The Exotic Pseudogap Phase in the Cuprates

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Origin of the Pseudogap : Umklapp Processes in both p-p & p-h scattering channels

R.Konik, Rice & A. Tsvelik PRL `05 & K.-Y. Yang, Rice & F. C. Zhang PRB '06

Superconductivity : Leggett Modes ? : Work in Progress

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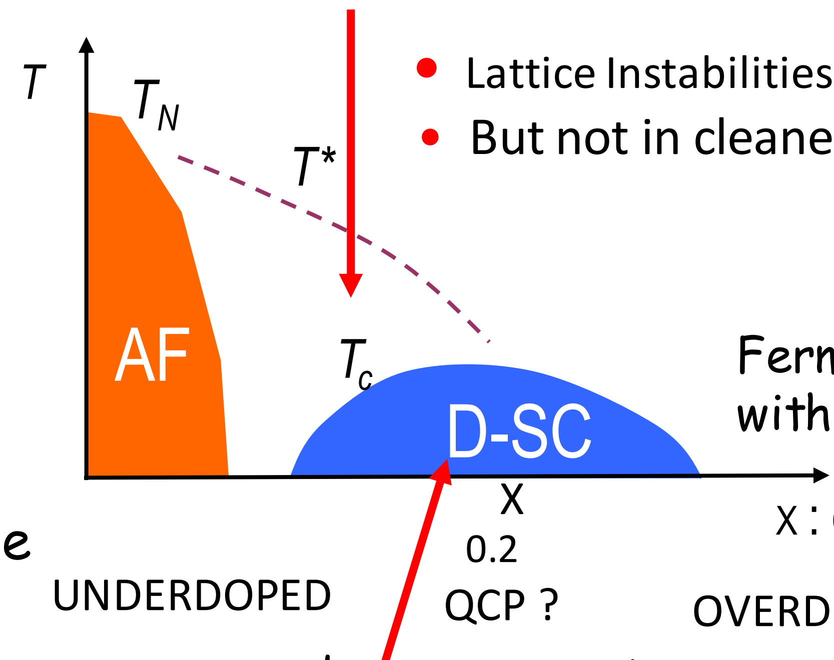
Crossover from Large Fermi surface metal to Mott insulator

Pseudogap Phase ??
Hall effect : doped Mott insulator

- Lattice Instabilities in some cuprates
- But not in cleanest cuprates



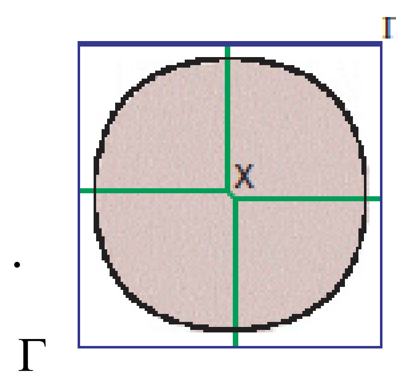
Mott Insulator
=> Charge Gap
=>No Fermi Surface

UNDERDOPED

OVERDOPED

Fermi Liquid Metal[??]
with Large Fermi Surface

d-wave symmetry
Kotliar&Liu '88,Zhang et al'88 . . .



Vignolle et al Nature 2008

Strongly interacting fermions –no small parameter !

Mott Insulating State viewed in k-space

Real space	***k***-space
Underlying lattice	Umklapp scattering processes allowed -> Momentum conserved modulo {***G***}
Band filling 1 el./site	Surface in ***k***-space enclosing an area of ½ - Brillouin zone.

Conclusion ; Examine growing Umklapp processes as x ↓
connecting ***k*** – points on
a U-surface :

a) spanned by elastic U- scattering processes

b) enclosing an area of ½ -Brillouin zone.

Key Features at the Onset of the Pseudogap

- PSgap grows out of SCgap at antinodal at T*: T* ↑ & SC Tc ↓ as doping x ↓
- PSgap => large change in Electronic Properties : NB ***Short not Long*** Range Order
- Breakup of Fermi Surface -> 4 Pockets(Arcs) centered on nodal directions
- Onset of PSgap changes Charge carriers to the Holes in a Mott State

Open Question – What is the origin of the pseudogap ?

Is it associated with a symmetry breaking transition
e.g. in the lattice, AF magnetism, orbital currents etc
or perhaps with strong fluctuations due to many competing instabilities ?

or

Is it a precursor to the Mott insulating state and simply a crossover
driven by Short Range Ordered d-wave Pairing & AF correlations ?

