The Abdus Salam
International Centre
for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

2357-23

Innovations in Strongly Correlated Electronic Systems: School and Workshop

6 - 17 August 2012

Probing iron-based superconductivity by photoelectrons

Hong DING

Institute of Physics, Chinese Academy of Sciences
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Probing iron-based superconductivity by photoelectrons

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ICTP workshop of New Innovations in Strongly Correlated Electron Systems
August 14, 2012

Collaborators

ARPES:

IOP: T. Qian, P. Richard, J. Dong, Y.-B. Huang, X.-P. Wang, N. Xu, Y.-B. Shi, H. Miao, P. Zhang, J. Bowen

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Tohoku Univ.: K. Nakayama, T. Kawahara, K. Sugawara, T. Arakane, Y. Sekiba, A. Takayama, S. Souma, T. Sato, T. Takahashi

Renmin Univ.: Z.-H. Liu, W.-C. Jin, S.-C. Wang

PSI: M. Shi, X.-Y. Cui, E. Razzoli, M. Radovic

BESSY: E. Rienks, S. Thirupathaiah

UVSOR: K. Terashima *ALS*: A. Fedorov

Theory:

IOP: X. Dai, Z. Fang *BC*: Z. Wang IOP/*Purdue*: J.-P. Hu

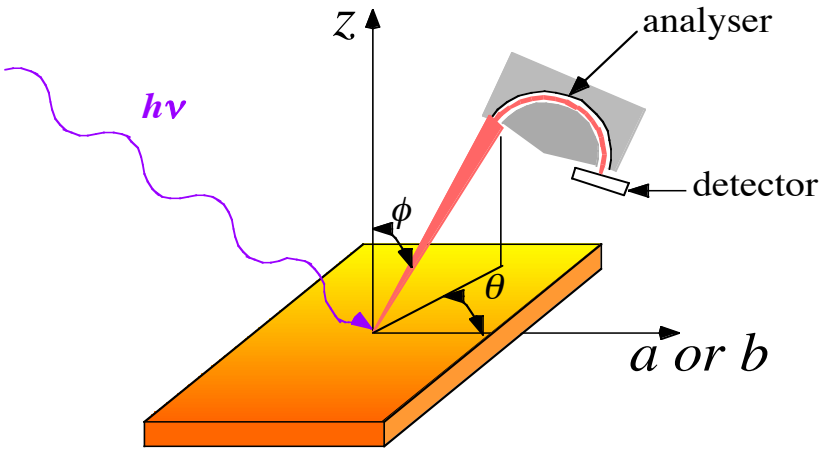
Samples:

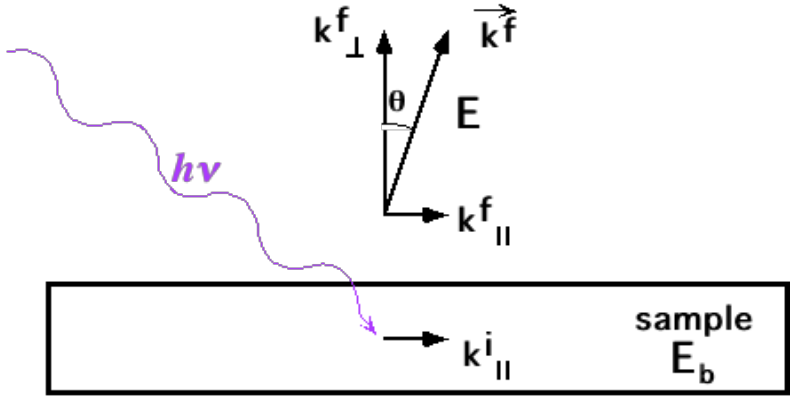
IOP: G.-F. Chen , N.-L. Wang, X.-L. Chen

Nanjing Univ.: H.-H. Wen *Zhejiang Univ.*: G.-H. Cao, Z.-A. Xu, M.-H. Fang

UT: C.-L. Zhang, P.-C. Dai *BNL*: G.-D. Gu

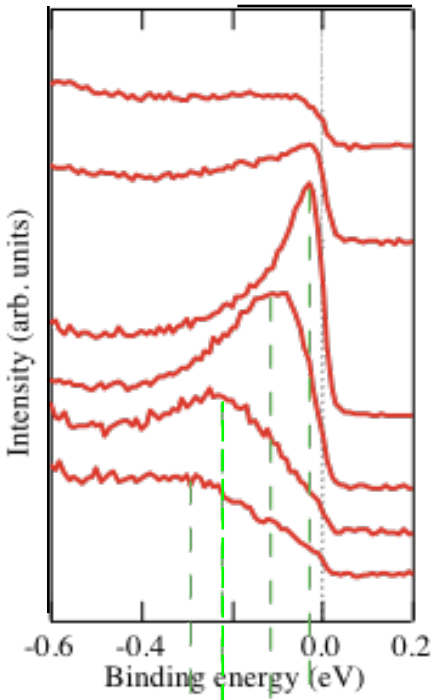
ARPES maps band structure and Fermi surface

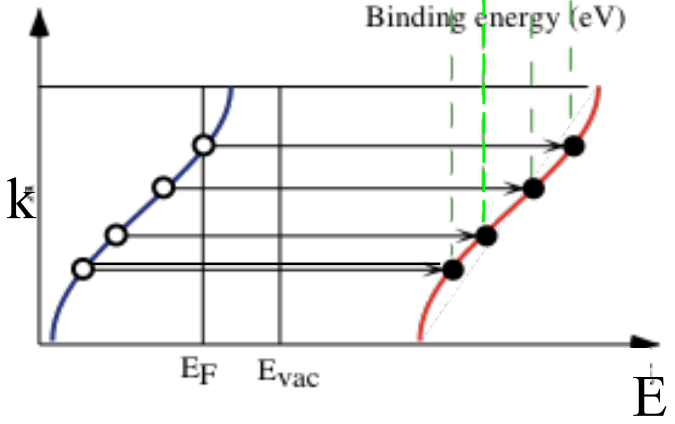




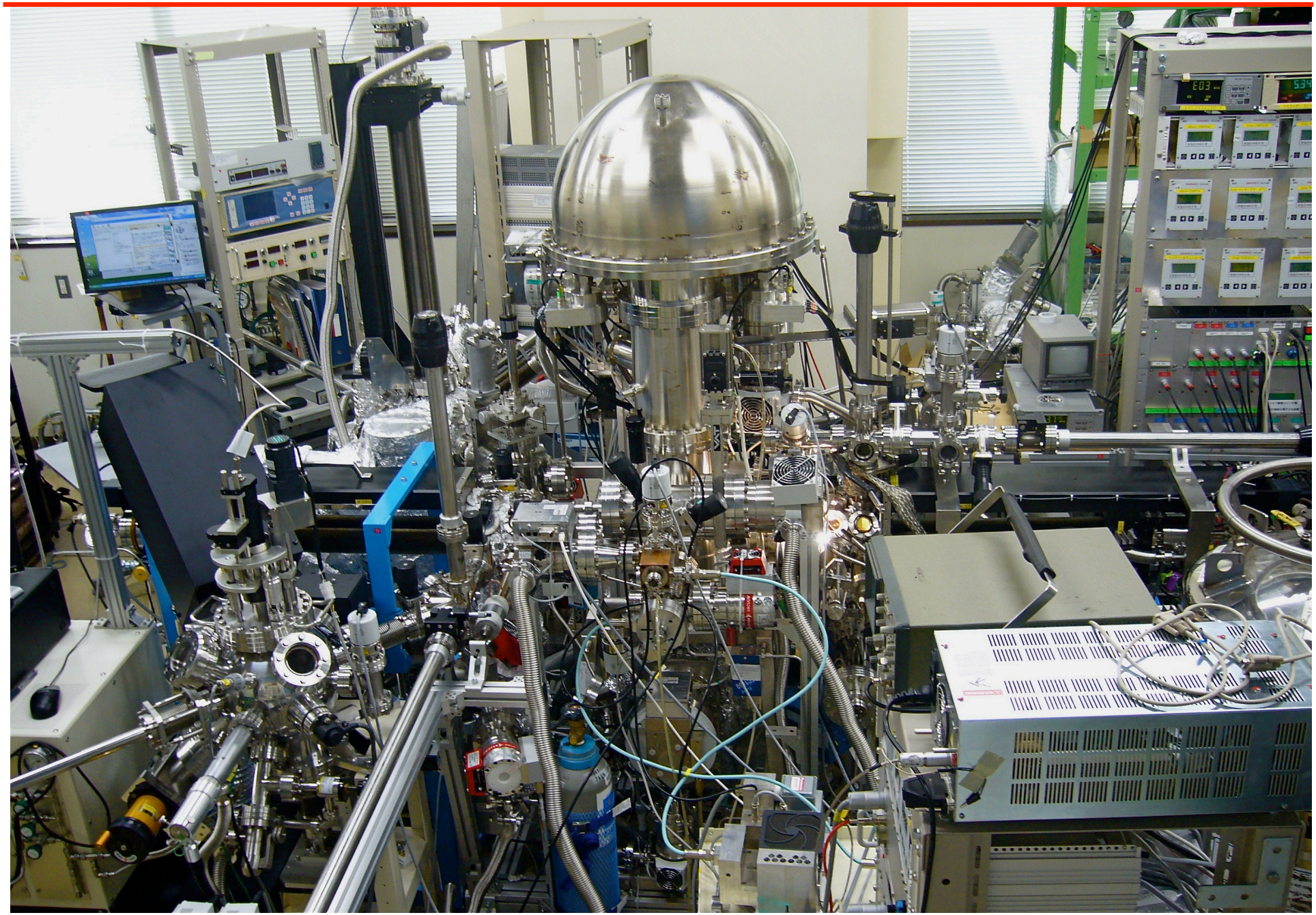
$E = h\nu - W - E_b \qquad k^f_{II} = k^i_{II}$

$$k^f_{II} = \sqrt{\frac{2mE}{\hbar^2}} \sin\theta$$

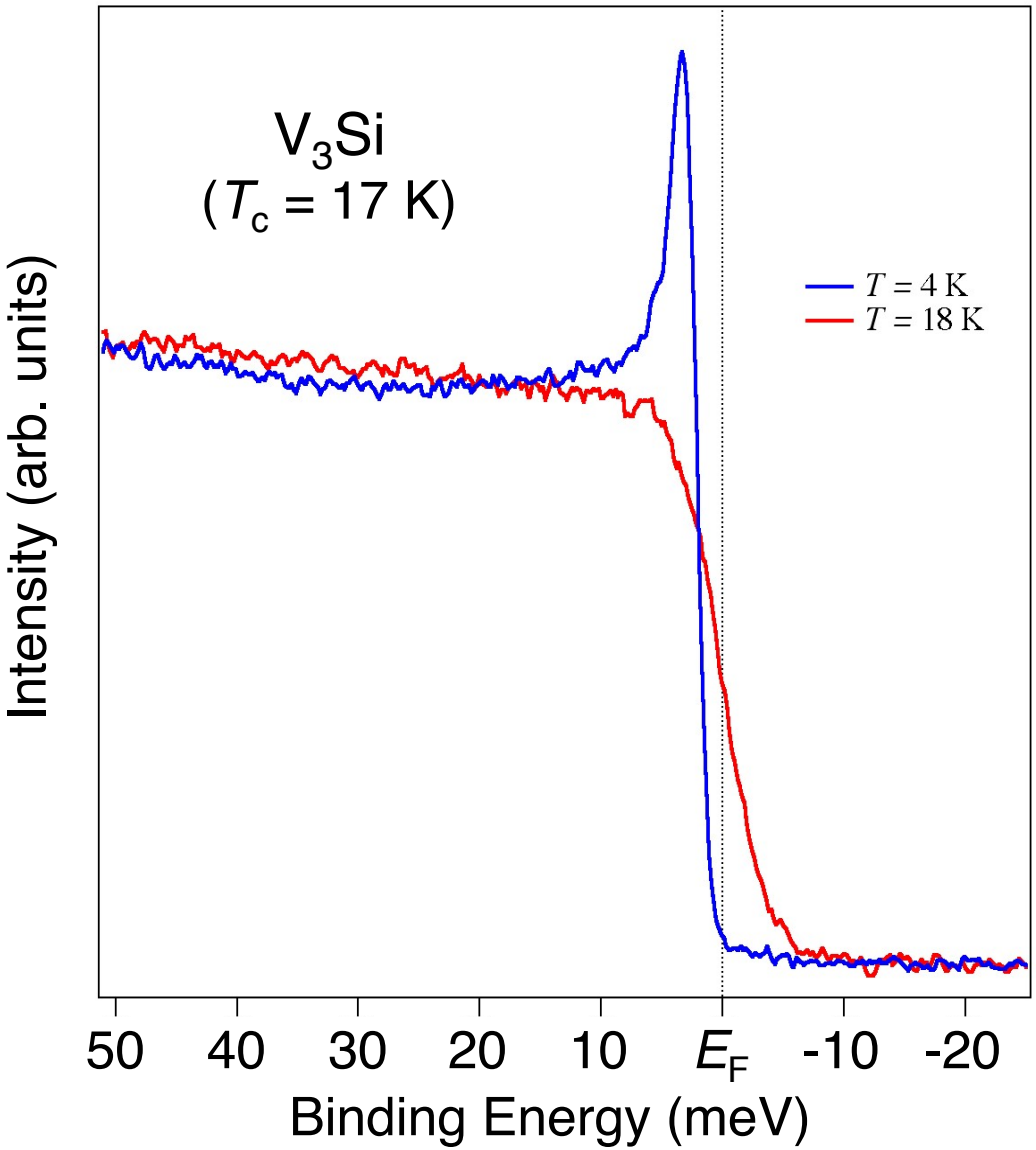




Ultrahigh-resolution ARPES spectrometer



Ultrahigh-resolution ARPES spectrometer



Energy resolution:

0.9 meV @ MCP

Angular resolution: 0.2°

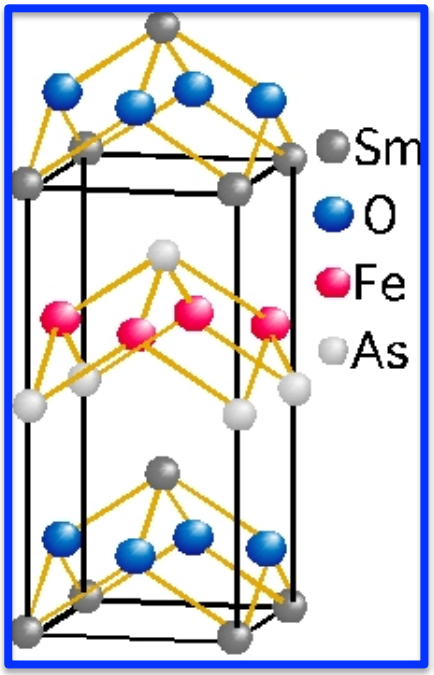
Photons:

Xe and He discharge lamps

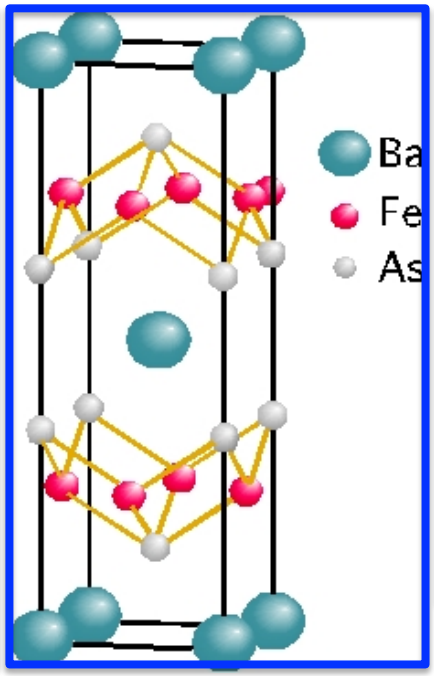
Lowest T: 3.5 K

Vacuum: < 2×10^{-11} Torr

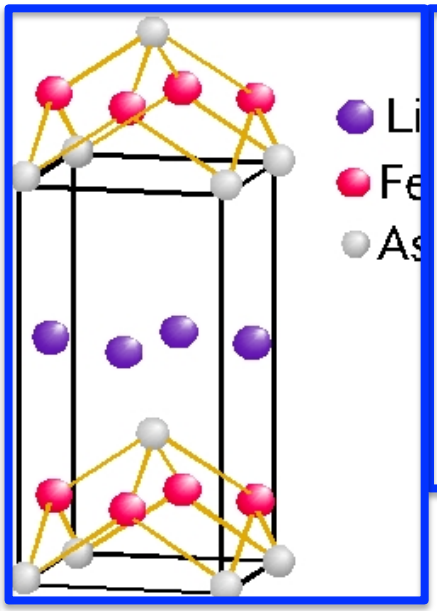
Crystal structure of iron-based superconductors



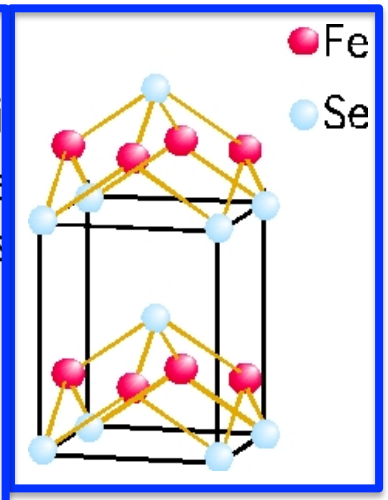
1111



122

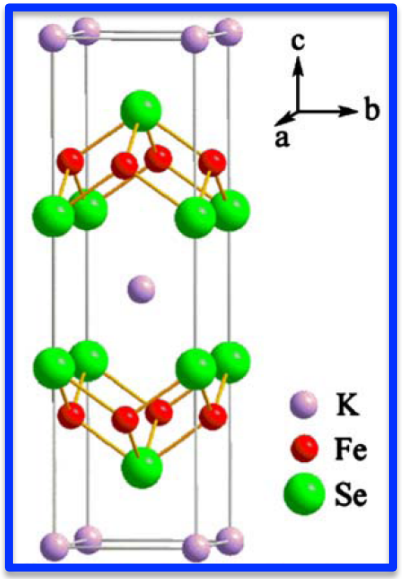


111

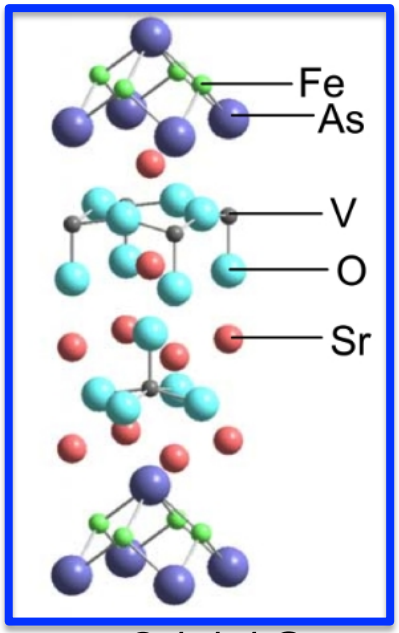


11

Universality in
Fermi surface topology
& superconducting gap?

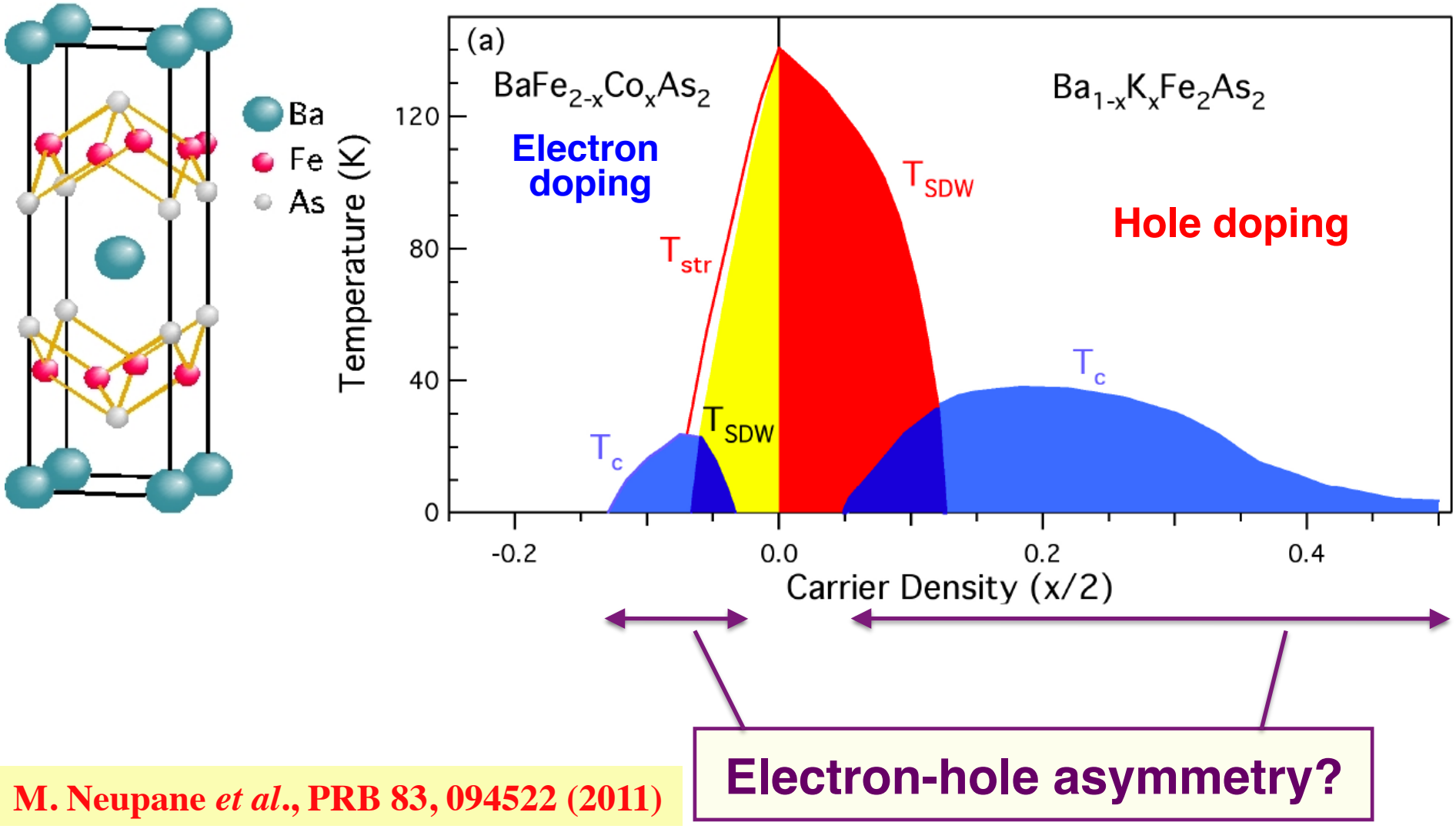


122'



