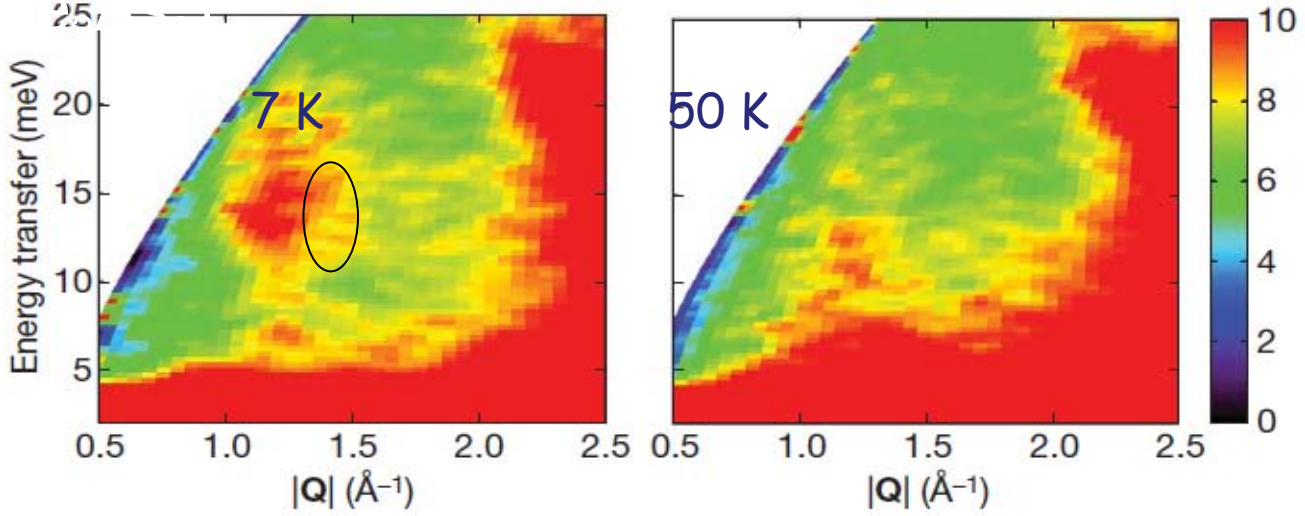
The location of line node remains same with P doping.

S+- or S++

Experiments which support S± superconductivity

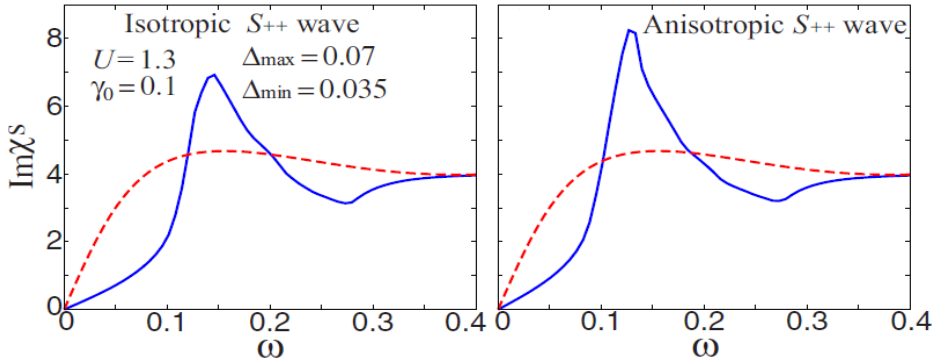
1. Neutron resonant scattering
2. Absence of NMR coherence peak — Y. Nakai
3. Quasiparticle interference — T. Hanaguri

Inelastic neutron scattering (resonance peak?)



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

Question: Is the observed “resonance peak” an indicative of S+-?

