Angle Resolved Photoemission Spectroscopy

Dan Dessau
University of Colorado, Boulder
Dessau@Colorado.edu

ARPES for studies of superconductivity.

Measurements of

- Band structures (E vs. k), Fermi surfaces, and orbital symmetries.
  - Particularly important for correlated electron systems where band theory has limited applicability
- Superconducting gaps as a function of k, T, doping
- Pseudogaps as a function of k,T, doping
- Self-energy effects/dynamics (many-body interactions, electron-electron, electron-boson) as a function of k, T, doping
- Non-equilibrium physics using ultrafast pump-probe ARPES

Compared to other spectroscopies:

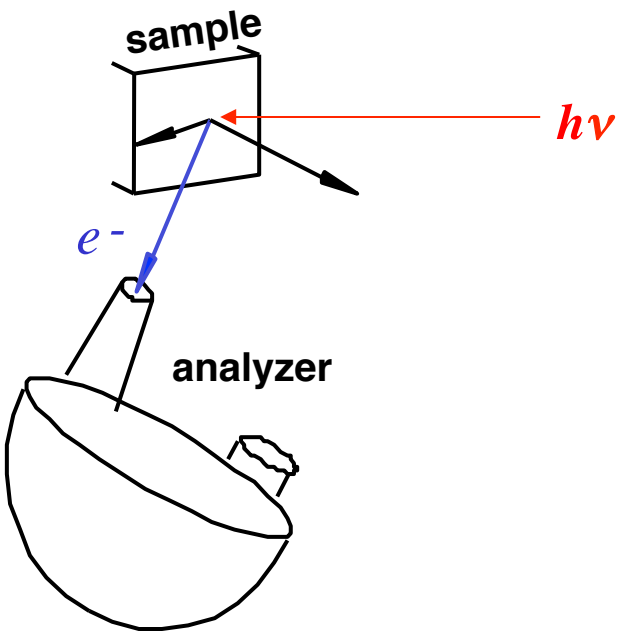
- The k resolution is unique. Arguably the most direct of all spectroscopies.
- Surface sensitive. Requires high quality surfaces for studies of "bulk" physical effects. Laser-ARPES has improved this somewhat.
- Energy resolution (~ 1-20 meV scale) and base temperatures (2-15K) still somewhat limited.
- Spatially averaged (typically 50 microns and up). NanoARPES with 10 nm spatial scale is coming.
- Only measures the occupied states, though at elevated temperatures some states above E_F are thermally occupied.
- Still developing rapidly.

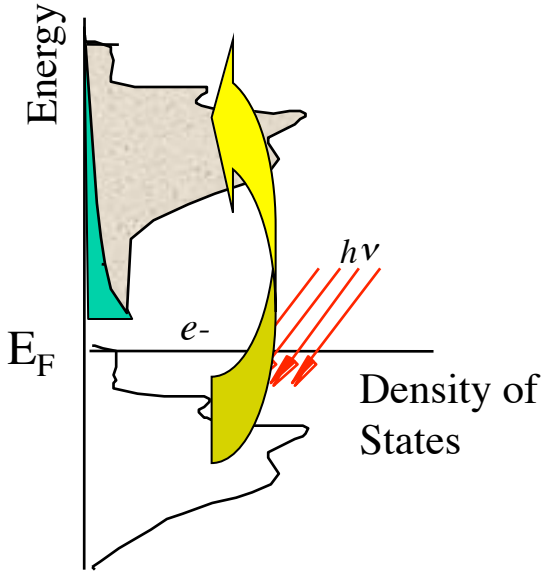
Plan

- Discussion of the technique. Main principles early on. More detailed or subtle issues later, as needed.
- Cover a number of case studies, mostly from the p-type cuprates Bi2212 and Bi2201. These have the best cleaved surfaces and have been the most studied by ARPES and STM. They are also "dirtier" than many other cuprates.
  - Some discussion of n-type cuprates if time allows. Minimal on other p-type cuprates.
- Focus on the case studies where ARPES has made the largest initial impacts, and/or where it is uniquely suited to answer a critical question or open a new line of thought. Partially historical in nature.
- Early studies focused more on peak tracking, using older ideas of FL theory (even if FL theory fails). Most recent studies are able to bring real quantitative accuracy, even in the presence of disorder. Are directly connecting to transport, thermodynamics, etc.
- Topics: Evolution of electronic structure from the parent Mott state, Fermi surfaces and Fermi arcs, superconducting gaps, pseudogaps, self-energy effects, etc.

Introduction to the ARPES technique (basics)

Photoemission Spectroscopy





High K.E. Low B.E.

Low K.E. High B.E.

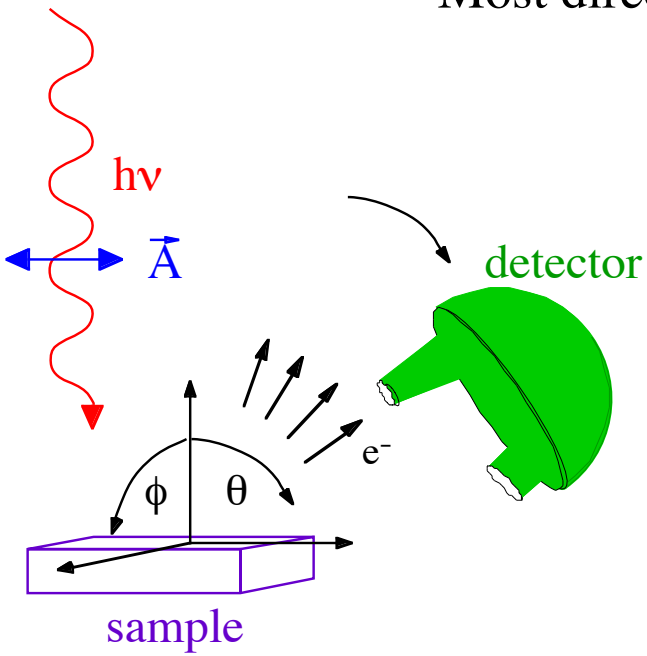
Primary electrons – no scattering events. Contain information of the electron spectral function

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

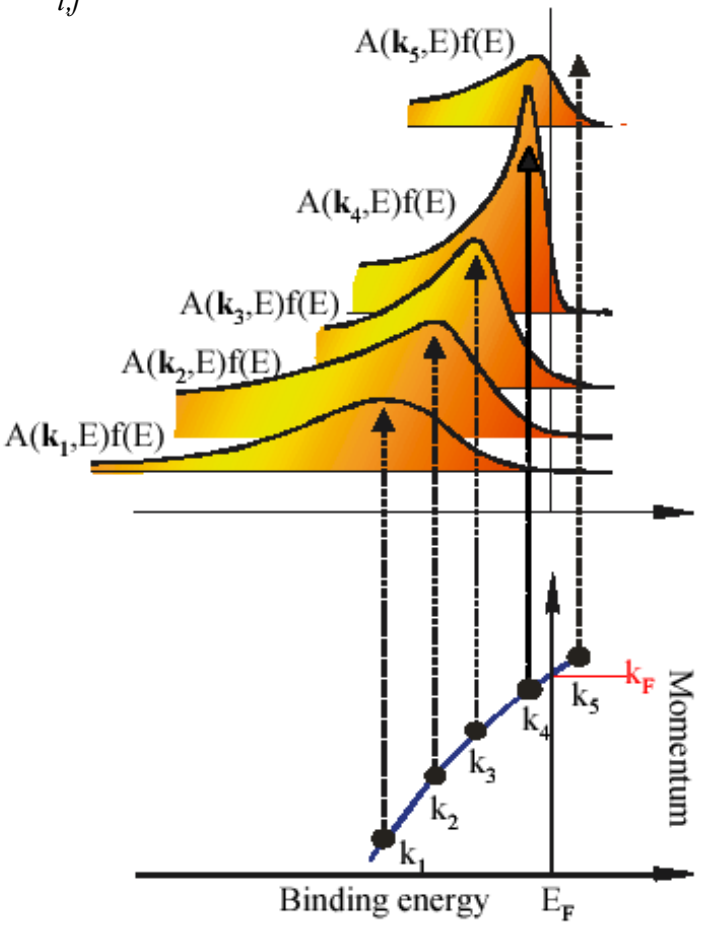
$$E_{kin} = \hbar\omega - \Phi - |E_B|$$

Angle Resolved Photoemission (ARPES)
A momentum resolved spectroscopy

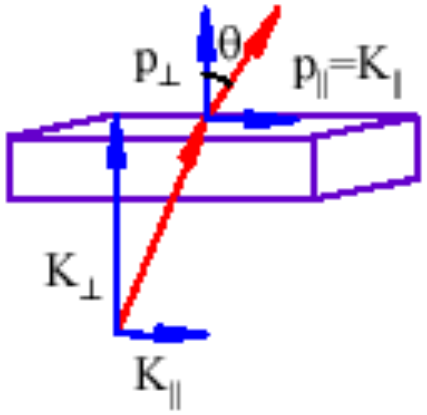
Most direct way to measure E vs. k of a solid.



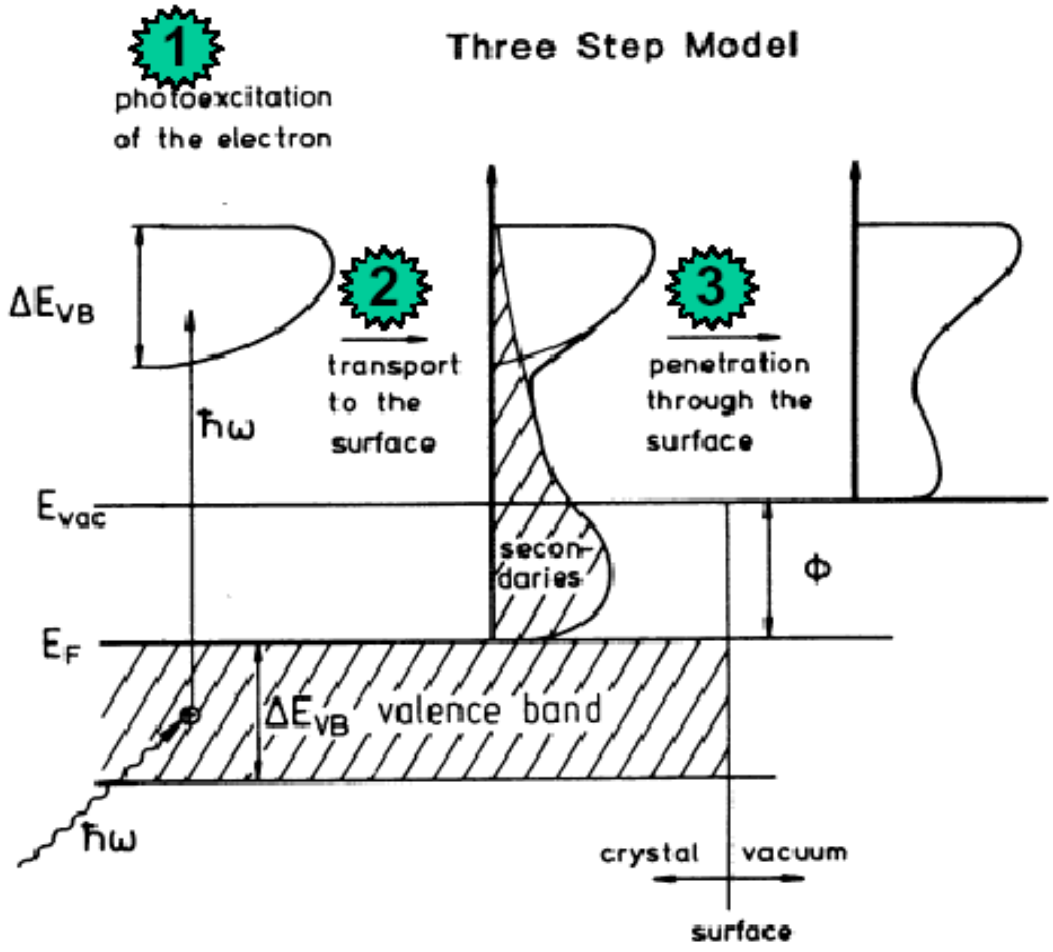
$$\text{Intensity} \propto \sum_{i,f} \left| \langle f | \vec{\mathbf{p}} \cdot \vec{\mathbf{A}} | i \rangle \right|^2 A(\vec{\mathbf{k}}, E) f(E)$$



Electron momentum
Parallel to the surface is
conserved



Three Step Model
W.E. Spicer

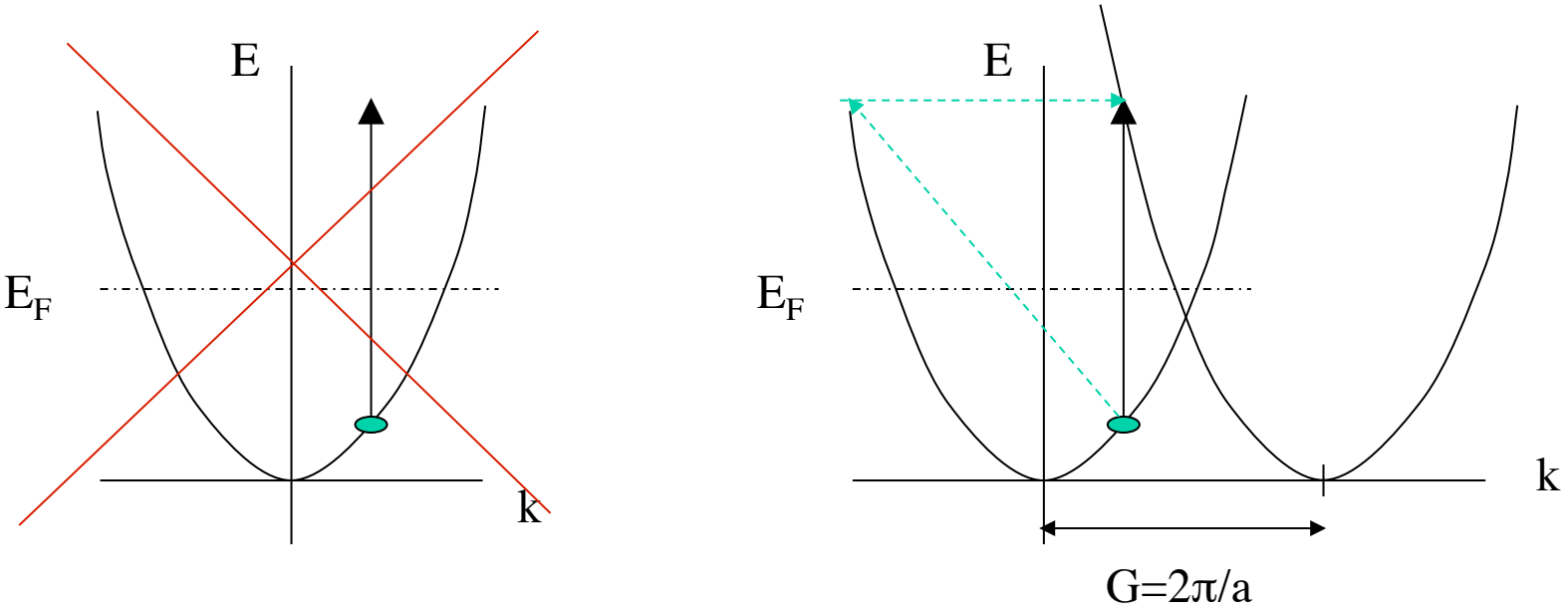


"One-step" models in which the photoemission process is considered as a single quantum mechanical event are more accurate, but not as illuminating.

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.



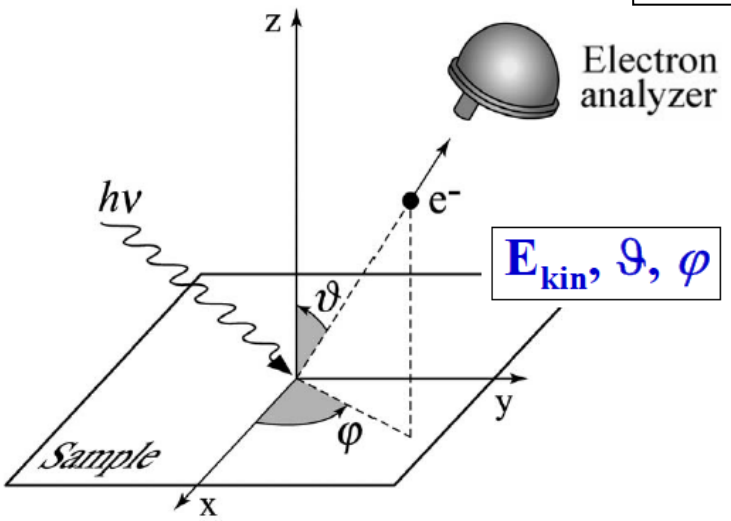
The vertical transition is allowed by considering the extended zone scheme and employing a reciprocal lattice vector G=2π/a (the lattice degree of freedom takes care of the "missing" momentum).

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

Angle Resolved Photoemission (ARPES)
→k-resolved electronic structure

$E_{kin}=h\nu-\Phi-E_i$



$$\mathbf{K} = \mathbf{p}/\hbar = \sqrt{2mE_{kin}}/\hbar$$

$$K_x = \frac{1}{\hbar}\sqrt{2mE_{kin}}\sin\vartheta\cos\varphi$$

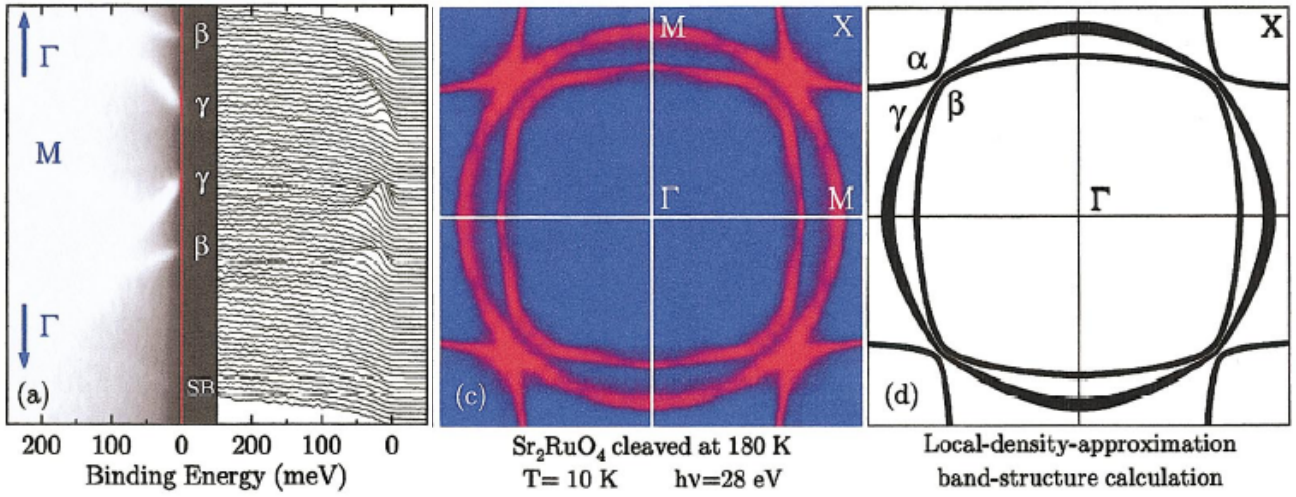
$$K_y = \frac{1}{\hbar}\sqrt{2mE_{kin}}\sin\vartheta\sin\varphi$$

$$K_z = \frac{1}{\hbar}\sqrt{2mE_{kin}}\cos\vartheta$$

Example 2D compound

Peak tracking - measure E vs. k, Fermi surfaces, etc.

Sr_2RuO_4 Fermi Surface
Damascelli and Shen
PRL 2000



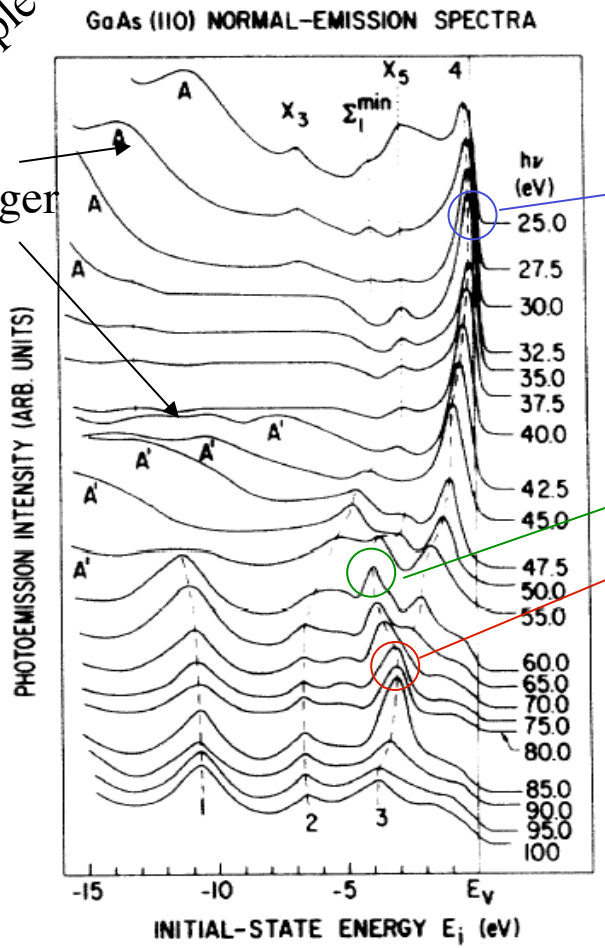
PHYSICAL REVIEW B VOLUME 21, NUMBER 8 15 APRIL 1980

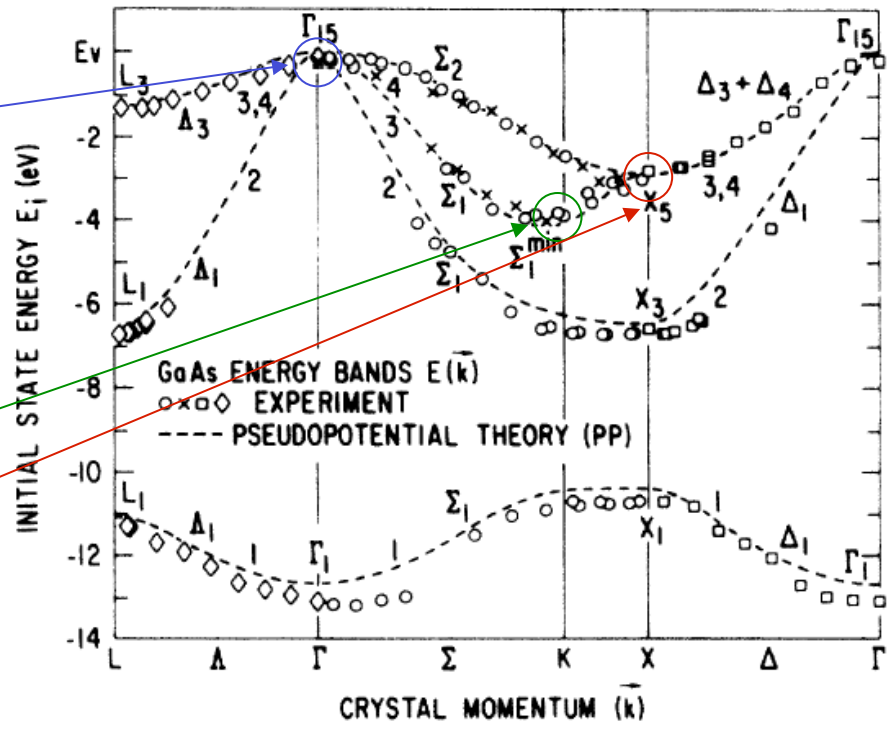
Angle-resolved photoemission, valence-band dispersions $E(\vec{k})$, and electron and hole lifetimes for GaAs

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)

Example 3D compound

Auger





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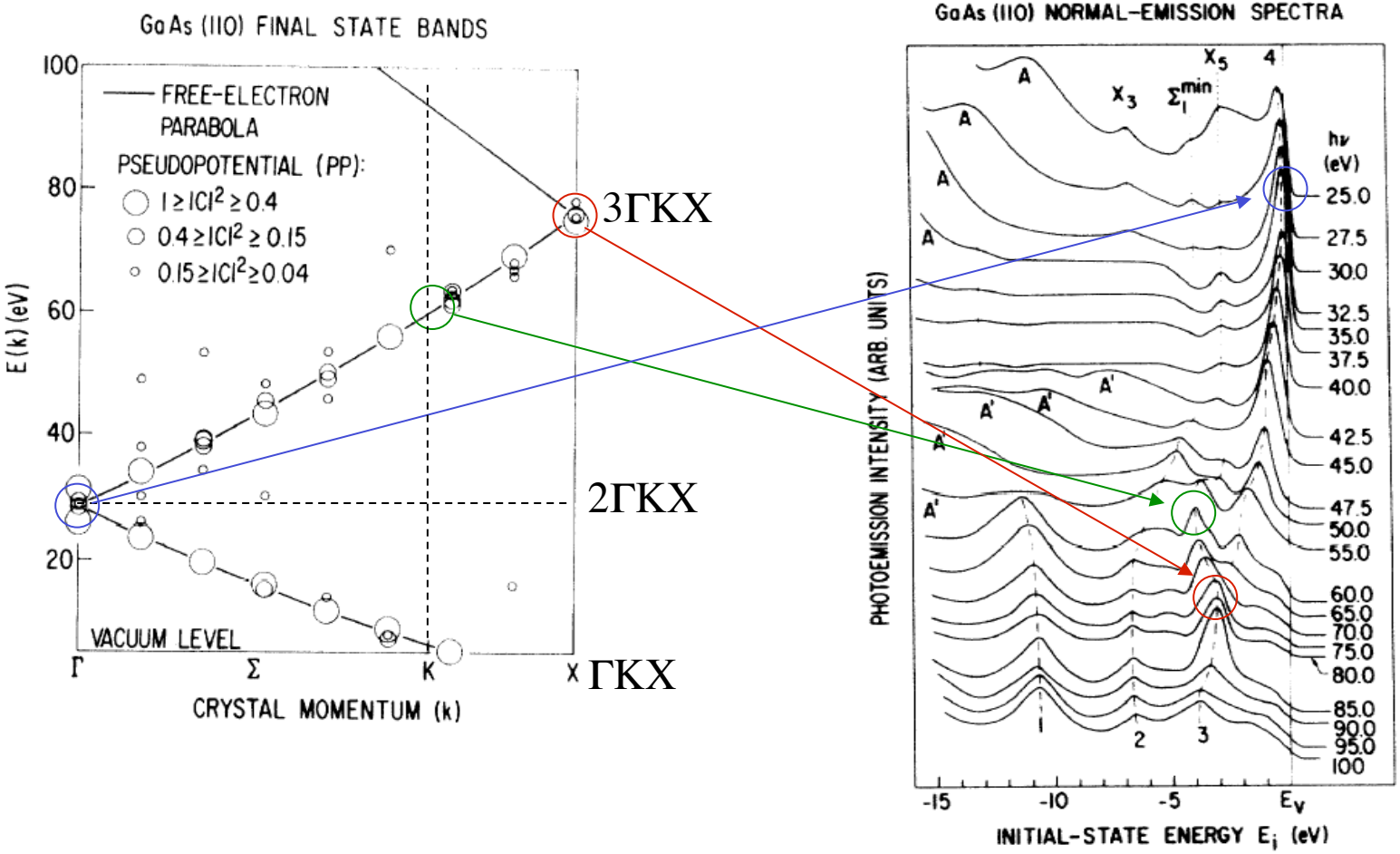
Example 3D compound

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



Matrix Element for Photoemission

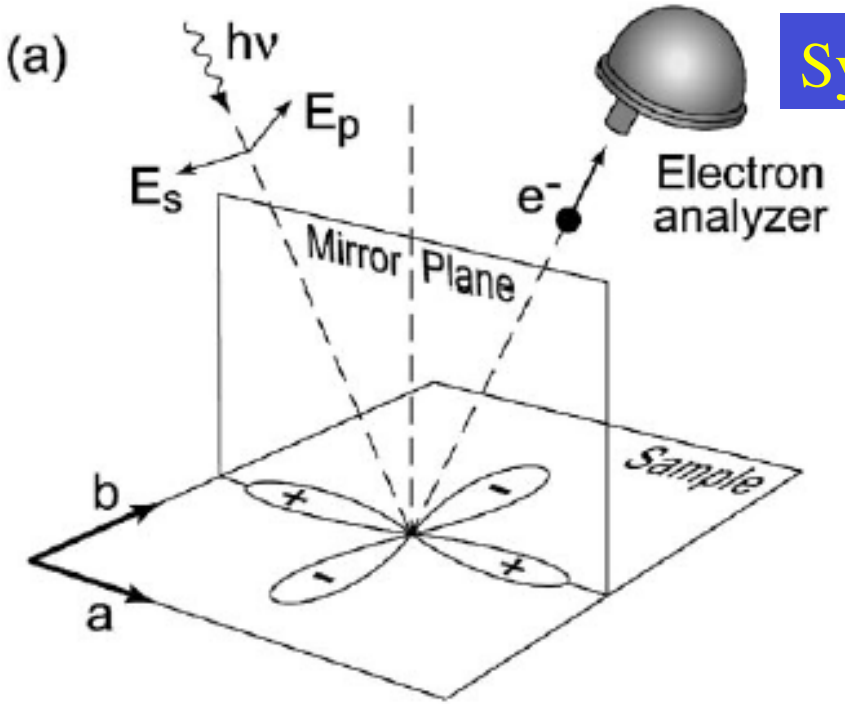
Perturbation Theory gives Fermi's Golden Rule for transition probability

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

For dipole allowed transitions,

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

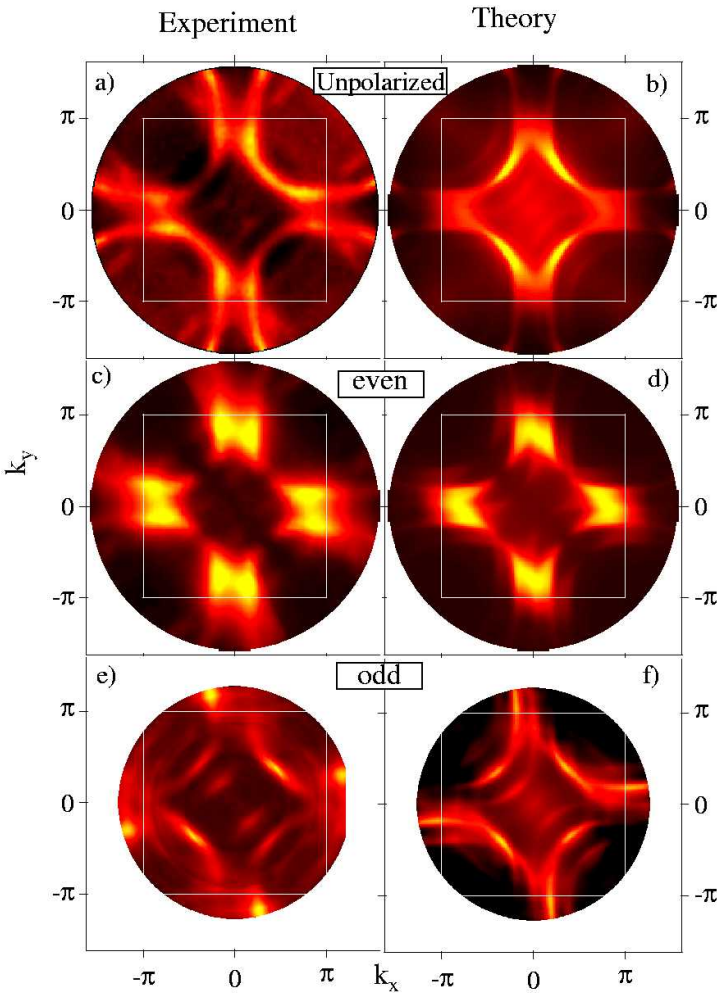
Symmetry Analysis



E field

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

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.



