

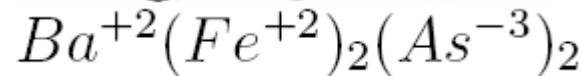
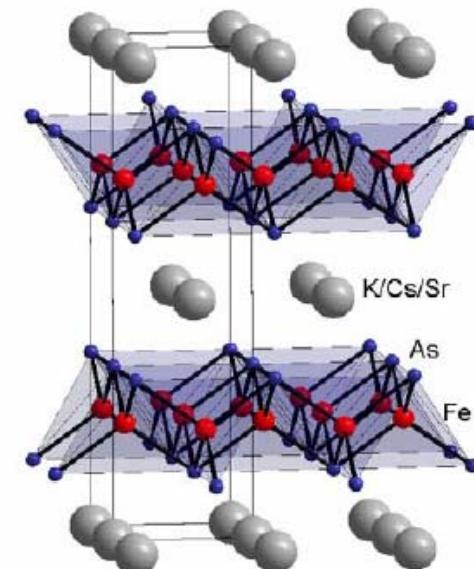
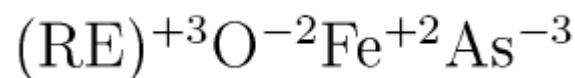
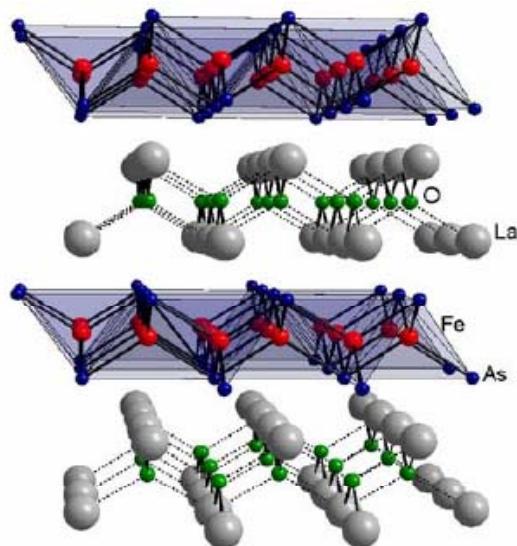
# **New results in the pysics of superconducting ferro-pnictides: theory, experiment, and applications**

## Theory

1. O.V. Dolgov, A.A. Golubov, D. Parker,  
**“Microwave response of superconducting pnictides: extended S+- model”**,  
New Journal of Physics 11, 075012 (2009).
2. A.A. Golubov, A. Brinkman, Yukio Tanaka, I. I. Mazin, and O. V. Dolgov,  
**“Andreev Spectra and Subgap Bound States in Multiband Superconductors”**  
Phys. Rev. Lett. 103, 077003 (2009)
3. O.V. Dolgov, I. I. Mazin, D. Parker and A.A. Golubov **“Interband superconductivity: contrasts between Bardeen-Cooper-Schrieffer and Eliashberg theories”**, Physical Review B **79**, 060502 R (2009)

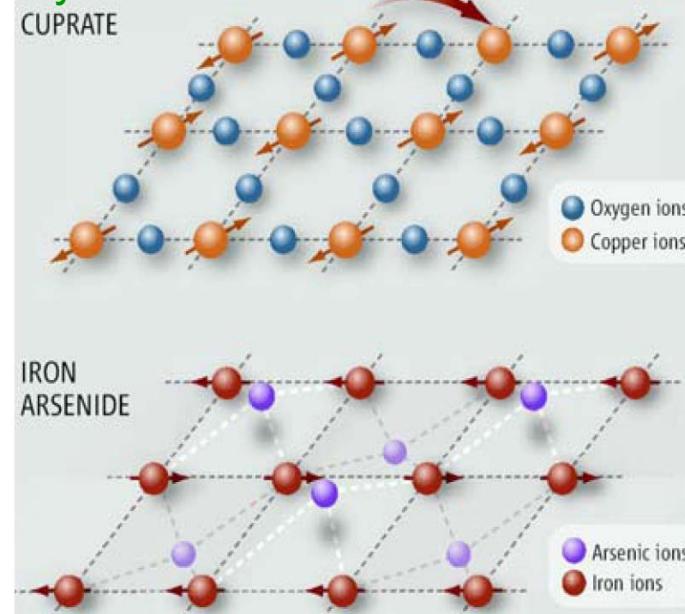
## Experiment

1. V.N.Zverev, A.V.Korobenko, G.L.Sun, D.L.Sun, C.T.Lin, and A.V.Boris, «**Transport properties and the anisotropy of  $Ba_{1-x}K_xFe_2As_2$  single crystals in normal and superconducting states**» Письма в ЖЭТФ, 90(2), 140-143 (2009)
2. A.N. Lavrov, L.P. Kozeeva, M.R. Trunin, V.N. Zverev “**Competition and coexistence of antiferromagnetism and superconductivity in  $RBa_2Cu_3O_{6+x}$  ( $R=Lu, Y$ ) single crystals**” Phys. Rev. B 79, 1 (2009)
3. L.Ya.Vinnikov, D.E.Boinagrov, V.N. Zverev and J. Karpinski, **Abniosotropy of the vortex structure and resistivity in the basal plane  $YBCO(248)$  single crystals**, JETP, vol.109, №2, 280-285 (2009)
4. M.R. Eskildsen, L.Ya. Vinnikov, T.D. Blasius, I.S. Veshchunov, T.M. Artemova, J.M. Densmore, C.D. Dewhurst, N.Ni, A.Kreyssig, S.L. Bud'ko, P.C. Canfield, and A.I. Goldman **Vortices in superconducting  $Ba(Fe0.93Co0.07)_2As_2$  studied via small-angle neutron scattering and Bitter decoration** Phys. Rev. B 79, 100501(R) (2009)
5. M.R. Eskildsen, L.Ya. Vinnikov, T.D. Blasius, I.S. Veshchunov, T.M. Artemova, J.M. Densmore, C.D. Dewhurst, N.Ni, A. Kreyssig, S.L. Bud'ko, P.. Canfield, and A.I. Goldman, **Vortex imaging in Co-doped  $BaFe2As2$** , Physica C 469, 529-534 (2009)
6. M.R. Eskildsen, L.Ya. Vinnikov, T.D. Blasius, I.S. Veshchunov, T.M. Artemova, J.M. Densmore, C.D. Dewhurst, N.Ni, A. Kreyssig, S.L. Bud'ko, P.C. Canfield, and A.I. Goldman, “**Vortices in superconducting  $Ba(Fe_{0.93}Co_{0.07})_2As_2$  studied via small-angle neutron scattering and Bitter decoration**”, Phys. Rev. B 79, 100501 (R) (2009).
7. Л.Я. Винников, Д.Э. Бойнагров, В.Н. Зверев, И.С. Вещунов, Я. Карпински, **Анизотропия вихревой структуры и электросопротивления в базисной плоскости монокристаллов  $YBa_2Cu_4O_8$** , ЖЭТФ, вып.8, том 136, (2009)



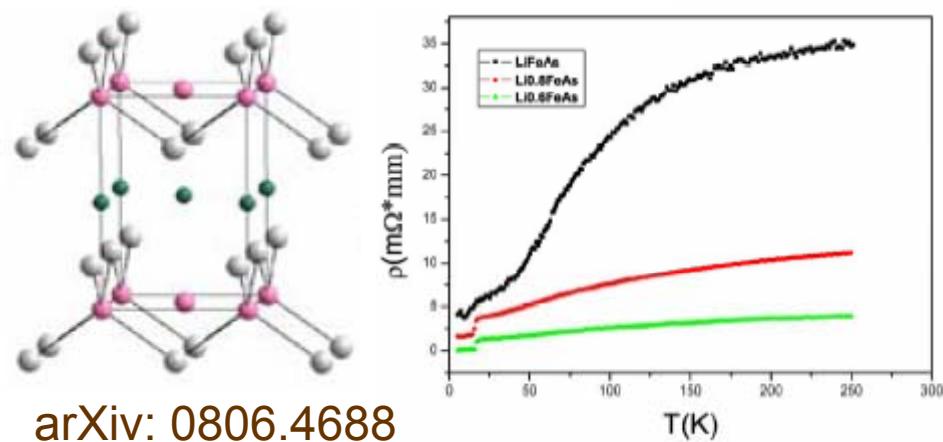
## Basic crystal structure of FeAs superconductors

CuO<sub>2</sub> as compared with FeAs layers:

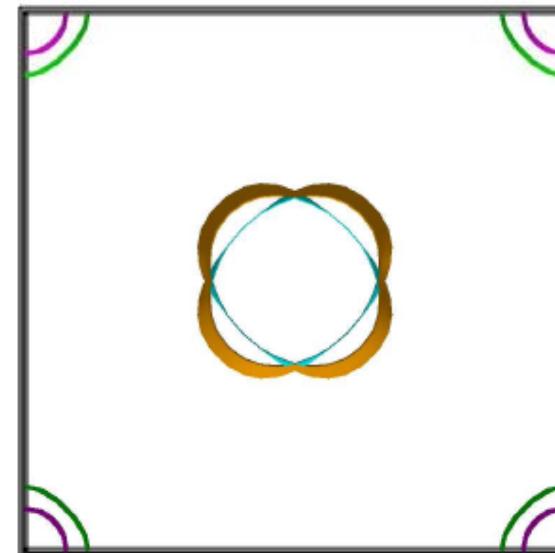
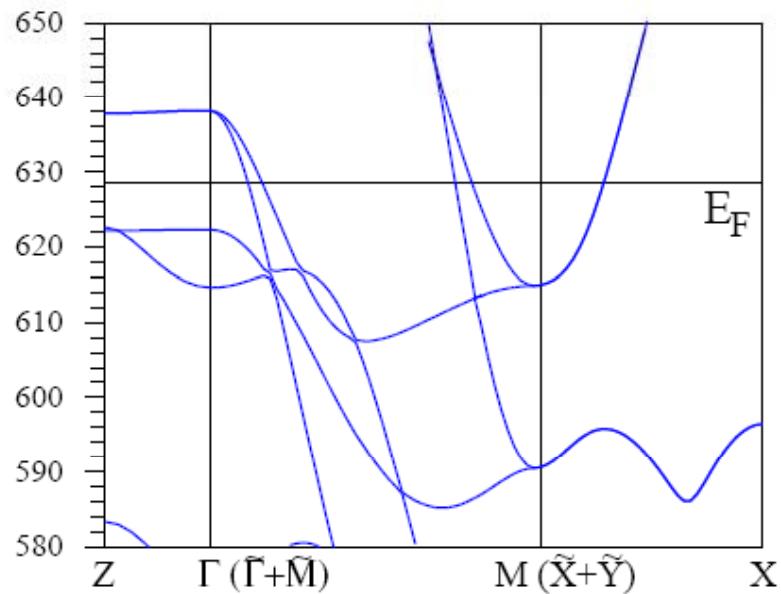