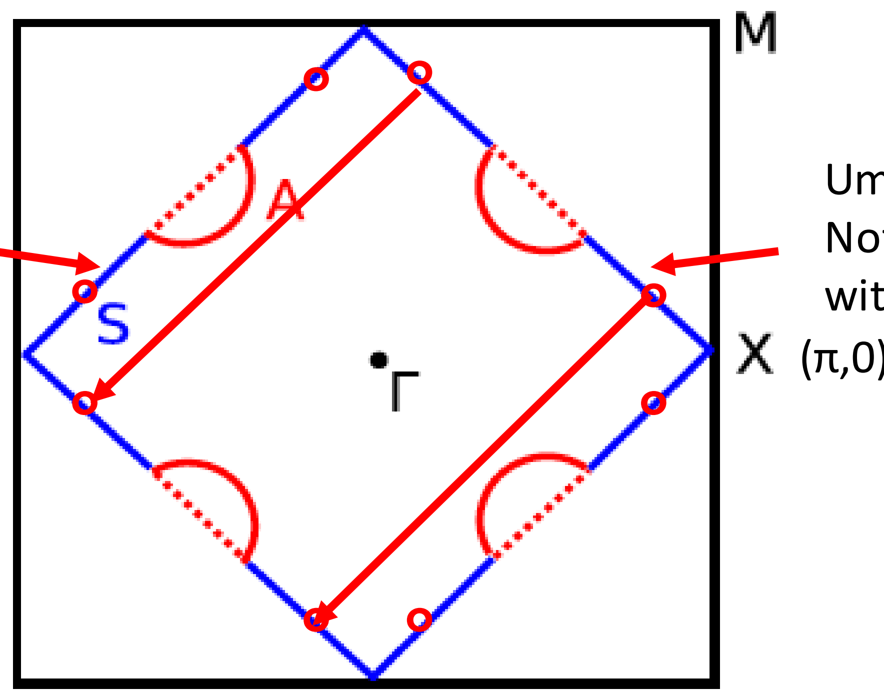
2D Square Lattice Hubbard Model

8 S-points degenerate on the Umklapp surface[AF BZ] connected by p-p & p-h Normal & U-scattering processes

=> Diagonalize Scattering Matrix derived from 1-Loop FRG which has strong p-h & p-p U-scattering thru (π,π)

=> Strong Similarities to ½ -filled 2-leg Hubbard Ladder A Groundstate with SRO in d-wave pp & AF channels

=> Compromise between conflicting d-wave pp & AF order



8 S-points —> Groundstate with RVB Charge & Spin gaps caused by U-processes

Ansatz for Propagator. => Pairing Self-Energy with Energy Gap on the U - surface [NOT Fermi surface]