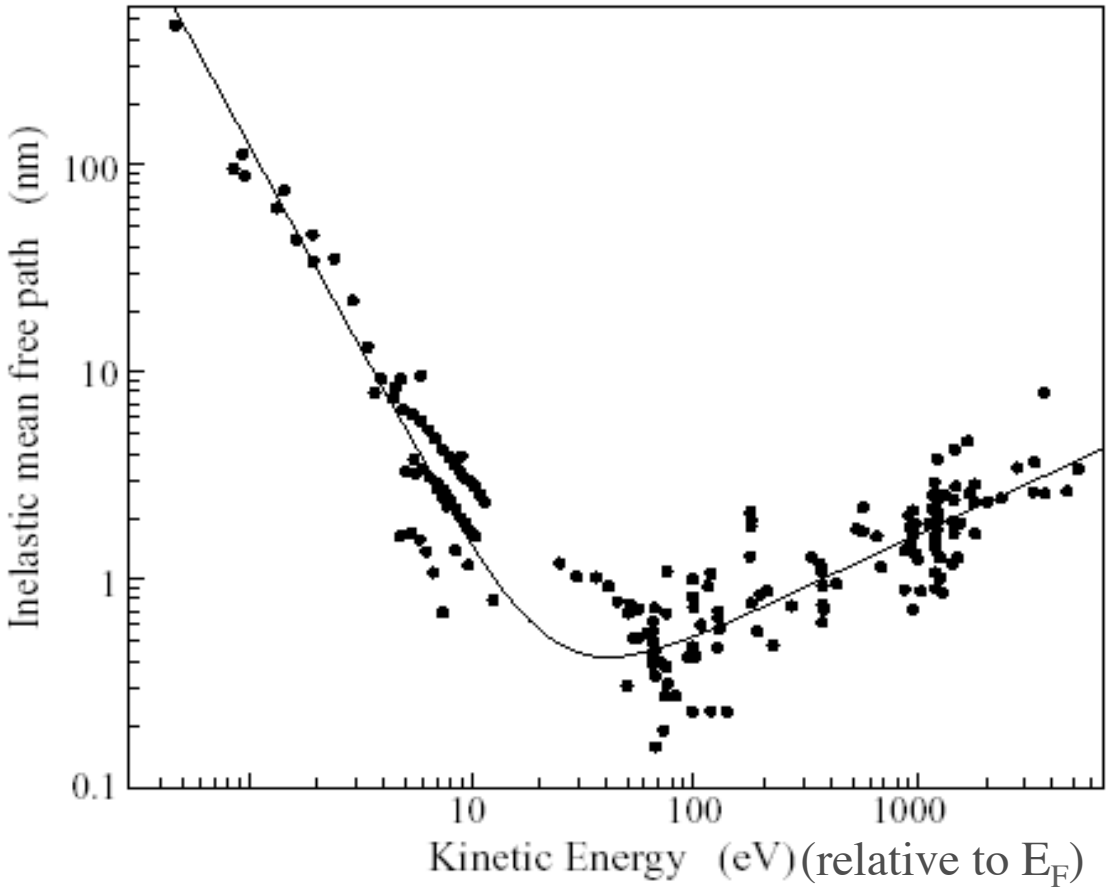
Bansil group.

Powerful method for selecting out the spectral contribution from various initial-state symmetry states/orbitals.

Surface sensitivity – electron kinetic energy

"Universal Curve"

Can be an advantage or a disadvantage!

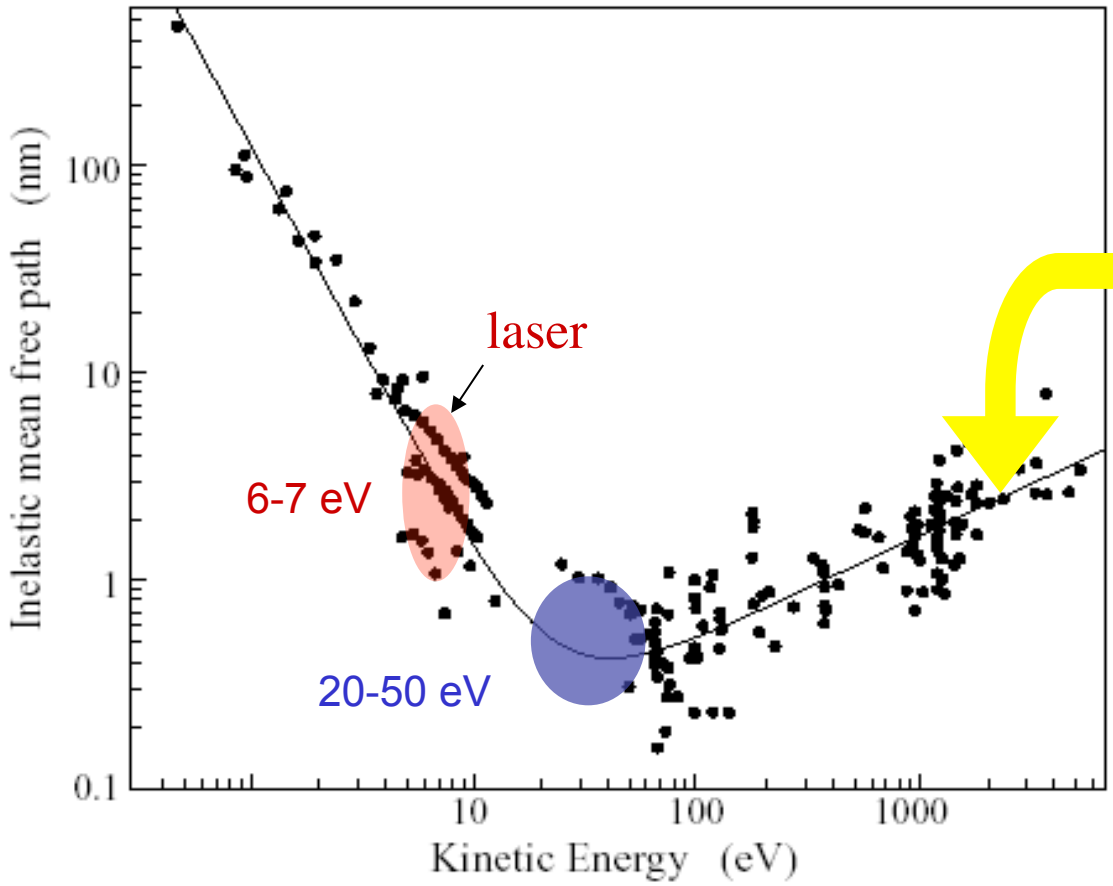


M. P. Seah and W. A. Dench, *Surf. Interface Anal.* **1**, 2 (1979).

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

Decreasing interaction times.

Surface sensitivity – electron kinetic energy

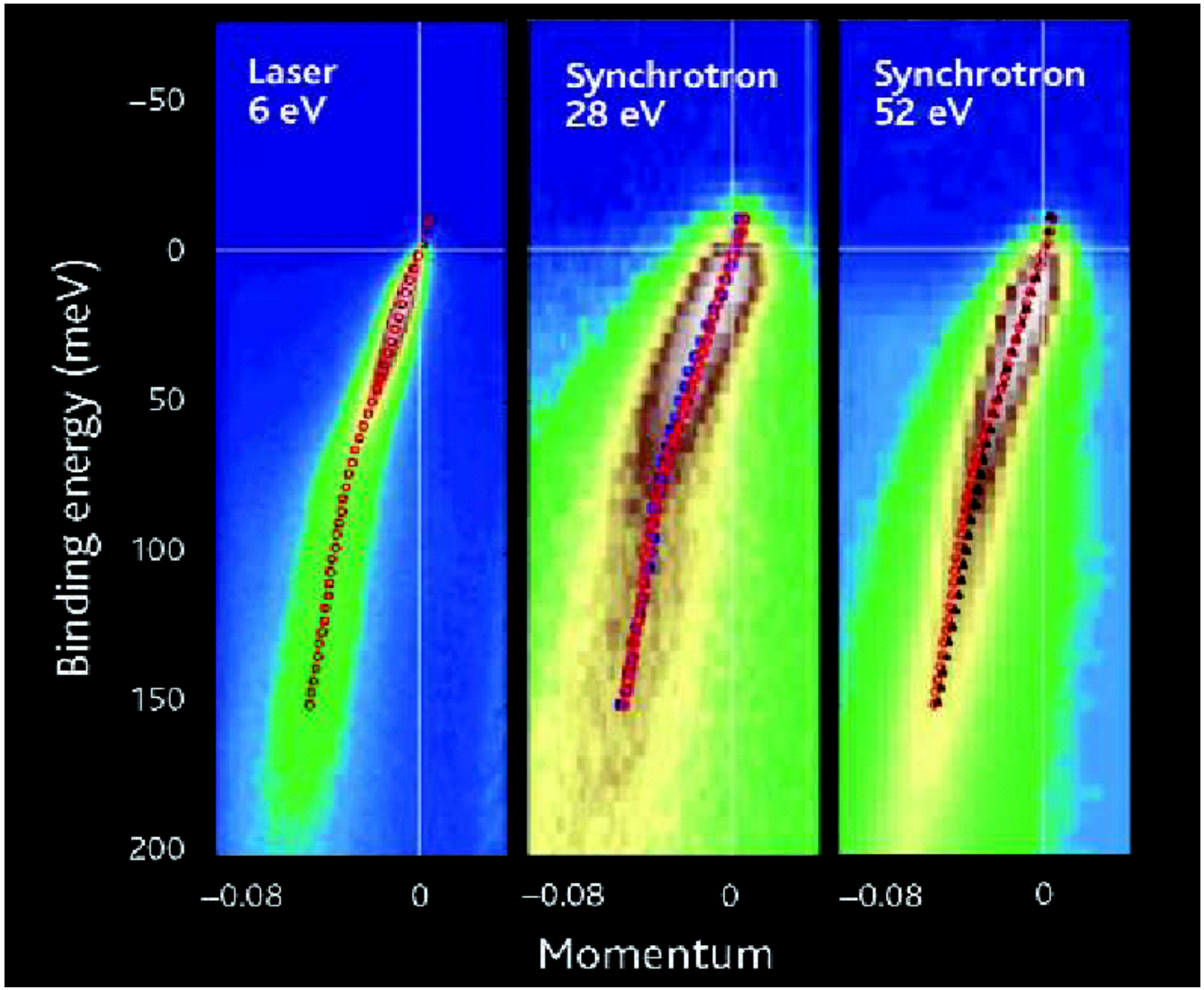


New efforts here

→Laser-ARPES is 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).

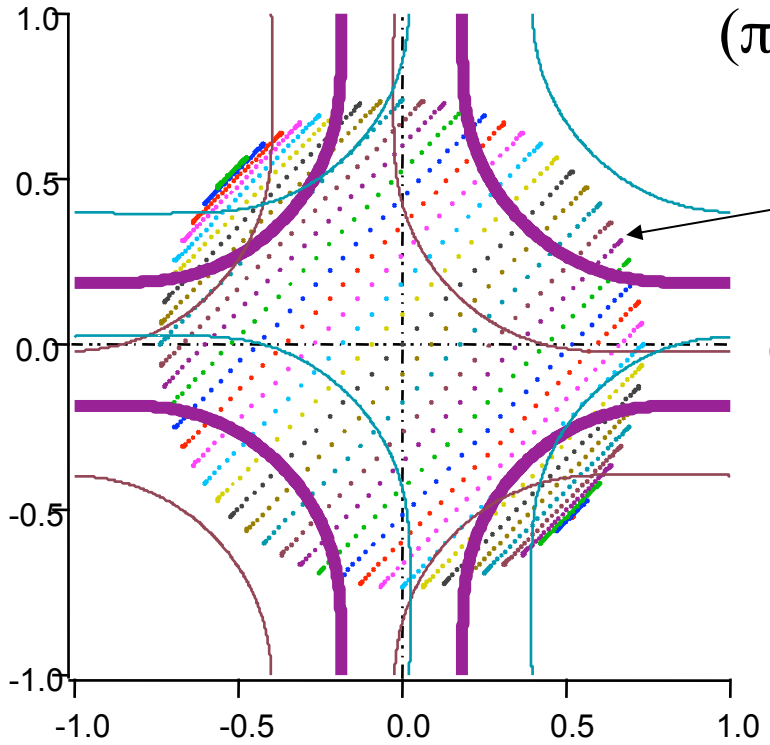
ARPES dispersion along the nodal line of $Bi_2Sr_2CaCu_2O_8$
T ~ 20K



Published by AAAS

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

Resolution and k-space effect



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

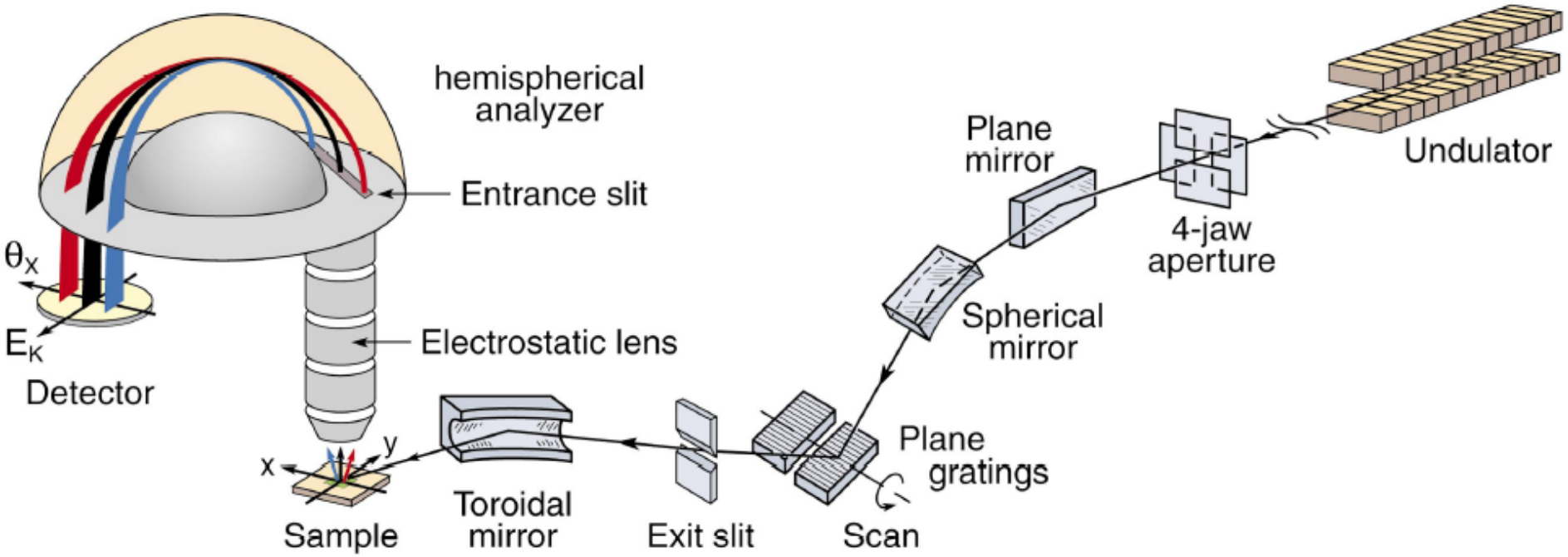
$$\hbar k_{//} = \sqrt{2mE_k}\sin\theta$$

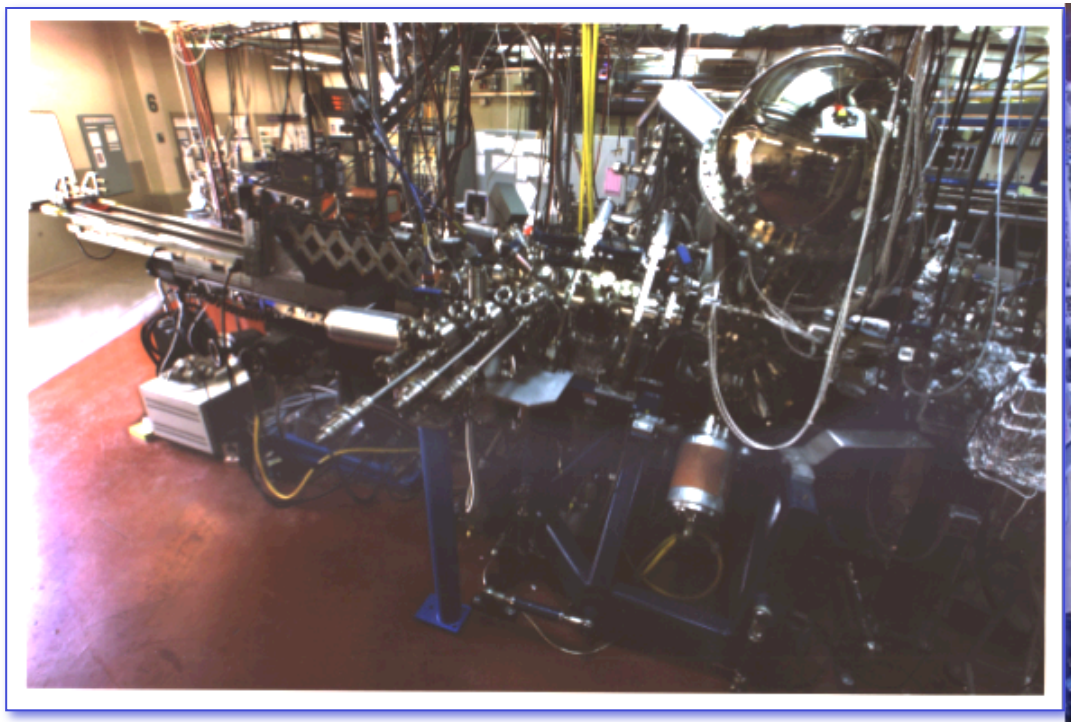
- For the same angular resolution, the k resolution at low E is superior.
- k resolution translates to E widths if the peak is dispersive.

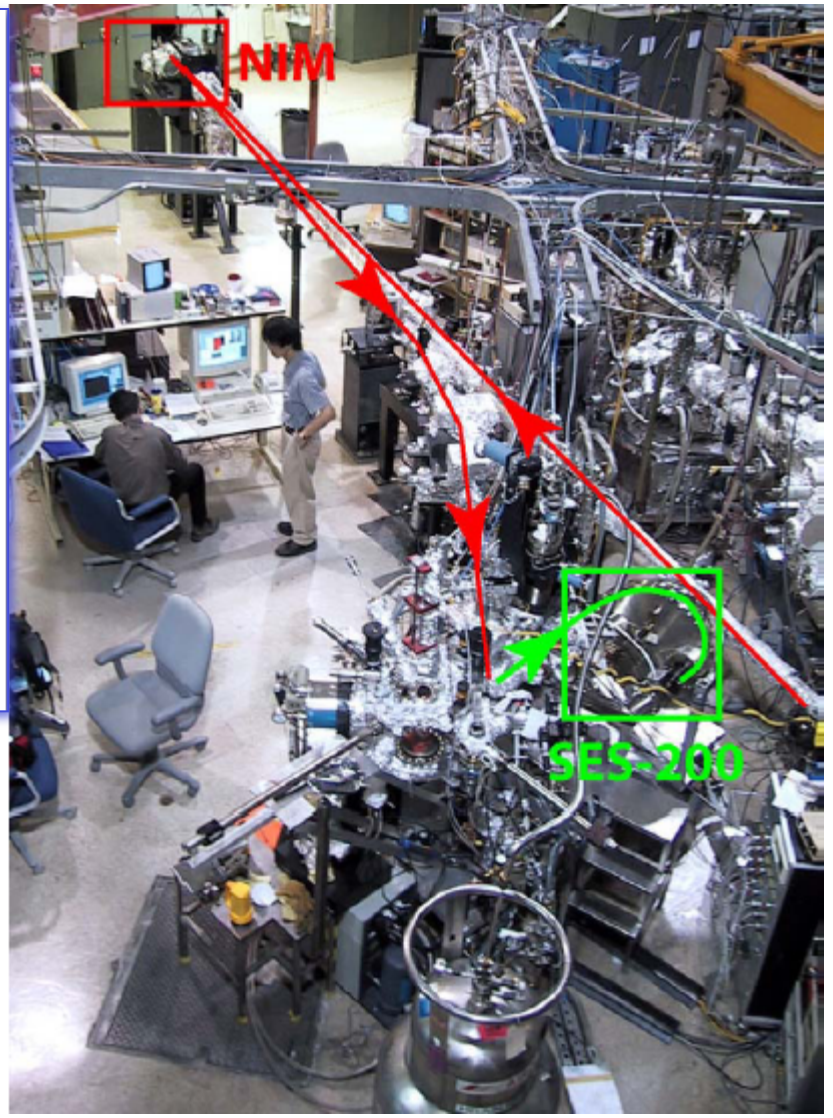
  For nodal states & $\pm$ .15 degree angular resolution,

  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





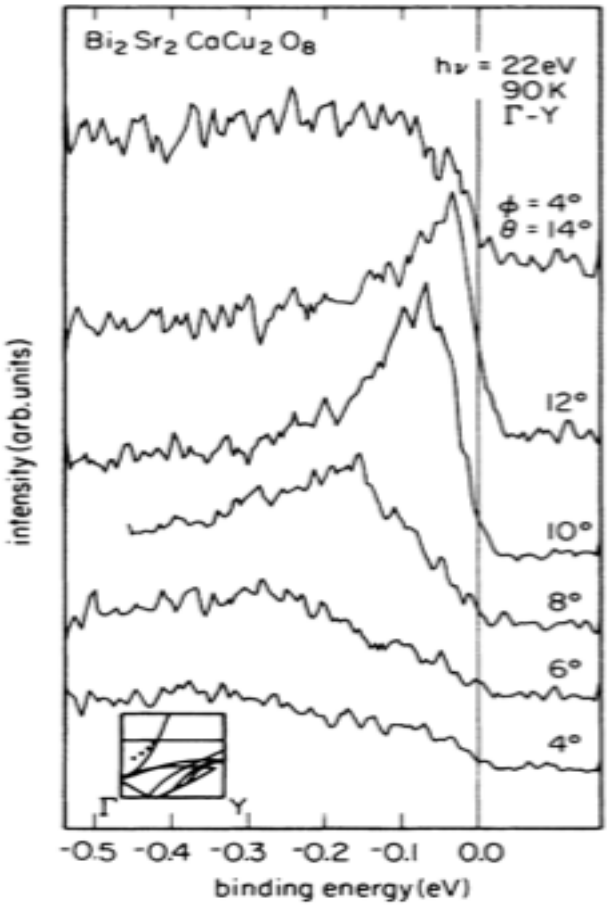


- UHV analysis chamber (10^{-11} Torr)
- 5 or 6 axis, He cooled sample manipulators
- Load-Lock transfer system
- Samples may be cleaved in UHV

Band dispersions, Fermi surfaces, etc.

ARPES compared to LDA band structure.

Normal state near-optimal Bi2212 along the nodal line.

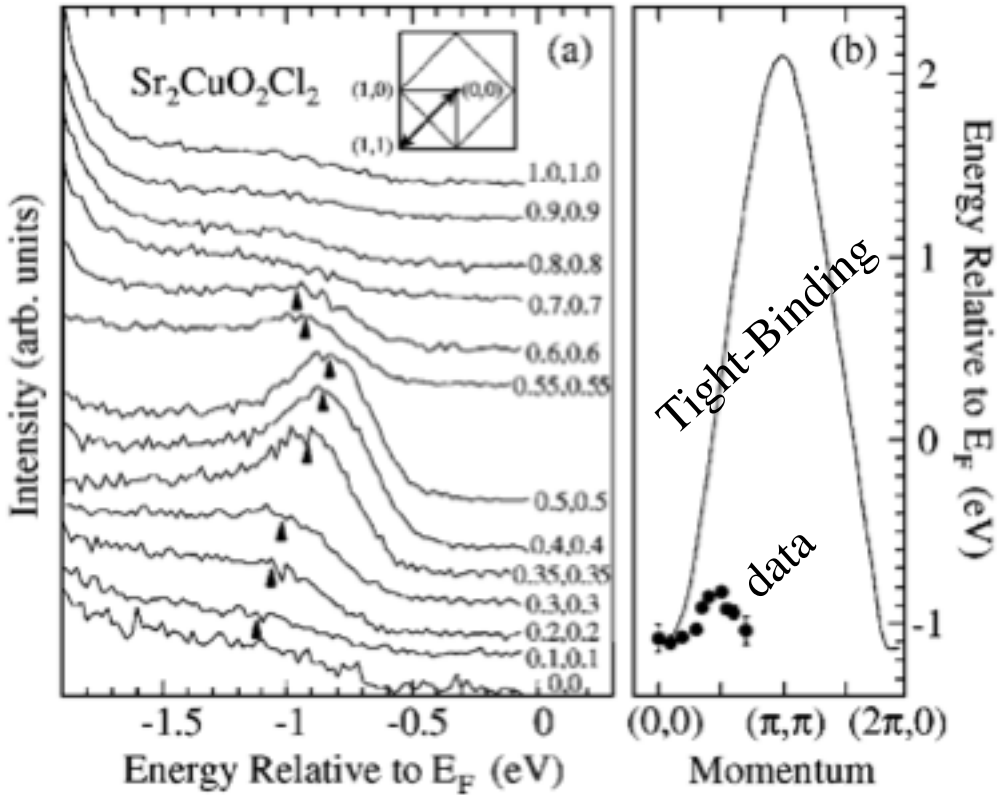


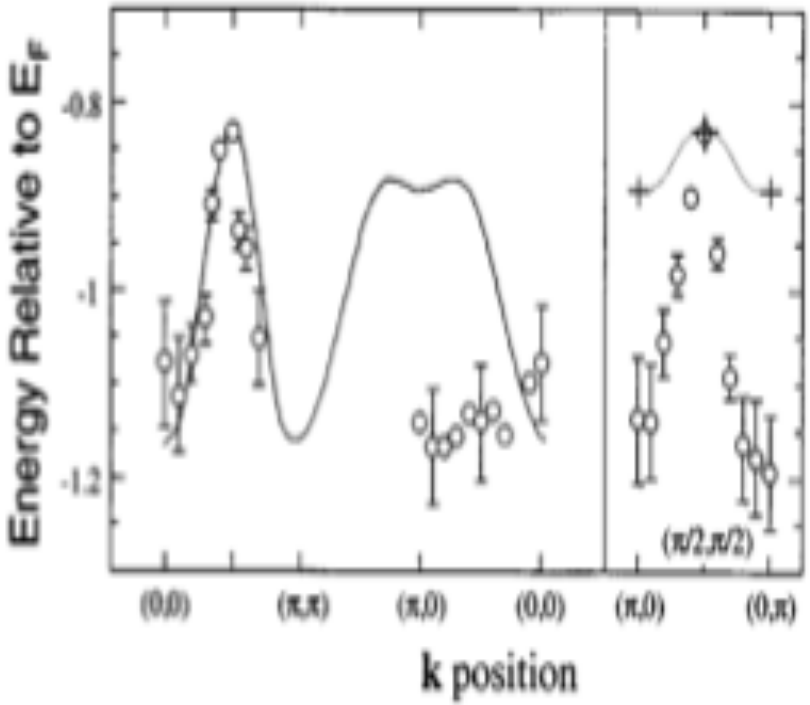
~ a factor of two mass enhancement compared to LDA.

C.G. Olson et al., PRB 1990

E versus k Relations and Many Body Effects in the Model Insulating Copper Oxide $Sr_2CuO_2Cl_2$

Wells et al. 1994, 1995



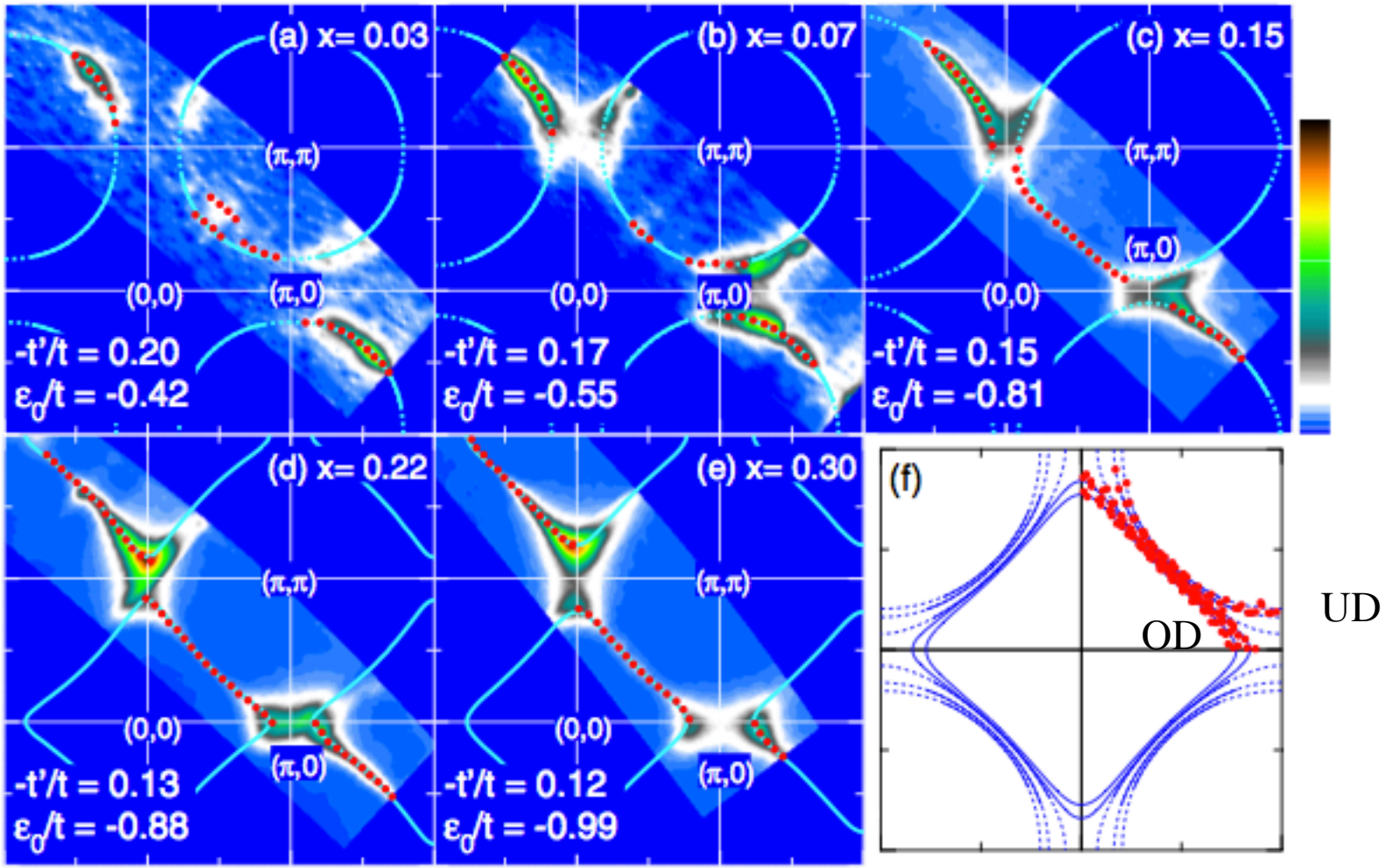


t-J model calculation (solid line) predicts a bandwidth W~2.2J.

