Electronic Anisotropy of Fe-based Superconductors

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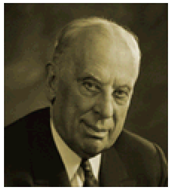
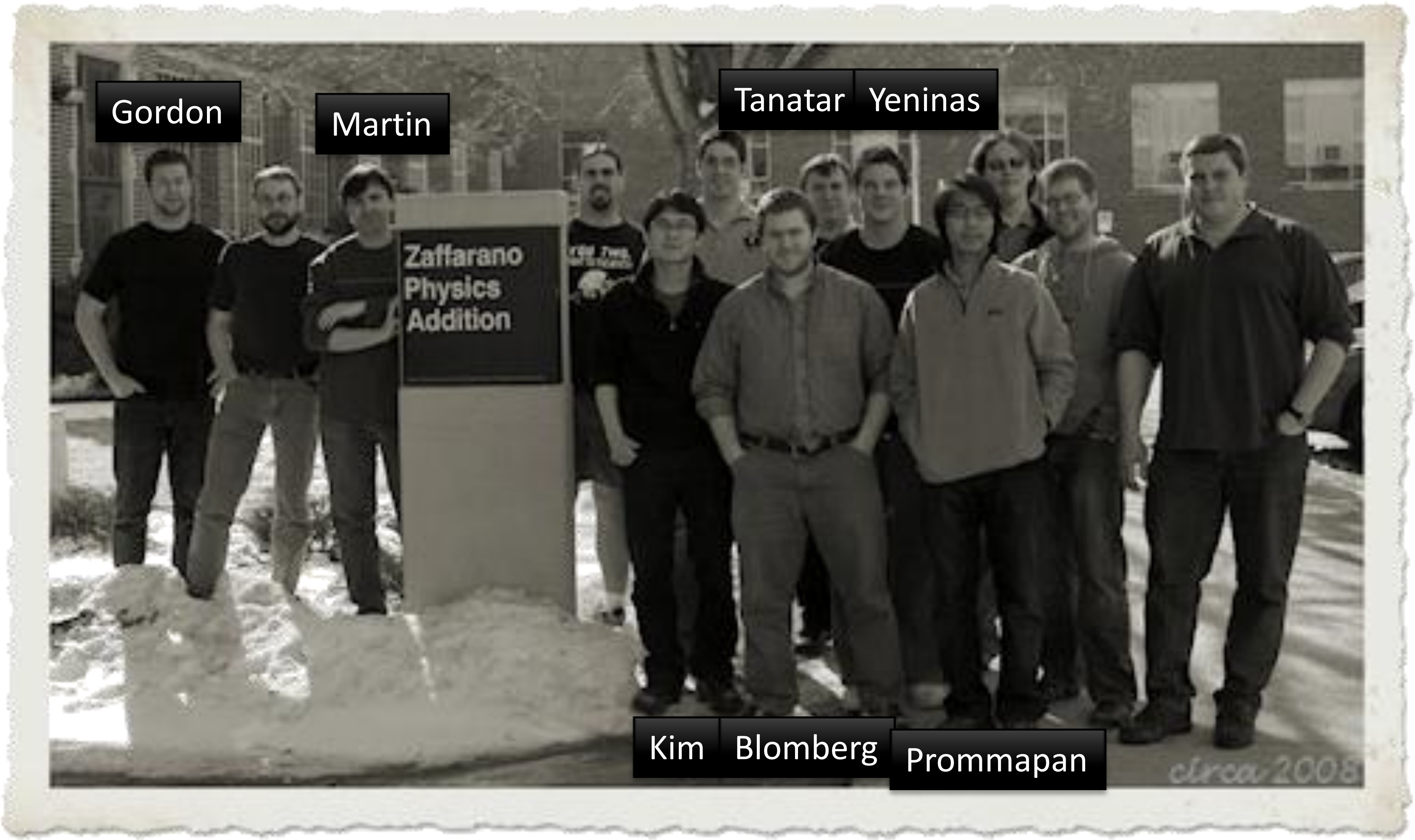
Workshop on Iron-Based Superconductors

19 January 2011



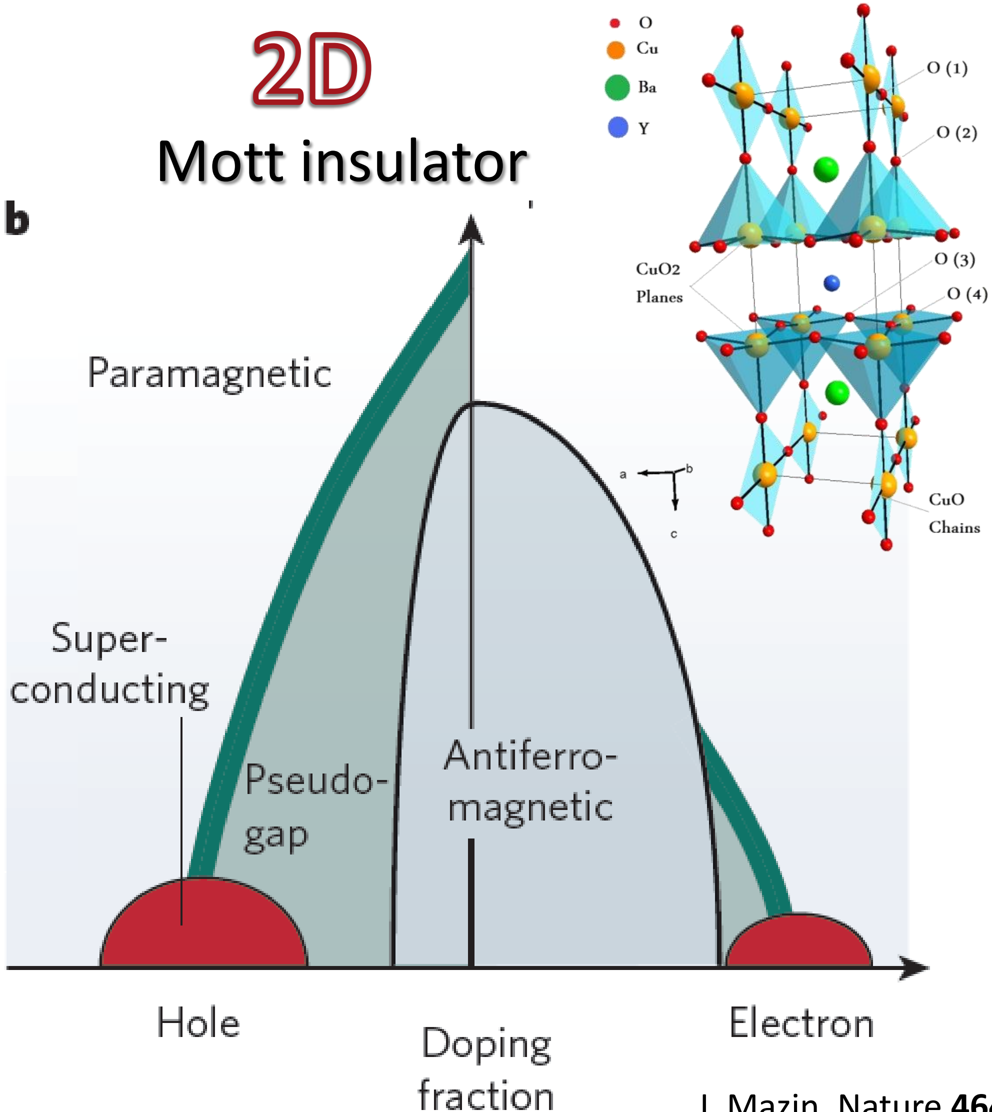
Superconductivity & Magnetism Low-T Laboratory



phase diagram

2D

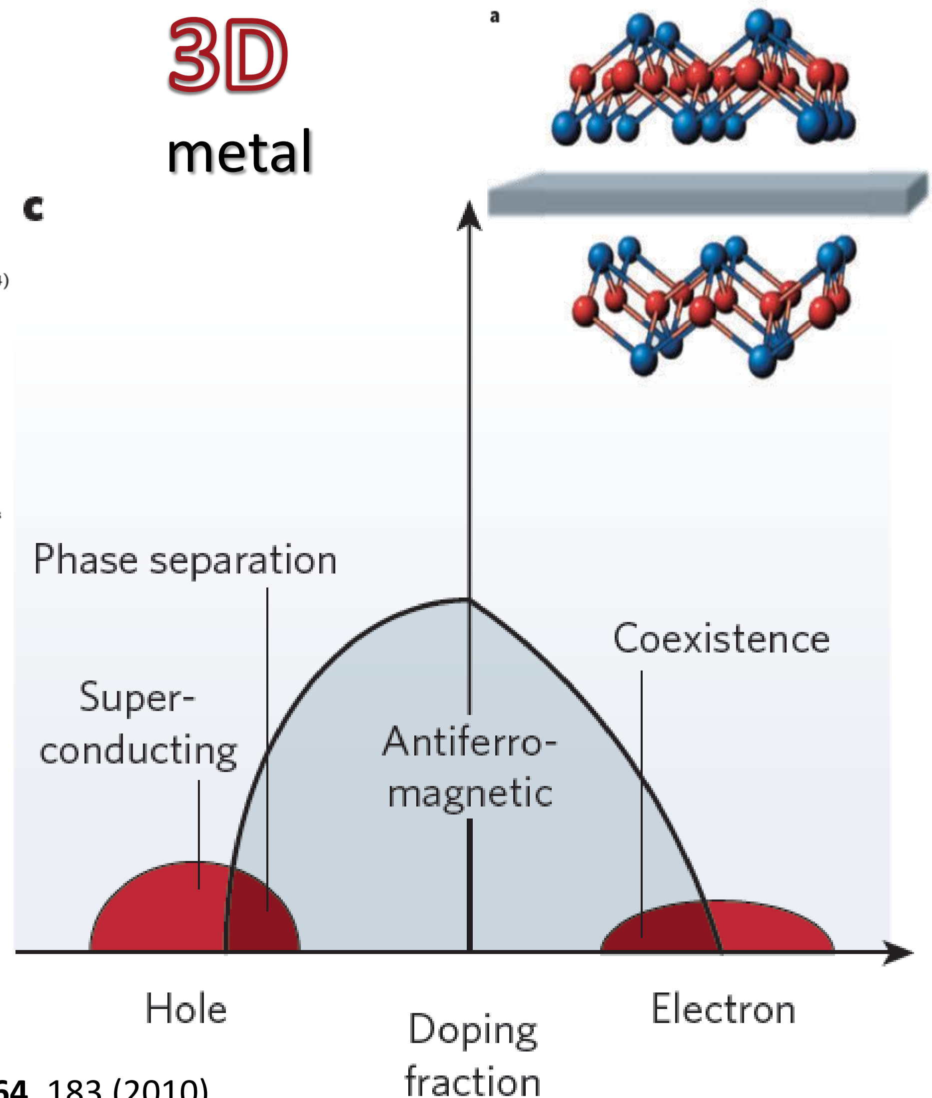
Mott insulator



cuprates

3D

metal



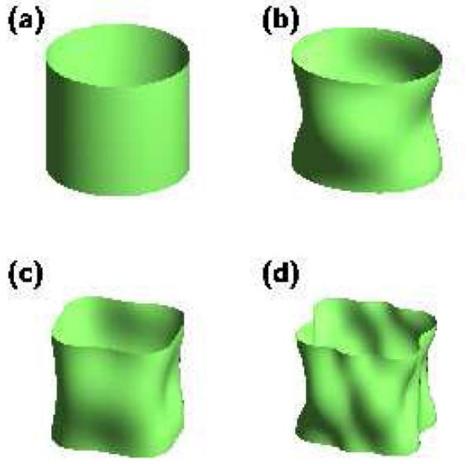
Fe-based superconductors

I. Mazin, Nature **464**, 183 (2010)

3D bandstructure

Cuprates: Single 2D FS, d-wave gap

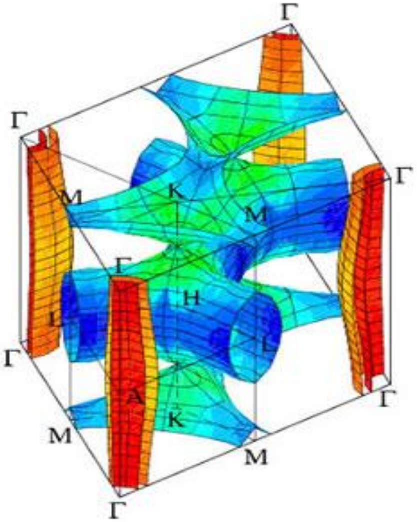
TlBaCuO



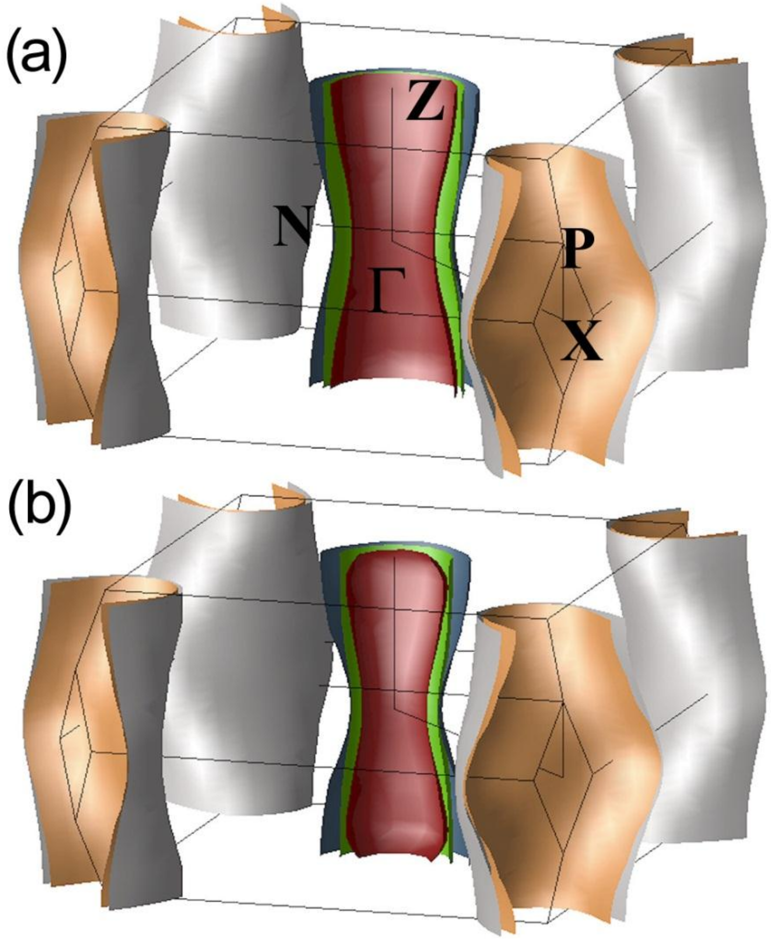
N. Hussey *et al.* Nature **425**, 814 (2003)

MgB_2

TWO s-wave gaps

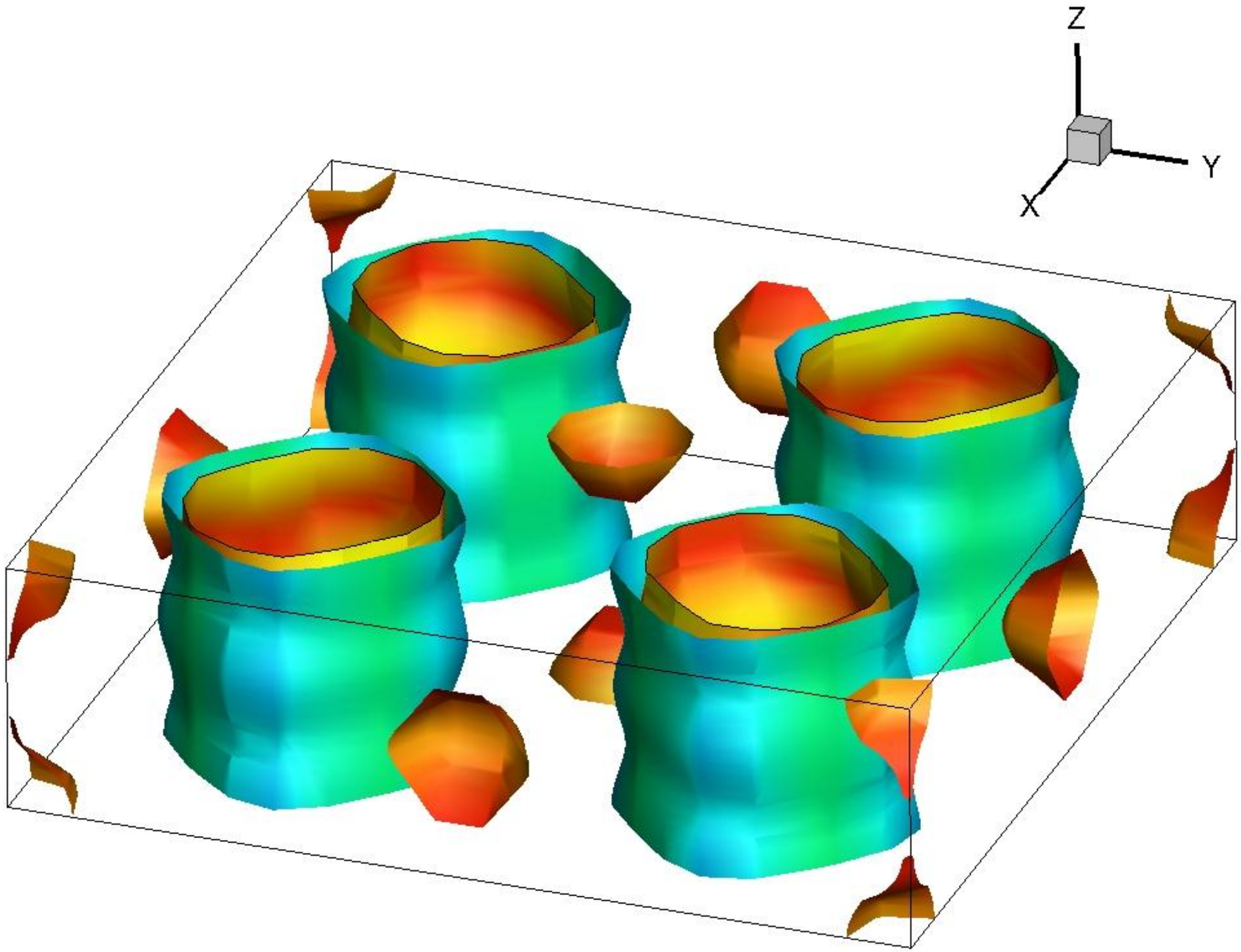


BaCo-122: Multiple gaps, 3D FS



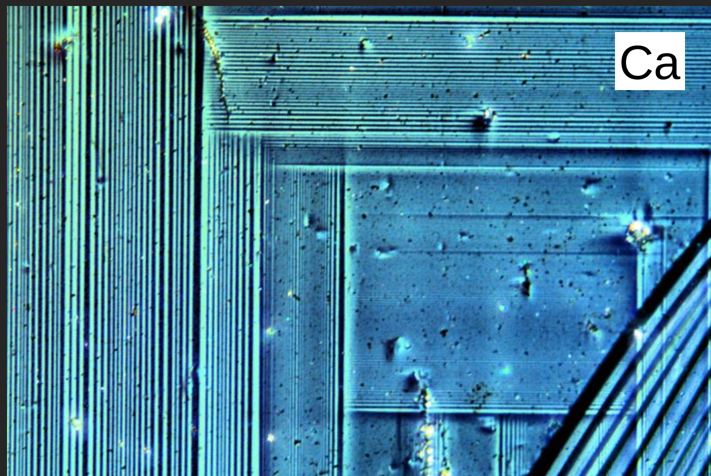
R. Gordon *et al.,* Phys. Rev. Lett. **102**, 127004 (2009)

