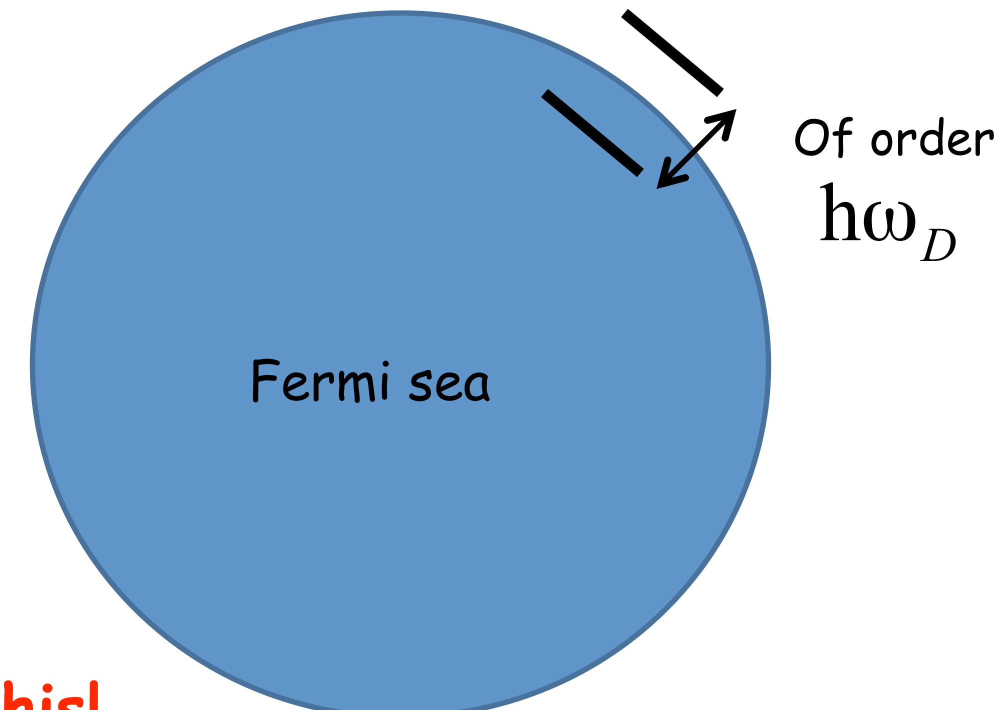
MECHANISM

requires going beyond BCS theory to include inelastic scattering

In conventional superconductors we use Eliashberg theory to include the electron-

A serious limitation of BCS theory is that it is not good for relating the T_c value to microscopic parameters characterizing the normal state complexities of a metal.

$$T_c = 1.13\hbar\omega_D e^{-1/N(0)V}$$



Just qualitative model
Not quantitative in its conceptualization

Need to go beyond this!

Interaction beyond band structure are introduced through a self energy

Think of electron as propagating in a medium consisting of all other electrons and phonon i.e. lattice vibrations AND in cuprates spin fluctuations [magnetism is around the corner]

Electron acquires a lifetime [imaginary part of self energy] and

Electron spectral density

$$A(\mathbf{k},\omega) = \frac{1}{\pi}\frac{\Sigma''(\mathbf{k},\omega)}{[\omega - \varepsilon_{\mathbf{k}} - \Sigma'(\mathbf{k},\omega)]^2 + [\Sigma''(\mathbf{k},\omega)]^2}$$