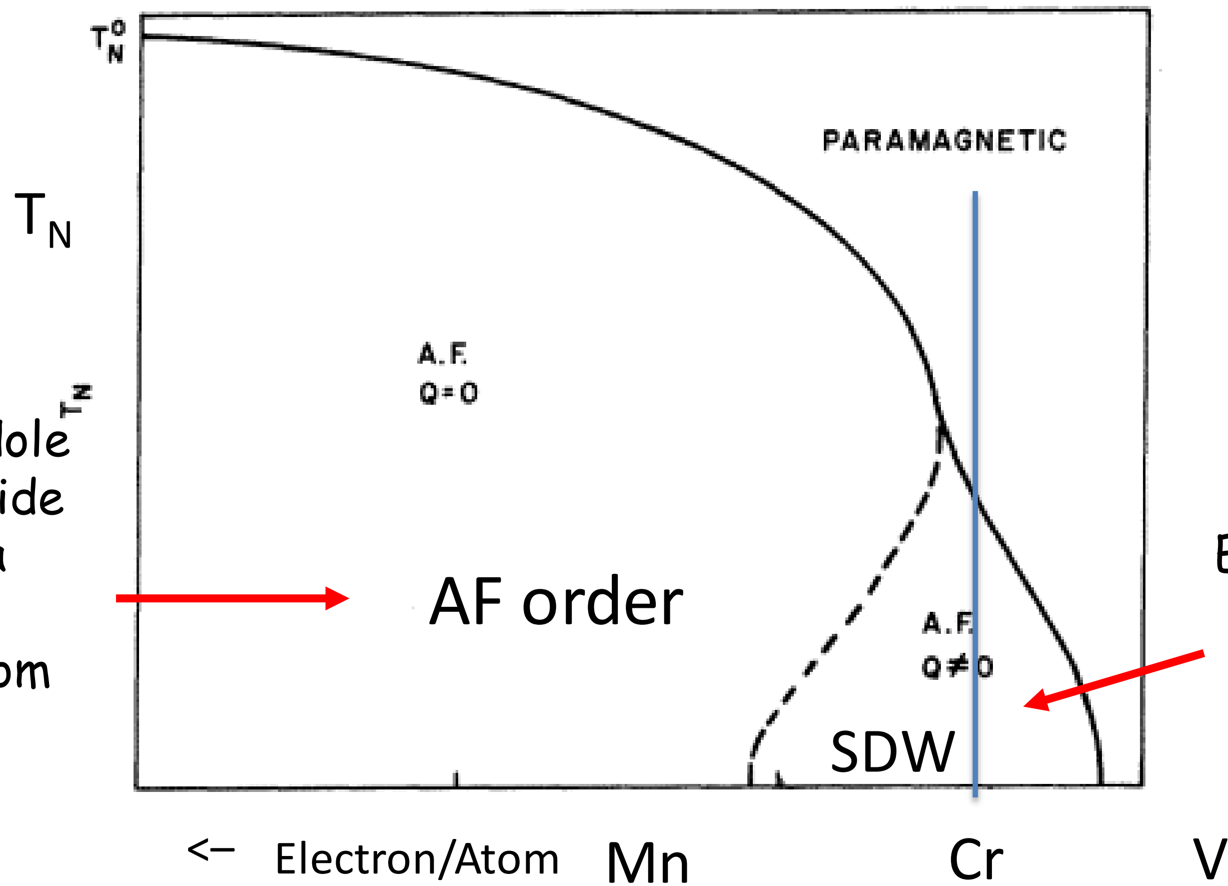
Yang, Rice & Zhang PRB '06

Maximize U-Scattering Processes: e.g. AF state in Cr alloys

Pure Cr Band Structure : Unequal Electron & Hole Pockets + Other Fermi Surface = Reservoir

BUT Commensurate AF order requires ***equal*** occupation of Electron & Hole Pockets

Equal El. & Hole Pockets in wide Range of e/a => Electron transfer from Reservoir