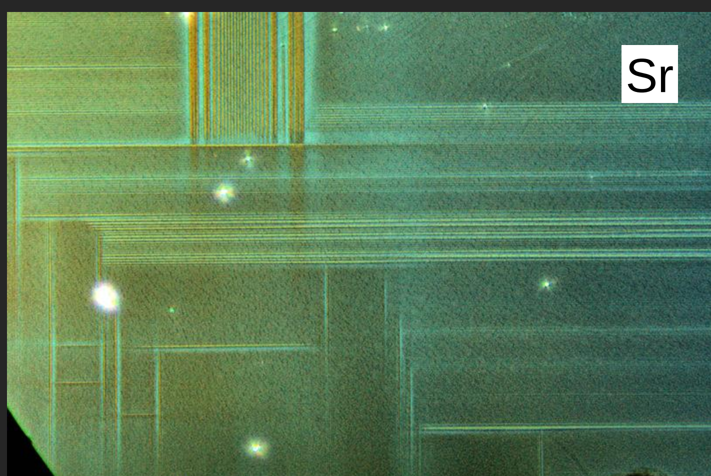
KFe_2Se_2

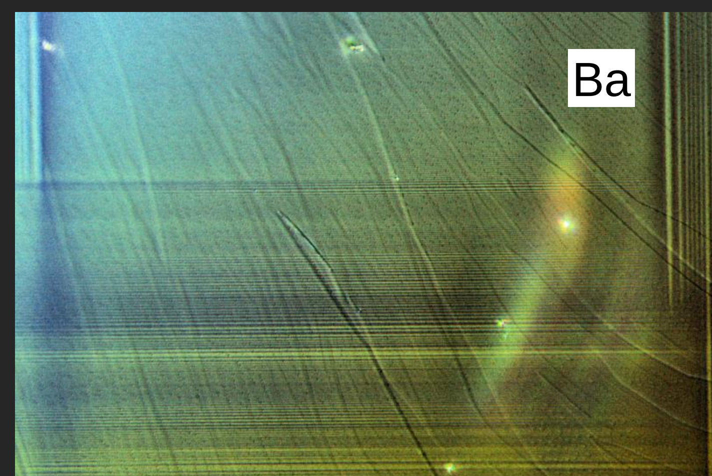


V. Antropov (Ames)

domains in orthorhombic / AFM phase



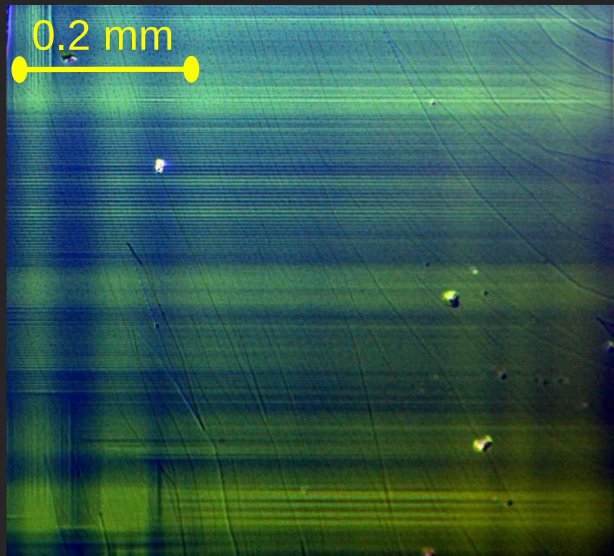


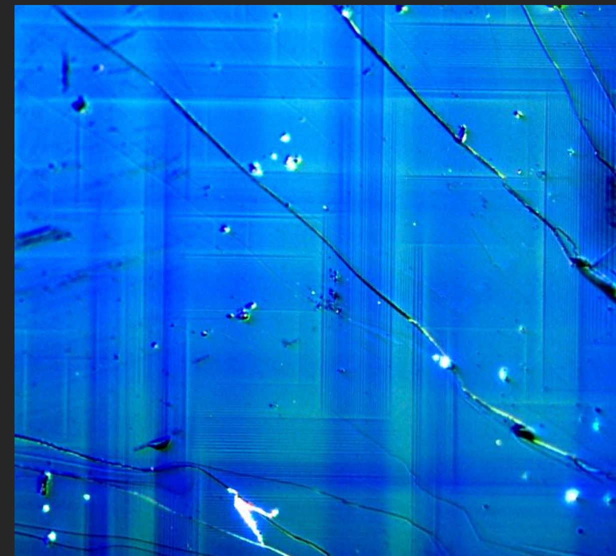


M. A. Tanatar *et al.*, Phys. Rev. B 79, 180508 (2009)

domains in doped FeCo122

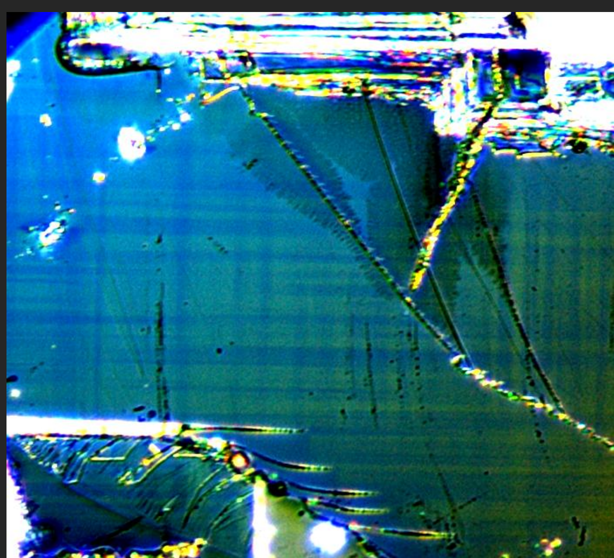
x = 0

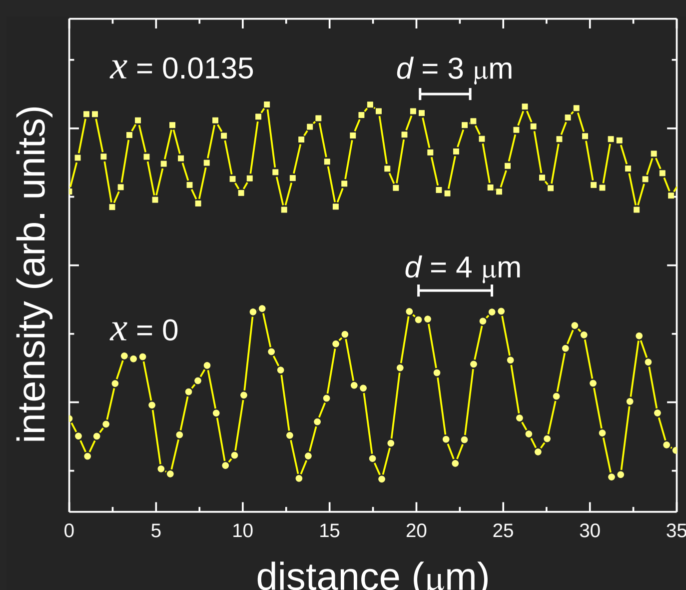




x = 0.0135

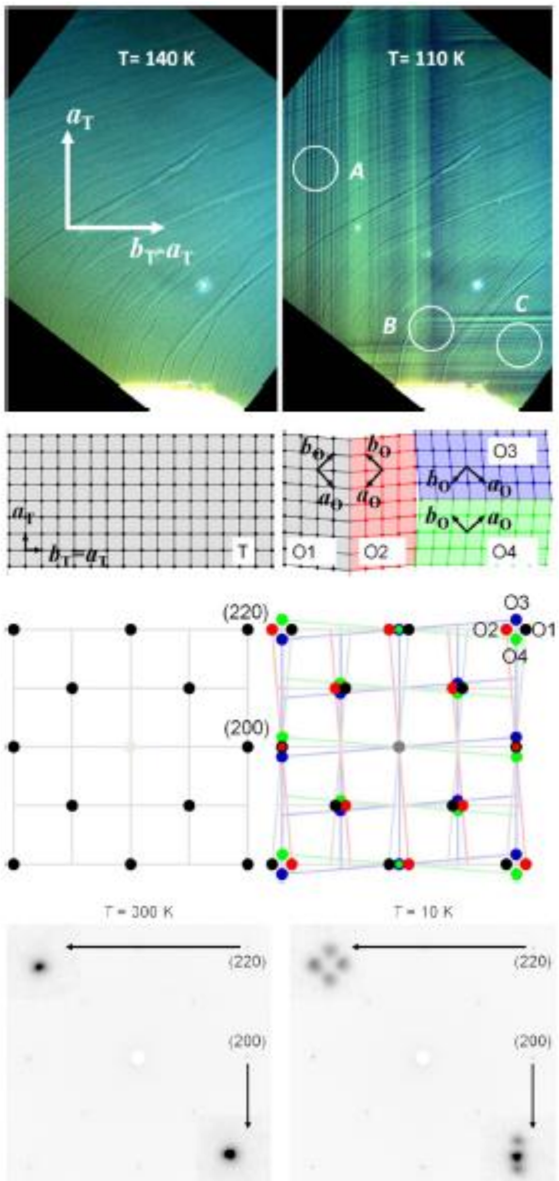
x = 0.054

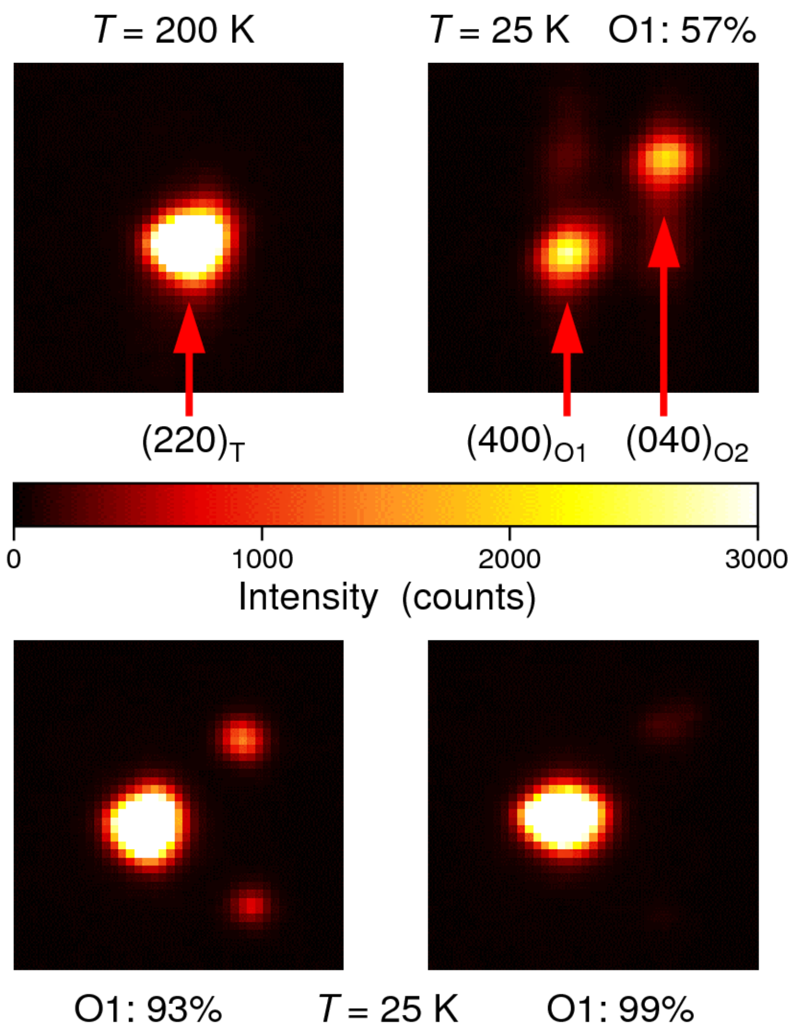


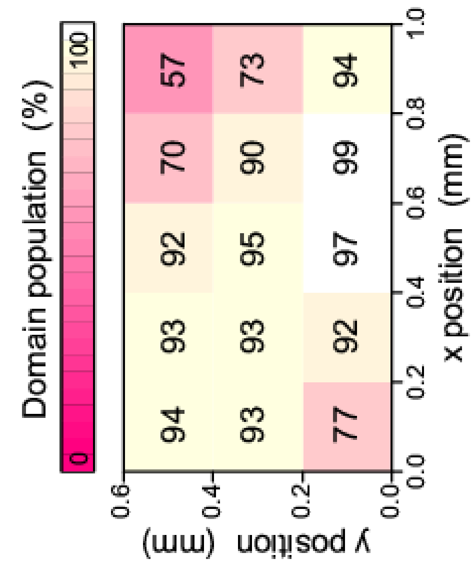


R. Prozorov *et al.*, Phys. Rev. B **80**, 174517 (2009)

high – energy x-ray

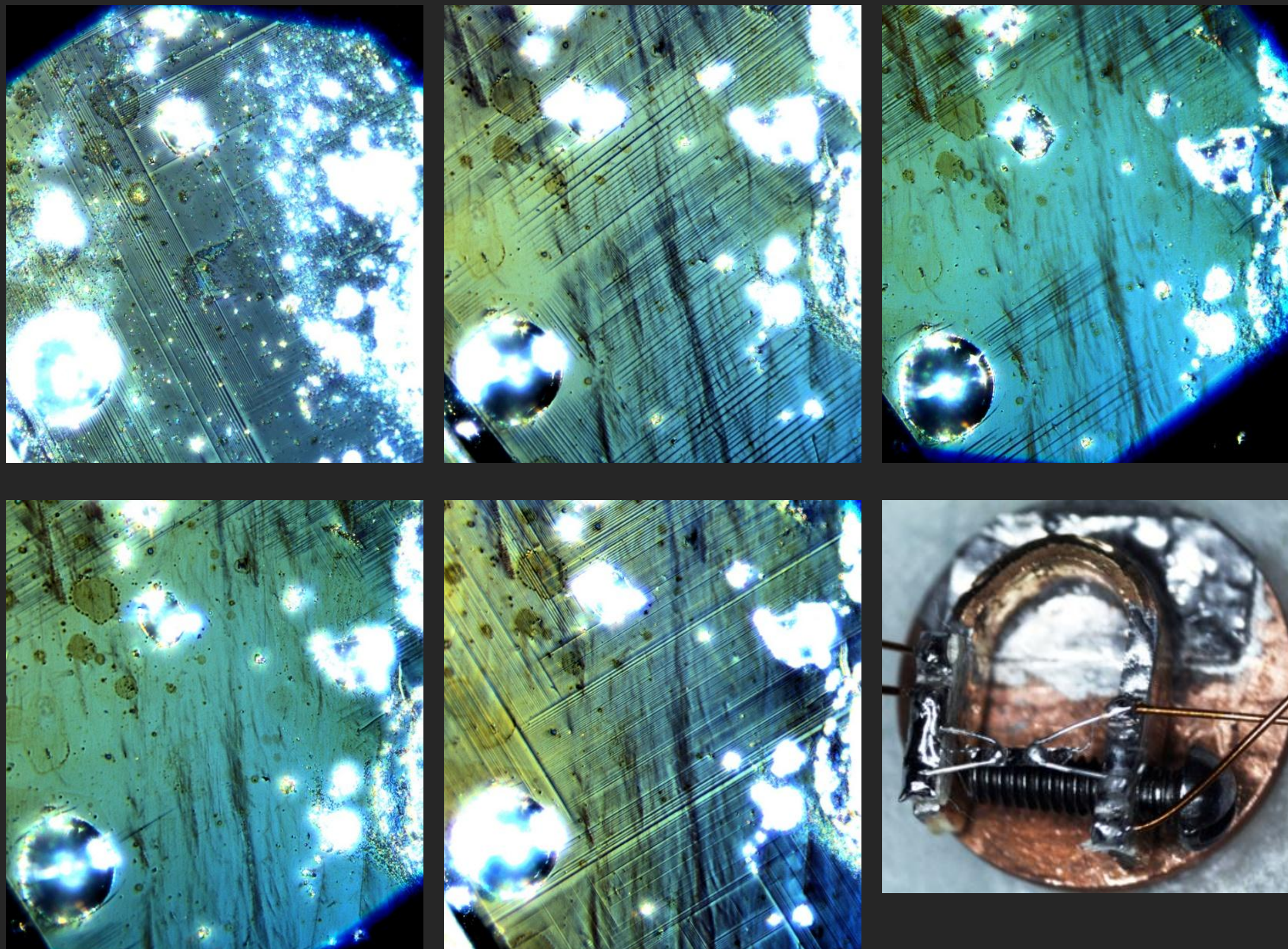






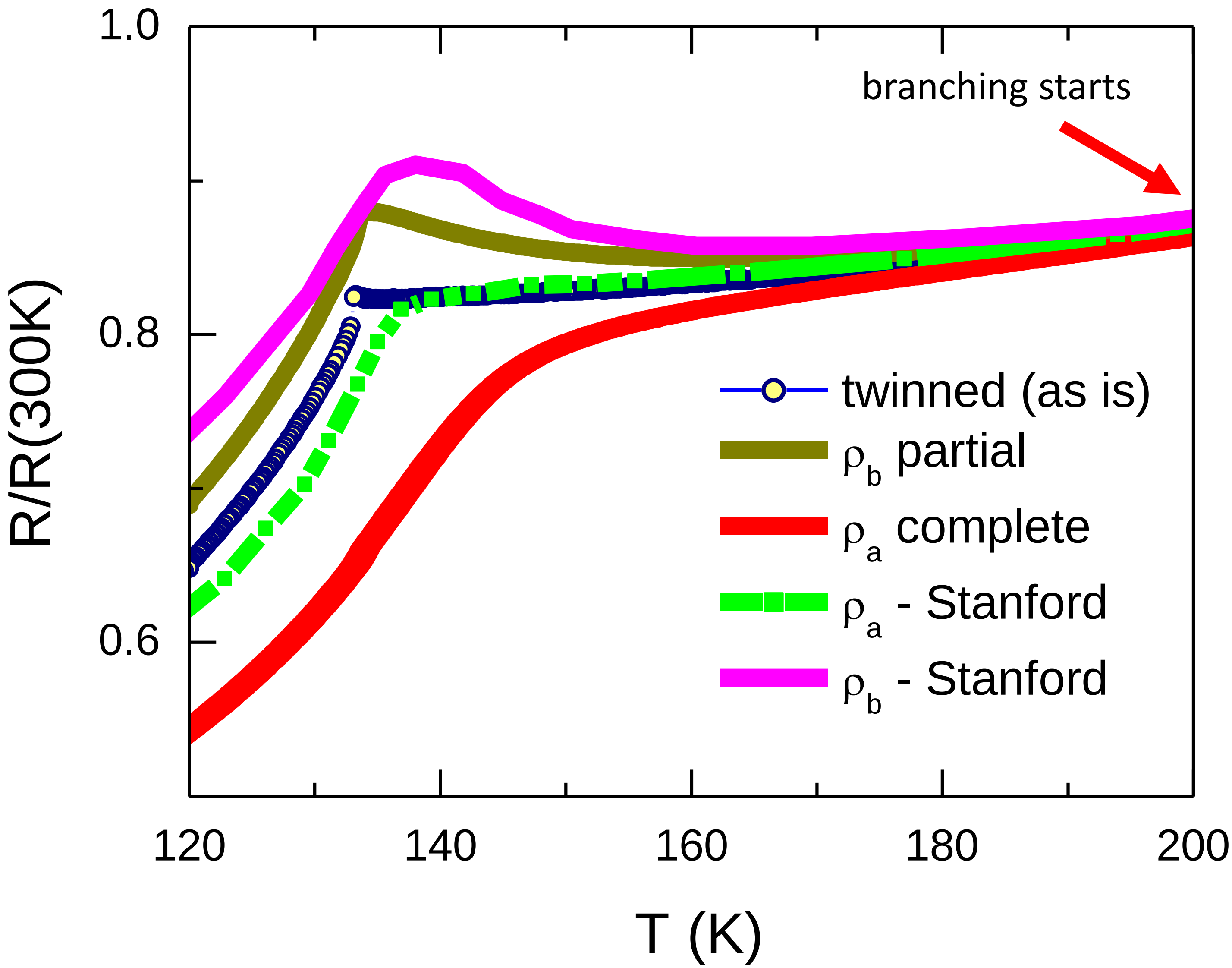
Domain distribution map
200 μm spot
high energy x-ray

de-twinning

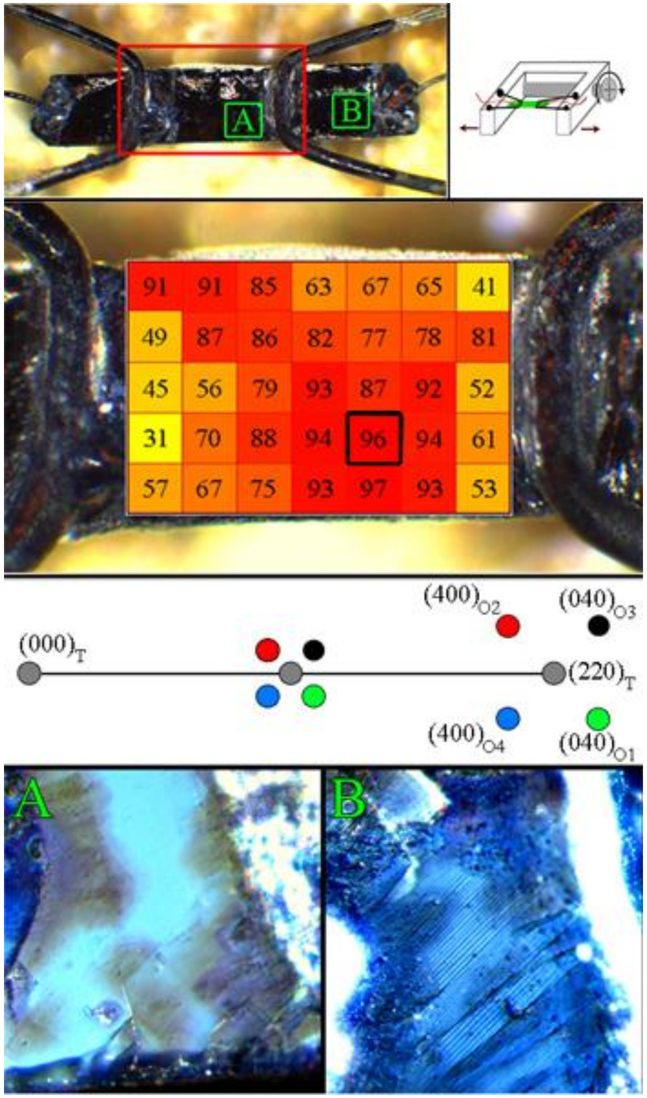


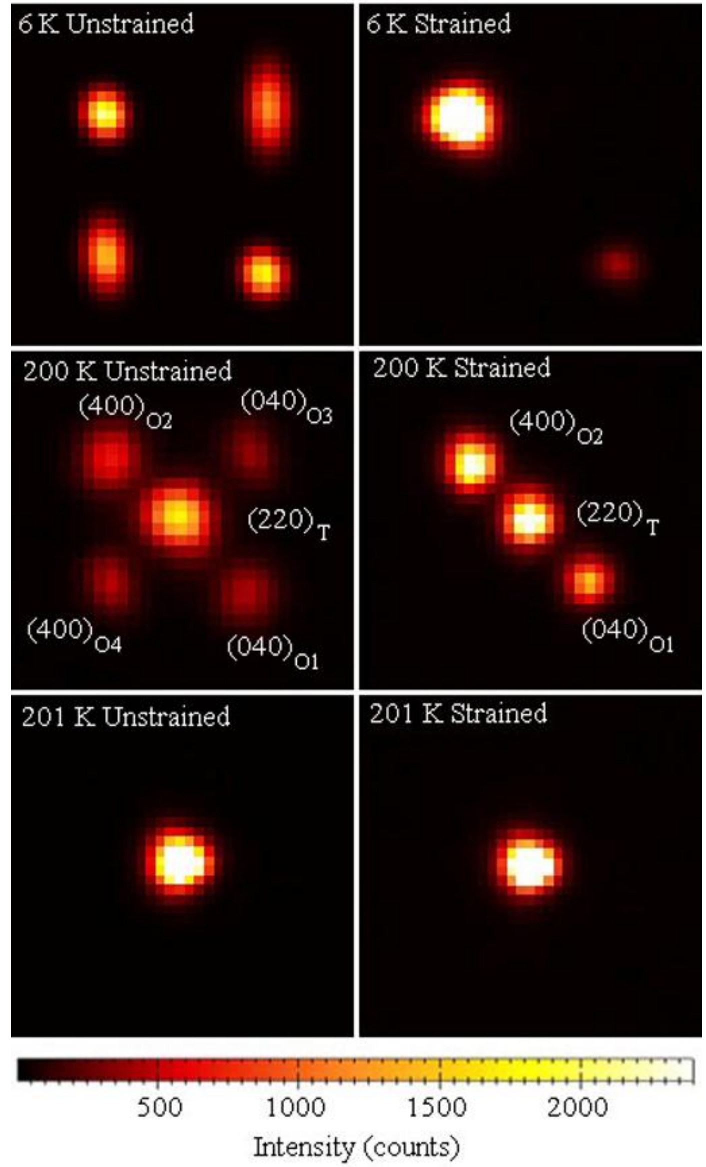
M. A. Tanatar *et al.*, Phys. Rev. B **81**, 184508 (2010)

Ba122 – anisotropy in both ORT & TET!

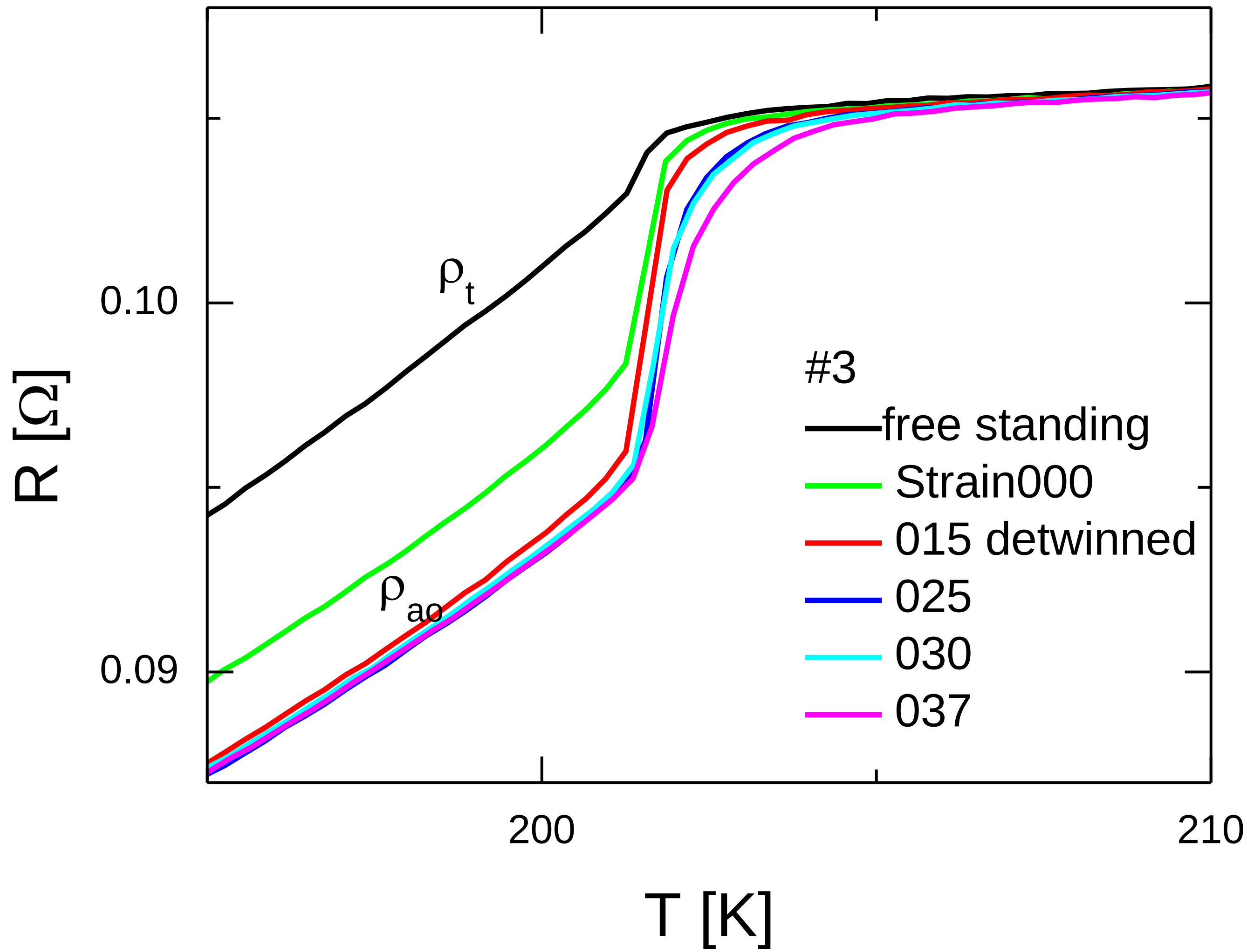


Sr122

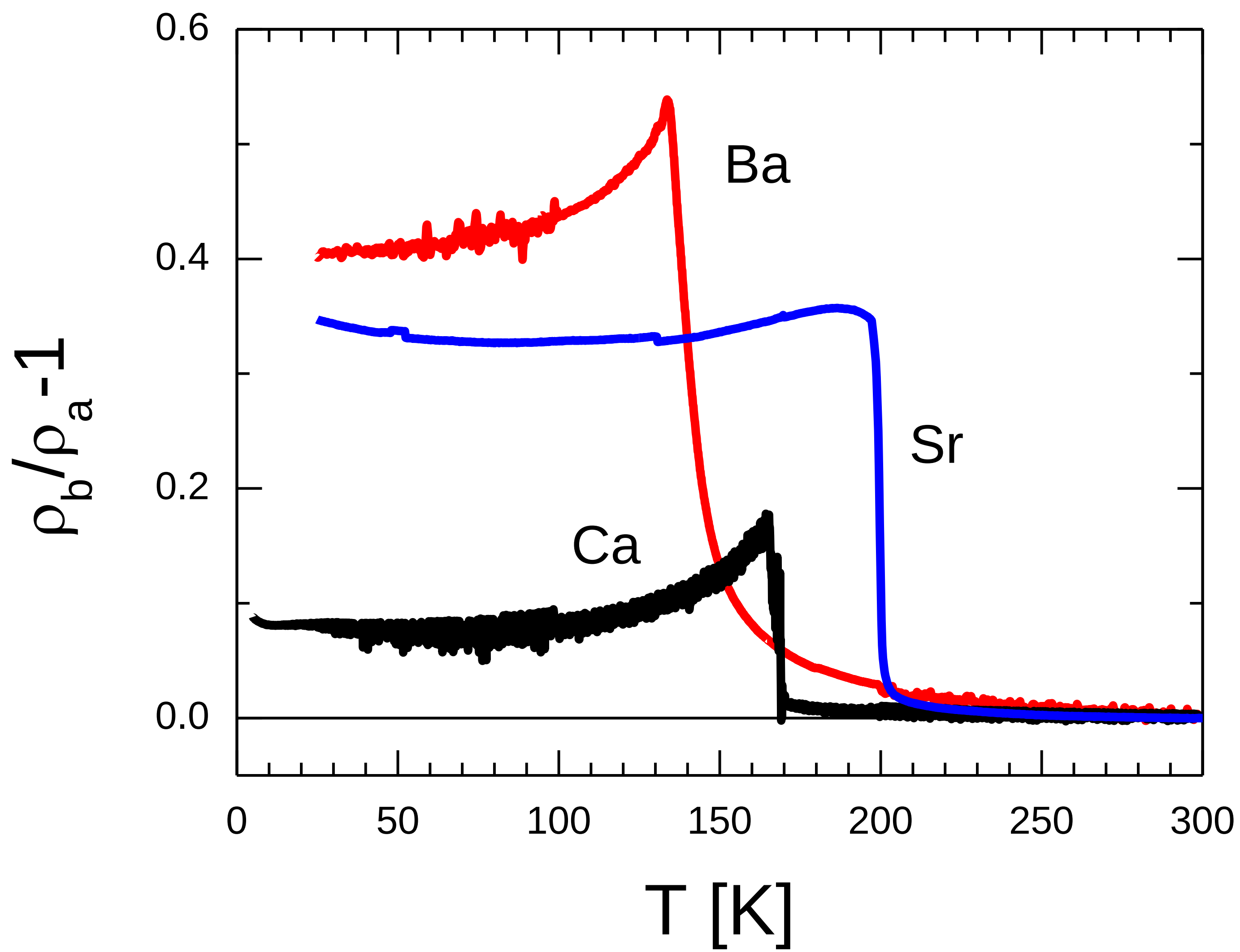

A
B
91 91 85 63 67 65 41
49 87 86 82 77 78 81
45 56 79 93 87 92 52
31 70 88 94 96 94 61
57 67 75 93 97 93 53
$(000)_T$
$(400)_{O2}$
$(040)_{O3}$
$(220)_T$
$(400)_{O4}$
$(040)_{O1}$
A
B


6 K Unstrained
6 K Strained
200 K Unstrained
$(400)_{O2}$
$(040)_{O3}$
$(220)_T$
$(400)_{O4}$
$(040)_{O1}$
200 K Strained
$(400)_{O2}$
$(220)_T$
$(040)_{O1}$
201 K Unstrained
201 K Strained
500
1000
1500
2000
Intensity (counts)

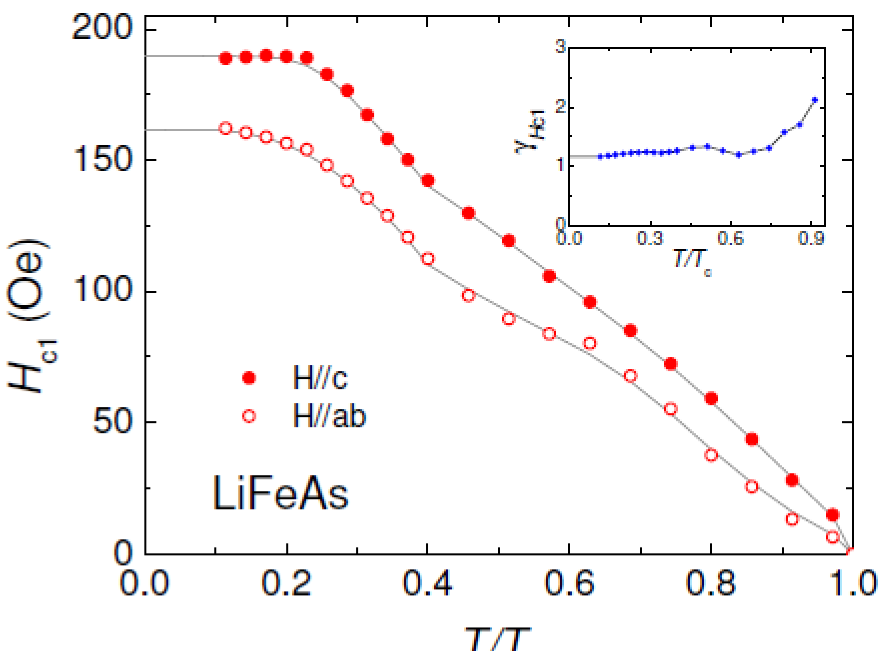
effect of strain

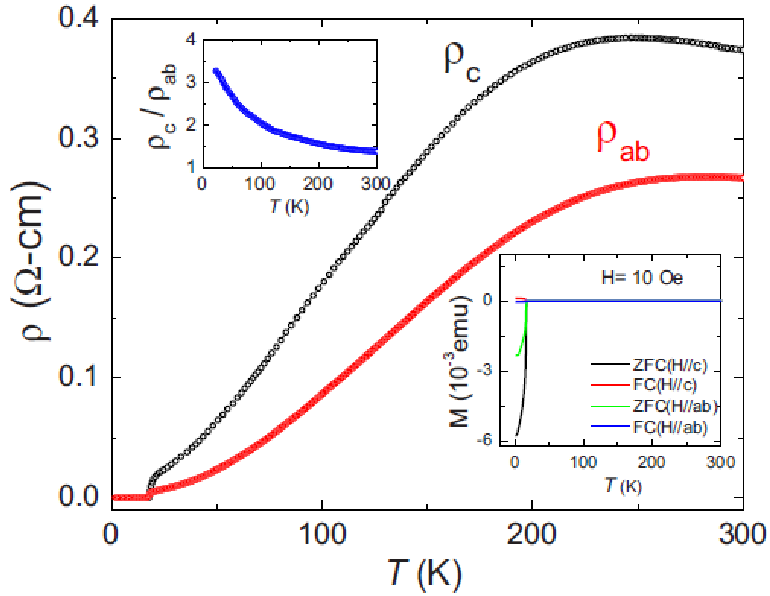


comparison of anisotropies



anisotropy: case of LiFeAs





Prof. Kwon (SKKU)

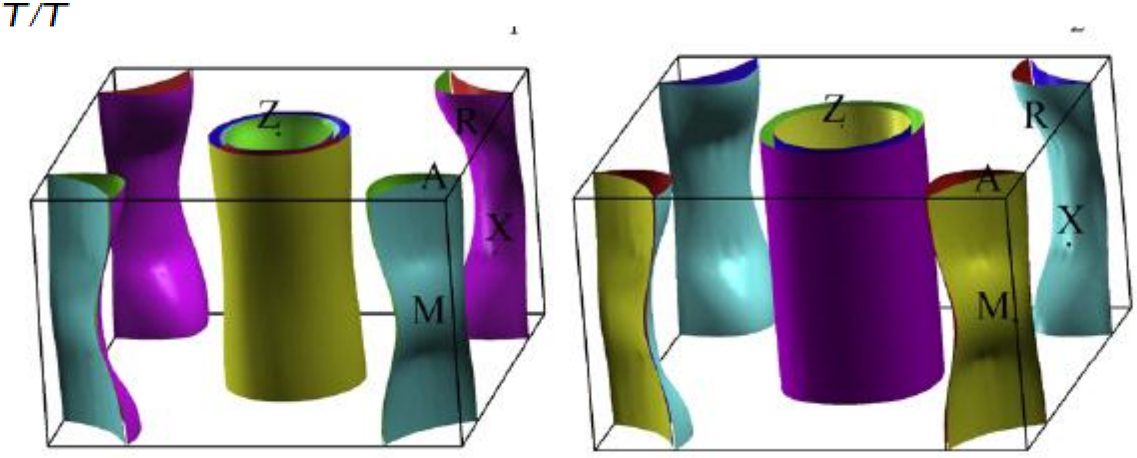
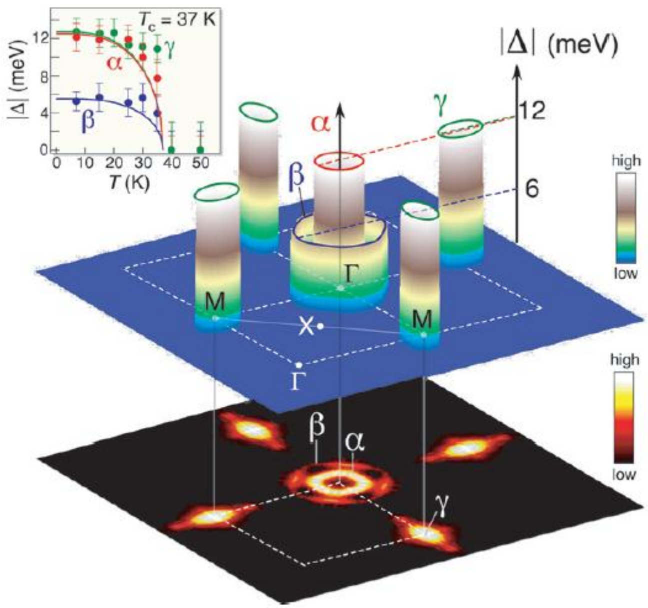
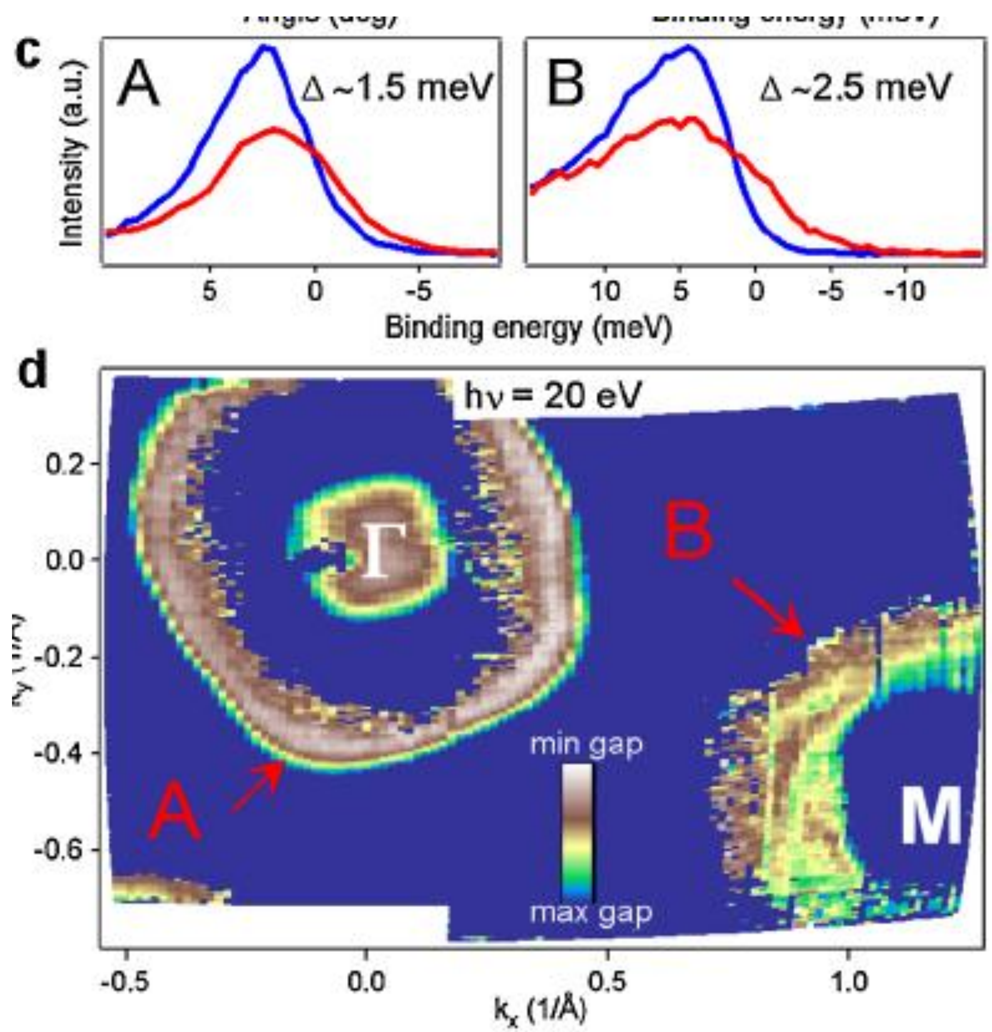


Fig. 3. (Color online) The Fermi surfaces of LiFeP (1) and LiFeAs (2).

