Important aspects related to the pairing mechanism of iron-based superconductors revealed by ARPES

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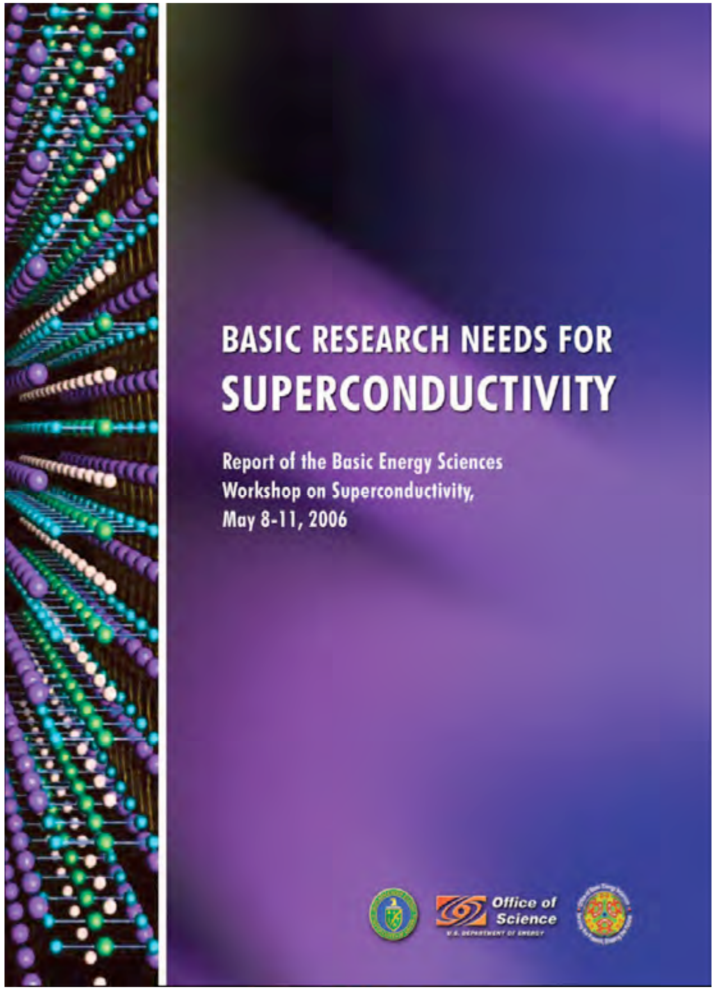
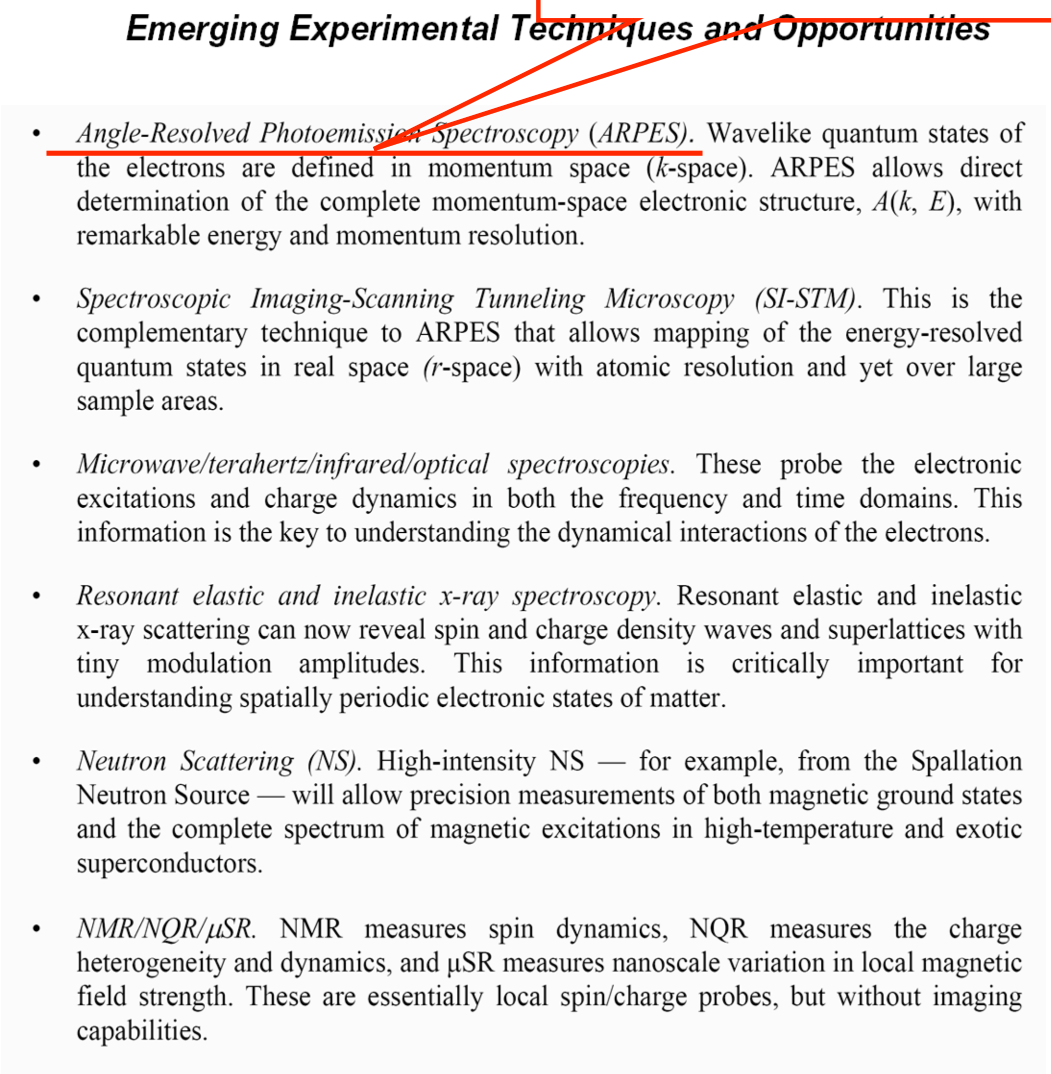
美国能源部报告



BASIC RESEARCH NEEDS FOR
SUPERCONDUCTIVITY

Report of the Basic Energy Sciences
Workshop on Superconductivity,
May 8-11, 2006

角分辨光电子能谱



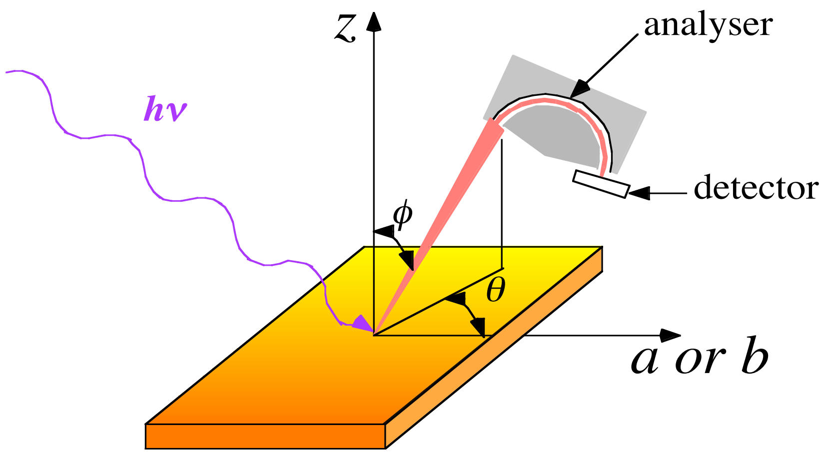
Emerging Experimental Techniques and Opportunities

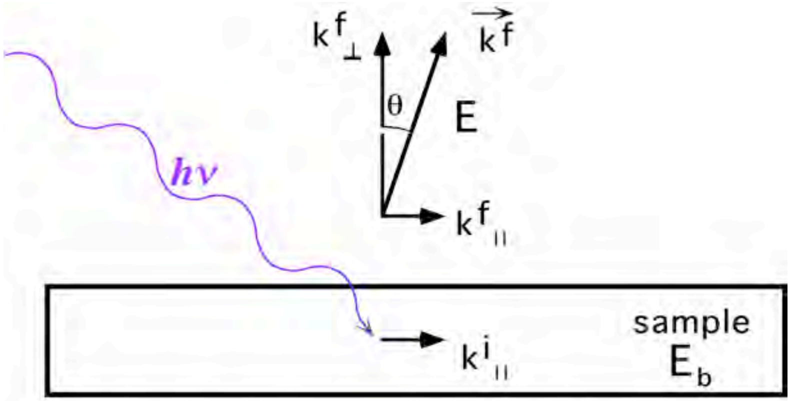
- *Angle-Resolved Photoemission Spectroscopy (ARPES)*. Wavelike quantum states of the electrons are defined in momentum space (*k*-space). ARPES allows direct determination of the complete momentum-space electronic structure, *A*(*k*, *E*), with remarkable energy and momentum resolution.
- *Spectroscopic Imaging-Scanning Tunneling Microscopy (SI-STM)*. This is the complementary technique to ARPES that allows mapping of the energy-resolved quantum states in real space (*r*-space) with atomic resolution and yet over large sample areas.
- *Microwave/terahertz/infrared/optical spectroscopies*. These probe the electronic excitations and charge dynamics in both the frequency and time domains. This information is the key to understanding the dynamical interactions of the electrons.
- *Resonant elastic and inelastic x-ray spectroscopy*. Resonant elastic and inelastic x-ray scattering can now reveal spin and charge density waves and superlattices with tiny modulation amplitudes. This information is critically important for understanding spatially periodic electronic states of matter.
- *Neutron Scattering (NS)*. High-intensity NS — for example, from the Spallation Neutron Source — will allow precision measurements of both magnetic ground states and the complete spectrum of magnetic excitations in high-temperature and exotic superconductors.
- *NMR/NQR/μSR*. NMR measures spin dynamics, NQR measures the charge heterogeneity and dynamics, and μSR measures nanoscale variation in local magnetic field strength. These are essentially local spin/charge probes, but without imaging capabilities.

