ARPES on $Tl_2Ba_2CuO_{6+\delta}$: Probing the Electronic Structure of Overdoped Cuprates

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Vancouver, B.C.

QUANTUM MATERIALS AT UBC

Electronic Structure of Solids

Theoretical modeling & fabrication of nanostructured materials

George Sawatzky

ARPES on Complex Systems

Low-energy electronic structure
Photoelectron spectroscopies

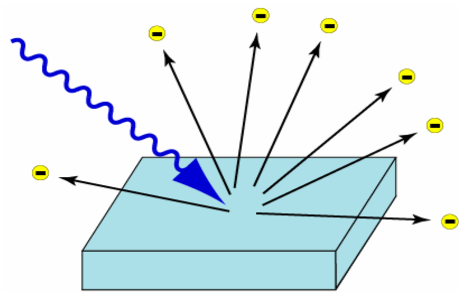
Andrea Damascelli

Scanning Tunneling Microscopy

Self Assembly & atomic manipulation of nanostructured materials

Johannes Barth

ARPES ON COMPLEX SYSTEMS



Angle Resolved PhotoElectron Spectroscopy

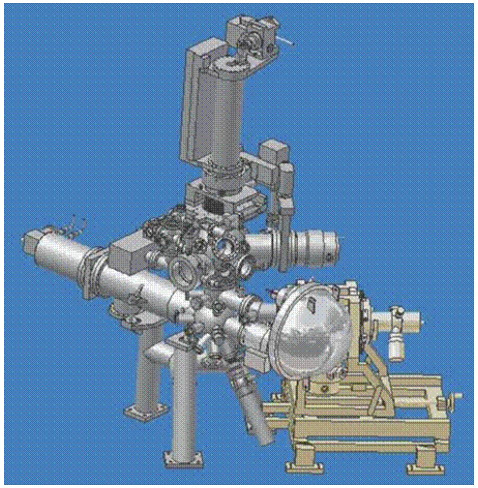
FIRST EVIDENCE FOR THE QUANTIZATION OF LIGHT!

Velocity and direction of the electrons in the solid

Low-energy Electronic Structure → Macroscopic Physical Properties

Superconductivity, *Magnetism*, *Density Waves*, ...

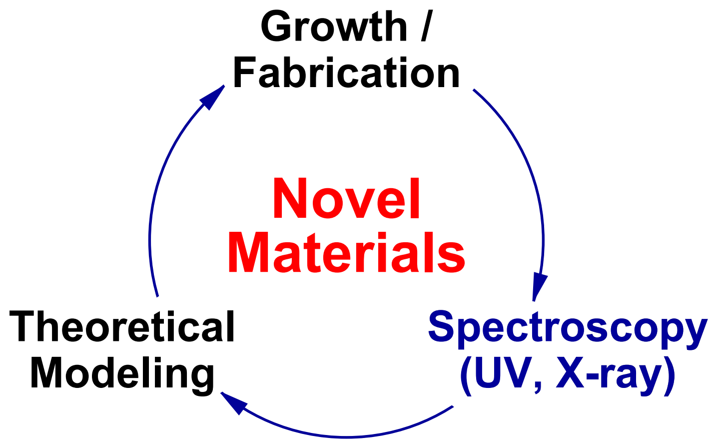
ARPES @ UBC



Canadian Light Source Inc.

Synchrotron based spectroscopies

Comprehensive Material Science Program Across Canada



1. Orbital excitations in orbital-ordered ferromagnets

2. Magnetic fluctuations and p-wave superconductivity in $Ca_{2-x}Sr_xRuO_4$

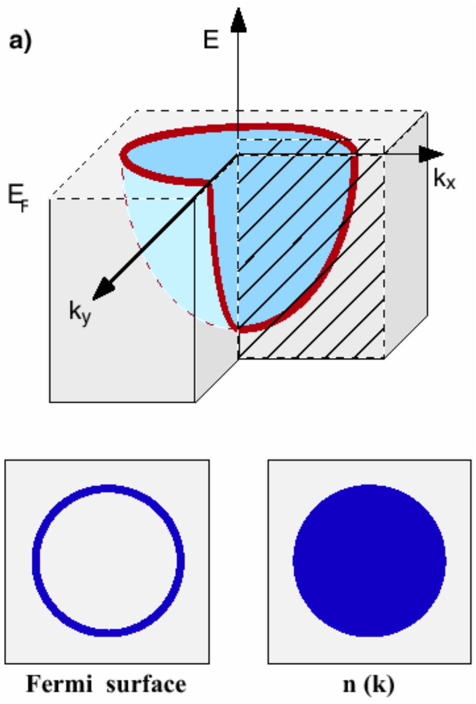
3. Nanoscale phase separation and chemical disorder in the high-Tc superconductors

4. Challenging the Mystery of High-Tc Superconductivity: ARPES on $Tl_2Ba_2CuO_{6+d}$

5. TM-Oxide nanostructures: novel magnets, nanowires, and metal-insulator transition

Understanding the Solid State: Electrons in Reciprocal Space

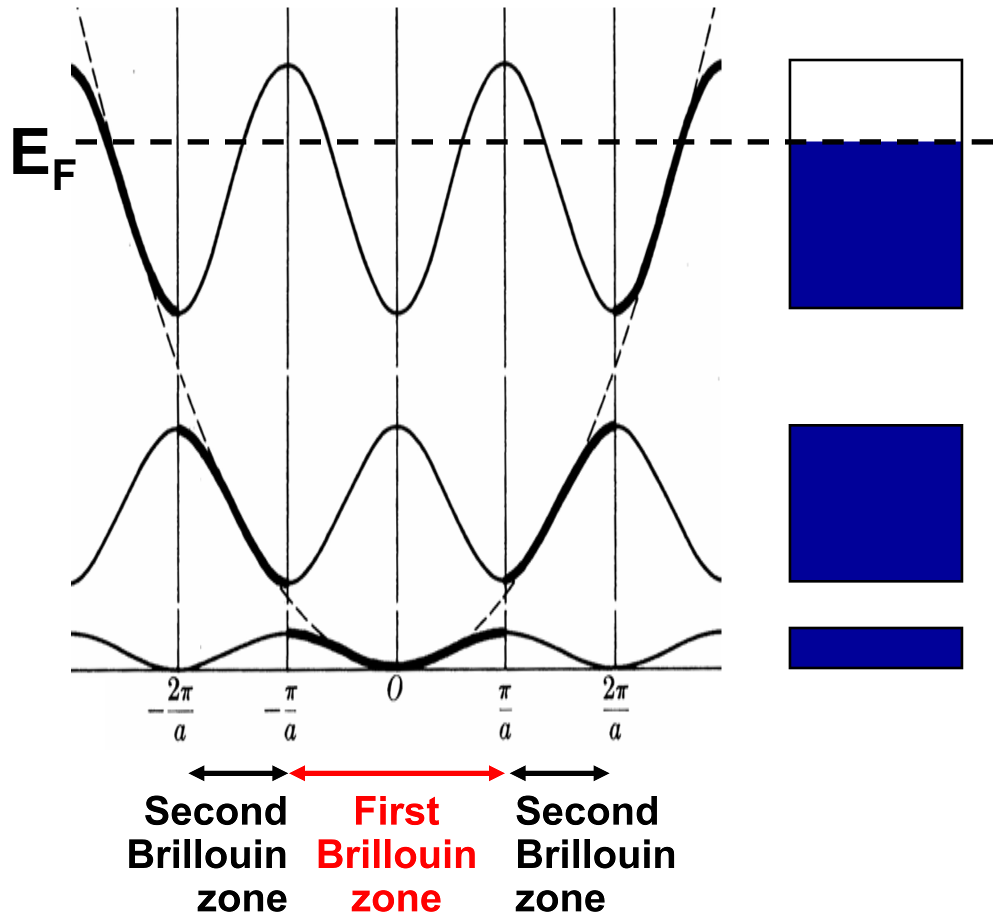
Many properties of a solids are determined by electrons near E_F (conductivity, magnetoresistance, superconductivity, magnetism)



Only a narrow energy slice around E_F is relevant for these properties (kT=25 meV at room temperature)

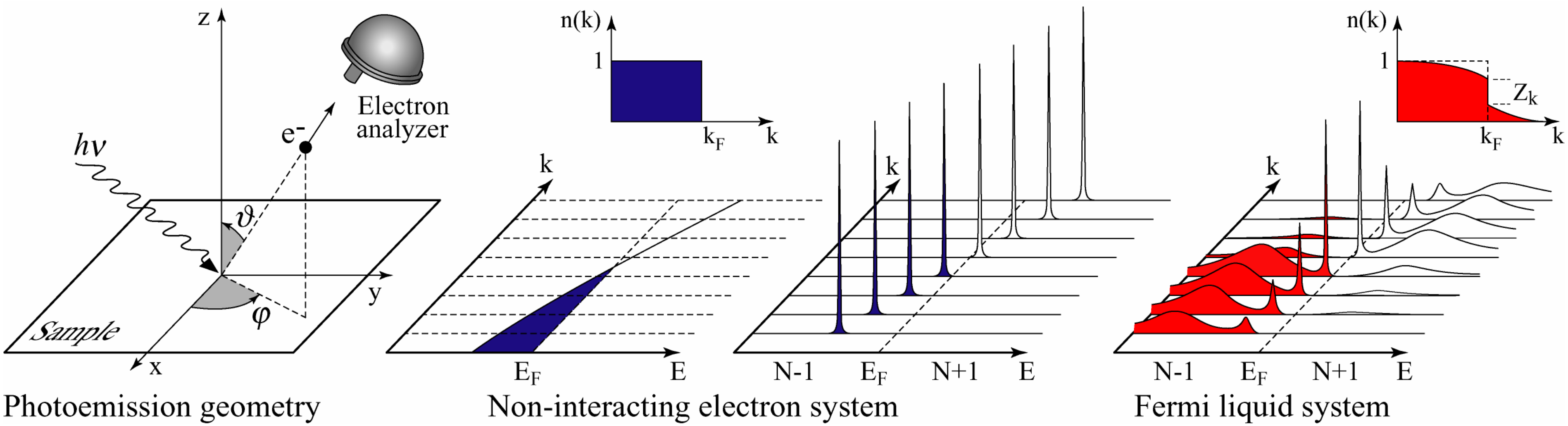
Allowed electronic states

Repeated-zone scheme



ARPES: The One-Particle Spectral Function

A. Damascelli, Z. Hussain, Z.-X Shen, Rev. Mod. Phys. **75**, 473 (2003)



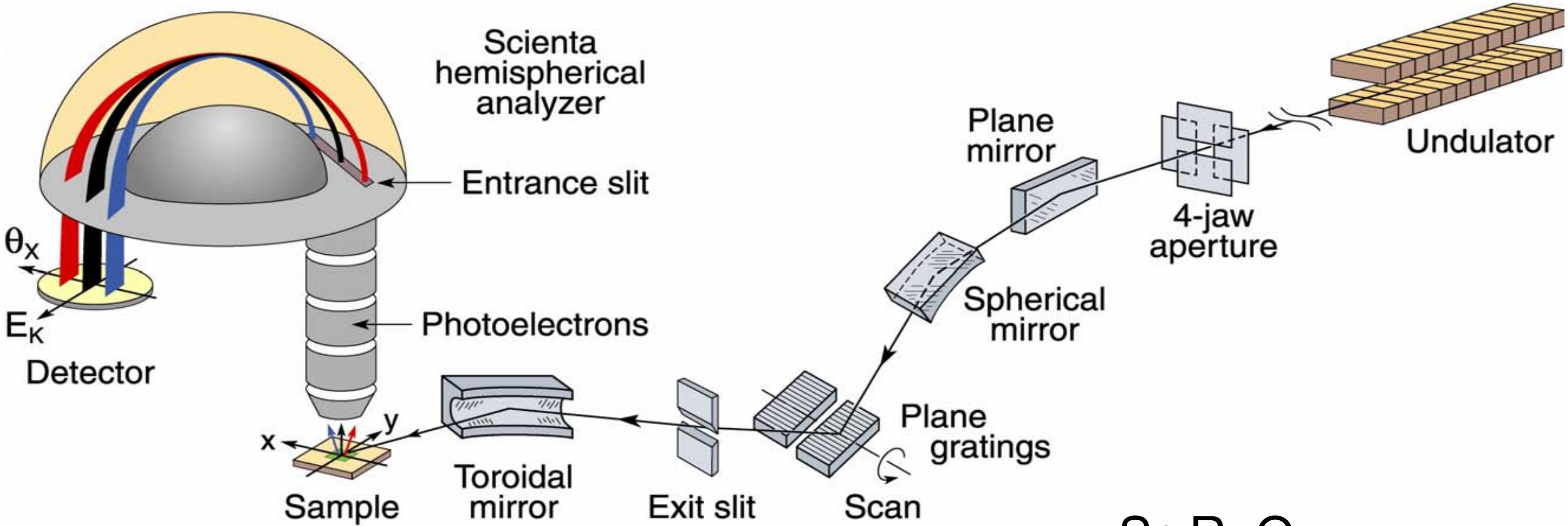
Photoemission intensity: $I(k,w)=I_0\,|M(k,w)|^2 f(w)\,A(k,w)$

Single-particle spectral function

$$A(\mathbf{k},\omega)=-\frac{1}{\pi}\frac{\Sigma''(\mathbf{k},\omega)}{[\omega-\epsilon_{\mathbf{k}}-\Sigma'(\mathbf{k},\omega)]^2+[\Sigma''(\mathbf{k},\omega)]^2}$$

S(**k**,w) **: the "self-energy" captures the effects of interactions**

Angle-Resolved Photoemission Spectroscopy

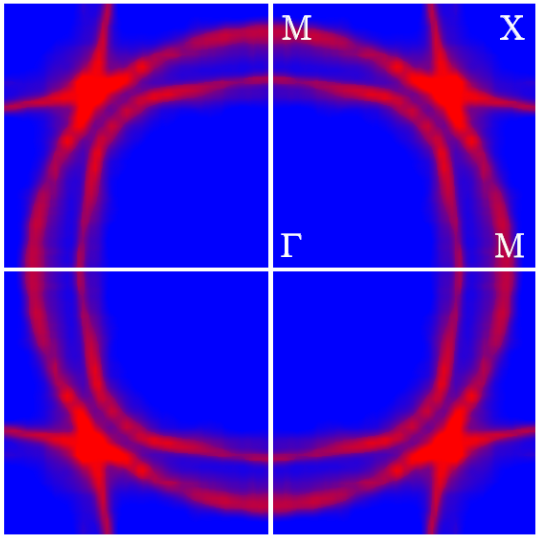


Parallel multi-angle recording

- Improved **energy resolution**
- Improved **momentum resolution**
- Improved **data-acquisition efficiency**

	ΔE (meV)	*Δθ*
past	*20-40*	*2°*
now	*2-10*	*0.2°*

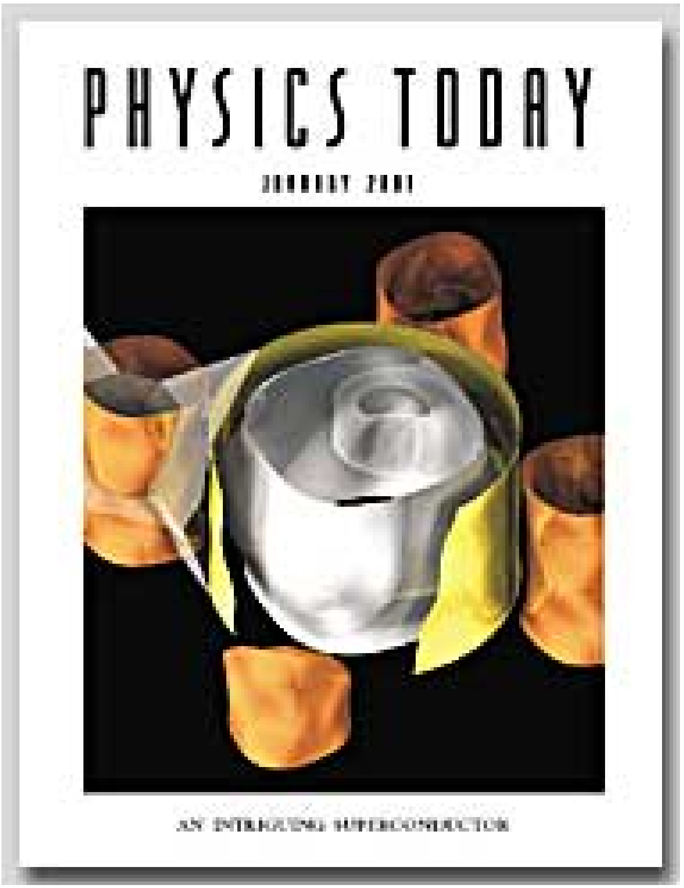
Sr_2RuO_4



A. Damascelli *et al.*, PRL **85**, 5194 (2000)

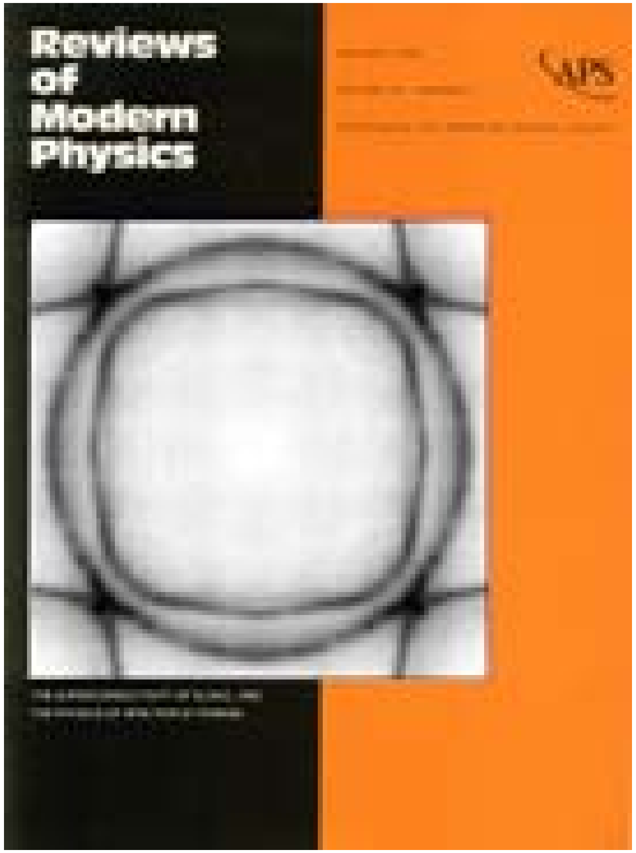
Normal State Fermi Surface of Sr_2RuO_4

de Haas-van Alphen



Maeno, Rice & Manfred, PT **1**, 42 (2001)

