A simple effective theory for AF correlated superconductors; Interface high T_c superconductivity

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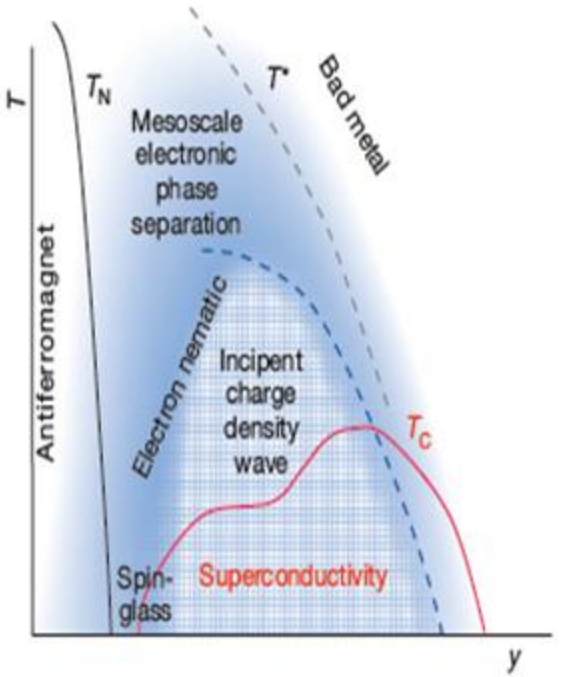
- H. Zhai, F. Wang and D.-H. Lee, PRB 80, 064517 (2009).
- F. Wang and D.-H. Lee, Science,332,200 (2011)
- J.C. Davis and D.-H. Lee, PNAS 110, 17623 (2013).
- J.J Lee et al, Nature accepted.

Antiferromagnetically Correlated Superconductors

Cu-based Superconductors (Cuprates)

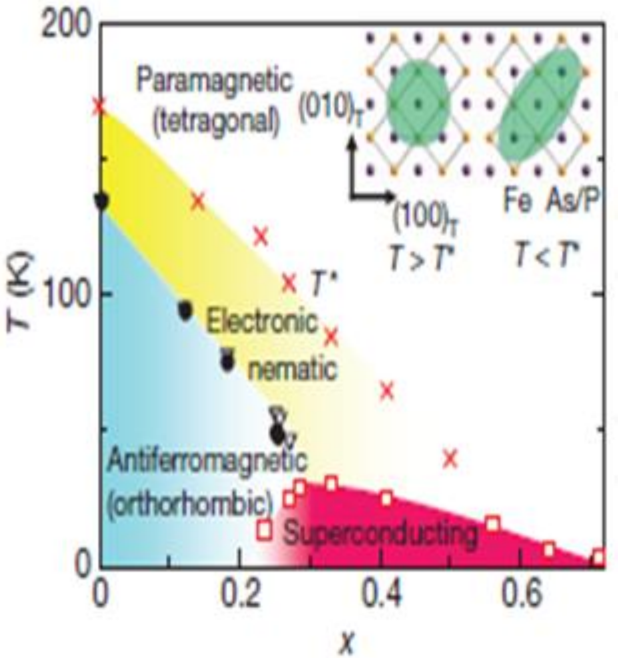
$YBa_2Cu_3O_{6+y}$



Fradkin, Kivelson, Nature Physics 864 (2012)

Fe-based Superconductors

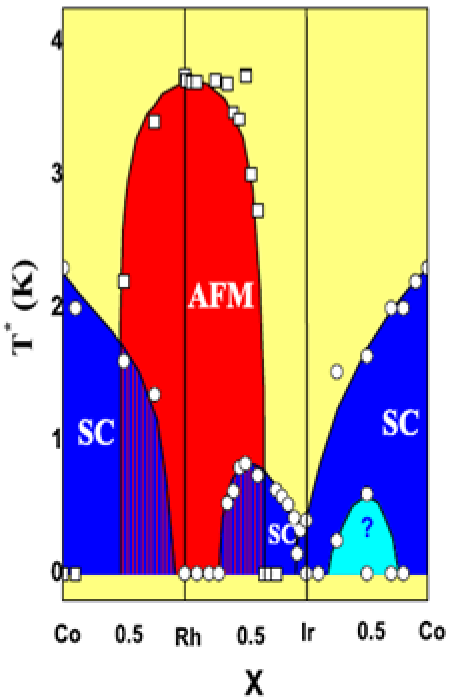
$BaFe_2(As_{1-x}P_x)_2$



Matsuda et al, Nature 486, 382 (2012)

Heavy fermion Superconductors

$CeM_{1-x}M'_xIn_5$



Pagliuso et al, Phys. Rev. B 64, 100503 (2001)

Note the "intertwined" orders.

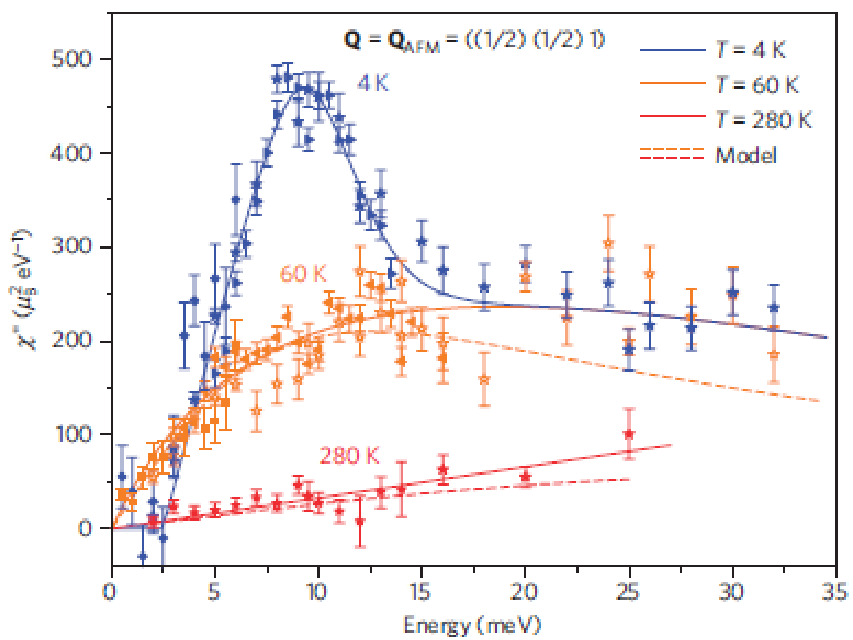
Strong spin fluctuation in the normal state of $Ba(Fe,Co)_2As_2$

LETTERS
PUBLISHED ONLINE: 20 DECEMBER 2009 | DOI: 10.1038/NPHYS1483
nature physics

Normal-state spin dynamics and temperature - dependent spin-resonance energy in optimally doped $BaFe_{1.85}Co_{0.15}As_2$

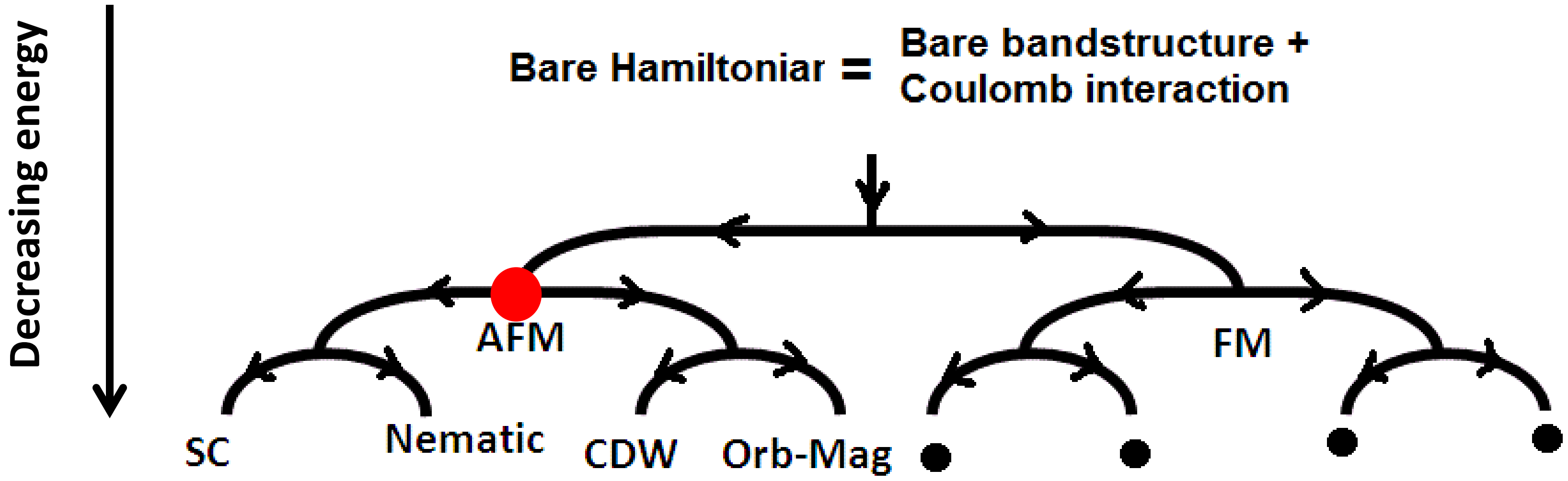
D. S. Inosov[1], J. T. Park[1], P. Bourges[2], D. L. Sun[1], Y. Sidis[2], A. Schneidewind[3,4], K. Hradil[4,5], D. Haug[1], C. T. Lin[1], B. Keimer[1] and V. Hinkov[1]*

The total spectral weight at 60 K, integrated over Q and ω up to 35 meV, is $\chi''_{60\,K} = 0.17\,\mu_B^2$/f.u., and is thus comparable to underdoped $YBa_2Cu_3O_{6+x}$.