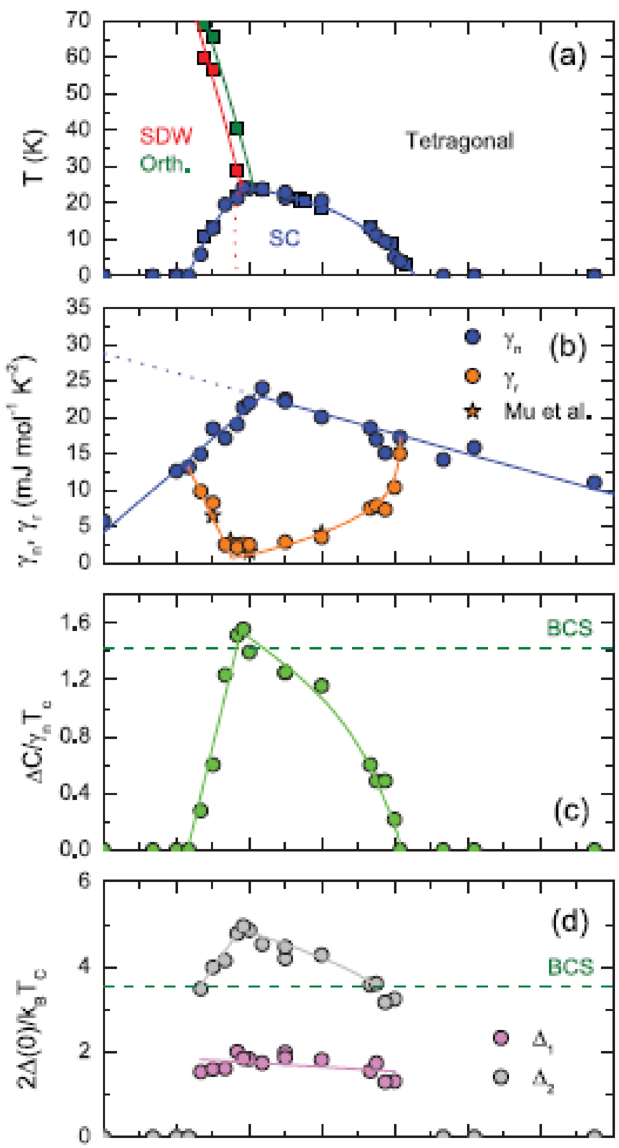
Two (an)isotropic gaps in pnictides



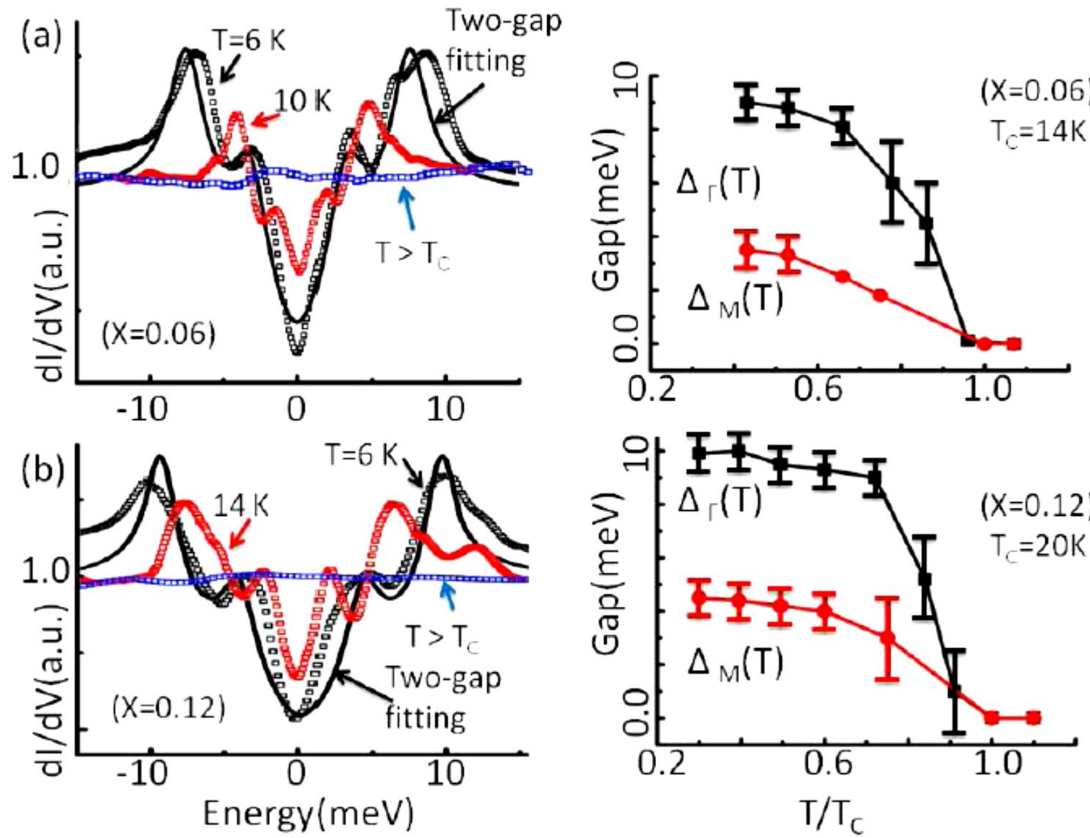
ARPES, BaK122
H.Ding *et al.* Europhys. Lett. 83, 47001 (2008)



LiFeAs
S. V. Borisenko *et al.,* Phys. Rev. Lett. **105**, 067002 (2010)

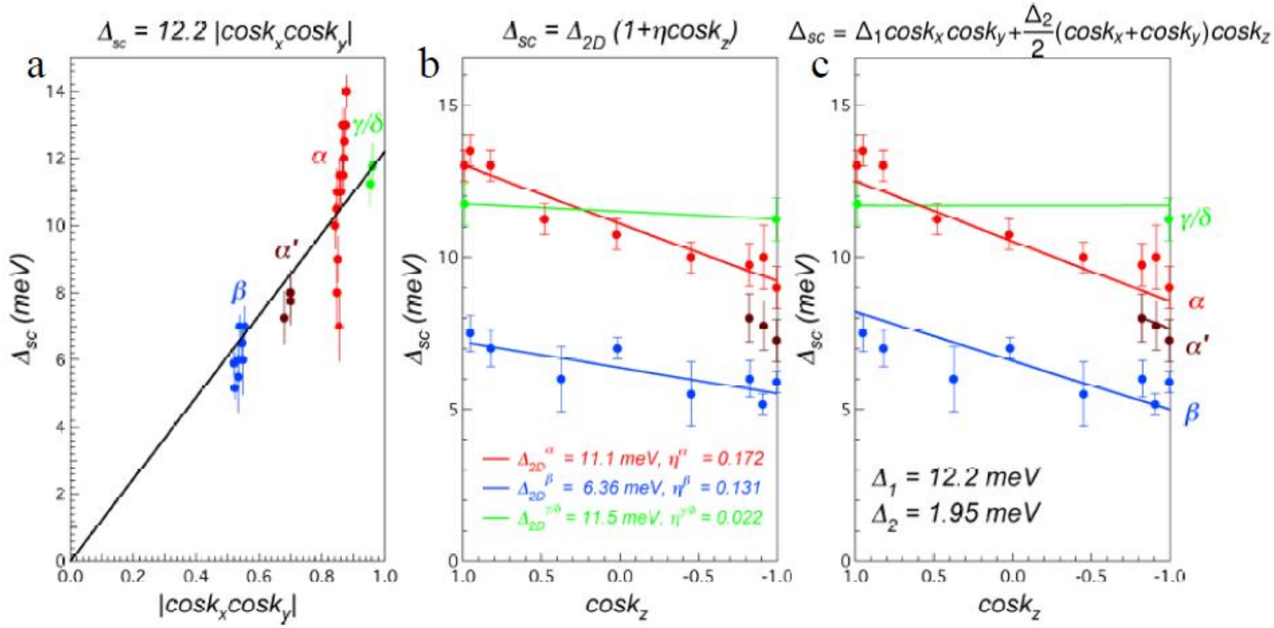


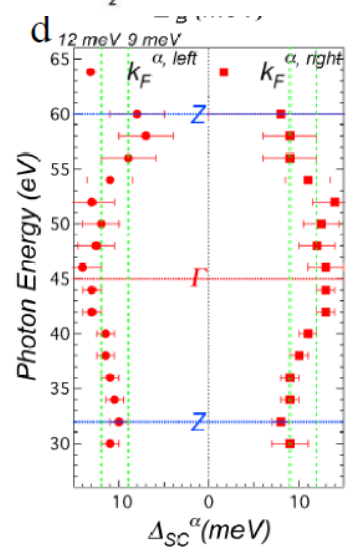
C_p FeCo122
F. Hardy et al., EPL 47008 (2010)

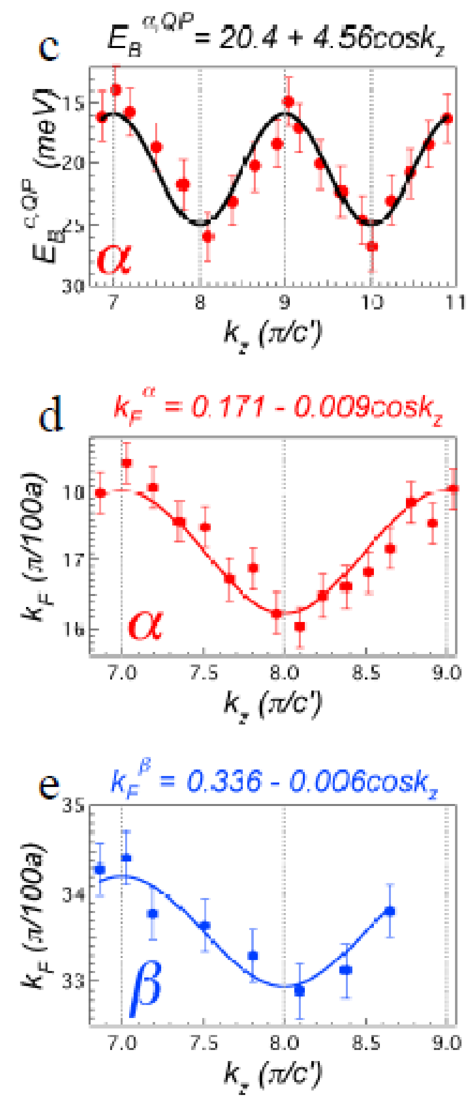


Tunneling FeCo122
M. L. Teague et al., (2010)

3D structure





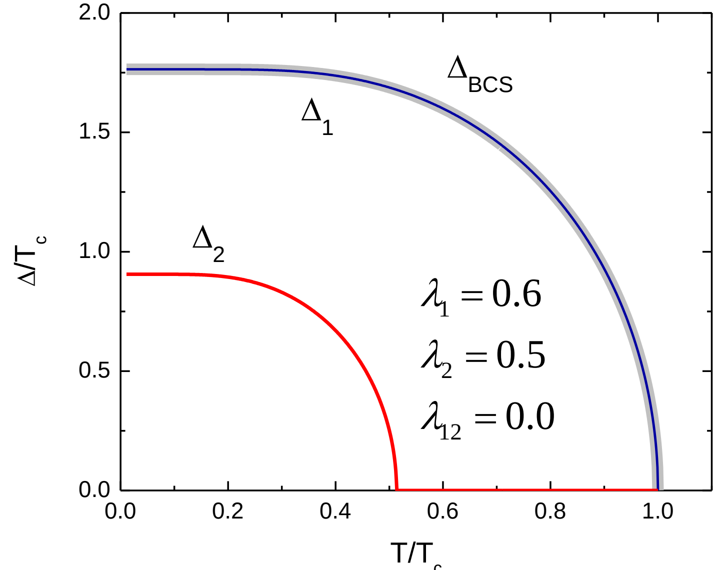


$Ba_{0.6}K_{0.4}Fe_2As_2$, H. Ding et al., arXiv:1006.3958

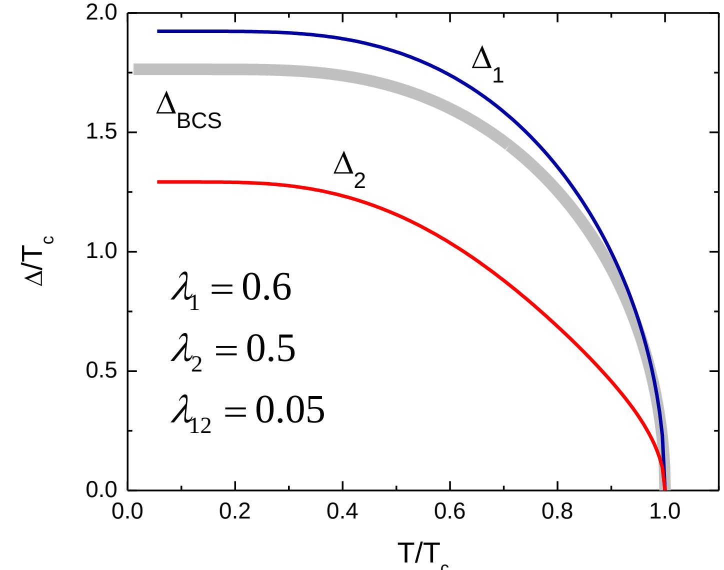
London penetration depth

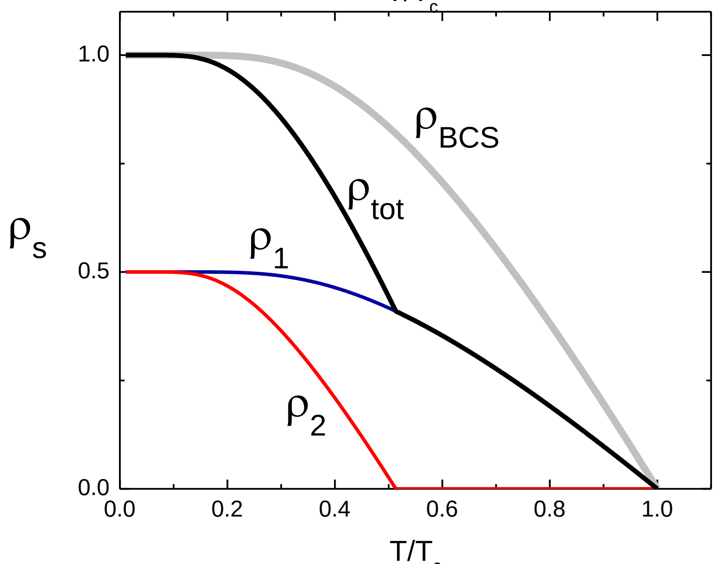
self-consistent description (Eilenberger)

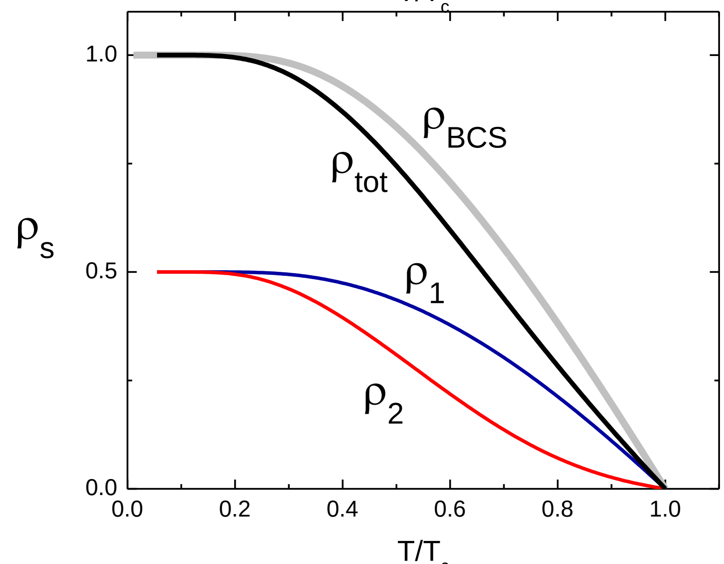
$$\frac{\Delta_1(T)}{\Delta_1(0)} = \frac{\Delta_{BCS}(T)}{\Delta_{BCS}(0)} = \frac{\Delta_2(T)}{\Delta_2(0)}$$



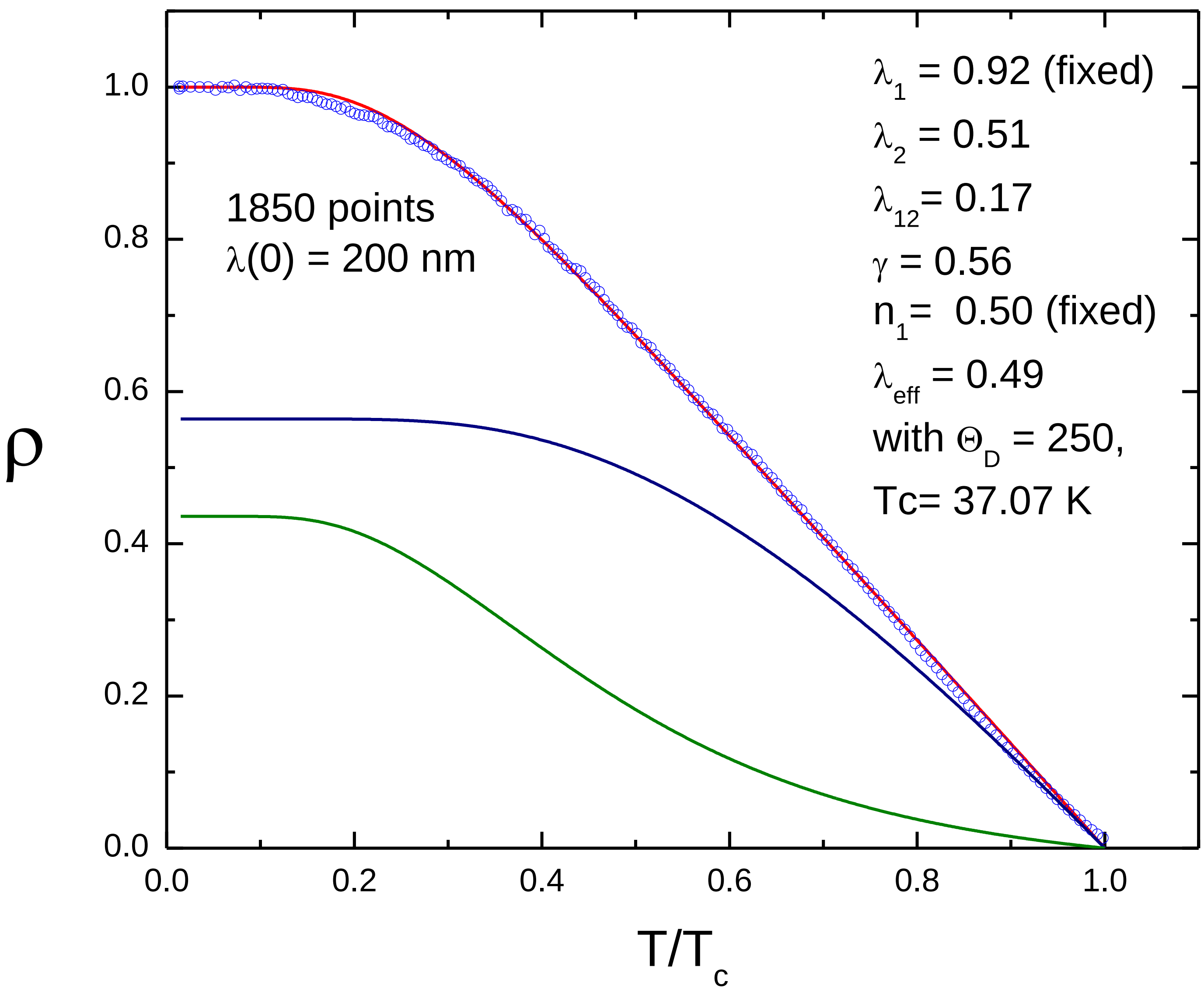
$$\frac{\Delta_1(T)}{\Delta_1(0)} \approx \frac{\Delta_{BCS}(T)}{\Delta_{BCS}(0)} \neq \frac{\Delta_2(T)}{\Delta_2(0)}$$





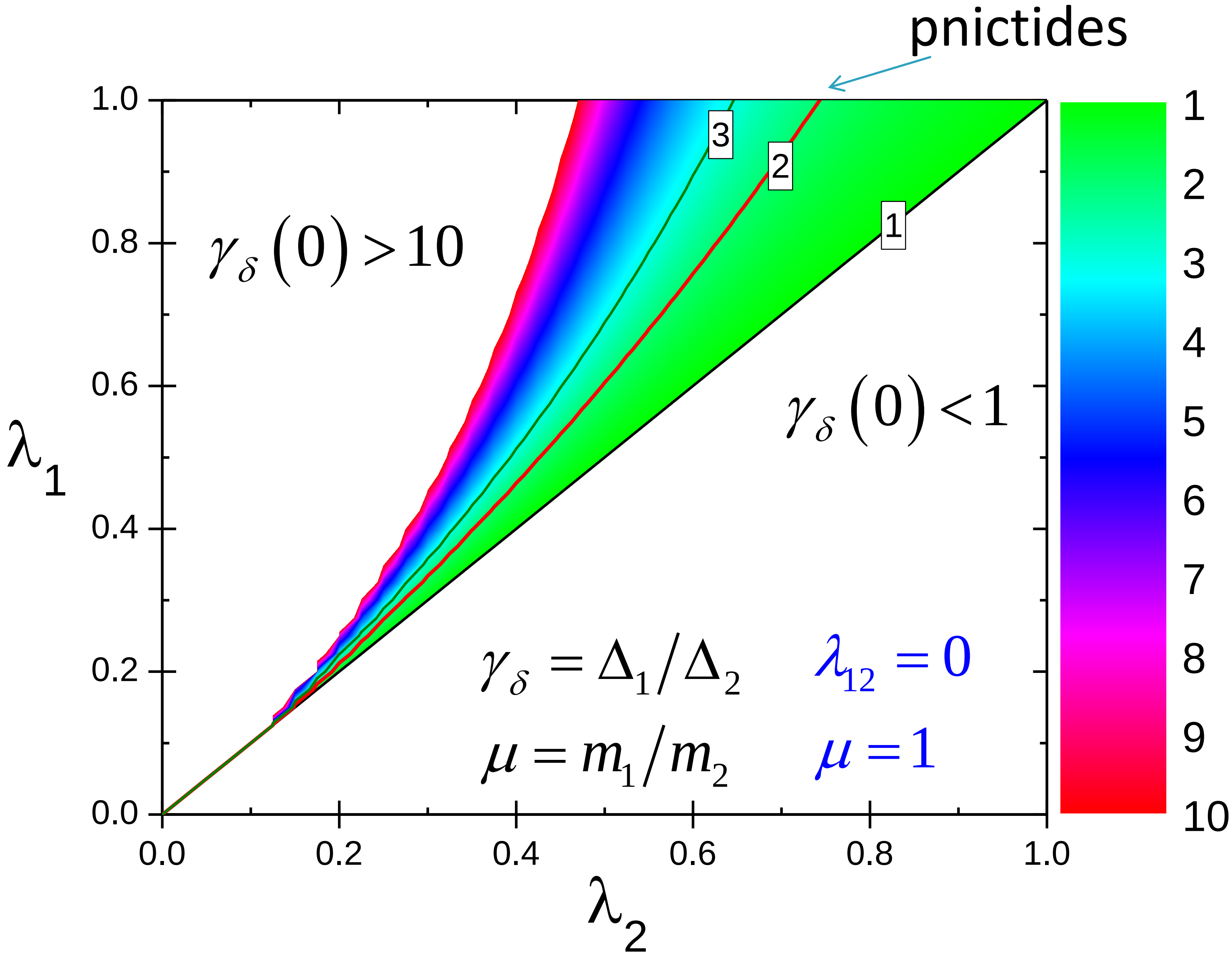


BaK122

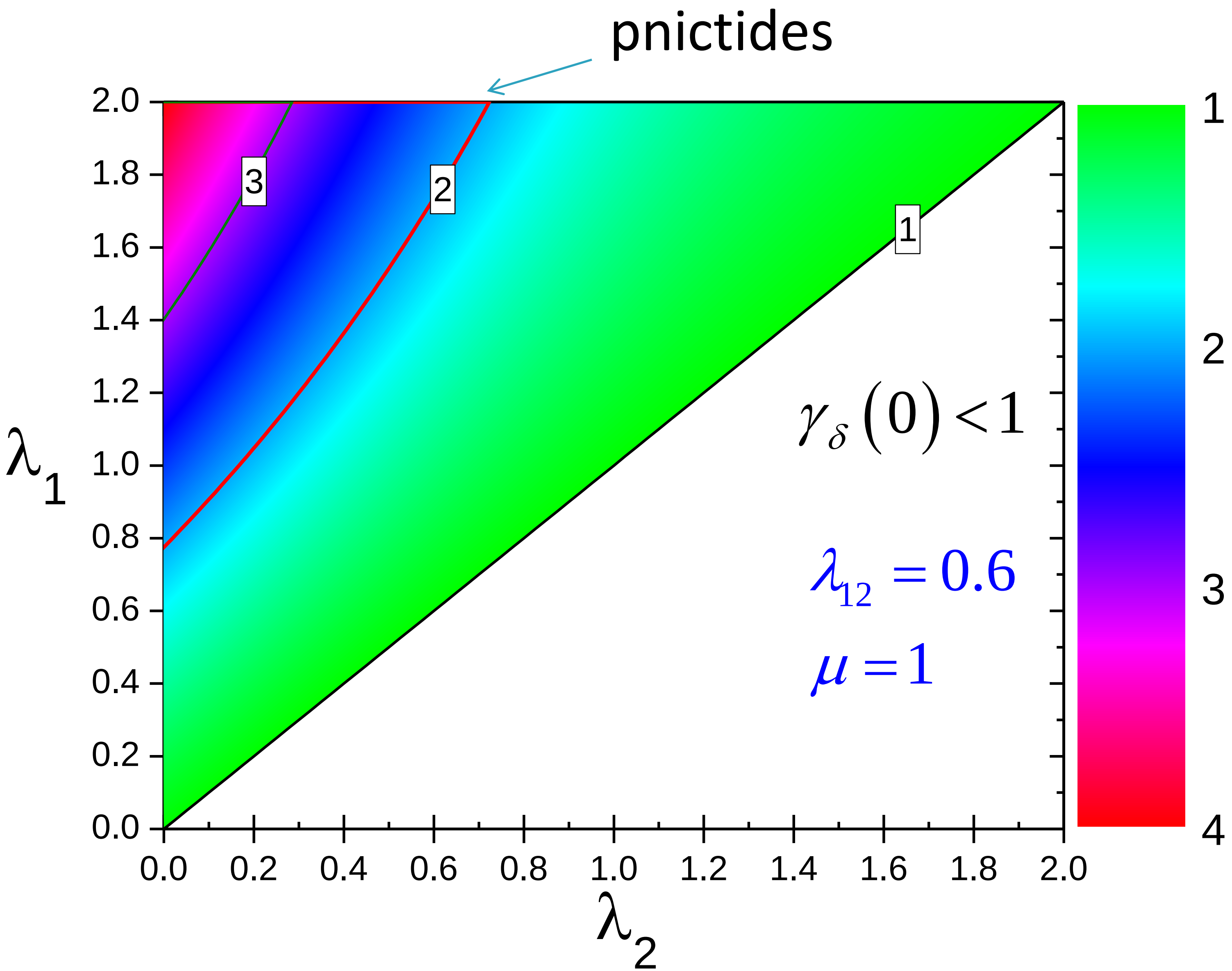


1.0
0.8
0.6
0.4
0.2
0.0
ρ
0.0
0.2
0.4
0.6
0.8
1.0
T/T c
1850 points
λ(0) = 200 nm
λ 1 = 0.92 (fixed)
λ 2 = 0.51
λ 12 = 0.17
γ = 0.56
n 1 = 0.50 (fixed)
λ eff = 0.49
with Θ D = 250,
Tc= 37.07 K