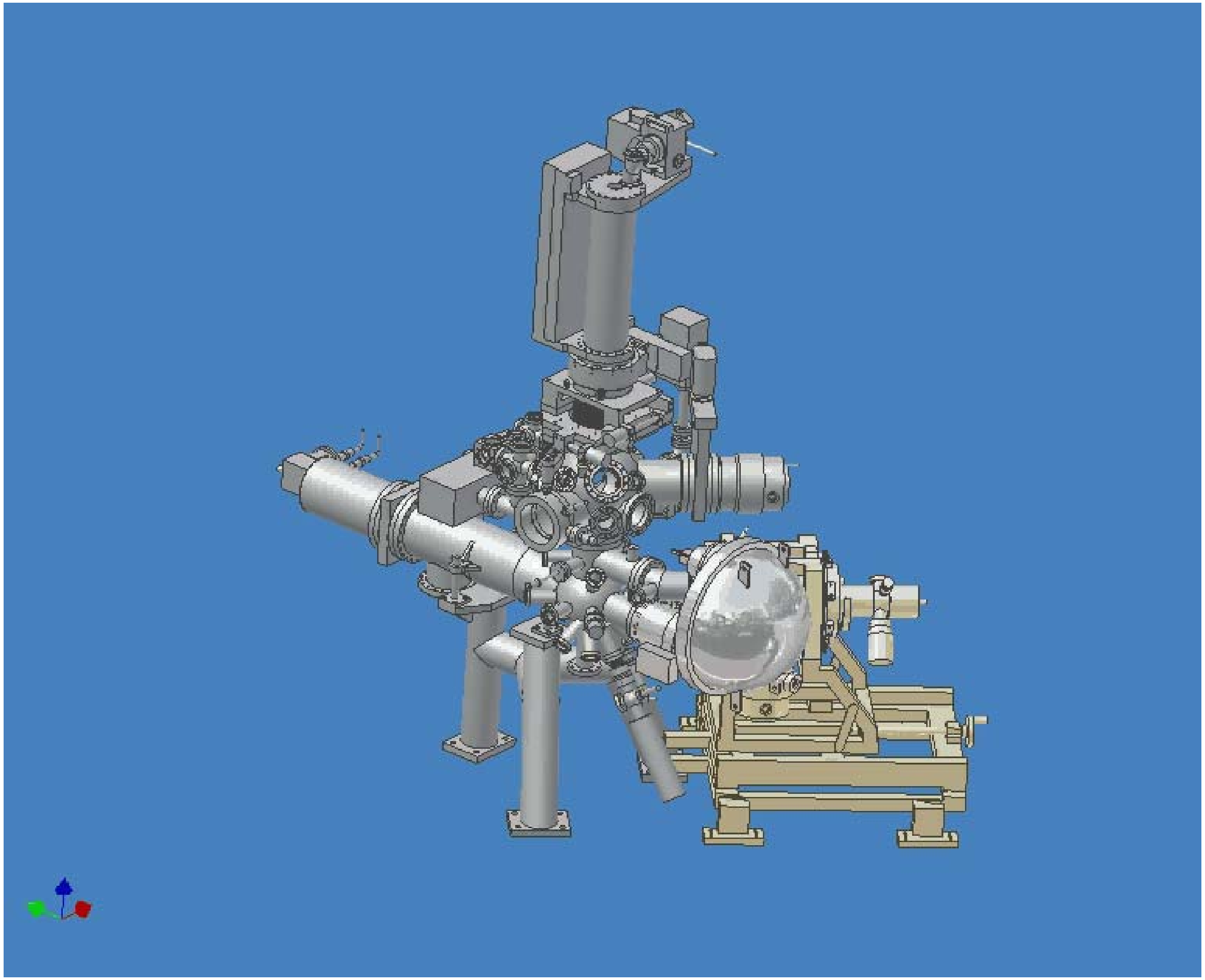
ARPES



Mackenzie & Maeno, RMP **75**, 657 (2003)

ARPES ON COMPLEX SYSTEMS

- High energy resolution
  $\Delta E < 1\,meV$
- High angular precision
  $\pm$ 0.1º
- Low base temperature
  ~ 2 K
- Photon energies
  H_2, He, Ne
- Polarization control
  linear
- Ultra-high vacuum
  ~ 10^{-11} torr
- Surface / Thin films
- LEED - RHEED



$Tl_2Ba_2CuO_{6+\delta}$: Collaborators

- **ARPES at UBC:**

  M. Platé, J. Mottershead, S. Hossain, S. Wang, P. Bloudoff, T. Pedersen, R. Norman, F. Cao, N. Ingle, **A. Damascelli**

- **Band Structure Calculations:**

  Ilya Elfimov

- **Samples:**

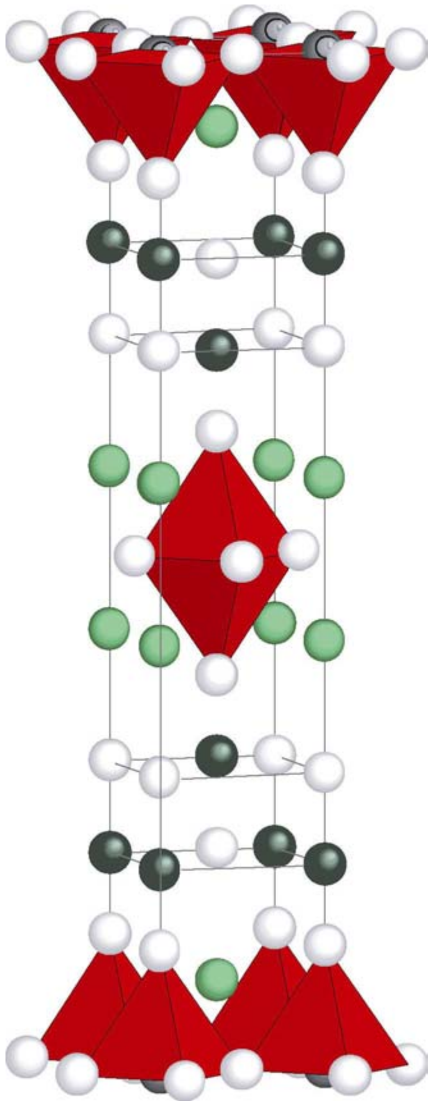
  $Tl_2Ba_2CuO_{6+\delta}$

  D. Peets, Ruixing Liang, D.A. Bonn, W.N. Hardy

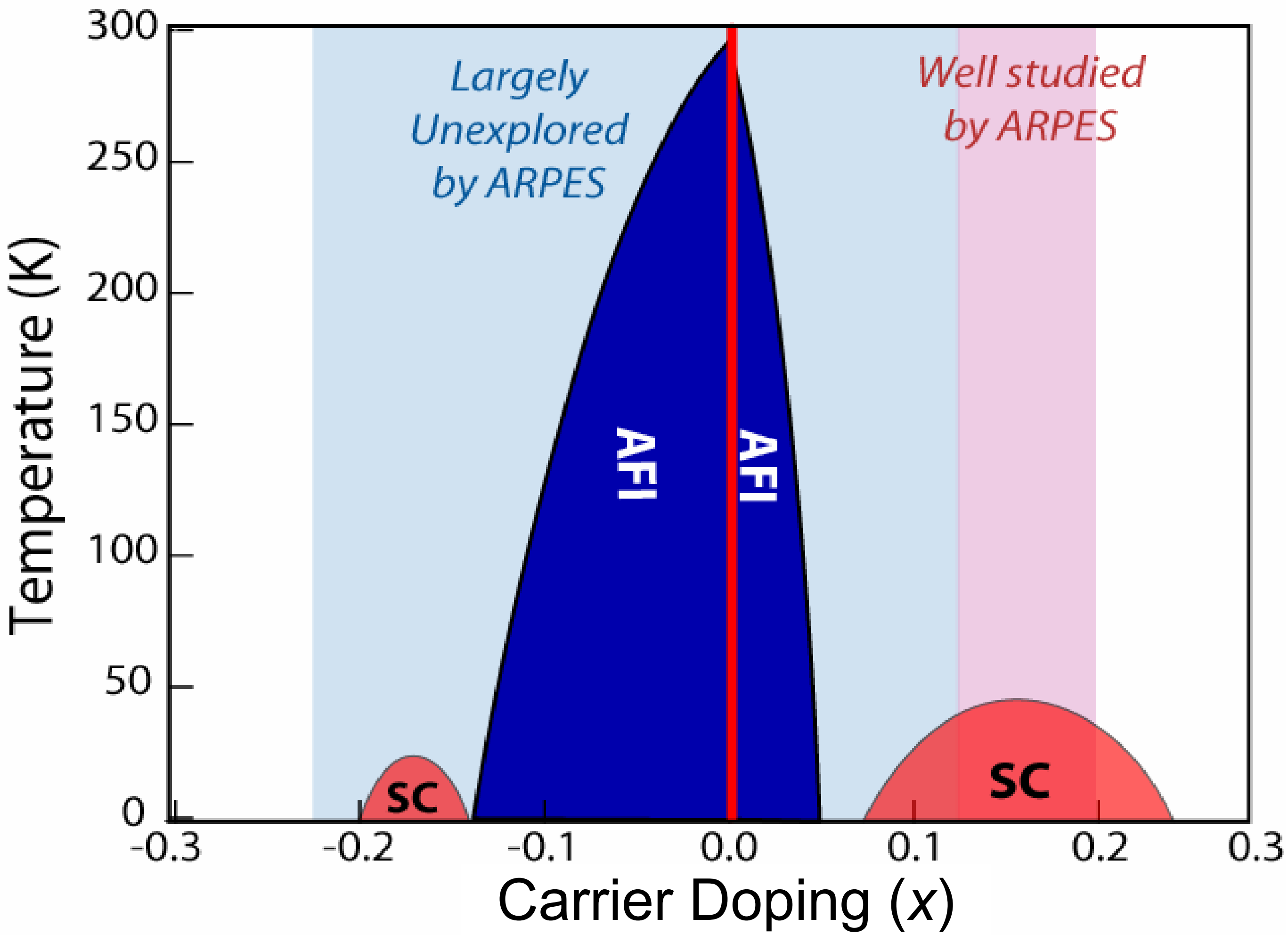
- **ARPES Experiments:**

  Swiss Light Source – SIS Beamline

  S. Chiuzbaian, M. Falub, M. Shi, L. Patthey



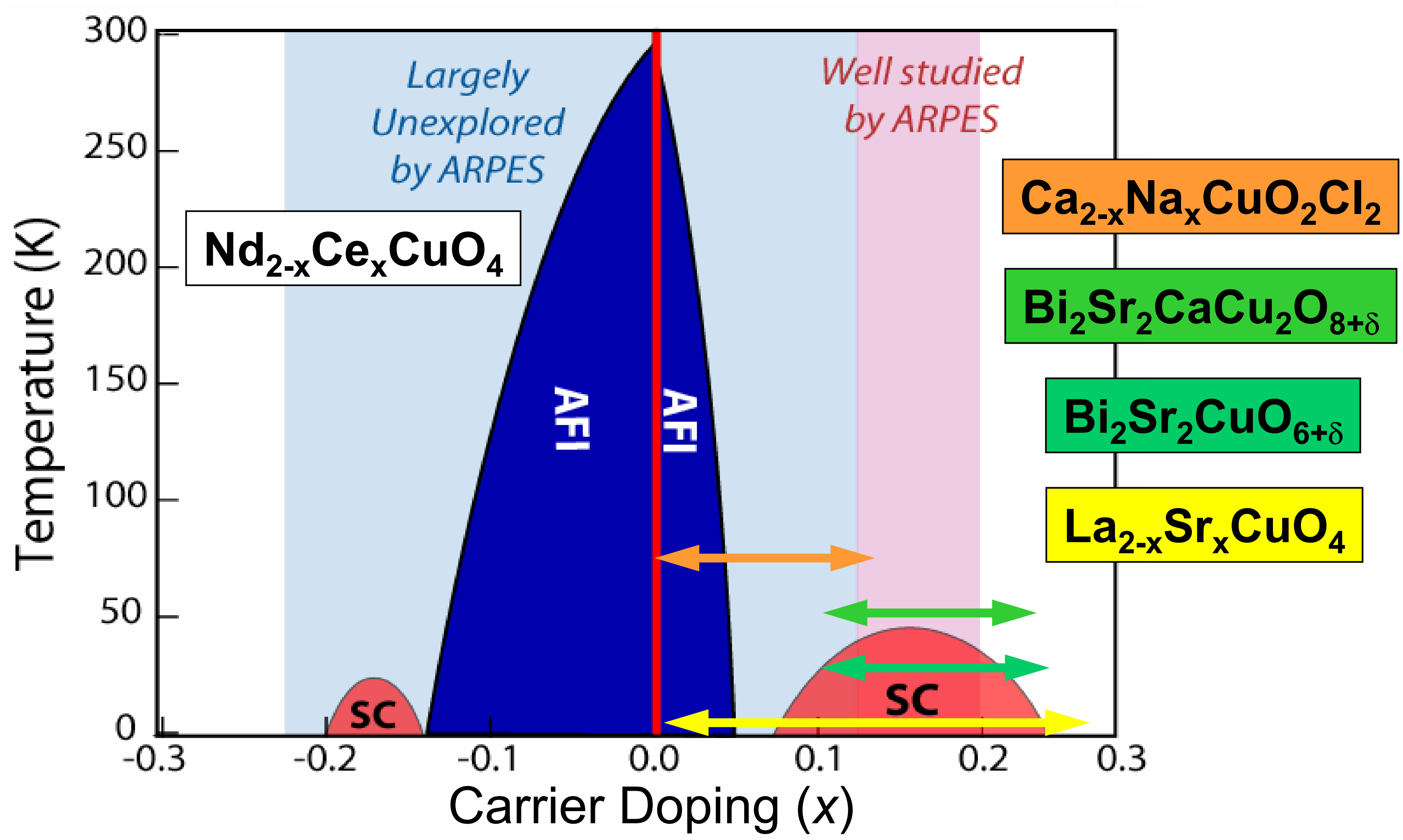
High-Temperature Superconductors



High-Temperature Superconductors

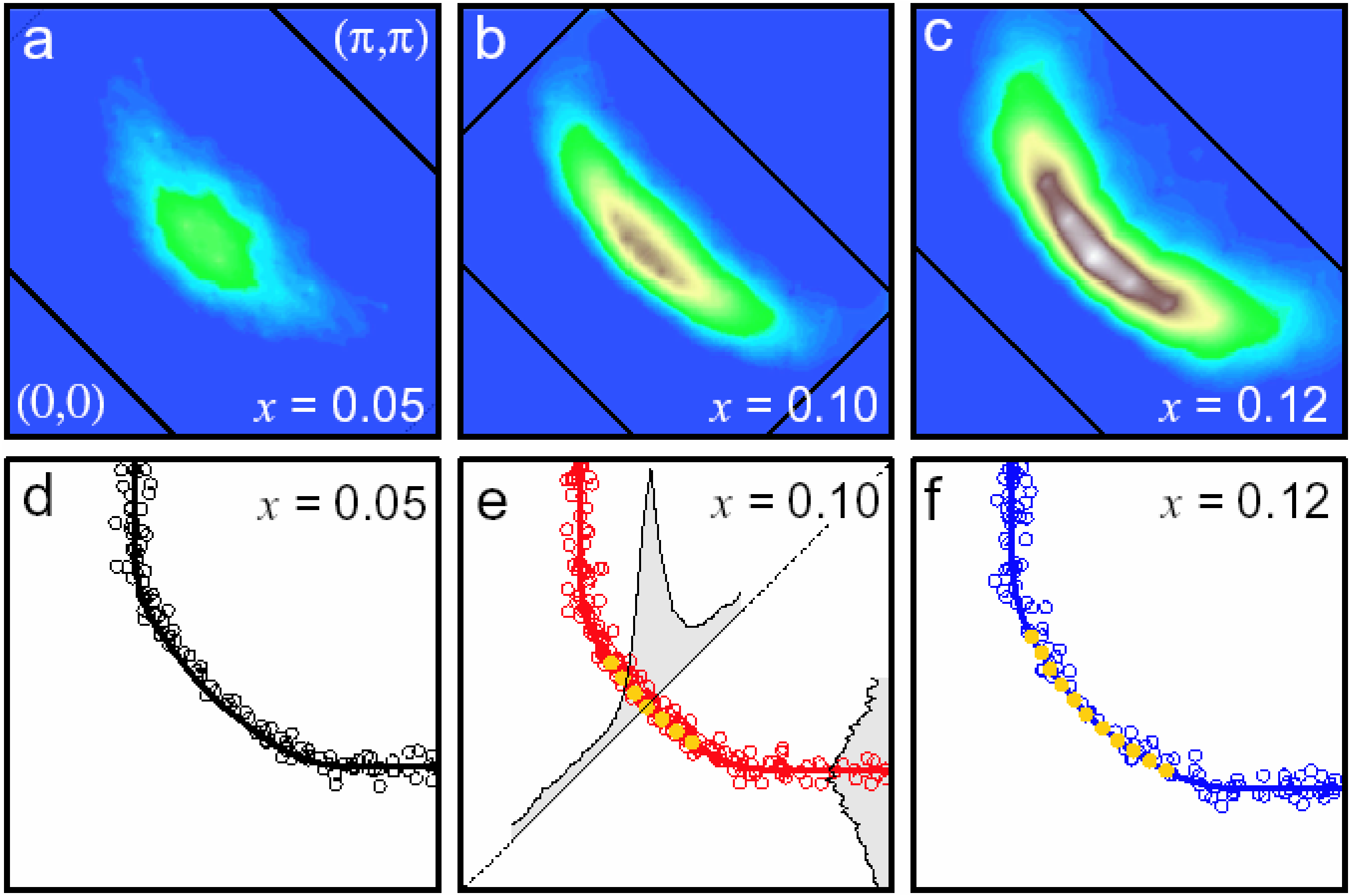
H. Eisaki et al., PRB **69**, 064512 (2004)