21113

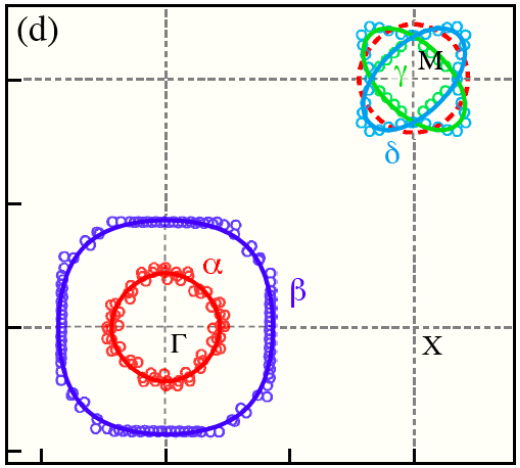
Phase diagram of Ba122 system

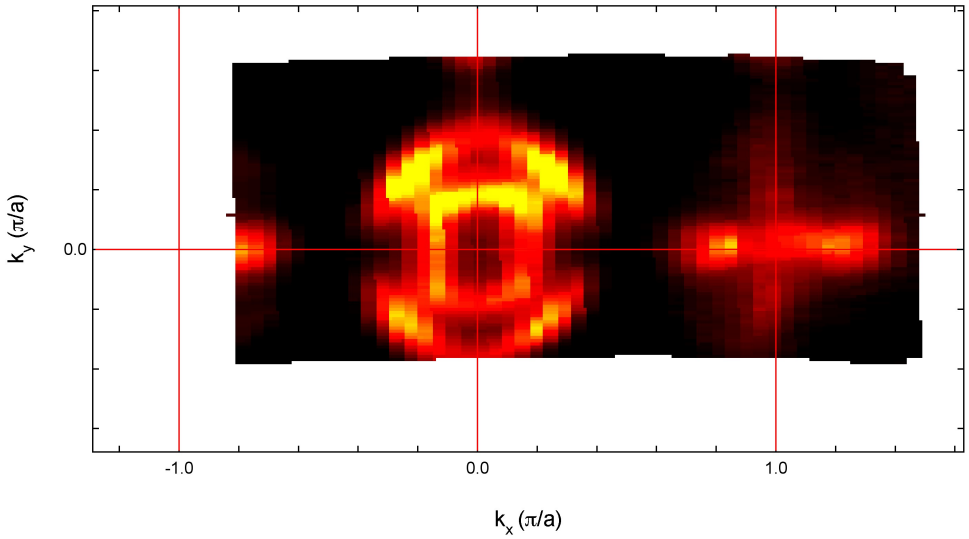


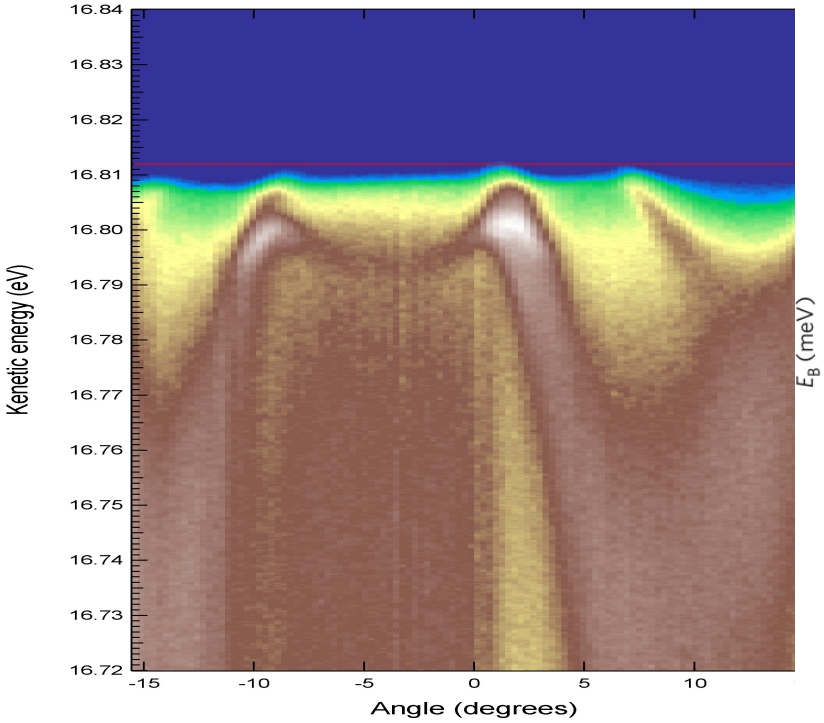
M. Neupane *et al.*, PRB 83, 094522 (2011)

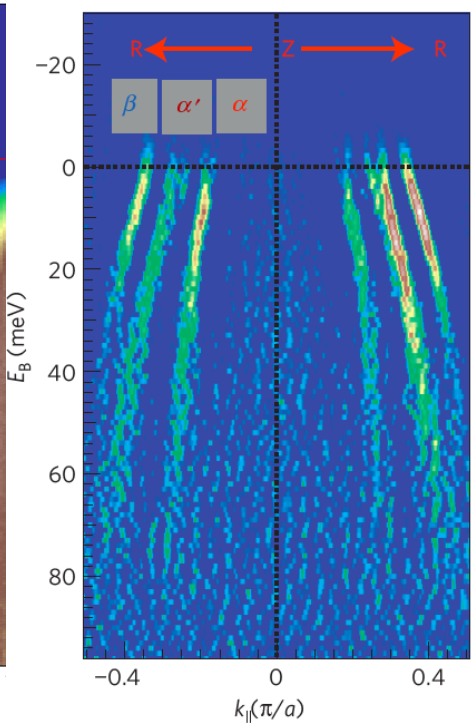
Electron-hole asymmetry?

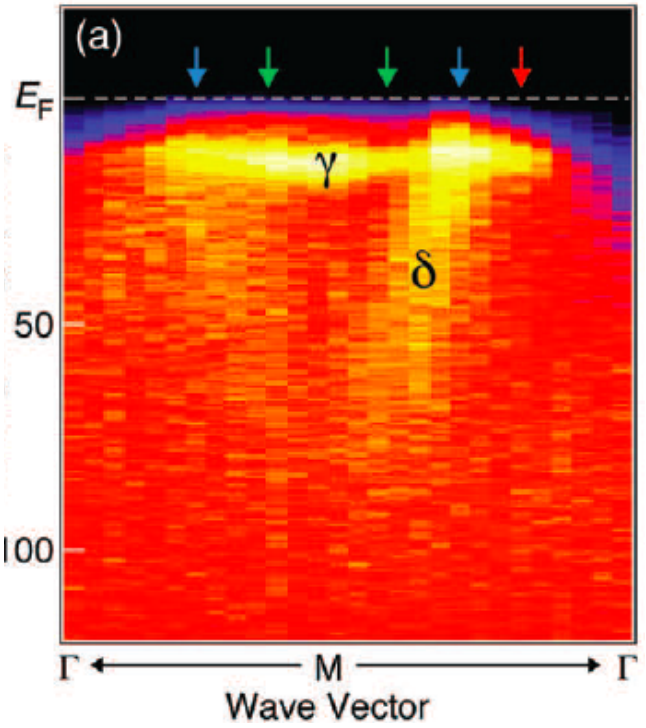
ARPES observation of five bands and five FSs



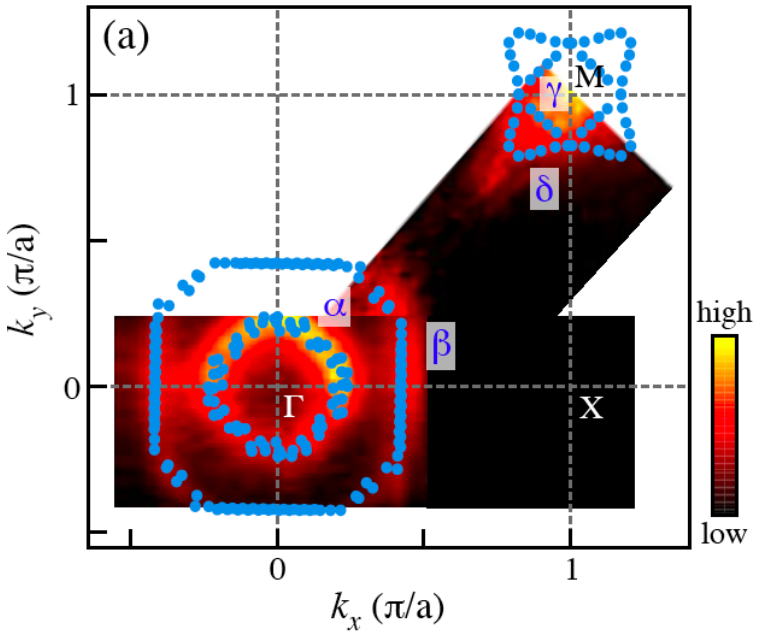


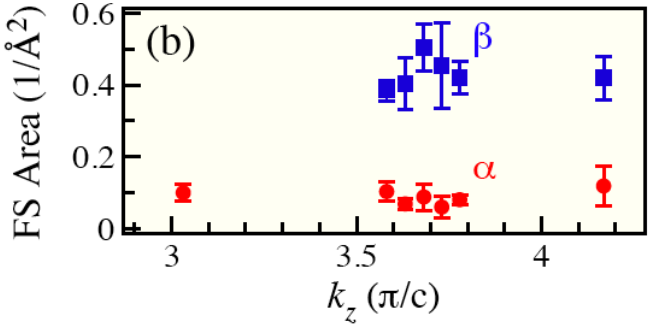






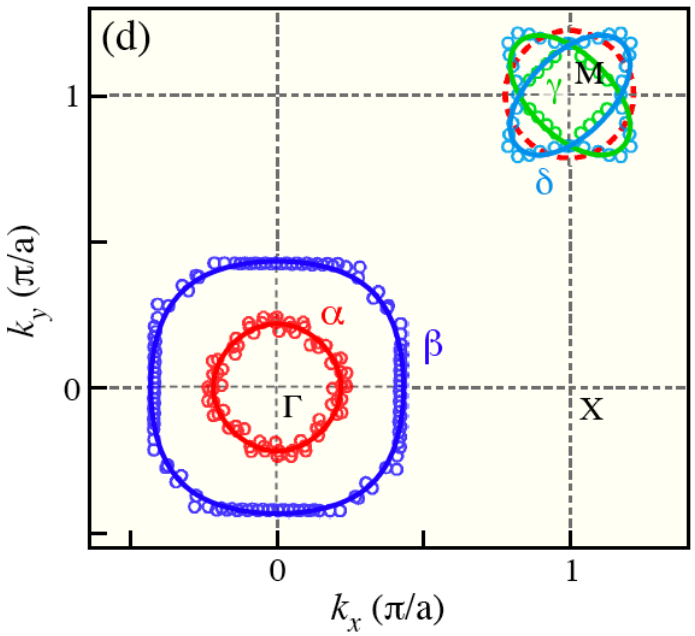
Band structure and Fermi surface of pnictides

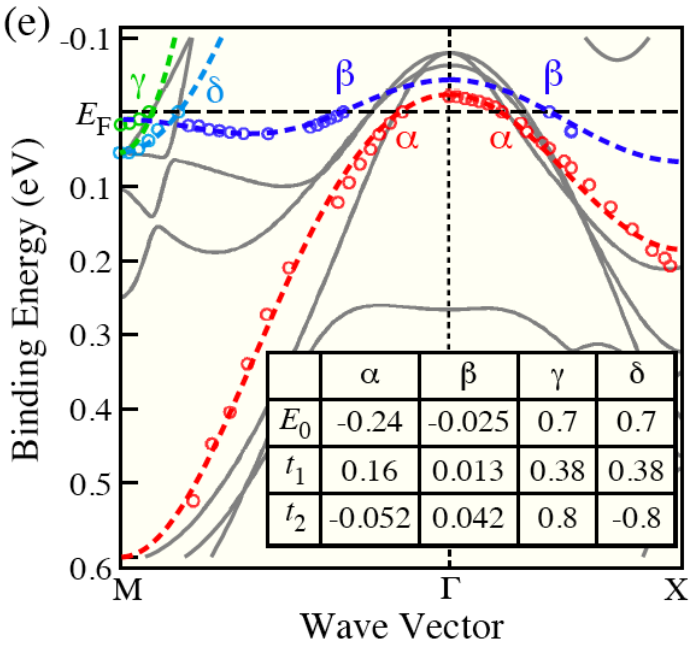




(c)	Fermi velocity (eVÅ)	LDA [5]	
		$k_z=0$	$k_z=\pi$
α (Γ-M)	0.50 ± 0.10	1.70	0.98
β (Γ-M)	0.22 ± 0.04	0.98	0.82
γ (Γ-M)	0.32 ± 0.06	1.48	0.90
δ (Γ-M)	0.48 ± 0.10	4.32	1.48

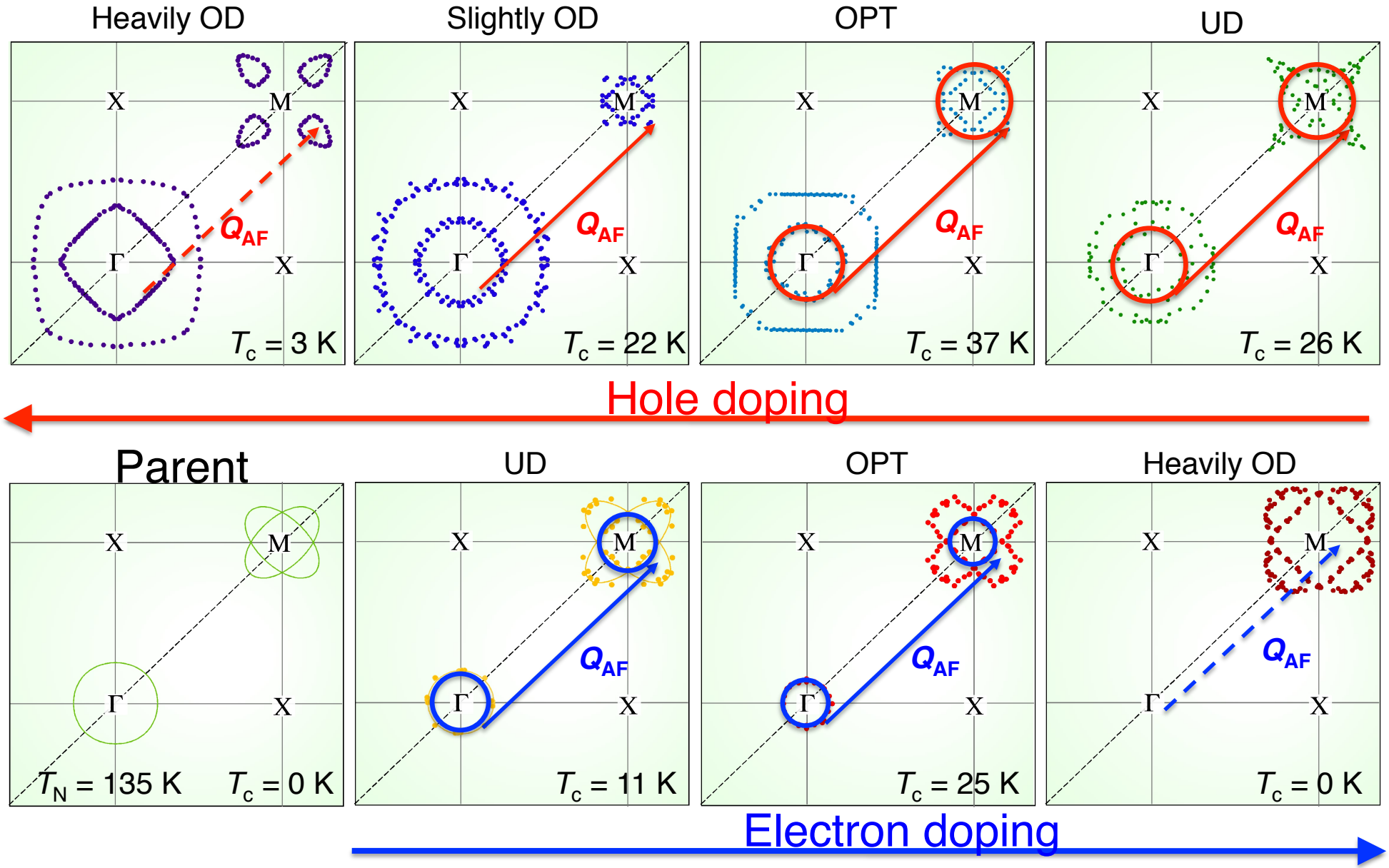
H. Ding *et al.*
JPCM **23**,
135701 (2011)



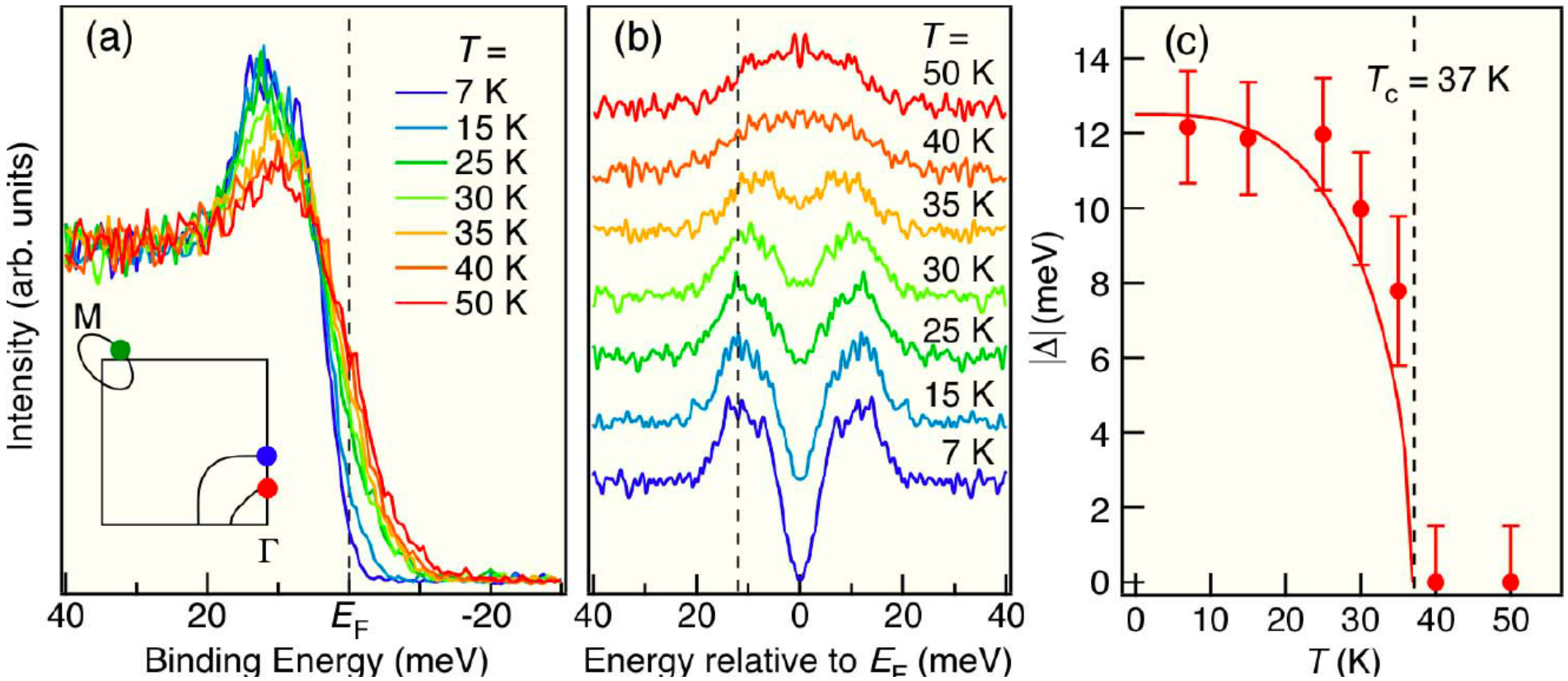


	α	β	γ	δ
E_0	-0.24	-0.025	0.7	0.7
t_1	0.16	0.013	0.38	0.38
t_2	-0.052	0.042	0.8	-0.8

Fermi surface evolution in “122”: quasi-nesting?