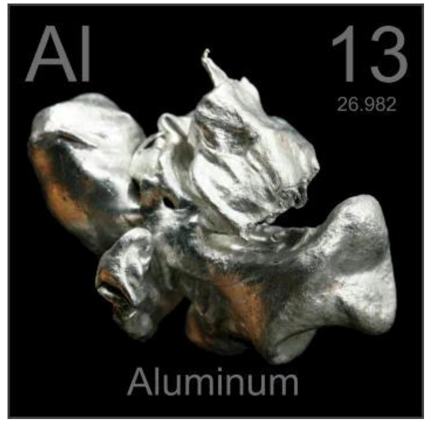
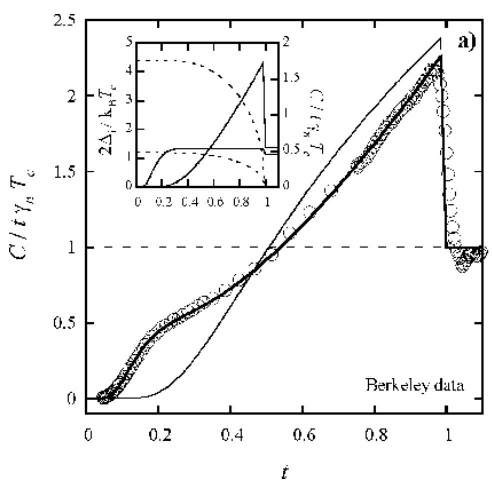
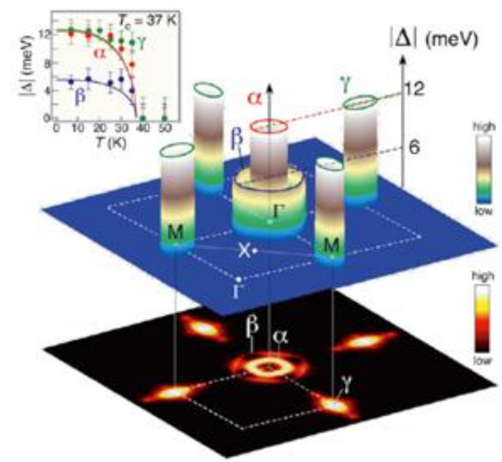
gap ratio in a two-band superconductor



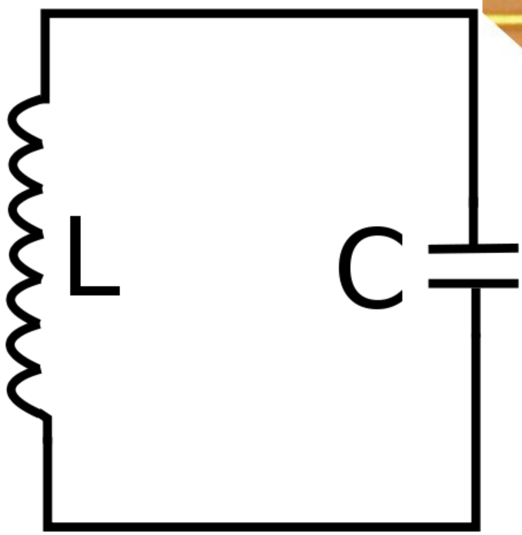
need substantial λ_{ii}

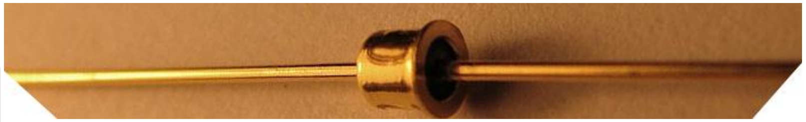


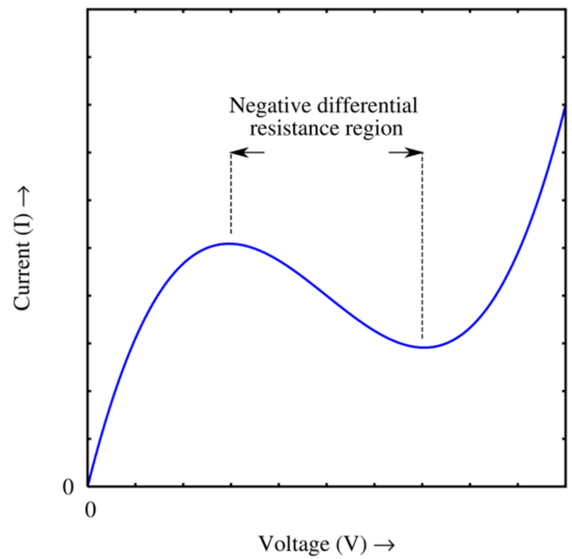
zoology of the gaps

	same sign	sign change
single gap		
multigap		

the experiment: tunnel – diode resonator







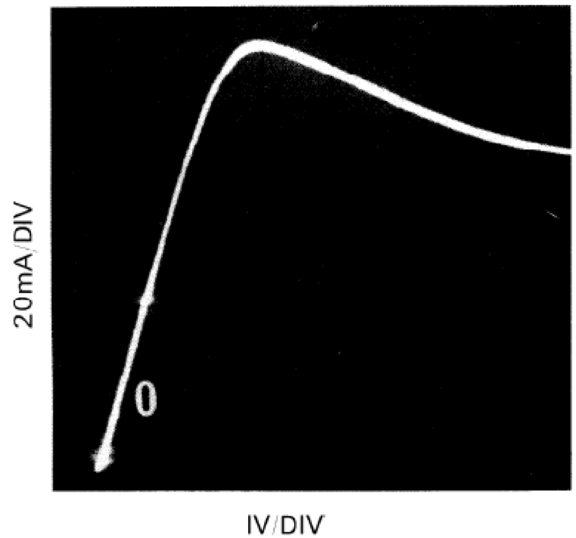
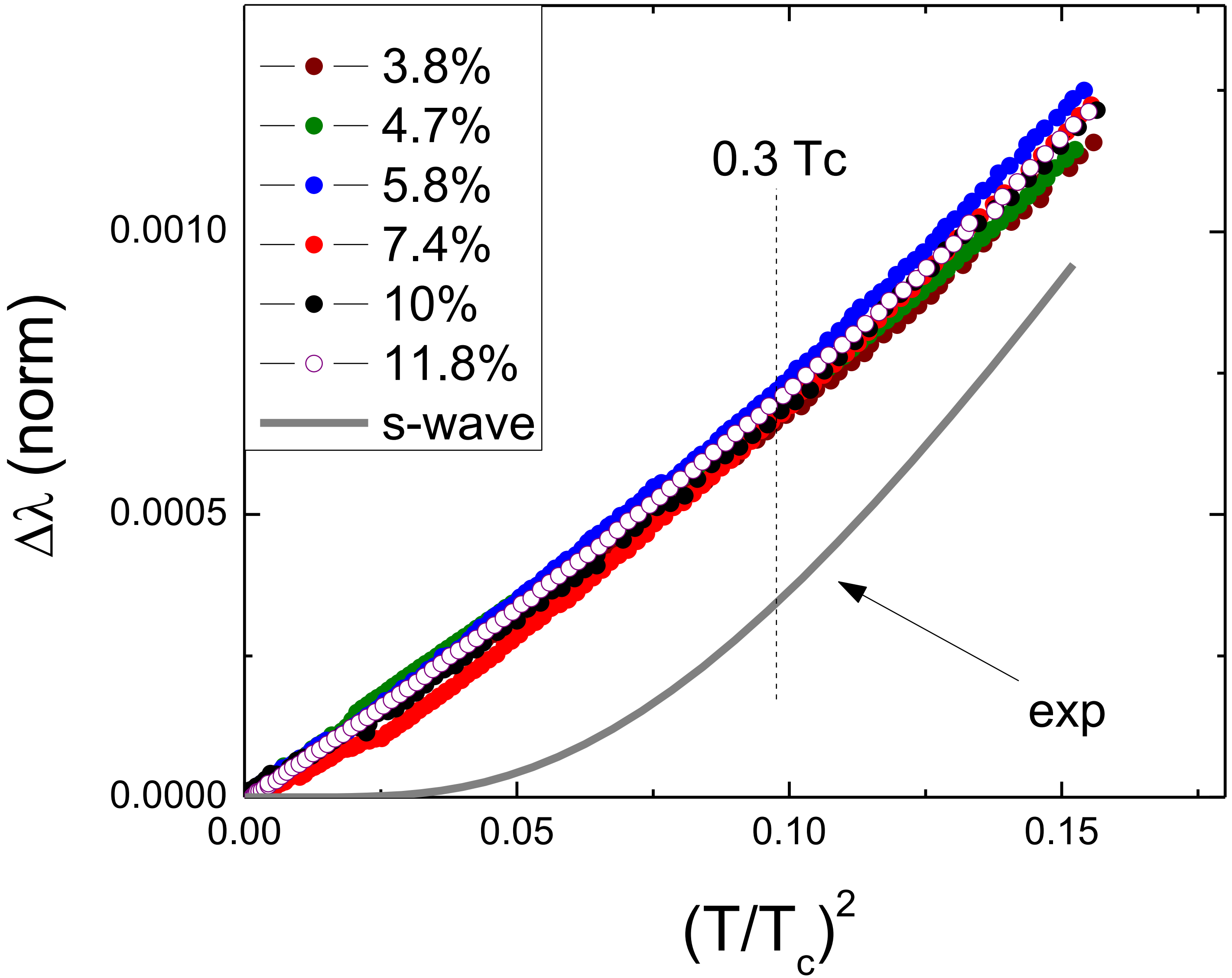


Fig. 14. Current-voltage characteristic at room temperature of a 70Å-period, GaAs-$Ga_{0.5}Al_{0.5}As$ superlattice.

"The original version of the paper was rejected for publication by Physical Review on the referee's unimaginative assertion that it was 'too speculative' and involved 'no new physics.'

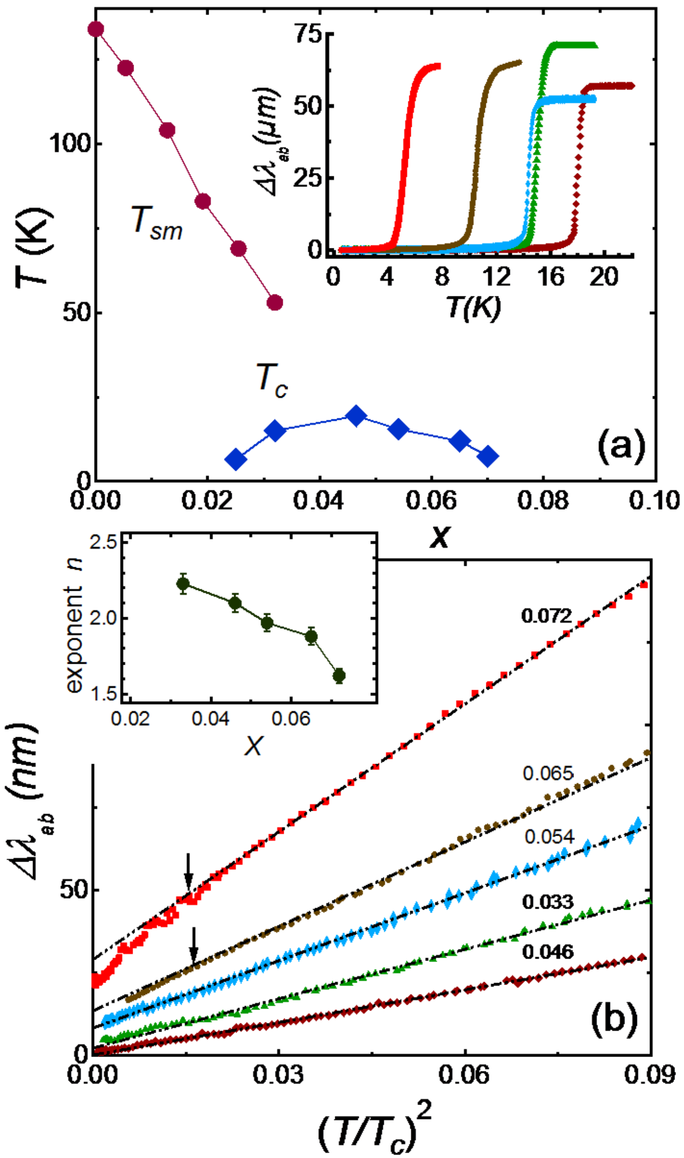
\- *Reona (Leo) Esaki*

universal power-law behavior of $\lambda(T)$ in Co-122



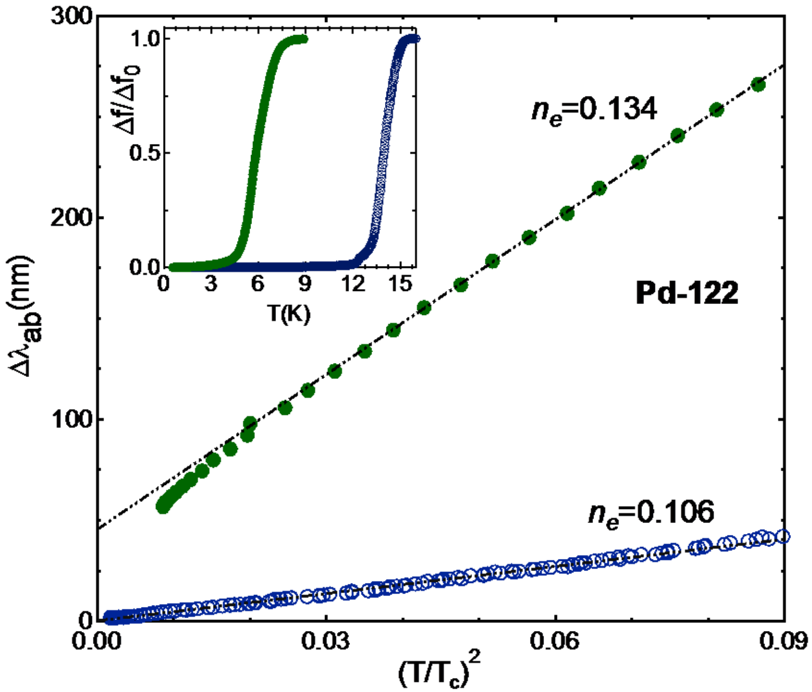
R. T. Gordon *et al.*, Phys. Rev. Lett. **102**, 127004 (2009); Phys. Rev. B **79**, 100506(R) (2009)

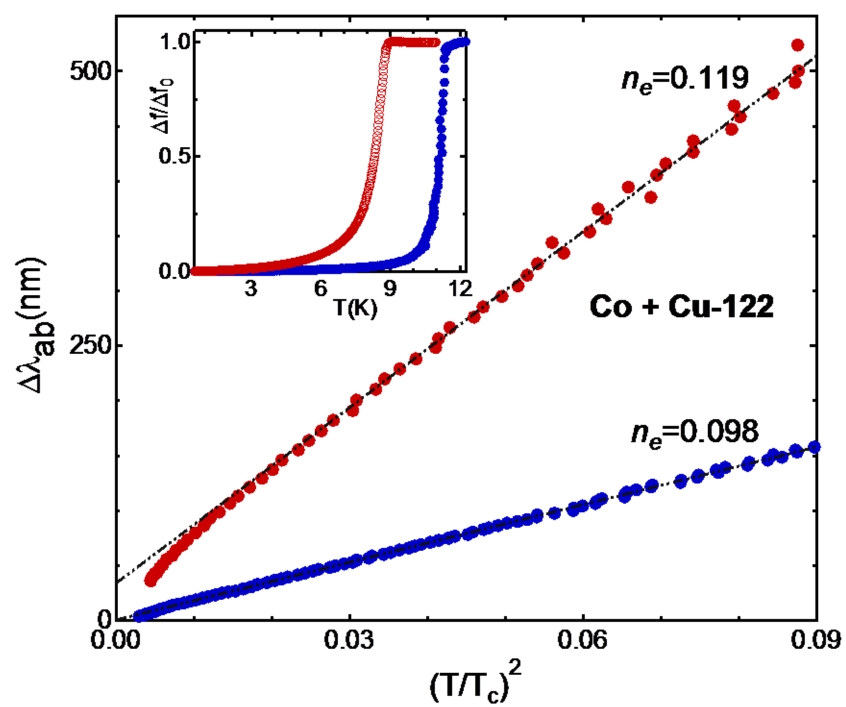
$Ba(Fe_{1-x}Ni_x)_2As_2$ single crystals



C. Martin *et al.*, Phys. Rev. B **81**, 060505(R) (2010)

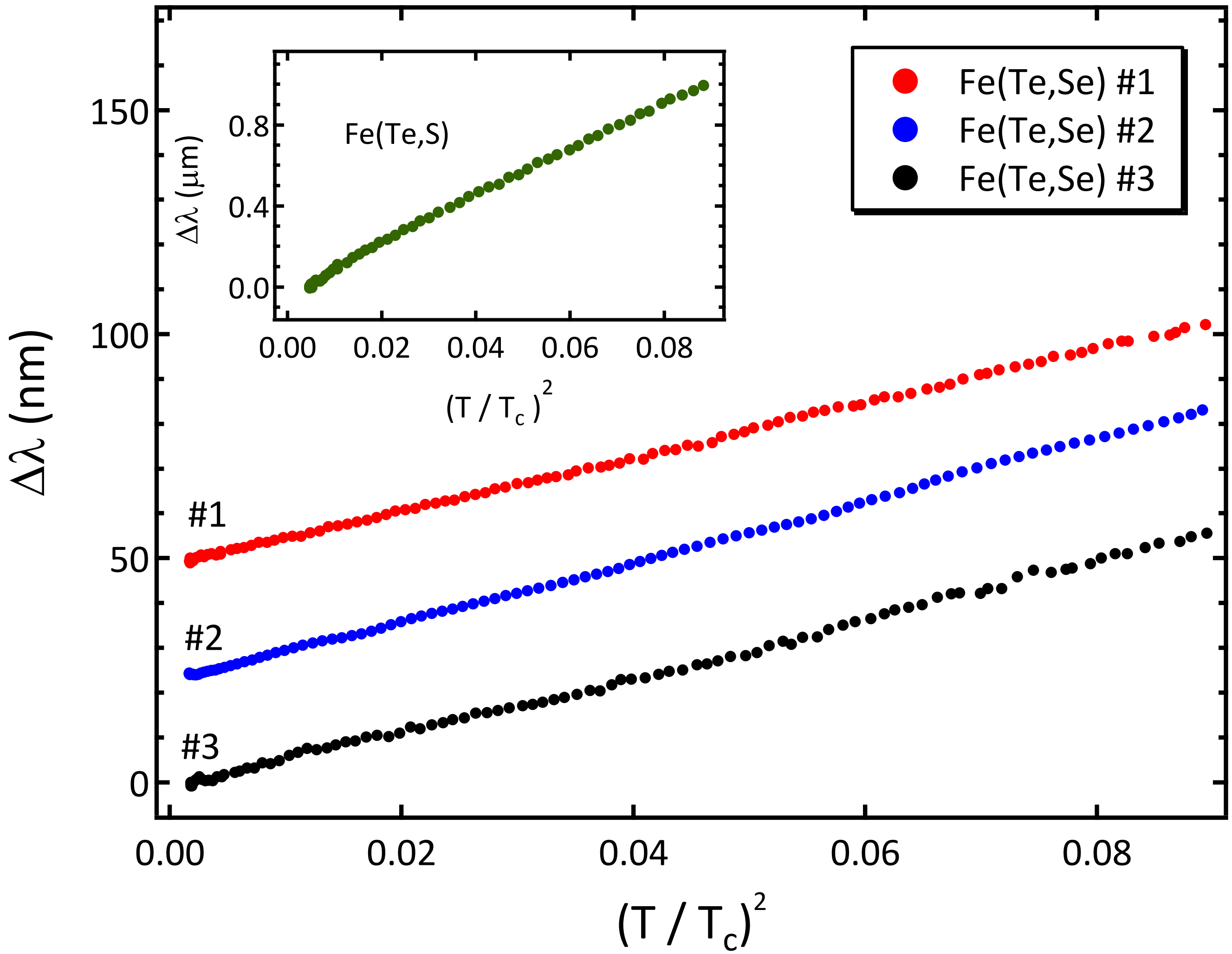
$Ba(Fe_{1-x}T_x)_2As_2$ (T = Pd, Co+Cu)





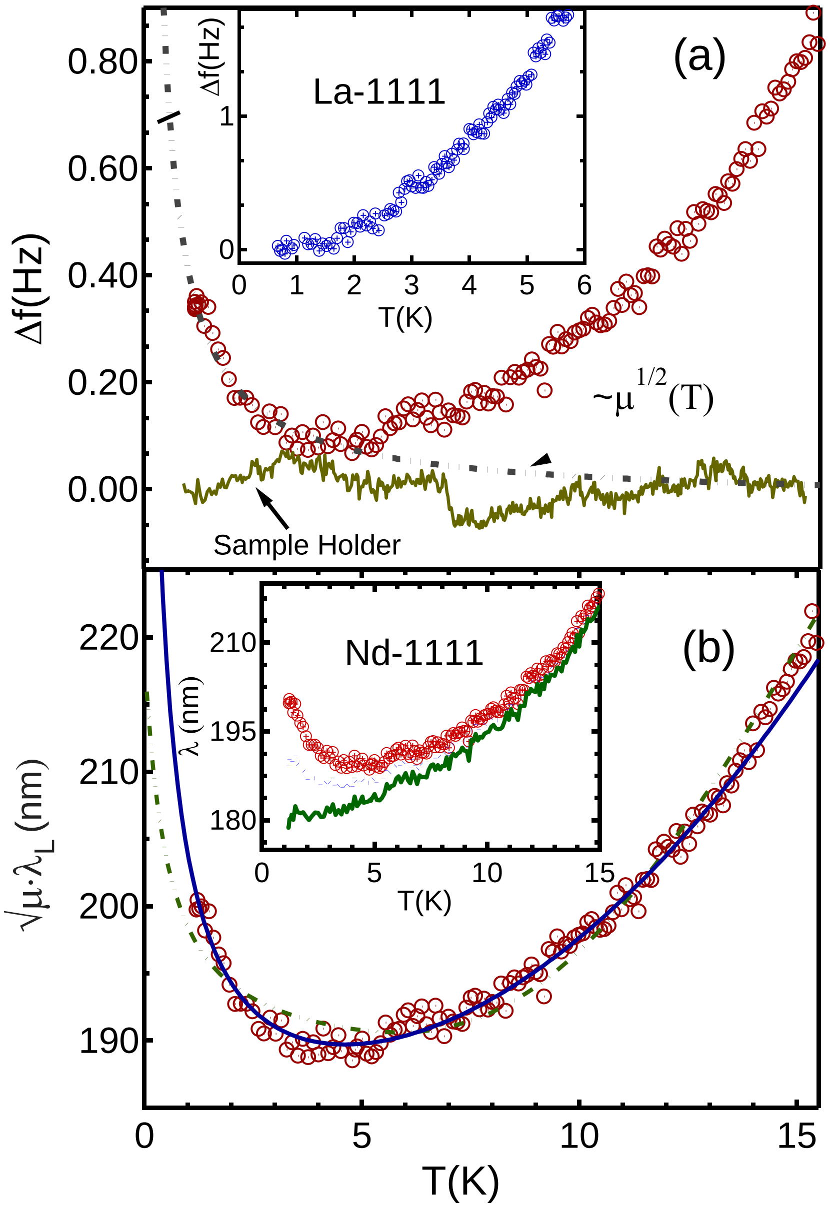
C. Martin *et al.*, SUST **23**, 065022 (2010)

“11” system - Fe(Te,Se)



H. Kim *et al.*, Phys. Rev. B **81**, 180503 (2010)

$RFeAsO_{1-x}F_y$ single crystals (R-1111)



J. R. Cooper, PRB **54**, 3753 (1996)

$$4\pi\chi \simeq \mu\frac{\lambda(\mu)}{R}\tanh\frac{R}{\lambda(\mu)} - 1$$

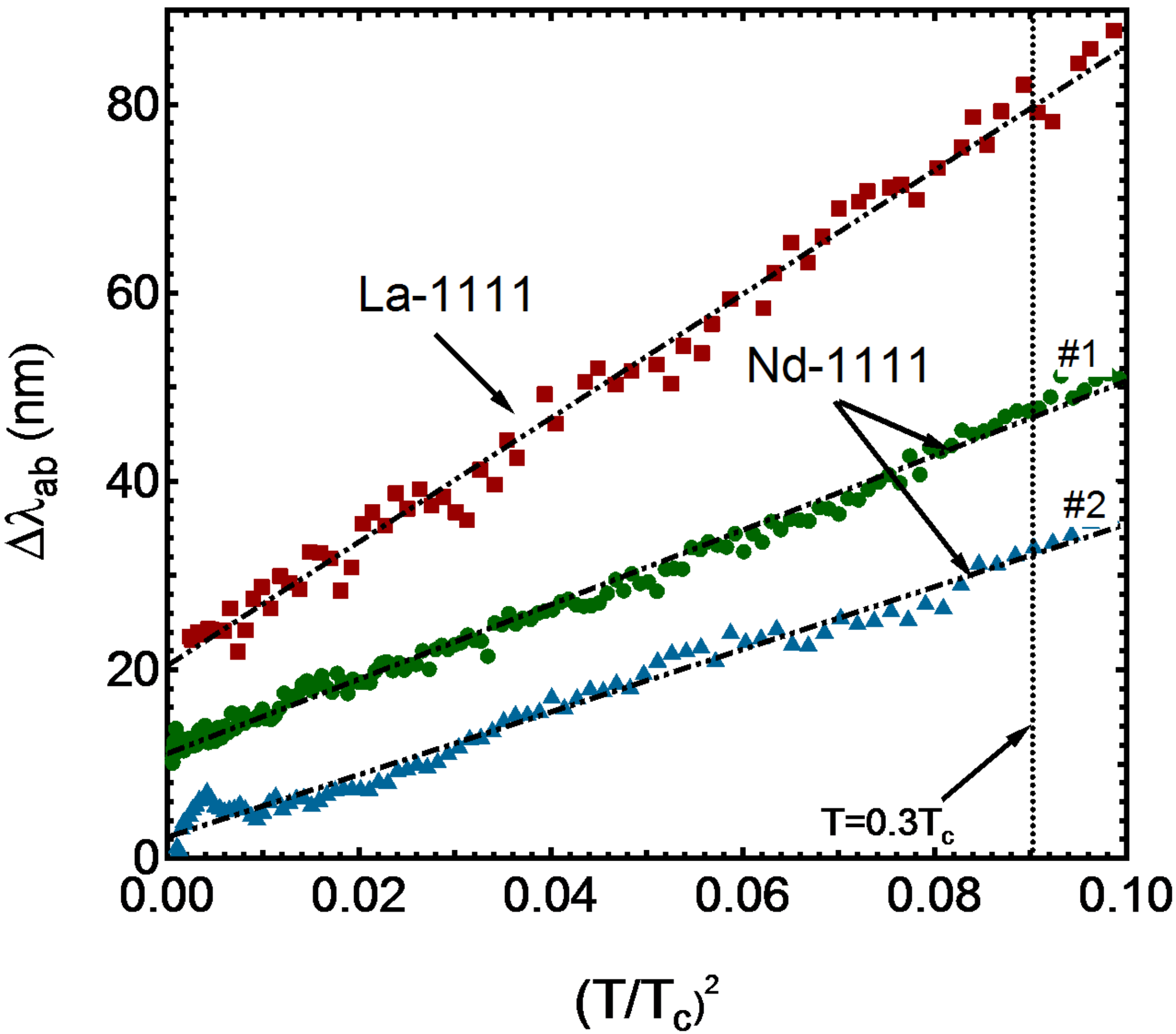
$$\lambda(\mu) = \frac{\lambda_L}{\sqrt{\mu}}$$

$$\Delta f(T) \propto \sqrt{\mu(T)}\lambda_L(T)$$

C. Martin *et al.*, arXiv:0807.0876

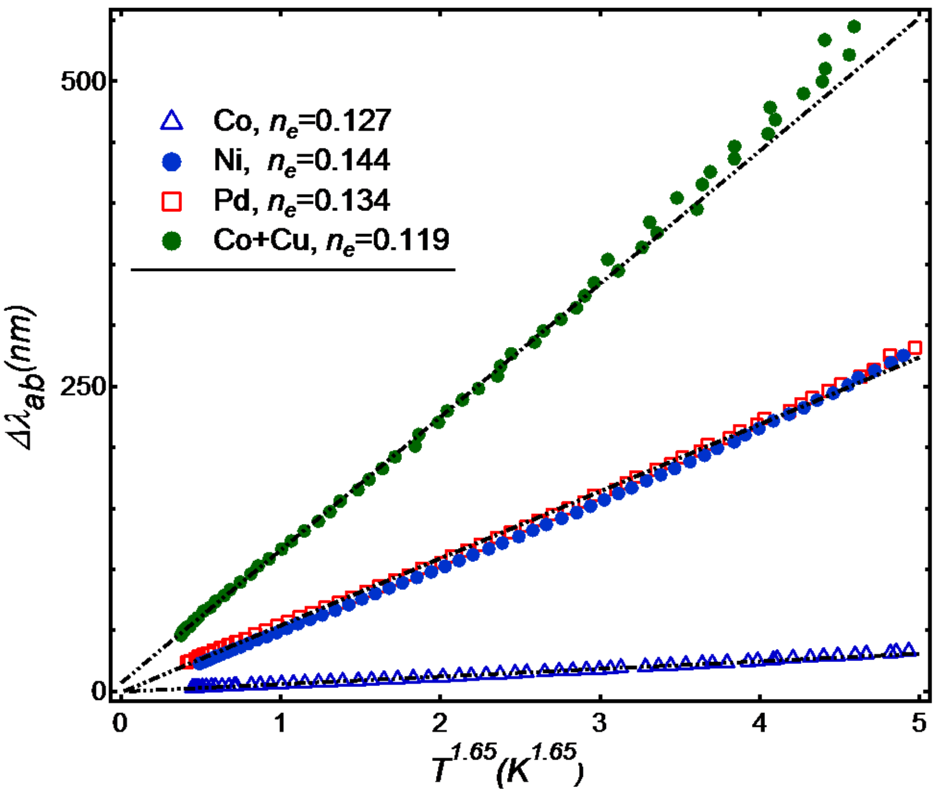
C. Martin *et al.*, arXiv:0903.2220
Phys. Rev. Lett. **102**, 247002 (2009)

