Congratulations to KITS

Wherever there is Fuchun, there is a center.

The KITS 2017 Forum: New Horizon in Condensed Matter Physics
UCAS, Beijing, March 27-29, 2017

Laser ARPES on High Temperature Superconductors and Topological Materials

Xingjiang ZHOU
（周兴江）

National Lab for Superconductivity
Institute of Physics,
Chinese Academy of Sciences,
Beijing, China

Laser ARPES Group at the Institute of Physics, CAS, Beijing

Staff : **X. J. ZHOU**, **Guodong LIU**, **Shaolong HE**, **Lin ZHAO**, **Jun ZHANG**, **Li YU**

Postdoc : **Jin Mo Bok**

Ph. D Students: **Wentao Zhang, Daixiang MOU, Junfeng HE, Chaoyu CHEN, Yingying PENG, Xu LIU, Ya FENG, Zhuojin XIE, Yan LIU, Hemian YI, Yuxiao Zhang, Aiji LIANG, Defa LIU, Bing SHEN, Cheng HU, Chenlu WANG, Yan ZHANG, Xuan SUN, Yong HU, Ying DING, Jianwei HUANG, Wenjuan ZHAO , Jing LIU, Yu XU, Shoupeng LV, Qiang GAO, Ping AI, Cong LI**

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

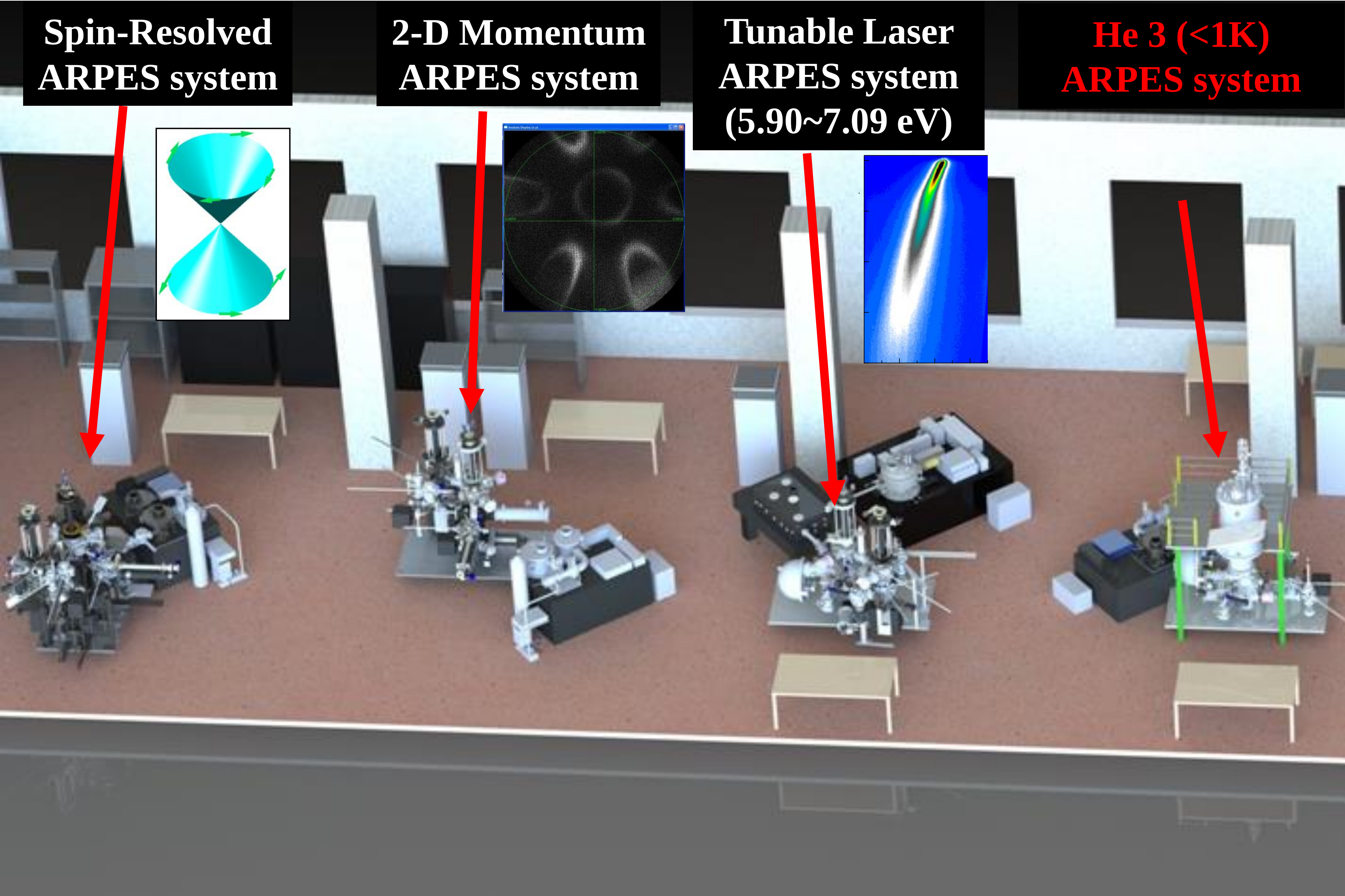
- **Sample Characterization**

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

- **Theoretical analysis**

Jin Mo Bok, Jong Jue Bae, Han-Yong Choi, SungKyunKwan University, Suwon, Korea
Chandra Varma, University of California at Riverside, CA, USA.

VUV Laser-ARPES Lab at IOP



Spin-Resolved ARPES system

2-D Momentum ARPES system

Tunable Laser ARPES system (5.90~7.09 eV)

He 3 (<1K) ARPES system

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

- Super-high resolution (better than 1 meV);
- High data statistics;
- High stability with time.

Highlights of
ARPES on Some Topological Materials

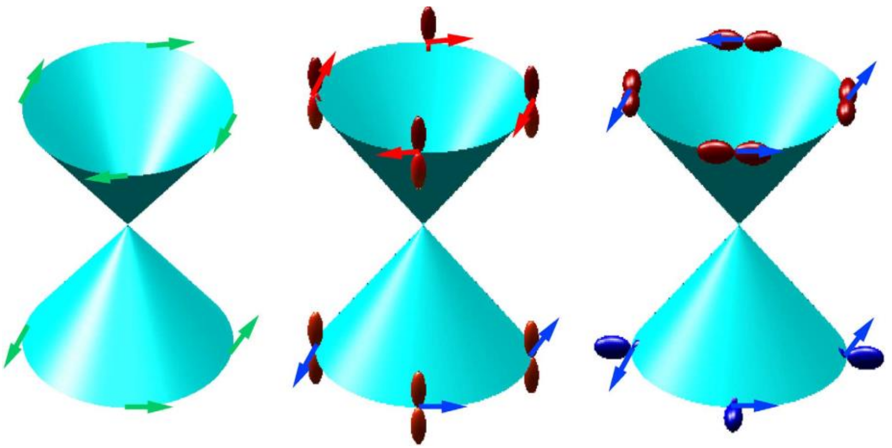
nature COMMUNICATIONS

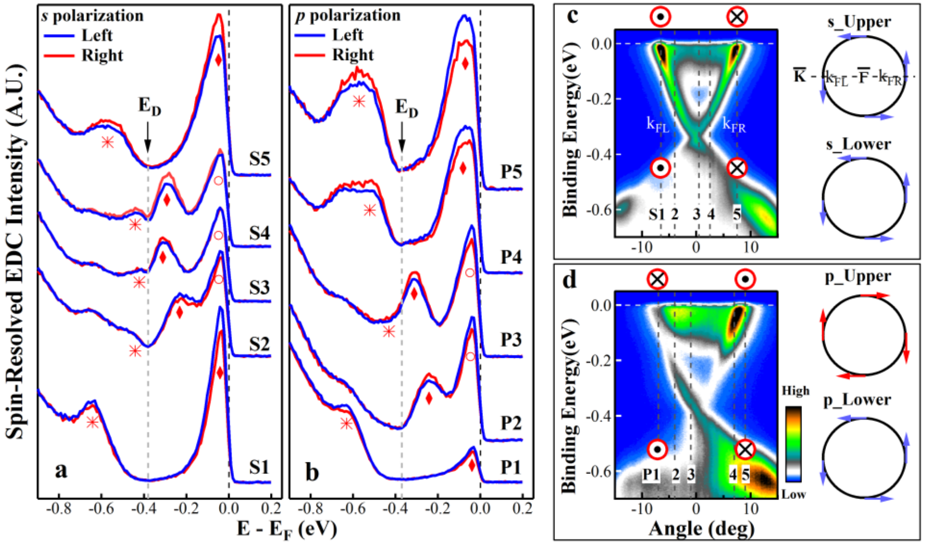
ARTICLE

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



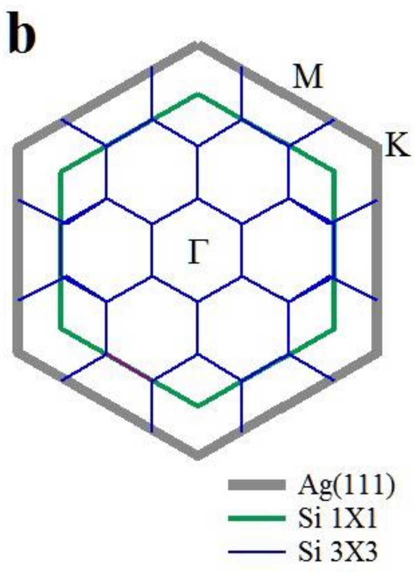


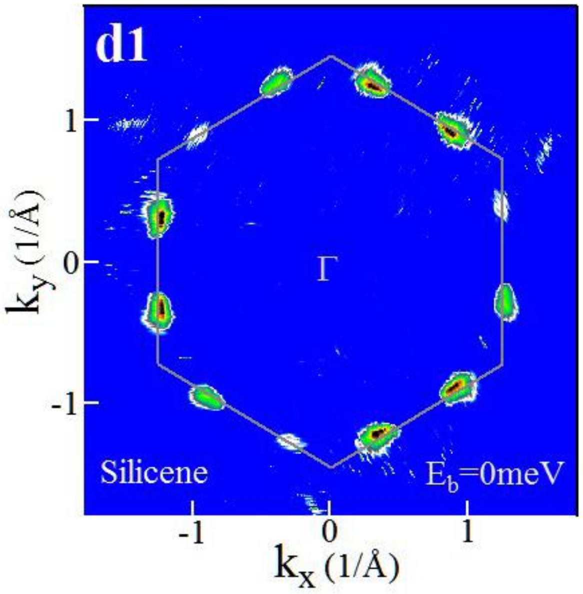
Direct evidence of spin-orbital locking in topological insulator Bi_2Se_3.

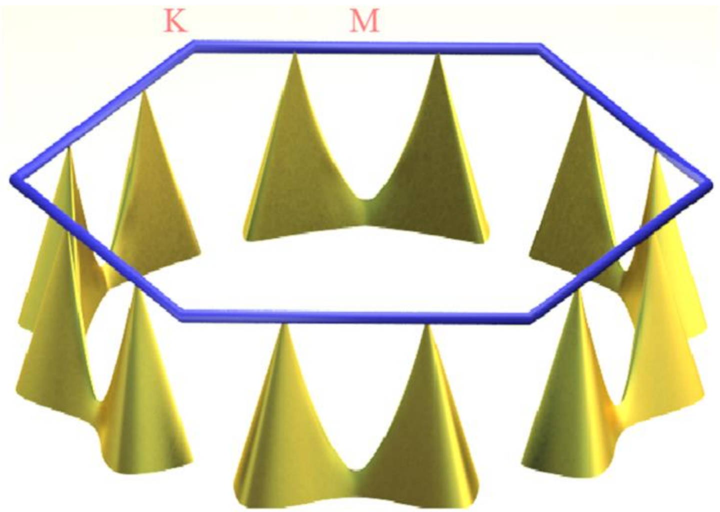
Z. J. Xie, S. L. He, X. J. Zhou et al., Nature Communications 5 (2014) 3382.

Direct evidence of interaction-induced Dirac cones in a monolayer silicene/Ag(111) system

Ya Feng[a,1], Defa Liu[a,1], Baojie Feng[a,1], Xu Liu[a,1], Lin Zhao[a], Zhuojin Xie[a], Yan Liu[a], Aiji Liang[a], Cheng Hu[a], Yong Hu[a], Shaolong He[a], Guodong Liu[a], Jun Zhang[a], Chuangtian Chen[b], Zuyan Xu[b], Lan Chen[a], Kehui Wu[a,c], Yu-Tzu Liu[d,e], Hsin Lin[d,e], Zhi-Quan Huang[f], Chia-Hsiu Hsu[f], Feng-Chuan Chuang[f], Arun Bansil[g], and X. J. Zhou[a,c,h,2]







1. **First direct observation of Dirac cones in monolayer silicene(3X3)/Ag(111);**
2. **It consists of 6 pairs of Dirac cones on the edges of Ag(111) Brillouin zone;**
3. **It is due to interaction between silicene(3X3) and Ag(111).**

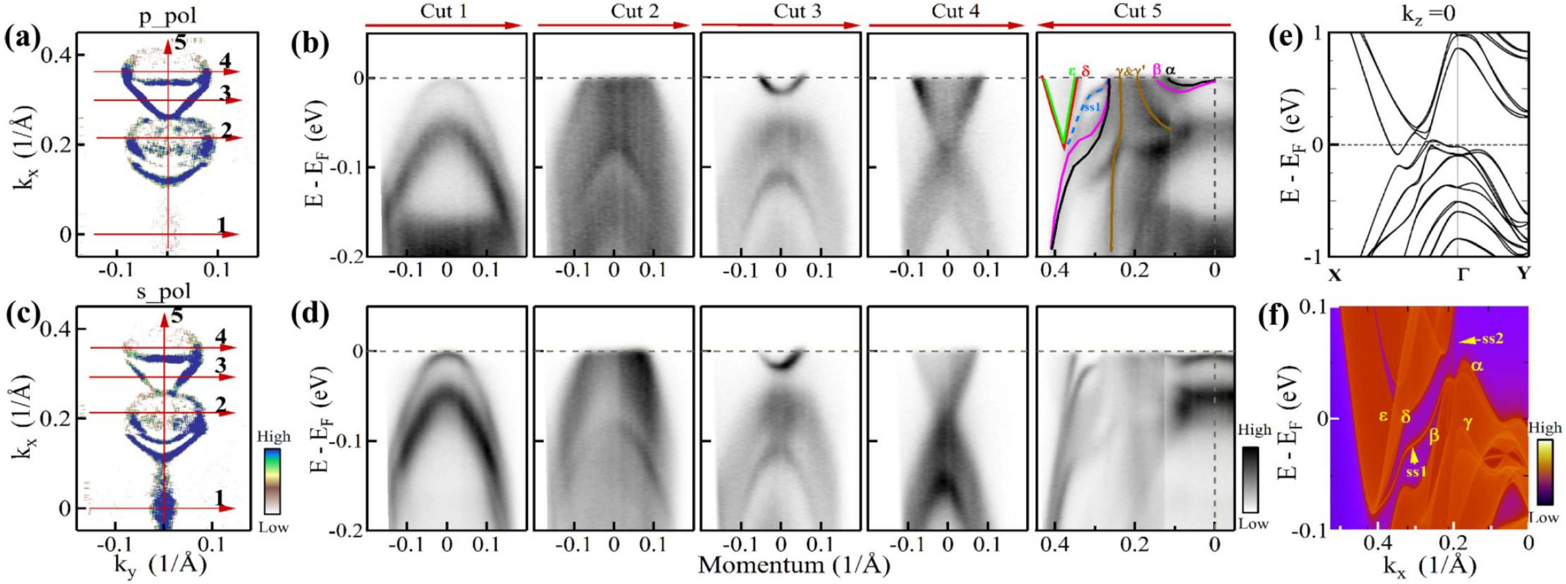
Ya Feng, X. J. Zhou et al., PNAS 113 (2016) 14656.

RAPID COMMUNICATIONS

PHYSICAL REVIEW B **94**, 241119(R) (2016)

Observation of Fermi arc and its connection with bulk states in the candidate type-II Weyl semimetal WTe_2

Chenlu Wang,[1] Yan Zhang,[1] Jianwei Huang,[1] Simin Nie,[1] Guodong Liu,[1,*] Aiji Liang,[1] Yuxiao Zhang,[1] Bing Shen,[1] Jing Liu,[1] Cheng Hu,[1] Ying Ding,[1] Defa Liu,[1] Yong Hu,[1] Shaolong He,[1] Lin Zhao,[1] Li Yu,[1] Jin Hu,[2] Jiang Wei,[2] Zhiqiang Mao,[2] Youguo Shi,[1] Xiaowen Jia,[3] Fengfeng Zhang,[4] Shenjin Zhang,[4] Feng Yang,[4] Zhimin Wang,[4] Qinjun Peng,[4] Hongming Weng,[1,5] Xi Dai,[1,5] Zhong Fang,[1,5] Zuyan Xu,[4] Chuangtian Chen,[4] and X. J. Zhou[1,5,6,†]

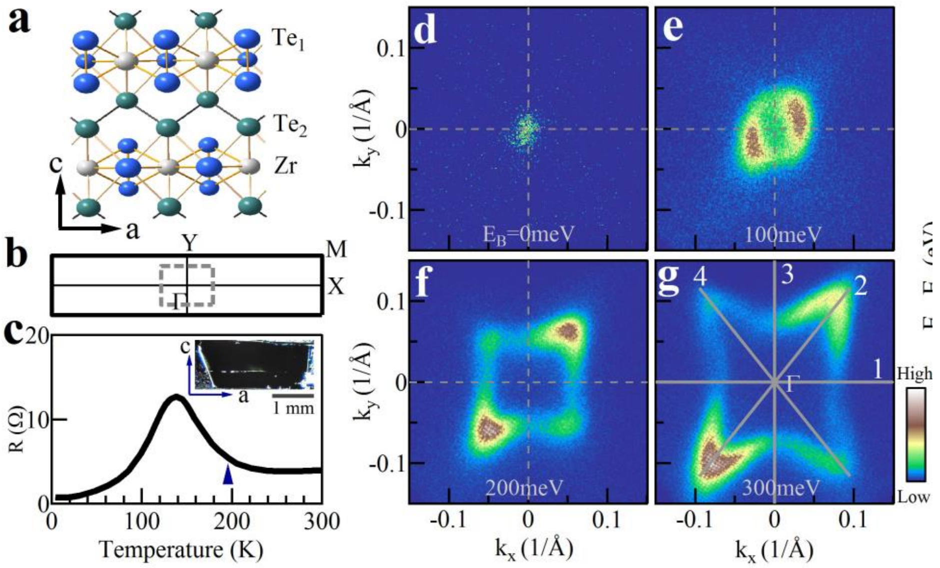


1. **Clearly resolve a complete Fermi surface of WTe_2;**
2. **Clearly identify the surface state;**
3. **Experimental results consistent with type II Weyl semimetal nature of WTe_2.**

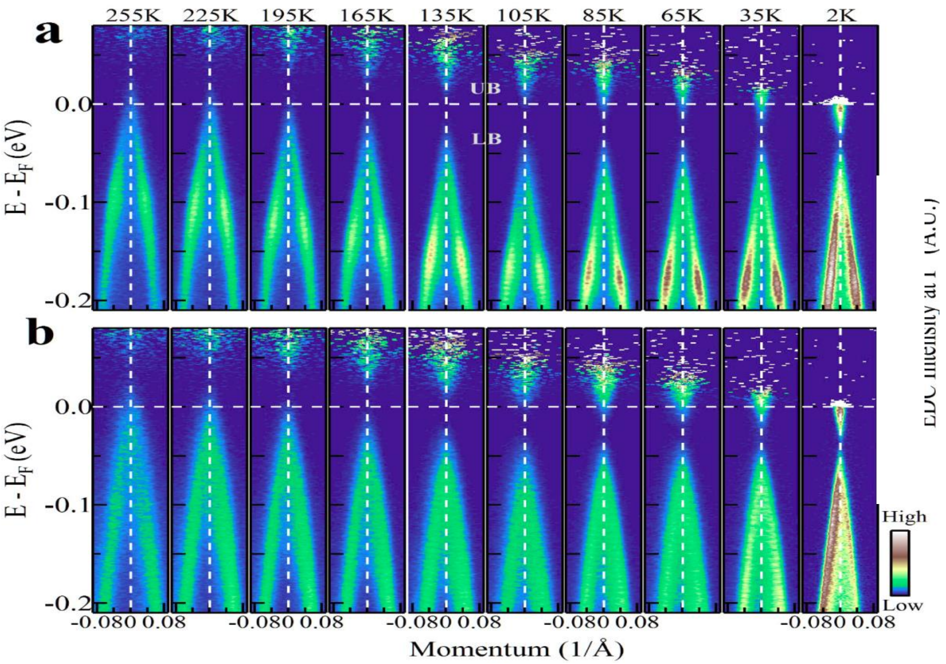
Chenlu Wang, Guodong Liu, X. J. Zhou et al., Phys. Rev. B 94 (2016) 241119(R).

Temperature-Induced Lifshitz Transition and Topological Nature of $ZrTe_5$

Fermi Surface



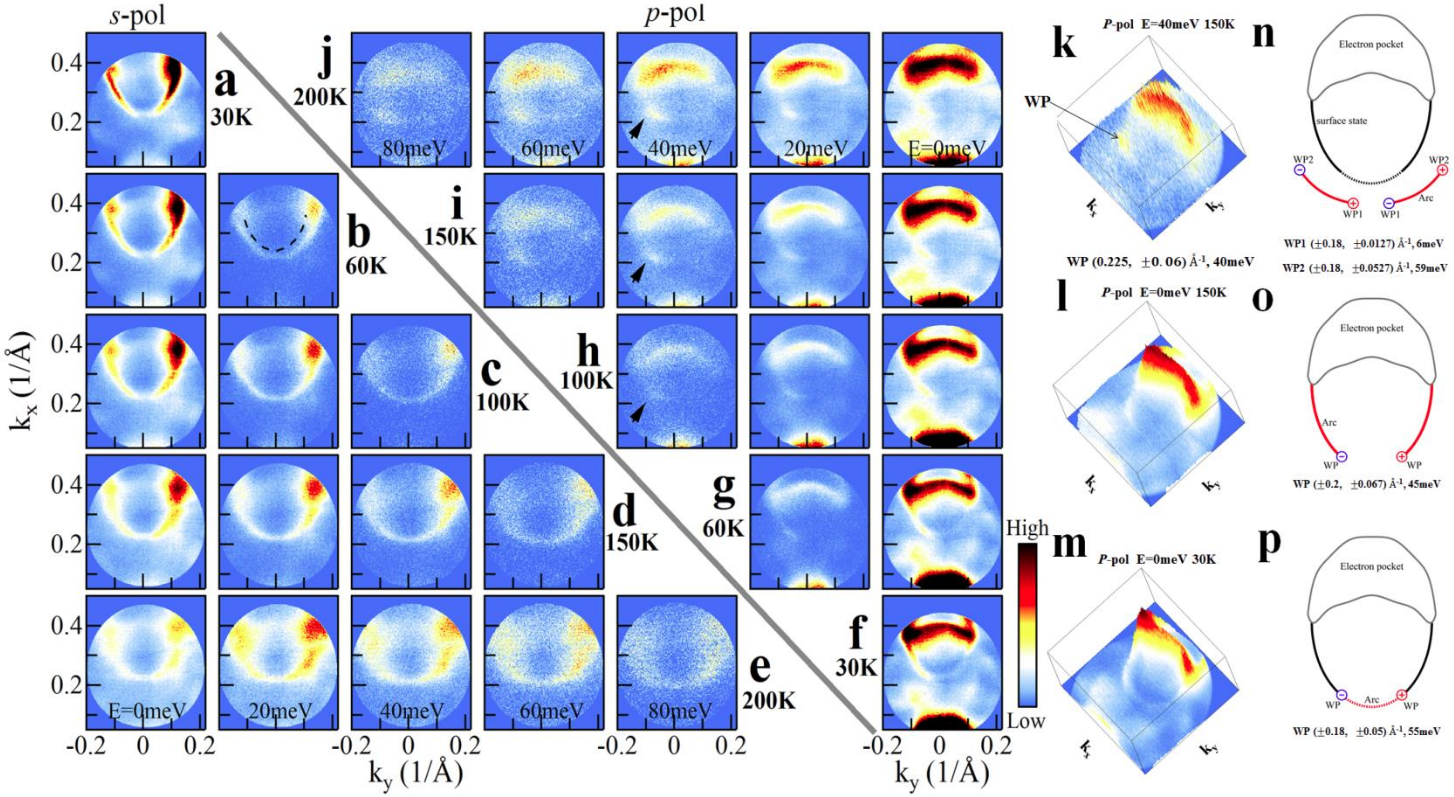
Temperature Dependence of Bands



- ➢ **Electronic evidence of the temperature-induced Lifshitz transition in $ZrTe_5$;**
- ➢ **Solves the long-time puzzle on transport anomaly at ~135 K;**
- ➢ **Signature of edge states in $ZrTe_5$; it is a weak topological insulator.**

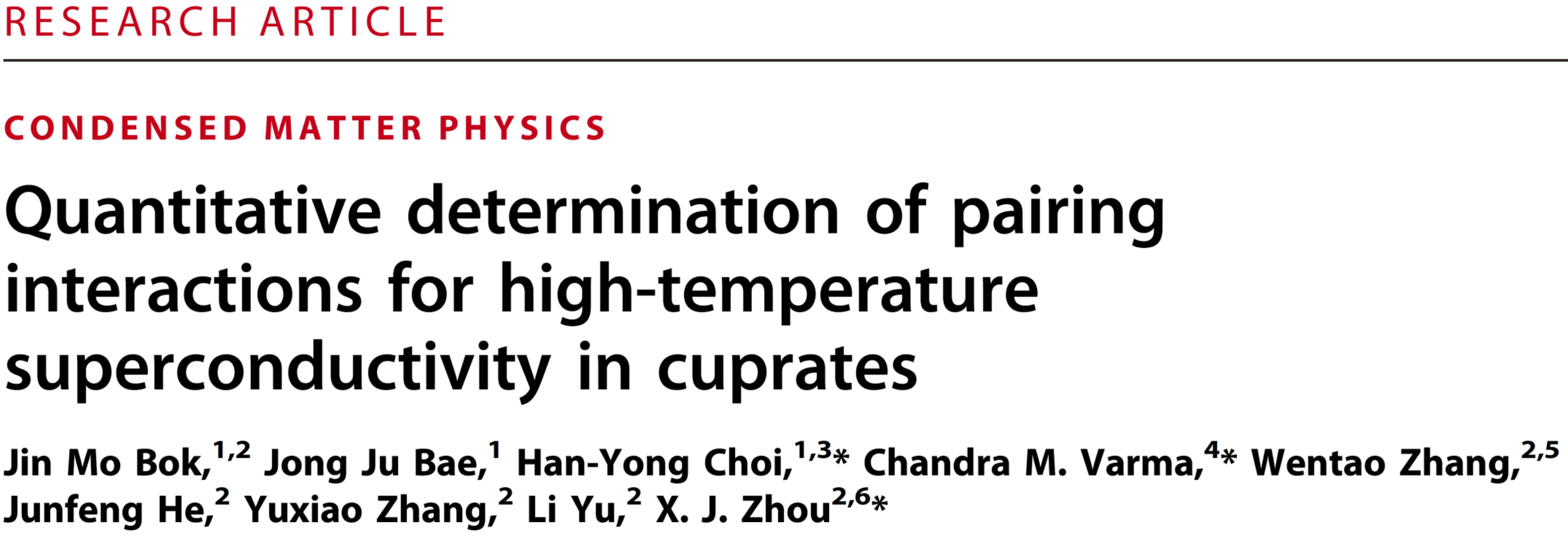
Yan Zhang, G. D. Liu, X. J. Zhou et al., arXiv:1602.03576,
to appear in Nature Communcations.

Evidence of Type II Weyl Semimetal State in $MoTe_2$



- ➢A single branch of surface state is identified that connects bulk hole pockets and bulk electron pockets;
- ➢Detailed temperature-dependent ARPES measurements show high intensity spot-like features that is 40 meV above the Fermi level.

Aiji Liang, X. J. Zhou et al., arXiv:1604.01706 (2016).


RESEARCH ARTICLE

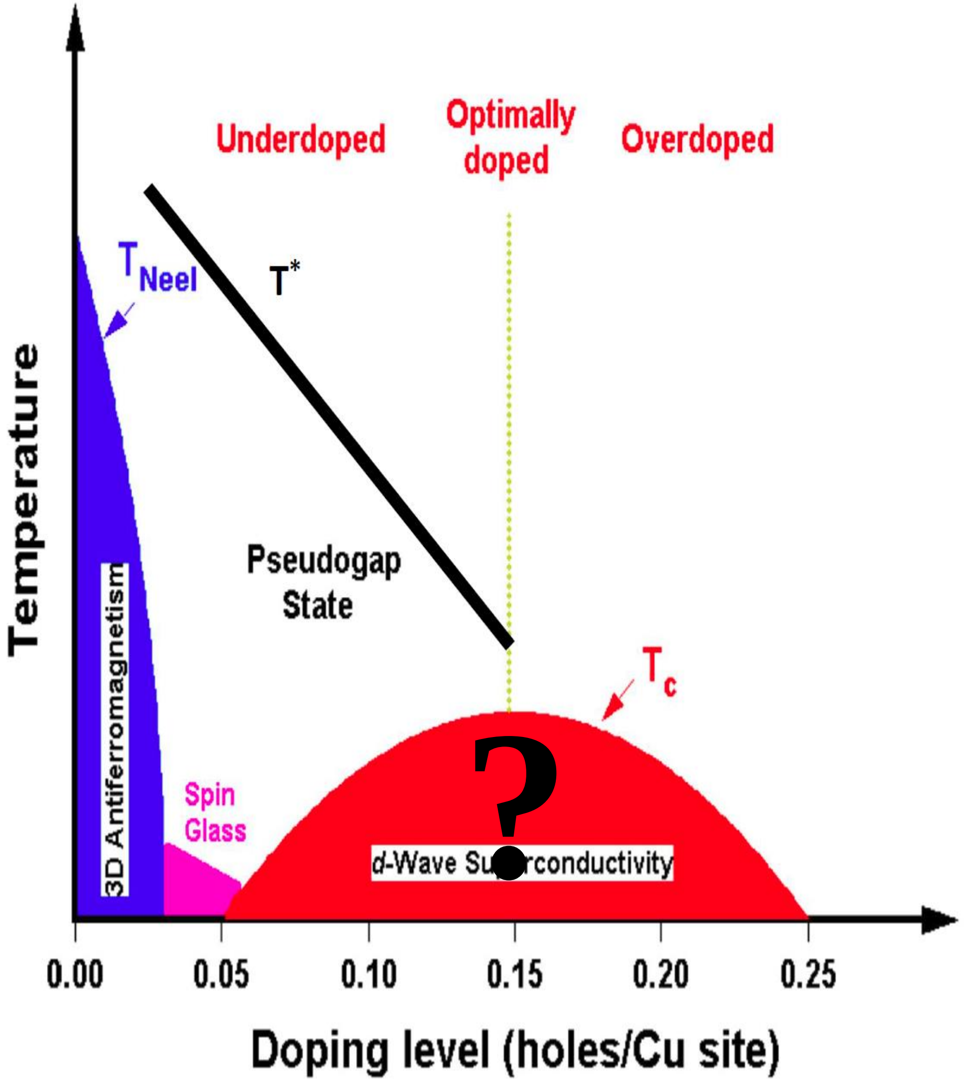
CONDENSED MATTER PHYSICS

Quantitative determination of pairing interactions for high-temperature superconductivity in cuprates

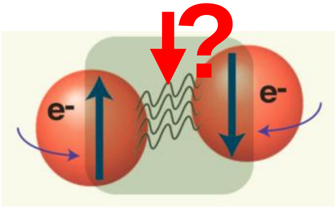
Jin Mo Bok,[1,2] Jong Ju Bae,[1] Han-Yong Choi,[1,3]* Chandra M. Varma,[4]* Wentao Zhang,[2,5]
Junfeng He,[2] Yuxiao Zhang,[2] Li Yu,[2] X. J. Zhou[2,6]*

Science Advances 2, e1501329 (2016)

Mechanism of High Temperature Superconductivity



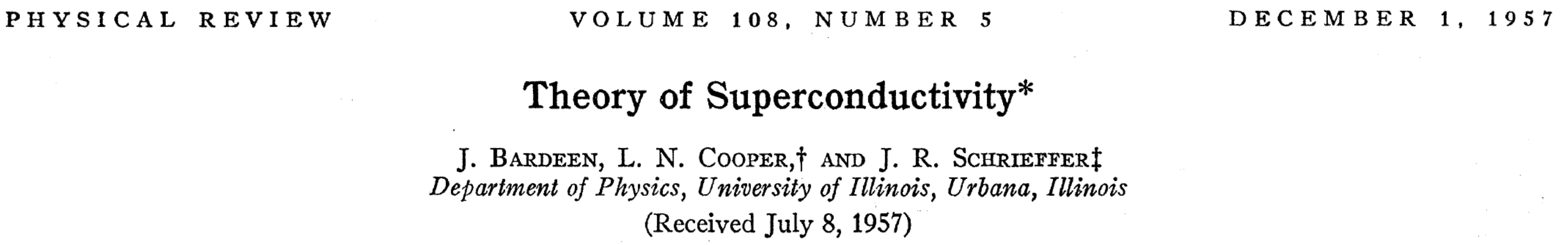
- High temperature superconductivity in cuprates still involves electron pairing.



- Origin of the electron Pairing?

  1. Glue or not glue?
  2. What is the glue?

BCS Theory for Conventional Superconductivity



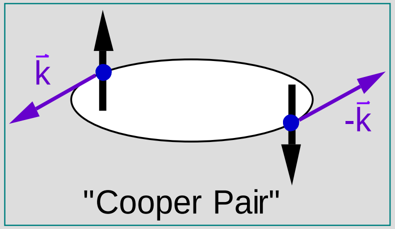
PHYSICAL REVIEW VOLUME 108, NUMBER 5 DECEMBER 1, 1957

Theory of Superconductivity*

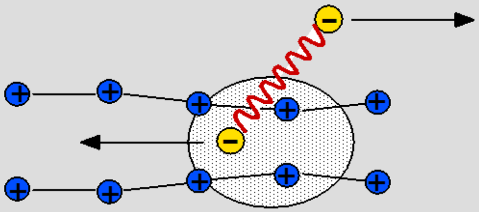
J. Bardeen, L. N. Cooper,† and J. R. Schrieffer‡
Department of Physics, University of Illinois, Urbana, Illinois

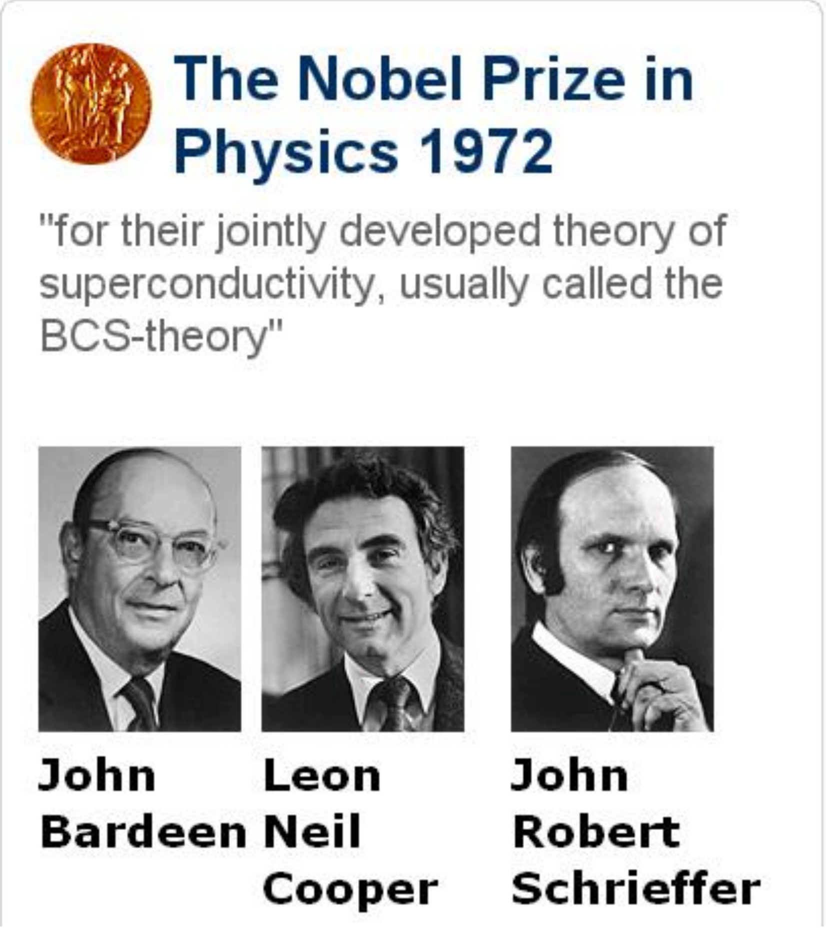
(Received July 8, 1957)

- Formation of Cooper pairs in the superconducting state;



- The pairing is mediated by exchanging phonons.