Real part self energy

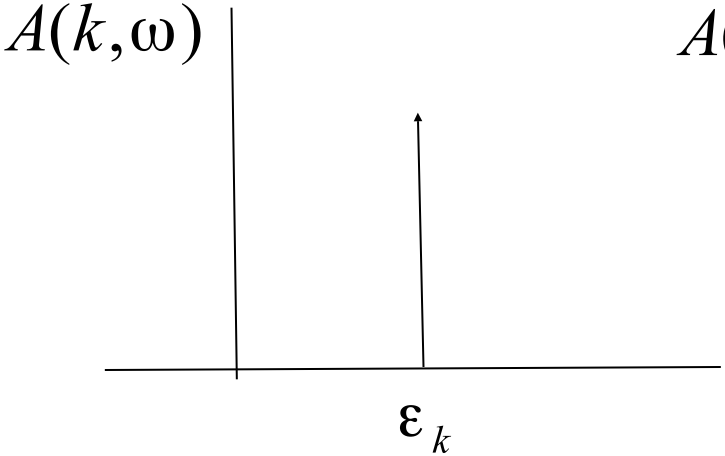
Imaginary part self energy

Self energy $\Sigma(\mathrm{k},\omega)$ gives renormalizations

Electron Spectral Function A(k,ω)

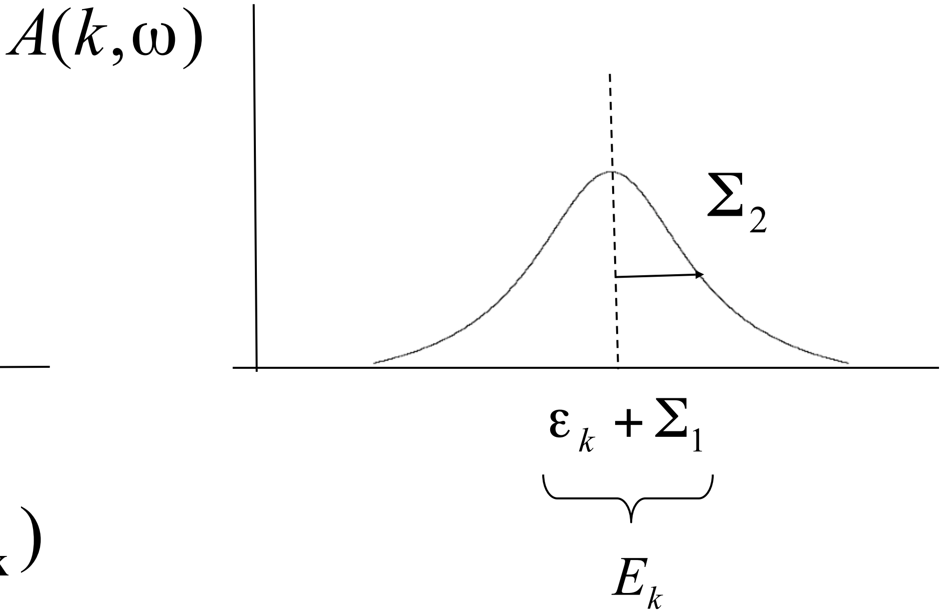
A(k,ω) is measured in Angle-Resolved Photoemission Spectroscopy (ARPES)

$$A(\mathbf{k},\omega) = \frac{1}{\pi}\frac{|\Sigma_2|}{(\omega - \varepsilon_{\mathbf{k}} - \Sigma_1)^2 + \Sigma_2^2}$$



$$A(\mathbf{k},\omega) = \delta(\omega - \varepsilon_{\mathbf{k}})$$

Non-interacting case



Interacting case

To describe the electron -phonon interaction as it enters Eliashberg theory, in principle we need:

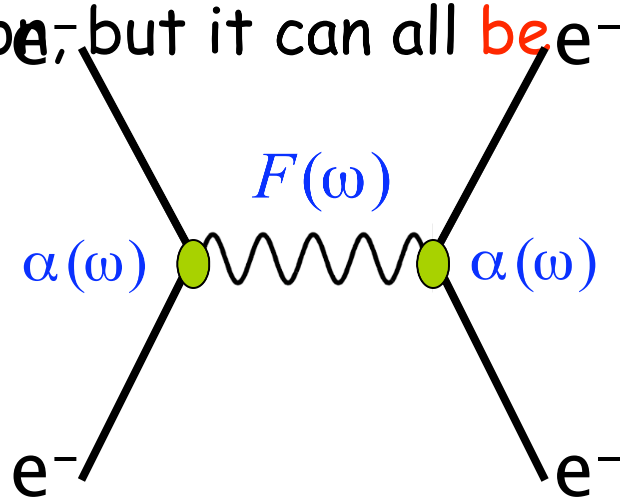
1] phonons -frequencies and polarization vectors

