Designing phase-sensitive symmetry tests for Fe-based superconductors

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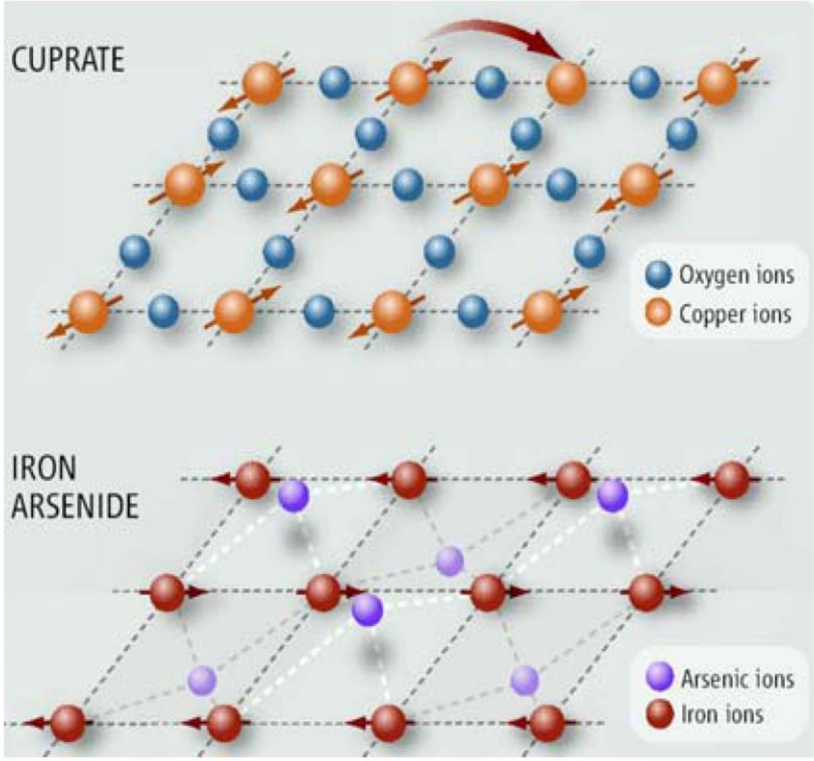

In collaboration with

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Nagoya University, Japan

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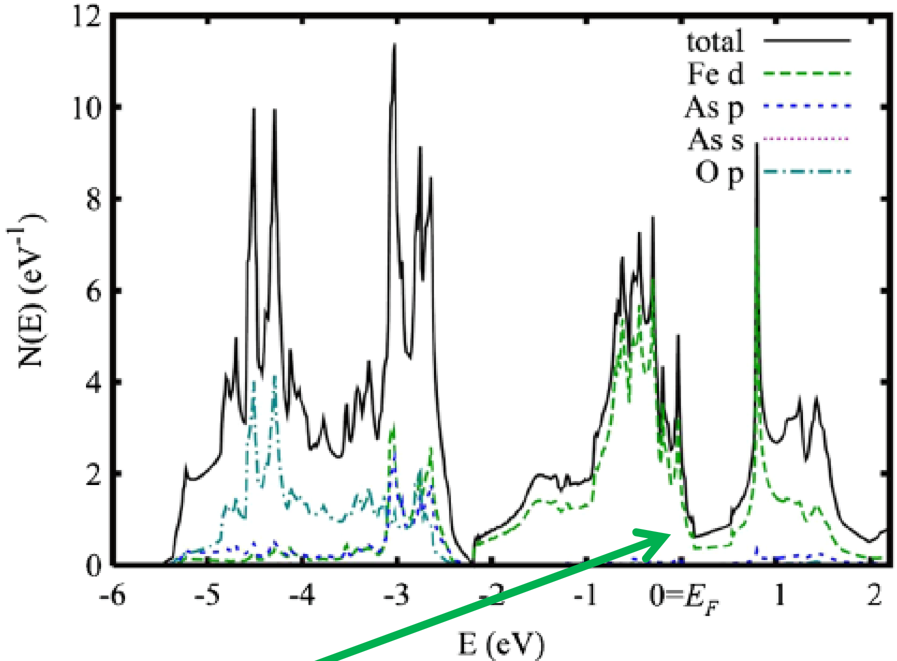
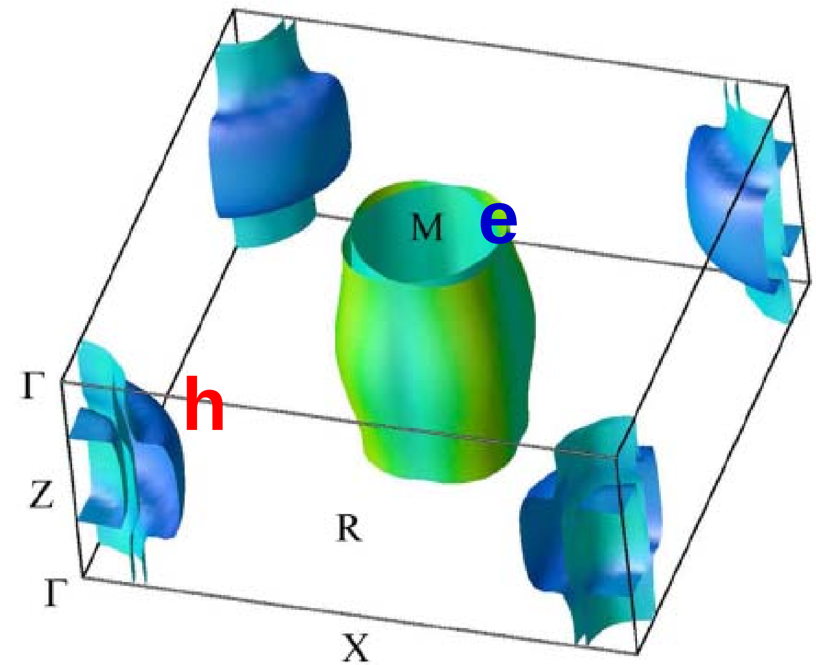
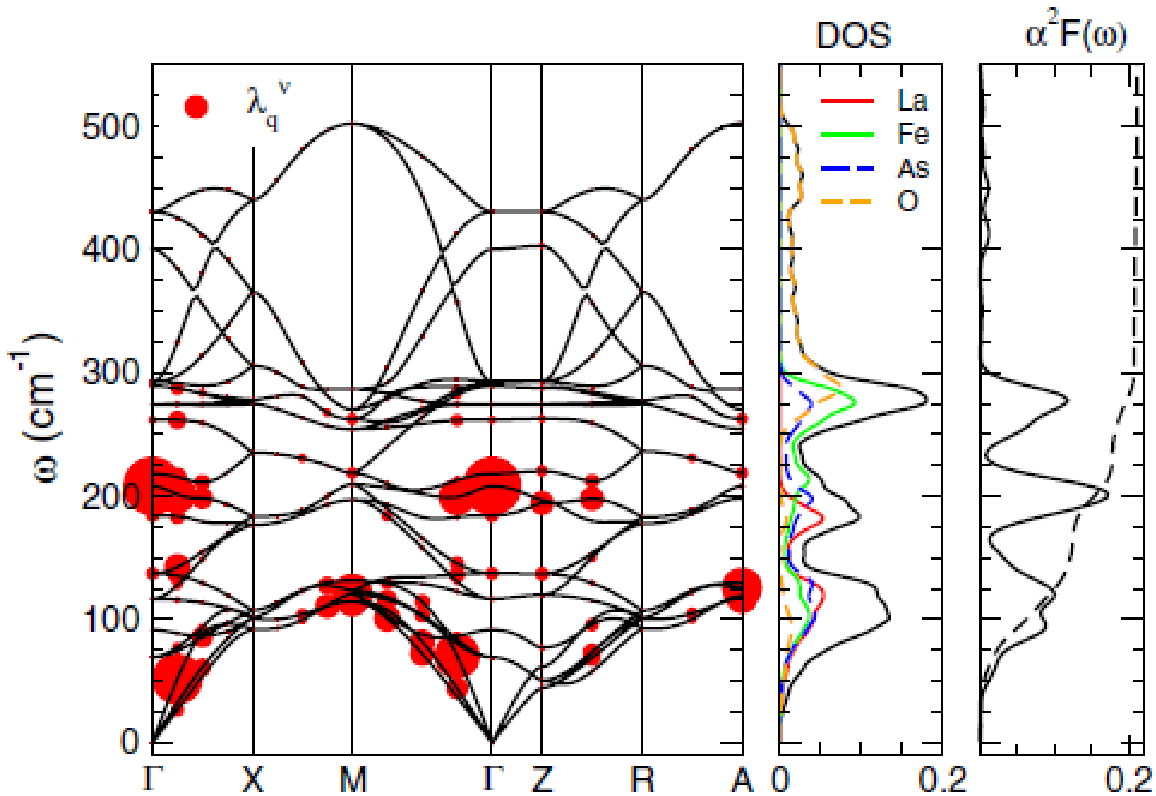
Electronic Structure