ARPES observation of superconducting gap



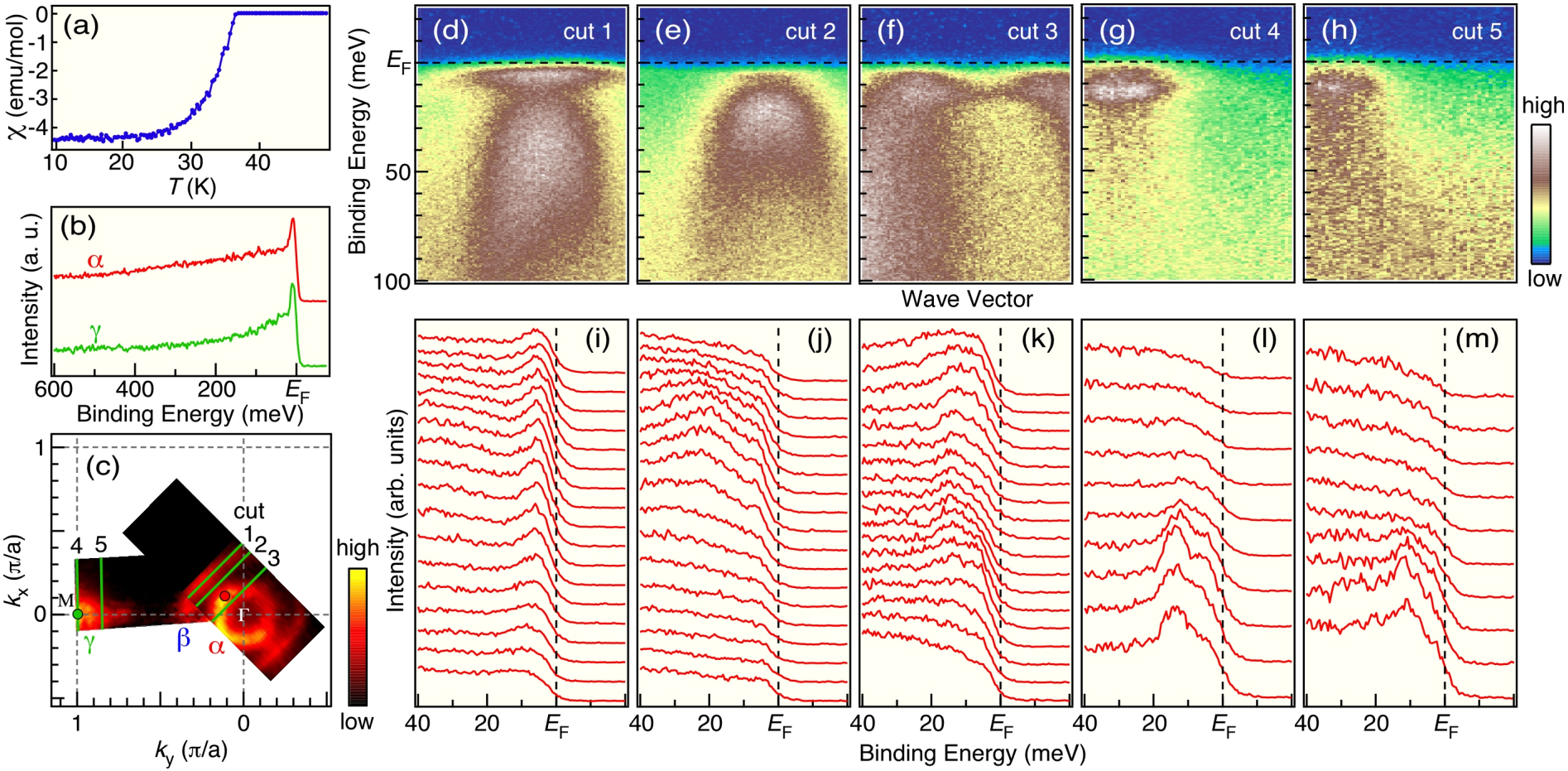
H. Ding *et al.*, EPL 83, 47001 (2008)

$2\Delta/T_c \sim 7$

Observation of a shoulder at low energy

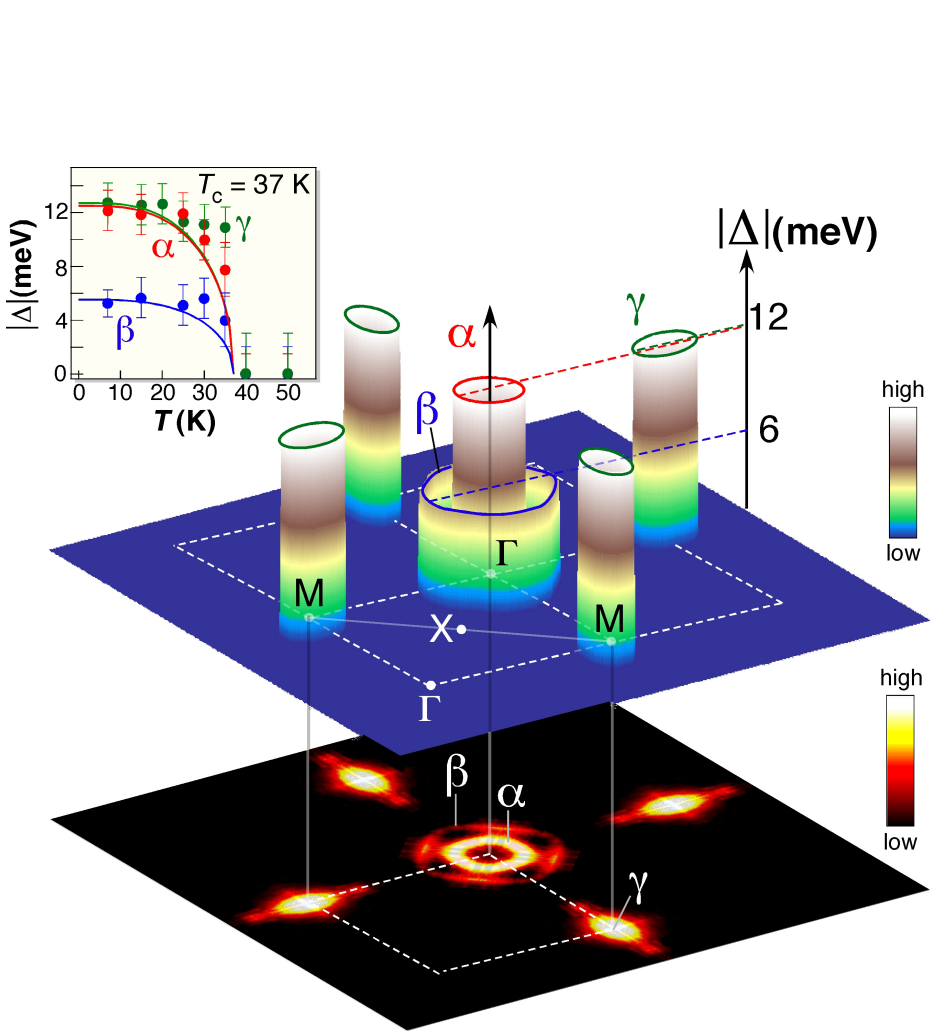
It may be due to impurity scattering effect

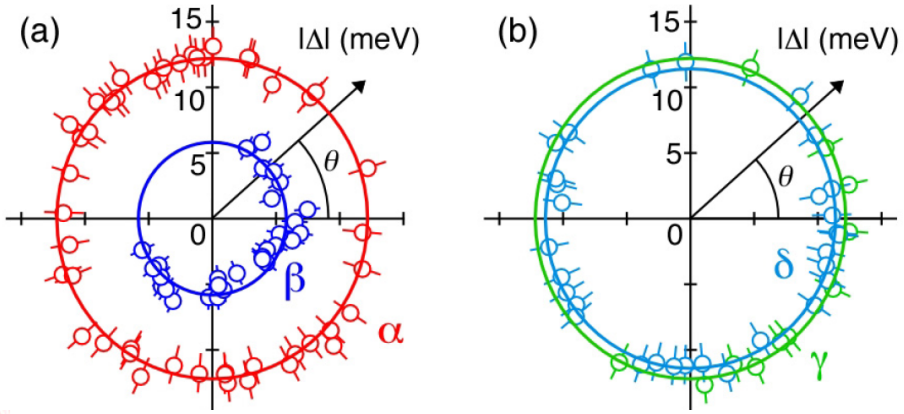
since it is sample dependent

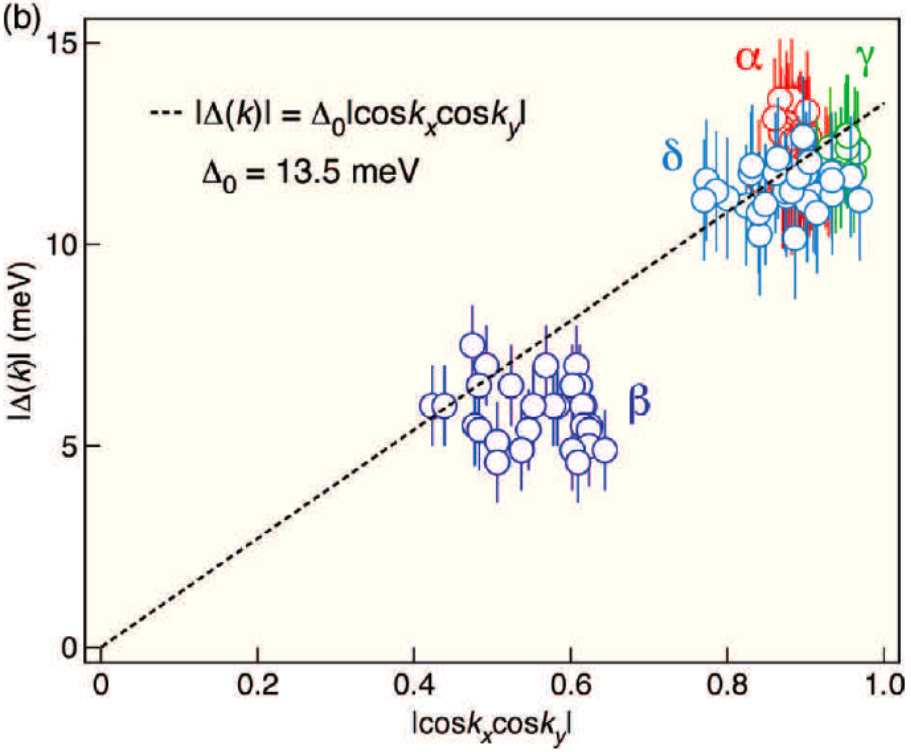


H. Ding *et al.*, EPL 83, 47001 (2008)

Nodeless SC gap in $Ba_{0.6}K_{0.4}Fe_2As_2$ (T_c = 37K)





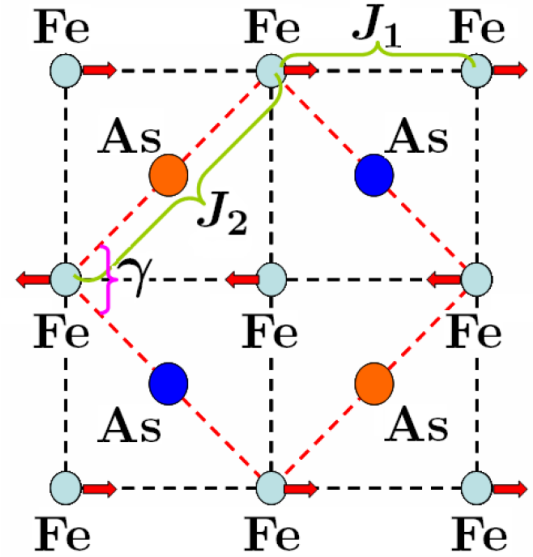


H. Ding *et al.*, EPL 83, 47001 (2008)

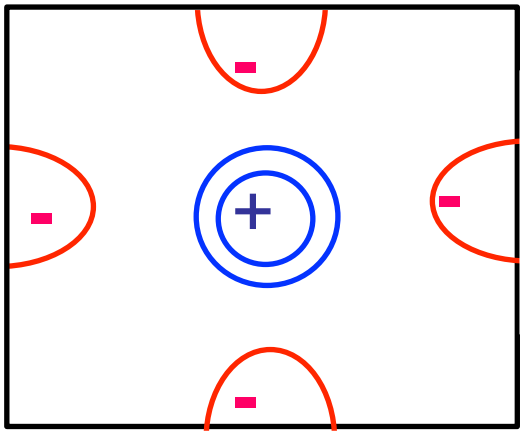
K. Nakayama *et al.*, EPL 85, 67002 (2009)

$J_1 - J_2$ model predicts almost isotropic s± gap

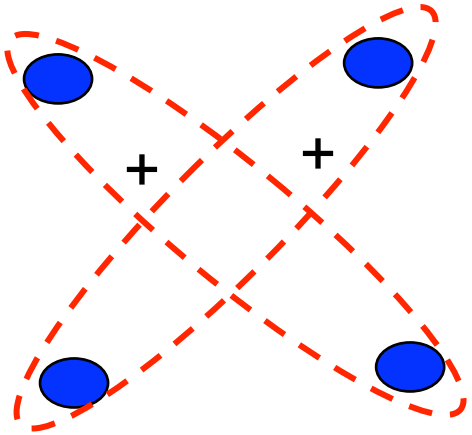
local interactions
J_1- J_2



Order parameters in momentum Space



Real space configuration of pairing symmetry



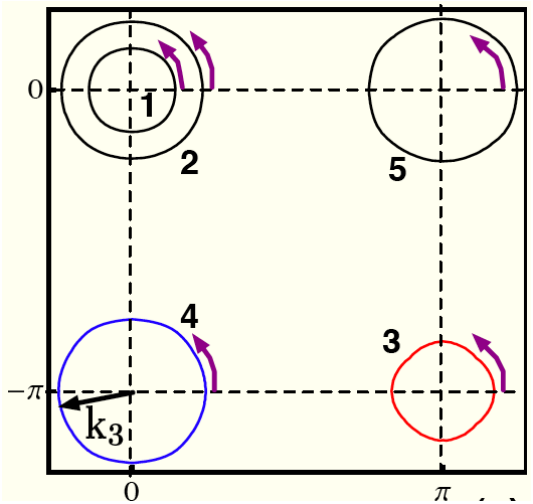
pnictides: large J_2 and FS topology favor $\Delta = \Delta_0 \cos k_x \cos k_y$, s±-wave

cuprates: large J_1 and FS topology favor $\Delta = \Delta_0 (\cos k_x - \cos k_y)/2$, d-wave

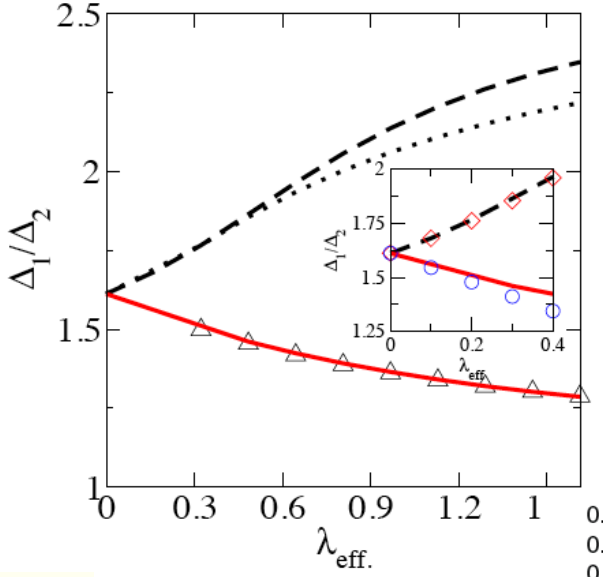
K. Seo, A. B. Bernevig, J. Hu PRL 101, 206404 (2008)

Most weak-coupling theories predict anisotropic s± gap

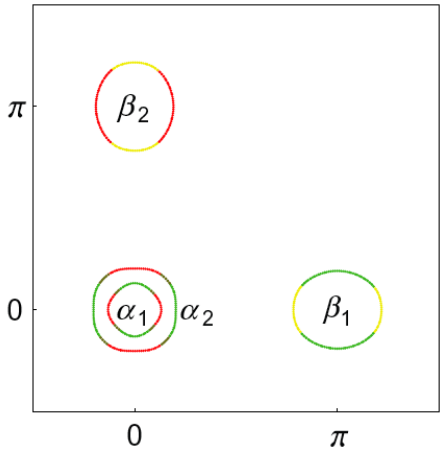
D.H. Lee
EPL 85, 37005 (2009)

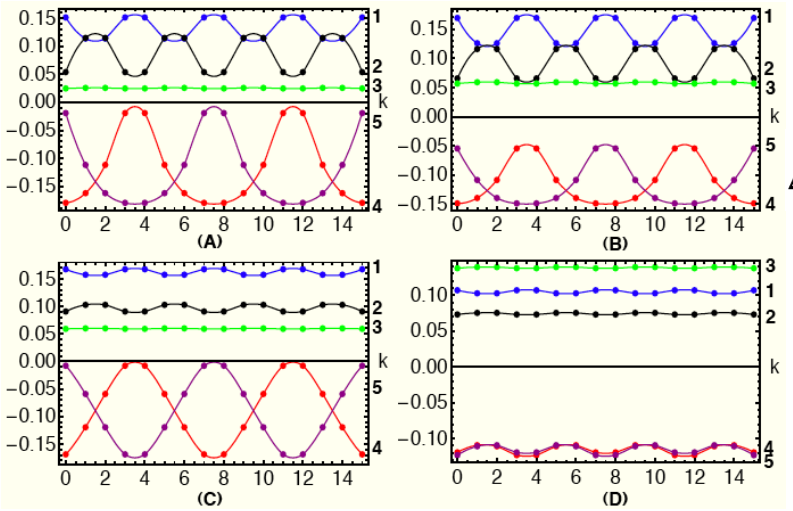


I. Mazin
PRB 79, 060502 (2009)



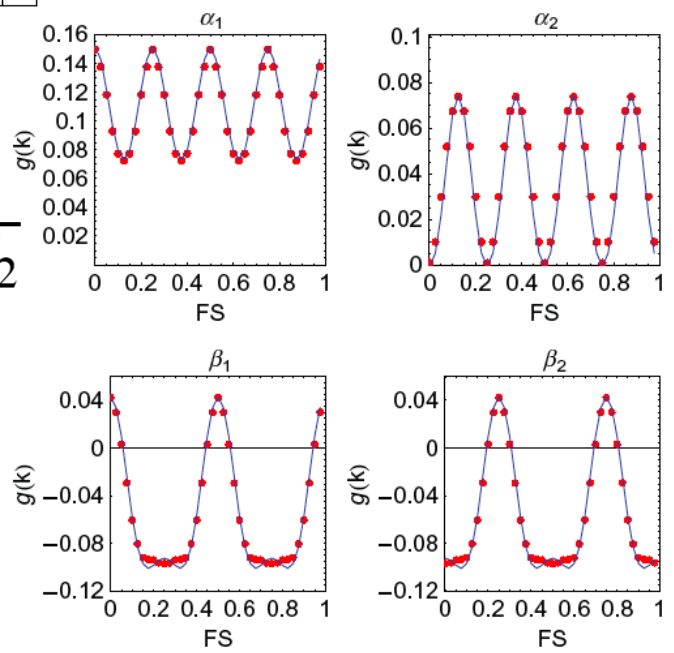
S. Graser
NJP 11, 025016 (2009)



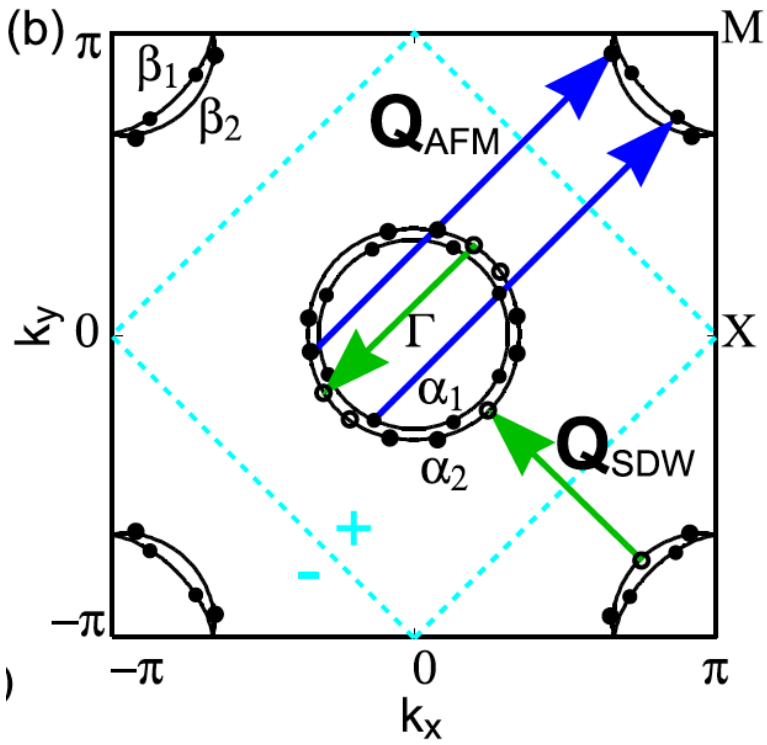


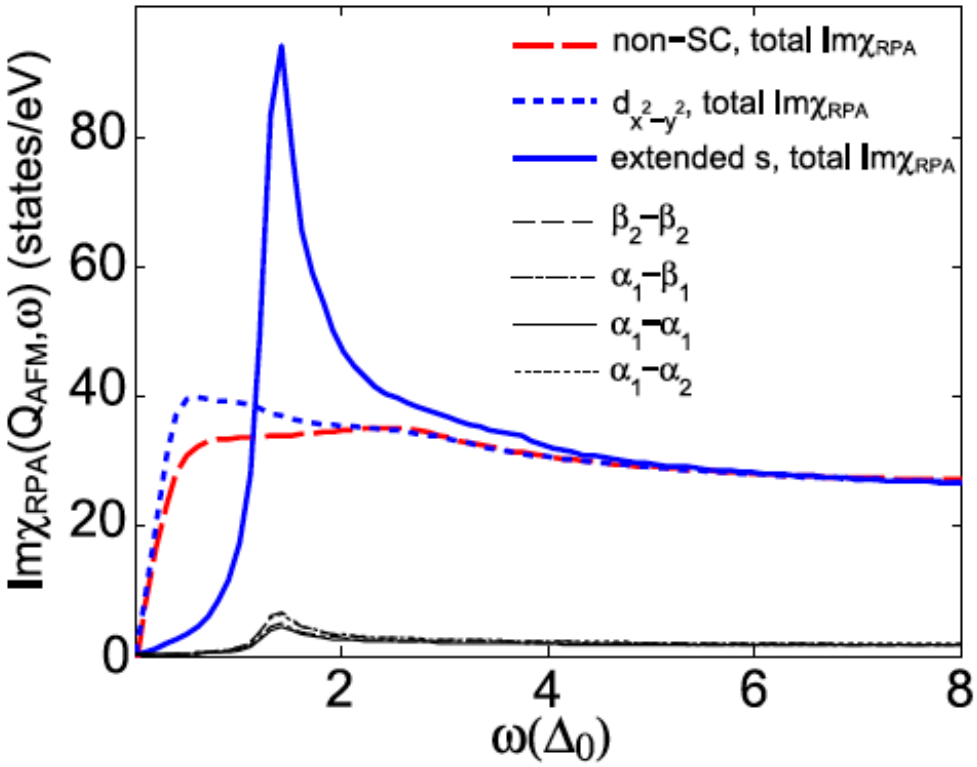
$$\Delta_2/\Delta_1 = \sqrt{N_1/N_2}$$

when $\lambda_{eff} \rightarrow 0$



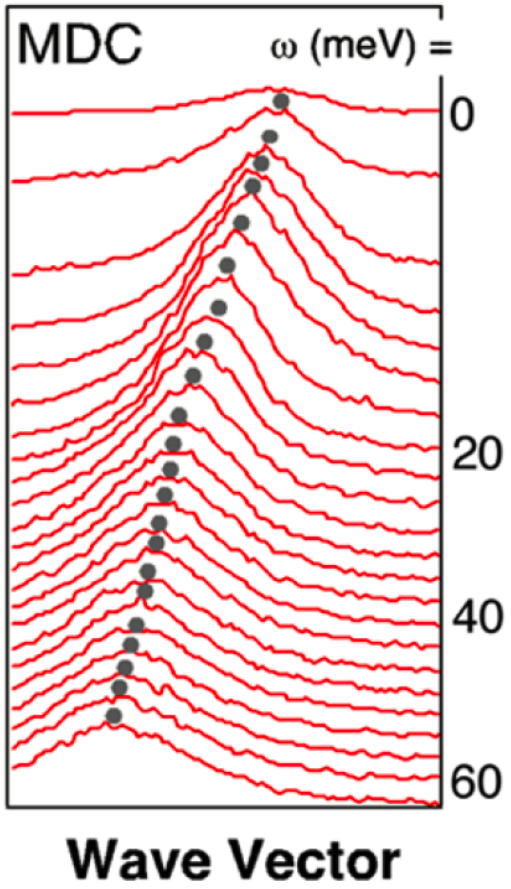
Resonant mode supports *s*±

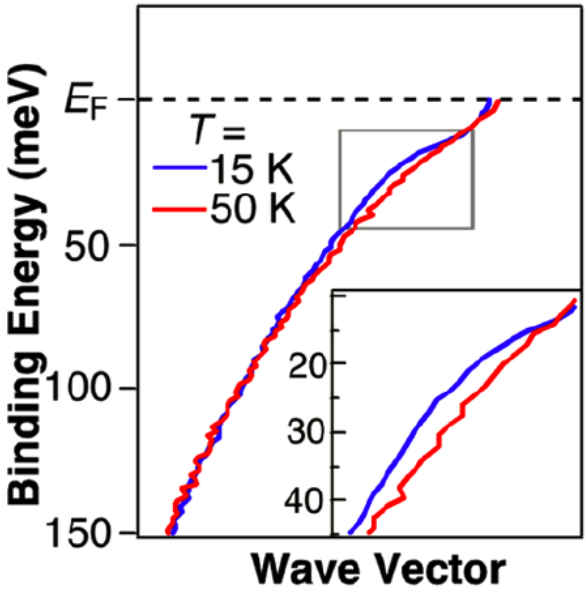


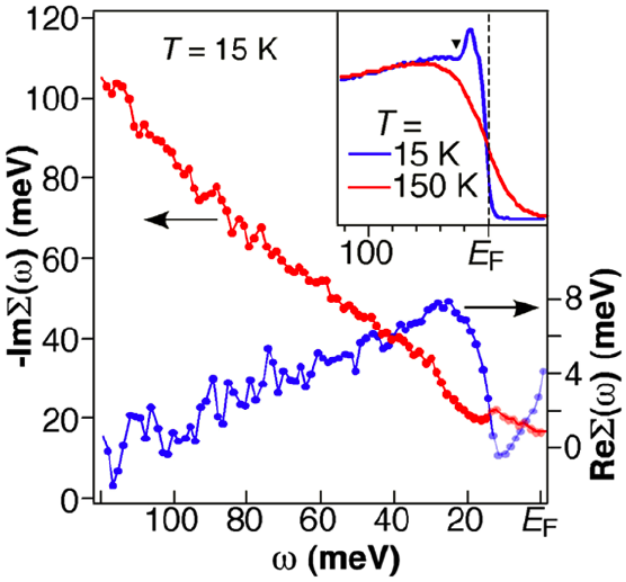


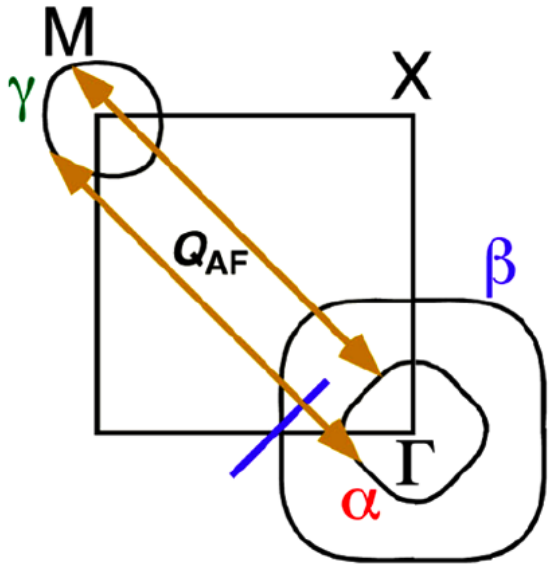
M.M. Korshunov and I. Eremin, Phys. Rev. B 78, 140509 (R) (2008)

