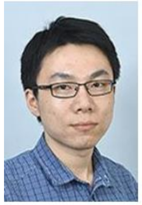
The Transformation of the Superconducting Gap to an Insulating Pseudogap with Decreasing Hole Density in the Cuprates

T. Maurice Rice
ETH Zurich & Brookhaven National Lab.

A priori treatment of strong correlations easier in **r –** space.

BUT the Pseudogap is in **k-** space.

k- space analysis requires postulating low energy effective interactions which leads to qualitative results only

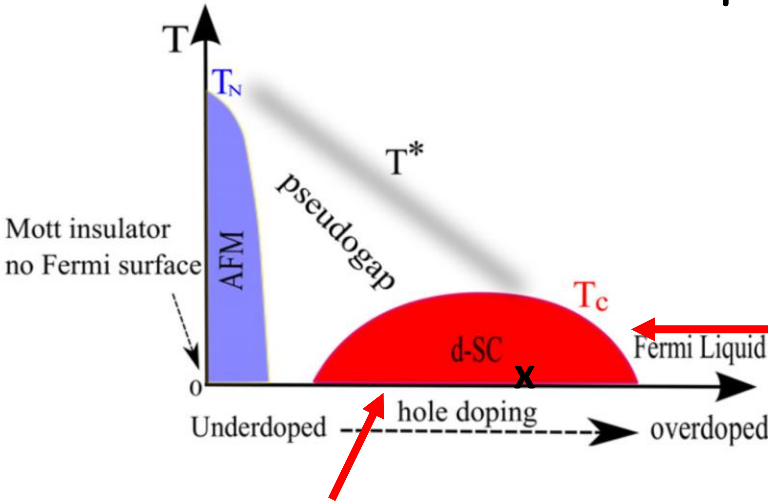


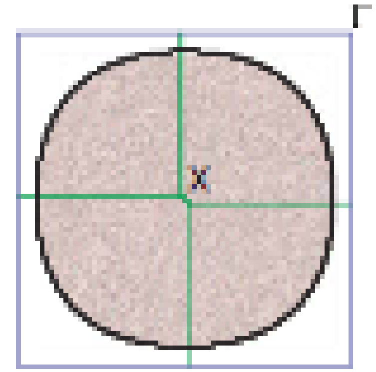

Y.-H. Liu, W.-S.Wang, Q.-H. Wang, F.C.Zhang & T. M. Rice arXiv1703.03695

Also Y. H. Liu, R. Konik. T.M.Rice & F.C.Zhang Nature Commun. **7** 10378 (2016)
Giant Phonon Anomalies associated with the Pseudogap

Phase diagram of cuprates :

Fermi Surface Evolution : Overerdoped to Underdoped : Full Fermi surface in overdoped region

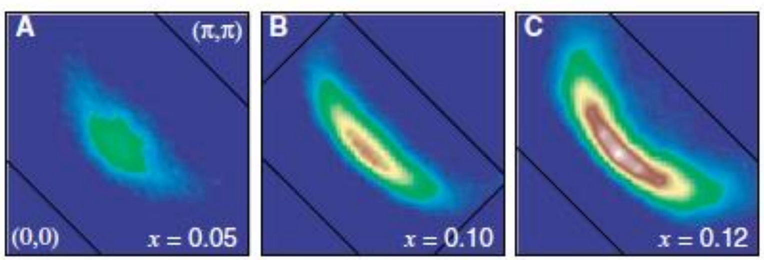




Fermi Surface from Quantum Oscillations
B. Vignolle et al Nature 2008

Pseudogapped Fermi surface in underdoped region : $T < T^*$

- Breakup of Fermi Surface -> 4 disconnected Pockets(Arcs)
- Centered on nodal direction ARPES : Norman . . . Hong Ding (1998)



ARPES on $Ca_{2-x}Na_xCuO_2Cl_2$
Kyle M. Shen et al Science 2005

Pseudogap is located at antinodal region

Precursor of the Mott Insulator ?

Pseudogap Phase only Short Range Order

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 decreases connecting ***k*** – points on a U-surface :

U -surface a) spanned by elastic U- scattering processes

b) enclosing an area of ½ -Brillouin zone.

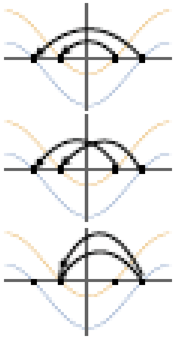
How to describe a Short Range Ordered State ?

