Discussion of General Properties of $s_{\pm}$ Superconductors

Igor Mazin, Naval Research Laboratory, Washington D. C.

Collaborators:

Michelle Johannes, David Parker (Naval Research Lab)
David Singh (Oak Ridge National Lab)
Oleg Dolgov (MPI Stuttgart)
Sasha Golubov (Twente)
Yukio Tanaka (Nagoya)
Jorg Schmalian (Ames)

"I am sure there are good reason to study these things, but I missed them due to absence"

Bel Kaufman, Up the Down Staircase

Physics authors/titles Oct 2005 (200 skipped) - Microsoft Internet Explorer

File Edit View Favorites Tools Help

Back Search Favorites Media

Address http://www.arxiv.org/list/physics/0510?200

The theoretical oriented scientist cannot be envied, because nature, i.e. the experiment, is a relentless and not very friendly judge of his work. In the best case scenario it only says "maybe" to a theory, but never "yes" and in most cases "no". If an experiment agrees with theory it means "perhaps" for the latter. If it does not agree it means "no". Almost any theory will experience a "no" at one point in time - most theories very soon after they have been developed.

Title: Theoretical remark on the superconductivity of metals

Authors: Albert Einstein

OUTLINE

1. **Whence $s_{\pm}$?**
   - **or: why was it so easy to predict the right pairing symmetry?**
   - **or: why does the spin-fluctuation mechanism lead to d-wave in cuprates and to $s_{\pm}$ in pnictides?**
   - **or: why are neither nesting nor J_2 superexchange necessary for $s_{\pm}$?**
2. **Other players besides spin fluctuations: What do they want? Can they induce nodes?**
   - **Phonons**
   - **Zone-center [$\equiv J_1$ superexchange] spin fluctuations**
   - **Coulomb avoidance**

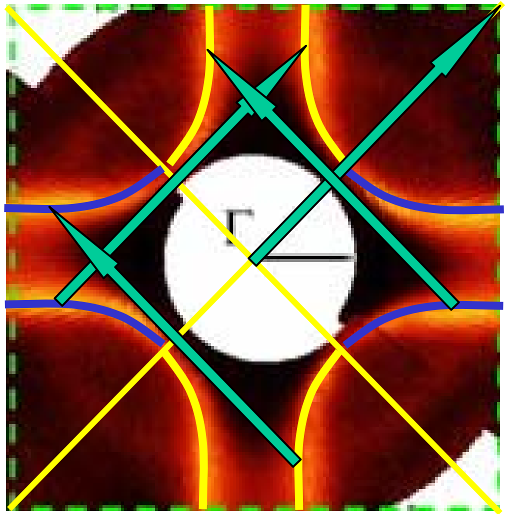
OUTLINE

3. $s_{\pm}$ gaps
   - Gap ratio; weak coupling vs. strong coupling
   - Nodes or no nodes?

4. $s_{\pm}$-specific properties
   - impurities and coherence factors
     - inversed Abrikosov-Gor'kov law
     - inversed coherence factors for q~(π,π) scattering: $1/TT_1$, χ(q) (neutrons), quasiparticle scattering
   - phase-sensitive tunneling effects
     - Andreev bound states
     - c-axis Josephson
     - Paramagnetic Meissner
     - π-junctions: finite-angle design
     - π-junctions: "sandwich" design
     - "fork circuits"

Raman excitations?

Leggett mode?



Fermi surface of BSCCO measured by ARPES (http://en.wikipedia.org/wiki/Fermi_surface)

Superexchange interaction is peaked at Q=(π,π)

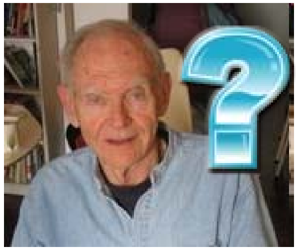
It is perfectly well matching the fermiology of high-Tc cuprates

There are two ingredients in this recipe: (1) Fermiology and (2) momentum dependence of spin-fluctuations

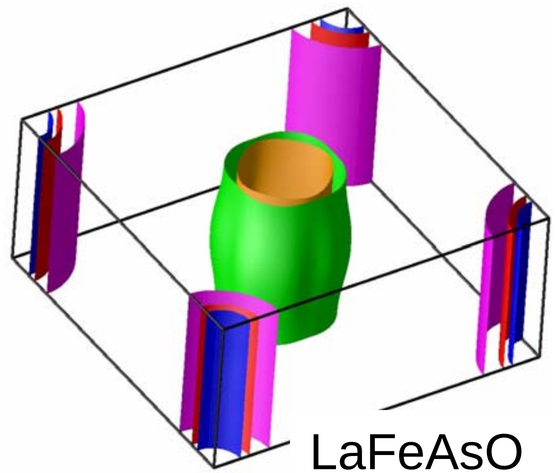
$$\Delta_{\mathbf{k}\alpha} = \sum_{\mathbf{q}\beta} V_{\mathbf{kq},\alpha\beta} \Delta_{\mathbf{q}\beta} F(\Delta_{\mathbf{q}\beta}, T)$$

If $\Delta_{\alpha k}$ and $\Delta_{q\beta}$ have opposite sign, a negative (repulsive) *V* can still be pairing.

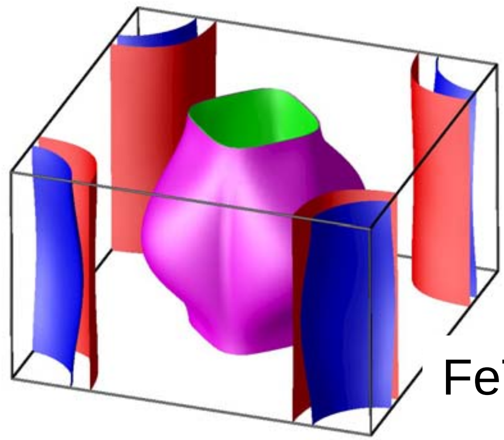
What about pnictides?