High-Temperature Superconductors



FS and Pseudogap in Underdoped Cuprates

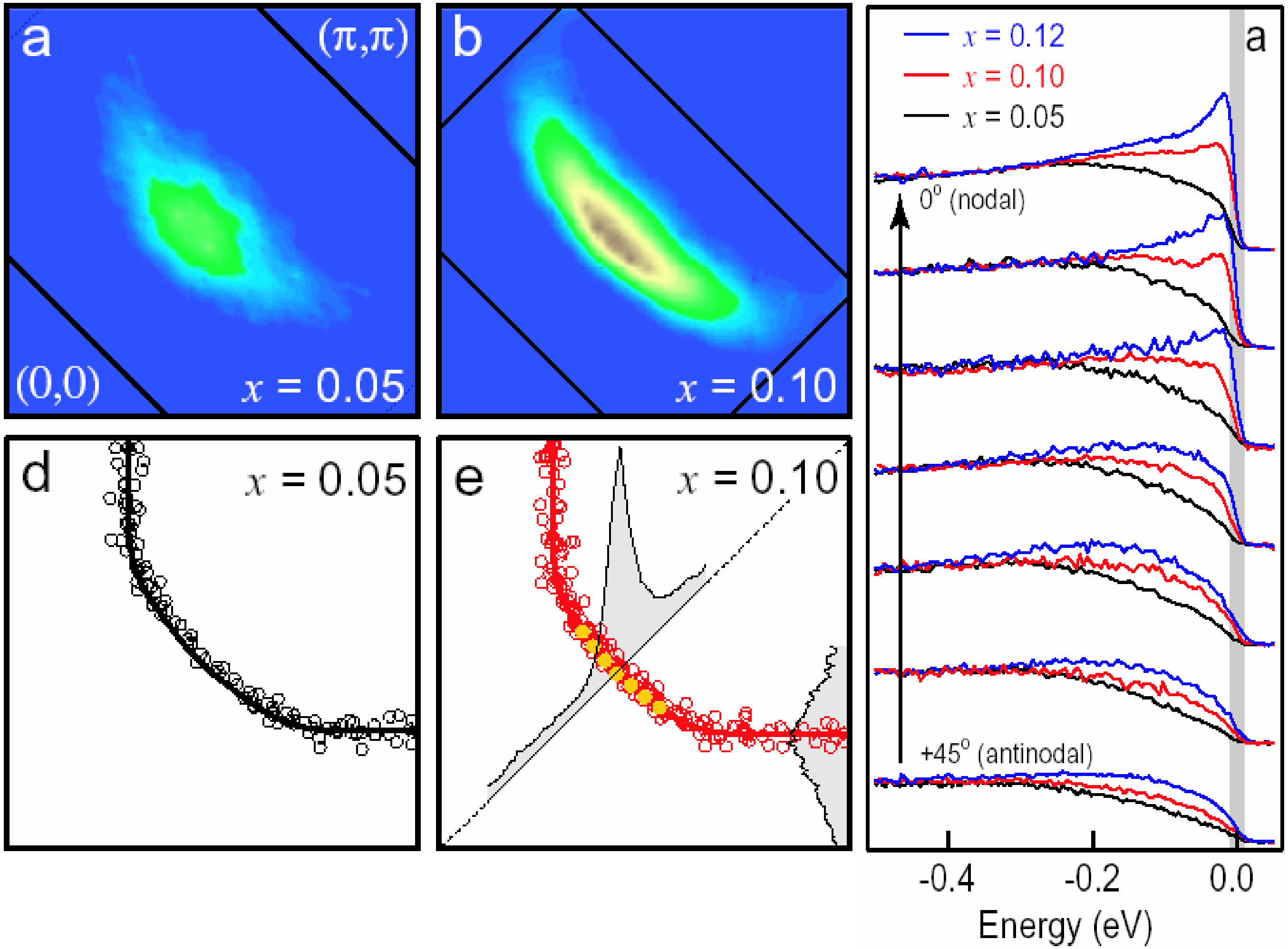
ARPES on $Ca_{2-x}Na_xCuO_2Cl_2$



K.M. Shen *et al.*, Science **307**, 901 (2005)

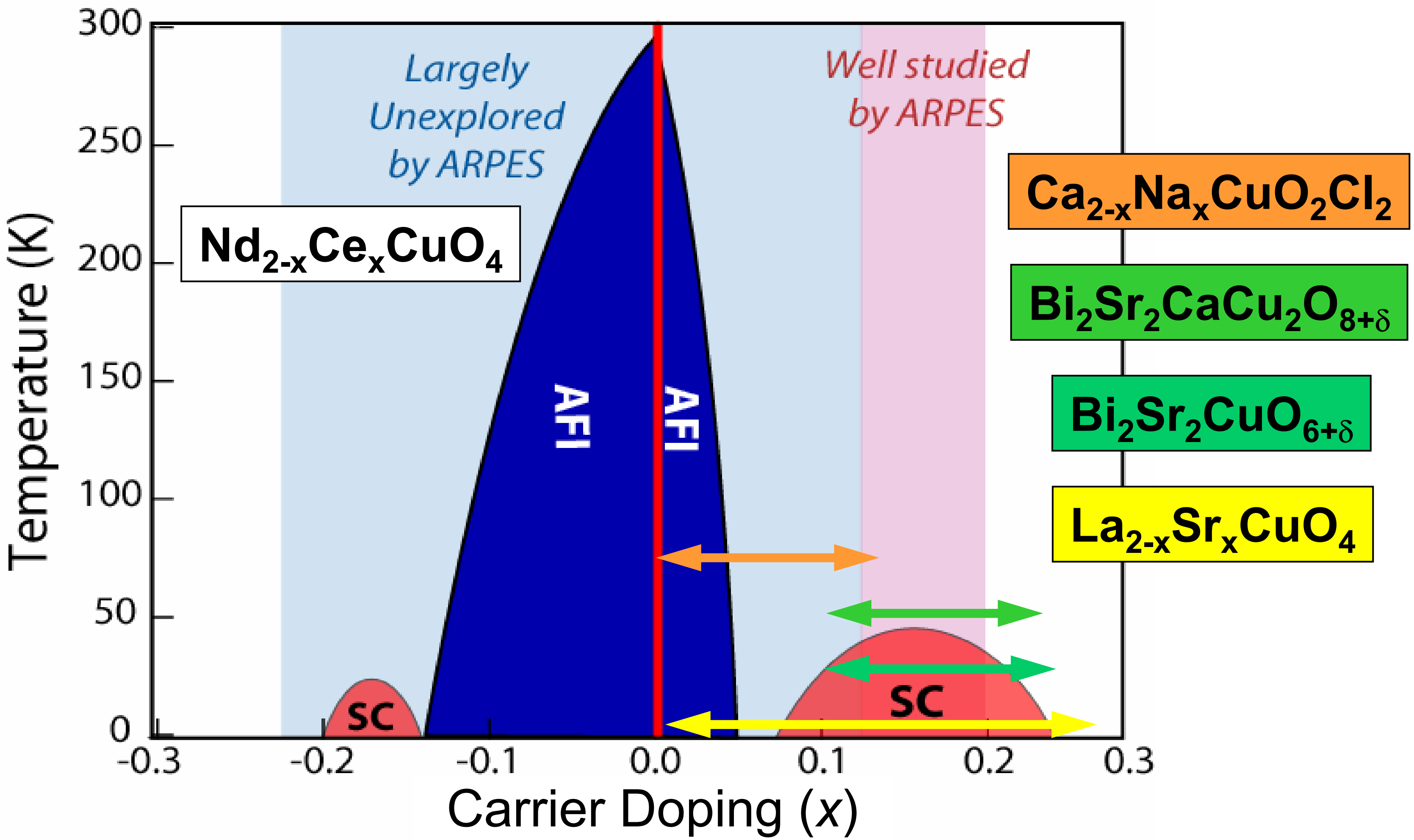
FS and Pseudogap in Underdoped Cuprates

ARPES on $Ca_{2-x}Na_xCuO_2Cl_2$

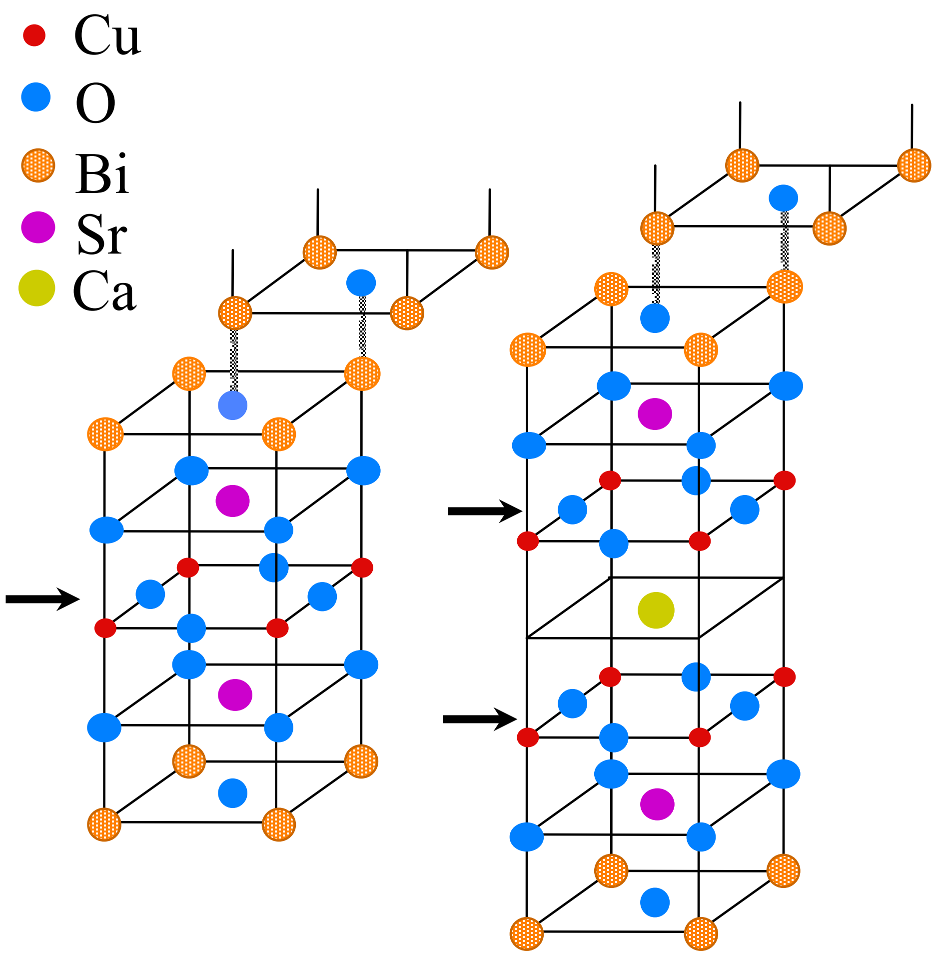


K.M. Shen *et al.*, Science **307**, 901 (2005)

High-Temperature Superconductors



Bilayer Splitting in $Bi_2Sr_2CaCu_2O_{8+\delta}$

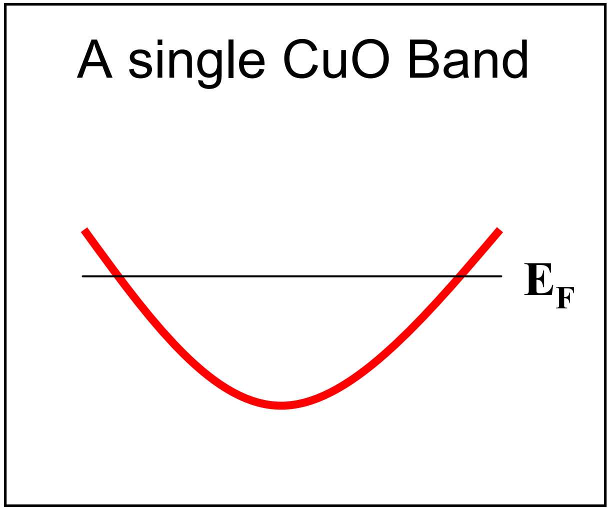


$Bi_2Sr_2Cu_1O_{6+\delta}$

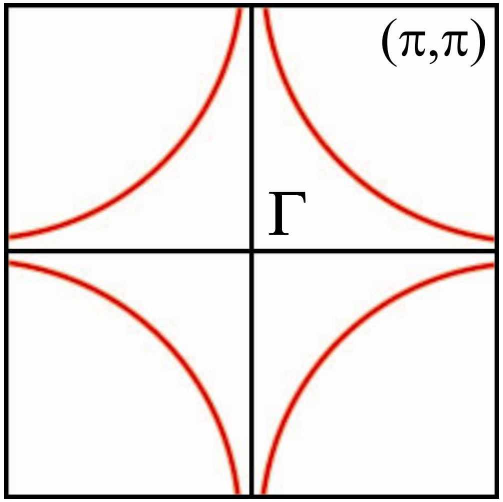
Bi2201

$Bi_2Sr_2Ca_1Cu_2O_{8+\delta}$

Bi2212

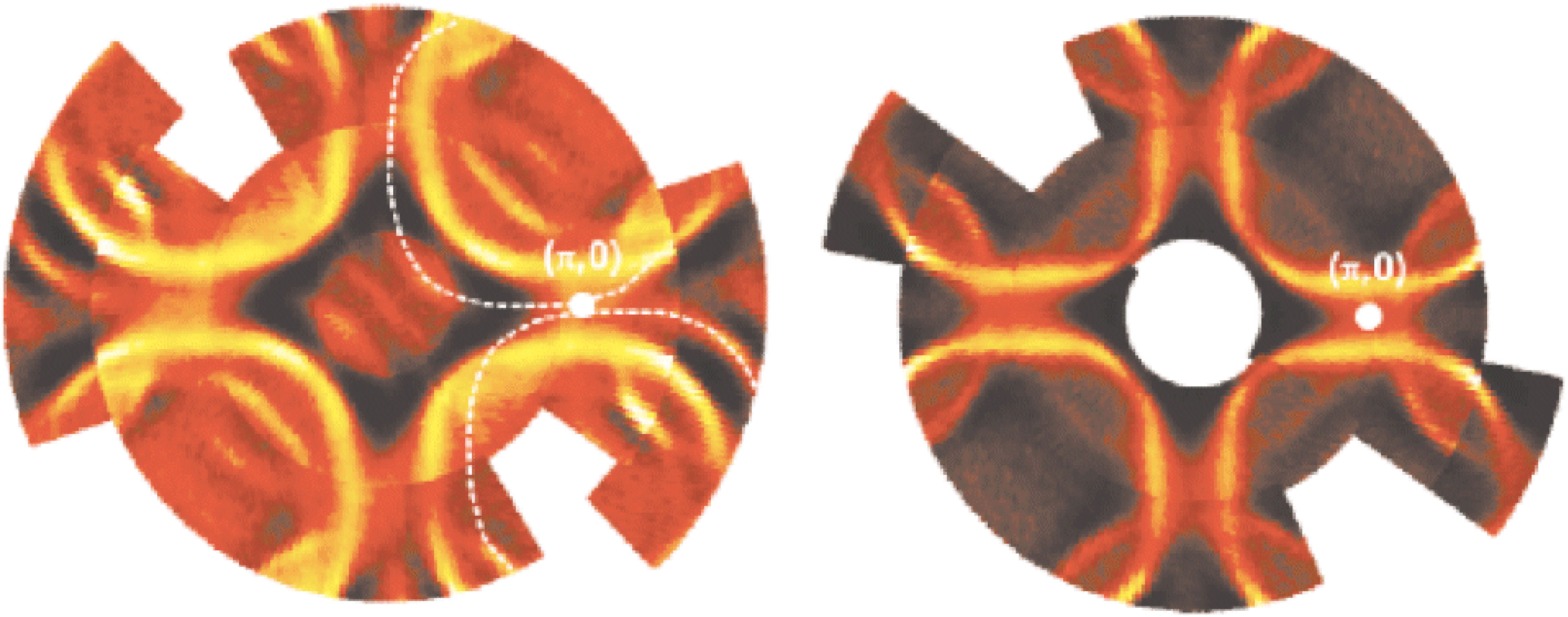


One FS Sheet



A. I. Liechtenstein *et al.*, PRB **54**, 12505 (1996)

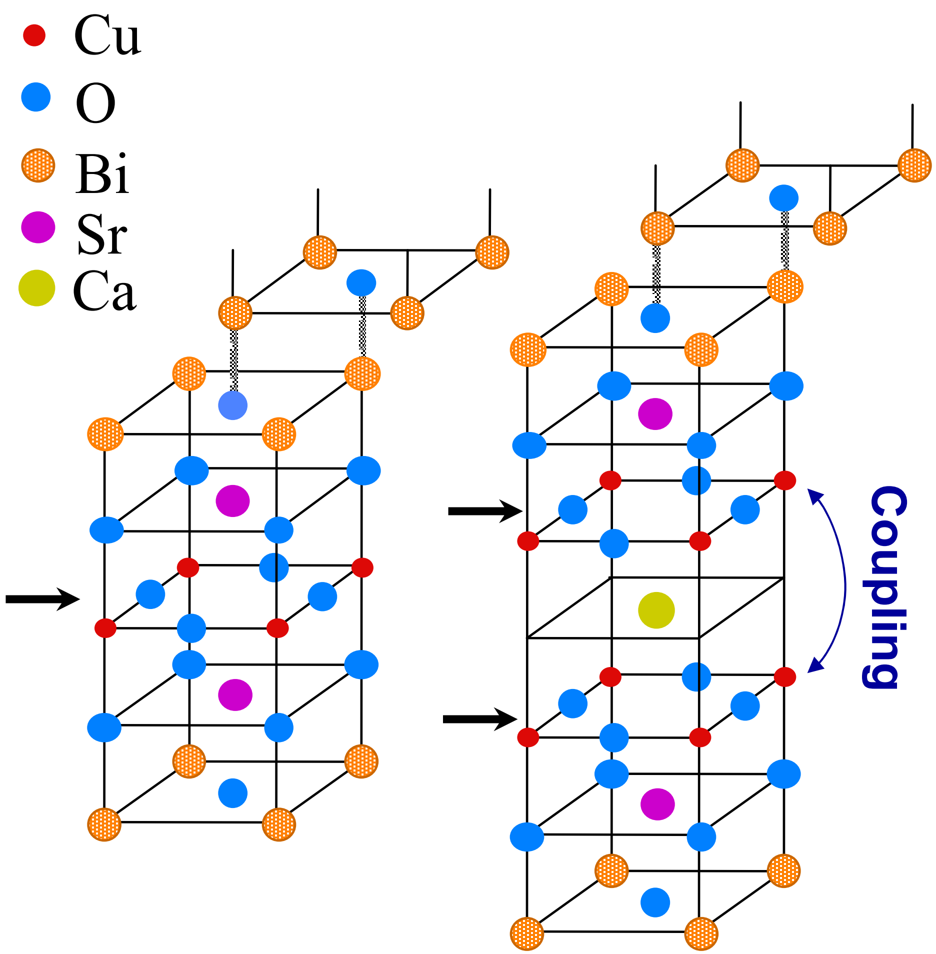
Bilayer Splitting in Pb-$Bi_2Sr_2CaCu_2O_{8+\delta}$



Pristine Bi2212 Pb-doped Bi2212

A.A. Kordyuk, M.S. Golden, et al., PRL 89, 077003 (2002)

