# Angle Resolved Photoemission Spectroscopy

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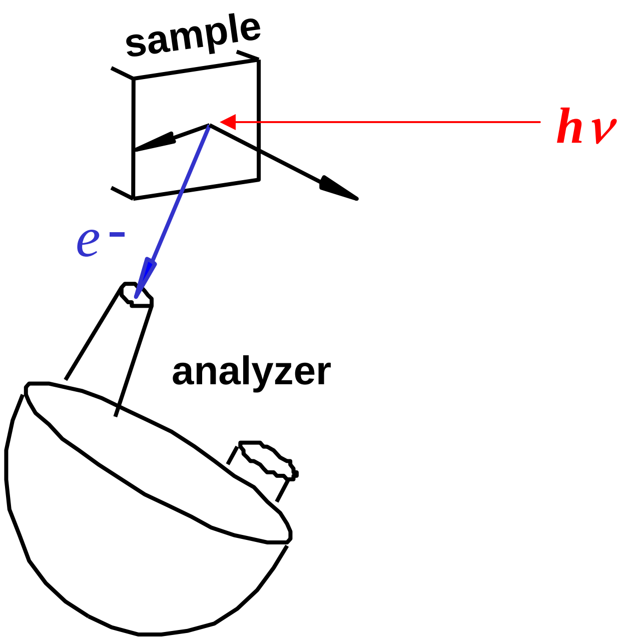
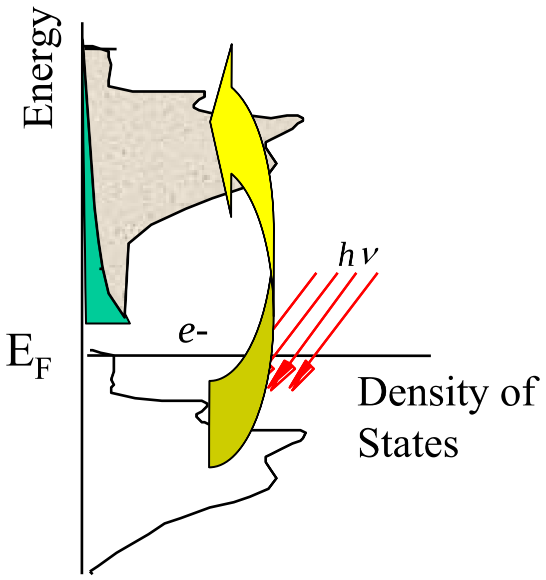
# Photoemission Spectroscopy





High K.E.   Low B.E.

Low K.E.  High B.E.

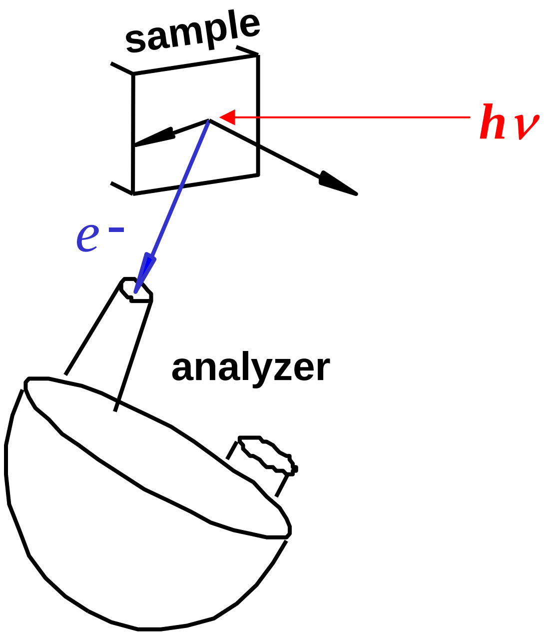
Primary electrons – no scattering events.
Contain information of the electron
spectral function

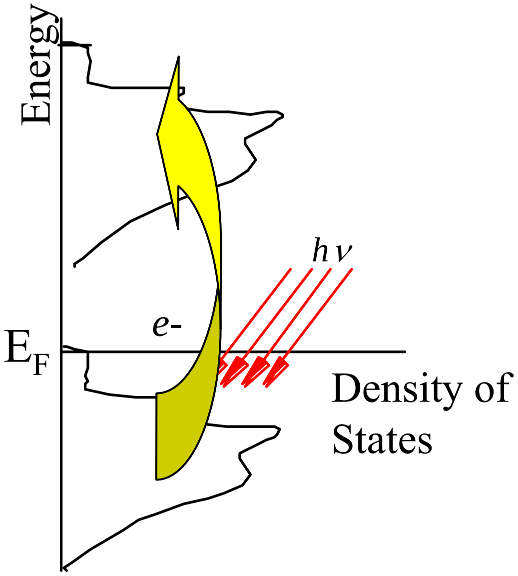
Secondary electrons (inelastic
background) – increases with decreasing
kinetic energy.

$$E_{kin} = \hbar\omega - \Phi \; - |E_B|$$

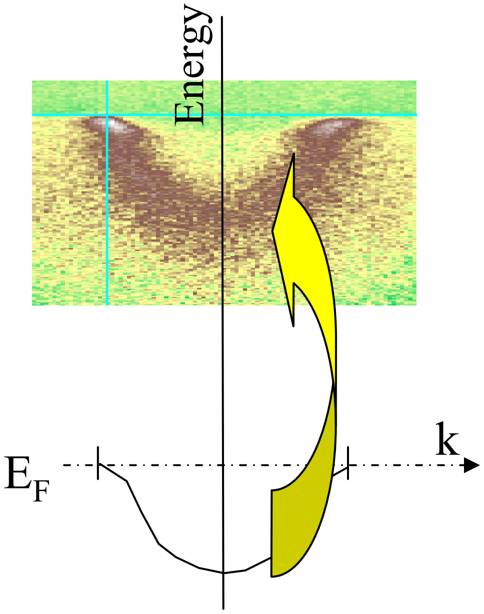
# Angle Resolved Photoemission (ARPES)

Most direct way to measure quantum mechanical “dance” of electrons in a solid.





Angle-integrated
→ Density of States

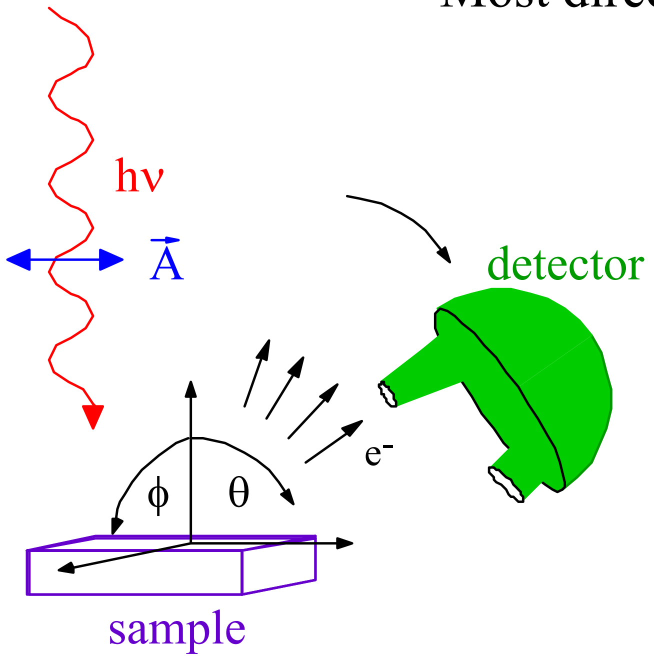


Angle-Resolved (ARPES)
→ k-dependent elect. structure

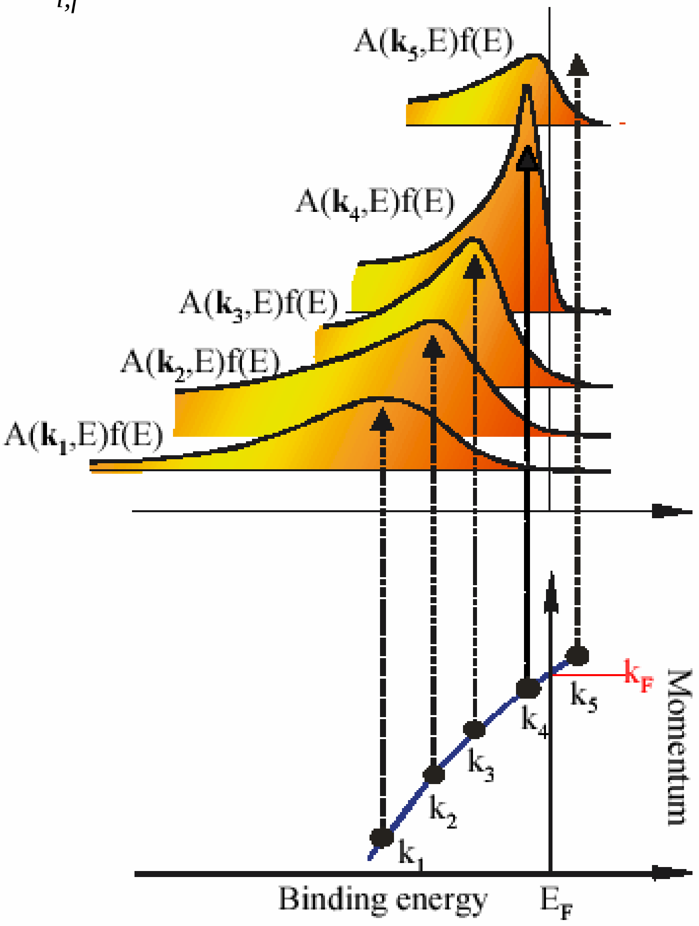
Interested in critical details of the lowest energy interactions near $E_F$.
→ Requirement for the highest spectral resolution and sensitivity.

# Angle Resolved Photoemission (ARPES)
# A momentum resolved spectroscopy

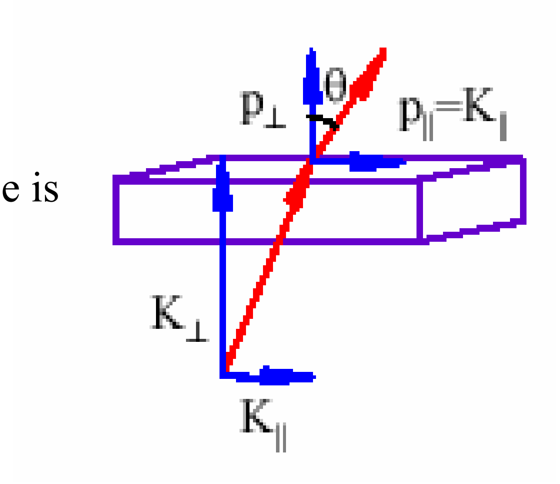
Most direct way to measure E vs. k of a solid.



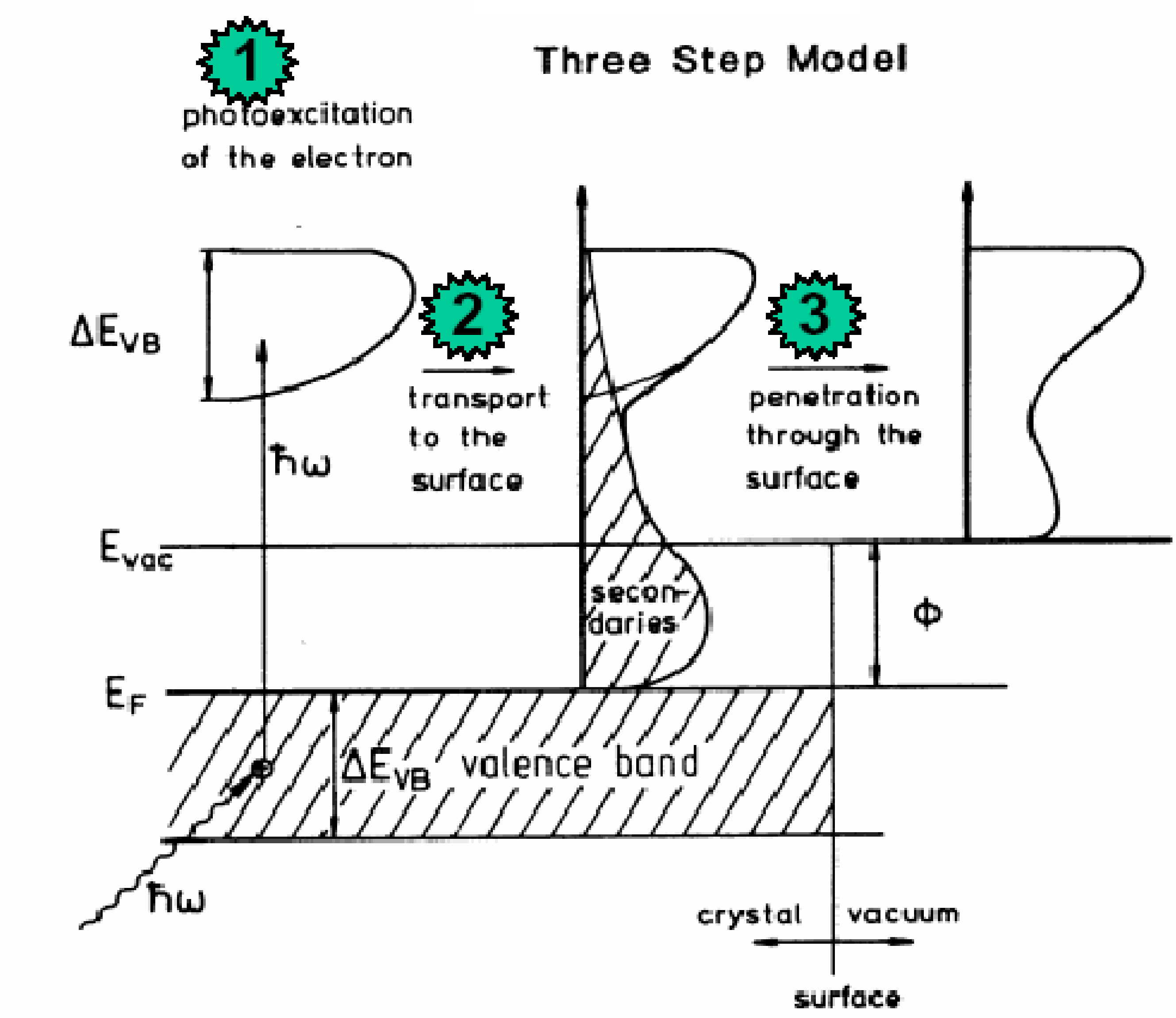
$$\text{Intensity} \propto \sum_{i,f} \left| \left\langle f \middle| \vec{\mathbf{p}} \bullet \vec{\mathbf{A}} \middle| i \right\rangle \right|^2 A(\vec{\mathbf{k}}, E)\, f(E)$$



Electron momentum
Parallel to the surface is
conserved



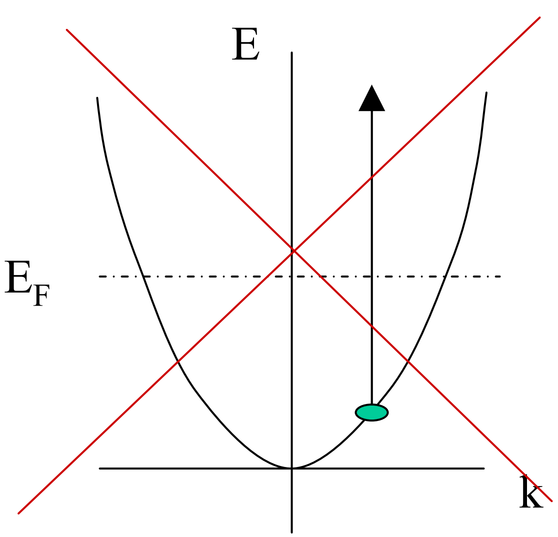
# Three Step Model
W.E. Spicer

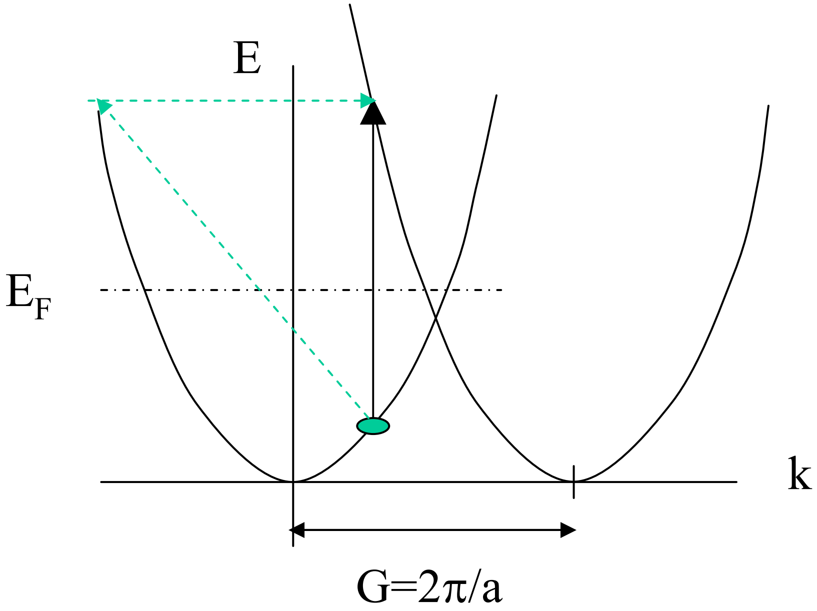


# Momentum Conservation

Photons of a few hundred eV or less carry negligible momentum compared to the typical electron momentum scales in a solid.

Therefore we consider “vertical” transition processes. For a free electron parabola there would be no final state and the process is forbidden.





The vertical transition is allowed by considering the extended zone scheme and employing a reciprocal lattice vector $G=2\pi/a$ (the lattice degree of freedom takes care of the “missing” momentum).

PHYSICAL REVIEW B VOLUME 21, NUMBER 8 15 APRIL 1980

## Angle-resolved photoemission, valence-band dispersions $E(\vec{k})$, and electron and hole lifetimes for GaAs

T.-C. Chiang, J. A. Knapp,* M. Aono,† and D. E. Eastman
*IBM Thomas J. Watson Research Center, Yorktown Heights, New York 10598*
(Received 3 December 1979)

$$E_f(\vec{k}) = \hbar^2 |\vec{k}|^2/2m + E_0 = \hbar^2(k_\parallel^2 + k_\perp^2)/2m + E_0$$

Final Bloch states. $E_o$ = "bottom of Muffin tin" – starting point for parabolic band dispersions = -9.34 eV for GaAs.

$$E_f(\vec{k}) = E_i(\vec{k}) + h\nu$$

Direct or k-conserving transitions.

$$E_f = E_k + e\Phi$$

$e\phi$ = work function of sample, $E_k$=kinetic energy

$$\hbar k_\parallel = (2mE_k)^{1/2}\sin\theta = [2m(E_i + h\nu - e\Phi)]^{1/2}\sin\theta$$

Projection to parallel component of momentum

$$\hbar k_\perp = [2m(E_k\cos^2\theta - V_0)]^{1/2} = \{2m[(E_i + h\nu - e\Phi)\cos^2\theta - V_0]\}^{1/2}$$

$V_o = E_o - e\phi$ ="Inner potential". Usually just a fitting parameter.

Normal emission: theta=0 $\hbar k_\parallel = 0$ $\hbar k_\perp = [2m(E_i + e\Phi - E_0)]^{1/2}$

# 2D compounds

- Can ignore $k_z$ dispersion.
- Need not vary photon energy to map out Fermi surface and high symmetry directions.
- Less final state broadening.  Intrinsic initial-state linewidths can be studied.
- Usually much better cleaved surfaces

# Fermi Surface, Surface States, and Surface Reconstruction in $Sr_2RuO_4$

A. Damascelli, D. H. Lu, K. M. Shen, N. P. Armitage, F. Ronning, D. L. Feng, C. Kim, and Z.-X. Shen
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*and CREST-JST, Kawagushi, Saitama 332-0012, Japan*

Example 2D compound

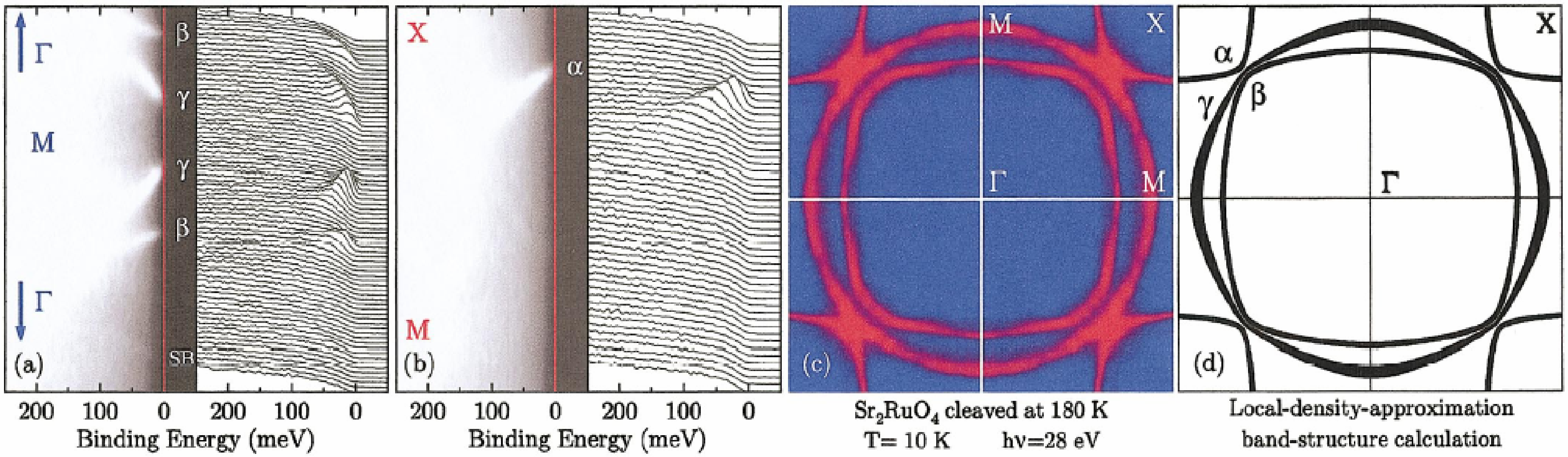

FIG. 9. Photoemission results from $Sr_2RuO_4$: ARPES spectra and corresponding intensity plot along (a) Γ-*M* and (b) *M*-*X*; (c) measured Fermi surface; (d) calculated Fermi surface (Mazin and Singh, 1997). From Damascelli *et al.*, 2000 (Color).

