KITP, Santa Barbara
2014/10/09, 11:15AM

Laser ARPES on High Temperature Superconductors

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Colleagues and Collaborators

➢Laser ARPES System Development, Maintenance and Improvement;

Chuangtian Chen, Yong Zhu, Guochun Zhang, Xiaoyang Wang
Technical Institute of Physics and Chemistry, CAS, China
Zuyan Xu, Guiling Wang, Hongbo Zhang, Yong Zhou, IOP, CAS, China

➢Single Crystal Samples

Genda Gu, Brookhaven National Lab
Takao Sasagawa, Tokyo Institute of Technology

➢Sample Characterization
W. Lu, X. L. Dong, Z.-X. Zhao, IOP, Chinese Academy of Sciences, Beijing.

➢Theoretical analysis
Han-Yong Choi, SungKyunKwan University, Suwon, Korea
Chandra Varma, University of California at Riverside, CA, USA.

Outline

- **VUV Laser-Based ARPES;**

- **Laser ARPES on High-Tc Cuprate Superconductors:**

  a. Nodal Gap and insulator-superconductor transition in La-Bi2201;

  b. Evolution of nodal-kink and antinodal kink in Bi2212;

  (*c. Extraction of Eliashberg Functions in Bi2212.*)

- **Summary.**

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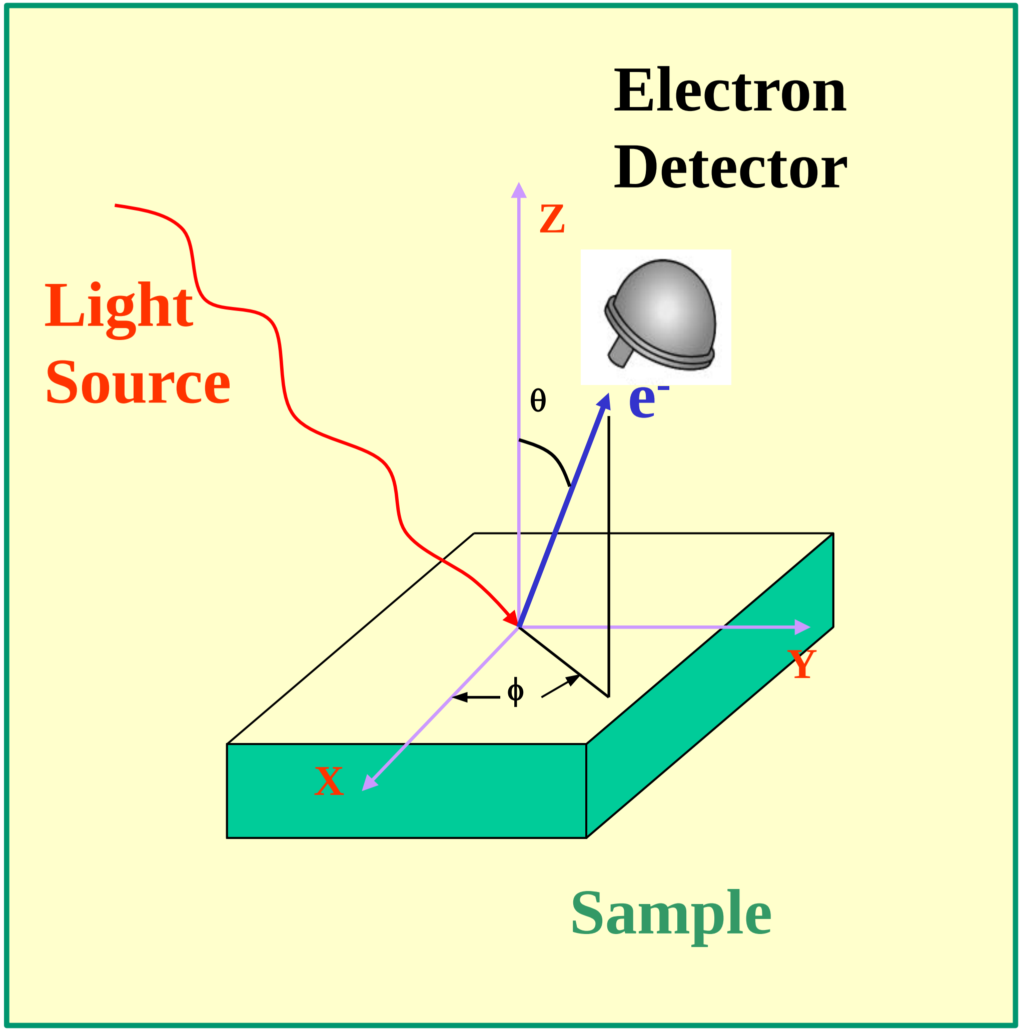
- **Summary.**

Angle-Resolved Photoemission Spectroscopy (ARPES)



Photoemitted electrons in Vacuum along different angles

$$E_{kin}, K_{||}$$

Energy Conservation: $E_B = h\nu - E_{kin} - \Phi$

Momentum Conservation: $K_{||} = k_{||} + G_{||}$

Electronic States in Solid:

$$\Psi(E, k, s)$$

E-Energy;

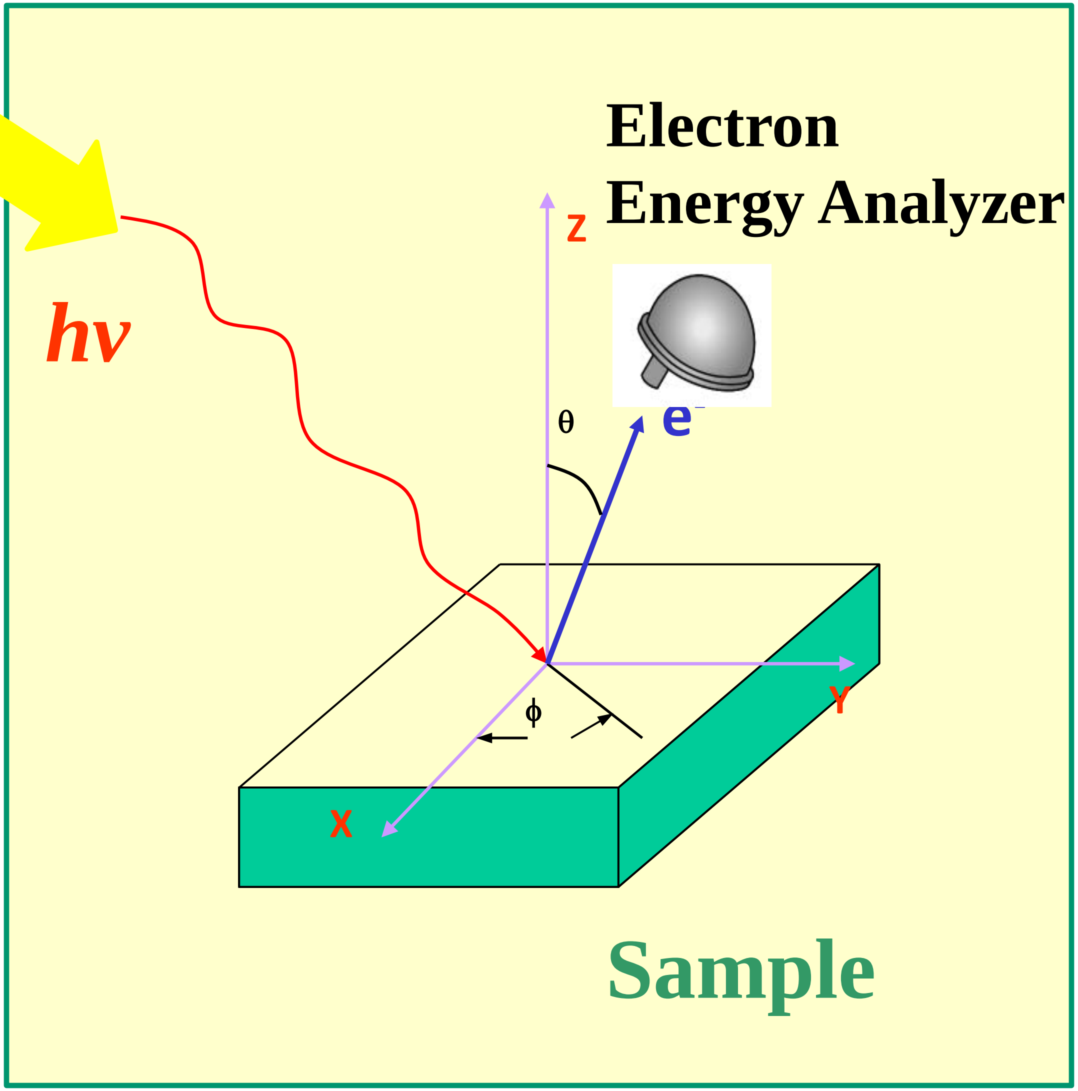
k-Momentum;

s-Spin.

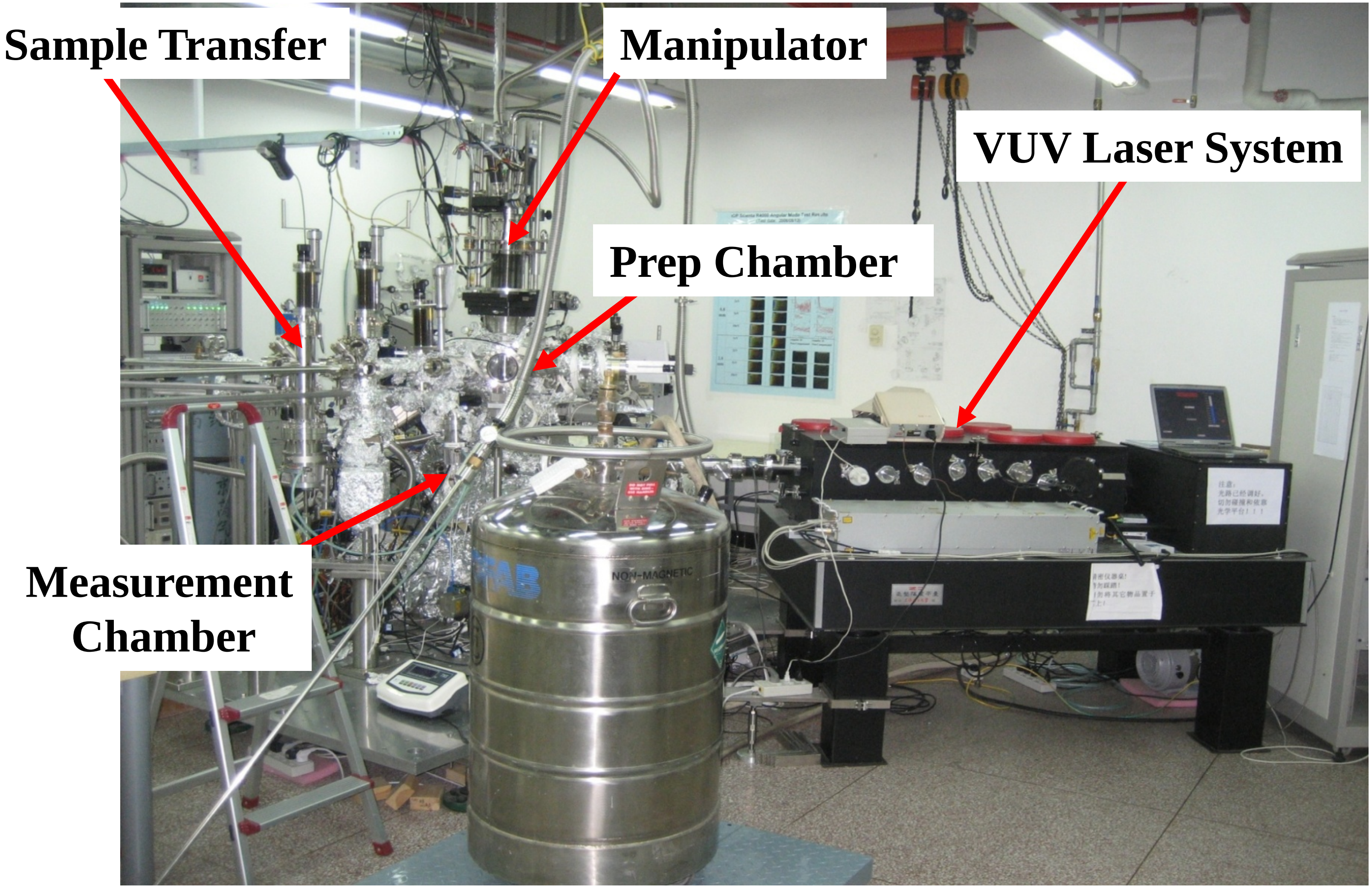
VUV Laser for Photoemission Spectroscopy

- **Synchrotron Radiation**
- **Gas Discharge Lamp**
  He I, hv=21.2 eV
  He II, hv=40.8 eV
- **VUV Laser**
  hv=6.994 eV

VUV---
VacuumUltra-Violet
hv>6.5 eV



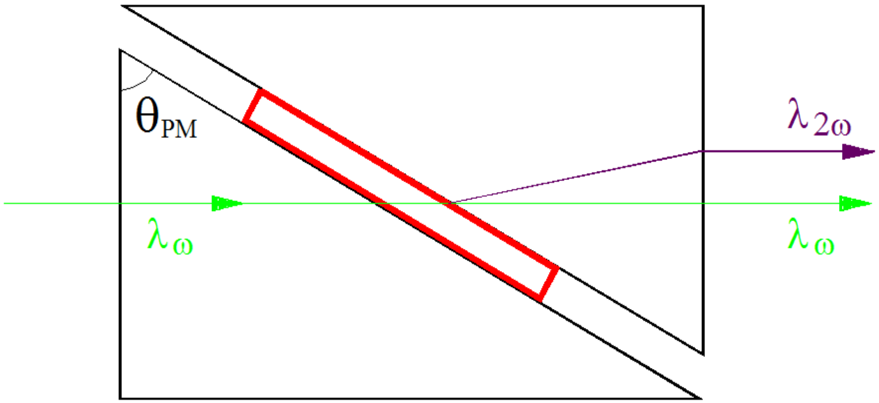
VUV Laser ARPES System at IOP

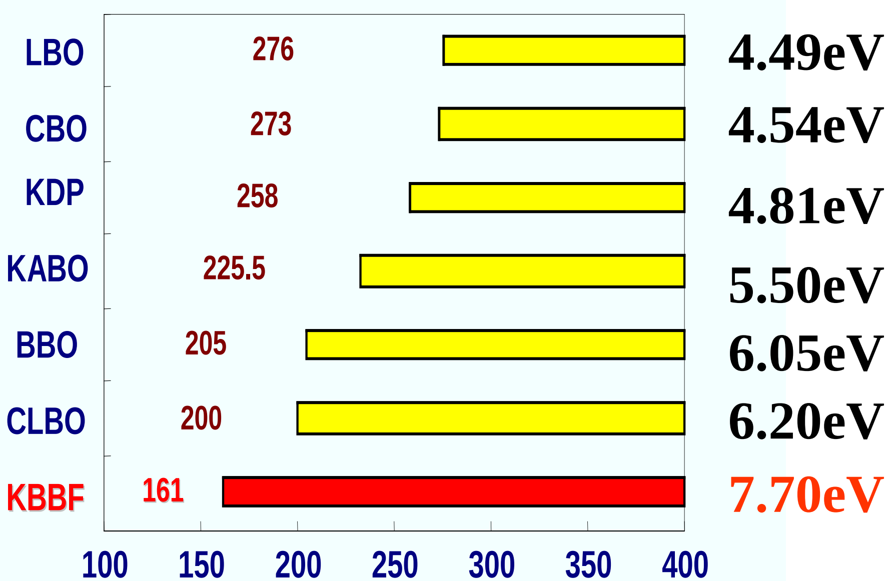


(Started development in early 2004, commissioned by the end of 2006)

Guodong Liu, X. J. Zhou *et al.*, Rev. Sci. Instrum. 79 (2008) 023105.

$KBe_2BO_3F_2$ (KBBF): New Non-Linear Optical Crystal





Second Harmonic Wavelength (nm)

NATURE|Vol 457|19 February 2009

NEWS FEATURE

China's crystal cache

A Chinese laboratory is the only source of a valuable crystal. **David Cyranoski** investigates why it won't share its supplies.

One of Daniel Dessau's prized possessions is a small crystal of potassium beryllium fluoroborate (KBBF). Dessau, a solid-state physicist at the University of Colorado at Boulder, uses the crystal to convert the light of a US$100,000 laser into a deep ultraviolet, a good wavelength for studying the surface of superconductors. But because the laser light gradually degrades the crystal, Dessau has to save it for special projects. "It is a beautiful crystal," he says. "It would really move the field forward — if people could get it."

But Dessau can't get any more of it. Nor can Peter Johnson, a condensed-matter physicist at Brookhaven National Laboratory in Upton, New York, who was once promised it by Chuangtian Chen, the Chinese physicist who runs the only laboratory that knows how to make the crystals. And nor can any of a host of other solid-state physicists outside China. "There has been a limited release," says Johnson. "I don't know the politics behind it."

In fact, the politics is simple. The Chinese government is squeezing the crystal for every bit of academic and, eventually, commercial potential it can yield. In October 2008, the finance ministry sidestepped traditional scientific funding channels and started throwing 180 million renminbi (US$26 million) at a three-year national project to find better ways to produce and use KBBF. China has selected a handful of groups to work with Chen's crystal, including teams studying the newest type of superconductor, called pnictides.

China's monopoly of this crystal is no fluke. At a time when materials scientists and solid-state physicists elsewhere are seeing a lack of investment, their counterparts in China are surging ahead in a wide range of materials research for much the same reasons as they did with KBBF. The nation has accumulated a great depth of crystal-growing know-how over the past three decades; it has steadfast government support; and its scientists are willing to subsume themselves in a large team effort and take on the often thankless, sometimes dangerous and always tedious trial-and-error task of synthesizing new materials. "Many great discoveries in this field come from putting things together and getting the temperature and timing just right," says Christos Panagopoulos, a materials researcher at Nanyang Technological University in Singapore. The discovery process "doesn't require genius", he says.

"You need a lot of equipment and you need to move slowly."
— Chuangtian Chen

KBBF's ability to shorten the wavelength, and thereby boost the frequency, of laser light is an example of 'nonlinear' optics, a field that first blossomed in the 1960s as lasers became more widespread in laboratories. Under ordinary circumstances, light passing through water, glass or any other material will perturb the atoms only slightly, so that they vibrate in sync with the light wave. As a result, light can be reflected, refracted, scattered and absorbed ad infinitum without its frequency being affected. Nonlinear effects are evident only when the light is so intense that the vibrations it causes compete with the binding forces on the atoms. When highly perturbed, as in the case of high-intensity lasers, the atoms can absorb the energy of the incoming light and re-emit the light with a frequency that is double, triple or even some higher multiple of the original. A variety of materials have been discovered that can boost laser light to frequencies that the lasers alone cannot produce, and each has a set of signature frequencies that it can achieve.

China might easily have fallen behind in this field, as it did in so many others. Just as nonlinear optics started coming into its own, China was caught up in the Cultural Revolution, a particularly dark period starting in the mid-1960s when many academics were criticized as being elitist or impractical and sent to do farm work for 're-education'.

