Nodal-antinodal quasiparticle anisotropy reversal in the overdoped high-Tc cuprates

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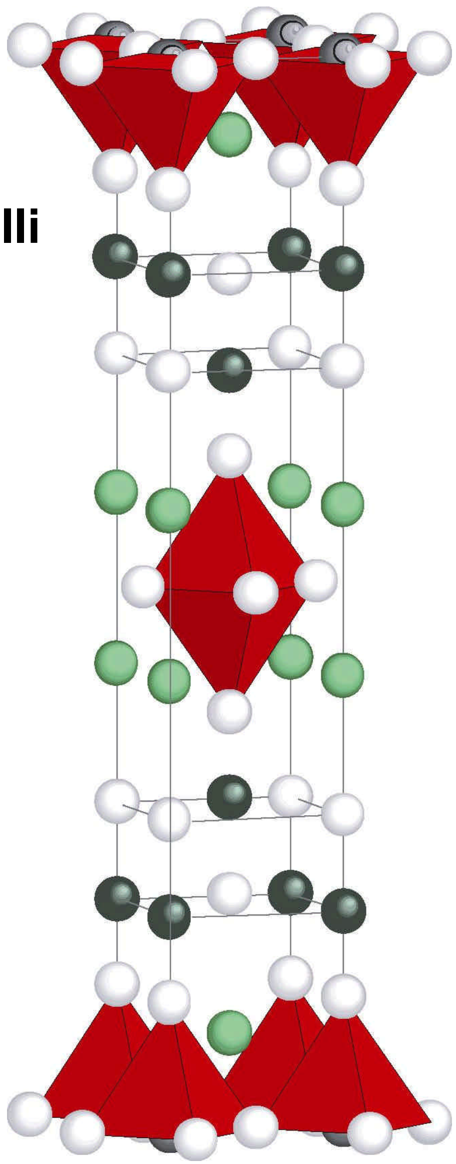
ARPES on $Tl_2Ba_2CuO_{6+\delta}$: Collaborators



- **ARPES at UBC:**

  M. Platé, J. Mottershead, S. Hossain, C. Veenstra, R. Wicks, B. Wu, K. Nguyen, K. Guenter, T. Roth, N. Ingle, **A. Damascelli**

- **Band Structure Calculations:**

  Ilya Elfimov

- **Samples:**

  $Tl_2Ba_2CuO_{6+d}$

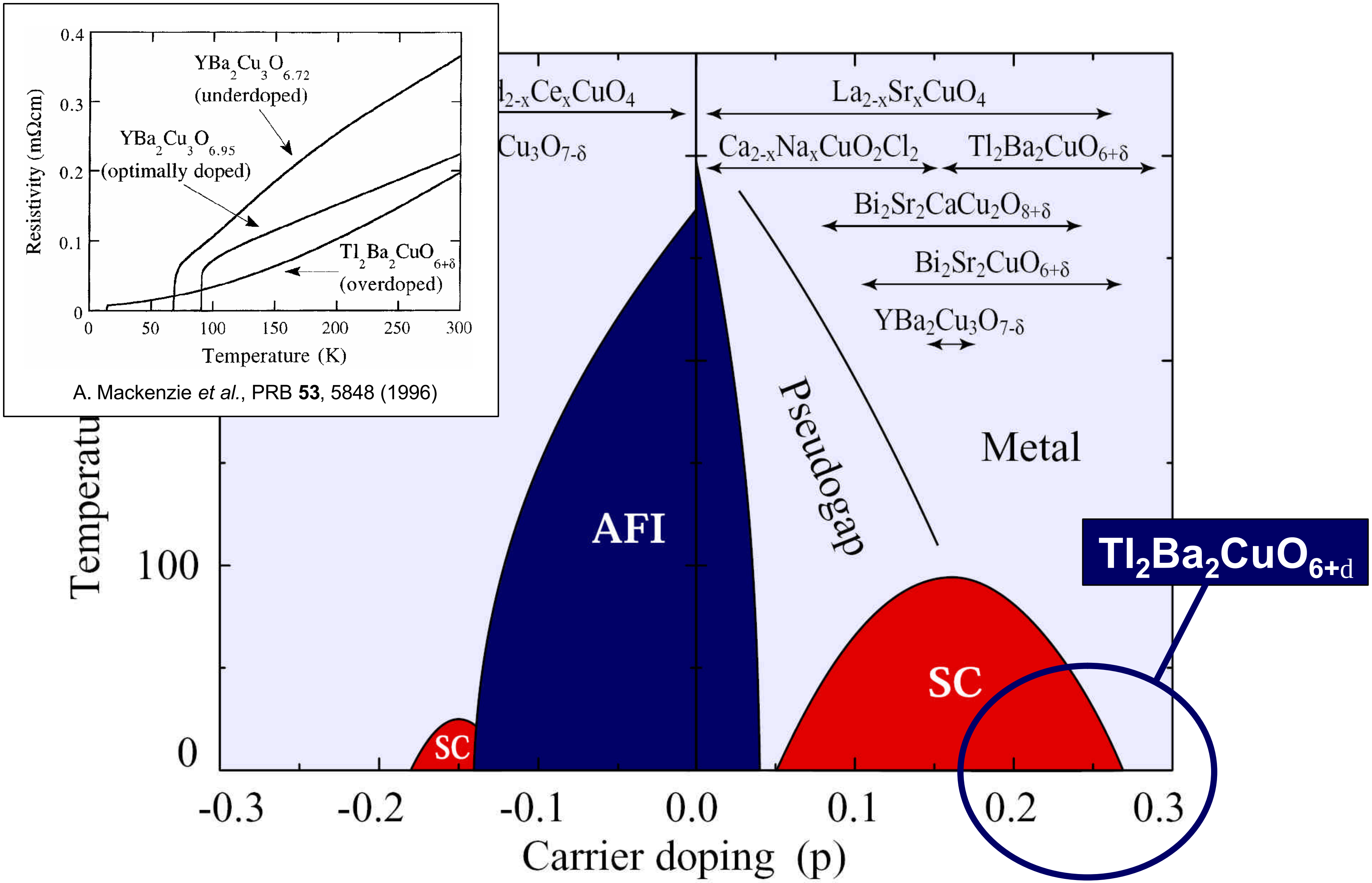
  D. Peets, Ruixing Liang, D.A. Bonn, W.N. Hardy

- **ARPES Experiments:**

  Swiss Light Source – SIS Beamline

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

High-Temperature Superconductors



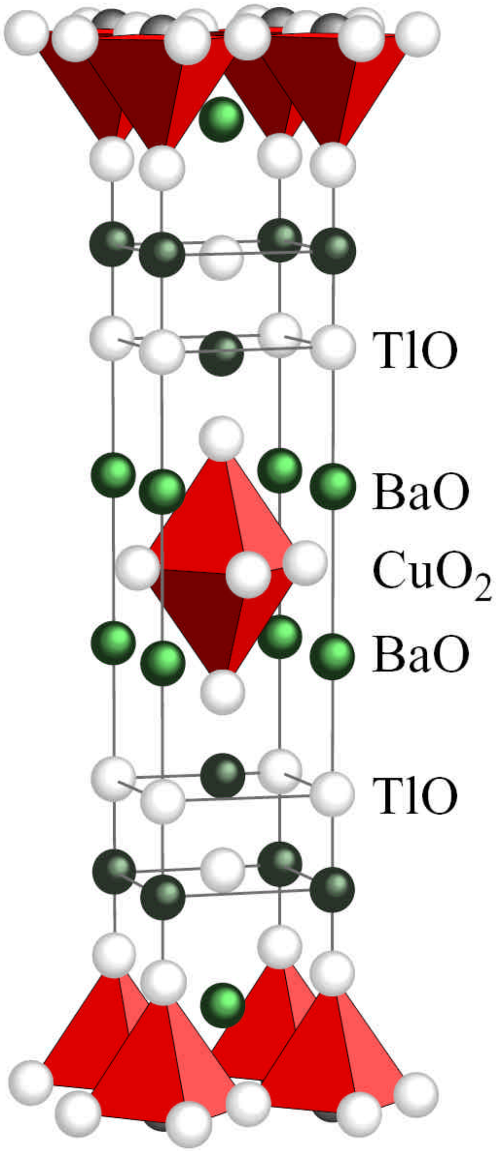
A. Mackenzie *et al.*, PRB **53**, 5848 (1996)

Why $Tl_2Ba_2CuO_{6+\delta}$?

$Tl_2Ba_2CuO_{6+d}$: 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)

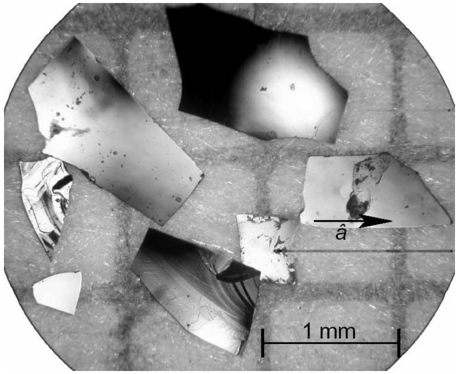


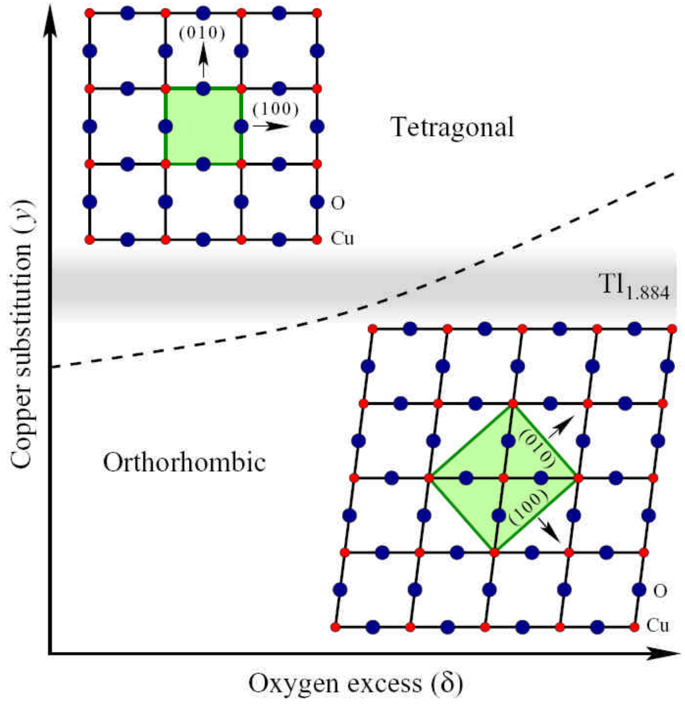
Orthorhombic vs. Tetragonal $Tl_2Ba_2CuO_{6+\delta}$

- **High-quality single crystals:**

Orthorhombic Tl2201 grown by self-flux method

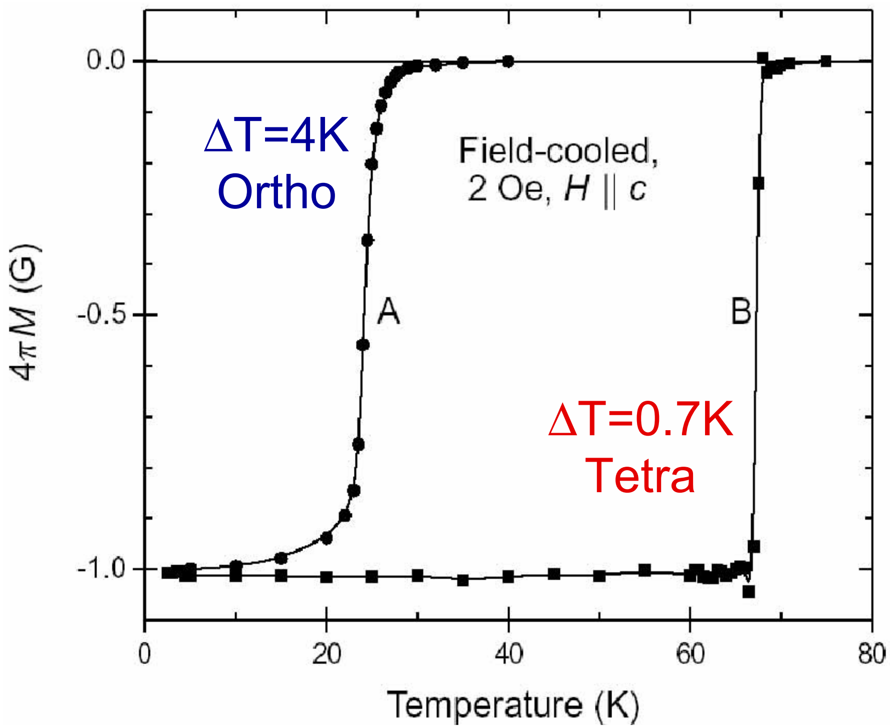
D. Peets, Ruixing Liang, D.A. Bonn, W.N. Hardy





