Glide symmetry in iron-based superconductors

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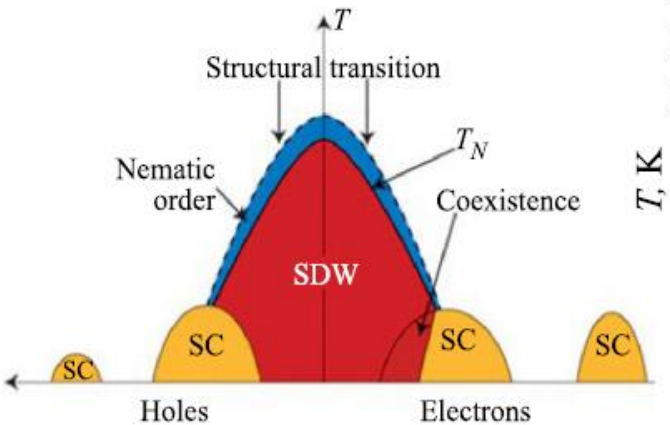
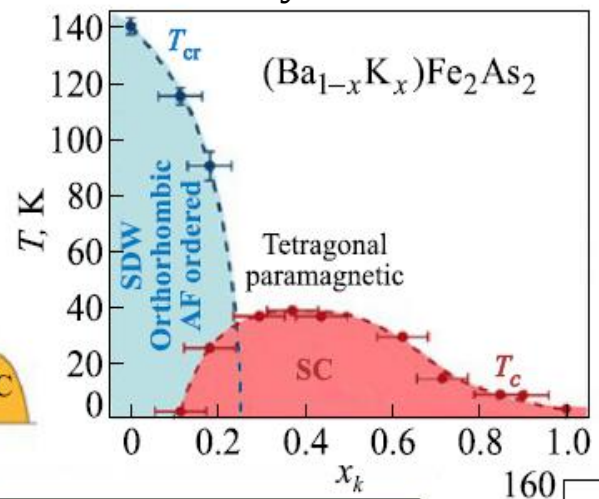
1. Introduction
2. Translation symmetry breaking, Glide symmetry & orbital parity
3. Spectral function
4. Superconducting gap structure

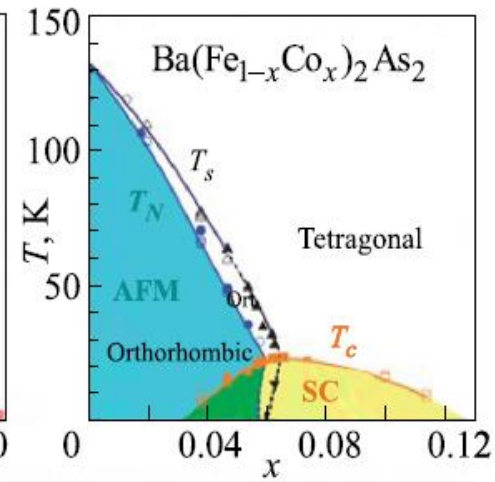
Phase Diagram

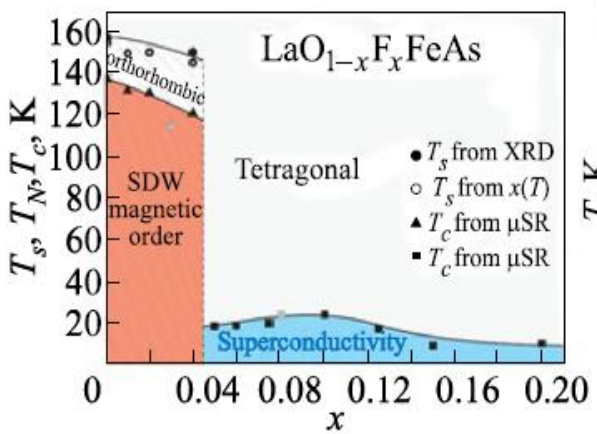
H.H. Wen *et al.*,
Ann. Rev. Condens. Matter Phys. 2011

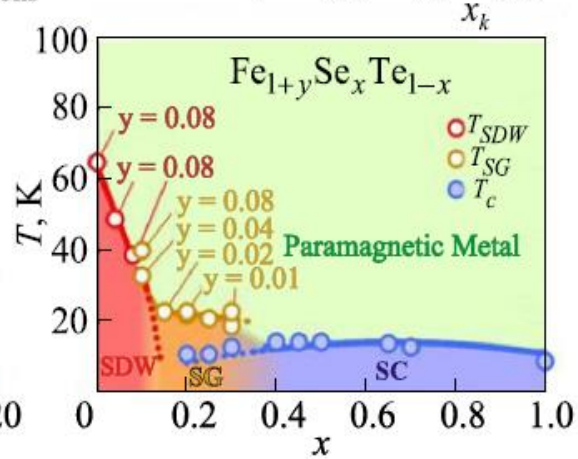


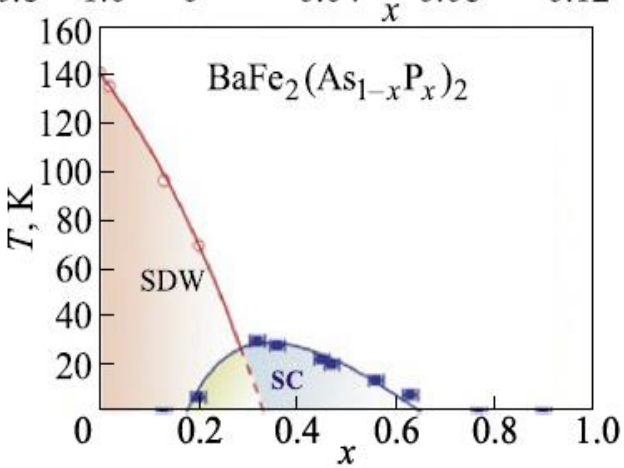


S. Nandi *et al.*, PRL 2010









H. Luetkens *et al.*,
Nature Mater. 2009

N. Katayama *et al.*, JPSJ 2010

S. Jiang *et al.*,
J. Phys.: Condens. Matter 2009

Experiments: Gap Structure

ARPES/ STM / tunneling

1. X.-P. Wang *et al*., EPL 2011
   $Tl_{0.63}K_{0.37}Fe_{1.78}Se_2$
2. H. Ding *et al*., EPL 2008
   $Ba_{0.6}K_{0.4}Fe_2As_2$
3. D. Mou *et al*., PRL 2011
   $(Tl_{0.58}Rb_{0.42})Fe_{1.72}Se_2$
4. H. Miao *et al*., PRB 2012
   $FeTe_{0.55}Se_{0.45}$
5. K. Umezawa *et al*., PRL 2012
   LiFeAs, T_c=18K
6. K. Okazaki, *et al*., PRL 2012
   $FeTe_{0.6}Se_{0.4}$
7. Y. Zhang *et al*., Nature Mater. 2011
8. Y. Zhang *et al*., Nature Phys. 2012
9. S. V. Borisenko et al., PRL 2010
10. …

Experiments: Bulk Measurement

Linear λ(T)

PRL 102, 147001 (2009) PHYSICAL REVIEW LETTERS week ending 10 APRIL 2009

Evidence for a Nodal-Line Superconducting State in LaFePO

J. D. Fletcher,[1] A. Serafin,[1] L. Malone,[1] J. G. Analytis,[2] J.-H. Chu,[2] A. S. Erickson,[2] I. R. Fisher,[2] and A. Carrington[1]

PRL 108, 047003 (2012) PHYSICAL REVIEW LETTERS week ending 27 JANUARY 2012

Nodal versus Nodeless Behaviors of the Order Parameters of LiFeP and LiFeAs Superconductors from Magnetic Penetration-Depth Measurements

K. Hashimoto,[1] S. Kasahara,[2] R. Katsumata,[1] Y. Mizukami,[1] M. Yamashita,[1] H. Ikeda,[1] T. Terashima,[2] A. Carrington,[3] Y. Matsuda,[1] and T. Shibauchi[1]

STM/STS
dI/dV

Direct Observation of Nodes and Twofold Symmetry in FeSe Superconductor

Can-Li Song,[1,2] Yi-Lin Wang,[2] Peng Cheng,[1] Ye-Ping Jiang,[1,2] Wei Li,[1] Tong Zhang,[1,2] Zhi Li,[2] Ke He,[2] Lili Wang,[2] Jin-Feng Jia,[1] Hsiang-Hsuan Hung,[3] Congjun Wu,[3] Xucun Ma,[2]* Xi Chen,[1]* Qi-Kun Xue[1,2]

$1/T_1 \sim T$

RAPID COMMUNICATIONS

PHYSICAL REVIEW B 81, 020503(R) (2010)

^{31}P and ^{75}As NMR evidence for a residual density of states at zero energy in superconducting $BaFe_2(As_{0.67}P_{0.33})_2$

Yusuke Nakai,[1,2,*] Tetsuya Iye,[1,2] Shunsaku Kitagawa,[1,2] Kenji Ishida,[1,2] Shigeru Kasahara,[3] Takasada Shibauchi,[1] Yuji Matsuda,[1] and Takahito Terashima[3]

$\kappa_0(H)/T$

PHYSICAL REVIEW X 2, 011010 (2012)

Robust Nodal Superconductivity Induced by Isovalent Doping in $Ba(Fe_{1-x}Ru_x)_2As_2$ and $BaFe_2(As_{1-x}P_x)_2$

X. Qiu,[1] S. Y. Zhou,[1] H. Zhang,[1] B. Y. Pan,[1] X. C. Hong,[1] Y. F. Dai,[1] Man Jin Eom,[2] Jun Sung Kim,[2] Z. R. Ye,[1] Y. Zhang,[1] D. L. Feng,[1] and S. Y. Li[1,*]

RAPID COMMUNICATIONS

PHYSICAL REVIEW B 81, 220501(R) (2010)

Line nodes in the energy gap of superconducting $BaFe_2(As_{1-x}P_x)_2$ single crystals as seen via penetration depth and thermal conductivity

K. Hashimoto,[1,2] M. Yamashita,[1] S. Kasahara,[3] Y. Senshu,[1] N. Nakata,[1] S. Tonegawa,[1] K. Ikada,[1] A. Serafin,[2] A. Carrington,[2] T. Terashima,[3] H. Ikeda,[1] T. Shibauchi,[1] and Y. Matsuda[1]