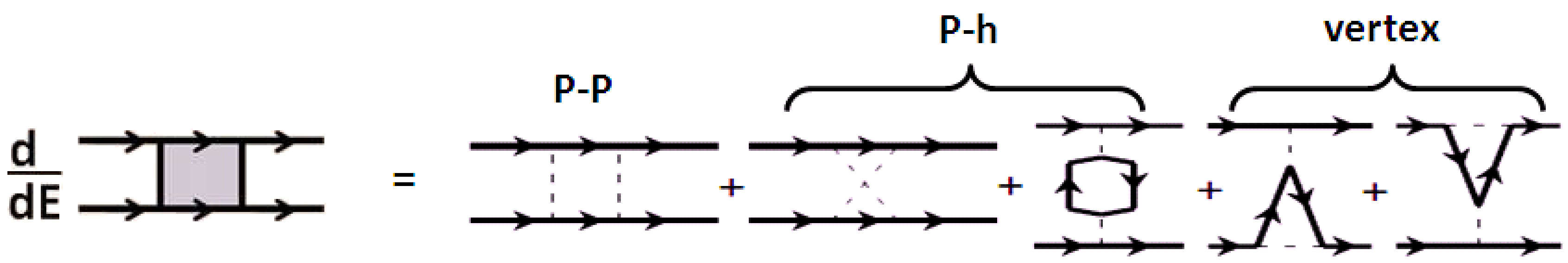
The interaction responsible for Cooper pairing is an effective interaction.

- For strongly correlated systems the evolution of the effective Hamiltonian as a function of energy can go through many unexpected modifications.



Capture the effective Hamiltonian at the energy scale at which bifurcation occurs helps understanding the mechanism for intertwined phases.

In recent years attempts at deriving the effective pairing interaction through perturbative renormalization group calculation have been made.



Copper-based SC

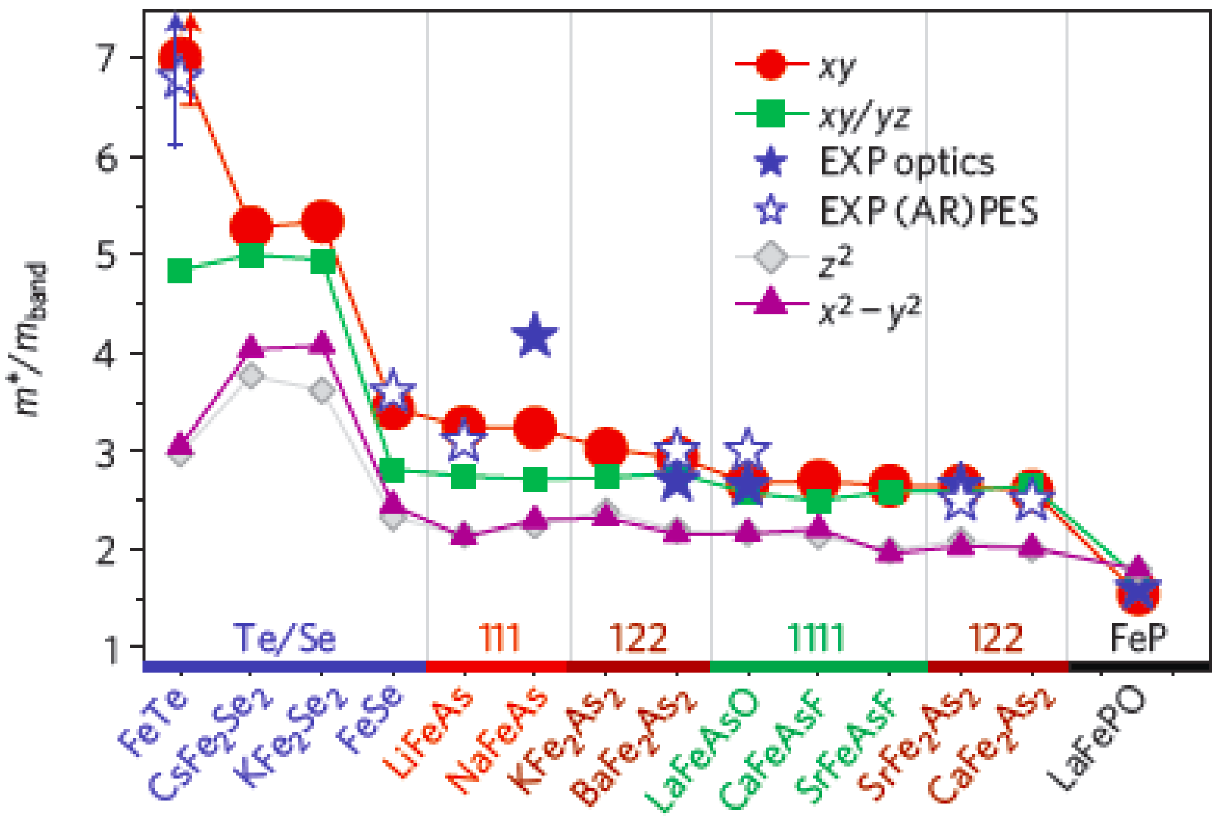
- Honerkamp, Rice *et al*, PRB 63, 035109 (2001).

Iron-based SC

- F. Wang et al, PRL 102,047005 (2009); H. Zhai *et al*, PRB 80, 064517 (2009); F. Wang and Lee, Science 332, 200 (2011).
  R. Thomale et al, Phys. Rev. B 80, 180505 (2009).

*A derivation of the effective interaction valid for strong coupling is lacking.

DFT+DMFT results for the correlation strength in Fe-based superconductors



Yin, Haule, Kotliar, Nature Materials 10, 932 (2011)

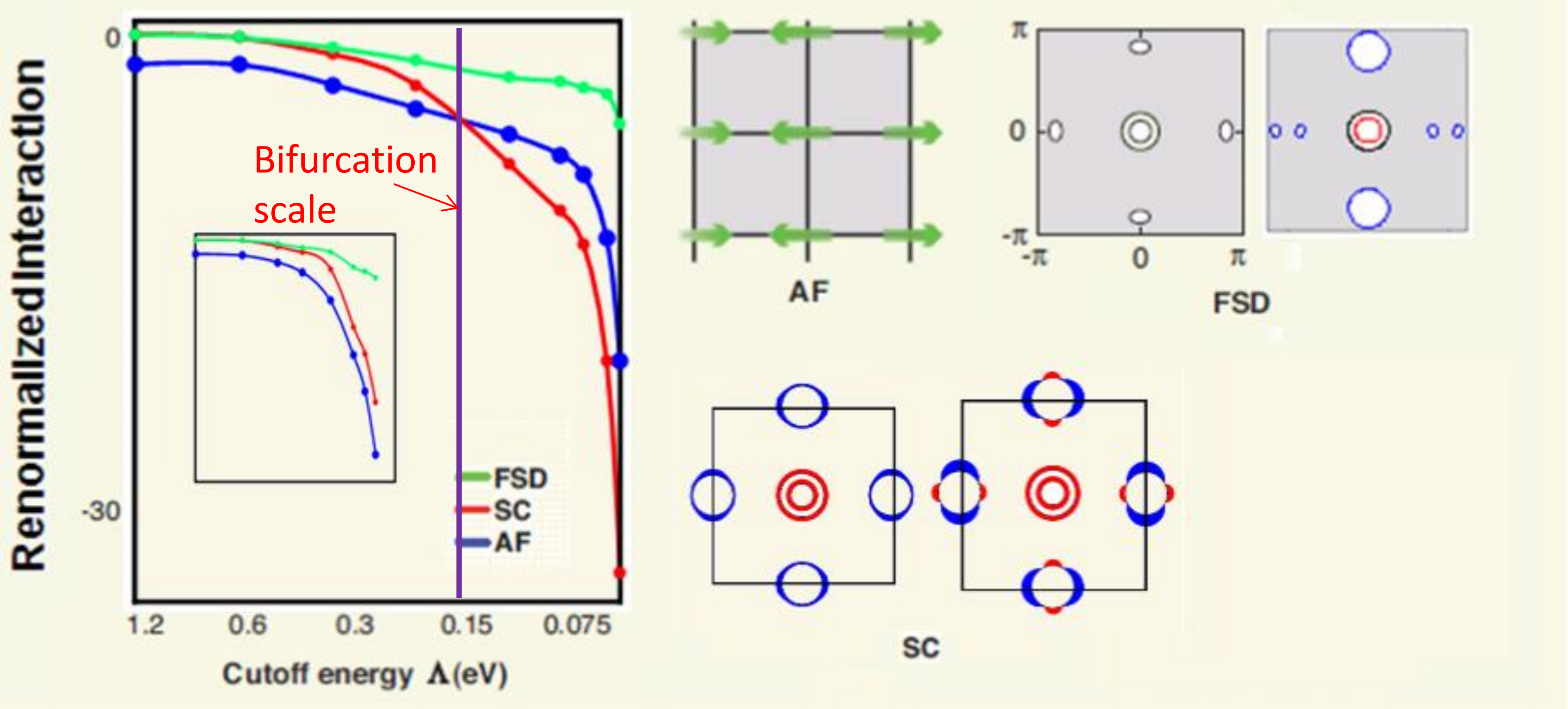
Strong correlation : Q. M. Si, E. Abrahams, Phys. Rev. Lett. 101, 076401 (2008).

