Anisotropic superconducting gap revealed by angle resolved specific heat and STM measurements in iron pnictide superconductors

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KITP 2011, Santa Barbara

Nanjing University

Established in 1902

- **Beijing**
- **Nanjing**
- **Shanghai**

Acknowledgements:

- IOP, CAS: Bing Zeng, Cong Ren, Lei Shan, Huan Yang, Bing Shen
- IOP, CAS: Tao Xiang (Simulation)
- Naval Research Lab, USA: Igor I Mazin, (Theory and LDA calclation)
- Houston university: Shuheng Pan (STM)
- Nanjing University: Qianghua Wang (theory)
- ……

Outline of the talk

- Brief introduction to the pairing symmetry of iron pnictide superconductors
- Bulk evidence for anisotropic gaps in $FeSe_{0.45}Te_{0.55}$ revealed by angle resolved specific heat
- Doping induced evolution from nodeless to nodal gaps in $Ba(Fe_{1-x}Co_x)_2As_2$ and $Ba(Fe_{1-x}Ni_x)_2As_2$ revealed by specific heat, point contact tunneling measurements.
- Specific heat and STM measurements in $Ba_{1-x}K_xFe_2As_2$
- Concluding remarks

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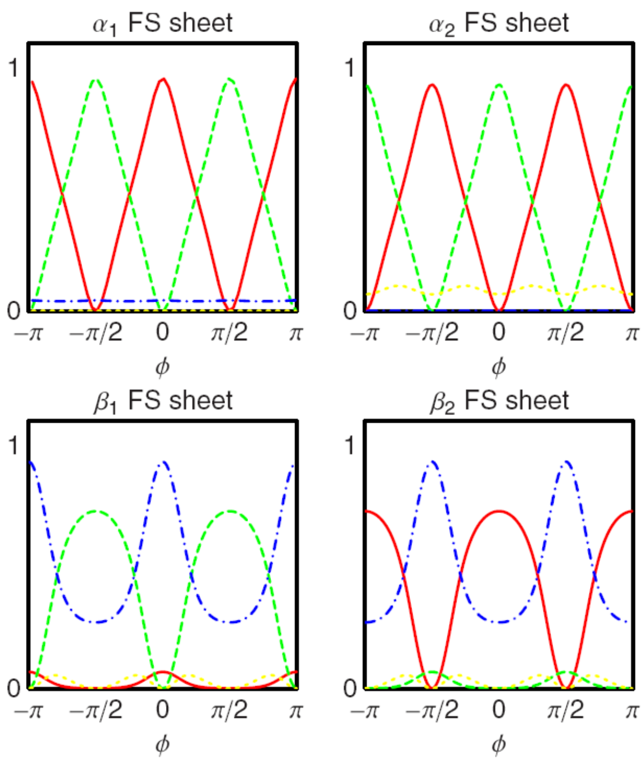
Debates on the gap structure in the iron pnictide superconductors

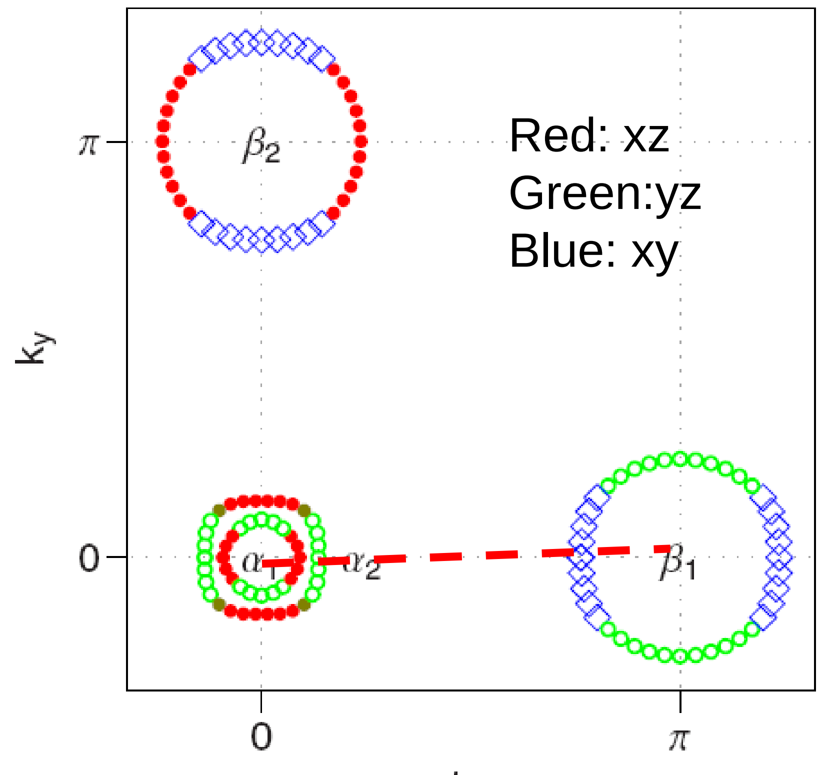
ARPES: Most of the time ***Isotropic full*** gap at the FSs.	• H. Ding et al., EPL2008; • L. Zhao et al., CPL2008
Superfluid density: power law T-dependence: nodal gap or S± pairing under impurity scattering? In LaFePO, one finds clear evidence of nodal gap. Overdoping induces the appearance of c-axis nodes.	• R. Prozorov PRL2009, PRB2009 • J. D. Fletcher et al., PRL2009, • C. W. Hicks et al. PRL2009 • C. Martin et al., PRB2010 • J.-Ph.Reid et al. PRB2010
NMR: Low-T, $1/T_1T$ shows power law of T: nodal gap or the S± pairing under impurity scattering? Normal state $1/T_1T$: Coincidence of the vanishing SC and AF spin fluctuation	• K. Matano et al., EPL2008 • F. L. Ning PRL 2010
Thermodynamics and transport : s-wave with a very small gap; c-axis nodes.	X. G. Luo PRB2009 G. Mu PRB2009

It seems that nodal gap exists in LaFePO, $BaFe_2As_{2-x}P_x$, KFe_2As_2, in other systems it remains unclear yet. The FS may be fully gapped but with strong gap modulation.

PHYSICAL REVIEW B 79, 224510 (2009)

Origin of gap anisotropy in spin fluctuation models of the iron pnictides



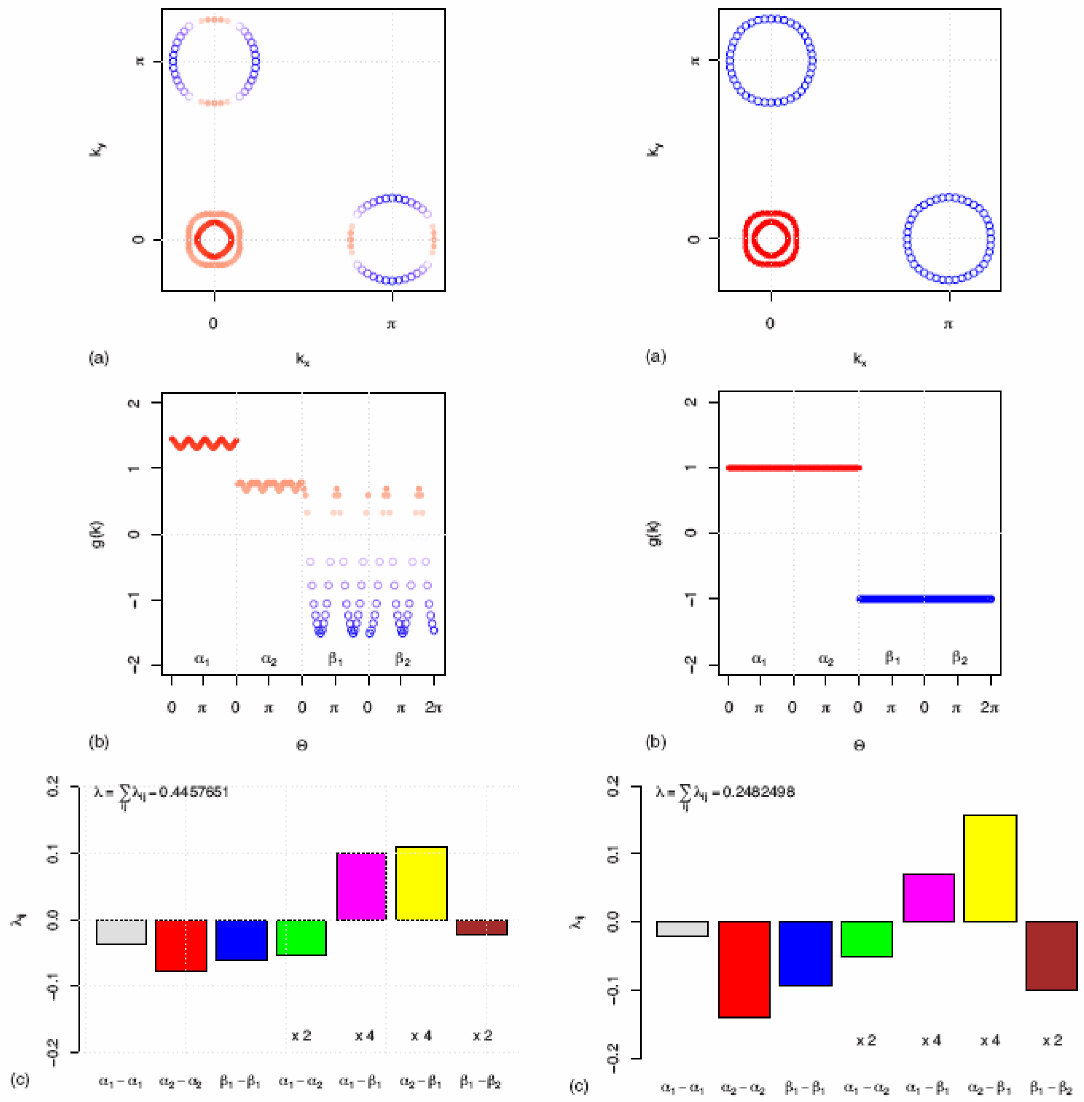


Orbital weights on different FSs.

These were calculated using a five-orbital d_{xz} ,d_{yz} ,d_{xy} ,d_{x2-y2} ,d_{3z2-r2} tight-binding fit to the density functional theory band-structure calculations

- **Maier, T. A., Graser, S., Scalapino, D. J. & Hirschfeld, P. J. *Rev. B* 79, 224510 (2009).**
- **Kuroki, K. *et al. Phys. Rev. B* 79, 224511 (2009).**
- **Wang, F., Zhai, H. & Lee, D. H. *EPL* 85, 37005 (2009).**

Orbital dependent interaction via AF spin fluctuation

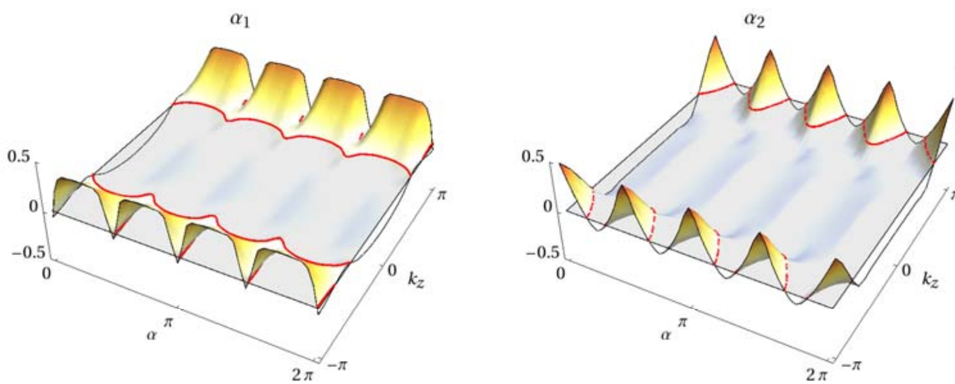


The nodes can appear, but not enforced by symmetry and at accidental positions!

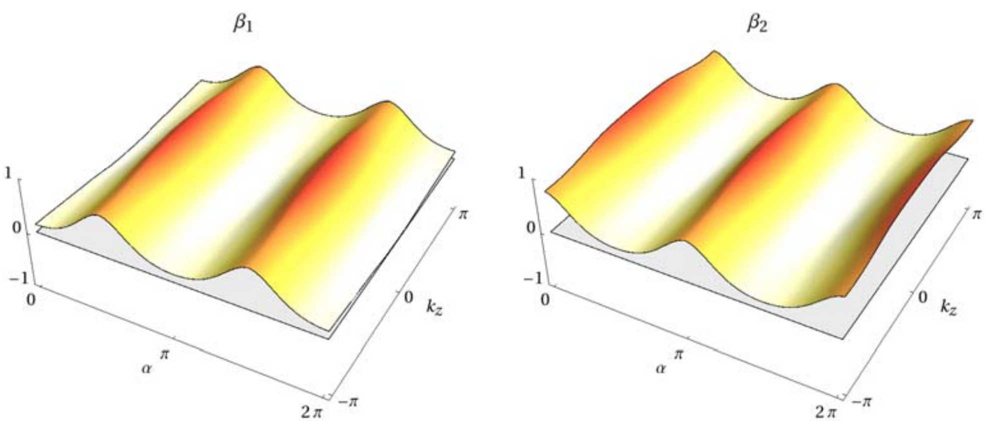
S. Graser, A. Kemper, T. A. Maier, H.-P. Cheng, P. J. Hirschfeld, and D. J. Scalapino. **Phys. Rev. B 81, 214503 (2010)**

Other Similar studies:

- **K. Kuroki et al., PRB79, 224511 (2009).**
- **F. Wang, H. Zhai, D. H. Lee, EPL 85, 37005 (2009).**



Horizontal but segment like nodal lines on hole pockets



Electron-FS: highly anisotropic s-wave, accidental nodes are expectable!

Implications for ab/c axis penetration

depth and thermal conductivity

Expected gap in 122

Courtesy of S. Graser

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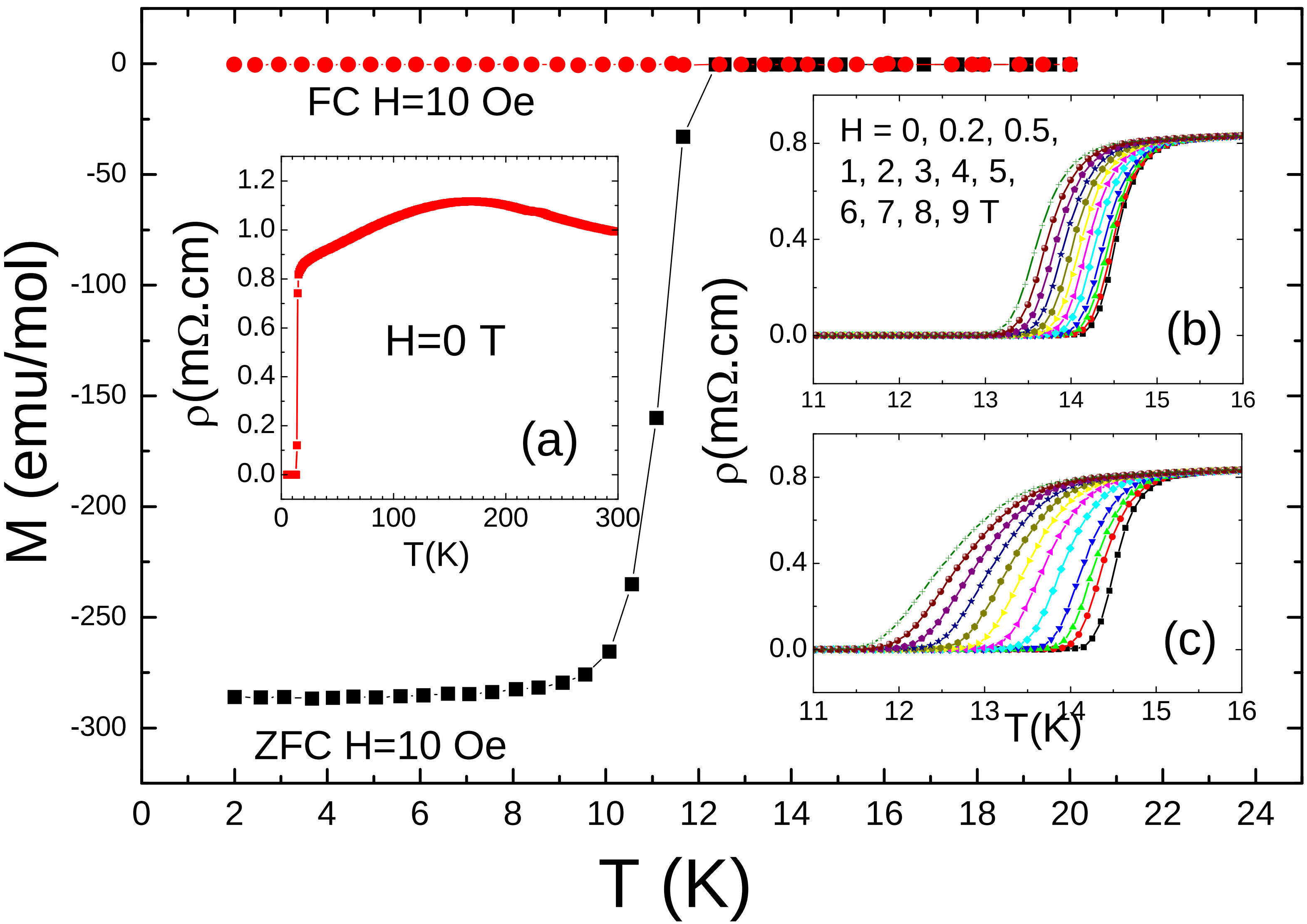
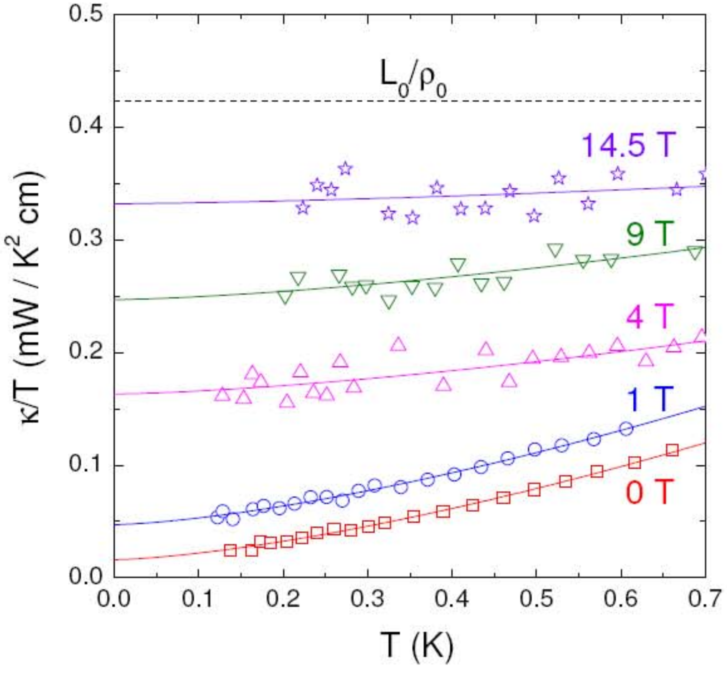
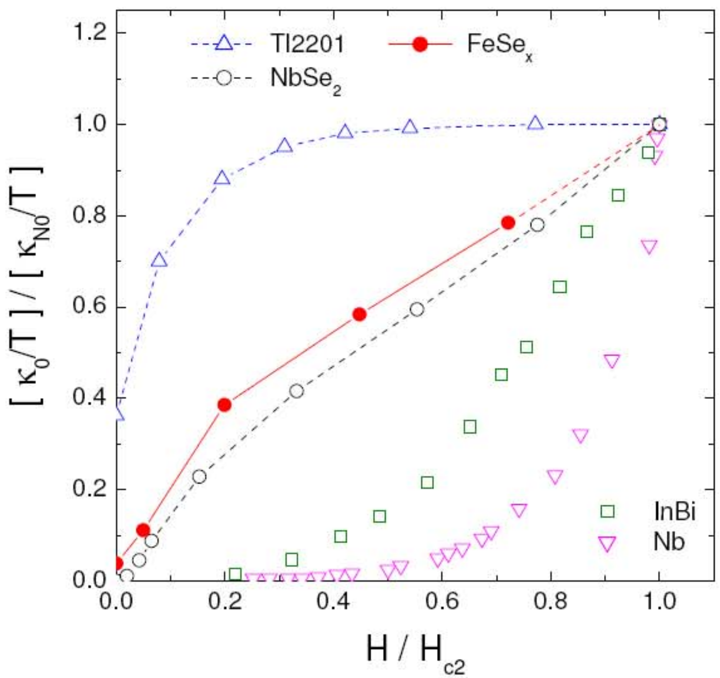
$FeSe_{0.4}Te_{0.6}$ single crystals



Multi-gap nodeless superconductivity in iron selenide $FeSe_x$: evident from quasiparticle heat transport

J. K. Dong et al., PRB80, 024518(2009).





$$\frac{\kappa_0}{T} = \frac{k_B^2}{6c}\frac{k_F v_F}{\Delta_0} = 140\mu W / K^2 cm$$

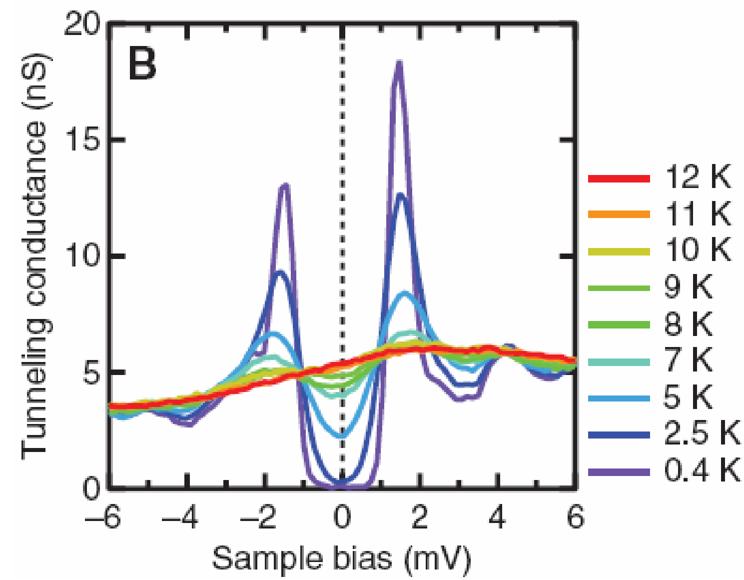
Universal thermal conductivity coefficient at T=0 for line nodes!