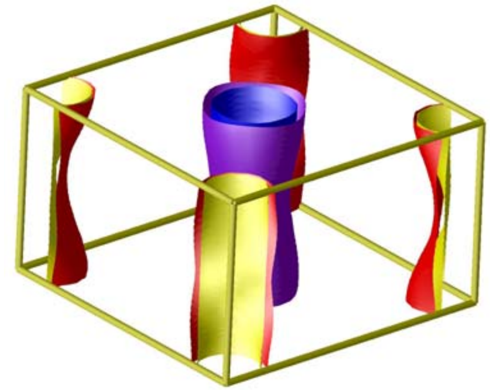
Cooking an $s_{\pm}$ state: ingredient 1 - Fermiology



LaFeAsO

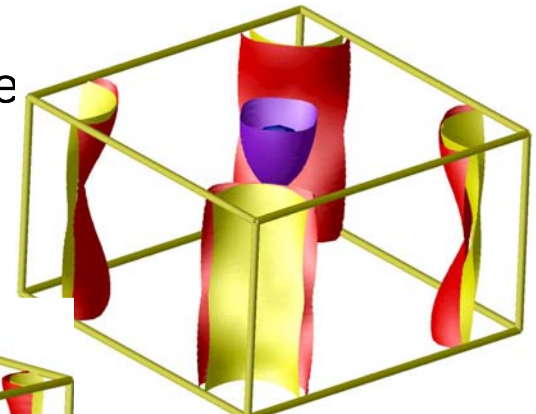


FeTe

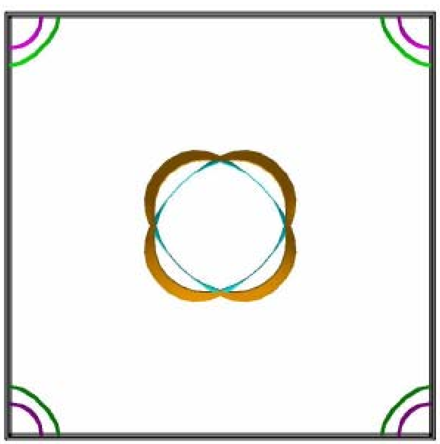


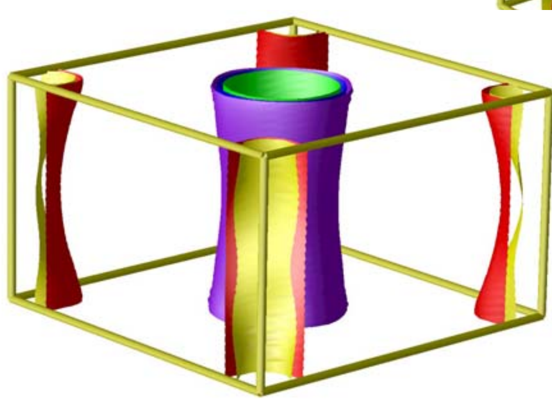
$BaFe_2As_2$

Ba122 – 10%e

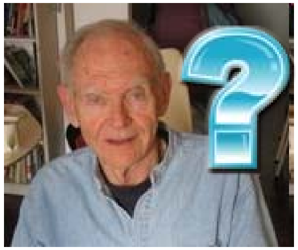


1111 – 10%e





Ba122 – 10%h

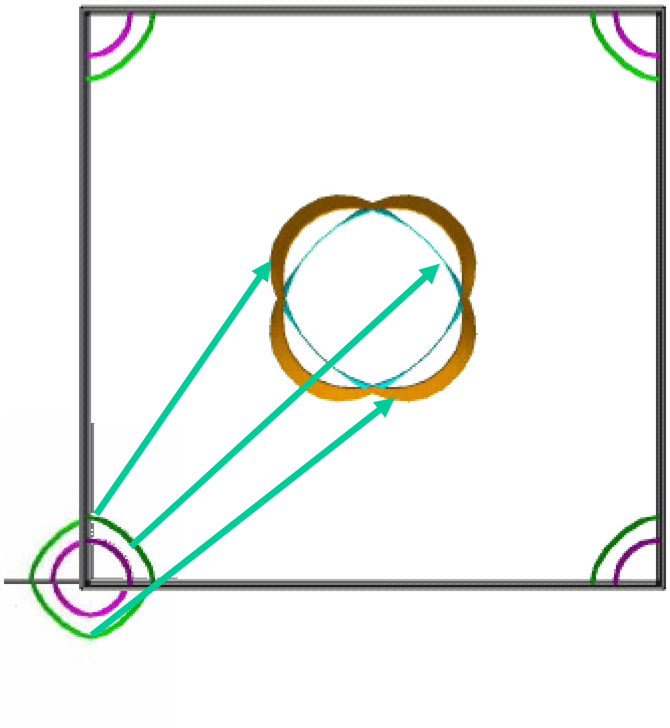


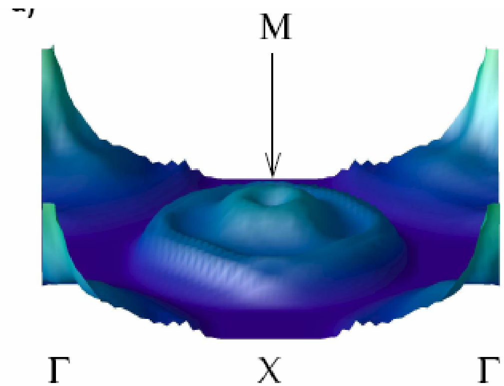
Is there nesting of Fermi surfaces in the actual materials and what conclusions can be drawn from the answer?