Functional RG results

F. Wang et al, arXiv 0805.3343 (May 2008)
F. Wang et al, PRL 102,047005 (2009)
H. Zhai et al, Phys. Rev. B 80, 064517 (2009).
F. Wang and DHL, Science, 332, 200 (2011).

H= bandstructure + Hubbard Hunds model   U=4eV, V=2 eV, J=0.7 eV.

Three leading instabilities



Strong correlation

A variational Monte-Carlo study using partially projected WF

$$|\psi\rangle = g_1^{\hat{N}_1} g_2^{\hat{N}_2} \hat{P}_{N_e} |\psi_{MF}\rangle,$$

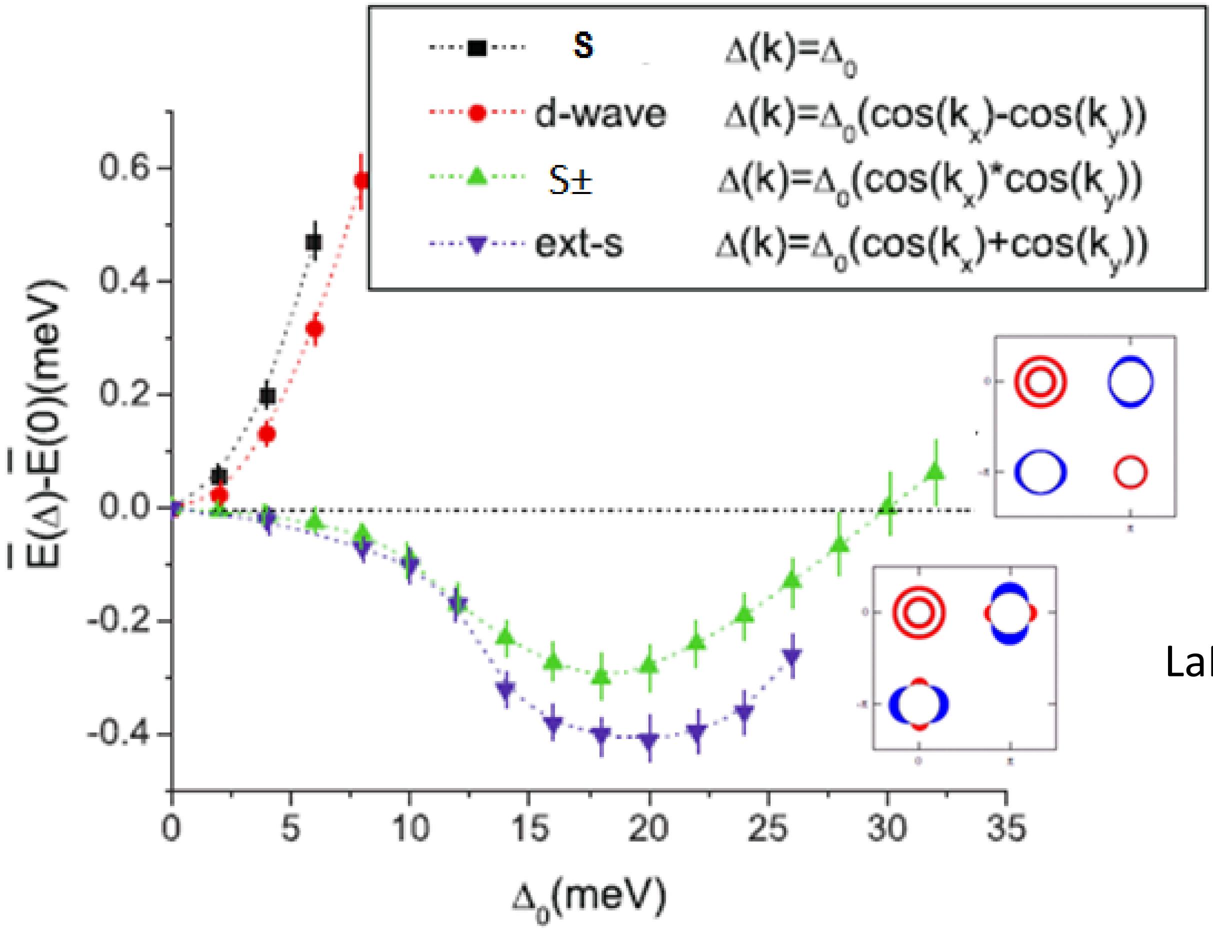
where

$$\hat{N}_1 = \sum_{i,\mu} \hat{n}_{i\mu\uparrow} \hat{n}_{i\mu\downarrow}, \quad \hat{N}_2 = \sum_{i,\mu<\nu} \hat{n}_{i\mu} \hat{n}_{i\nu}.$$

F. Yang et al, PRB 83, 134502 (2011)

Cooper pairing

Band structure + Hubbard Hunds model U=4eV, V=2 eV, J=0.7 eV.

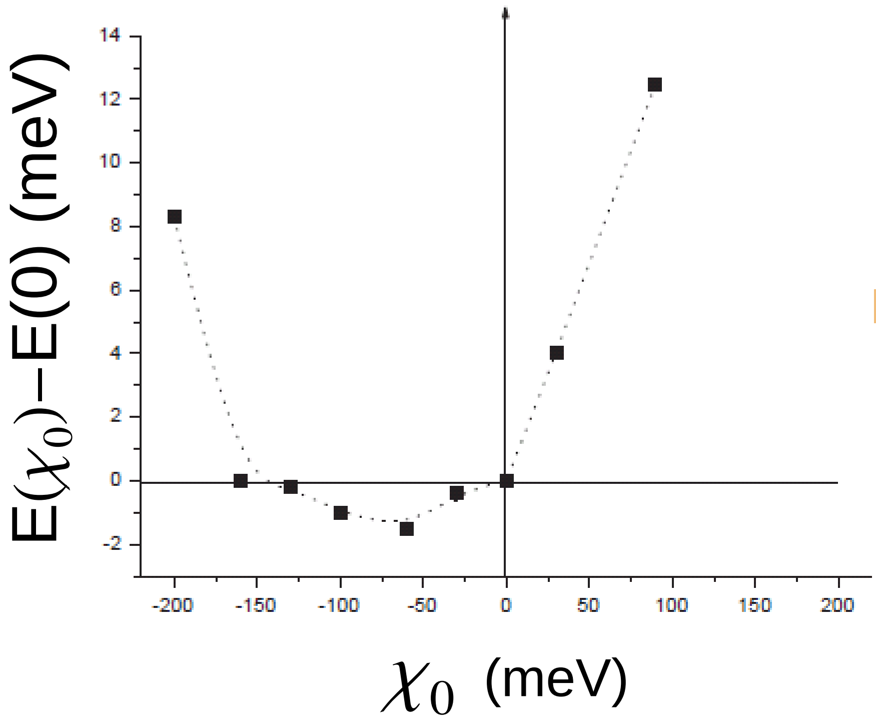


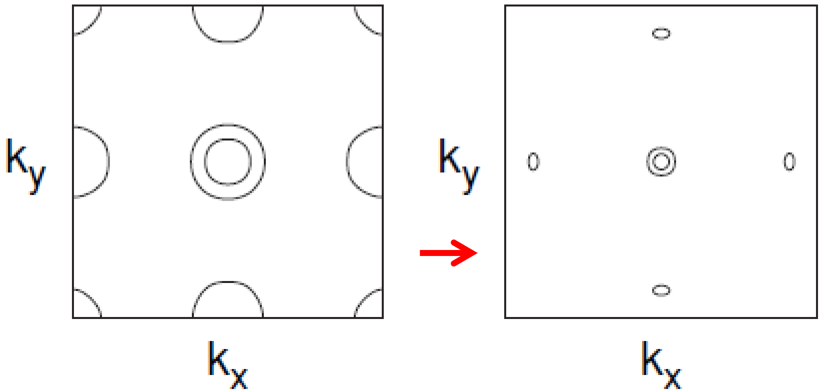
Fe(Se,Te)

LaFePO

Fermi surface distortion

$$H_{MF} = \sum_{\mathbf{k}\alpha\sigma} (\varepsilon^{\alpha}_{\mathbf{k}} + \chi(\mathbf{k})) n_{\mathbf{k}\alpha\sigma} \qquad \chi(\mathbf{k}) = \chi_0 \cos k_x \cos k_y$$

