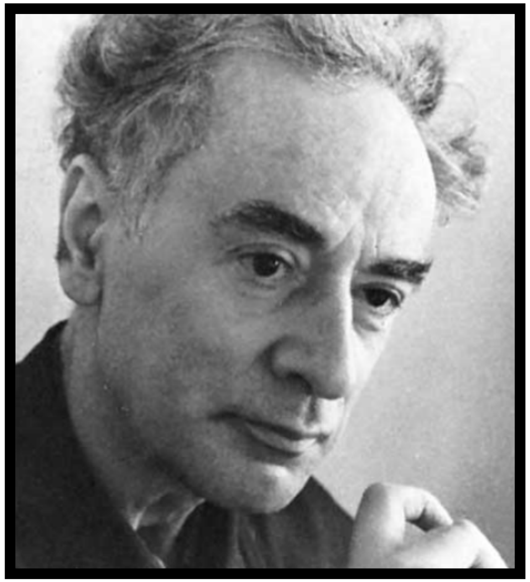
Landau Congress

100 years of Lev Landau

Memorial meeting

Moscow, June 19-20, 2008



Some Mysteries about High-Temperature Superconductors

Elihu Abrahams
Rutgers University

RUTGERS CENTER FOR MATERIALS THEORY

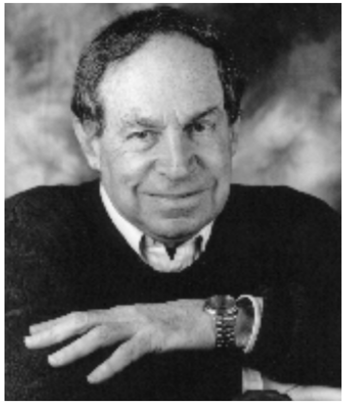
WHY I AM HERE

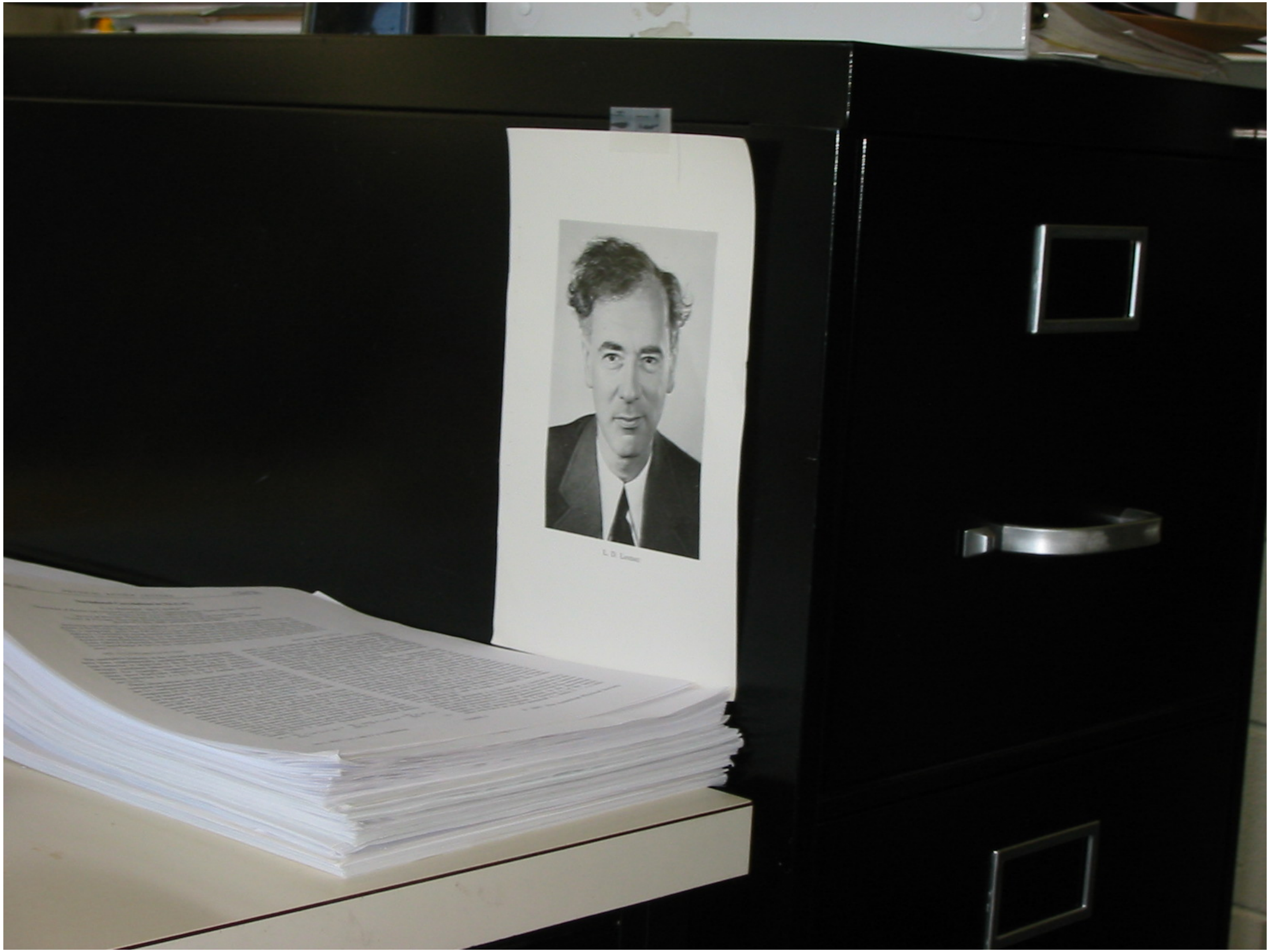
Elihu Abrahams
Rutgers University

10TH LOW TEMPERATURE PHYSICS CONFERENCE, MOSCOW 1966

US/USSR Workshops in Condensed Matter Theory 1968, 1970, 1974, 1978, 1988

D. PINES I.M. KHALATNIKOV





Back in 1986

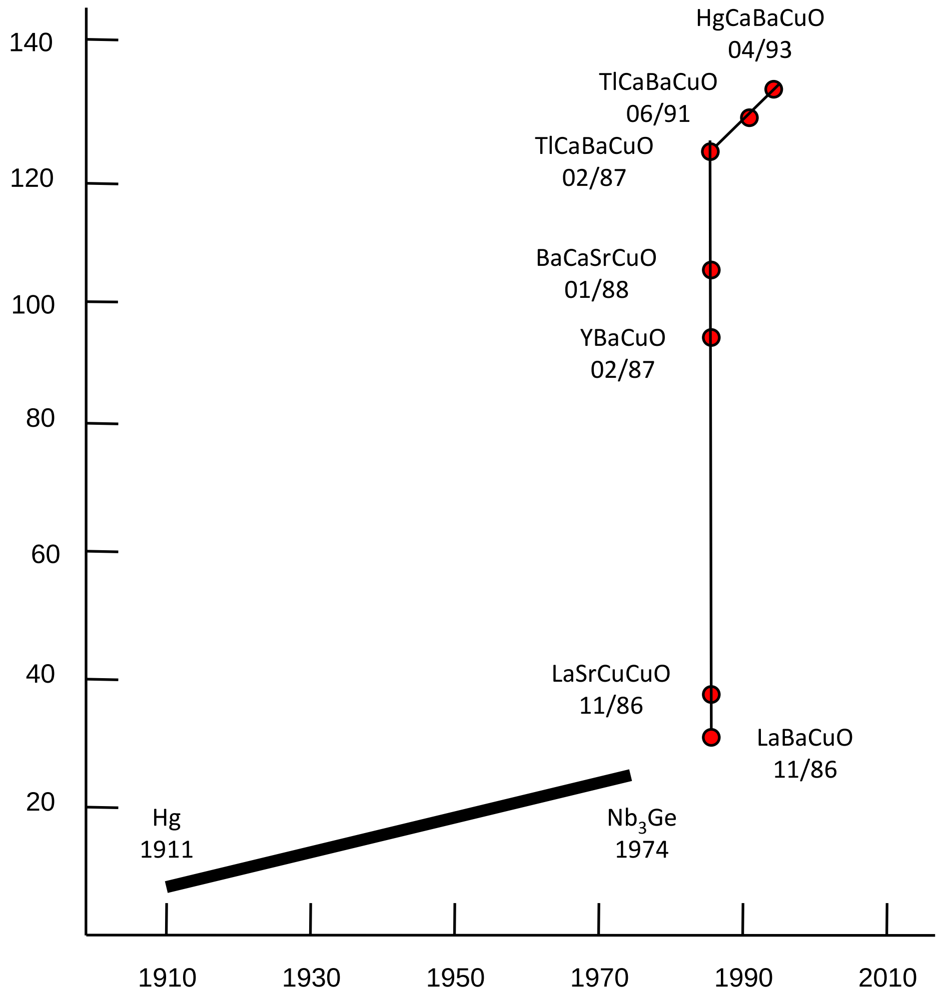
Z. Phys. B – Condensed Matter **64**, 189-193 (1986)

