Cuprates - An Overview

Michael Norman

Materials Science Division
Argonne National Laboratory

Norman, Science (2011)
Norman, Handbook of Magnetism (2007)
Norman, Pines & Kallin, Adv. Phys. (2005)
Norman & Pepin, Rep. Prog. Phys. (2003)

Cali – June 30, 2011

So, what does it mean to say we have “solved” the problem of high temperature superconductivity

???

Example - ^{3}He

Ferromagnetic spin fluctuations suppress s-wave superconductivity
(Berk & Schrieffer - PRL 1966)

Ferromagnetic spin fluctuations promote p-wave superconductivity
(Fay & Layzer - PRL 1968) - predicted such in Pd and ^{3}He

p-wave superfluidity discovered in ^{3}He
(Osheroff, Richardson, Lee - PRL 1972)

Spin fluctuation theory can explain the stabilization of the A phase
(Anderson & Brinkman - PRL 1973)

Direct mapping of normal state Landau parameters to pair potential
(Patton & Zaringhalam; Serene, Rainer, & Sauls, …)

Everything and the kitchen sink contributes - charge, spin, current,
(Leggett - RMP 1976)

Microscopic models for ^{3}He

1. van der Waals - Emery & Sessler
2. spin fluctuations - Layzer & Fay, Anderson & Brinkman, Levin & Valls, …
3. polarization potential - Bedell & Pines
4. nearly localized - Vollhardt & Wolfle

Where does the energy savings come from?

For α=1/2, ΔE is equivalent to the change in ion kinetic energy

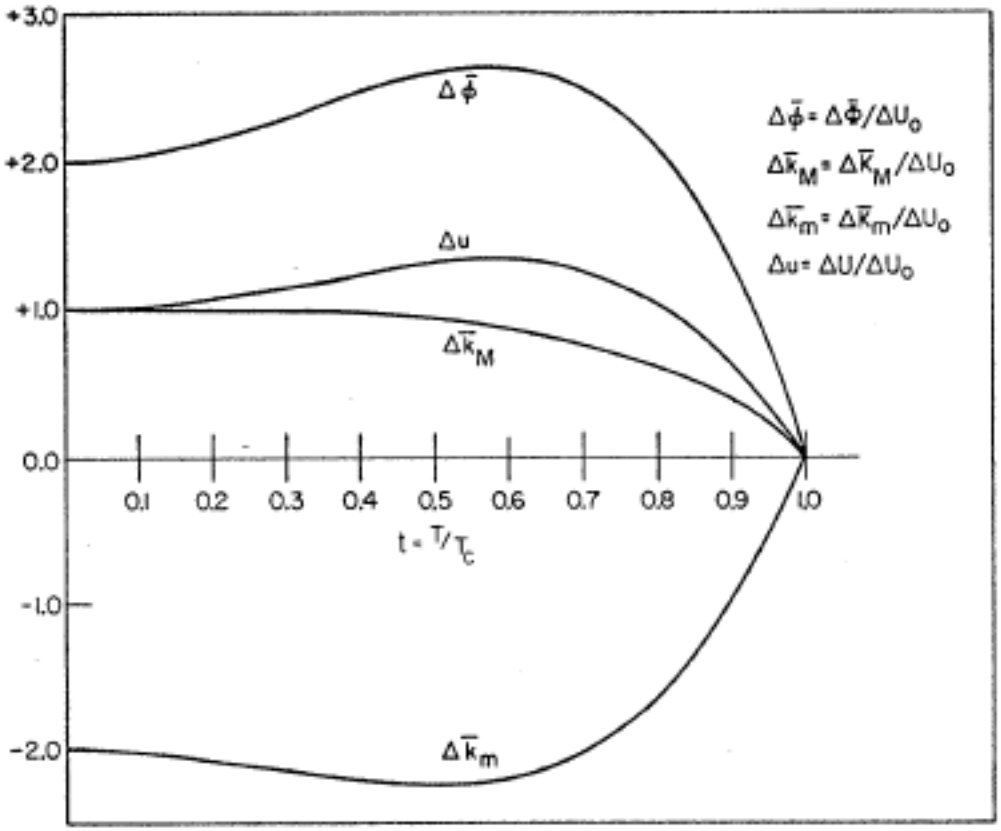


FIG. 1. The dependence of $\Delta\bar{k}_m$, $\Delta\bar{k}_M$, and $\Delta\bar{\phi}$ on the reduced temperature $t = T/T_c$.

Chester, Phys Rev (1956)

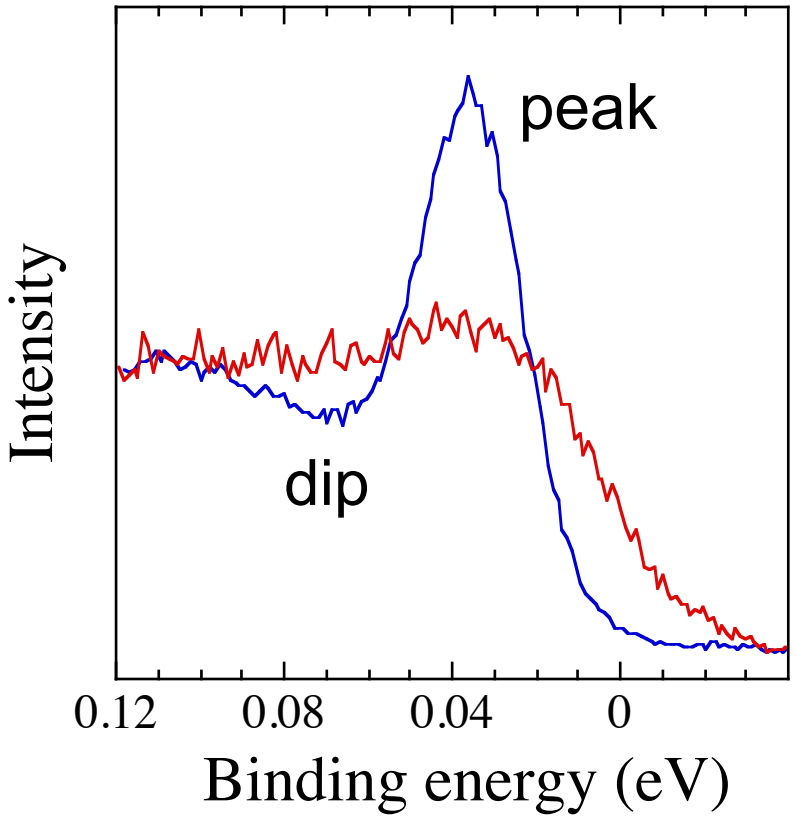
Relation of ΔE to the Spectral Function

$$U_N - U_S = \sum_{\mathbf{k}} \int_{-\infty}^{+\infty} d\omega (\omega + \epsilon_k) f(\omega) [A_N(\mathbf{k},\omega) - A_S(\mathbf{k},\omega)]$$

$$U_N - U_S = \sum_{\mathbf{k}} \epsilon_k [n_N(\mathbf{k}) - n_S(\mathbf{k})] + \int_{-\infty}^{+\infty} d\omega\, \omega f(\omega) [N_N(\omega) - N_S(\omega)]$$

Norman *et al.*, PRB (2000)

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



Incoherent normal state

Coherent superconductor

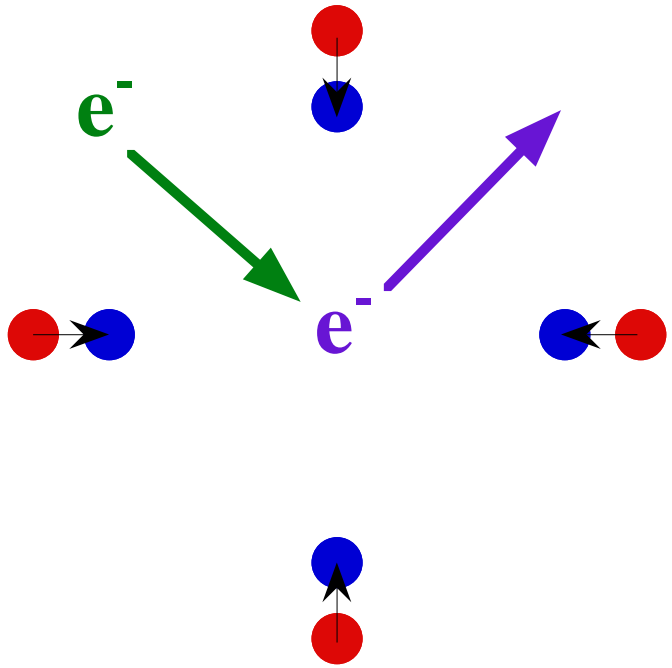
Norman *et al.*, PRL (1997)

Question of Retardation limiting T_c
(Morel & Anderson, Anderson & Cohen)

$\Omega_{phonon} \sim \omega_D$

$$U \rightarrow \frac{U}{1+\ln(U/\omega_D)}$$

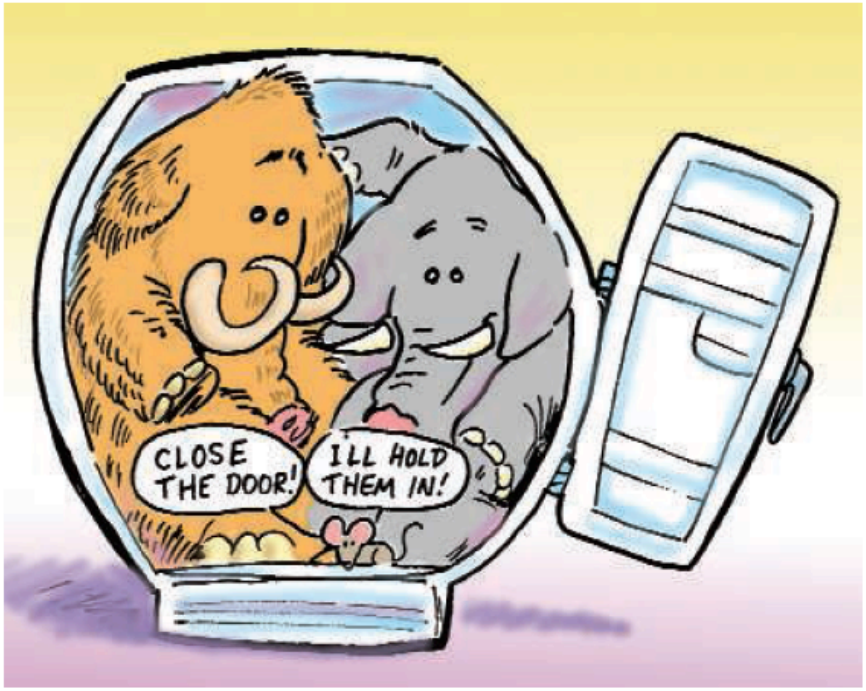
$T_c << \omega_D$



What is the origin of pairing?

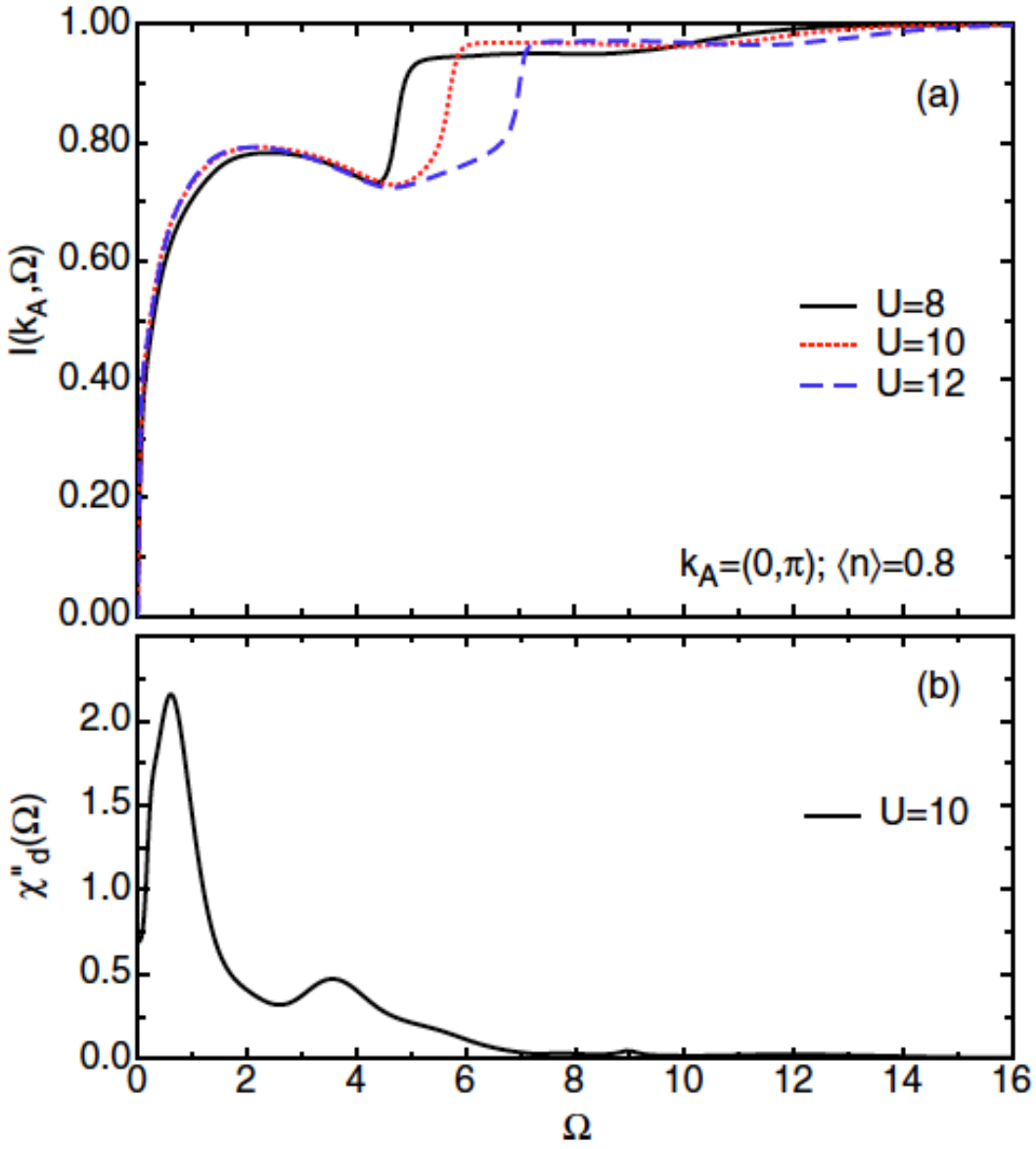
Is there a pairing glue?

Is it instantaneous?



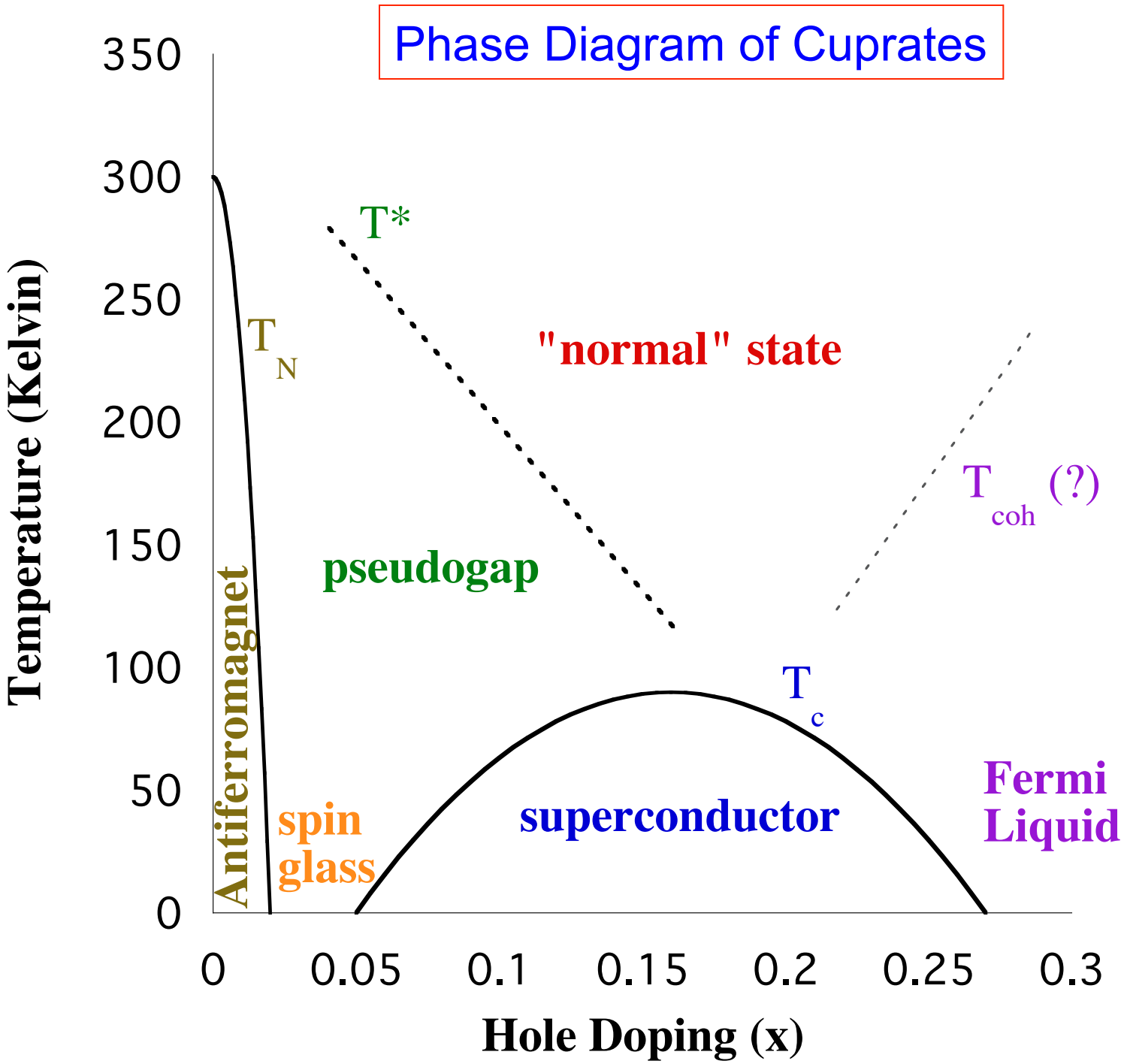
"We have a mammoth and an elephant in our refrigerator—do we care much if there is also a mouse?"

