Experimental identification of HTSC pairing mechanism

by unification of modern momentum resolving techniques

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FPS’06, Zvenigorod, Russia

The complexity of HTSC properties is caused by the complexity of their electronic structure

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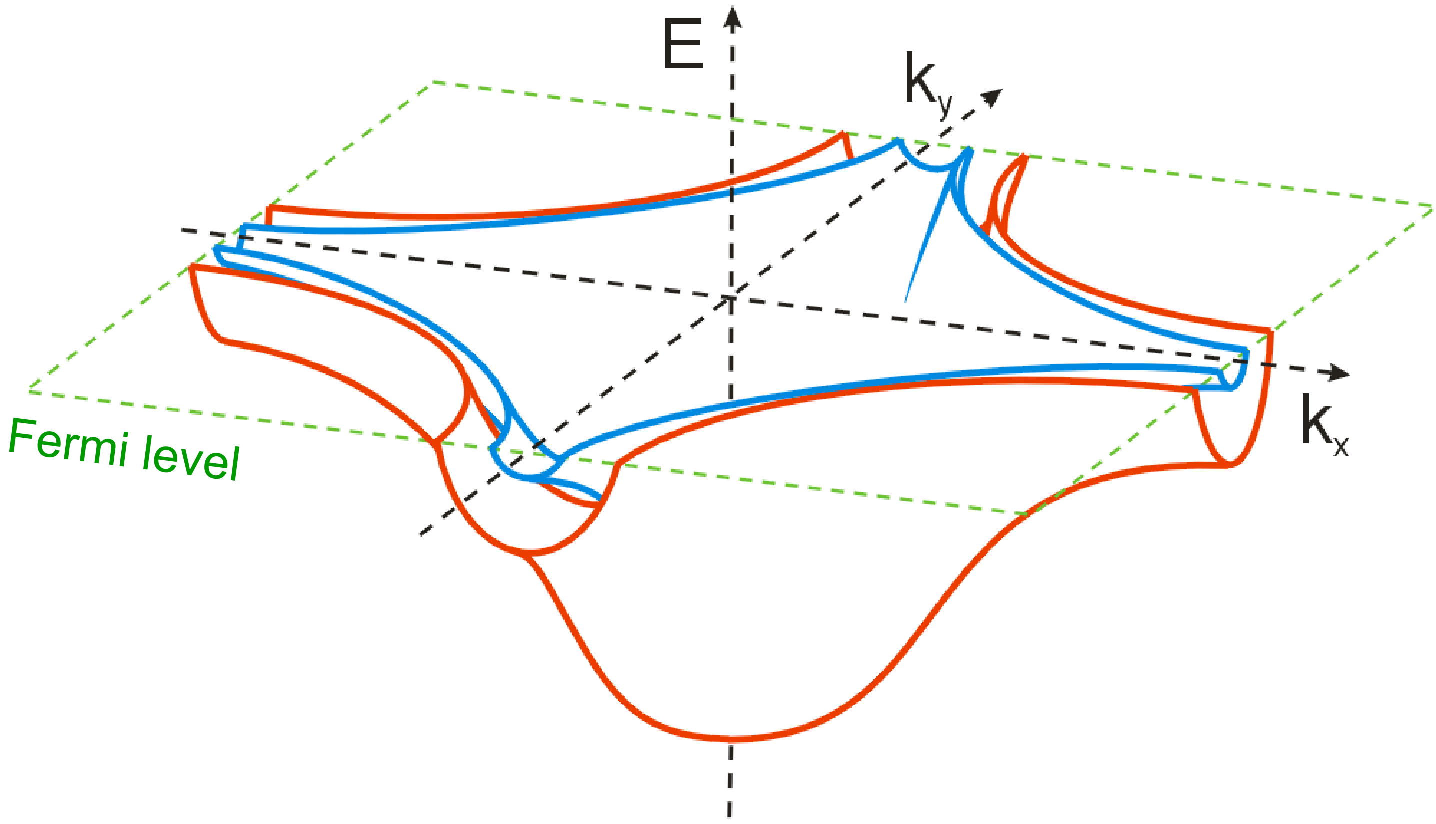
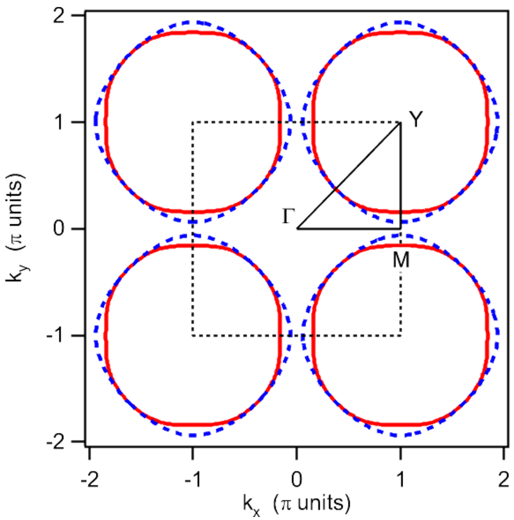
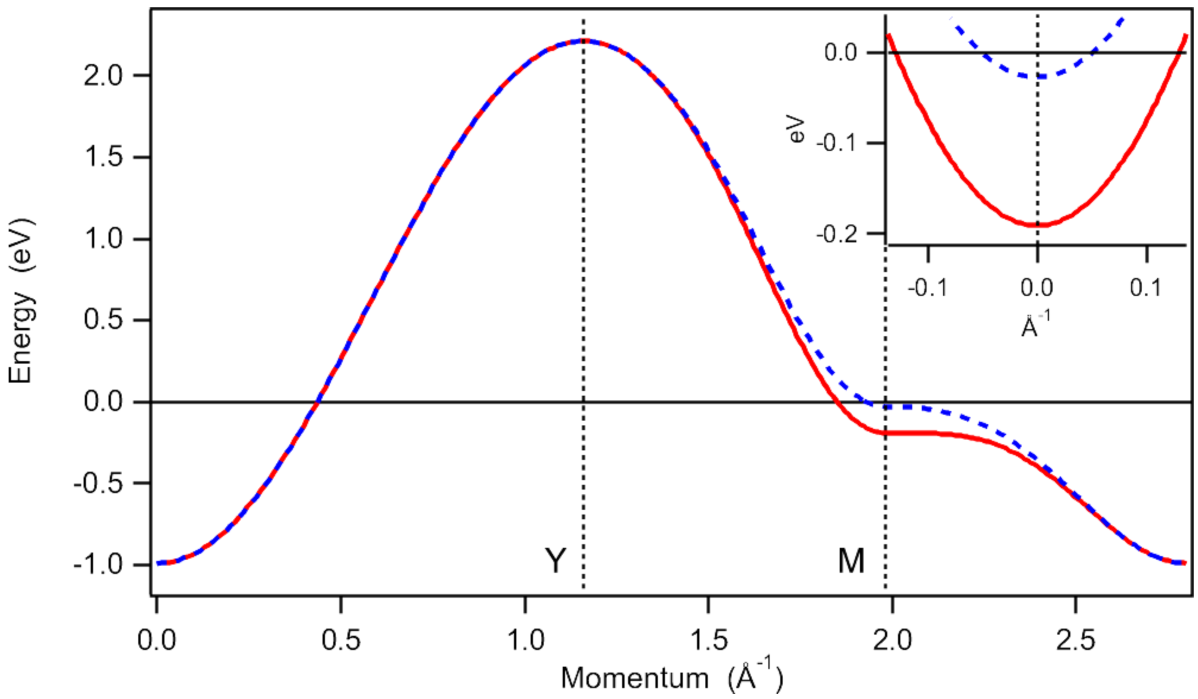


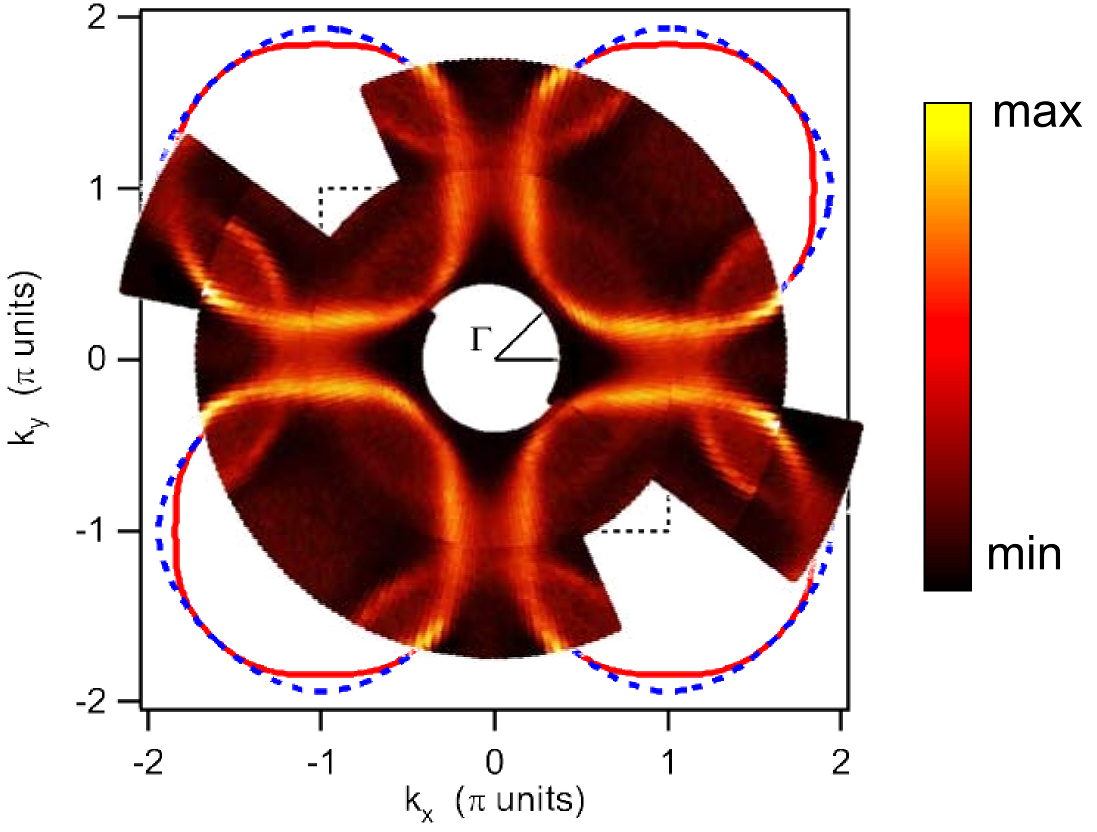
The **complexity** of HTSC properties is caused by the complexity of their **electronic structure**





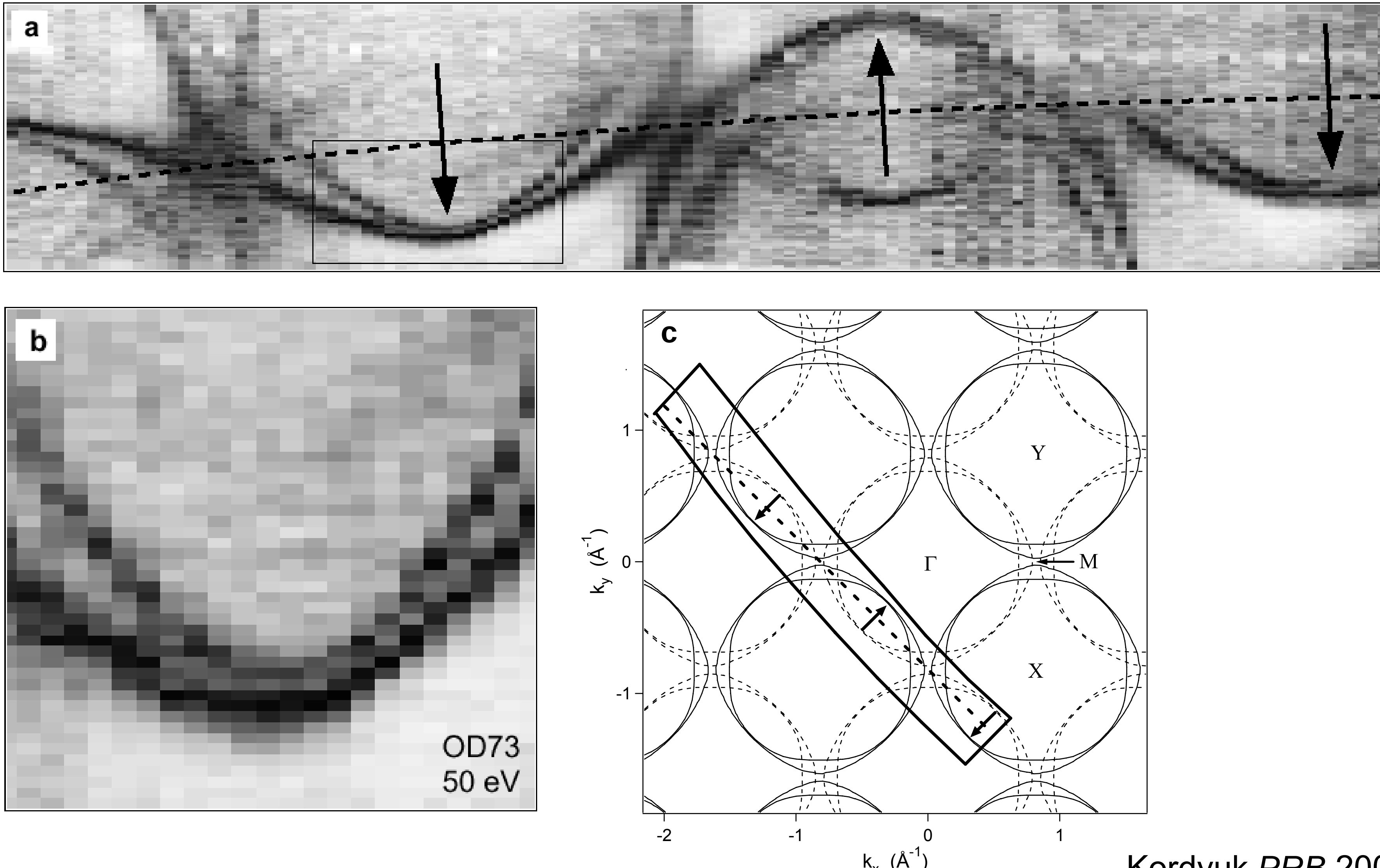
Kordyuk *PRB* 2003

Electronic strucrure of HTSC is
bare band dispersion



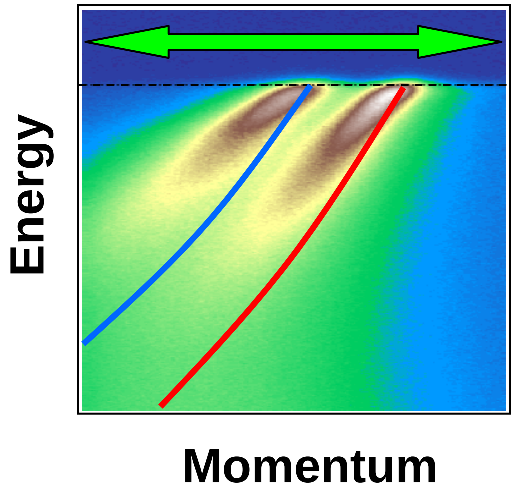
Kordyuk *PRB* 2002

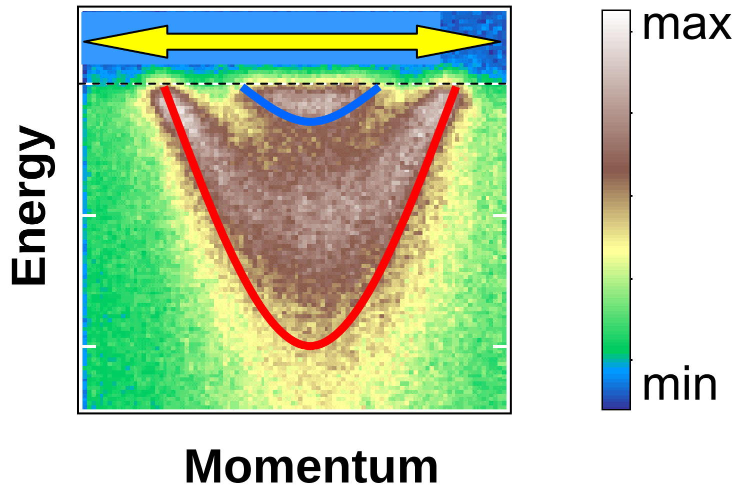
Electronic strucrure of HTSC is bare band dispersion

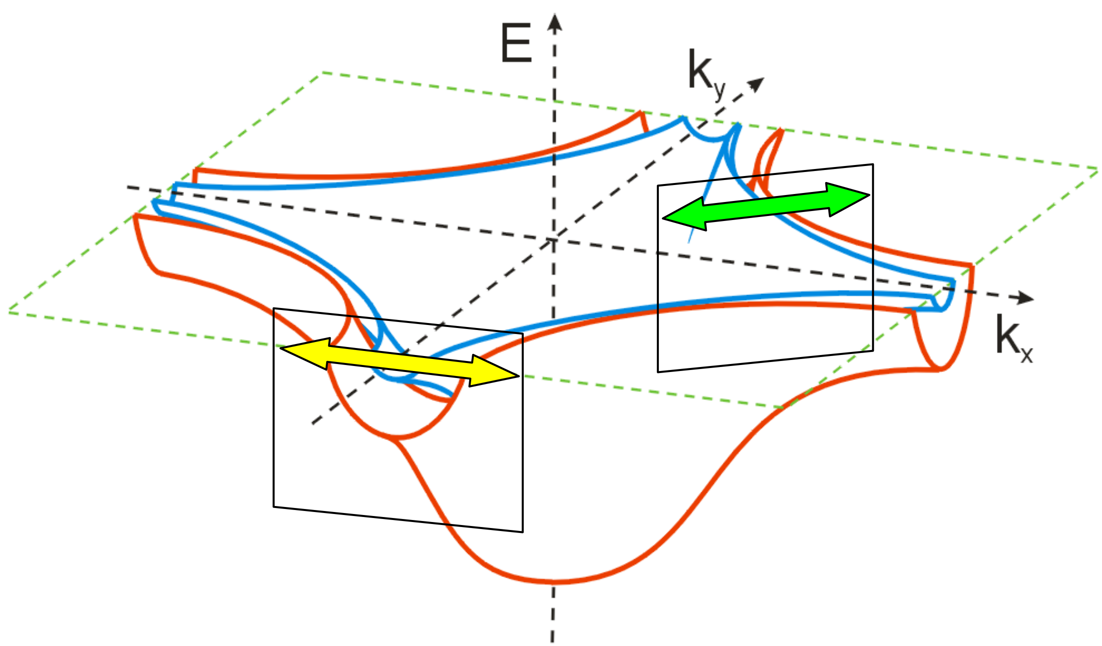


Kordyuk *PRB* 2004

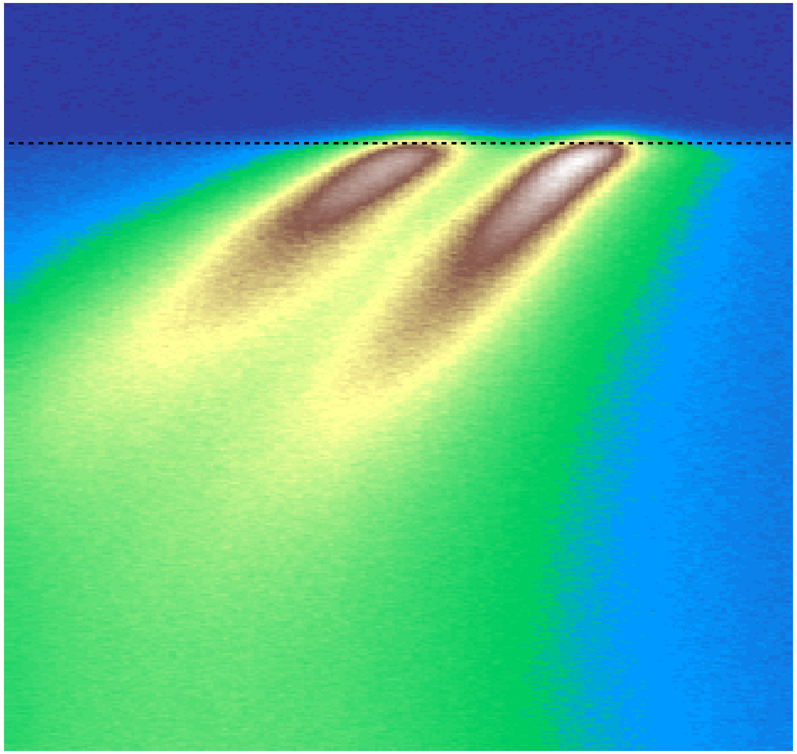
Electronic strucrure of HTSC is bare band dispersion + self-energy



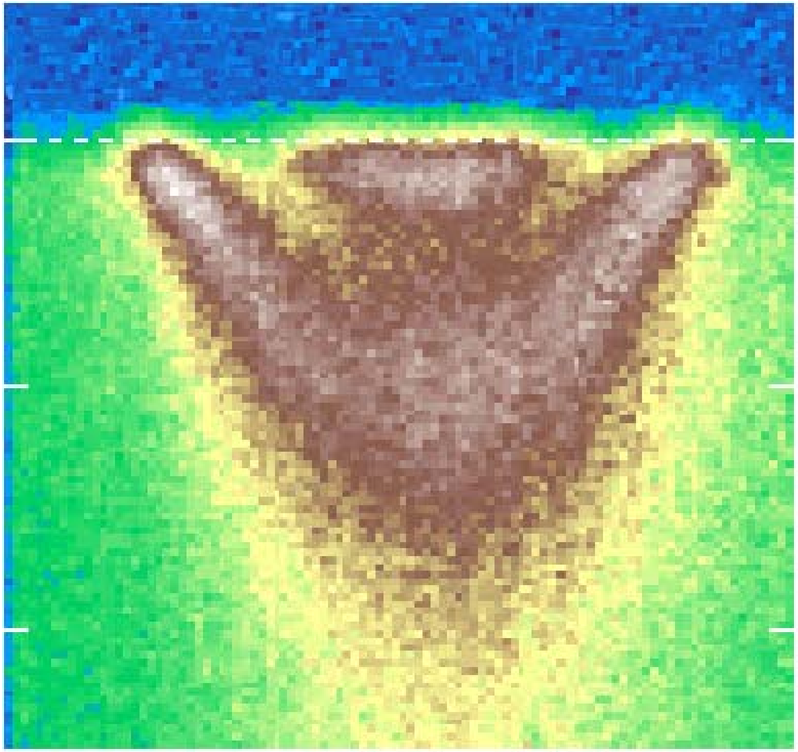




Electronic strucrure of HTSC is bare band dispersion + self-energy



2006

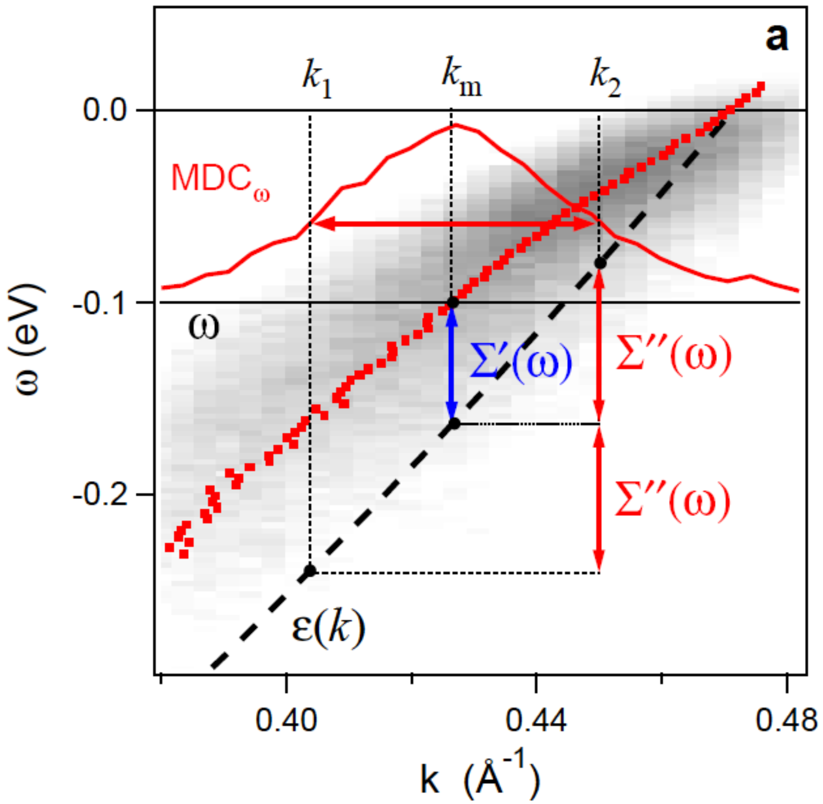


2002

Borisenko *PRL* 2003

Both $\varepsilon_{\mathbf{k}}$ and $\Sigma(\omega)$ can be derived from experiment

$$A(\mathbf{k},\omega) = \operatorname{Im} G = \operatorname{Im}\left(\frac{1}{\omega - \varepsilon_{\mathbf{k}} - \Sigma(\mathbf{k},\omega)}\right)$$

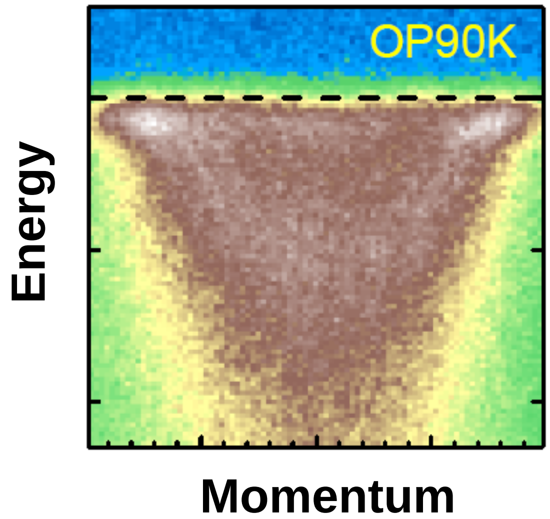


$$I(\mathbf{k},\omega) = A(\mathbf{k},\omega) f(\omega)$$

$$\Sigma(\omega) = \Sigma'(\omega) + \Sigma''(\omega)$$

Kordyuk *PRB* 2005

Quasiparticle spectral function in the superconducting state



$$\Sigma(\mathbf{k},\omega) \text{ and } \Delta(\mathbf{k},\omega)$$

?

$$A = \operatorname{Im} G_{11} = \operatorname{Im}\left[\frac{\omega - \Sigma + \varepsilon_{\mathbf{k}}}{(1-\Delta^2/\omega^2)(\omega-\Sigma)^2 - \varepsilon_{\mathbf{k}}^2}\right]$$

Scalapino *PR* 1966

1. During the last decade, the conception of the HTSC phenomenon evolved **from complexity to simplicity**, which is a simple result of continued development of experimental techniques.

2. Now, in the optimal for superconductivity doping range, the cuprates much resemble a **normal metal** with **well predicted electronic band structure**, but with rather **strong electron-electron interaction**.

3. This principal disentanglement of the complex physics from complex structure reduced the mystery of HTSC to a tangible **problem of interaction** responsible for quasi-particle formation and superconducting pairing.

