High Tc superconductors

IMPRS Focus Course „Superconductivity“

Friday lecture

Michael A. Sentef

with material from Mike Norman‘s 2011 talk
„High-Temperature Superconductivity – After 25 years, where are we at?“

It All Started Back in 1986

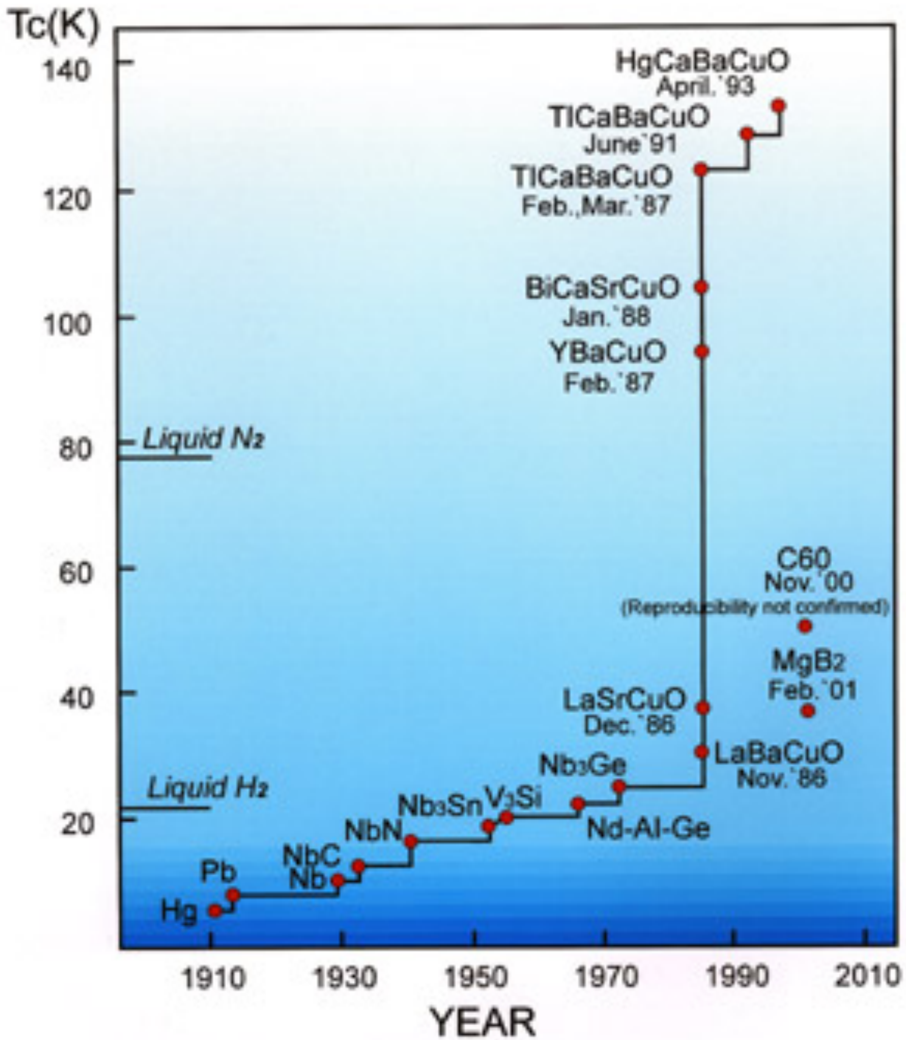
Z. Phys. B – Condensed Matter 64, 189–193 (1986)

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)



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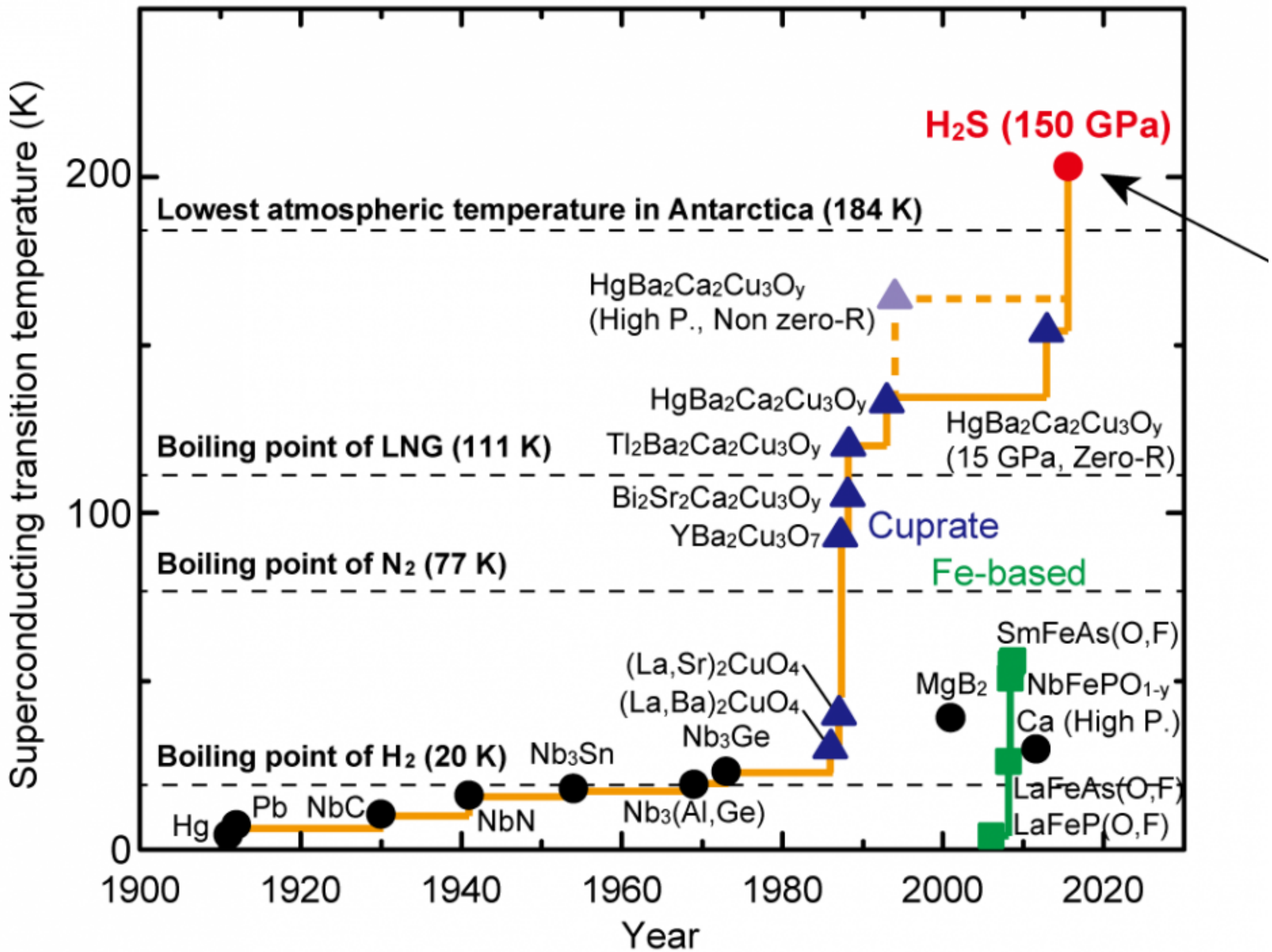
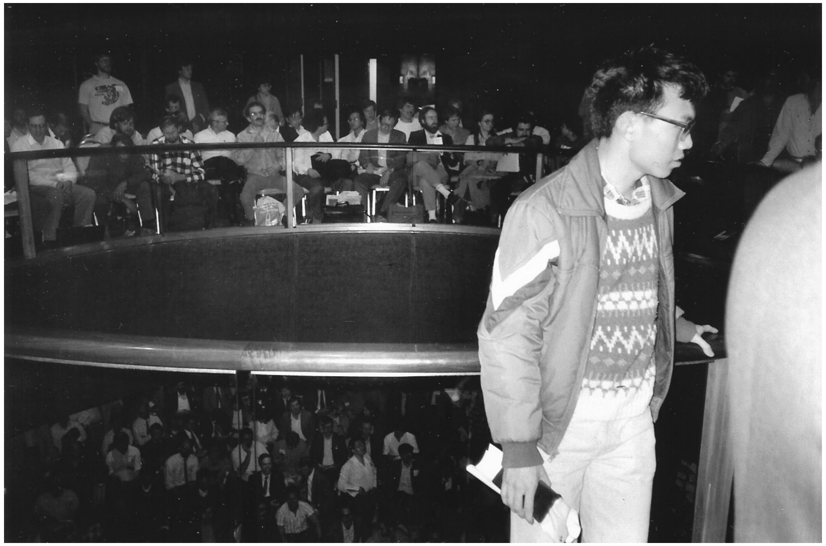