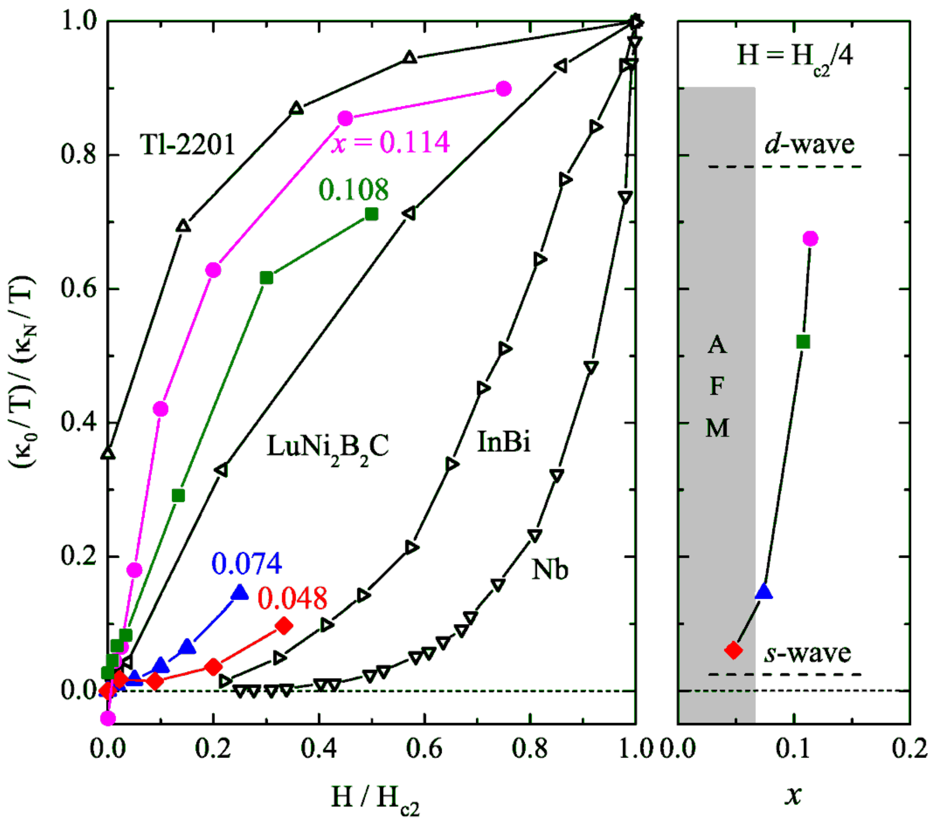
"1111" $RFeAsO_{1-x}F_x$



C. Martin *et al.*, Phys. Rev. Lett. **102**, 247002 (2009)

overdoped regime: large gap anisotropy

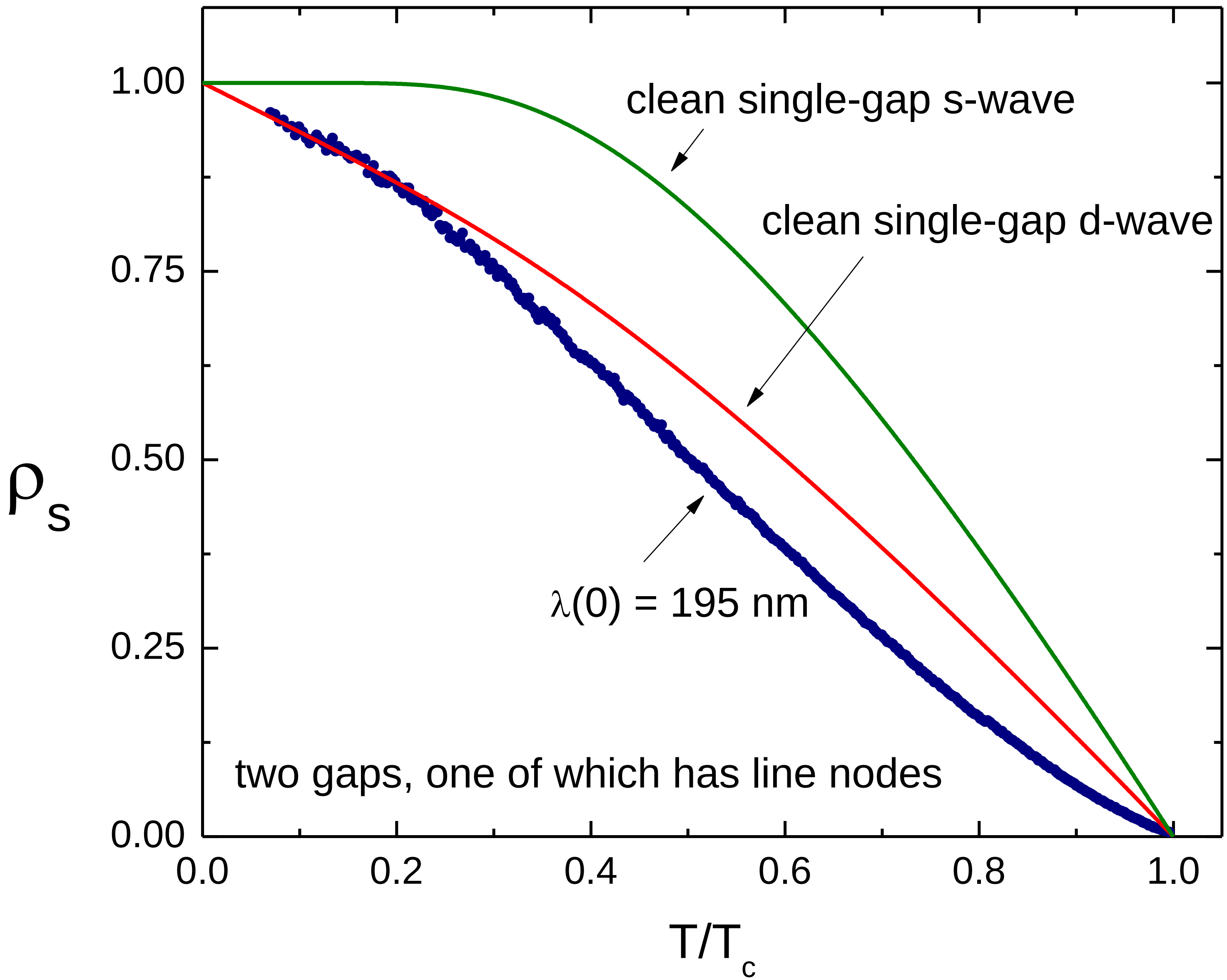




C. Martin *et al.*, SUST **23**, 065022 (2010)

M. A. Tanatar *et al.*, Phys. Rev. Lett. **104**, 067002 (2010)

$BaFe_2(AsP)_2$



clean single-gap s-wave
clean single-gap d-wave
λ(0) = 195 nm
two gaps, one of which has line nodes
ρs
1.00
0.75
0.50
0.25
0.00
0.0
0.2
0.4
0.6
0.8
1.0
T/Tc

conclusion: $\lambda_{ab}(T)$

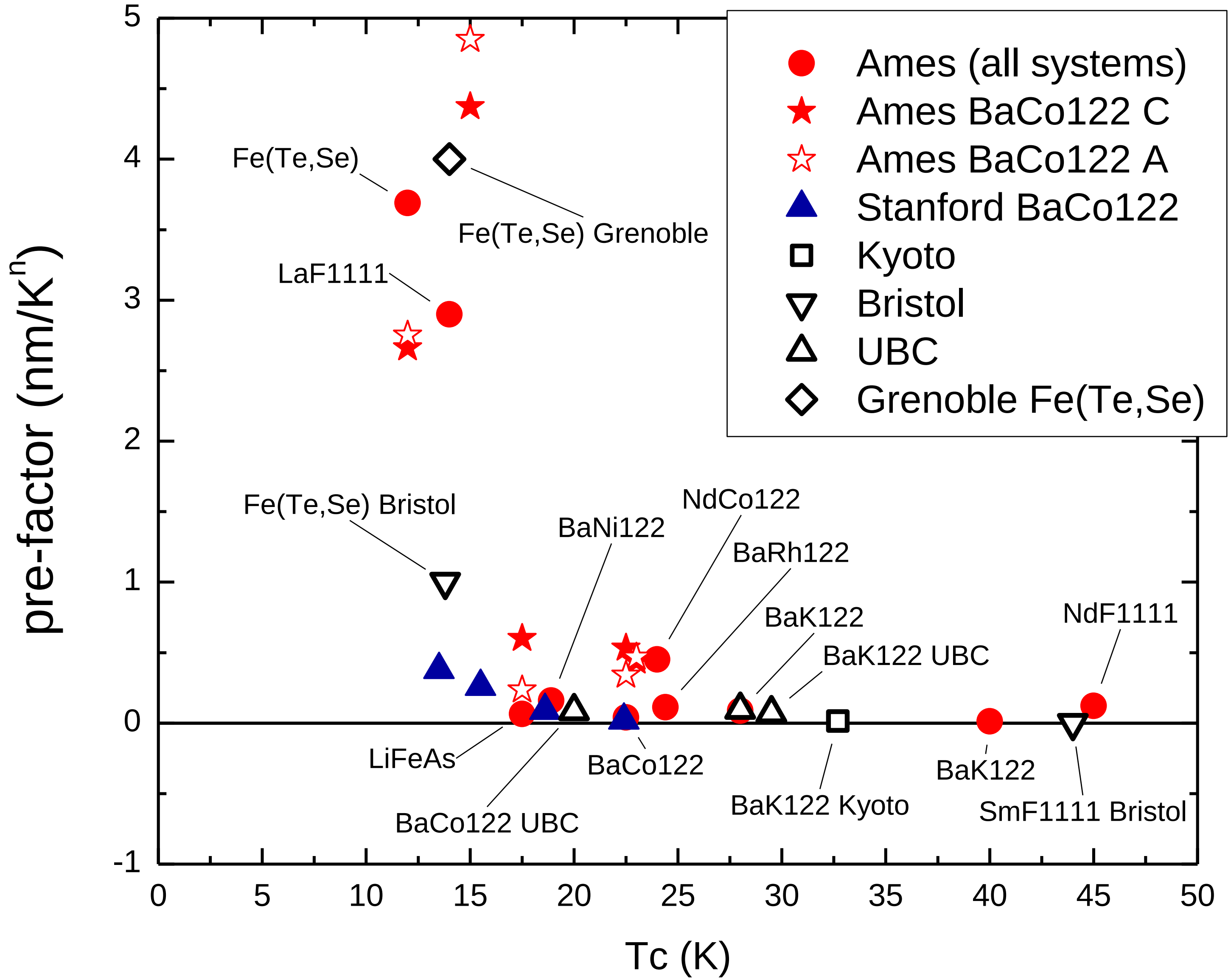
in all iron-based superconductors

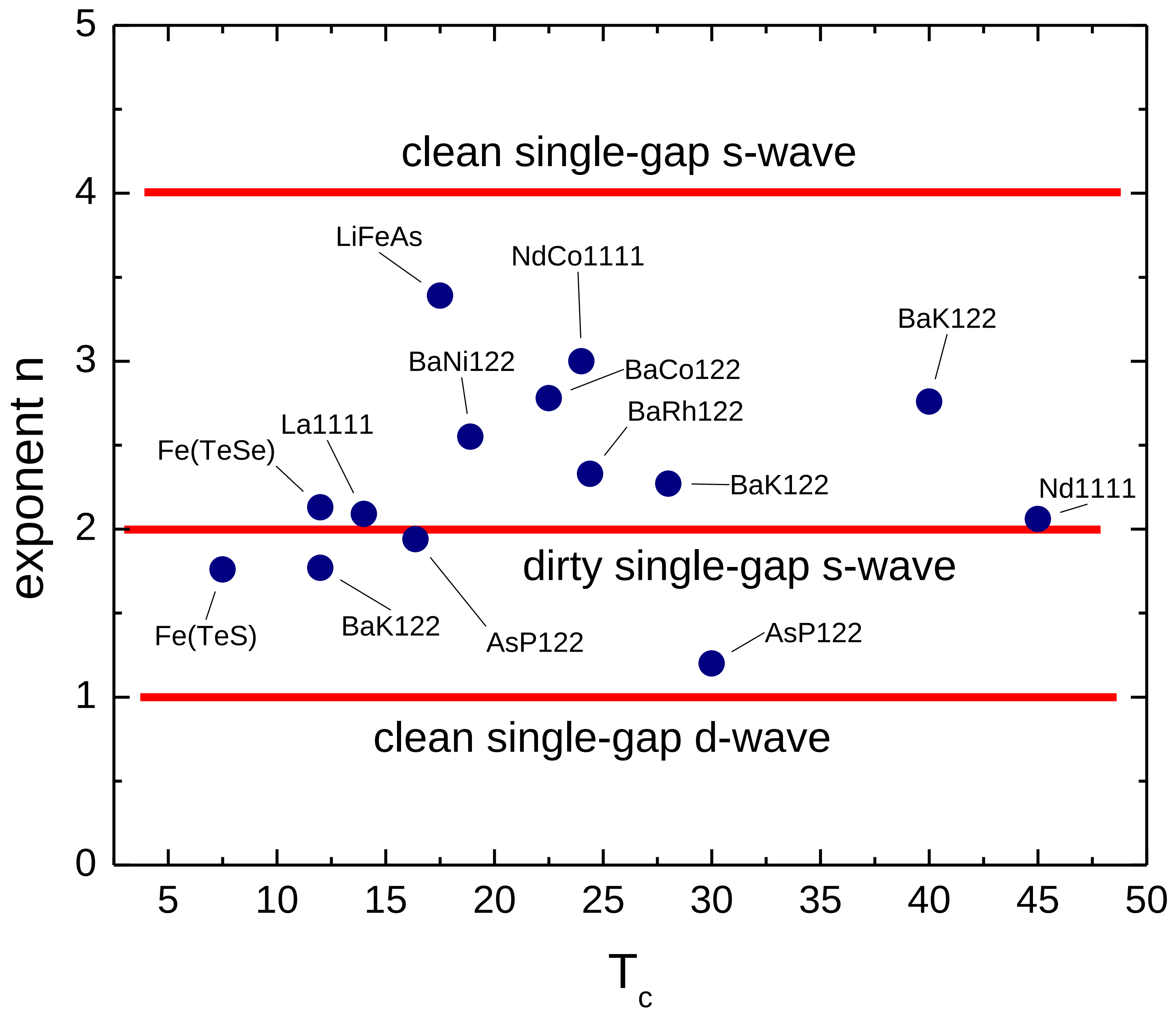
$$\lambda_{ab}(T) = \lambda_{ab}(0) + AT^n$$

$2 < n < 3$ in most doped Fe-based superconductors
$n \approx 1.xx$ in P – doped materials

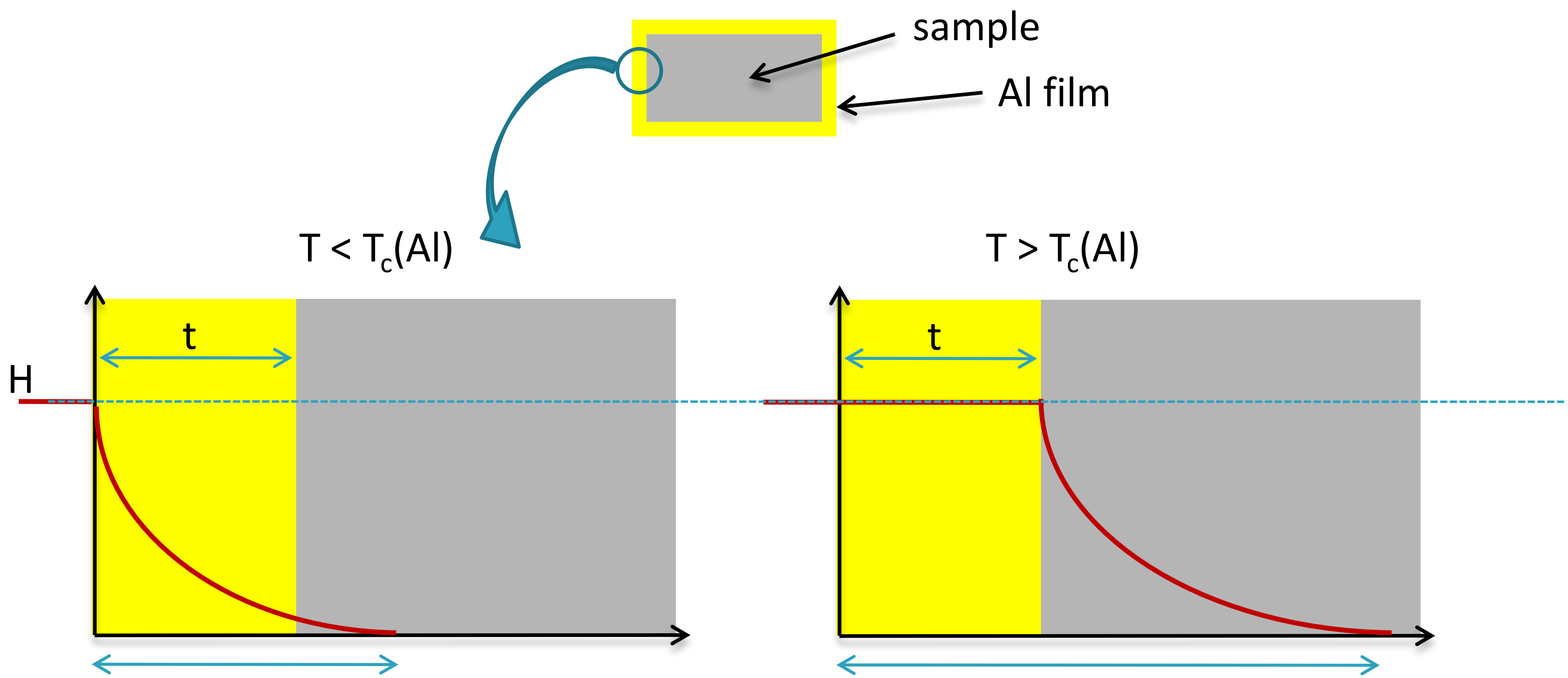
large in-pane gap anisotropy in the overdoped regime

comparison with other measurements




clean single-gap s-wave
dirty single-gap s-wave
clean single-gap d-wave
exponent n
T c
LiFeAs
NdCo1111
BaK122
BaNi122
BaCo122
BaRh122
La1111
Fe(TeSe)
BaK122
Nd1111
Fe(TeS)
BaK122
AsP122
AsP122
0
1
2
3
4
5
5
10
15
20
25
30
35
40
45
50

the absolute value of $\lambda(0)$



$$\lambda_{eff}\left(T < T_c^{Al}\right) = \lambda_{Al}\frac{\lambda + \lambda_{Al}\tanh\left(t/\lambda_{Al}\right)}{\lambda_{Al} + \lambda\tanh\left(t/\lambda_{Al}\right)}$$

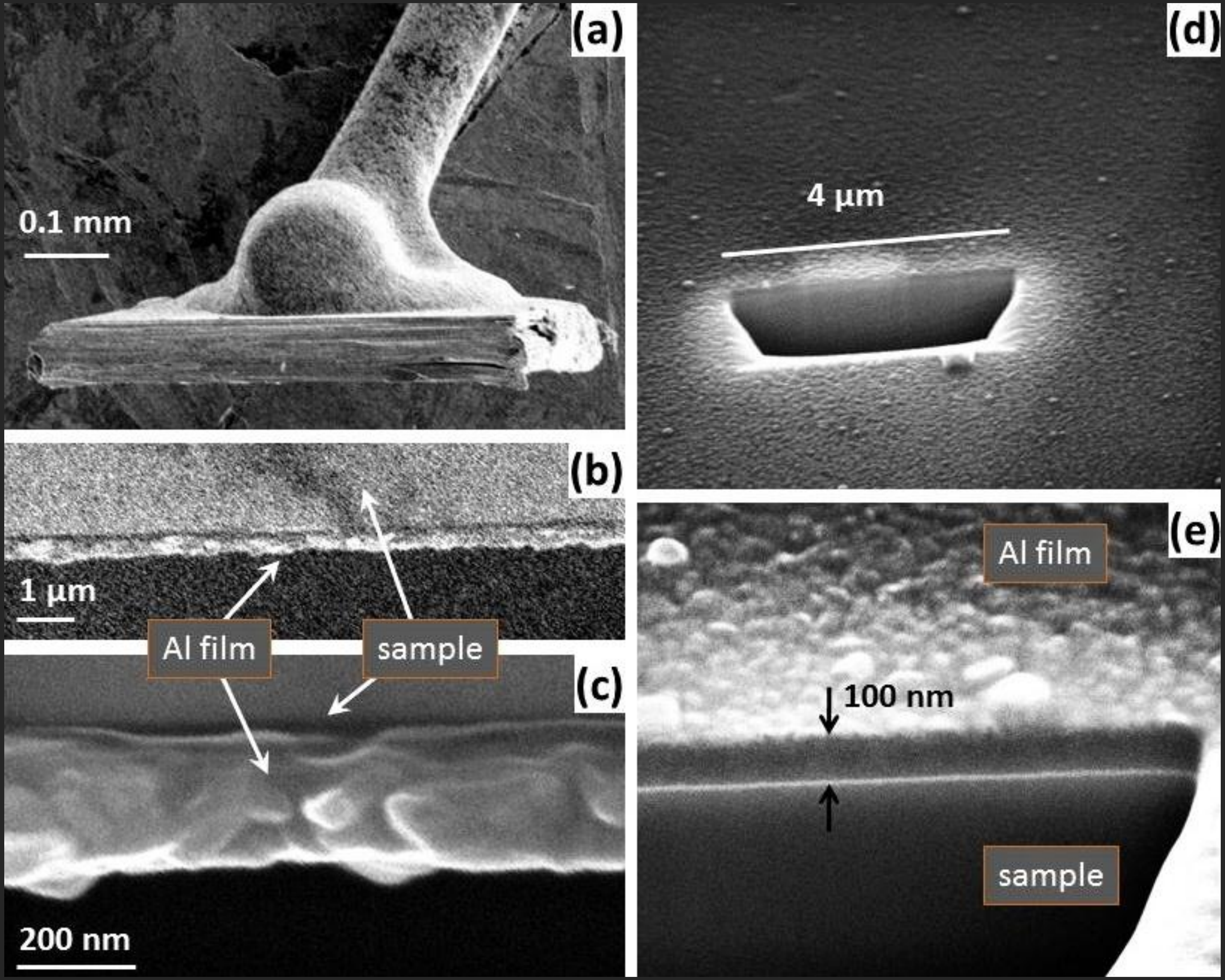
$$\lambda_{eff}\left(T > T_c^{Al}\right) = t + \lambda$$

t ≈ 1000 Å

$\lambda_{Al} \approx$ 500 Å

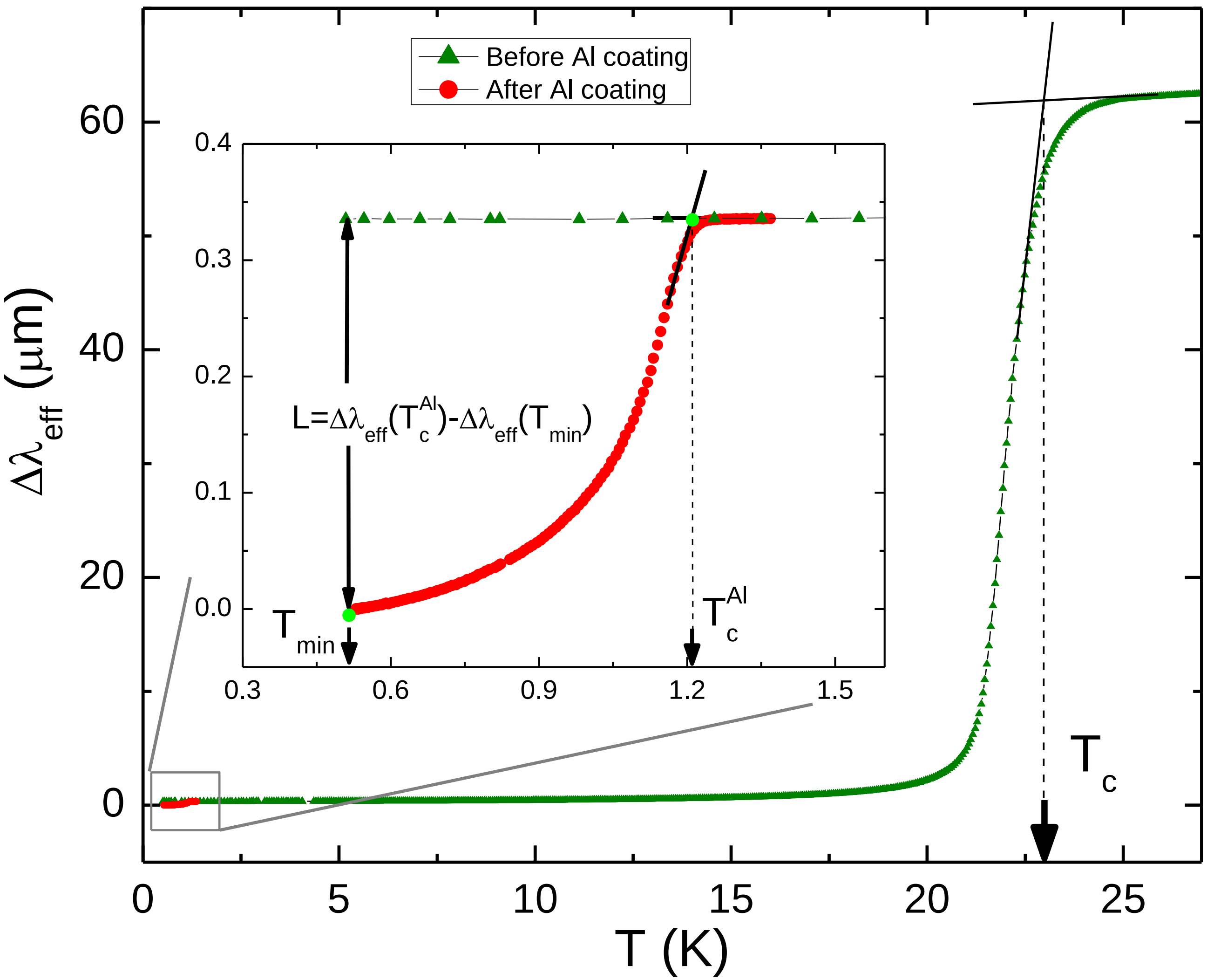
$$\Delta\lambda_{eff} = \lambda_{eff}\left(T > T_c^{Al}\right) - \lambda_{eff}\left(T << T_c^{Al}\right)$$ ← measured

