united nations educational, scientific and cultural organization

international atomic energy agency

the
abdus salam
international centre for theoretical physics

ICTP 40th Anniversary

SMR.1572 - 19

Workshop on
Novel States and Phase Transitions in Highly Correlated Matter

12 - 23 July 2004

Phase diagram of cuprates - spectroscopic perspective

Adam KAMINSKI
Iowa State University
Department of Physics & Astronomy
Iowa, Ames 50014
U.S.A.

Phase diagram of cuprates - spectroscopic perspective

Adam Kamiński
Iowa State University and Ames Laboratory

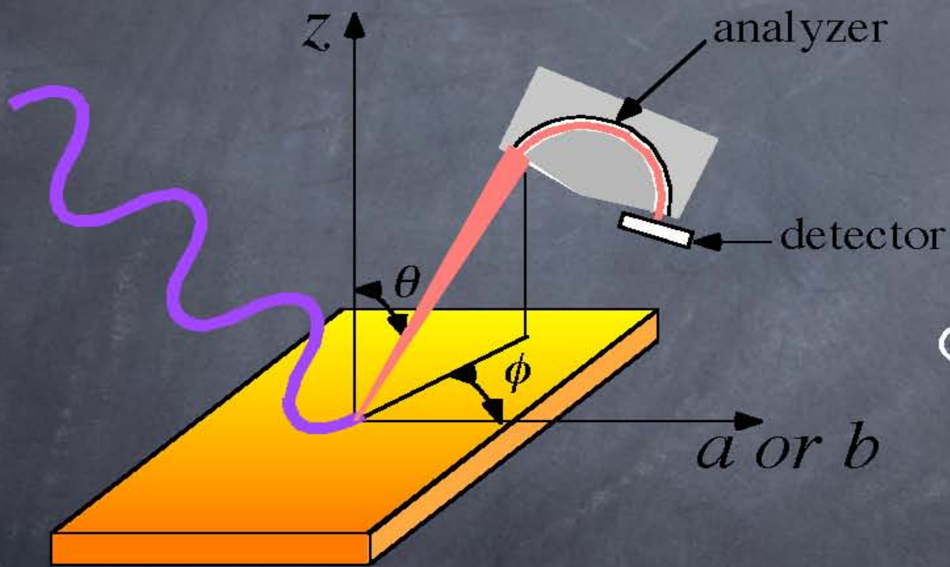
Funded by:
US Department of Energy
National Science Foundation
The Royal Society of Great Britain

J. C. Campuzano A. F. Santander U. Chatterjee	University of Illinois at Chicago, IL
S. Rosenkranz M. R. Norman W. G. Cullen H. You	Material Science Division, Argonne National Laboratory, IL
M. Randeria	Tata Institute, Mumbai, India
H. M. Fretwell	University of Wales Swansea, Swansea, UK
Z. Z. Li H. Raffy	Universite de Paris-Sud, Orsay, France
C. Olson	Ames Laboratory & Iowa State University, IA
H. Höchst	Synchrotron Radiation Center, Madison, WI
C. M. Varma	Lucent Technologies, NJ
T. Takahashi Takafumi Sato	Tohoku University, Sendai, Japan
Kazuo Kadowaki	University of Tsukuba, Tsukuba, Japan

Outline:

- what can we learn about electrons in solids from ARPES
- properties of the collective mode observed in cuprates
- time reversal symmetry violation the pseudogap region
- coherent and incoherent states
- the underlying normal state of cuprates

Angle Resolved PhotoEmission Spectroscopy (ARPES)



We need:

binding energy - E_b

initial momentum - k^i

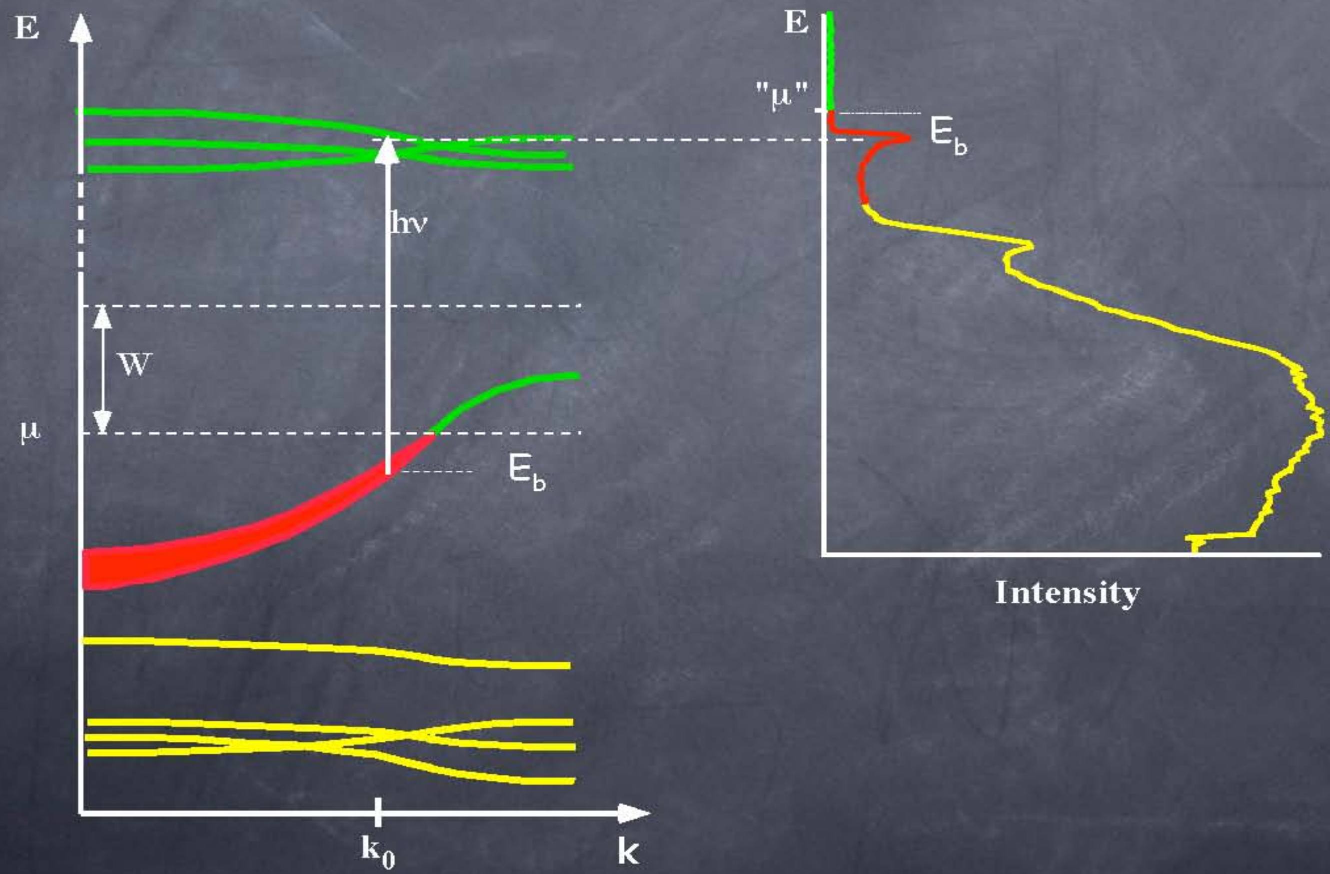
Quasi 2D system: $k^i_\perp = 0$

$$k^i_\parallel = k^f_\parallel = \sqrt{2mE}\,\sin(\theta)/\hbar$$

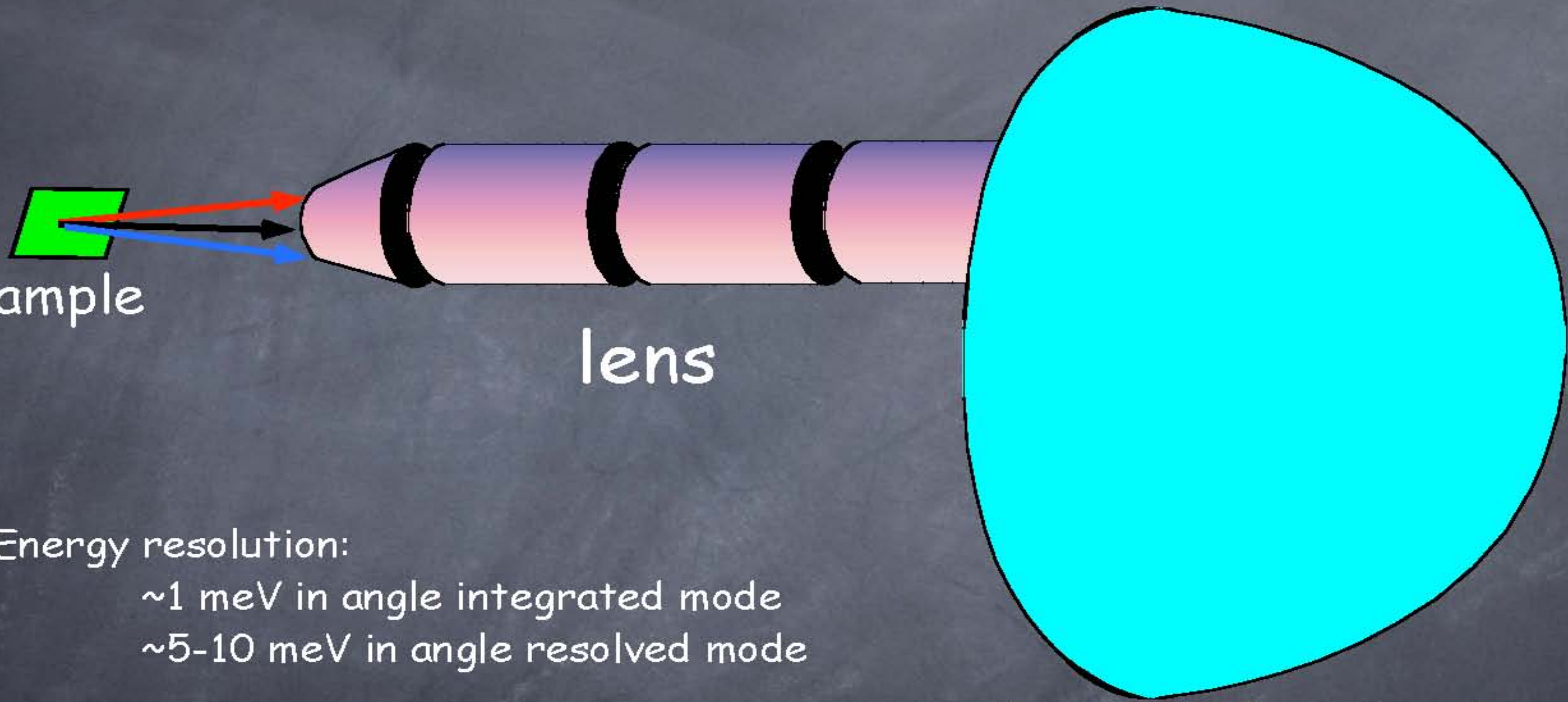
$$E_b = E - h\nu + W$$

Relation between

band structure & ARPES spectrum



Electron analyzer



Energy resolution:

~1 meV in angle integrated mode

~5-10 meV in angle resolved mode

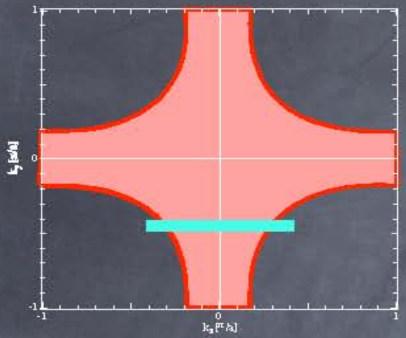
Momentum resolution:

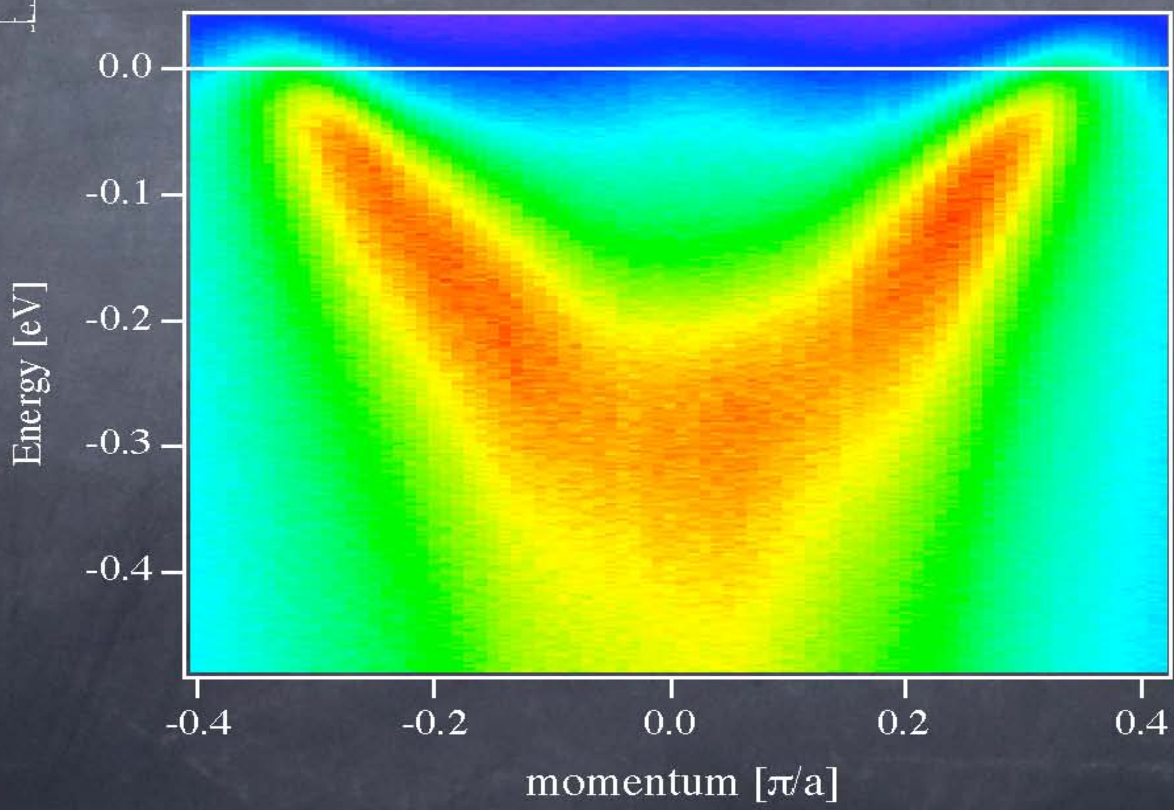
~0.005 A^{-1} at 22 eV (~1/200 BZ)