Anderson, Science 317, 1705 (2007)

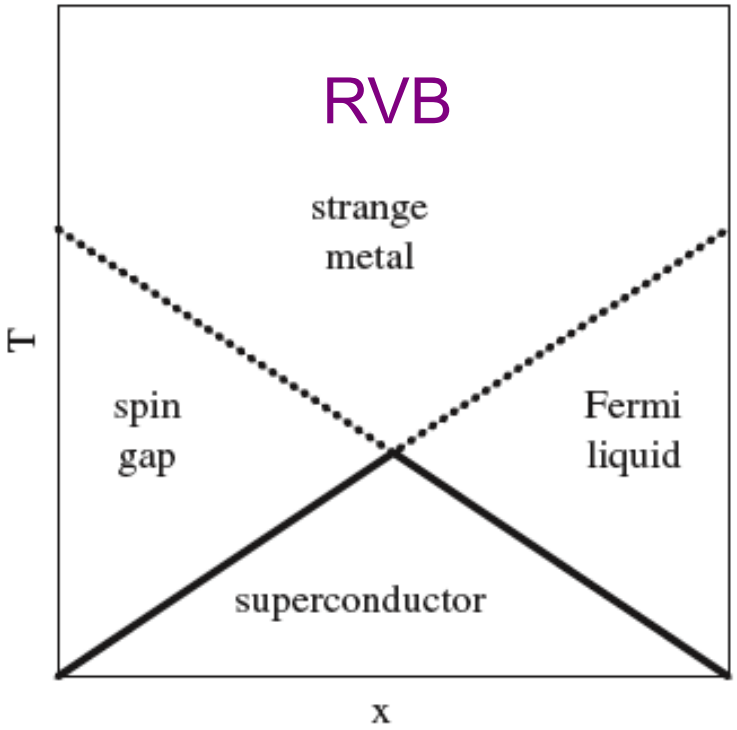


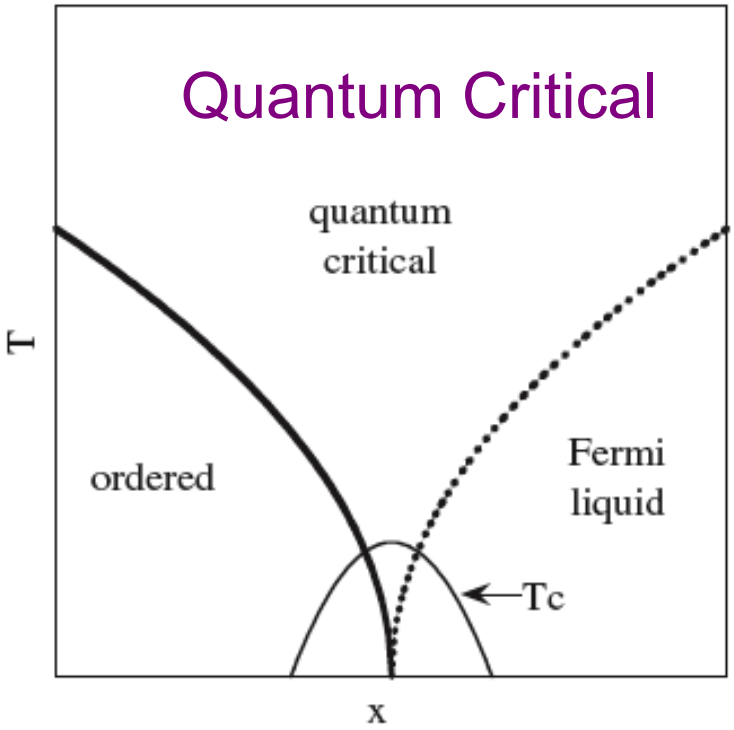
$$I(k_A, \Omega) = \frac{\frac{2}{\pi}\int_0^{\Omega} \frac{\phi_2(k_A,\omega')}{\omega'} d\omega'}{\frac{2}{\pi}\int_0^{\infty} \frac{\phi_2(k_A,\omega')}{\omega'} d\omega'}$$

Maier, Poilblanc, Scalapino, PRL 100, 237001 (2008)

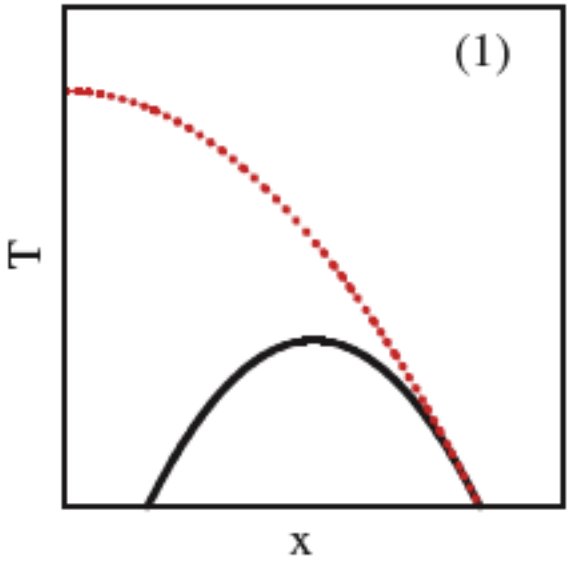

Phase Diagram of Cuprates
Temperature (Kelvin)
350
300
250
200
150
100
50
0
0
0.05
0.1
0.15
0.2
0.25
0.3
Hole Doping (x)
T*
T N
"normal" state
T coh (?)
pseudogap
T c
Antiferromagnet
spin glass
superconductor
Fermi Liquid

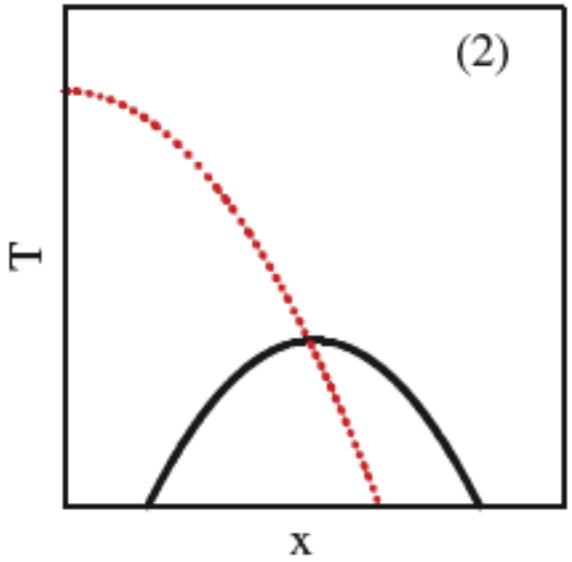
Two Theories of the Phase Diagram

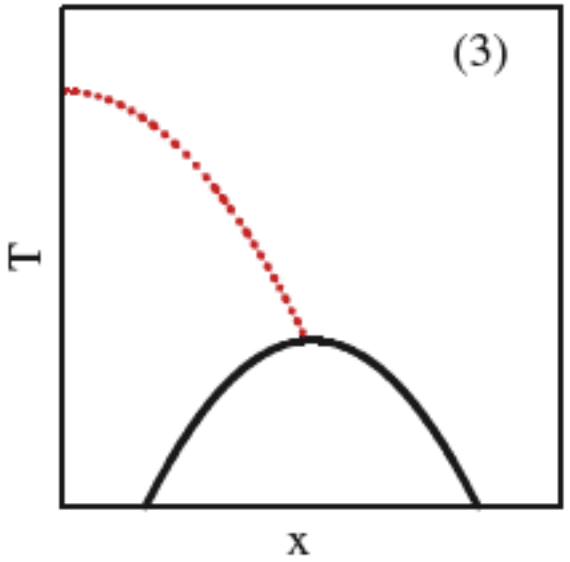




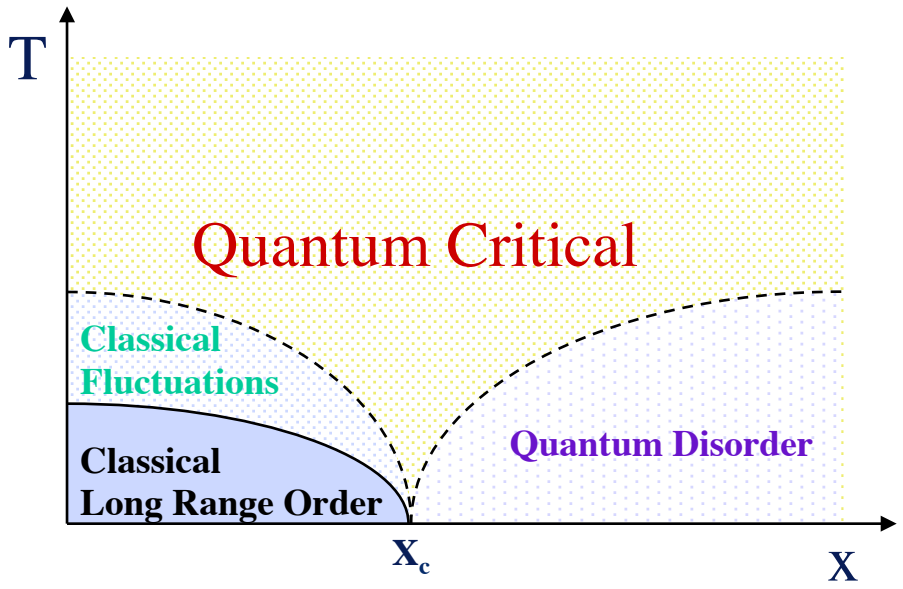
Relation of T* to T_c





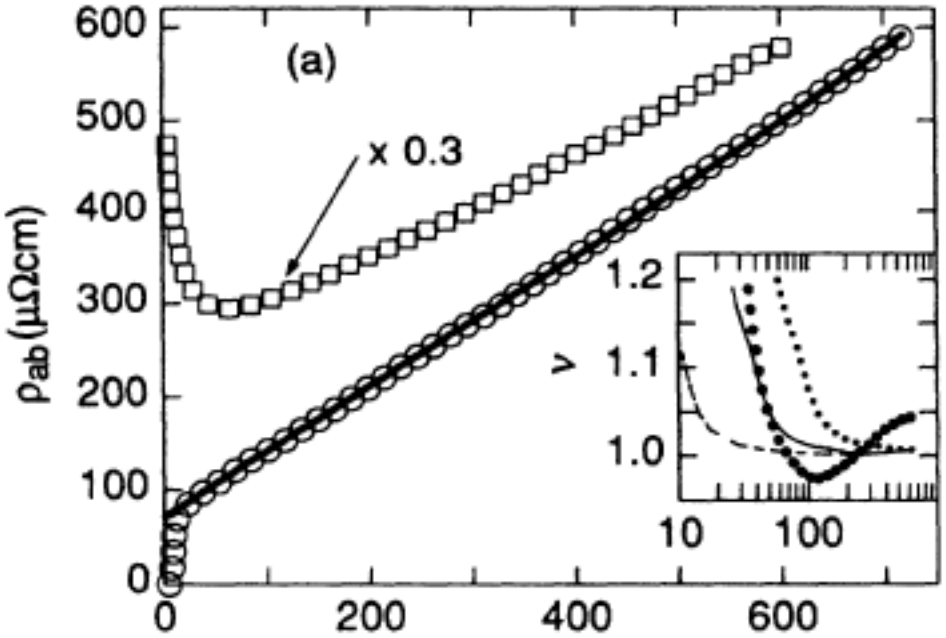


Quantum Critical Scenario



In a quantum critical scenario, an “ordered” phase exists on one side of the critical point, the corresponding “quantum Disordered” phase (Fermi liquid) is on the other side.

Linear T Resistivity

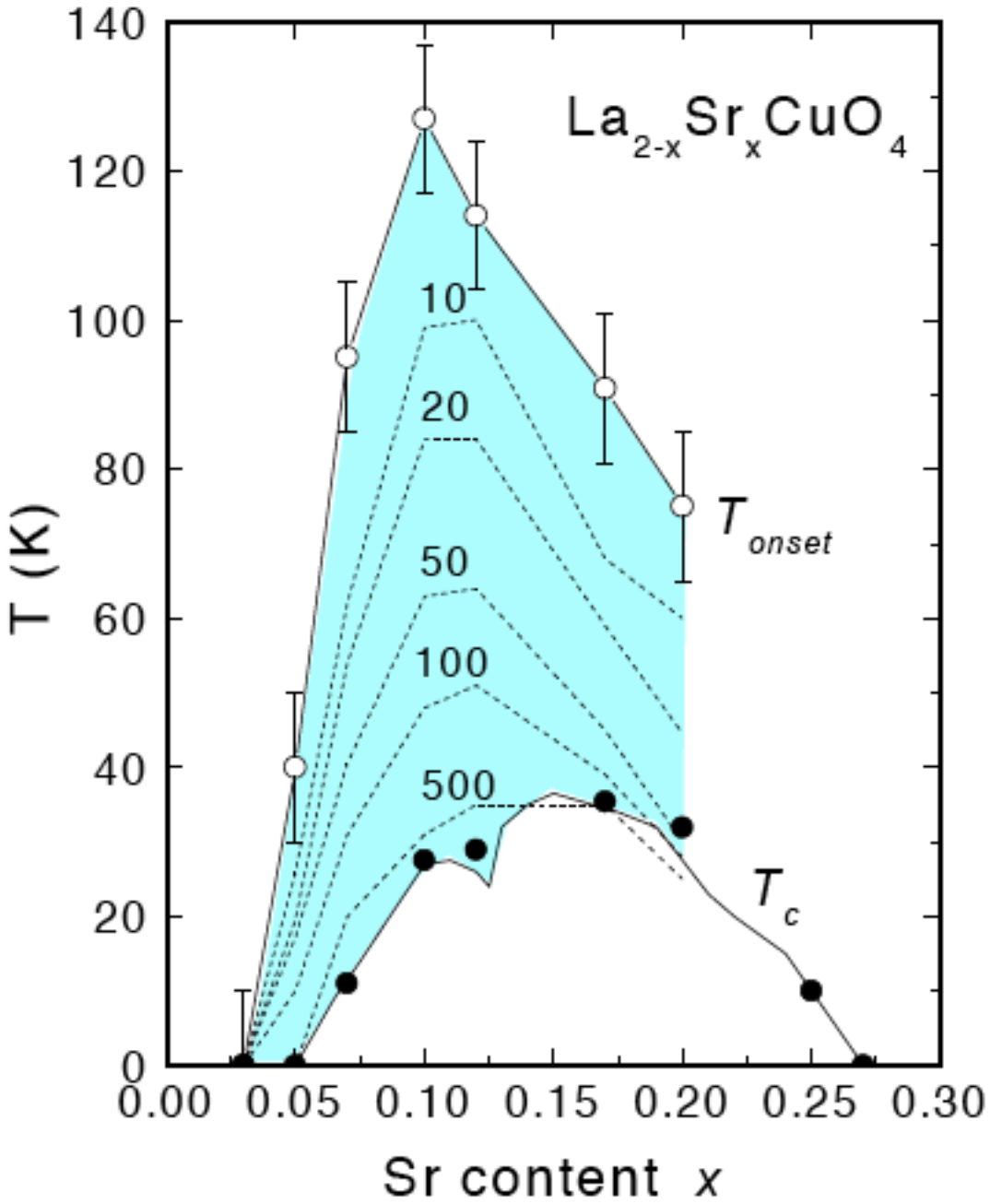


Martin *et al.*, Phys Rev B (1990)

What is the Pseudogap?

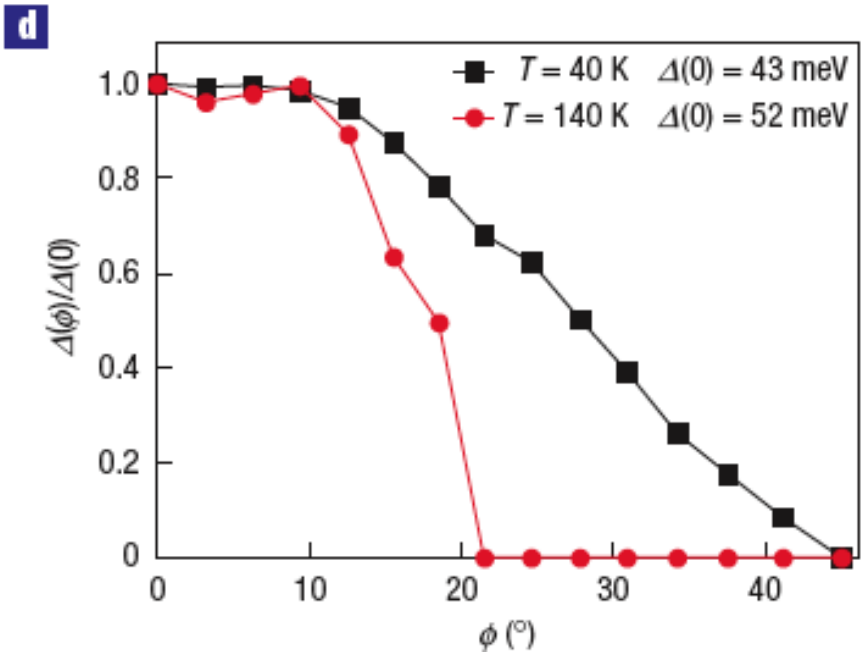
1. Spin singlets
2. Pre-formed pairs
3. Spin density wave
4. Charge density wave
5. d density wave
6. Orbital currents
7. Flux phase
8. Stripes/nematic
9. Valence bond solid/glass
10. Combination?