Tetragonal (a=3.865Å; c=23.247Å)

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



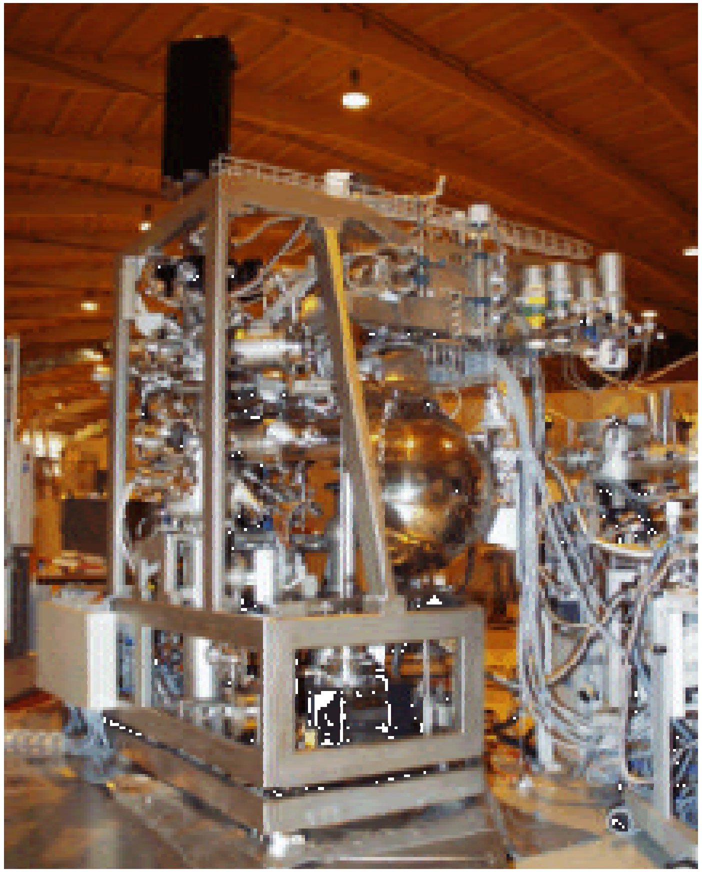
Peets et al., cond-mat/0609250 (2006)

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

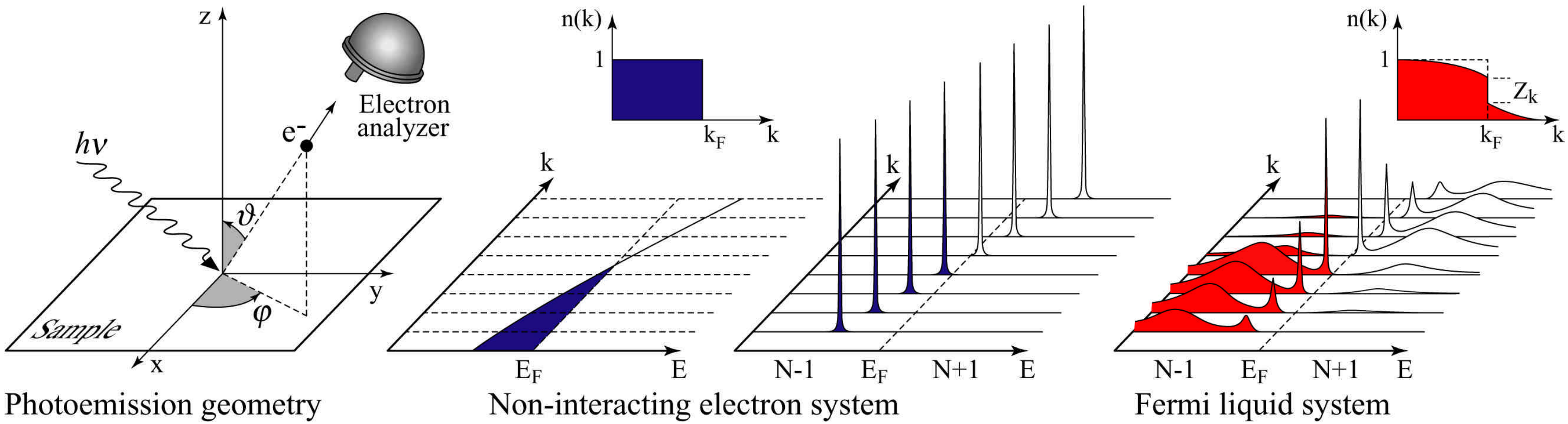
- **ARPES**

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

- **Spin resolved ARPES**

ARPES: The One-Particle Spectral Function

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



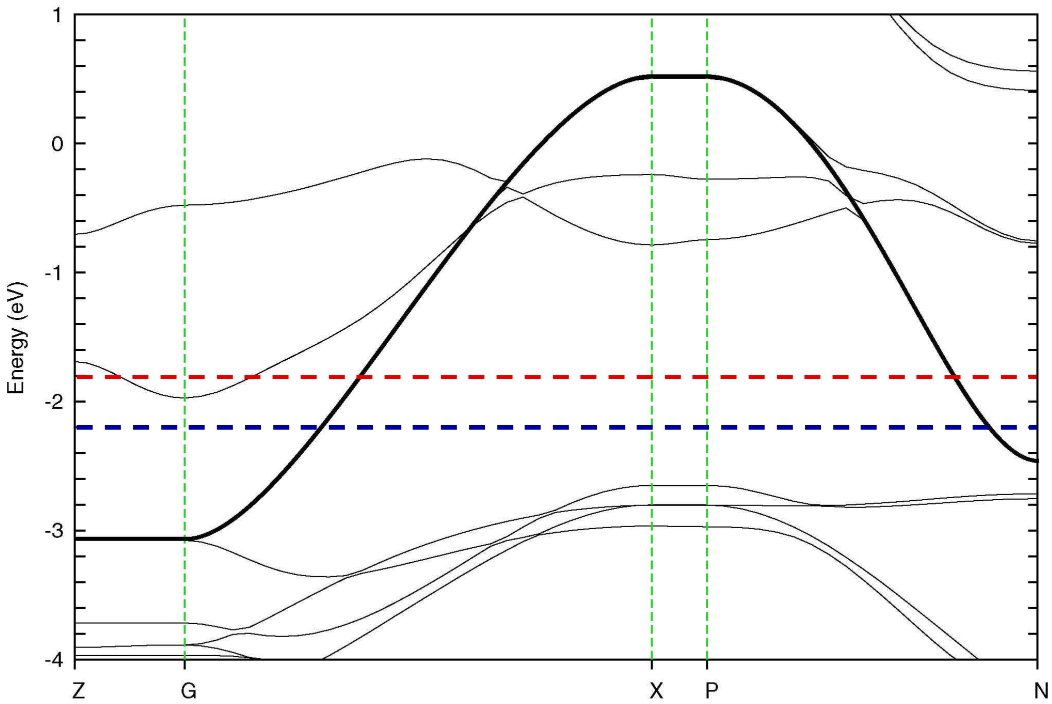
Photoemission intensity: $I(k,w)=I_0\,|M(k,w)|^2 f(w)\,A(k,w)$

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**

Tl2201: Low energy electronic structure

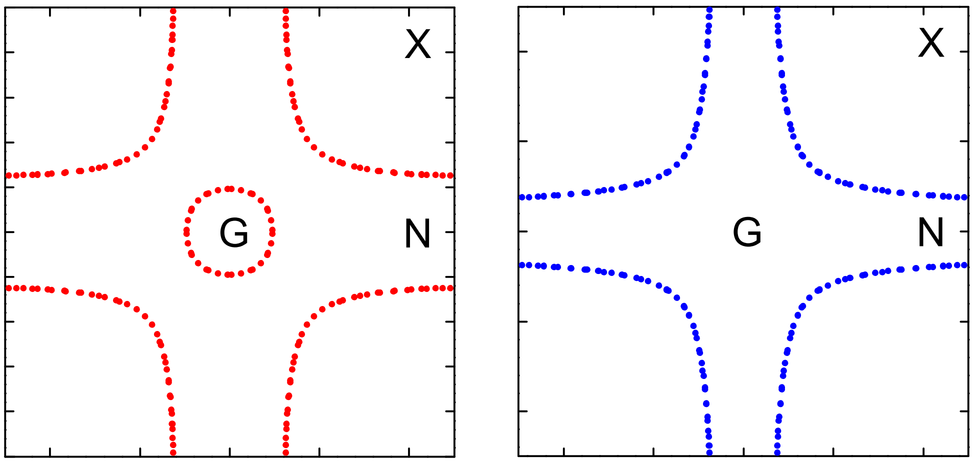


$Tl^{3+}:Ba^{2+}:Cu^{2+}:O^{2-}$ in ratios 2:2:1:6

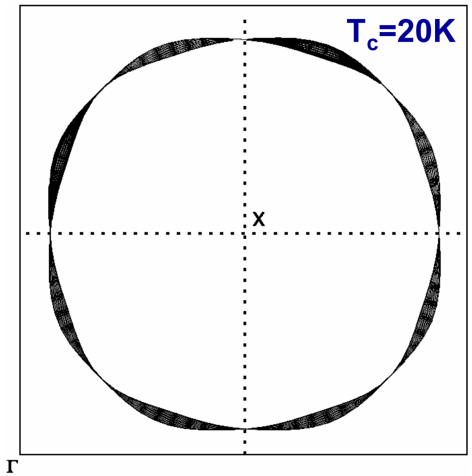
Charge Transfer Insulator

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

Tl2201: Optimally Doped SC

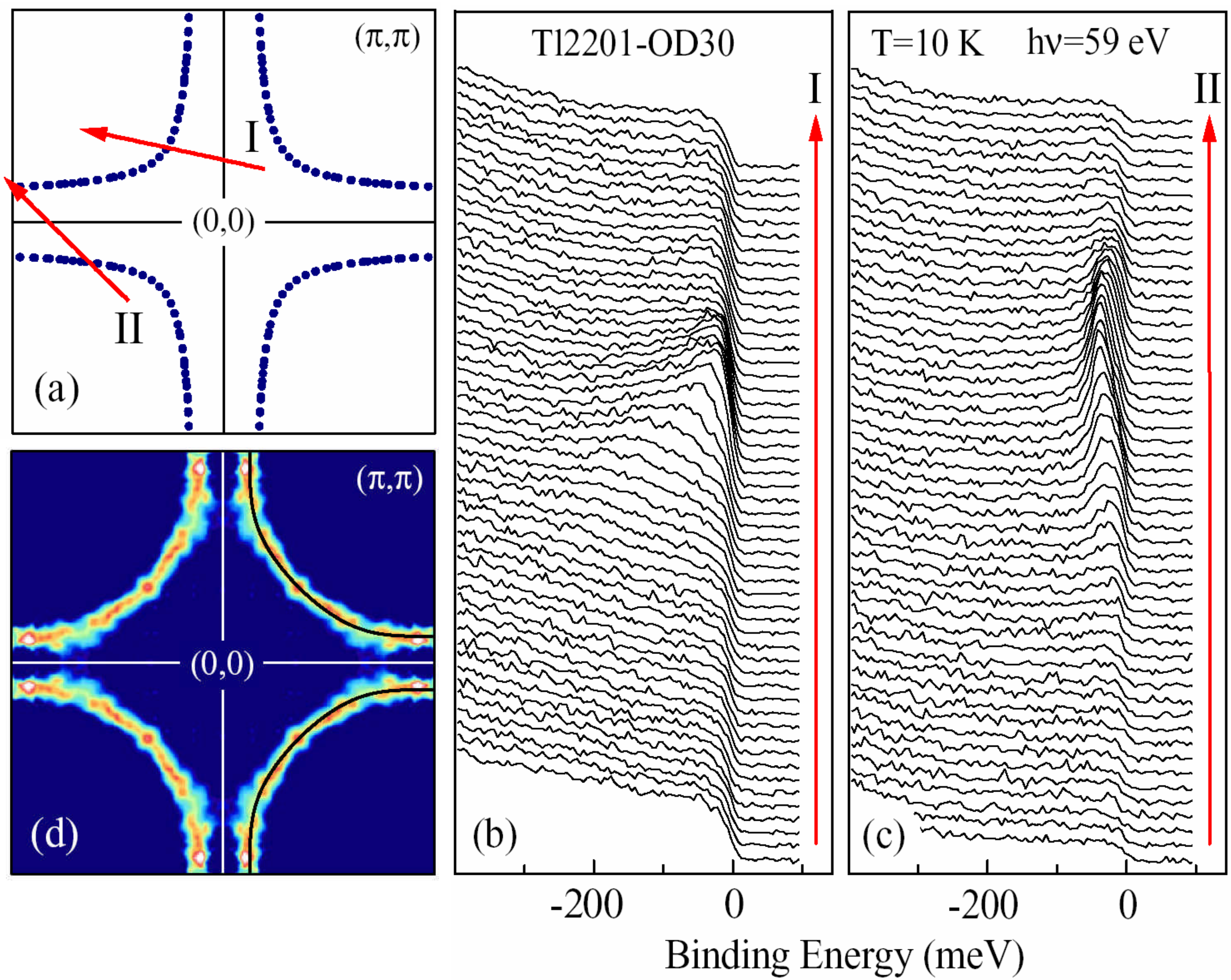


Elfimov (2004)