The Nobel Prize in Physics 1972

"for their jointly developed theory of superconductivity, usually called the BCS-theory"

John Bardeen

Leon Neil Cooper

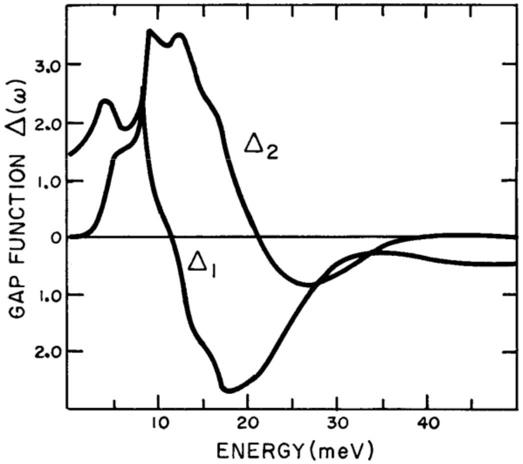
John Robert Schrieffer

Experimental Validation of the BCS Theory in Conventional Superconductors – Pairing Eliashberg Function

$$\frac{N_s(\omega)}{N_n} = \mathrm{Re}\left\{\frac{\omega}{\sqrt{\omega^2 - \Delta^2(\omega)}}\right\}$$

Schrieffer, Scalapino,Wilkins
Phys. Rev. Lett. 10(1963)336.

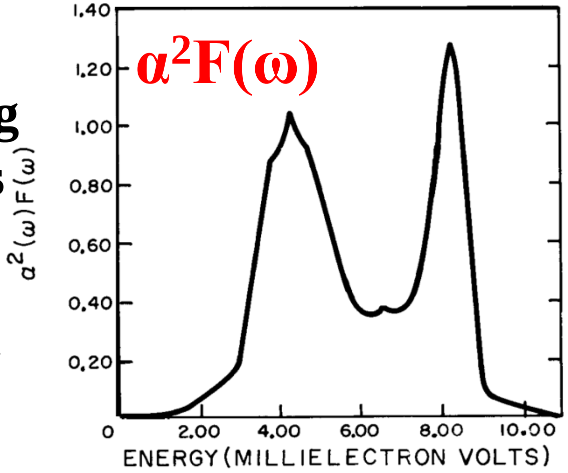
Complex Gap Function



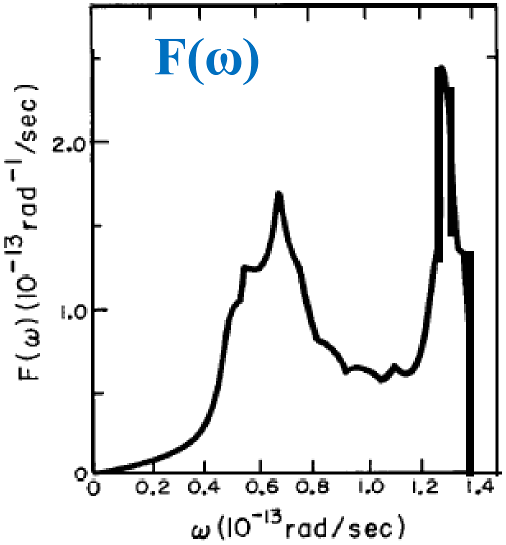
Eliashberg Equations

Inversion

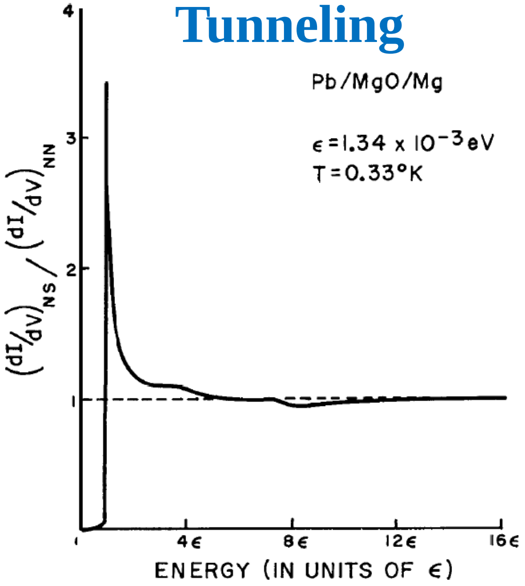
McMillan
Rowell
Phys. Rev. Lett.
14 (1965)108.



Neutron Scattering



Tunneling



Giaever, Phys. Rev. 126 (1962)941

Simulation

Theories or Models

J. Bardeen,
Nobel Lecture, 1972.

Tunneling: Not Sufficient for *d*-Wave Superconductors

- **For *s*-wave superconductors:**

  Normal self-energy and pairing self-energy have the same symmetry.

- **For *d*-wave superconductors:**

  Normal self-energy has the full symmetry of lattice.

  Pairing self-energy has a *d*-wave symmetry.

Eliashberg Equations for *d*-Wave Pairing

$$\Sigma(\theta,\omega) = \int_{-\infty}^{\infty} d\epsilon \int_{-\infty}^{\infty} d\epsilon' S(\omega,\epsilon,\epsilon') N_1(\epsilon) \underbrace{\alpha^2 F^{(+)}(\theta,\epsilon')}_{\text{Normal Eliashberg Function}} \quad \boxed{\varepsilon_N(\theta,\omega)}$$

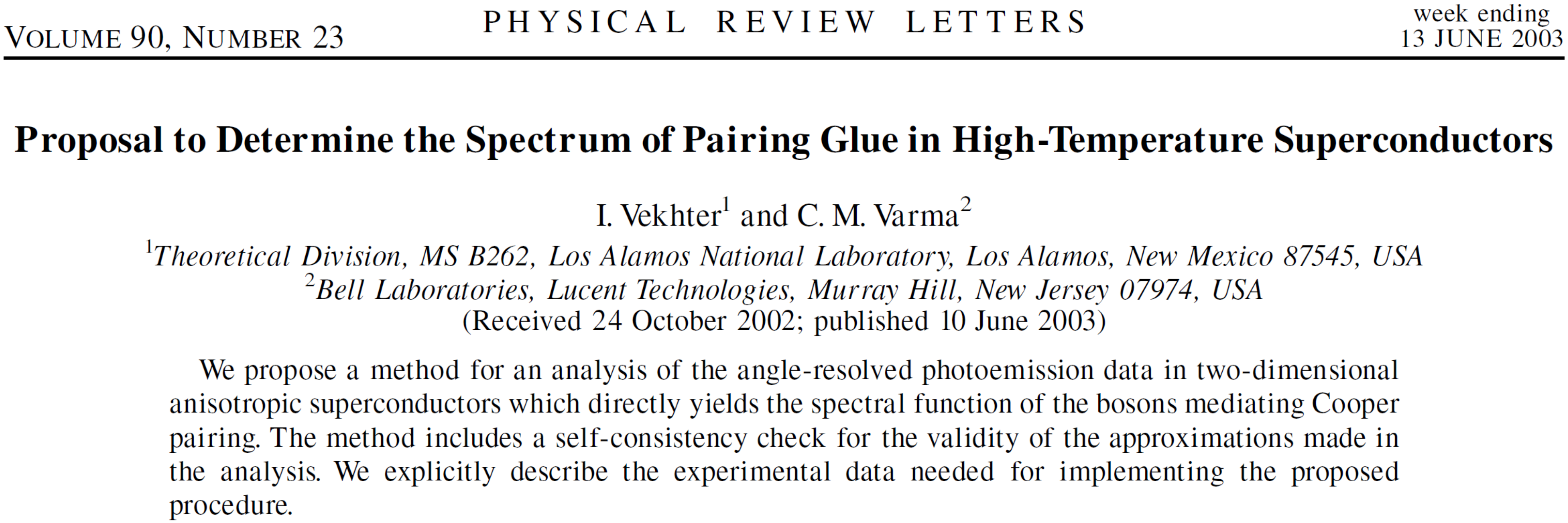
$$\phi(\omega) = -\int_{-\infty}^{\infty} d\epsilon \int_{-\infty}^{\infty} d\epsilon' S(\omega,\epsilon,\epsilon') D_1(\epsilon) \underbrace{\alpha^2 F^{(-}(\theta,\epsilon')}_{\text{Pairing Eliashberg Function}} \quad \boxed{\varepsilon_P(\theta,\omega)}$$

$$S(\omega,\epsilon,\epsilon') = \frac{f(\epsilon) + n(-\epsilon')}{\epsilon + \epsilon' - \omega - i\delta} \qquad N_1(\epsilon) \equiv \left\langle Re \frac{W(\theta',\epsilon)}{\sqrt{W^2(\theta',\epsilon) - \phi^2(\epsilon)\sin^2(2\theta')}} \right\rangle_{\theta'}$$

$$D_1(\epsilon) \equiv \left\langle \frac{1}{v_F(\theta')} Re \frac{\phi(\epsilon)\sin^2(2\theta')}{\sqrt{W^2(\theta',\epsilon) - \phi^2(\epsilon)\sin^2(2\theta')}} \right\rangle_{\theta'}$$

Therefore, TWO Eliashberg functions are required, $\varepsilon_N(\omega,k)$ and $\varepsilon_p(\omega,k)$.

ARPES, with its unique momentum resolving capability, emerges as a powerful tool in extracting the normal self-energy and pairing self-energy in the superconducting state



VOLUME 90, NUMBER 23 PHYSICAL REVIEW LETTERS week ending 13 JUNE 2003

Proposal to Determine the Spectrum of Pairing Glue in High-Temperature Superconductors

I. Vekhter[1] and C. M. Varma[2]

[1]*Theoretical Division, MS B262, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*
[2]*Bell Laboratories, Lucent Technologies, Murray Hill, New Jersey 07974, USA*

(Received 24 October 2002; published 10 June 2003)

We propose a method for an analysis of the angle-resolved photoemission data in two-dimensional anisotropic superconductors which directly yields the spectral function of the bosons mediating Cooper pairing. The method includes a self-consistency check for the validity of the approximations made in the analysis. We explicitly describe the experimental data needed for implementing the proposed procedure.

Stringent Requirements on Data to Extract Pairing Self-Energy

Paring self-energy is extracted from the subtle superconductivity-induced change, *i. e.*, the net change between the superconducting state and the normal state.

$$\frac{N_s(\omega)}{N_n} = \mathrm{Re}\left\{\frac{\omega}{\sqrt{\omega^2 - \Delta^2(\omega)}}\right\}$$

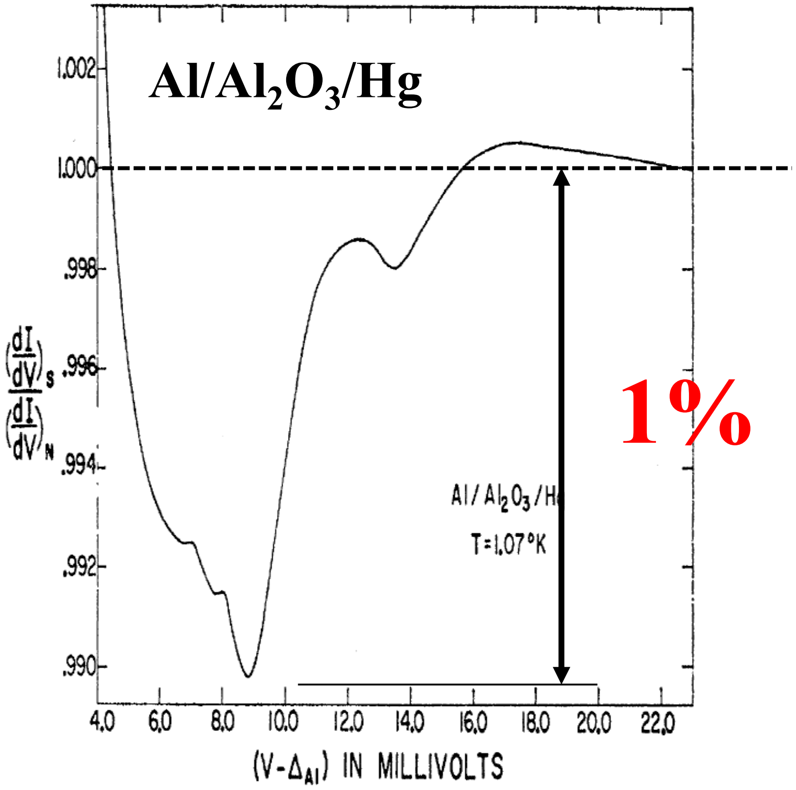
$\sim \; \frac{1}{2}(\Delta/\omega)^2$

~ 1%

for Bi2212

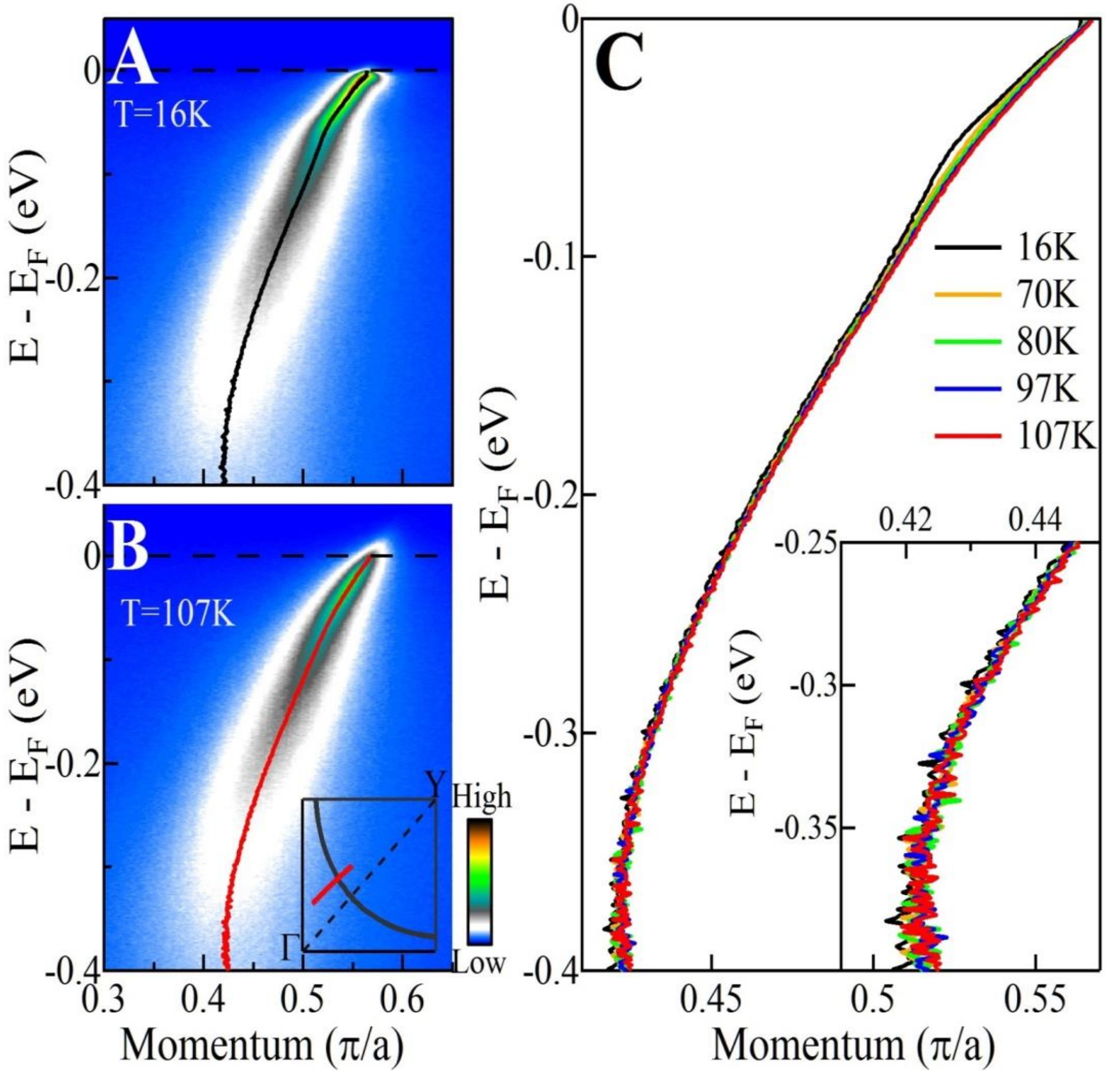
Δ=40meV, ω=0.4 eV

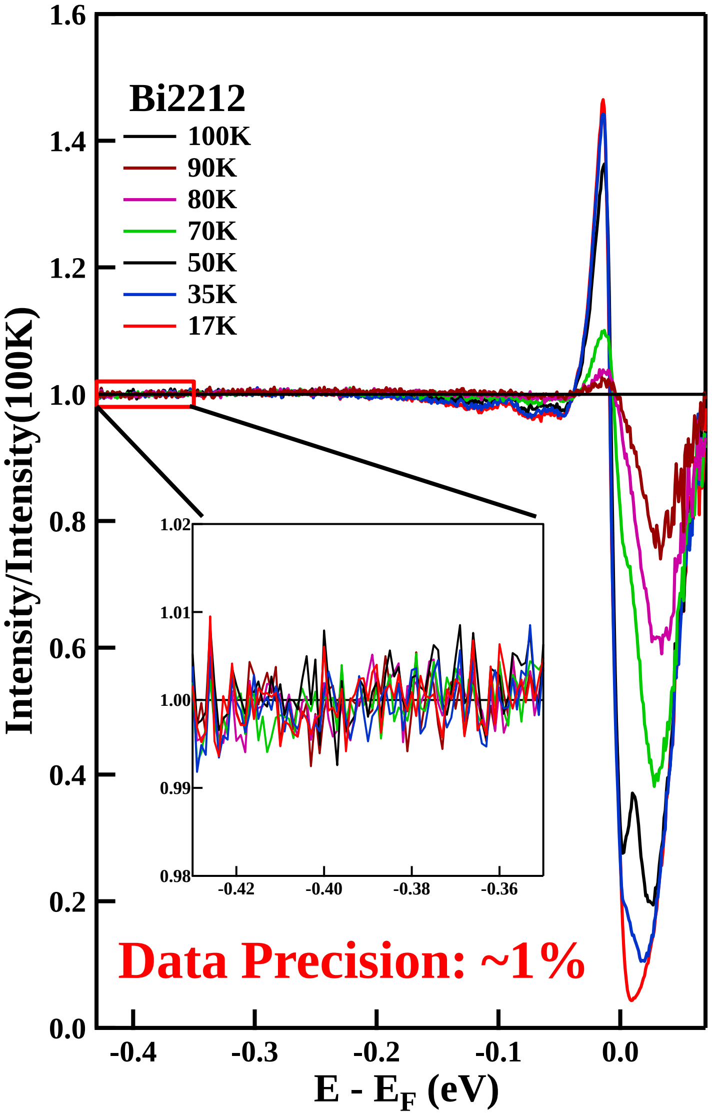
High precision (~1%) is necessary



S. Bermon et al.,
Phys. Rev. 135 (1964) A306.

High Precision Laser ARPES on Bi2212

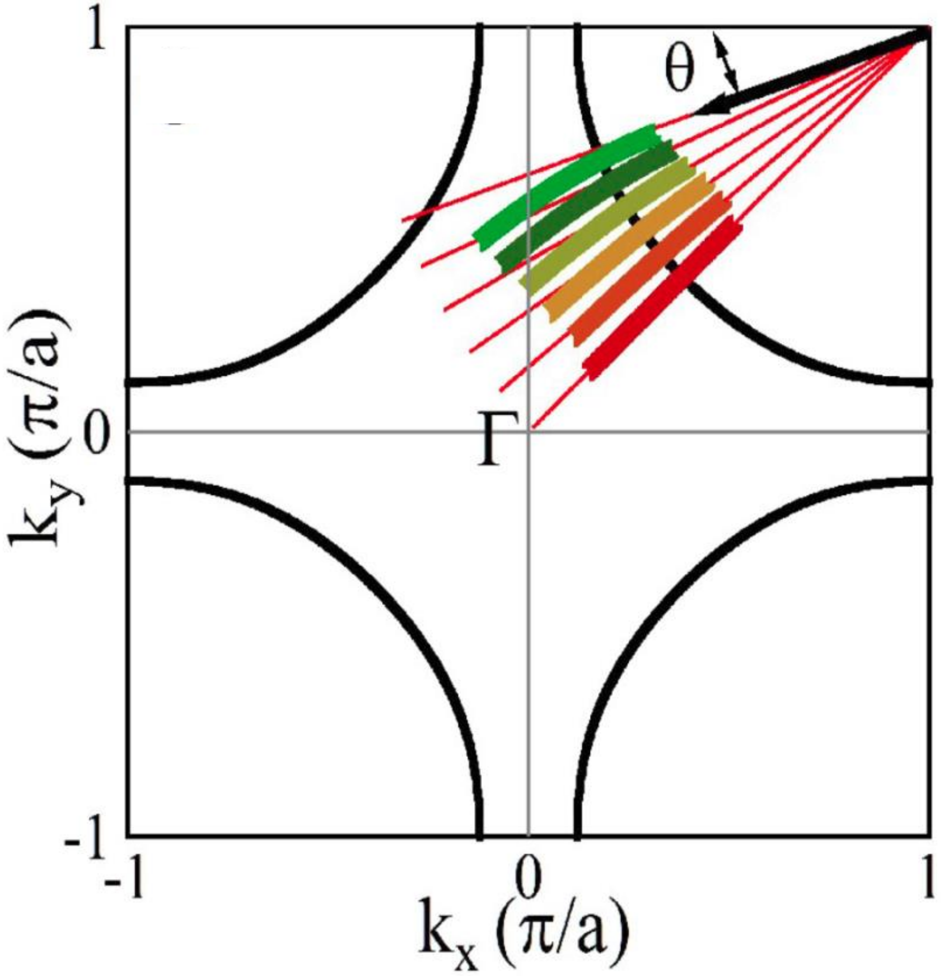




Data Precision: ~1%

J. M. Bok, H. Y. Choi, C. Varma, X. J. Zhou et al., Science Advances 2, e1501329 (2016).

High Precision Laser-ARPES Measurements



- Different momentum cuts;
- Each cut at different temperatures above and below Tc;
- Different Bi2212 samples

Extraction of Normal Self-energy and Pairing Self-energy

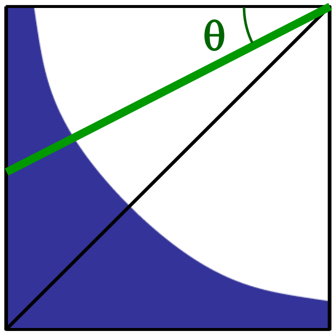
- ☐ **Single particle spectral function,**

$$A(k,\omega)=\frac{1}{\pi}\operatorname{Im}\{G(k,\omega)\}$$

- ☐ **Green's function in superconducting state,**

$$G(k,\omega)=\frac{Z(\omega)\omega+\epsilon_k}{(Z(\omega)\,\omega)^2-\epsilon_k^2-\phi^2(\theta,\omega)}$$

gap parameter $\phi(\theta,\omega)=\phi(\omega)\cos(2\theta)$



ε_K—Bare band -- from band structure calculations.

Above Tc in the normal state, $\phi(\theta,\omega)=0$

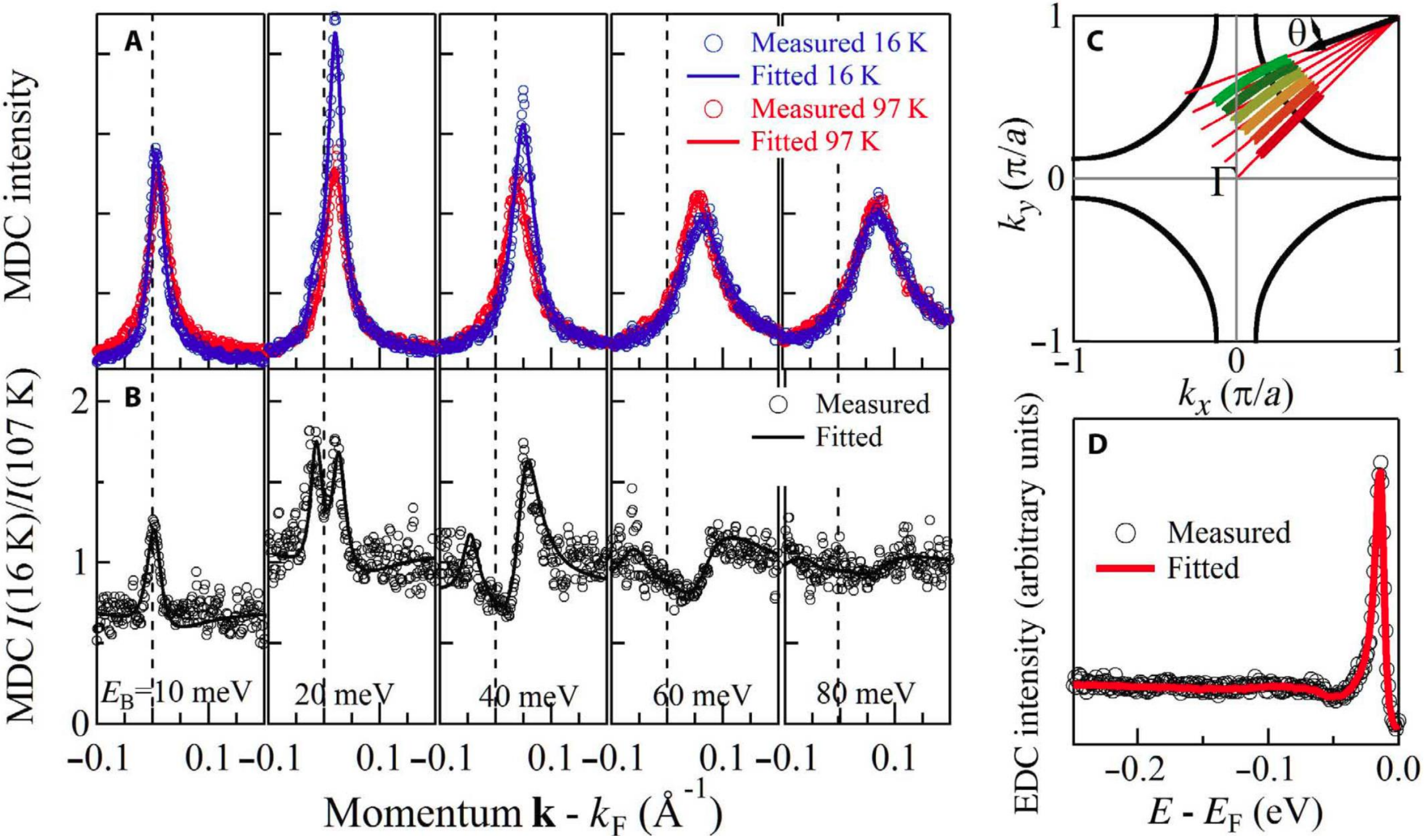
→ Normal self-energy $\Sigma(\omega)=(1-\omega)Z(\omega)$;

Below Tc in the superconducting state,

→ Normal self-energy $\Sigma(\omega)=(1-\omega)Z(\omega)$;

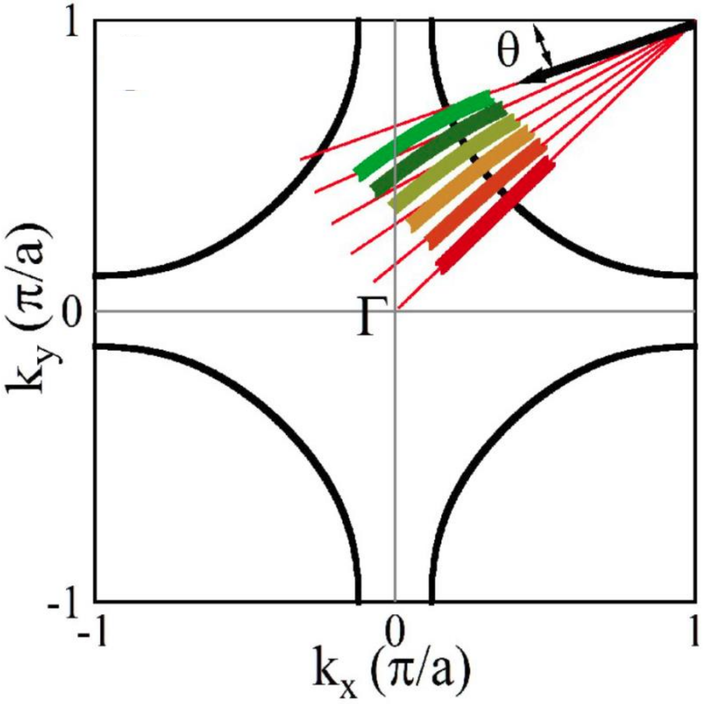
Pairing self-energy $\phi(\omega)$

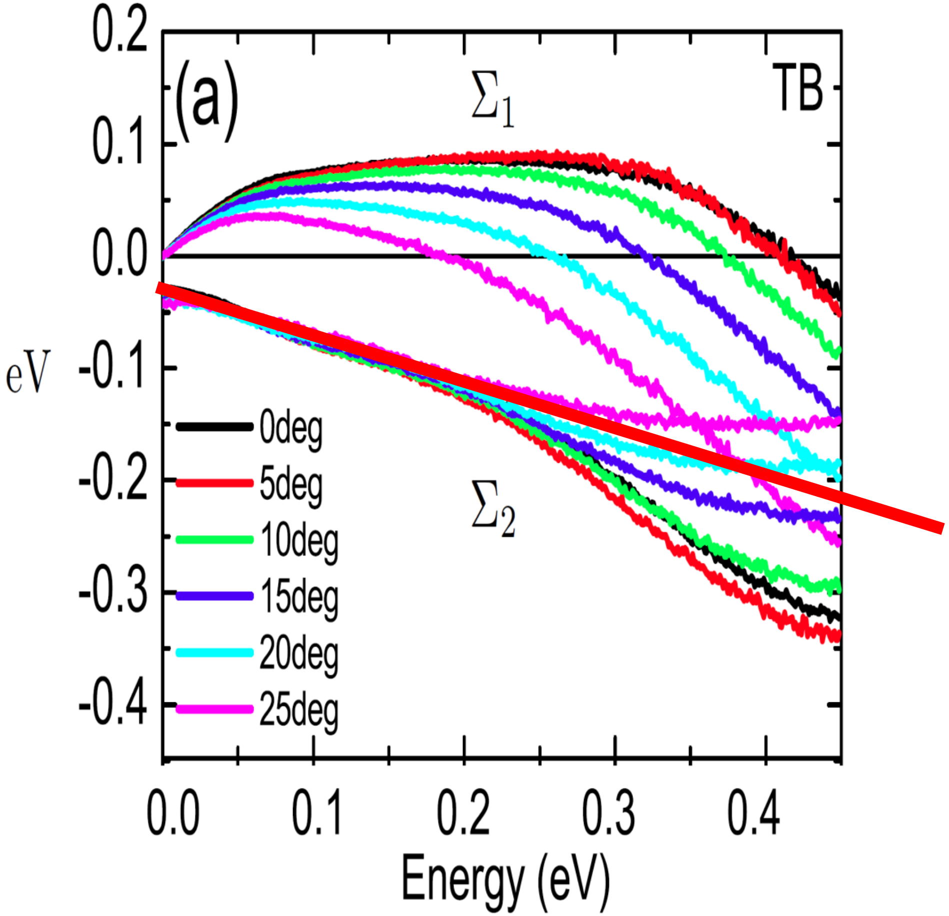
Fitting of MDCs to Get Normal and Pairing Self-Energies



J. M. Bok, H. Y. Choi, C. Varma, X. J. Zhou et al., Science Advances 2, e1501329 (2016).

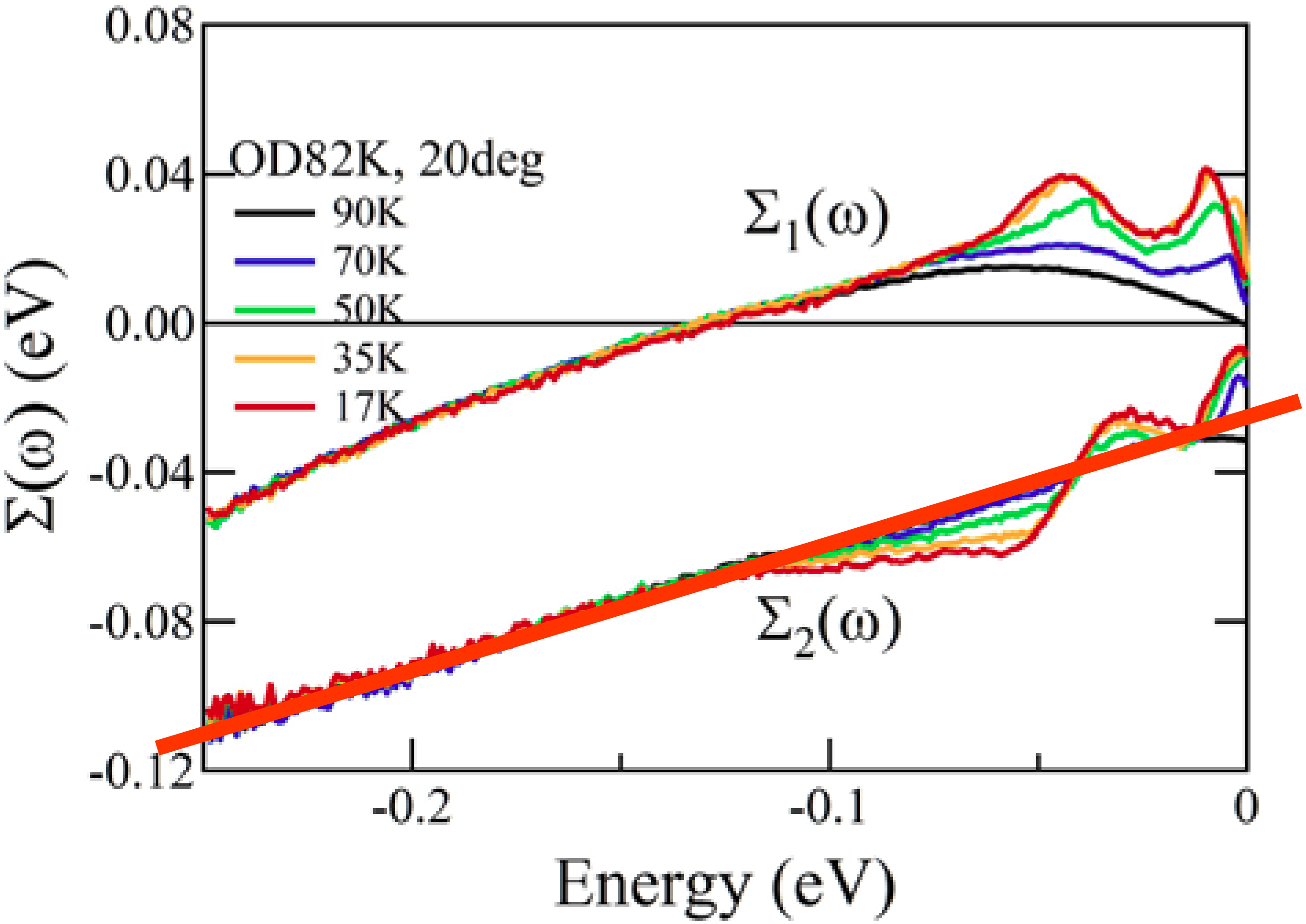
Normal Self-Energy Σ Determined above Tc





1. $\Sigma_2(\omega,k)$ is nearly angle-independent below an angle-dependent cut-off;
2. $\Sigma_2(\omega,k)$ is nearly linear in energy.