κ/T and $\lambda^{-2}(T)$

$\kappa(\phi)$

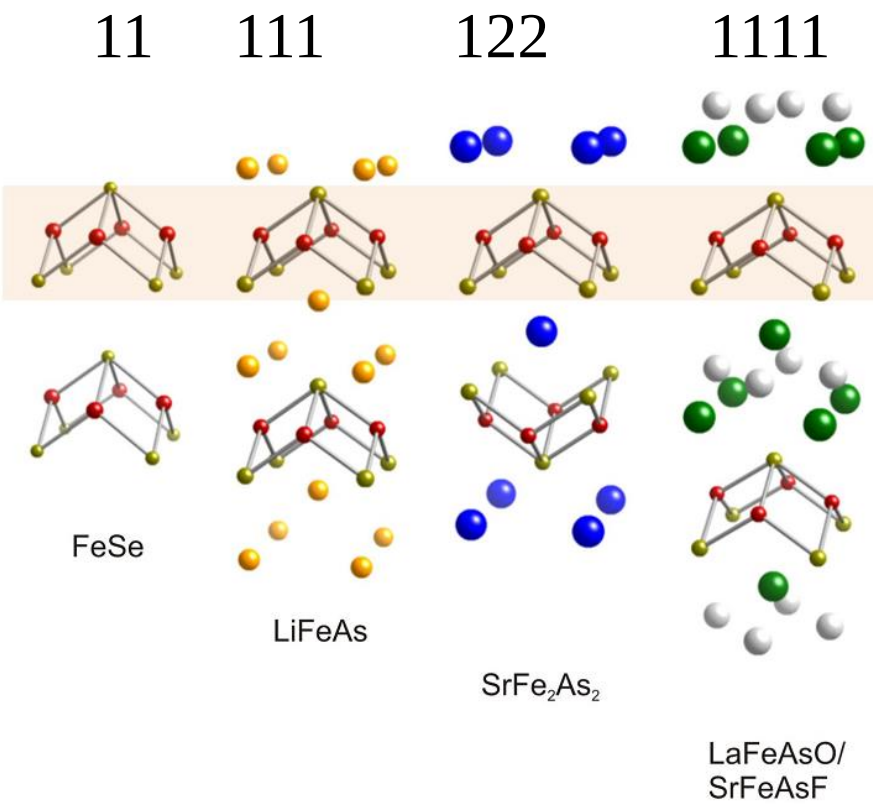
RAPID COMMUNICATIONS

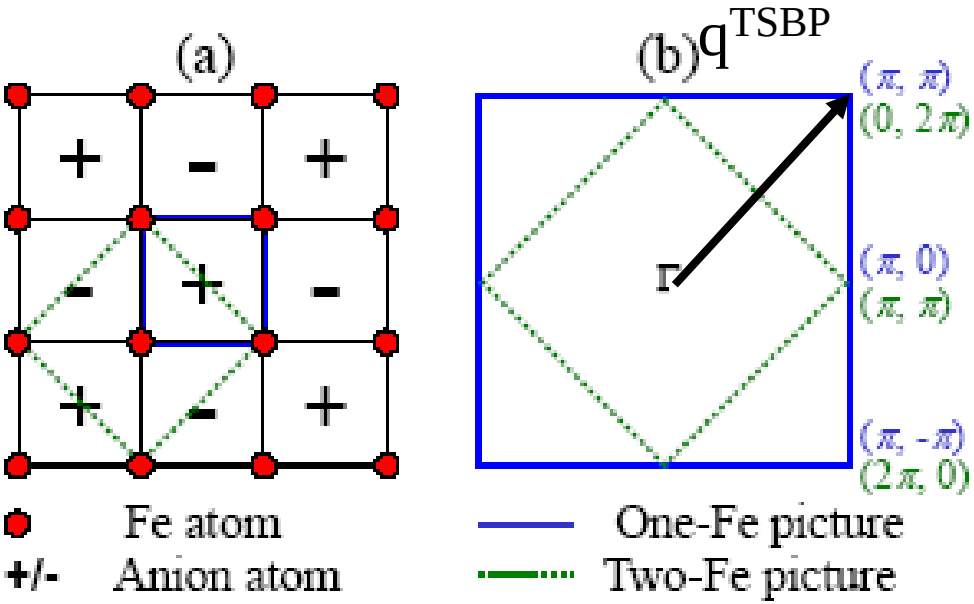
PHYSICAL REVIEW B 84, 060507(R) (2011)

Nodal gap structure of superconducting $BaFe_2(As_{1-x}P_x)_2$ from angle-resolved thermal conductivity in a magnetic field

M. Yamashita,[1] Y. Senshu,[1] T. Shibauchi,[1] S. Kasahara,[2] K. Hashimoto,[1] D. Watanabe,[1] H. Ikeda,[1] T. Terashima,[2] I. Vekhter,[3] A. B. Vorontsov,[4] and Y. Matsuda[1]

Crystal Structure & TSBP

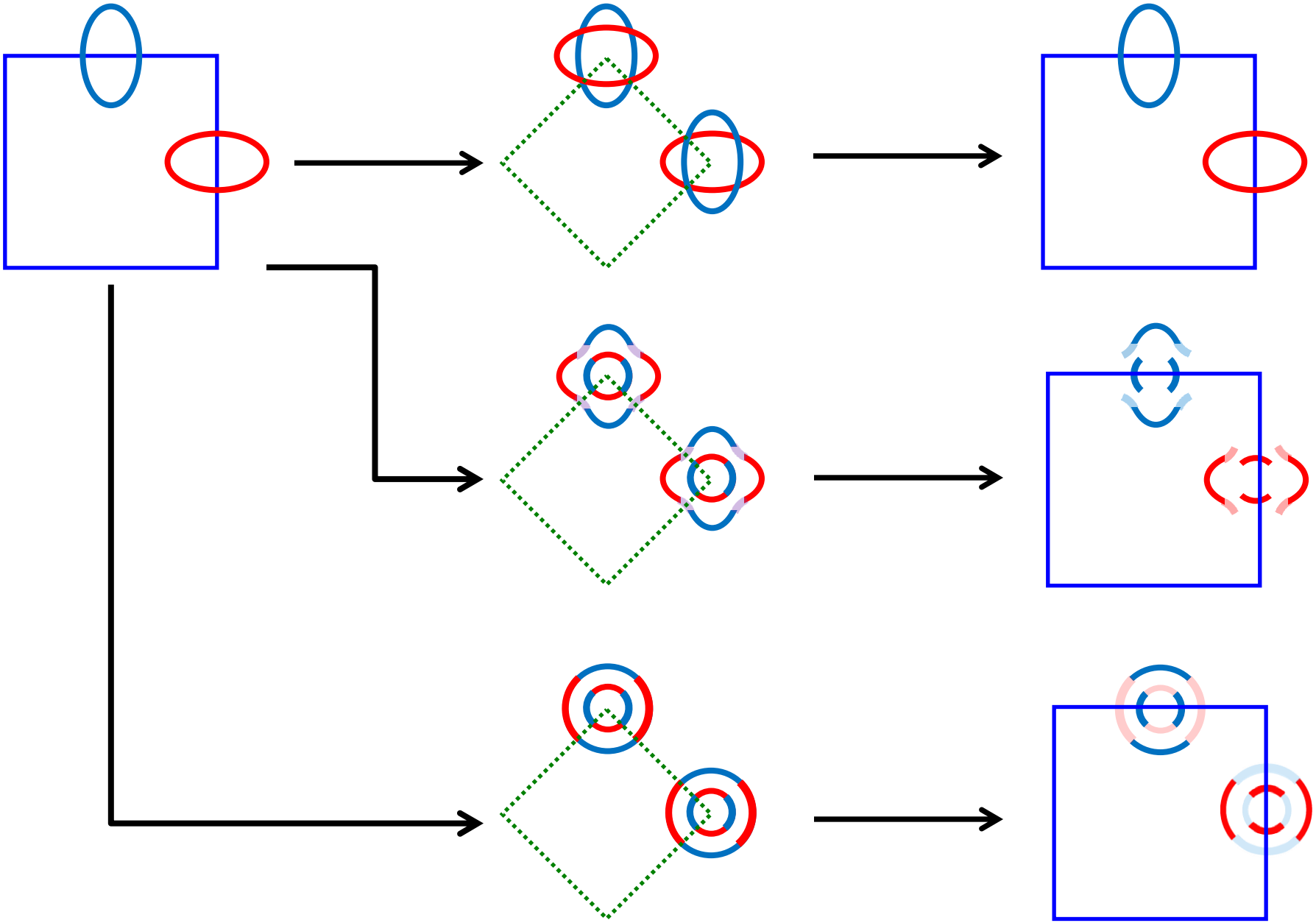




Fe-based superconductor
Multiple orbitals
Broken translation symmetry
Glide symmetry
Three-dimensional

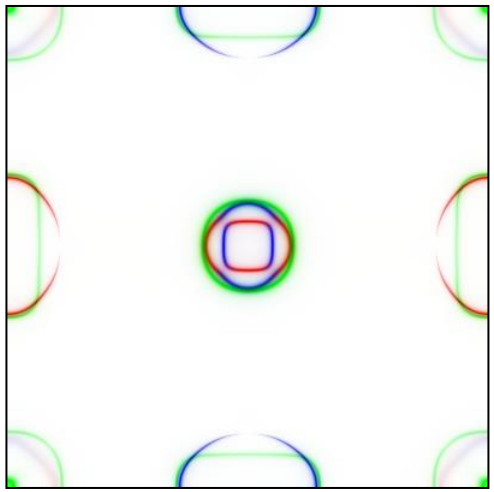
J. Paglione and R. L. Greene, Nature Phys. 2010