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

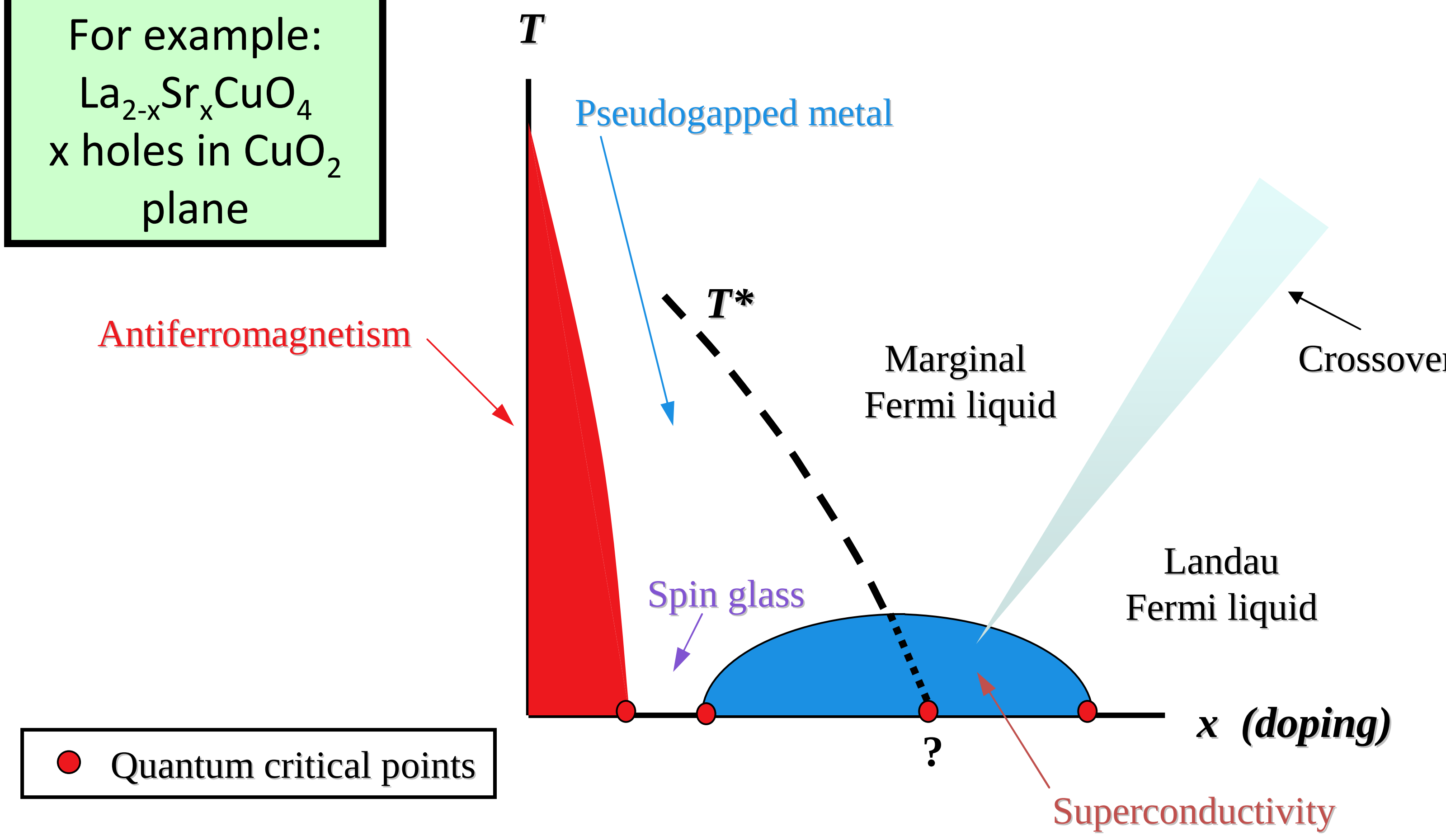
Received April 17, 1986

T_c vs t


140
120
100
80
60
40
20
HgCaBaCuO
04/93
TlCaBaCuO
06/91
TlCaBaCuO
02/87
BaCaSrCuO
01/88
YBaCuO
02/87
LaSrCuCuO
11/86
LaBaCuO
11/86
Hg
1911
Nb3Ge
1974
1910
1930
1950
1970
1990
2010

Schematic phase diagram of a high-T_c superconductor

For example:
$La_{2-x}Sr_xCuO_4$
x holes in CuO_2
plane



Competition: Almost everything is a mystery

Theories connected with high-T_c superconductivity

Spin fluctuations
Anisotropic phonons
Excitons
Charge fluctuations
Plasmons
Circulating currents
Bipolarons
Resonating valence bonds
Stripes
Interlayer tunneling/Kinetic
energy lowering
Spin bags
Spin liquids

Flux phases
BCS/BEC crossover
Marginal Fermi liquid
Van Hove singularities
Quantum criticality
Anyon superconductivity
Time reversal violation
Dynamical mean field theory
Slave bosons
Gauge theory
d density waves
Gossamer superconductivity
SO(5)

Reflections on Theory

Some important quotes:

"It's so hard that … ght'."

"It is dark law."

PESSIMISTS

"It could be that … son that the mechanism hasn't been found."

"We are close to a theoretical consensus on the magnetic origin ---"

"The supercondu… detail."

OPTIMISTS

"The cause of hig… y is no mystery" - and - "If it is acce… why no one wants to accept it."

"Eighty percent of the field is against anything – especially anything that might solve the problem."

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

The theory question

Has the "problem" of the theory of high-T_c been solved?

If so, what is it?

The model solution:

Theory of Superconductivity*

J. Bardeen, L.N. Cooper,† and J.R. Schrieffer‡
Department of Physics, University of Illinois, Urbana, Illinois
(Dated: July 8, 1957)

A theory of superconductivity is presented .... The ground state of a superconductor ... is lower in energy than the normal state by an amount proportional to an average $(\hbar\omega)^2$, consistent with the isotope effect. .... The theory yields a second order phase transition and Meissner effect in the form suggested by Pippard. Calculated values of specific heats and penetration depths and their temperature variation are in good agreement with experiment. There is an energy gap for individual-partiicle excitations which decreases from about $3.5kT_c$ at $T = 0°$K to zero at T_c. Tables of matrix elements of single-particle operators between the excited-satte superconducting wave functions, useful for perturbation expansions and calculations of transition probabilities, are given.

I. INTRODUCTION

II. THE GROUND STATE

A. Ground-State Energy

B. Energy gap at $T = 0°$K

III. EXCITED STATES

A. Minimization of the Free Energy

B. Critical Field and Specific Heat

IV. CALCULATION OF MATRIX ELEMENTS

V. ELECTRODYNAMIC PROPERTIES

A. The Meissner Effect

B. Current Density

C. Penetration Depths

VI. CONCLUSION

APPENDIX A. CORRECTIONS TO GROUND STATE ENERGY
APPENDIX B. CHANGE IN ZERO-POINT ENERGY OF LATTICE VIBRATIONS
APPENDIX C. EVALUATION OF THE KERNEL IN THE PIPPARD INTEGRAL
APPENDIX D. CORRELATION OF ELECTRONS OF OPPOSITE SPIN

Comprehensive BCS Theory!

- Ultrasonic attenuation
- NMR $1/T_1$
- Thermal conductivity
- Microwave conductivity
- Infrared absorption

Теория сверхпроводимости в купратах

XXXX, YYYY и ZZZZ
Институт сильно взаимодействующей физики Рога и копыта, где-то

Абстракт: Предлагается теория сверхпроводимости в купратах ...

I. EFFECTIVE HAMILTONIANS

A. Ground State

B. Normal State

II. THE PHASE DIAGRAM

A. Undoped State

III. NORMAL STATE PROPERTIES

A. Transport

B. Thermodynamics

IV. UNDERDOPED REGION

A. Origin and behavior of the Pseudogap

B. Transport and Thermodynamics

C. Nernst Effect

D. Evolution of the Fermi Surface

E. Magnetic Oscillations

V. SUPERCONDUCTING STATE

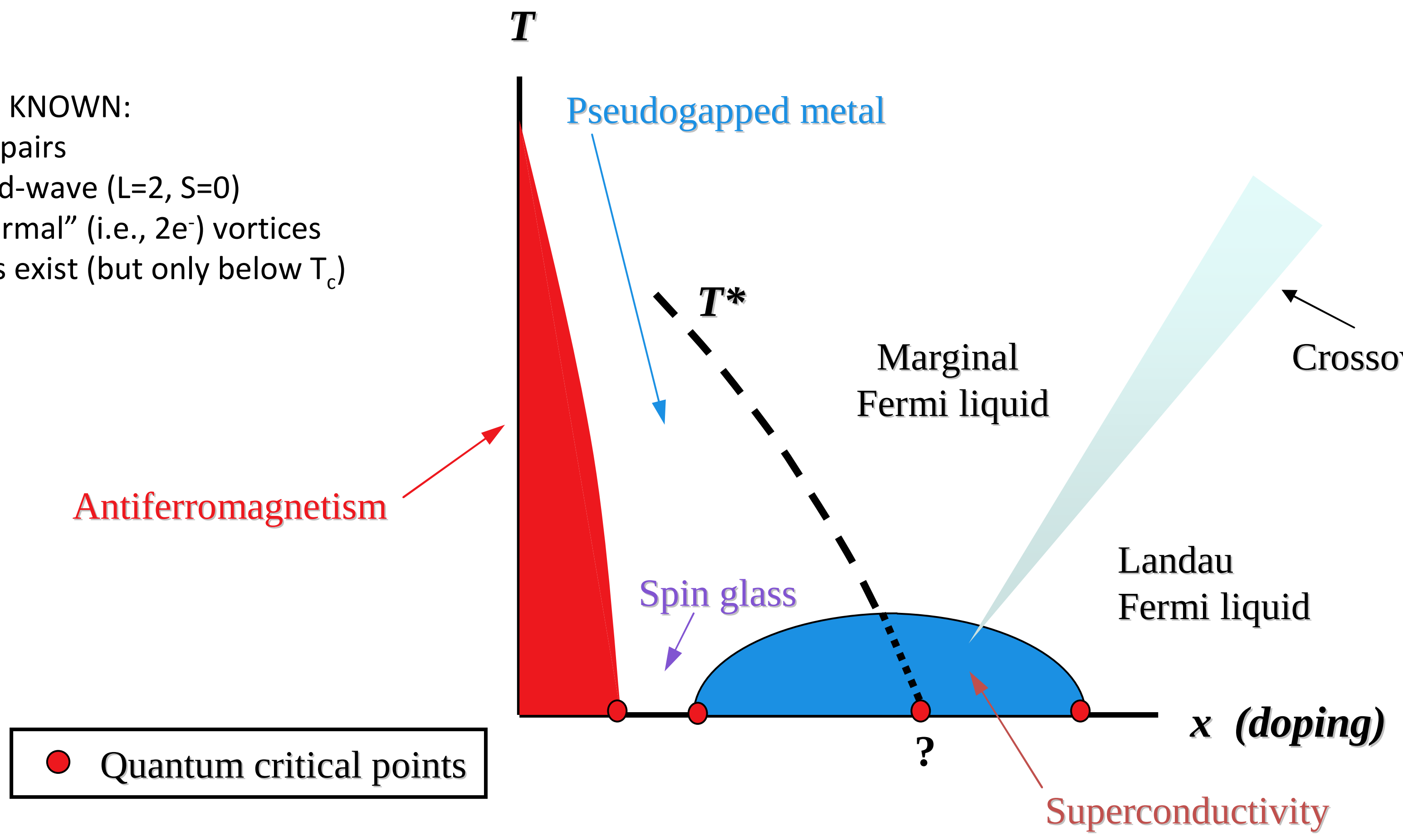
A. Energy gap and Tunneling

B. Transport and Thermodynamics

Comprehensive high-T_c theory

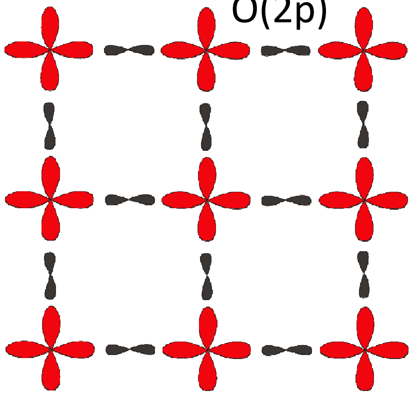
Schematic phase diagram of a high-T_c superconductor

WHAT ELSE IS KNOWN:
There are $2e^-$ pairs
The pairs are d-wave (L=2, S=0)
There are “normal” (i.e., $2e^-$) vortices
Quasiparticles exist (but only below T_c)



All these behaviors need to be explained!