Homing in on HTSC

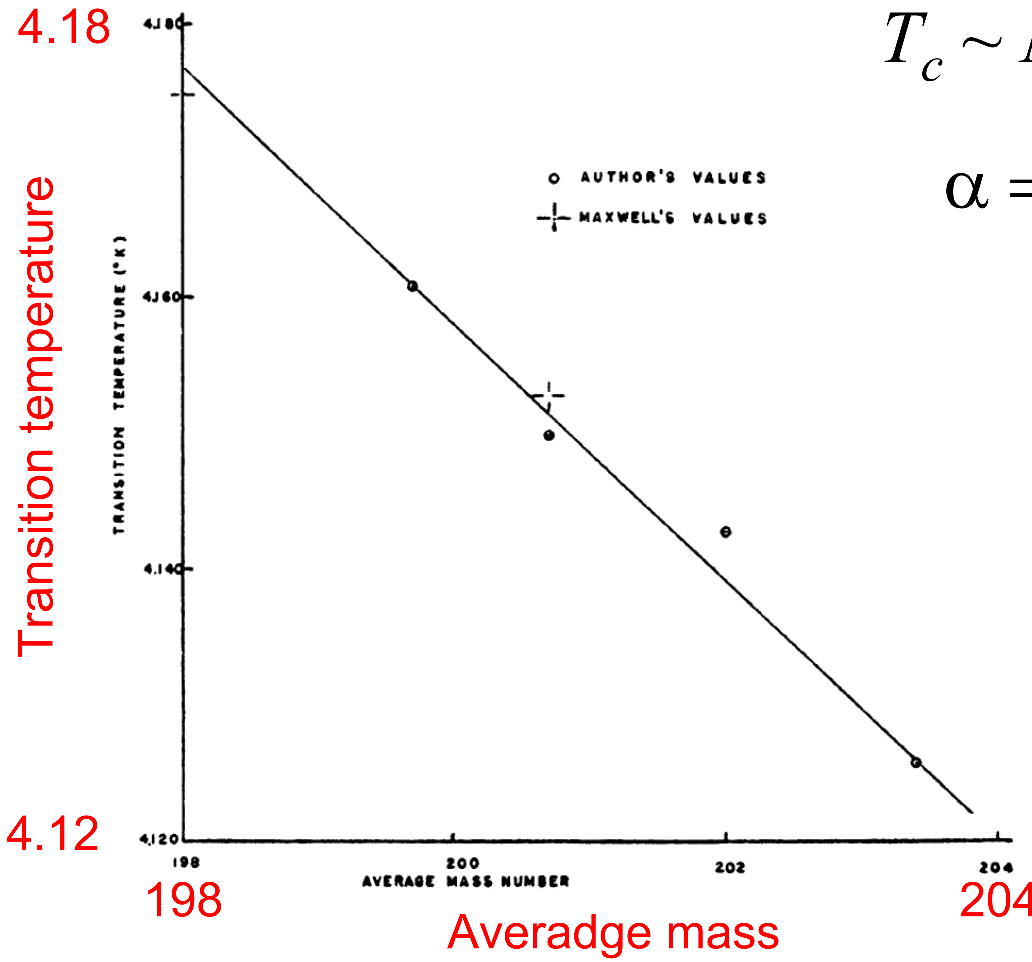
BREAKTHROUGH OF THE YEAR

Areas to Watch in 2006

Homing in on high-T_c. In 1986, physicists discovered that certain compounds laden with copper and oxygen carry electricity without resistance, some now at temperatures as high as 138 kelvin. Twenty years later, researchers still aren't sure precisely how high-T_c superconductors work. But a variety of exquisitely sensitive experimental techniques should cull the vast herd of possible explanations.

SCIENCE VOL 310 23 DECEMBER 2005

The isotope effect?



$$T_c \sim M^{-\alpha}$$

$$\alpha = 0.5$$

Maxwell and Reynolds et al. *PR* 1950

The isotope effect?

Conventional SC

effect on *Tc* only

negligible on other electronic properties

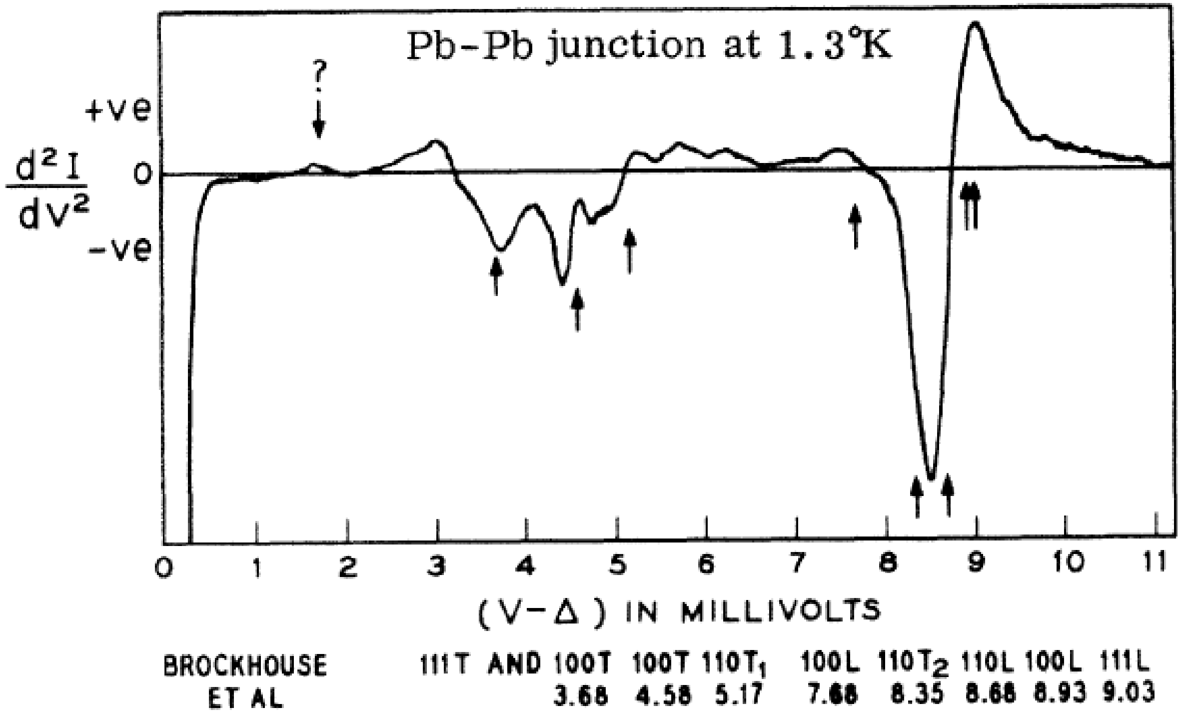
HTSC

effect is *unconventional*

it is weak on *Tc*:
α ~ 0.05 at OpD
but up to 0.5 at UD

It is comparably large on other electronic properties, e.g. electron effective mass

“Fingerprints" of the phononic spectrum in tunneling differential conductance



Rowell *PRL* 1963

Eliashberg equations

$$\Delta(\omega)=\frac{1}{Z(\omega)}\int_0^{\omega_c} d\omega'\,\mathrm{Re}\left\{\frac{\Delta(\omega')}{(\omega'^2-\Delta^2(\omega'))^{1/2}}\right\}[K_+(\omega',\omega)-N(0)U_c]$$

$$[1-Z(\omega)]\omega=\int_0^{\infty} d\omega'\,\mathrm{Re}\left\{\frac{\omega'}{(\omega'^2-\Delta^2(\omega'))^{1/2}}\right\}K_-(\omega',\omega)$$

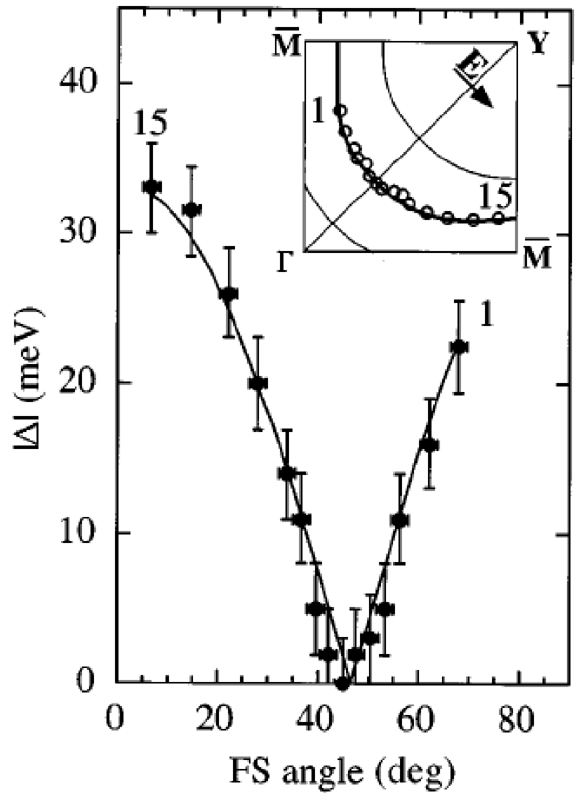
$$K_\pm(\omega,\omega')=\sum_\lambda\int_0^\infty d\nu\,\alpha_\lambda{}^2(\nu)F_\lambda(\nu)\left[\frac{1}{\omega'+\omega+\nu+i\delta}\pm\frac{1}{\omega'-\omega+\nu-i\delta}\right]$$

el-ph coupling constant

phonon DOS

Scalapino *PR* 1966

HTSC?

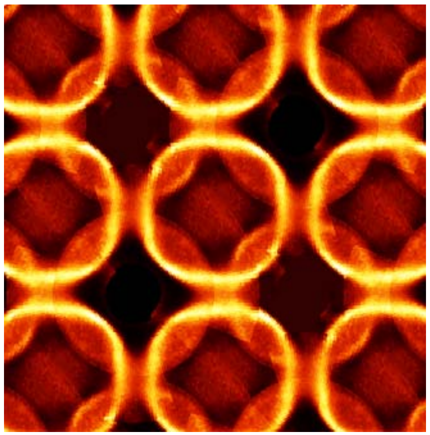


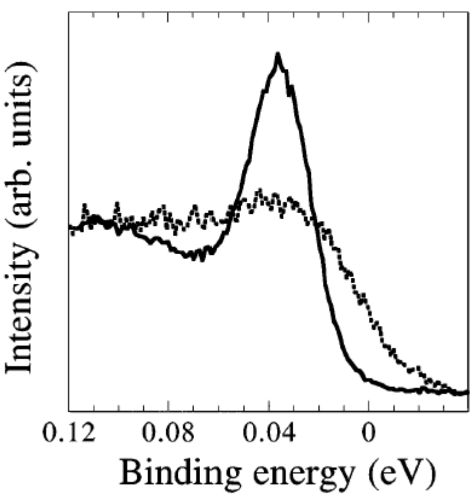
Ding *PRB* 1996

In HTSC, the *d*-wave gap washes out any fine structure in the momentum integrated tunneling spectra

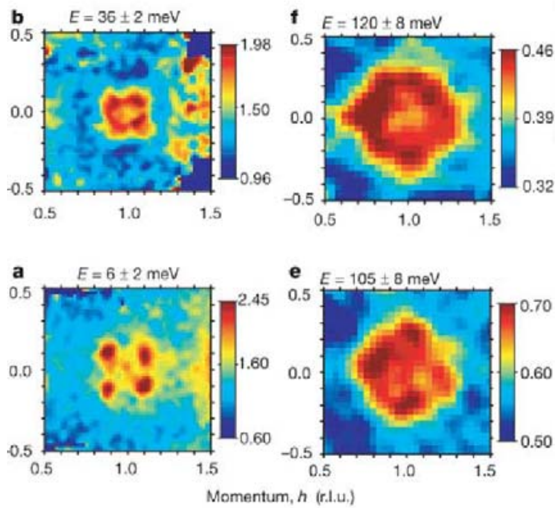
Modern momentum resolving techniques

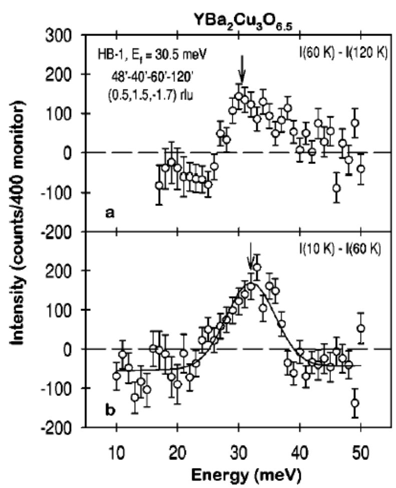
ARPES



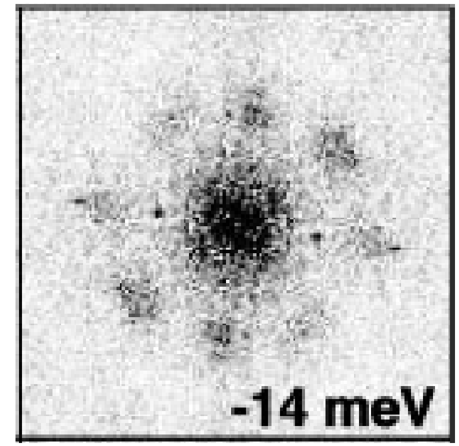


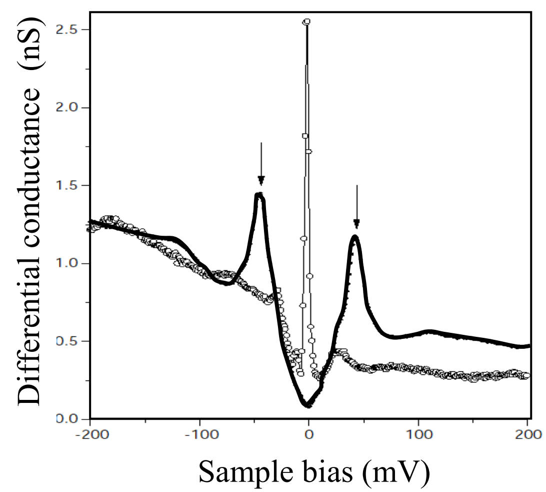
INS





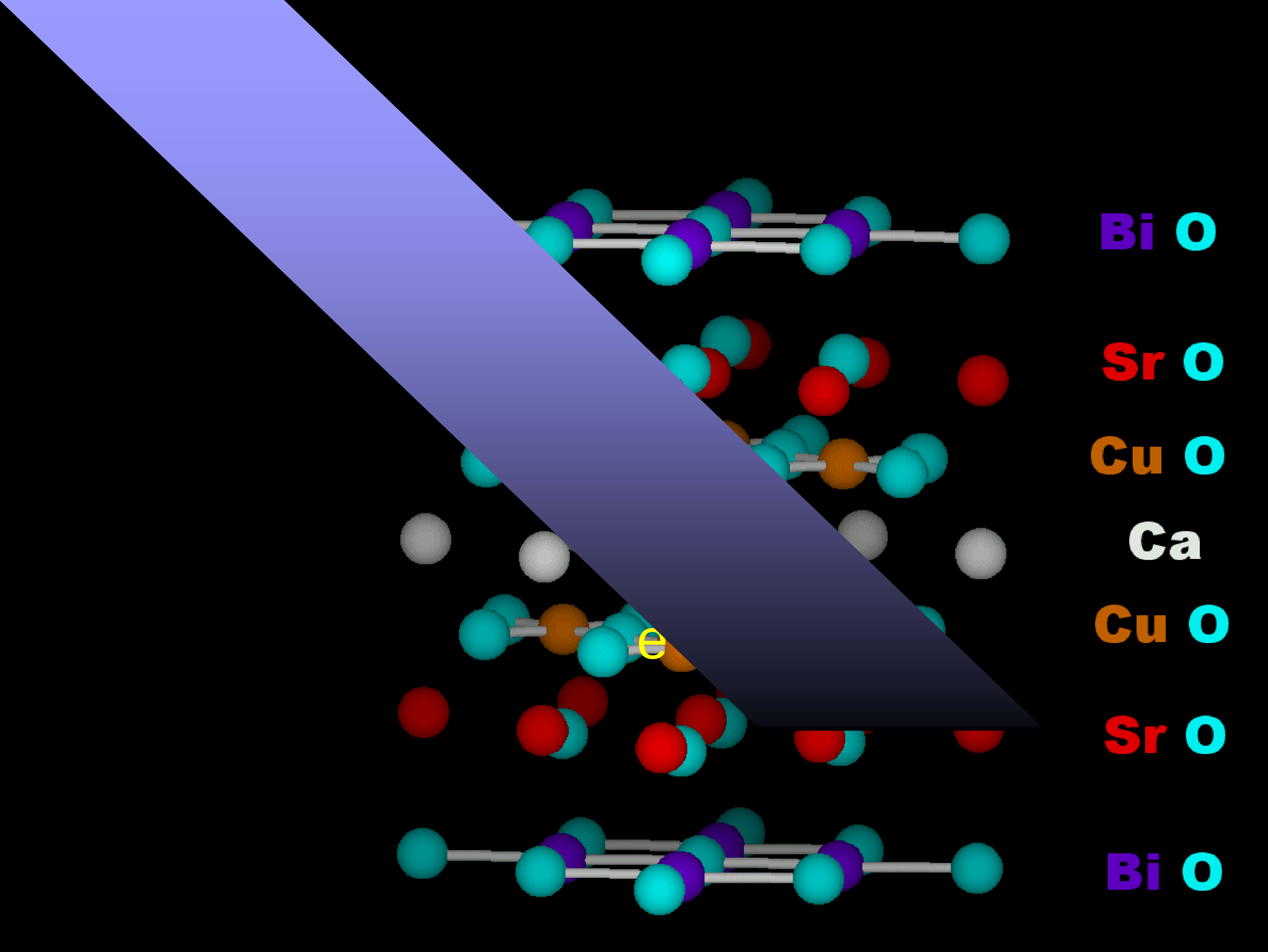
STS



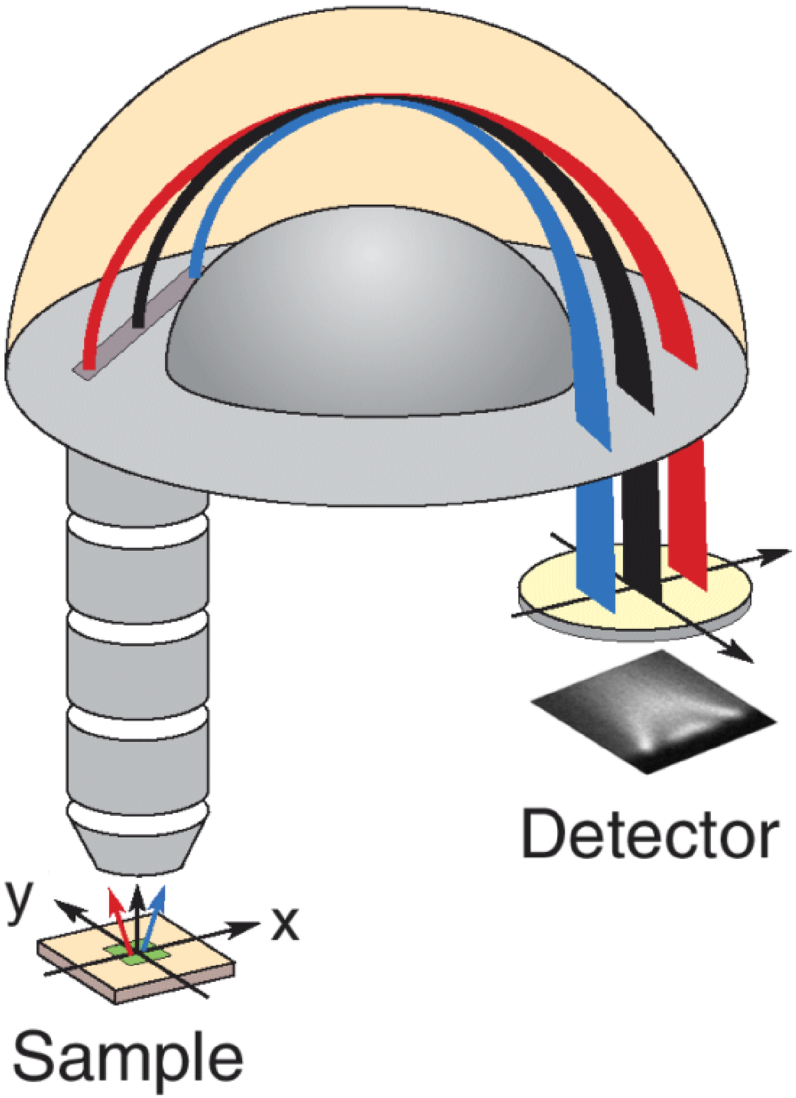


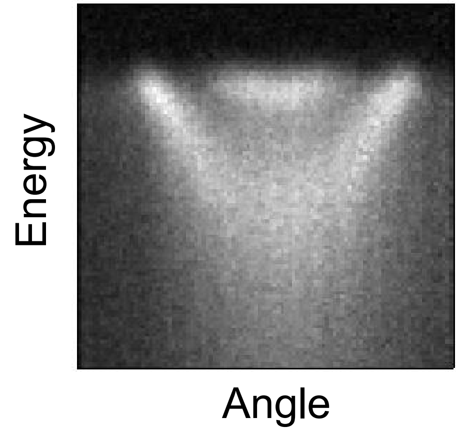
Short introduction to ARPES

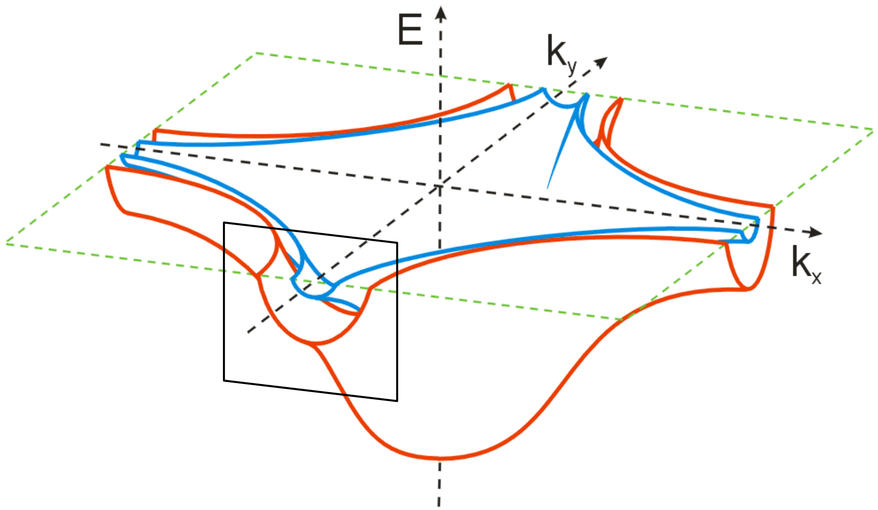
the most direct tool to explore the momentum-energy space of the electrons in solids