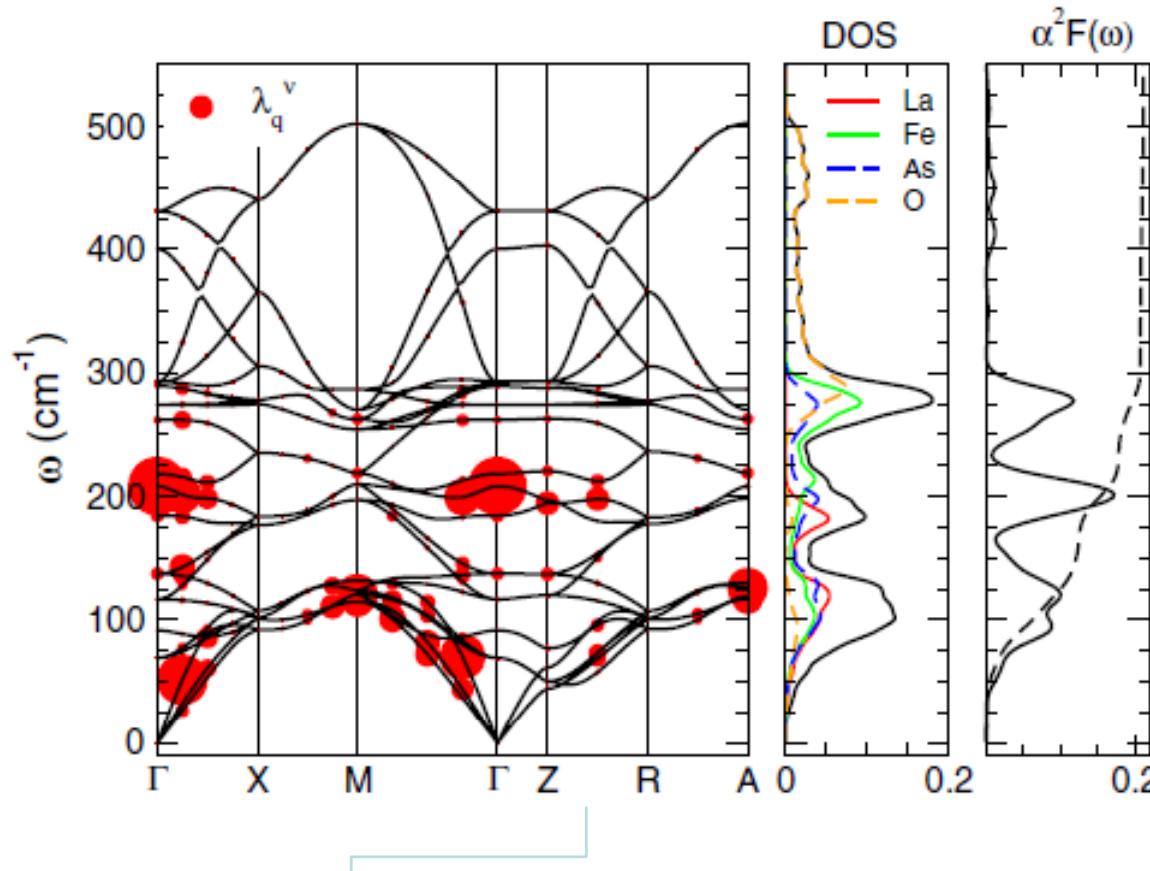
The superconductivity at 18 K in Li<sub>1-x</sub>FeAs compounds

X.C.Wang, Q.Q.Liu, Y.X.Lv, W.B.Gao, L.X.Yang, R.C.Yu, F.Y.Li, C.Q.Jin\*



# Band structure





$$\lambda = 0.21 \quad (\text{for Al } \lambda=0.44)$$

Not sufficient to explain SC!

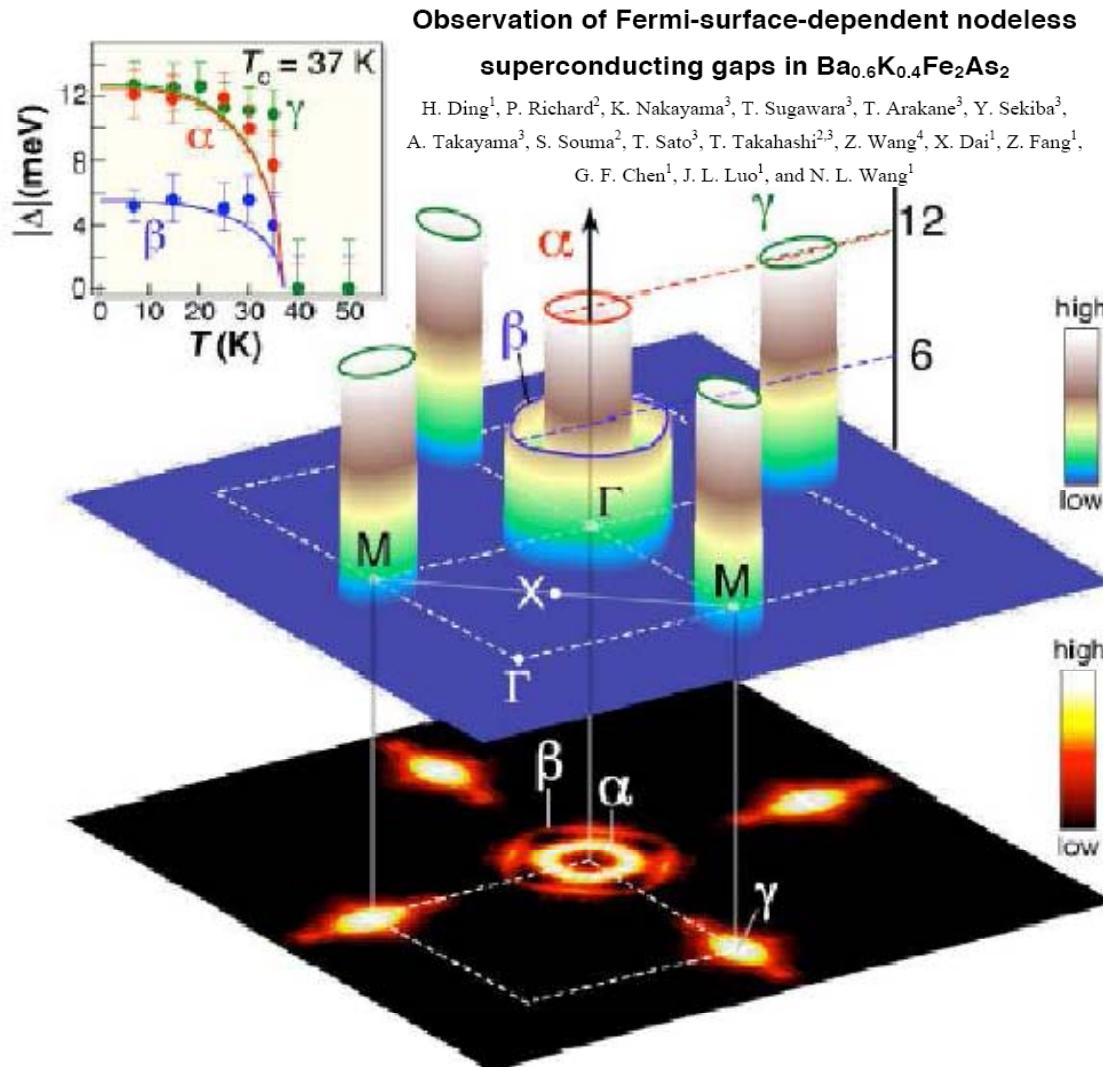
L. Boeri, O.V. Dolgov, and A.A. Golubov, PRL 101, 026403 (2008);

D.J. Singh and M.-H. Du, PRL 100, 237003 (2008)

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

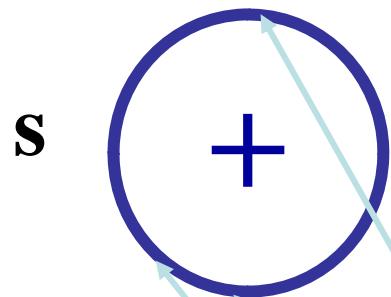
$$\lambda(\omega) = 2 \int_0^\omega d\Omega \alpha^2 F(\Omega) / \Omega$$

# Superconducting gap – ARPES data



Schematic picture of superconducting gaps in  $\text{Ba}_{0.6}\text{K}_{0.4}\text{Fe}_2\text{As}_2$ . Lower picture represents Fermi surfaces (ARPES intensity), upper insert – temperature dependence of gaps at different Sheets of the Fermi surface.

## Repulsive pairing interactions in the $s_{+/-}$ channel:



$$\lambda_s = N(0) \langle \langle V(\mathbf{q}) \rangle \rangle_{\text{FS}}$$

s-wave:  
 $V > 0$  for all  $\mathbf{q}$

Spin fluctuation  
exchange repulsive, but  
pairing for all  $\mathbf{q}$ 's!

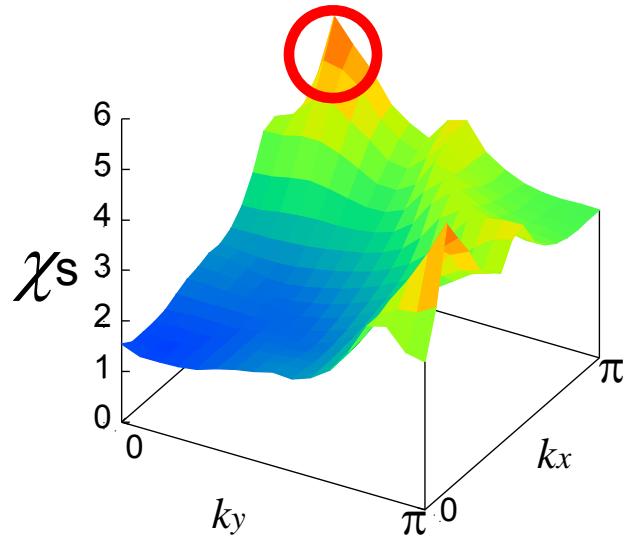
Simple model: spin sluctuations with spectral function

$$B_{ij}(\omega) = \lambda_{ij} \frac{\omega \Gamma \Omega_{sf}^2}{(\Omega_{sf}^2 - \omega^2)^2 + (2\omega\Gamma)^2}$$

Schuttler and Norman (1996)

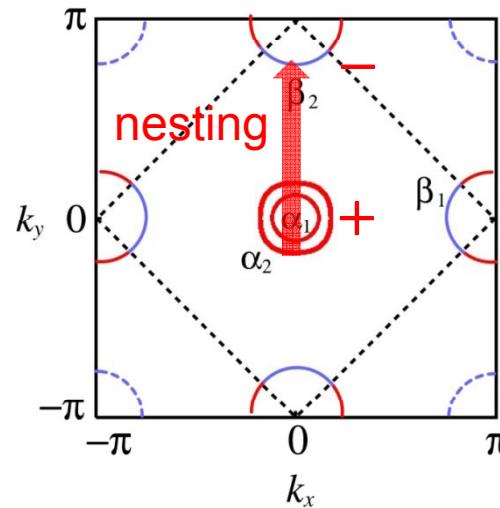
Parameters:  $\Omega_{sf} = 25\text{meV}$ ,  $\lambda_{11} = \lambda_{22} = 0.5$ ,  $\lambda_{12} = \lambda_{21} = -2$   $T_c=27\text{K}$

