The Exotic Pseudogap Phase in the Cuprates

T. M. Rice ETH Zurich &
Brookhaven Natl. Lab.

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

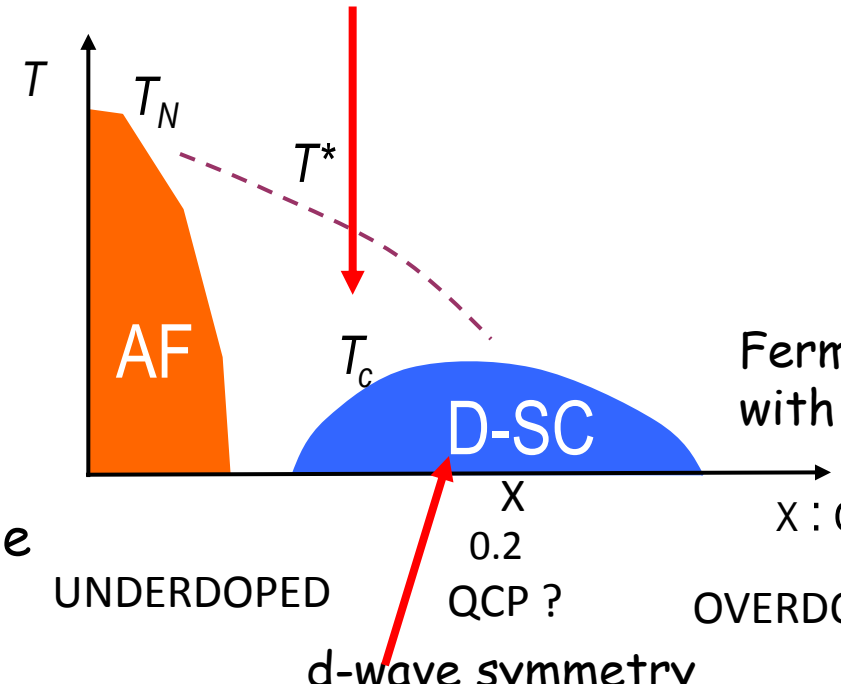
K.-Y. Yang, Rice & F. C. Zhang PRB '06

Superconductivity : Leggett Modes ? : Work in Progress

Collaborators: Robert Konik BNL
Ye-Hua Liu ETH & Fuchun Zhang, Zhejiang U Hangzhou
W.S. Wang & Q.H. Wang, Nanjing U

Crossover from Large Fermi surface metal to Mott insulator

Pseudogap Phase ??
Precursor to the Mott insulator

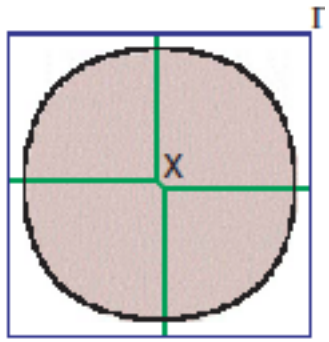


Mott Insulator

=> Charge Gap
=>No Fermi Surface

Fermi Liquid Metal[?]
with Large Fermi Surface

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

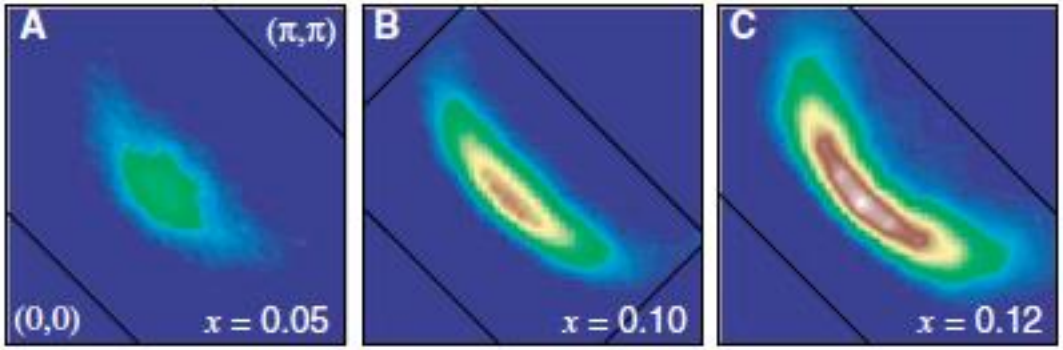


Strongly interacting fermions –no small parameter !