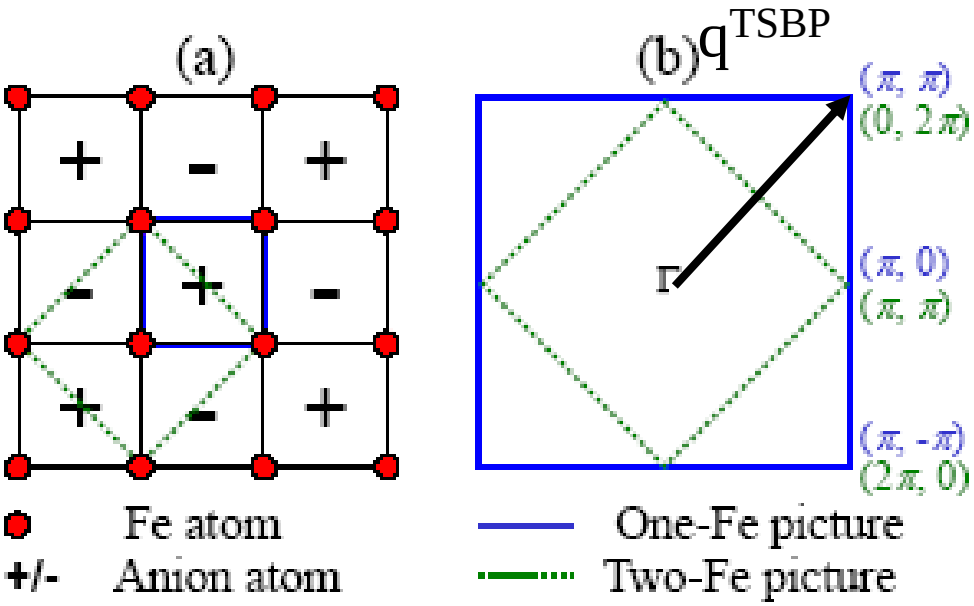
Zone Folding: Traditional view



Crystal Structure & TSBP

Ba122





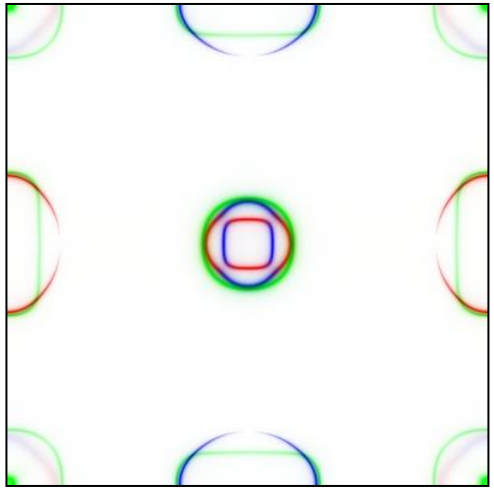
d_{z2}, d_{x2-y2} and d_{xy}

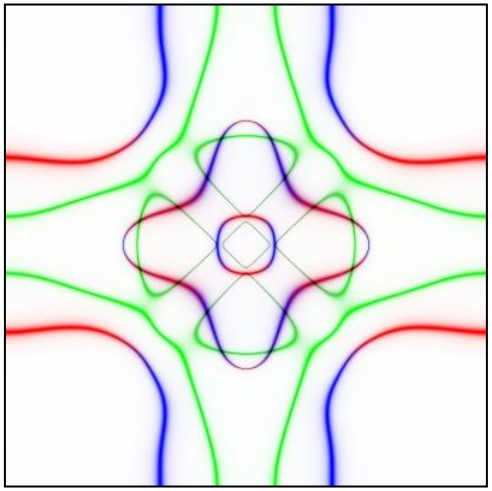
d_{xz} d_{yz}

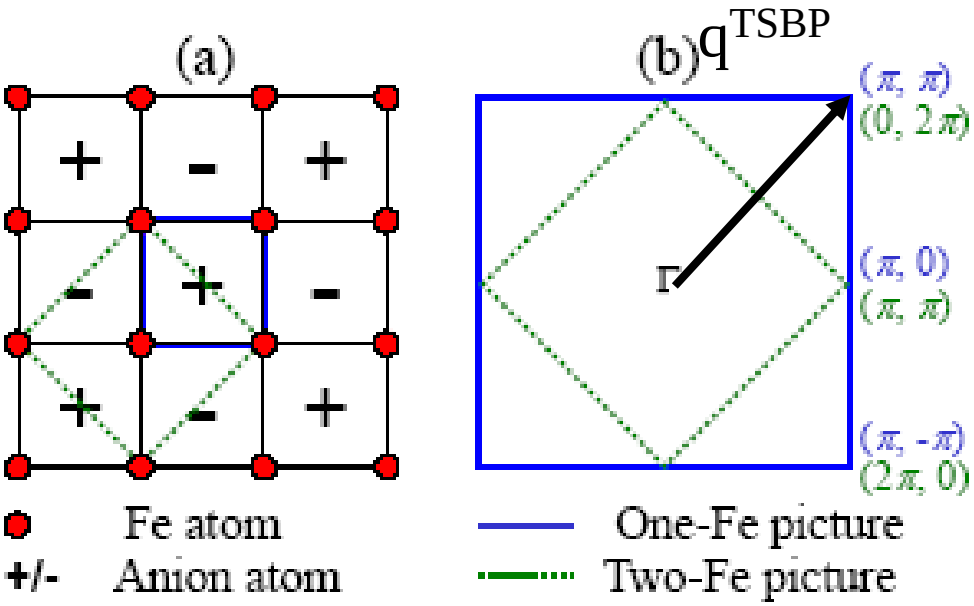
CHLIN *et. al.*, PRL (2011); Ku, Berlijn & Lee, PRL 104, 216401 (2010)

Crystal Structure & TSBP

Ba122







d_{z2}, d_{x2-y2} and d_{xy}

d_{xz} d_{yz}

CHLIN *et. al.*, PRL (2011); Ku, Berlijn & Lee, PRL 104, 216401 (2010)

PHYSICAL REVIEW B **78**, 144517 (2008)

Spin-triplet *p*-wave pairing in a three-orbital model for iron pnictide superconductors

Patrick A. Lee and Xiao-Gang Wen
Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
(Received 12 September 2008; published 28 October 2008)

We examine the possibility that the superconductivity in the newly discovered FeAs materials may be caused by the Coulomb interaction between *d* electrons of the iron atoms. We find that when the Hund's rule ferromagnetic interaction is strong enough, the leading pairing instability is in spin-triplet *p*-wave channel in the weak-coupling limit. The resulting superconducting gap has nodal points on the two-dimensional Fermi surfaces. The $\boldsymbol{k}$ dependent hybridization of several orbitals around a Fermi pocket is the key for the appearance of the spin-triplet *p*-wave pairing.

$z \to -z$ (see Fig. 1). Thus, if we combine the translation and the reflection P_z, then the electron hopping Hamiltonian H has a symmetry described by a reduced unit cell with only one Fe per unit cell (see Fig. 1). Since $[P_z T_x, H] = [P_z T_y, H] = [P_z T_x, P_z T_y] = 0$, we can use the eigenvalues of $P_z T_x$ and $P_z T_y$ to label the single-body energy eigenstates

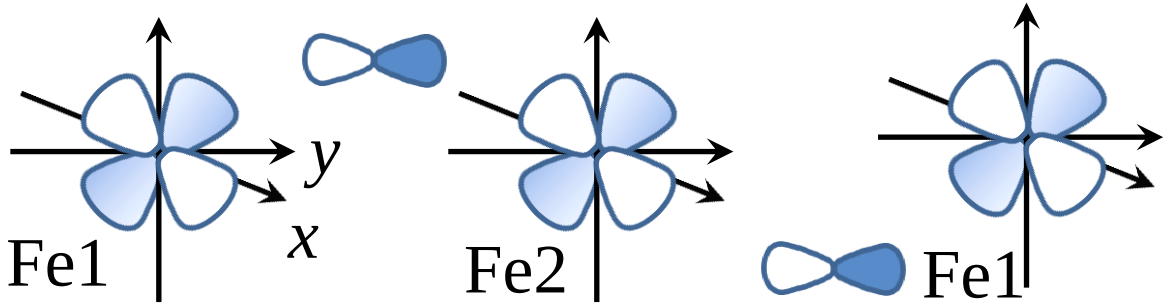
$$P_z T_x |\tilde{\boldsymbol{k}}\rangle = e^{i\tilde{k}_x} |\tilde{\boldsymbol{k}}\rangle, \quad P_z T_y |\tilde{\boldsymbol{k}}\rangle = e^{i\tilde{k}_y} |\tilde{\boldsymbol{k}}\rangle, \tag{1}$$

even — d_{z^2}, $d_{x^2-y^2}$ and d_{xy}

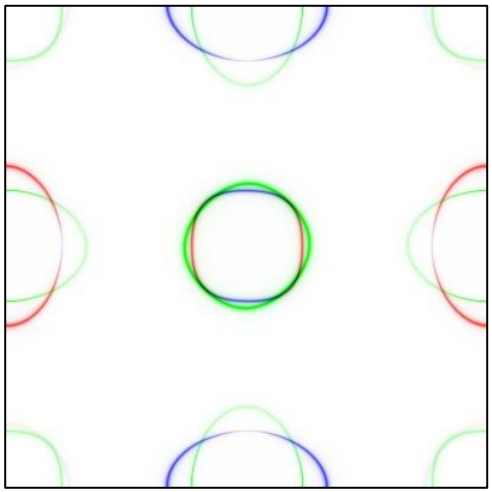
odd — d_{xz} — d_{yz}

TSBP with Parity in 2D

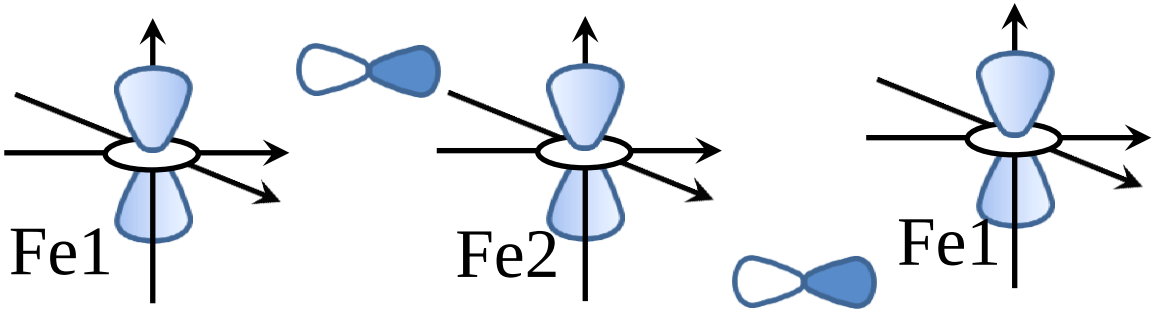
Odd (yz) to Odd (yz)



FeTe $\boldsymbol{k_z} = \pi$



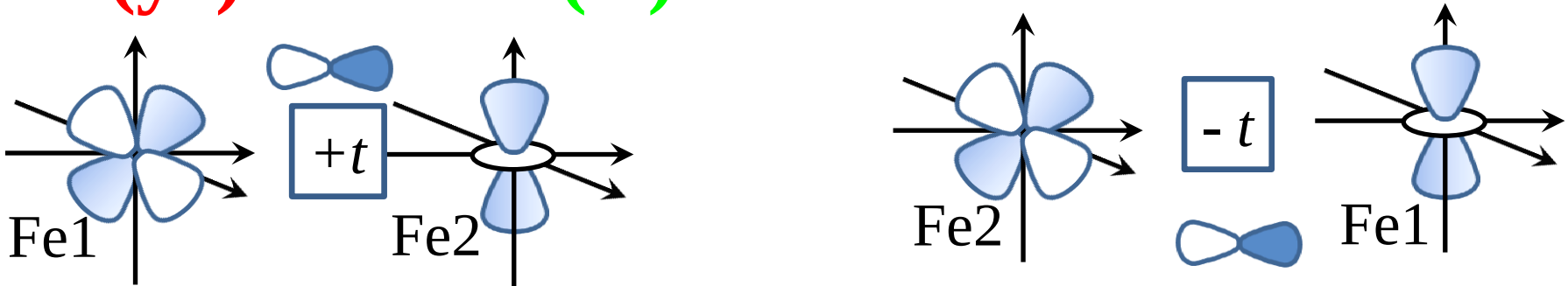
Even (z^2) to Even (z^2)



d_{z2}, $d_{x2\text{-}y2}$ and d_{xy}

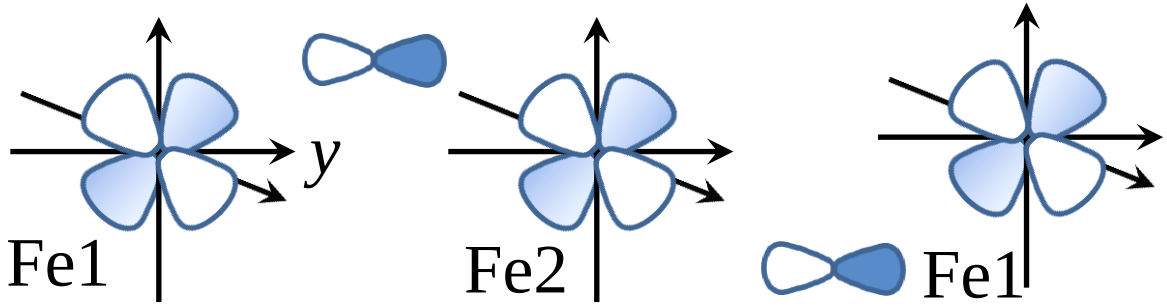
d_{xz} d_{yz}

Odd (yz) to Even (z^2)

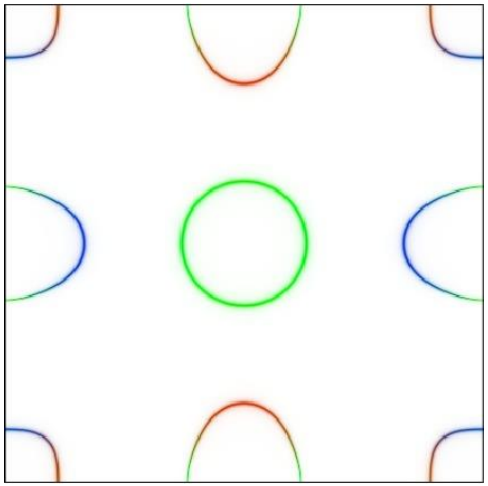


Local Gauge Transformation (I)

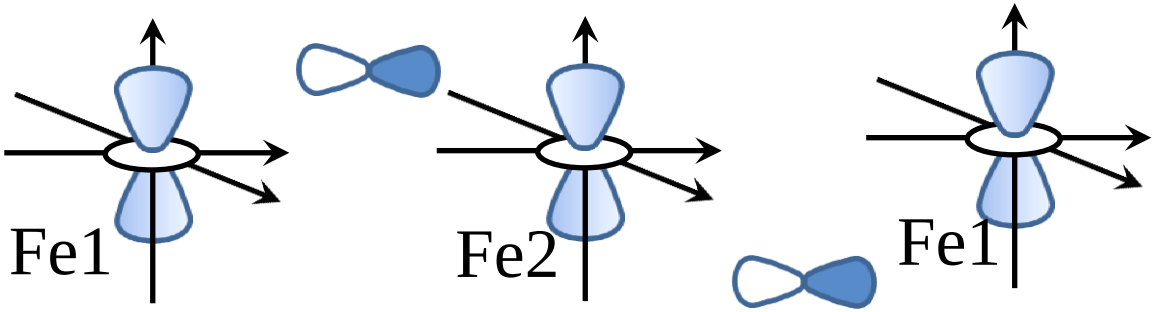
Odd (yz) to Odd (yz)