# Mechanism of $s_{+-}$ wave superconductivity



spin susceptibility

$Q=(0,\pi)$  stripe AF



$s_{+-}$  wave gap function

$s_{+-}$  wave changes sign of gap function along nesting vector

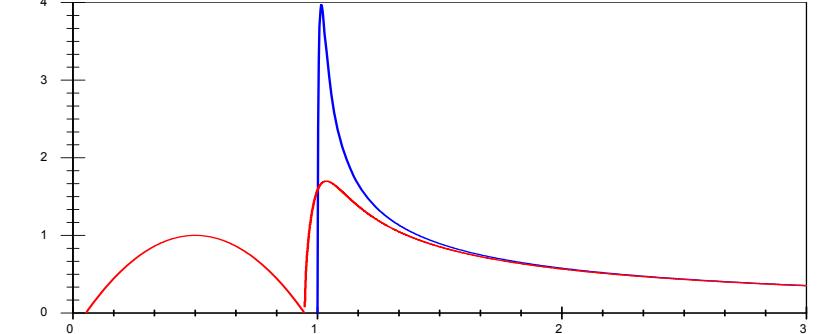
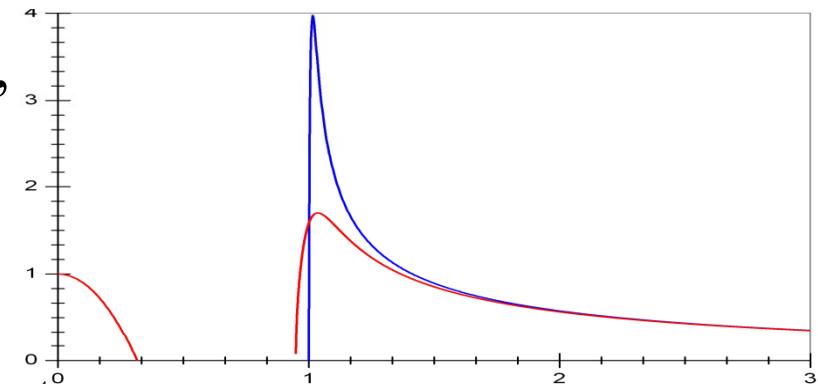
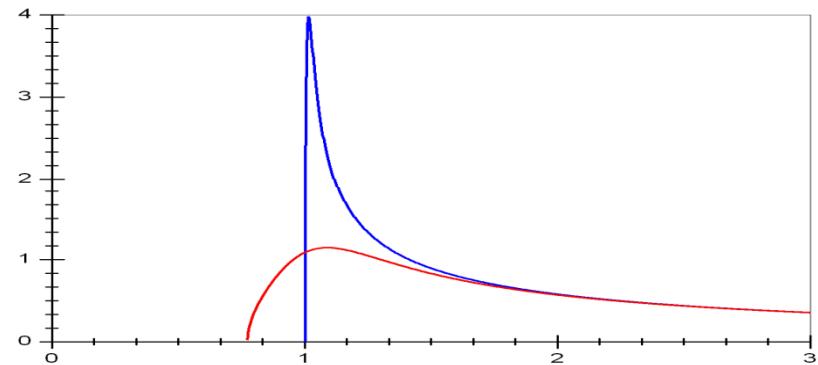


superconductivity mediated by the stripe AF spin fluctuation

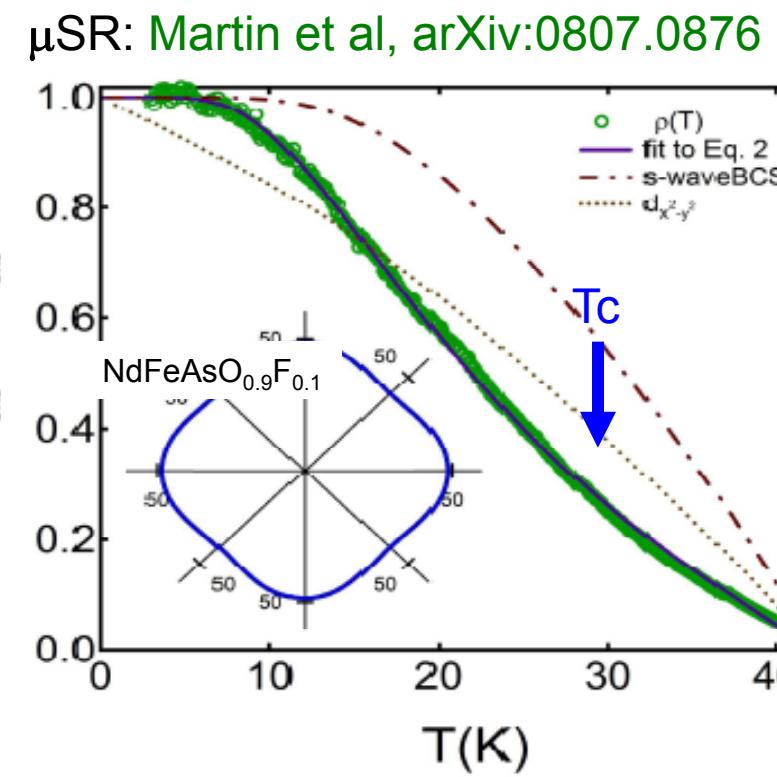
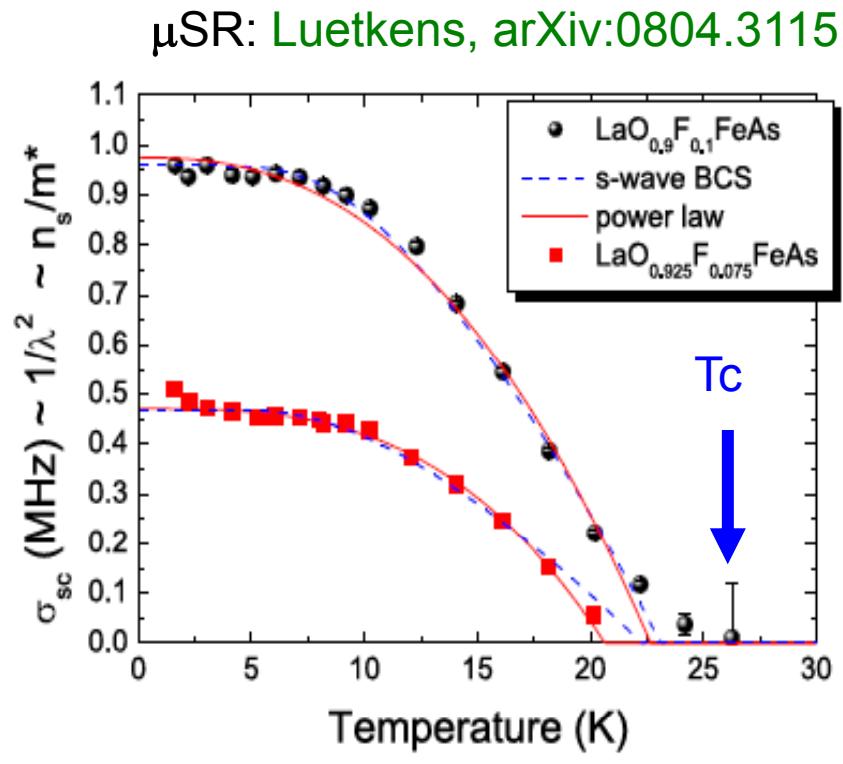
Mazin et al, PRL **101**, 057003 (2008); Kuroki et al, PRL **101**, 087004(2008)

# 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 T<sub>c</sub> suppression, zero-energy bound state
4. Intermediate limit: finite energy bound state, simulates power law



# Superfluid density $n_s$ : experiment



## Superfluid density: the model

$$1/\lambda_{L,\alpha\beta}^2(T) \equiv (\omega_{p,\alpha\beta}^{sf}(T)/c)^2 = \sum_{i=\sigma,\pi} \left( \frac{\omega_{p,i}^{\alpha\beta}}{c} \right)^2 \pi T \sum_{n=-\infty}^{\infty} \frac{\tilde{\Delta}_i^2(n)}{[\tilde{\omega}_i^2(n) + \tilde{\Delta}_i^2(n)]^{3/2}}$$

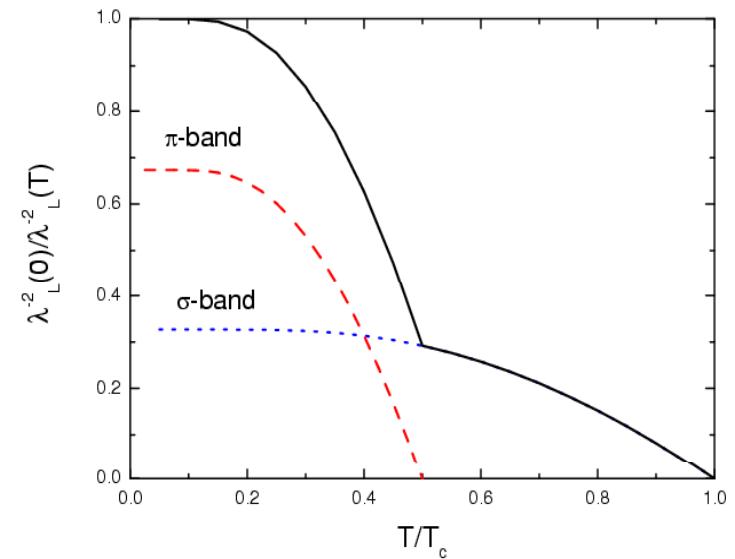
where  $\tilde{\omega}(n) = \omega_n Z(\omega_n)$  and  $\tilde{\Delta}(\omega_n) = \Delta(\omega_n)Z(\omega_n)$  are the solutions of the Eliashberg equations.