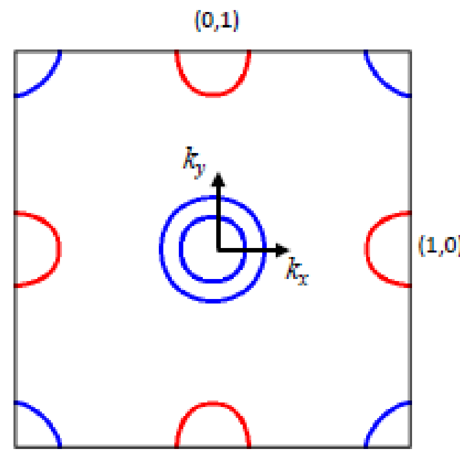


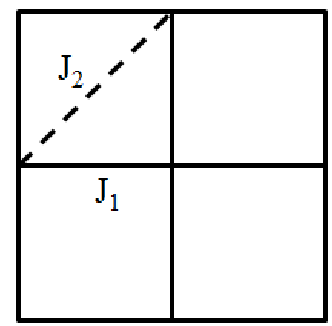


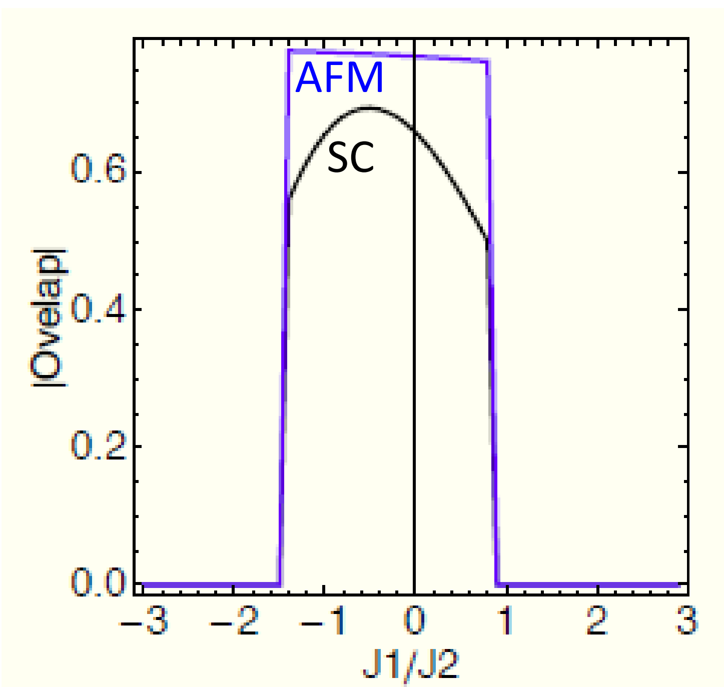
F. Yang et al, PRB 83, 134502 (2011)

A hint at the effective interaction

$$H_{eff} = \boxed{\sum_{\mathbf{k}}{}' \sum_{s} \epsilon(\mathbf{k}) n_s(\mathbf{k})} + \boxed{\sum_{i,j} J_{ij} \mathbf{S}_i \cdot \mathbf{S}_j}$$





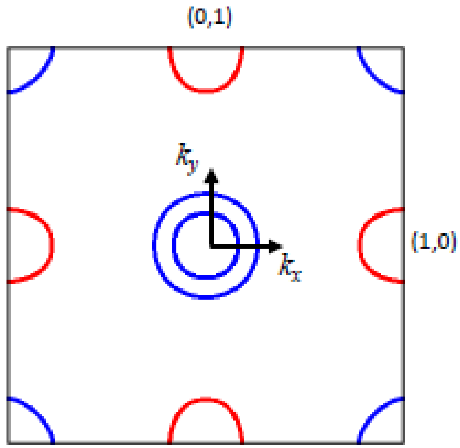


Overlap= the overlap between the FRG order parameters for AFM and SC with those of the effective Hamiltonian

H. Zhai et al, Phys. Rev. B 80, 064517 (2009)

Consequences of the effective Hamiltonian

$$H_{eff} = \sum_{\mathbf{k}}{}' \sum_{s} \epsilon(\mathbf{k}) n_s(\mathbf{k}) + \sum_{i,j} J_{ij} \mathbf{S}_i \cdot \mathbf{S}_j$$

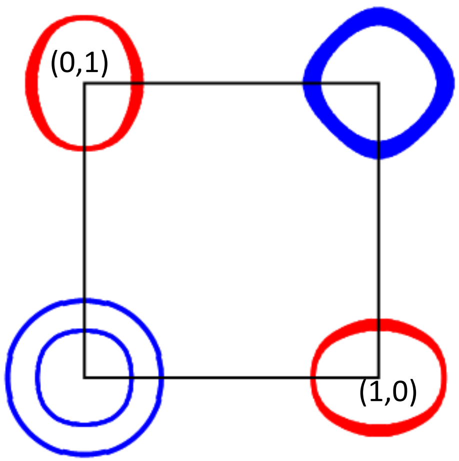


Iron-based SC

JC Davis and DHL, PNAS 110, 17623 (2013).

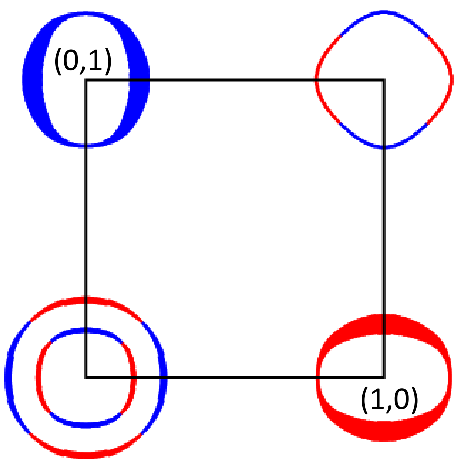
1. Cooper pairing

Leading order parameter



Symmetry : S±

Sub-leading order parameter



Symmetry : d-wave

S. Graser et al, New J. Phys. 11, 025016 (2009)

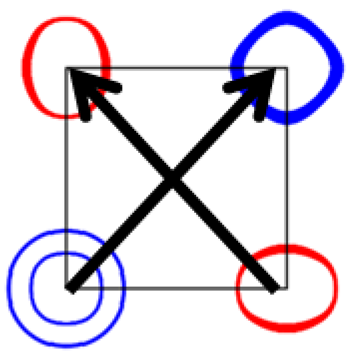
J. Hu and H. Ding, Scientific Reports, 2, 381 (2012)

JC Davis and DHL, PNAS 110, 17623 (2013).

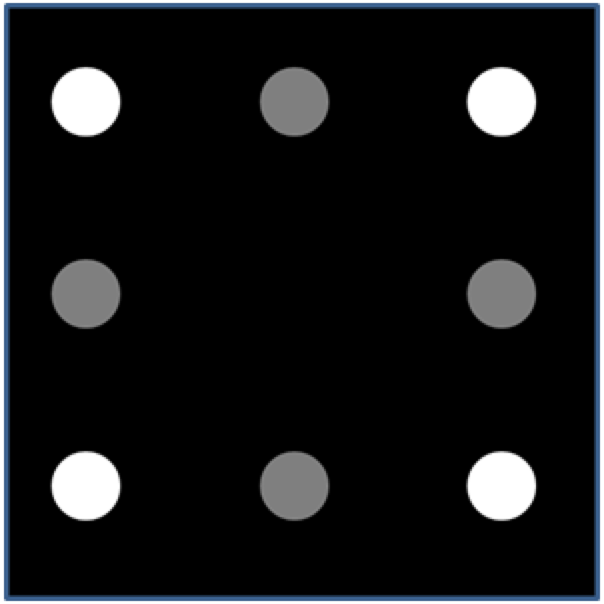
F. Wang, H. Zhai, and D.-H. Lee, EuroPhys. Lett. **85**, 37005 (2009).

Y.Y. Zhang et al, Phys. Rev. B **80**, 094528 (2009).

If impurity scattering is *particle-number conserving*;
H=0 time reversal invariant,
H>0 additional non-time reversal breaking terms contributes.



magnetic scattering



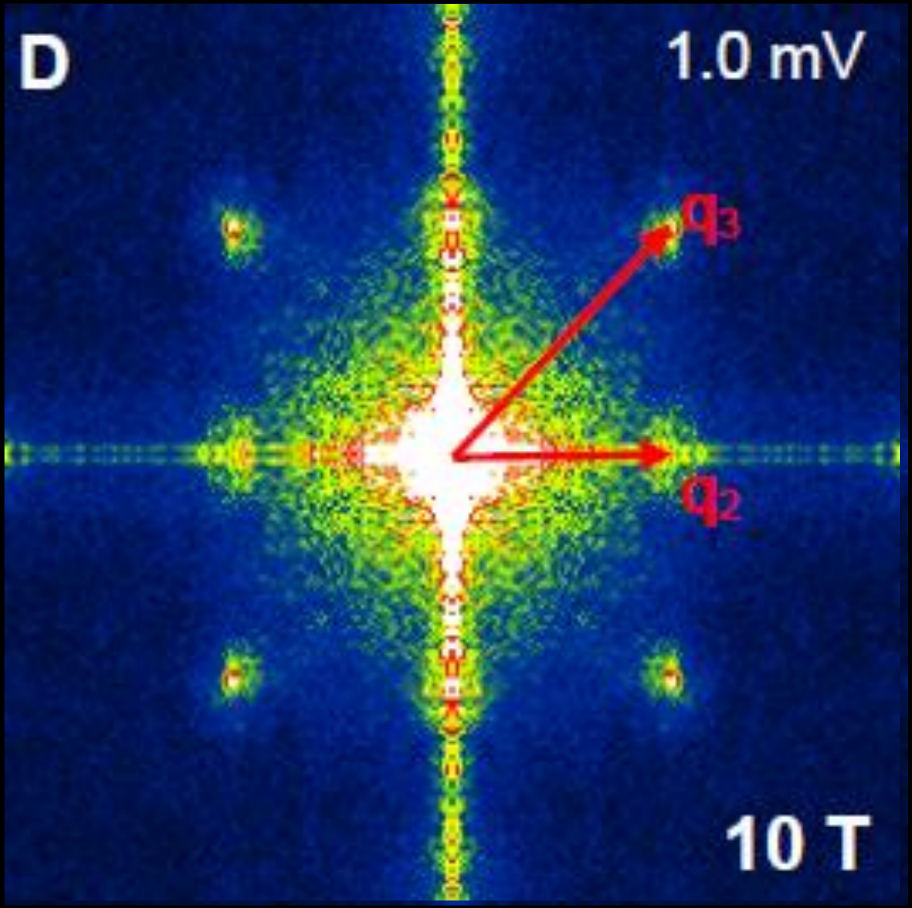
SI-STM on $Fe_{1+x}(Se,Te)$

T_c ~ 13 K

T ~ 1.6 K

$dI/dV_{+E}/dI/dV|_{-E}$

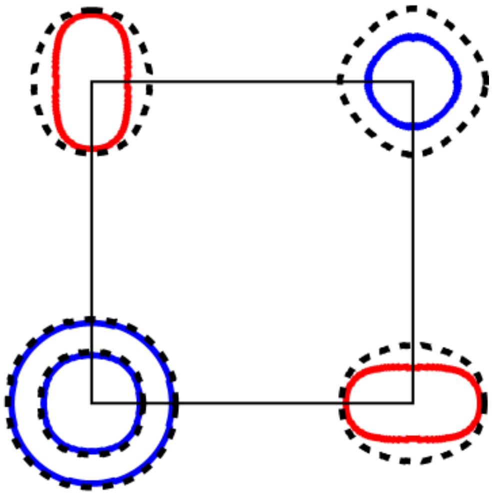
34 nm × 34 nm, -20 mV/0.1 nA



Hanaguri et al, *Science* **328**,474 (2010)