Bi O
Sr O
Cu O
Ca
Cu O
e
Sr O
Bi O

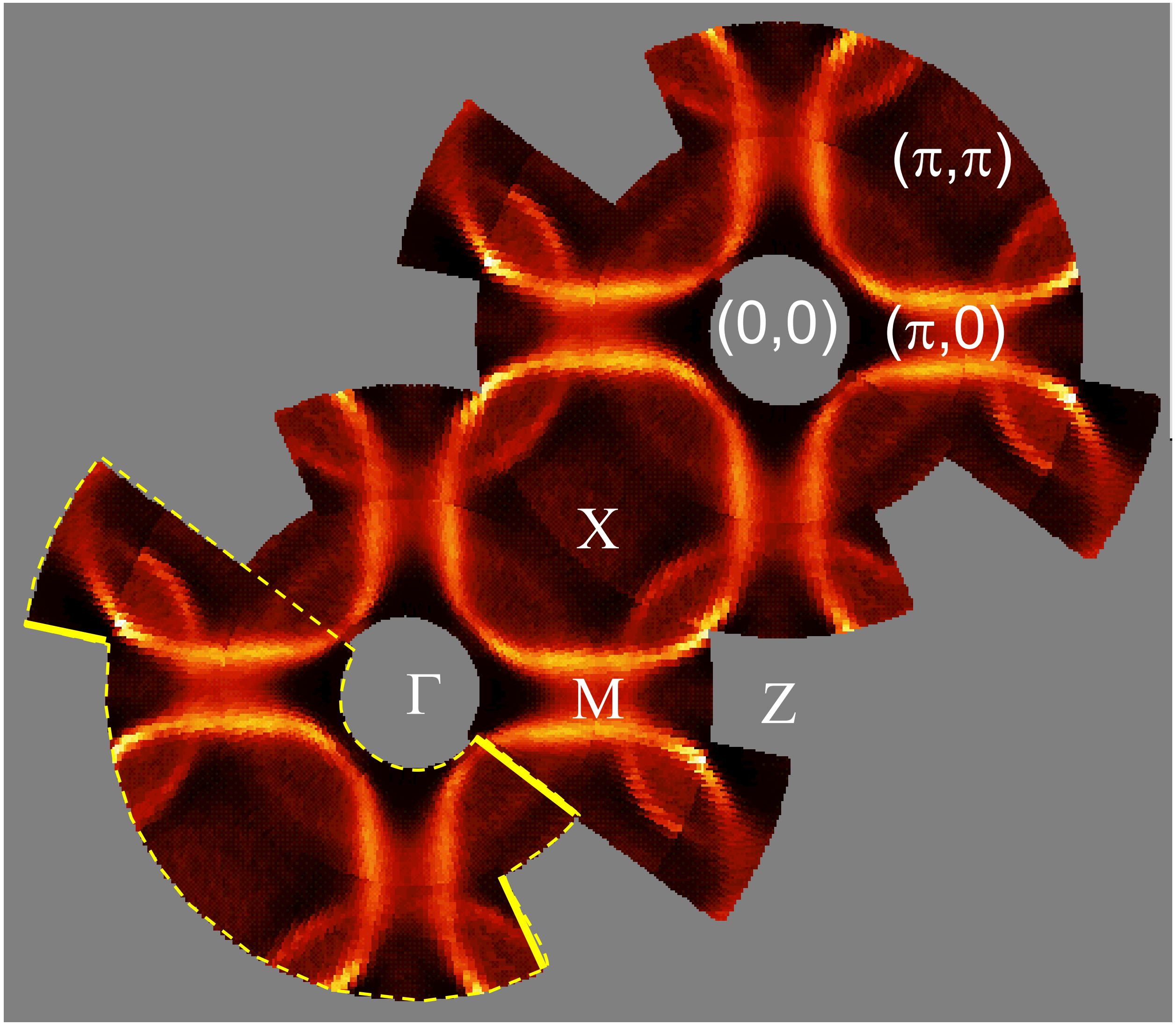
Angle Resolved Analyser





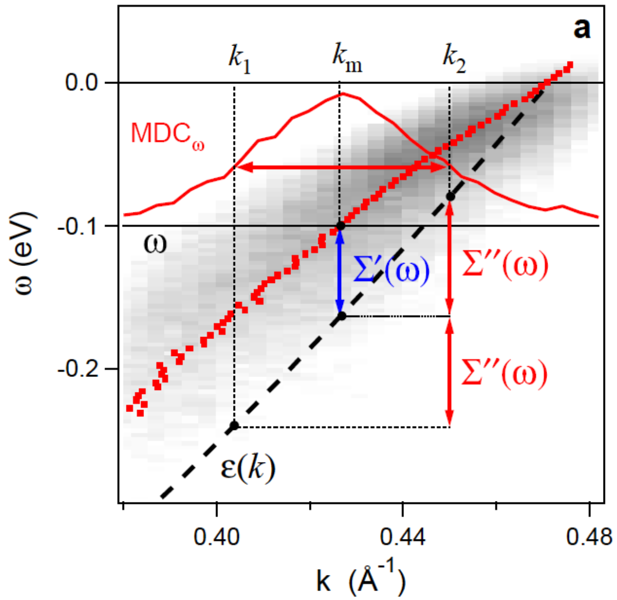


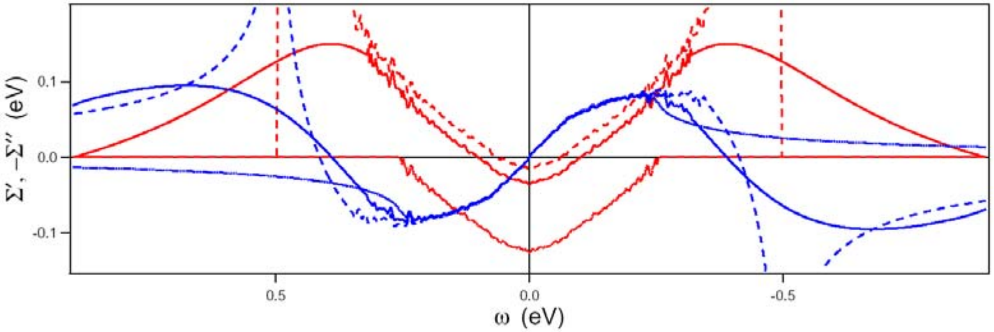
Fermi-surface map

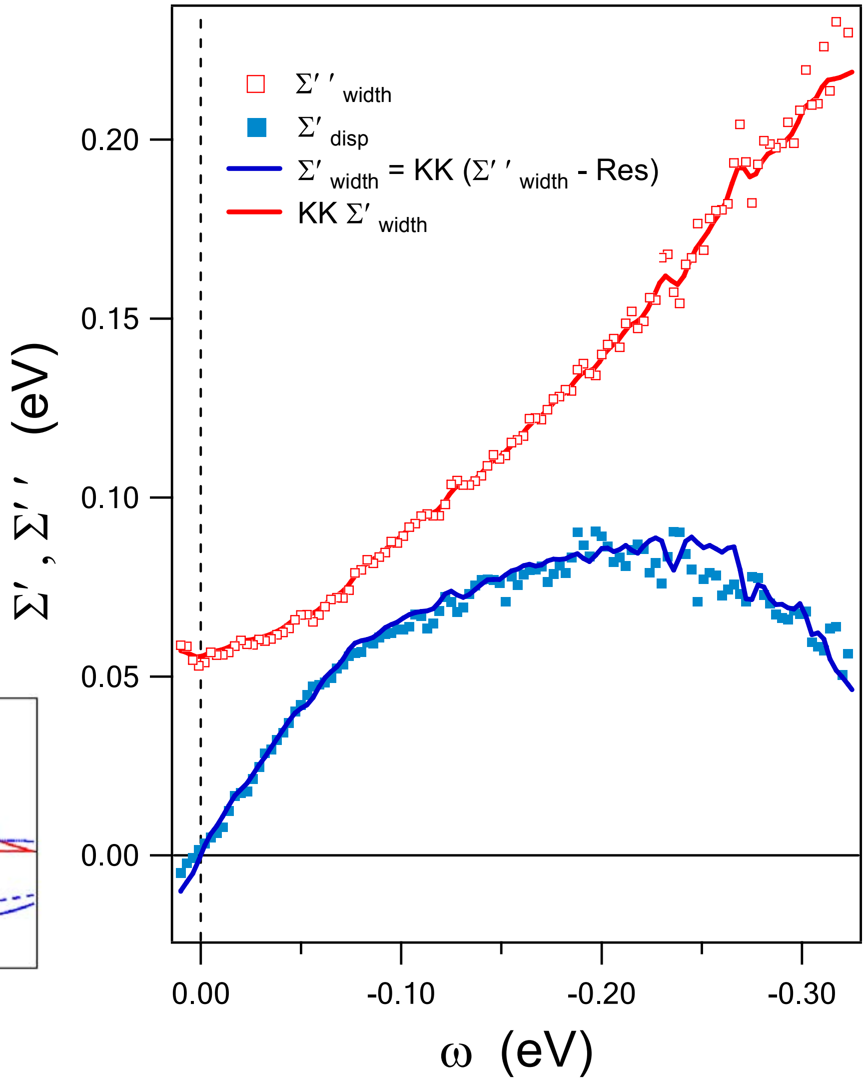


Kramers-Kronig transform

$$\Sigma'(\omega) = \mathrm{KK}\ \Sigma''(\omega)$$

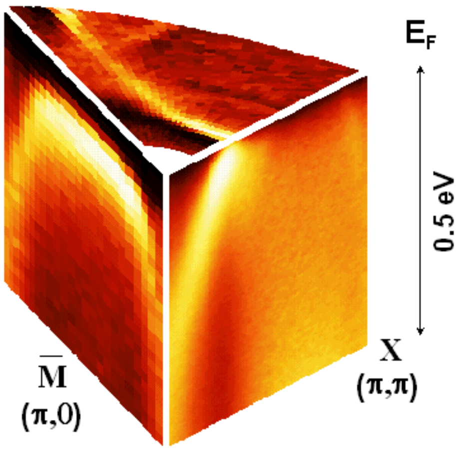


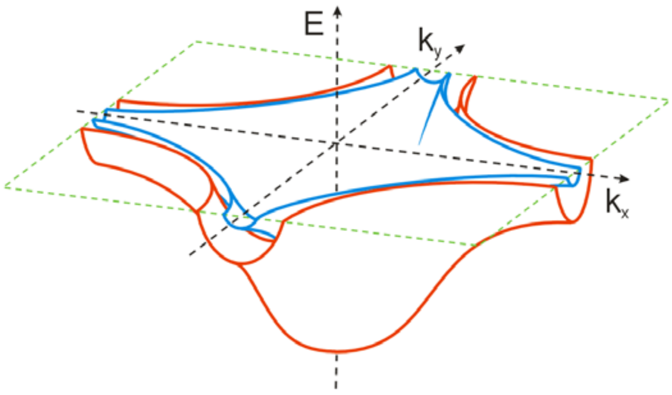


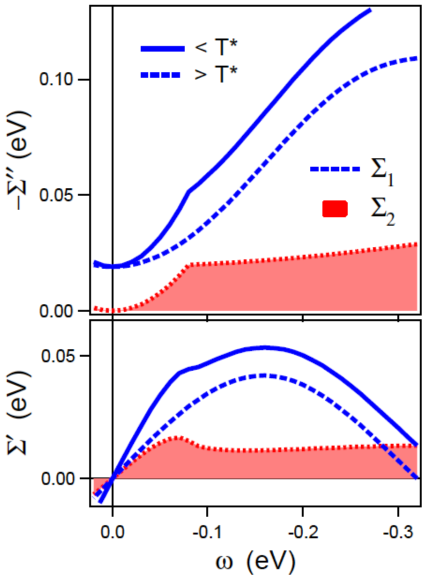


Kordyuk *PRB* 2005

ARPES provides







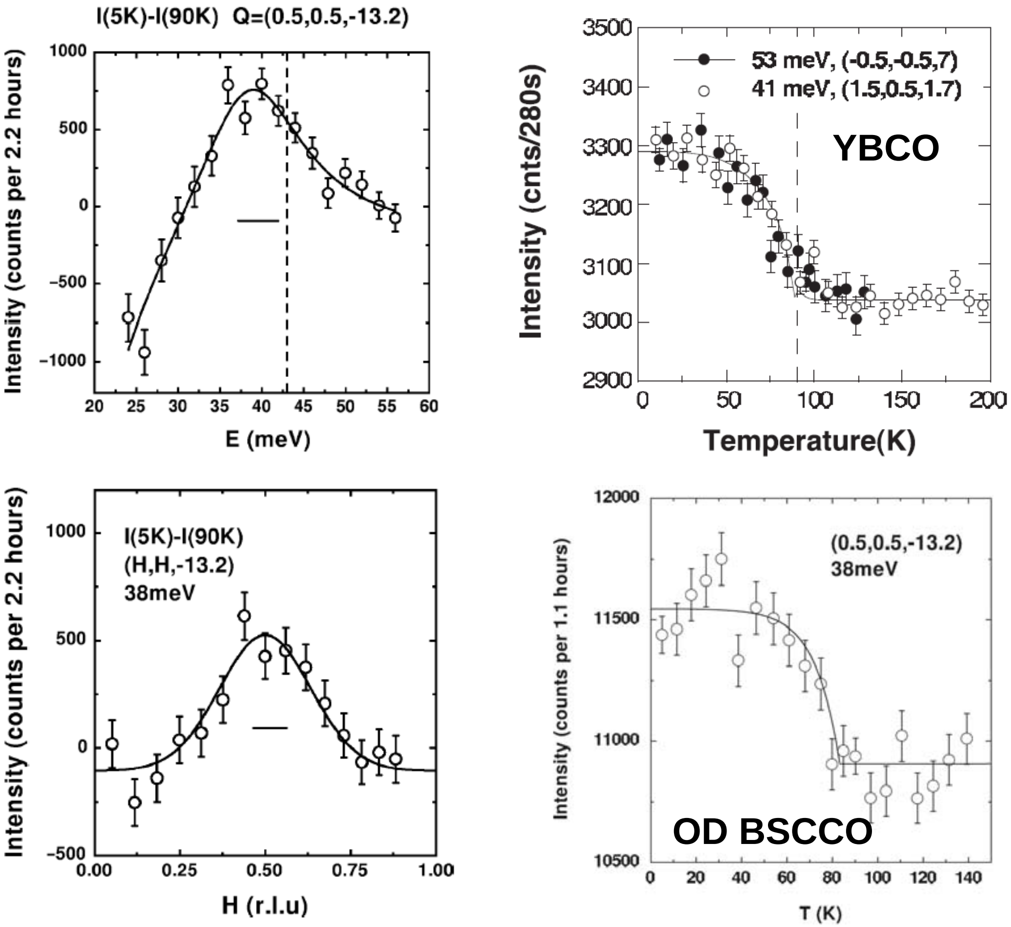
$A(\mathbf{k},\omega)\, f(\omega) \longrightarrow \varepsilon_{\mathbf{k}} + \Sigma(\mathbf{k},\omega)$

$+$

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

Inelastic Neutron Scattering

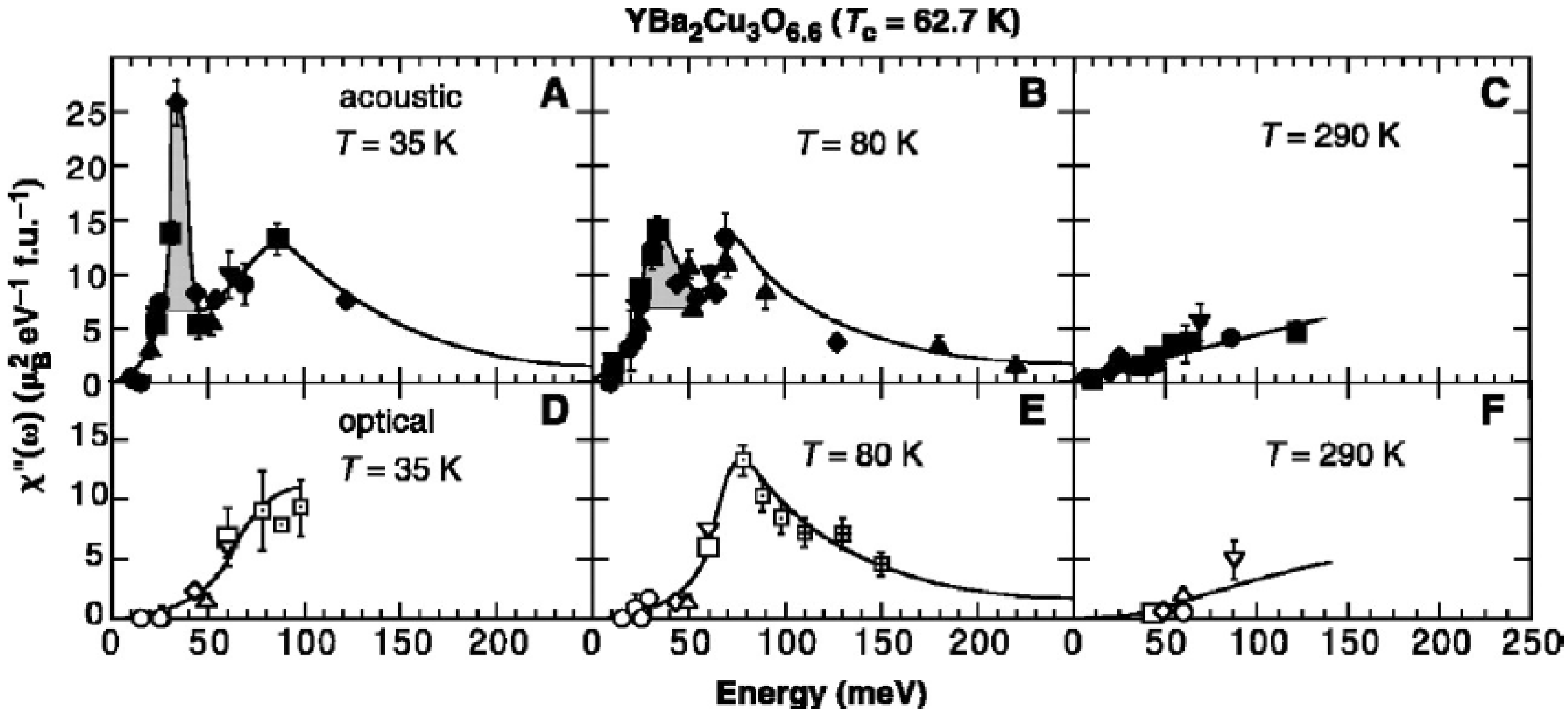
"Neutron resonance"



He *PRL* 2001, *Science* 2002, Pailhes *PRL* 2004

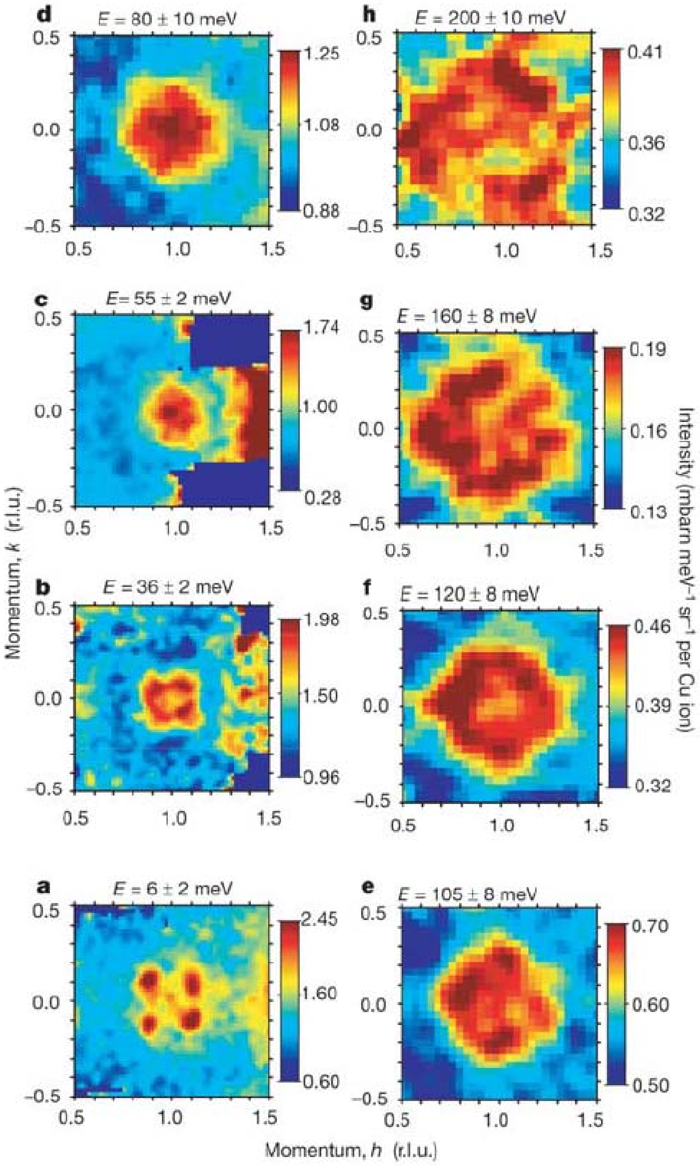
Spin susceptibility

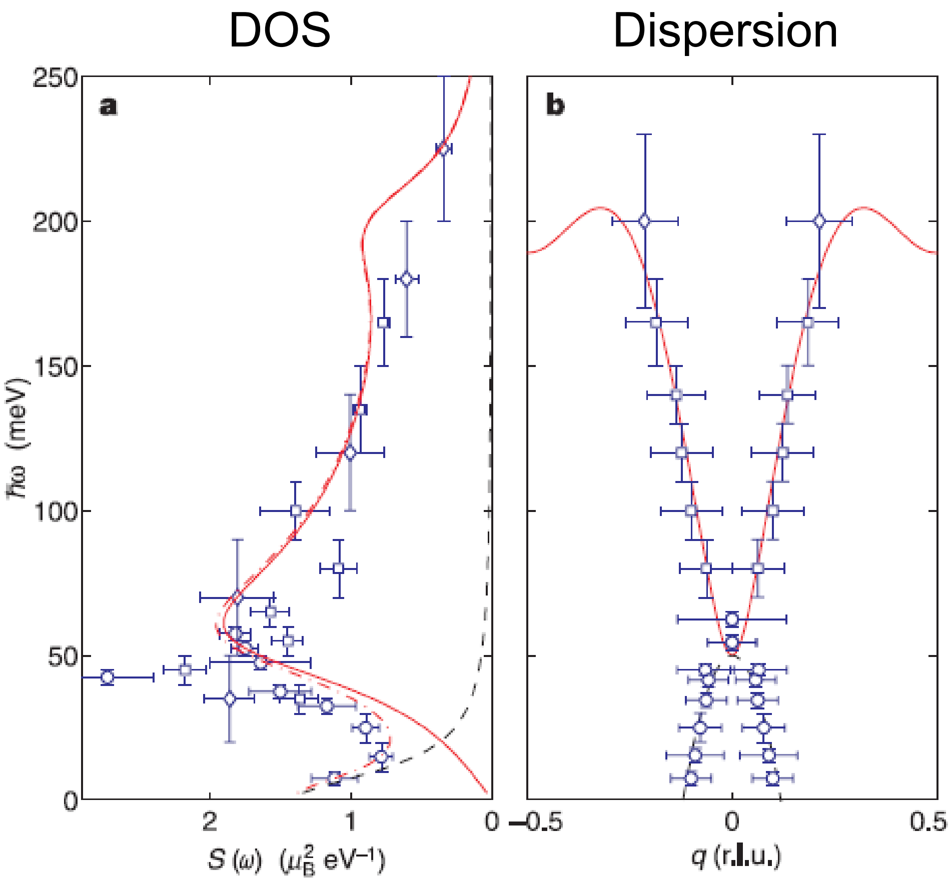
$\chi(\omega)$



Dai *Science* 1999

Spin susceptibility structure

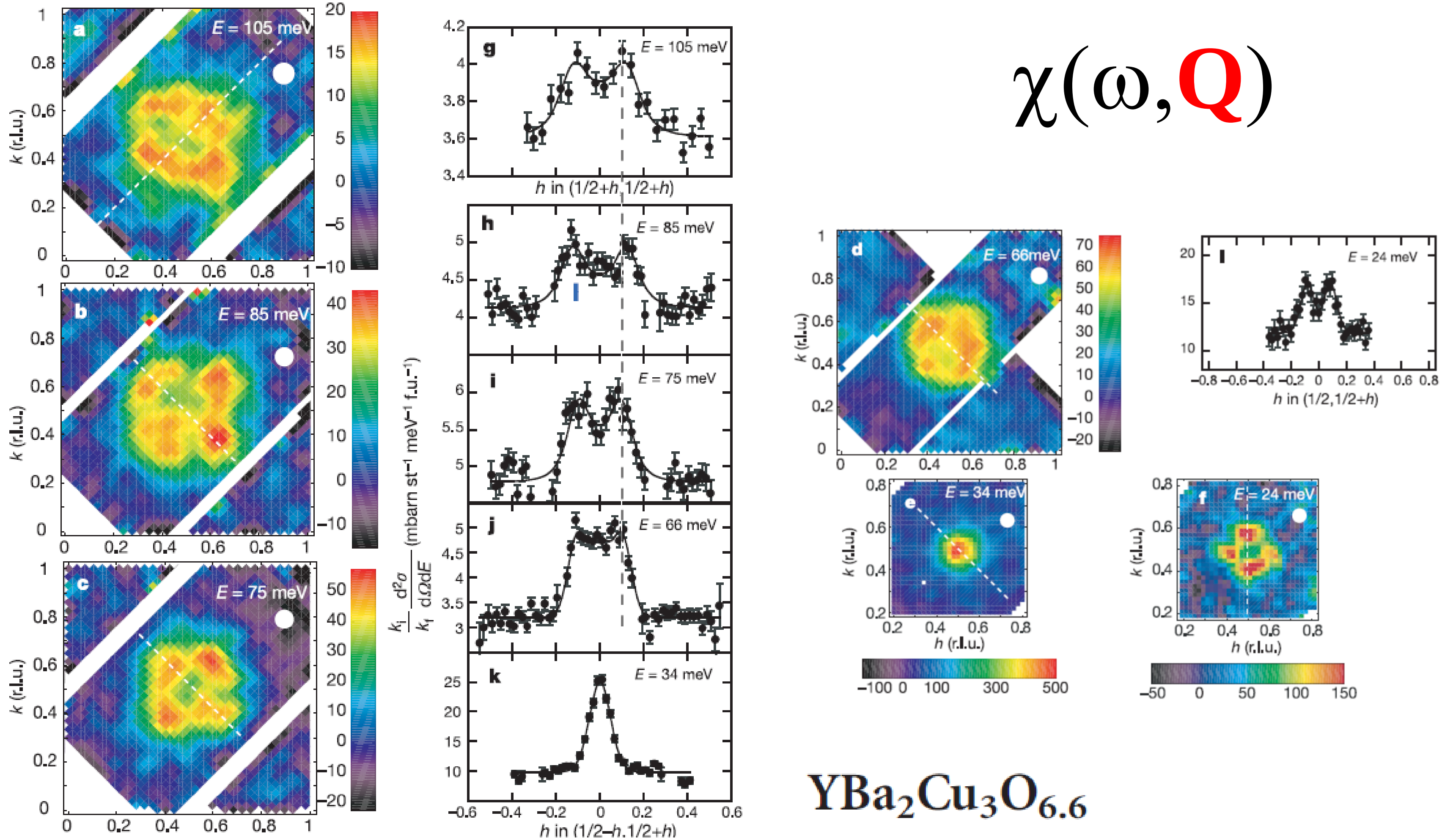




$La_{2-x}Ba_xCuO_4$ ('Zurich' oxide)

Tranquada *Nature* 2004

Spin susceptibility structure

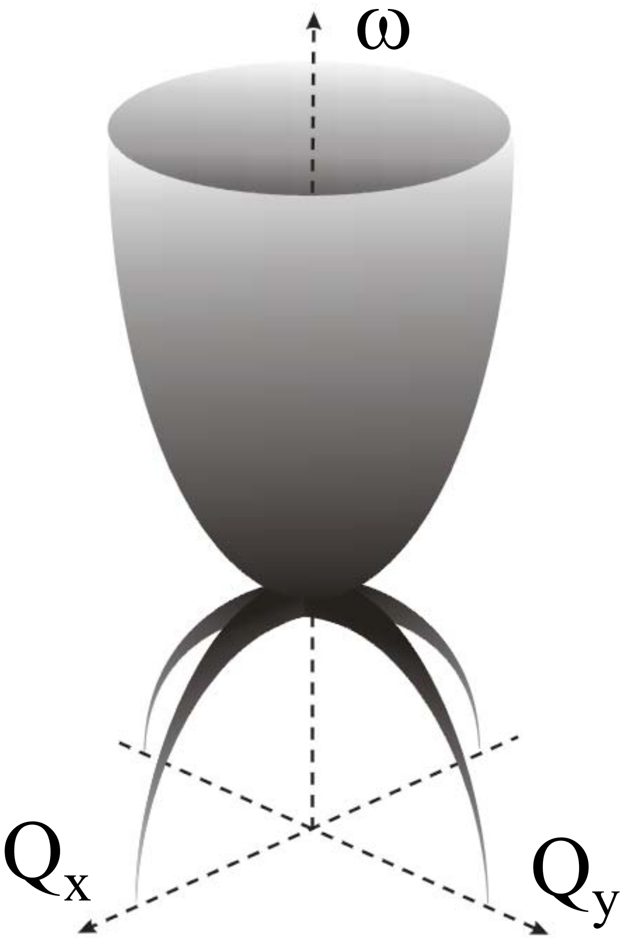


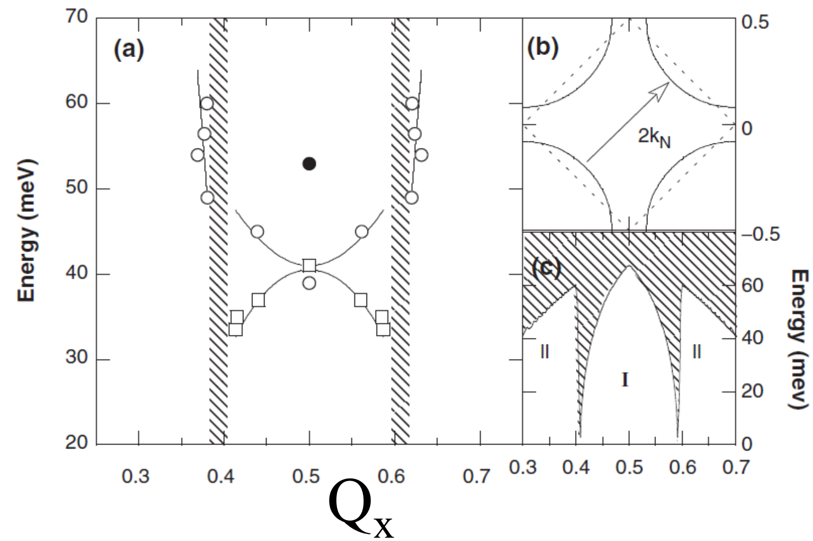
$$\chi(\omega, \mathbf{Q})$$

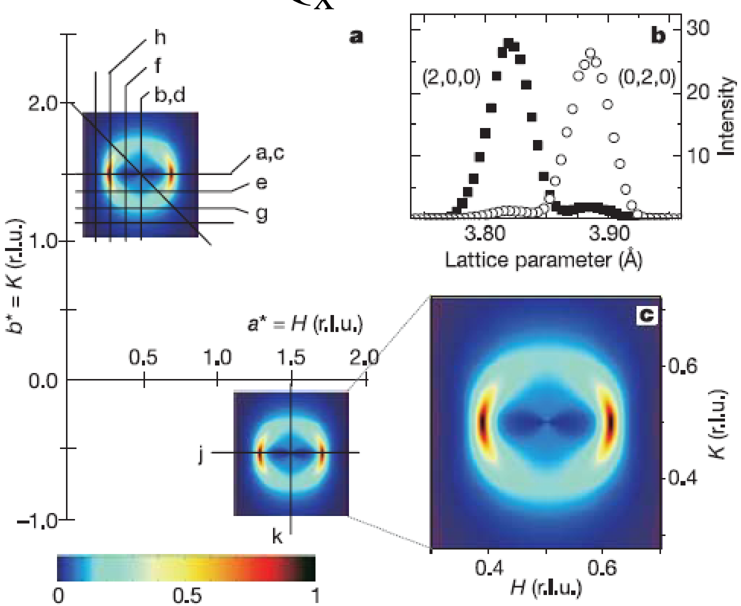
$YBa_2Cu_3O_{6.6}$

Hayden *Nature* 2004

Spin susceptibility structure







$YBa_2Cu_3O_{6.6}$

Hinkov *Nature* 2004

Looking for "fingerprints"

if 2nd order perturbation theory works

① $(\Delta,\Sigma) = EE(\Delta,\Sigma,\varepsilon,\chi)$ **SC**

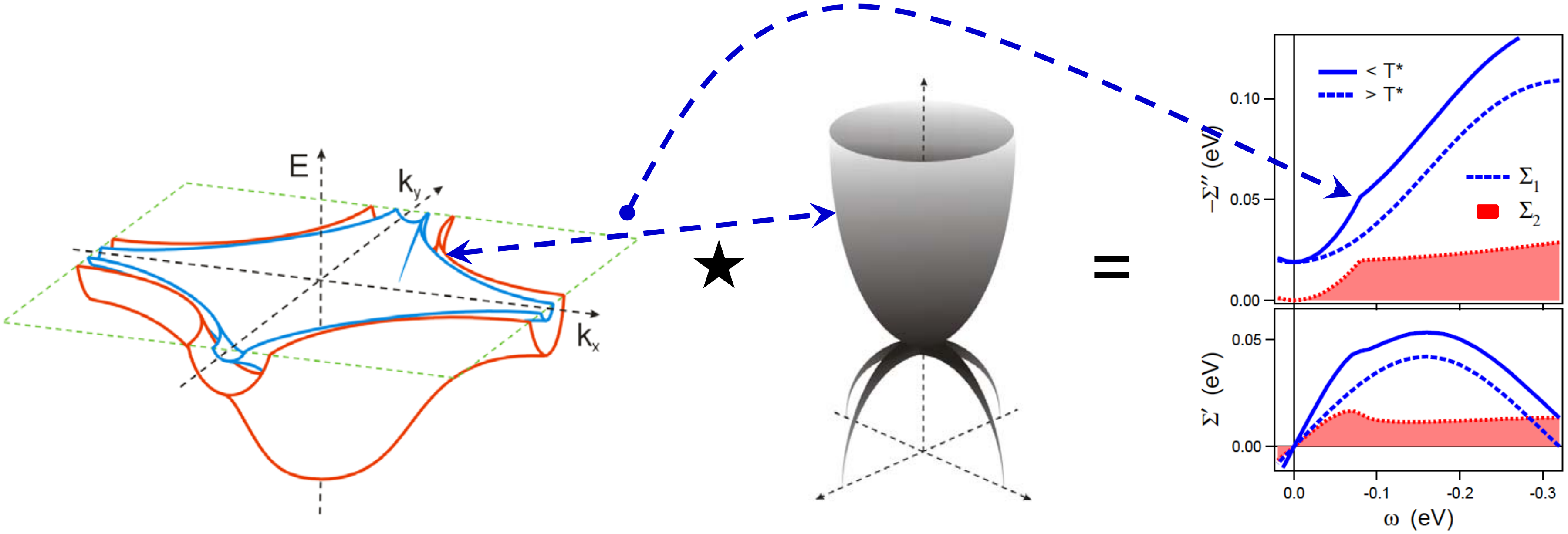
$\Sigma \sim (G \star \chi)_{\mathbf{k},\omega}$ **N**