材料科学：

角分辨光电子能谱—研究新奇量子现象的首选实验手段。

ARPES maps band structure and Fermi surface

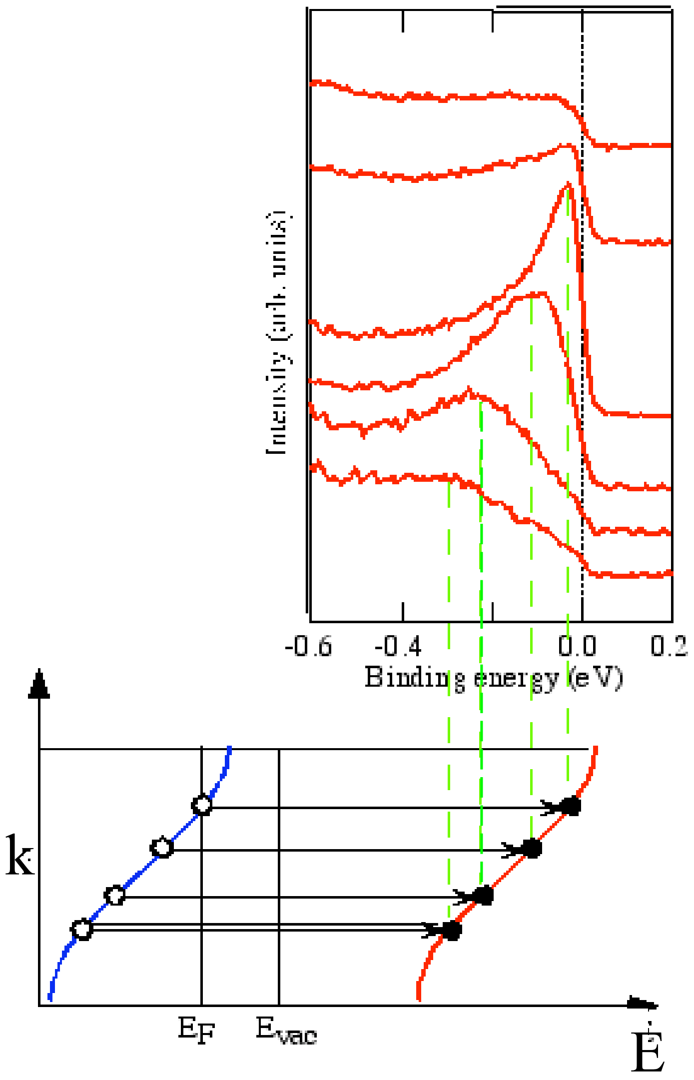




$E = h\nu - W - E_b$

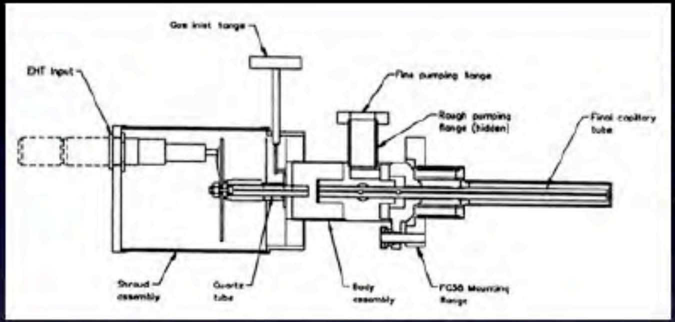
$k^f_\parallel = k^i_\parallel$

$$k^f_\parallel = \sqrt{\frac{2mE}{\hbar^2}}\ \sin\ \theta$$



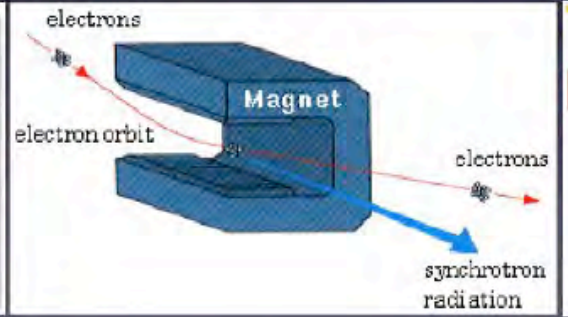
Photon Sources

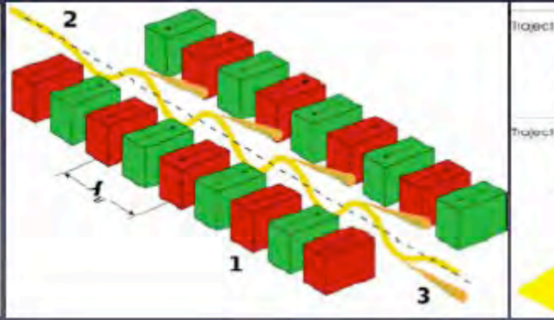
Laboratory source

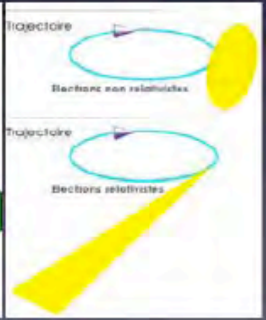


- rare gas discharge lamps
- x-ray tubes
- 10^{14} photons/second

Synchrotron source

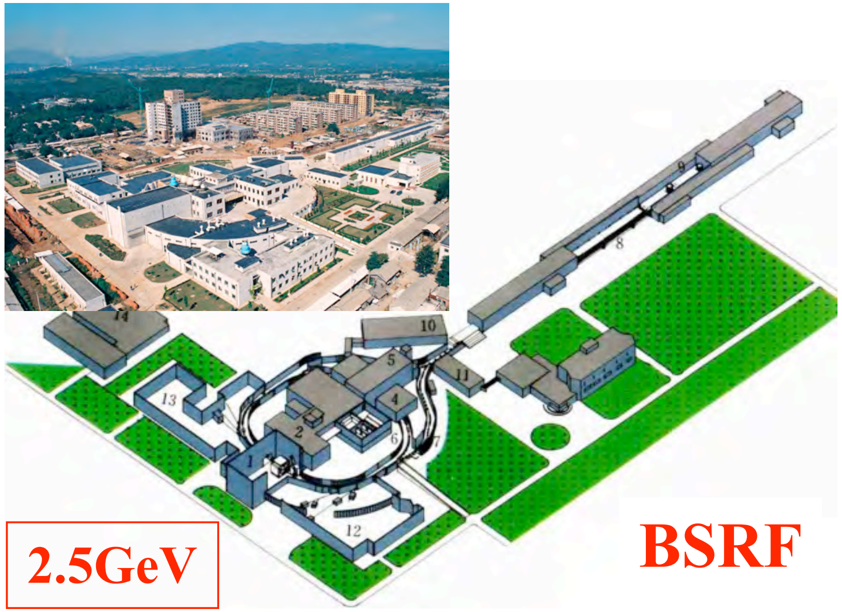






- 10^{15} photons/second

中国大陆的三个同步辐射装置



2.5GeV

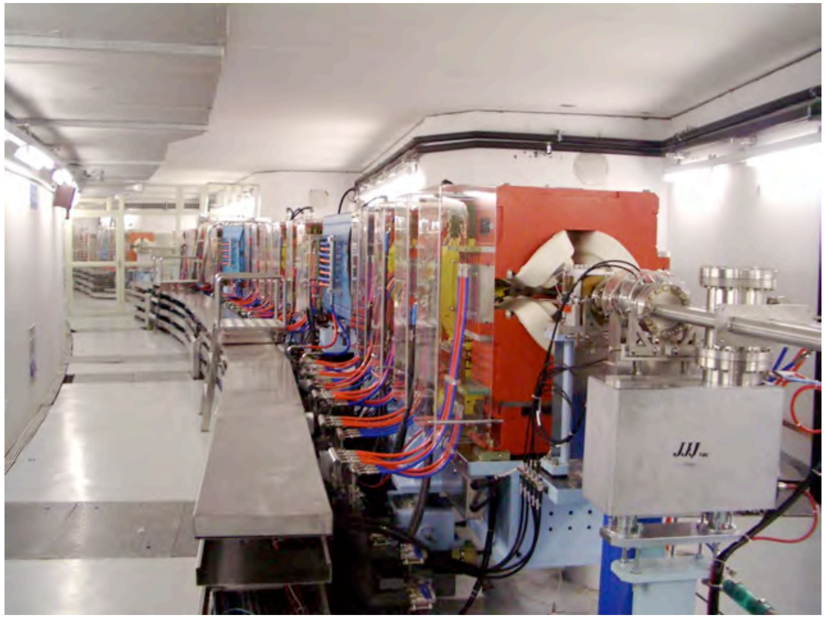
BSRF

800MeV

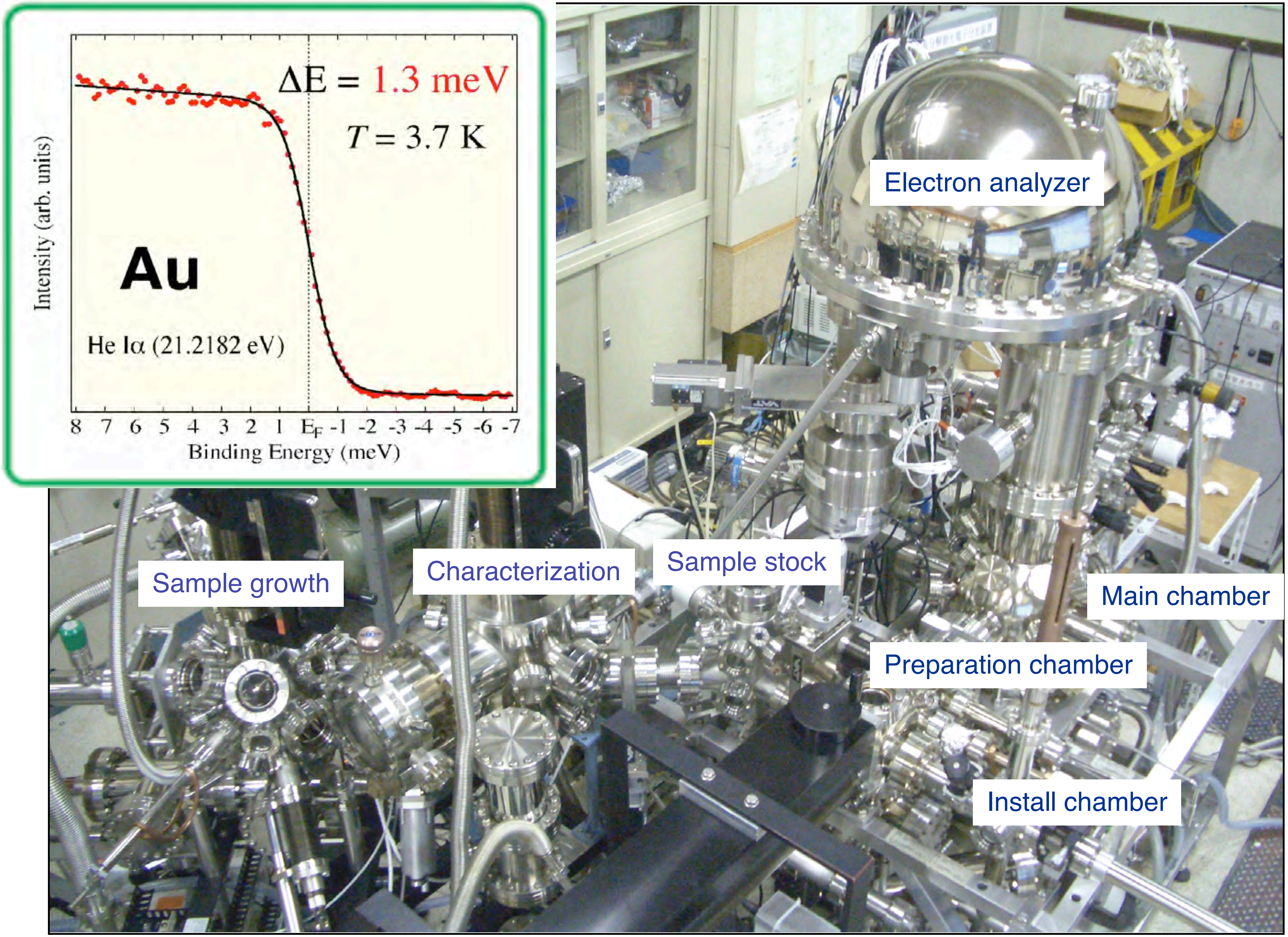
SSRF

3.5GeV

上海光源 (2009年4月验收）

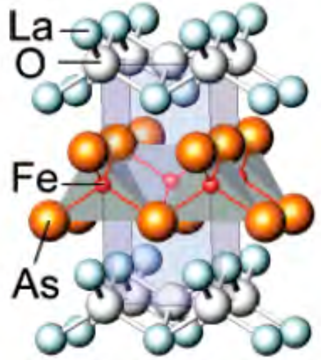


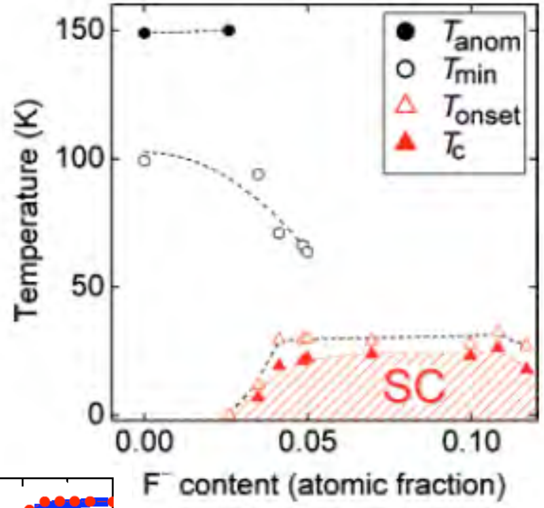
Ultrahigh-resolution ARPES system



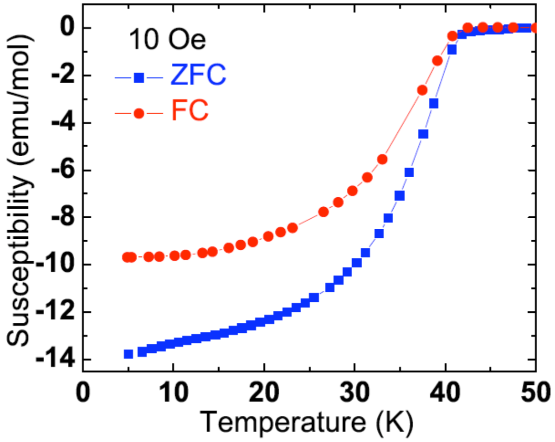
The new iron-based high-T_c (up to 56K) superconductors

$LaFeAsO_{1-x}F_x$ (T_c = 26K)
H. Hosono, Japan
Feb. 23, 2008

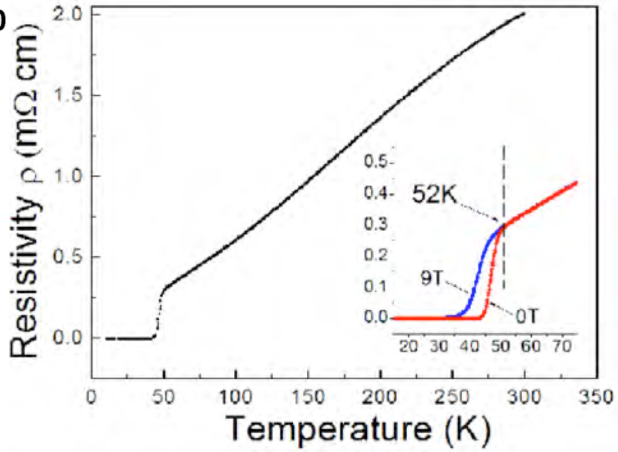




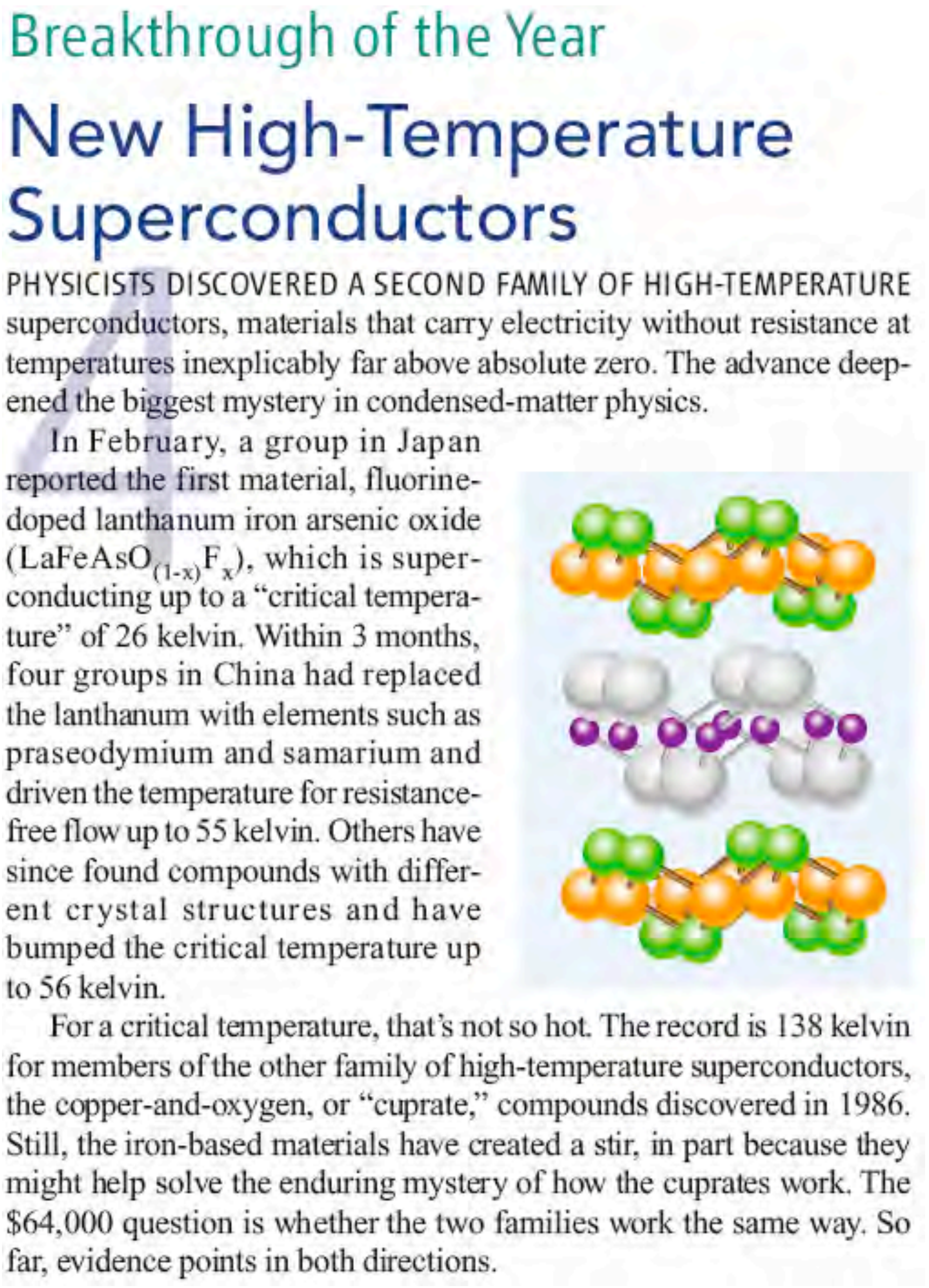
$SmFeAsO_{1-x}F_x$ (T_c = 43K)
X.H. Chen, USTC, China
$CeFeAsO_{1-x}F_x$(T_c = 41K)
N.L. Wang, IOP, China
March 25-26, 2008



$PrFeAsO_{1-x}F_x$ (T_c = 52K)
Z.X. Zhao, IOP, China
March 28, 2008



科学杂志：2008年十大突破之一



Breakthrough of the Year

New High-Temperature Superconductors

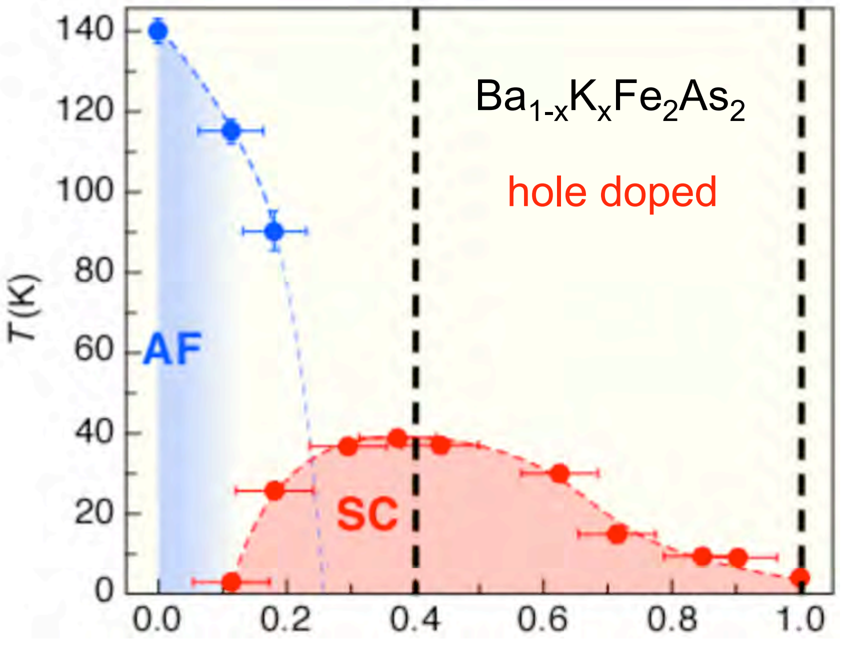
PHYSICISTS DISCOVERED A SECOND FAMILY OF HIGH-TEMPERATURE superconductors, materials that carry electricity without resistance at temperatures inexplicably far above absolute zero. The advance deepened the biggest mystery in condensed-matter physics.

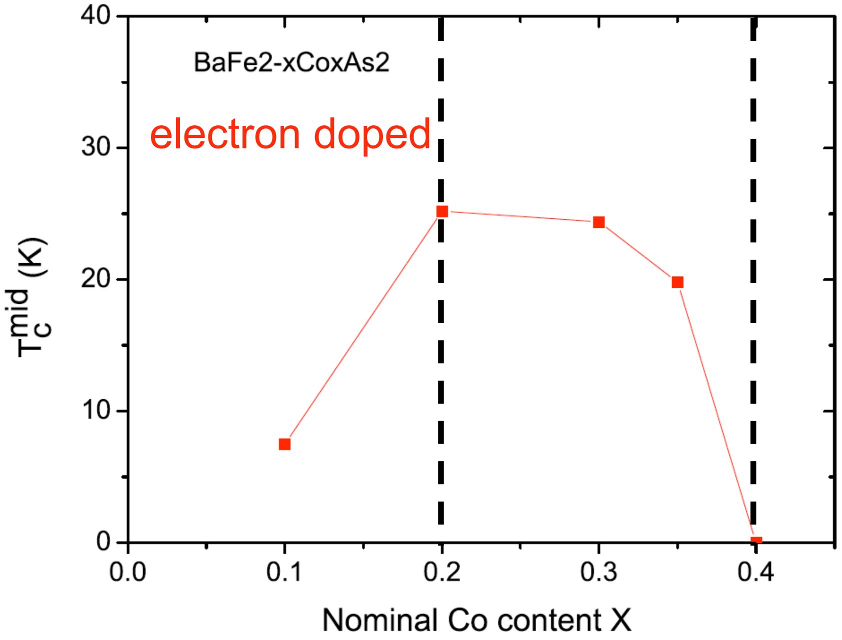
In February, a group in Japan reported the first material, fluorine-doped lanthanum iron arsenic oxide ($LaFeAsO_{(1-x)}F_x$), which is superconducting up to a “critical temperature” of 26 kelvin. Within 3 months, four groups in China had replaced the lanthanum with elements such as praseodymium and samarium and driven the temperature for resistance-free flow up to 55 kelvin. Others have since found compounds with different crystal structures and have bumped the critical temperature up to 56 kelvin.

For a critical temperature, that’s not so hot. The record is 138 kelvin for members of the other family of high-temperature superconductors, the copper-and-oxygen, or “cuprate,” compounds discovered in 1986. Still, the iron-based materials have created a stir, in part because they might help solve the enduring mystery of how the cuprates work. The $64,000 question is whether the two families work the same way. So far, evidence points in both directions.