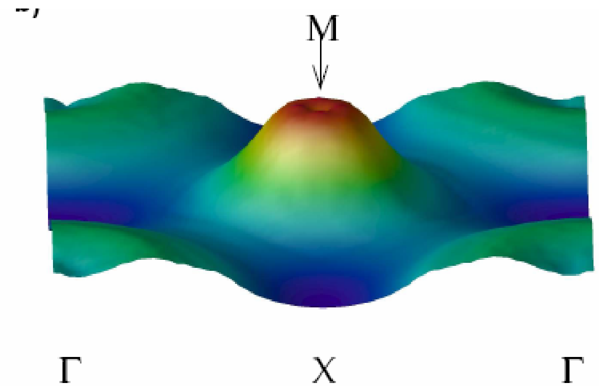
Cooking an $s_{\pm}$ state: ingredient 2 – spin fluctuation

$$\mathrm{Re}\,\chi_0(\mathbf{q},\omega\to 0)=\sum_{\mathbf{k}}\frac{f_{\mathbf{k+q}}-f_{\mathbf{k}}}{\varepsilon_{\mathbf{k+q}}-\varepsilon_{\mathbf{k}}}$$

$$\frac{\mathrm{Im}\,\chi_0(\mathbf{q},\omega)}{\omega}\Big|_{\omega\to 0}=\sum_{\mathbf{k}}\delta(\varepsilon_{\mathbf{k+q}}-E_F)\,\delta(\varepsilon_{\mathbf{k}}-E_F)$$







$\mathrm{Im}\ \chi_0(\mathbf{q},\omega)/\omega|_{\omega\to 0}$

$\mathrm{Re}\ \chi_0(\mathbf{q},0)$

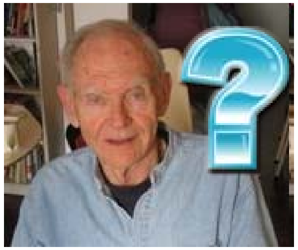
fully pairing for the $s_{\pm}$ state (sharp nesting not needed)

Origin of spin fluctuations: not important!

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

For a Mott-Hubbard system, $J(\mathbf{q},\omega)$ is main factor – magnetic interaction is *local in real space*

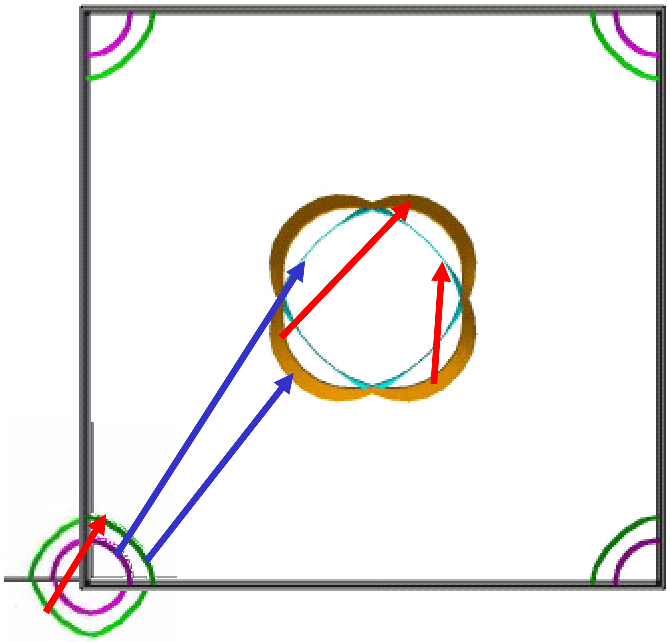
For LFAO, we expect the structure to come mainly from non-interacting part, interaction is *local in momentum space*



What properties of pnictides inform us as to where to look for higher temperature superconductors? – *Strong q-dependent fluctuations favorably matching the Fermi surface topology*

IF it were a Mott-Hubbard system, the nearest neighbor superexchange ($\{0,0\}$, J_1) would be pair-breaking, and the 2nd neighbors superexchange ($\{\pi,\pi\}$, J_2) would be pairing.

Some clarification about phonons



these phonons are pairing, positive isotope effect

these phonons are pair-breaking, negative isotope effect.

1. First principles calculations of e-ph coupling give vanishing $\lambda_{e\text{-}ph}$. They <u>*are reliable*</u> for a truly nonmagnetic ground state

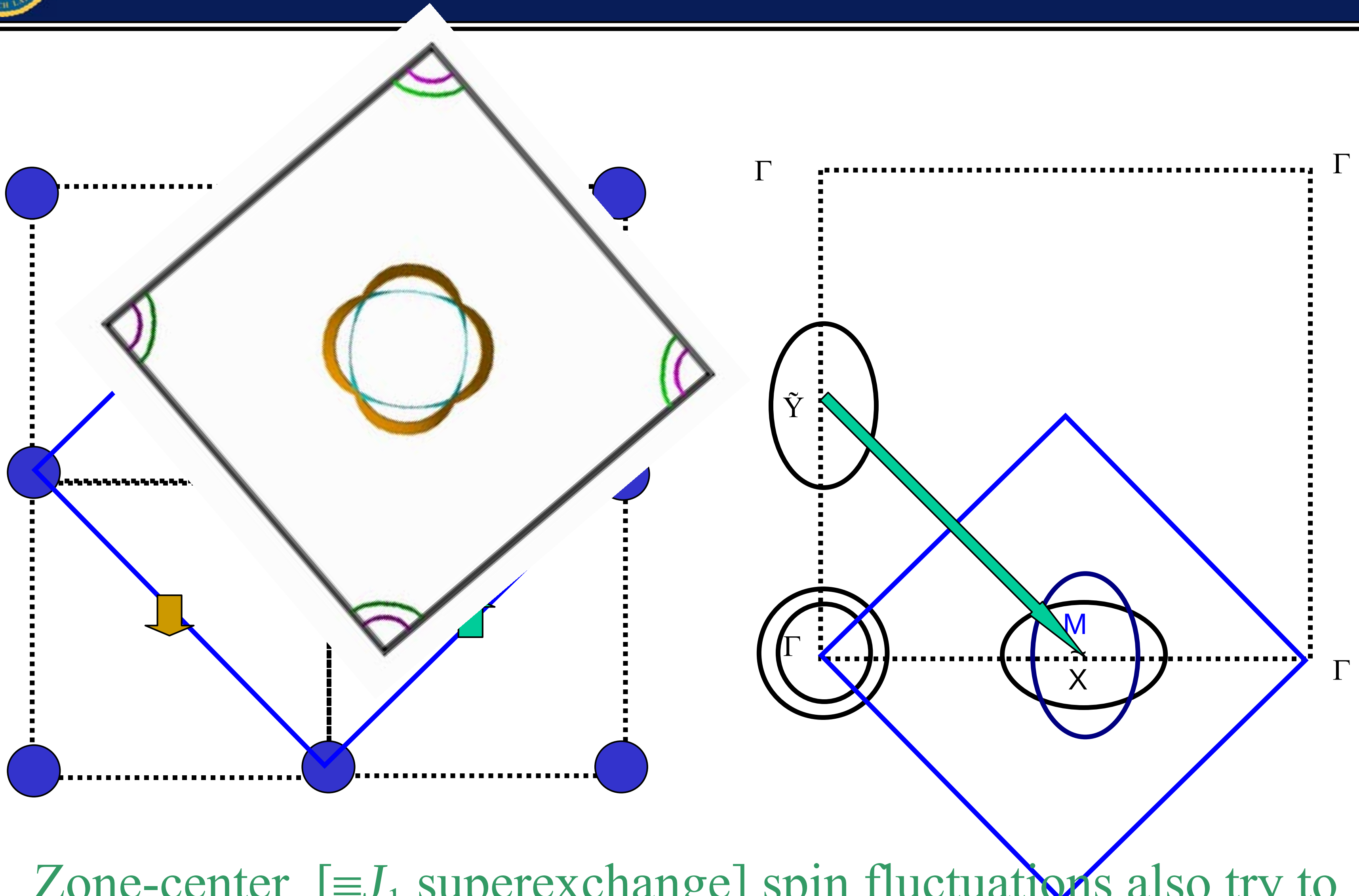
2. Magnetoelastic coupling in these materials is *spectacularly strong*.