FeTe $\boldsymbol{k_z} = \pi$



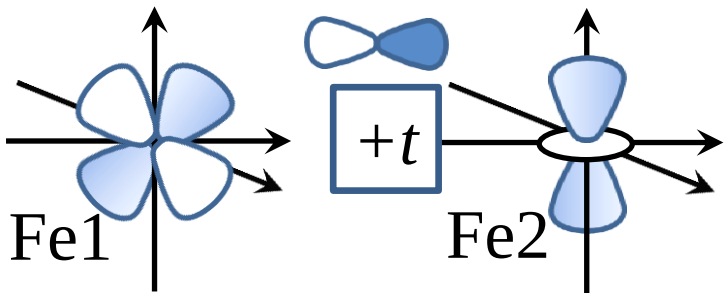
Even (z^2) to Even (z^2)

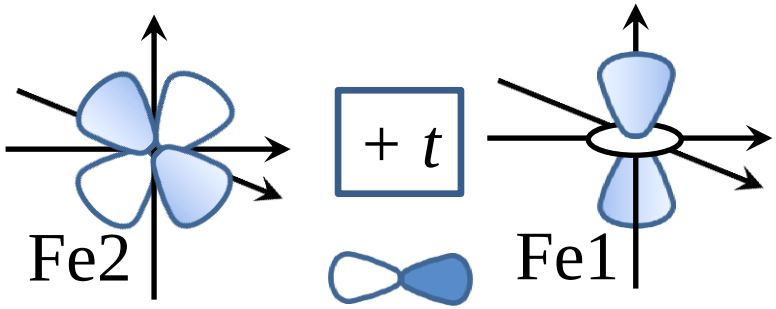


d_{z2}, $d_{x2\text{-}y2}$ and d_{xy}

d_{xz} d_{yz}

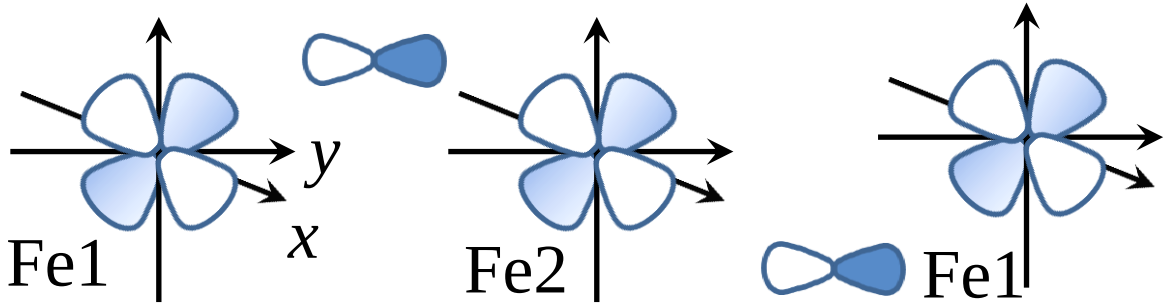
Odd (yz) to Even (z^2)



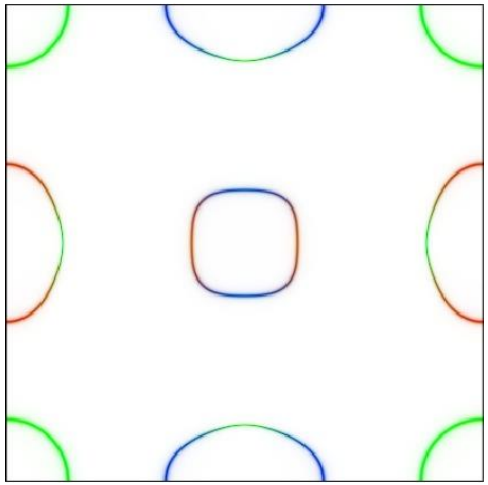


Local Gauge Transformation (II)

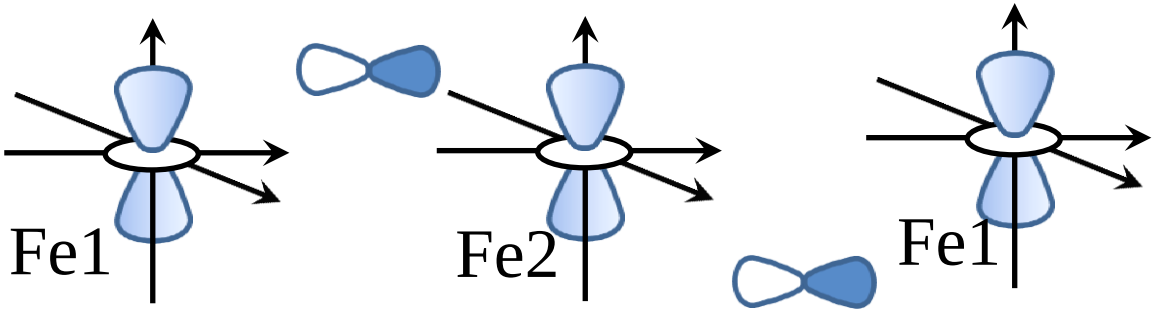
Odd (yz) to Odd (yz)



FeTe $\boldsymbol{k_z} = \pi$



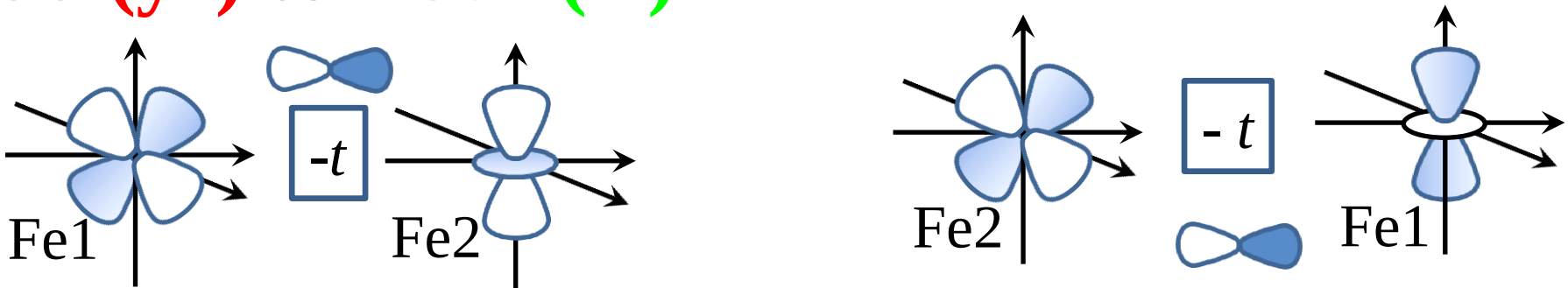
Even (z^2) to Even (z^2)



d_{z2}, $d_{x2\text{-}y2}$ and d_{xy}

d_{xz} d_{yz}

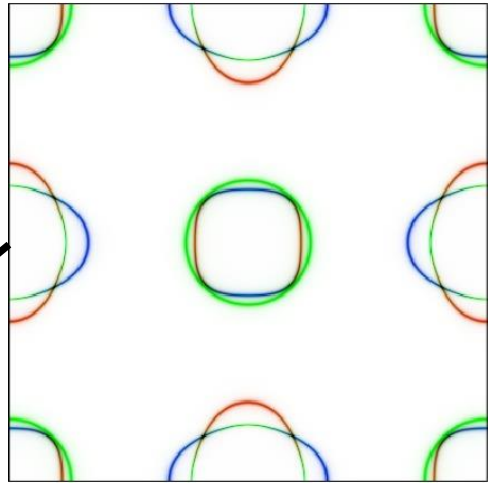
Odd (yz) to Even (z^2)



Local Gauge Transform in k space

FeTe

$\boldsymbol{k_z} = \pi$



d_{z^2}, $d_{x^2\text{-}y^2}$ and d_{xy}

d_{xz} d_{yz}

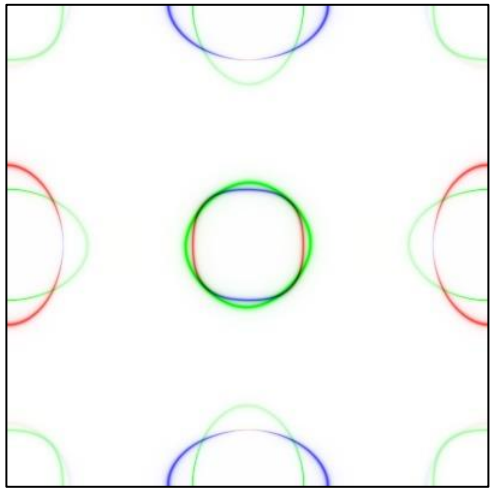
$\hat{a}_{xz}(k)$

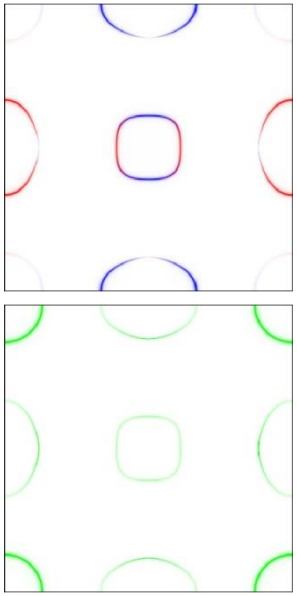
$\hat{a}_{xy}(k)$

$\hat{c}_{xz}(k)$

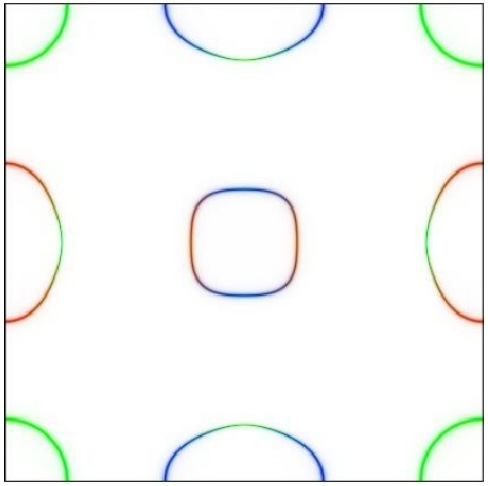
$\hat{c}_{xy}(k+Q)$

A(k,w)





