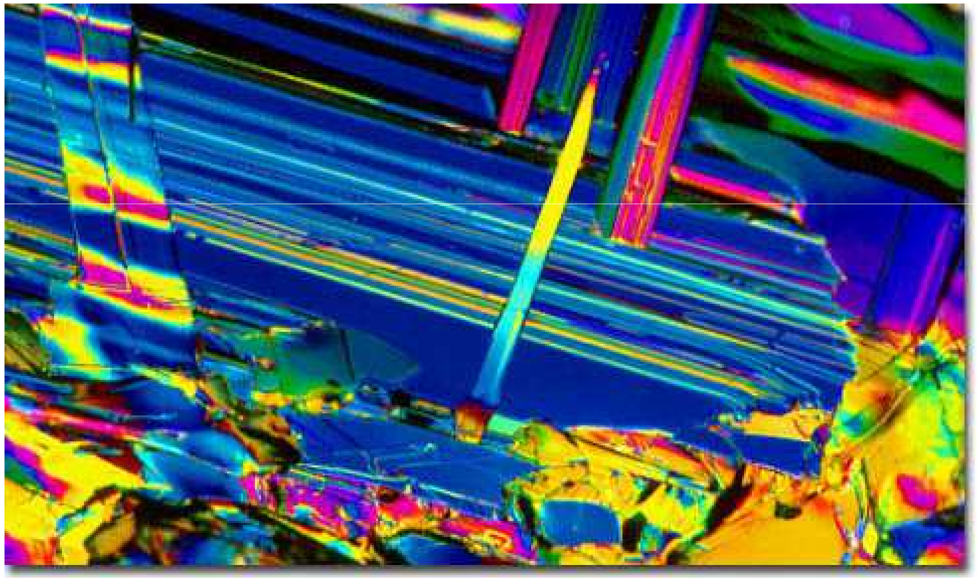
High Temperature Superconductivity - After 23 years, where are we at?

Michael Norman
Materials Science Division
Argonne National Laboratory



Norman and Pepin, Rep. Prog. Phys. (2003)
Norman, Pines, and Kallin, Adv. Phys. (2005)

It All Started Back in 1986

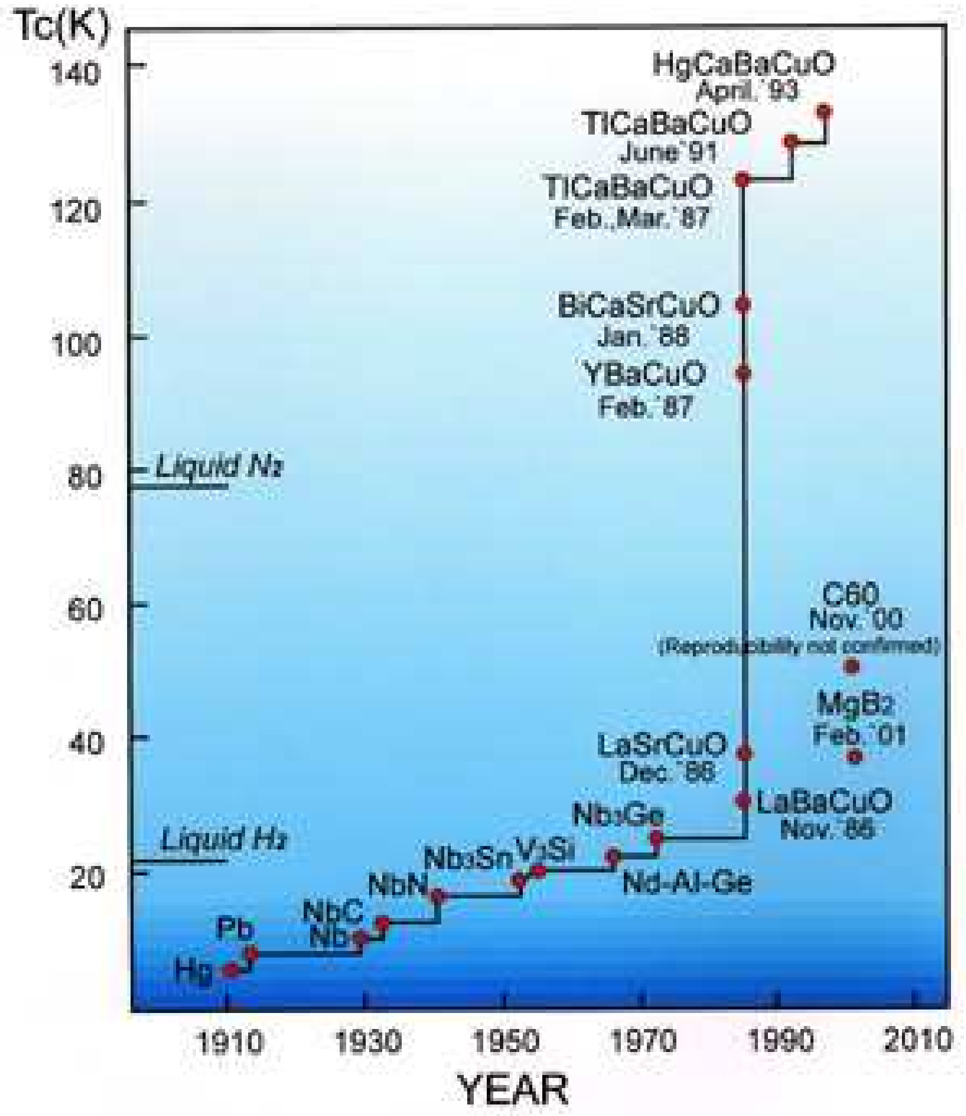
Z. Phys. B – Condensed Matter 64, 189–193 (1986)

Possible High T_c Superconductivity in the Ba – La – Cu – O System

J.G. Bednorz and K.A. Müller
IBM Zürich Research Laboratory, Rüschlikon, Switzerland

Received April 17, 1986

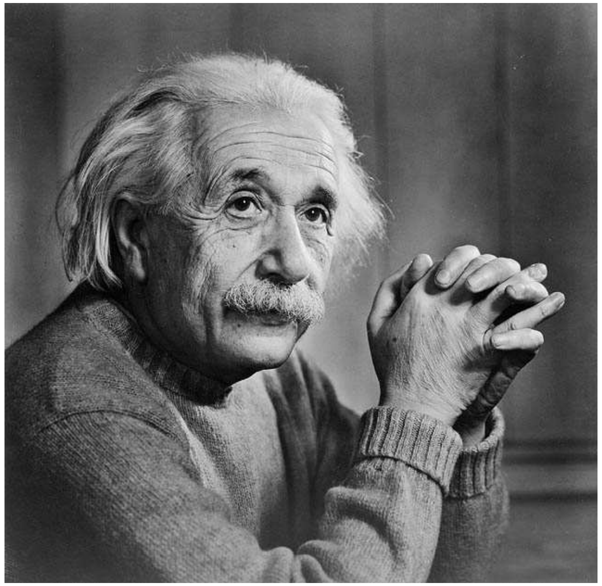
T_c Shot Up Like a Rock
(many cuprates superconduct above 77K)



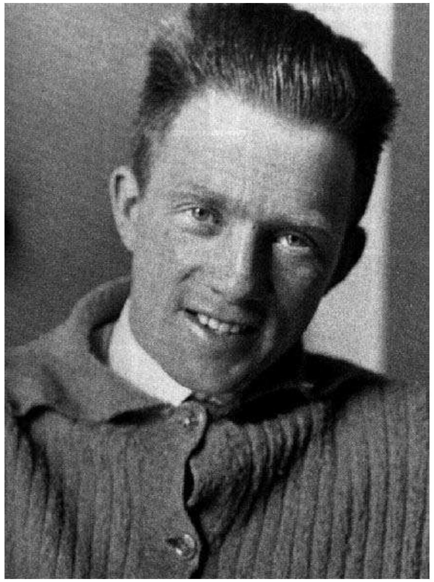
Great Promises Were Made

May 11, 1987

The Path to a Microscopic Theory was Littered with Many Famous Physicists



Einstein



Heisenberg

Landau

Feynman

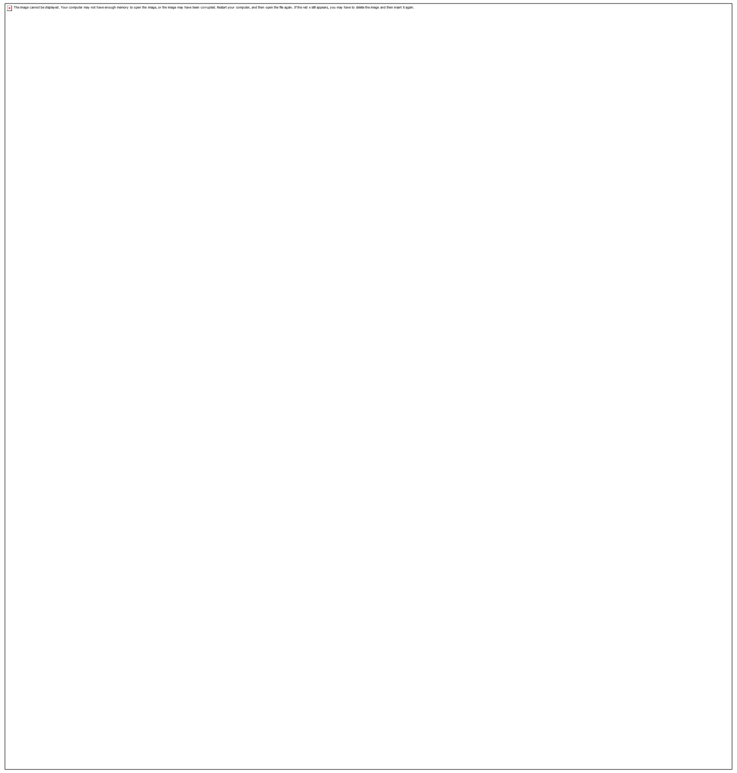
Eventually, Three Guys in Illinois Got It Right
(Bardeen, Cooper, Schrieffer - 1956, 1957)

Rules of B. Matthias for discovering new superconductors

1. high symmetry is best
2. peaks in density of states are good
3. stay away from oxygen
4. stay away from magnetism
5. stay away from insulators
6. stay away from theorists

From Steve Girvin's lecture (Boulder Summer School 2000) courtesy of Matthew Fisher

Everything You Wanted to Know About Pair Formation
(But Were Afraid to Ask)



(the electron-phonon case)

1. 1st e^- attracts + ions
2. Ions shift position from red to blue
3. 1st e^- moves away
4. 2nd e^- sees + ion hole and moves
   to former position of 1st e^-

Interaction is local in space
(s-wave pairs, L=0, S=0)
but retarded in time
(T_c << Debye frequency)

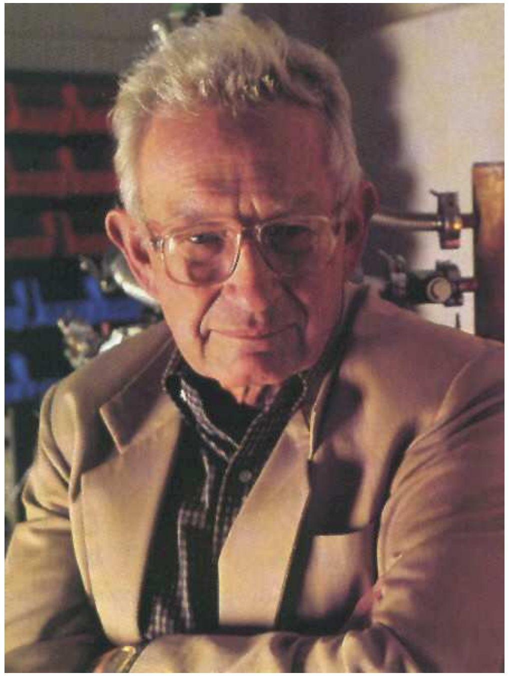
But cuprates have d-wave pairs! (L=2, S=0)

van Harlingen; Tsuei & Kirtley - Buckley Prize -1998

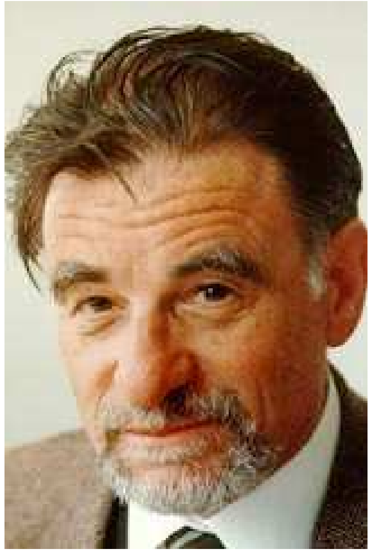
Artwork by Gerald Zeldin (2000)

Alexei Abrikosov
(small q phonons)

Bob Laughlin
(competing phases)



Phil Anderson
(RVB; interlayer tunneling; RVB)



Karl Mueller
(bipolarons)

Bob Schrieffer
(spin bags)

Tony Leggett
(interlayer Coulomb)

Theories Connected with High T_c Superconductivity

1. Resonating valence bonds
2. Spin fluctuations
3. Stripes
4. Anisotropic phonons
5. Bipolarons
6. Excitons
7. Kinetic Energy lowering
8. d-density wave
9. Charge fluctuations
10. Flux phases
11. Gossamer superconductivity
12. Spin bags
13. SO(5)
14. BCS/BEC crossover
15. Plasmons
16. Spin liquids

Not to Mention

Interlayer tunneling

Marginal Fermi liquid

van Hove singularities

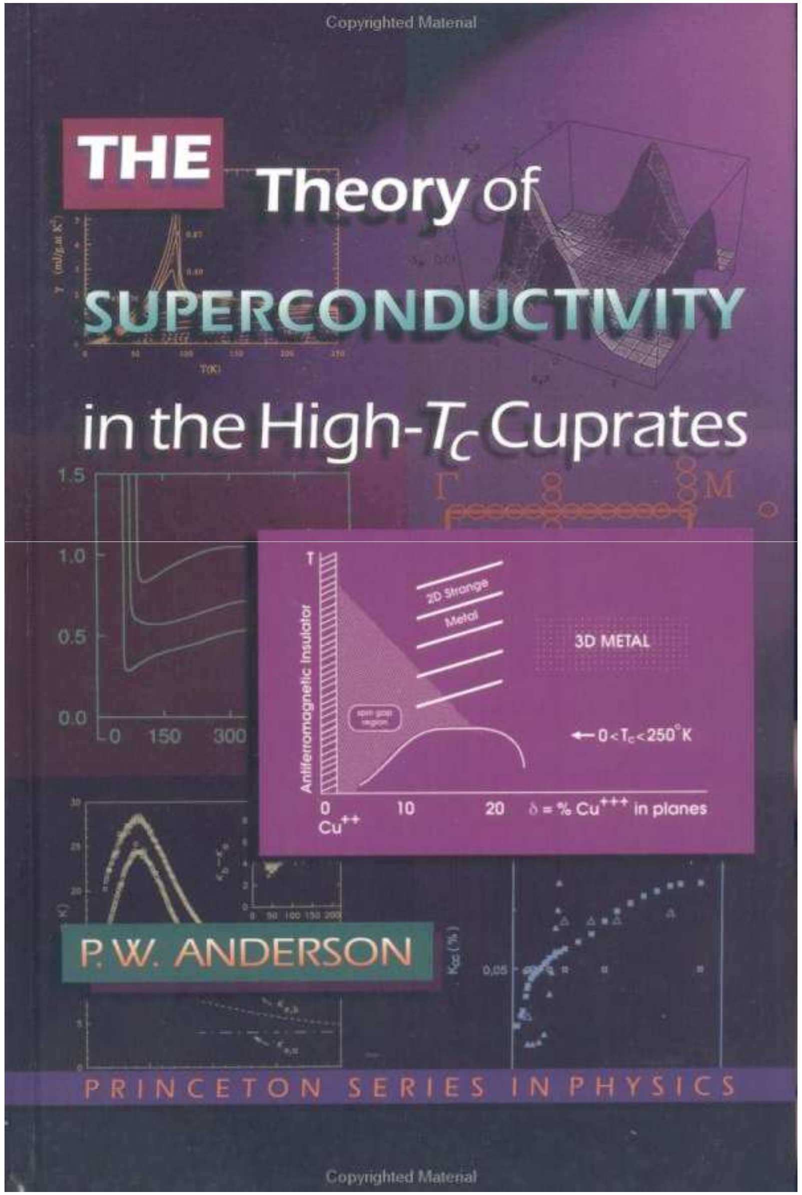
Quantum critical points

Anyon superconductivity

Slave bosons

Dynamical mean field theory

Famous Books



Famous Quotes

Abrikosov - Nobel Lecture - Dec. 2003

“On this basis I was able to explain most of the experimental data about layered cuprates . . .