② $\chi_{it} \sim (G \star G)_{\mathbf{k},\omega}$ "itinerant" magnetism

①

$G \star \chi \sim \Sigma$

$$\Sigma(\mathbf{k},\omega) \sim \int G(\mathbf{k}+\mathbf{Q},\omega+\Omega)\,\chi(\mathbf{Q},\Omega)\,d\mathbf{Q}\,d\Omega$$

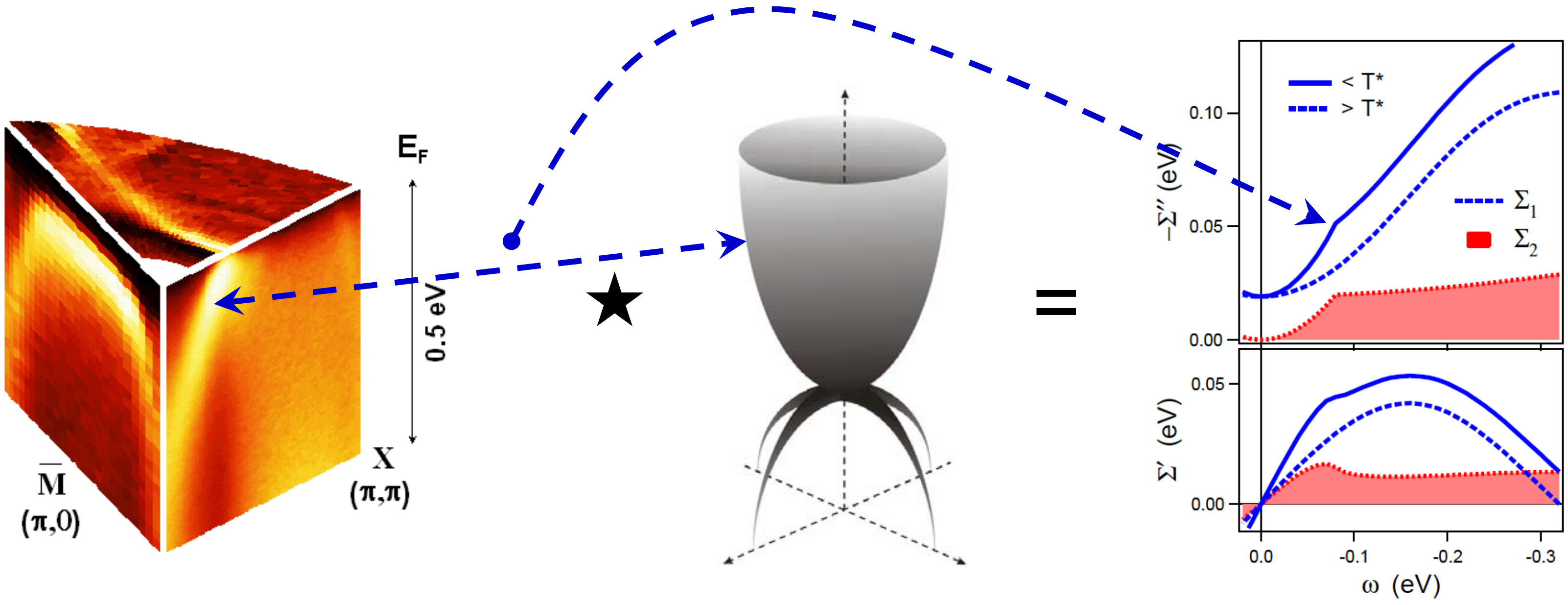


k, ω　　**Q**, Ω　　**k**, ω

①

$$G_{exp} \star \chi_{exp} \sim \Sigma_{exp}$$

ARPES **INS** **ARPES**



k, ω **Q**, Ω **k**, ω

①

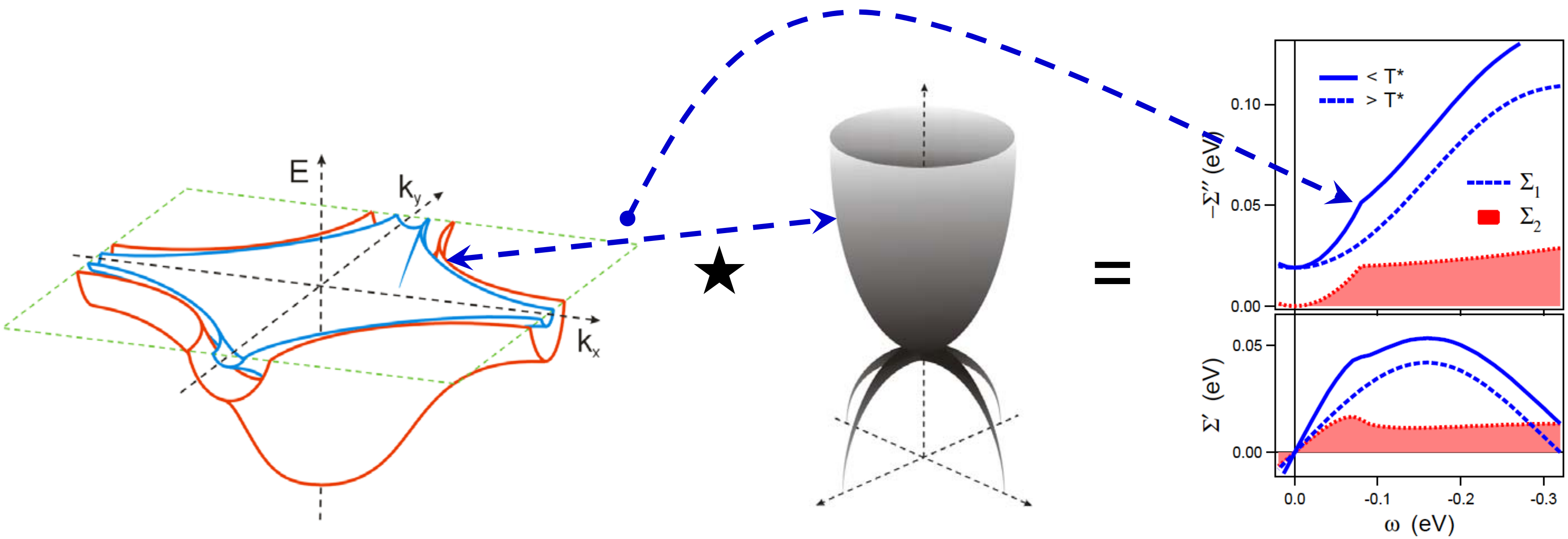
LDA or ARPES

$$G_0 \star \chi_{exp} \sim \Sigma_i$$

INS

$$G_i^{-1} = G_0^{-1} + \Sigma_i$$

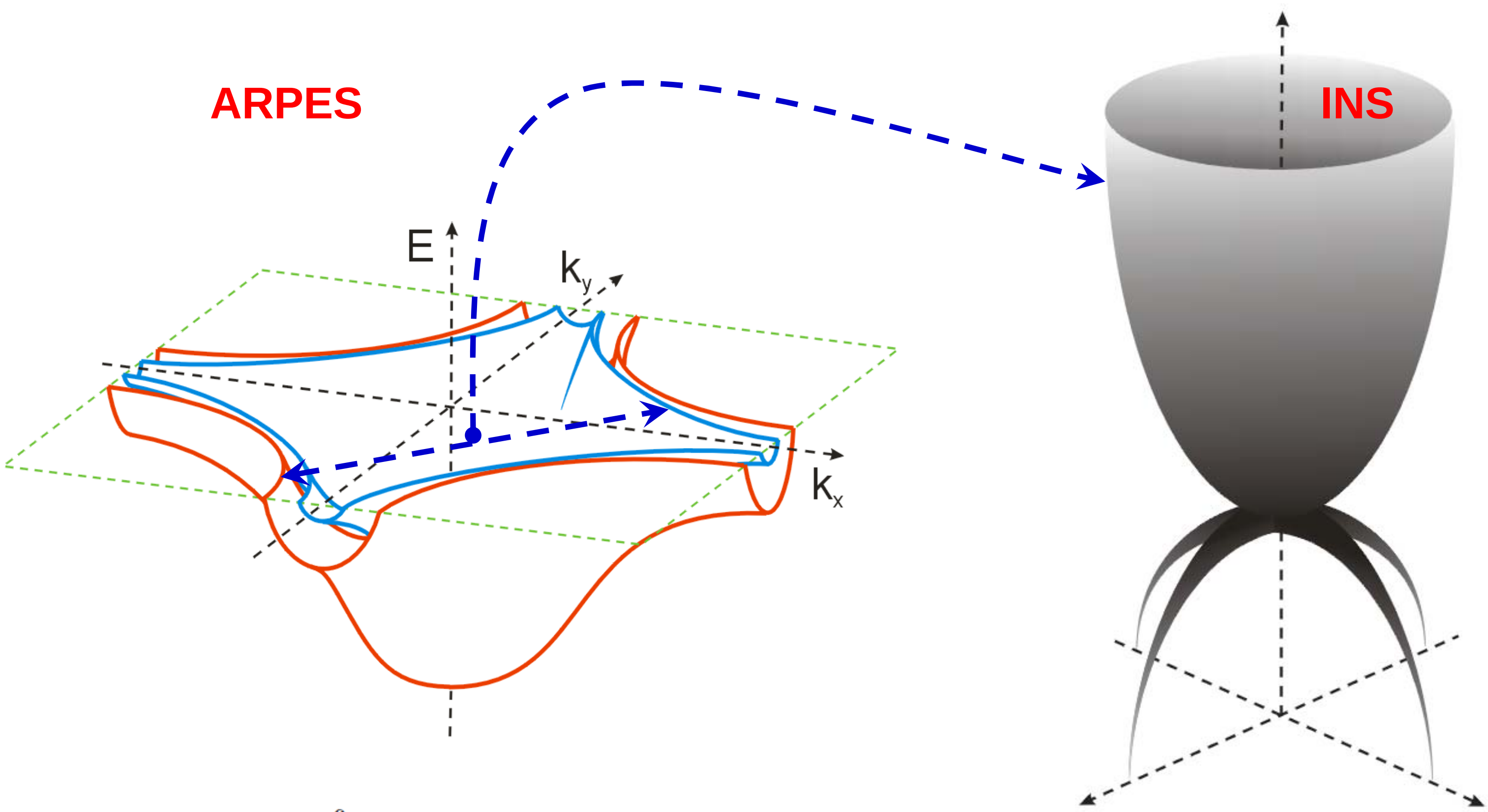
ARPES



k, ω **Q**, Ω **k**, ω

we + Hinkov & Keimer + Dahm & Scalapino 2006

② itinerant $\chi \sim G \star G$



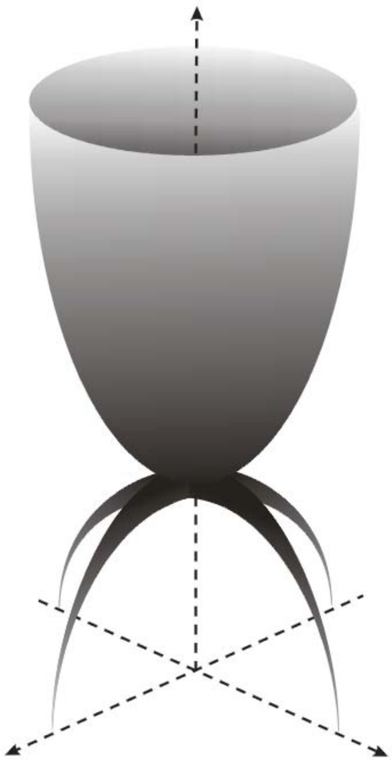
$$\chi_0(\mathbf{Q},\Omega) \propto -2i\int G(\mathbf{k},\omega)G(\mathbf{k}+\mathbf{Q},\omega+\Omega)\,d^2k\,d\omega$$

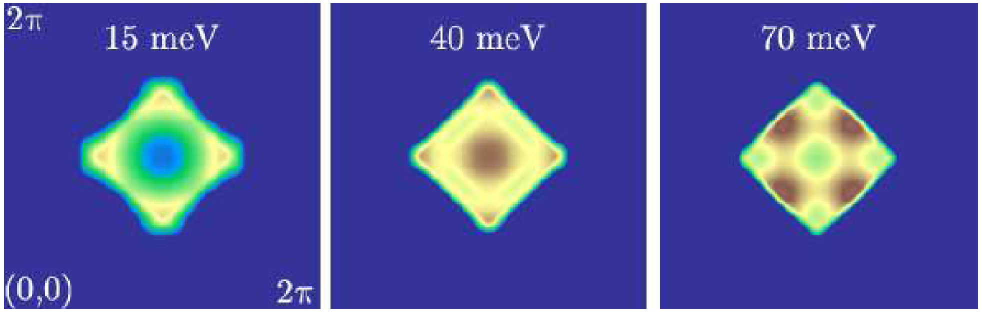
$$\chi(\mathbf{Q},\Omega) = \chi_0(\mathbf{Q},\Omega)/[1+J_Q\,\chi_0(\mathbf{Q},\Omega)]$$ RPA

we + Eremin 2006

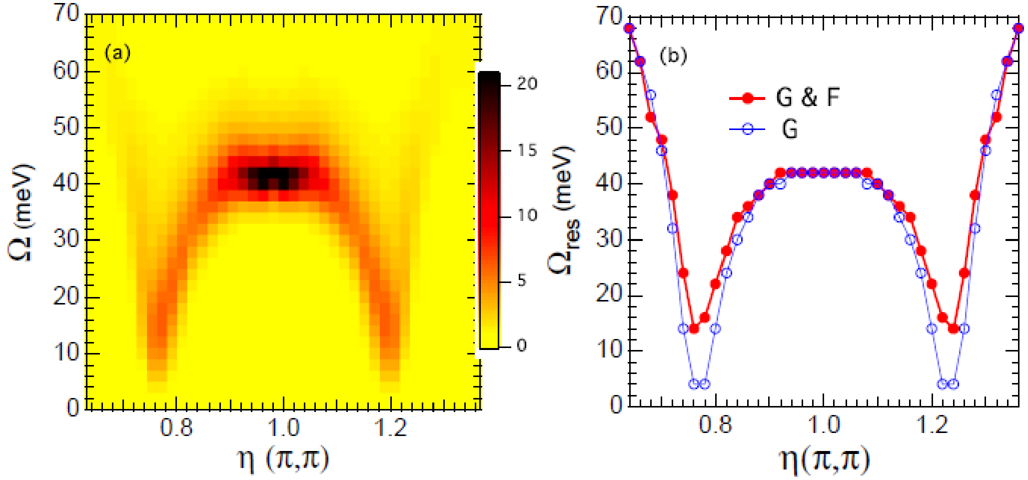
②

$\chi \sim G \star G$





Inosov 2006



Chatterjee 2006

Some conclusions

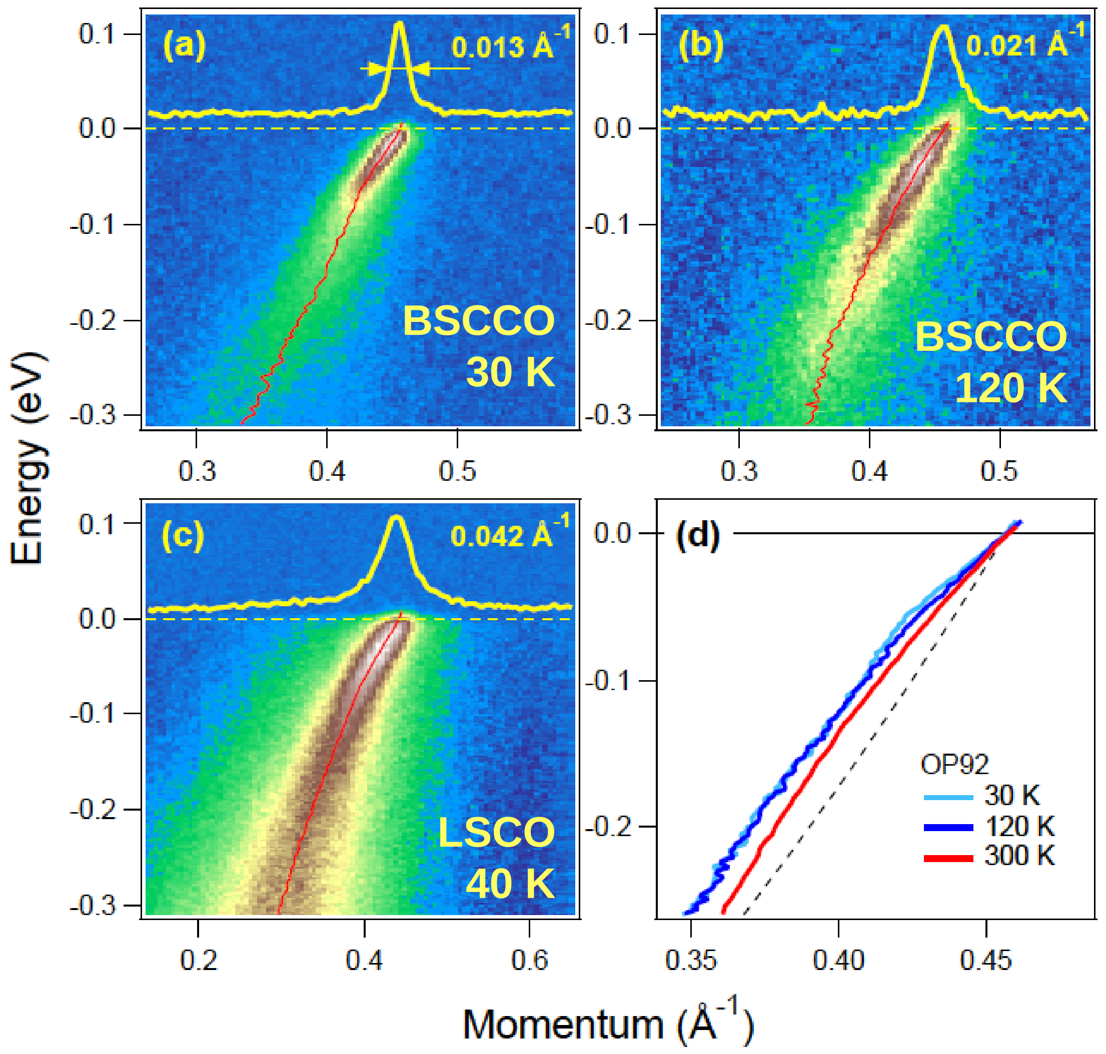
- "Fingerprints" of bosons should be identified in scattering (Σ) and pairing (Δ) spectra.
- The converging of the techniques needs refinement and reevaluation of earlier results.
- The problem of space inhomogeneity in cuprates seems to be crucial for HTSC understanding: **STS**

New results

- Fine details of the self-energy: BSCCO, nodal direction
  - xT – evolution of the bosonic channel
  - parity of the bosons
  - magnetic isotope effect
  - impurity scattering mechanism

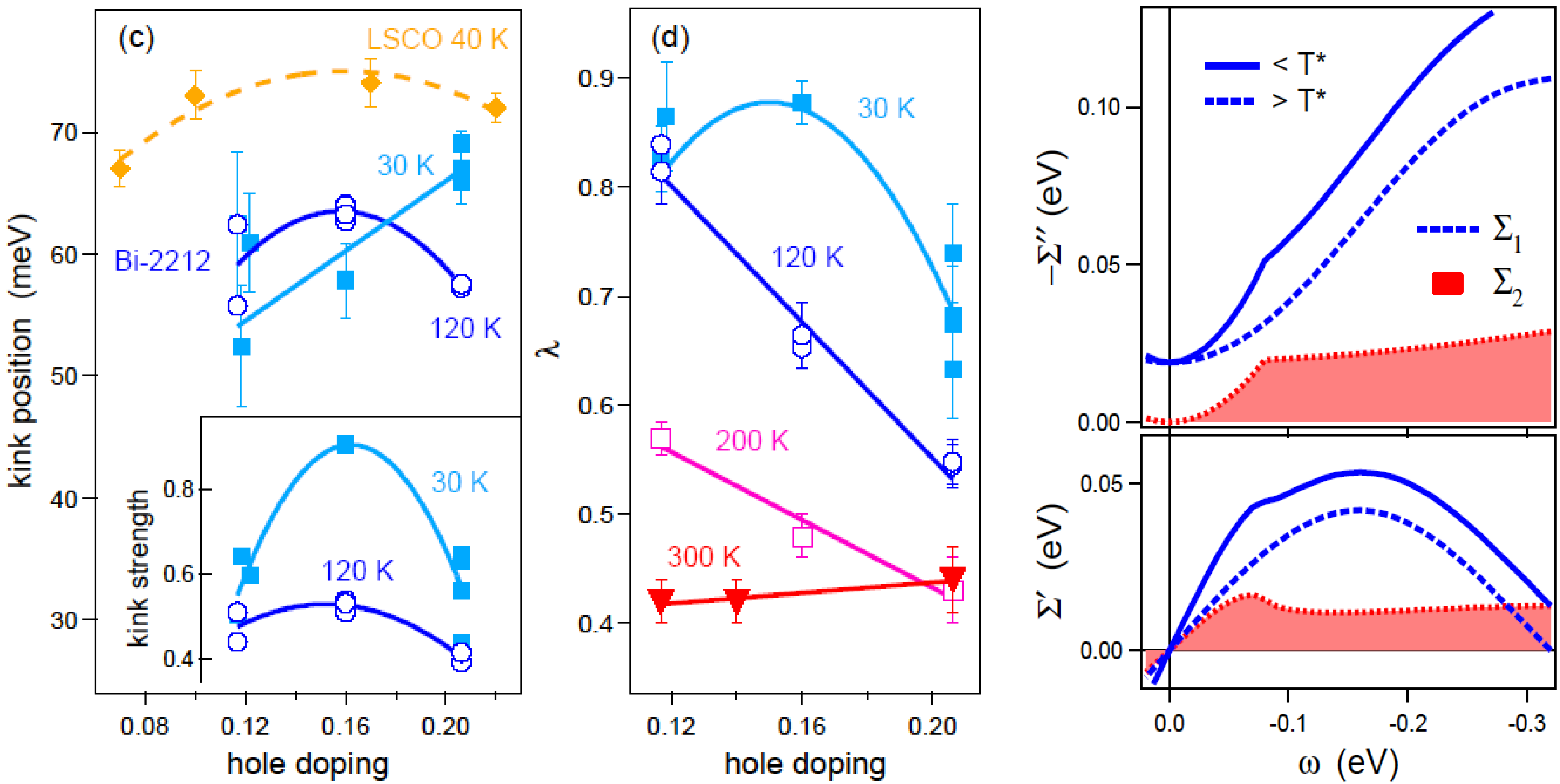
- Universality of HTSC: **YBCO**, LSCO
  -