The case of weakly coupled bands (MgB2)

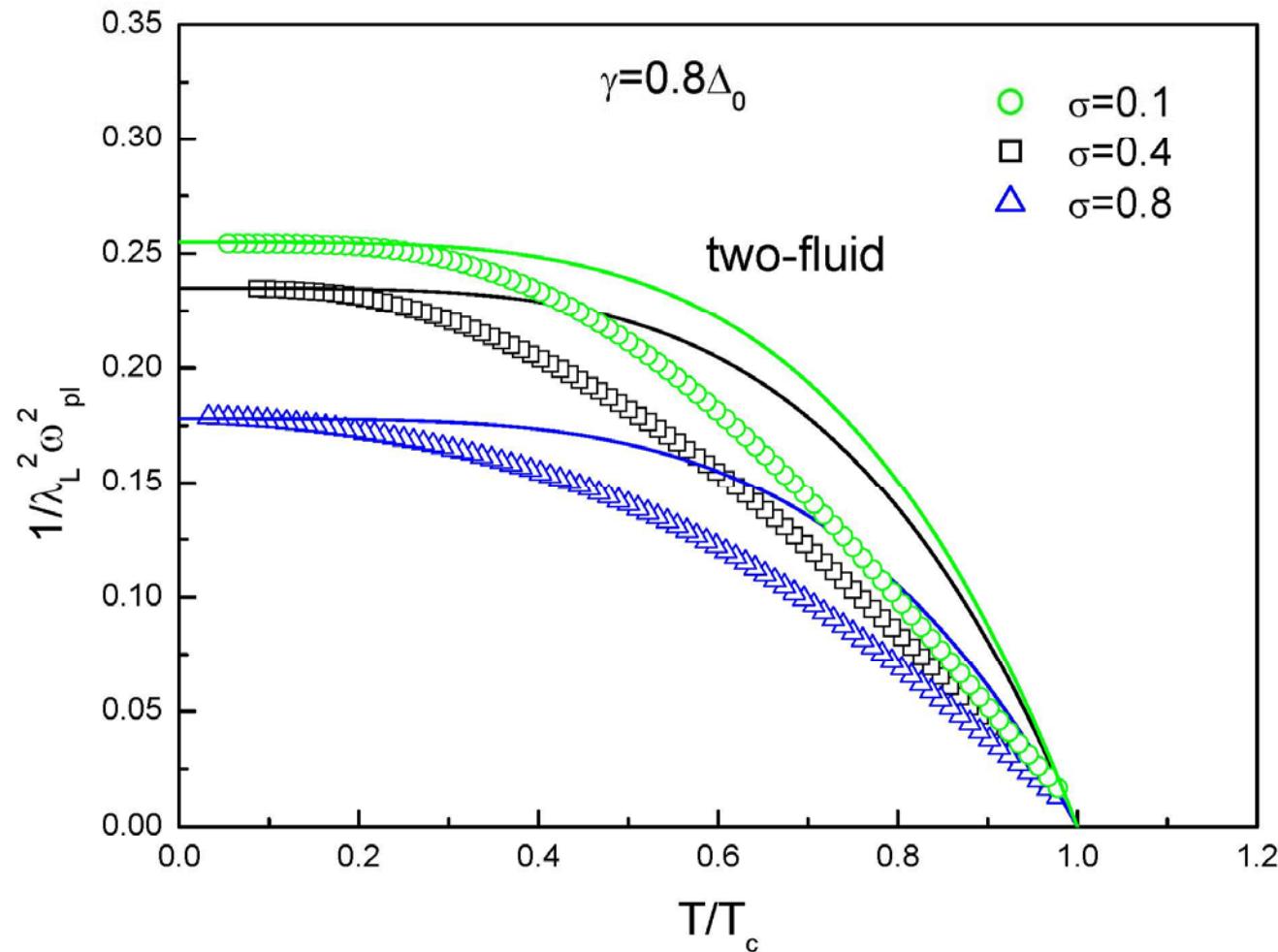
## Effects of impurities

$$\Delta_i \rightarrow \Delta_i^0 + \sum_j \gamma_{ij} \Delta_j / 2\sqrt{\omega_n^2 + \Delta_j^2},$$

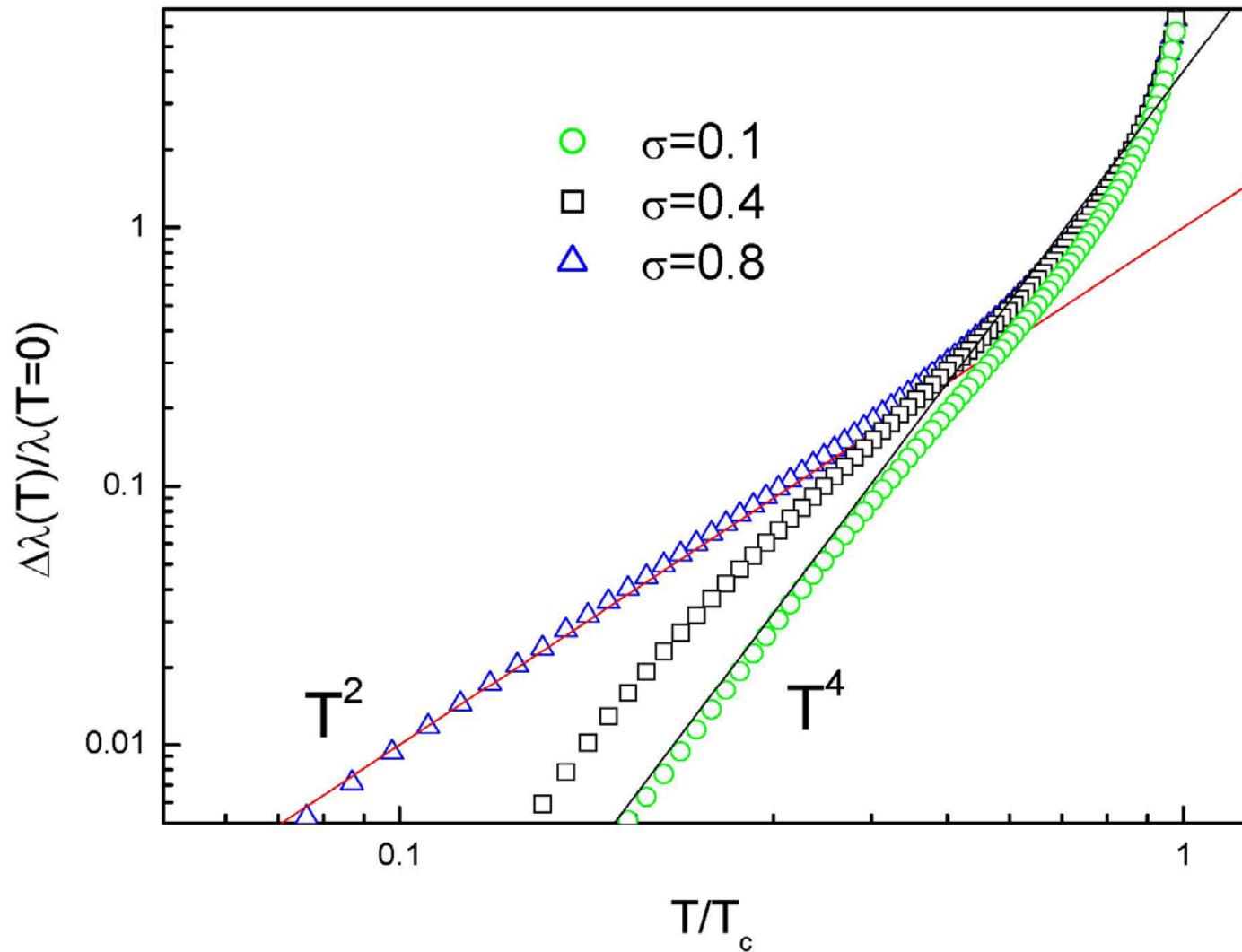
$$Z(\omega_n) \rightarrow Z^0(\omega_n) + \sum_j \gamma_{ij} / 2\sqrt{\omega_n^2 + \Delta_j^2}$$



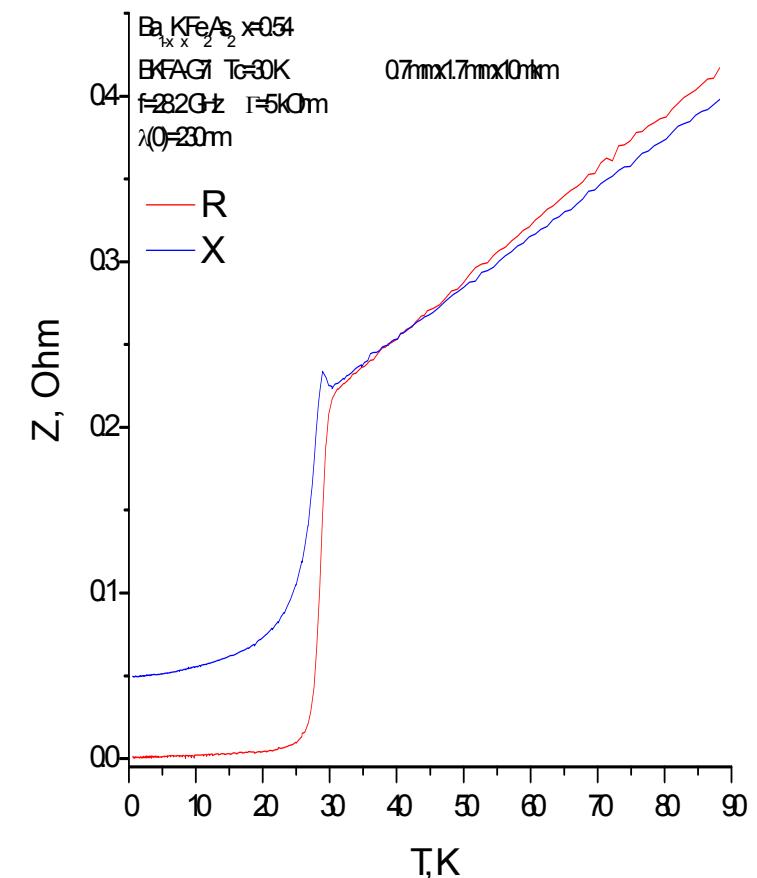
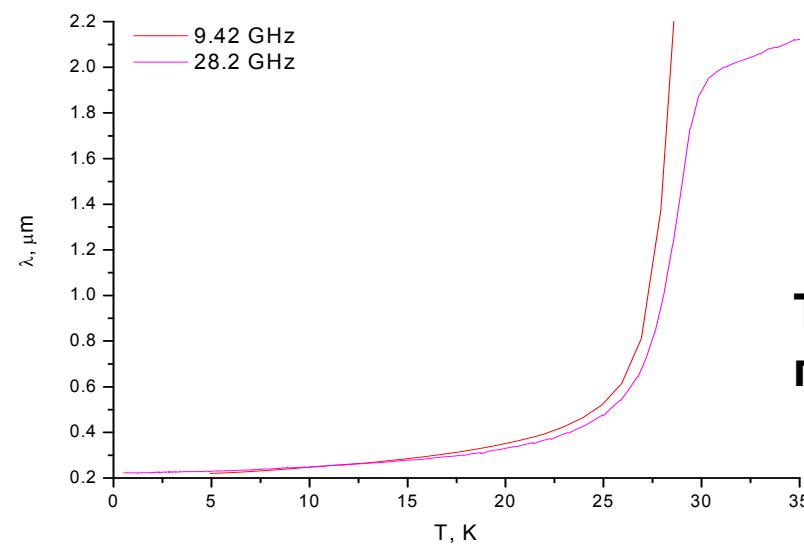
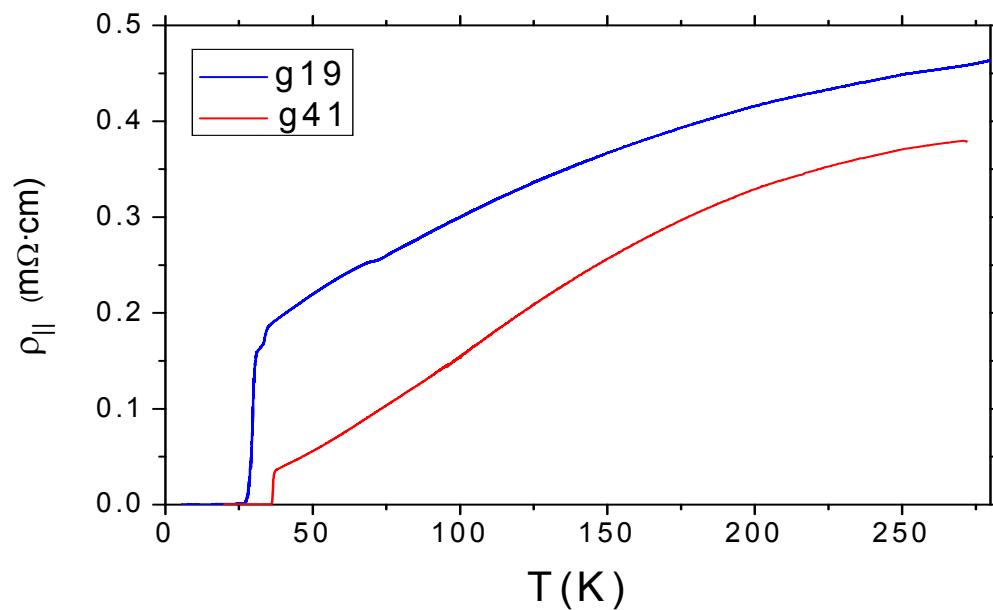
## Magnetic field penetration depth: calculations for various scattering rates