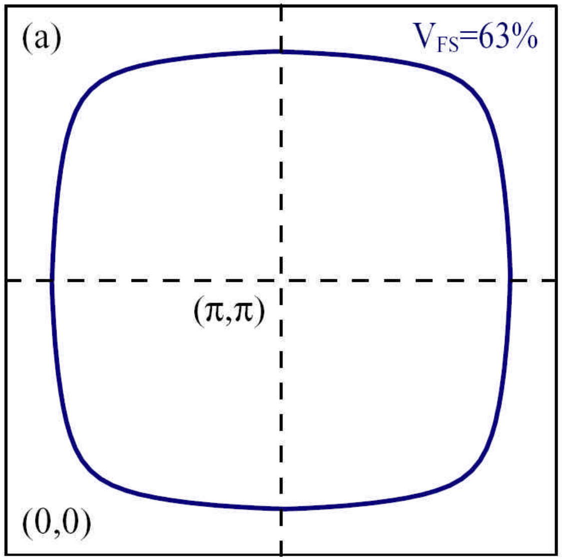
Hussey et al, Nature **425**, 814 (2004)

Tl2201 : ARPES Results

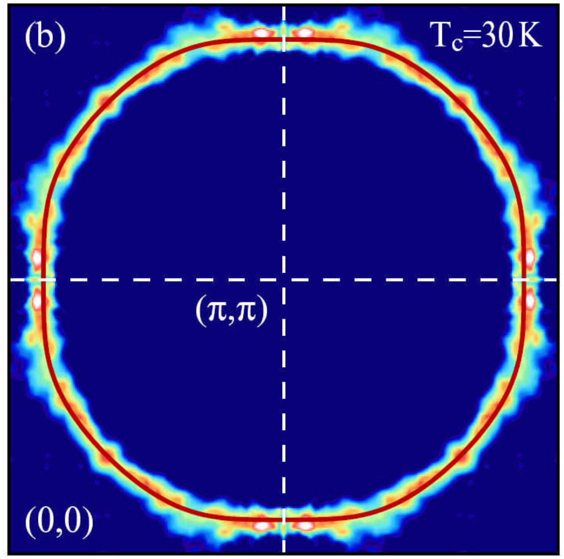


Tl2201 : Fermi Surface Volume

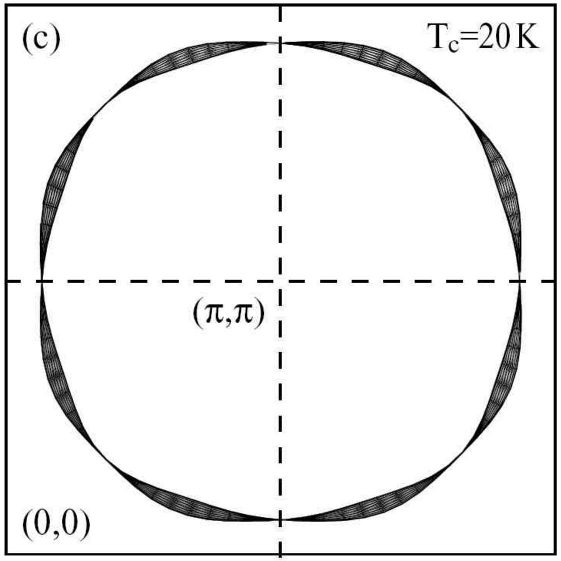
LDA



ARPES



AMRO

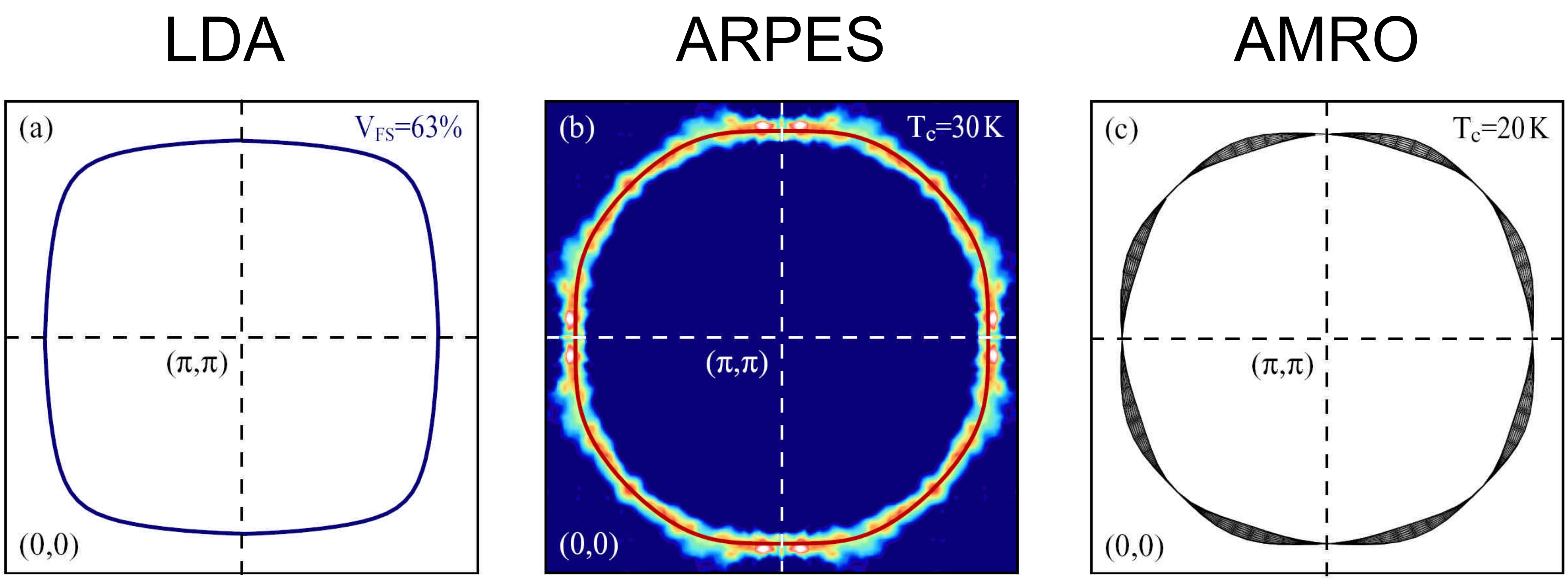


Hussey et al, Nature **425**, 814 (2004)

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



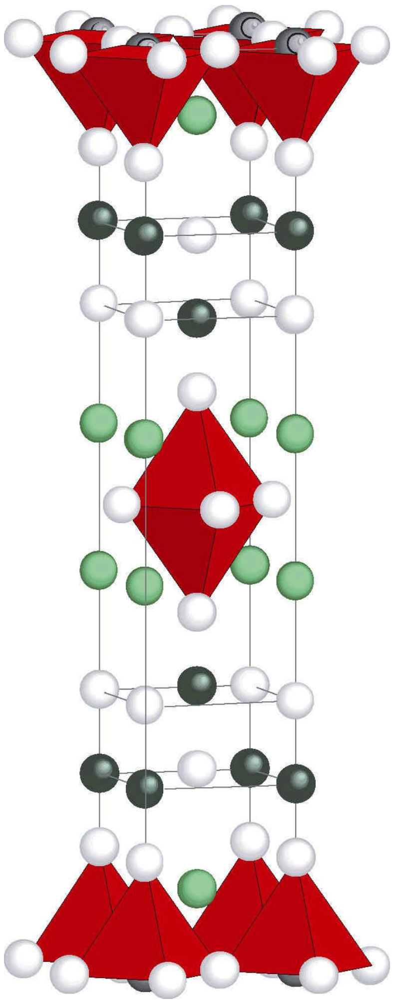
Hussey et al, Nature **425**, 814 (2004)

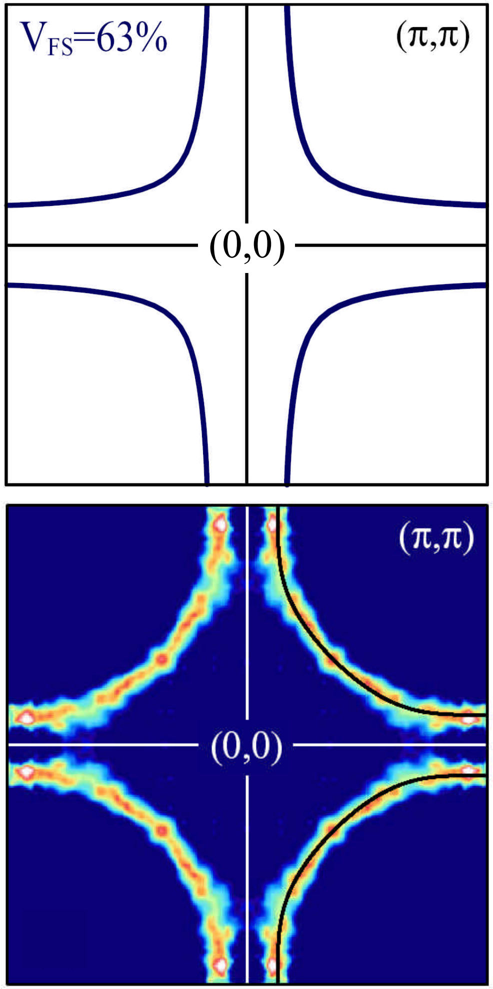
Tight binding FS fit

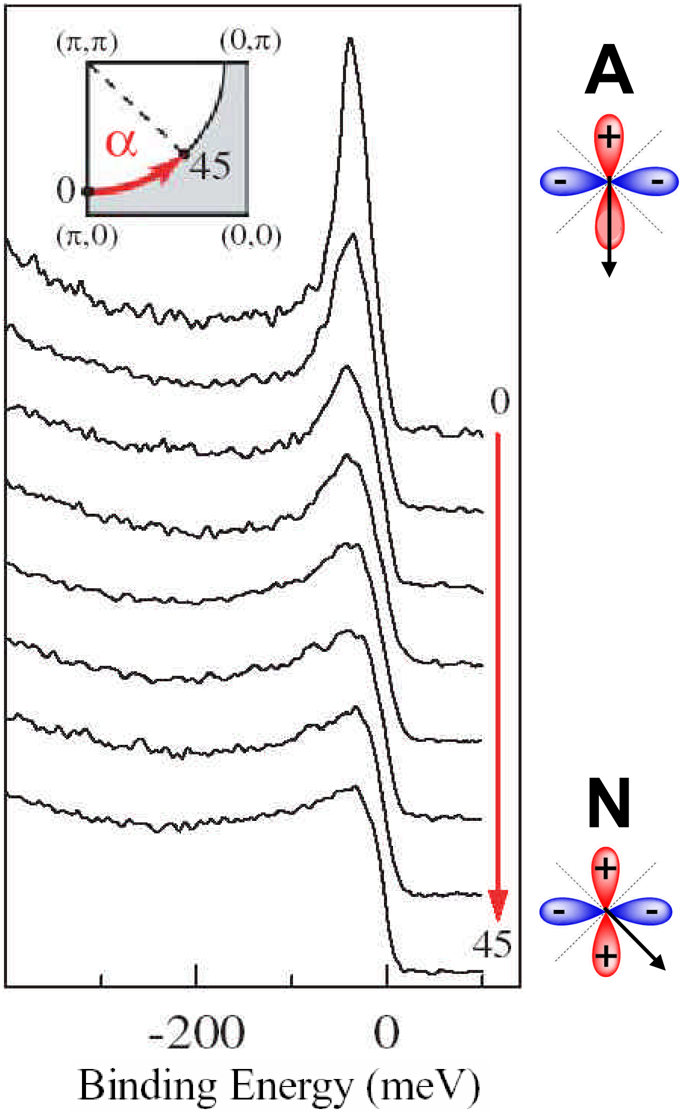
$$\epsilon_{\mathbf{k}} = \mu + \frac{t_1}{2}(\cos k_x + \cos k_y) + t_2 \cos k_x \cos k_y + \frac{t_3}{2}(\cos 2k_x + \cos 2k_y)$$
$$+ \frac{t_4}{2}(\cos 2k_x \cos k_y + \cos k_x \cos 2k_y) + t_5 \cos 2k_x \cos 2k_y$$

$$\mu = 0.2438,\ t_1 = -0.725,\ t_2 = 0.302,\ t_3 = 0.0159,\ t_4 = -0.0805,\ t_5 = 0.0034$$