As a result I can state that
the so called “mystery” of high-T_c
superconductivity does not exist.”

Ten Weeks of High T_c
(to the tune of Twelve Days of Christmas)

KITP Web Site
High T_c Program - Fall 2000

On the first week of the program
Friend Philip said to me
All simply RVB
(All sim-pl-ee R-r V B)

On the second week of the program
Friend Douglas said to me
Pair in a d-wave
All simply RVB

On the third week of the program
Friend David said to me
It's magnons
Pair in a d-wave
All simply RVB

On the fourth week of the program
Friend Chandra said to me
Four current rings (fo-or current rings)
It's magnons
Pair in a d-wave
All simply RVB

At the end of the program
Friend Philip said to me
Big Tent is stretching
Visons escaping
Visons are gapping
Slave spinons pairing
T sym-try breaking
Stripes fluctuating
S - O - 5
Four current rings
It's magnons
Pair in a d-wave
All simply RVB

--Ilya Gruzberg
Smitha Vishveshwara
Ilya Vekhter
Aditi Mitra
Senthil
Matthew Fisher

Why is the High T_c Problem So Hard to Solve?

(Laughlin's Lecture for Teachers - KITP, 2000)

Theory of Everything

$$\mathcal{H} = -\sum_j \frac{\hbar^2}{2m}\nabla_j^2 - \sum_\alpha \frac{\hbar^2}{2M_\alpha}\nabla_\alpha^2 - \sum_{j,\alpha}\frac{Z_\alpha e^2}{|r_j - R_\alpha|} + \sum_{j<k}\frac{e^2}{|r_j - r_k|} + \sum_{\alpha<\beta}\frac{Z_\alpha Z_\beta e^2}{|R_\alpha - R_\beta|}$$

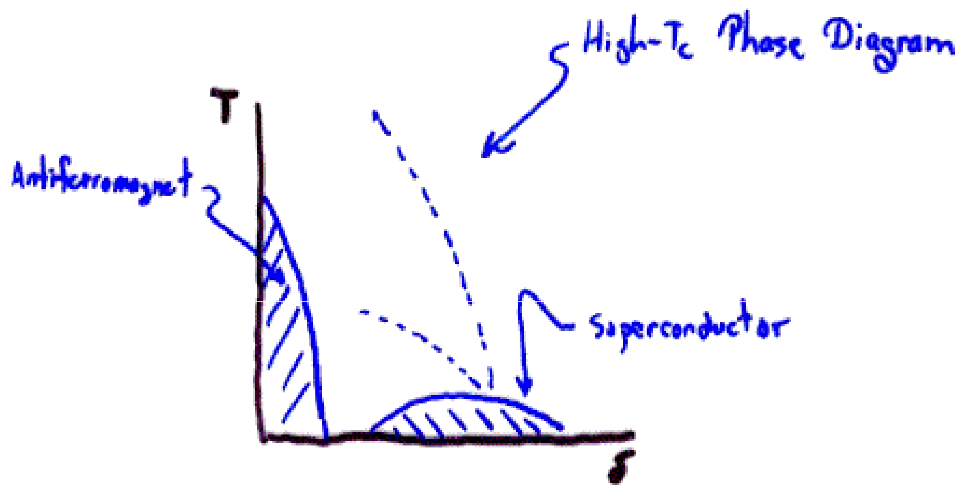
- Hydrogen atom
- Methane molecule
- water
- Air
- Rocks
- Concrete
- Steel
- Glass
- Plastic
- Buildings
- Cities
- Continents

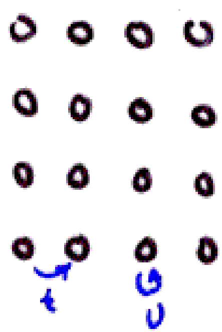
- Proteins
- DNA
- Viruses
- Bacteria
- Yeast
- Slime mold
- Butterflies
- Sharks
- Rats
- Lawyers
- Ebola virus
- Legislatures
- Civilizations

- Flowers
- Trees
- Cows
- Cheese
- Sauce Bernais
- Computers
- Television
- Cars
- Jets
- Lawnmowers
- Sewage
- Spotted Owls

...

Unprotected Calculation Fails

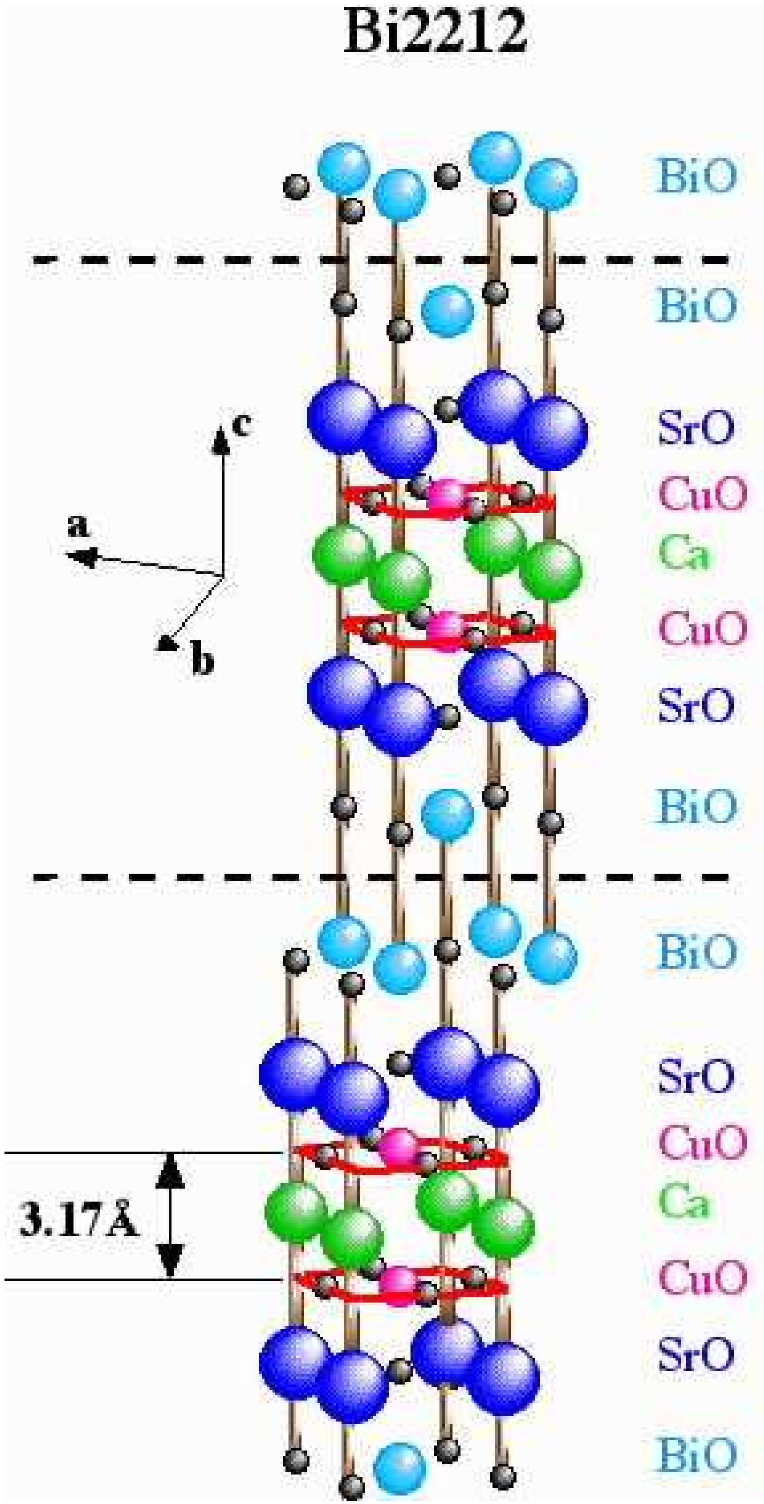




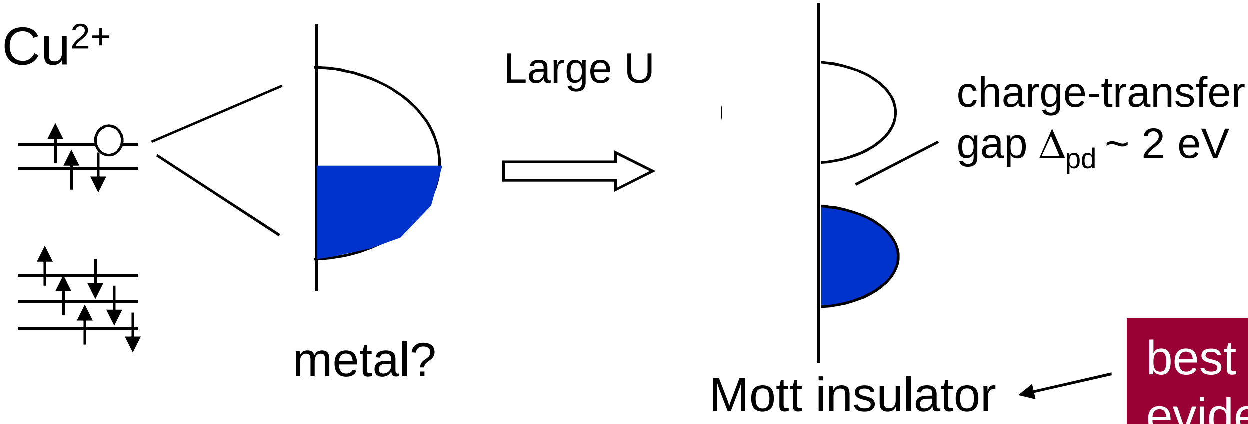
$$\mathcal{H} = t \sum_{\langle jk \rangle \sigma} c_{j\sigma}^\dagger c_{k\sigma} + U \sum_j n_{j\uparrow} n_{j\downarrow}$$

Doesn't work

Electronic Structure of Cuprates

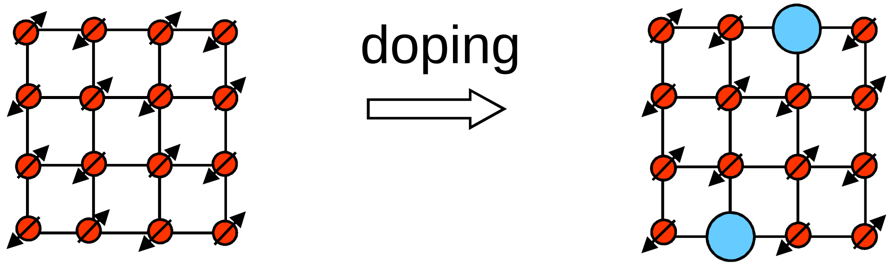


Short tutorial on cuprates



best evidence for large U

antiferromagnet J~1400 K



$$H = -t \sum_{i,j,\sigma} c^{+}_{i\sigma} c_{j\sigma} + U \sum_{i} n_{i\uparrow} n_{i\downarrow}$$ Hubbard

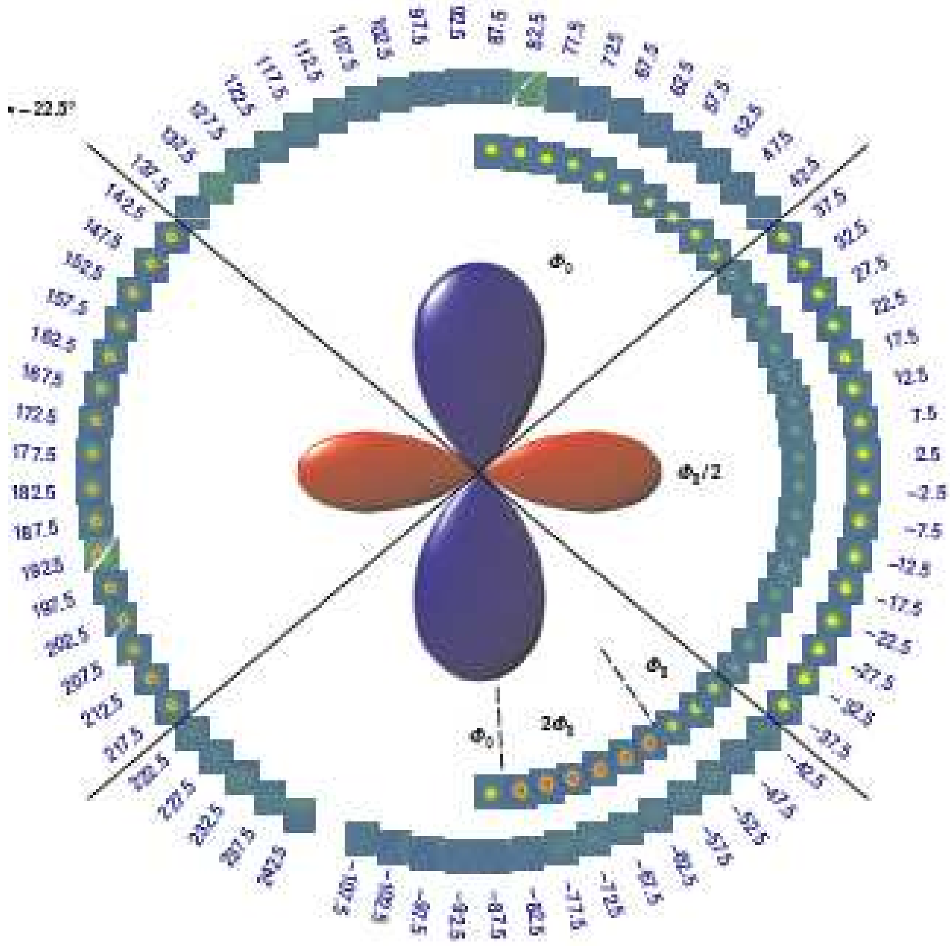
t = 0.3 eV, U = 2 eV, $J = 4t^2/U$ = 0.12 eV