- Use a Wave- Packet Formalism localized in both **k** & **r** - Space
  Approximate as a Lattice of Strongly Correlated Supercells
  - Ossadnik arXiv 1305.2534 & 1603.04041

- Energy Spectrum of Single Supercells Decisive:

e.g $\frac{1}{2}$ –filled 2-Leg Hubbard Ladder with U-scattering processes

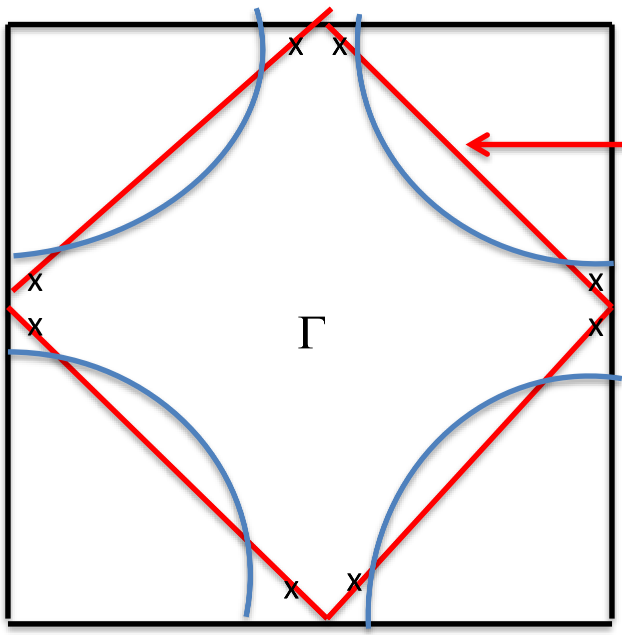
Isolated Unique Insulating Groundstate
with Charge Gap and Spin Gap
1- & 2- particle gaps & S =1 gap



SRO : d-wave pairing & AF (π,π)
=> D-Mott Insulator Balents – Fisher '96 & '98
Continuous Crossover between weak and Strong Coupling.

Extend to 2D Square Lattice near $\frac{1}{2}$ - filling ?

Umklapp Scattering Surface in 2D



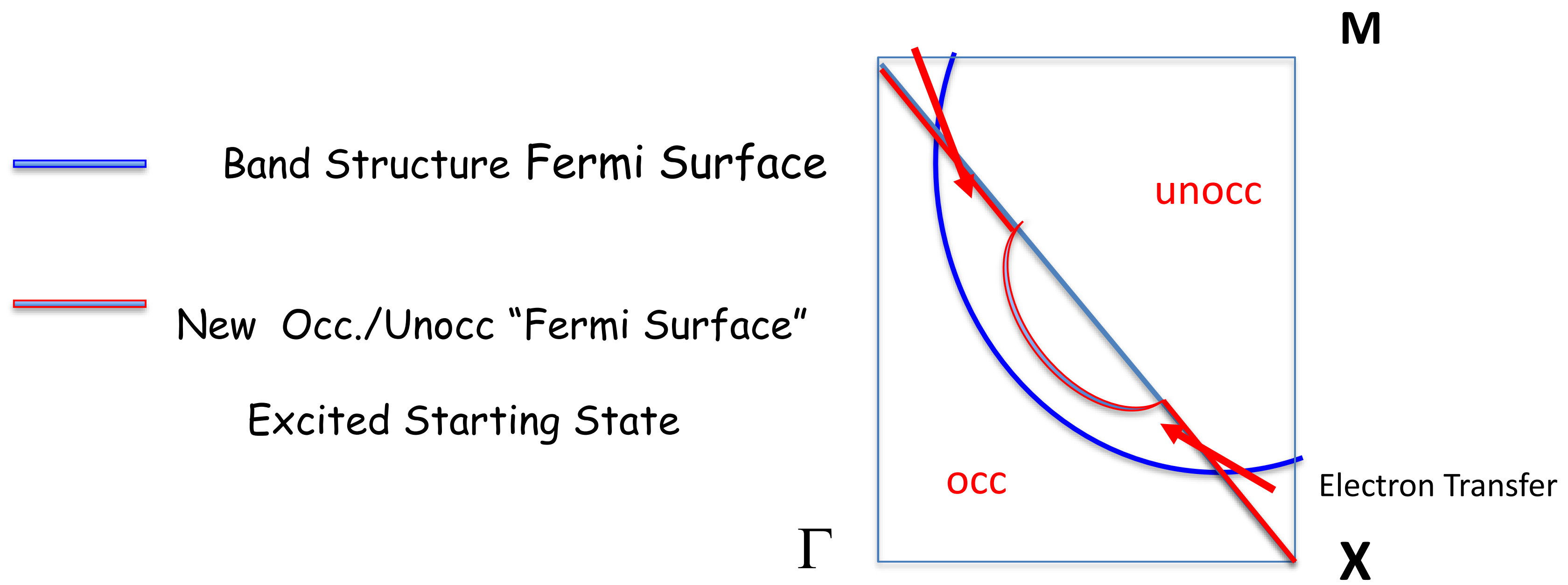
Umklapp Scattering Surface
Not at constant energy with nnn hopping
BUT 8 x–points are degenerate and are connected by U -processes

Scattering in 1-Loop FRG gives a low energy effective model :

Strong p-h Umklapp - AF (π,π) & d-wave Cooper pair scatterings [Honerkamp et al '01, Q. H. Wang et al]

