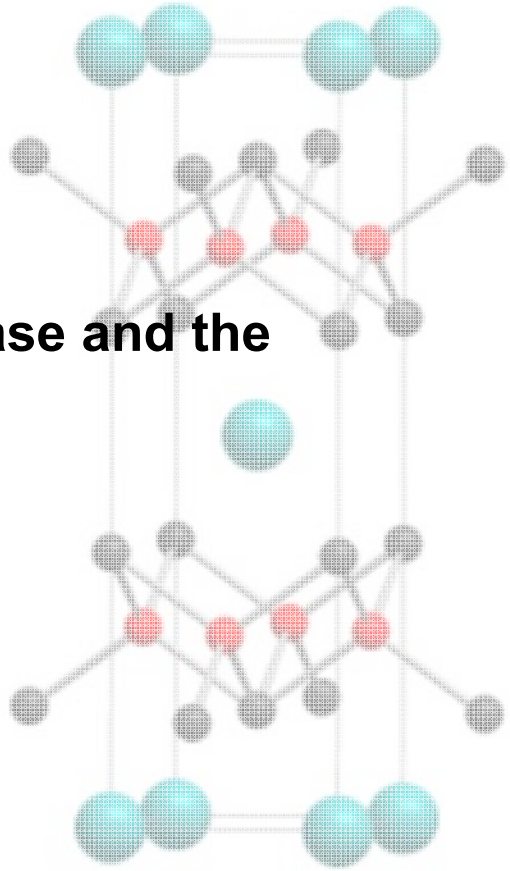
"Novel Superconductors and Synchrotron Radiation: state of the art and perspective"
Adriatico Guest House, Trieste, December 10-11, 2014

ARPES studies of Fe pnictides: Nature of the antiferromagnetic-orthorhombic phase and the superconducting gap

Atsushi Fujimori
University of Tokyo



- **Nature of the AFM-orthorhombic (AFO) phase and the "nematic phase":**
  - **Band folding *versus* C_4 symmetry breaking**
- **Superconducting gap anisotropy**

Collaborators

Photoemission expt

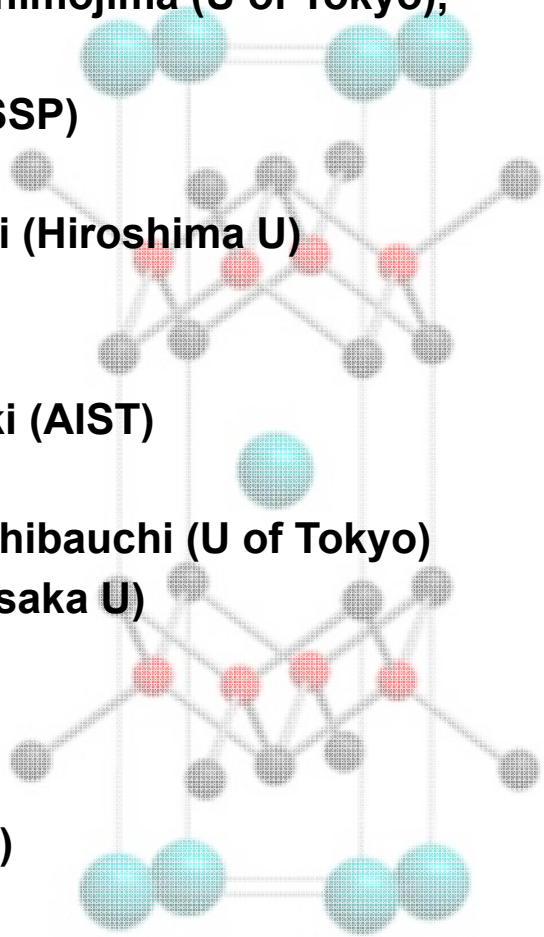
K. Koshiishi, L. Liu, H. Suzuki, J. Xu, K. Okazaki, T. Shimojima (U of Tokyo),
T. Yoshida (Kyoto U), S. Ideta (TUS)
K. Ono, H. Kumigashira (KEK-PF), Y. Ohta, S. Shin (ISSP)
M. Hashimoto, D. Lu, Z.-X. Shen (Stanford U)
A. Ino, M. Arita, H. Anzai, H. Namatame, M. Taniguchi (Hiroshima U)

Samples

K. Kihou, C.-H. Lee, T. Ito, Y. Tomioka, A. Iyo, H. Eisaki (AIST)
S. Uchida (U of Tokyo)
Y. Matsuda, S. Kasahara, T. Terashima (Kyoto U), T. Shibauchi (U of Tokyo)
T. Kobayashi, S. Miyasaka, M. Nakajima, S. Tajima (Osaka U)

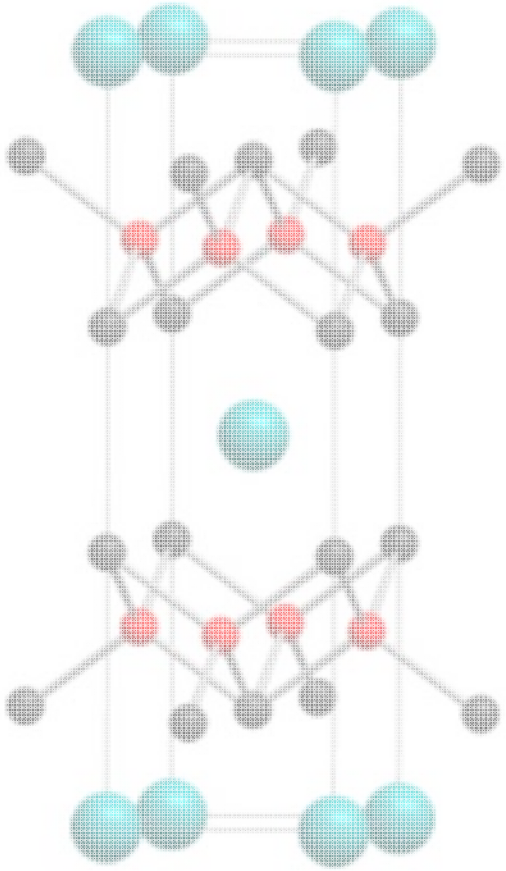
Theory

R. Arita (RIKEN), H. Ikeda (Ritsumeikan U)
H. Kontani, T. Saito (Nagoya U.) S. Onari (Okayama U)

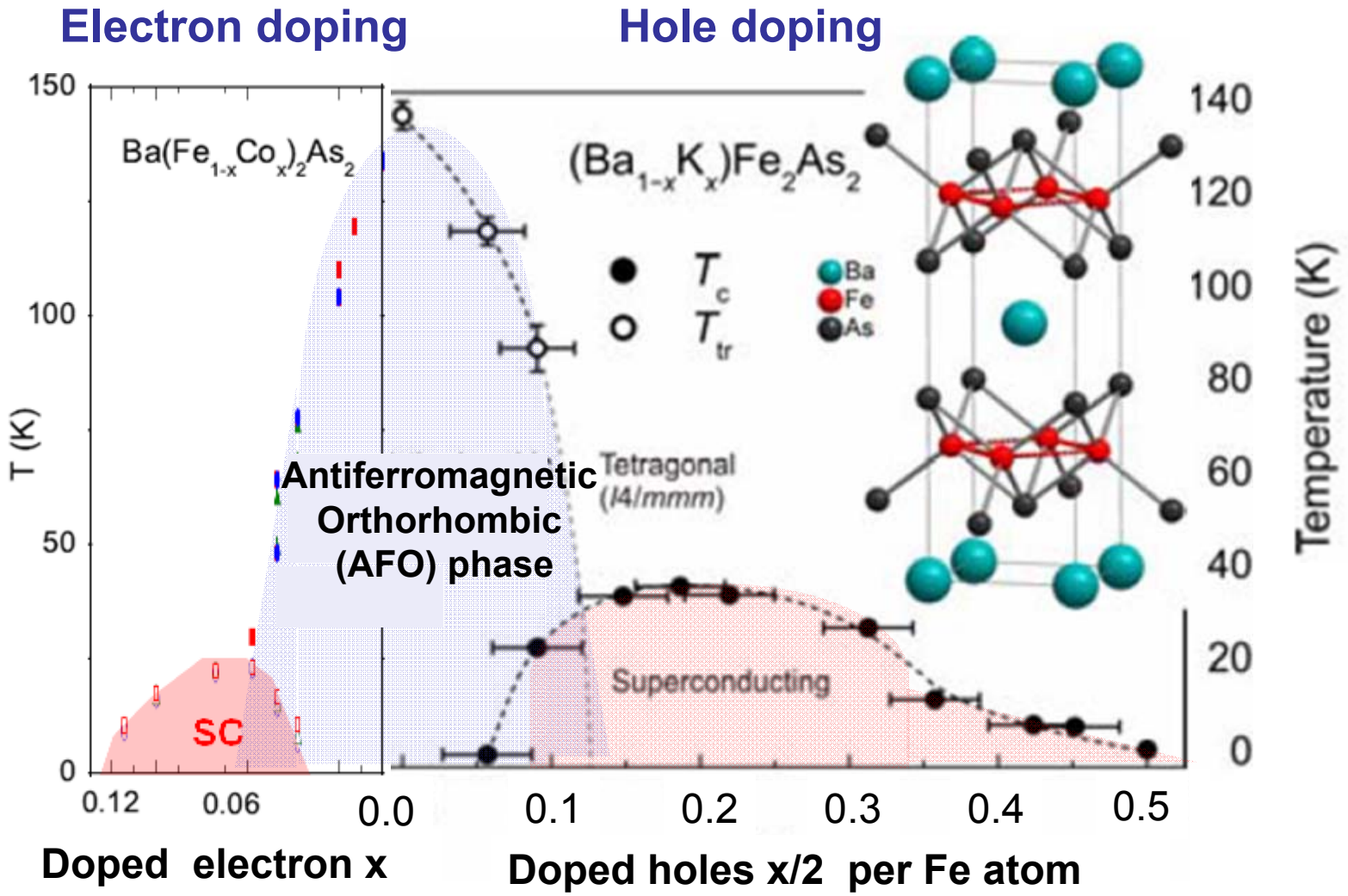


Outline

- **Nature of the AFM-orthorhombic (AFO) phase and the "nematic phase":**
  - **Band folding *versus* C_4 symmetry breaking**
- **Superconducting gap anisotropy**



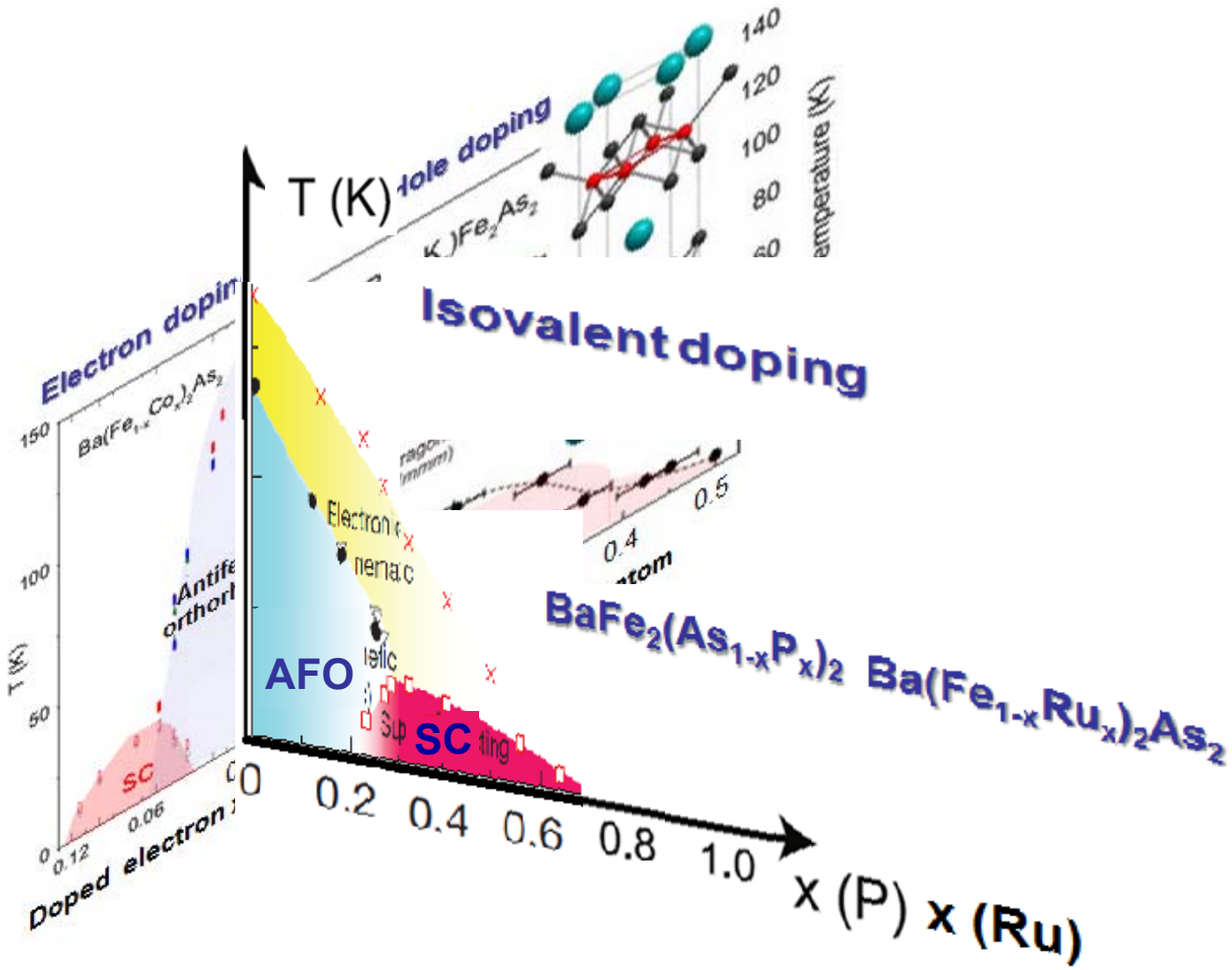
Phase diagram of Fe-based superconductors



N. Ni *et al*., PRL '08

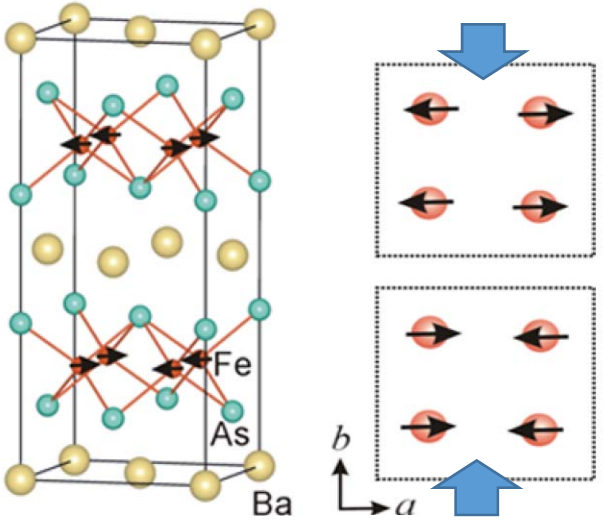
M. Rotter *et al*., Angew. Chem. Int. Ed. '08