Collection angle:

±7 deg, newer models ±15 deg

Example of ARPES data



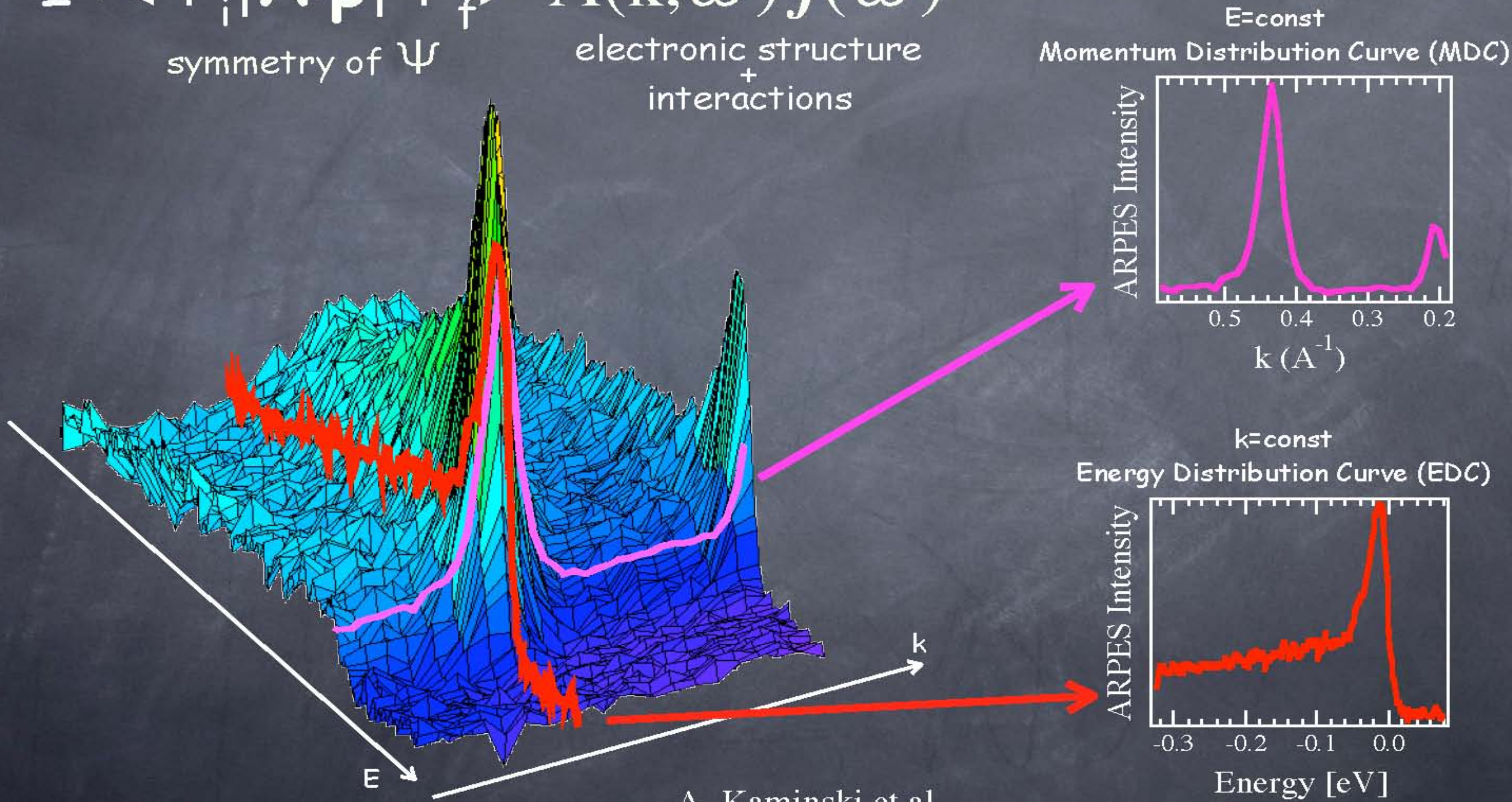


ARPES intensity

$$I = \langle \Psi_i | \mathbf{A \cdot p} | \Psi_f \rangle^2 A(k,\omega)\, f(\omega)$$

symmetry of Ψ

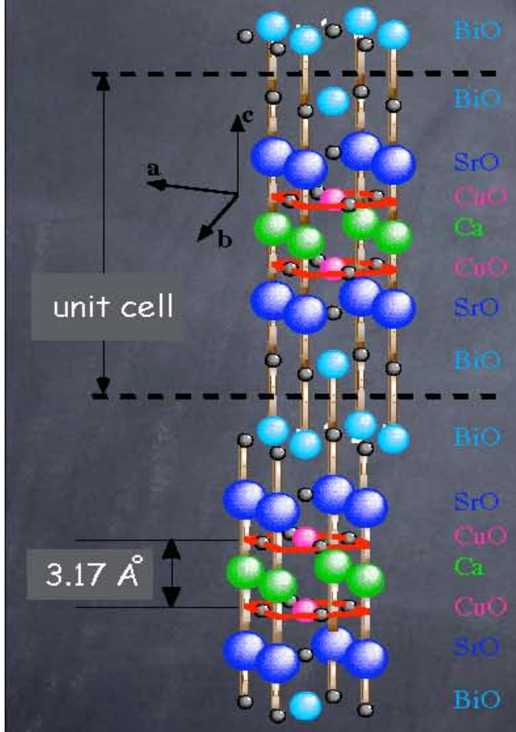
electronic structure + interactions



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

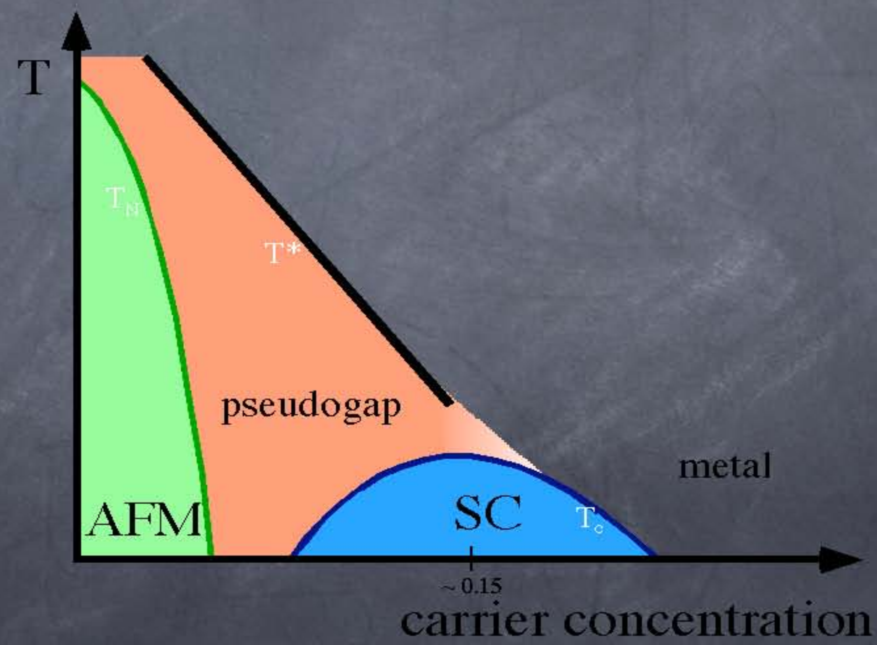
Spectral function describes probability of removing (or adding) an electron to the system

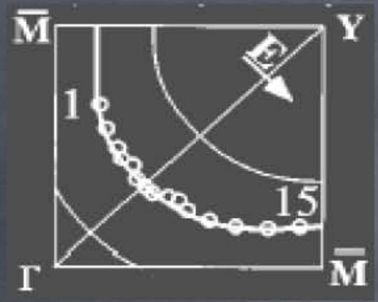
High temperature superconductors



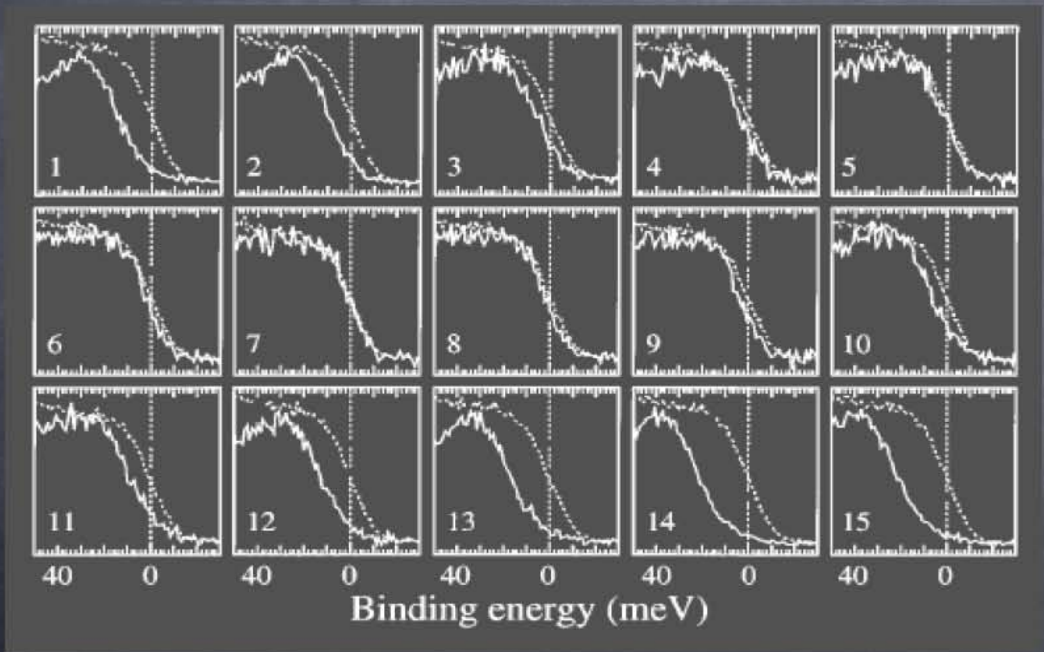
$Bi_2Sr_2CaCu_2O_{8+d}$

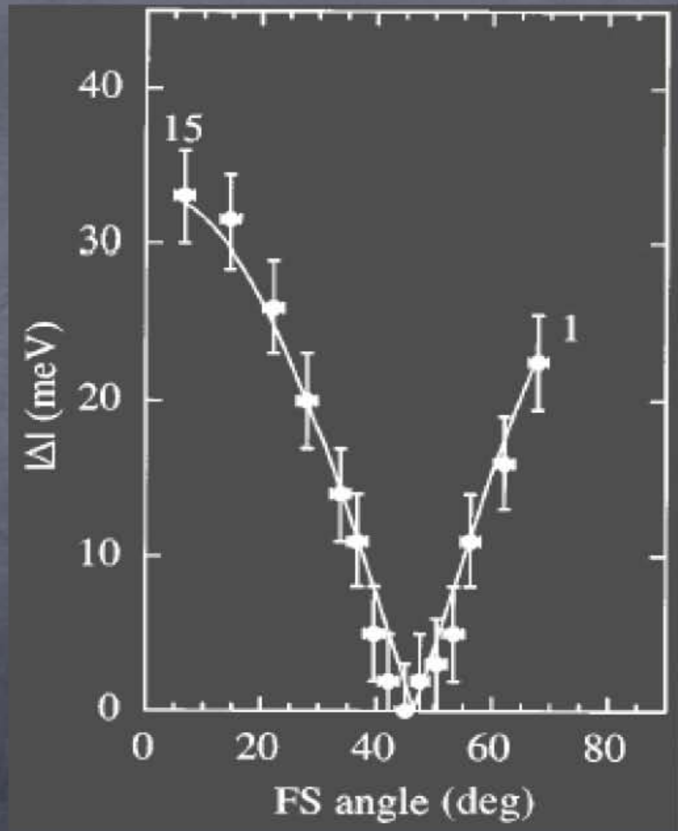
What is the mechanism?
What is the pseudogap state?
What is the physics of the abnormal state above Tc?