Modifying the Starting Occ / Unocc Surface to Maximize Umklapp Scattering

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



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

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

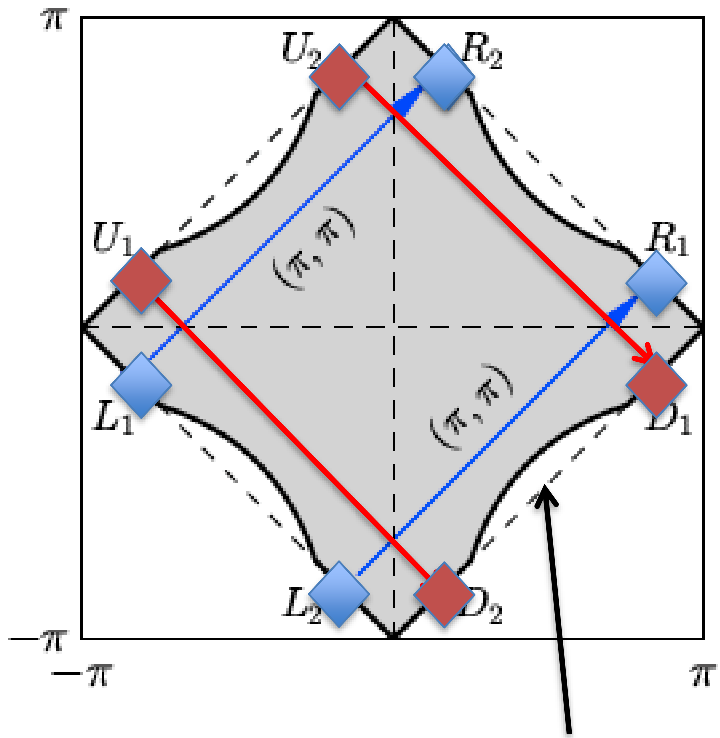
U-Scattering Processes on the U-Surface

(π, π) U Scattering Processes connect the perpendicular (1,1) & (1,-1) directions separately
i.e. not between {U,D} & {R,L} patches => Treat each separately as 2-Leg Ladders

Map each set of {R ,L} and {U, D } patches to 2-Leg Ladders with **k** – dependent parameters

=> Pseudogap Energy Gaps to add both 1-el (E_1) & 2-els (E_2) leading to Insulating behavior

⇒ also SRO AF (π,π) in dSC (T < Tc) & normal states (T > Tc)



Pair Scattering Processes on the 4 Fermi Arcs => d-wave SC pairing => E_2 =0

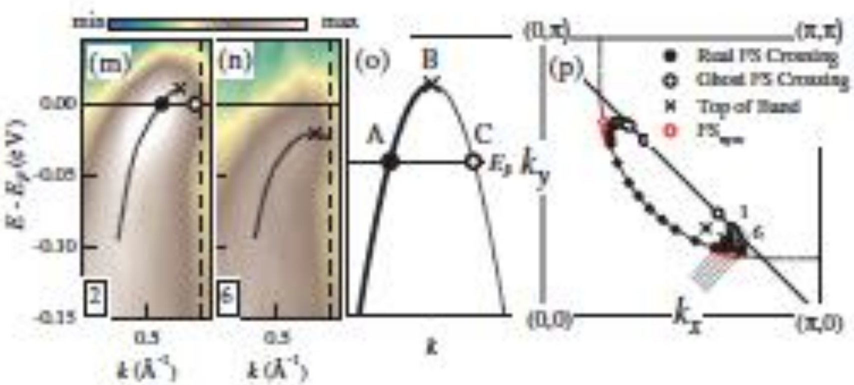
YRZ Ansatz for propagator with Energy Gap fixed on US

$$G^{RVB}(k,\omega) = \frac{g_t}{\underbrace{\omega - \xi(k)}_{\text{orignal FS}} - \underbrace{\Delta_R^2/[\omega + \xi_0(k)]}_{\text{open gap at US}}} + G_{inc}$$

