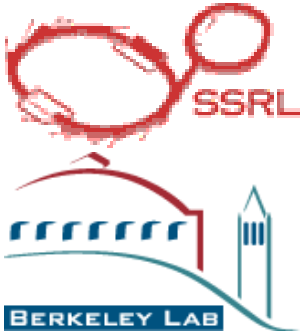
Electron spectroscopy on high temperature superconductors and other novel materials

Gey-Hong Gweon



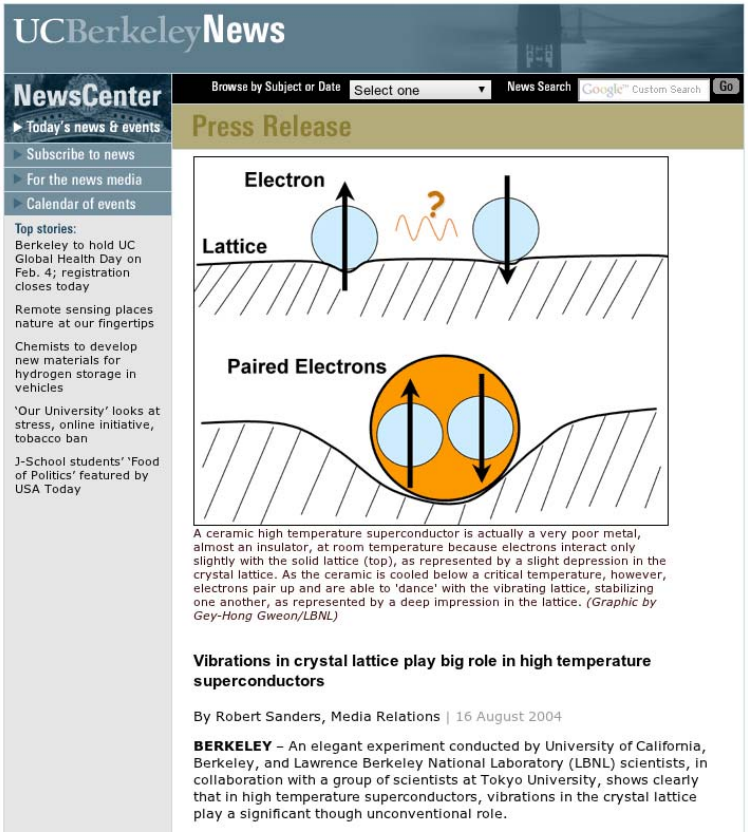
Credits

- Simon Bell
- Gregory Kaminsky
- Ahram Kim
- Jianqiao Meng
- Matthew Brunner
- Brandon McGuire
- James Hinton
- Jacob Stanley
- Sriram Shastry
- Andrew Laforge
- Arthur Ramirez
- Zack Shlesinger
- Dave Belanger

- S.-I. Lee, K.-H. Lee, H.-G. Lee (POSTECH, Korea)
- Genda Gu, J. S. Wen, Z. J. Xu (Brookhaven N. Lab.)
- Takao Sasagawa (Tokyo Institute of Technology)
- Kai Rossnagel (Kiel)

HTSCs and other correlated semi-metals ($TiTe_2$, Topological insualtor)

My interest



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Press Release

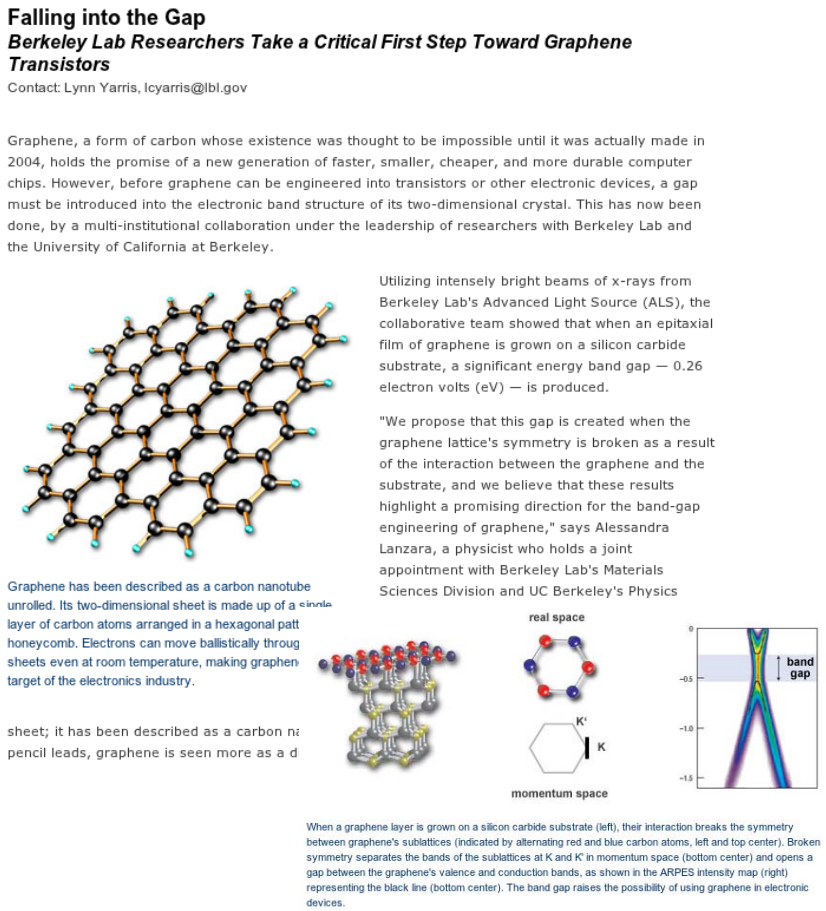
A ceramic high temperature superconductor is actually a very poor metal, almost an insulator, at room temperature because electrons interact only slightly with the solid lattice (top), as represented by a slight depression in the crystal lattice. As the ceramic is cooled below a critical temperature, 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.

Gweon et al., Nature 2004



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 Lanzara, a physicist who holds a joint appointment with Berkeley Lab's Materials Sciences Division and UC Berkeley's Physics

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 patt honeycomb. Electrons can move ballistically throug sheets even at room temperature, making graphen target of the electronics industry.

sheet; it has been described as a carbon na pencil leads, graphene is seen more as a d

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.

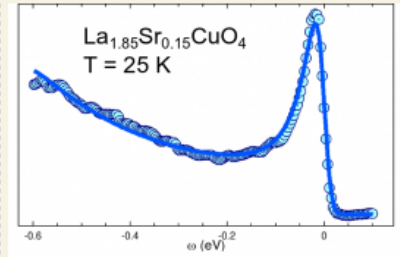
Zhou, Gweon et al., Nature Materials 2007

My interest

New Work Solves Conundrum in High Temperature Superconductivity

SSRL Science Summary, 2011 - Kelen Tuttle

Angle-Resolved Photoelectron Spectroscopy Superconductors



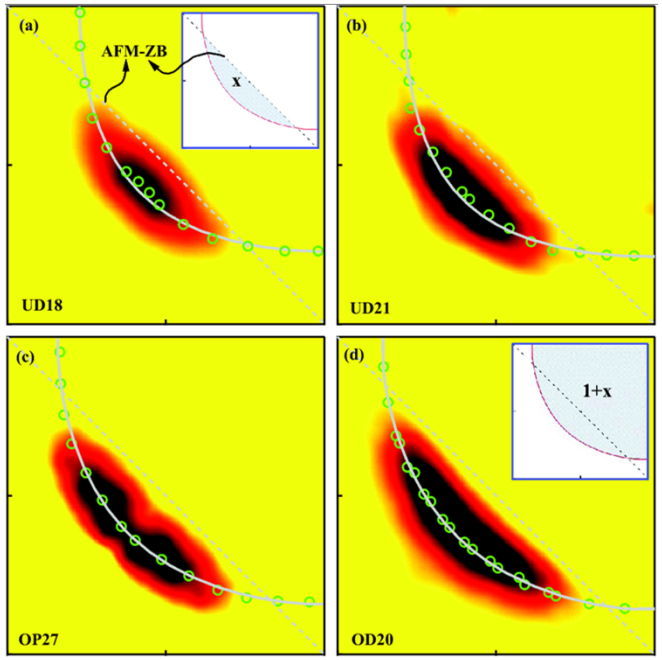
An examplary fit of ARPES data using the ECFL theory. In this fit, the very wide energy of the data are fit including the rising background, thanks to the ``caparison factor" of the ECFL theory.

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.

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



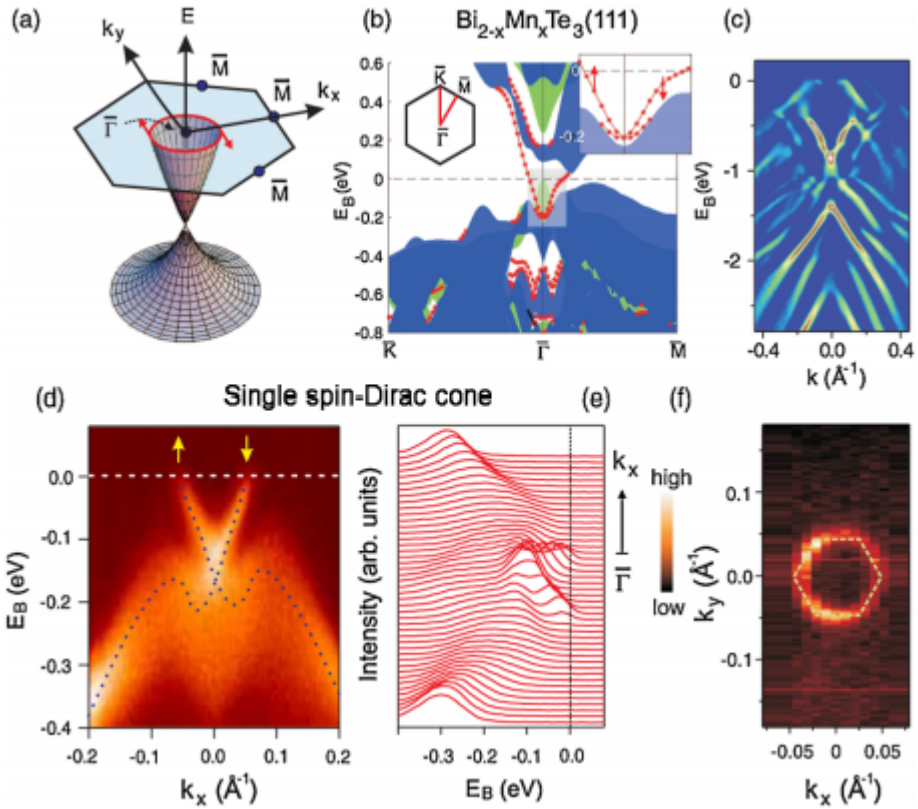
Meng, Gweon et al., PRB RC 11

Invitation to March meeting, Book chapter, Special journal issue

My interest

Topological Insulator

Insulating bulk
Conducting surface
Robust conducting surface
guaranteed by topology