ARPES on $Tl_2Ba_2CuO_{6+\delta}$

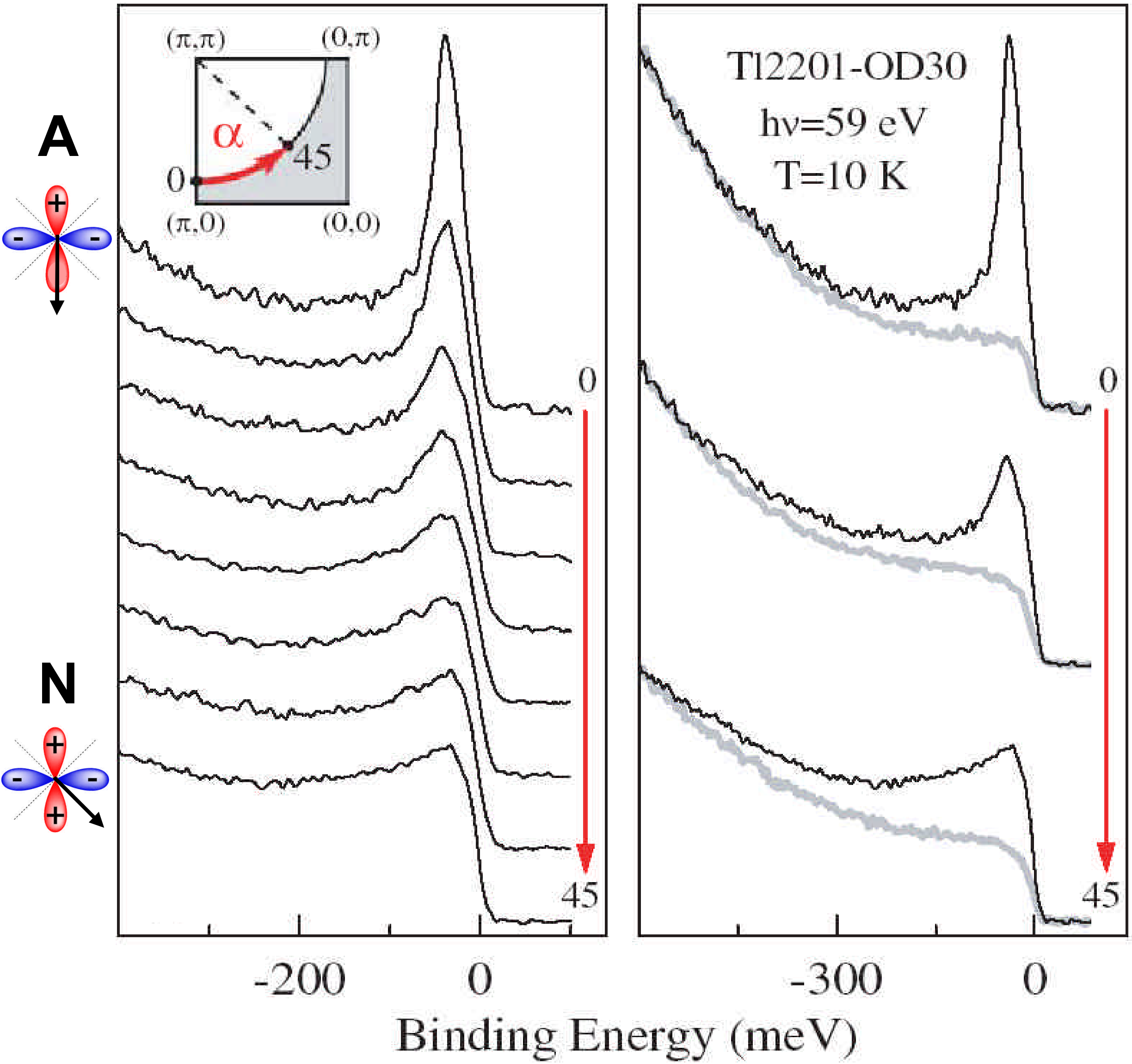




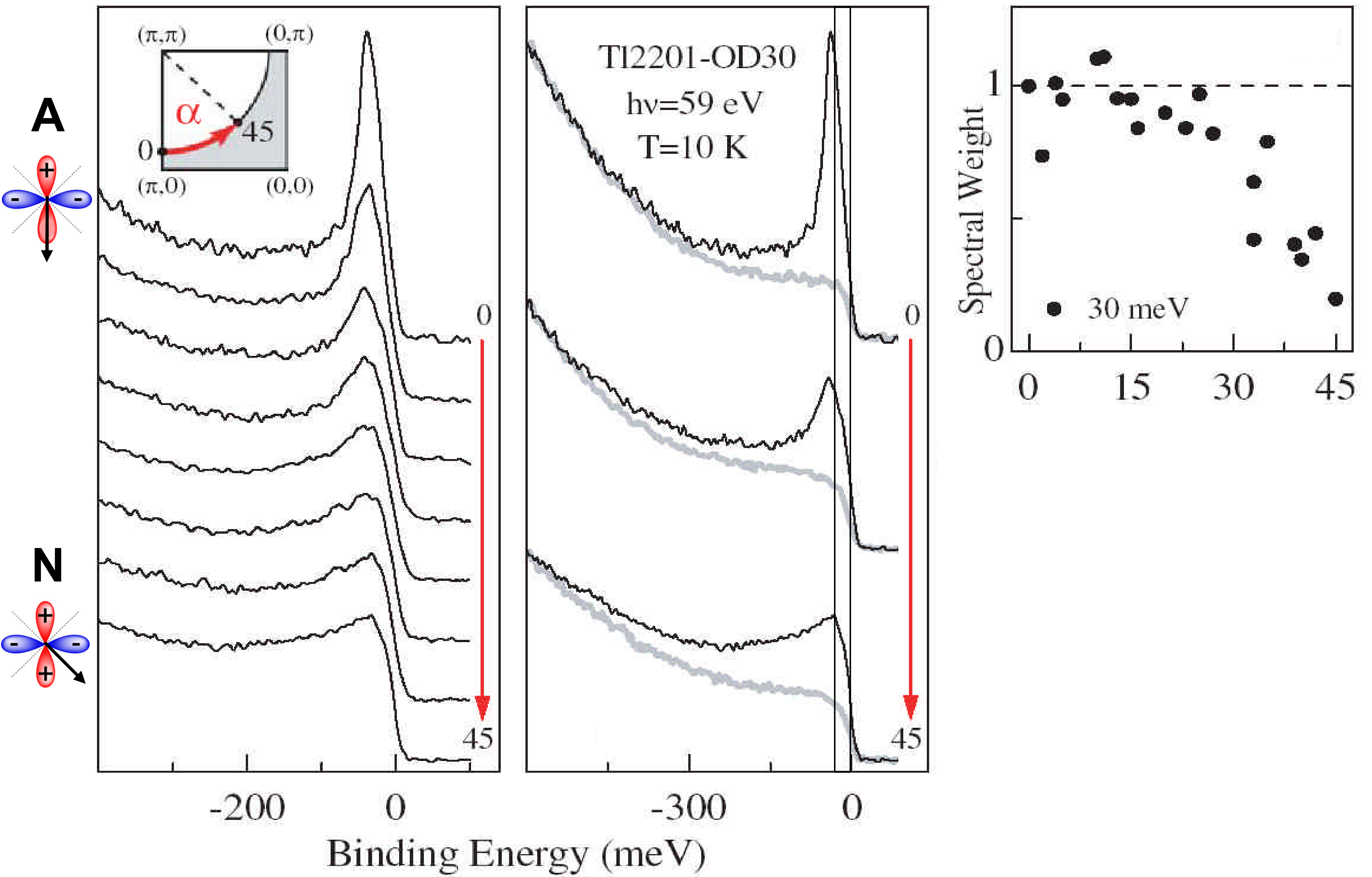


$$A(\mathbf{k},\omega) = -\frac{1}{\pi}\frac{\Sigma''(\mathbf{k},\omega)}{[\omega - \epsilon_{\mathbf{k}} - \Sigma'(\mathbf{k},\omega)]^2 + [\Sigma''(\mathbf{k},\omega)]^2}$$

