Electron spectroscopy
on
high temperature superconductors
and
other novel materials

Gey-Hong Gweon

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SSRL

BERKELEY LAB

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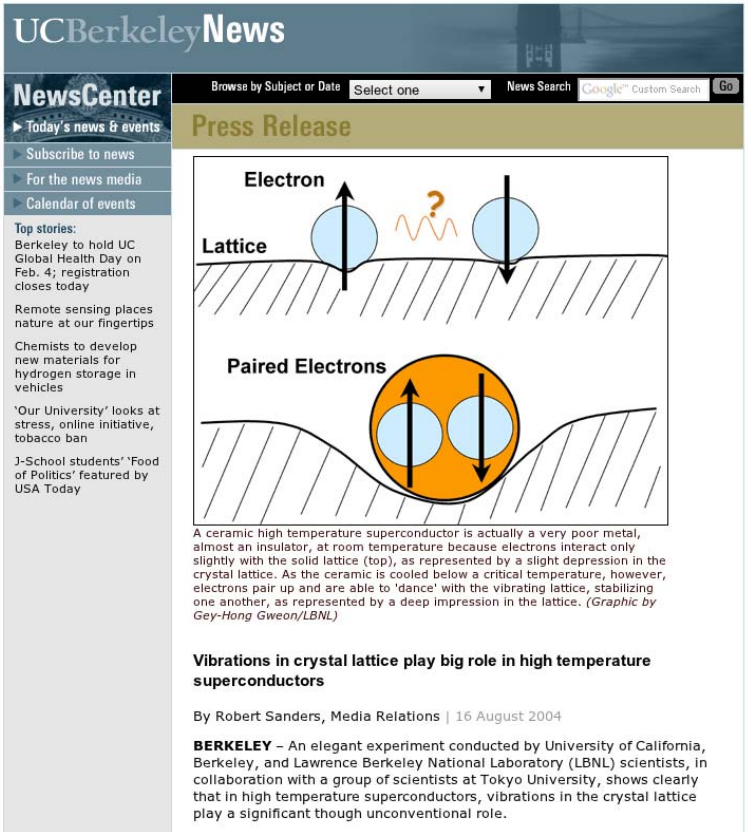
ARPES on Novel Materials



Top stories:

Berkeley to hold UC Global Health Day on Feb. 4; registration closes today

Remote sensing places nature at our fingertips

Chemists to develop new materials for hydrogen storage in vehicles

'Our University' looks at stress, online initiative, tobacco ban

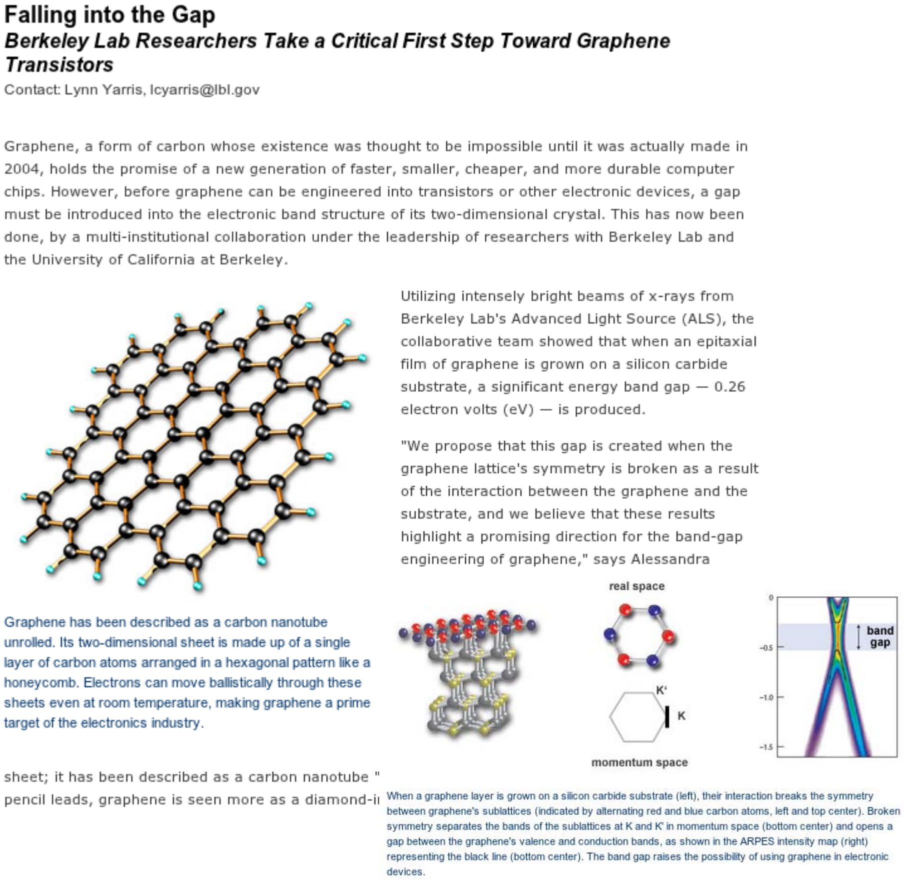
J-School students' 'Food of Politics' featured by USA Today

A ceramic high temperature superconductor is actually a very poor metal, almost an insulator, at room temperature because electrons interact only slightly with the solid lattice (top), as represented by a slight depression in the crystal lattice. As the ceramic is cooled below a critical temperature, however, electrons pair up and are able to 'dance' with the vibrating lattice, stabilizing one another, as represented by a deep impression in the lattice. *(Graphic by Gey-Hong Gweon/LBNL)*

Vibrations in crystal lattice play big role in high temperature superconductors

By Robert Sanders, Media Relations | 16 August 2004

BERKELEY – An elegant experiment conducted by University of California, Berkeley, and Lawrence Berkeley National Laboratory (LBNL) scientists, in collaboration with a group of scientists at Tokyo University, shows clearly that in high temperature superconductors, vibrations in the crystal lattice play a significant though unconventional role.



Falling into the Gap

Berkeley Lab Researchers Take a Critical First Step Toward Graphene Transistors

Contact: Lynn Yarris, lcyarris@lbl.gov

Graphene, a form of carbon whose existence was thought to be impossible until it was actually made in 2004, holds the promise of a new generation of faster, smaller, cheaper, and more durable computer chips. However, before graphene can be engineered into transistors or other electronic devices, a gap must be introduced into the electronic band structure of its two-dimensional crystal. This has now been done, by a multi-institutional collaboration under the leadership of researchers with Berkeley Lab and the University of California at Berkeley.

Utilizing intensely bright beams of x-rays from Berkeley Lab's Advanced Light Source (ALS), the collaborative team showed that when an epitaxial film of graphene is grown on a silicon carbide substrate, a significant energy band gap — 0.26 electron volts (eV) — is produced.

"We propose that this gap is created when the graphene lattice's symmetry is broken as a result of the interaction between the graphene and the substrate, and we believe that these results highlight a promising direction for the band-gap engineering of graphene," says Alessandra

Graphene has been described as a carbon nanotube unrolled. Its two-dimensional sheet is made up of a single layer of carbon atoms arranged in a hexagonal pattern like a honeycomb. Electrons can move ballistically through these sheets even at room temperature, making graphene a prime target of the electronics industry.

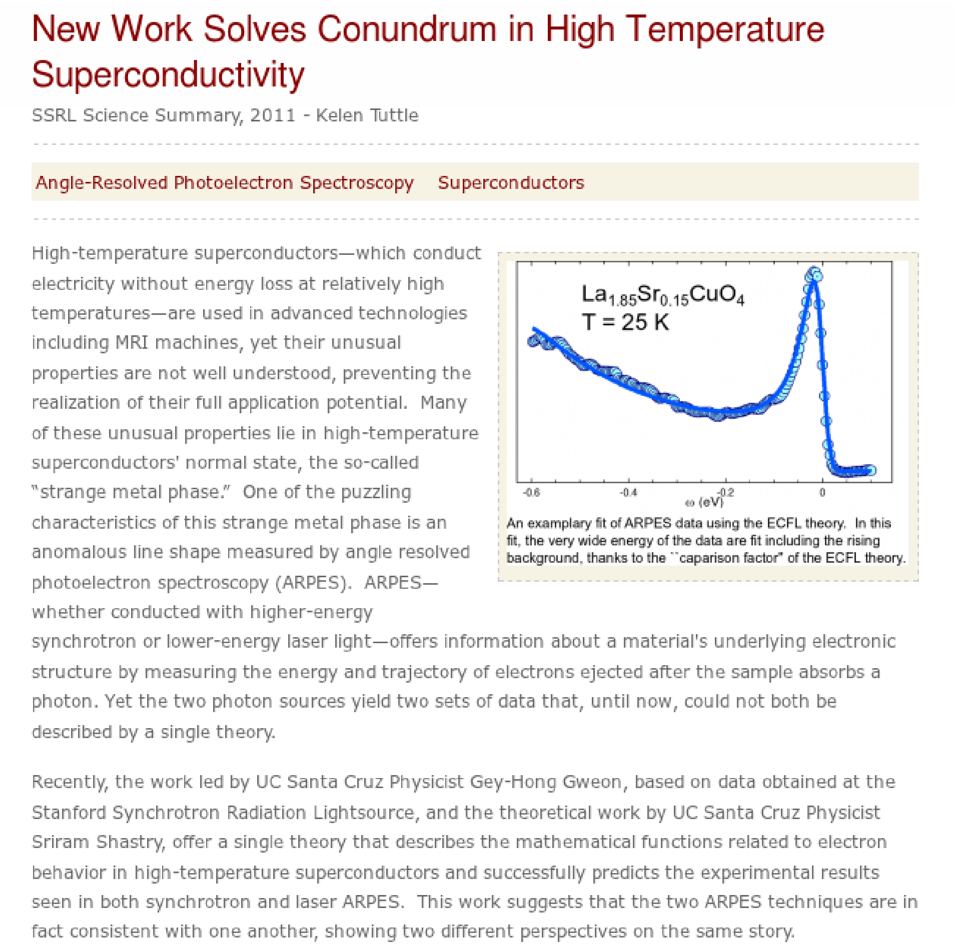
sheet; it has been described as a carbon nanotube "
pencil leads, graphene is seen more as a diamond-i

When a graphene layer is grown on a silicon carbide substrate (left), their interaction breaks the symmetry between graphene's sublattices (indicated by alternating red and blue carbon atoms, left and top center). Broken symmetry separates the bands of the sublattices at K and K' in momentum space (bottom center) and opens a gap between the graphene's valence and conduction bands, as shown in the ARPES intensity map (right) representing the black line (bottom center). The band gap raises the possibility of using graphene in electronic devices.

Gweon et al., Nature 2004
Graf, Gweon et al., PRL 2007 (High-E kink)

Rollings, Gweon et al., JPCS 2006
Zhou, Gweon et al., Nature Materials 2007

ARPES on high Tc Cuprates



New Work Solves Conundrum in High Temperature Superconductivity

SSRL Science Summary, 2011 - Kelen Tuttle

Angle-Resolved Photoelectron Spectroscopy Superconductors

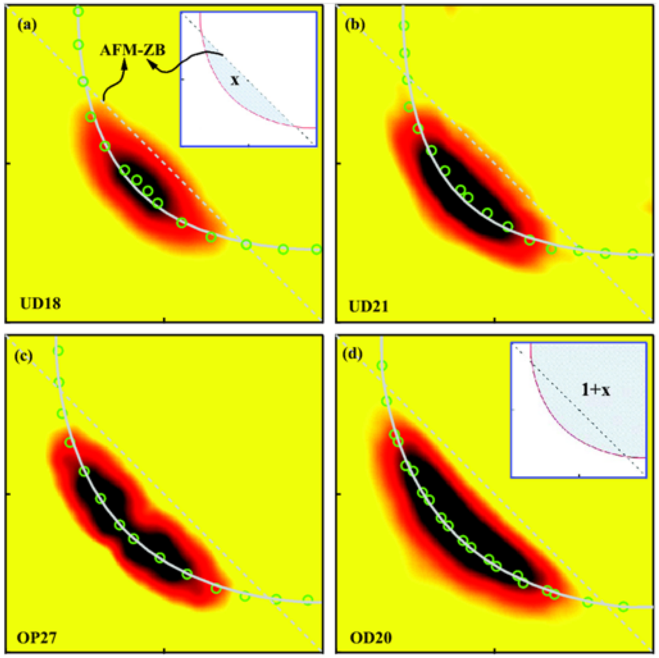
High-temperature superconductors—which conduct electricity without energy loss at relatively high temperatures—are used in advanced technologies including MRI machines, yet their unusual properties are not well understood, preventing the realization of their full application potential. Many of these unusual properties lie in high-temperature superconductors' normal state, the so-called "strange metal phase." One of the puzzling characteristics of this strange metal phase is an anomalous line shape measured by angle resolved photoelectron spectroscopy (ARPES). ARPES—whether conducted with higher-energy synchrotron or lower-energy laser light—offers information about a material's underlying electronic structure by measuring the energy and trajectory of electrons ejected after the sample absorbs a photon. Yet the two photon sources yield two sets of data that, until now, could not both be described by a single theory.

