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ICTP 40th Anniversary

SCHOOL ON SYNCHROTRON RADIATION AND APPLICATIONS
In memory of J.C. Fuggle & L. Fonda

19 April - 21 May 2004

Miramare - Trieste, Italy

1561/18

Photoemission as a Solid State Spectroscopy: Many-Body Effects, Applications to Complex Materials

Juerg Osterwalder

School on Synchrotron Radiation and Applications, ICTP Trieste, May 3-6, 2004

Photoemission as a Solid State Spectroscopy: Many-Body Effects, Applications to Complex Materials

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Lecture 4

- Many-Body Effects in Photoemission
- NiO: an Example for a Strongly Correlated System
- Theoretical Concepts: Sudden Approximation, Spectral Function
- Interpretation of Line Widths, Relation to Photoemission Experiments
- Energy Distribution Curves vs. Momentum Distribution Curves

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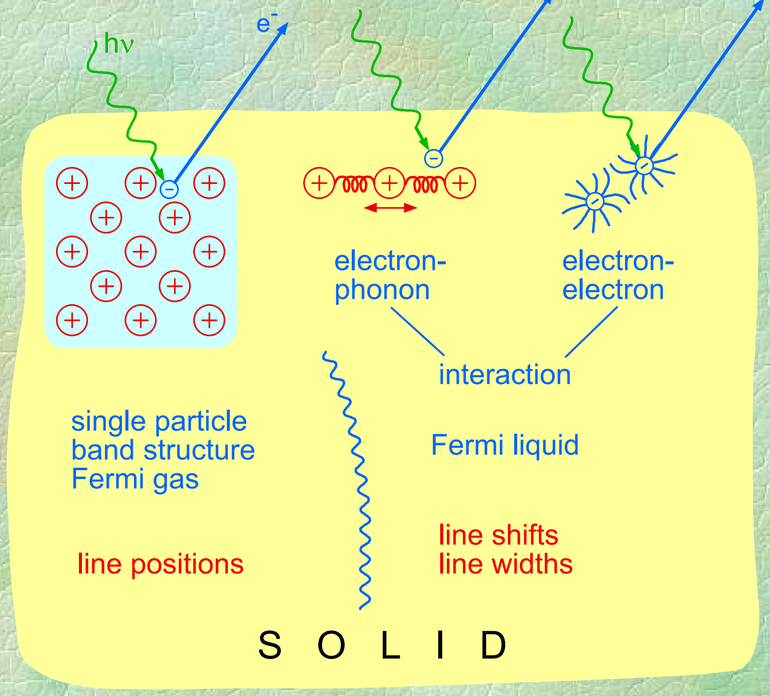
Solid State Spectroscopy

Photoemission as a



electron-phonon

electron-electron

interaction

single particle
band structure
Fermi gas

line positions

Fermi liquid

line shifts
line widths

S O L I D

⇒ Understanding

electrical
magnetic
optical
superconducting
thermal

properties

Manybody Effects in Photoemission

So far: one-electron picture (Fermi gas !)

But: electrons interact
with electrons
with phonons
with ...

Two types of phenomena:

- e^- - interaction in the initial state

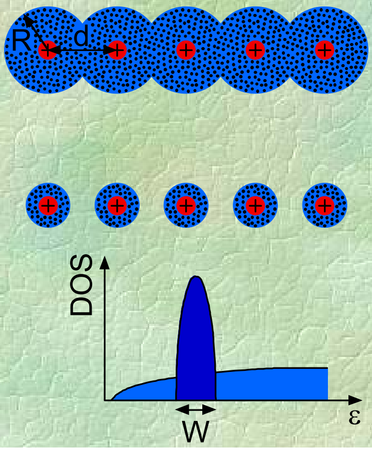
  → hot tropic in solid state physics
  (strongly correlated materials,
  Fermi liquids → non-Fermi liquids)

- e^- - interaction during the photoemission process

  → satellites, line shapes, line positions

  important for interpretation of spectra !

Two extreme types of states



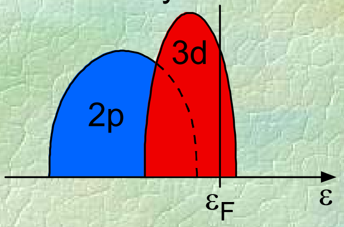
R - d : large overlap (s, p)
large dispersion ε (k)
nearly free electrons
→ one-electron picture !

R << d : little overlap (d, f)
little dispersion
tight binding
→ correlation effects !

NiO: an Example for a Strongly Correlated System

NiO
$3d^8$ $2p^6$

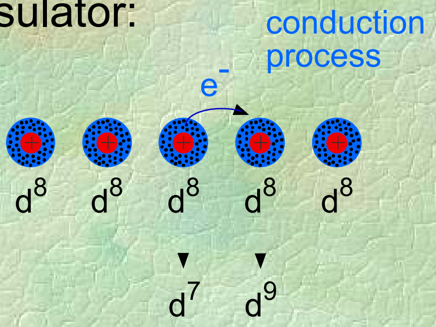
band theory:



→ predicts a metal

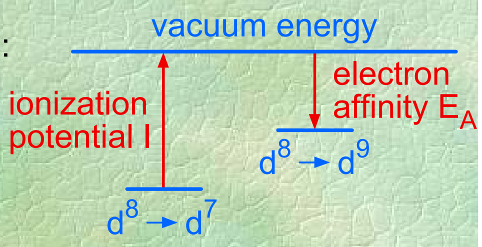
But: experiment shows insulating gap (4 eV) !

Mott Insulator:



"reaction": $2\,d^8 \rightarrow d^7 + d^9 - U$

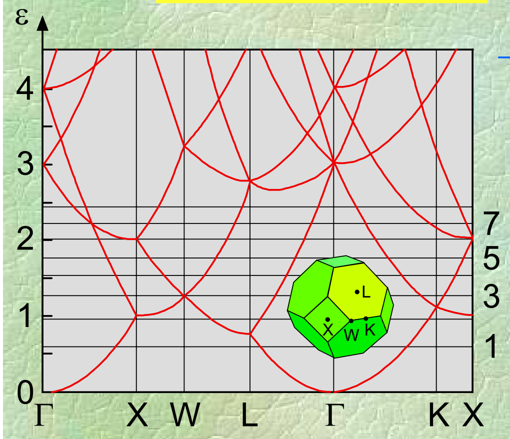
energetics:



$$U = I - E_A$$

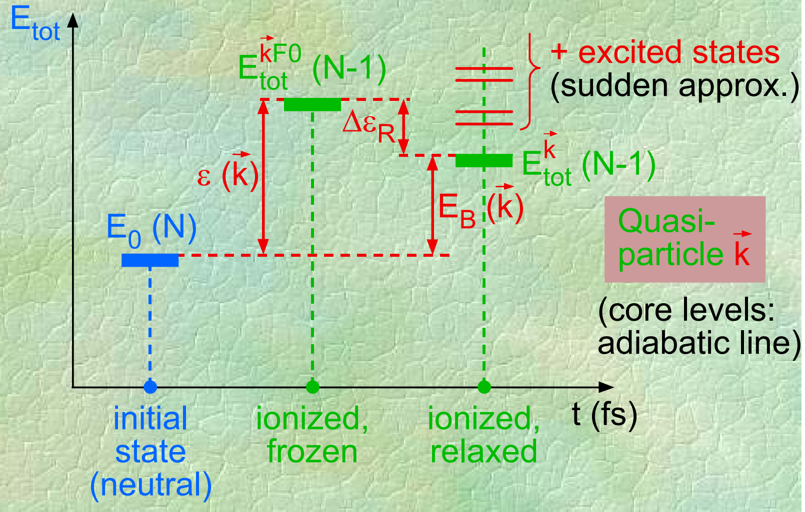
free ions : U = 18 eV
solid state: reduced (O charge transfer)

Theoretical Concepts



→ Theory:
energy eigenvalues

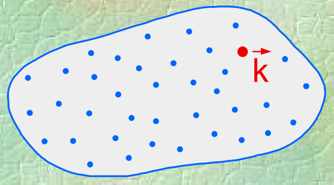
Total-Energy Diagram:



Quasi-
particle $\vec k$

(core levels:
adiabatic line)

Koopman's Theorem:



N electrons

$$\varepsilon(\vec k) = E_{tot}^{\vec k,SCF}(N) - E_{tot}^{\vec k,F0}(N-1) < 0$$

"frozen orbitals"

The Photocurrent I

Atoms, Molecules:

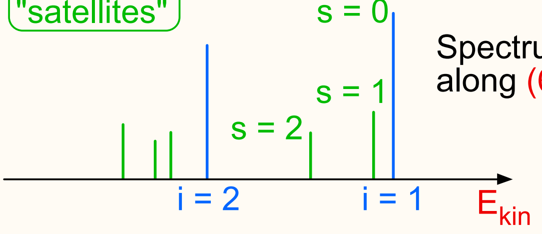
$$I \sim \sum_{f,i,k} |\langle \phi_{f,E_{kin}} | \vec r_k \cdot \vec\varepsilon \,|\, \phi_{i,k}(\vec r_k) \rangle|^2 \sum_s |c_s^{i,k}|^2 \,\delta(E_{kin} + E_s(N-1) - E_o(N) - h\nu)$$

various
final states
(angles, ...)

various orbitals

various atoms

excited
final states
"satellites"