In-plane thermal transport measurements finds a negligible κ_0/T at T=0 K, this excludes a vertical line nodes, like a d-wave gap. While the strong field dependence suggests a very small gap, or a highly anisotropic gap.

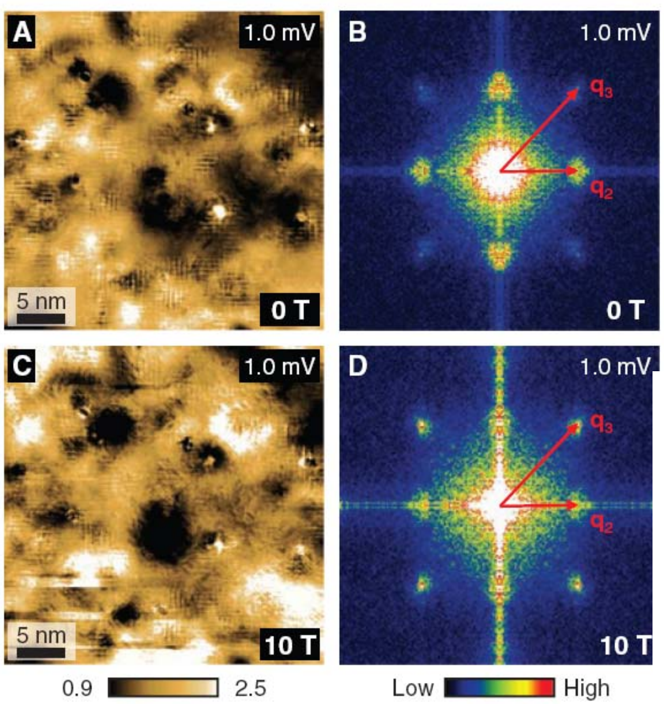
Unconventional *s*-Wave Superconductivity in Fe(Se,Te)

T. Hanaguri,[1,2*] S. Niitaka,[1,2] K. Kuroki,[2,3] H. Takagi[1,2,4]

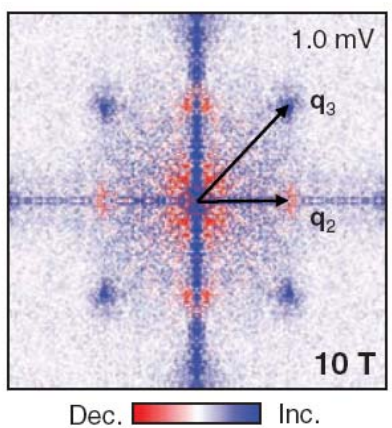
T. Hanagury et al., Science 428, 474 (2010)

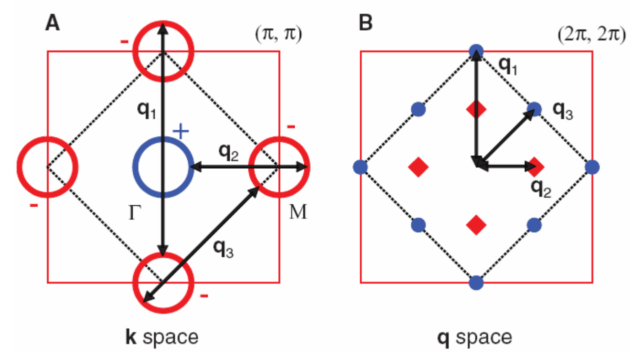


Δ = 1.4 me V!

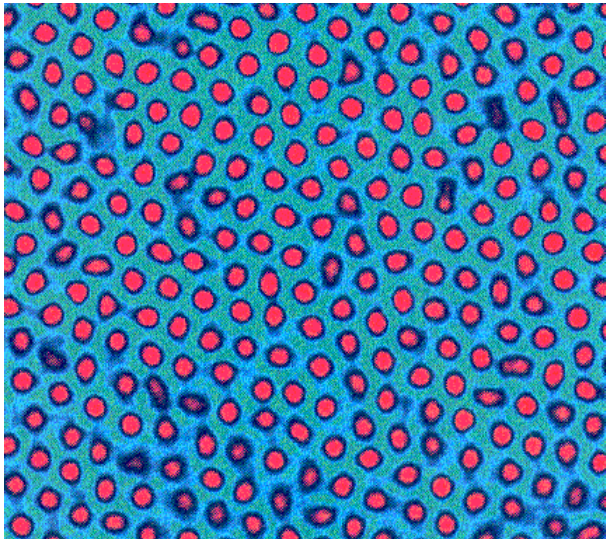


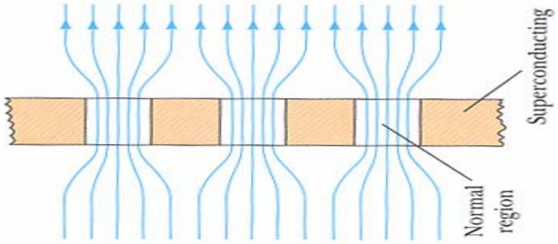
Magnetic field–induced change in QPI intensities indicates the s±-wave symmetry.



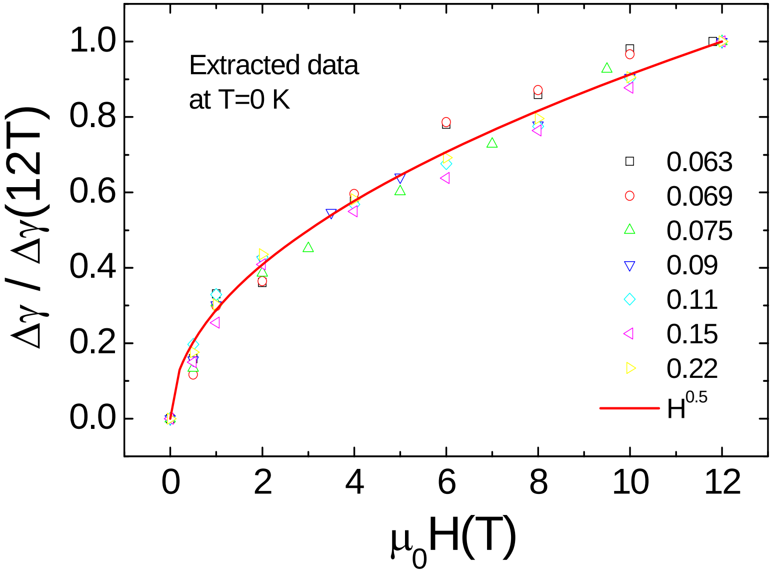


Quasiparticle DOS in Mixed State with Vortices





Two components for quasiparticles: Localized core state (s-wave) and de-localized extended states in d-wave case.

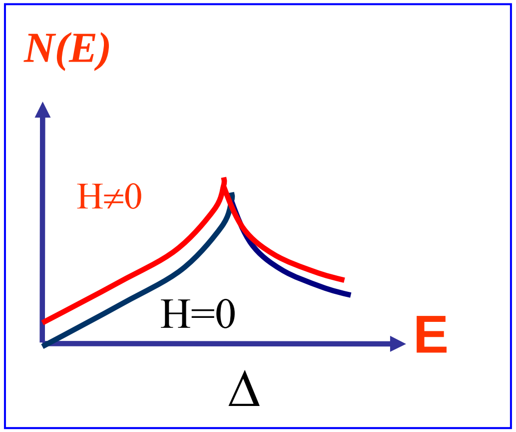


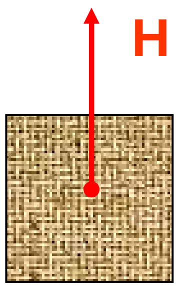
- **S-wave, $C_e/T \propto H$**
- **D-wave, $Ce/T \propto H^{1/2}$**

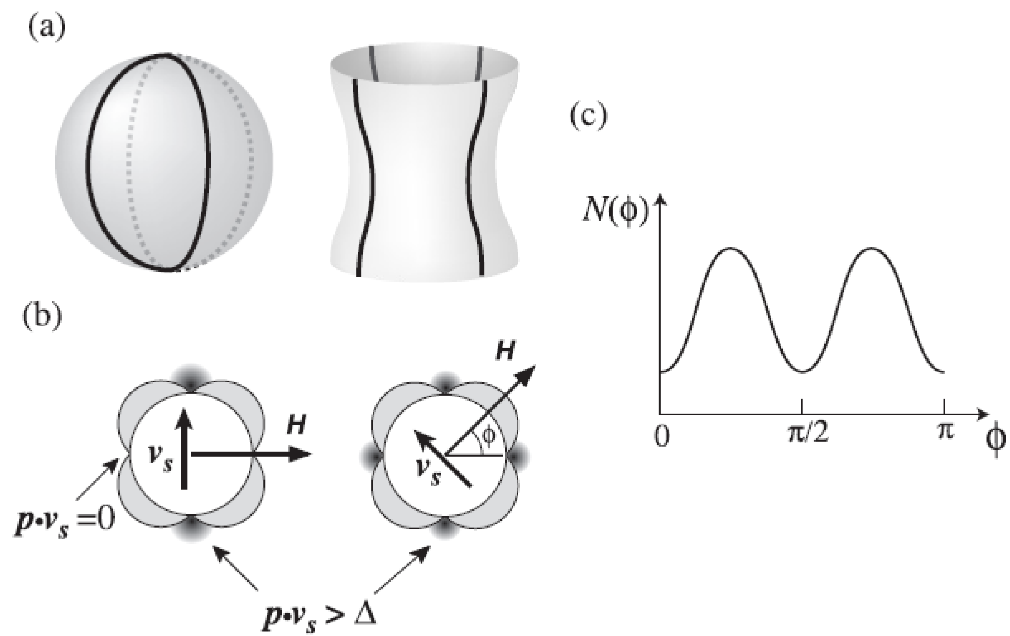
Doppler shift effect

- Phys. Rev. B70, 214505(2004).
- Phys. Rev. B 72, 134507(2005).

Angle Resolved Specific Heat:
a powerful tool to detect the nodal gap symmetry







Y. Matsuda, J. Phys.: Cond. Matter 18, R705 (2006).

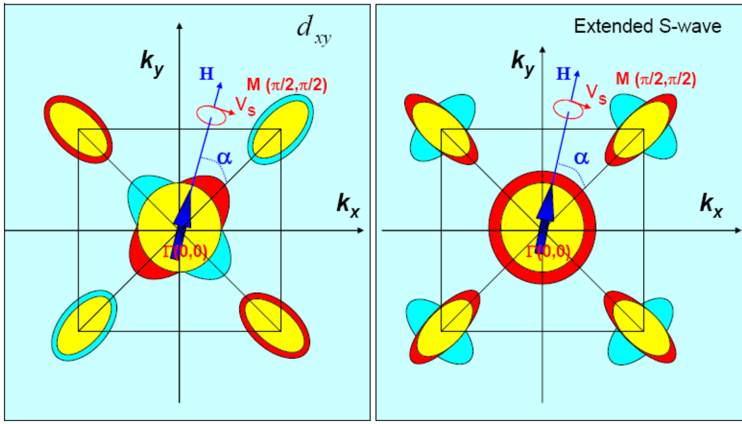
$$\delta E = m\vec{v}_s \bullet \vec{v}_F = \frac{E_H}{\rho}\left(\vec{v}^{(i)}_{F,y}\cos\alpha - \vec{v}^{(i)}_{F,x}\sin\alpha\right)\sin\beta$$

$$E^{(i)}_H = a\hbar\tilde{v}_F\left(\frac{2H}{\pi\Phi_0}\right)^{1/2}$$

$$N^{(i)}_0 = \left\langle \min\left[1, \left(\frac{E^{(i)}_H}{\Delta_k}\right)^2 \left(\vec{v}^{(i)}_{F,y}\cos\alpha - \vec{v}^{(i)}_{F,x}\sin\alpha\right)^2\right]\right\rangle_{FS}$$

Angle Resolved Specific Heat:

a powerful tool to detect the nodal gap symmetry



1. d-wave:

$$\Delta_k = \Delta_0 \sin k_x \sin k_y$$

$$N_0 = N_M + N_\Gamma^0 \int_0^{2\pi} \frac{d\varphi}{2\pi} \min\left[1, \frac{A}{\cos^2 2\varphi} \sin^2(\varphi - \alpha)\right]$$

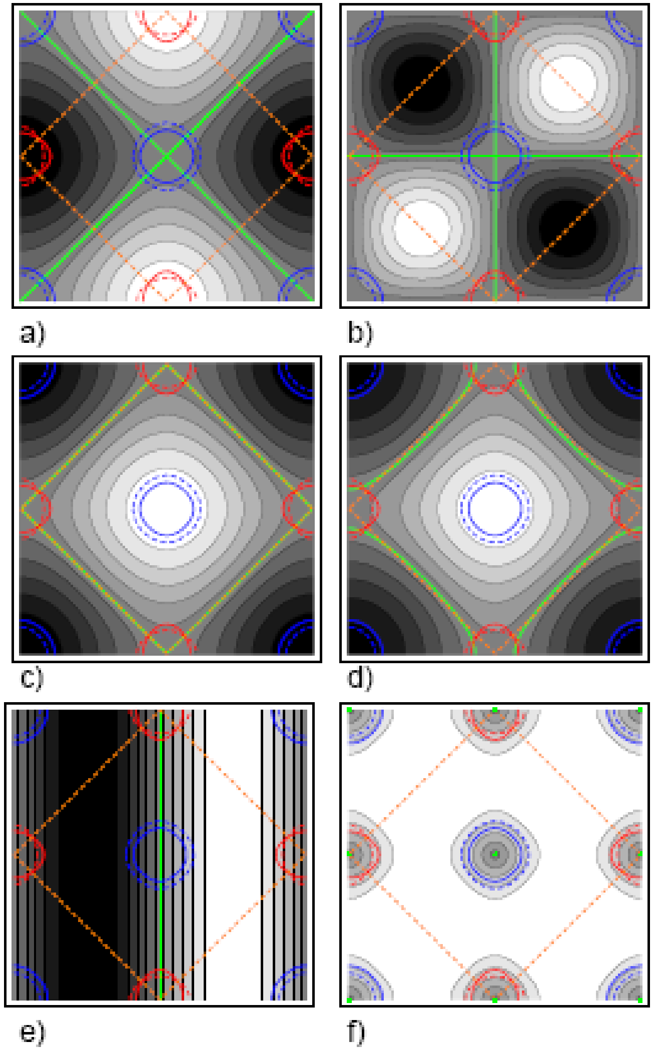
$$A = 2a^2 \hbar^2 v_F^2 H / \pi \Phi_0 \Delta_0^2$$

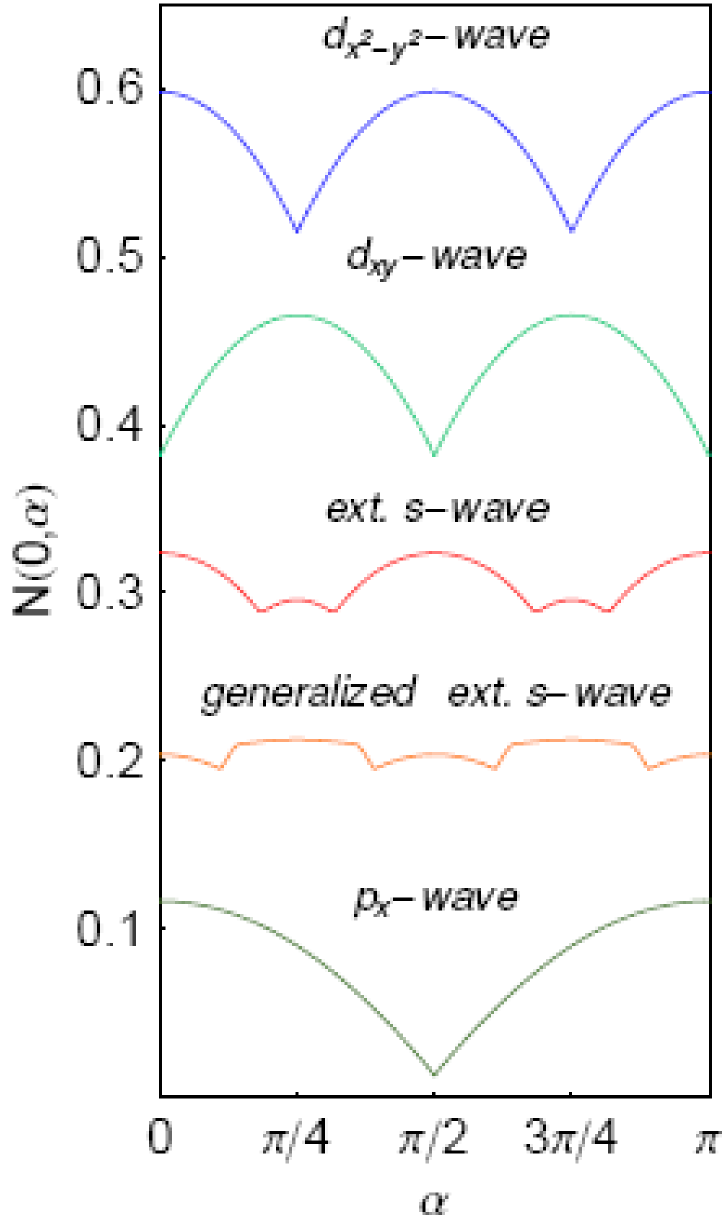
2. Extended s-wave:

$$\Delta_k = \Delta_0 \cos k_x \cos k_y$$

$$N_0(\alpha) = N_\Gamma + \tfrac{1}{2} N_M^0 \left[\int_0^{2\pi} \frac{d\varphi}{2\pi} \min\left[1, \frac{A}{\cos^2 2\varphi}\left[\frac{(h\tan\varphi\cos\alpha - \sin\alpha)^2}{h^2\tan^2\varphi + 1}\right]\right]\right]$$

$$+ \tfrac{1}{2} N_M^0 \left[\int_0^{2\pi} \frac{d\varphi}{2\pi} \min\left[1, \frac{A}{\cos^2 2\varphi}\left[\frac{(\tan\varphi\cos\alpha - h\sin\alpha)^2}{\tan^2\varphi + h^2}\right]\right]\right]$$