A($\tilde{p}$,w) in math space

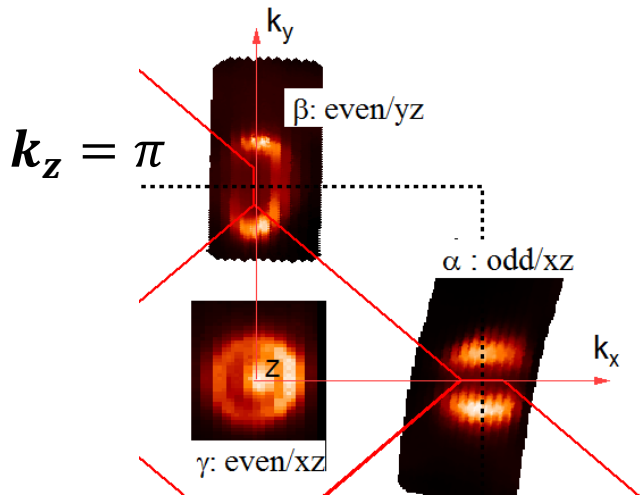


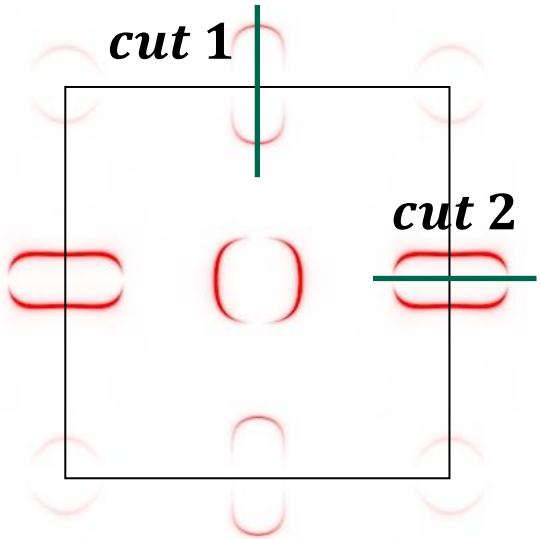
k=physical momentum

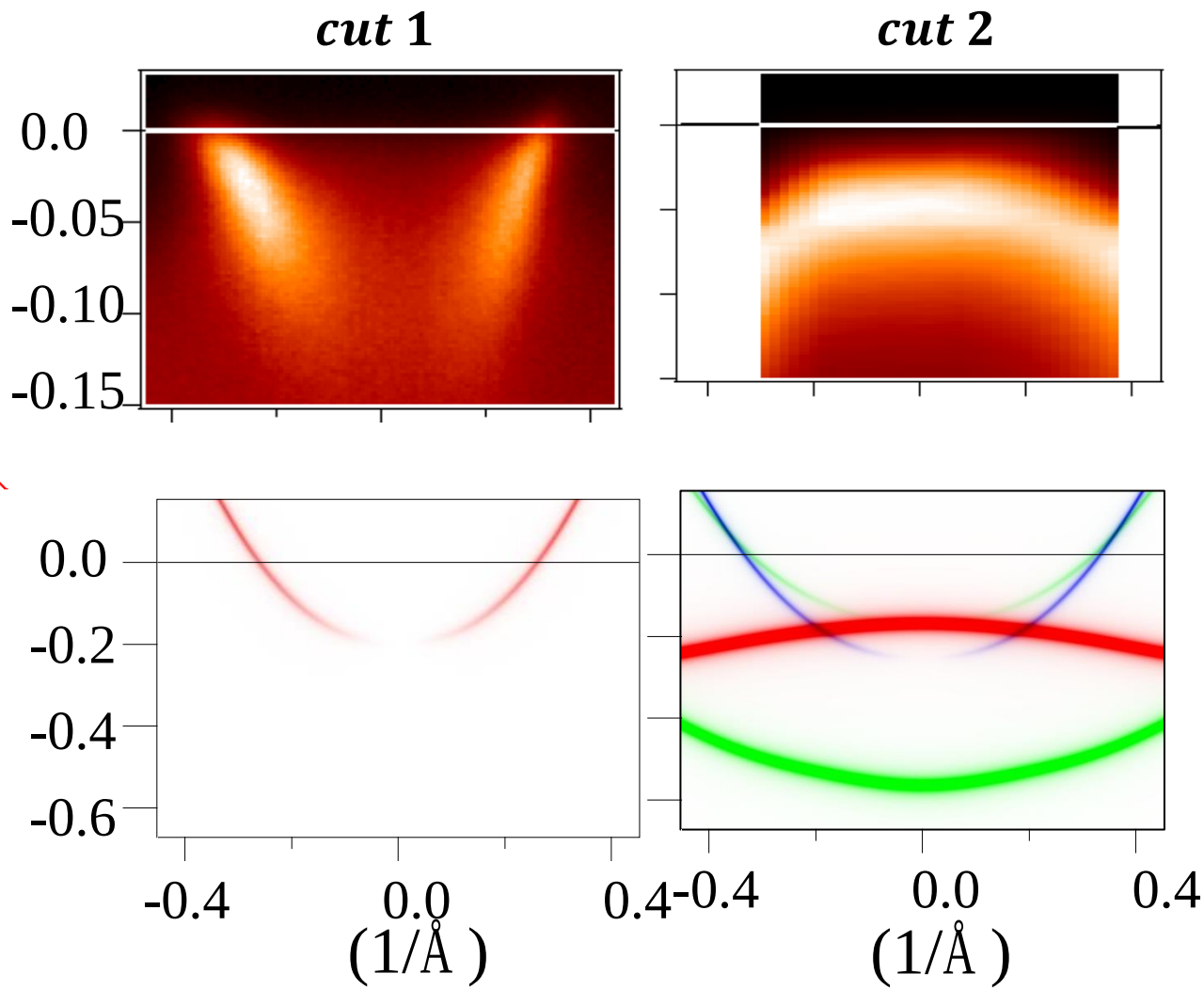
$\tilde{\boldsymbol{p}}$ =pseudo-momentum

Possible Orbital Misinterpretation

$Ba(Fe_{0.92}Co_{0.02})_2As_2$



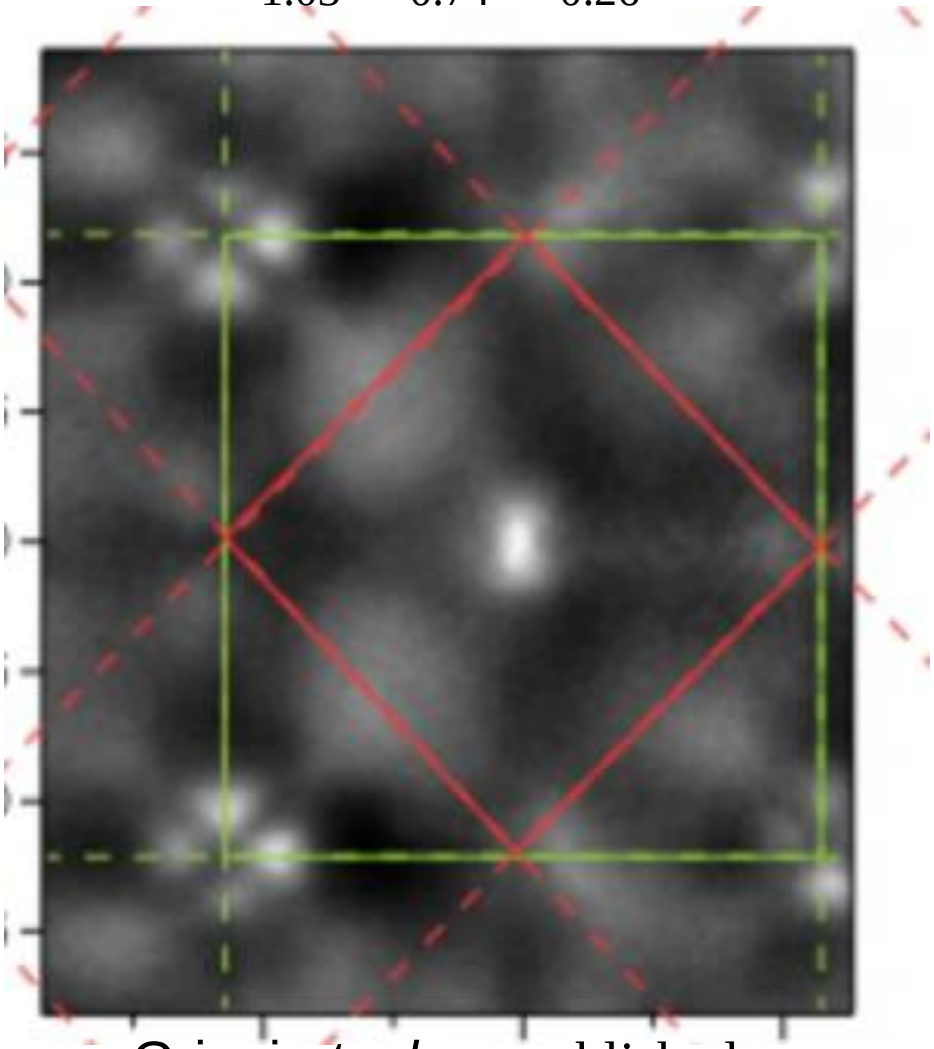




Brouet *et. al.*, PRB 86, 075123 (2012)