Bilayer Splitting in $Bi_2Sr_2CaCu_2O_{8+\delta}$

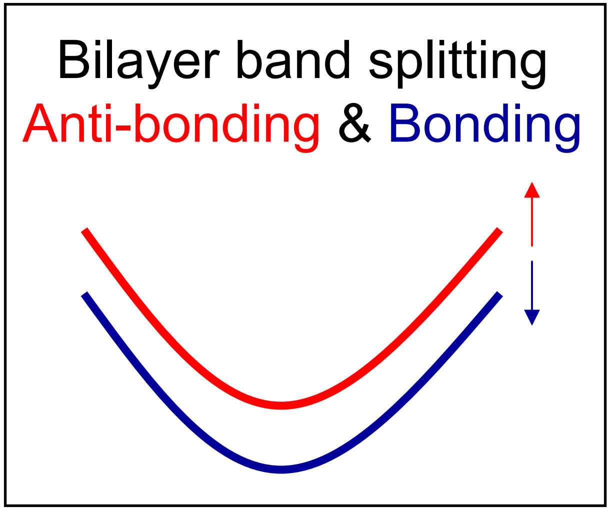


$Bi_2Sr_2Cu_1O_{6+\delta}$

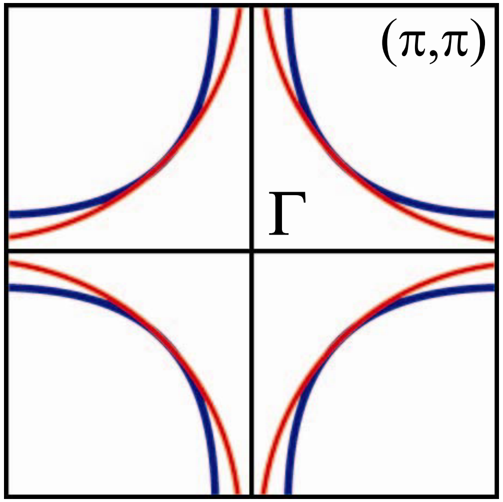
Bi2201

$Bi_2Sr_2Ca_1Cu_2O_{8+\delta}$

Bi2212



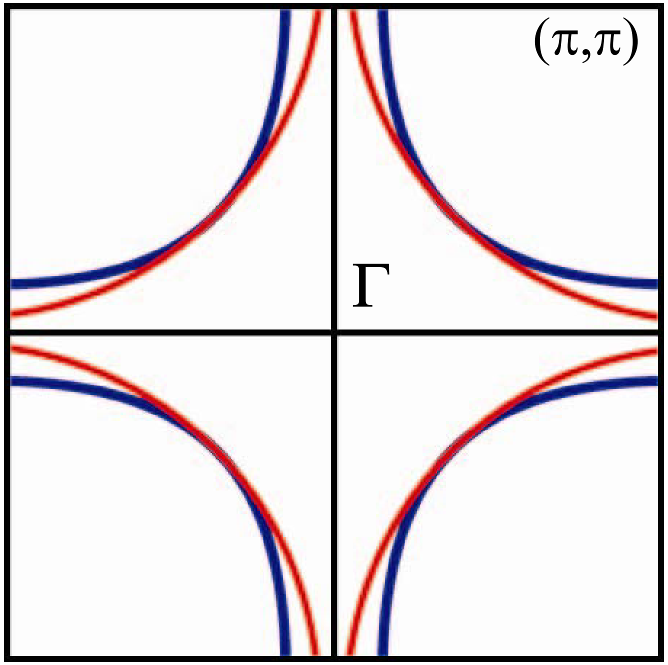
Two FS Sheets



A. I. Liechtenstein *et al.*, PRB **54**, 12505 (1996)

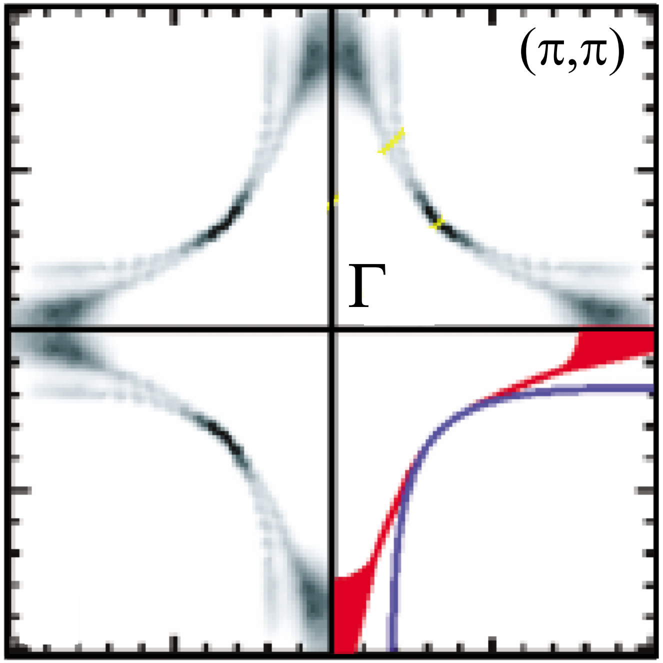
Bilayer Splitting in Pb-$Bi_2Sr_2CaCu_2O_{8+\delta}$

FS with bilayer splitting



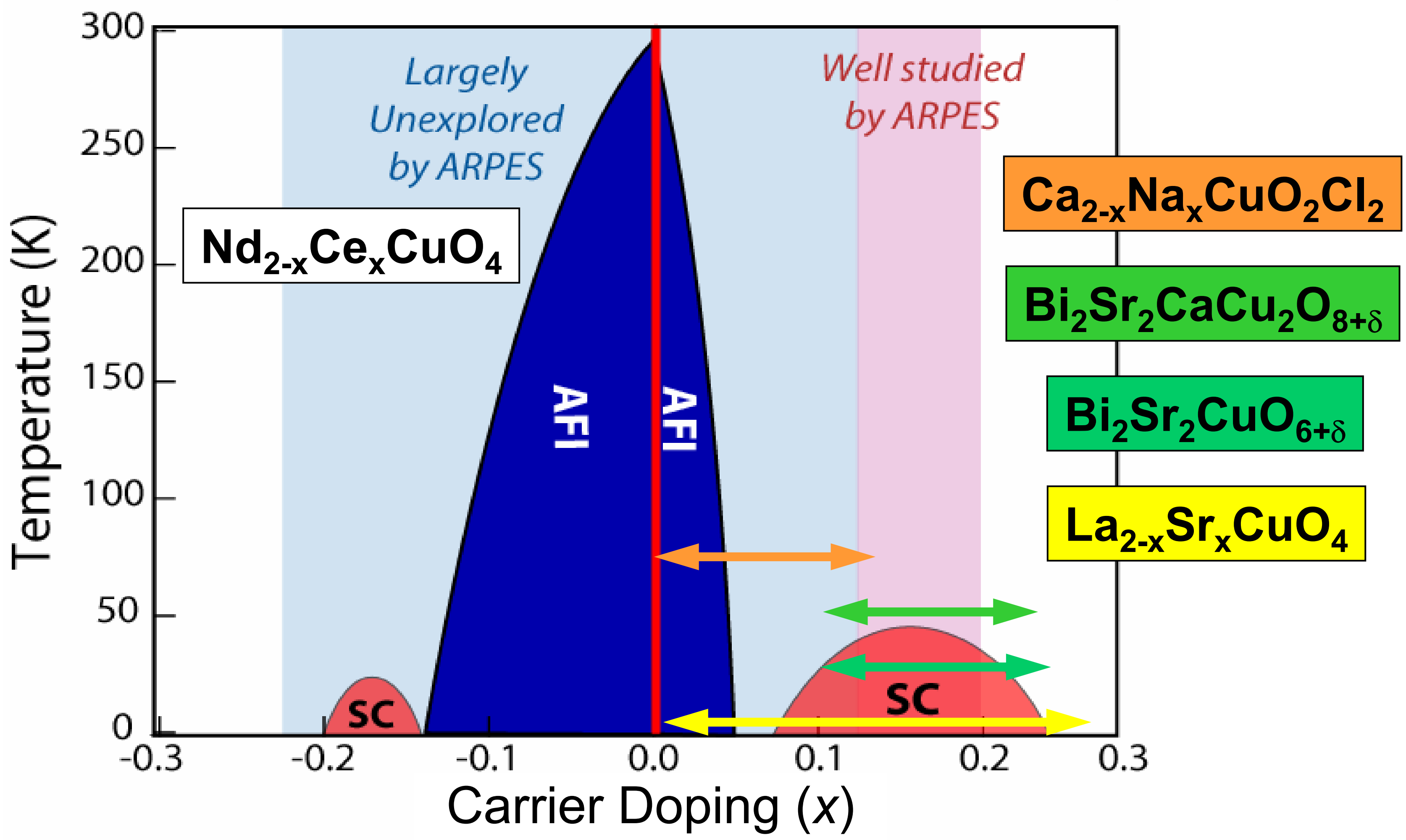
A. I. Liechtenstein *et al*., PRB **54**, 12505 (1996)

Overdoped Bi2212
Normal state



P.V. Bogdanov *et al.*, PRL **89**, 167002 (2002)

High-Temperature Superconductors

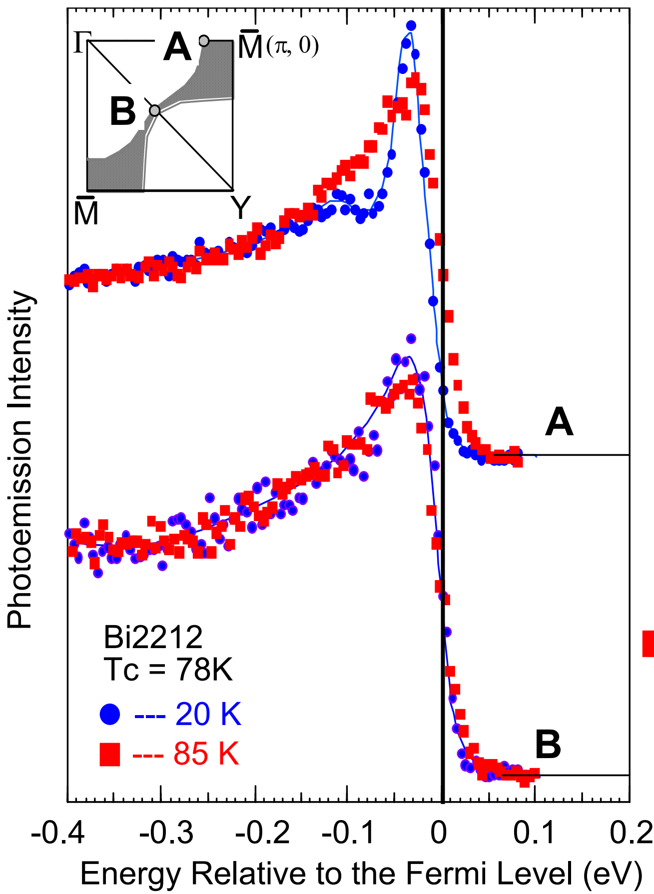


High-Temperature Superconductors: Bi2212

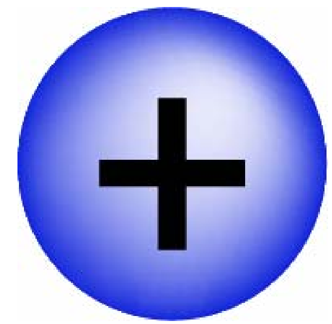
VOLUME 70, NUMBER 10 PHYSICAL REVIEW LETTERS 8 MARCH 1993

Anomalously Large Gap Anisotropy in the *a-b* Plane of $Bi_2Sr_2CaCu_2O_{8+\delta}$

Z.-X. Shen,[1,2] D. S. Dessau,[1,2] B. O. Wells,[1,2,a] D. M. King,[2] W. E. Spicer,[2] A. J. Arko,[3] D. Marshall,[2] L. W. Lombardo,[1] A. Kapitulnik,[1] P. Dickinson,[1] S. Doniach,[1] J. DiCarlo,[1,2] A. G. Loeser,[1,2] and C. H. Park[1,2]



"*s*-wave"



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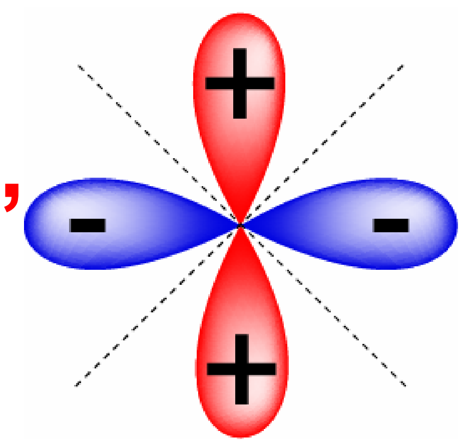
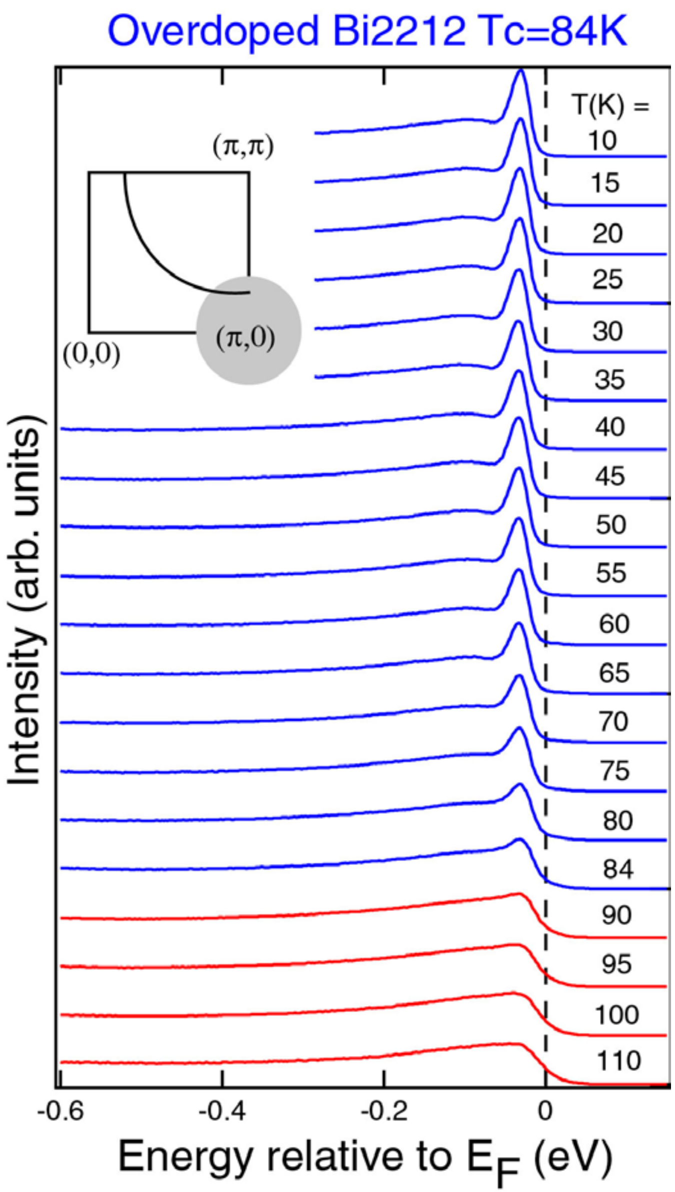
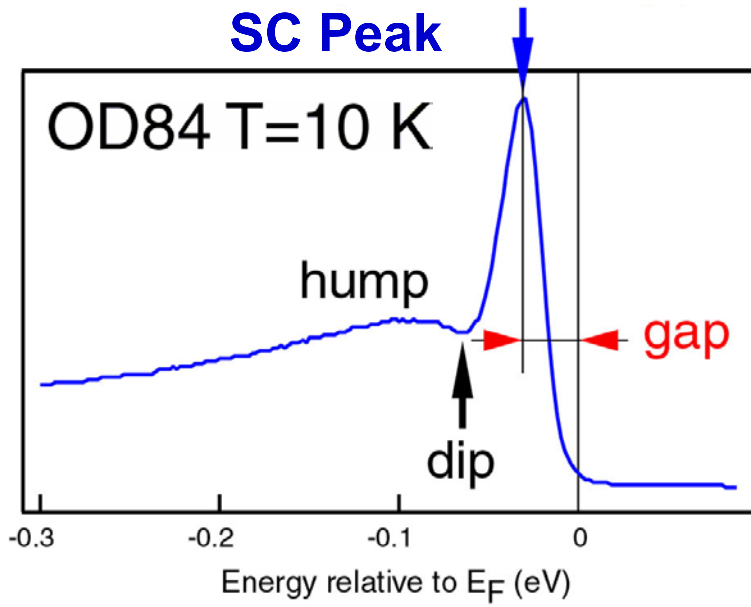


SC signatures from ARPES on $Bi_2Sr_2CaCu_2O_{8+\delta}$





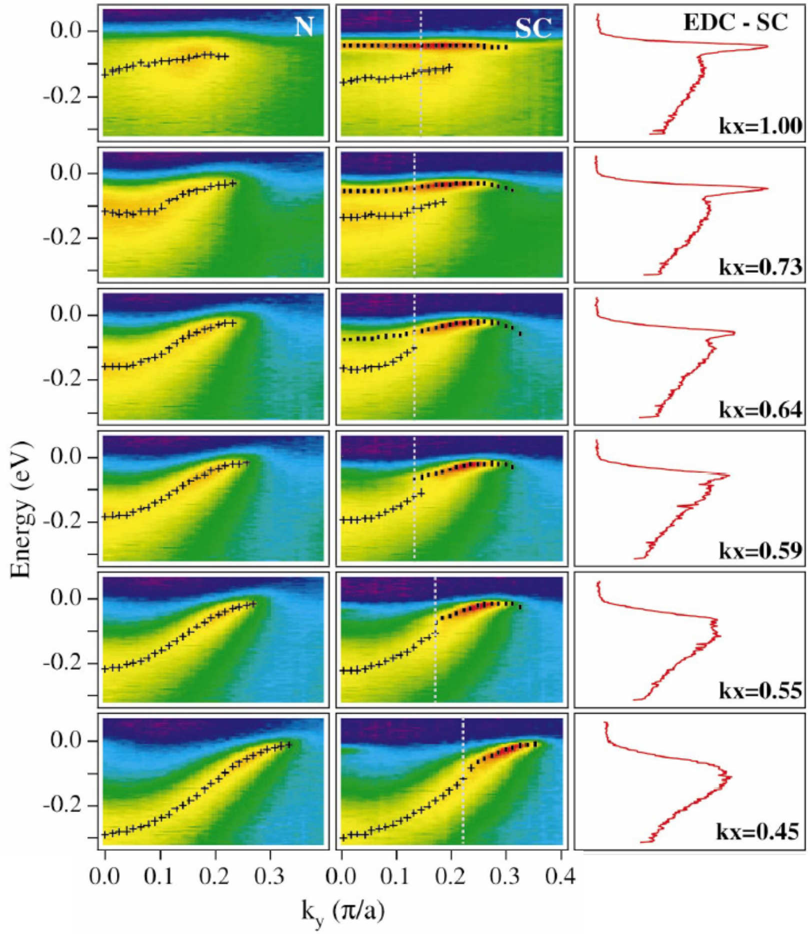
Pairing

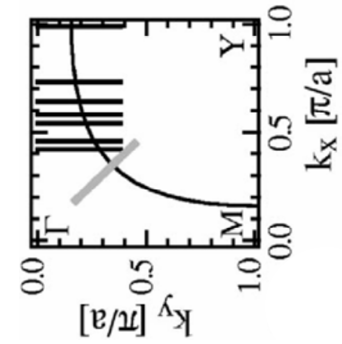
d-wave SC Gap

Phase coherence

Feng *et al.*, Science **289**, 277 (2000)