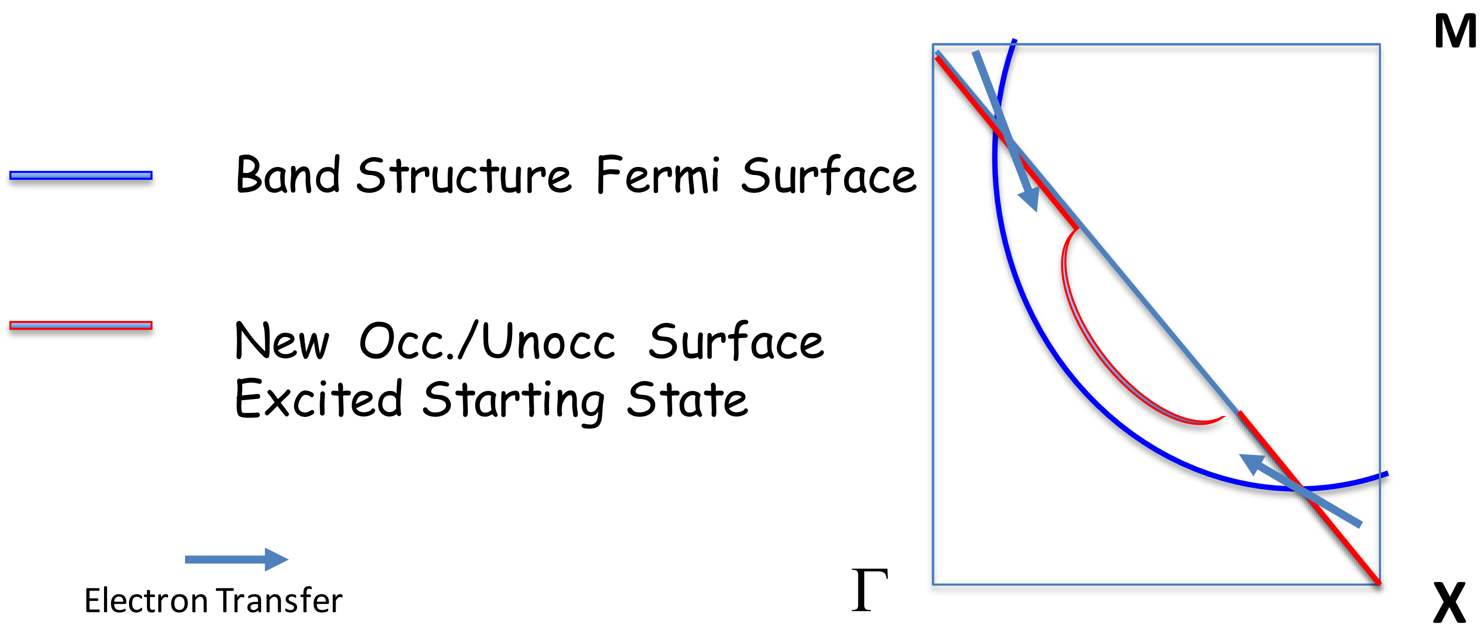


Electron < Hole
Pocket Pocket

Larger Energy Gap & T_N if AF is commensurate thru' extra U – scattering
=> Energy Gain compensates cost of electron transfer from reservoir

Modifying the Starting Occ / Unocc Surface to Maximize Umklapp Scattering

Maximize Overlap Occ/Unocc Surface with U-Surface with fixed electron count



Turning on Interactions => Large SRO Pairing & AF Gap fixed on U-surface

=> Real Gap Function with Insulating Character opens on the U-surface

YRZ Ansatz for Green`s Fn. in analogy with coupled ladders

K.-Y. Yang, Rice & F. C. Zhang PRB '06 see R.Konik, Rice & A. Tsvelik PRL `05

- RVB Gap $\Delta_R(k)$ opens on p-p Umklapp Surface (= AF Brillouin Zone in 2D)

$$G^{YRZ}(\mathbf{k},\omega) = \frac{g_t}{\omega - \xi(\mathbf{k}) - \Delta_R^2/(\omega + \xi_0(\mathrm{k}))} + G_{inc}$$

Pairing Self Energy but with energy gap fixed on the U-surface NOT Fermi surface

$$\xi_0(\mathbf{k}) = -2t(x)(\cos k_x + \cos k_y)$$
$$\Delta_R(\mathbf{k}) = \Delta_0(x)(\cos k_x - \cos k_y)$$
$$\xi(\mathbf{k}) = -2t(x)(\cos k_x + \cos k_y) - 4t'(x)\cos k_x \cos k_y - 2t''(x)(\cos 2k_x + \cos 2k_y) - \mu_p$$

nn nnn nnnn hopping

$\Delta_0(x) \rightarrow 0$ at $x = x_c$(= 0.2) : RVB Gap from Renorm. Mean Field Theory -F. C. Zhang et al `88

NB. 2-Leg Hubbard Ladder with SRO d-wave p-p pairing and AF at ½ -filling

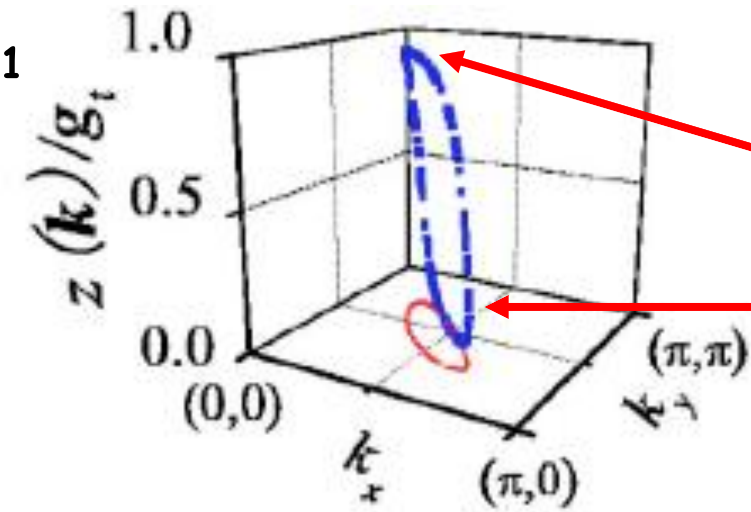
AF order => Charge Gap & Pairing order => Spin Gap