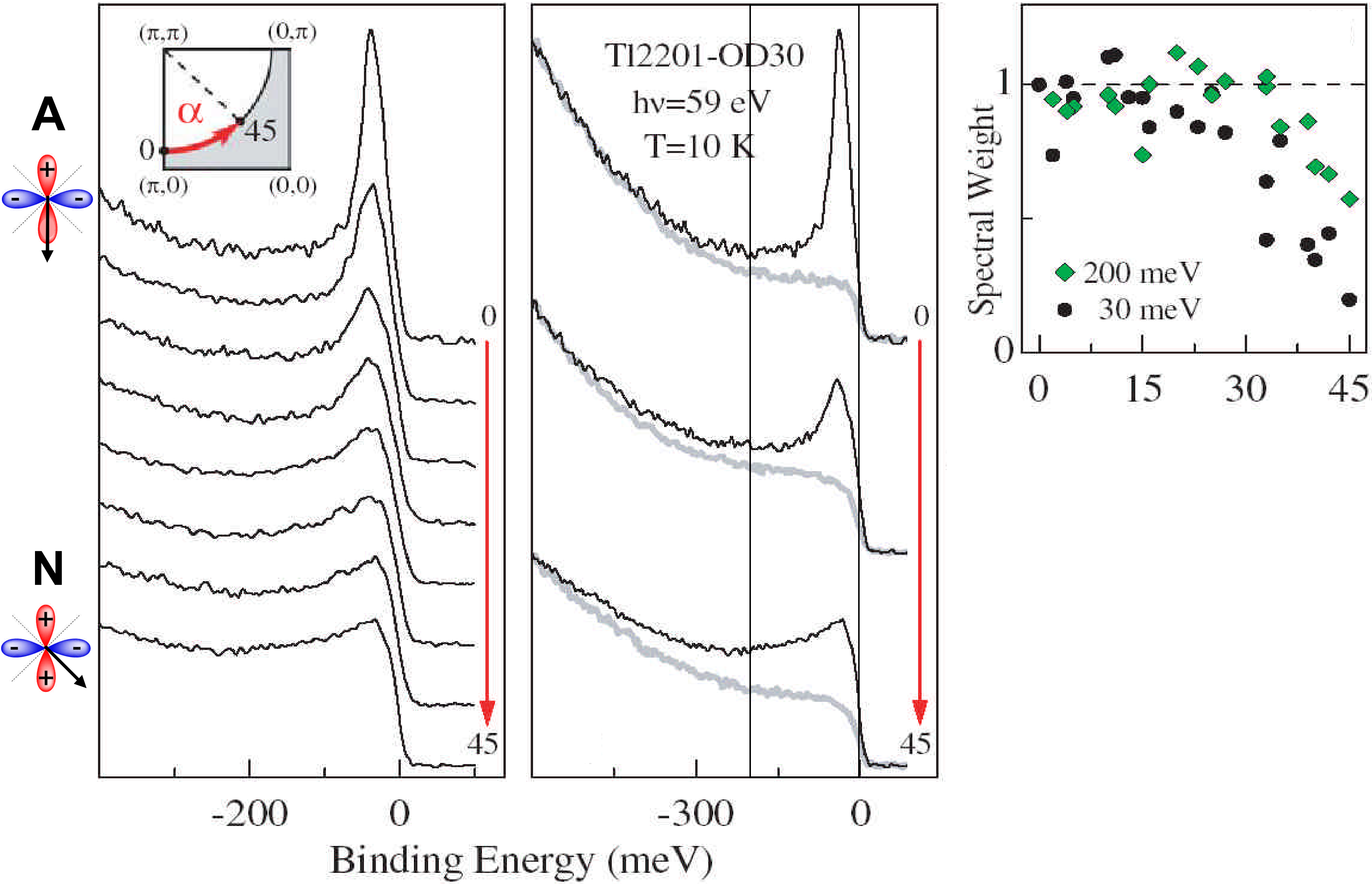
Tl2201: Lineshape evolution around FS



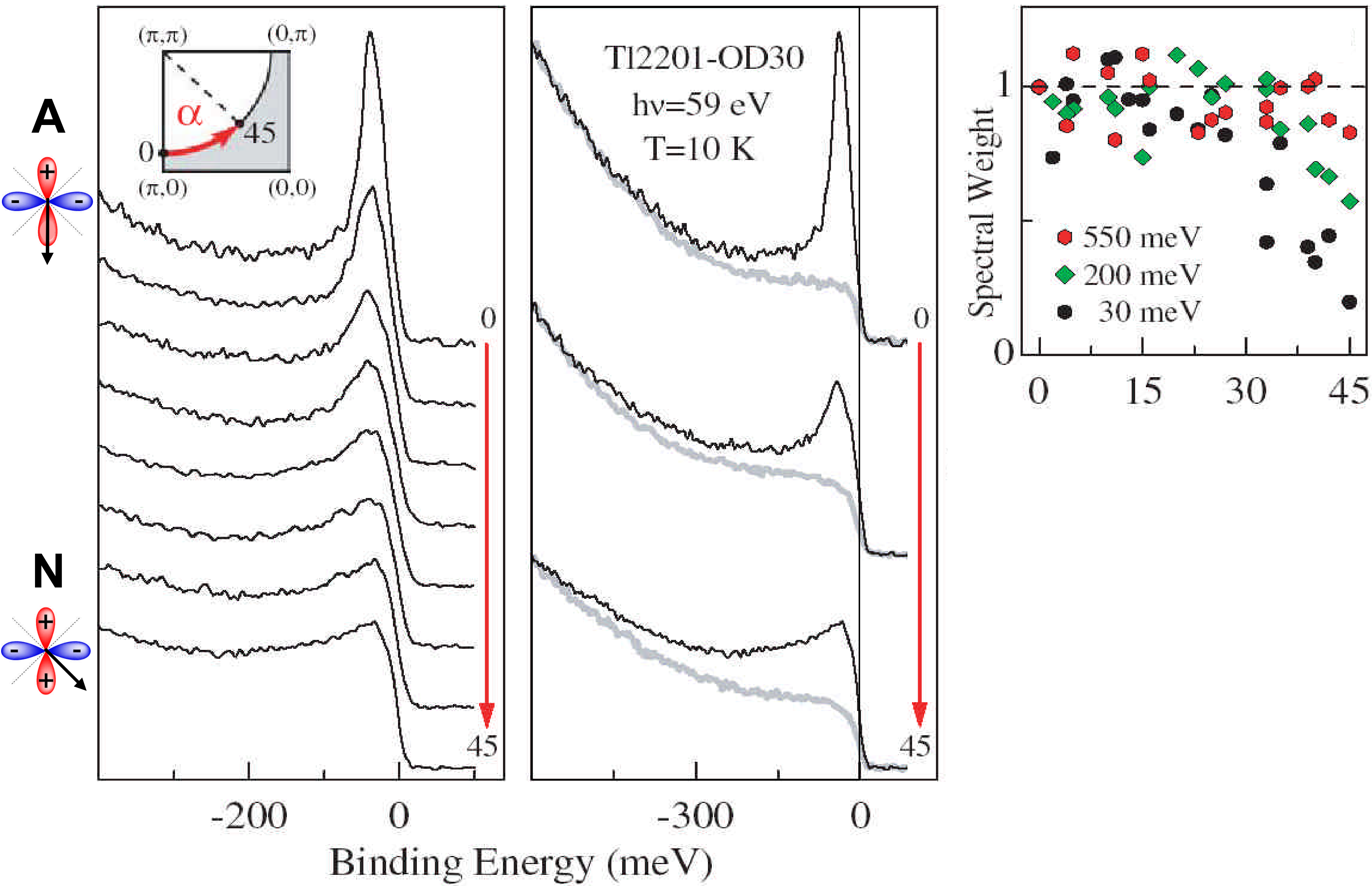
Tl2201: Lineshape evolution around FS



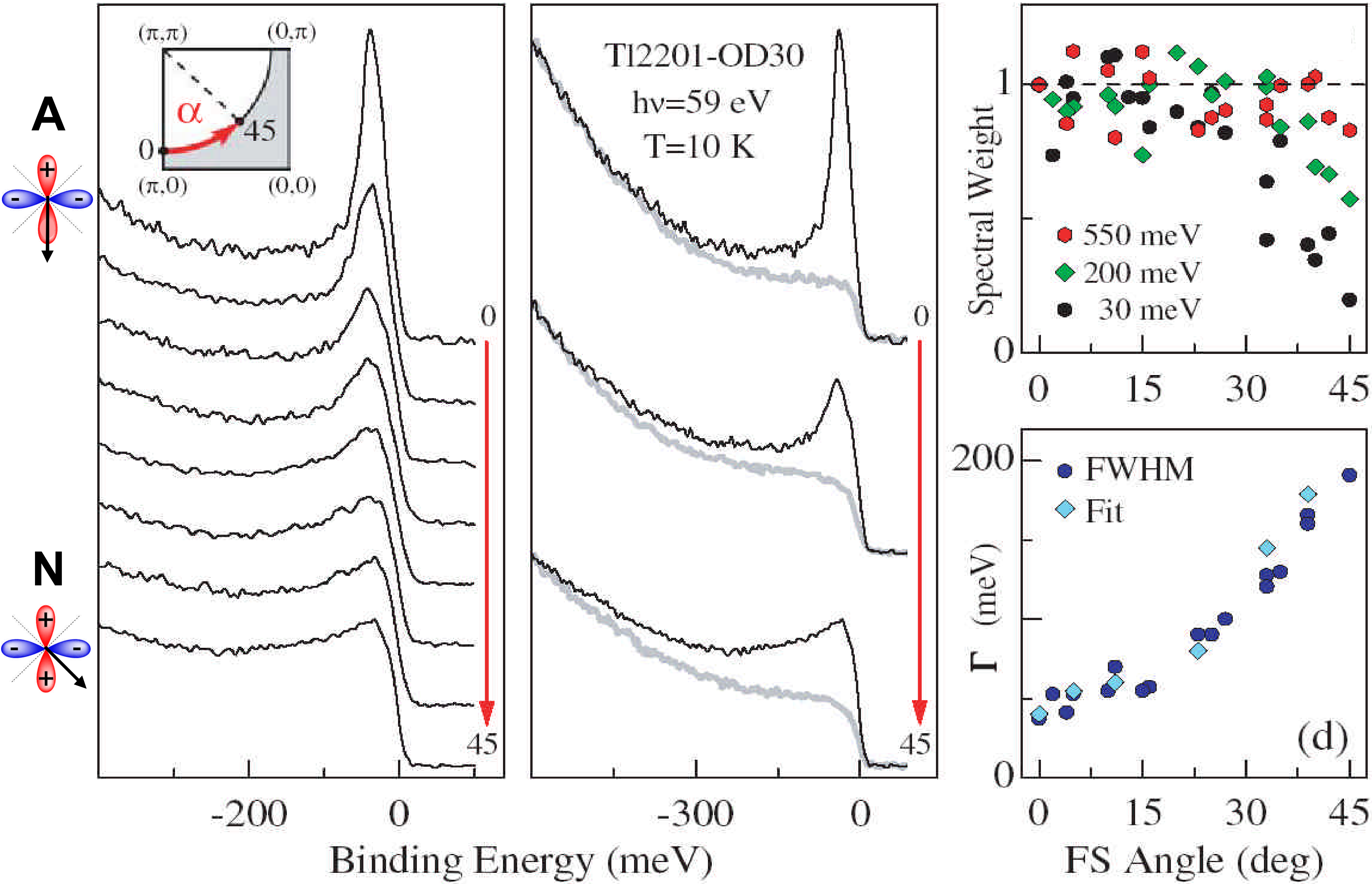
Tl2201: Lineshape evolution around FS



Tl2201: Lineshape evolution around FS

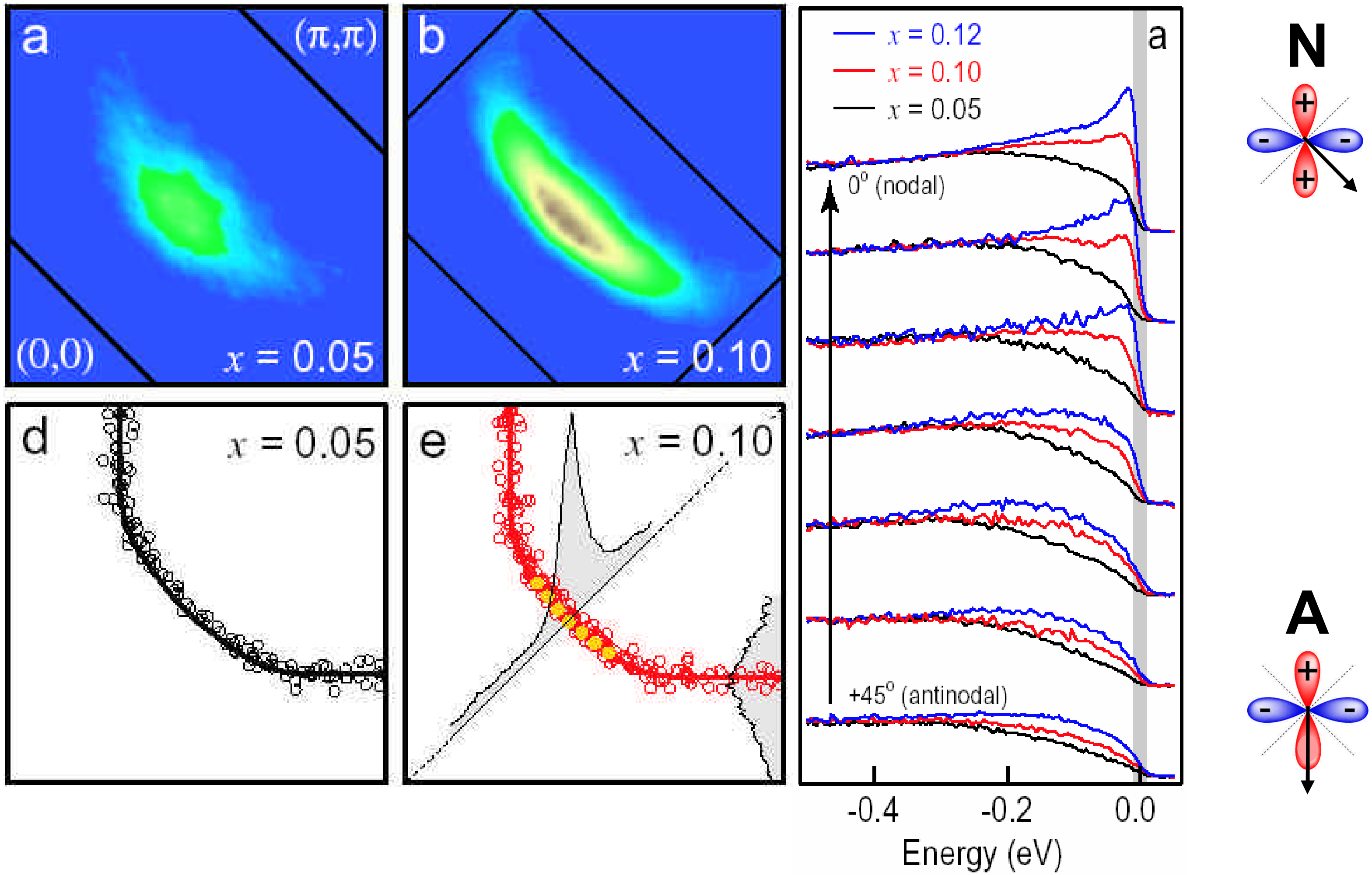


Tl2201: Lineshape evolution around FS



FS and Pseudogap in Underdoped Cuprates

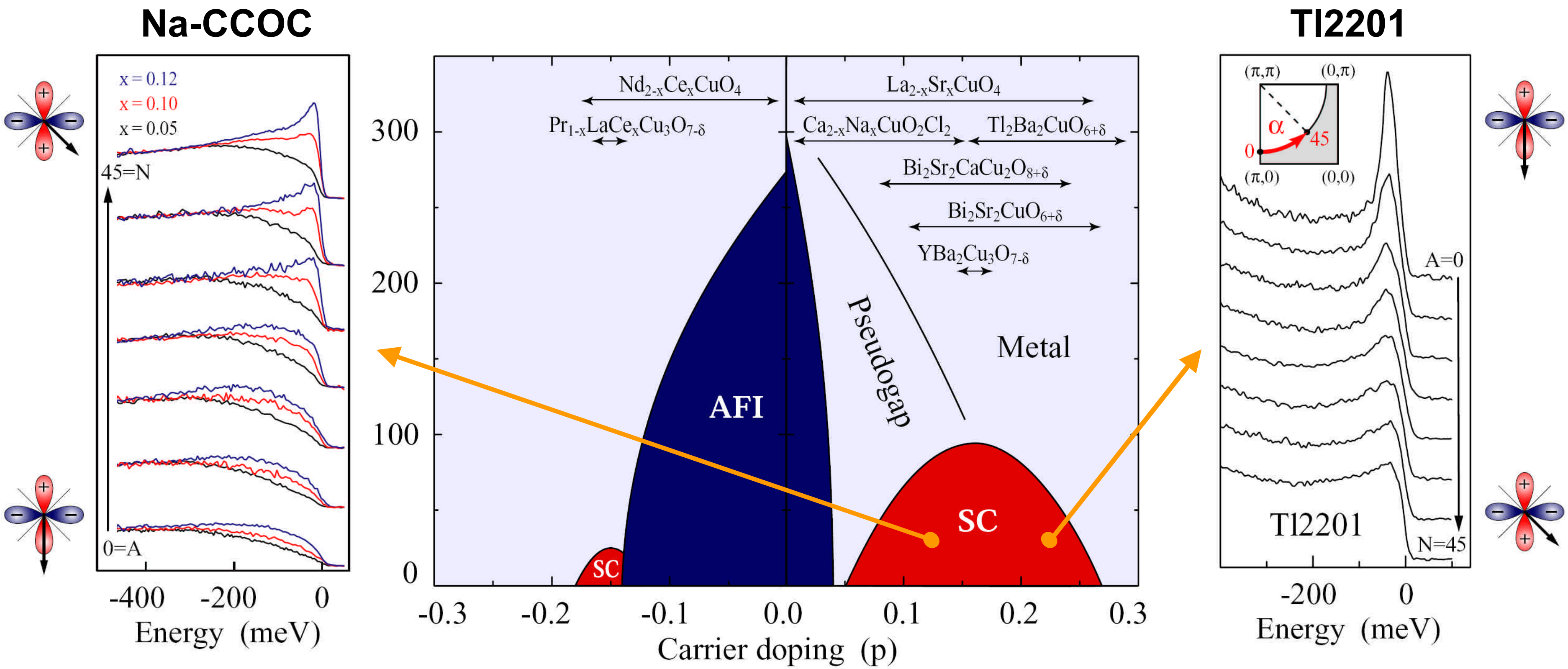
ARPES on $Ca_{2-x}Na_xCuO_2Cl_2$



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

Nodal-Antinodal Anisotropy in the Cuprates

Quasiparticle anisotropy reversal