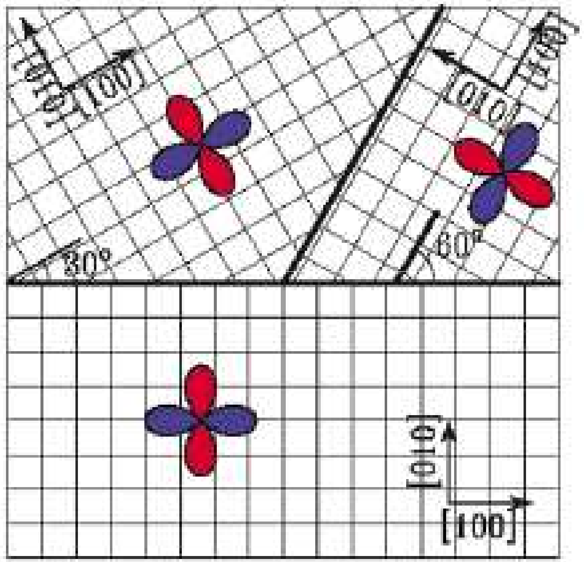
(slide from Anderson & Ong)

Phase Diagram of Cuprates

What We DO Know

1. There are $2e^-$ pairs
2. The pairs are d-wave (L=2, S=0)
3. There are "normal" (i.e., $2e^-$) vortices
4. Quasiparticles exist (but only below T_c)





d-wave pairing observed by phase sensitive tunneling -

van Harlingen, Kirtley & Tsuei

Kirtley *et al*, Nat. Phys. (2006)

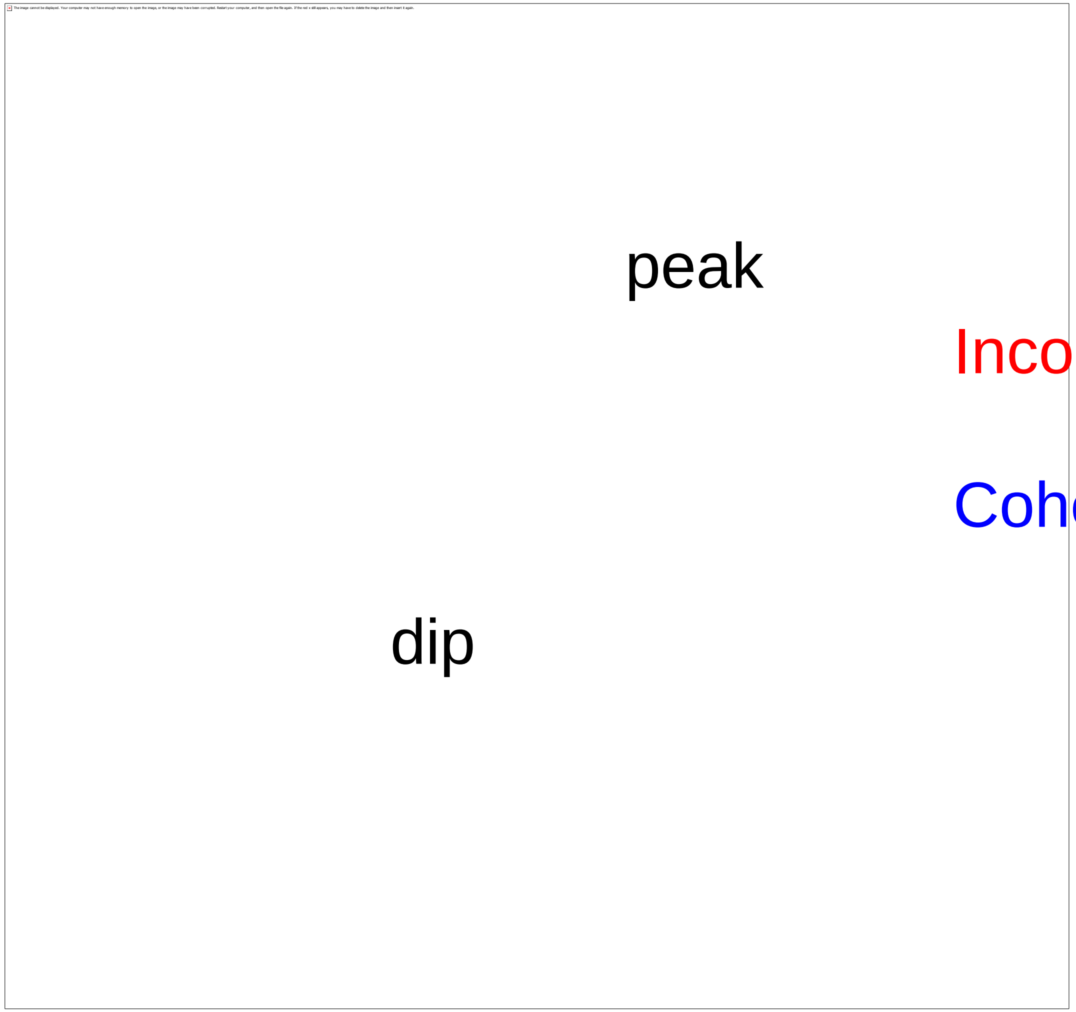
Extraction of the Superconducting Energy Gap from Photoemission

Ding *et al.*, PRL (1995) & PRB (1996)

Δ_k --> $\cos(k_x) - \cos(k_y)$ --> Implies pair interaction peaked for near-neighbors

Bi2212, T_c=87K

Photoemission spectrum above and below T_c at momentum $k=(\pi,0)$ for Bi2212



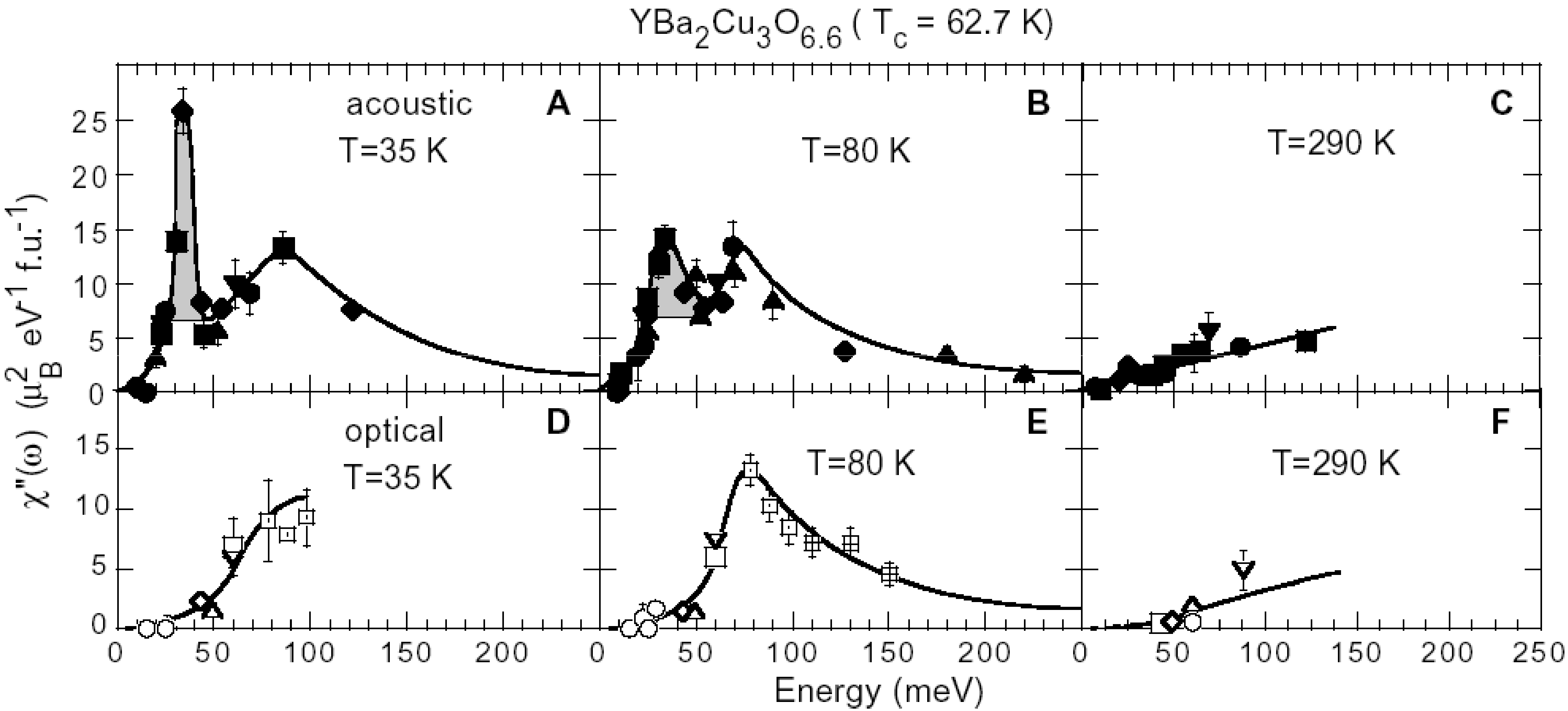
Incoherent normal state

Coherent superconductor

Norman *et al*, PRL (1997)

Neutron Spin Resonance below T_c (S=1 excitation)

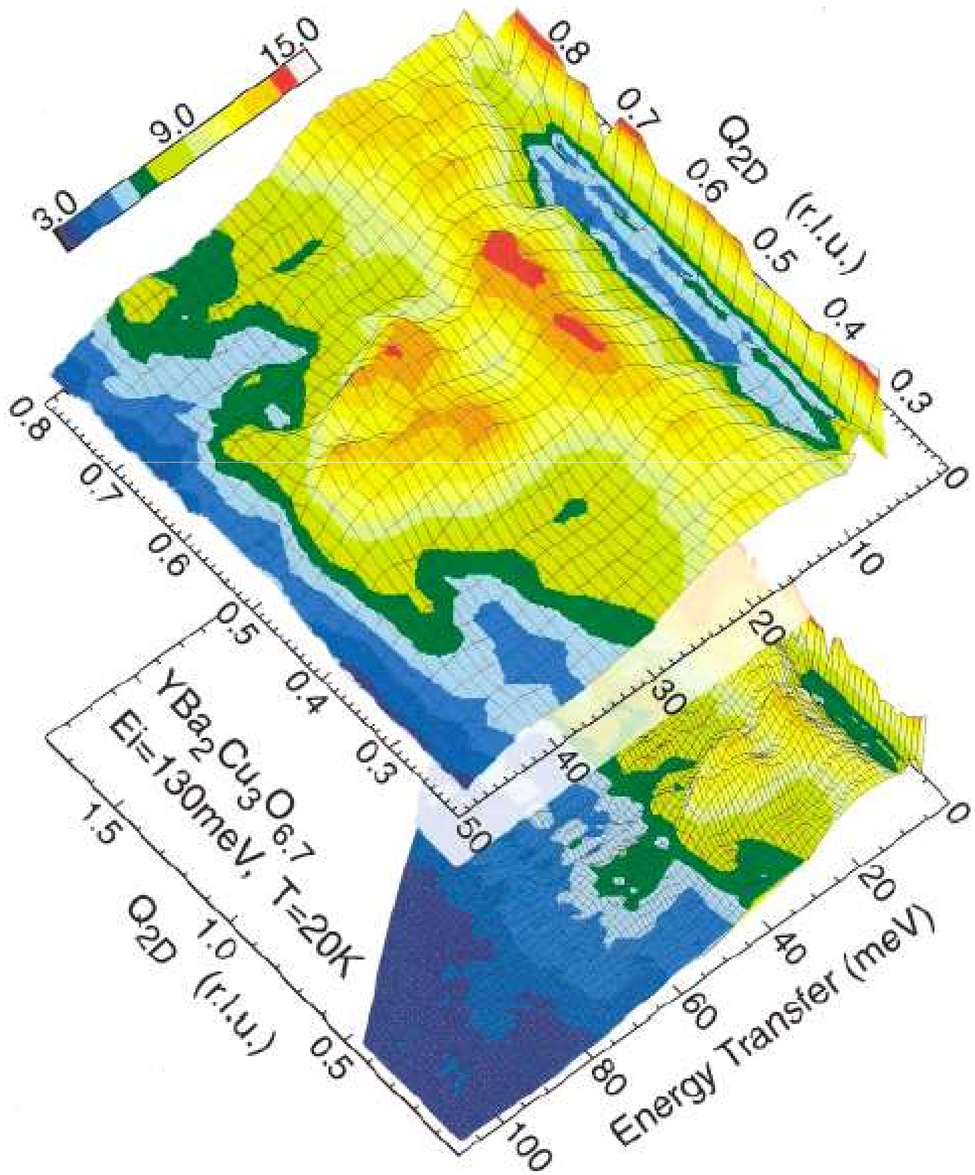
Rossat-Mignod/Bourges, Mook/Dai, Keimer/Fong

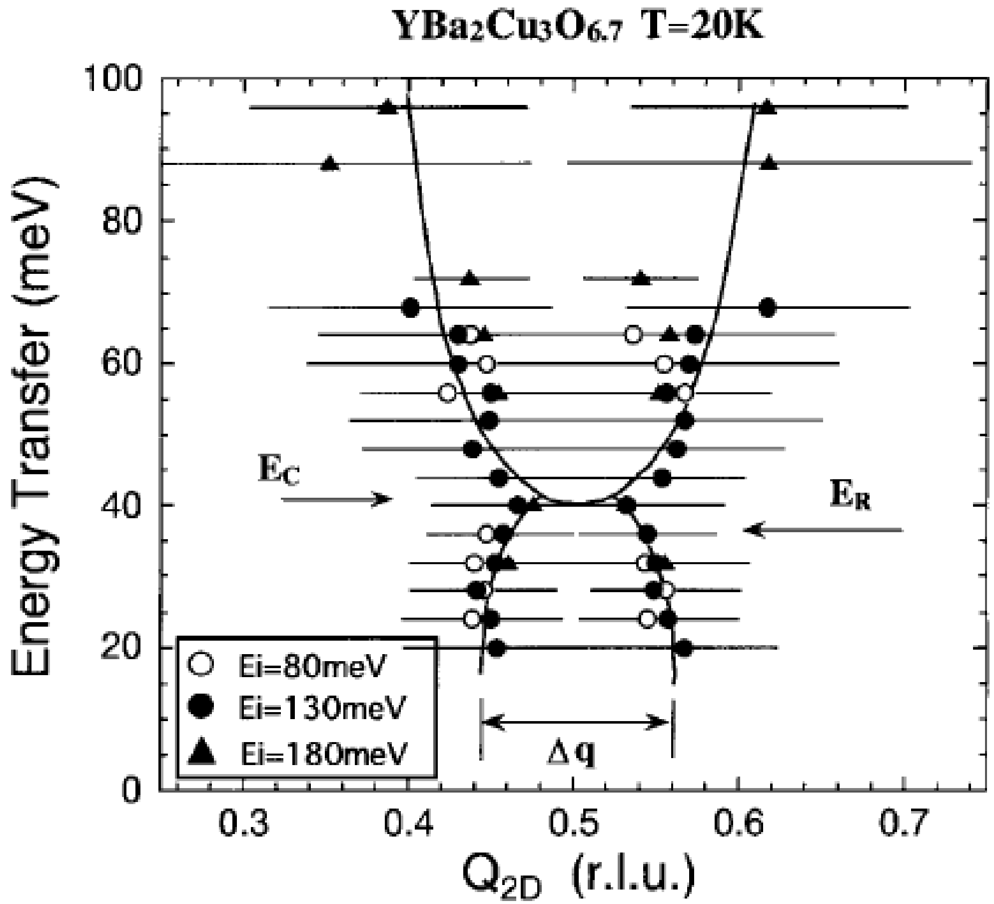


Dai *et al*, Nature (1999)