Fe^{2+} 3d^6-states

Weak splitting: all 5 orbitals ($d_{x^2-y^2}$, d_{3z^2-1}, d_{xy}, d_{xz}+d_{yz}) are near of the E_F





L. Boeri, O.V. Dolgov, and A.A. Golubov, PRL 101, 026403 (2008); D.J. Singh and M.-H. Du, PRL 100, 237003 (2008)

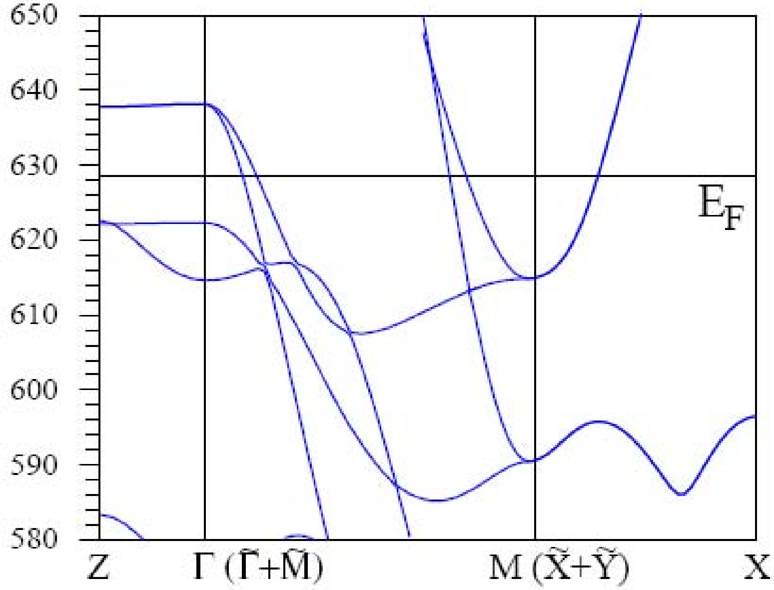
$$\alpha^2F(\omega) = \frac{1}{N(0)}\sum_{nm\mathbf{k}} \delta(\varepsilon_{n\mathbf{k}})\delta(\varepsilon_{m\mathbf{k+q}}) \times \times \sum_{\nu\mathbf{q}} |g_{\nu,\, n\mathbf{k},\, m(\mathbf{k+q})}|^2 \delta(\omega - \omega_{\nu\mathbf{q}});$$

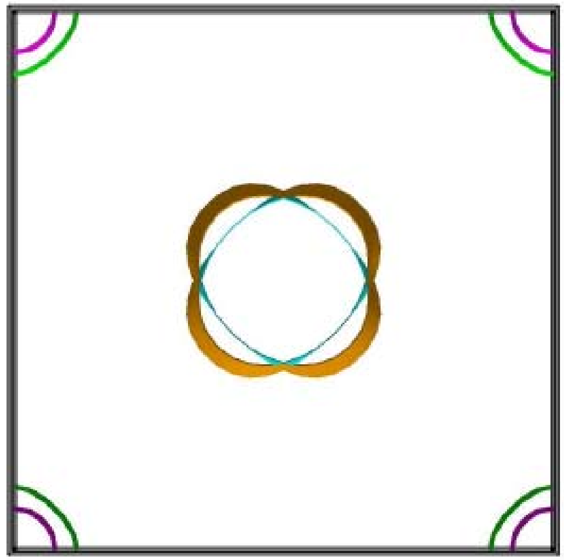
$$\lambda(\omega) = 2\int_0^{\omega} d\Omega \alpha^2 F(\Omega)/\Omega$$

$\lambda = 0.21$ (for Al λ=0.44)

Not sufficient to explain SC!