Hsieh, Hasan, et al.
PRL 2009

Superconductivity = dance of electron pairs

Kamerling Onnes (1911)

BCS theory (1957)

Bound Pair

Binding energy = SC gap

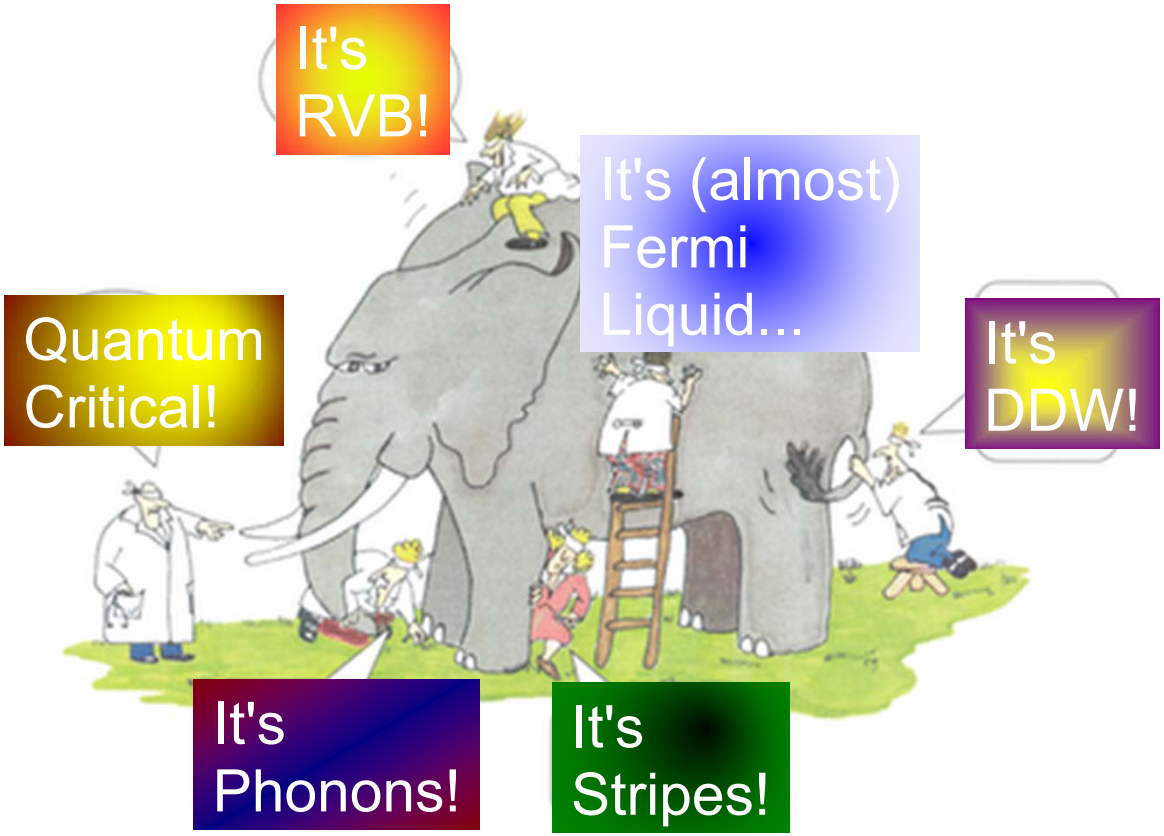
All to the same tune!
Phase coherent SC condensate

Phys. Today, March '04

Dual nature of high temperature superconductors

- Strong interaction leads to a high temperature superconductivity, but …
- it can also lead to other phenomena that are not necessarily useful...
- Charge order is such an example.
- Understanding charge order is a crucial part in understanding the high temperature superconductivity.

High temperature superconductivity



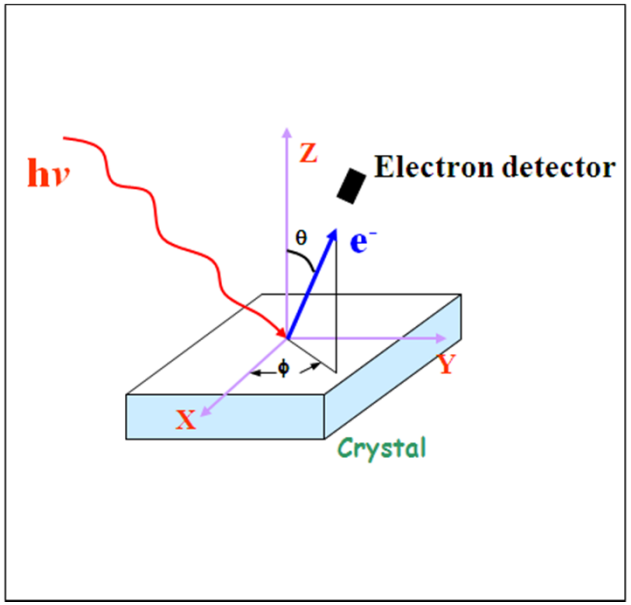
http://middleschooladvisory101.blogspot.com/2009/04/blind-man-and-elephant.html

How to "see" electrons…

- For conventional superconductors, the tunneling spectroscopy (Giaever, Nobel prize '73) has been critically helpful.
- For high temperature superconductors, similar techniques ARPES and STS have been very enlightening.

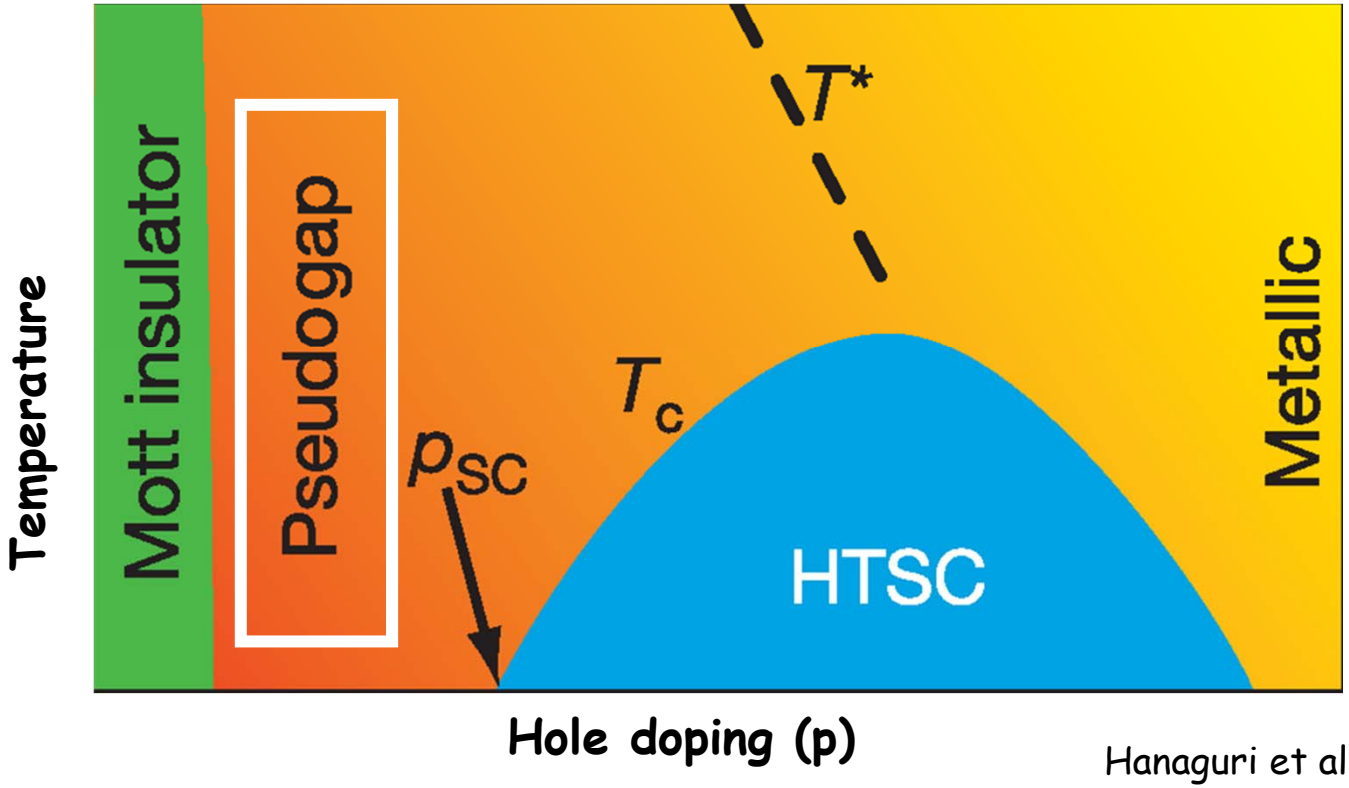
Electron spectroscopy on high temperature superconductors

- ARPES : Angle Resolved Photo-Electron Spectroscopy
  - Sophisticated photoelectric
  - effect experiment
  - Measures the momentum
  - resolved density of states



- STS : Scanning Tunneling Spectroscopy
  - Measures the spatially resolved density of states