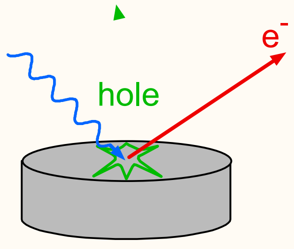


Spectrum
along $(\theta, \phi) = f$

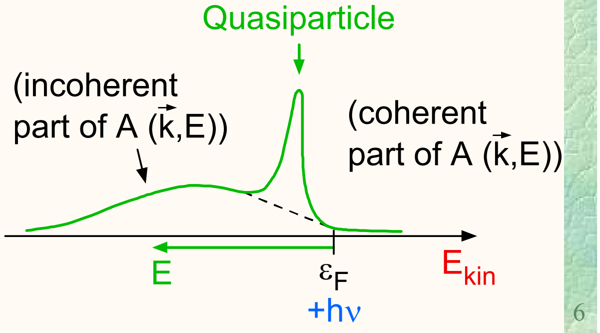
Solids:

$$I \sim \sum_{f,i,\vec k} |\langle \phi_{f,E_{kin}} | \vec r_k \cdot \vec\varepsilon \,|\, \phi_{i,\vec k} \rangle|^2 A(\vec k, E)$$

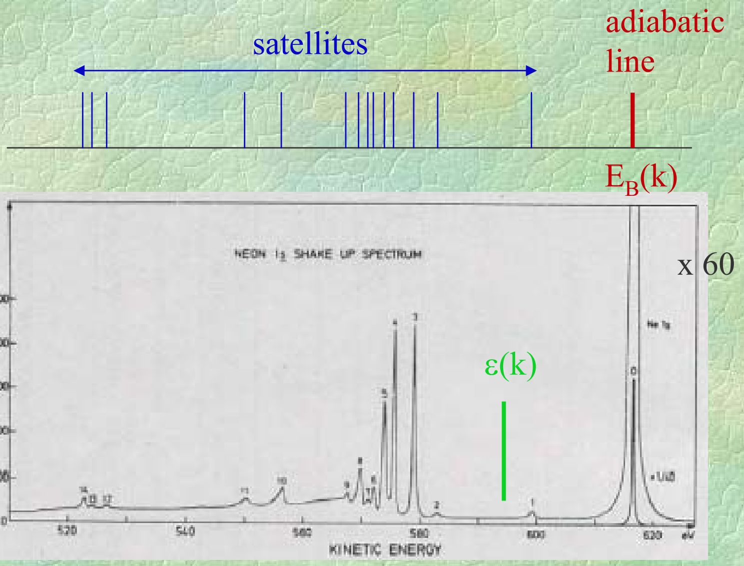
"Spectral
Function"



sea of excitations



The Photocurrent from Neon 1s



satellites

adiabatic line

$E_B(k)$

x 60

$\varepsilon(k)$

… and also Coupling to Lattice Degrees of Freedom - e.g. Adsorbate Vibrations

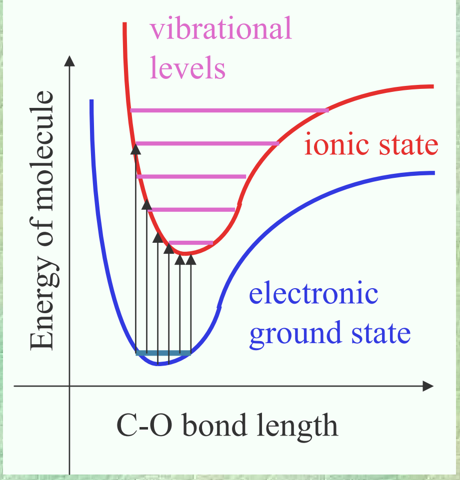
$$E_{kin} = h\nu - (E_{final} - E_{initial})$$

Photoelectron

Electronic or vibronic excitations

Ground state

(chemical shift)



vibrational levels

ionic state

electronic ground state

Energy of molecule

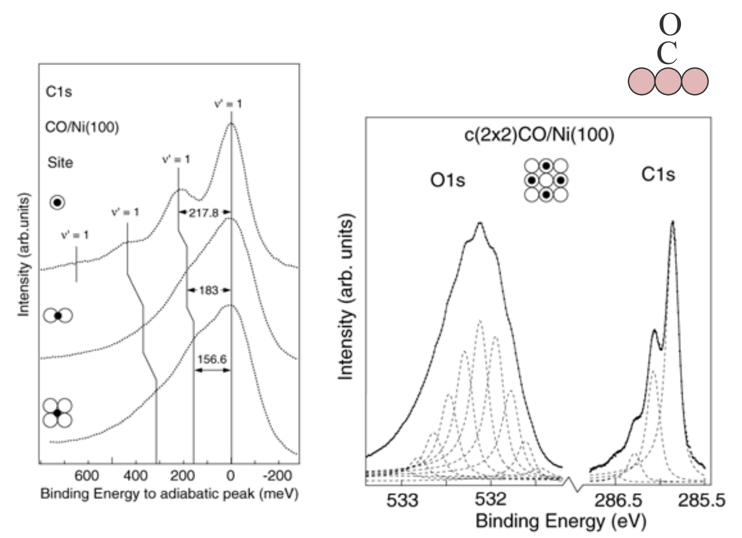
C-O bond length

=> Franck-Condon Principle

E_{final} depends on

… bonding site

… where the photohole sits



Föhlisch et. al Phys. Rev. Lett. 81 (1998) 1730

Spectral Functions

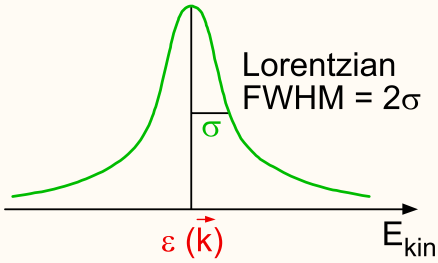
... can be calculated by Greens Function Formalism:

$$A(\vec{k},E) = \frac{1}{\pi}\,\Im m\,\{G_+(\vec{k},E)\}$$

independent particles (no interactions):

$$G^o_+(\vec{k},E) = \frac{1}{E - \varepsilon(\vec{k}) - i\sigma}$$

$$A(\vec{k},E) = \frac{1}{\pi}\,\frac{\sigma}{(E - \varepsilon(\vec{k}))^2 + \sigma^2}$$



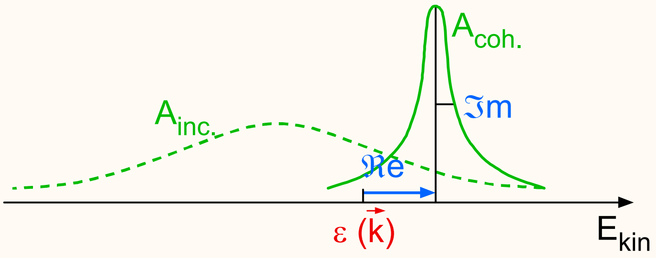
Lorentzian
FWHM = 2σ

with interactions:

$$G_+(\vec{k},E) = \frac{1}{E - \varepsilon(\vec{k}) - \quad(\vec{k},E)}$$

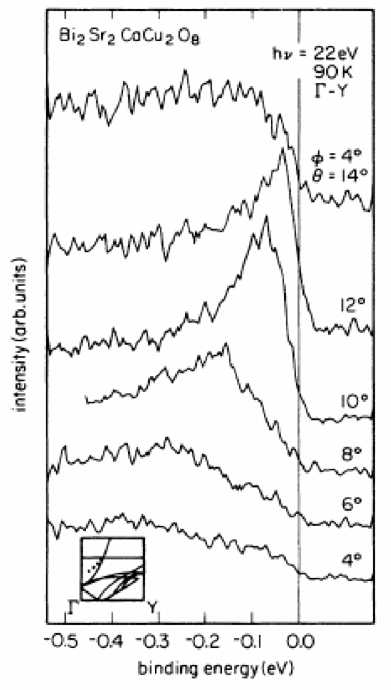
Self energy
=> need Hamiltonian of system !

$$A(\vec{k},E) \sim \frac{\Im m\,\{\quad(\vec{k},E)\}}{[E - \varepsilon(\vec{k}) - \Re e\quad]^2 + [\Im m\quad]^2}$$



Experimental Situation on Line Widths

Fermi-liquid theory: Line width $\Delta E \sim (E-E_F)^2$



Experiment on HTC material:

$\Delta E \sim (E-E_F)$

=> non-Fermi-liquid ?

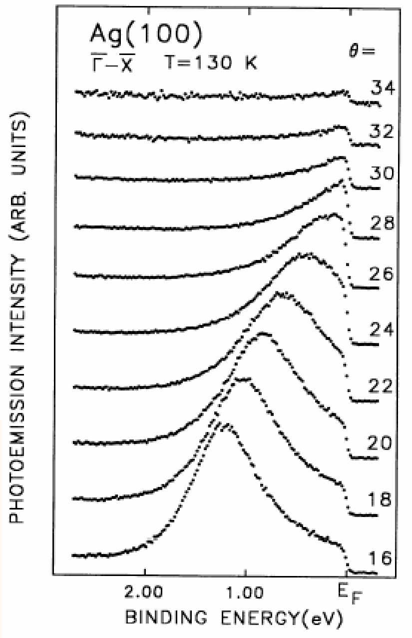
C. G. Olson et al.,
PRB 42, 381 (1990)

… but:

Silver (a much simpler material) even shows a growing line width towards EF !

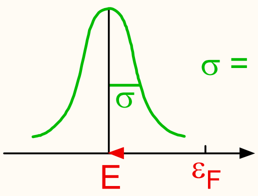
?

Y. Hwu et al.,
PRB 45, 5438 (1992)



⇒One needs to know the technique well !