orignal FS open gap at US

YES nnn hopping NO

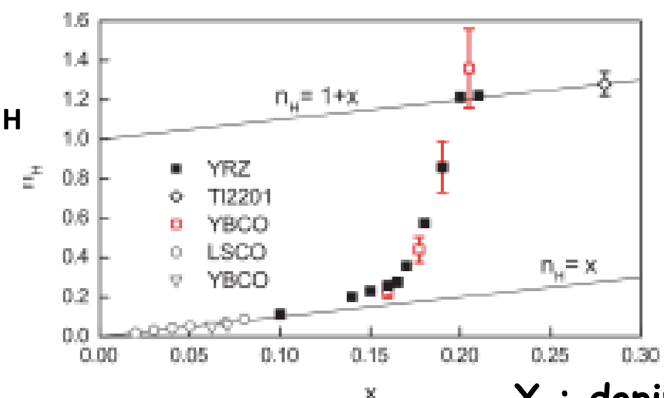
Yang, Rice, Zhang, PRB '06



ARPES H. B. Yang et al, PRL 2011 BNL

Hall Effect at onset of Pseudogap

n_H

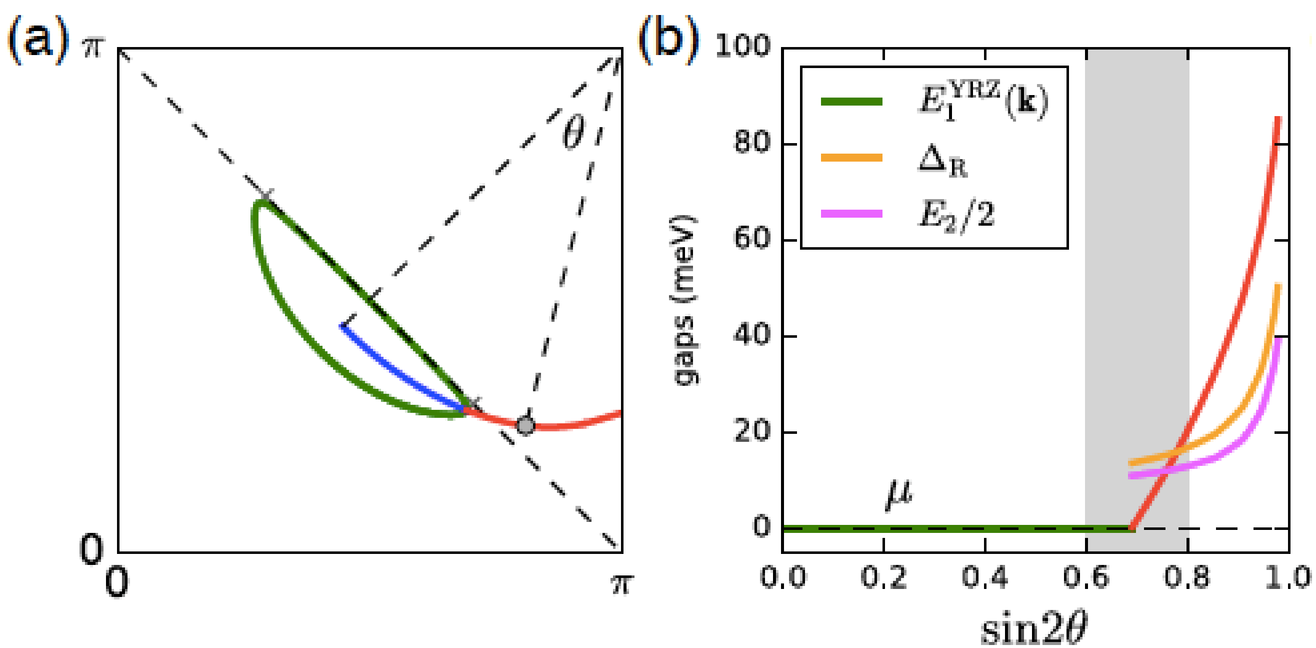


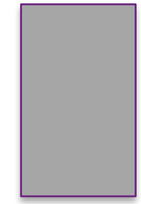
X : doping

J. G. Storey, EPL 2016

Expts : Taillefer group 2016

Normal State Energies





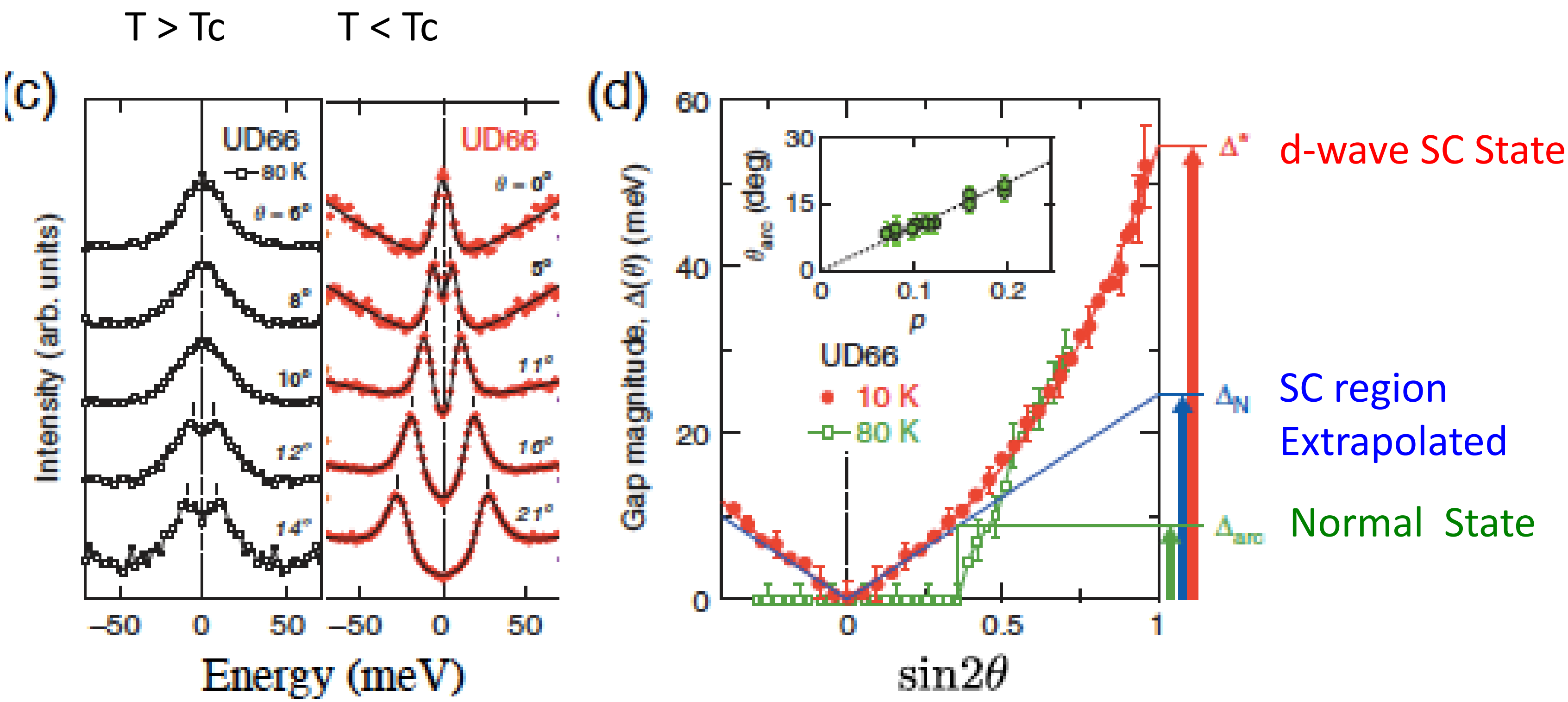
Transition Region

Single Particle Energy : along Nodal Pocket (YRZ form)

Minimum hole energy not along Umklapp Surface