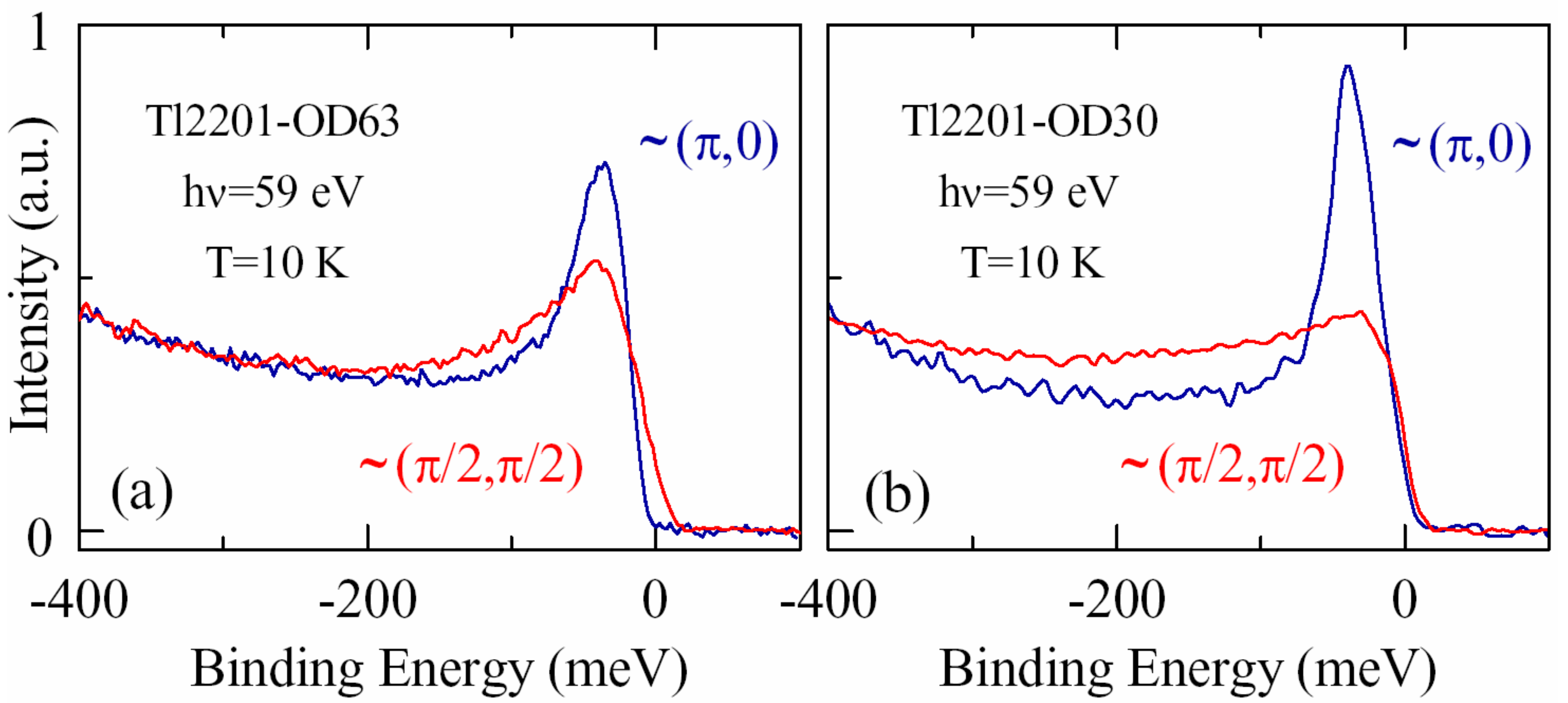
Across optimal doping

Platé, Mottershead, Damascelli et al., PRL **95**, 077001 (2005)

Peets, Mottershead, Damascelli et al., NJP **9**, 28 (2007)

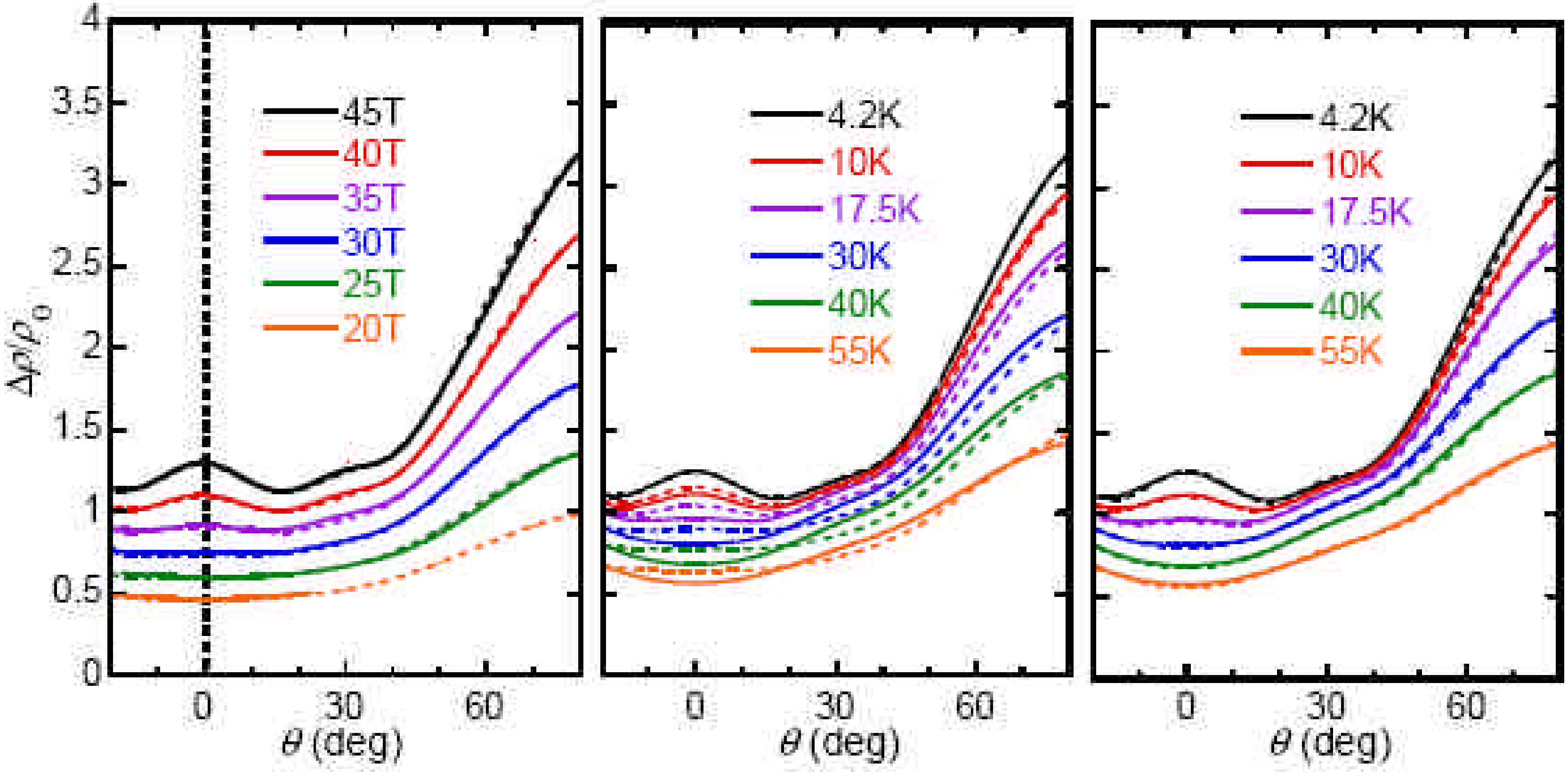
$Tl_2Ba_2CuO_{6+\delta}$: ARPES Results

OverDoped-63K; T_c=2/3·$T_{c,max}$ OverDoped-30K; T_c=1/3·$T_{c,max}$



Polar AMRO in overdoped Tl2201 (T_c = 15K)

Changing *B* | Changing *T* (t) | Changing *T* (t)



$$w_c t = \frac{eBt}{m^*}$$

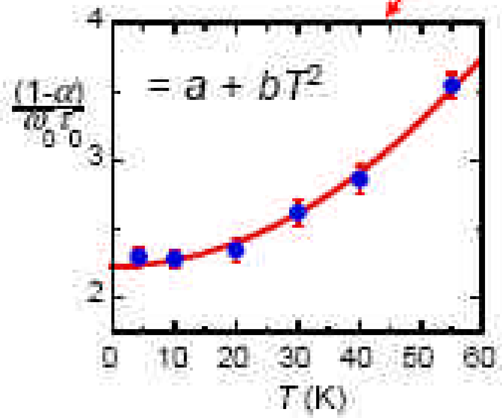
All other parameters unchanged

Ditto

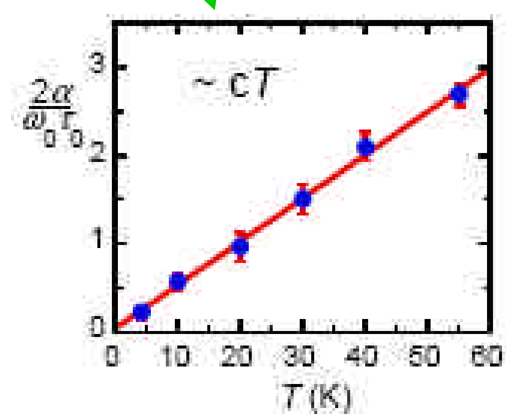
$$\frac{1}{w_c t} = \frac{1}{w_0 t_0}\left(1 + a \cos 4f\right)$$