An examplary fit of ARPES data using the ECFL theory. In this fit, the very wide energy of the data are fit including the rising background, thanks to the ``caparison factor" of the ECFL theory.

Recently, the work led by UC Santa Cruz Physicist Gey-Hong Gweon, based on data obtained at the Stanford Synchrotron Radiation Lightsource, and the theoretical work by UC Santa Cruz Physicist Sriram Shastry, offer a single theory that describes the mathematical functions related to electron behavior in high-temperature superconductors and successfully predicts the experimental results seen in both synchrotron and laser ARPES. This work suggests that the two ARPES techniques are in fact consistent with one another, showing two different perspectives on the same story.

Gweon et al., PRL 11

Pseudo-gap and charge order in high temperature superconductors

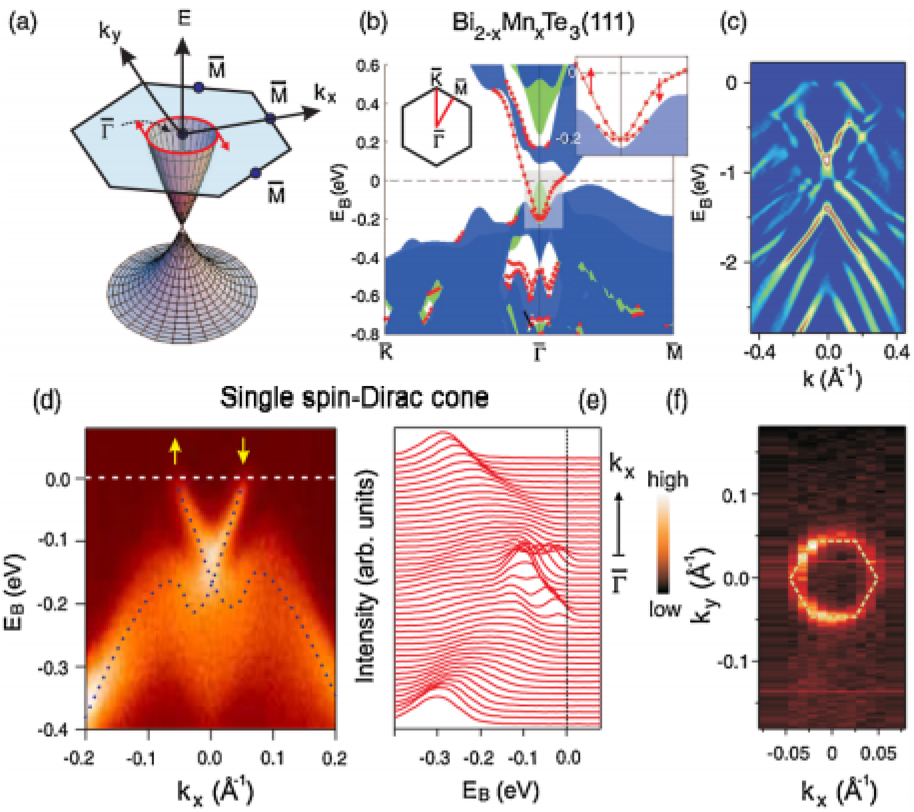


Meng, Gweon et al., PRB RC 11

ARPES on New Quantum Materials

Topological Insulator

Insulating bulk
Conducting surface
Robust conducting surface
guaranteed by topology



Hsieh, Hasan, et al.
PRL 2009

On-going Research

- High Tc superconductors
  - Strange normal state line shapes (“non-Fermi liquid”)
  - Fermi surface sum rule (“Luttinger sum rule”)
  - Line shapes of quasi-1D cuprates (“Luttinger liquid”)
- Topological insulators
  - Bulk carrier density
  - Normal line shapes
- TiTe2 (reference to High Tc), LaCoO3

Superconductivity

- Novel state of matter

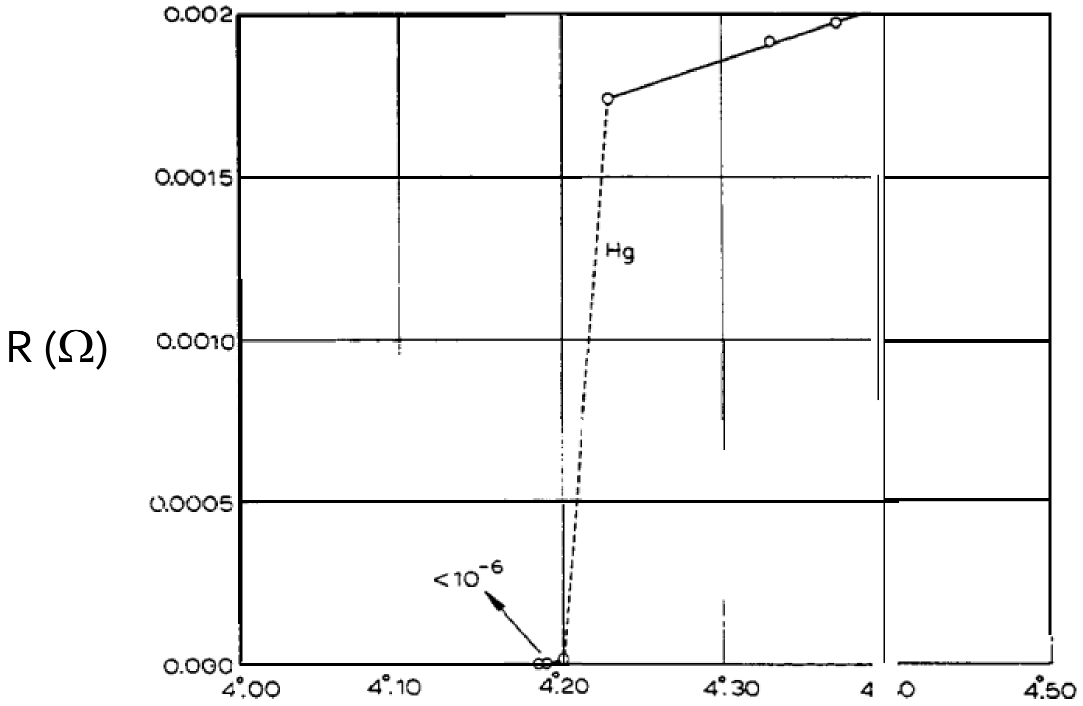
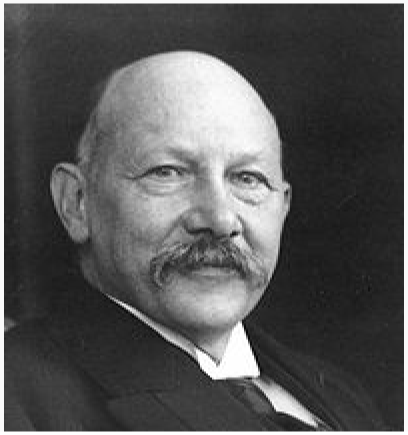


Fig. 17.

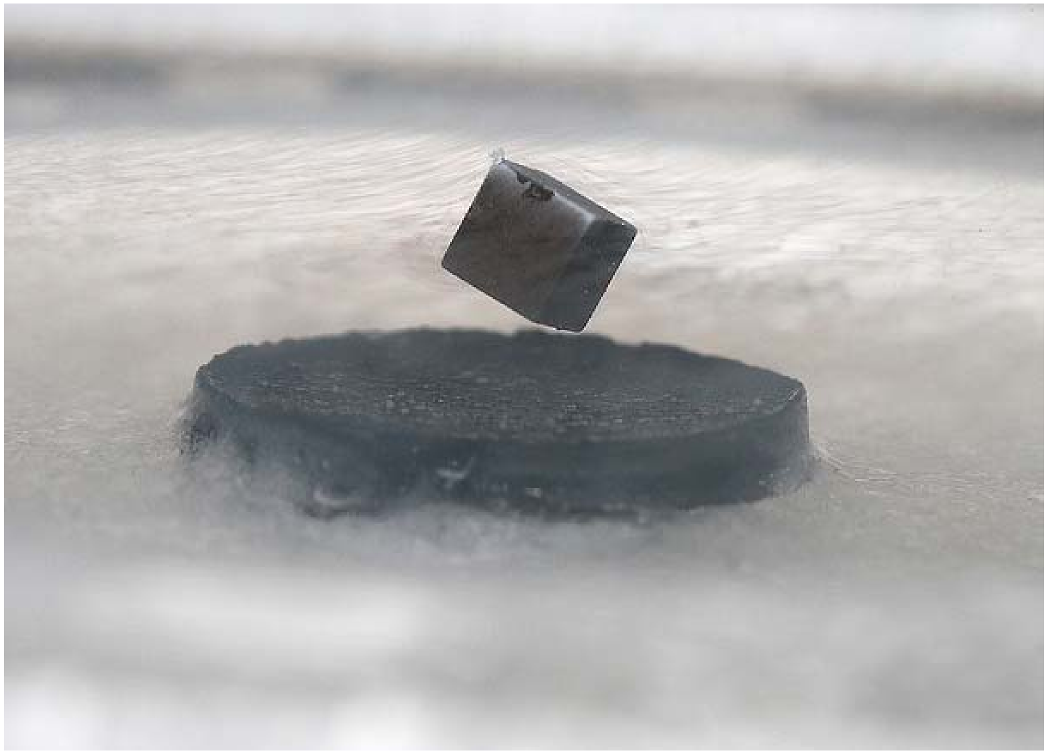


H. Kamerlingh Onnes

1911

Superconductivity

- Meissner effect (1933)



$$\vec{B} = \vec{H} + 4\pi\vec{M} = 0$$

Superconductivity

- Exclusion of the EM field (massive photons)

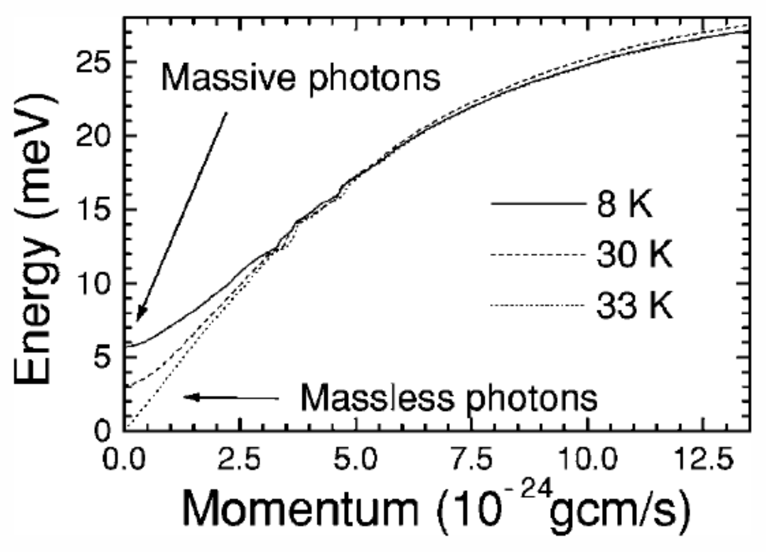
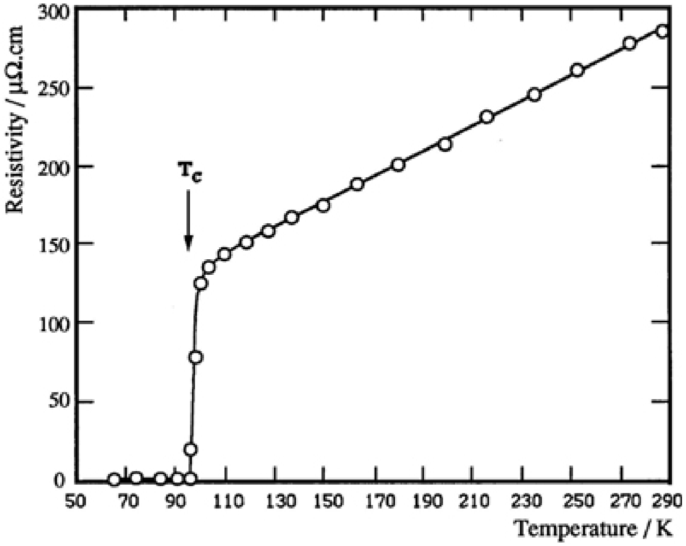


Fig. 4. Energy-momentum dispersion of photons polarized along the c-direction in $La_{1.85}Sr_{0.15}CuO_{4+\delta}$ for different temperatures. T_c of this sample is 33 K. The photons travelling inside the superconductor become massive, when the U(1) gauge symmetry is broken in the superconductor to which the photons are coupled.