Effective hamiltonians



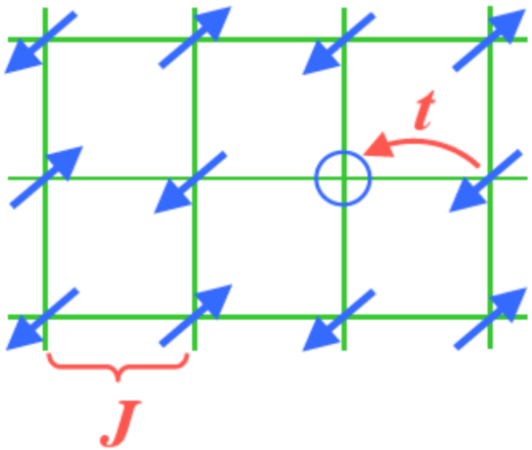
The maximal minimal model: 3-band model

$$\begin{aligned}\mathcal{H} &= \sum \epsilon_d n_d + \sum \epsilon_p n_p \\ &+ t \sum (c^+_{d\sigma} c_{p\sigma} + h.c.) + t' \sum (c^+_{p\sigma} c_{p\sigma} + h.c.) \\ &+ U_d \sum n_{d\uparrow} n_{d\downarrow} + V \sum n_d n_p\end{aligned}$$

The minimal minimal model: Hubbard model

$$\mathcal{H} = -t \sum_{\langle ij \rangle \sigma} (c^+_{i\sigma} c_{j\sigma} + h.c.) + U \sum_i n_{i\uparrow} n_{i\downarrow}$$

Zhang Rice

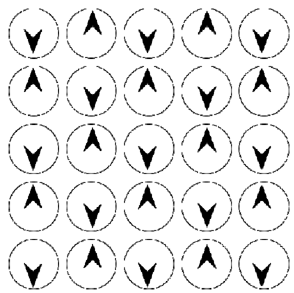


The optimistic minimal model: t-J model

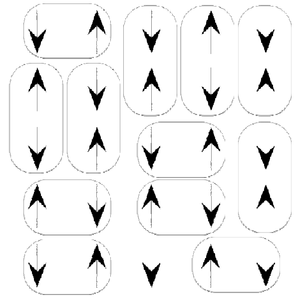
$$\mathcal{H} = -t\, P \sum_{\langle ij \rangle \sigma} (c^+_{i\sigma} c_{j\sigma} + h.c.) P + J \sum_{\langle ij \rangle} S_i \cdot S_j$$

RVB phase diagram

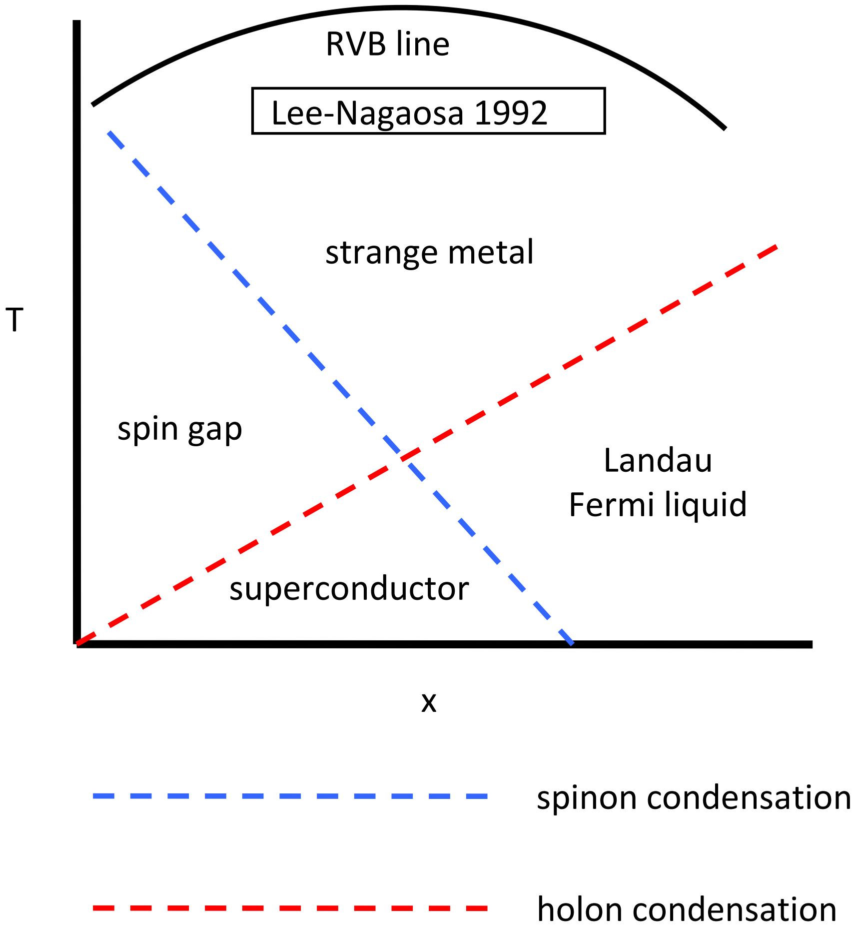
(the t-J model is enough)

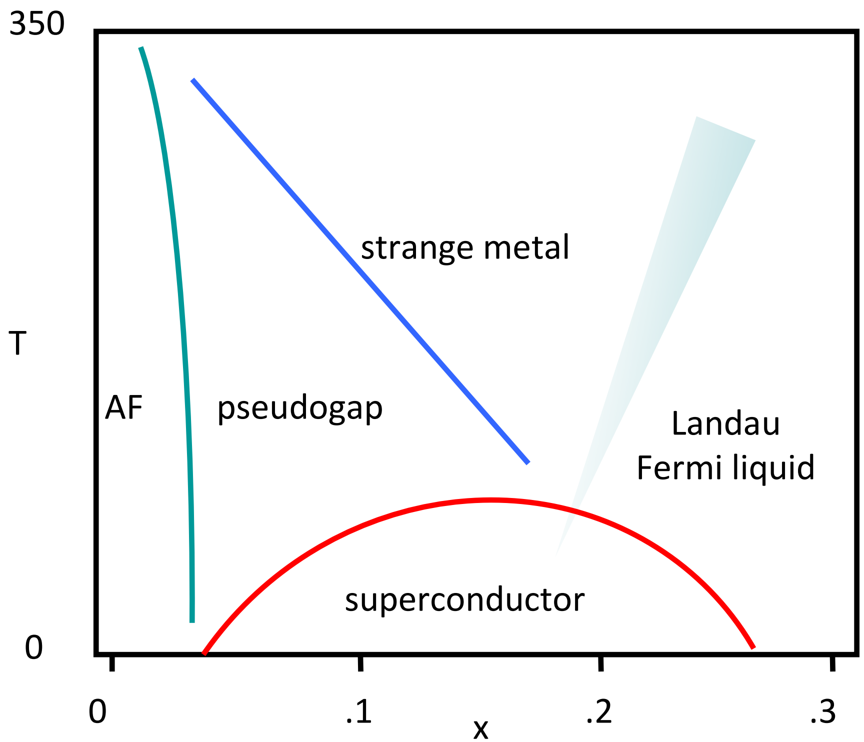


Neel state



RVB spin singlet liquid

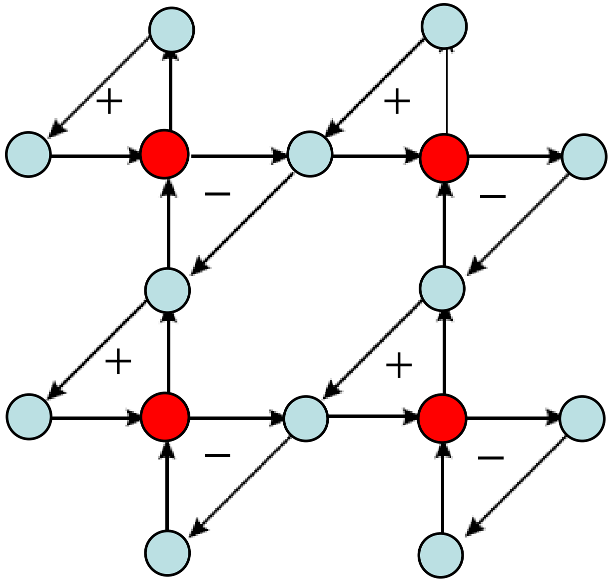




Circulating currents

T breaking, translation symmetry preserved, or not?

(You need the 3-band model!)