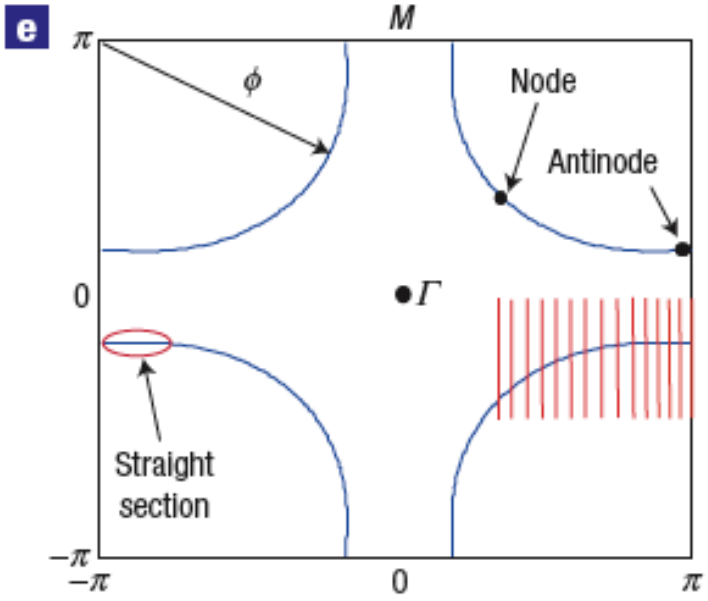
A Nernst signal (due to fluctuating vortices?) appears above T_c

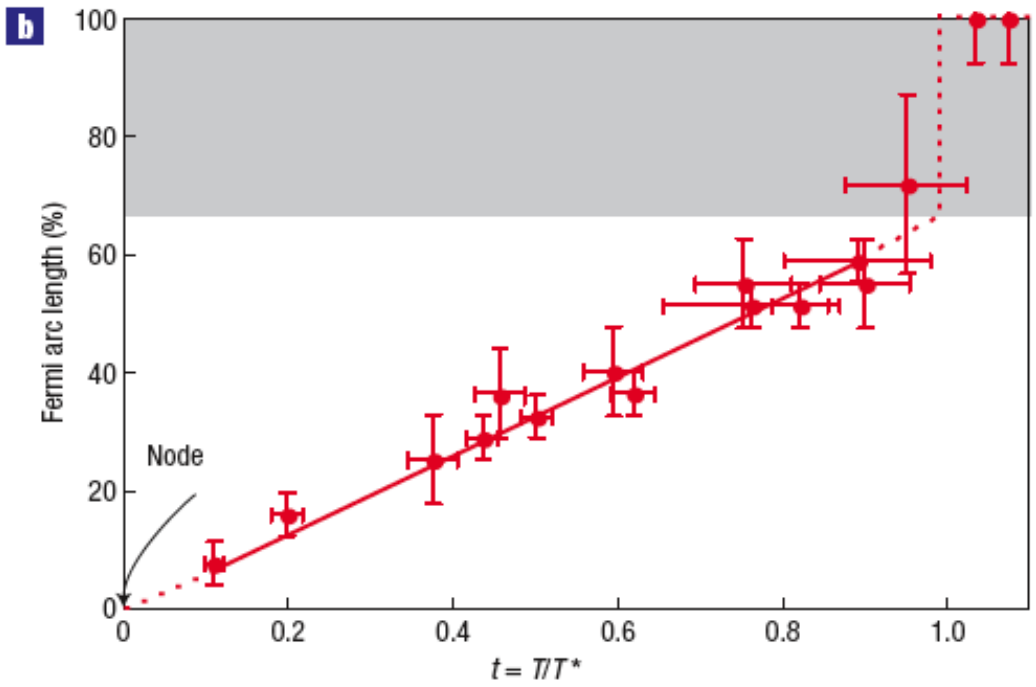


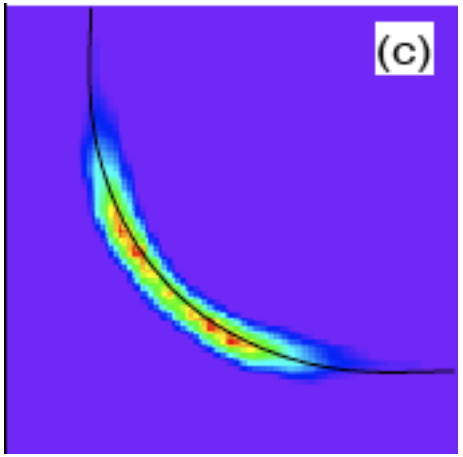
Wang *et al.*
PRB (2001)

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



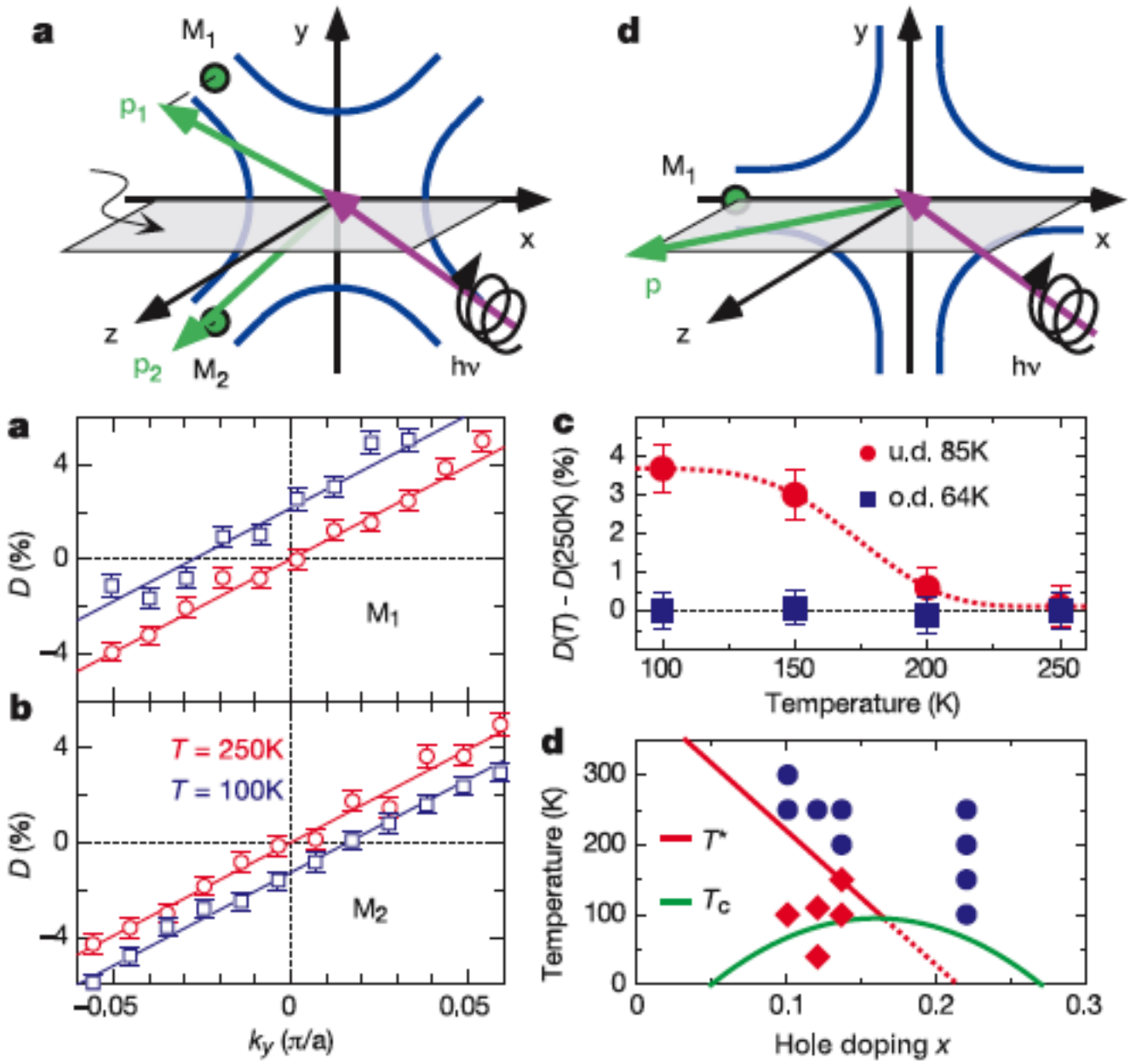






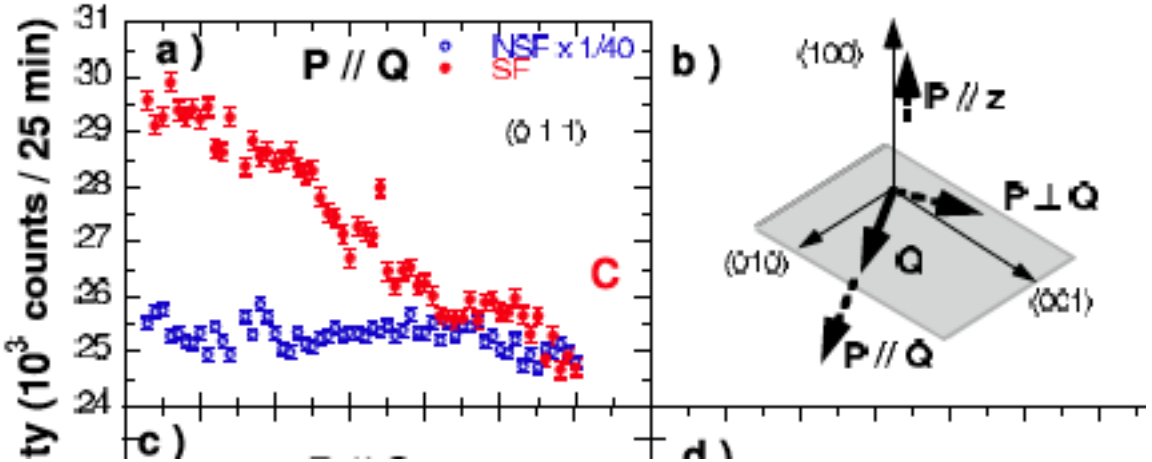
Kanigel *et al.*
Nat. Phys. (2006)

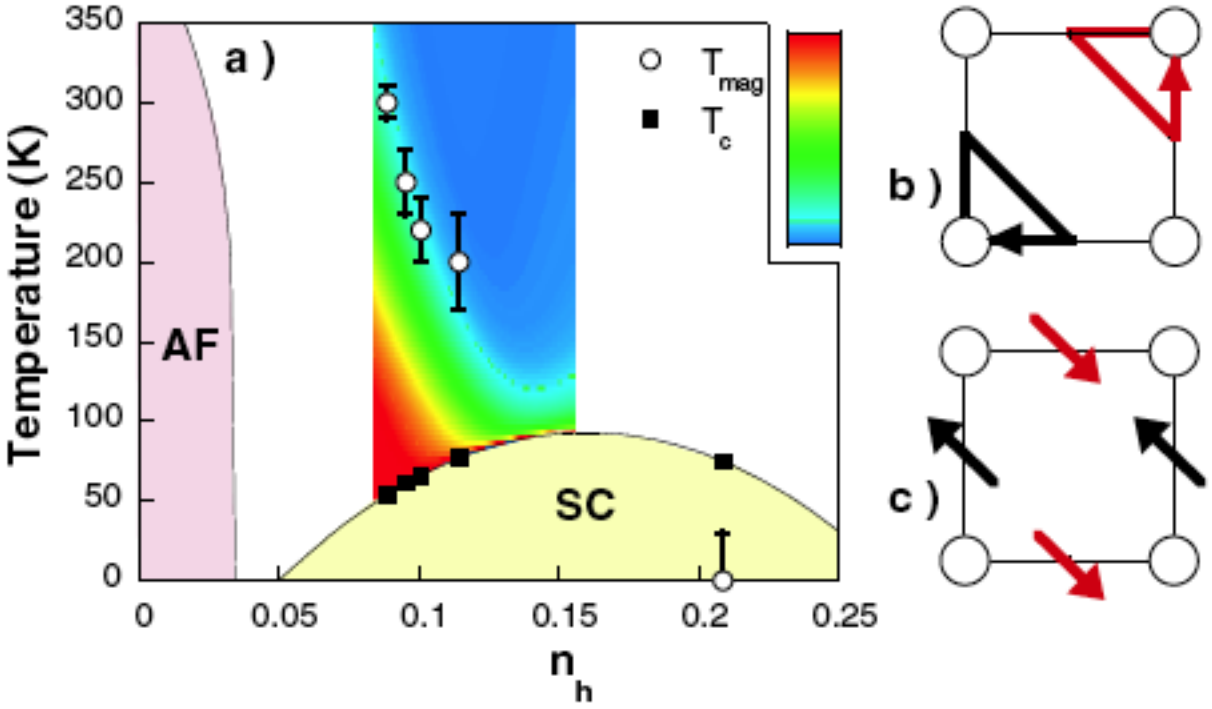
Circular dichroism above T_c in the pseudogap phase



Kaminski *et al.*
Nature (2002)

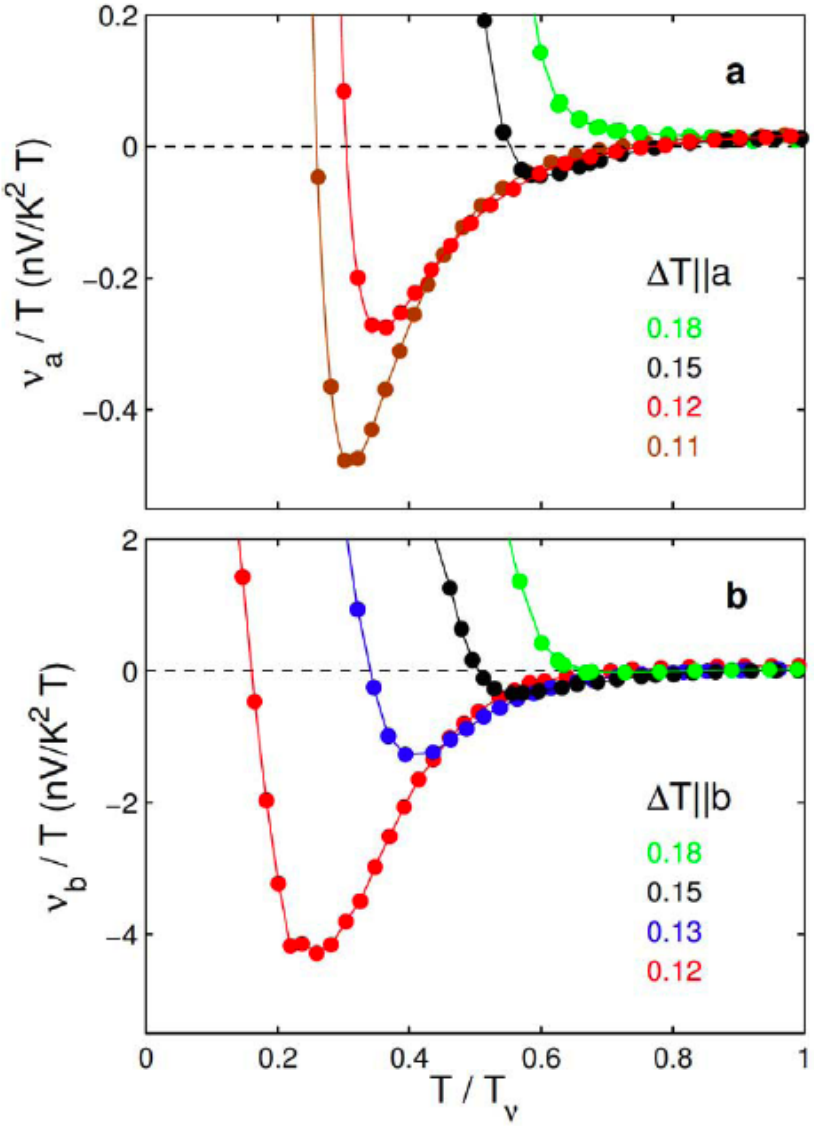
Orbital moments above T_c in the pseudogap phase (Bourges, Greven, Kapitulnik)

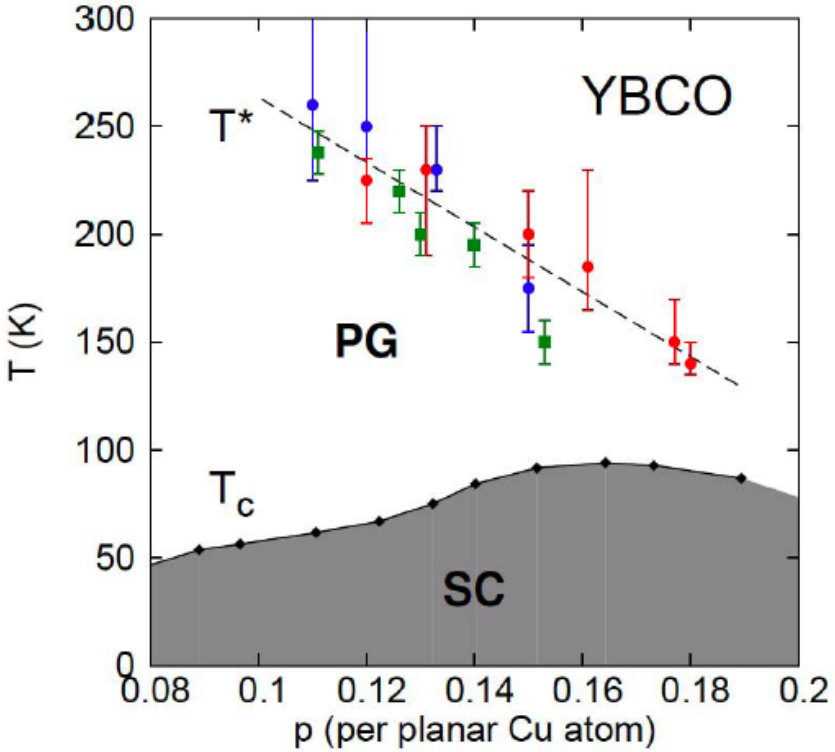




Fauque *et al.*
PRL (2006)

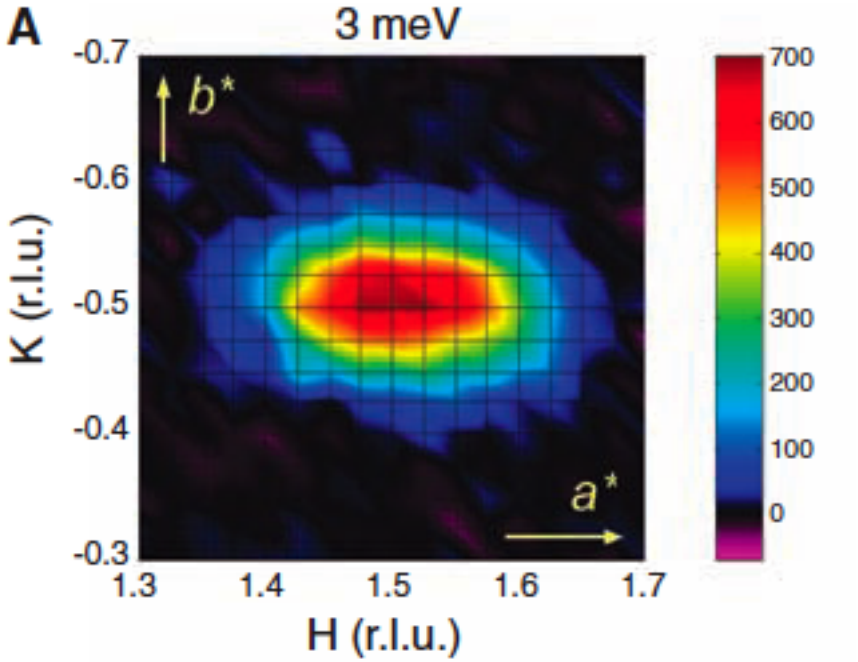
Anisotropic Nernst signal below T^* (a nematic?)