Normal Self-Energy Σ determined below Tc

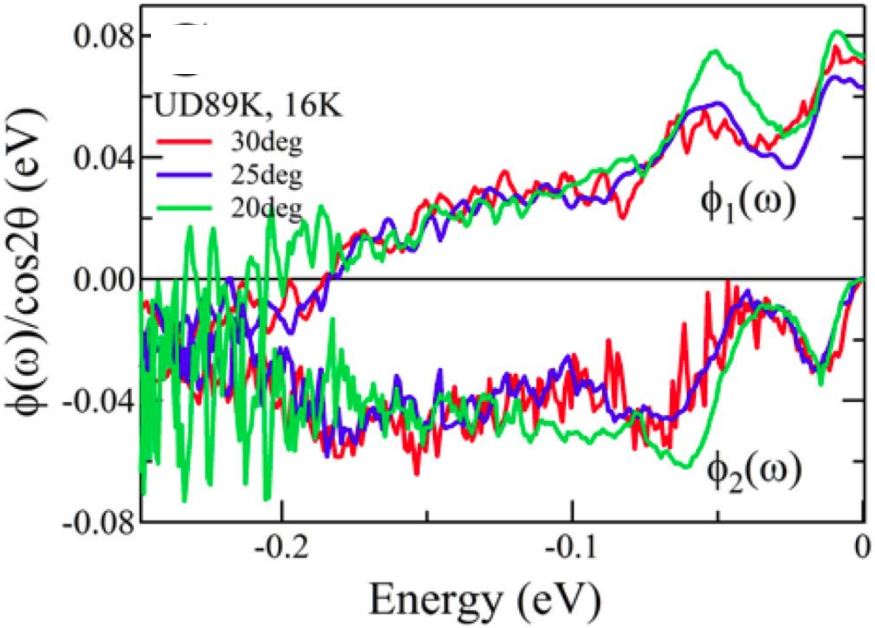


Σ_2 (ω,k) is nearly linear to energy.

J. M. Bok, H. Y. Choi, C. Varma, X. J. Zhou et al., Science Advances 2, e1501329 (2016).

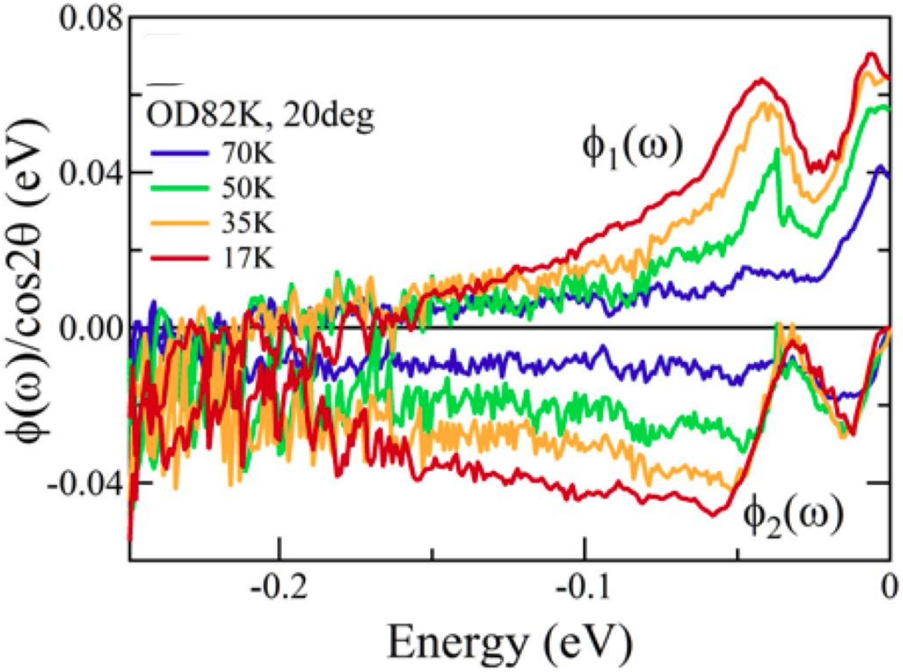
Pairing Self-Energies in Bi2212

Angle-Dependence



$\phi(\omega)/\cos 2\theta$ is independent of θ to 10% accuracy.

Temperature-Dependence



$\phi(\omega)$ increases below Tc.

J. M. Bok, H. Y. Choi, C. Varma, X. J. Zhou et al., Science Advances 2, e1501329 (2016).

Deduction of Normal Eliashberg Function
and
Pairing Eliashberg Function

Eliashberg Equations for *d*-Wave Pairing

$$\Sigma(\theta,\omega) = \int_{-\infty}^{\infty} d\epsilon \int_{-\infty}^{\infty} d\epsilon' S(\omega,\epsilon,\epsilon') N_1(\epsilon) \underline{\alpha^2 F^{(+)}(\theta,\epsilon')}$$

$$\boxed{\varepsilon_N(\theta,\omega)}$$

Normal Eliashberg Function

$$\phi(\omega) = -\int_{-\infty}^{\infty} d\epsilon \int_{-\infty}^{\infty} d\epsilon' S(\omega,\epsilon,\epsilon') D_1(\epsilon) \underline{\alpha^2 F^{(-}(\theta,\epsilon')}$$

$$\boxed{\varepsilon_P(\theta,\omega)}$$

Pairing Eliashberg Function

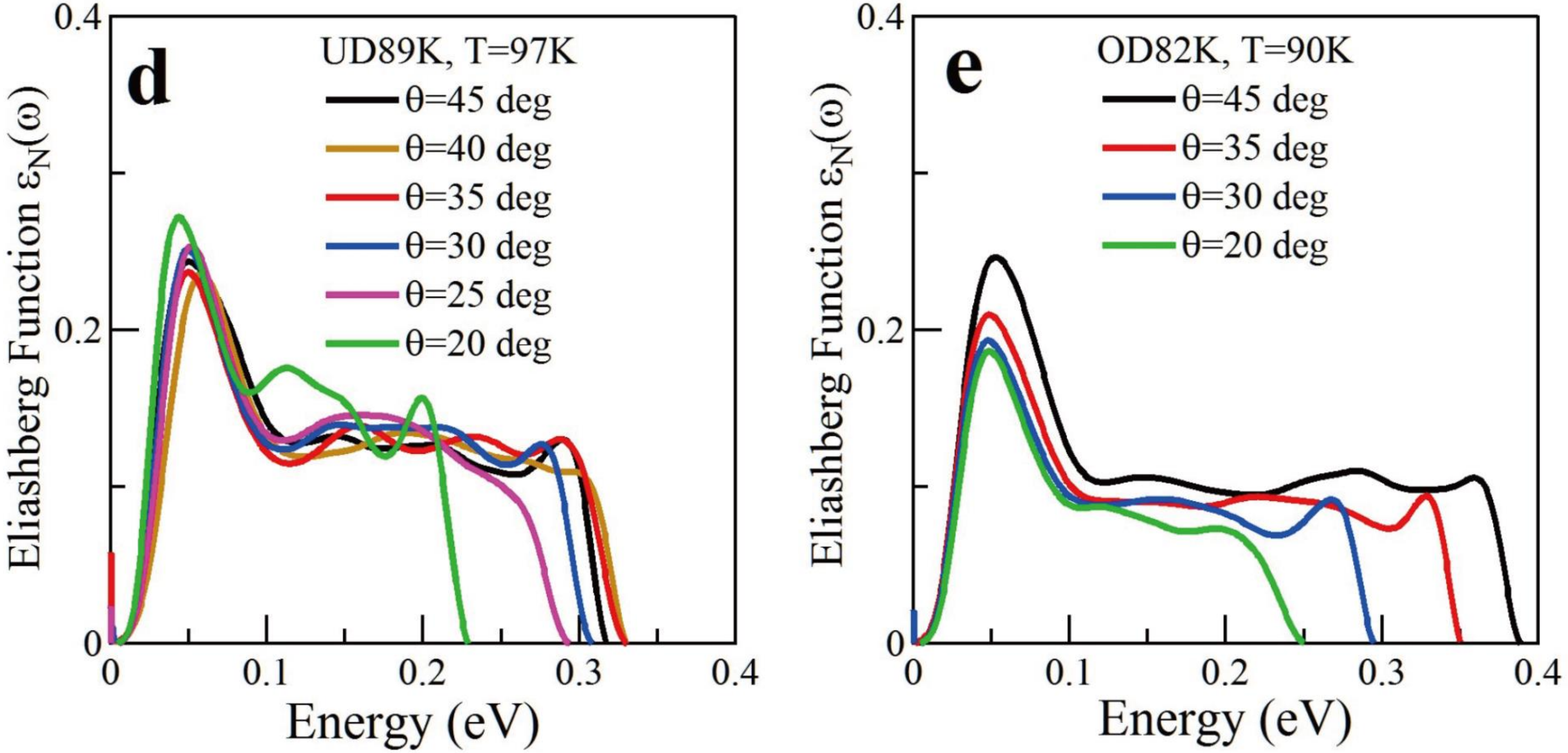
$$S(\omega,\epsilon,\epsilon') = \frac{f(\epsilon)+n(-\epsilon')}{\epsilon+\epsilon'-\omega-i\delta}$$

$$N_1(\epsilon) \equiv \left\langle Re \frac{W(\theta',\epsilon)}{\sqrt{W^2(\theta',\epsilon)-\phi^2(\epsilon)\sin^2(2\theta')}} \right\rangle_{\theta'}$$

$$D_1(\epsilon) \equiv \left\langle \frac{1}{v_F(\theta')} Re \frac{\phi(\epsilon)\sin^2(2\theta')}{\sqrt{W^2(\theta',\epsilon)-\phi^2(\epsilon)\sin^2(2\theta')}} \right\rangle_{\theta'}$$

A. Sandvik, D. J. Scalapino & N. E. Bickers, Phys. Rev. B 69, 094523 (2004).

Eliashberg Functions Extracted above Tc in Normal State



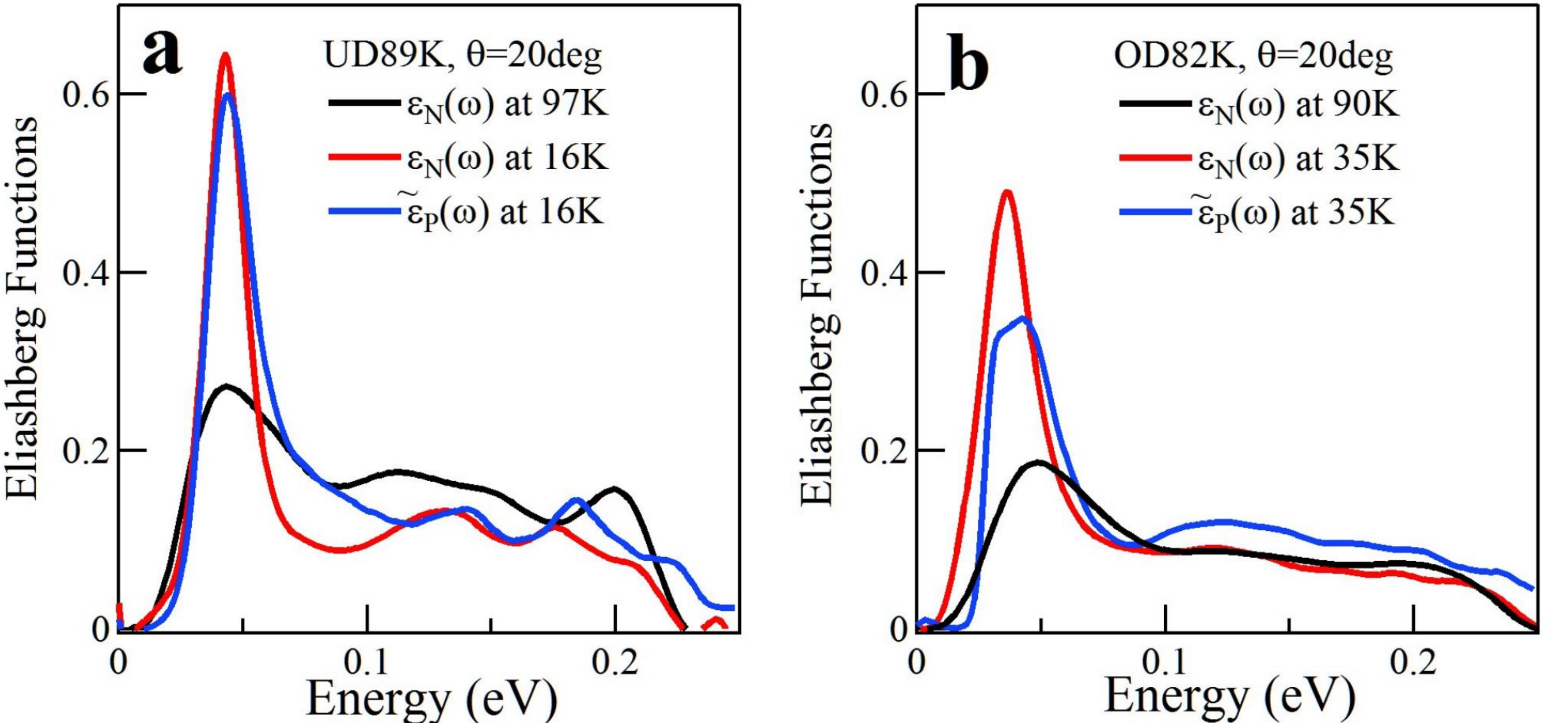
- Consist of a peak and a high-energy tail;

  --~50 meV peak may be from phonons;

- Nearly momentum-independent except for the cut-off.

Such fluctuation spectra lead to all normal state properties.

Normal and Pairing Eliashberg Functions



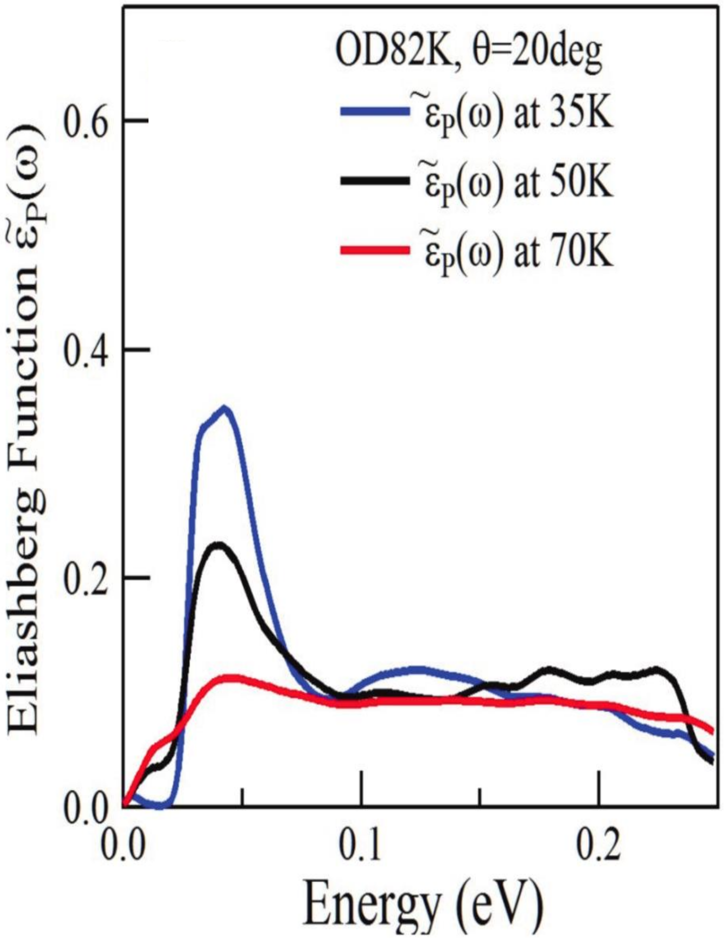
At low temperature in the superconducting state,

$$\varepsilon_N(\omega) \quad = \quad \tilde{\varepsilon}_P(\omega)$$

It is the same interaction that dictates the anomalous normal state properties and electron pairing in the superconducting state.

Pairing Eliashberg Functions

--Fluctuations that give high Tc *d*-wave superconductivity



- For temperature near Tc, no ~50meV bump in ε_P (ω);

- ~50meV feature is possibly superconductivity-induced.

P. B. Littlewood and C. M. Varma,
J. Appl. Phys. 69, 4979 (1991).

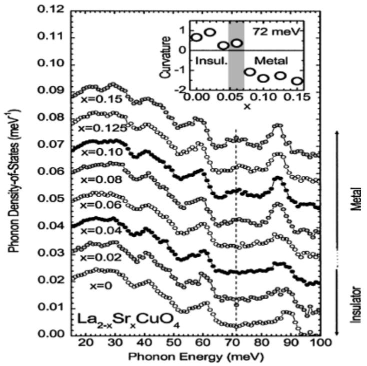
The most important information is in self-energies just below Tc.

Comparison with and Examination on Superconductivity Theories

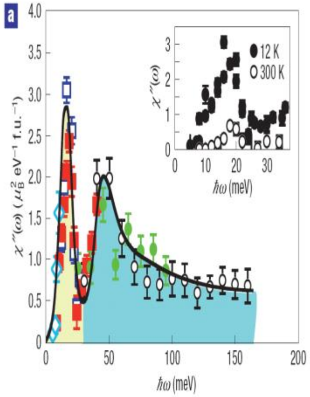
These results can be used to check on superconductivity theories of high temperature superconductors:

- Phonons; X
- Spin fluctuations; X
- Hubbard model; X
- Quantum critical fluctuations √
- ……

Phonon DOS in LSCO

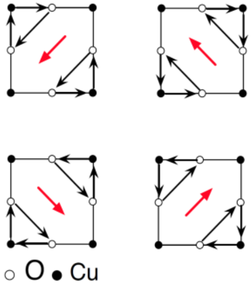


Spin Fluctuation in LSCO



Vignolle et al.,
Nat. Phy. 3(2007)163.

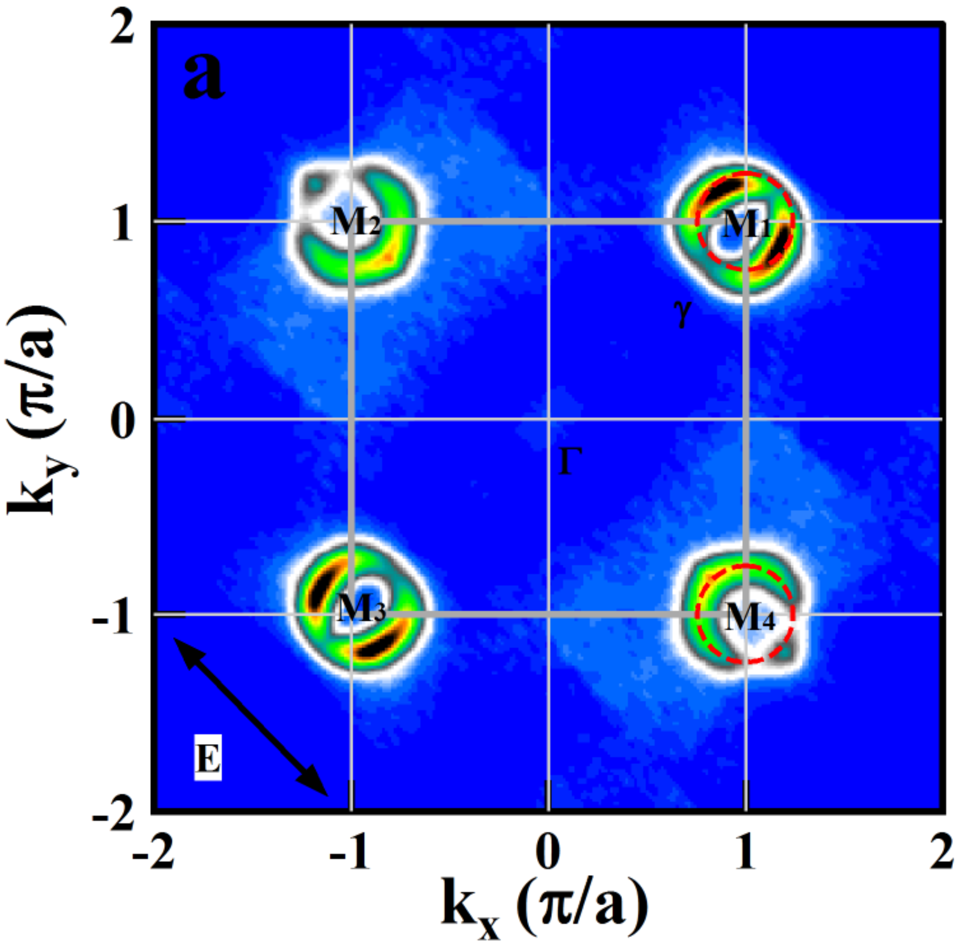
Loop Currents



J. M. Bok, H. Y. Choi, C. Varma, X. J. Zhou et al., Science Advances 2, e1501329 (2016).

Superconductivity Mechanism in Iron-Based Superconductors

—Pairing Eliashberg functions in single-layer FeSe to be extracted



Single-layer FeSe/$SrTiO_3$ is ideal:

1). Simple electronic structure;

2). Record high Tc~65K;

3). Nearly isotropic superconducting gap.

Ideal system for studying mechanism of superconductivity in the iron-based superconductors

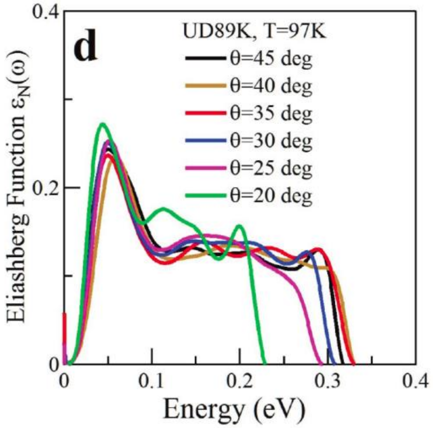
D. F. Liu , X. J. Zhou et al., Nature Communications 3, 931 (2012).
S. L. He, X. J. Zhou et al., Nature Materials 12, 605 (2013).

Summary

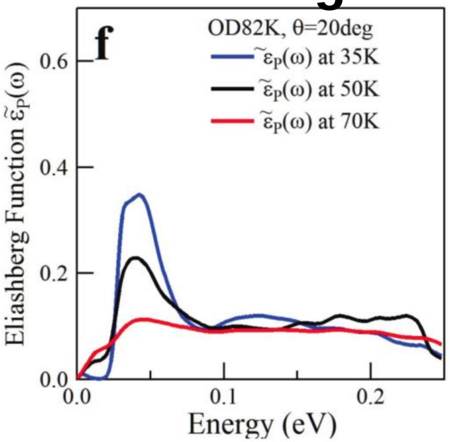
Laser ARPES of unprecedented accuracy and stability quantitatively analyzed to:

- Normal self-energy $\Sigma(\theta,\omega)$ exhibits weak momentum dependence;
- Pairing self-enery $\phi(\omega)/\cos 2\theta$ is independent of θ to 10% accuracy.
- $\varepsilon_P(\omega)/\cos(2\theta) \approx \varepsilon_N(\omega)$ for T<<Tc in the superconducting state;
- Near Tc, $\varepsilon_P(\omega)/\cos(2\theta) \approx \varepsilon_N(\omega)$ minus ~50meV bump.

Normal



Pairing



These results are definitive and can be used to compare with calculations of different models of superconductivity.

Thanks

A Central Paradox of d-Wave Superconductivity in Cuprates

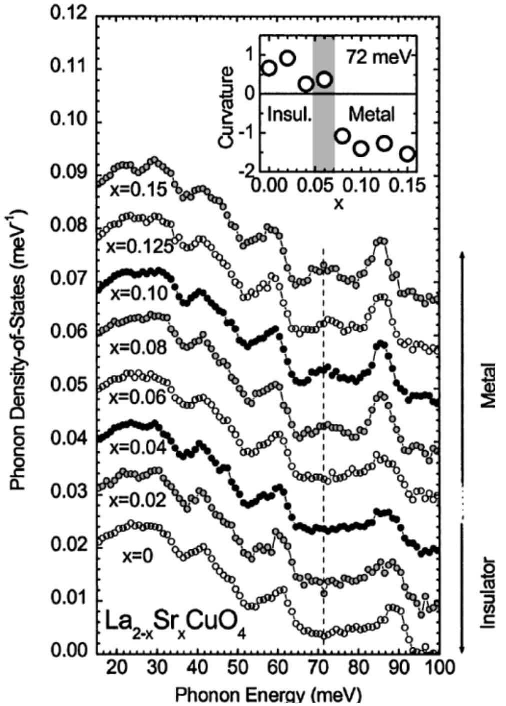
How the same frequency-independent fluctuations

that dominantly scatter at angles ± $\pi/2$ in the attractive channel to give rise to a d-wave pairing

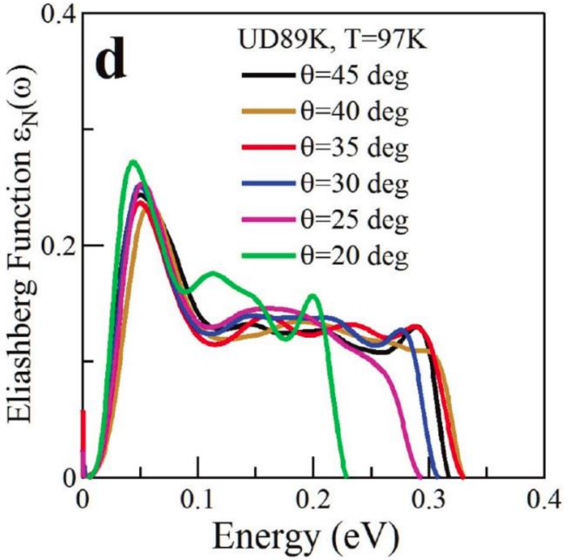
and lead to a nearly angle-independent repulsive scattering in the normal channel with the full symmetry of the lattice?

Implications and Comparison with Some Theoretical Models

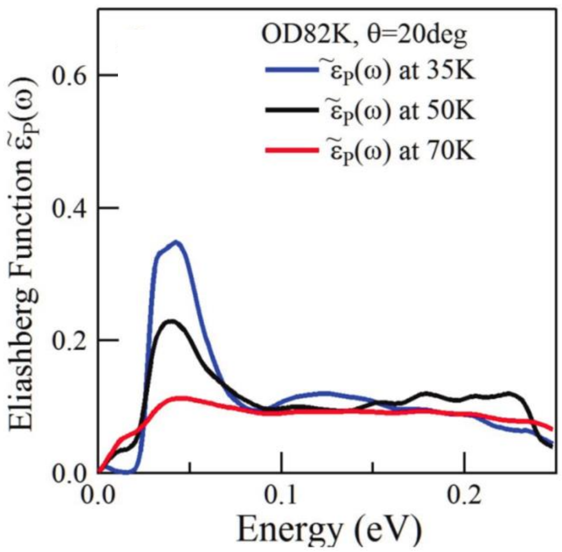
Phonons in High-Tc Cuprate Superconductors

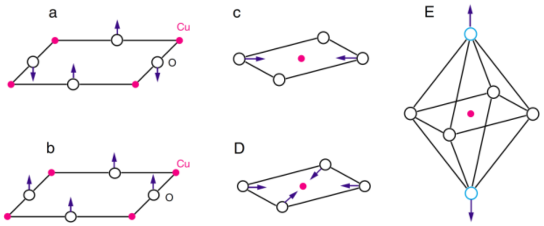


Normal



Pairing





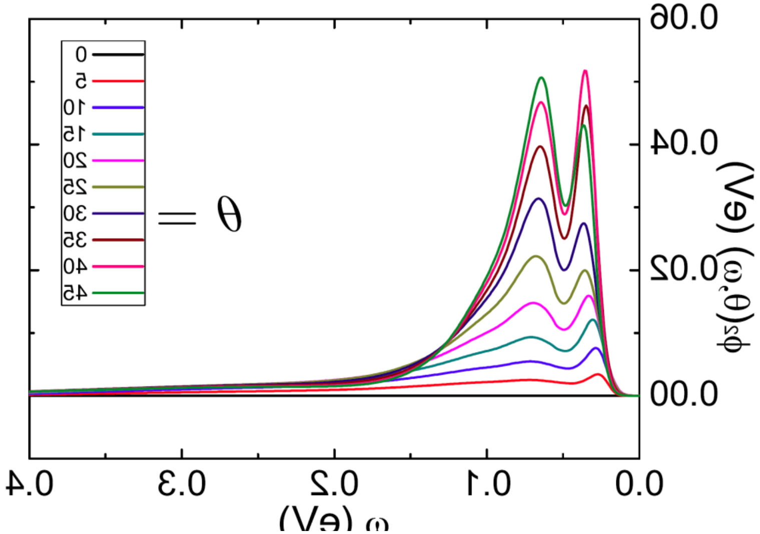
The phonon frequency is limited to within 100 meV.

R. J. McQueeney *et al.*,
Phys. Rev. Lett. **87**, 077001 (2001).

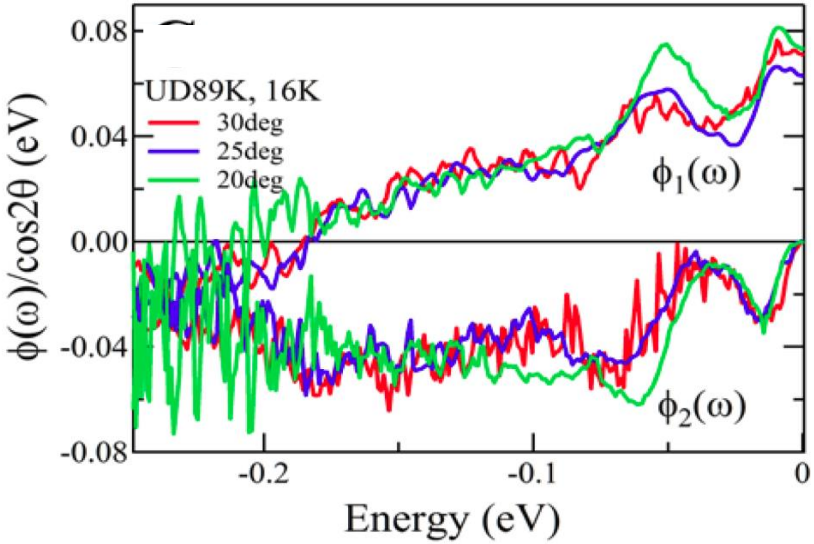
- ➢ Phonons can not account for the observed pairing interaction;
- ➢ Phonons are present in normal Eliashberg function;
- ➢ Phonons do not enter into pairing Eliashberg fucntion.

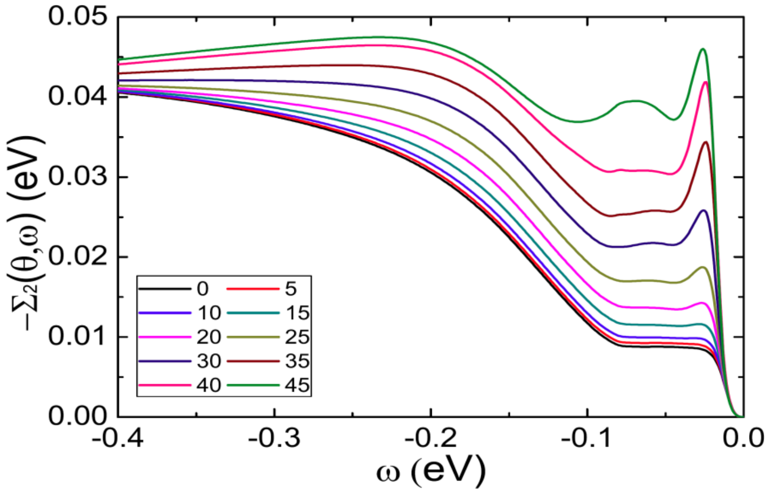
Comparison with Spin Fluctuations

Simulated



Measured





Frequency-dependence, **No**

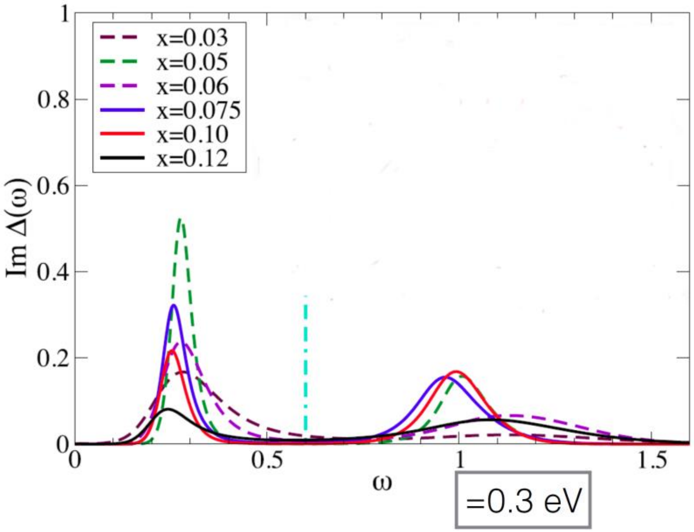
Normal self-energy, **No**

Relation between two Eliashberg functions, **No**

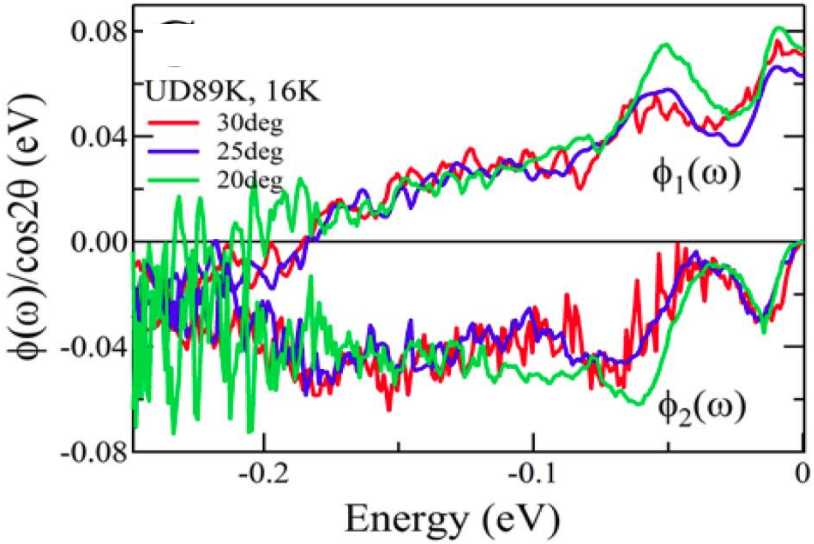
H. Y. Choi, J. Phys. C **25**, 365702 (2013).
B. Vignolle et al., Nature Physics 3(2007)163.