But Chen, now a spritely 71-year-old at the Technical Institute of Physics and Chemistry

J. RIORDAN

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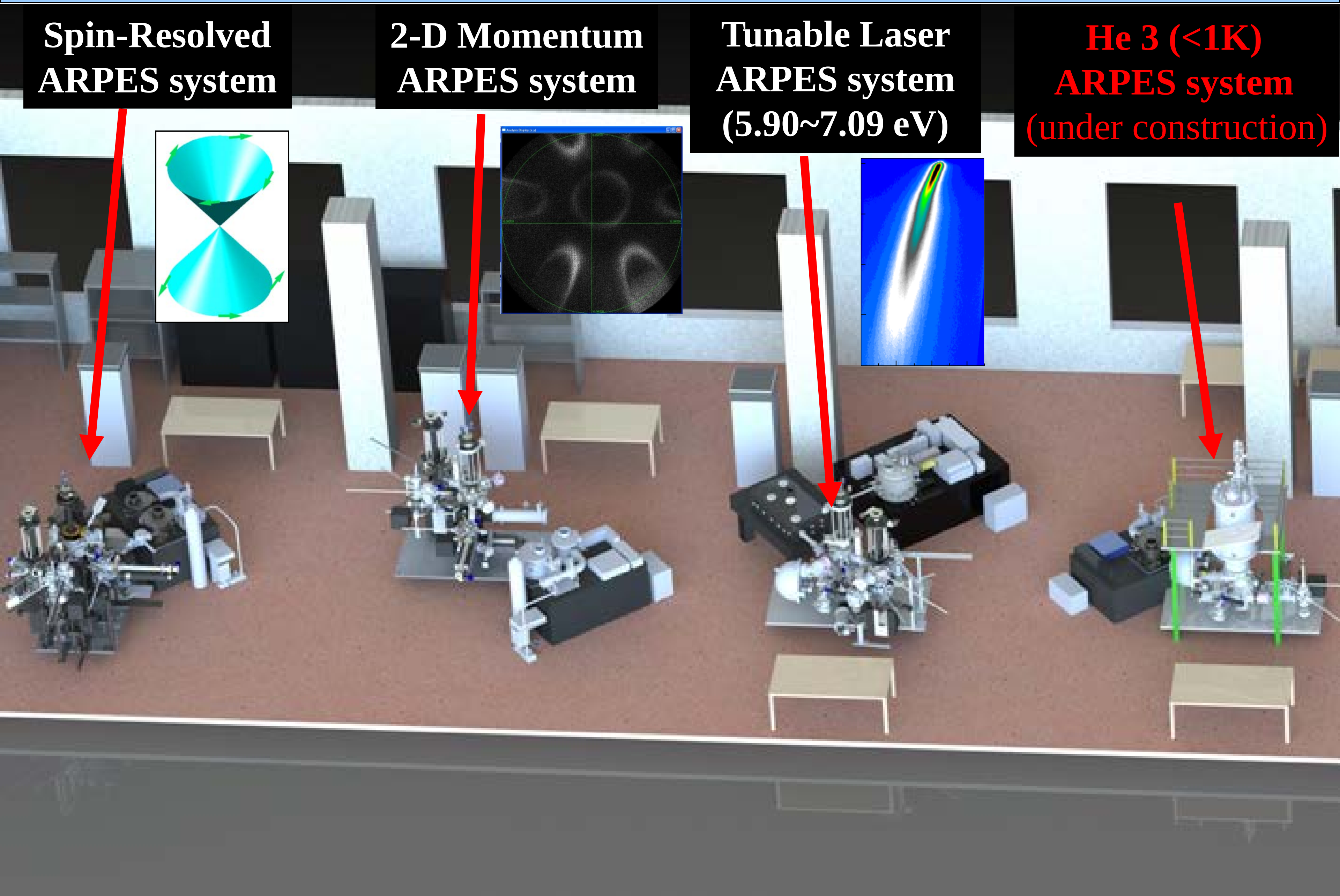
Nature Report, February, 2009

Advantages and Disadvantages of VUV Laser ARPES

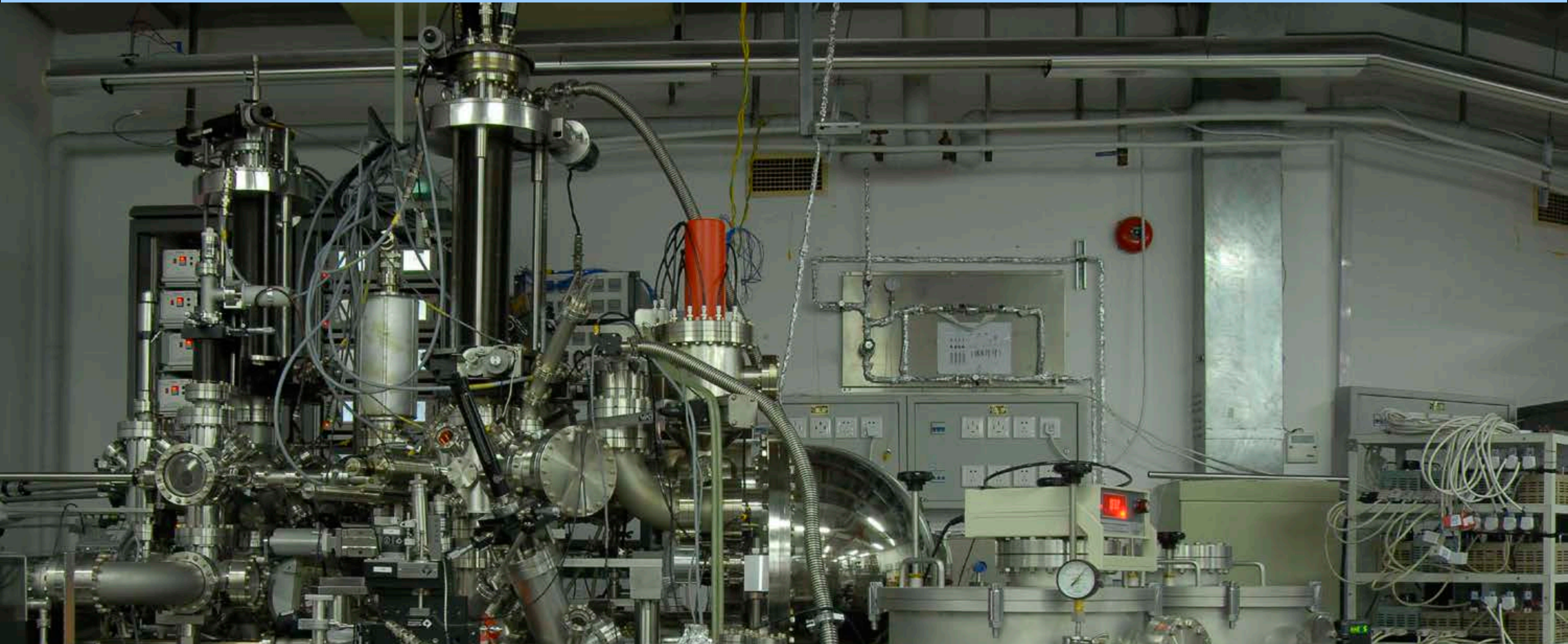
Light Source	VUV Laser	Synchrotron
Energy Resolution (meV)	0.36	5~15
Momentum Resolution ($Å^{-1}$)	0.0036 (6.994eV)	0.0091 (21.1eV)
Photon Flux(Photons/s)	10^{14}~10^{15}	10^{12}-10^{13}
Electron Escape Depth (Å)	30~100	5~10
Photon Energy Tunability	Limited	Tunable
k-Space Coverage	Small	Large

Laser and Synchrotron are complementary.

VUV Laser Photoemission Lab at IOP



VUV Laser Spin-Resolved ARPES



- ARPES (E, k) → Spin-Resolved ARPES (E, k, s)
- Energy Resolution: From 50~100meV for Synchrotron to 2.5 meV for VUV-laser
- Photon flux: Increase by 100~1000 times.

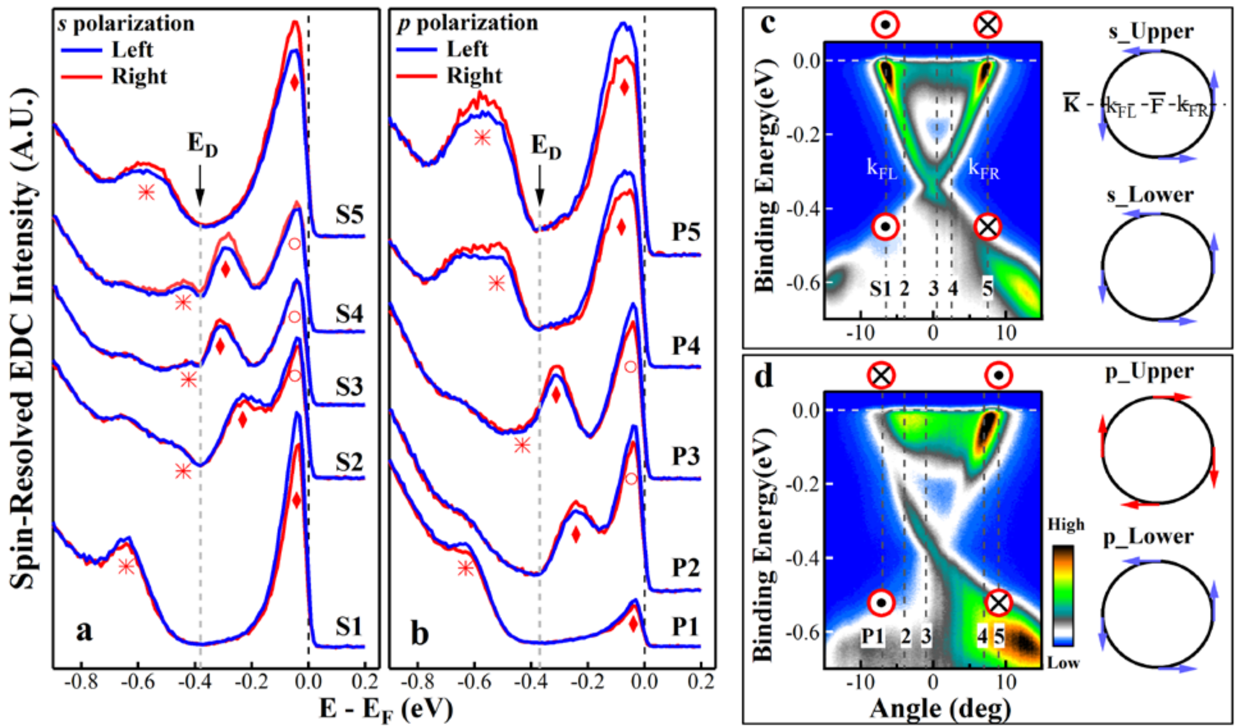
nature COMMUNICATIONS

ARTICLE

Received 29 May 2013 | Accepted 5 Feb 2014 | Published 28 Feb 2014

DOI: 10.1038/ncomms4382

Orbital-selective spin texture and its manipulation in a topological insulator

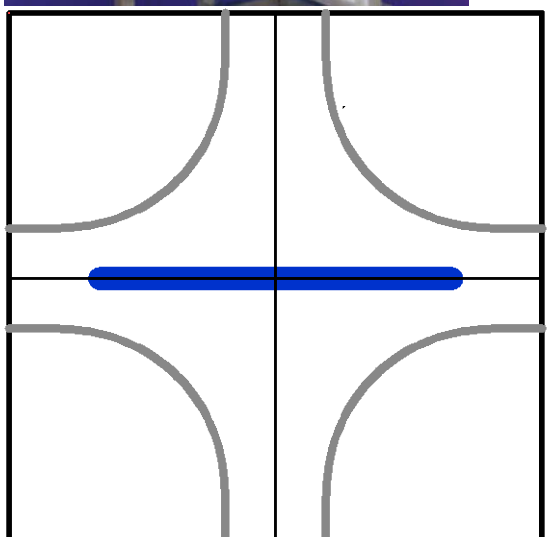


Z. J. Xie, S. L. He, X. J. Zhou et al., Nature Communications 5 (2014) 3382.

VUV Laser 2D Momentum ARPES: From 1D to 2D Angular Detection

Hemi-Spherical Analyzer

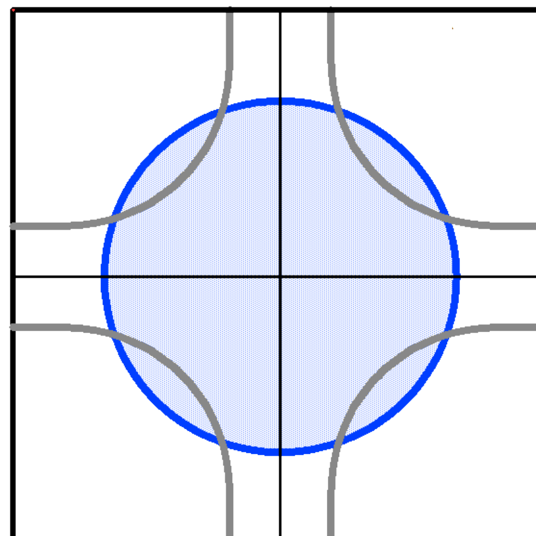
- Energy Res.: better than 1meV
- Angular Res: 0.1~0.4 Degree
- Angle Range: 1D: +-15 Deg.



Angle Detection: 1D Line

Time-of-Flight Analyzer

- Energy Res.: ~0.15meV
- Angular Res.: 0.08 Degree
- Angle Range: 2D:+-15Deg.



Angle Detection 2D Plane

Efficiency of Angle Detection Improved by 250 times

Outline

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  b. Evolution of nodal-kink and antinodal kink in Bi2212;

- Summary.

nature COMMUNICATIONS

Yingying Peng

ARTICLE

Received 5 Mar 2013 | Accepted 18 Aug 2013 | Published 20 Sep 2013

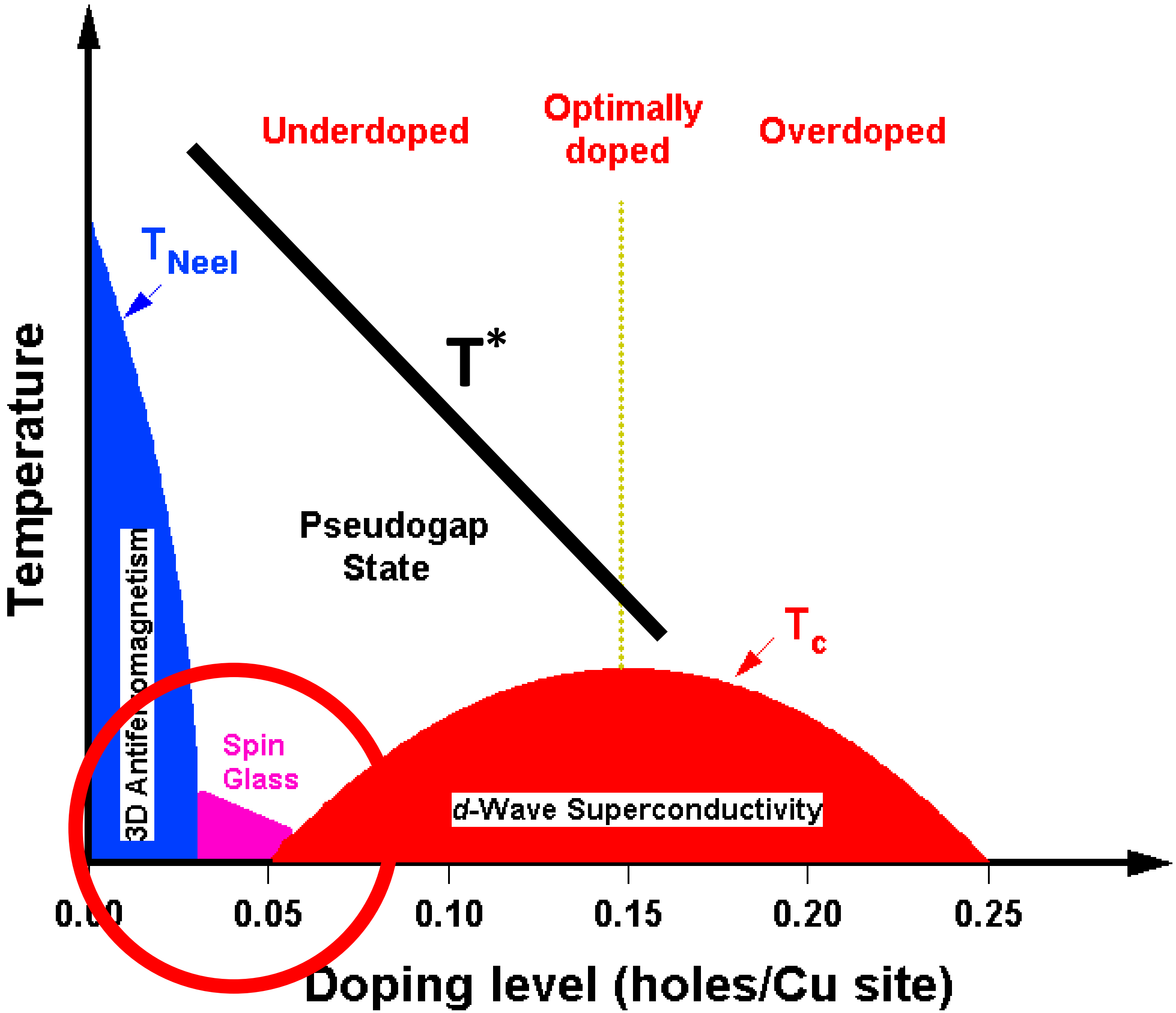
DOI: 10.1038/ncomms3459

Disappearance of nodal gap across the insulator–superconductor transition in a copper-oxide superconductor

Yingying Peng[1], Jianqiao Meng[1], Daixiang Mou[1], Junfeng He[1], Lin Zhao[1], Yue Wu[1], Guodong Liu[1], Xiaoli Dong[1], Shaolong He[1], Jun Zhang[1], Xiaoyang Wang[2], Qinjun Peng[2], Zhimin Wang[2], Shenjin Zhang[2], Feng Yang[2], Chuangtian Chen[2], Zuyan Xu[2], T.K. Lee[3] & X.J. Zhou[1]

Discussions with
Maurice Rice, Fuchung Zhang, Dunghai Lee, Chandra Varma,
Tao Xiang, Zhengyu Weng.......

Electronic Phase Diagram of Cuprates



$Bi_2(Sr,La)_2CuO_6$ (La-Bi2201) System

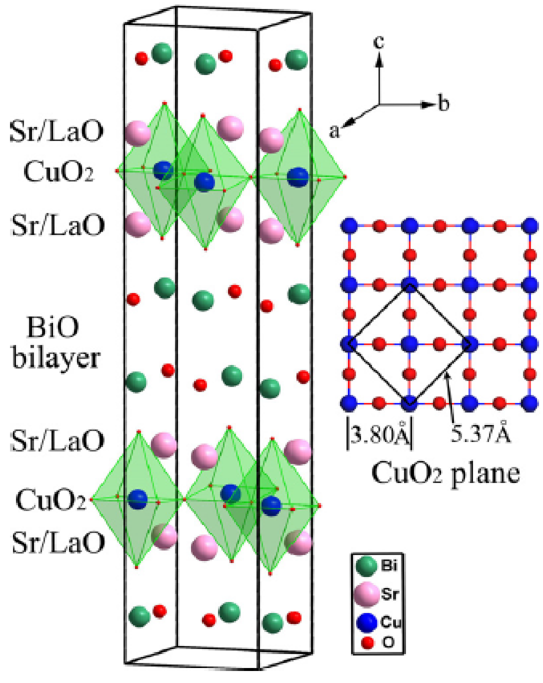
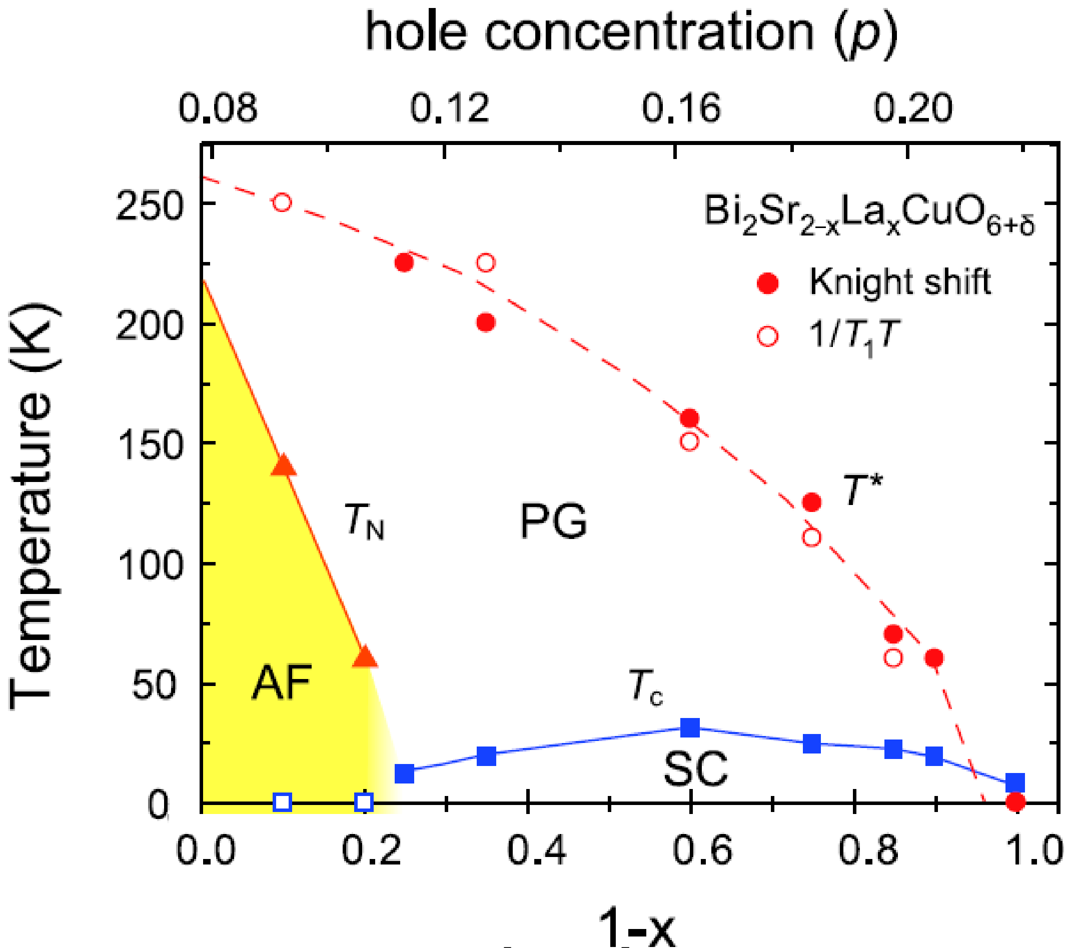


Figure 1. Basic crystal structure of $Bi_2Sr_{2-x}La_xCuO_6$. Unit cell parameters are $a = 5.362$ Å, $b = 5.374$ Å, $c = 24.622$ Å. The CuO_2 plane is also schematically shown in the figure.