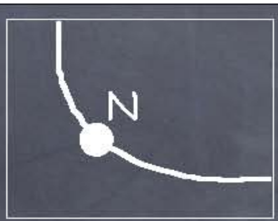


d-wave symmetry of order parameter



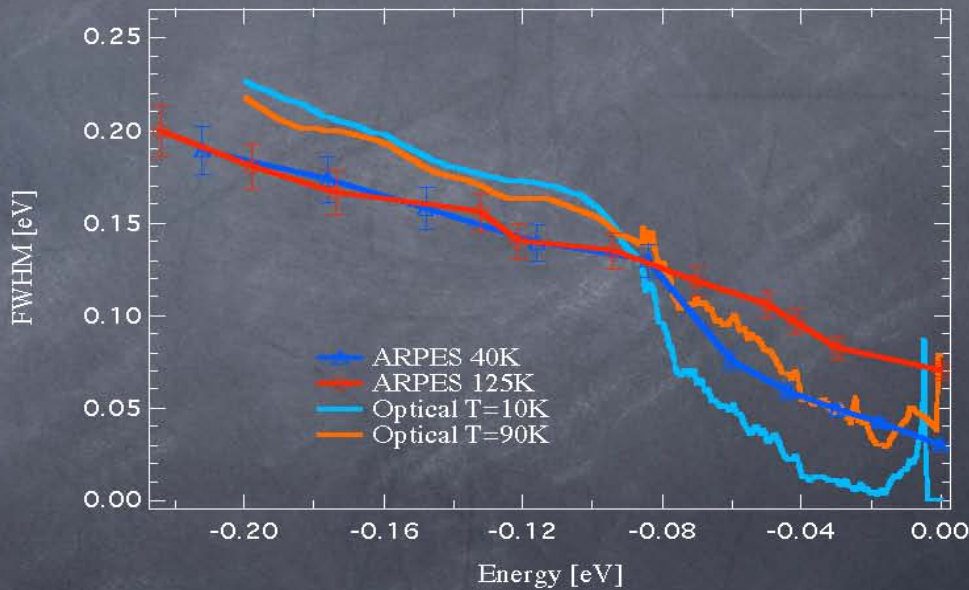


H. Ding et al., *Phys. Rev.* B **54**, 9678 (1996)



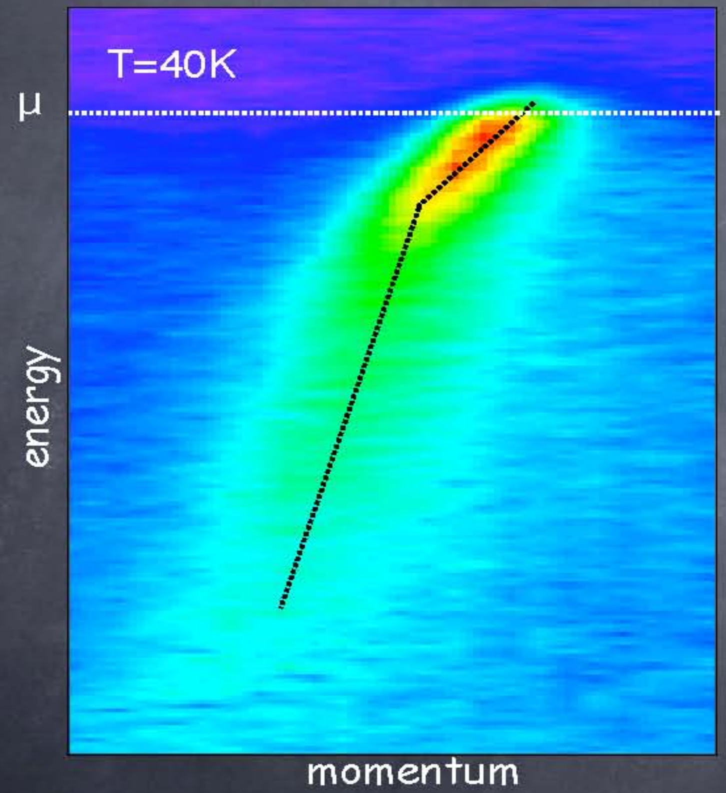
Nodal quasiparticles and changes in scattering rate

suppression of scattering rate below Tc

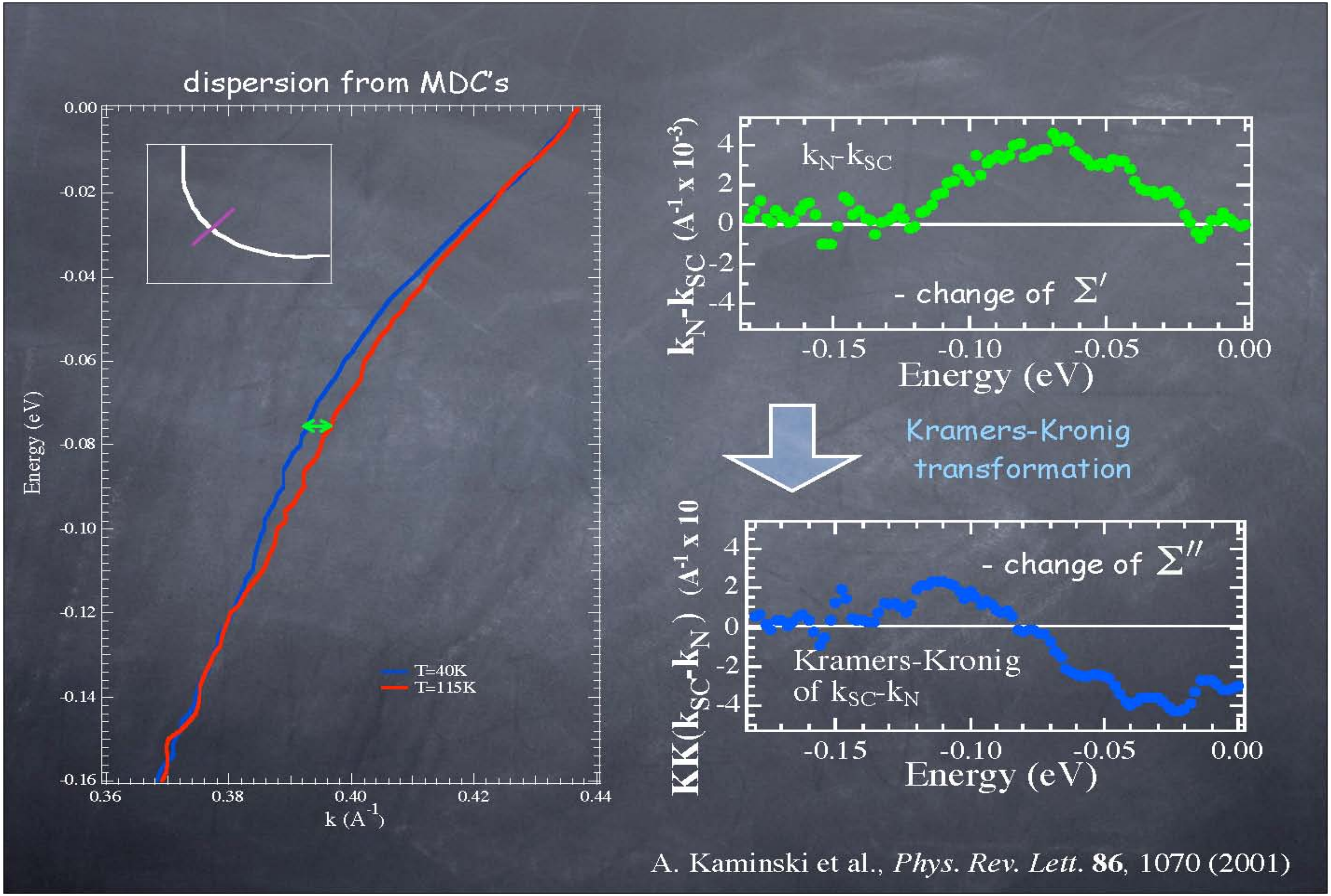


A. Kaminski et al., *Phys. Rev. Lett.* **84**, 1788 (2000)

Renormalization effects along nodal direction



T. Valla et al., *Science* **24**, 2110 (1999)
P.V. Bogdanov et al., *Phys. Rev. Lett.* **85**, 2581 (2001)
A. Kaminski et al., *Phys. Rev. Lett.* **86**, 1070 (2001)


dispersion from MDC's
Energy (eV)
k (A-1)
T=40K
T=115K
kN-kSC
- change of Σ′
kN-kSC (A-1 x 10-3)
Energy (eV)
Kramers-Kronig
transformation
- change of Σ″
Kramers-Kronig
of kSC-kN
KK(kSC-kN) (A-1 x 10
Energy (eV)
A. Kaminski et al., Phys. Rev. Lett. 86, 1070 (2001)

Collective mode(s) in cuprates

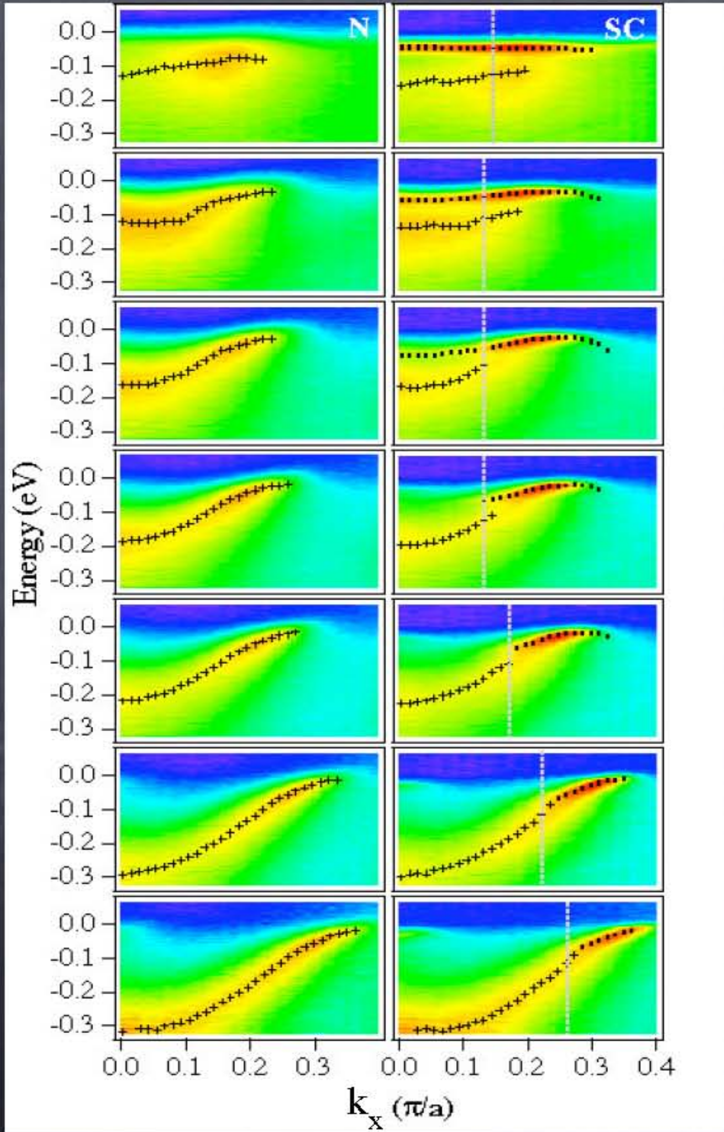
Neutron resonance camp:

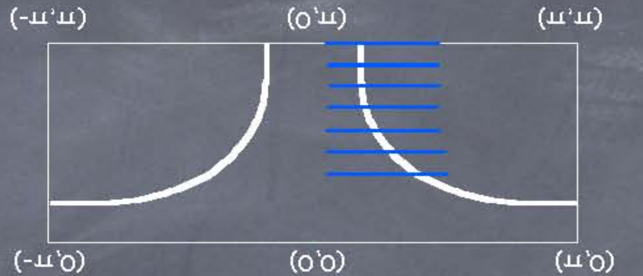
Rosat-Mignod et al. (INS)
B. Keimer, P. Bourges et al. (INS)
Z. X. Shen and J. R. Schrieffer (ARPES)
M. R. Norman, J. C. Campuzano, H. Ding et al. (ARPES)
M. R. Norman and M. Eschrig (theory)
Ar. Abanov and A. V. Chubukov (theory)

Phonon camp:

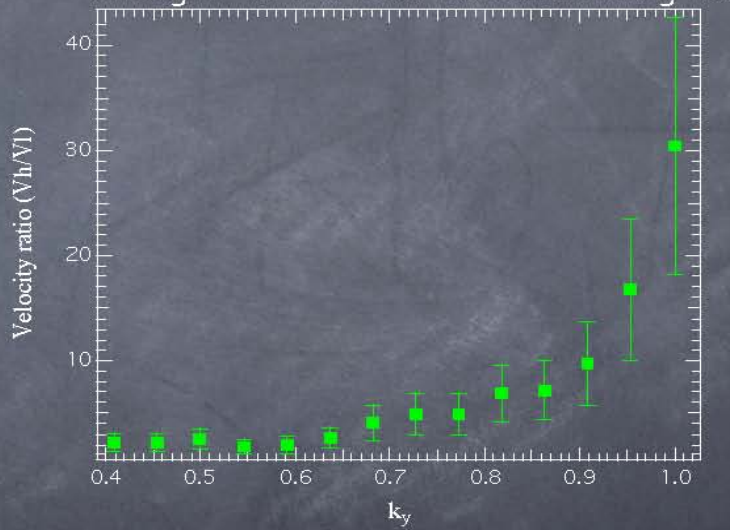
Z. X. Shen, A. Lanzara (ARPES)

Momentum anisotropy of renormalization effects





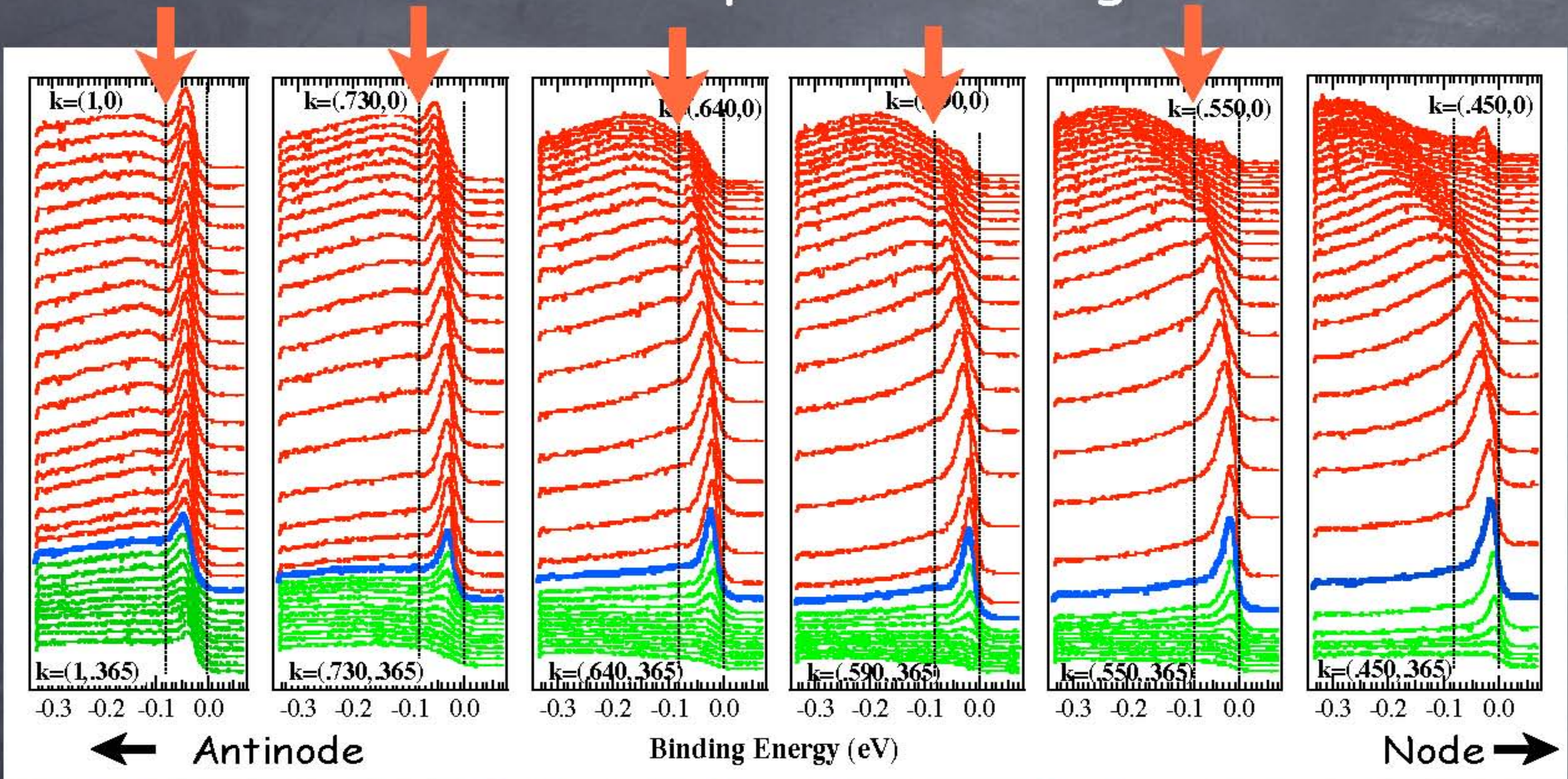
"strength" of the renormalization along FS