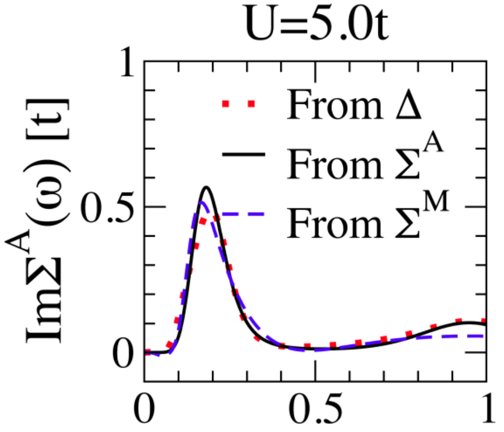
Comparison with DMFT Calculations on the Hubbard Model

Calculated



Measured





Frequency-dependence, **No**

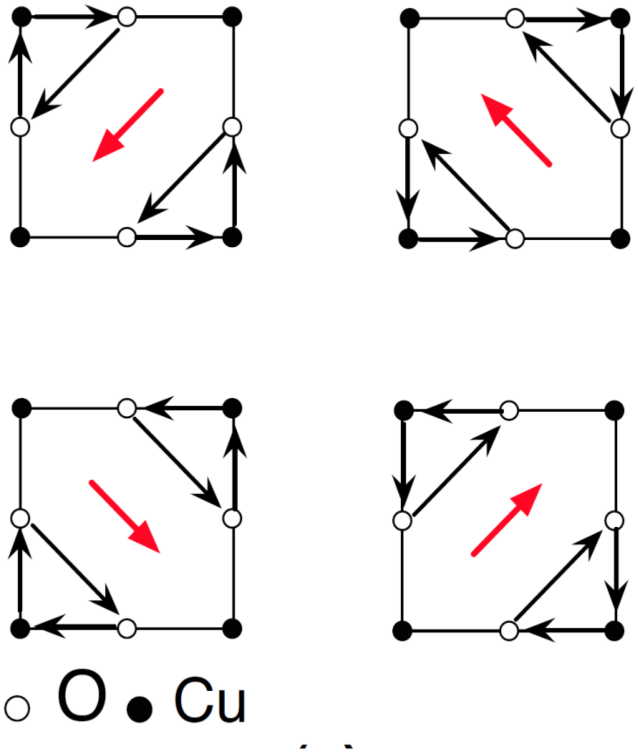
Normal self-energy, **No**

Relation between Two Eliashberg functions, **No**

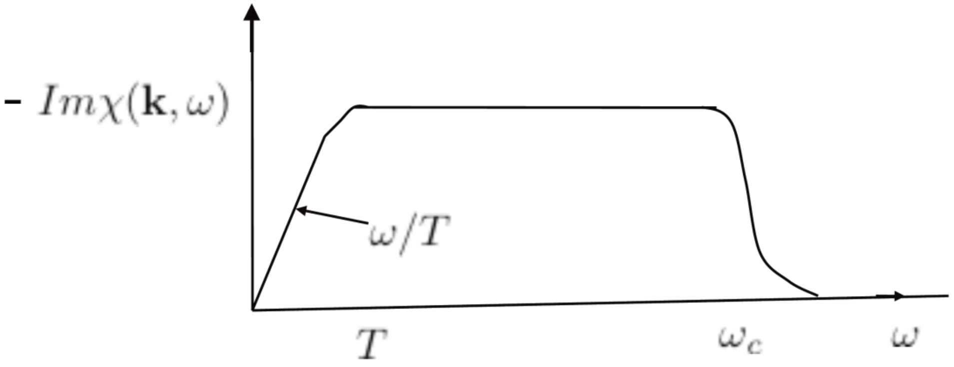
E. Gull, A. J. Millis,
Phys. Rev. B 90, 041110 (2014);
Phys. Rev. B 91, 085116 (2015).

Quantum Critical Fluctuations

Loop Currents



Proposed Fluctuation Function

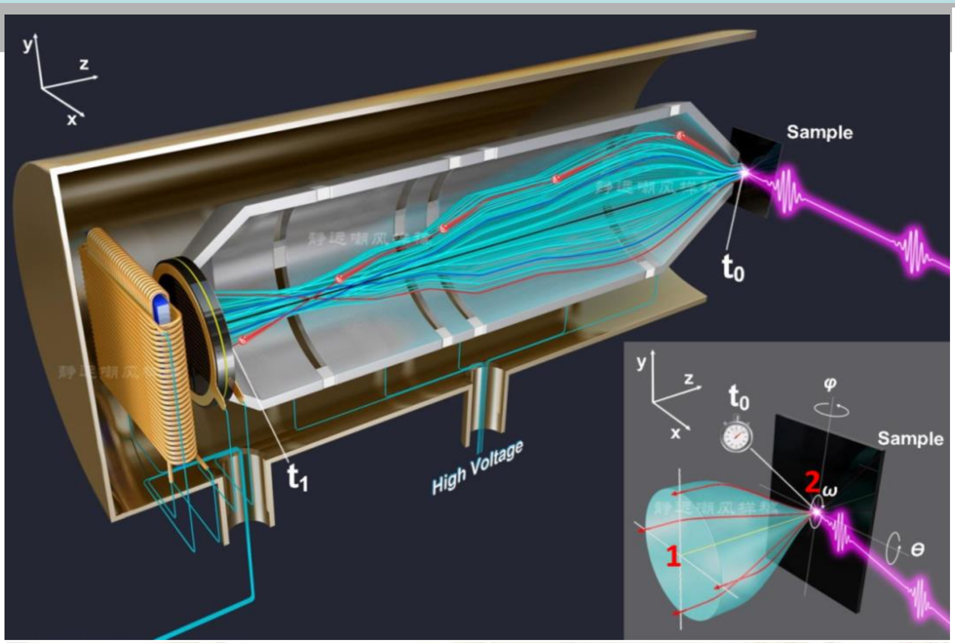


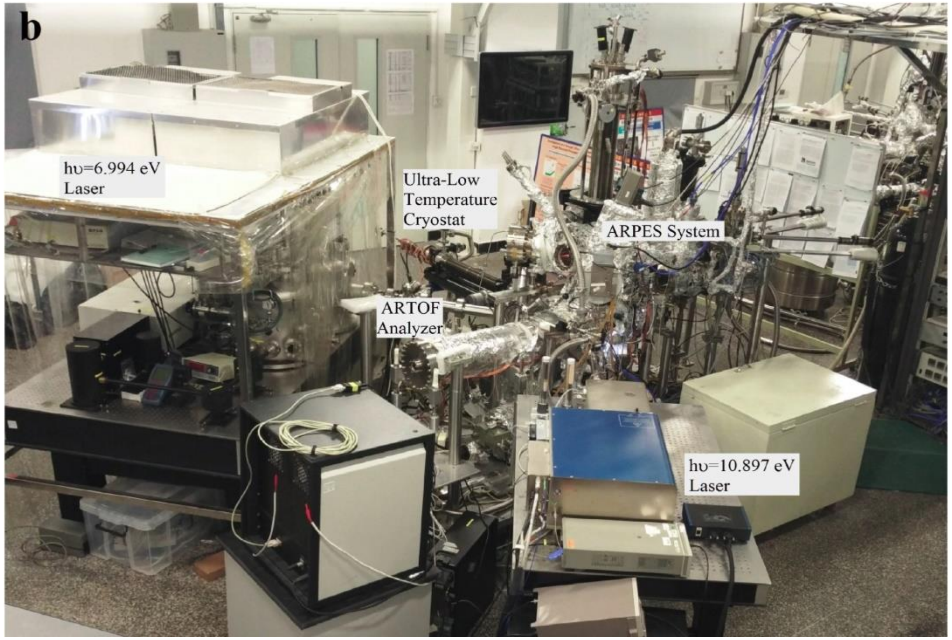
These properties are predicted from the theory of Quantum Critical Flutuations' of loop-current order.

M. E. Simon and C. M. Varma, Phys. Rev. Lett. 89, 247003 (2002).
V. Aji, C. M. Varma et al., Phys. Rev. B 81, 064515 (2010).

Future Directions

Further Precision Improvement—ARToF-ARPES

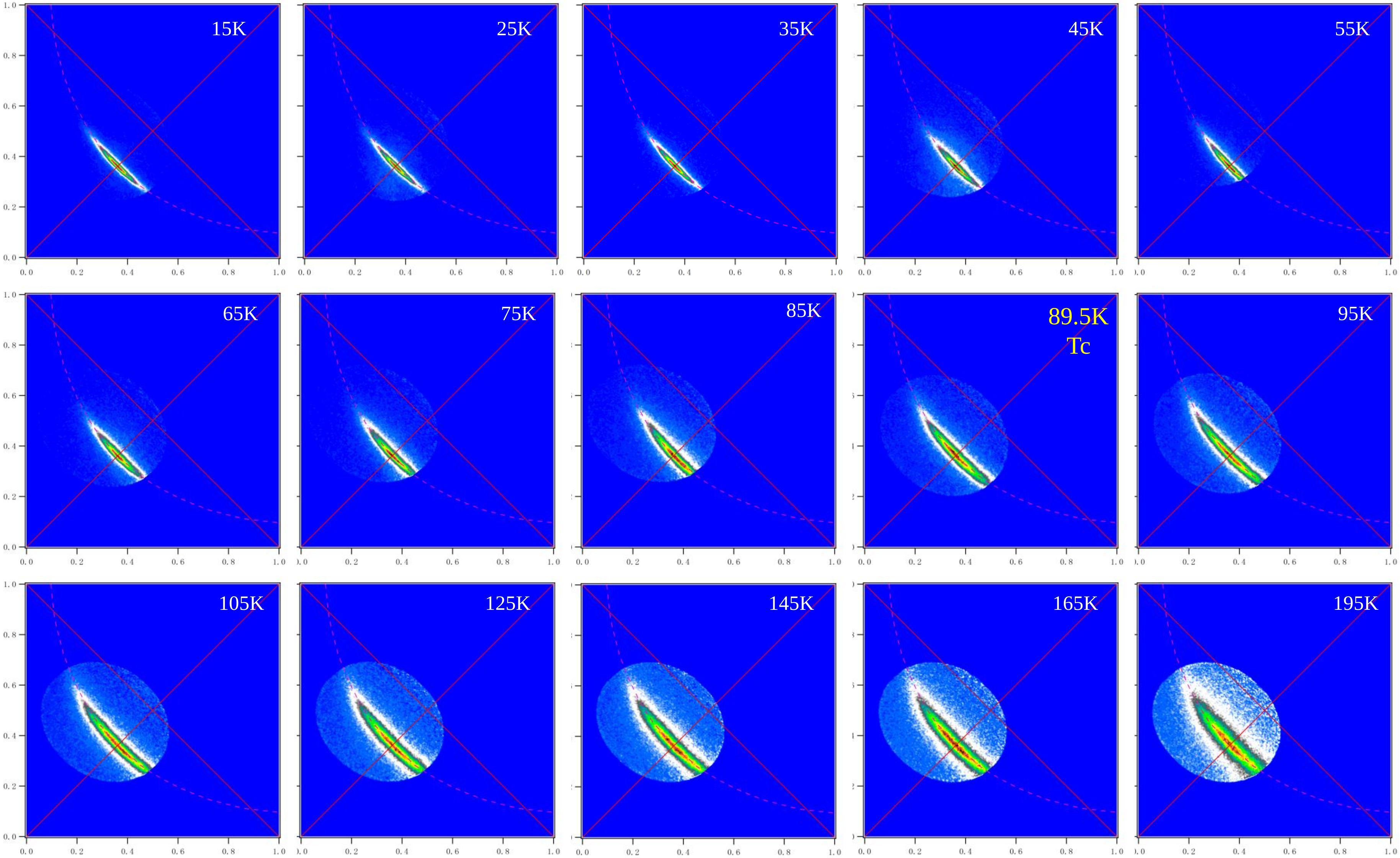




Advantages :

- **2-dimensioanl momentum coverage simultaneously;**
- **Super-high resolutions:**
  Energy Resolution: ~0.1meV
  Angular Resolution: 0.05 Deg
- **Weak non-linearity effect;**
- **7 eV and 11 eV lasers.**

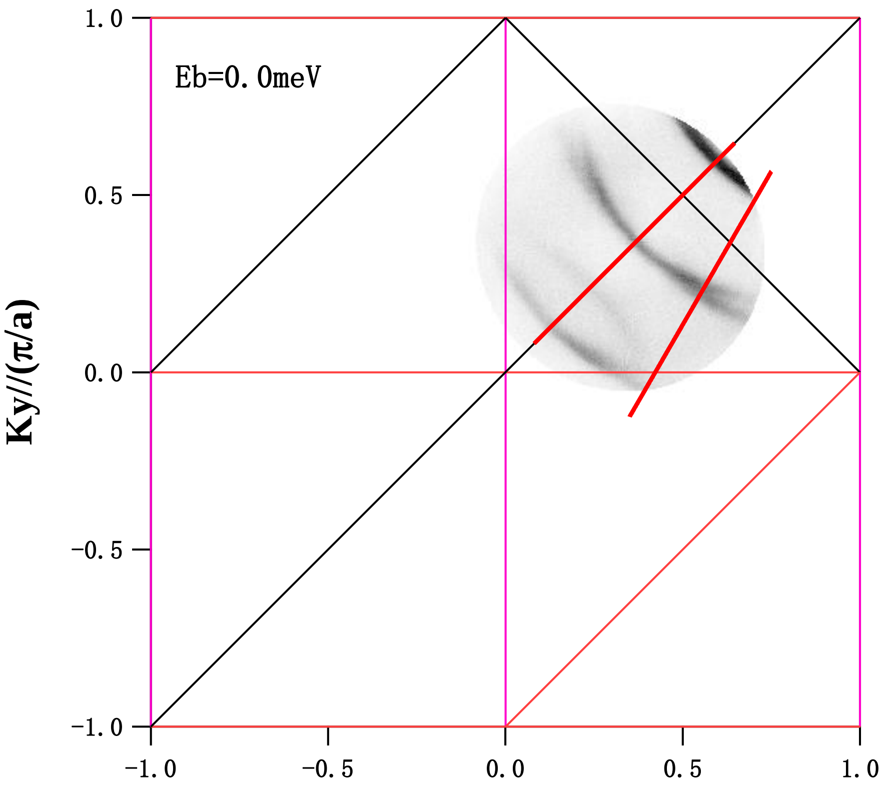
Laser ARToF-ARPES on Bi2212 (hv=7 eV)



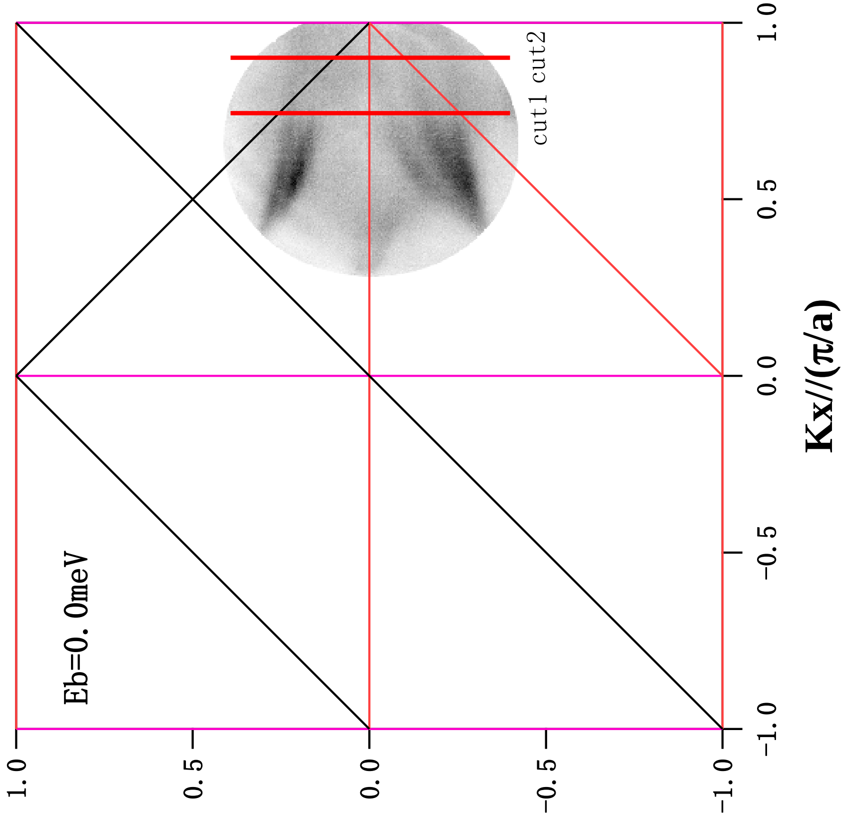
Yuxiao Zhang, X. J. Zhou et al., unpublished.

11eV Laser-ARTOF on Bi2212

Nodal Region



Anti-nodal Region



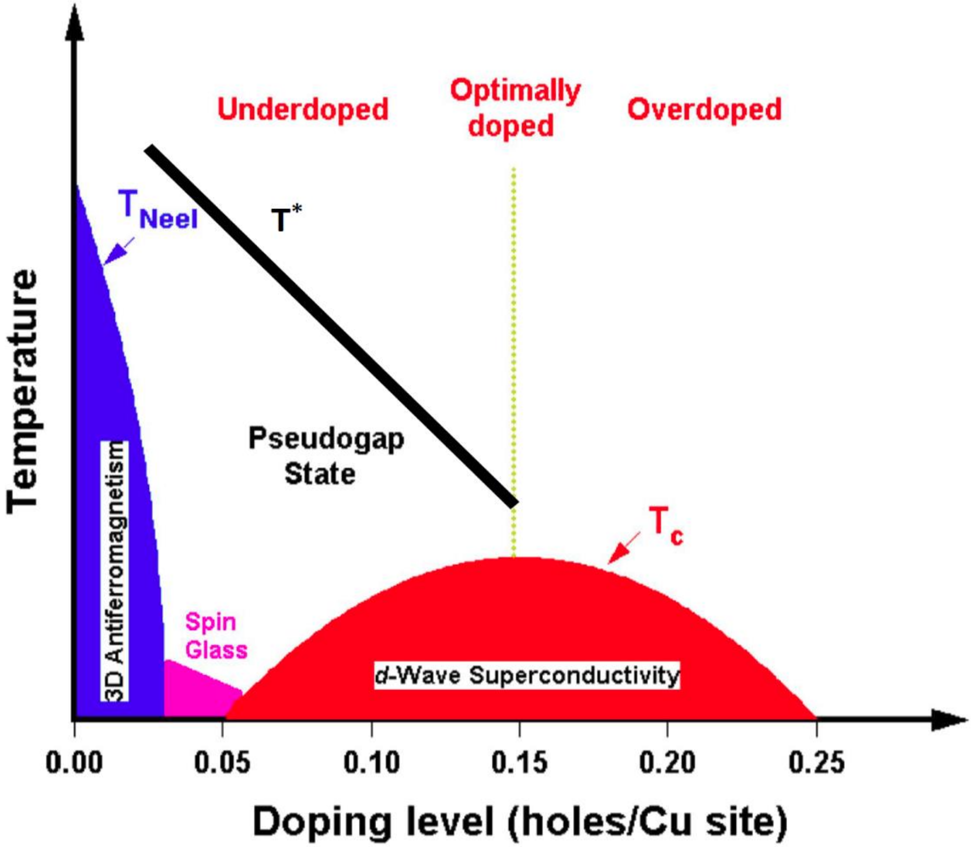
1. Cover larger momentum space at one time;

2. Reach (π,0) antinodal region.

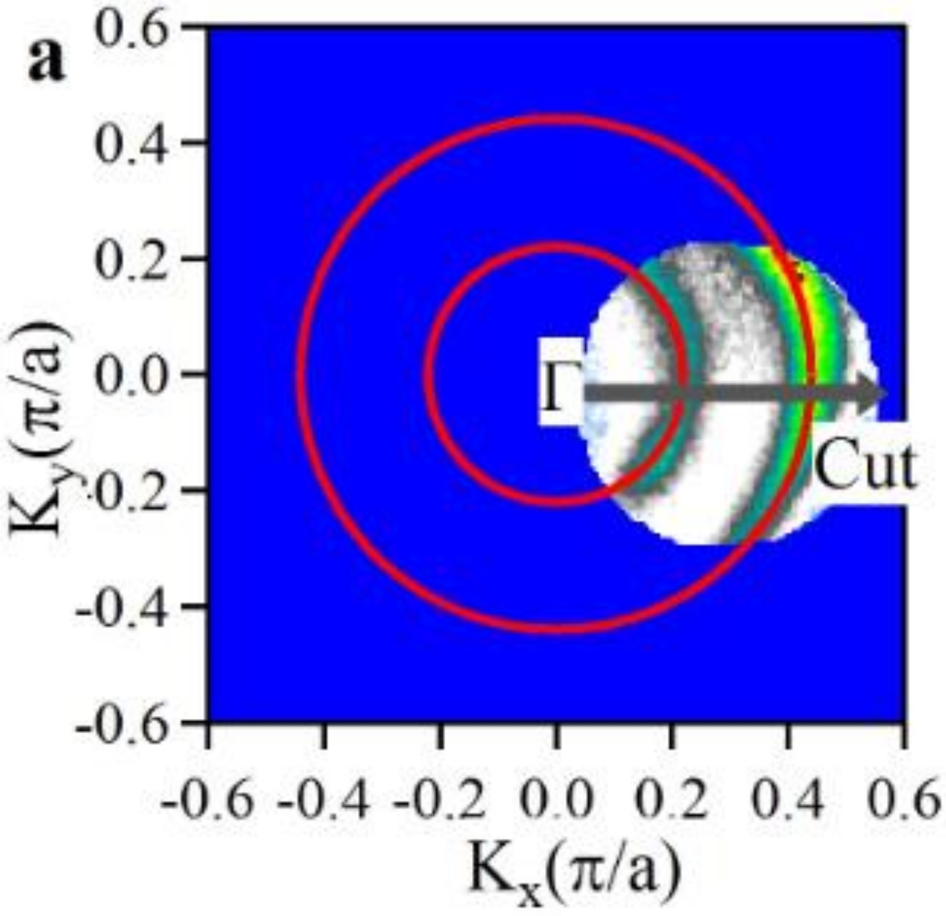
Jing Liu, Ping Ai, Qiang Gao, X. J. Zhou et al., unpublished.

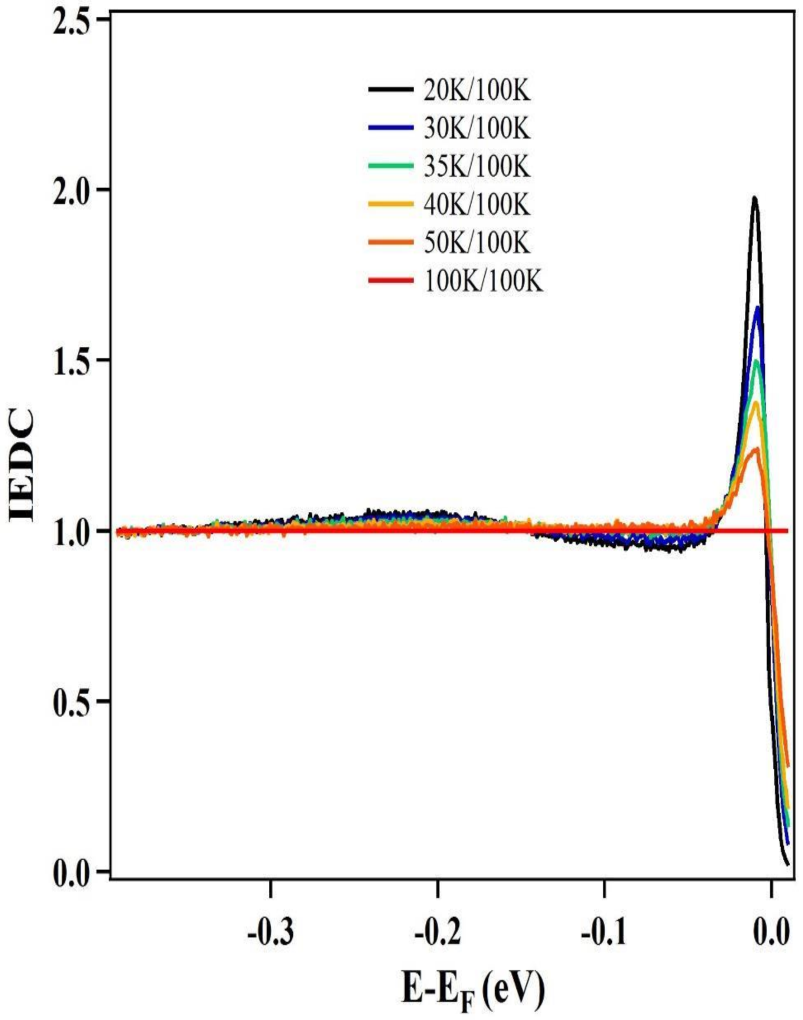
Further Work in Cuprates

1. Extend to different dopings;
2. Extend to different systems (Bi2212, Bi2201).



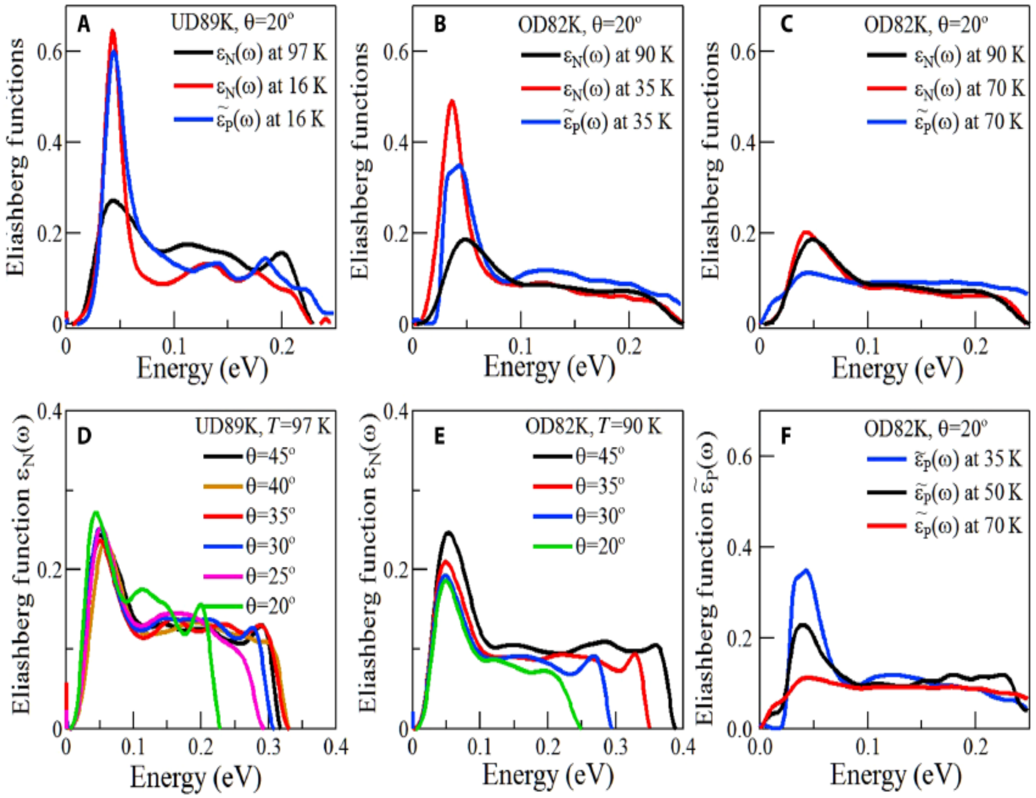
Laser ARTOF-ARPES on $(Ba_{0.6}K_{0.4})Fe_2As_2$





Jianwei Huang, X. J. Zhou et al., unpublished.

Calculation of Tc
from Deduced Pairing Eliashberg Functions



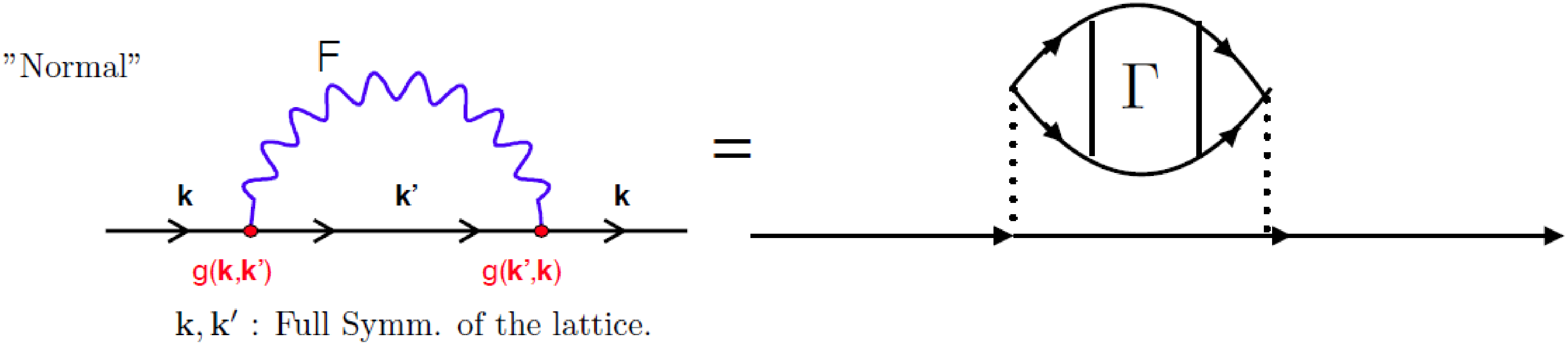
Calculated Tc~135 K for UD89K sample

Calculated Tc~90K for OD82K sample

J. M. Bok, H. Y. Choi, C. Varma, X. J. Zhou et al., Science Advances 2, e1501329 (2016).

Superconductivity-Induced Features in Self-Energies

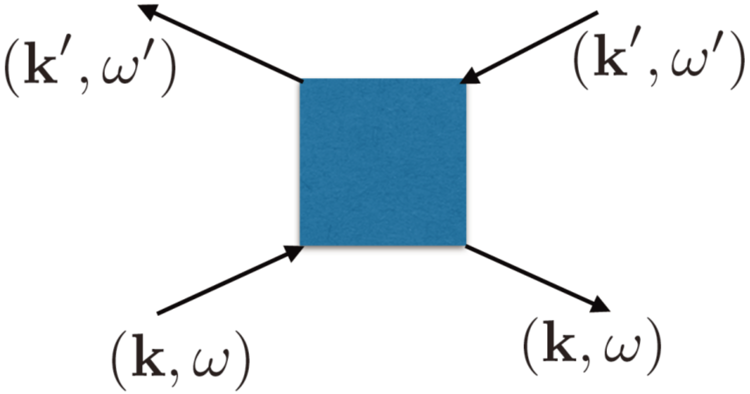
For any electronic mechanism of pairing,
self-energies below Tc changes up to an energy of 3Δ.



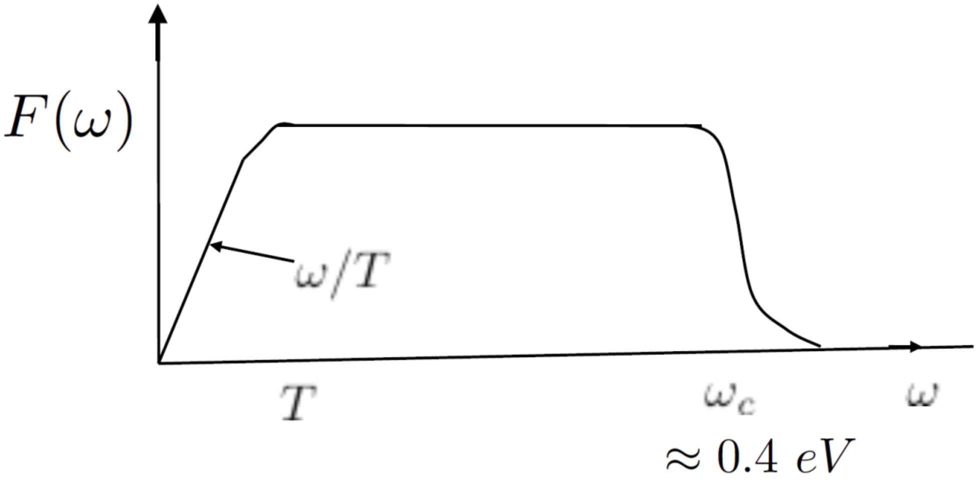
Therefore, the most important information is in self-energies just below Tc.

P. B. Littlewood and C. M. Varma, J. Appl. Phys. 69, 4979 (1991).

The Irreducible Interaction Deduced among Fermions

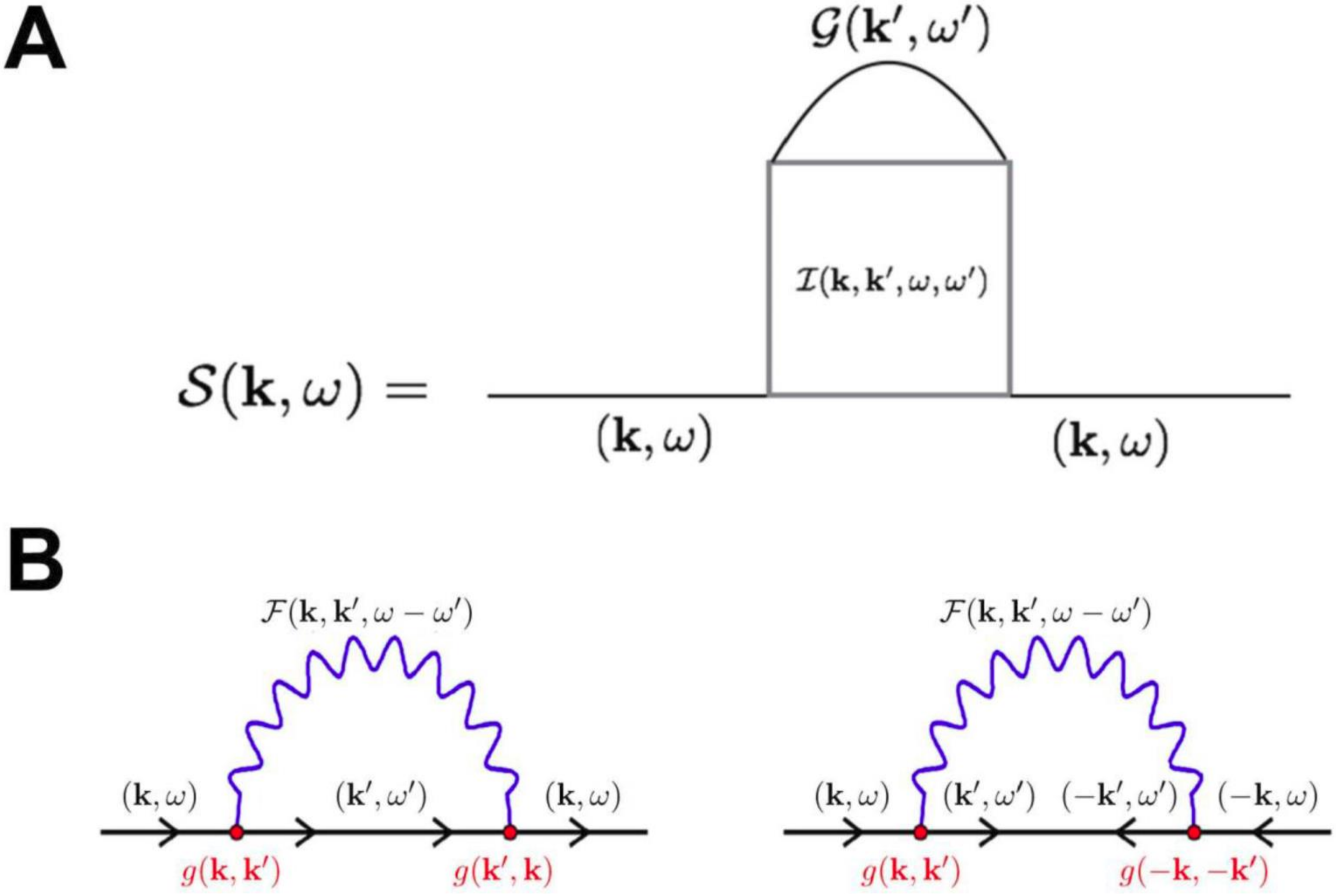


$$I(\mathbf{k}, \mathbf{k}', \omega - \omega') \approx g_0 \Big(\underset{\substack{\uparrow \\ \text{Repulsive}}}{1} - \underset{\substack{\uparrow \\ \text{Attractive}}}{\cos(2\theta_{\mathbf{k}})} \cos(2\theta'_{\mathbf{k}}) \Big) F(\omega - \omega')$$



$$g_0 N(0) \approx 0.15$$

Validity of Eliashberg Functions in Cuprates?



Refer to Supplementary of J. M. Bok et al., Science Advances 2, e1501329 (2016).