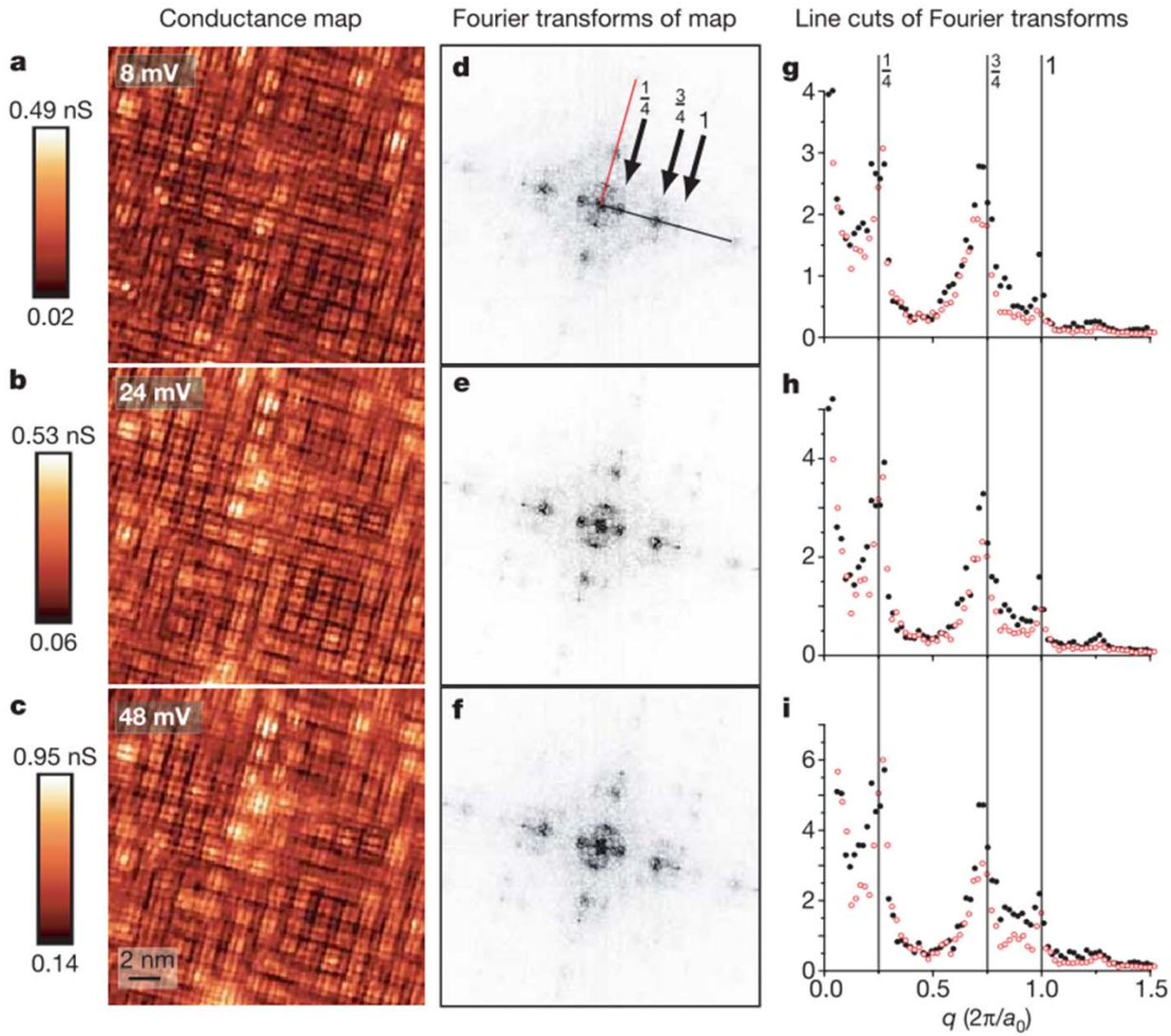
Electron spectroscopy on high temperature superconductors



Hanaguri et al., Nature '04

Is there a charge/spin order in the pseudo-gap phase?
If so, what is the origin?

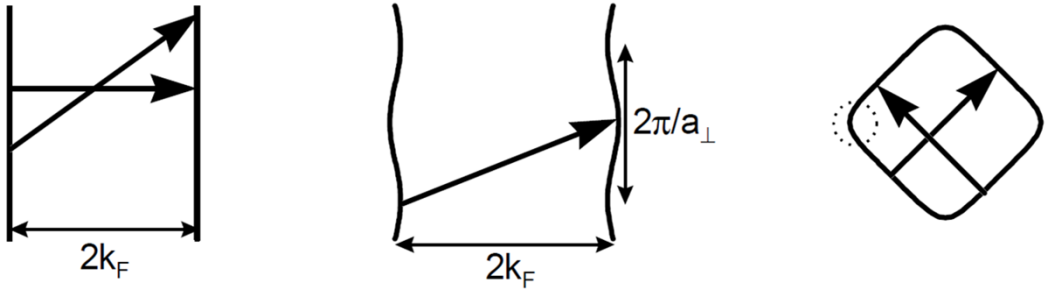
Charge order in Na-CCOC

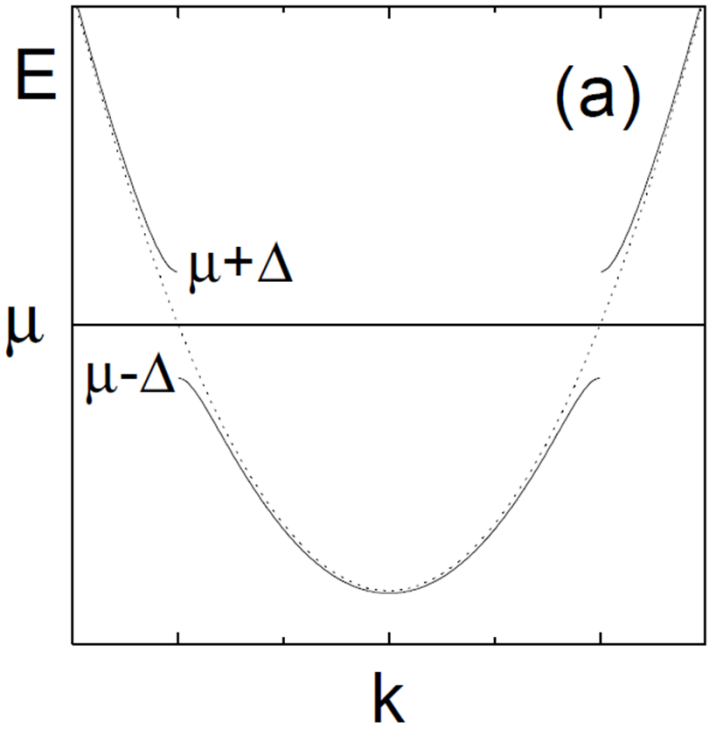


Hanaguri et al.
Nature 04

Origin of charge order?

Weak correlation scenario





- Fermi surface nesting
- Charge order ($2k_F$)
- Gap opening at μ

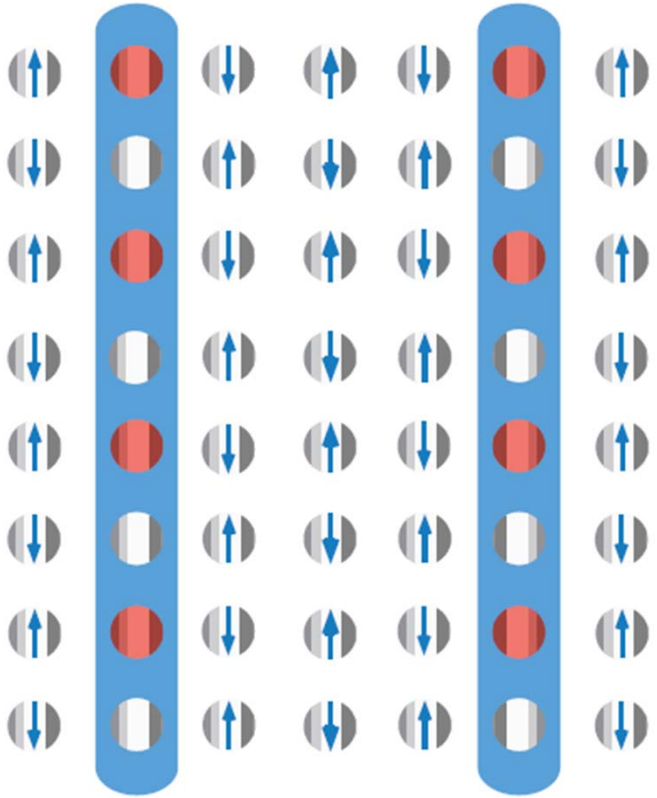
Peierls (1955)

Origin of charge order?

Strong correlation scenario

Charge order driven by Coulomb replusion (U) or exchange interaction (J), …

Stripes, Wigner crystal, pair density wave, ...



Question

- Which one is it? The strong correlation scenario or the weak correlation scenario?

- In the weak coupling scenario, the FS nesting is essential. In the strong coupling scenario, it is not, although it won't hurt.