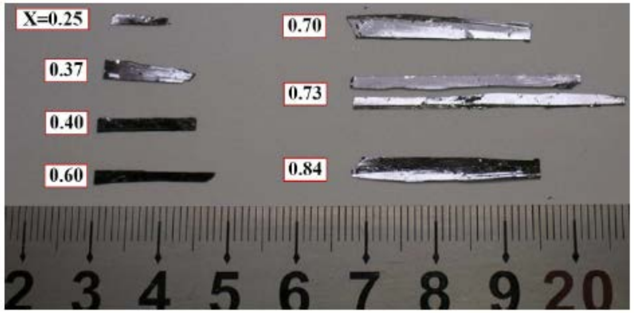
H. Eisaki et al.,
Phys. Rev. B 69, 064512 (2004).

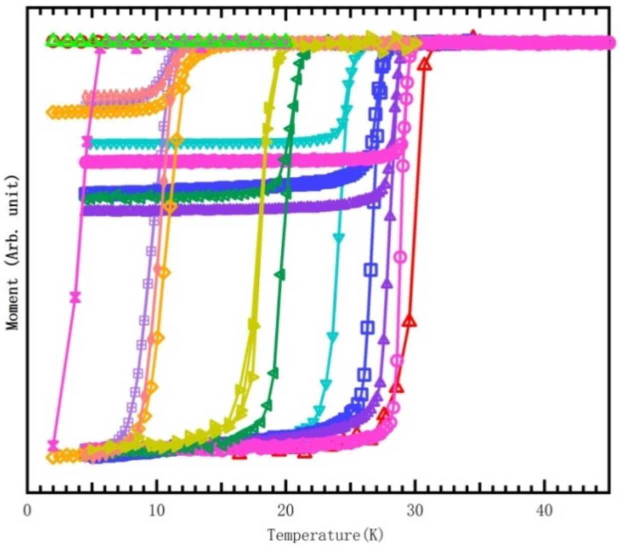


S. Kawasaki et al.,
Phys. Rev. Lett. 105, 137002 (2010).

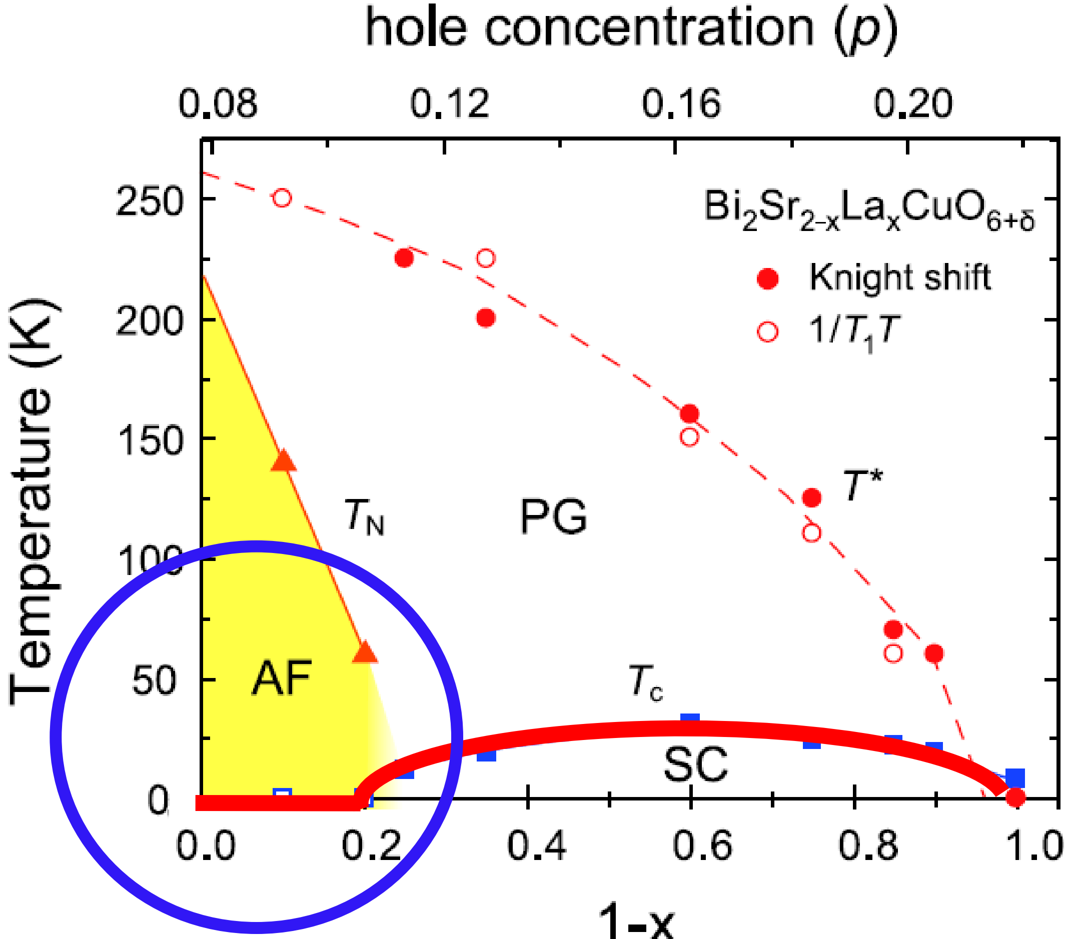
- **Single CuO_2 layer in a unit cell;**
- **Wide range of doping levels;**
- **Relatively Low Tc, beneficial for normal state study.**

$Bi_2(Sr,La)_2CuO_6$ (La-Bi2201) System





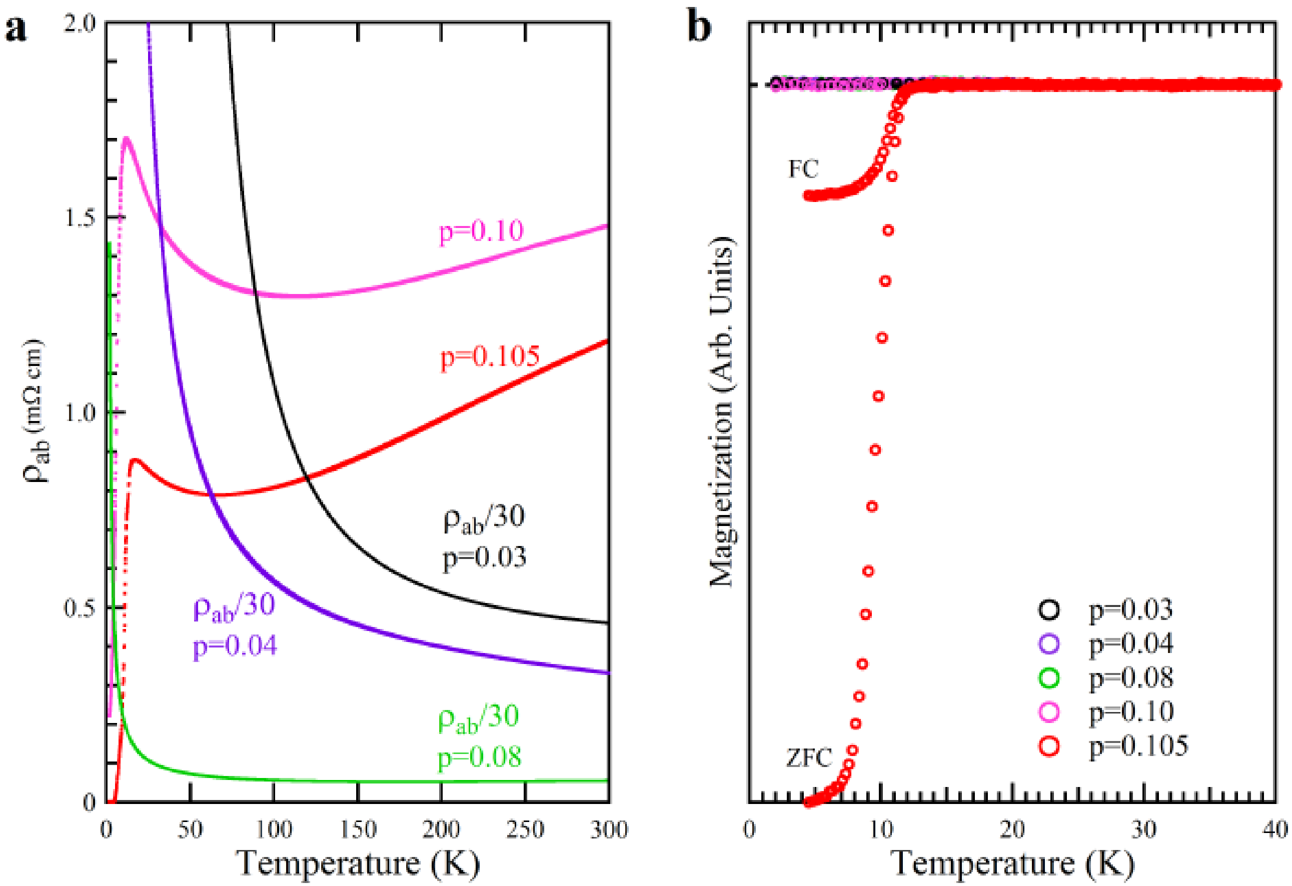
Y. Y. Peng, X. J. Zhou et al.,
Nature Communications 4 (2013)2459.



S. Kawasaki et al.,
Phys. Rev. Lett. 105, 137002 (2010).

The doping covers a wide range, in particular, the insulator-metal-superconductor transition region.

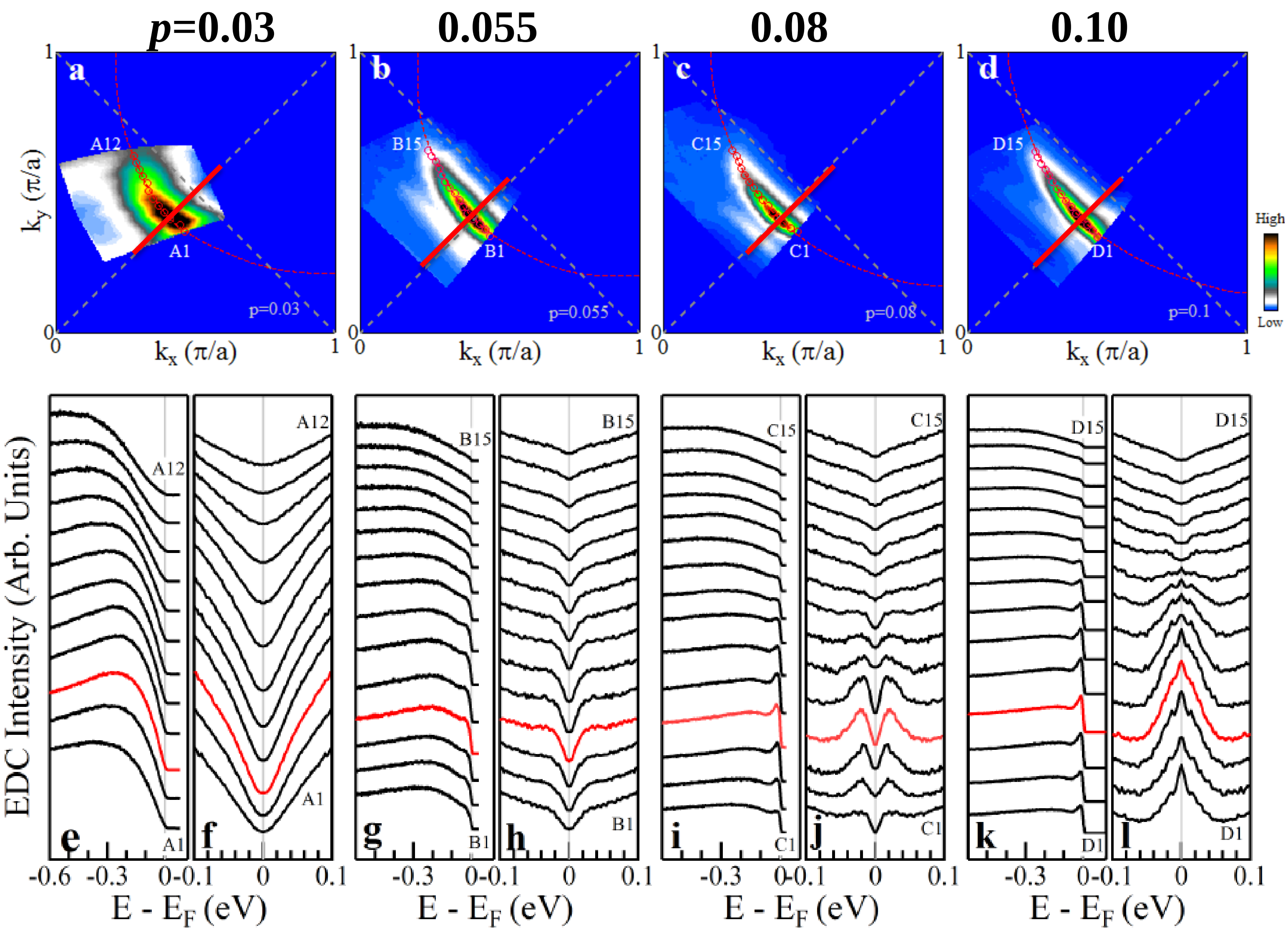
Transport Properties of Heavily-Underdoped La-Bi2201



An insulator-superconductor transition at *p*~0.10:

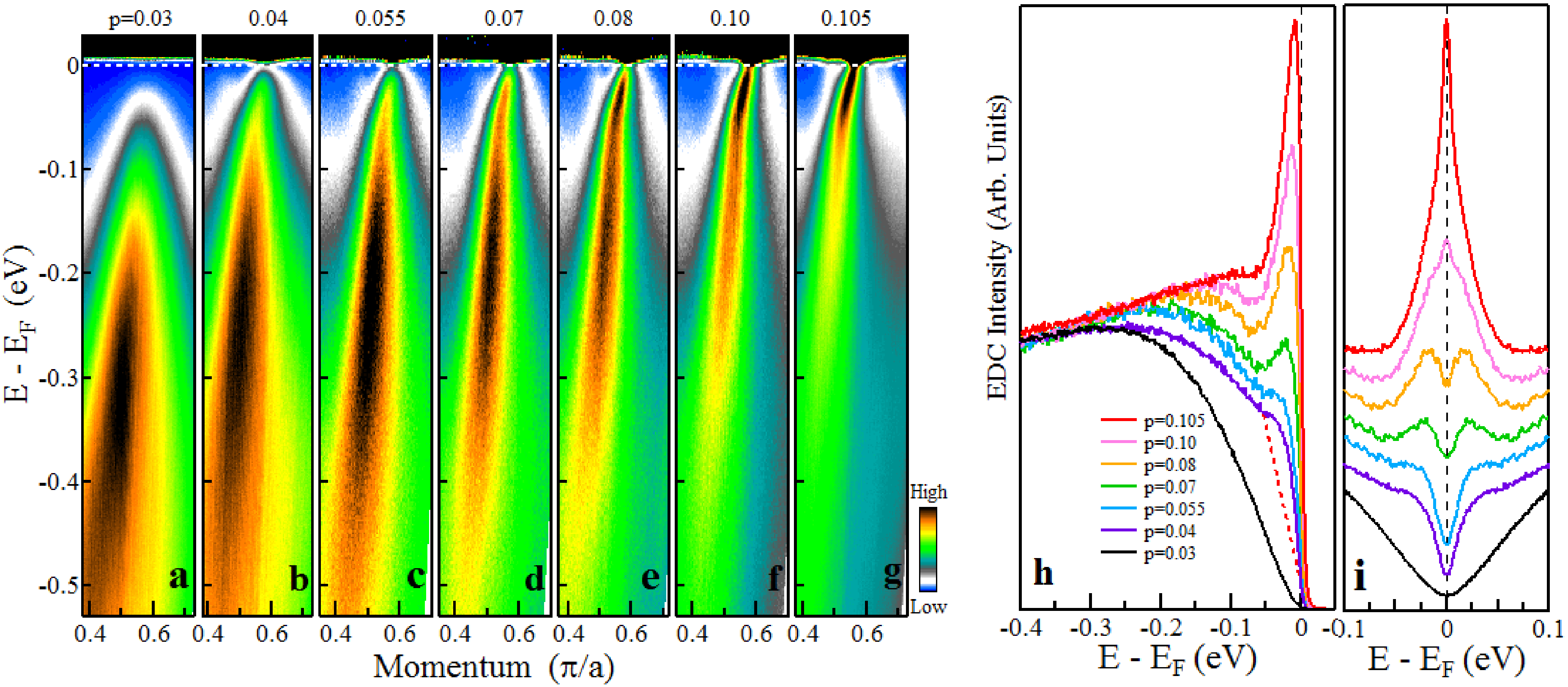
***p*<0.10, Insulator → *p*>0.10 superconductor**

Doping Evolution of "Fermi Surface"



Nodal gap exists for *p*<0.10 → "Fermi surface" is fully gapped)

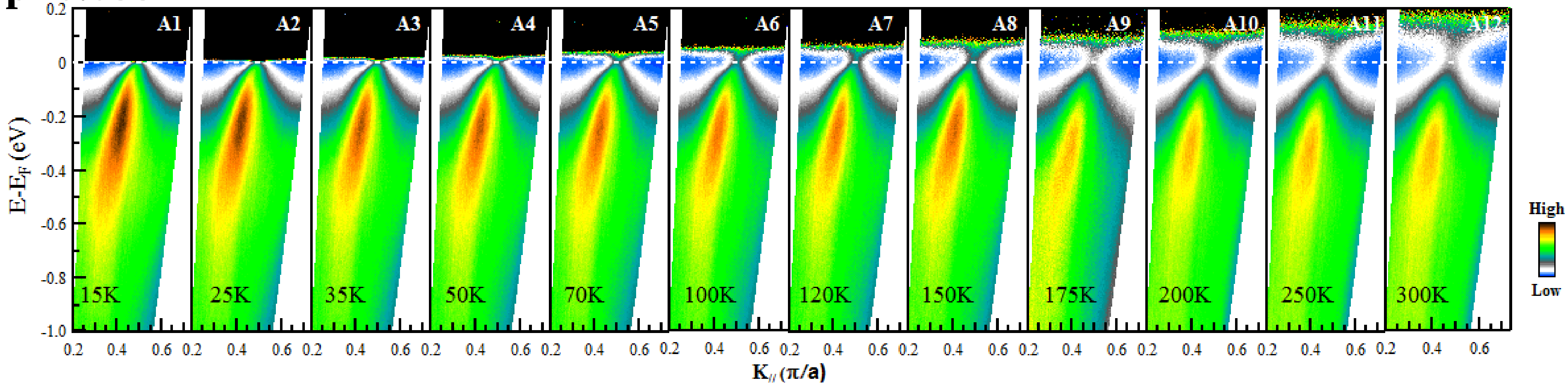
Doping Evolution of Nodal Band and the Nodal Gap

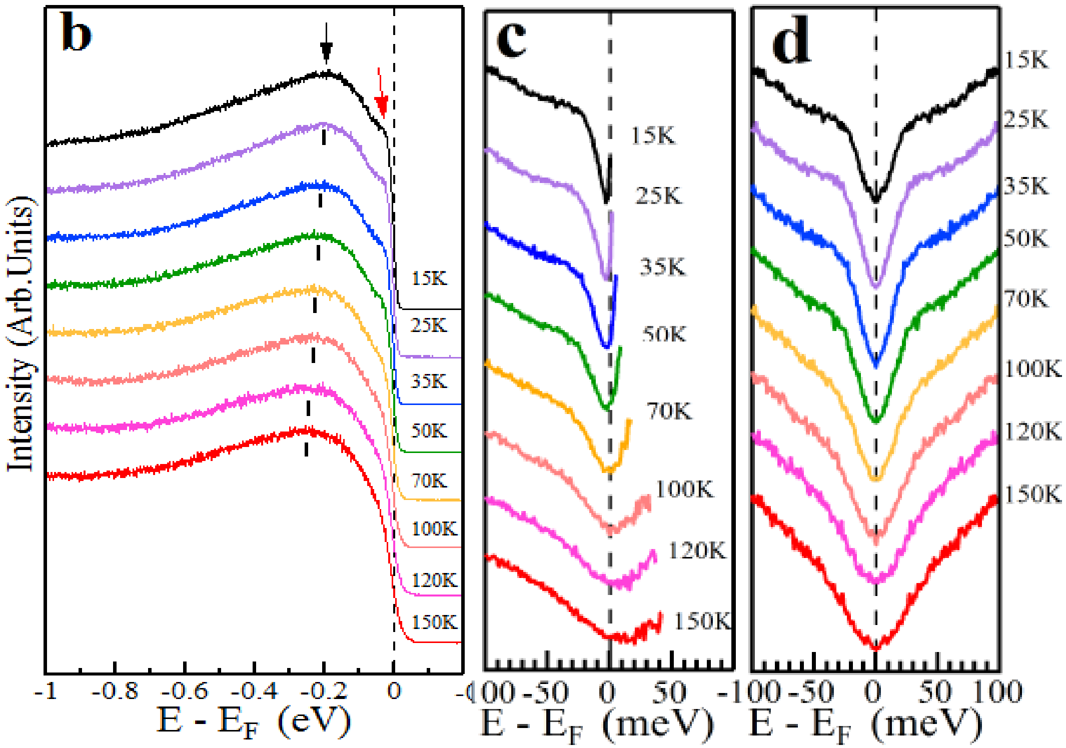


- ➢**Spectral weight transfers from high energy to Fermi level;**
- ➢**Coherence peak appears at low doping and gets sharper with increasing doping;**
- ➢**Nodal gap decreases with increasing doping and closes at *p*~0.10.**