R. Prozorov *et al.*, Appl. Phys. Lett. **77**, 4202 (2000)
R. T. Gordon *et al.*, Phys. Rev. B **82**, 054507 (2010)



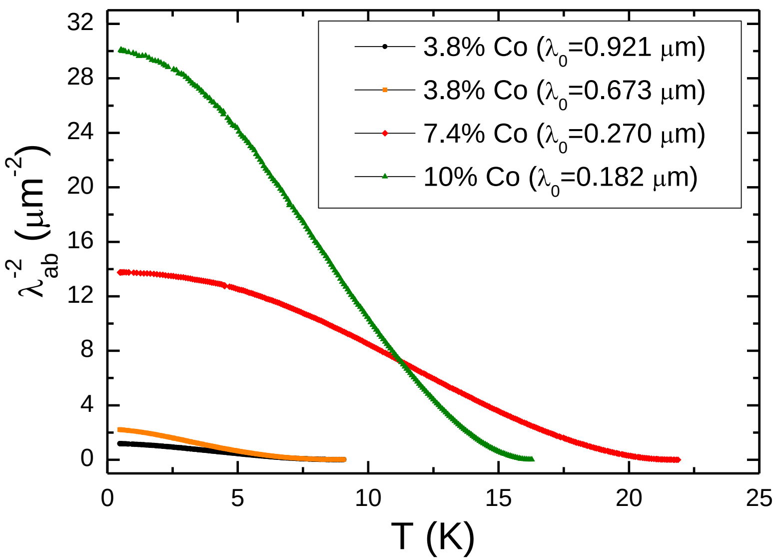
R. T. Gordon *et al.*, Phys. Rev. B **82**, 054507 (2010)

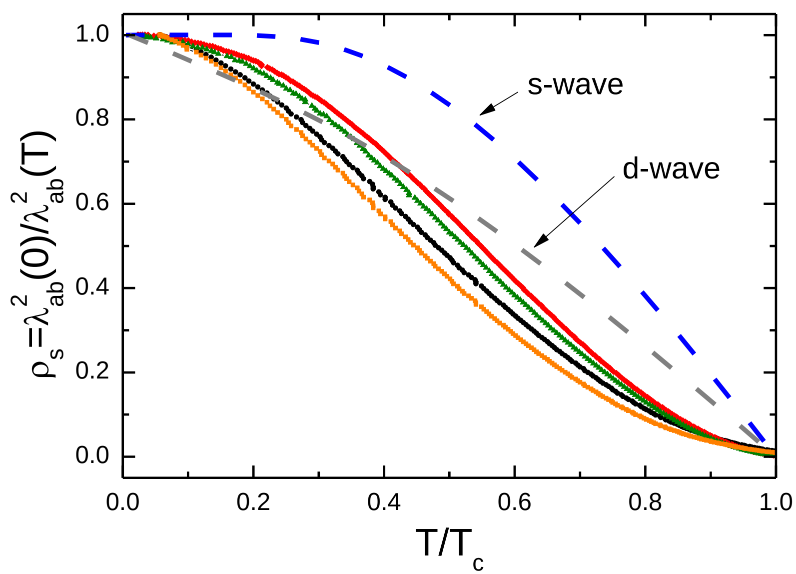
$\lambda(0)$ in $Ba(Fe_{0.93}Co_{0.07})_2As_2$

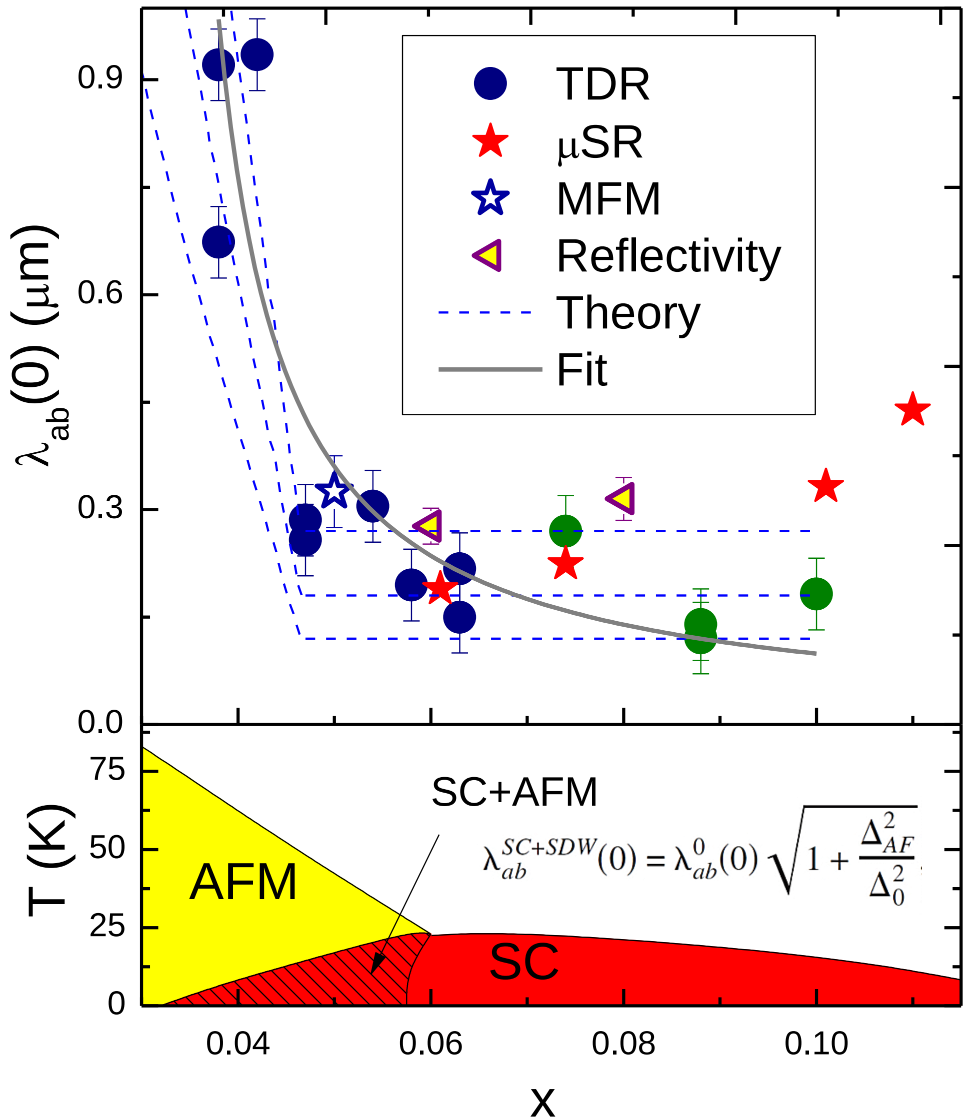


R. T. Gordon *et al.*, Phys. Rev. B **82**, 054507 (2010)

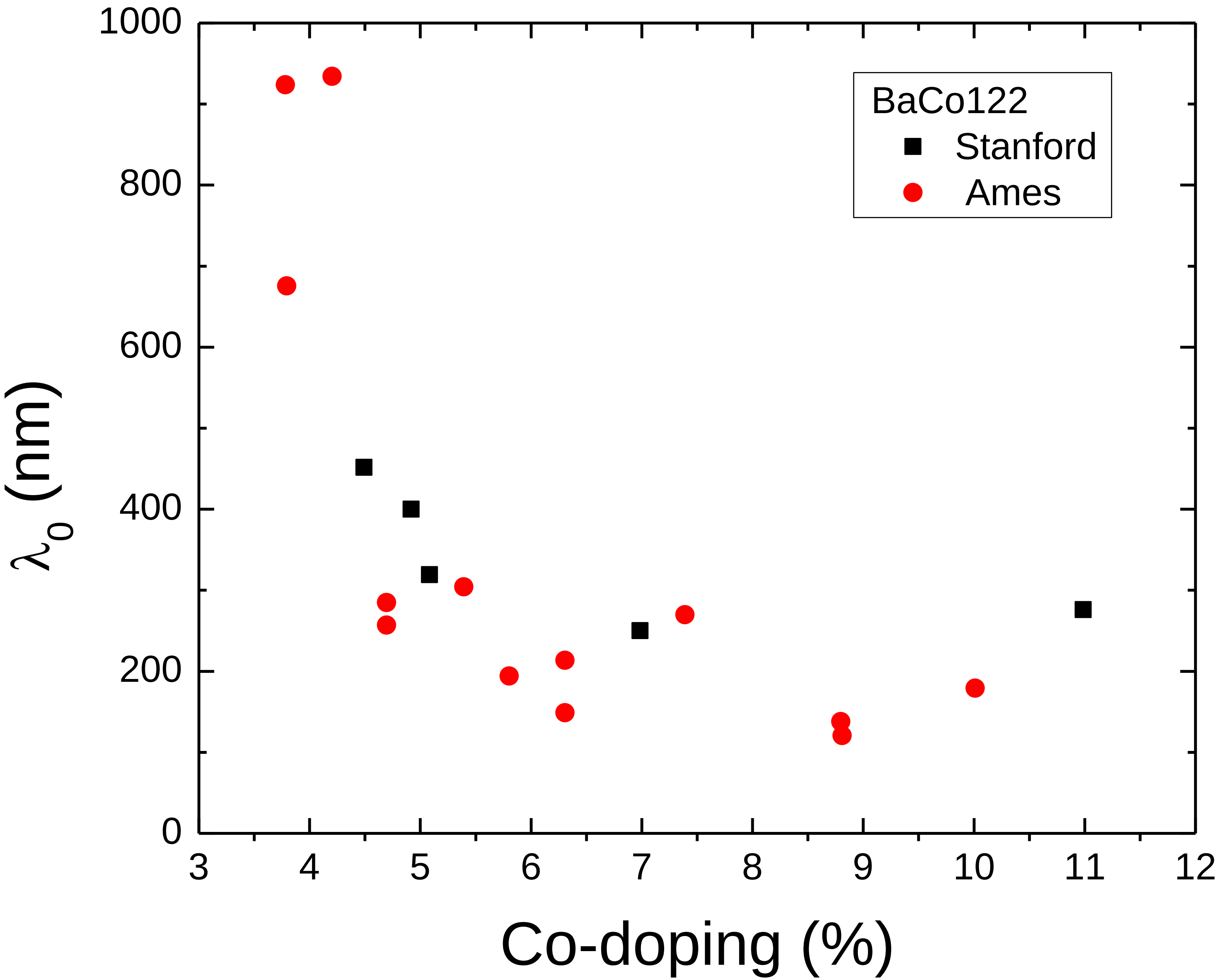
λ(0) vs. x







R. T. Gordon *et al.*, Phys. Rev. B **82**, 054507 (2010)


BaCo122
Stanford
Ames
1000
800
600
400
200
0
λ0 (nm)
3
4
5
6
7
8
9
10
11
12
Co-doping (%)

pairbreaking for general FS and any gap symmetry

$f(\mathbf{r},\mathbf{k_F},\omega)$ $\quad \Delta(\mathbf{r},T,\mathbf{k_F}) = \Psi(\mathbf{r},T)\Omega(\mathbf{k_F}), \langle\Omega^2\rangle = 1$ - order parameter.

$g^2 + ff^+ = 1$ $\quad$ Simplify: $\langle\Omega\rangle = 0$ (applicable to d-wave and $s_\pm$) $\quad \hbar = k_B = 1$

Introduce normal and spin-flip scattering in Born approximation.

$$\frac{1}{\tau_\pm} = \frac{1}{\tau} \pm \frac{1}{\tau_m} \quad \text{or} \quad \rho = \frac{\hbar}{2\pi T_c \tau}, \quad \rho_\pm = \rho \pm \rho_m$$

V. G. Kogan, Phys. Rev. B **80**, 214532 (2009)
V. G. Kogan, C. Martin, R. Prozorov, Phys. Rev. B **80**, 014507 (2009)

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for strong pair-breaking, at all temperatures: $f \ll 1, g \approx 1 - ff^+/2$

$$\frac{\Psi\left(1-t^2\right)}{12\pi T \rho_+^2} = \sum_{\omega>0}^{\infty}\left(\frac{\Psi}{\omega^+} - \langle \Omega f \rangle\right)$$

- self-consistent gap equation with $\omega_+ = \omega + \left(2\tau_\pm\right)^{-1}$

$$\Psi^2 = \frac{2\pi^2\left(T_c^2 - T^2\right)}{3\left\langle\Omega^4\right\rangle - 2}$$

- without fields. It gives Abrikosov-Gor'kov result for $\Omega = 1$

A. A. Abrikosov and L. P. Gor'kov, Zh. Eksp. Teor. Fiz. **39**, 1781 (1960). Sov. Phys. JETP **12**, 1243 (1961).

response to fields and currents

Weak supercurrents and fields leave the OP amplitude unchanged, but cause the condensate, i.e., Δ and the amplitudes f to acquire an overall phase $\theta(\mathbf{r})$:

$$\Delta = \Delta_0 e^{i\theta} \qquad f = (f_0 + f_1)e^{i\theta}$$

$$g = g_0 + g_1 \qquad f^+ = (f_0 + f_1^+)e^{-i\theta}$$

$$\mathbf{j} = -4\pi |e| N(0) T \,\mathrm{Im} \sum_{\omega>0} \langle \mathbf{v} g \rangle$$

$$\langle X \rangle = \oint_{FS} X \frac{d^2\mathbf{k}_F}{(2\pi)^3 \hbar N(0) |\mathbf{v}|}$$

with: $$\frac{4\pi}{c} j_i = -(\lambda^2)^{-1}_{ik} a_k$$

$$\frac{2\pi}{\phi_0}\mathbf{a} \equiv \nabla\theta + \frac{2\pi}{\phi_0}\mathbf{A}$$ gauge – invariant vector potential

$$\left(\lambda^2\right)^{-1}_{ik} = \frac{8\pi^2 e^2 N(0) T}{c^2} \left\langle v_i v_k \Omega^2 \right\rangle \Psi^2 \sum_{\omega>0} \frac{1}{\omega_+^3}$$

for strong scattering, $$\sum_{\omega>0} \frac{1}{\omega_+^3} = -\frac{1}{16\pi^3 T^3} \psi''\left(\frac{\rho^+}{2t} + \frac{1}{2}\right) \approx \frac{\tau_+^2}{\pi T}$$

in real units: $$\left(\lambda^2\right)^{-1}_{ik} = \frac{16\pi^3 e^2 N(0) k_B^2 \tau_+^2}{c^2 \hbar^2 (3\langle\Omega^4\rangle - 2)} \left\langle v_i v_k \Omega^2 \right\rangle \left(T_c^2 - T^2\right)$$

$$\Delta\lambda(T) = \eta \frac{T^2}{T_c^3}, \; \lambda(0) = \frac{2\eta}{T_c}$$ where $$\eta = \frac{c\hbar}{8\pi k_B \tau_+} \sqrt{\frac{3\langle\Omega^4\rangle - 2}{\pi e^2 N(0) \langle v_a^2 \Omega^2 \rangle}}$$

strong pair-breaking in pnictides

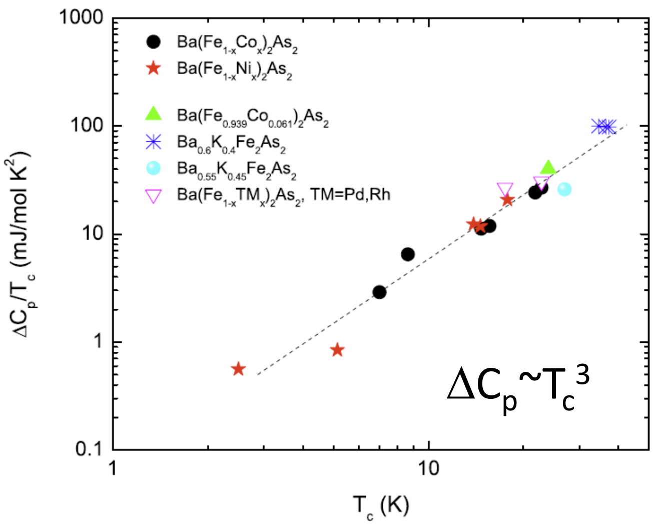
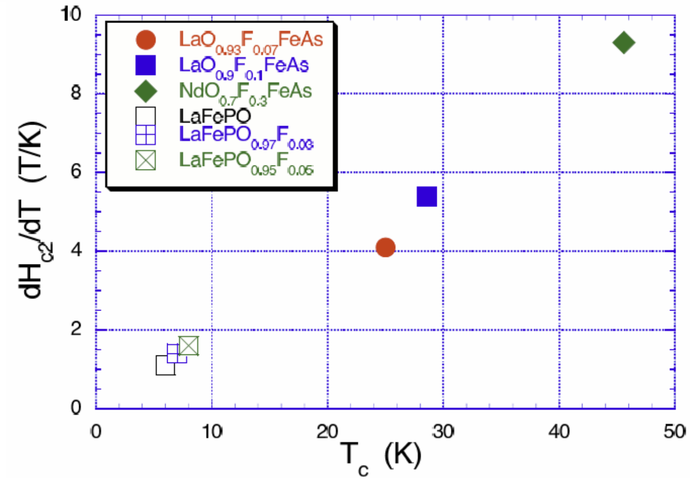


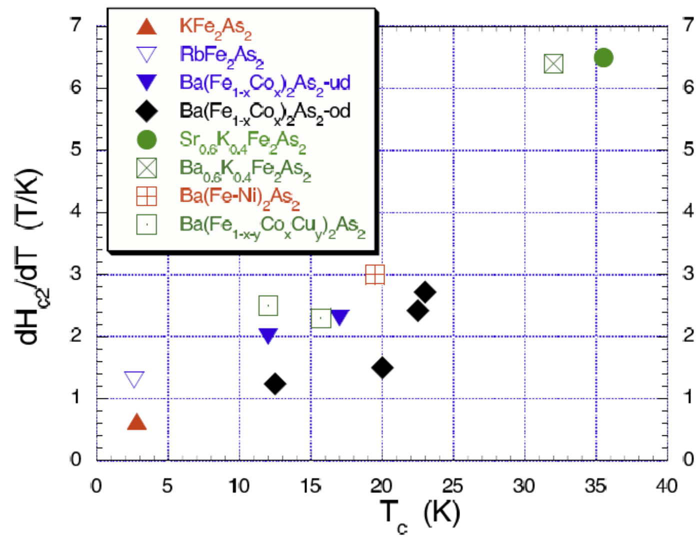
FIG. 3. (Color online) $\Delta C_p/T_c$ vs T_c for $Ba(Fe_{1-x}Co_x)_2As_2$ (circles) and $Ba(Fe_{1-x}Ni_x)_2As_2$ (stars) plotted together with literature data for $Ba(Fe_{0.939}Co_{0.061})_2As_2$ (Ref. 8), $Ba_{0.55}K_{0.45}Fe_2As_2$ (Ref. 18), $Ba_{0.6}K_{0.4}Fe_2As_2$ (Refs. 19–21) and $Ba(Fe_{0.943}Rh_{0.057})_2As_2$ and $Ba(Fe_{0.957}Pd_{0.043})_2As_2$ (Ref. 22). Dashed line has a slope $n=2$ and is a guide for the eyes.

S. L. Bud'ko et al., Phys. Rev. B **79**, 220516 (2009)

$$\Delta C = C_s - C_n = \frac{16\pi^4 k_B^4 N(0)\tau_+^2}{3\hbar^2(3\langle\Omega^4\rangle - 2)}\, T_c^3\,.$$

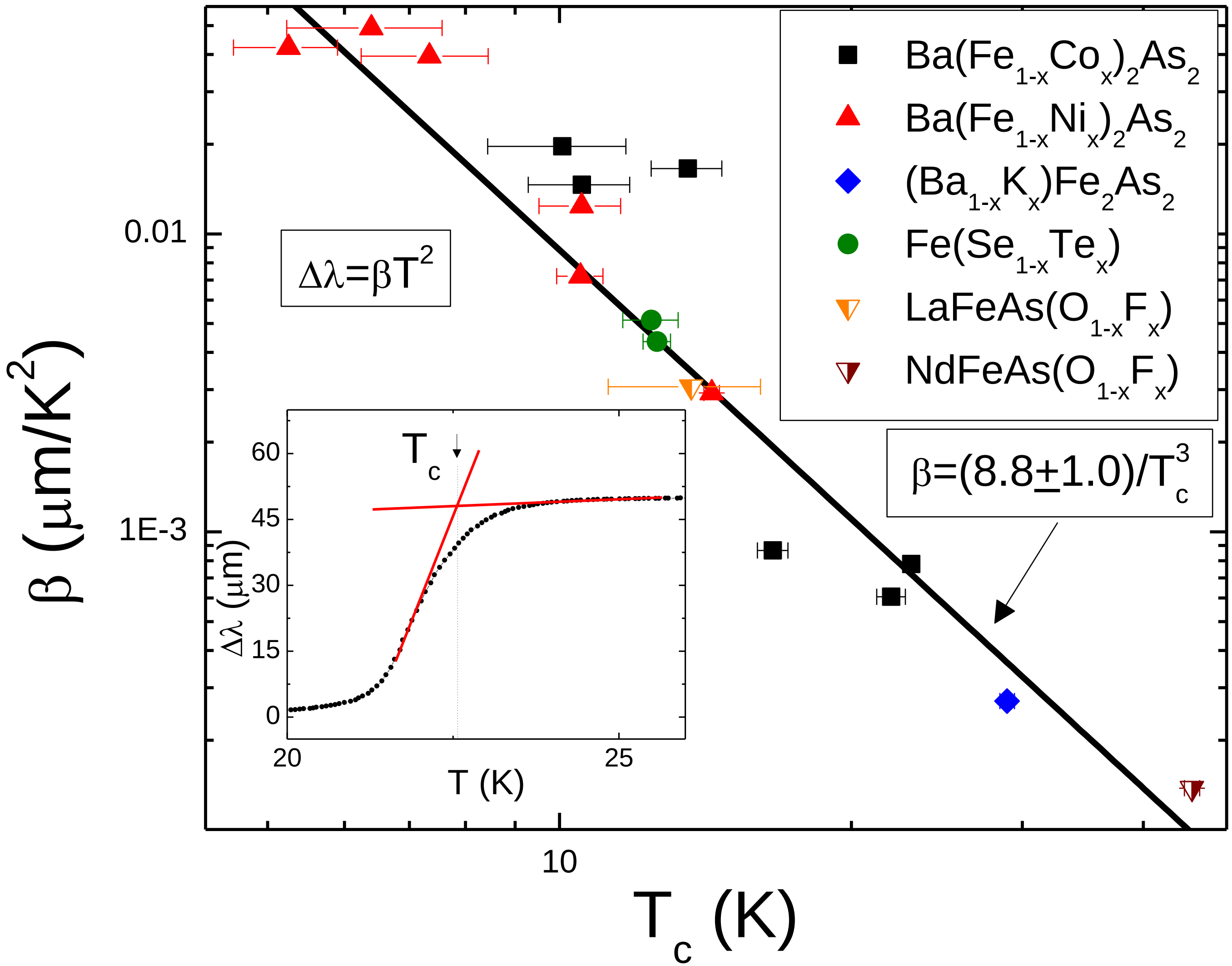
$$\frac{dH_{c2,c}}{dT} = -\frac{2\pi\phi_0 k_B^2}{3\hbar^2\langle\Omega^2 v_a^2\rangle}\, T_c \qquad \frac{dH_{c2,ab}}{dT} = -\frac{2\pi\phi_0 k_B^2}{3\hbar^2\sqrt{\langle\Omega^2 v_a^2\rangle\langle\Omega^2 v_c^2\rangle}}\, T_c$$





V. G. Kogan, Phys. Rev. B **80**, 214532 (2009)

scaling of $\Delta\lambda(T) = \beta T^2$



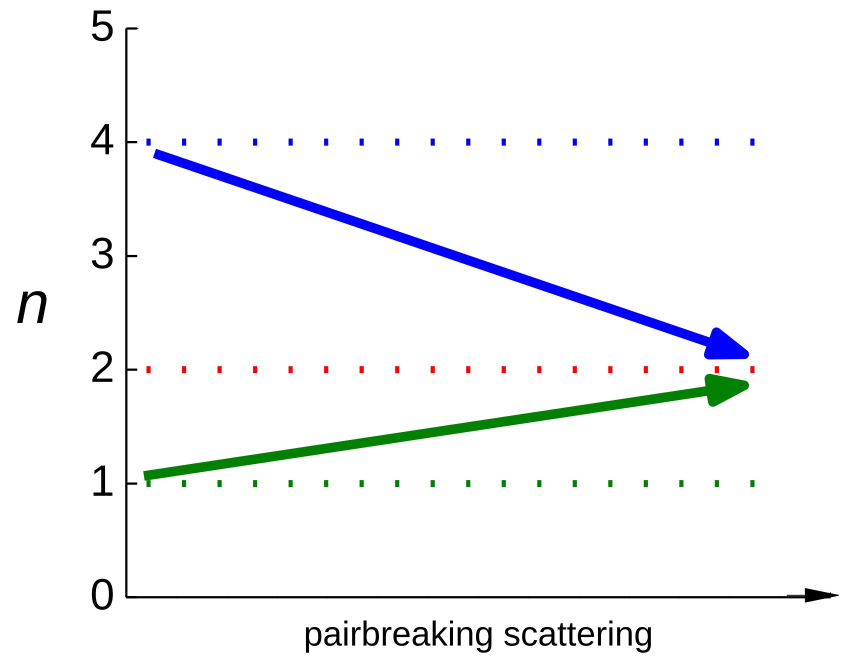
V. G. Kogan, C. Martin, R. Prozorov, Phys. Rev. B **80**, 014507 (2009)

summary: effect of scattering on $\Delta\lambda(T)$

$$\Delta\lambda = \beta T^n$$

line nodes

$$\Delta\lambda(T) \propto \begin{cases} T & \text{- clean} \\ T^2 & \text{- dirty} \end{cases}$$



pairbreaking s-wave ($s_{\pm}$)

$$\Delta\lambda(T) \propto \begin{cases} \sqrt{\frac{\pi\Delta(0)}{2T}} e^{-\Delta(0)/T} \propto T^4 & \text{- clean} \\ T^2 & \text{- dirty} \end{cases}$$

1.4 GeV $^{208}Pb^{56+}$ irradiation of Fe{Co,No}-122

Irradiation at

Argonne Tandem Linear Accelerator System (ATLAS)

flux: $\sim 5\times10^{11}\ \frac{\text{ions}}{\text{m}^2\text{s}}$

ion penetration length: ~60-70 μm

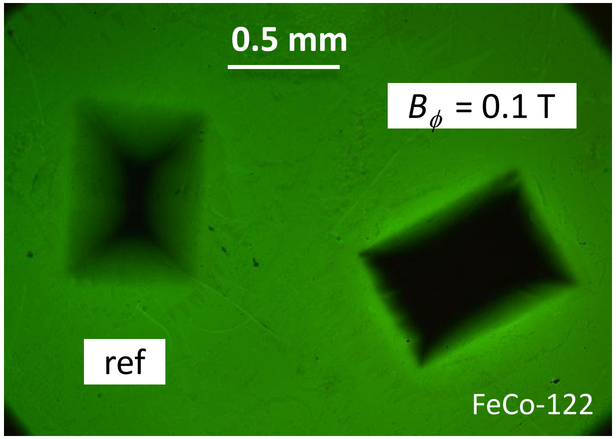
density of defects *n* [tracks/cm^2] is parameterized by the matching field:

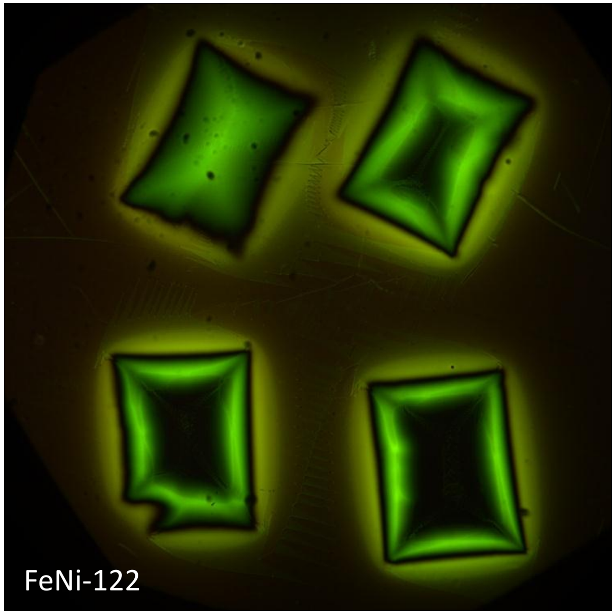
$$B_\phi = n\phi_0$$

we used fluences in the range up to

$$B_\phi = 2\,T$$

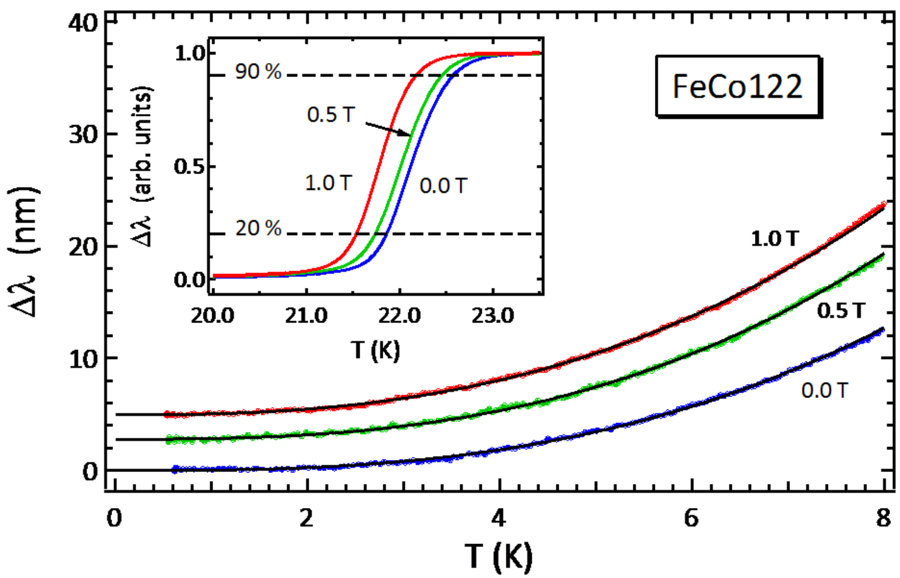
corresponding to the mean distance of 32 nm between the ion tracks