Cooper Pair Energy (per Hole) along Umklapp Surface
Indicating pairing short range correlations $E_1 > E_2 > 0$

ARPES{ single hole} Spectra{Symmetrized} Anzai et al(2013) on UD BSCCO sample Tc = 66K

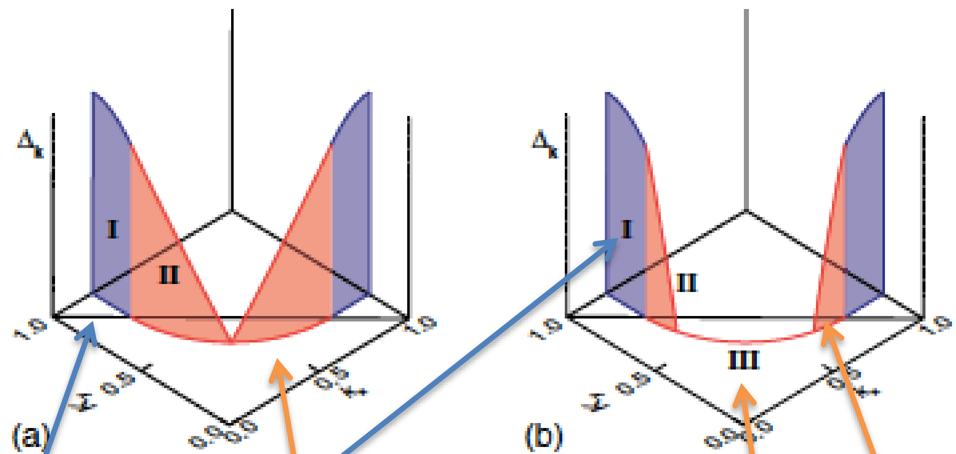


Energy Symmetrized ARPES Spectra
Note: Pairing Fluctuations at crossover
T ~Tc broadens peaks

Single Particle Energy Gaps
Note: Pseudogap constant at T > Tc

Scanning Tunneling Microscopy Results for $E_1(\mathbf{k})$ - Davis Group

Fujita et al JPSJ (2012)