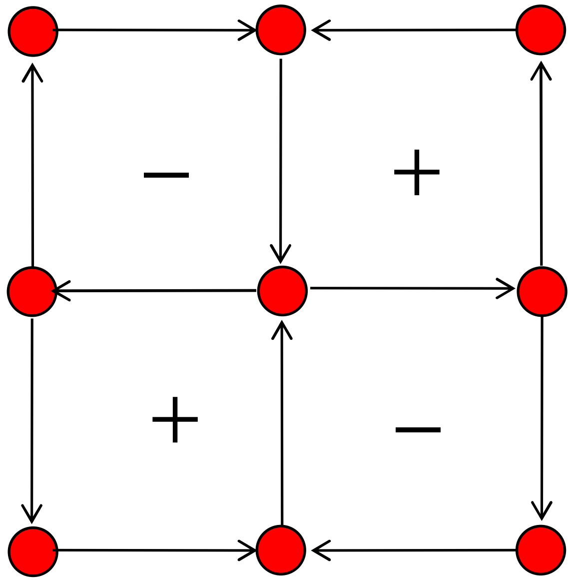
Simon and Varma 2002

t (Cu-O)
t' (O-O)
U_{Cu}(mean field)

Cu

O

(Hubbard model works!)

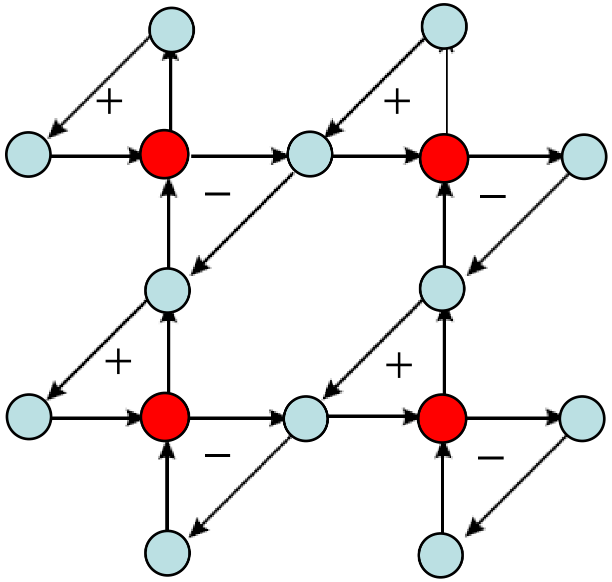


Chakravarty, et al 2001
"d-density wave"
Unit cell is doubled

Circulating currents

T breaking, translation symmetry preserved

(You need the 3-band model!)



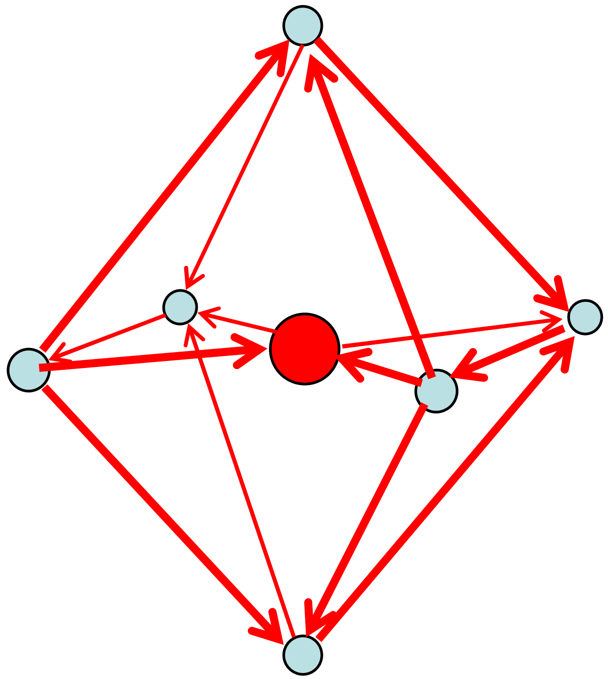
Simon and Varma 2002

t (Cu-O)
t' (O-O)
U_{Cu}(mean field)

Cu

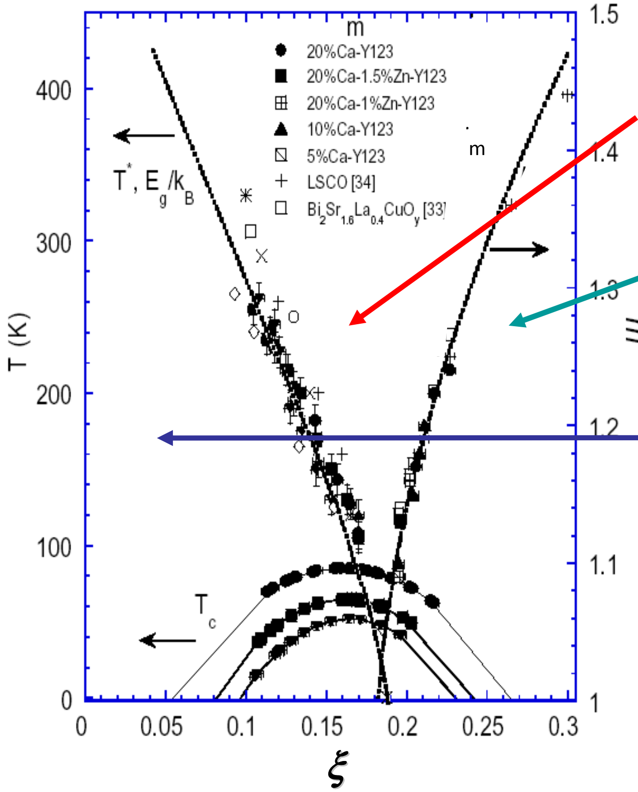
O

(And: you need apical oxygens!)



C. Weber et al 2008
Li, Bourges et al 2008

Quantum critical point ?

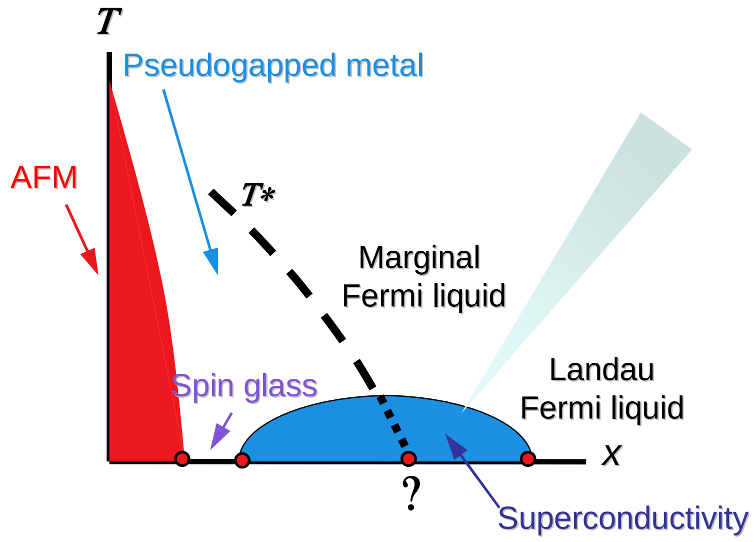


The marginal Fermi liquid region, ρ □ T

Overdoped region, $\rho = \rho_0 + \alpha T^\mu$

Pseudogap region, E_γ from specific heat, T* from various

Naqib et al 2002



Quantum critical points

Marginal Fermi liquid phenomenology: Varma, Littlewood, Schmitt-Rink, Abrahams, Ruckenstein 1989

Raman scattering

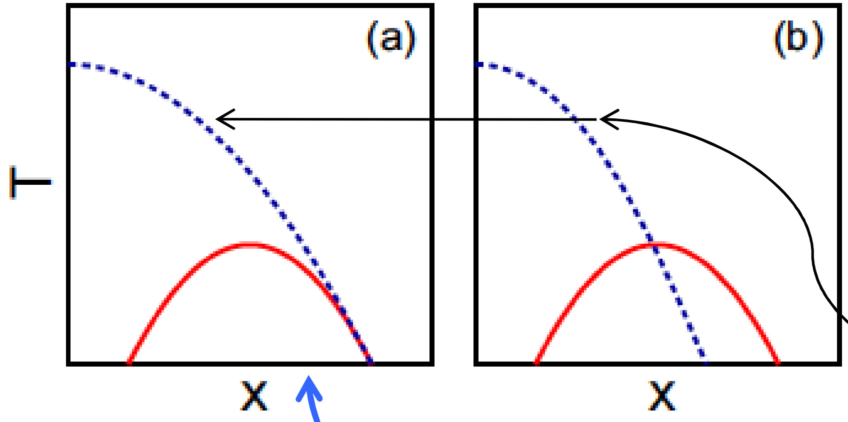
Spectral function (ARPES)

Linear-T resistivity

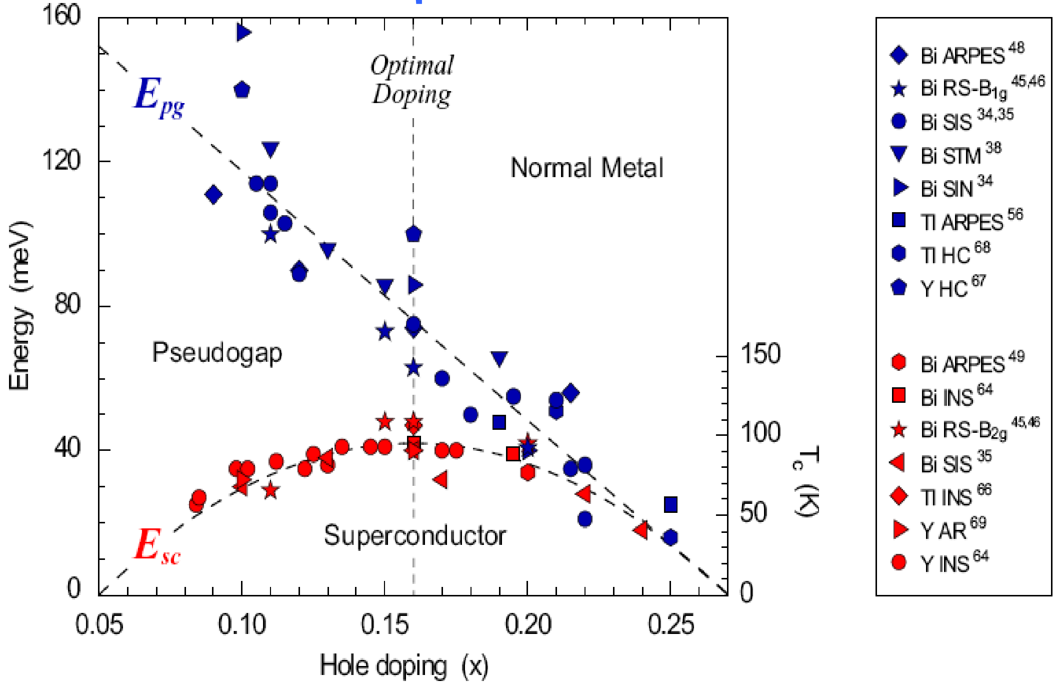
Assumes ω/T scaling of correlator.