Temperature Evolution of the Nodal Gap

p=0.055

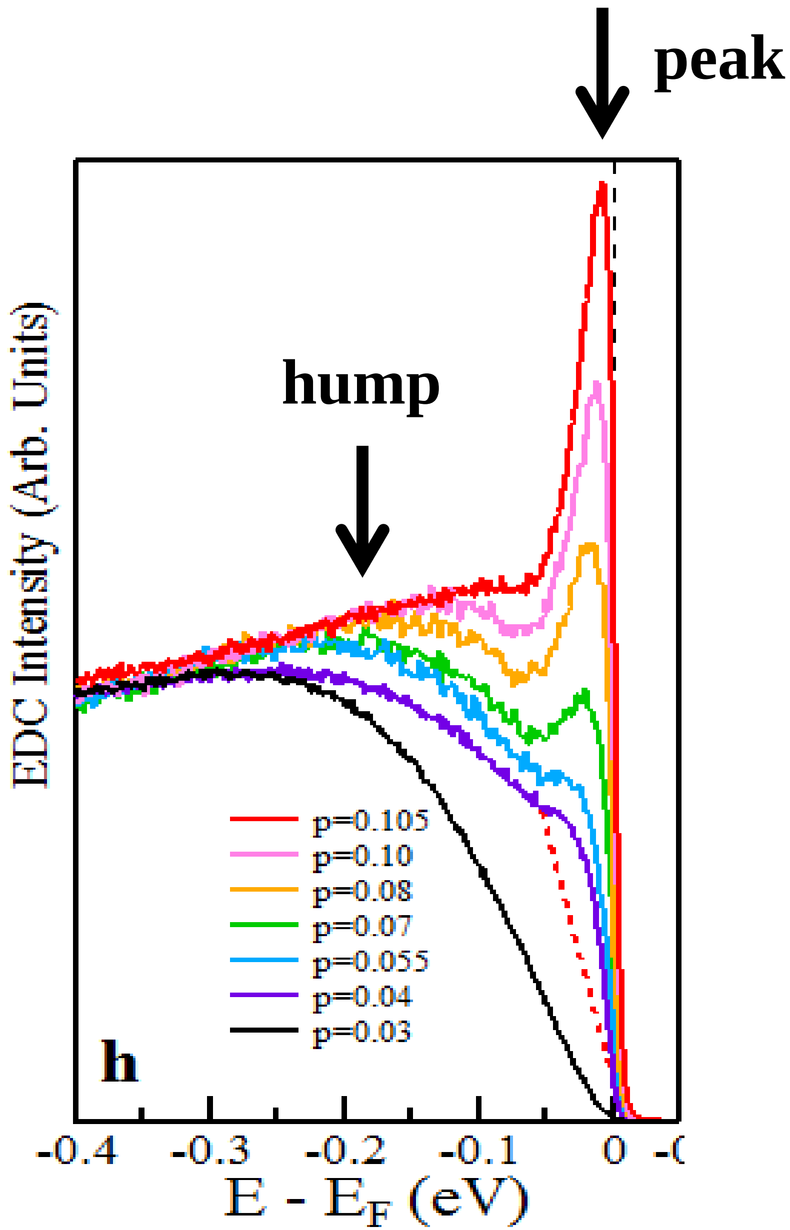




- ✓ **Nodal gap persists up to 300K.**
- ✓ **Coherence peak vanishes above 150K.**
- ✓ **Particle-hole symmetry.**

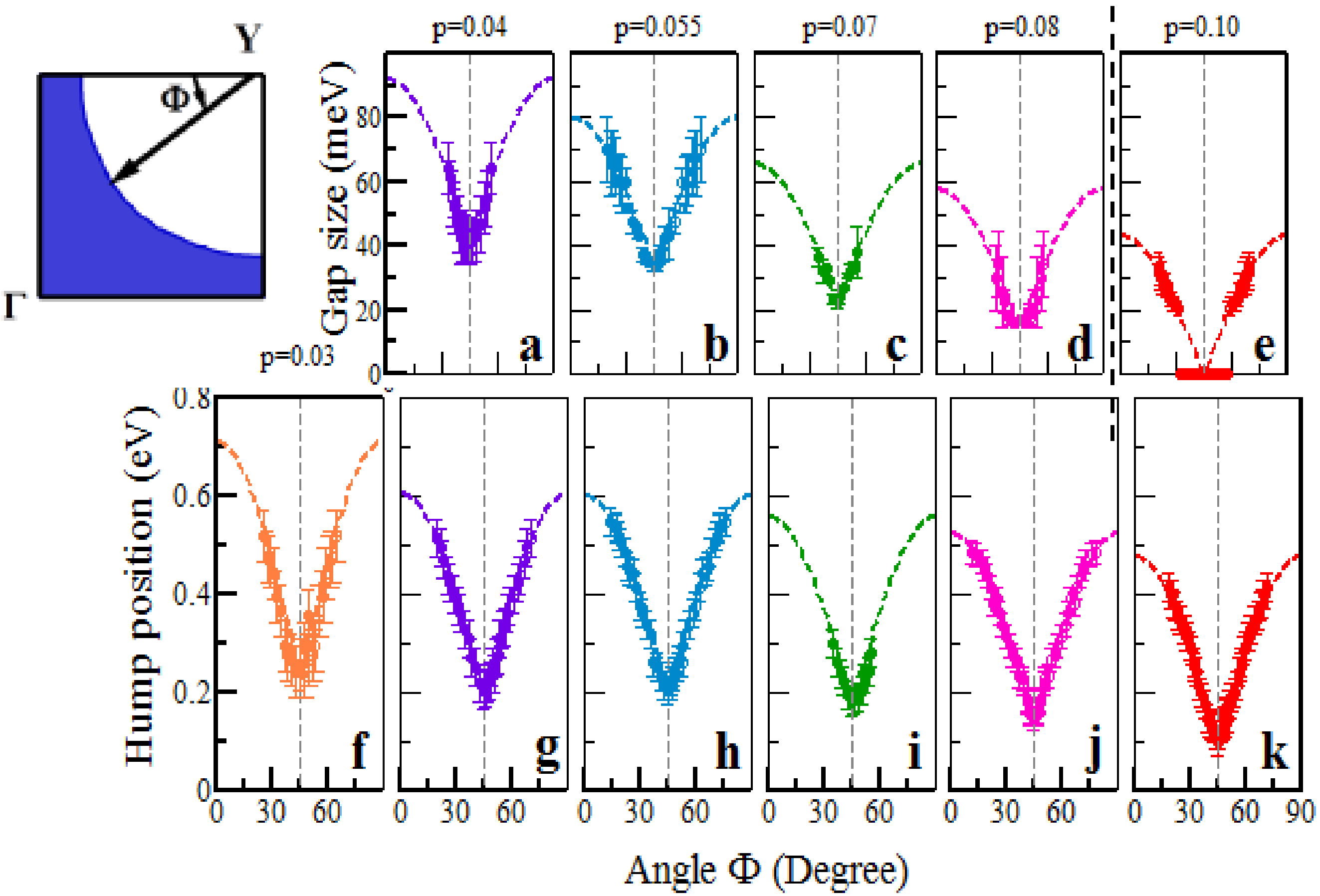
Y. Y. Peng, X. J. Zhou et al.,
Nature Communications 4 (2013)2459.

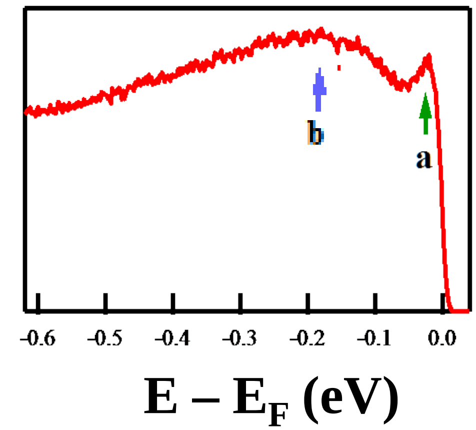
Nodal EDC Lineshape – Coherence Peak + Hump



Momentum Dependence of the Energy Gap

"Fermi surface" fully gapped.

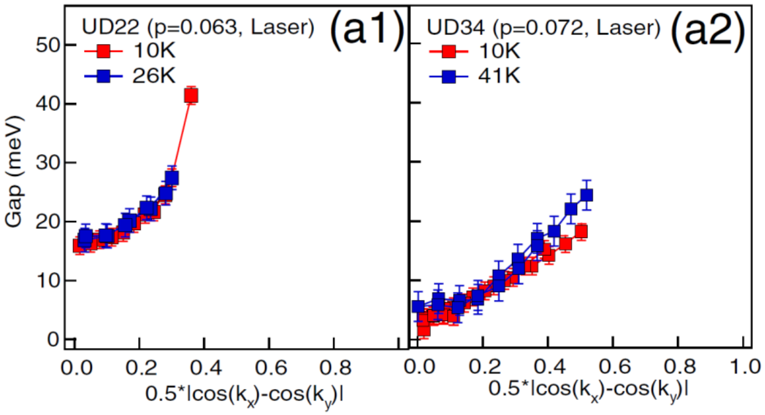


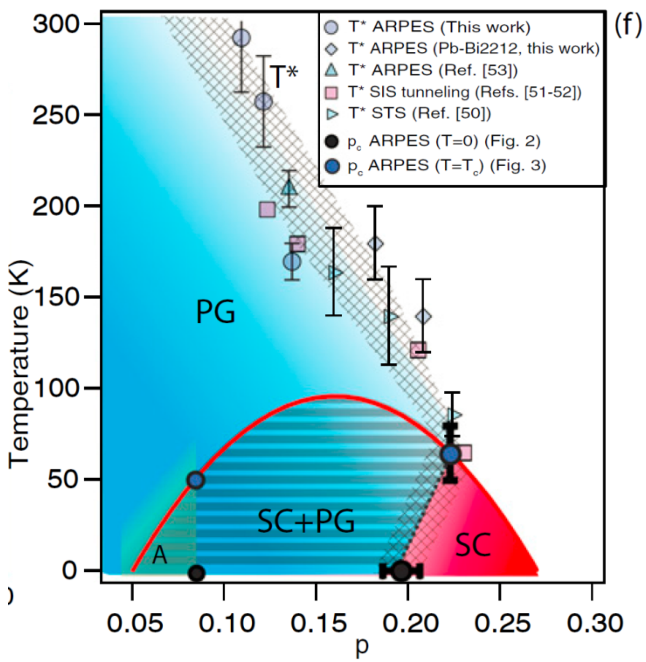


- **Gap ----- d-wave like** $\Delta = \Delta_0 \cos(2\Phi) + \Delta_N$
- **Hump ----- d-wave like** $P_h = P_{h0} \cos(2\Phi) + P_{hN}$

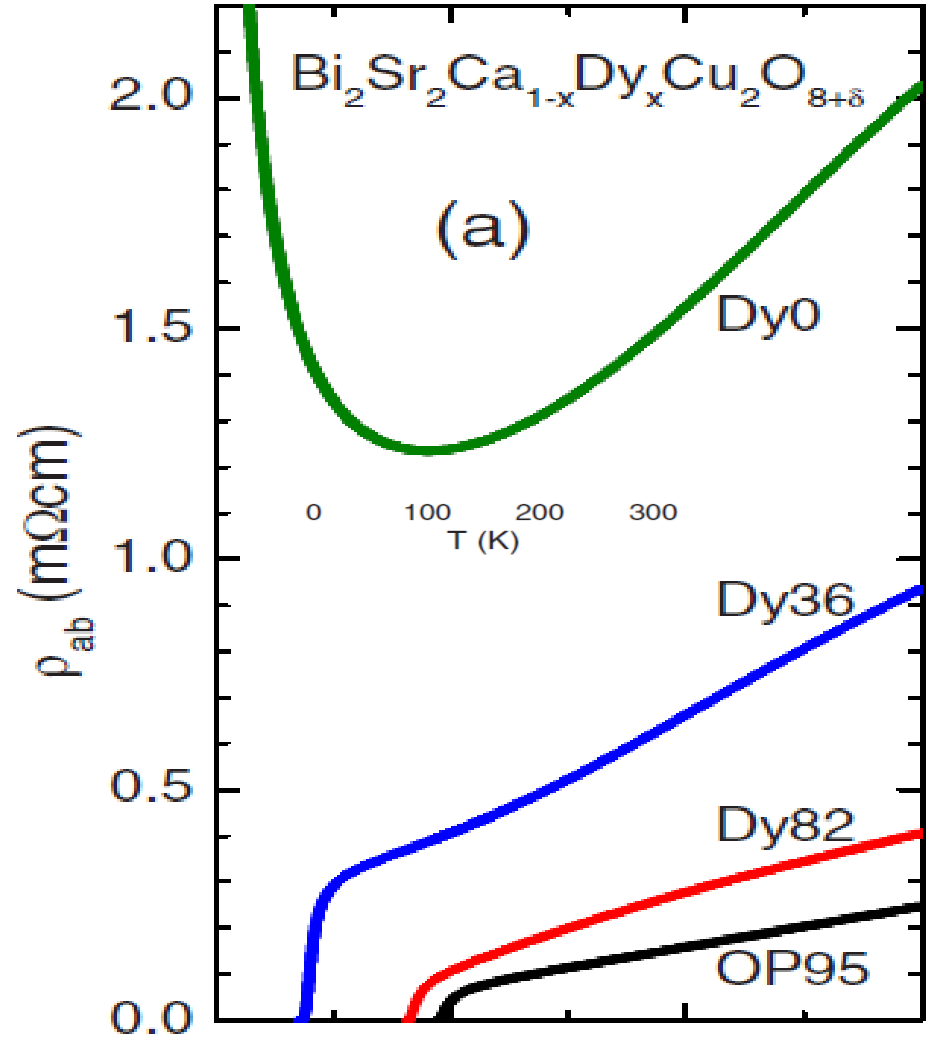
Y. Y. Peng, X. J. Zhou et al., Nature Communications 4 (2013)2459.

Nodal Gap in Bi2212





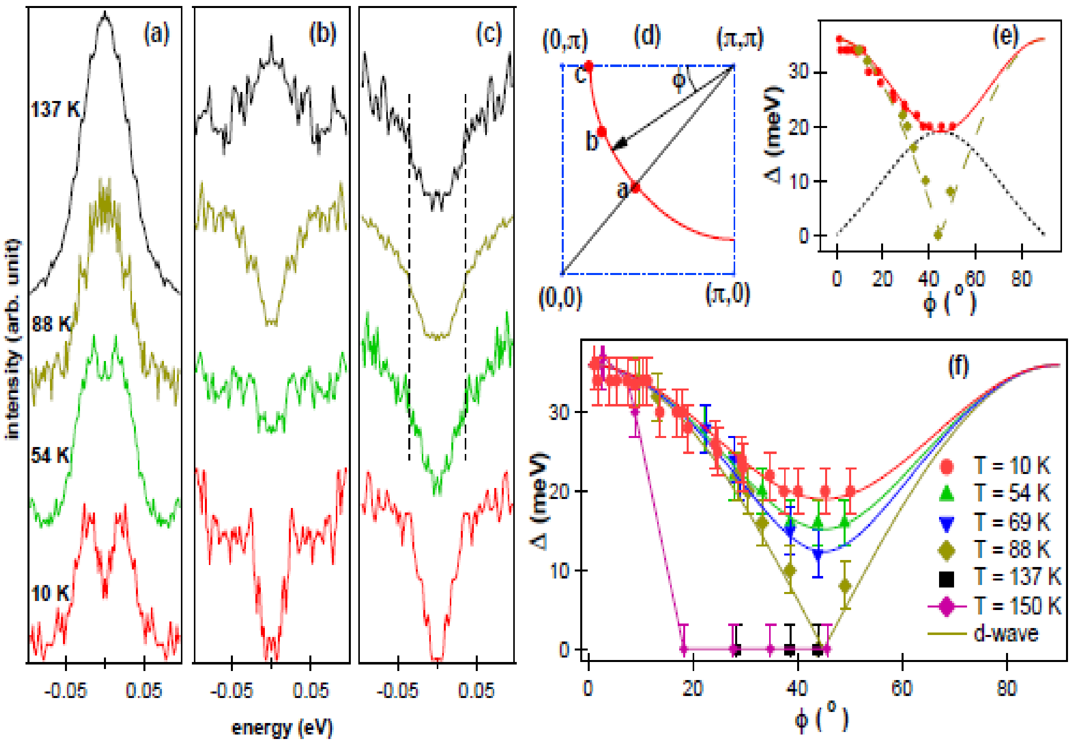
I. Vishik, Z. X. Shen et al., PNAS 6, 18332(2012).



X. F. Sun et al., Phys. Rev. B 77 (2008) 094515.

Nodal Gap in LSCO

LSCO (x = 0.08, Tc = 20 K)