Many Body effects in the Quasiparticle Dispersion



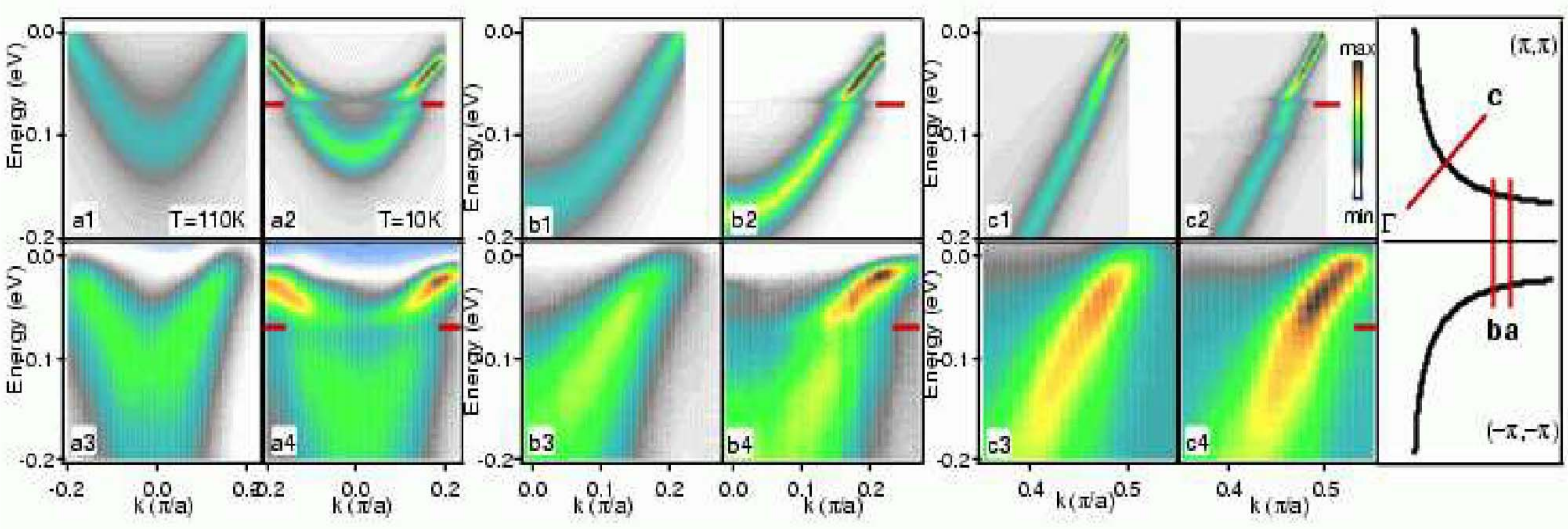


Kaminski et al.,
PRL 86, 1070 (2001)

Mechanism for High-T_C { **Magnetic fluctuations ?** / **Electron-phonon coupling ?**

Many Body effects in the Quasiparticle Dispersion

Cuk, Devereaux, Shen, et al., PRL (2004)



Mechanism for High-T_C { **Magnetic fluctuations ?** / **Electron-phonon coupling ?**

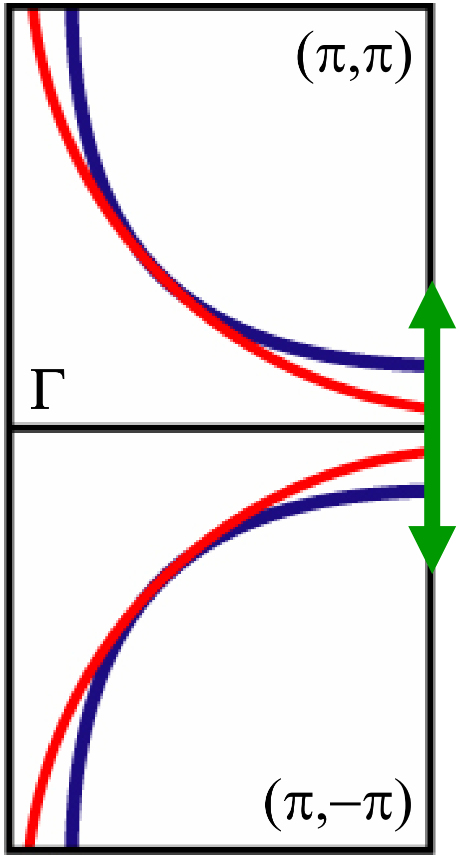
Bilayer Splitting in $Bi_2Sr_2CaCu_2O_{8+\delta}$

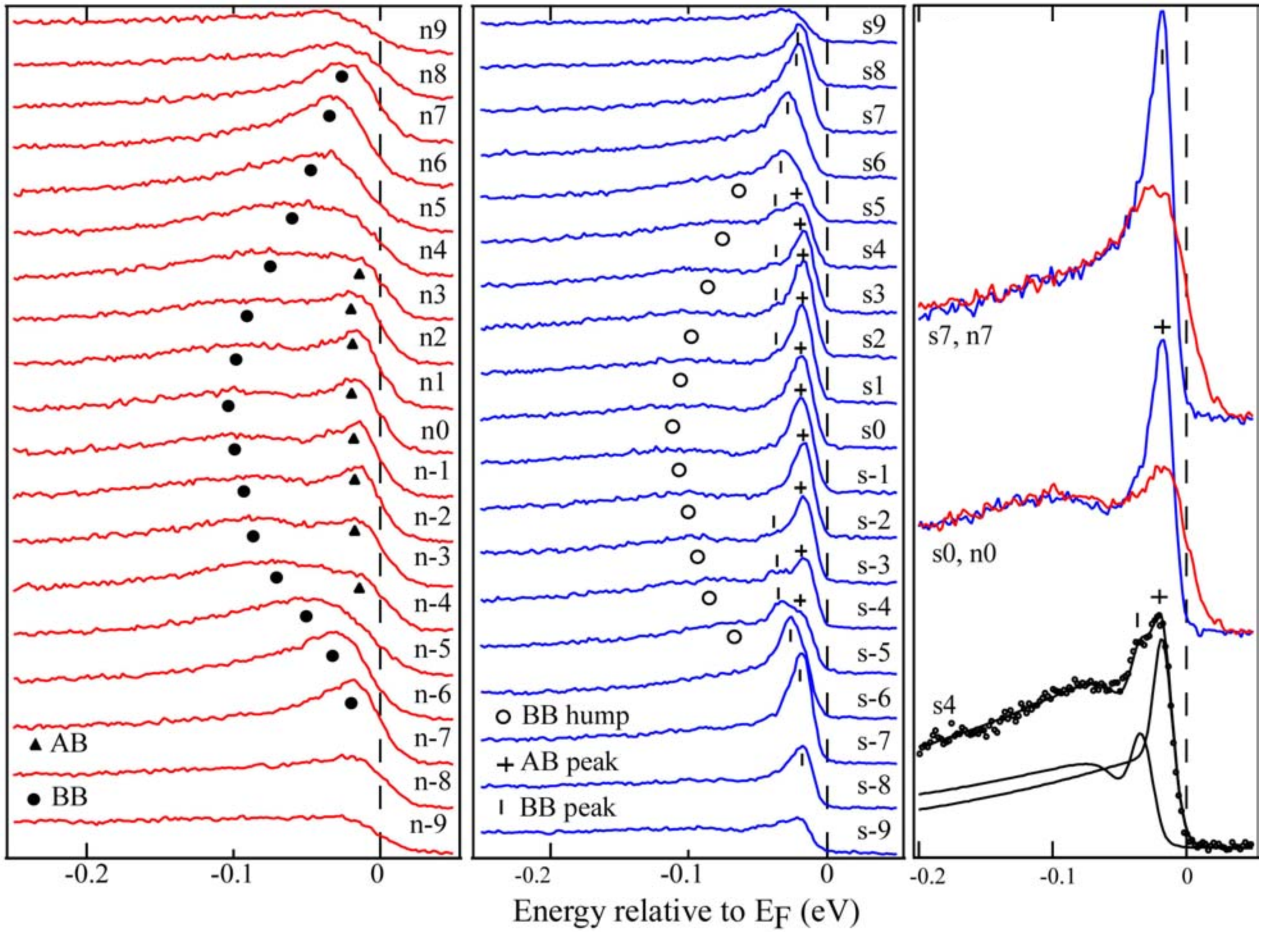
Bilayer Split Fermi Surface

Normal State T=90K

SC State T=10K

Normal & SC State Data





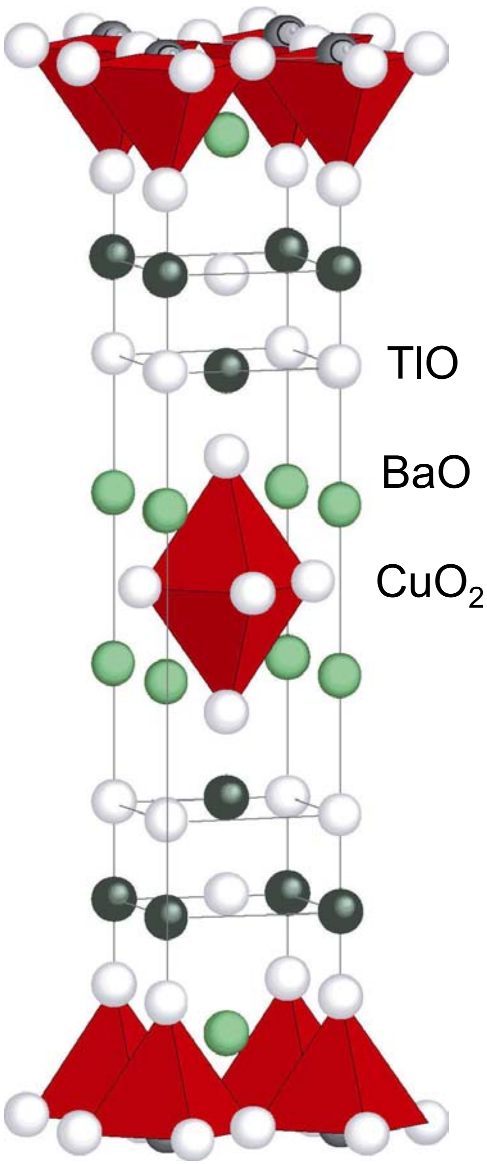
Feng, Damascelli *et al.*, PRL **86**, 5550 (2001)

Why $Tl_2Ba_2CuO_{6+\delta}$?

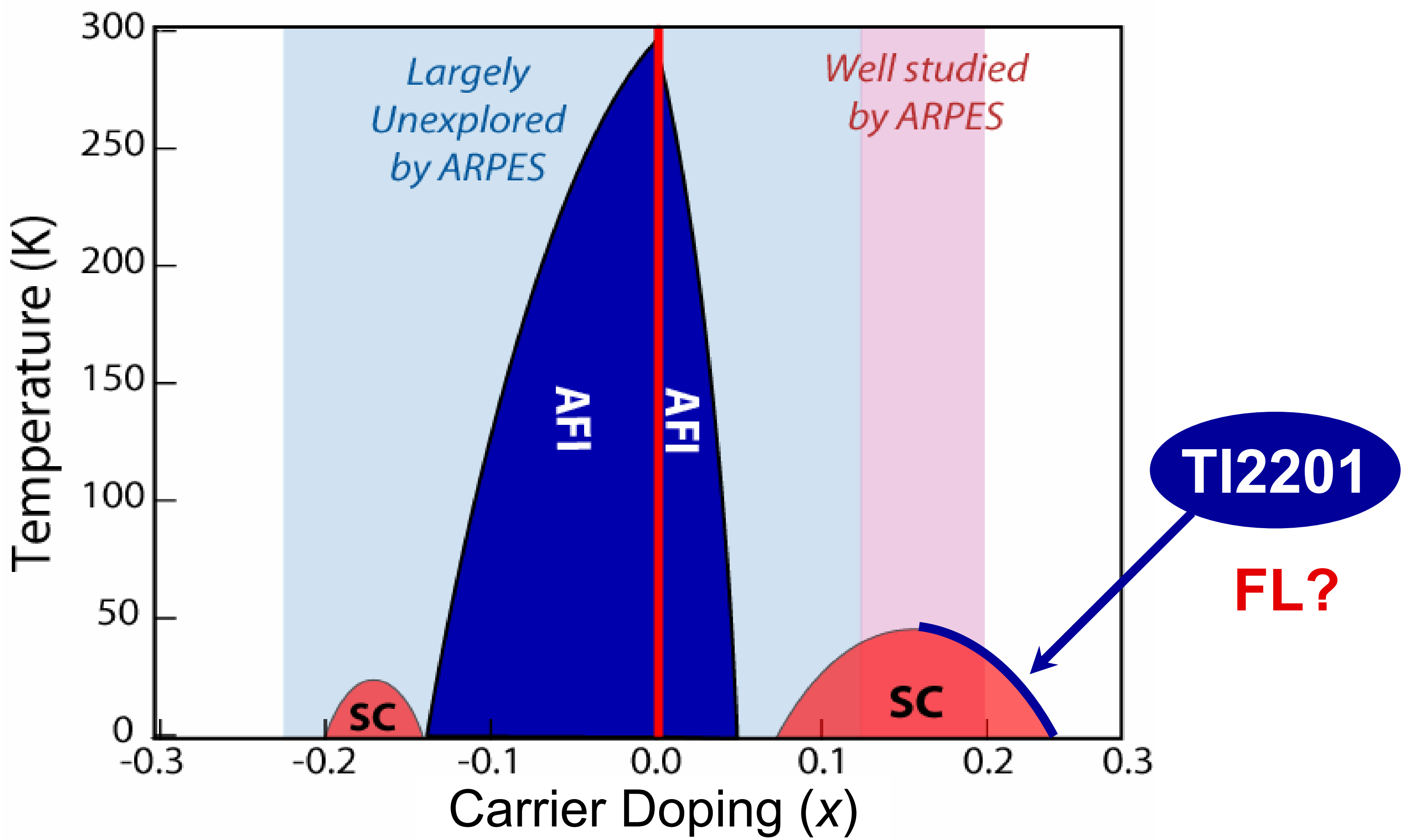
$Tl_2Ba_2CuO_{6+\delta}$: **ideal HTSC material**

- Single CuO_2 plane material
- Very high transition: T_c(opt)=93K
- No additional CuO chains
- No structural distortions
- Low cation disorder (T/O structure)

- $d_{x^2-y^2}$ SC gap (Tsuei et al., Nature 1997)
- (π,π) resonant mode (He et al., Science 2002)
- FS from AMRO (Hussey et al., Nature 2003)



ARPES on $Tl_2Ba_2CuO_{6+\delta}$



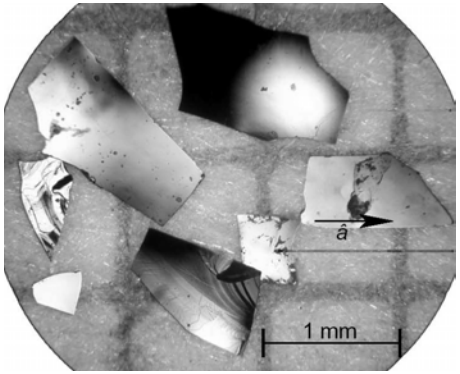
Paring mechanism? **Quantum criticality?**

Orthorhombic $Tl_2Ba_2CuO_{6+\delta}$

- **High-quality single crystals:**

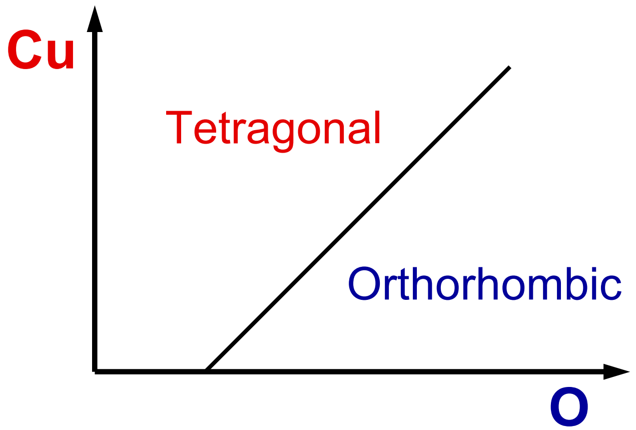
Orthorhombic Tl2201 grown by self-flux method

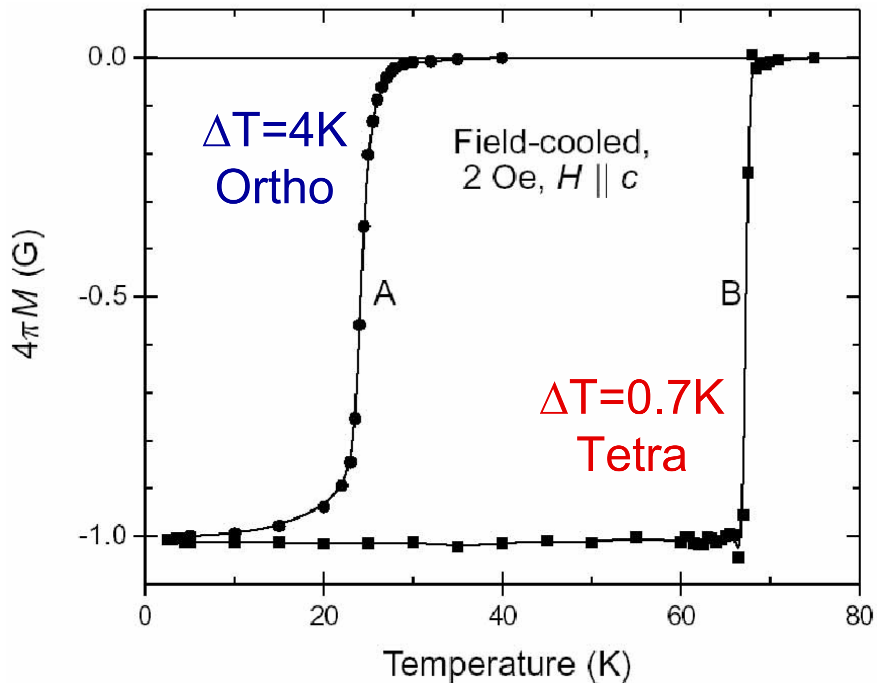
D. Peets, Ruixing Liang, D.A. Bonn, W.N. Hardy



Tetragonal (a=3.865Å; c=23.247Å)

Orthorhombic (a=5.458Å; b=5.485; c=23.201Å)