## Magnetic field penetration depth: low T

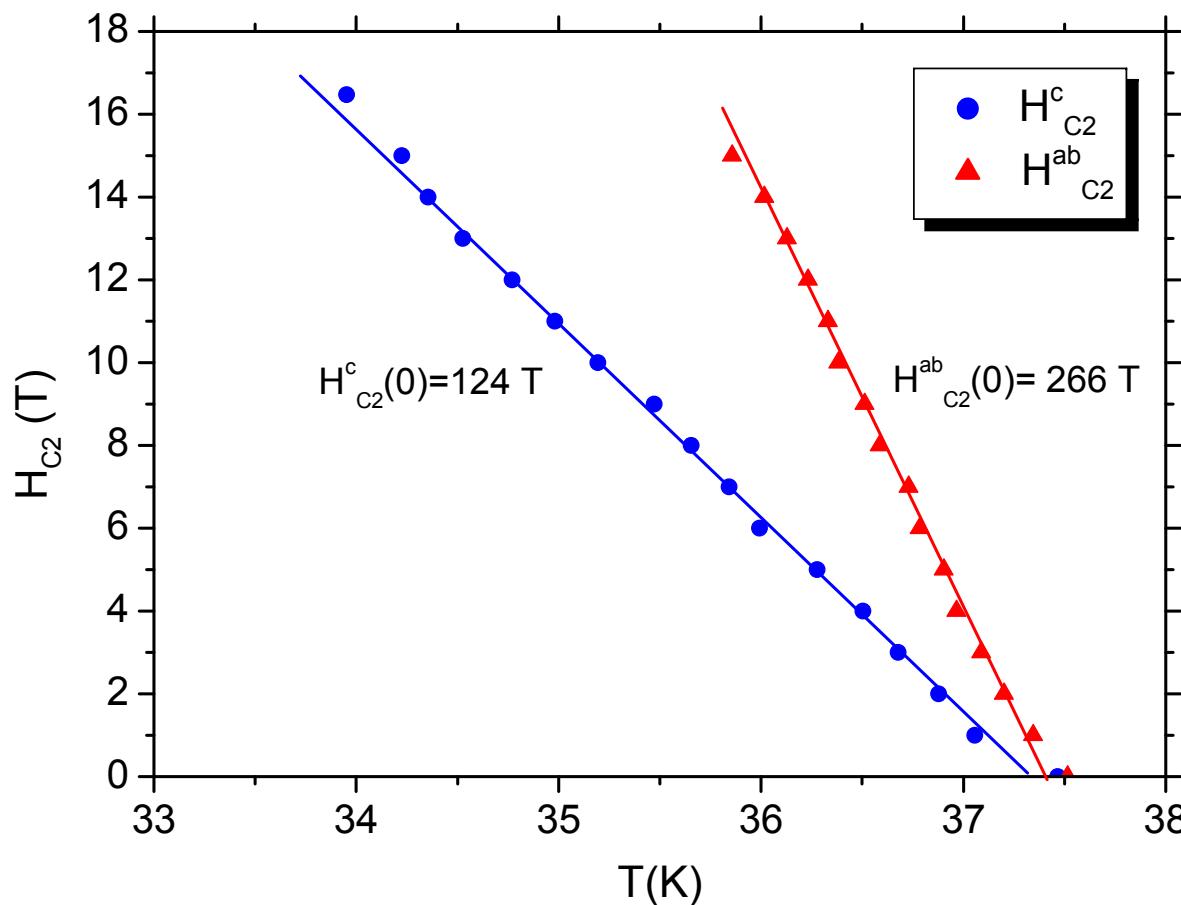


# Transport properties of $\text{Ba}_{1-x}\text{K}_x\text{Fe}_2\text{As}_2$ single crystals (LEK ISSP)



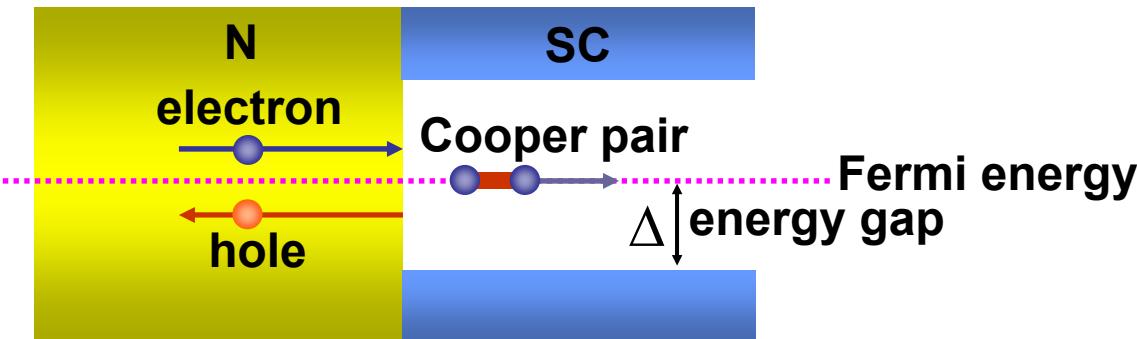
Температурная зависимость глубины проникновения поля

V.N.Zverev, A.V.Korobenko, G.L.Sun, D.L.Sun, C.T.Lin, and A.V.Boris,  
«Transport properties and the anisotropy of  $\text{Ba}_{1-x}\text{K}_x\text{Fe}_2\text{As}_2$  single  
crystals in normal and superconducting states»  
Письма в ЖЭТФ, 90(2), 140-143 (2009)

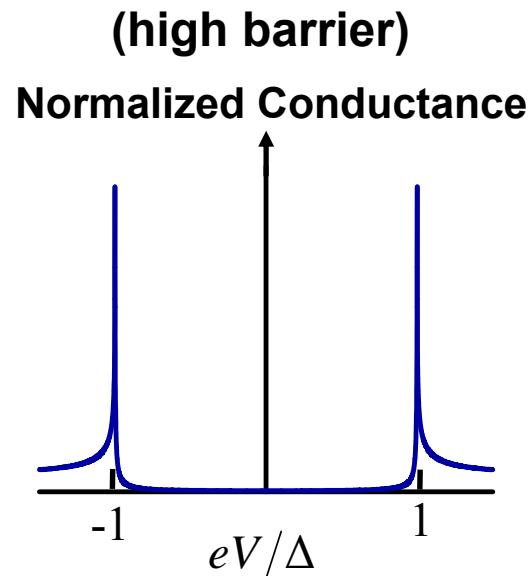
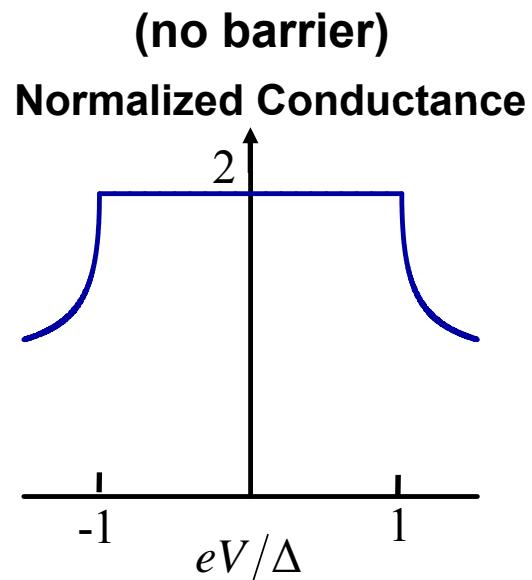


# Tunneling: the BTK theory

## Andreev reflection



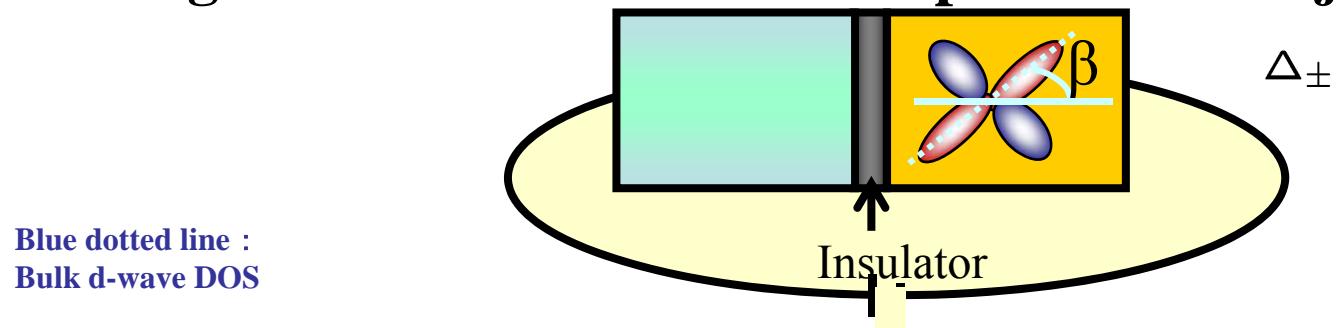
(N: Normal metal, SC: superconductor)