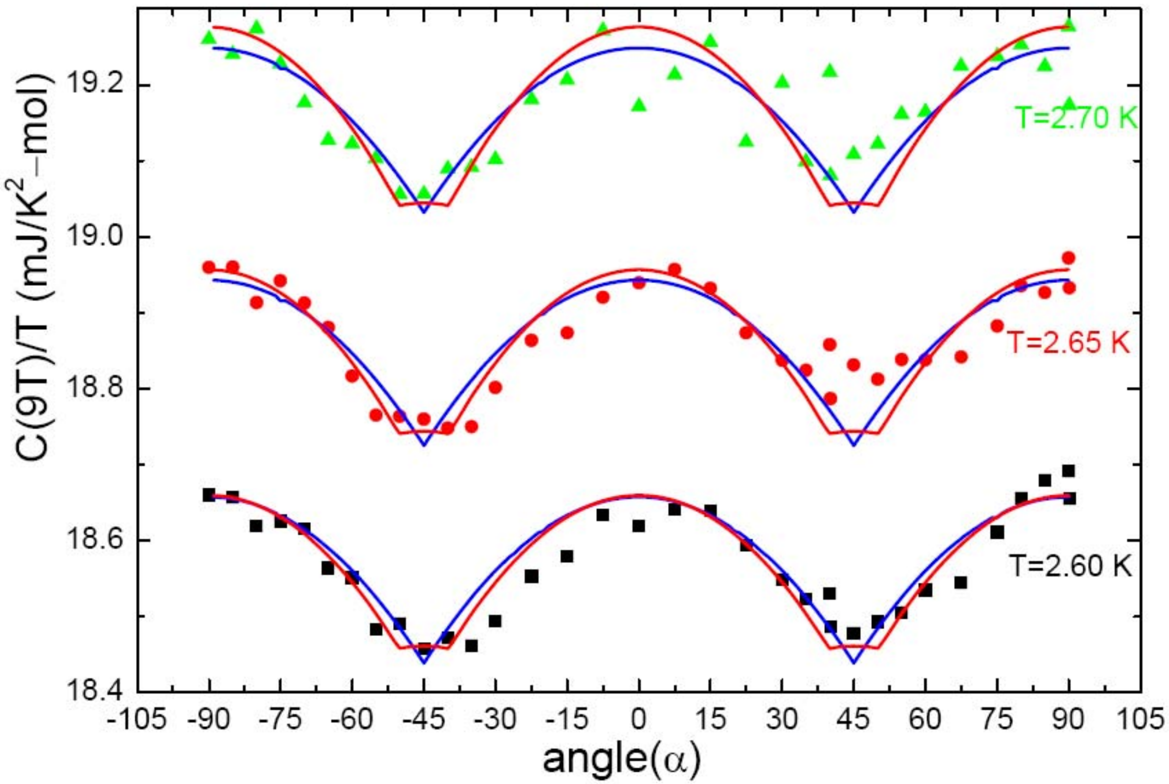


$\Delta = a+b(\cos k_x+\cos k_y)$

S. Graser et al., Phys. Rev. B 77, 180514(R) (2008)

$FeSe_{0.4}Te_{0.6}$ single crystals

4-fold oscillations of SH with in-plane field



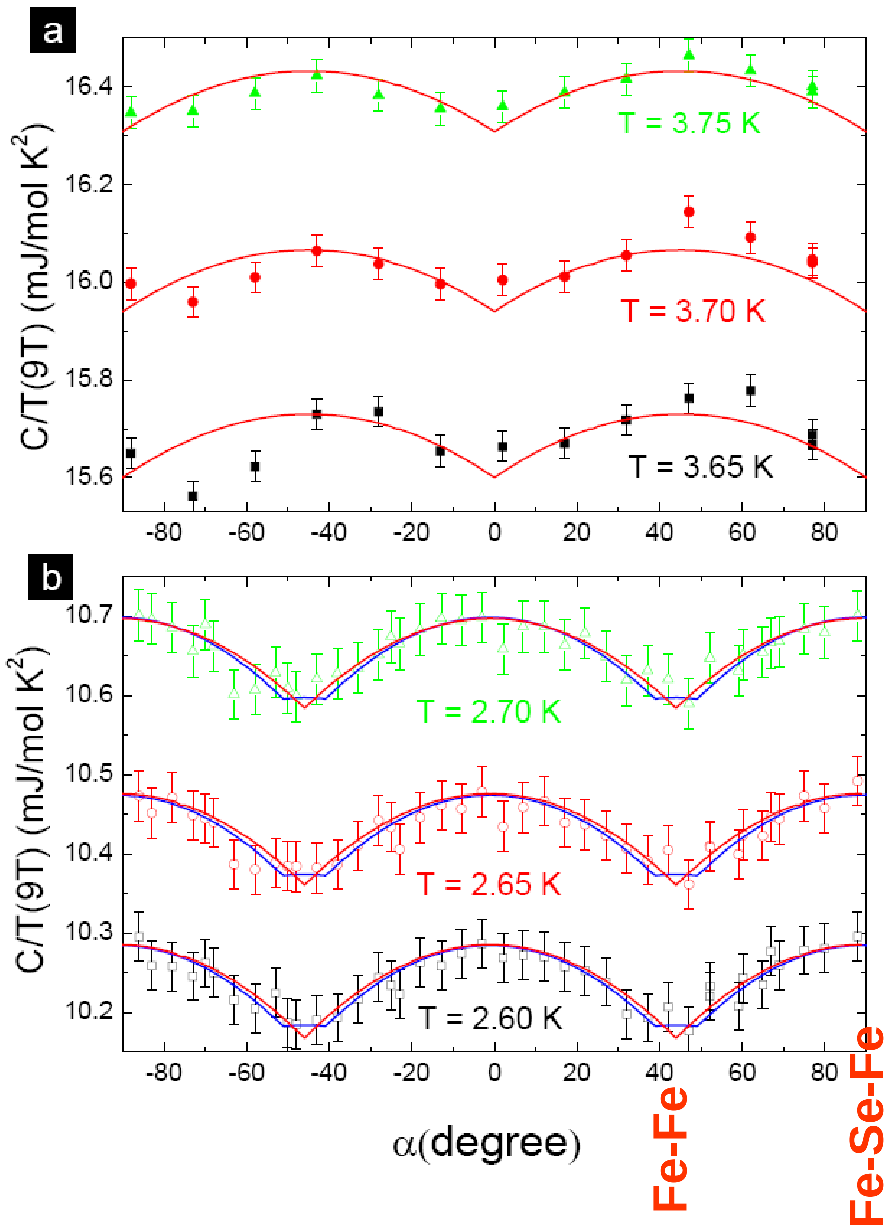
- d_{xy}-wave gap?
- Extended S-wave gap

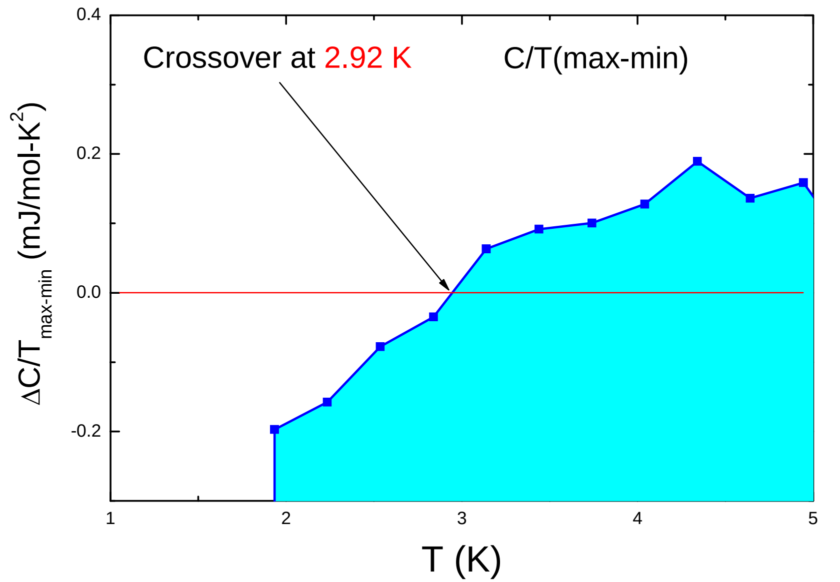
With ellipticity ratio h=a/b of the M-FS smaller than 1.2

Bing Zeng et al. arXiv:1007.3597. Nature Communications 2010

4-fold oscillations of SH with 9T in-plane field

B. Zeng ……HHW, Nature Comm. 1, 157 (2010)





For d-wave (2D case)

- Vorontsov, A. B. and Vekhter, I. *Phys. Rev. B* **75, 224501 (2007).** *Phys. Rev. B* **79, 064525 (2009).**
- An, K. et al., *Phys. Rev. Lett.* **104, 037002 (2010).**

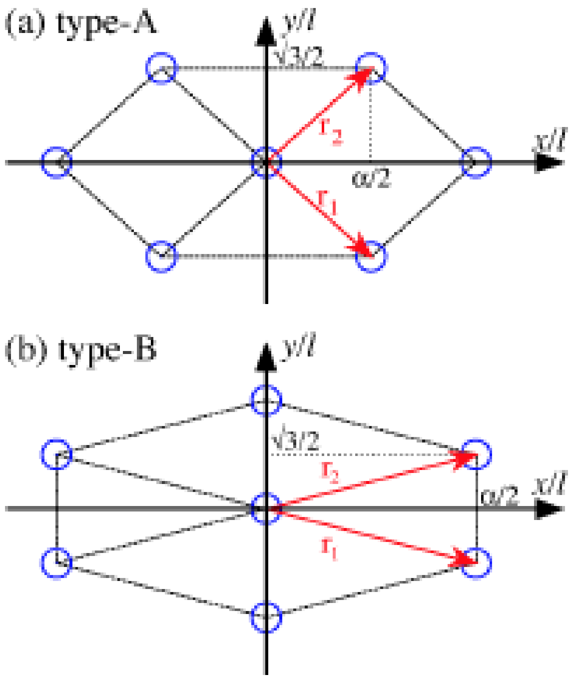
For Iron-pnictides

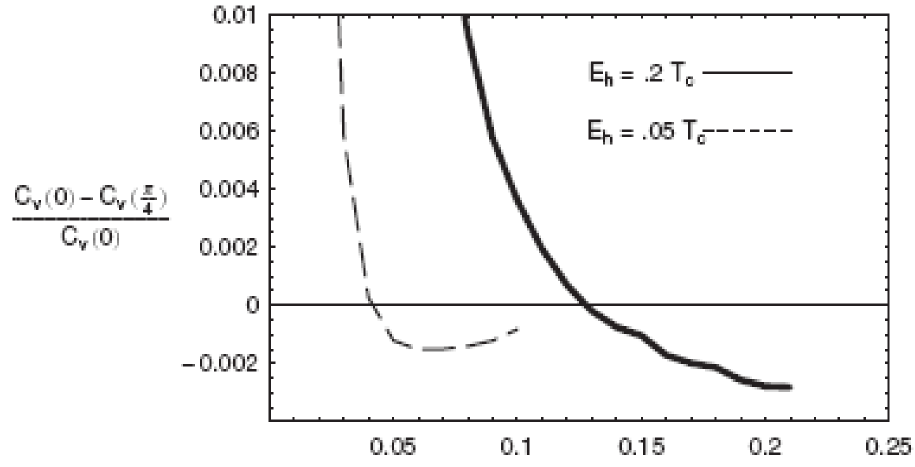
- Vorontsov, A. B. and Vekhter, I. **Phys. Rev. Lett. 105, 187004 (2010)**
- Chubukov, A. V. and Eremin, I. **PRB82, 060504(R)(2010)** .

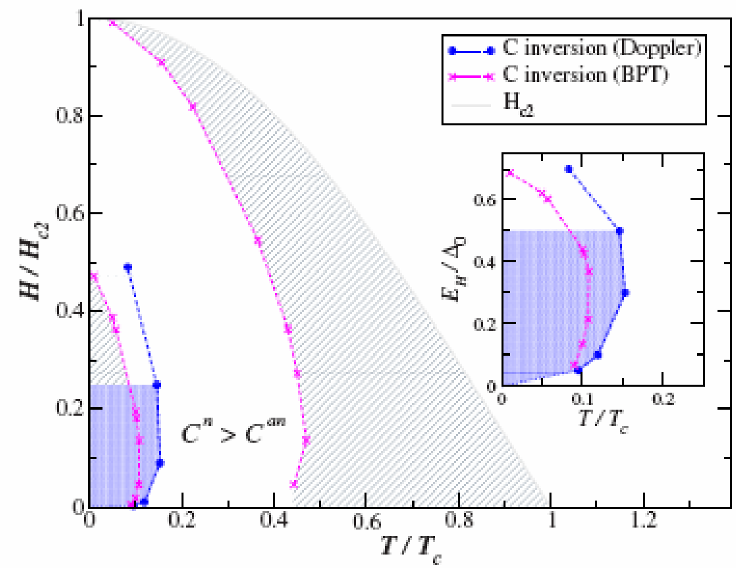
PHYSICAL REVIEW B 79, 064525 (2009)

Inversion of specific heat oscillations with in-plane magnetic field angle in two-dimensional *d*-wave superconductors

G. R. Boyd,[1] P. J. Hirschfeld,[1] I. Vekhter,[2] and A. B. Vorontsov[2,*]



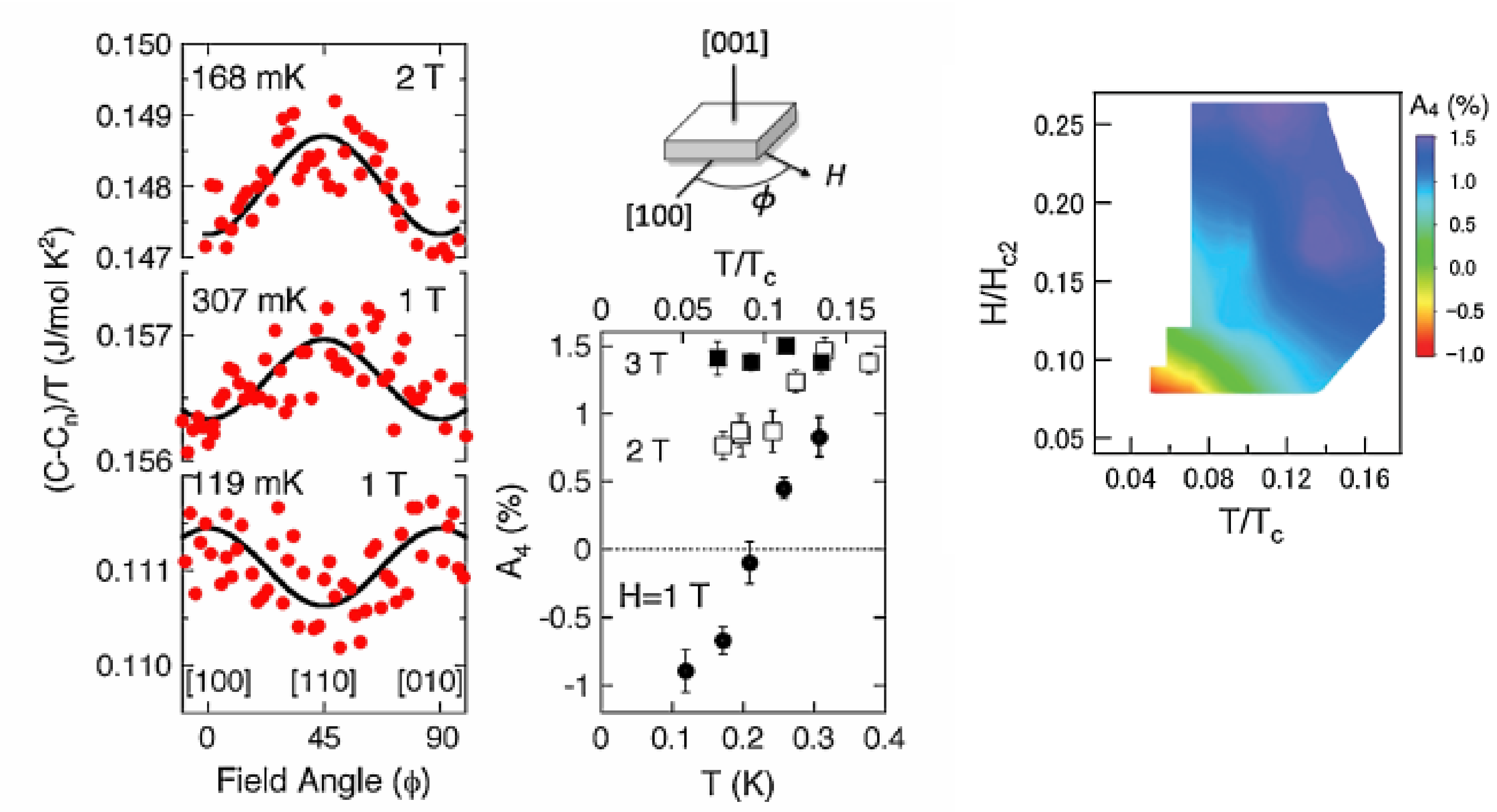




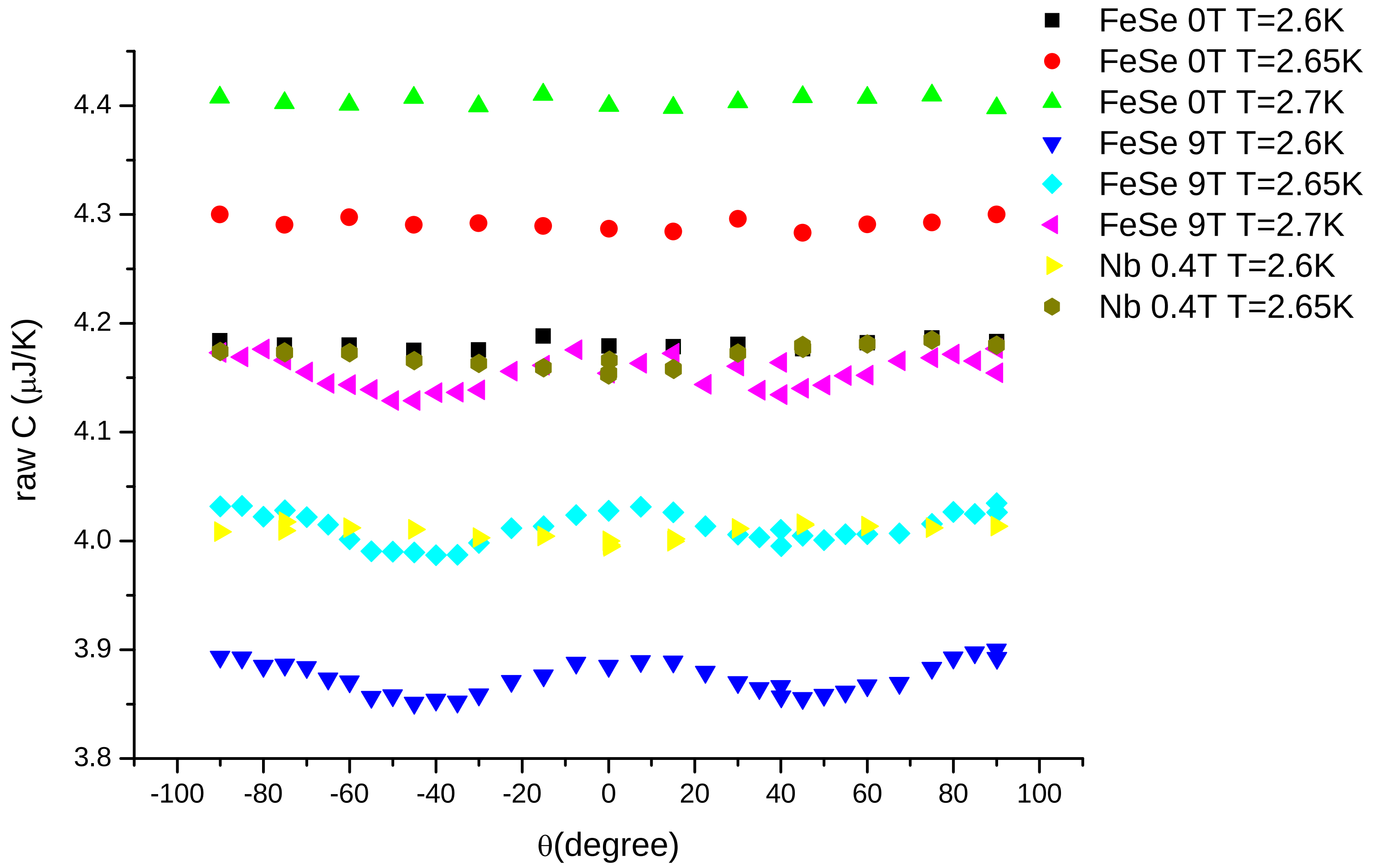
The free energy corresponding to two different kind of vortex patterns are quite close to each other, which makes this crossover!