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*IBM Thomas J. Watson Research Center, Yorktown Heights, New York 10598*

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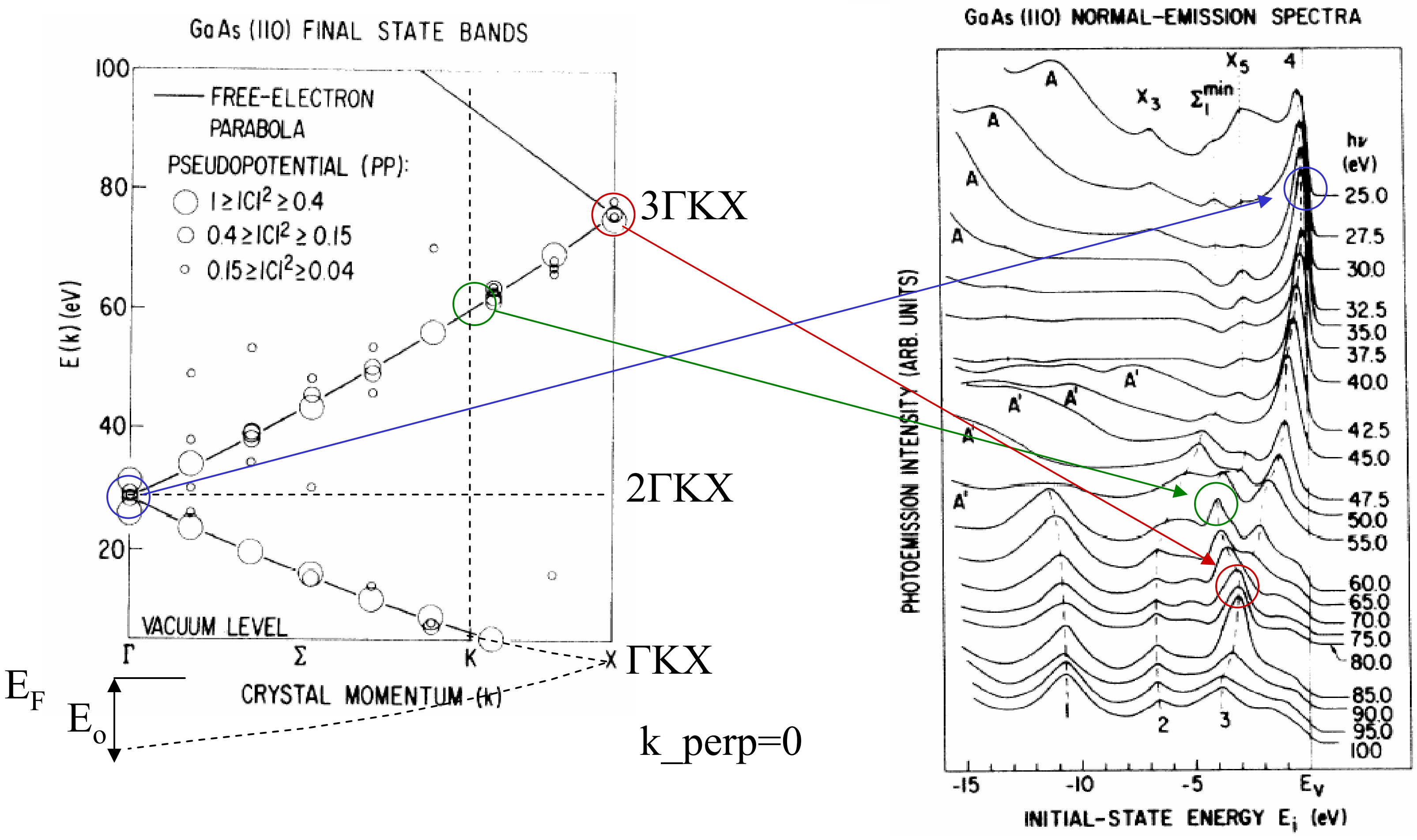
Example 3D compound

Normal emission: theta=0

$$\hbar k_{\parallel} = 0$$

$$\hbar k_{\perp} = [2m(E_i + e\Phi - E_0)]^{1/2}$$



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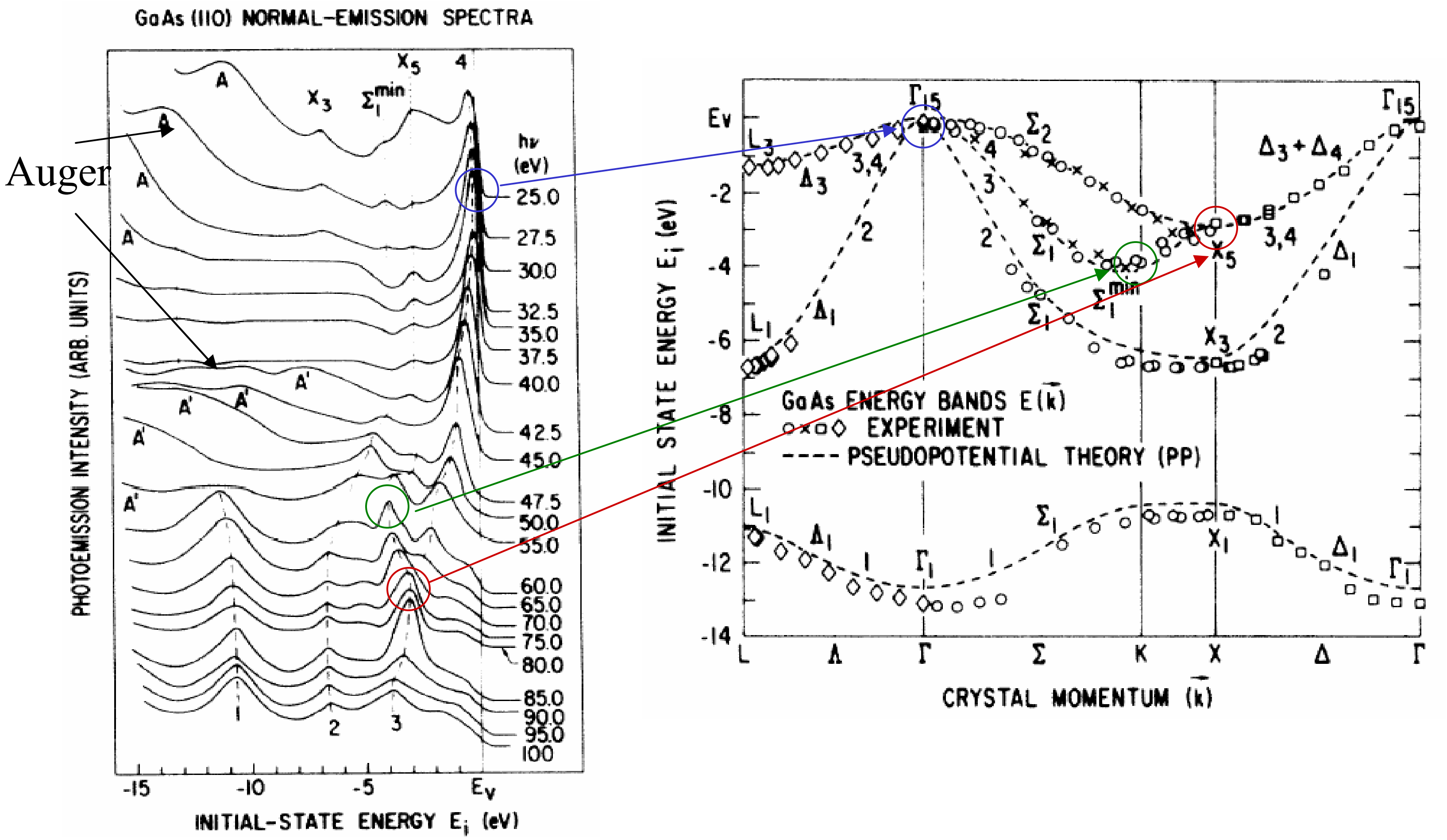
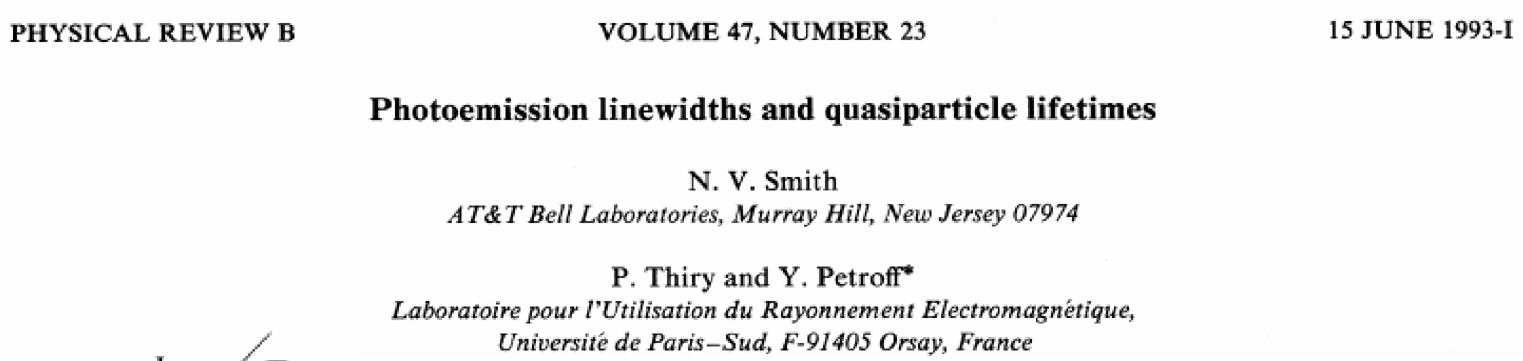


# 2D compounds

- Can ignore $k_z$ dispersion.
- Need not vary photon energy to map out Fermi surface and high symmetry directions.
- Less final state broadening. Intrinsic initial-state linewidths can be studied.
- Usually much better cleaved surfaces



PHYSICAL REVIEW B VOLUME 47, NUMBER 23 15 JUNE 1993-I

# Photoemission linewidths and quasiparticle lifetimes

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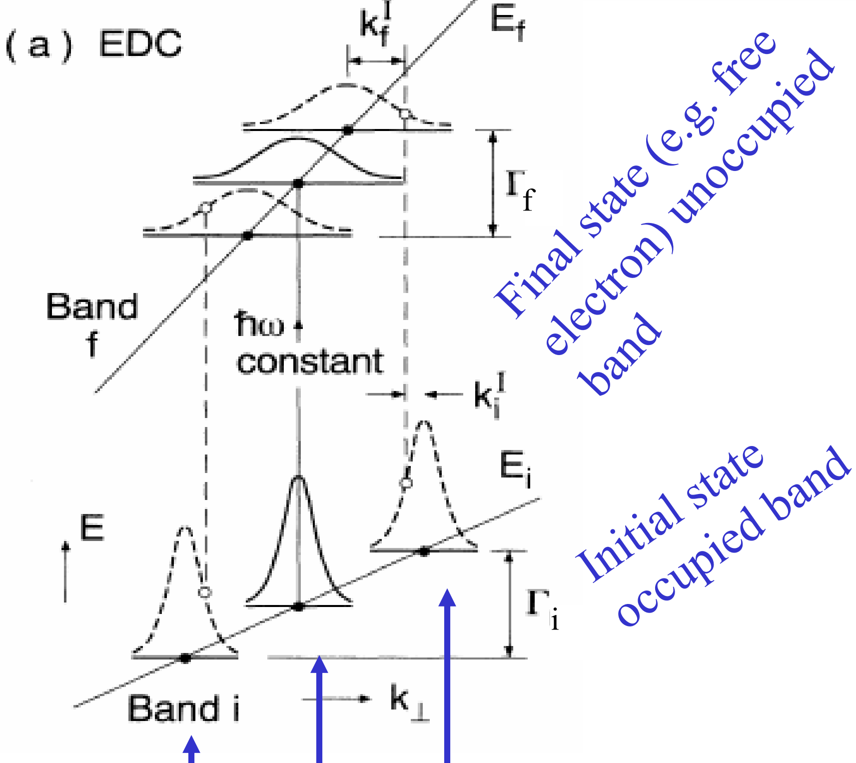
*Université de Paris–Sud, F-91405 Orsay, France*



Final state (e.g. free electron) unoccupied band

Initial state occupied band

Measured linewidths $\Gamma_m$ have a contribution from the lifetimes of the initial state (lifetime $\Gamma_i$) and final state (lifetime $\Gamma_f$).

$$\Gamma_m = \frac{\Gamma_i/|v_{i\perp}| + \Gamma_f/|v_{f\perp}|}{\left| \frac{1}{v_{i\perp}}\left[1 - \frac{m v_{i\parallel}\sin^2\theta}{\hbar k_\parallel}\right] - \frac{1}{v_{f\perp}}\left[1 - \frac{m v_{f\parallel}\sin^2\theta}{\hbar k_\parallel}\right] \right|}$$

Nearly 2D limit: $v_{i\ \mathrm{perp}}$ small. Near isolation of $\Gamma_i$.

$$\Gamma_m = \Gamma_i + \left|\frac{v_{i\perp}}{v_{f\perp}}\right| \Gamma_f .$$

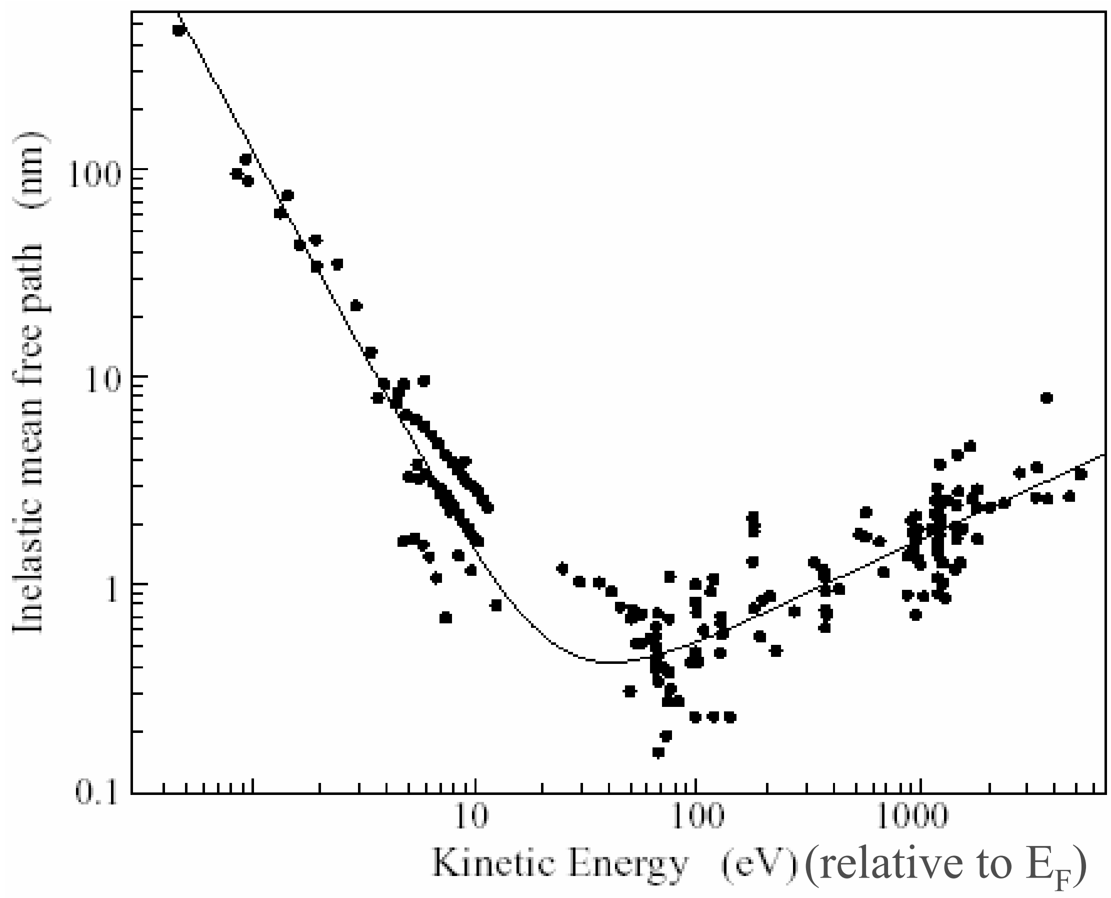
$k_{\mathrm{perp}}$ (and hν) value with half maximum intensity

$k_{\mathrm{perp}}$ (and hν) value with maximum intensity (cross section)

# Surface sensitivity – electron kinetic energy

## "Universal Curve"

Can be an advantage or a disadvantage!

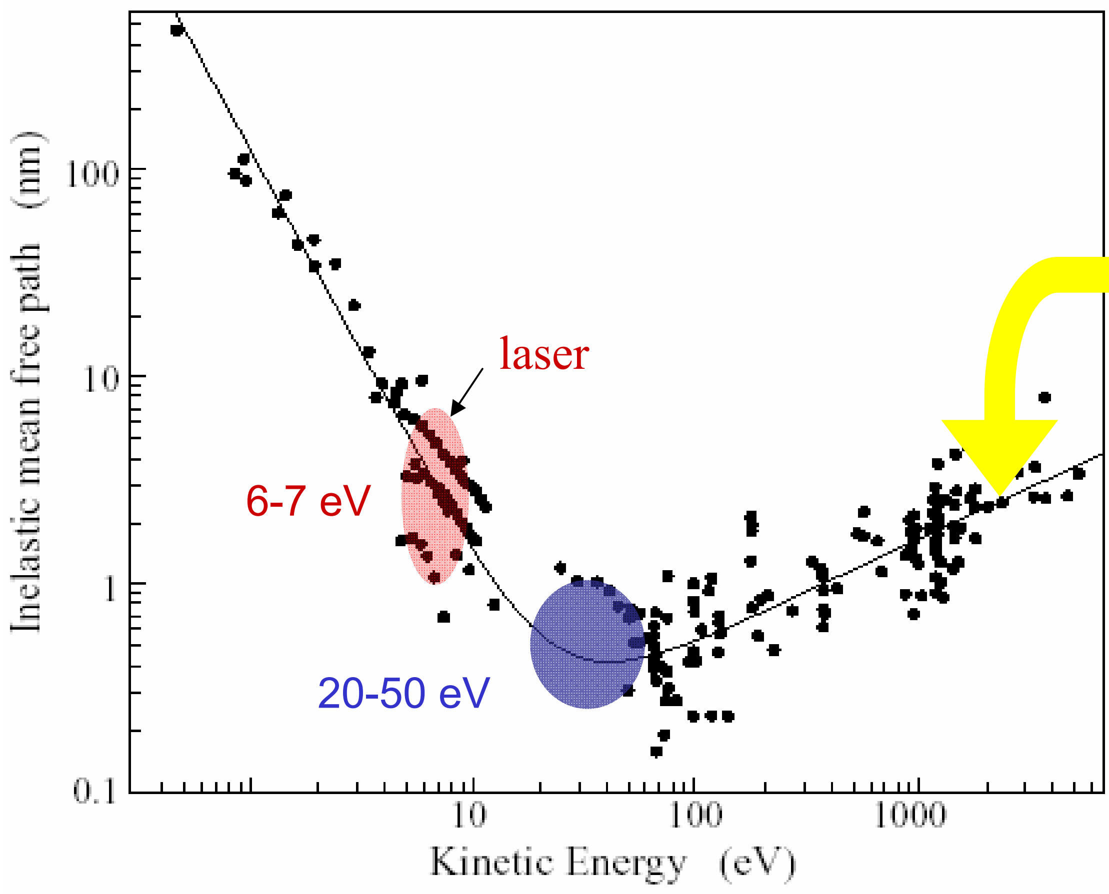


Decreasing phase space for excitations (plasmons, e-h pairs, etc.)

Decreasing interaction times.

M. P. Seah and W. A. Dench, *Surf. Interface Anal.* **1**, 2 (1979).

# Surface sensitivity – electron kinetic energy



Other efforts here as well.

→3-10 times more bulk sensitive than standard ARPES
Very helpful for studies of "bulk" physics.

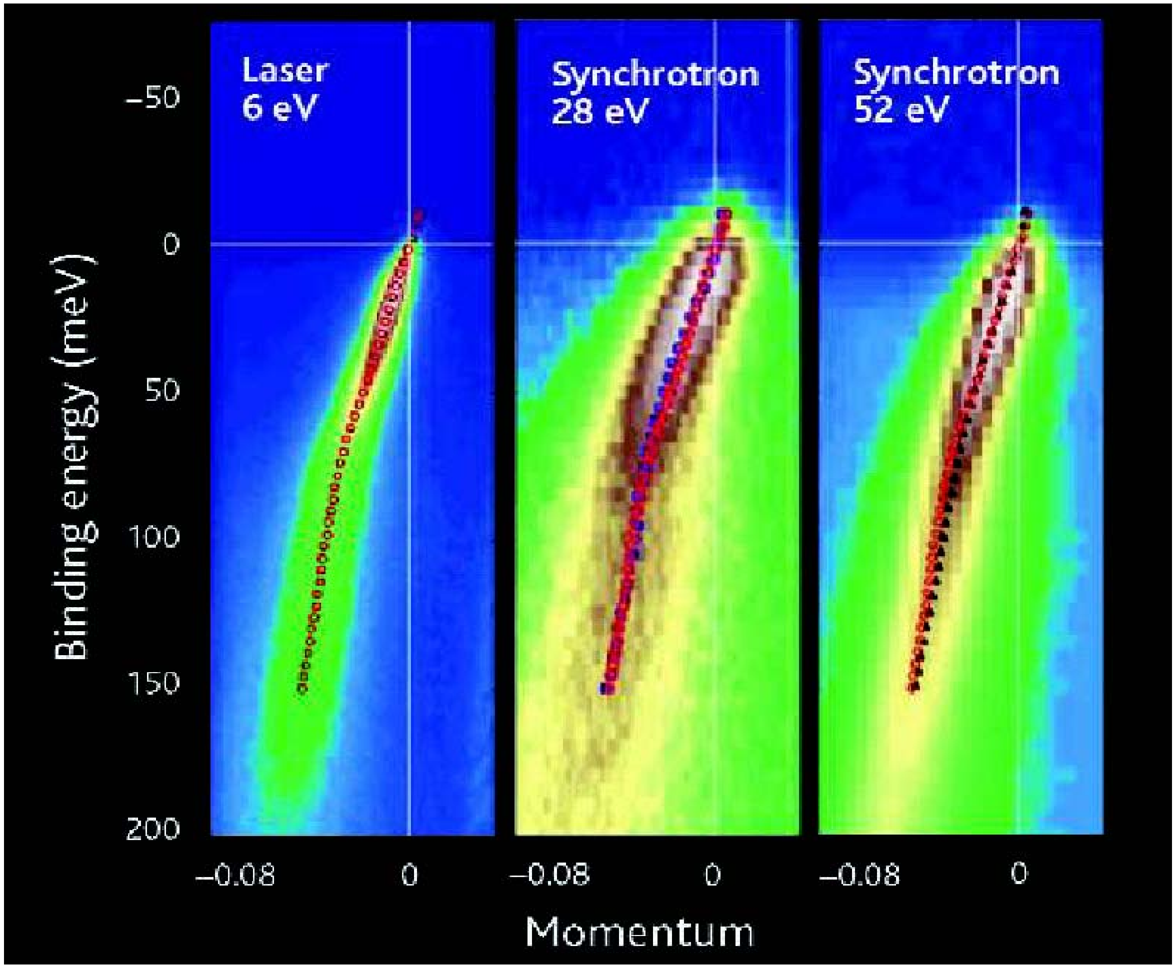
M. P. Seah and W. A. Dench, *Surf. Interface Anal*. **1**, 2 (1979).