SC state; I : Pseudogap

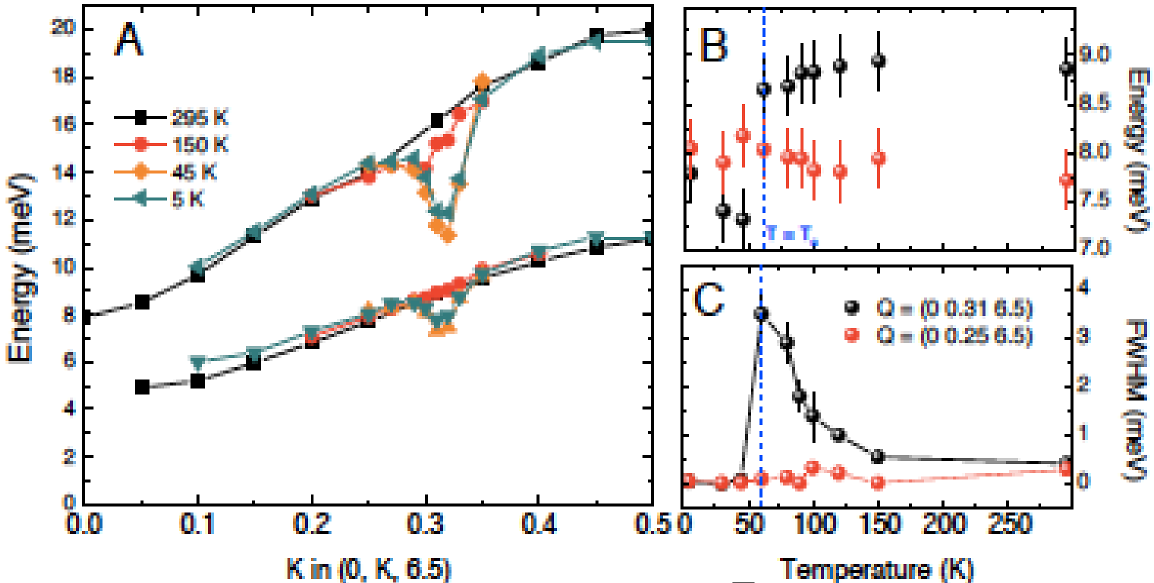
II : d-wave SC gap

Normal state; II : Transition Region

III : Nodal Fermi Arc

Unusual Giant Phonon Anomaly accompanies pairing Fluctuations

IXS Scattering Expts. LeTacon et al 2014



Dispersion

Damping

T_c T^{ons} = 150K of pairing fluctuations

$T^{ons} > T > Tc$: Strong Damping of Phonons increasing as T -> T_c

Not a softening as a precursor to a CDW instability

T < Tc Damping disappears and Dispersion dip appears

Conclusion : GPA is associated with the anomalous pairing fluctuations

Puzzle : How are Finite Energy & Finite Wavevector Phonons

coupled to Superconductivity Fluctuations at ($\boldsymbol{k}$,ω) ≈ 0 ?

Answer => Y. H. Liu, R. Konik. T.M.Rice & F.C.Zhang

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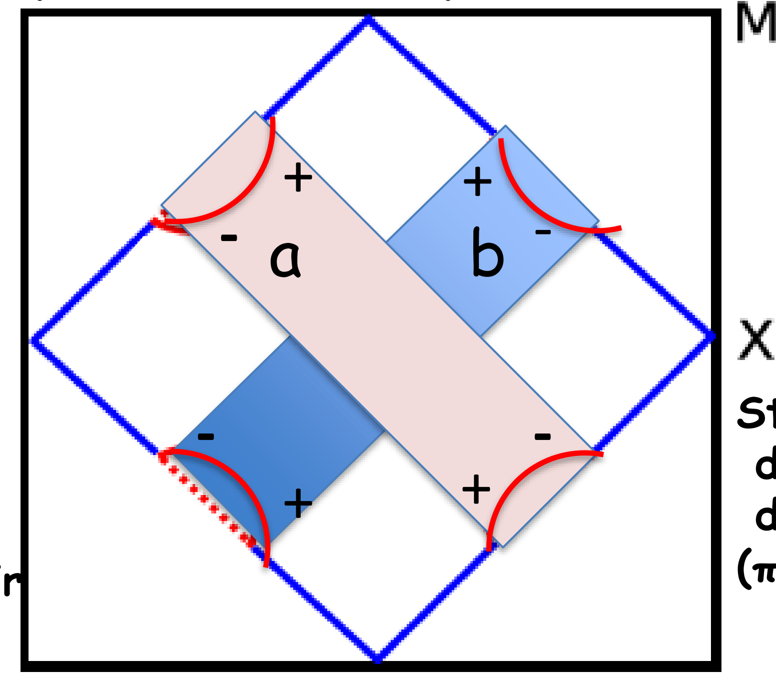
Fermi Surface Breakup => SC Breakup into 2 sets of Cooper"subbands"?



d-wave symmetry Driver in overdoped region: Large Antinodal SC gaps connected by Strong Repulsive(π,π) Cooper pair scattering are absent in pseudogap region

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

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

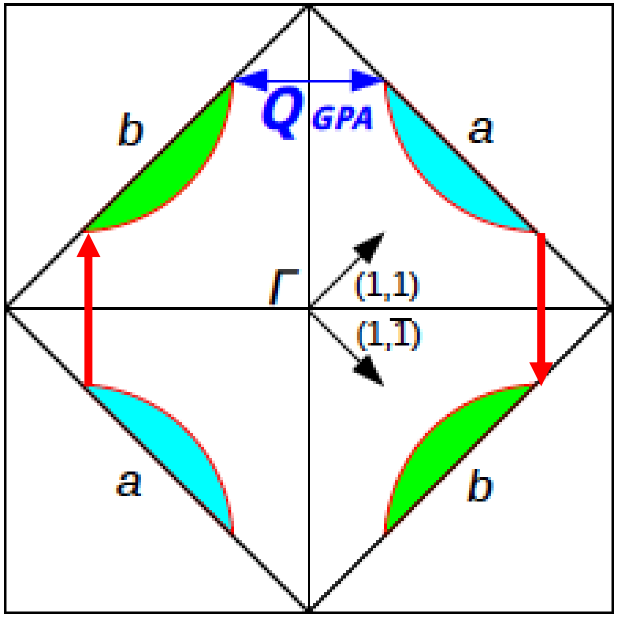
$$\Delta^*_a \Delta_b \sim \Sigma_{k,k'} V(k,k')\{\langle c^+_{k,\sigma} c^+_{-k,-\sigma}\rangle_{a+} \langle c_{k',\sigma} c_{-k',-\sigma}\rangle_{b+} + (a-,b-)$$
$$+ \langle c^+_{k,\sigma} c^+_{-k,-\sigma}\rangle_{a+} \langle c_{k',\sigma} c_{-k',-\sigma}\rangle_{b-} + (a-,b+)\}$$