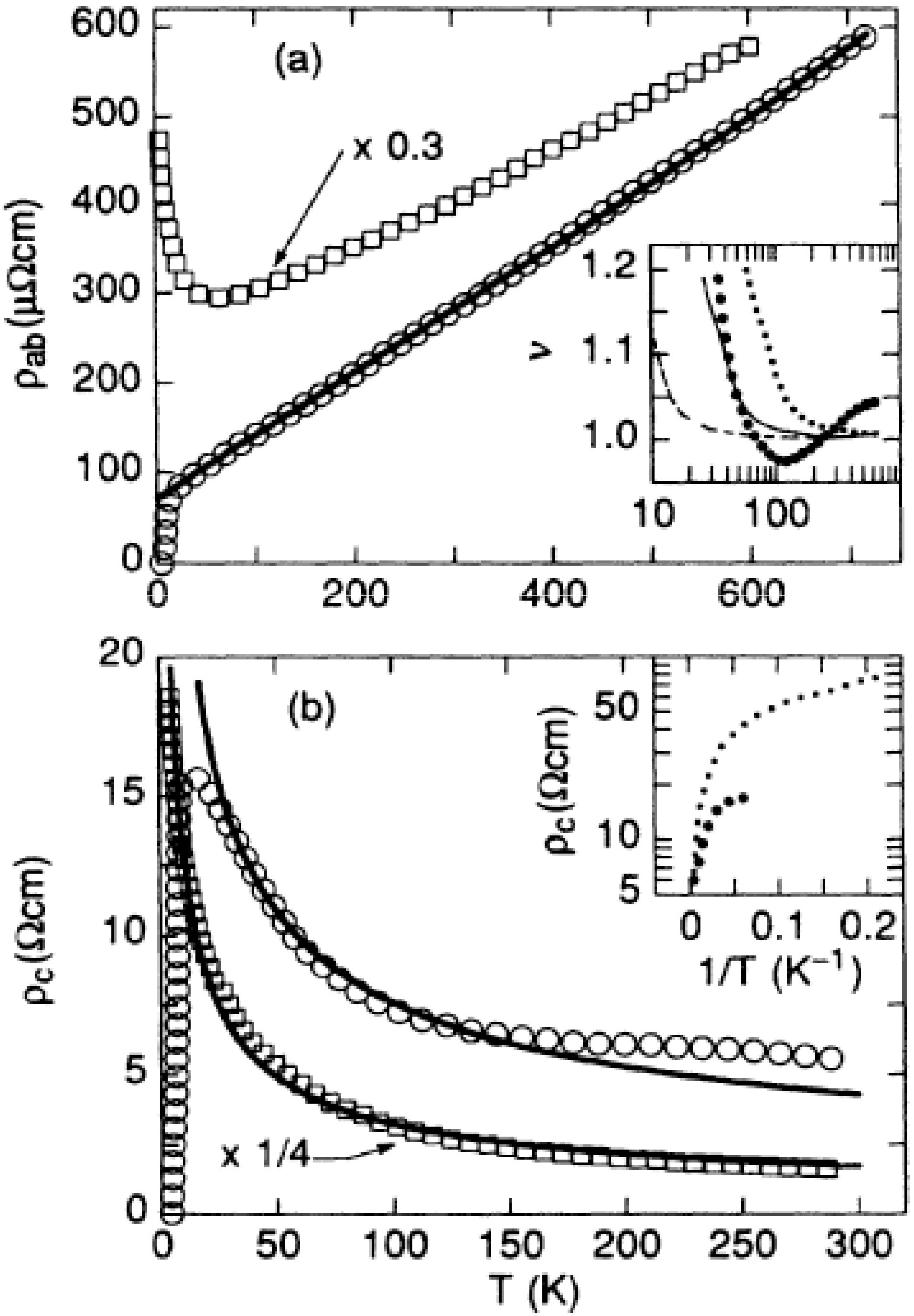
Dispersion of magnetic excitations has the form of an hourglass

Arai *et al*, PRL (1999)





The "strange metal" phase exhibits linear T resistivity

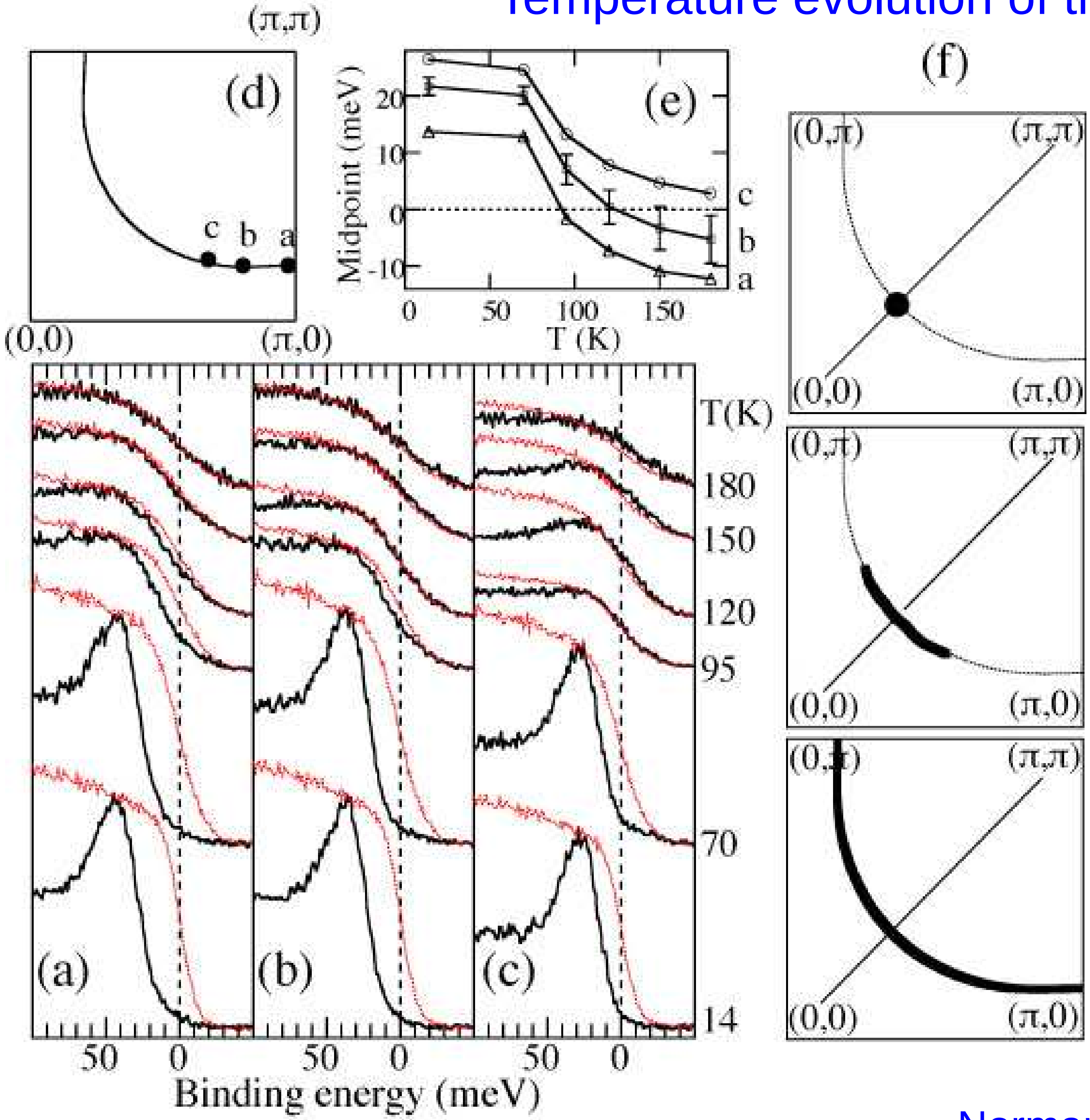


Martin *et al*
PRB (1990)

What is the Pseudogap?

1. Pre-formed pairs
2. Spin density wave
3. Charge density wave
4. d density wave
5. Orbital currents
6. Flux phase
7. Stripes
8. Combination?

Temperature evolution of the Fermi surface



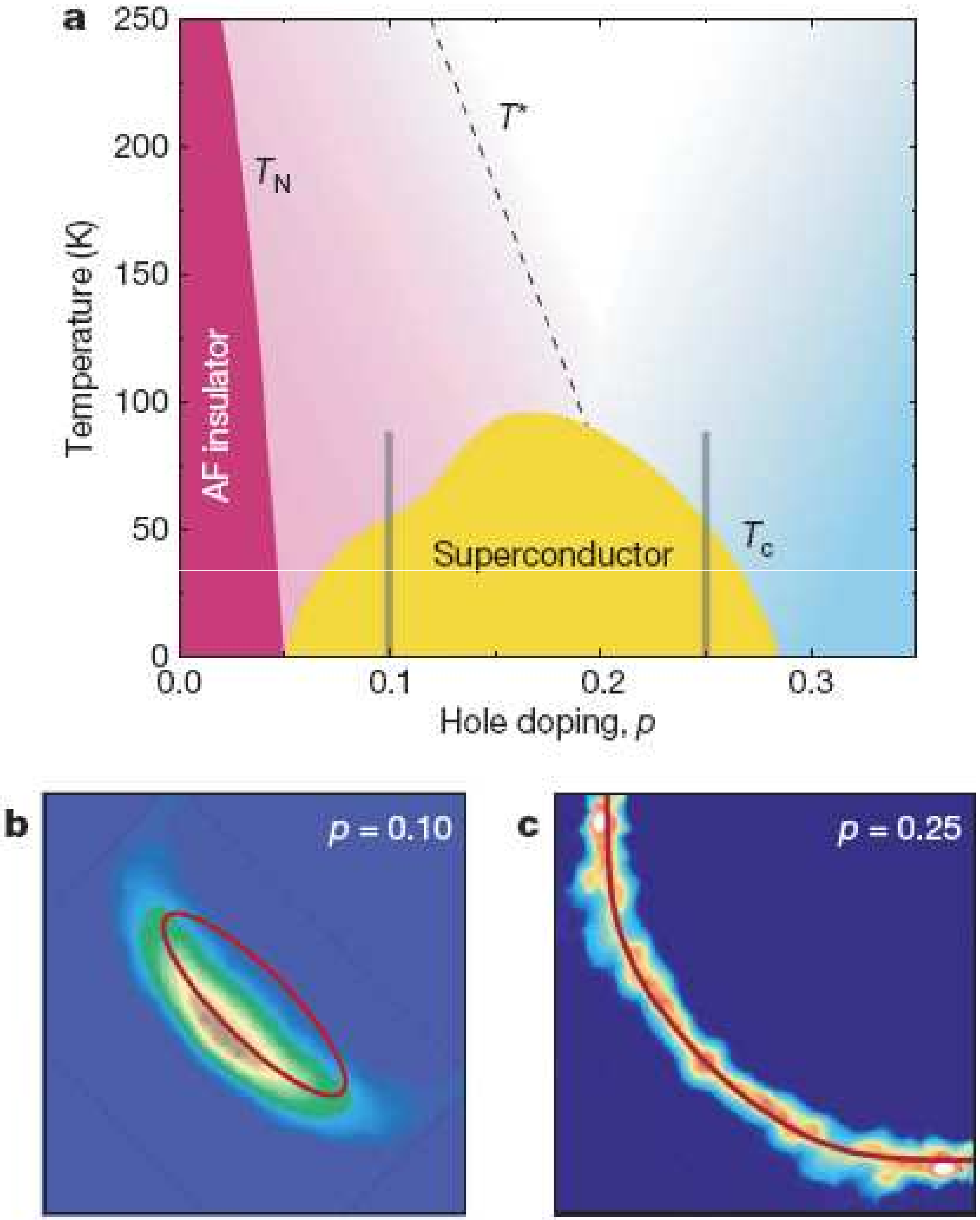
$T < T_c$

$T_c < T < T^*$

$T > T^*$

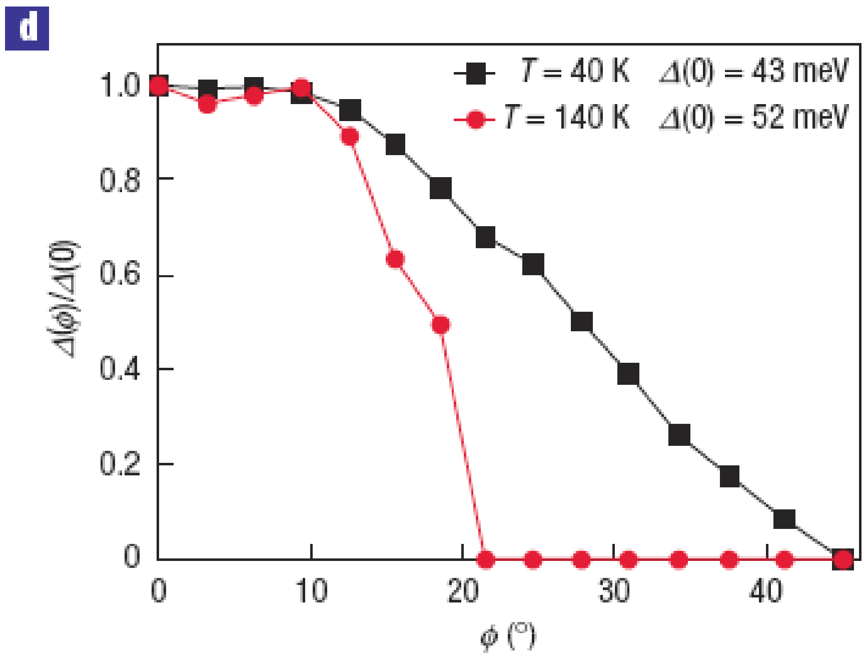
Norman *et al.*, Nature (1998)