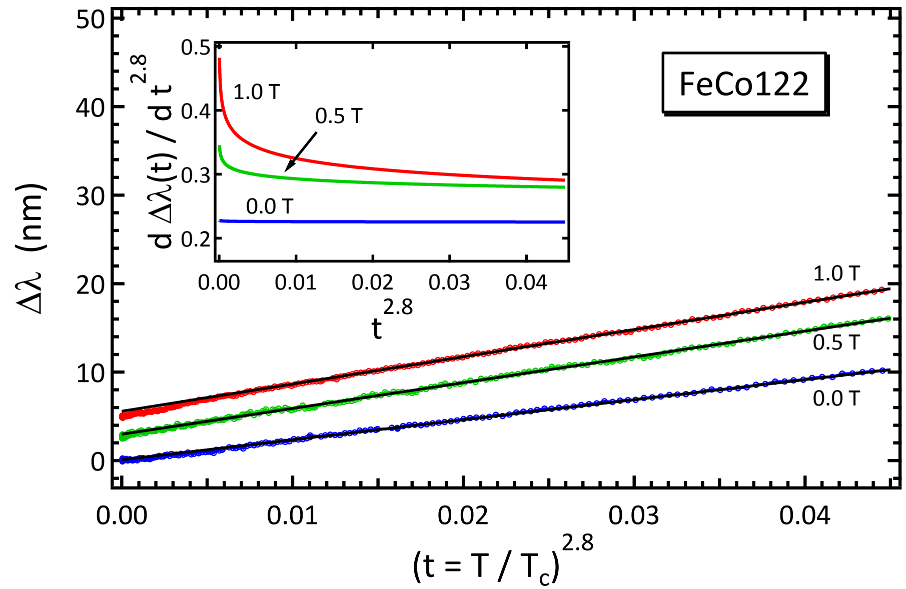


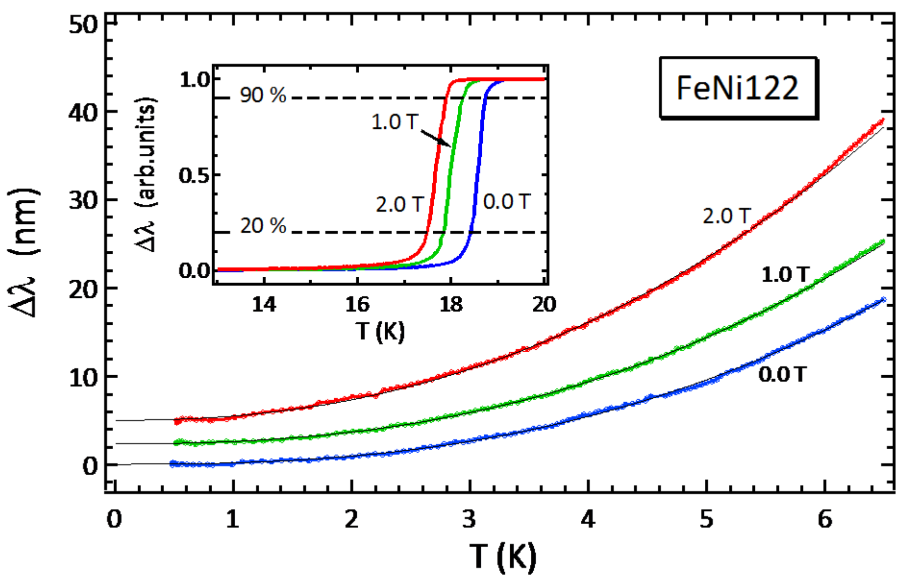


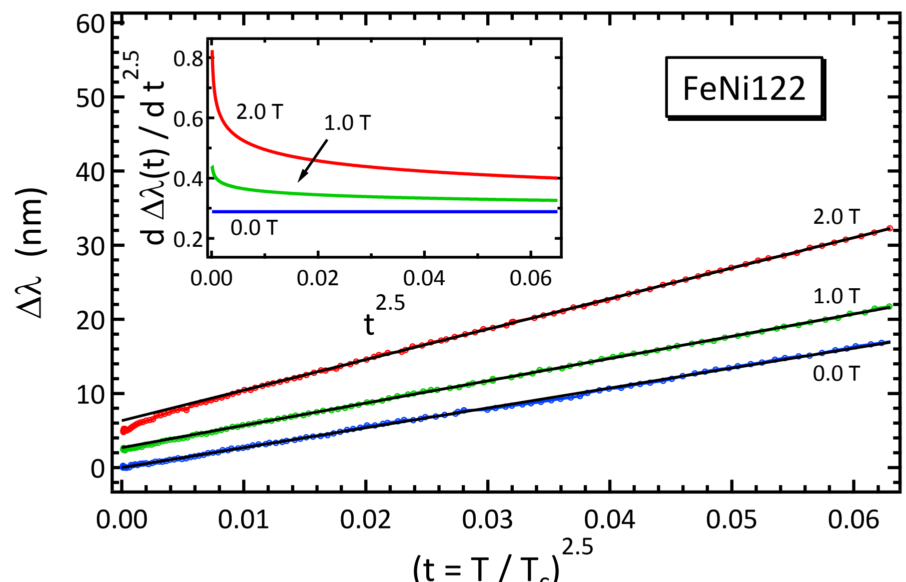
R. Prozorov *et al.*, Phys. Rev. B **81**, 094509 (2010)

London penetration depth



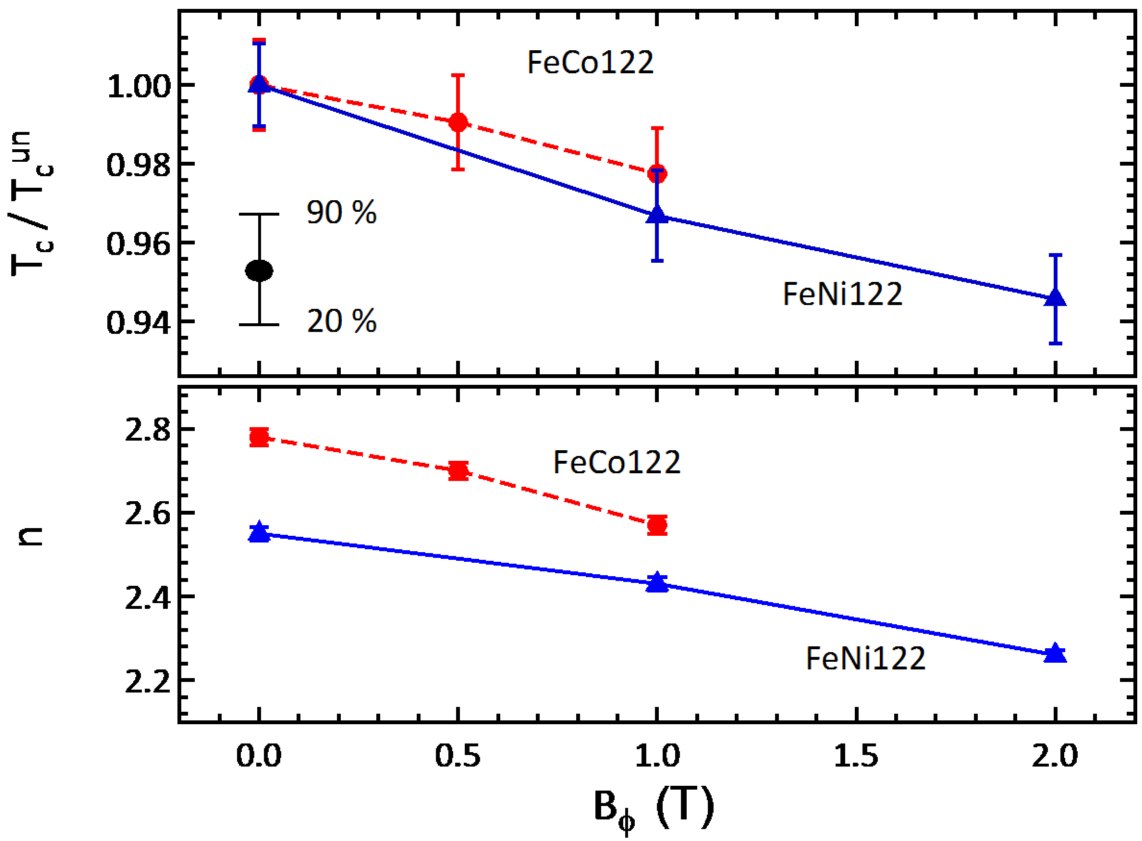






H. Kim *et al.*, PRB **82**, 060518(2010)

two independent parameters: T_c and n



d-wave:

n=1 (clean) → n=2 (dirty)

$s_\pm$:

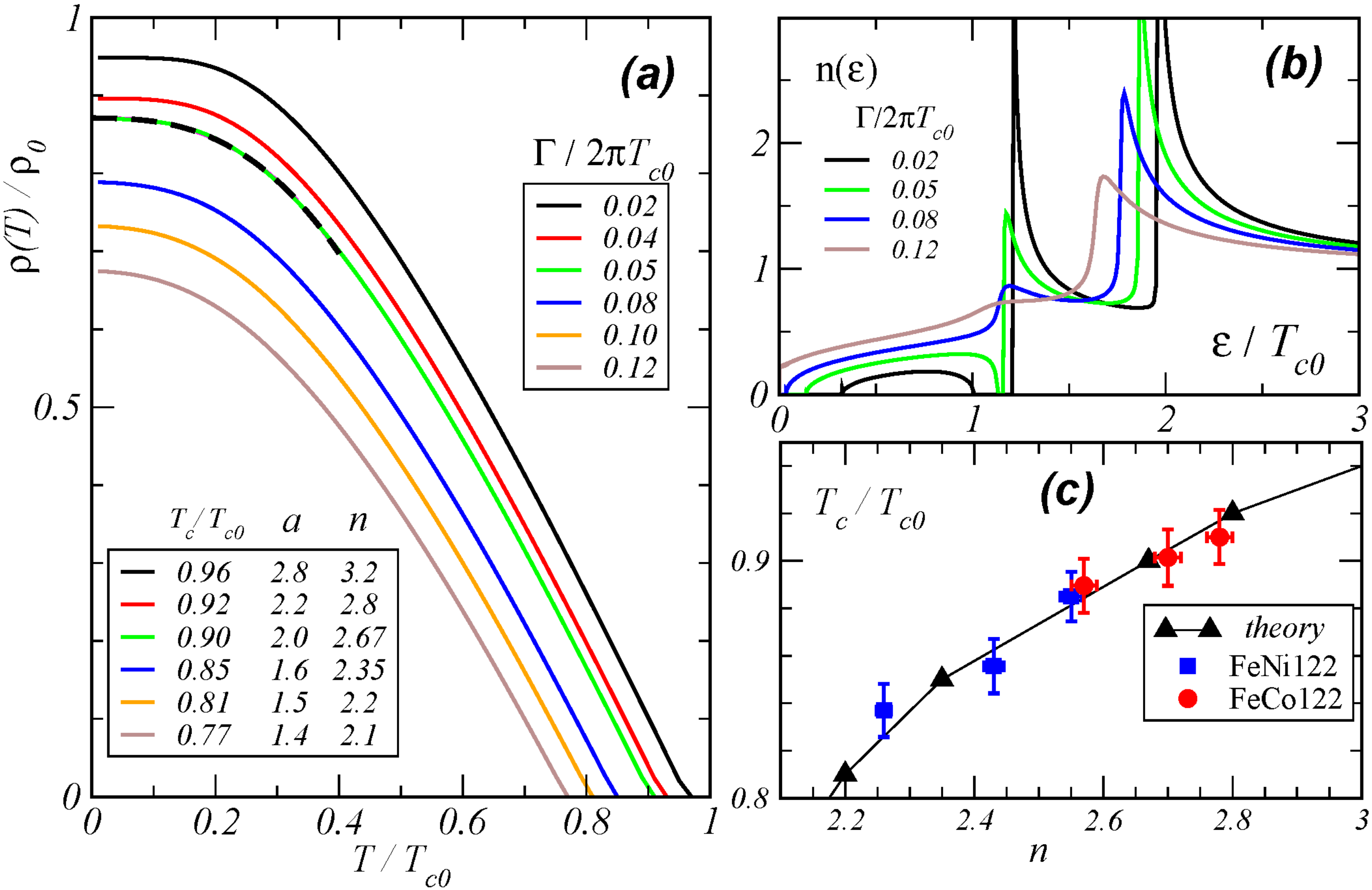
n=4 (exp, clean) → n=2 (dirty)

qualitative agreement with $s_\pm$

H. Kim *et al.,* PRB-R 82, 060518 (2010)

what about quantitative agreement?

pairbreaking with $s_{+/-}$ pairing: numerics

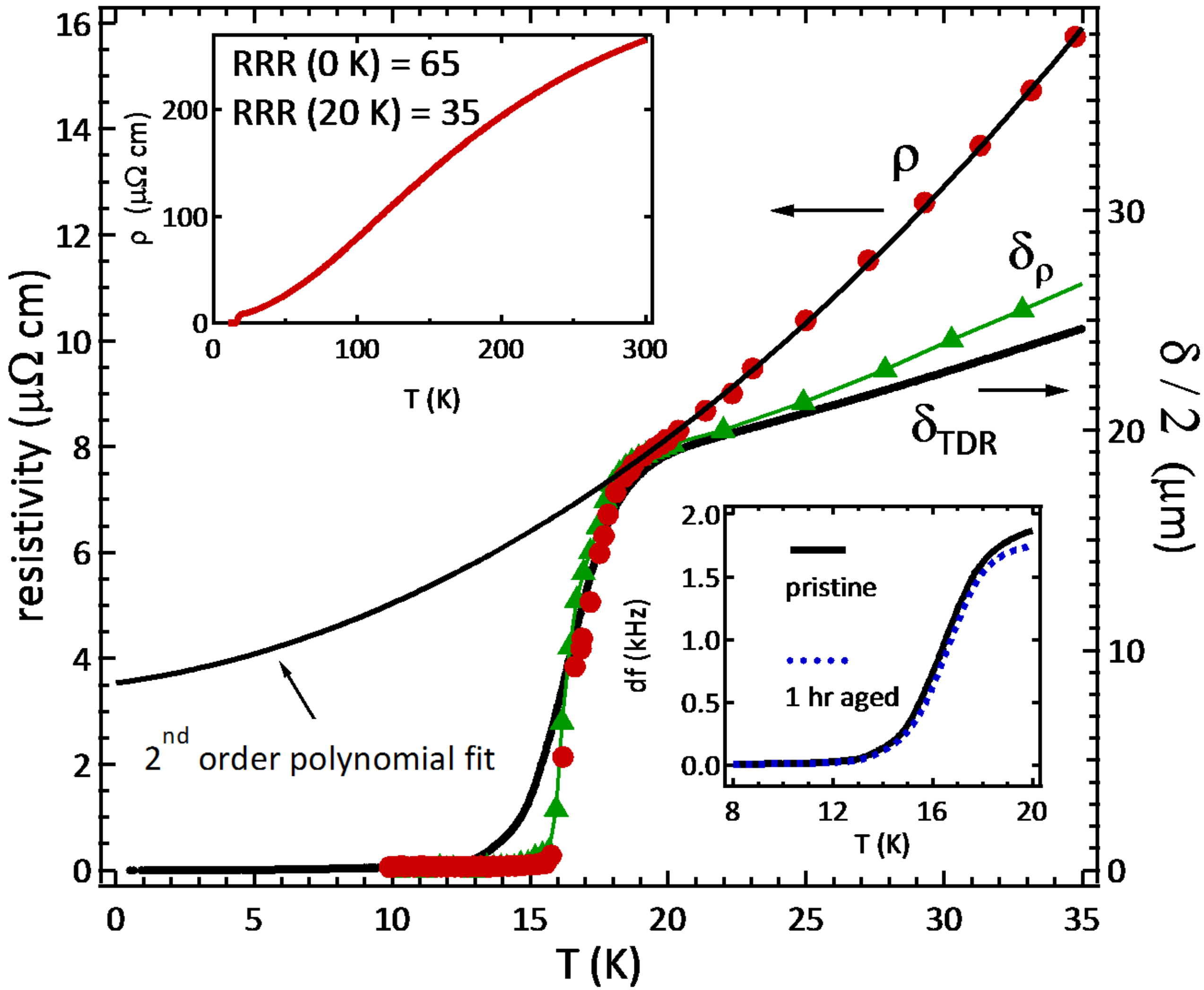


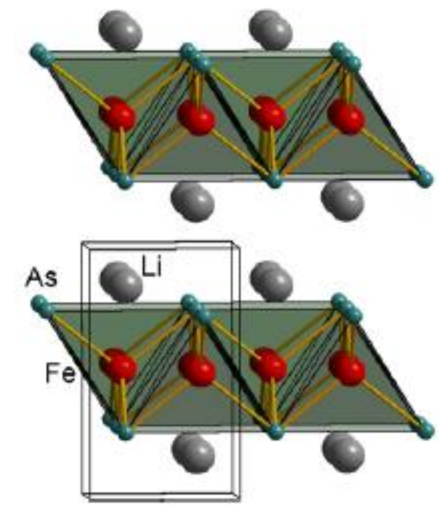
H. Kim *et al.*, PRB **82**, 060518(2010)

conclusion

power-law behavior of $\lambda_{ab}(T)$
in charge - doped pnictides
comes from pair-breaking
scattering + anisotropy

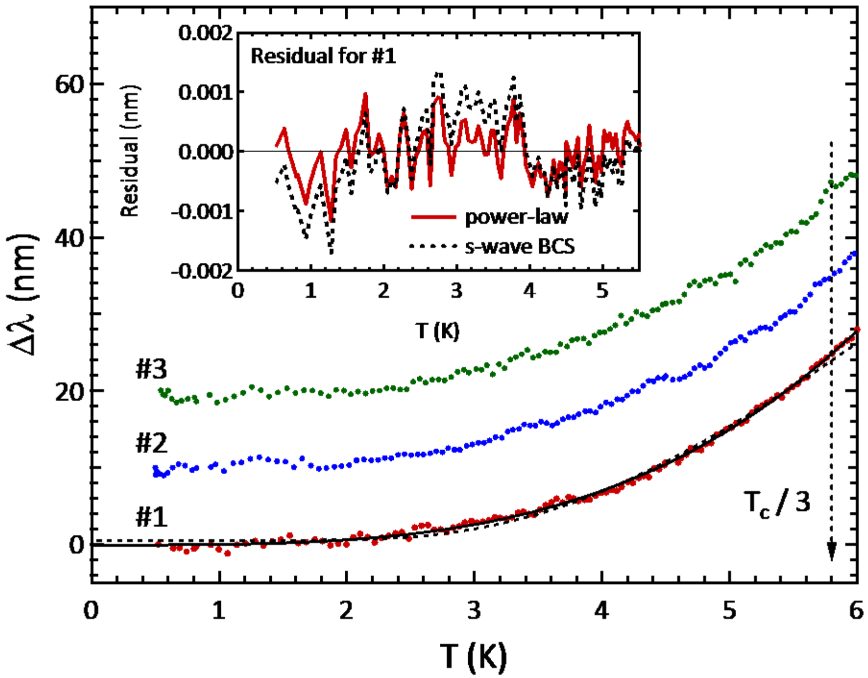
LiFeAs

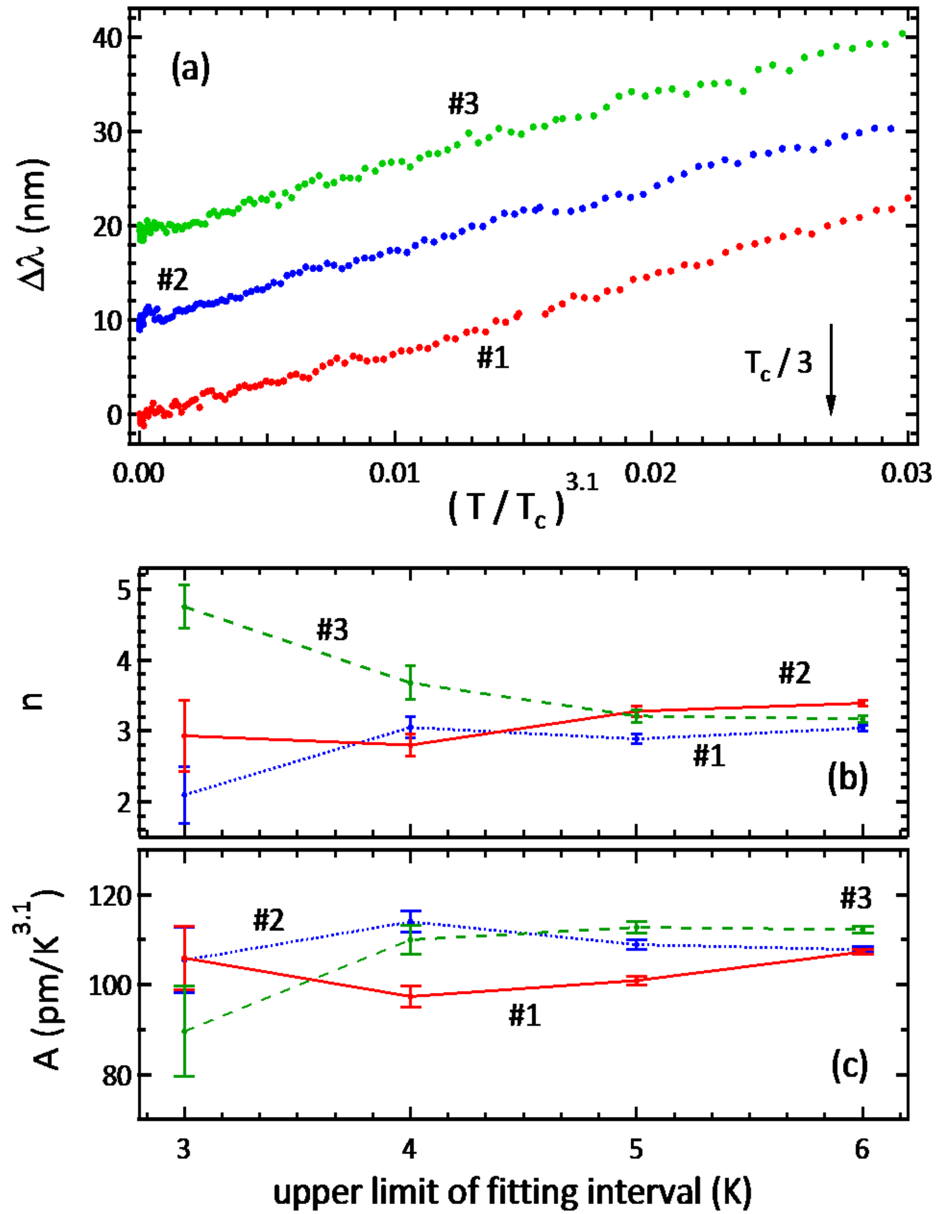




H. Kim *et al.*, arxXiv_1008.3251

penetration depth

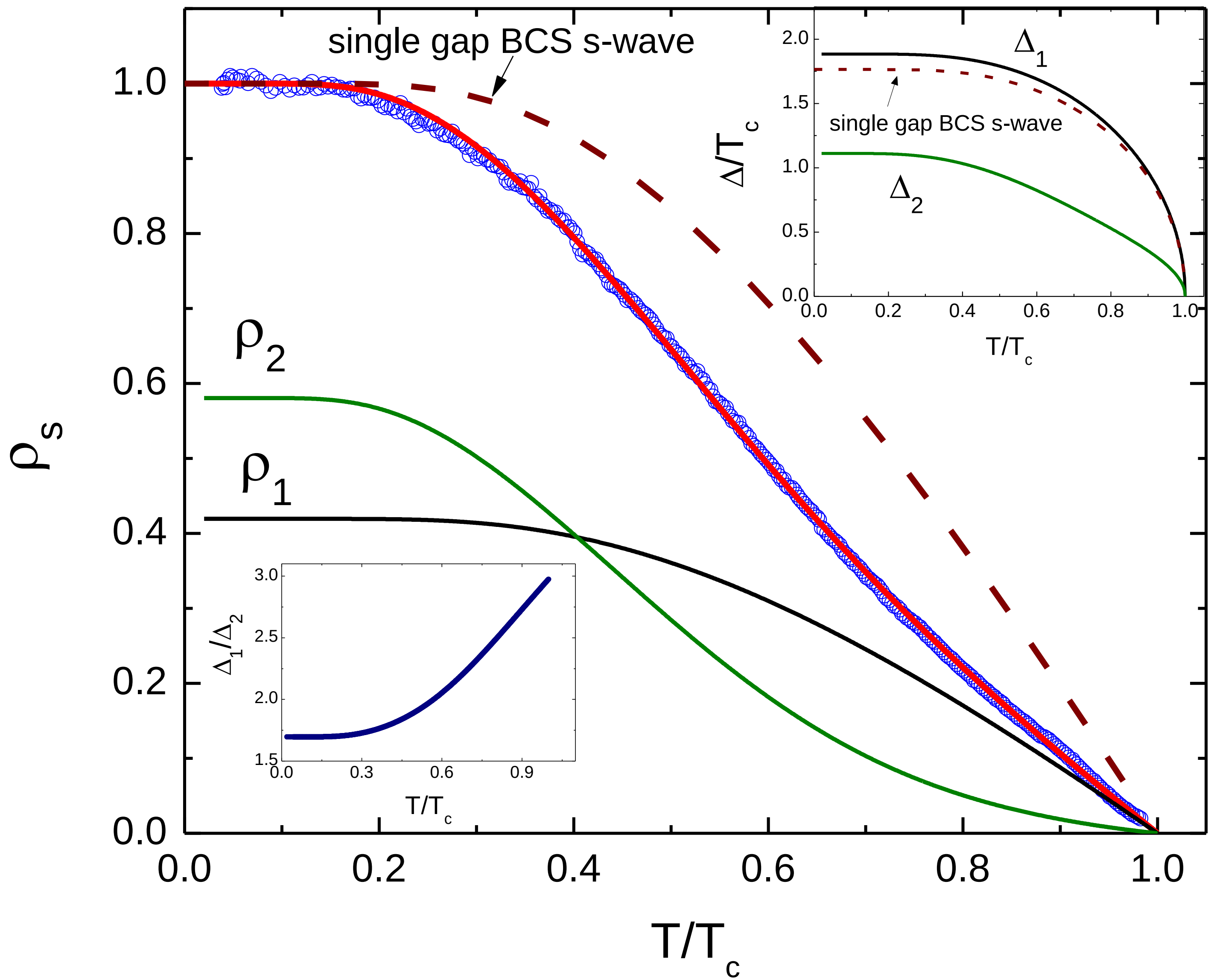




$$\Delta\lambda \sim T^{3-3.4}$$

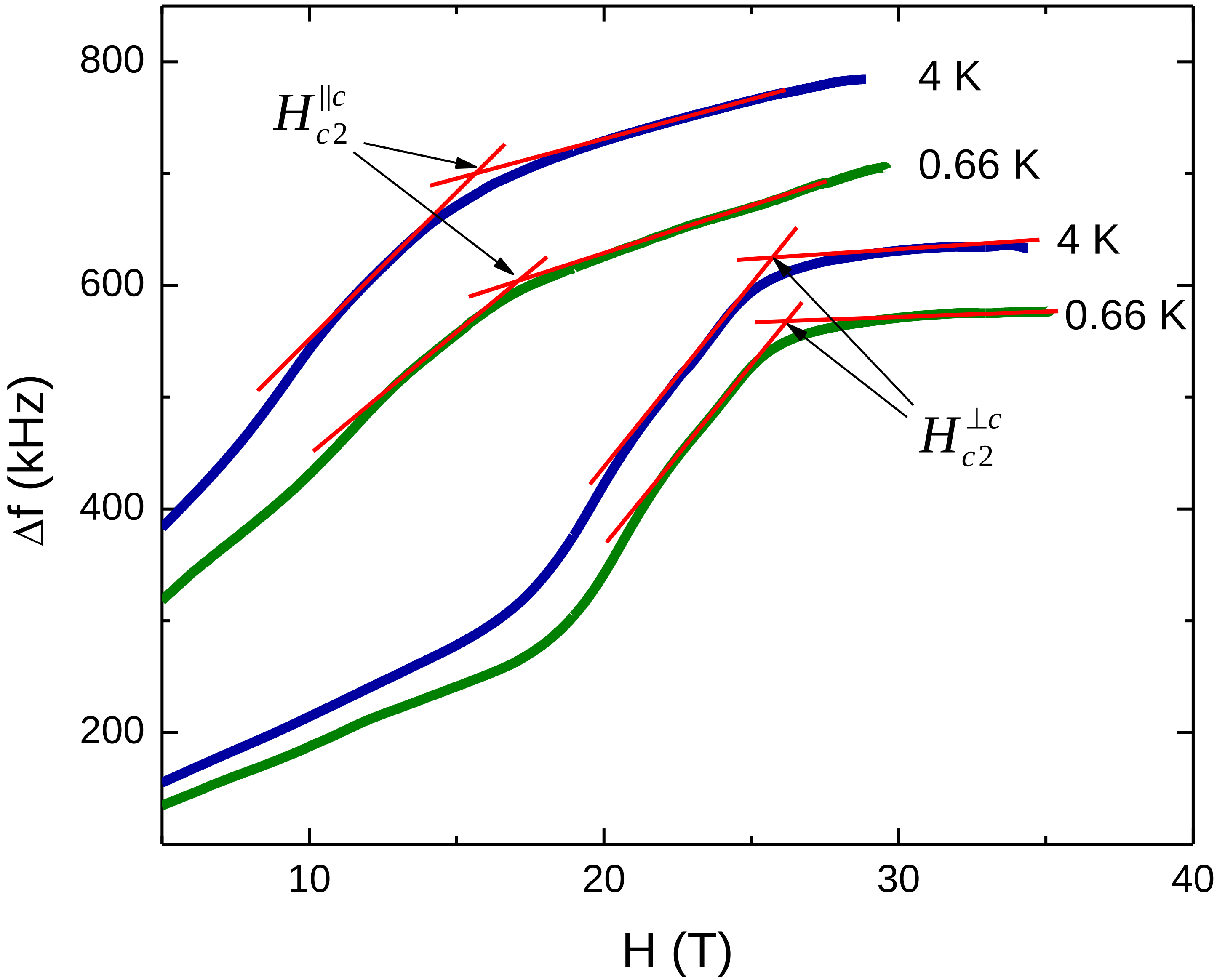
this is practically exponential
(esp. with two-gap scenario)