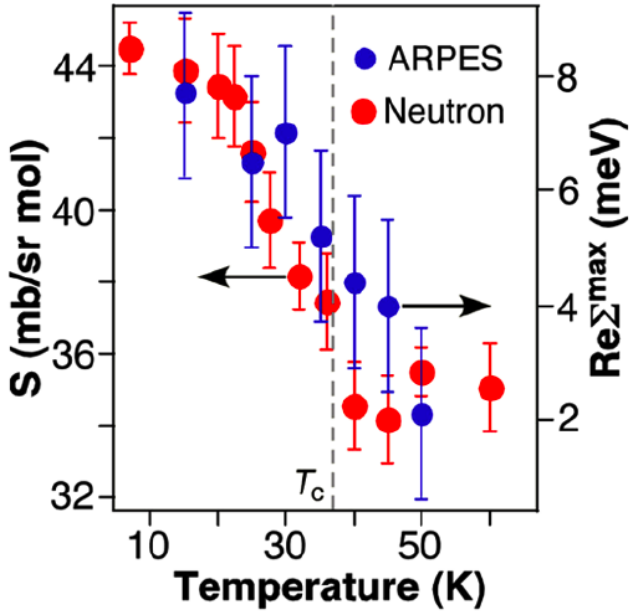
A FS-dependent "kink" observed in SC state









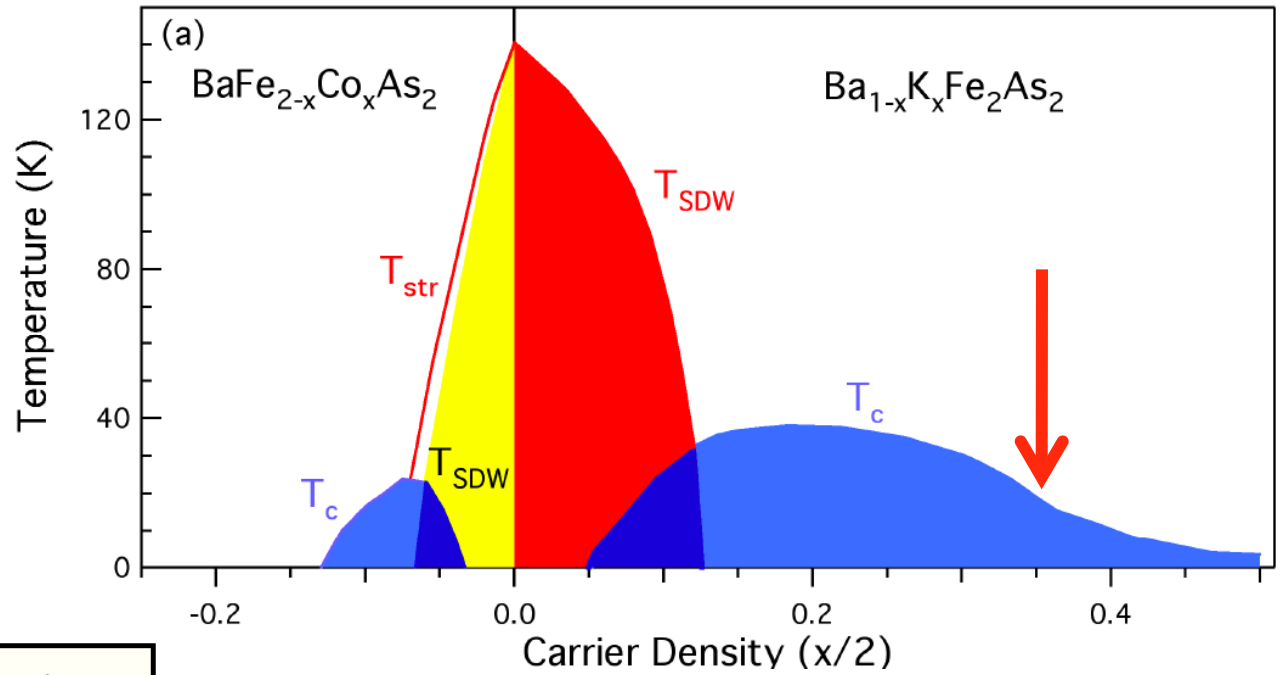


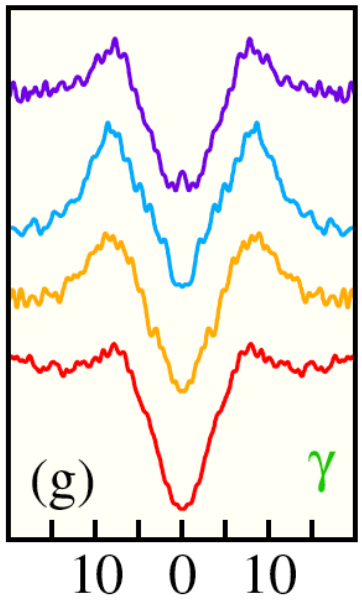
P. Richard *et al.*, PRL 102, 047003 (2009)

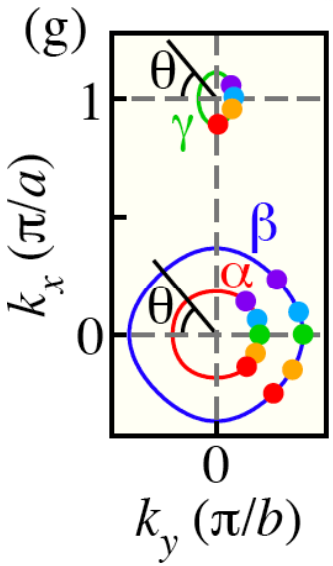
A.D.Christianson et al., Nature **456**, 930 (2008)

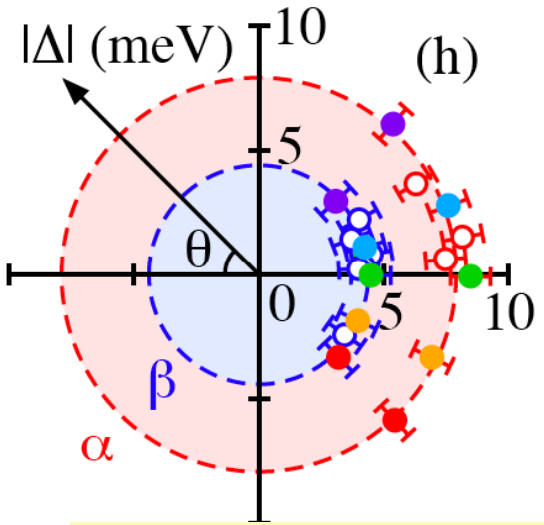
Ω ~ 13 meV, similar to neutron resonance mode ~ 14 meV

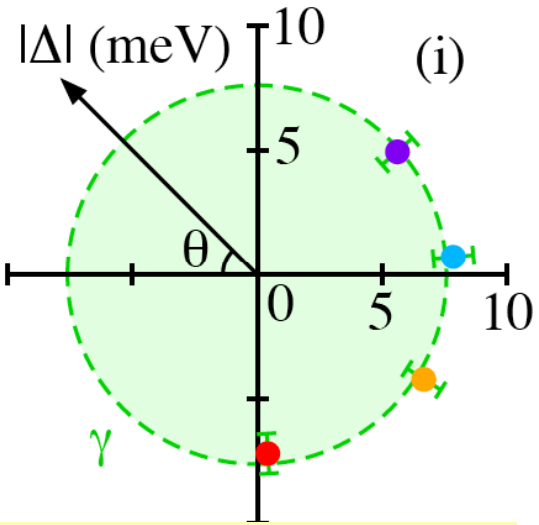
overdoped $Ba_{0.3}K_{0.7}Fe_2As_2$ ($T_c \sim 20K$)





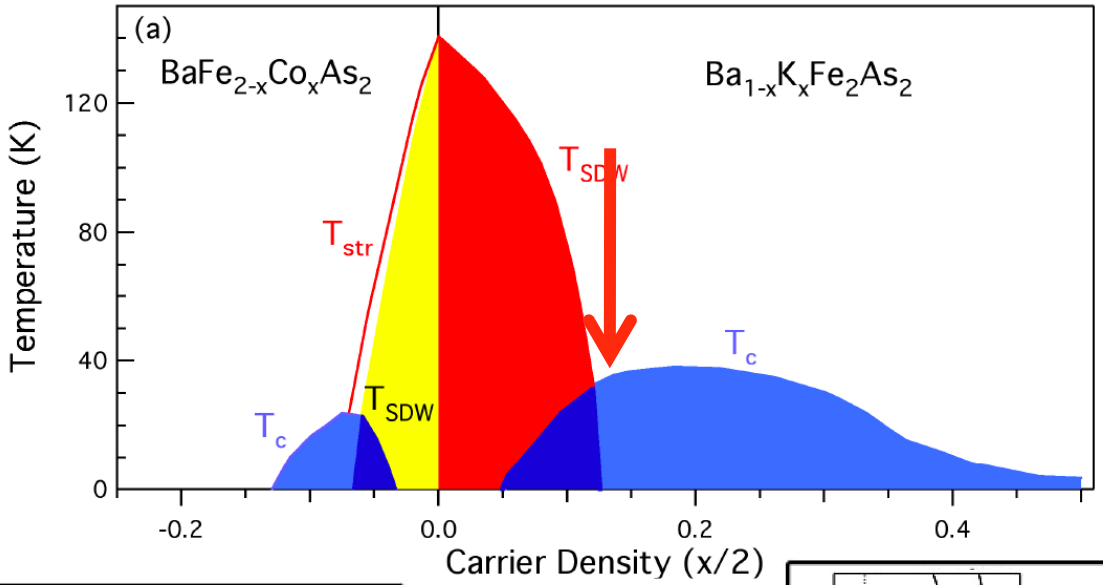




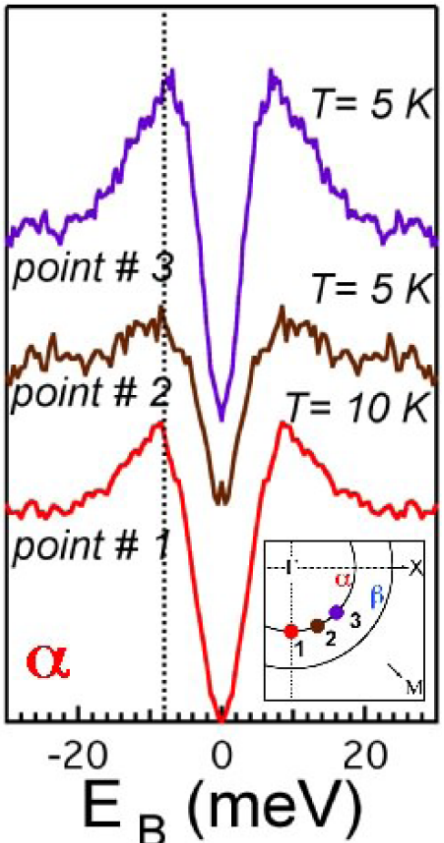


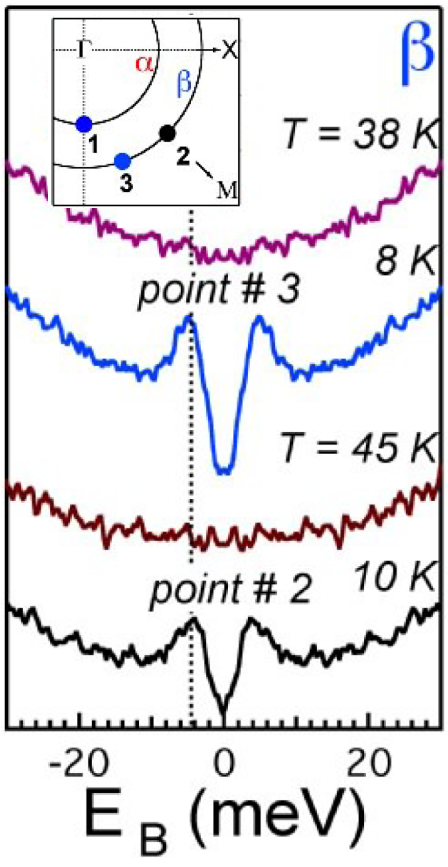
K. Nakayama *et al.*, PRB 83, 020501(R) (2011)

Underdoped $Ba_{0.75}K_{0.25}Fe_2As_2$ (T_c = 26K)

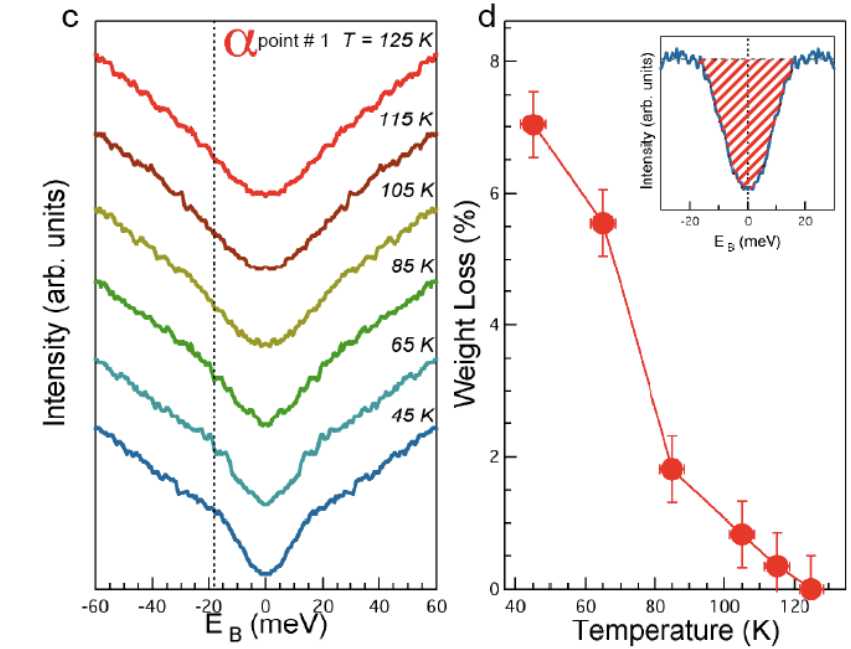


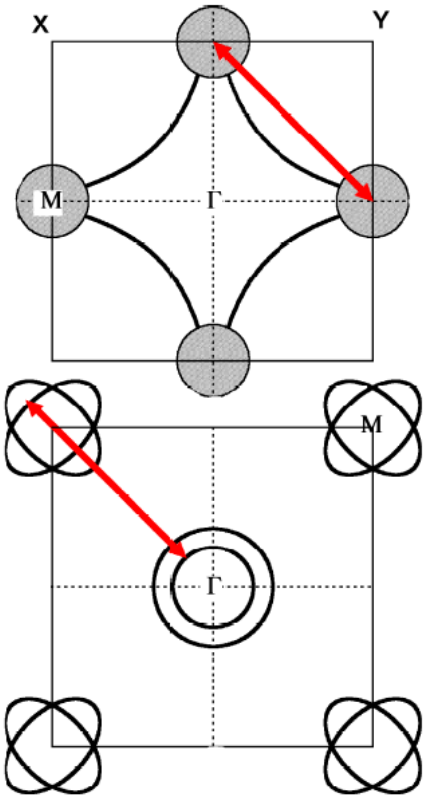
Y.-M. Xu *et al.*, Nature Communications 2, 392 (2011)