Vignolle et al Nature 2008

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 direction
  ARPES : Norman . . . . Hong Ding (1998)



Γ

$Ca_{2-x}Na_xCuCl_2O_2$ -Shen et al '05

ARPES signal within ± 10 meV of Fermi energy

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 ?

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 $\frac{1}{2}$ - 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 $\frac{1}{2}$ -Brillouin zone.

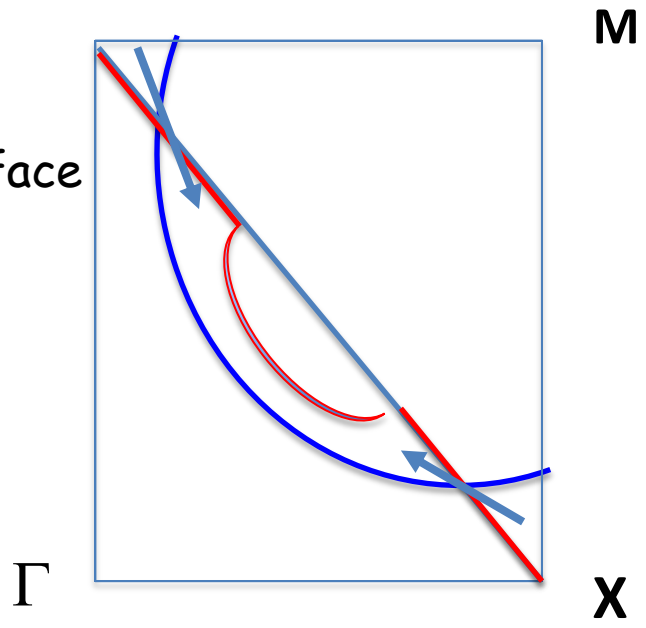
Modifying the Starting Occ / Unocc Surface to Maximize Umklapp Scattering

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

Band Structure Fermi Surface

New Occ./Unocc Surface
Excited Starting State

Electron Transfer

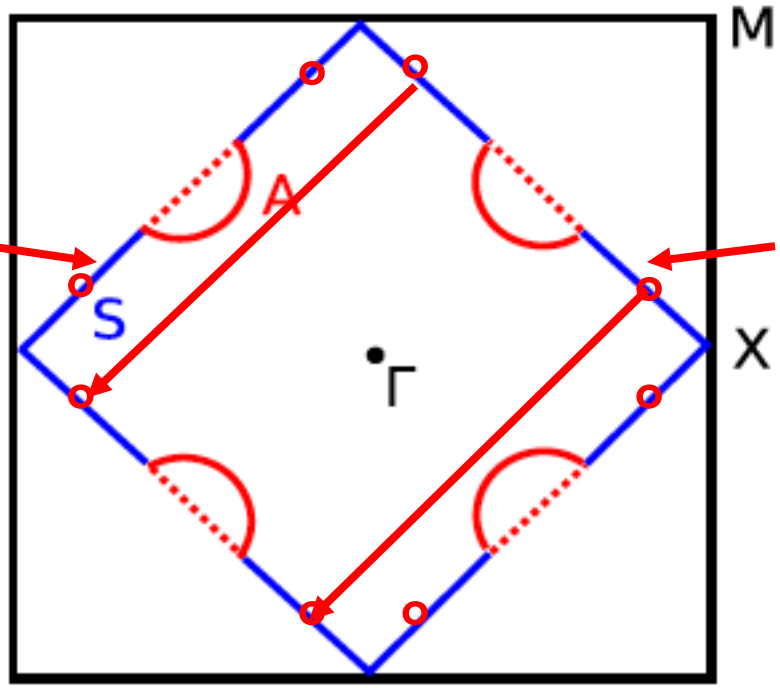


Turning on Interactions => Large SRO Pairing & AF Gap fixed on U-surface

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

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 $\frac{1}{2}$ -filled 2-leg Hubbard Ladder
A Groundstate with SRO in d-wave pp & AF channels
=> Compromise between conflicting d-wave pp & AF order



RVB Charge Gap

Umklapp p-p processes
Driver of Mott state

Umklapp Surface
Not at constant energy
with nnn hopping

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
Yang, Rice & Zhang PRB '06 [NOT Fermi 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