The renormalization effects are strongest at the antinode

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

EDC's in the superconducting state

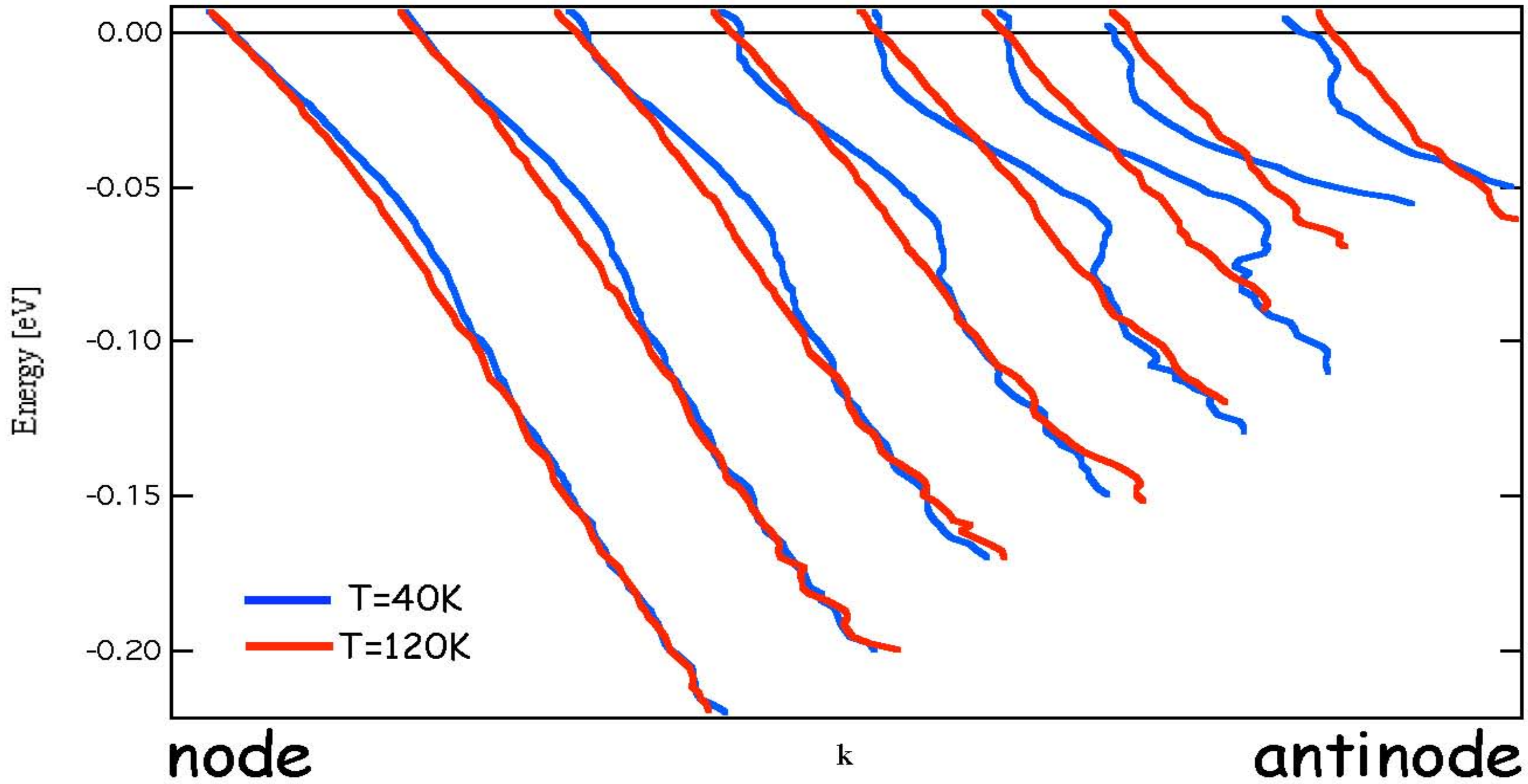


The energy of the collective mode is momentum indepndent

Since the dip occurs at the same energy throughout the Brilloiun zone it cannot be caused by the bilayer splitting - instead it is a signature of many body interactions

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

MDC dispersion in normal and superconducting states



The mode is only observed in superconducting state

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

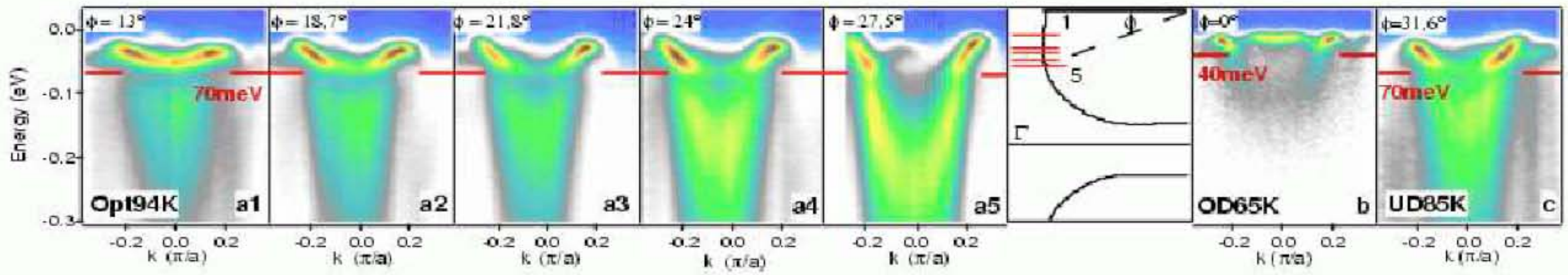
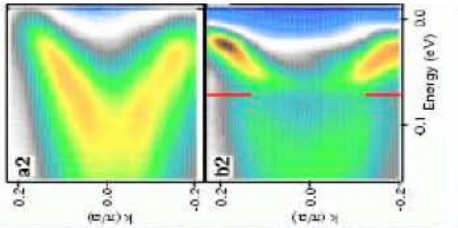
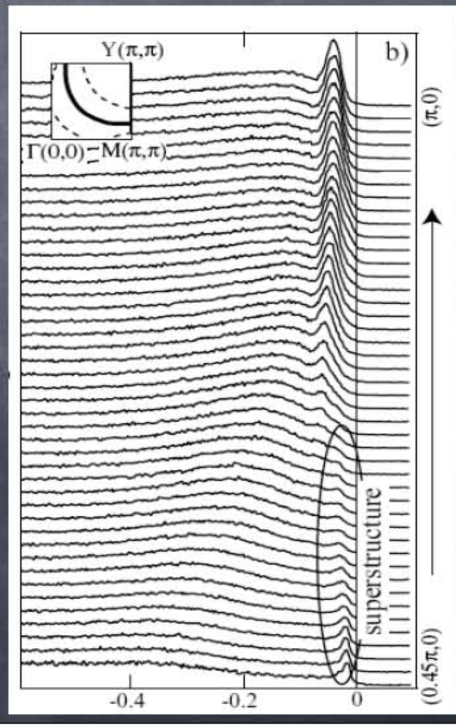


FIG. 3: The image plots in a1-a5)are cuts taken parallel to $(0,\pi)$-(π,π) at the locations indicated in the zone at 15K for an optimally doped sample (94K). b) and c) are spectra taken parallel to $(0,\pi)$-(π,π) at the k-space locations indicated for over-doped (65K) and under-doped samples (85K) respectively.



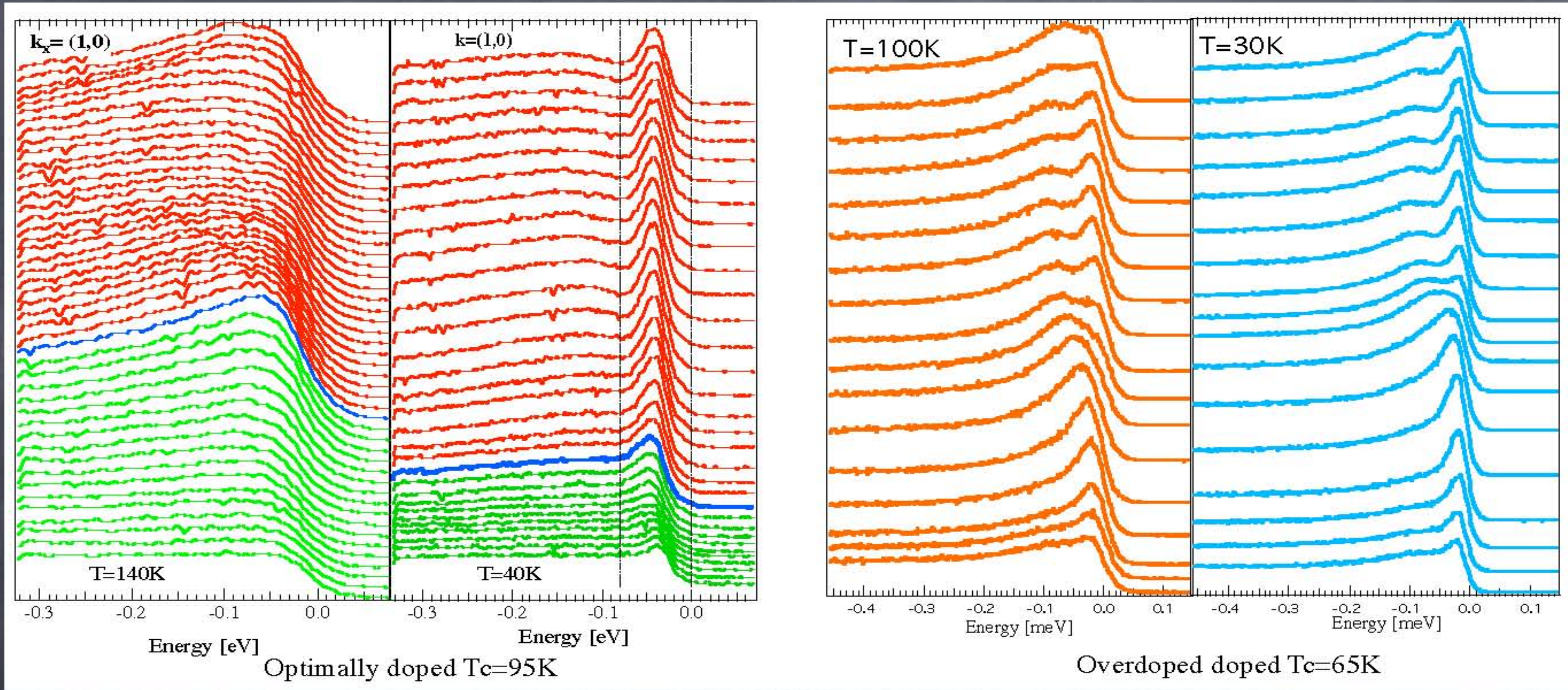
T. Cuk, Z. X. Shen et al., cond-mat/0403521 v2 (2003)



All properties of the collective mode in the superconducting state of optimally dopedoped samples were recently confirmed by data by of Cuk et al. and He et al.

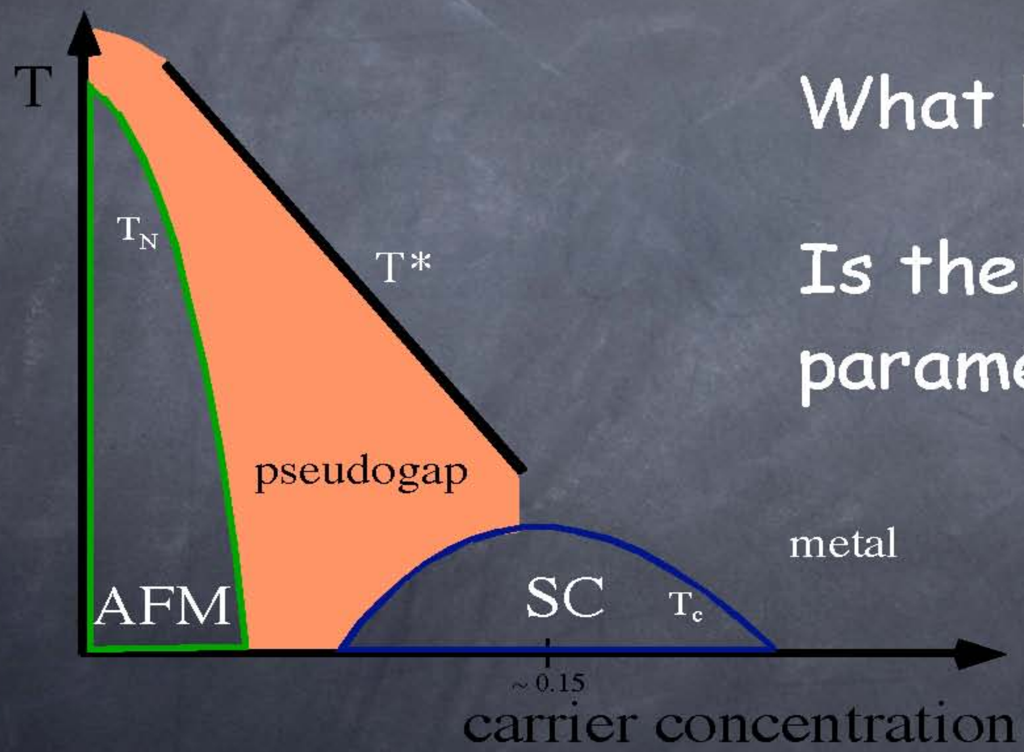
R. H. He, D. L. Feng et al., cond-mat/0402247 (2004)

Doping dependence of renormalization effects



While the interaction with the collective mode leads to a very strong renormalization at optimal doping, the spectra from heavily overdoped samples are barely affected by the superconducting transition.
This indicates that the collective mode is either very weak or absent at high doping levels, which is consistent with INS and infrared measurements.