Band structure (hole doped)

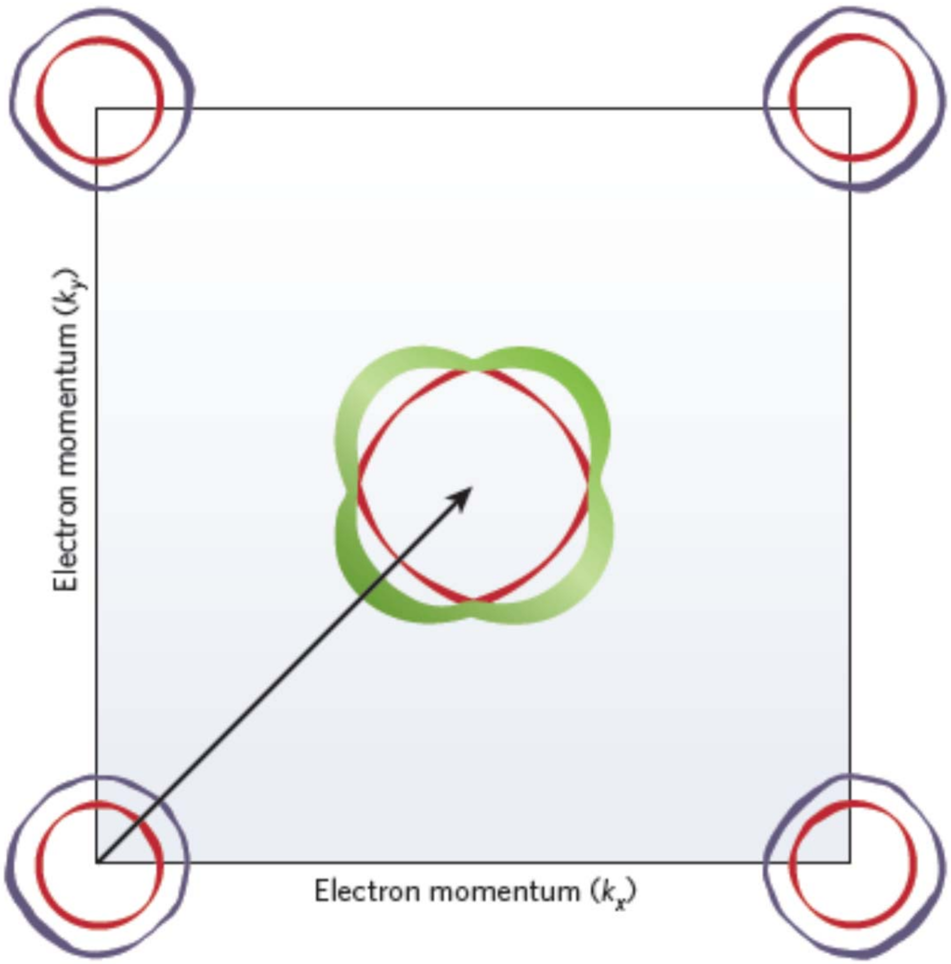




Spin fluctuations

$$\chi(\mathbf{q},\omega) = \frac{\chi_0(\mathbf{q},\omega)}{1- J(\mathbf{q},\omega)\ \chi_0(\mathbf{q},\omega)}$$

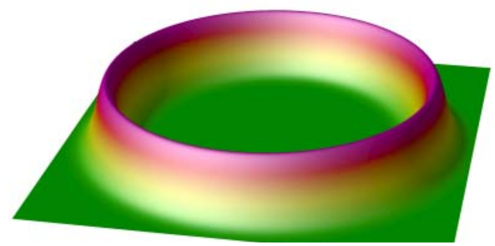
Berk-Schrieffer theory (1970's) :
$J(\mathbf{q},\omega)$ -magnetic interaction



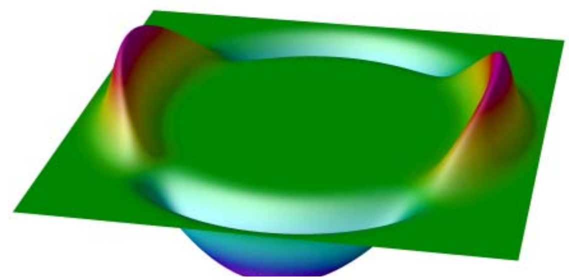
A typical Fermi surface of an iron-pnictide superconductor, projected onto the k_x –k_y plane