Courtesy of Nigel Hussey

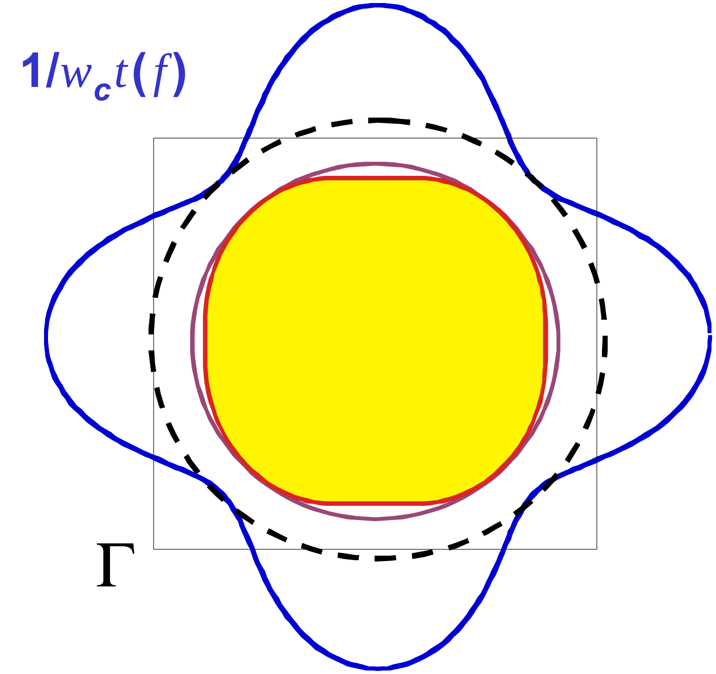
$$\frac{1}{w_0 t_0}(1 + a\cos 4f) = \frac{1-a}{w_0 t_0} + \frac{2a}{w_0 t_0}\cos^2 2f$$

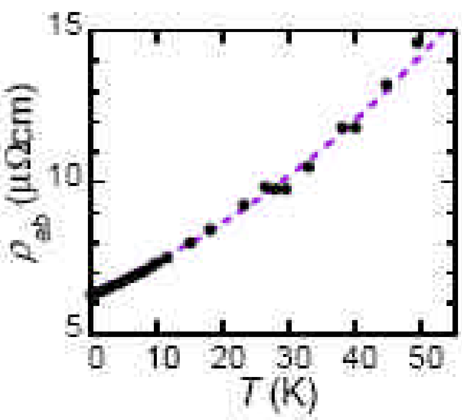


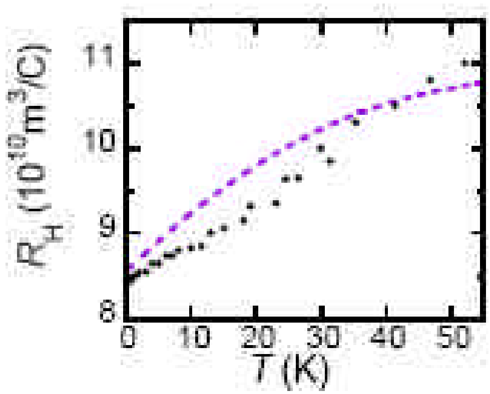
G(*T*) at the nodes



Additional scattering along (p,0)



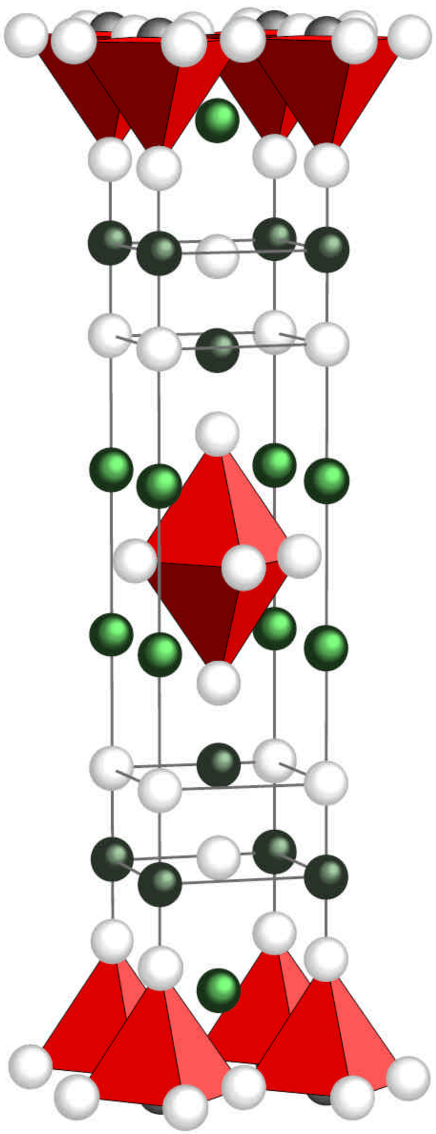




Origin of *T*-linear resistivity and $R_H(T)$ due to additional scattering that is maximal at (p, 0) & increases linearly with *T*

Courtesy of Nigel Hussey

Tl2201: Anisotropic Electronic Scattering?



Anisotropy reversal:

Are the Tl2201 **ARPES** data consistent with **AMRO** results in overdoped cuprates?

SC

NS

What does ARPES probe?

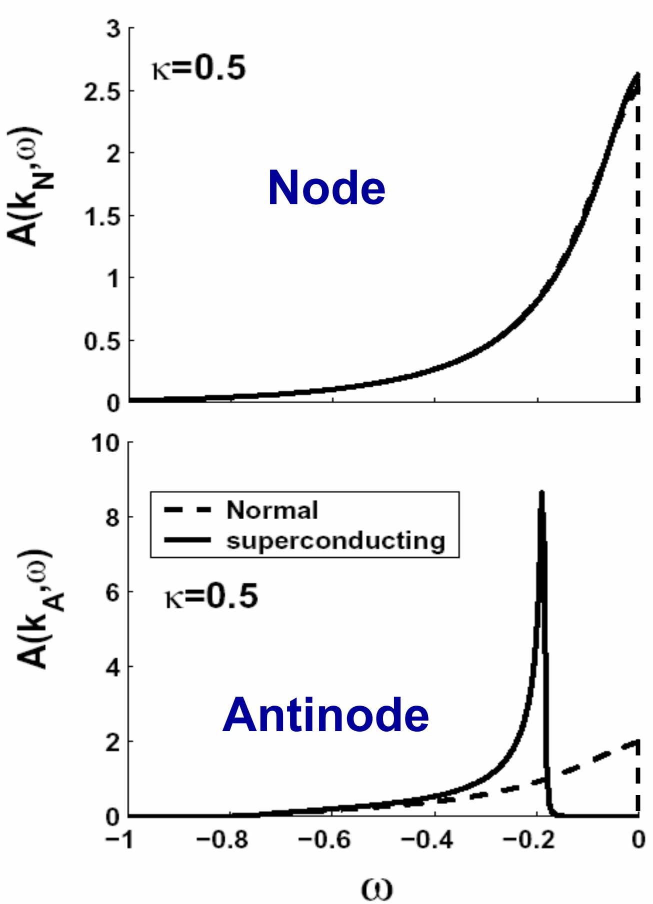
$$\Sigma_{tot} = \Sigma_{el,f} + \Sigma_{\mathrm{el,u}} + \Sigma_{\mathrm{inel}}$$

- ~~Resolution broadening~~
- ~~Residual Kz dispersion~~
- Impurity scattering

T-dependent Coherent Enhancement at Antinodes

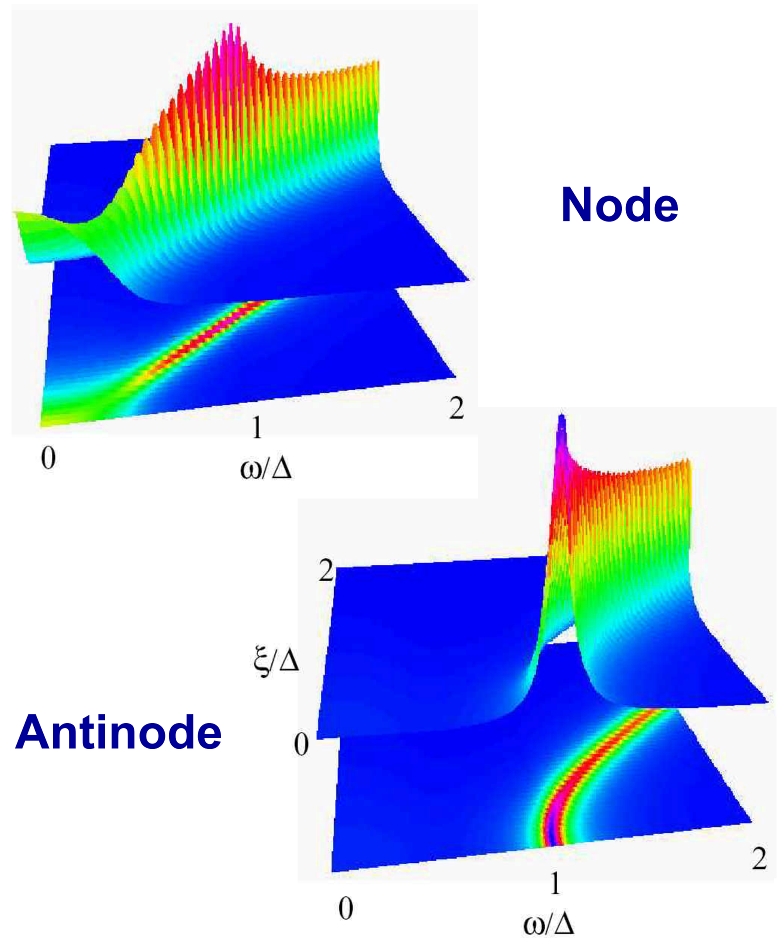
$$\Sigma_{tot} = \Sigma_{el,f} + \Sigma_{\mathrm{el,u}} + \Sigma_{\mathrm{inel}}$$

Small-Angle Elastic Scattering



Zhu, Hirschfeld, Scalapino, PRB 2004

Unitary Limit beyond Born Appr.