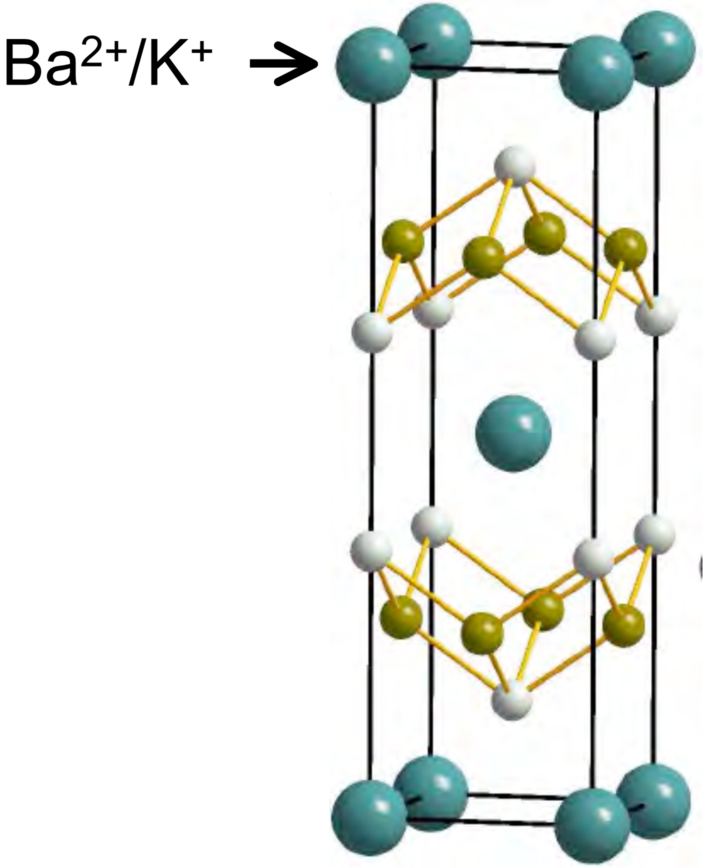
Phase diagram of “122” compounds

$BaFe_2As_2$



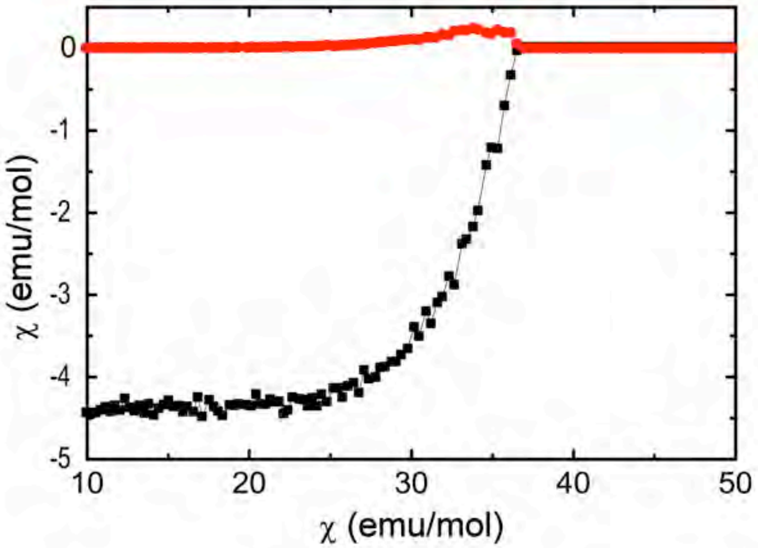


Optimally hole doped samples

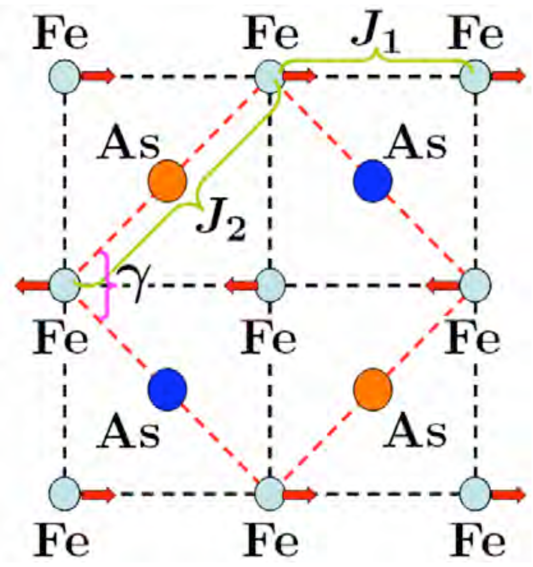


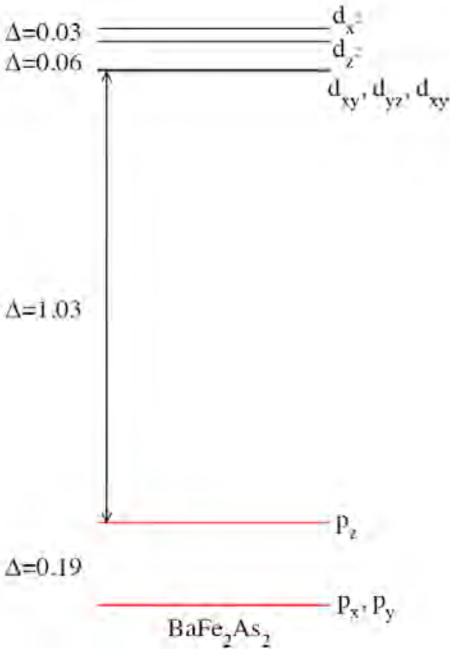
$Ba_{0.6}K_{0.4}Fe_2As_2$

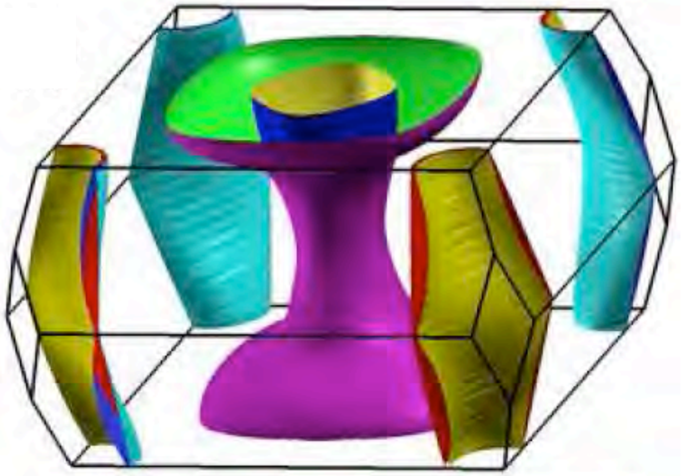
$T_c = 37$ K

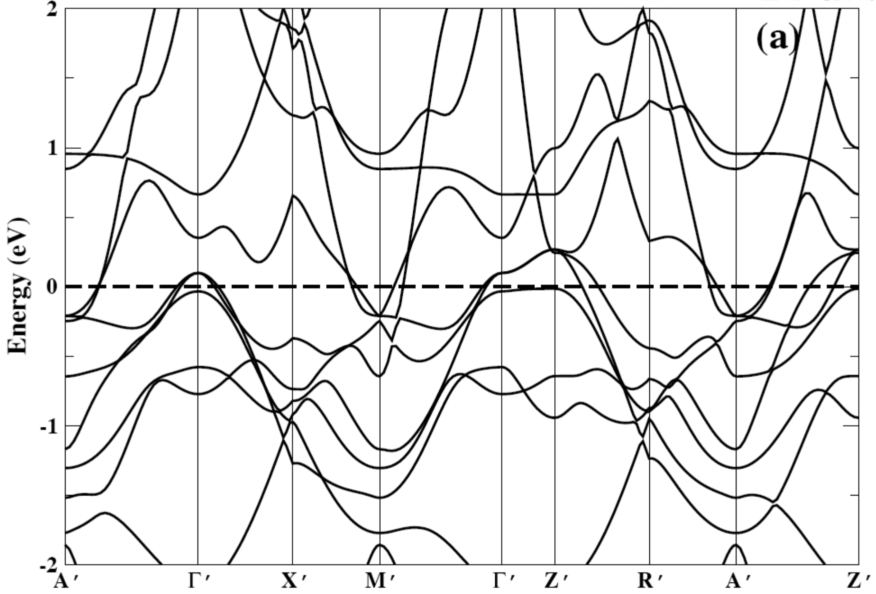


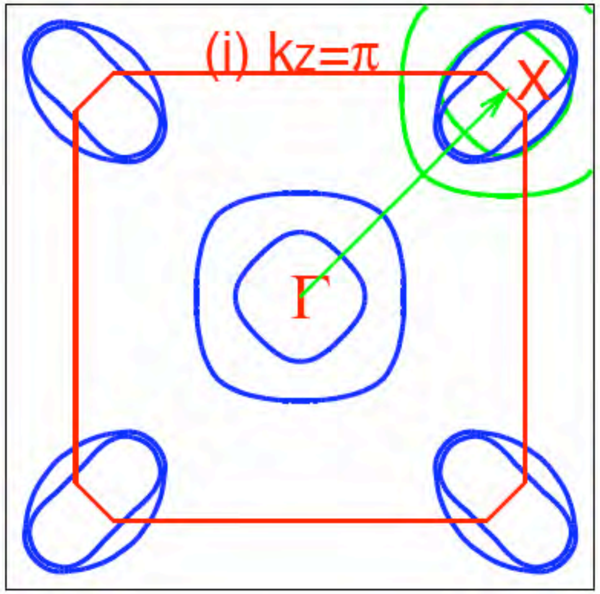
Calculated band structure and Fermi surface



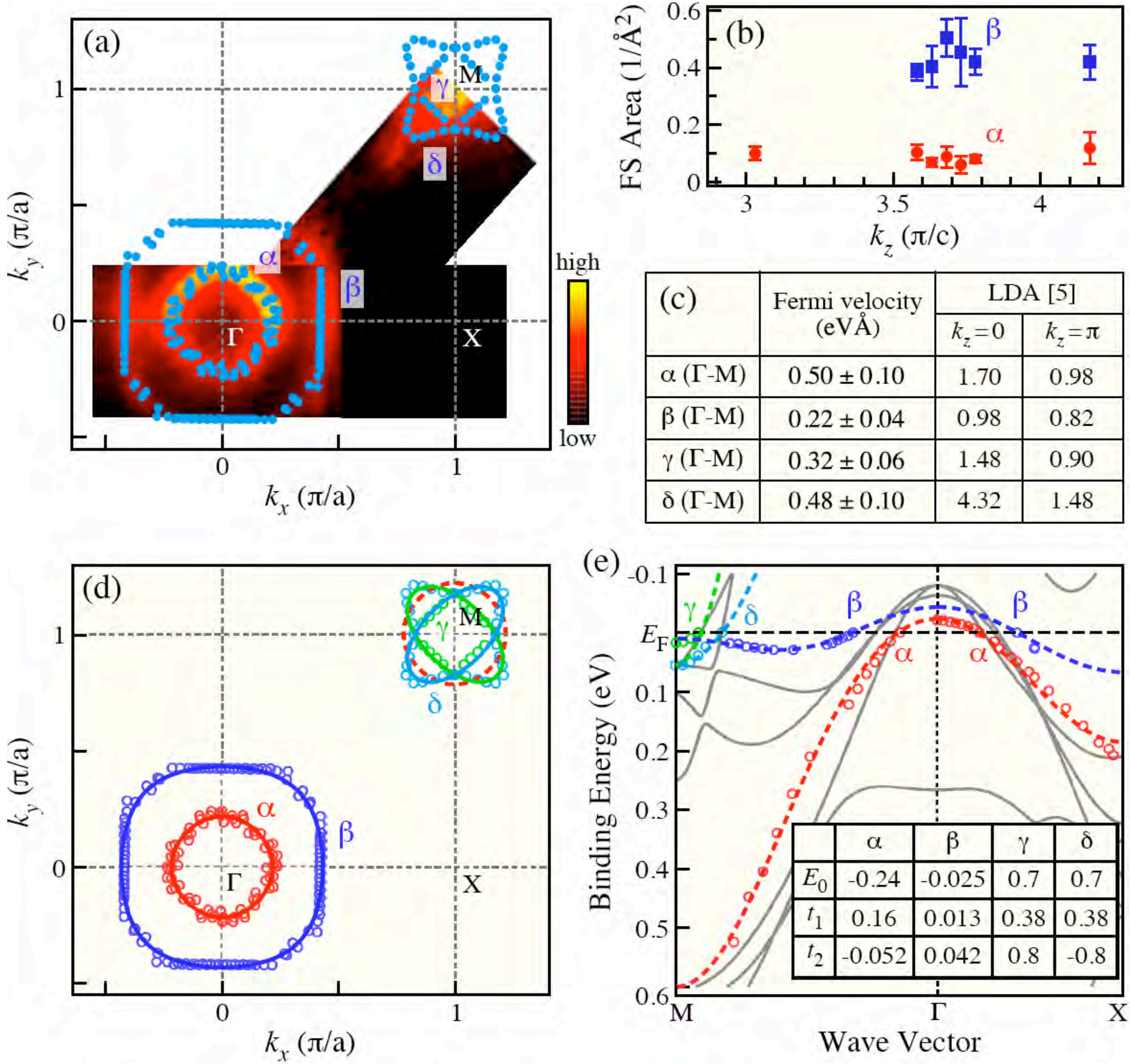








A complete picture of band structure and FS



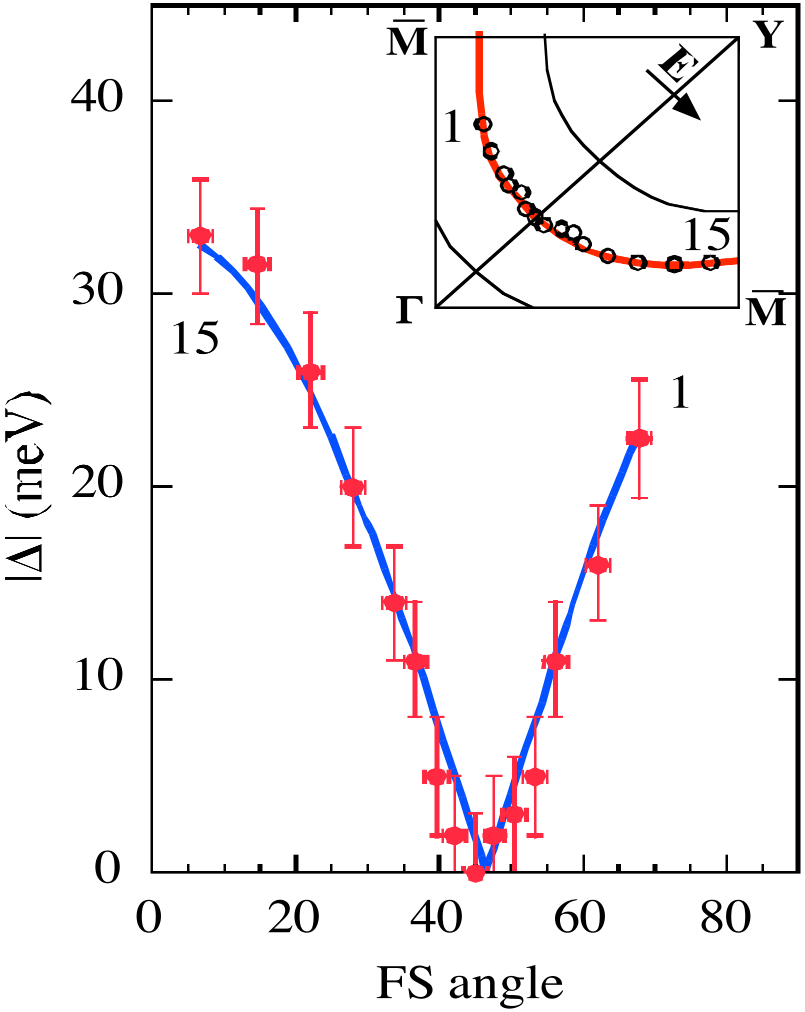
(c)	Fermi velocity (eVÅ)	LDA [5]	
		$k_z=0$	$k_z=\pi$
α (Γ-M)	0.50 ± 0.10	1.70	0.98
β (Γ-M)	0.22 ± 0.04	0.98	0.82
γ (Γ-M)	0.32 ± 0.06	1.48	0.90
δ (Γ-M)	0.48 ± 0.10	4.32	1.48

	α	β	γ	δ
E_0	-0.24	-0.025	0.7	0.7
t_1	0.16	0.013	0.38	0.38
t_2	-0.052	0.042	0.8	-0.8

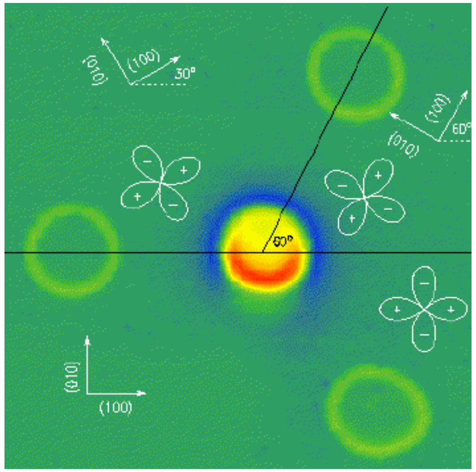
H. Ding *et al*.
arXiv: 0812.0534

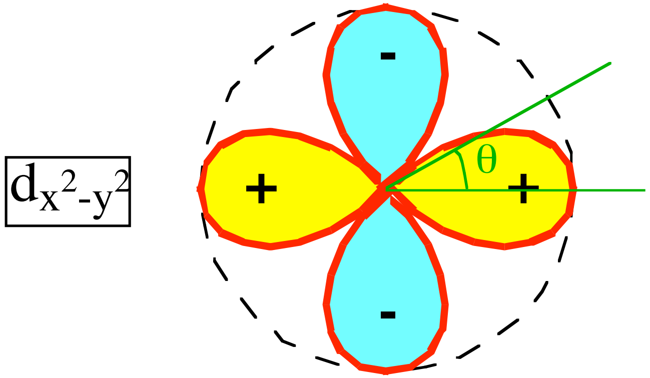
SC gap symmetry is crucial in understanding the SC mechanism