However

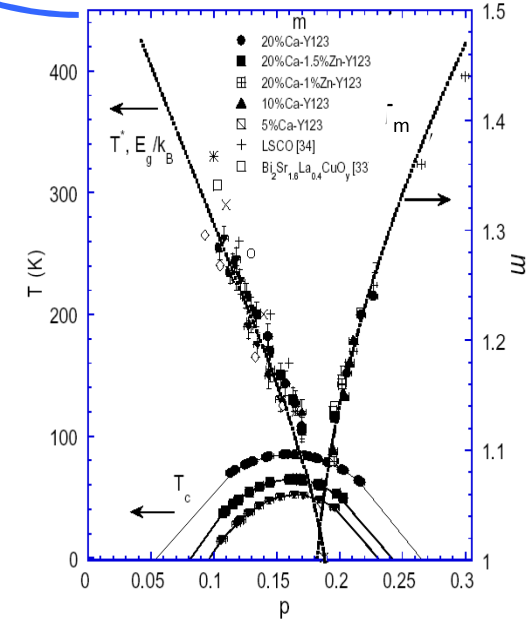
(do not be blinded by guides to the eye)



Is this a phase transition?
Circulating currents?
d-density wave?, SDW?



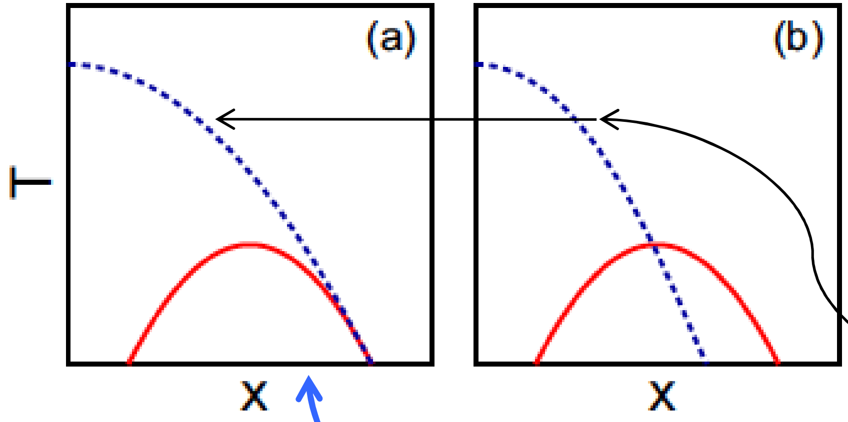
Hüfner et al 2007



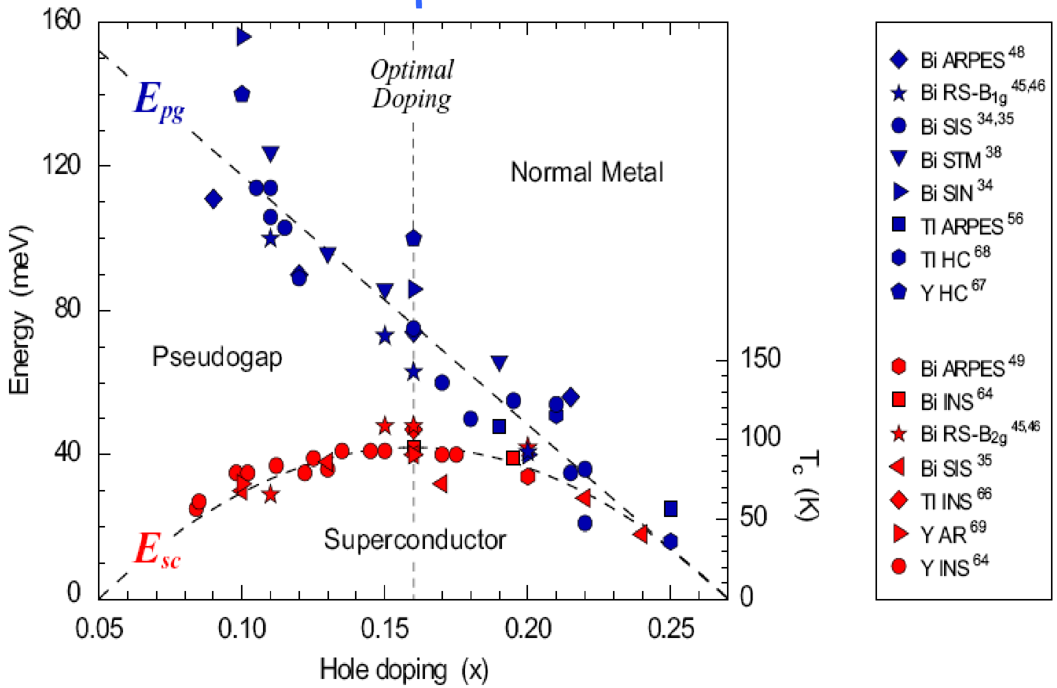
Naqib et al 2002

However

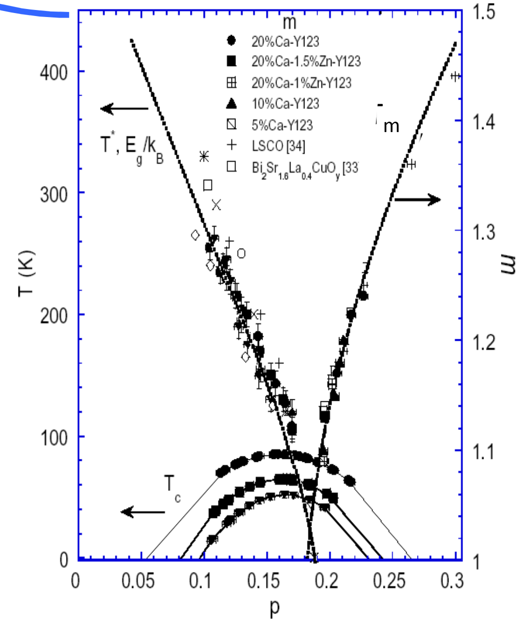
(do not be blinded by guides to the eye)



Is this the onset of pairing,
without long range order.
Phase fluctuations?