credit: Osaka University

Woodstock of Physics - March 1987

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THE
SUPERCONDUCTIVITY
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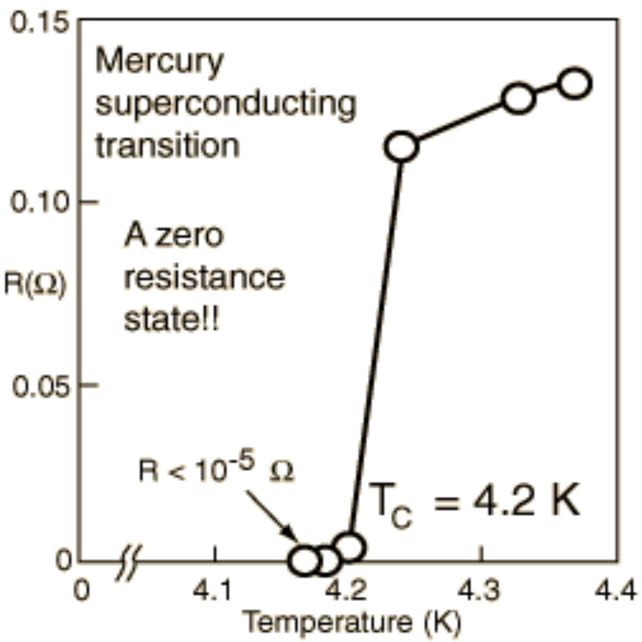
[Superconductors:]

(1) They are perfect conductors

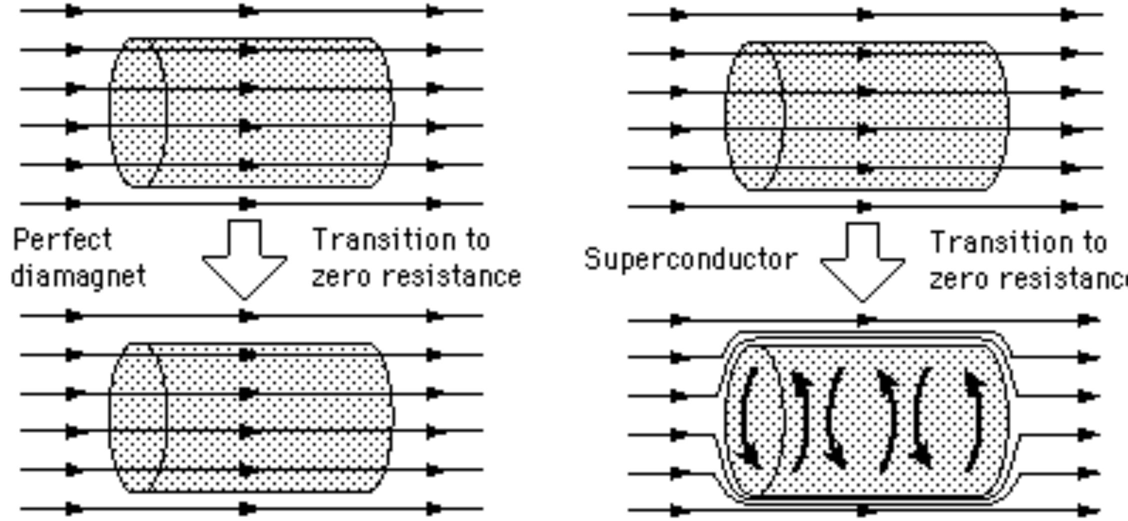
(2) They expel magnetic flux

Zero resistance

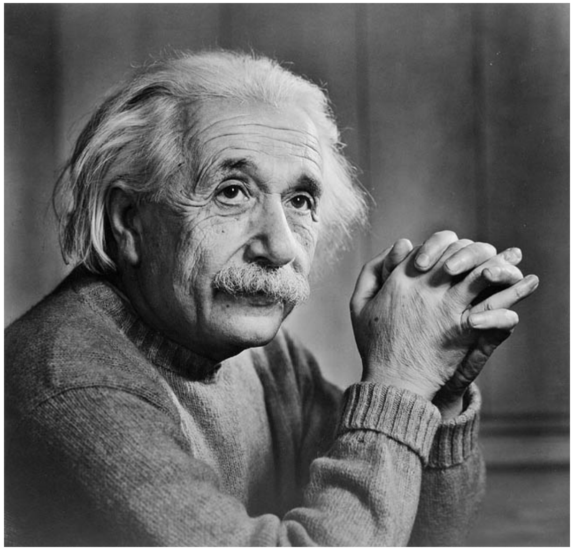


H. K. Onnes (1911)

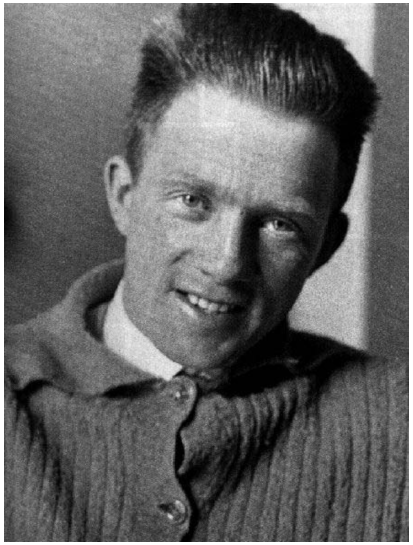
Meissner effect (1933)



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)

A (Very) Short History of Superconductivity

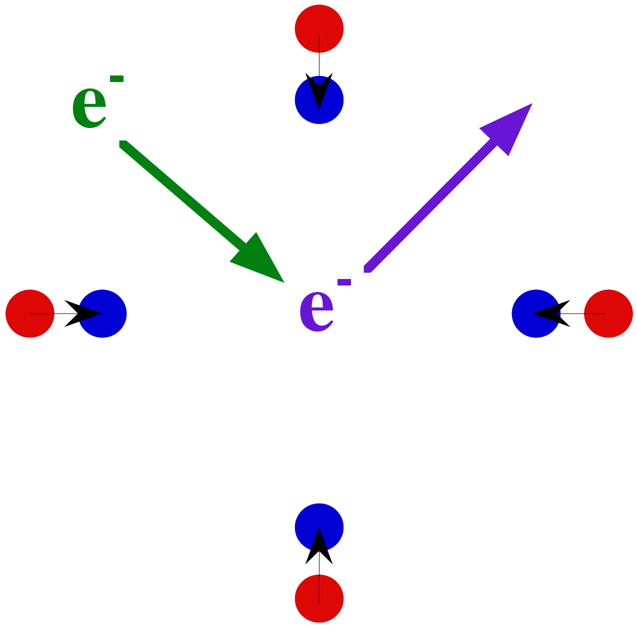
1. London theory - rigidity to macroscopic perturbations implies a "condensate" (1935,1950)
2. Ginzburg-Landau (Ψ) theory - order parameter for condensate (1950)
3. Isotope effect (Maxwell, Serin & Reynolds, Frohlich, 1950)
4. Cooper pairs (1956)
5. Bardeen-Cooper-Schrieffer (**BCS**) microscopic theory (1957)
6. Type-II superconductors (Abrikosov vortices, 1957)
7. Connection of BCS to Ginzburg-Landau (Gorkov, 1958)
8. Strong coupling superconductivity (Eliashberg, Nambu, Anderson, Schrieffer, Wilkins, Scalapino …, 1960-1963)
9. p-wave superfluidity in ^{3}He (Osheroff, Richardson, Lee, 1972; Leggett, 1972)
10. Heavy Fermion Superconductivity (Steglich, 1979)
11. High Temperature Superconductivity (Bednorz & Muller, 1986)
12. Iron Arsenides (Hosono, 2008)