d-wave in cuprates

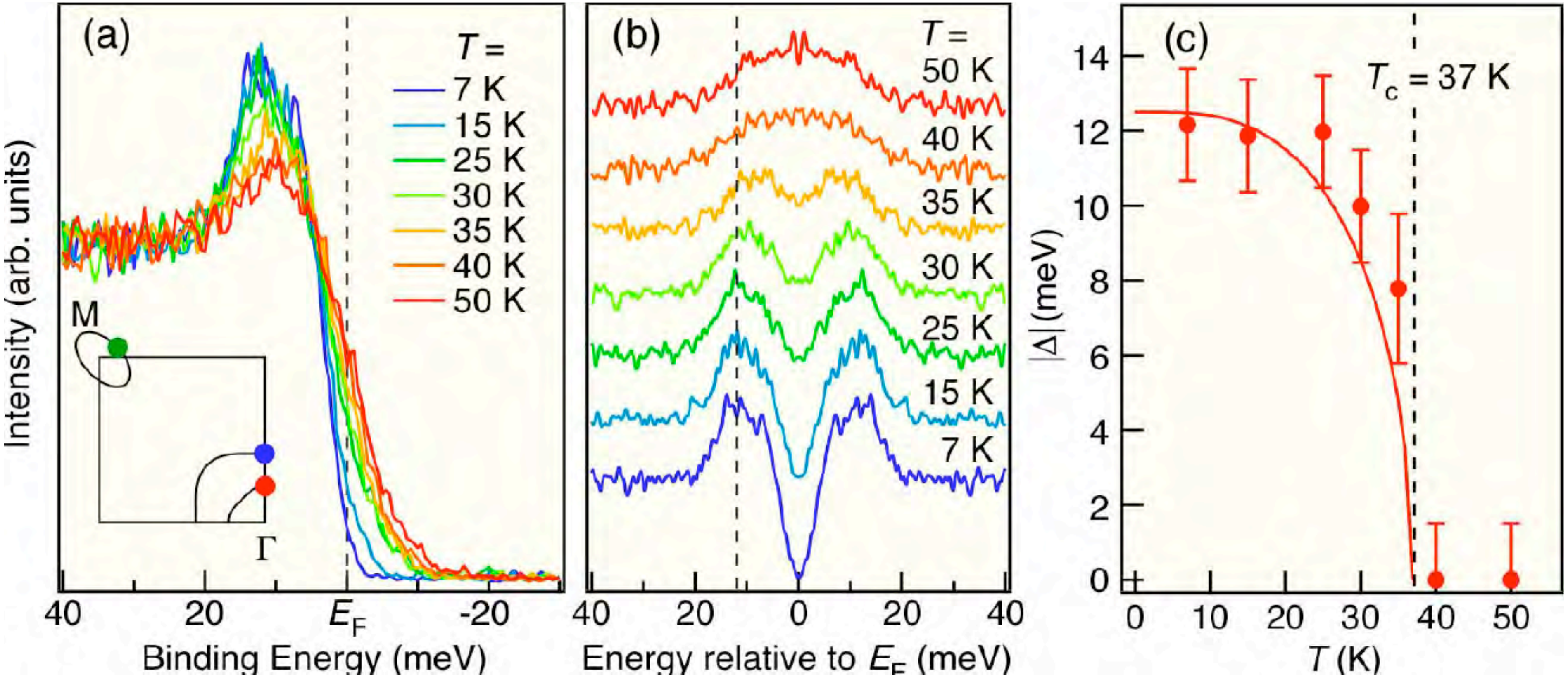


Half-Integer Flux Quantum Effect



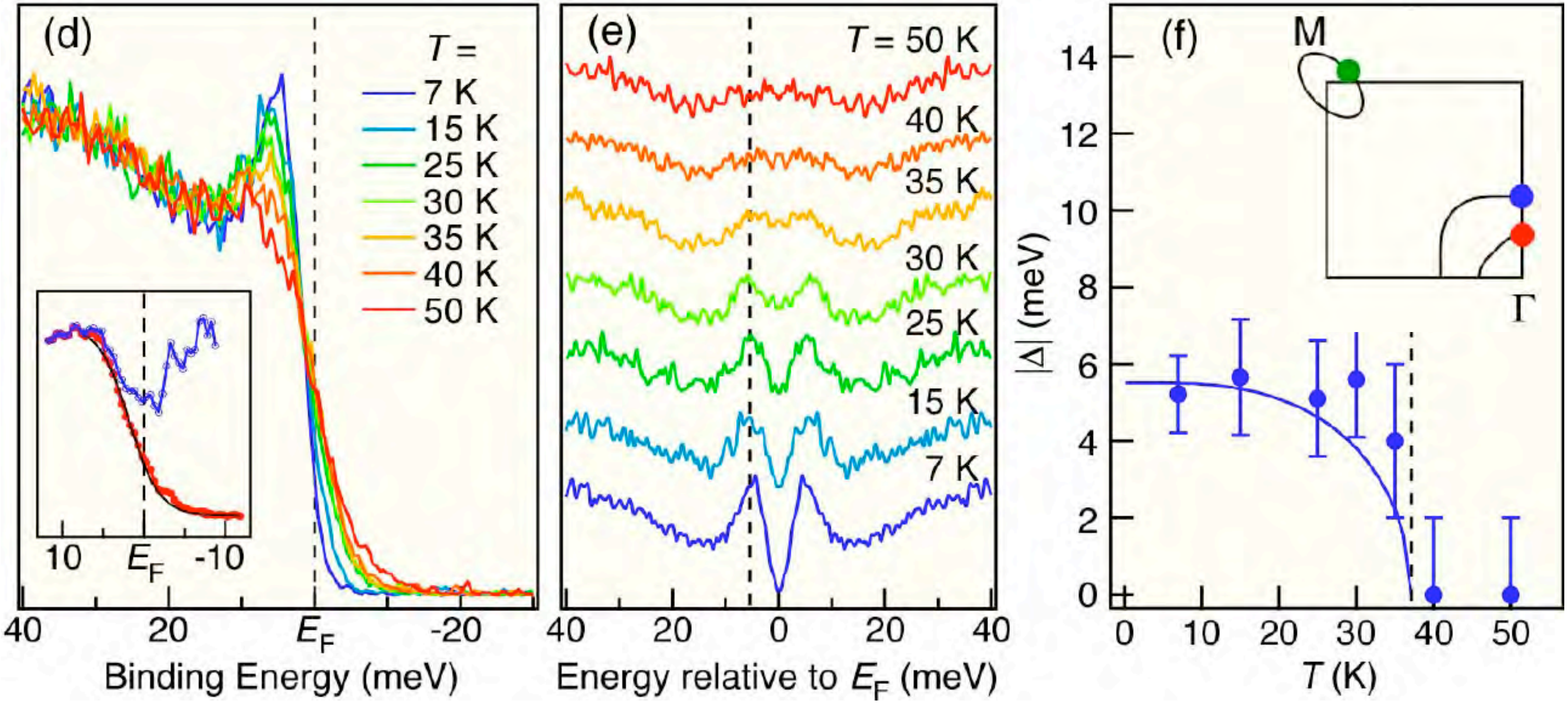


T-dependence of the SC gap at the α FS



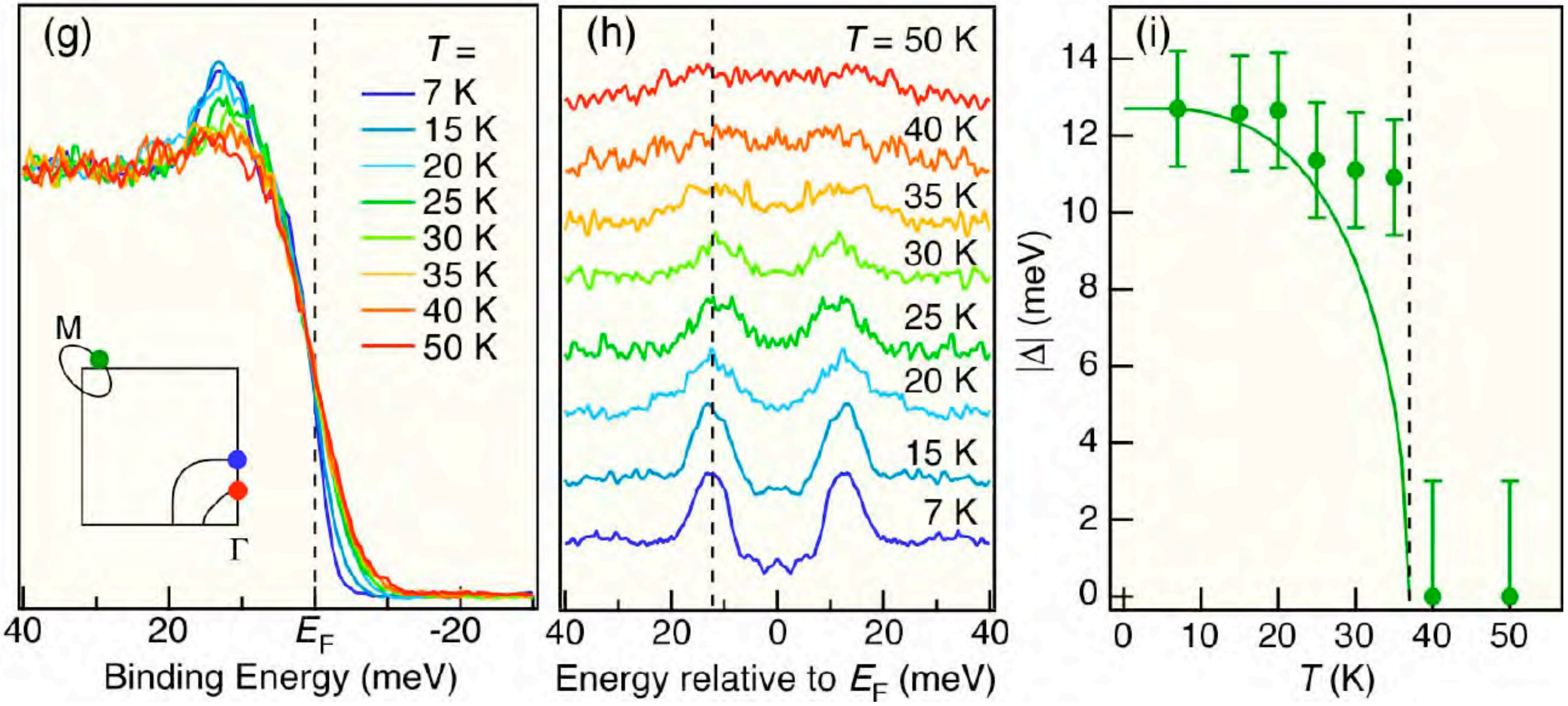
$\boxed{2\Delta/T_c \sim 7}$

T-dependence of the SC gap at the β FS



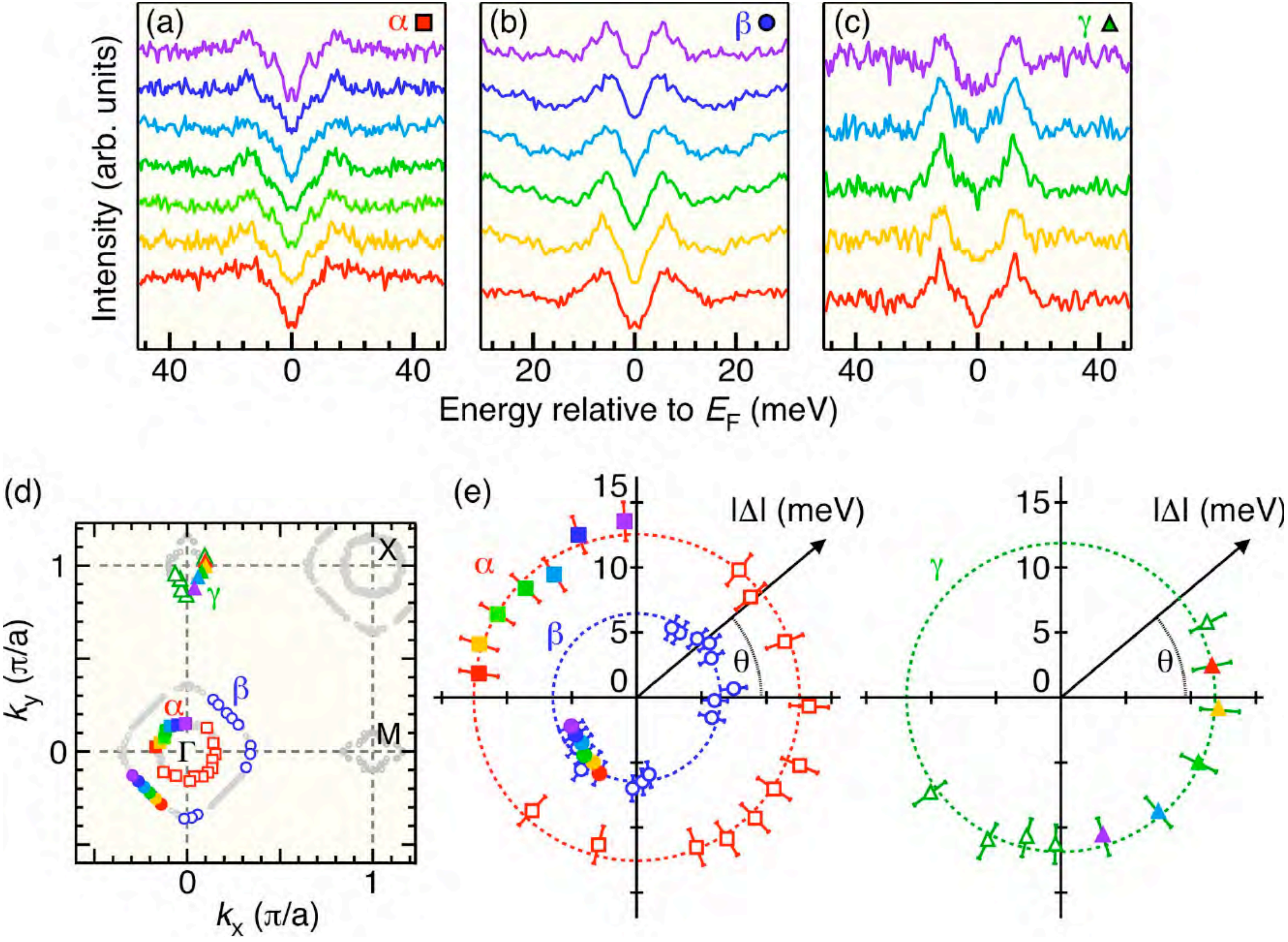
$\boxed{2\Delta/T_c \sim 3.6}$

T-dependence of the SC gap at the γ FS

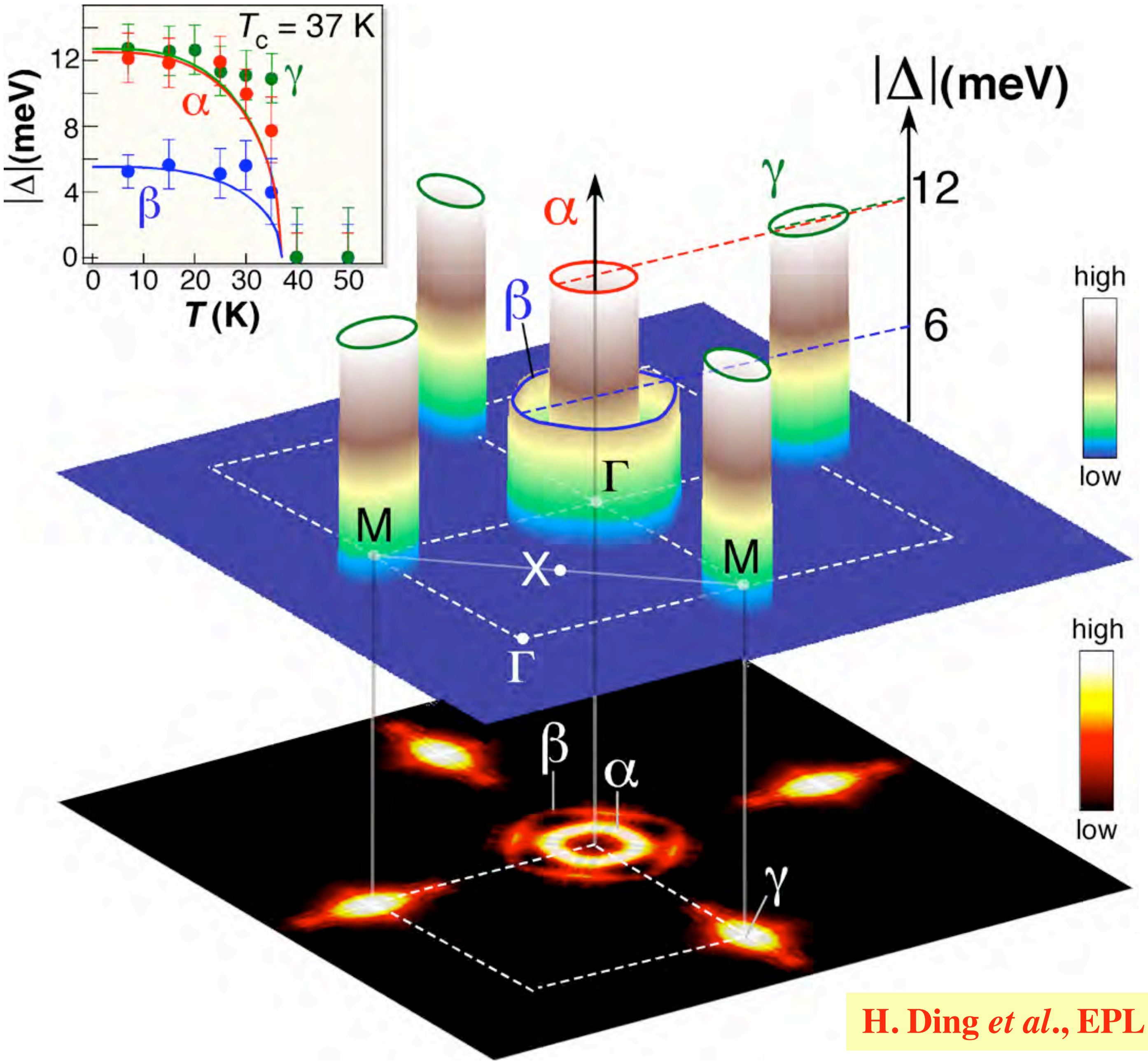


$2\Delta/T_c \sim 7$

Momentum dependence of the superconducting gap

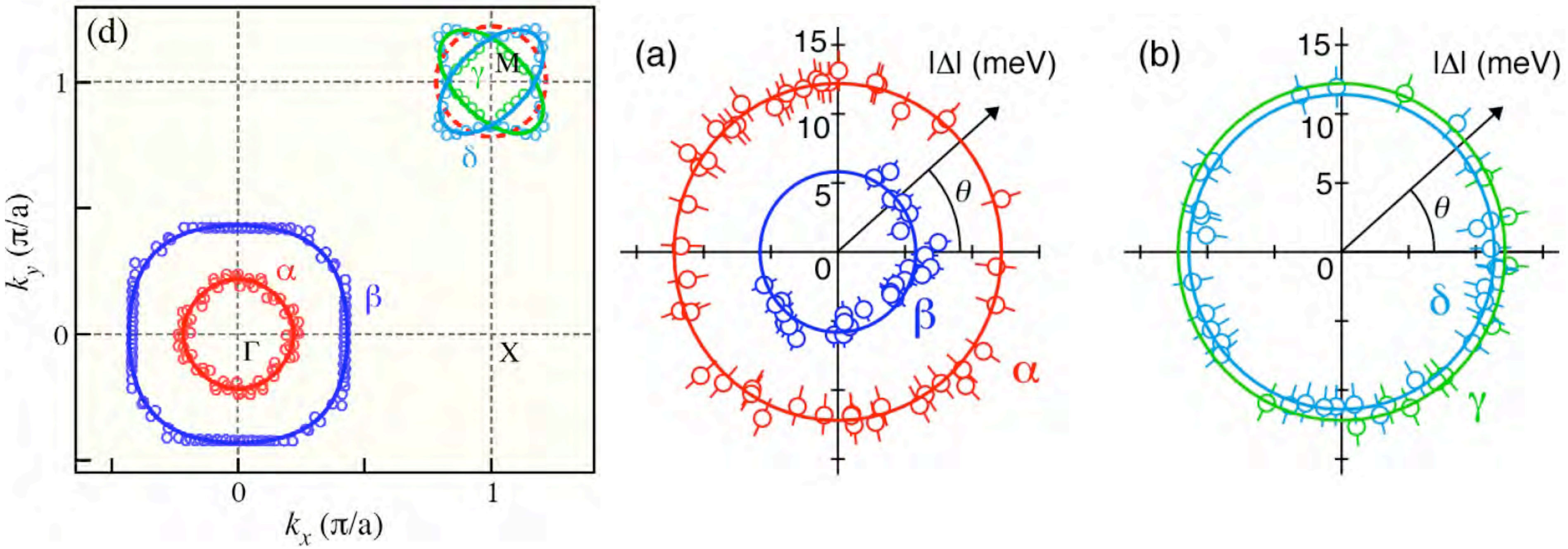


Fermi surface dependent but isotropic pairing



H. Ding *et al*., EPL 83, 47001 (2008)

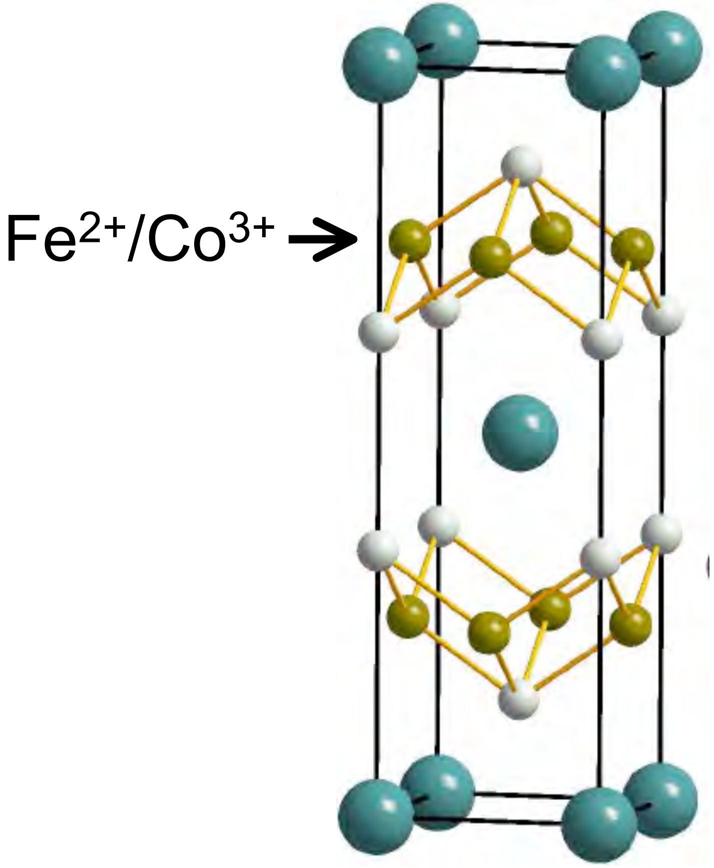
In optimally hole doped samples, good FS nesting between the inner (α) hole pocket and the electron pockets



Strong pairing also happens to these FSs!