2] electronic band structure and wavefunctions

3] coupling between electron and an ion displaced from equilibrium

This is a lot of detailed information, but it can all be condensed into a single function: th

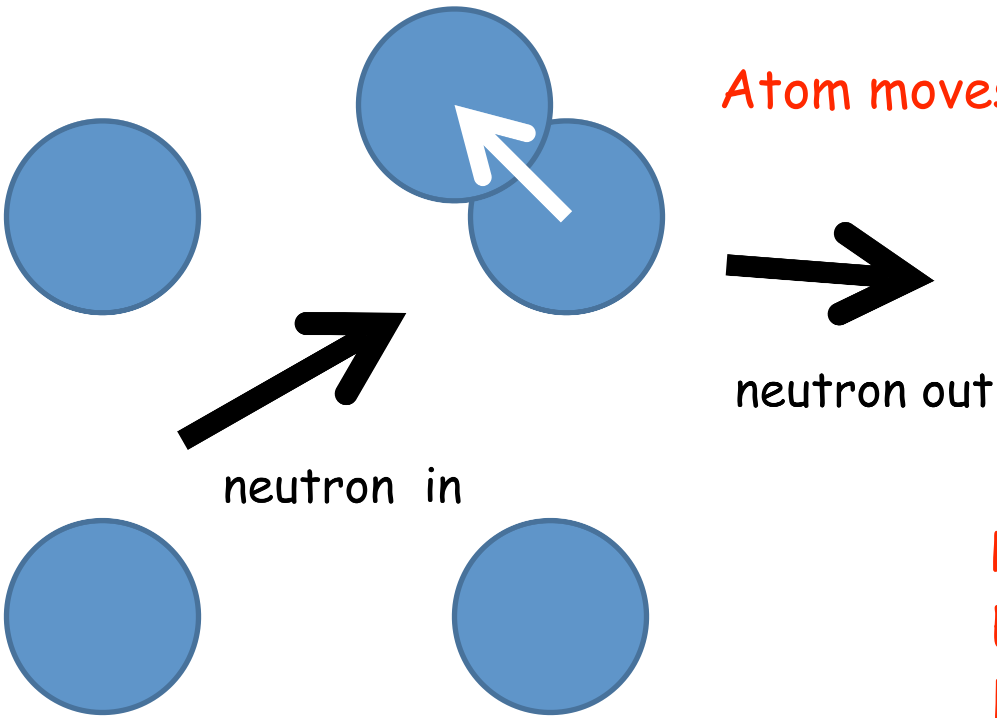
$$\alpha^2(\omega)F(\omega) \equiv \alpha^2 F(\omega)$$



Analogous to the phonon frequency distribution $F(\omega)$ or the electronic density of states $N(\varepsilon)$.

Phonons: dispersion ω(k), frequency distribution F(ω)

Lattice vibrations or phonons are measured by inelastic neutron scattering

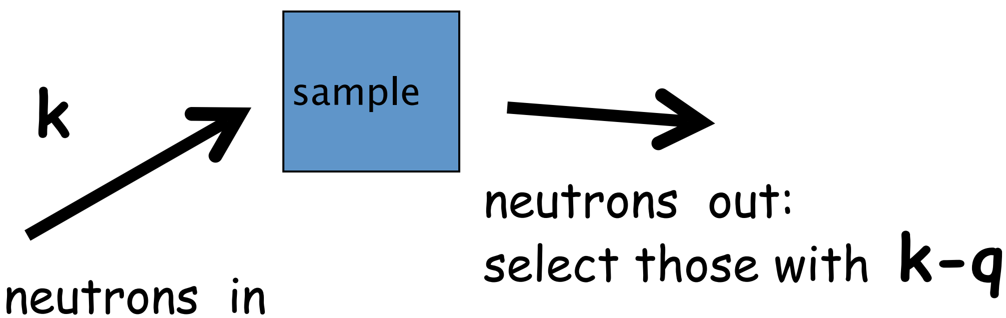


Phonon is created:
Energy and momentum lost by neutron.
Goes into the phonon

Neutron groups

definite momentum transfer to phonon analyzed as a function of energy transfer to phonon