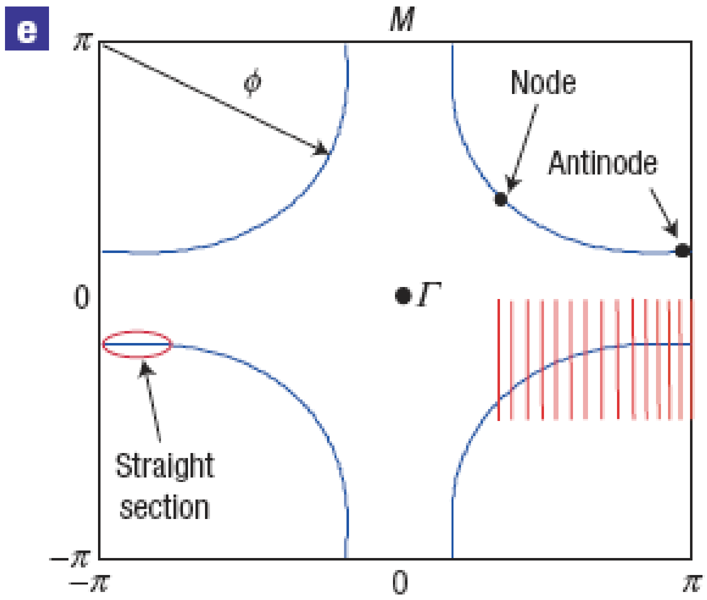
Evolution of the Fermi surface with doping

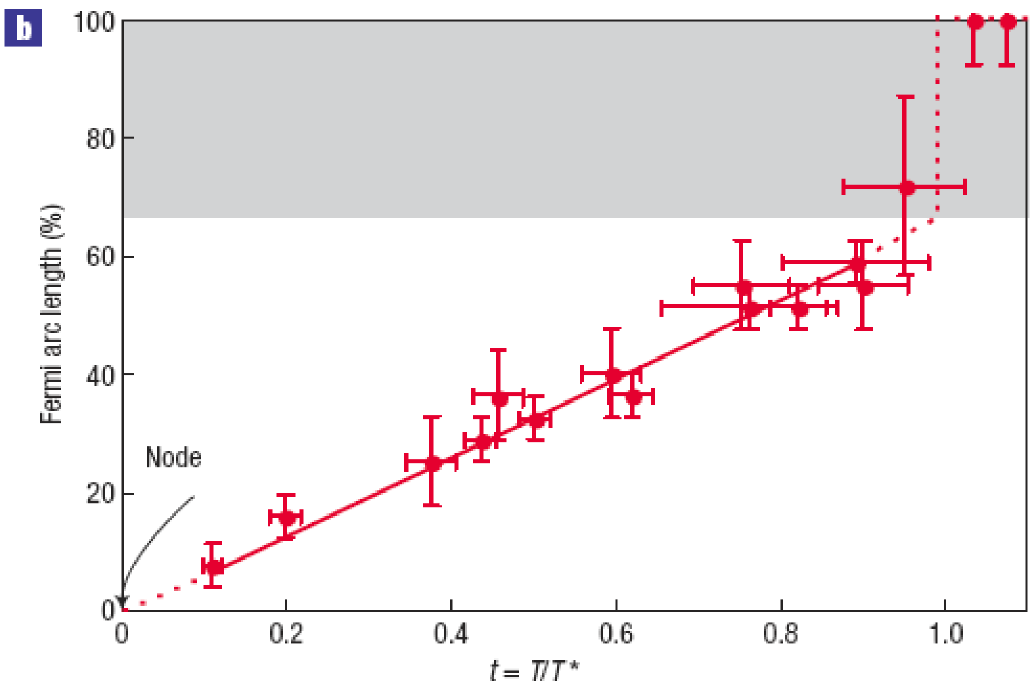


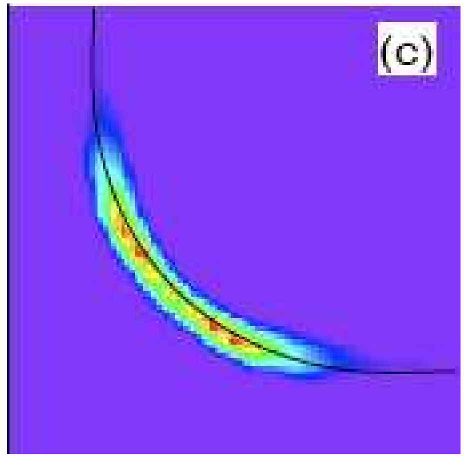
Doiron-Leyraud *et al*
Nature (2007)

Is the T=0 limit of the pseudogap phase a nodal metal?



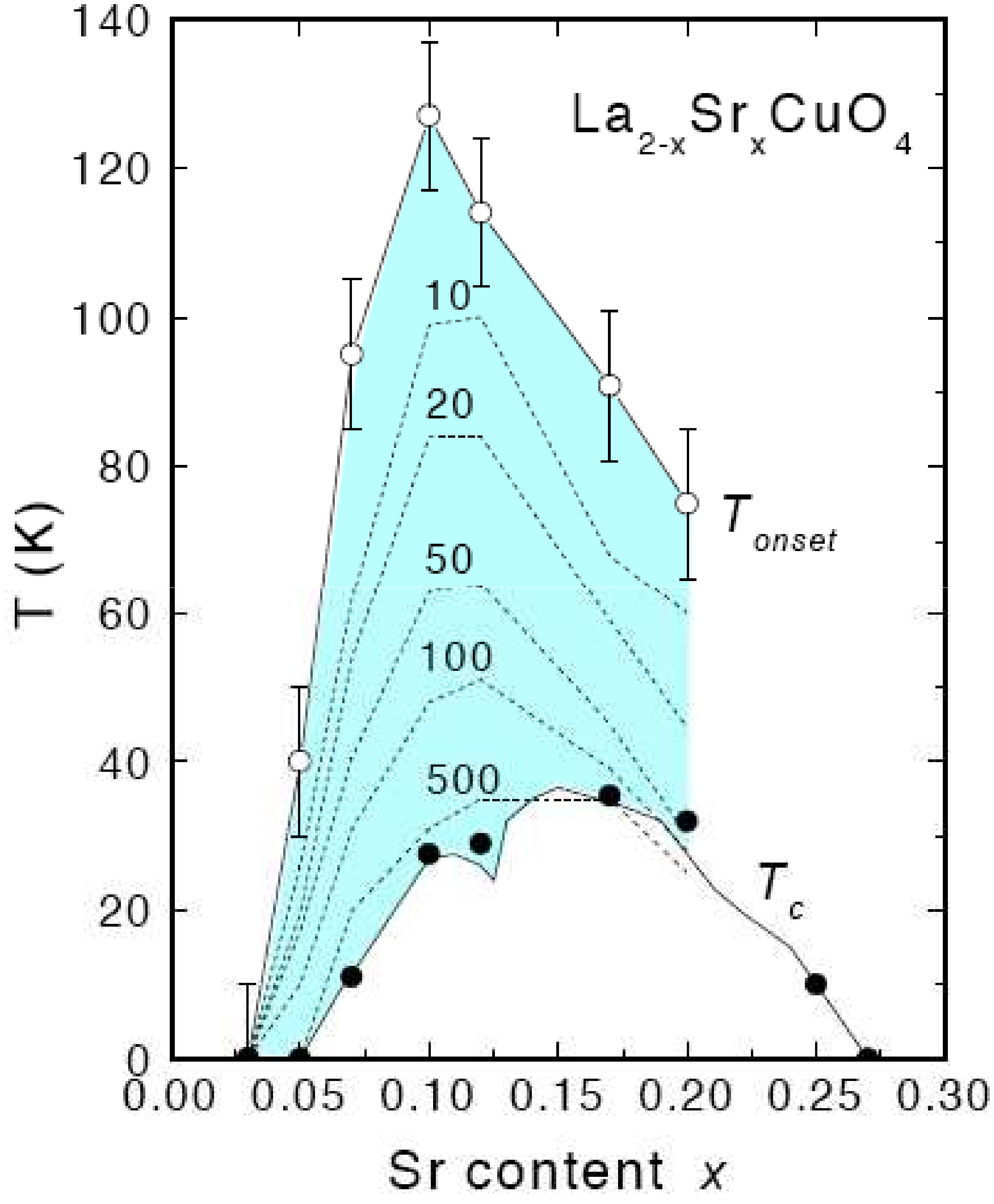






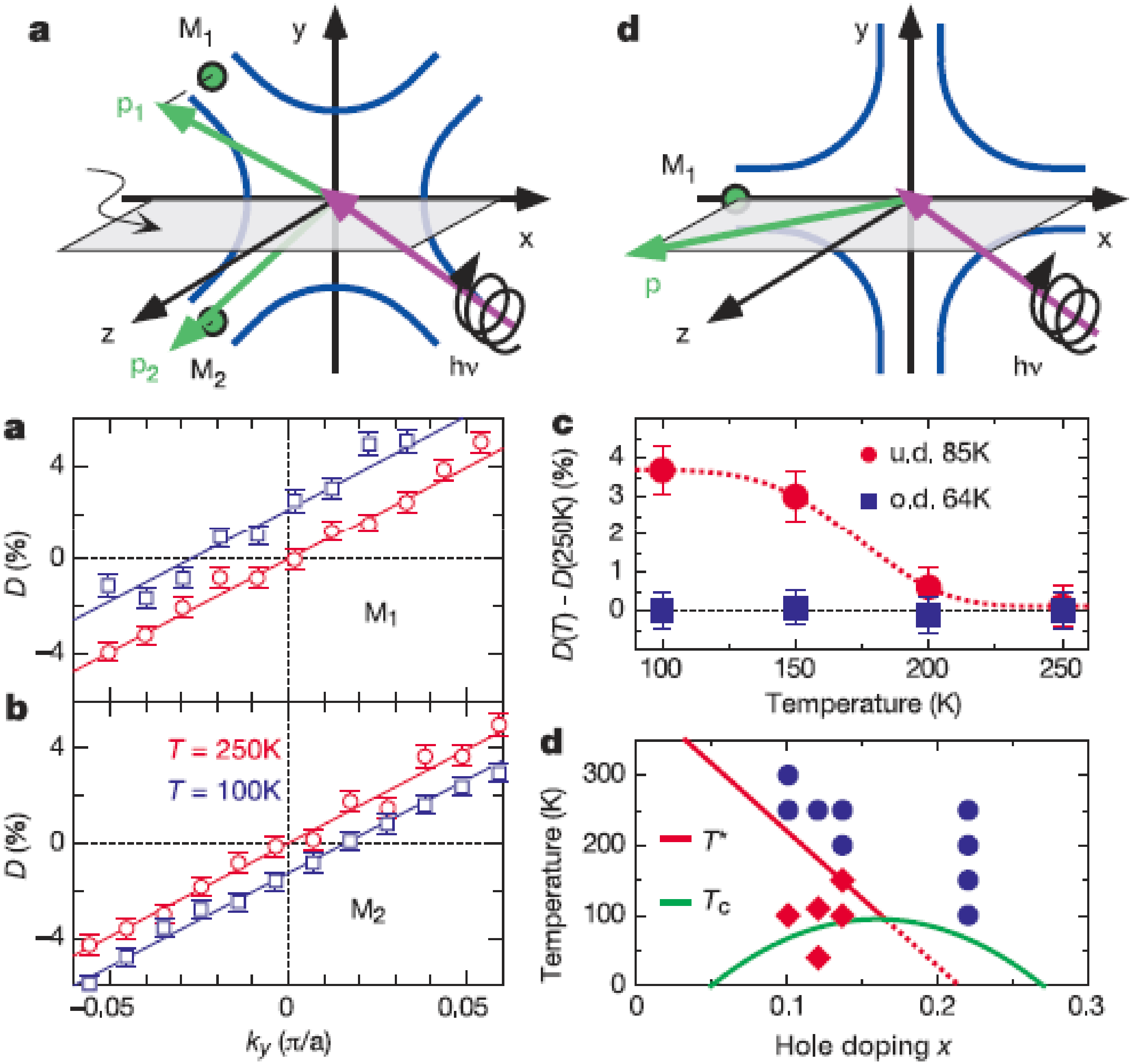
Kanigel *et al*
Nat. Phys. (2006)

A Nernst signal (due to fluctuating vortices?) appears above T_c



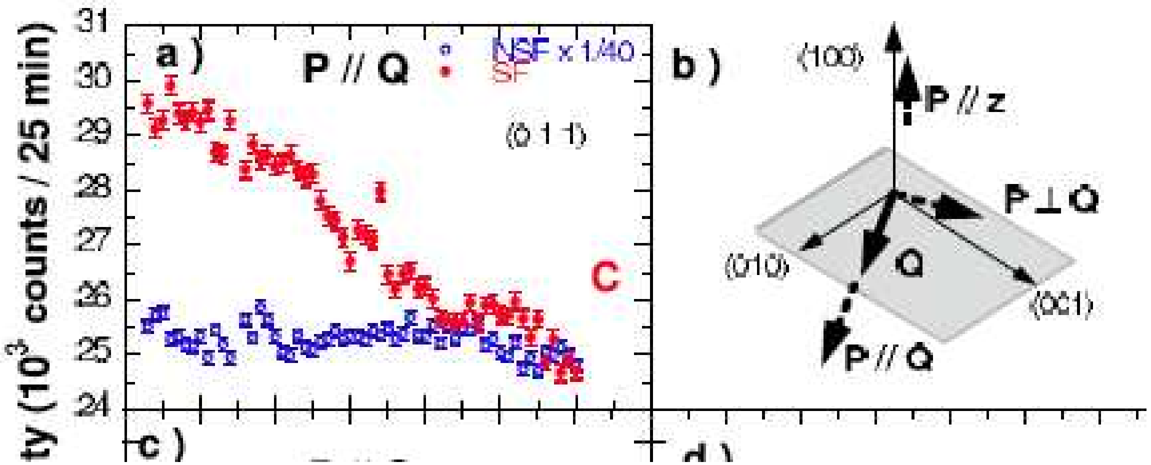
Wang *et al*
PRB (2001)

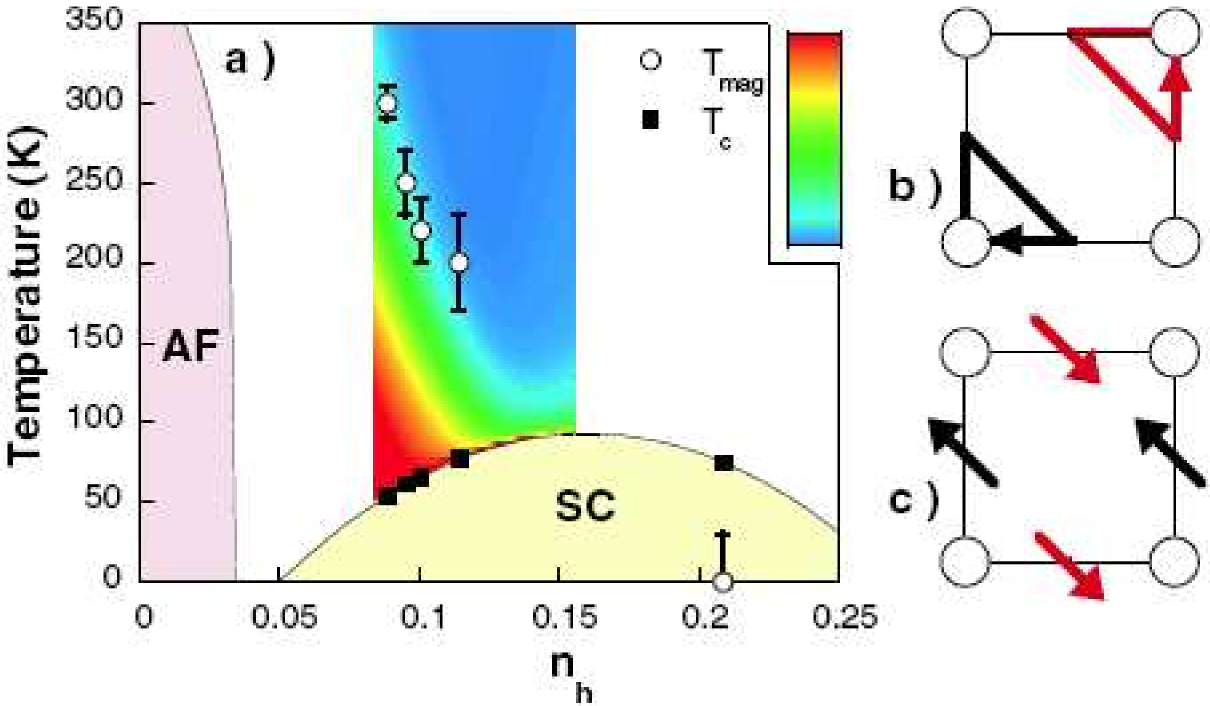
Circular dichroism above T_c in the pseudogap phase?