D. van Der Marel, J. Sc, vol. 17, 559 ('04)
Also, see K. Kadowaki, et al., Phys. Rev. B vol. 56, 5617 (1997).

High temperature superconductivity

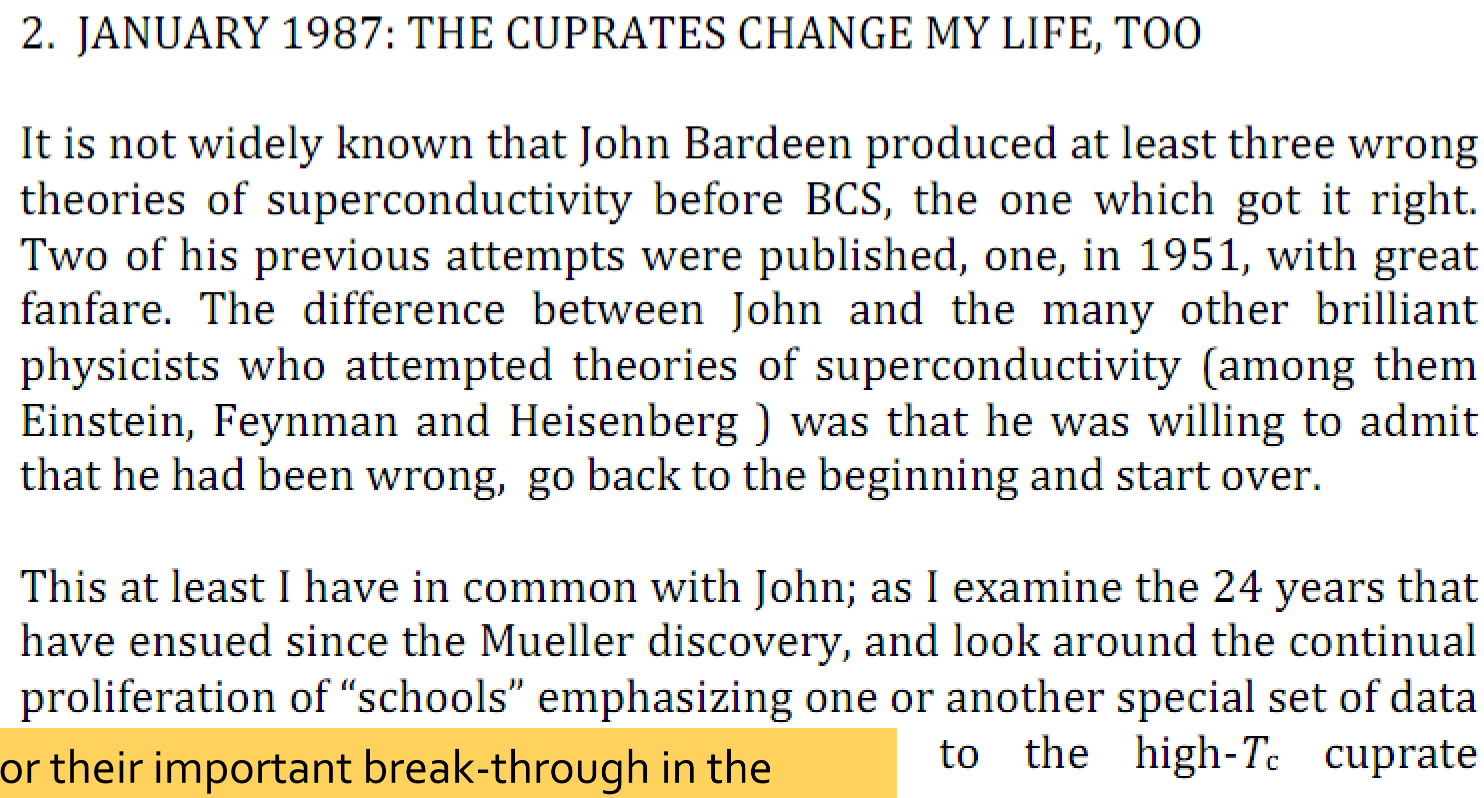
- Bednorz and Müllller



"for their important break-through in the discovery of superconductivity in ceramic materials" (1987)

http://www-outreach.phy.cam.ac.uk/physics_at_work/2005/exhibit/irc.php

Superconductors fascinate



2. JANUARY 1987: THE CUPRATES CHANGE MY LIFE, TOO

It is not widely known that John Bardeen produced at least three wrong theories of superconductivity before BCS, the one which got it right. Two of his previous attempts were published, one, in 1951, with great fanfare. The difference between John and the many other brilliant physicists who attempted theories of superconductivity (among them Einstein, Feynman and Heisenberg) was that he was willing to admit that he had been wrong, go back to the beginning and start over.

This at least I have in common with John; as I examine the 24 years that have ensued since the Mueller discovery, and look around the continual proliferation of "schools" emphasizing one or another special set of data

to the high-T_c cuprate

P. W. Anderson, 2010

"for their important break-through in the discovery of superconductivity in ceramic materials" for Bednorz and Müllller

Conventional SC and High-Tc SC (HTSC)

- Conventional SC – the normal state is well-understood. A **good metal** described by the Landau theory. Cool down a good metal – we get a superconductor!

- High Tc – the normal state is a **bad metal**. Cool down a bad metal – we get a high Tc!

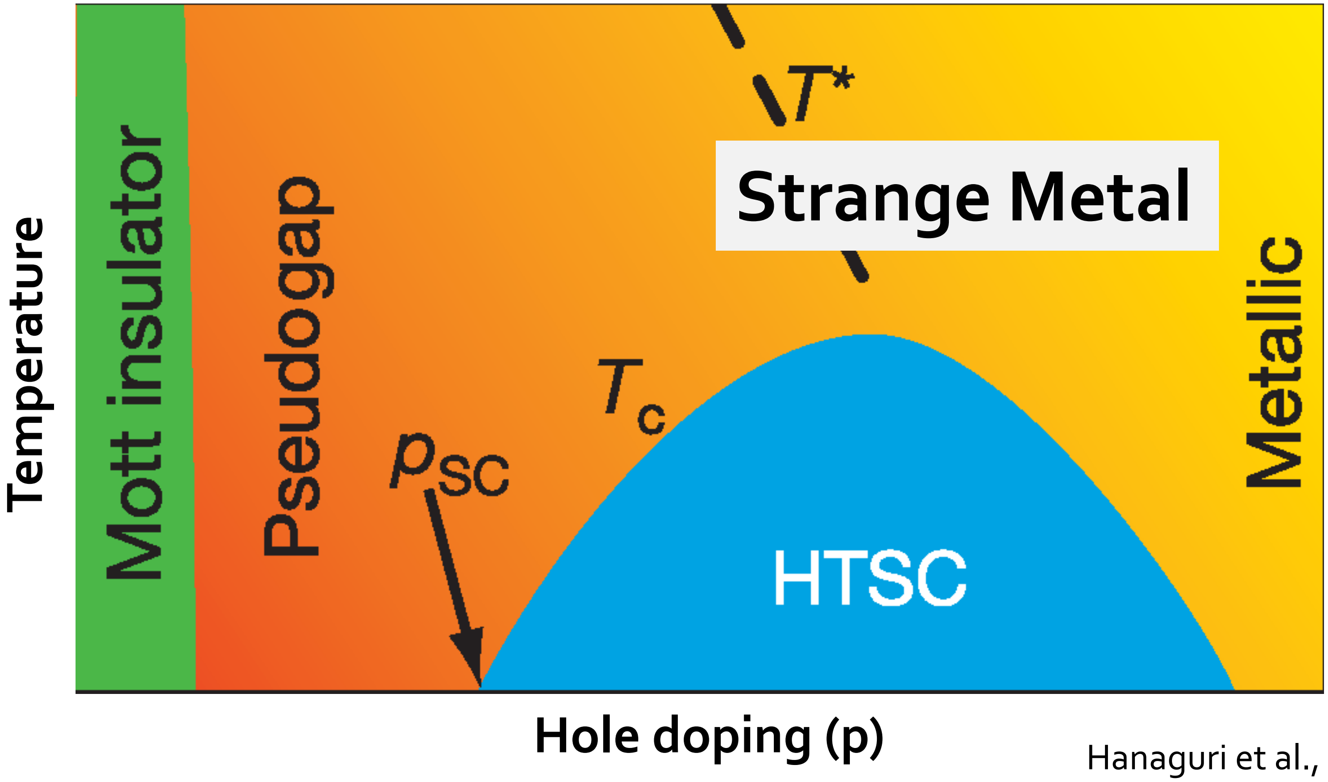
Why study strange normal phase?

A few months after the discovery of the cuprate high-T_c superconductors, it became clear that the 'normal' metal well above the superconducting transition temperature, T_c, was also very unusual. One of the soubriquets often applied to this phase is 'strange metal'[1]; another is 'marginal Fermi liquid'[2].

Anderson, Nat Phys, 2006

This 'strange metal' phase continues to be of much theoretical interest. Here we show it is a consequence of projecting the doubly occupied amplitudes out of a conventional Fermi-sea wavefunction (Gutzwiller projection), requiring no exotica such as a mysterious quantum critical point.