Various symmetries of the superconducting order parameter

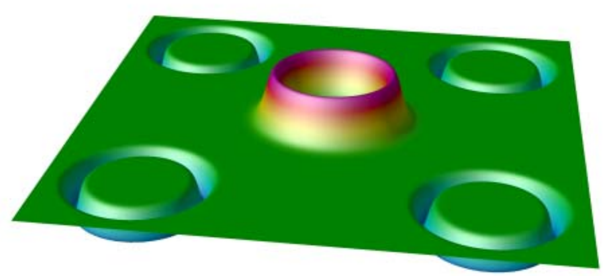
(a) a conventional S-wave



(b) a d-wave, as in cuprates

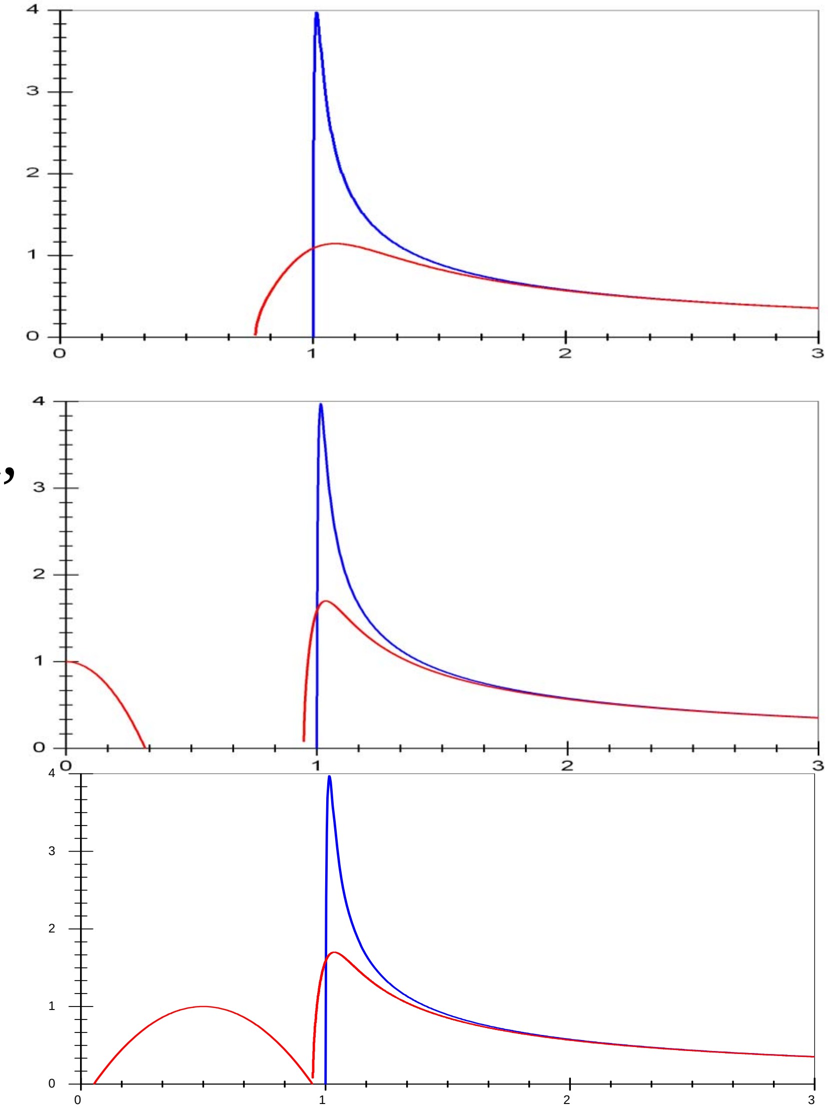


(c) $s\pm$ wave (pnictides ?)



Impurity scattering in the $s_{+/-}$ state

1. Nonmagnetic impurities are pair breaking
2. Born limit: no coherence peak, exponential at low T
3. Unitary limit: weak Tc suppression, zero-energy bound state
4. Intermediate limit: finite energy bound state, simulates power law



Disorder induced transition between s_{+-} and s_{++} states in two-band superconductors

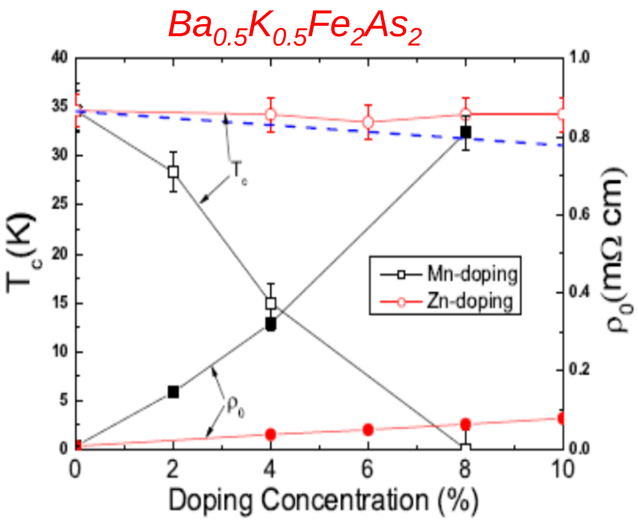
D.V. Efremov, M.M. Korshunov, O.V. Dolgov, A.A. Golubov, and P.J. Hirschfeld,' Disorder-induced transition between s± and s++ states in two-band superconductors', Phys. Rev. B **84**, 180512 (2011).

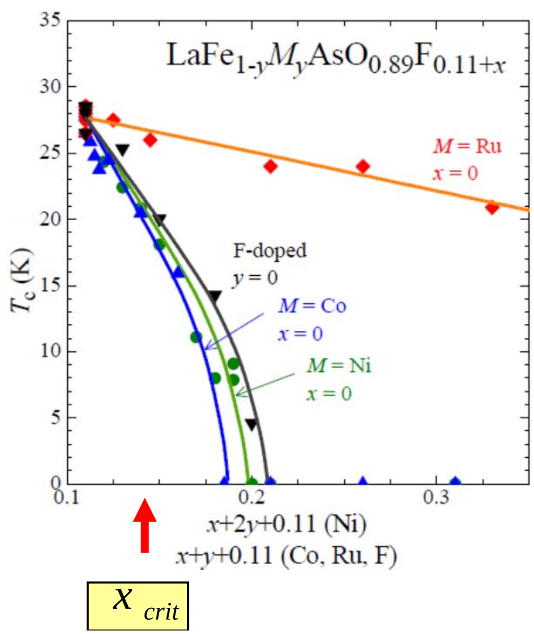
D.V. Efremov, A.A. Golubov, and O.V. Dolgov, 'Manifestations of impurity induced s± ⇒ s++ transition: multiband model for dynamical response functions', New J. Phys. **15**, 013002 (2013).

- Experiments in favor s_{+-}
  - NMR
    - Absence of Hebel-Schlichter peak
    - $1/T_1 \sim T^3 - T^5$
  - Resonance peak in neutron scattering experiments

- Experiments in favor s_{++}
  - Absence or weak *suppression* of T_c by *nonmagnetic* impurities.

Nonmagnetic impurities vs magnetic.





•Common wisdom: The impurity in S_{+-} superconductors *suppress T_c in the same way as paramagnetic impurity in common superconductors*. T_c is given by Abrikosov-Gorkov formula:

$$\ln\left(\frac{T_{c0}}{T_c}\right) = \Psi\left(\frac{1}{2} + \frac{\Gamma_S}{2T_c}\right) - \Psi\left(\frac{1}{2}\right)$$

The critical value $(T_c(\Gamma_{crit}) = 0)$ of the scattering rate is given:

$$\Gamma_{cr} / T_{c0} \approx 1.12$$

Onari, Kontani, PRL**103**, 17701(2009)

- Can T_c *in* $s+\_$ *superconductors* be *robust* against interband scattering?
- If yes, what is the physical reason?

T_c: nonmagnetic impurities, weak coupling limit.

$$\lim_{T \to T_c} \tilde{\omega}_{na} = \omega_{na} + (\cancel{\gamma_{aa}} + \gamma_{ab}) sign(\omega_n)$$

$$\lim_{T \to T_c} \tilde{\Delta}_{na} = \Delta_{na} + \left(\cancel{\gamma_{aa}} \frac{\tilde{\Delta}_{na}}{|\tilde{\omega}_{na}|} + \gamma_{ab} \frac{\tilde{\Delta}_{nb}}{|\tilde{\omega}_{nb}|} \right)$$