Sign Reversal of Field-Angle Resolved Heat Capacity Oscillations in a Heavy Fermion Superconductor $CeCoIn_5$ and $d_{x^2-y^2}$ Pairing Symmetry

K. An,[1] T. Sakakibara,[1] R. Settai,[2] Y. Onuki,[2] M. Hiragi,[3] M. Ichioka,[3] and K. Machida[3]



Comparison of the data of $FeSe_{0.4}Te_{0.6}$ at H=9T, 0T and the Nb



$FeSe_{0.45}Te_{0.55}$ single crystals

$$\Delta C/T = 0.12 mJ/mol-K^2$$

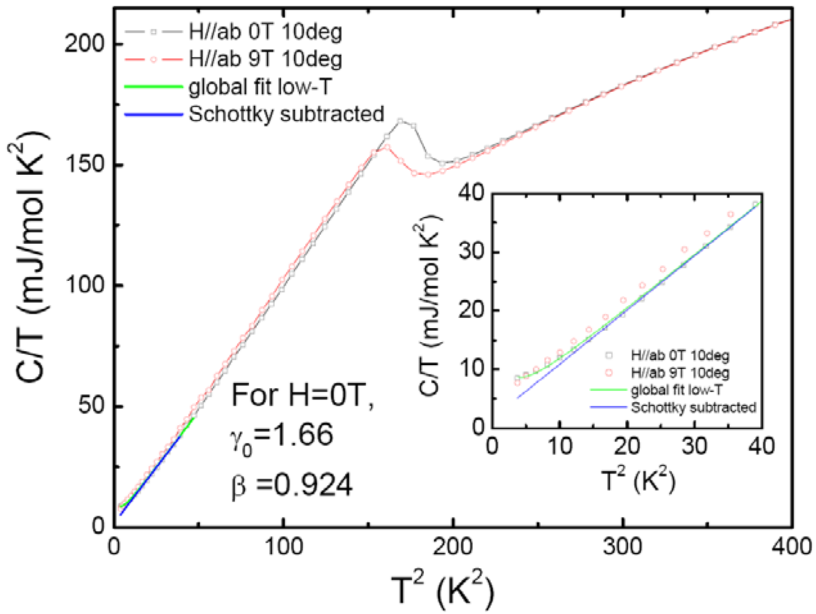
$$\gamma = \gamma_{ph} + \gamma_0 + (\gamma_e^h + \gamma_e^e)$$

$$\gamma_{ph} = \beta T^2$$

$$\beta = 0.924 mJ/mol-K^4$$

$$\gamma_0 = 1.66 mJ/mol-K^2$$

$$(\gamma_e^h + \gamma_e^e) \approx 3 mJ/mol-K^2$$



$$C_{total}/T = \gamma_0 + C_{ph}/T + \gamma_{Sch} = \gamma_0 + \beta T^2 + n\left(\frac{g\mu_B H_{eff}}{k_B T}\right)^2 \frac{\exp(g\mu_B H_{eff}/k_B T)}{[1+\exp(g\mu_B H_{eff}/k_B T)]^2}$$

If at 9 T

$$\gamma_e^h = \gamma_e^e = 1.5 mJ/mol-K^2$$

$$\Delta\gamma/\gamma_e^e = 0.12/1.5 = 8\%$$

Theory prediction: 5-10%

Gap function → Temperature ↓	$\Delta_k = \Delta_0 \sin k_x \sin k_y$	$\Delta_k = \Delta_0 \cos k_x \cos k_y$
T = 2.60 K	γ_e^h=0.97, γ_e^e=1.944	γ_e^h=1.904, γ_e^e=1.06
T = 2.65 K	γ_e^h=0.95, γ_e^e=1.901	γ_e^h=1.851, γ_e^e=1.06
T = 2.7 K	γ_e^h=0.93, γ_e^e=1.884	γ_e^h=1.824, γ_e^e=1.07

nature COMMUNICATIONS

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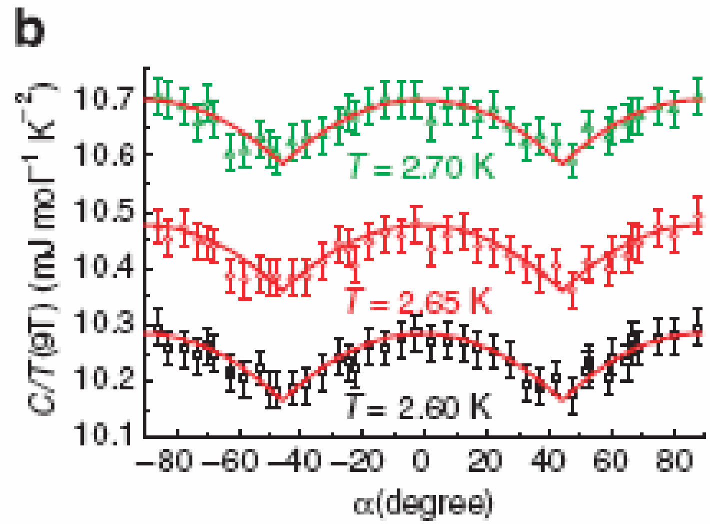
ARTICLE

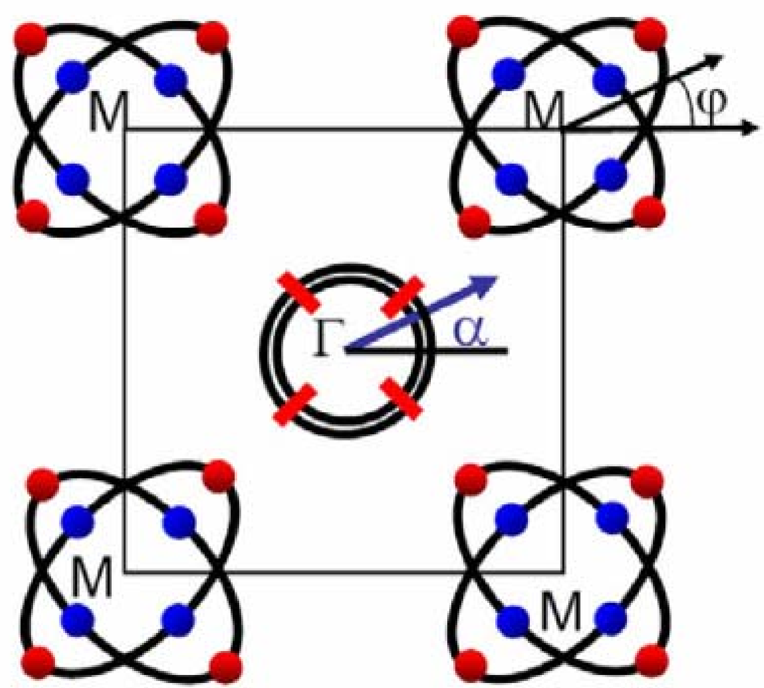
Received 6 Apr 2010 | Accepted 18 Oct 2010 | Published 16 Nov 2010

DOI: 10.1038/ncomms1115

Anisotropic structure of the order parameter in $FeSe_{0.45}Te_{0.55}$ revealed by angle-resolved specific heat

B. Zeng[1], G. Mu[1], H.Q. Luo[1], T. Xiang[1], I.I. Mazin[2], H. Yang[1,3], L. Shan[1], C. Ren[1], P.C. Dai[1,4,5] & H.-H. Wen[1,3]

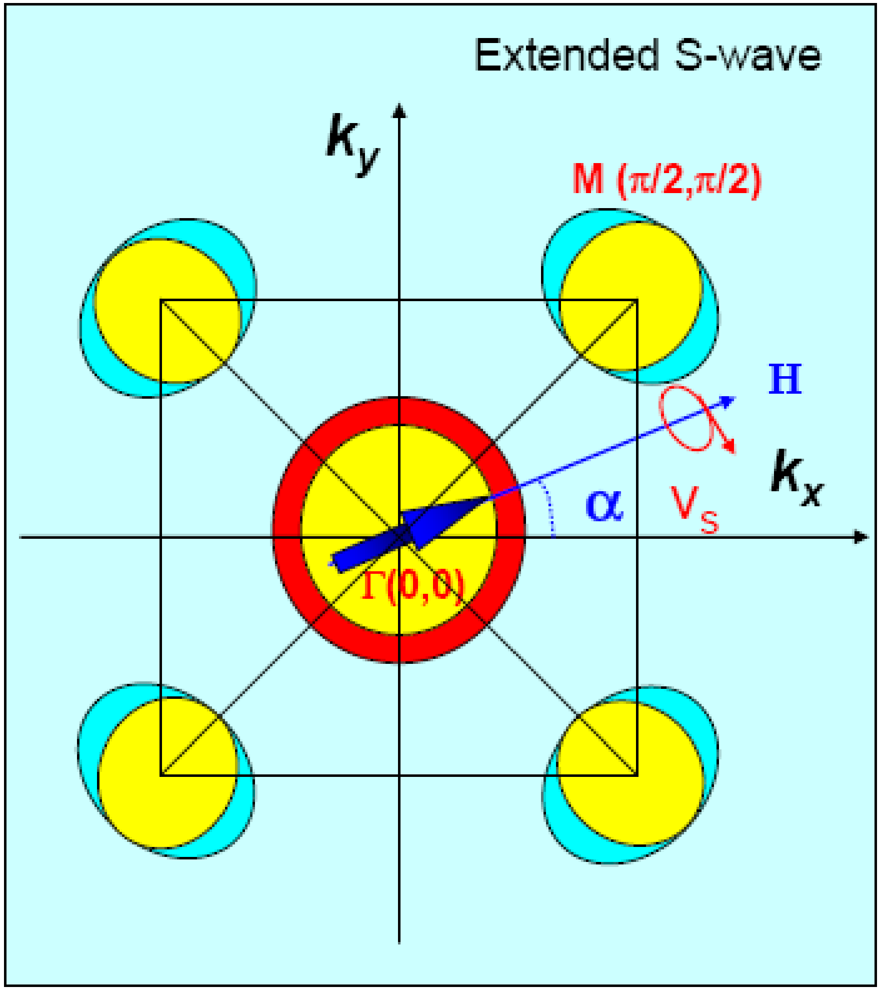


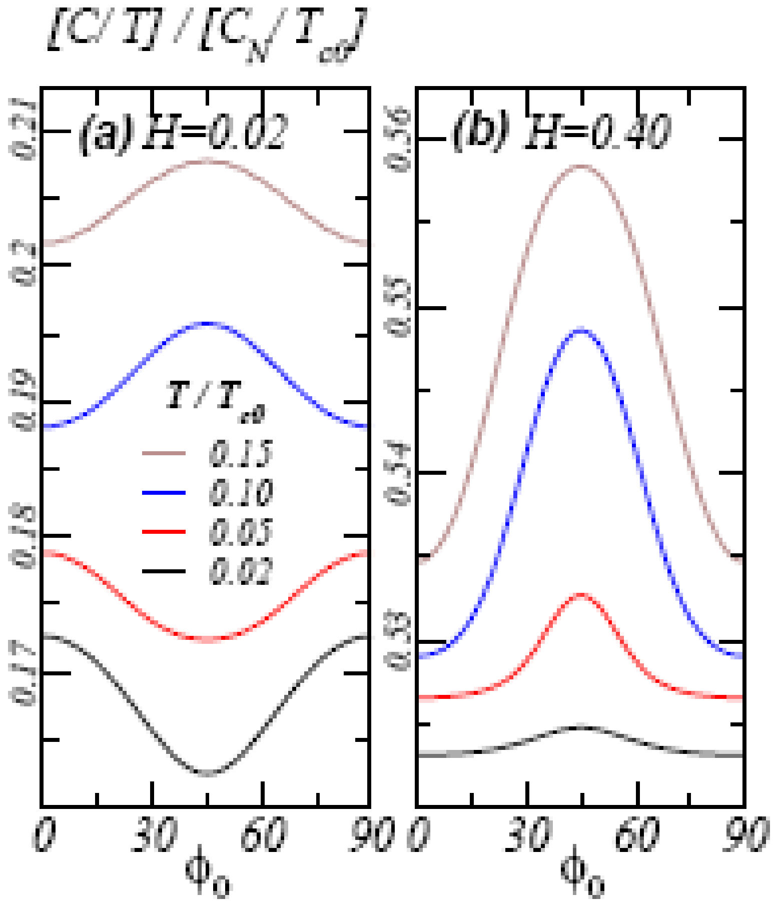


- **Vertical d-wave nodes on the hole pockets: unlikely**
- **Extended s-wave: accidental minimum of gaps on M-FS are possible**

B. Zeng ……HHW.
Nature Comm. 1, 157 (2010)

- Vorontsov, A. B. and Vekhter, I.
  Phys. Rev. Lett. 105, 187004 (2010)
- Chubukov, A. V. and Eremin, I.
  PRB82, 060504(R)(2010)





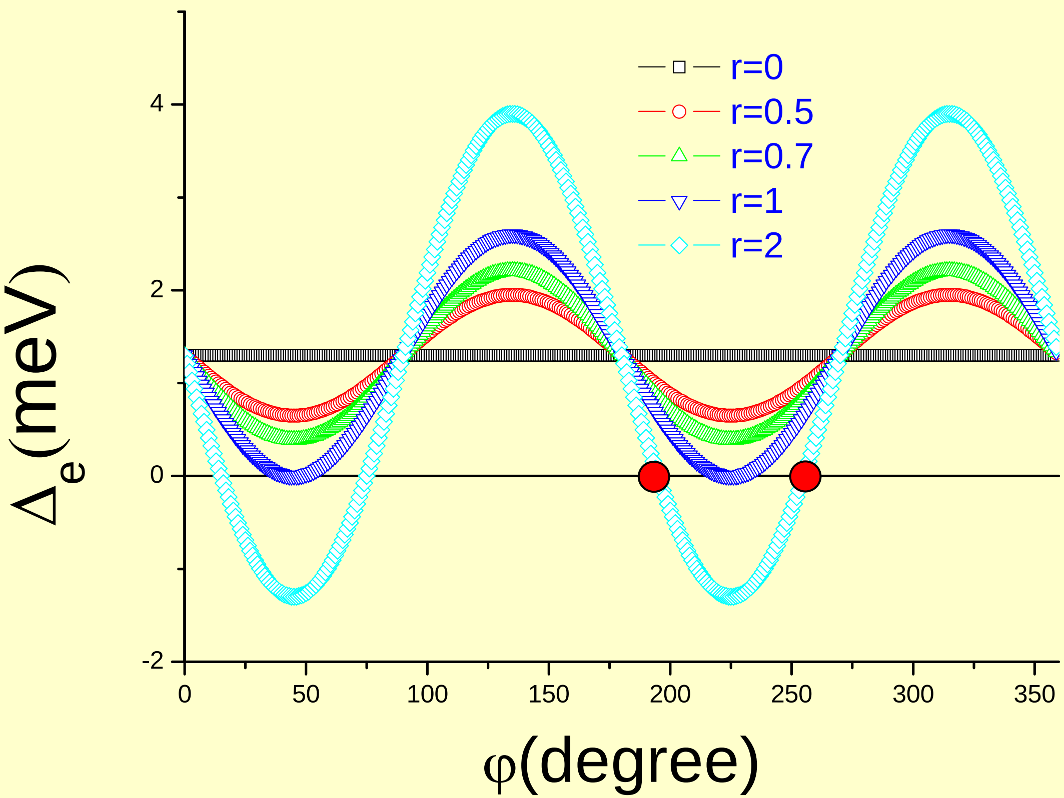
Qualitatively consistent with the theory

Extended s-wave gap:

$\Delta = a+b(\cos k_x+\cos k_y)$

- Vorontsov, A. B. and Vekhter, I. Phys. Rev. Lett. 105, 187004 (2010)
- Chubukov, A. V. and Eremin, I. PRB82, 060504(R)(2010)

On the M-FS: $$\Delta_e = \Delta_0[1 - r\sin 2\varphi]$$



- **|r|<1: nodeless, gap minimum at φ=45**
- **|r|>1: accidental nodes around φ=45**

Our present case: r=0.5-1

More overdoping Stronger intra-pocket scattering
A pair of accidental nodes expected??

B. Zeng…HHW, Nature Comm. 1, 157 (2010)

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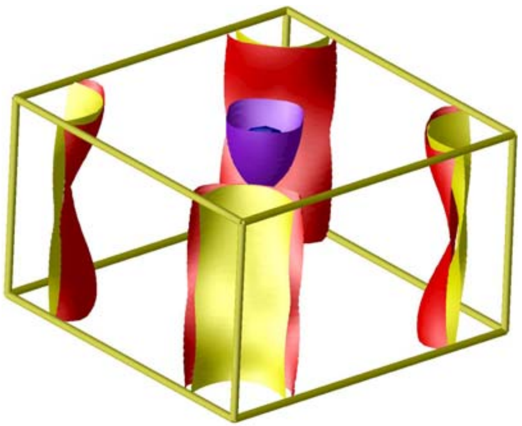
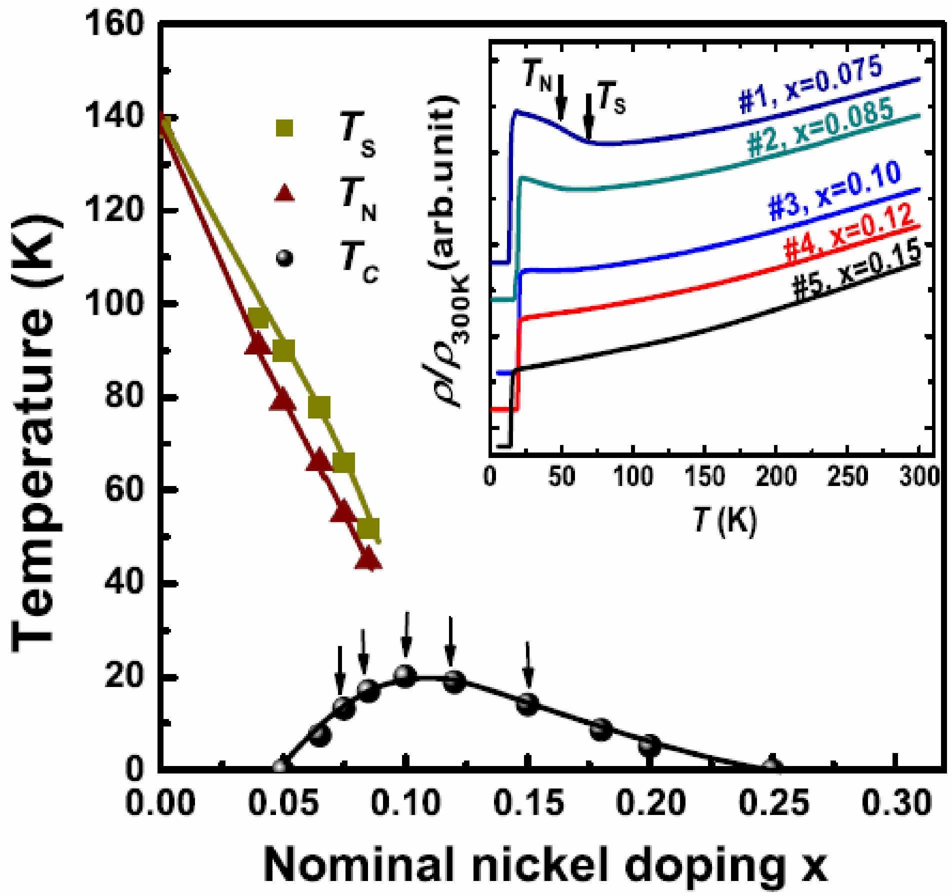
Doping induced evolution of the pairing interaction: from inter-pocket to intra-pocket dominated scattering?



$$\Delta_e = \Delta_0[1 - r\sin 2\varphi]$$



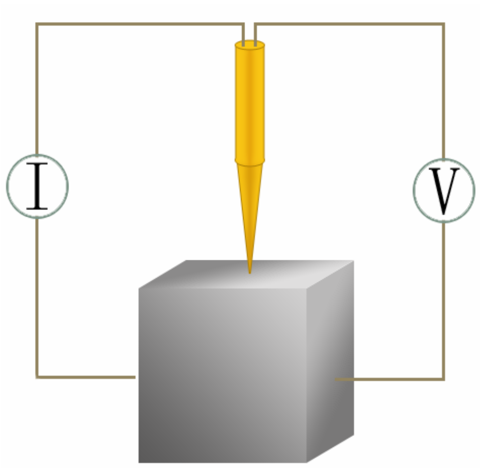
BTK theory:

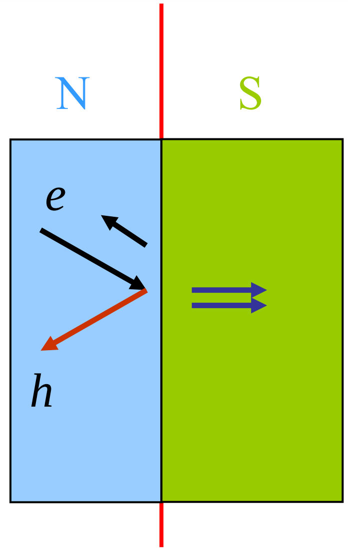
Andreev reflection

$$I_{NS} = 2N(0)ev_F\mathscr{A}\int_{-\infty}^{\infty}(f_0(E-eV)-\{A(E)f_0(E+eV)+B(E)f_0(E-eV)$$

$$+[1-A(E)-B(E)]f_0(E)\})dE$$

$$=2N(0)ev_F\mathscr{A}\int_{-\infty}^{\infty}[f_0(E-ev)-f_0(E)][1+A(E)-B(E)]dE\ .$$





Probability:

A: Andreev reflection, two electron tunneling

B: Single particle tunneling

G.E. Blonder, M. Tinkham, and T.M. Klapwijk, *Phys. Rev. B 25, 4515 (1982).*

BTK fitting:

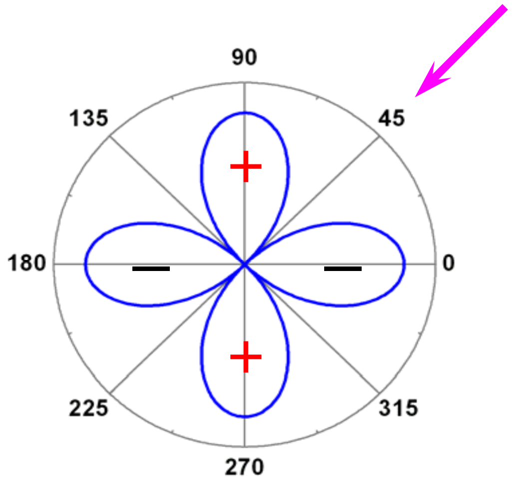
$$G_N(V)=\int_{-\infty}^{\infty}\frac{df(E-V,T)}{dV}[1+A_N(E,Z)-B_N(E,Z)]dE$$

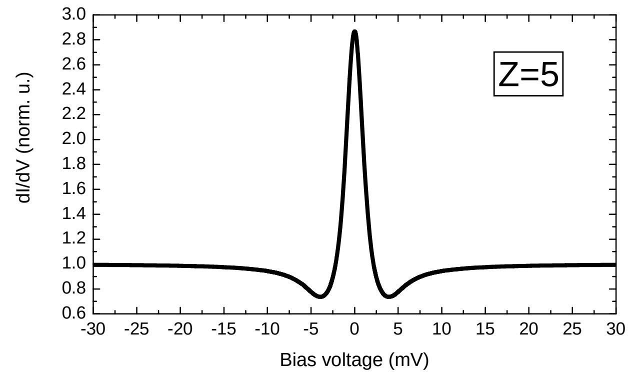
	$\|E\|<\Delta$	$\|E\|>\Delta$
$G_N\|_{T=0}(E)=1+A_N-B_N$	$\dfrac{2(1+\beta^2)}{\beta^2+(1+2Z^2)^2}$	$\dfrac{2\beta}{1+\beta+2Z^2}$

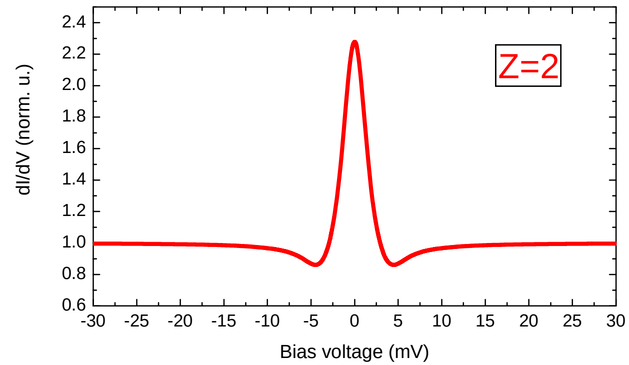
$$\beta=E/(\sqrt{|\Delta^2-E^2|})\qquad Z=\frac{mH}{\hbar^2 k_F}=H/\hbar v_F$$

Four parameters: T-temperature;
Δ-SC gap;
Z-barrier height;
Γ-broadening parameter.