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 <u>oxygen</u>
4. stay away from <u>magnetism</u>
5. stay away from <u>insulators</u>
6. stay away from <u>theorists</u>

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)

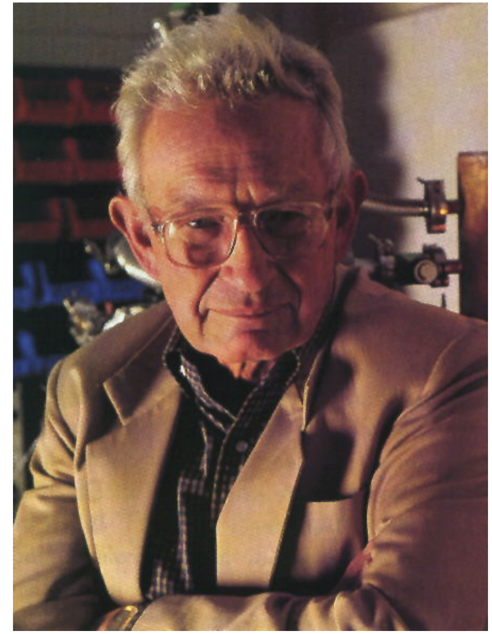
But cuprates have
d-wave pairs!
(L=2, S=0)

van Harlingen;
Tsuei & Kirtley -
Buckley Prize -1998

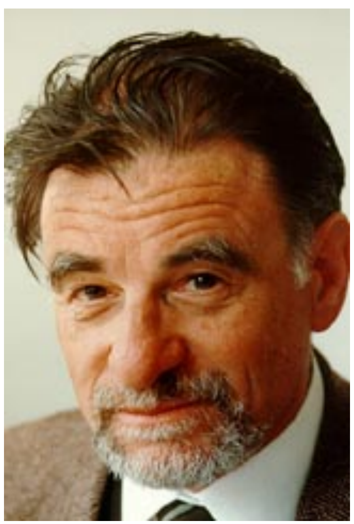
Artwork by
Gerald Zeldin (2000)

Alex Abrikosov
(small q phonons)

Bob Laughlin
(competing phases)



Phil Anderson
(RVB; interlayer tunneling; RVB)

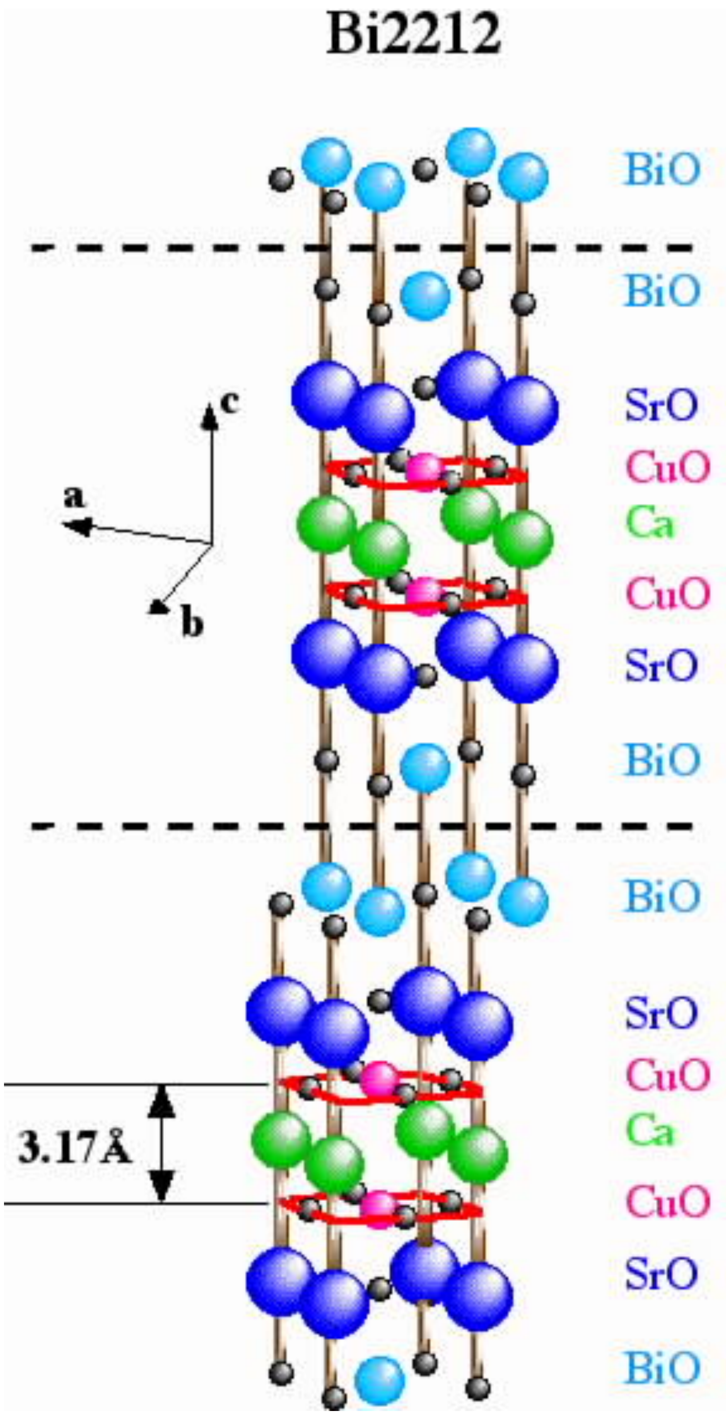


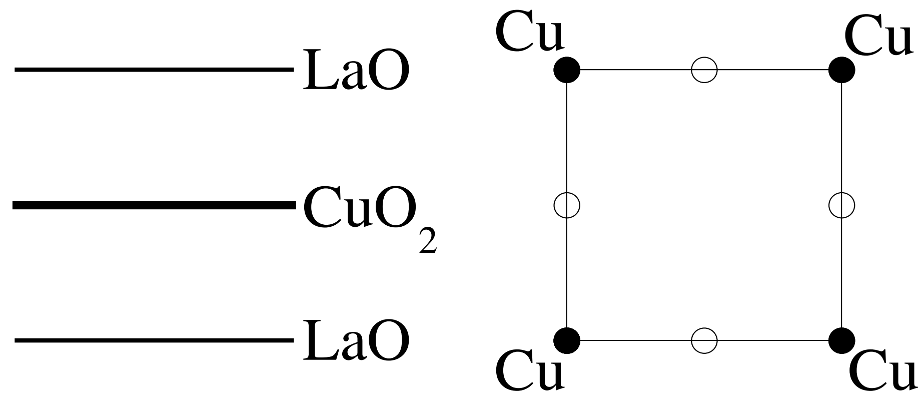
Karl Mueller
(bipolarons)

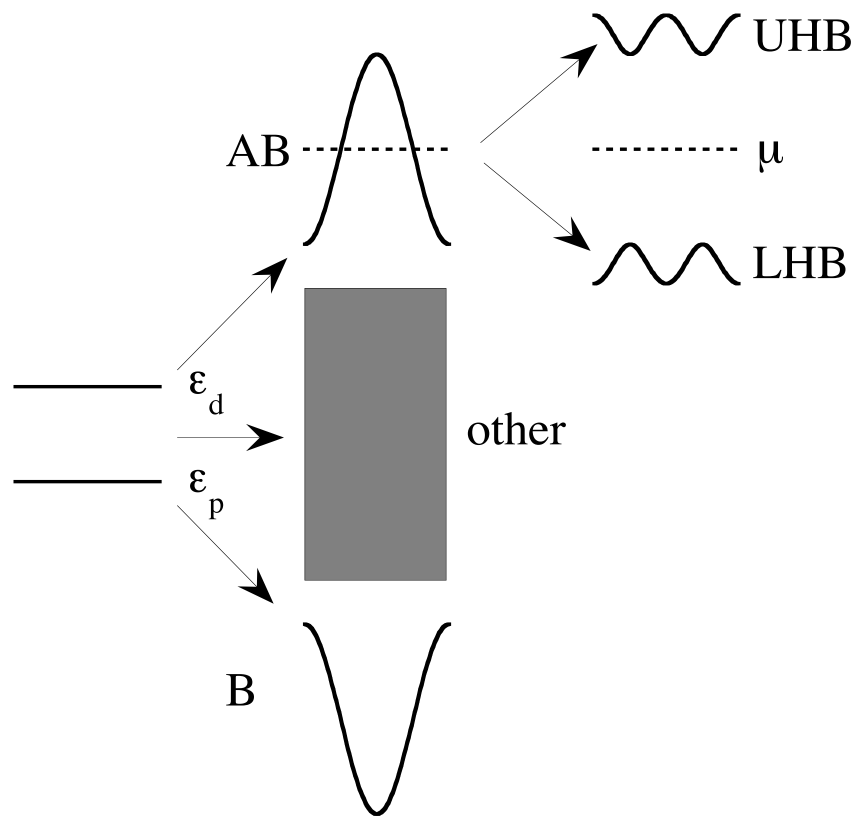
Bob Schrieffer
(spin bags)