Charge order in Bi-2201

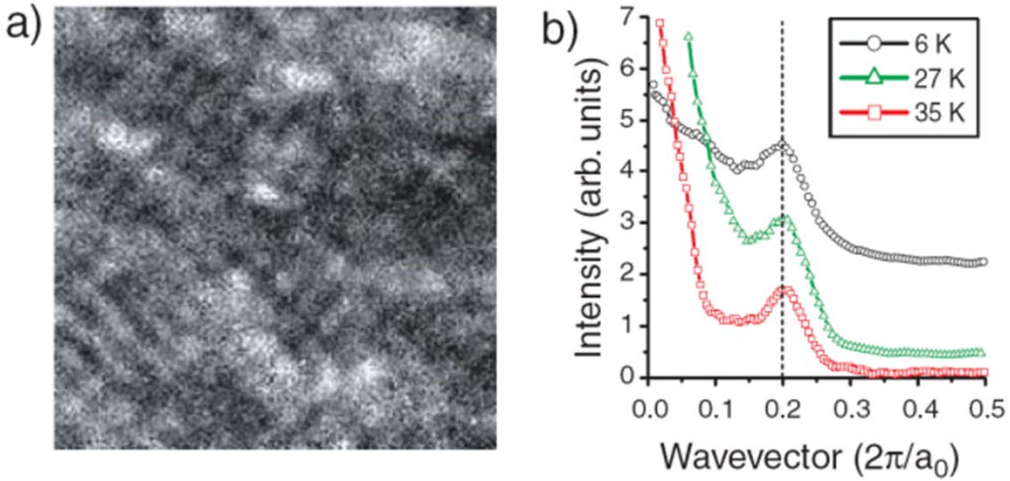
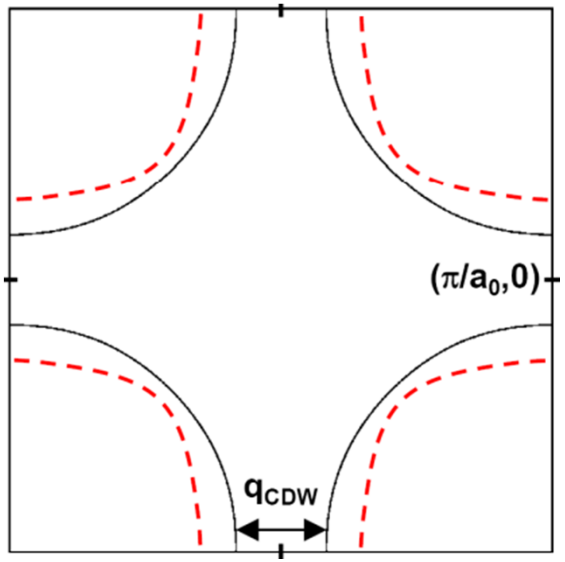
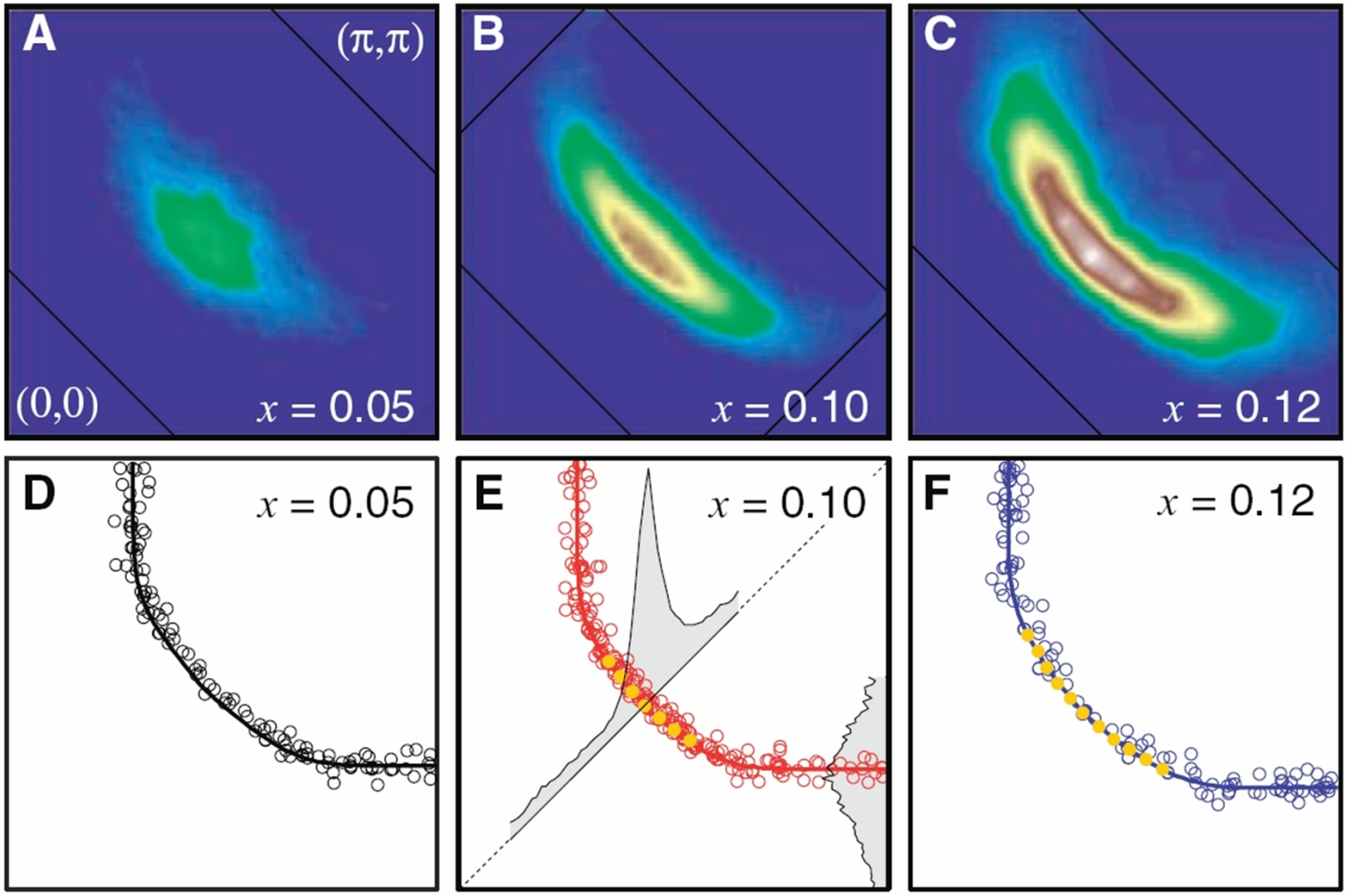


Fig. 3. Temperature independence of the checkerboard. (A) 300 Å, 10 mV conductance map of the underdoped T_C = 32 K sample measured at T = 35 K, slightly above T_C. The checkerboard is qualitatively unchanged from low temperatures (Fig. 2B). **(B)** Line cuts along the atomic lattice direction of FT-LDOS maps at this and lower temperatures indicate that the checkerboard wavevector is temperature independent (vertical line).



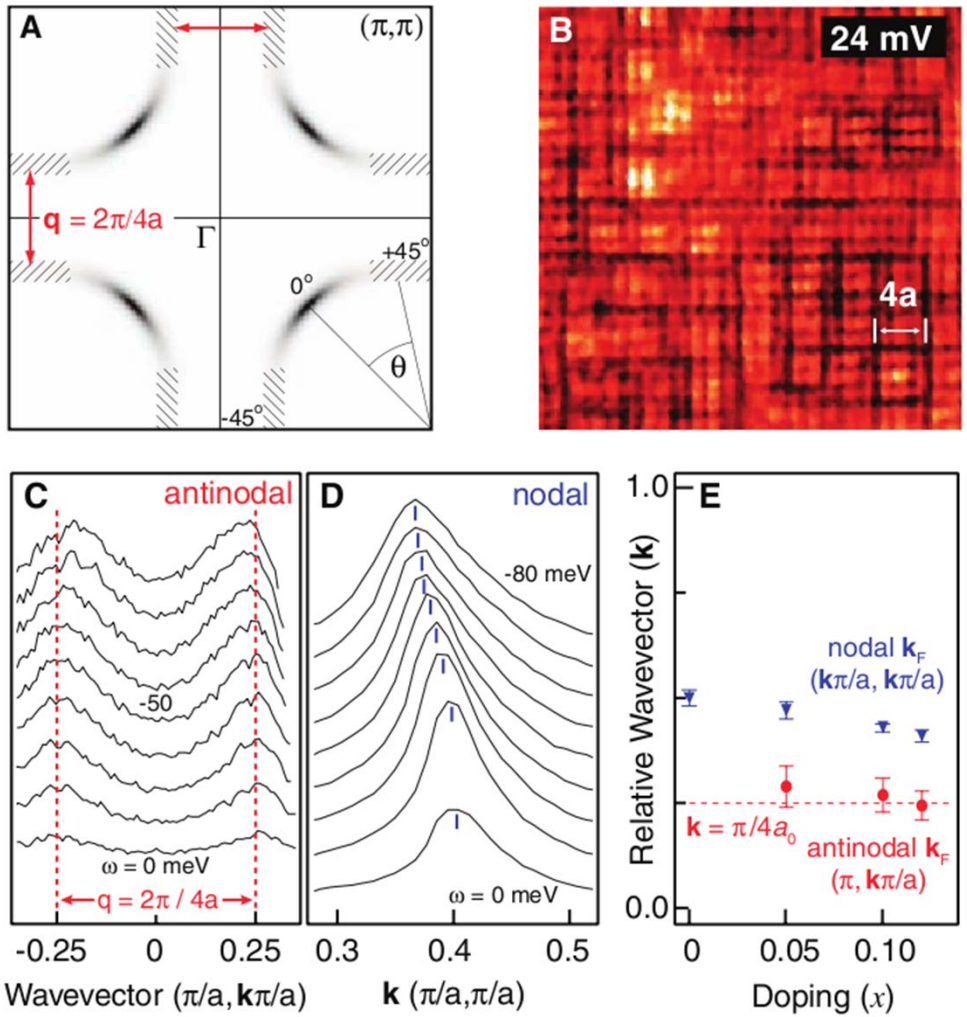
Wise et al., Nature Physics, 4, 696–699 (2008)