Kaminski *et al*
Nature (2002)

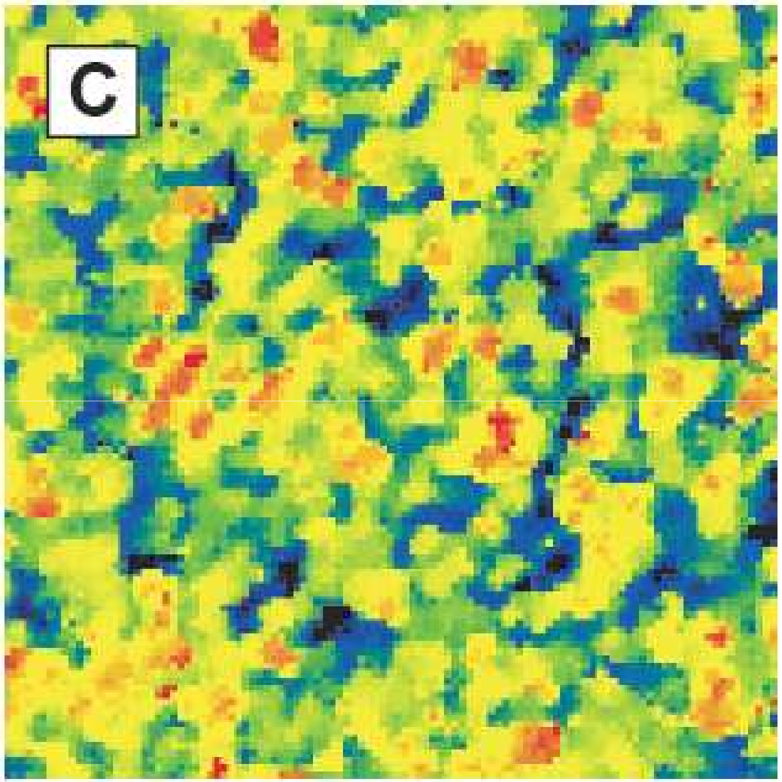
Orbital moments above T_c in the pseudogap phase?



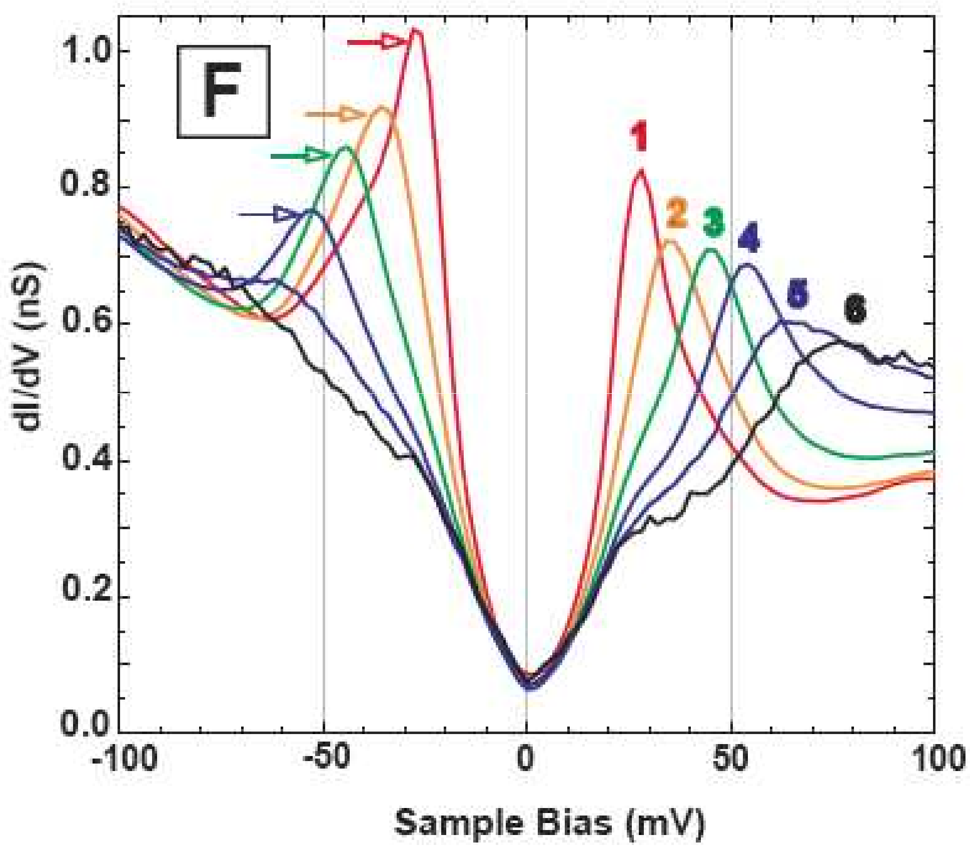


Fauque *et al*
PRL (2006)

Scanning tunneling spectra show strong spatial inhomogeneity

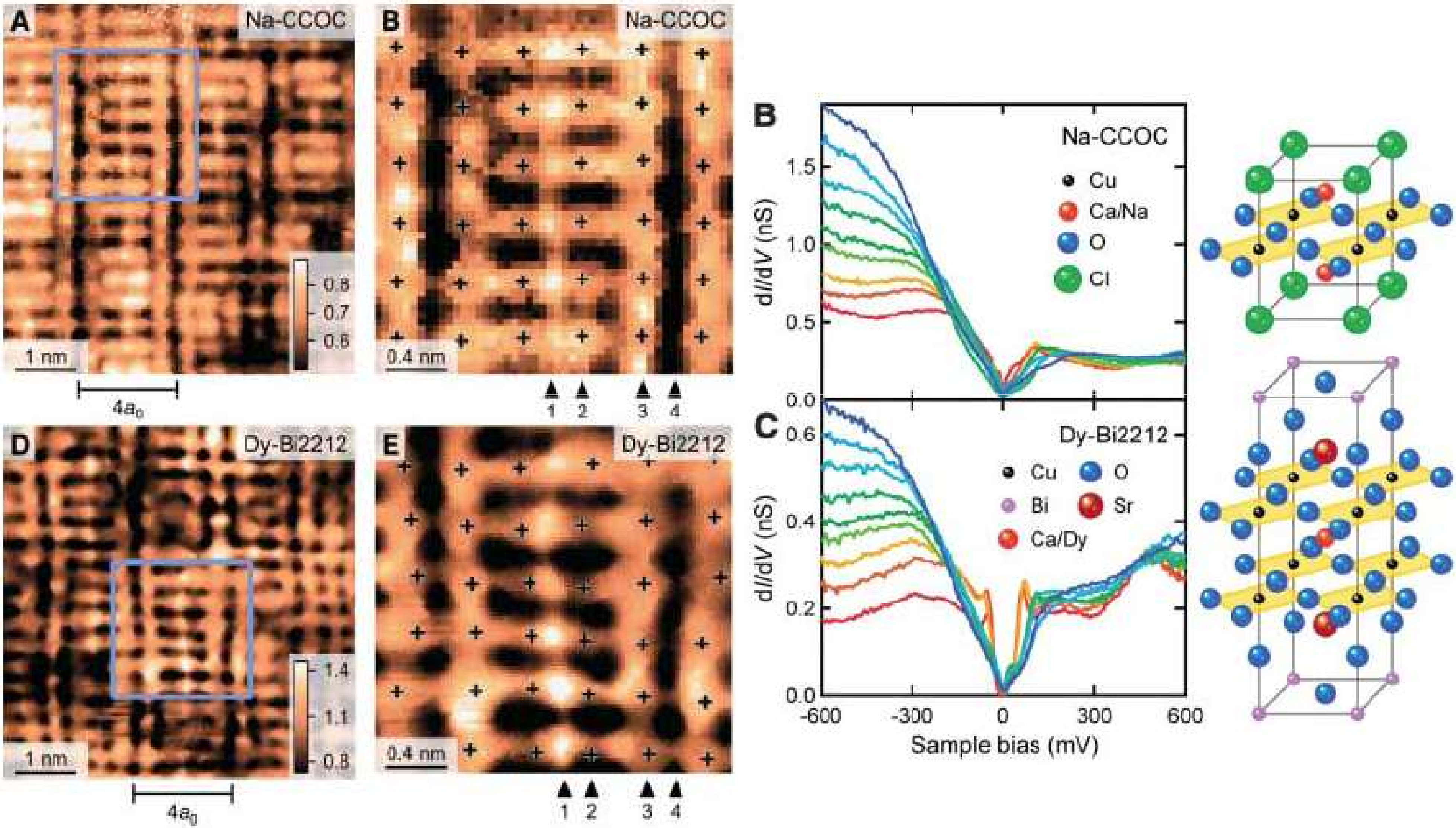


“gap map”



McElroy *et al*, PRL (2005)

Hole Density shows a “4a period bond centered electronic glass”



Kohsaka *et al*, Science (2007)

The Resonating Valence Bond State in La_2CuO_4 and Superconductivity

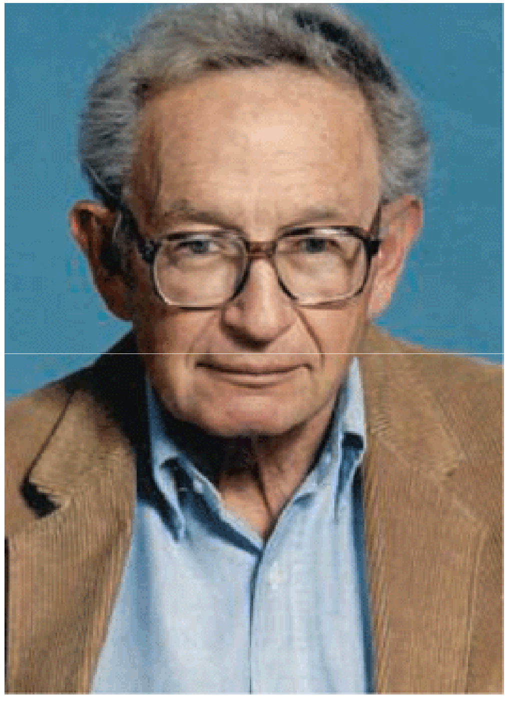
P. W. ANDERSON

The oxide superconductors, particularly those recently discovered that are based on La_2CuO_4, have a set of peculiarities that suggest a common, unique mechanism: they tend in every case to occur near a metal-insulator transition into an odd-electron insulator with peculiar magnetic properties. This insulating phase is proposed to be the long-sought "resonating-valence-bond" state or "quantum spin liquid" hypothesized in 1973. This insulating magnetic phase is favored by low spin, low dimensionality, and magnetic frustration. The preexisting magnetic singlet pairs of the insulating state become charged superconducting pairs when the insulator is doped sufficiently strongly. The mechanism for superconductivity is hence predominantly electronic and magnetic, although weak phonon interactions may favor the state. Many unusual properties are predicted, especially of the insulating state.

RECENTLY HIGH-TEMPERATURE SUPERCONDUCTIVITY has been observed in a number of doped lanthanum copper oxides near a metal-insulator transition (*1*), a pattern exhibited previously by $(Ba,Pb)BiO_3$ (*2*). The crystal structure suggests that the Cu^{2+} is in an $S = 1/2$, orbitally nondegenerate state, strongly hybridized to reexamine the idea of the "resonating valence-bond" (RVB) state (*5*).

Early doubts about the nature of the ground state of the antiferromagnetic Heisenberg Hamiltonian

$$H = J\sum_{i\,nn\,j} \vec{S}_i \cdot \vec{S}_j \qquad (1)$$



Science, February 1987

RVB has its critics

Hiawatha's Valence Bonding

by R.B. Laughlin
Department of Physics, Stanford University, Stanford, California

With apologies to Lewis Carroll (and H. W. Longfellow)

[EDITOR'S NOTE: The author's Nobel Prize is not in the field of literature]

Introduction

Since all men have imperfections
Hanging bones inside their closets
That they trust no one will notice
Absent tips on where to find them,
It will shock no one to learn that
Even mighty Hiawatha
Famous Chief of myth and legend
Of a noble man of Nature
Was a total fabrication
Of a team of gifted spin docs
Hired later for this purpose.
He was really just a tech nerd
Who cared only for equations
And explaining all behavior
From the basic laws of physics
Armed with only mathematics.
And the tragic Ludwig Boltzmann
Who ascribed these laws to counting
But fell victim to depression
When he found no one believed him
And so killed himself by jumping
From an Adriatic tower.
Hiawatha saw that Maxwell's
Guessing missing laws of motion
Needed for predicting light waves,

Bob Laughlin
Annals of Improbable Research, May-June 2004

RVB (“resonating valence bond”) is a strong coupling theory for cuprates developed by Phil Anderson and his colleagues

It postulates a liquid of spin singlets

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Neel Lattice RVB

RVB Model (Anderson-Baskaran - 1987, Kotliar - 1988, Gros-Rice-Zhang, Lee-Nagaosa-Wen, Randeria-Trivedi, etc.)