It is natural to expect that doping with holes should give a small pocket centered at (π/2,π/2)

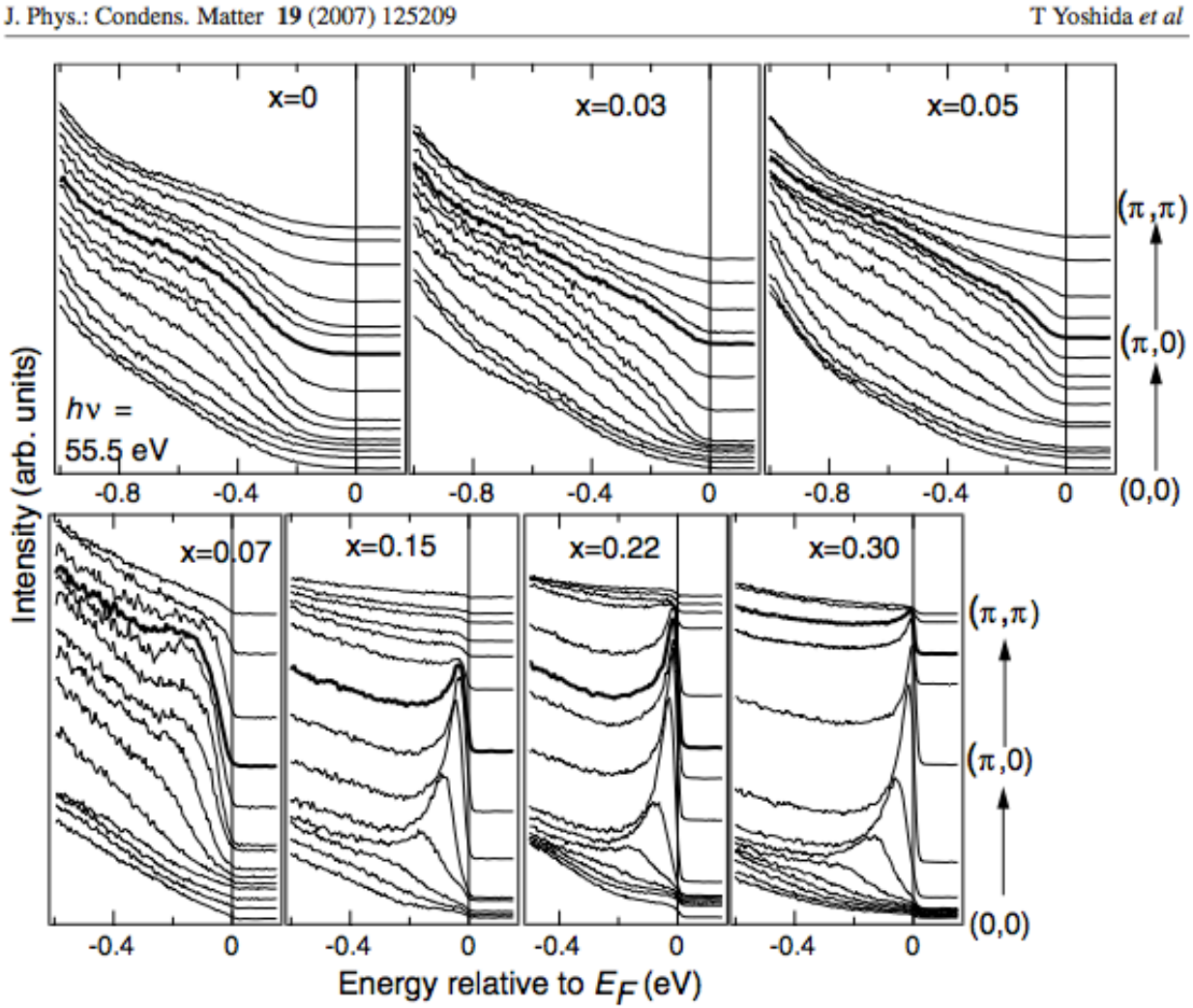
Fermi surface mapping vs hole doping level in $La_{2-x}Sr_xCuO_4$

J. Phys.: Condens. Matter **19** (2007) 125209 T Yoshida *et al*



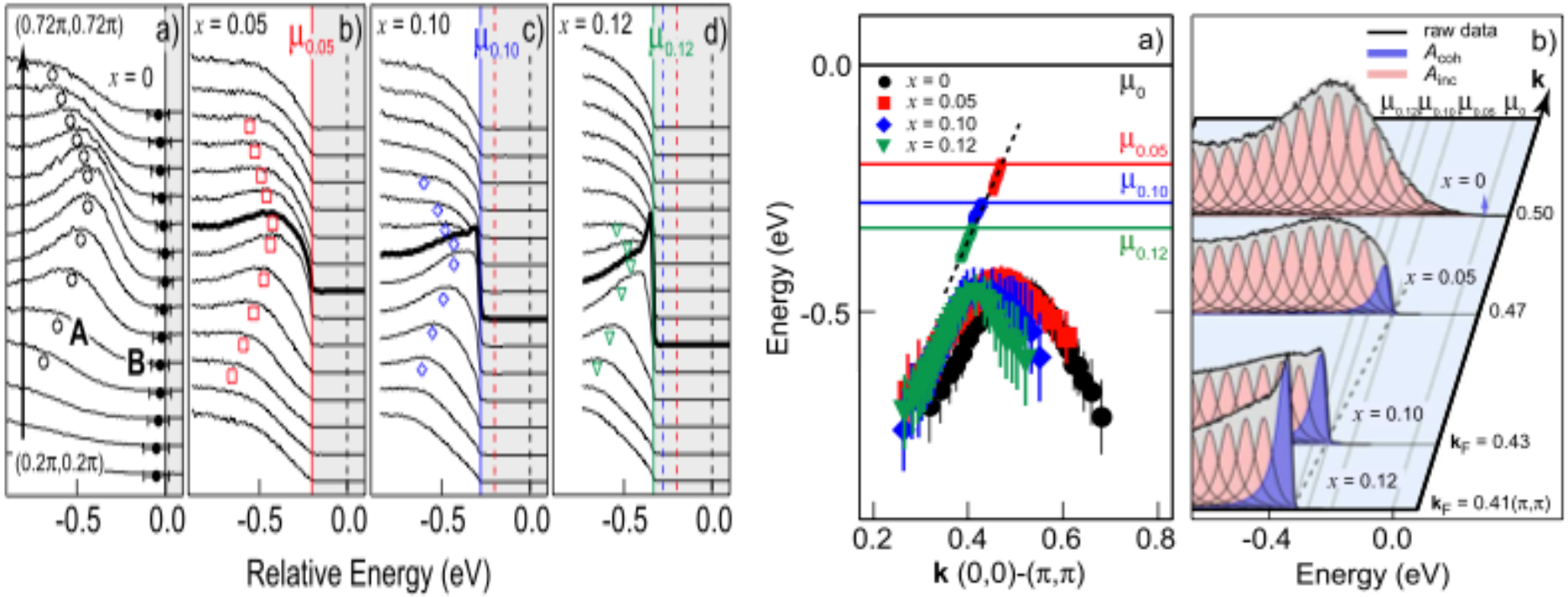
There is a locus of low energy states that is large and centered at the zone corner (UD) or the zone center (OD).

Nodal cut band dispersion vs hole doping level in $La_{2-x}Sr_xCuO_4$



The spectral peaks are very broad and low intensity for UD. A very different type of doping evolution than for a normal semiconductor. Also not what is naively expected for doping the Mott insulator (no small pocket).

Na-doped $Ca_2CuO_2Cl_2$



K. Shen, Z-X Shen, PRL 2004

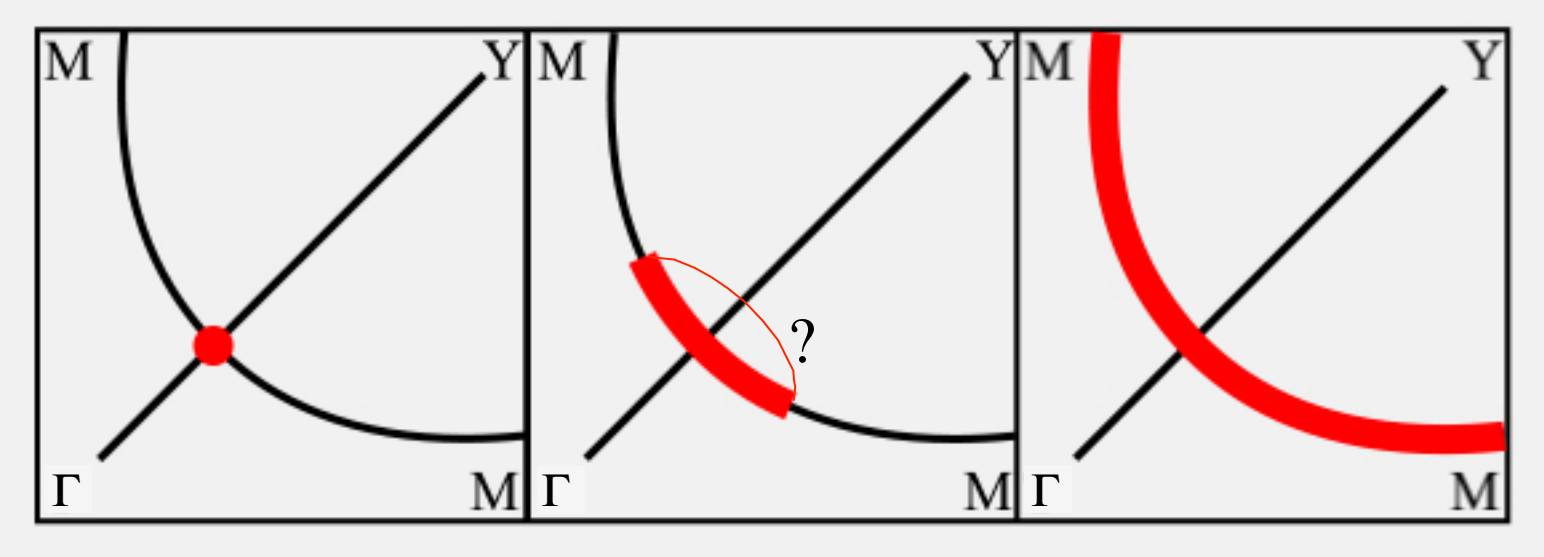
Interpretation put forward: The majority of the dispersive peak is an incoherent superposition of many Franck-Condon-broadened loss peaks. The zero-loss peak with weight Z is the quasiparticle, with Z vanishingly small for low doping.

Q: Why is the dispersion of the sharp peak independent of doping? This is to first-order inconsistent with a varying Z.

Fermi arcs

Another aspect of the Fermi surface that deviates from conventional is that of the "Fermi arcs", which are small discontinuous portions centered around the nodal directions.

The origin and phenomenology is still heavily debated, but nominally these are argued to be long and connected at high T or OD, and short/disconnected at low T, UD.



Truly truncated? Closed by a weak "shadow" piece on the back side? Made of quasiparticles?

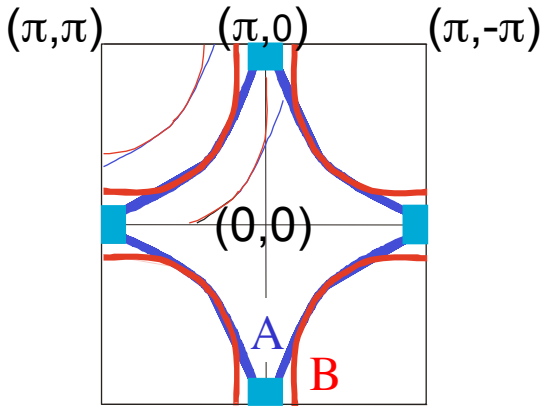
Will cover later in more detail.

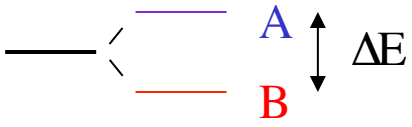
Bilayer Splitting in double-layer cuprates

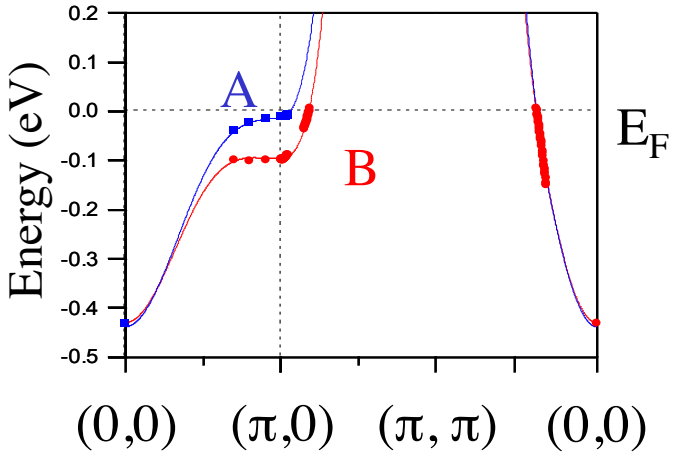
BILAYER SPLITTING = 2 PIECES OF FS Bonding plus Antibonding band

Due to electronic coupling between the pair of CuO_2 planes per unit cell

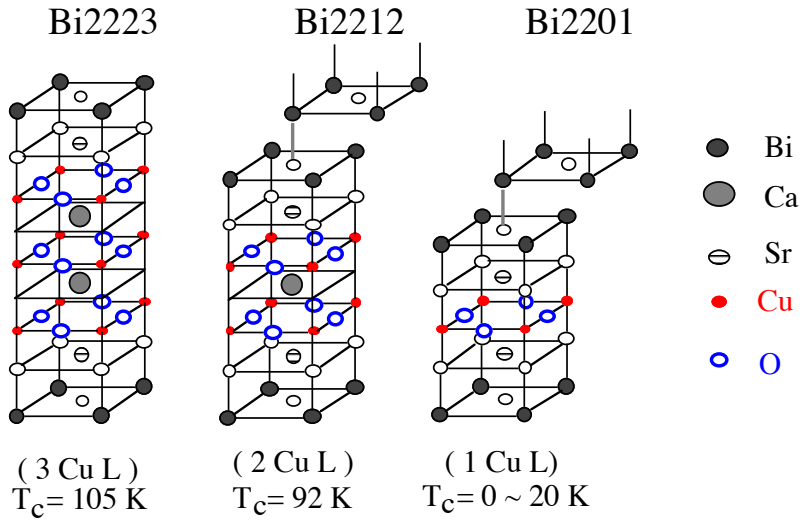
Superstructure bands exist as well.







ΔE ~ 100 meV.

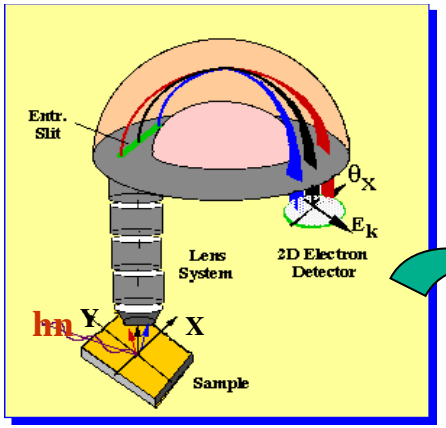


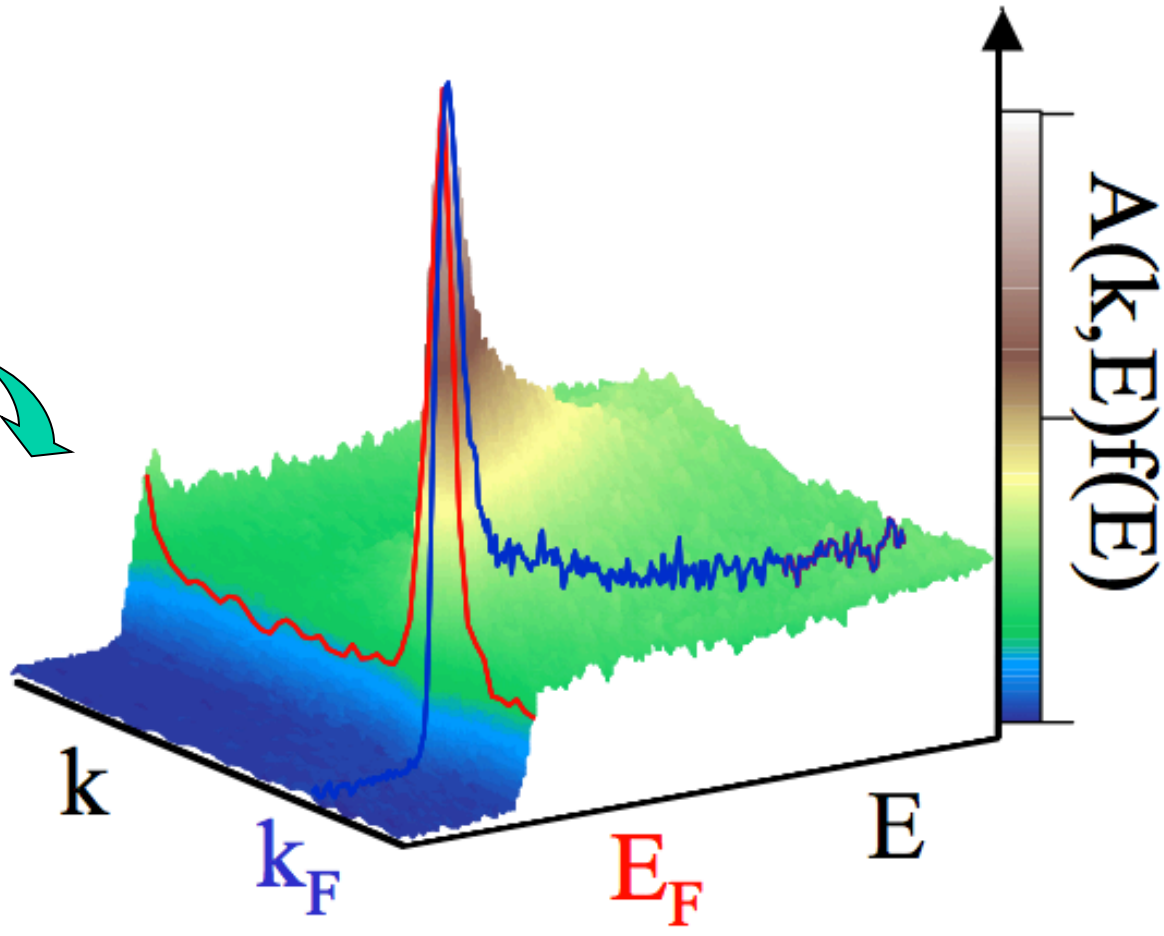
Y.D. Chuang et al, Phys. Rev. Lett. **87**, 117002 (2001))

2D detection (in energy and momentum)

EDCs and MDCs

Two dimensional electron detection





Energy Distribution Curve (EDC)

Momentum Distribution Curve (MDC)

A.D. Gromko, University of Colorado Thesis

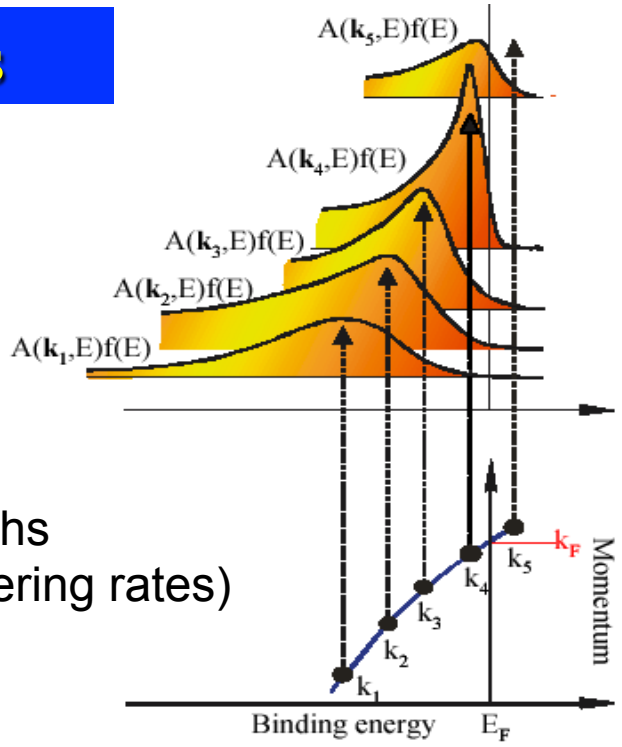
ARPES peak widths and lineshapes

Spectral Function A(k,ω) = -Im G(k,ω)

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

Renormalized dispersion
(e.g. kinks, mass renormalization)

Peak widths
(Lifetimes or scattering rates)



Peak widths and lineshapes in cuprates are not understood.
Marginal Fermi Liquid vs. Fermi Liquid?
Is there a real qp peak in cuprates or not?

Shen & Schrieffer PRL 1997
Laughlin PRL,1997
Casey, Dessau, Anderson Nat Phys 2008
& many many others.

When the peak is absent or broad, can we utilize the standard concepts of solids?

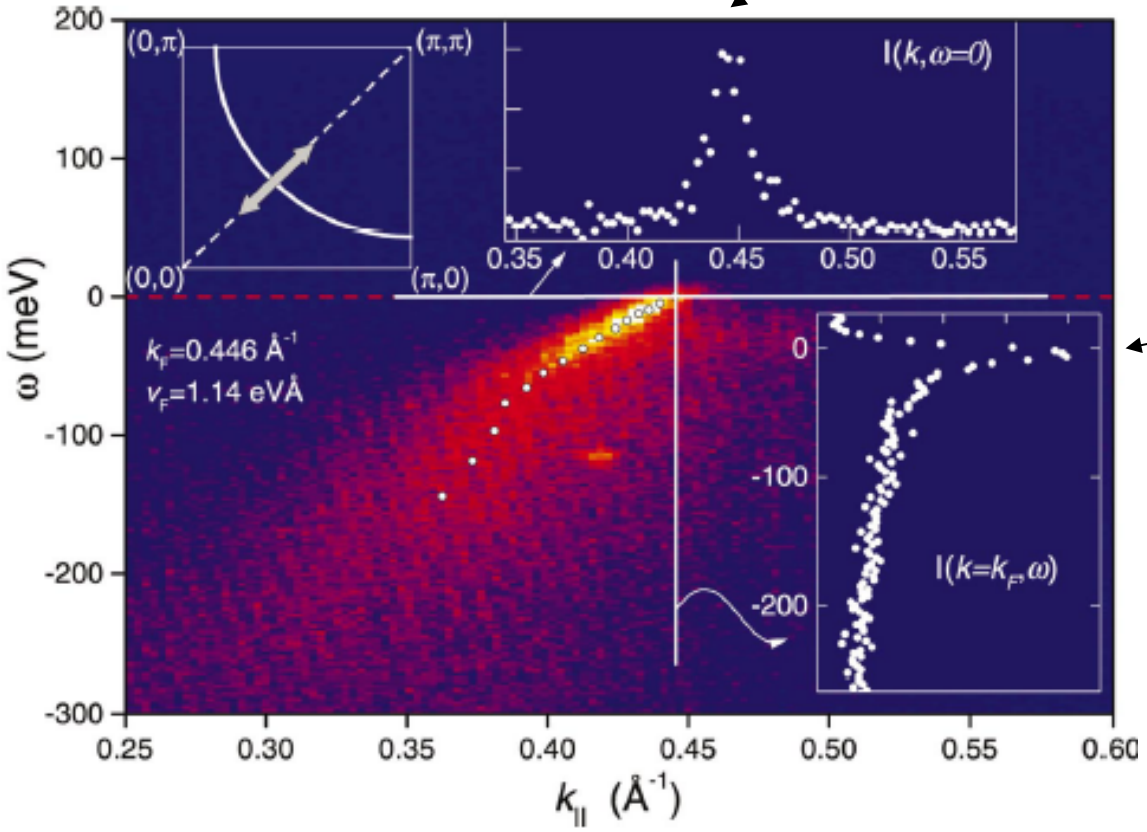
2D detection: high T_c superconductor $Bi_2Sr_2CaCu_2O_8$

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]

24 SEPTEMBER 1999 VOL 285 SCIENCE

Momentum Distribution Curve (MDC)

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



Energy Distribution Curve (EDC)

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

$1/\tau$ ~ scattering rate

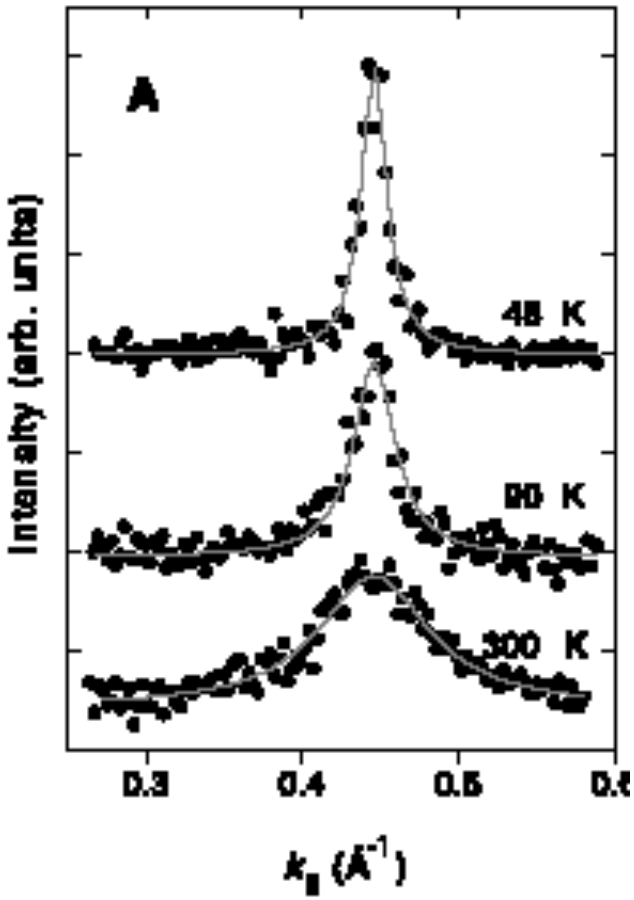
τ ~ quasiparticle lifetime

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

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

2D detection on the high Tc superconductor $Bi_2Sr_2CaCu_2O_8$

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?

These are in general self-energy effects, and should show up in both the real and imaginary parts of the self-energy.

In general: MDC better for large velocities, EDC better for very small velocities. Since Σ usually a much stronger function of E than k, MDCs usually simpler.

ARPES on Cuprates II

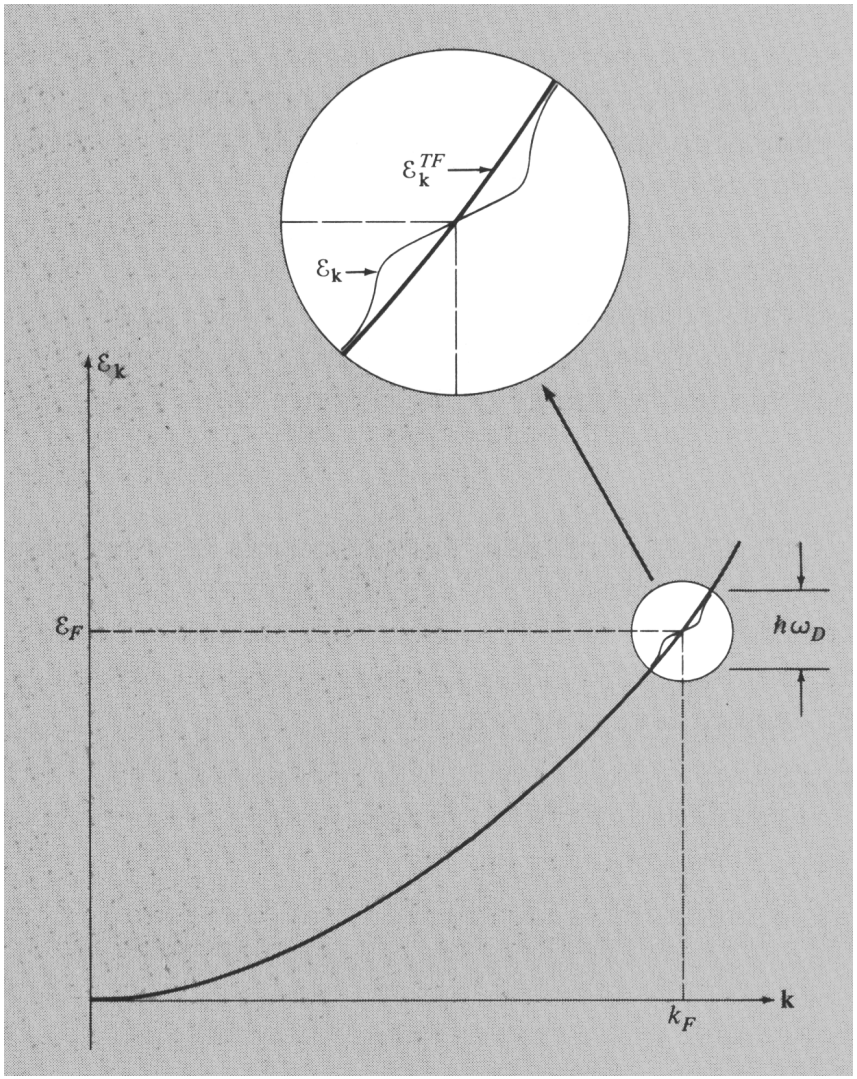
Dan Dessau
University of Colorado, Boulder
Dessau@Colorado.edu

- Kinks or dispersion anomalies (mostly SC state, beyond gap)
  - Nodal ~ 65 meV. Most clear in SC state.
  - Antinodal ~ 40-65 meV as a function of doping. SC only
  - Low E nodal kink ~ 10 meV. SC only
  - High E anomaly (all T, all k) ~ 300 meV

- SC gaps
- Pseudogaps, arcs
- Self energy effects inside the gap

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



Self energies in conventional superconductors Via Structure in the tunneling density of states

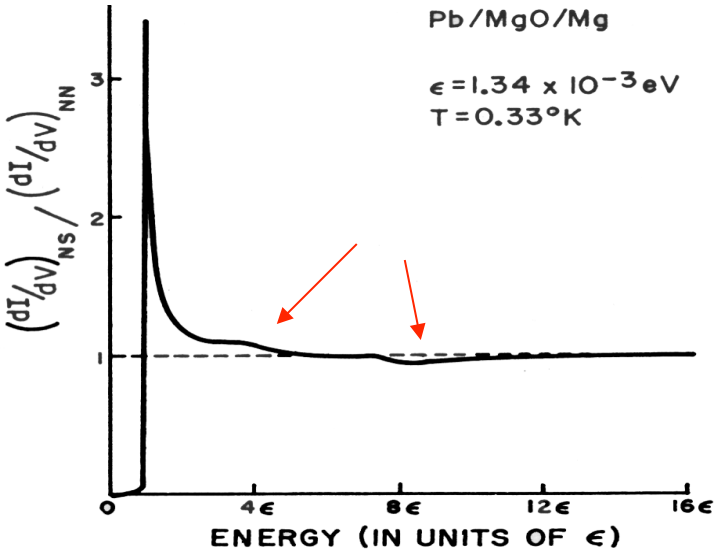
==> Confirmation that phonons mediate the pairing

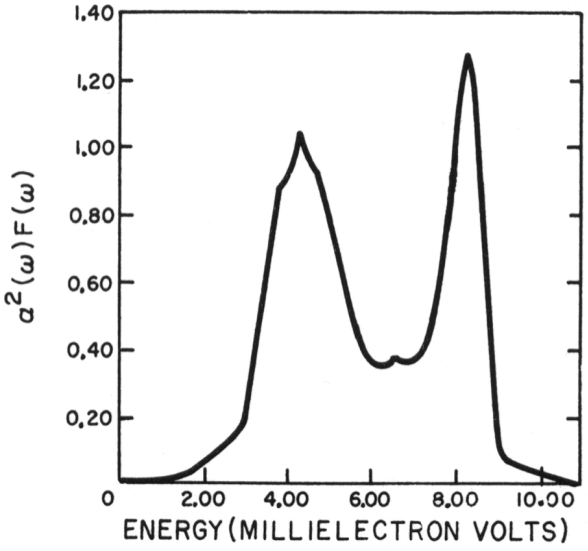
From Nobel Lecture, John Bardeen, 1972

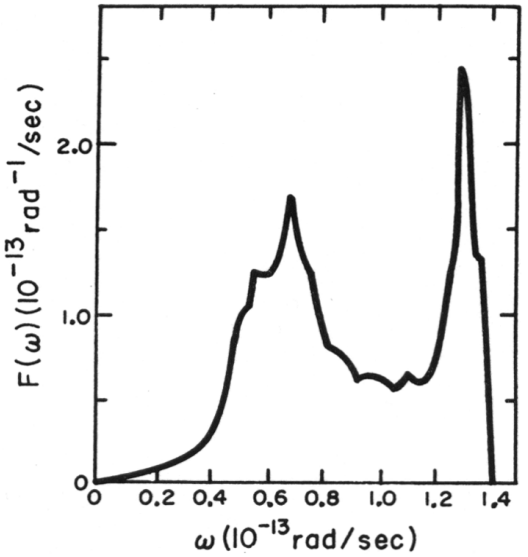
Tunneling Spectrum (Density of States)

Phonon spectrum (times coupling constant) extracted from tunneling data

Phonon spectrum measured from Neutron scattering







Tunneling spectroscopy on High T_c: Gap is k-dependent (d-wave).