Barrier strength

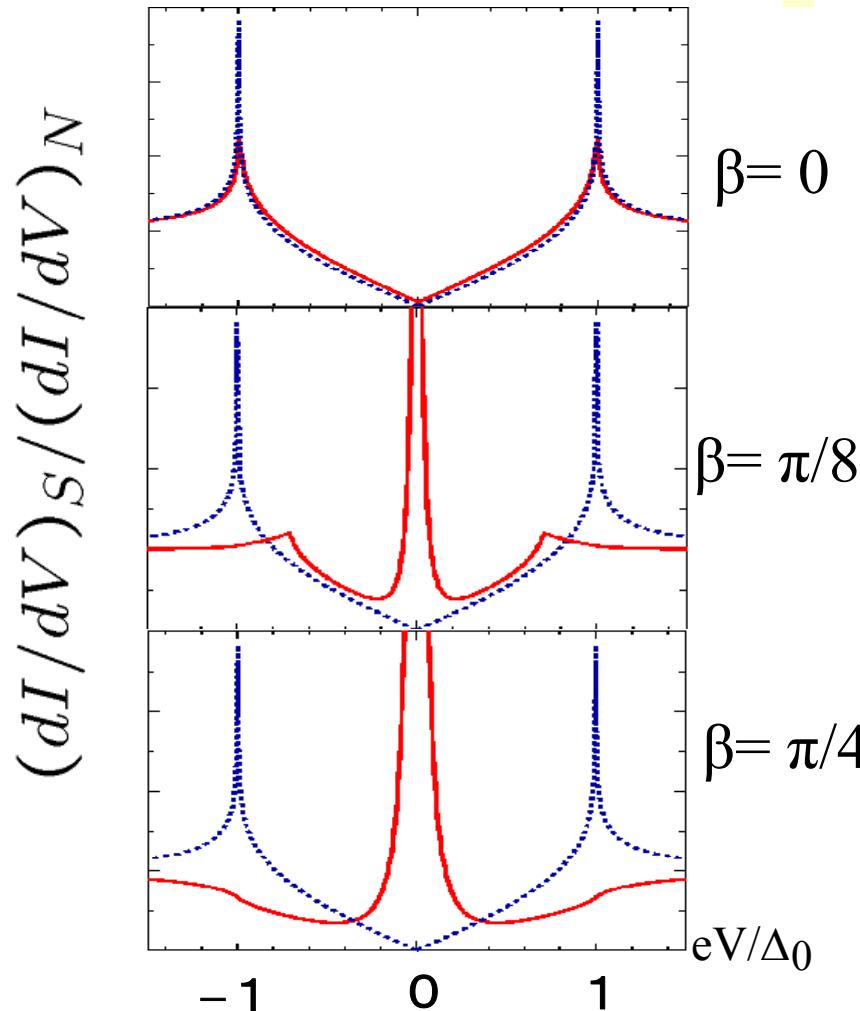
$$Z = H / \hbar v_F$$

# Tunneling conductance in d-wave superconductor junction (ballistic)

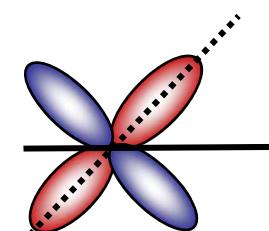
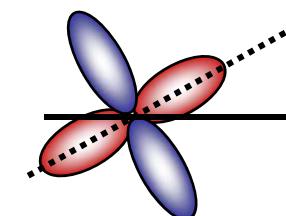
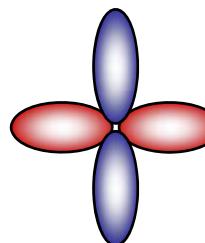


$$\Delta_{\pm} = \Delta_0 \cos[2(\theta \mp \beta)]$$

**Bruder (1990)**  
**Blonder Tinkham**  
**Klapwijk (1982)**



**Tanaka Kashiwaya (1995)**  
Phys Rev Lett 74 3451 (1995)



**ZBCP**  
Zero bias conductance peak

Mid gap Andreev  
resonant state

**Surface bound state**  
**Hu (1994)**  
**Buchholtz (1981)**  
**Hara Nagai(1986)**  
**Matsumoto Shiba(1995)**

# **Andreev spectra and Subgap bound states in multiband superconductors**

A.A. Golubov, A. Brinkman, Y. Tanaka  
I.I Mazin, and O.V. Dolgov

Phys. Rev. Lett. **103** 077003 (2009)

**Not so simple as compared to d-wave  
p-wave case (single band)**

## Tunneling in N/N(two band) junctions

A.A. Golubov et al, PRL **103**, 077003 (2009)

$$\Psi_L(x) = \psi_k(x) + b\psi_{-k}(x)$$

$$\Psi_R(x) = c[\phi_p(x) + \alpha_0\phi_q(x)]$$



Mixing coefficient  $\alpha_0$  defines the ratio of probability amplitudes for an electron crossing the interface from the left to tunnel into the first or second band on the right.

## The boundary conditions at the N/S interface ( $x=0$ )

$$\Psi_N(0) = \Psi_S(0),$$

$$\frac{\hbar^2}{2m} \frac{d}{dx} \Psi_S(0) - \frac{\hbar^2}{2m} \frac{d}{dx} \Psi_N(0) = H \Psi_N(0)$$

**H is the strength of the interface barrier**

$$\Psi = \Psi_N \theta(-x) + \Psi_S \theta(x),$$

$$\Psi_N = \psi_k \begin{pmatrix} 1 \\ 0 \end{pmatrix} + a \psi_k \begin{pmatrix} 0 \\ 1 \end{pmatrix} + b \psi_{-k} \begin{pmatrix} 1 \\ 0 \end{pmatrix},$$

$$\Psi_S = c \left[ \varphi_p \begin{pmatrix} u_1 \\ v_1 e^{-i\phi_1} \end{pmatrix} + \alpha_0 \varphi_q \begin{pmatrix} u_2 \\ v_2 e^{-i\phi_2} \end{pmatrix} \right]$$

$$+ d \left[ \varphi_{-p} \begin{pmatrix} v_1 \\ u_1 e^{-i\phi_1} \end{pmatrix} + \alpha_0 \varphi_{-q} \begin{pmatrix} v_2 \\ u_2 e^{-i\phi_2} \end{pmatrix} \right]$$

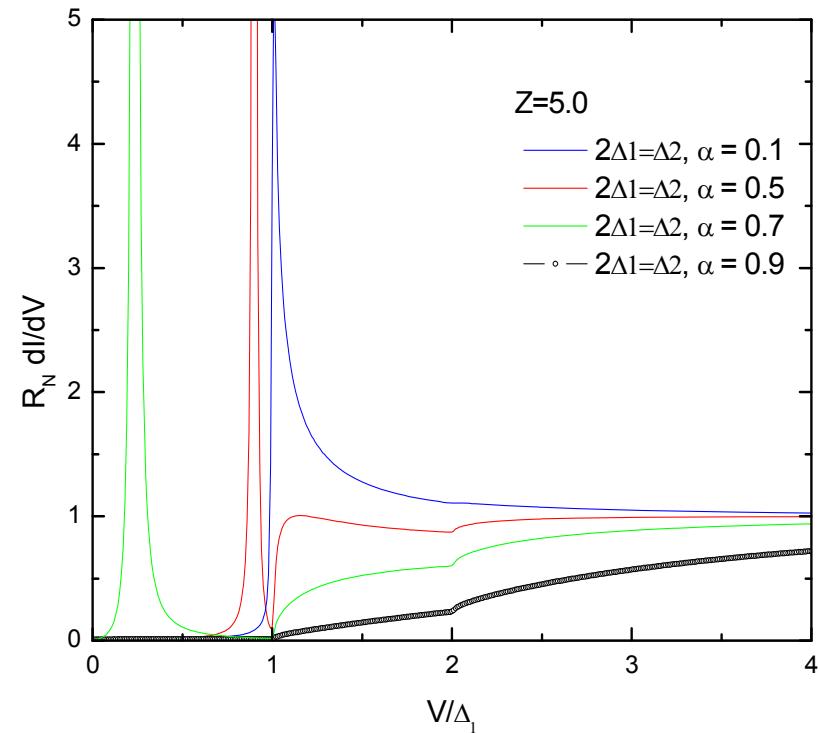
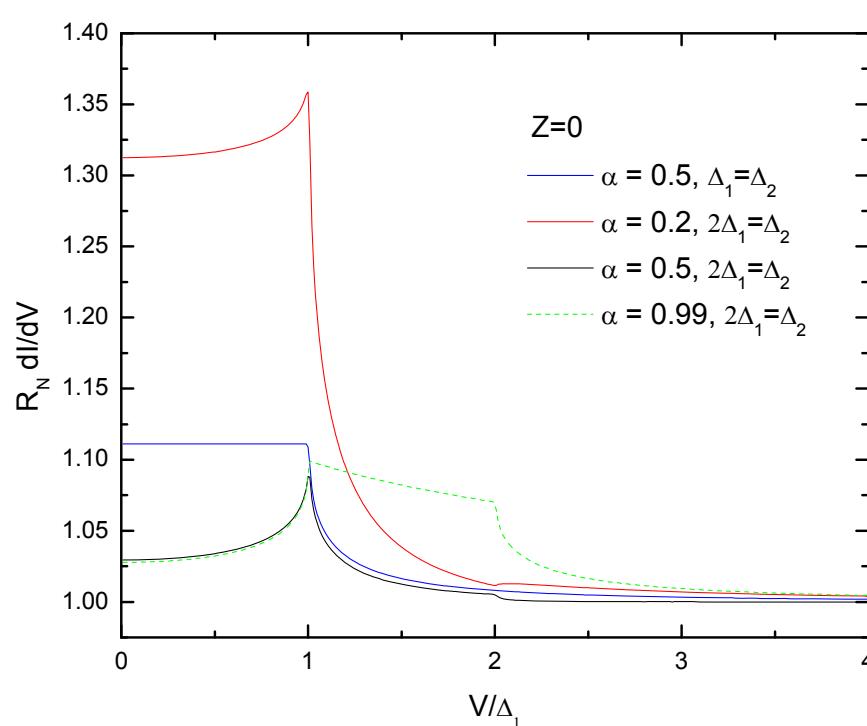
Coefficients are determined from boundary condition