Intrasubband Pairing Scale > > Intersubband Pairing Scale
=> Low Energy Leggett Mode due to Intersubband Phase Fluctuations; Leggett ('66)

How do Intersubband Phase Fluctuations couple to Phonons ?

An intersubband Q- phonon moves a single QP between subbands.

Cooper Pairs require Absorption & Emission of Q –phonons.



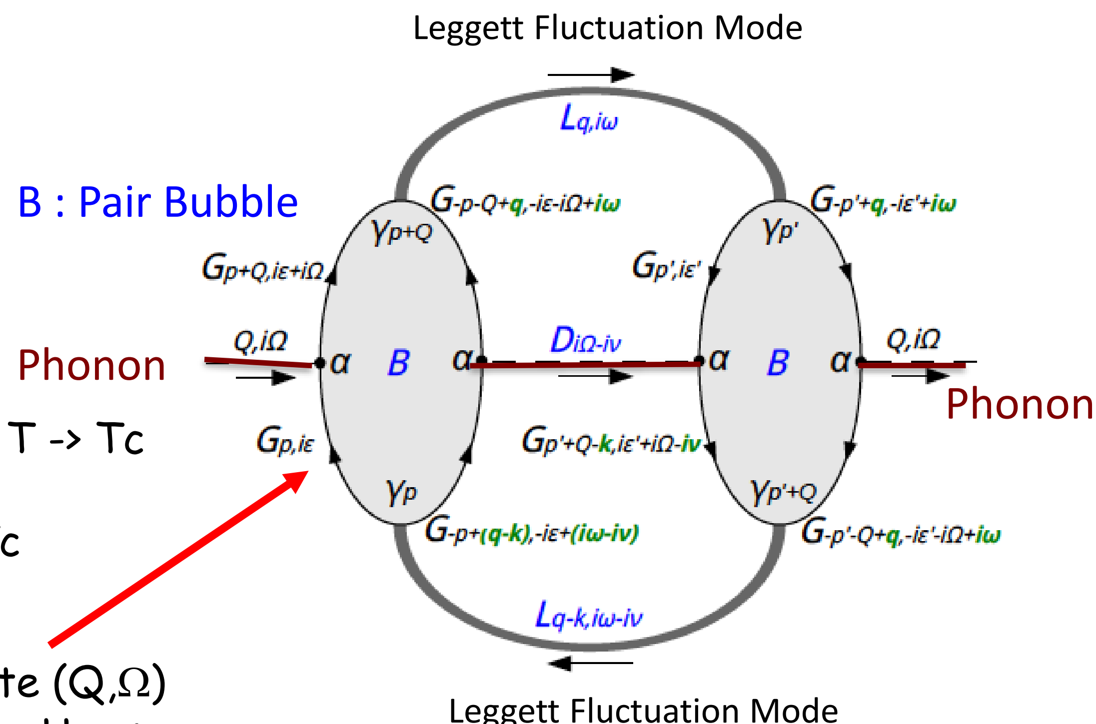
GPA : Giant Phonon Anomaly

T > Tc Leggett Mode Propagator

$$L^R_{\mathbf{q},\omega} = \frac{T}{cN_0}\frac{1}{i\omega - \Gamma^{(\mathrm{LM})}_{\mathbf{q}}}$$

$$\Gamma^{(\mathrm{LM})}_{\mathbf{q}} = \tau^{-1} + Dq^2$$

Phonon Self Energy



Overdamped Leggett Fluctuations as T -> Tc

Finite Energy Leggett Mode at T < Tc

Absorbing a Phonon with finite (Q,Ω)
& Emitting a nearby Phonon scatters
a Cooper pair from subband *a* -> *b*