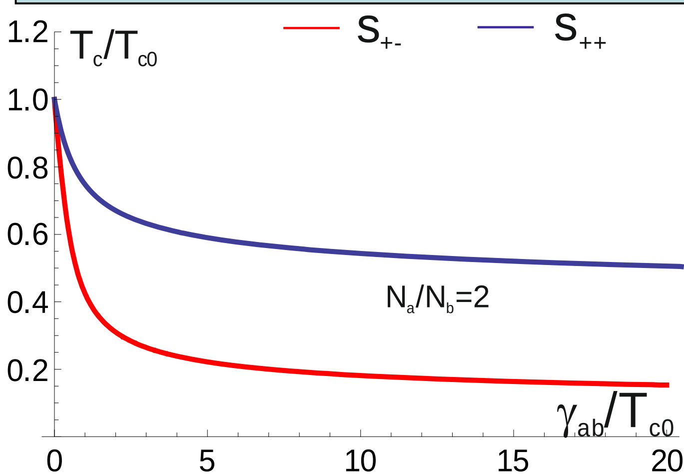
$$\gamma_{aa} = \frac{1}{2} n \pi N_a \left\langle |u|^2 \right\rangle_{FS} \qquad \gamma_{ab} = \frac{1}{2} n \pi N_b \left\langle |v|^2 \right\rangle_{FS}$$

$$\langle \lambda \rangle_{FS} = \frac{1}{N_a + N_b} \left[N_a (\lambda_{aa} + \lambda_{ab}) + N_b (\lambda_{ba} + \lambda_{bb}) \right]$$

$$\langle \lambda \rangle_{FS} > 0$$

saturation to the finite value

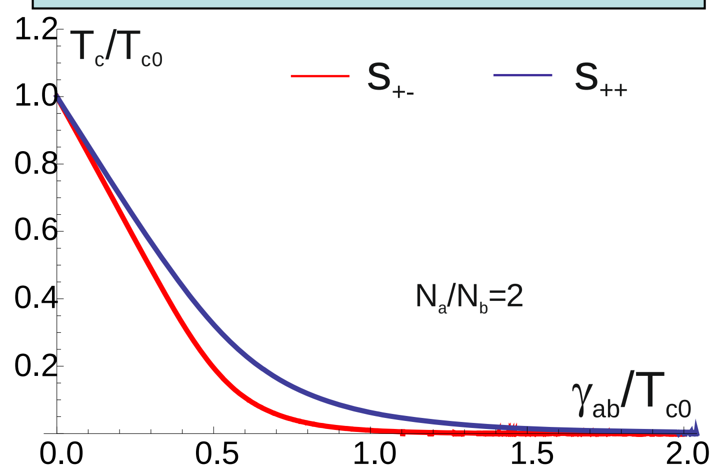
$$T_{c\infty}^{BCS} \propto W e^{-\frac{1}{\langle \lambda \rangle_{FS}}}$$

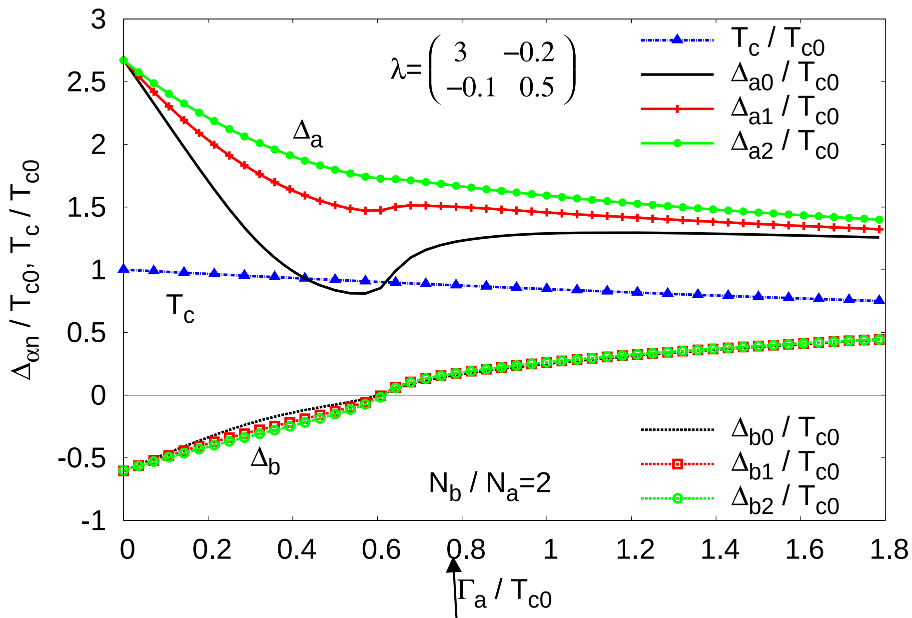


$$\langle \lambda \rangle_{FS} < 0$$

critical impurity scattering

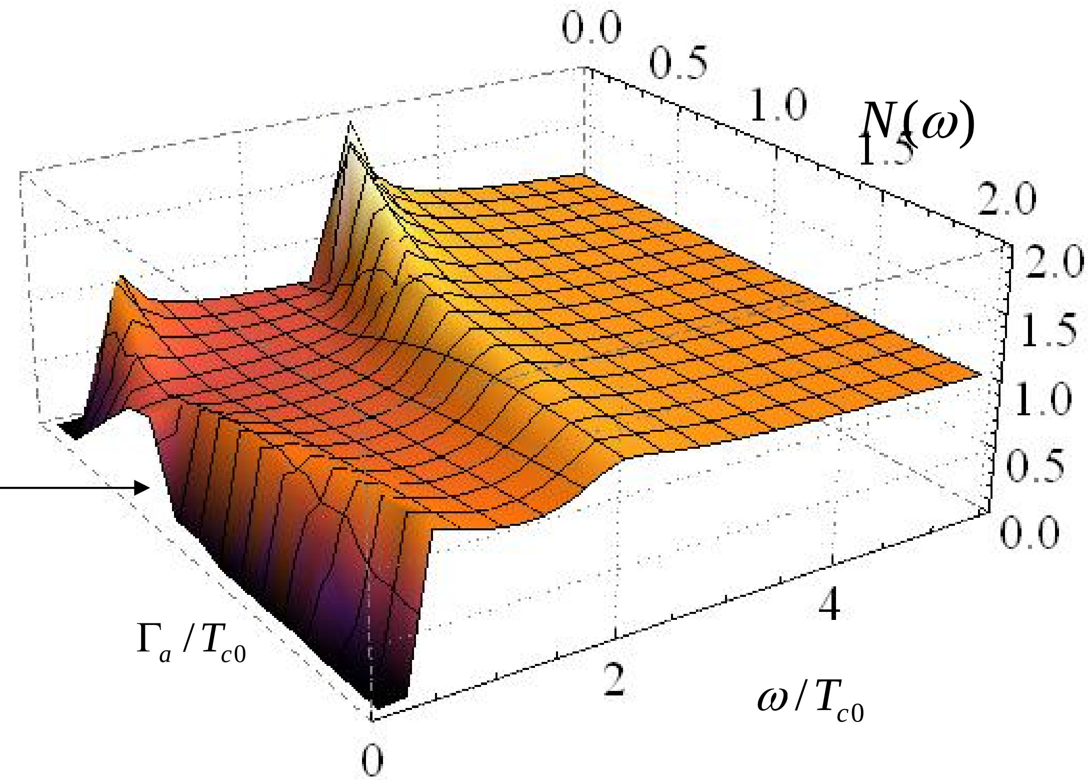
$$\gamma_{crit}^{BCS} \propto W e^{-\frac{\langle \lambda \rangle_{FS}}{\lambda_{aa}\lambda_{bb} - \lambda_{ab}\lambda_{ba}}}$$