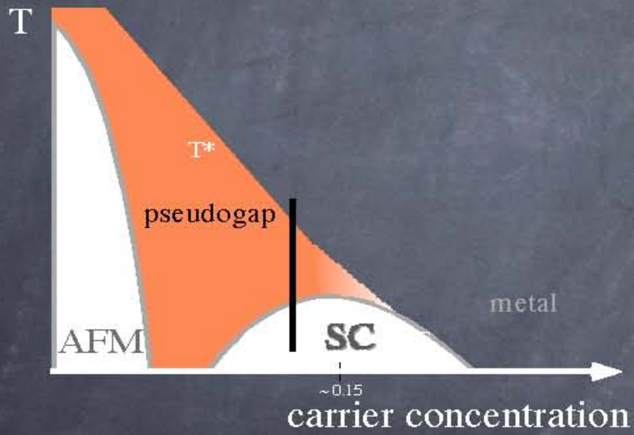
Time reversal symmetry violation in pseudogap state of cuprates

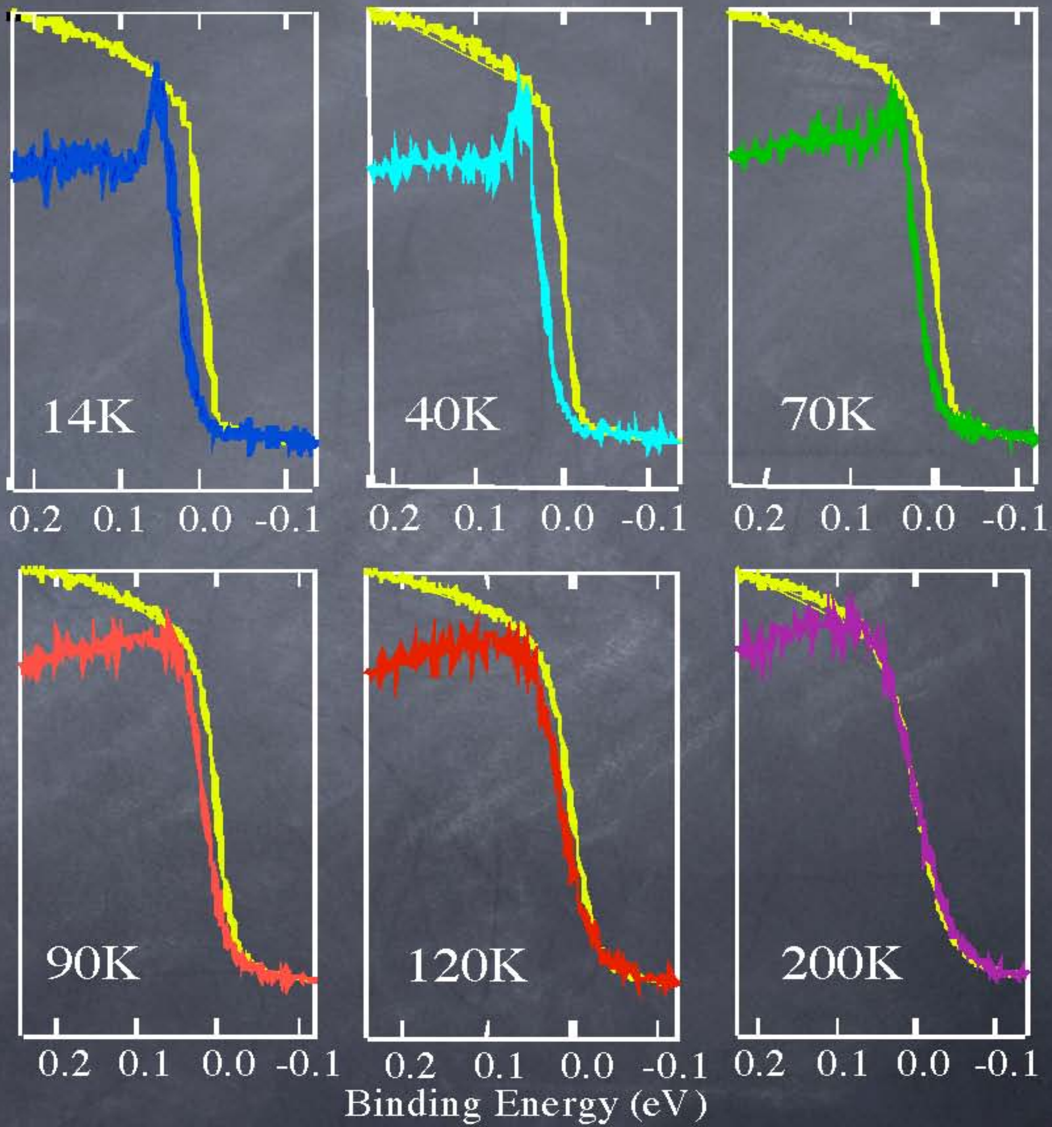


What happens at T*?

Is there a hidden order parameter?

Pseudogap in underdoped samples (T_c~87K)

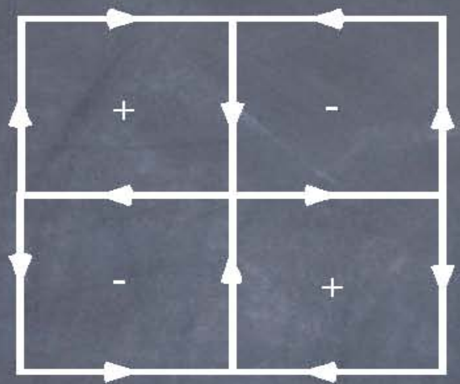




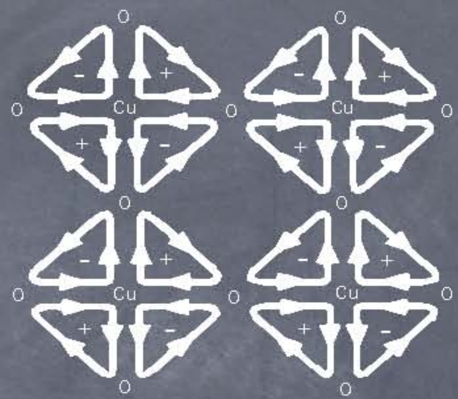
H. Ding et al., *Nature* **382,** 51 (1996)

Circulating currents?

P. W. Anderson, G. Kotliar, I. Affleck, J. B. Marston
C. M. Varma
R. B. Laughlin, S. Chakravarty, P. A. Lee



T. C. Hsu, J. B. Marston, I. Affleck,
Phys. Rev. B **43**, 2866 (1991)



C. M., Varma,
Phys. Rev. B **55**, 14554 (1997).

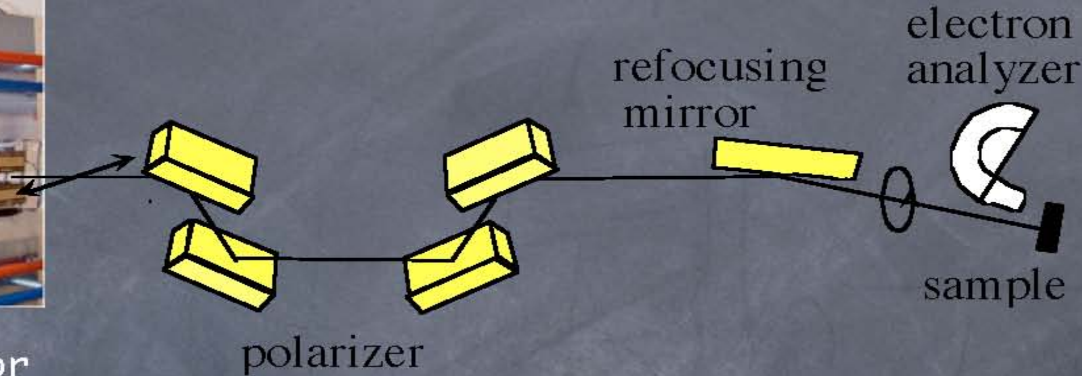
ARPES intensity:

$$I = \langle \Psi_i | \mathbf{A}\cdot\mathbf{p} | \Psi_f \rangle^2 A(k,\omega) f(\omega)$$

symmetry of Ψ_i

electronic structure
+
interactions

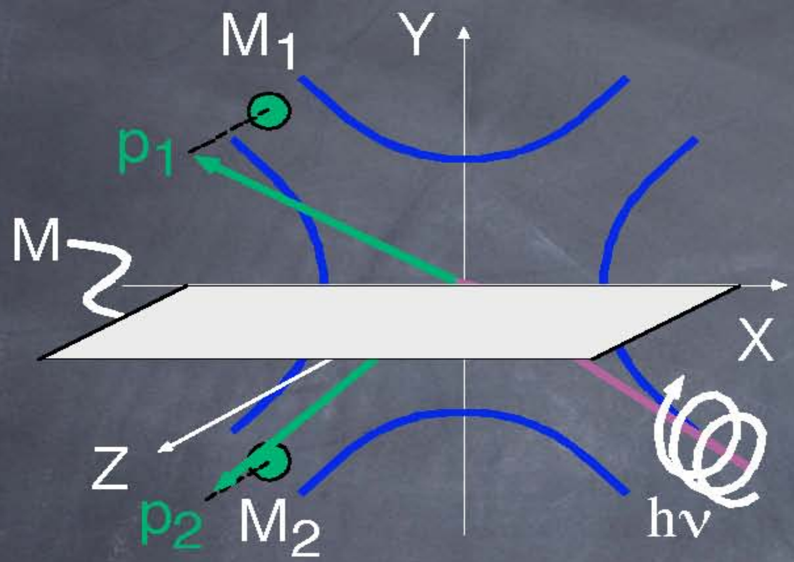
Experimental setup



undulator + monochromator
Synchrotron Radiation Center

Dichroism signal:

$$D = |\langle\Psi_f(p)|\, R\, |\Psi_i(k)\rangle|^2 - |\langle\Psi_f(p)|\, \mathbf{L}\, |\Psi_i(k)\rangle|^2 \sim \mathbf{I}_{\mathbf{RCP}} - \mathbf{I}_{\mathbf{RCP}}$$



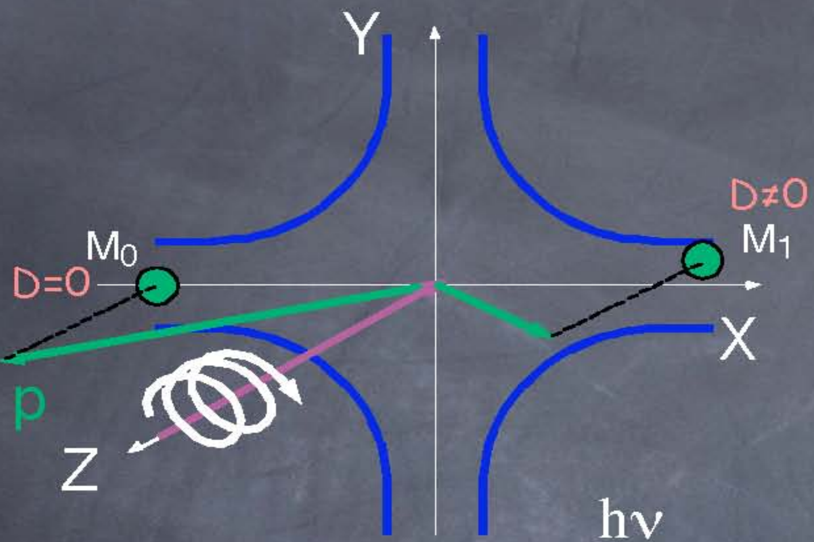
"Geometric dichroism"
due to experimental setup

$$\mathscr{R}\,|\Psi_i(k)\rangle = \mathscr{R}\,\{|\Psi_{is}(k)\rangle + |\Psi_{ia}(k)\rangle\} = |\Psi_{is}(k)\rangle - |\Psi_{ia}(k)\rangle$$

$$\mathscr{R}\,|\Psi_f(p)\rangle = \mathscr{R}\,\{|\Psi_{fs}(k)\rangle + |\Psi_{fa}(k)\rangle\} = |\Psi_{fs}(k)\rangle - |\Psi_{fa}(k)\rangle$$

$D \neq 0$

D. Venus *Phys. Rev.* B **48**, 6144 (1993)



Even in absence of time reversal symmetry breaking D=0 only at the mirror planes of the crystal

$$\mathscr{R}^{-1}\, R\, \mathscr{R} = L$$

$$|\langle \Psi_f(p)\,|\,L\,|\,\Psi_i(k)\rangle|^2 = |\langle \Psi_f(p)|\, \mathscr{R}^{-1}\, R\, \mathscr{R}\, |\Psi_i(k)\rangle|^2$$

$$\mathscr{R}\, |\Psi_i(k)\rangle = |\Psi_i(k)\rangle \quad ; \quad \mathscr{R}\, |\Psi_f(p)\rangle = |\Psi_f(p)\rangle$$

$$D = |\langle \Psi_f(p)|\, R\, |\Psi_i(k)\rangle|^2 - |\langle \Psi_f(p)|\, \mathscr{R}^{-1}\, R\, \mathscr{R}\, |\Psi_i(k)\rangle|^2 = 0$$