$$u_{1,2} = \sqrt{(E + \sqrt{E^2 - \Delta_{1,2}^2})/2E},$$

$$v_{1,2} = \sqrt{(E - \sqrt{E^2 - \Delta_{1,2}^2})/2E},$$

# Tunneling conductance in the $s_{\pm}$ case

$$Z = H / \hbar v_{FN} \quad \text{H – the barrier height}$$

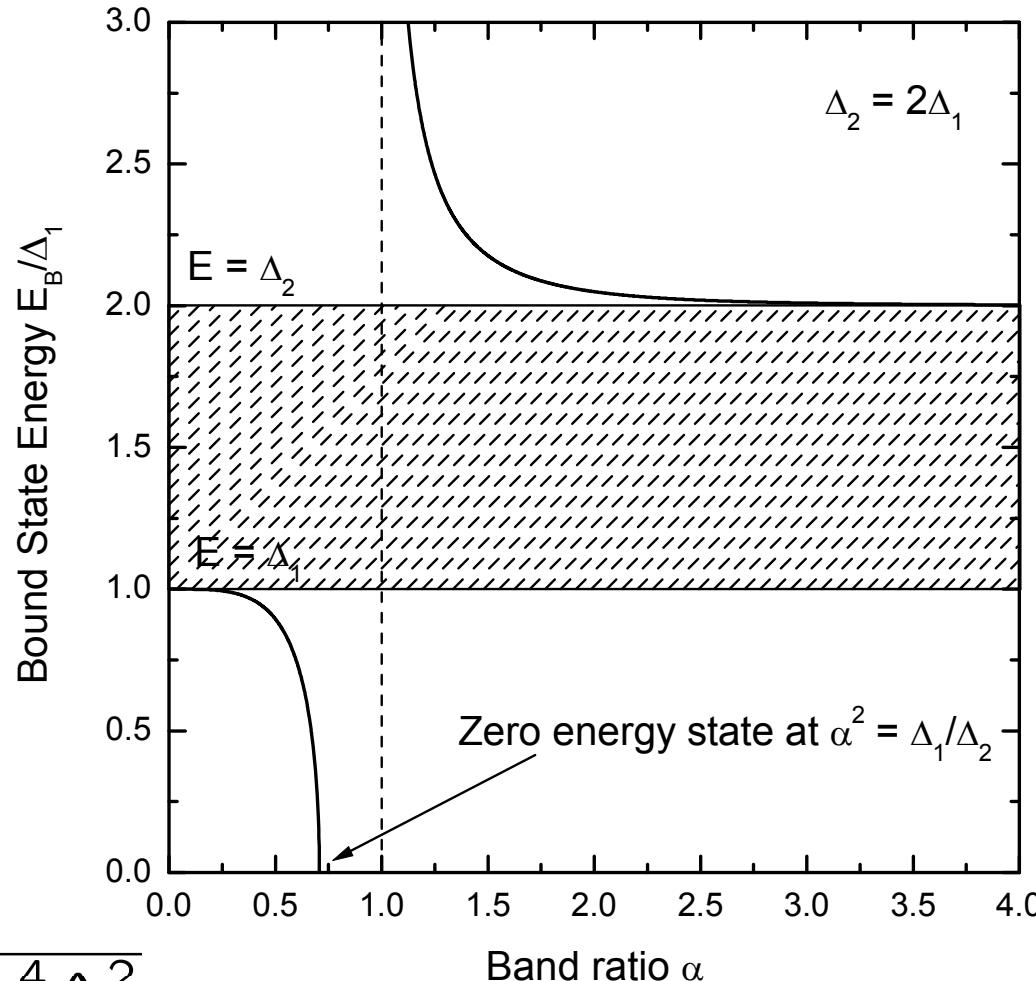


**Andreev conductance is suppressed due to destructive interband interference**

**Bound states appear at finite energy for large Z**

# Tunneling regime: Surface bound states

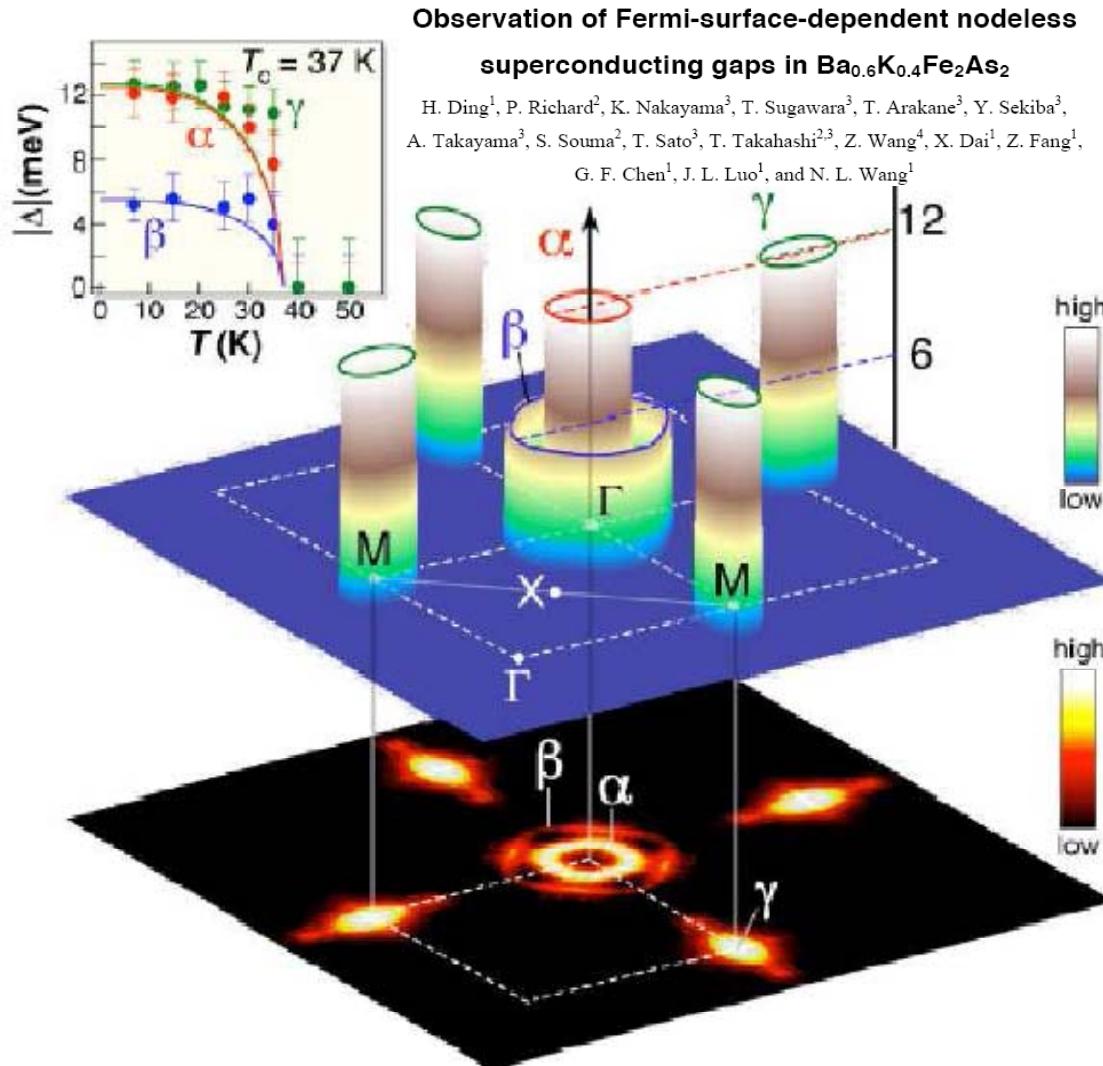
$s_{\pm}$  model



$$E_B = \sqrt{\frac{\Delta_1^2 - \alpha^4 \Delta_2^2}{1 - \alpha^4}}$$

Zero energy state (quite exceptional case)

# Superconducting gap – ARPES data



Schematic picture of superconducting gaps in  $\text{Ba}_{0.6}\text{K}_{0.4}\text{Fe}_2\text{As}_2$ . Lower picture represents Fermi surfaces (ARPES intensity), upper insert – temperature dependence of gaps at different Sheets of the Fermi surface.

## Four-band Eliashberg model:

P. Popovich, et. al. [arXiv:1001.1074](https://arxiv.org/abs/1001.1074)) :

### Spin fluctuations with spectral function

$$B_{ij}(\omega) = \lambda_{ij} \frac{\omega\Gamma\Omega_{sf}^2}{(\Omega_{sf}^2 - \omega^2)^2 + (2\omega\Gamma)^2}$$

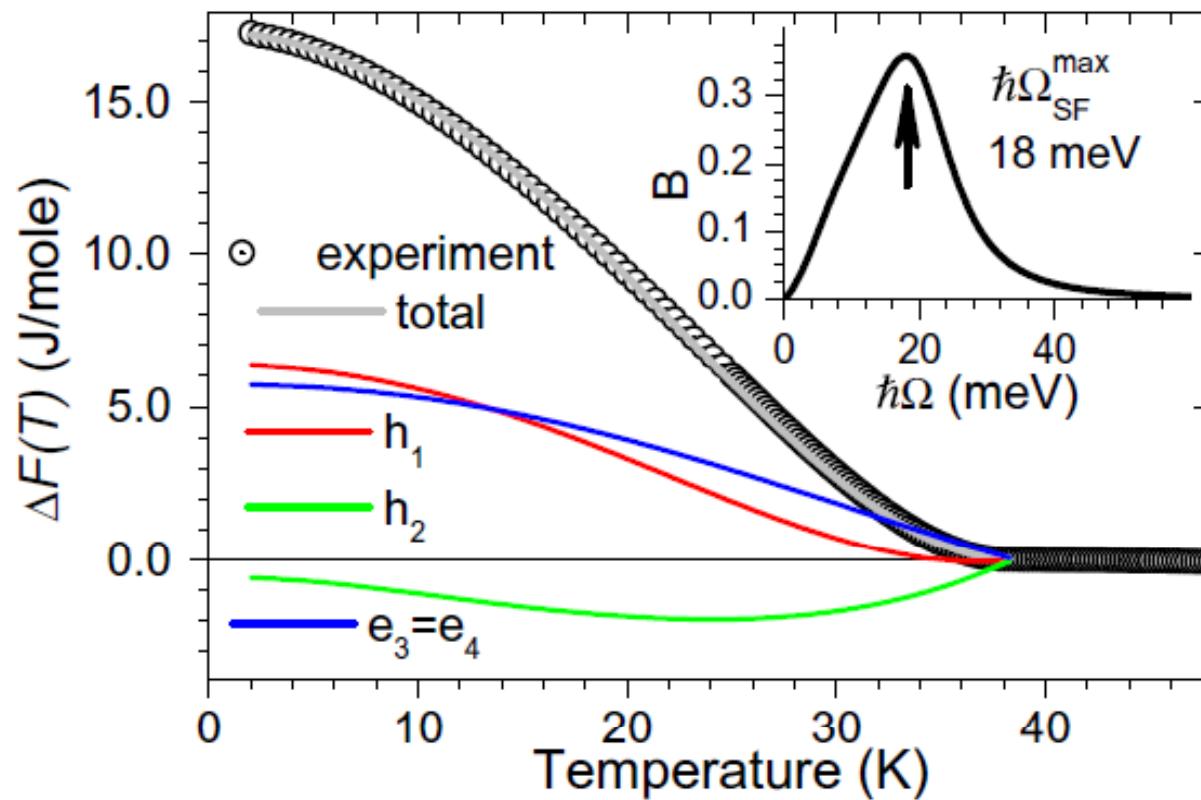

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$\hbar\Omega_{SF}^{\max} = 18 \text{ meV}$				
$\hat{\lambda}$	$\begin{pmatrix} 0.2 & 0 & -1.0 & -1.0 \\ 0 & 0.2 & -0.2 & -0.2 \\ -3.41 & -1.01 & 0.2 & 0 \\ -3.41 & -1.01 & 0 & 0.2 \end{pmatrix}$			
$(N_1^h, N_2^h, N_1^e, N_2^e), \text{Ry}^{-1}$	$(29 \ 43 \ 8.5 \ 8.5)$			
$\lambda^{av}$	$1.89$			
$(\Delta_1^h, \Delta_2^h, \Delta_1^e, \Delta_2^e), \text{meV}$	$(-8.5 \ -3.6 \ 9.2 \ 9.2)$			
$T_c, \text{K}$	$38.5$			
$\text{MSE}, (\text{J/mol})^2$	$0.015$			