superfluid density

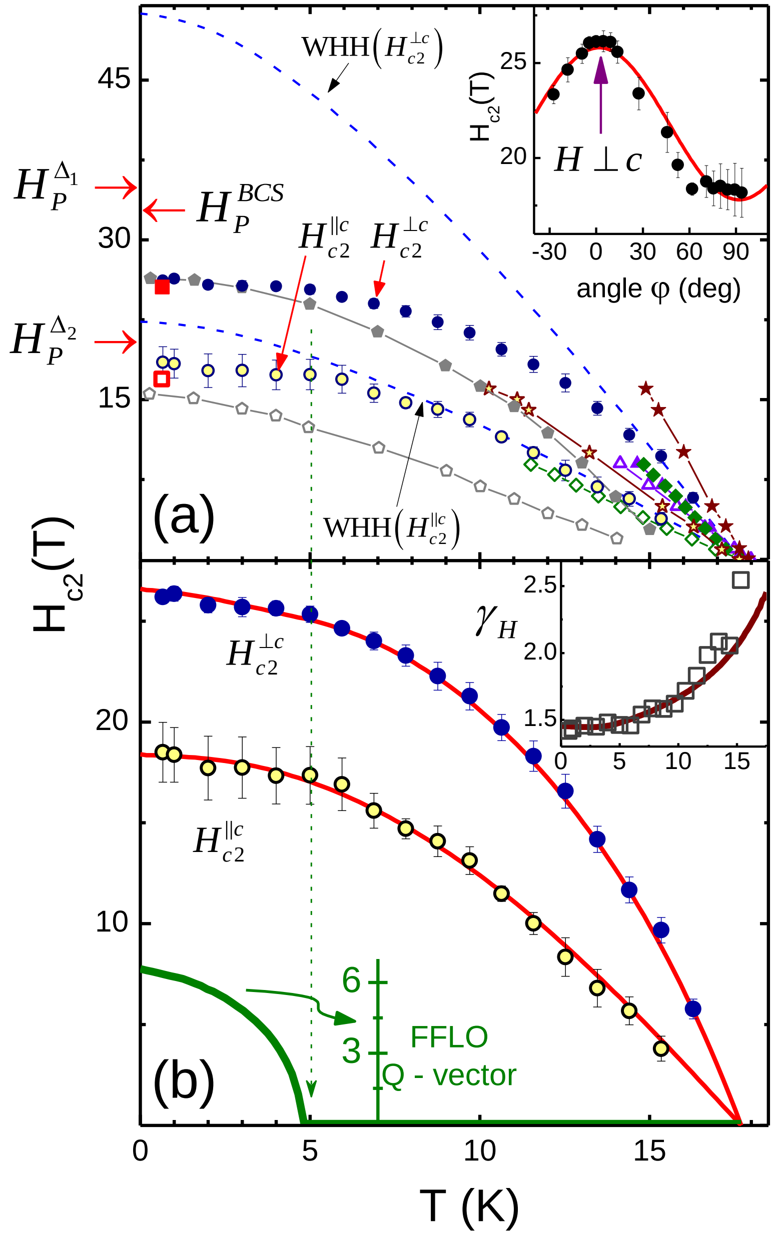


clean weak-coupling two-gap BCS works in the entire T-range

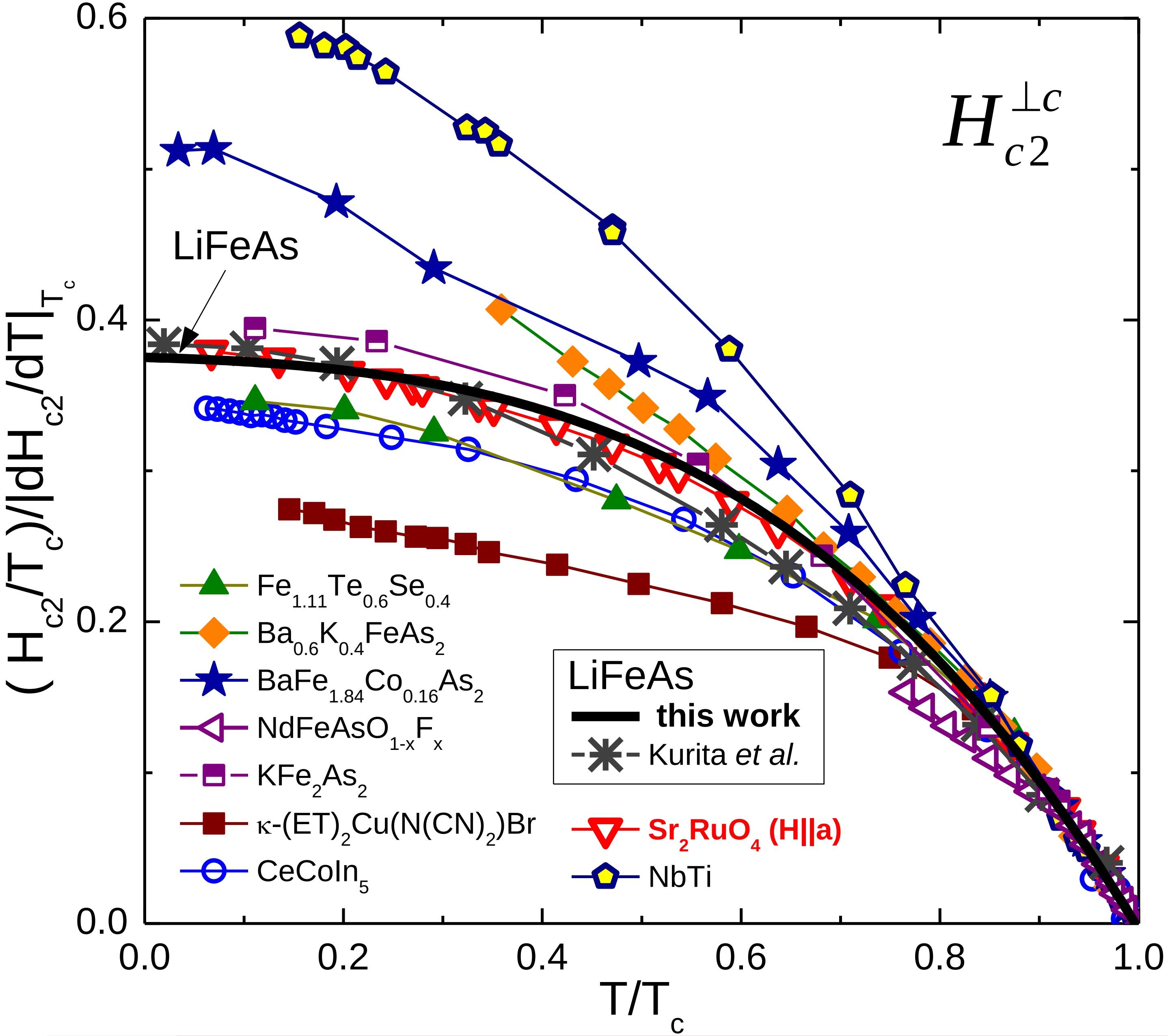
upper critical field



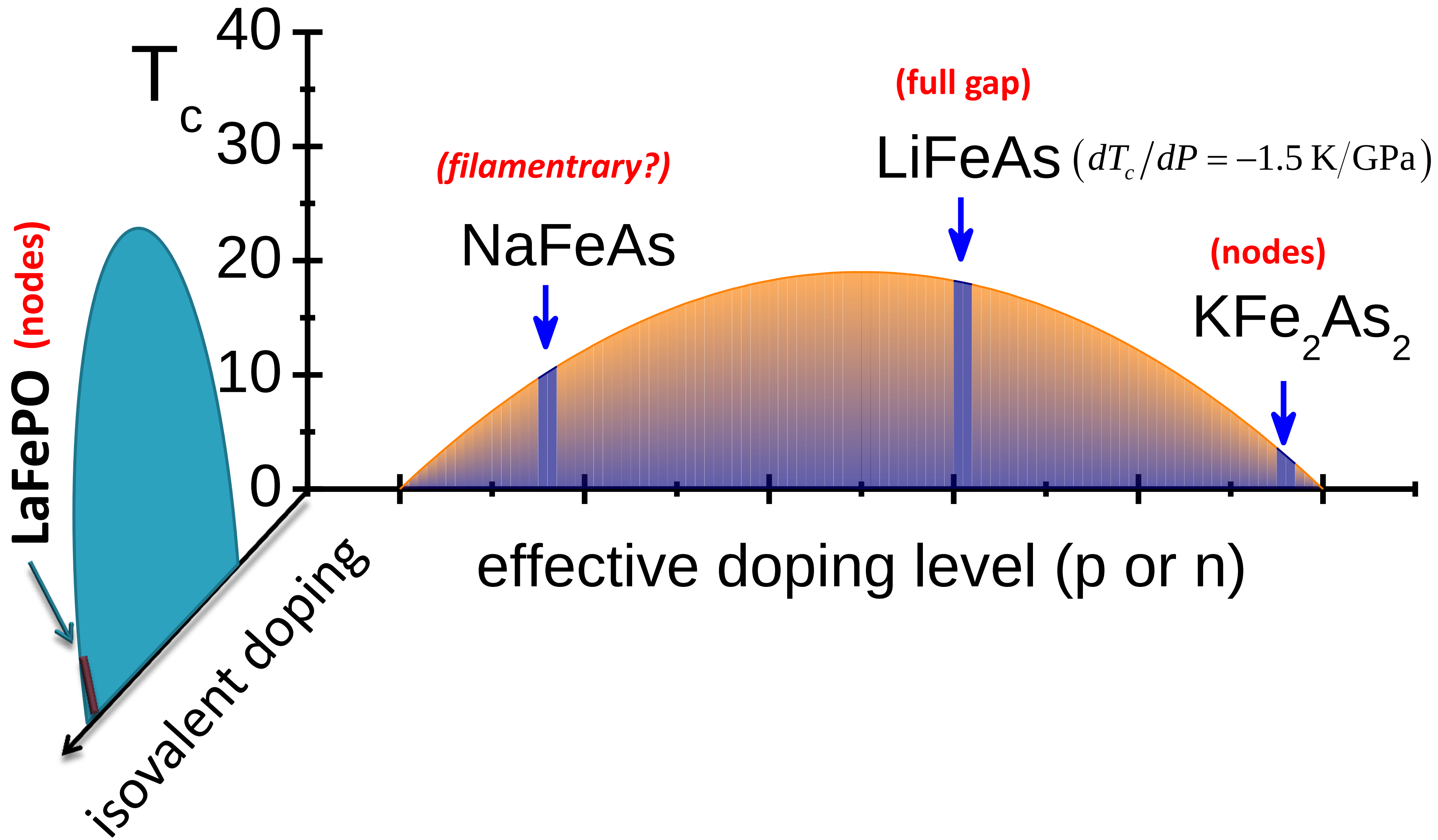
Pauli limiting and possible FFLO state



comparison with other systems

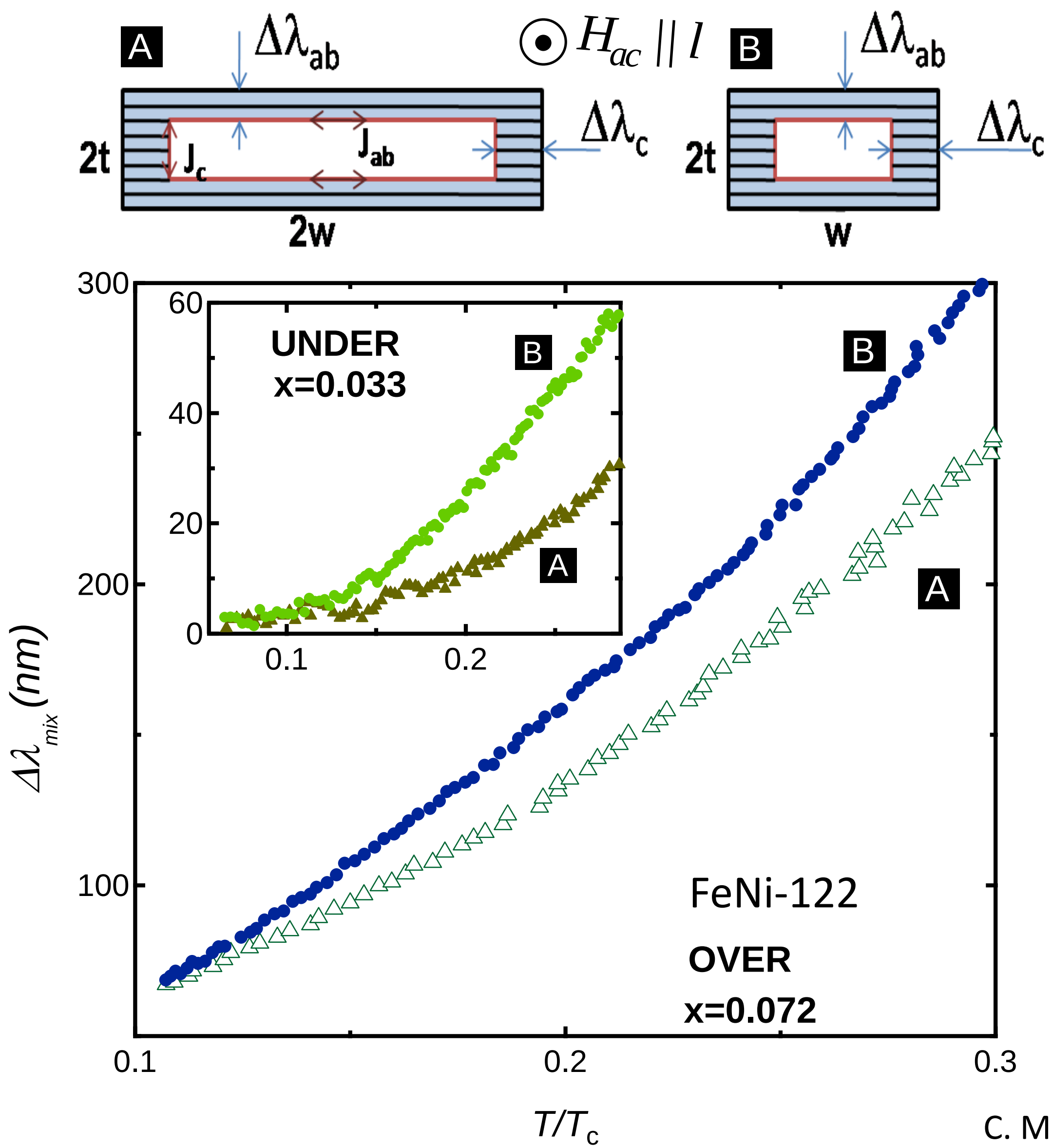


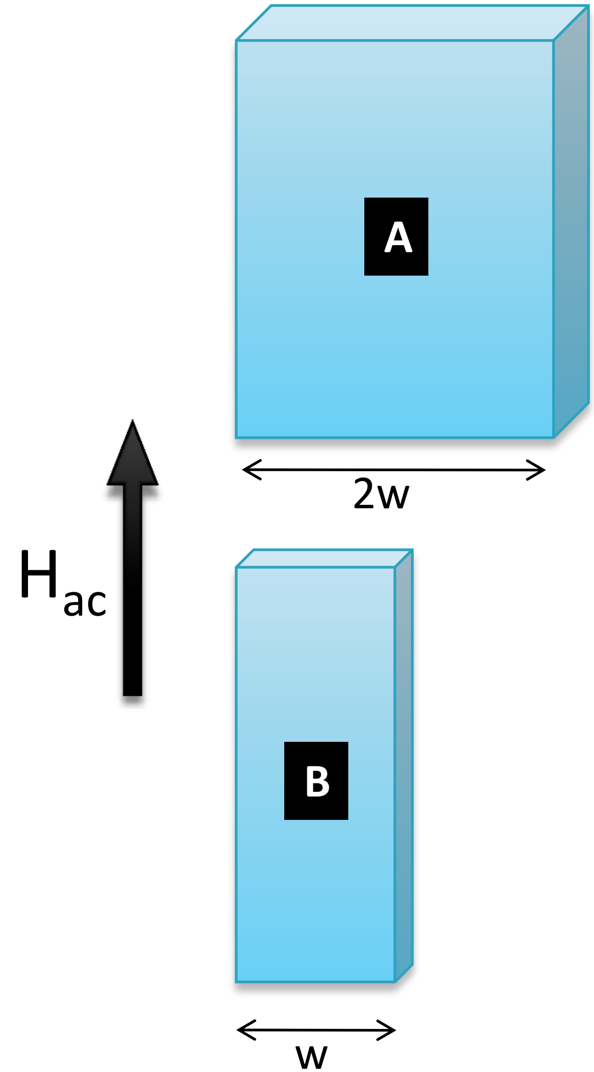
stoichiometric pnictides



are there nodes in the overdoped state?

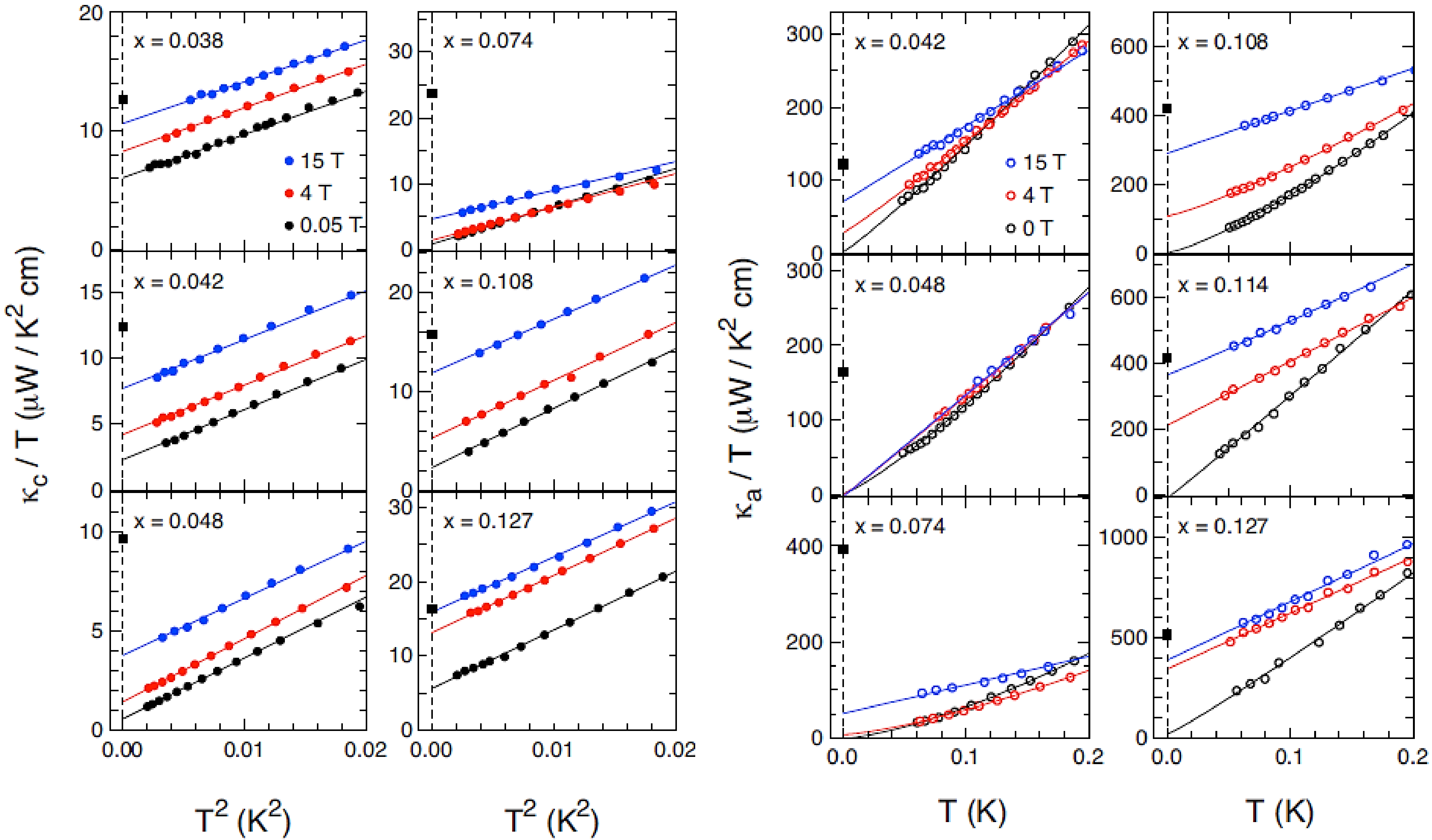
λ_c





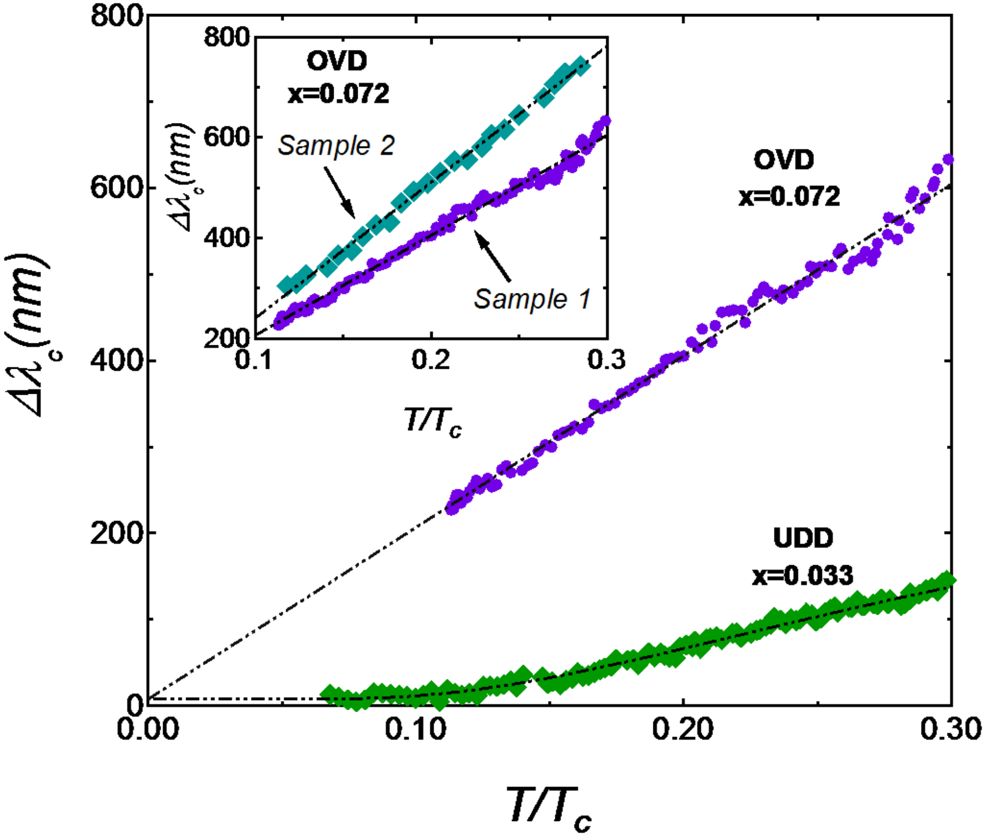
C. Martin *et al.*, Phys. Rev. B 81, 060505 (2010)

c-axis thermal conductivity

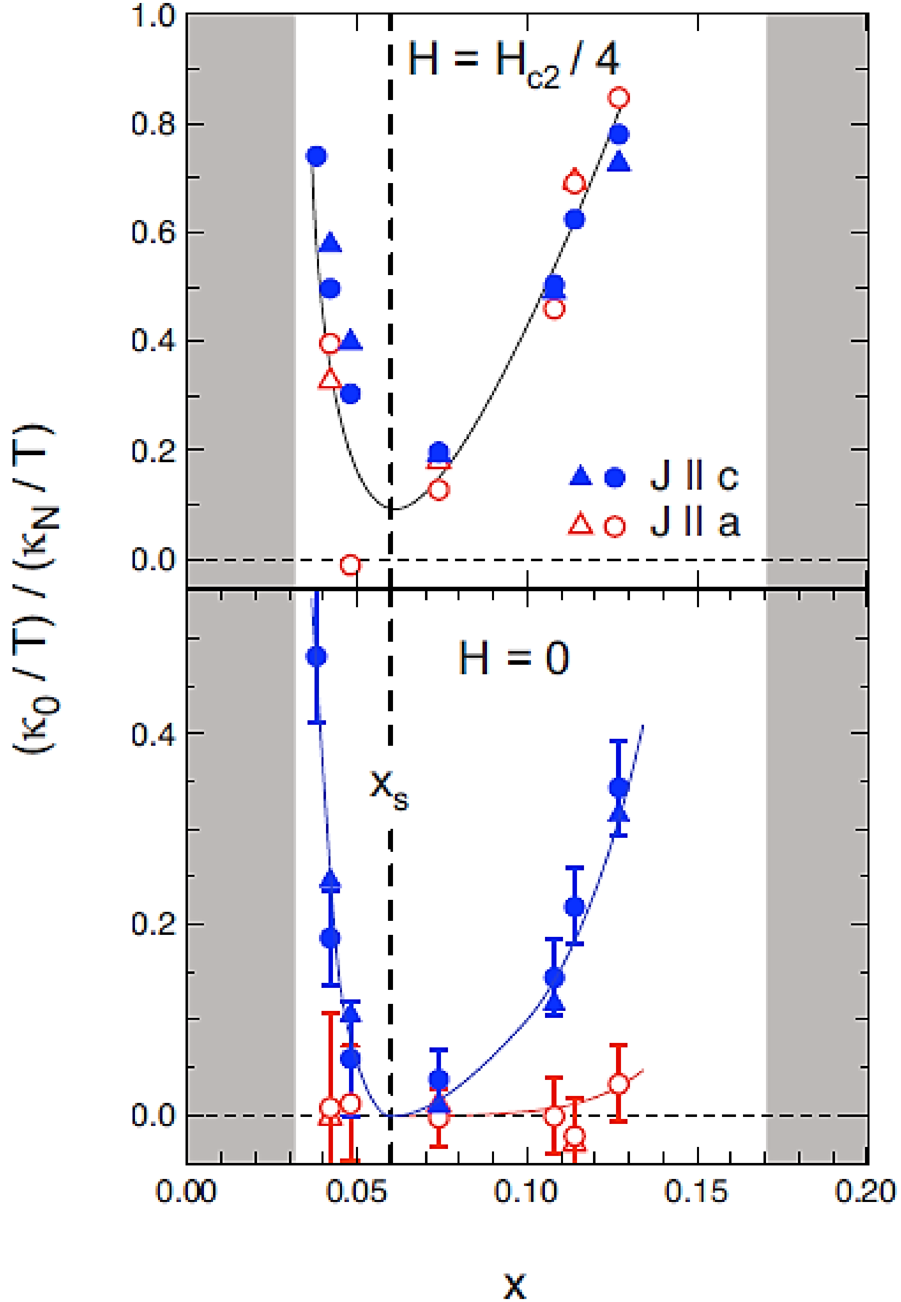


H = 0, 4 15 T

J.-Ph. Reid *et al.*, Phys. Rev. B **82**, 064501 (2010)



C. Martin *et al.*, Phys. Rev. B **81**, 060505 (2010)



J.-Ph. Reid *et al.*, Phys. Rev. B **82**, 064501 (2010)

conclusions

- it appears that Fe-based superconductors represents most complex system so far
- low anisotropy. Three - dimensional bandstructure
- Modulated 3D gap. Possibly with doping-dependent nodes
- fully gapped at optimal doping developing significant anisotropy in the overdoped regime
- unconventional s-wave pairing with many options for nodes (that are not symmetry imposed)
- clear signatures of two distinct gaps
- Pauli limited H_{c2}, possible FFLO state
- significant effects of pair-breaking scattering