D. Venus *Phys. Rev.* B **48**, 6144 (1993)

Time reversal symmetry breaking state:

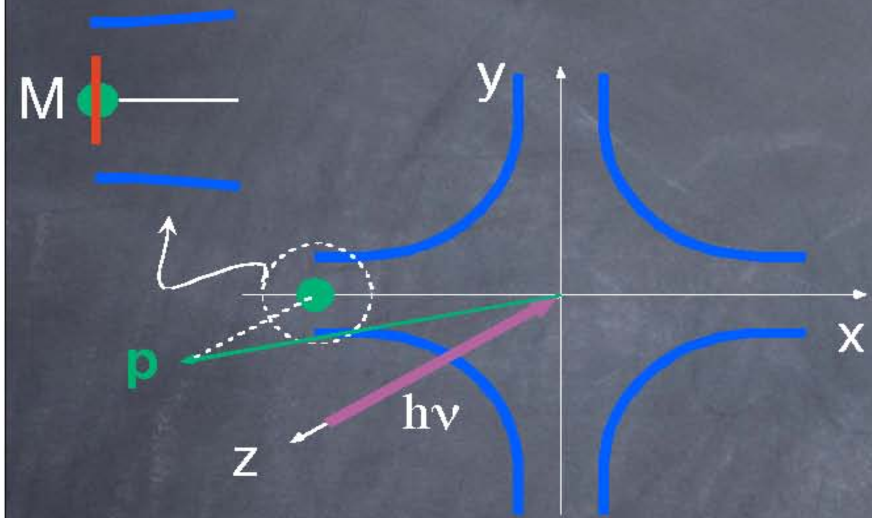
$$| \Psi_i(k) \rangle = | \Psi_e(k) \rangle + \theta \, | \Psi_o(k) \rangle \}$$

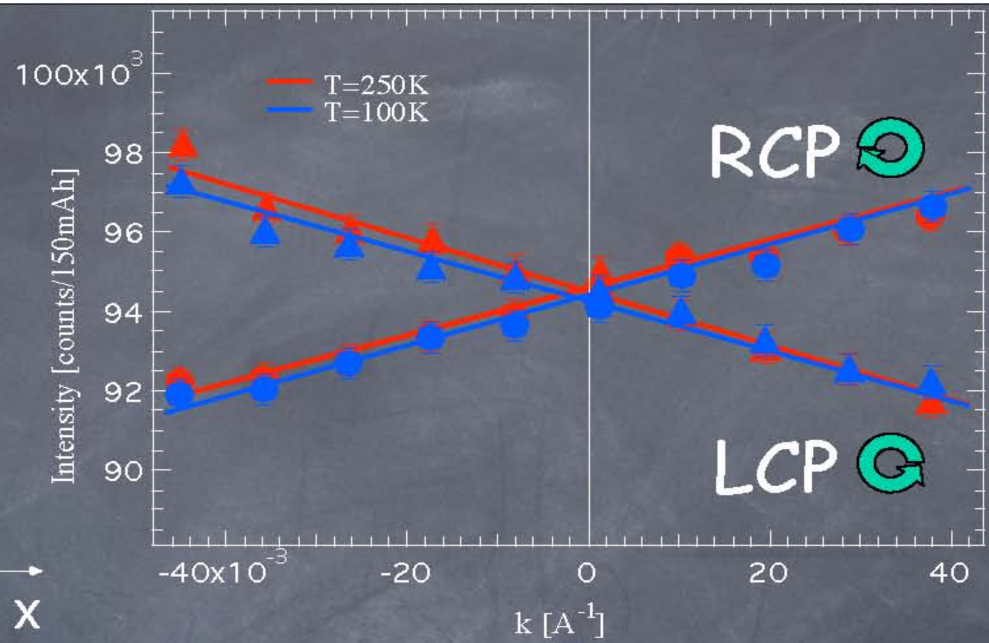
$$\mathscr{T} \, |\Psi_i(k)\rangle = \mathscr{T} \, \{|\Psi_e(k)\rangle + \theta \, |\Psi_o(k)\rangle\} = |\Psi_e(k)\rangle - \theta \, |\Psi_o(k)\rangle$$

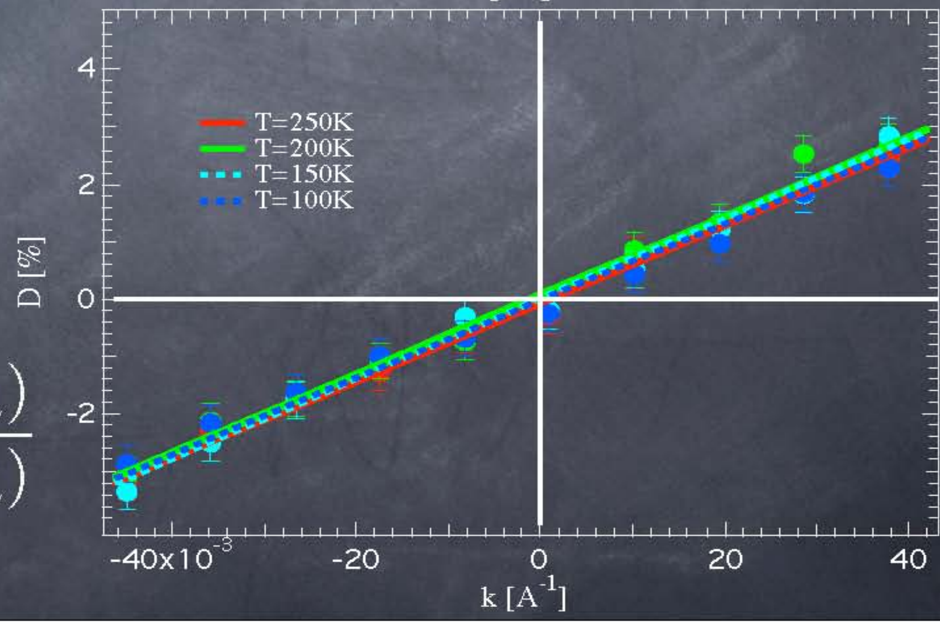
$$D \sim 4\,\theta \;\mathrm{Re}\, \{ | \langle\Psi_{fe}(p)| \; R \; |\Psi_{ie}(k)\rangle | \;\; |\langle\Psi_{ie}(k)| \; R \; |\Psi_{fo}(p)\rangle | +$$
$$+ | \langle\Psi_{fo}(p) | \; L \; | \Psi_{io}(k)\rangle | \;\; | \langle\Psi_{io}(k)| \; L \; |\Psi_{fe}(p)\rangle | + \ldots . \} \neq 0$$