Phase diagram of Fe-based superconductors

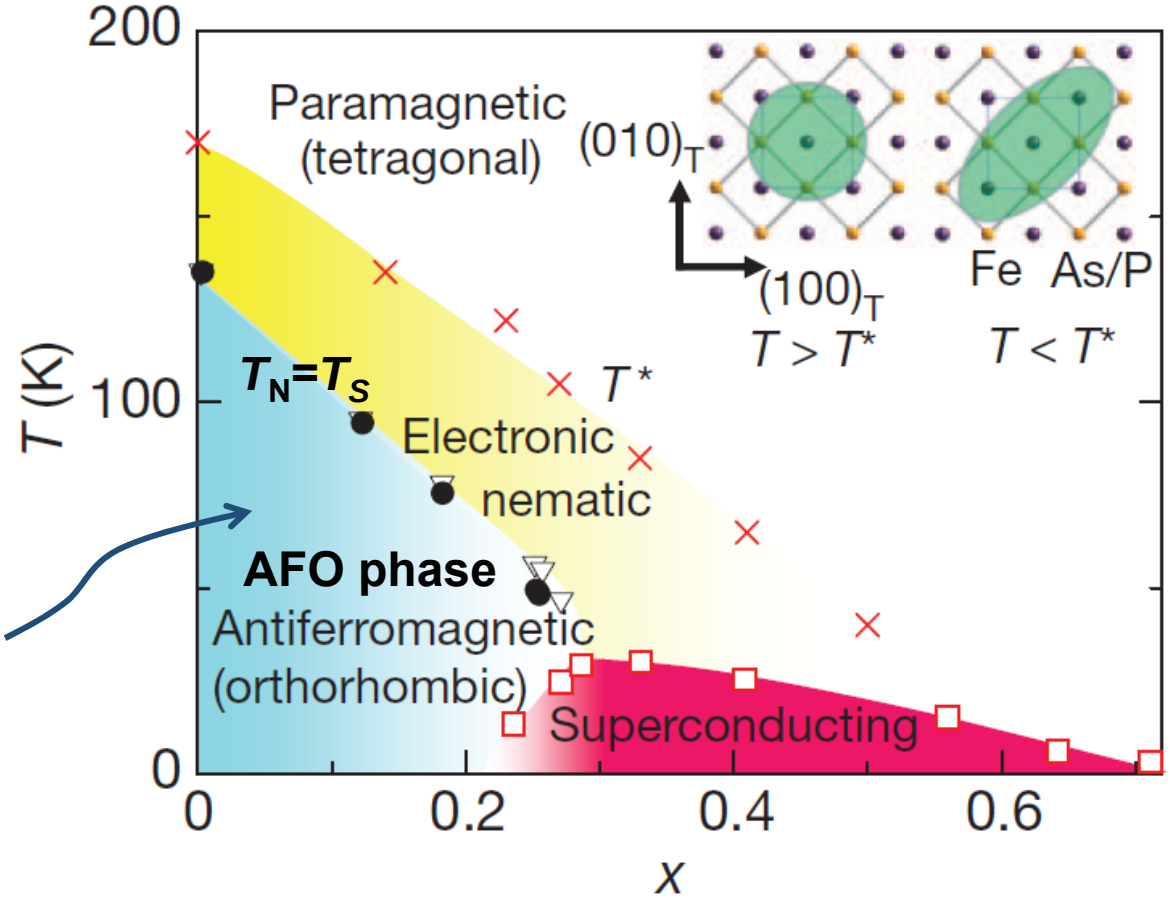


Magneto-structural transition and possible electronic "nematic phase"

Antiferromagnetic -orthorhombic (AFO) phase

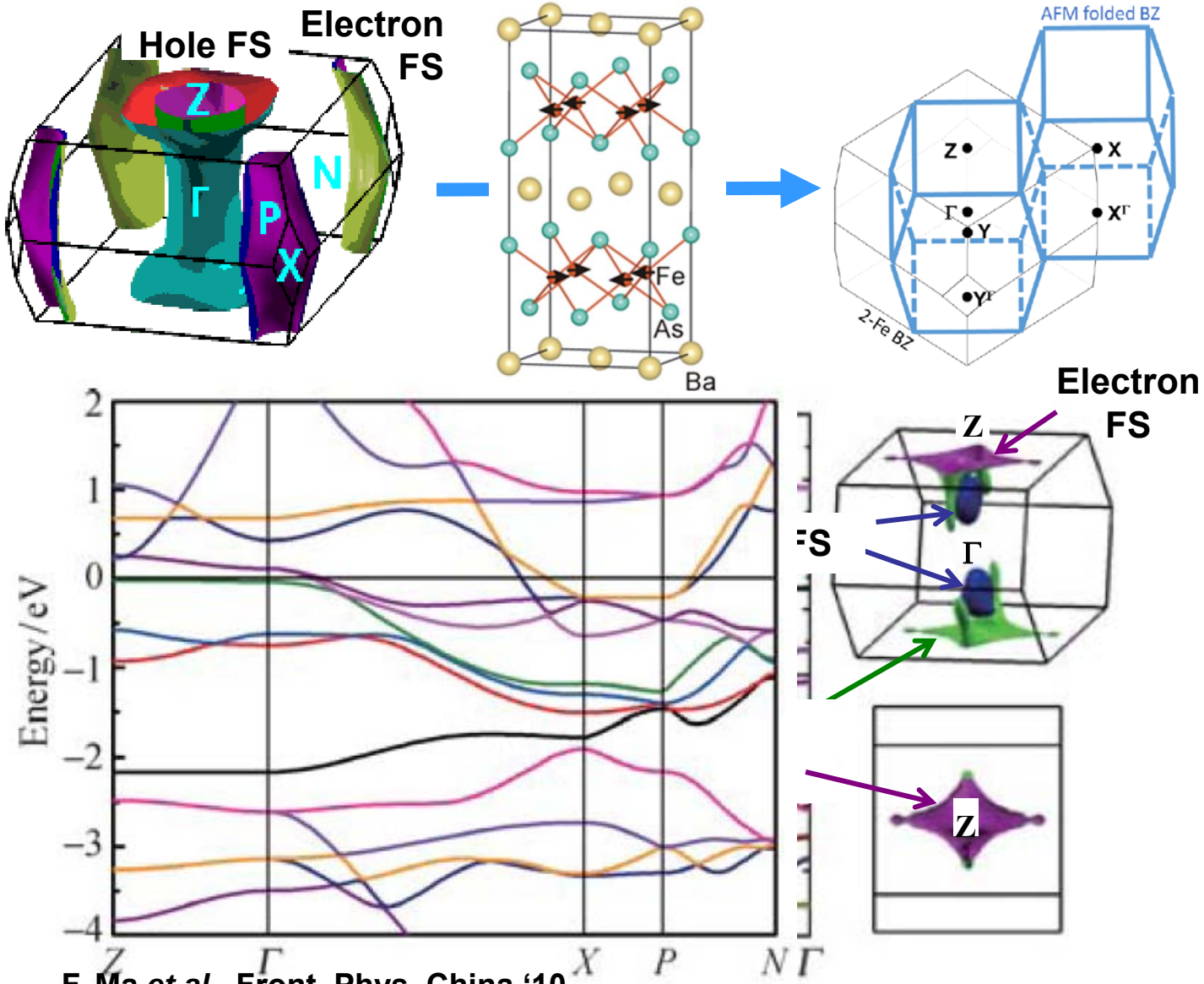


Q. Huang *et al.*, PRL '08



S. Kasahara *et al.*, Nature '13

Folded Fermi surfaces of $BaFe_2As_2$ in the AFO phase

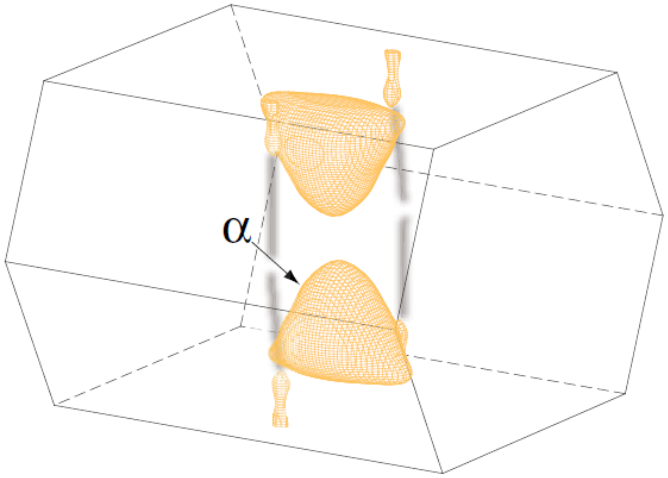


F. Ma *et al.*, Front. Phys. China '10

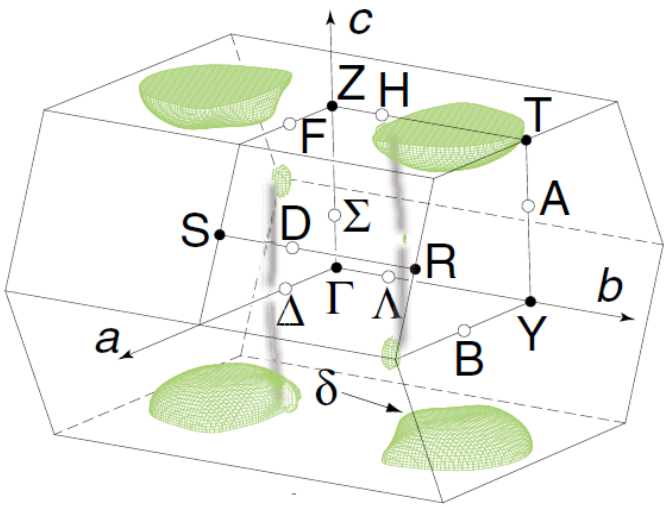
Folded Fermi surfaces of $BaFe_2As_2$ in the AFO phase

LDA calculation

Hole FS



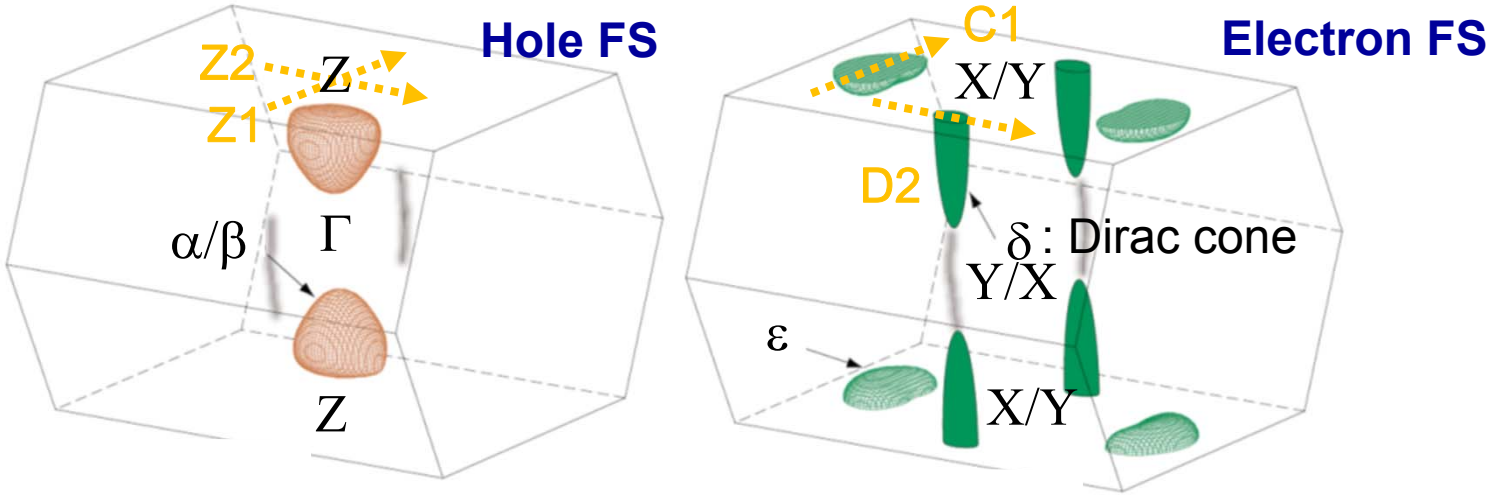
Electron FS



T. Terashima *et al.*, PRL '11

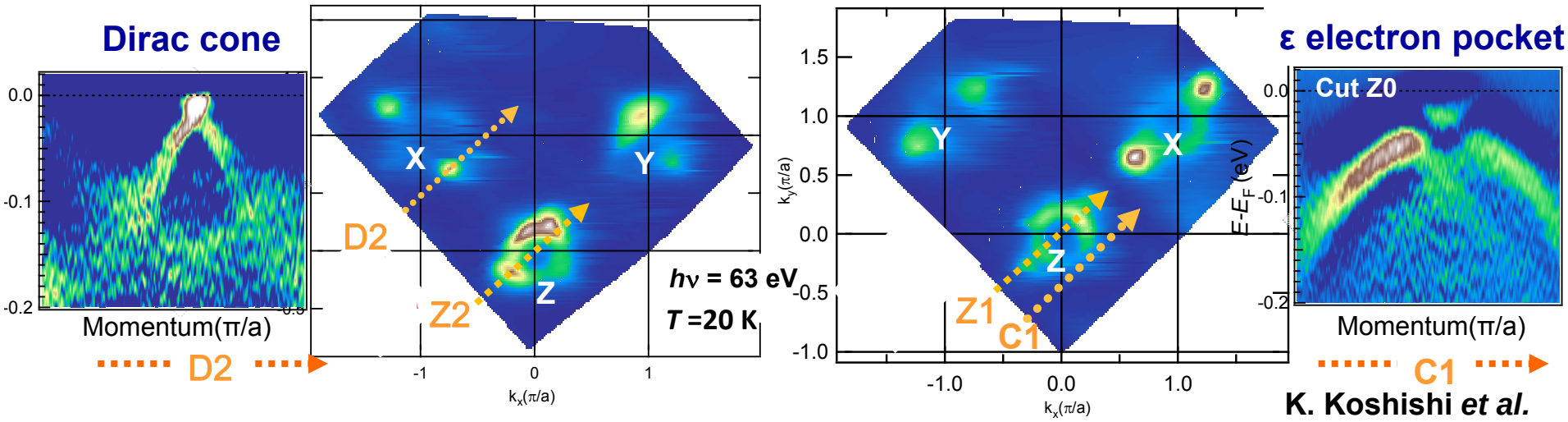
Folded Fermi surfaces of $BaFe_2As_2$ in the AFO phase by ARPES