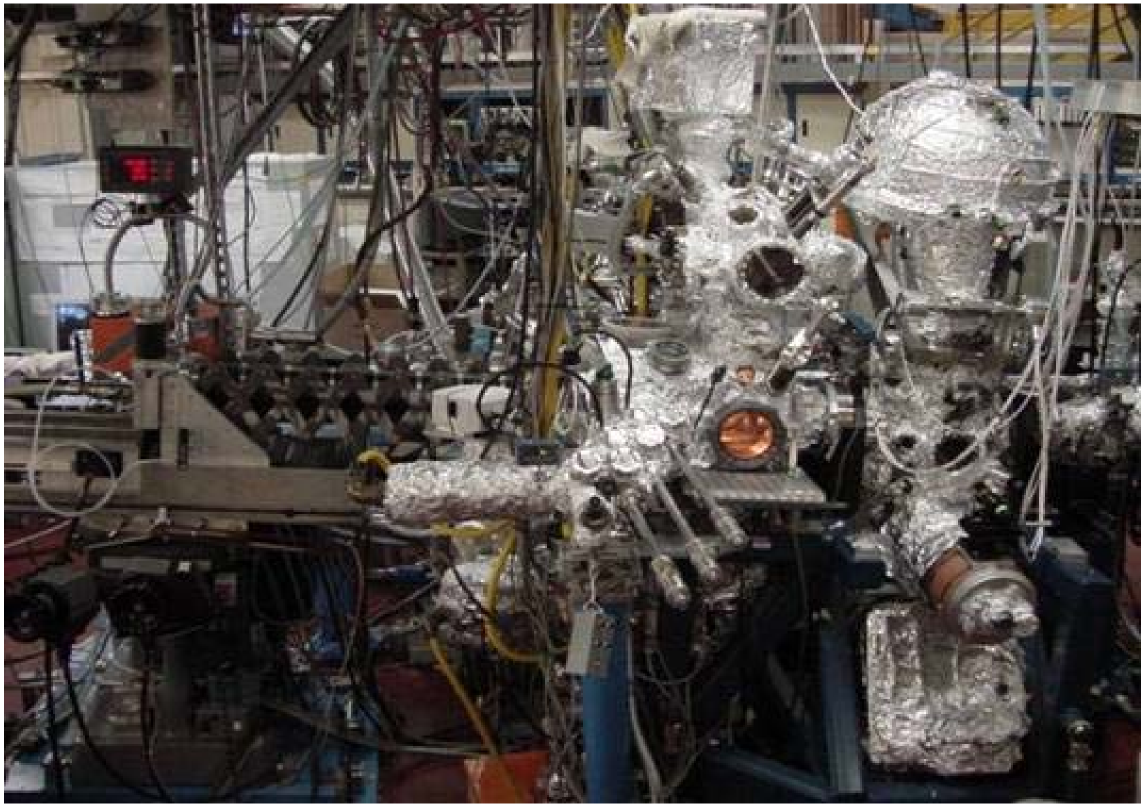
HTSC Phase Diagram

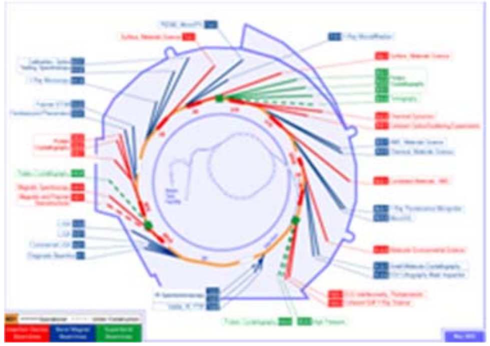


Hanaguri et al., Nature 2004

High Tc Superconductors and Electron Spectroscopy (ARPES)

- **A**ngle **R**esolved **P**hoto-**E**lectron **S**pectroscopy

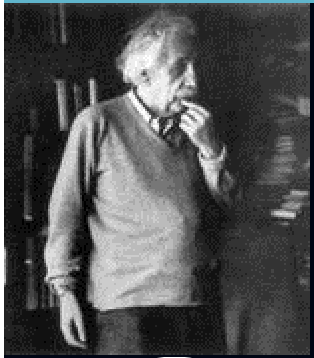




Measures the k-resolved DOS
$A(k, \omega)$

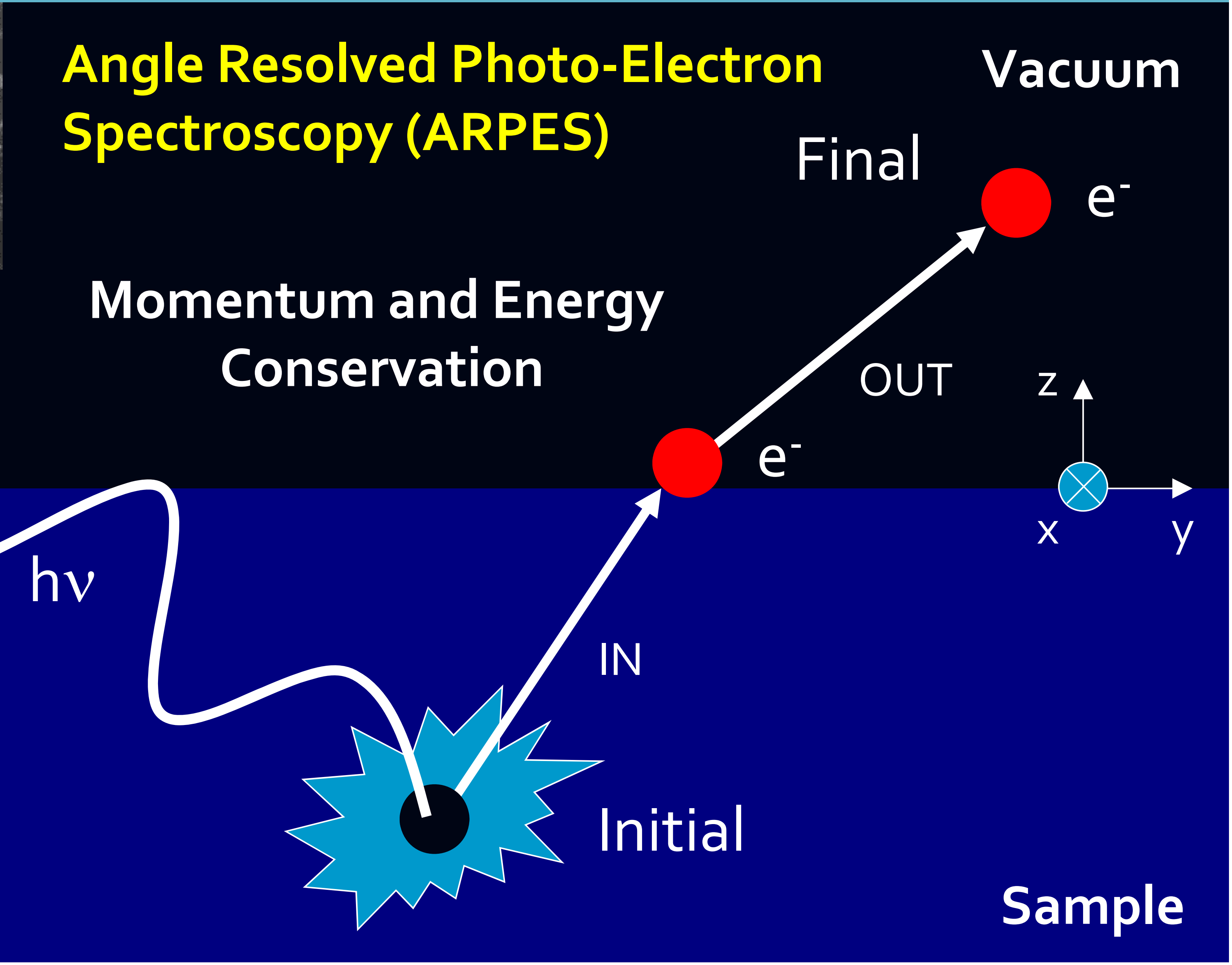
"Finger prints" or "pictures" of electrons/holes

Einstein and Photoelectric Effect



Angle Resolved Photo-Electron Spectroscopy (ARPES)

Momentum and Energy Conservation



Strange ARPES line shapes

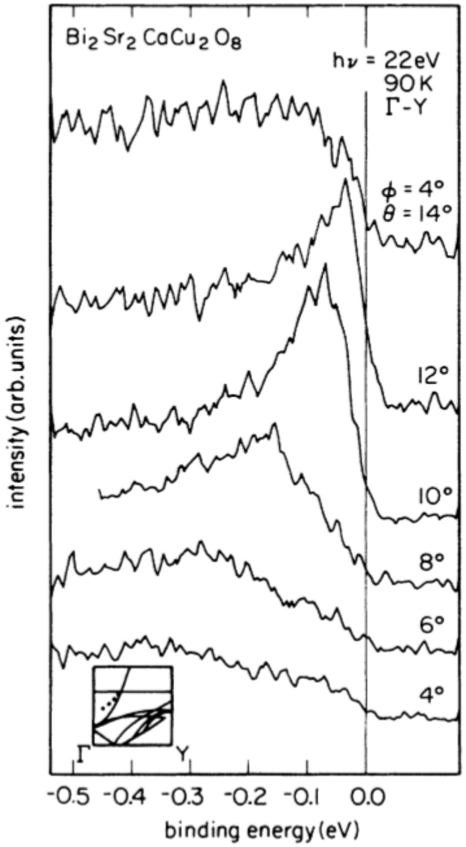


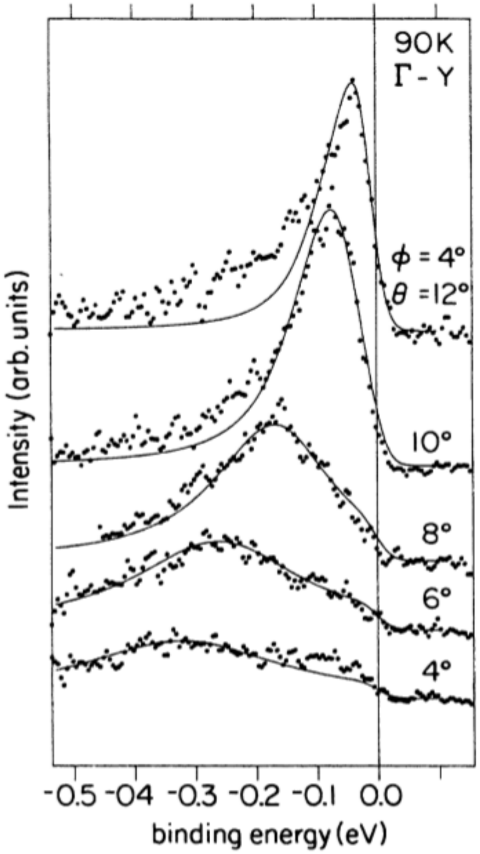
FIG. 1. Angle-resolved energy distribution curves fo
angles along the Γ-Y direction in the Brillouin zone us
tons of energy 22 eV. The inset shows the measu
dispersion (dots) and the calculated bands from Ref. 8.

Non-Lorentzian Line Shapes! (Strong Asymmetry and large background)

Width is roughly linear in peak position

$$\mathrm{Im}\Sigma \propto \omega?$$

Marginal Fermi liquid (MFL) provided explanation and good fits (Abrahams and Varma PNAS 2000, Kaminski et al. PRB 2001)



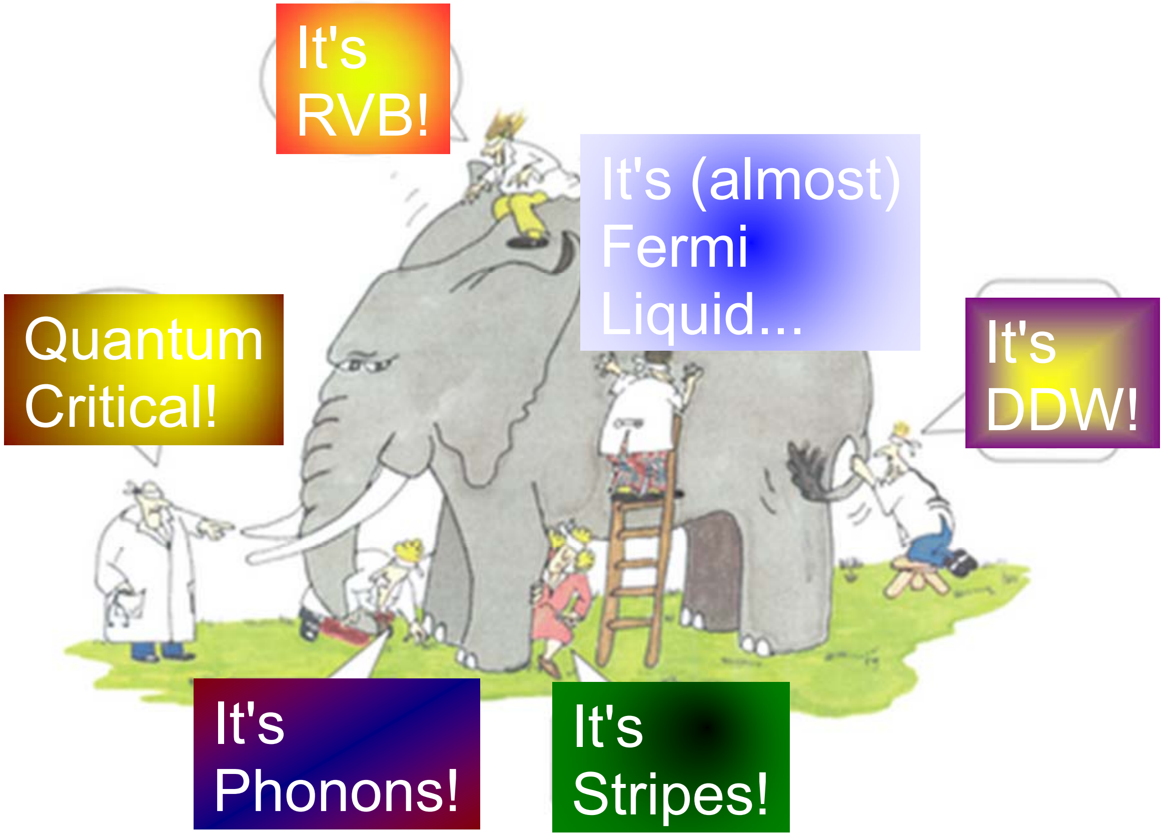
5. Spectra of Fig. 1 with background removed. The
the fits using a linear energy-dependent broadening as
d in the text.