2. **Q**=0 Fermi surface instability

Leading order parameter



Symmetry : S-wave

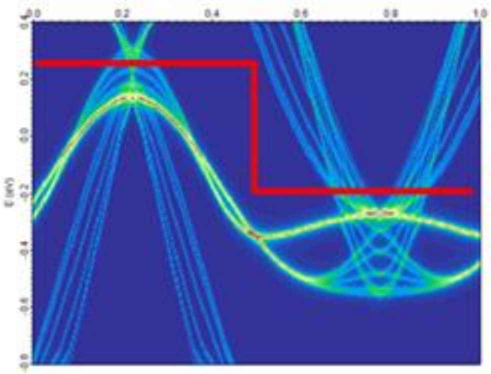
No symmetry breaking

Net effect transfer of electrons from electron pockets to hole pockets → Relative shift in the electron and hole bands.

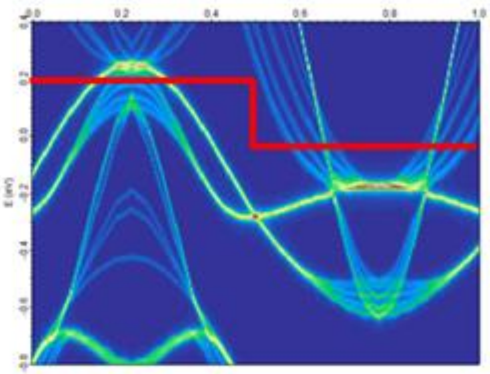
JC Davis and DHL, PNAS 110, 17623 (2013).

A relative shift is necessary to make the theory band structure similar to the ARPES data

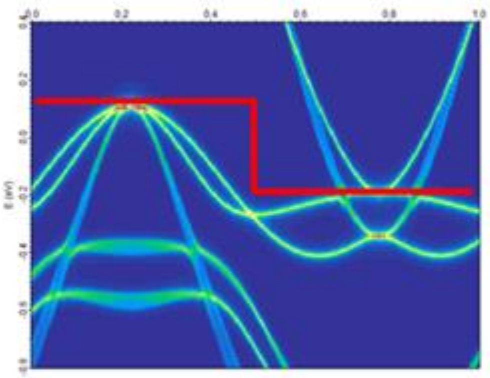
11



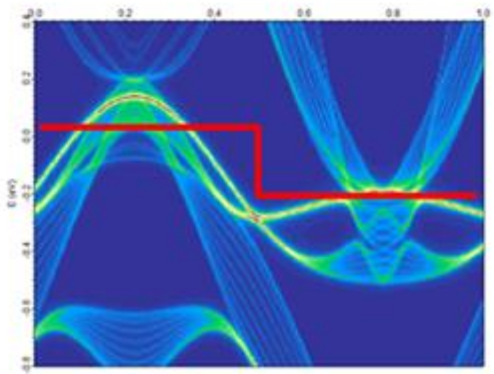
111



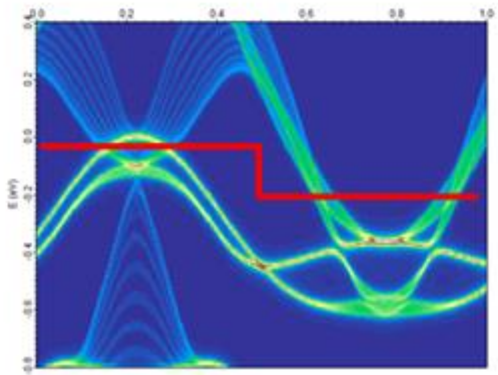
1111



122



245(122)

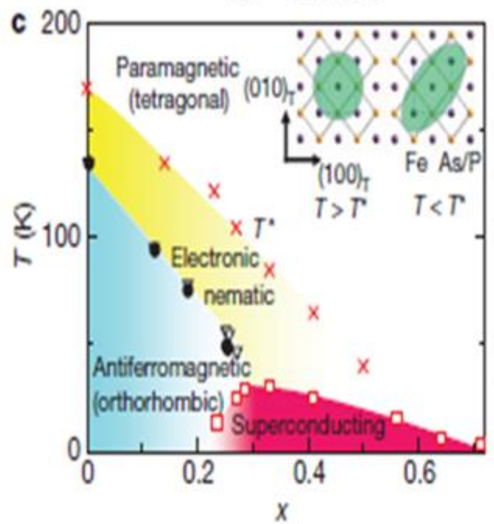


Curtsey of S.V. Borisenko

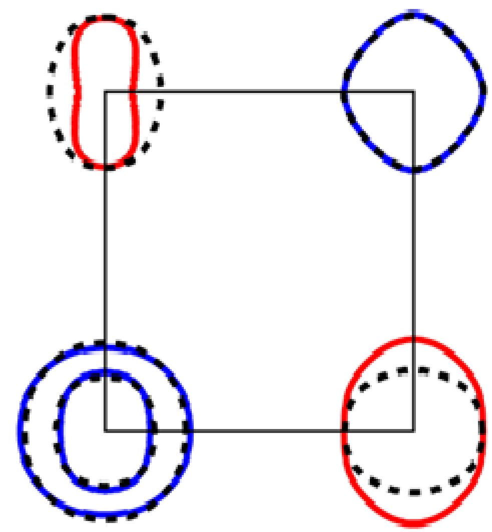
2. **Q**=0 Pomeranchuk instability

- Chuang, T. M.*et al*. ,Science 327, 181–184 (2010).
- Chu, J-H.*et al*. Science 329, 824–826 (2010).
- Yi, M.*et al*. Proc. Natl Acad. Sci. USA 108, 6878–6883 (2011).
- Matsuda et al, Nature 486, 382 (2012).

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



Sub-leading order parameter



Symmetry : Break C_4 -> nematic order

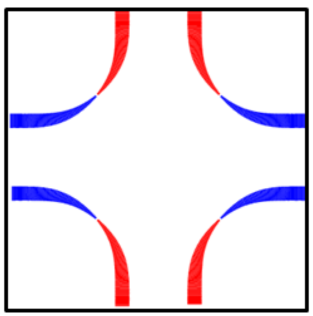
Couple to spin nematicity.

JC Davis and DHL, PNAS 110, 17623 (2013).

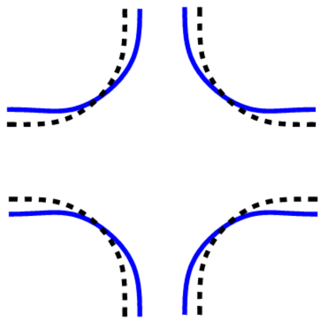
A nearest neighbor AF exchange interaction also can accounts for the instabilities lurking around in the cuprates.

JC Davis and DHL, PNAS 110, 17623 (2013).

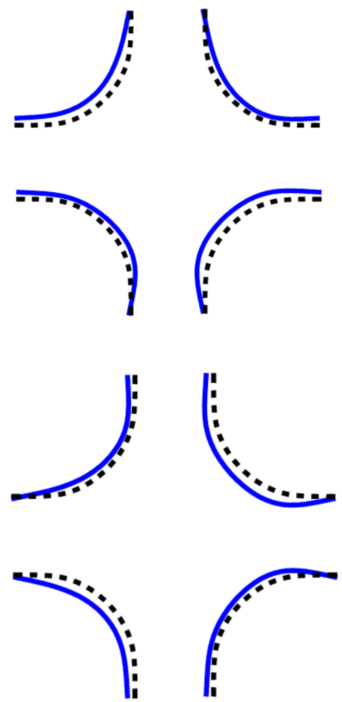
Cooper Pairing



Fermi surface instabilities

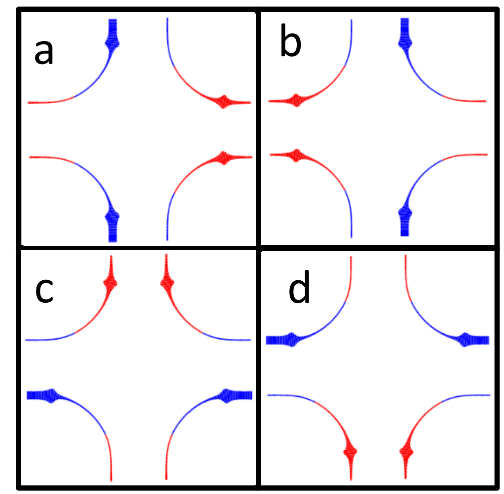


Leading



Sub-leading
Break T

Charge density wave



$\mathbf{Q}=(\pm\delta, 0), \quad (0,\pm\delta)$

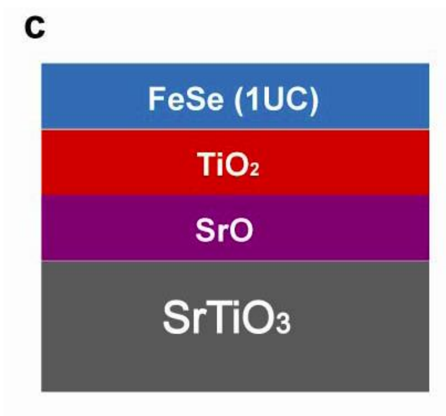
$$\Delta_{-Q}(\mathrm{k}) = \Delta_{Q}(\mathrm{k}-\mathbf{Q})^*$$