E. Razzoli et al., Phys. Rev. Lett. 110 (2013)047004

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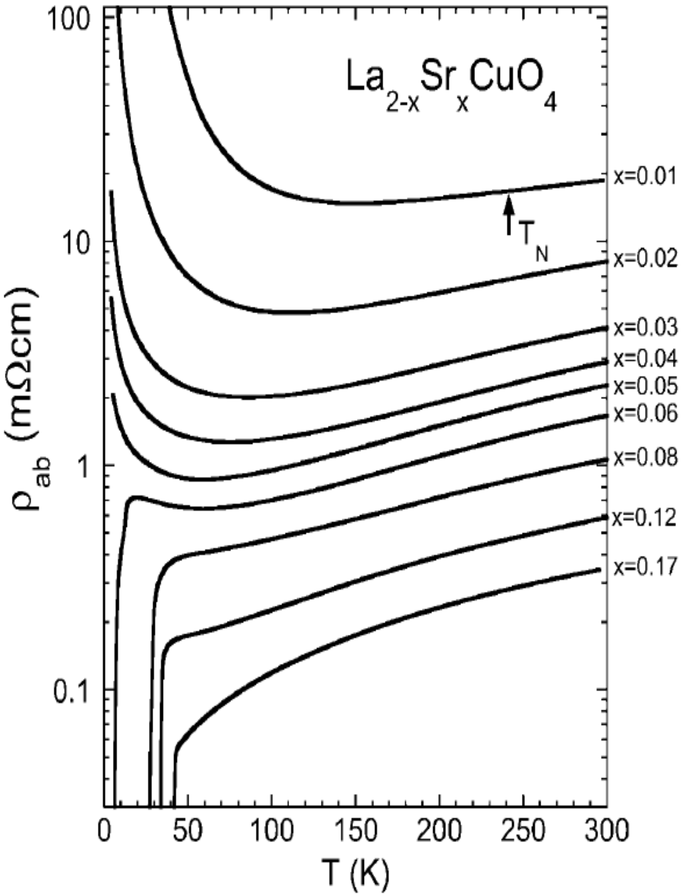
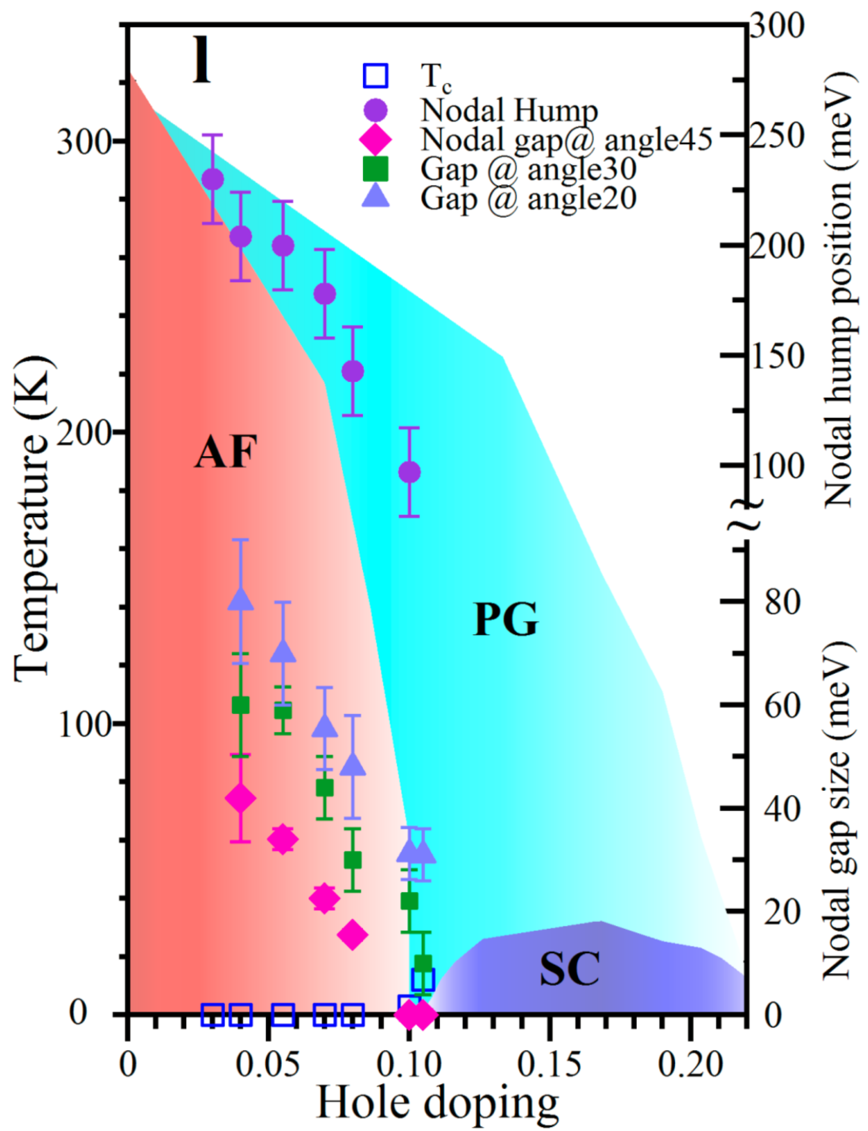
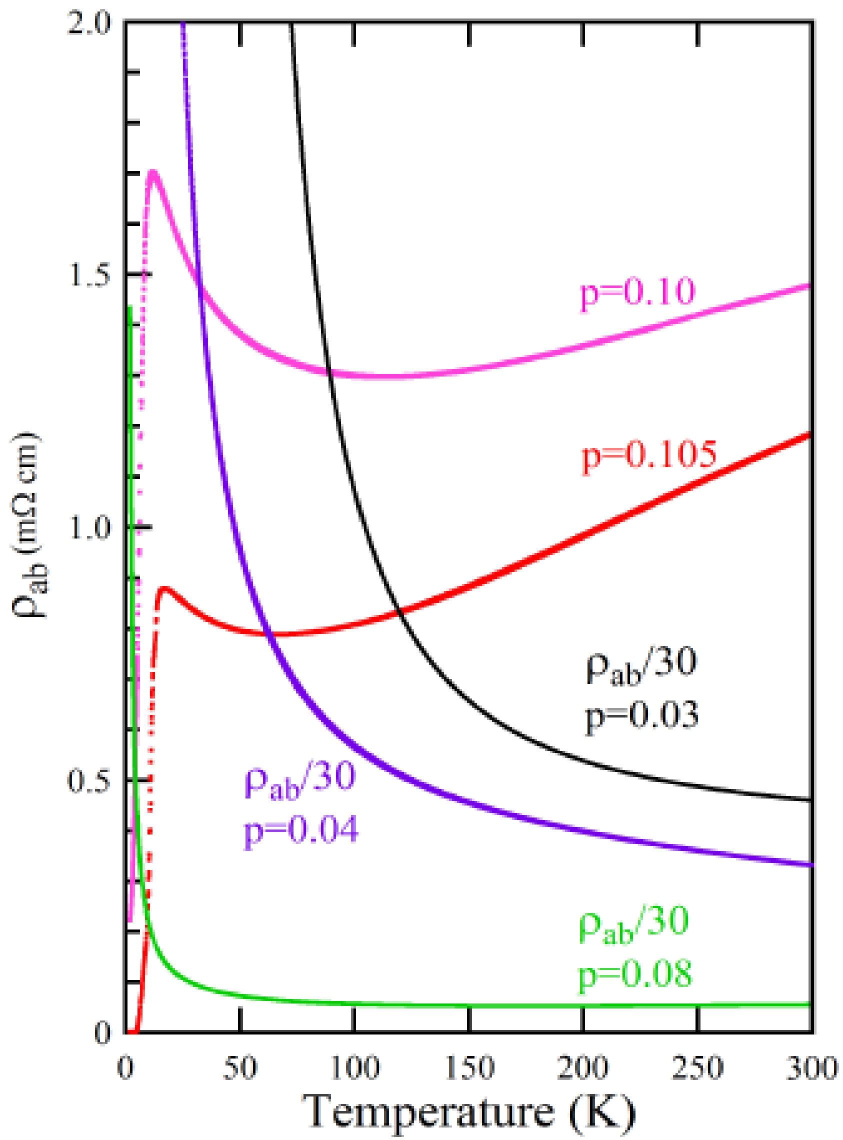


Y. Ando et al.,
Phys. Rev. Lett. 87(2001) 017001.

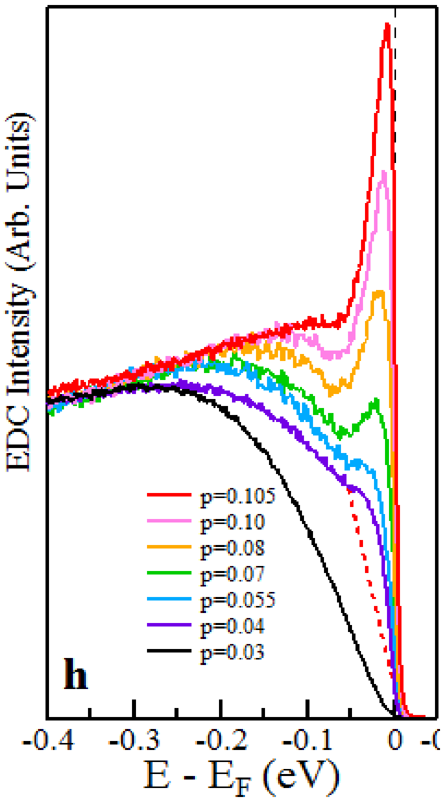
Consistency between ARPES and Transport in La-Bi2201

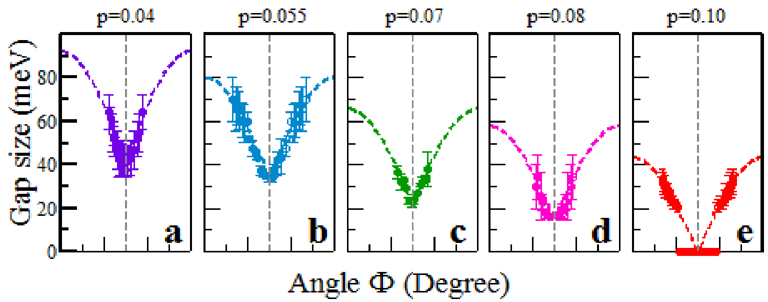


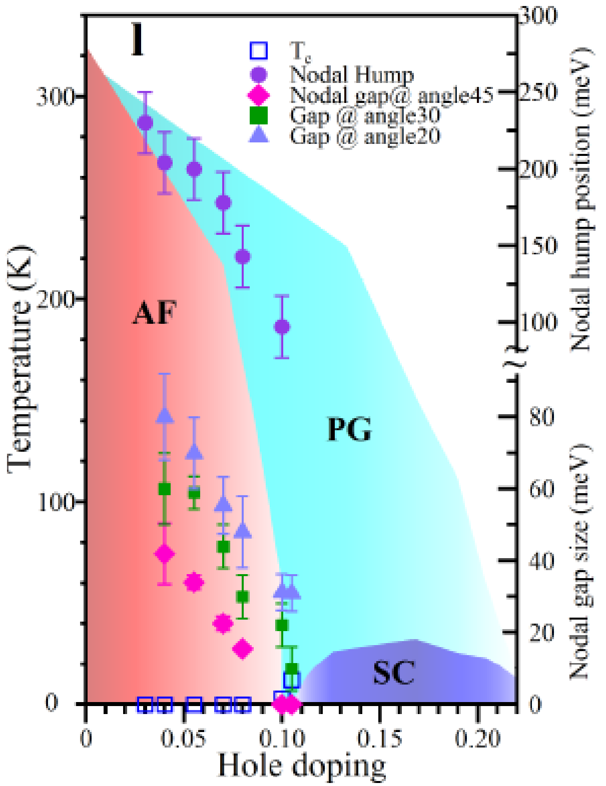


Y. Y. Peng, X. J. Zhou et al., Nature Communications 4 (2013)2459.

Main Experimental Observations







- ➢ **EDC lineshape—peak-dip-hump;**
- ➢ ***d*-wave-like gap form;**
- ➢ **Near p~0.10, (1). The 3D antiferromagnetic order disappears;**
  (2). Superconductivity starts to emerge;
  (3). Nodal gap gets to zero.

Origin of the Nodal Gap?-Open Question

- **Pure electron correlation?**
- **Small polaron formation?**
- **Disorder effect?** T. M. Rice, F. C. Zhang et al.
- **Topological superconductor?**
  Y. M. Liu, T. Xiang, D. H. Lee, Nature Phys. 10 (2014) 634.
- **Strong electron-phonon coupling + antiferromagnetism?**

1. At a critical doping of *p*~0.10, there is an insulator-superconductor transition in Bi2201;

2. A close connection between the nodal gap, antiferromagnetism and superconductivity.

Outline

- VUV Laser-Based ARPES;
- Laser ARPES on High-Tc Cuprate Superconductors:

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  b. Evolution of nodal-kink and antinodal kink in Bi2212;

  c. Extraction of Eliashberg Functions in Bi2212.

- Summary.

PRL **111,** 107005 (2013) PHYSICAL REVIEW LETTERS week ending 6 SEPTEMBER 2013

Coexistence of Two Sharp-Mode Couplings and their Unusual Momentum Dependence in the Superconducting State of $Bi_2Sr_2CaCu_2O_{8+\delta}$ Revealed by Laser-Based Angle-Resolved Photoemission

Junfeng He,[1] Wentao Zhang,[1] Jin Mo Bok,[2] Daixiang Mou,[1] Lin Zhao,[1] Yingying Peng,[1] Shaolong He,[1] Guodong Liu,[1] Xiaoli Dong,[1] Jun Zhang,[1] J. S. Wen,[3] Z. J. Xu,[3] G. D. Gu,[3] Xiaoyang Wang,[4] Qinjun Peng,[4] Zhimin Wang,[4] Shenjin Zhang,[4] Feng Yang,[4] Chuangtian Chen,[4] Zuyan Xu,[4] H.-Y. Choi,[2] C. M. Varma,[5] and X. J. Zhou[1,*]

Junfeng HE

Power of ARPES – A Tool for Many-Body Effects

Under the sudden approximation, photoemission measures
single-particle spectral function

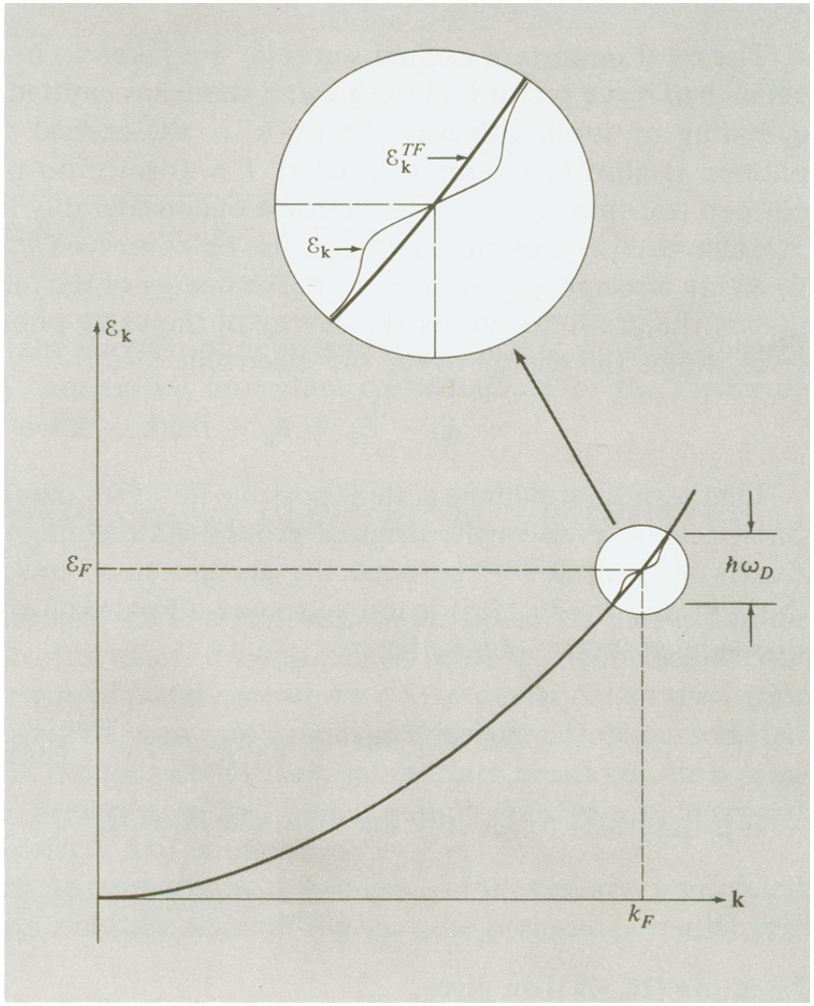
$$A(k,\omega) = \frac{1}{\pi} \frac{\mathrm{Im}\,\Sigma}{[\hbar\omega - E_k^0 - \mathrm{Re}\,\Sigma]^2 + [\mathrm{Im}\,\Sigma]^2}$$

Electron self-energy: $\Sigma = \mathrm{Re}\,\Sigma + i\,\mathrm{Im}\,\Sigma$

Many-Body Effects: **Interaction of electrons with other entities**

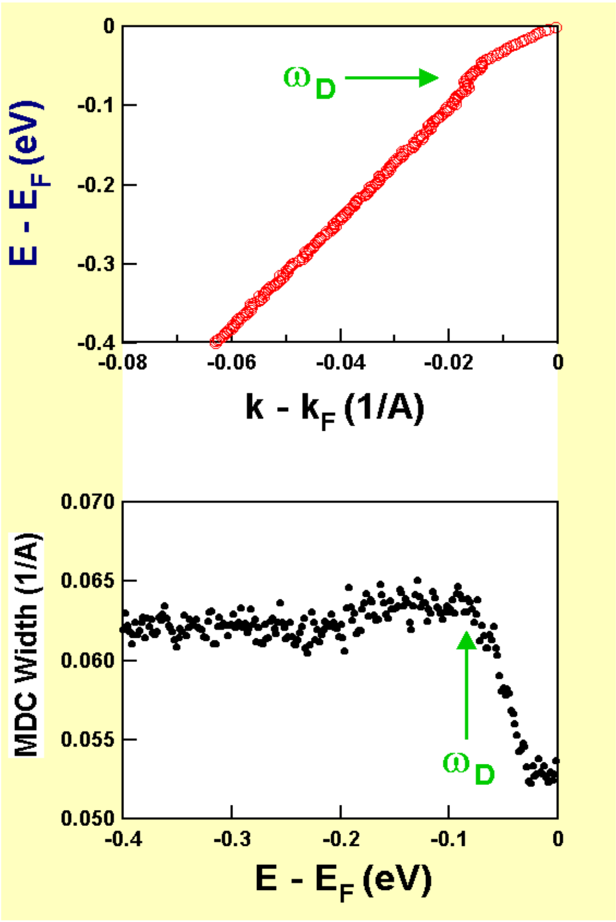
such as other electrons, impurity, disorder, phonons, magnons and etc.

Manifestation of Many-Body Effects: Band Renormalization



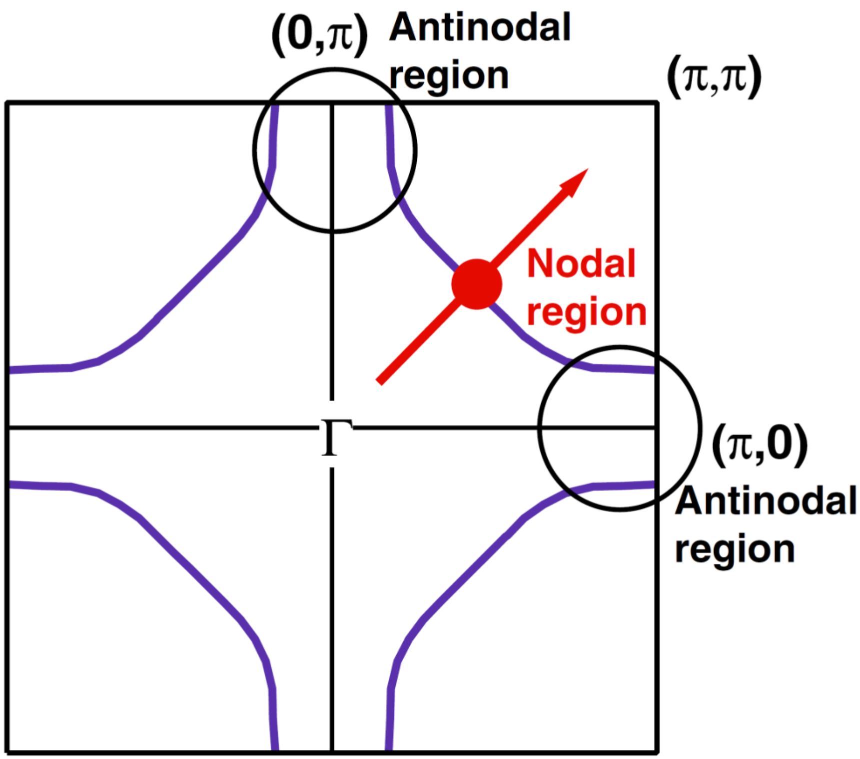
Ashcroft-Mermin, Solid State Phyics

Be(0001) Surface State

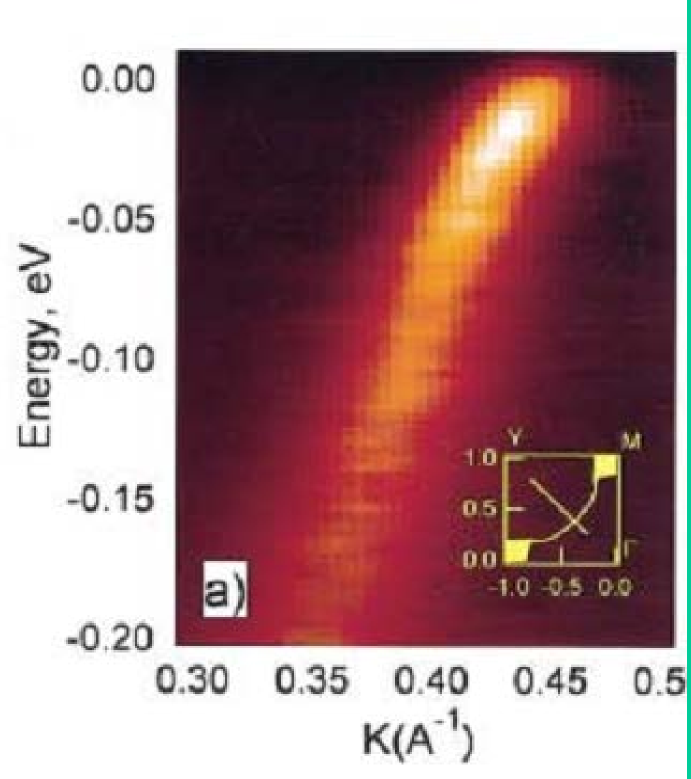


Hengsberger et al., PRL 83(1999)592.
S. Lashell et al., PRB 61(2000)2371.
S. J. Tang et al., Phys. Stat. Solidi. 241(2004)2345.

Nodal Kink in Cuprate Superconductors



~70meV nodal kink



P. V. Bogdanov et al., Phys. Rev. Lett. 85, 2581 (2000).

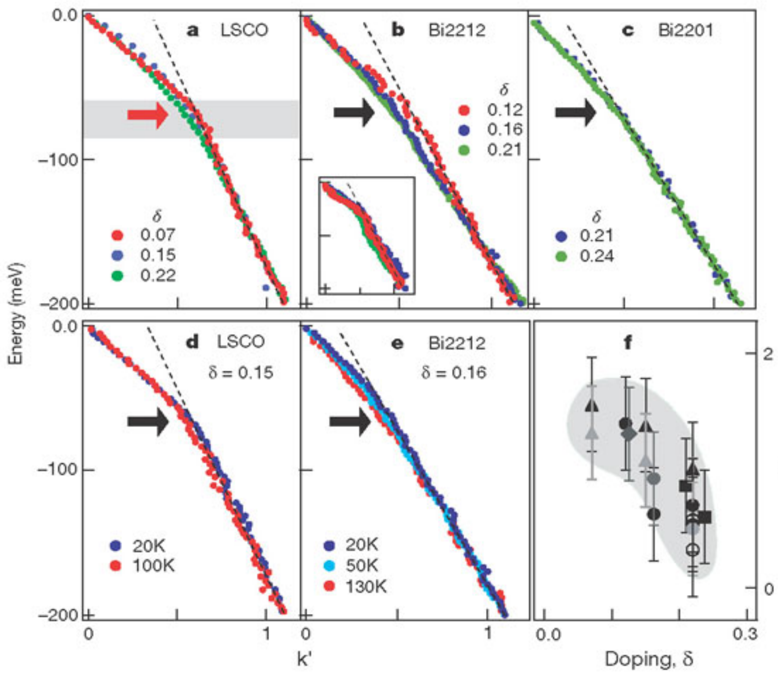
A. Kaminski et al., Phys. Rev. Lett. 86, 1070 (2001).