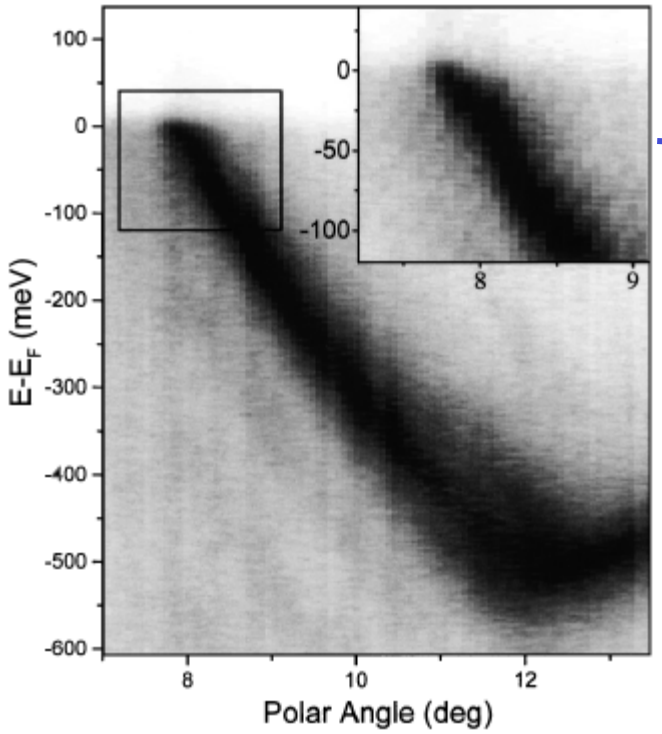
--> Superposition of many gap sizes, structures, etc.

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)



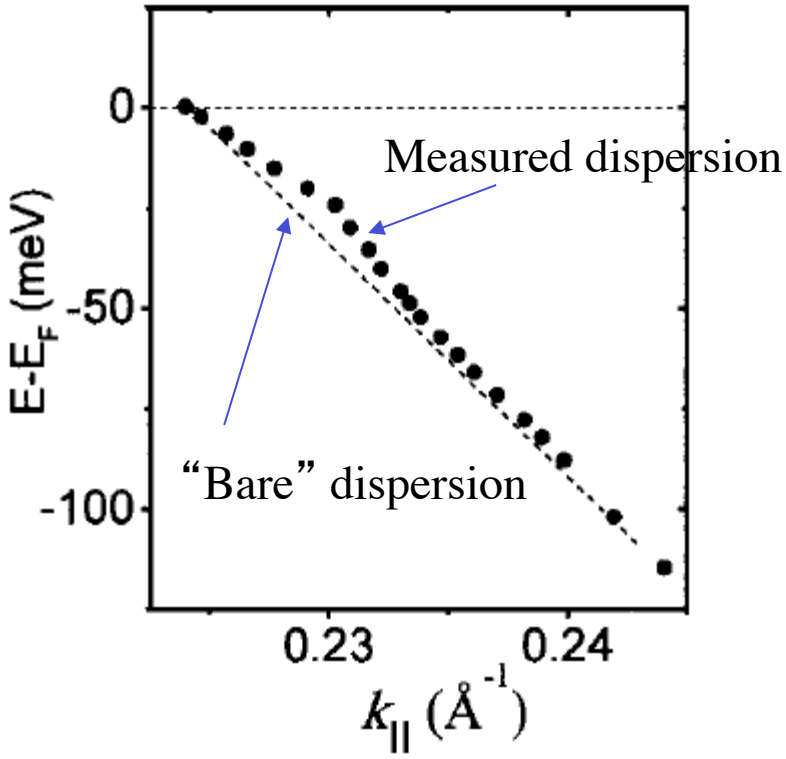
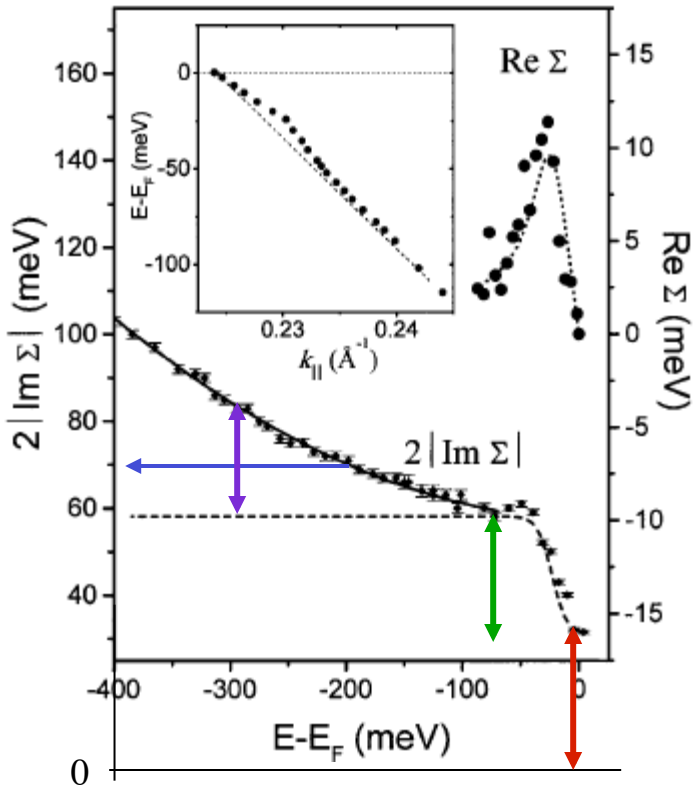


FIG. 1. ARPES intensity plot of the Mo(110) surface recorded along the $\overline{\Gamma}$-$\overline{N}$ line of the surface Brillouin zone at 70 K. Shown in the inset is the spectrum of the region around k_F taken with special attention to the surface cleanliness.

"Kink effect"

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

FWHM of quasiparticle peak



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

ImΣ and ReΣ related through Kramers-Kronig relations (weighted integral over all energies).

Electron-electron scattering

Coupling to phonons

Impurities, finite resolution, final state effects, etc.

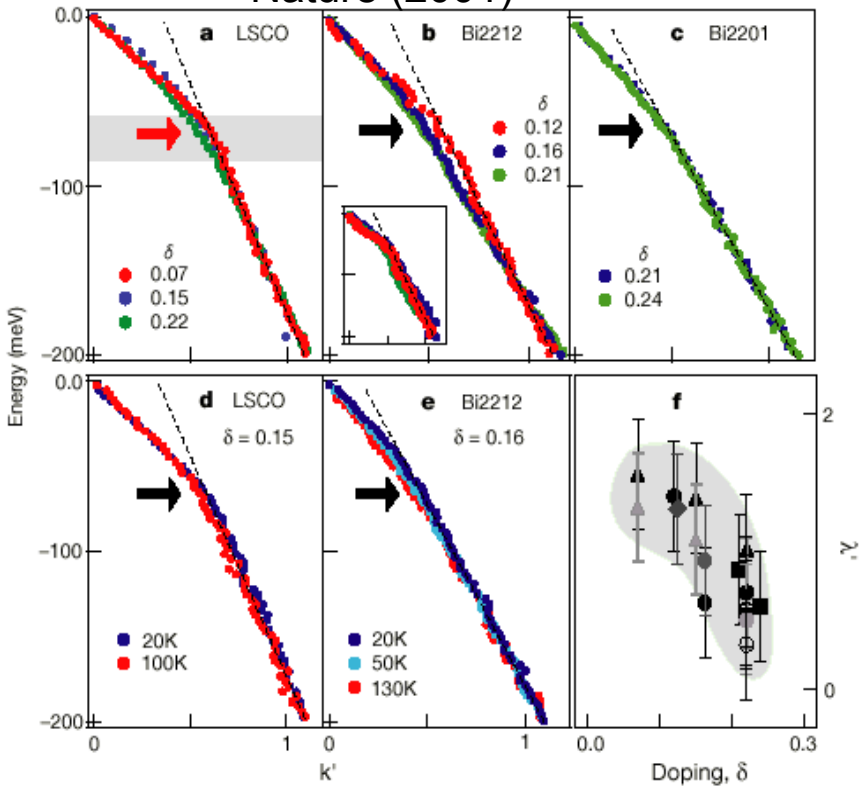
In principle the ARPES spectral function contains all the info about the single-particle many-body fermionic interactions. This plus bosonic measurements from neutrons or inelastic x-rays should give a nearly complete picture of the many-body physics.

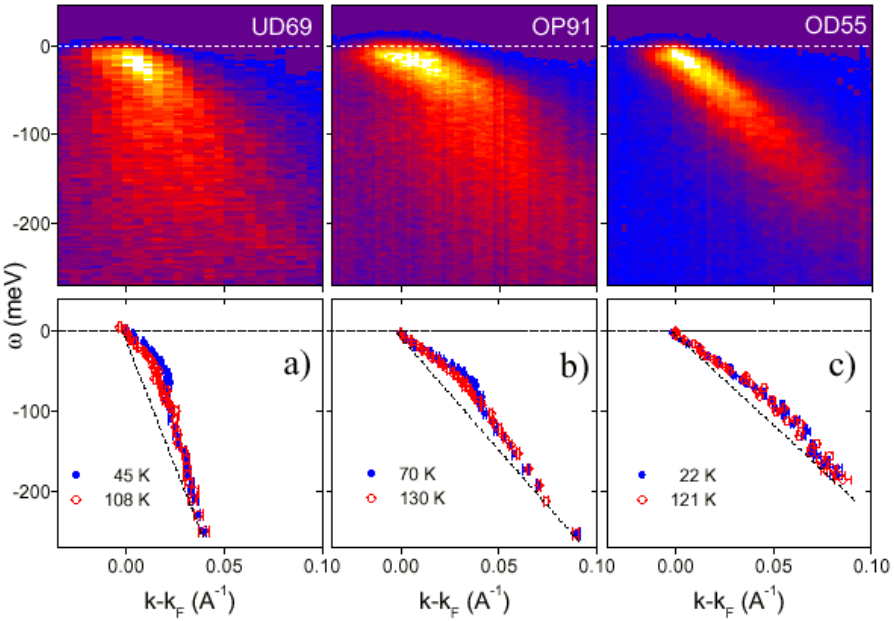
kinks in cuprates
(π,π) direction (nodal direction of d-wave gap)

Stanford Group
Lanzara et al.
Nature (2001)

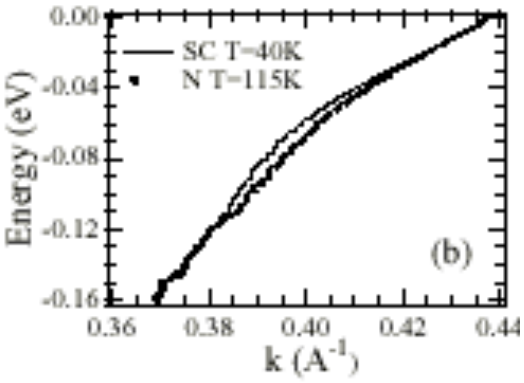
Kink energy scale ~ 65 meV

Brookhaven Group
Johnson et al.
PRL (2001).





Argonne Group
Kaminski et al.
PRL (2001)

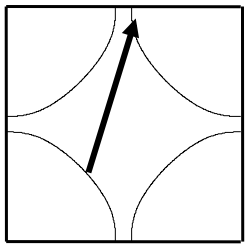


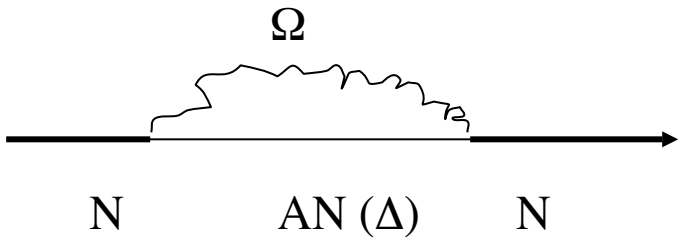
Origin of boson that is causing this kink?
- Phonon?
- "41 meV" Neutron magnetic resonance mode?

Electron-Boson Coupling and SC Gap Referencing (SC state)

Self-energy term has an intermediate set of states at k' that are summed over. The set of k' is not a-priori known.

- If nodal-antinodal (e.g. magnetic resonance mode, B_{1g} phonon) then gap referencing (to an average around the FS) needed. Mode should shift by gap average upon entering SC state. Mode ~ 30-40 meV.



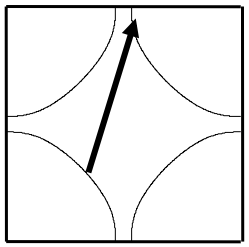


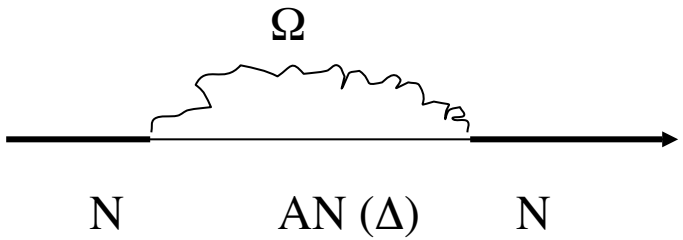
Most data is inconsistent with an energy shift of the kink energy (same kink energy in N and SC state, or no kink in the N state).

Electron-Boson Coupling and Gap Referencing (SC state)

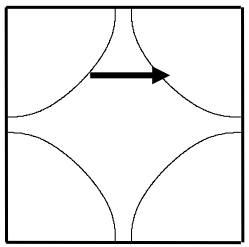
Self-energy term has an intermediate set of states at k' that are summed over. The set of k' is not known.

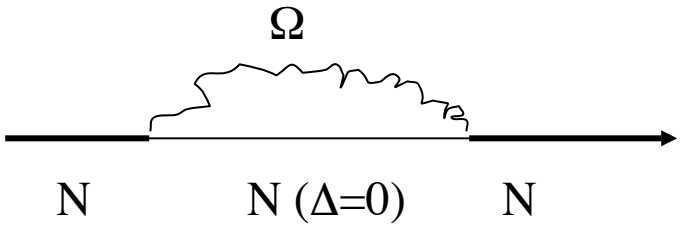
- If nodal-antinodal (e.g. magnetic resonance mode, B_{1g} phonon) then gap referencing (to an average around the FS) needed. Mode should shift by gap average upon entering SC state. Mode ~ 30-40 meV.



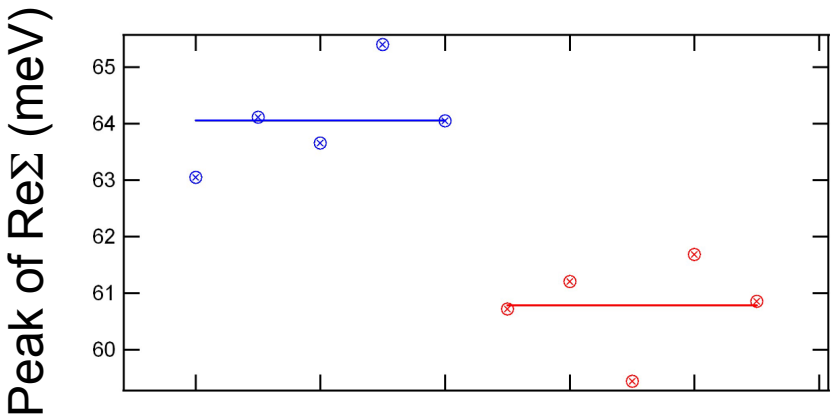


- If nodal-nodal (e.g. LO phonon) then no gap referencing needed. Mode energy = nodal kink energy = 65 meV.





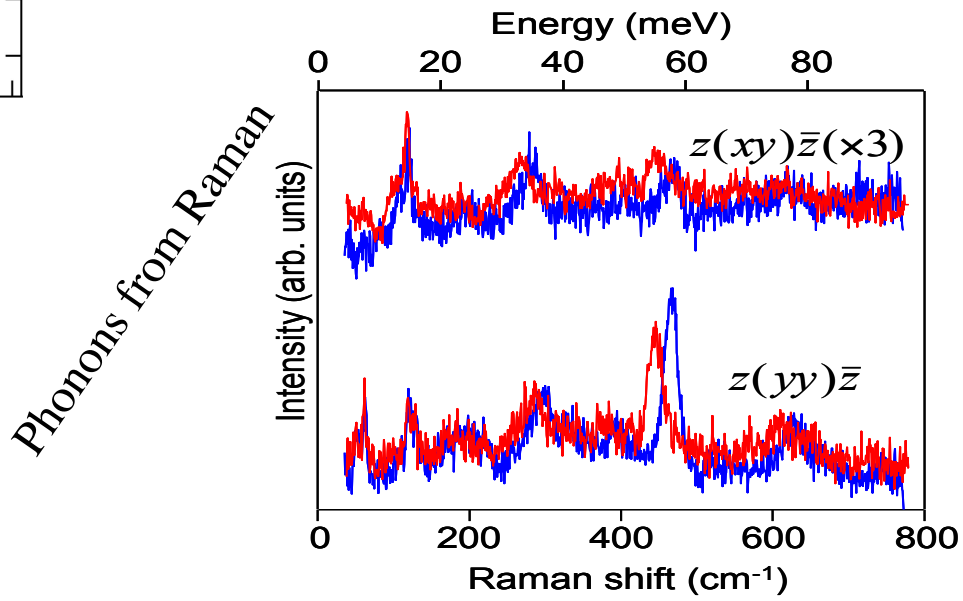
Isotope Effect study of the nodal kink (SC state)

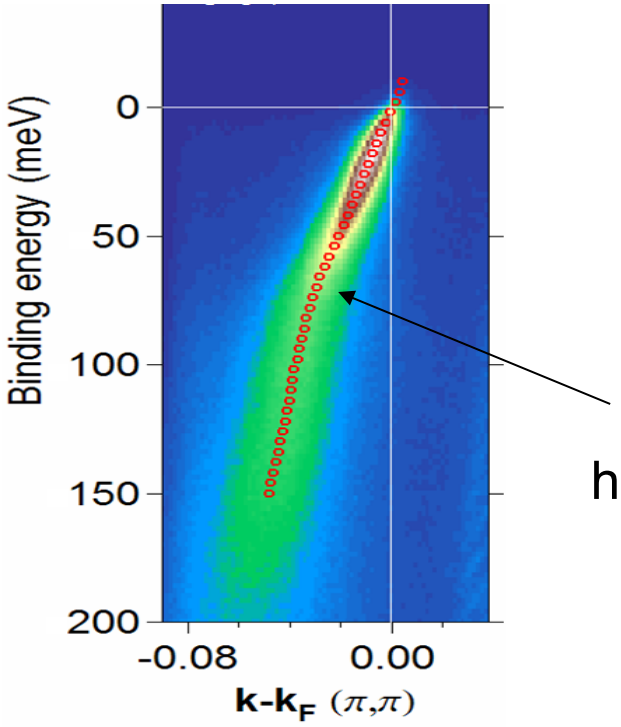


^{16}O

^{18}O

Kink softening of 3.4 ± 0.5 meV

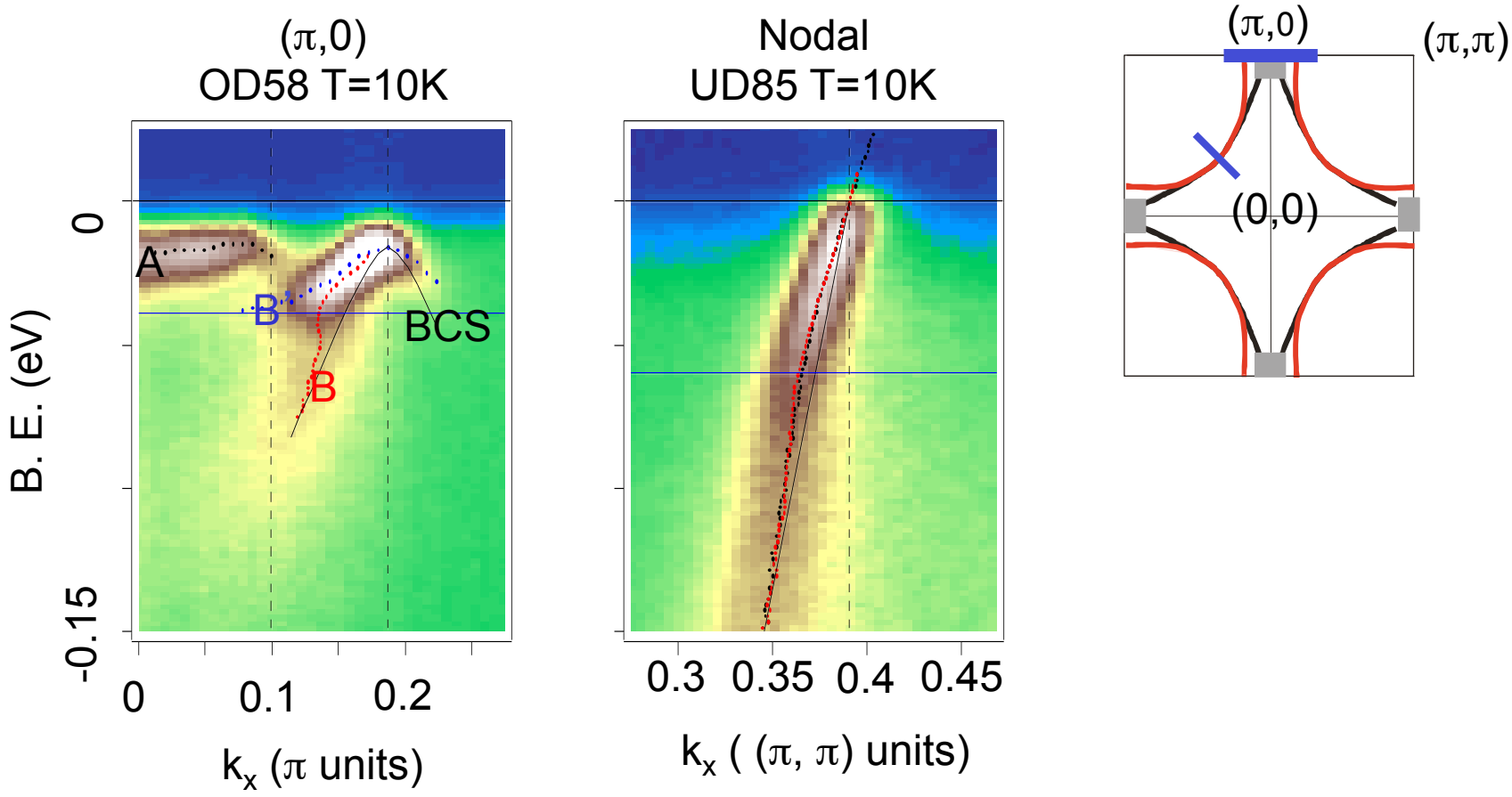




Nodal kink positively fingerprinted as having a major contribution from electron-phonon coupling.

H. Iwasawa, D.S.D. et al., PRL 101, 157005 (2008)

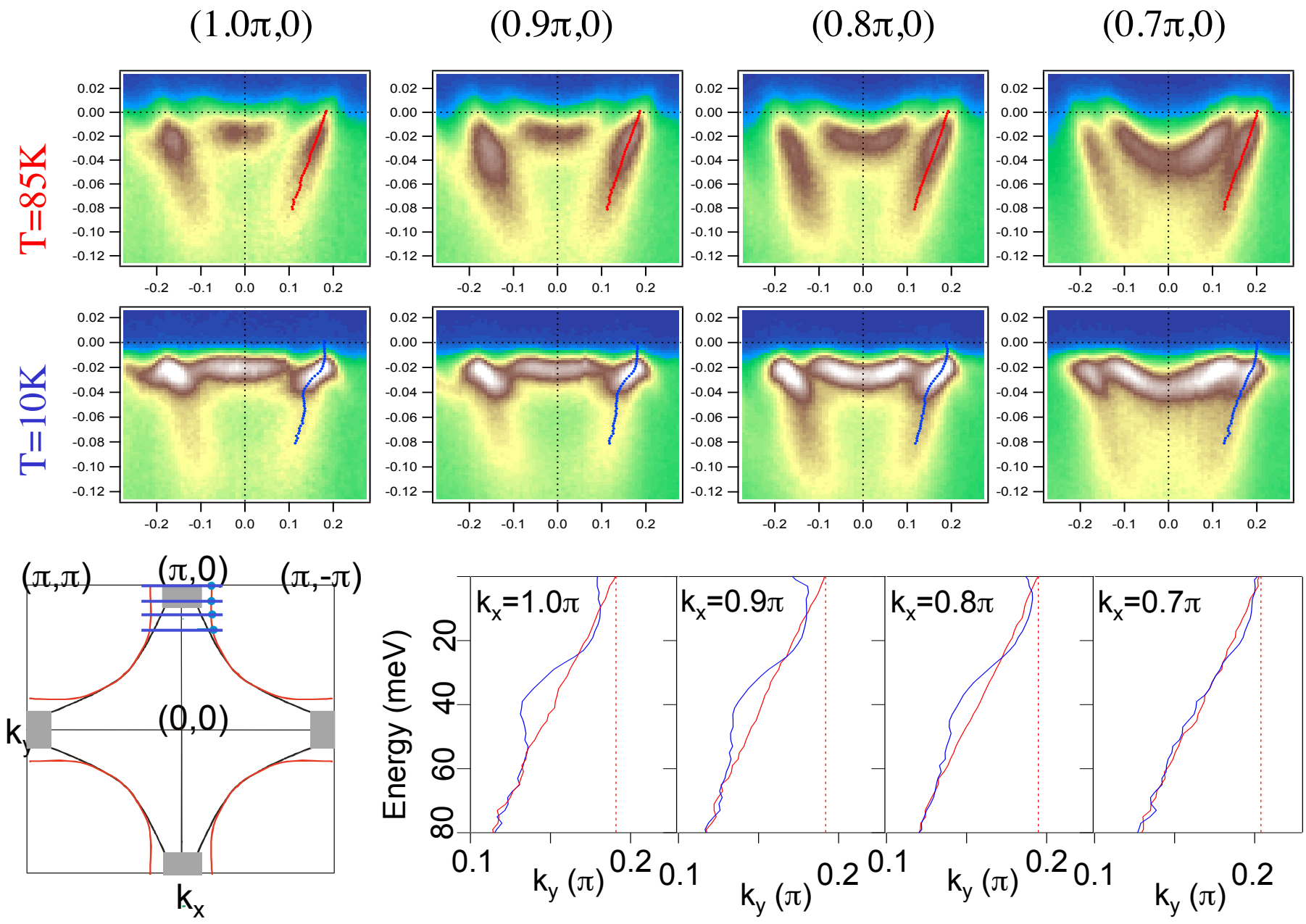
(π,0) kink vs. nodal kink



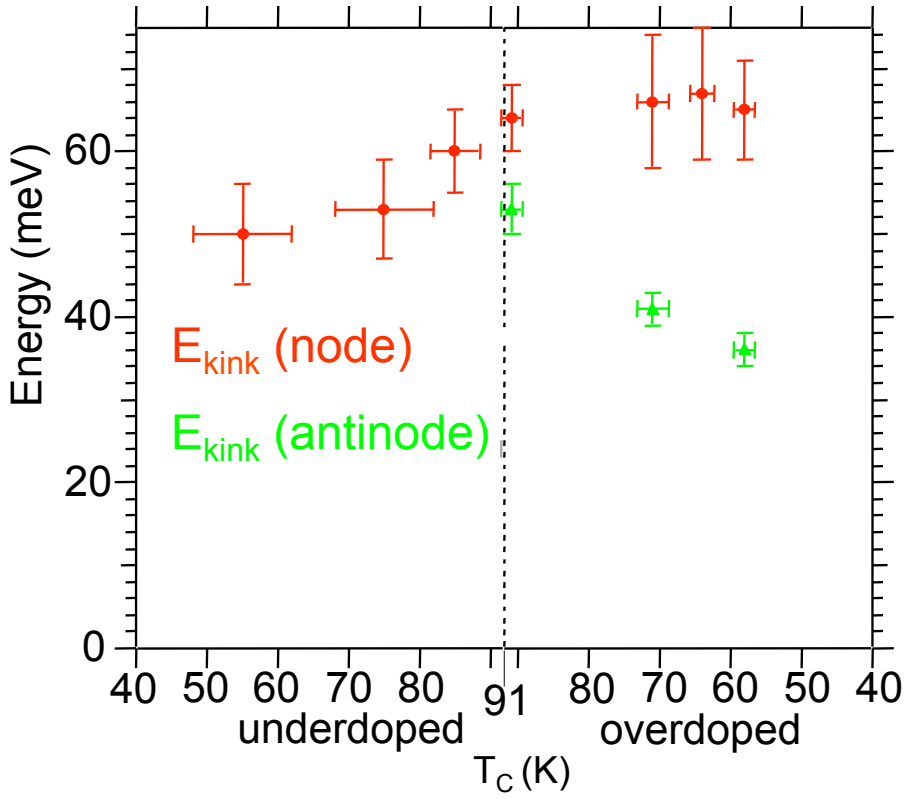
(π,0) kink is much stronger than nodal kink,
shows much stronger T dependence, and is at a different (lower) energy.

A.D. Gromko, D.S.D. et al. Phys. Rev. B **68**, 174520 (2003).

k-dependence of the kink near (π,0) T_c=71K OD Bi2212



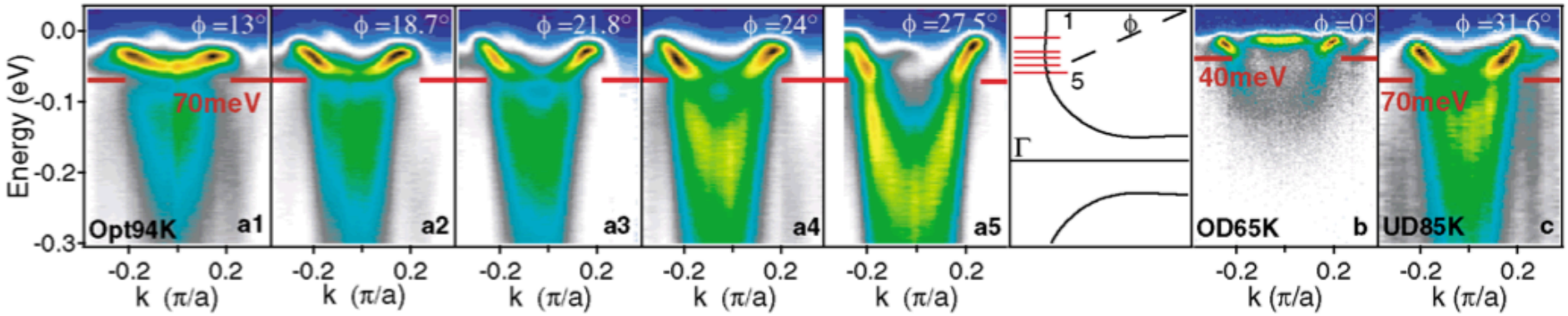
Doping dependence of kink energies (Bi2212)



Gromko et al., Phys. Rev. B **68**, 174520 (2003).

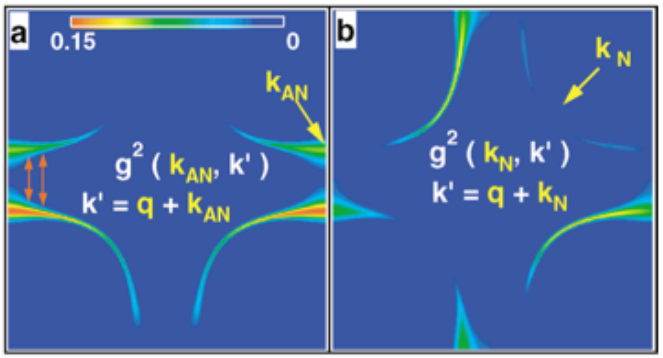
- Nodal and Antinodal kinks have different energy scales, different k-dependence, different T dependences ==> different phenomena.