$$\Lambda = \begin{pmatrix} 3 & -0.2 \\ -0.1 & 0.5 \end{pmatrix}$$

Density of States



gapless regime

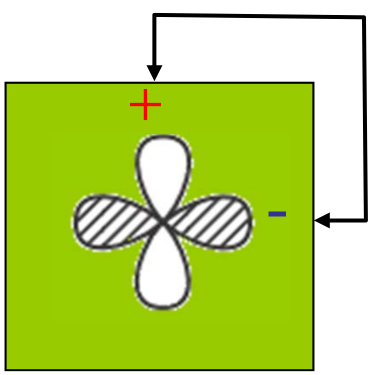
Designing phase-sensitive symmetry tests for Fe-based superconductors:

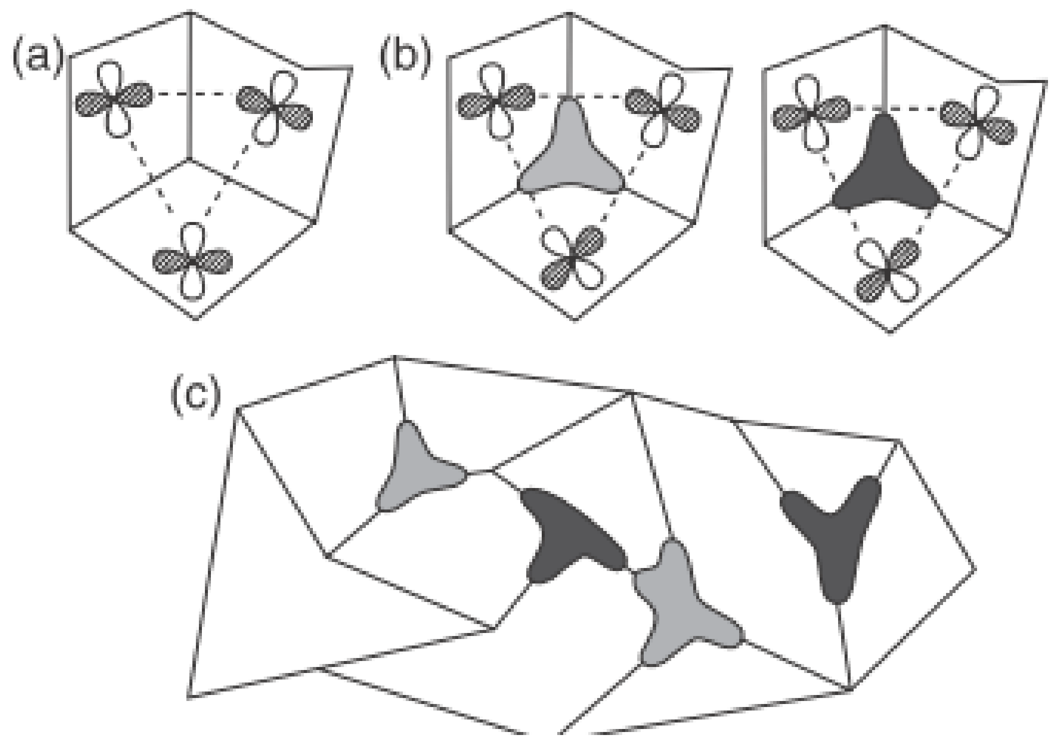
s_{+-} *and* s_{++} *states in two-band superconductors*

Josephson effects in pnictide junctions

- <u>c-axis Josephson</u>: *observed (UMD group)*
- <u>Paramagnetic Meissner</u> (Wohlleben) effect*; not observed (K.A. Moler et al, JPSJ)*

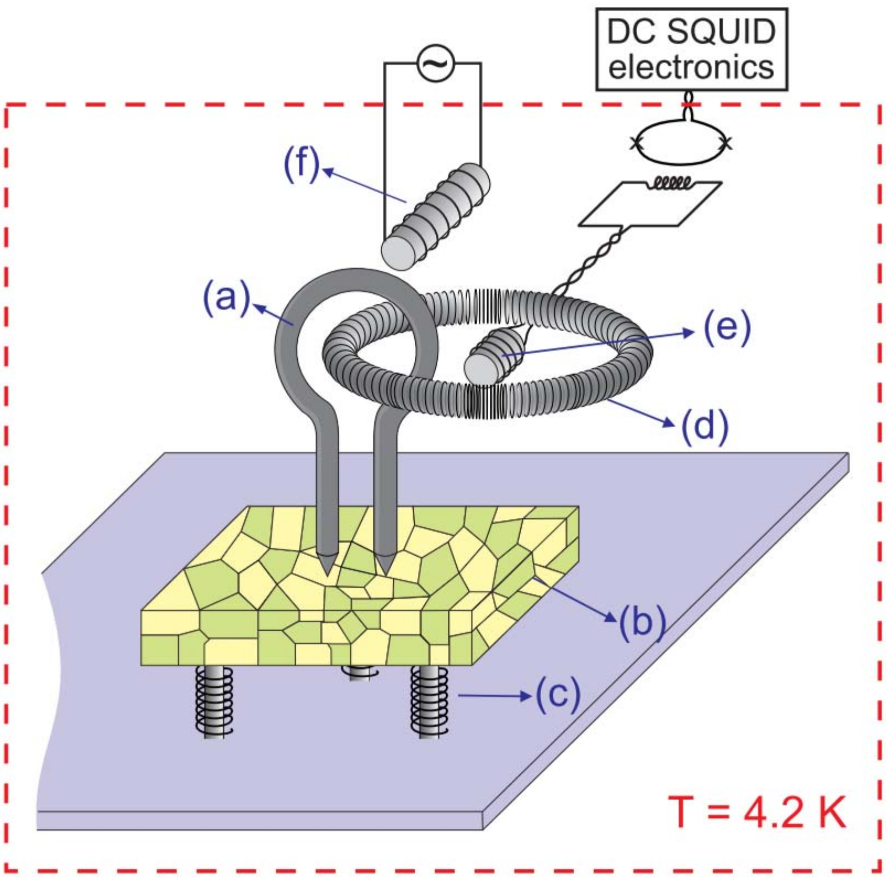
D-wave symmetry: corner junctions and tricrystal rings





Sign change of the order parameter

IBM group (Tsuei et al), Nature, 2010



Half-integer fluxes detected (in a small fraction of loops).