LDA adjusted to de Haas-van Alphen experiment



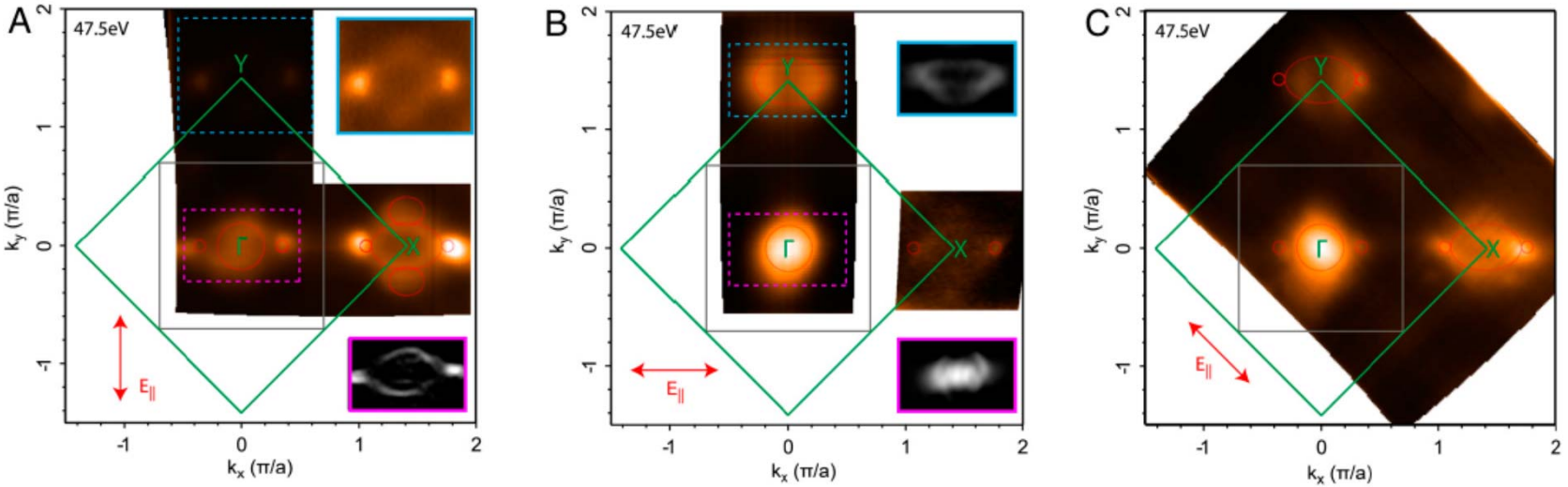
ARPES for k_z ~ Z, detwinned

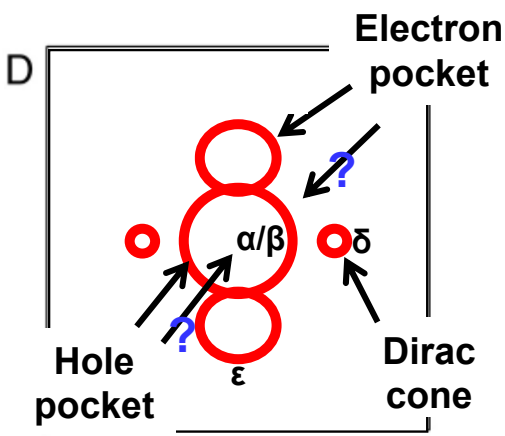
T. Terashima et al., PRL '11



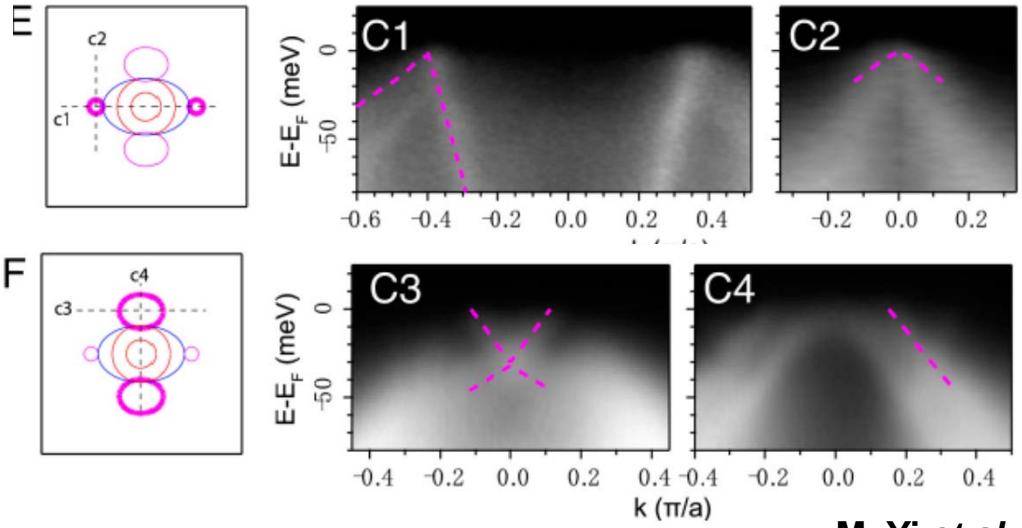
K. Koshishi *et al.*

Folded Fermi surfaces of $BaFe_2As_2$ in the AFO phase revealed by ARPES





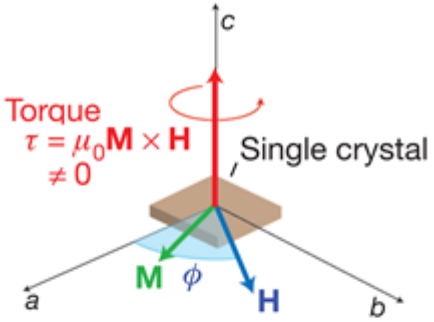
K. Koshiishi *et al*.

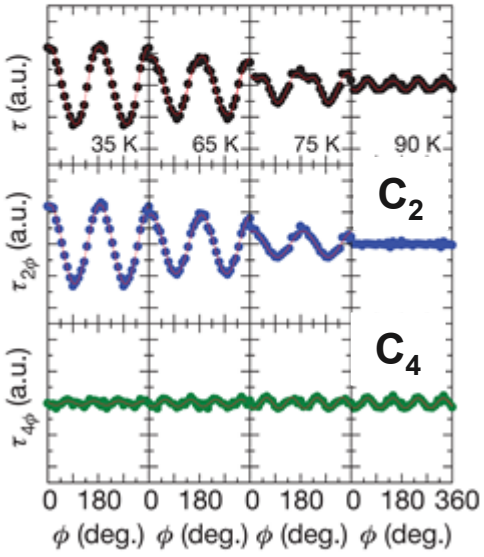


M. Yi *et al.*, PNAS '11

C_4 symmetry breaking in the AFO and "nematic" phases of $BaFe_2(As_{1-x}P_x)_2$

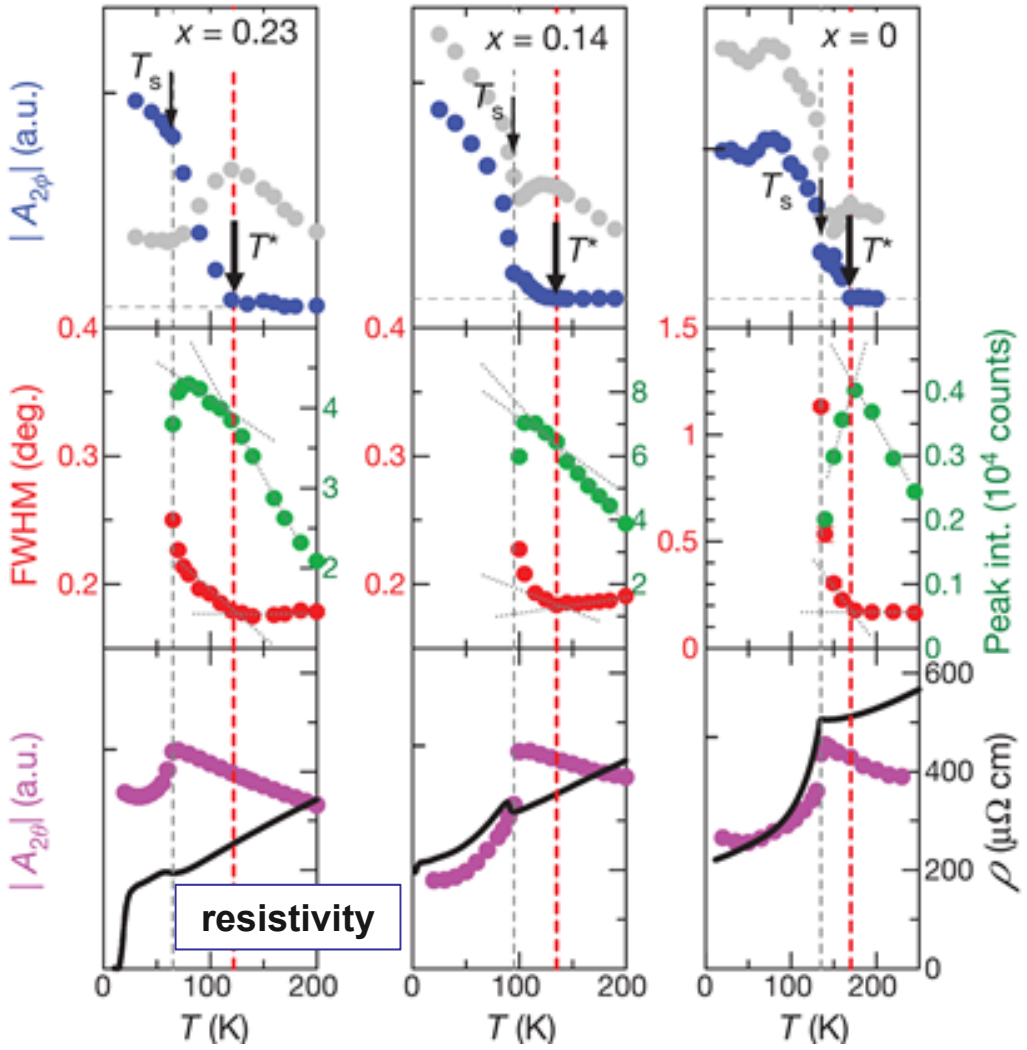
Magnetic torque measurements





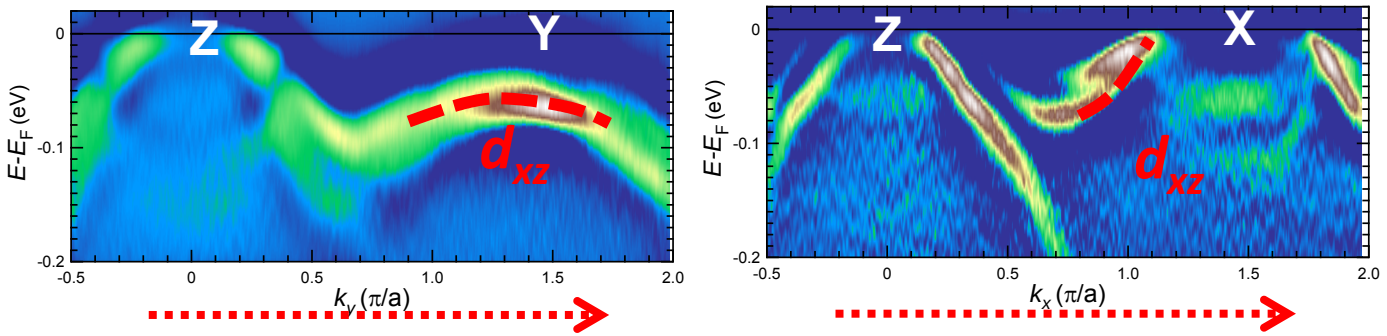
Magnetic torque

X-ray diffraction

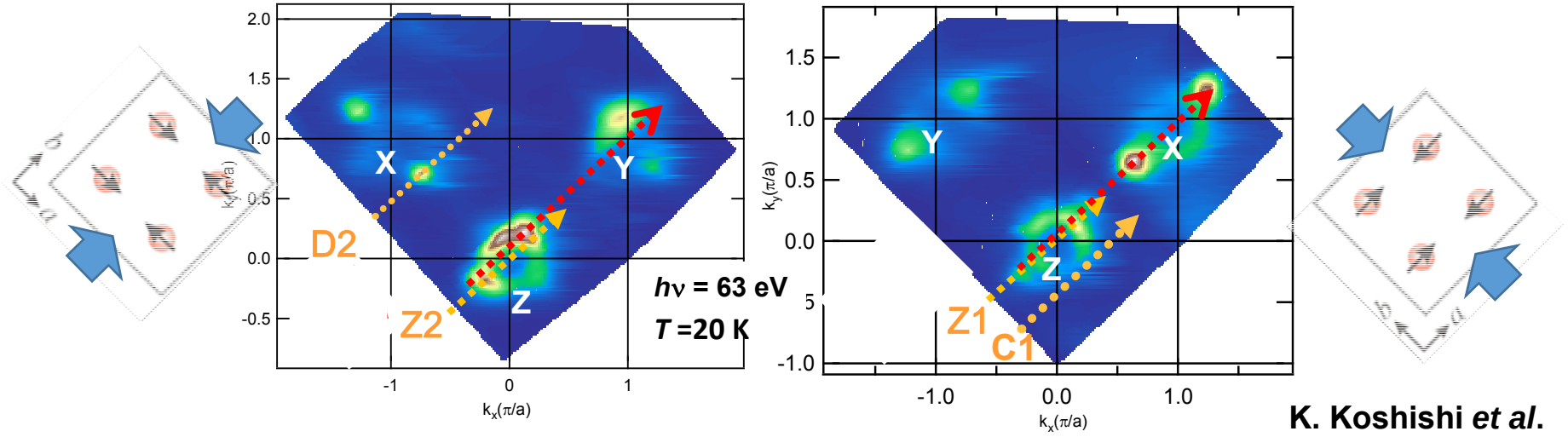


S. Kasahara *et al.*, Nature '12

Anisotropic band dispersions in the AFO phase of $BaFe_2As_2$ – C_4 symmetry breaking