Gives $\omega(q)$ relationship



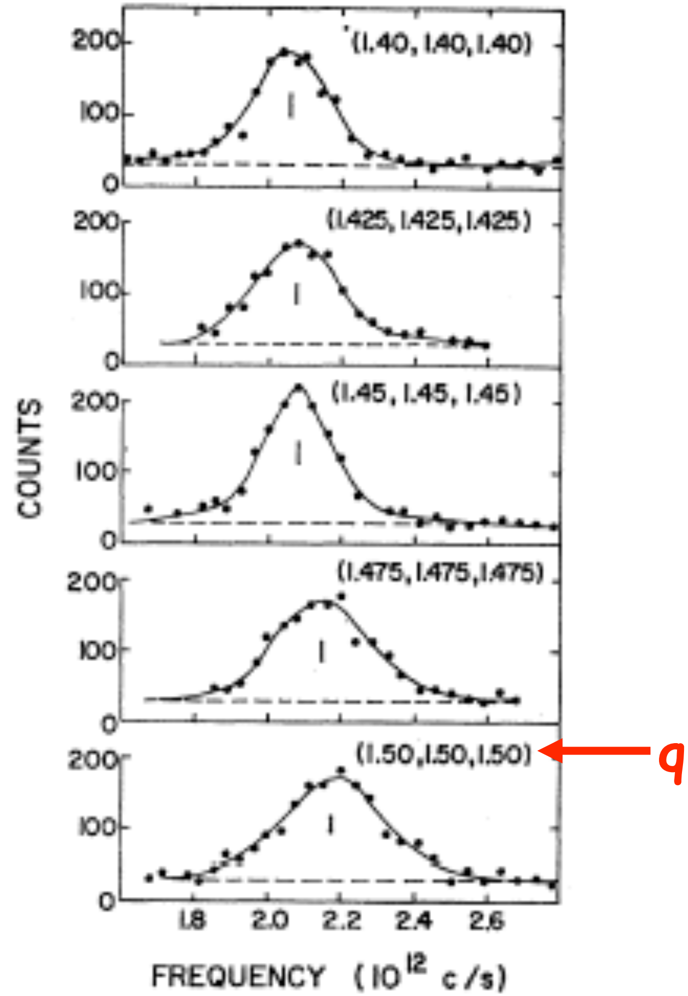


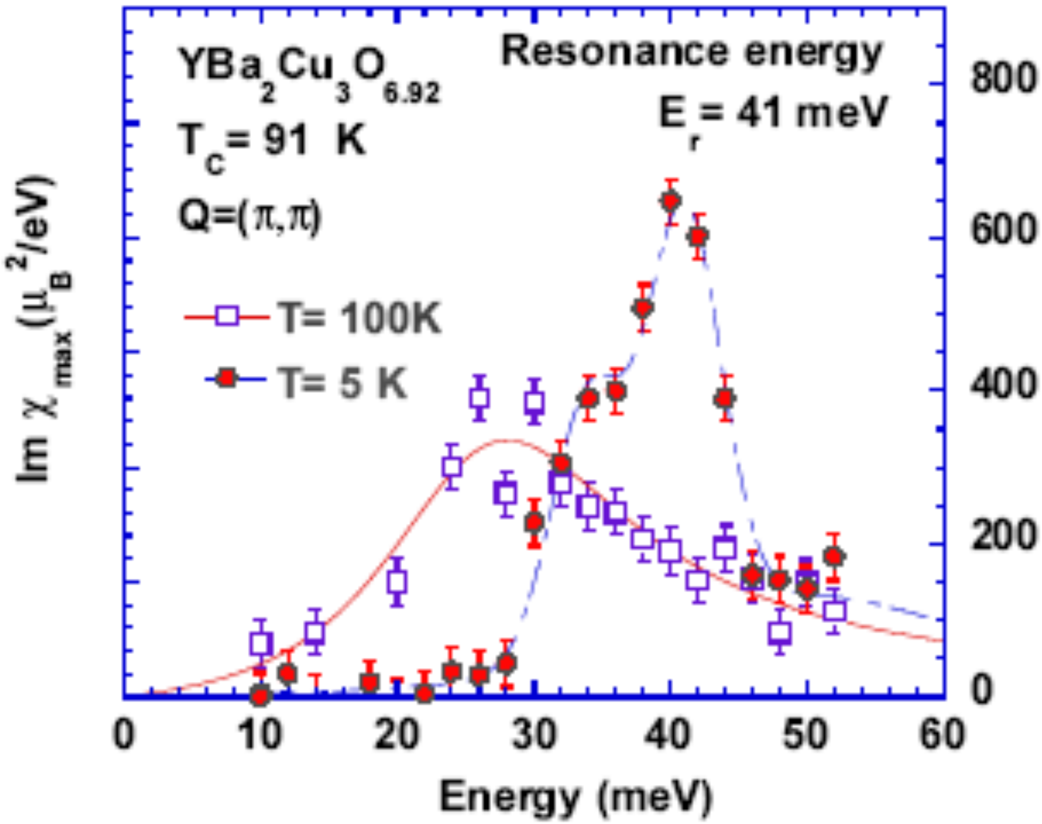
Fig. 4.10. A set of 'constant q' scans in Pb taken at various points along the diagonal in the Brillouin zone. Reproduced from Ref. [89]

B. Brockhouse et al., Phys. Rev. **128**, 1099 (1962).

For the high Tc oxides spin polarized inelastic neutron scattering [monitor spin flip] can be used to get the magnetic excitations