Evolution of the kink



Kordyuk *PRL* 2006

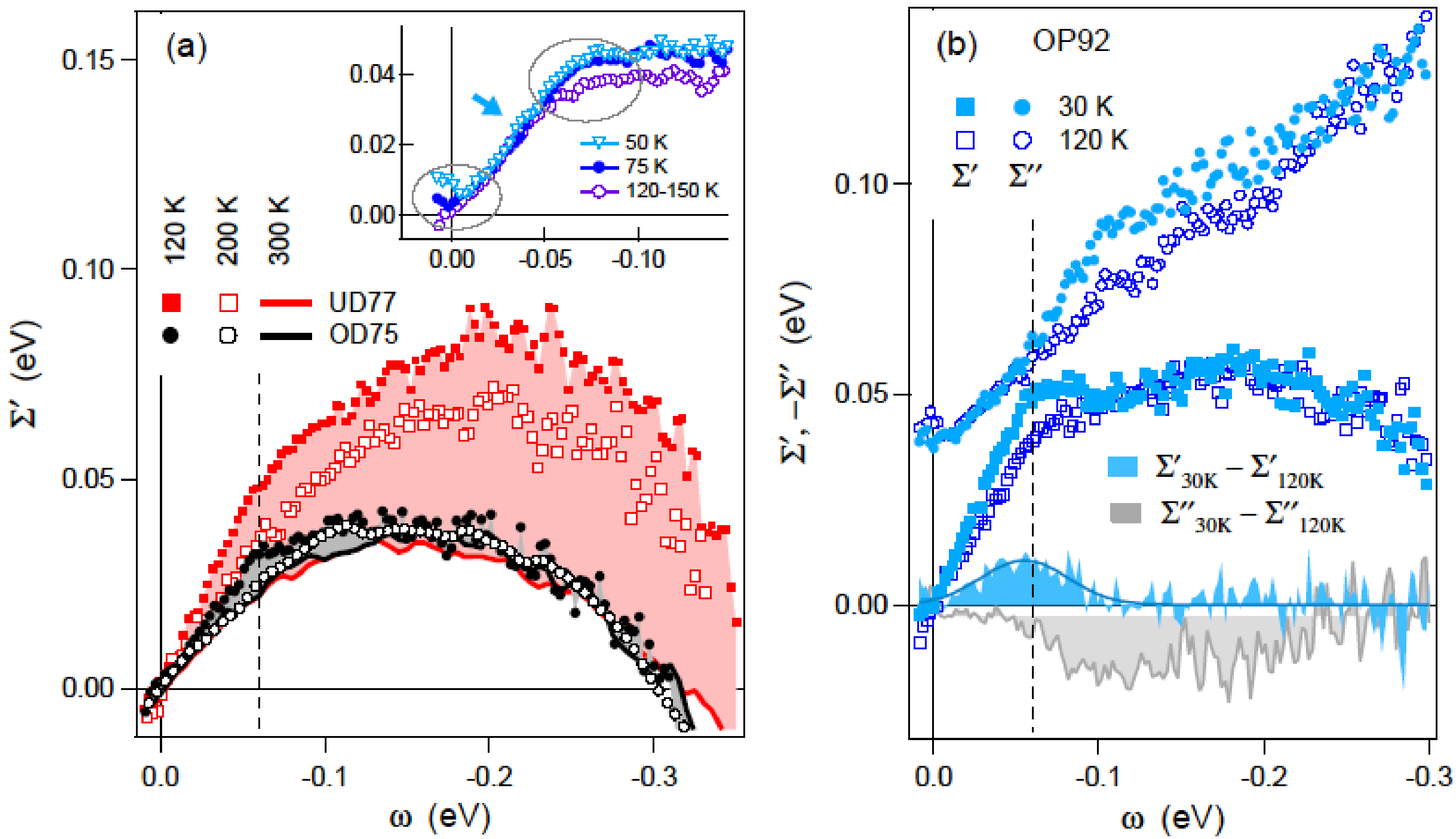
Parameters of the kink → 2 channels



$$\lambda = -\left(\frac{d\Sigma'}{d\omega}\right)_{\omega=0}$$

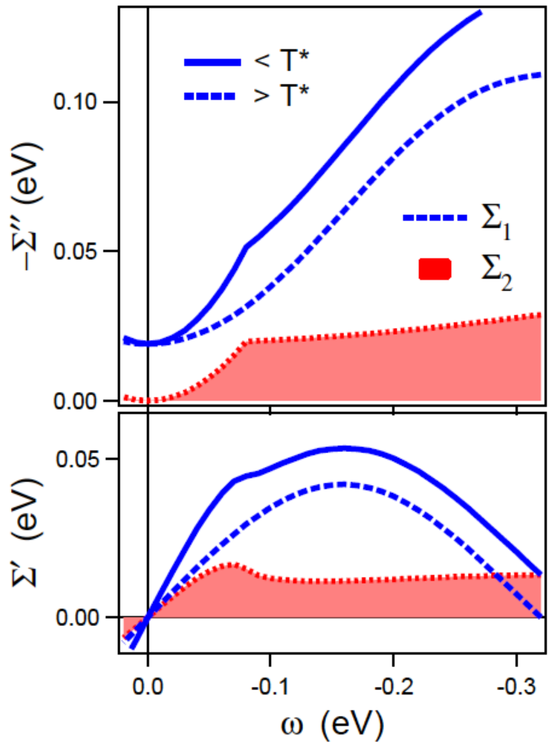
Kordyuk *PRL* 2006

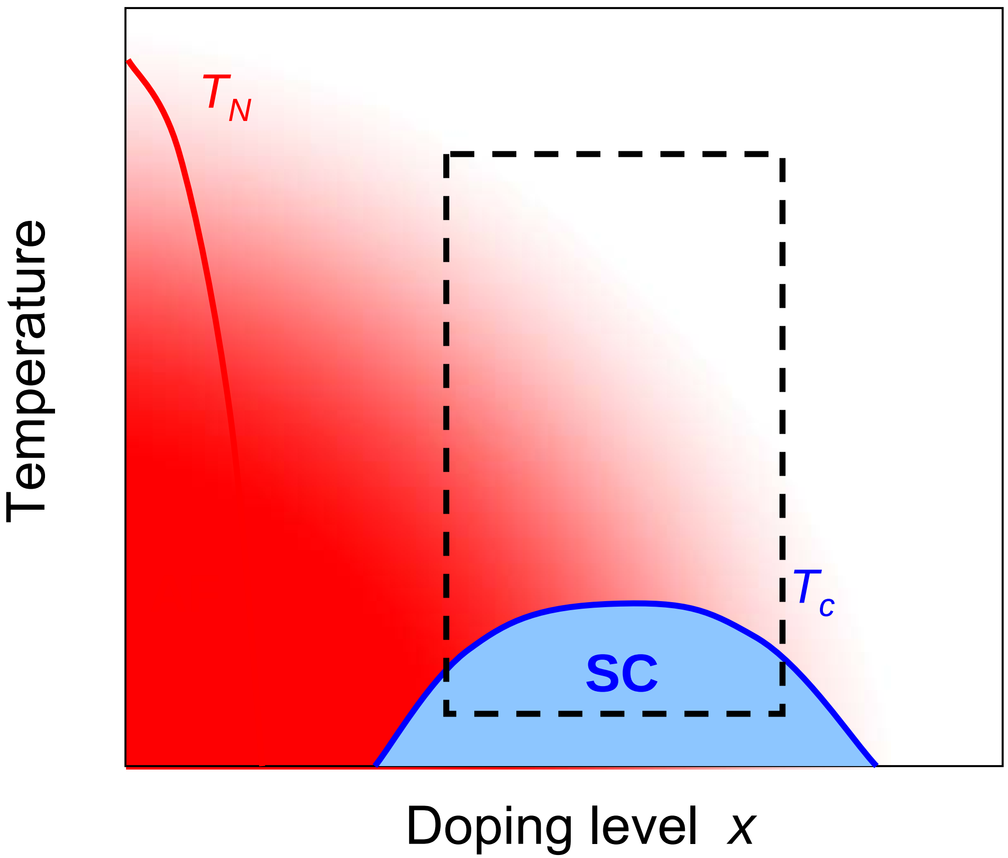
Evolution of the self-energy



Kordyuk *PRL* 2006

Intensity of the bosonic channel





Two channels

1 "Fermionic"

mainly xT-independent

featureless: $\Sigma'' \sim \omega^2$, $\Sigma' \sim \omega$

simple e-e interaction
(charge channel –
Auger-like decay)
FL

2 "Bosonic"

critically depends on (*x,T*)

energy structure:

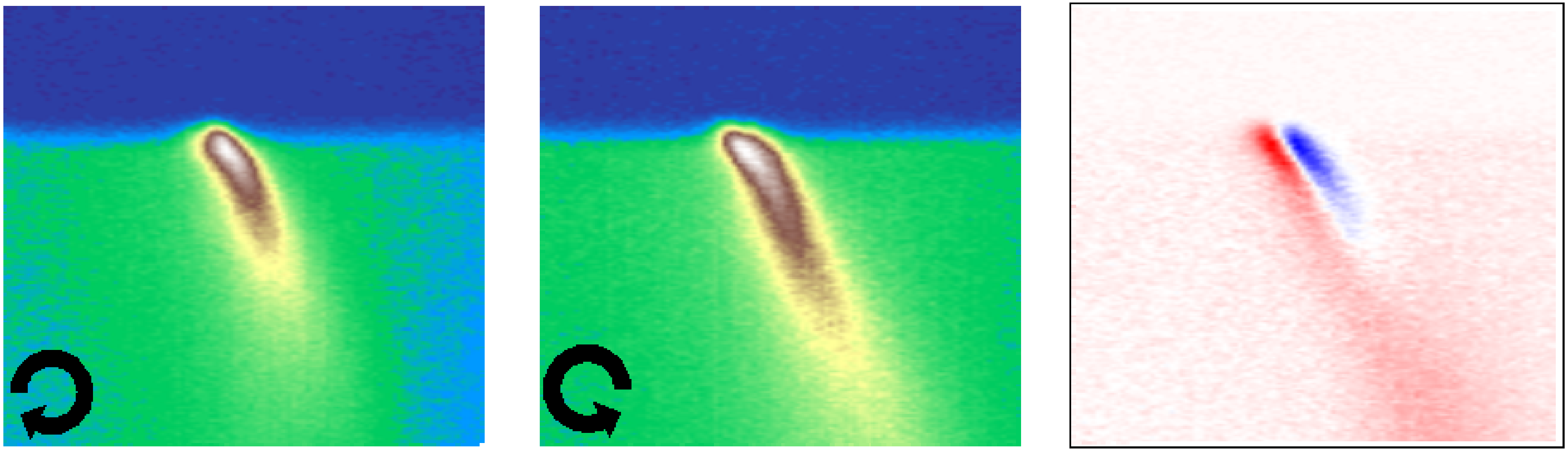
(i) kinky,
ω_k *mainly xT*-independent

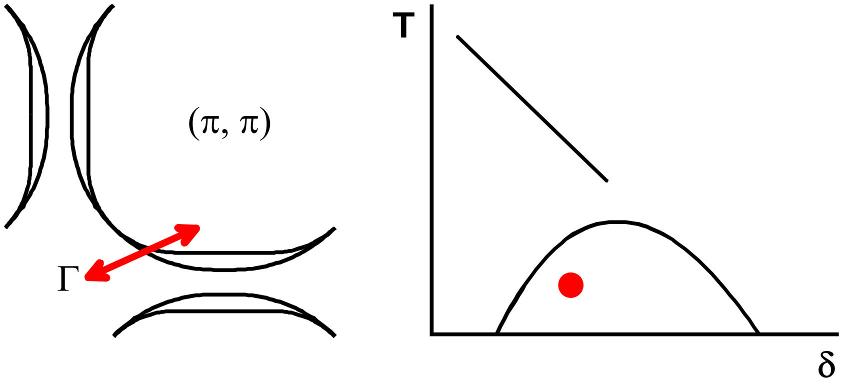
(ii) step-like,
does not confined at low ω

~~phonons~~, ~~gap~~ → SF

Parity

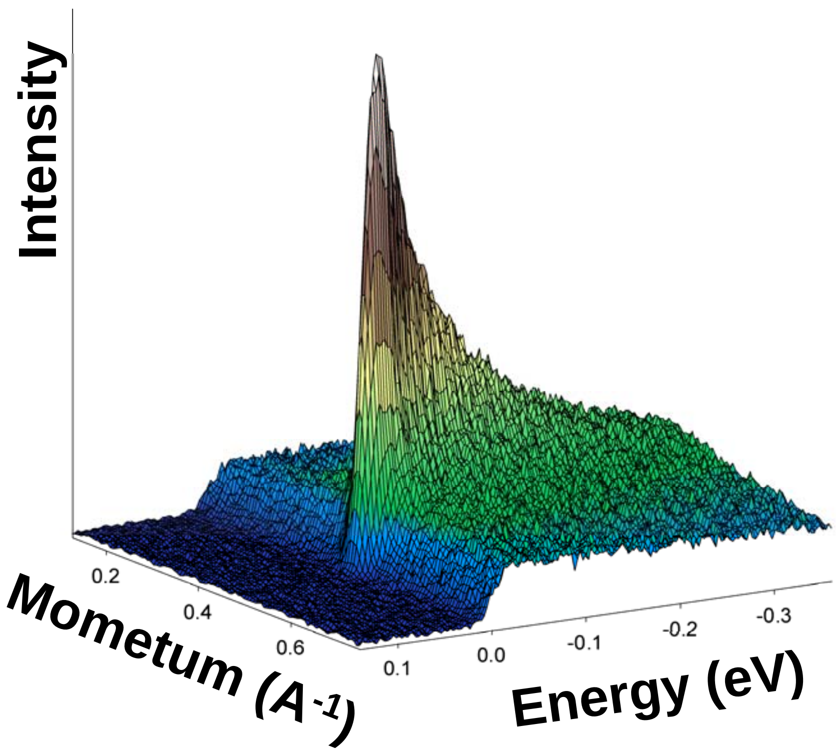
Parity of the scattering by circularly polarized light



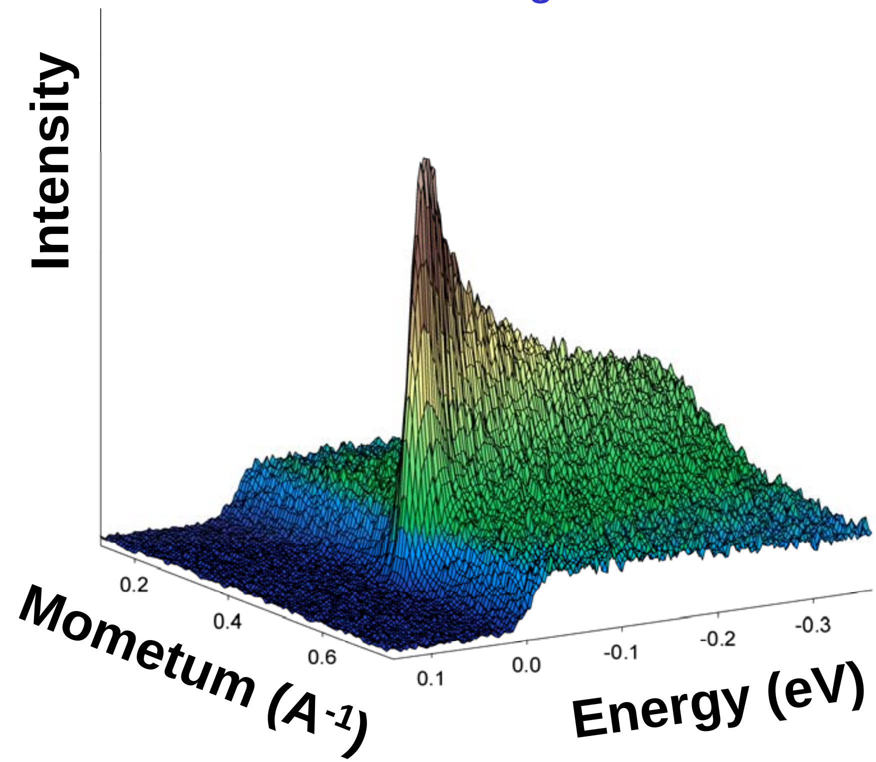


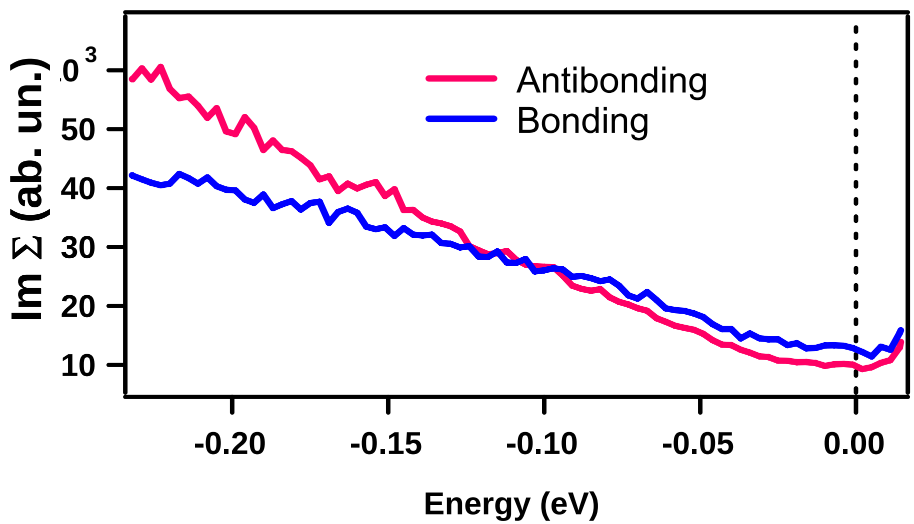
Borisenko *PRL* 2006

Antibonding



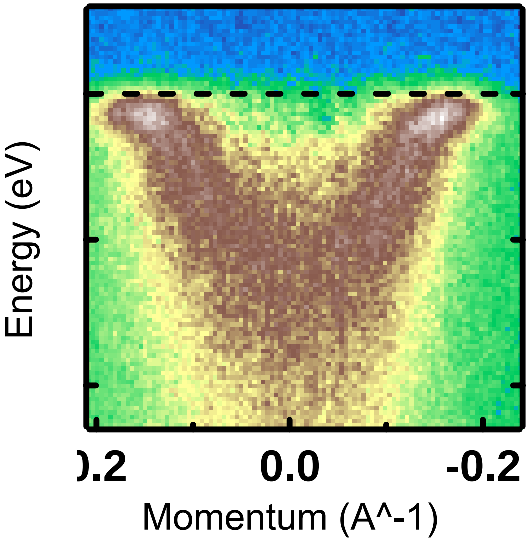
Bonding

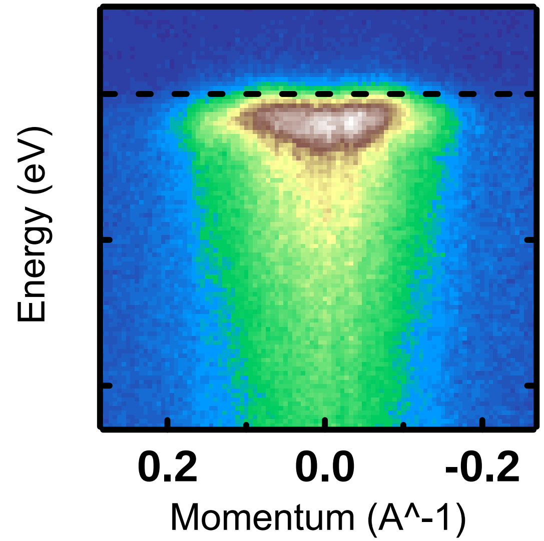




Borisenko *PRL* 2006

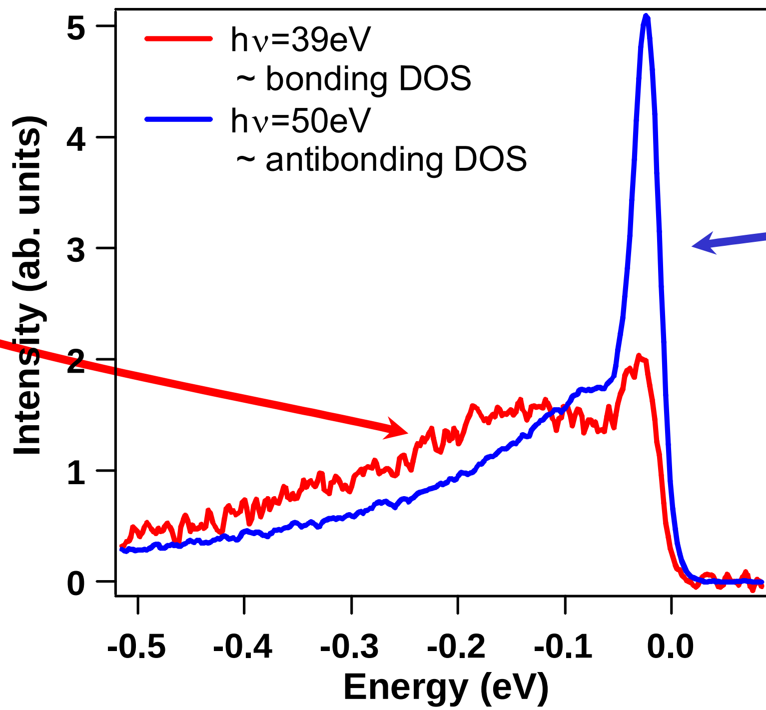
Bonding and antibonding densities of states





B

A



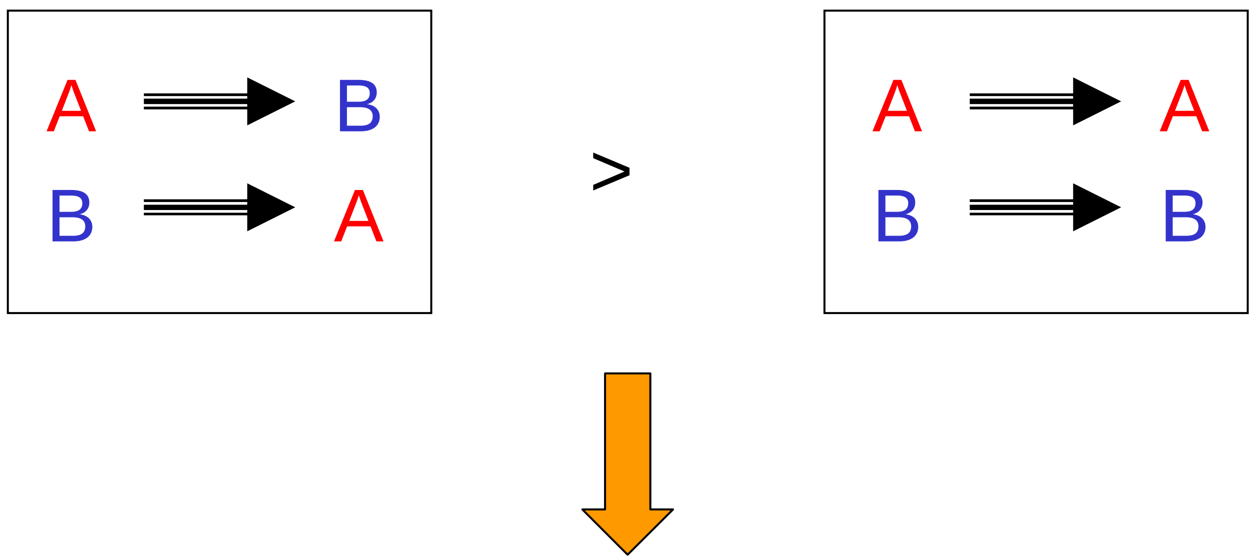
scattering
rate ~

•**Scattering rate (bonding band) ~ density of states of the antibonding band**

•**Scattering rate (antibonding band) ~ density of states of the bonding band**

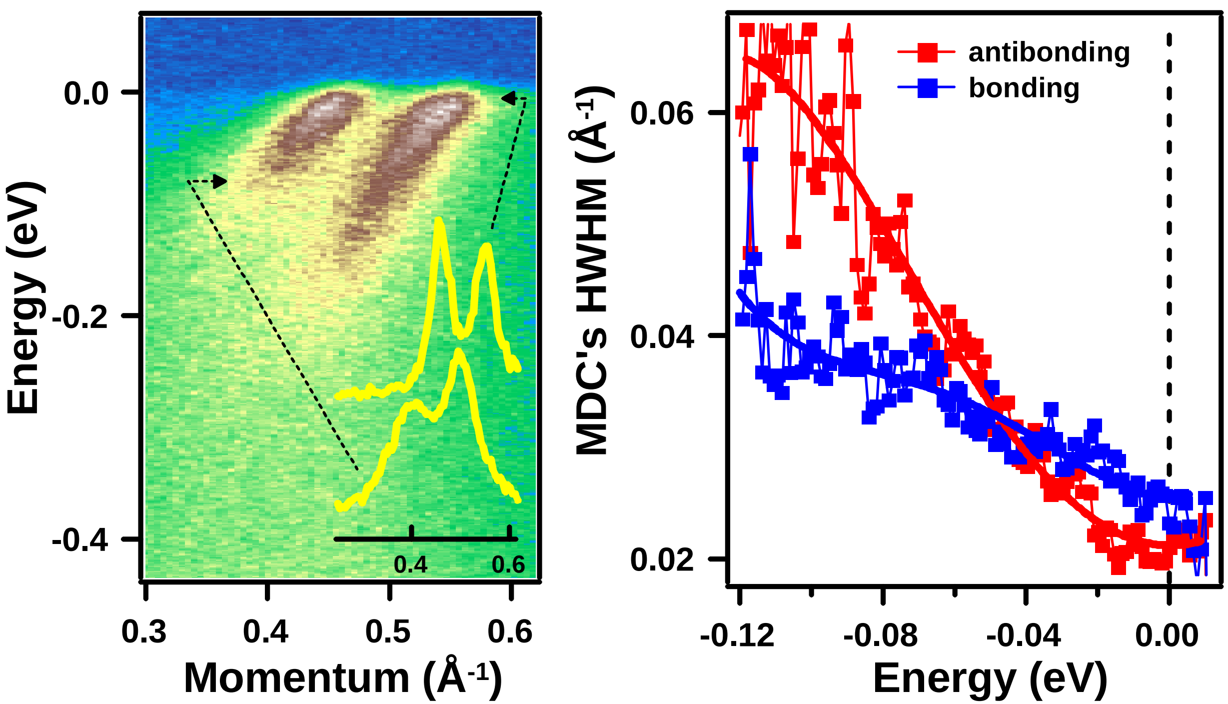
Interband scattering

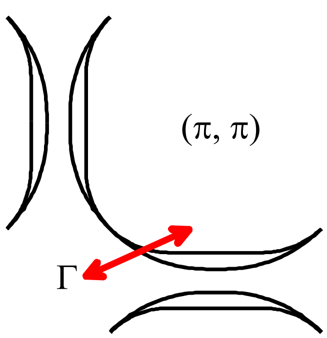
Intraband scattering

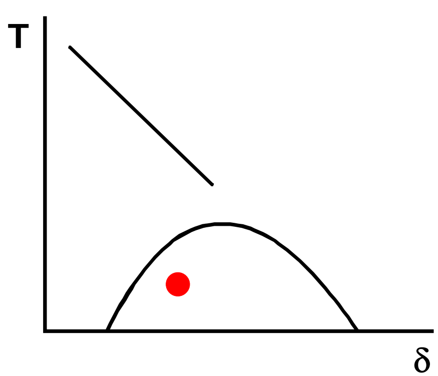


The boson which mediates the scattering is ODD with respect to the layers exchange within a bilayer!