ARPES in Na-CCOC



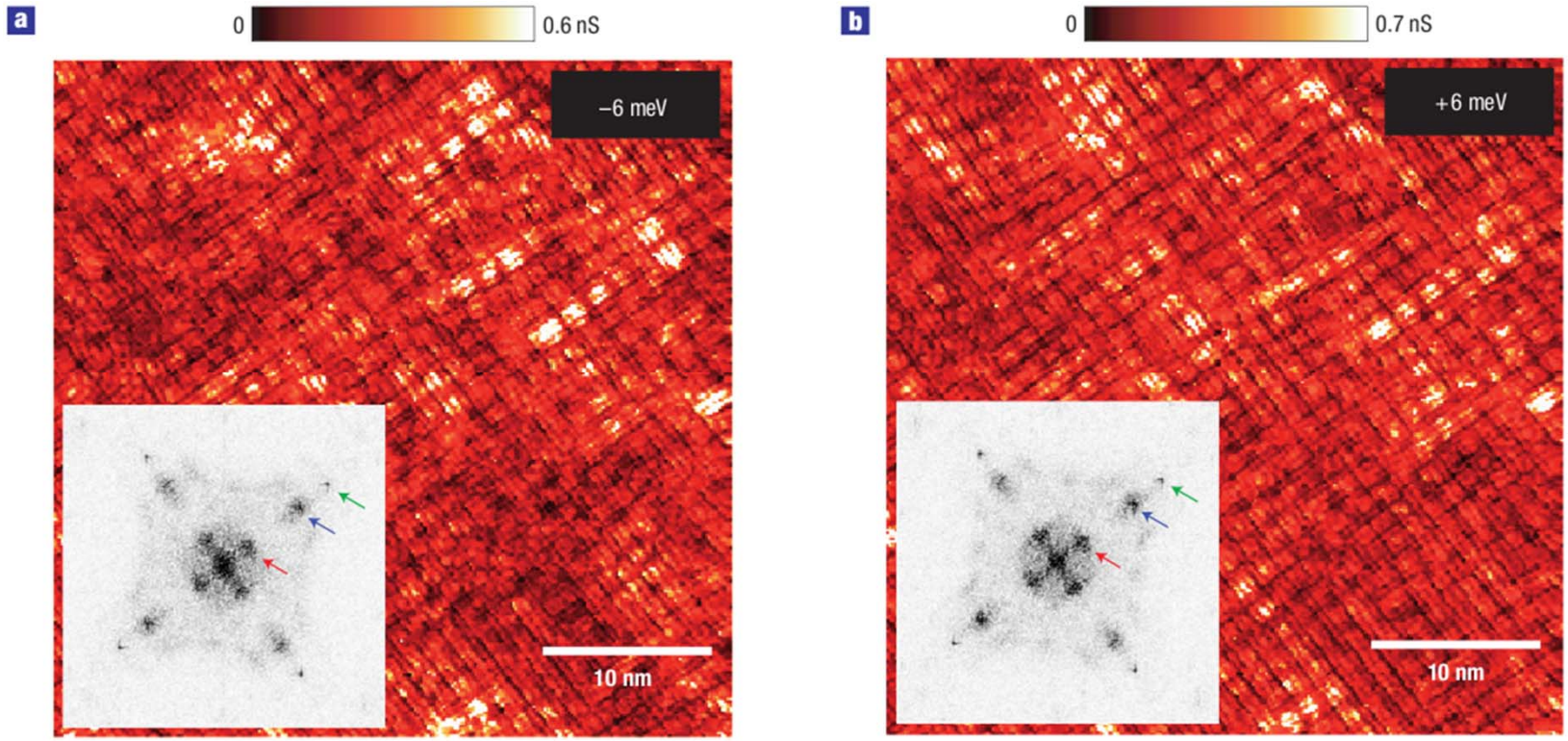
Shen et al., Science 05

ARPES in Na-CCOC



Shen et al., Science 05

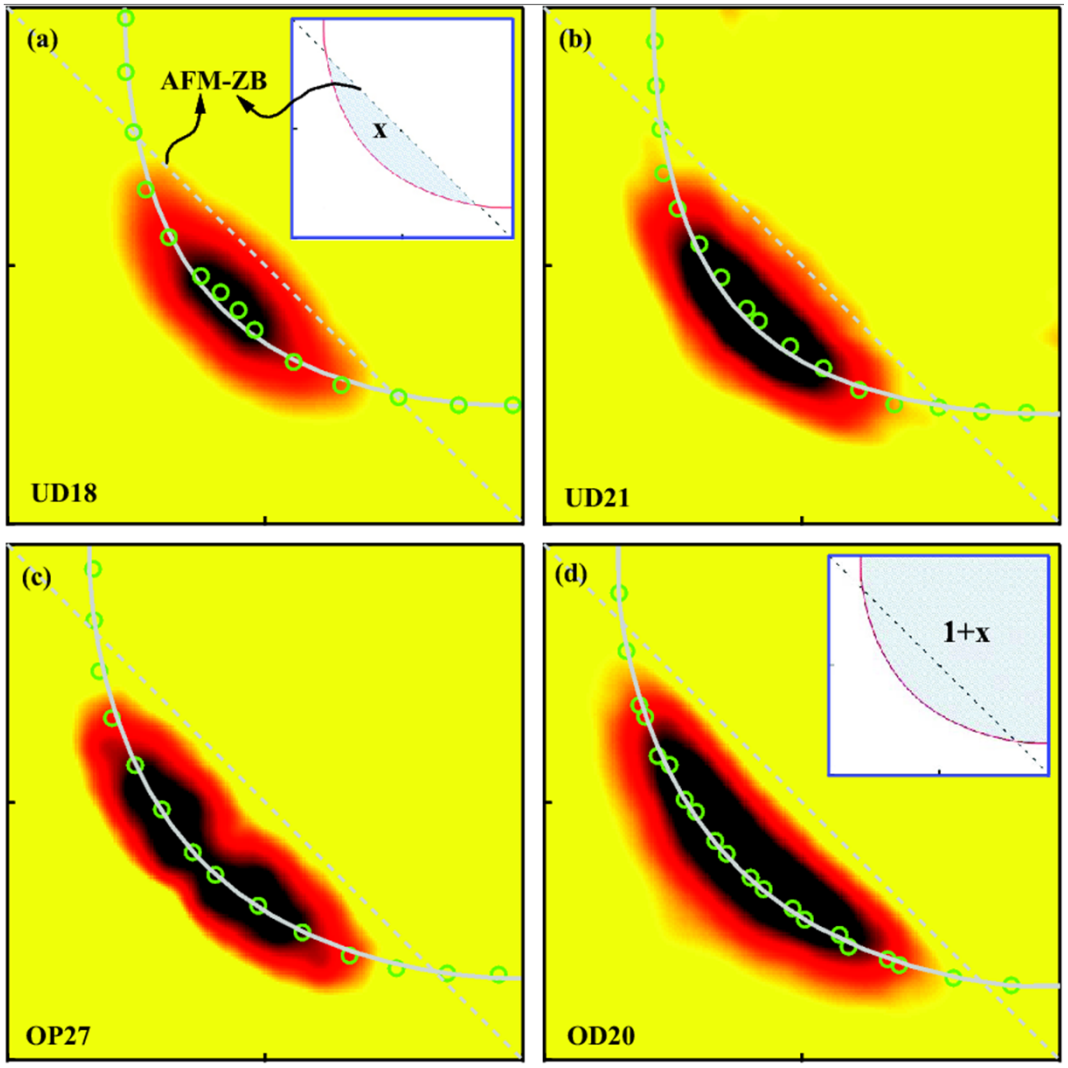
Charge order in Na-CCOC



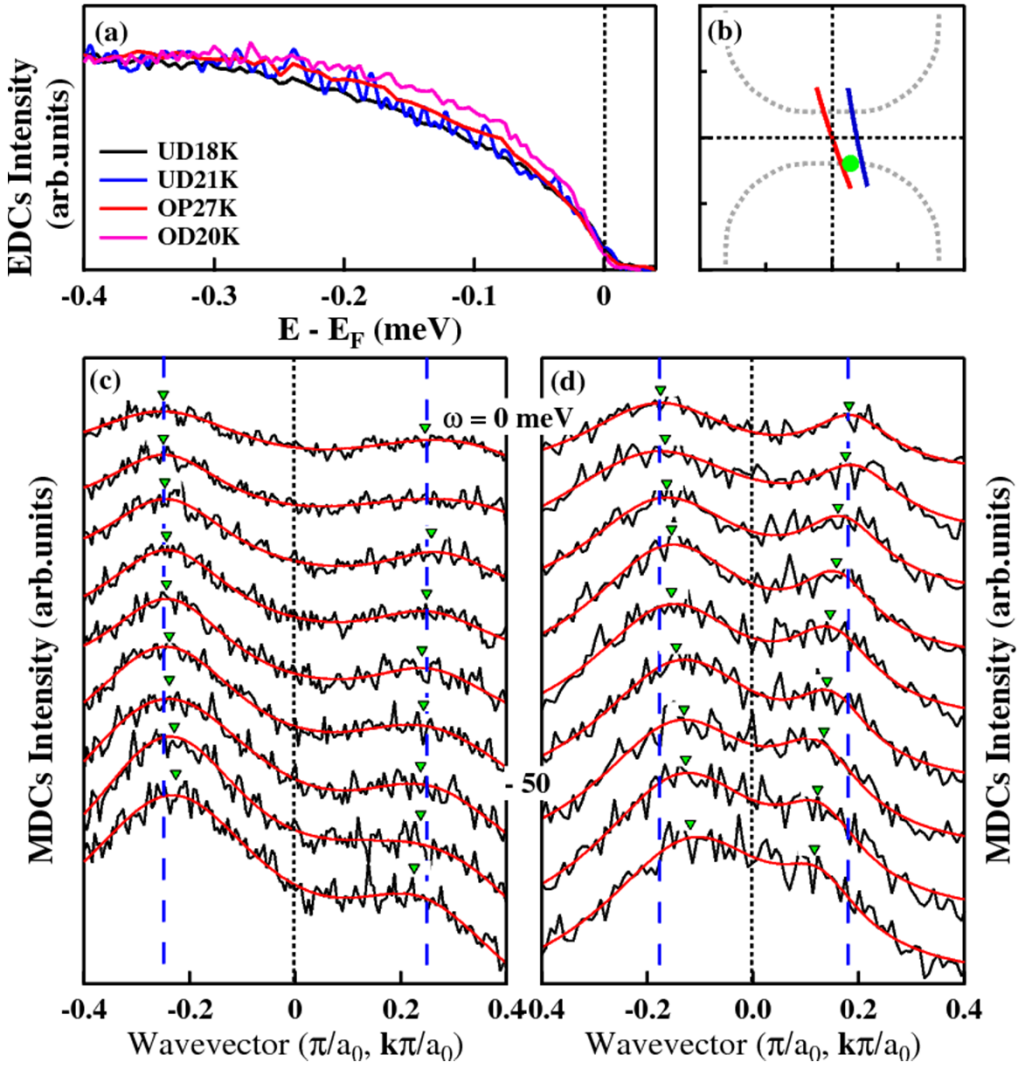
T_c = 28 K, Optimally Doped
The same ¼ (red arrow), ¾ (blue arrow) pattern