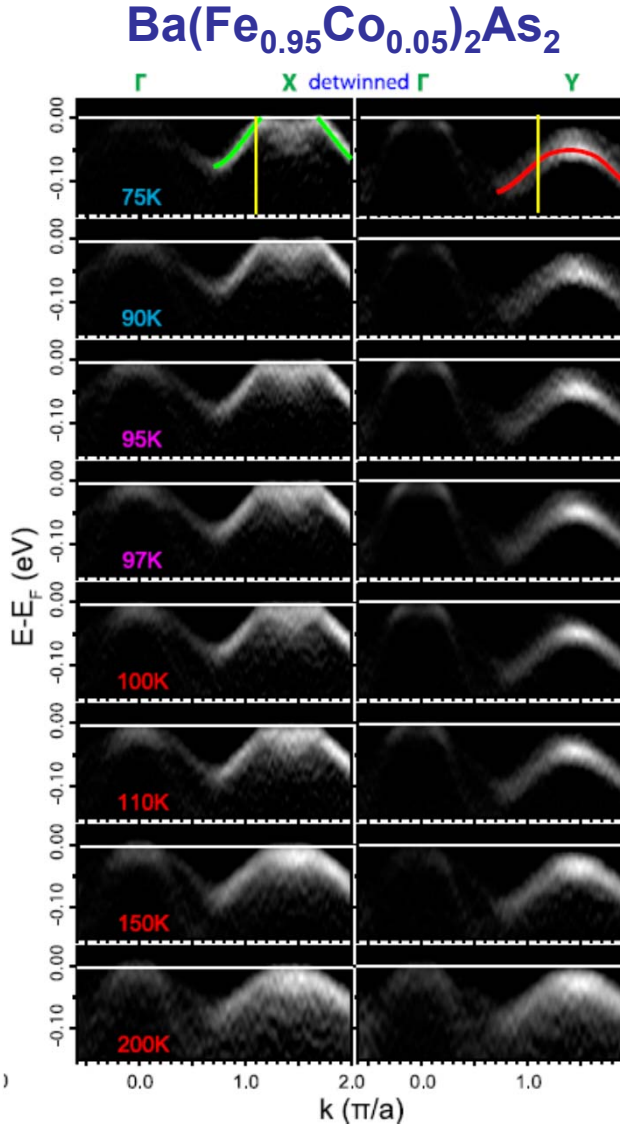


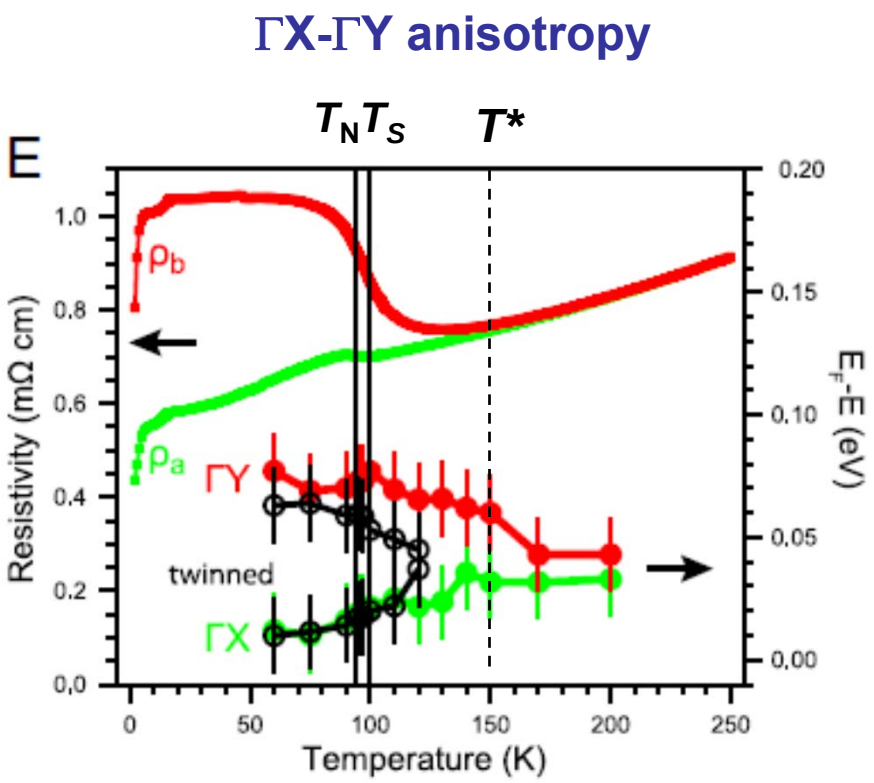
ARPES for k_z ~ Z, detwinned



K. Koshishi *et al*.

Persistence of the anisotropic band dispersions above $T_{N,S}$

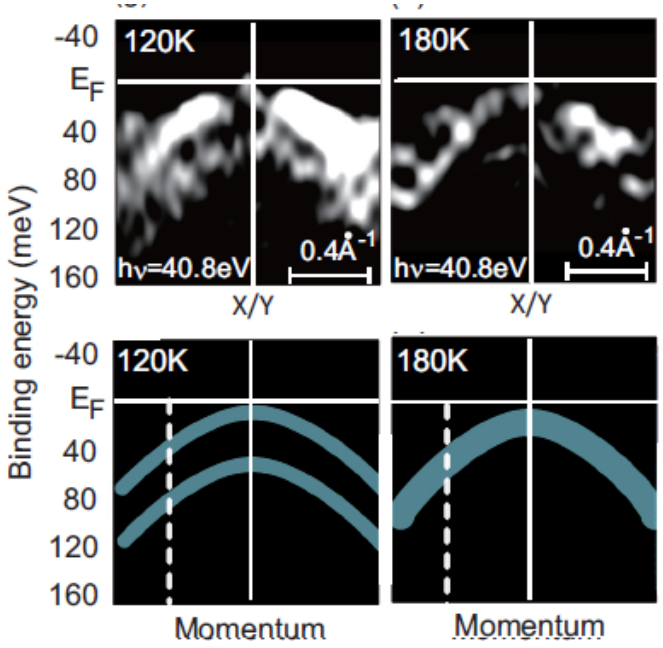




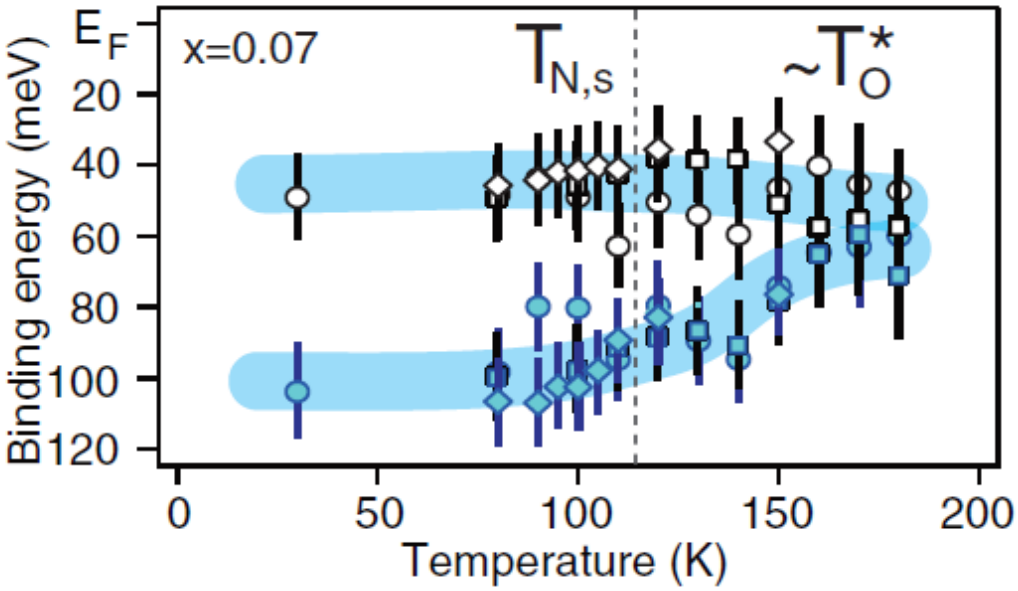
M. Yi *et al.*, PNAS '11

Persistence of the anisotropic band dispersions above $T_{N,S}$

$BaFe_2(As_{0.93}P_{0.07})_2$

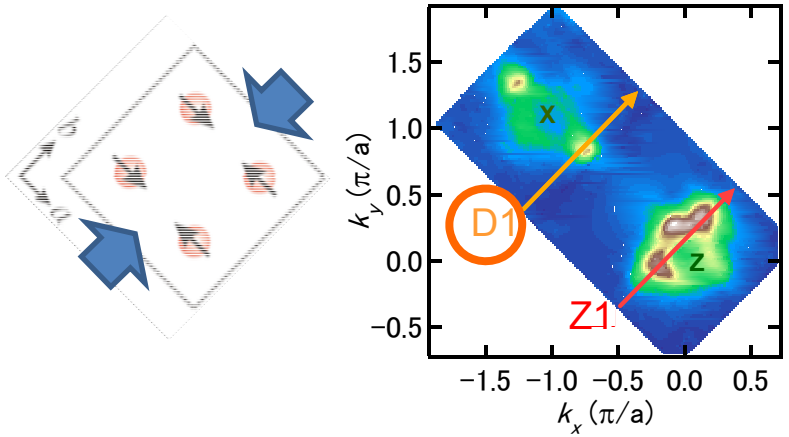


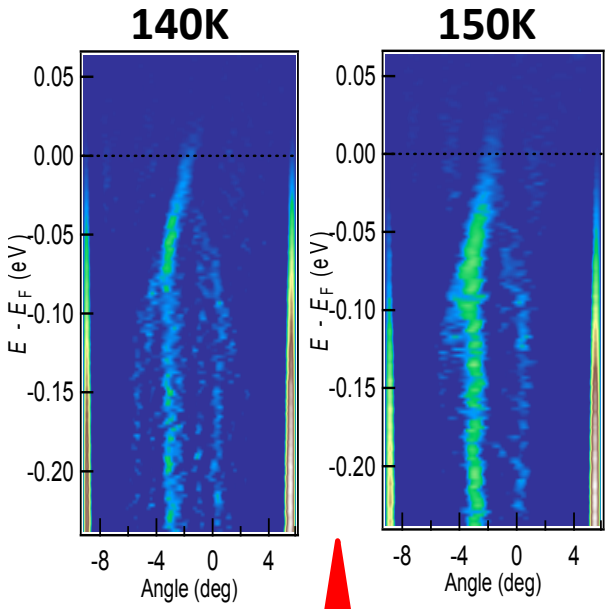
ΓX-ΓY anisotropy



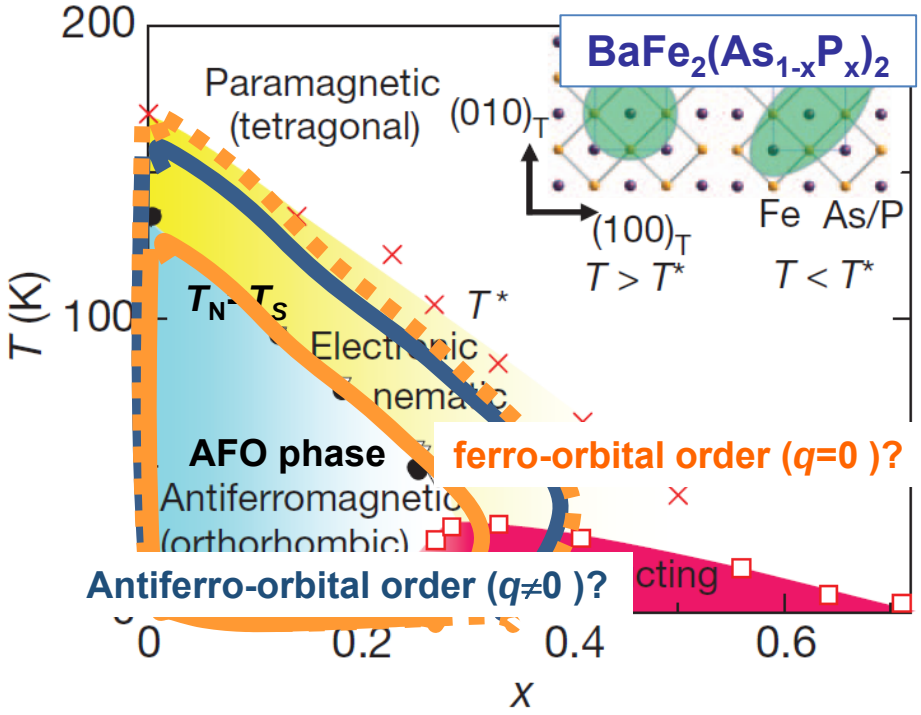
T. Shimojima *et al.*, PRB '14

C_4 symmetry breaking and band folding in Fe-based superconductor: Possible antiferro-orbital order





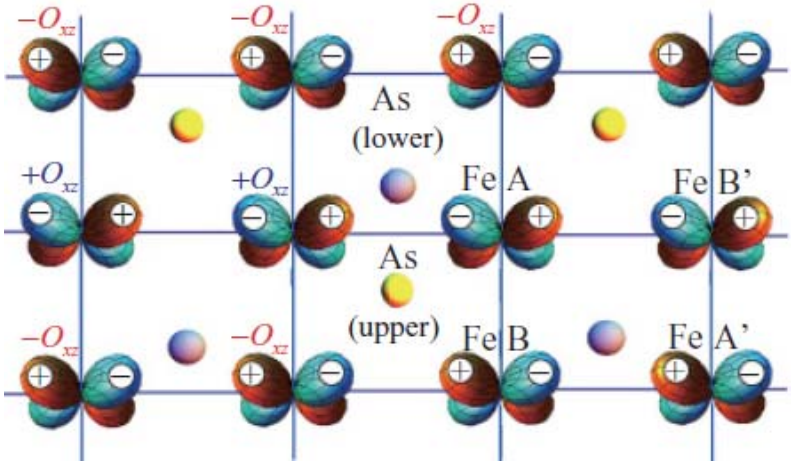
$T_{N,S}$ = 142 K

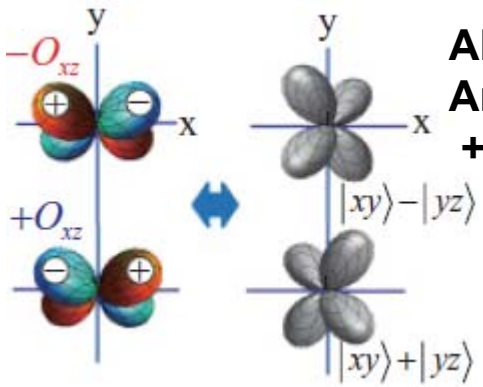


K. Koshishi *et al*.

Possible antiferro-orbital order below *T**

O_{xz} antiferro-quadrupole (AFQ) order?

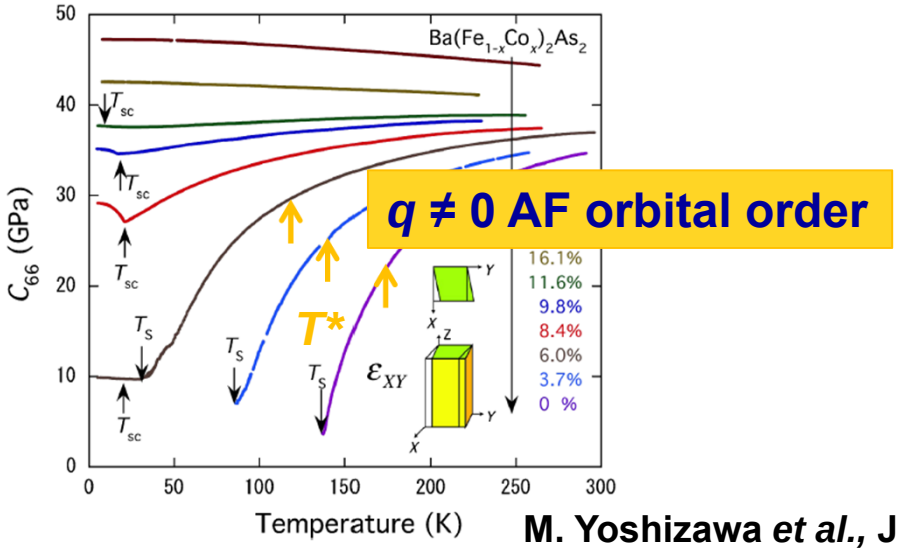




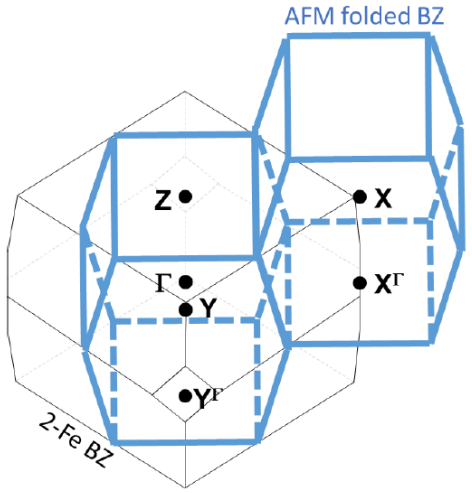
AFQ order = Antiferro-orbital + Ferro-orbital order

H. Kontani *et al.*, RB '11

Elastic constant C_{66}



$q \neq 0$ AF orbital order

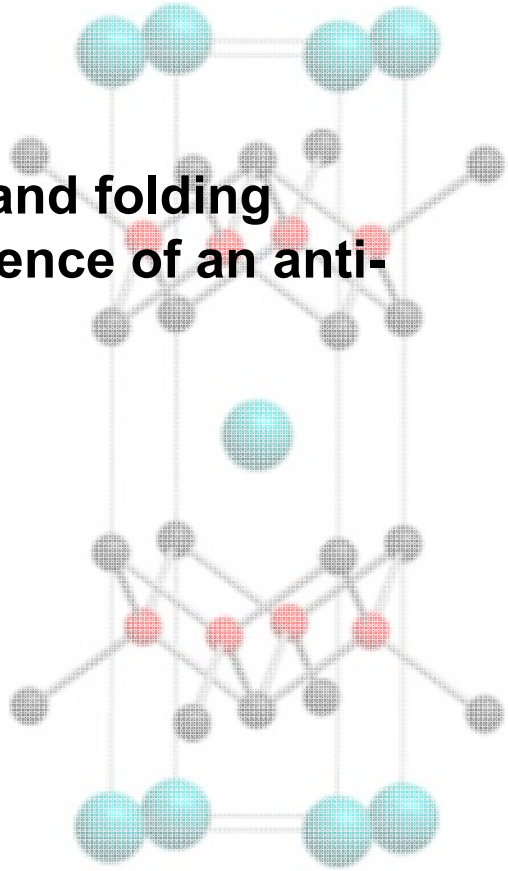


M. Yoshizawa *et al.*, JPSJ '12

Summary – AFO and "nematic" phases

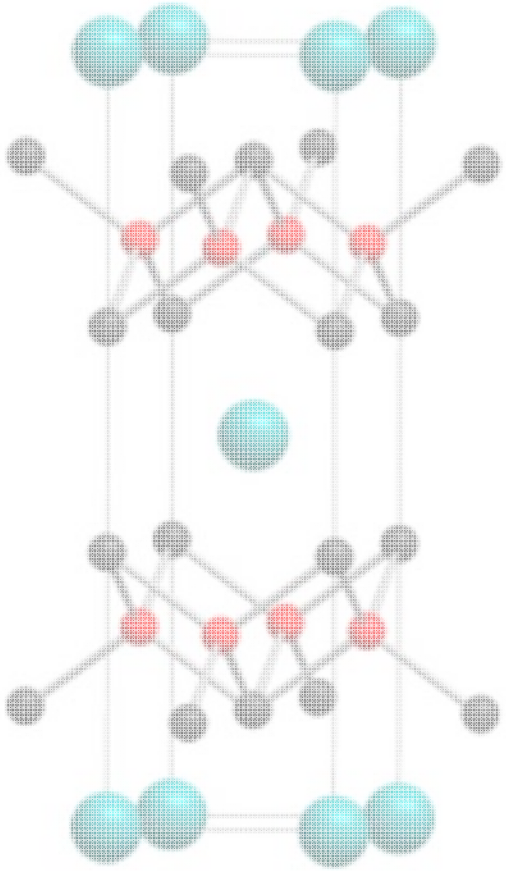
- **Folded electron and hole Fermi surfaces in the AFO phase revealed by ARPES are in almost perfect agreement with those deduced from the Subunikov-de Haas measurements.**