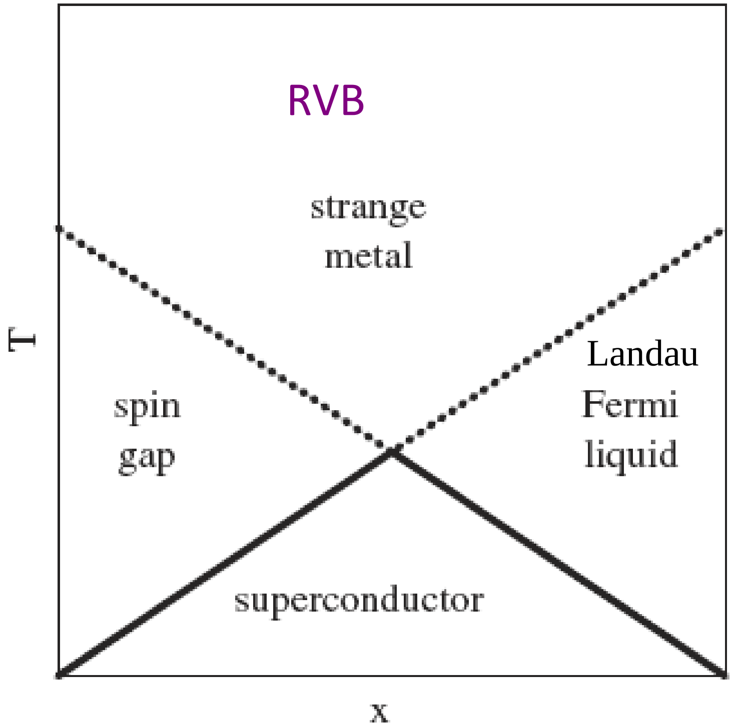


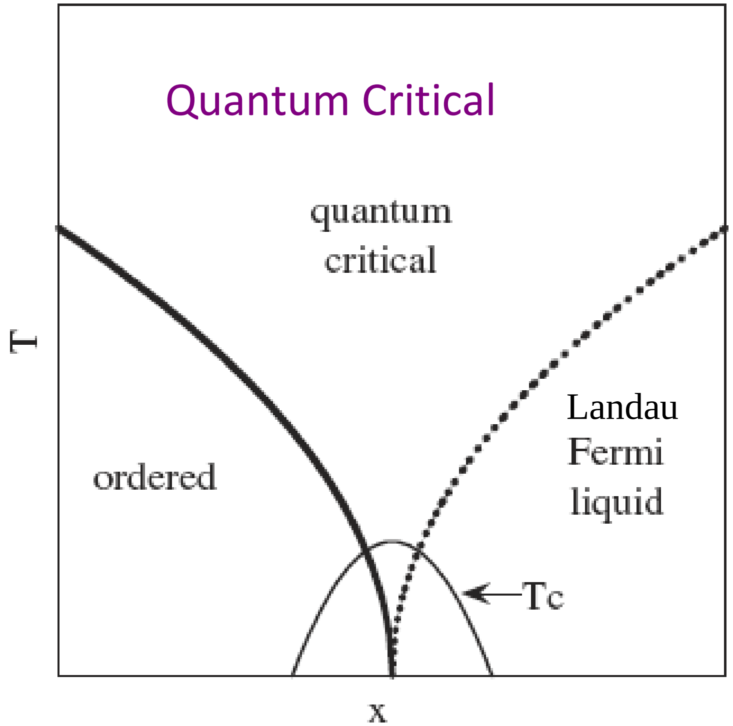
Hüfner et al 2007

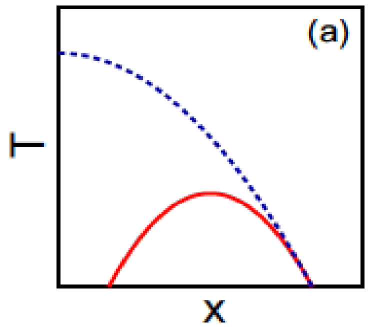


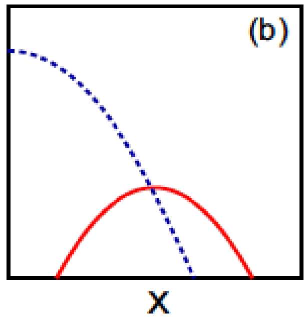
Naqib et al 2002

Two Theories of the Phase Diagram







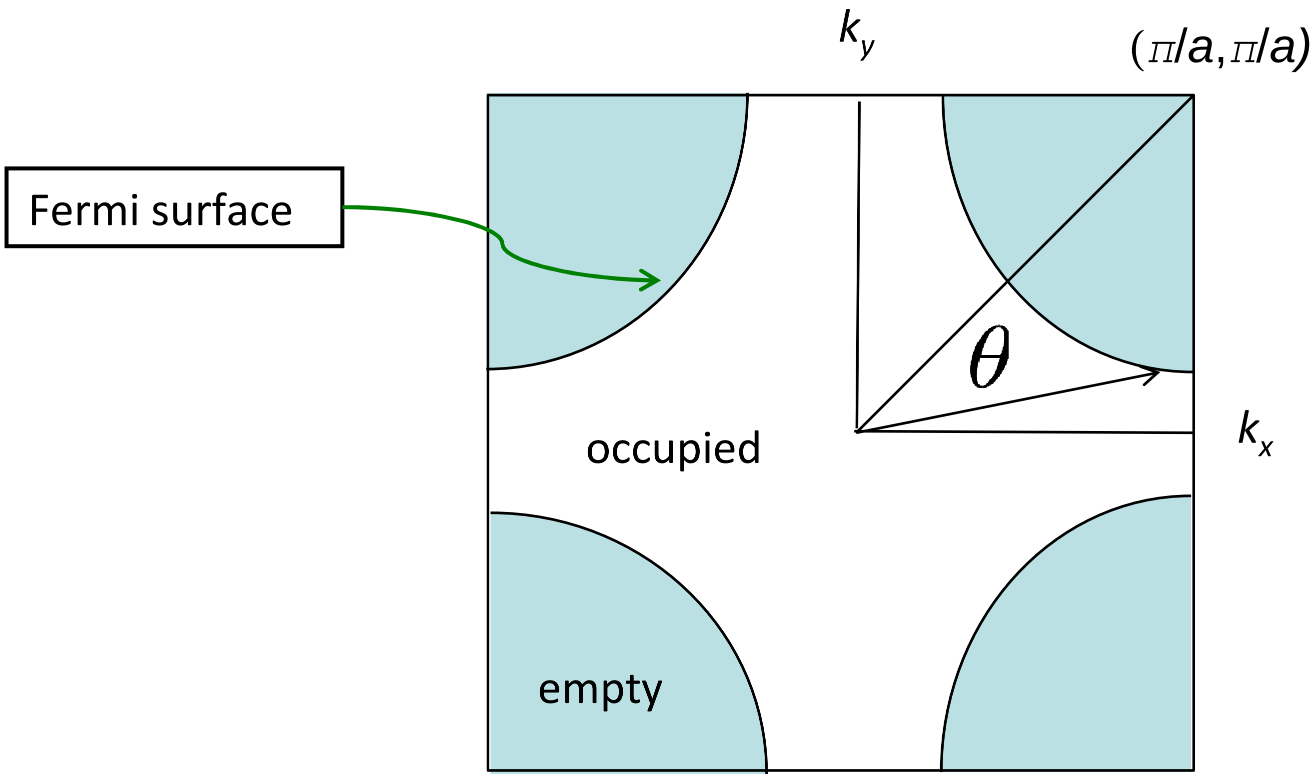


Some mysteries of the pseudogap:

1. What causes it?- preformed pairs, sdw, ddw, circulating currents, stripes, cdw, resonating valence bonds?
2. Does the pseudogap phase have an order parameter?
   - Is T* a phase transition line to a competing phase?
3. Do the pseudogap and the superconducting gap coexist below T_c? One gap or two?
4. What is the nature of electronic states below T*?
5. What is the correct position of the T* line?
   - Is there a hidden quantum critical point?
6. What is the origin of “Fermi arcs?”

Fermi surface of optimally-doped cuprate

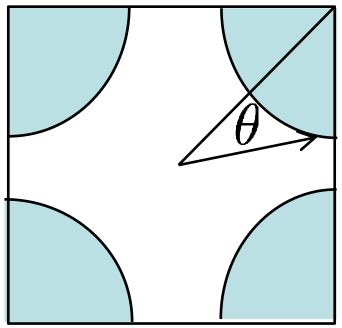
Angle-Resolved Photoemission Spectroscopy (ARPES)



Brillouin zone

Marginal Fermi Liquid fits to ARPES

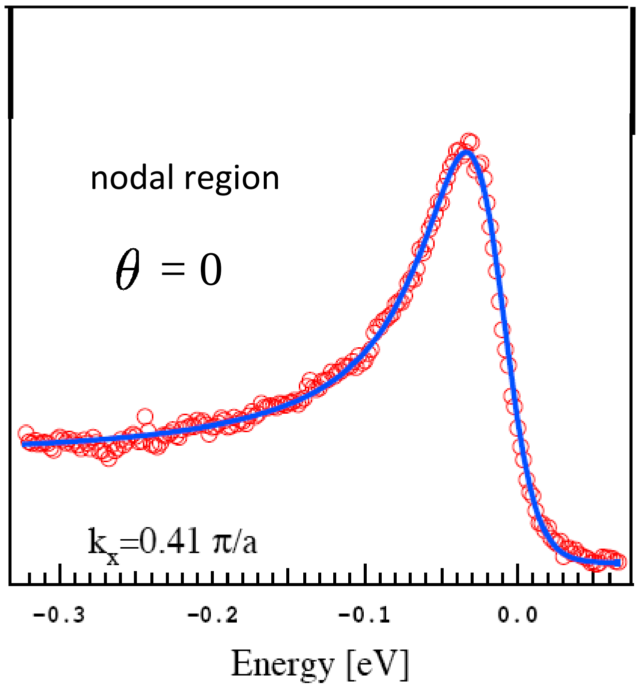
$$\mathcal{A}(\mathbf{k},\omega) = -\frac{1}{\pi}\frac{\Sigma_2(\mathbf{k},\omega)}{[\omega-\varepsilon_k-\Sigma_1(\mathbf{k},\omega)]^2+[\Sigma_2(\mathbf{k},\omega)]^2}$$

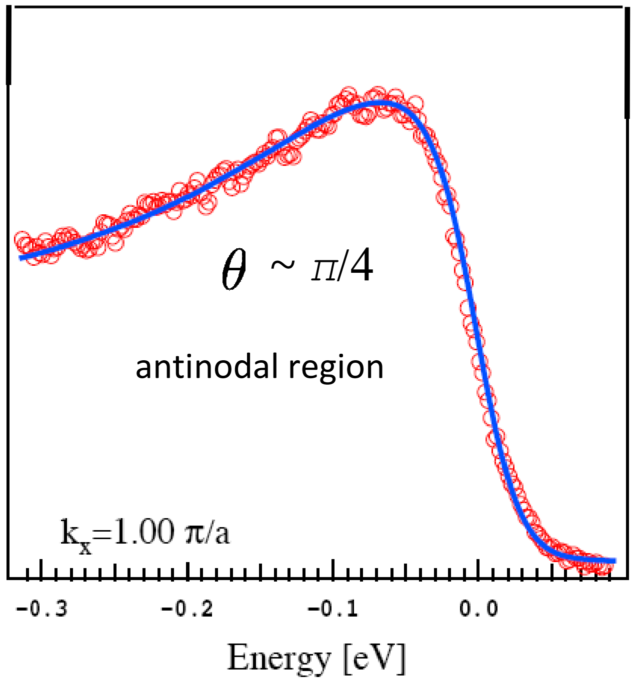


Kaminski et al 2005
MFL scenario gives

$$\Sigma_2(\omega) = a(\theta) + b\omega$$

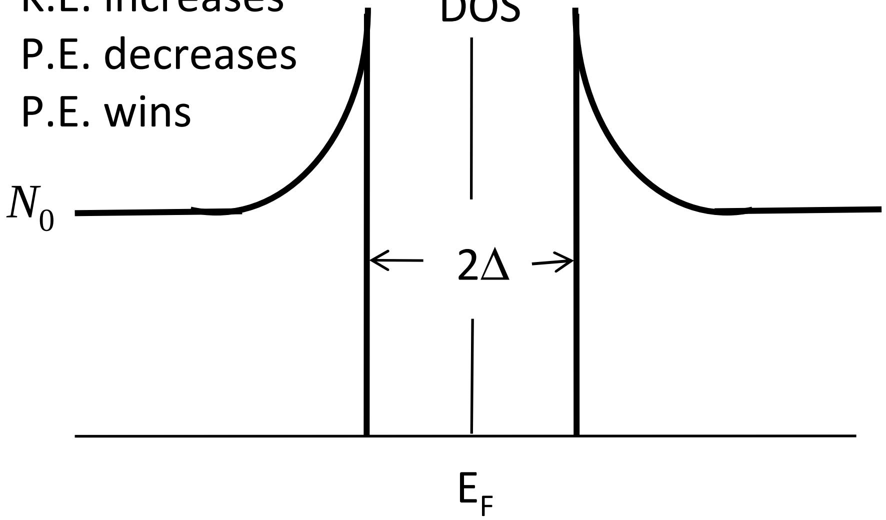
Where does this come from?