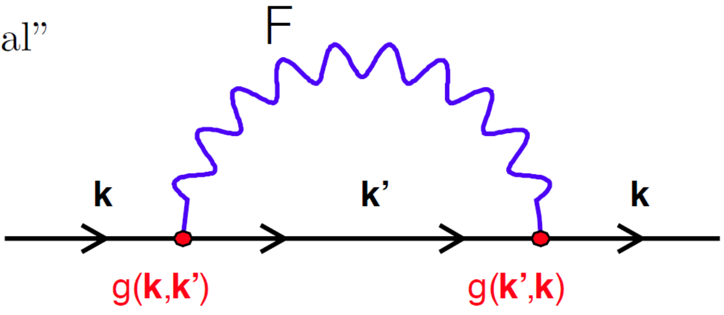
Check with Chandra Varma since he has successfully persuaded two theorists.

The Central Paradox of Superconductivity in Cuprates.

- The normal state self-energy is angle-independent;
- Superconductivity is d-wave which requires dominant scattering near angle π/2.

$\Sigma(\mathbf{k},\omega)$

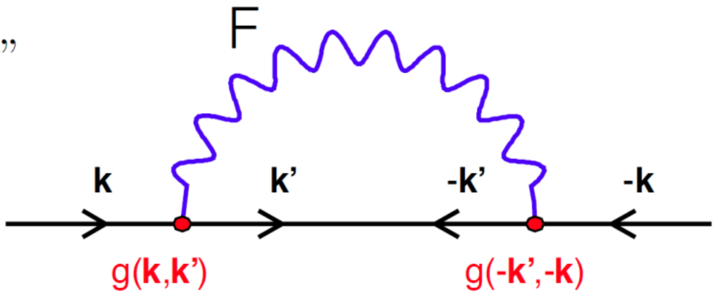
"Normal"



$\mathbf{k},\mathbf{k}'$: Full Symm. of the lattice.

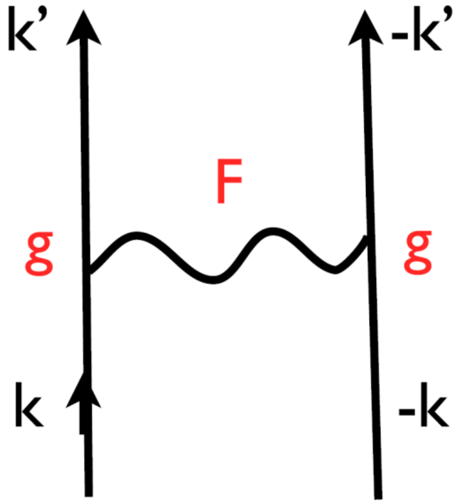
$\Delta(\mathbf{k},\omega)$

"Pairing"



$\mathbf{k}$, $-\mathbf{k}$ and intermediate state $(\mathbf{k}', -\mathbf{k}')$ have symmetry of D-wave.

Fermion Pairing: An Important General Point



$$: \quad g^2(k,k')F(k,k',\omega) = \sum_\ell V_\ell(|k|,|k'|,\omega)P_\ell(\mathbf{k}\cdot\mathbf{k}')$$

Symmetry of Pairing determined by Angular distribution of scattering from k to k':

S-wave: isotropic scattering of fermions.

P-wave: preferred forward (near 0-angle) and backward (near π) scattering of fermions.

D-wave: preferred scattering at +/- (π /2) .
Requires angle-dependent scattering

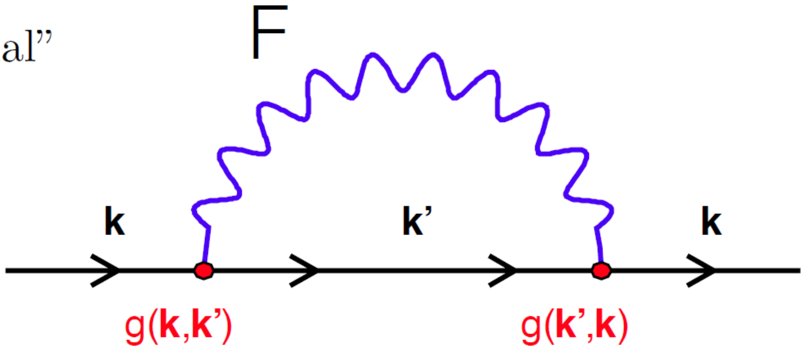
For fixed lengths $|\mathbf{k}, \mathbf{k}'| = |\mathbf{k}_F|$,

$$g(\mathbf{k}, \mathbf{k}')g(\mathbf{k}', \mathbf{k}) = g(\mathbf{k}, \mathbf{k}')g(-\mathbf{k}, -\mathbf{k}')$$

$$= -\frac{1}{2}\left(1 - \cos 2\theta_k \cos 2\theta'_k - \sin 2\theta_k \sin 2\theta'_k\right)$$

$\Sigma(\theta, \omega)$

”Normal”

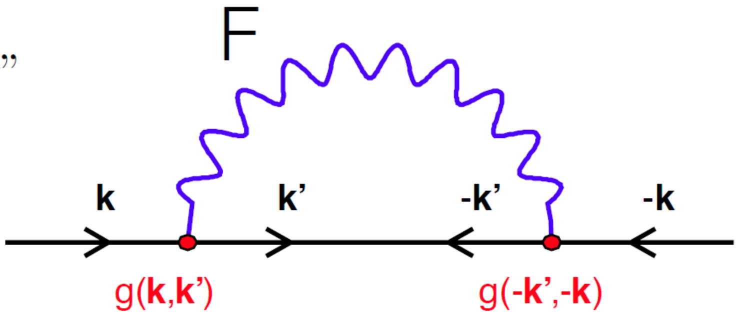


Only contribution from vertices: 1 , Repulsive.

$\mathbf{k}, \mathbf{k}'$: Full Symm. of the lattice.

$\phi(\theta, \omega)$

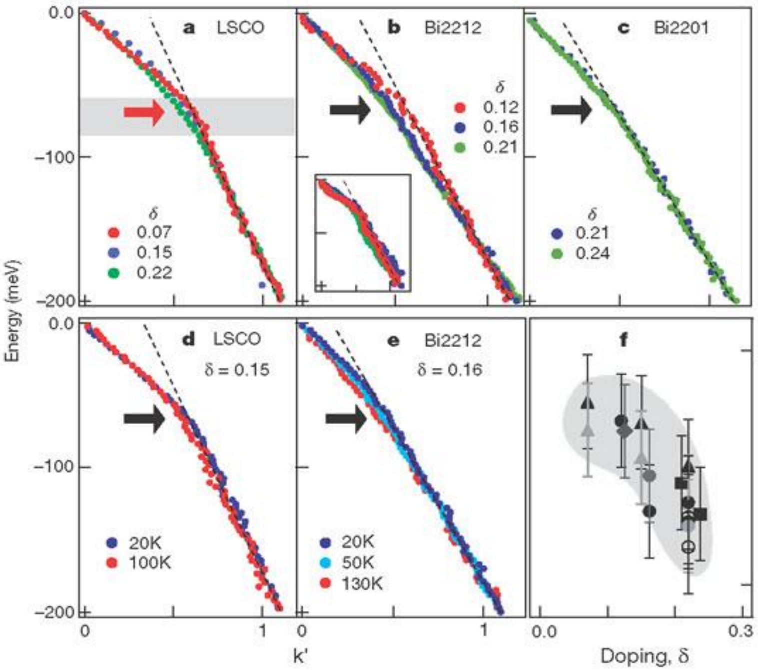
“Pairing”



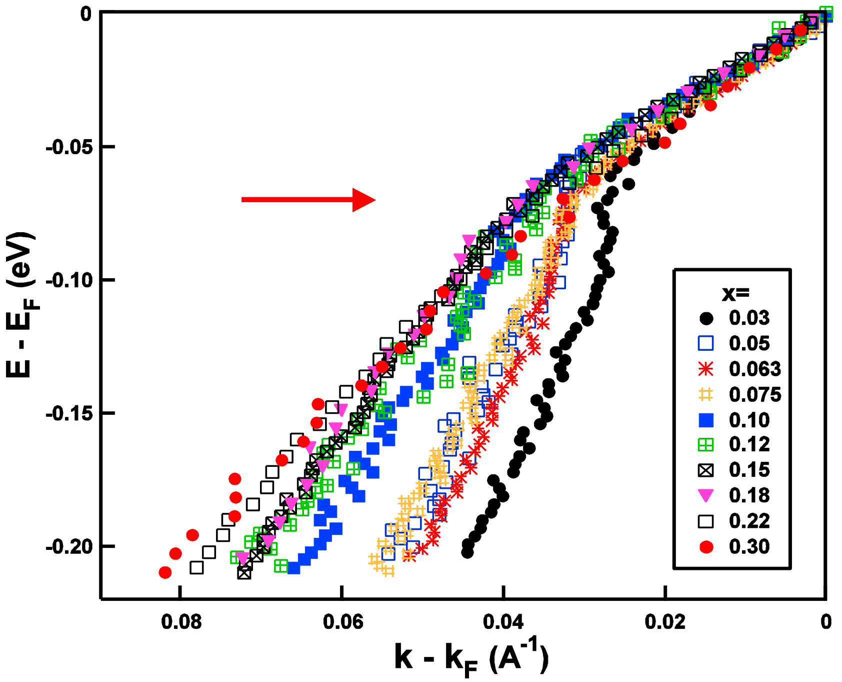
Only contribution from vertices: either second or third term, Attractive.

$\mathbf{k}, -\mathbf{k}$ and intermediate state $(\mathbf{k}', -\mathbf{k}')$ have symmetry of D-wave.

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?

Ordinary Tunneling: Not Useful for *d*-Wave Superconductors

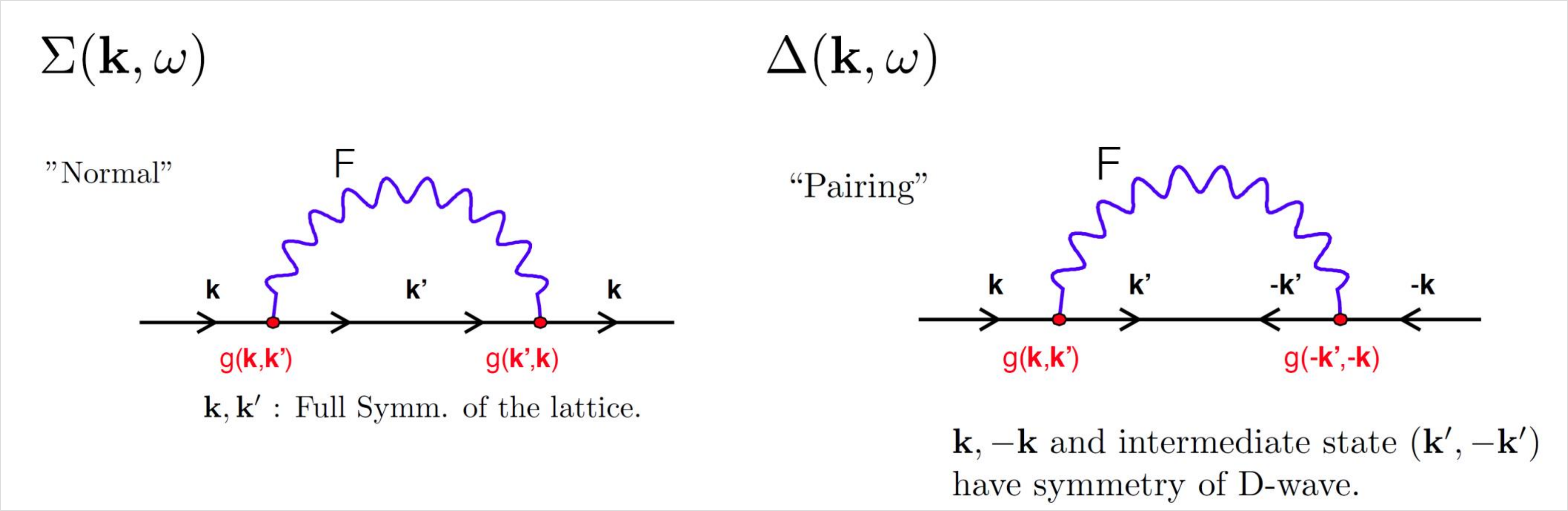
- **For *s*-wave superconductors:**

  Normal self-energy and pairing self-energy have the same symmetry.

- **For *d*-wave superconductors:**

  Normal self-energy has the full symmetry of lattice.

  Pairing Energy has *d*-wave symmetry.



$\Sigma(\mathbf{k}, \omega)$

$\Delta(\mathbf{k}, \omega)$

$\mathbf{k}, \mathbf{k}'$: Full Symm. of the lattice.

$\mathbf{k}, -\mathbf{k}$ and intermediate state $(\mathbf{k}', -\mathbf{k}')$ have symmetry of D-wave.

Correspondingly, TWO Eliashberg Functions are required, $\varepsilon_N(\omega,k)$ and $\varepsilon_S(\omega,k)$.

Eliashberg Equations for *d*-Wave Pairing

$$\Sigma(\theta,\omega) = \int_{-\infty}^{\infty} d\epsilon \int_{-\infty}^{\infty} d\epsilon' S(\omega,\epsilon,\epsilon') N_1(\epsilon) \underline{\alpha^2 F^{(+)}(\theta,\epsilon')} \quad \boxed{\varepsilon_N(\theta,\omega)}$$

Normal Eliashberg Function

$$\phi(\omega) = -\int_{-\infty}^{\infty} d\epsilon \int_{-\infty}^{\infty} d\epsilon' S(\omega,\epsilon,\epsilon') D_1(\epsilon) \underline{\alpha^2 F^{(-}(\theta,\epsilon')} \quad \boxed{\varepsilon_P(\theta,\omega)}$$

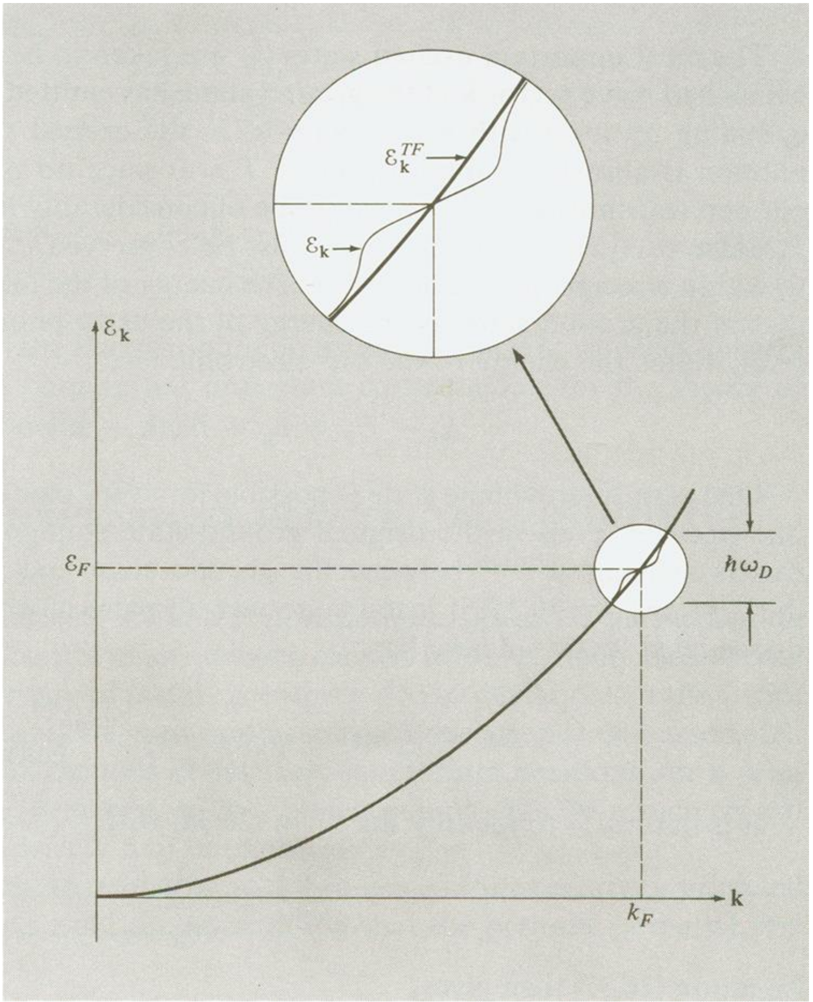
Pairing Eliashberg Function

$$S(\omega,\epsilon,\epsilon') = \frac{f(\epsilon)+n(-\epsilon')}{\epsilon+\epsilon'-\omega-i\delta} \qquad N_1(\epsilon) \equiv \left\langle Re \frac{W(\theta',\epsilon)}{\sqrt{W^2(\theta',\epsilon)-\phi^2(\epsilon)\sin^2(2\theta')}} \right\rangle_{\theta'}$$

$$D_1(\epsilon) \equiv \left\langle \frac{1}{v_F(\theta')} Re \frac{\phi(\epsilon)\sin^2(2\theta')}{\sqrt{W^2(\theta',\epsilon)-\phi^2(\epsilon)\sin^2(2\theta')}} \right\rangle_{\theta'}$$

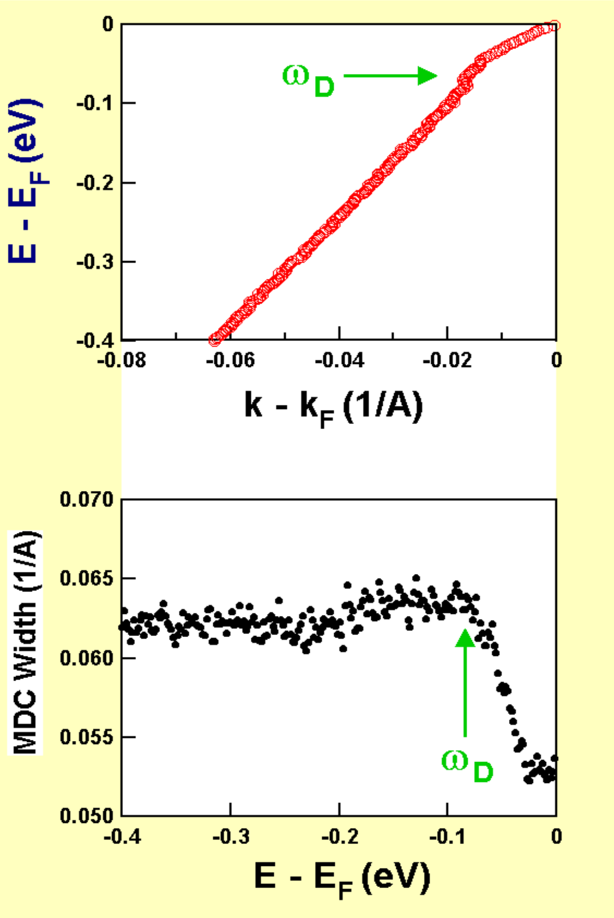
A. Sandvik, D. J. Scalapino & N. E. Bickers, Phys. Rev. B 69, 094523 (2004).

Manifestation of Many-Body Effects: **Band Renormalization**



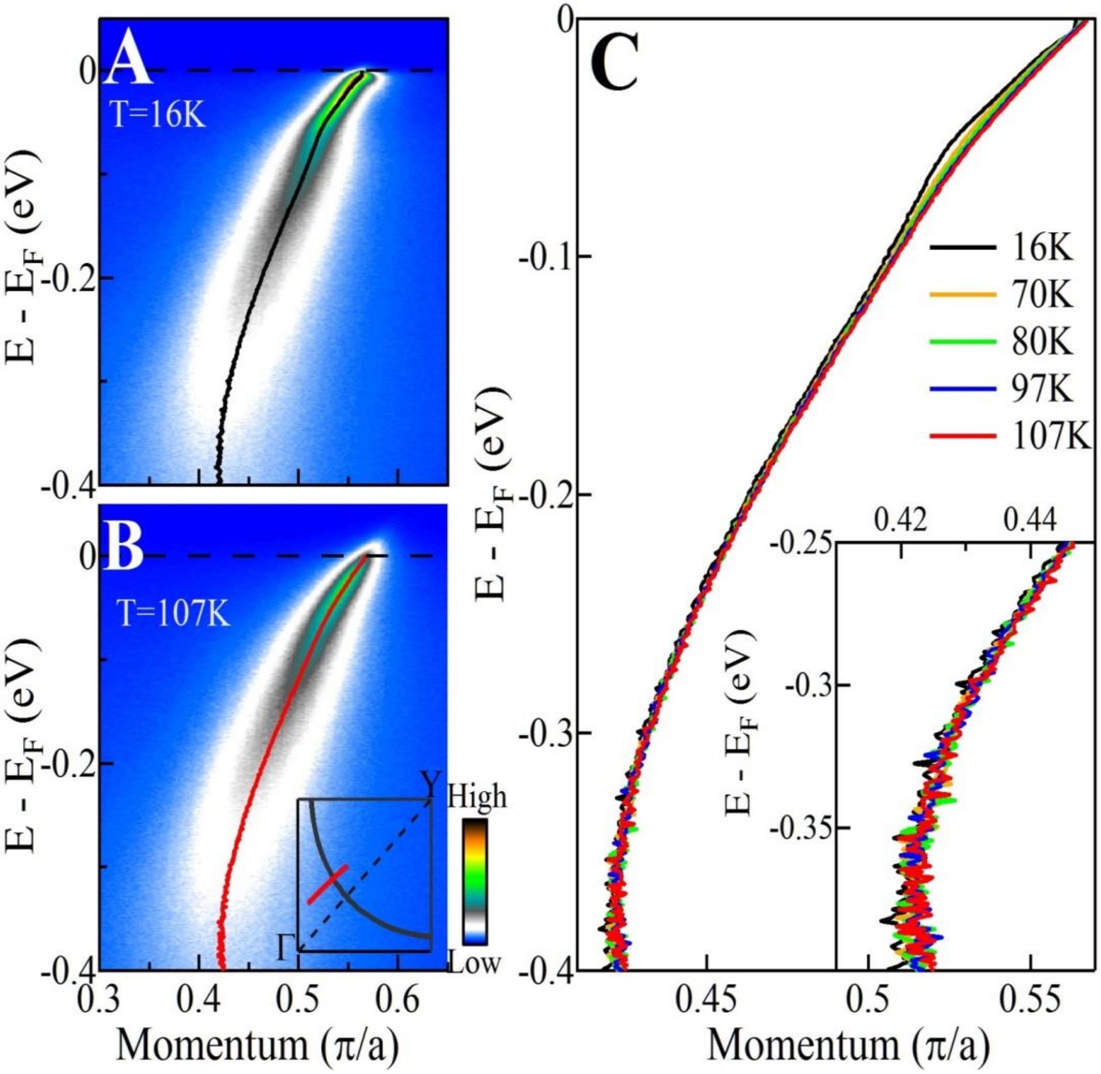
Ashcroft-Mermin, Solid State Phyics

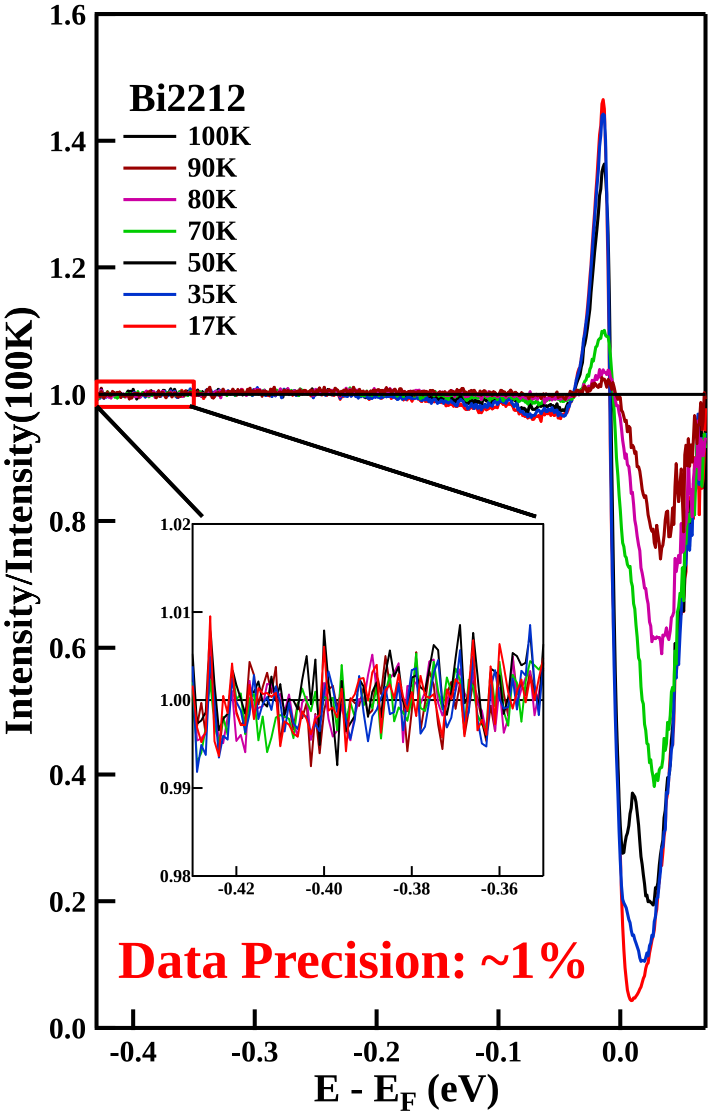
Be(0001) Surface State



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.

High Precision Laser ARPES on Bi2212

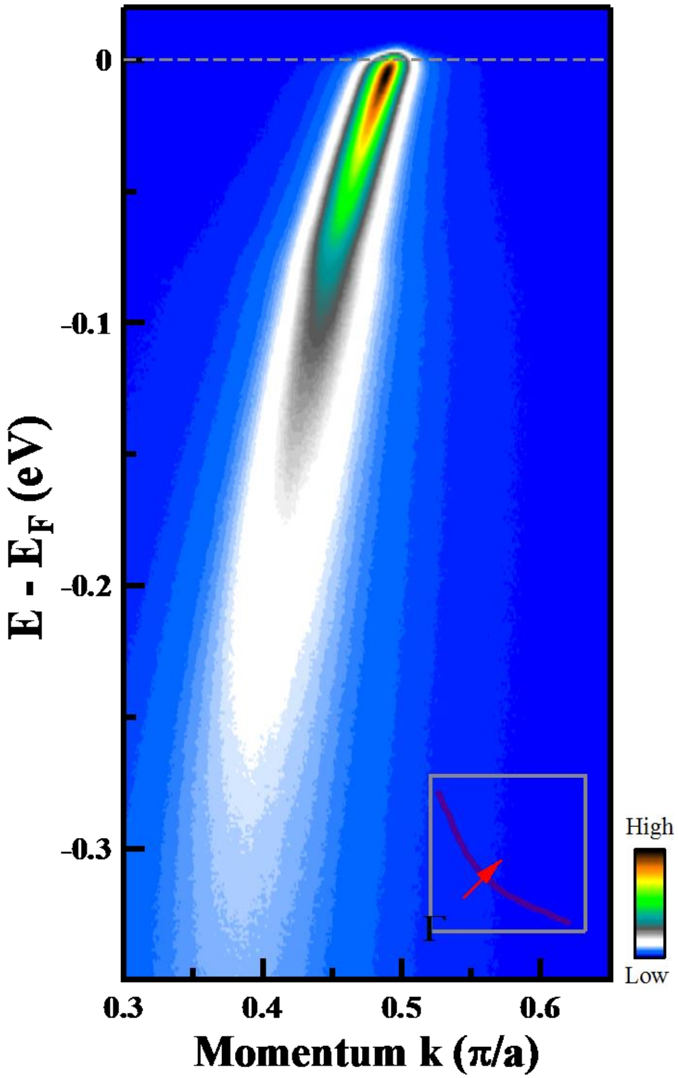




Data Precision: ~1%

J. M. Bok, H. Y. Choi, C. Varma, X. J. Zhou et al., Science Advances 2, e1501329 (2016).

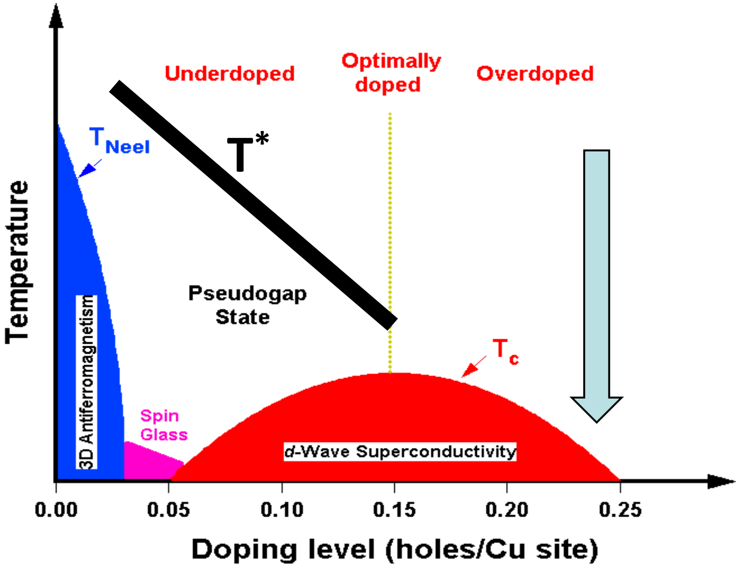
Laser ARPES on Nodal Dispersion of Pb-Bi2201



Heavily Overdoped, Tc=5K

- close to Fermi liquid
- Weak magnetic excitation

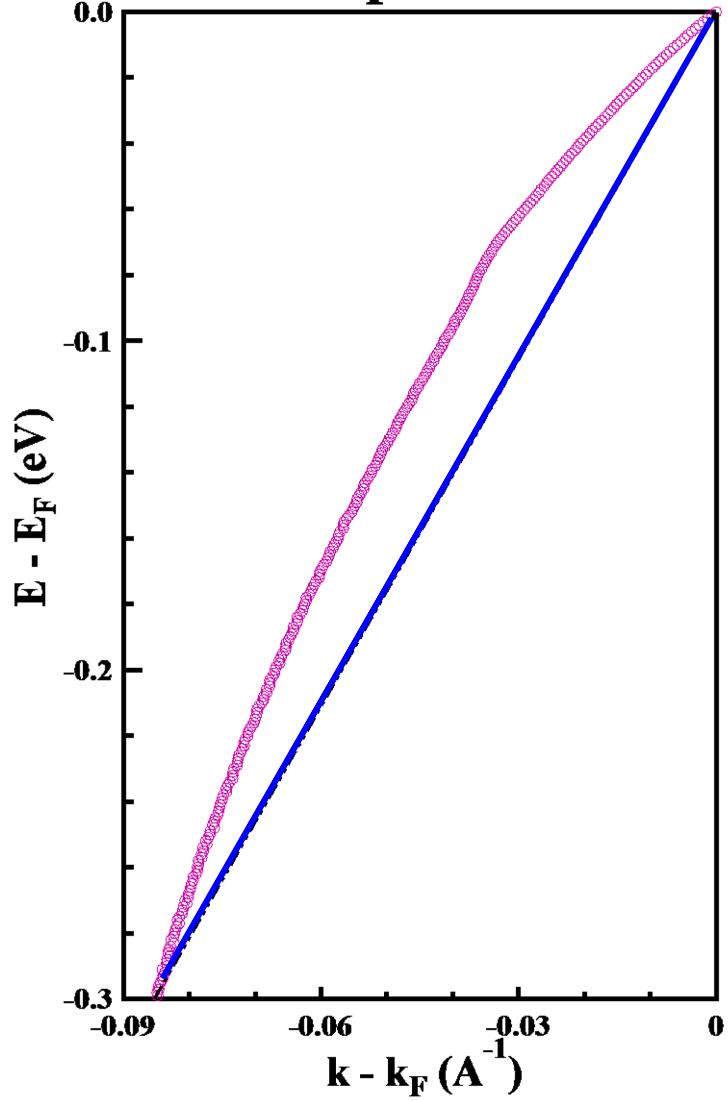
Energy Resolution: 1.0 meV



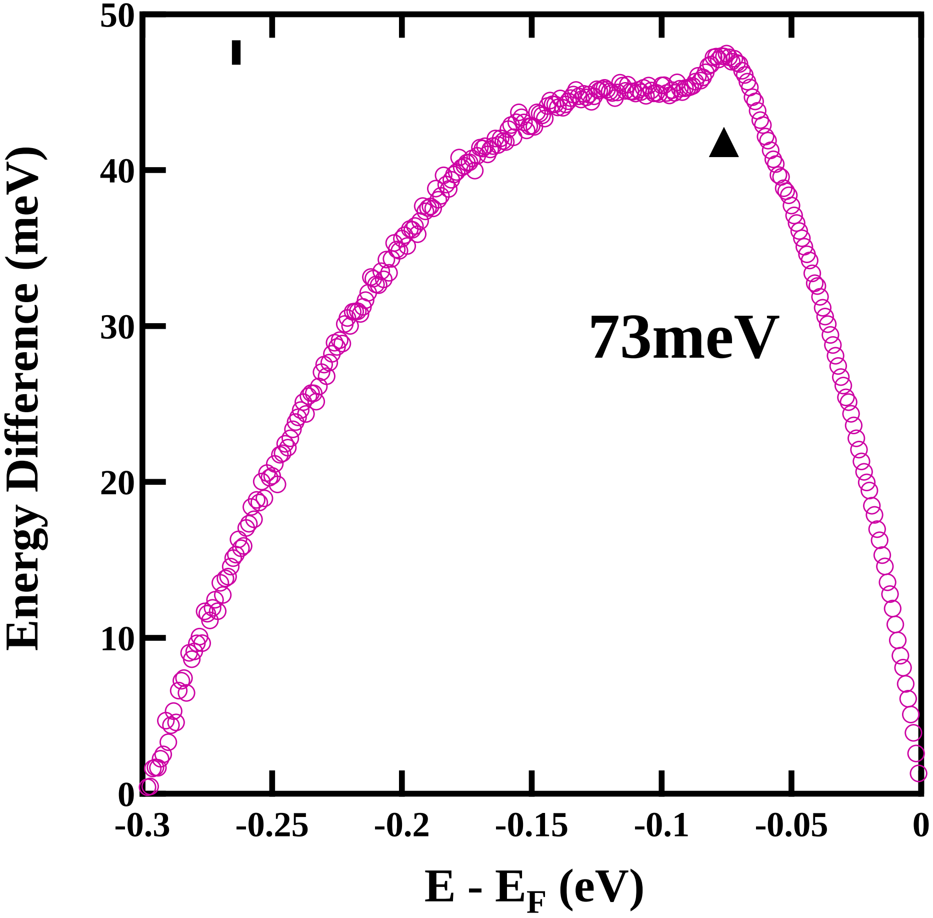
Lin Zhao, J. R. Shi, X. J. Zhou et al., Phys. Rev. B 83 (2011)184515

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

Dispersion



Effective Self-Energy

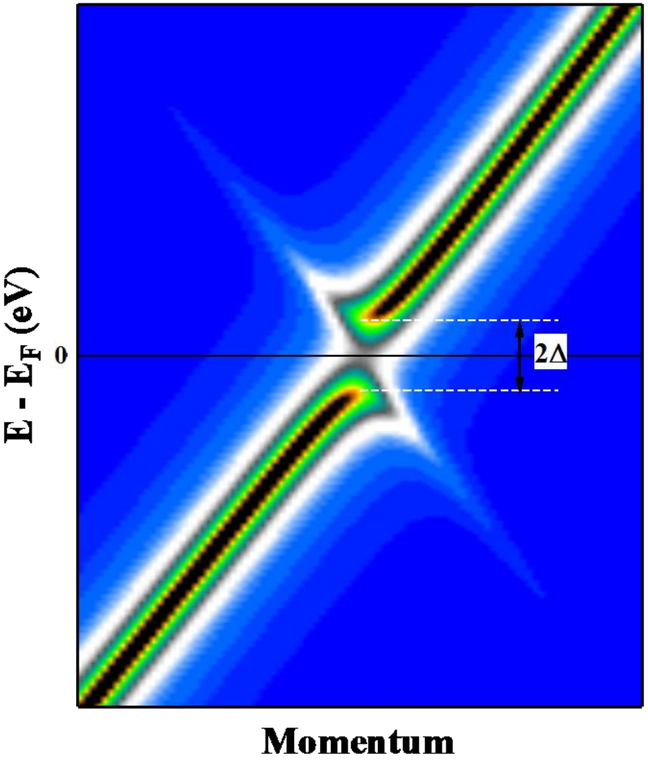


Lin Zhao, J. R. Shi, X. J. Zhou et al., Phys. Rev. B 83 (2011)184515

Reveal Superconducting Features

Bogoliubov Quasiparticle in the Superconducting State

A(k, ω)