Strong interband scattering in YBCO





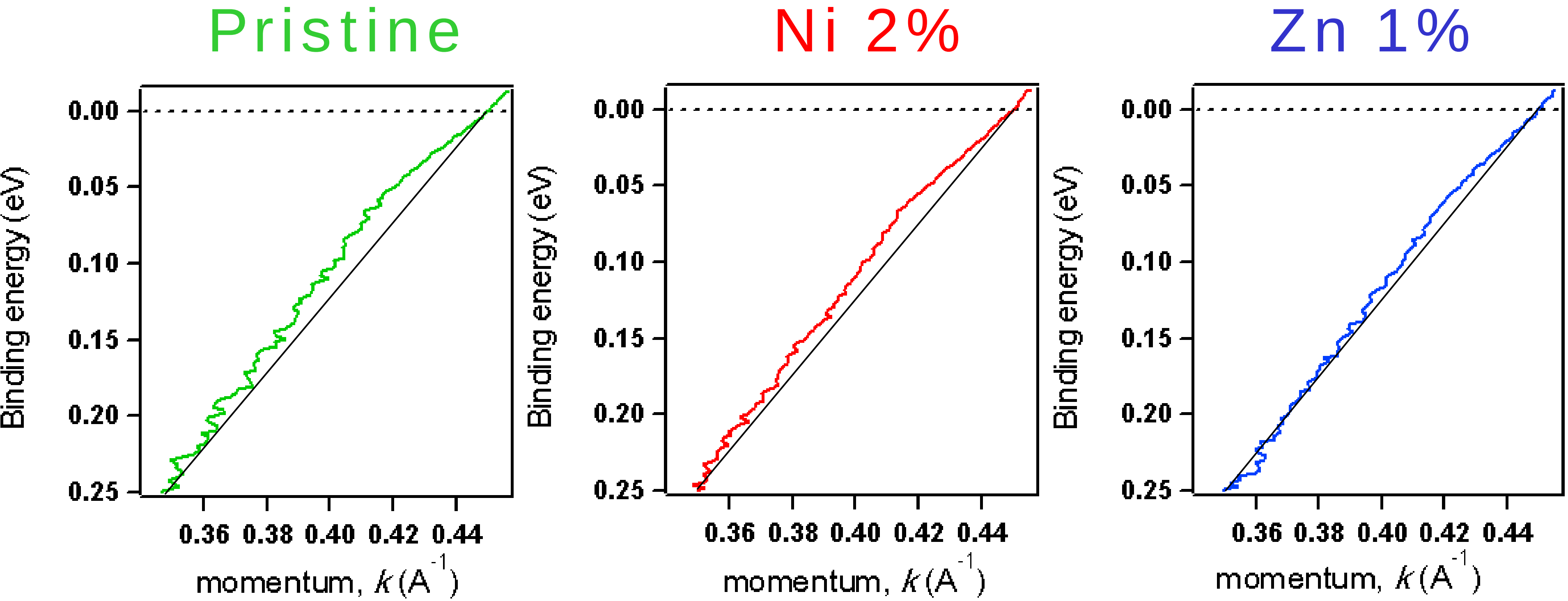


Borisenko *PRL-2* 2006

"Magnetic isotope effect"

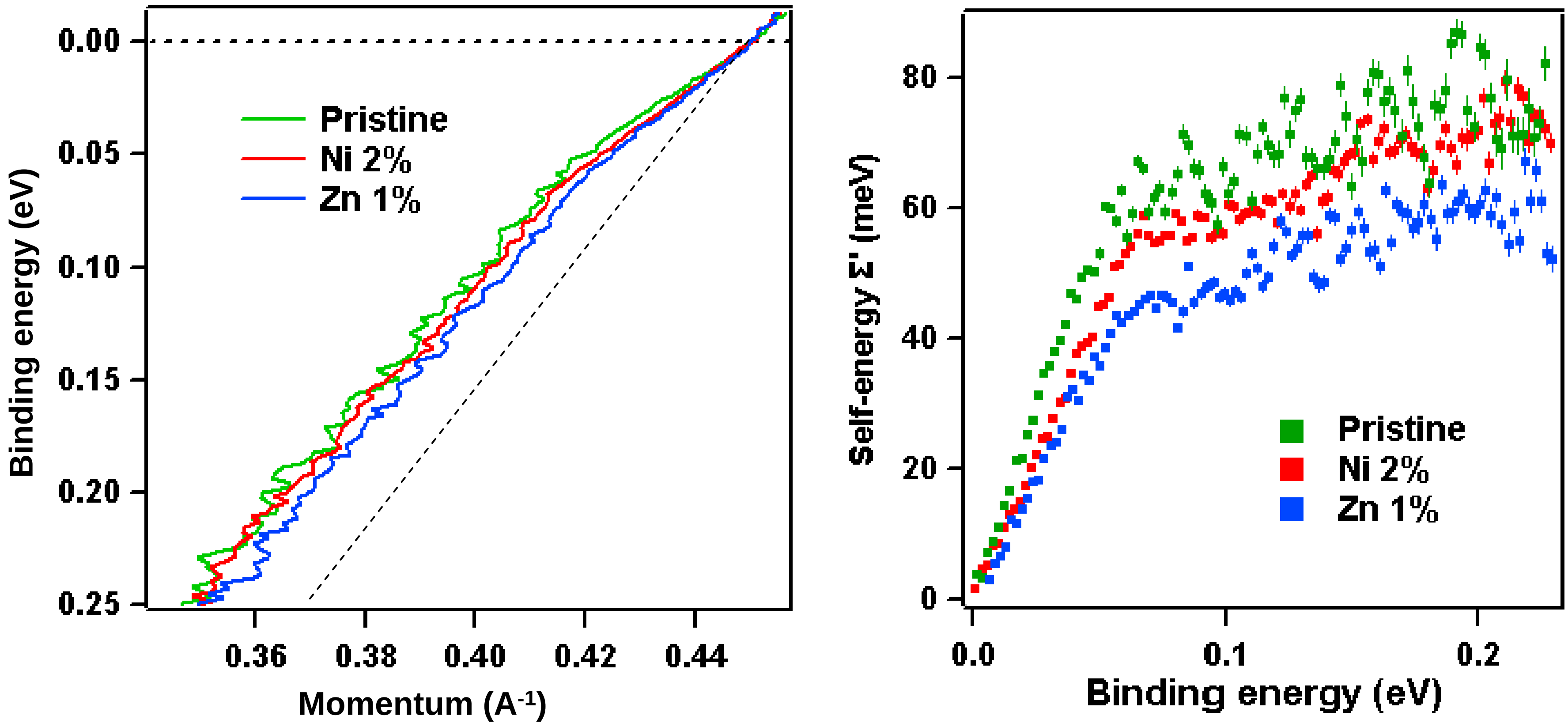
Doping pristine BSCCO with Zn and Ni impurities

Γ–(π, π) spectra, T < Tc



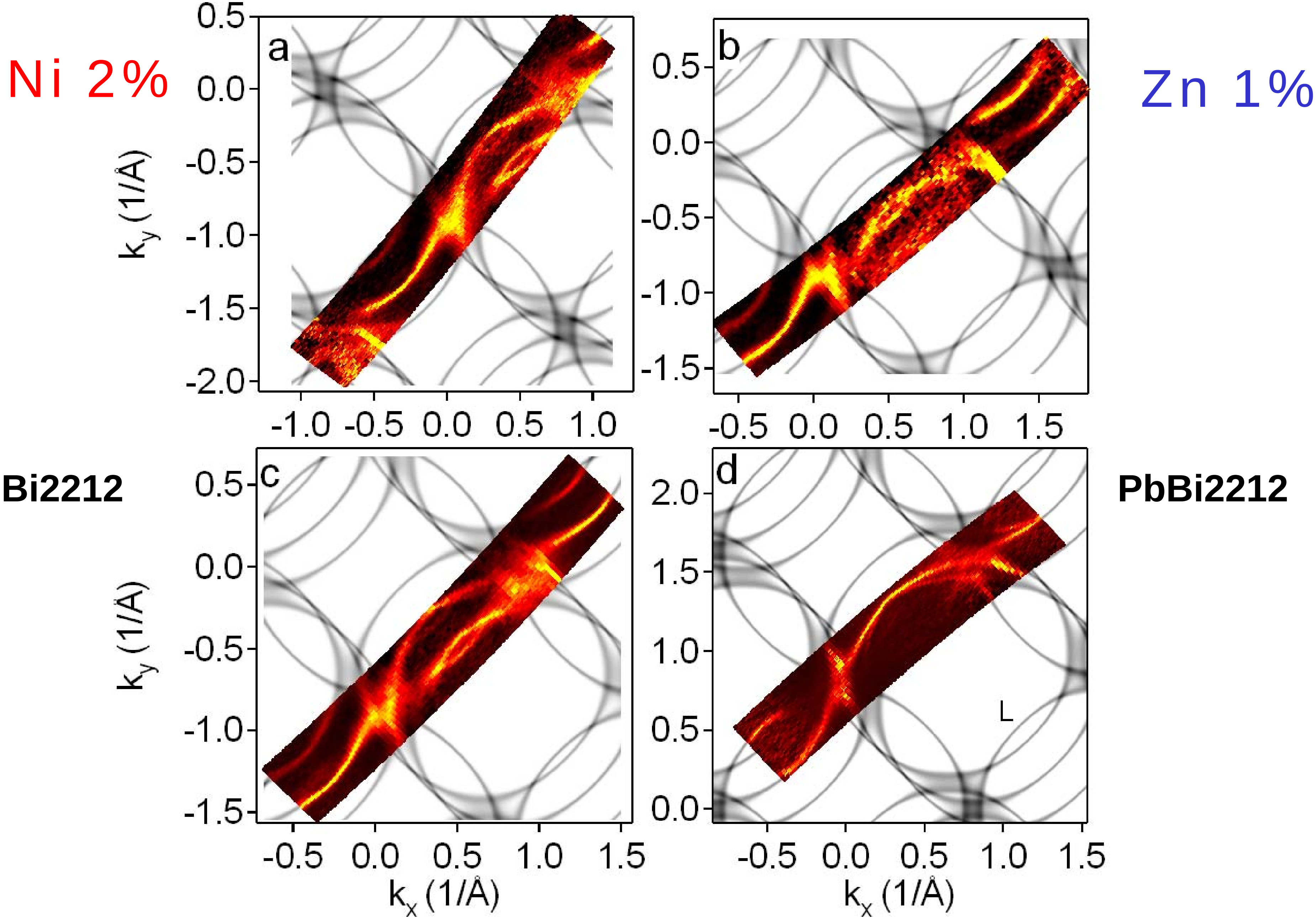
Zabolotnyy *PRL* 2006

"Kinks" and impurities

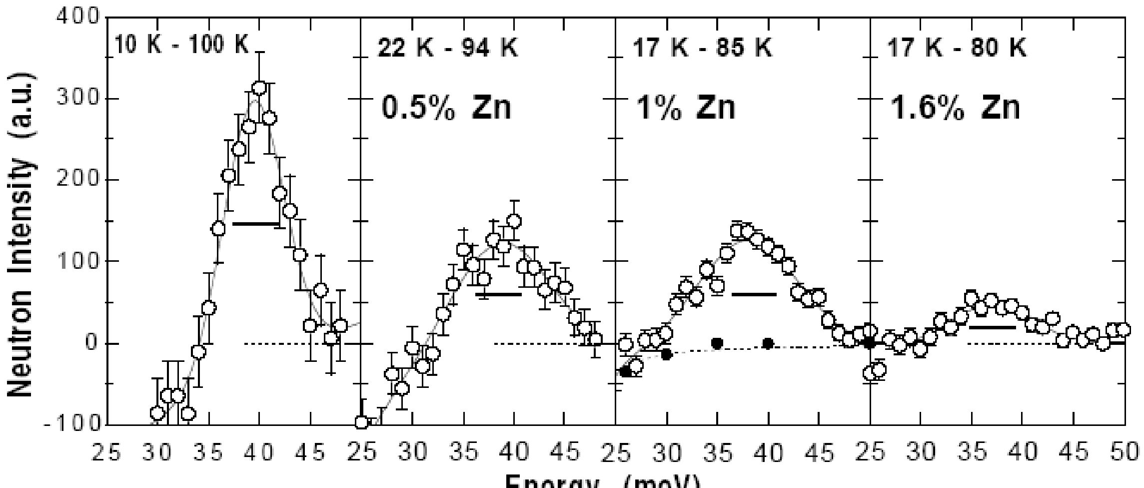


Zabolotnyy *PRL* 2006

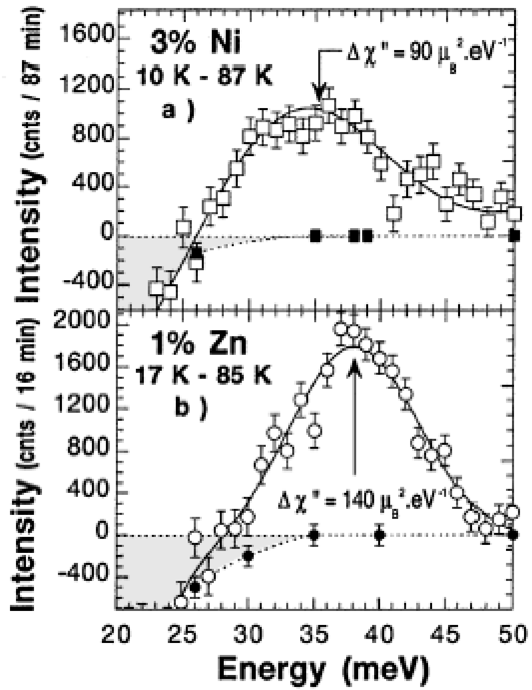
What about the doping level?



What is known from the neutron scattering ?



l. Difference spectrum of the neutron intensities at low temperature and T> T_c, in $YBa_2(Cu_{1-y}Zn_y)_3$



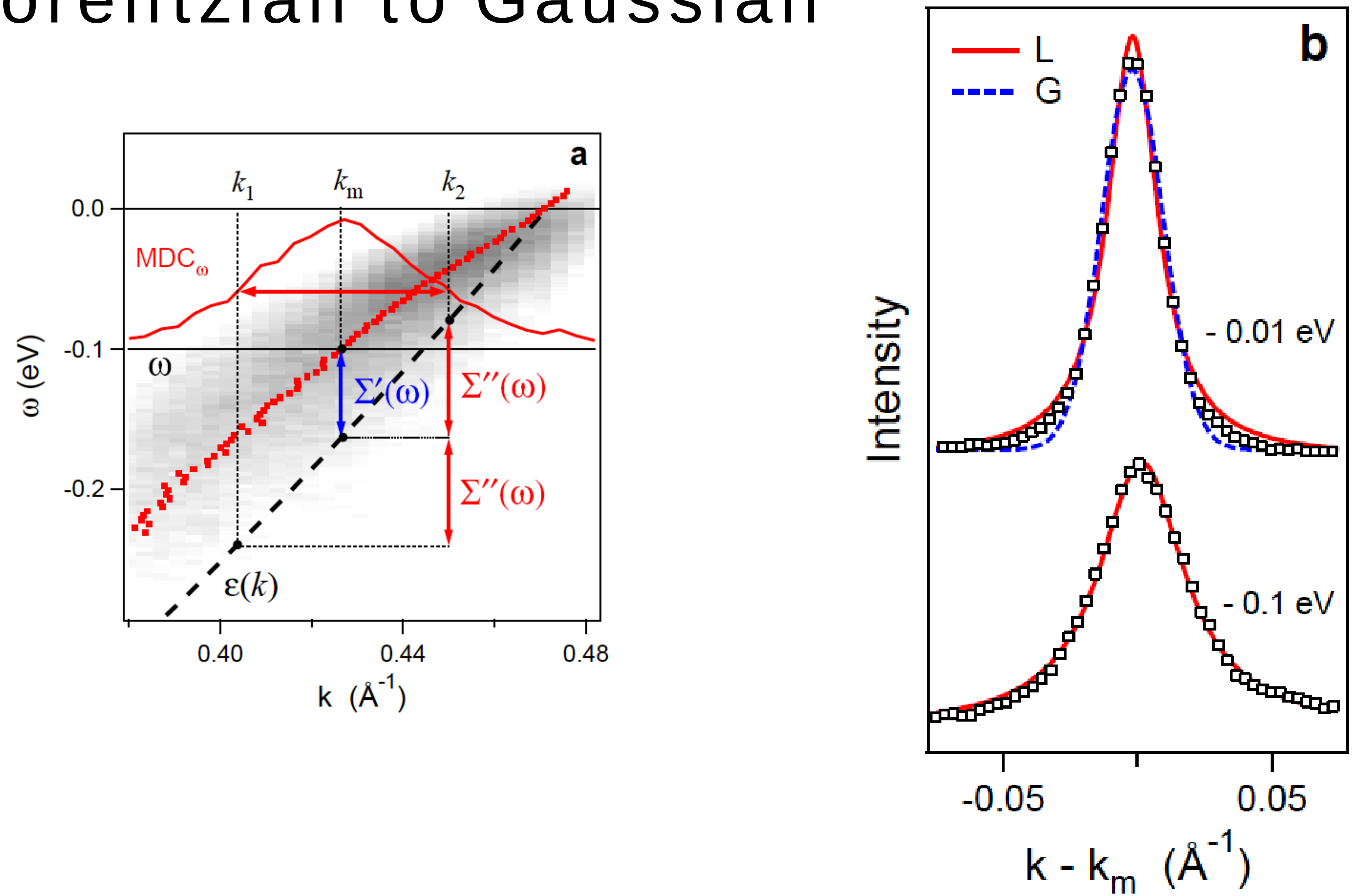
Y.Sidis et al. cond-mat/2000

Y.Sidis et al. PRL2000

Fine details

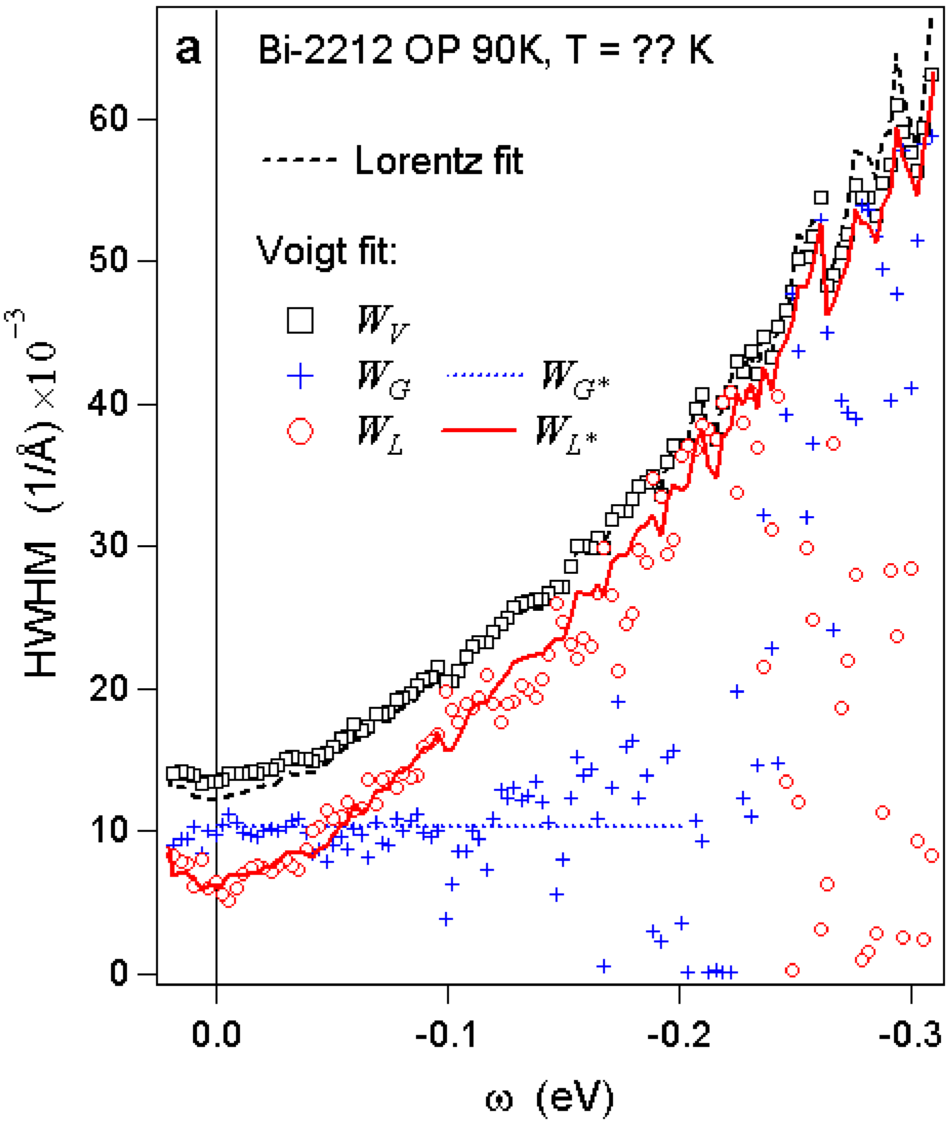
impurity scattering mechanism

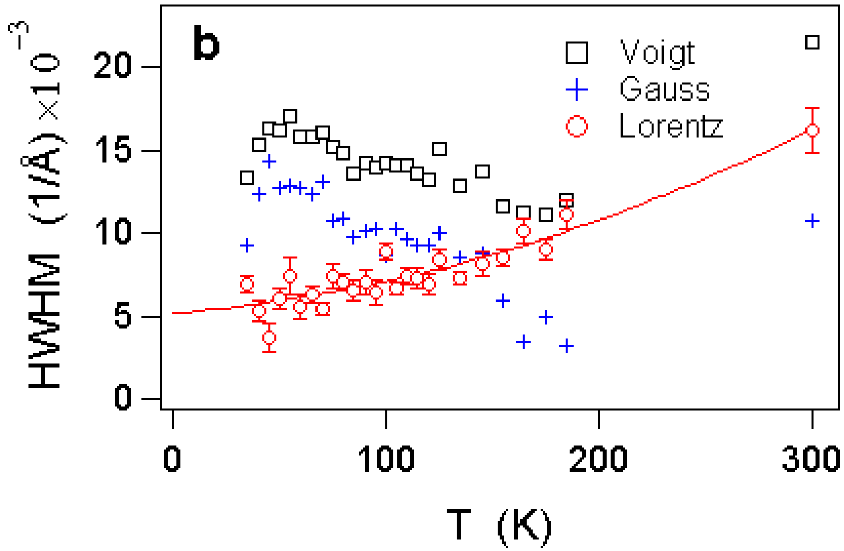
Lorentzian to Gaussian



Evtushinsky *cond-mat/0605100*

Voigt fitting procedure





$$W_V = V(W_L, W_G)$$

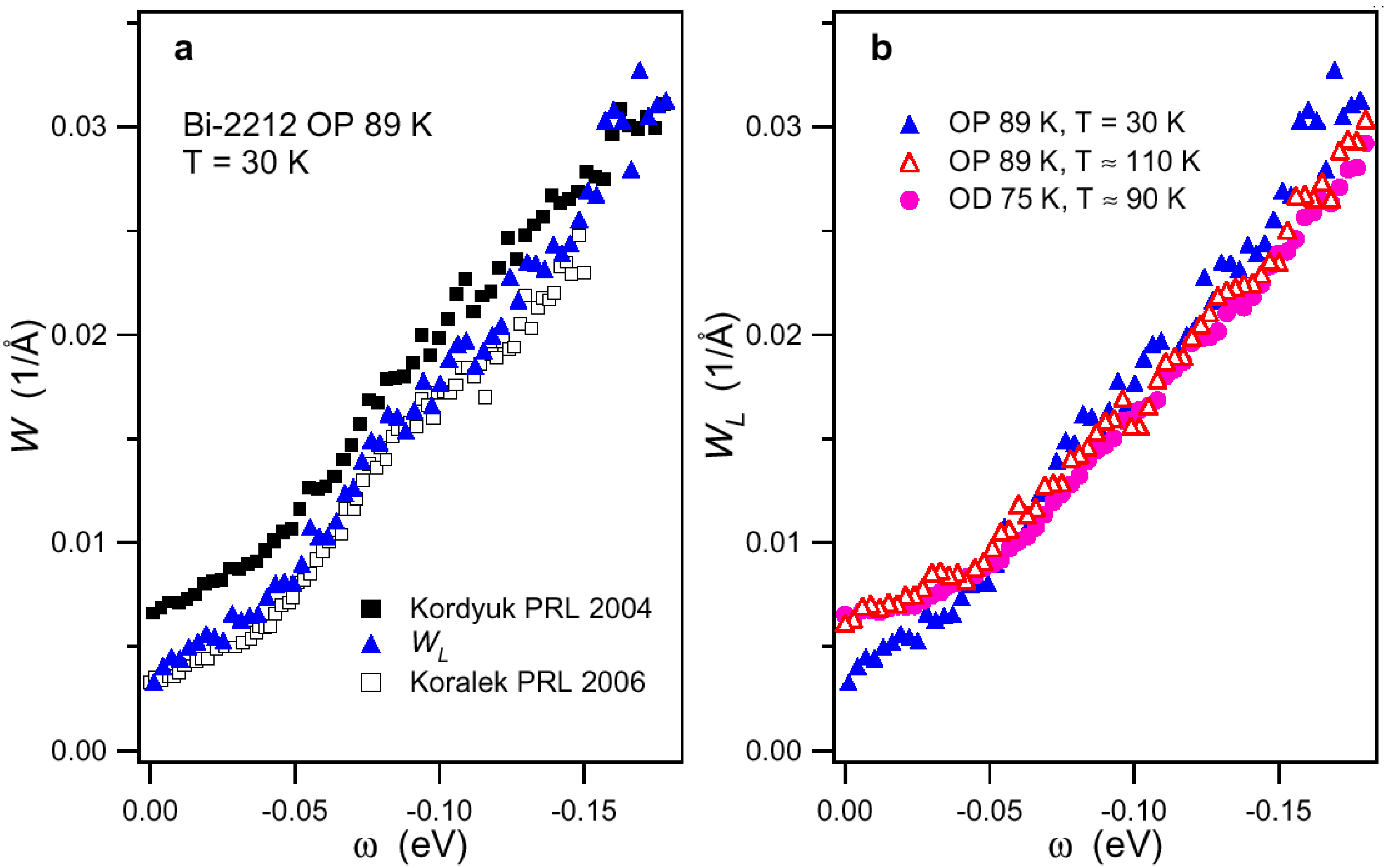
$$= \frac{W_L}{2} + \sqrt{\frac{W_L^2}{4} + W_G^2}$$

Evtushinsky *cond-mat/0605100*

Now for the self-energy:

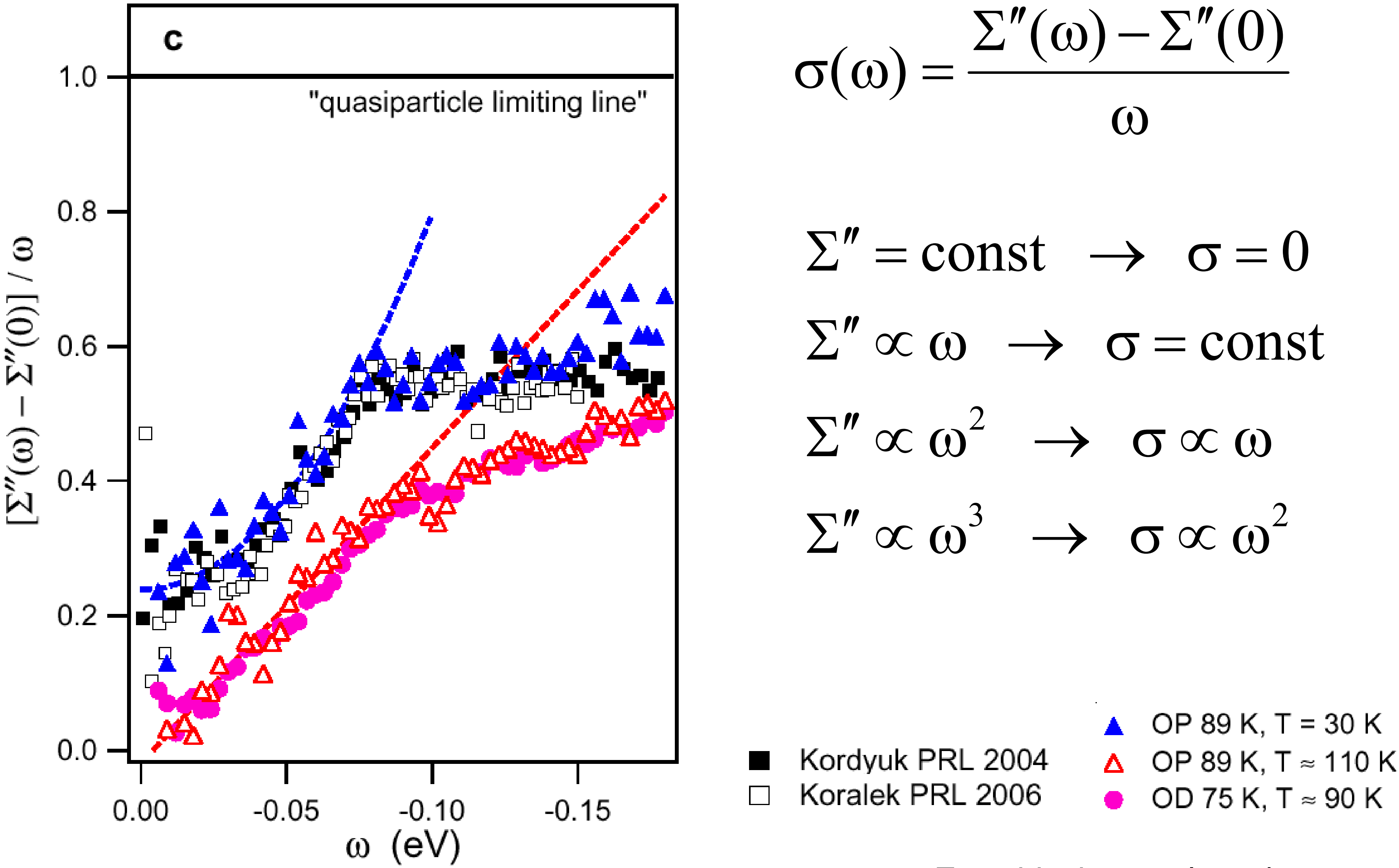
1. Real impurity scattering
2. Careful energy dependence
3. Careful temperature dependence