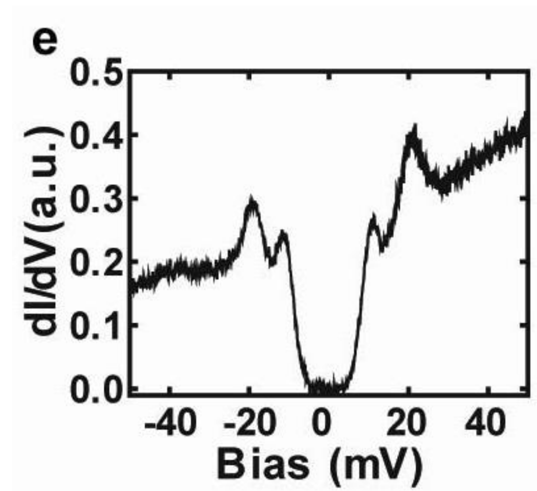
Interface high T_c superconductivity

CHIN. PHYS. LETT. Vol. 29, No. 3 (2012) 037402

Interface-Induced High-Temperature Superconductivity in Single Unit-Cell FeSe Films on $SrTiO_3$ *

WANG Qing-Yan(王庆艳)[1,2†], LI Zhi(李志)[2†], ZHANG Wen-Hao(张文号)[1†], ZHANG Zuo-Cheng(张祚成)[1†], ZHANG Jin-Song(张金松)[1], LI Wei(李渭)[1], DING Hao(丁浩)[1], OU Yun-Bo(欧云波)[2], DENG Peng(邓鹏)[1], CHANG Kai(常凯)[1], WEN Jing(文竞)[1], SONG Can-Li(宋灿立)[1], HE Ke(何珂)[2], JIA Jin-Feng(贾金锋)[1], JI Shuai-Hua(季帅华)[1], WANG Ya-Yu(王亚愚)[1], WANG Li-Li(王立莉)[2], CHEN Xi(陈曦)[1], MA Xu-Cun(马旭村)[2**], XUE Qi-Kun(薛其坤)[1**]



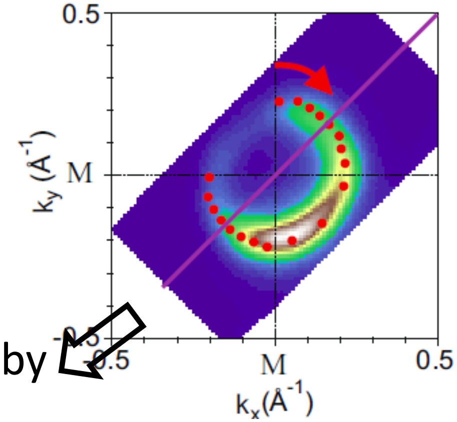


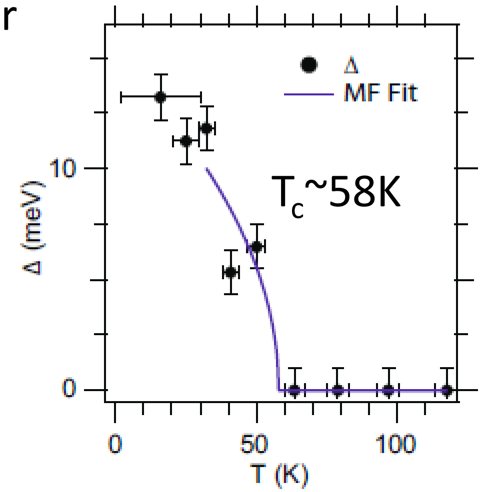
- Liu, D. *et al. Nat. Commun.* **3,** 931 (2012).
- Tan, S. *et al. Nat. Mater.* **12,** 634–640 (2013).
- He, S. *et al. Nat. Mater.* **12,** 605–610 (2013).

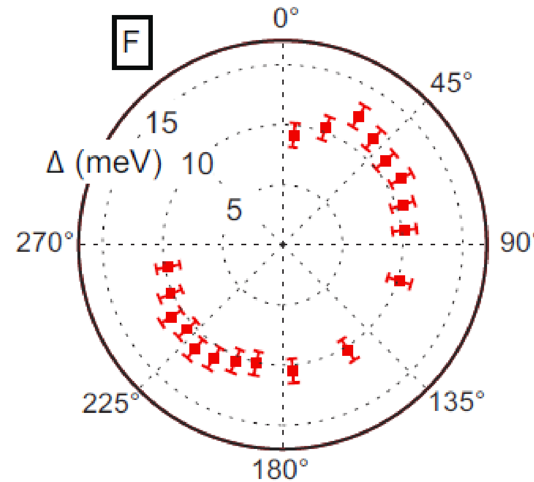
To date, highest ARPES gap opening temperature ~ 75K

J.J Lee et al, Nature accepted.

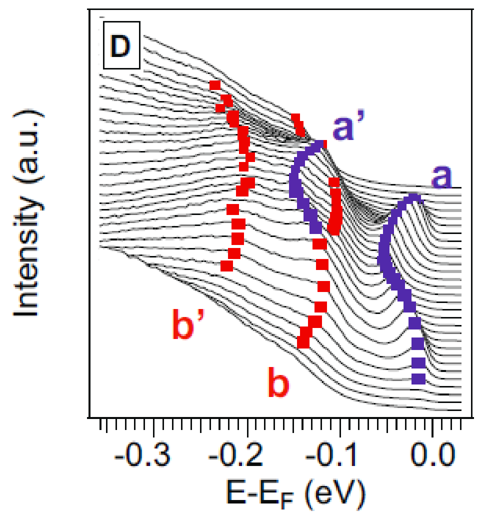
Only electron pockets around zone corner