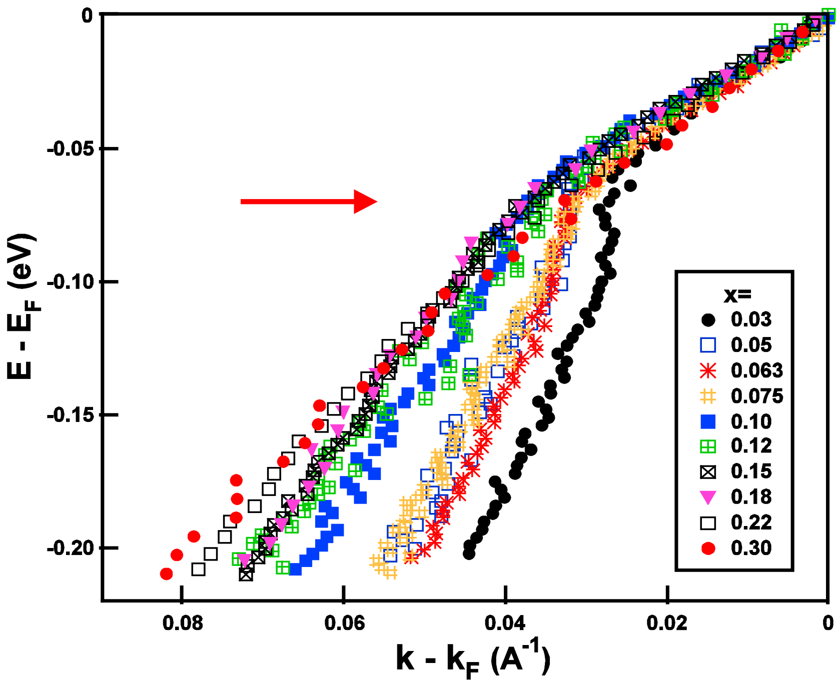
P. Johnson et al., Phys. Rev. Lett. 87, 177007 (2001).

A. Lanzara et al., Nature (London) 412, 510 (2001).

X. J. Zhou et al., Nature (London) 423, 398 (2003).

Ubiquitous Existence of Nodal "KINK"





A. Lanzara, X. J. Zhou, Z.-X. Shen ***et al., Nature 412, 510 (2001).***

X. J. Zhou ***et al., Nature 423, 398 (2003).***

P. V. Bogdanov et al., Phys. Rev. Lett. 85, 2581 (2000);
A. Kaminski et al., Phys. Rev. Lett. 86, 1070 (2001);

P. Johnson et al., Phys. Rev. Lett. 87, 177007 (2001).
A. Kordyuk et al., Phys. Rev. Lett. 97, 017002 (2006).

Kink is present

(1). In various materials;
(2). At various dopings;
(3). Above Tc and below Tc

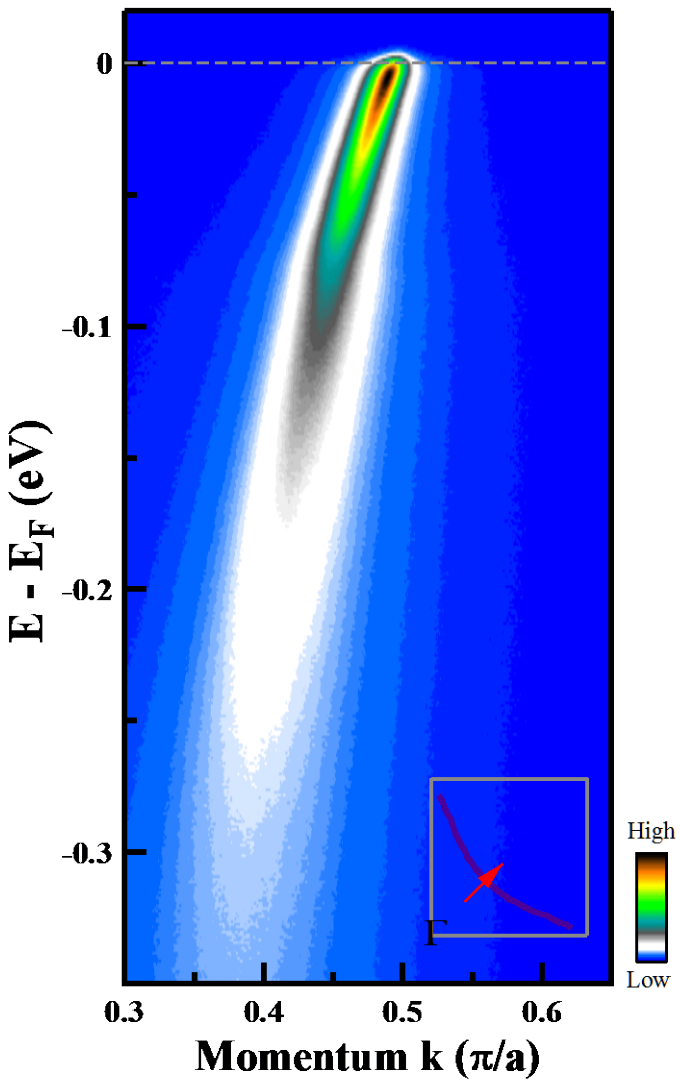
Electron coupling with Bosons:

Phonons

or

Magnetic Resonance Mode?

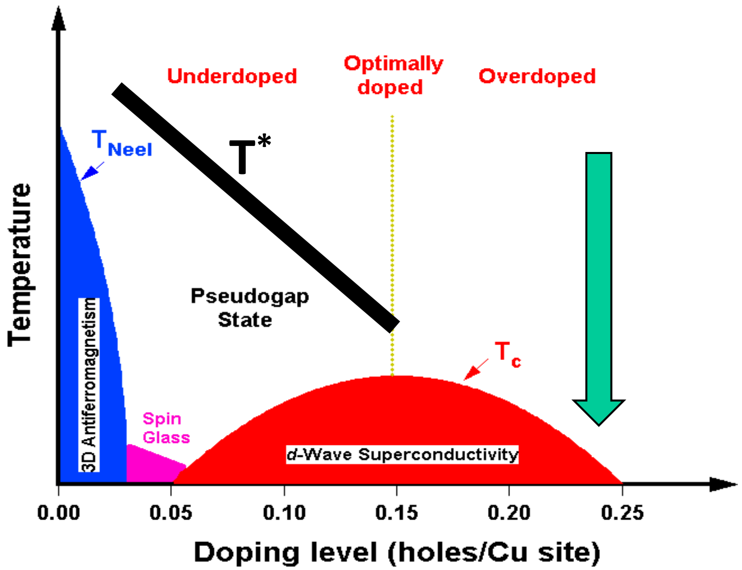
Laser ARPES on Nodal Dispersion of Pb-Bi2201



Heavily Overdoped, Tc=5K

- close to Fermi liquid
- Weak magnetic excitation

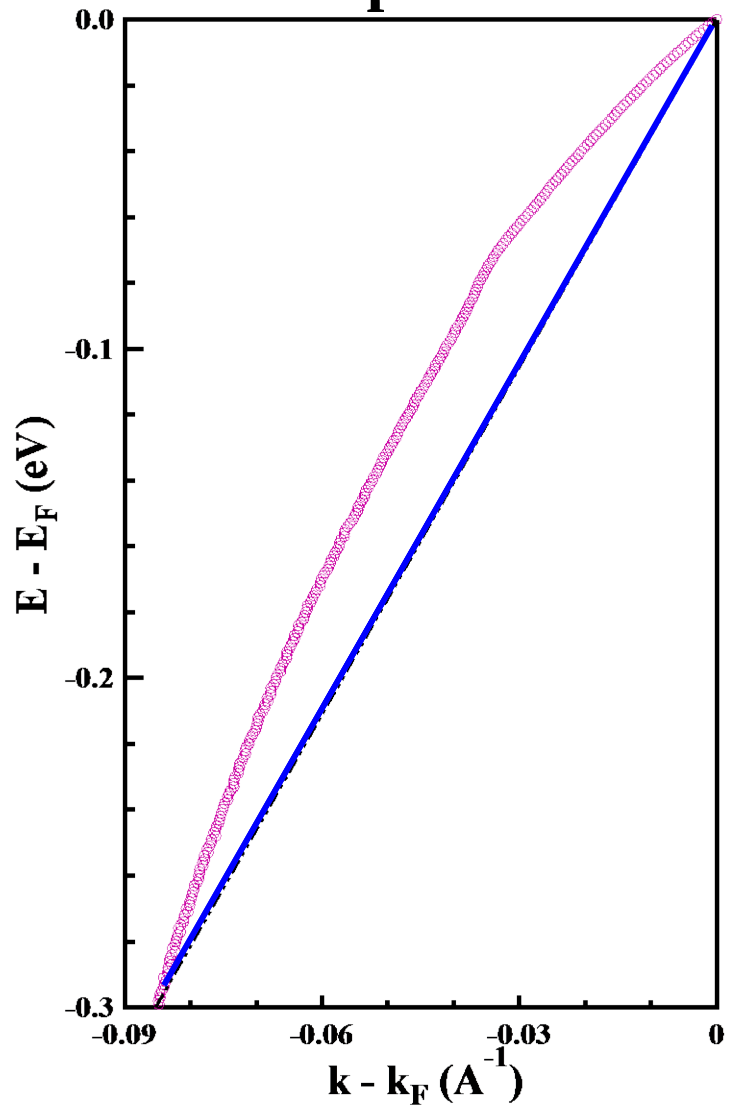
Energy Resolution: 1.0 meV



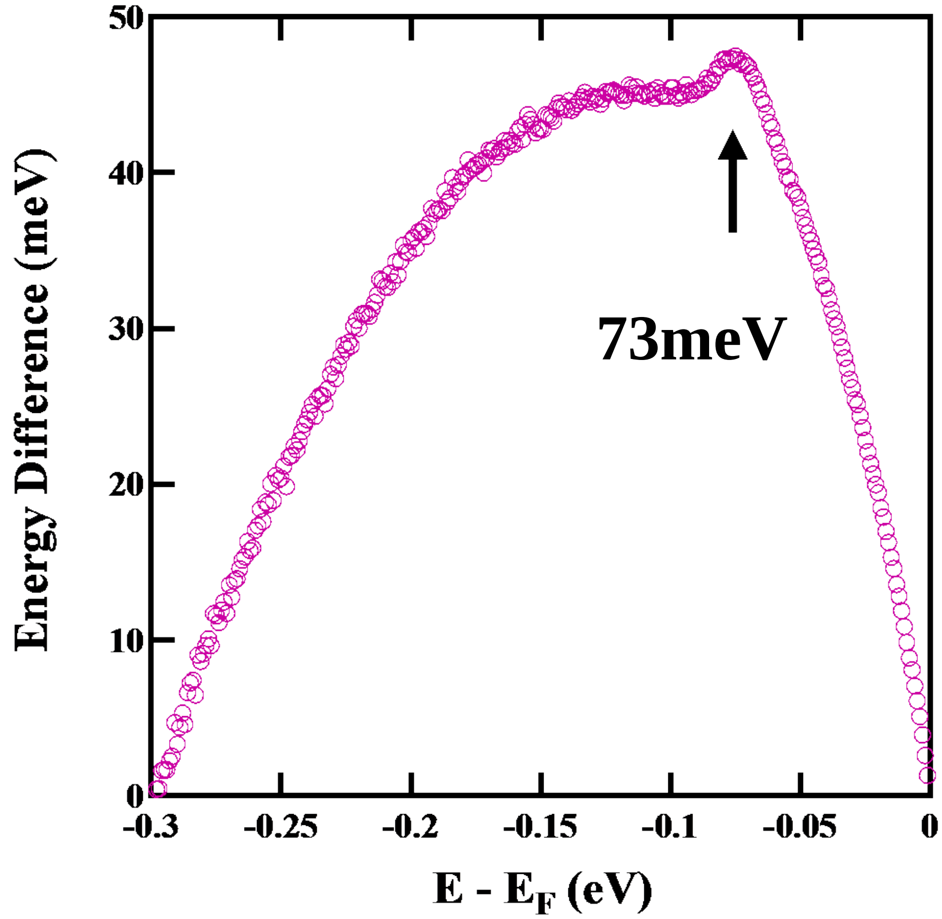
Lin Zhao, J. R. Shi, X. J. Zhou et al., Phys. Rev. B 83 (2011)184515

Nodal "Self-Energy" in Pb-Bi2201 (Tc=5K, Heavily Overdoped)

Dispersion



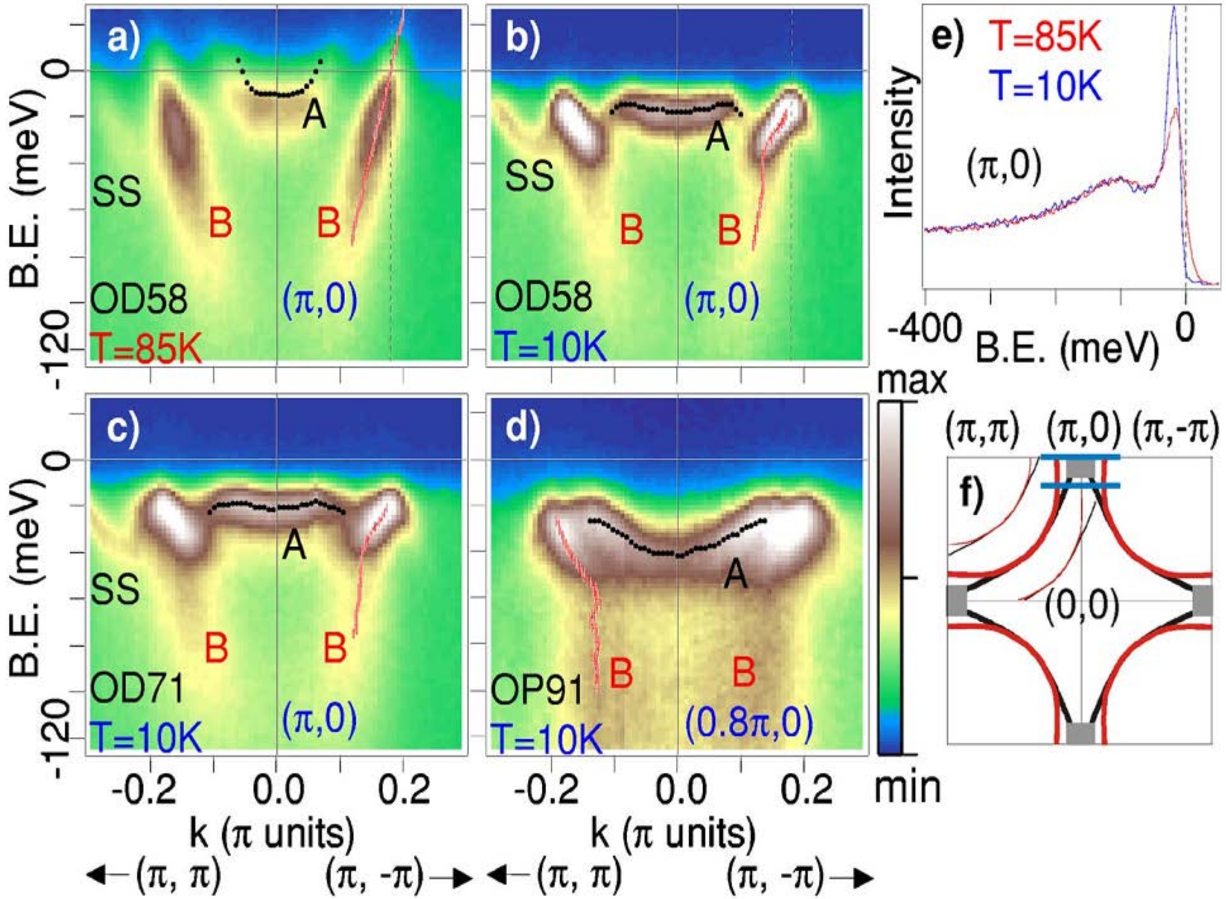
Effective Self-Energy



Lin Zhao, J. R. Shi, X. J. Zhou et al., Phys. Rev. B 83 (2011)184515

Antinodal Kink in Cuprate Superconductors

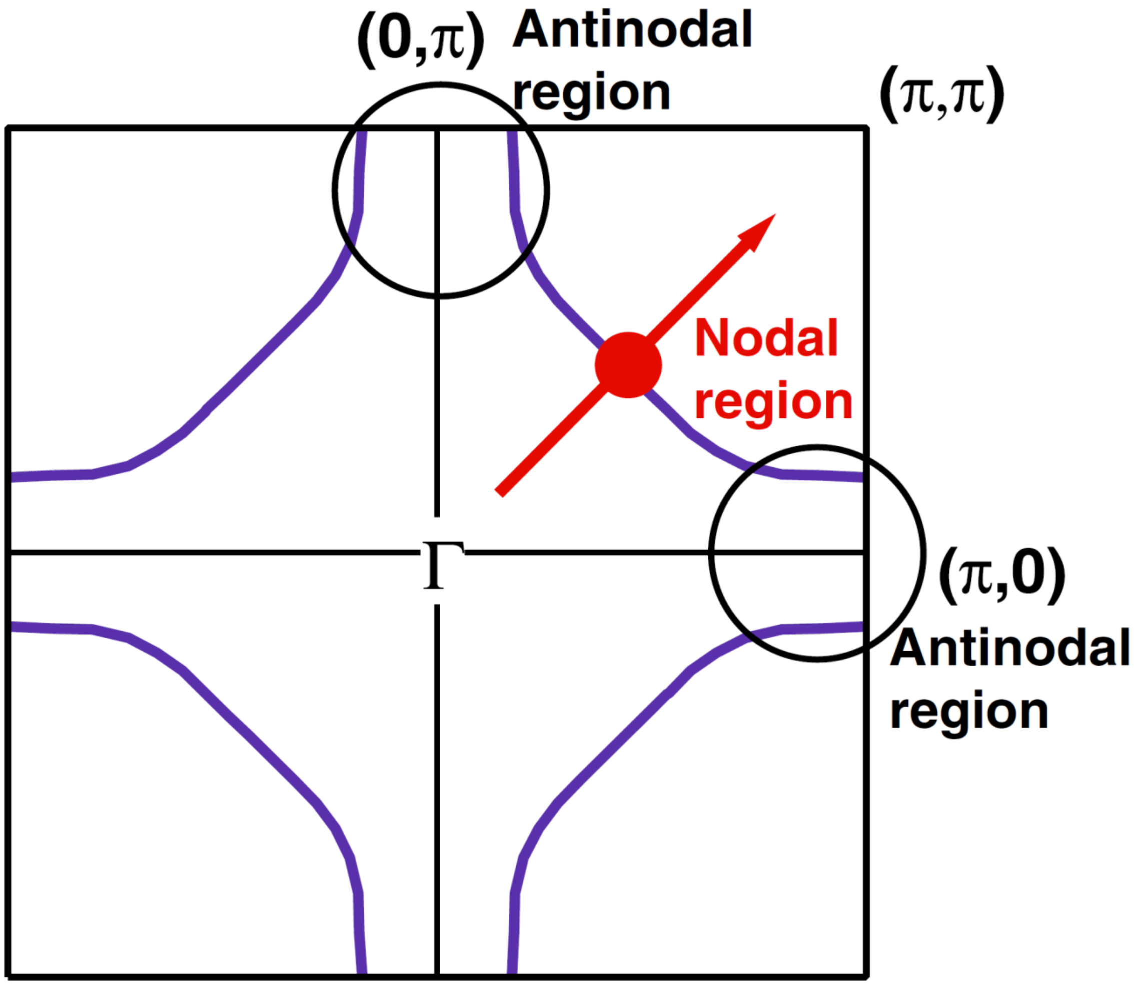
~40meV antinodal kink



A. D. Gromko et al., Phys. Rev. B 68, 174520 (2003);
T. K. Kim et al., Phys. Rev. Lett. 91, 167002 (2003);
T. Sato et al., Phys. Rev. Lett. 91, 157003 (2003);
T. Cuk et al., Phys. Rev. Lett. 93, 117003 (2004).