=> A Compromise State between the d-Pairing & AF Instabilities

YRZ => Full Fermi Surface breaks up into 4 Nodal Pockets

ARPES : Johnson Group BNL

H.B. Yang et al Nature '08 & PRL'11



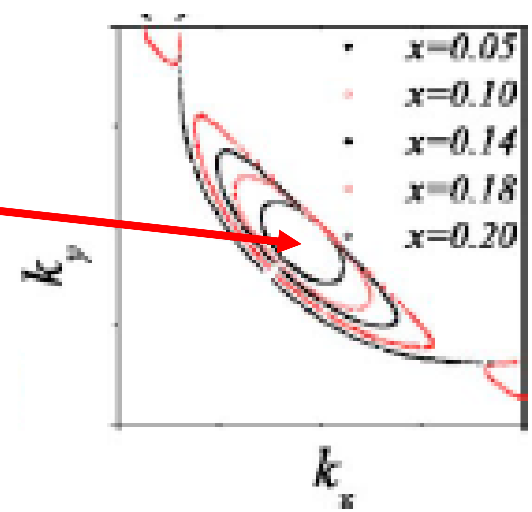
Front Large

QP Spectral Weight
very anisotropic
looks like an Arc

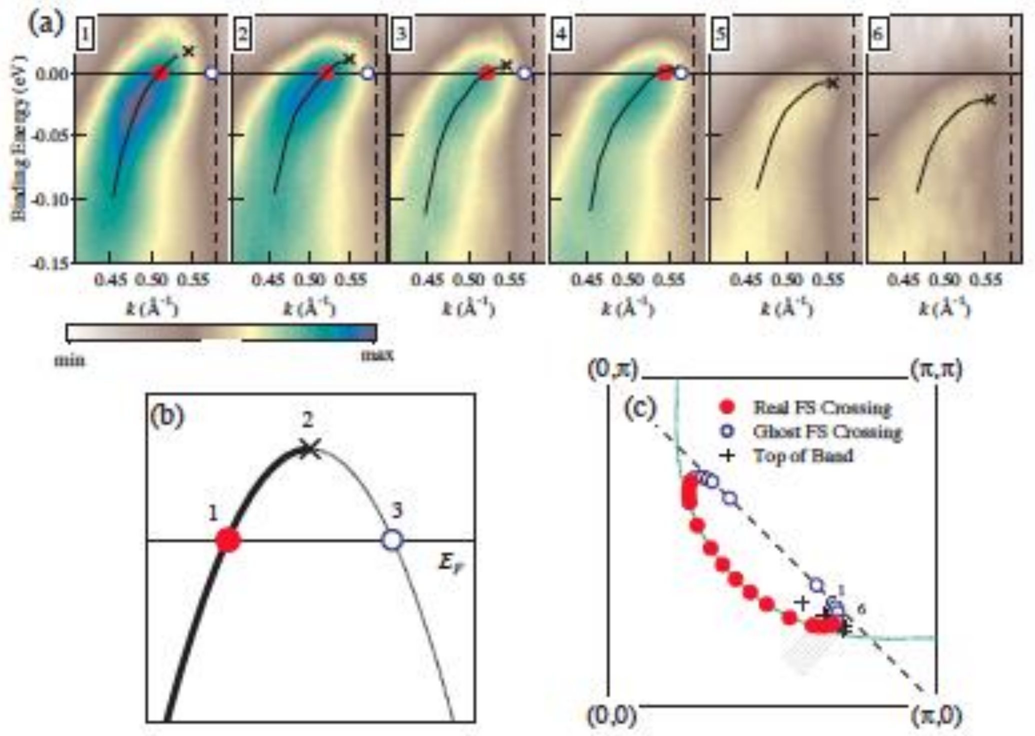
Back Small

Pocket arises due to back-bending of the
'Bogoliubov' Quasiparticle dispersion
leading to particle – hole asymmetry in the pocket

N.B. Pocket Area = x/4
Pocket ends in a Dirac point as x -> 0



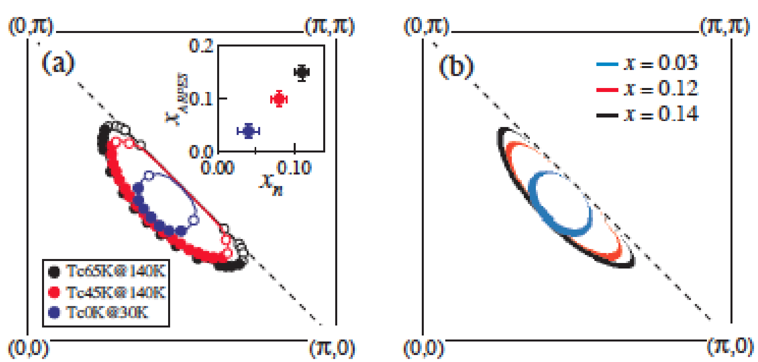
ARPES with Enhanced Resolution – BNL Group H.-B. Yang et al PRL 2011