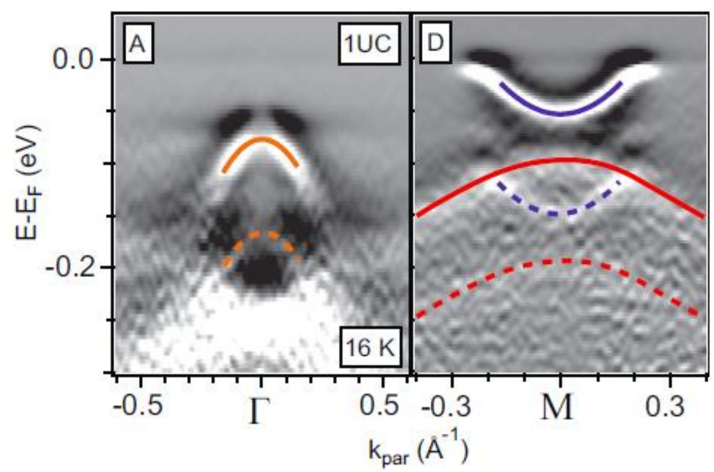




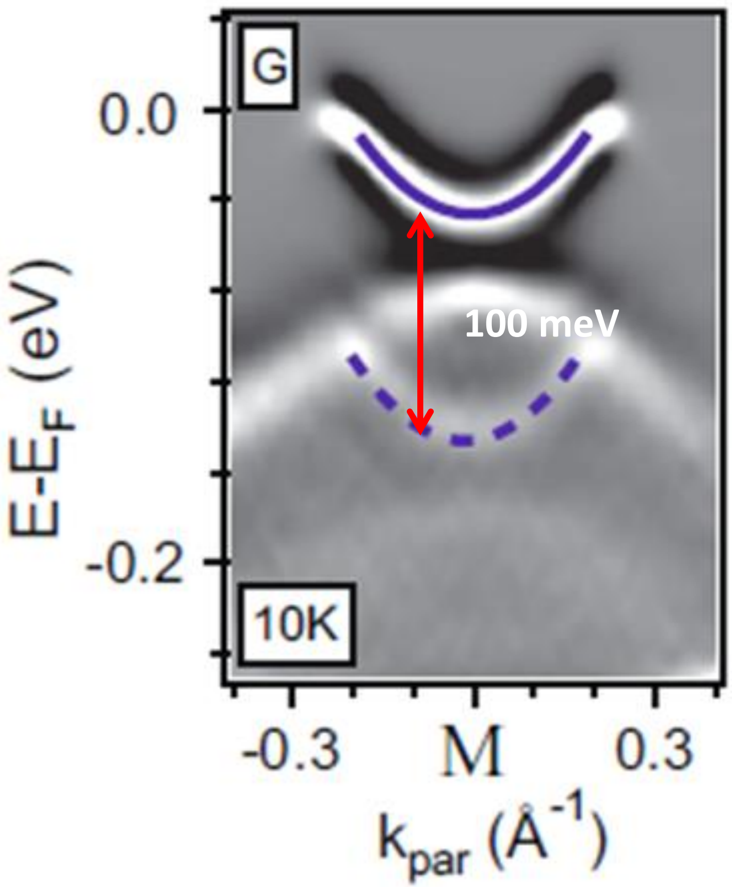


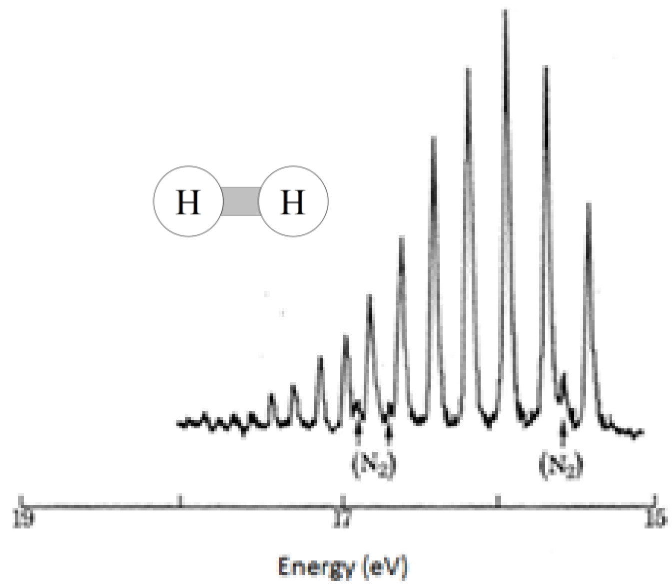
Electron doped by the substrate





- Only 1 UC film show replica band.
- Only one unit cell film shows energy gap.
- Films with ≥ 2UC thickness has nearly bulk FeSe bandstructure. (no charge transfer).





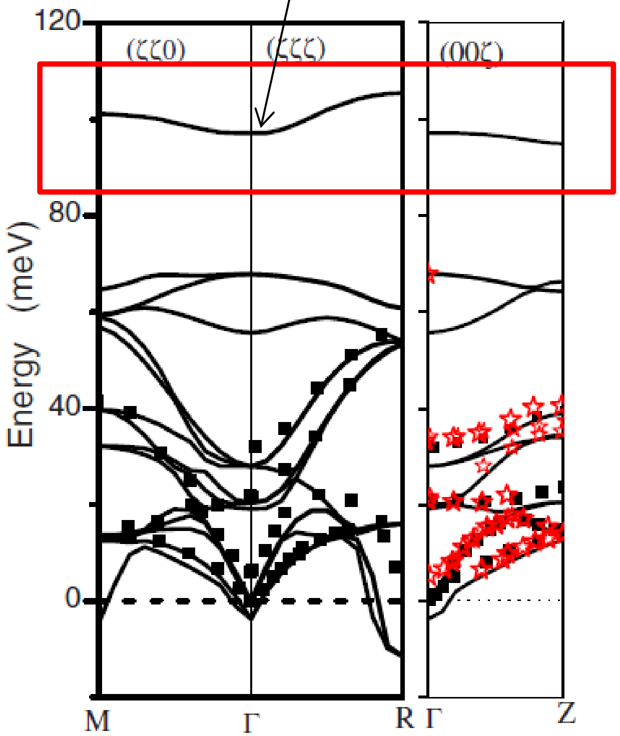
Turner, Phil. Trans. Roy. Soc. Lond. A. 268, 7 (1970)

Interpretation: replica bands are due to phonon shake off.

J.J Lee et al, Nature accepted.

Also seen in neutron scattering by Stirling, J. Phys. C, Solid St. 5,2711 (1971)

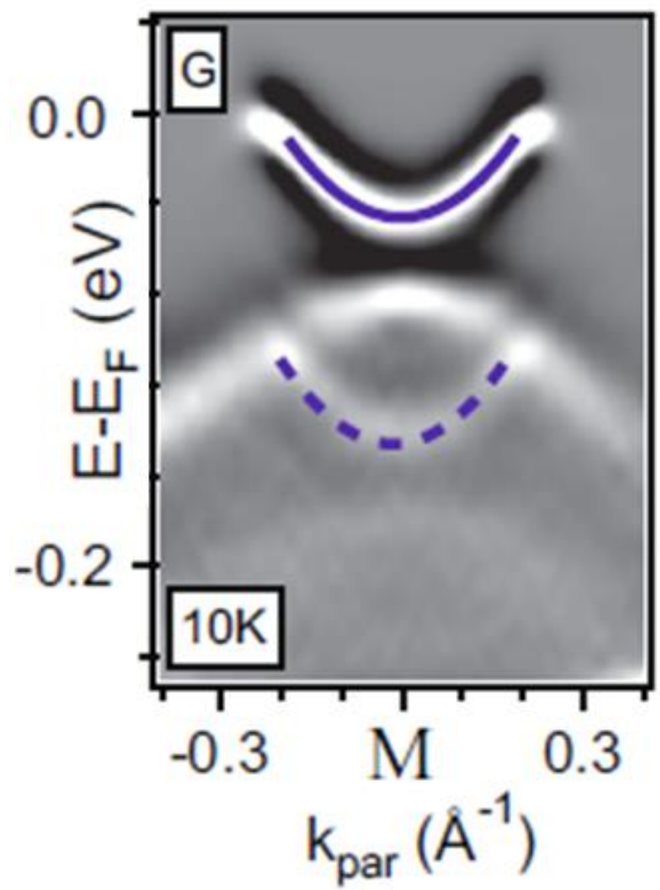
LDA phonon dispersion

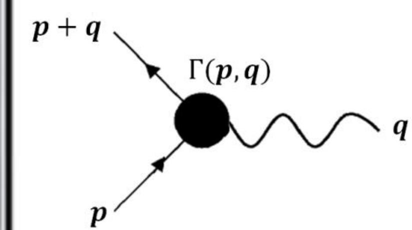


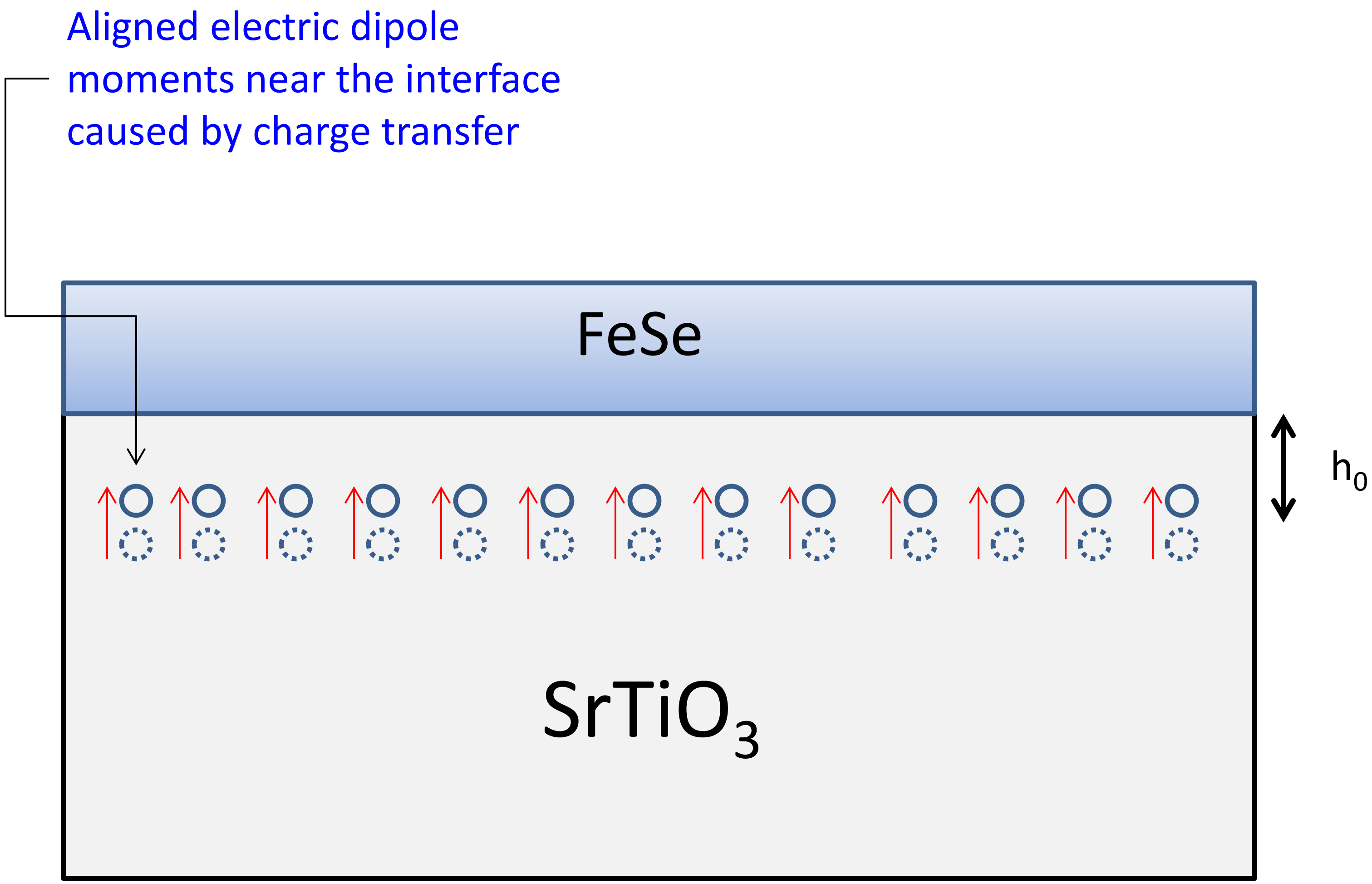
Choudhury et al, PRB **77**, 134111 (2008)

Dominant oxygen motion

In order for the replica band to follow the dispersion of the main band closely, $\Gamma(\boldsymbol{p}, \boldsymbol{q})$ needs to sharply peaked at $\boldsymbol{q} = \mathbf{0}$.