- **Not only C_4 symmetry breaking but also band folding survive above $T_{N,S}$, suggesting the persistence of an anti-ferro-orbital order above $T_{N,S}$ up to T^*.**



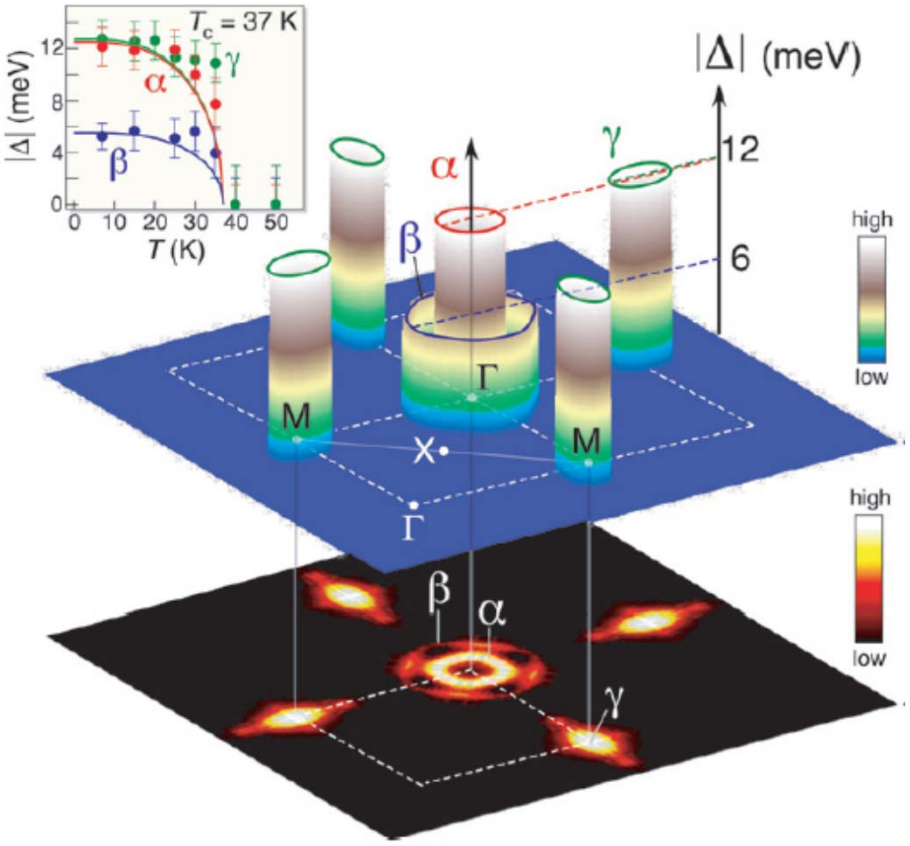
Outline

- **Nature of the AFM-orthorhombic (AFO) phase and the "nematic phase":**
  - **Band folding *versus* C_4 symmetry breaking**
- **Superconducting gap anisotropy**



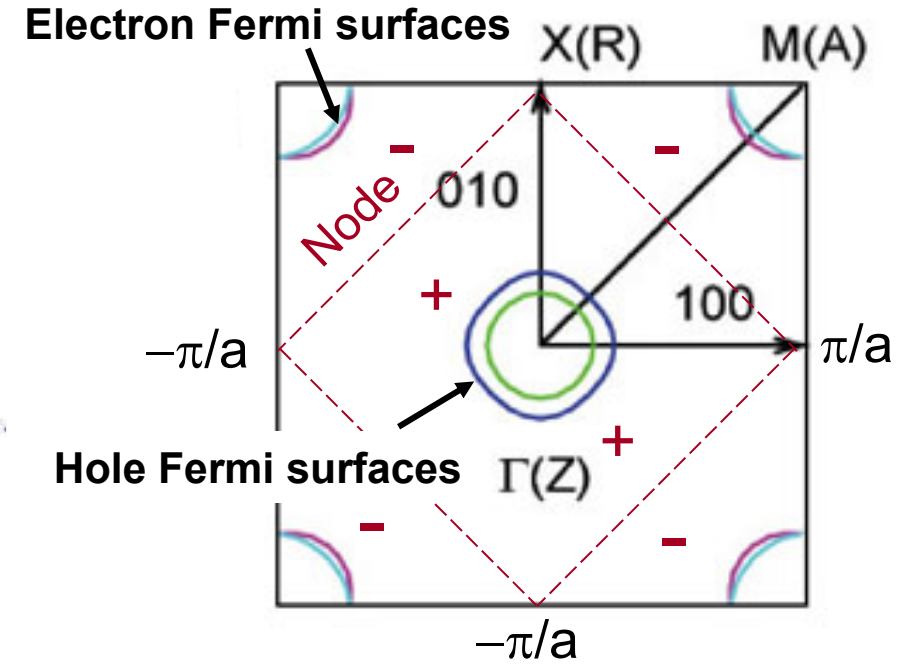
Nodeless $s_{\pm}$ superconducting gap in Fe pnictides

Superconducting gap of $K_{0.4}Ba_{0.6}Fe_2As_2$



H. Ding *et al.*, Europhys. Lett. '08

$s_{\pm}$-wave superconductivity



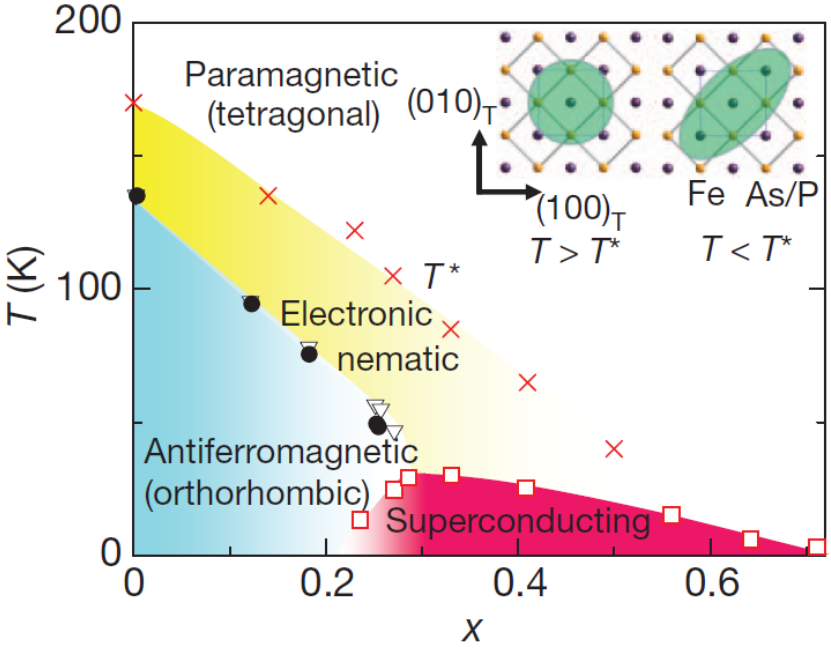
Order parameter

$$\Delta(k) = \Delta_0(\cos k_x a + \cos k_y a)/2$$

K. Kuroki *et al.*, PRB '09

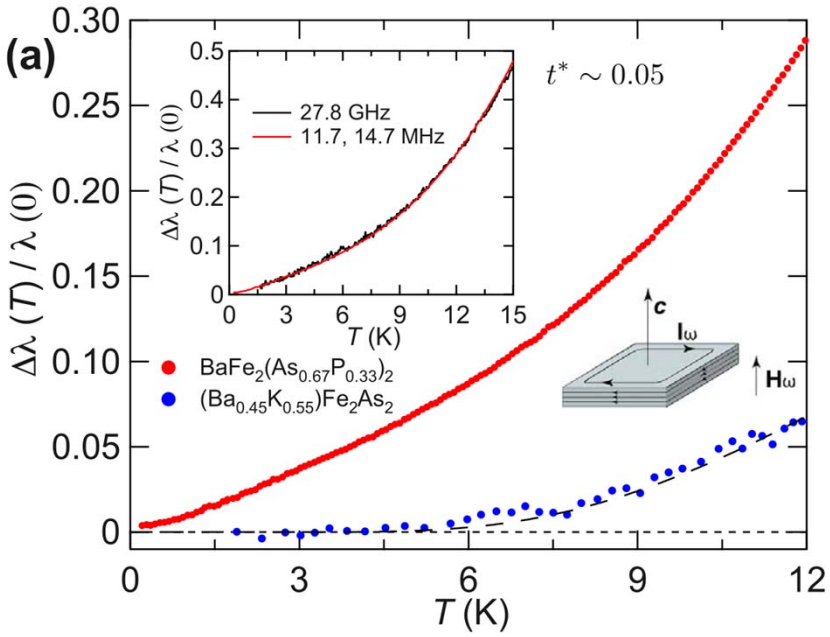
Superconductivity with line nodes in $BaFe_2(As_{1-x}P_x)_2$

Phase diagram



S. Kasahara *et al.*, Nature '13

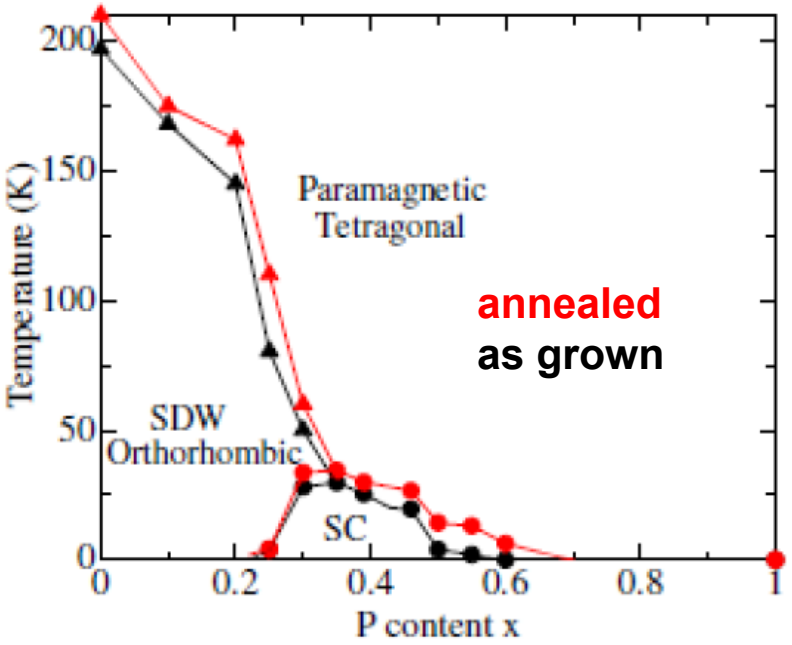
Penetration depth



K. Hashimoto *et al.*, PRB '10

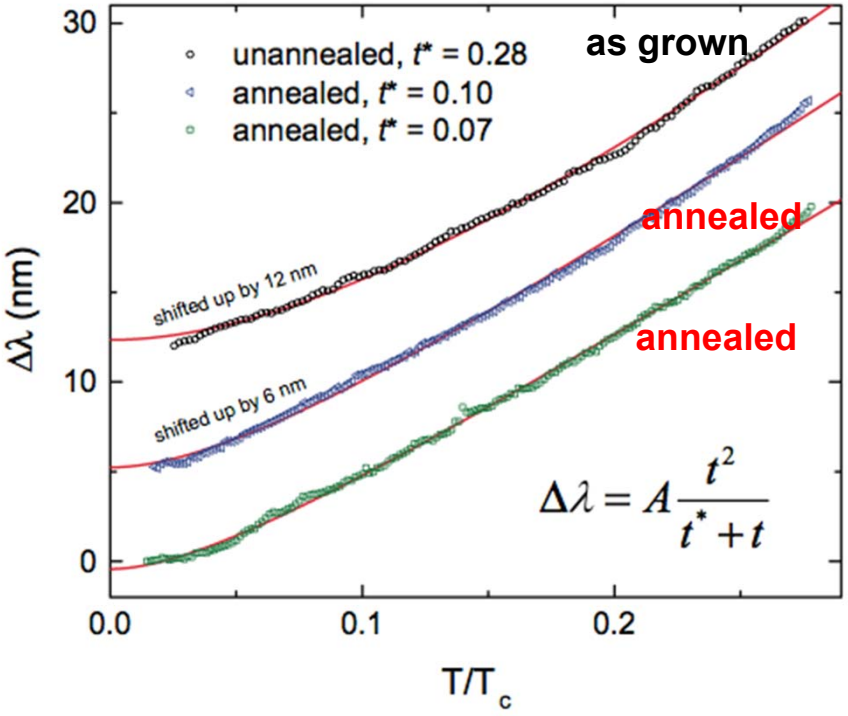
Superconductivity with line nodes in $SrFe_2(As_{1-x}P_x)_2$