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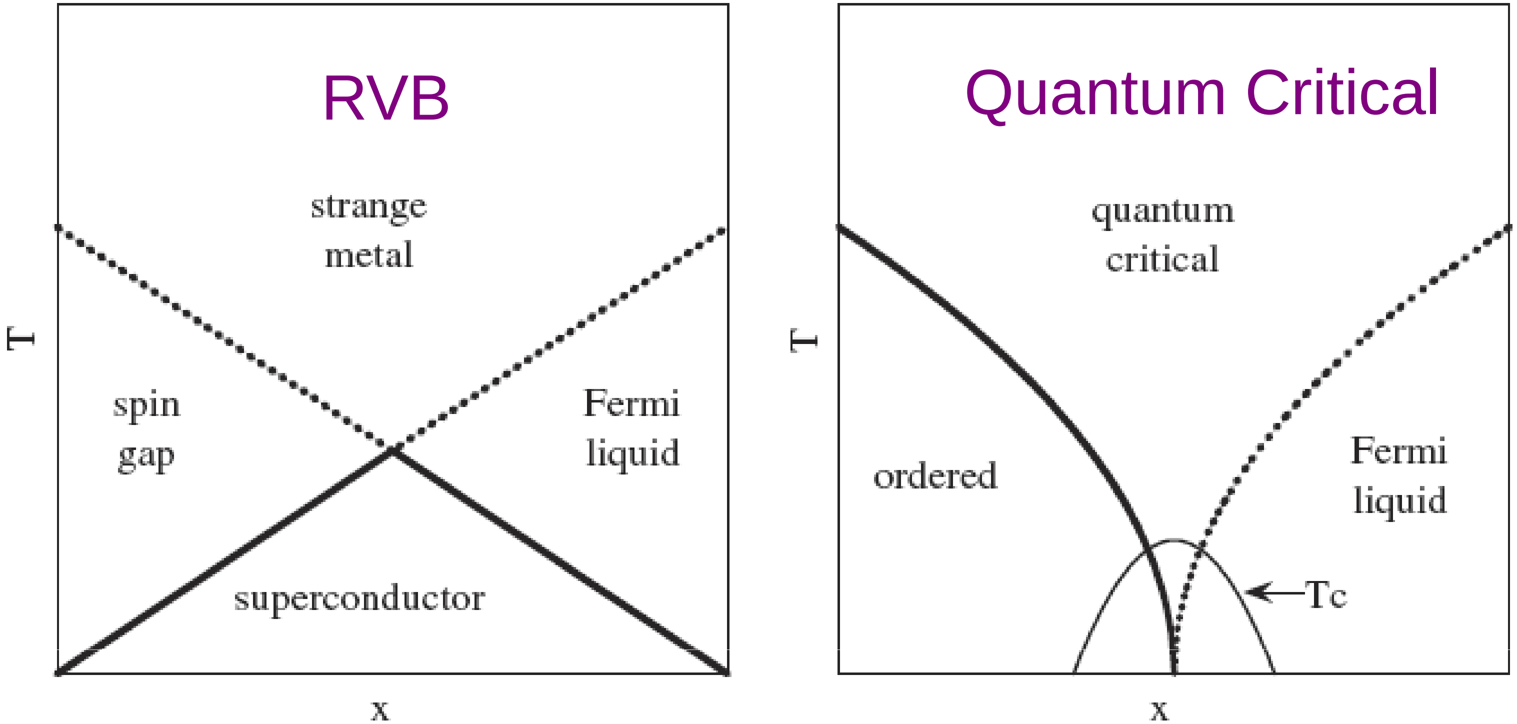
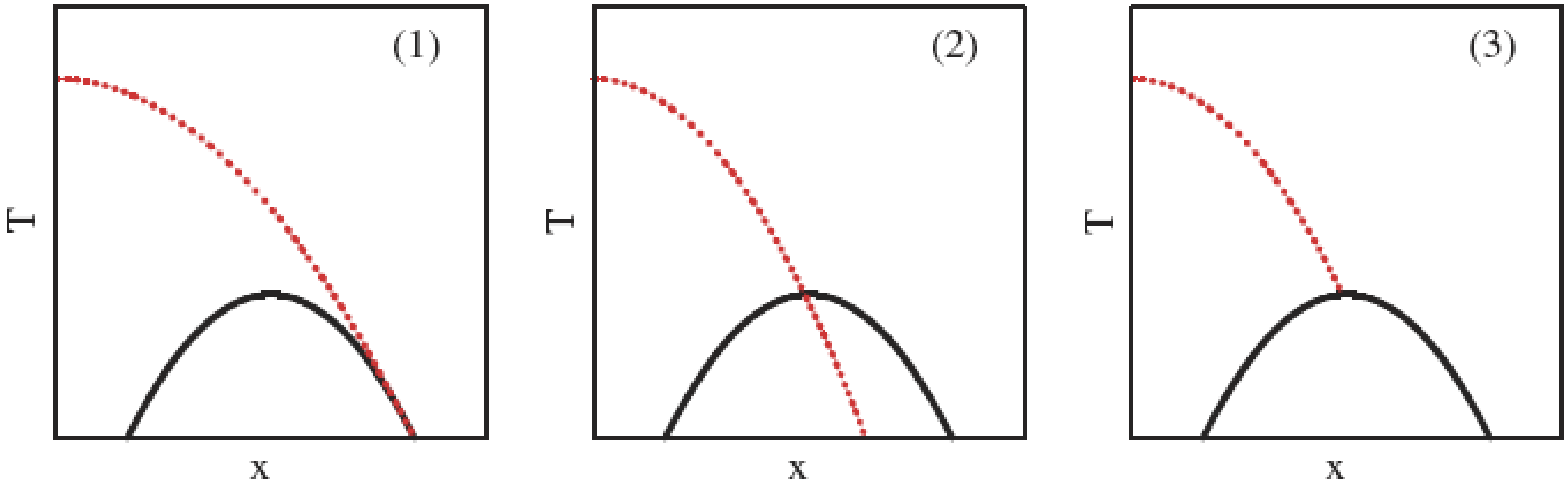
The pseudogap phase corresponds to a d-wave pairing of spins (left panel). At zero doping, this is quantum mechanically equivalent to an orbital current phase (middle panel). The spin gap, Δ, is not equivalent to the superconducting order parameter, Δ_{sc}, as it would be in BCS theory (right panel).

Two Theories of the Phase Diagram



Relation of T* to T_c



“Emery-Kivelson” picture
Nature (1995)

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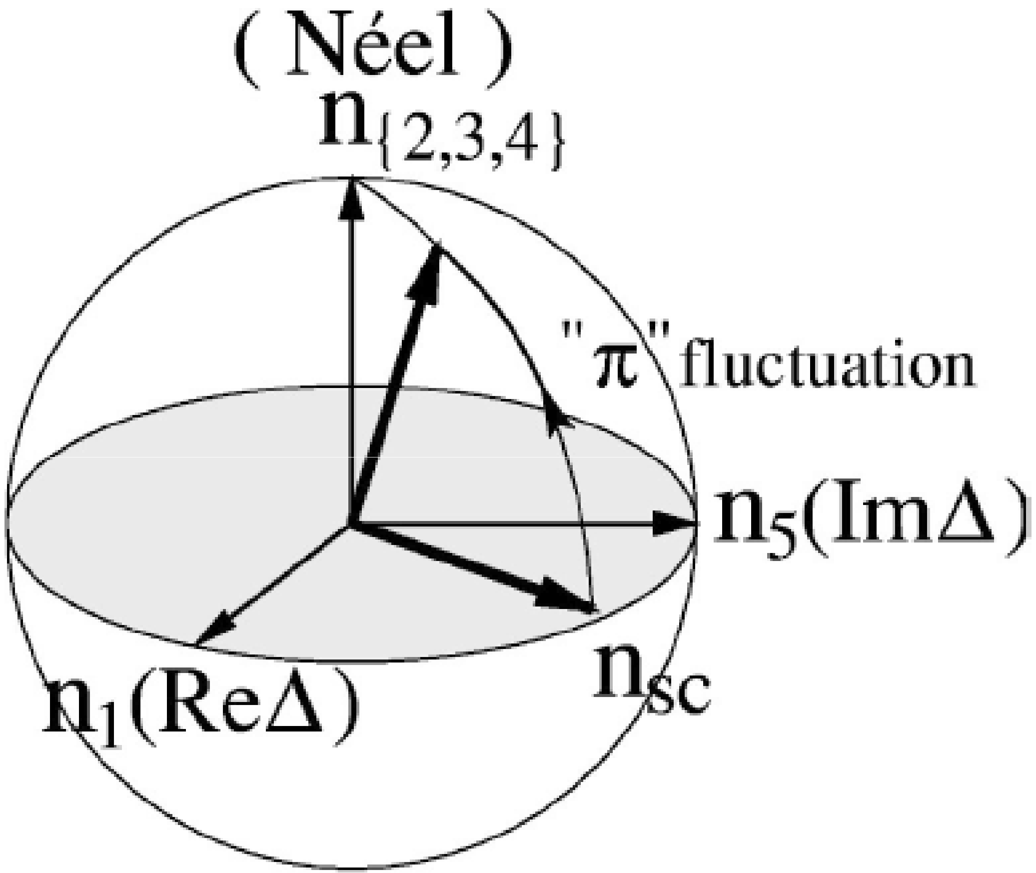
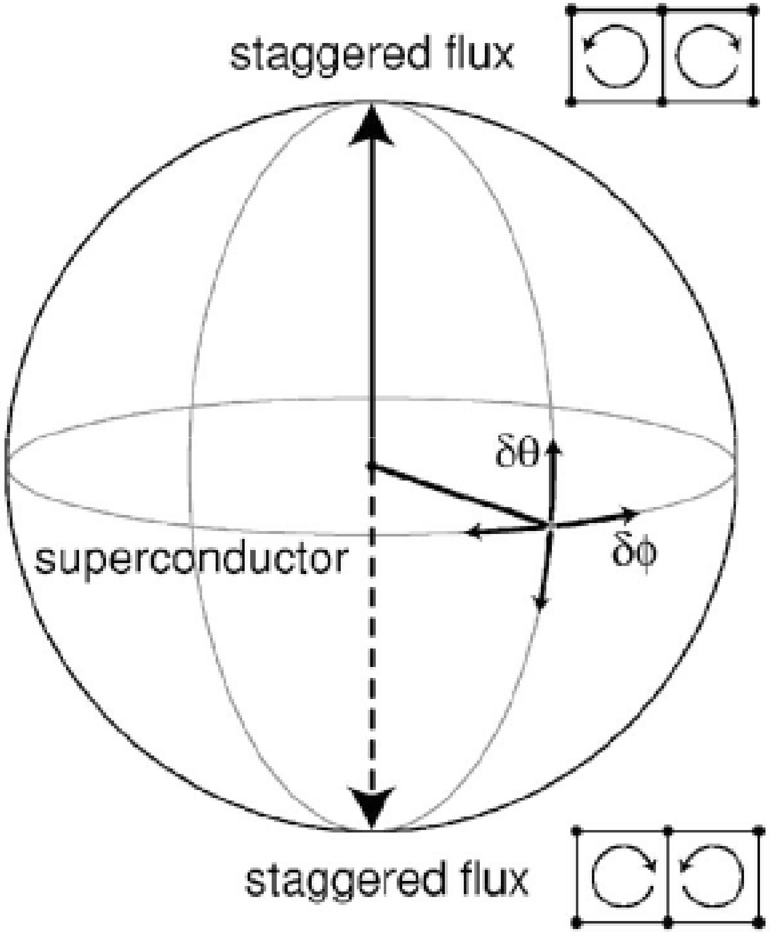
Pairing occurs below mean field transition temperature

Coherence occurs below phase ordering temperature

Superconductivity occurs only below both temperatures

SO(5) vs SU(2)



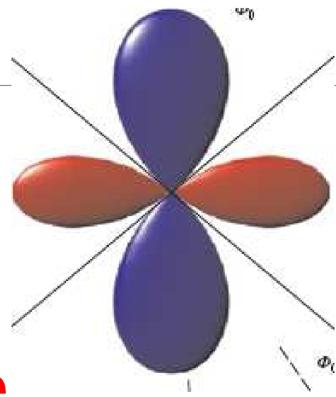


Demler, Hanke, and Zhang Lee, Nagaosa, and Wen

Rev Mod Phys (2004) Rev Mod Phys (2006)

Antiferromagnetic spin fluctuations can lead to d-wave pairs
(an e^- with up spin wants its neighbors to have down spins)

Heavy Fermions - Varma (1986), Scalapino (1986)
High T_c - Scalapino (1987), Pines (1991)