Other studies on the (π,0) kink



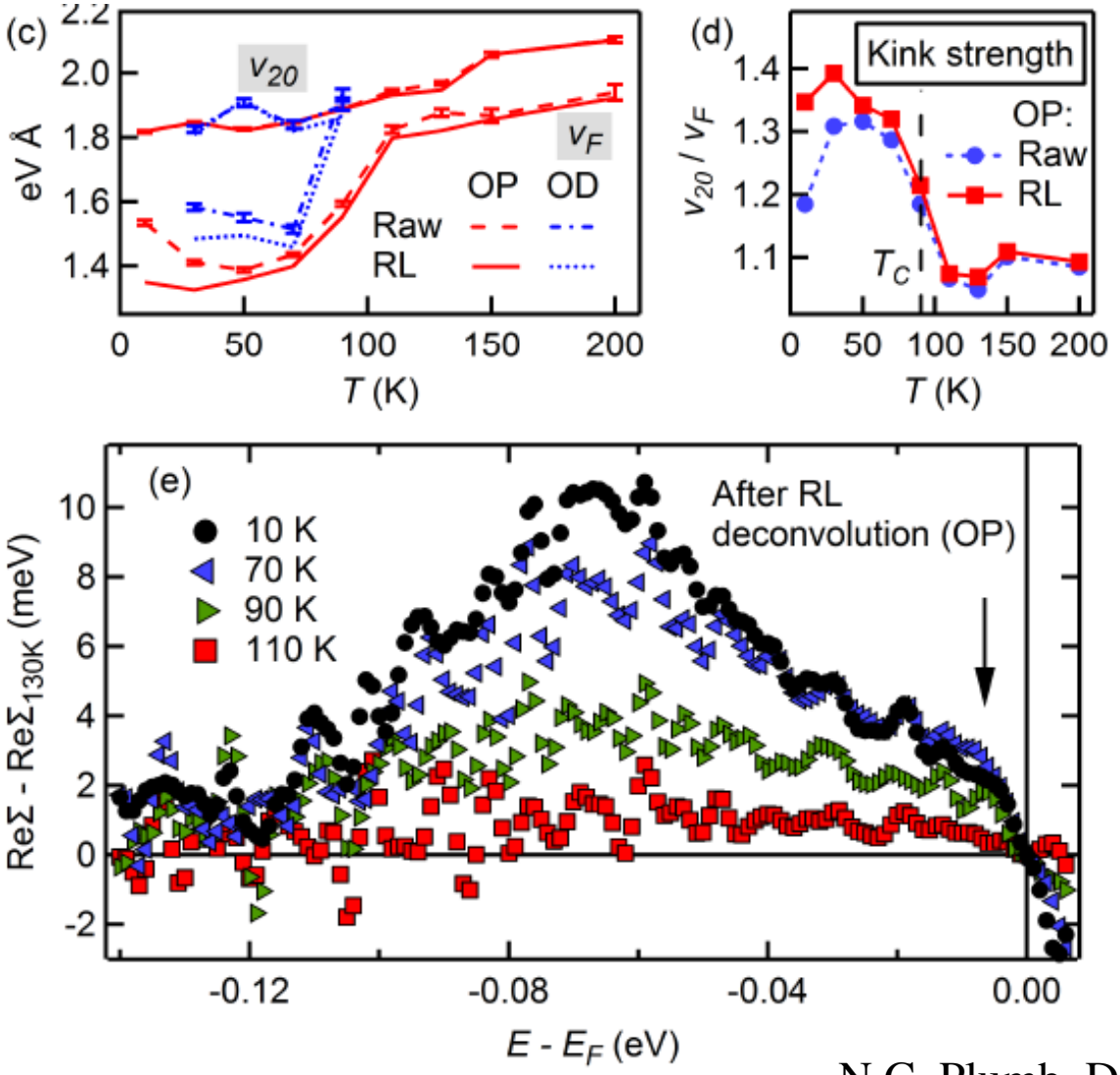
"Phenomenological agreements with neutron and Raman experiments suggest that this mode is the B_{1g} oxygen bond-buckling phonon."

Calculation of $g^2(k,k')$ (electron-phonon vertex)



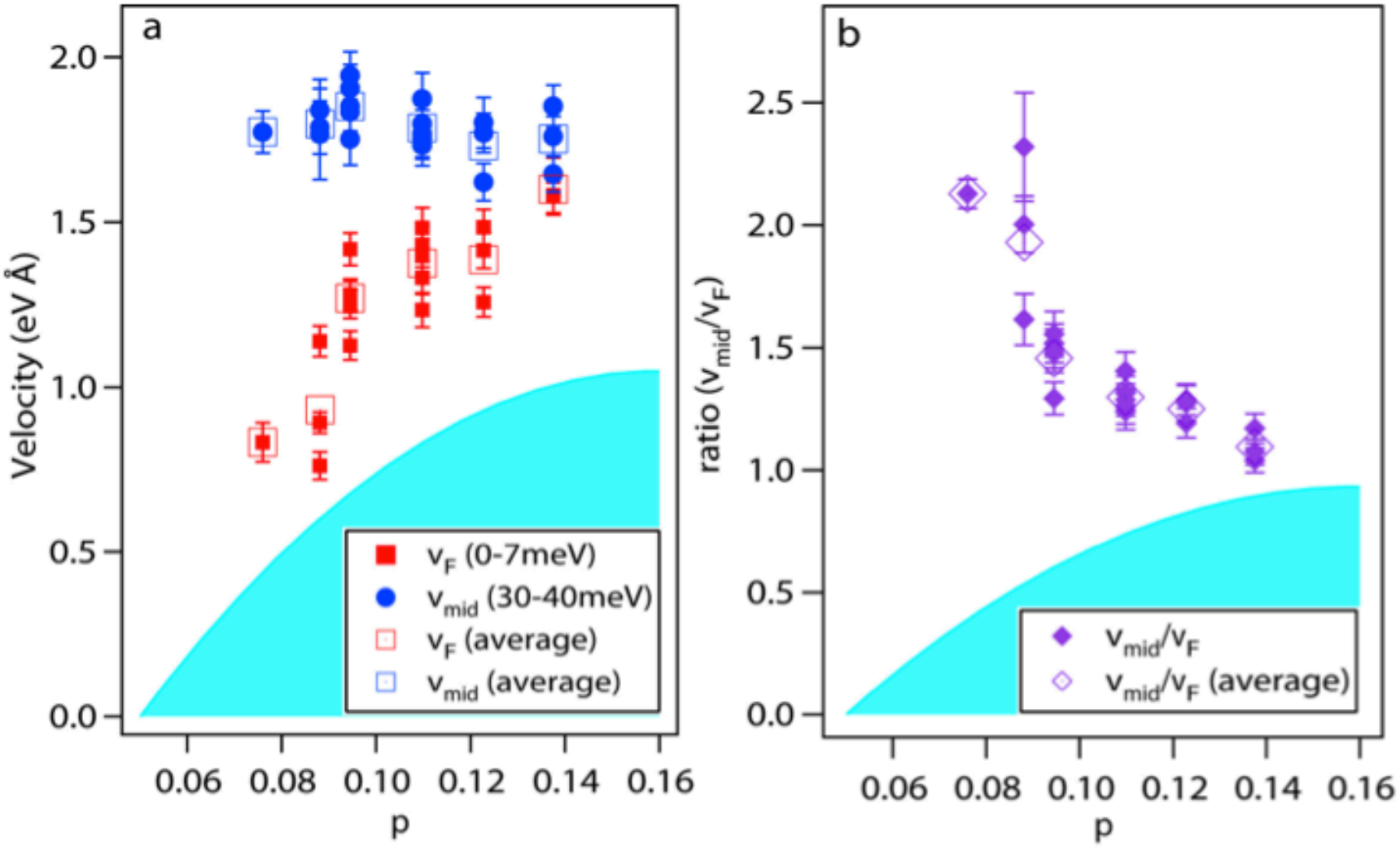
T. Cuk, ZX Shen, T. Devereaux et al, PRL 2004

10 meV scale kink at node in Bi2212
Only visible in SC state



N.C. Plumb, D.S.D. PRL (2010)

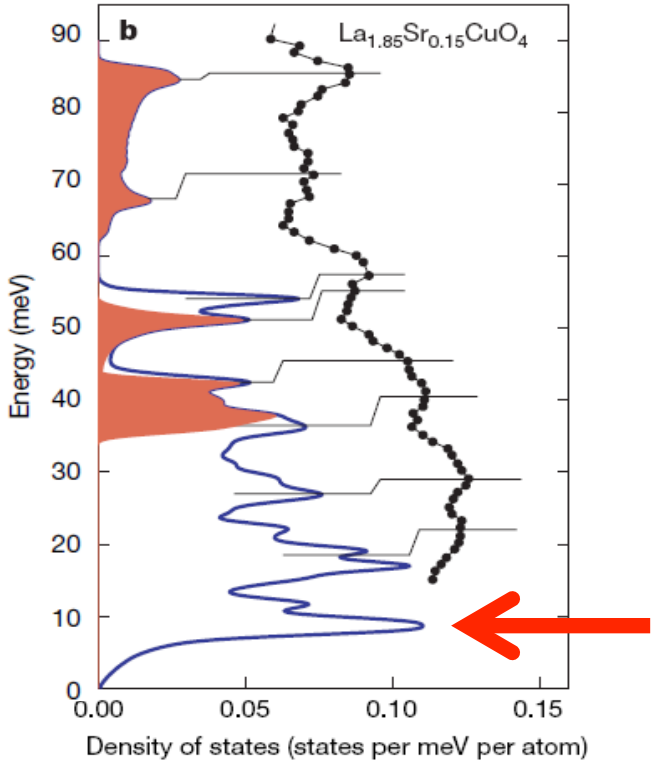
Doping dependence of the low energy (< 10 meV) kink



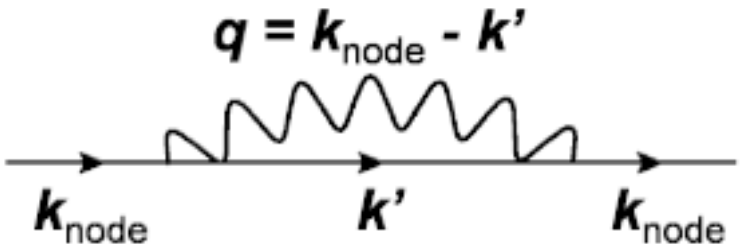
Low E kink stronger for UD samples.

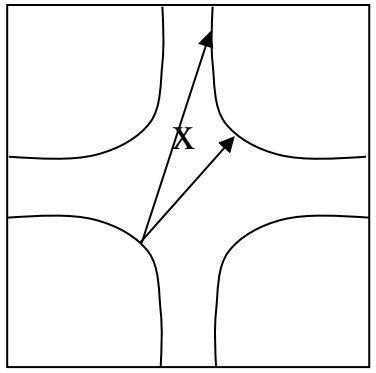
Vishik, Shen 2010

Possibility of phonons?



Phonon DOS: Giustino, Cohen & Louie, Nature **452**, 975 (2008).

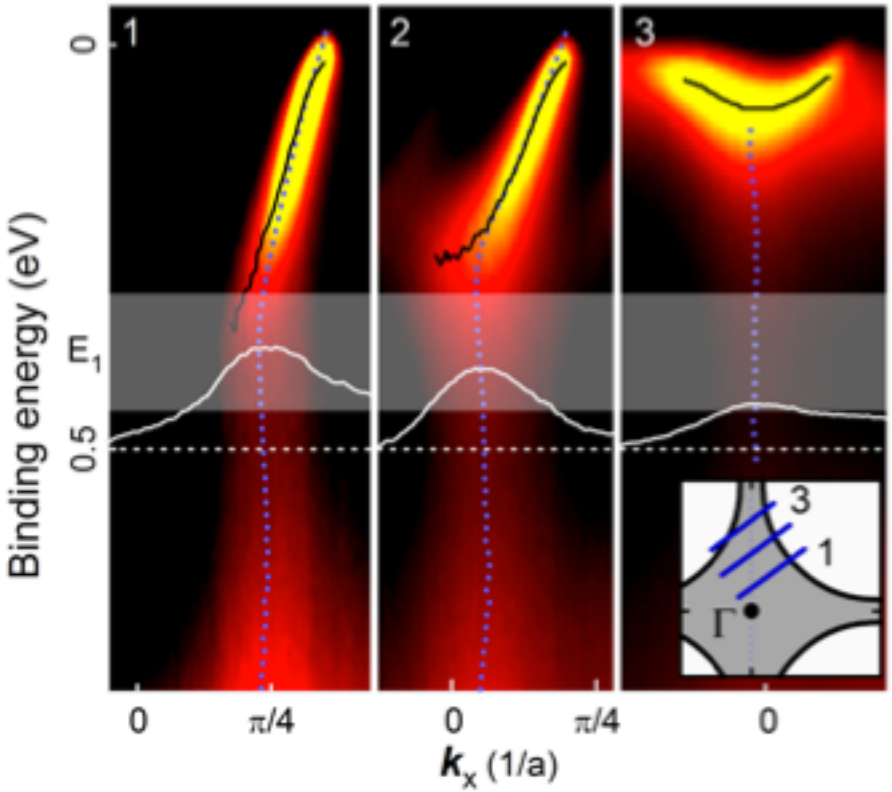




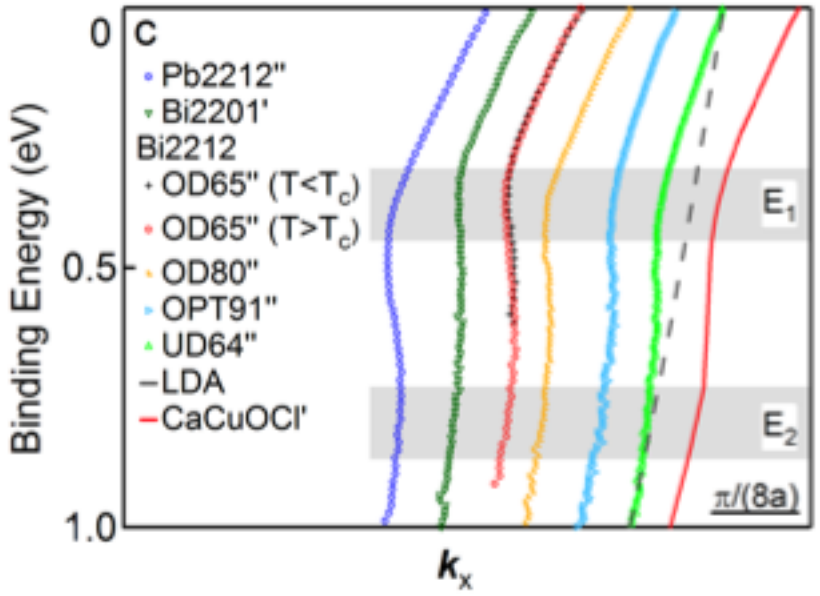
If phonons:
- Extreme forward scattering required.
- Why kink turns on at T_c?

Johnston and Devereaux studied this in detail. Unusual case where $\Omega < \Delta$. (PRL 2012)

High energy anomaly or kink

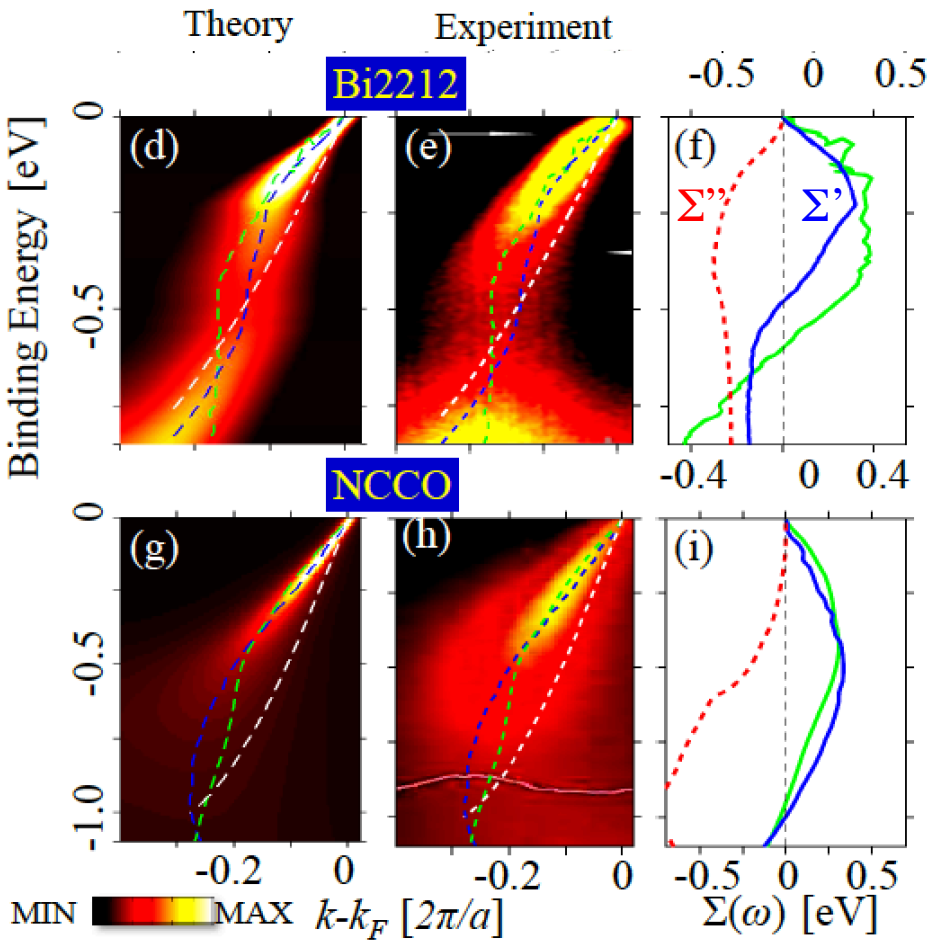


MDC-derived dispersion



Graf, Lanzara 2006

A new energy scale (~ 0.3 eV)? Interplay of different energy scales?
An issue of background/scattered weight/matrix elements?
Zero crossing of ReSigma?



Tanmoy Das, R. Markiewicz, A. Bansil

arXiv:1407.5722v1

Superconducting order parameter symmetry

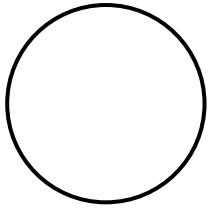
SC gap Δ = magnitude of order parameter. Varies as a function of k in a d-wave SC

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

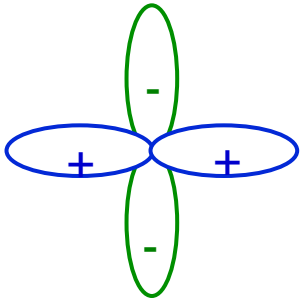
Antisymmetric under exchange

χ(spin) : known to be a singlet (S=0) ↓↑

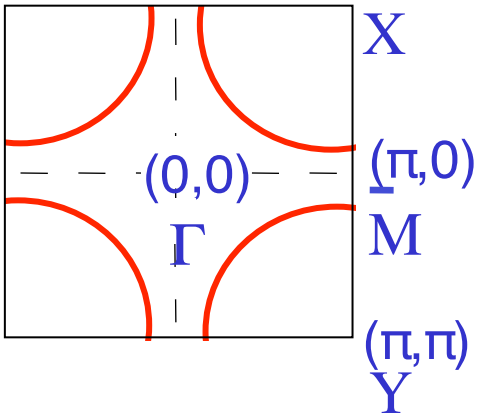
S = 0, l = 0
-- s-wave superconductor
(conventional SC)



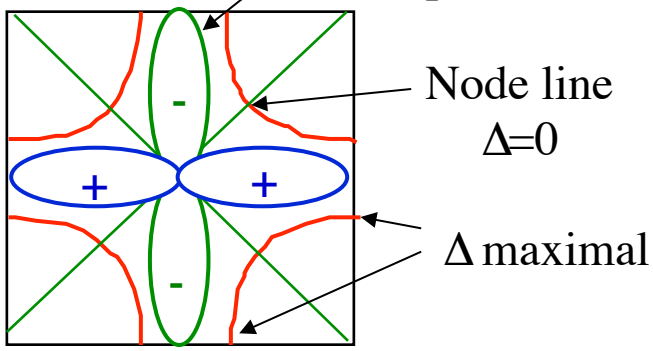
S = 0, l = 2
-- d-wave superconductor
(HTSCs - pretty sure)



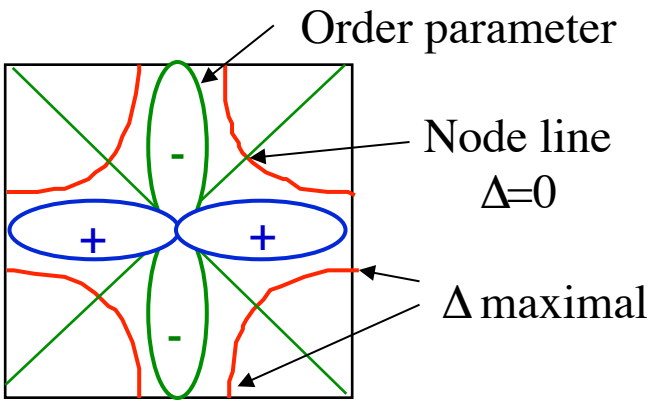
Hole-like Fermi Surface



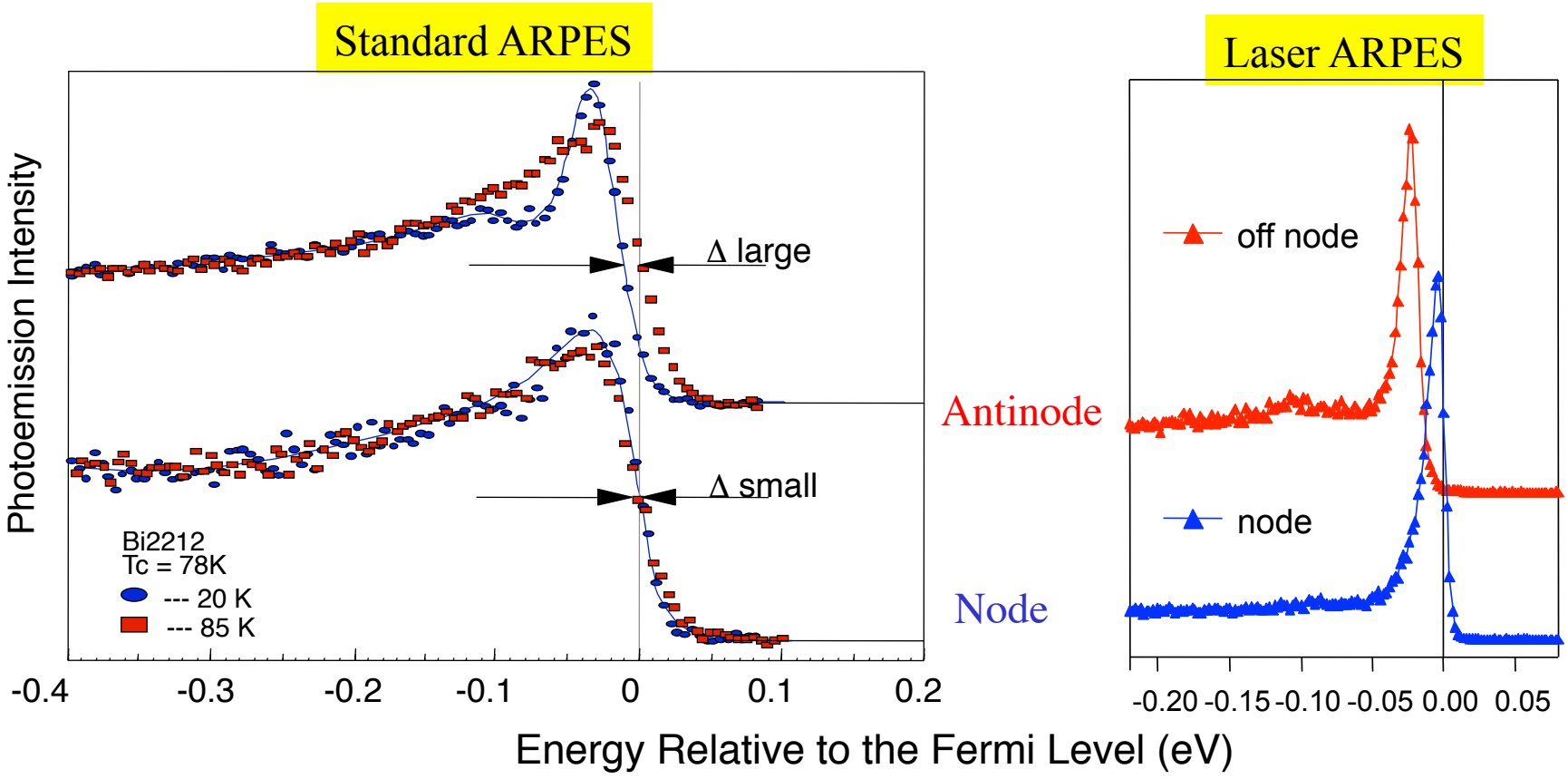
d-wave SC gap - maximal near (π,0)



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



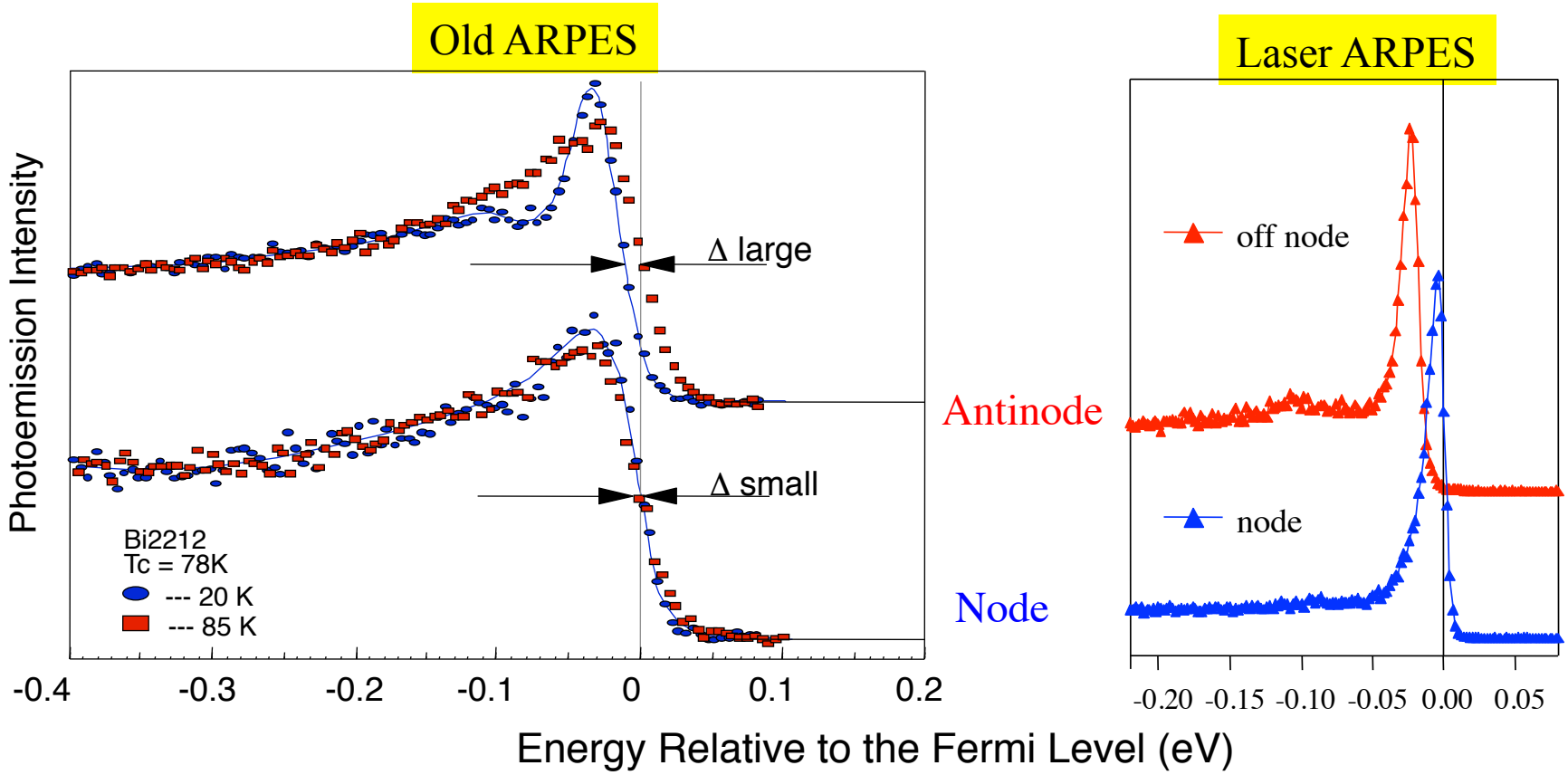
k-space dependence of superconducting energy gap Δ
→Symmetry of Cooper pair wavefunction is d-wave (l=2)



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)

Measurement of the d-wave superconducting gap



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)

How to **quantitatively** determine the gap magnitude?

- Midpoint of the leading edge?
- Peak separation of symmetrized EDCs?
- Fit to model spectral function?

Qualitative problems when Δ is small or T is large.

How to understand the self energies or scattering rates (peak broadening)?

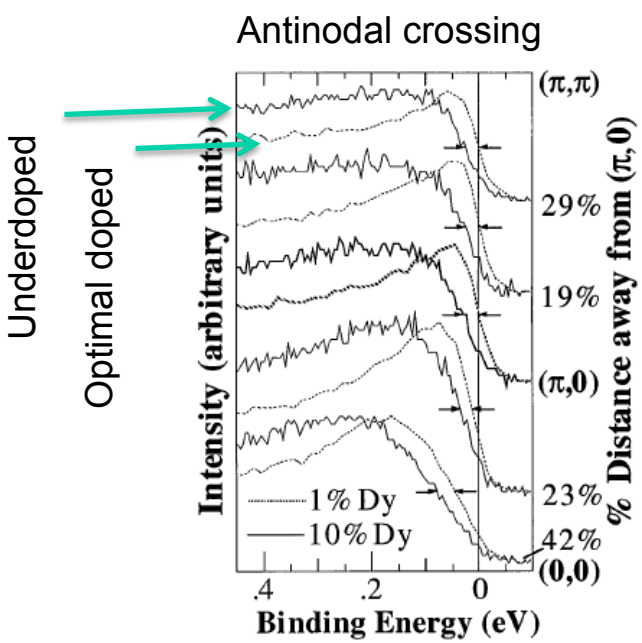
Pseudogaps

Original ARPES pseudogap study in cuprates. Arcs and pockets.

VOLUME 76, NUMBER 25 PHYSICAL REVIEW LETTERS 17 JUNE 1996

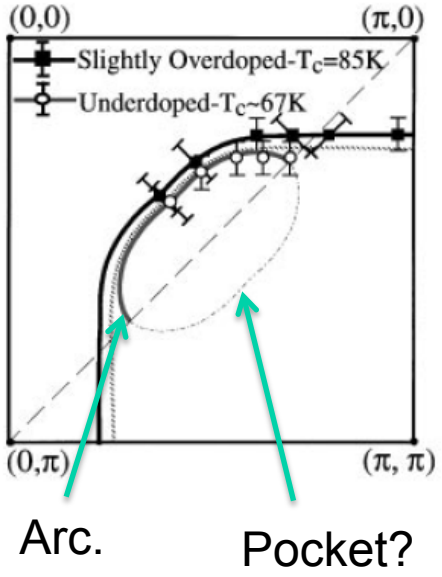
Unconventional Electronic Structure Evolution with Hole Doping in $Bi_2Sr_2CaCu_2O_{8+\delta}$: Angle-Resolved Photoemission Results

D. S. Marshall,[1] D. S. Dessau,[1,2,5] A. G. Loeser,[1,2] C-H. Park,[1,2] A. Y. Matsuura,[1] J. N. Eckstein,[3] I. Bozovic,[3] P. Fournier,[4] A. Kapitulnik,[4] W. E. Spicer,[1] and Z.-X. Shen[1,2,4]



T=100K (above T_c)

UD sample has loss of spectral weight at antinodal crossing, but states never reach E_F.