Hanaguri et al.
Nature 07

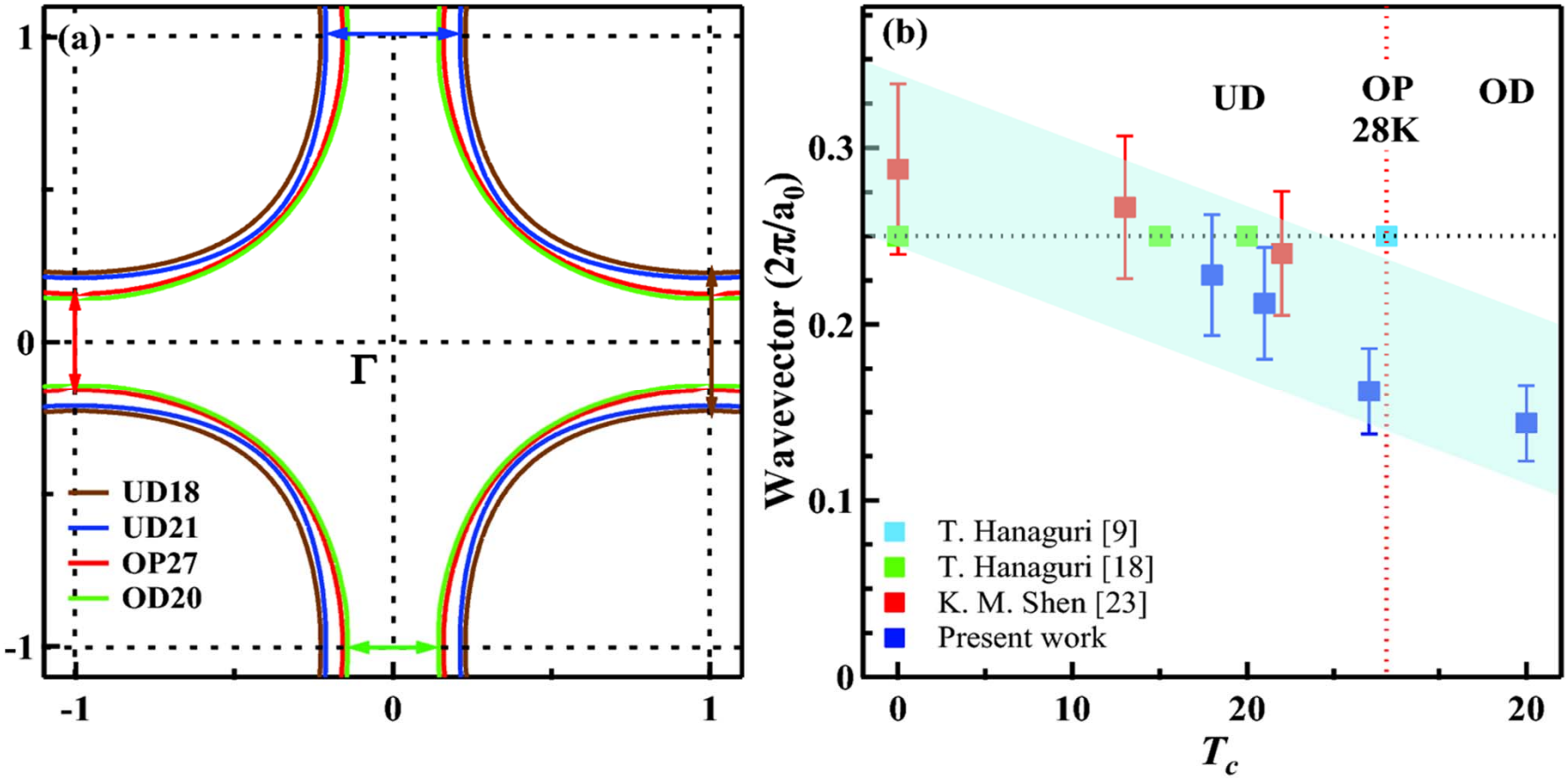
“Fermi surface” data



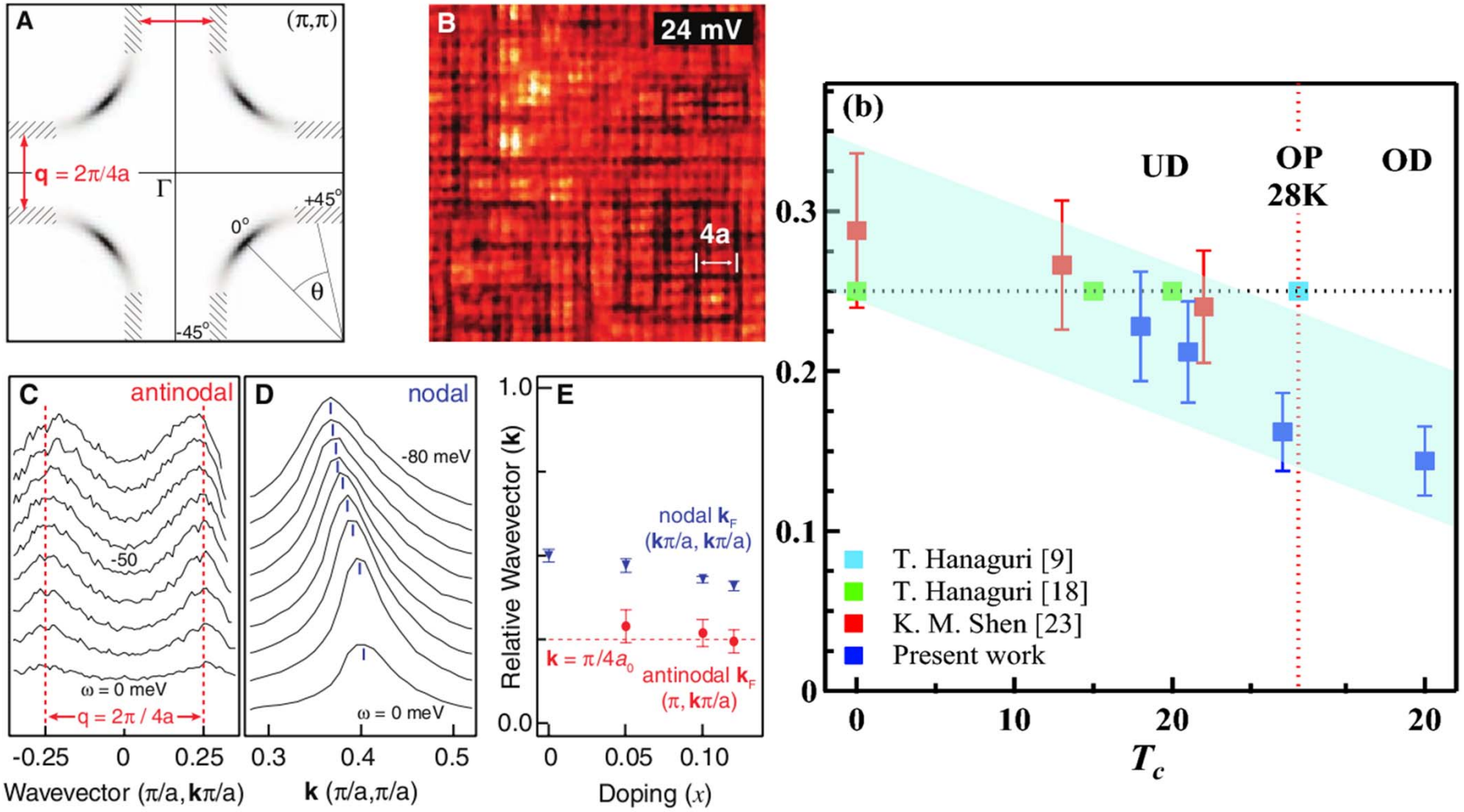
MDC dispersions



Comparison of nesting and CO vectors



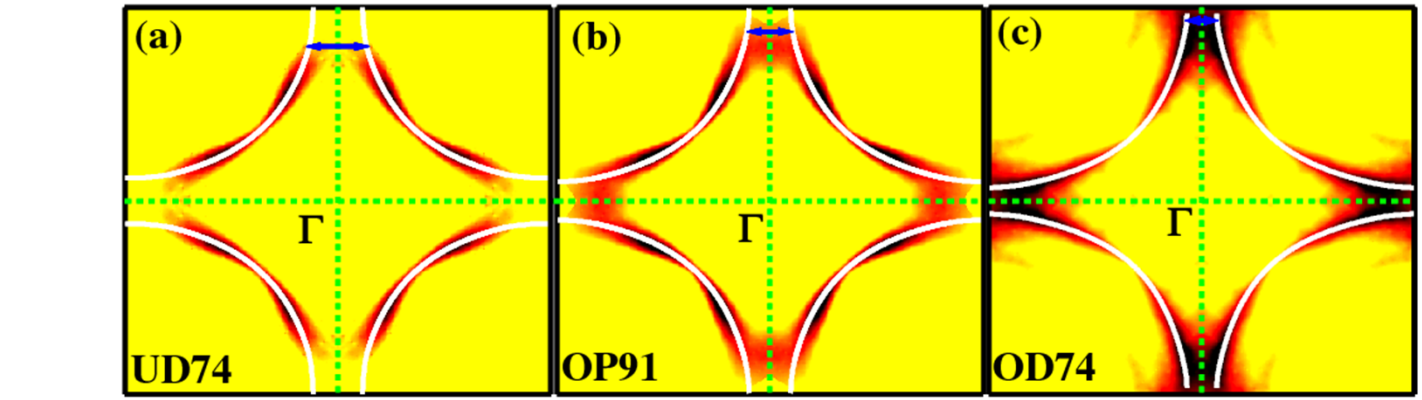
Comparison of nesting and CO vectors

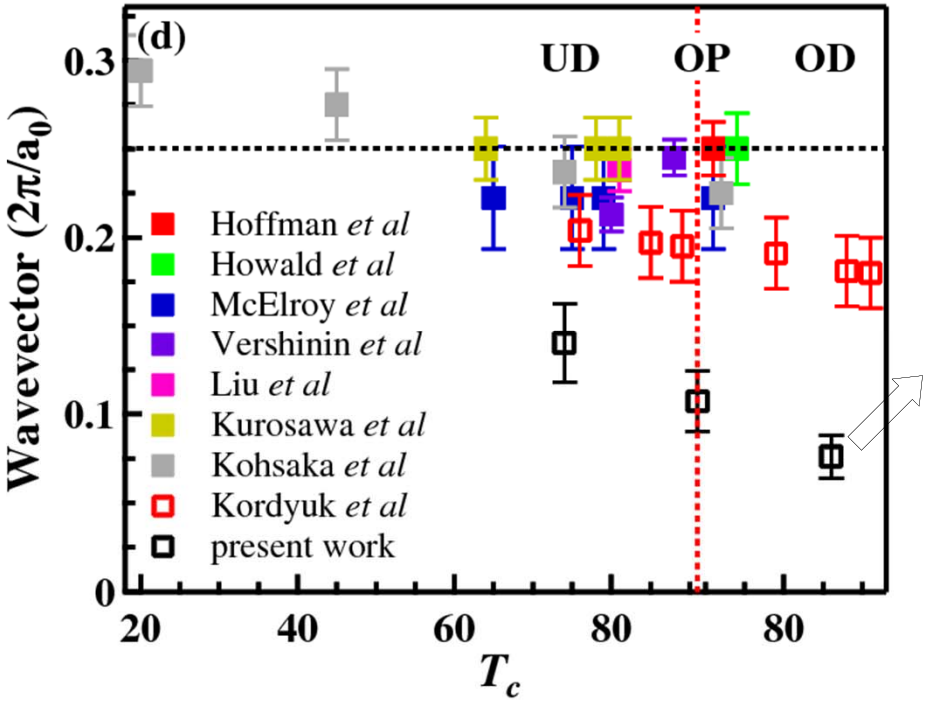


Shen et al., Science 2005

Our results, PRL in review, 2011

Bi2212 data

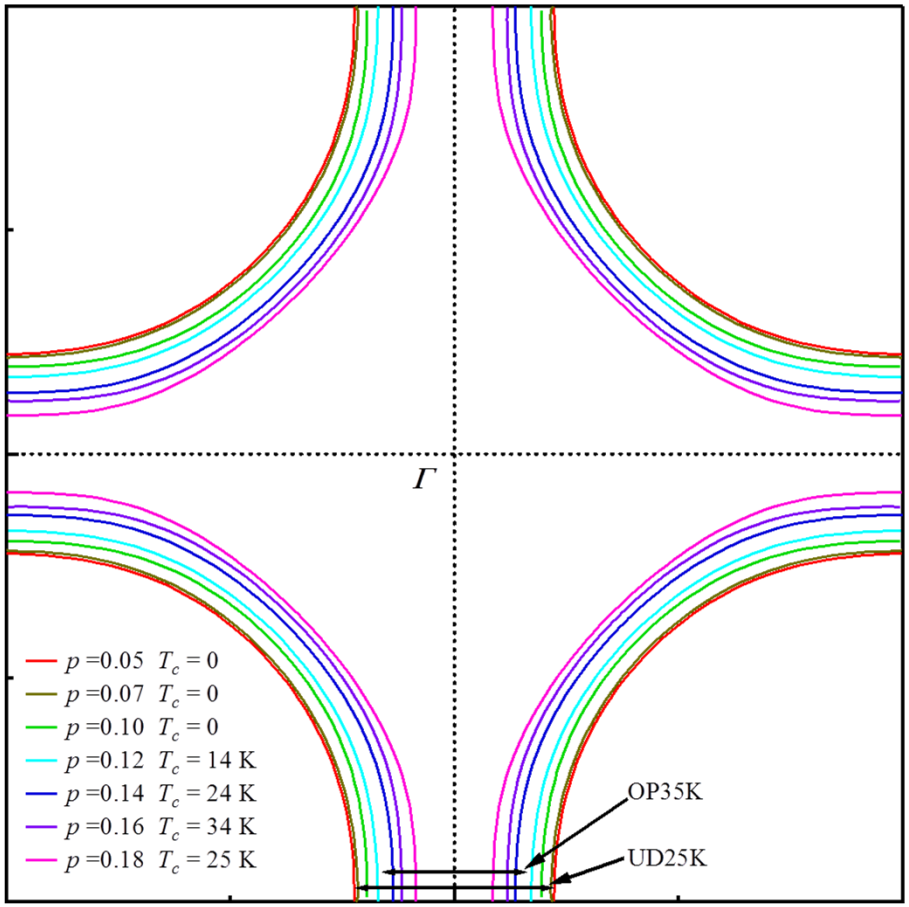




Our ARPES data

Compilation of STS data and ARPES data

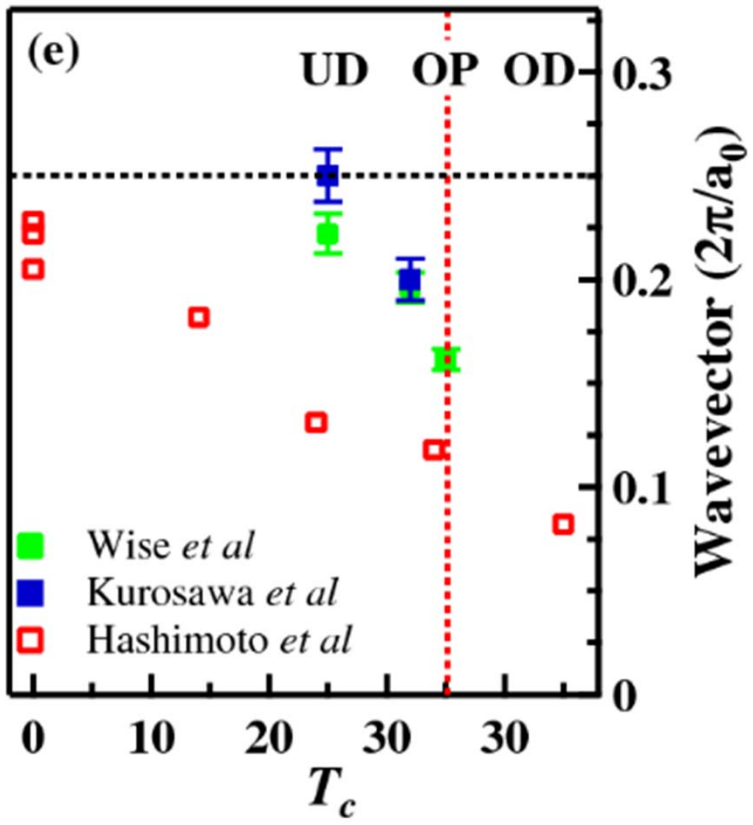
Bi2201 data



FS data by Hashimoto *et al.* Nature 2010

The black arrows corresponding to checkerboard wave vector (Wise *et al*)

Bi2201 data

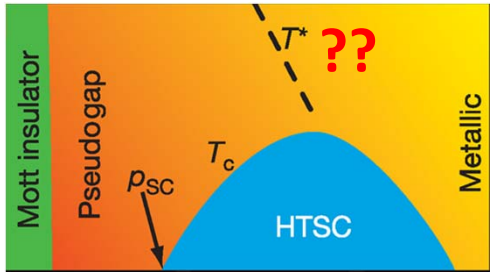

(e)
UD
OP
OD
0.3
0.2
0.1
0
Wavevector ($2\pi/a_0$)