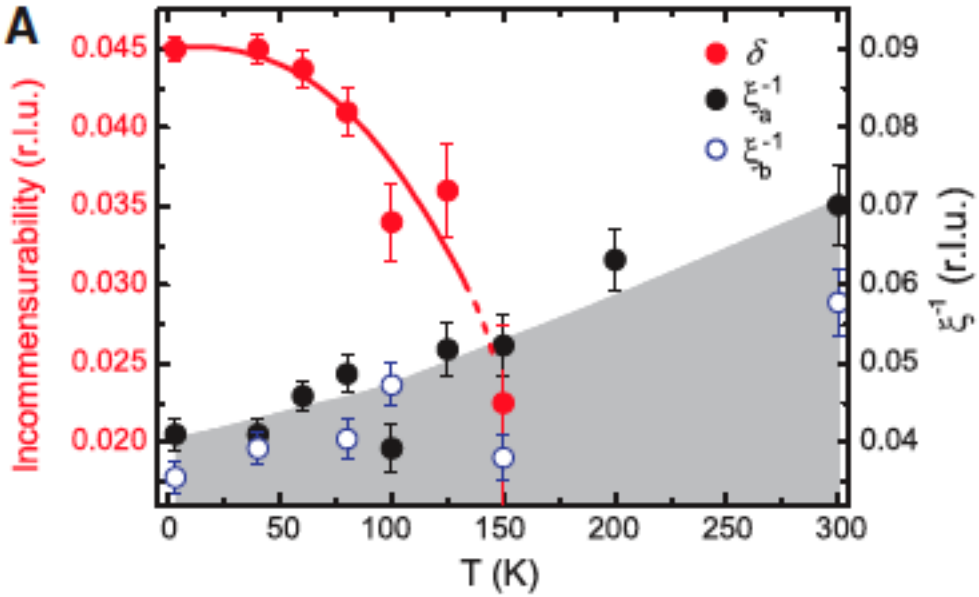




Daou *et al.*, Nature (2010)

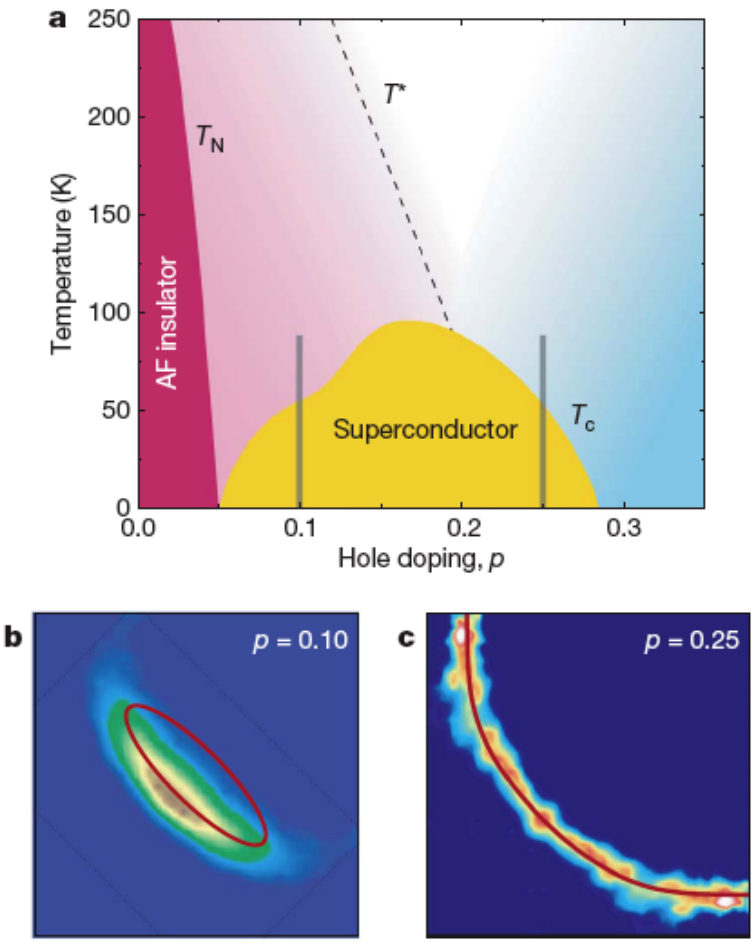
Anisotropic Spin Response below T*
(a nematic?)



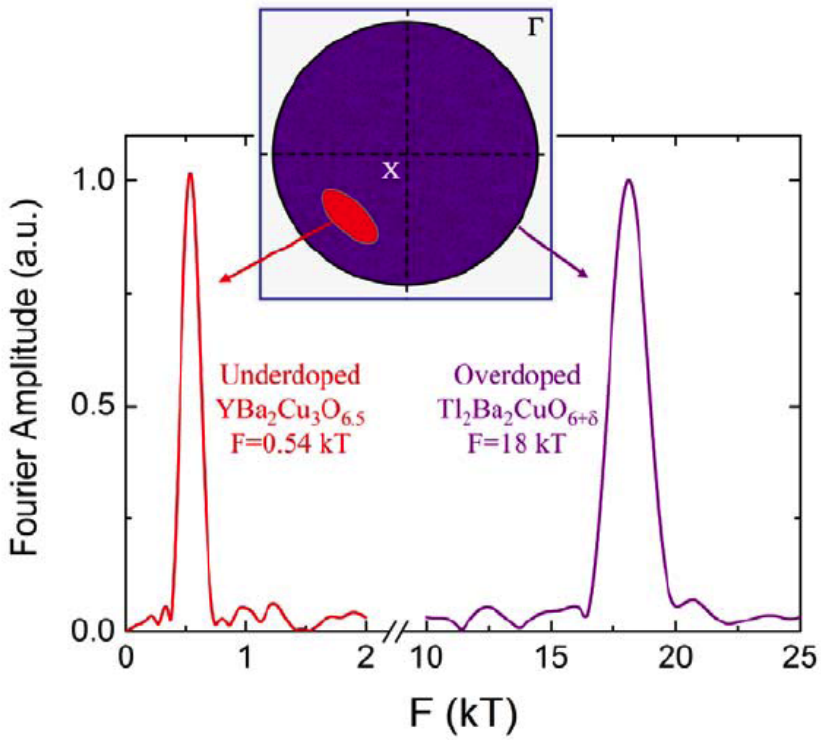


Hinkov *et al.*, Science (2008)

Evolution of the Fermi surface with doping - dHvA



Doiron-Leyraud *et al.*, Nature (2007)
(underdoped - small Fermi surface)

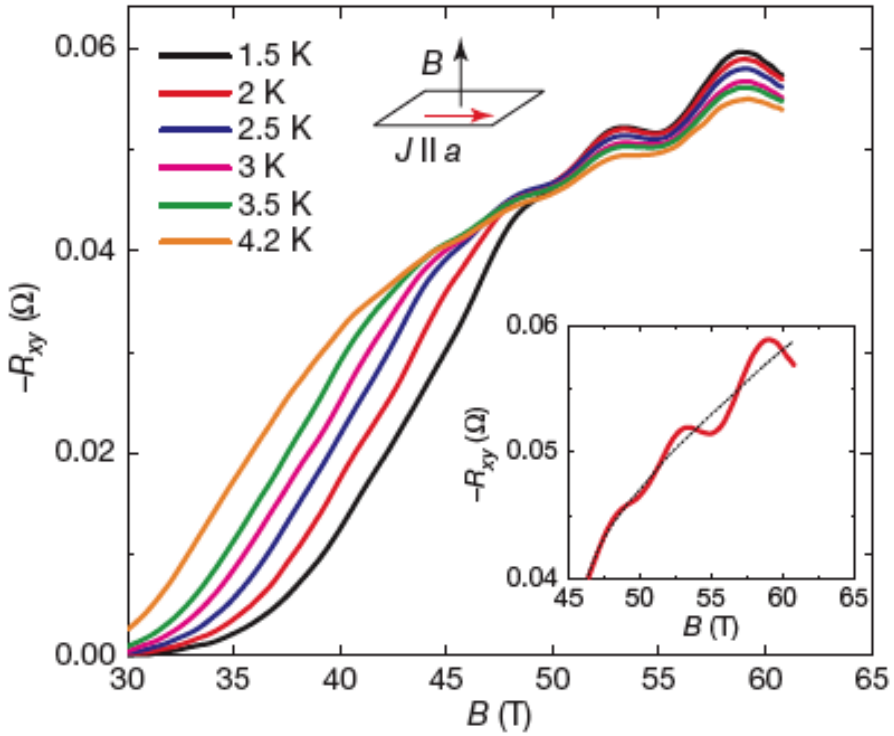


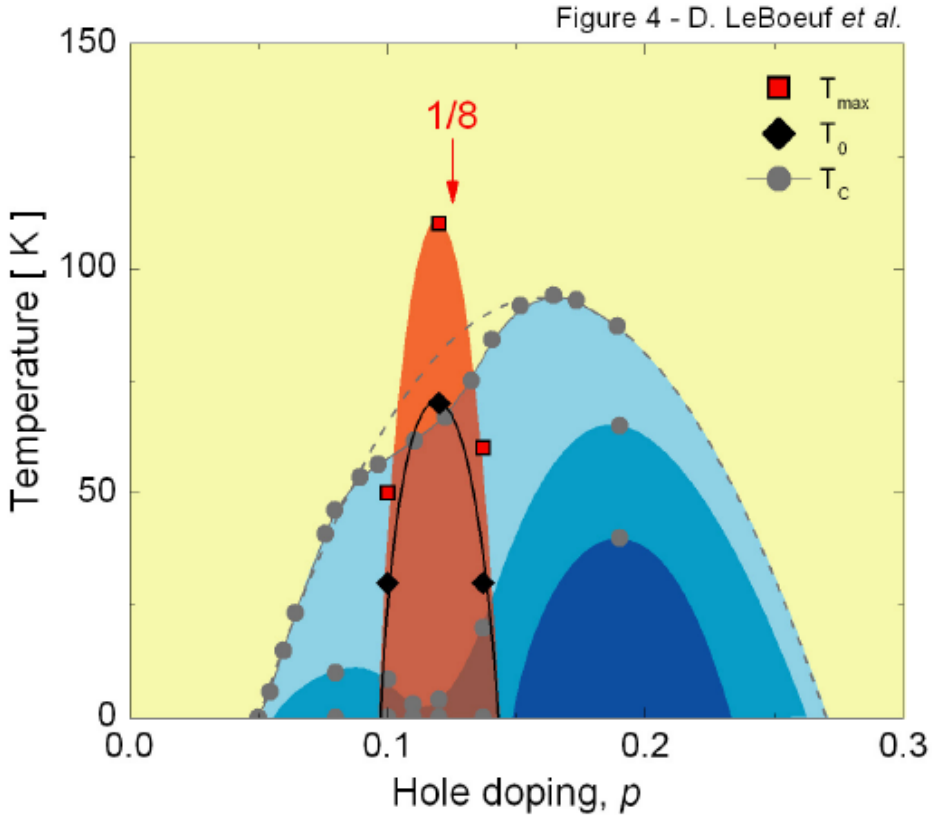
Vignolle *et al.*, Nature (2008)
(overdoped - large Fermi surface)

electron pockets due to magnetic stripes?

The Hall number is negative!

$R_H < 0$ forms a dome around 1/8

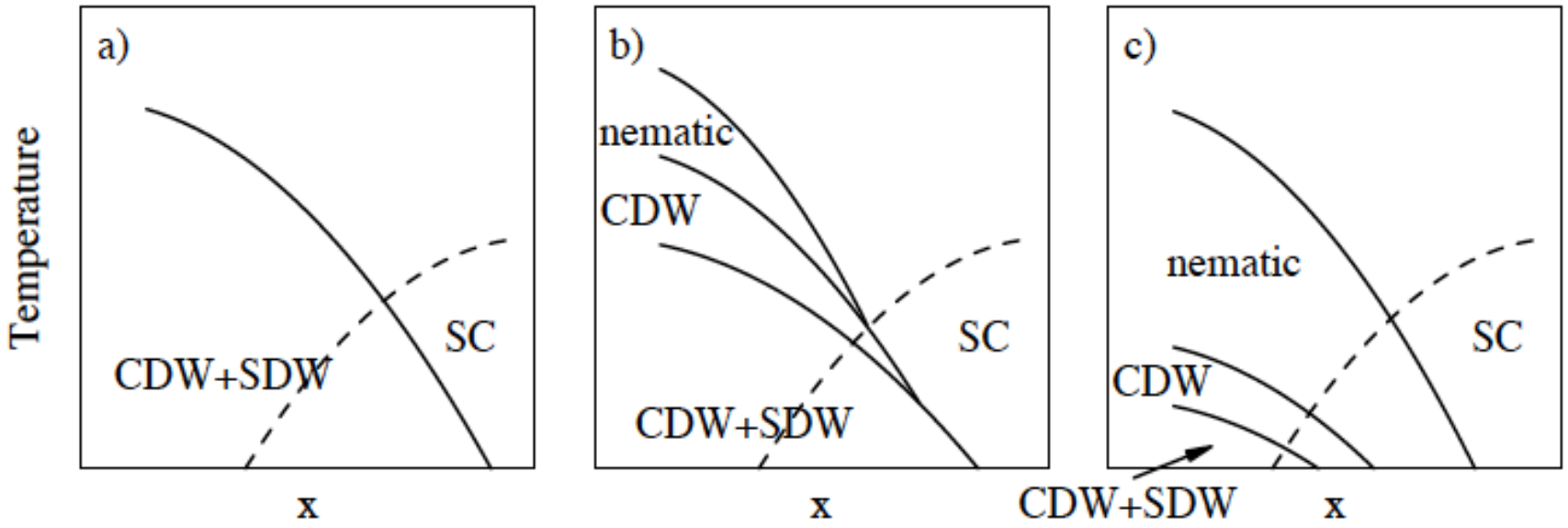




Doiron-Leyraud *et al.*
Nature (2007)

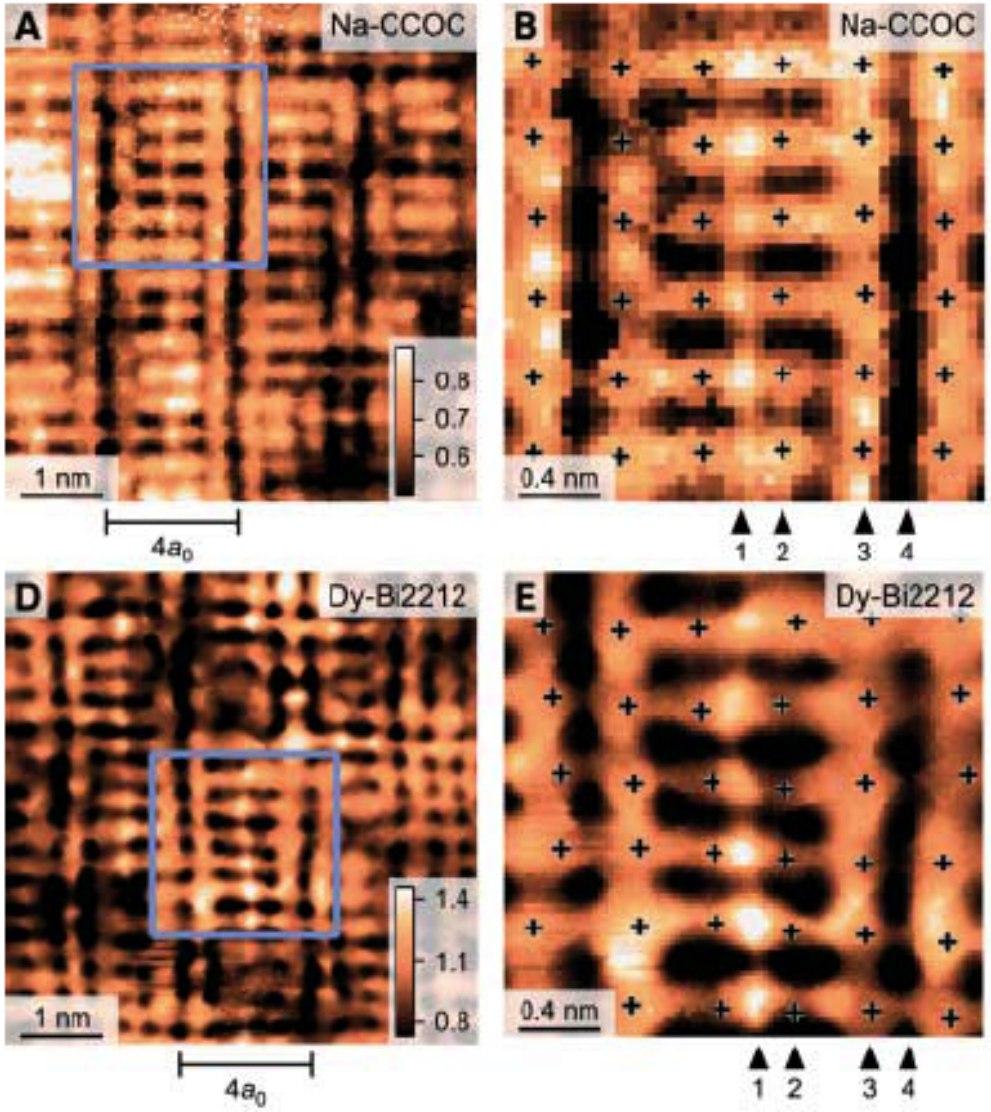
LeBoeuf *et al.*, Nature (2007)
and PRB (2011)

Is the Pseudogap a Nematic Phase?