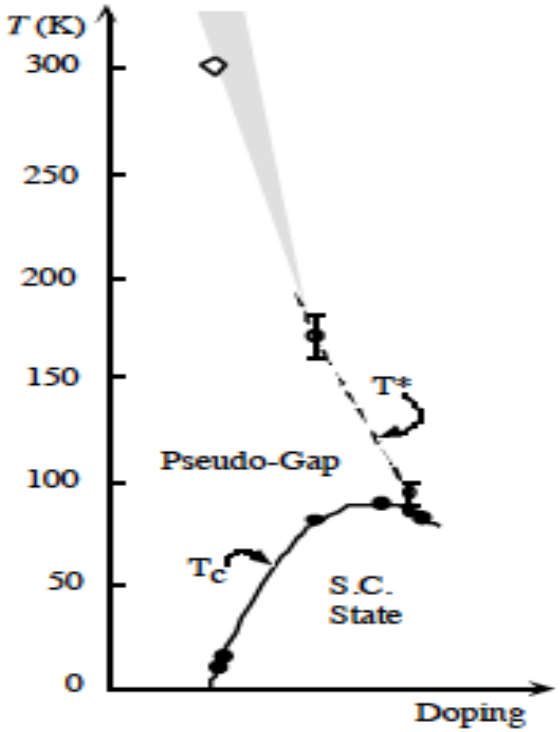


- Pgap is max at (π,0), vanishes on diagonal. d-wave like the SC gap. Precursor to SC?
- Pgap persists up to T*. Onset of pairing?
- With increasing underdoping, pgap at antinode grows, remaining Fermi arc shrinks.
- Length of arc increases with increasing temperature (as pgap shrinks).

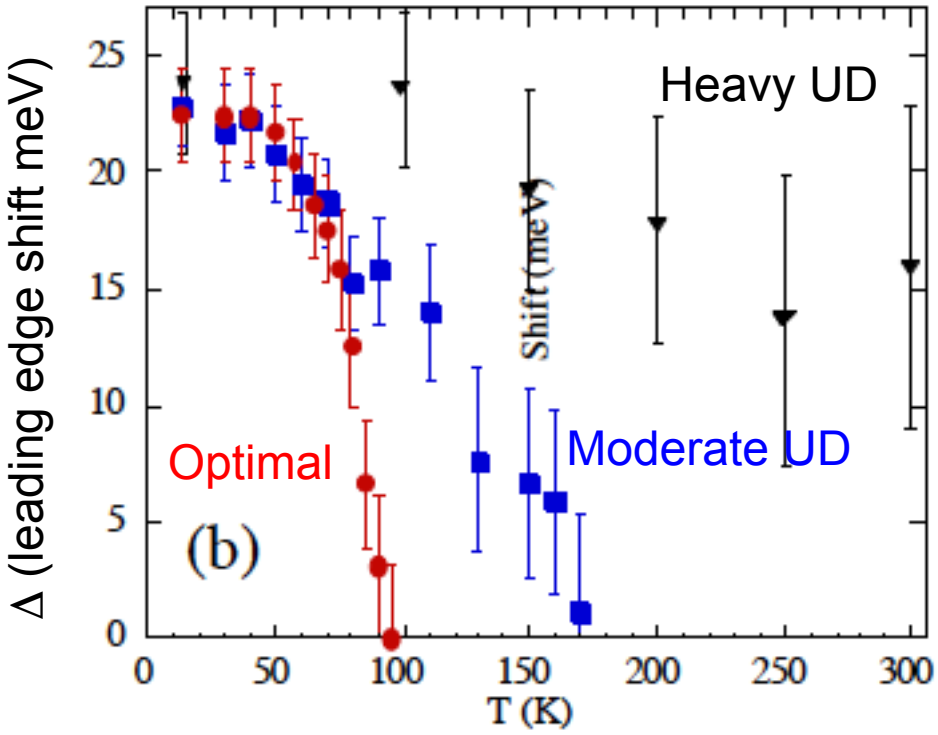
- Issues of band topology. Closed on backside to form pockets?

Spectroscopic evidence for a pseudogap in the normal state of underdoped high T_c superconductors

H. Ding[1,2], T. Yokoya[3], J.C. Campuzano[1,2], T.Takahashi[3], M. Randeria[4], M.R. Norman[2], T. Mochiku[5,6], K. Kadowaki[5,6], and J. Giapintzakis[7]

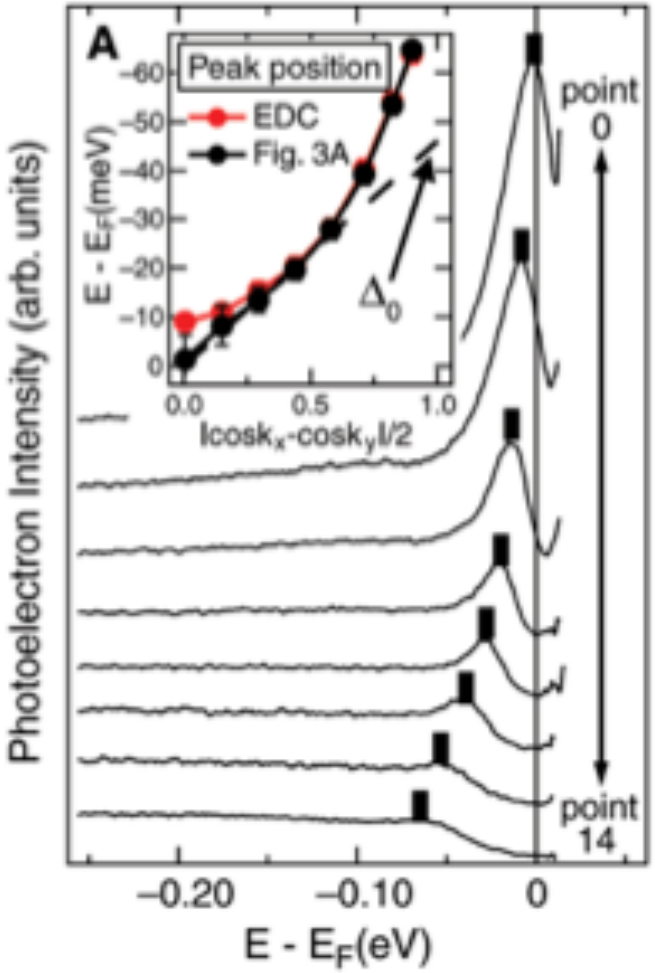


Antinodal gap vs T for different dopings



Nature **382**, 51-54 (4 July 1996)

"Hockey stick" in the gap function
T_c=50K underdoped Bi2212

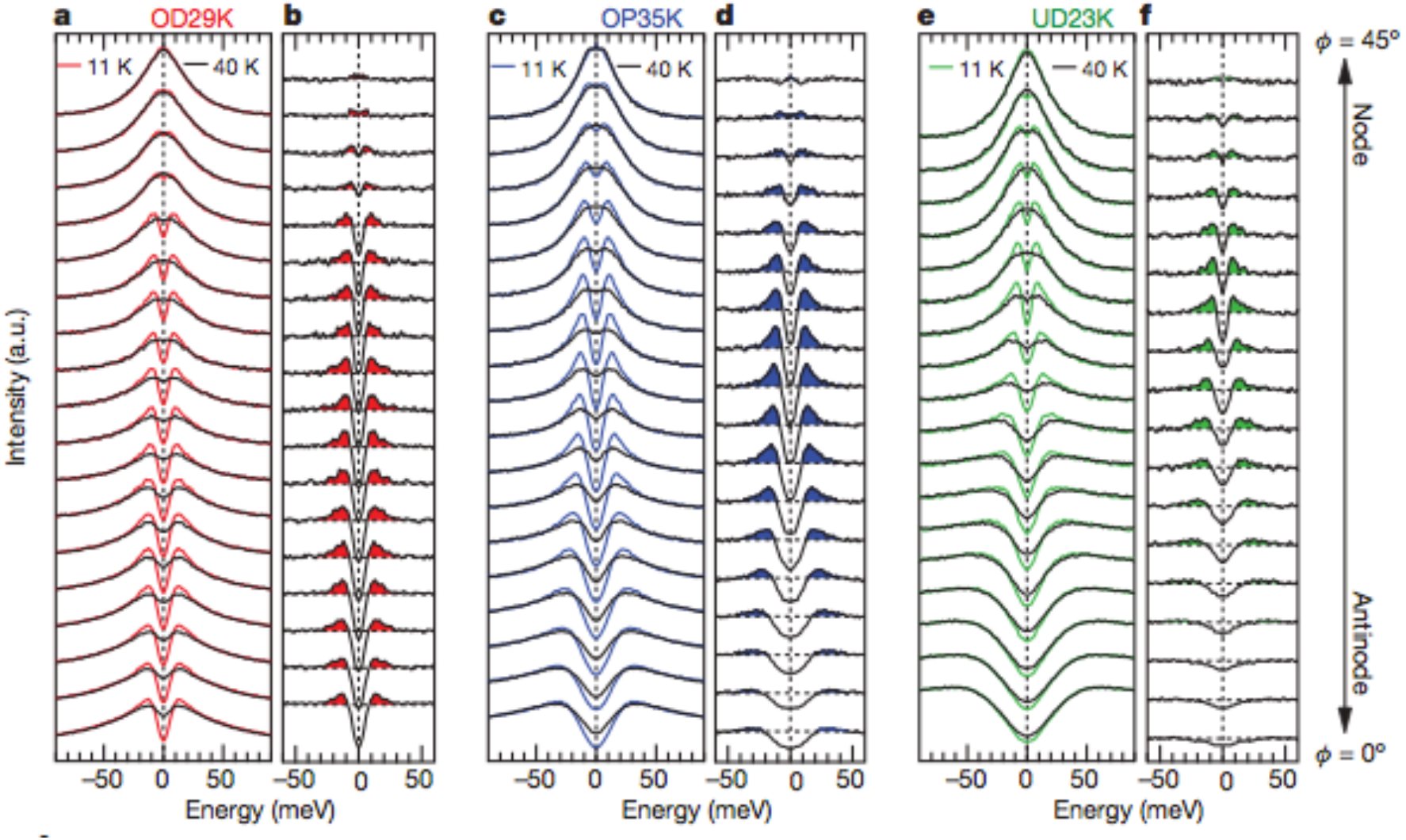


- Peak-position analysis.
- Increase in the gap magnitude in antinodal regime <u>beyond</u> the expectations from the pure SC d-wave form.
- Absent for overdoped samples, strong effect for underdoped samples.
- Is this indicative of a different form for the SC gap, or is it due to a different origin of the gap in the antinodal regime?

Tanaka, Shen et al. Science 2006

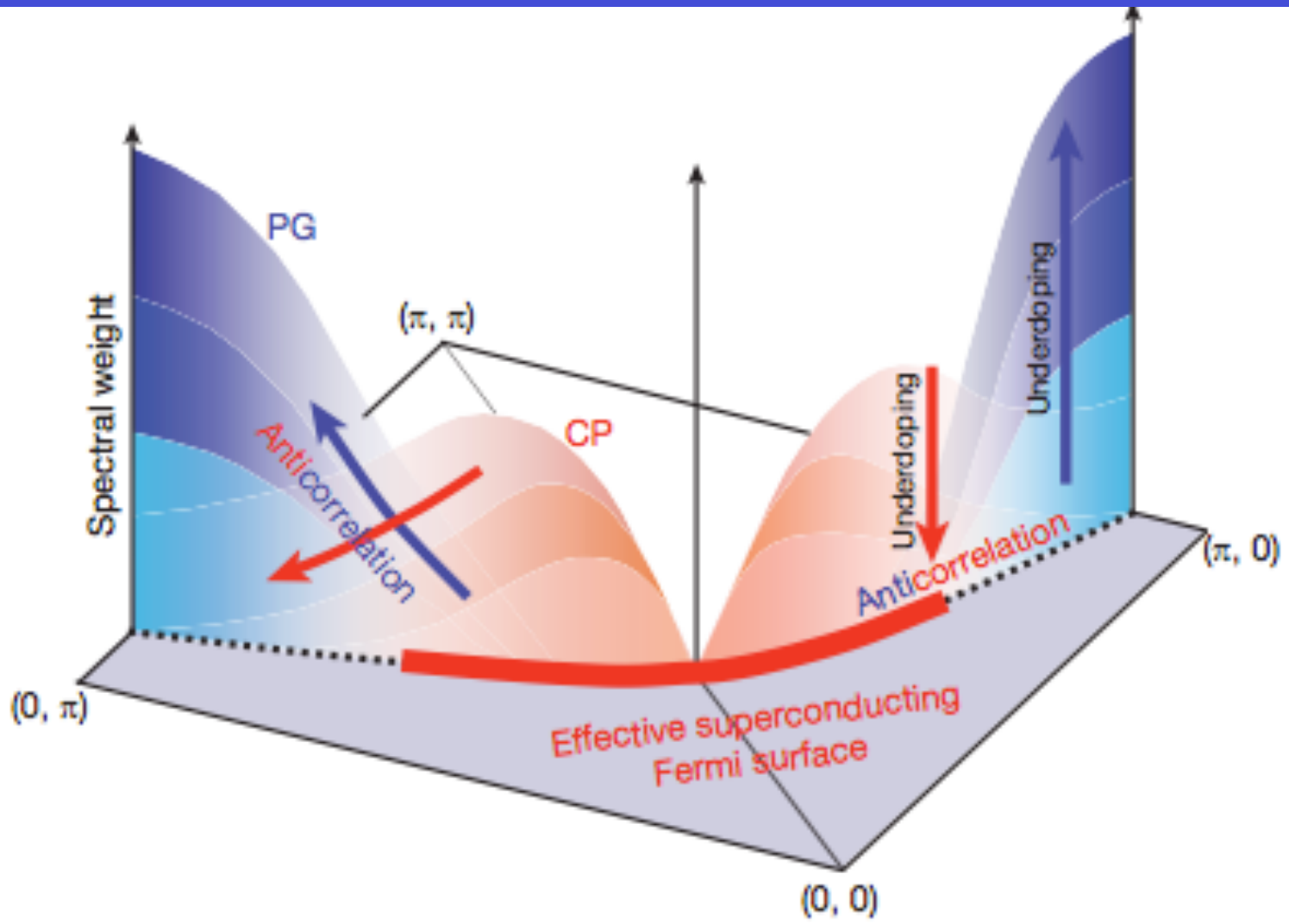
Competition between the antinodal pseudogap and the SC gap (single layer Bi2201)

Symmetrized EDCs at $k=k_F$ around the zone



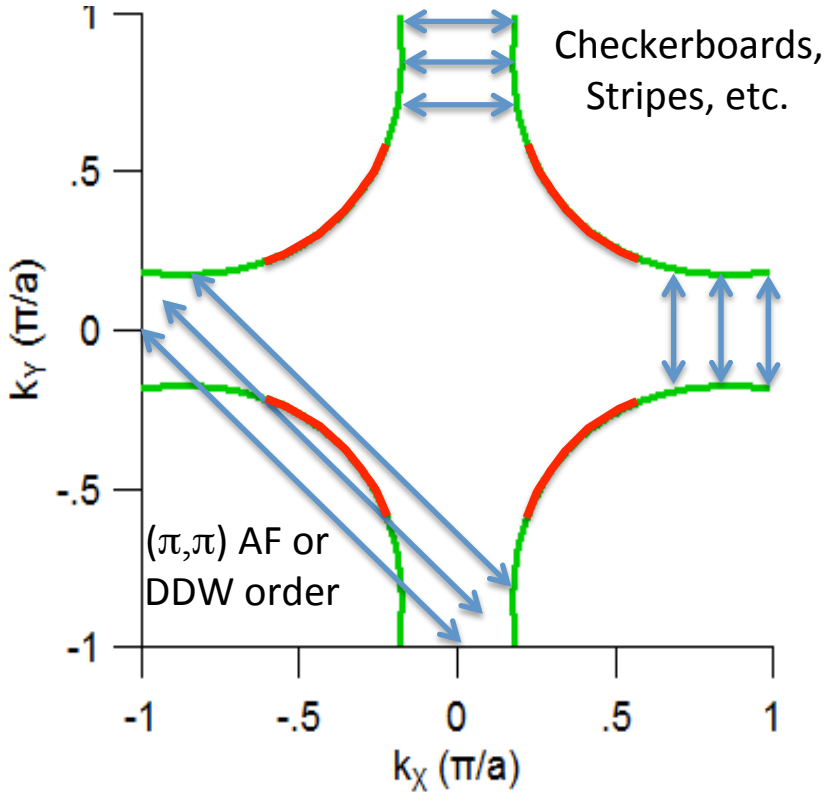
Kondo, Kaminski et al. Nature 2009

Competition between the antinodal pgap and the SC gap (Bi2201)



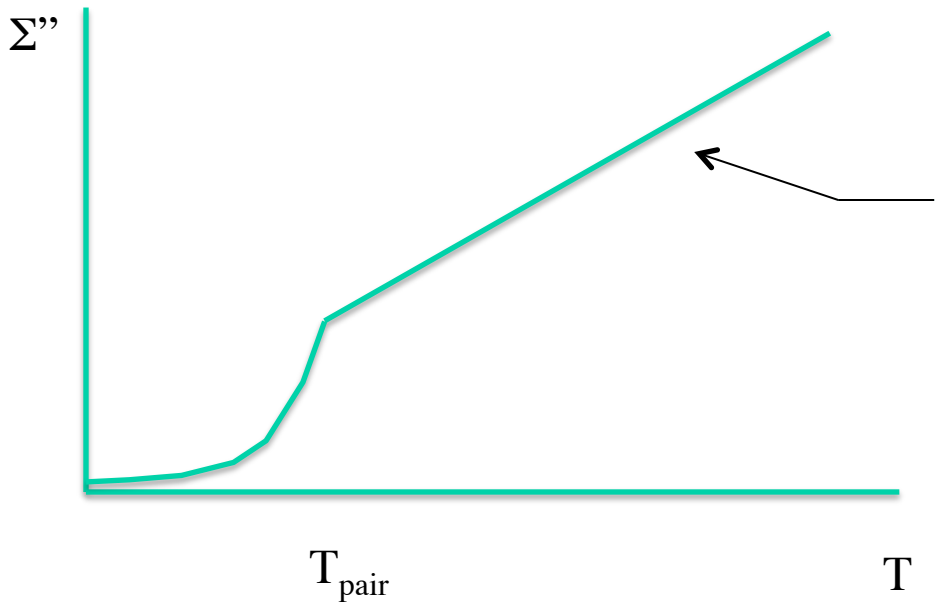
Kondo et al. Nature 2009

Near-node (away from the pseudogap) is the cleanest place to study the superconductivity



Self energy effects inside the gap

In addition to the opening of the d-wave SC gaps, there are dramatic drops in the single particle scattering rates (presumably due to the opening of the gaps themselves).

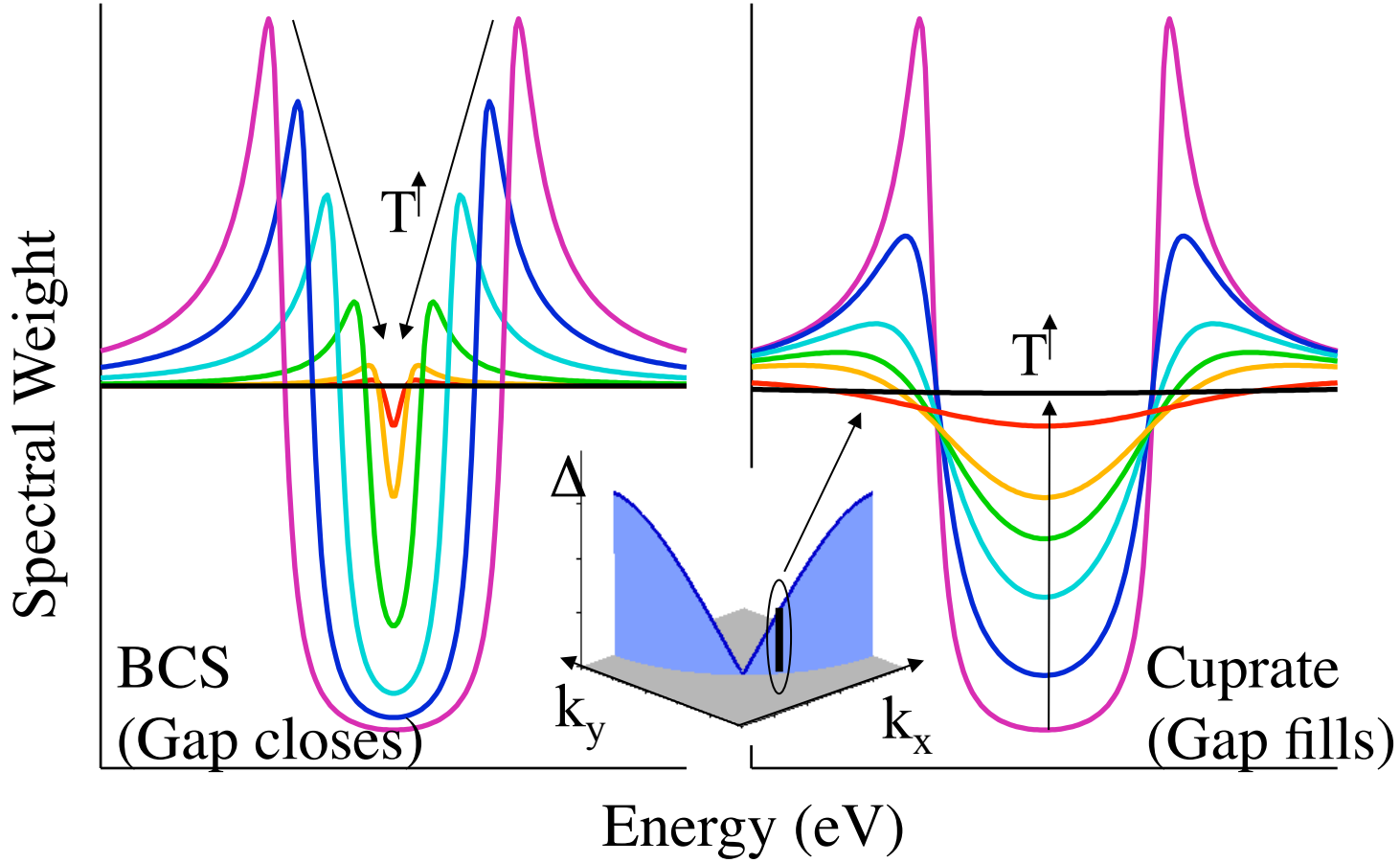


Linear-in-T scattering of the normal “strange metal” state.
Marginal Fermi Liquid” state, or better the “Power Law Liquid” state.

T. J. Reber, D.S.D. et al.
arXiv 1509.01611 (2015)

We wish to access these scattering rates at low energy inside the gap. MDC analysis methods fail because there are no MDC peaks inside the gap. EDC lineshapes have never been understood.

Closing/Filling of the gaps with temperature

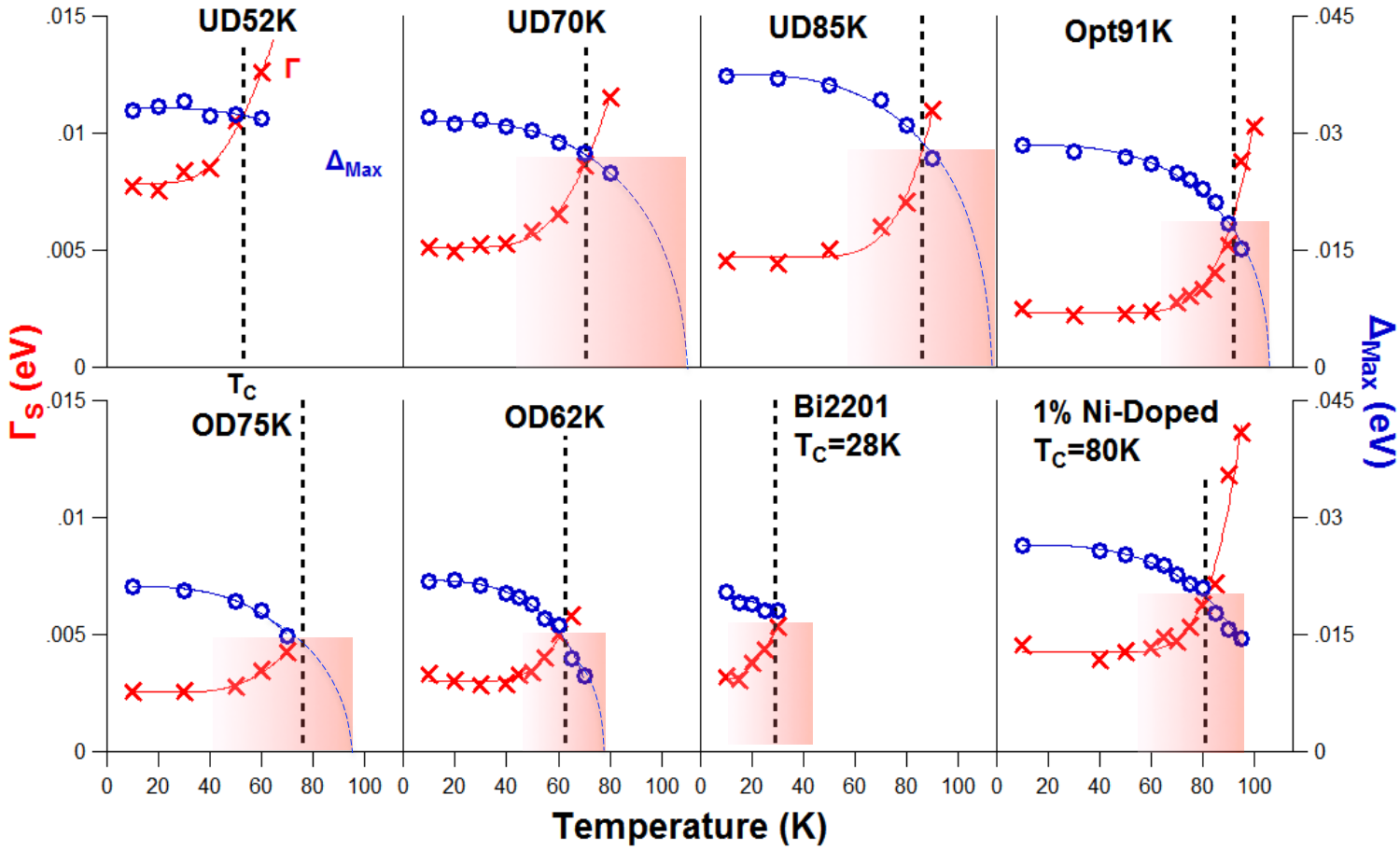


The filling of the gap in cuprates is due to the rapidly rising Γ (scattering rate) with temperature. This is a phenomenology observed in essentially all spectroscopies on cuprates, but has been difficult to quantify.

T. J. Reber, D.S.D. et al.

Crossover between superconductive pairing (Δ) and a self-energy term (Γ) occurs at/sets the T_c in cuprates.

Near nodal data uncontaminated by pseudogap effects.



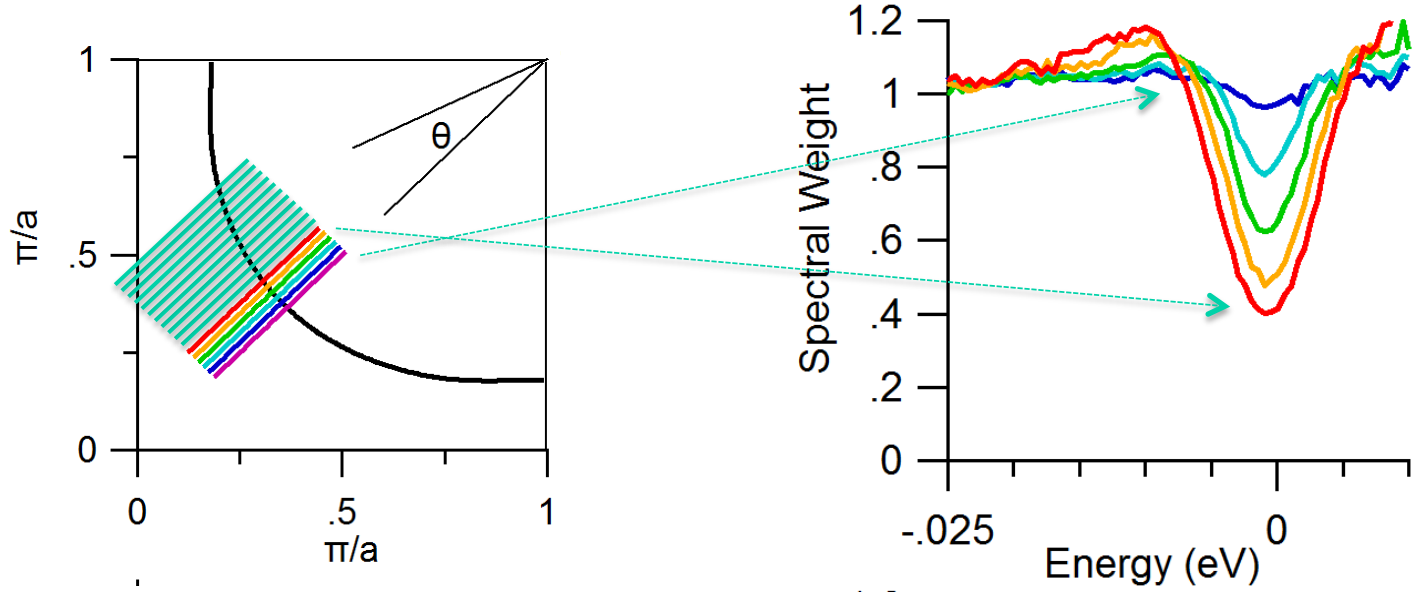
Pairing (Δ) extends well above T_c in all cases (indicates pre-formed pairs above T_c, which condense at T_c). Γ "fills in" the gap.

T.J. Reber, D.S.D. et al, arXiv 1508.06252

New method for analyzing gaps and scattering rates. Tomographic Density of States (TDoS)

Tomographic = sliced or sectioned.

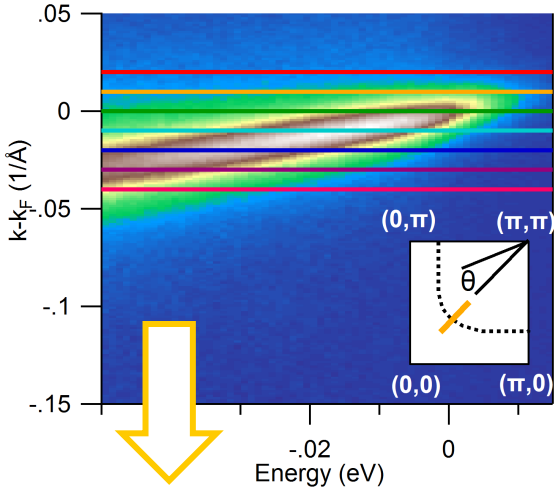
Flat DOS modulated by d-wave SC gap.

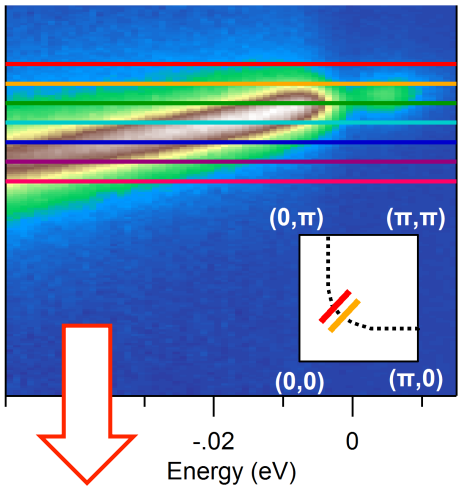


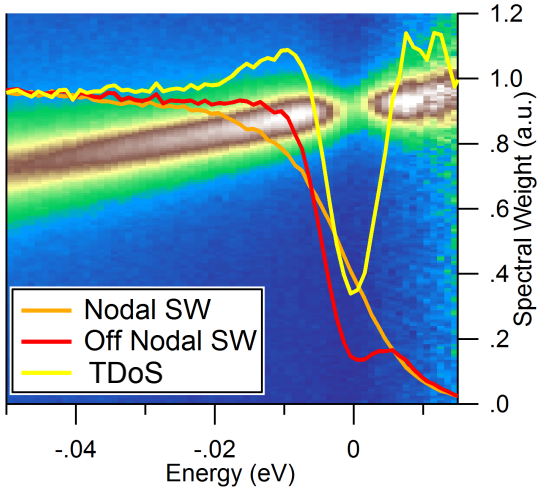
Quantitative determination of gaps and scattering rates (via Dynes tunneling formula).