Energy dependence



Evtushinsky *cond-mat/0605100*

Reduced self-energy function



$$\sigma(\omega) = \frac{\Sigma''(\omega) - \Sigma''(0)}{\omega}$$

$$\Sigma'' = \text{const} \quad \rightarrow \quad \sigma = 0$$

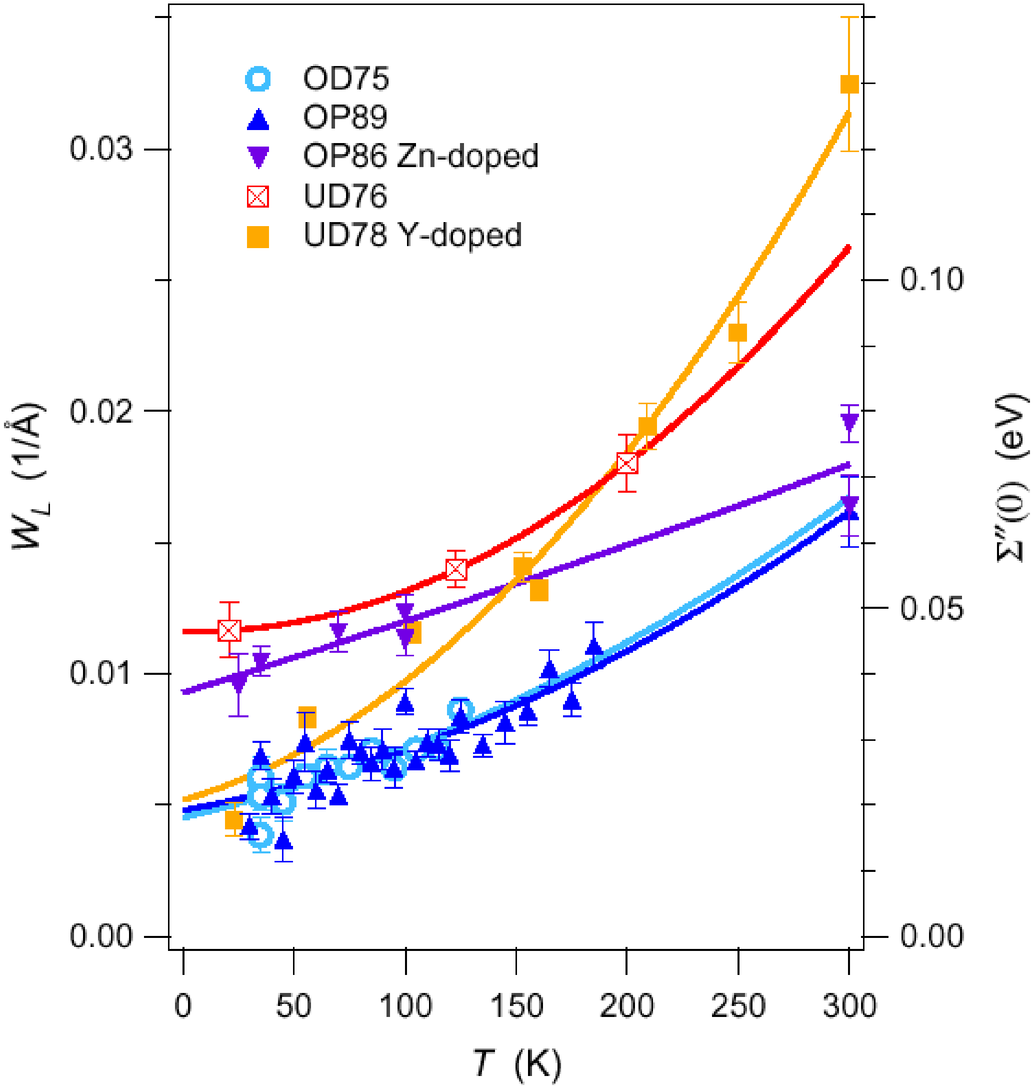
$$\Sigma'' \propto \omega \quad \rightarrow \quad \sigma = \text{const}$$

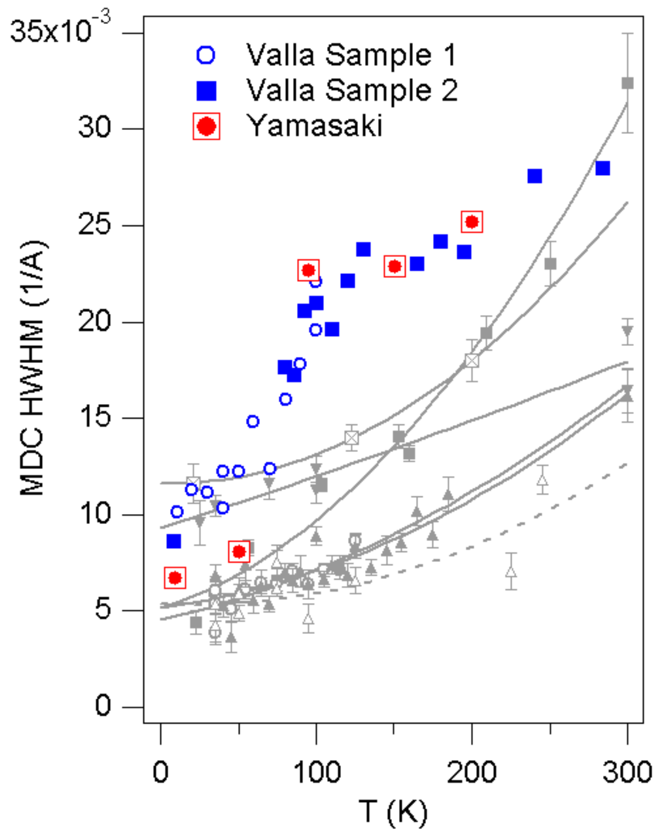
$$\Sigma'' \propto \omega^2 \quad \rightarrow \quad \sigma \propto \omega$$

$$\Sigma'' \propto \omega^3 \quad \rightarrow \quad \sigma \propto \omega^2$$

Evtushinsky *cond-mat/0605100*

Temperature dependence



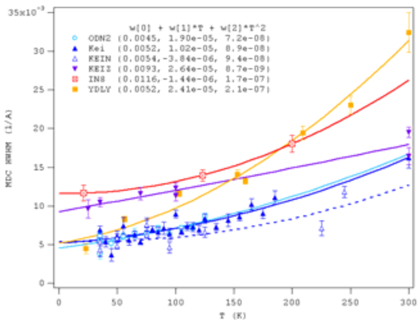


pseudo-gap

no "arcs" !

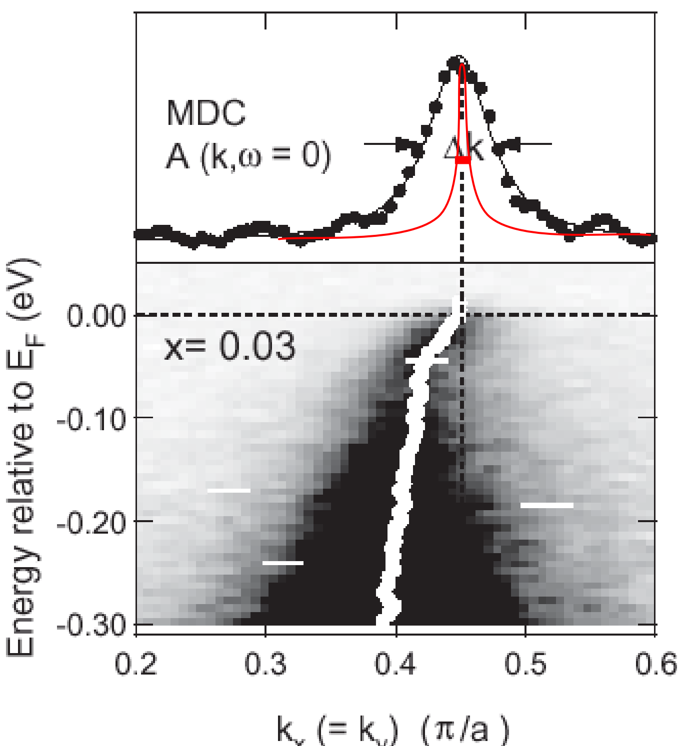
Evtushinsky *cond-mat/0605100*

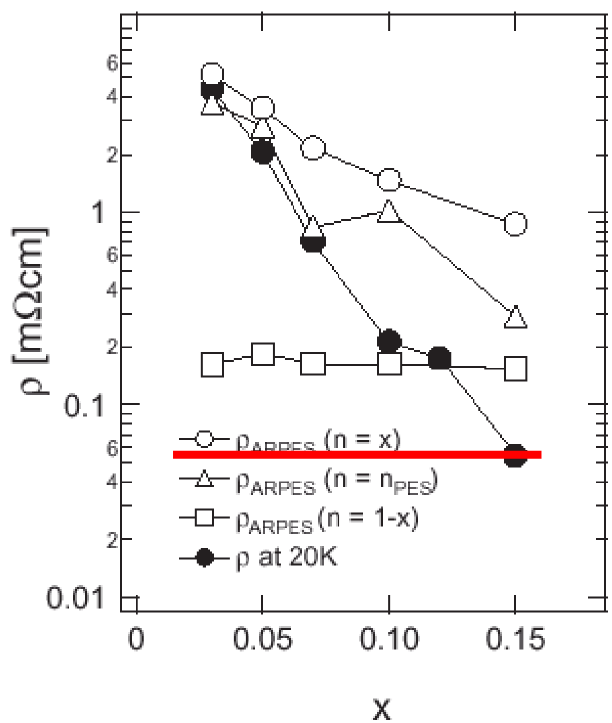
Impurity scattering



$$\rho_0 = \frac{m^*}{ne^2\tau} \approx \frac{k_F}{ne^2\hbar}\frac{\Sigma''_{im}}{v_r}$$

forward or unitary?





$n(x)$?

inhomogeneity

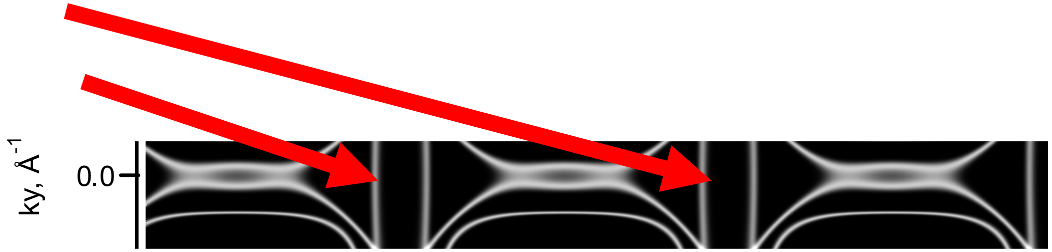
Yoshida *Physica B* 2004

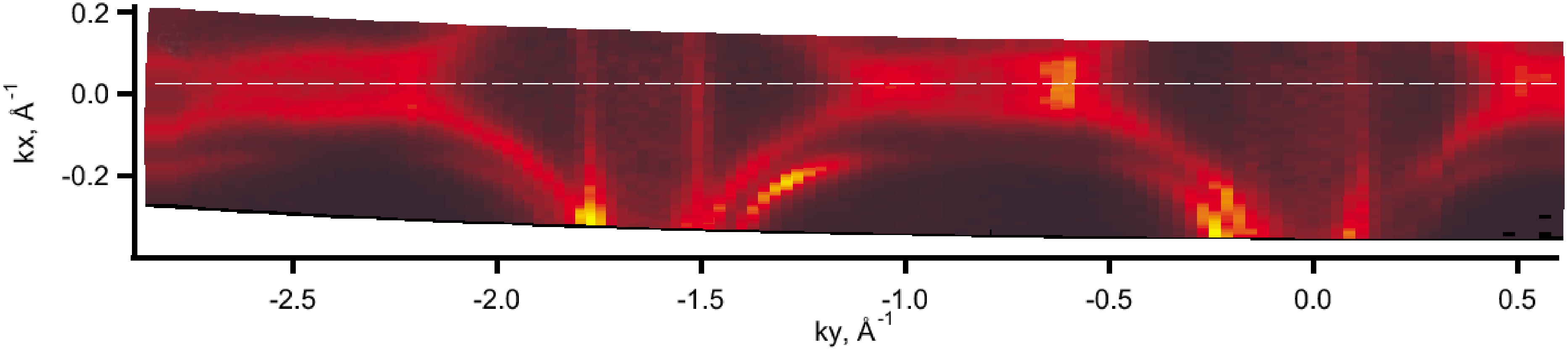
YBCO

Fermi surface of YBCO

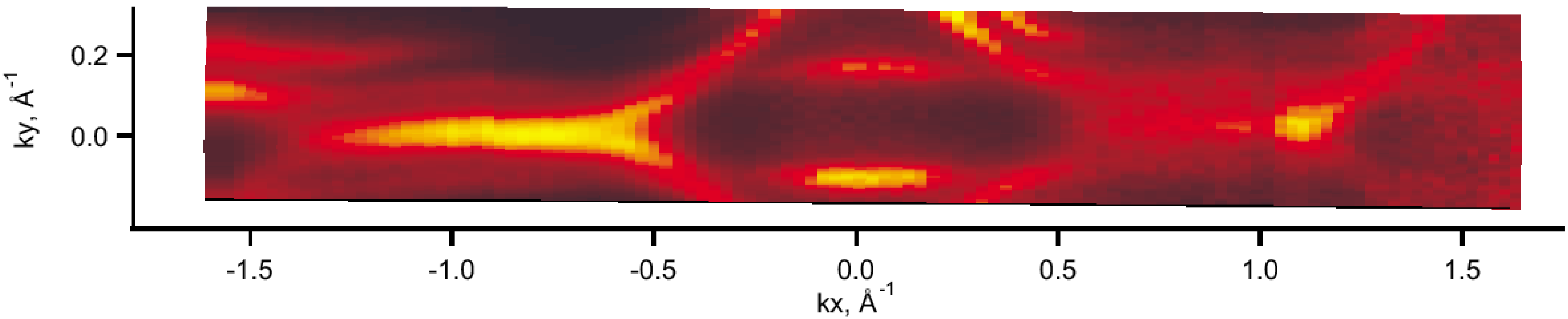
O. K. Andersen et al.

Chain states

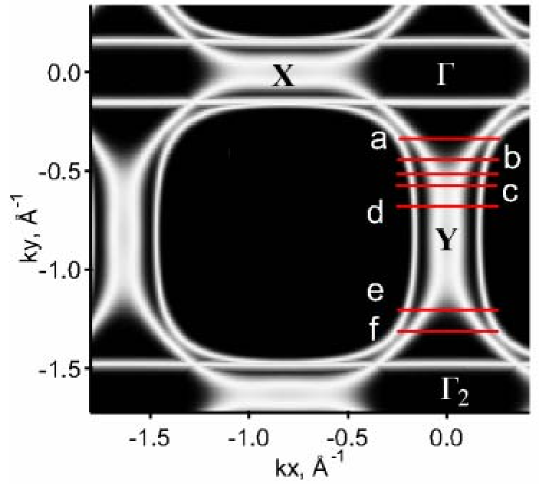


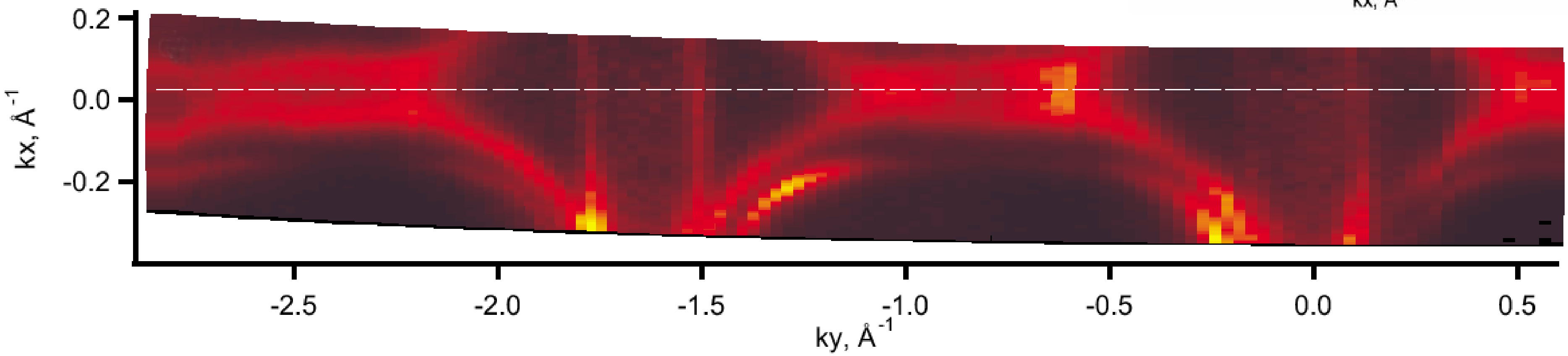


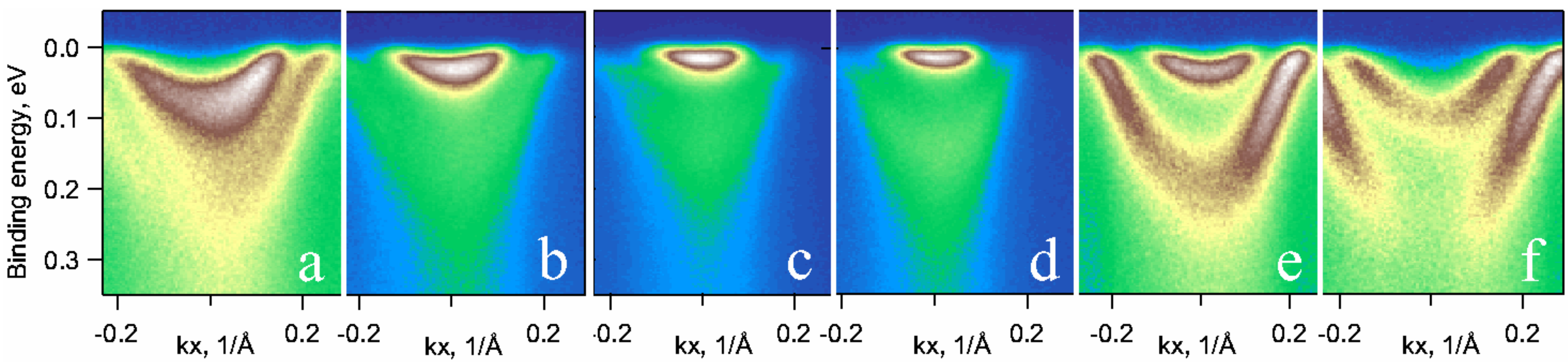
Fermi surface of YBCO



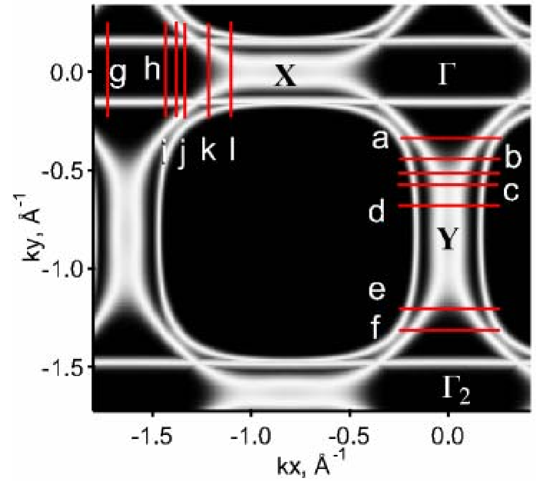
Electronic structure of YBCO

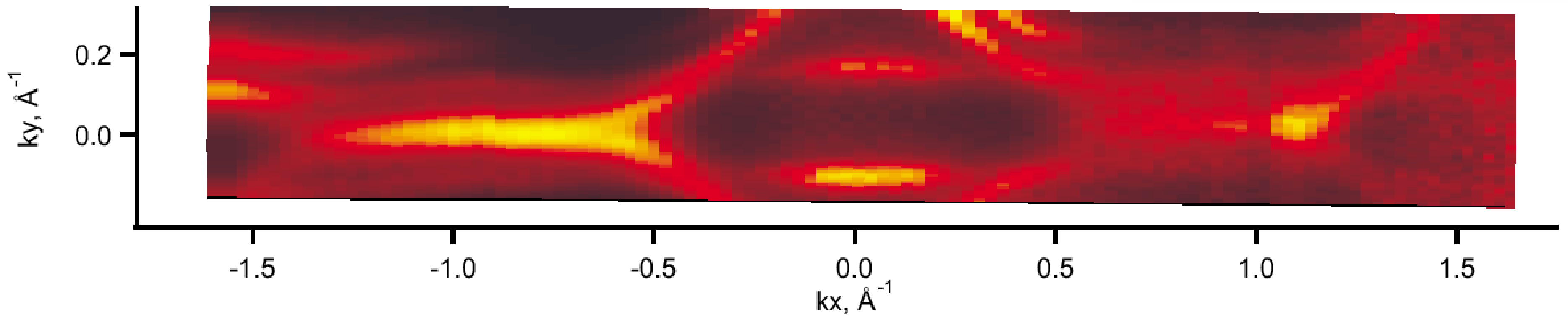


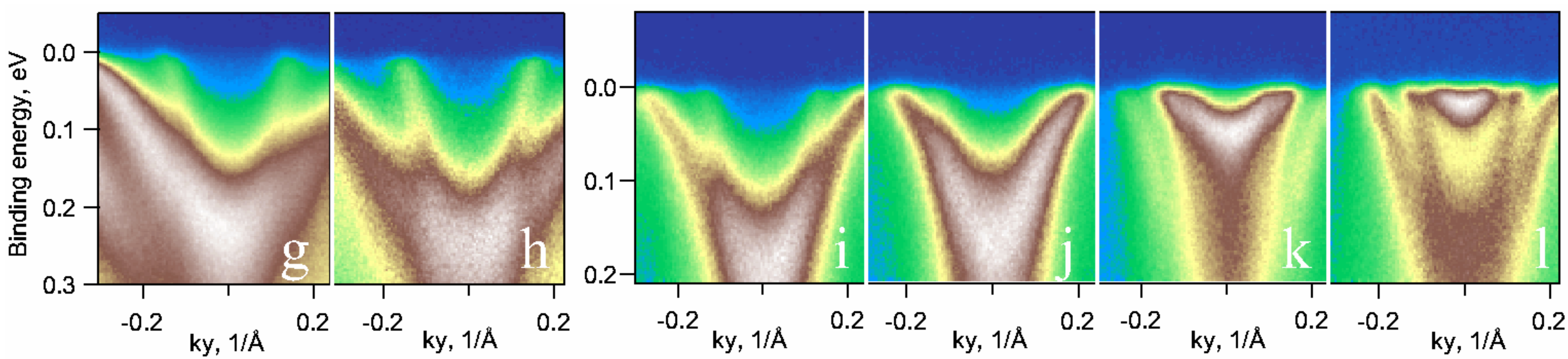




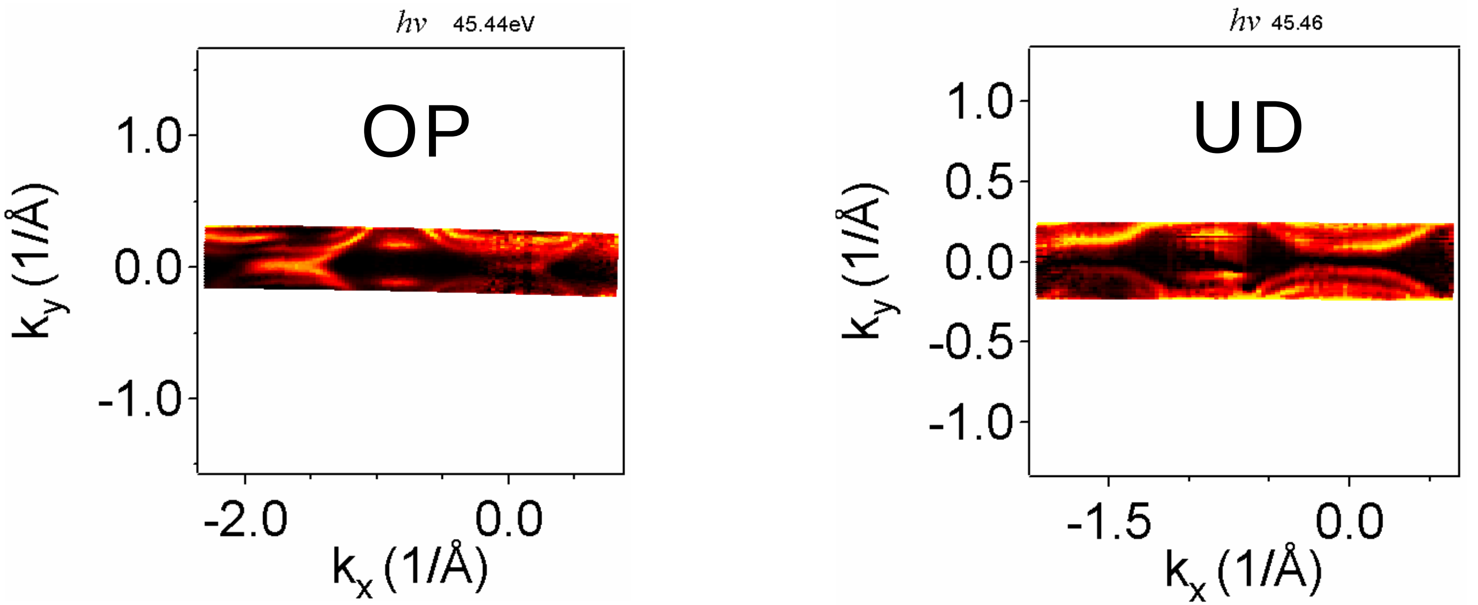
Electronic structure of YBCO



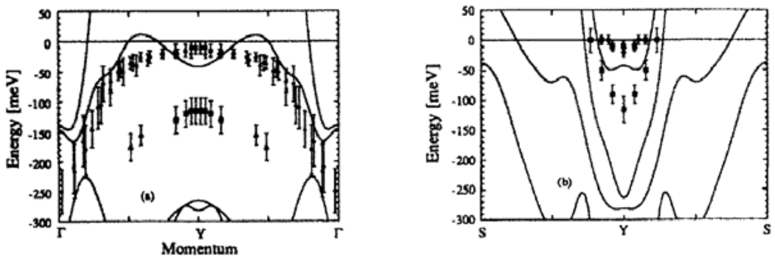




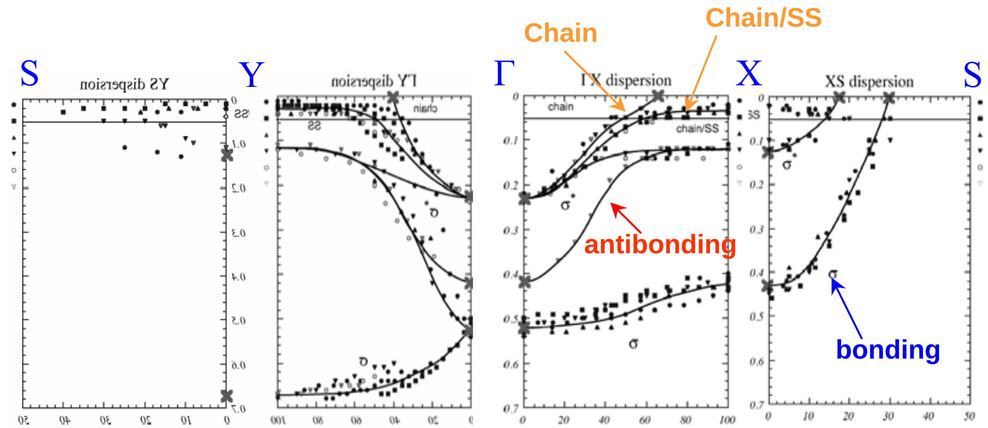
Underdoped and optimally doped



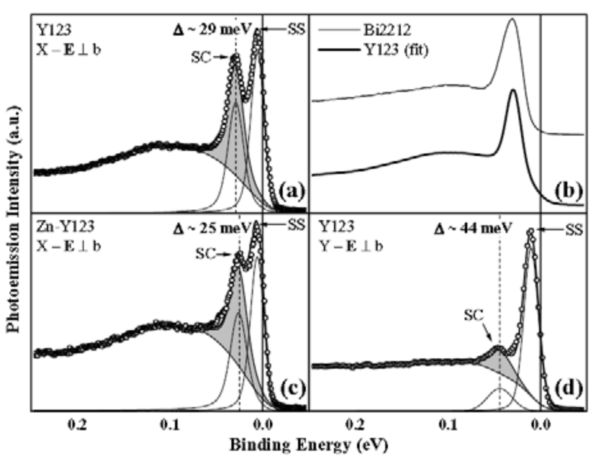
Some of the previous work on YBCO



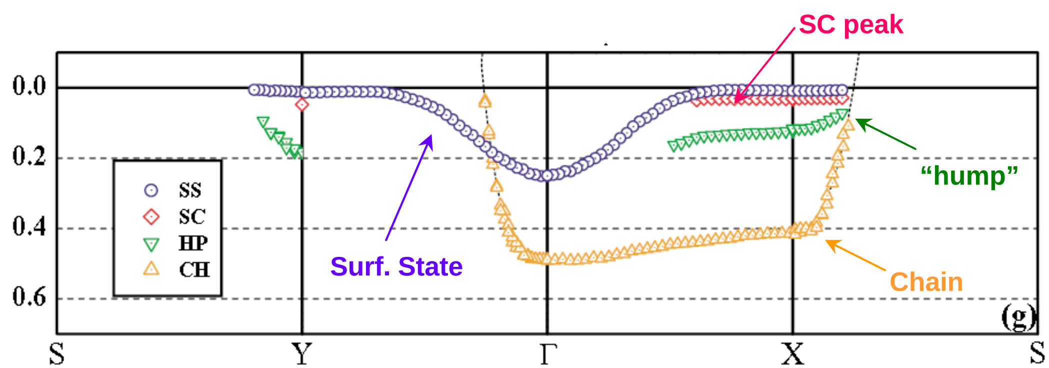
K. Gofron *et al.*, J. Phys. Chem. Solids **54**, 1193 (1993)