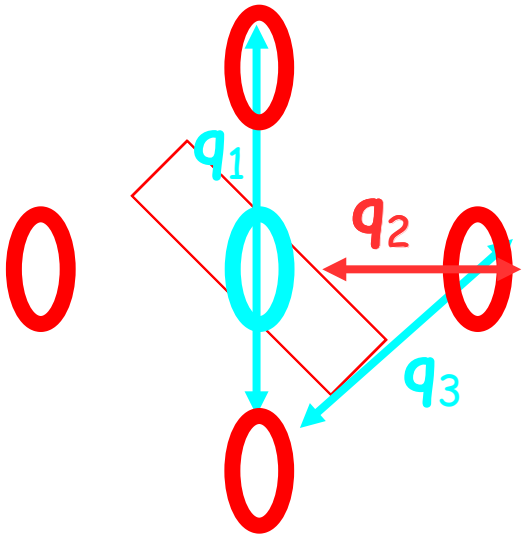


H. Kontani

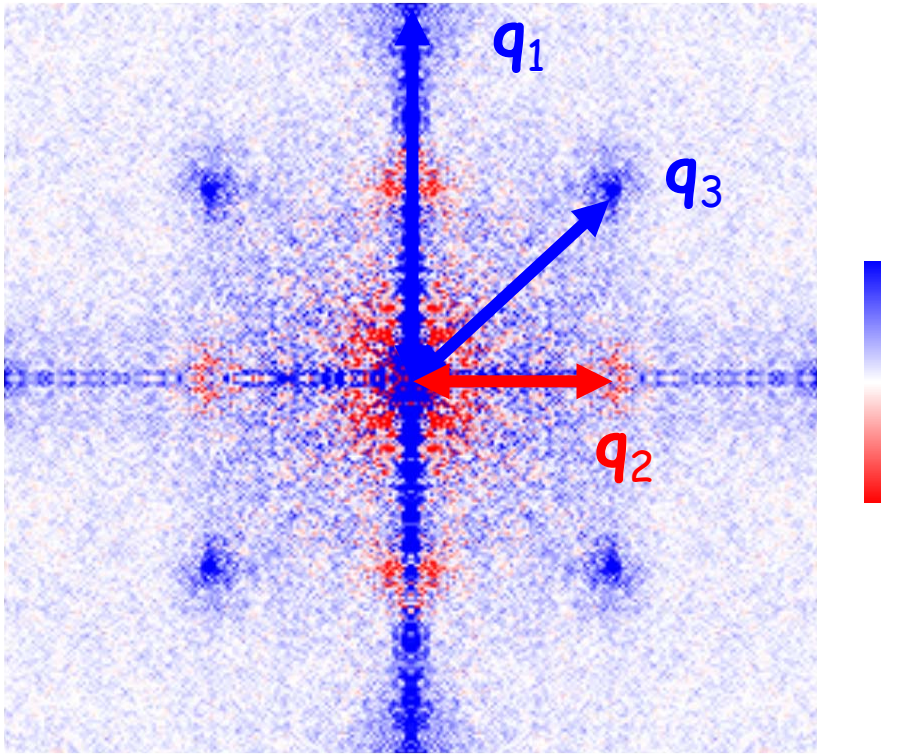
Phase-sensitive STM on an iron chalcogenide