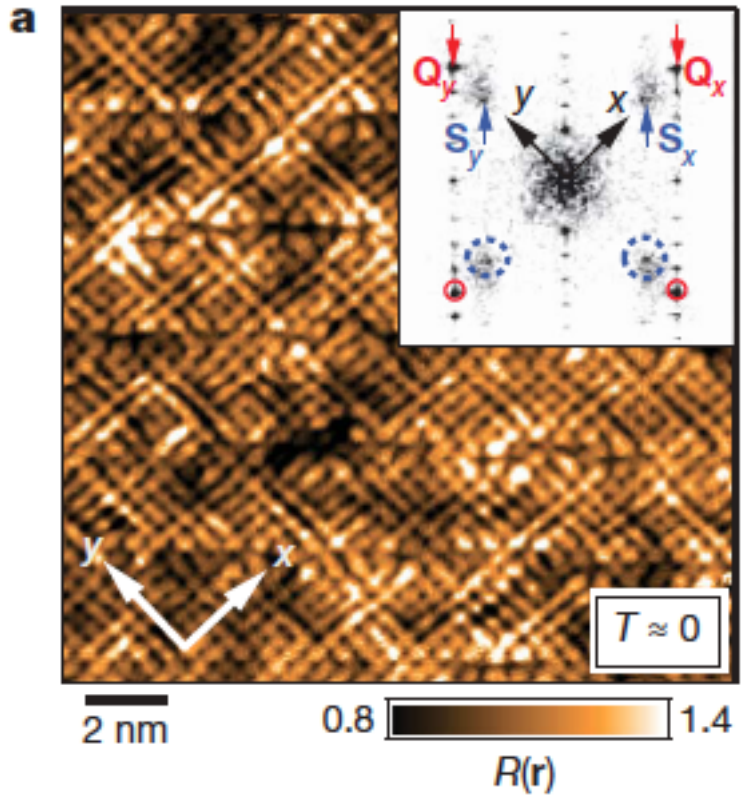


Vojta, Adv. Phys. (2009)

hole density shows a “4a period bond centered electronic glass” & the pseudogap exhibits a nematic anisotropy

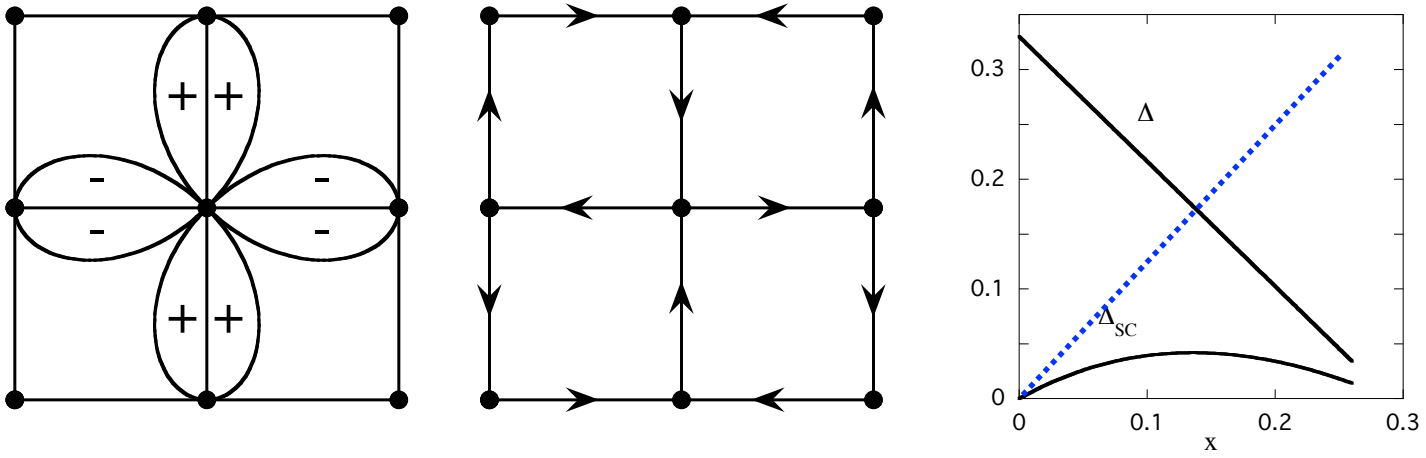


Kohsaka *et al.*, Science (2007)



Lawler *et al.*, Nature (2010)

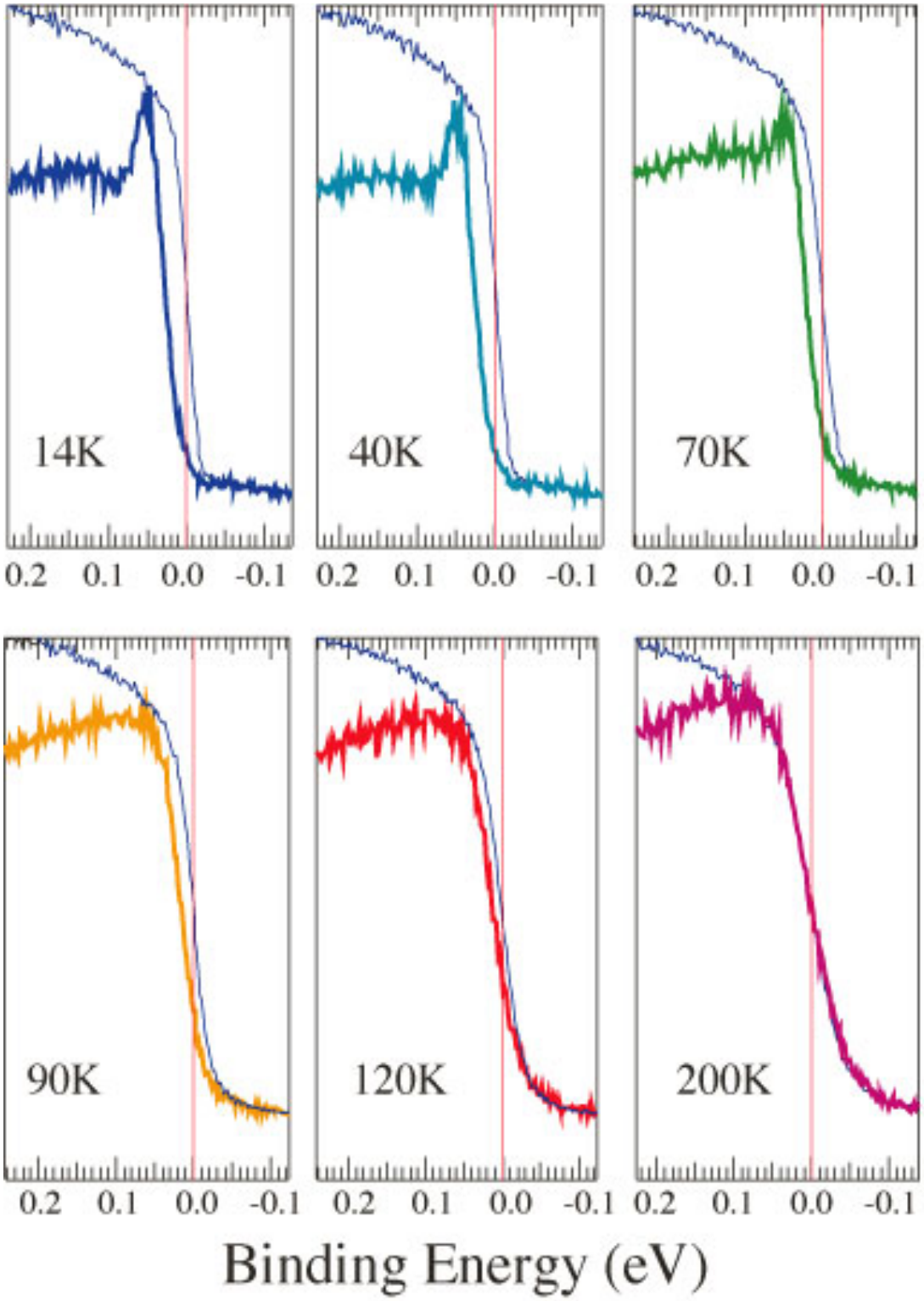
RVB Model (Anderson, Lee & Nagaosa, Randeria & Trivedi, etc.)

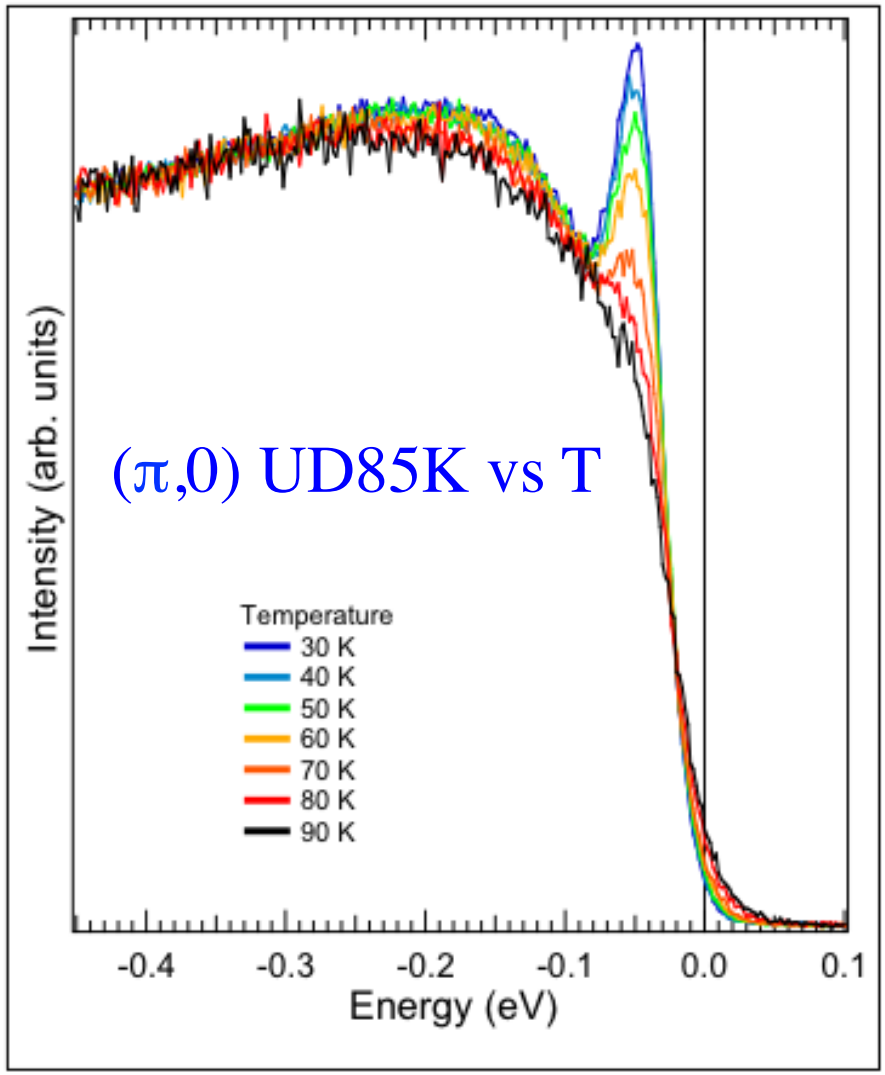


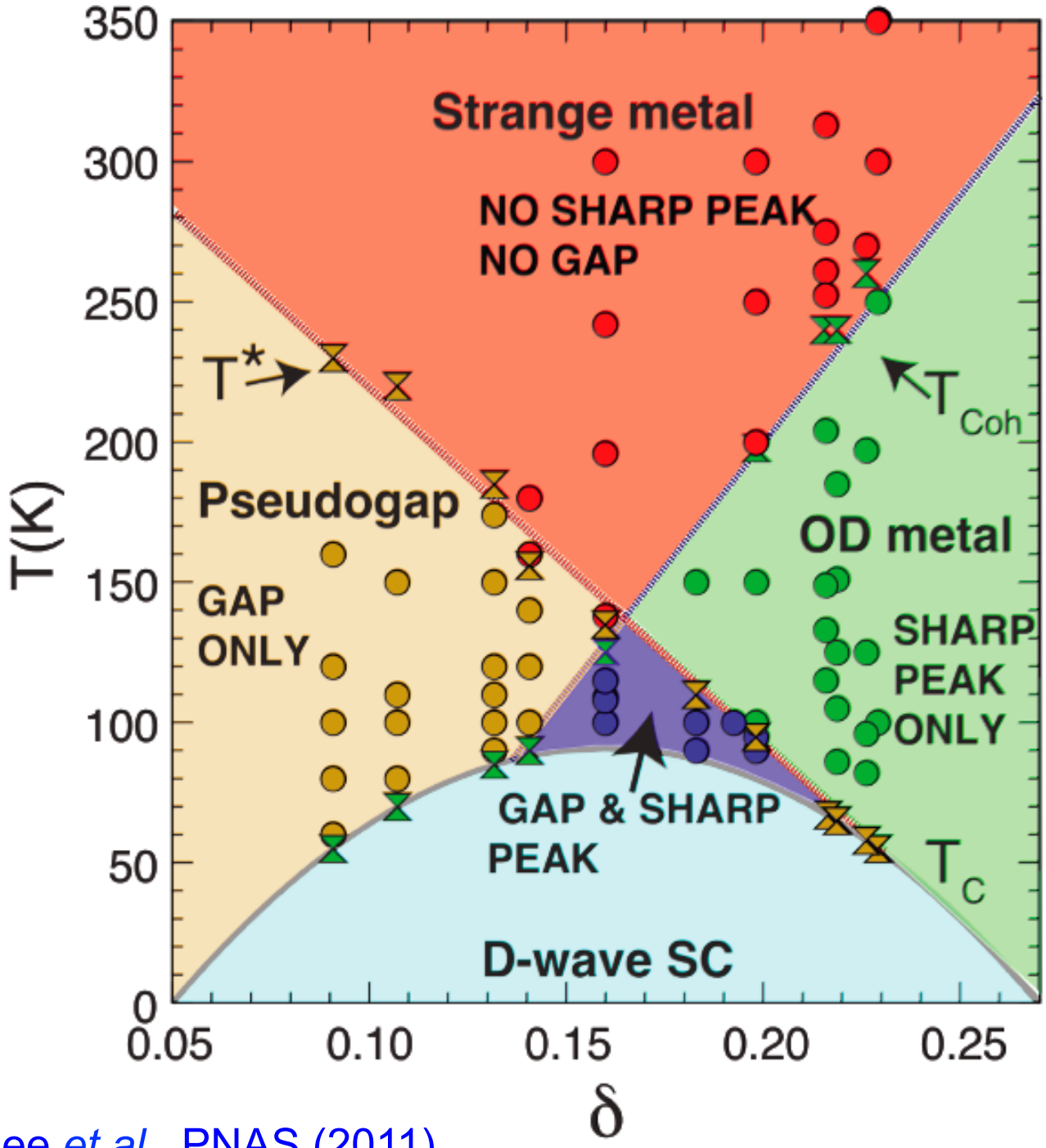
Pseudogap phase corresponds to a d-wave pairing of spins (left). At half filling, this is quantum mechanically equivalent to a staggered flux state (middle). The spin gap, Δ, is not equivalent to the superconducting order parameter, Δ_{sc} (right).

ARPES (Bi2212)

<-- Antinode UD83K vs T





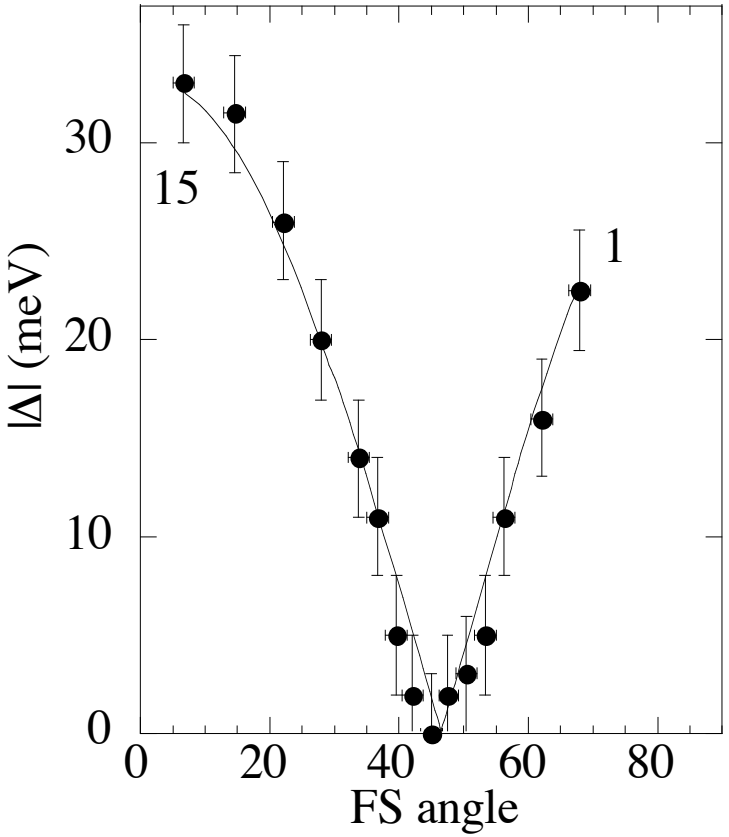


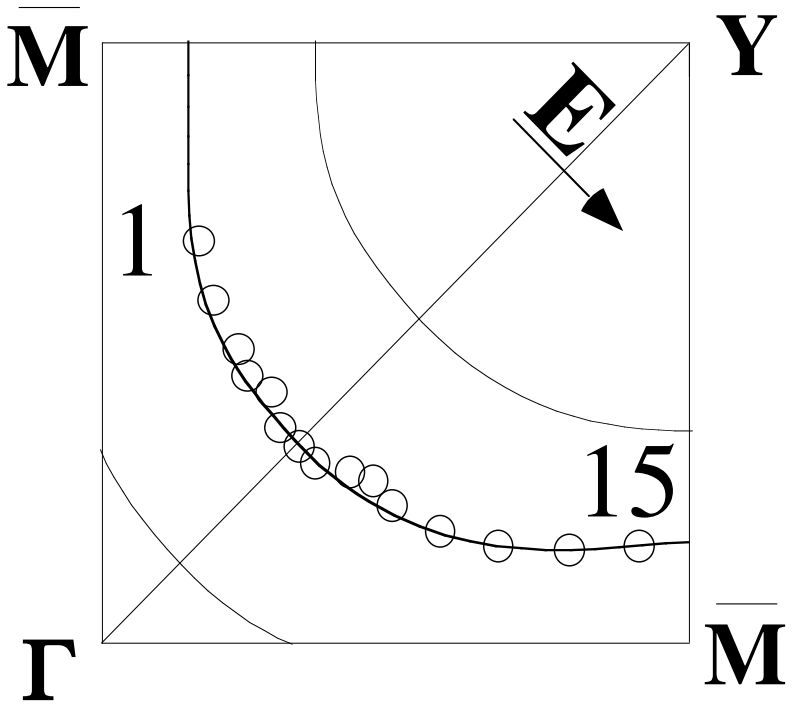
Chatterjee *et al.*, PNAS (2011)

Extraction of the Superconducting Energy Gap from Photoemission

Ding *et al*., PRB (1996) following the pioneering work of Shen *et al*., PRL (1993)