Wise *et al*
Kurosawa *et al*
Hashimoto *et al*
0
10
20
30
30
T_c

Conclusions

- Charge order in Na-CCOC, BISCO superconductors are related to strong correlations, rather than Peierls type Fermi surface instability
- Also, the way the “Fermi surface” deviates from the simple Peierls type instability agrees with the prediction from the “t-J model” based calculation (Yang, Rice, Zhang, PRB 2009).

Microscopic theory of High Tc?

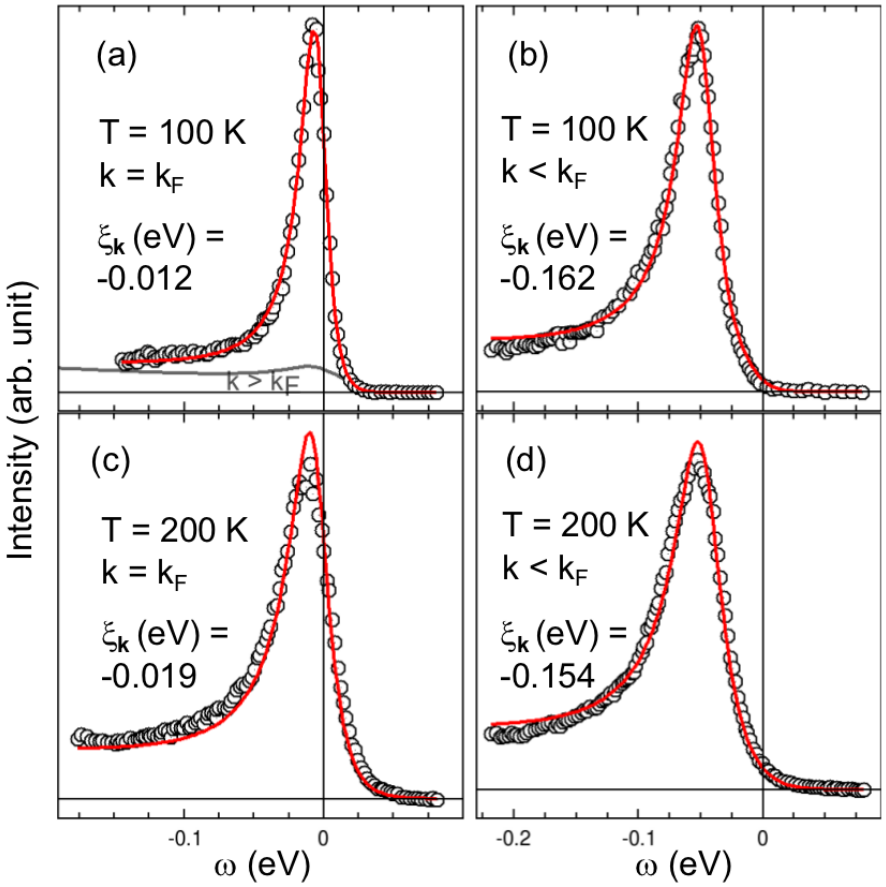
The hard part is describing the normal state properly.



- Varma: Marginal Fermi liquid theory
- **Anderson**: Hidden Fermi liquid theory
- **Shastry**: Extremely Correlated Fermi liquid theory

Both Anderson's model and Shastry's model are based on the "t-J" model (strong correlation model).