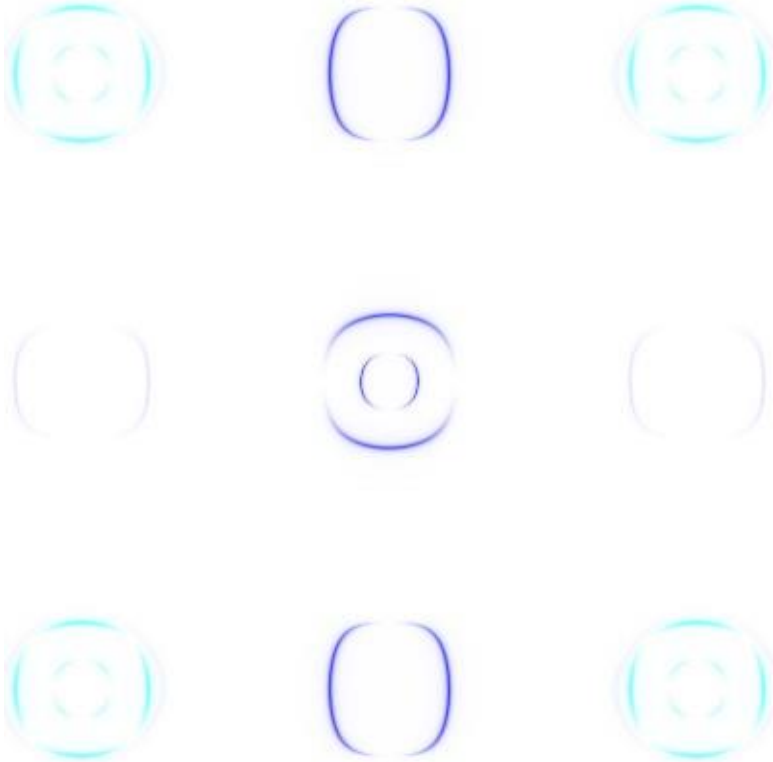
Parity-Switching TSBP

$Fe_{1.03}Te_{0.74}Se_{0.26}$



Grioni *et. al.*, unpublished

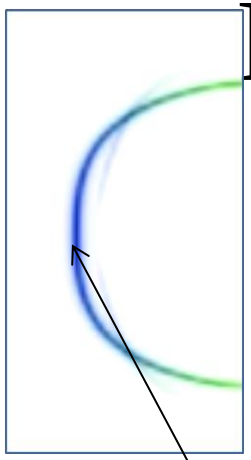
FeTe



d_{z^2} d_{xz}

Weight x 5

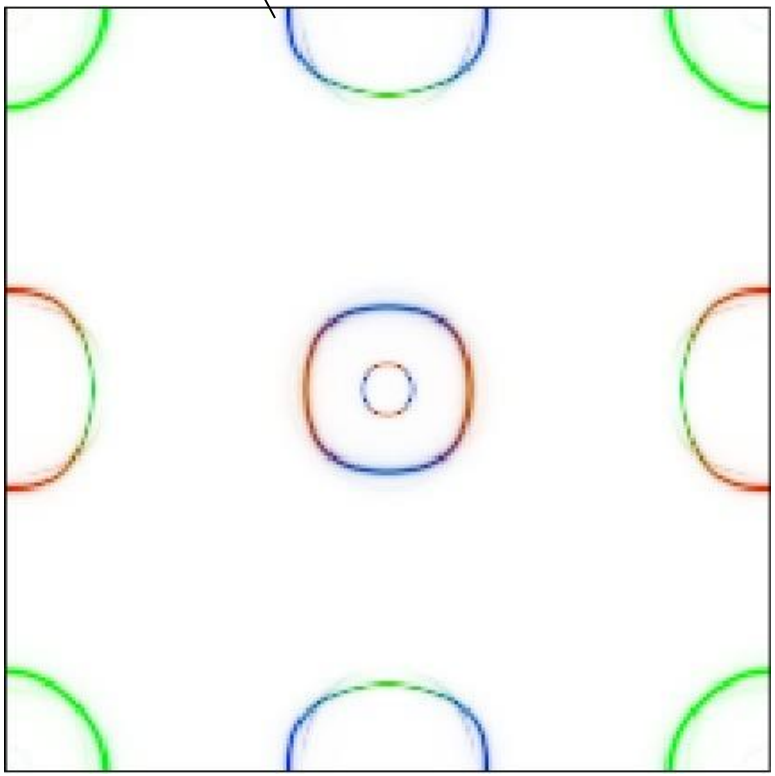
Local Gauge NOT Panacea



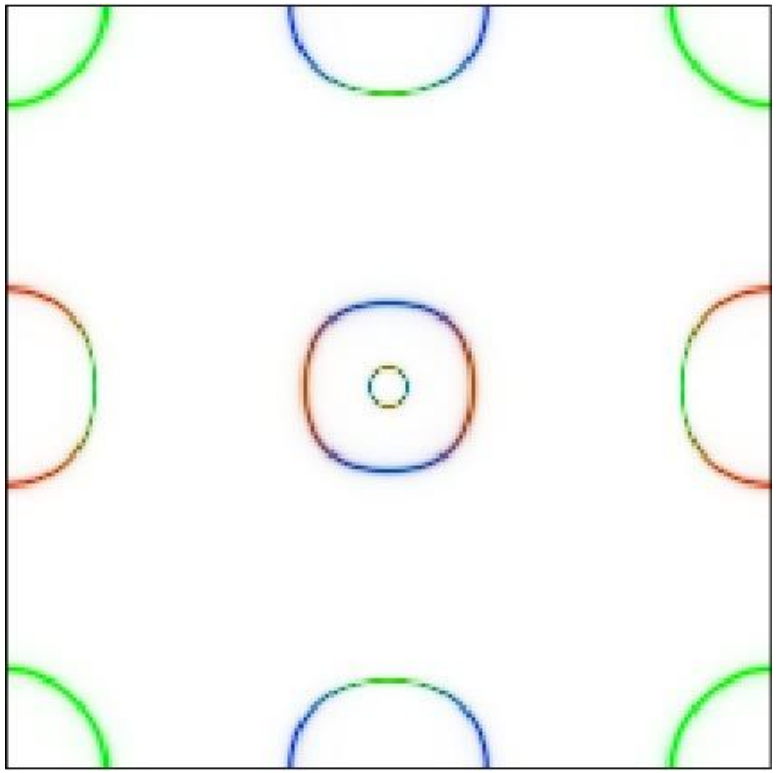
$[P_Z T_x, H_0]$=0; $[P_Z T_y, H_0]$=0; $[T_Z, H_0]$=0

But $[P_z T_x, T_z] \neq 0$!!

$\boldsymbol{k_z} = 0.5\pi$

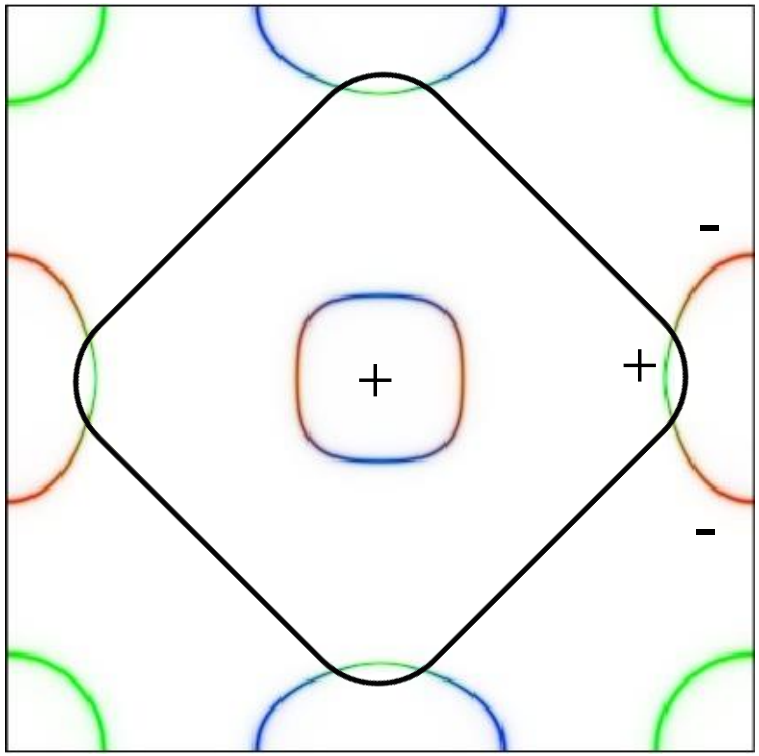


3D effective 5-orb model



Single Gap Structure in Math Space

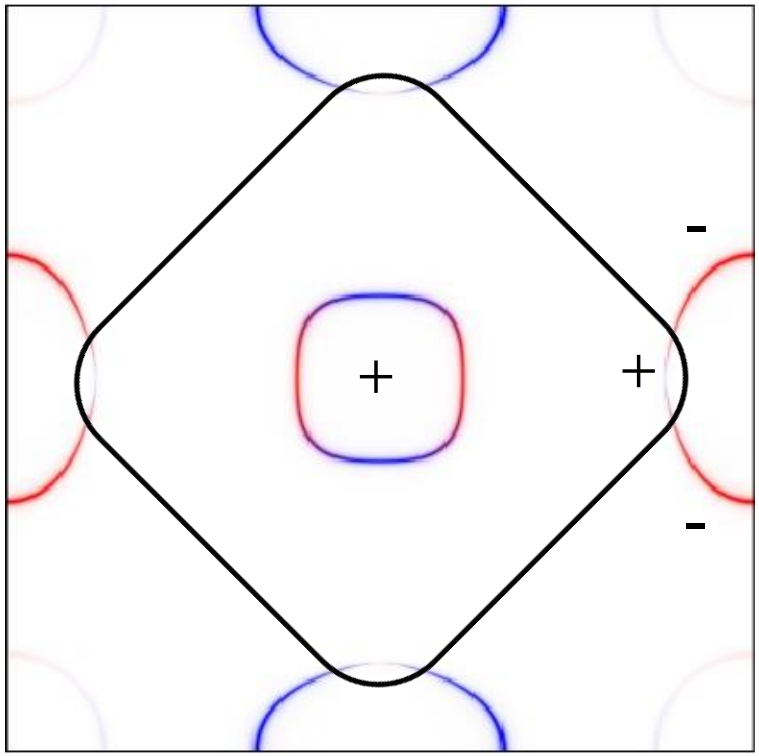
$$\Delta(k) \sim \Delta_{s+-}(\cos k_x \cos k_y) + \Delta_{s++}(\cos k_x + \cos k_y)$$



d_{xz} d_{yz} d_{z^2}, $d_{x^2-y^2}$ and d_{xy}

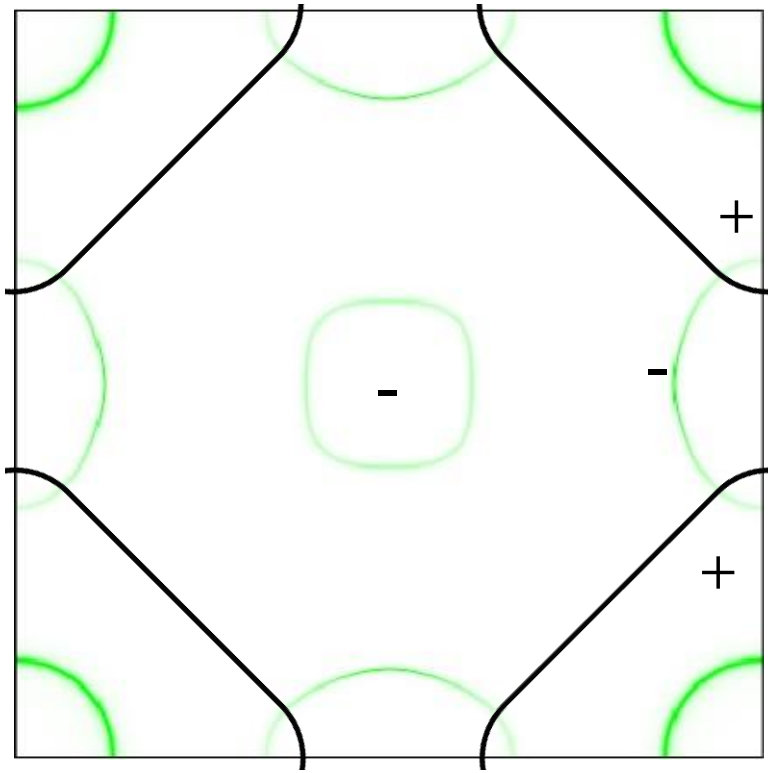
Orbital Parity Selective Nodal Structure

Odd pairty nodal lines



$\Delta(odd, k) \sim \Delta_{s+-}(\cos k_x \cos k_y)$
$+\ \Delta_{s++}(\cos k_x + \cos k_y)$

Even pairty nodal lines



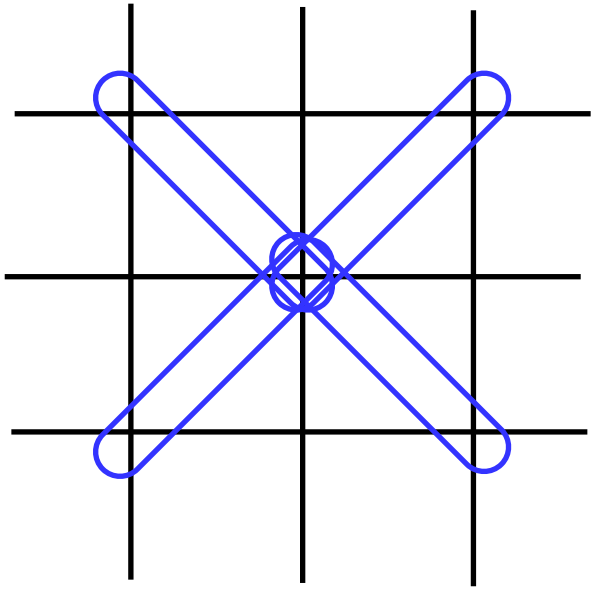
$\Delta(even, k) \sim \Delta_{s+-}(\cos k_x \cos k_y)$
$-\ \Delta_{s++}(\cos k_x + \cos k_y)$