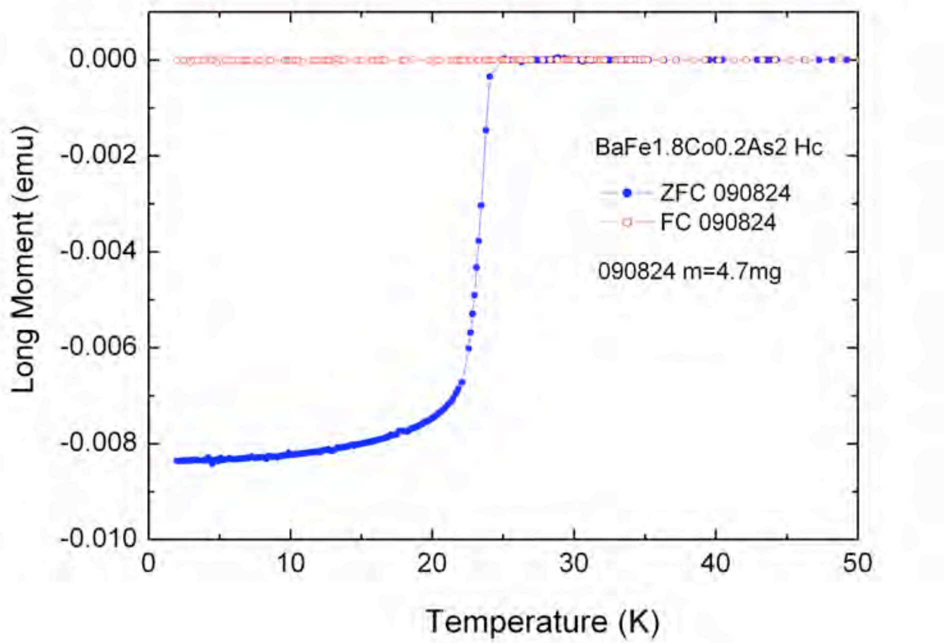
$2\Delta/k_BT_c$ = 7.7, 3.6, 7.7, and 7.2
for α, β, γ, and δ

Optimally electron doped samples

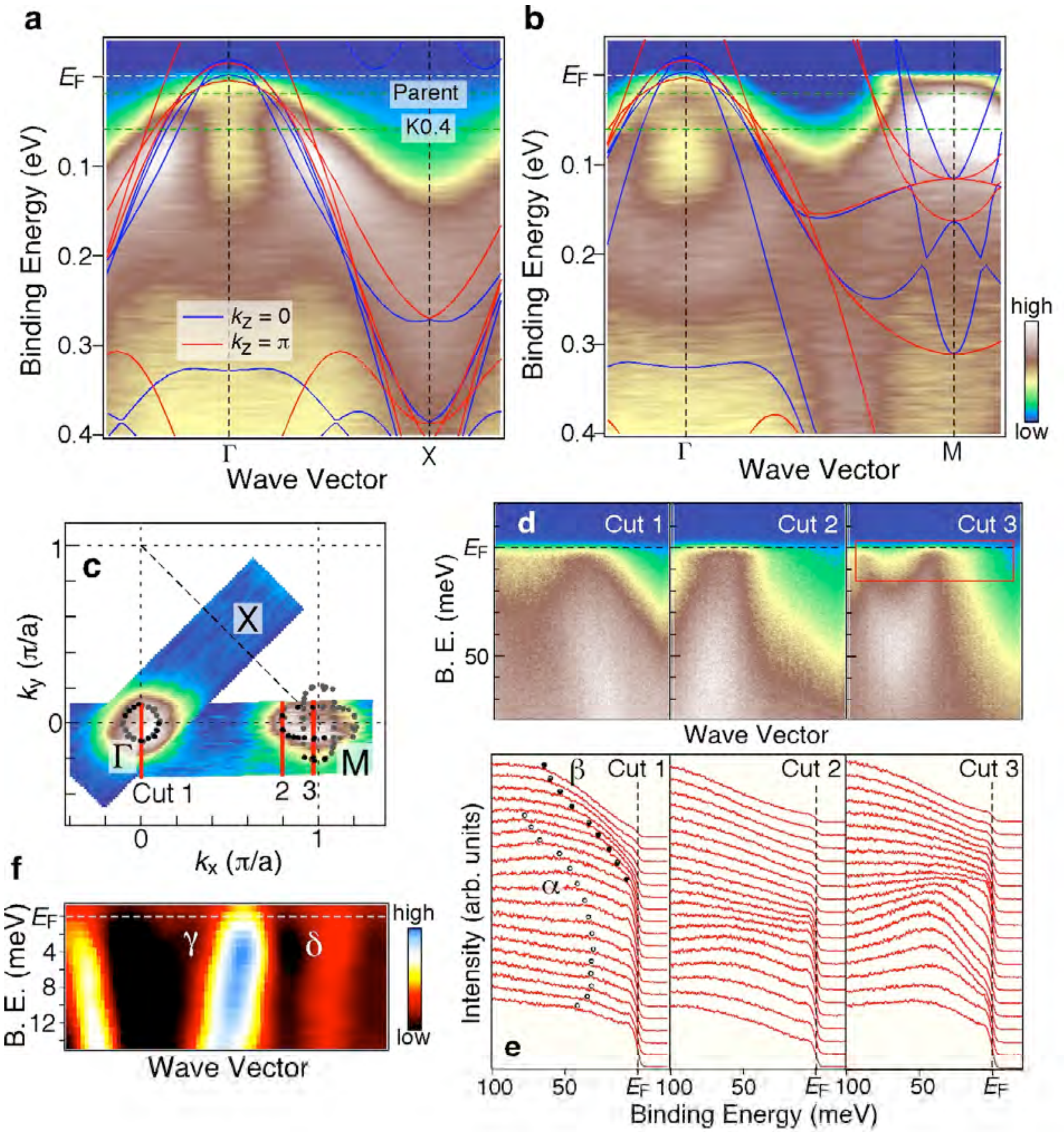


$BaFe_{1.85}Co_{0.15}As_2$ ($T_c = 25.5$ K)

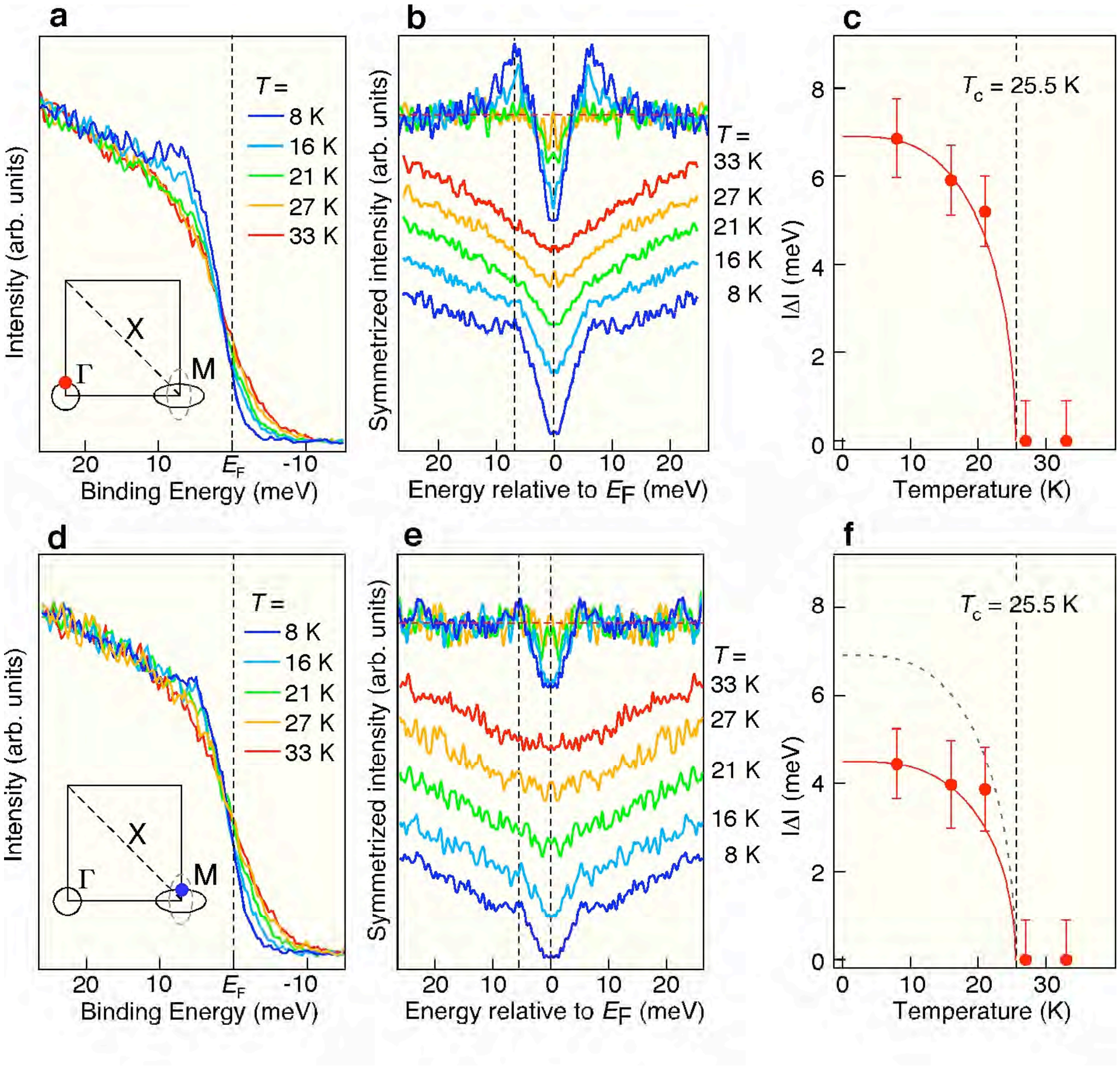
Nominal Co = 0.2



Band structure and FS in $BaFe_{1.85}Co_{0.15}As_2$



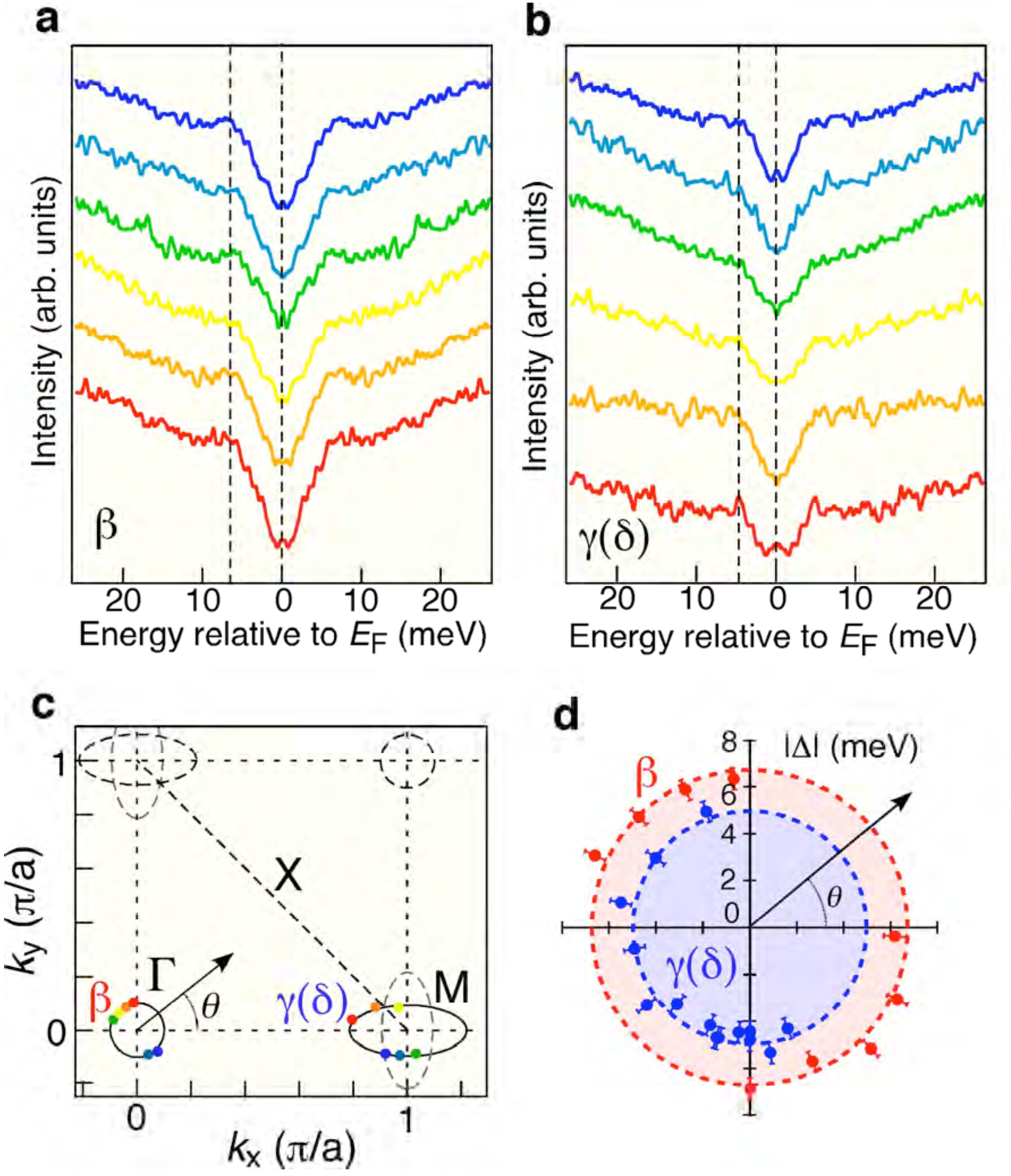
Temperature dependence of the SC gaps



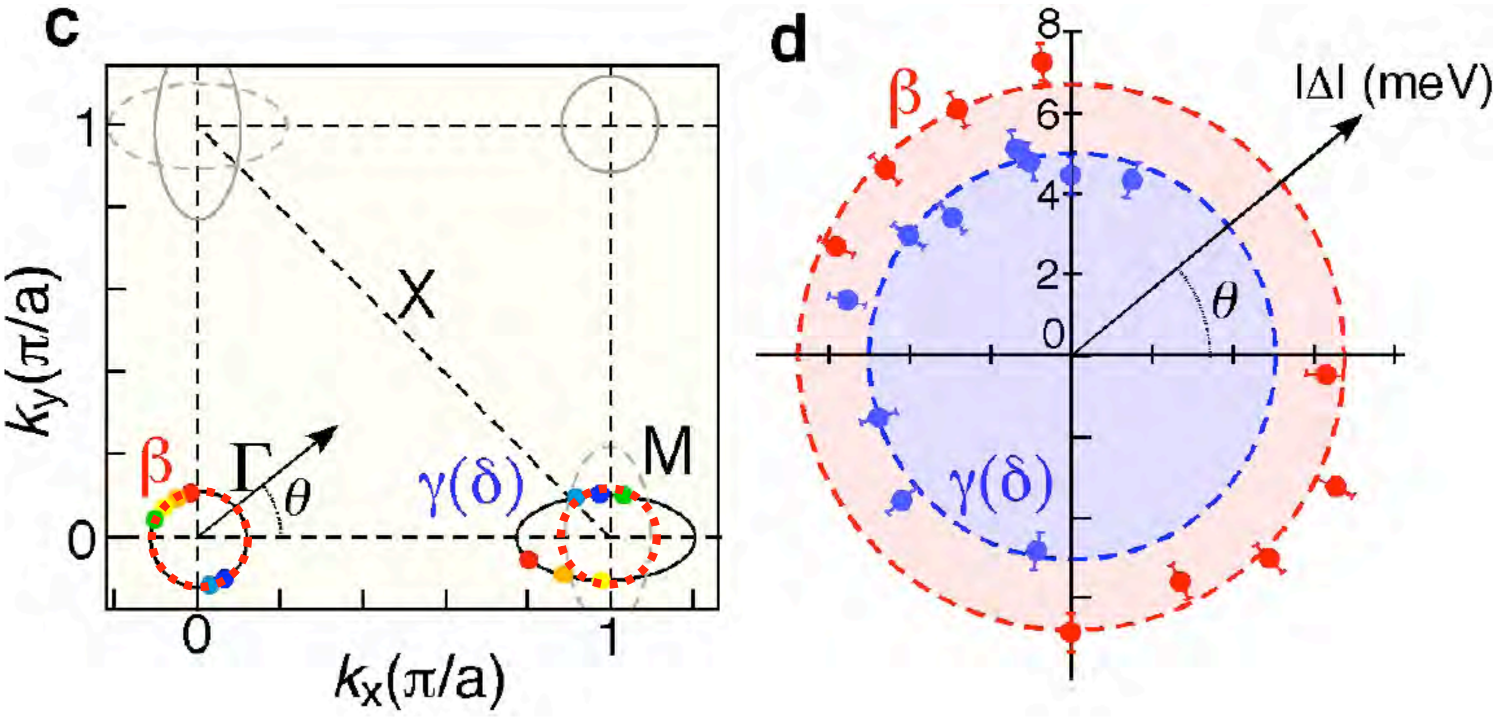
$2\Delta_\beta / k_B T_c = 6$

$2\Delta_\delta / k_B T_c = 4.5$

Momentum dependence of the SC gaps



In optimally electron doped samples, good FS nesting between the outer (β) hole pocket and the electron pockets



Strong pairing also happens to these FSs!