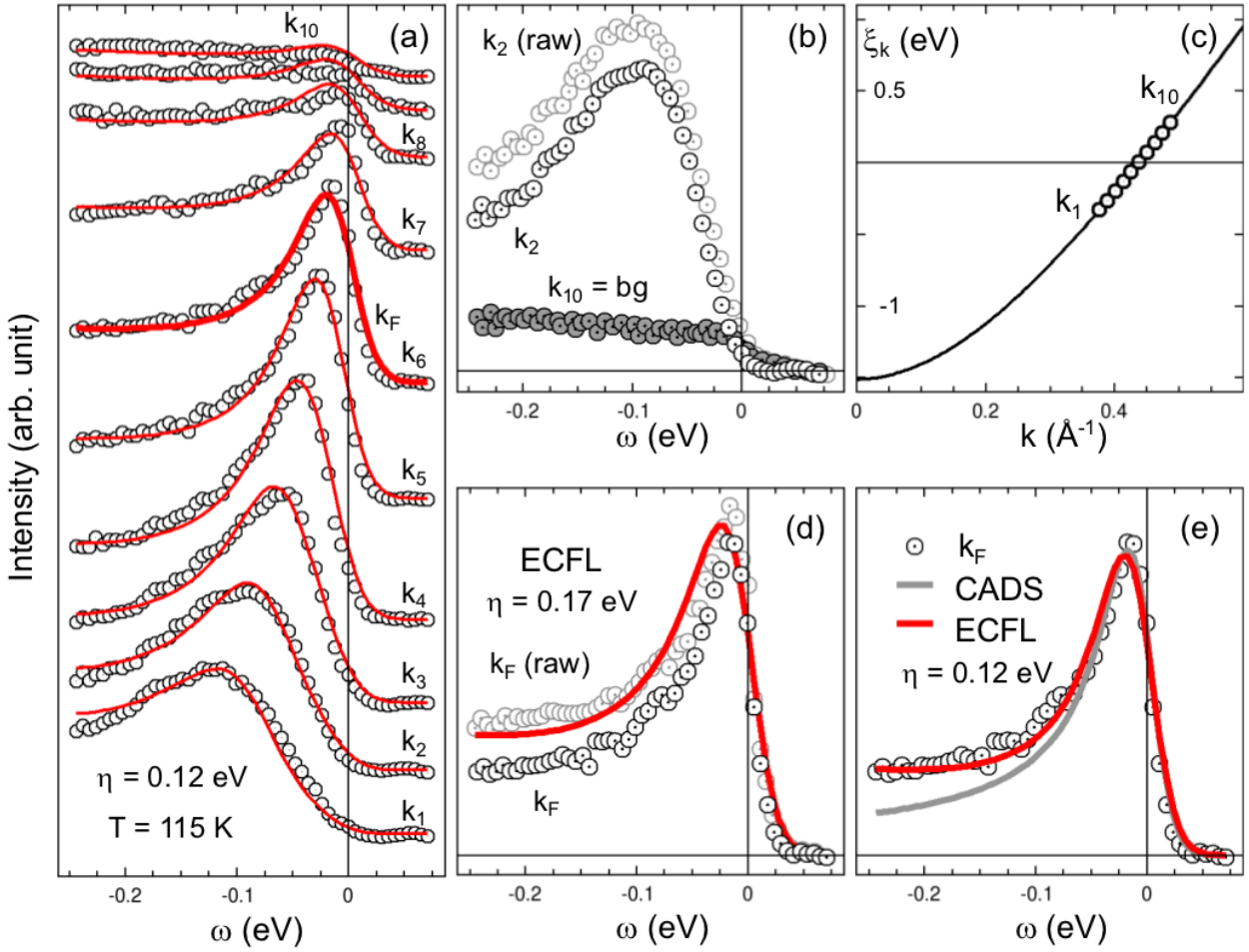
ECFL description of HTSC line shapes



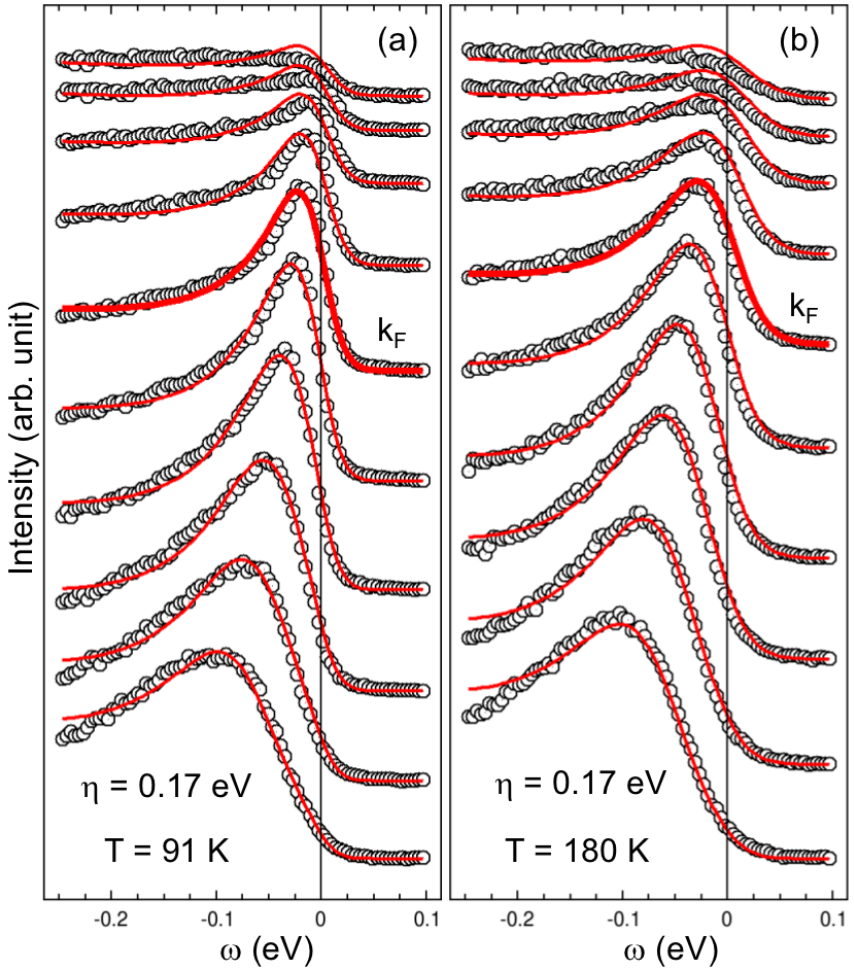
Laser ARPES Data

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

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



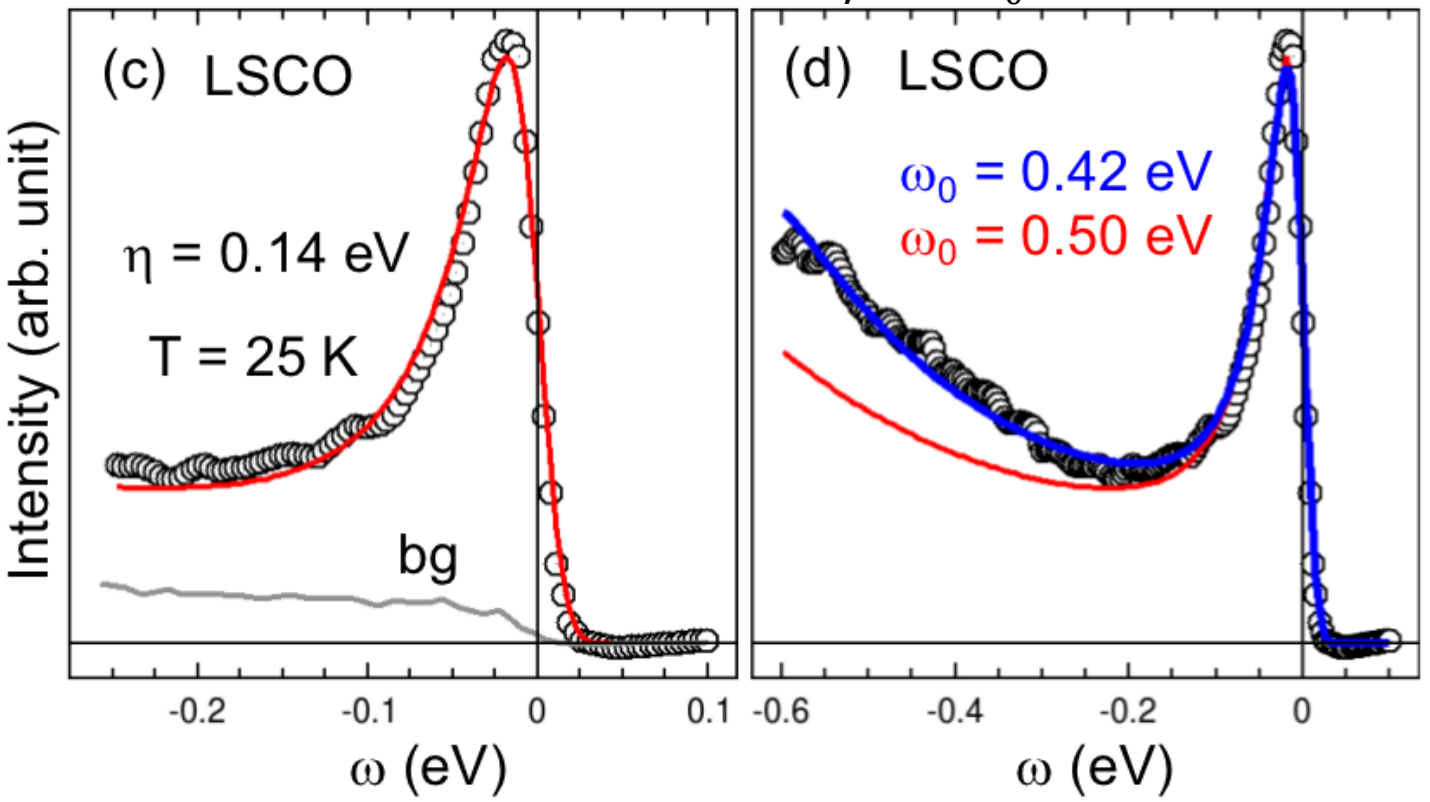
Conventional ARPES data (GHG, 11)
The only free fit parameter is η!



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.

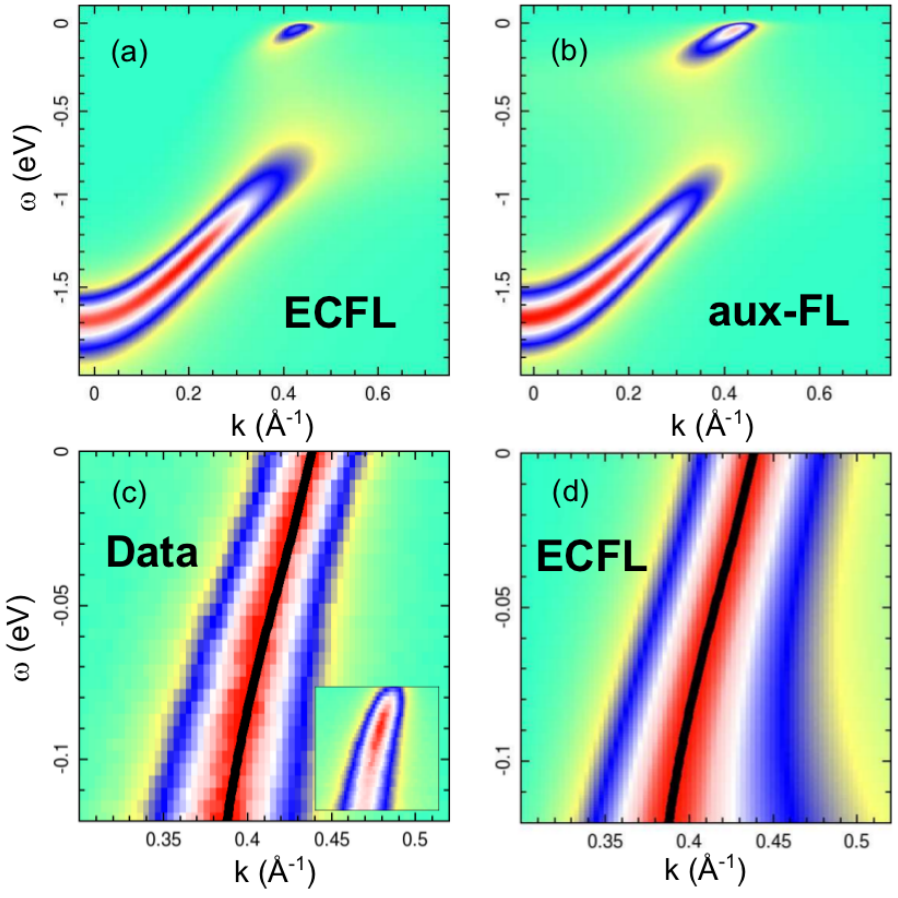


The Naturalness of the Theory

- 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."
- Other theories such as MFL and HFL do not have these features (except that MFL has theory for one of the two kinks).

The Naturalness of the Theory

- ARPES "kinks"



High Energy kink

Graf, GHG et al., PRL 07

Lanzara et al., Nature 01
GHG et al., PRL 06

Low Energy kink

The Naturalness of the Theory

- The ECFL theory has two ARPES kinks – unprecedented details!
- The ECFL theory is the first to fit the ARPES data across techniques and cuprate families.

Conclusions

- The ECFL theory provides a function that seems very favorable to the description of the ARPES data on High Tc.
- Both this work and the charge order work confirm the importance of strong (or extreme!) correlation physics.