Ortho as-grown $Tl_{1.88}Ba_2Cu_{1.11}O_{6+\delta}$

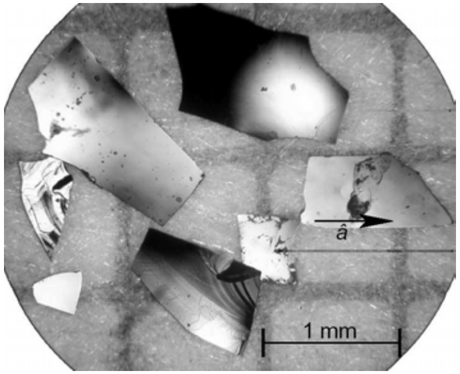
Peets et al., cond-mat/0211028

Orthorhombic $Tl_2Ba_2CuO_{6+\delta}$

- **High-quality single crystals:**

Orthorhombic Tl2201 grown by self-flux method

D. Peets, Ruixing Liang, D.A. Bonn, W.N. Hardy



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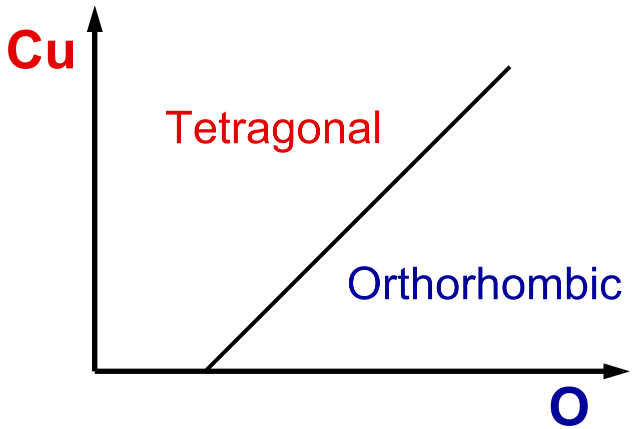
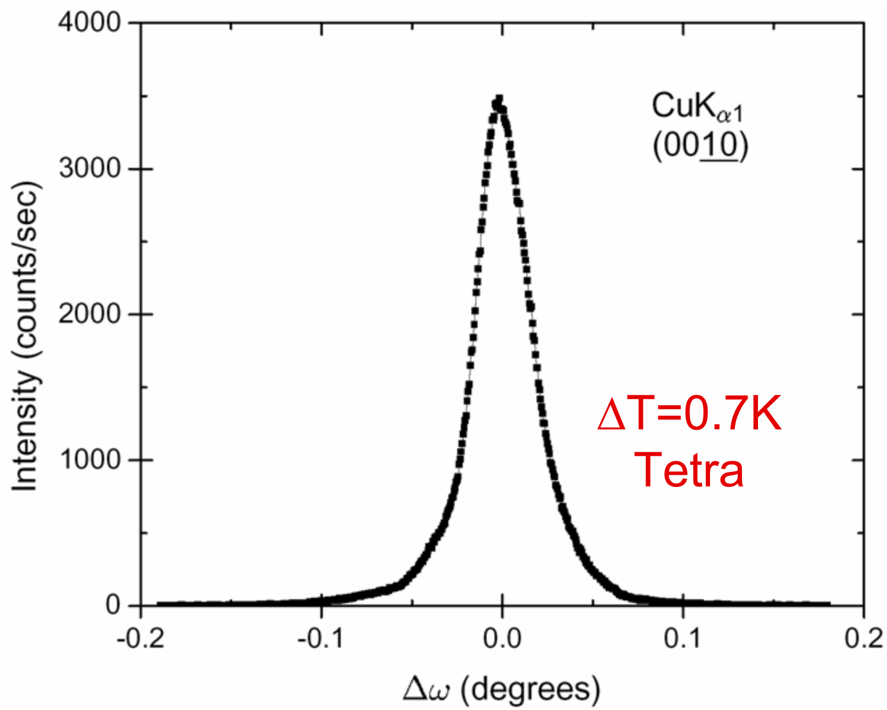




Ortho as-grown $Tl_{1.88}Ba_2Cu_{1.11}O_{6+\delta}$

Peets et al., cond-mat/0211028

Swiss Light Source – SIS Beamline

- **ARPES Experiments:**

  Surface and Interface Spectroscopy Beamline

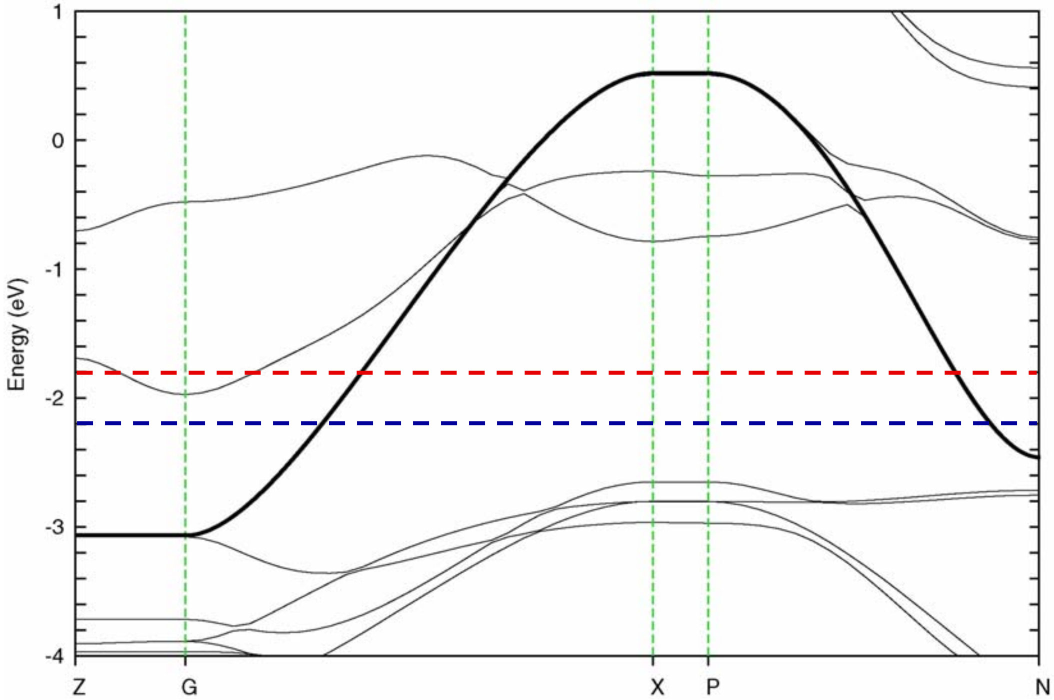
  S. Chiuzbaian, M. Falub, M. Shi, **L. Patthey**

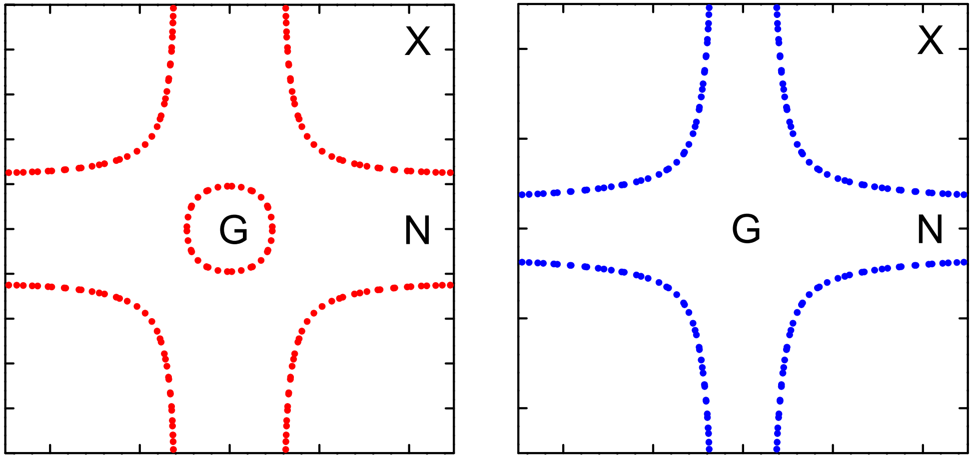
- **Twin Undulator**
- **Monochromator**

  Energy Range: 10-800 eV
  Polarization: circular/planar
- **ARPES**

  Detector: SES2002
  $E/\Delta E > 10^4$; $\Delta k = 0.3^o$
  Low T: 10-300K
  spot size: 20x20 μm^2
- **Spin resolved ARPES**

Tl2201: Low energy electronic structure





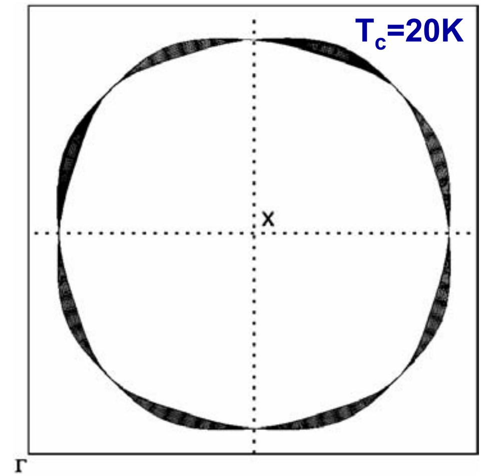
Elfimov (2004)

Tl^{3+}:Ba^{2+}:Cu^{2+}:O^{2-} in ratios 2:2:1:6

Charge Transfer Insulator

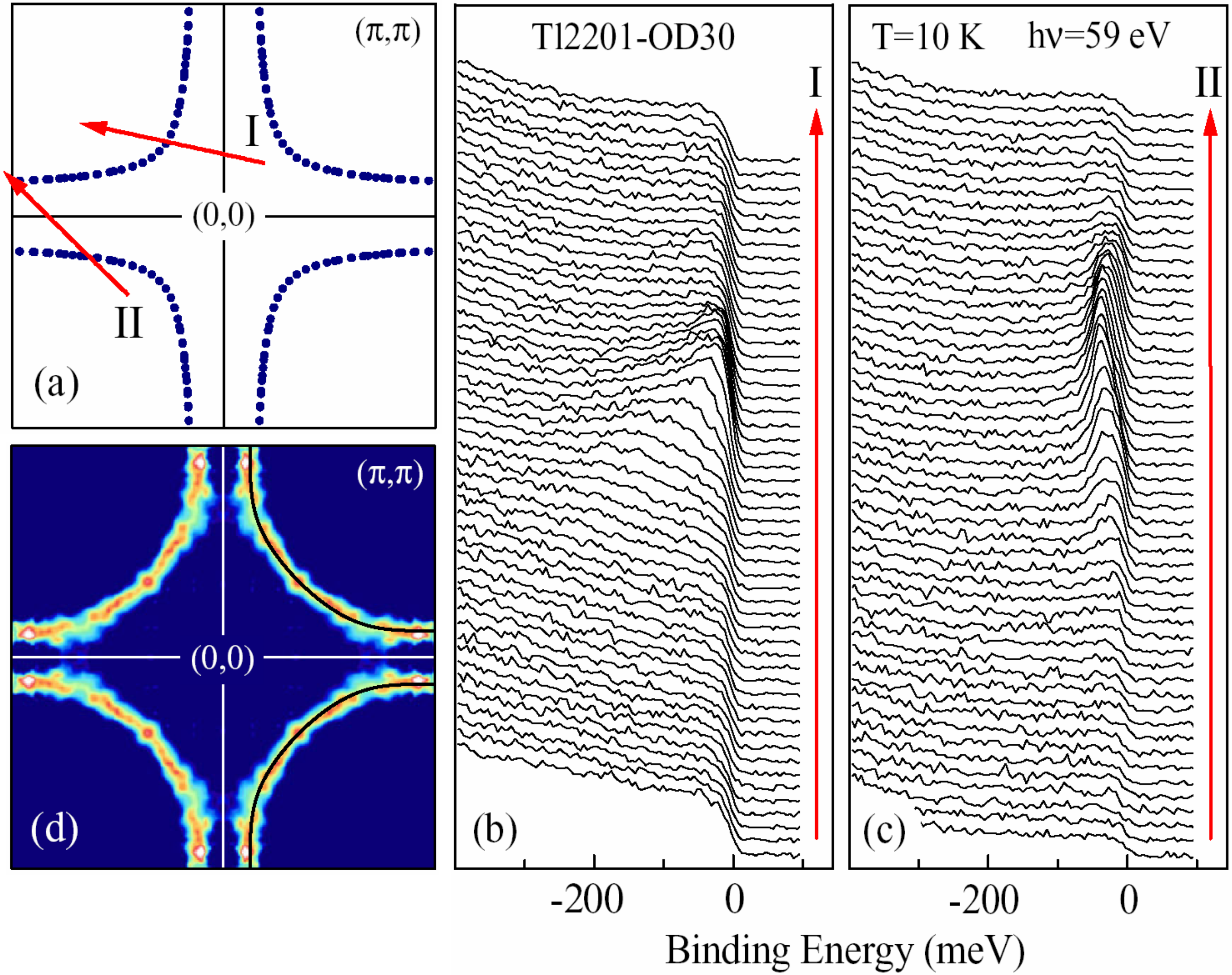
- Short Tl-O distance
  - ➡ CuO band not ½ filled
- Cu-Tl substitution
  - ➡ Additional hole-doping

Tl2201: Optimally Doped SC



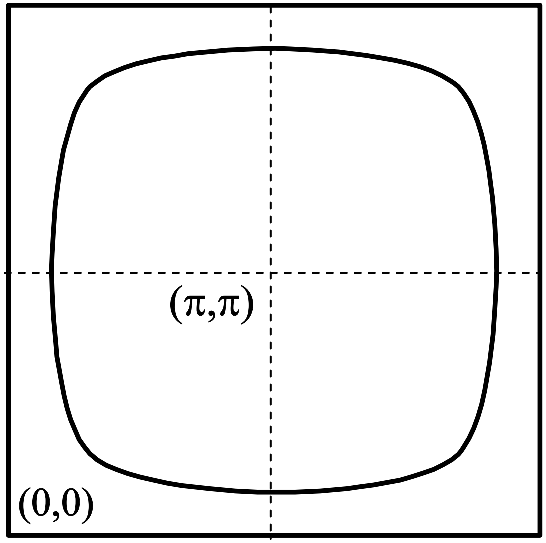
Hussey et al, Nature **425**, 814 (2004)

Tl2201 : ARPES Results

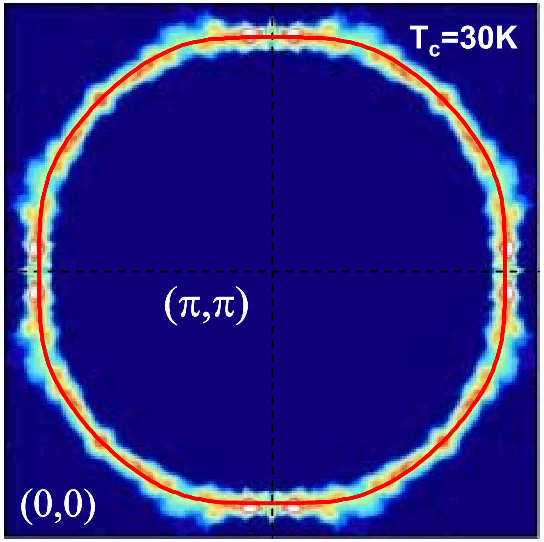


Tl2201 : Fermi Surface Volume

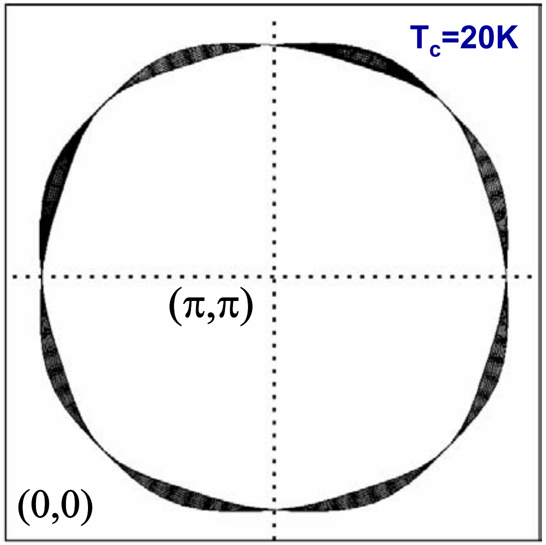
LDA



ARPES



AMRO



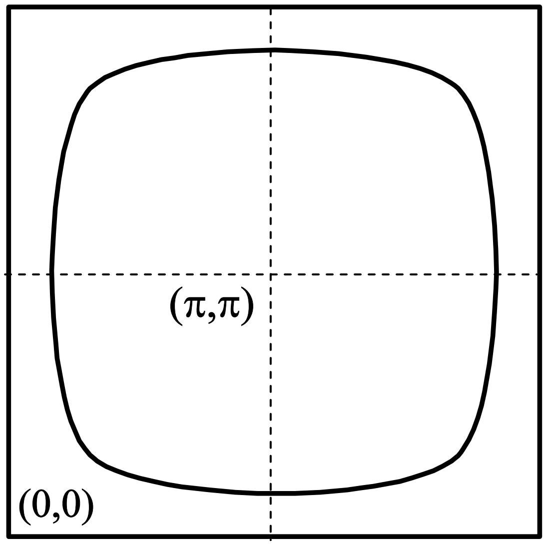
Hussey et al, Nature **425**, 814 (2004)

Hole FS volume

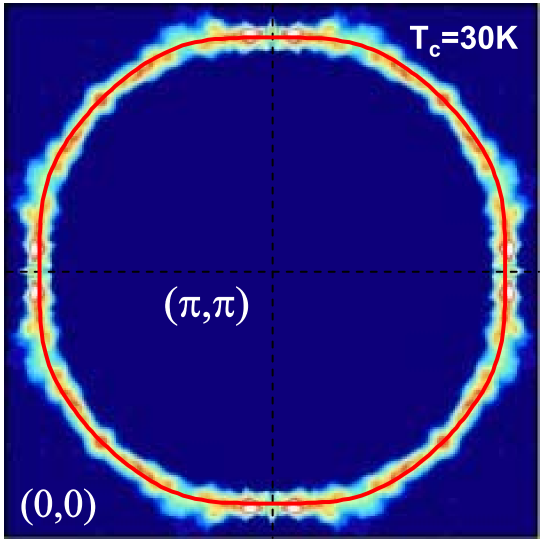
LDA	ARPES	AMRO
63%	63%	62%
p=0.26/Cu	p=0.26/Cu	p=0.24/Cu

Tl2201 : Fermi Surface Volume

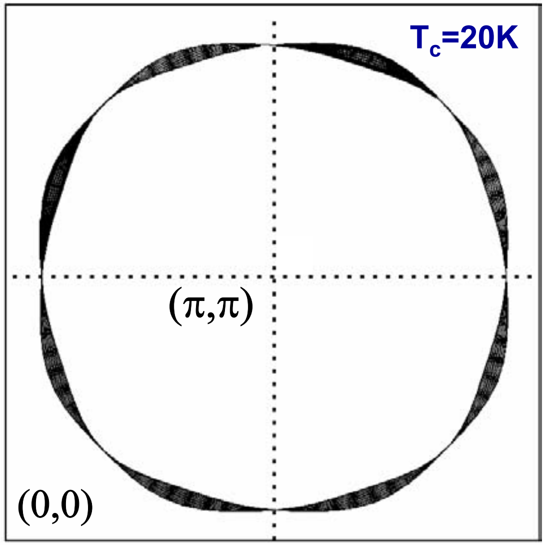
LDA



ARPES



AMRO

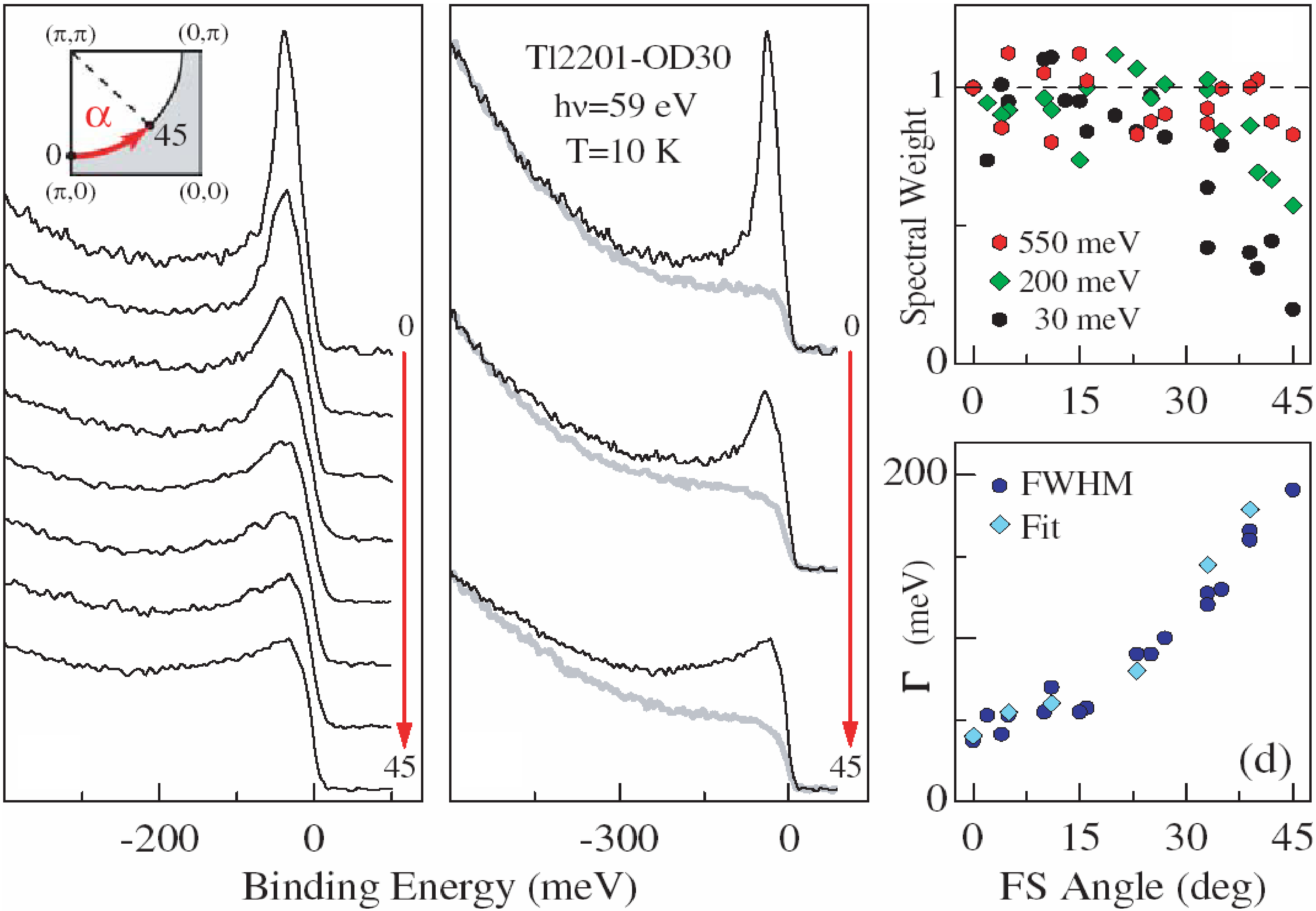


Hussey et al, Nature **425**, 814 (2004)