M. C. Schabel *et al.*, Phys. Rev. B **57**, 6090 (1998)



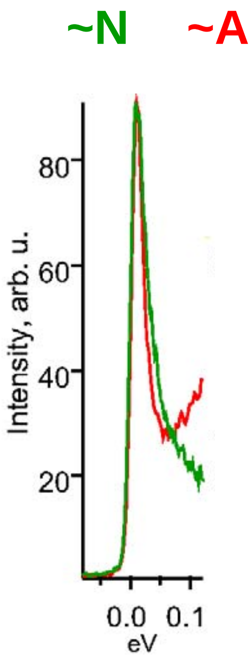
D. H. Lu *et al.*, Phys Rev. Lett **86**, 4370 (2001)



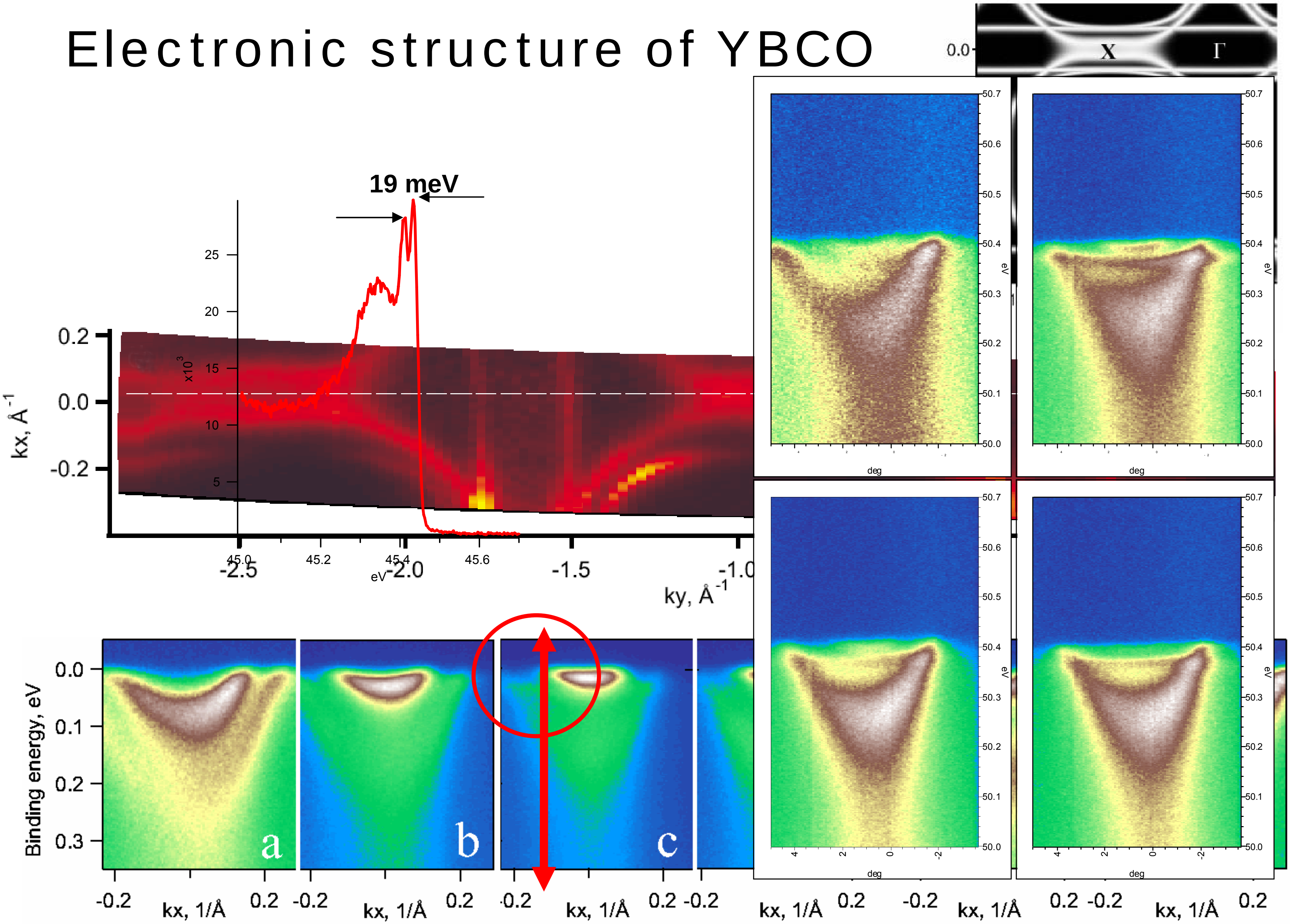
D. H. Lu *et al.*, Phys Rev. Lett **86**, 4370 (2001)

YBCO: Gap?

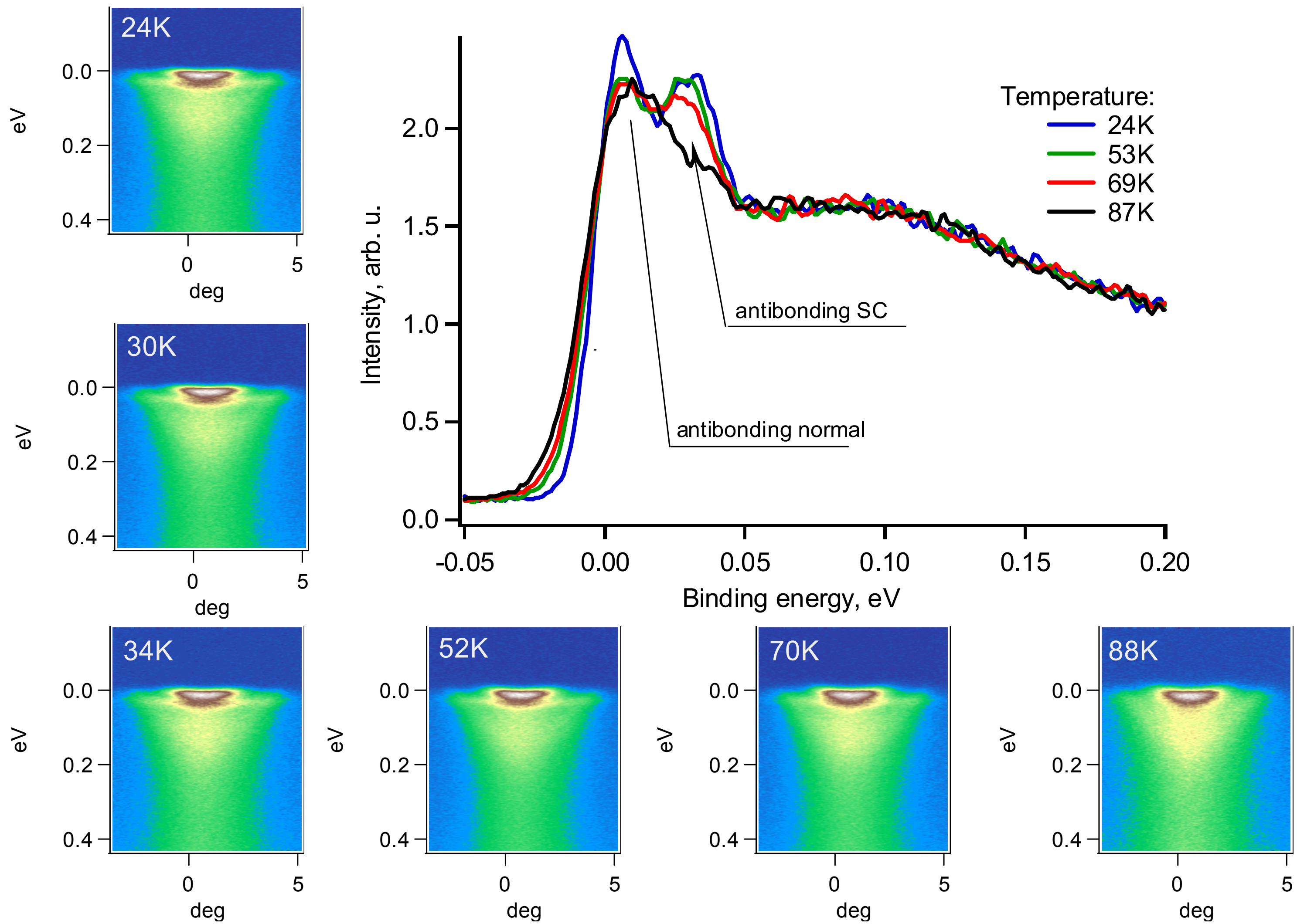
YBCO 6.85



Electronic structure of YBCO



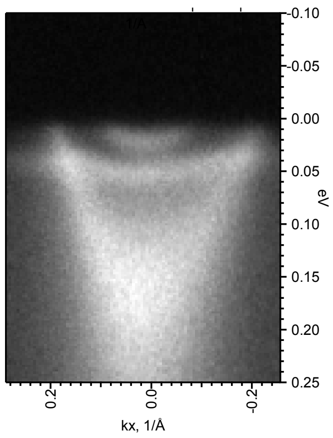
Temperature dependence.

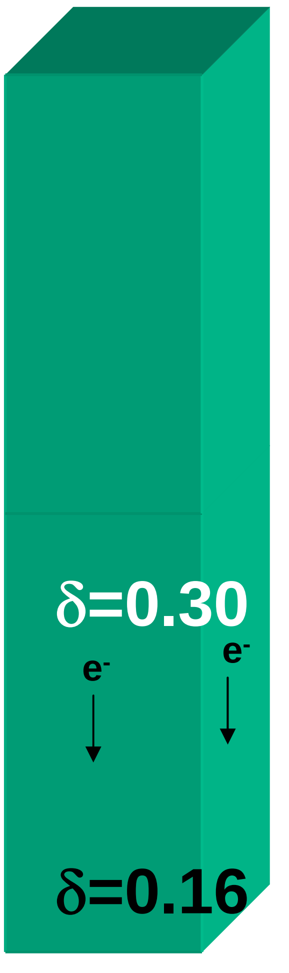


V. Zabolotnyy et al.

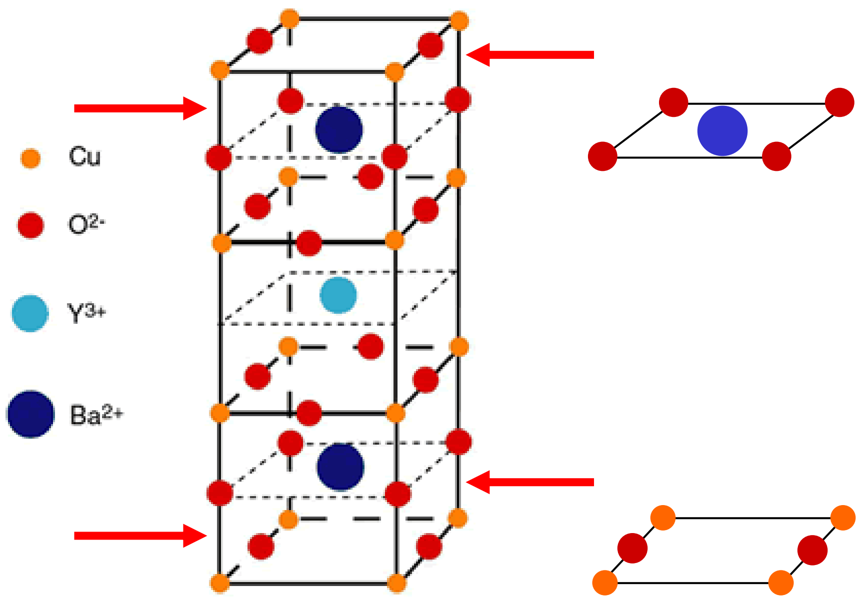
Superconducting component

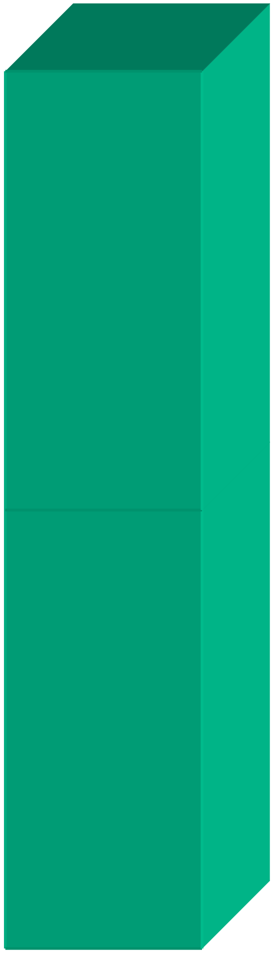
experiment

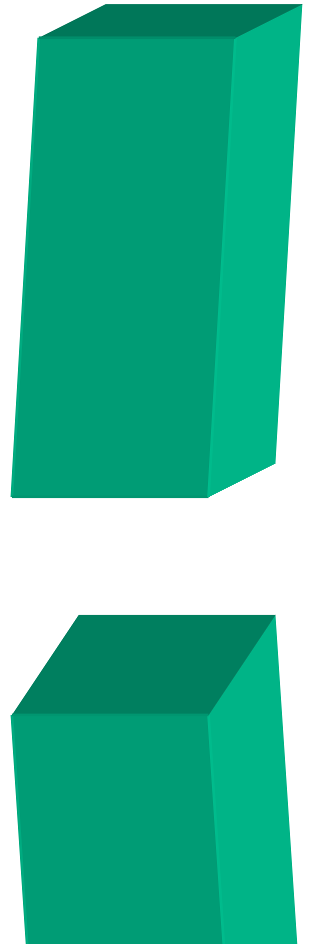


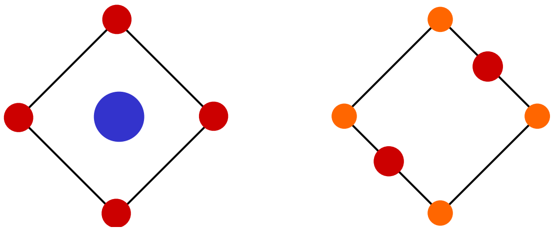


δ=0.30
e-
e-
δ=0.16

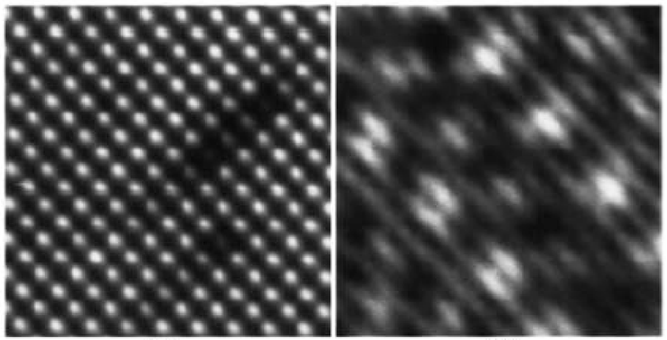

Cu
O^{2-}
Y^{3+}
Ba^{2+}







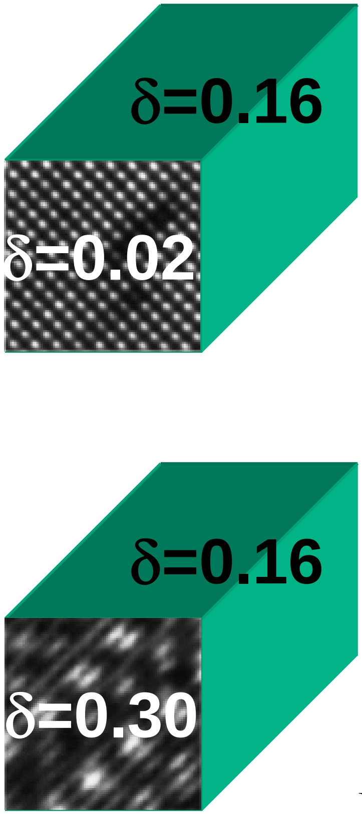
Pan, Hudson, and Davis

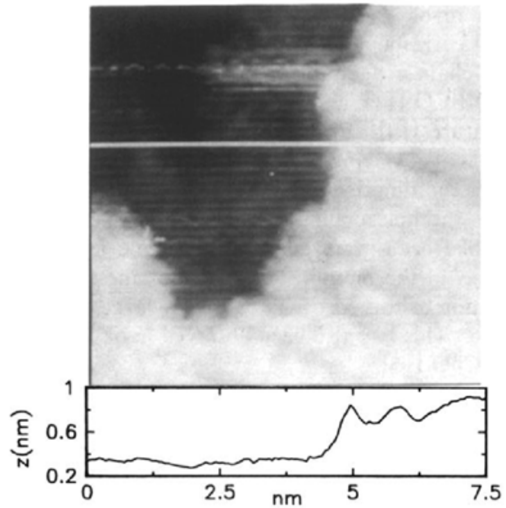


(a) (b)

Rev. Sci. Instrum., Vol. 70, 1999

FIG. 7. Images of two surfaces which were exposed after cleavage of single crystal YBCO. (a) BaO plane ($I = 1$ nA, $V_{sample} = 100$ mV) with clear atomic resolution and several defects (darker sites). (b) CuO chain plane ($I = 30$ pA, $V_{sample} = 60$ mV), showing atomic resolution overlaid with a strong DOS modulation. Both images are 50 Å square.

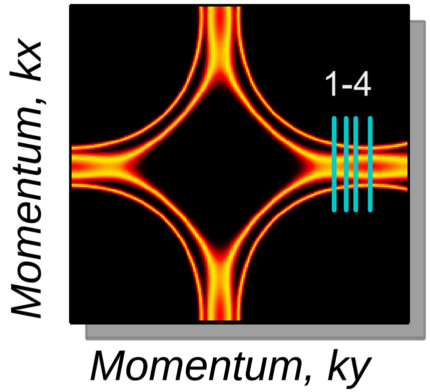


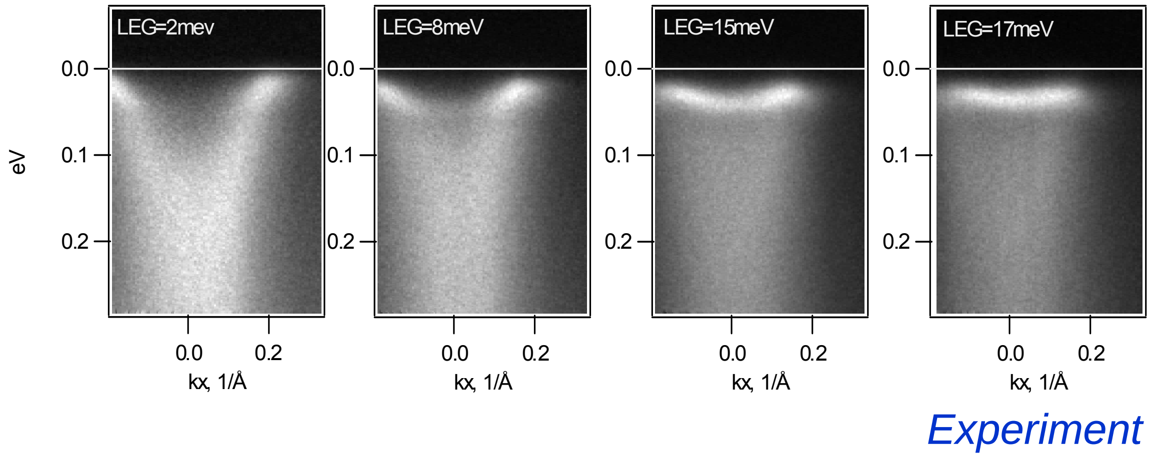


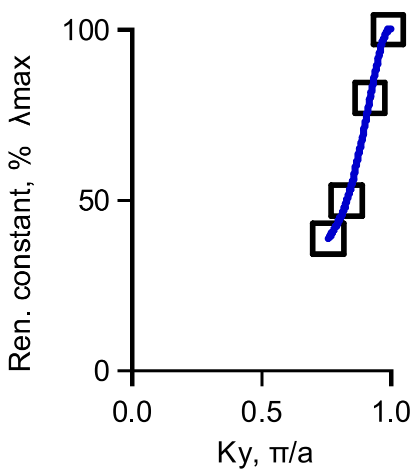
Edwards et al, *Phys. Rev. Lett*. **70**, 2967 (1992)

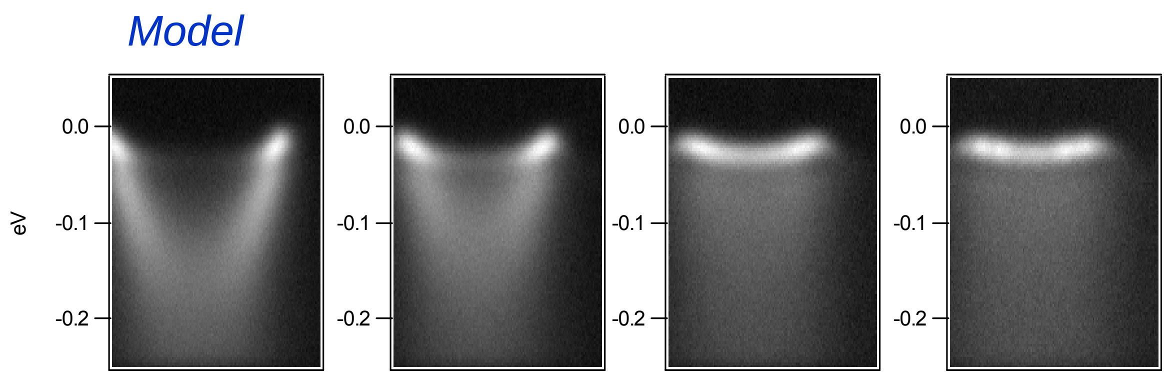
Momentum dependence in Ca-YBCO

200510 SLS\Ca-YBCO









V. Zabolotnyy et al.

Conclusions (material aspect)

- BSCCO compound is the most suitable for investigation by ARPES. We need careful INS data on phonons and spin-fluctuations.
- Preliminary ARPES results on YBCO show possibility to suppress the surface component and carefully measure the relevant to superconductivity quasiparticle spectrum from the bulk and compare it to INS results.
- It seems unlikely to get relevant to superconductivity information from LSCO neither by ARPES nor by STS.

General conclusions

- Magnetic excitations strongly couples to the conduction electrons—and are, thus, the most probable candidate for mediation of the electron pairing in HTSC.

- The unification of the momentum resolving techniques are required:
  (1) to identify **ultimately** the "fingerprints" of the relevant bosonic spectrum in both S(**k**, w) and D(**k**, w);
  (2) to determine the origin of the bosonic spectrum (the degree of itinerancy, in case of spin-fluctuations);
  (3) to understand the role of space inhomogeneity in pairing.

- The current rate of improvement of all of the described techniques suggests that these problems will be solved very soon.

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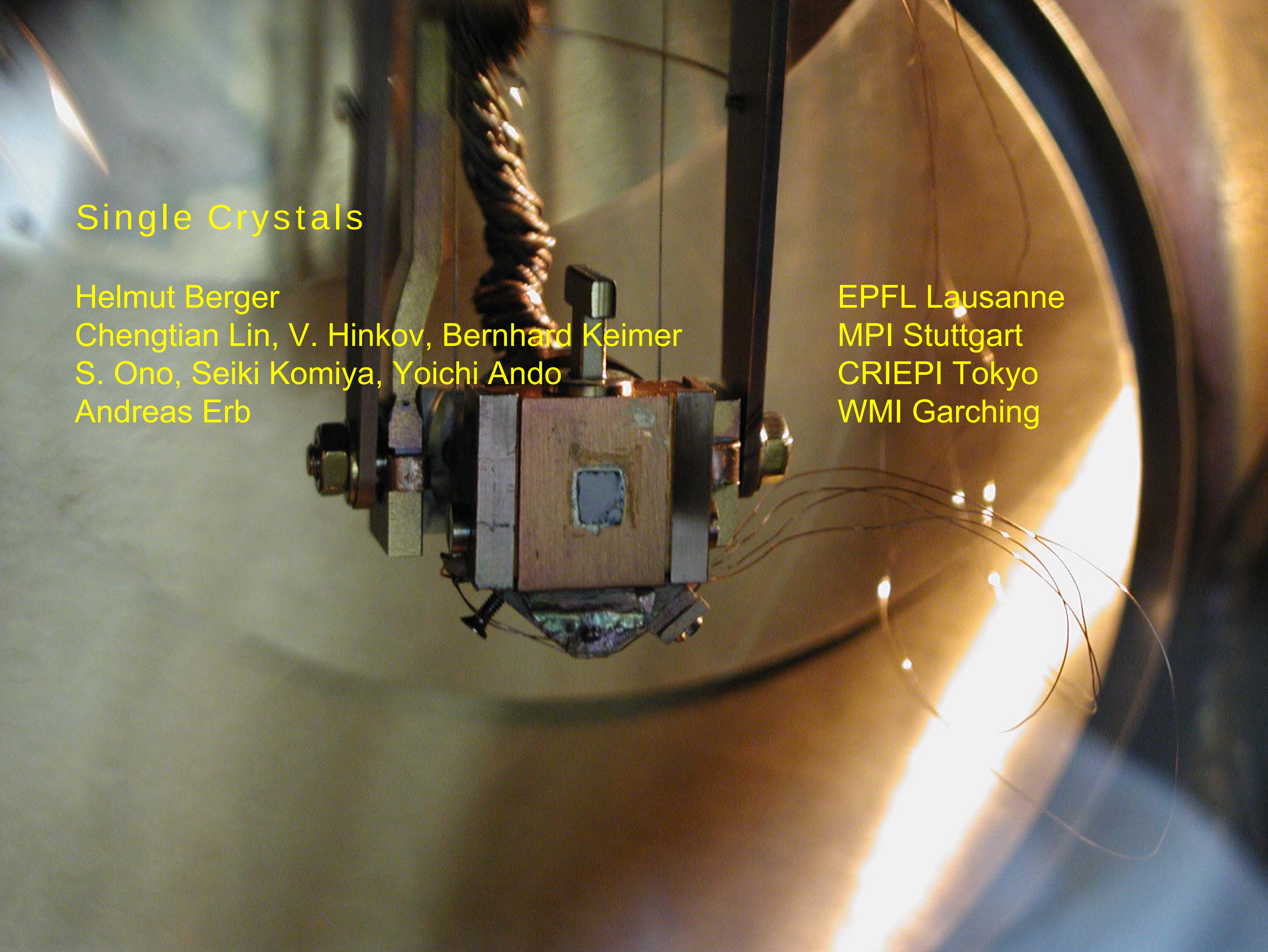
Andreas Koitzsch, Jochen Geck,
Vladimir Zabolotny, Dmytro Inosov,
Roland Hübel, Martin Knupfer, Jörg Fink, Bernd Büchner


Single Crystals
Helmut Berger
Chengtian Lin, V. Hinkov, Bernhard Keimer
S. Ono, Seiki Komiya, Yoichi Ando
Andreas Erb
EPFL Lausanne
MPI Stuttgart
CRIEPI Tokyo
WMI Garching

Synchrotron Light

Rolf Follath — BESSY Berlin
Stefano Turchini, Cesare Grazioli — ELETTRA Trieste
Ming Shi, Luc Patthey — SLS Villigen