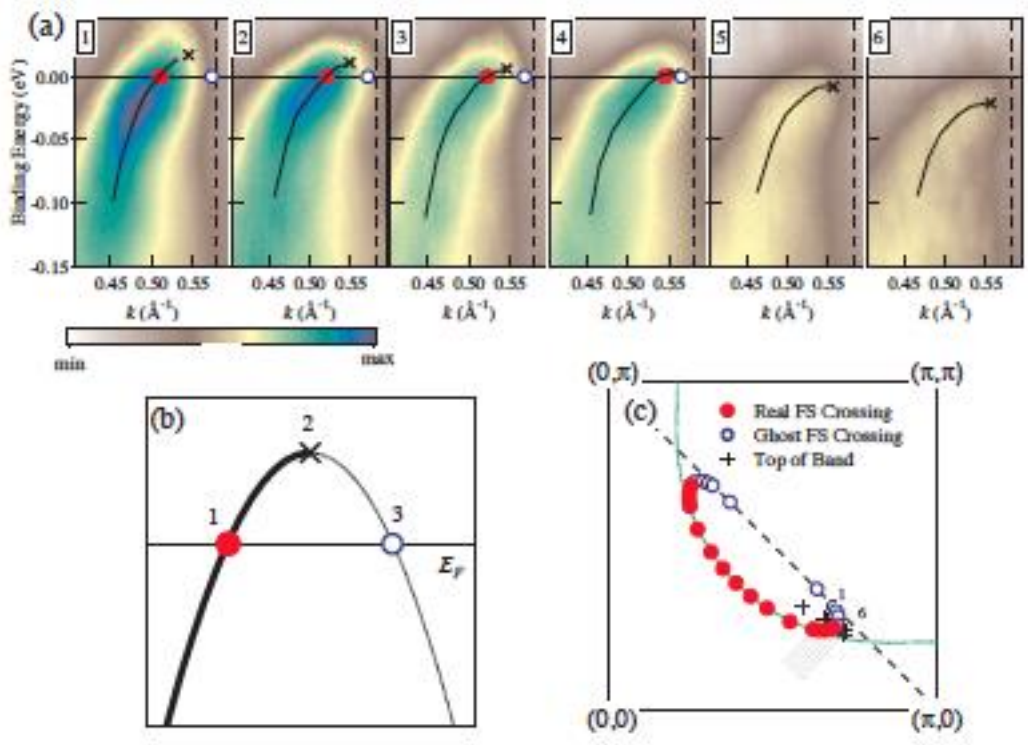
$$\xi_0(\mathbf{k}) = -2t(x)(\cos k_x + \cos k_y)$$
$$\Delta_R(\mathbf{k}) = \Delta_0(x)(\cos k_x - \cos k_y)$$
$$\xi(\mathbf{k}) = -2t(x)(\cos k_x + \cos k_y) - 4t'(x)\cos k_x \cos k_y - 2t''(x)(\cos 2k_x + \cos 2k_y) - \mu_p$$

nn nnn nnnn hopping

$\Delta_0(x)$ –> 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 $\frac{1}{2}$ -filling
AF order => Charge Gap & Pairing order => Spin Gap
=> A Compromise State between the d-Pairing & AF Instabilities

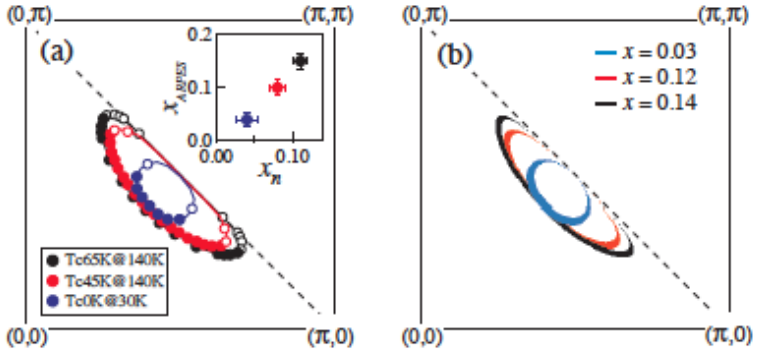
ARPES with Enhanced Resolution – BNL Group H.-B. Yang et al PRL 2011