3. We do not know what sort of enhancement phonon-magnon interaction may provide.

4. Isotope effect in systems with variable T_c is notoriously hard to measure (cf. CaC_6, possibly $MgNiC_3$).

If strong enough, these phonons can induce nodes

Unfolding the Brillouin zone



Zone-center [≡J_1 superexchange] spin fluctuations also try to create nodes

Coulomb avoidance

d-wave:

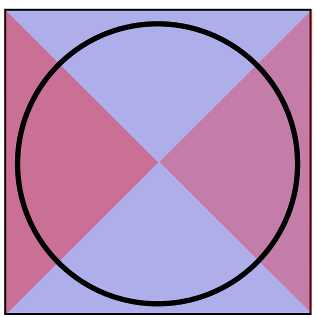
$$\Delta_k = \Delta_0[\cos(k_x a) - \cos(k_y a)]$$

$$\Delta(\mathbf{r}) = \Delta_0[\delta(x \pm a) - \delta(y \pm a)]$$

$s_{\pm}$-wave

$$\Delta_k = \Delta_0[\cos(k_x a)\cos(k_y a)]$$

$$\Delta(\mathbf{r}) = \Delta_0 \delta(x \pm a)\delta(y \pm a)$$

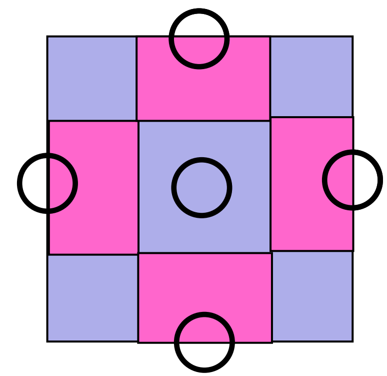


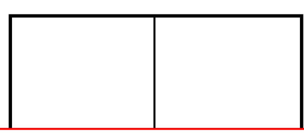
Condition for complete avoidance (Hubbard repulsion):

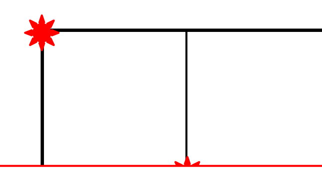
$<\Delta>=0$

If $\Delta_1/\Delta_2=\alpha$, $U\rightarrow\infty$

$\lambda/\lambda_0=2/(\alpha^{-1}+\alpha)$♦0.8







Δ_1/Δ_2 is set by the DOSs (more later).

Therefore Coulomb wants to create nodes on the FS with the larger gap

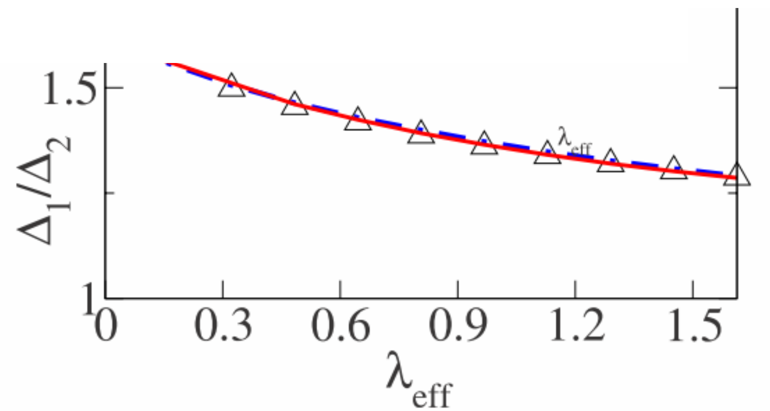
(Scalapino, Hirschfeld et al, Chubukov et al)

Gap ratio

BCS (weak coupling)

It is not that easy to provide a gap ratio of 2!