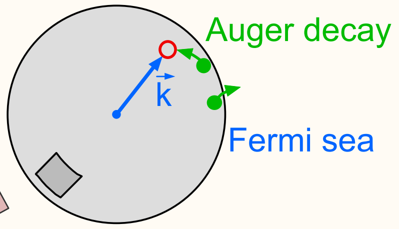
Interpretation of Line Widths



$\sigma = \Im m \quad (\vec{k},E) \sim \frac{\hbar}{\Delta t}$

Q.P. Life time

dominant hole decay processes:

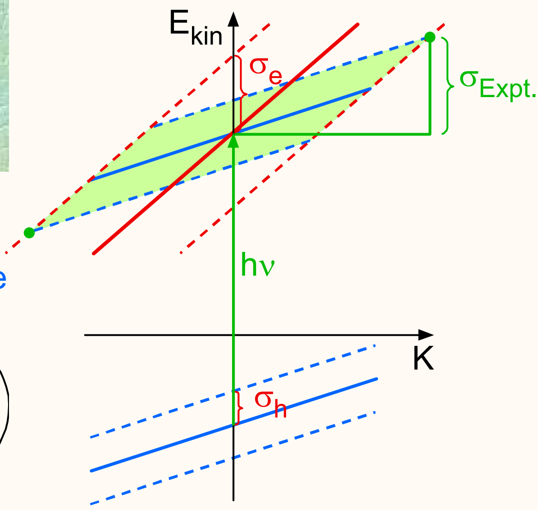


Fermi liquid theory

$\rightarrow \Delta t \sim \frac{1}{E^2}$

$\rightarrow \boxed{\sigma \sim E^2}$

Caution !



Photoemission measures hole lifetime $\frac{1}{\sigma_h}$ and photoelectron lifetime

normal emission:

(P.Thiry, 1981)

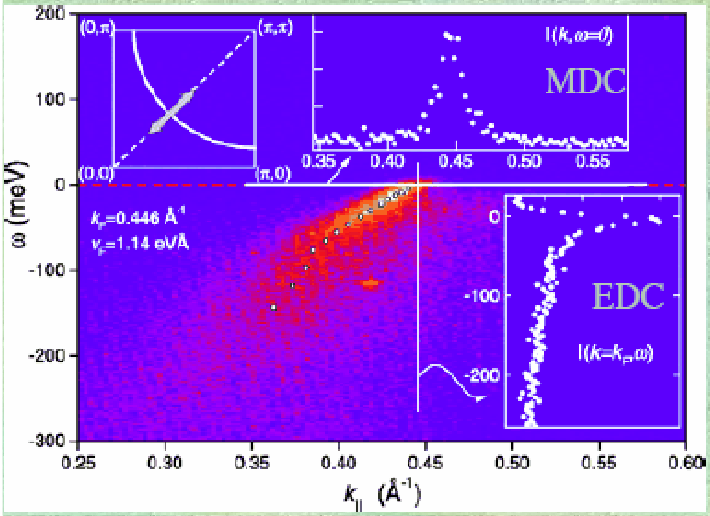
$$\sigma_{Expt.} = \frac{\nu_e^{\perp} \bullet \nu_h^{\perp}}{\nu_e^{\perp} - \nu_h^{\perp}} \cdot \left(\frac{\sigma_h}{\nu_h^{\perp}} + \frac{\sigma_e}{\nu_e^{\perp}} \right)$$

group velocities $\frac{\partial \varepsilon}{\partial k_{\perp}}$

(we measure E_{kin}, not k !)

Energy Distribution Curves (EDCs) and Momentum Distribution Curves (MDCs)

Example: Dispersion Plot from BSCCO High Temperature Superconductor

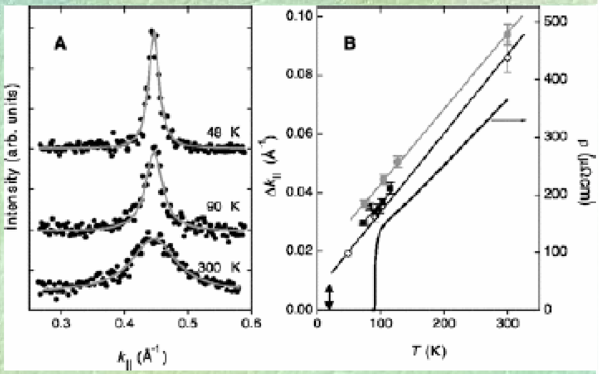


Line Width Δk in MDCs is related to the mean free path Λ of the electrons near E_F and thus to the scattering rate:

$$\hbar v_k \Delta k = \frac{\hbar v_k}{\Lambda} \approx | 2\Im\Sigma(\vec{k},\omega) |$$

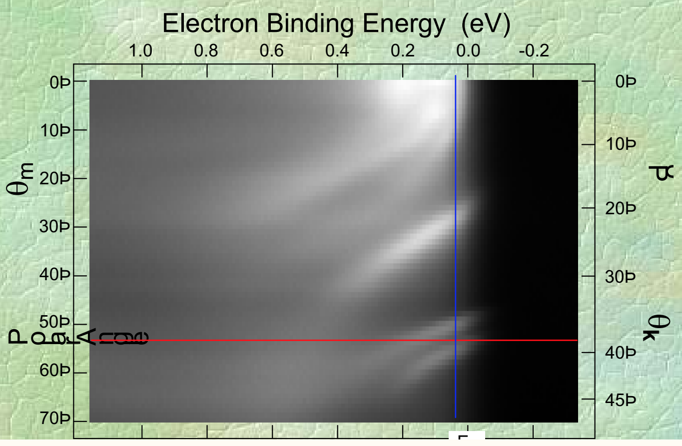
(v_k is the electron group velocity)

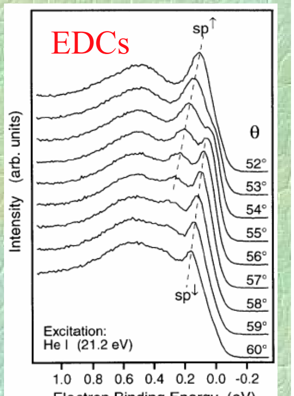
⇒ Connection between photoemission data and sample resistivity

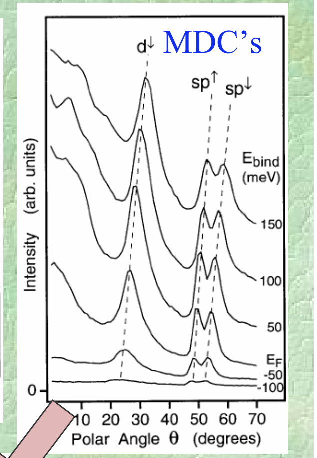


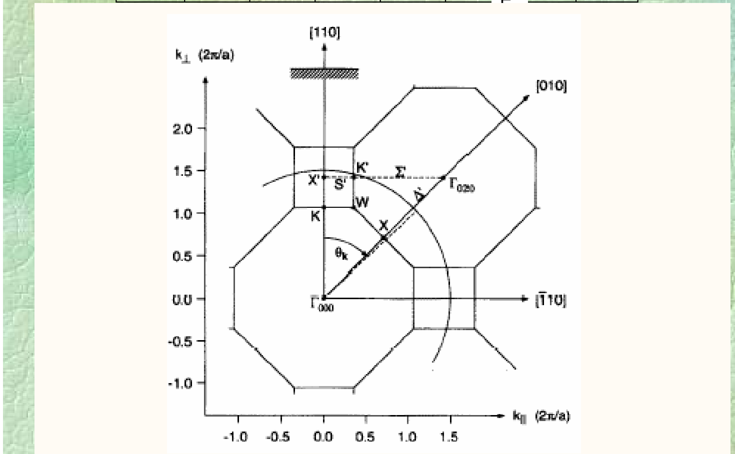
T. Valla et al. Science 285, 2110 (1999)

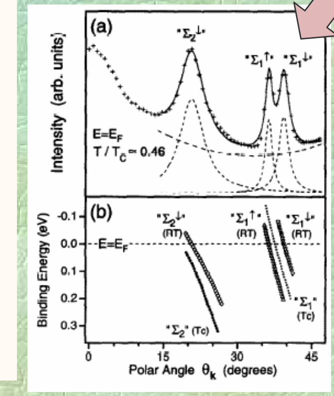
Extracting Energy Dispersion











… often more accurately from MDCs ! (simpler line shapes)

School on Synchrotron Radiation and Applications, ICTP Trieste, May 3-6, 2004

Photoemission as a Solid State Spectroscopy: Many-Body Effects, Applications to Complex Materials

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Lecture 5

- Electron-Electron Interaction: Weak Effects in Photoemission from Cu
- Electron-Electron Interaction: Strong Effects in Photoemission from Ni and Co
- Electron-Phonon Interaction: Renormalization of Dispersion by Phonons
- Applications: Observation of a Giant Kohn Anomaly on H/Mo(110)
- Applications: Photoemission from High and Low T_c Superconductors