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

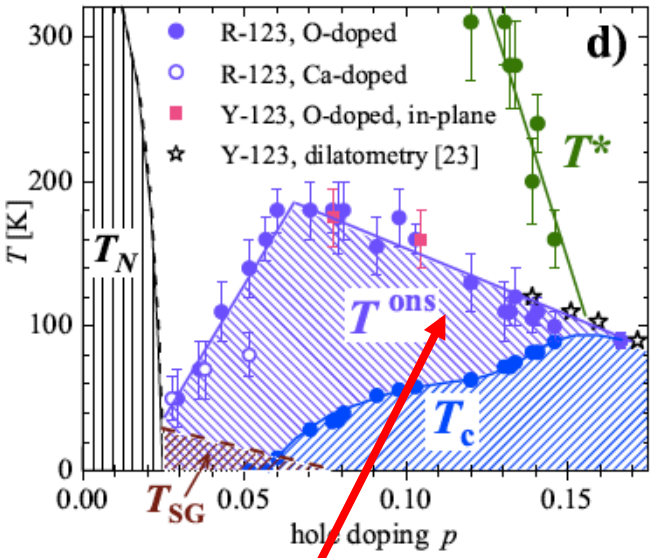
Recent results on Anomalous Superconducting Properties

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 ?

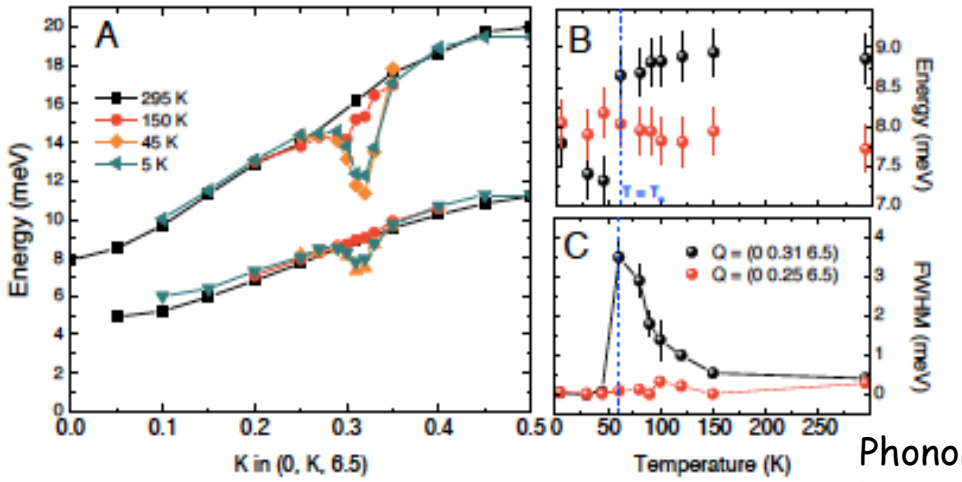
Superconductivity Changes in Pseudogap Phase !

Wide SC Fluctuation Region



Giant Phonon Anomaly

Phonon Energy



Phonon Energy

Phonon Linewidth

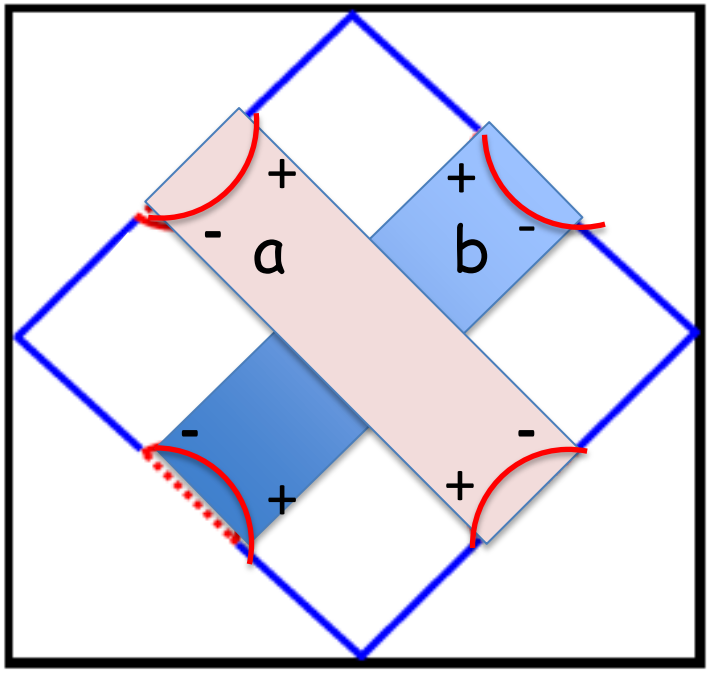
Onset Temperature of SC fluctuations from measurements of c-axis Josephson plasmon Dubroka . . . Bernhard PRL 2010