Phase diagram



T. Kobayashi *et al.*, PRB '13

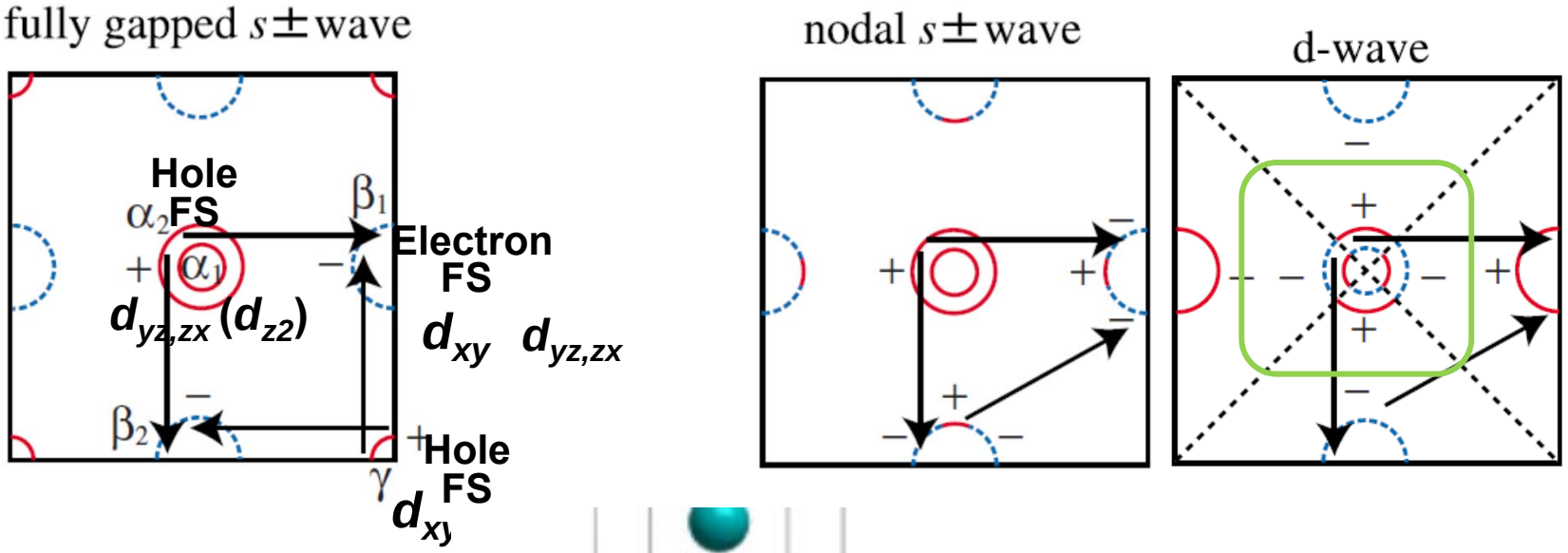
Penetration depth

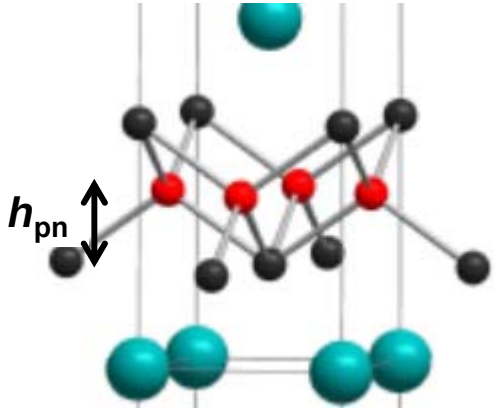


J. Murphy *et al.*, PRB '13

Line nodes in order parameter according to spin-fluctuation mechanism

high ⟵ Pnictogen height h_{Pn} ⟶ low

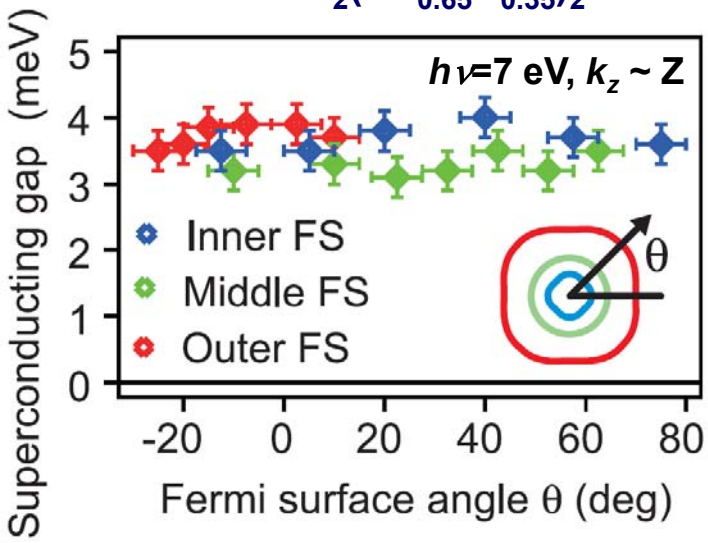




K. Kuroki *et al.*, PRB '09

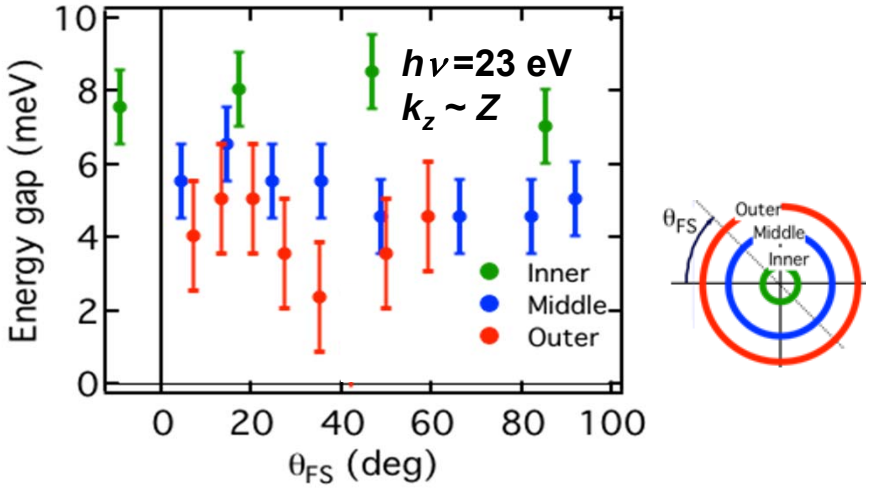
Superconducting gap on hole Fermi surfaces of $BaFe_2(As_{0.65}P_{0.35})_2$ and $SrFe_2(As_{0.65}P_{0.35})_2$

$BaFe_2(As_{0.65}P_{0.35})_2$



FS *in*dependent, nearly isotropic

$SrFe_2(As_{0.65}P_{0.35})_2$



FS dependent, nearly isotropic

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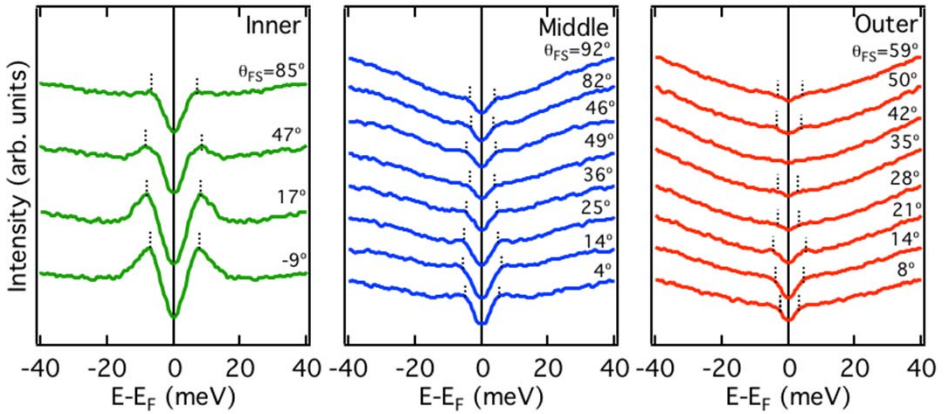
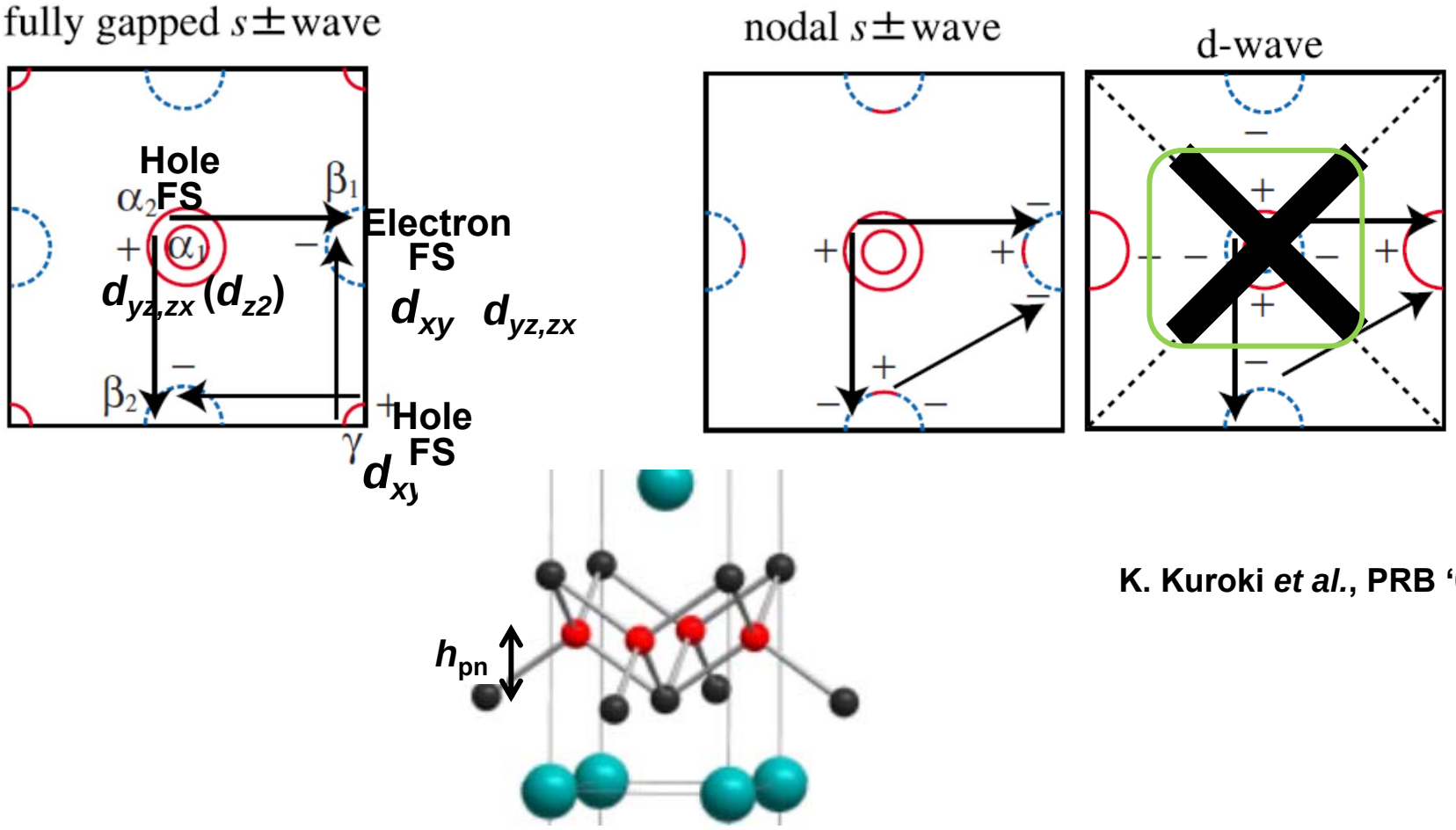


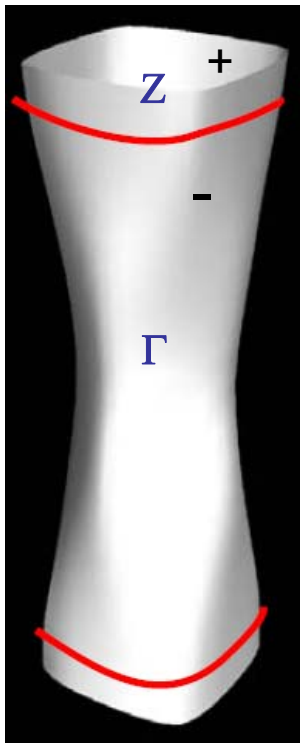
Line nodes in order parameter according to spin-fluctuation mechanism

high ⟵ Pnictogen height h_{Pn} ⟶ low



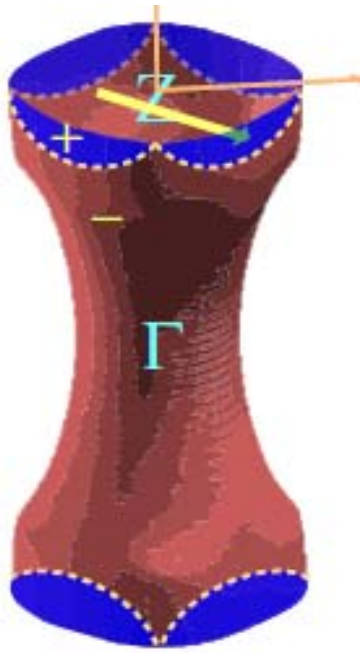
K. Kuroki *et al.*, PRB '09

Possibility of horizontal line nodes in spin-fluctuation mechanism



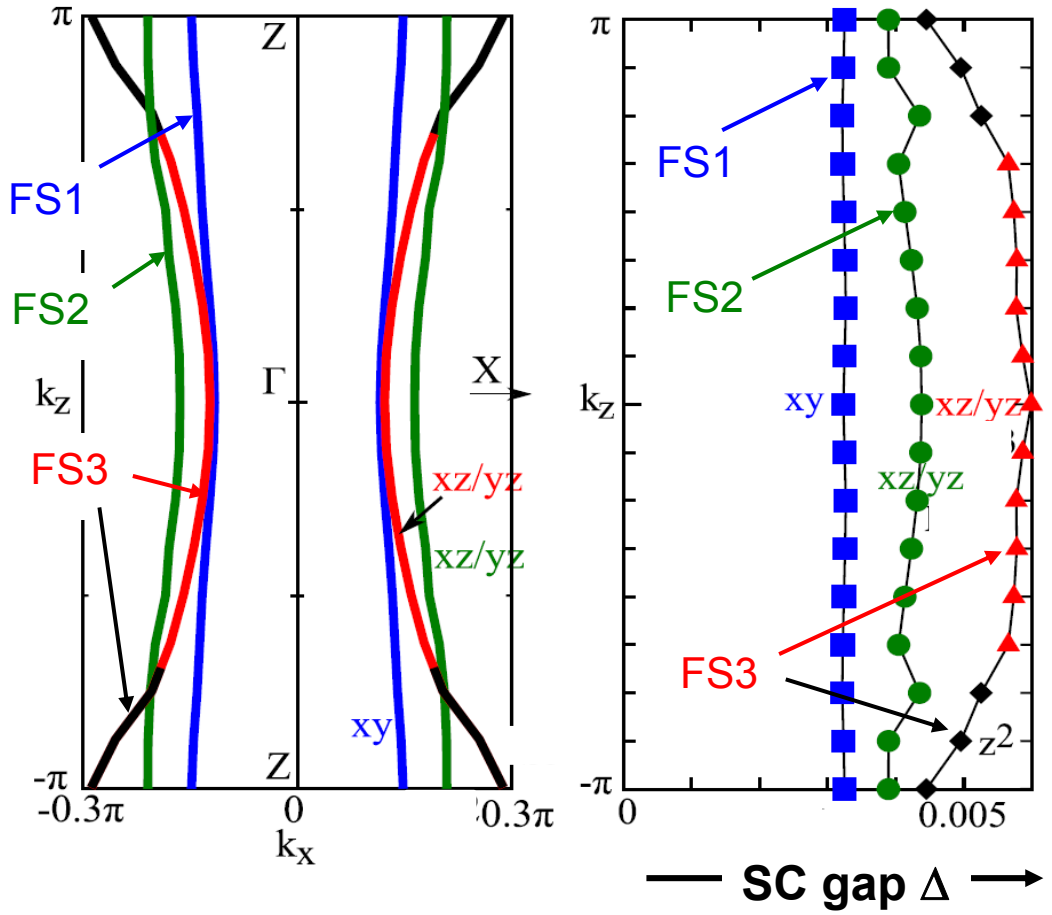
S. Graser *et al.*, PRB ’10.

Hole FS



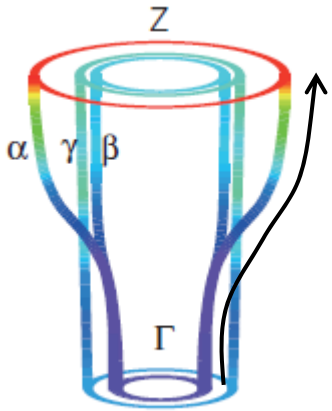
K. Suzuki *et al.*, JPSJ ‘11

Superconducting gap on hole Fermi surfaces: Combined spin and orbital fluctuations