T. Hanaguri

$Fe_{1+x}(Se,Te)$



FT-Z map 1.0 meV



$s_{\pm}$-wave symmetry

Issue: no quantitative microscopic theory

Gap function of Fe-pnictide

Two parties

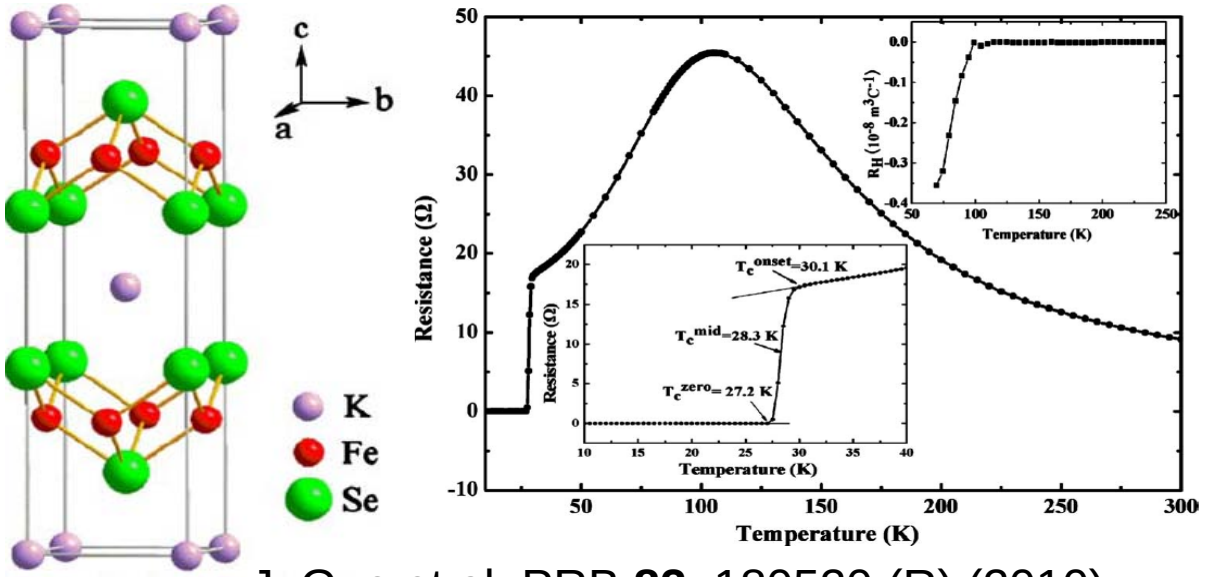
US and Europe	Majority S+-
China	Presumably S+-
Japan	Majority is not S+-

Third party has come into the game

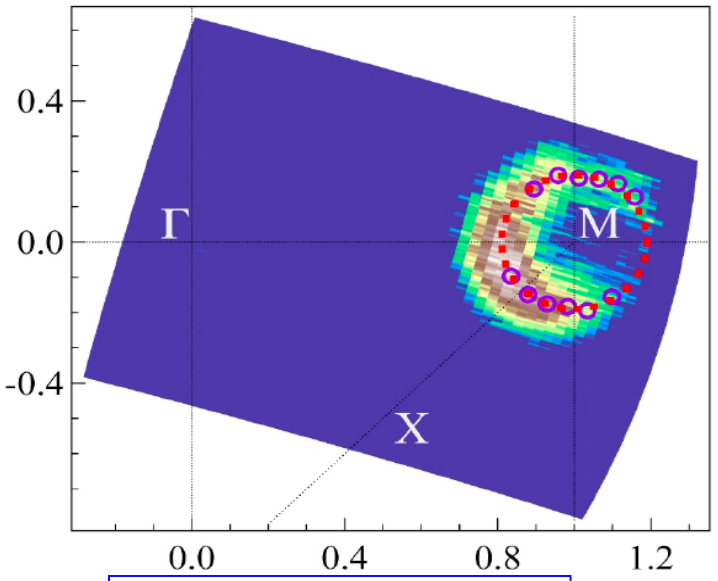
p-wave superconductivity in LiFeAs !!