**Condensed-Matter Physics**

# Researchers Turn Up the Heat in Superconductivity Hunt

ARPES dispersion along the nodal line of $Bi_2Sr_2CaCu_2O_8$

T ~ 20K



www.sciencemag.org SCIENCE VOL 310 25 NOVEMBER 2005 1271

*Published by AAAS*

J.D. Koralek, D.S.D. et.al, Phys. Rev. Lett. **96**, 017005 (2006)

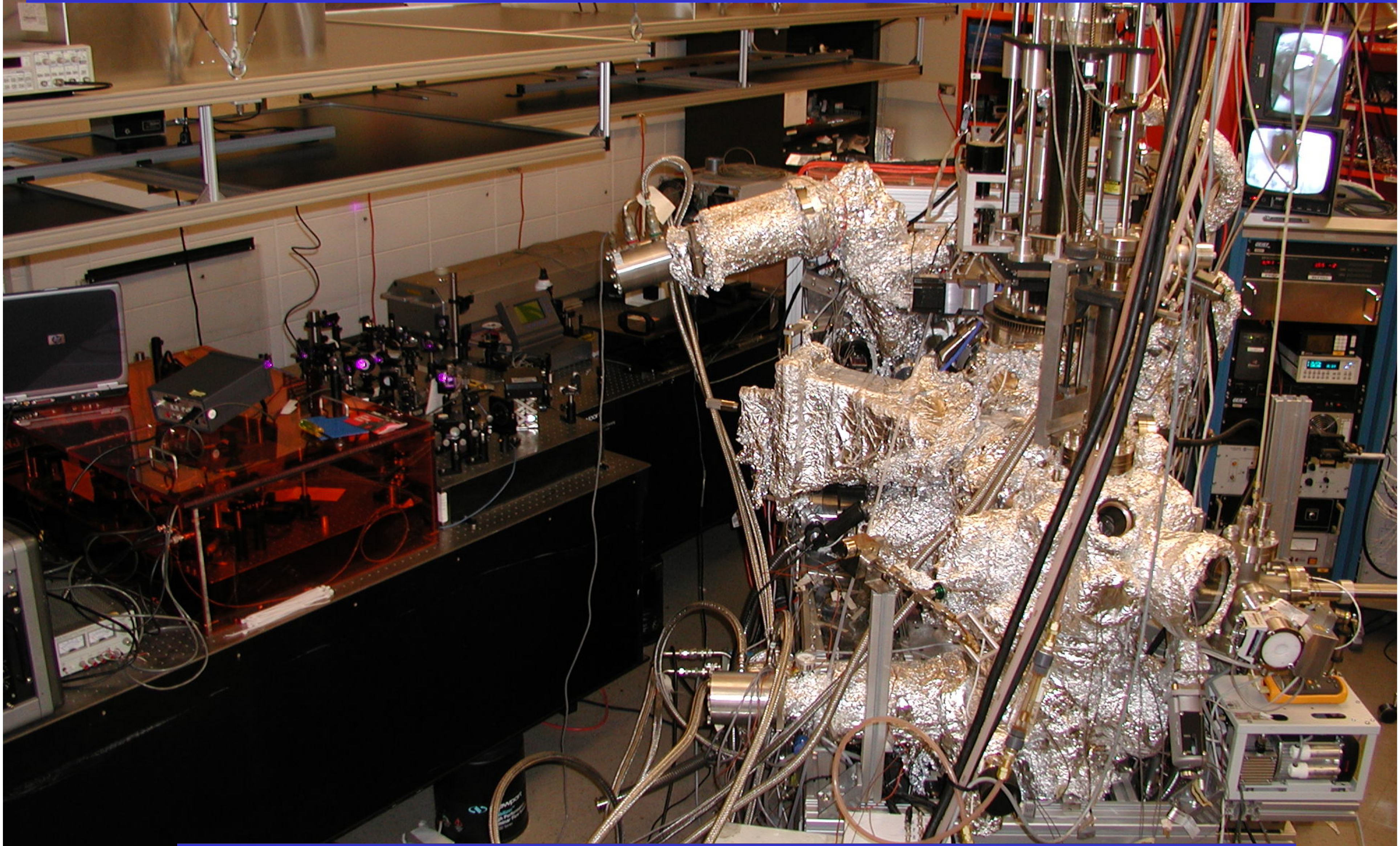
# Low photon energy ARPES

- Improved **k** and E resolution
- Improved bulk sensitivity
- Reduced background
- Decreased space-charge effect
- Increased final state lifetimes (less k_perp broadening)

# Disadvantages of low-energy ARPES

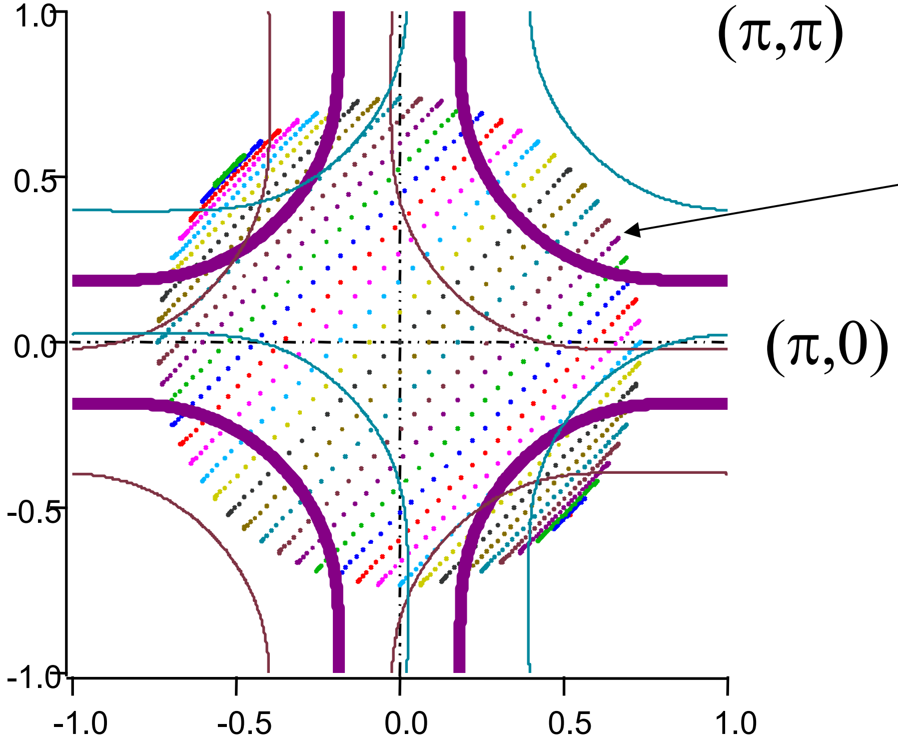
- Potential issues with breakdown of the sudden-approximation
- Technically more challenging (Electron analyzers don’t like low kinetic energy)
- Often a lack of matrix element/photon energy control
- Not many synchrotron beamlines.

# Laser-ARPES lab, University of Colorado, room G235



**6 – 7 eV photons**
**CW to few hundred femtosecond, 80-100 MHz rep rate**

# Resolution and k-space effect



Range of k-space accessible in Bi2212 at hv= 6 eV

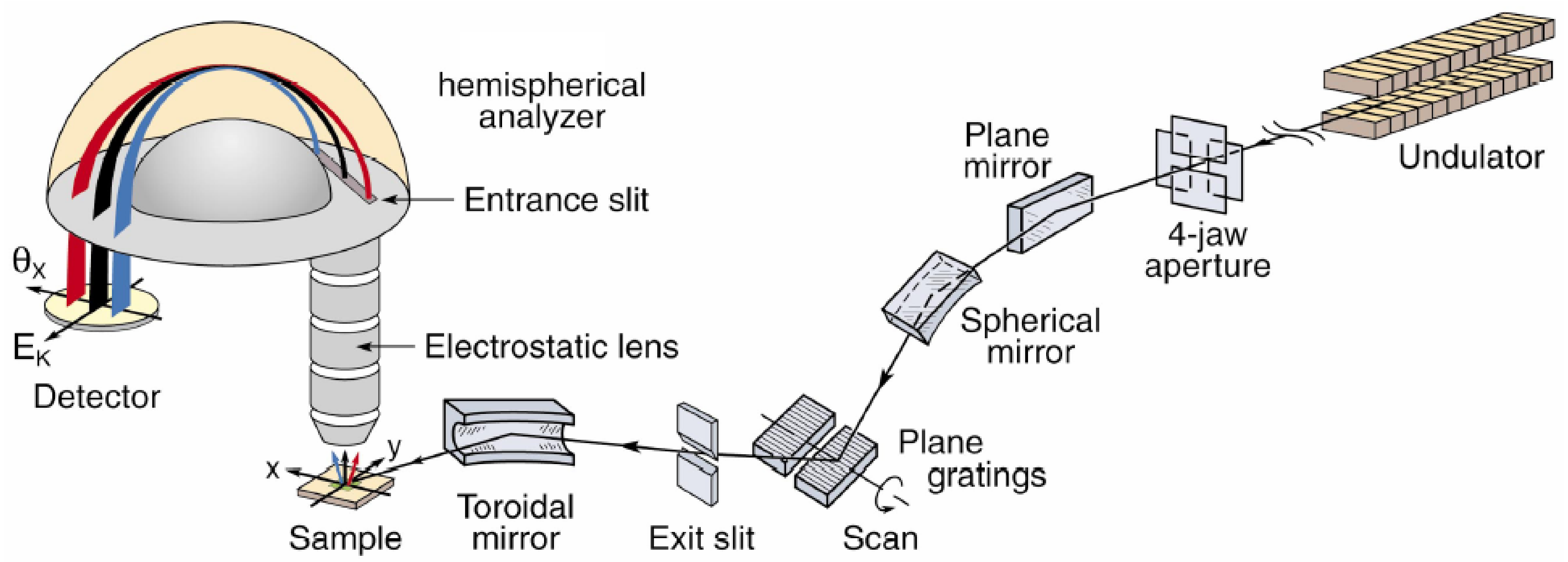
$$\hbar k_{//} = \sqrt{2mE_k}\,\sin\theta$$

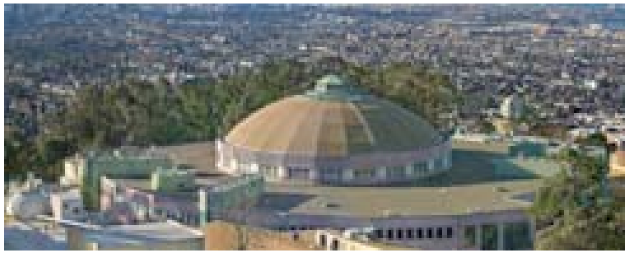
- For the same angular resolution, the k resolution at low E is superior.
- k resolution translates to E widths if the peak is dispersive.

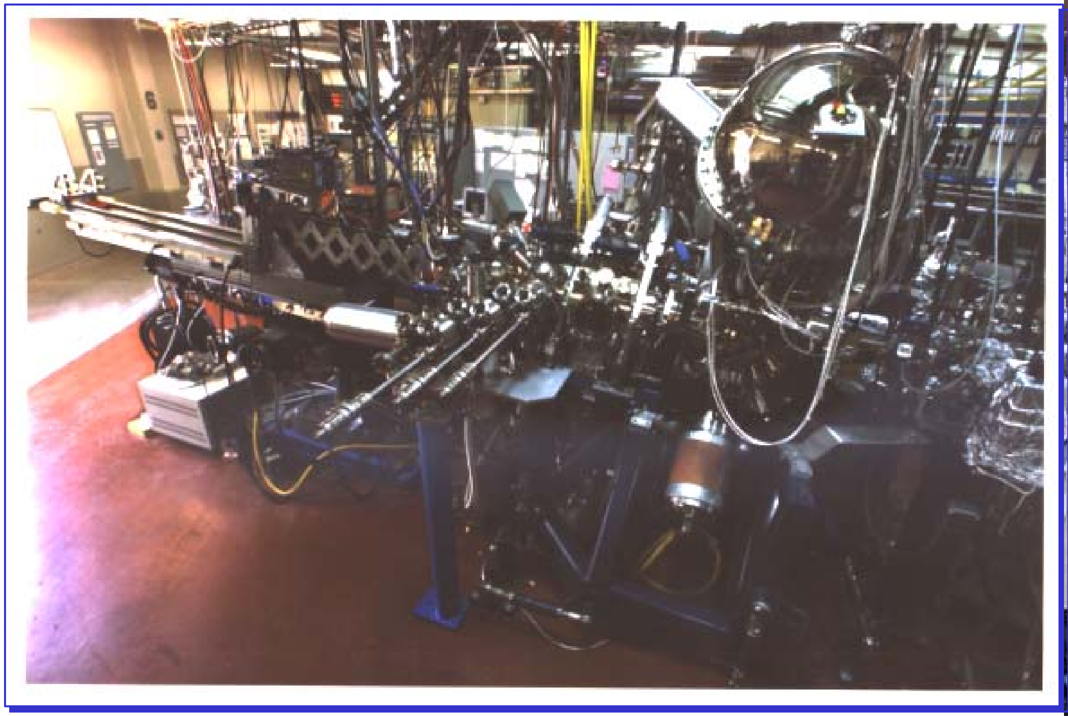
  For nodal states & ± .15 degree angular resolution,

  5 meV broadening for hv=6eV, 38 meV for hv=52 eV.
- However – relatively small range of k-space accessible.

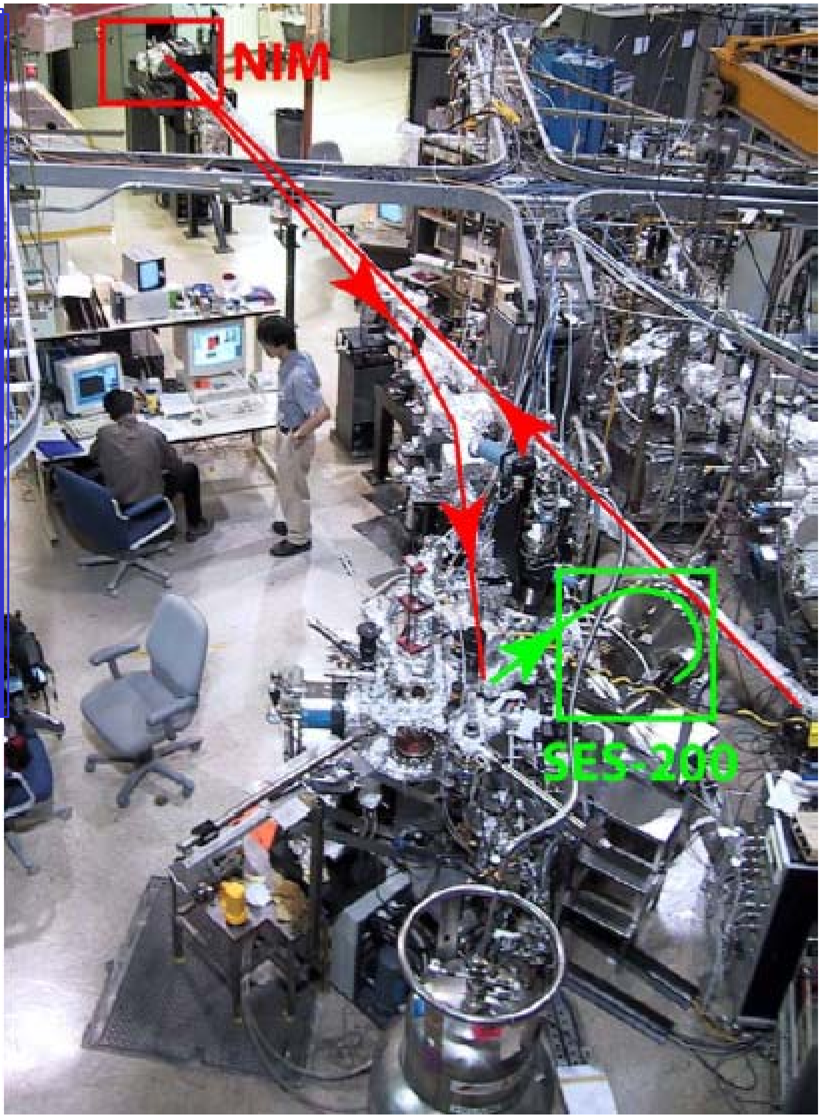
# Typical synchrotron beamline for ARPES







- UHV analysis chamber ($10^{-11}$ Torr)
- 5 or 6 axis, He cooled sample manipulators
- Load-Lock transfer system
- Samples may be cleaved in UHV



# Matrix Element for Photoemission

**Perturbation Theory gives Fermi's Golden Rule for transition probability**

$$w = \frac{2\pi}{\hbar}\left|\left\langle \psi_f \left| H_{\text{int}} \right| \psi_i \right\rangle\right|^2 \delta(E_f - E_i - \hbar\omega)$$

**For dipole allowed transitions,**

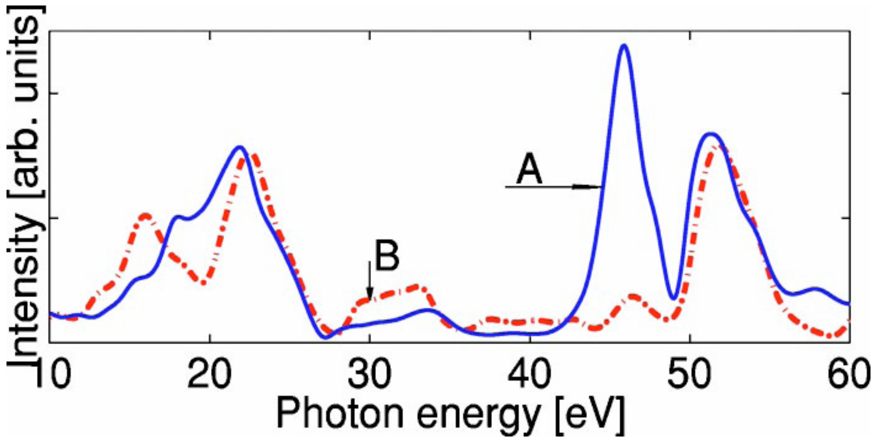
$$H_{\text{int}} = \frac{e}{mc}\mathbf{A}\cdot\mathbf{p}$$

PHYSICAL REVIEW B **69**, 094515 (2004)

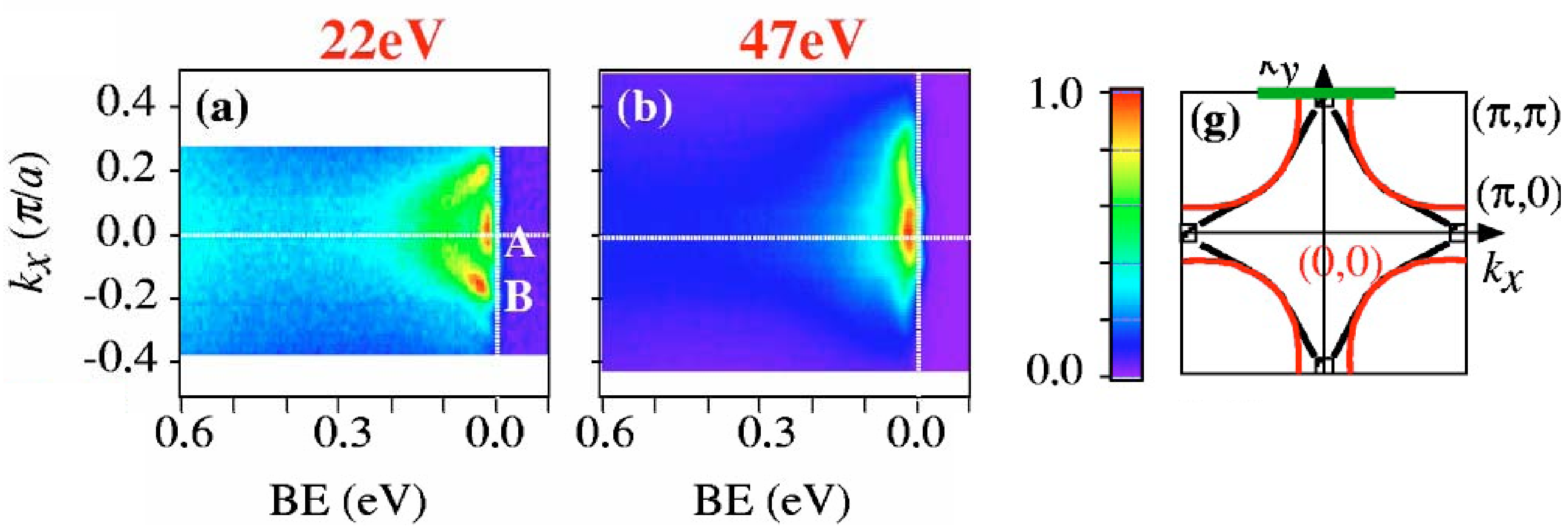
# Bilayer splitting and coherence effects in optimal and underdoped $Bi_2Sr_2CaCu_2O_{8+\delta}$

Y.-D. Chuang,[1,2] A. D. Gromko,[1] A. V. Fedorov,[1,2] Y. Aiura,[3] K. Oka,[3] Yoichi Ando,[4] M. Lindroos,[5,6]
R. S. Markiewicz,[5] A. Bansil,[5] and D. S. Dessau[1]

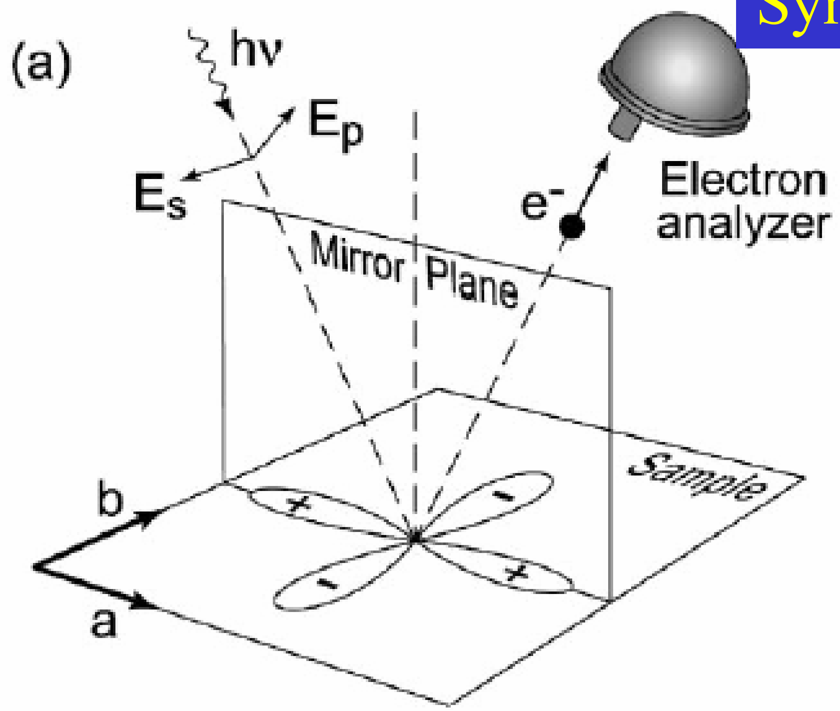
One-step-model matrix element calculations.
Antibonding (A) vs. Bonding (B) bands.



Experiment.