Olson, PRB '90

How much do we understand?

- Many theories have been, and are being, proposed to crack the mystery.
  - Marginal Fermi liquid theory (Varma '89)
  - Fermi liquid theory (Olson '90)
  - Hidden Fermi liquid theory (Anderson '11)
  - Extremely correlated Fermi liquid theory (Shastry '11)

High temperature superconductivity



http://middleschooladvisory101.blogspot.com/2009/04/blind-man-and-elephant.html

The New ECFL Theory

- Extremely Correlated Fermi Liquid Theory
  (t-J model solution)

  Shastry, Phys. Rev. Lett. 107, 056403 (2011)
- What is new? The ECFL solution is a novel solution to the t-J model.

t-J Hamiltonian

$$H = P\ t \sum_{\langle i,j \rangle} c^{\dagger}_{i,\sigma} c_{j,\sigma}\, P + J \sum_{\langle i,j \rangle} \vec{S}_i \cdot \vec{S}_j$$

$$\langle i, j \rangle = \text{nearest neighbor site indices}$$

$$P = \prod_i \left(1 - n_{i,\uparrow} n_{i,\downarrow}\right) \qquad \text{(Gutzwiller projection)}$$

$$n_{i,\sigma} = c^{\dagger}_{i,\sigma} c_{i,\sigma}$$

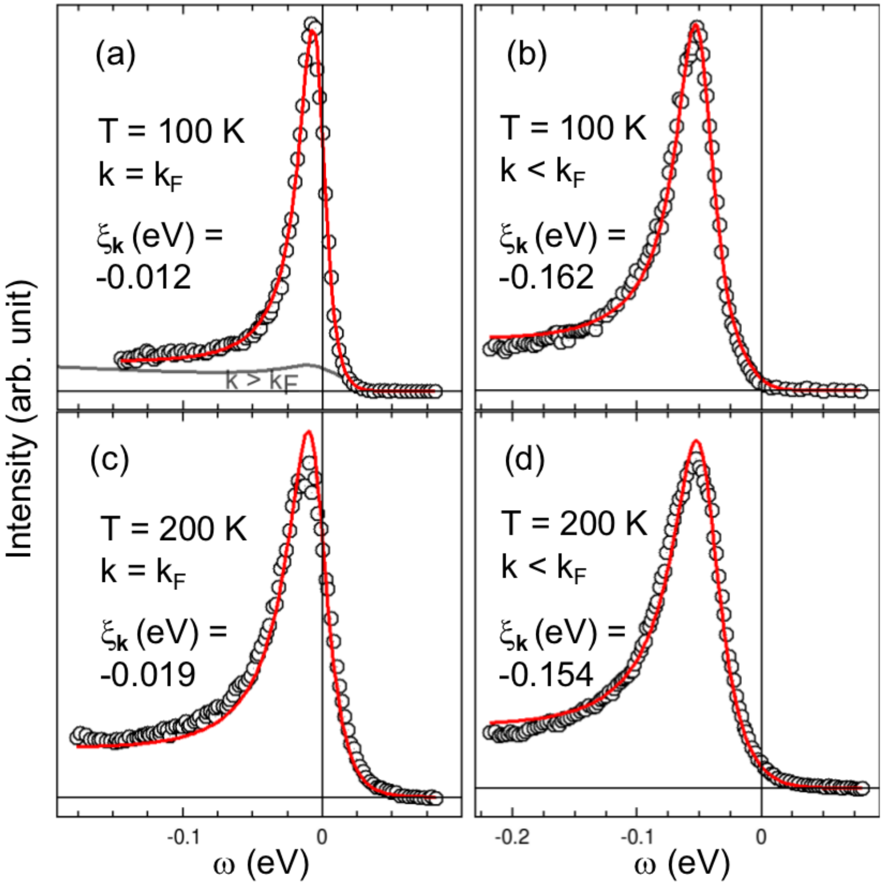
Physics for the parameter regime that flows to the $U = \infty$ fixed point

Rice 1988
Anderson

sECFL

GHG, Shastry, Gu, PRL, '2011

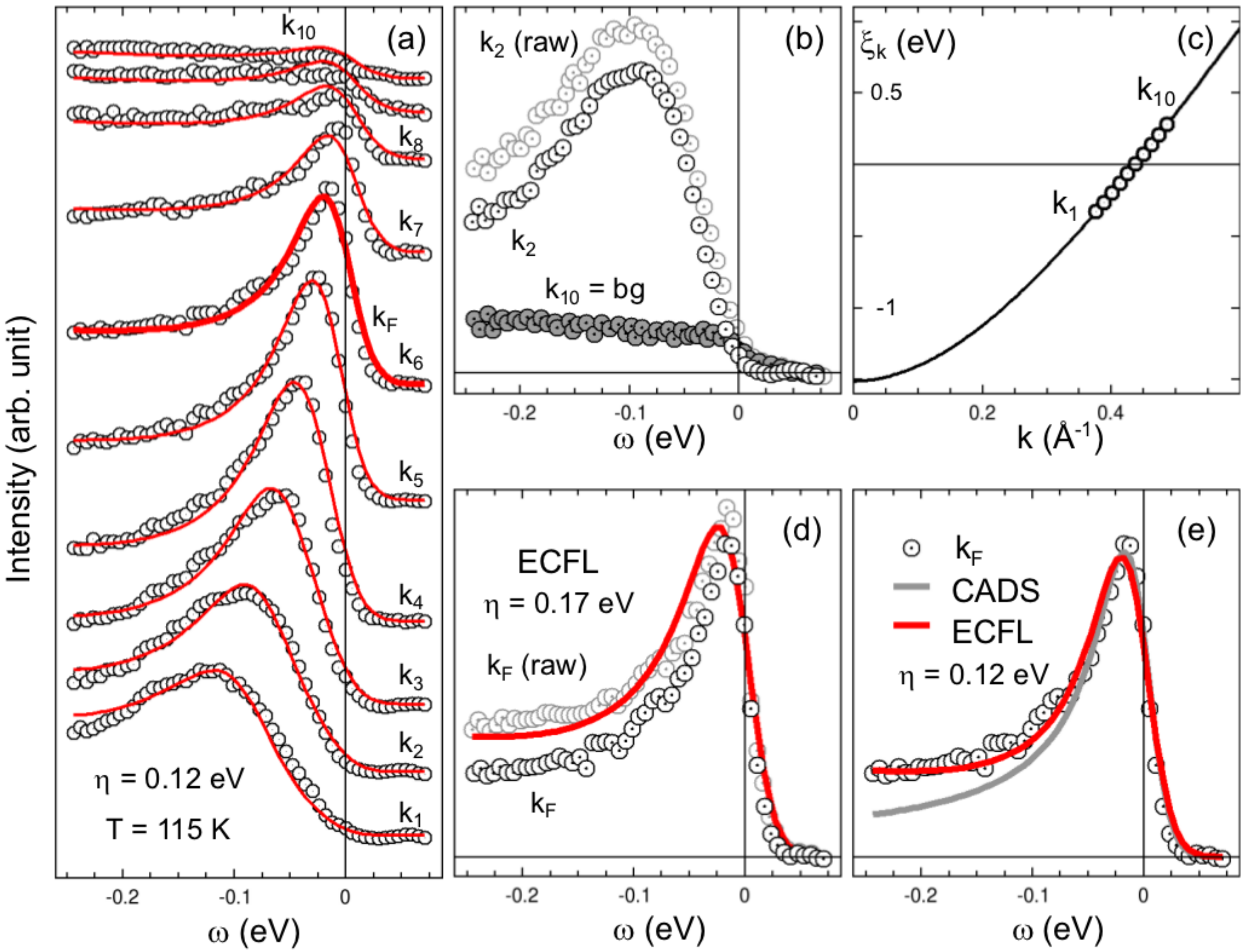
How well does the theory work?



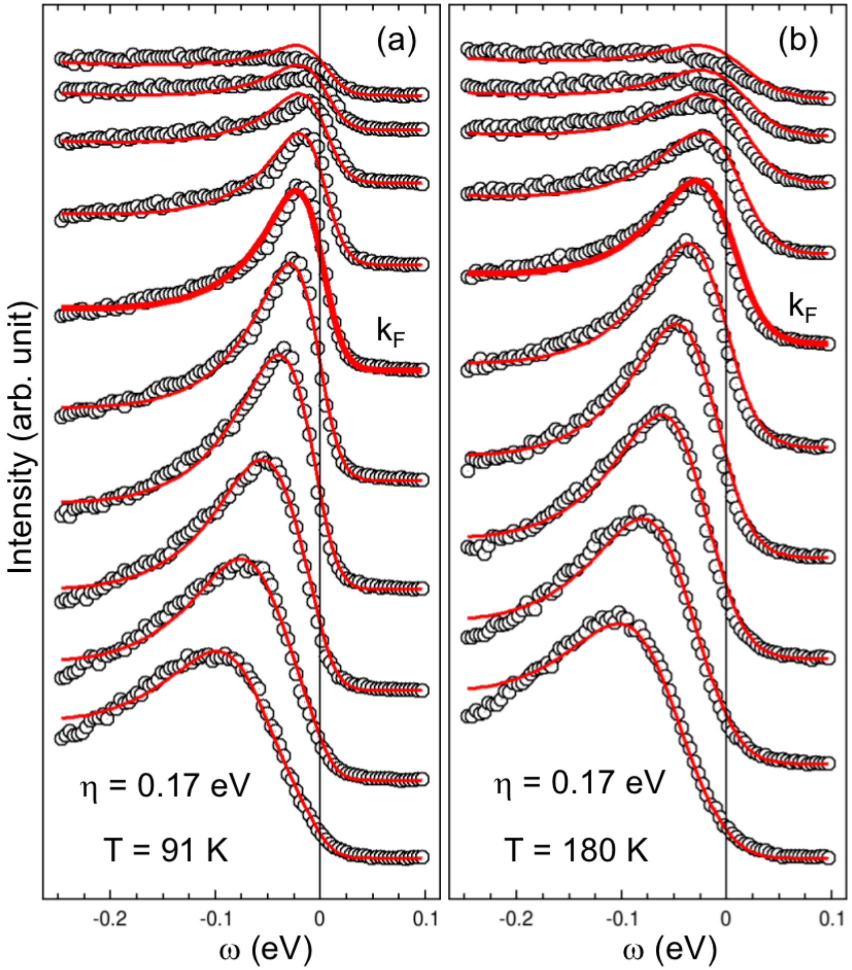
Laser ARPES Data
Photon energy = 6 eV
Sharp peaks

$\omega_0 = 0.5$ eV
is the main
fit parameter
outcome

Conventional ARPES data (Kaminski, 01)
The only free fit parameter is η!