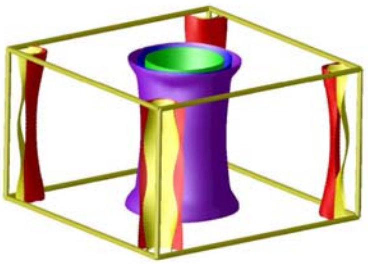
Various interpretations possible, but all of them require sign change of the order parameter

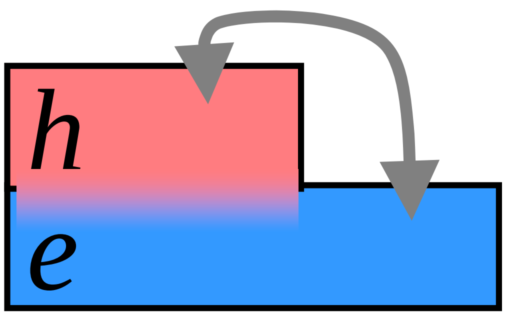
-> indicates sign changes

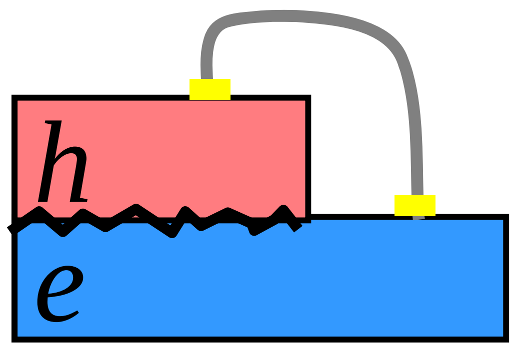
Phase sensitive experiments

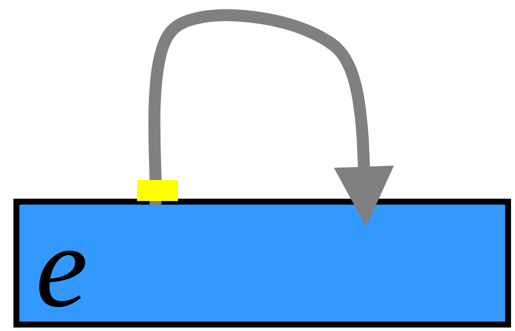
A.A. Golubov and I.I. Mazin, Appl. Phys. Lett. ***102****, 032601(2013)*

Designing phase-sensitive tests for Fe-based SC’s



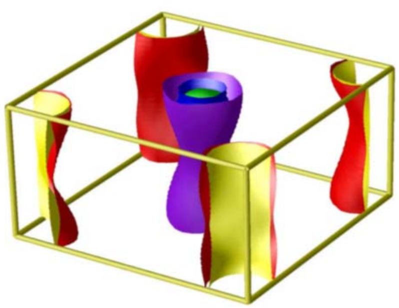






h+ e-

h+ **e-**



h+ e-

e+ **h-**

h+ **e-**

(a) Tunnel regime:

$$T_{\mathbf{k}} = \frac{4m_0^2\hbar^2K^2v_Lv_R}{\hbar^2m_0^2K^2(v_L+v_R)^2 + (\hbar^2K^2 + m_0^2v_L^2)(\hbar^2K^2 + m_0^2v_R^2)\sinh^2(dK)}.$$

The conductance is exponentially suppressed if $k_{\|}^2/2m_0 \lesssim 2(U-E_F)$.

(b) Point contact regime:

The conductance is angle-independent

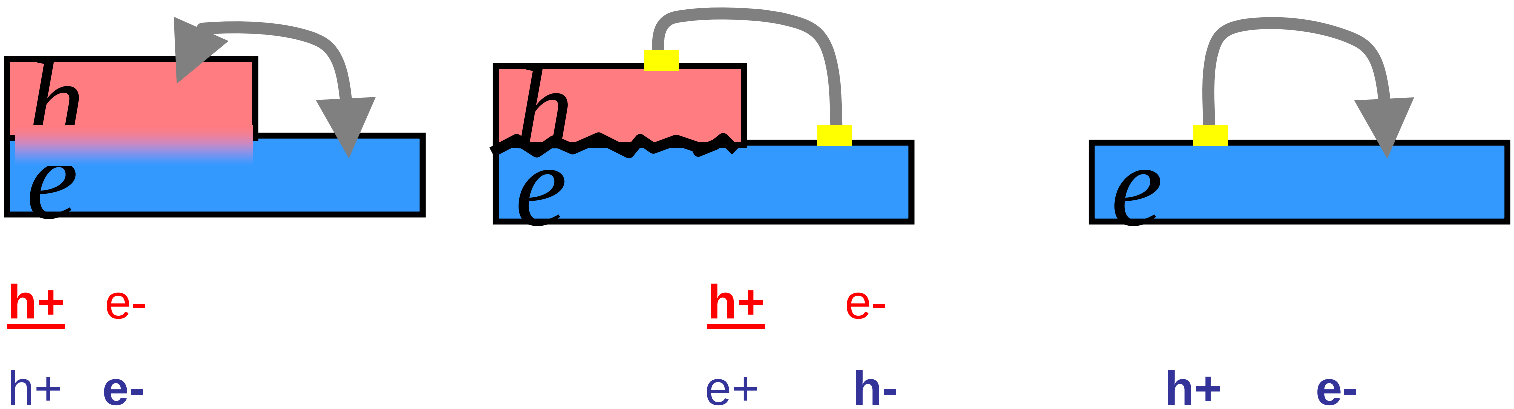
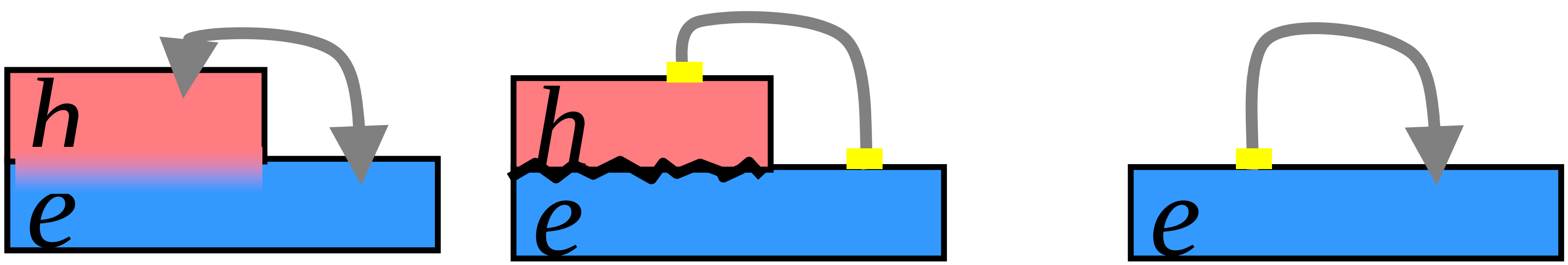