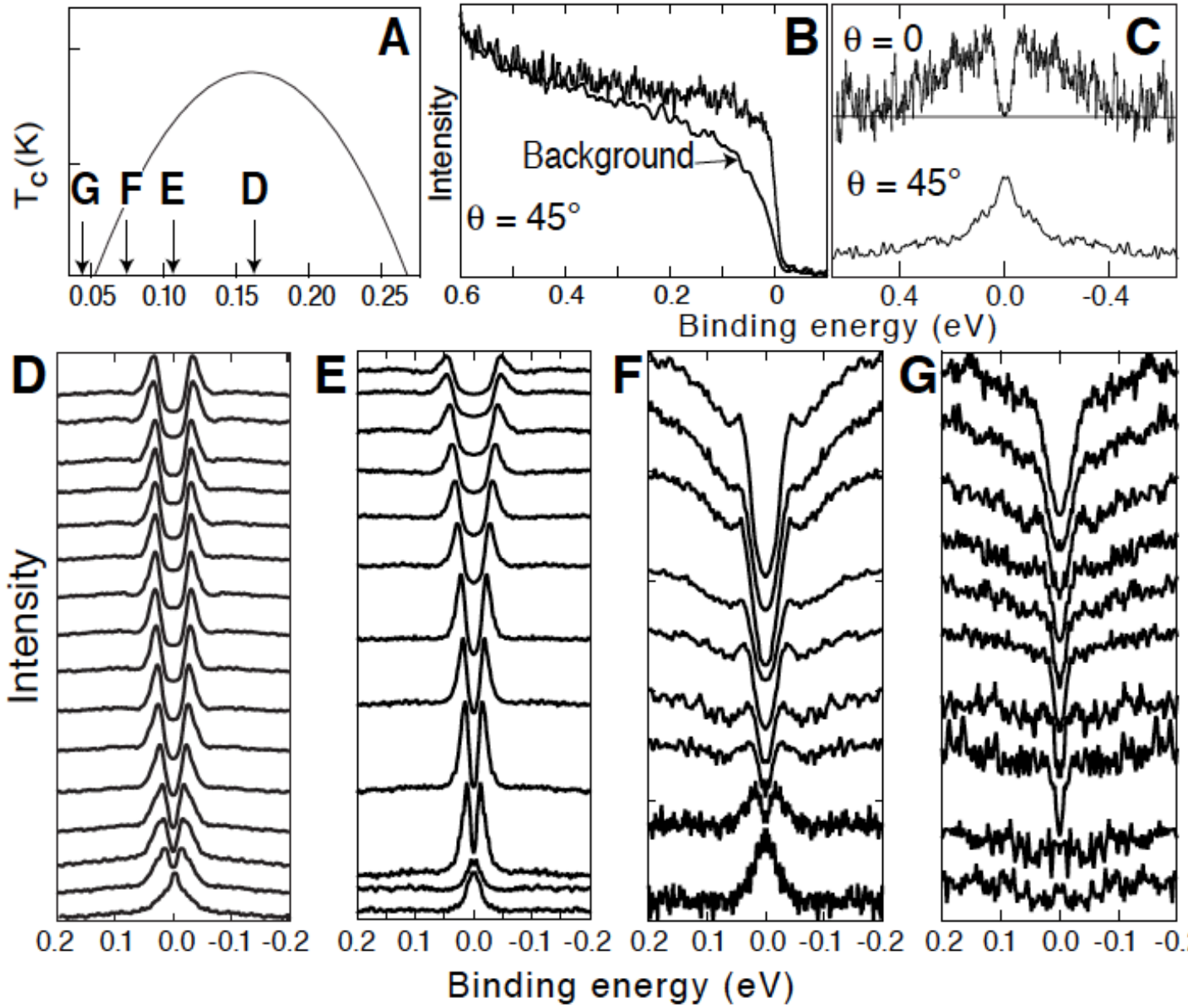
Δ_k --> $\cos(k_x) - \cos(k_y)$ --> Implies pair interaction peaked for near-neighbors





Bi2212, T_c=87K

Doping Dependence of the Gap Anisotropy

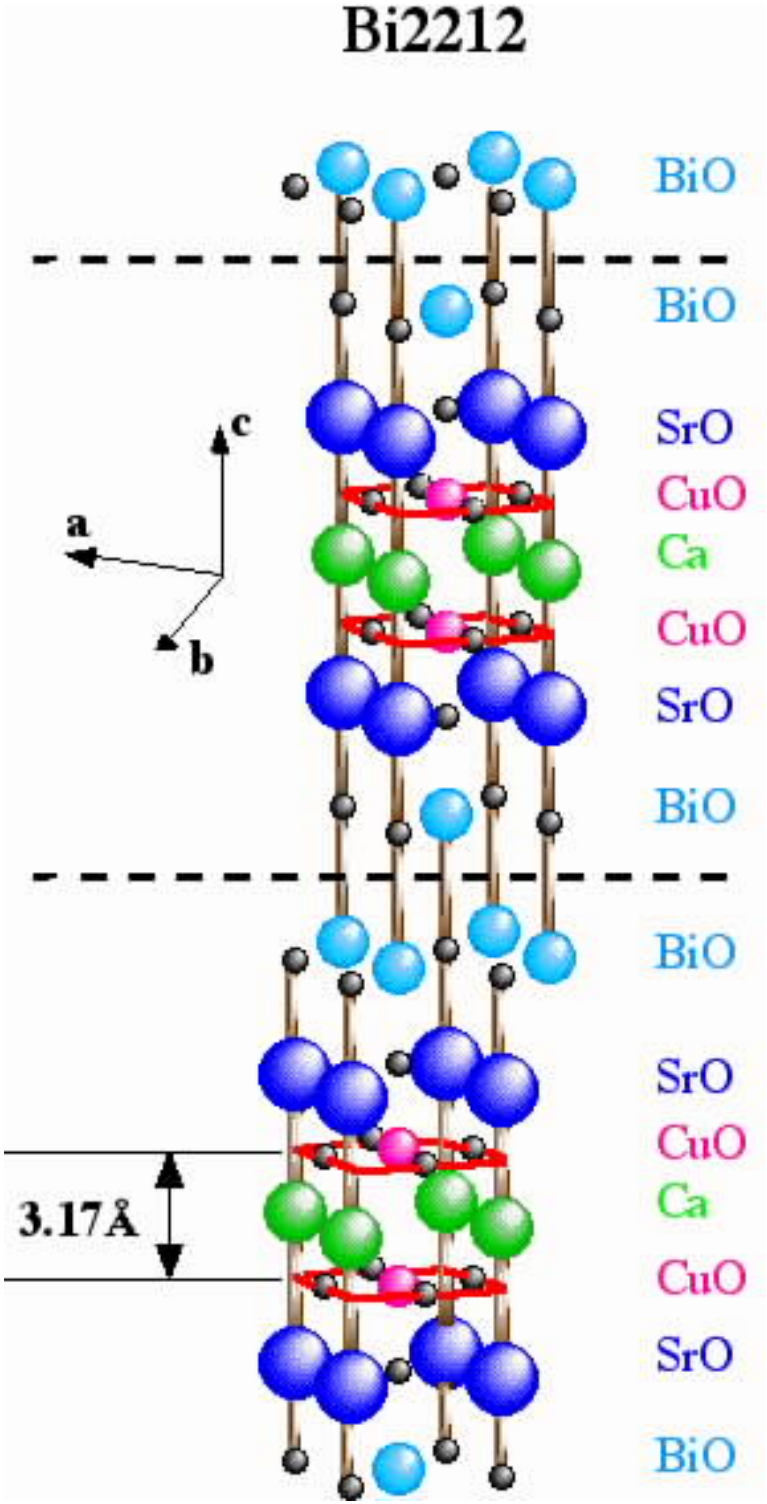


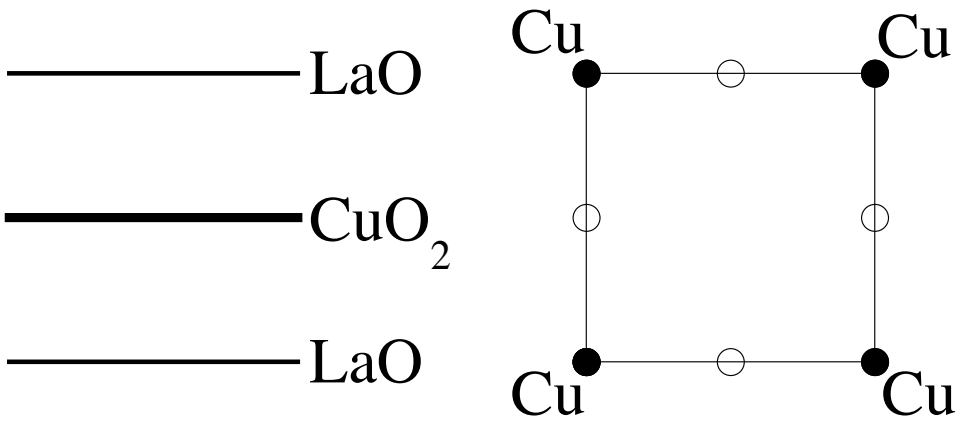
optimal

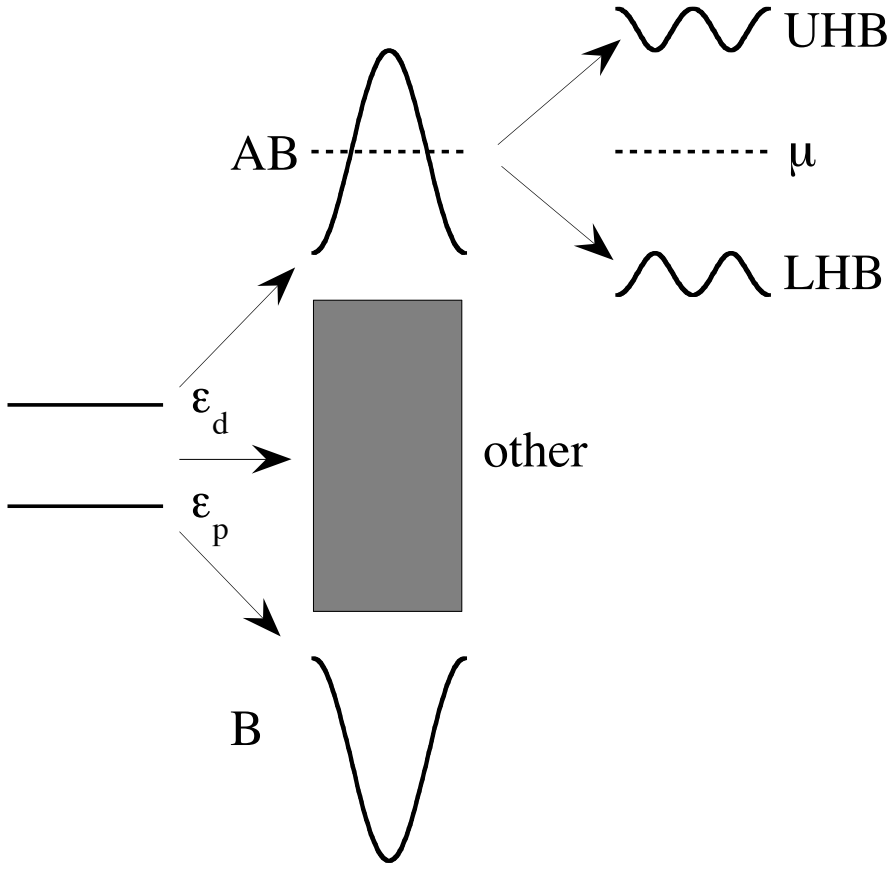
insulator

Chatterjee *et al.*, Nat. Phys. (2010)

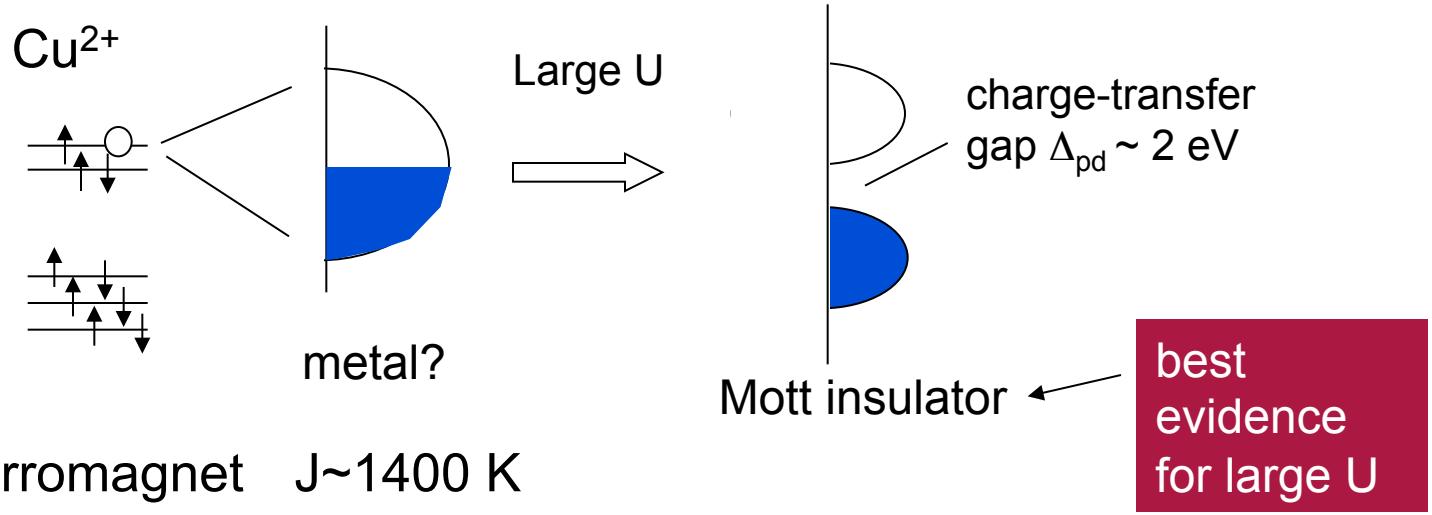
Electronic Structure of Cuprates



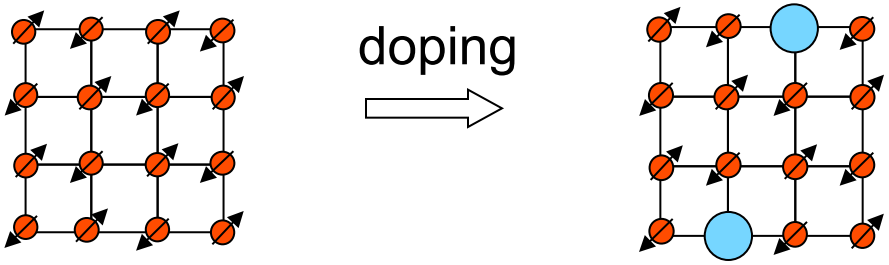




Short (and biased!) tutorial on cuprates



antiferromagnet J~1400 K



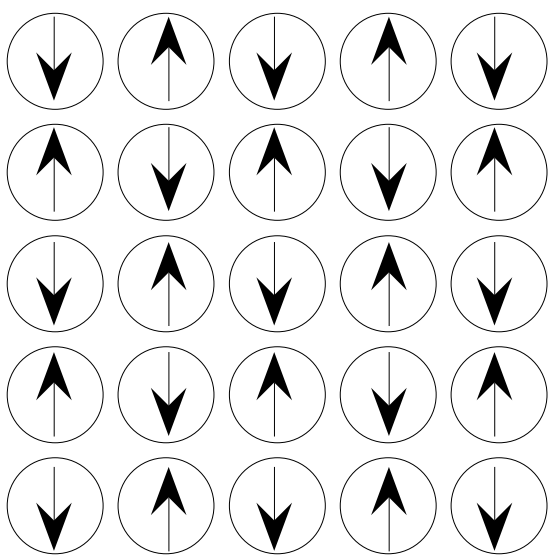
$$H = -t \sum_{i,j,\sigma} c^{+}_{i\sigma} c_{j\sigma} + U \sum_{i} n_{i\uparrow} n_{i\downarrow}$$ Hubbard

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

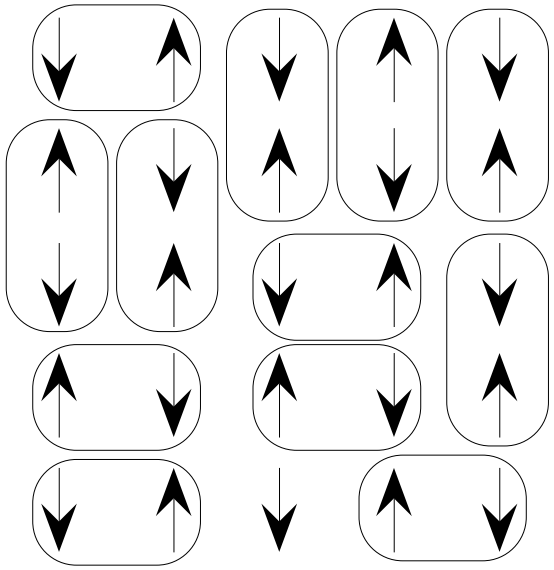
(slide from Anderson & Ong)