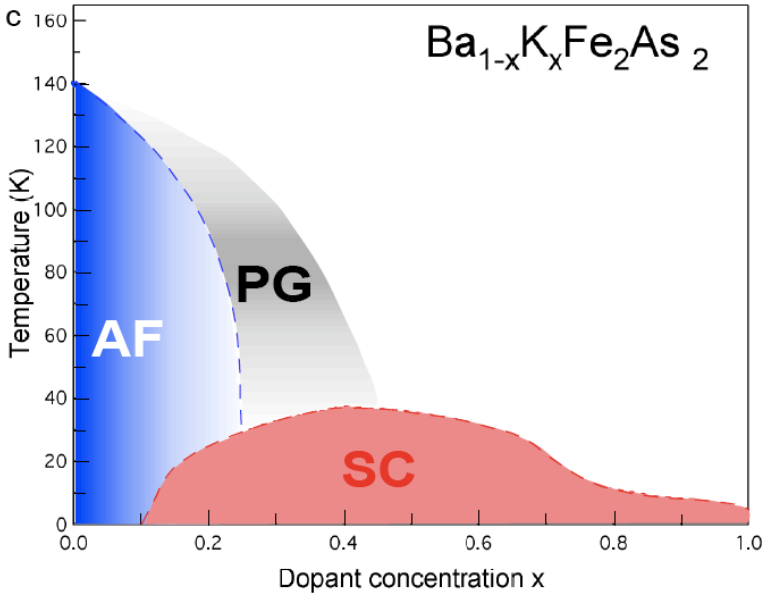


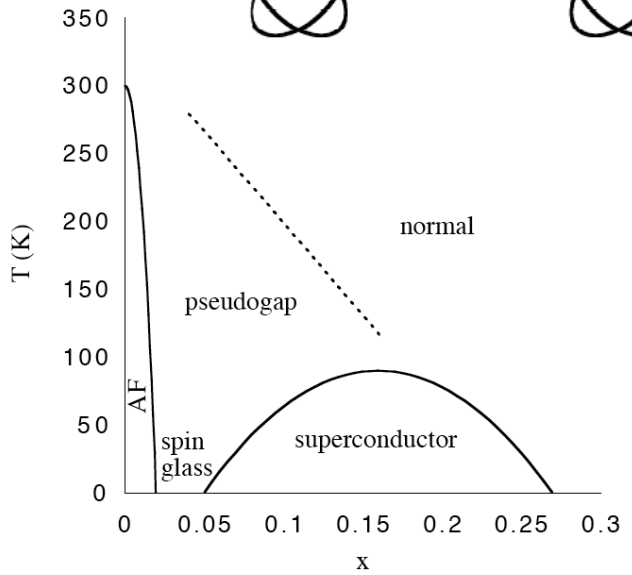


A distinct pseudogap emerges on the nesting FS region

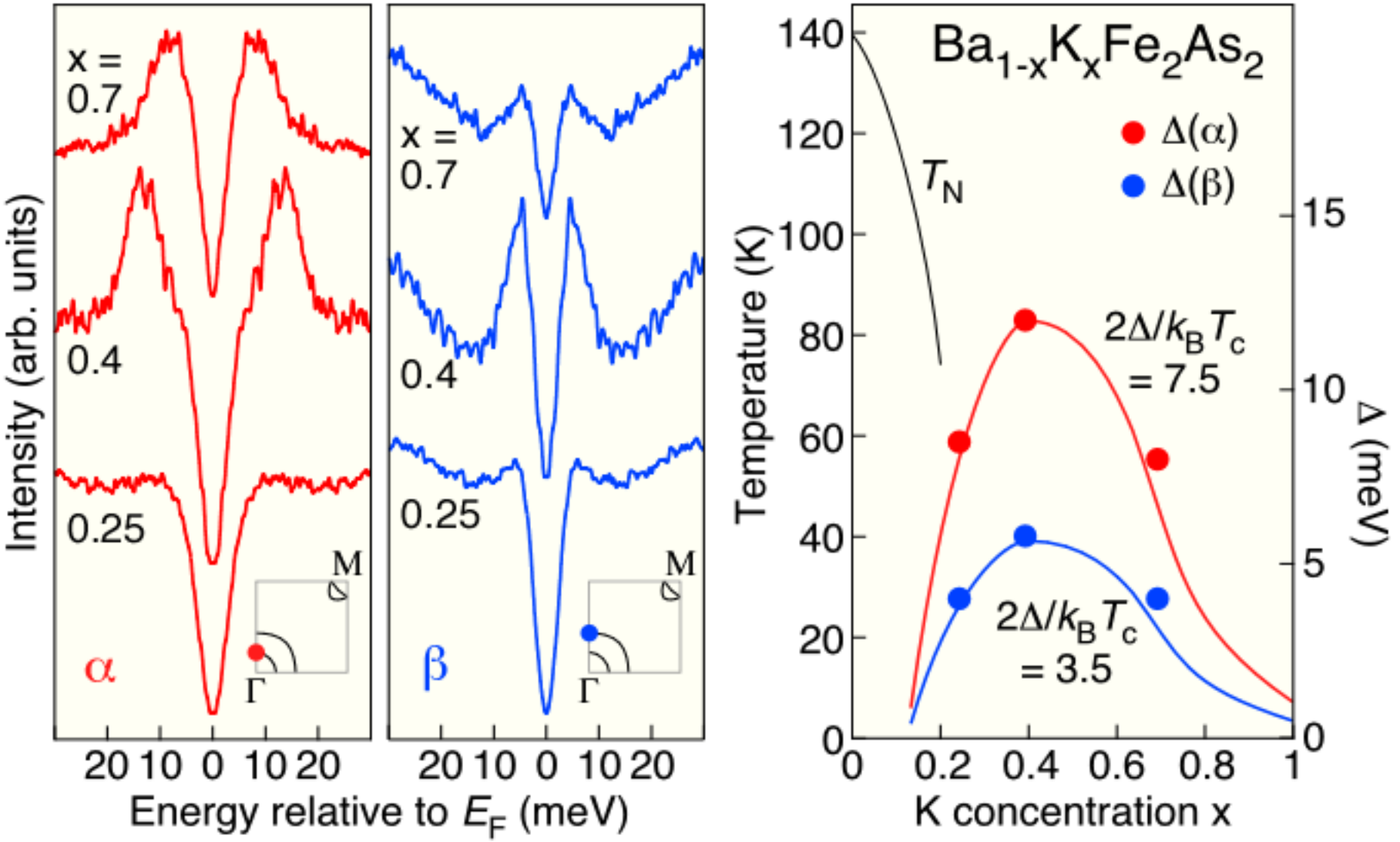






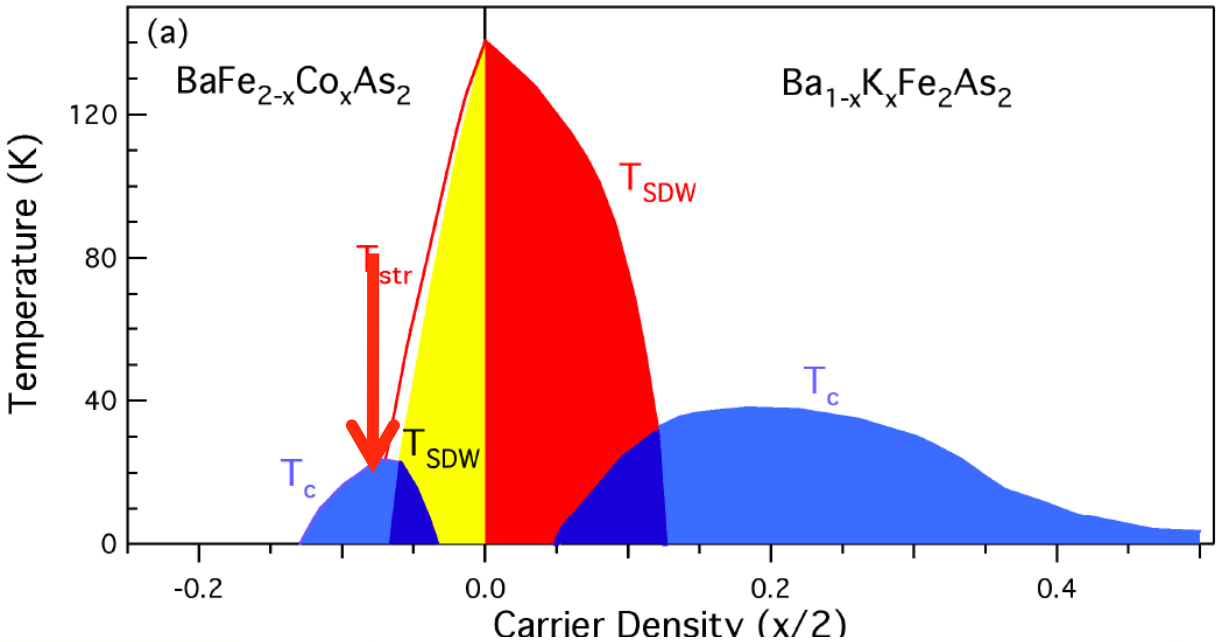


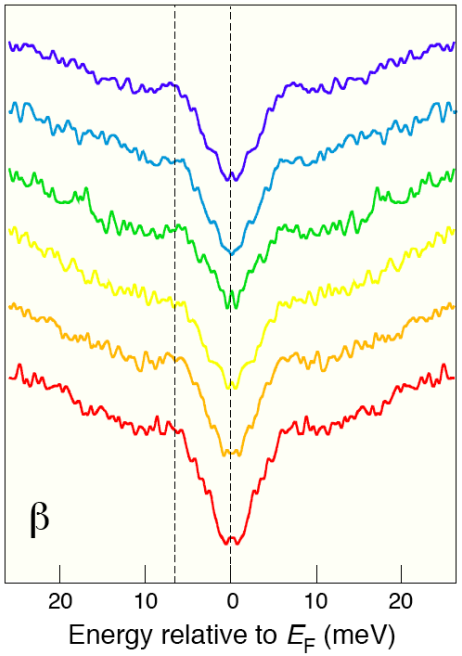
Doping dependence of the SC gaps in $Ba_{1-x}K_xFe_2As_2$

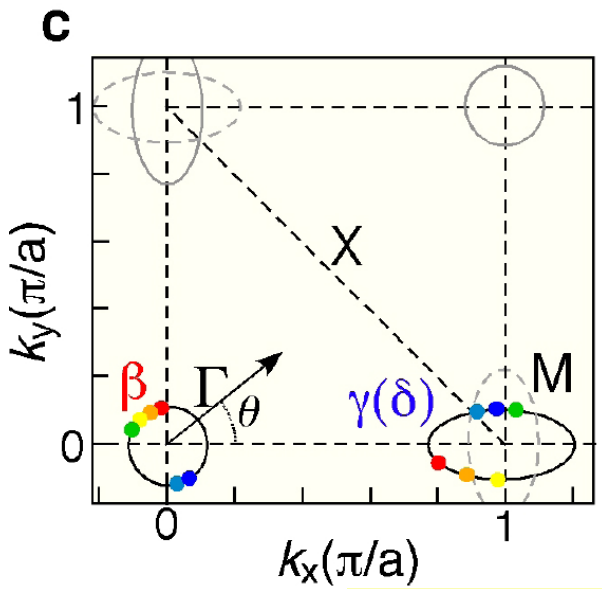


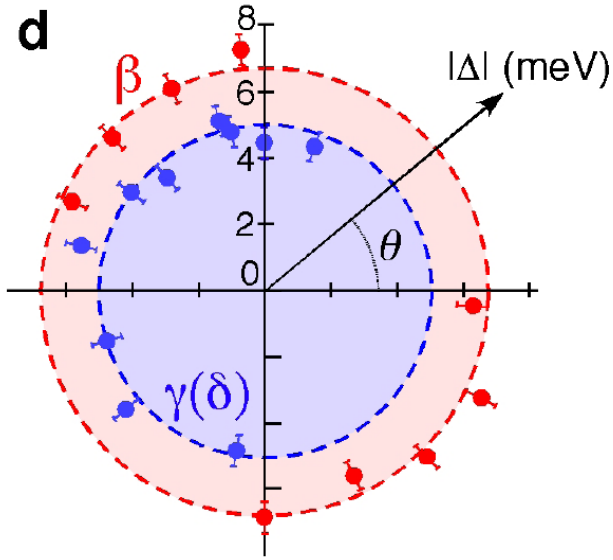
K. Nakayama *et al.*, PRB 83, 020501(R) (2011)

Electron doped $BaFe_{1.85}Co_{0.15}As_2$ (T_c = 25.5K)



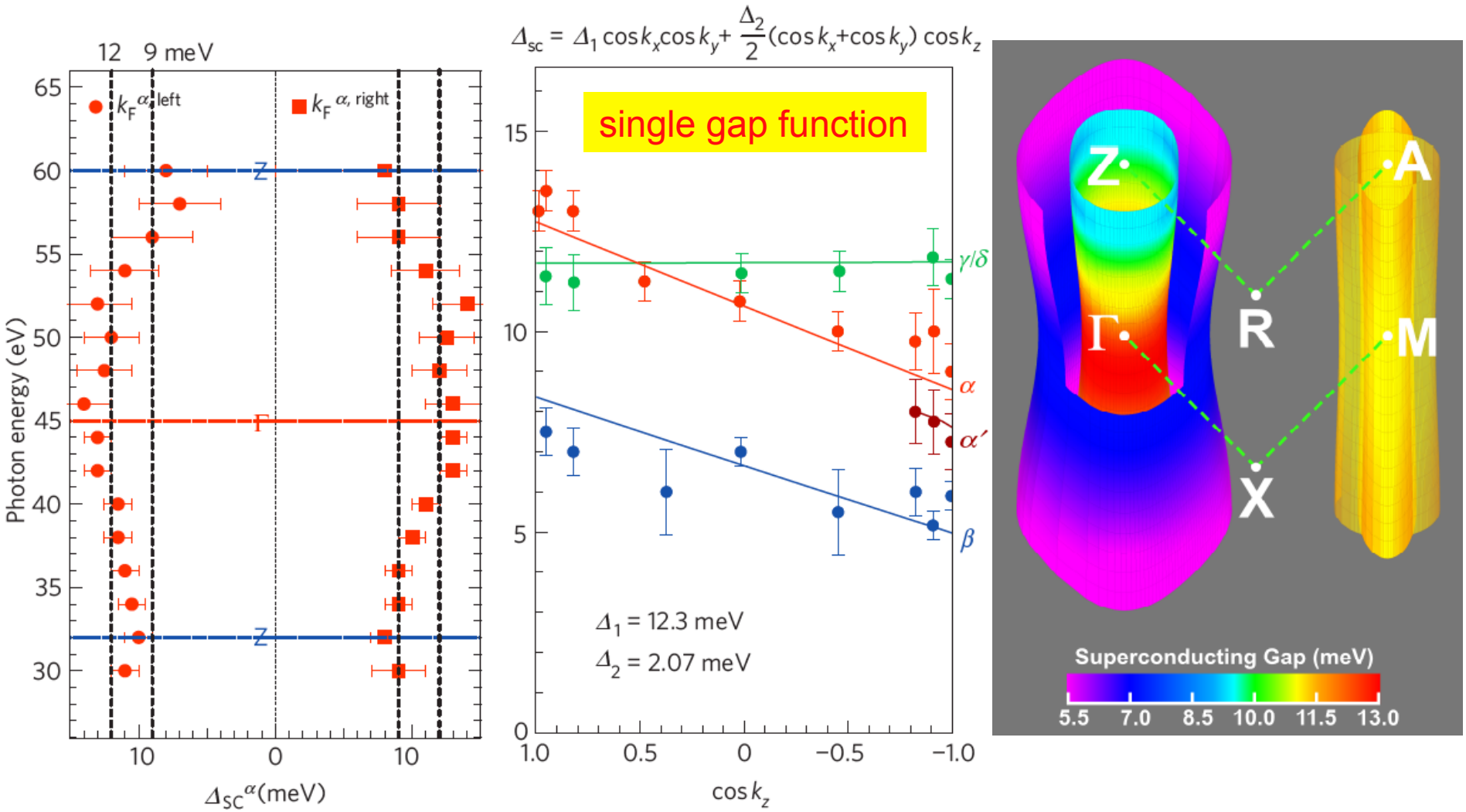






K. Terashima et al, PNAS 106, 7330 (2009)

kz dependence of SC gaps



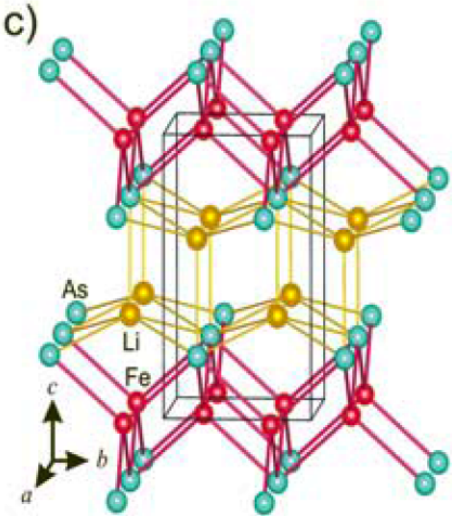
$J_{ab} = 30$

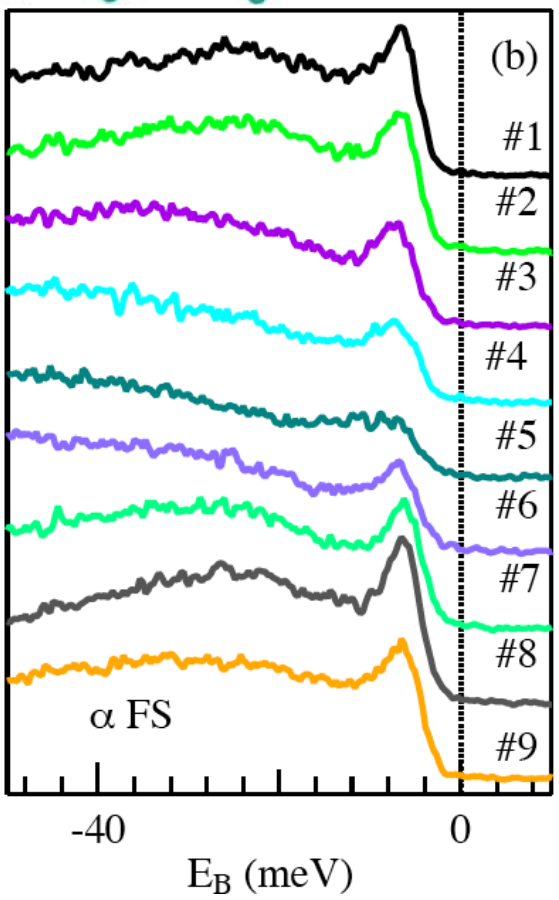
$J_c = 5$

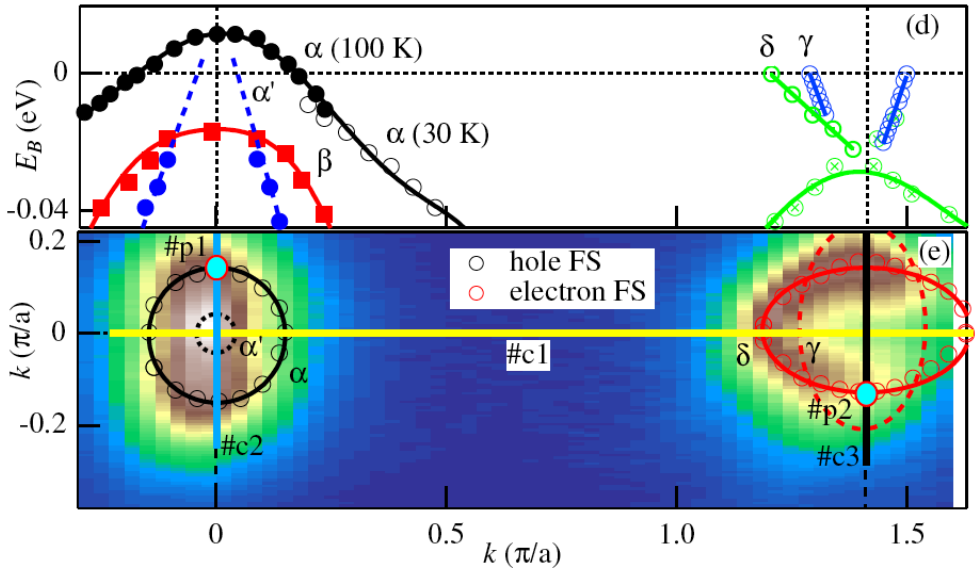
$\Delta_2/\Delta_1 \approx J_c/J_{ab} \approx 0.17$

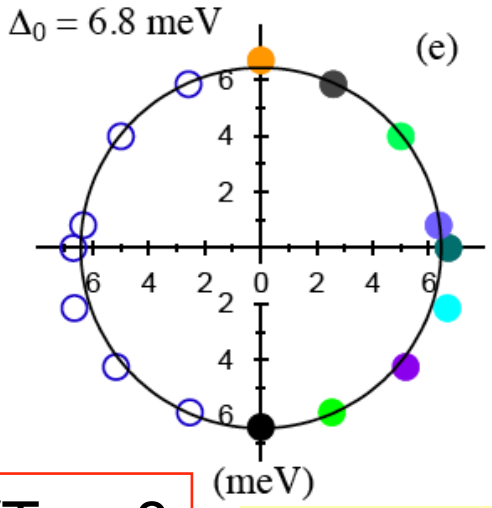
Y.-M. Xu *et al.*, Nature Physics 7, 198 (2011)

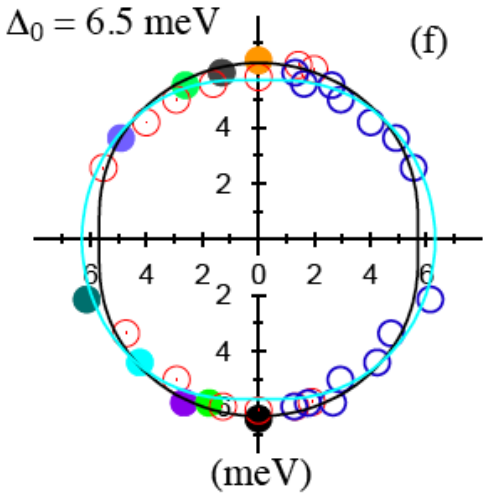
"111" - $NaFe_{0.95}Co_{0.05}As$ (T_c = 18K)
non-polar surface







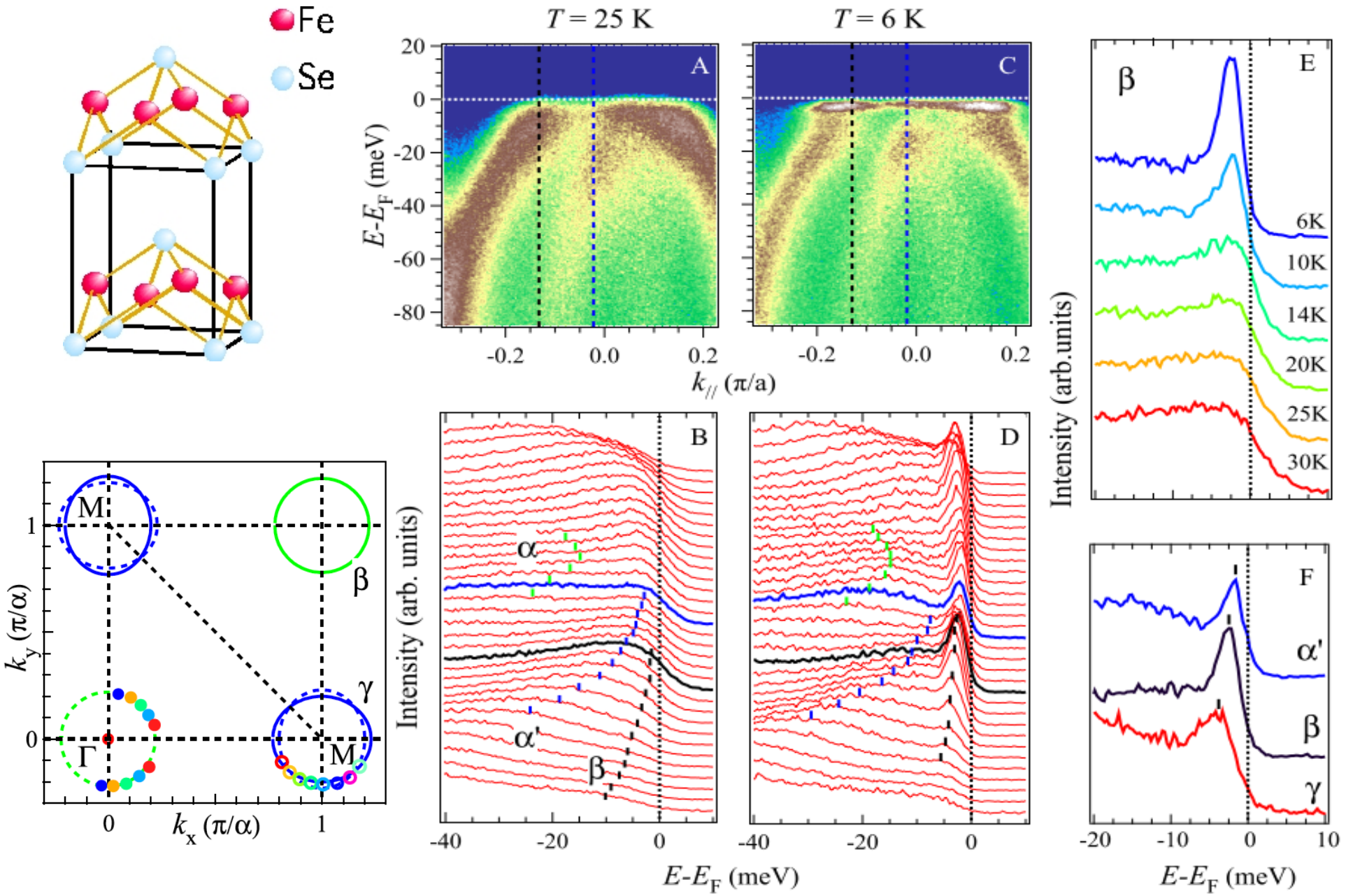


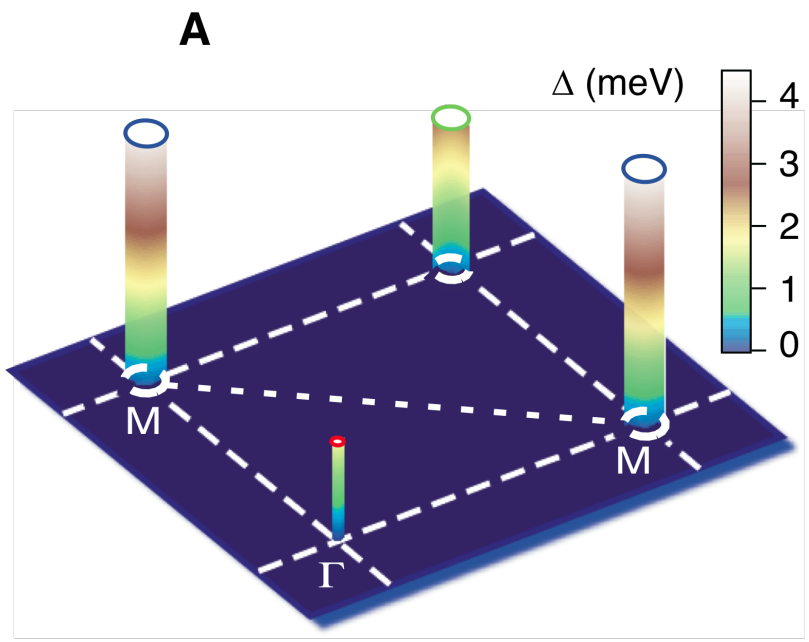


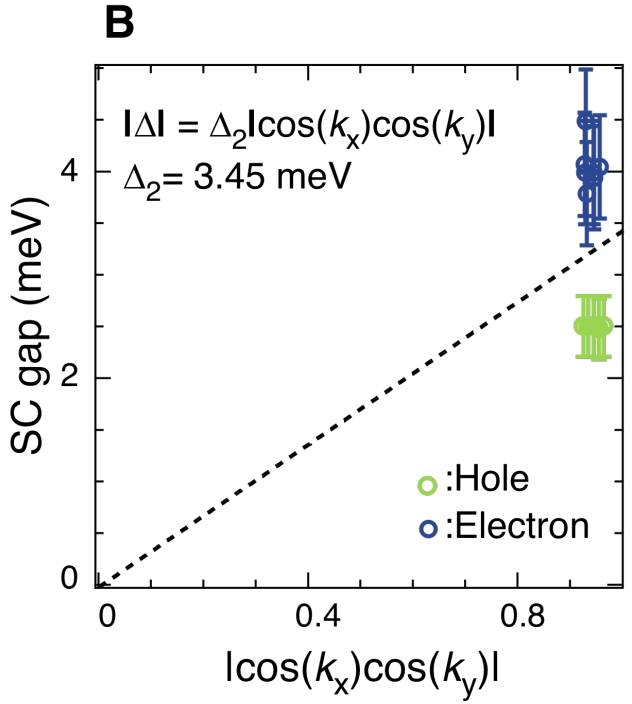
$2\Delta/T_c \sim 8$

Z.-H. Liu *et al.*, PRB 84, 064519 (2011)