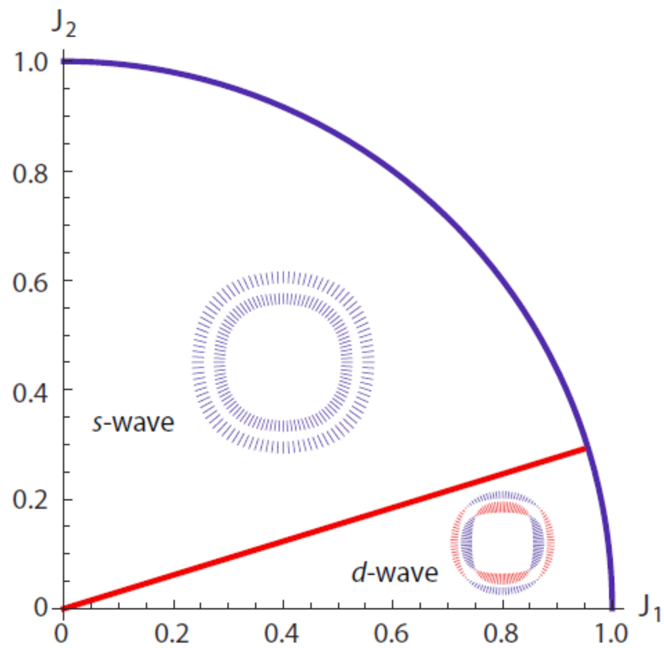


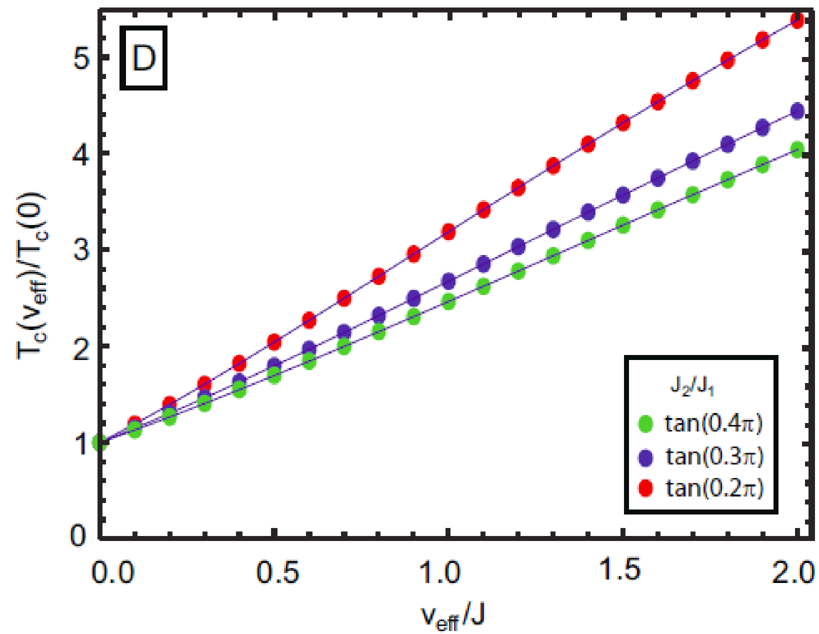




$$\delta\Phi(\mathbf{q}_{\|}) = \sqrt{\frac{\epsilon_{\|}}{\epsilon_{\perp}}}\left(\frac{2\pi q_{\mathrm{eff}}}{\sqrt{\epsilon_{\perp}}}\right) e^{-\left(|\mathbf{q}_{\|}| h_0 \sqrt{\epsilon_{\|}/\epsilon_{\perp}}\right)} \delta h(\mathbf{q}_{\|})$$

$$H_{\rm eff} = \sum_{\mathbf{k}}{}' \sum_{\sigma} \epsilon(\mathbf{k}) c^{\dagger}_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma} + 2\sum_{i,j} J_{ij} \vec{S}_i \cdot \vec{S}_j - \sum_{\mathbf{k},\mathbf{p},\mathbf{q}} \sum_{\sigma,\sigma'} \left(\frac{v_{\rm eff}}{2\pi q_0^2} e^{-|\mathbf{q}|/q_0} \right) c^{\dagger}_{\mathbf{k}+\mathbf{q},\sigma} c_{\mathbf{k}\sigma} c^{\dagger}_{\mathbf{p}-\mathbf{q}\sigma'} c_{\mathbf{p}\sigma'}.$$





Donglai Feng, Monday talk.

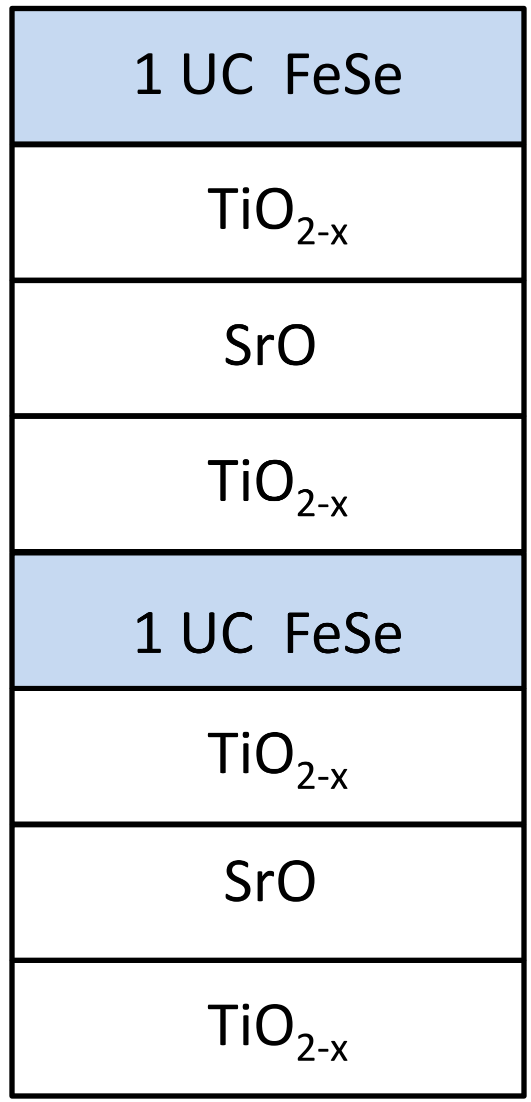
Intensity of the replica band /Intensity of the main band ⇨ electron-phonon interaction strength ⇨ effective electron-electron attraction

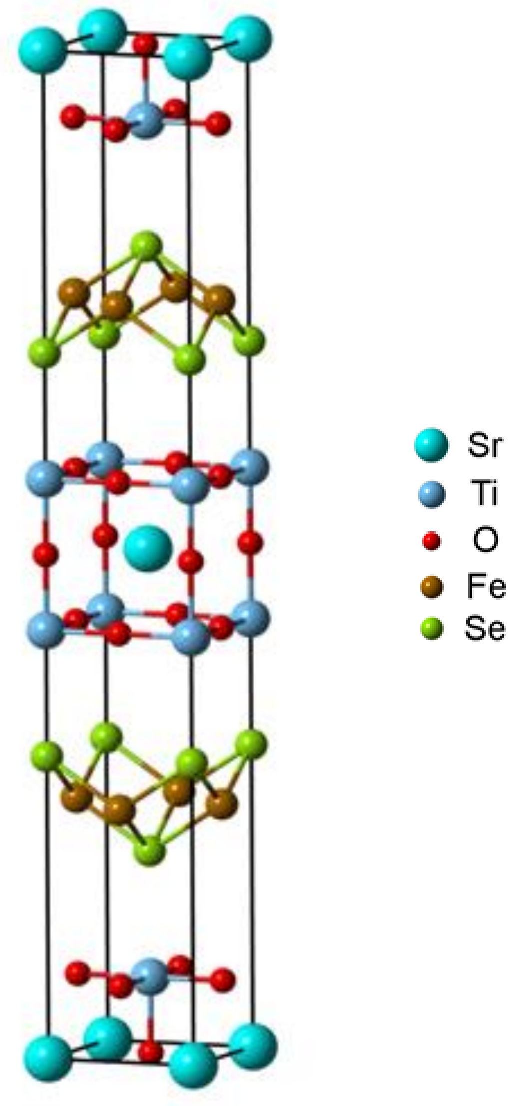
⇨ $v_{eff}/\sqrt{J_1^2 + J_2^2} \geq \frac{1}{3}$ ⇨ T_c enhancement ≥ 1.5 !

Y.-Y. Xiang, F. Wang, D. Wang, Q.-H. Wang, and D.-H. Lee, Phys. Rev. B 86 134508 (2012).

Proposal of a bulk High Tc superconductor

$SrTi_2O_{5-2x}Fe_2Se_2$





How to derive the low energy effective theory for strongly correlated materials ?

Thank you !