- three (four) band effects are important
- other interactions (phonons, intraband spin fluctuations etc) are important



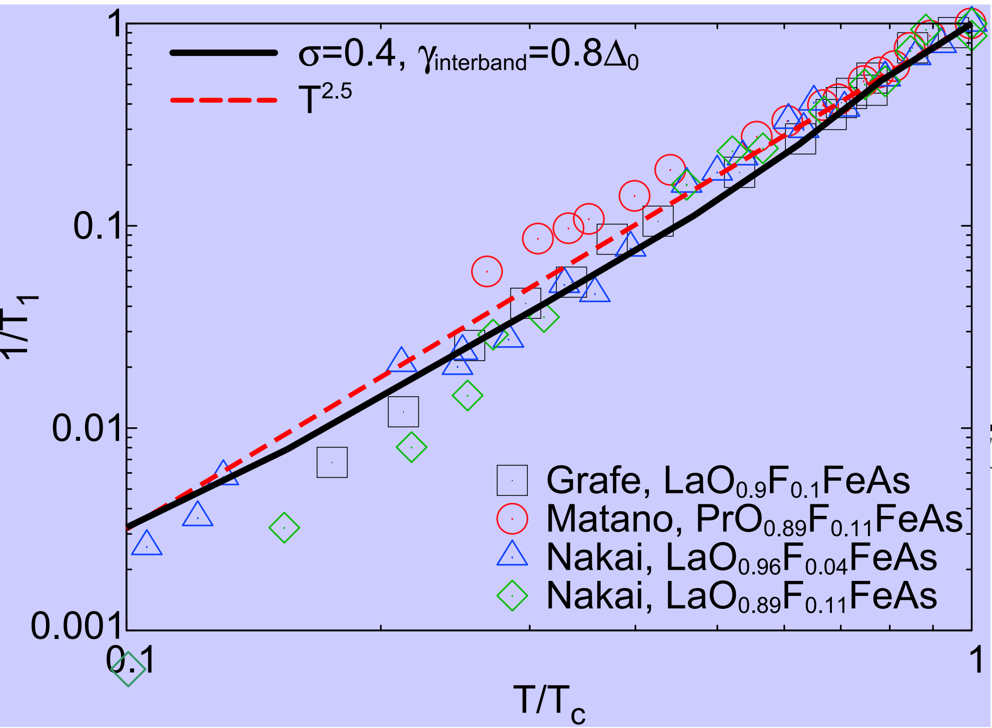
Eliashberg (strong coupling)

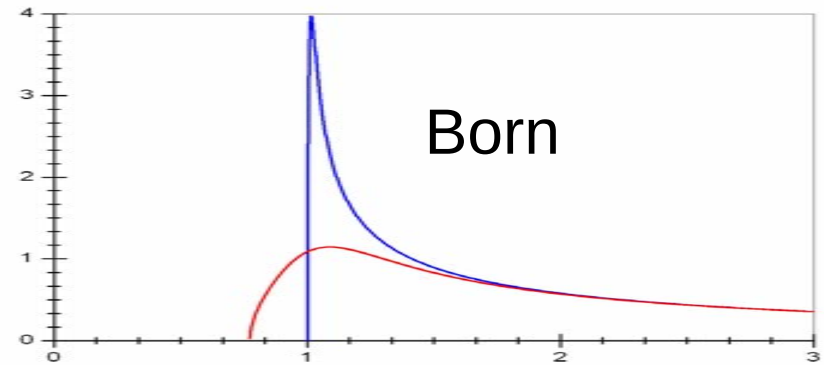
$$\begin{cases} \Delta_1(1+\lambda_{12} = \lambda_{12}\Delta_2 \ln(1.13\omega_c/T_c) \\ \Delta_2(1+\lambda_{21}) = \lambda_{21}\Delta_1 \ln(1.13\omega_c/T_c) \end{cases}$$

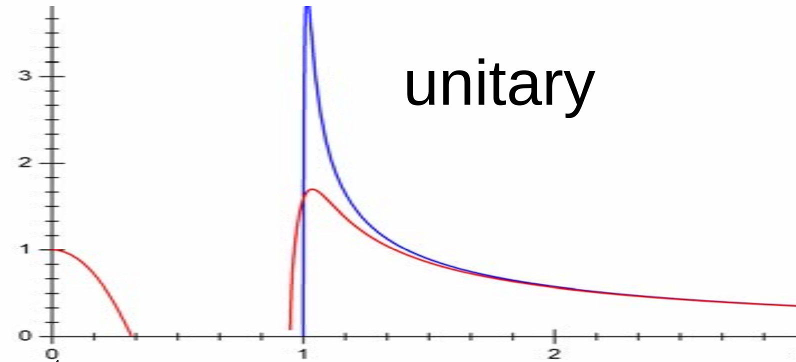
$$\frac{\Delta_1(T)}{\Delta_2(T)} = -\sqrt{N_2/N_1}\left(1+\frac{\sqrt{\lambda_{12}\lambda_{21}}\ln(N_2/N_1)}{4}+\frac{\lambda_{21}-\lambda_{12}}{2}\right)$$

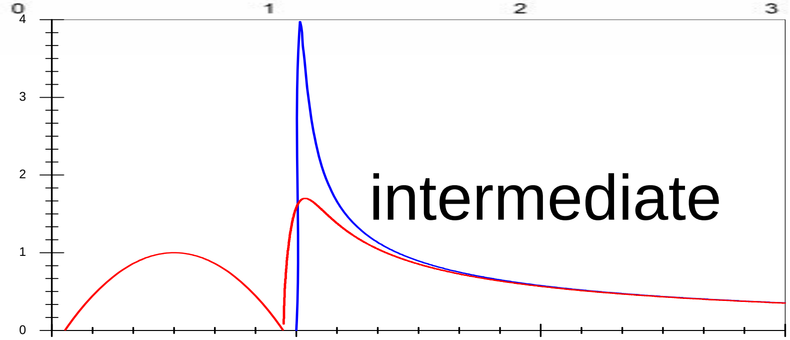
$s_{\pm}$-specific properties

Impurity scattering: reversed Ab









are pair-breaking and magnetic impurities are not.