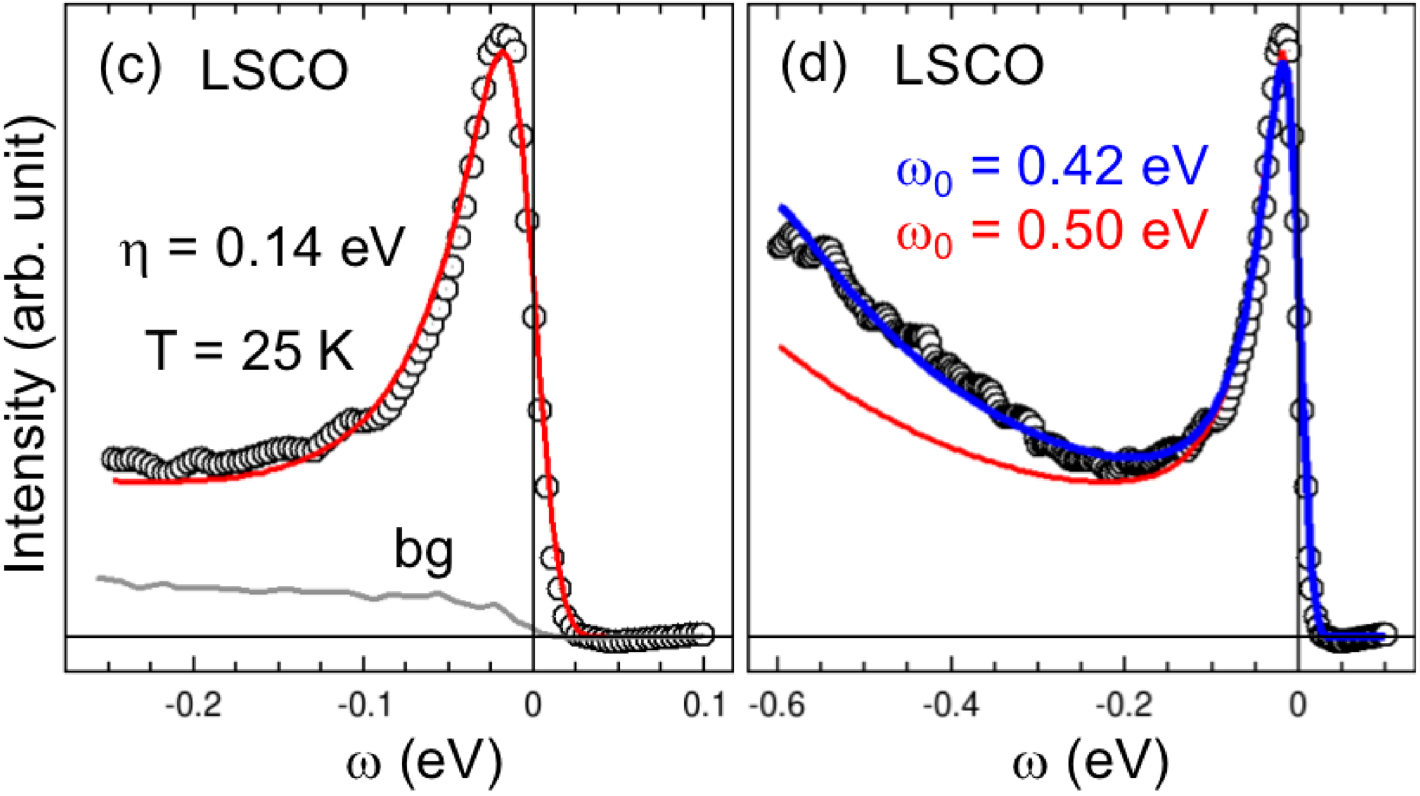
Conventional ARPES data (GHG, 11)
The only free fit parameter is η!



GHG, Shastry, Gu, Phys. Rev. Lett., 107, 056404 (2011)

Conventional ARPES data (Yoshida, 07)
The only free fit parameter is η!

Play with ω_0 a bit.

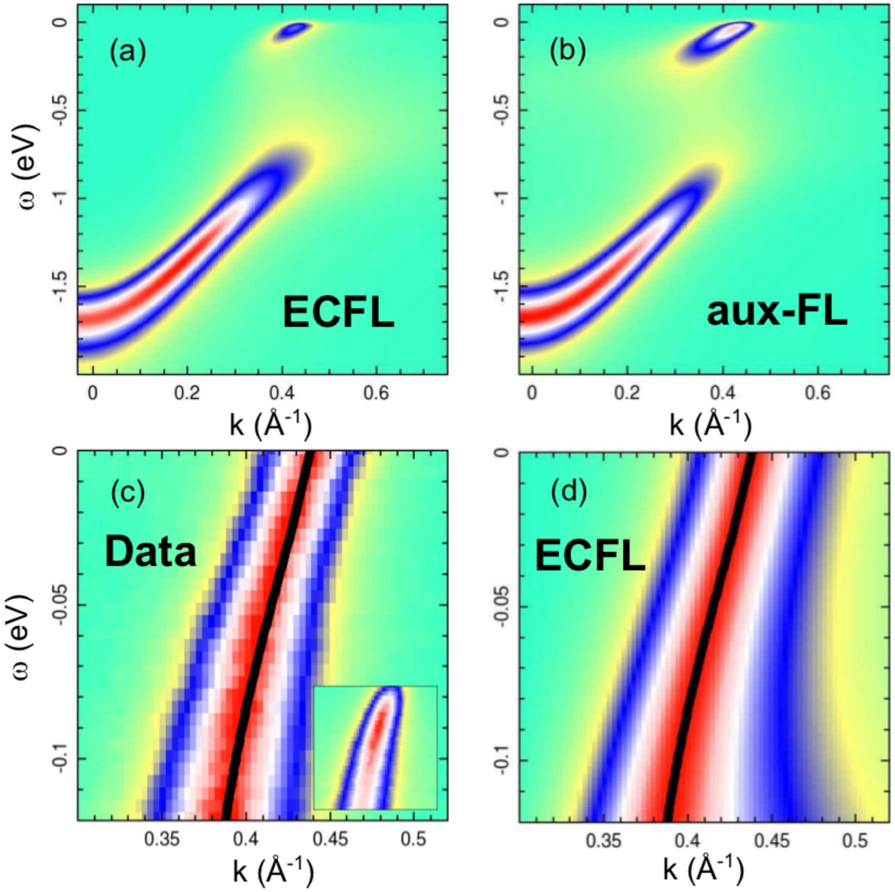


Success of the Theory

- For the first time, **EDCs** are explained well for different experiments (laser ARPES, conventional ARPES), and different samples (BISCO, LSCO).
- Satisfies the global particle sum rule.
- Energy scales are not arbitrary, but locked with respect to each other.
- The energy scales are natural candidates for explaining what we call “ARPES kinks.”

Success of the Theory

- ARPES “kinks”

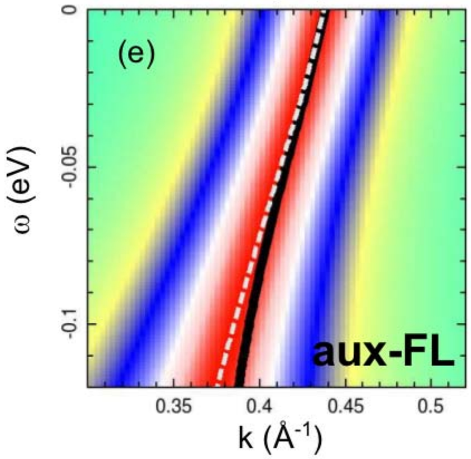


High Energy kink

Graf, GHG et al., PRL 07

GHG et al., PRL 06

Low Energy kink



$_{p}$ECFL

K Matsuyma, GHG, under review in PRL

Phenomenological ECFL

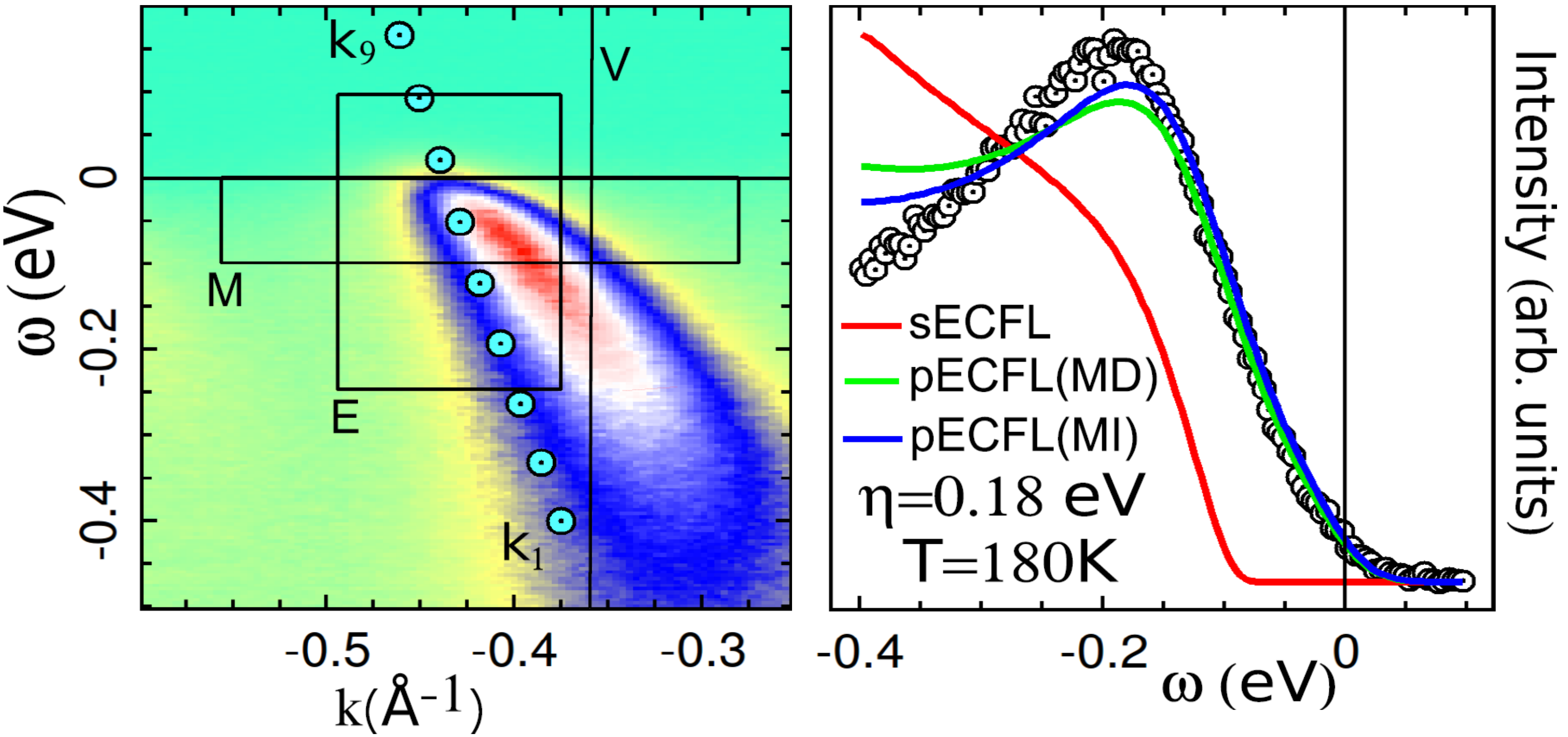
- Simplified ECFL (sECFL) and phenomenological ECFL (pECFL) are both phenomenological efforts (pECFL more so) that parallel more first principles approach (Shastry, Hansen).

- The goal is to recognize features of the theory and the experiment that agree (or not), while paying attention to global sum rules, energy scales, analyticity, causality, etc.