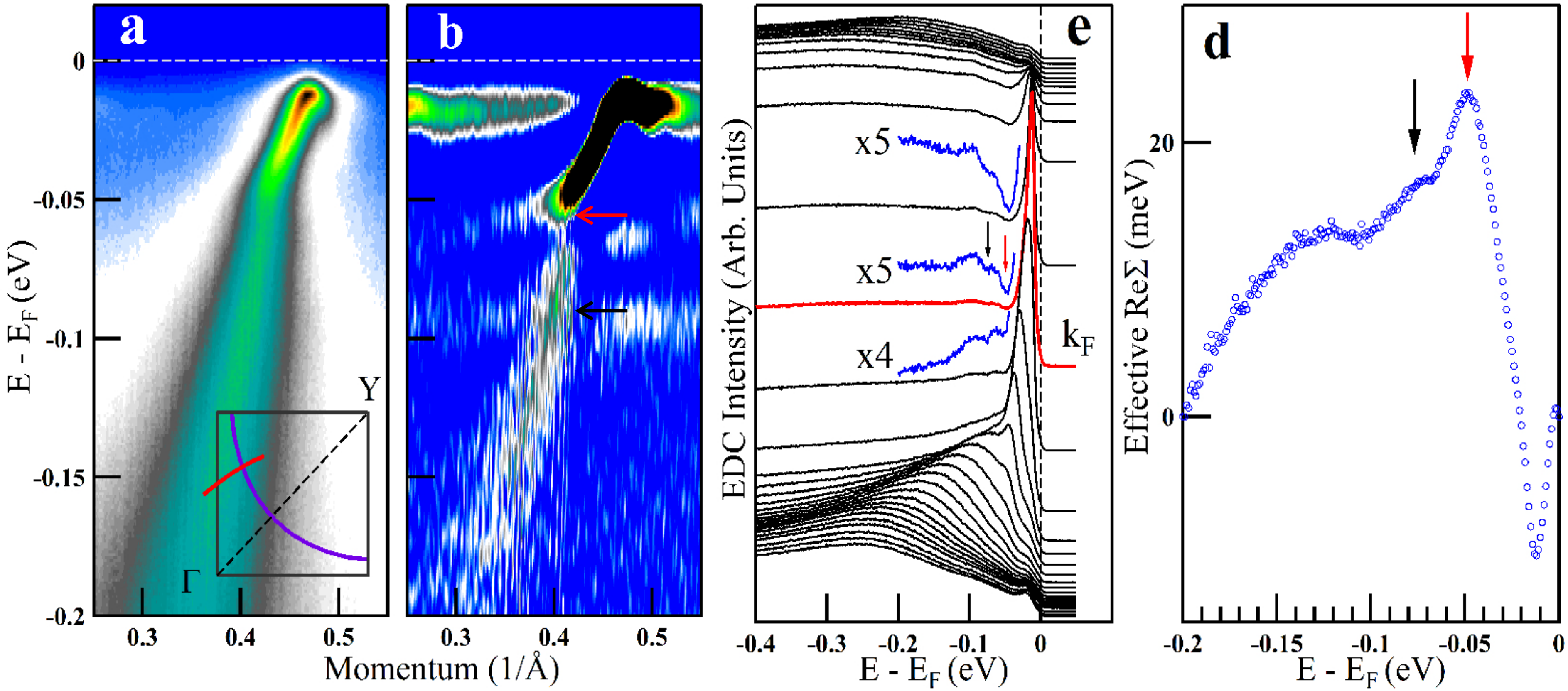
Relation between Nodal Kink and Antinodal Kink?

How does 70meV nodal kink evolve into 40meV antinodal kink?



Observation of Coexisting Two Energy Scales (HI and LW)

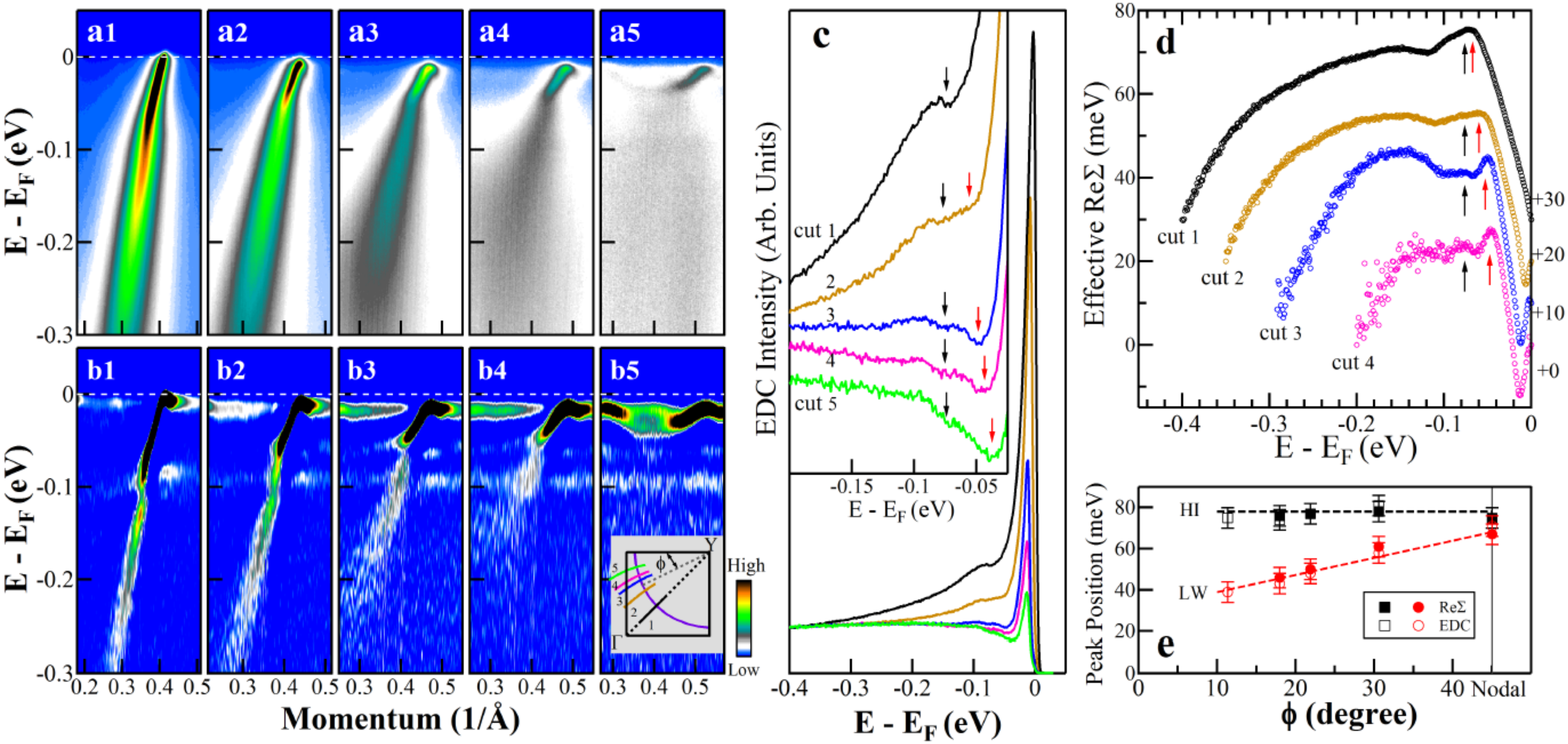
OD82K Bi2212 at 17K (Superconducting state)



Junfeng He, H. Y. Choi, C. Varma, X. J. Zhou et al.,
Phys. Rev. Lett. 111 (2013) 107005.

Momentum Dependence of the Two Energy Scales

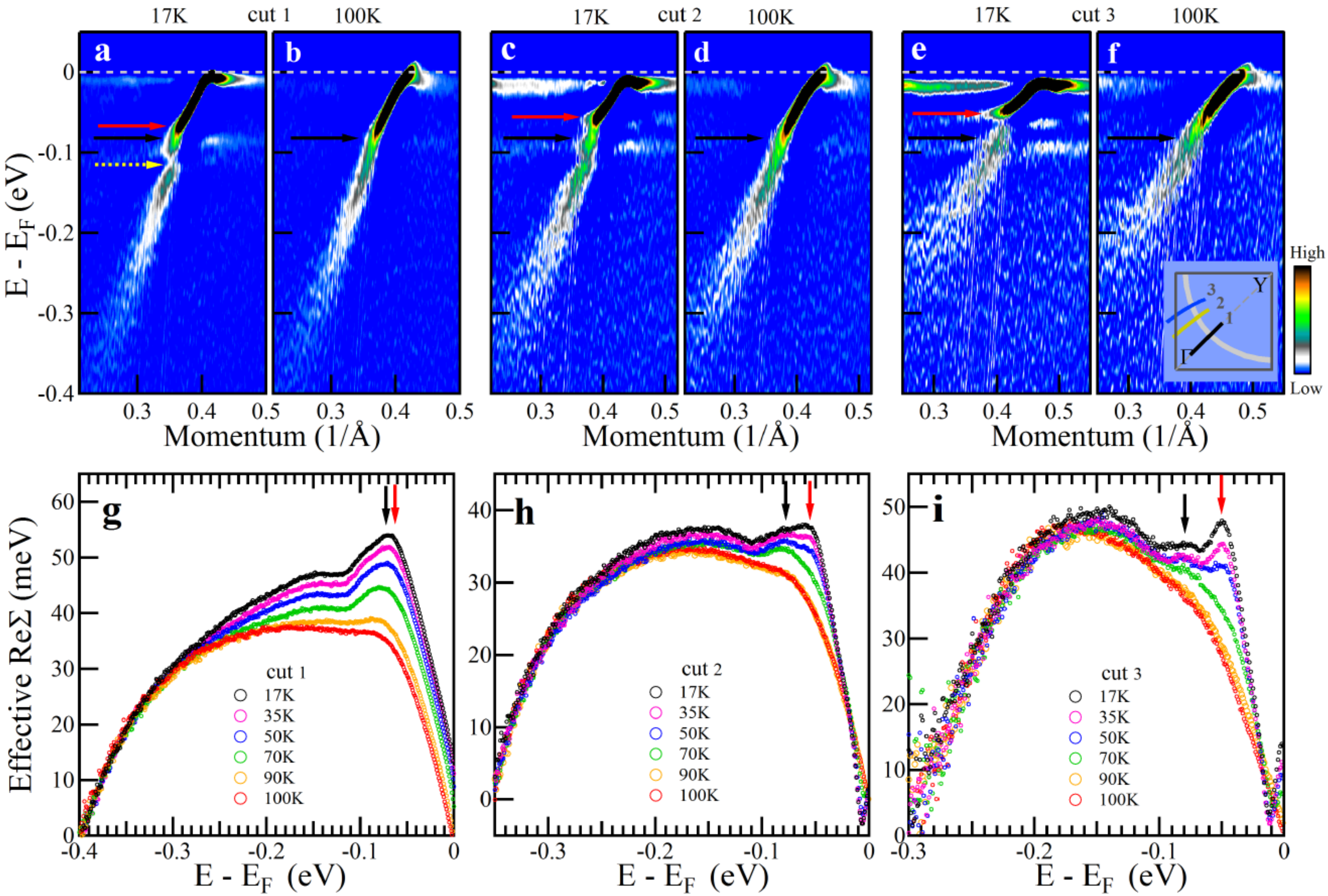
OD82K Bi2212 at 17K



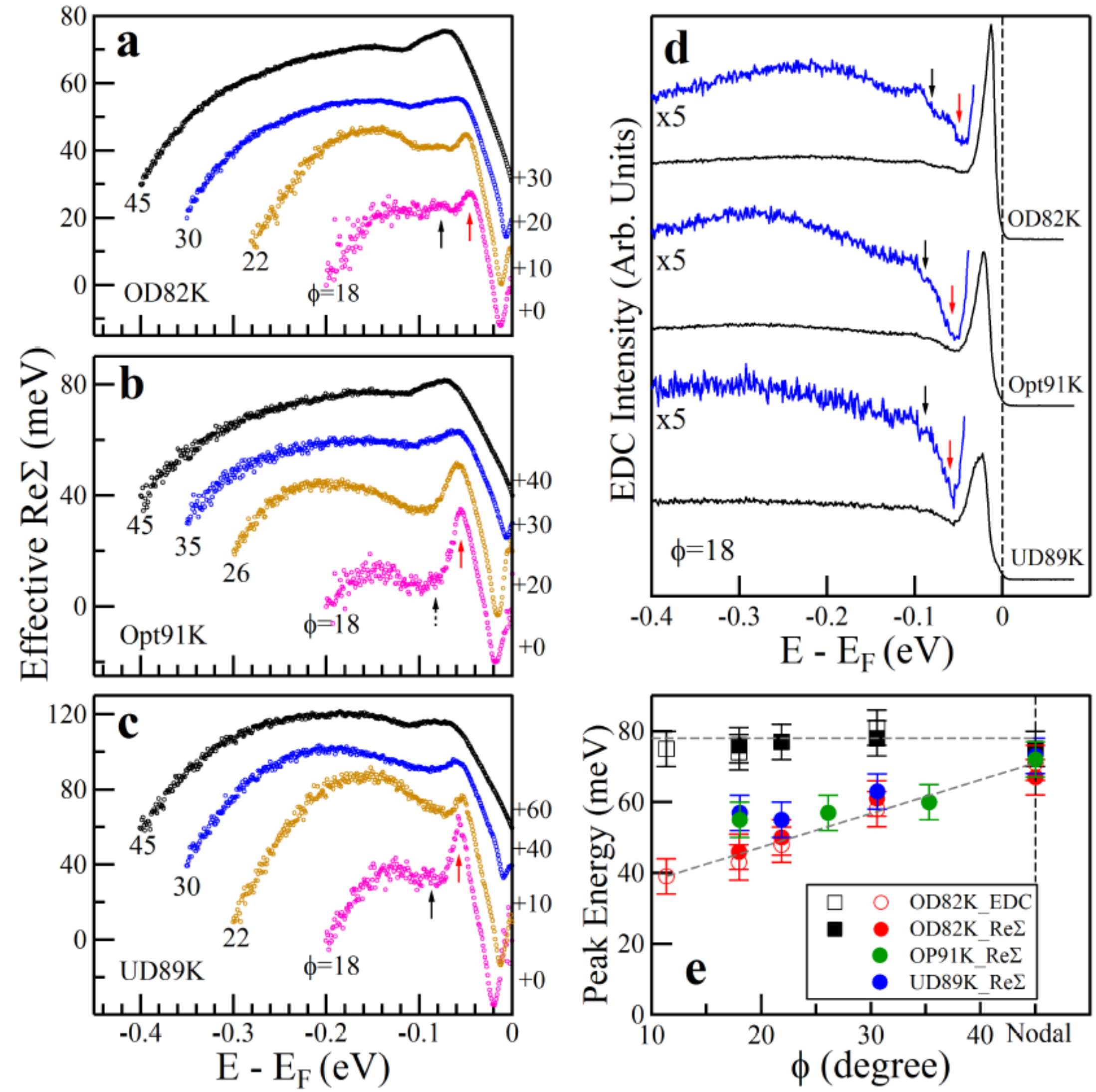
- **The high energy feature HI stays near 78meV and varies little with momentum.**
- **The low energy feature LW varies obviously with momentum, dropping from 67meV for the nodal cut to 40meV near the antinodal region.**

Temperature Dependence of the Two Energy Scales

OD82K Bi2212

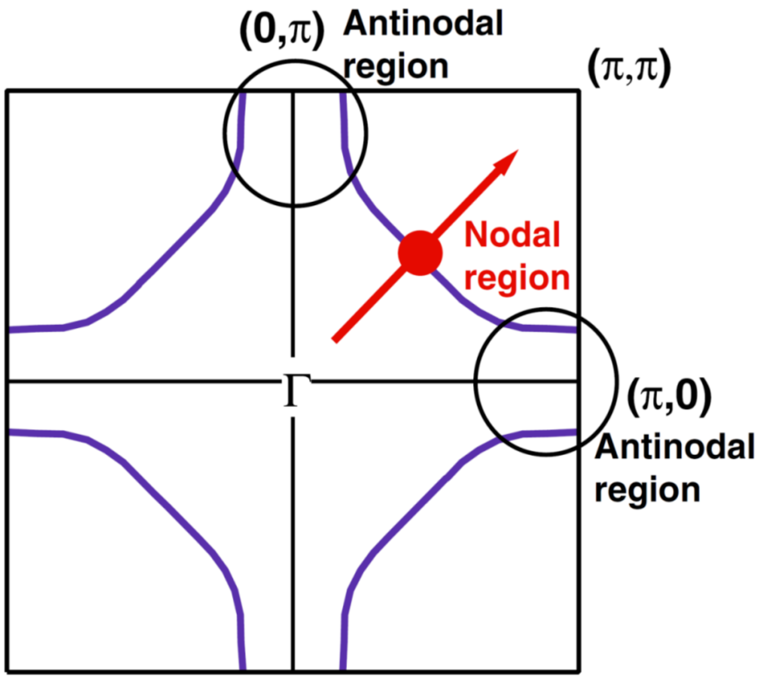


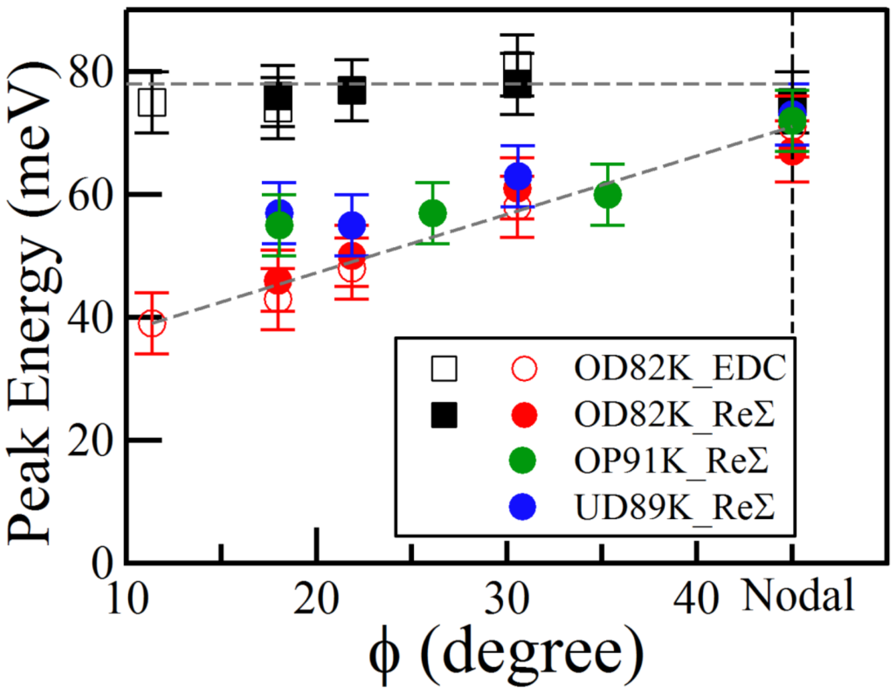
Doping Dependence of the Two Energy Scales



Junfeng He, H. Y. Choi, C. Varma, X. J. Zhou et al.,
Phys. Rev. Lett. 111 (2013) 107005.