Tight binding FS fit

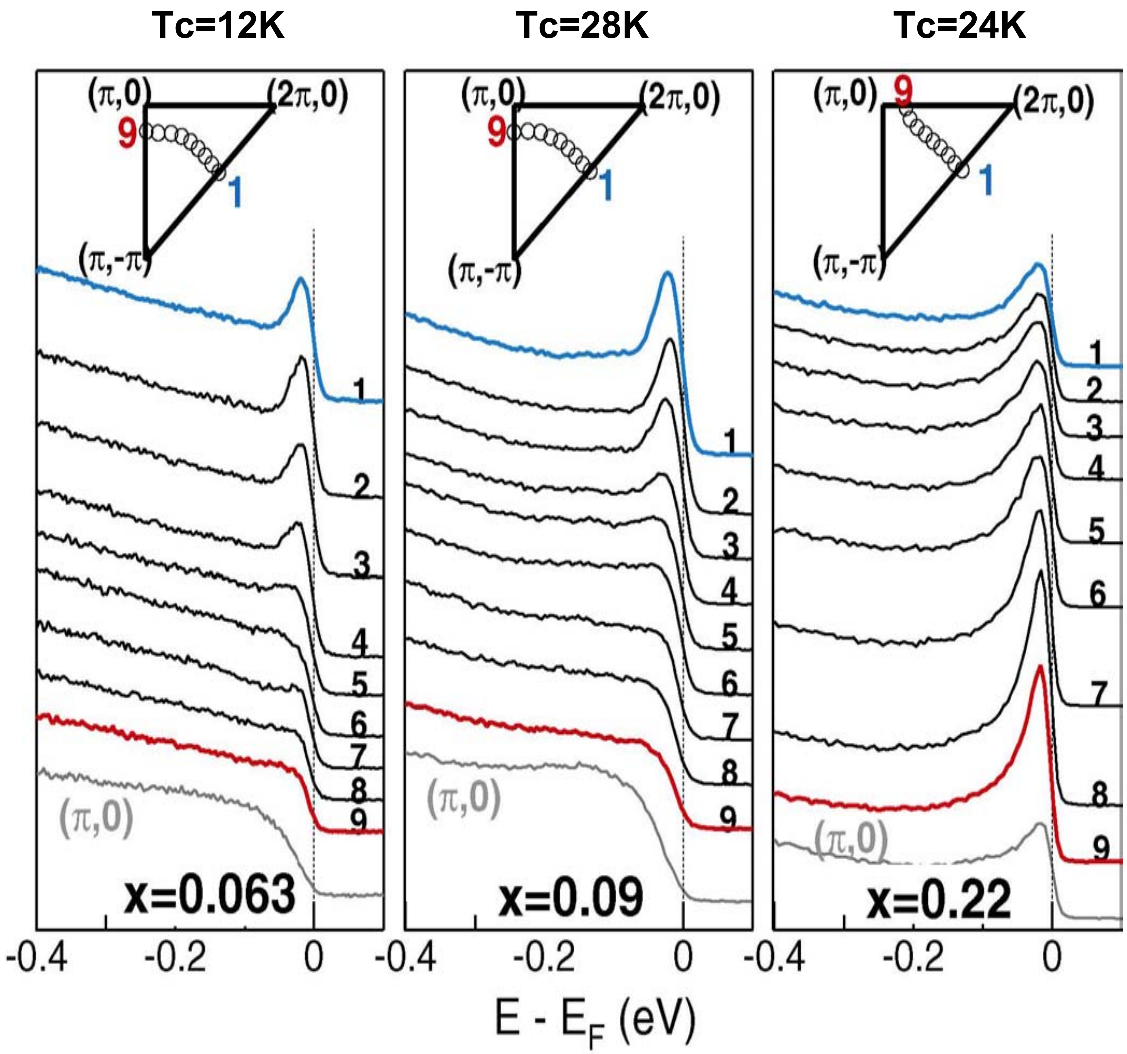
$$\epsilon_{\mathbf{k}} = \mu + \frac{t_1}{2}(\cos k_x + \cos k_y) + t_2 \cos k_x \cos k_y + \frac{t_3}{2}(\cos 2k_x + \cos 2k_y)$$
$$+ \frac{t_4}{2}(\cos 2k_x \cos k_y + \cos k_x \cos 2k_y) + t_5 \cos 2k_x \cos 2k_y$$

Tl2201: Lineshape evolution



$Tl_2Ba_2CuO_{6+\delta}$: Lineshape evolution

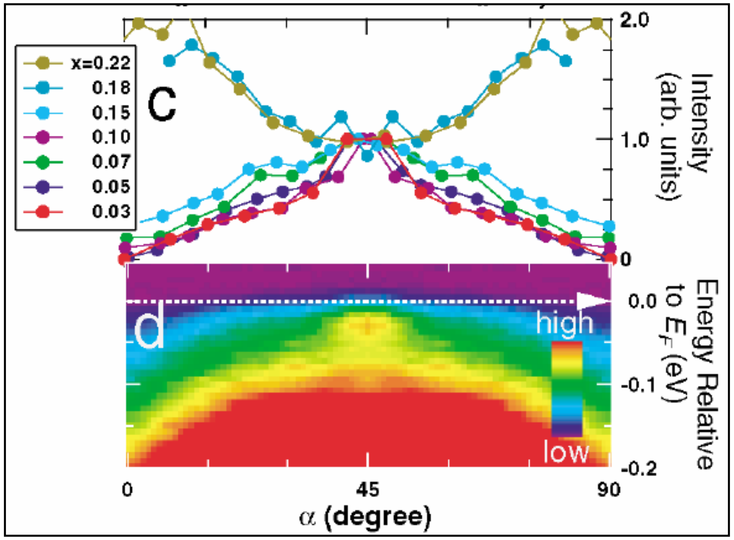
LSCO



X.J. Zhou et al., PRL **92**, 187001 (2004)

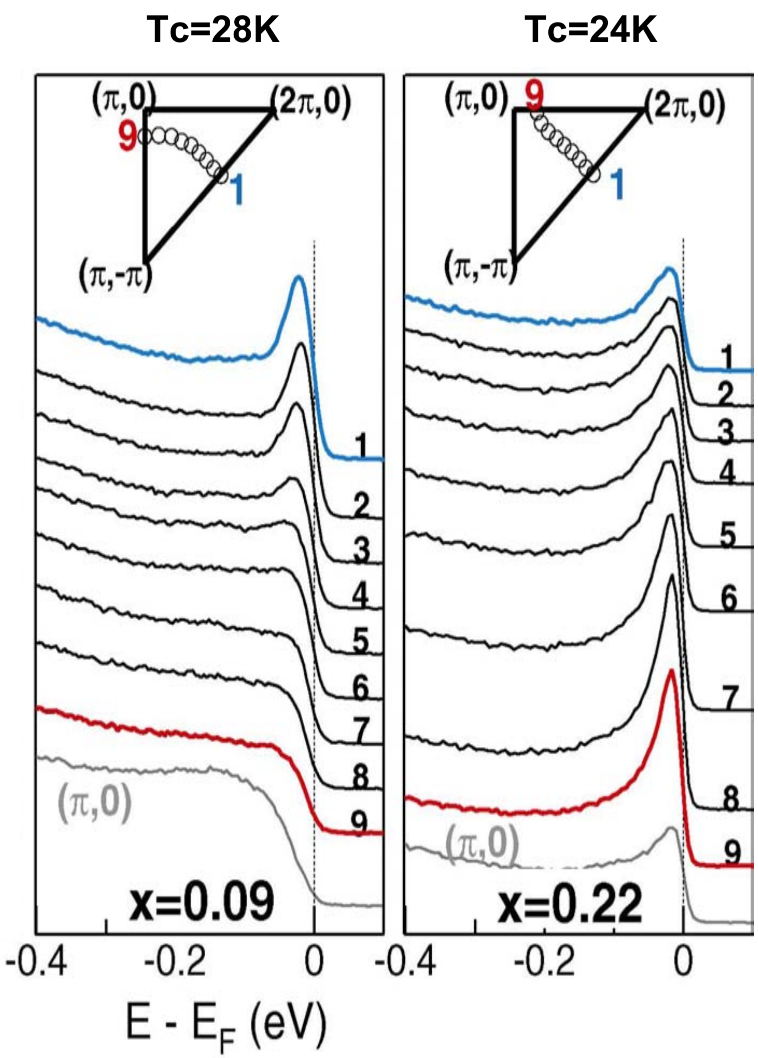
$Tl_2Ba_2CuO_{6+\delta}$: Lineshape evolution

Integrated Spectral Weight



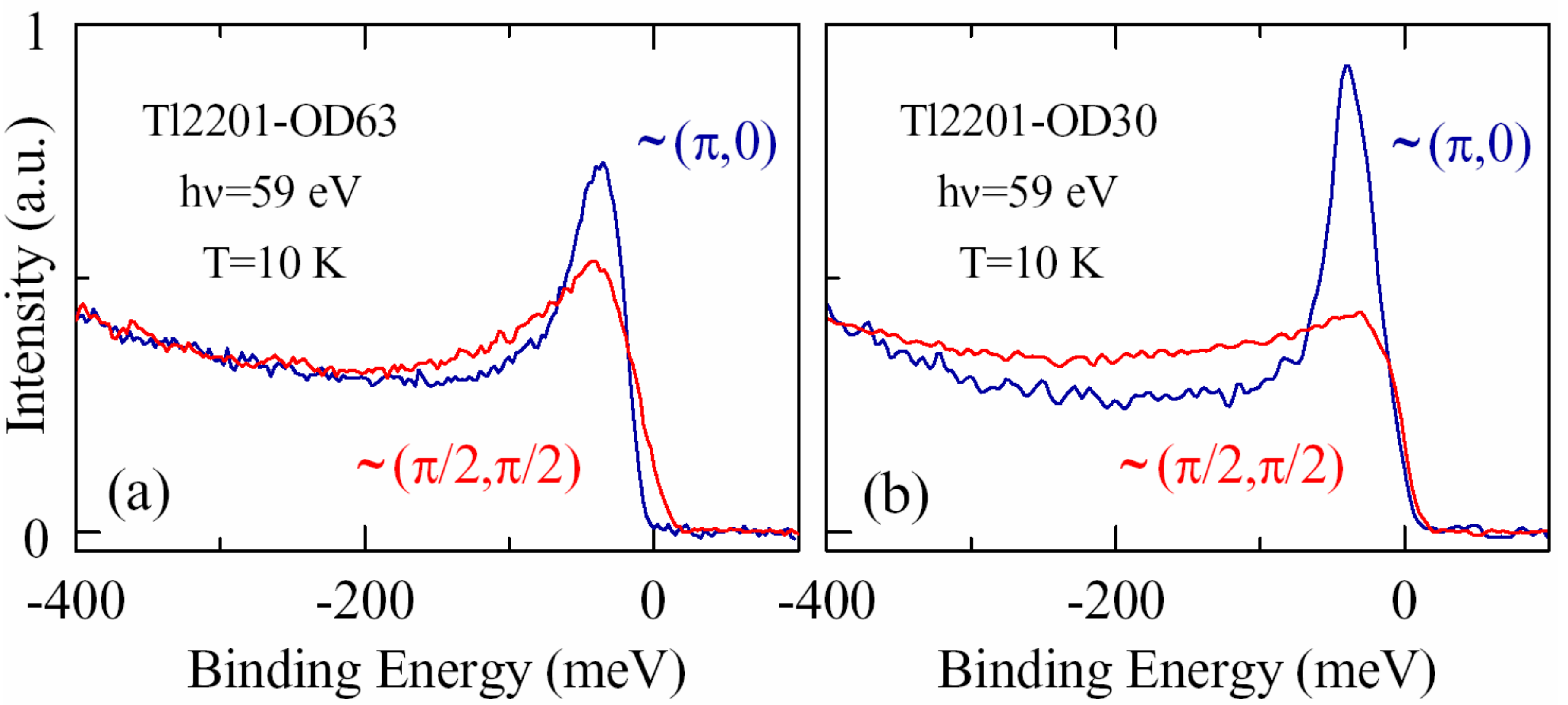
T. Yoshida et al., PRL **91**, 027001 (2003)

LSCO

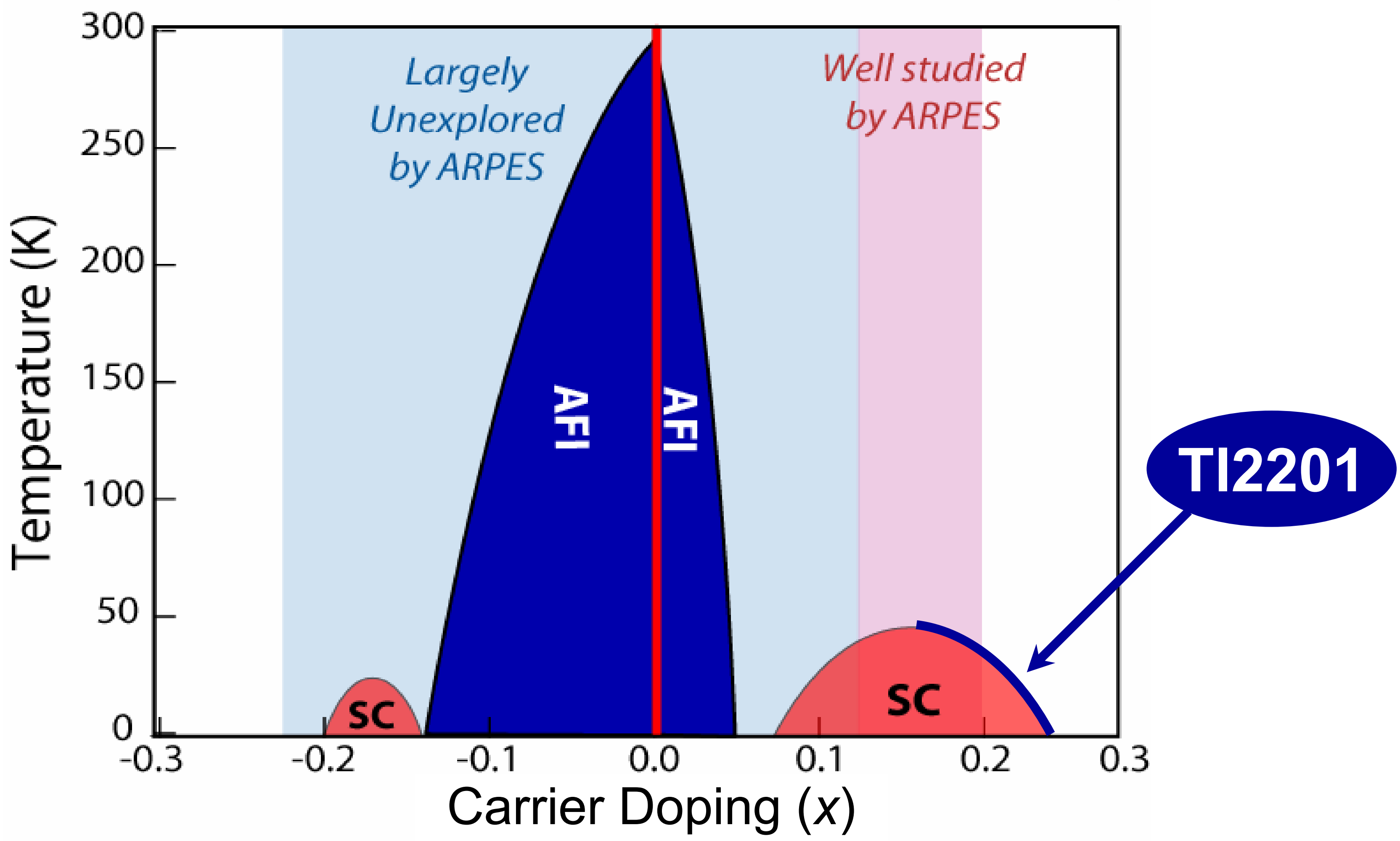


X.J. Zhou et al., PRL **92**, 187001 (2004)

$Tl_2Ba_2CuO_{6+\delta}$: ARPES Results

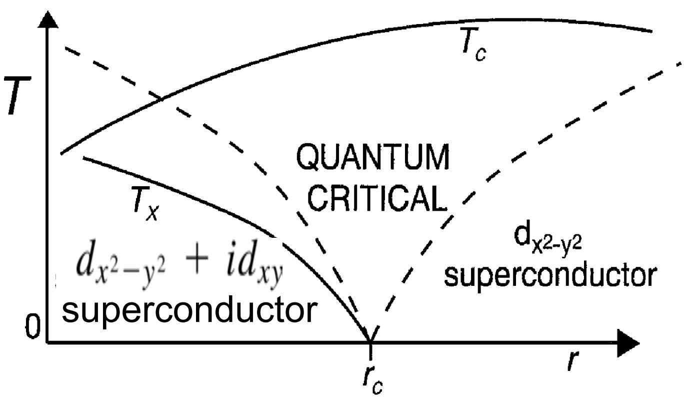


ARPES on $Tl_2Ba_2CuO_{6+\delta}$



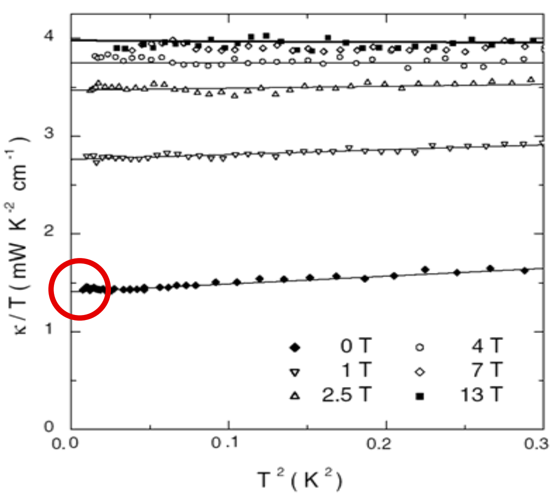
Paring mechanism? **Quantum criticality?**