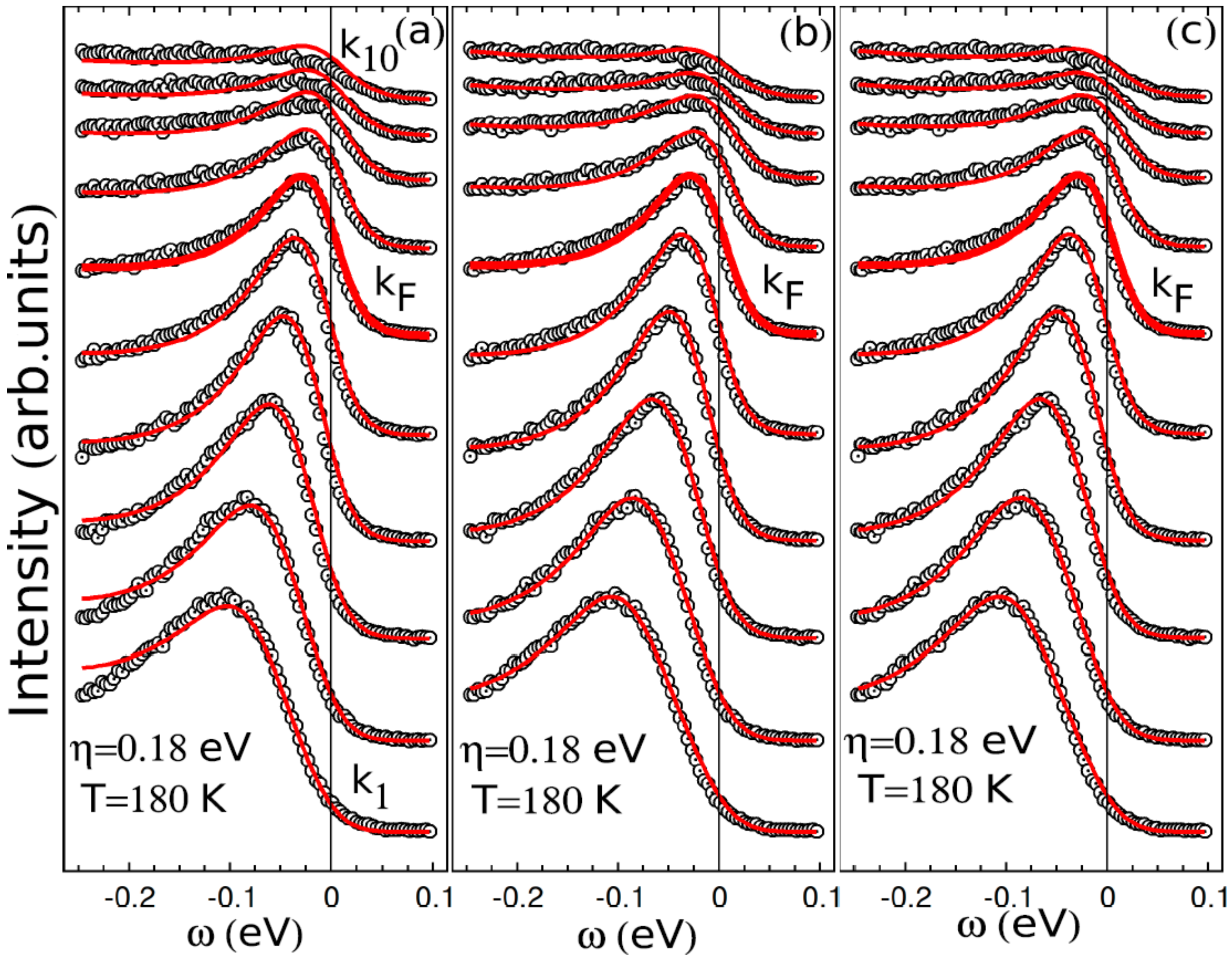
- Keep the strengths of sECFL.

- Extend the sECFL to make it more powerful.

Line shape fits (MDC)



Line shape fits (EDC)



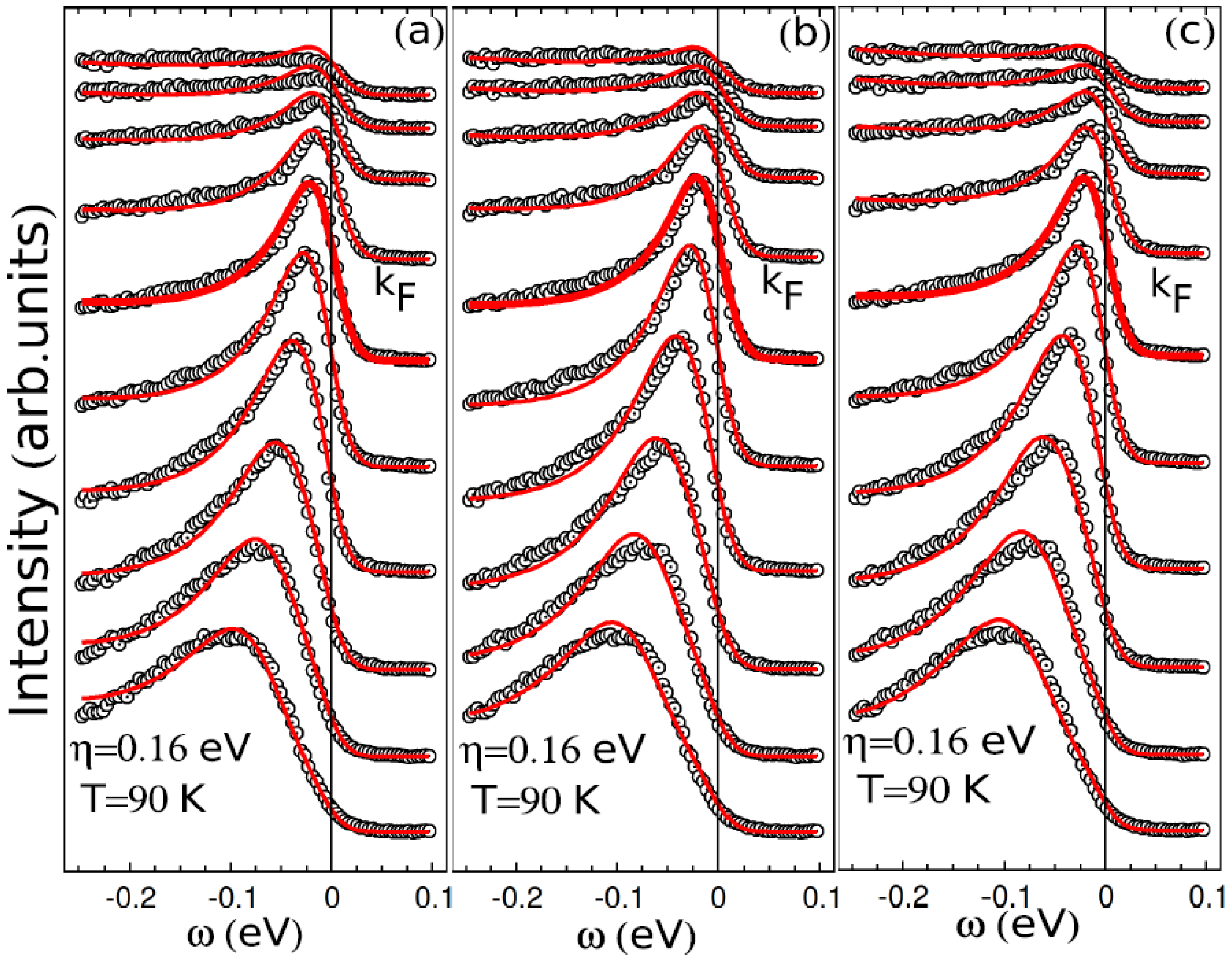
sECFL

pECFL (MD)

pECFL (MI)

Bi2212
OPT91

Line shape fits (EDC)



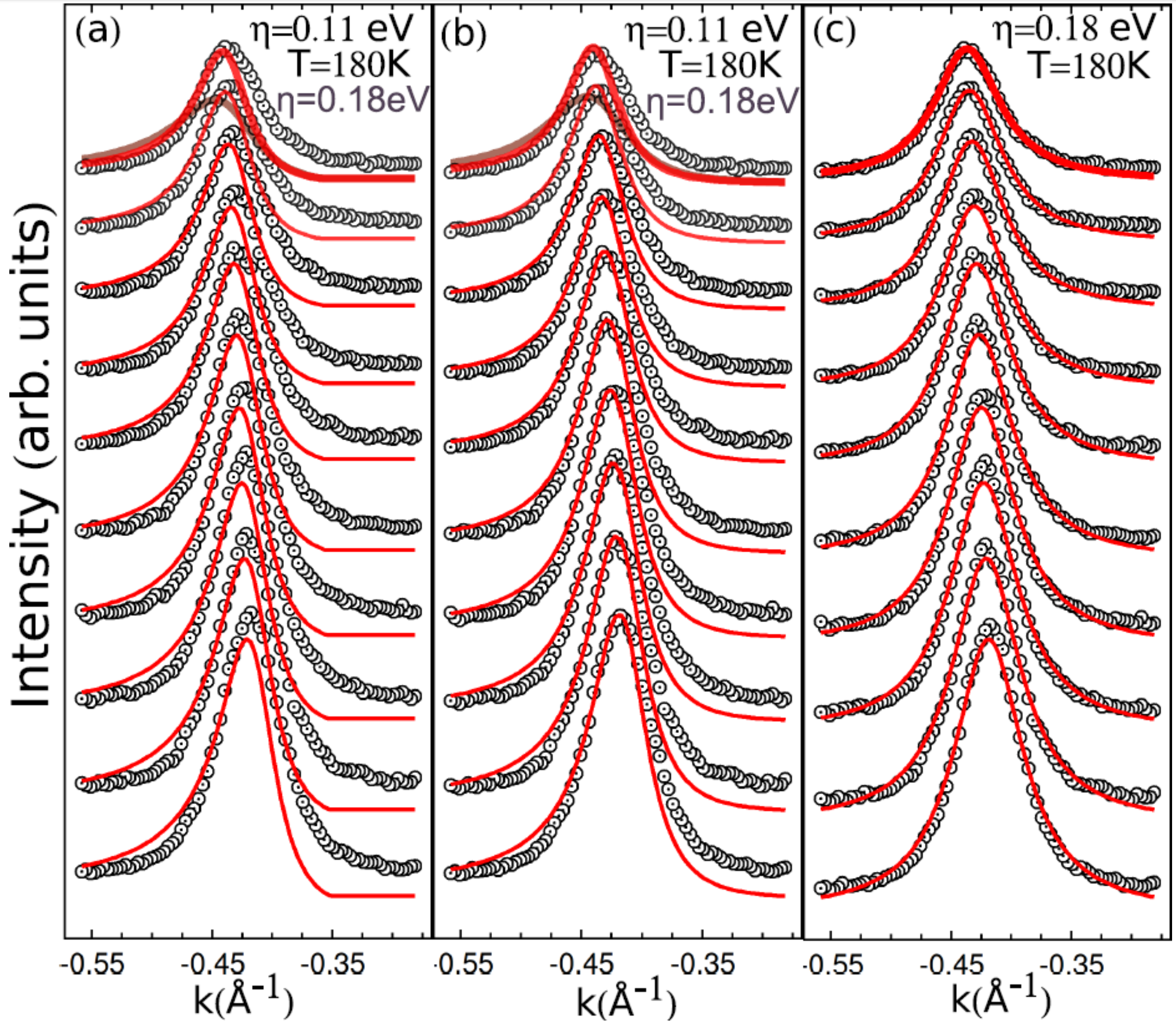
Bi2212
OPT91

sECFL

pECFL (MD)

pECFL (MI)

Line shape fits (MDC)