Relation between Nodal and Antinodal Kinks Solved



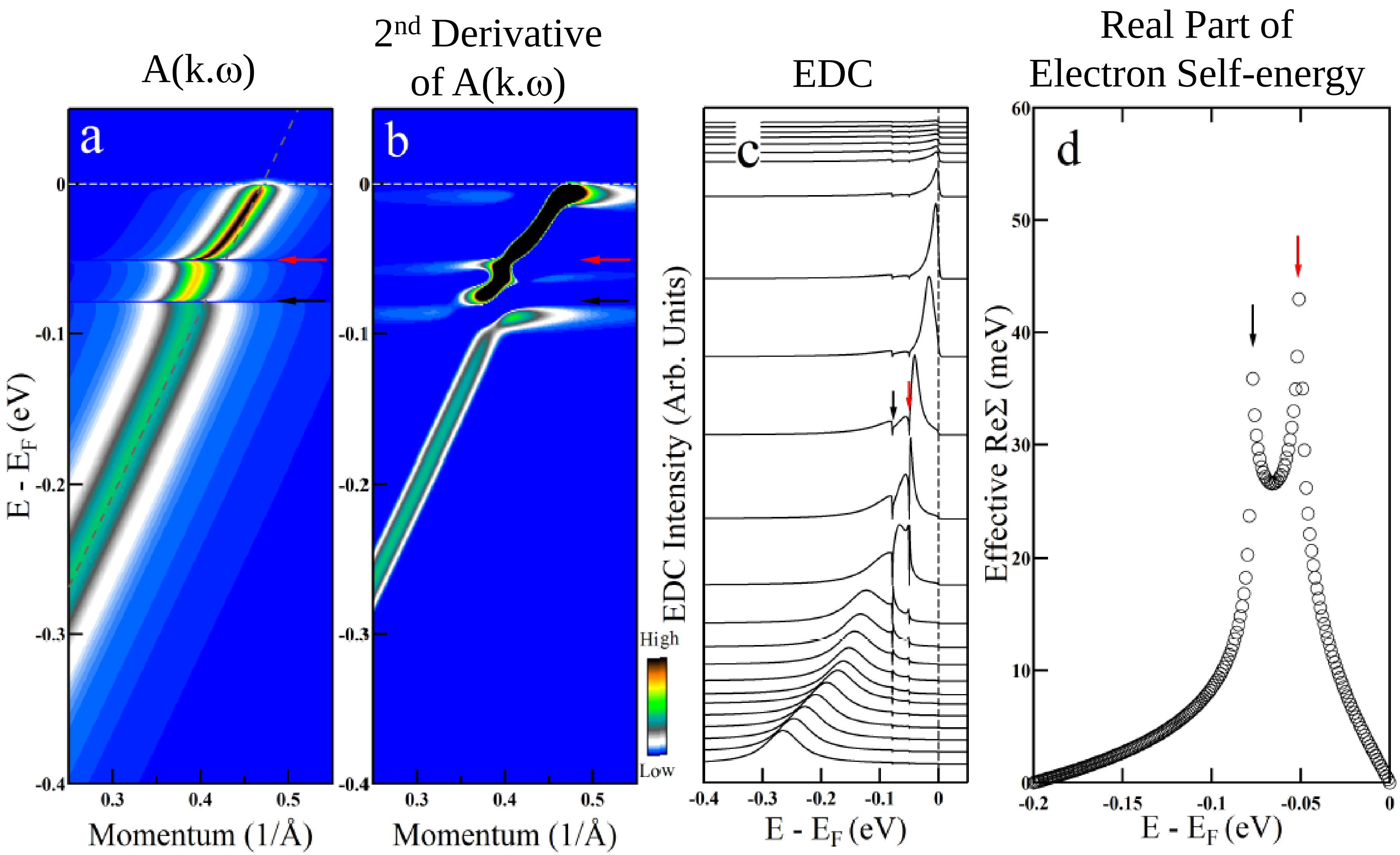


- **HI (~70meV) and LW (~40meV) energy scale coexist;**
- **HI(~70meV) scale changes little in energy when moving from nodal to antinodal regions;**
- **LW(~40meV) scale changes from 40meV near antinodal region to 70 meV near nodal region.**

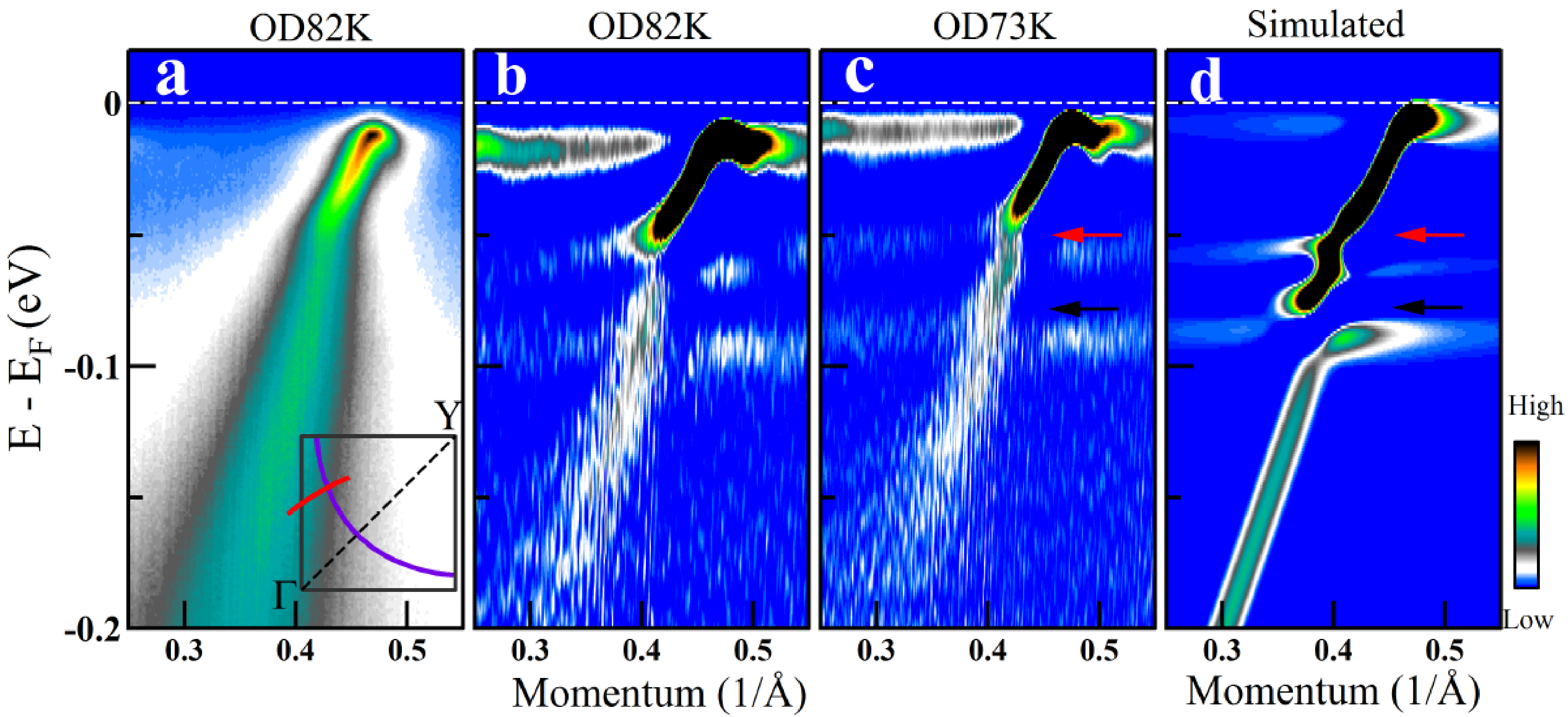
Nature of the Two Energy Scales?

—Open Question

Simulation: Electron Coupling with Two Phonon Modes

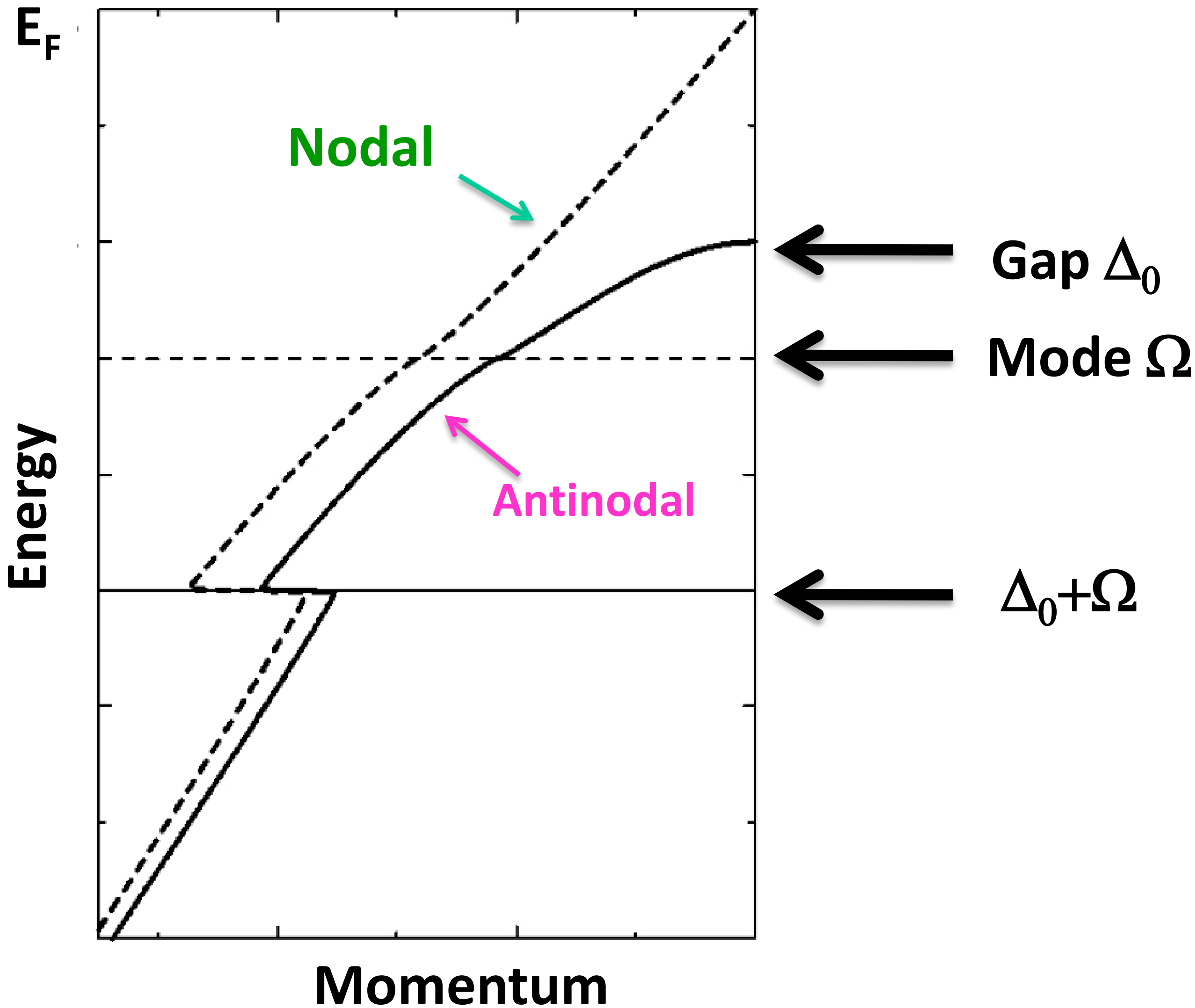


Comparison between Experiment and Simulation



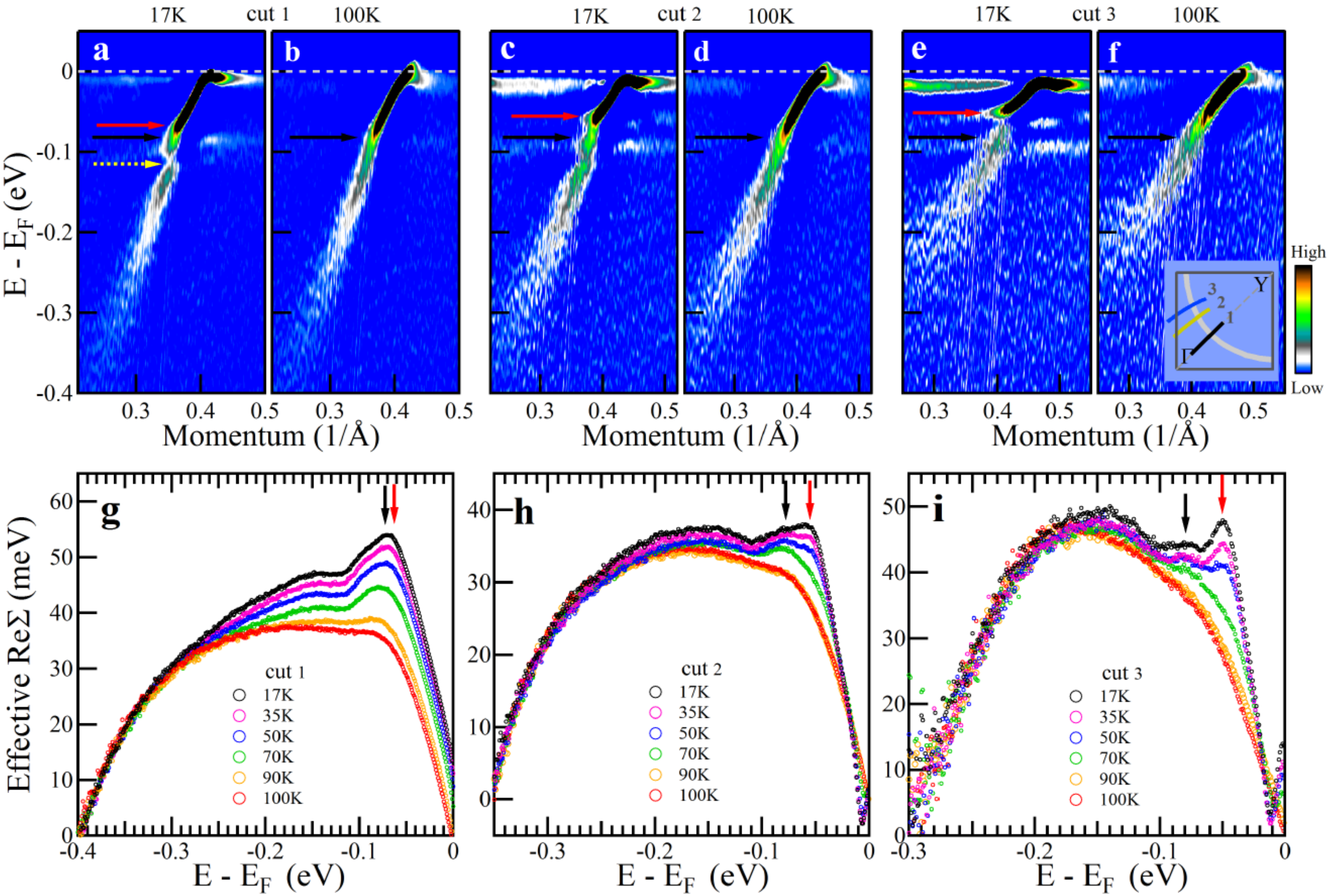
Junfeng He, H. Y. Choi, C. Varma, X. J. Zhou et al., Phys. Rev. Lett. 111 (2013) 107005.

Electron-Phonon Coupling in a *d*-Wave Superconductor in the Isotropic Coupling Picture



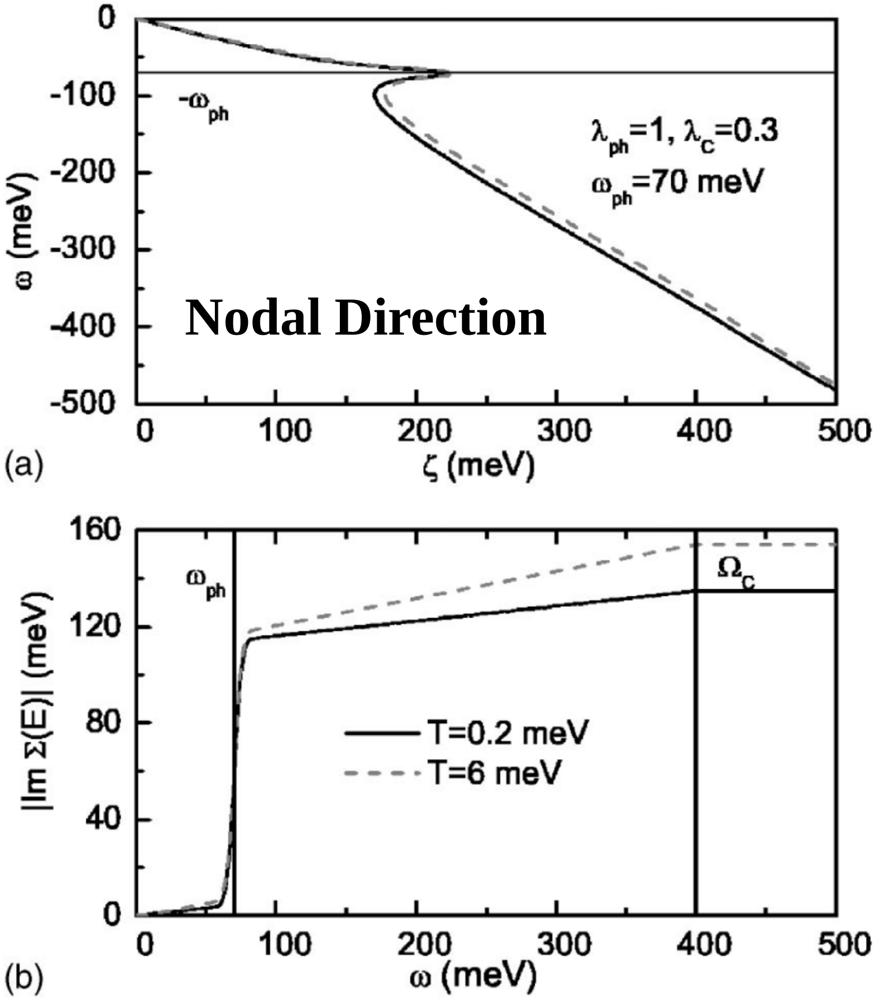
A. W. Sandvik, D. J. Scalapino et al., Phys. Rev. B 69(2004)094523

Unusual Temperature Dependence of Mode Coupling



No indication of mode energy shift by Δ above and below Tc.

Electron-Phonon Coupling in a d-Wave Superconductor in the Forward Scattering Picture



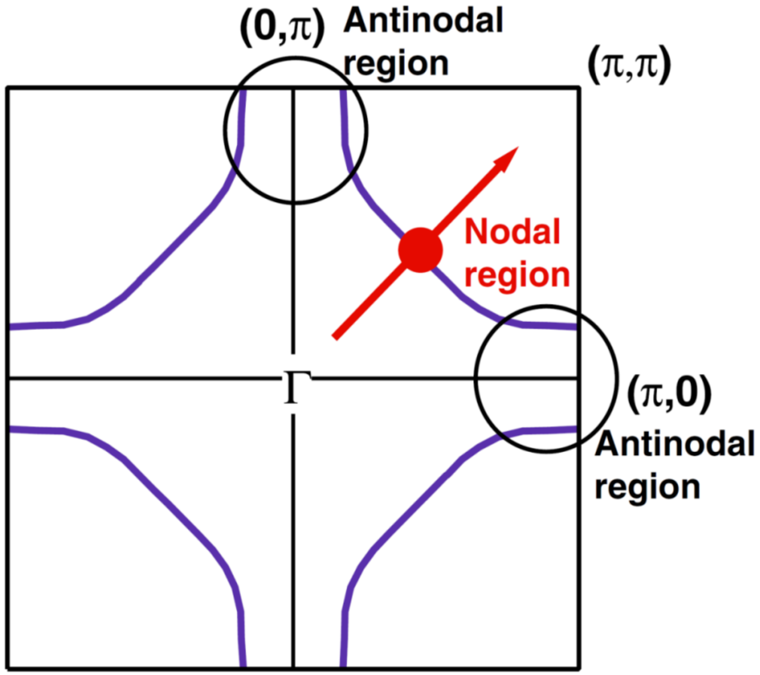
Above Tc,
Mode at Ω;

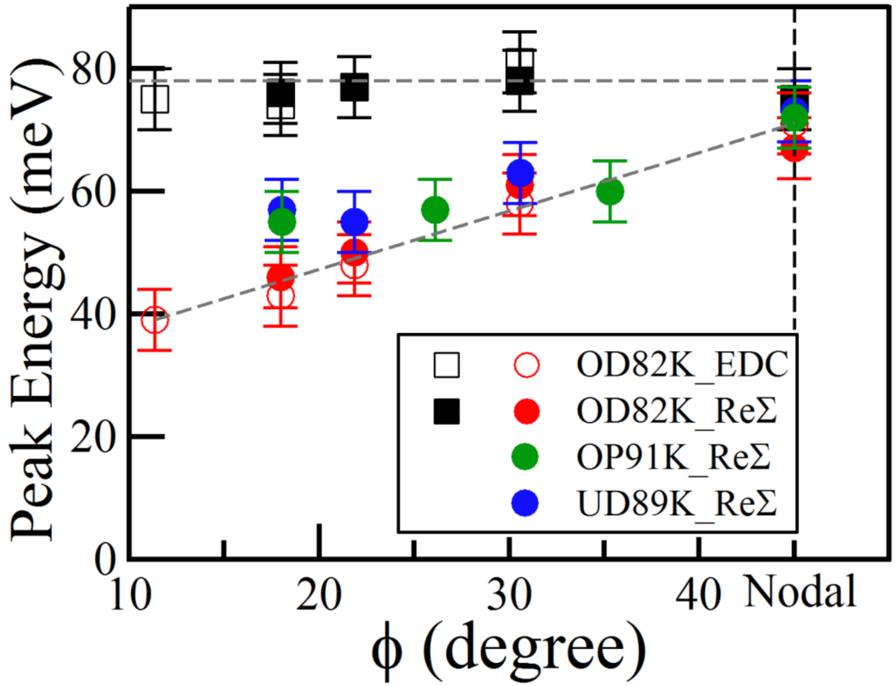
Below Tc,
Mode shifted to Δ+Ω

Δ–Local energy gap.

M. L. Kulic and O. V. Dolgov, Phys. Rev. B 71 (2005) 092505.
S. Johnston et al., Phys. Rev. Lett. 10 (2012) 166404.

Unusual Momentum Dependence of Mode Coupling





The electron-phonon coupling either in isotropic coupling picture or forward scattering picture, cannot account for The observed momentum dependence.

1.Two clear sharp modes in the superconducting state;

2. Evolution of nodal kink and anti-nodal kink is solved;

3. Open issues on the origin of theses two modes remain.

Summary

- **Laser-ARPES has become a powerful tool in studying High-Tc Superconductors:**
- **Nodal gap identified in heavily underdoepd region;**
- **Relation between nodal kink and antinodal kink solved; origin of the two modes remains open questions;**
- **(Extraction of Eliashberg functions.)**

Thanks