J. v. den Brink

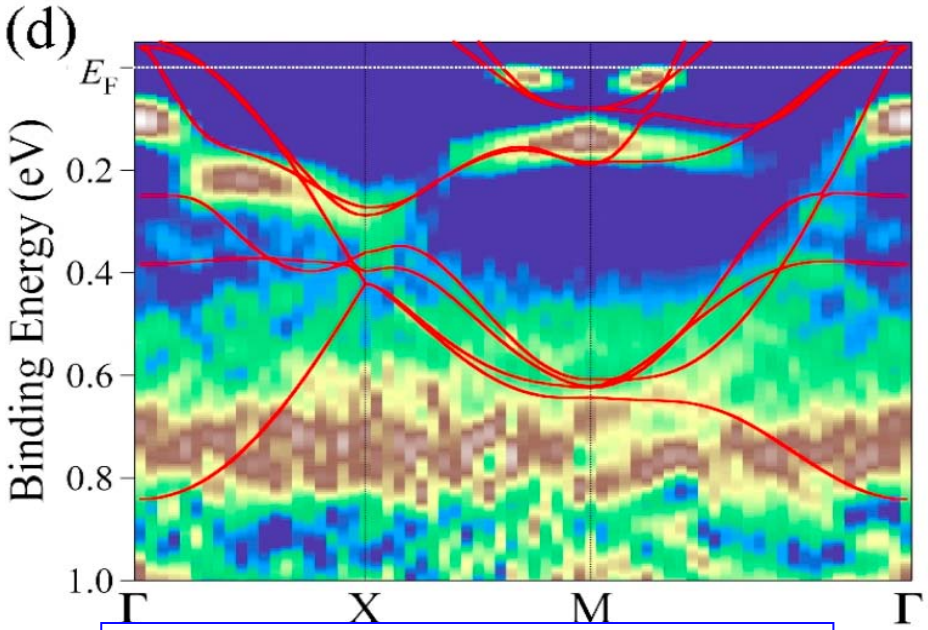
New "122" – $KFe_{2-x}Se_2$ (T_c ~ 31K)



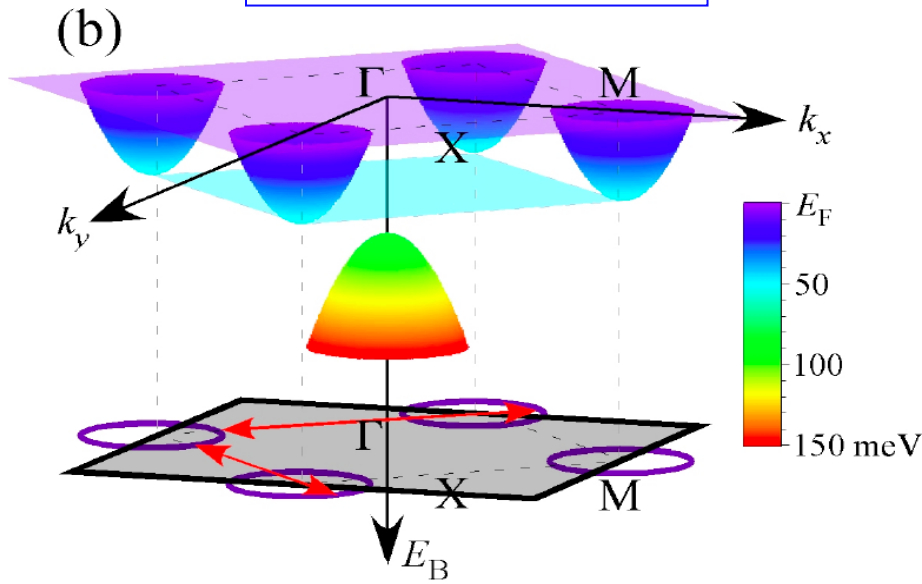
J. Guo et al, PRB **82**, 180520 (R) (2010)



Absence of hole FS



Bandwidth renormalization = 2.5



T. Qian et al, arXiv:1012.6017

Questions for gap structure

Gap anisotropy, Nodal or fully gapped?

Why is the nodal structure material dependent?

What kind of interaction gives rise to nodal gap structures?

What is the relation between the gap anisotropy and orbital character?

S+- or S++

S+- AFM fluctuation mediated

S++ Orbital fluctuation mediated

Can S+- explain the impurity effect?

Can S++ explain the coexistence of SDW and SC?

Symmetry other than A_{1g}

Is the pairing symmetry of KFe_2As_2(heavily hole doped, no electron sheets) nodal d-wave?

What is the pairing symmetry of newly found high T_c KFe_2Se_2 (heavily electron doped, no hole sheets) ? Nodeless d-wave?

Conclusion

There are still quite a few open questions on magnetism, orbital physics, superconducting gap structure and pairing mechanism.

Need more experiments, new materials and theories.