T. J. Reber, D.S.D. et al. Nature Physics **8**, 606–610 (2012)

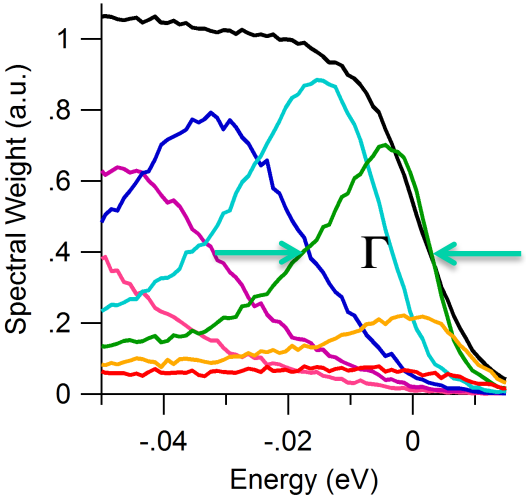
Creating the Tomographic Density of States (TDoS)

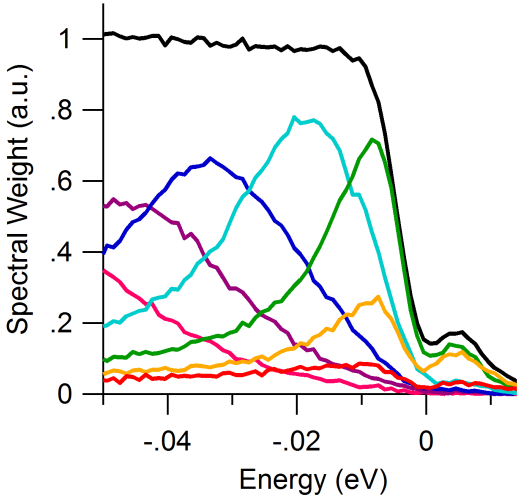






Sample:
Bi2212
T: 50 K
T_C: 91 K
hv:7 eV





Colored: EDCs along one cut.
Black: Sum of ~ 170 EDCs = spectral weight curves.
Yellow (above): Normalized spectral weights = TDoS

The weight above E_F is real (no symmetrization has been done).

EDC peak widths (scatt rates) ~ 15 meV or greater. Full scattering, including heterogeneous contribution.
TDoS scattering rate ~ 2-3 meV – homogeneous contribution?

Fitting to Dynes's Tunneling Formula (1978)

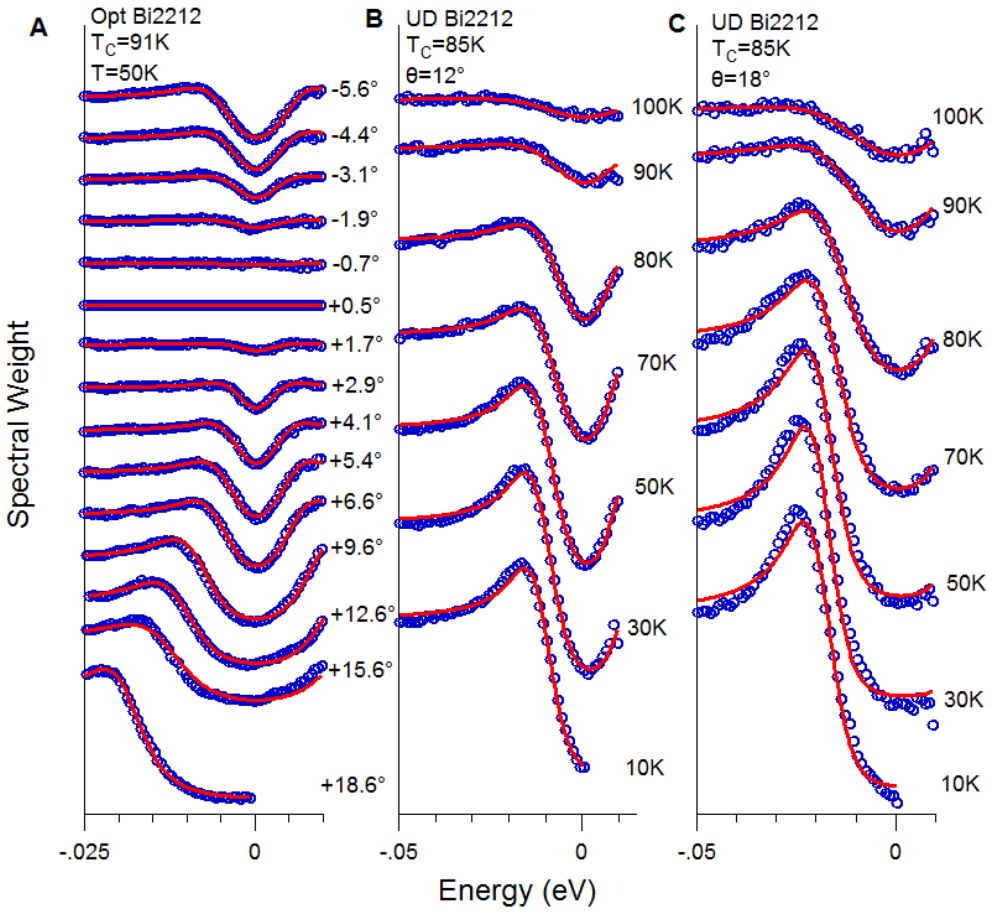
$$I_{TDoS}(\omega) = \rho_{Dynes}(\omega) = \mathrm{Re}\frac{\omega + i\Gamma}{\sqrt{(\omega + i\Gamma)^2 - \Delta^2}}$$

Represents a broadened BCS DOS.

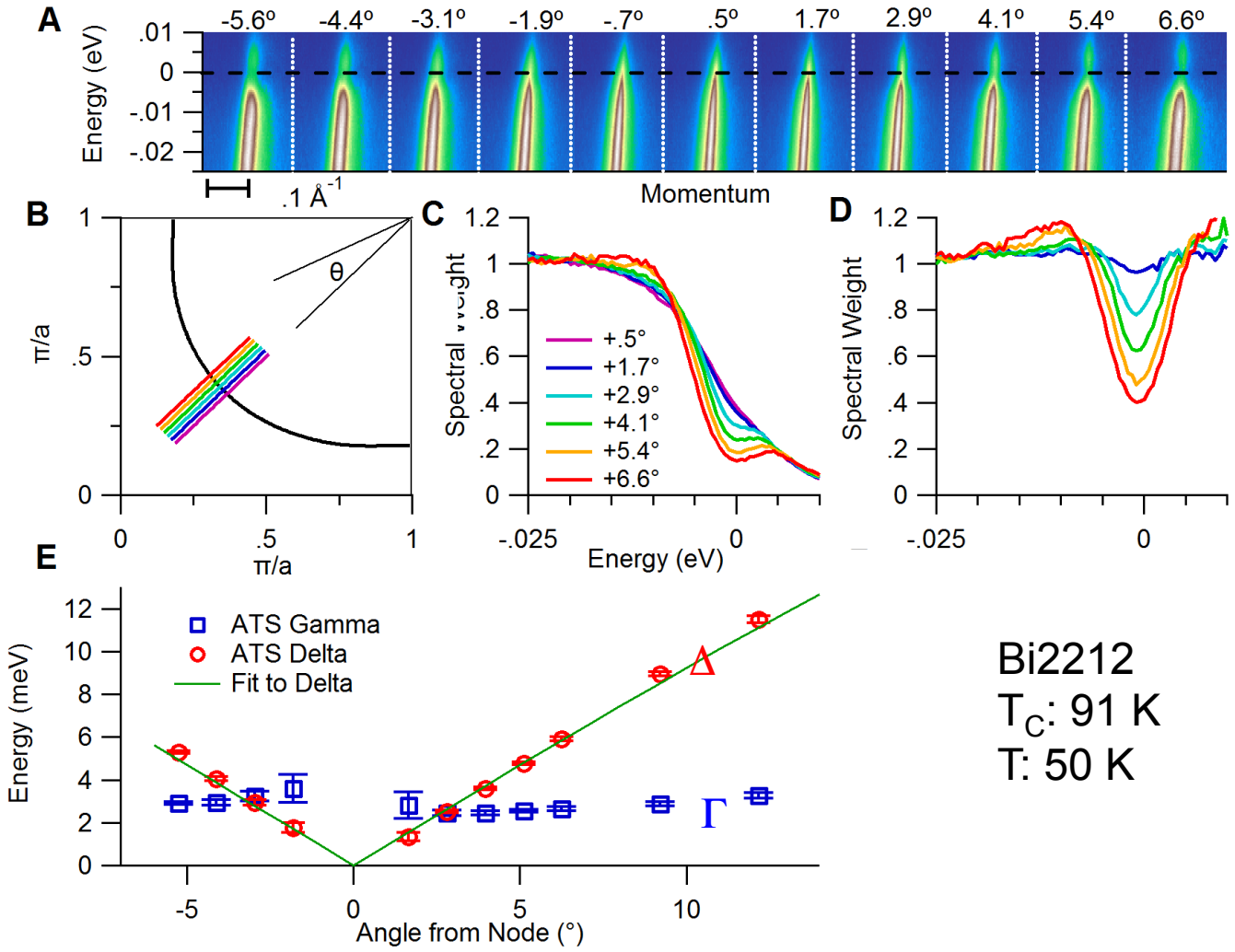
The TDoS are well fit by the Dynes formula over the full range of accessible angles and temperatures.

Each fit gives: pairing strength Δ, and pair-breaking rate Γ.

Similar fits of actual tunneling in cuprates are not nearly as successful because of the d-wave nature of Δ, the van-Hove in the DOS, etc.



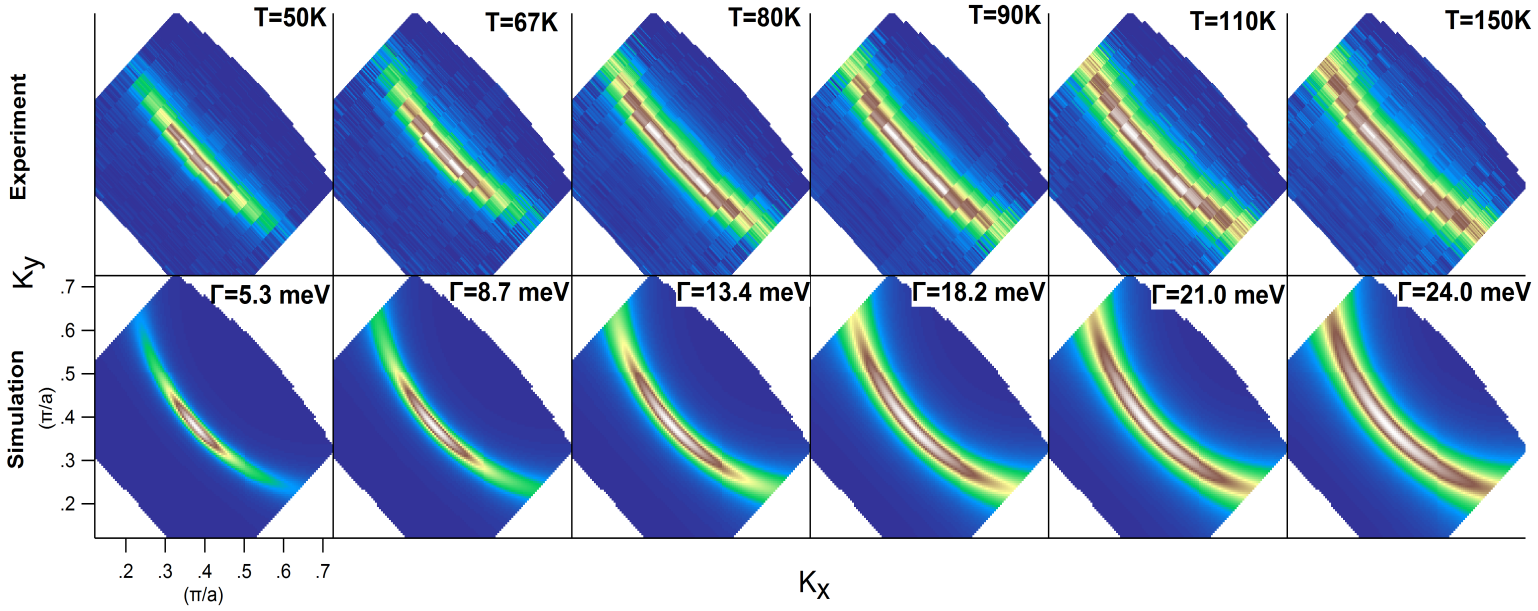
Near-Nodal Angular Evolution of TDoS



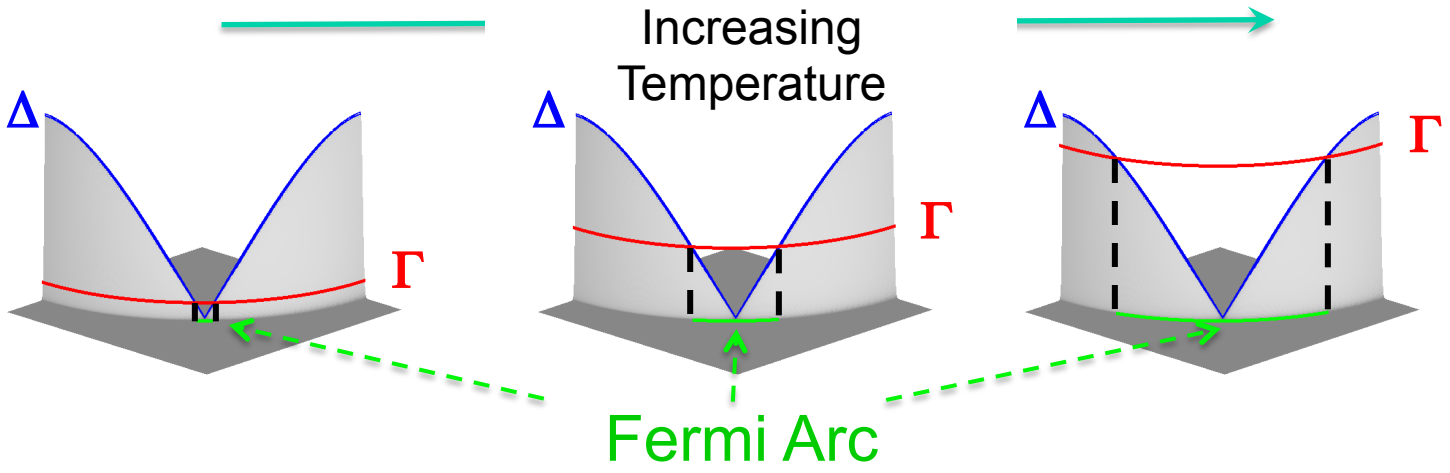
Bi2212
T_C: 91 K
T: 50 K

The TDoS extracts a d-wave Δ with a nearly isotropic Γ in the near nodal region. Improved accuracy and precision over previous techniques for determining Δ or Γ.

Temperature dependence of Fermi Arc Measured (top) and simulated (bottom)

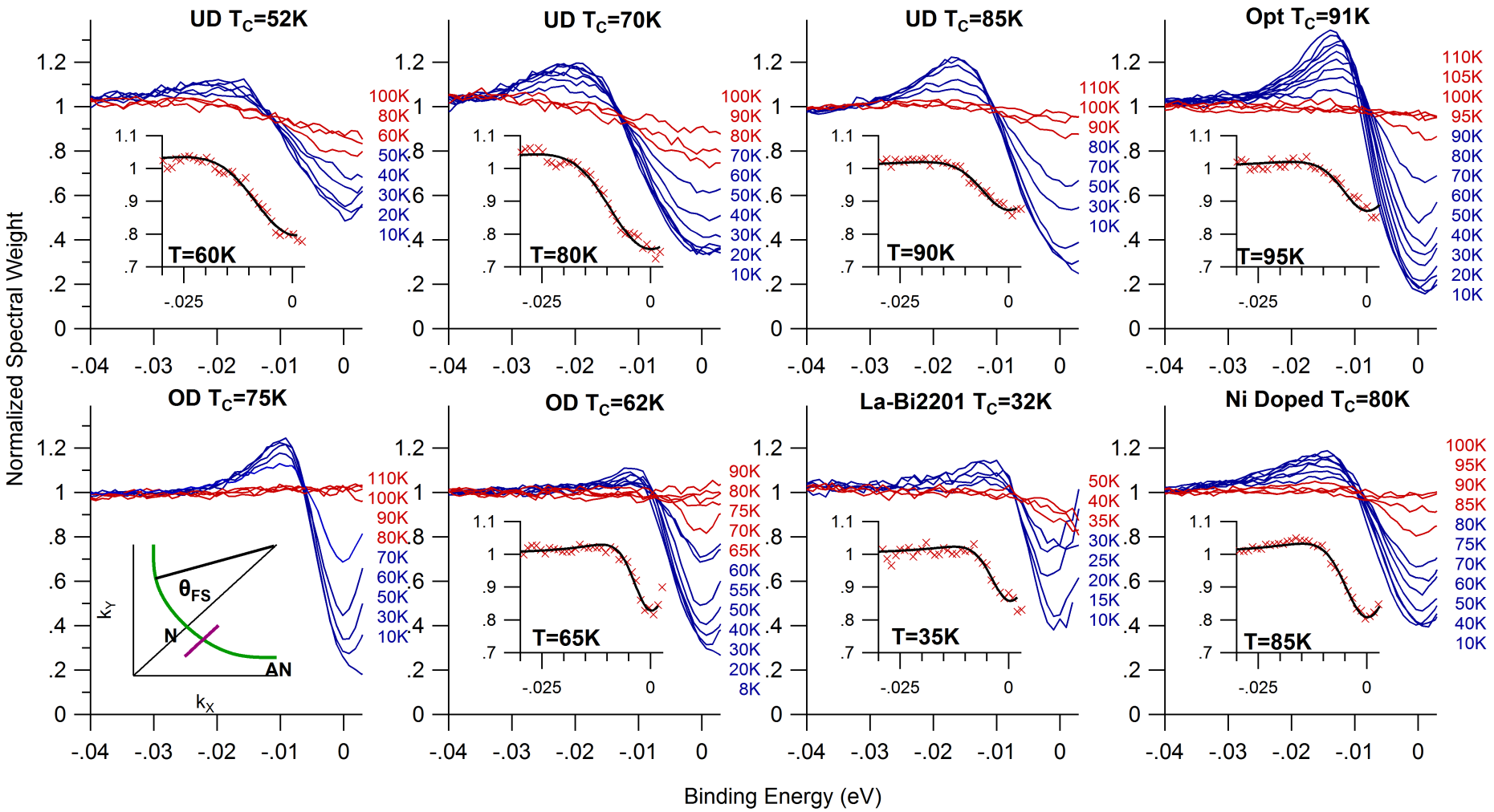


Sample:
UD
Bi2212
T_C: 67 K
hv:7 eV



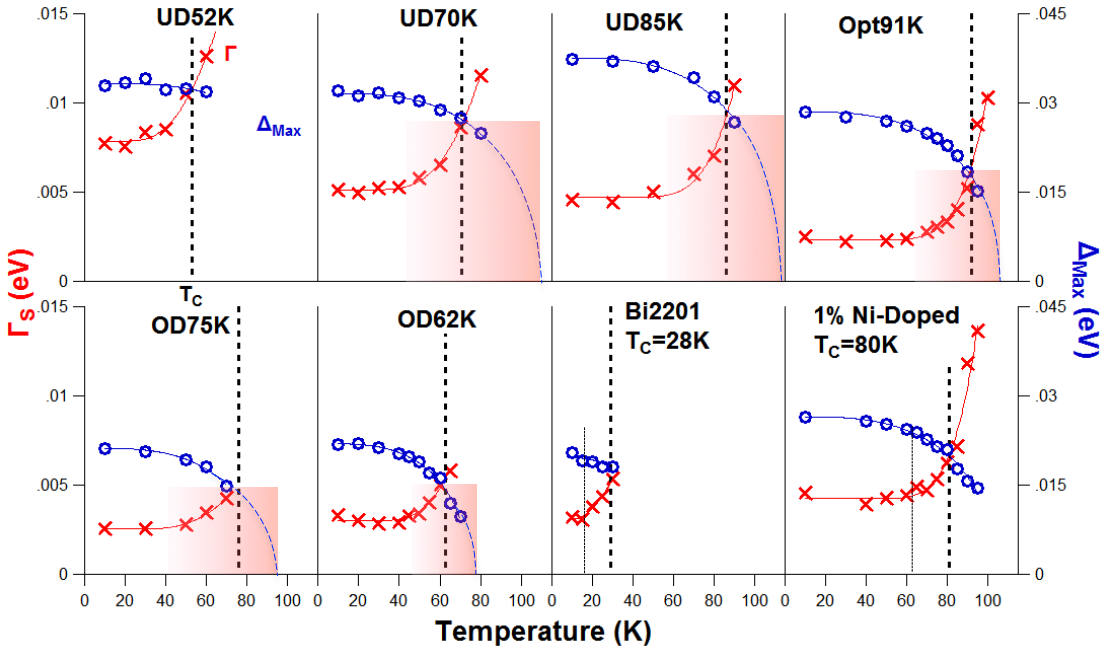
T. J. Reber et al. Nature Physics **8**, 606–610 (2012)

Near-nodal TDoS's for many doping levels, and in the SC state and non-superconducting (pre-pairing) state



T.J. Reber, D.S.D. et al, arXiv 1508.06252

Why does the crossover seem to set T_C?

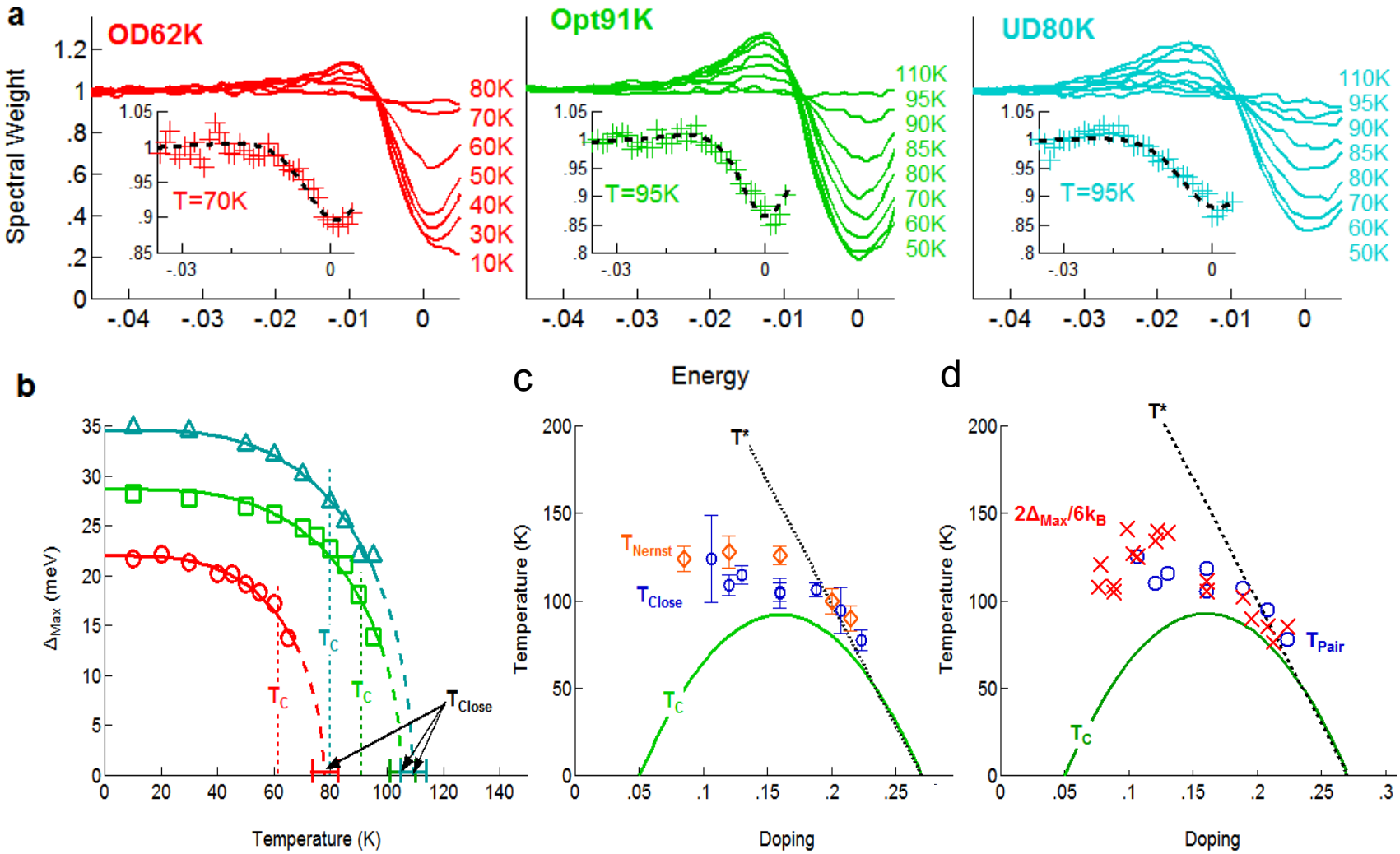


Pairs are broken at the same rate that they are created.
- pair density low while gap still large.

Pairs need to be dense enough and long-lived enough for phase coherence to form (at T_C).

Similar physics observed in granular aluminum, where localization becomes very important – Γ is tuned by varying grain size. SC disappears when Γ crosses Δ (static effect – in contrast to the dynamic effect observed here).

Doping Dependence of T_{Close}

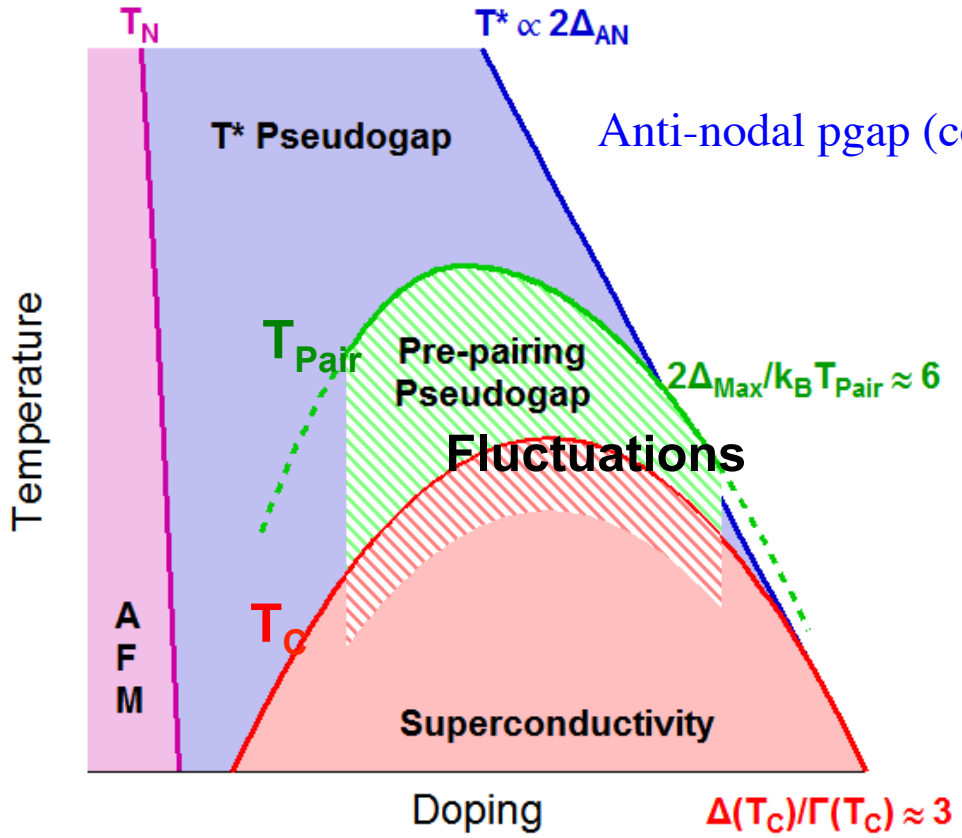


Pre-pairing observed at all dopings studied.
T_{Close} matches T_{Onset} as found in Nernst expts.
Wang/Ong et al. *PRL* (2005)

Qualitative match to Josephson Plasma Resonance expts on UD YBCO.
Bubroka/Bernhard et al. PRL (2011)

T.J. Reber, D.S.D et al. arXiv 2015

Doping phase diagram from gap measurements



Superconductivity (from near-nodal measurements):

-$2\Delta_{NN}$ and T_{close} (not T_c) are proportional with a ratio of ~ 6.

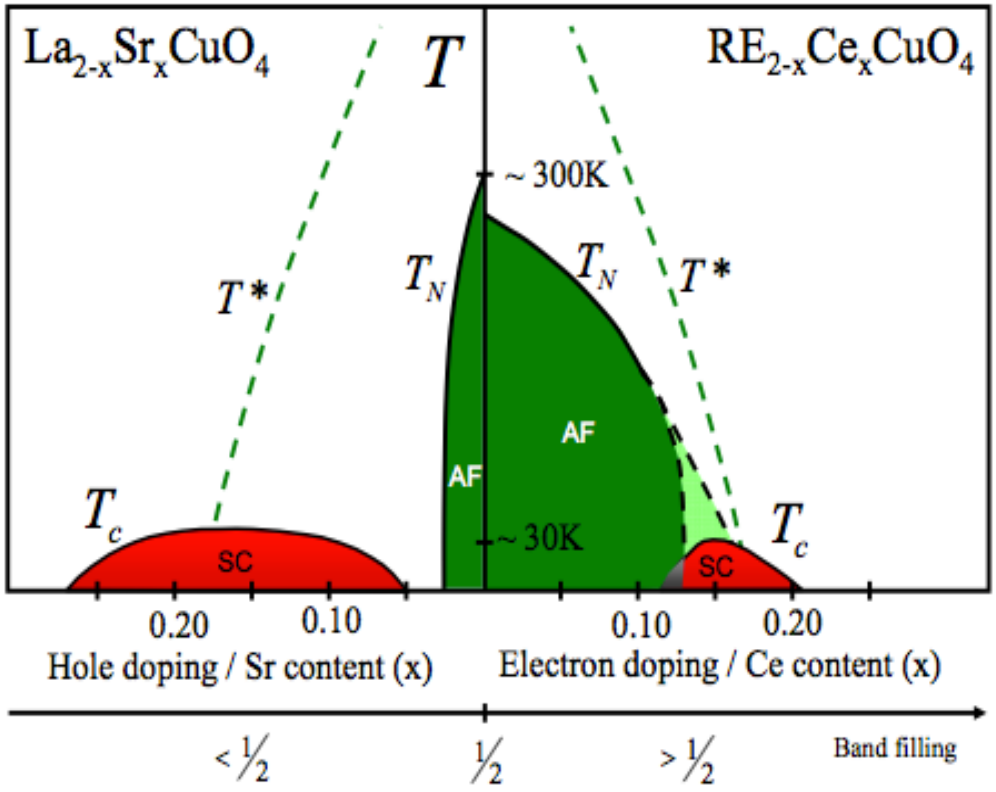
-strong coupling both in UD and OD regimes.

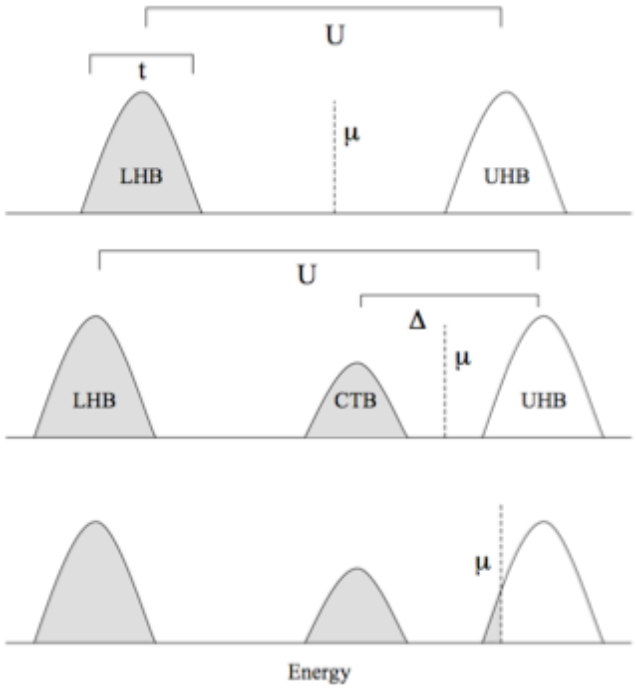
T*/pseudogap (from antinodal measurements):

- Distinct from superconductivity.