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



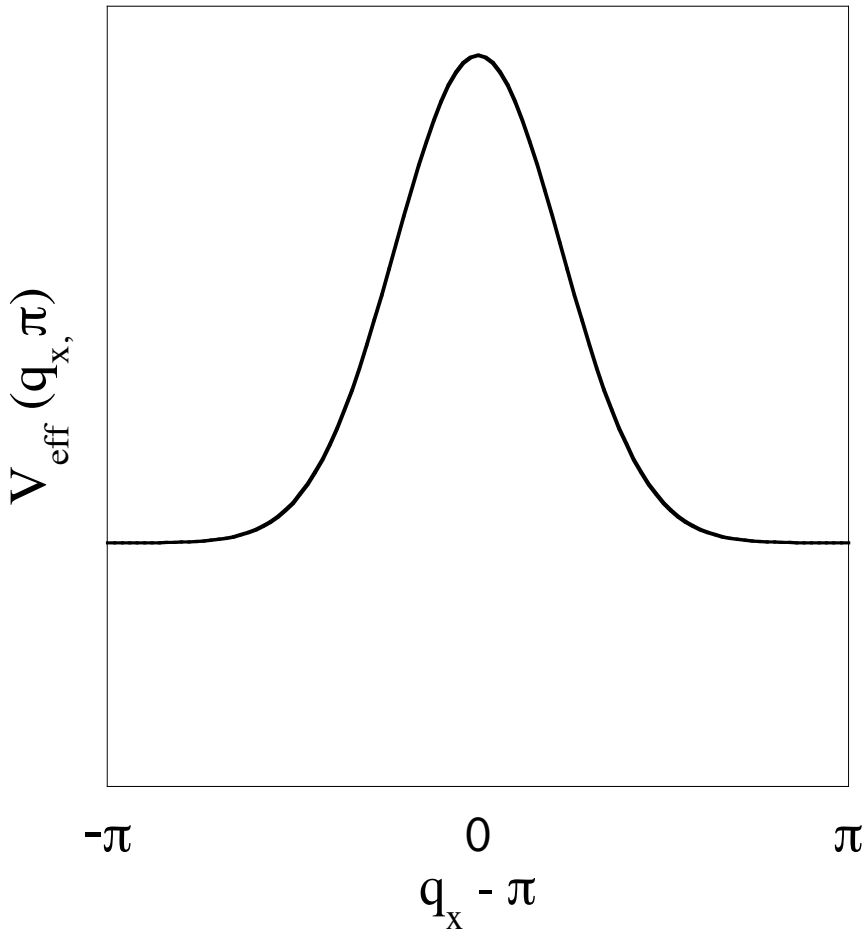
Neel Lattice

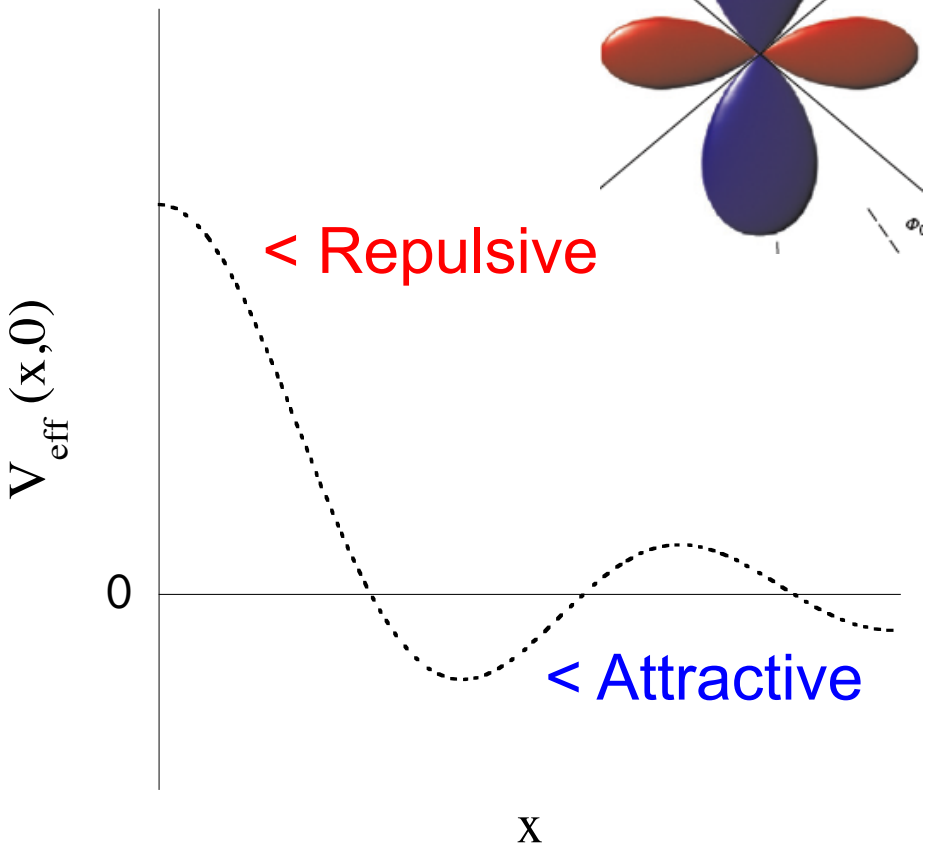


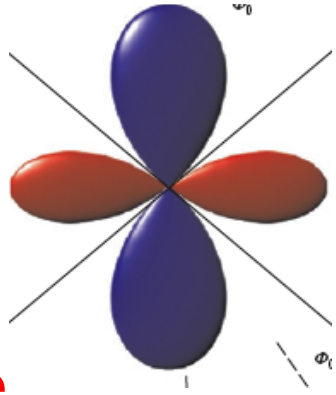
RVB

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)







(plots from Doug Scalapino)

There is no Migdal theorem (Hertz, Levin & Beal-Monod)

This is in contrast to electron-phonon theory where the self-energy can be approximated to one loop order (that is, vertex corrections are of order ω_D/E_F).

Recent work on 2D AF spin fluctuations:

Abanov, Chubukov & Schmalian, Adv Phys (2003)

Melitski & Sachdev - PRB (2010)

Is the Hubbard model superconducting?

Relation of χ to the Exchange Energy and Specific Heat

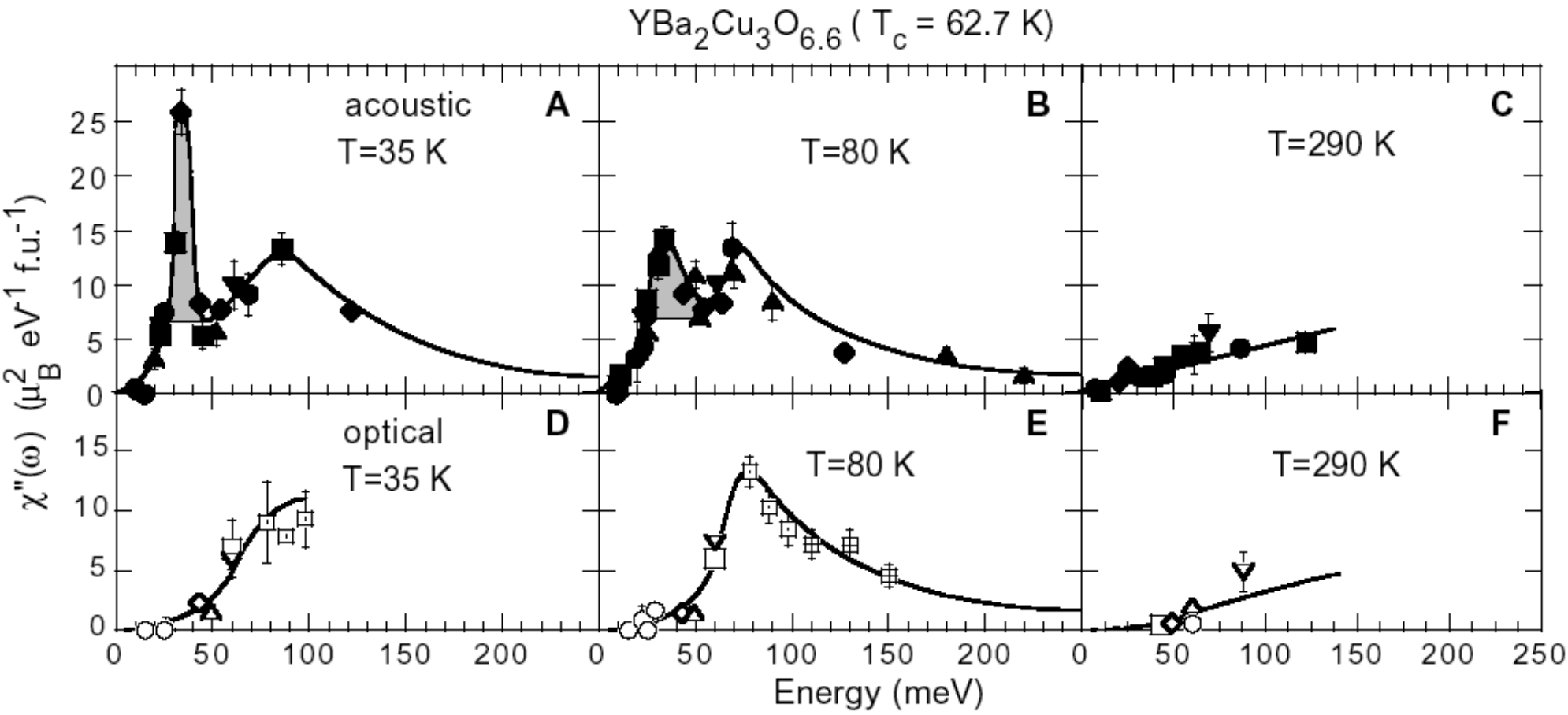
$$E_J \simeq \frac{3}{(g\mu_{\rm B})^2}(\frac{a}{2\pi})^2 \int \frac{d(\hbar\omega)}{\pi} \int dq_x dq_y \frac{1}{2} J[\cos(q_x a) + \cos(q_y b)] \frac{[\chi''_{ac}(q_x, q_y, \omega) + \chi''_{op}(q_x, q_y, \omega)]}{1 - \exp(-\hbar\omega/kT)}$$

$$C_J^{res}(x,T) \simeq \frac{dE_J^{res}}{dT} = -\frac{3}{4\mu_{\rm B}^2} J \frac{d}{dT} \left(\int \frac{d(\hbar\omega)}{\pi} \frac{\chi''_{res}(\omega)}{1 - \exp(-\hbar\omega/kT)} \right) = -\frac{J}{2\mu_B^2} \frac{d\langle m_{res}^2 \rangle}{dT}$$

Scalapino & White, PRB (1998)
Demler & Zhang, Nature (1998)
Dai *et al.,* Science (1999)

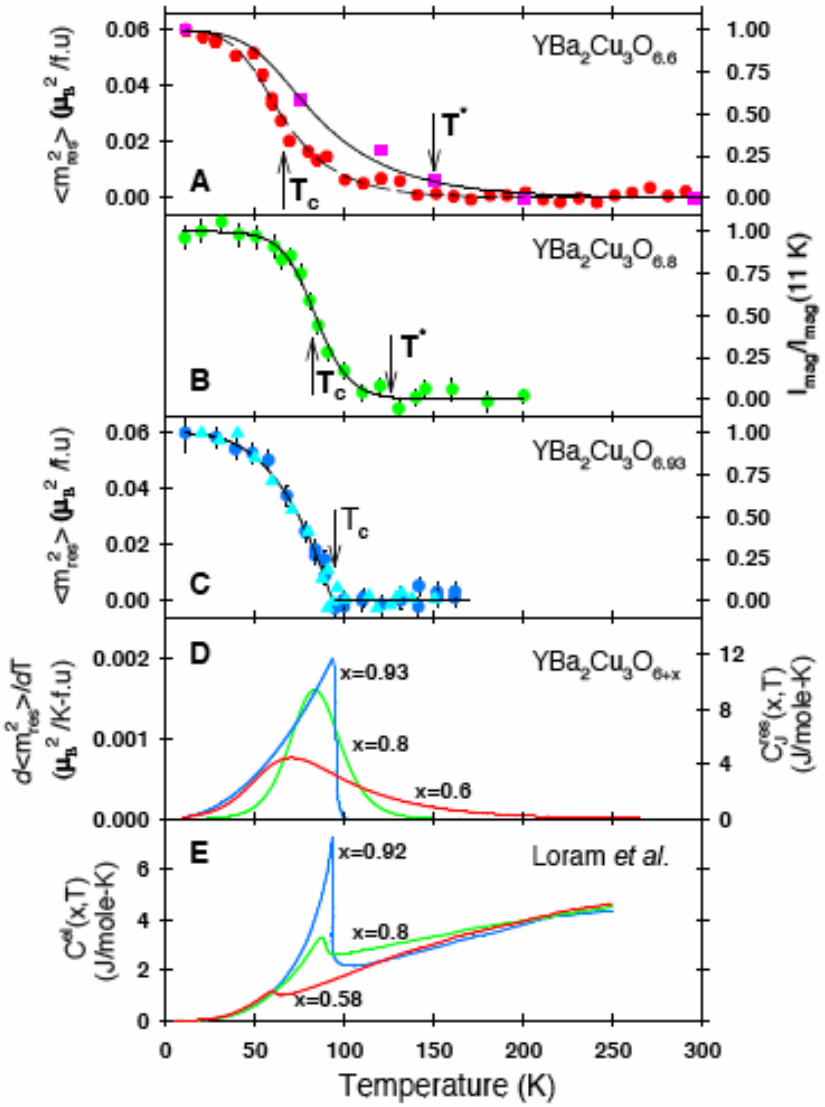
Neutron Spin Resonance below T_c (S=1 excitation)

Rossat-Mignod, Bourges, Mook, Dai, Keimer, …



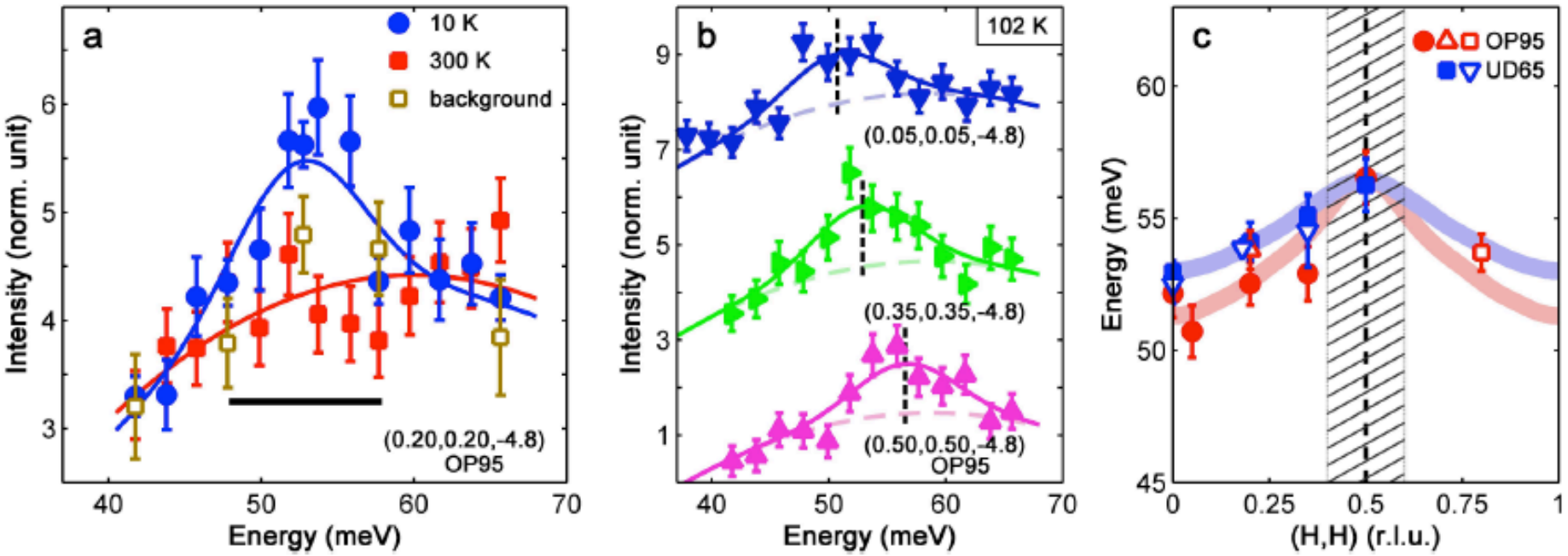
Dai *et al.*, Nature (1999)

Lowering of the Exchange Energy Below T_c

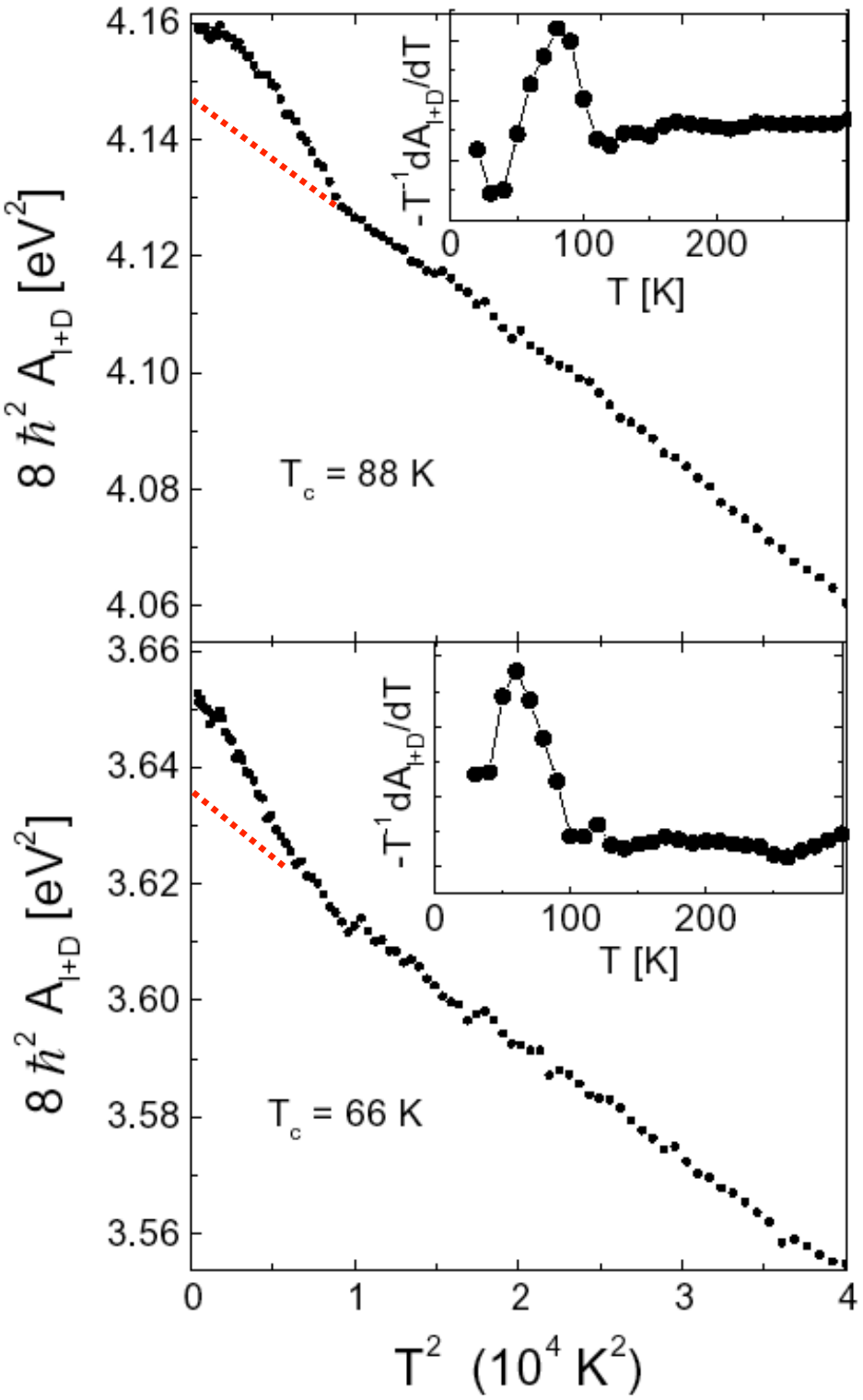


Dai *et al.*, Science (1999)
Woo *et al.*, Nat. Phys. (2006)