C. Varma, *Phys. Rev.* B **61**, R3804, (2000)
M. E. Simon, C. Varma, *Phys. Rev. Lett.* **89**, 247003-1 (2002)

Overdoped sample
Tc=65K



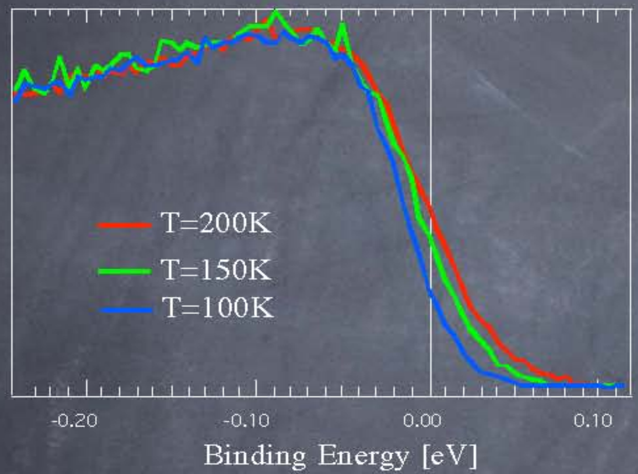


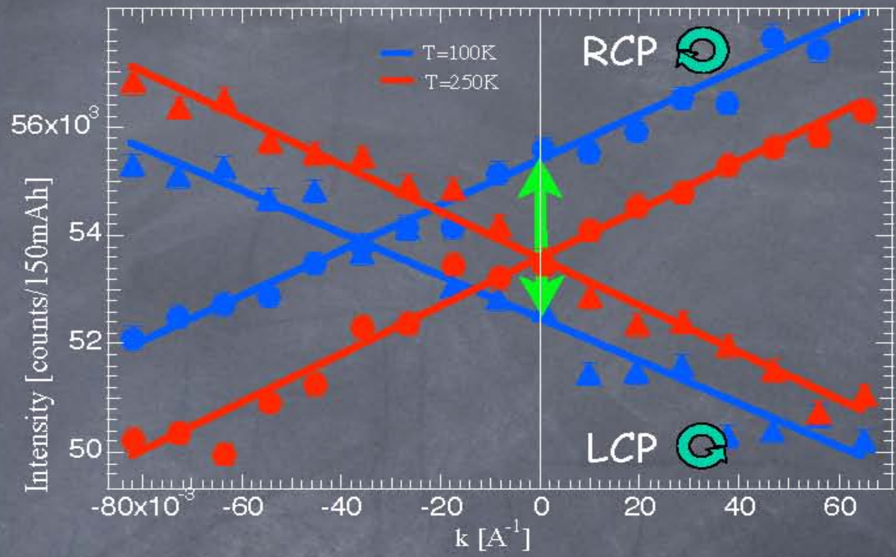


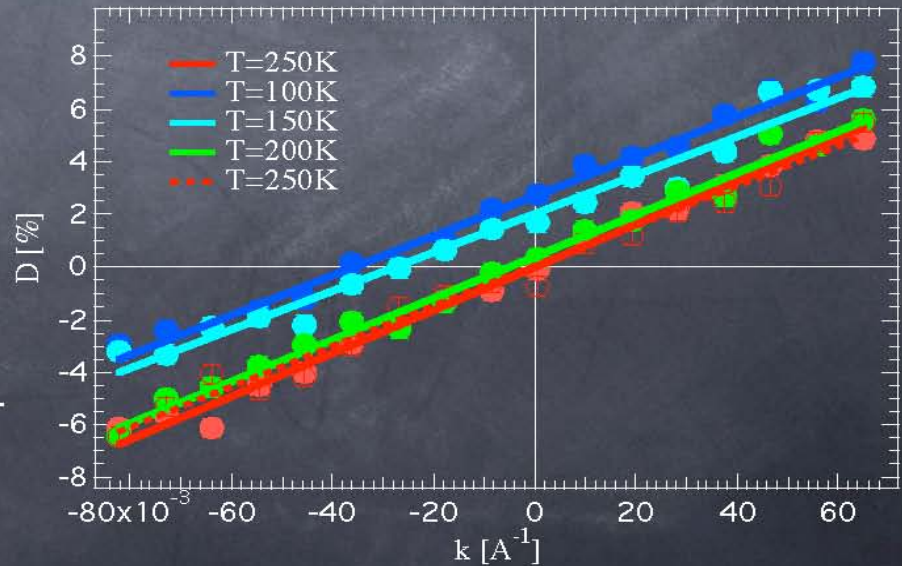
$$D = \frac{(I_R - I_L)}{(I_R + I_L)}$$

Underdoped sample

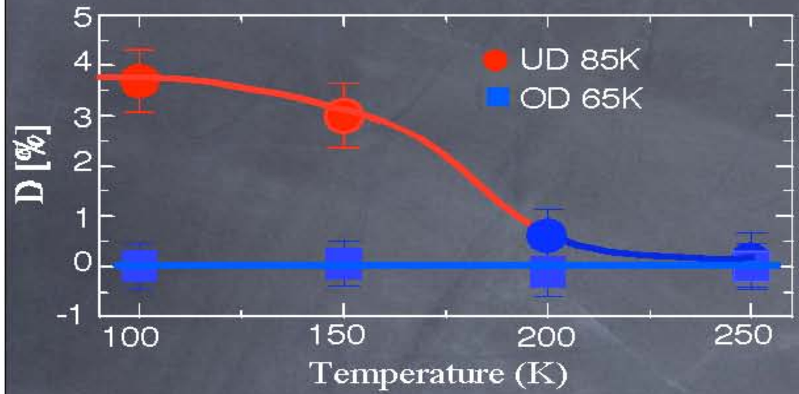
Tc=85K



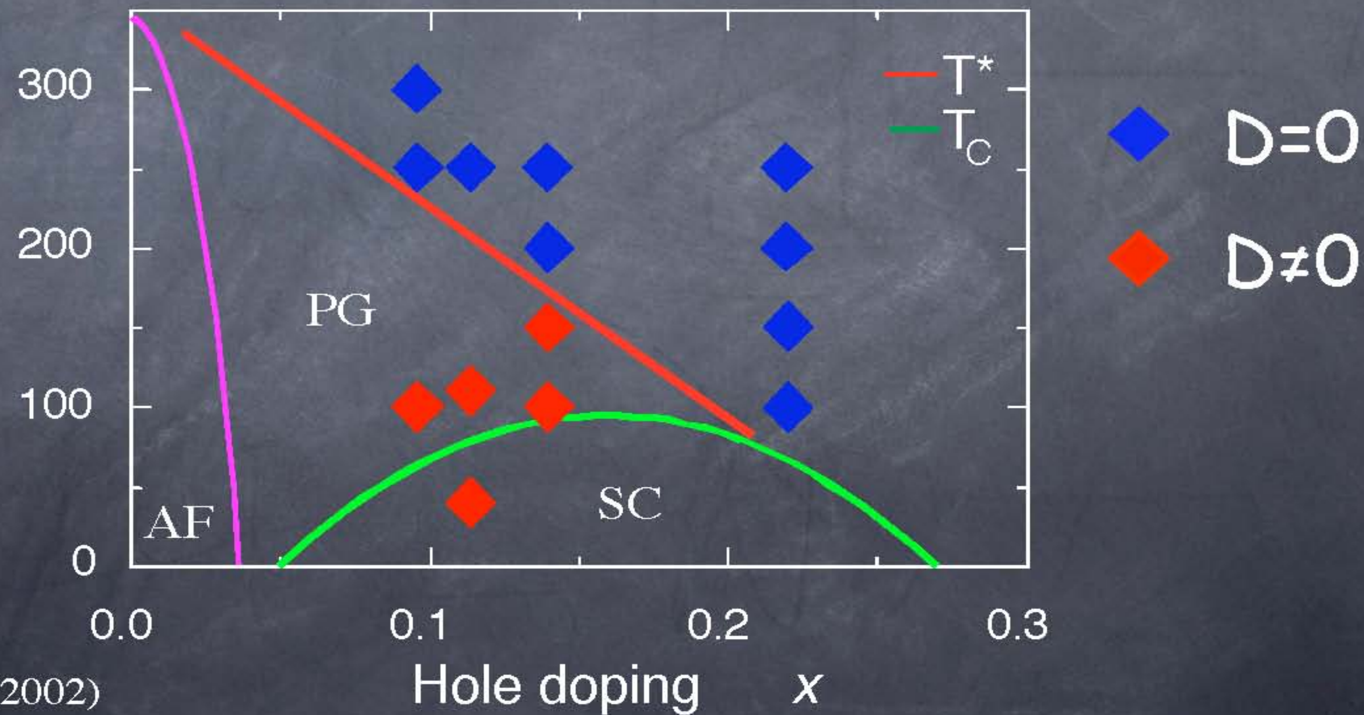




$$D = \frac{(I_R - I_L)}{(I_R + I_L)}$$

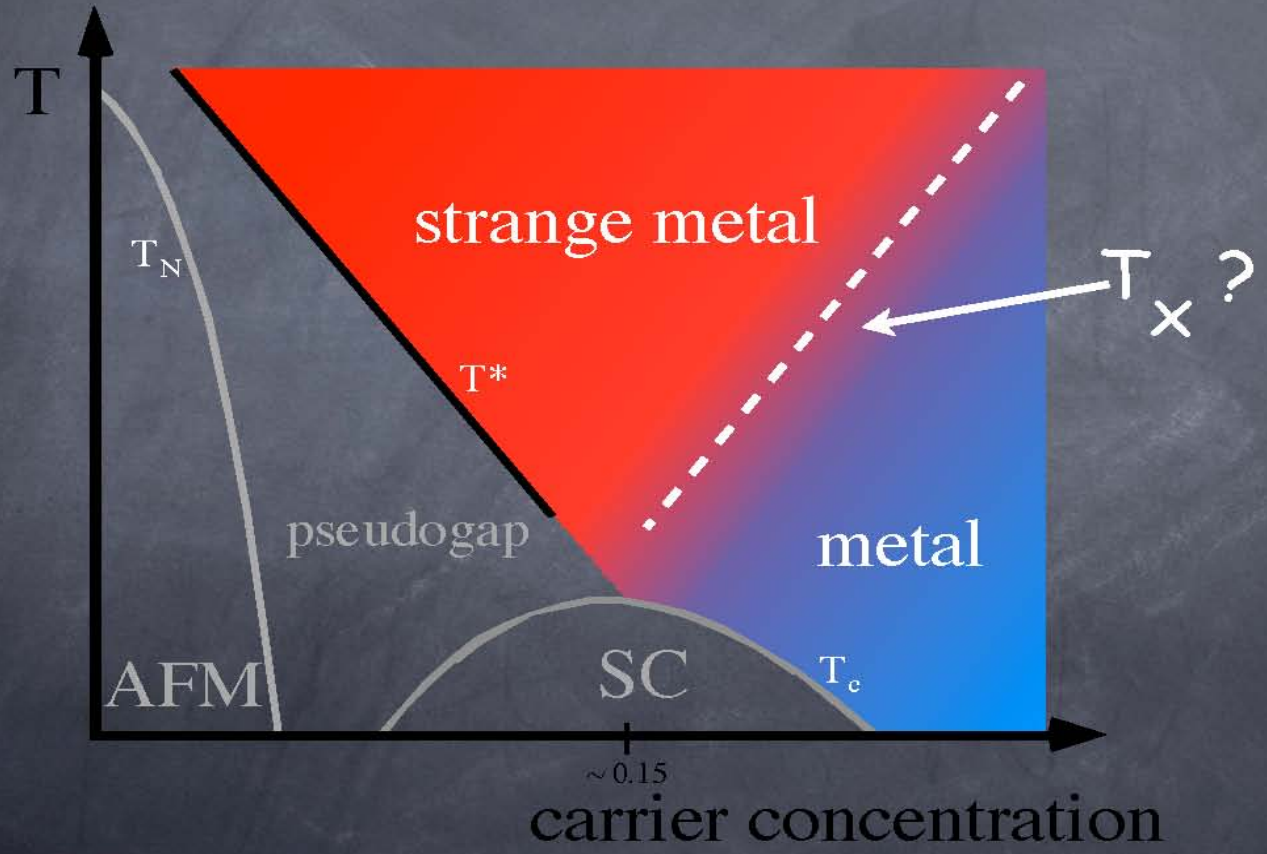


Observation of dichroism signal at the mirror plane indicates that time reversal symmetry is violated in the pseudogap state

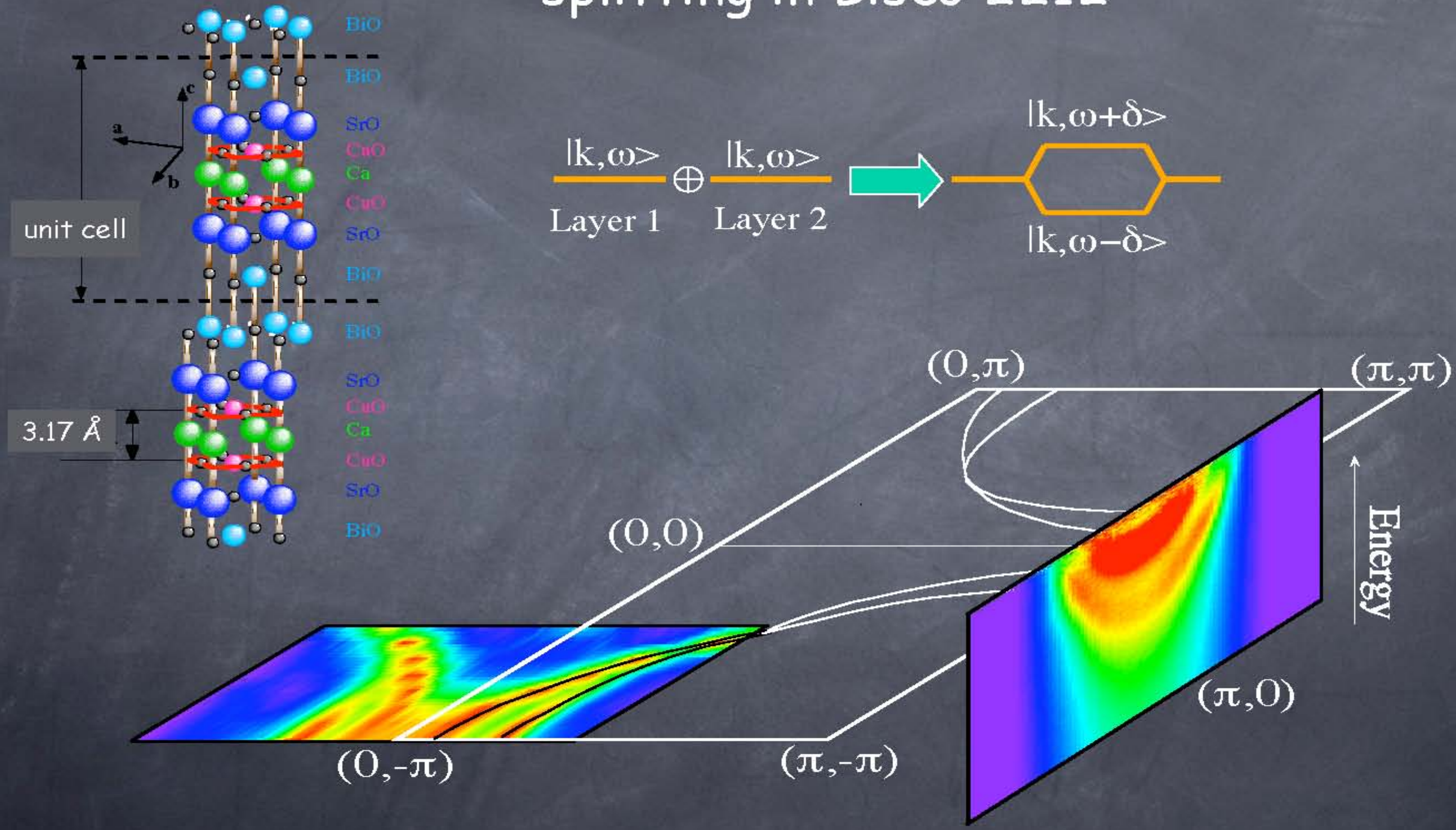


Kaminski et al.,
Nature **416**, 610 (2002)

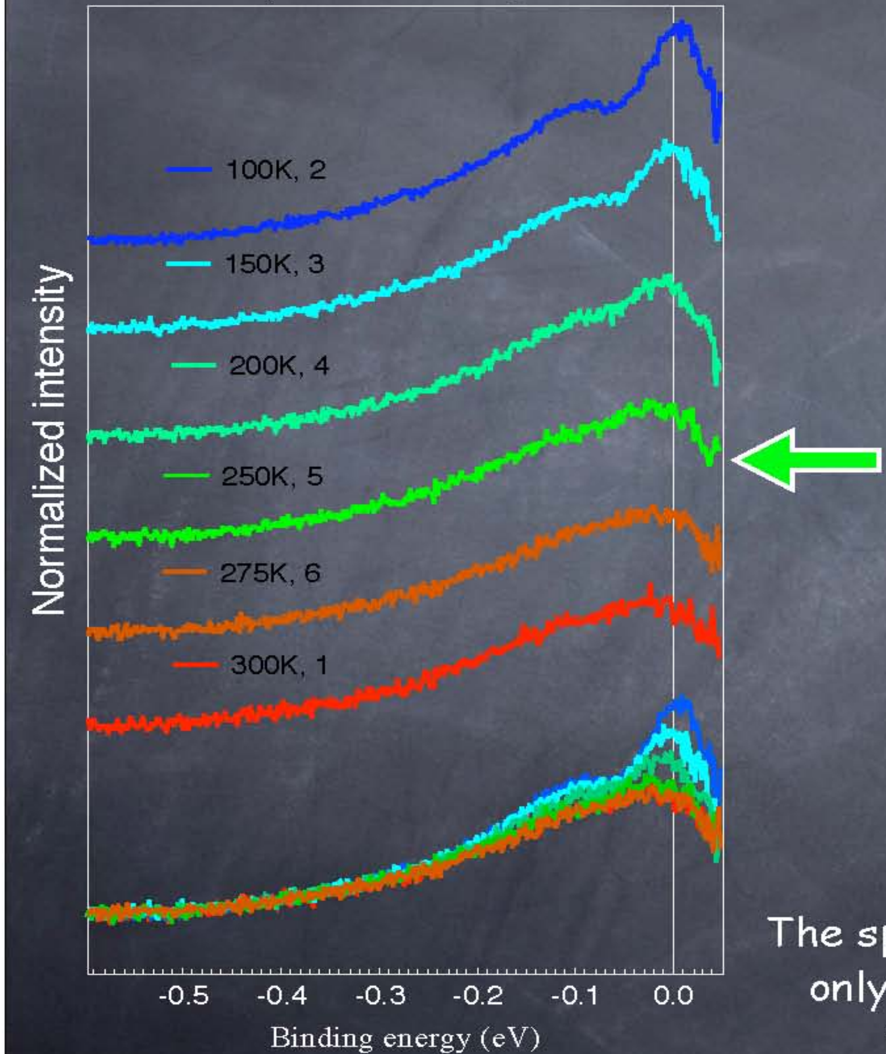
Coherent and incoherent states

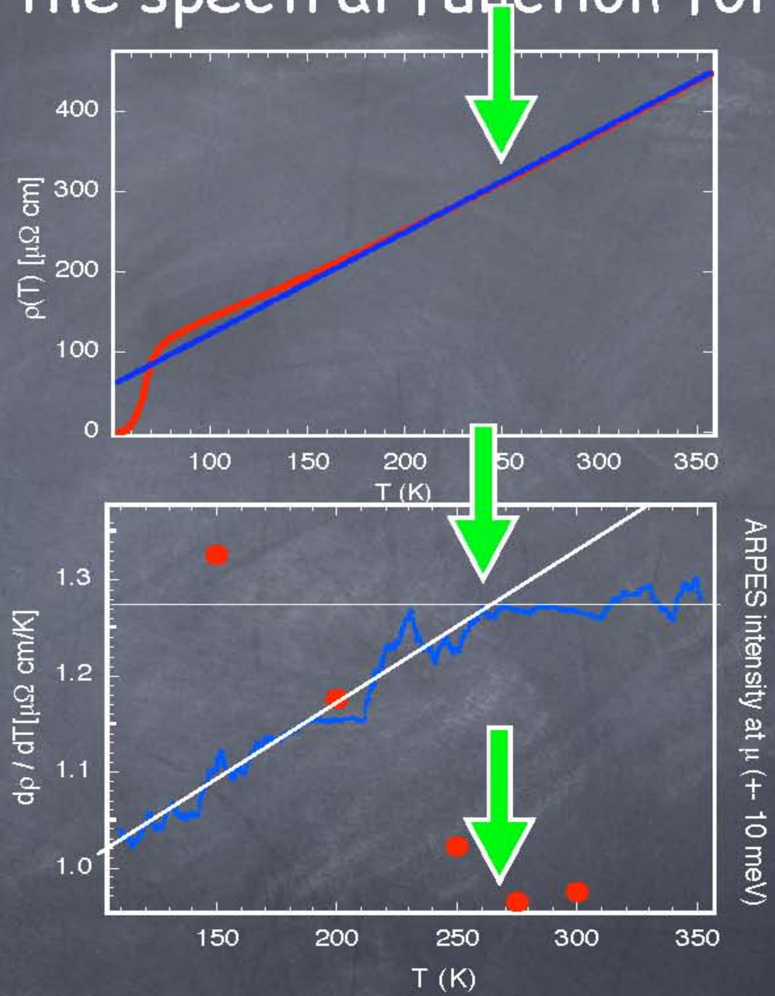


We can probe coherence by looking at bilayer splitting in Bisco 2212



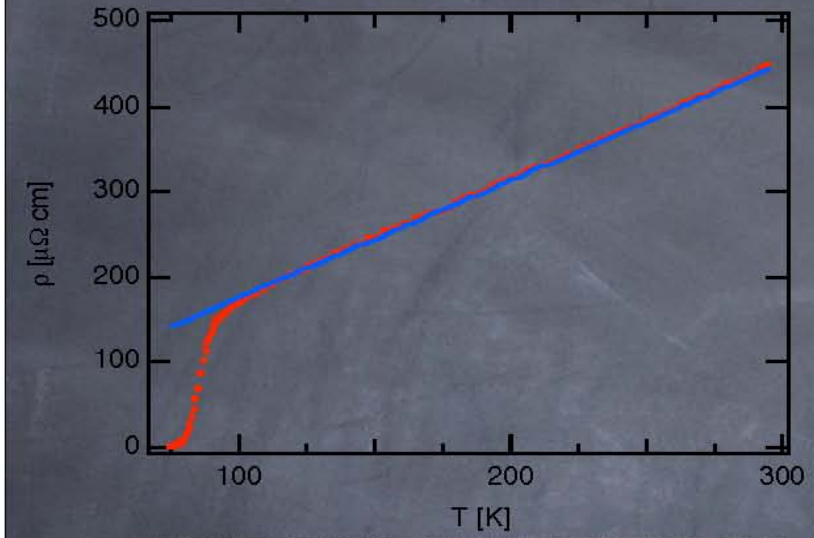
Temperature dependence of the spectral function for overdoped sample Tc=65K