Tony Leggett
(interlayer Coulomb)

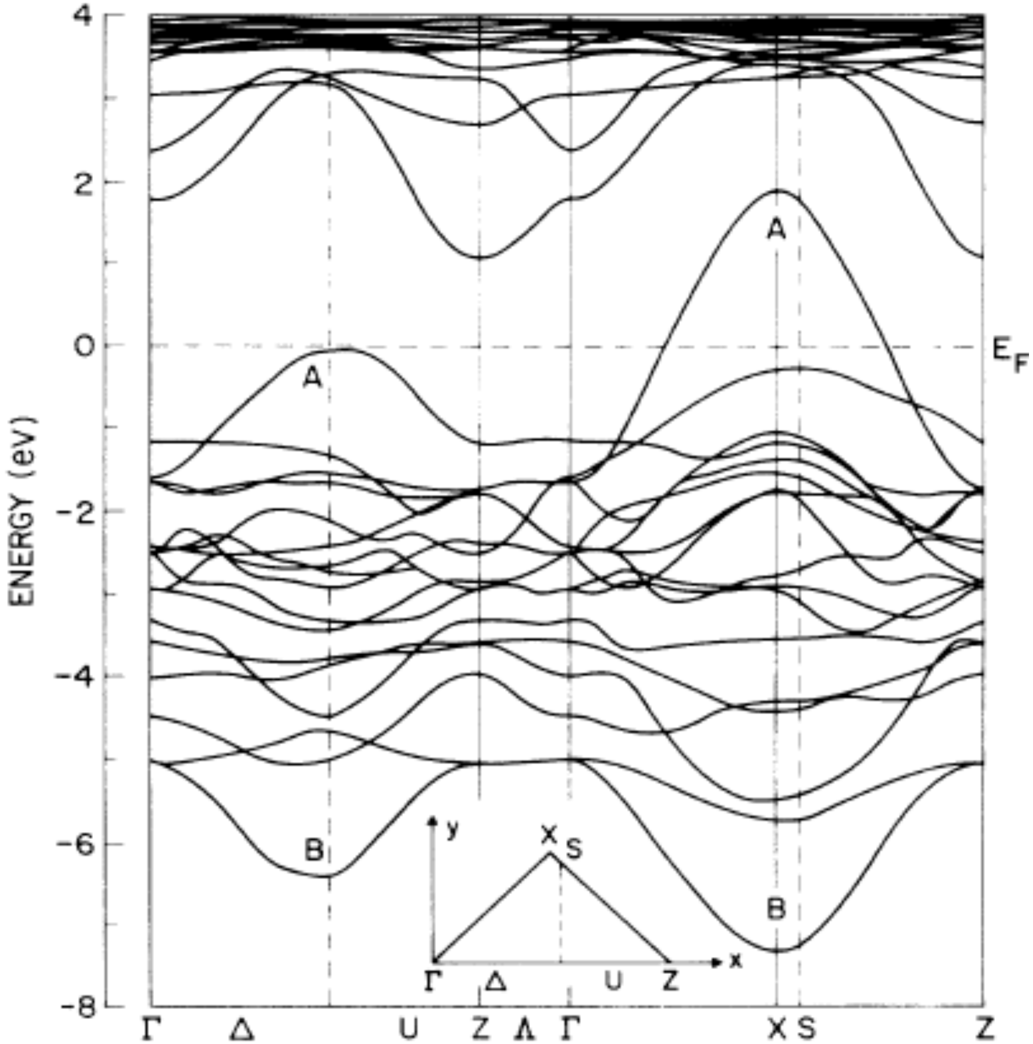
Electronic Structure of Cuprates



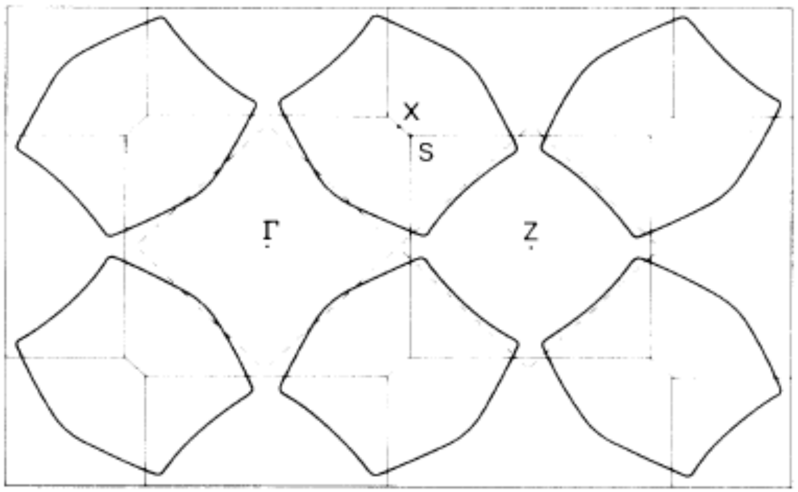




Electronic structure from density functional theory



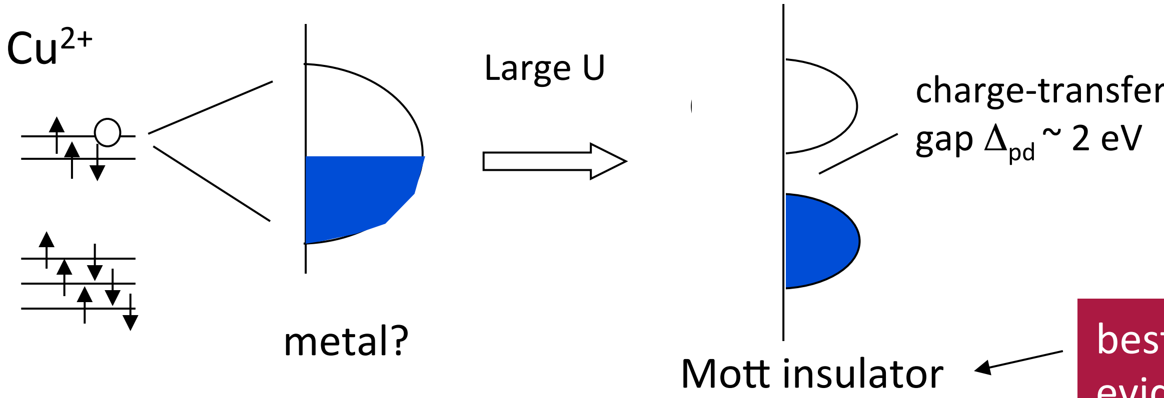
Energy vs Momentum



Fermi surface

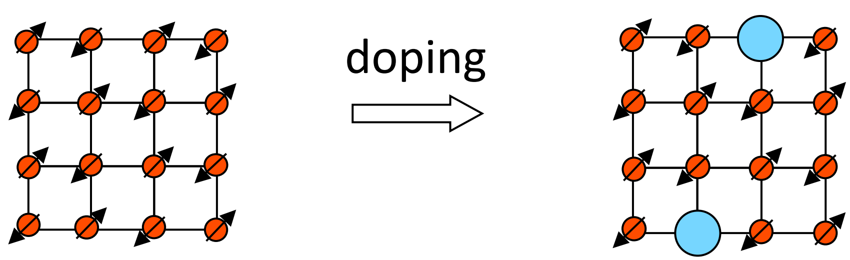
Len Mattheiss
PRL (1987)