spin waves or spin fluctuations[damping]

- **See a very famous 41mev resonance In YBCO ,different energies in other materials**

Famous 41 mev spin one resonance



YBCO

Bourges et. al. see later for reference

Phonon frequency distribution

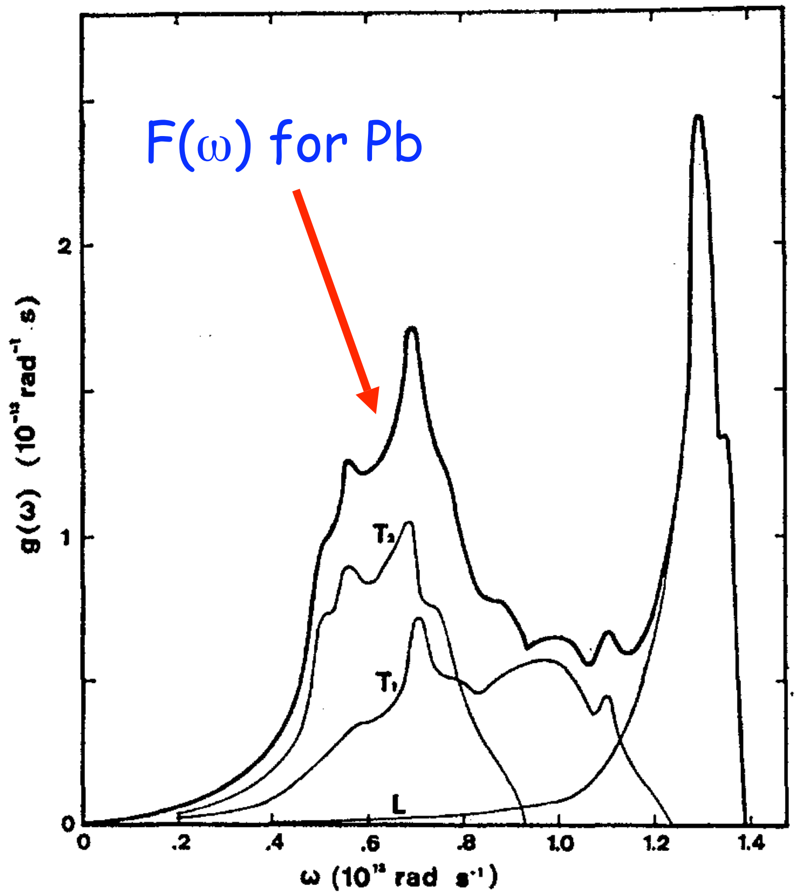
$$F(\omega) = \frac{1}{N} \sum_{\mathbf{k}j} \delta(\omega - \omega_j(\mathbf{k}))$$