$$2\Delta/k_BT_c = 6,\ \ 4.5$$

for β, γ(δ)

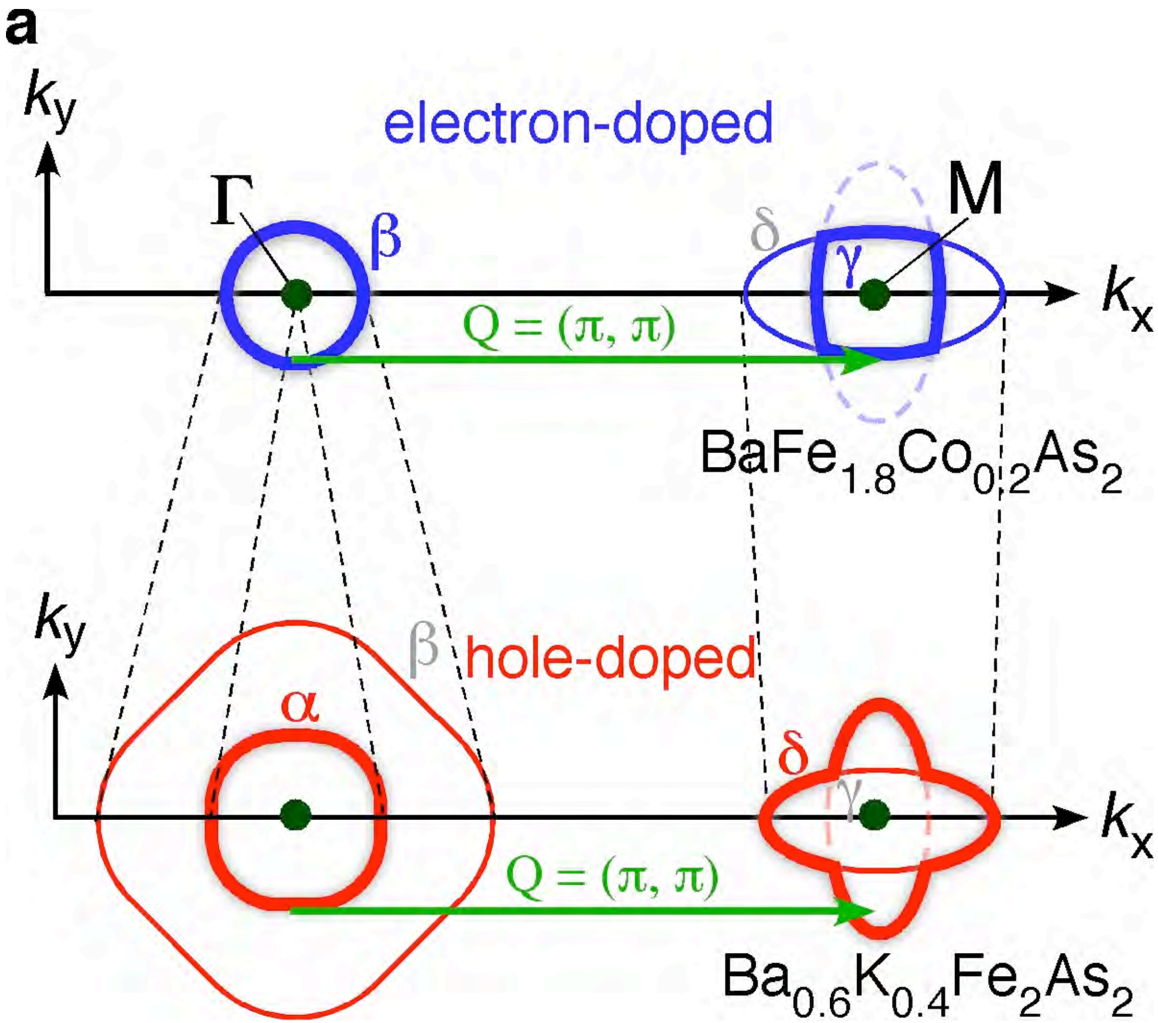
K. Terashima *et al*., arXiv: 0812.3704

FS nesting induced strong pairing

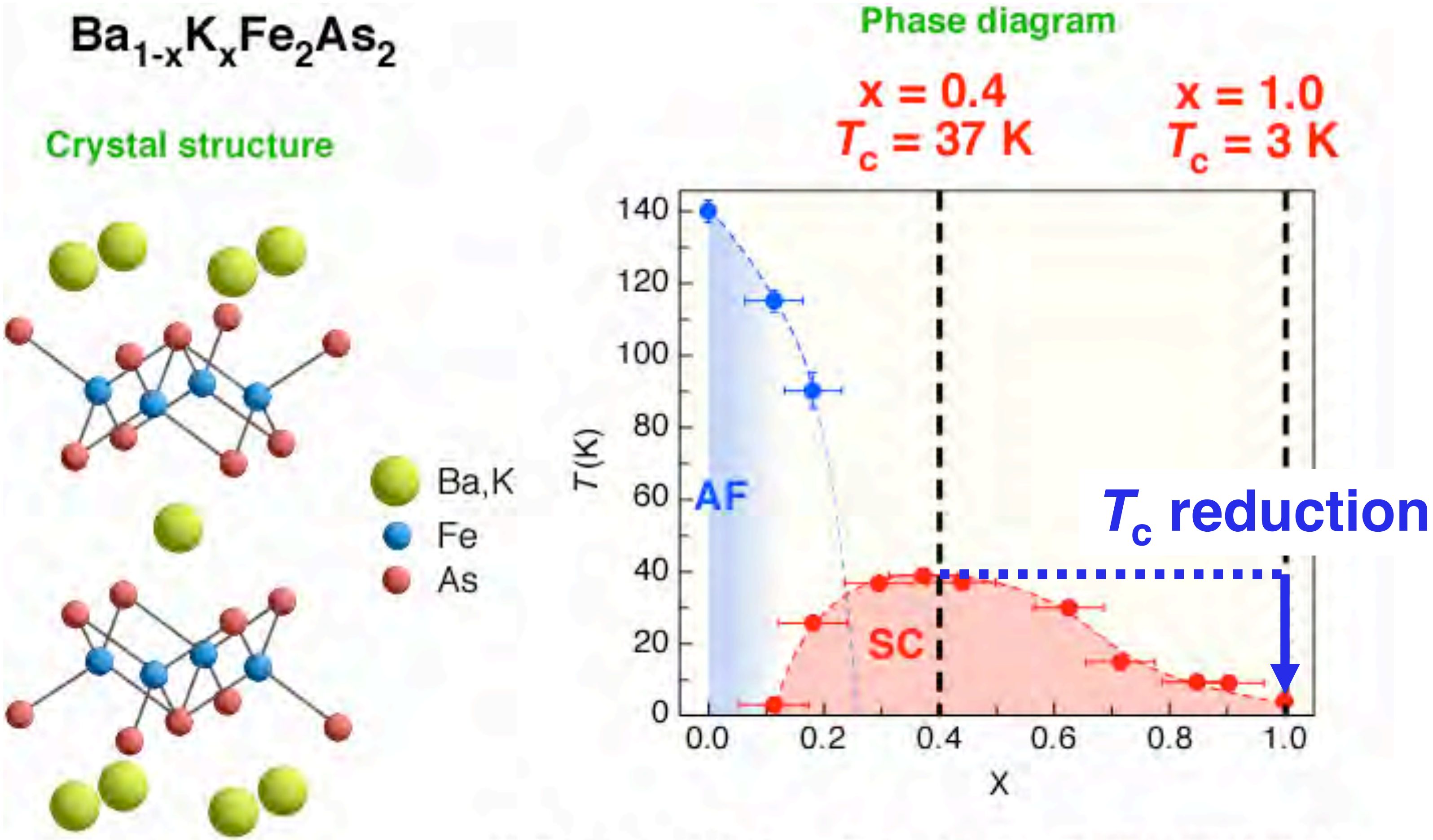
$2\Delta_\beta/k_BT_c = 6$

$2\Delta_\beta/k_BT_c = 3.6$

$2\Delta_\alpha/k_BT_c = 7.7$

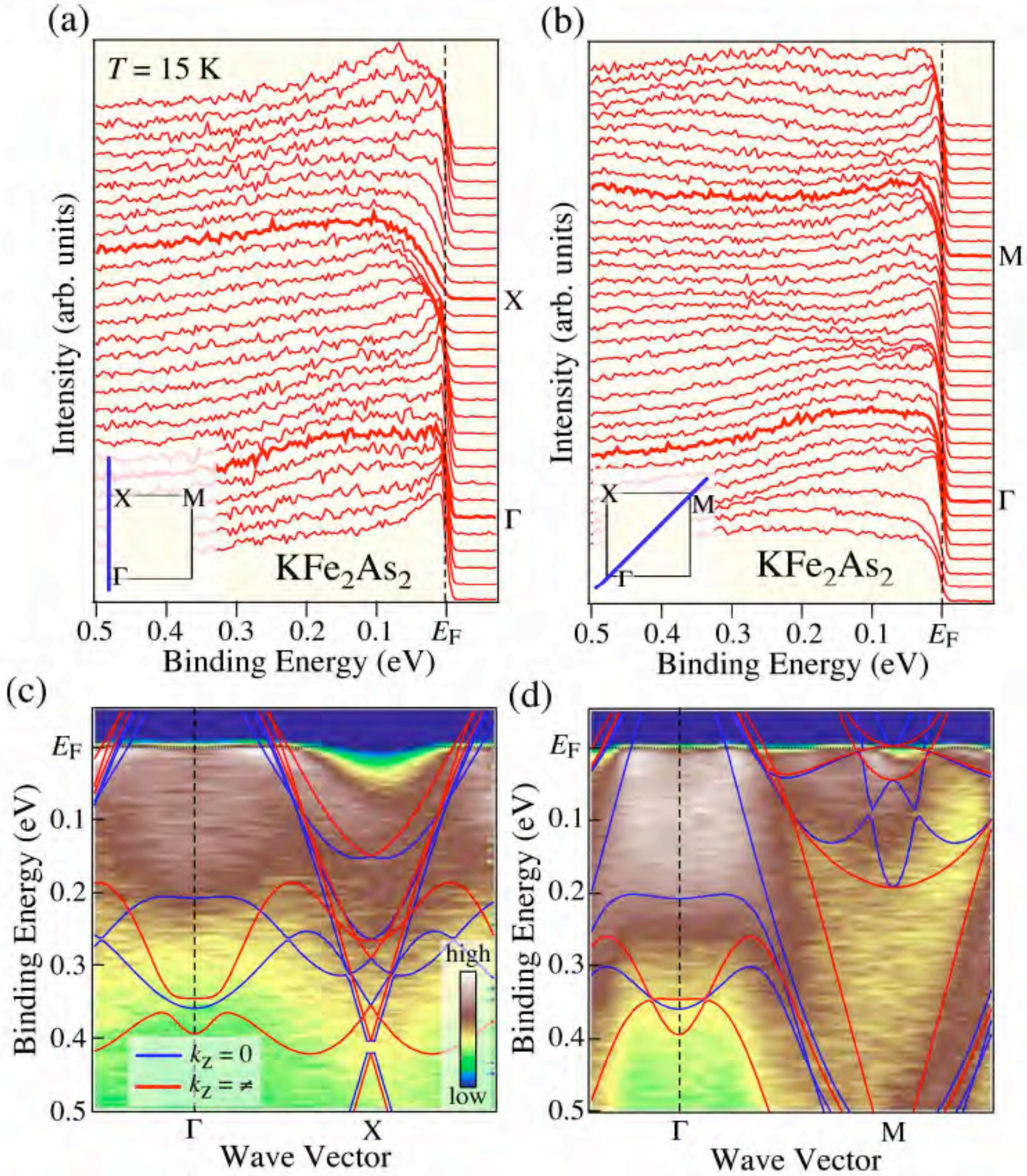


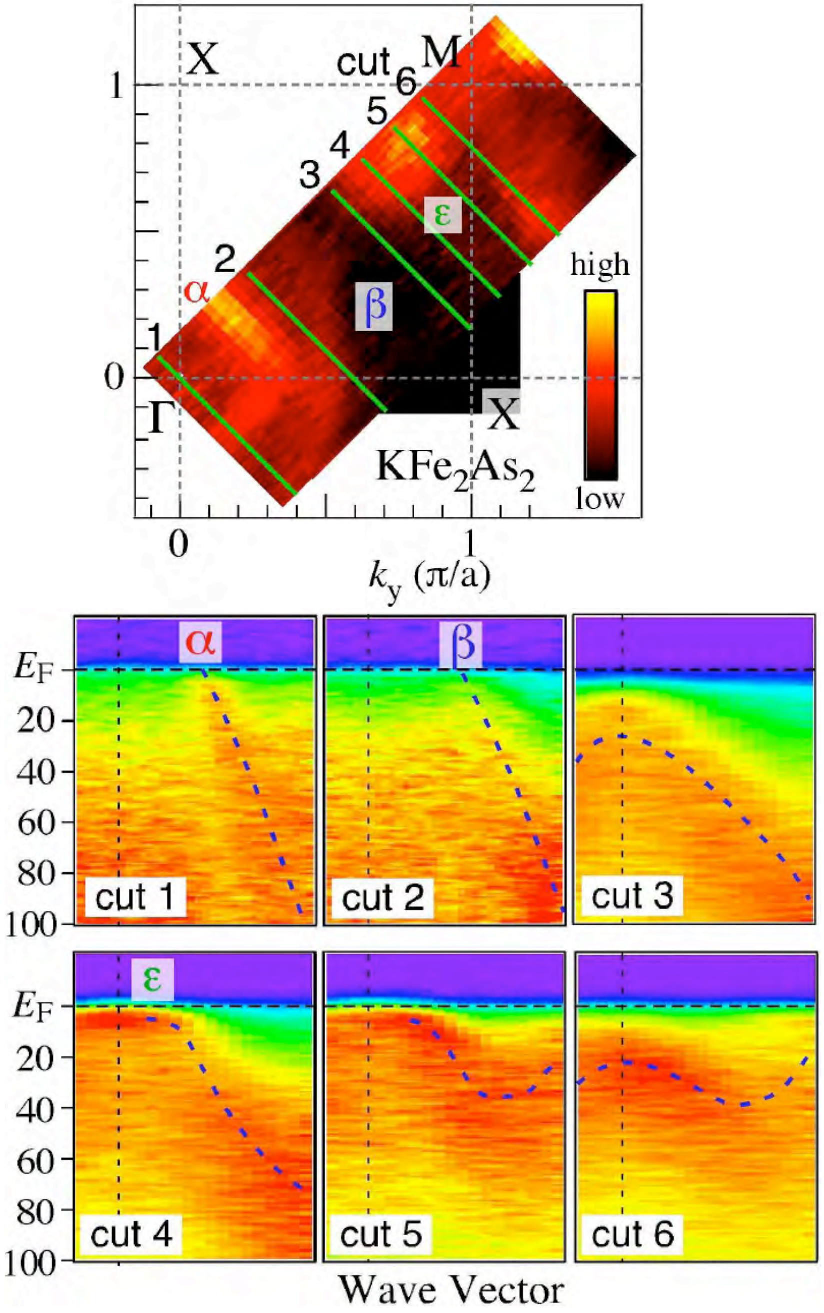
Collapse of T_c in heavily hole doped samples



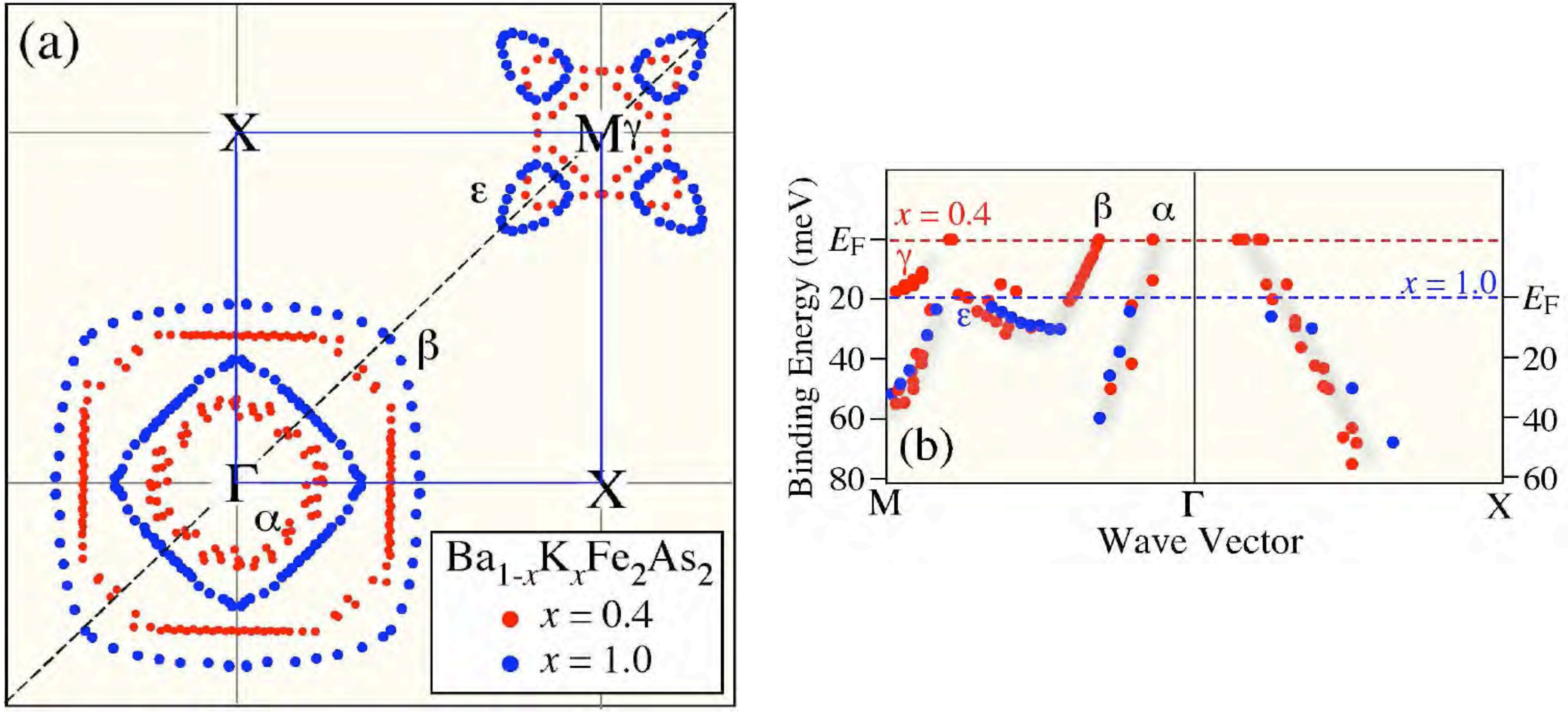
M. Rotter *et al.*, Angew. Chem. Int. Ed. **47**, 7949-7952 (2008).