Wakabayashi, Rice, Sigrist, PRB 2006

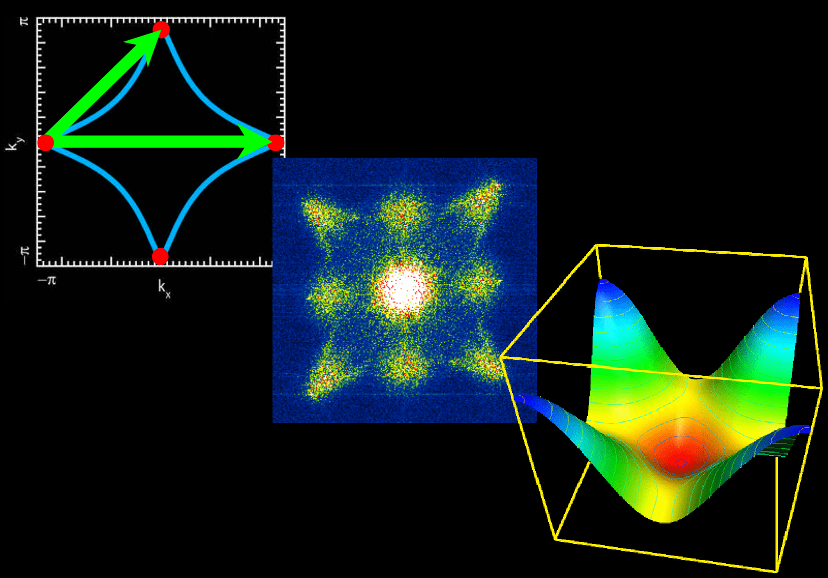
Bi2212: Quasiparticle Interference at High Overdoping

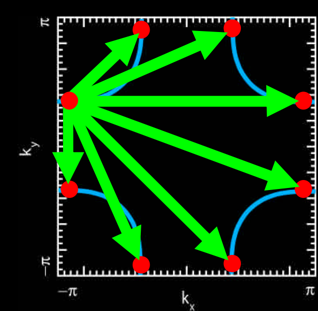
- Antinodal (near gap energy) interference signal is dominated by scattering between (0,±p) and (±p ,0)

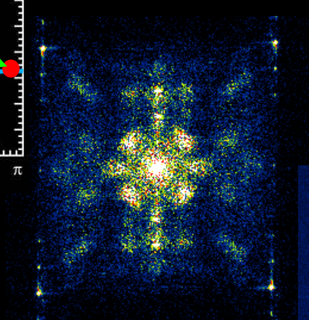
- Consistent with Van Hove singularity crossing the Fermi surface

- Nodal (low energy) quasiparticle interference signals no longer visible

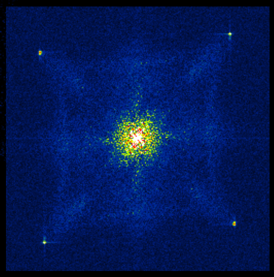
- Consistent with decoherence of nodal states





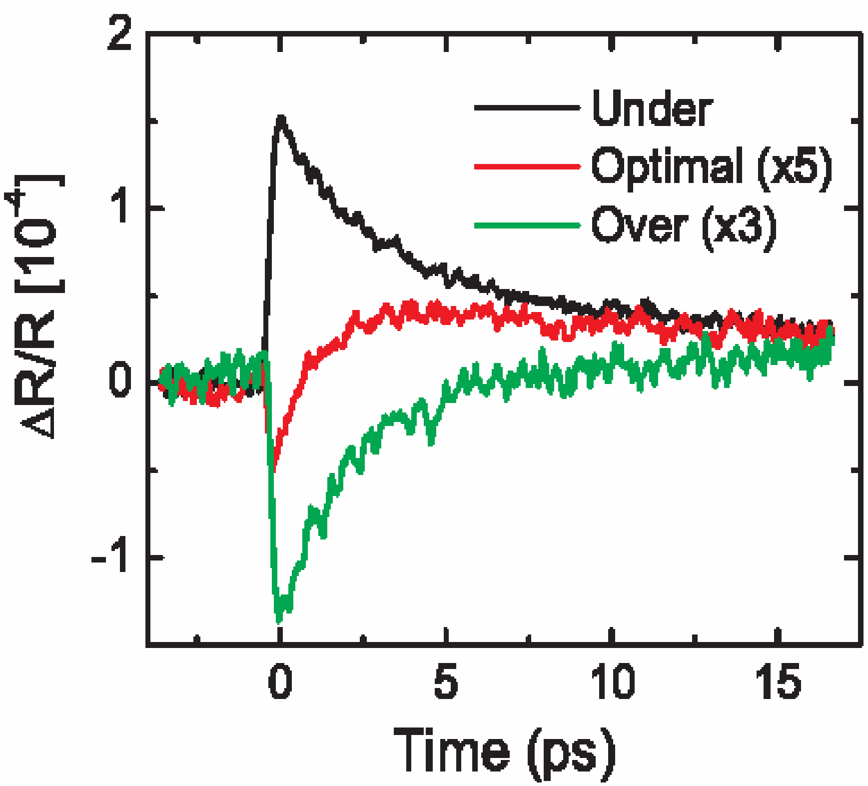


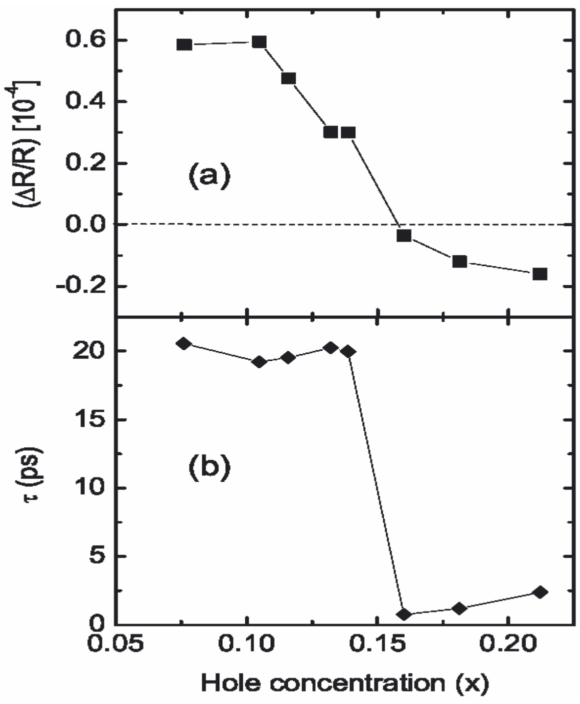
Slezak and Davis, 2006



Time-resolved Photoinduced Reflectivity

Abrupt transition in QP dymanics





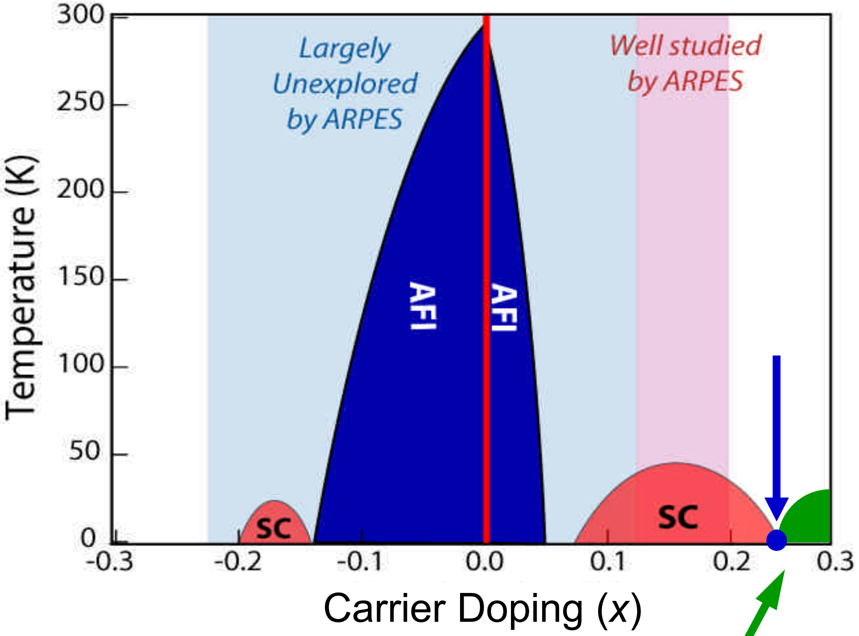
Across optimal doping

N. Gedik et al., PRL **95**, 117005 (2005)

Quasiparticle Anisotropy Reversal: Implications

Many quantities change abruptly beyond x=0.2

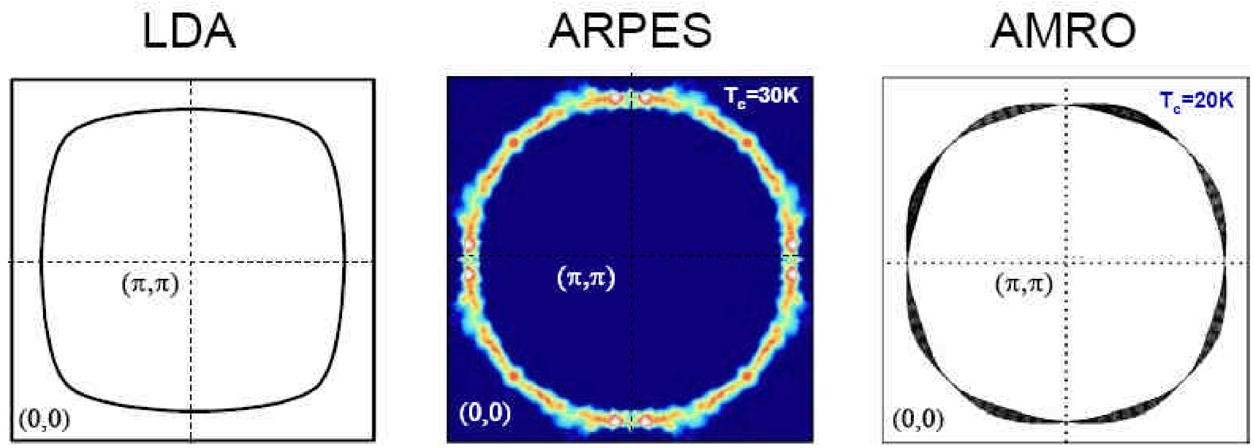
- **Electronic Specific Heat**
  (Loram, JPCS 2001)
- **Muon Spin Relaxation**
  (Panagopoulos, SSC 2003)
- **Low-T Hall Number**
  (Boebinger, 2006)
- **ARPES: QP lifetime**
  (Plate, Mottershead, Damascelli, PRL 2005)
- **Optical Conductivity**
  (Molegraaf, van der Marel, Science, 2002;
  Gedik, Orenstein, PRL 2005; Ma, Wang, PRB 2006)
- **Scanning Tunneling Microscopy**
  (Slezak and Davis, 2006)



Kopp, Ghosal, Chakravarty
Competing Ferromagnetism?
cond-mat/0606431

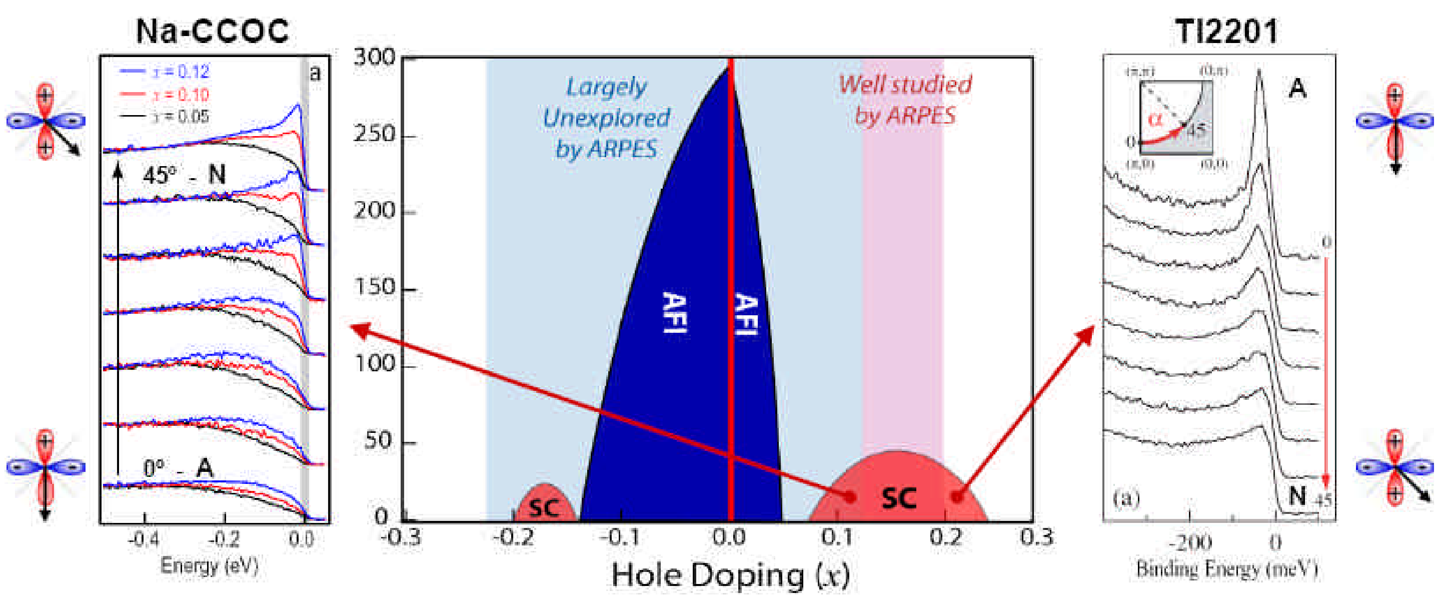
ARPES on Tl2201: Conclusions

Normal State Fermi Surface



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

Quasiparticle Anisotropy Reversal



Platé, Mottershead, Damascelli et al., PRL **95**, 077001 (2005)
Peets, Mottershead, Damascelli et al., NJP **9**, 28 (2007)