d_{xz} d_{yz} d_{z^2}, $d_{x^2-y^2}$ and d_{xy}

Real Space Pairing

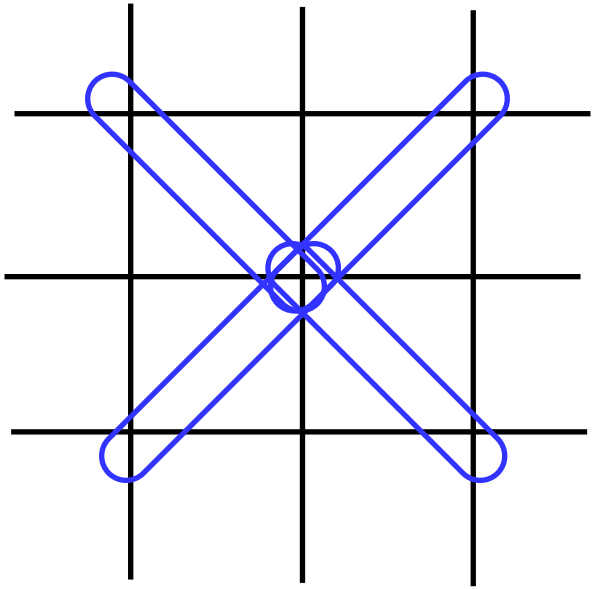
xz/yz

$$\Delta(odd, k) \sim \Delta_{s+-}(\cos k_x \cos k_y)$$



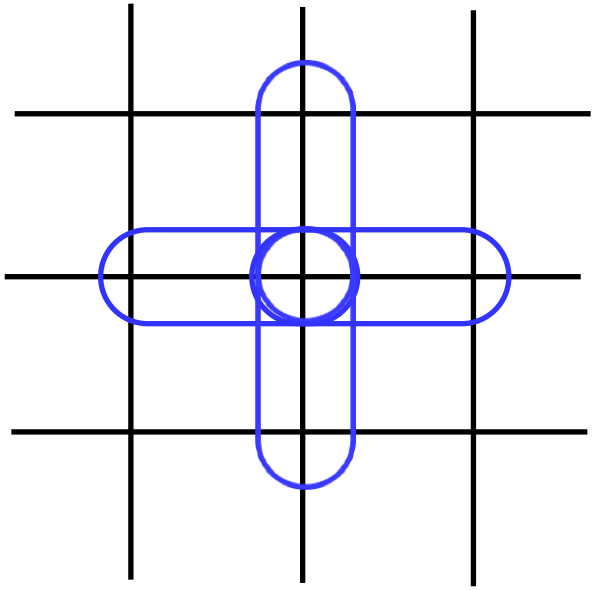
xy

$$\Delta(even, k) \sim \Delta_{s+-}(\cos k_x \cos k_y)$$



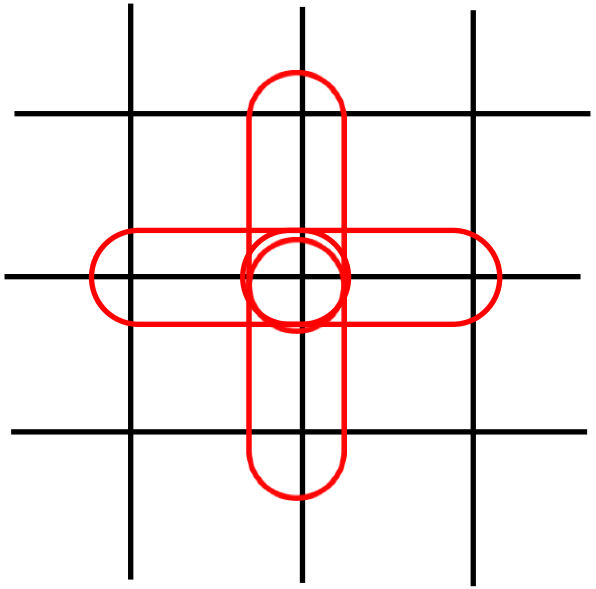
Real Space Pairing

xz/yz



$$\Delta(odd, k) \sim$$
$$+\ \Delta_{s++}(\cos k_x + \cos k_y)$$

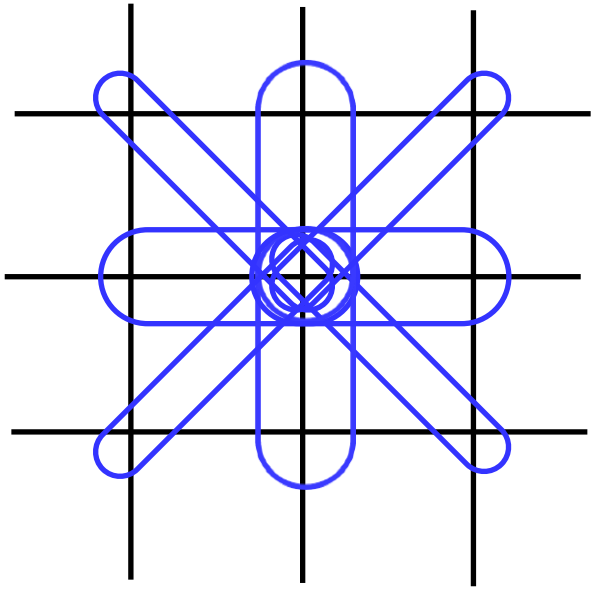
xy



$$\Delta(even, k) \sim$$
$$-\ \Delta_{s++}(\cos k_x + \cos k_y)$$

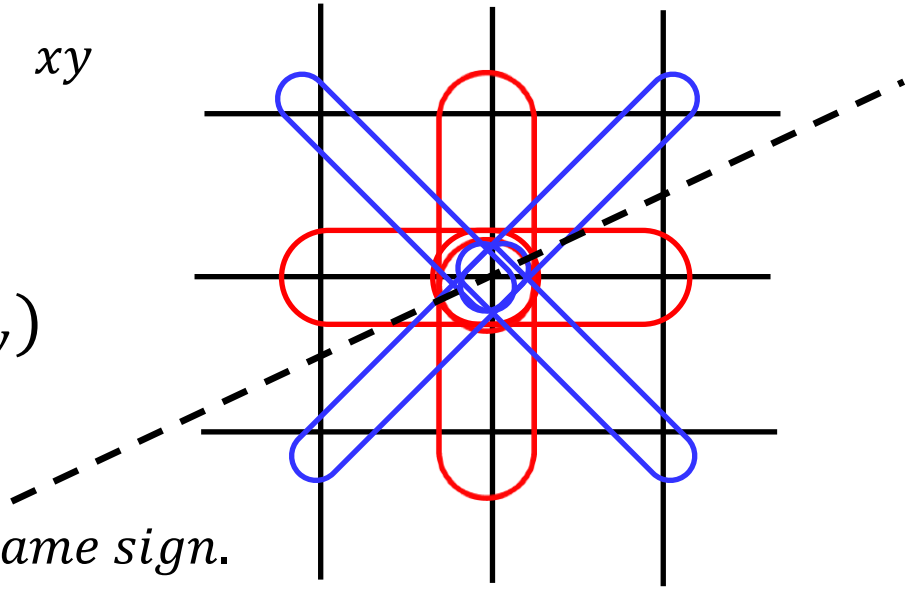
Real Space Pairing

xz/yz



$$\Delta(odd,k) \sim \Delta_{s+-}(\cos k_x \cos k_y) + \Delta_{s++}(\cos k_x + \cos k_y)$$

xy



$$\Delta(even,k) \sim \Delta_{s+-}(\cos k_x \cos k_y) - \Delta_{s++}(\cos k_x + \cos k_y)$$

Nodes if two gaps share the same sign.