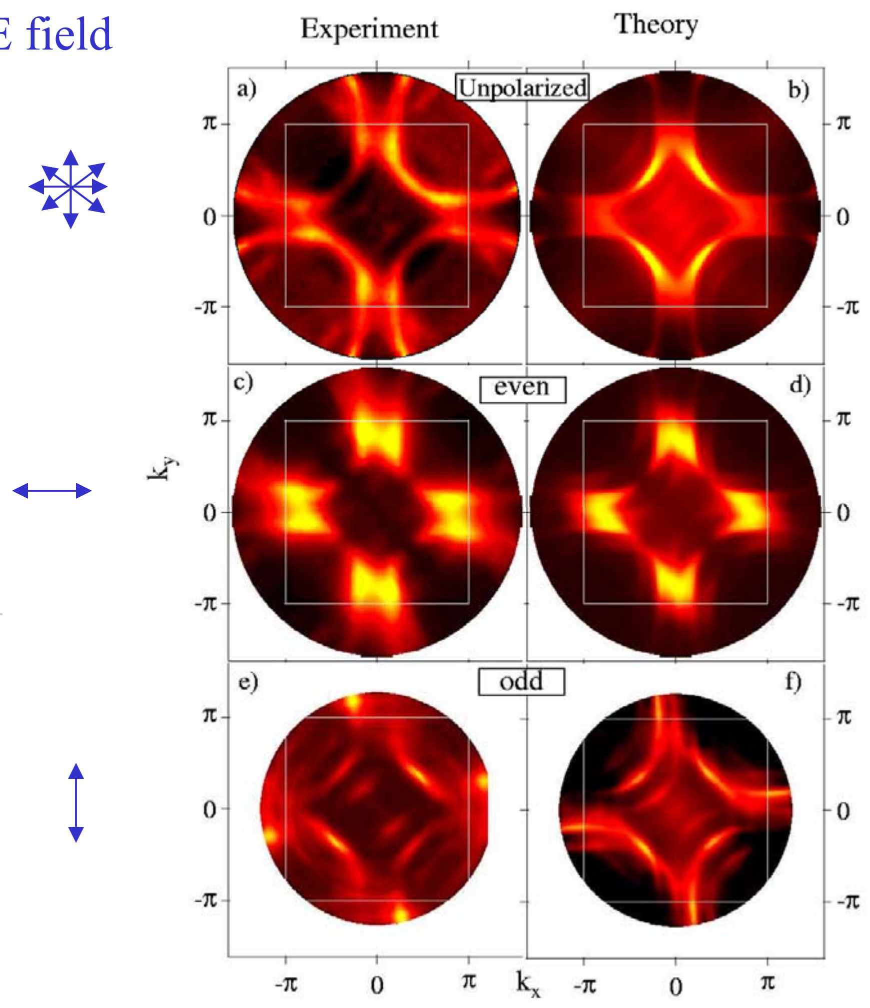


# Symmetry Analysis



$$\langle \phi_f^{\mathbf{k}}|\mathbf{A}\cdot\mathbf{p}|\phi_i^{\mathbf{k}}\rangle \begin{cases} \phi_i^{\mathbf{k}} \ \text{even} \ \langle +|+|+\rangle \Rightarrow \mathbf{A} \ \text{even} \\ \phi_i^{\mathbf{k}} \ \text{odd} \ \langle +|-|-\rangle \Rightarrow \mathbf{A} \ \text{odd.} \end{cases}$$

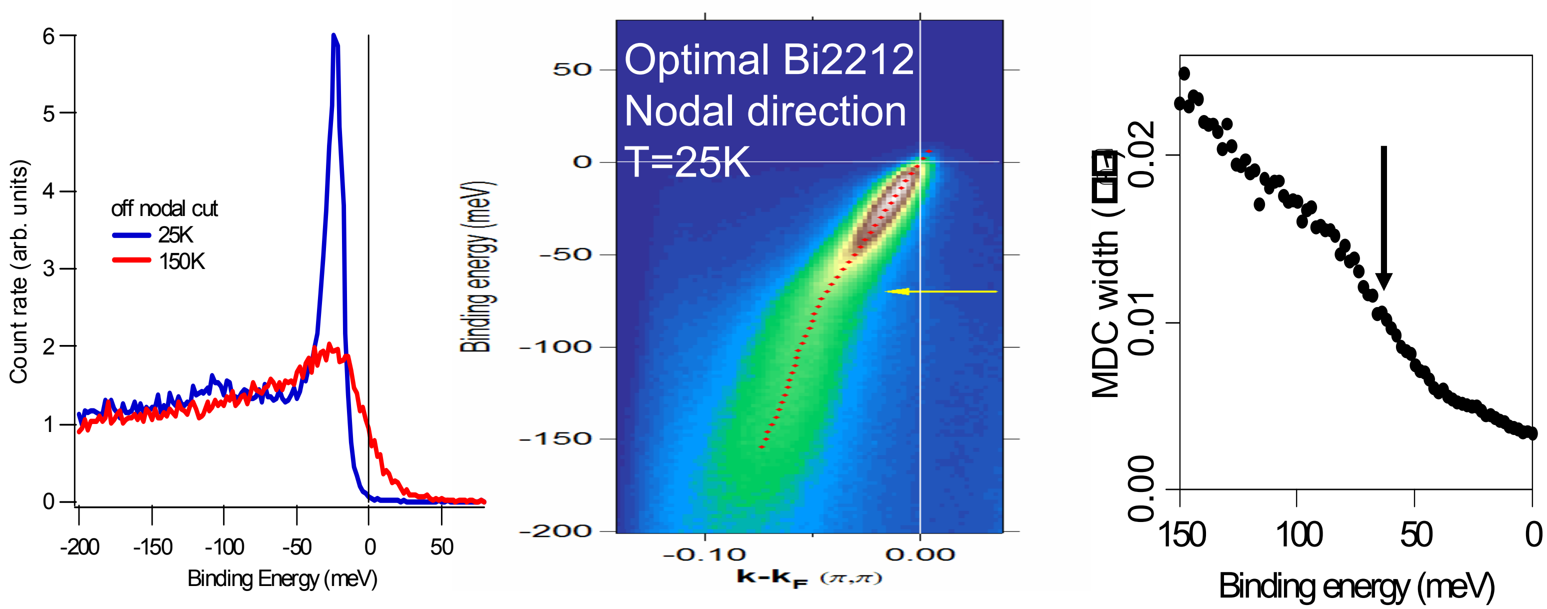
The matrix element is integrated over all space. The integration axis of interest here is perpendicular to a chosen mirror plane.
If net odd symmetry, then the matrix element integrates to exactly zero.



# Sudden Approximation – does not appear to be a big issue.

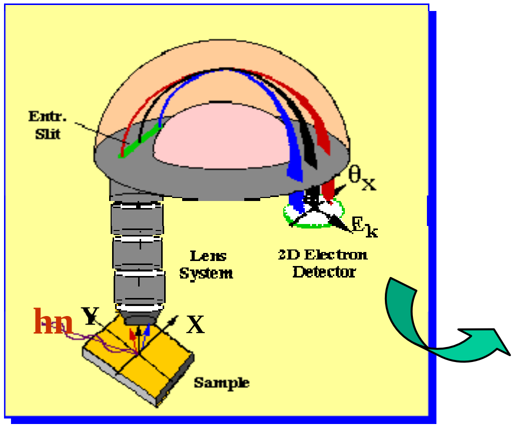
•Old “rule of thumb” - need hv>15-20 eV.  Based upon plasmon loss peaks in core level spectra.

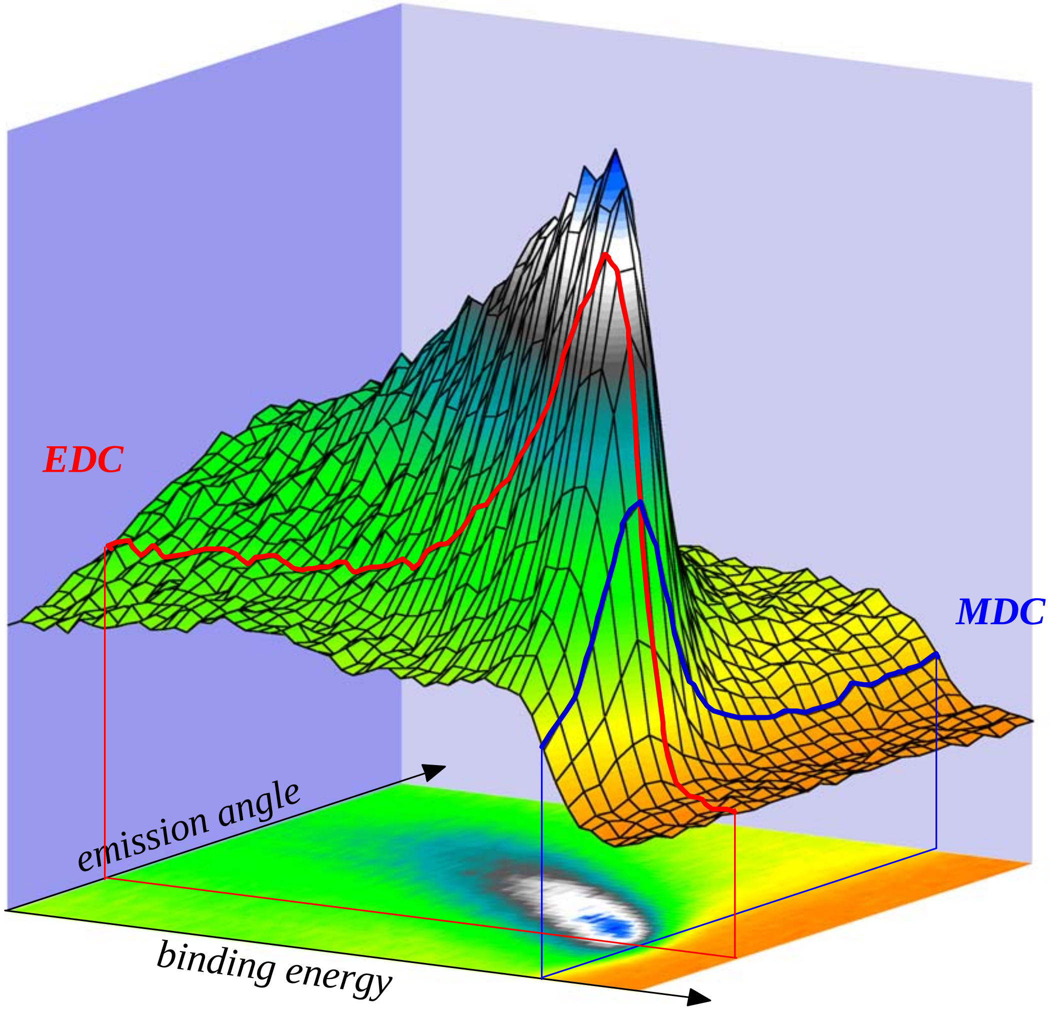
•Our Expt:  All low energy or “quasiparticle” physics found to be similar in the 6 eV spectra as for the 20-50 eV spectra (velocities, kinks, SC gaps). Deeper (phonon scale) loss peaks also clearly observed, and with similar intensity as in high hv expts.



•Can not fully be in the sudden approximation – not enough energy to excite certain loss features (high energy plasmons, Mott excitations, etc.)

# Two dimensional electron detection



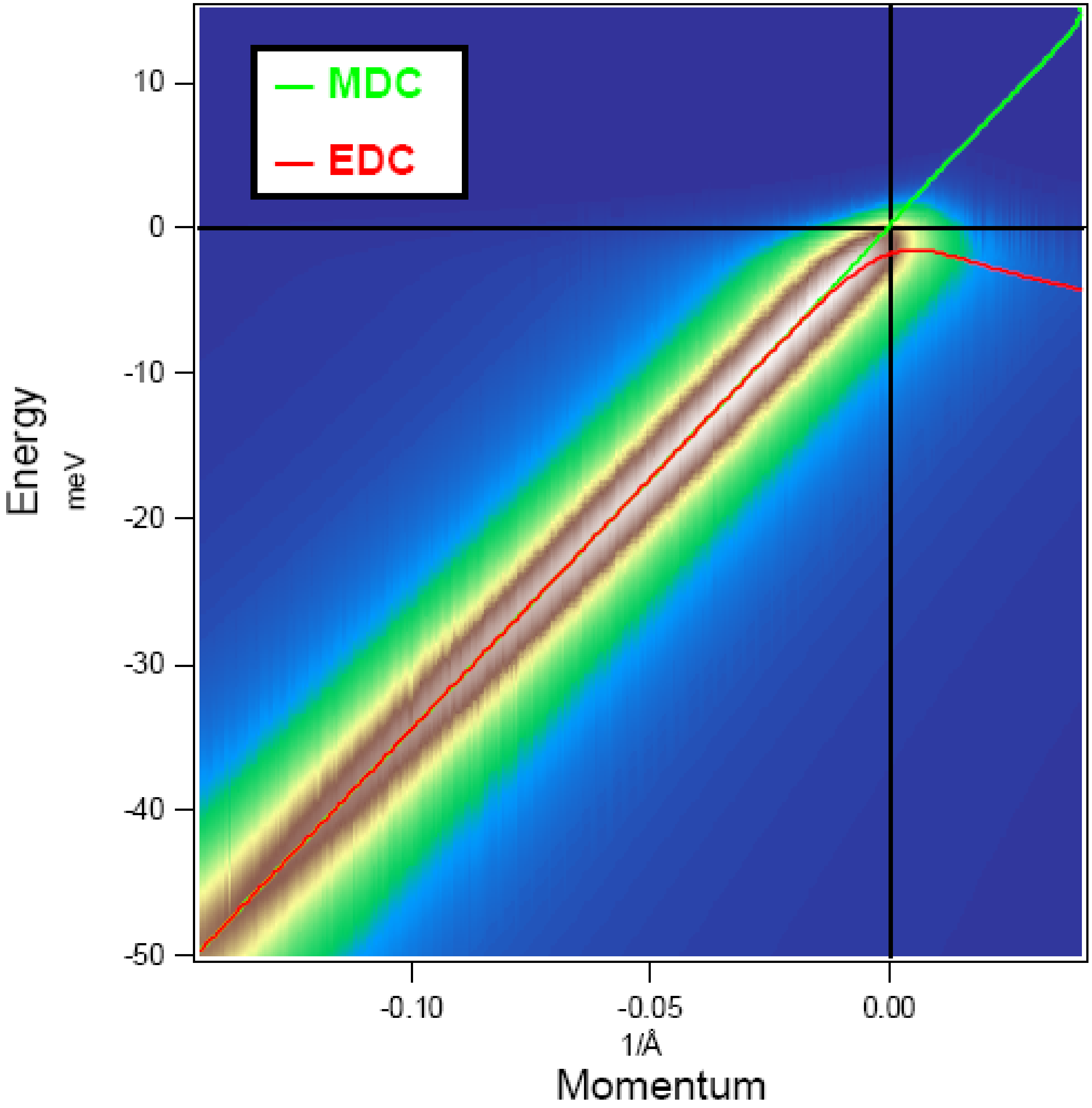


Energy Distribution Curve (EDC)

Momentum Distribution Curve (MDC)

A.D. Gromko, University of Colorado Thesis

# Resolution effects, gaps, and EDC and MDC dispersions (just following the peaks)



T=10K

Base Simulation

Fermi-Liquid like band dispersing through $E_F$.

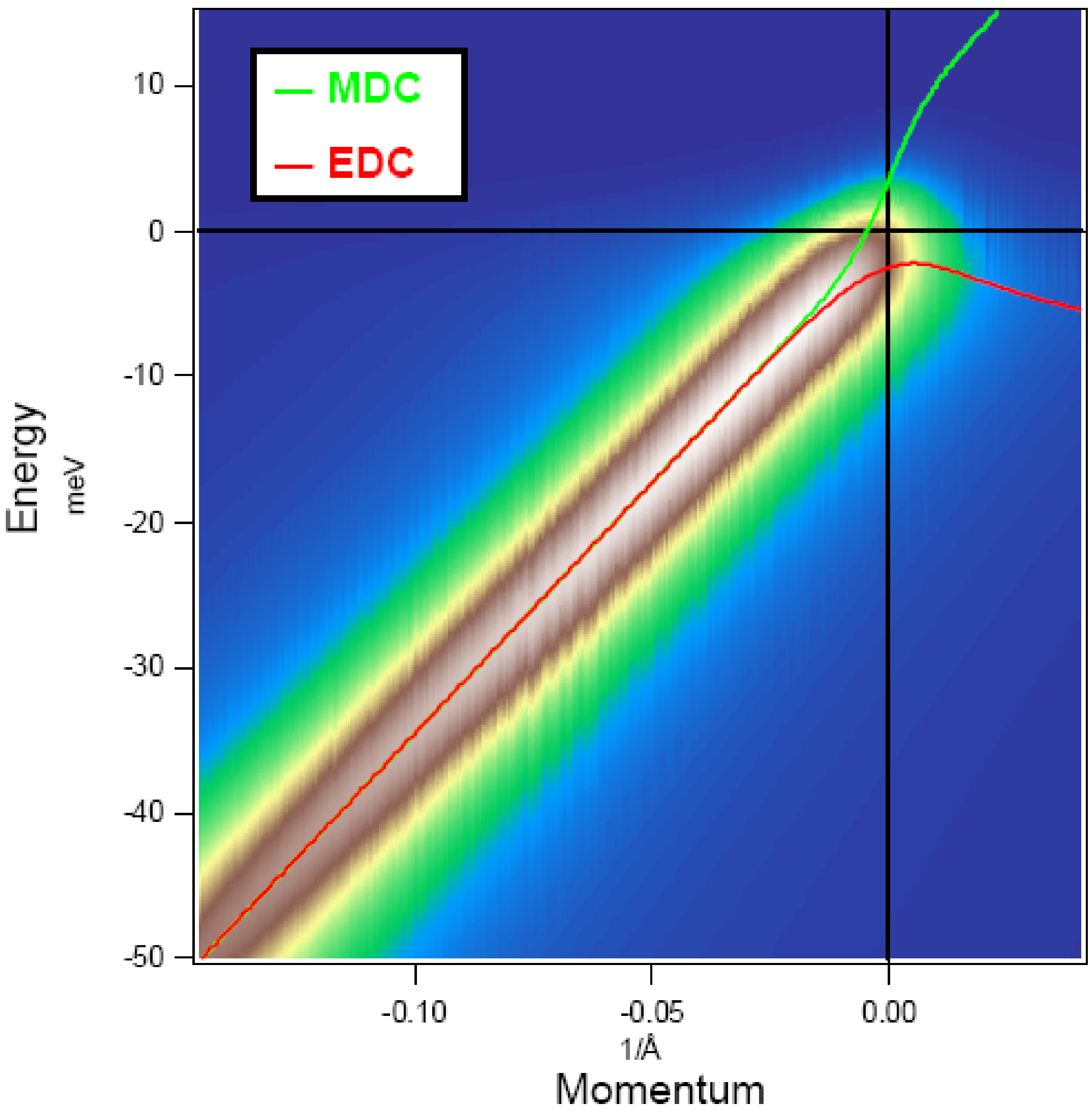
Eres σ = .5 meV

Δ = 0 meV

MDC fit is accurate

EDC dispersion is not.

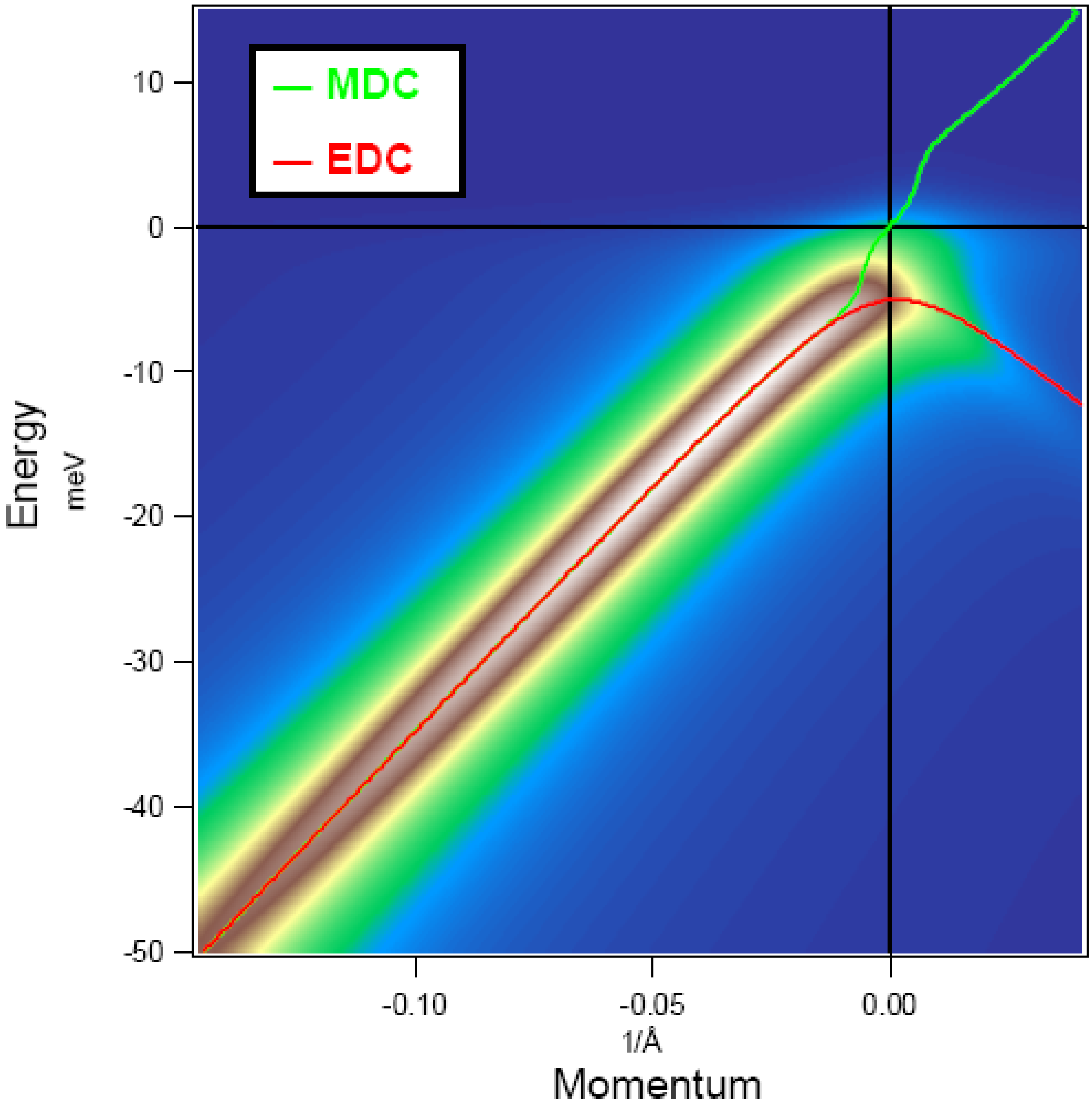
T. Reber



T=10K

Energy Resolution

σ = 2.5 meV



T=10K

Gapped

Δ = 5 meV

σ=0.5 meV

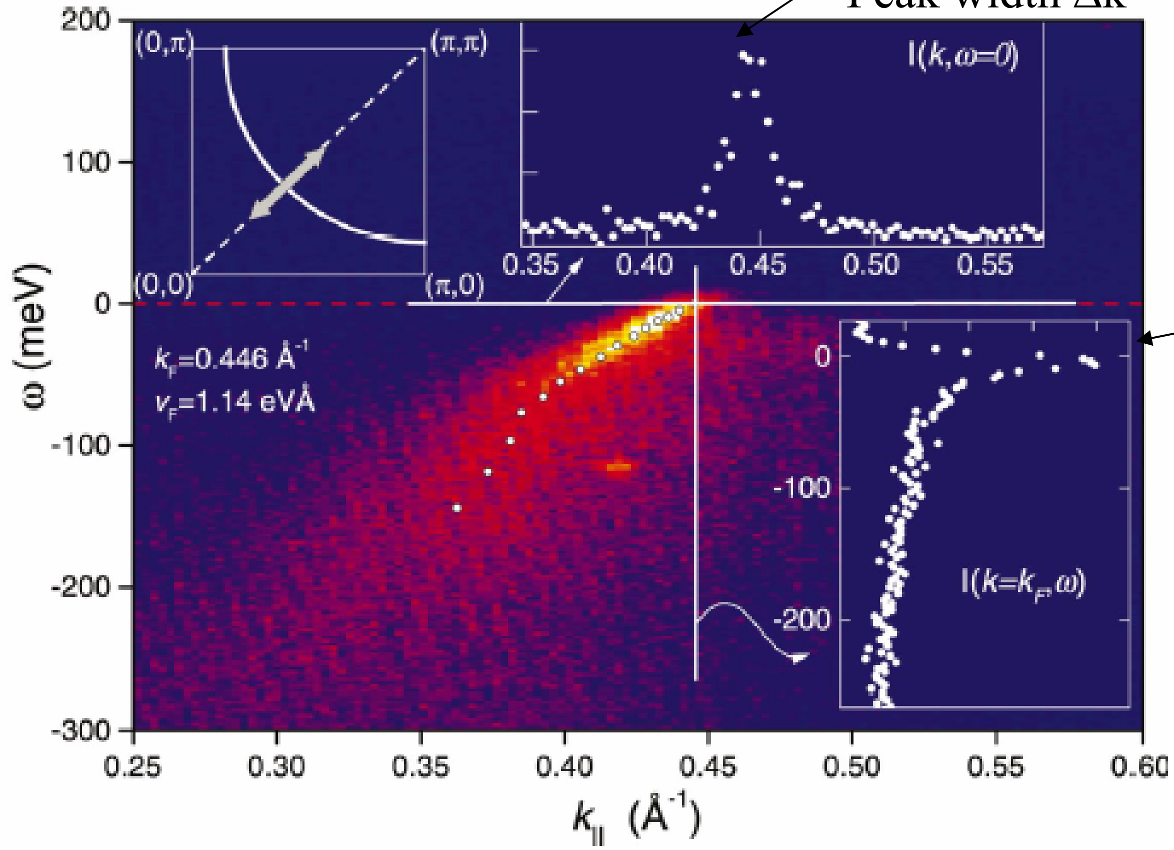
EDC dispersion is accurate
MDC is not

# 2D detection on the high Tc superconductor $Bi_2Sr_2CaCu_2O_8$

**T. Valla,[1] A. V. Fedorov,[1] P. D. Johnson,[1] B. O. Wells,[1,4]
S. L. Hulbert,[2] Q. Li,[3] G. D. Gu,[5] N. Koshizuka[6]**

Momentum Distribution Curve (MDC)

Peak width $\Delta k = 1/\lambda$: $\lambda$=electron mean free path.