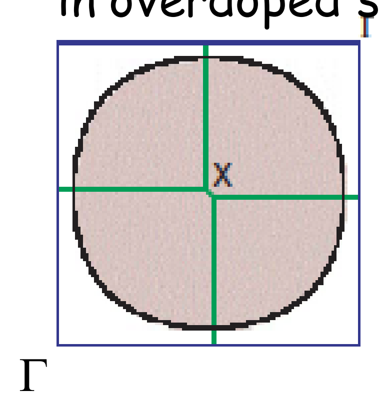
Fermi Surface "Arcs" are closed pockets with anisotropic Quasiparticle weights

QP dispersion extrapolated form maximum

Evolution of Nodal Pockets with doping in underdoped samples



Full Fermi Surface in overdoped samples

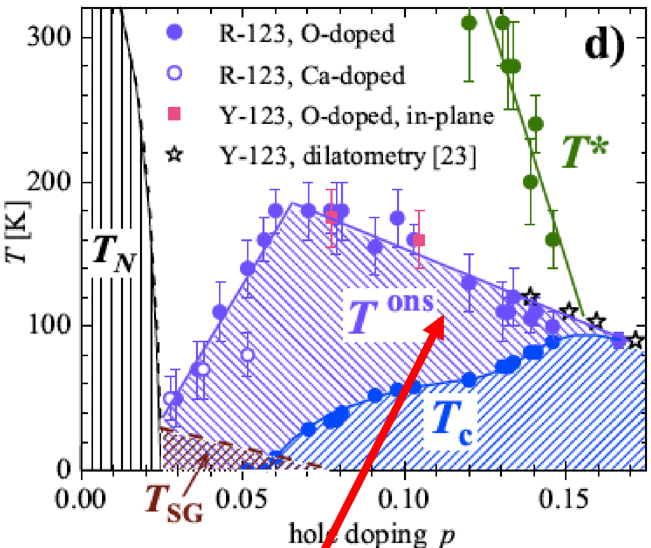


Anomalous Superconducting Properties appear at the transition from overdoped into the Pseudogap Phase

- Wide T-region of Superconducting Fluctuations
- The Giant Phonon Anomaly appears at the onset of PSgap
- Fermi Surface Breakup => Superconducting State Breakup ?

Superconductivity Changes in Pseudogap Phase !