Inversed coherence factors for q~(π,π) scattering

Constructive and destructive coherence factors:

$E_kE_{k'}-\Delta_k\Delta_{k'}$: *destructive for* $\Delta_k\Delta_{k'}>0$*, cancels DOS*

$E_kE_{k'}+\Delta_k\Delta_{k'}$: *constructive for* $\Delta_k\Delta_{k'}>0$*, peaks as DOS*

This is reversed if $\Delta_k\Delta_{k'}<0$ (as known in cuprates)

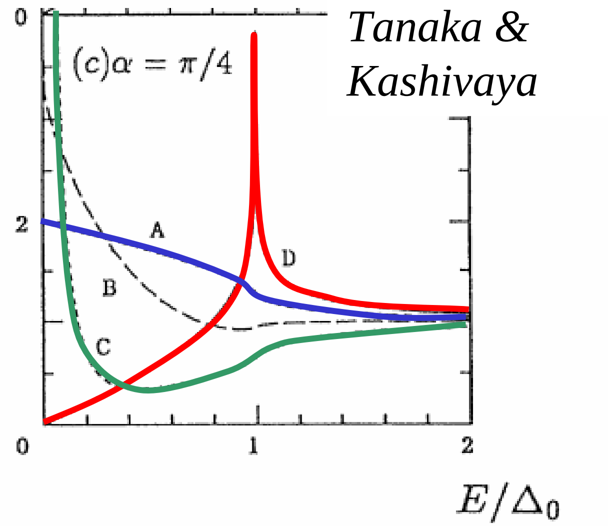
Expect no coherence peak in $1/TT_1$ (assuming main fluctuations at $Q=\{\pi,\pi\}$)

Expect a coherence peak in Imχ at $Q=(\pi,\pi)$

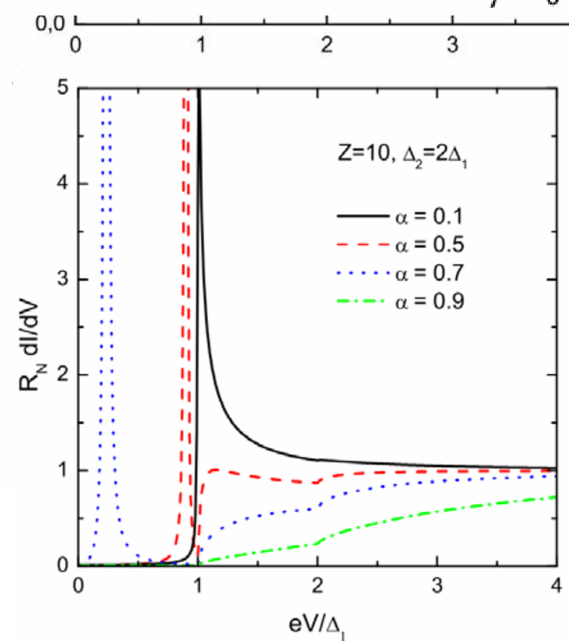
…more subtle (but maybe detectable) effects in phonon renormalization, quasiparticle scattering etc.

Phase-sensitive tunneling effects: Andreev bound states

1. Recall d-wave: (i) in the high-transparency limit σ(0)=2, (ii) in the low-transparency limit σ(0)→∞ (ZB bound state), and (iii) the result depends on angle.
2. In $S_{\pm}$ (i) in the high-transparency limit σ(0)<2, (ii) in the low-transparency limit $\sigma(E_B)\to\infty$ (finite-bias bound state), and (iii) the result depends on the ratios of the gaps and of the e/h barrier transparency.



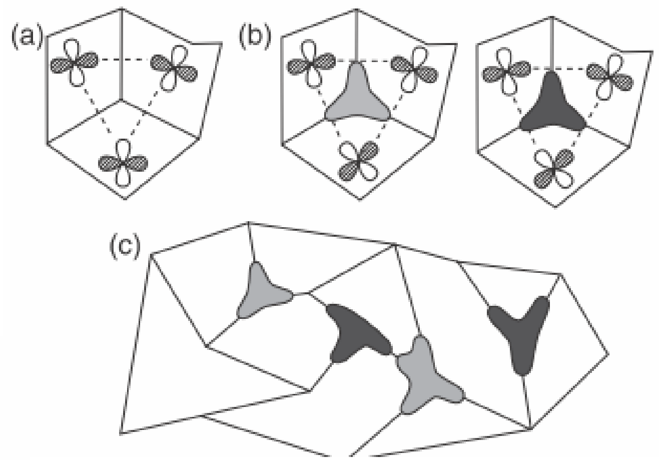
Tanaka & Kashivaya

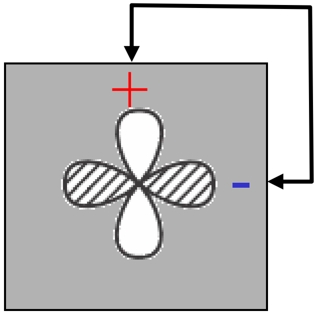


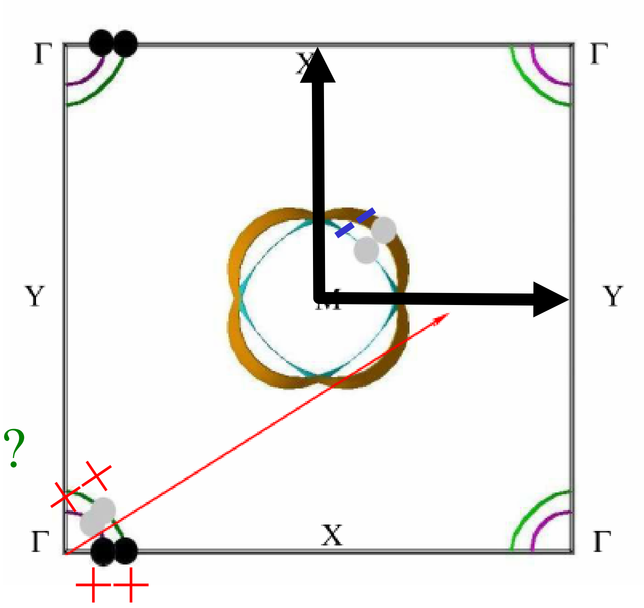
There are new effects, but they are very difficult to single out experimentally