Energy Distribution Curve (EDC)

Peak width $\Delta E = \hbar/\tau$

$1/\tau$=scattering rate

$\tau$=quasiparticle lifetime

$$\Delta E = \Delta k * dE/dk = \Delta k * v$$

MDCs are usually more symmetric than EDCs (simple Lorentzian). → easier to fit

2110 24 SEPTEMBER 1999 VOL 285 SCIENCE www.sciencemag.org

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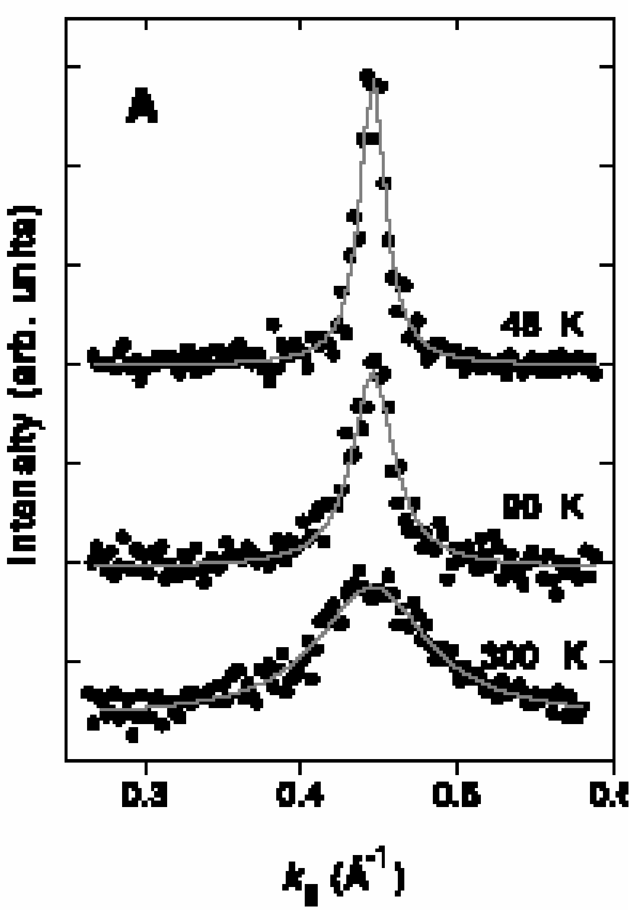
Valla et al., Science (1999)



Lorentzian MDC fits as as a function of temperature.

Broader peaks at higher T →shorter photohole lifetimes.

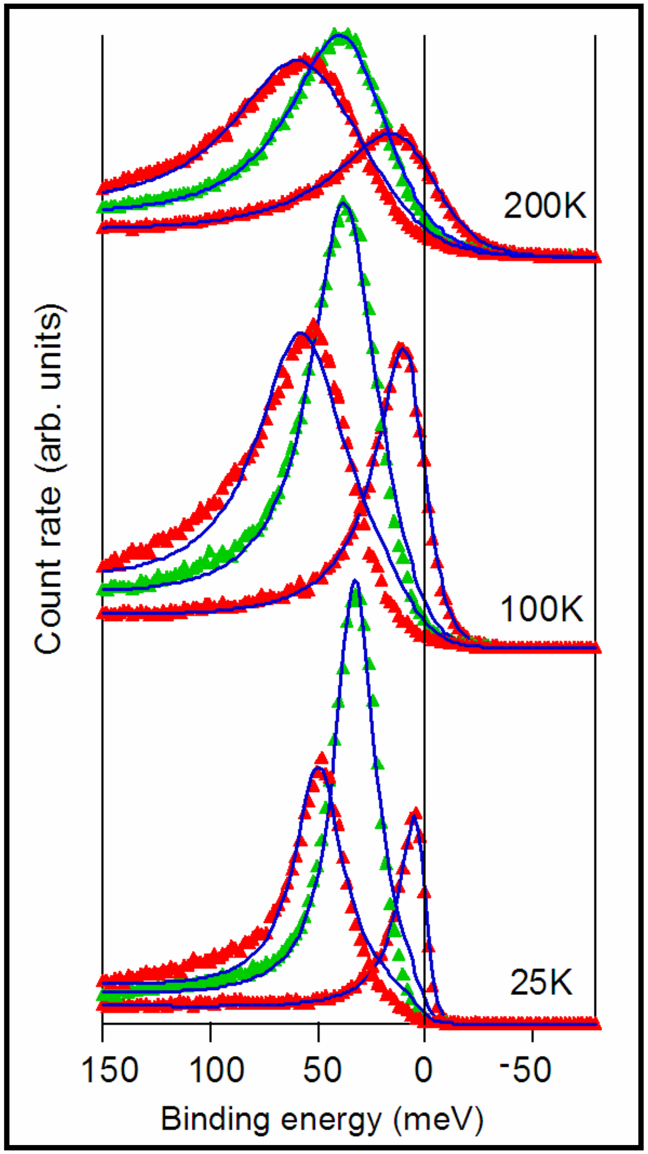
Origin: Electron-electron scattering? Electron-phonon? Electron-impurity?

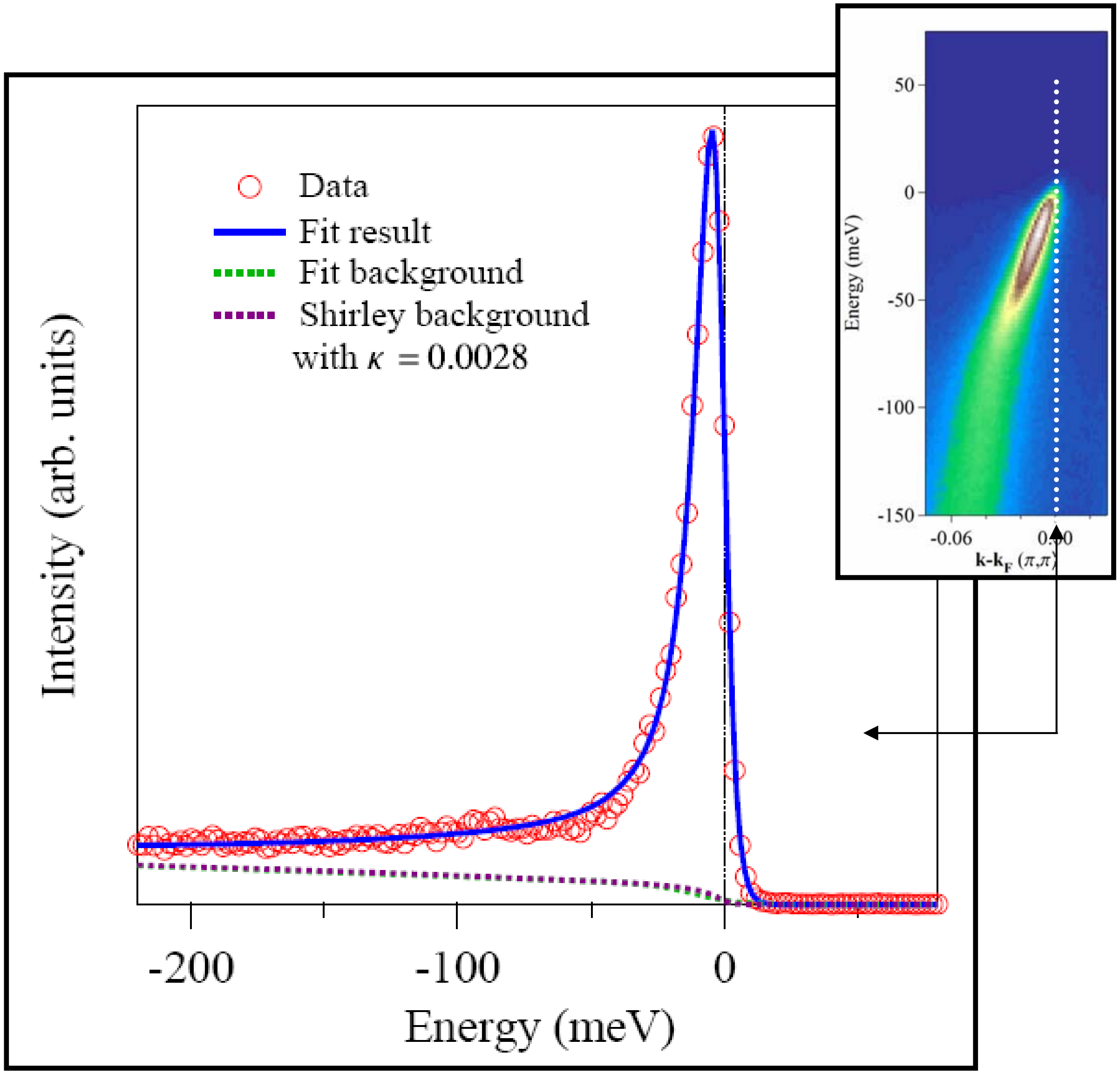
The same mechanisms for scattering also affect other probes (optics, transport, etc.).

Are the interactions responsible for the superconducting pairing?

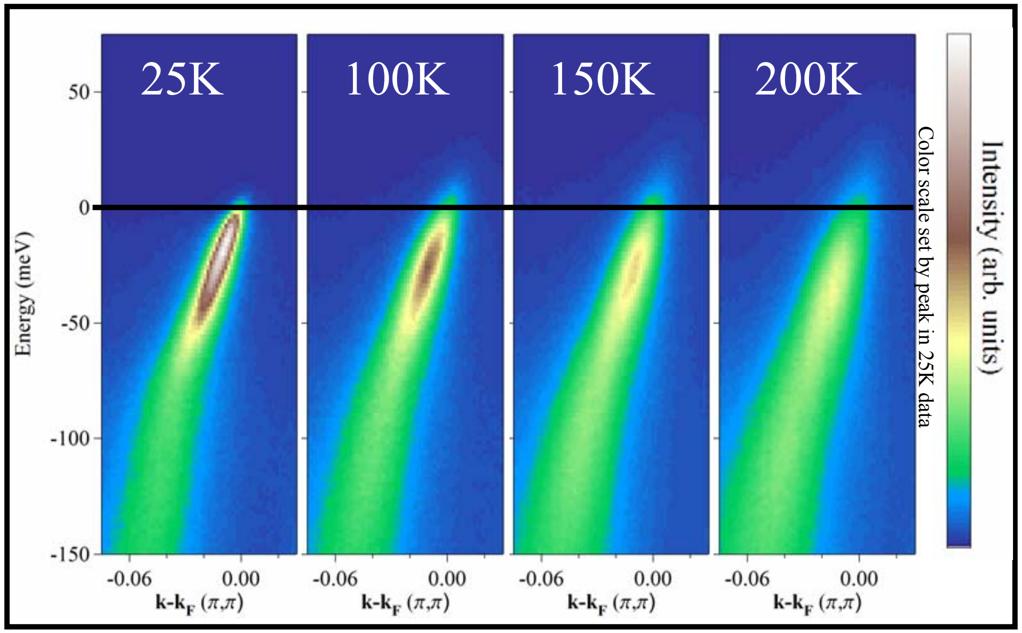
# Lorentzian EDC fitting (nodal OP Bi2212)

**$I_{ARPES}$ = [Lorentzian x Fermi] + Background**



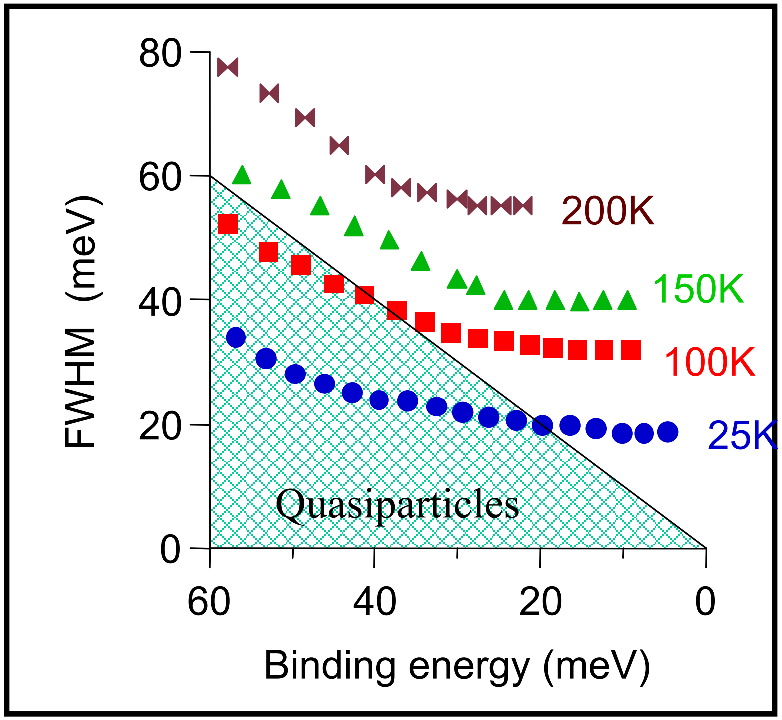


# Nodal Quasiparticles in Bi2212



← Raw data

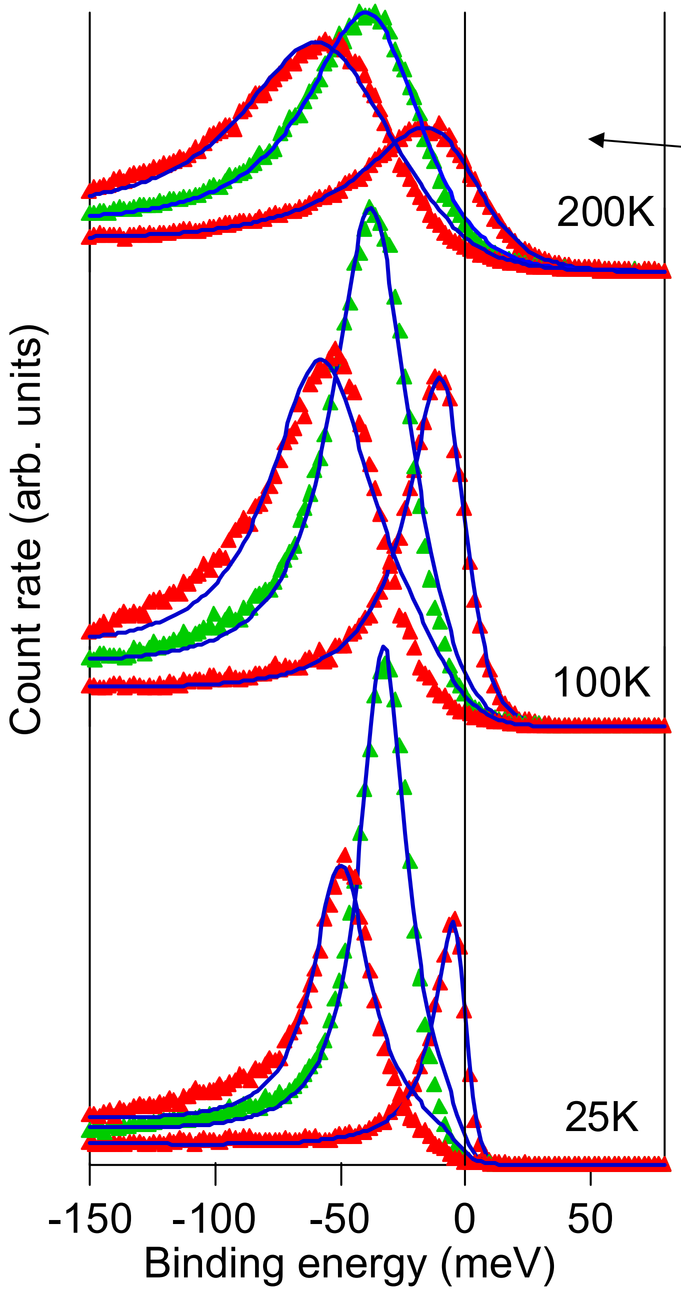
Lorentzian EDC full-widths



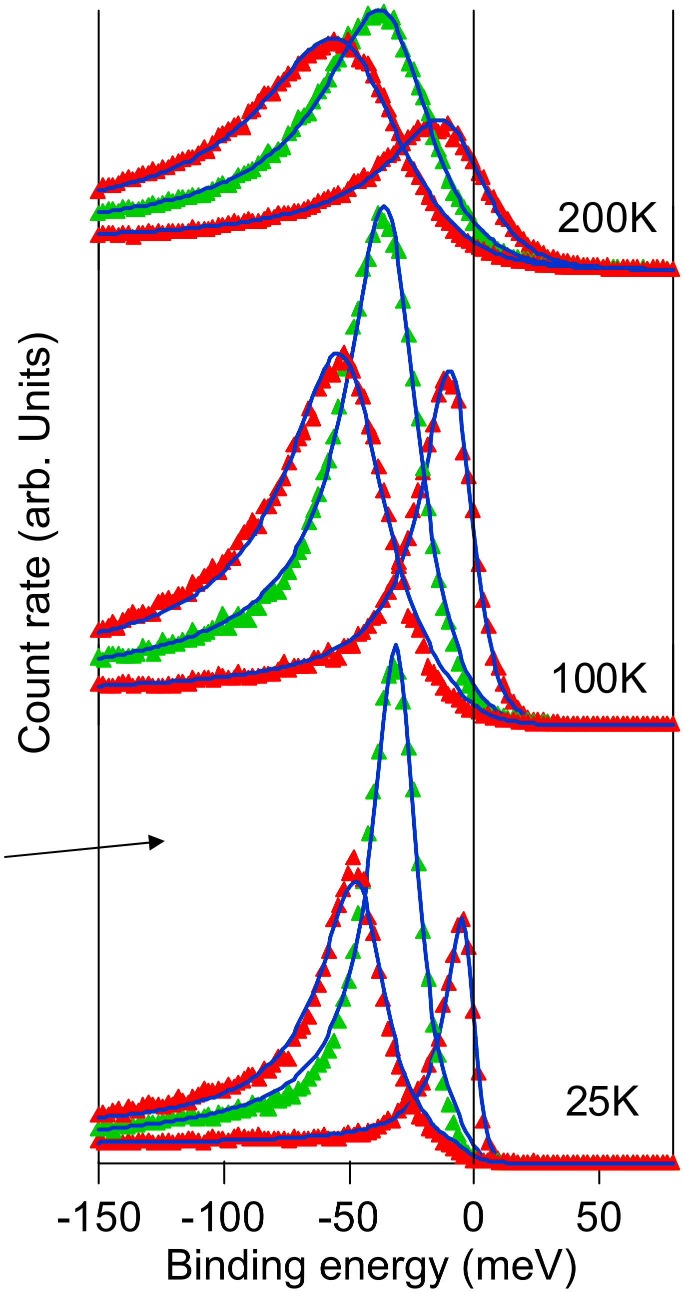
Operational definition of a quasiparticle – spectral peaks that are sharper than their energy

J.D. Koralek *et al. Phys. Rev. Lett.* **96**, 017005 (2006)

# Fermi Liquid lineshape gives improved fits



Lorentzian



Fermi liquid

# Anderson – effect of Gutzwiller projection on ARPES lineshape

$$G(k,\omega) = \iint dx\,dt\, e^{i(kx-\omega t)}\, t^{-p} / (x - v_F t)$$

$p=.25(1-x)^2$ x is doping level

$$Intensity = \mathrm{Im}\{G\} = \mathrm{Im}\{\frac{f(\omega/T)}{[(v_F k - \omega) + i\Gamma]^{1-p}}\}$$

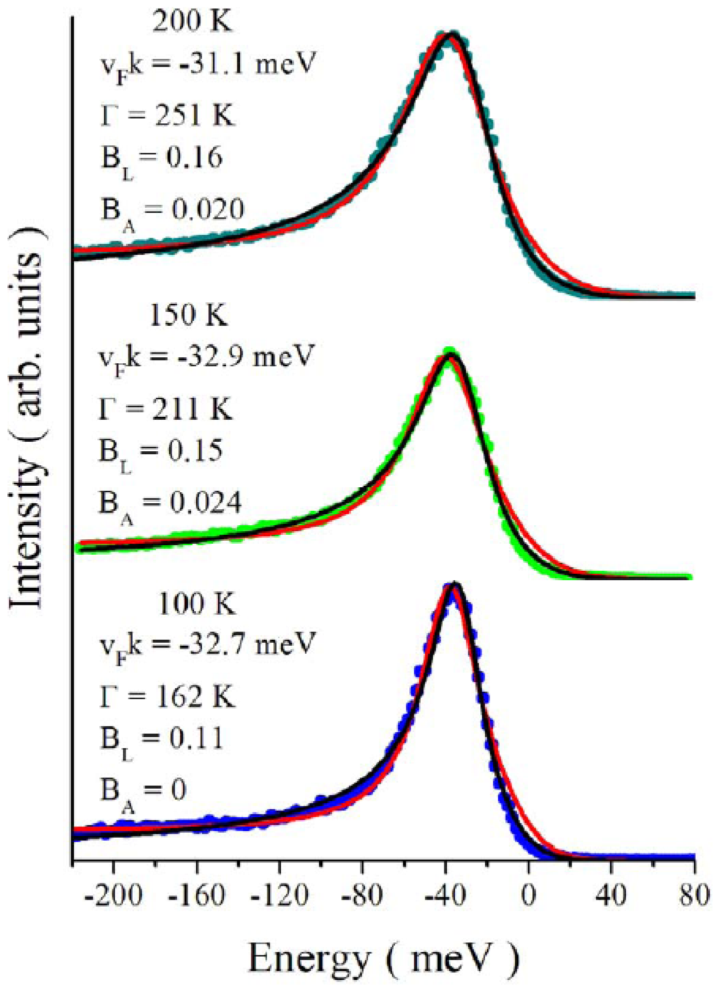
$$= f(\omega/T)\frac{\sin\left[(1-p)\cot^{-1}([\omega - v_F k]/\Gamma)\right]}{[(\omega - v_F k)^2 + (\Gamma)^2]^{(1-p)/2}}$$

$$f = 1/(1+e^{\hbar\omega/k_B T})$$

Main empirical difference to FL: reduced background

Red – Lorentzian

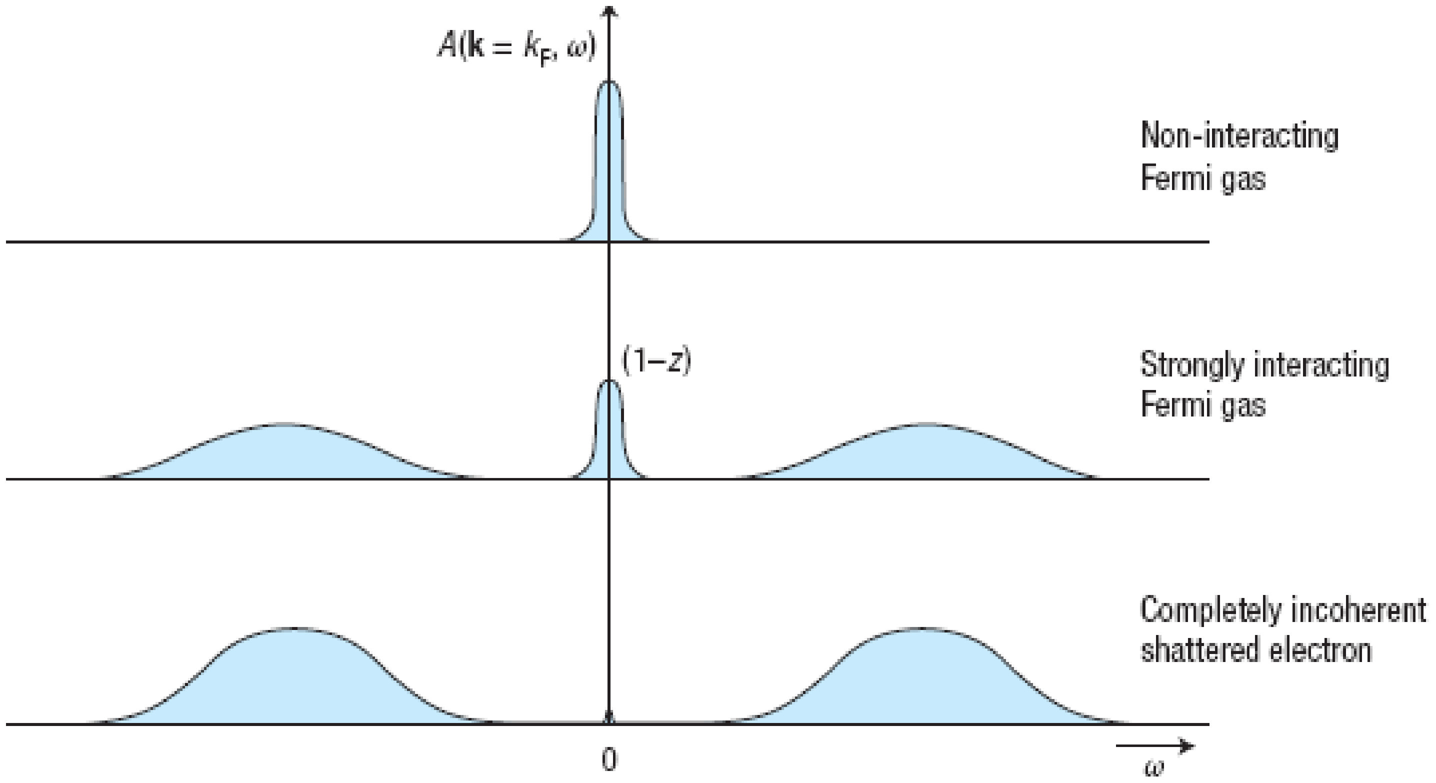
Black – Gutzwiller projected



P.A. Casey, J.D. Koralek, N.C. Plumb, D.S. Dessau, P.W. Anderson, Nature Physics **4**, 210 (2008)