Barrier strength:

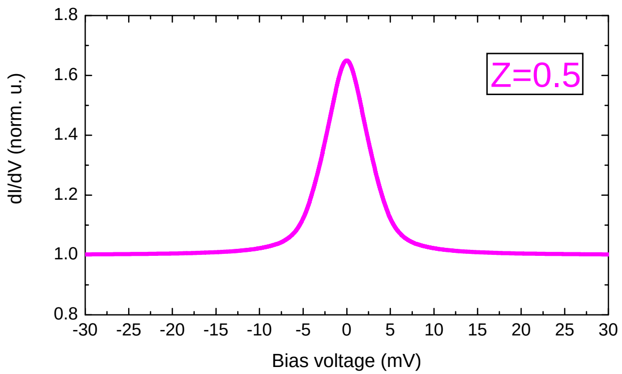


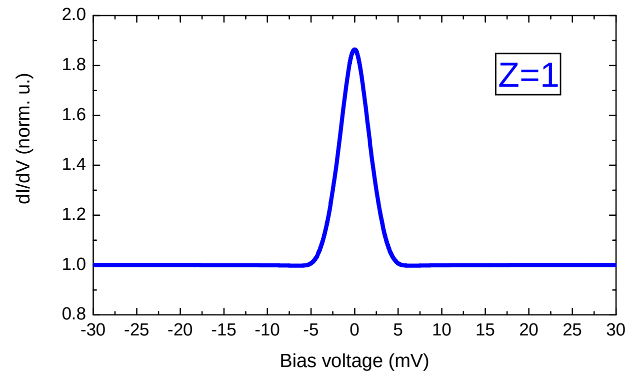


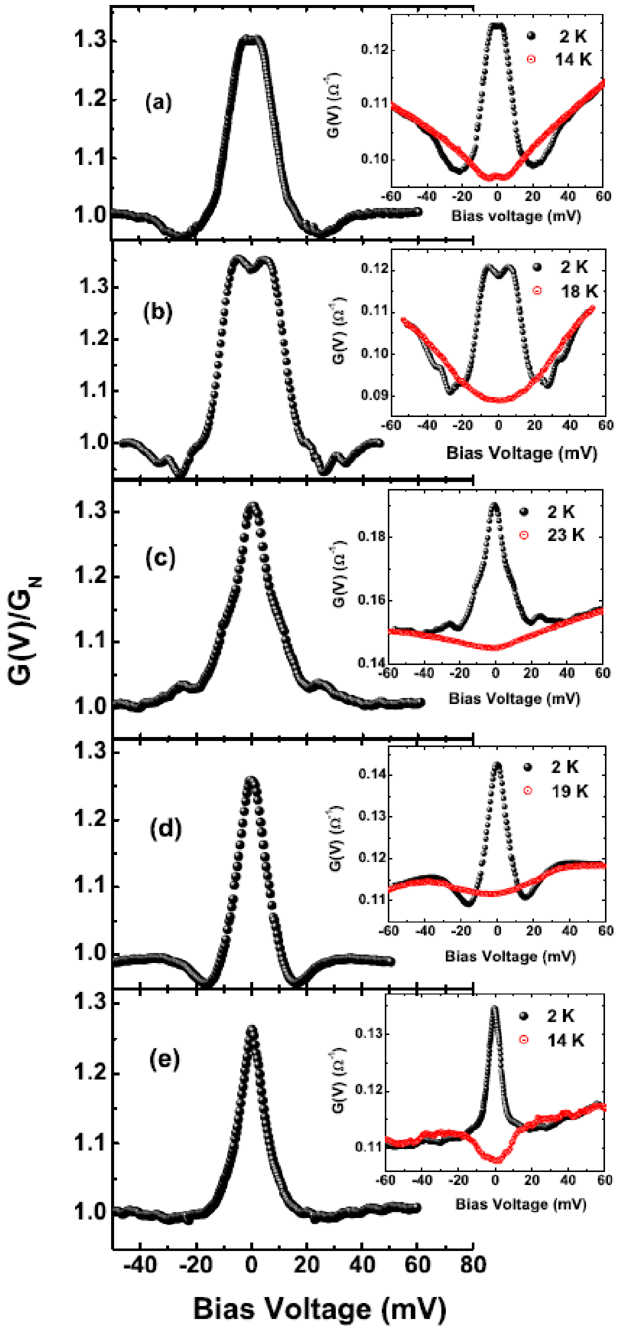


T=2K, Δ_0=5meV,

α=45^o, Γ=1meV.



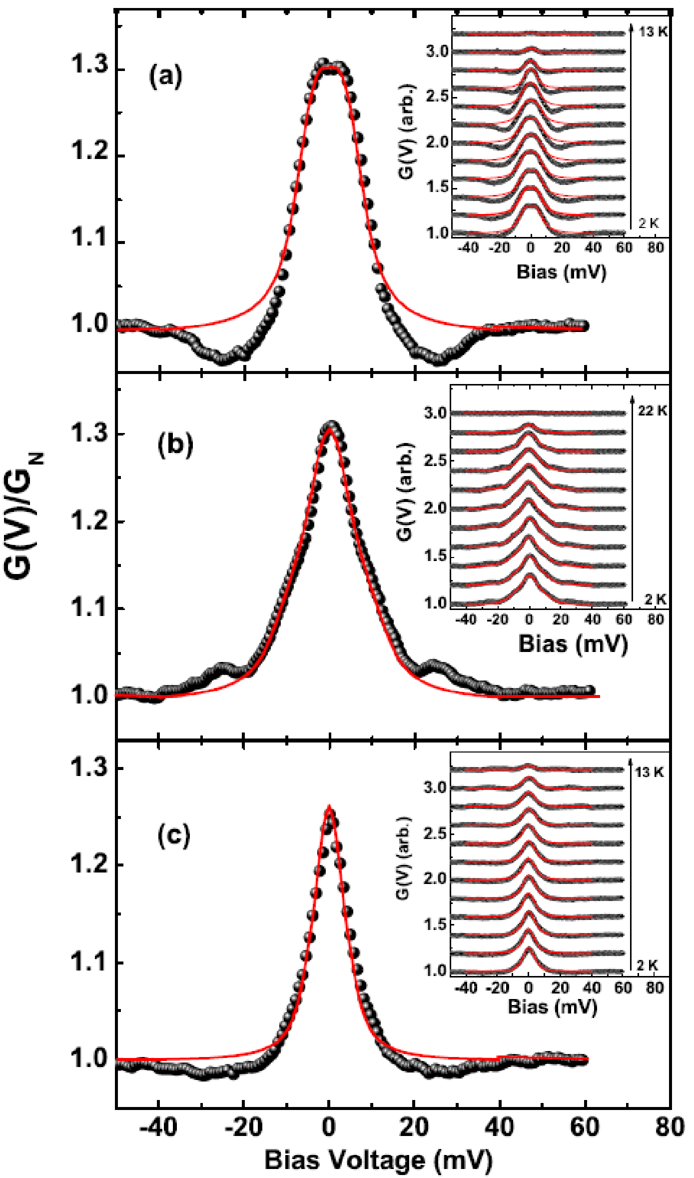




Underdoped

Optimal doped

Overdoped



Cong Ren et al., to be published

$$\Delta_\Gamma = \Delta_h$$ isotropic gap

$$\Delta_M = \Delta_e\left[1 - r - r\cos 2\phi\right]$$ anisotropic gap

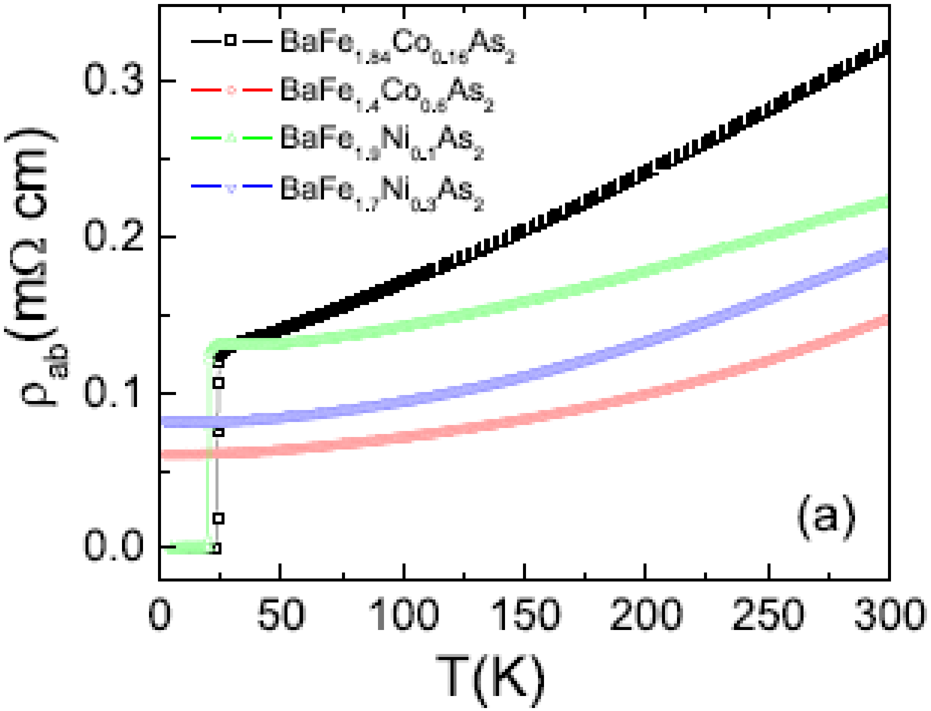
$$G = wG_\Gamma + (1-w)G_M$$

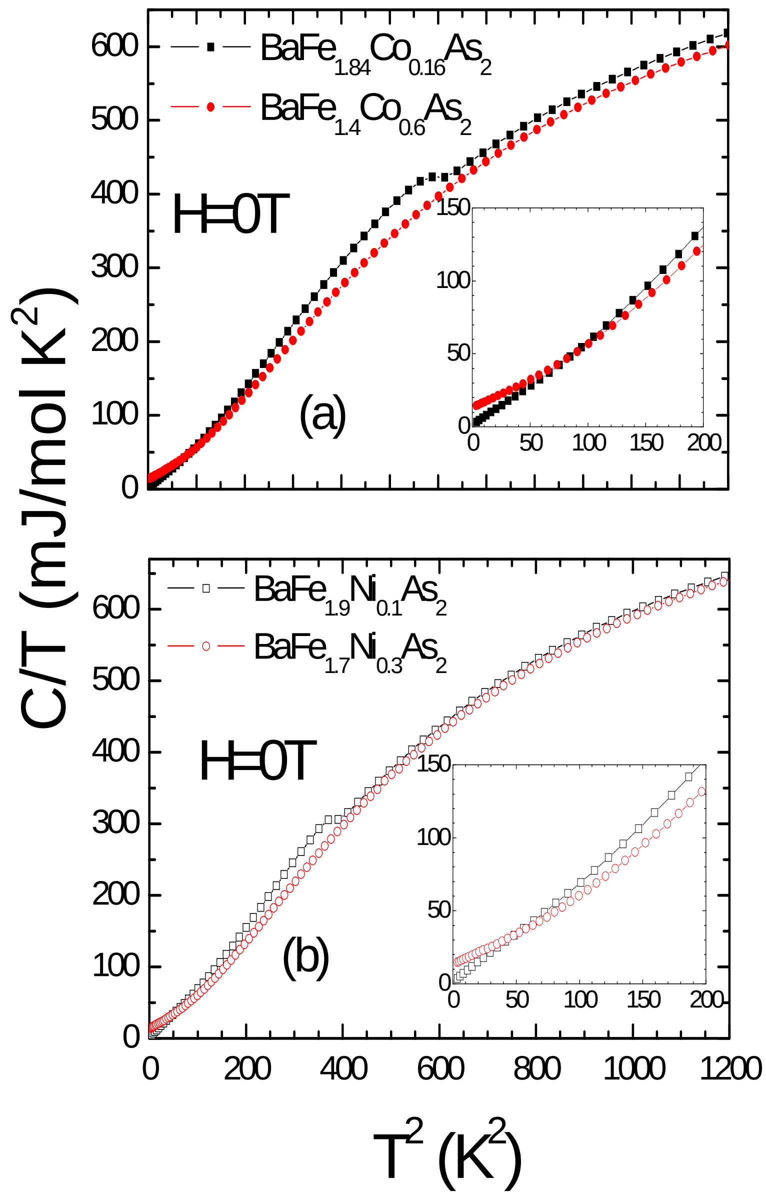
sample	T_c	Δ_h(meV)	Δ_e(meV)	Z	γ	r
#1	13.2	7.5 ± 0.4	5.0 ± 0.3	0.30	2.8	0.1
#2	17.3	6.8 ± 0.4	10.3 ± 0.4	0.45	2.3	0.18
#3	20.5	4.2 ± 0.3	12.0 ± 0.5	0.19	2.5	0.7
#4	18.6	2.7 ± 0.4	8.3 ± 0.4	0.22	1.9	0.8
#5	14.1	2.3 ± 0.3	6.0 ± 0.3	0.22	1.7	0.95

r = 0.5
Crossover point of nodal gap

This unfortunately cannot distinguish the vertical nodes or the horizontal nodes.

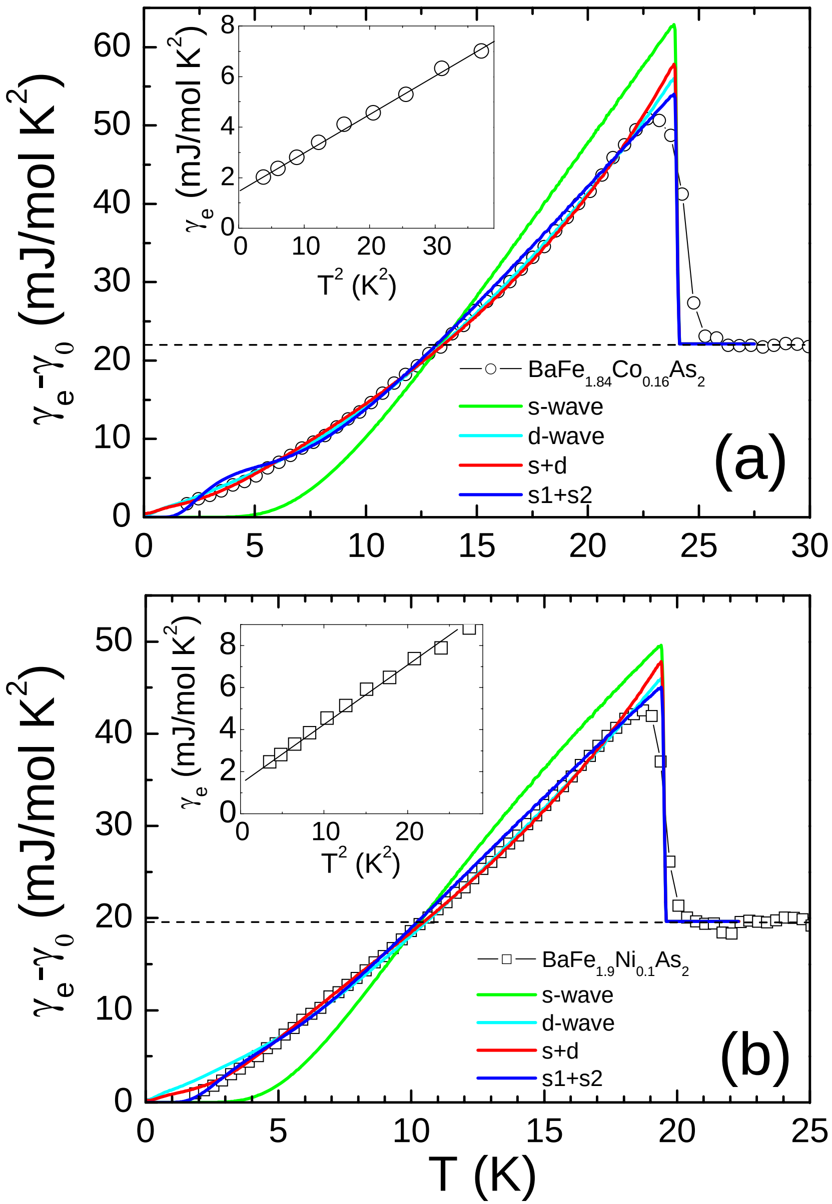
Specific heat in $Ba(Fe_{1-x}Co_x)As_2$ and $Ba(Fe1\text{-}xNi_x)_2As_2$: possible segments of nodal lines or point nodes





- Measure the SH for an optimally doped and an very overdoped non-SC samples.
- Determine the phonon part from the overdoped sample
- Remove the phonon part and get the electronic part of the superconducting sample.

Optimally doped $Ba(Fe_{1-x}Co_x)As_2$ and $Ba(Fe_{1-x}Ni_x)_2As_2$



$$\gamma_e = \frac{4N(0)}{k_B T^3}\int_0^{\hbar\omega_D}\int_0^{2\pi}\frac{e^{\zeta/k_BT}}{(1+e^{\zeta/k_BT})^2}\left(\varepsilon^2 + \Delta^2(\theta,T) - \frac{T}{2}\frac{d\Delta^2(\theta,T)}{dT}\right)d\theta\, d\varepsilon, \qquad (5)$$

- **The low temperature part has a quadratic T-dependence**

$$\gamma_e = \gamma_0 + \alpha T^2$$

- **The global fitting is more close to a single band d-wave! (but it is not!)**

- **Models with two components: d+s or s1+s2**

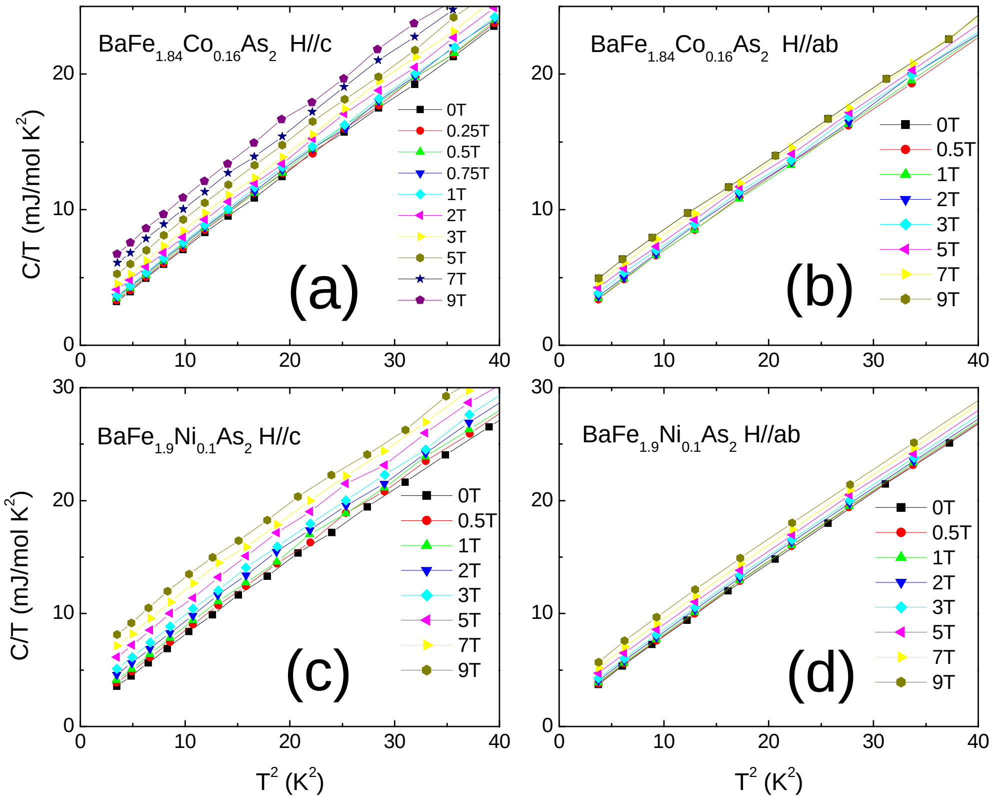
Co-doped sample.