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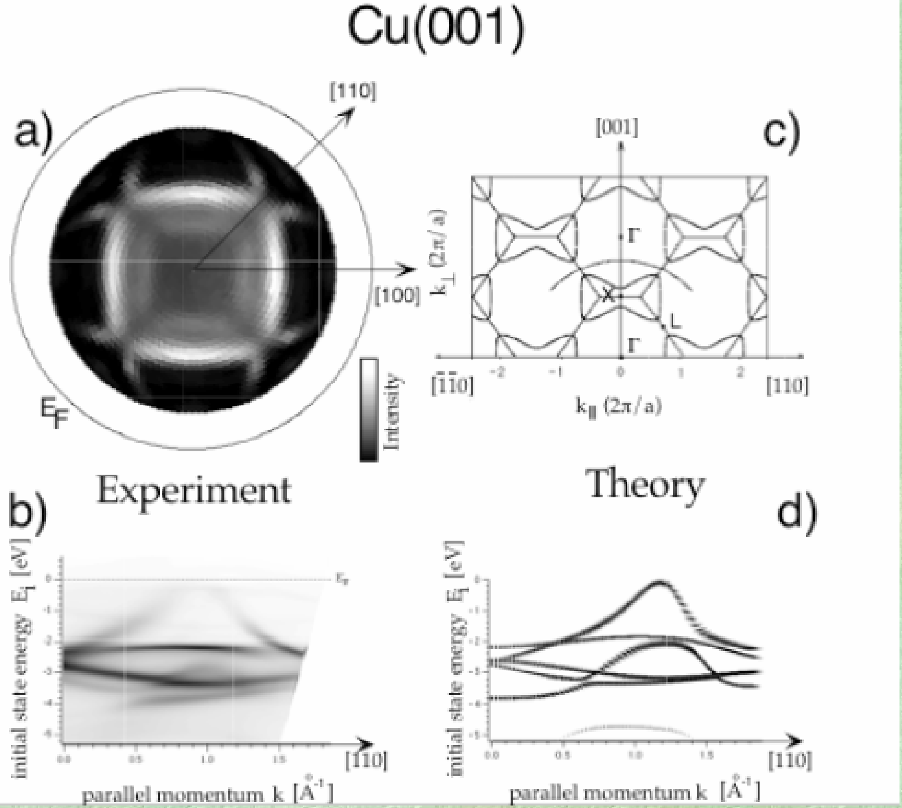
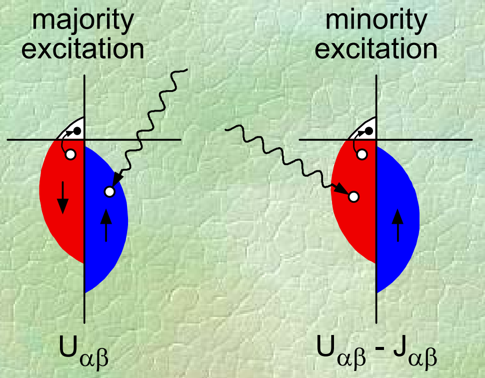
Weak Electron-Electron Interaction Effects in Photoemission from Cu



Courtesy P. Aebi, University of Neuchatel

Valence Photoemission from Ni

$3d^{9.4}$ → correlation effects in the 3d channel

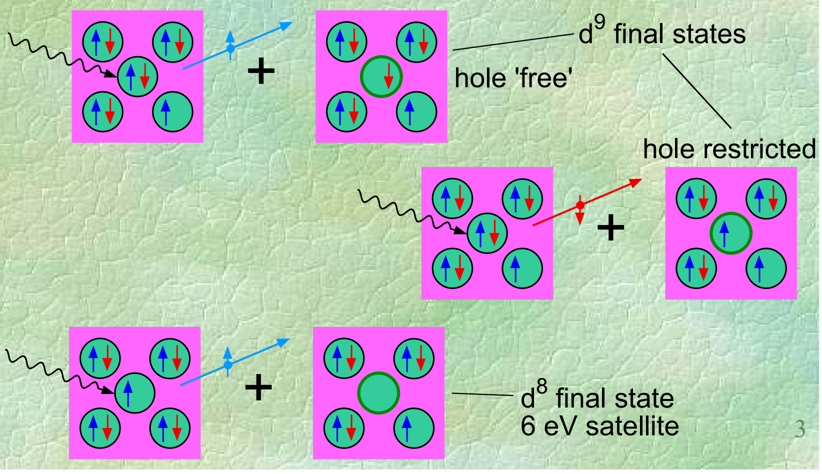


"3-body scattering approximation"

F. Manghi et al.,
PRL 73, 3129 (1994).

Pictorial:

majority photoelectron minority photoelectron



d^9 final states

hole 'free'

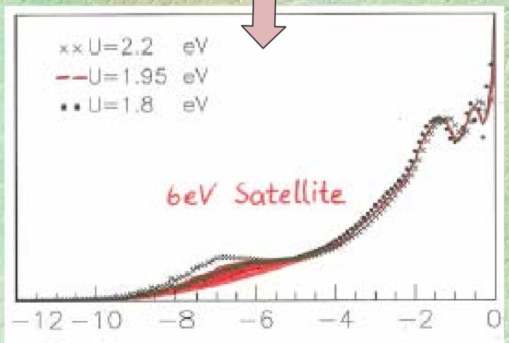
hole restricted

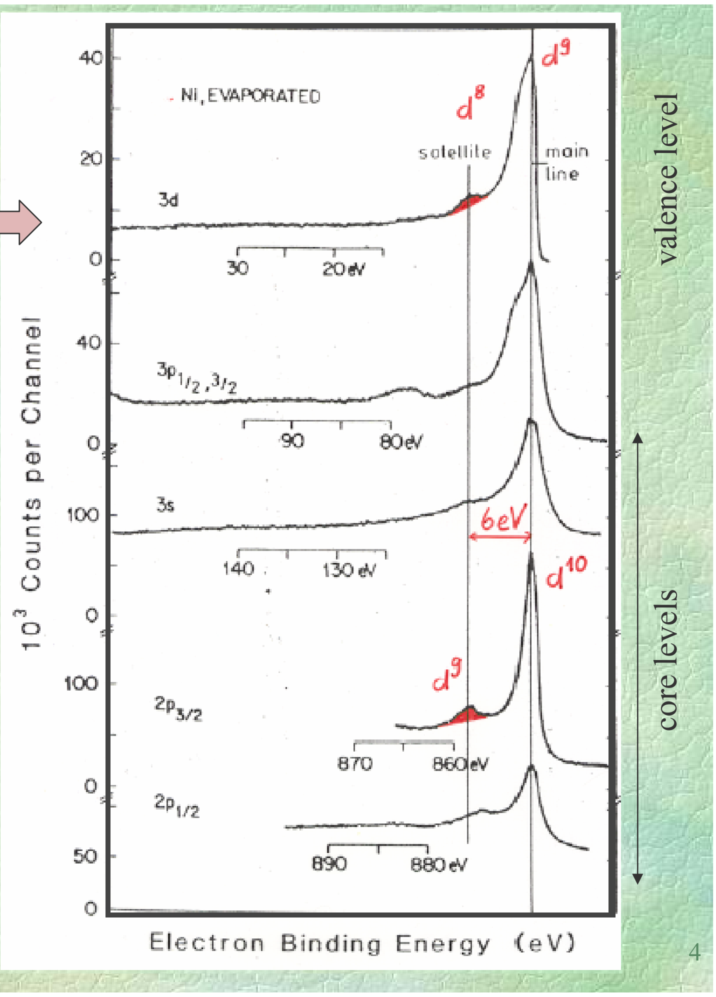
d^8 final state
6 eV satellite

The 6 eV Satellite in Ni Metal

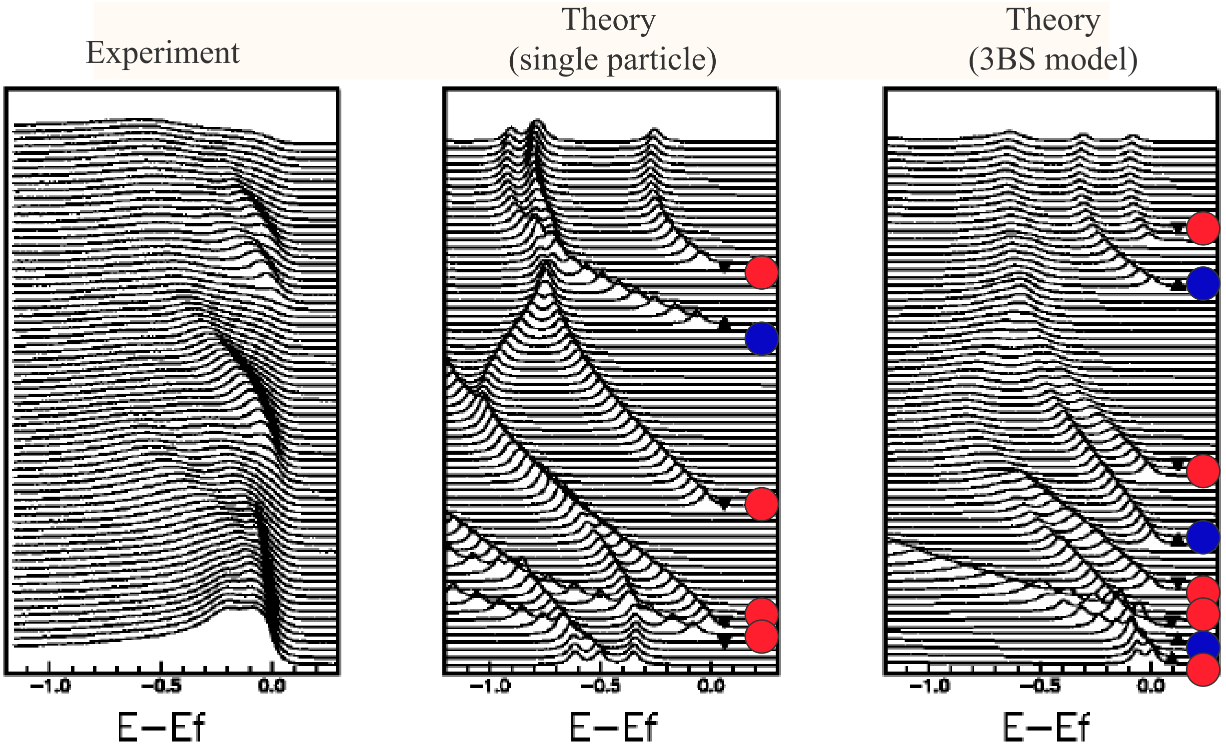
Experiments: Each photohole is accompanied by a 6 eV satellite
(S. Hüfner, Photoelectron Spectroscopy (Springer, Berlin 1995))