## SUPERCONDUCTORS

# The electron shatters



Nandini Trivedi
**is in the Department of Physics, Ohio State University, 191 West Woodruff Avenue, Columbus, Ohio 43210, USA.**
**e-mail: trivedi.15@osu.edu**

# Coherent vs. Incoherent states

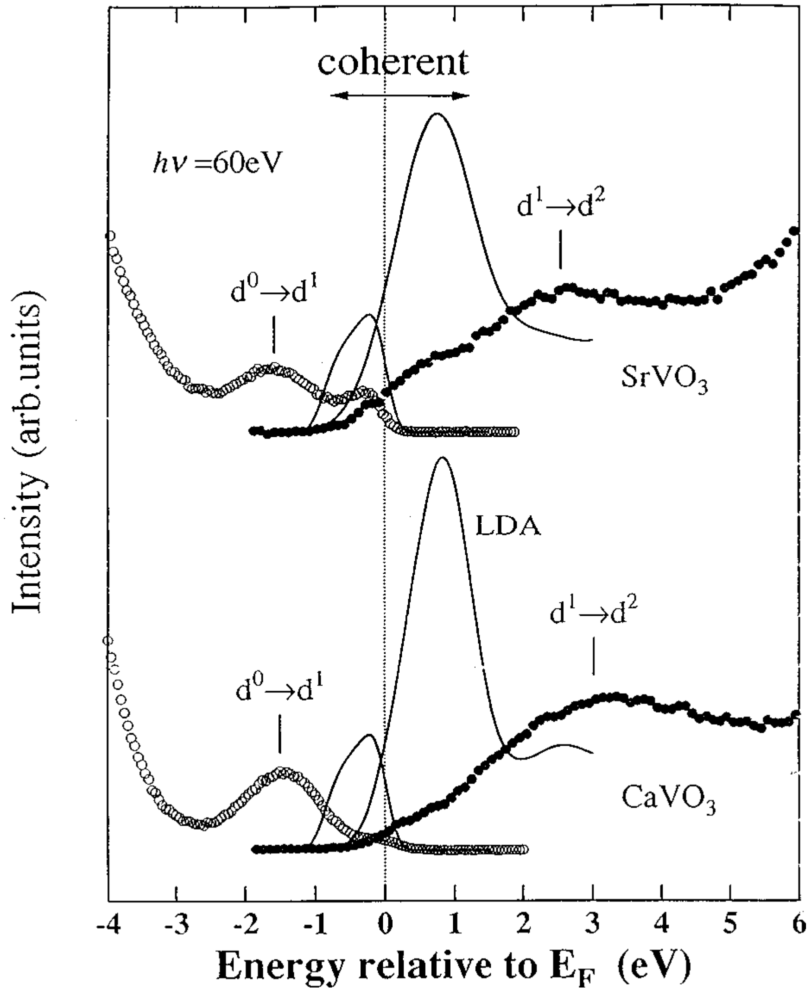
Different operational meanings for a coherent state.

a) A true Landau quasiparticle

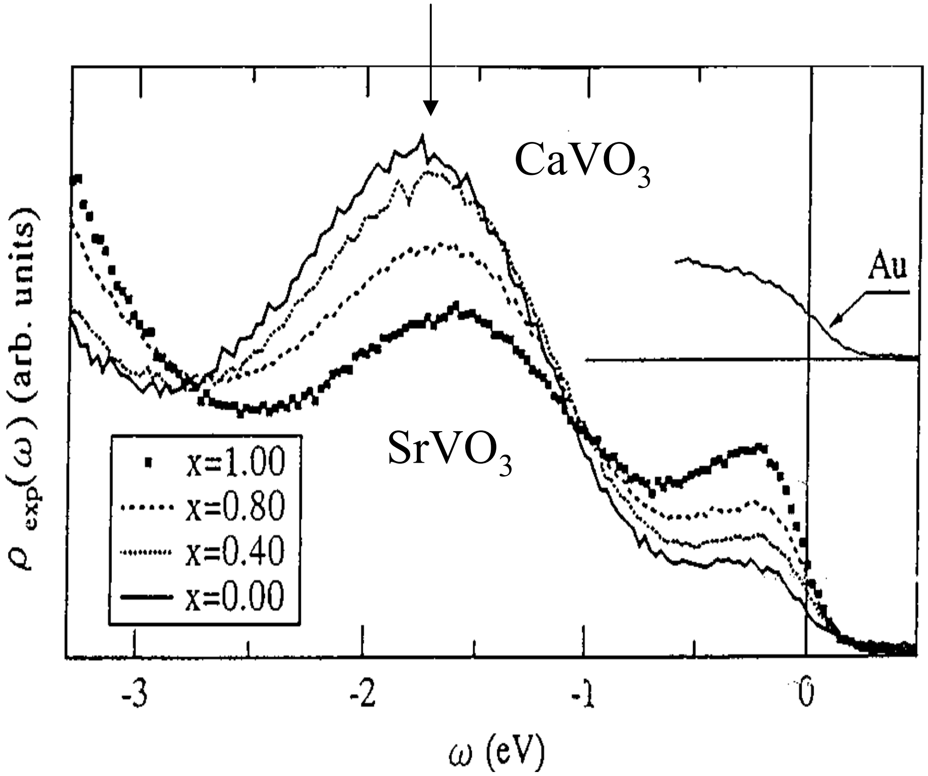
b) A “sharp” spectral peak near $E_F$.

c) A dispersive spectral peak, even if it is broad.

# Bandwidth control $d^1$ system – varying U/W ratio



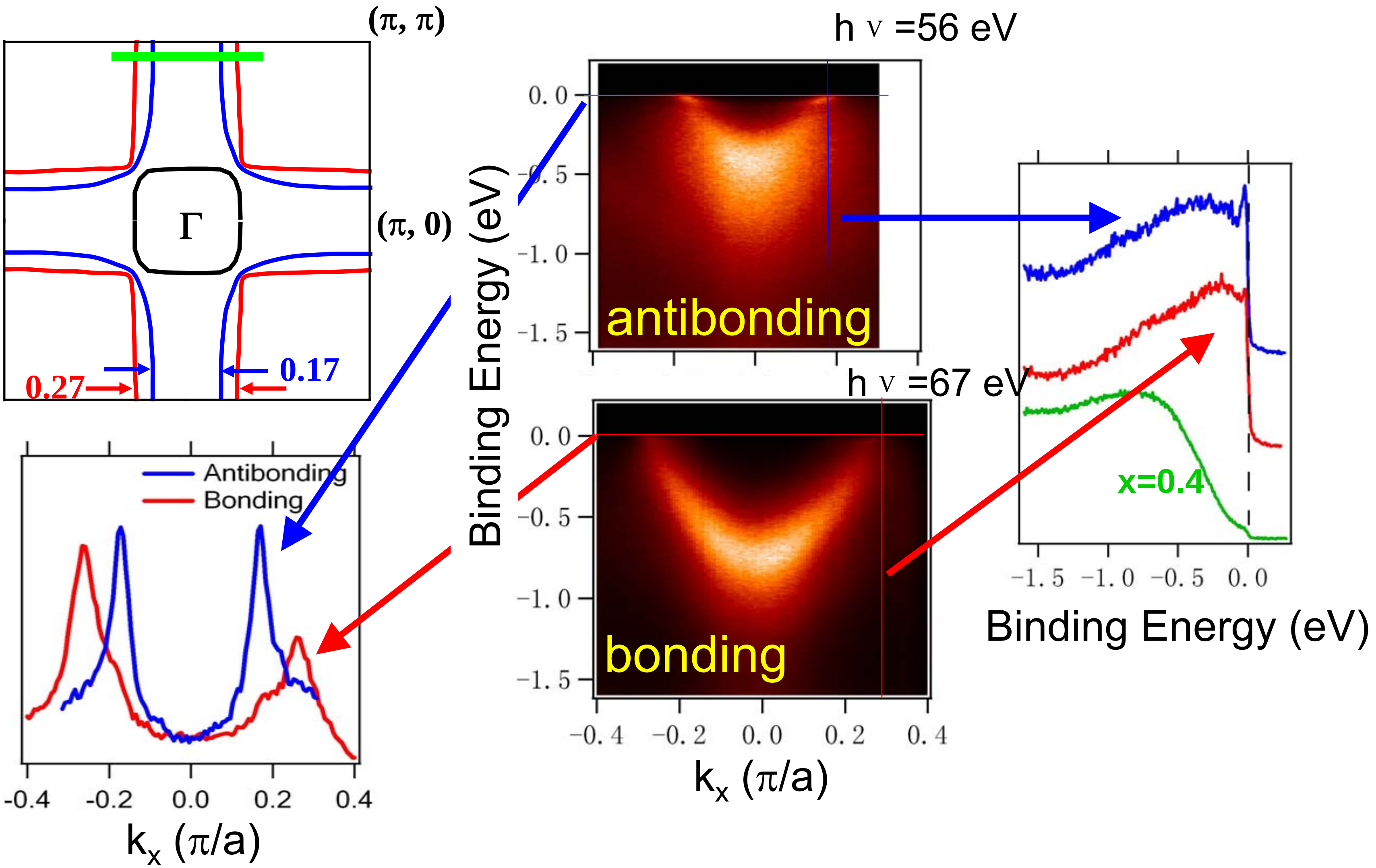
Photoemission and inverse-photoemission spectra of $SrVO_3$ and $CaVO_3$ in the V 3*d* band region compared with a LDA band-structure calculation of Takegahara (1994). From Morikawa *et al.*, 1995.



d1→d0
Lower Hubbard band or incoherent portion

Angle-integrated photoemission spectra of $Ca_{1-x}Sr_xVO_3$ (Inoue *et al.*, 1995)

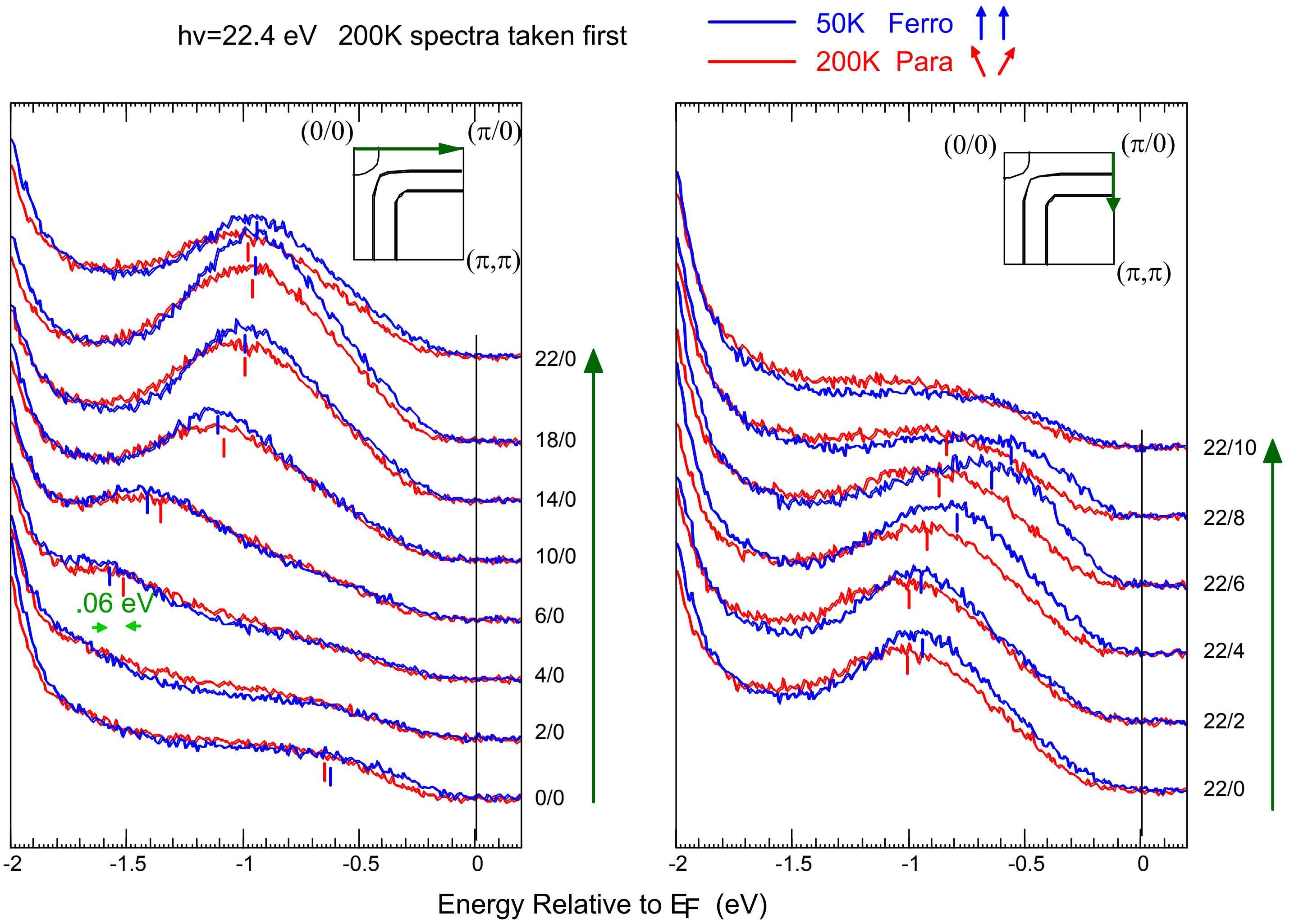
# Bi-layer split band structure in x=0.36, 0.38 compounds



Different photon energies are utilized to pick up the A and B bands.

Z. Sun et al., Phys. Rev. Lett. 97, 056401 (2006

# Temperature dependence of (LaSr)$Mn_2O_7$ x=.4 $T_c$ ~ 130K


hv=22.4 eV 200K spectra taken first

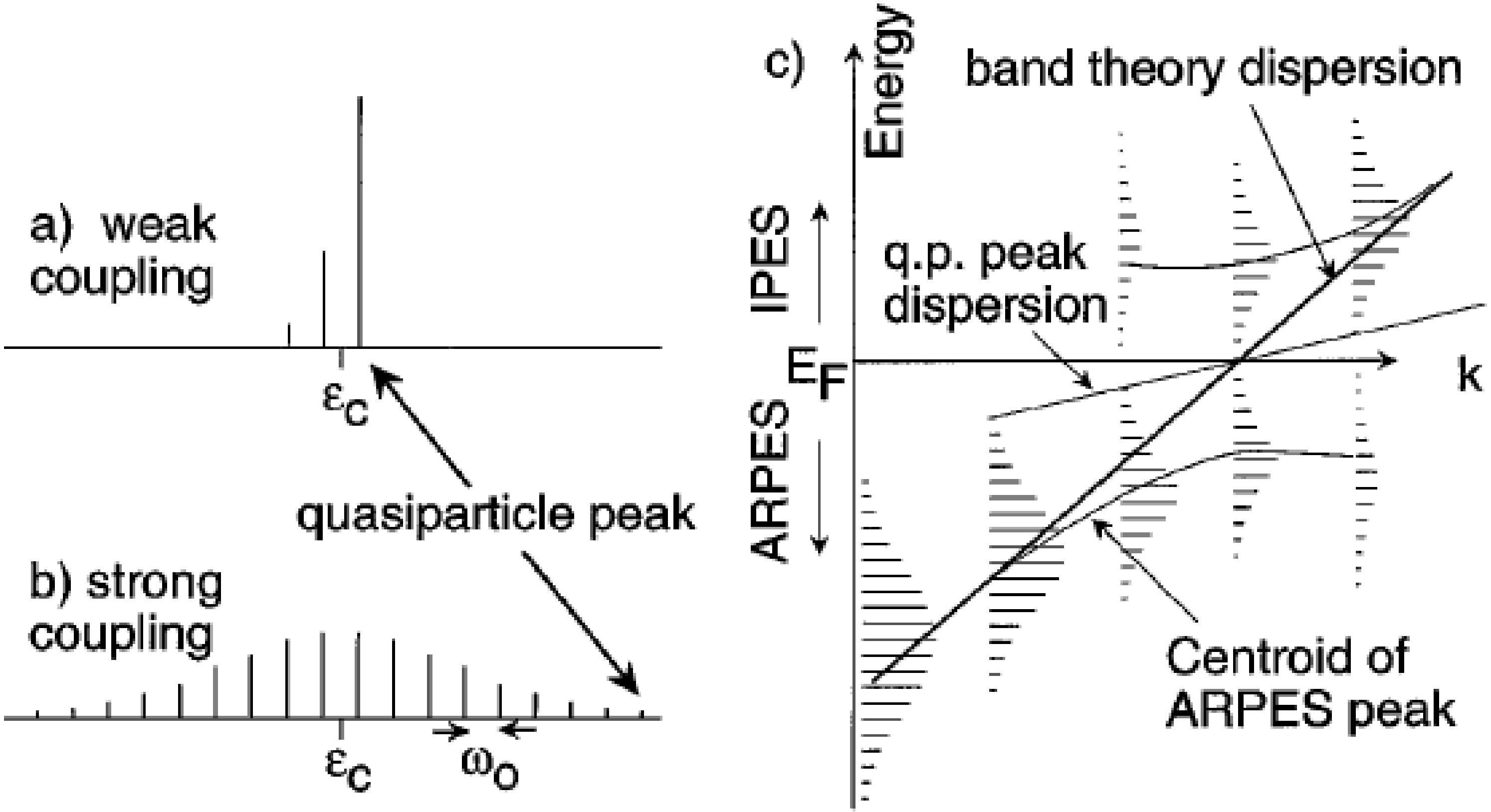
Bandwidth change : .06 eV/1.5 eV = 4%. Much less than the DE prediction of 30%.
==> DE relevant but not key effect.

T. Saitoh et al., PRB (2000)

VOLUME 81, NUMBER 1 PHYSICAL REVIEW LETTERS 6 JULY 1998

# *k*-Dependent Electronic Structure, a Large "Ghost" Fermi Surface, and a Pseudogap in a Layered Magnetoresistive Oxide

D. S. Dessau,[1] T. Saitoh,[1,*] C.-H. Park,[2] Z.-X. Shen,[2] P. Villella,[1] N. Hamada,[3,†] Y. Moritomo,[3,‡] and Y. Tokura[3]

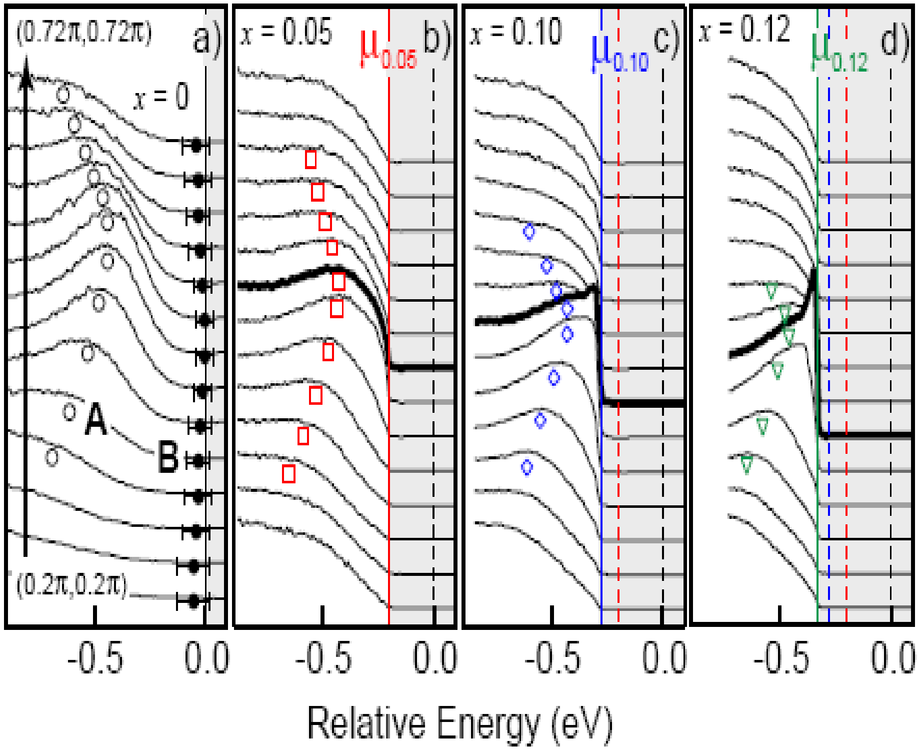


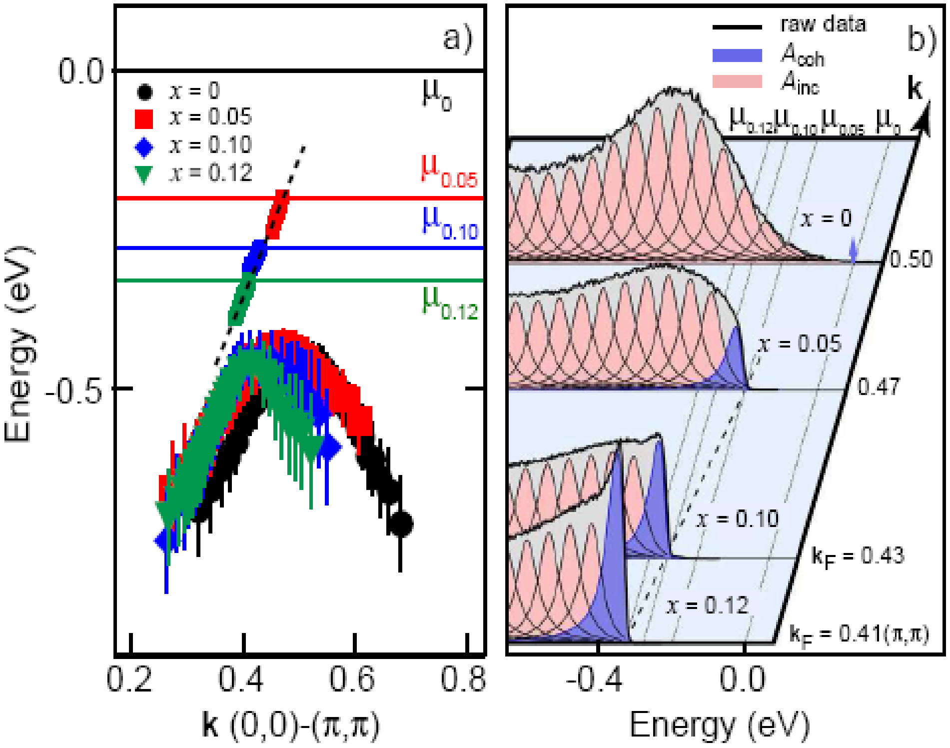
PRL **93,** 267002 (2004) PHYSICAL REVIEW LETTERS week ending 31 DECEMBER 2004

# Missing Quasiparticles and the Chemical Potential Puzzle in the Doping Evolution of the Cuprate Superconductors

K. M. Shen,[1] F. Ronning,[1,*] D. H. Lu,[1] W. S. Lee,[1] N. J. C. Ingle,[1] W. Meevasana,[1] F. Baumberger,[1] A. Damascelli,[1,†]
N. P. Armitage,[1,‡] L. L. Miller,[2] Y. Kohsaka,[3] M. Azuma,[4] M. Takano,[4] H. Takagi,[3] and Z.-X. Shen[1]

$Ca_{2-x}Na_xCuO_2Cl_2$

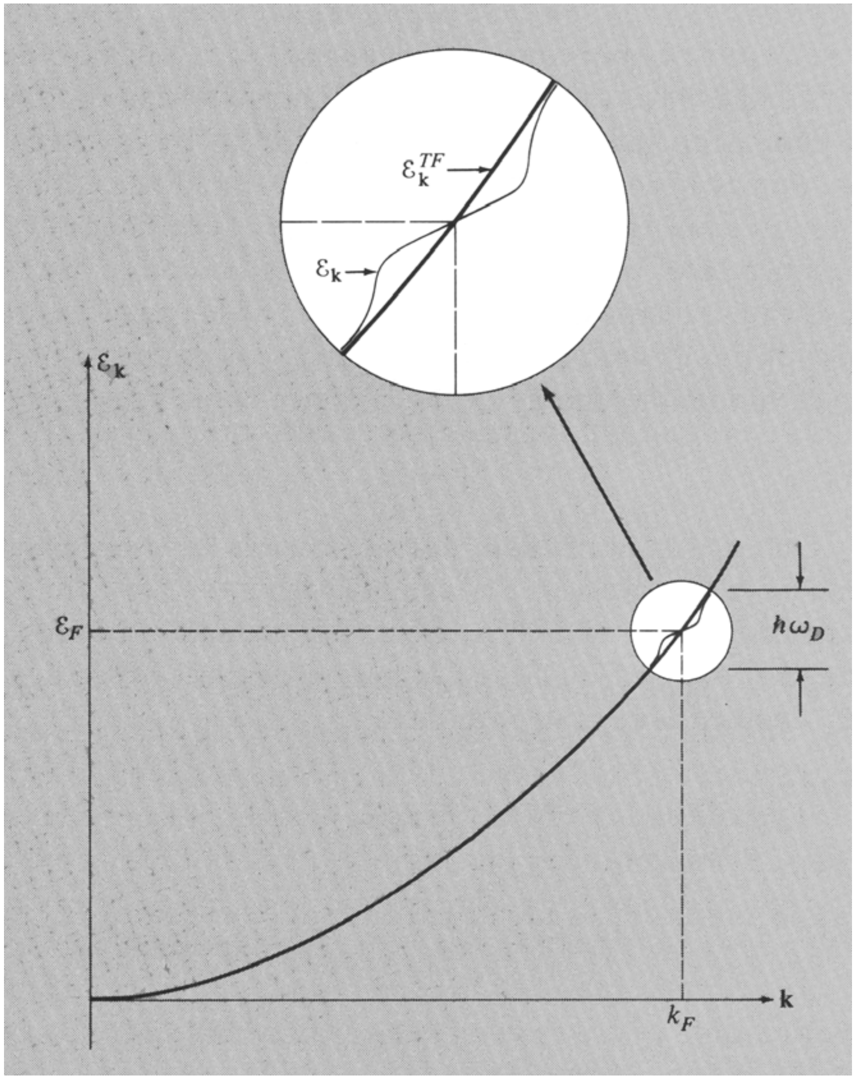




Q: If qp weight Z is strongly doping dependent, why is qp mass ~ constant with doping?