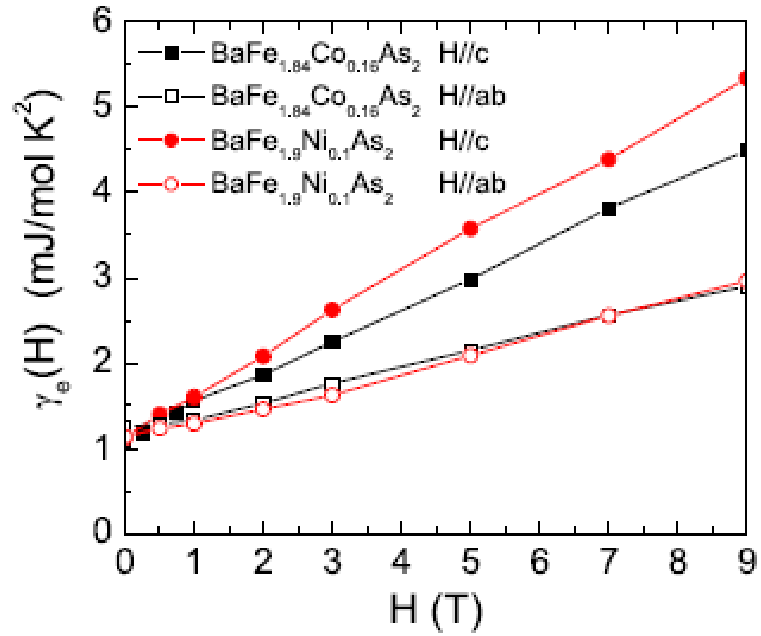
model	Δ_1(meV)	fraction 1	Δ_2(meV)	fraction 2
single s	4.2	100%	-	-
single d	5.4	100%	-	-
s+d	2.4	17%	5.9	83%
s+s	1.0	25%	4.25	75%

Ni-doped sample.

model	Δ_1(meV)	fraction 1	Δ_2(meV)	fraction 2
single s	3.1	100%	-	-
single d	4.1	100%	-	-
s+d	2.0	29%	4.7	71%
s+s	1.15	29%	3.3	71%

Specific heat in $Ba(Fe_{1-x}Co_x)As_2$ and $Ba(Fe1\text{-}xNi_x)_2As_2$:
possible segments of nodal lines or point nodes





Both vertical or horizontal line nodes are impossible!
But small segments of line nodes or point nodes are possible!

$$E_H = \frac{a}{2}\tilde{v}_F\sqrt{\frac{\pi H}{\Phi_0}}$$

$$N(E) \propto E^2$$

$$\Delta N(H, E=0) \propto H$$

How to reconcile $\gamma_e = \gamma_0 + \alpha T^2$ and $\gamma_e - \gamma_0 \propto H$

1. Strong pair breaking within $S^{\pm}$ pairing

Like the penetration depth $\Delta\lambda \propto T^2$

Difficulty: the cleaner sample, the smaller γ_0, but "2" is robust!

2. Impurity scattering with line nodes:

Difficulty: linear field dependence $\gamma_e - \gamma_0 \propto H$, it would be nonlinear, close to $H^{1/2}$.

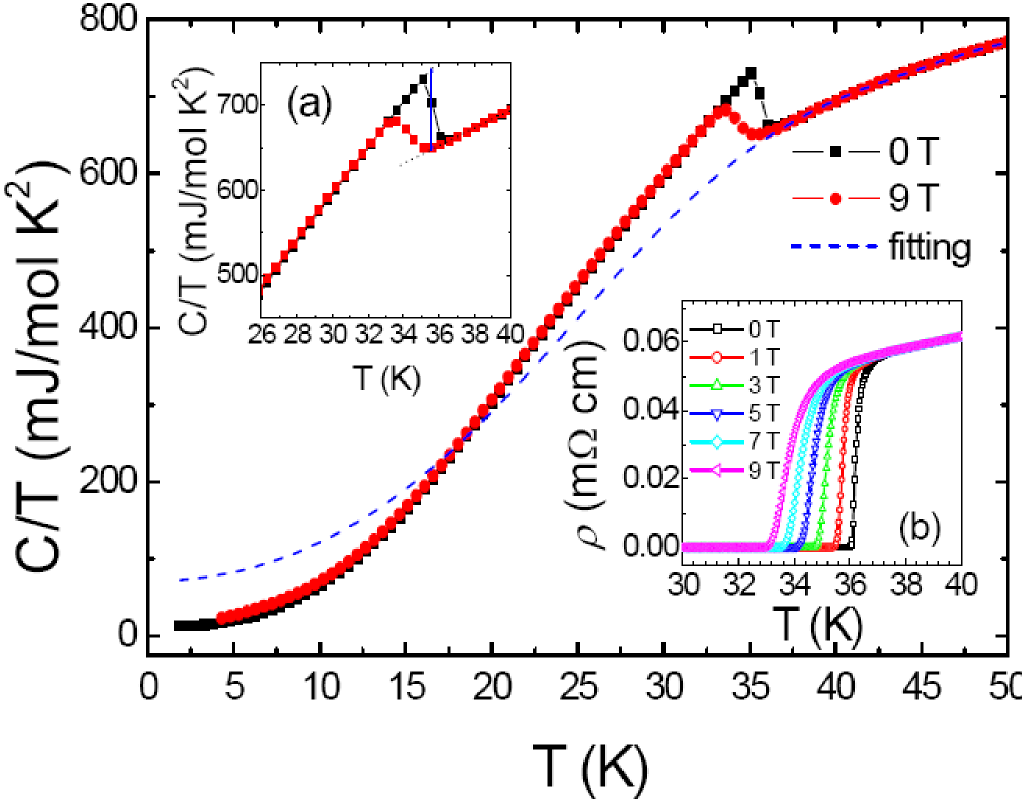
3. Point nodes or small segments of line nodes on some FS: fit both $\gamma_e = \gamma_0 + \alpha T^2$ and $\gamma_e - \gamma_0 \propto H$

Outline of the talk

- Brief introduction to the pairing symmetry of iron pnictide superconductors
- Bulk evidence for anisotropic gaps in $FeSe_{0.45}Te_{0.55}$ revealed by angle resolved specific heat
- Doping induced evolution from nodeless to nodal gaps in $Ba(Fe_{1-x}Co_x)_2As_2$ and $Ba(Fe_{1-x}Ni_x)_2As_2$ revealed by specific heat, point contact tunneling measurements.
- **Specific heat and STM measurements in $Ba_{1-x}K_xFe_2As_2$**
- Concluding remarks

Specific heat in $Ba_{1-x}K_xFe_2As_2$

Strong renormalization of the electron mass



$$\Delta C / T |_{T_c} = 98 - 102 mJ / molK^2$$

$$\frac{\Delta C}{\gamma_n T_c} = 1.43$$ **Weak coupling**

$$\frac{\Delta C}{\gamma_n T_c} \approx 2$$ **Strong coupling**

$$\gamma_n \geq 50 mJ / molK^2$$

$$\gamma_n = \frac{2\pi^2}{3} N(E_F) k_B^2 (1 + \lambda),$$

Extremely strong mass enhancement!
Consistent with ARPES data
H. Ding et al., arXiv:0812.0534

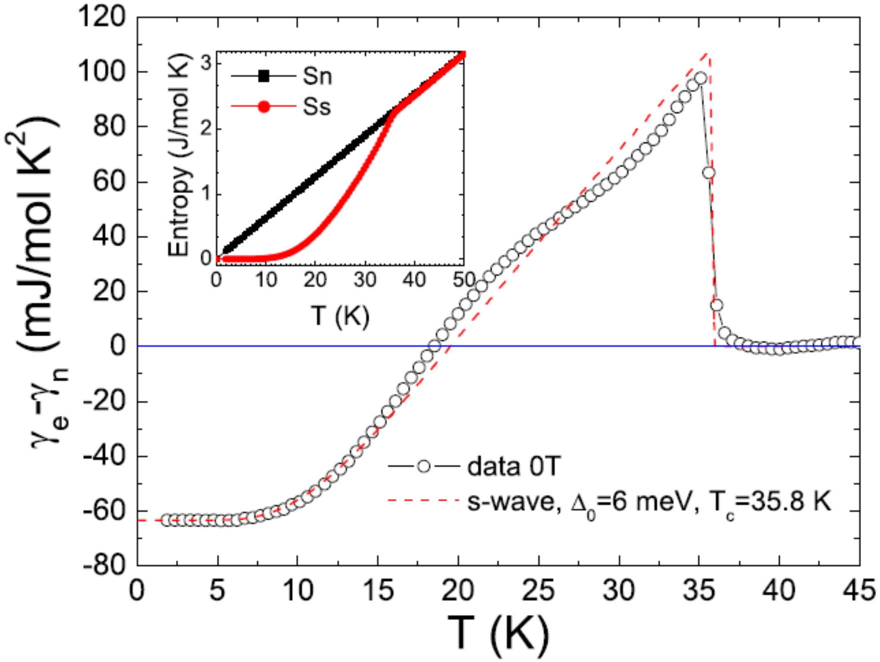
Gang Mu et al., Phys. Rev. B79, 174501 (2009)

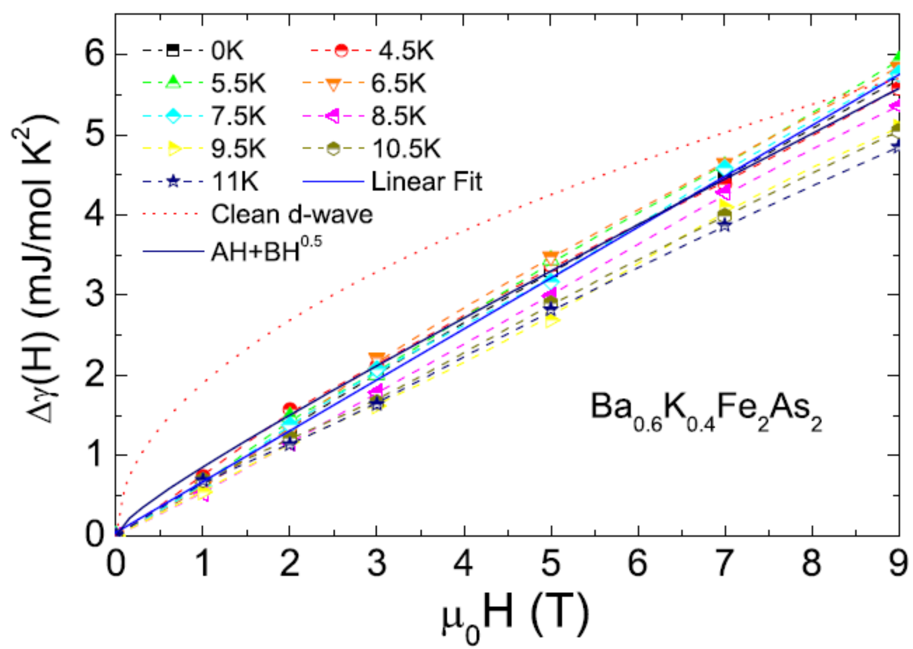
PHYSICAL REVIEW B **79**, 174501 (2009)

Low temperature specific heat of the hole-doped $Ba_{0.6}K_{0.4}Fe_2As_2$ single crystals

Gang Mu, Huiqian Luo, Zhaosheng Wang, Lei Shan, Cong Ren, and Hai-Hu Wen*

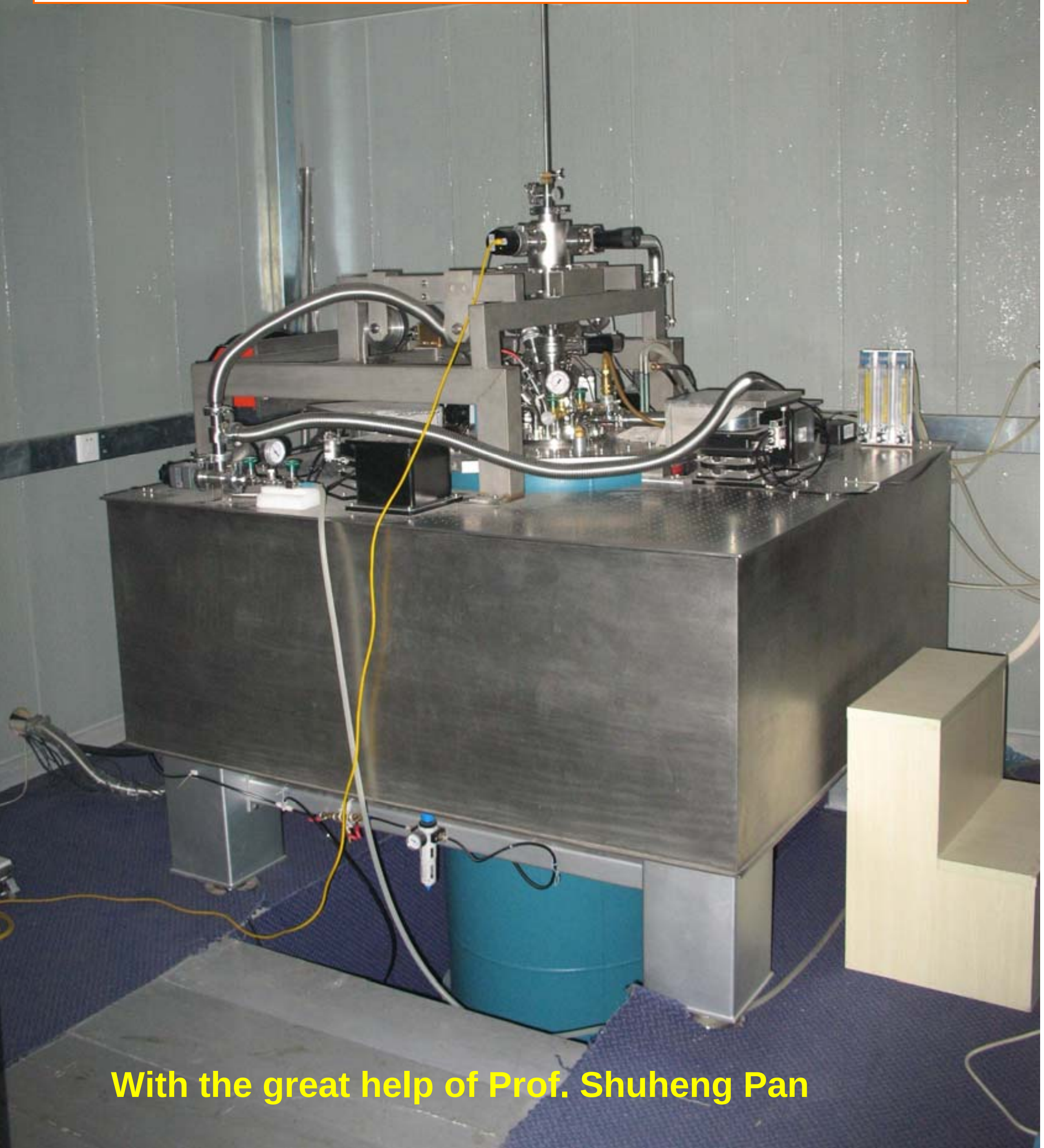
National Laboratory for Superconductivity, Institute of Physics and Beijing National Laboratory for Condensed Matter Physics, Chinese Academy of Sciences, P.O. Box 603, Beijing 100190, People's Republic of China



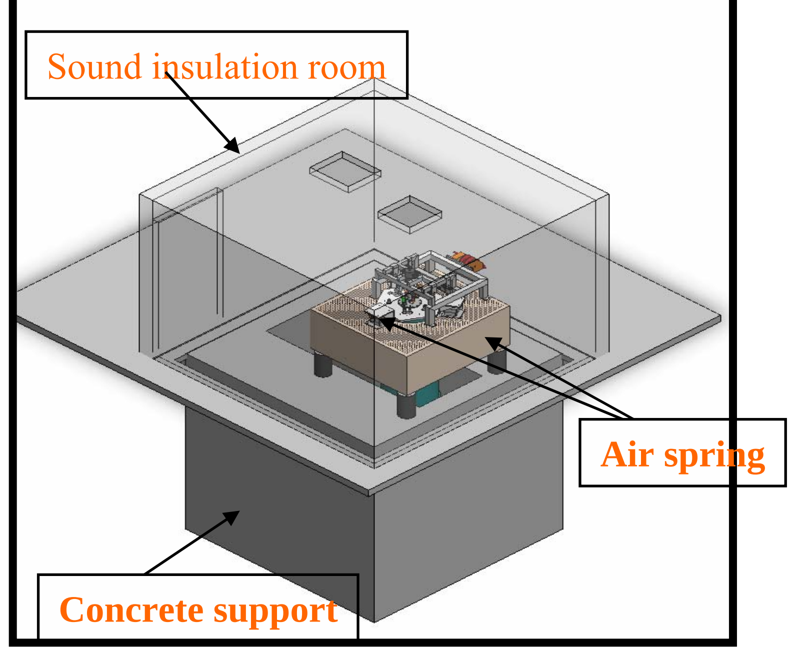


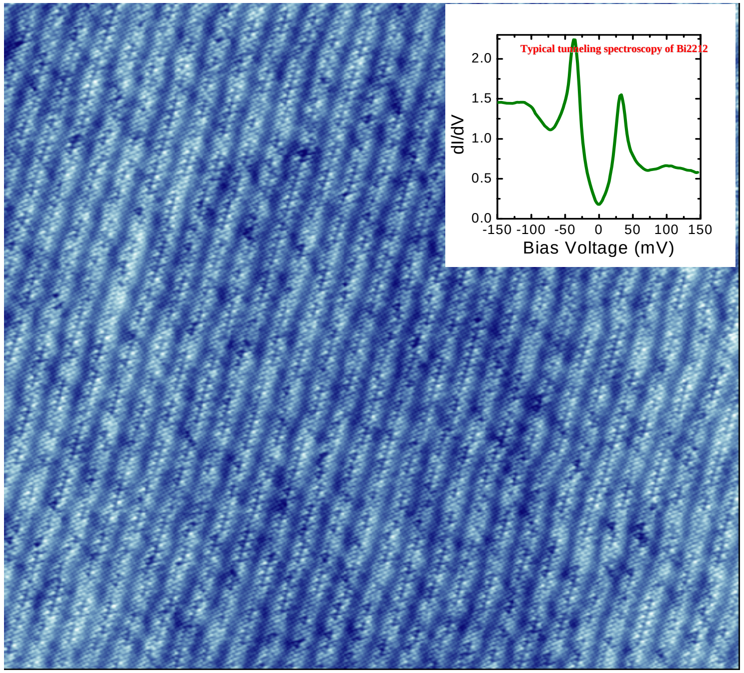
There are at least two components, one is s-wave with the gap of about 6 meV.