Weakly dispersive magnetic modes set in below T*
(spectral weight >> resonance)



Li *et al.*, Nature (2010)

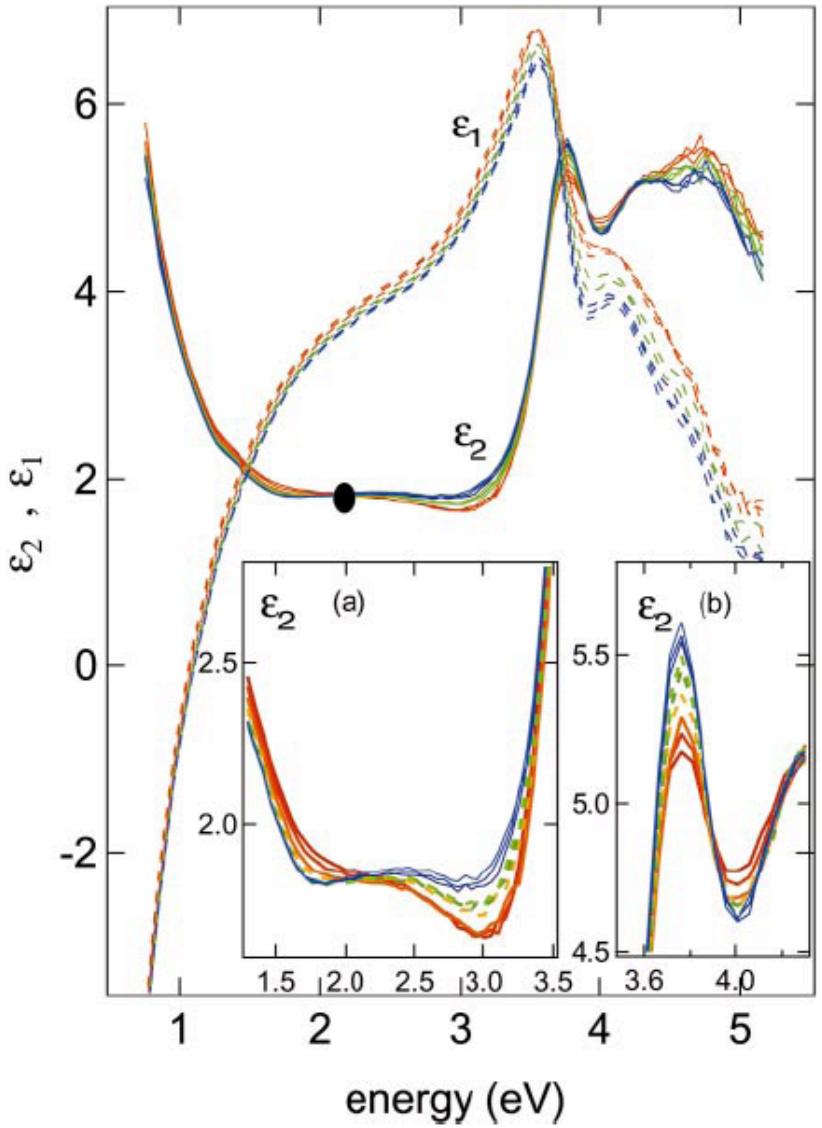


An increase is observed in the optical weight below T_c relative to the extrapolated behavior from above T_c

This implies a lowering of the electron kinetic energy

Molegraaf *et al.*, Science (2002)

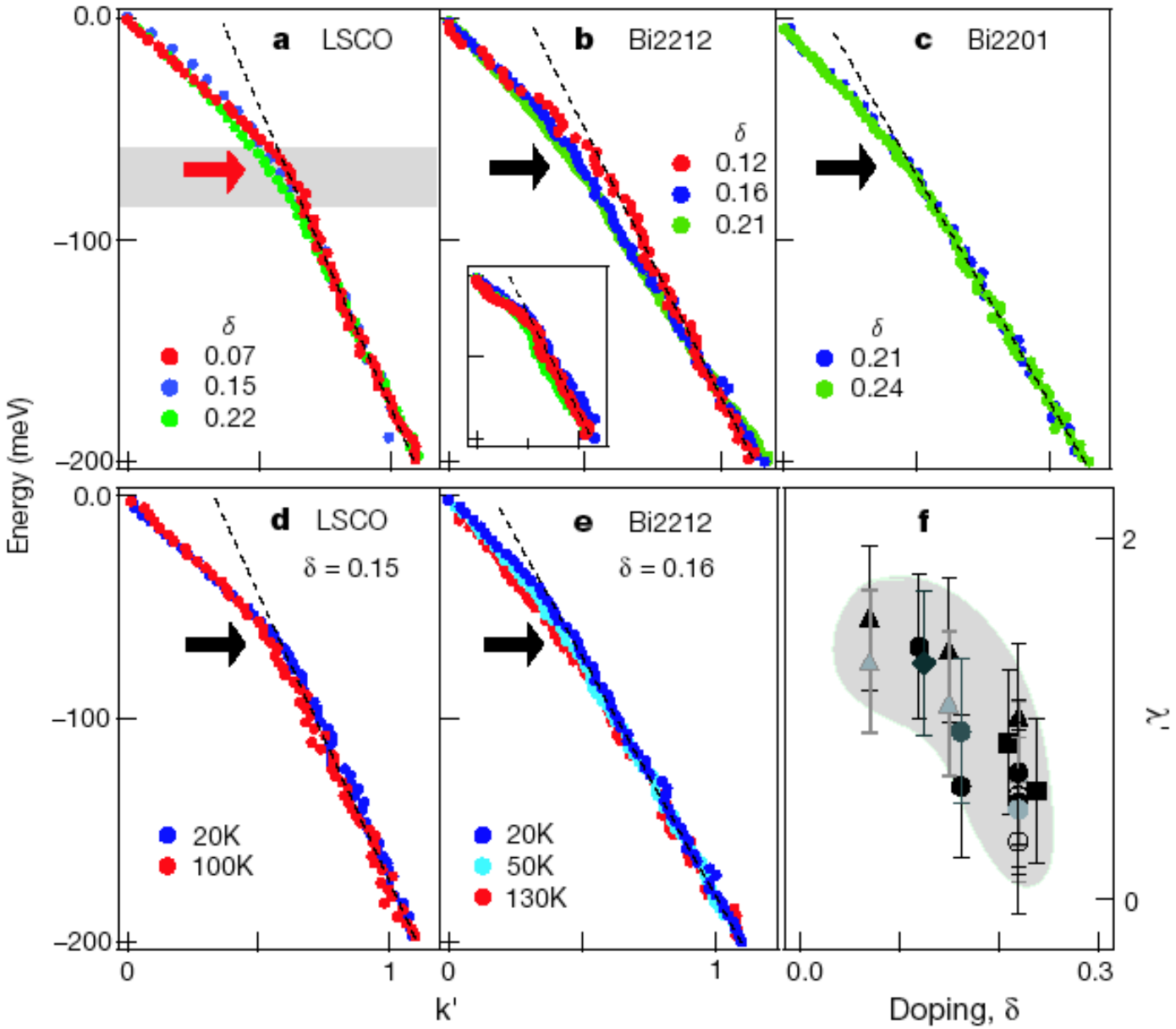
Superconducting induced changes in optics up to 5 eV



Rubhausen *et al.*, PRB (2001)

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

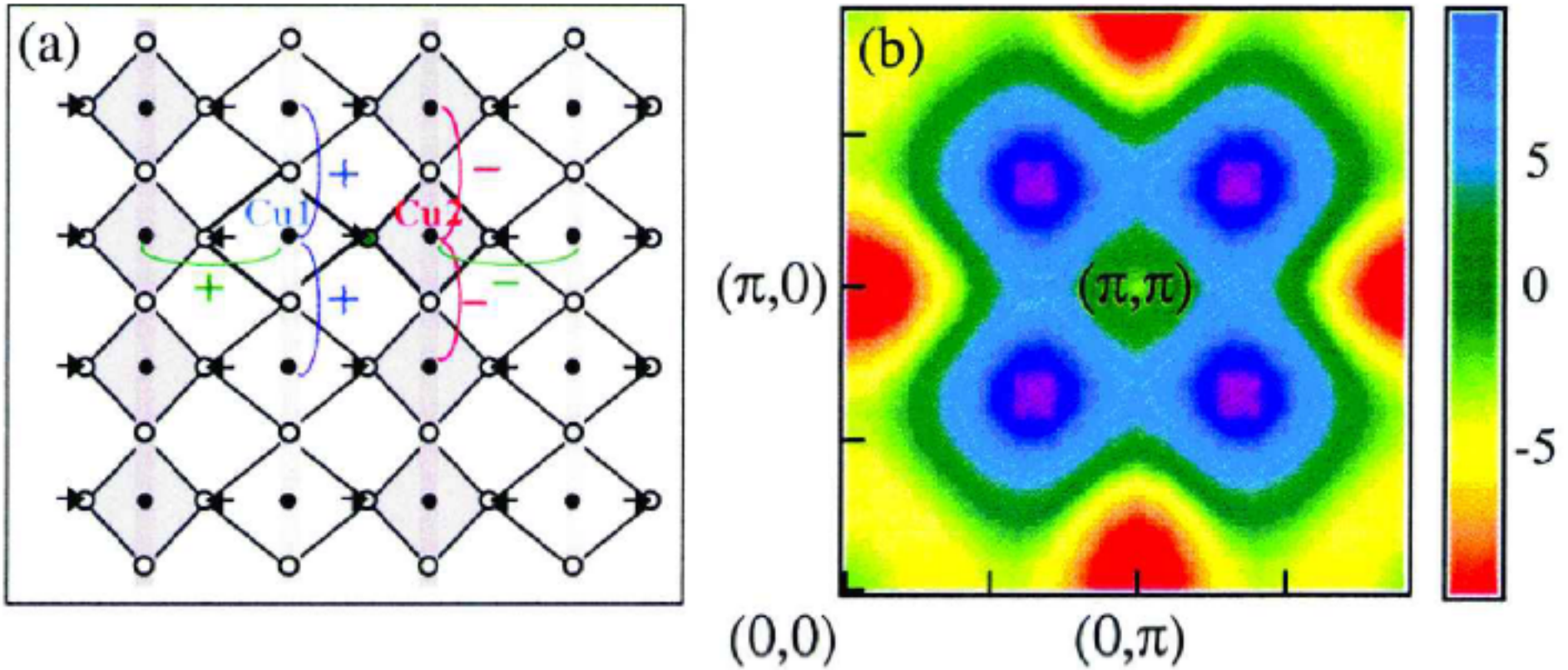
a phonon?



Lanzara *et al.*, Nature (2001)

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

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



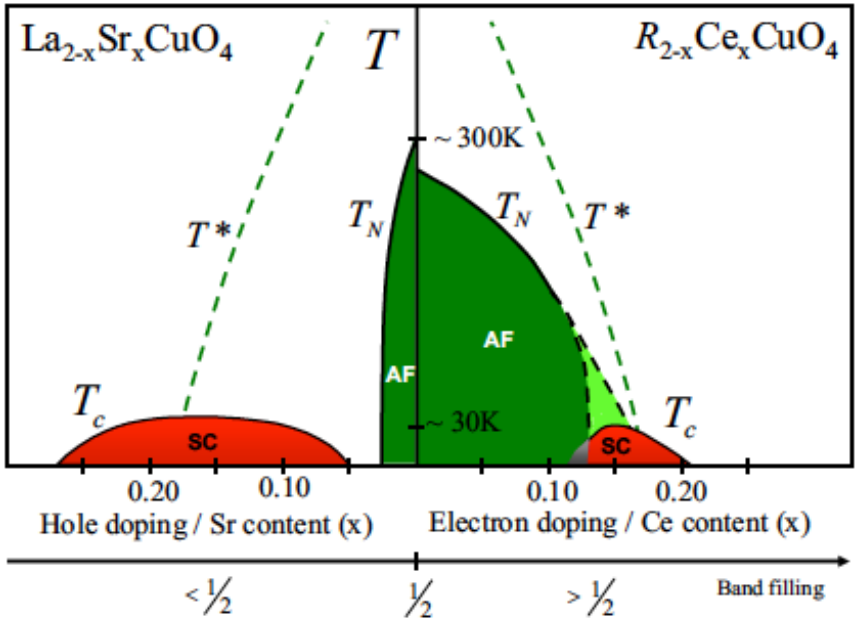
Invert ARPES, tunneling, optics, Raman to obtain α^2F (McMillan-Rowell)

Arnold, Mueller, & Swihart - PRL (1991)
Carbotte, Schachinger & Basov - Nature (2001)
Vekhter & Varma - PRL (2003)
Verga, Knigavko & Marsiglio - PRB (2003)
Bok *et al.* - PRB (2010)
Caprara *et al.* - arXiv (2010)

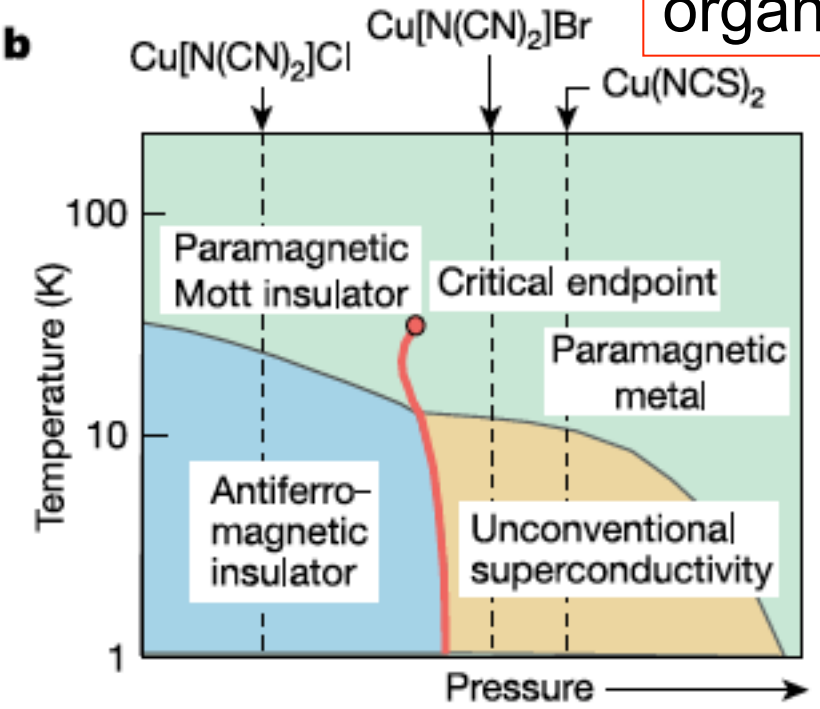
Issues

1. assumes Migdal's theorem
2. $\alpha^2F \leftrightarrow \Sigma \leftrightarrow \Sigma_{tr}$
3. s-wave kernel vs d-wave kernel
4. assumes all features are intrinsic

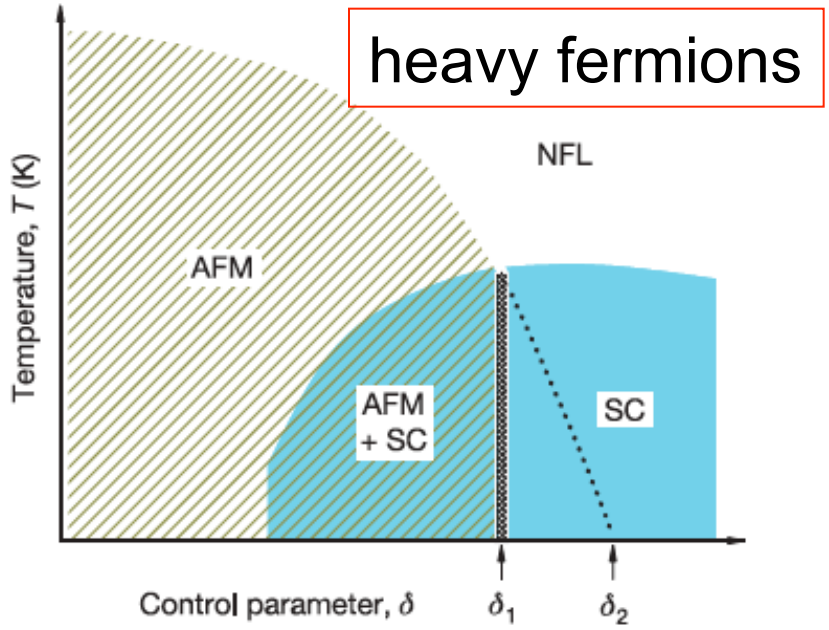
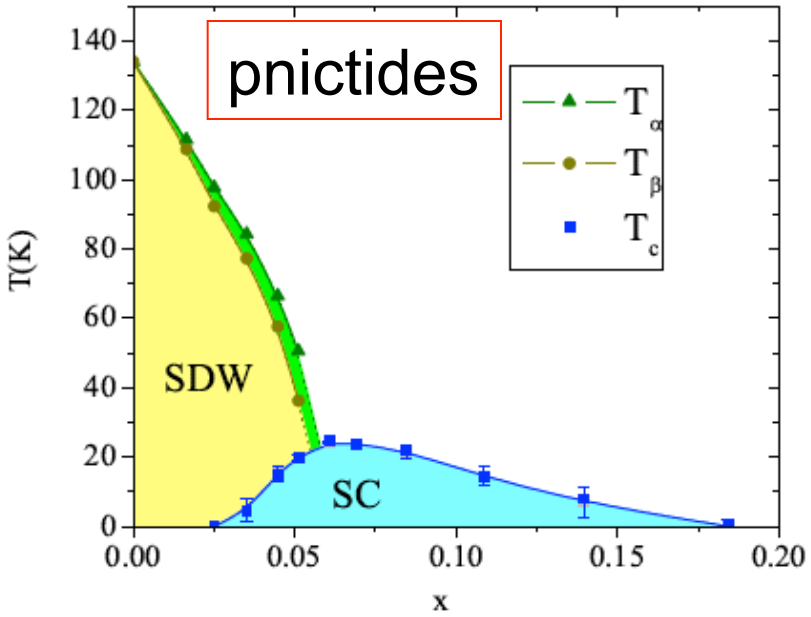
Similarity of Phase Diagrams



organics



heavy fermions



pnictides