# Changes in the carrier mass due to electron-phonon (or other electron-boson) coupling only affects the near-$E_F$ states

From Ashcroft and Mermin, Solid State Physics,1976



VOLUME 83, NUMBER 10 PHYSICAL REVIEW LETTERS 6 SEPTEMBER 1999

# Many-Body Effects in Angle-Resolved Photoemission: Quasiparticle Energy and Lifetime of a Mo(110) Surface State

T. Valla,[1] A. V. Fedorov,[1] P. D. Johnson,[1] and S. L. Hulbert[2]

$$A(\mathbf{k},\omega) \propto \frac{\mathrm{Im}\Sigma(\mathbf{k},\omega)}{[\omega-\varepsilon_{\mathbf{k}}-\mathrm{Re}\Sigma(\mathbf{k},\omega)]^2+[\mathrm{Im}\Sigma(\mathbf{k},\omega)]^2}$$

“spectral function” = ARPES weight (k,ω)

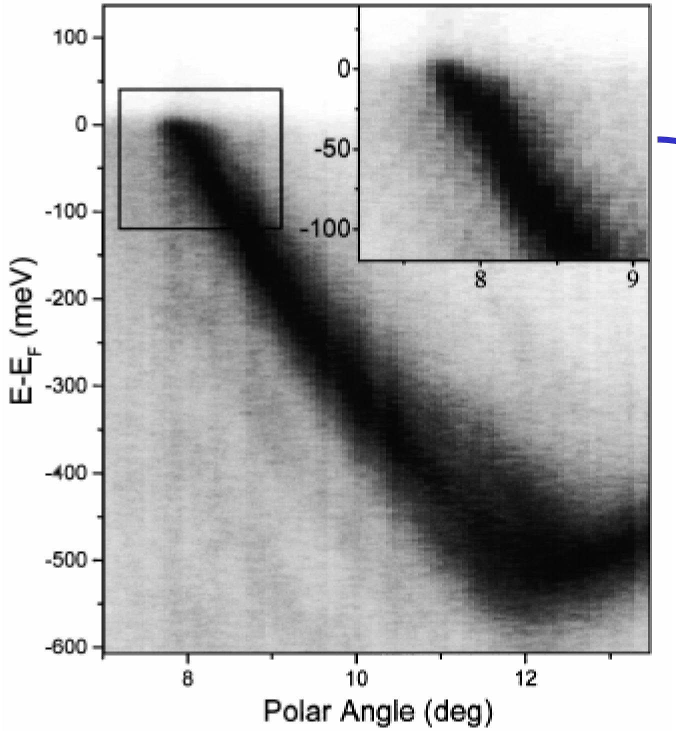
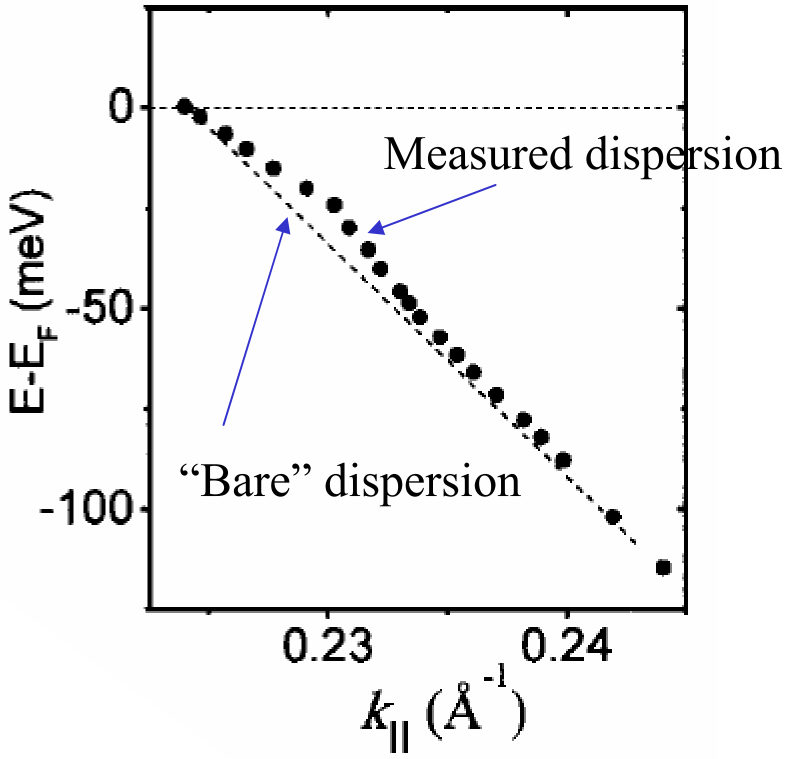


FIG. 1. ARPES intensity plot of the Mo(110) surface recorded along the $\overline{\Gamma}$-$\overline{N}$ line of the surface Brillouin zone at 70 K. Shown in the inset is the spectrum of the region around $k_F$ taken with special attention to the surface cleanliness.



Measured dispersion

“Bare” dispersion

“Kink effect”

VOLUME 83, NUMBER 10 PHYSICAL REVIEW LETTERS 6 SEPTEMBER 1999

## Many-Body Effects in Angle-Resolved Photoemission: Quasiparticle Energy and Lifetime of a Mo(110) Surface State

T. Valla,[1] A. V. Fedorov,[1] P. D. Johnson,[1] and S. L. Hulbert[2]

$$A(\mathbf{k},\omega) \propto \frac{\mathrm{Im}\Sigma(\mathbf{k},\omega)}{[\omega - \varepsilon_{\mathbf{k}} - \mathrm{Re}\Sigma(\mathbf{k},\omega)]^2 + [\mathrm{Im}\Sigma(\mathbf{k},\omega)]^2}$$

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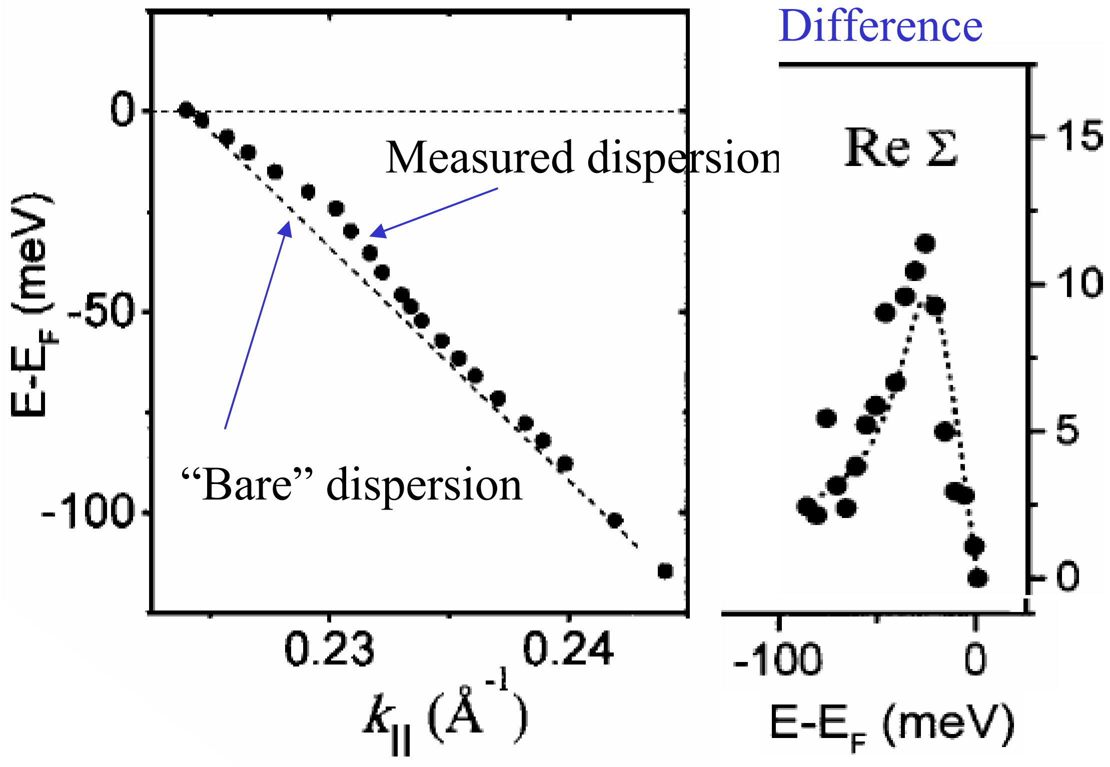


Measured dispersion

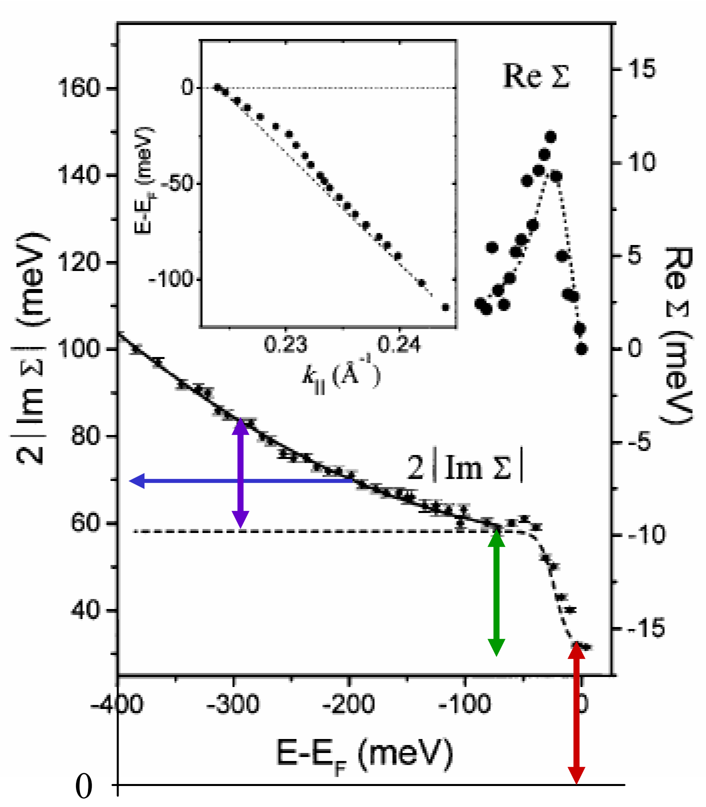
"Bare" dispersion

A(k,ω) peaks when $[\omega-\varepsilon_k-\mathrm{Re}\Sigma]=0$
or when
$\omega=\varepsilon_k+\mathrm{Re}\Sigma$
Bare band: ReΣ=0
Measured: ReΣ=finite.

Σ = electron "self energy". Here the "kink" is due to electron-phonon scattering. (Phonon lives at kink scale or ~ 30 meV).

$$A(\mathbf{k},\omega) \propto \frac{\mathrm{Im}\Sigma(\mathbf{k},\omega)}{[\omega - \varepsilon_{\mathbf{k}} - \mathrm{Re}\Sigma(\mathbf{k},\omega)]^2 + [\mathrm{Im}\Sigma(\mathbf{k},\omega)]^2}$$

FWHM of quasiparticle peak



ImΣ = width of spectral peak
Measurable in the same spectra.

ImΣ and ReΣ related through Kramers-Kronig relations.

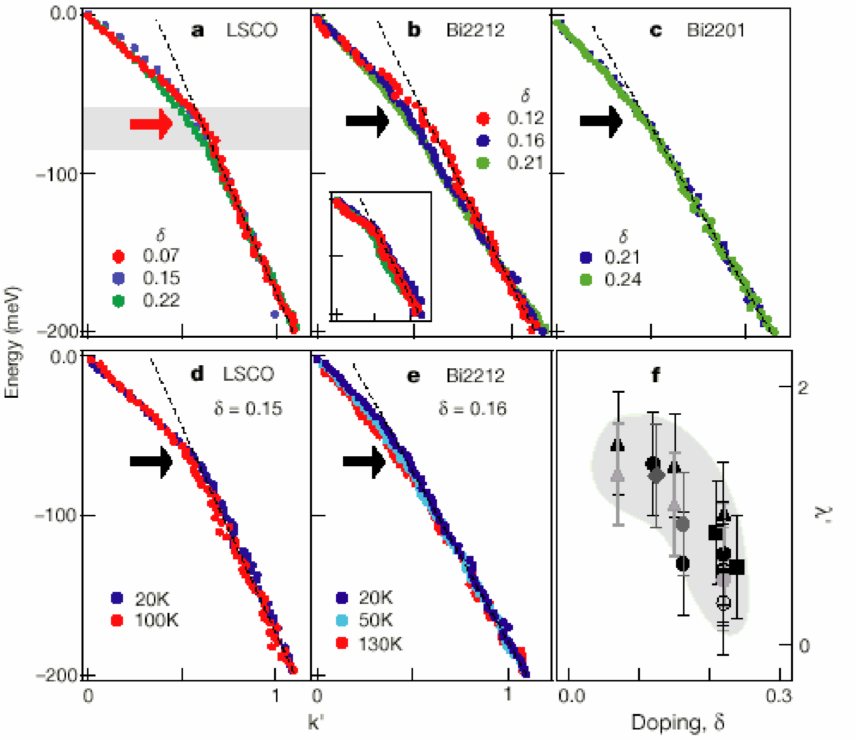
Electron-electron scattering

Coupling to phonons

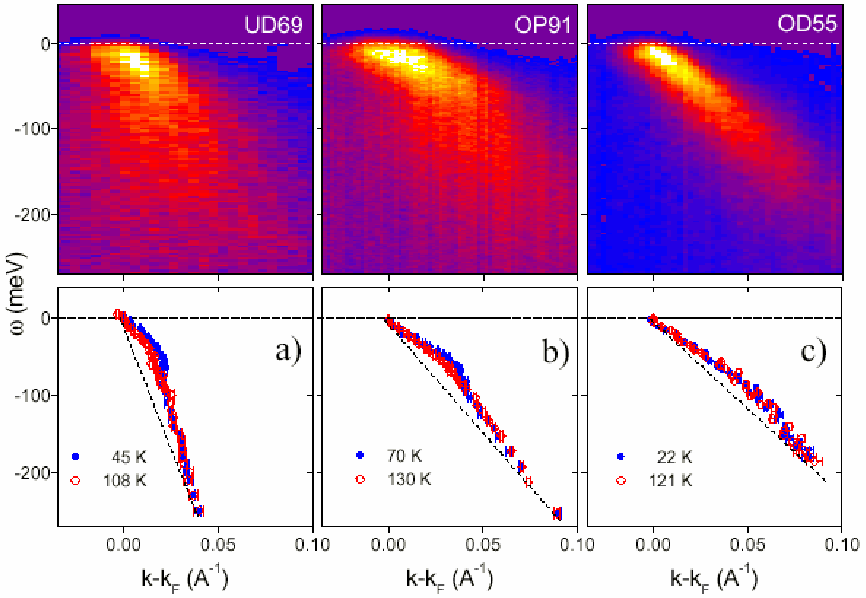
Impurities, finite resolution, final state effects, etc.

# Recent ARPES results - kinks in HTSC’s (π,π) direction (nodal direction of d-wave gap)

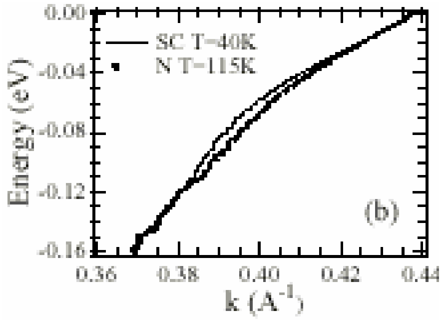
Stanford Group
Lanzara et al.
Nature **412**,510 (2001)



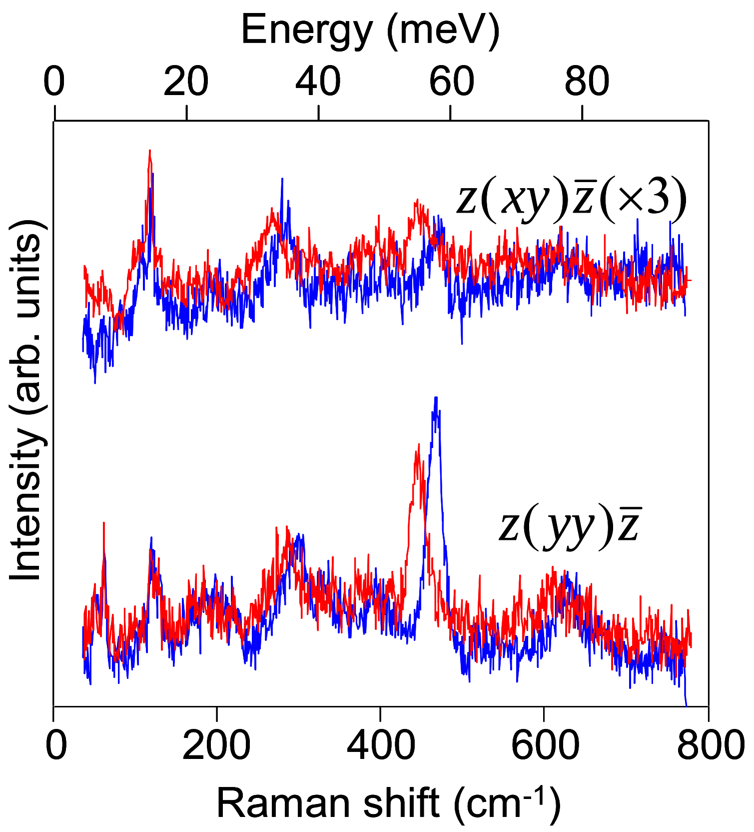
Brookhaven Group
Johnson et al.
*cond-mat*/0102260 (2001).