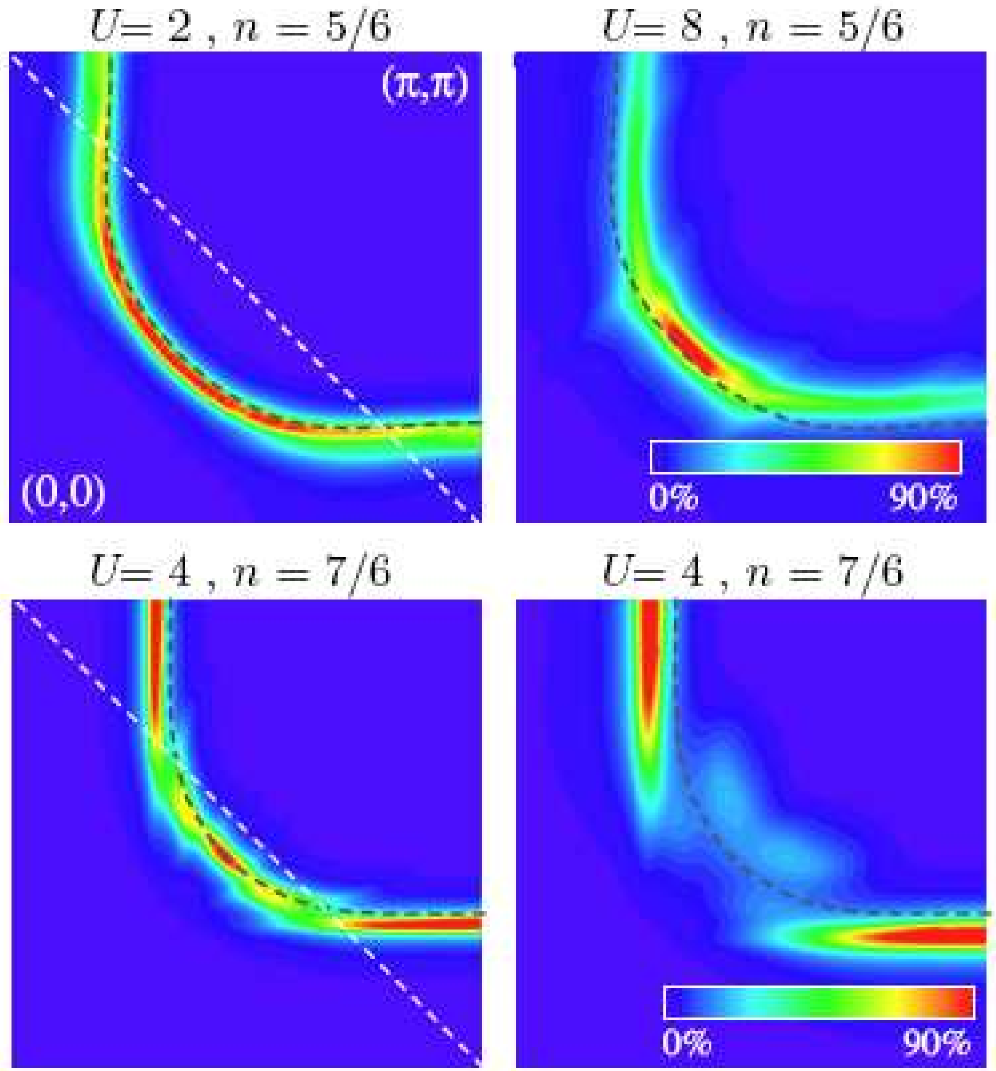


< Repulsive

< Attractive

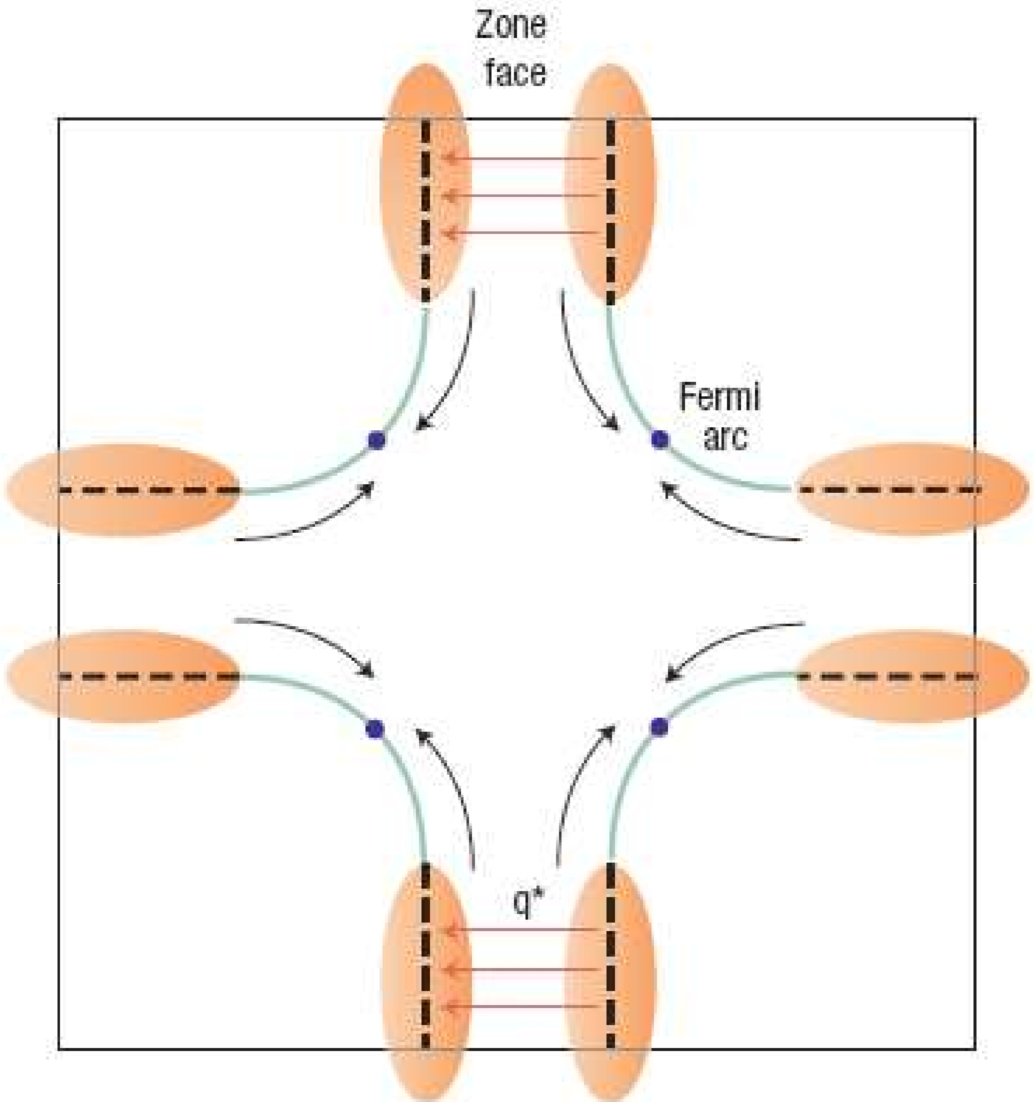
(plots from Scalapino)

Dynamical Mean Field Theory (Georges, Kotliar, Tremblay)
Magnetic correlations wipe out parts of the Fermi surface



Senechal & Tremblay
PRL (2004)

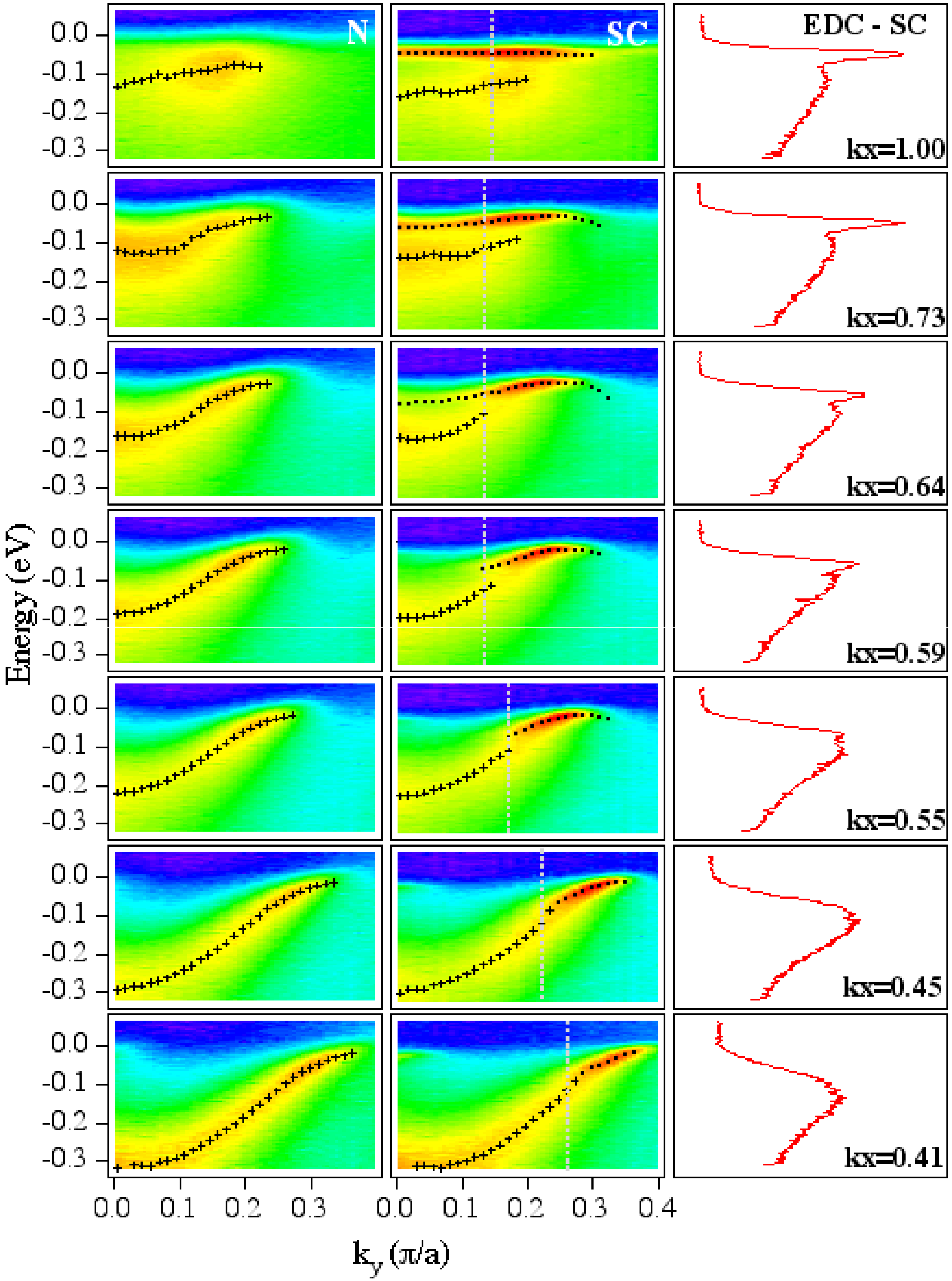
Does charge ordering wipe out part of the Fermi surface?



McElroy - Nat. Phys. (2006)

The dispersion kink at the node continuously evolves into a two branch dispersion (peak-dip-hump) as one approaches the anti-node

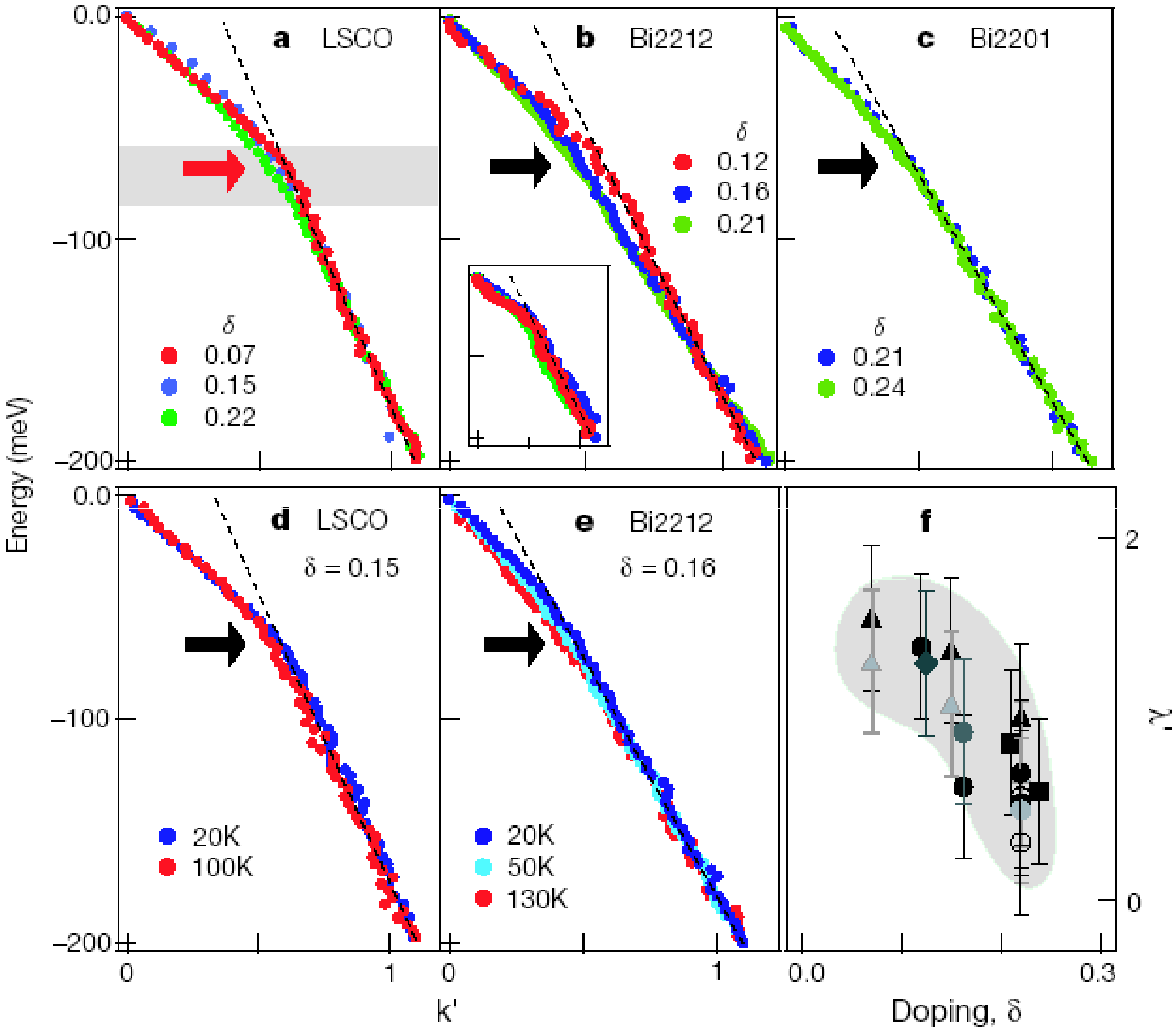
Spin resonance mode?



Kaminski *et al,* PRL (2001)

The kink is seen in a variety of the cuprates at the same energy

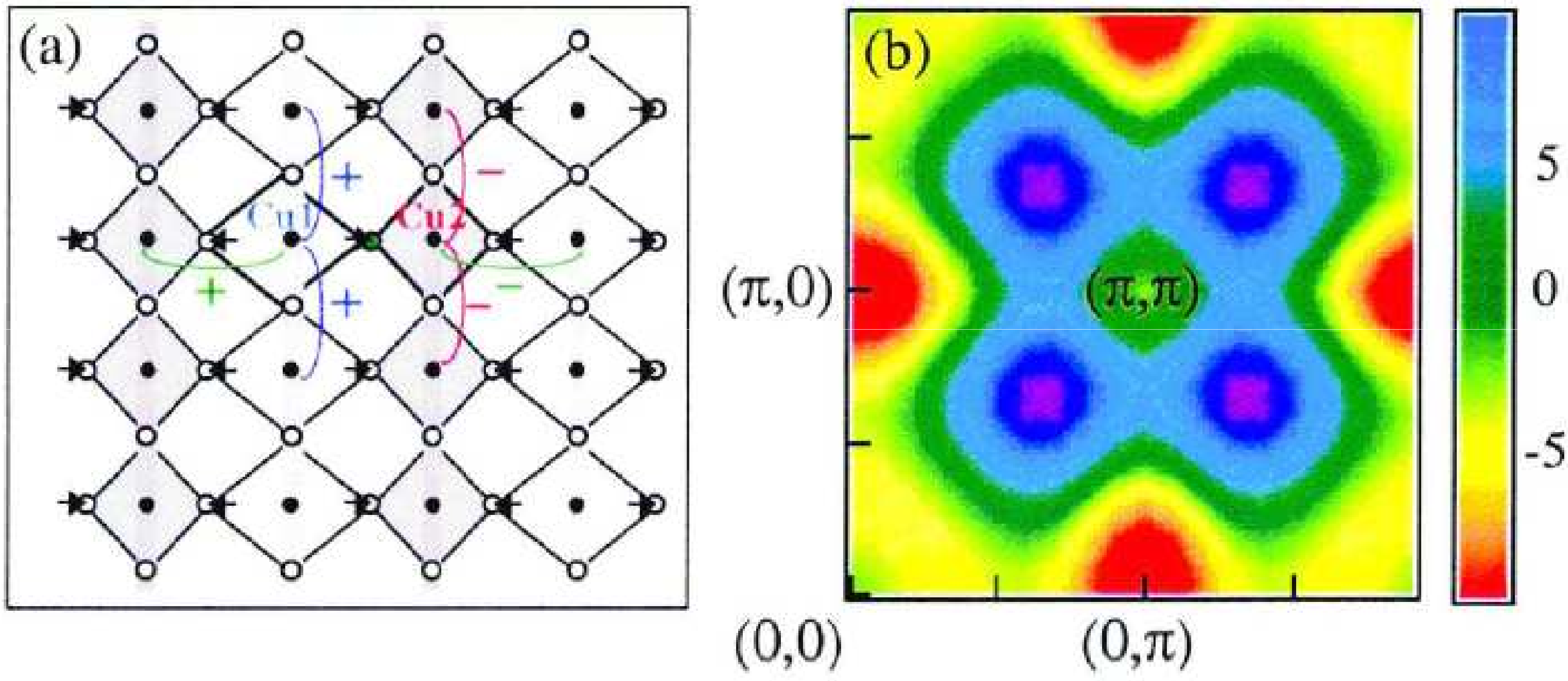
A phonon?



Lanzara *et al*, Nature (2001)

d-wave pairing due to a half-breathing phonon mode??

Shen, Lanzara, Ishihara, Nagaosa - Phil Mag B (2002)



Connection to Other Fields
(Cold Atoms, Nuclear Matter, …)