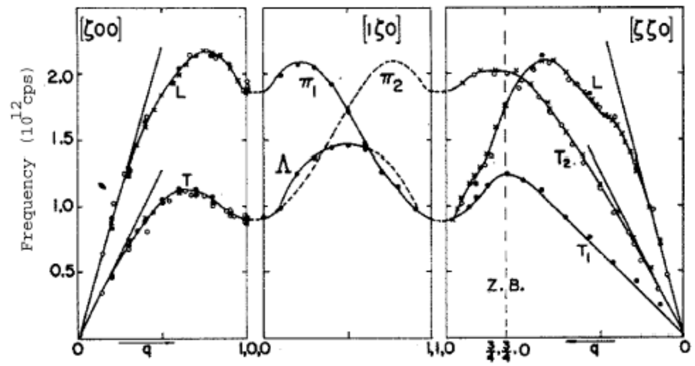
N is number of points in FBZ; j is phonon branch index

Note that frequency distribution is a single function while dispersion curves are many frames, one for each direction in FBZ, yet for the lattice specific heat knowing $F(\omega)$ is enough!! - much, much simpler

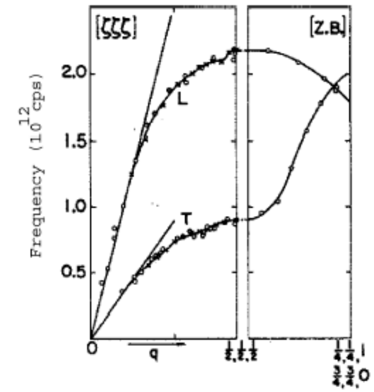
For simple metal, one atom per unit cell $F(\omega)$ is normalized to 3

F(ω) for Pb





ω(k)



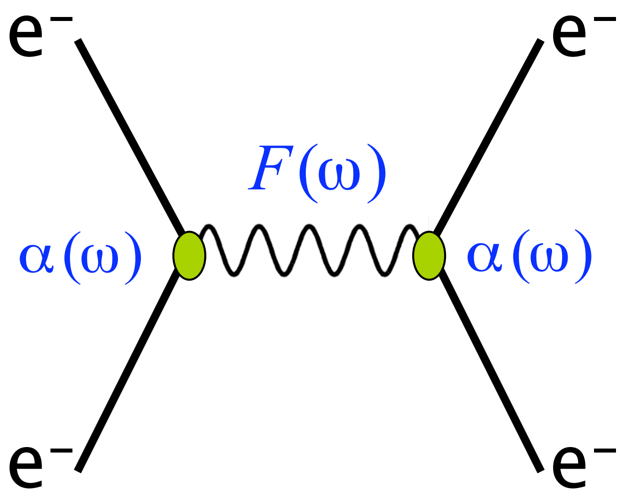
$$F(\omega) = \frac{1}{N} \sum_{\mathbf{k}j} \delta(\omega - \omega_j(\mathbf{k}))$$

Stedman et al., Phys. Rev. **162**, 549 (1967).