Short (and biased!) tutorial on cuprates



best evidence for large U

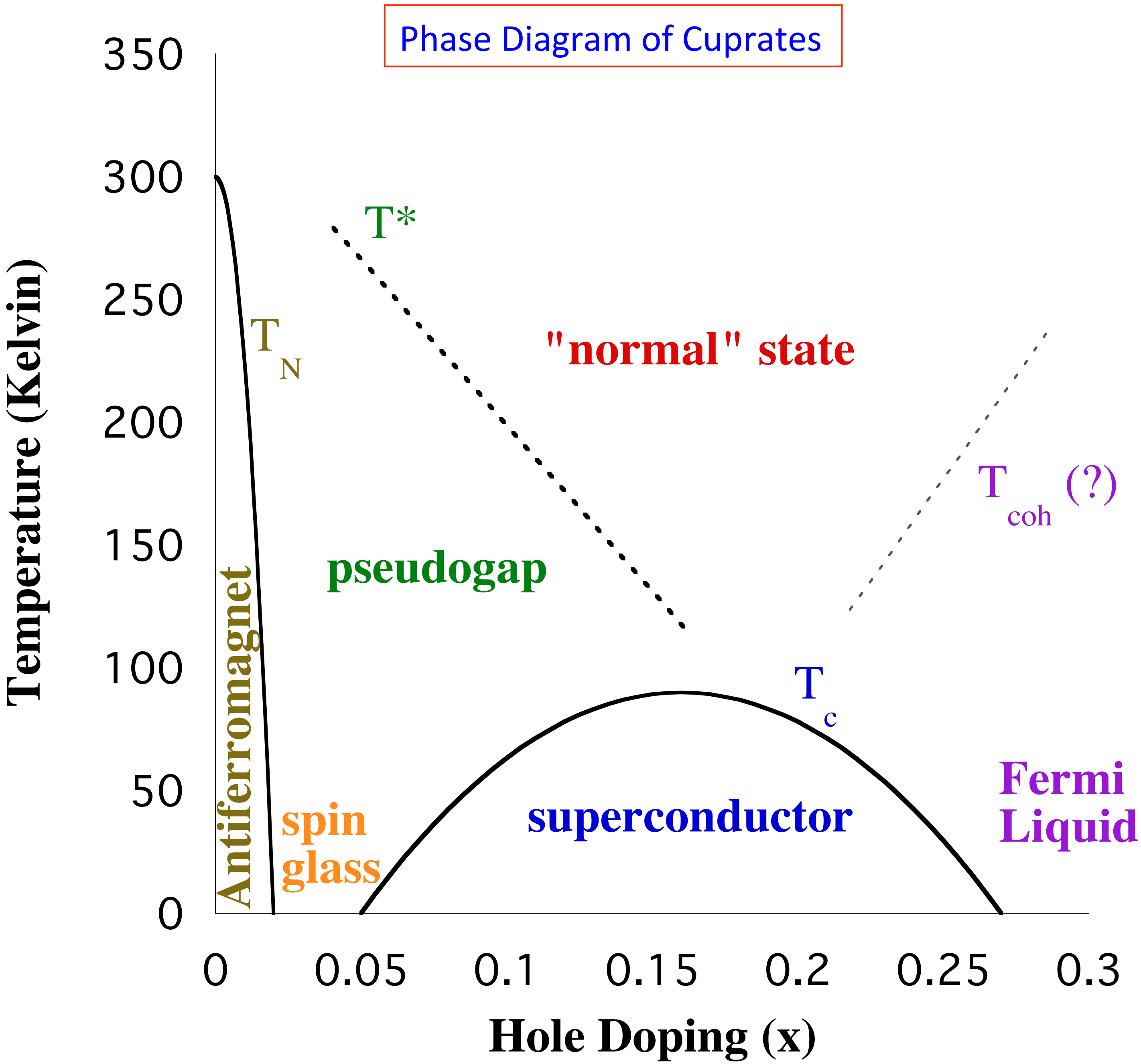
antiferromagnet J~1400 K



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

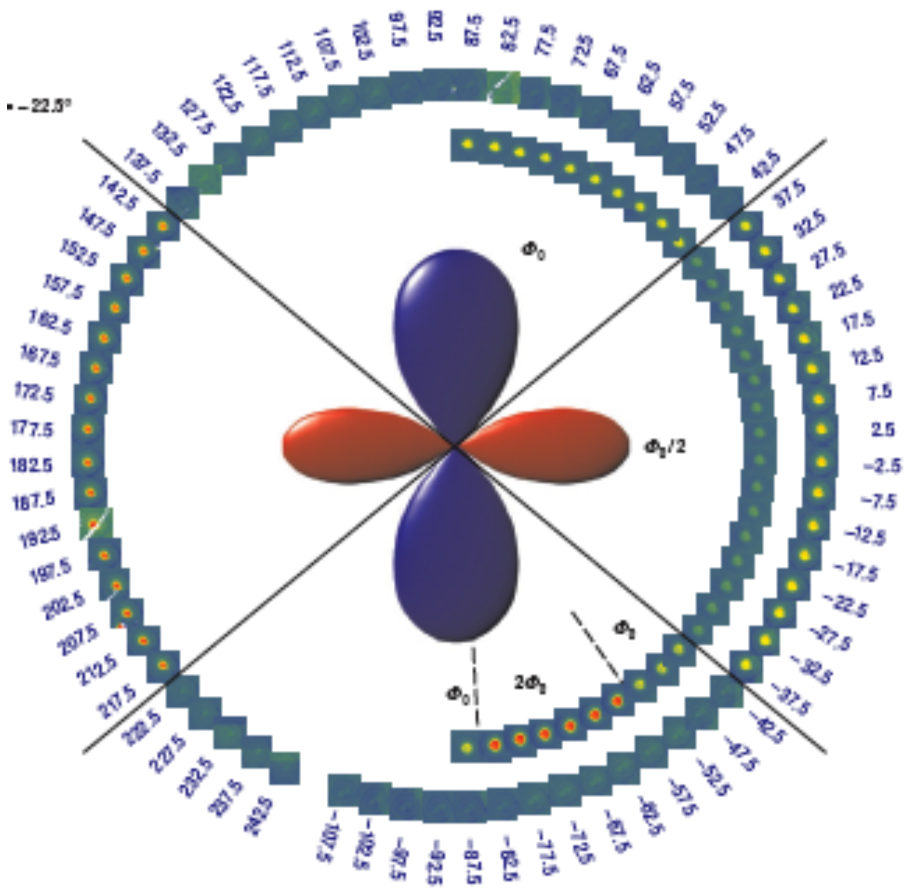
$t = 0.3$ eV, $U = 2$ eV, $J = 4t^2/U = 0.12$ eV

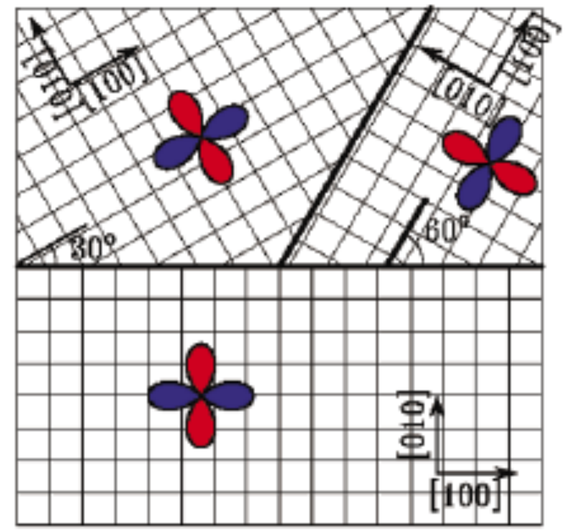
(slide from Phil Anderson)


Phase Diagram of Cuprates
350
300
250
200
150
100
50
0
Temperature (Kelvin)
T*
T
N
"normal" state
T
coh
(?)
pseudogap
Antiferromagnet
T
c
Fermi
Liquid
spin
glass
superconductor
0
0.05
0.1
0.15
0.2
0.25
0.3
Hole Doping (x)