In conventional BCS
Theory of Superconductivity

$$A_{BCS}(k,\omega) = \frac{1}{\pi}\left[\frac{|u_k|^2\Sigma}{(\omega - E_k)^2 + \Gamma^2} + \frac{|v_k|^2\Sigma}{(\omega + E_k)^2 + \Gamma^2}\right]$$

$$|u(k)|^2 = \frac{1}{2}\left(1 - \frac{E_k}{\sqrt{E_k^2 + |Z_k\Delta(k)|^2}}\right) \quad \text{and} \quad |v(k)|^2 = \frac{1}{2}\left(1 + \frac{E_k}{\sqrt{E_k^2 + |Z_k\Delta(k)|^2}}\right)$$

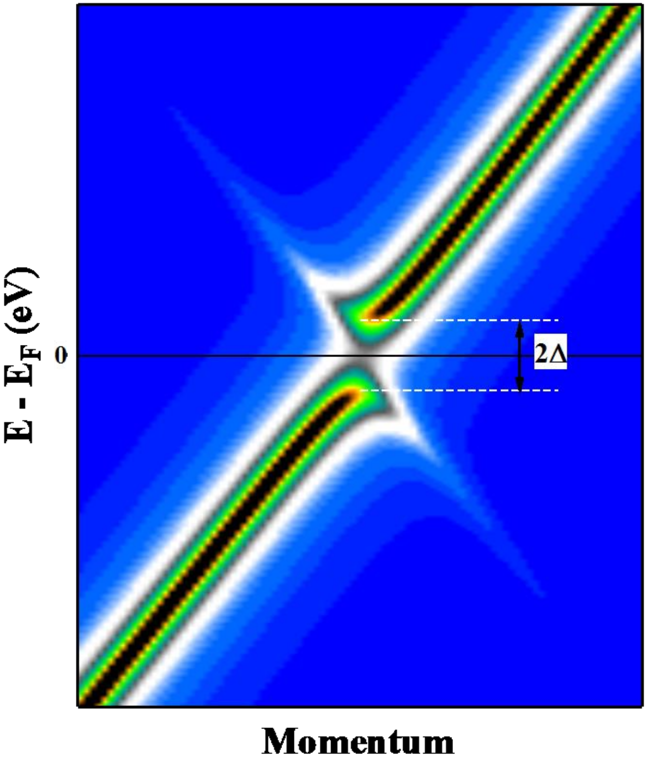
Characteristics of Bogoliubov Quasiparticle:

1. Two branches of dispersion bands
   Separated by 2D
   Centro-symmetric, A(k, w)=A(-k,-w)

2. Band back-bending

Simulated ARPES Images in the Superconducting State

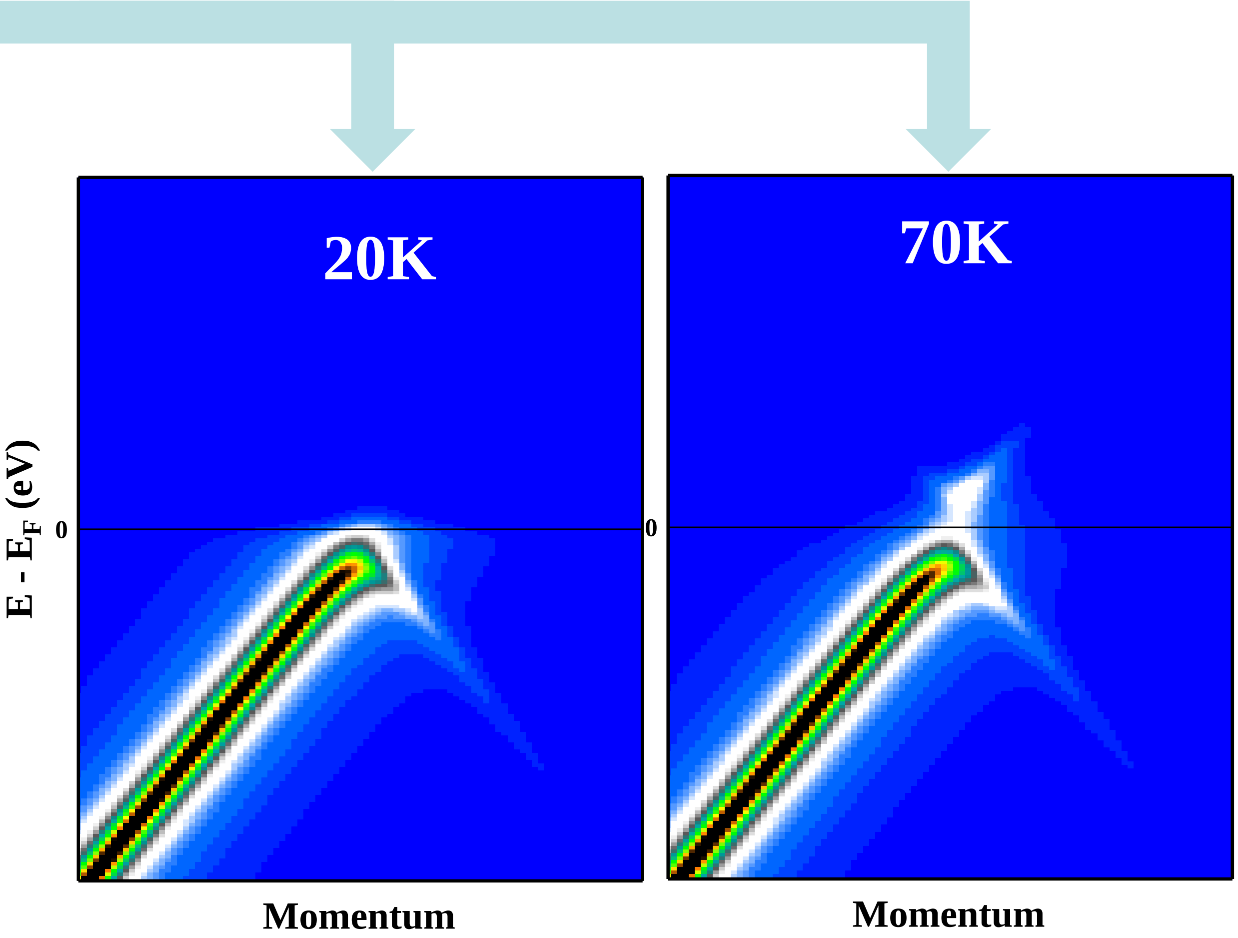
A(k, ω)



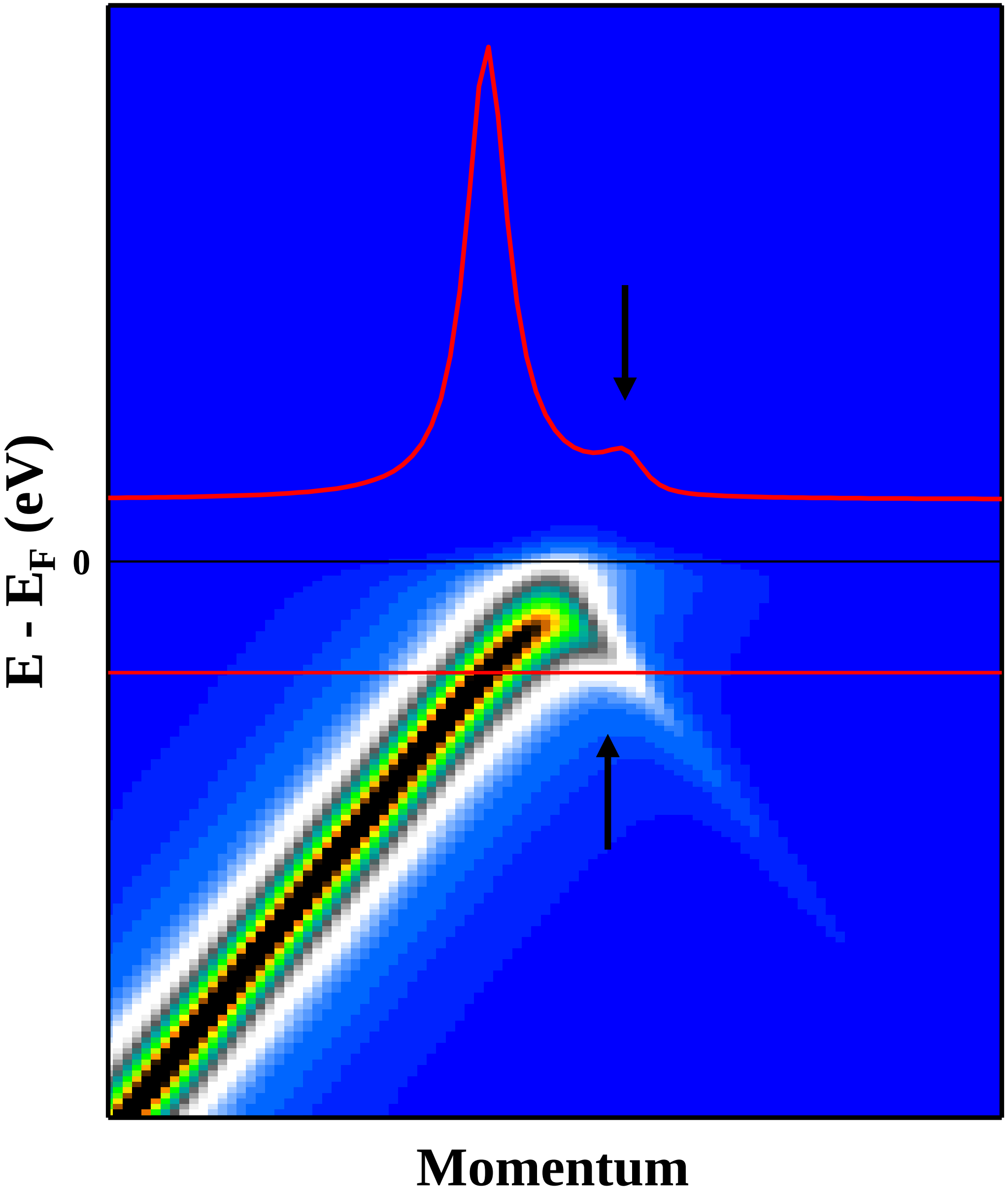
ARPES Measures:

$$I(\mathbf{k},\omega) = I_0(\mathbf{k},\nu,A)f(\omega)A(\mathbf{k},\omega)$$

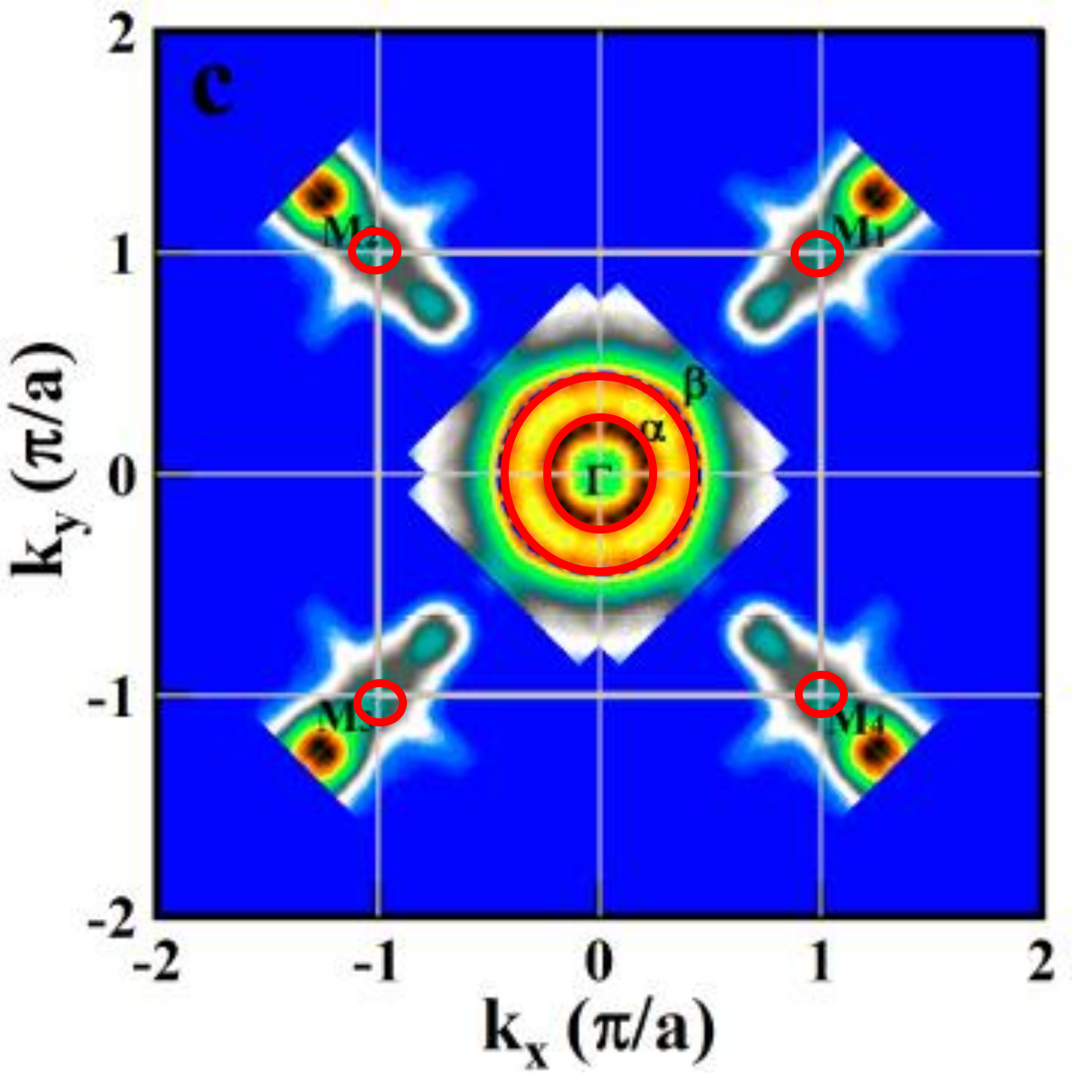
$$\mathrm{f}(\omega) = \frac{1}{exp(\frac{\omega}{k_BT})+1}$$ **Fermi distribution function**



Simulated Band Back-Bending in Lower Branch at Low Temperature



Poor Fermi Surface Nesting in $(Ba_{0.6}K_{0.4})Fe_2As_2$ (Tc~38K)



Fermi surface at Γ:

Two large hole-like
Fermi surface sheets;

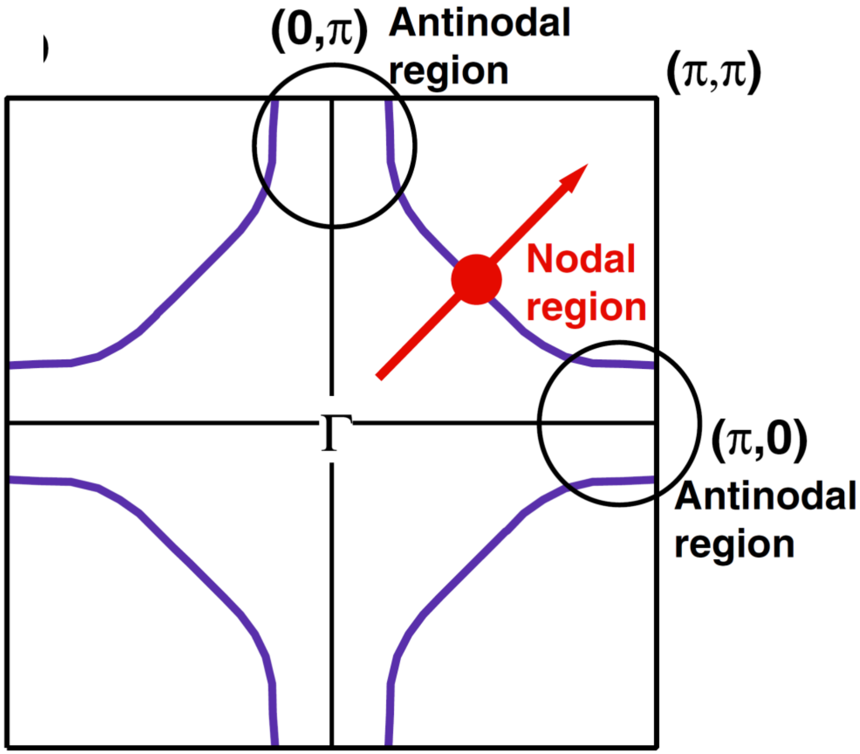
Fermi surface at M:

One tiny electron pocket
and
Four hole-like lobes

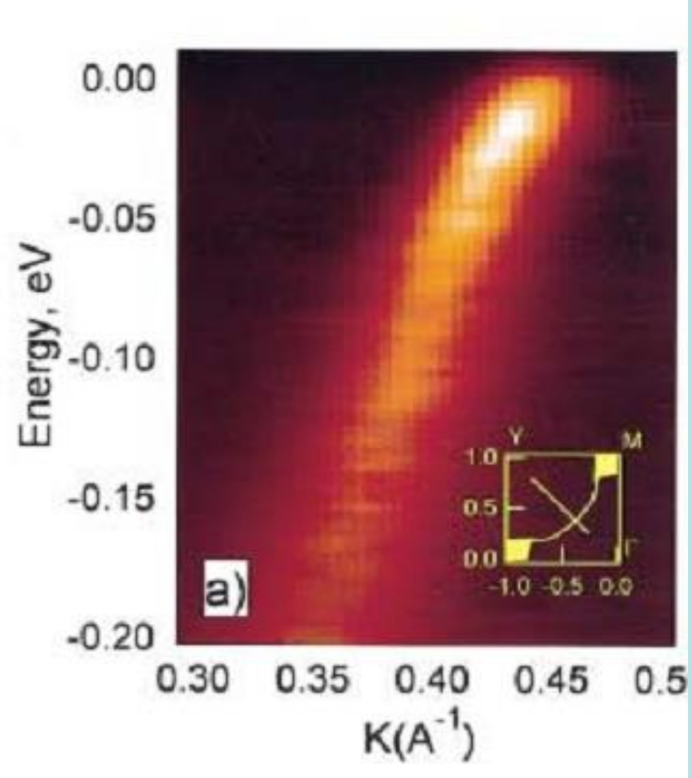
L. Zhou, X. J. Zhou et al., Chin. Phys. Lett. 25(2008) 4402

Many-Body Effects in Cuprates

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).

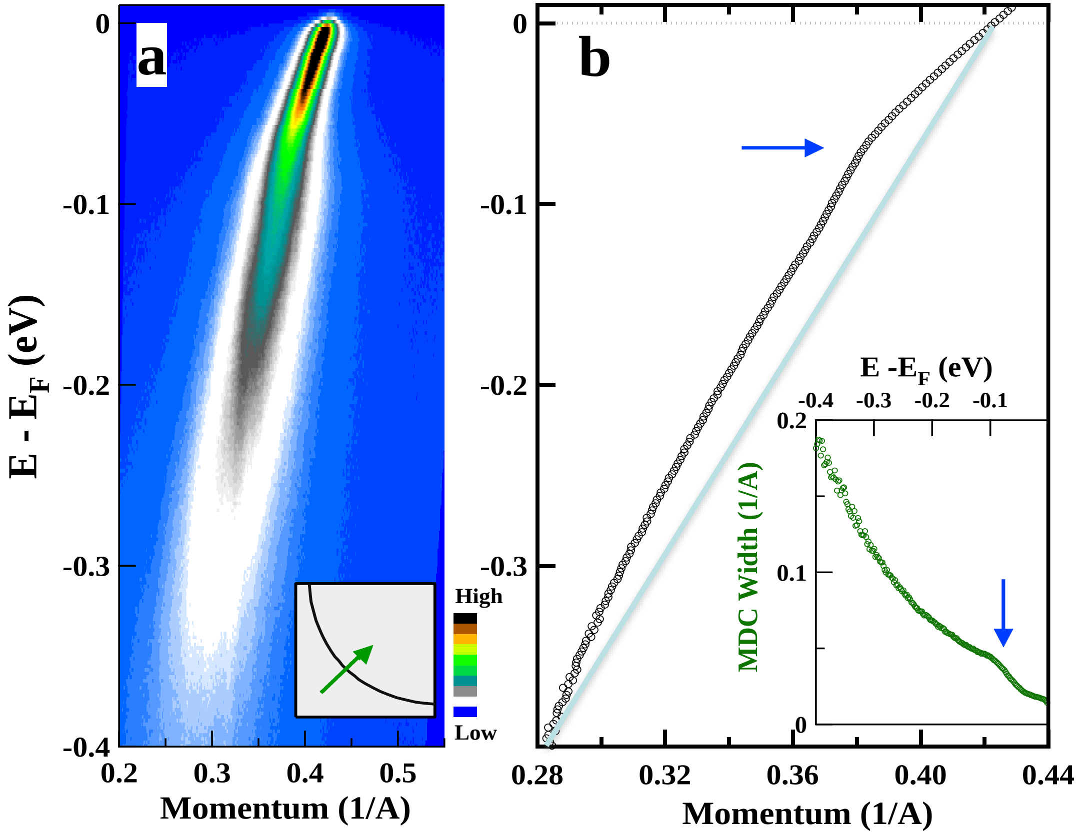
P. Johnson et al., Phys. Rev. Lett. 87, 177007 (2001).

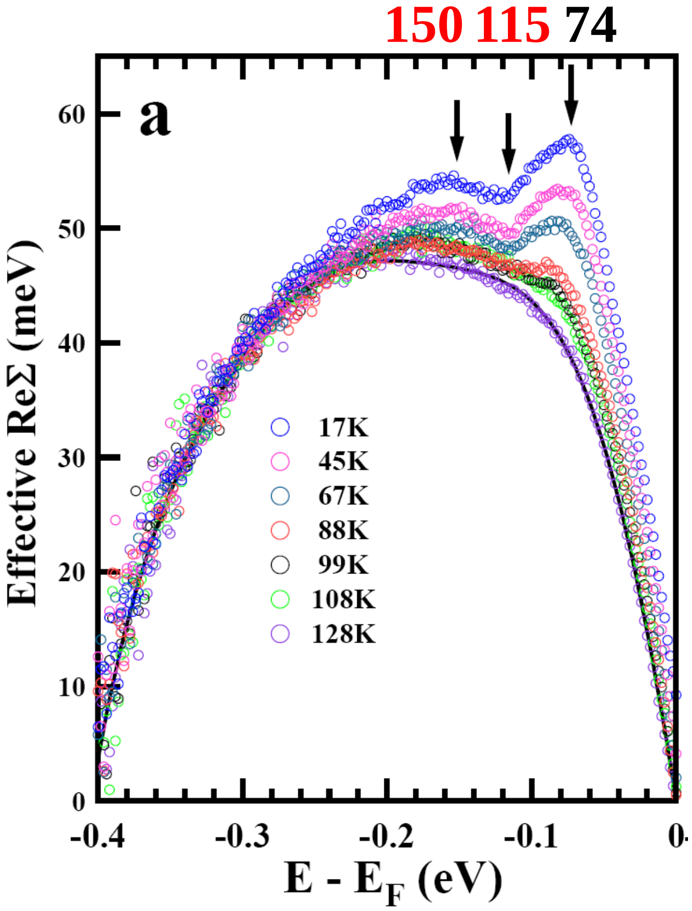
A. Lanzara et al., Nature (London) 412, 510 (2001).

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

Laser-ARPES on Many-Body Effects in Opt-Doped Bi2212:

Identification of a new form of electron coupling

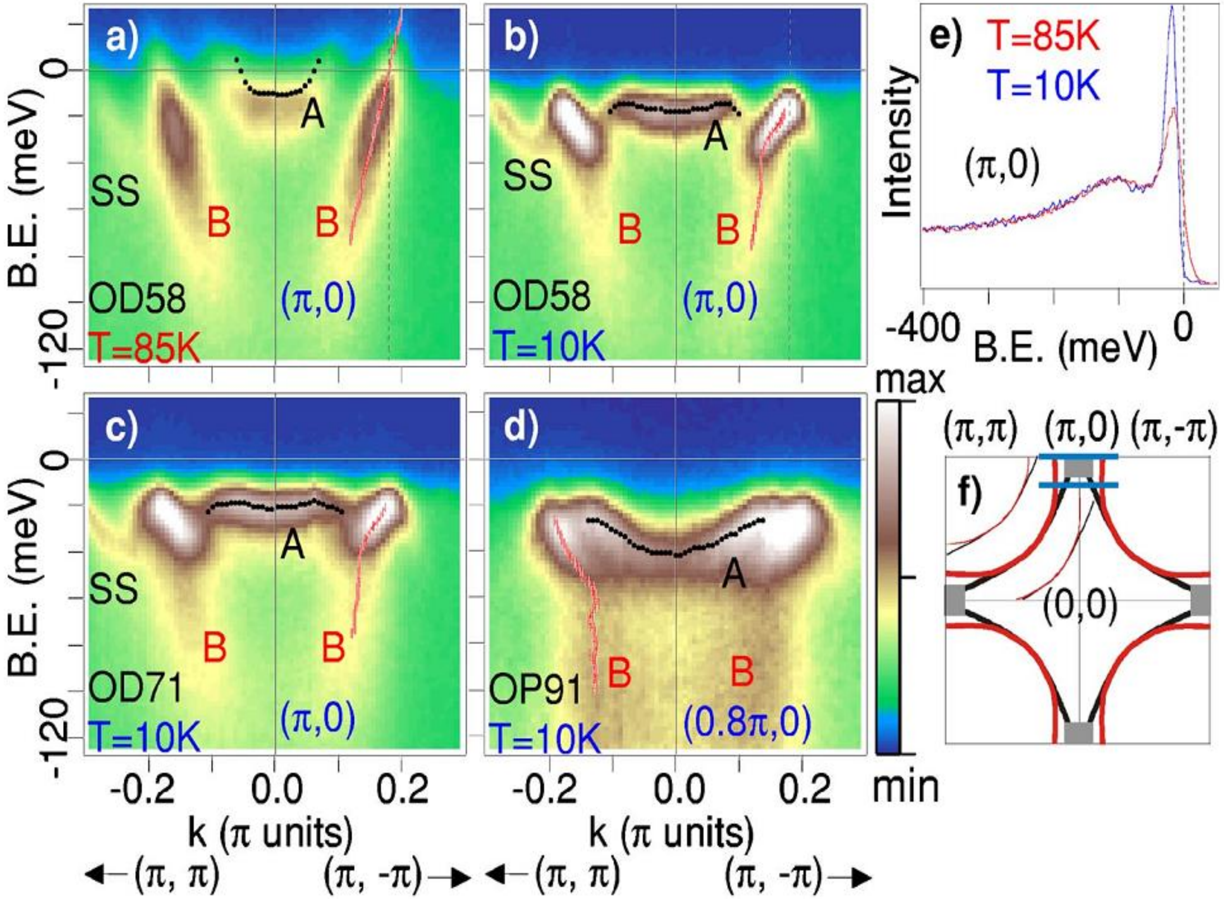




W. T. Zhang, X. J. Zhou et al., Phys. Rev. Lett. 100 (2008) 107002.

Antinodal Kink in Cuprate Superconductors

~40meV antinodal kink



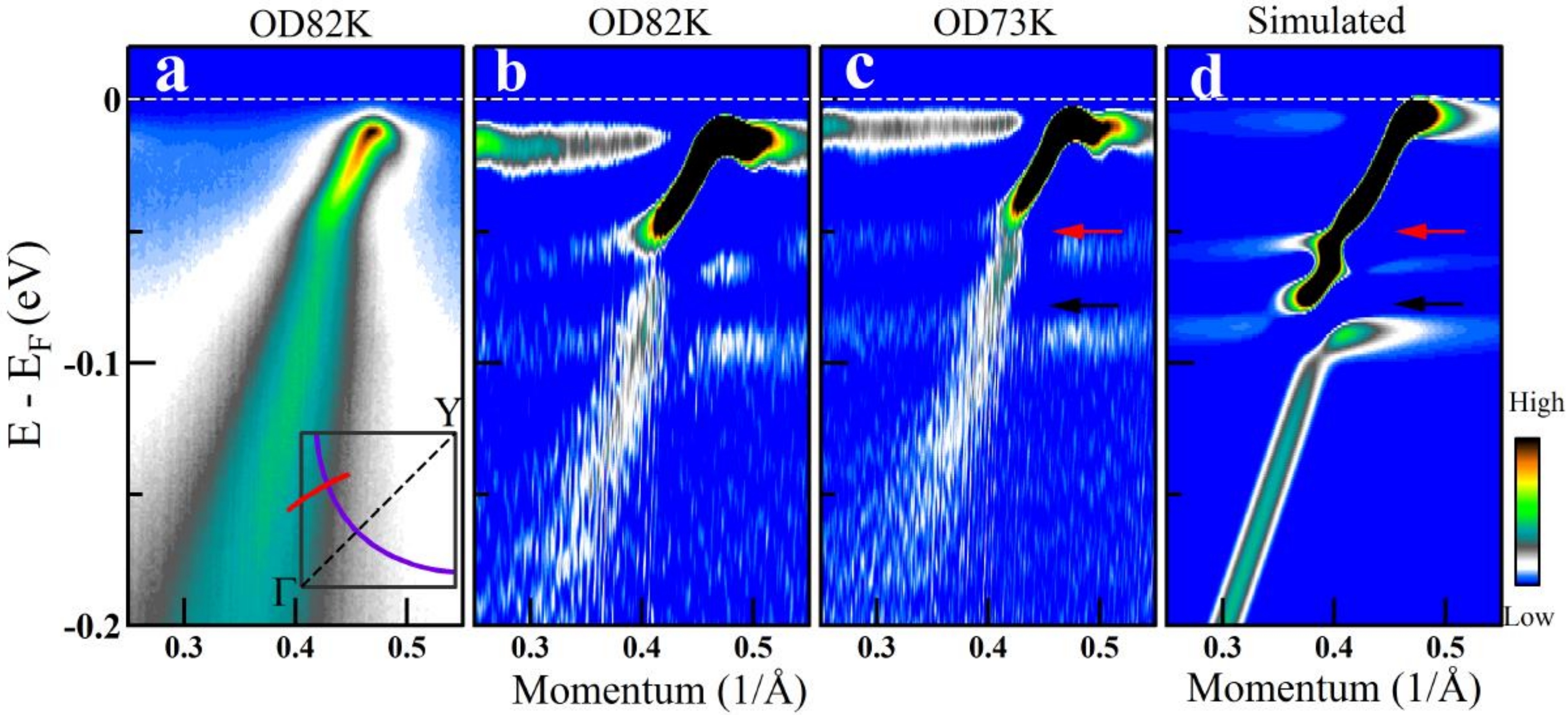
A. D. Gromko et al., Phys. Rev. B 68, 174520 (2003);
T. K. Kim et al., Phys. Rev. Lett. 91, 167002 (2003);
T. Sato et al., Phys. Rev. Lett. 91, 157003 (2003);
T. Cuk et al., Phys. Rev. Lett. 93, 117003 (2004).

Relation between Nodal Kink and Antinodal Kink?

How does 70meV nodal kink

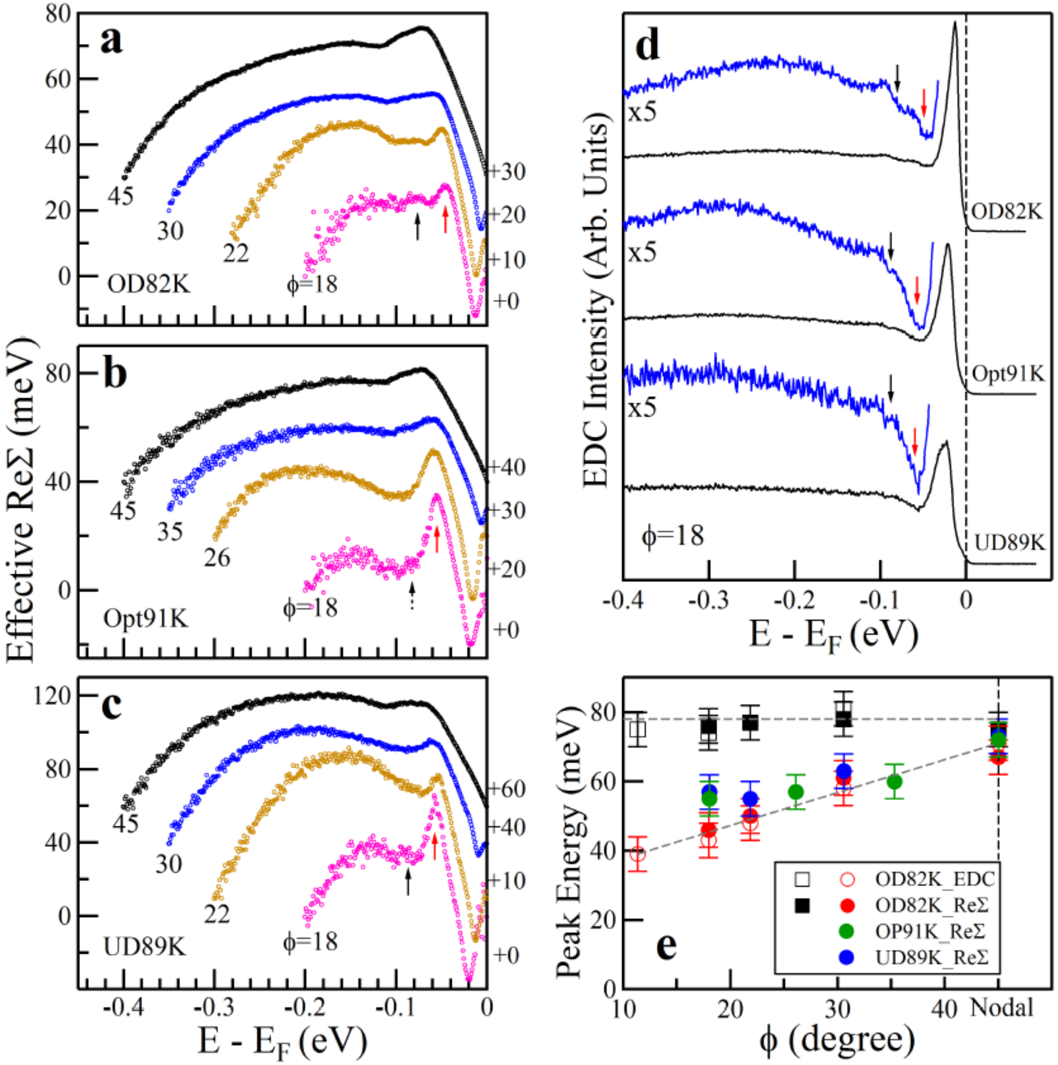
evolve into 40meV antinodal kink?