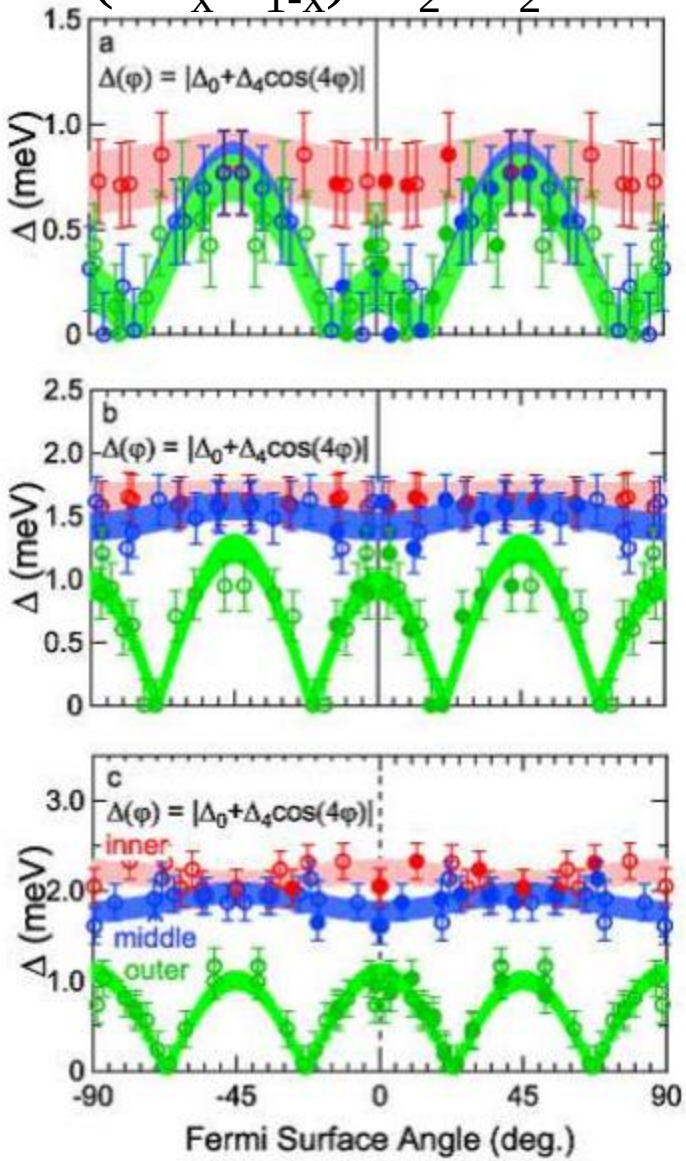
Experiment: ARPES

$(Ba_xK_{1-x})Fe_2As_2$

x=0.07

x=0.12

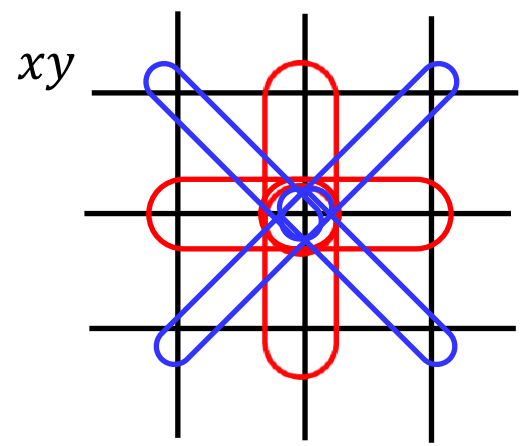
x=0.24



Ota *et. al.*, ArXiv 1307.7922

$$\Delta(odd,k) \sim (-\Delta_{s+-} + \Delta_{s++})\ \cos 4\varphi$$

$$\Delta(even,k) \sim (-\Delta_{s+-} - \Delta_{s++})\ \cos 4\varphi$$



Experiment: ARPES

$(Ba_xK_{1-x})Fe_2As_2$

x=0.07

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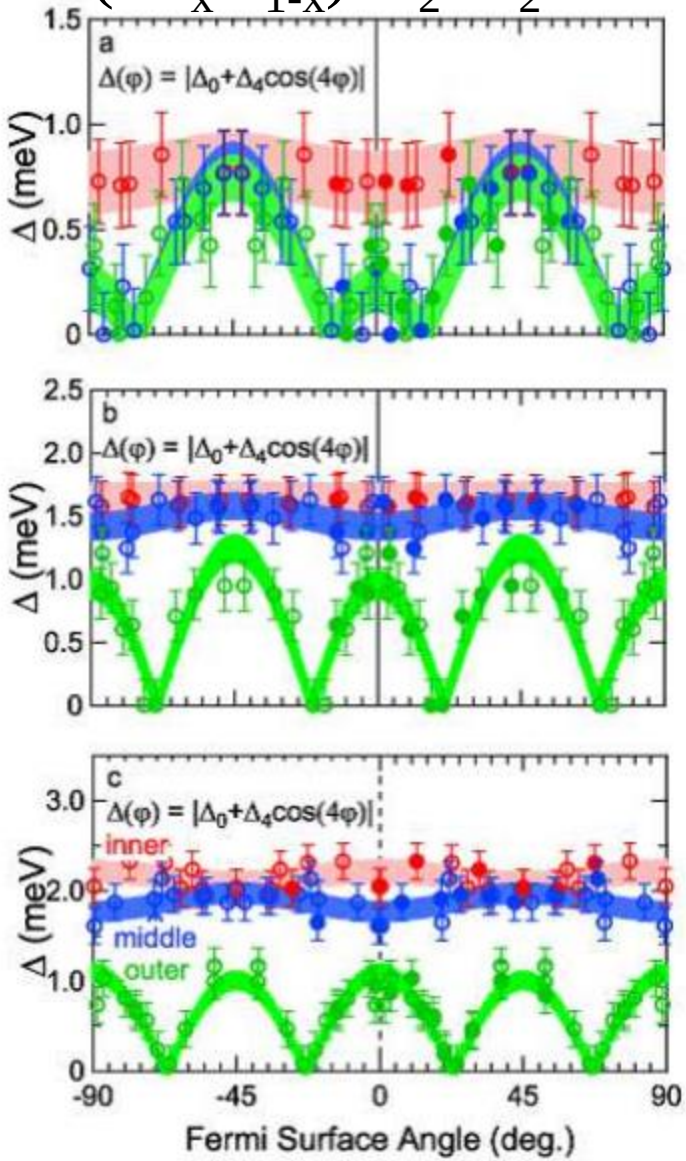
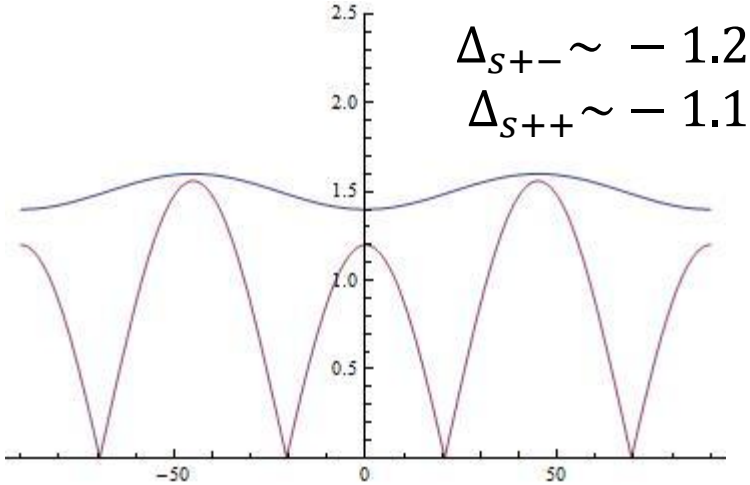


Ota *et. al.*, ArXiv 1307.7922

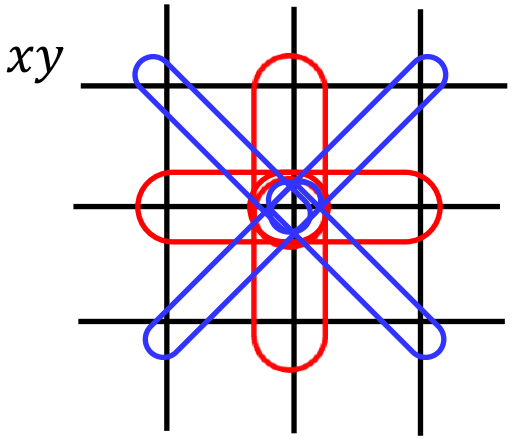


$\Delta_{s+-} \sim -1.2\ meV$

$\Delta_{s++} \sim -1.1\ meV$

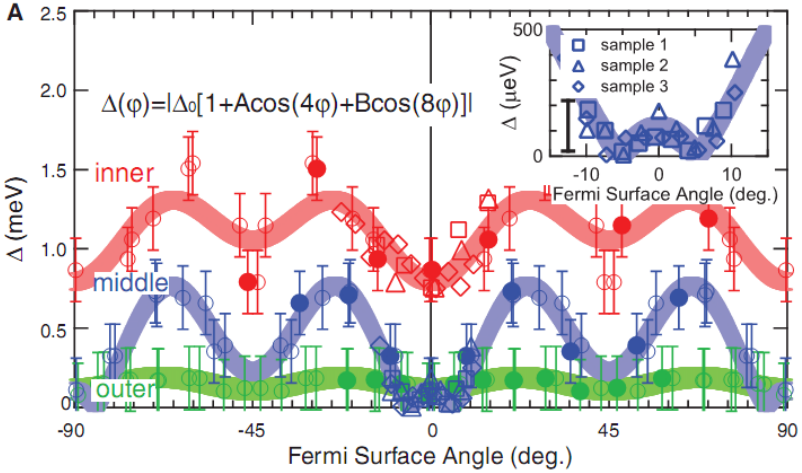
$$\Delta(odd,k) \sim (-\Delta_{s+-} + \Delta_{s++})\ \cos 4\varphi$$

$$\Delta(even,k) \sim (-\Delta_{s+-} - \Delta_{s++})\ \cos 4\varphi$$



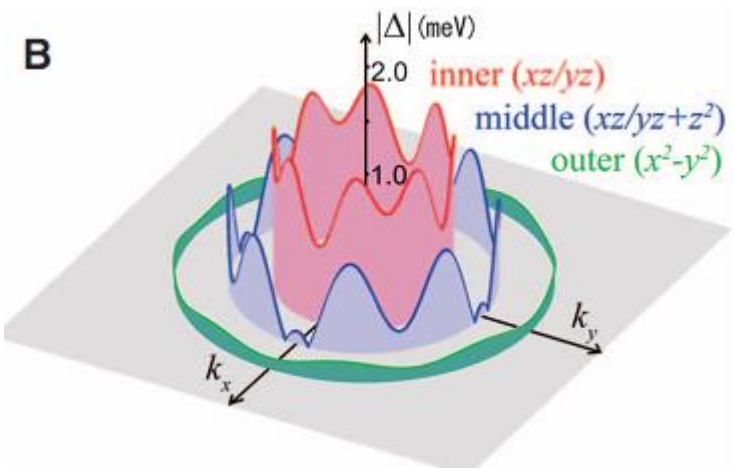
Experiment: ARPES

KFe_2As_2



$$\Delta(odd,k) \sim (-\Delta_{s+-} + \Delta_{s++}) \ \cos 4\varphi$$

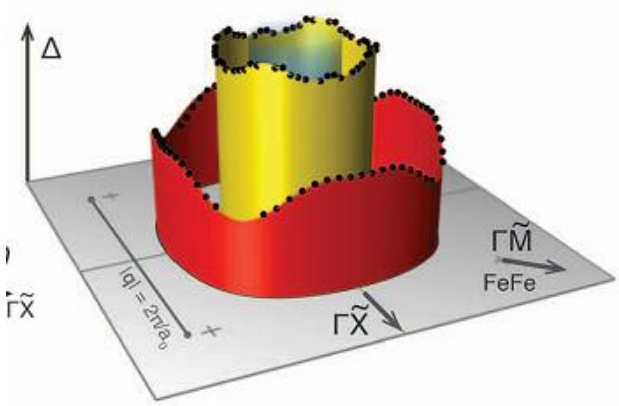
$$\Delta(even,k) \sim (-\Delta_{s+-} - \Delta_{s++}) \ \cos 4\varphi$$



Okazaki *et. al.*, Science 337, 1214 (2012)

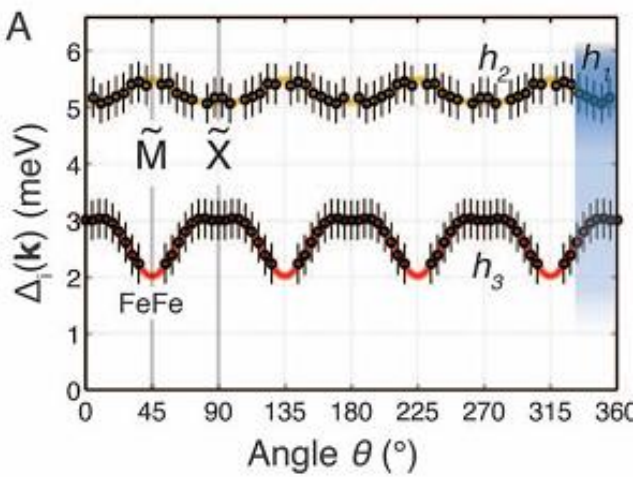
Experiment: STM

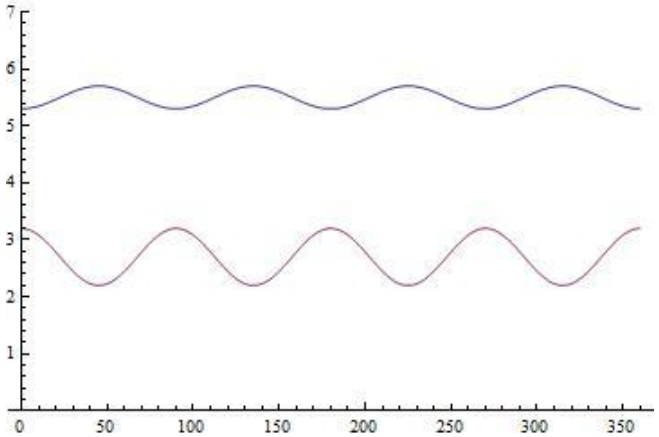
LiFeAs



$$\Delta(odd,k) \sim (-\Delta_{s+-} + \Delta_{s++})\ \cos 4\varphi$$

$$\Delta(even,k) \sim (-\Delta_{s+-} - \Delta_{s++})\ \cos 4\varphi$$



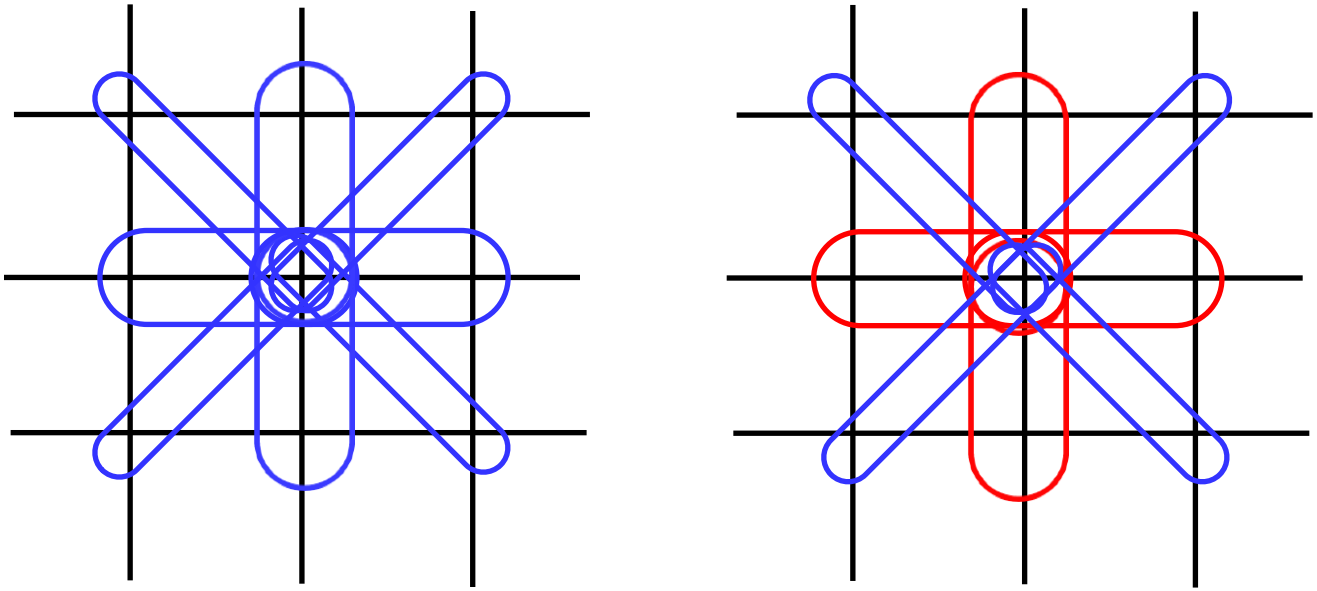


$\Delta_{s+-} \sim 0.4\ meV$
$\Delta_{s++} \sim 0.6\ meV$

Allen *et. al.*, Science 336, 563 (2012)

Conclusion

- Unique TSBP governed by glide symmetry
- Orbital parity selective spectral function
- Orbital parity selective gap structure



PRL 107, 257001 (2011)