"11" - $FeTe_{0.55}Se_{0.45}$ (T_c = 13K) non-polar surface

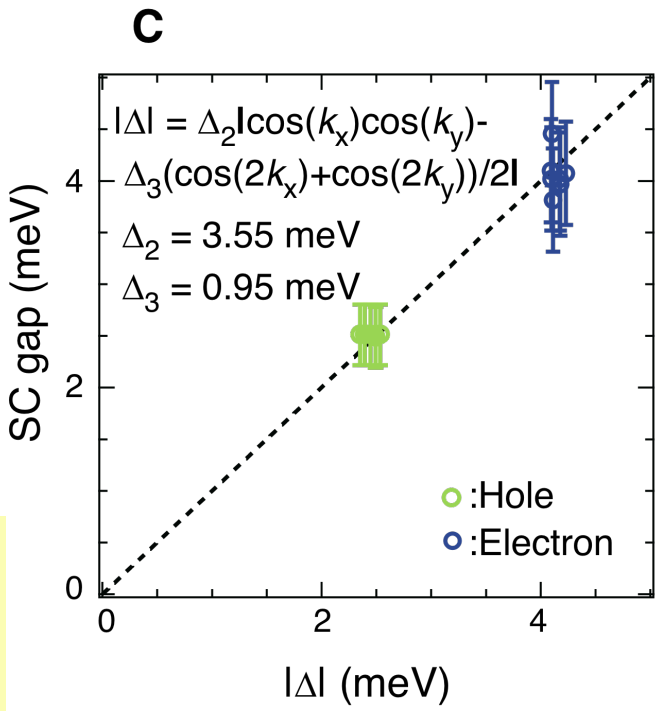


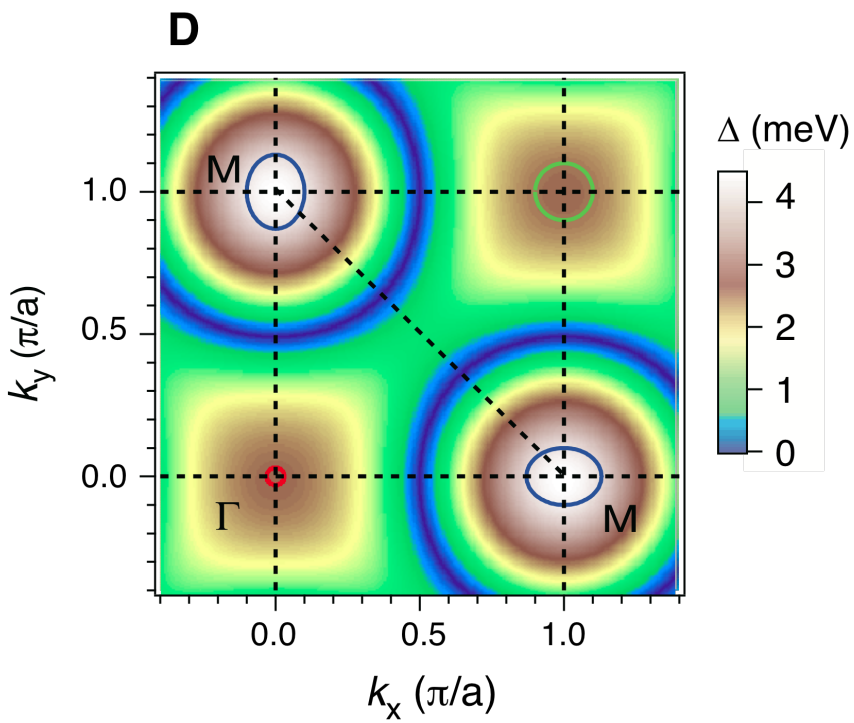




$J_1 = -34$
$J_2 = 22$
$J_3 = 6.8$

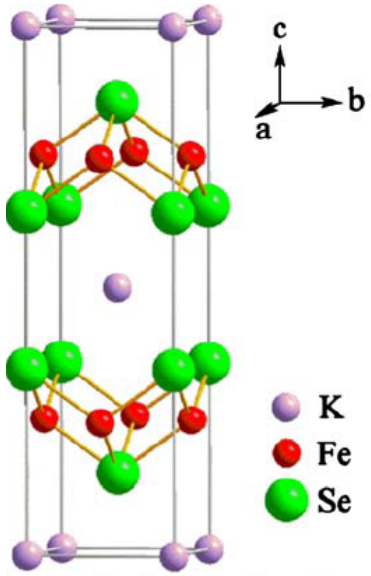
Δ_2/Δ_3
$\approx J_2/J_3$
≈ 0.3

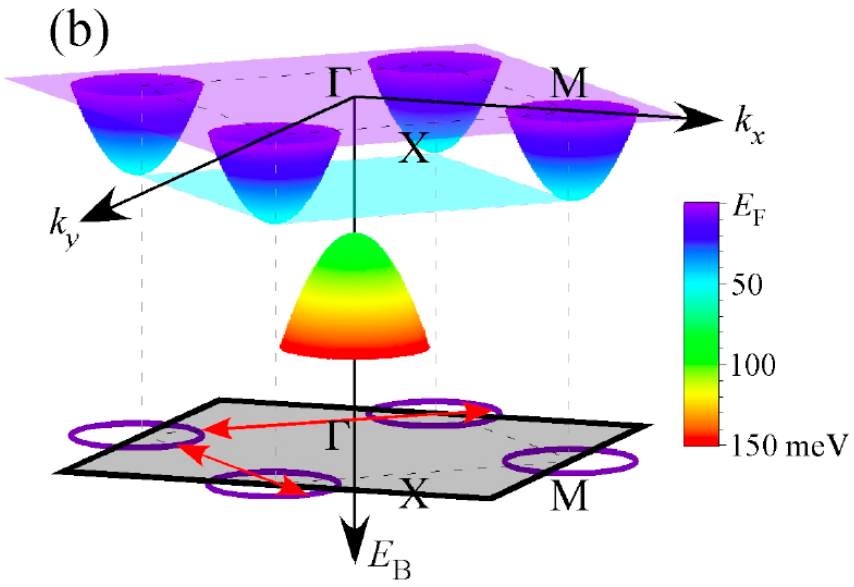


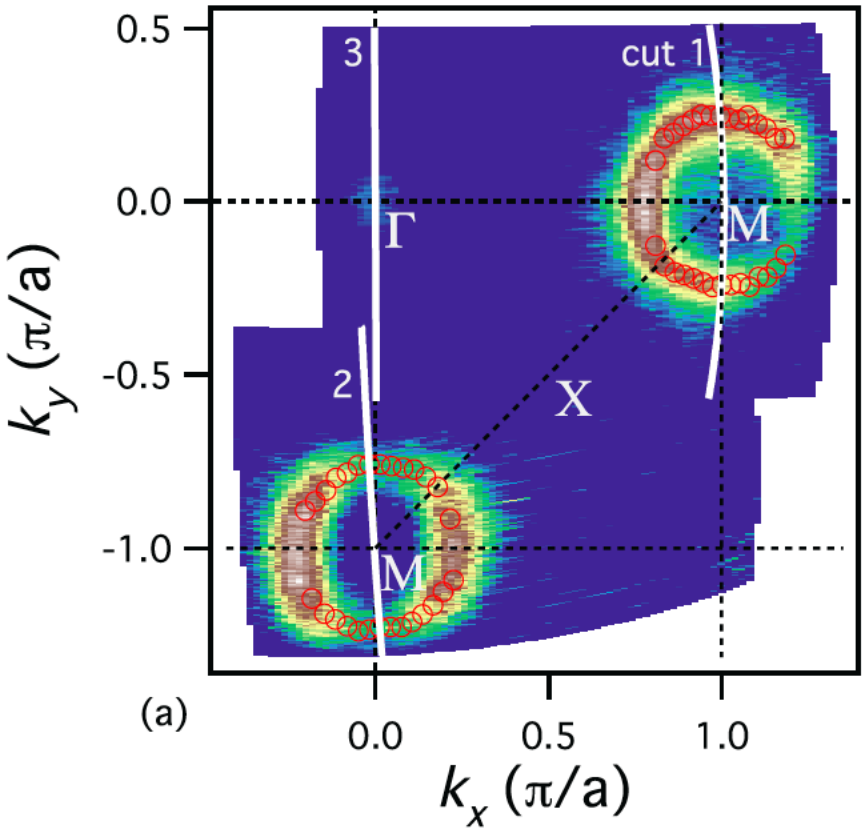


H. Miao *et al.*, PRB 85, 094506 (2012)

A new twist: $(Tl,K)_xFe_{2-y}Se_2$ ($T_c \sim 30K$)







T. Qian *et al.*, PRL 106, 187001 (2011)

$A_xFe_{2-y}Se_2$: electron doped SC

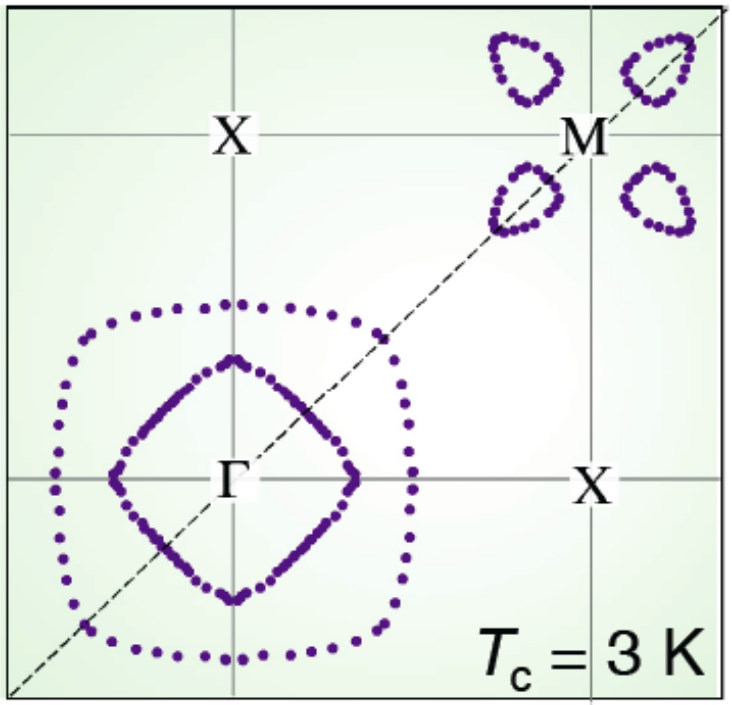
Se valence is 2-, while As valence is 3-

$A_xFe_{2-y}Se_2$: electron doping = x/2 – y,

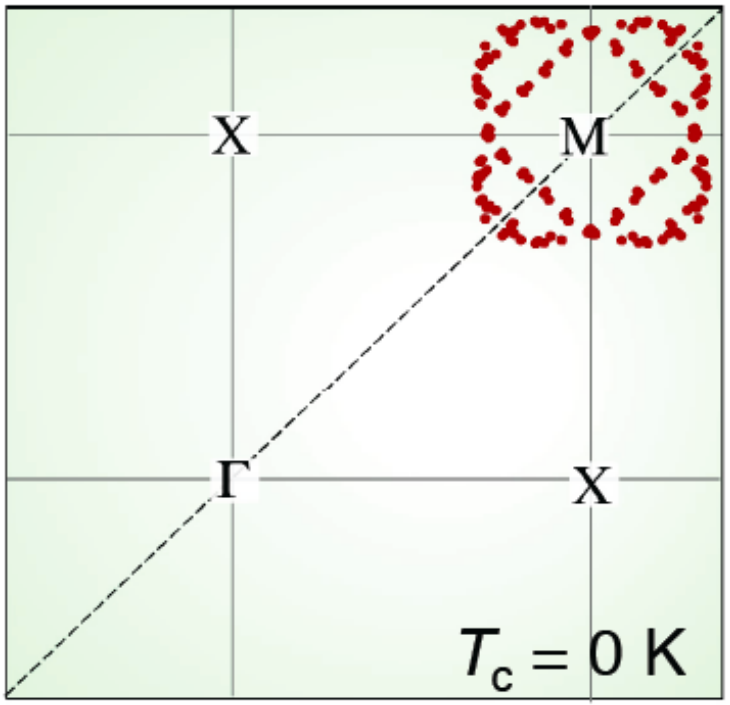
$K_{0.8}Fe_{1.8}Se_2$: electron doping = 0.2, T_c ~ 30K

$K_{0.8}Fe_{1.6}Se_2$ (245): electron doping = 0, insulator

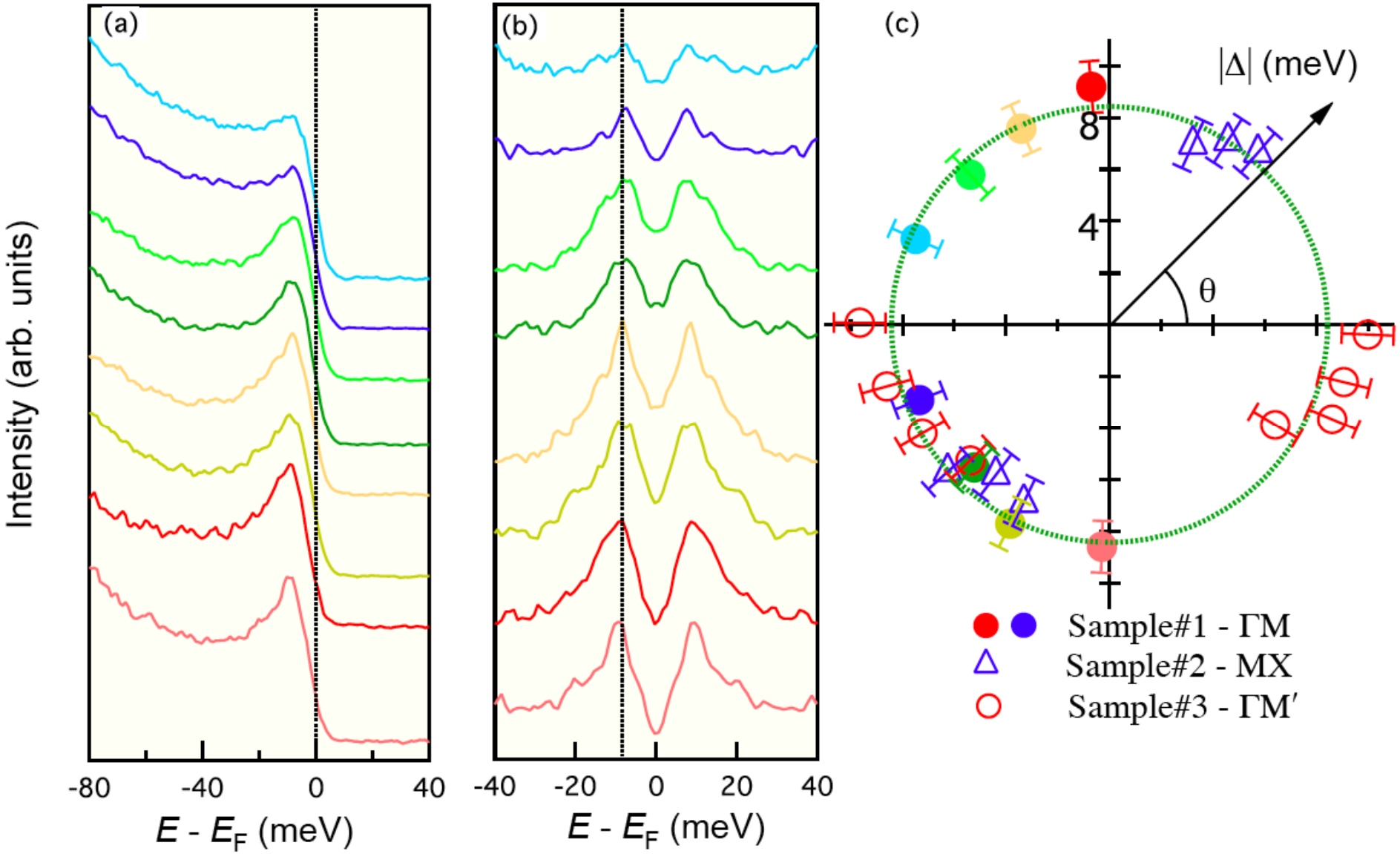
KFe_2As_2: heavily hole doped



$K(Fe_{1.8}Co_{0.2})_2As_2$: 20% electron doped



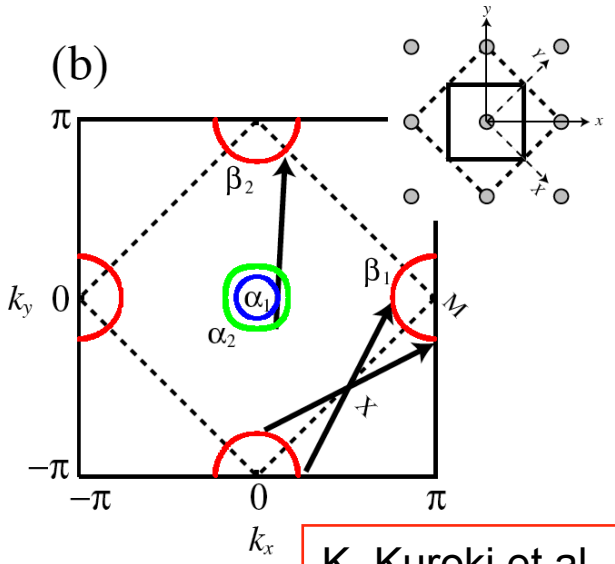
Isotropic SC gap on electron FS

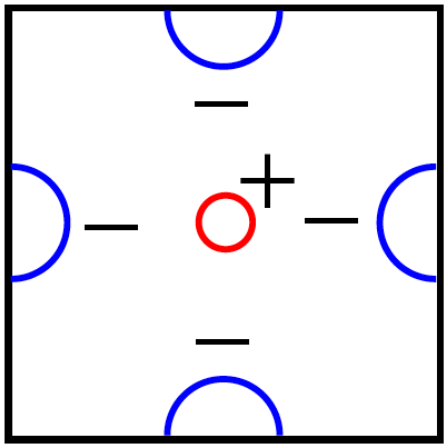


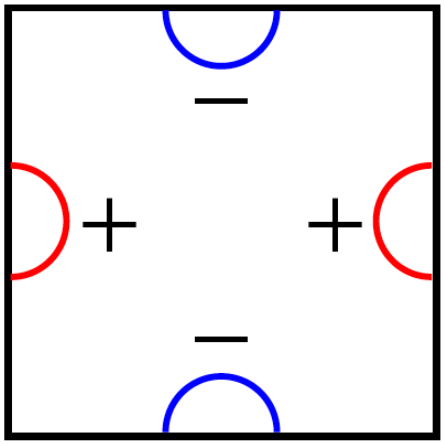
J1 < 0, FM, d-wave is not favored

X.-P. Wang *et al.*, EPL 93, 57001 (2011)

Possible SC gap symmetries

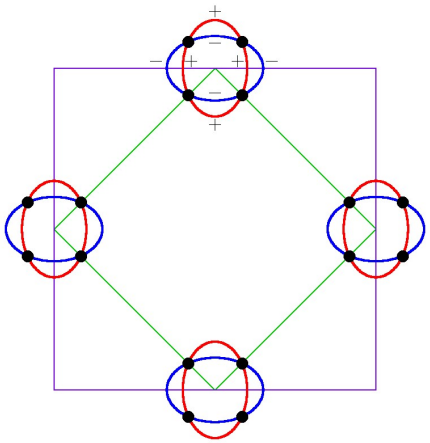




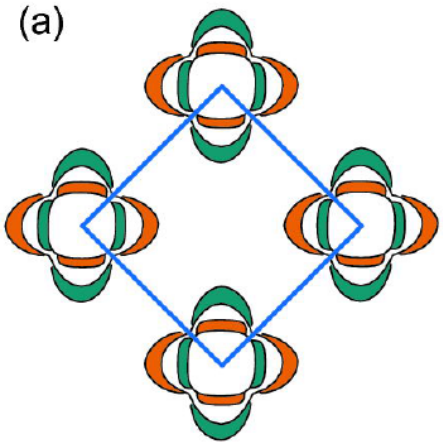


K. Kuroki et al., PRL **101**, 087004 (2008)

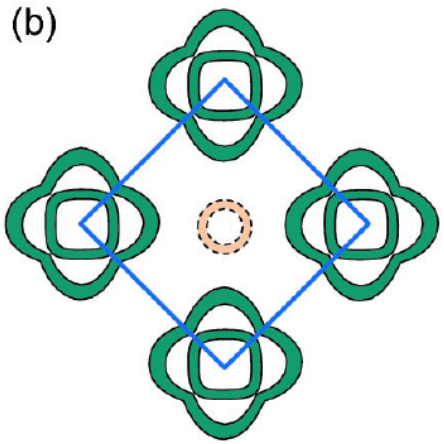
Note: Interband scattering between same type FSs is not good for pairing!