- Temperature : 1.8-50 K
- Magnetic field : 0-9 T
- Spatial resolution (z direction): 2 pm
- Spatial resolution (xy direction): 1 Å
- Energy resolution : 40 μ V
- Scan range at 4.2 K : 250×250 nm^2



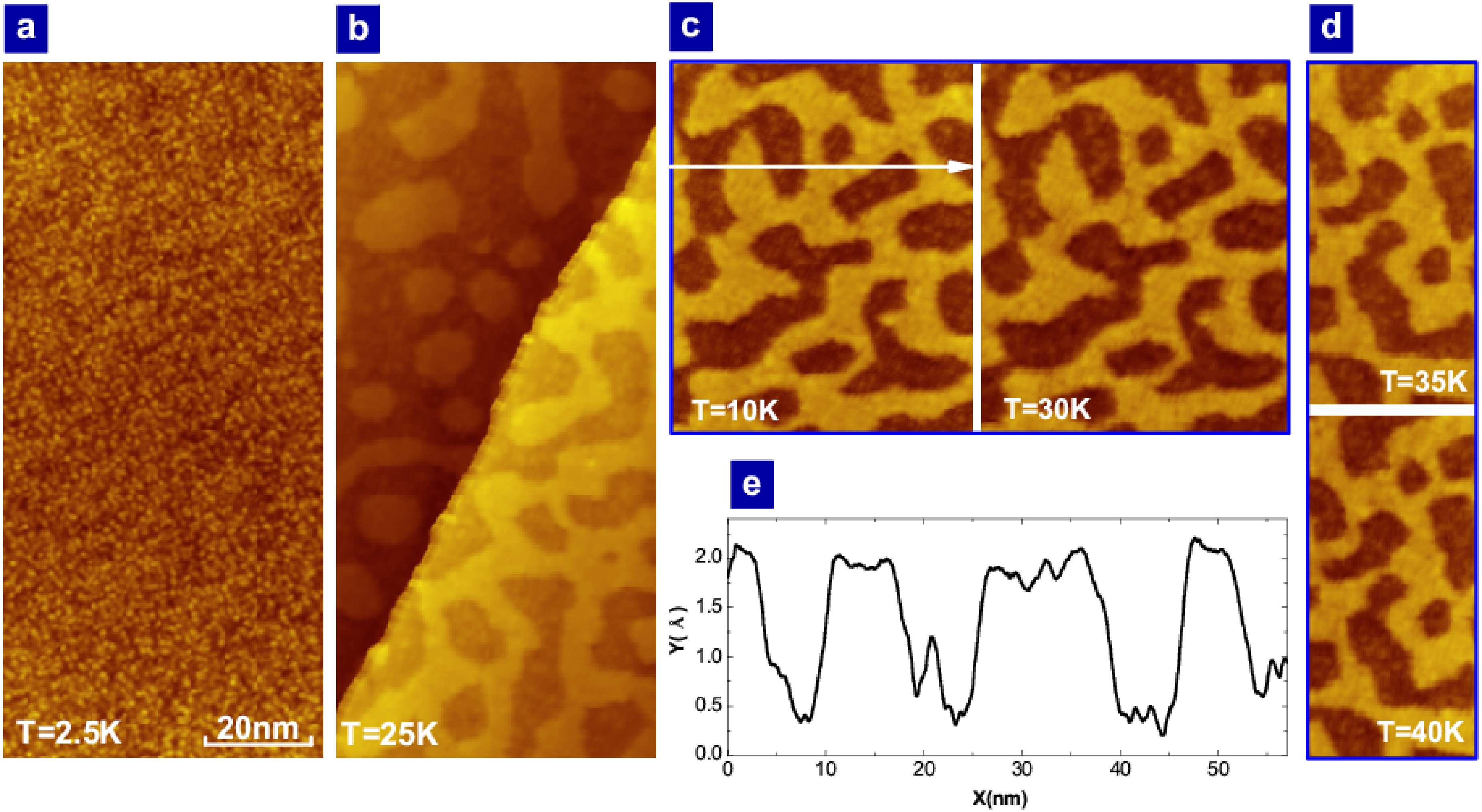
With the great help of Prof. Shuheng Pan



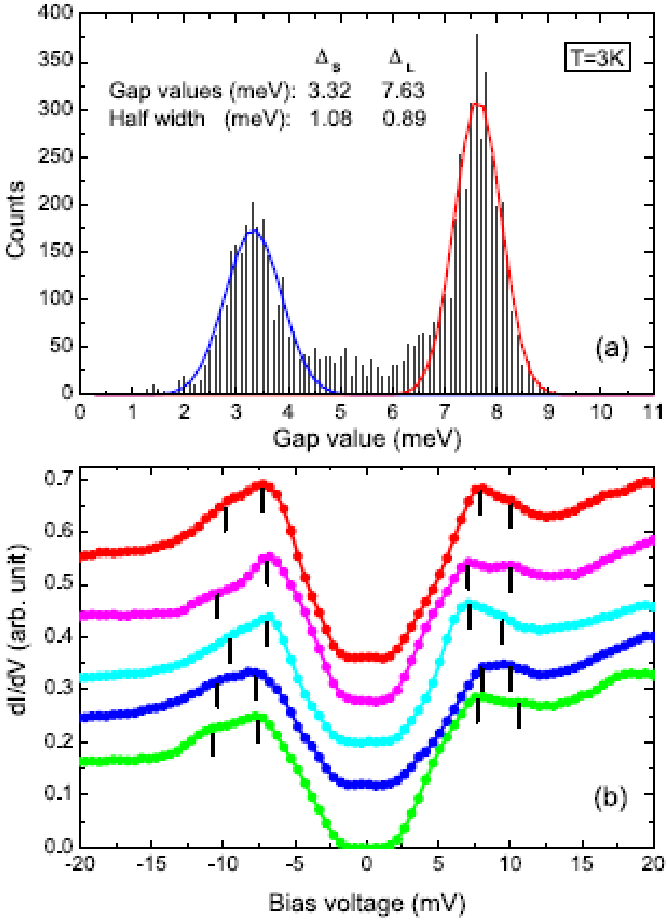


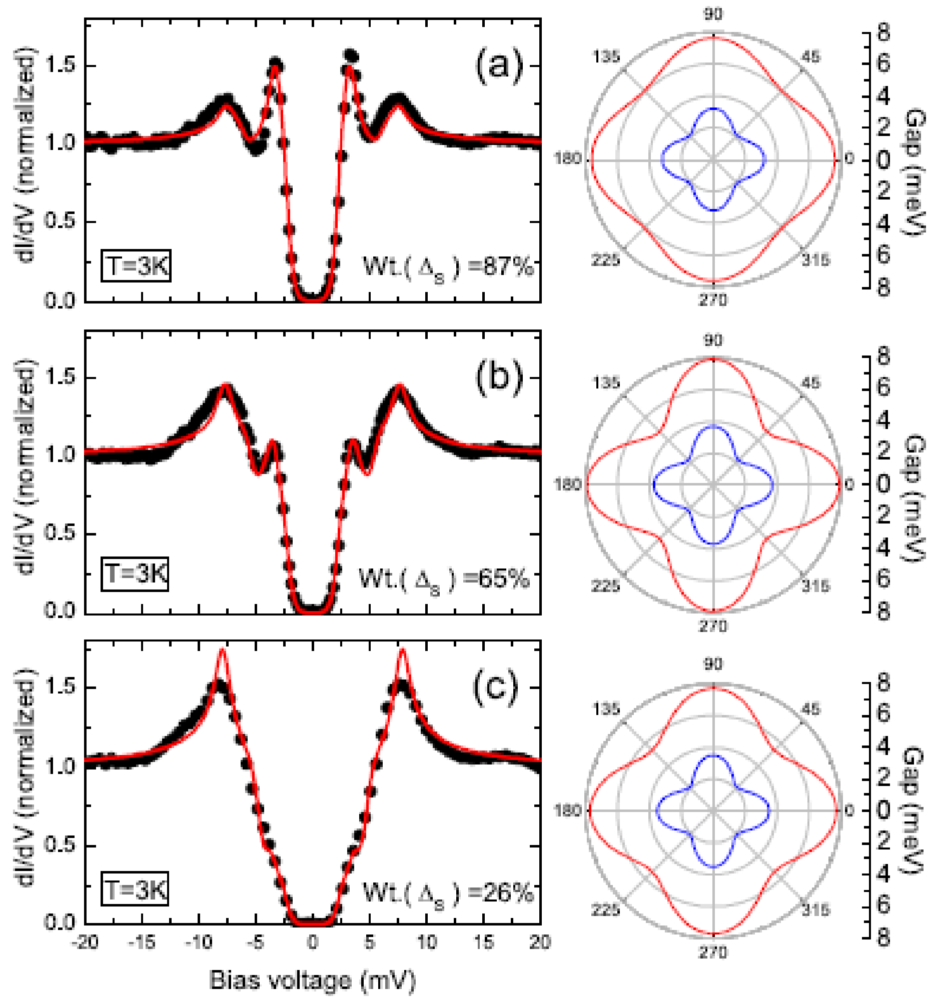
STM image of Bi-based HTS cuprates（700×700 Å²）

Low temperature cleavage leads to a stable surface state



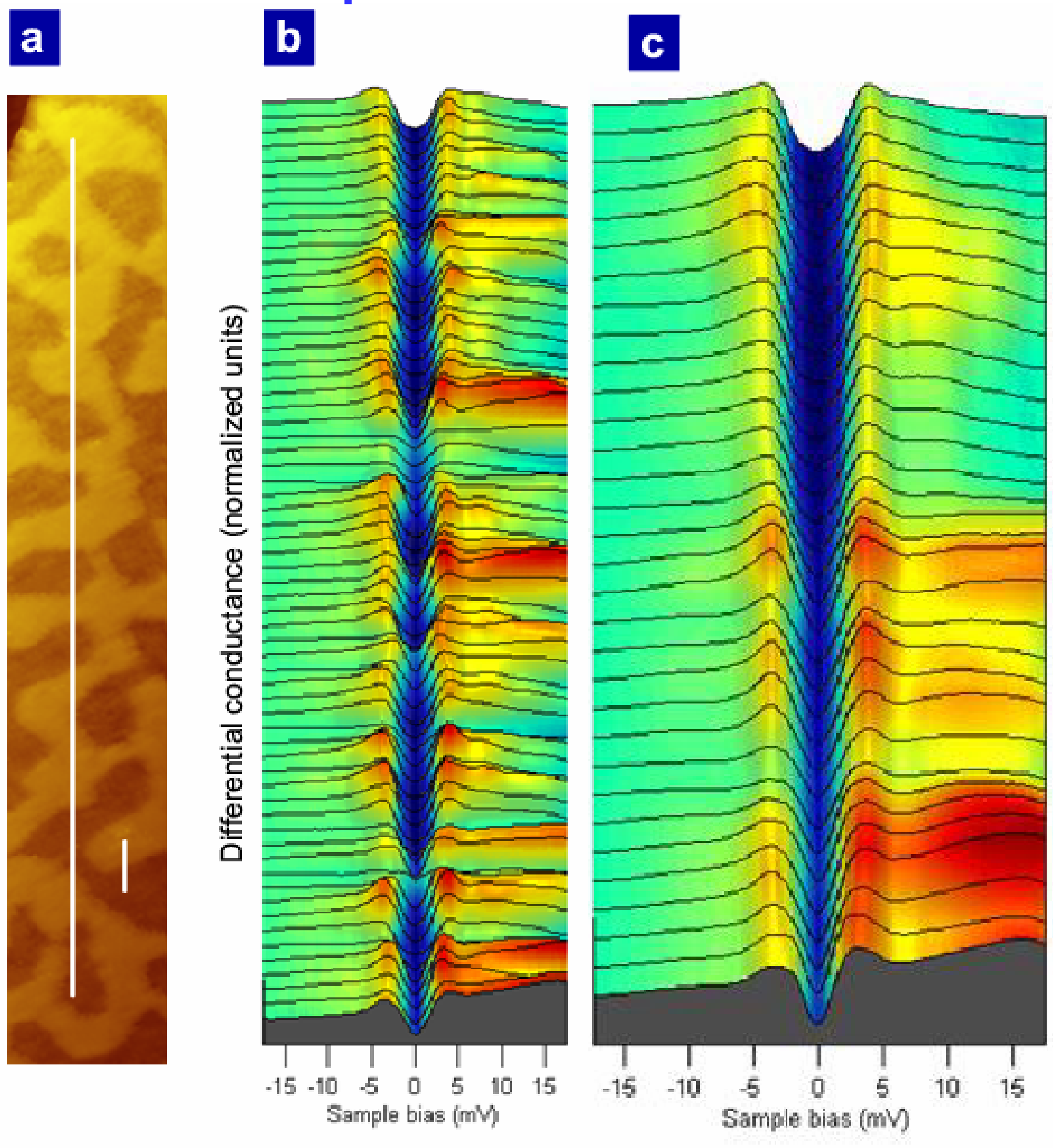
Multigap evidence from STM measurements in $Ba_{0.6}K_{0.4}Fe_2As_2$



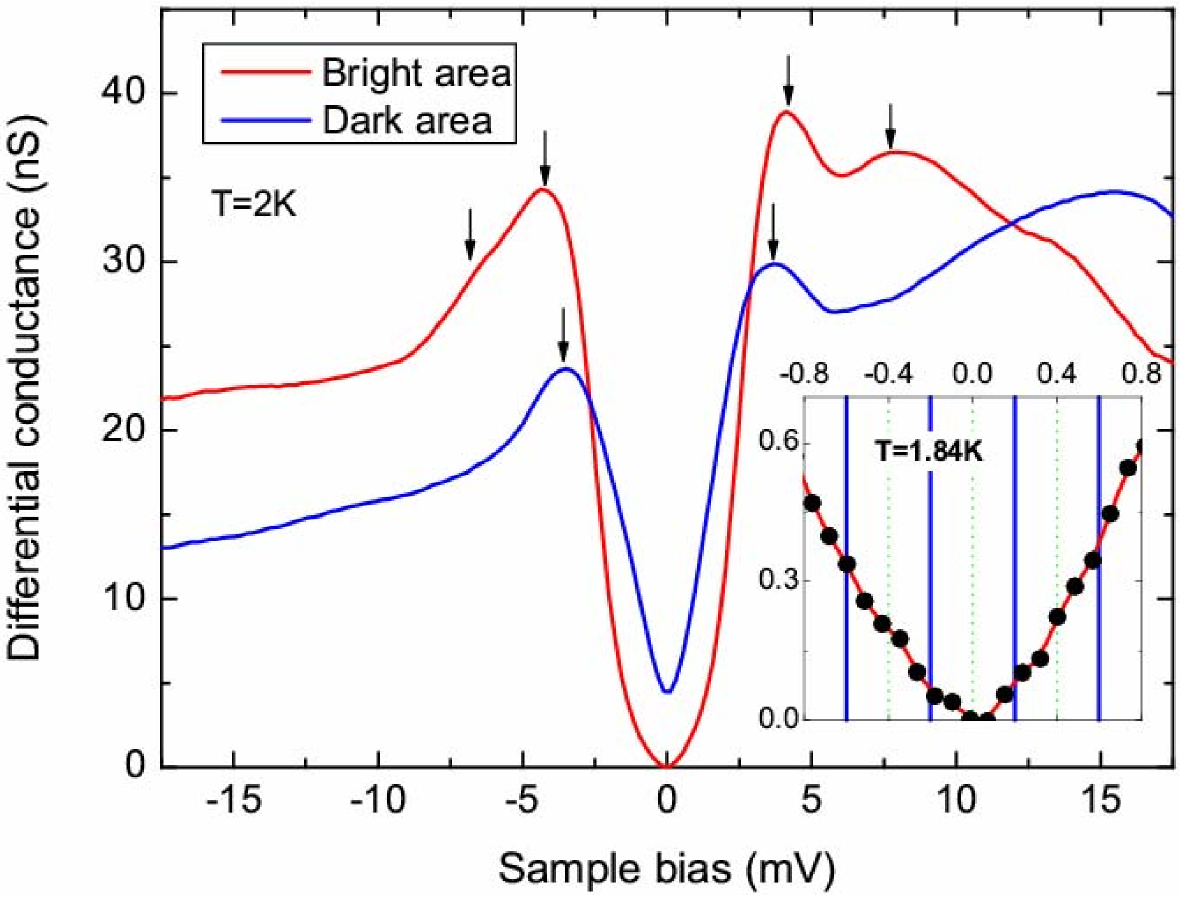


L. Shan et al,, PRB (R) 2011, in press.

Spatially resolved spectra in zero magnetic field at a temperature of 2K



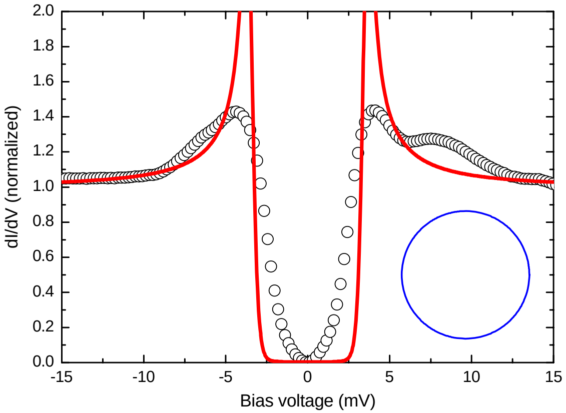
Comparison of two *dI/dV* spectra measured in bright and dark areas, respectively.



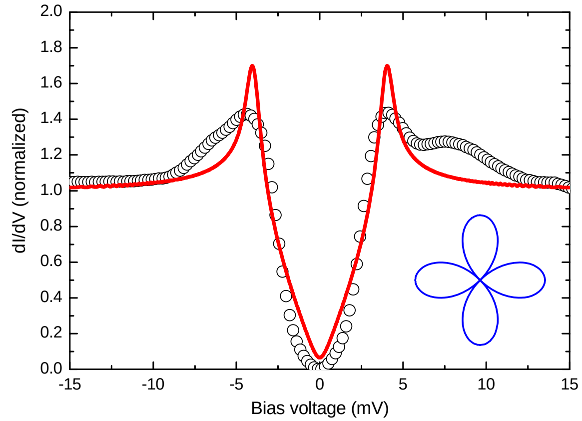
On this kind of stable surface, the spectrum is dominated by the 4 meV gap. The bottom is rounded, sometime touches zero!

Nodes or anisotropic gap?

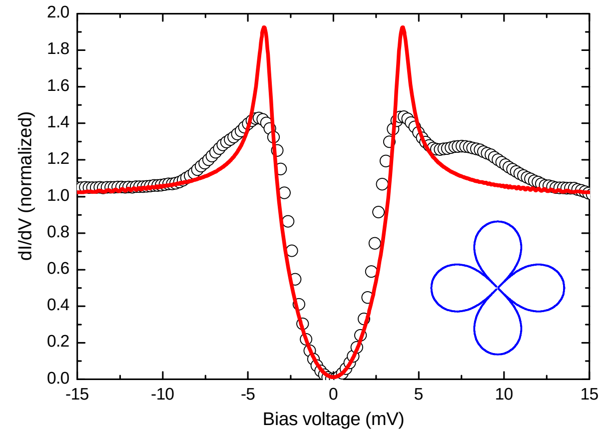
T=2K (site16-pt8)



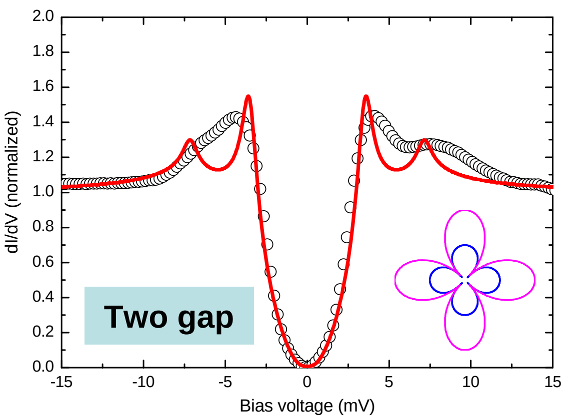
Δ =3.5 (meV)



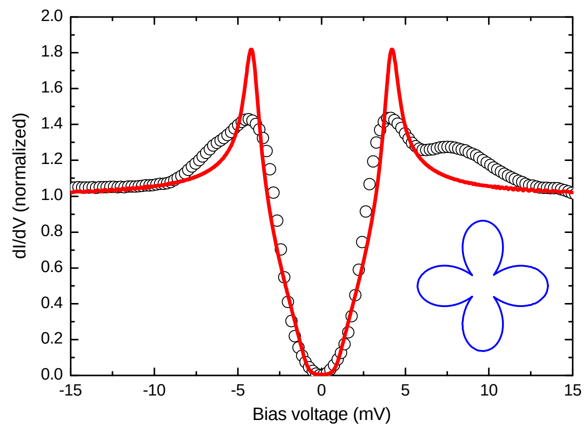
$\Delta(\theta)=4\cdot\mathrm{abs}[\cos(2\theta)]$ (meV)



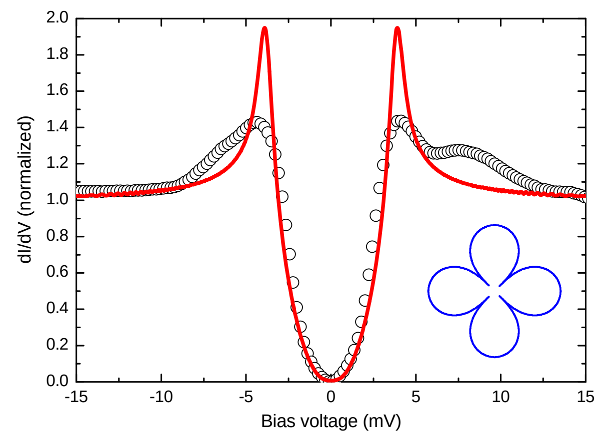
$\Delta(\theta)=4\cdot(\mathrm{abs}[\cos(2\theta)])^{0.5}$ (meV)



$\Delta1(\theta)=3.2\cdot((\mathrm{abs}[\cos(2\theta)])^{0.5}+0.1)$--75%
$\Delta2(\theta)=6.5\cdot(\mathrm{abs}[\cos(2\theta)]+0.1)$------25%