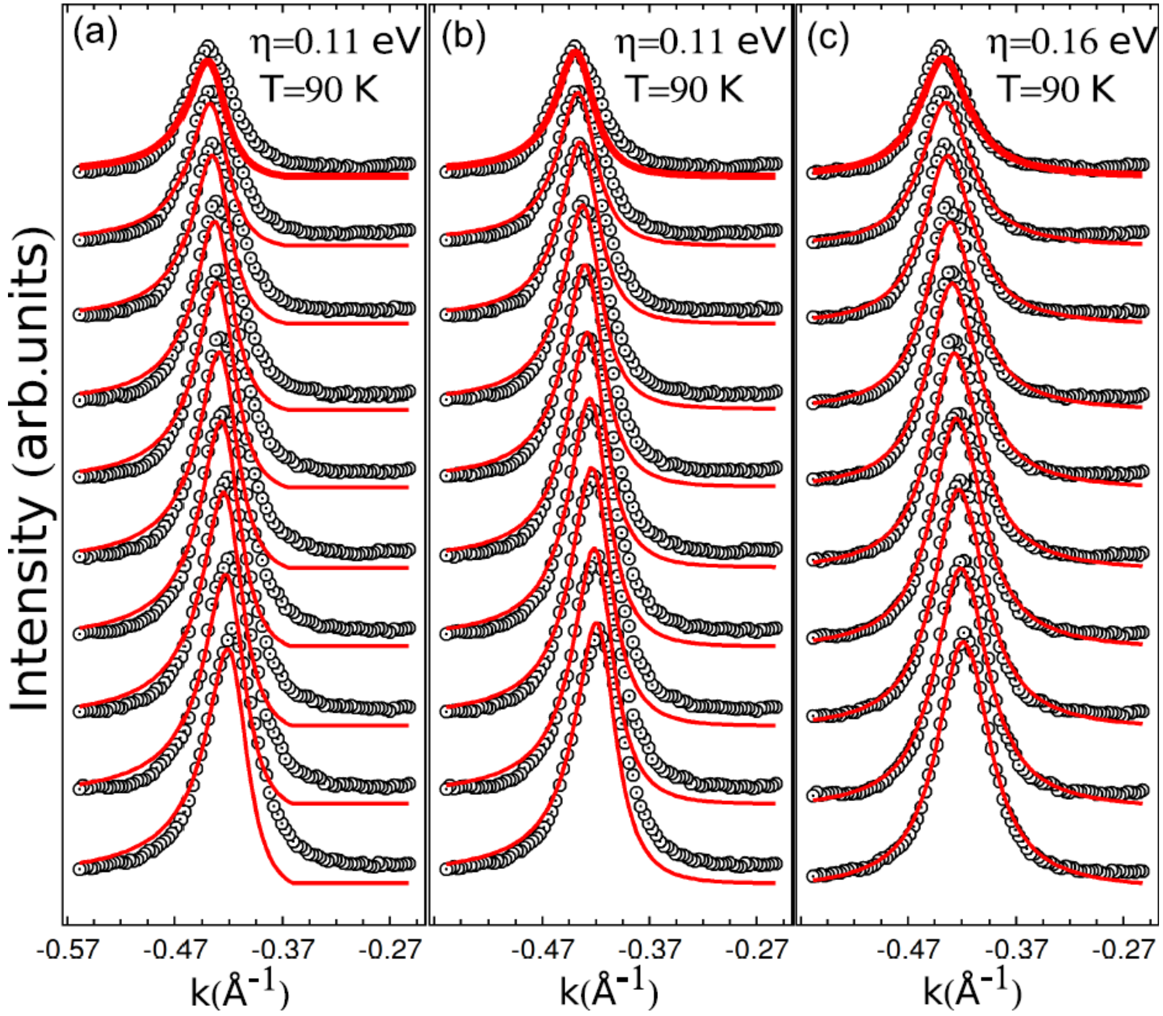
sECFL

pECFL (MD)

pECFL (MI)

Bi2212
OPT91

Line shape fits (MDC)



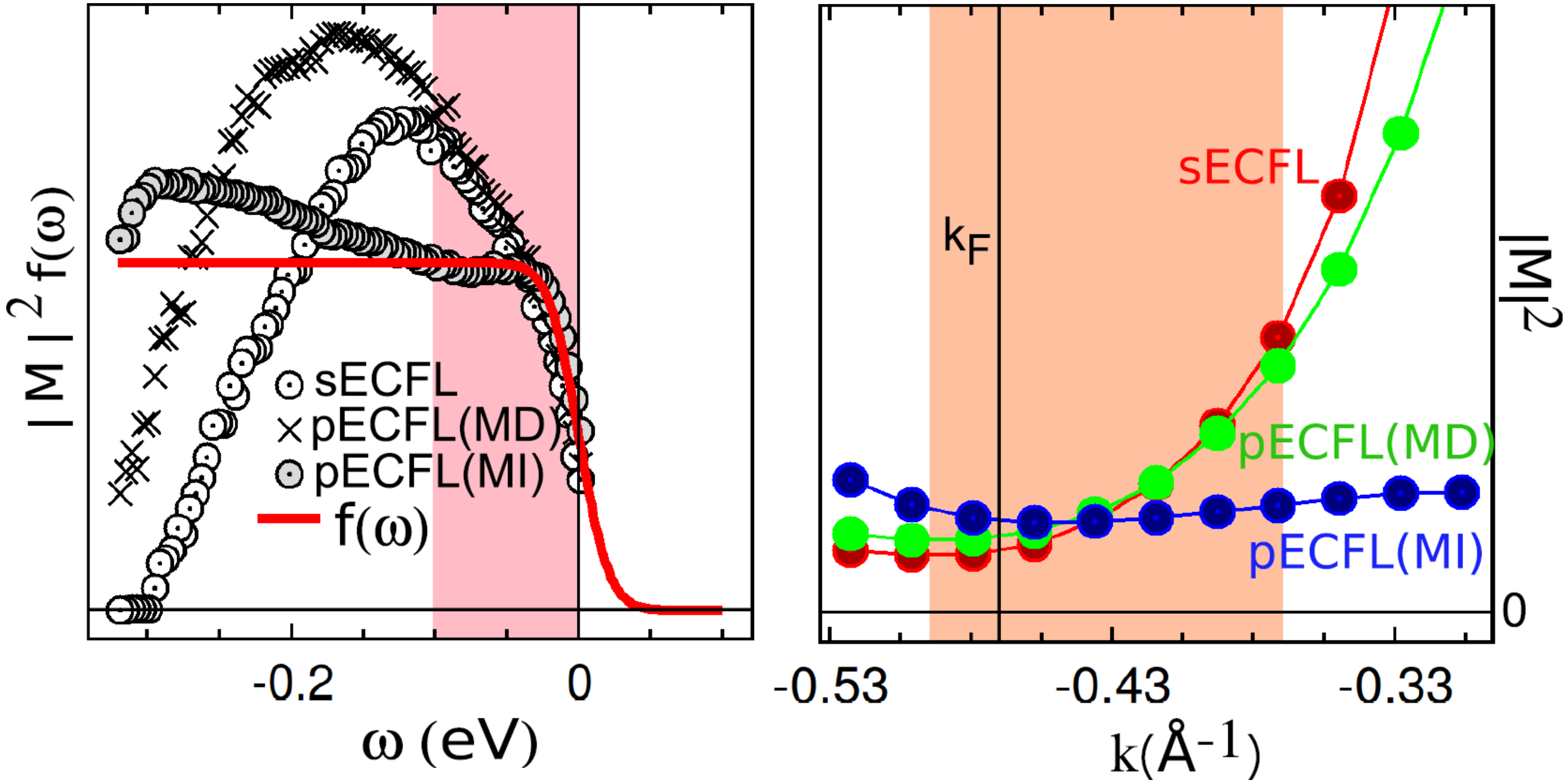
Bi2212
OPT91

sECFL

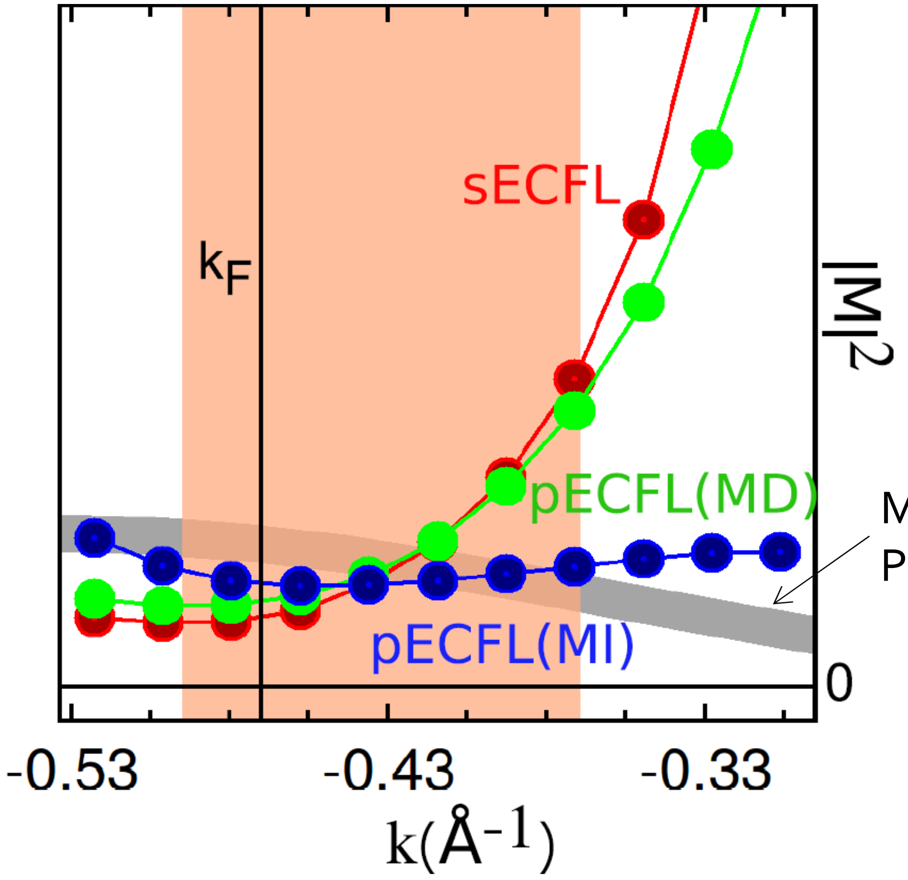
pECFL (MD)

pECFL (MI)

“Weight” parameters

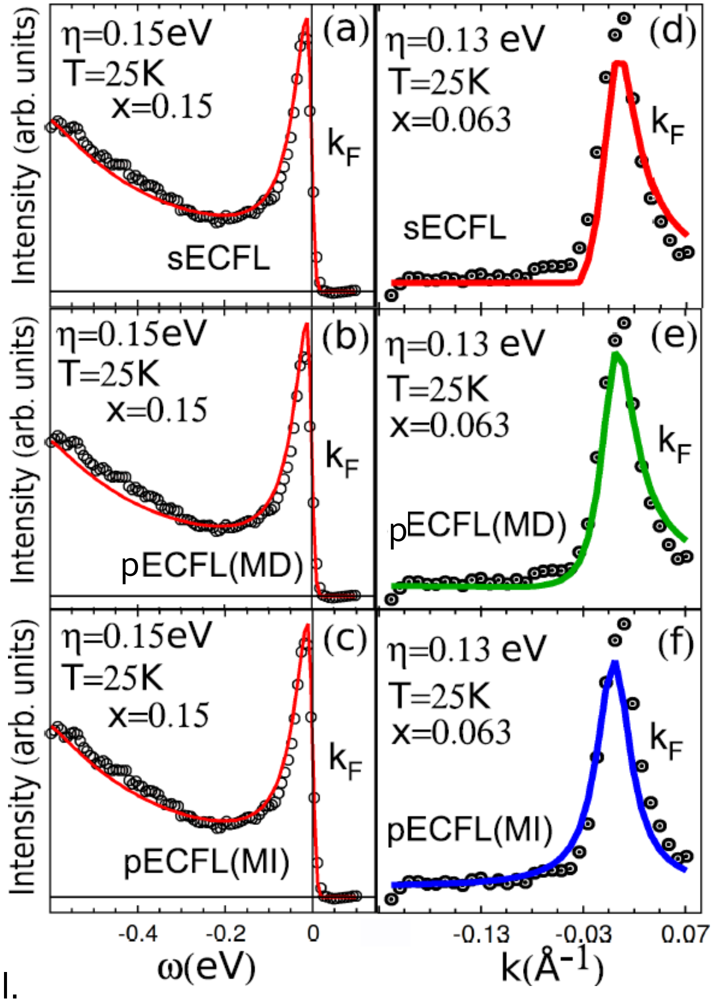


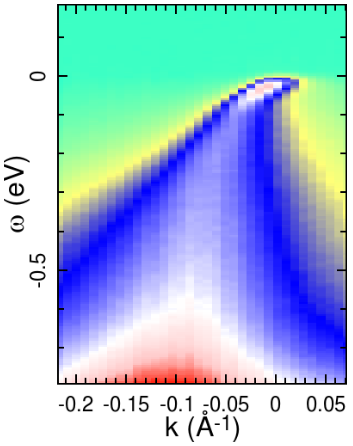
"Weight" parameters



Meevasana et al.
PRB, '08

Line shape fits (LSCO; EDC, MDC)





Data by Zhou, Yoshida, et al.

Conclusion

We are cracking the hardest part of the high Tc puzzle in Santa Cruz!!

Conclusions

The ECFL works extremely well!

- The asymmetry in the energy distribution curves (EDC) is described well by the ECFL model.
- The momentum distribution curves (MDCs) are described well by a phenomenological extension of the sECFL model.
- Unprecedented degree of success to understand the ARPES using a strongly correlated electron model.
- Universal features and non-universal features – future work.