Band Structure and Fermi Surface of KFe_2As_2



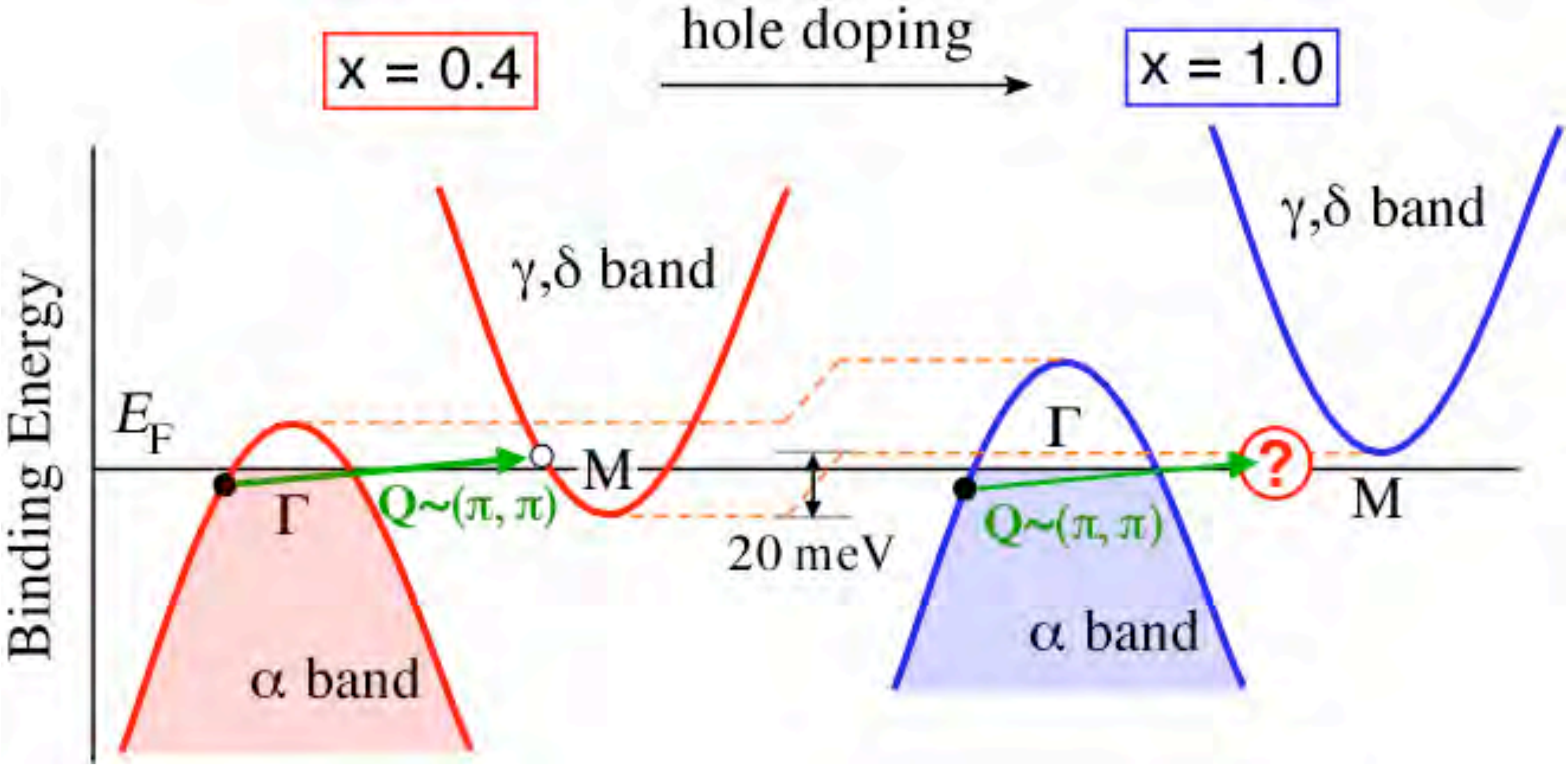


Doping evolution of Fermi surfaces of $Ba_{1-x}K_xFe_2As_2$



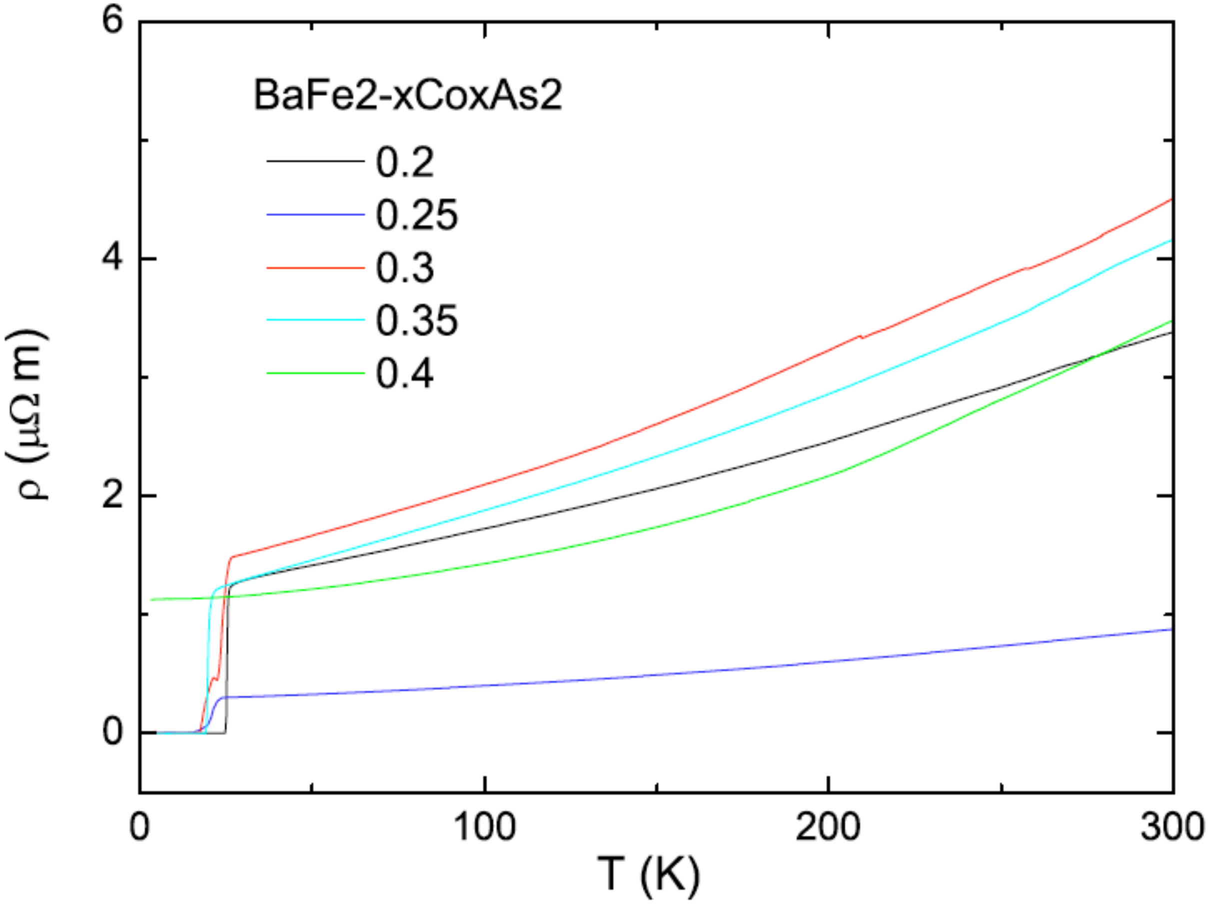
T. Sato *et al.*, arXiv: 0810.3047

Disappearance of electron FS pockets ⟷ collapse of T_c



- **Interband scattering via Q_{AF}**

Disappearance of T_c in heavily electron doped samples

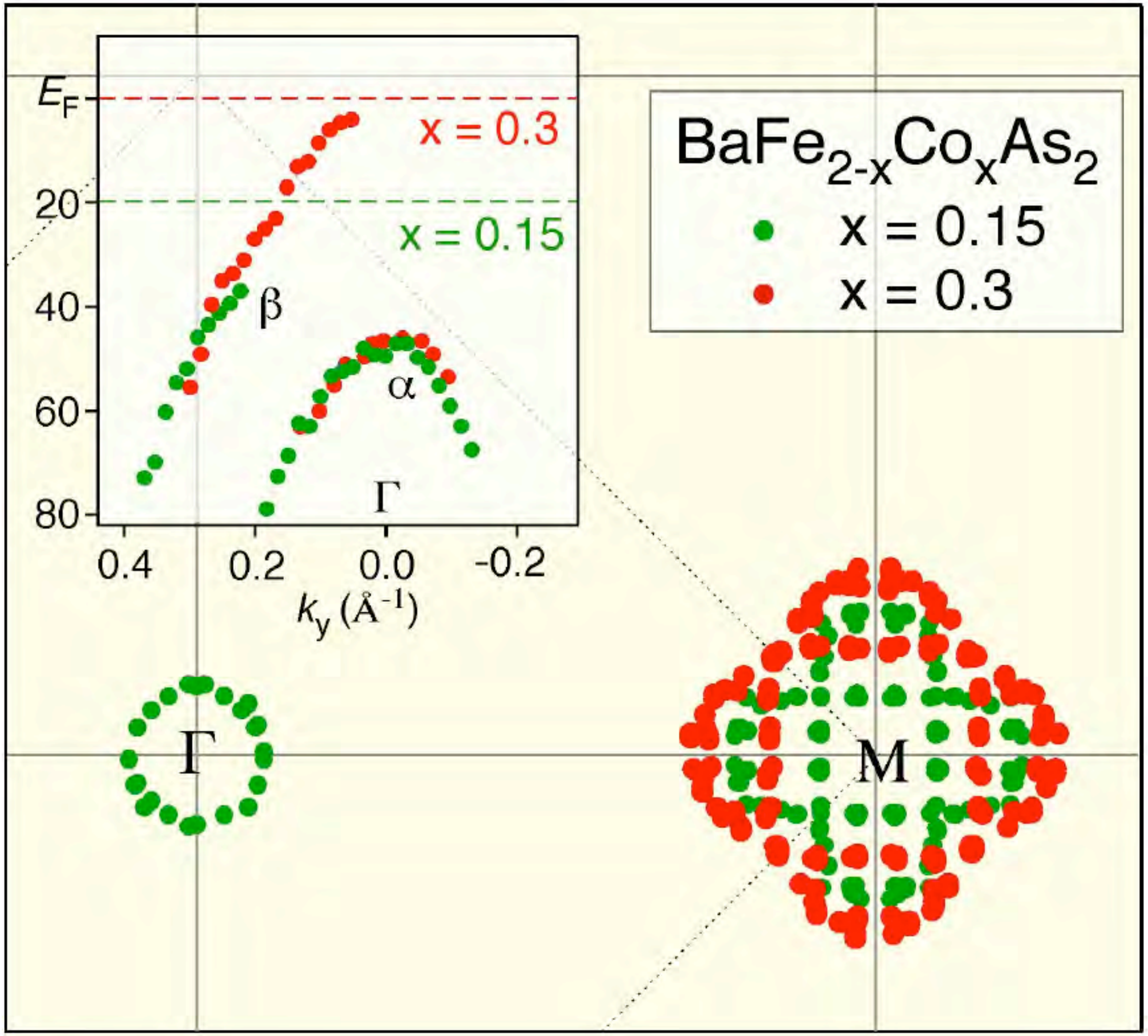


$BaFe_{1.7}Co_{0.3}As_2$

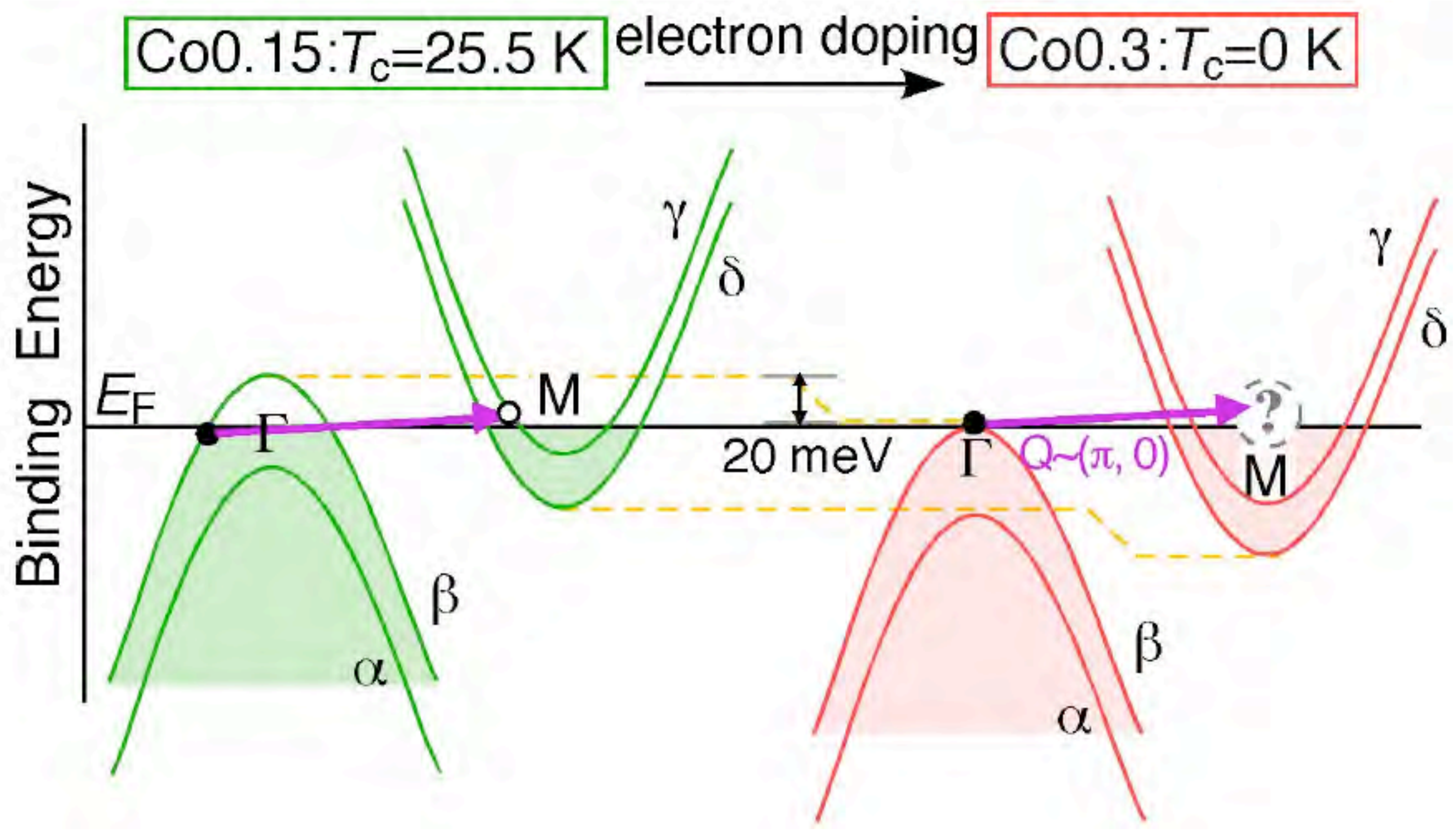
$T_c < 2$ K

Nominal Co = 0.4

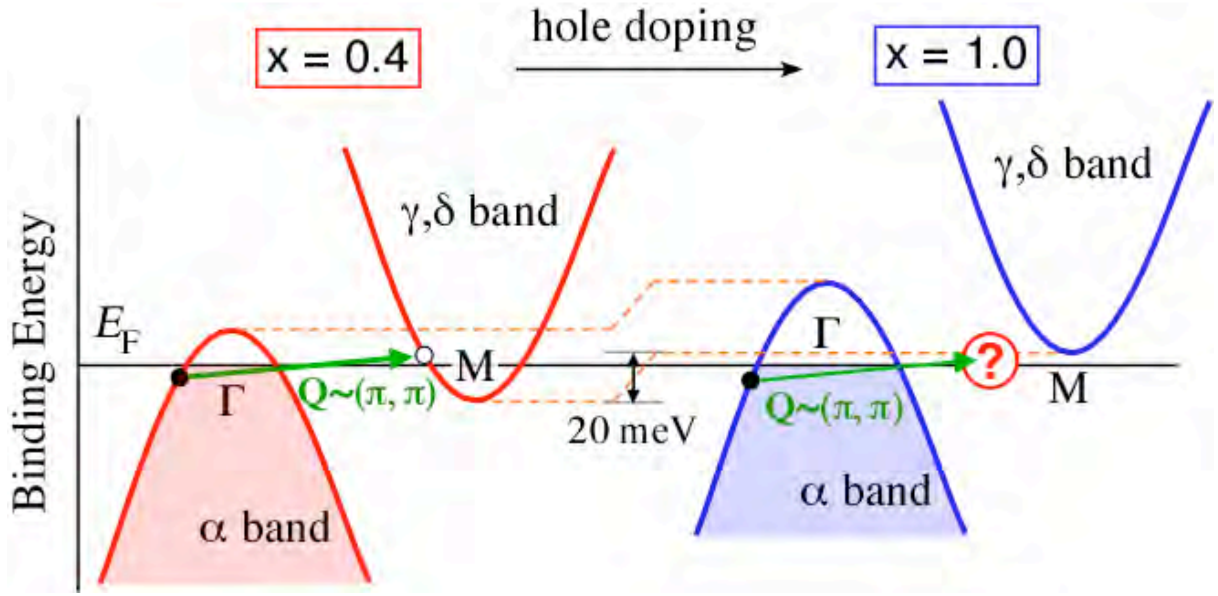
Doping evolution of Fermi surfaces of $BaFe_{2-x}Co_xAs_2$