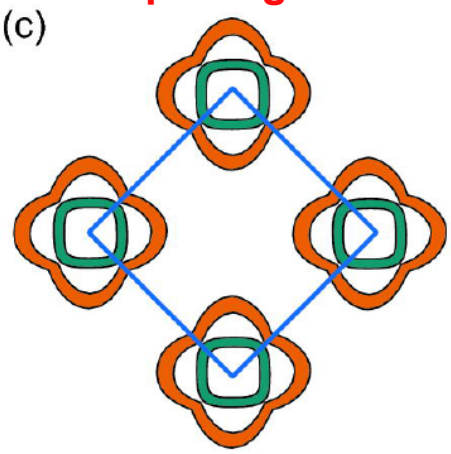
nodal d



"quasi − nodeless" d



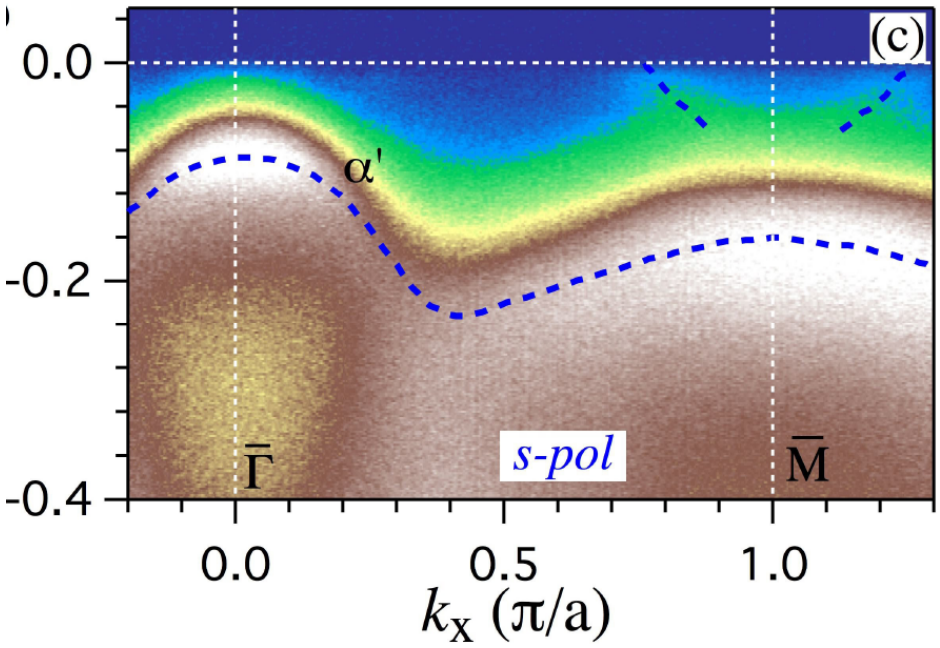
"incipient" $s_{\pm}$

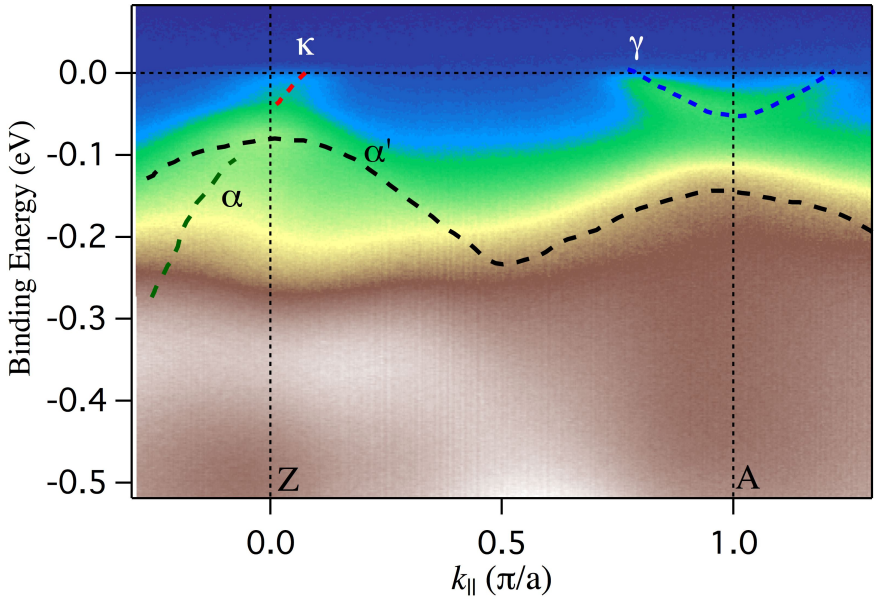


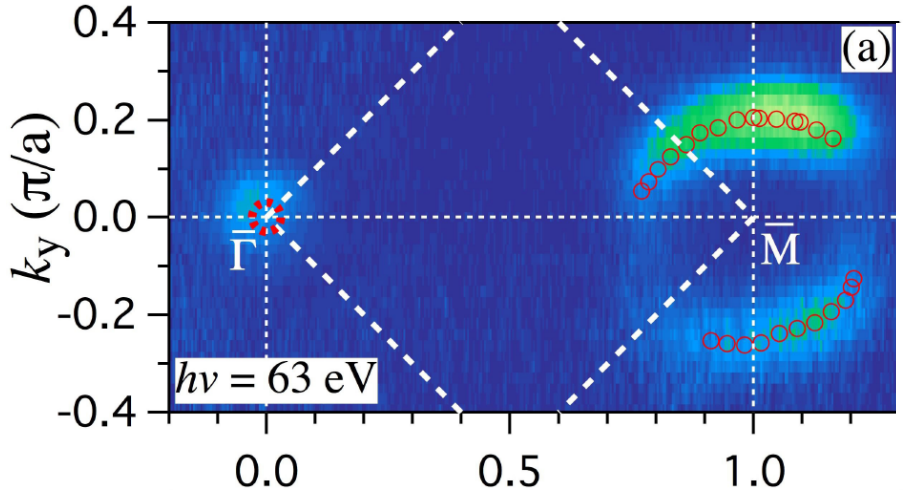
"bonding − antibonding" $s_{\pm}$

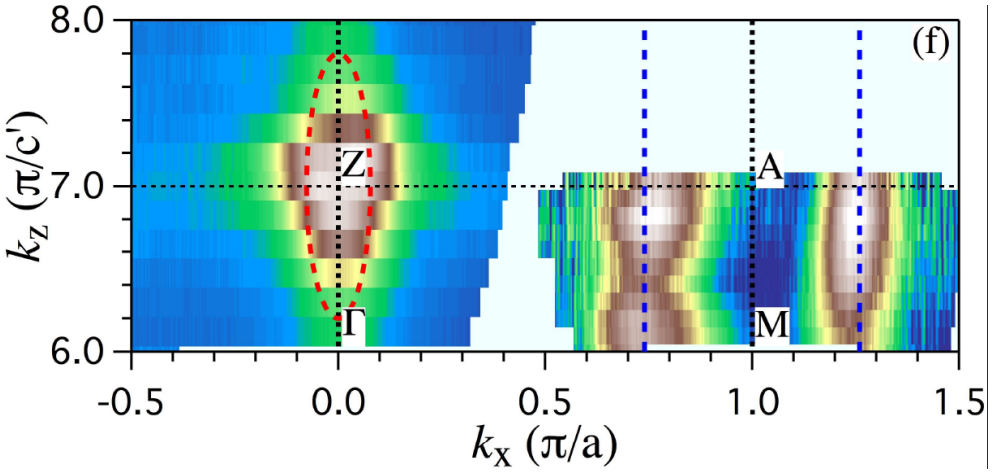
P. J. Hirschfeld et al., Rep. Prog. Phys. **74**, 124508 (2011)

3D electron FS pocket around Z

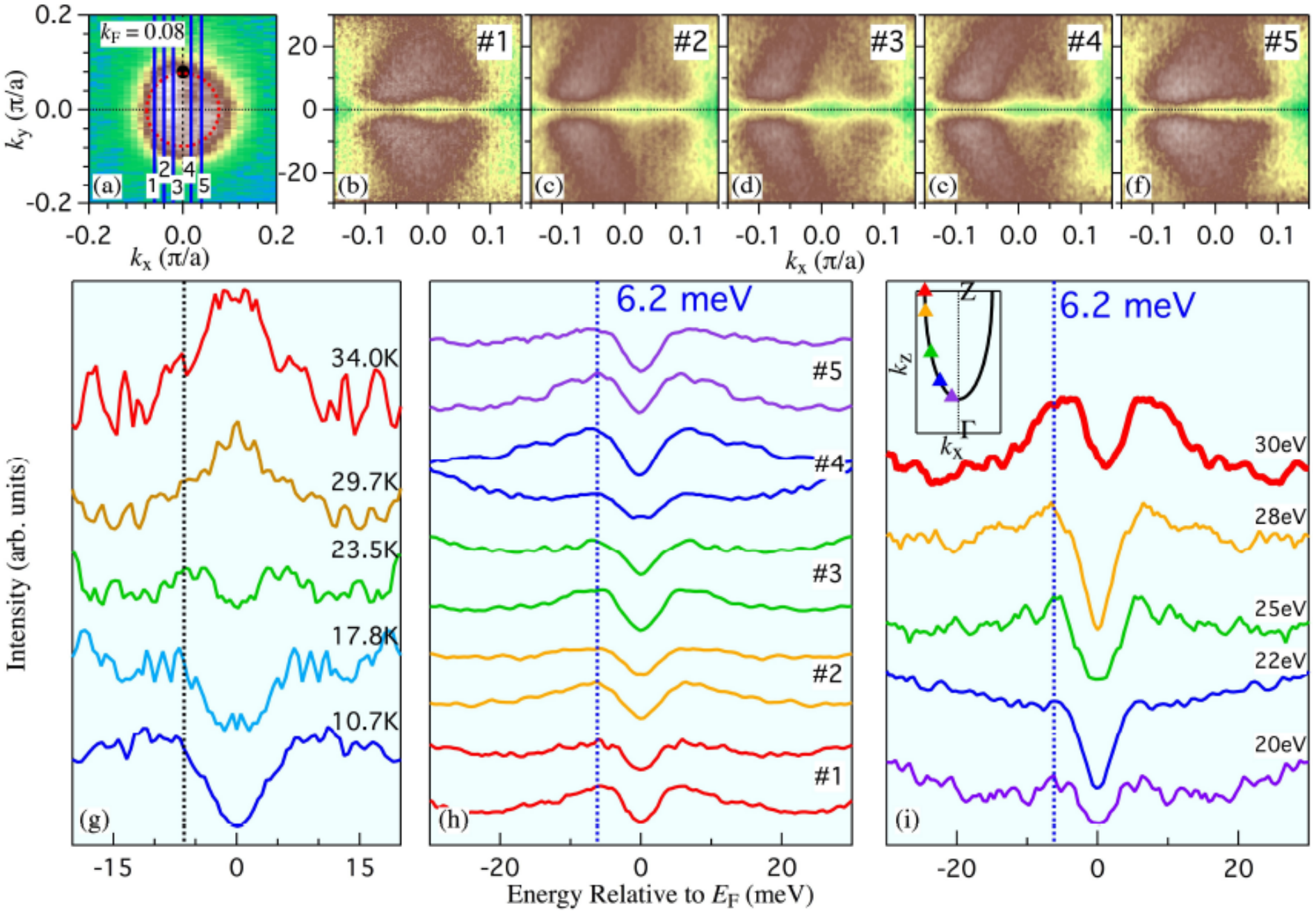




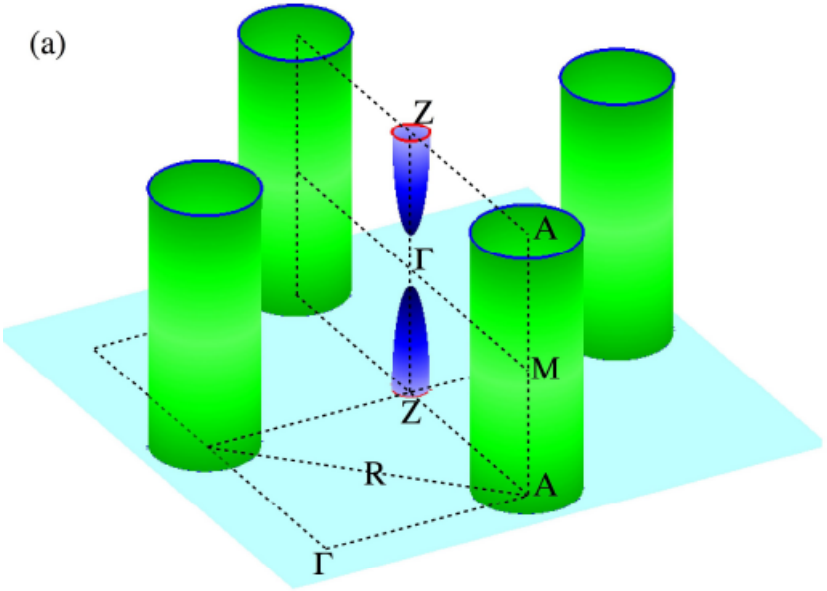


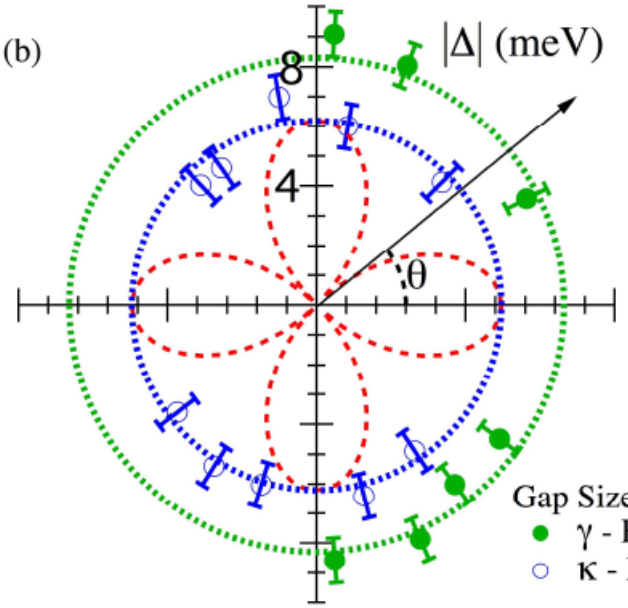


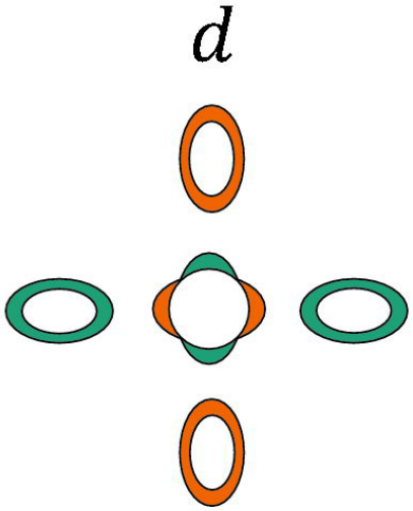
Isotropic SC gap on electron FS pocket around Z

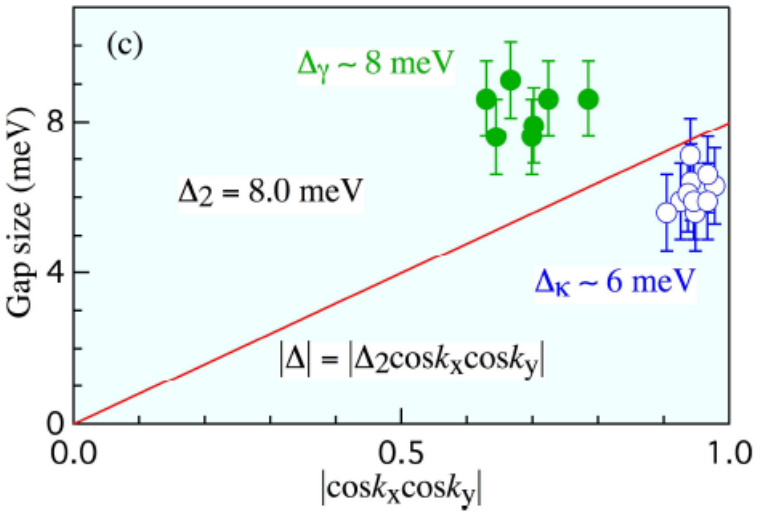


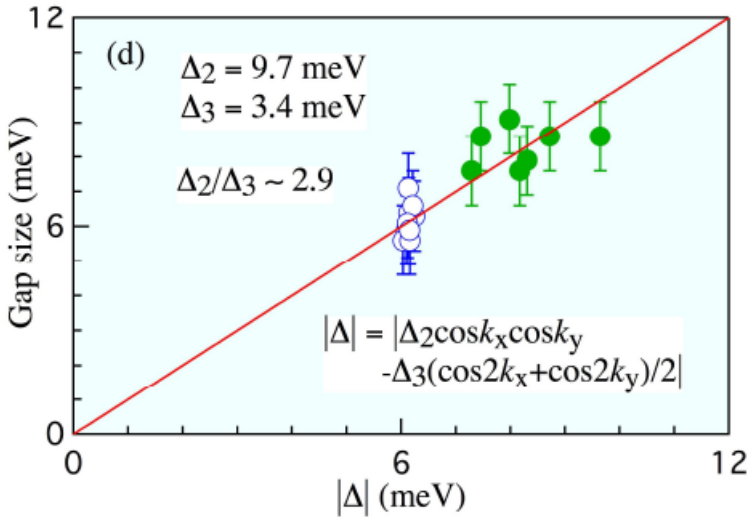
SC gap structure in (Tl,K)$Fe_{1.78}Se_2$







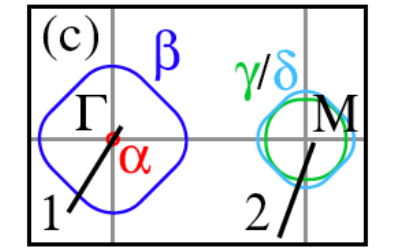


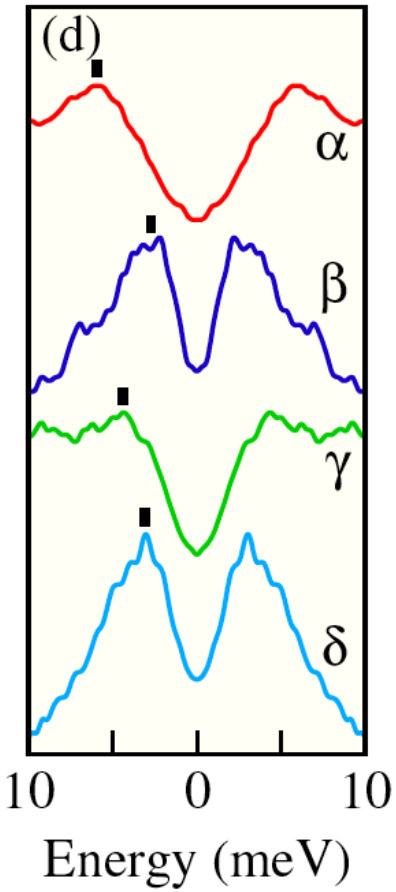


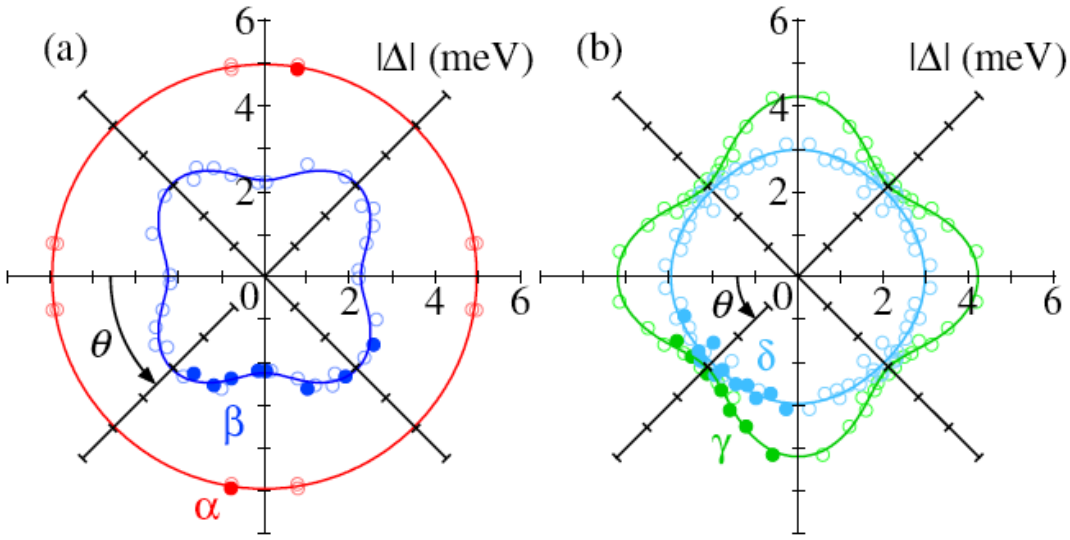
d-wave is ruled out!