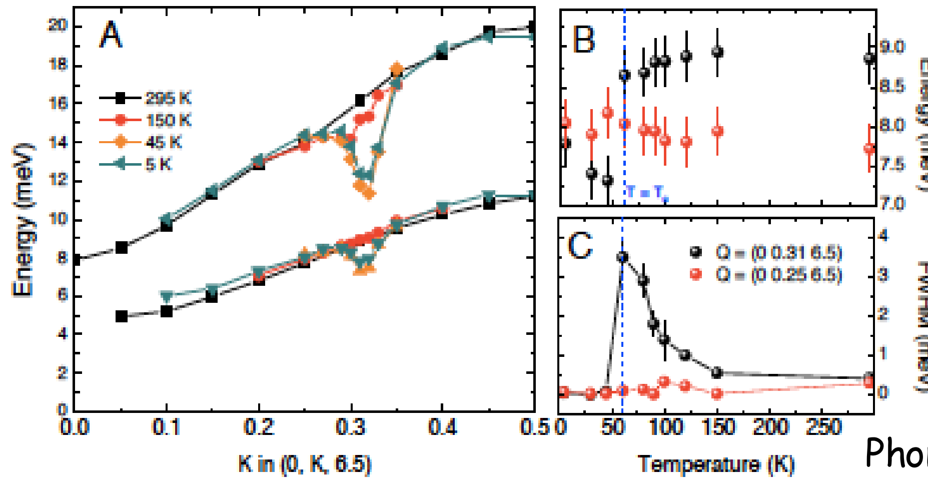
Wide SC Fluctuation Region



Phonon Energy

Giant Phonon Anomaly

Phonon Energy



Phonon Linewidth

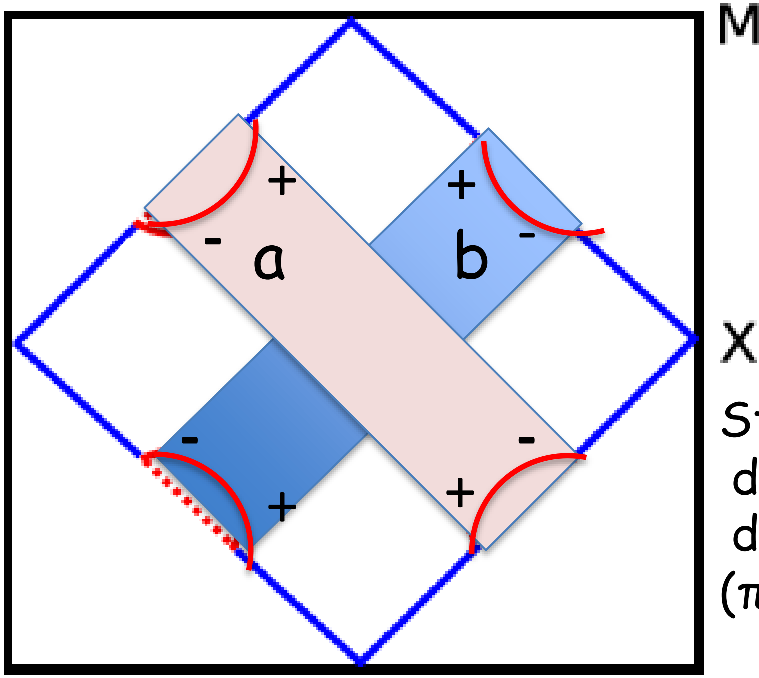
Onset Temperature of SC fluctuations from measurements of c-axis Josephson plasmon Dubroka . . . Bernhard PRL 2010

=

Onset Temperature of Giant Phonon Anomaly
Le Tacon - - Keimer Nat. Phys. 2014
Hayden Group PRL '13; Comin et al Science '14

Origin of these surprising anomalous effects ?

SC Breakup into 2 "bands"?



Strong Intraband { a & b} d-wave Pairing possible due to Strong Repulsive (π,π) Cooper pair scattering

Interband Cooper Pair Scattering may be weak due to cancellation of approximately equal and opposite sign regions

$$\Delta^*_a \Delta_b \sim \Sigma_{k,k'} V(k,k')\{<c^+_{k,\sigma} c^+_{-k,-\sigma}>_{a+} <c_{k',\sigma} c_{-k',-\sigma}>_{b+} + (a-,b-)$$
$$+ <c^+_{k,\sigma} c^+_{-k,-\sigma}>_{a+} <c_{k',\sigma} c_{-k',-\sigma}>_{b-} + (a-,b+)\}$$

Possibility - Intraband Pairing Scale > > Interband Pairing Scale => Leggett Mode

Leggett Mode in the PSgap Phase of the Cuprates ?

Leggett(1966) investigated a 2-Band BCS Model with interband pair scattering, J, weak compared to intraband pair scattering, V. Leggett found a collective mode due to interband phase oscillations[Cooper pair transfer] inside the SCgap in a 2-Band SC.

$\omega_L(q)^2 = \omega_o^2 + v^2/3$ with $\omega_o^2 = 16J\Delta^2 / \rho(V^2 - J^2)$ with $J << V$

Is there a similar Leggett Mode in PSphase => A collective mode at small (q,ω) in cuprates ?

NB. Interband Cooper pair transfer is a $q = 0$ process even though the individual quasiparticles in the Cooper pair undergo a finite q transfer.

Enhanced Superconducting Fluctuations in a 2-Component Superconductor with a low energy Leggett mode

2 Temperatures Scales:

a) T^{ons} : Onset of SC Fluctuations with $T^{ons} \approx \Delta_{max}/4$
Δ_{max} : SC Gap at pocket ends in ARPES – rises slightly as x ↓

b) T_{BKT} : Onset of Power Law Phase Correlations $T_{BKT} \sim x$ - (Emery-Kivelson '94)
=> Phase Locking between Components and 3D order at $T < T_{BKT}$

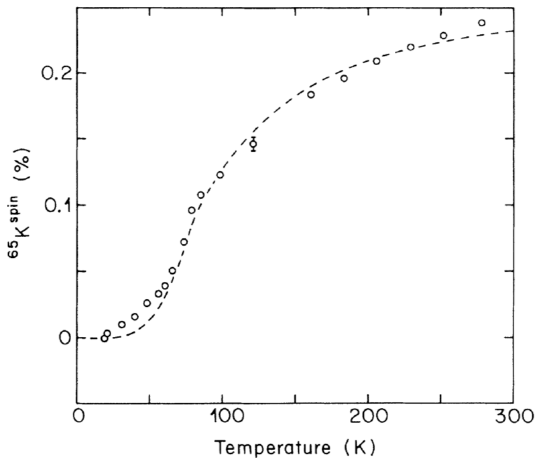
Intermediate Temperatures : $T^{ons} > T > T_{BKT}$?