Phase-sensitive tunneling effects: Josephson

- <u>c-axis Josephson</u> *distinguishes l≠0 symmetries from extended s; observed (R. Greene et al, PRL)*
- <u>Paramagnetic Meissner</u> (Wohlleben) effect; *not observed (K.A. Moler et al, JPSJ)*
- <u>π-junctions</u>: finite-angle design





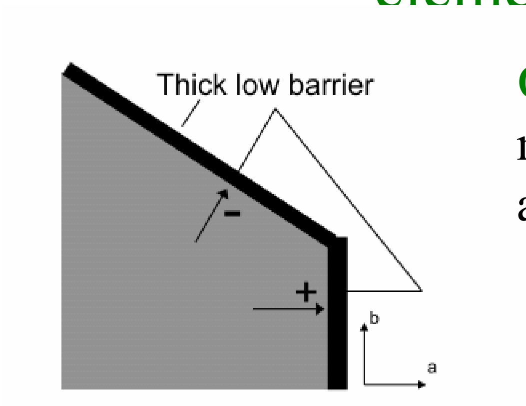


90º – does not work qualitatively
45º – matrix elements? Does not work quantitatively

Phase-sensitive tunneling effects: corner junctions

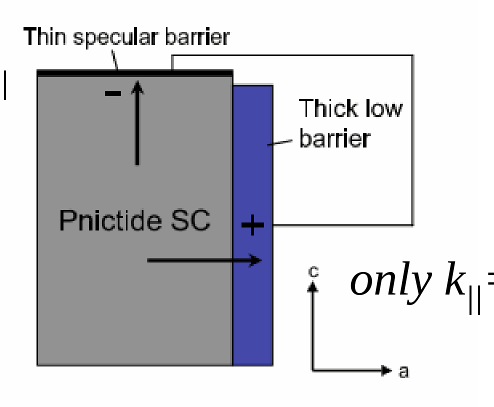
Can we influence matrix elements? – yes we can!

also suggested in another geometry by F.C. Zhang et al, 0906.0169



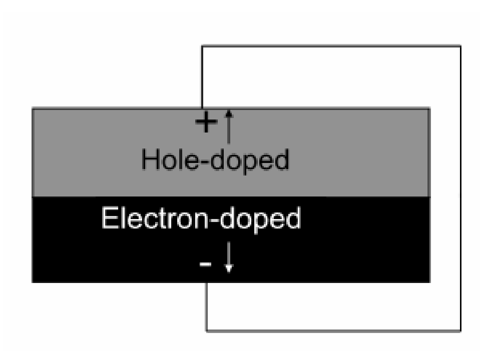
$\alpha<45^{o}$ (the gap difference may also be helpful – Wu and Phillips)

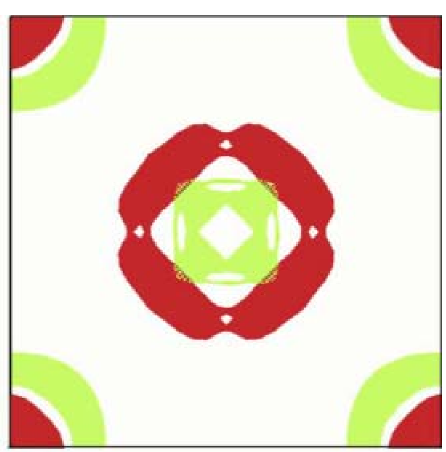
all $k_{||}$

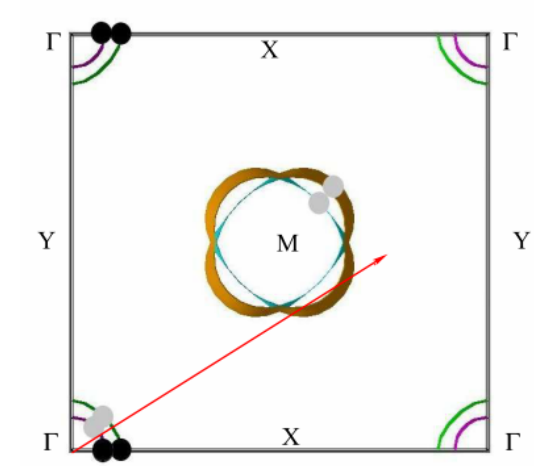


only $k_{||}=0$

Can we design a circuit without relying upon matrix elements? –



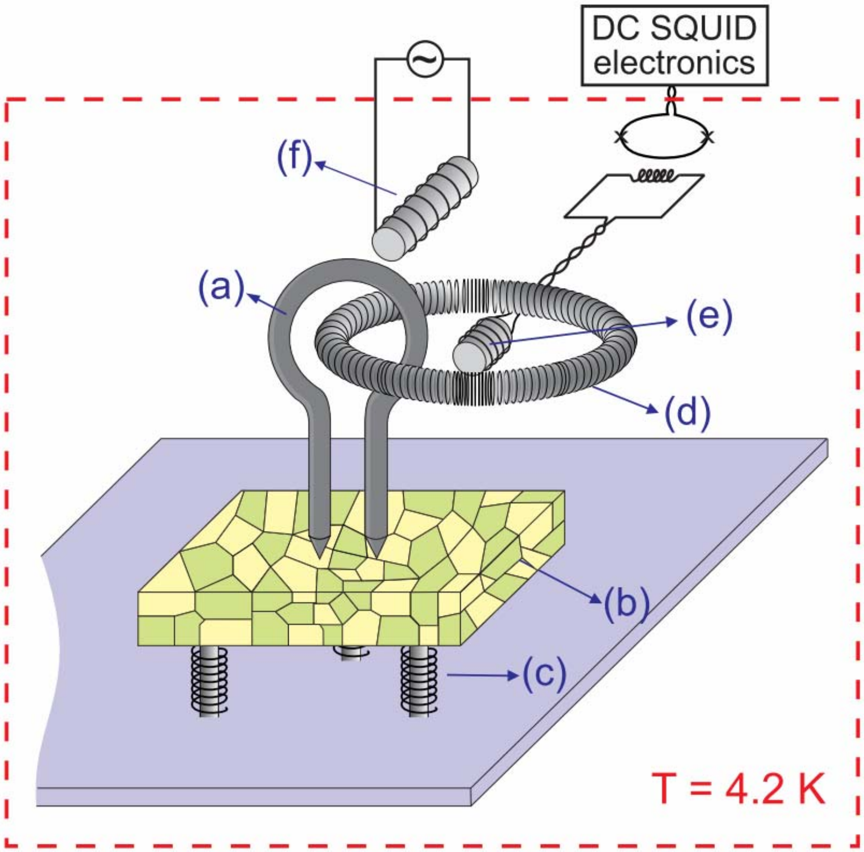




prerequisite: momentum conservation at the interface

Phase-sensitive tunneling effects: “fork circuits”