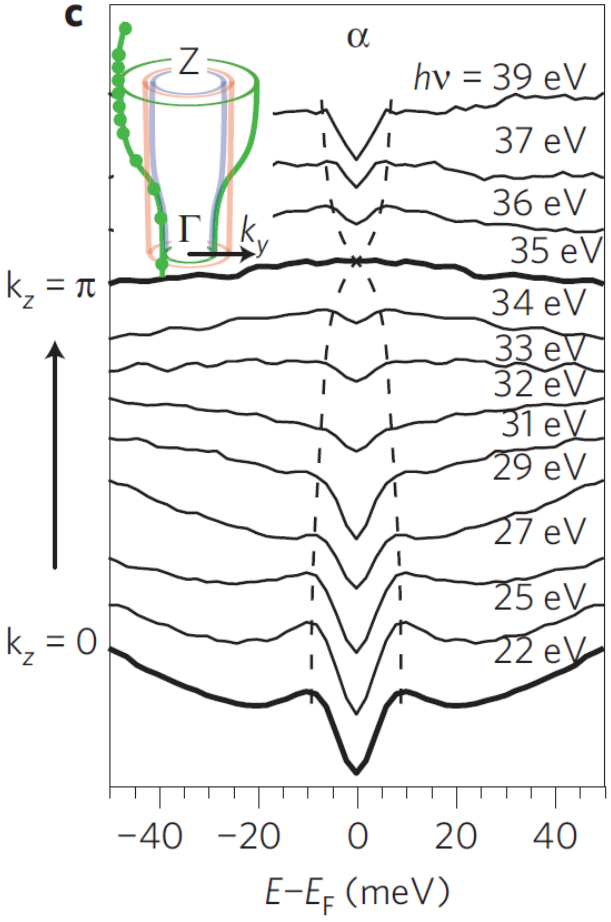


S. Onari and H. Kontani , PRL '12
T. Saito, S. Onari, H. Kontani, PRB '13

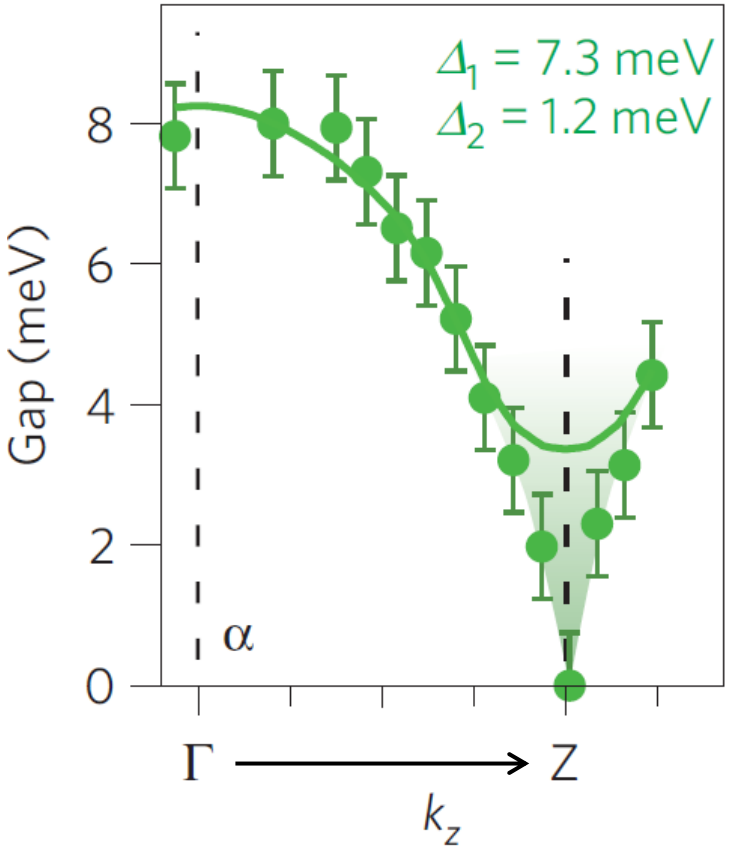
k_z dependence of the superconducting gap on hole Fermi surfaces of $BaFe_2(As_{0.70}P_{0.30})_2$



Outer FS



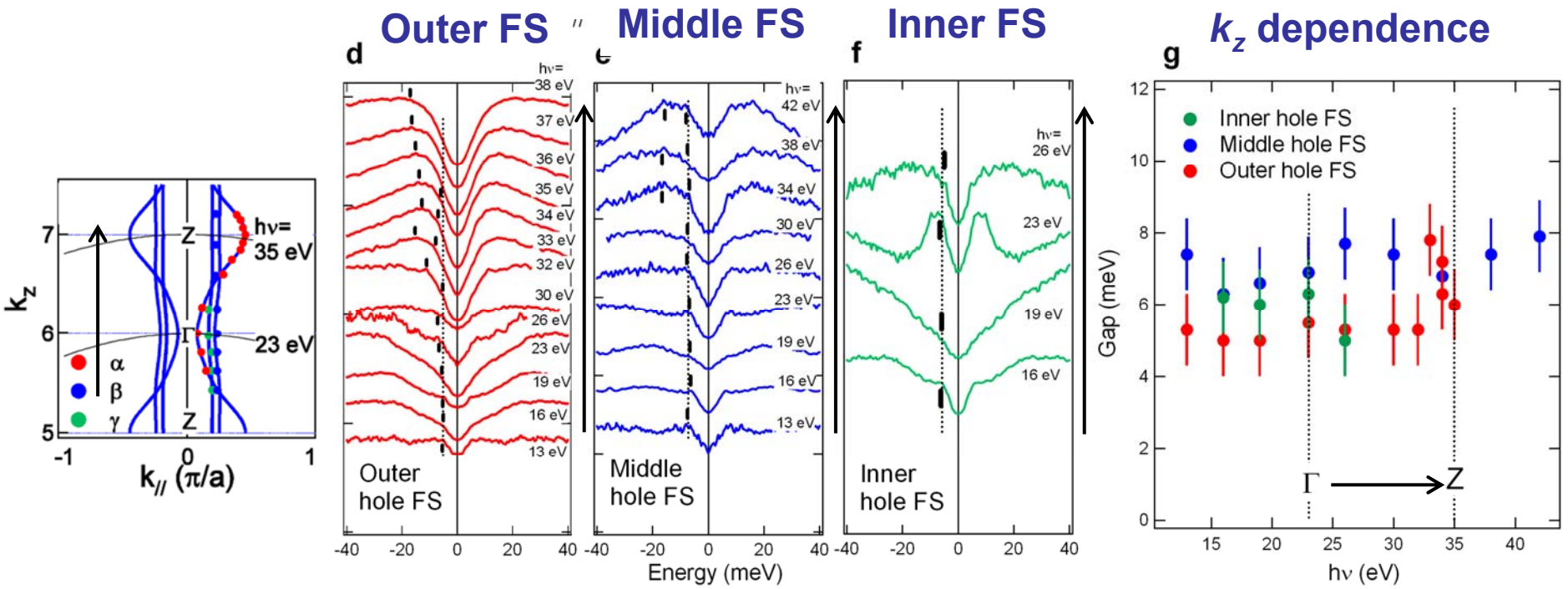
k_z dependence



Closes at k_z ~ Z

Y. Zhang *et al.*, Nat. Phys. '12

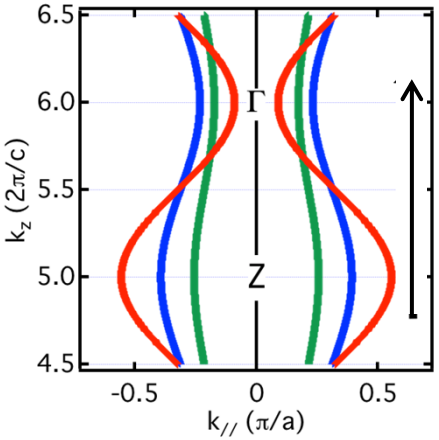
k_z dependence of the superconducting gap on hole Fermi surfaces of $BaFe_2(As_{0.70}P_{0.30})_2$

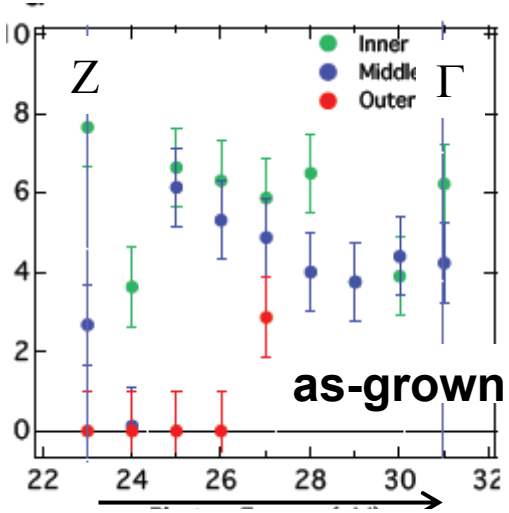


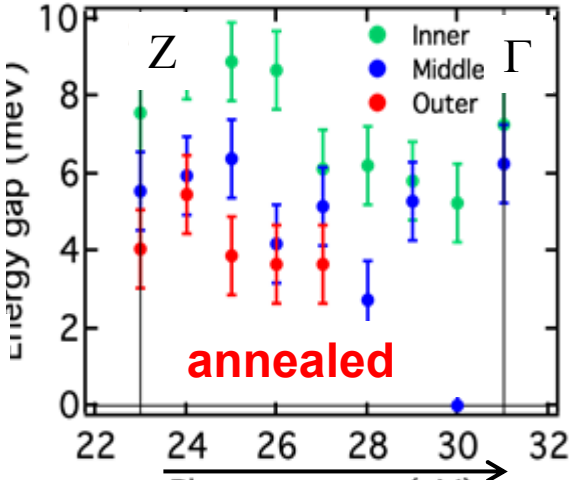
Nearly k_z *in*dependent

T. Yoshida *et al.*, Sci. Rep. '14

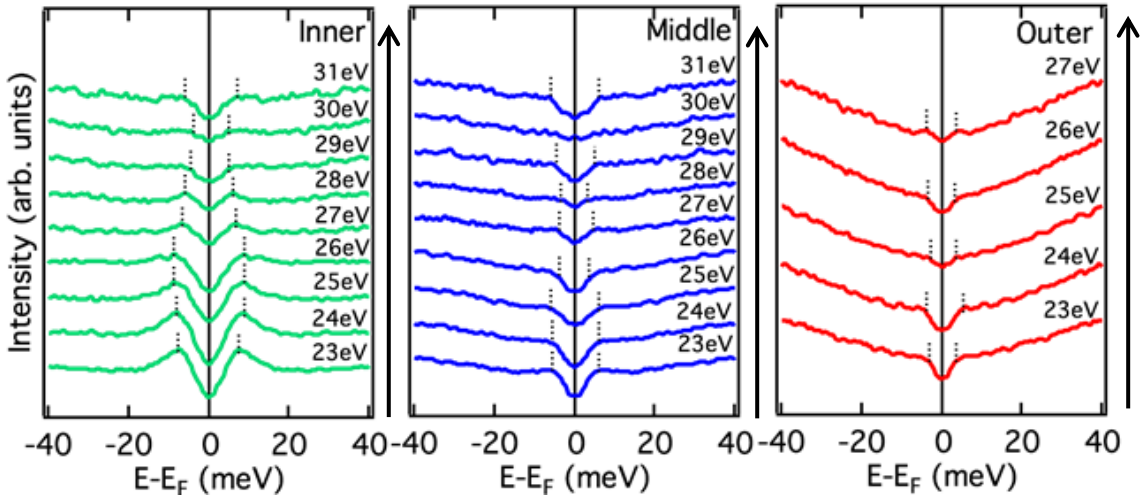
k_z dependence of the superconducting gap on hole Fermi surfaces of $SrFe_2(As_{0.65}P_{0.35})_2$







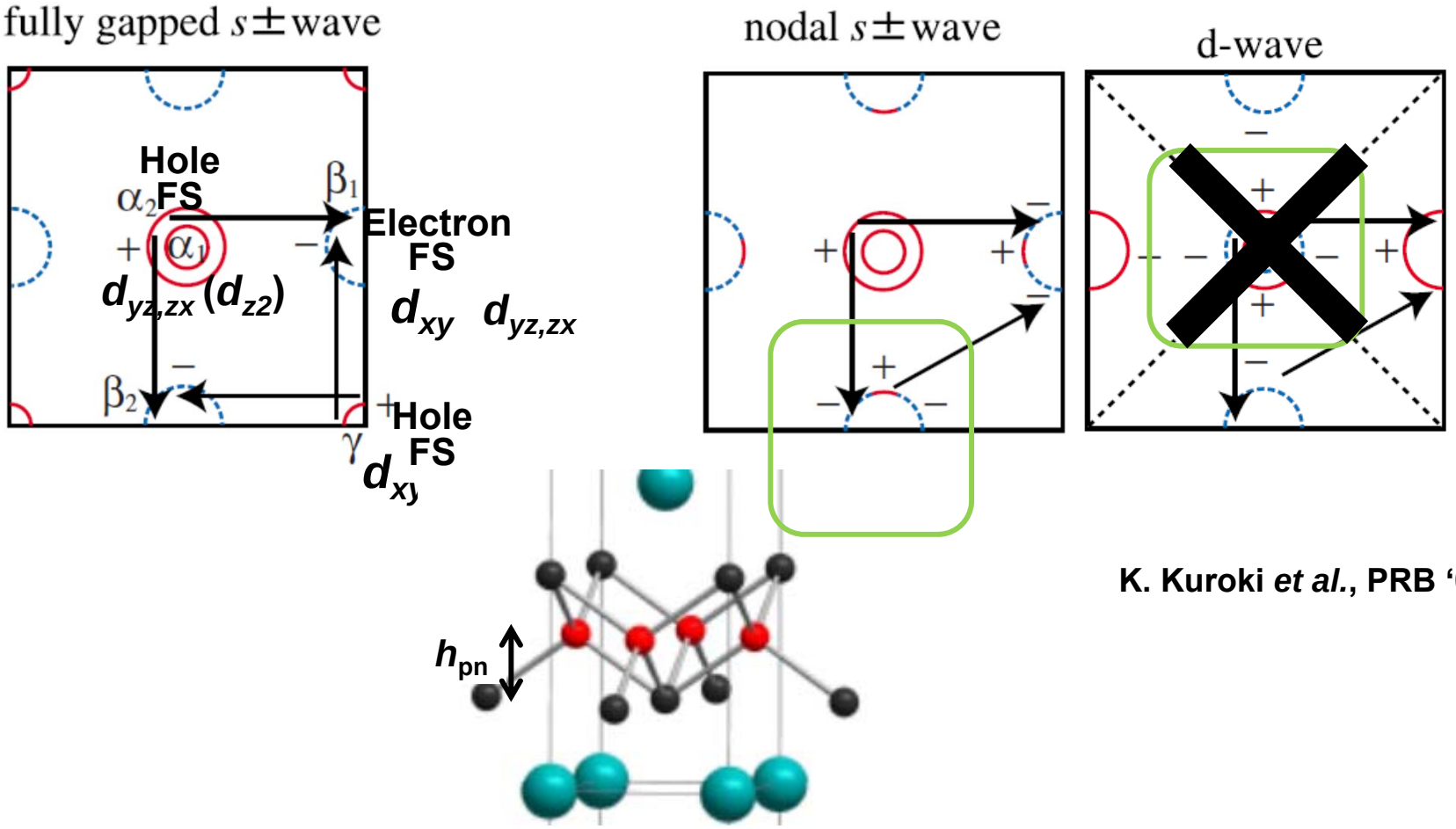
Gap minimum around k_z ~ Z **Gap opens around k_z ~ Z**



H . Suzuki *et al*.