Theory: 3BS Model
(F. Manghi et al., PRB 59, R10409 (1999)





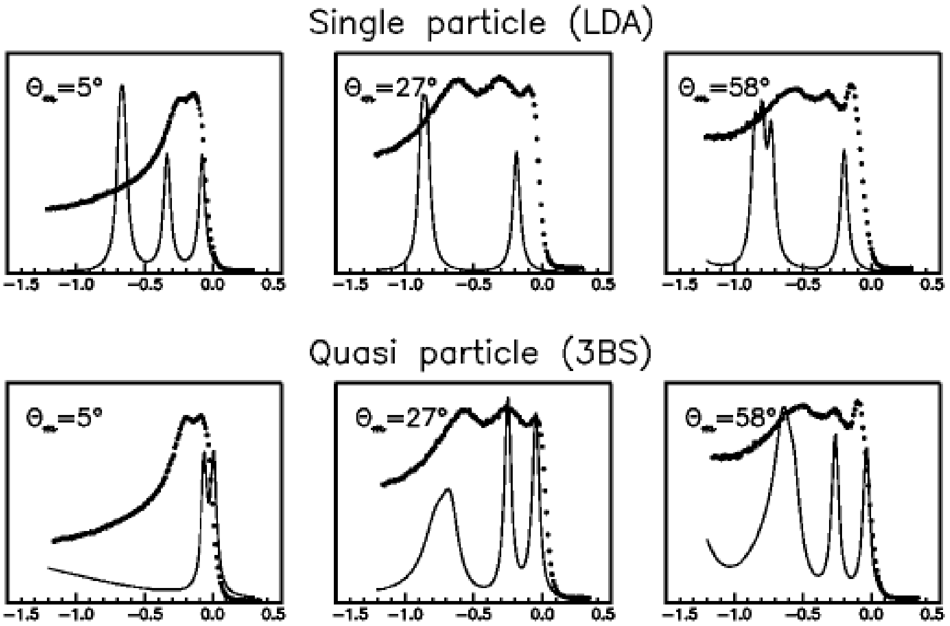
Renormalization of Band Dispersion by e-e Interaction: Ni



● Minority spin ● Majority spin

F. Manghi et al., PRB 59, R10409 (1999)

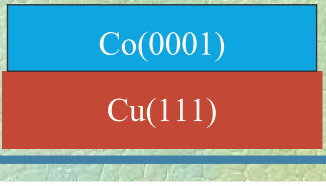
Quantitative Comparison of e-e Interaction Effects in Ni

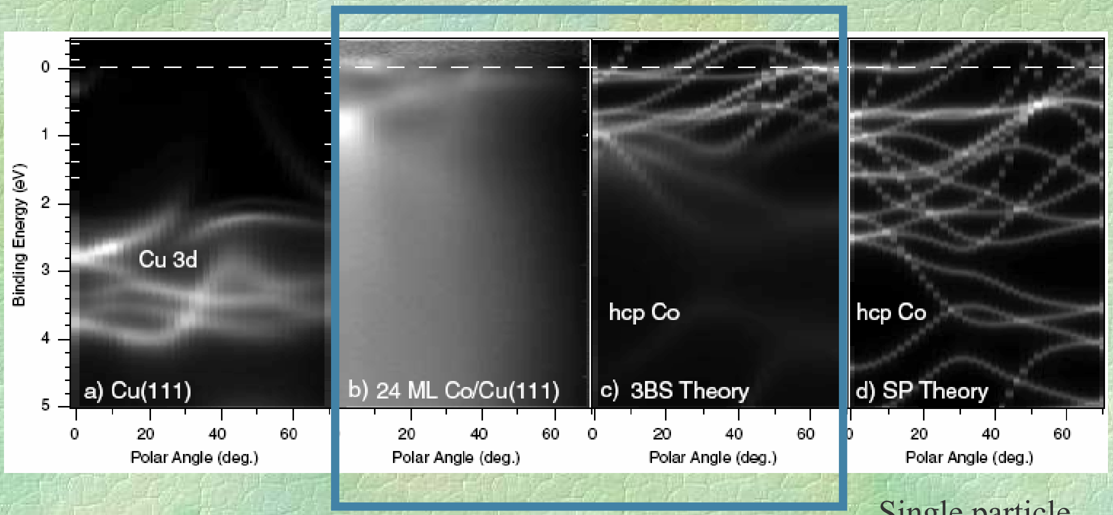


F. Manghi et al., PRB 59, R10409 (1999)

Even Stronger Renormalization in Cobalt

Sample:



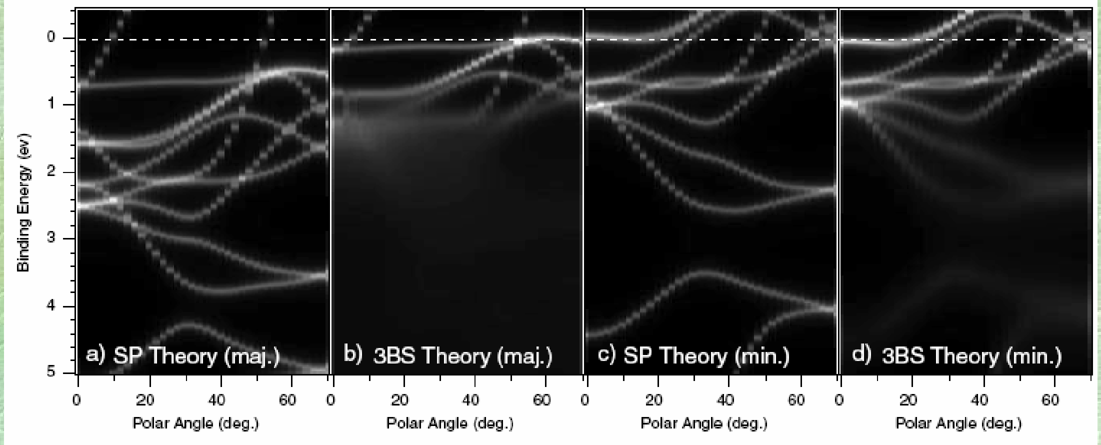


Single particle

Strong many-body effects !

S. Monastra et al., PRL 88, 236402 (2002)

Many-Body Effects are Strongly Spin Dependent



Majority spin

Minority spin

S. Monastra et al., PRL 88, 236402 (2002)

Electron-Phonon Interaction: Renormalization of Dispersion by Phonons

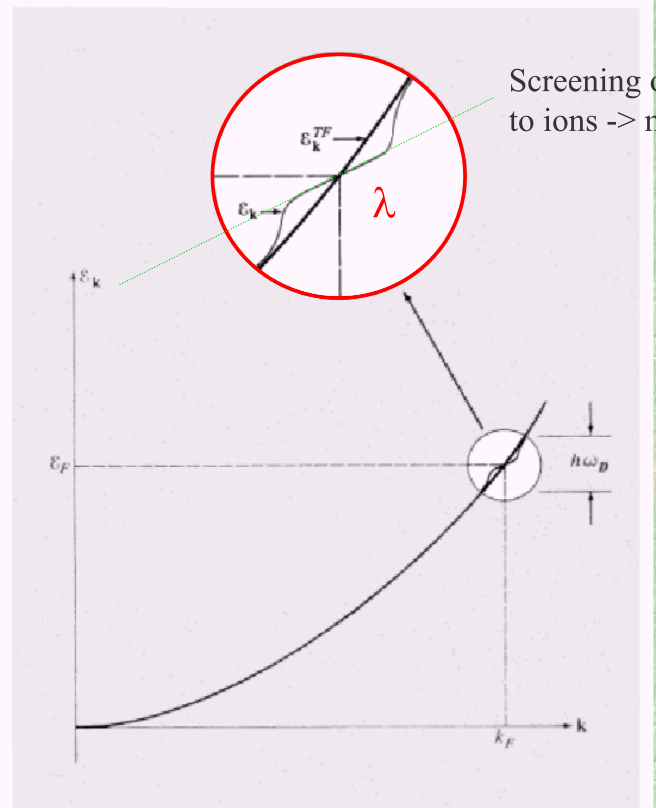
λ
electron-mode
coupling constant

Renormalization of m* by

$Z^{-1} = 1+\lambda$

Some values for λ:

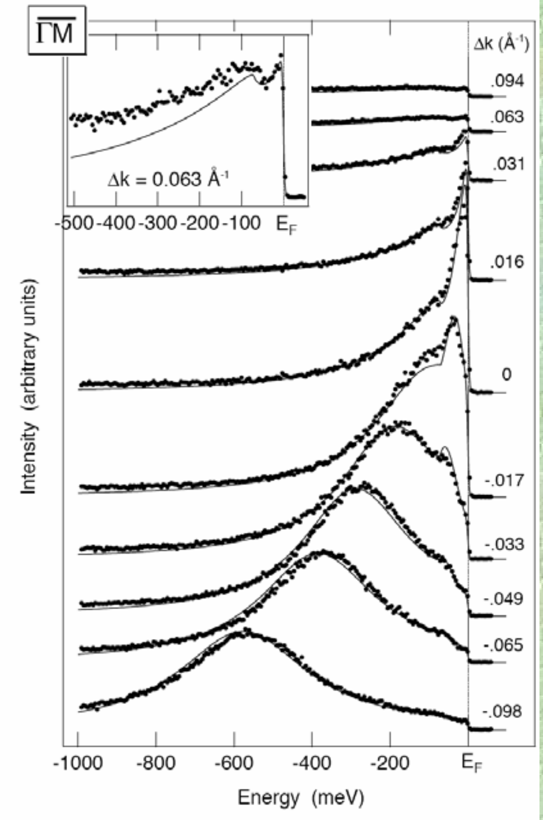
Cu	0.15
Be	0.24
Pb	1.50

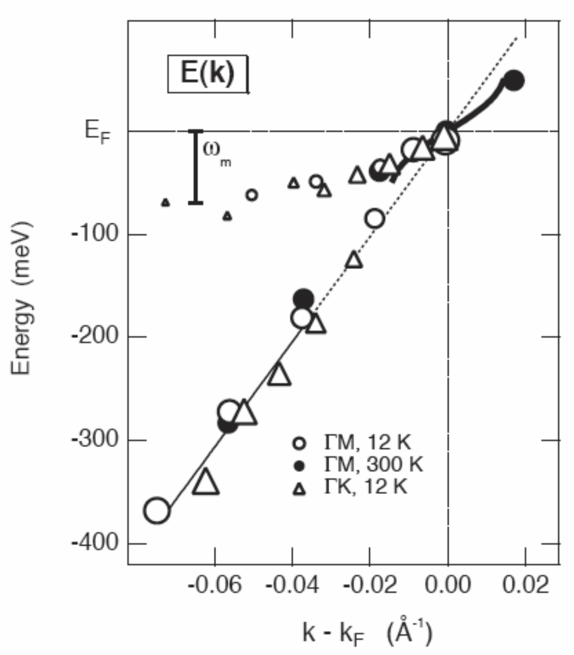


Screening of electrons due to ions -> m* increases !

Ashcroft, Mermin
"Solid State Physics"

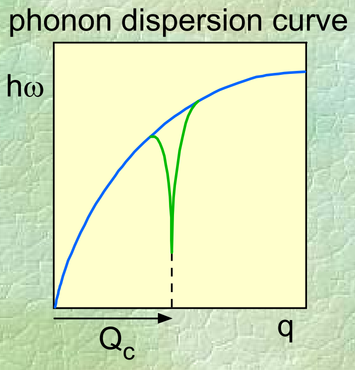
Observation of m* Renormalization in Beryllium

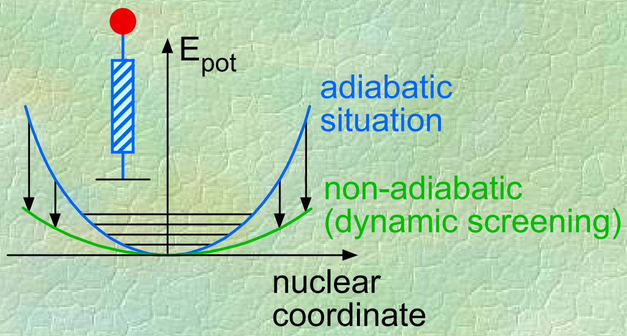


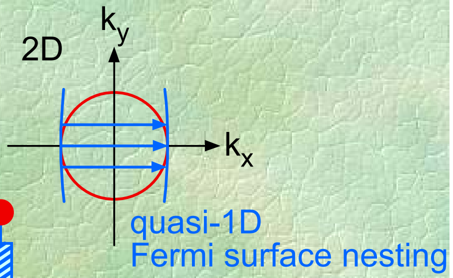


M. Hengsberger et al.,
PRL 83, 592 (1999).

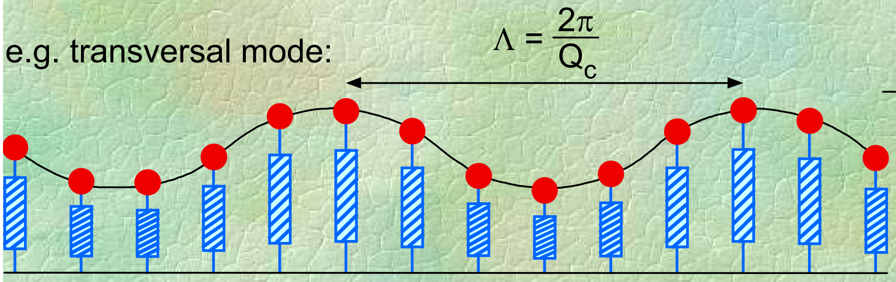
Giant Kohn Anomaly

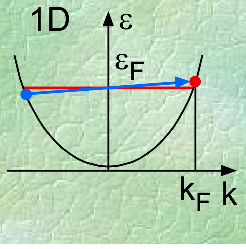






e.g. transversal mode:

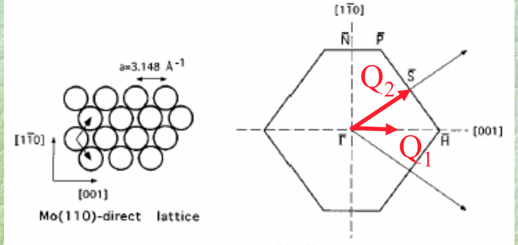


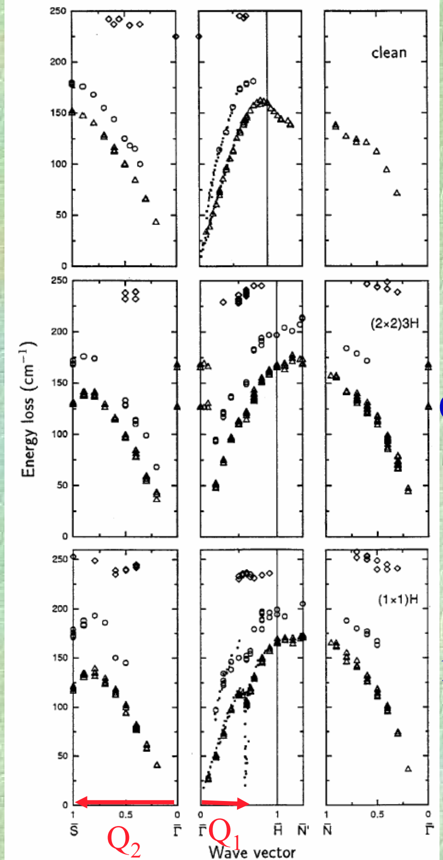


optimum screening:

- standing wave with same wave number ($Q_c = 2\,k_F$!)
- large phase space for e^- - hole pair excitations (low ε / high q)

Surface Phonon Modes for H/Mo(110) - A Giant Kohn Anomaly ?





clean

0.75 ML

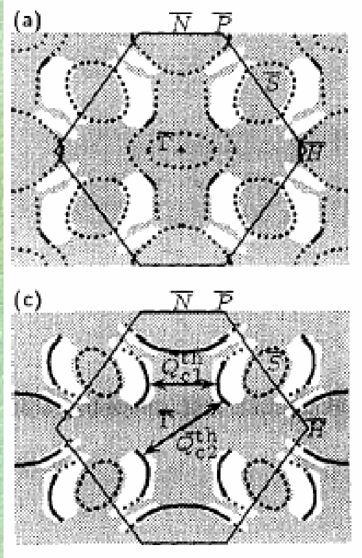
1 ML

HREELS Data

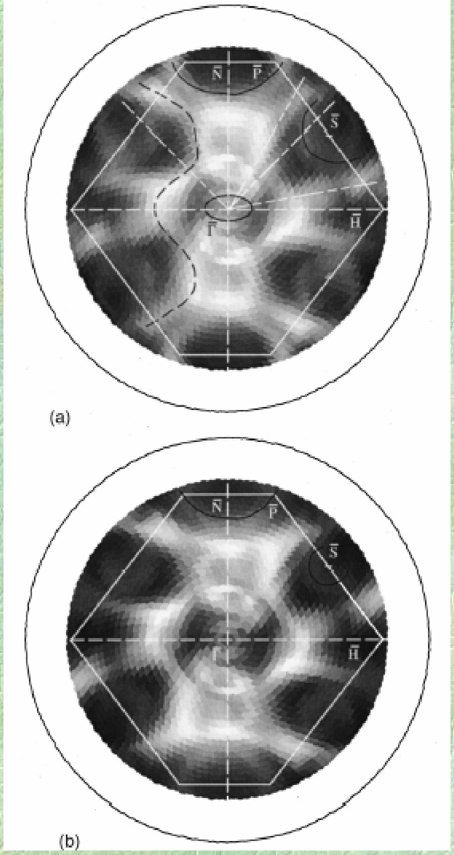
J. Kröger et al., PRB 55, 10895 (1997)

Fermi Surface Contours of Surface States on Mo(110)

Theory:



B. Kohler et al., PRL 74, 1387 (1995)

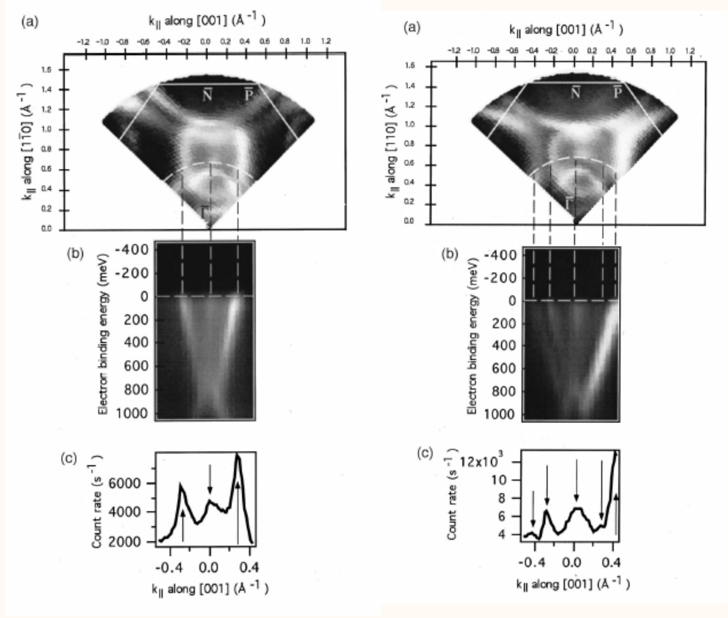


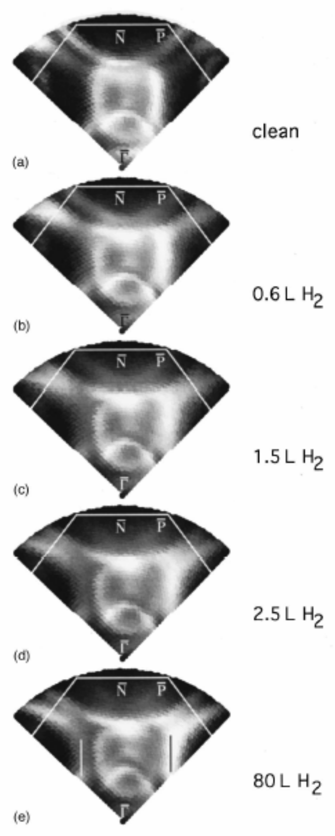
Clean Mo(110)

1 ML Hydrogen

J. Kröger et al., PRB 61, 14146 (2000).

Evolution of Fermi Surface Contours with Hydrogen Coverage

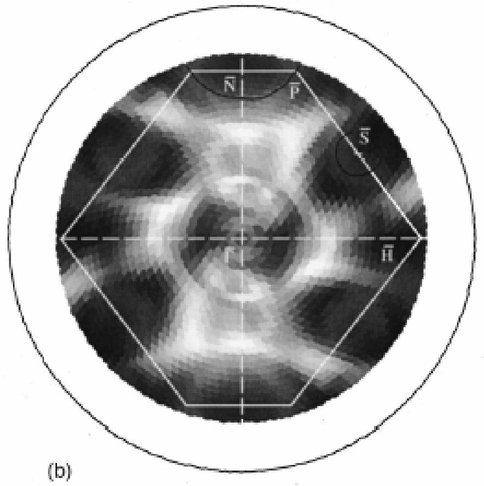


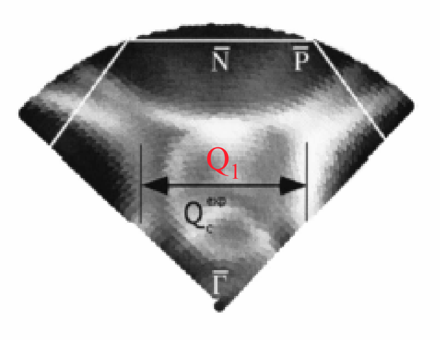


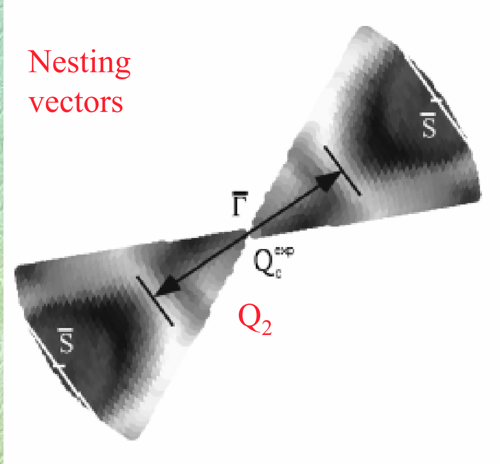
=> H-induced shift of Fermi surface contour

J. Kröger et al., PRB 61, 14146 (2000).

Fermi Surface Nesting on 1 ML H/Mo(110) Seen by Photoemission



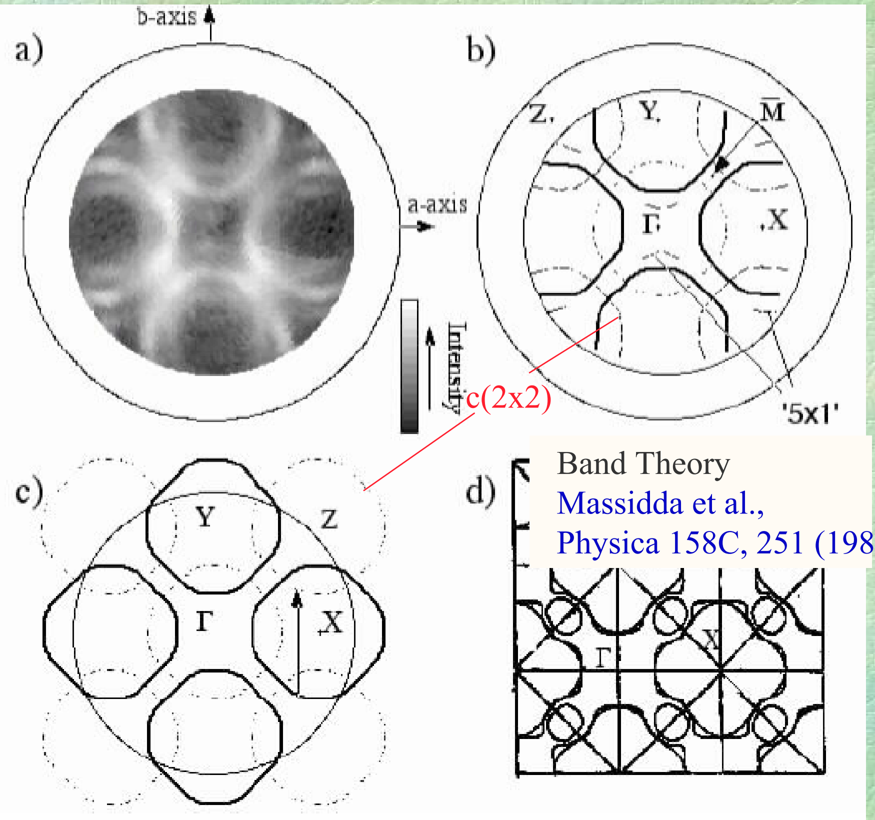



Nesting vectors

	Q_1(Å^{-1})	Q_2(Å^{-1})
EELS	0.90	1.22
PE	0.85	1.19
DFT	0.86	1.23

J. Kröger et al., PRB 61, 14146 (2000).

Fermi Surface Mapping on a High Temperature Superconductor: $Bi_2Sr_2CaCu_2O_{8+\delta}$ (001)



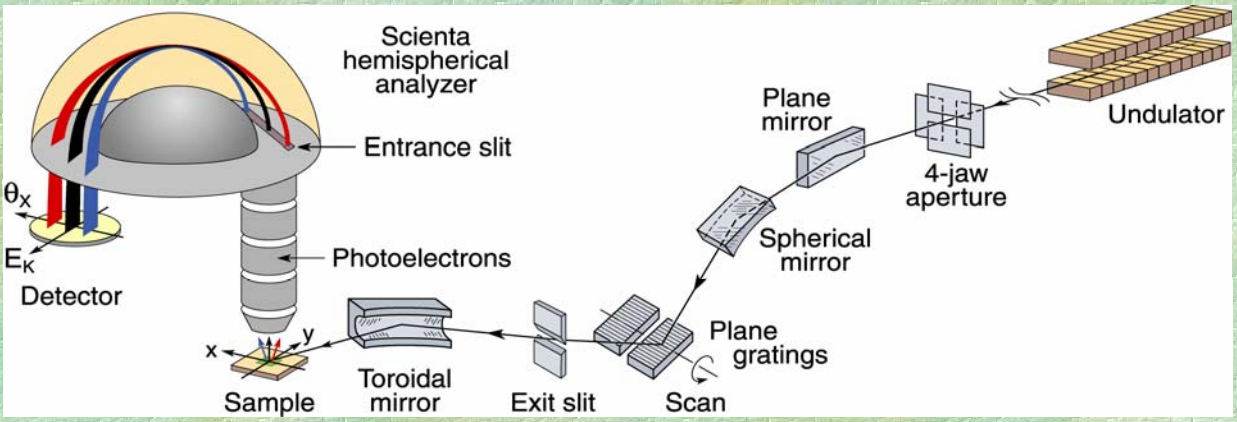
c(2x2)

Band Theory
Massidda et al.,
Physica 158C, 251 (1988)

P. Aebi et al.,
PRL 72, 2757 (1994)

High-Resolution Photoemission

A state-of-the-art photoemission beamline at Stanford (SSRL)