Almost Resonant Scattering of
Phonon ->
Phonon + 2 Overdamped Leggett Modes

Y. H. Liu, R. Konik. T.M.Rice & F.C.Zhang
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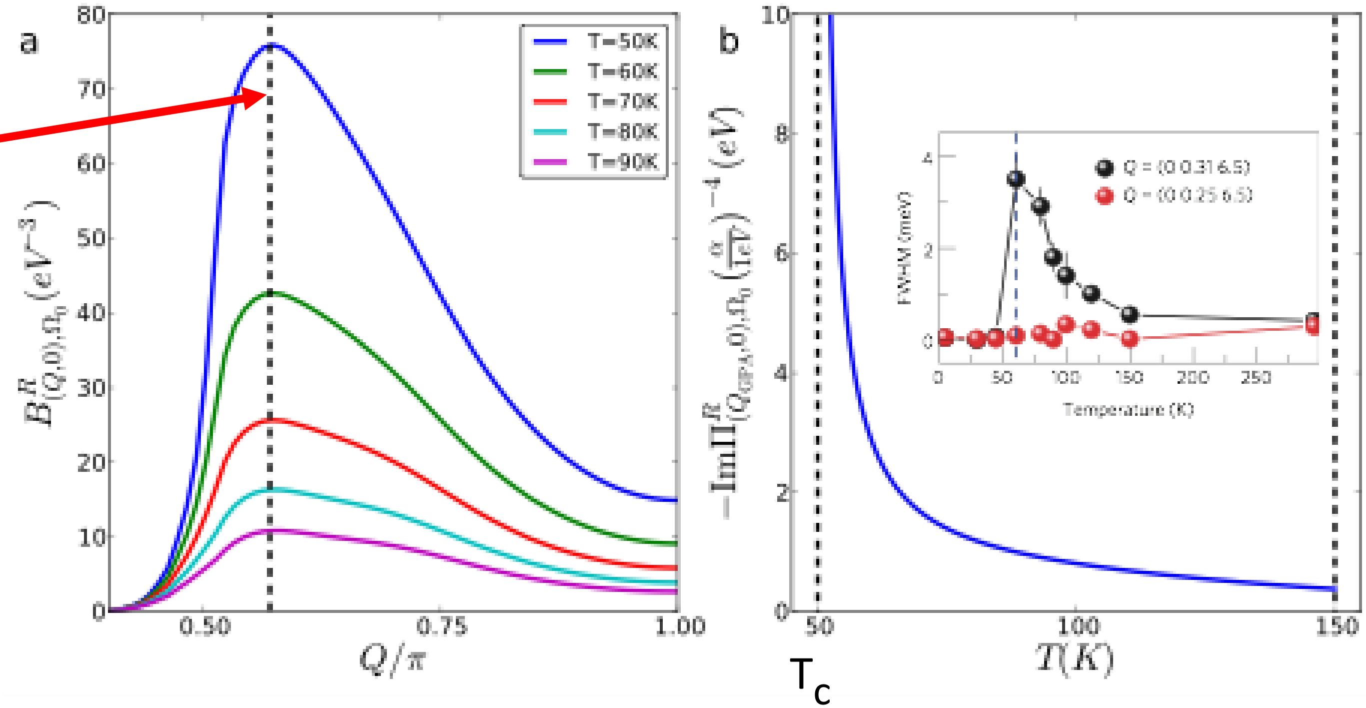
$T>T_c$ Strong Phonon Damping as T -> Tc at $Q \approx Q_{GPA}$

Q_{GPA}

B: Pair Bubble



T_c

$T<T_c$ GPA Very Weak Phonon Damping at $Q \approx Q_{GPA}$

$$
\begin{aligned}
\Pi &\propto \mathrm{Tr} I_{\mathbf{q},\mathbf{k},\Omega} \\
&= \mathrm{Tr} \int \frac{d\omega}{2\pi i}\frac{d\nu}{2\pi i} L_{\mathbf{q},\omega} L_{\mathbf{q}-\mathbf{k},\omega-\nu} D_{\Omega-\nu} \\
&= \frac{4\Delta^4}{N_0^2}\frac{1}{\omega_{\mathbf{q}}\omega_{\mathbf{q}-\mathbf{k}}}\frac{2\left(\Omega_0+\omega_{\mathbf{q}}+\omega_{\mathbf{q}-\mathbf{k}}\right)}{\Omega^2-\left(\Omega_0+\omega_{\mathbf{q}}+\omega_{\mathbf{q}-\mathbf{k}}\right)^2+i\delta}
\end{aligned}
$$

Finite Energy Leggett Mode => Damping -> 0
Dip in Phonon Dispersion remains at T = 0

Conclusions

- PS gap : Maximising U-scattering leads to Short Range Order due to conflicting AF & d-wave Pairing Correlations => YRZ Scenario

- Breakup of the Fermi Surface leads to 2-band Superconductivity with a soft Leggett mode and SC fluctuations over a large T interval > Tc in the Pseudogap phase

- Low Energy Intersubband Phase Fluctuations couple to Phonons and lead to Strong Phonon Damping at T > Tc but damping vanishes at T < Tc replaced by Dip in Phonon Dispersion

- Intrinsic Connection between Anomalous Pseudogap Phase, Enhanced Superconducting Fluctuations and Giant Phonon Anomalies

- No Static Long Range Charge Order – also not in NMR Wu et al Nature Commun. 2015

Y. H. Liu, R. Konik. T.M.Rice & F.C.Zhang Nature Commun. **7** 10378 (2016)