Tl2201: SC gap symmetry

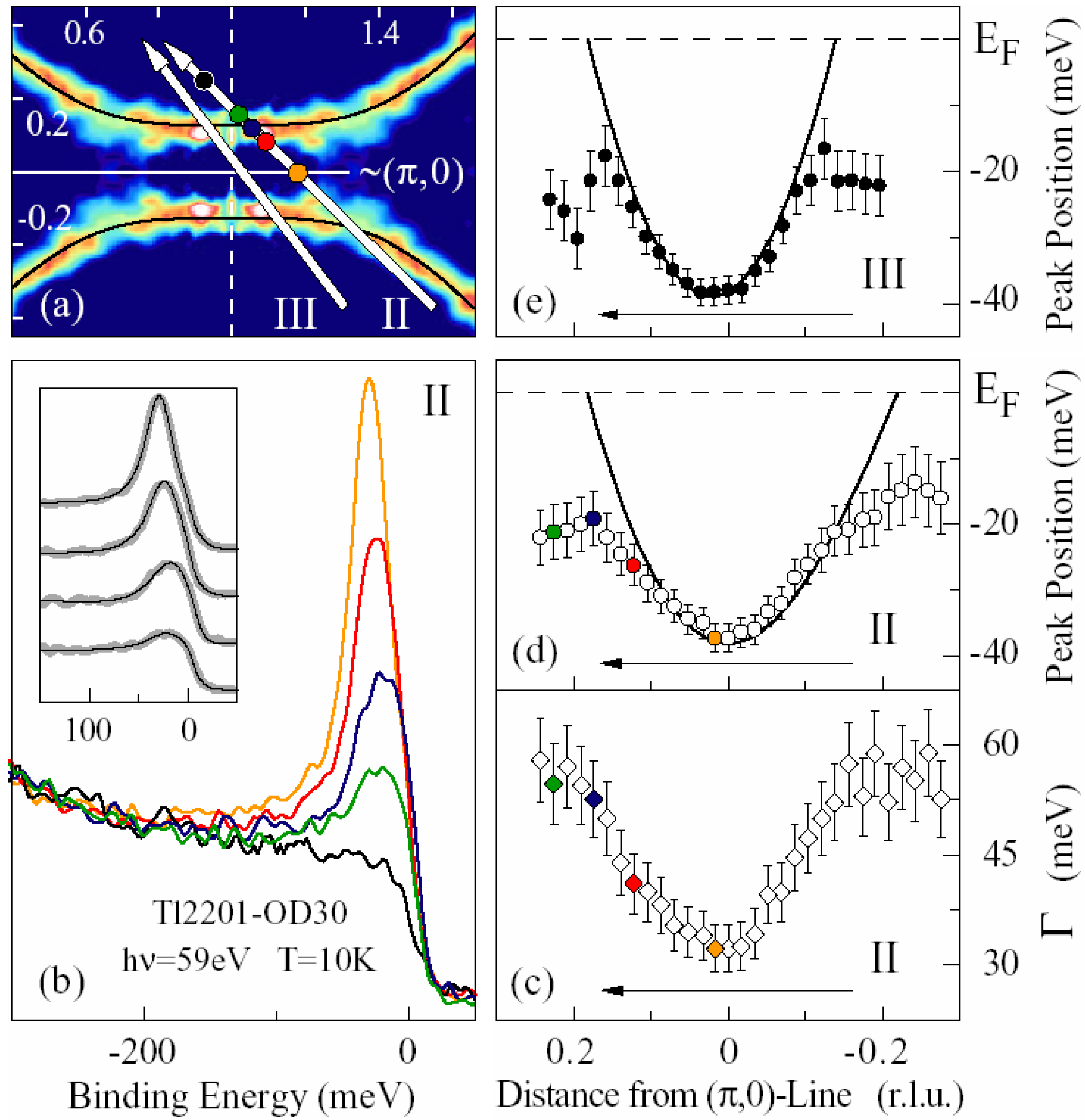


Vojta, Zhang, Sachdev, PRL 2000

Large residual linear term in heat conductivity



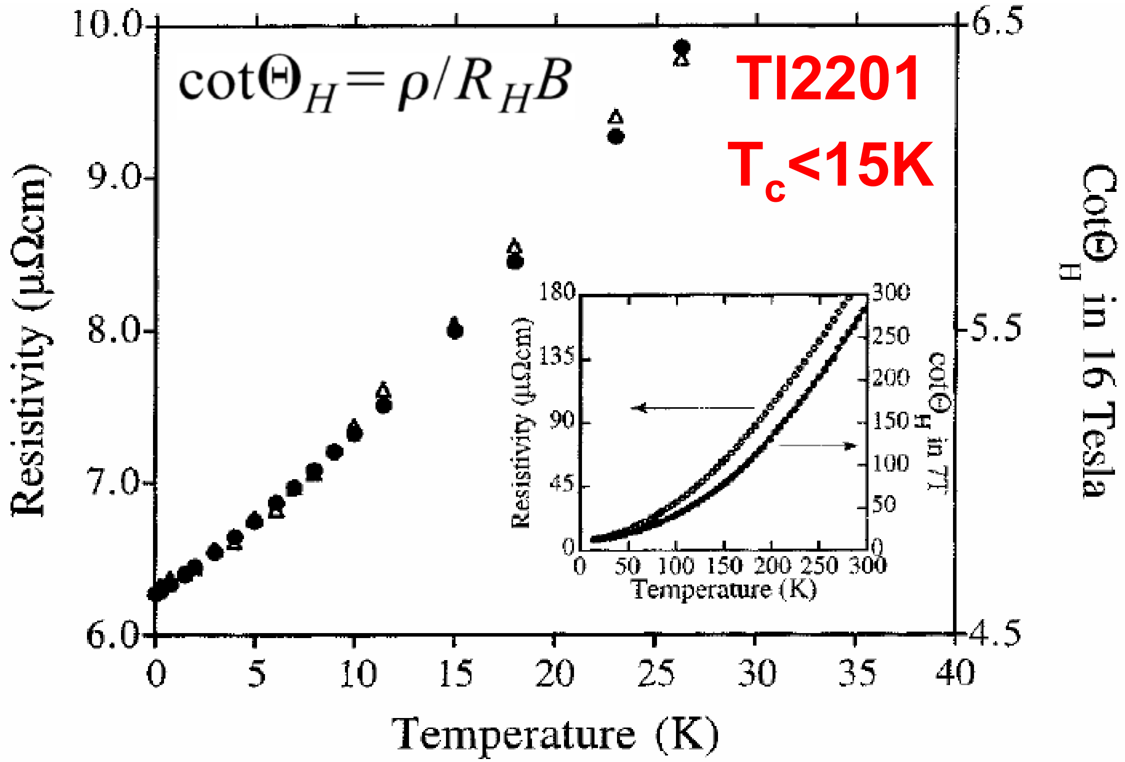
Proust et al., PRL 2002



Tl2201: Momentum Dependent Scattering?

Electronic scattering appears

isotropic in overdoped cuprates



A. Mackenzie *et al.*, PRB **53**, 5848 (1996)

Residual k_z-dispersion

Forward scattering

Tl2201: Small Angle Scattering?

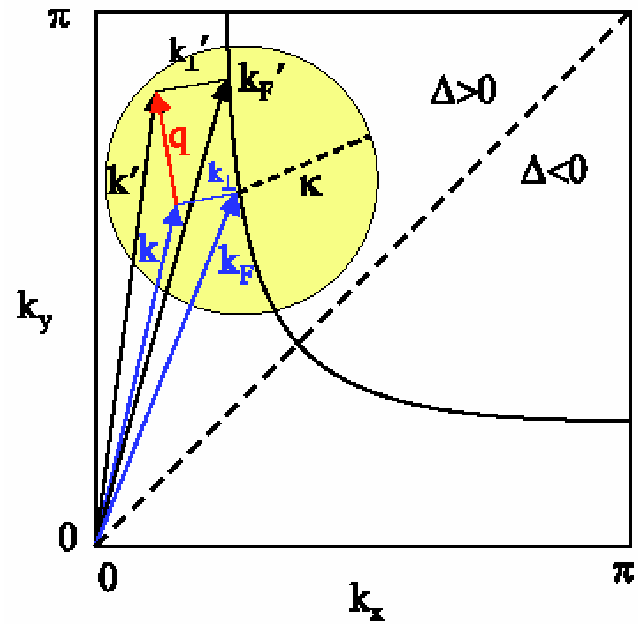
$$\boxed{\Sigma_{tot} = \Sigma_{el,f} + \Sigma_{\mathrm{el,u}} + \Sigma_{\mathrm{inel}}}$$

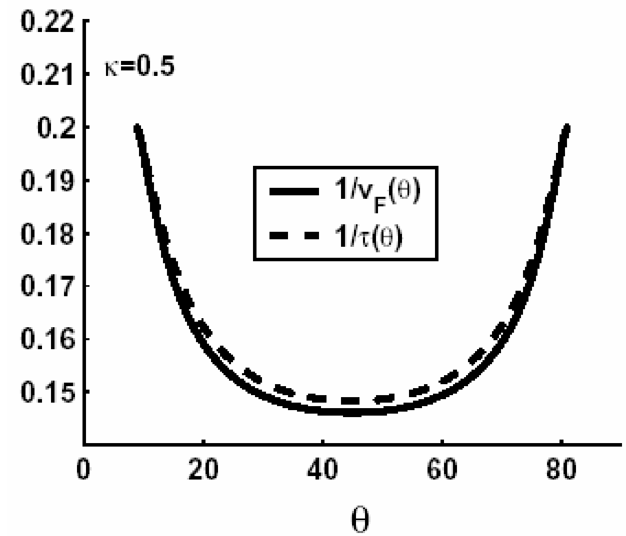
$$V(r) = V_0 e^{-\kappa r}$$

$$V_{\mathbf{k}\mathbf{k}'} = \frac{2\pi\kappa V_0}{((\mathbf{k}-\mathbf{k}')^2+\kappa^2)^{3/2}}$$

$$\Sigma(\mathbf{k},\omega) = n_I \sum_{k'} |V_{\mathbf{k}\mathbf{k}'}|^2 G^0(\mathbf{k}',\omega)$$

$$\boxed{-\Sigma''(\mathbf{k}_F,0) \equiv \Gamma_0(\mathbf{k}_F) = \frac{3\pi n_i V_0^2}{8|v_F(\mathbf{k}_F)|\kappa^3}}$$

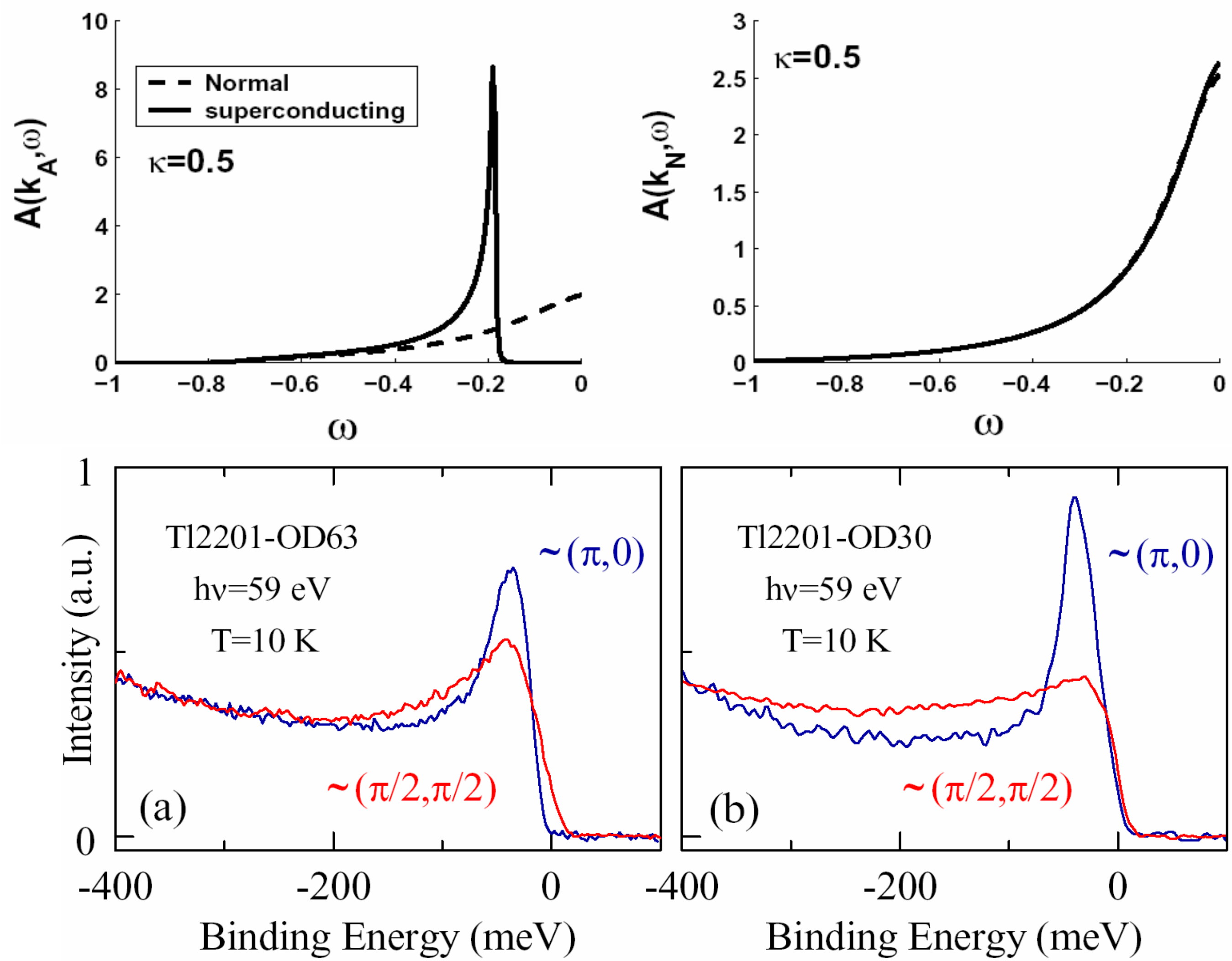




Zhu, P.J. Hirschfeld, & D.J. Scalapino, PRB **70**, 214503 (2004)

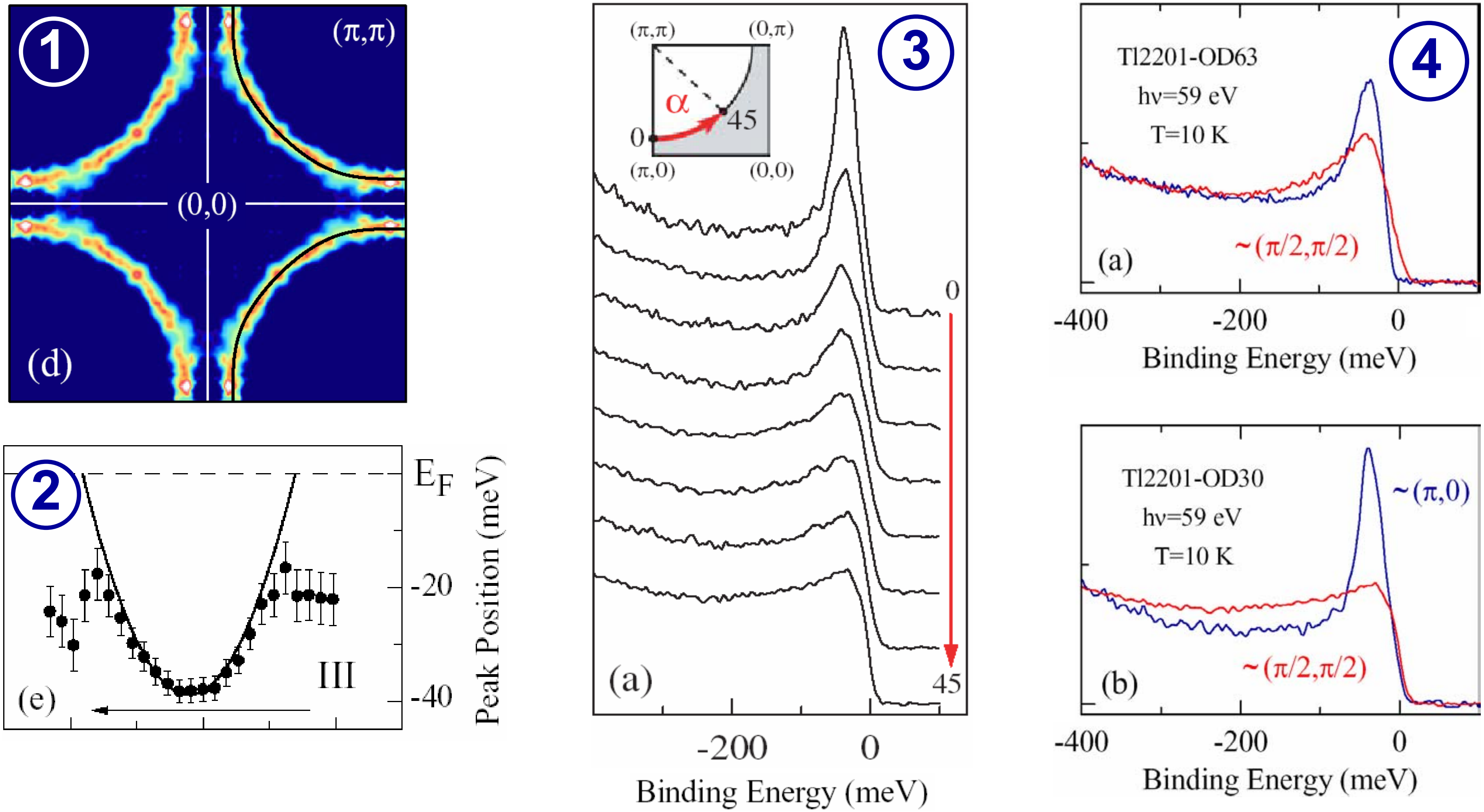
Tl2201: Small Angle Scattering?

Small Angle Scattering: strong T-dependence at $(\pi,0)$



Zhu, P.J. Hirschfeld, & D.J. Scalapino, PRB **70**, 214503 (2004)

ARPES on Tl2201: Conclusions



M. Platé, J. Mottershead, A. Damascelli, et al., cond-mat/0503117