TABLE I. Three suggested designs for probing the relative phases of the order parameter in Fe-based superconductors. A tunneling barrier here is assumed to be thick enough to filter through the "tunneling cone" effect only the states near the zone center (holes), while a point contact is supposed to collect current in all directions and thus be dominated by the majority carriers. The sign of the order parameter is selected in such a way that the current through the left (upper) contact is always considered positive.

	Design		
Fig. 1 panel	Left	Middle	Right
Upper/left contact	Point	Tunnel	Tunnel
Lower/right contact	Point	Tunnel	Point
Upper Δ_{hole}	−	+	+
Upper Δ_{elec}	+	−	−
Interface	Epitaxial	Rough	n/a
Lower Δ_{hole}	−	−	n/a
Lower Δ_{elec}	+	+	n/a
Upper contact current dominated by	Electrons	Holes	Holes
Lower contact current dominated by	Holes	Holes	Electrons

Golubov, Mazin,

APL ***102****, 032601(2013)*



h+ e-   **h+** e-

h+ **e-**   e+ **h-**   **h+** **e-**

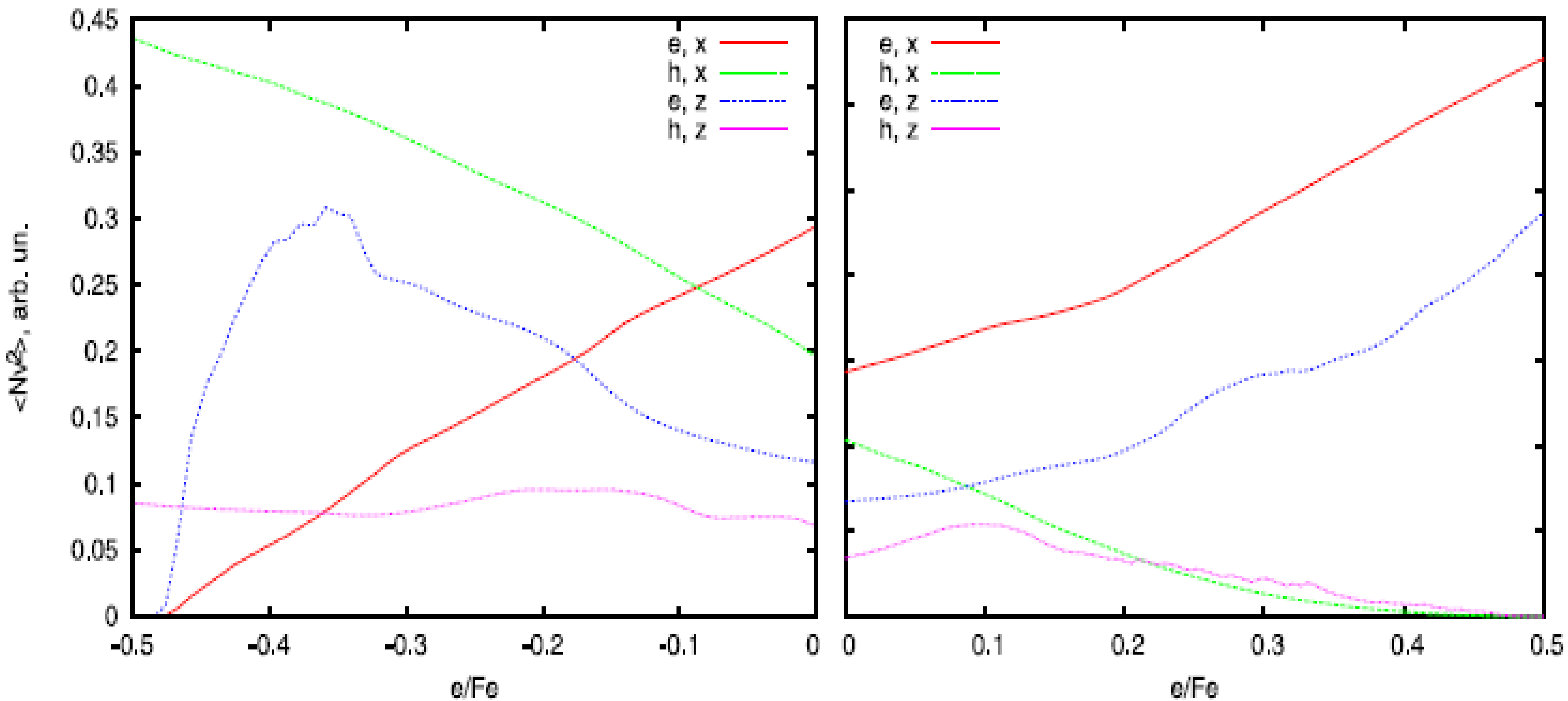


FIG. 2. Calculated transport function, $\langle N(E_F)v_F^2\rangle$, for the hole-doped (left panel) and electron-doped (right panel) $BaFe_2As_2$. Calculation for the electron-doped case was self-consistent in the virtual crystal approximation for the 10% Co doping and the rigid band approximation used around this composition. Similarly, the hole-doped composition was self-consistent for the 40% K doping and the rigid bands used thereafter.

Summary

- Impurity scattering: two regimes
  - saturation of T_c to the finite value for $\langle \lambda \rangle_{FS} > 0$
  - critical impurity scattering value for $\langle \lambda \rangle_{FS} < 0$
- With increasing strength of impurities there is transition $s_{+-} \longrightarrow s_{++}$ and T_c is stabilized.

Phys. Rev. B **84**, 180512 (2011); New J. Phys. **15**, 013002 (2013)

- Phase sensitive experiments may distinguish s_{+-} from s_{++}: we have suggested experimental designs.

Appl. Phys. Lett. **102**, 032601(2013)

Further study: incorporation of microscopic boundary conditions to evaluate Josephson current