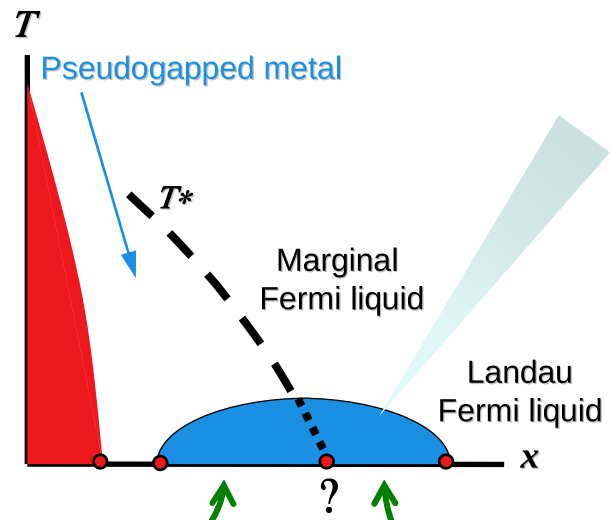
Condensation energy

BCS:
K.E. increases
P.E. decreases
P.E. wins



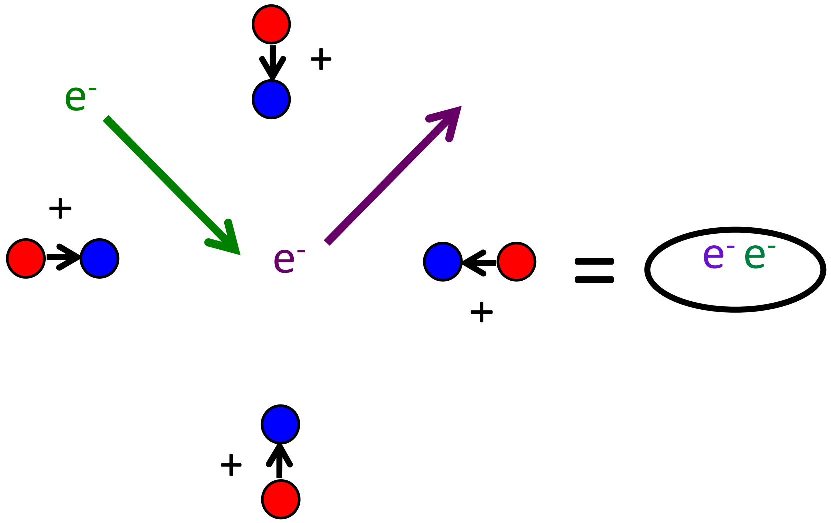
$\Delta = \omega_D \exp(-1/N_0 g)$

Large DOS (N_0) → large Δ



High T_c:
K.E. increases (overdoped)
K.E. decreases (underdoped)
who wins?

Everything (?) You Wanted to Know About Pair Formation
(The Tyranny of the "Glue")



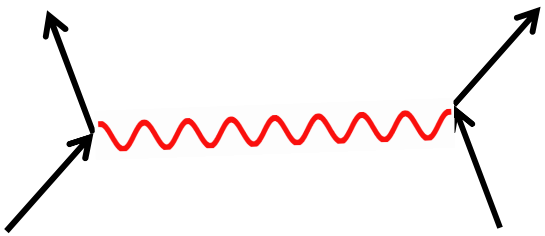
(the electron-phonon case)

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⁻

$$\mathcal{H} = K.E. + g \int d\mathbf{r}\, \psi^{+}_{\uparrow}(\mathbf{r})\psi^{+}_{\downarrow}(\mathbf{r})\psi_{\downarrow}(\mathbf{r})\psi_{\uparrow}(\mathbf{r})$$

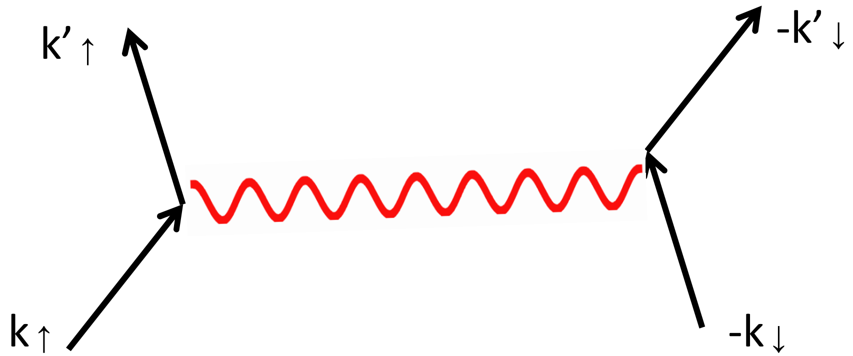
Interaction is local in space
(s-wave singlet pairs, L=0, S=0)
but retarded in time

or, Eliashberg's theory: phonon or spin fluctuation (L=2, S=0)



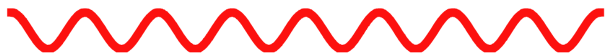
Large DOS (N_0) $\rightarrow$ large Δ

Eliashberg theory for retarded interaction



-Underlying well-defined normal state,

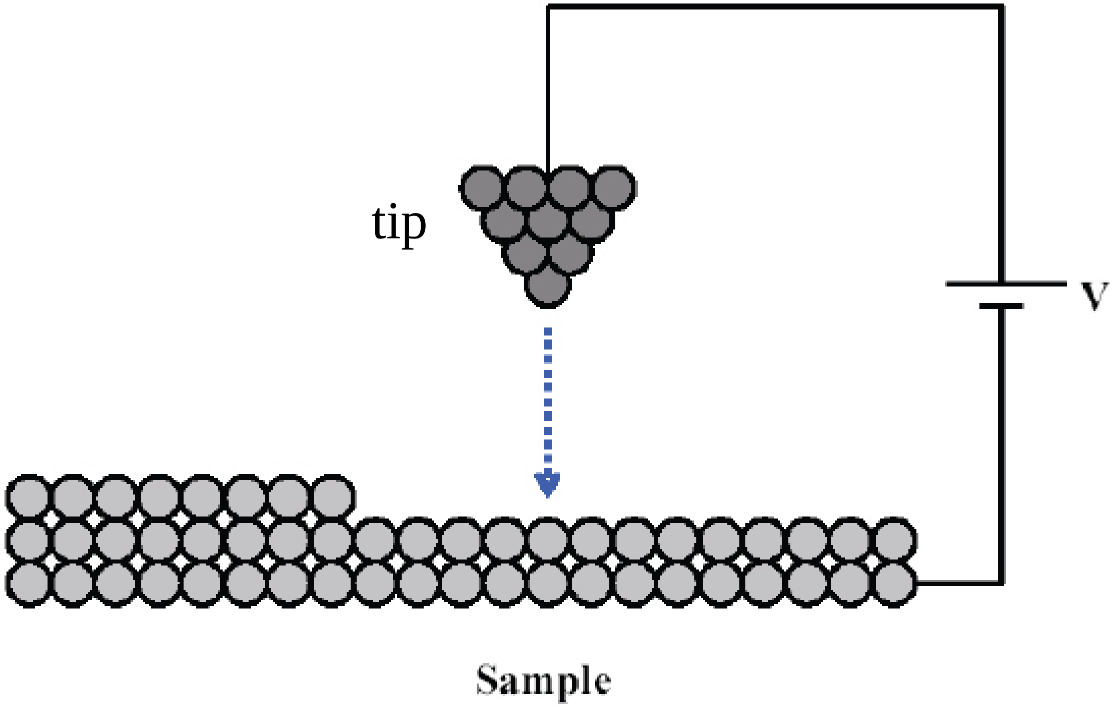
e.g. Landau Fermi liquid quasiparticles

and “pairing boson”. 

-For cuprates, it would be antiferromagnetic spin fluctuation → d-wave pairing.

-Large density of states → large energy gap

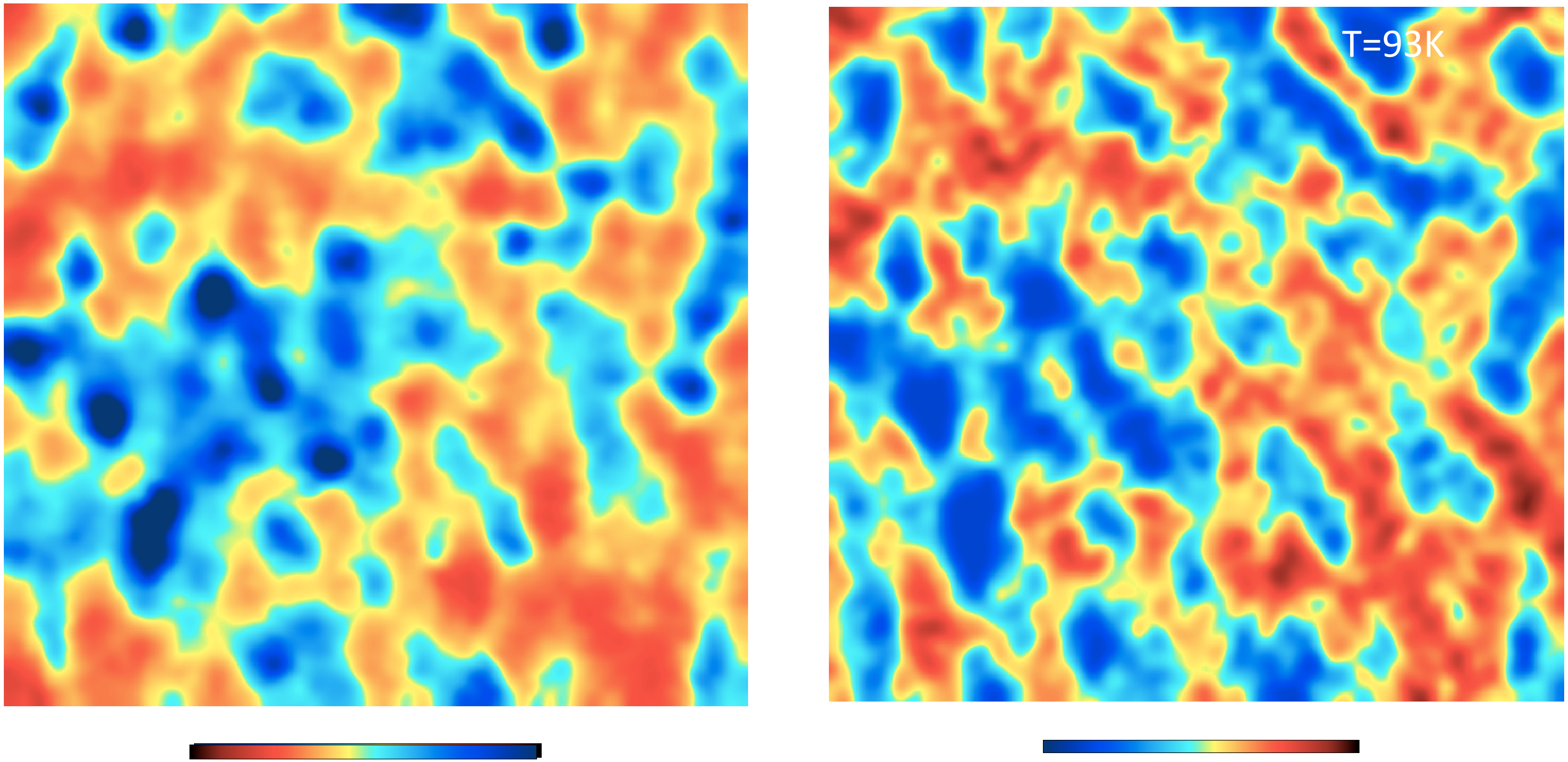
Scanning tunneling microscope
STM experiment