$\Delta(\theta)=3.2\cdot(\mathrm{abs}[\cos(2\theta)]+0.3)$



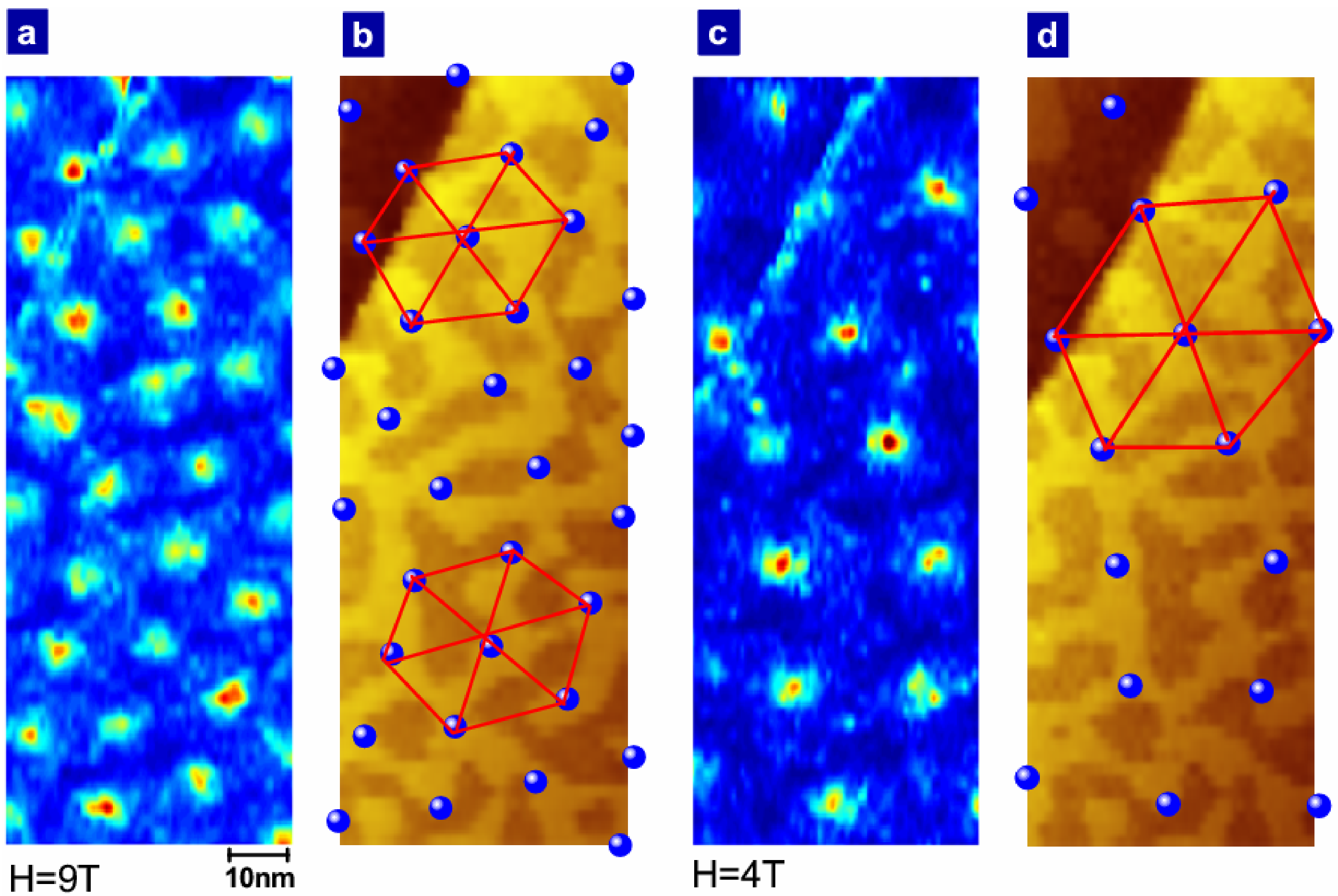
$\Delta(\theta)=3.5\cdot((\mathrm{abs}[\cos(2\theta)])^{0.5}+0.1)$

nature physics
ARTICLES
PUBLISHED ONLINE: XX MONTH XXXX | DOI:10.1038/NPHYS1908

Observation of ordered vortices with Andreev bound states in $Ba_{0.6}K_{0.4}Fe_2As_2$

Lei Shan[1]*, Yong-Lei Wang[1], Bing Shen[1], Bin Zeng[1], Yan Huang[1], Ang Li[2], Da Wang[3], Huan Yang[1], Cong Ren[1], Qiang-Hua Wang[3], Shuheng Pan[2] and Hai-Hu Wen[1,3]*

L. Shan et al. Nature Physics, In press.

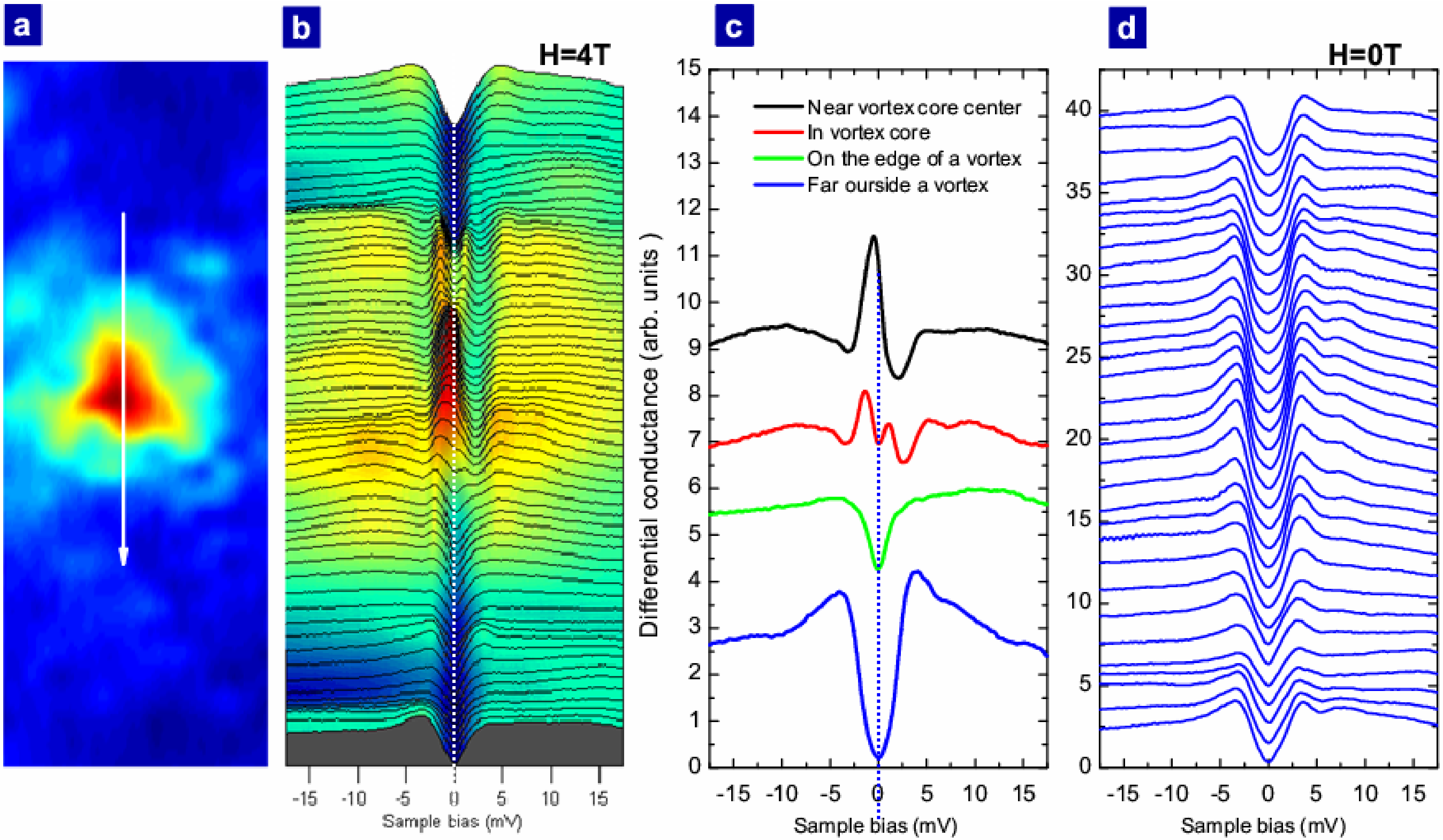


2.17×10^{-15} Wb

1.98×10^{-15} Wb

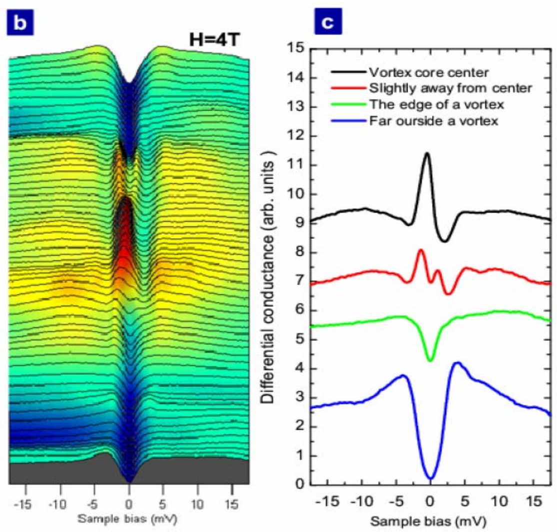
$$\Phi_0 = 2.07\times10^{-15}Wb$$

Andreev bound state within vortex cores is observed!

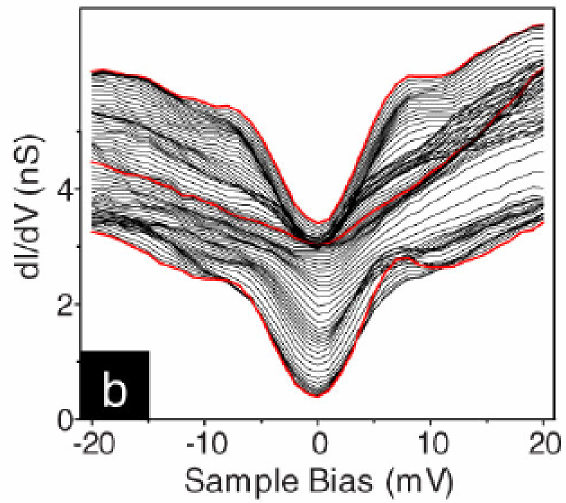


The Andreev bound states peaked at a negative bias, -0.5 meV.

Comparison between the vortex bound states in $Ba_{0.6}K_{0.4}Fe_2As_2$, $Ba(Fe_{1-x}Co_x)_2As_2$, cuprates and *2H-NbSe₂*



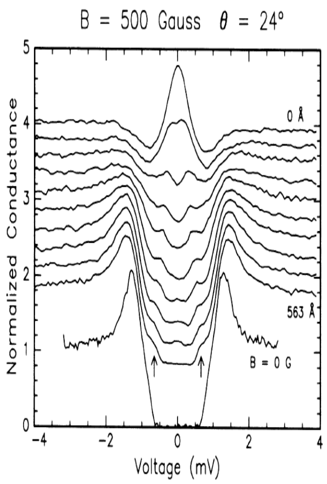
$Ba_{0.6}K_{0.4}Fe_2As_2$



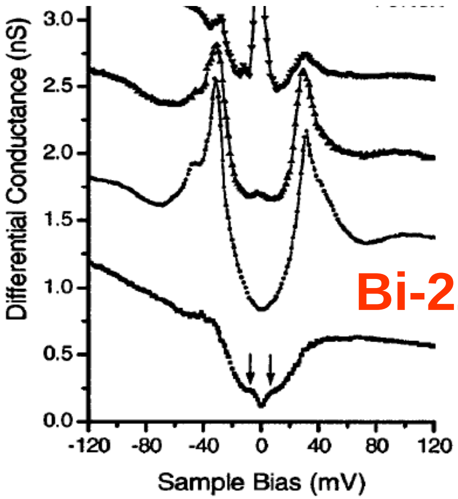
$Ba(Fe_{1-x}Co_x)_2As_2$

Origin of the difference:

- Fundamental difference of hole- and electron-doped samples
- Different scattering strength, Co-doping to the FeAs-planes



2H-NbSe2



Bi-2212

Different ground state:

- Correlation
- competing order
- itinerancy

F. H. Hess et al., PRL64, 2711(1990).

S. H. Pan et al., PRL85, 1536(2000).

Concluding Remarks

(1) **A fourfold oscillation of the low-T SH was observed in $FeSe_{0.45}Te_{0.55}$ with the in-plane magnetic field. This can be explained as highly anisotropic gaps with deep gap minima (along the Fe-Fe bond direction) on the electron-FS. This is consistent with the extended s-wave model with strong gap modulation on the electron pockets, as expected by the 5-orbital tight binding calculations.**

(2) Optimally Co-doped and K-doped Ba-122 do not show the fourfold oscillation, while overdoped $Ba(Fe_{1-x}Co_x)_2As_2$ shows some kind of oscillation. This is consistent with the doping dependence of the point contact tunneling data and the field dependence of the SH coefficient. Our data support the picture that the electron doping induces stronger gap anisotropy in the electron pocket.

(3) STM measurements on $Ba_{0.6}K_{0.4}Fe_2As_2$

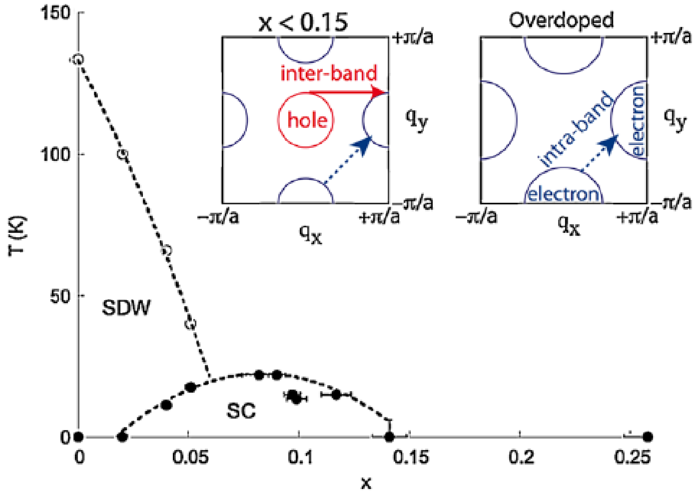
- ***Well ordered vortex lattice with a distorted triangular structure***
- ***Rounded or flat bottom of spectrum may suggest the nodeless gap but with anisotropy in the optimally doped BaK-122.*** **The tunneling spectrum generally exhibit the two gap feature. The** ***Andreev bound states (peaked at a negative bias -0.5 mV) within vortex cores were observed, in sharp contrast to Co-doped FeAs122.***

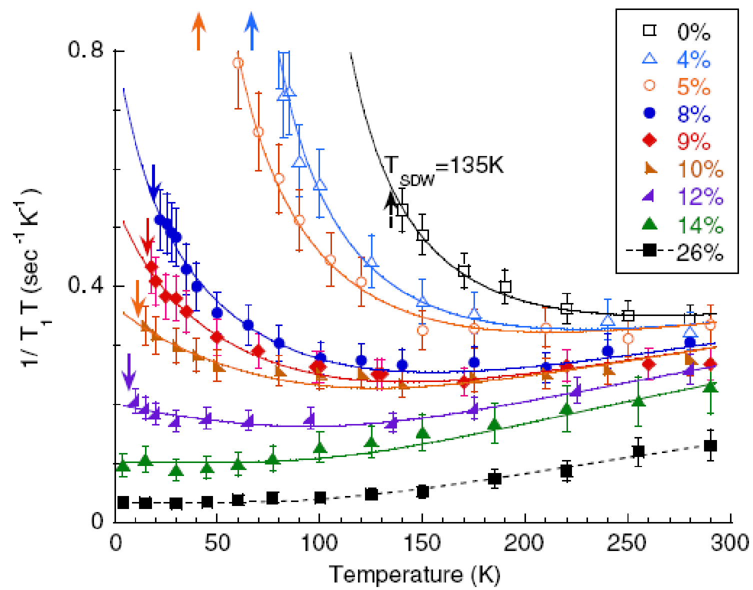
Thank you for your attention

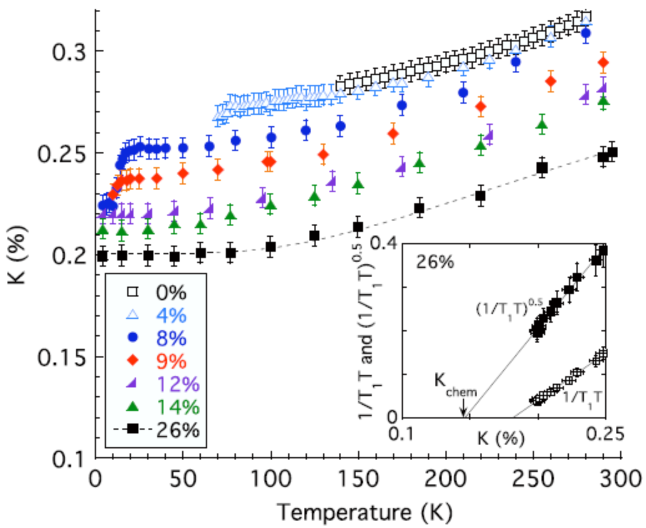
and happy new year!

Contrasting Spin Dynamics between Underdoped and Overdoped $Ba(Fe_{1-x}Co_x)_2As_2$

F. L. Ning,[1] K. Ahilan,[1] T. Imai,[1,2] A. S. Sefat,[3] M. A. McGuire,[3] B. C. Sales,[3] D. Mandrus,[3] P. Cheng,[4] B. Shen,[4] and H.-H Wen[4]





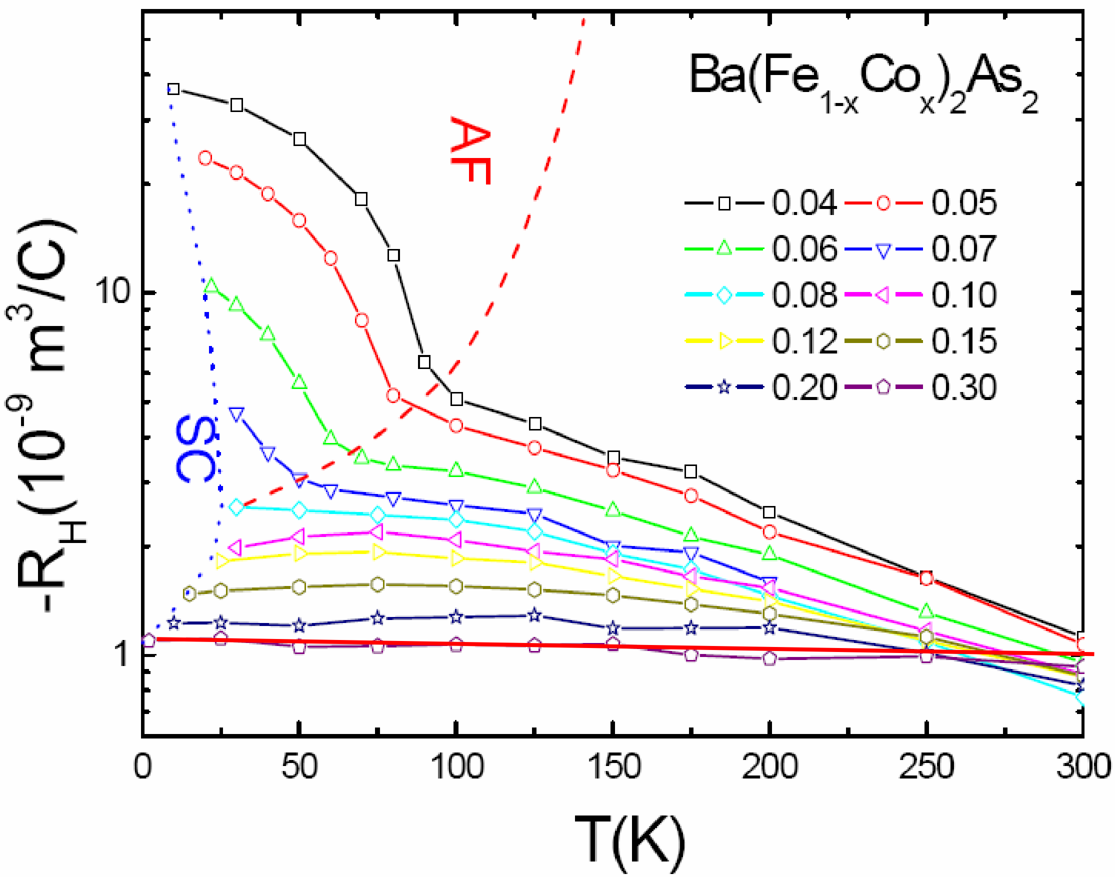


$$1/T_1T \propto \sum_q \left|A_{hf}(\vec{q})\right|^2 \chi''(\vec{q}, f)/f$$

$1/T_1T$ measures the q-intergral of the imaginary part of the dynamical spin susceptibility, reflecting the summation of all different q-modes of spin fluctuations.

F. L. Ning et al., PRL104, 037001(2010)

Superconductivity relies crucially on the multiband effect!



$$R_H = \frac{\sigma_e \mu_e + \sigma_h \mu_h}{(\sigma_e + \sigma_h)^2}$$

$$\sigma_i = n_i e^2 \tau_i / m_i$$

$$\mu_i = e_i \tau_i / m_i$$

Lei Fang et al., Phys.Rev.B80, 140508 (R) (2009)

1. **Underdoped region: AF and SC compete for DOS.**
2. **The strong temperature dependence in high-T is induced by multiband effect and together with novel scattering. Gradually one band dominates in the overdoped region, then the SC vanishes!**