Coexistence of Two Energy Scales in OD-Bi2212



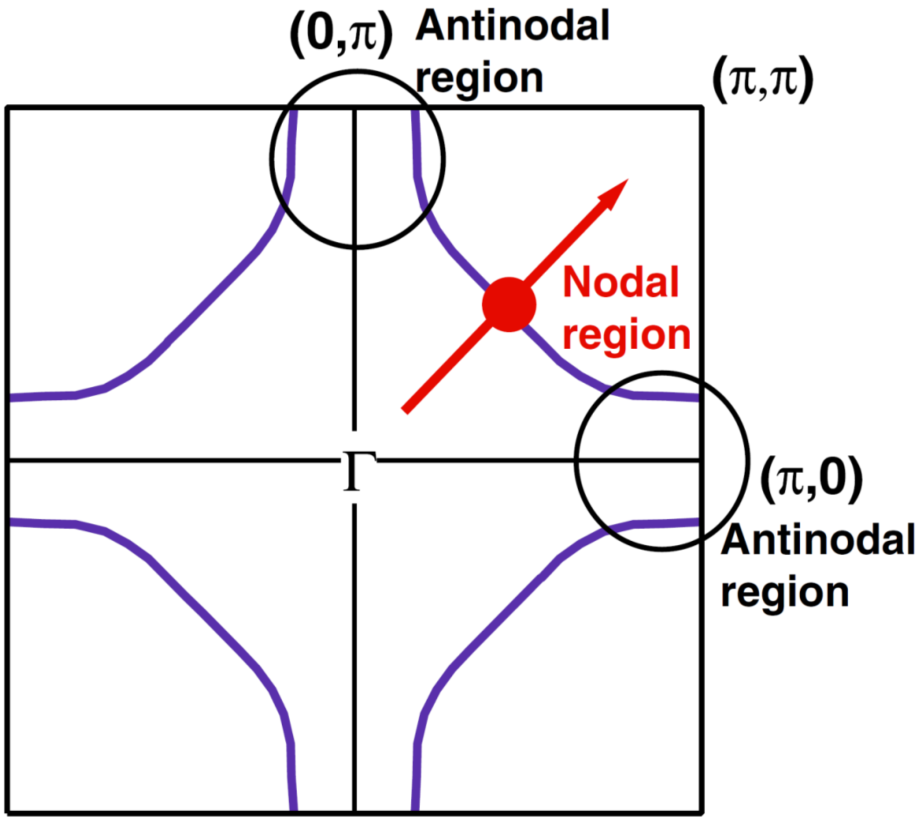
Junfeng He, H. Y. Choi, C. Varma, X. J. Zhou et al.,
Phys. Rev. Lett. 111 (2013) 107005.

Momentum and Doping Dependence of the Two 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



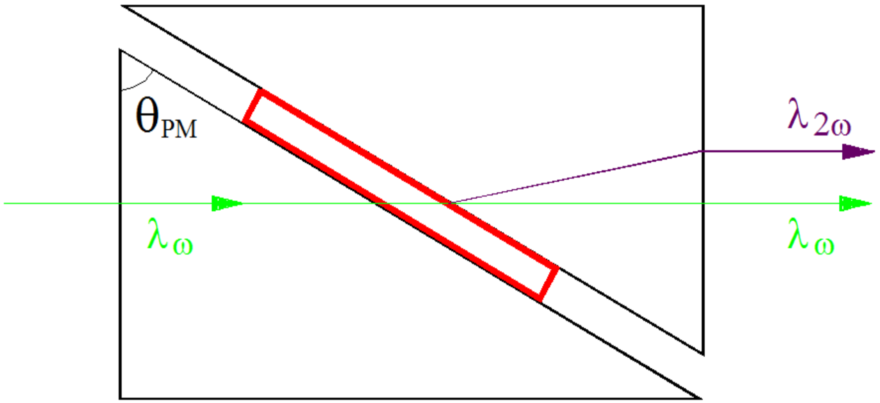
1. **70meV and 40meV energy scale coexist;**
2. **70meV scale changes little in energy when moving from nodal to antinodal regions;**
3. **40meV scale changes from 40meV near antinodal region to 70 meV near nodal region.**

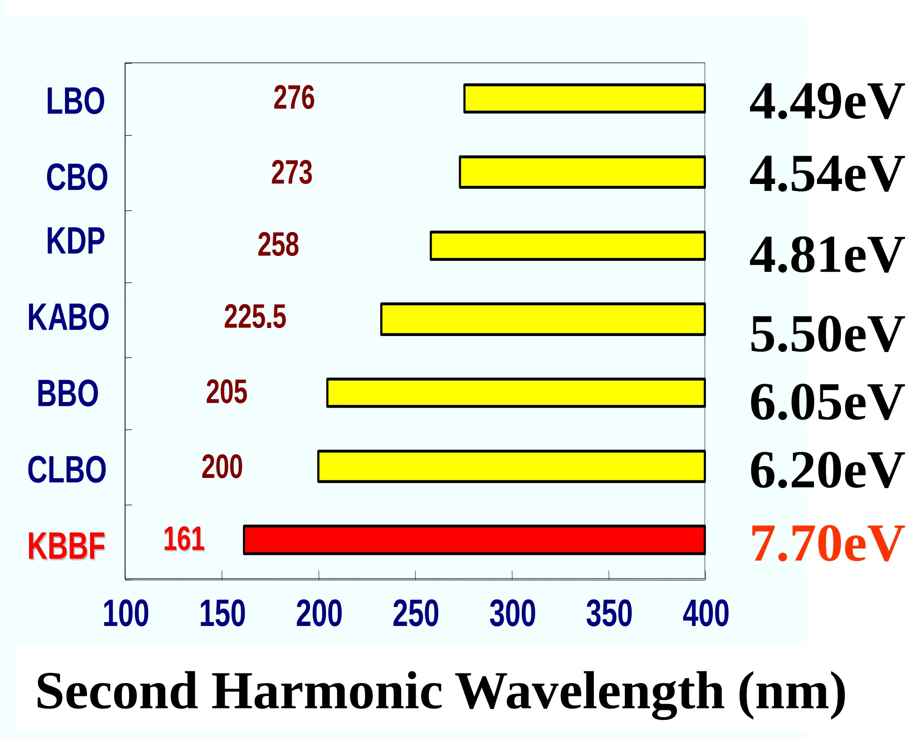
Junfeng He, H. Y. Choi, C. Varma, X. J. Zhou et al., Phys. Rev. Lett. 111 (2013) 107005.

Outline

- **Introduction to Laser-ARPES;**
- **Many-Body Effects in Cuprates;**
- **Quantitative Extraction of Pairing Interactions in Cuprates**
  1. Normal Self-Energy and Pairing Self-energy;
  2. Deduction of Normal Eliashberg Functions and Pairing Eliashberg Functions;
  3. Implications and Comparison with Theories;
- **Future Directions**

$KBe_2BO_3F_2$ (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.

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

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

J. RIORDAN

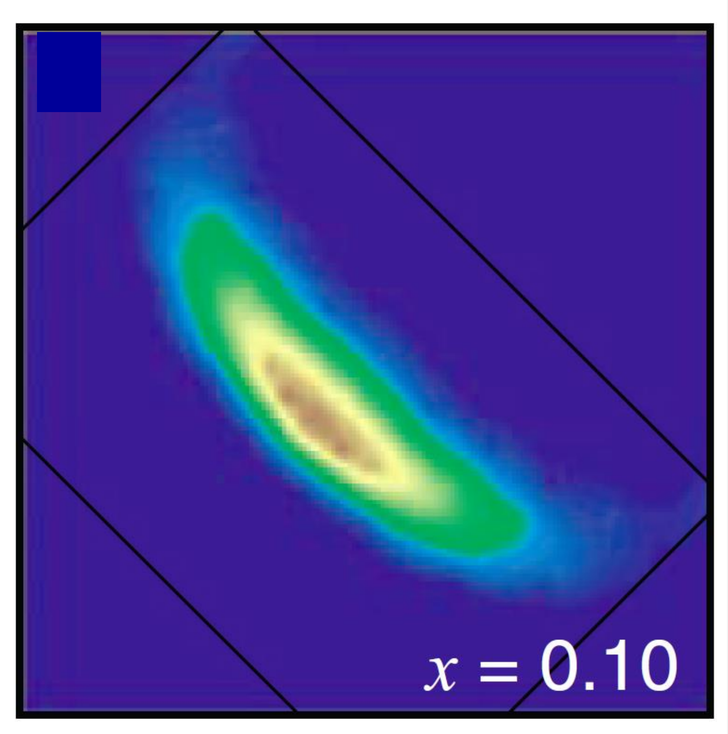
953

Nature Report, February, 2009

Tunneling Measurements – Momentum-Integrated

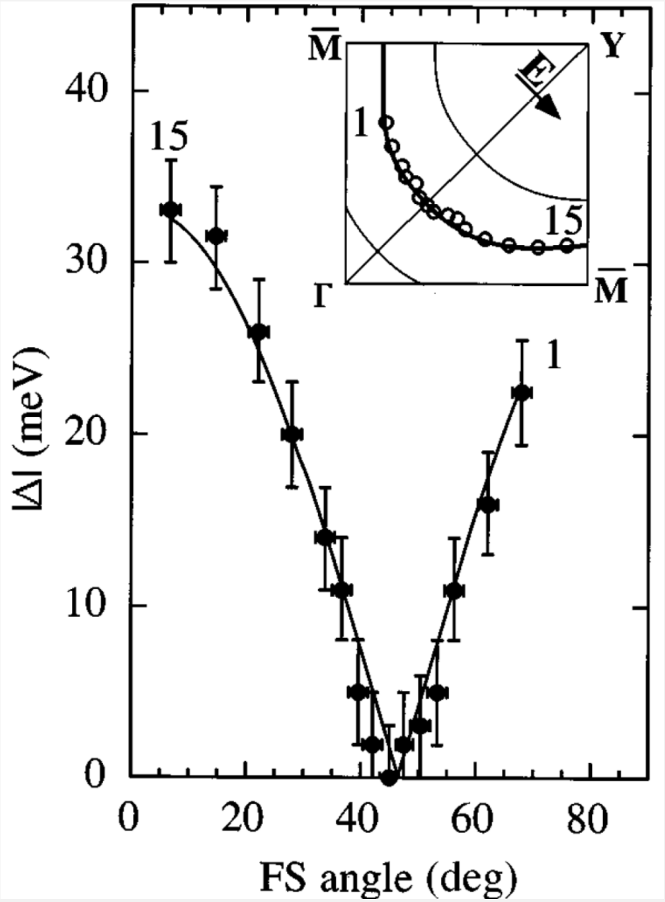
Complicated to interpret: due to strong anisotropy of electronic structure and gap structure in cuprates

Dichotomy between nodal and antinodal electronic states



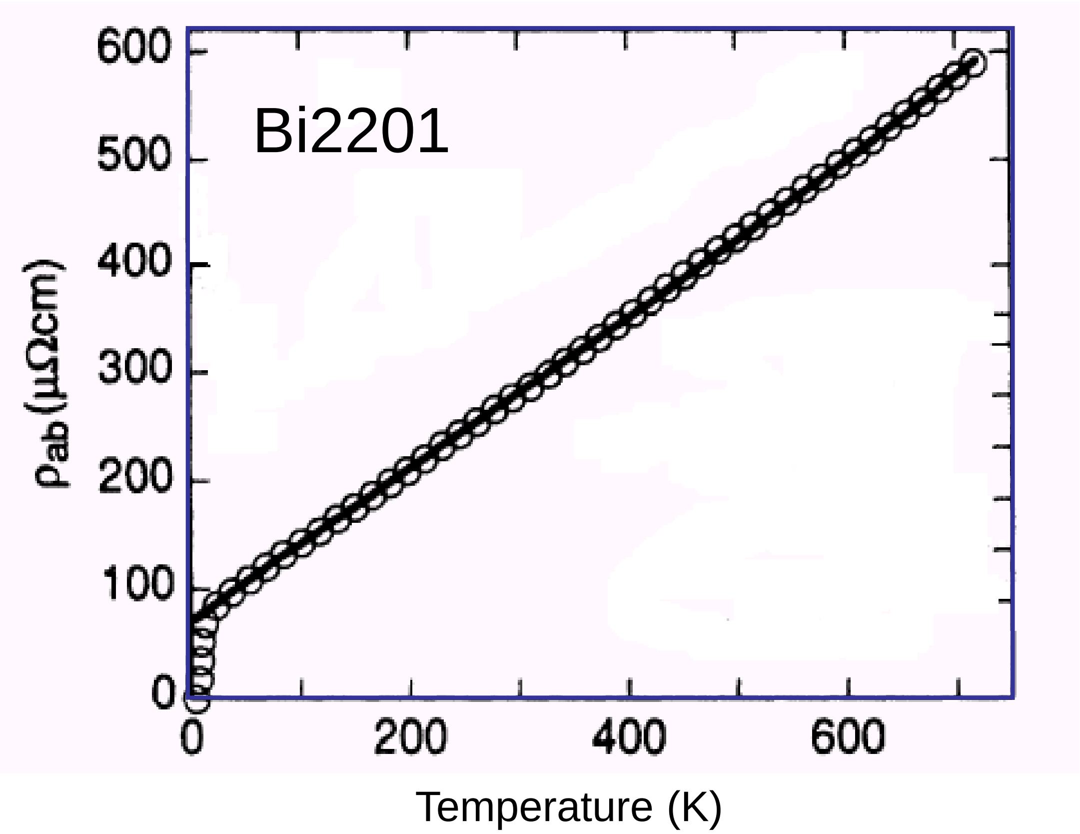
T. Yoshida et al., Phys. Rev. Lett. 91(2003)027001;
X. J. Zhou et al., Phys. Rev. Lett. 92(2004)187001;
K. M. Shen et al., Science 307(2005)901.

***d*-wave Energy Gap**



H. Ding et al., Phys. Rev. B 54 (1996)9678.

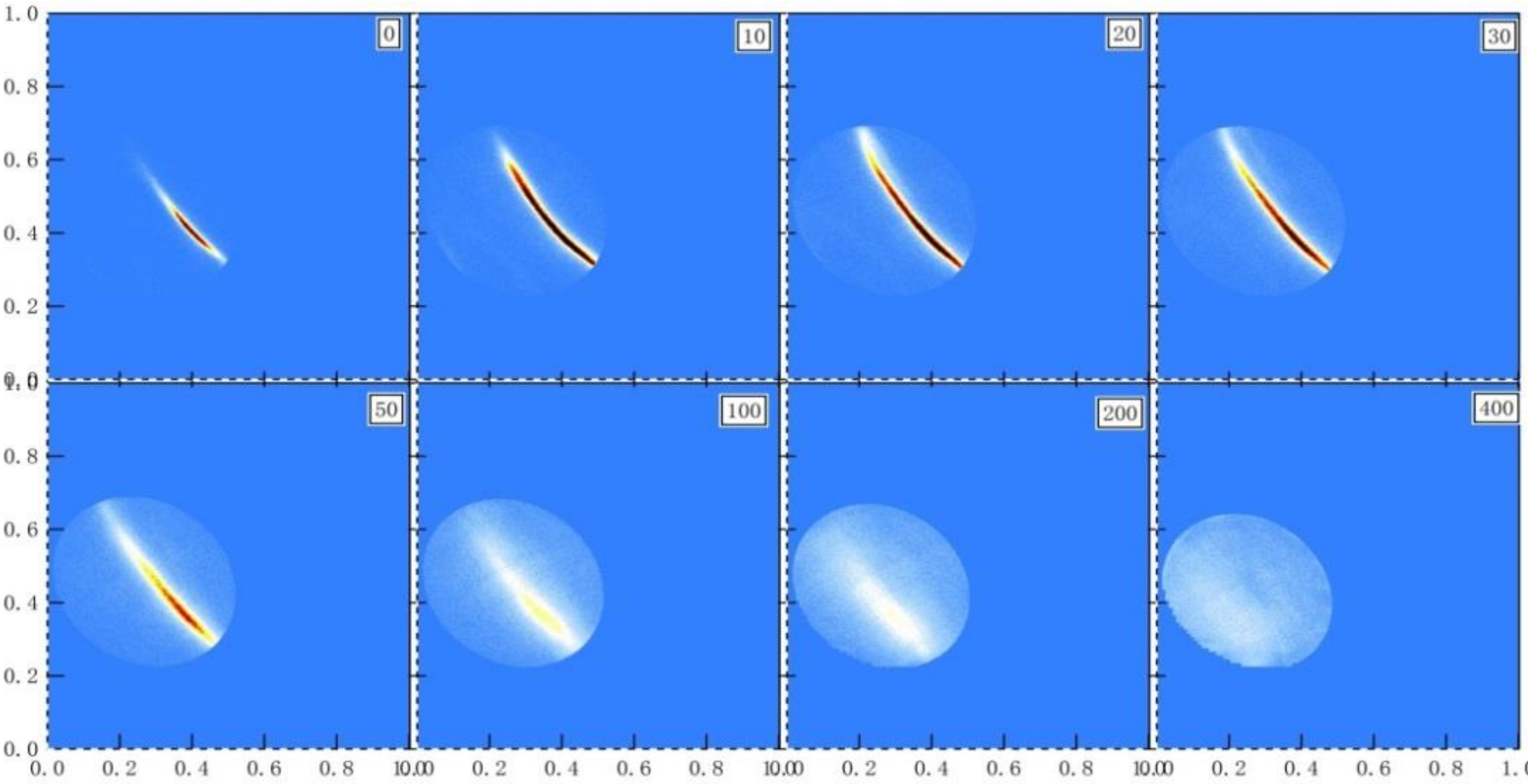
Anomalous Normal State Properties of Cuprate Superconductors



S. Martin et al., Phys. Rev. B 41(1990)846.
H. Takagi et al., Phys. Rev. Lett. 69 (1992) 2975.

In nearly-optimally doped HTSCs, from transport and other measurements, the single-particle self-energy: $\mathrm{Im}\Sigma \sim \omega$.

Laser ARToF-ARPES on Bi2212



Highly Stringent Requirements on Data to Extract Pairing Self-Energy

Paring self-energy is extracted from the subtle superconductivity-induced change, *i. e.*, the net change between the superconducting state and the normal state:

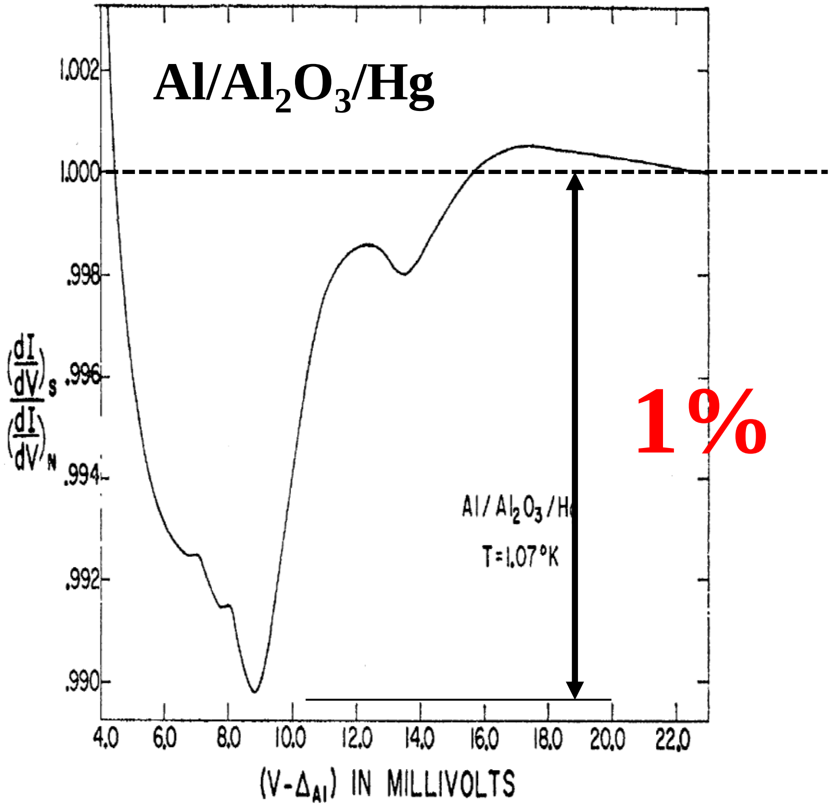
$$\frac{N_s(\omega)}{N_n} = \mathrm{Re}\left\{\frac{\omega}{\sqrt{\omega^2 - \Delta^2(\omega)}}\right\}$$

$\sim \ ½ \, (\Delta/\omega)^2$

~ 1%

for Bi2212

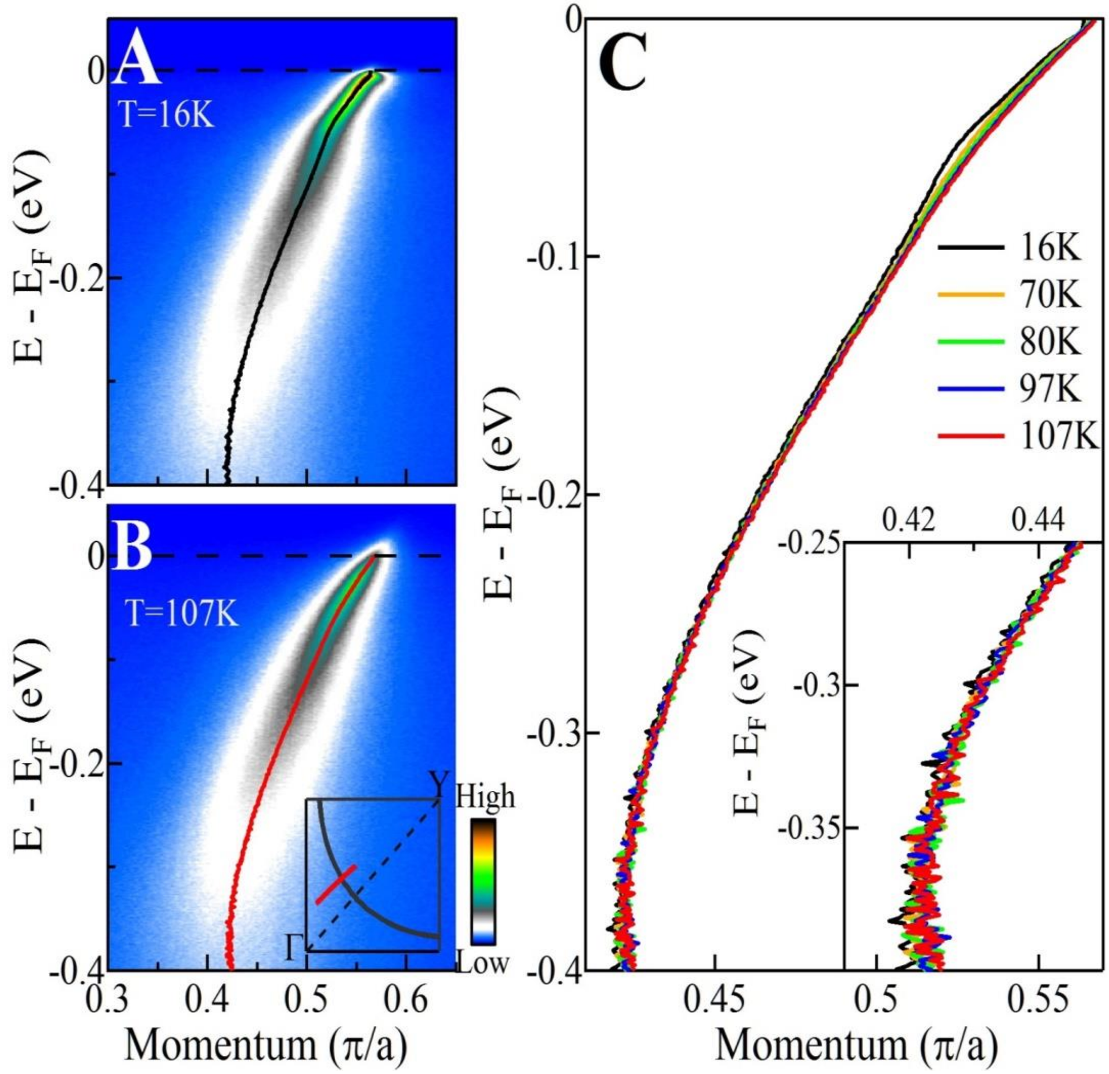
Δ=40meV, ω=0.4 eV



High precision (~1%) is necessary.

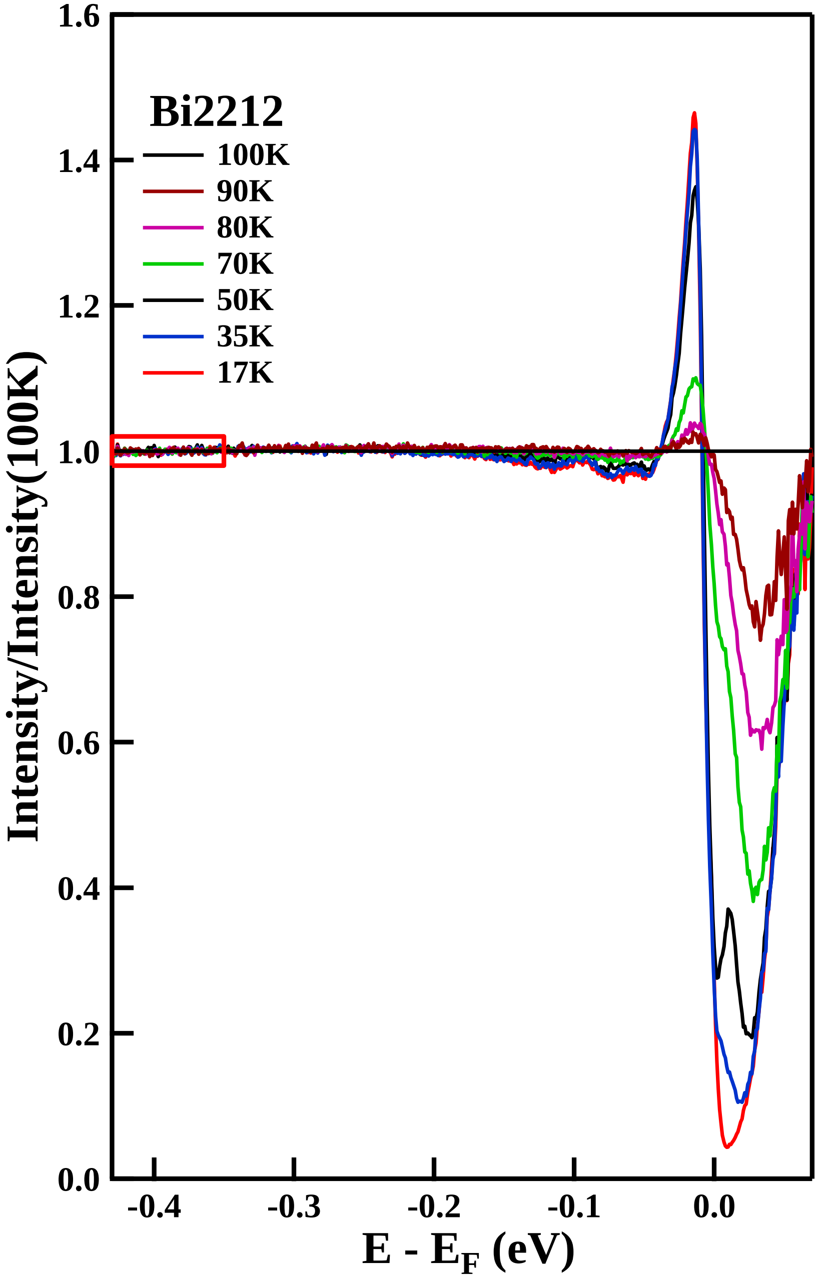
S. Bermon et al.,
Phys. Rev. 135 (1964) A306.

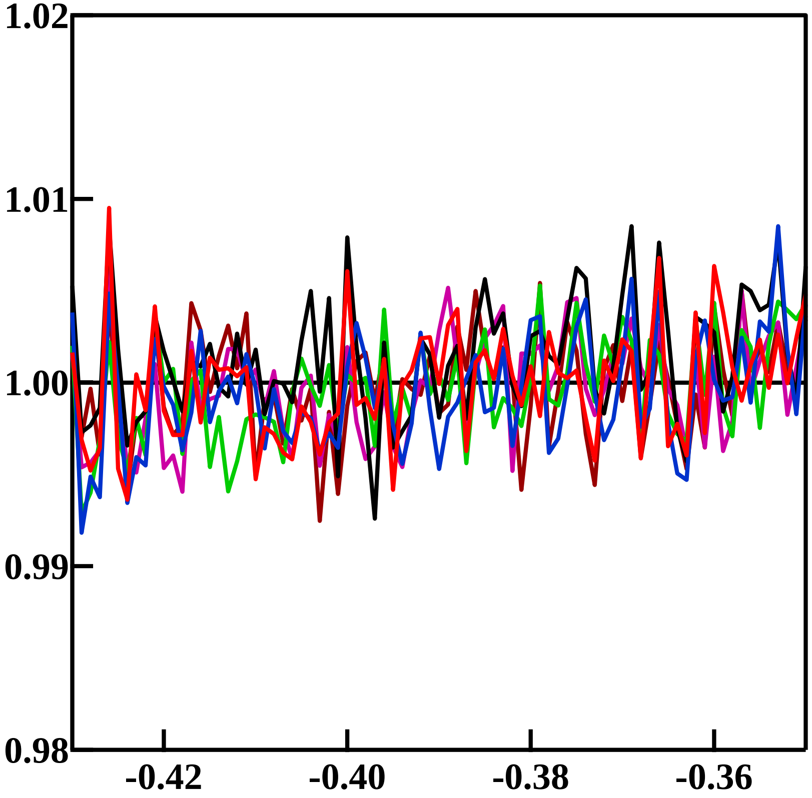
High Precision Laser ARPES Measurements on Bi2212



J. M. Bok, H. Y. Choi, C. Varma, X. J. Zhou et al., Science Advances 2, e1501329 (2016).

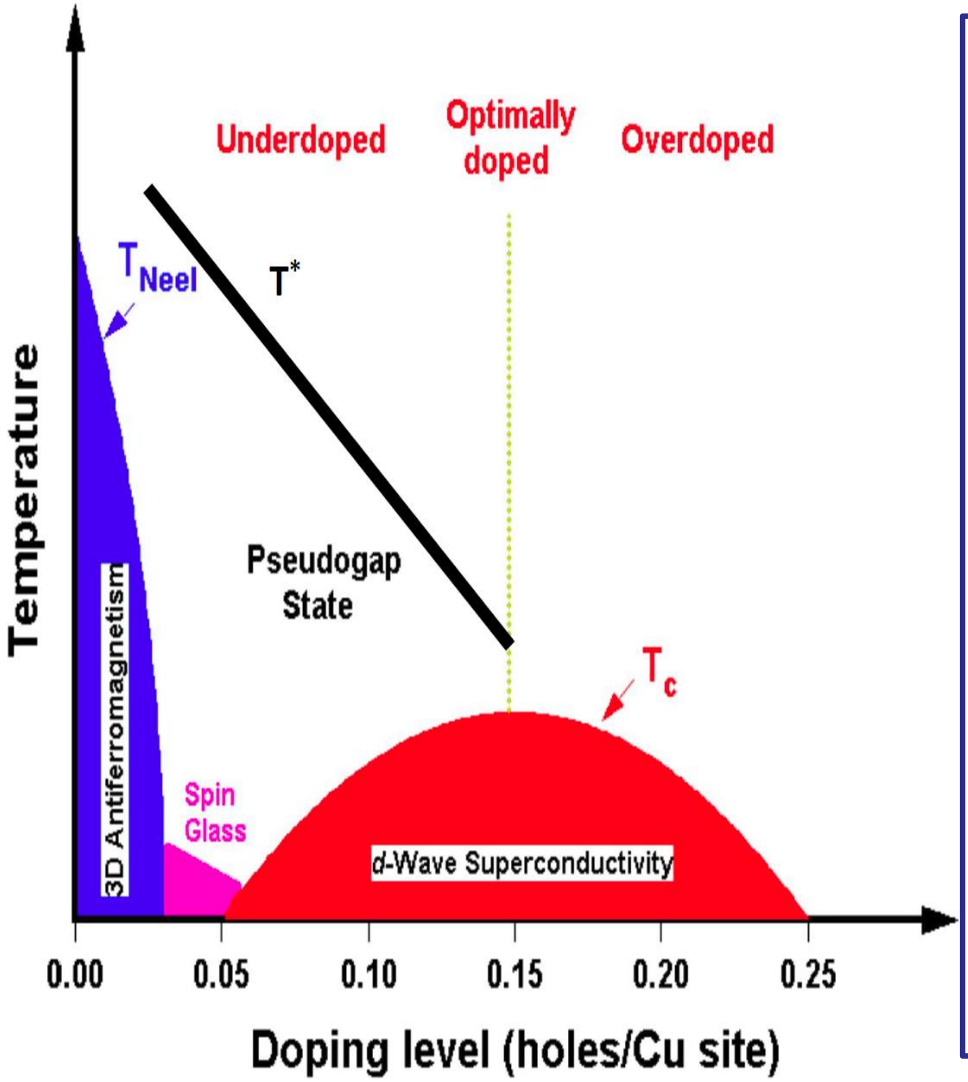
~1% Data Precision Achievable in Bi2212





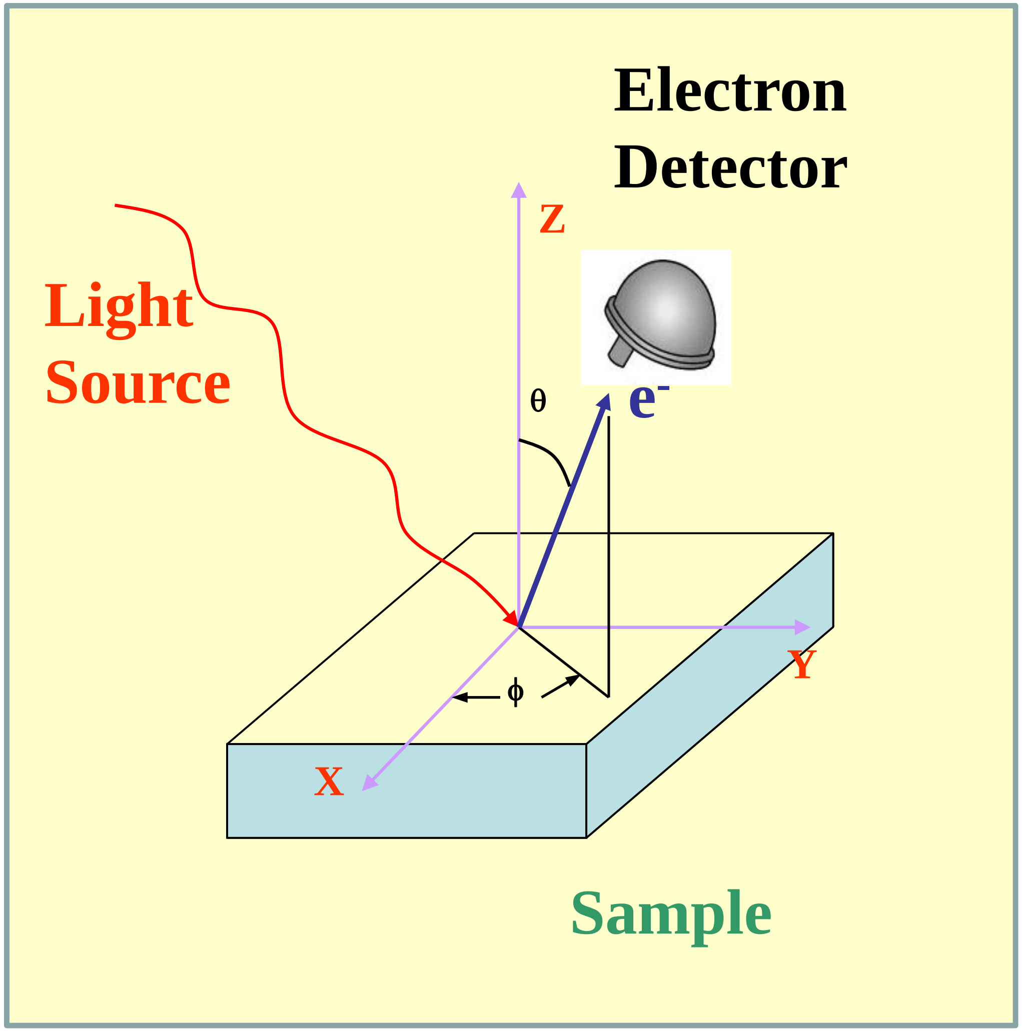
Data Precision: ~1%

Prominent Issues in Cuprate Superconductors



- **Anomalous normal state:**
  - --Linear resistivity-T;
  - --Pseudogap.
- **Unusual superconducting state:**
  - --High Tc;
  - --*d*-wave gap symmetry.

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.

Power of ARPES – A Tool for Probing 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.