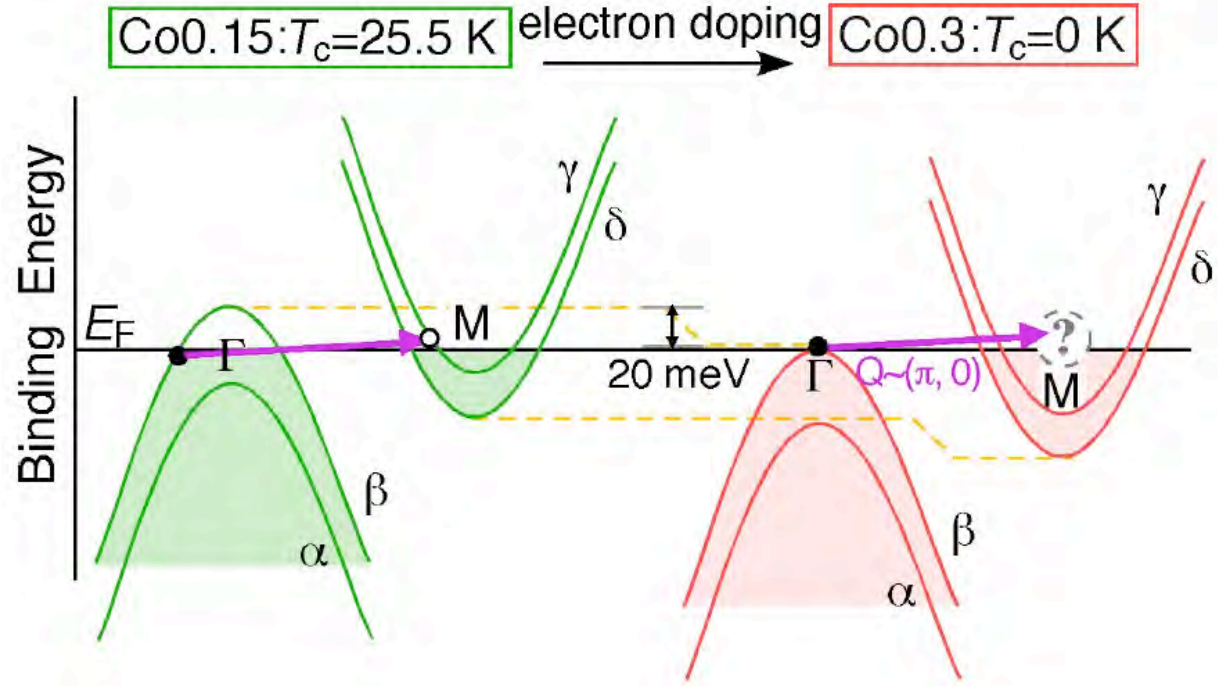


Disappearance of hole FS pockets ⟷ collapse of T_c



Vanish of interpocket Q_{AF} ⟷ collapse of T_c

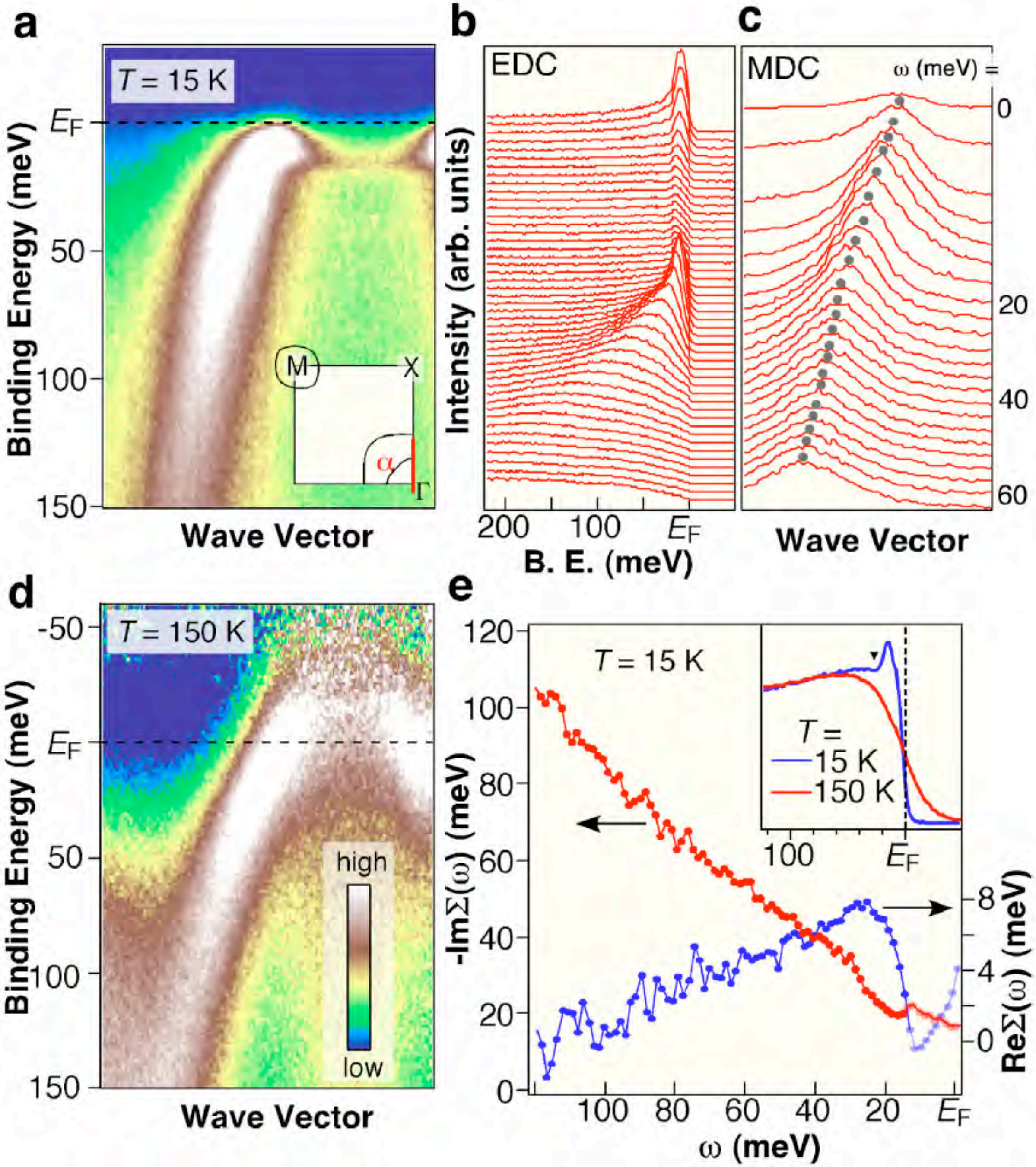


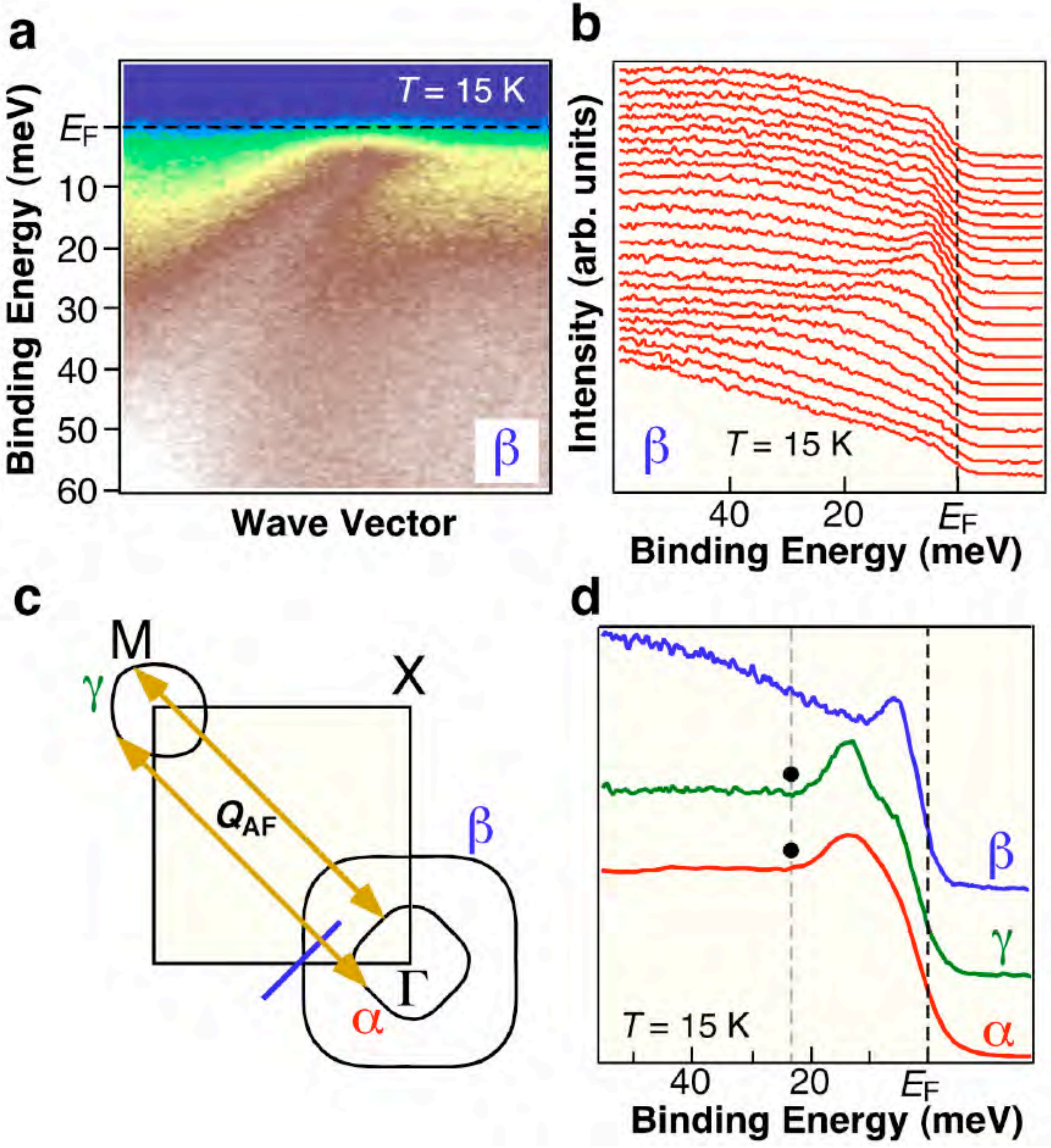


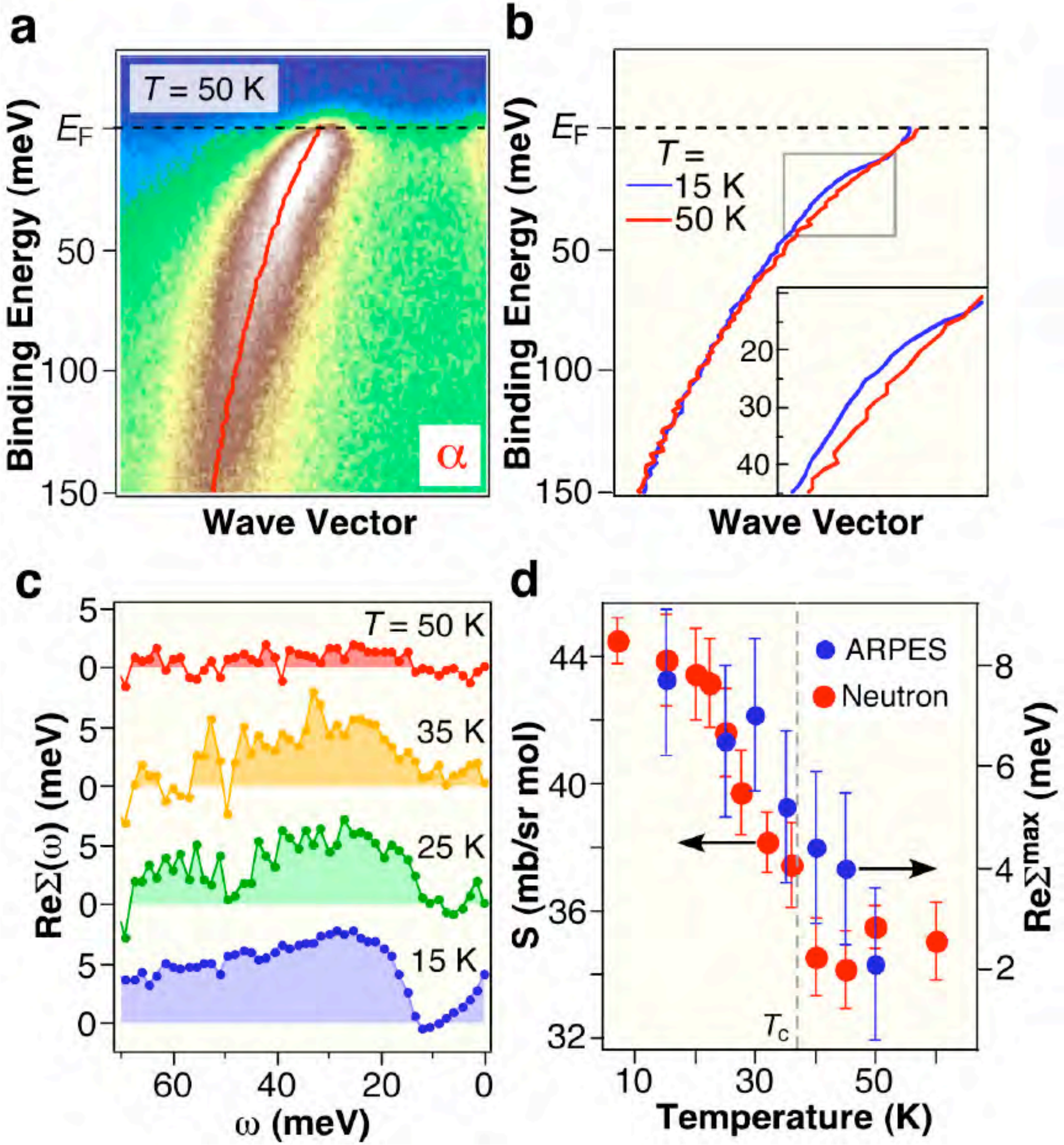
Observation of a dispersion kink in the superconducting state

P. Richard *et al*., arXiv: 0808.1809, PRL accepted

A low-energy kink observed in the α band

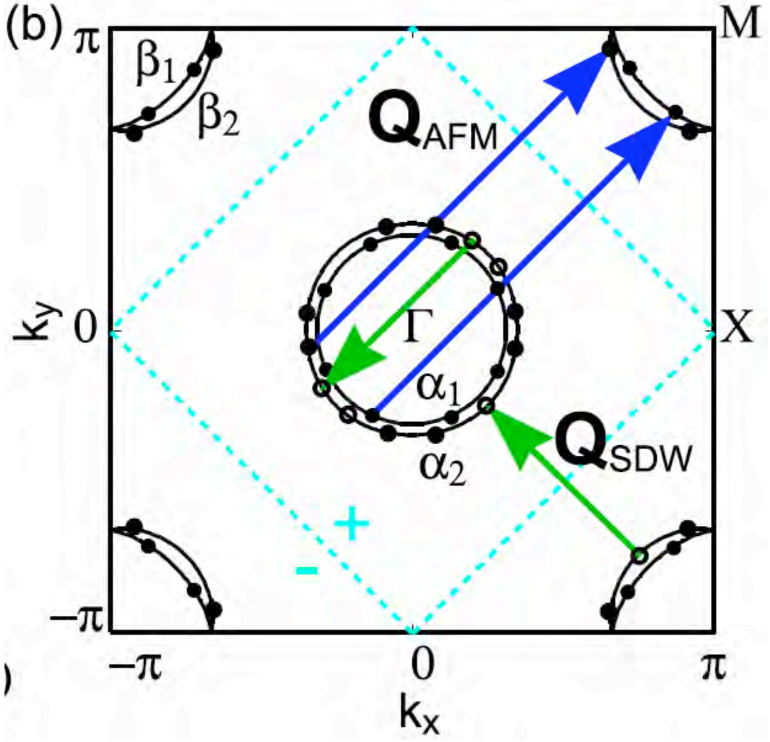


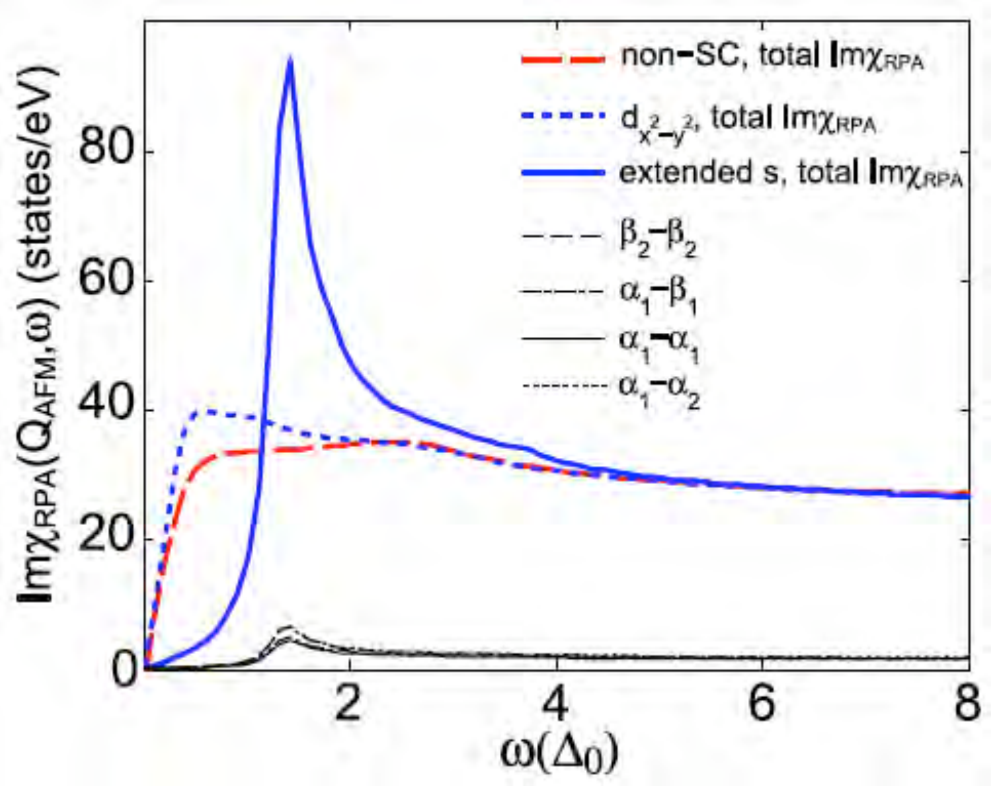

a
T = 15 K
E_F
Binding Energy (meV)
10
20
30
40
50
60
Wave Vector
β
b
Intensity (arb. units)
β
T = 15 K
40
20
E_F
Binding Energy (meV)
c
M
X
γ
Q_{AF}
β
Γ
α
d
β
γ
α
T = 15 K
40
20
E_F
Binding Energy (meV)



A.D.Christianson et al., arXiv:0807.3932

Consistent with antiphase *s-wave* (or $s^{\pm}$)





M.M. Korshunov and I. Eremin, cond-mat/0804.1793

Conclusions

Inter-pocket (π, π) interactions,
with spin nature,
play an important role in paring

Fermi surface nesting enhances pairing

谢谢！

欢迎北大学生来读研究生！

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