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 -

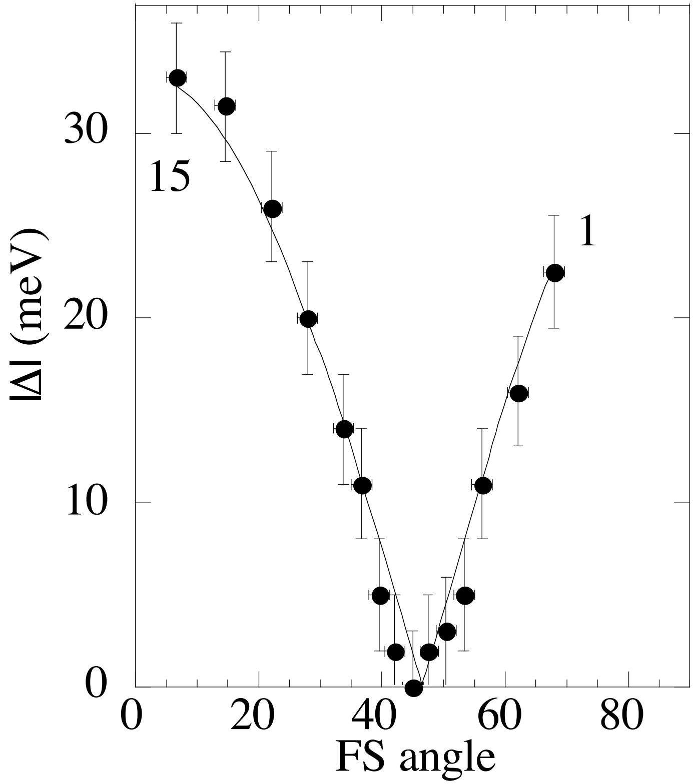
van Harlingen, Kirtley & Tsuei

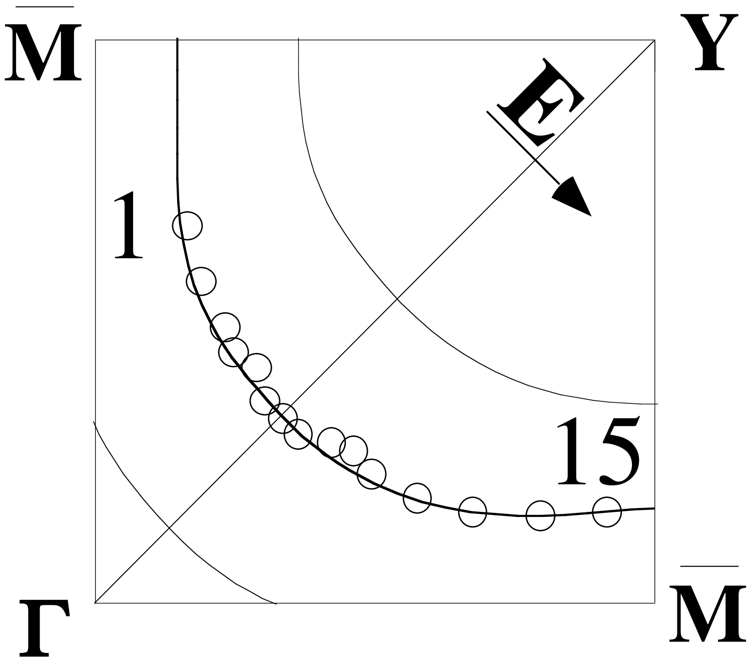
Kirtley *et al*, Nat. Phys. (2006)

Extraction of the Superconducting Energy Gap from Photoemission

Campuzano, Shen, Johnson – Buckley Prize (2011)

Δ_k --> $\cos(k_x a) - \cos(k_y a)$ --> Implies near-neighbor pairs



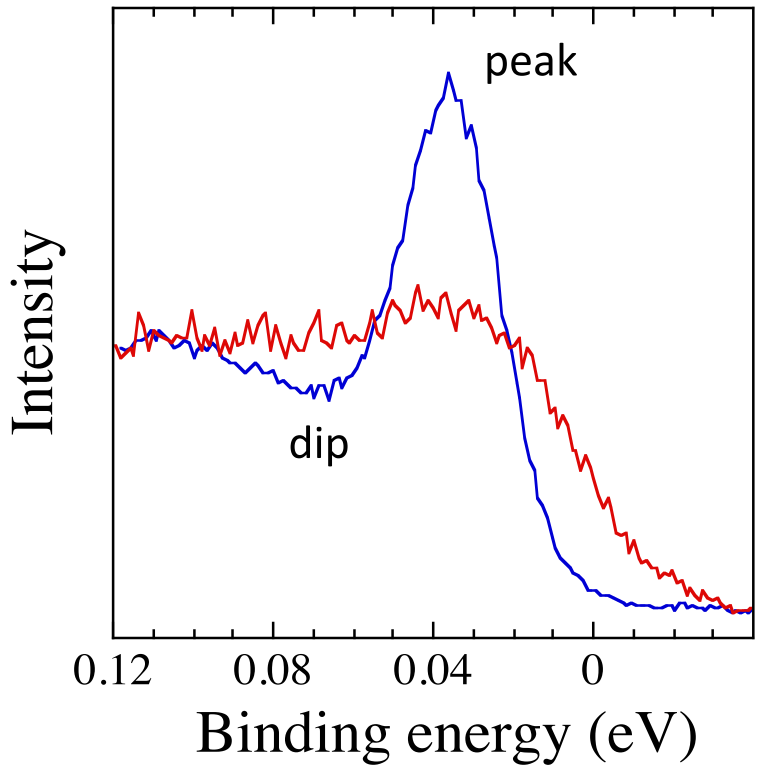


Bi2212, T_c=87K

Dirac cone

Ding *et al*., PRB (1996)