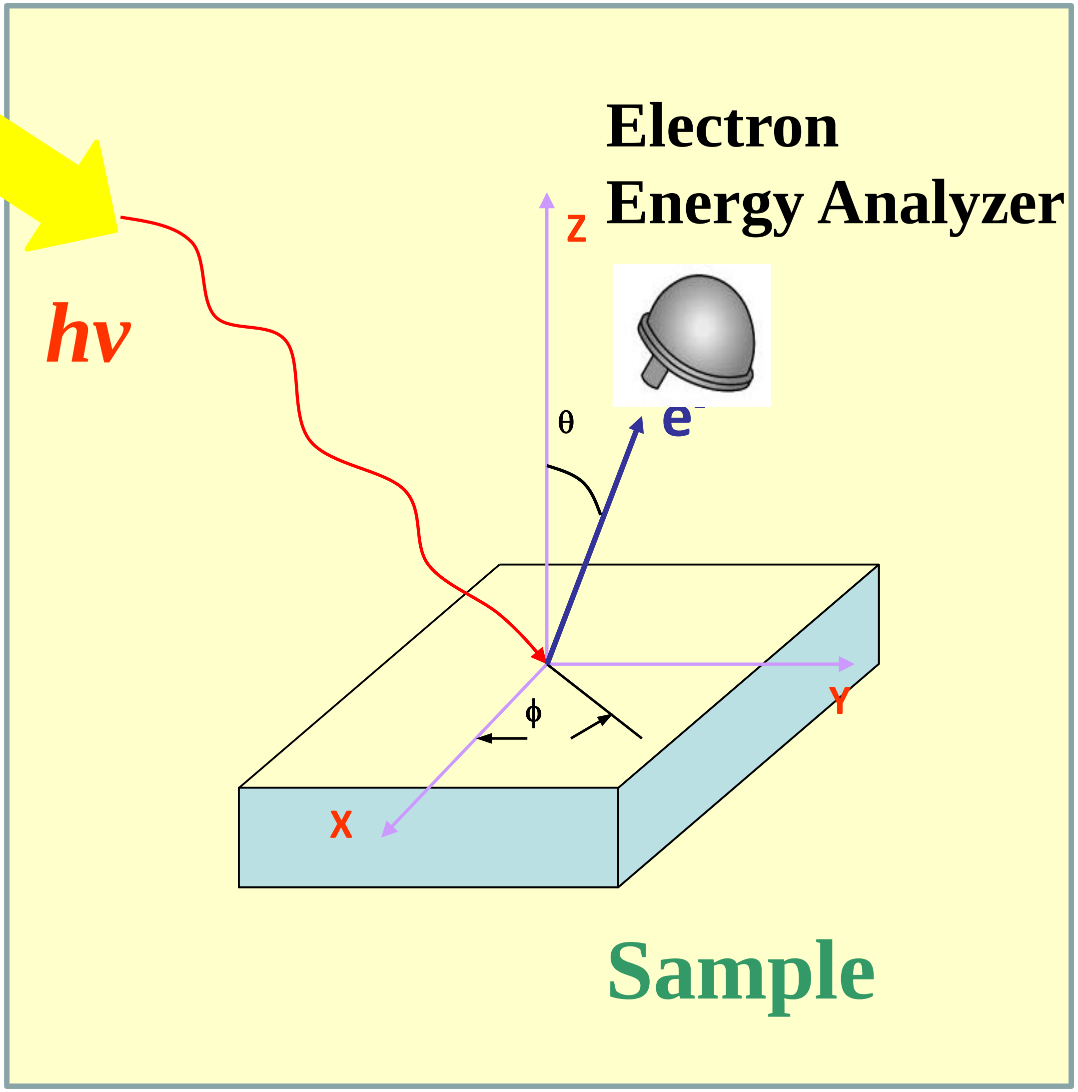
VUV Laser for Photoemission Spectroscopy

- **Synchrotron Radiation**

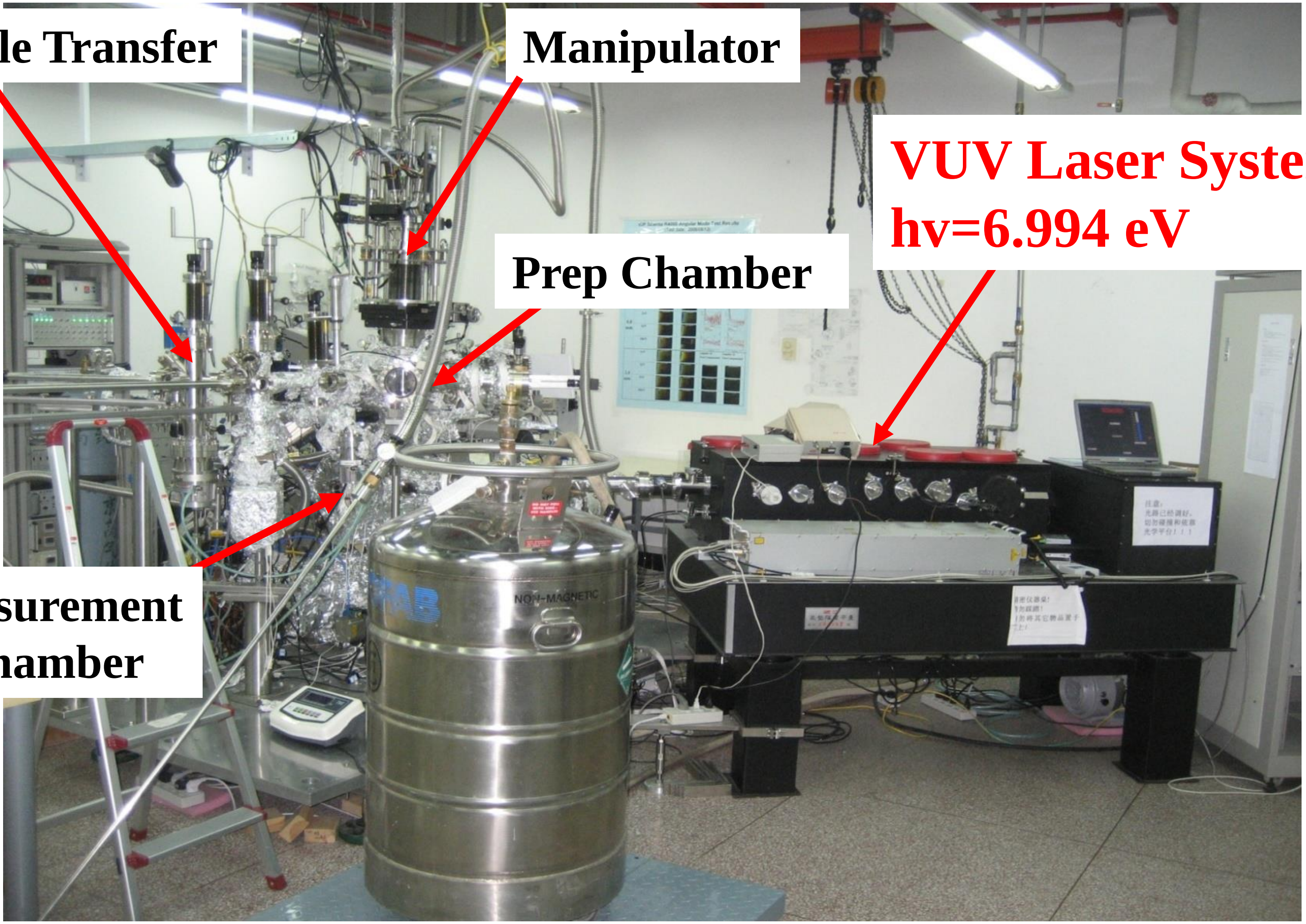
- **Gas Discharge Lamp**
  He I,   hv=21.2 eV
  He II, hv=40.8 eV

- **VUV Laser**
  hv=6.994 eV

VUV---
VacuumUltra-Violet
hv>6.5 eV



VUV Laser ARPES System Developed at IOP



Sample Transfer

Manipulator

Prep Chamber

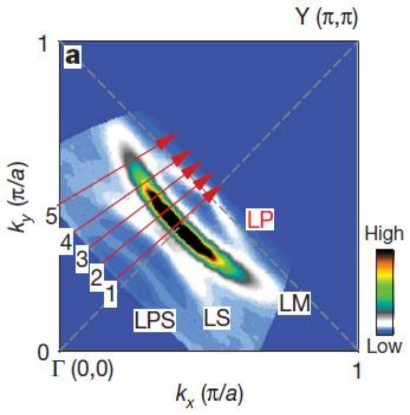
VUV Laser System
hv=6.994 eV

Measurement Chamber

(Started development in early 2004, commissioned by the end of 2006)
Guodong Liu, X. J. Zhou *et al.*, Rev. Sci. Instrum. 79 (2008) 023105.

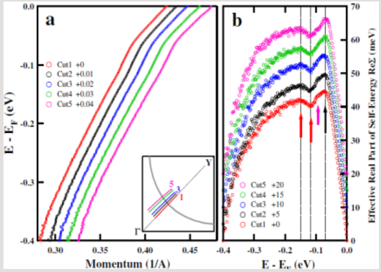
Laser ARPES on Cuprates --Highlights

Fermi Pocket in La-Bi2201



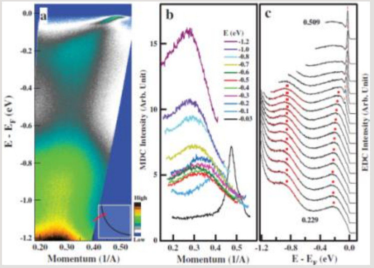
J. Q. Meng et al.,
Nature 462(2009)335.

New Energy Scale in Bi2212



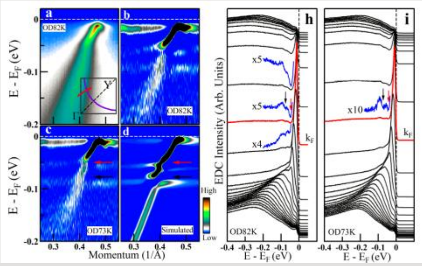
W. T. Zhang et al.,
Phys. Rev. Lett.
100(2008)107002.

High Energy Kink in Bi2212



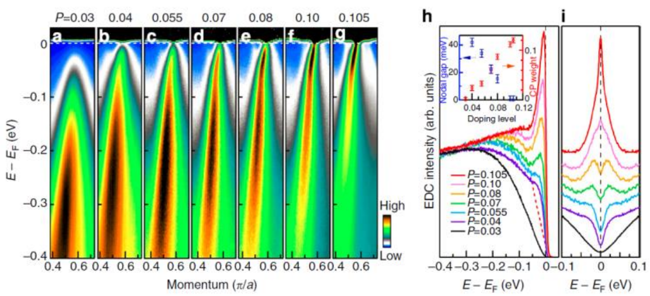
W. T. Zhang et al.,
Phys. Rev. Lett.
101(2008)017002.

Nodal and Antinodal Kink in Bi2212



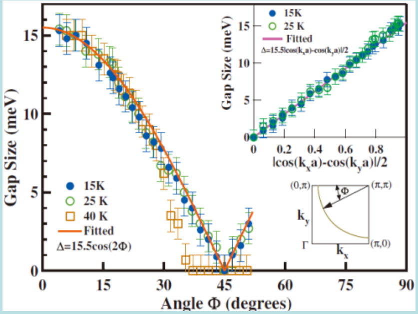
J. F. He et al.,
Phys. Rev. Lett.
111(2013)107005.

Insulator-Superconductor Transition in Bi2201



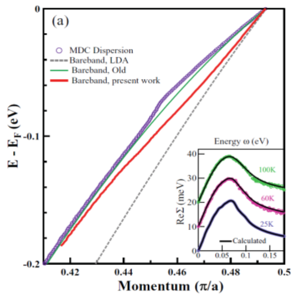
Y. Y. Peng et al.,
Nature Communications
4 (2013) 2459.

d-wave Gap in Bi2201



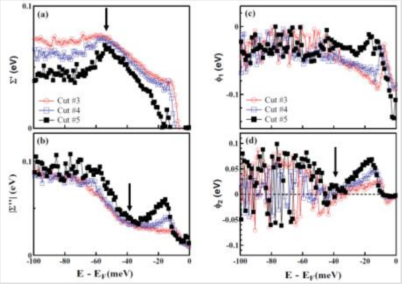
J. Q. Meng et al.,
Phys. Rev. B .
79(2009)024514.

Quantitative Self-Energy



L. Zhao et al.,
Phys. Rev. B .
83(2011)184515.

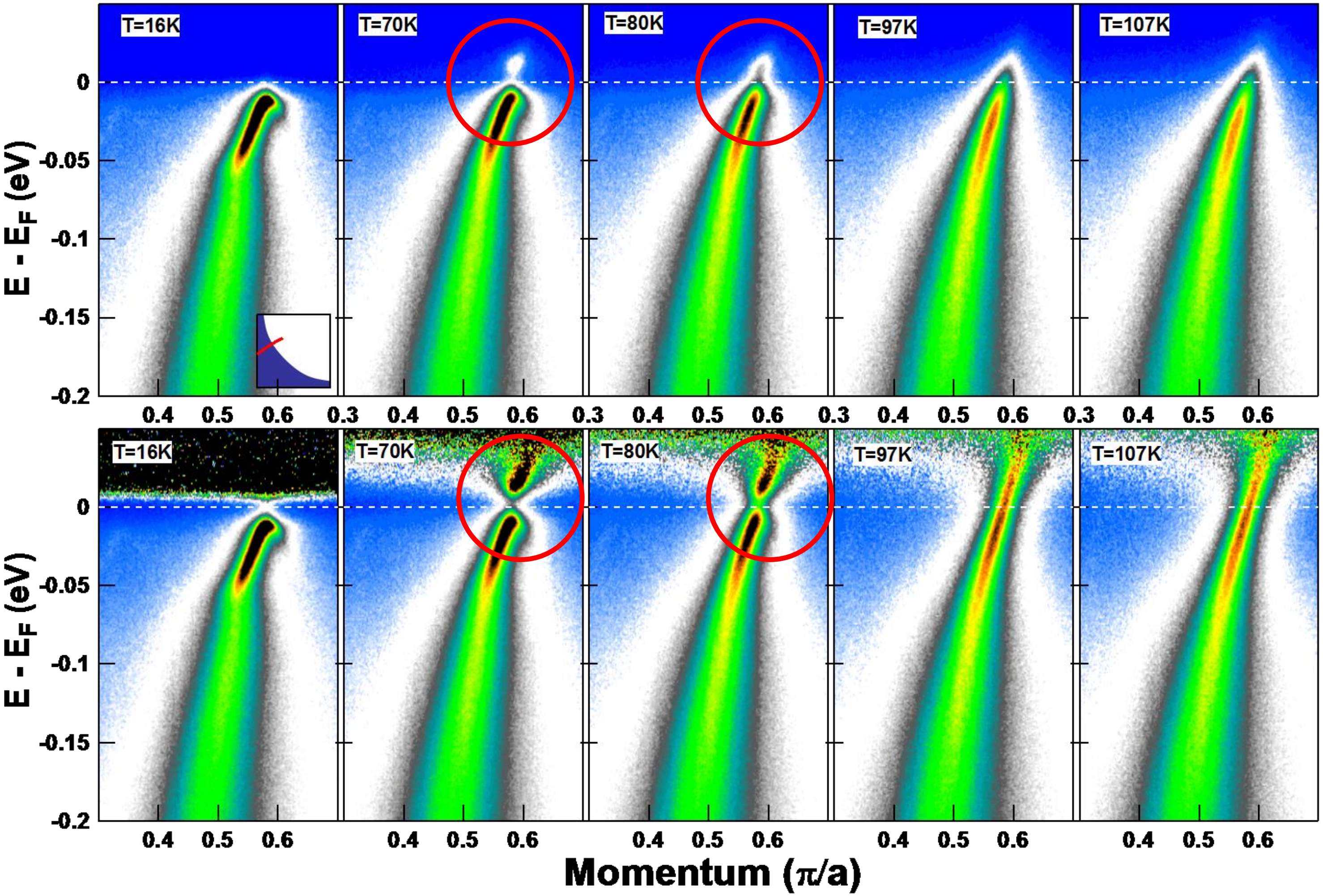
Self-Energies in SC State



W. T. Zhang et al.,
Phys. Rev. B .
85(2012)064514.

Laser ARPES on Bi2212—Two Branches of Dispersion

Obvious two branches of dispersion at 70K and 80K



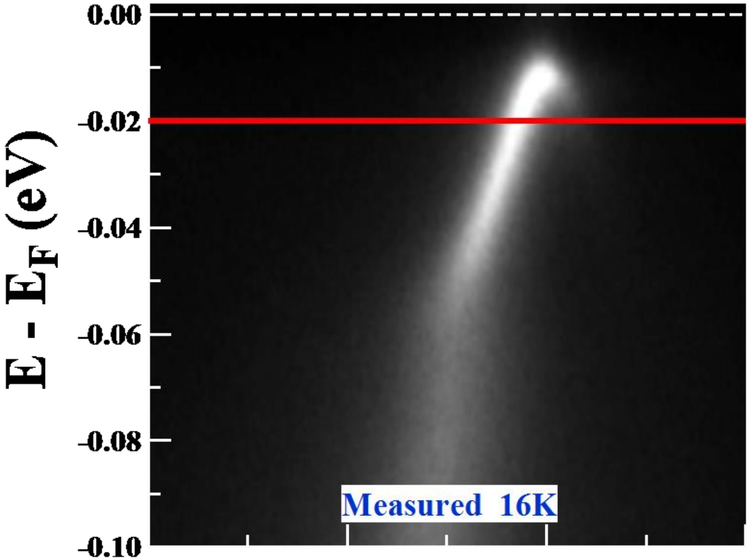
Tc=89K

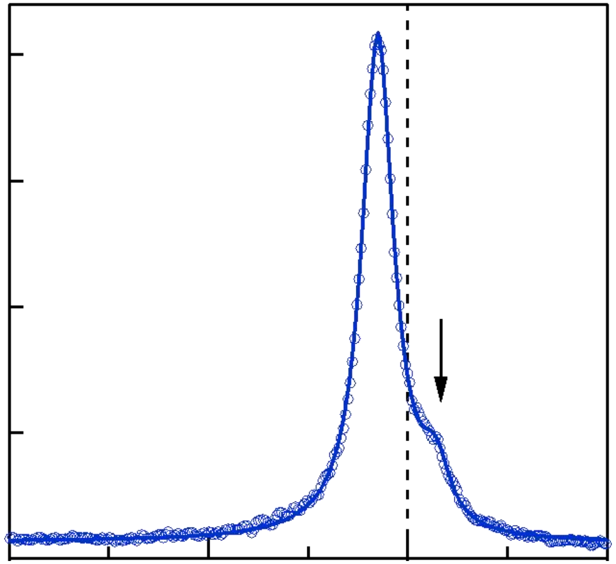
Original Data

Divide by Fermi Distribution Function

W. T. Zhang, H. Y. Choi, C. Varma, X. J. Zhou et al., Phys. Rev. B 85 (2012) 064514;

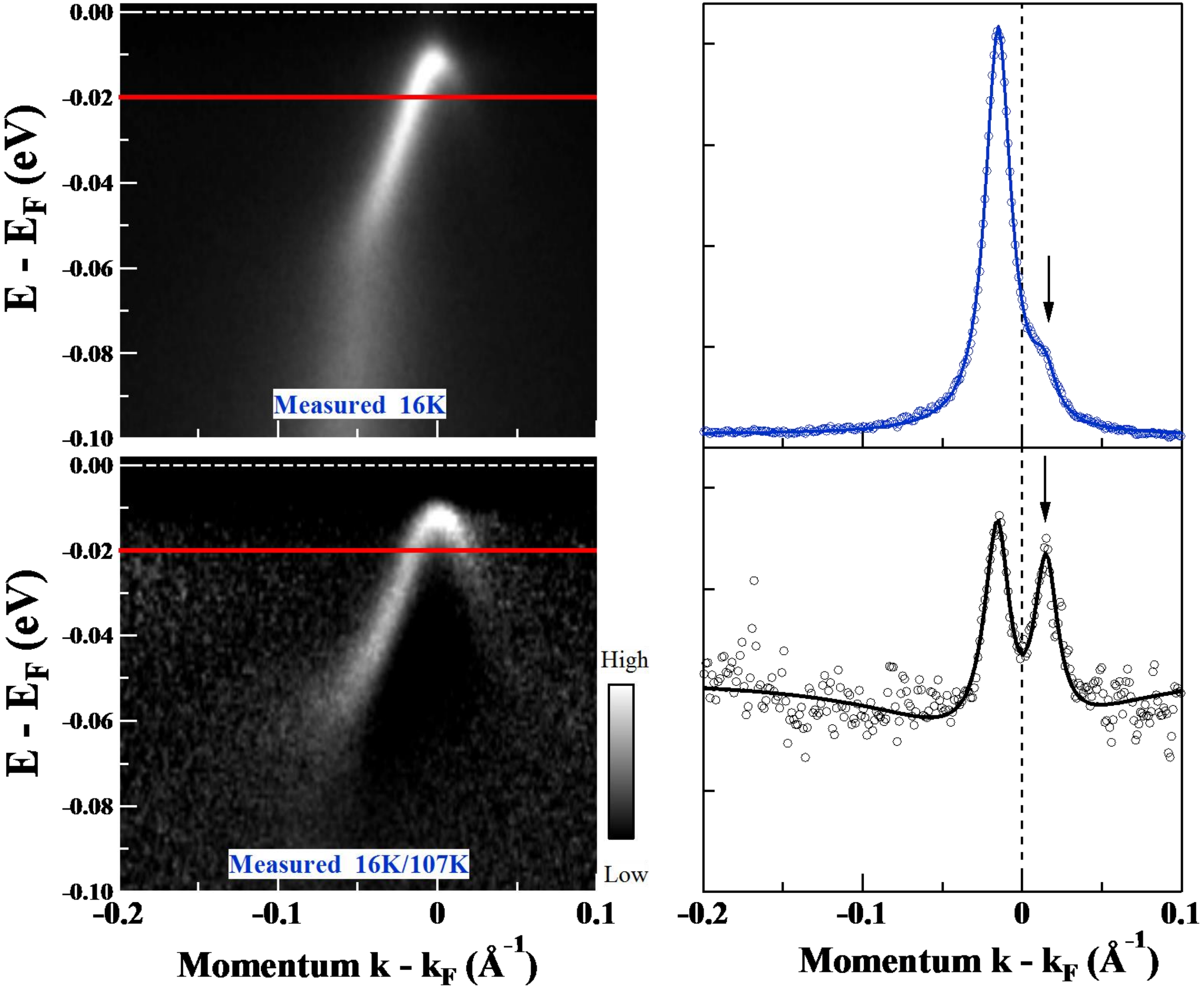
Observation of Band Back-Bending in Bi2212 at 16 K





16K

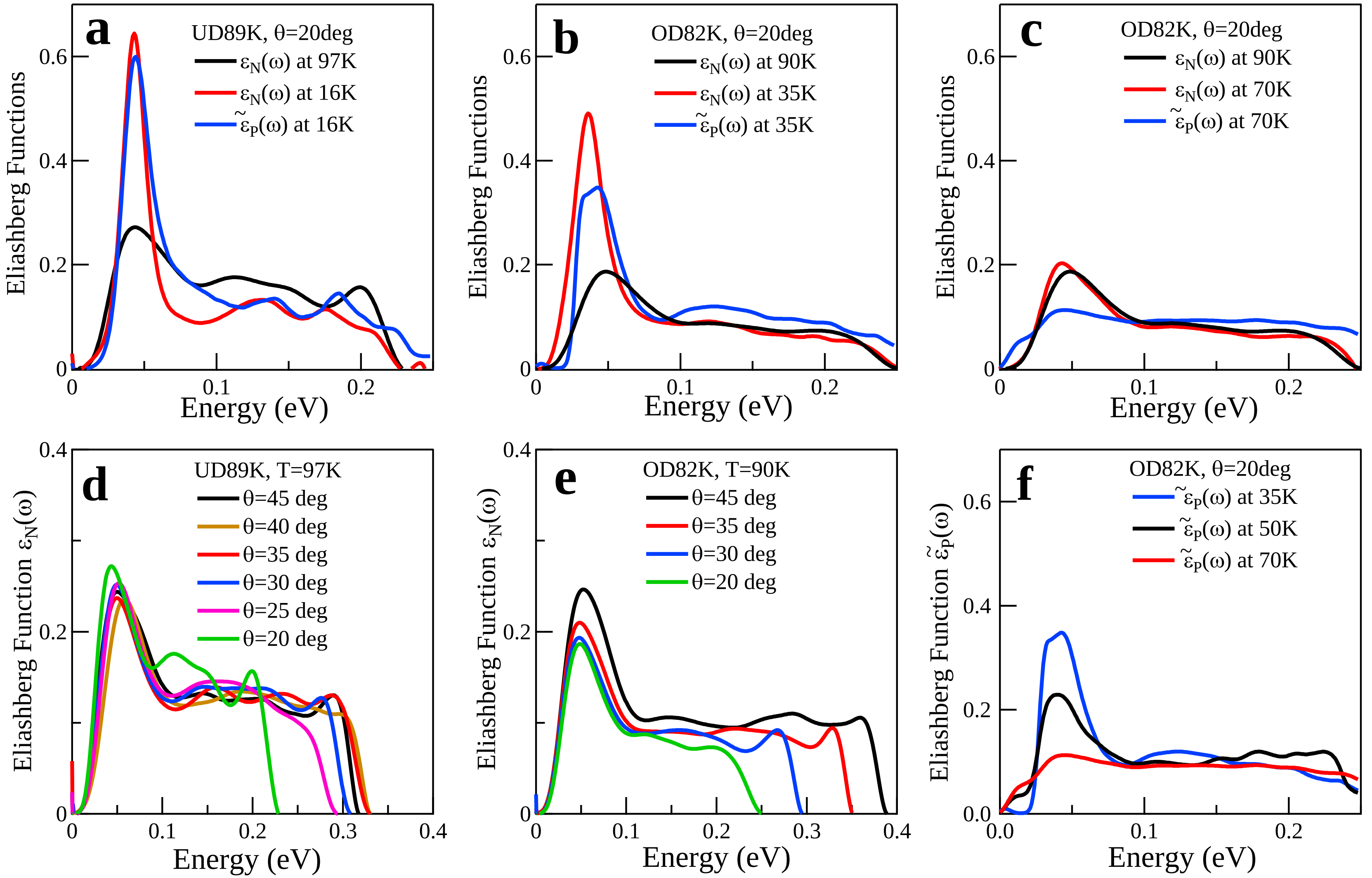
Observation of Band Back-Bending in Bi2212 at 16 K



16K

16K/107K

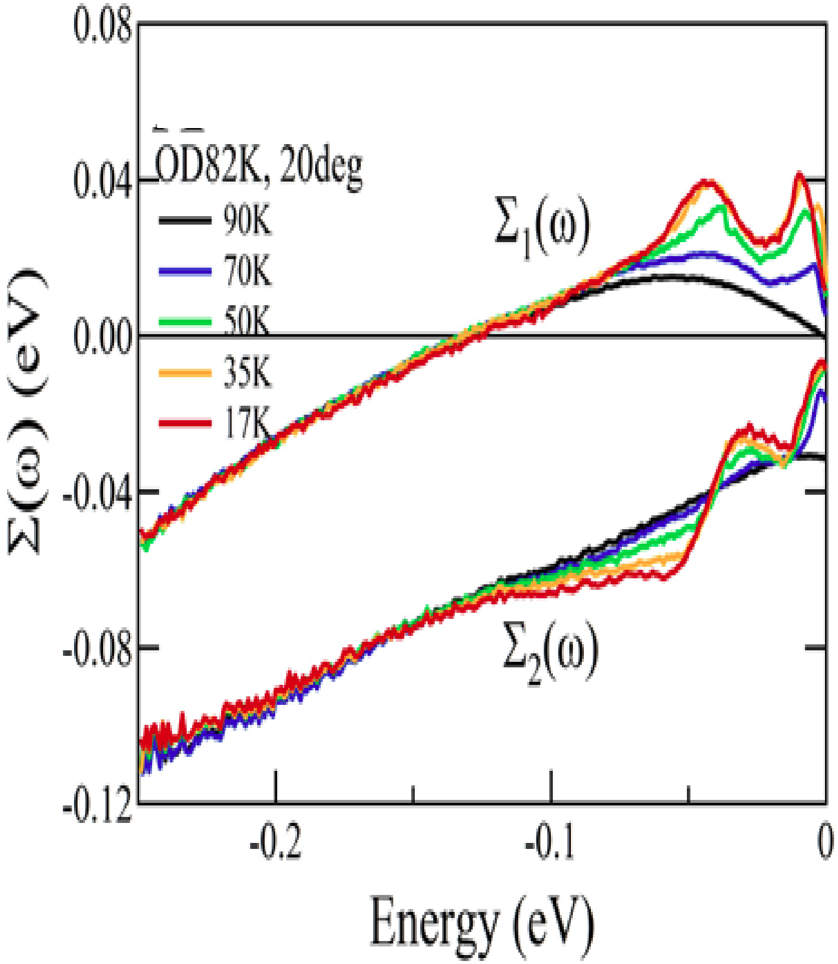
Eliashberg Functions of Bi2212



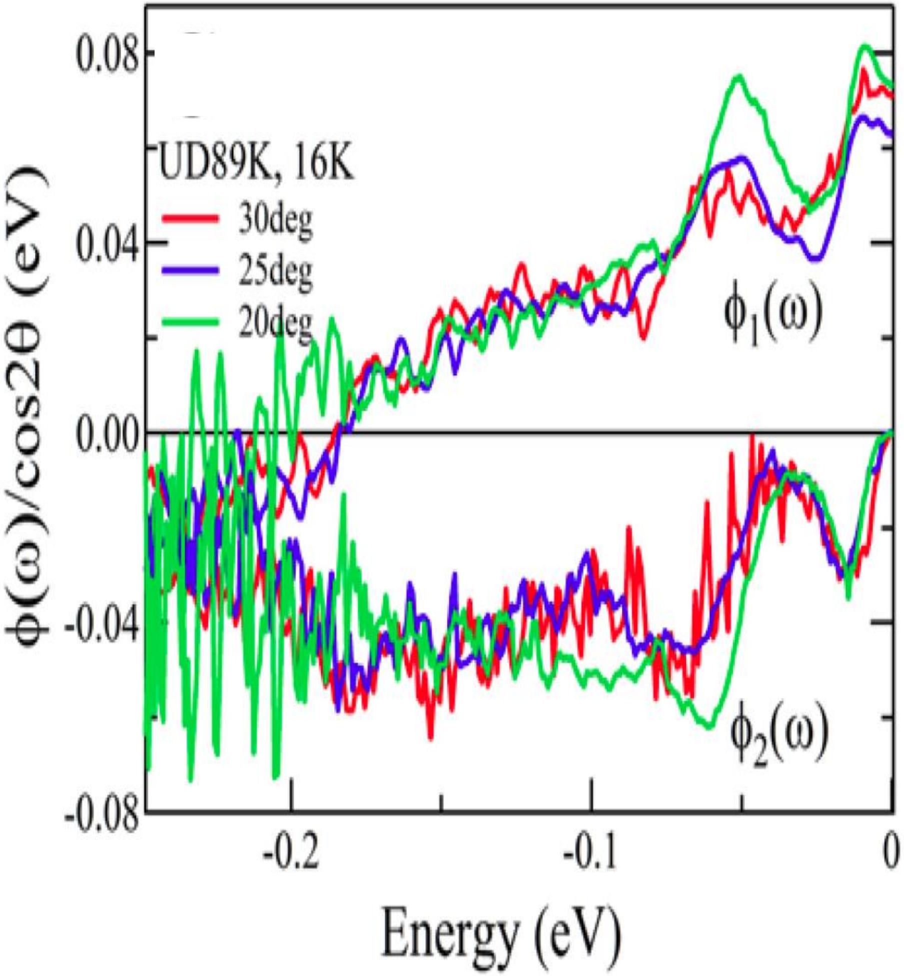
J. M. Bok, H. Y. Choi, C. Varma, X. J. Zhou et al., Science Advances 2, e1501329 (2016).

Extraction of Normal Self-Energy Σ and Pairing Self-Energy ϕ

Normal Self-Energy Σ



Pairing Self-Energy ϕ

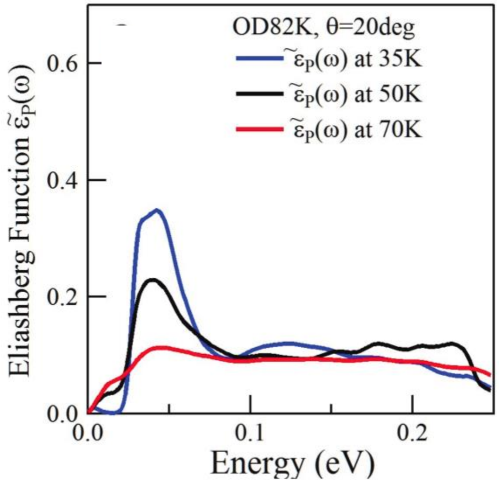


J. M. Bok, H. Y. Choi, C. Varma, X. J. Zhou et al., Science Advances 2, e1501329 (2016).

Salient Points and Implications of the Data and Analysis

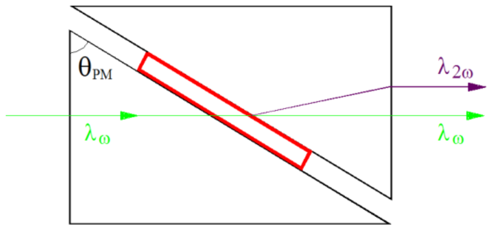
- **Normal self-energy $\Sigma(\theta,\omega)$ exhibits weak momentum dependence;**
- **Pairing self-enery $\phi(\omega)/\cos 2\theta$ is independent of θ to 10% accuracy.**
- **$\varepsilon_P(\omega)/\cos(2\theta) \approx \varepsilon_N(\omega)$ for T<<Tc in the superconducting state;**
- **Near Tc, $\varepsilon_P(\omega)/\cos(2\theta) \approx \varepsilon_N(\omega)$ minus ~50meV bump.**

It is the same interaction that dictates the anomalous normal state properties and electron pairing in the superconducting state.

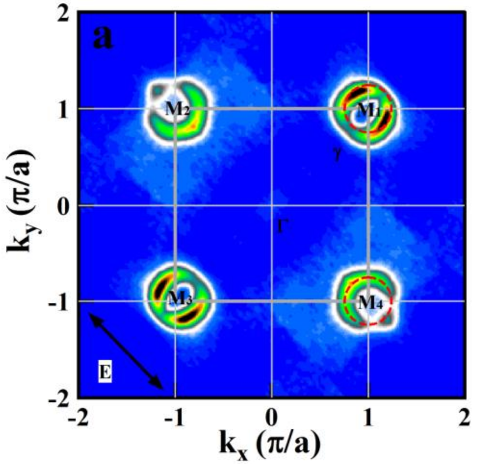


Summary

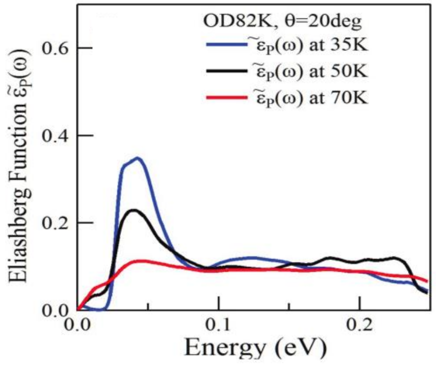
- Latest development of laser-based ARPES;



- Key electronic ingredients in dictating the mechanism of superconductivity in the iron-based supercondctors;



- First quantitative determination of the pairing Eliashberg functions puts strong constraints on the pairing mechanism of the cuprate superconductors.



Salient Points and Implications of the Data and Analysis

- Normal self-energy $\Sigma(\theta,\omega)$ exhibits weak momentum dependence;
- Pairing self-enery $\phi(\omega)/\cos 2\theta$ is independent of θ to 10% accuracy.
- $\varepsilon_P(\omega)/\cos(2\theta) \approx \varepsilon_N(\omega)$ for T<<Tc in the superconducting state;
- Near Tc, $\varepsilon_P(\omega)/\cos(2\theta) \approx \varepsilon_N(\omega)$ minus ~50meV bump.

It is the same interaction that dictates the normal state properties and superconducting state electron pairing.