=

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 sets of Cooper "subbands" a & b



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

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

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

Possibility - Intrasubband Pairing Scale > > Intersubband Pairing Scale
=> Leggett Mode

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)

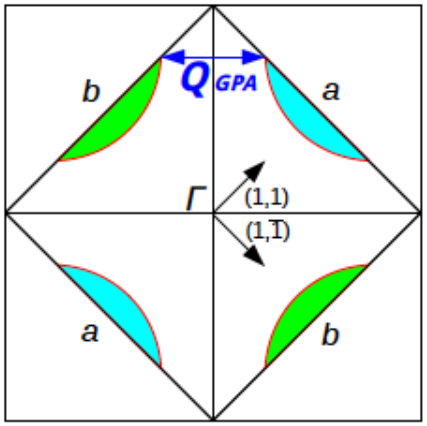
=> Phase Locking between Components and 3D order at $T < T_{BKT}$

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

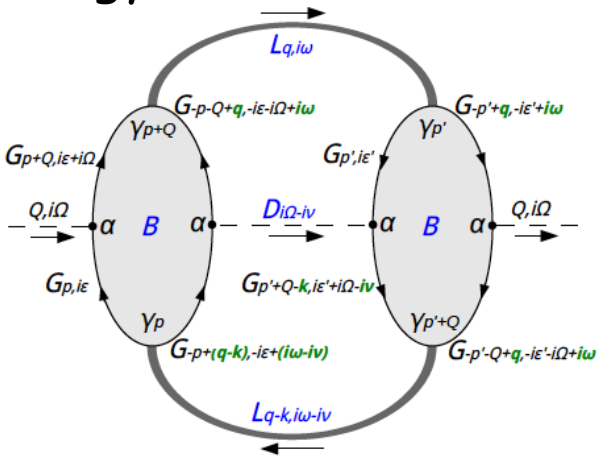
Strong Thermal Intersubband Phase Fluctuations:

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

Phonon Self Energy

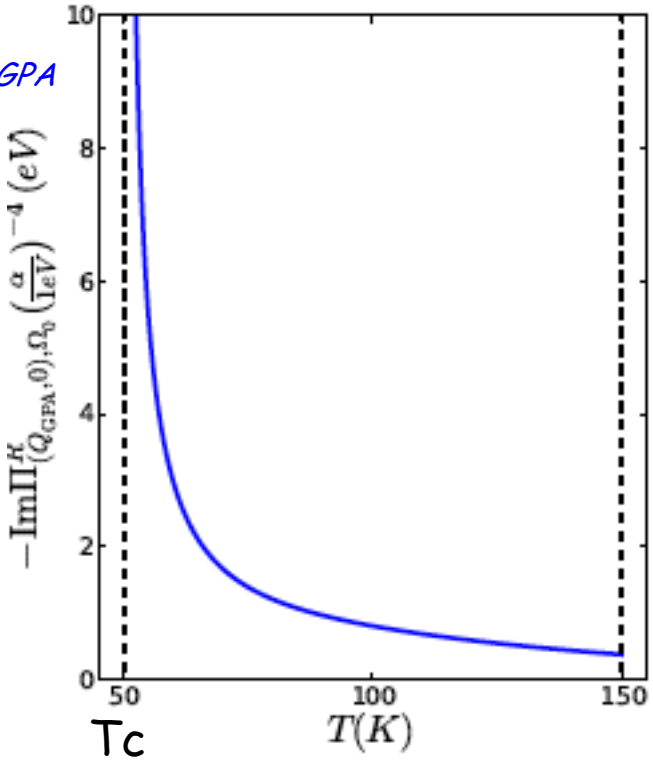


Leggett Fluctuation



Leggett Fluctuation

Phonon at Q_{GPA}
Damping
T -> Tc



T > Tc : Almost Resonant Scattering
Phonon -> Phonon + 2 Leggett Fluctuations

T < Tc: Finite Energy Leggett Mode
=> Small Damping

Y. H. Liu, R. Konik. T.M.Rice & F.C.Zhang
in preparation

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 Pseudogap phase

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