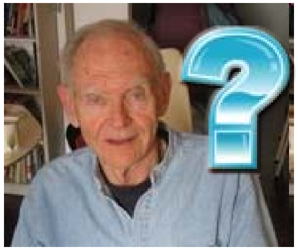
IBM group, cond-mat arXiv:0905.3571



Half-integer fluxes detected.

Why different grains have different signs? (“ These rich flux jump phenomena reflect the polycrystalline nature of the sample, which is believed to consist of an array of randomly distributed 0- and π-phase-shifted Josephson junctions”).

Probably, they reflect different local geometries and different barrier strength, as on the previous slide)



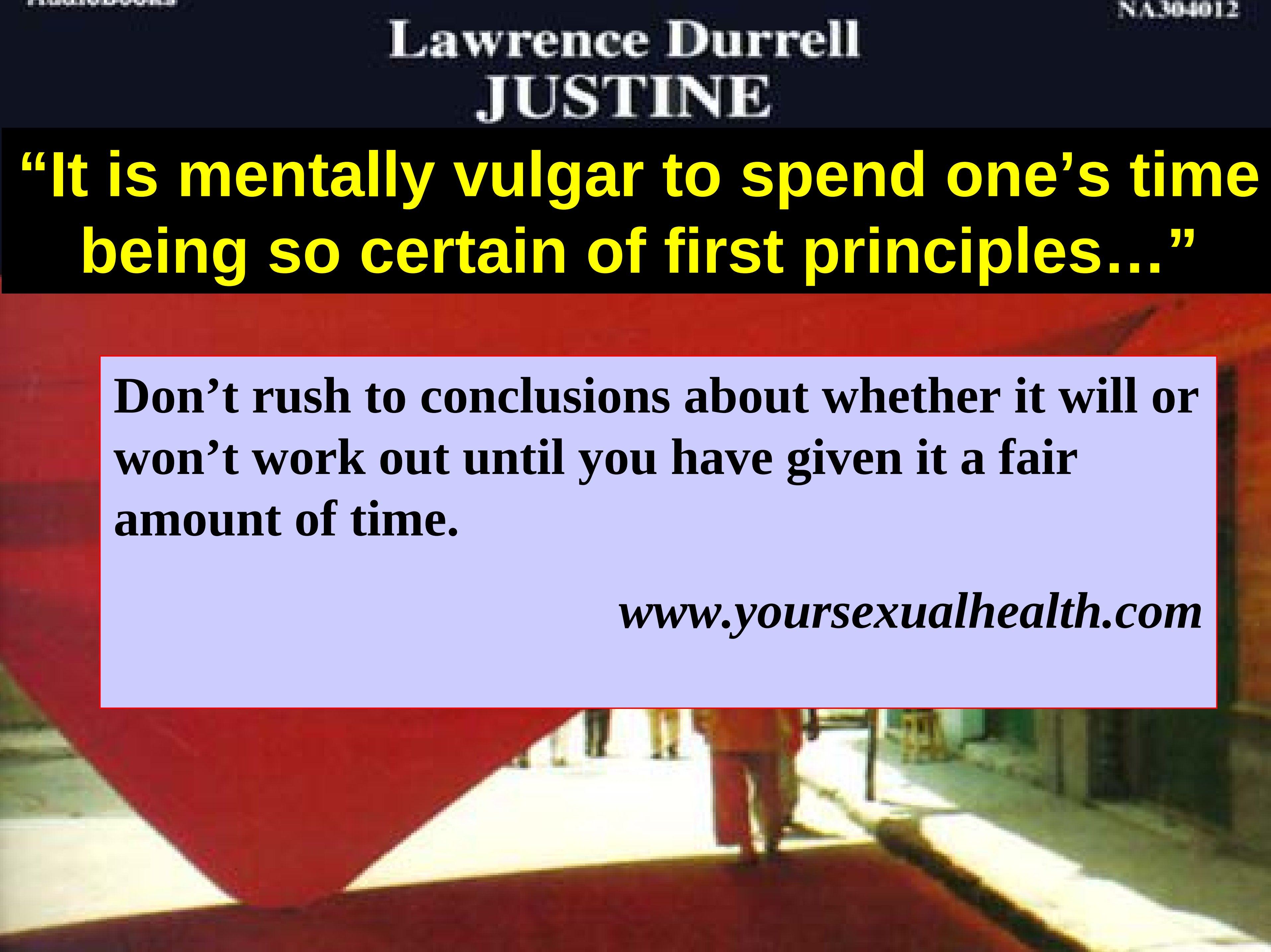
3. Is there a resolution of the conflicting results on the pairing symmetry and why is it important? *We know it is singlet (Knight), we know it is not d-wave (para-Meissner, 90^o Josephson, c-axis Josephson, ARPES), we more or less know that Δ changes sign (fork junctions). We see a resonant neutron mode.*

The results on pairing symmetry are not really conflicting.

There are conflicting results on the nodal structure/subgap excitation, but this is another, less important issue.

4. Is there orbital order in the antiferromagnetic state *(yes)* and does it matter *(no)*?

5. What is the nature of the quantum criticality *(probably Ising ordering of 2D Heisenberg magnets)* and will it tell us anything about the superconductivity *(?)*?



“It is mentally vulgar to spend one’s time being so certain of first principles…”

Don’t rush to conclusions about whether it will or won’t work out until you have given it a fair amount of time.

www.yoursexualhealth.com