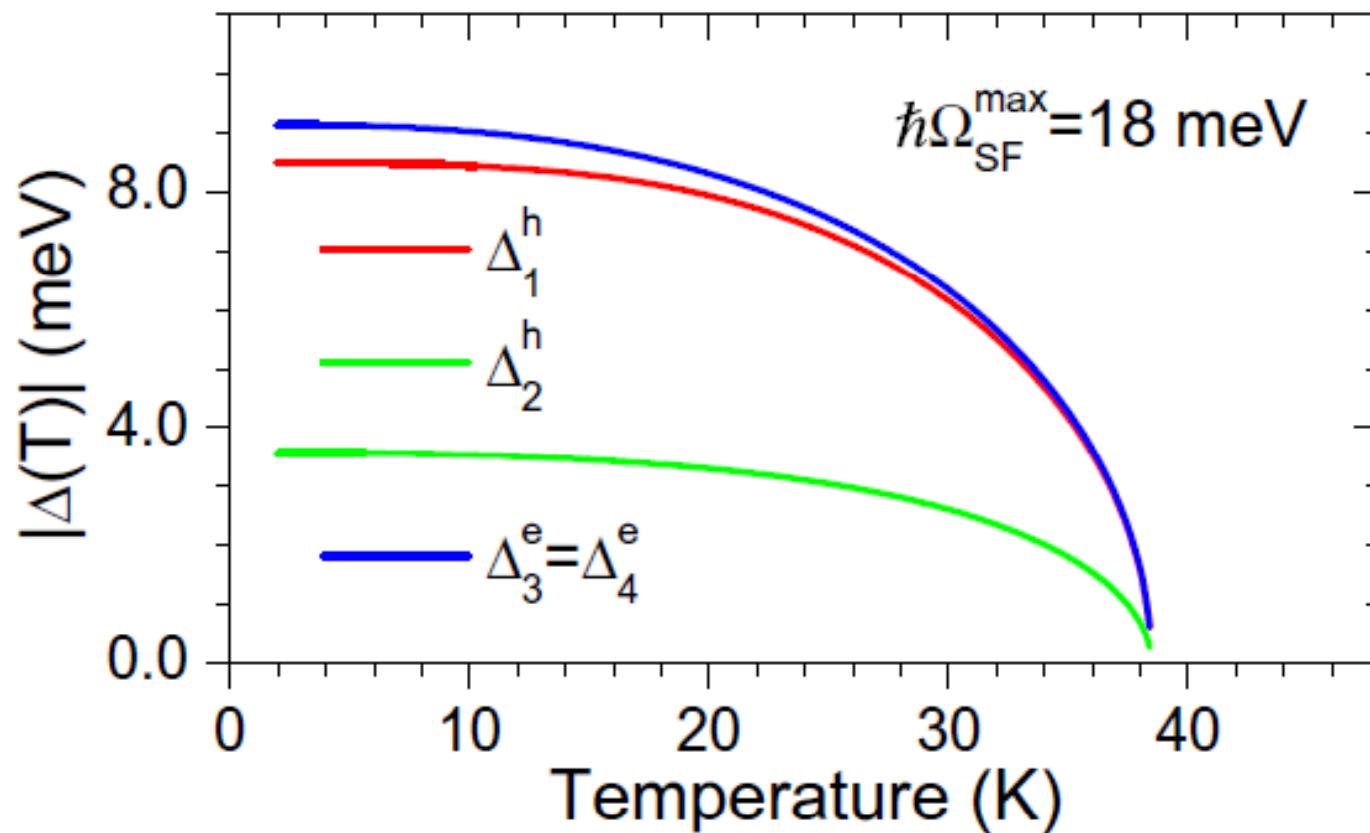
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# Calculation of free energies in 4-band model

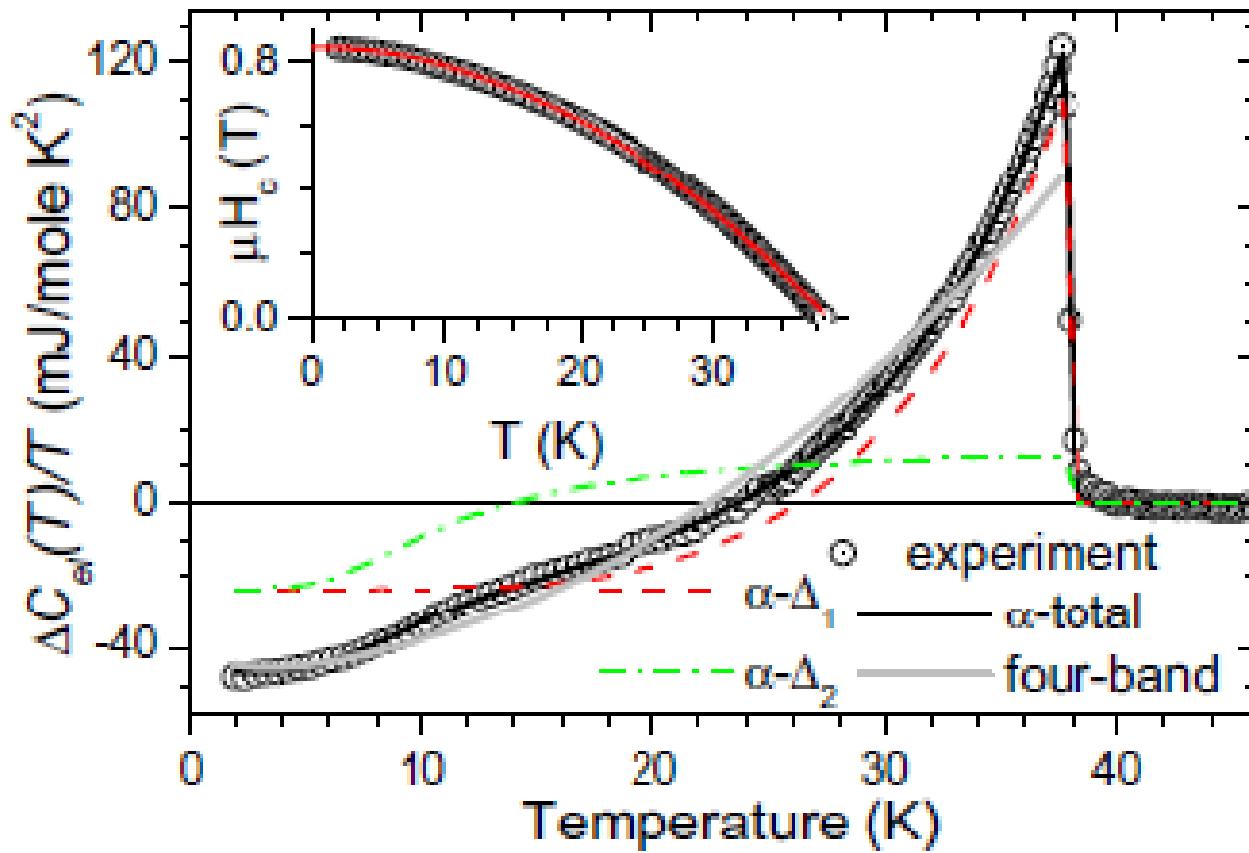
Experiment: BaKFeAs, Popovic *et al*



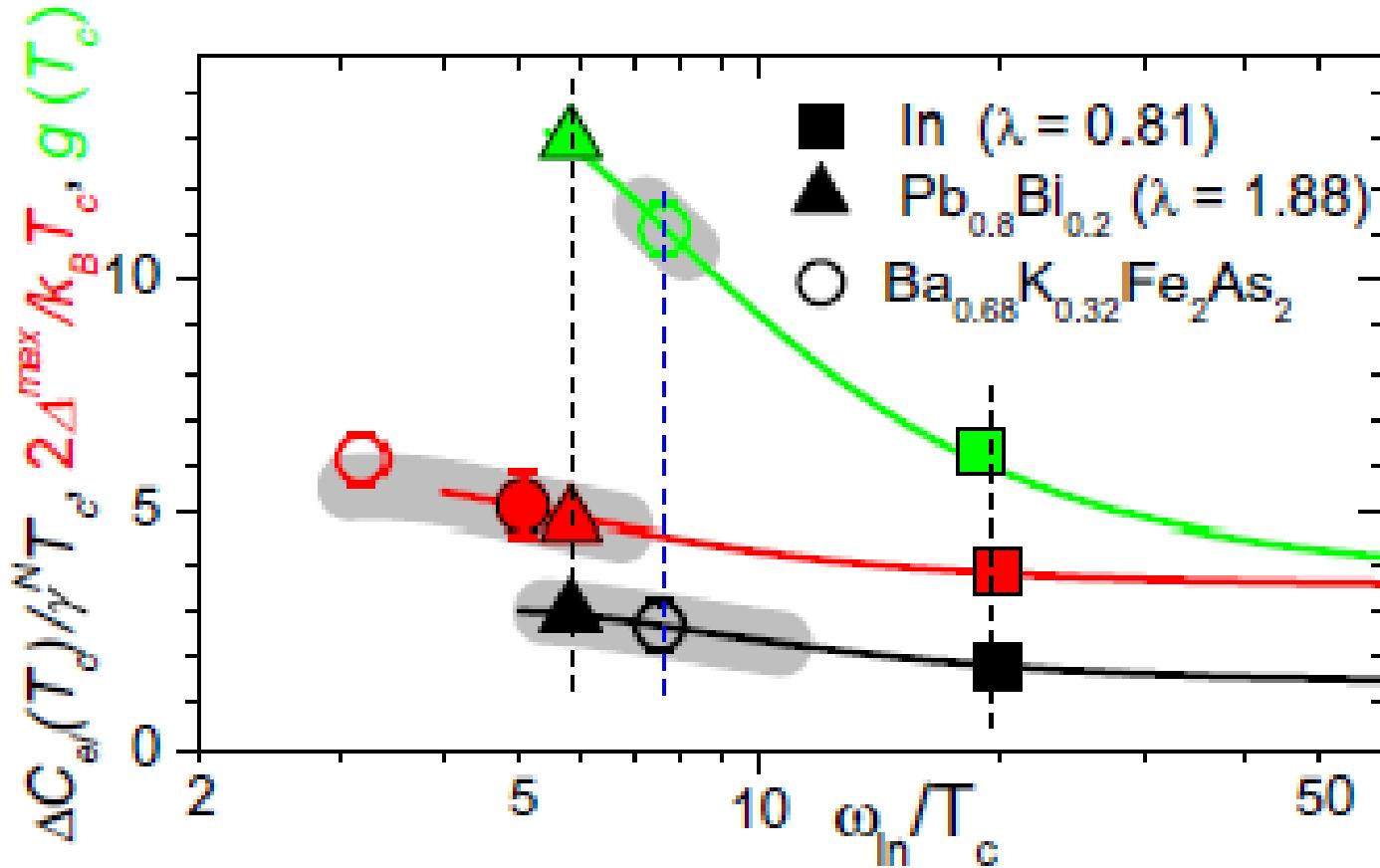
## Calculation of energy gaps in 4-band model



# Specific heat: theory and experiment



$$g(T_c) = -\left. \frac{\partial(\Delta C_{el} / \gamma^N)}{\partial T} \right|_{T_c}$$



The strong coupling regime suggests the interaction with low-energy (< 50 meV) excitations as the pairing mechanism  $\lambda_{av} \approx 1.9$

# Conclusions

- $s\pm$  pairing can explain some properties of superconducting *Fe-pnictides*.
- $T_c$  is robust against *unitary* interband scattering.
- The lack of an NMR Hebel-Slichter peak is consistent with the nodeless  $s\pm$  wave symmetry of the order parameter .
- The low-temperature power-law behavior of  $1/T_1$  can be also explained in the framework of the  $s\pm$  model but requires the impurity scattering beyond the Born limit.
- *Conductance Peak* can appear in *Andreev* and tunneling experiments, but, unlike nodal superconductors, at finite energy.
- Four-band Eliashberg model explains thermodynamic data in BaKFeAs