Strong Thermal Intercomponent Phase Fluctuations:

$$\langle e^{i\phi_1} e^{-i\phi_2} + e^{-i\phi_1} e^{i\phi_2} \rangle = A(T) \approx T/\sqrt{(T-T_{BKT})}$$

$YBa_2Cu_4O_8$: Signs of GPA but no static CDW - ideal Psgap Superconductor

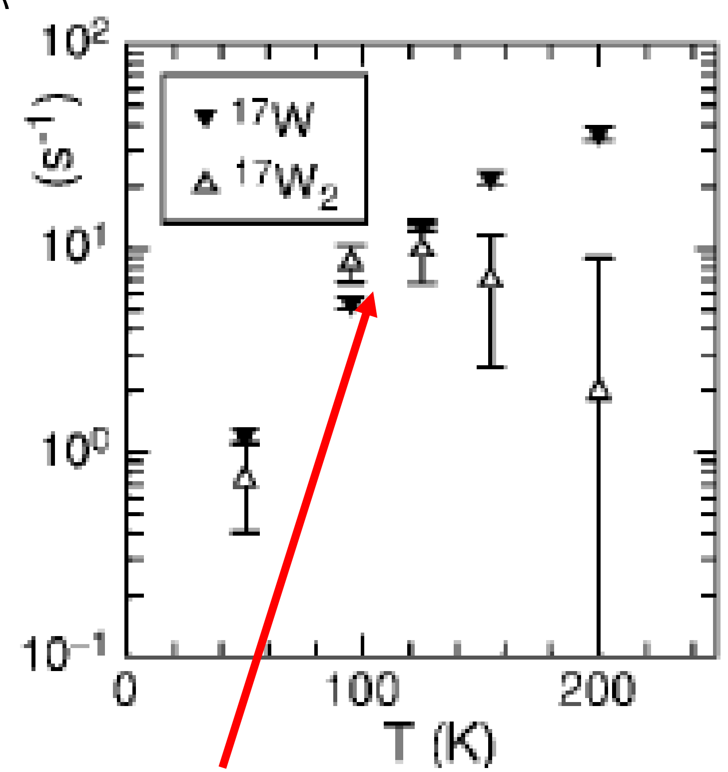
Cu Knight Shift shows Pseudogap at $T_C < T < T^*$



Bankay,Mali et al PRB ('94')

Tc = 80K

Suter,Mali et al PRL ('00)



NMR on planar O – sites Tomeno et al PRB '94

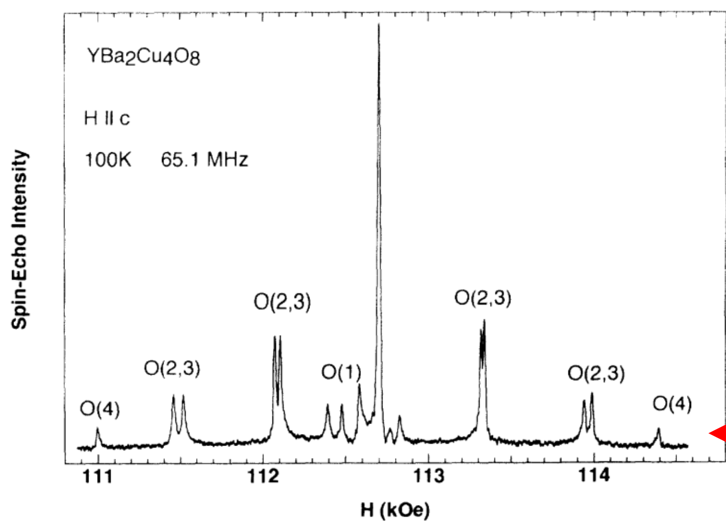


FIG. 3. ^{17}O NMR spectrum taken at 65.1 MHz and 100 K of aligned $YBa_2Cu_4O_8$ sample with *c* axis parallel to applied field.

$^{17}W_2$ – Anomalous Charge Relaxation in NMR on O-site with maximum at Tc

NB Charge Density agrees well with 'a priori' LDA calculations: No CDW
Ambrosch-Draxl et al PRB '91
Rodriguez et al PRB '97

No Static CDW order.

Conclusions

- PS gap : Consequence of increasing U-scattering which gives only Short Range Order due to conflicting AF & d-wave Pairing orders – YRZ Scenario

- Breakup of the Fermi Surface can lead to SC Breakup due to a soft Leggett mode and SC fluctuations over a large T interval in the Psuedogap phase

Open Question : Microscopy Theory of 2D SRO State which comprimises between d-wave pairing & AF order