T.J. Reber, D.S.D et al. arXiv (2015)

n-type cuprates



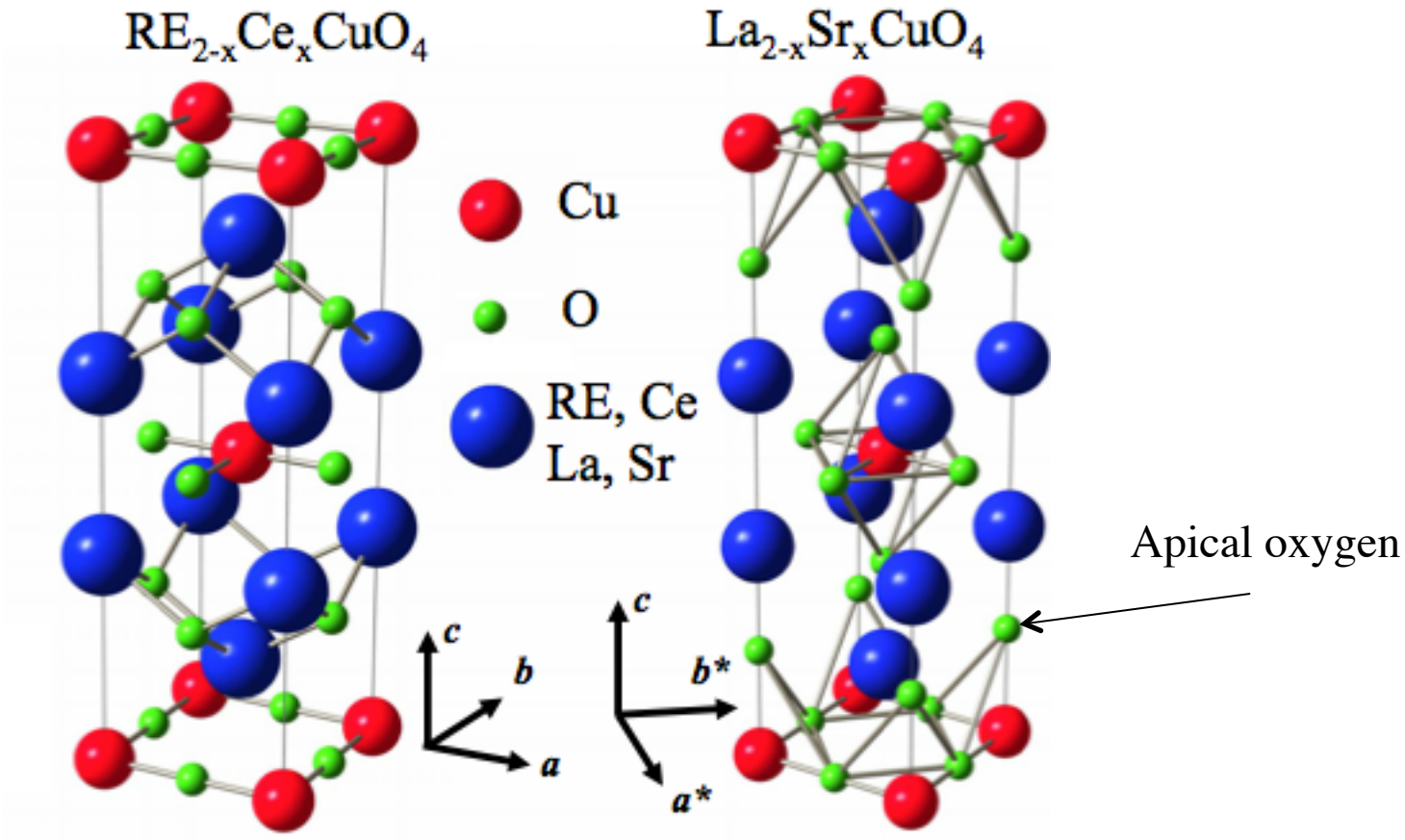


Armitage et al., Rev. Mod. Phys. 82, 2421-2487 (2010)

In the n-types:

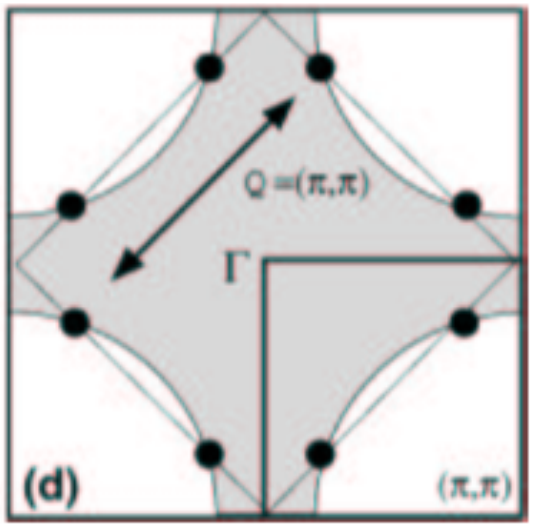
- Long range AF order extends much farther, out to the SC doping levels.
- SC dome covers a smaller doping range.
- Possible coexistence of SC and AF order.
- Slightly different crystal struture (lack of apical oxygen atom).

Crystal structure of n-and p-type cuprates

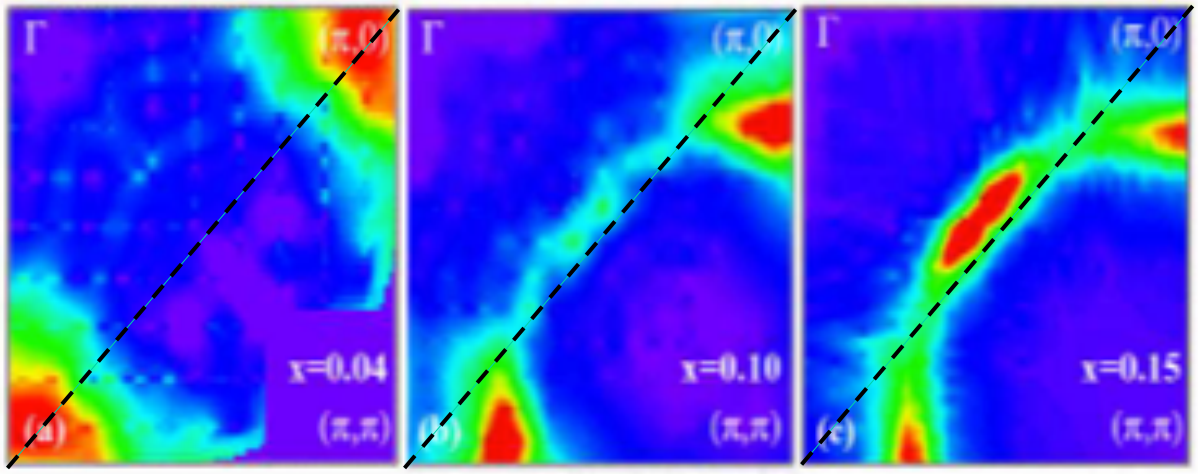


Armitage et al., Rev. Mod. Phys. 82, 2421-2487 (2010)

“hot spots” and FS arcs

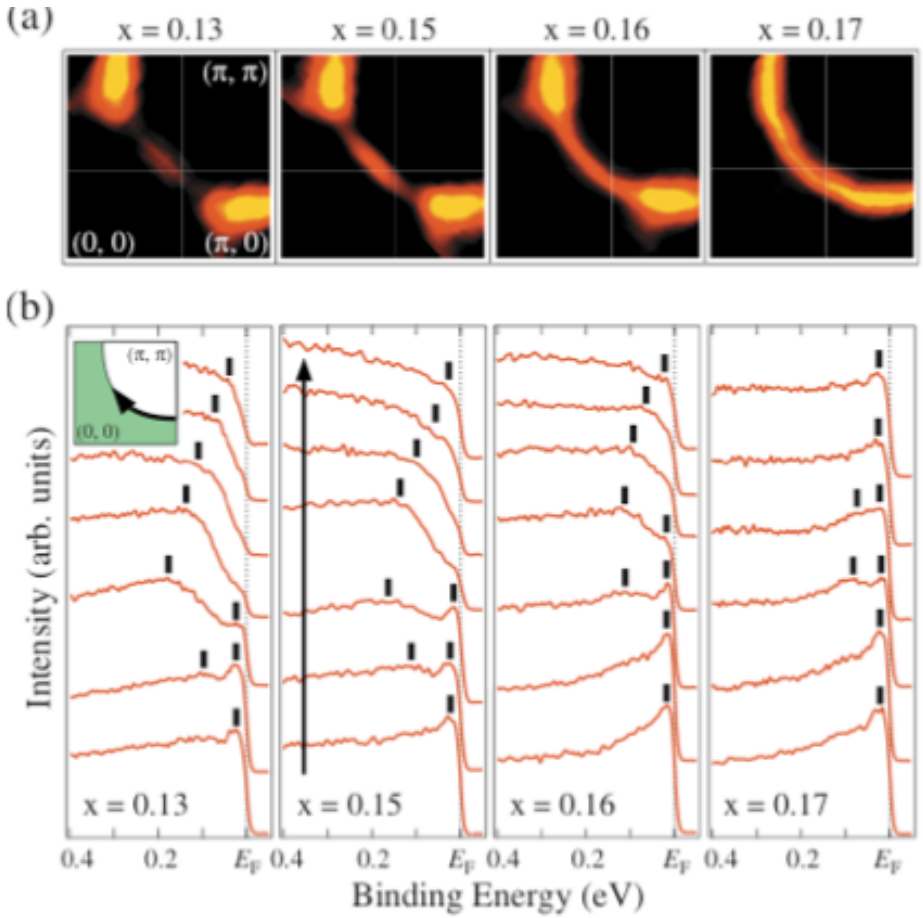


x=.04 x=.10 x=.15



Armitage et al., 2002

$Nd_{2-x}Ce_xCuO_4$

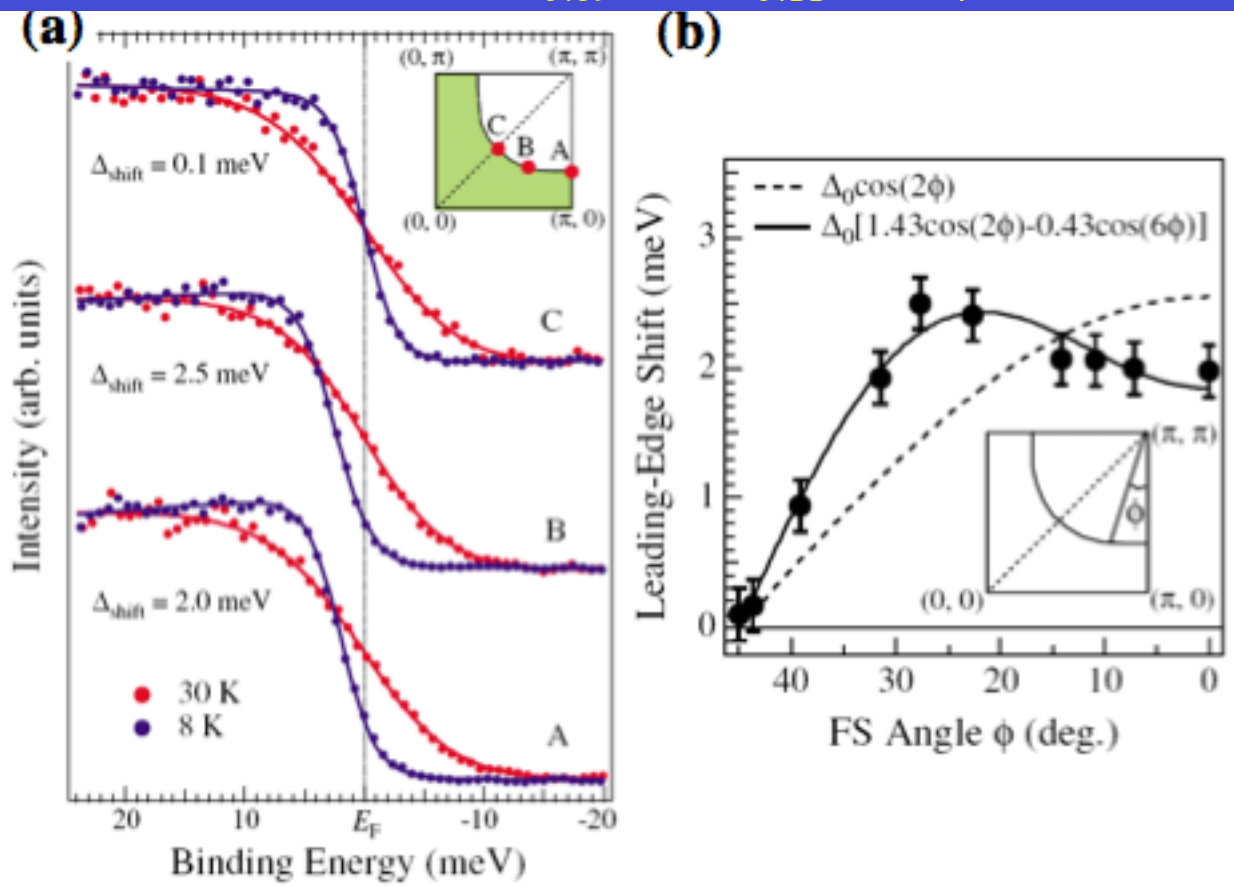


Hot spots go away at large doping levels.

Matsui 2007

Non-monotonic gap as a function of k

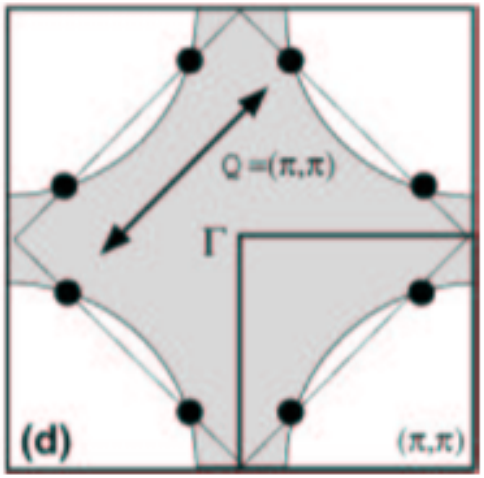
$Pr_{0.89}LaCe_{0.11}CuO_4$



Matsui 2005

Effect originally seen in polarized Raman spectroscopy (Blumberg 2002).
Maximum gap appears roughly at the locations of the hot spots.
→ (π,π) AF fluctuations driving the d-wave superconductivity

“hot spots” in p-type cuprates



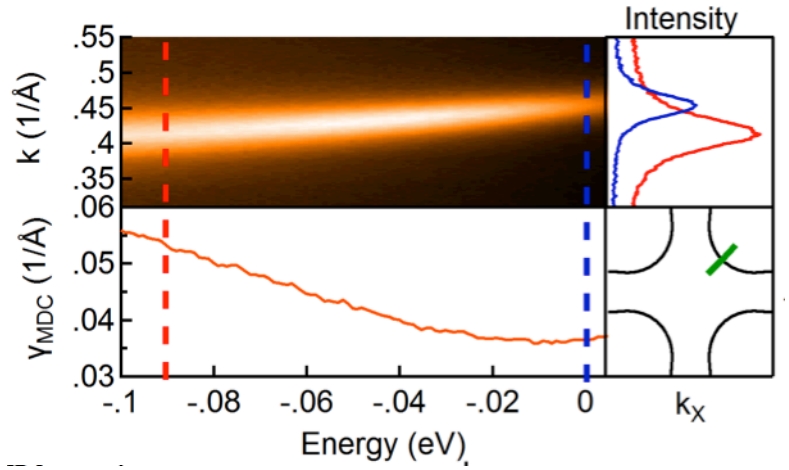
Many aspects of the data in p-type cuprates are consistent with hot spot physics, but it is not as incontrovertible as in the n-type cuprates.

N-state scattering rates (peak broadening) are stronger as one goes from the node to the antinode. In p-types there is no evidence that the scattering gets “colder” past the hot spots.

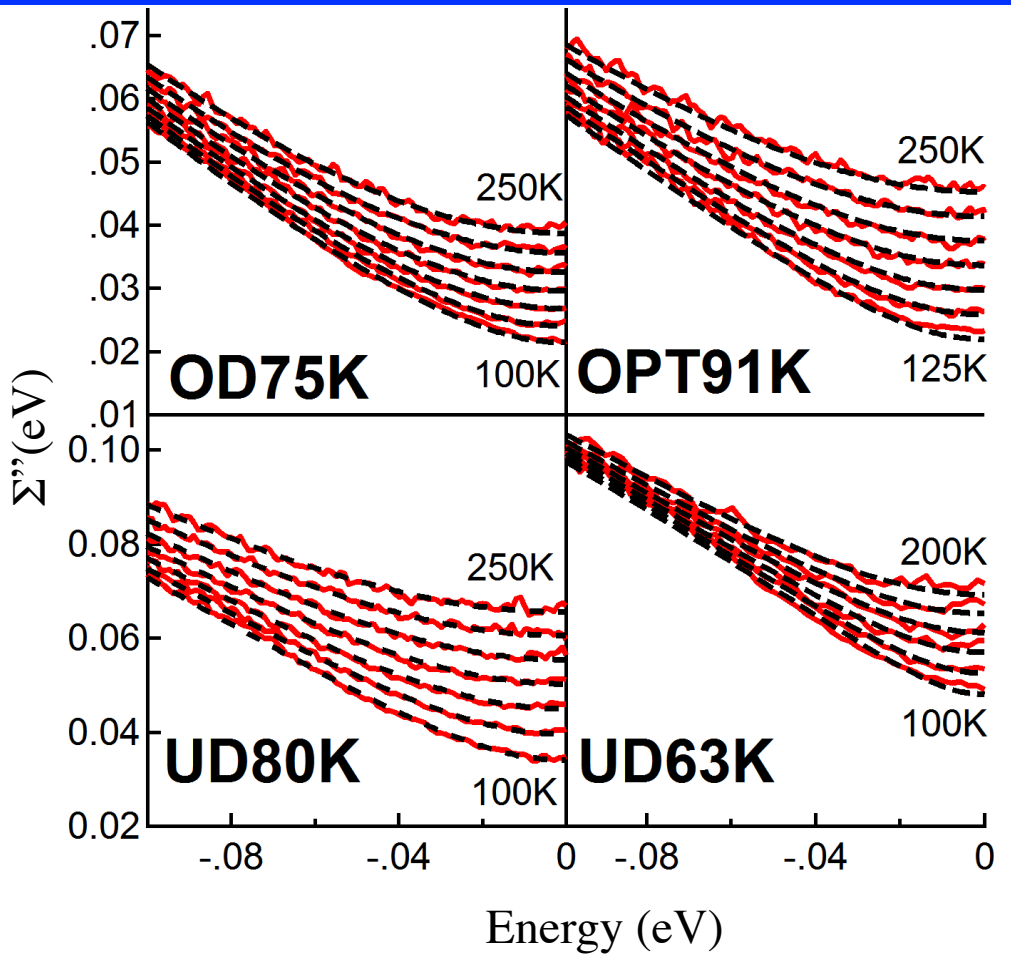
This is not inconsistent with broadly peaked AF scattering due to very short-ranged AF fluctuations. But then these would be hot regions and not hot spots.

Edges of the Fermi arcs (which are also not at all sharp in k-space) sometimes associated with the hot spots.

Normal-state nodal ARPES scattering rates (Σ") of Bi2212 as a function of ω,T, doping.



$$\Sigma''(\omega)=v_{bare}*\Gamma_{MDC}(\omega)/2$$

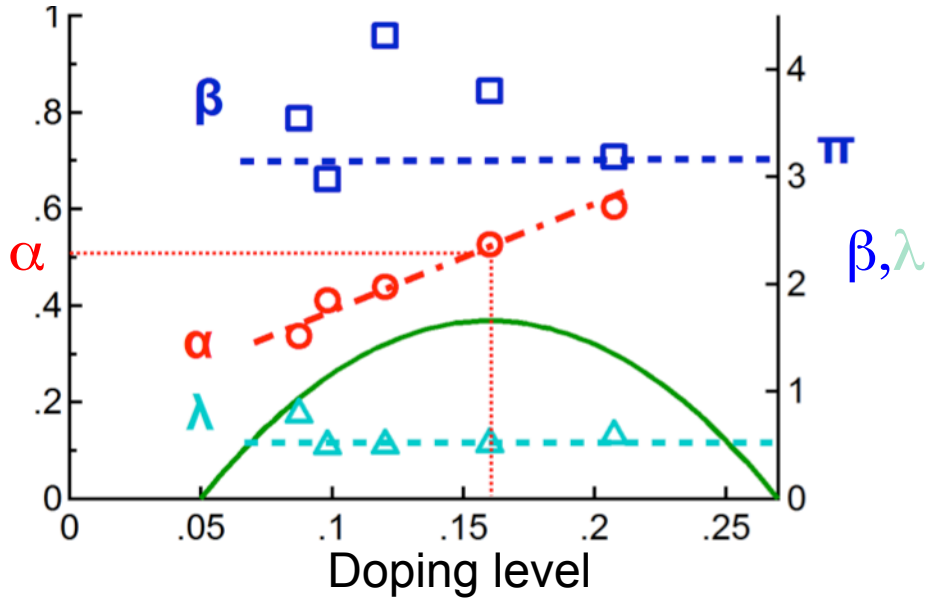


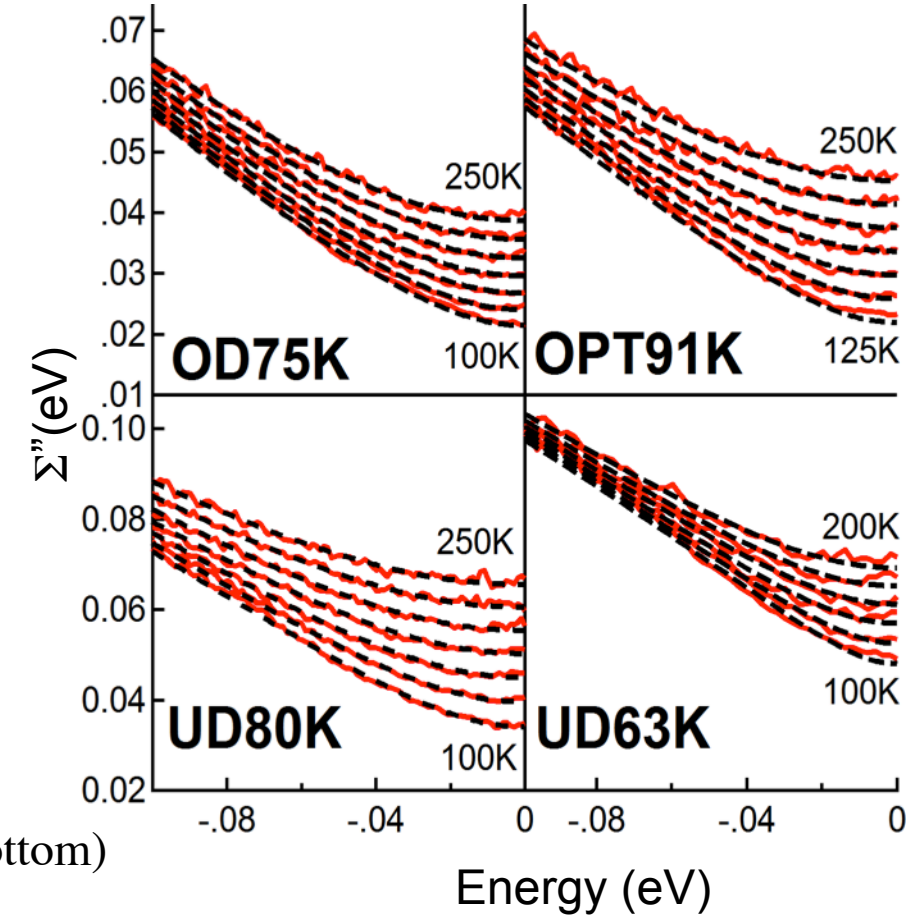
All data looks quadratic at low ω (FL-like), linear at high ω (MFL-like).

T.J. Reber, D.S.D., et al. arXiv (2015)

A new experiment-motivated ansatz for normal state Σ"
The Power Law Liquid (PLL)

$$\Sigma''_{PLL} = \Gamma_0 + \lambda \frac{[(\hbar\omega)^2 + (\beta k_B T)^2]^{\alpha}}{(\hbar\omega_N)^{2\alpha-1}}$$





ω_N (unit normalization) fixed at 0.5 eV (~ band bottom)

Γ_0=impurities+disorder (discussed later)

β~ π . Expected from Matsubara and Fermi Liquid (not previously proven).

λ = coupling strength ~ constant=0.5.

α= 0.5 : ω,T linear (Marginal Fermi Liquid).

α=1 : ω,T quadratic (True Fermi Liquid)

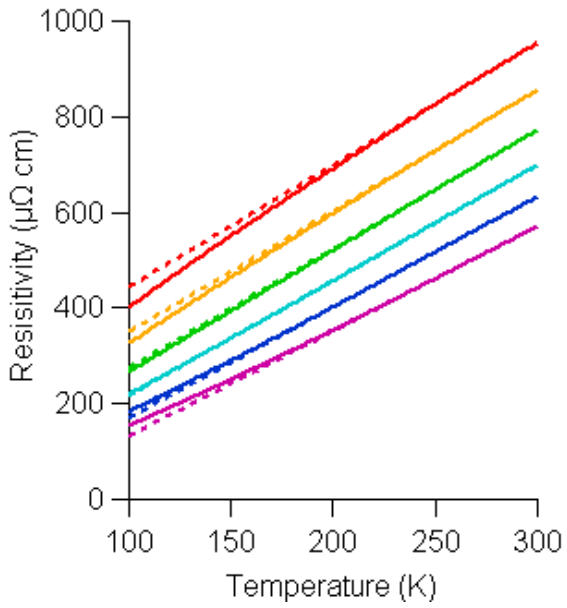
Entire evolution essentially controlled by the one parameter α.

T.J. Reber, D.S. Dessau arXiv (2015)

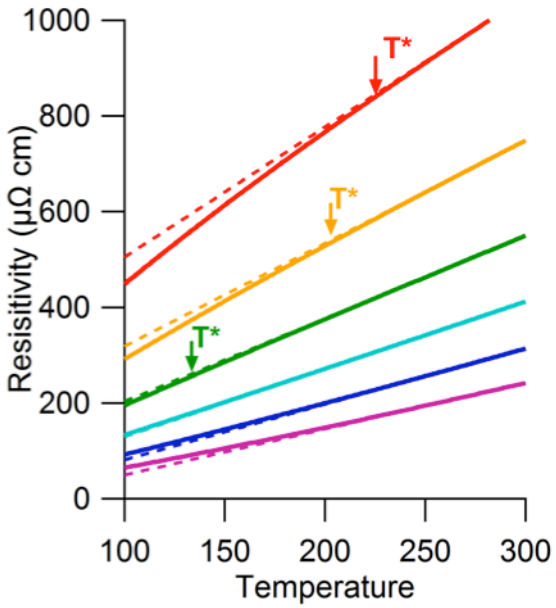
Resistivity vs T from Power Law Liquid Σ"

The most detailed connection/best agreement between ARPES and transport from any material.

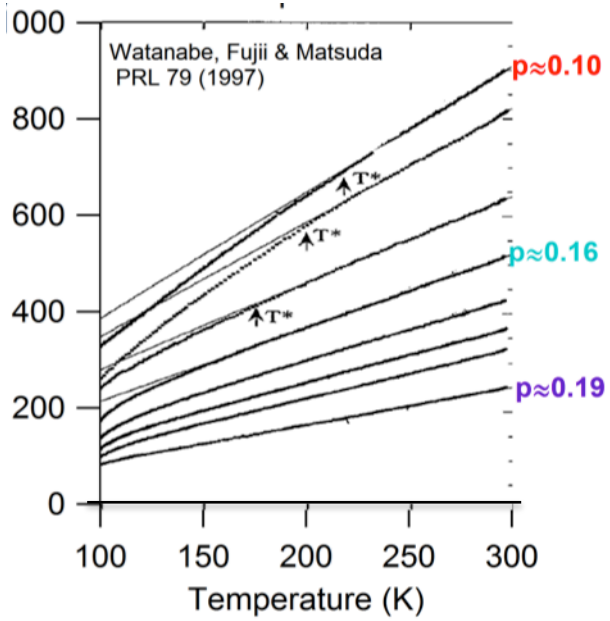
Boltzmann transport



Drude



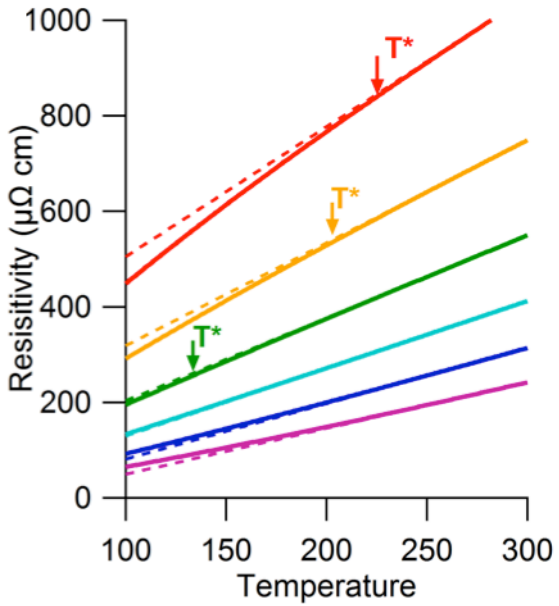
Transport Expt.

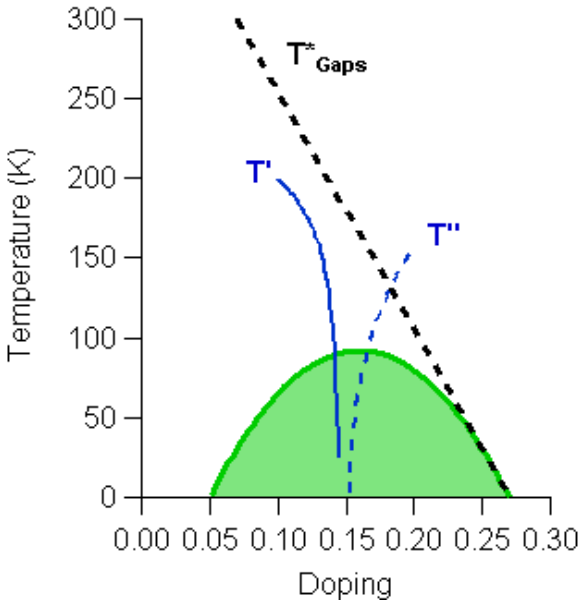


- Simplest assumption of a large tight-binding Fermi surface with fully isotropic PLL scattering rates over the full Fermi surface, with no spectral weight pseudogaps (i.e. no arcs or pockets). PLL offset Γ_0=0.
- "T*" curvature change closely mimics the experimental transport data.

Using actual fit for α.
Quinn's
TB parameters.

T* from the calculated (Power Law Liquid-based) resistivity





- Mimics a quantum critical point near optimal doping.
- PLL is actually scaleless and doesn't have the T* scale explicitly included in it.

Using actual fit for α.
Quinn's
TB parameters.

Origin of the PLL self energy?
Other precedents for power law scattering rates?

Luttinger liquid physics in 1D. PLL spectra (and ARPES data) don't have the power law spectral weight that the LL physics has. Extend these ideas to 2D? RVB?

Doped Hubbard model? Si, Kotliar 1993

Quantum critical phases?

Quantum gravity-based ideas (ADS/CFT)? Others?

The superconductivity is born out of these states. How is all this connected?