Measures electronic structure at surface with atomic resolution.

Normal state:
tunneling conductance proportional to DOS

Supercondicting state:
determine energy gap.


T=93K

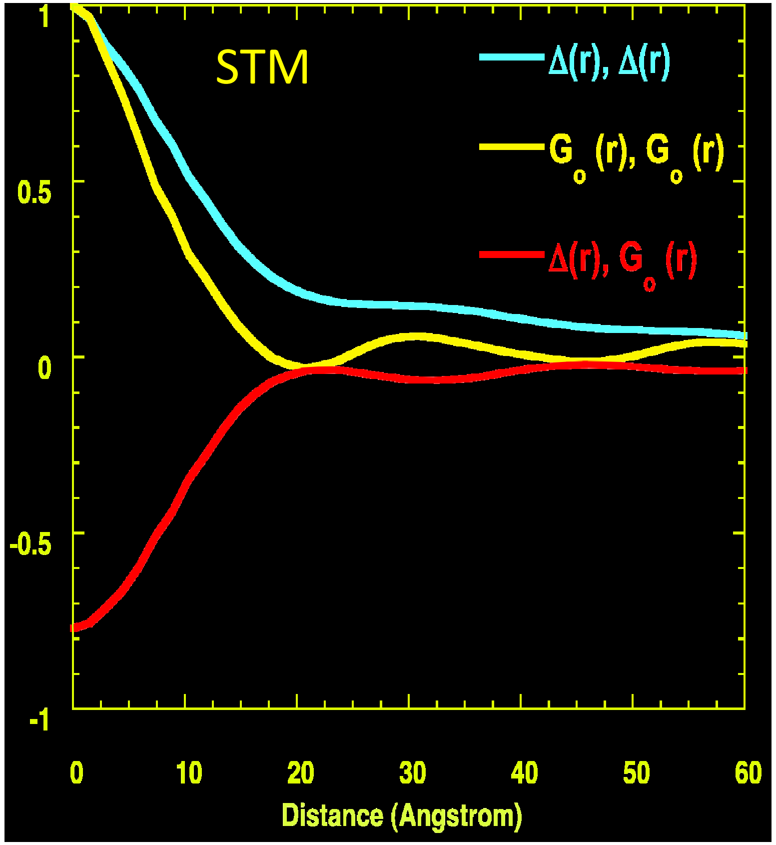
A possible resolution

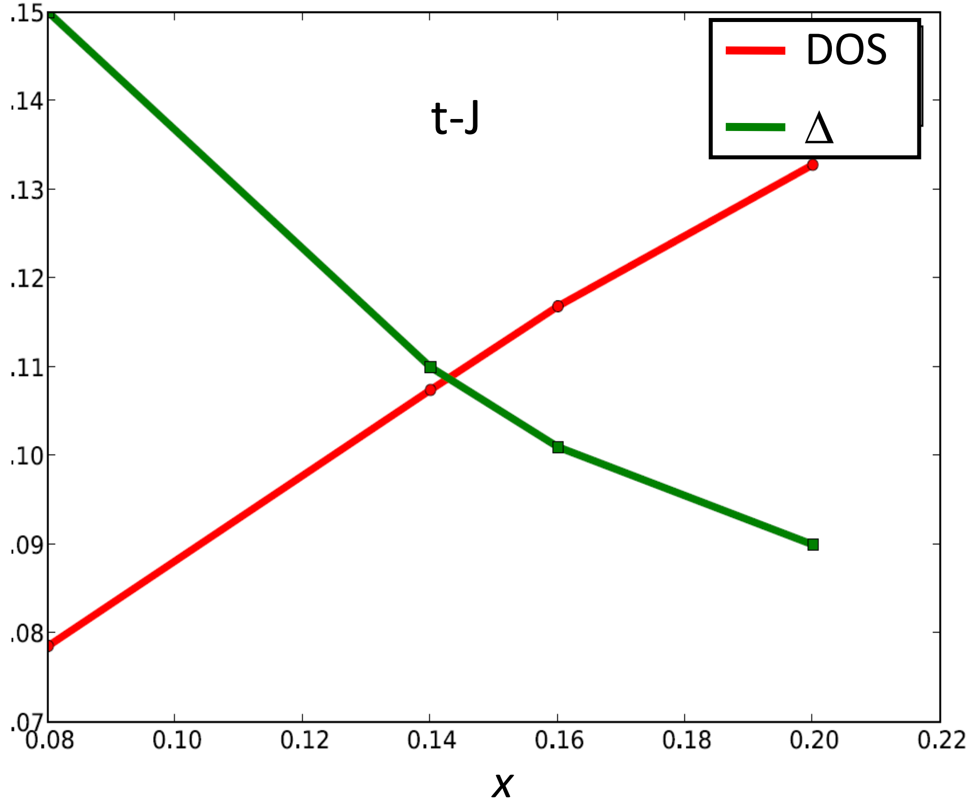
High-Tc cuprate superconductors are strongly-correlated superconductors.
Another example: the t-J model of strong correlation.

$$\mathcal{H} = -t\,P \sum_{\langle ij \rangle \sigma} (c_{i\sigma}^{+} c_{j\sigma} + h.c.) P + J \sum_{\langle ij \rangle} S_i \cdot S_j$$

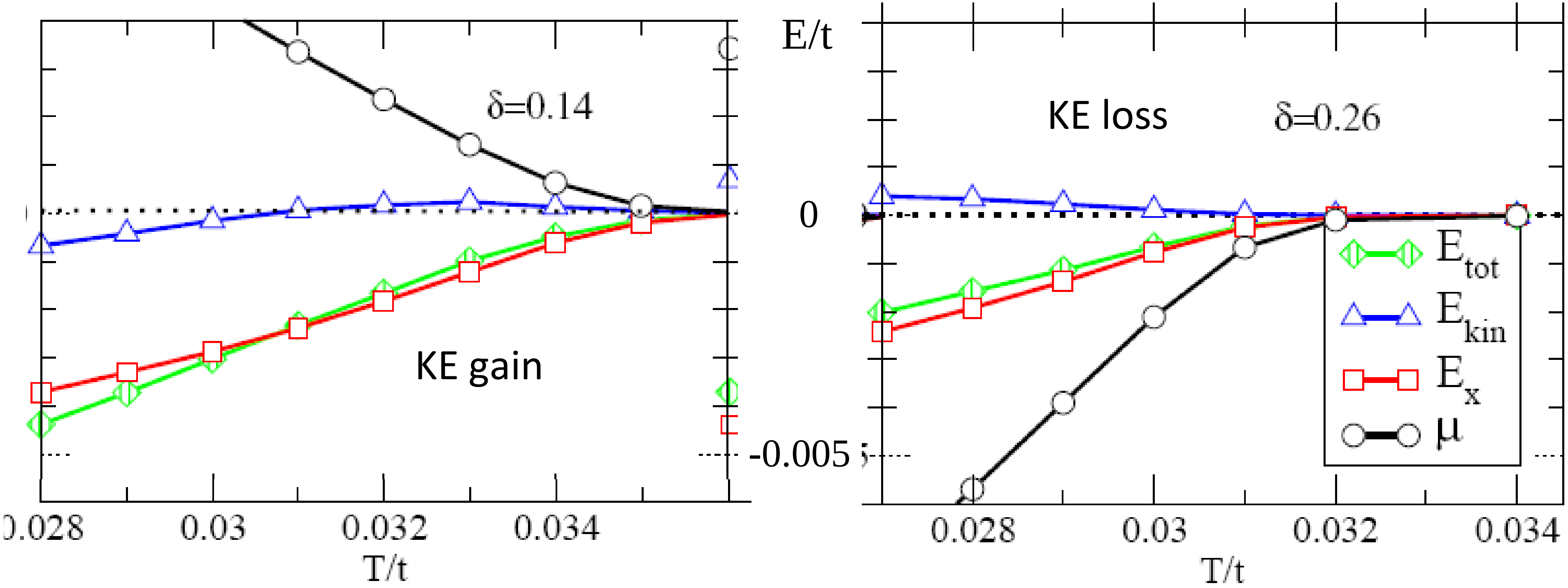
- Gives d-wave superconductivity, pseudogap, arcs, DOS-gap anticorrelation.
- There is no clear separation of kinetic and potential energies.
- Captures effects of proximity to Mott insulator at zero doping.

Anticorrelation of normal state DOS and superconducting gap





Energy difference between the normal and superconducting state of the t-J model. (K. Haule 2006)



Condensation energy is exchange energy

Superconductivity without a coherent normal state

A new paradigm for superconductivity?