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



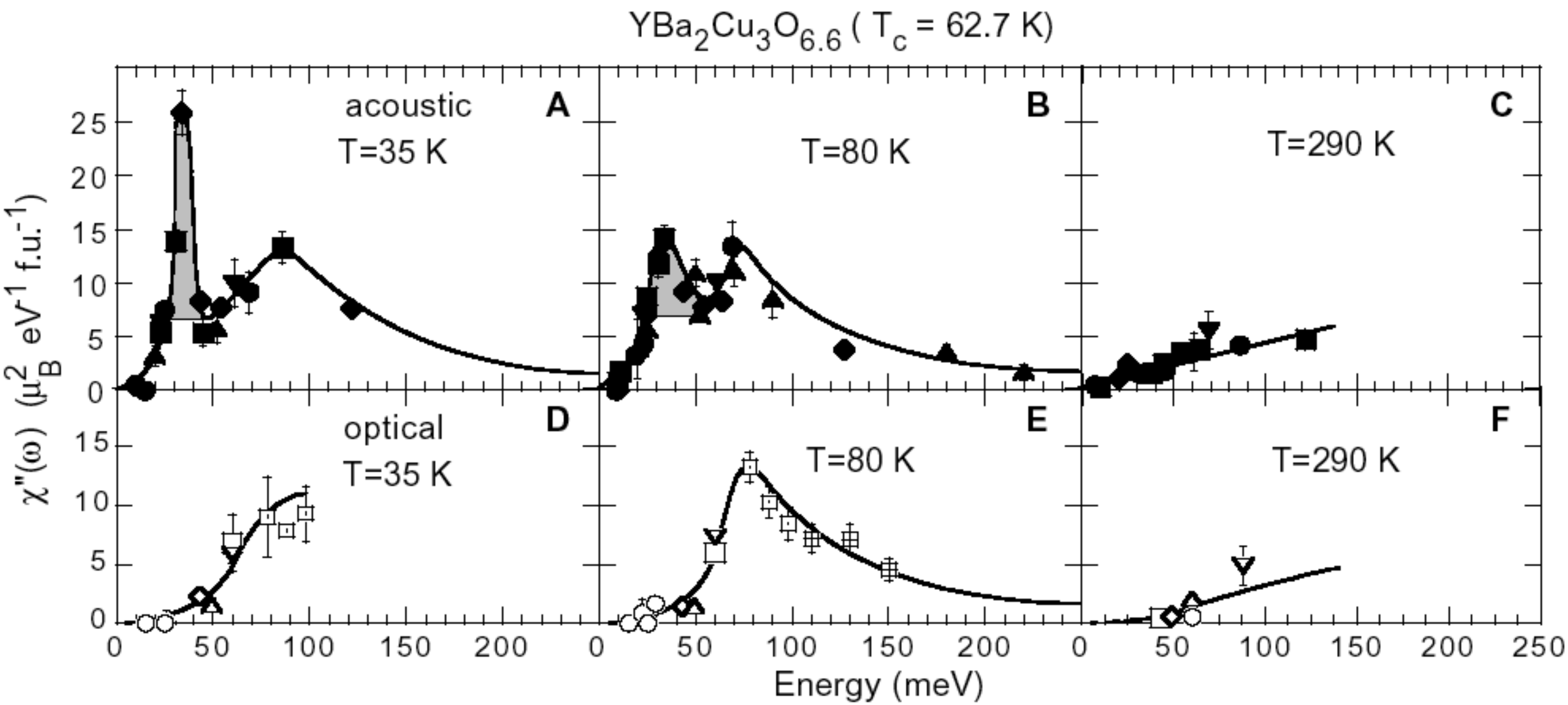
Incoherent normal state

Coherent superconductor

Norman *et al*, PRL (1997)

Neutron Spin Resonance (S=1 excitation)

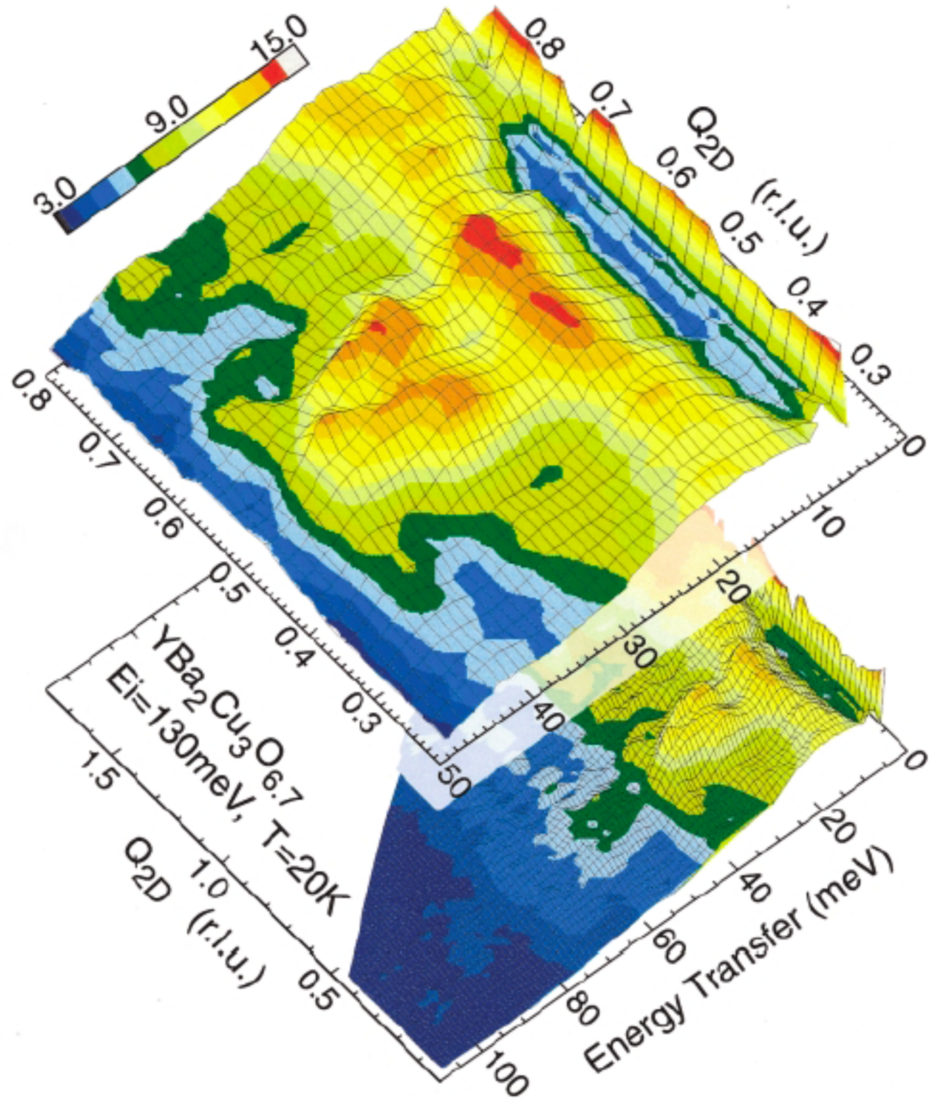
Rossat-Mignod/Bourges, Mook/Dai, Keimer/Fong

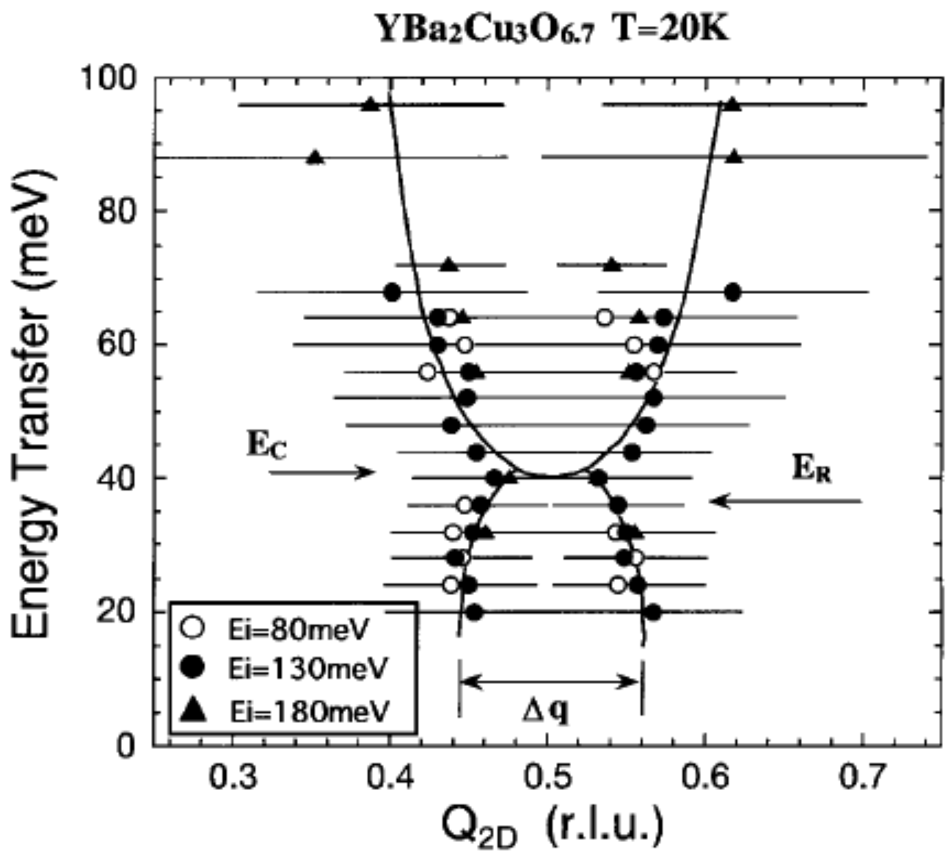


Dai *et al*, Nature (1999)