Argonne Group
Kaminski et al.
PRL **86**, 1070 (2001)



# Isotope substitutions in Bi2212
# Way to fingerprint a mode coupling as phonon originated or not



🟦 $^{16}O$

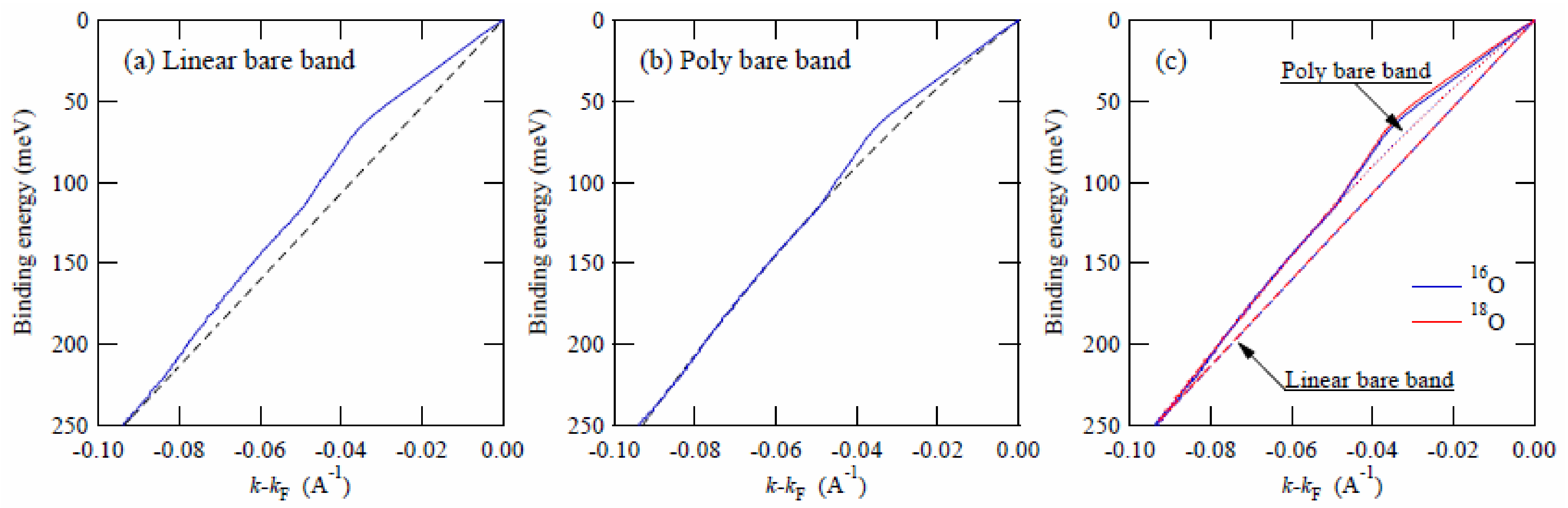
🟥 $^{18}O$

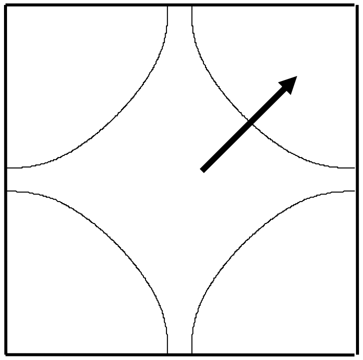
Throughout this presentation

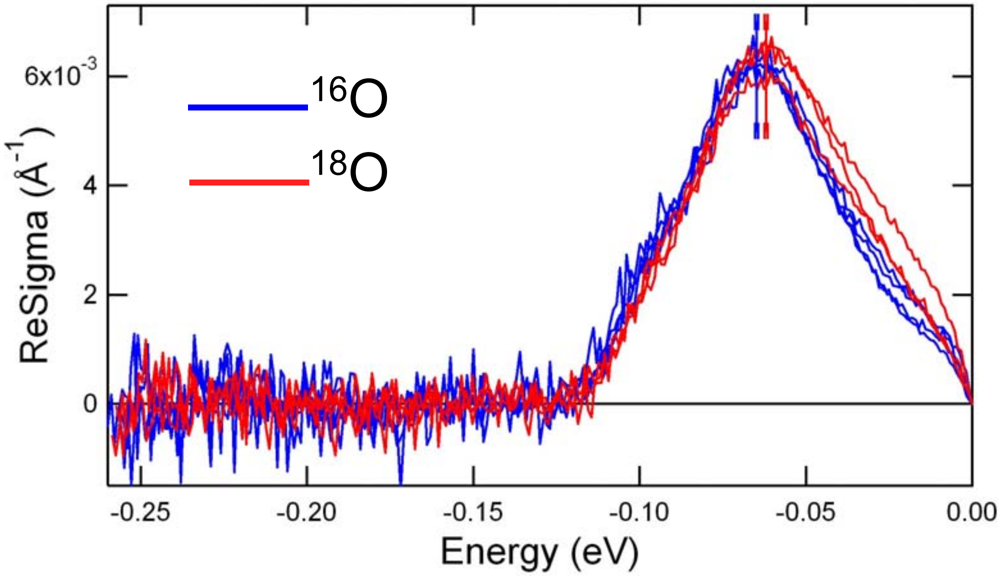
**Raman on our samples:**
- **near full substitution of $^{18}O$ for $^{16}O$**
- **~ 3 meV softening with substitution**

**-Same samples as used by J.Lee and J.C. Davis for isotope studies using STM**

# Search for a low energy scale (few meV) shift of the nodal kink



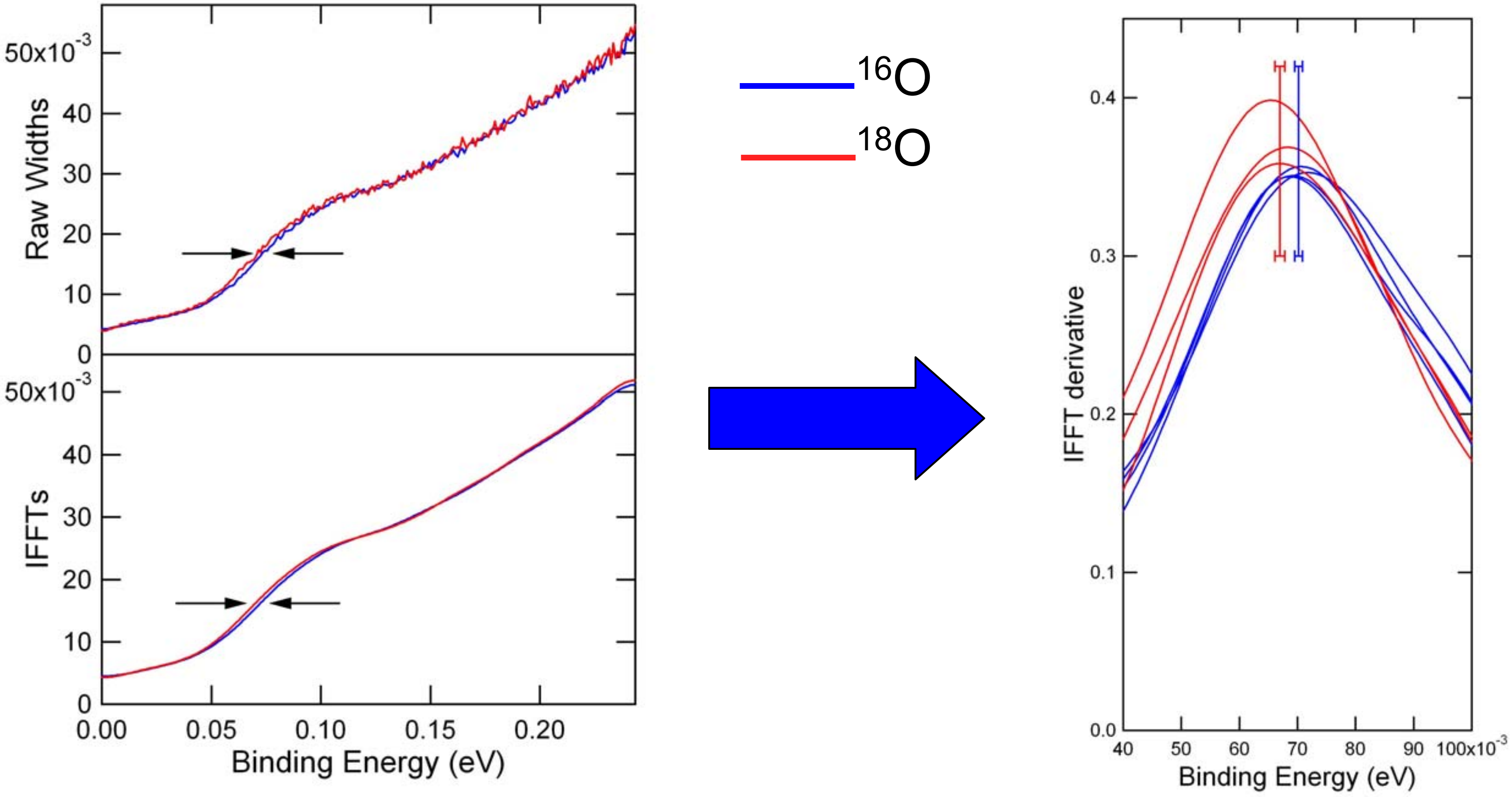




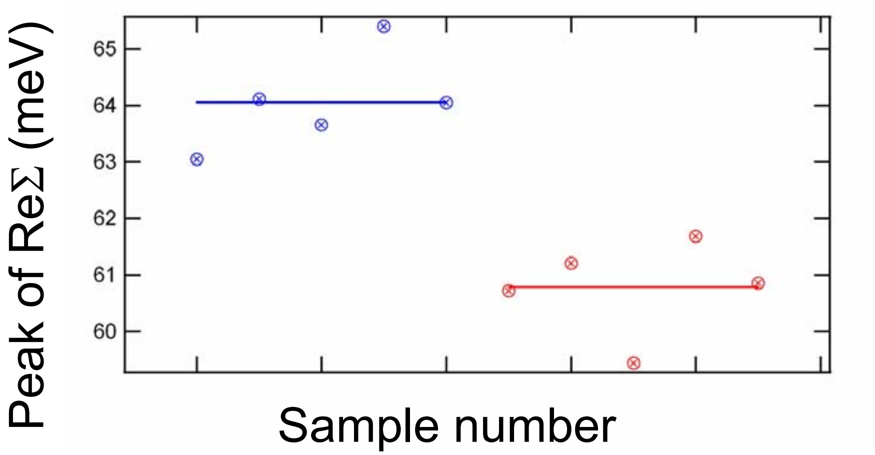
# Search for a low energy scale (few meV) shift of the kink, version 2

## Kink energy analysis method for ARPES widths (ImΣ)

a) Using ARPES widths (ImΣ), no assumed background is needed
b) Take derivative to try to find a well-defined peak



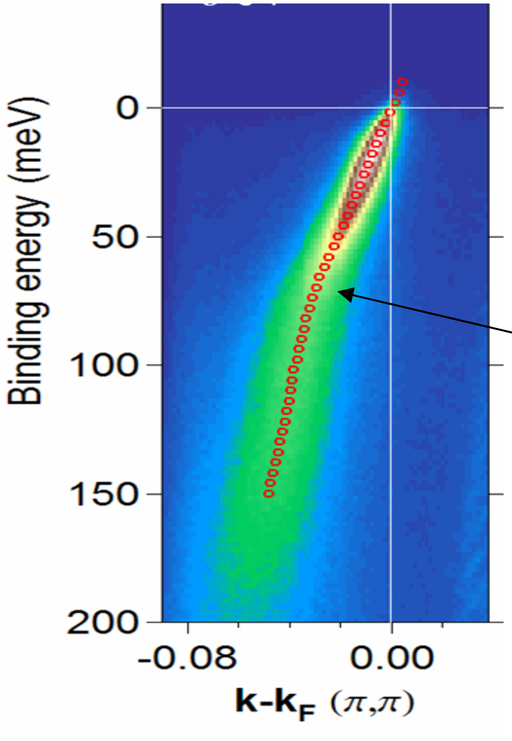
# Isotope Effect: Two methods, consistent results



$^{16}$O

$^{18}$O

Kink softening of 3.4 ± 0.5 meV



Nodal kink positively fingerprinted as originating from electron-phonon coupling.

H. Iwasawa, J.F. Douglas et al., (submitted)

# Superconducting order parameter symmetry

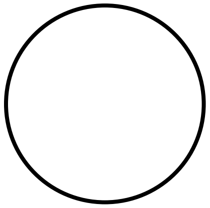
SC gap Δ = magnitude of order parameter. Varies as a function of k in a d-wave SC

$$\underline{\Psi(r1,\sigma1;r2,\sigma2)=\psi(\text{orbital})\bullet\chi(\text{spin})}$$

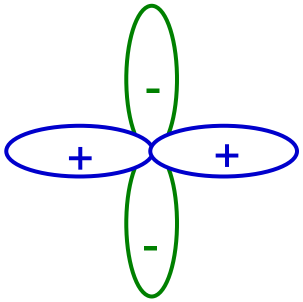
Antisymmetric under exchange

$\chi$(spin) : known to be a singlet (S=0) ↓↑

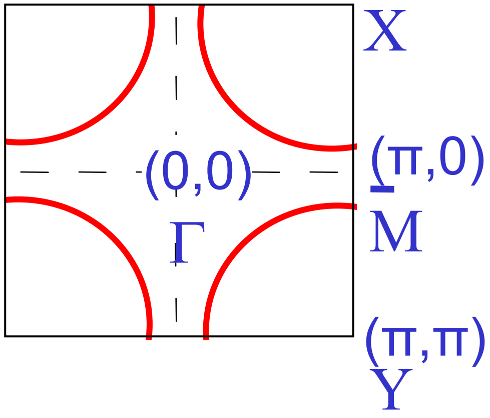
S = 0, l = 0
-- s-wave superconductor
(conventional SC)



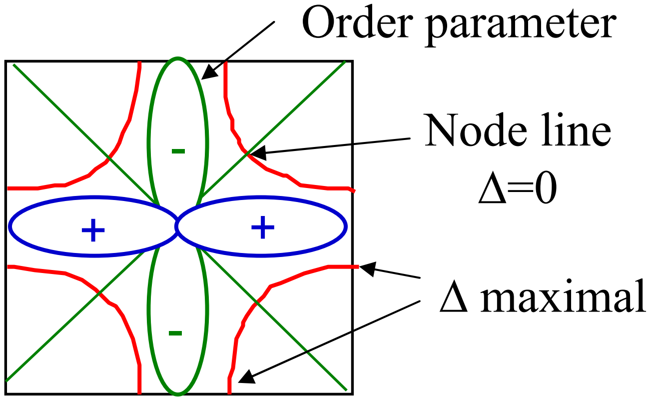
S = 0, l = 2
-- d-wave superconductor
(HTSCs - pretty sure)



Hole-like Fermi Surface



d-wave SC gap - maximal near (π,0)



Order parameter

Node line
Δ=0

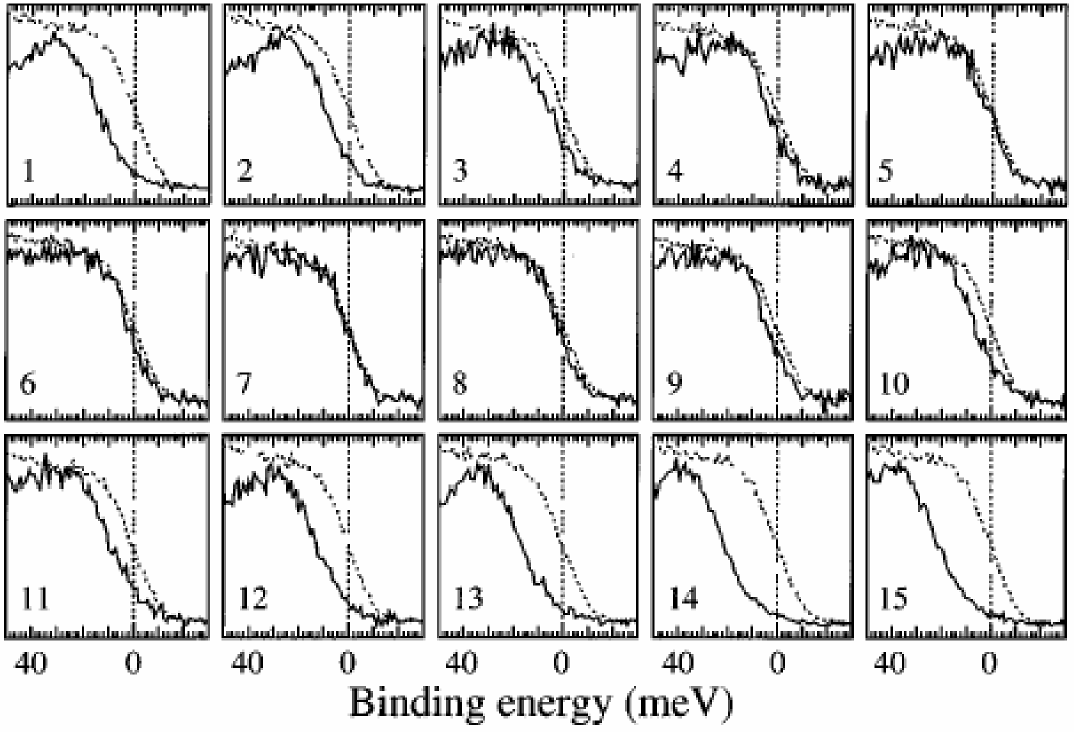
Δ maximal

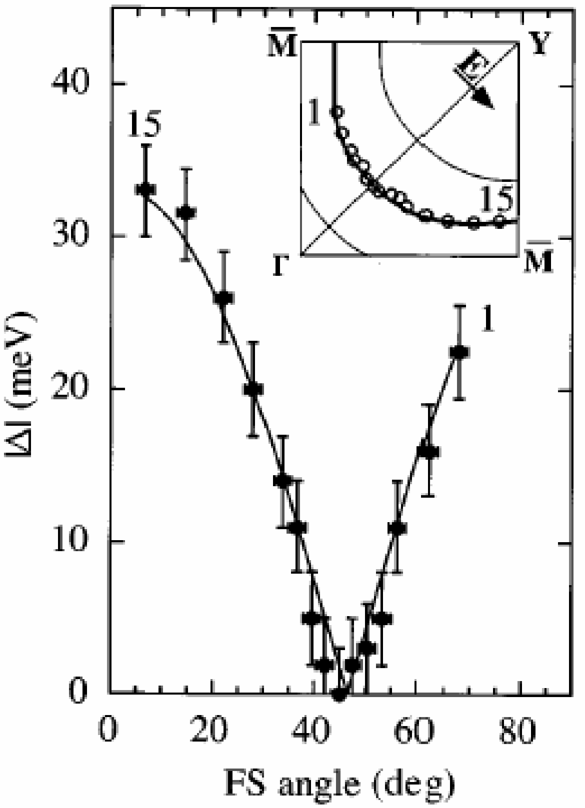
Z-X Shen, D.S. Dessau et al,
PRL **70**, 1553 (1993).

PHYSICAL REVIEW B VOLUME 54, NUMBER 14 1 OCTOBER 1996-II

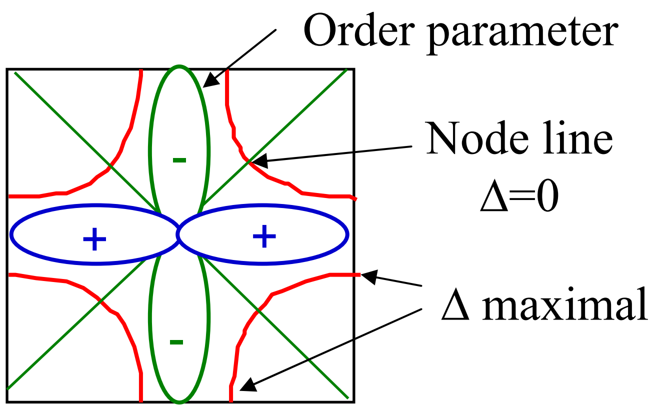
# Angle-resolved photoemission spectroscopy study of the superconducting gap anisotropy in $Bi_2Sr_2CaCu_2O_{8+x}$

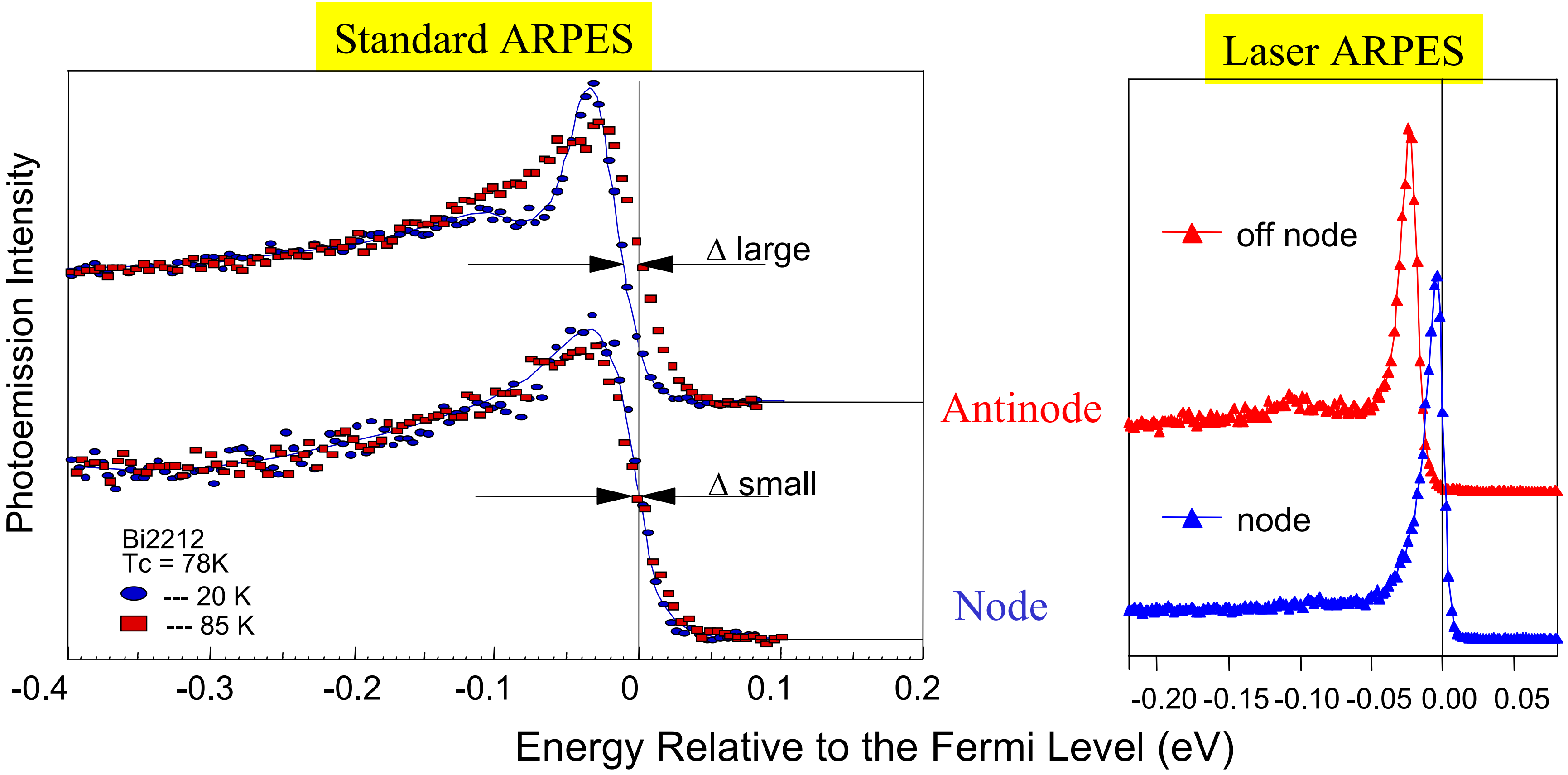
H. Ding, M.R. Norman, J.C. Campuzano, et al.





# k-space dependence of superconducting energy gap Δ →Symmetry of Cooper pair wavefunction is d-wave ($\ell$=2)





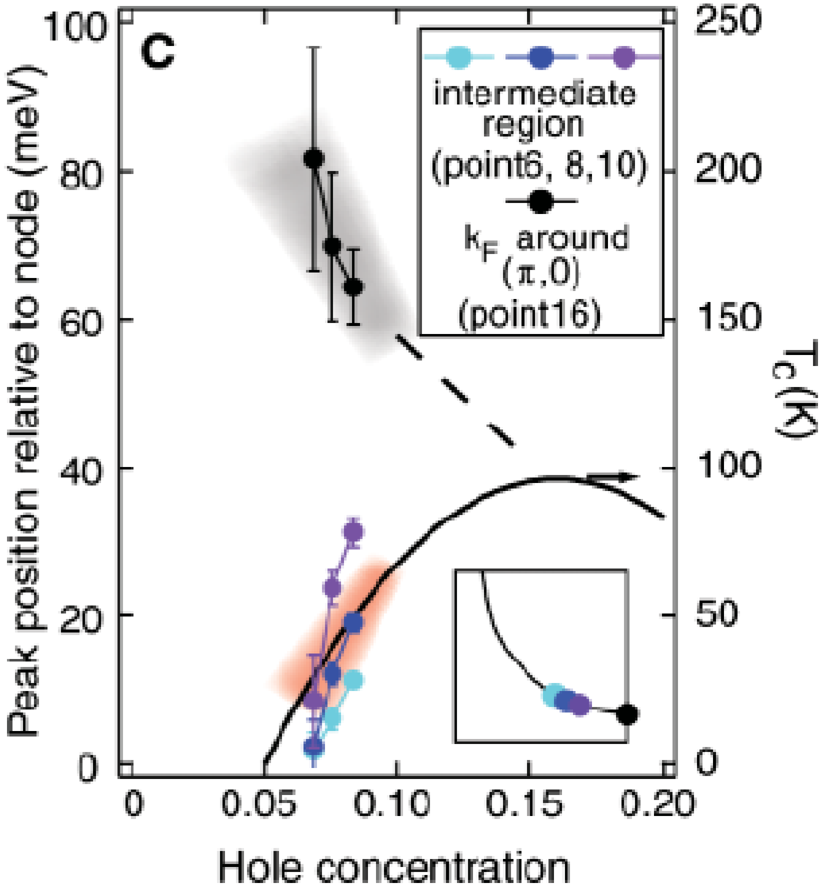
Z.-X. Shen, D.S.D. et al.,
Phys. Rev. Lett. **70** , 1553 (1993)

J.D. Koralek, D.S.D. et al.,
Phys. Rev. Lett. **96** , 017005 (2006)

# Distinct Fermi-Momentum–Dependent Energy Gaps in Deeply Underdoped Bi2212

Kiyohisa Tanaka,[1,2] W. S. Lee,[1] D. H. Lu,[1] A. Fujimori,[3] T. Fujii,[4] Risdiana,[5] I. Terasaki,[5]
D. J. Scalapino,[6] T. P. Devereaux,[7,8] Z. Hussain,[2] Z.-X. Shen[1]*

22 DECEMBER 2006 VOL 314 **SCIENCE** www.sciencemag.org



Possibility of two gaps:

a) Near node – opens at Tc, gap size tracks Tc

b) At antinode (the pseudogap) – stays open above Tc (to T*)

Competition or cooperation?