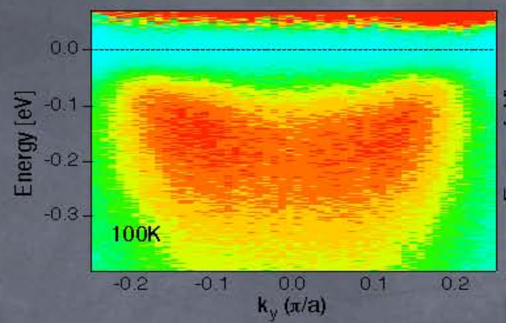


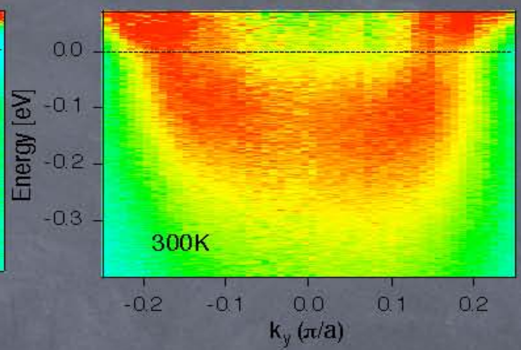


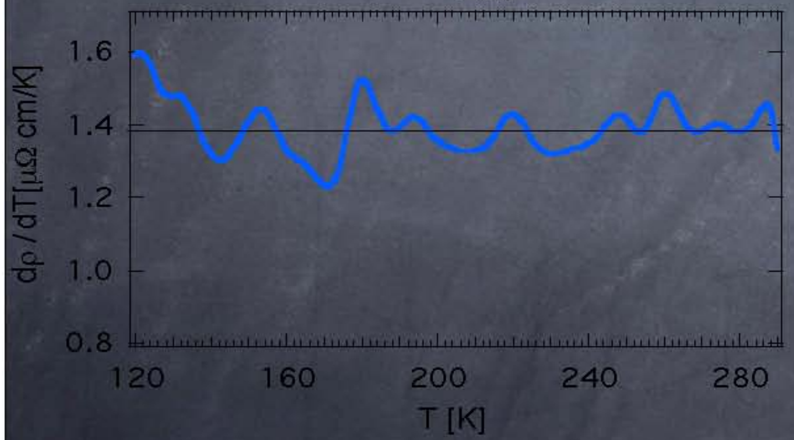
The spectral function changes with the temperature only below 250K. Above it becomes temperature independent and looses its coherent part

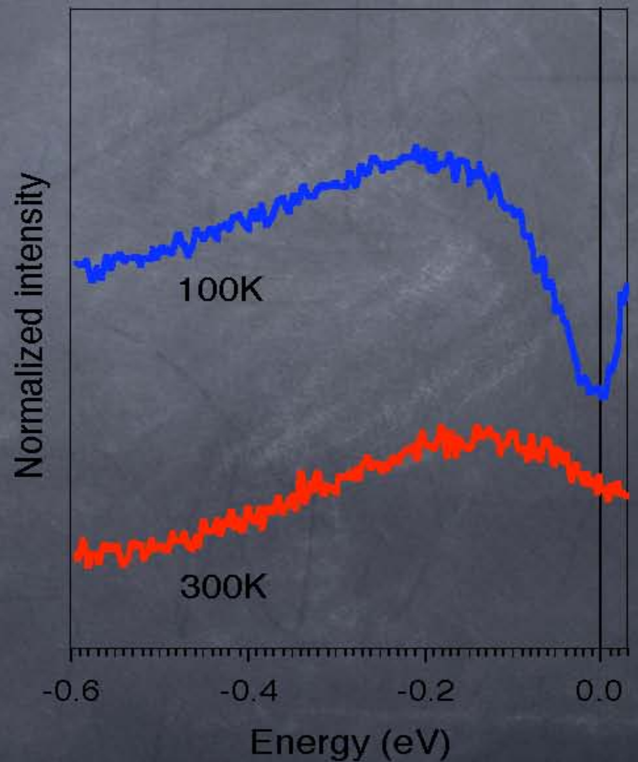
Optimally doped sample Tc=89K



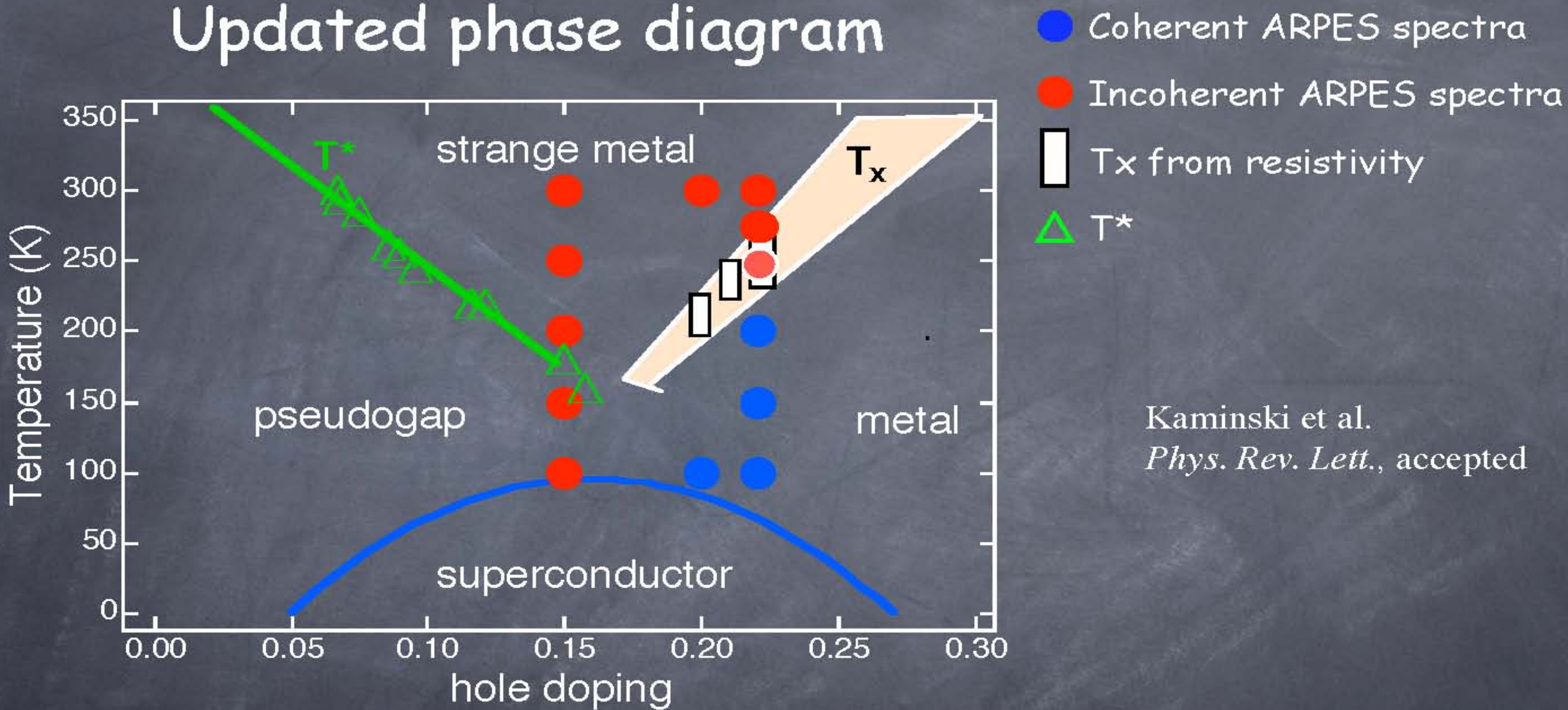








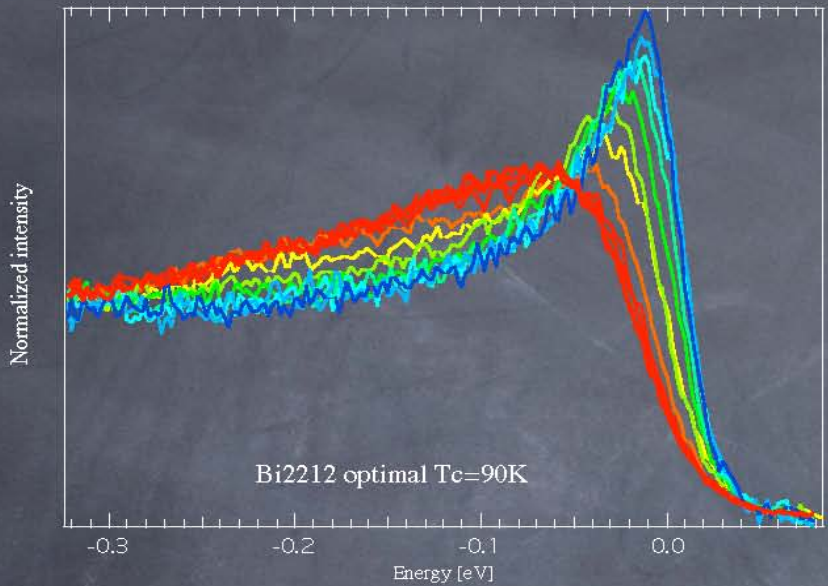
Updated phase diagram

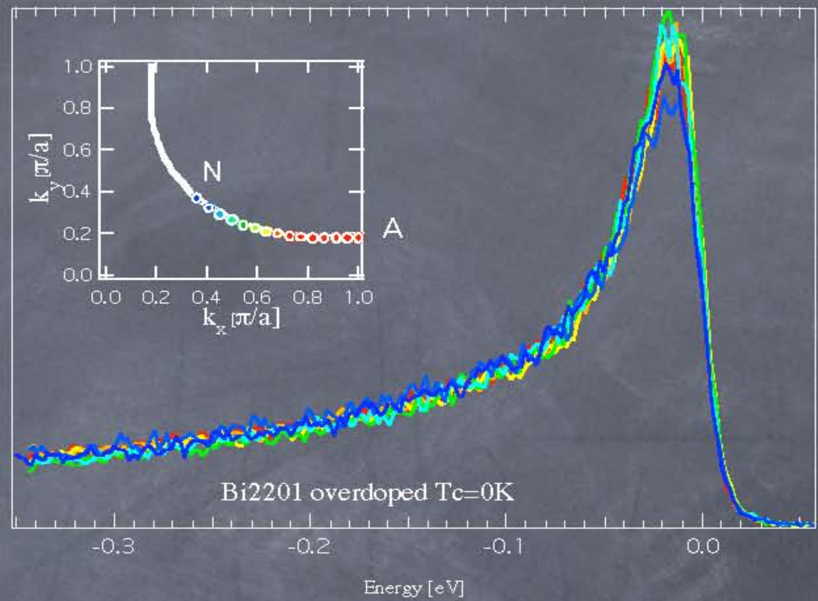


Kaminski et al.
Phys. Rev. Lett., accepted

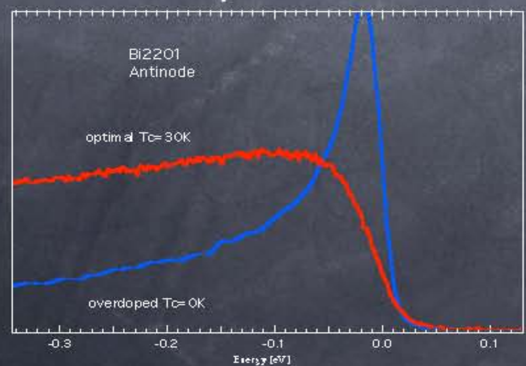
We observe a crossover transition from coherent state at low temperature and higher doping to incoherent state at higher temperature and lower doping

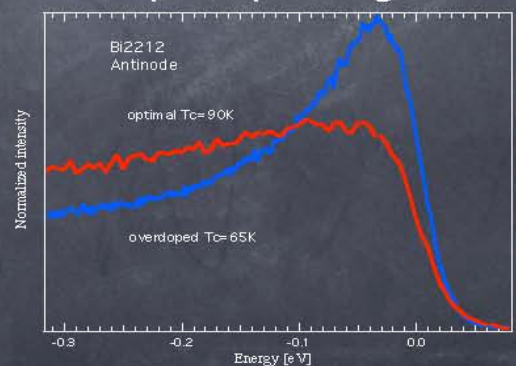
Anisotropy of the scattering rate





This anisotropy is observed in both single and double layer compounds - it is not due to bilayer splitting





Conclusions:

- all of the properties of collective mode observed by ARPES are consistent with ones of the resonant mode observed in neutron scattering experiments

- a dichroism signal is observed in underdoped samples below the pseudogap temperature T*, indicating broken Time Reversal Symmetry

- there is a crossover line in phase diagram separating regions of coherent and incoherent excitations