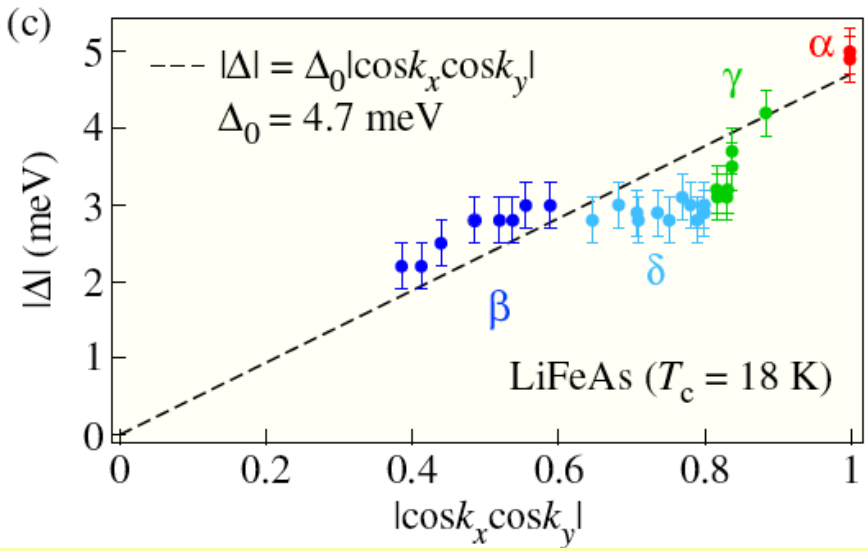
X.-P. Wang *et al.*, arXiv:1205.0996

Moderate gap anisotropy in LiFeAs



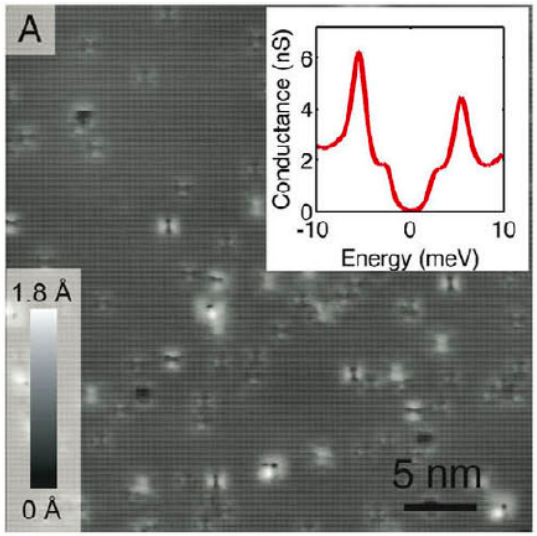


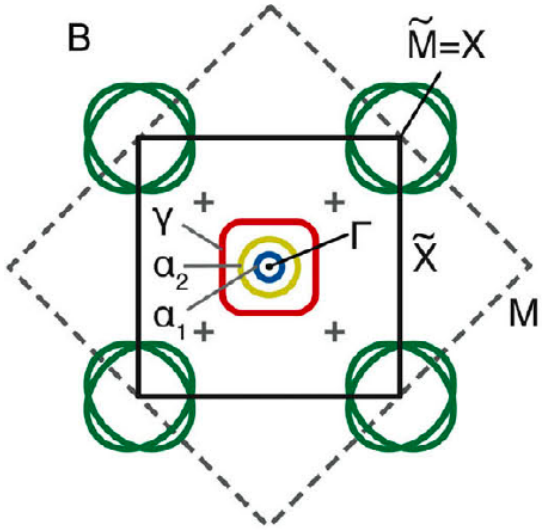


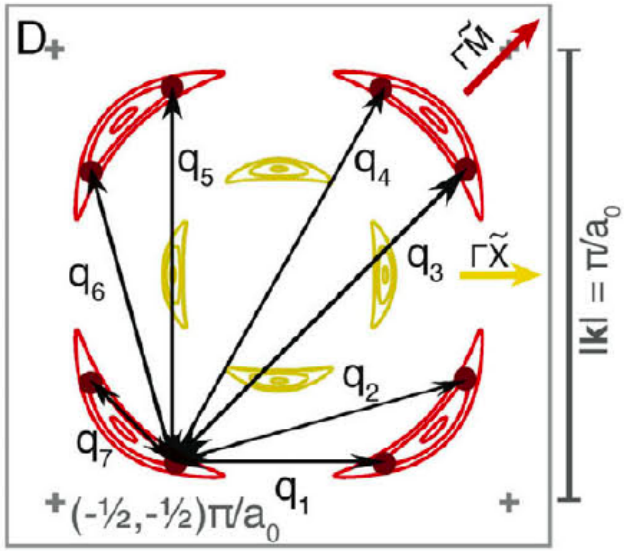


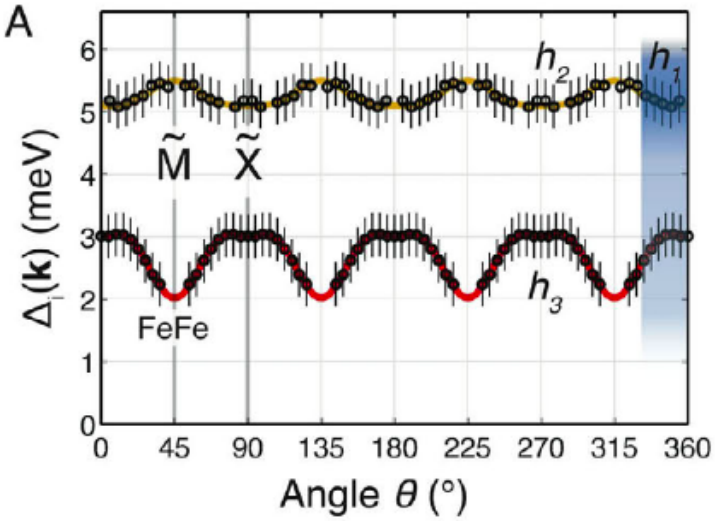
K. Umezawa et al, PRL 108, 037002 (2012)

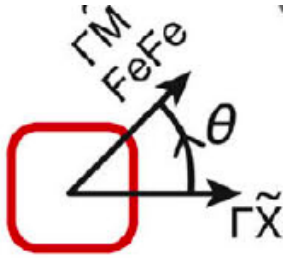
Moderate gap anisotropy in LiFeAs: STM results

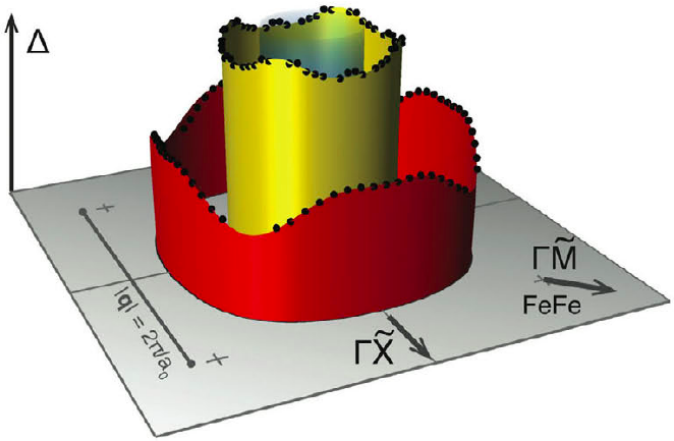






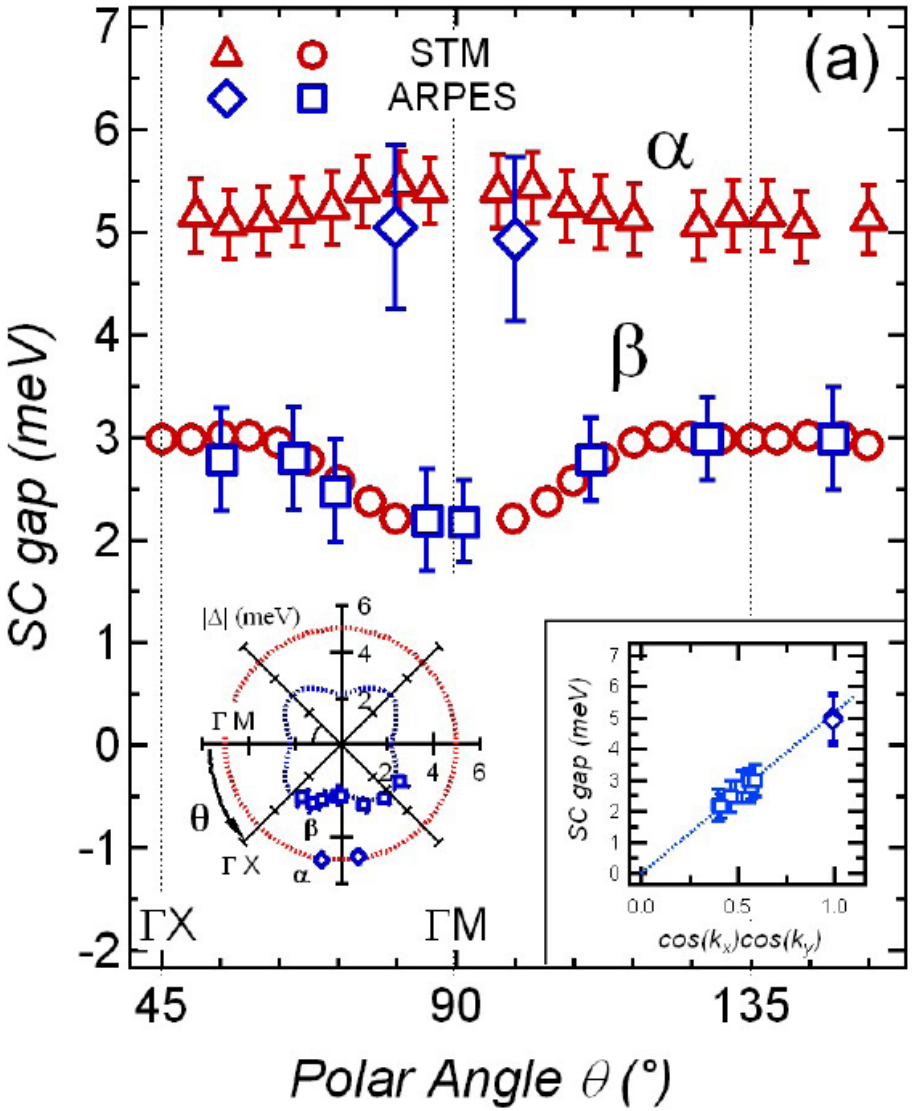


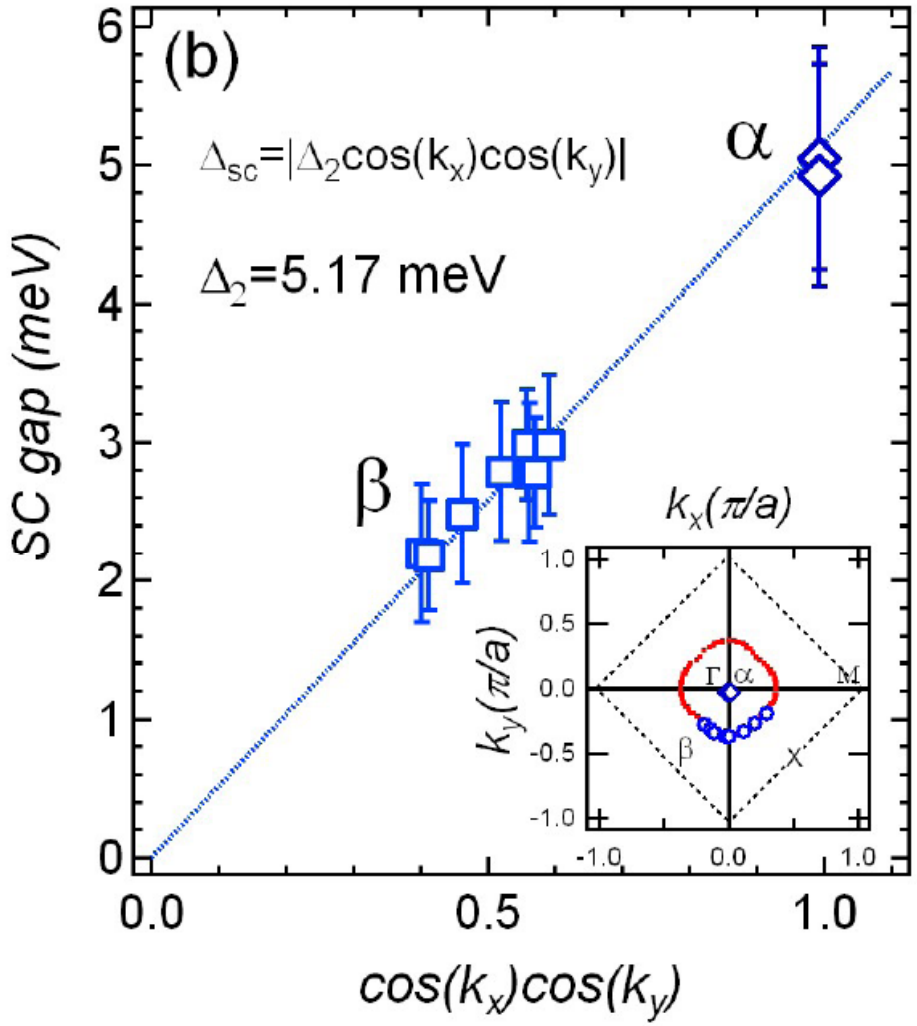




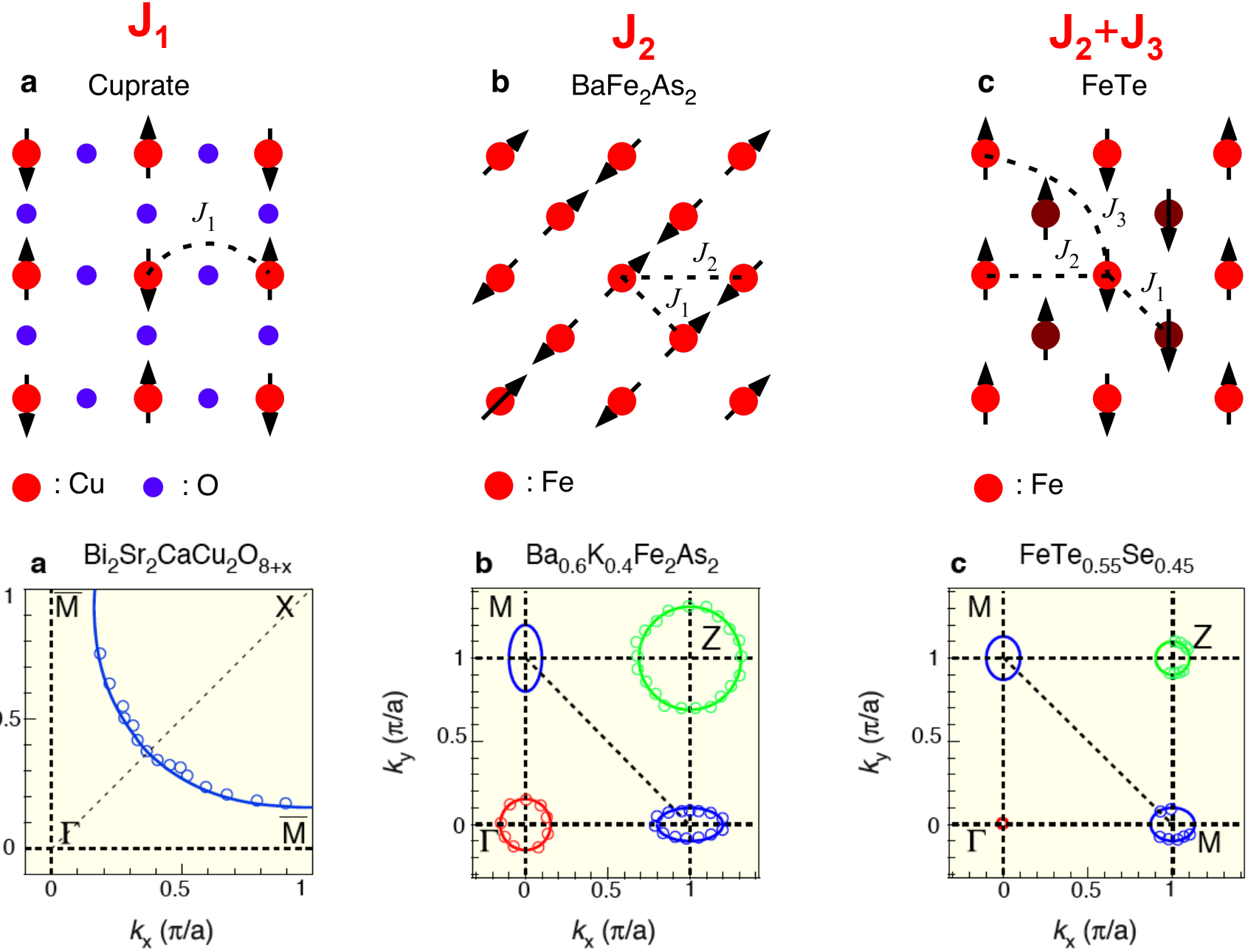
M. P. Allan et al., Science 336 563 (2012)

Comparison between ARPES and STM on LiFeAs consistent with $\cos k_x \cos k_y$

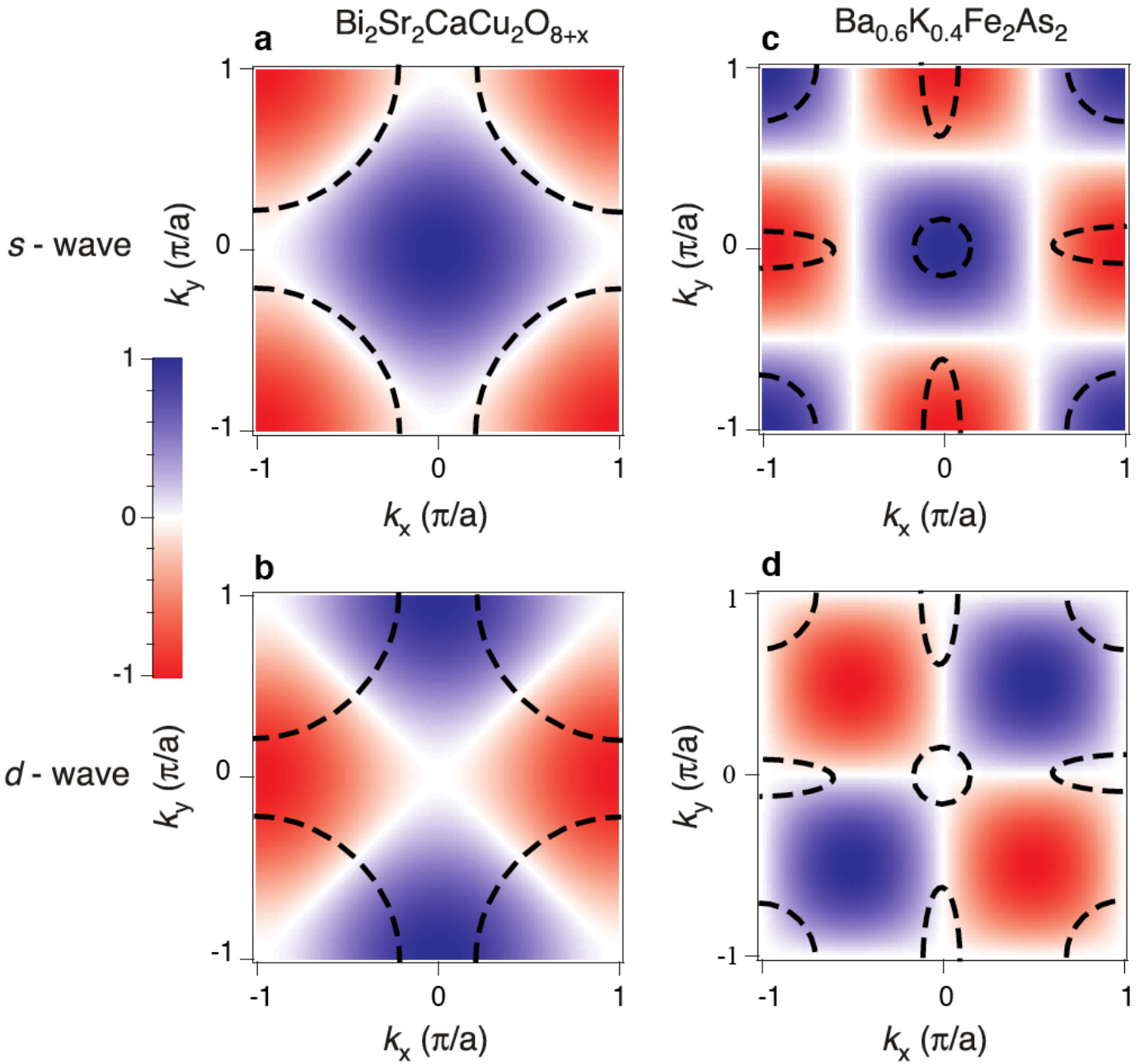




Three classes of high-T_c superconductors



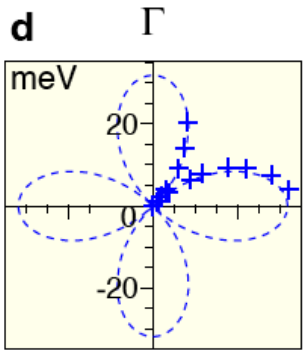
Overlap strength between pairing form factor and Fermi surface



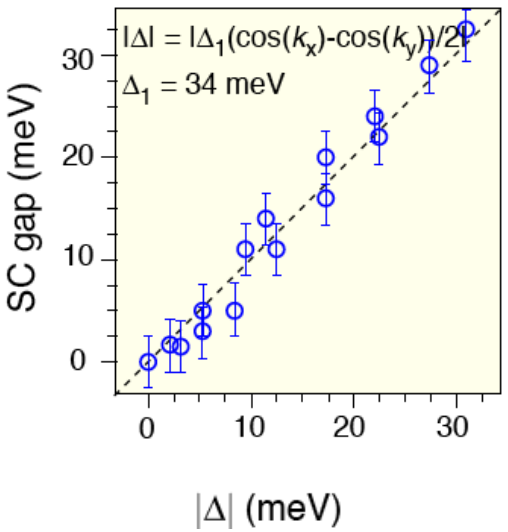
Three classes of high-T_c superconductors

J_1

$Bi_2Sr_2CaCu_2O_{8+x}$

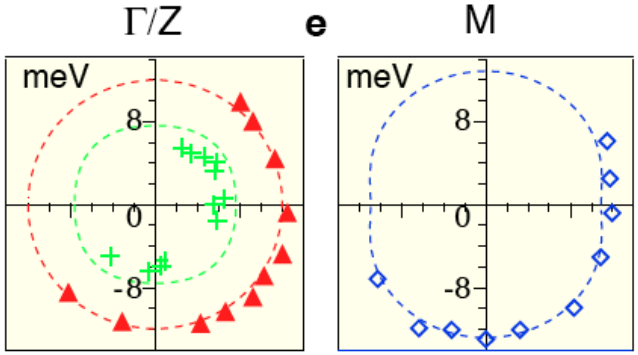


$|\Delta| = |\Delta_1(\cos(k_x)-\cos(k_y))/2|$

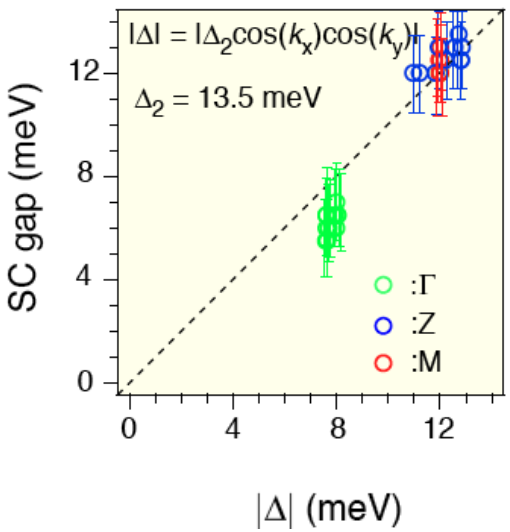


J_2

$Ba_{0.6}K_{0.4}Fe_2As_2$

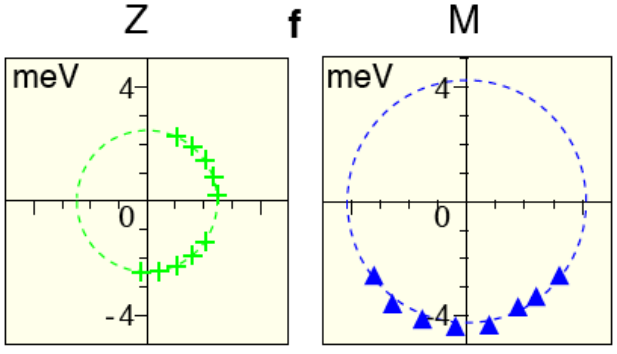


$|\Delta| = |\Delta_2\cos(k_x)\cos(k_y)|$

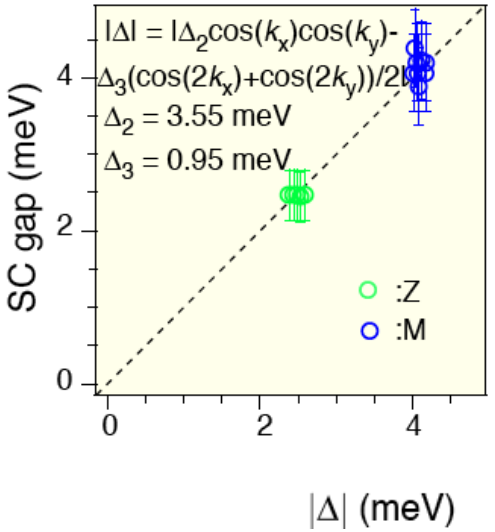


J_2+J_3

$FeTe_{0.55}Se_{0.45}$



$|\Delta| = |\Delta_2\cos(k_x)\cos(k_y)-\Delta_3(\cos(2k_x)+\cos(2k_y))/2|$



Summary

1. The SC gap of all iron-based superconductors measured by ARPES can by described approximately by J_1-J_2-J_3 model

2. A possible unified paradigm of high-T_c superconductivity:
   local AFM magnetic exchange
   + collaborative FS topology

J.-P. Hu and H. Ding, Scientific Reports 2, 381 (2012)