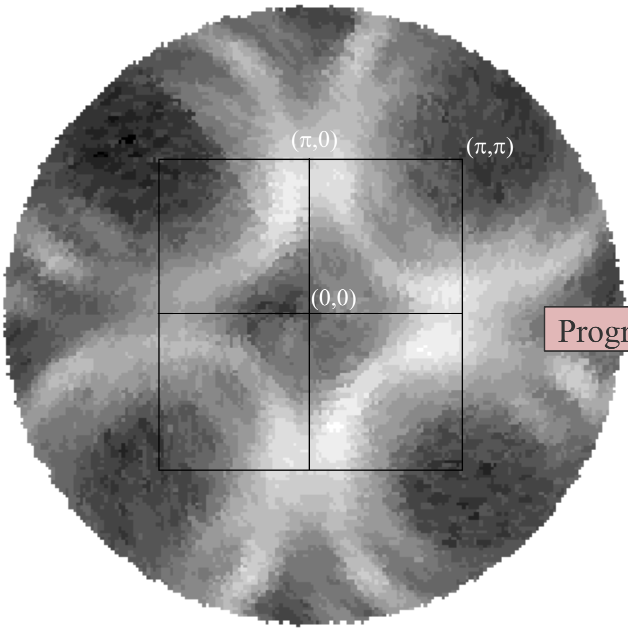


Highest resolution in energy <u>and momentum</u>

~ 2 meV in energy
~ 0.005 Å^{-1} in momentum

Courtesy Z.-X. Shen, Stanford University

Bi2212:
First Fermi surface mapping, superstructure contours

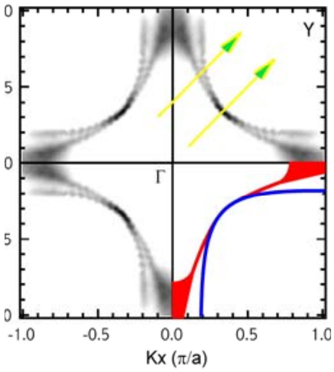


P. Aebi et al., Phys. Rev. Lett. 72, 2757 (1994).

Progress

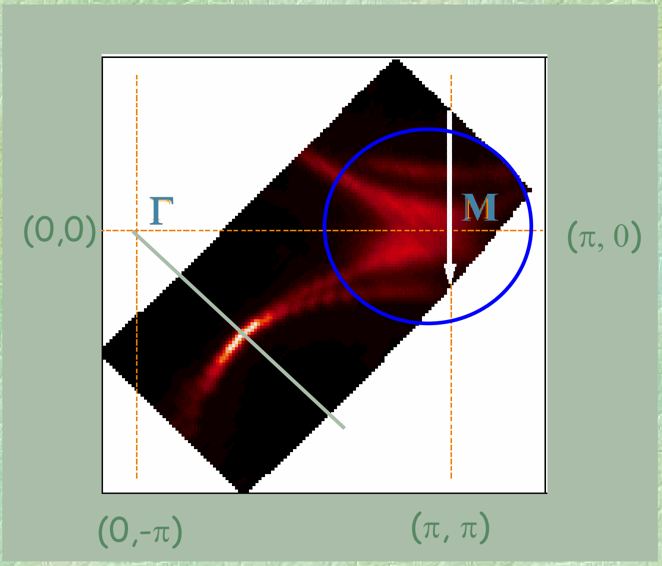
Pb-doped Bi2212:
-layer splitting

Two CuO layers
per unit cell



gdanov et al.,
ys. Rev. B 64, 180505 (2001)

Details on the Fermi Surface of BSCCO

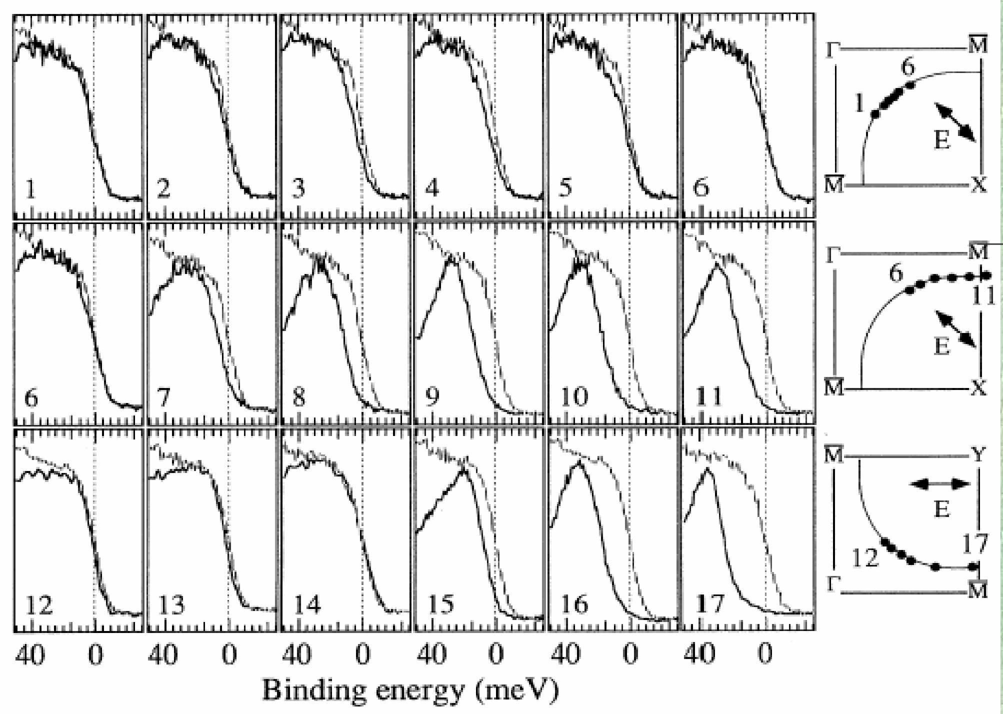


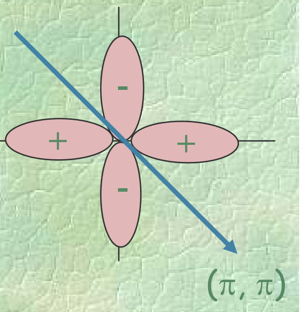
- Superstructure
- Superconducting Gap
- Bilayer Splitting

Courtesy Z.-X. Shen, Stanford University

Anisotropy of the Superconducting Gap in BSCCO

… need to measure spectra exactly on the Fermi surface !



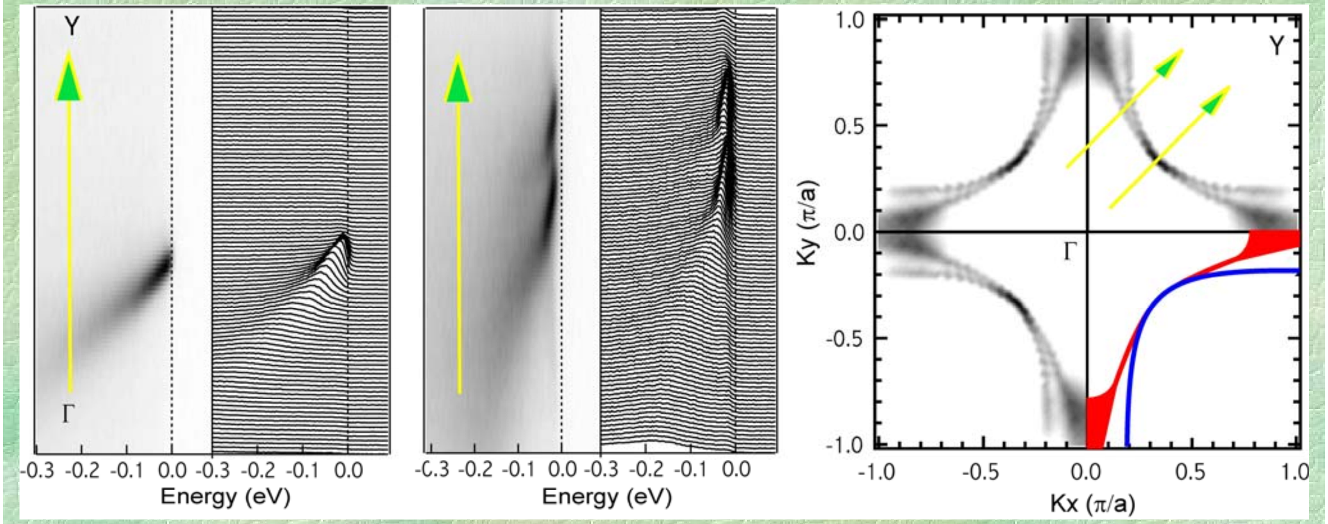


Δ=0

=> d-wave superconductor

H. Ding et al., PRL 74, 2784 (1995)

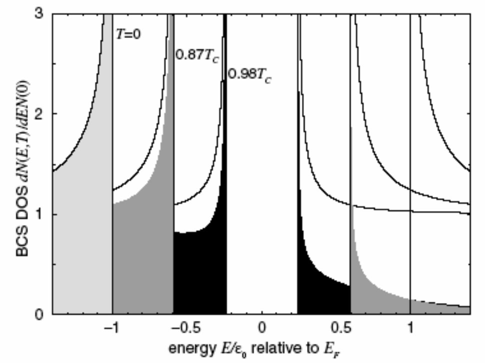
Pb-doped Bi2212: Bi-layer splitting



High energy and momentum resolution combined with improved sample enables the clear observation of bilayer splitting

Bogdanov et al. Phys. Rev. B 64, 180505 (2001)

In Conventional Superconductors it is Much Harder to See the Gap !



Density of states near E_F in the superconducting state: BCS model for different temperatures

Sample:

V_3Si

T_c = 17 K
Δ_{gap} = 5 meV

Instr. Res. 2.9 meV !

F. Reinert et al., PRL 85, 3930 (2000)