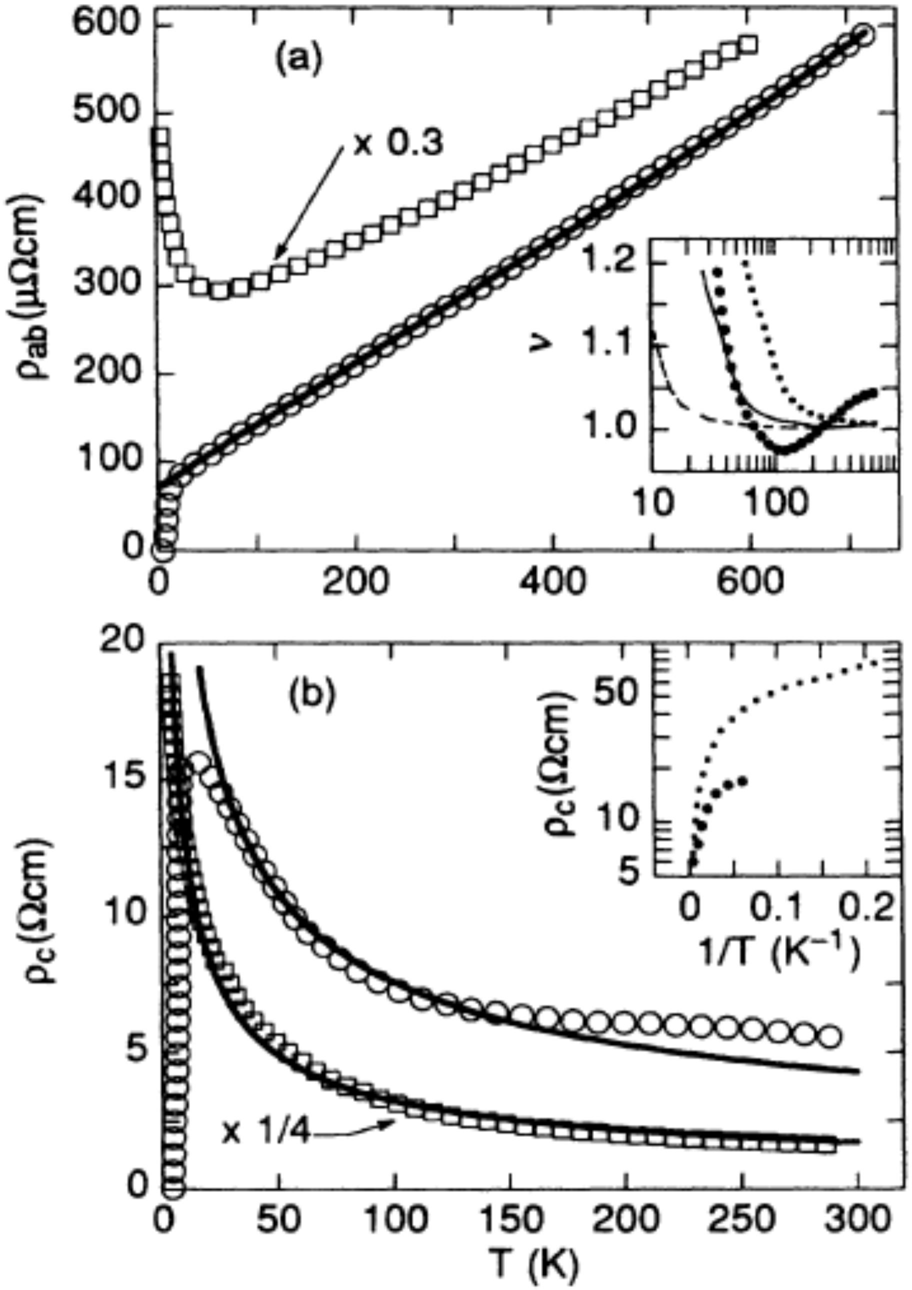
Dispersion of magnetic excitations has the form of an hourglass

Arai *et al*, PRL (1999)





The "strange metal" phase exhibits linear T resistivity



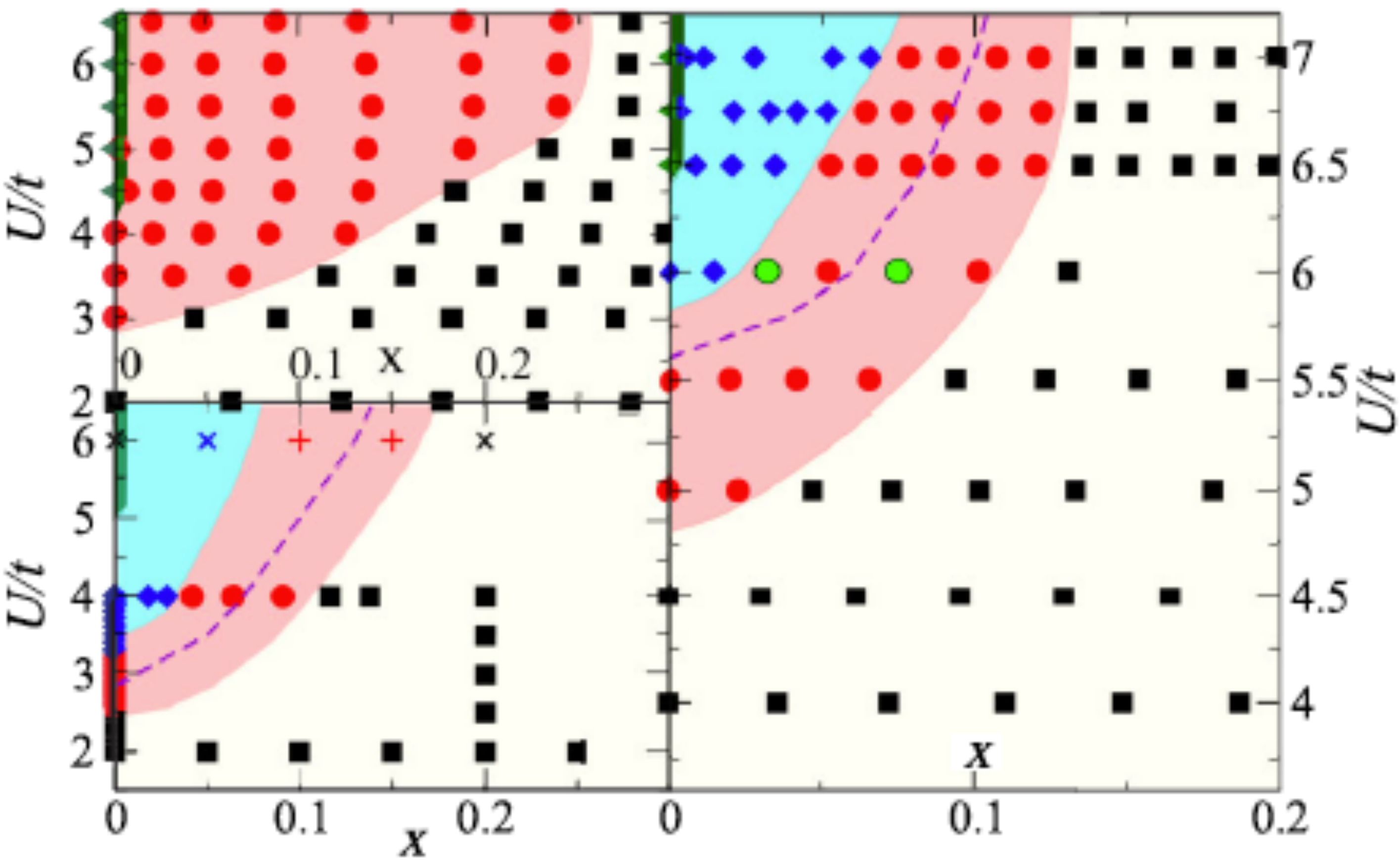
Martin *et al*
PRB (1990)

Insights from cluster many-body theories for the Hubbard model

PRL 110, 216405 (2013) PHYSICAL REVIEW LETTERS week ending 24 MAY 2013

Superconductivity and the Pseudogap in the Two-Dimensional Hubbard Model

Emanuel Gull,[1,2] Olivier Parcollet,[3] and Andrew J. Millis[4]



evidence for d-wave superconductivity in the Hubbard model (no phonons, just onsite repulsion U)

Rules of B. Matthias for discovering new superconductors

1. high symmetry is best
2. peaks in density of states are good

- stay away from <u>oxygen</u>
- stay away from <u>magnetism</u>
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Scanned at the American Institute of Physics

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

Paradigm shift!

high Tc materials are/have many things that conventional superconductors are/have not:

- terrible metals
- strong magnetic correlations
- lots of oxygen
- two-dimensional / anisotropic
- role of phonons still unclear but they are likely not the sole cause of high Tc
- possibly no pairing glue needed (but this is under debate)