Line nodes in order parameter according to spin-fluctuation mechanism

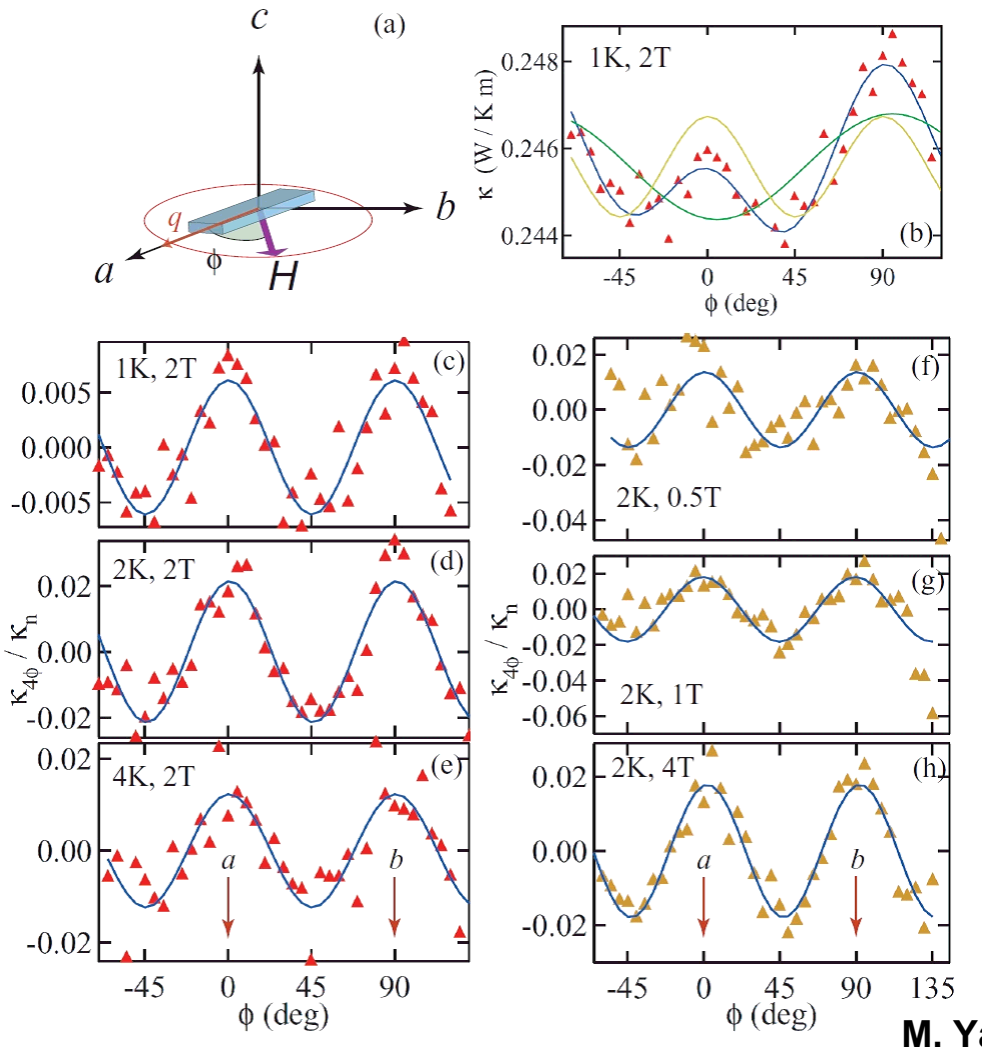
high ⟵ Pnictogen height h_{Pn} ⟶ low



K. Kuroki *et al.*, PRB '09

Four-fold symmetry of thermal conductivity in magnetic fields in $BaFe_2(As_{1-x}P_x)_2$

Angular dependence

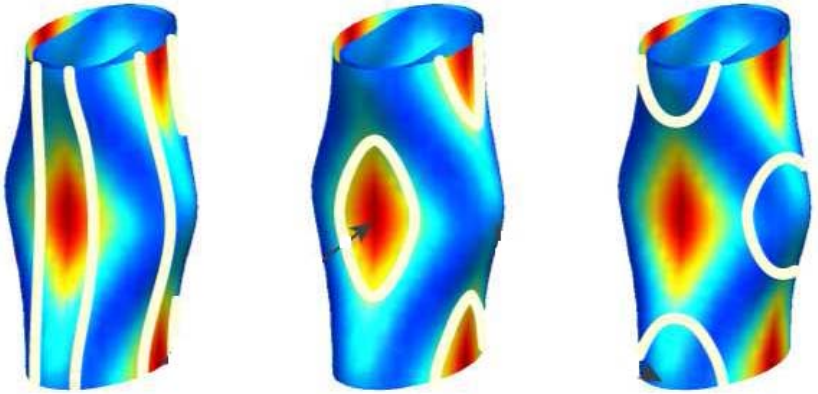


M. Yamashita *et al.*, PRB '11

Possible line nodes in superconducting gap on electron Fermi surfaces

Vertical line nodes

Loop-like line nodes

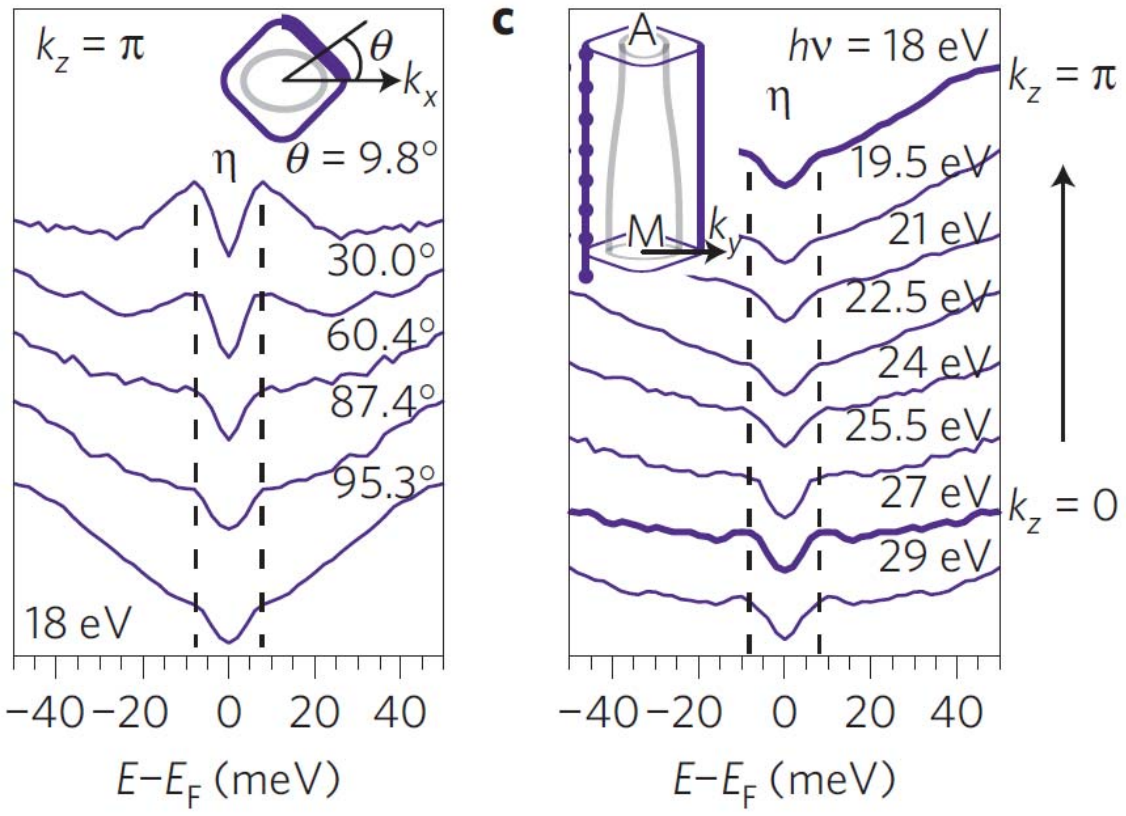


M. Yamashita *et al.*, PRB '11.

Loop-like line nodes

I. Mazin *et al.*, PRB '10

Superconducting gap on electron Fermi surfaces of $BaFe_2(As_{0.70}P_{0.30})_2$



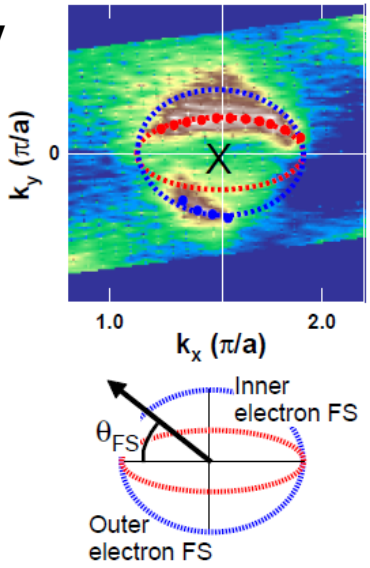
Isotropic

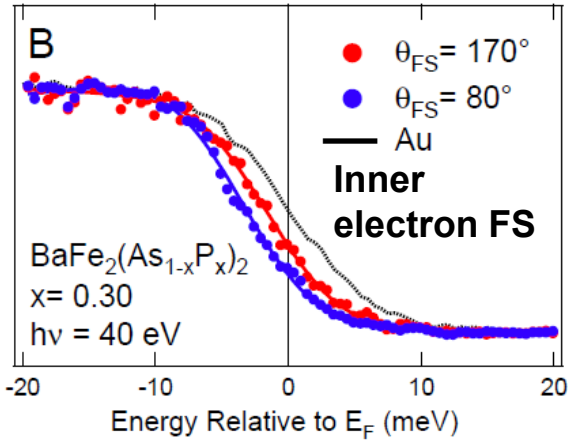
Y. Zhang *et al*., Nat. Phys. '12

Superconducting gap on electron Fermi surfaces of $BaFe_2(As_{0.70}P_{0.30})_2$

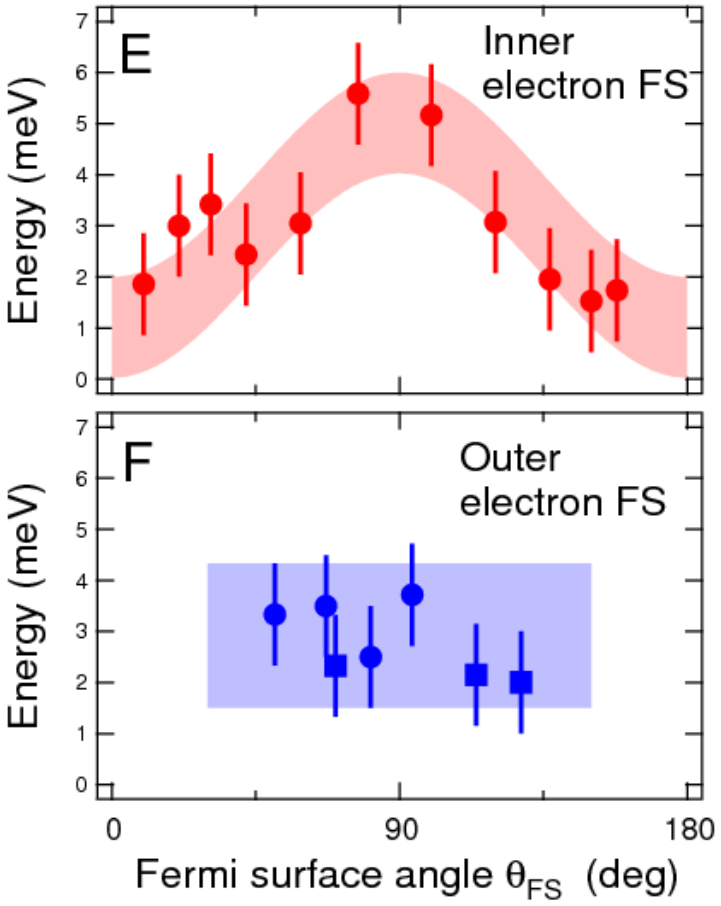
$h\nu$=40 eV

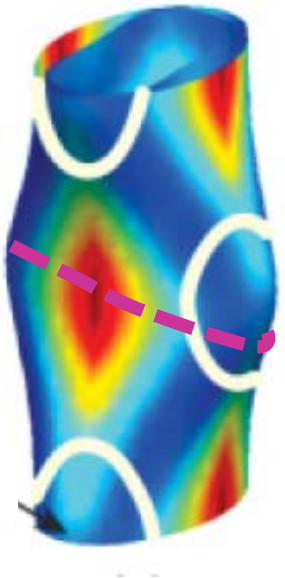
T_c=30 K





Gap magnitude

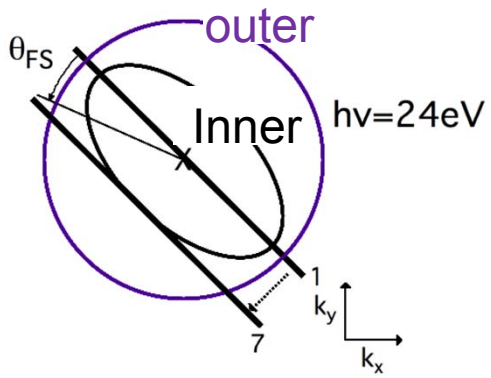


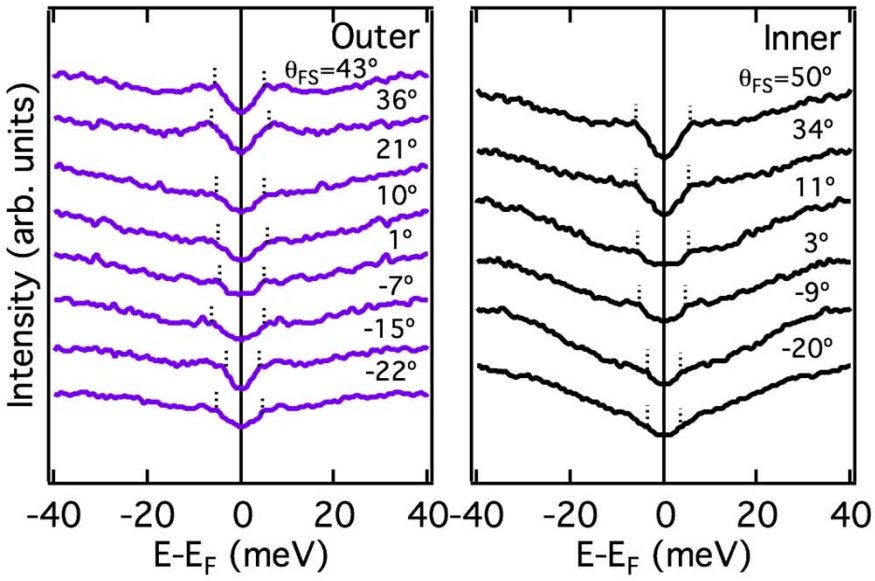


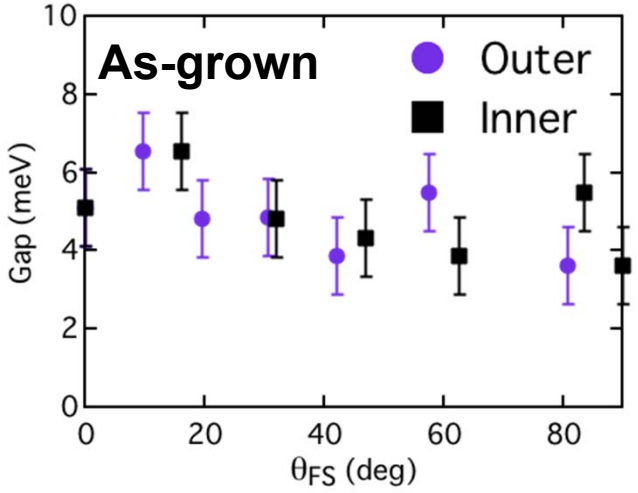
Anisotropy

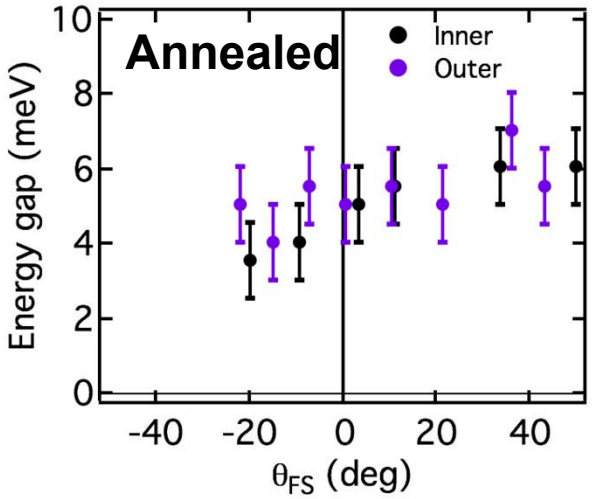
T. Yoshida *et al.*, Sci. Rep. '14

Superconducting gap on electron Fermi surfaces of $SrFe_2(As_{0.65}P_{0.35})_2$









Nearly isotropic

H . Suzuki *et al.*

Summary of ARPES experiments on gap anisotropy in isovalent-substituted 122 systems

		Hole FS	Electron FS
$BaFe_2(As,P)_2$ (x=0.30)	Y. Zhang *et al*.	$\|\Delta\|$ ~ 0 at k_z ~ Z	isotropic
(x=0.30, 0.38)	T. Yoshida *et al.*	$\|\Delta\|$ > 0 for all k_z	anisotropic
(x=0.35)	T. Shimojima *et al.*	$\|\Delta\|$ > 0 at k_z ~ Z	——
		FS-independent	
$SrFe_2(As,P)_2$ (x=0.35) before annealing	H. Suzuki *et al.*	$\|\Delta\|$ ~ 0 at k_z ~ Z	isotropic
after annealing		$\|\Delta\|$ > 0 for all k_z	isotropic
$Ba(Fe,Ru)_2As_2$ (x=0.35)	L. Liu *et al.*	$\|\Delta\|$ ~ 0 at k_z ~ Z	isotropic

Summary – Superconducting gap

- **Superconducting gap anisotropy is material, composition, and disorder dependent even in the limited number of isovalent P- and Ru-substituted systems:**
  - **Hole FS: Gap minimum or no minimum around k_z ~ Z.**
  - **Electron FS: Isotropic or anisotropic.**