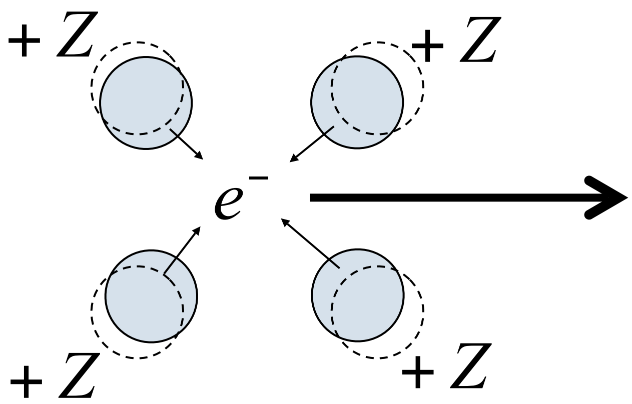
If you image these through the electrons use weighted distribution with electron-phonon weighting

$$\alpha^2(\omega)F(\omega) \equiv \alpha^2 F(\omega)$$

Analogous to the phonon frequency distribution $F(\omega)$ or the electronic density of states $N(\varepsilon)$.



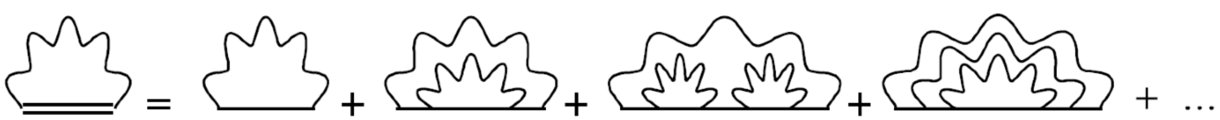
Furthermore,



Renormalization due to electron-phonon interaction can change dispersion curve (ie. energy-momentum relationship $\varepsilon_{\mathbf{k}}$).

Electron Self-Energy

$$\Sigma(\vec{k},\omega) =$$



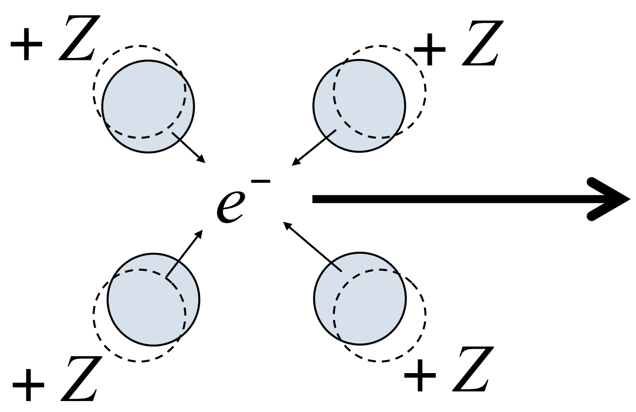
Medium changes electron energy dispersion curve and gives a finite lifetime to be in a particular k state, ie, $\varepsilon \rightarrow E + i\Gamma$

$$\Sigma(\omega) = \int_0^{\infty} d\Omega \alpha^2 F(\Omega) \ln\left|\frac{\Omega - \omega}{\Omega + \omega}\right| - i\pi \int_0^{|\omega|} d\Omega \alpha^2 F(\Omega)$$

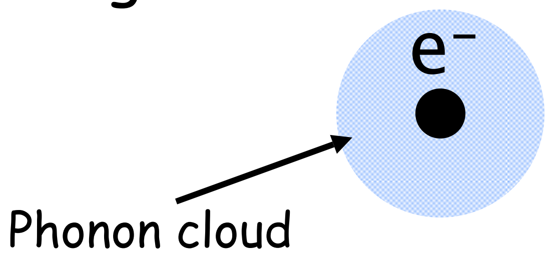
Example of how $\alpha^2F(\omega)$ determines properties

λ the electron-phonon mass renormalization

Electron pulls ions off equilibrium positions



Electron moves with polarization cloud of lattice charge



Heavier by $[1+\lambda]$
i.e. $m^*=m[1+\lambda]$

Electron spectral density for noninteracting case

$$A(\mathbf{k},\omega) = \delta(\omega - \varepsilon_{\mathbf{k}})$$

Want to include lifetimes, change to Lorentzian with width Γ, also change energy to E_k

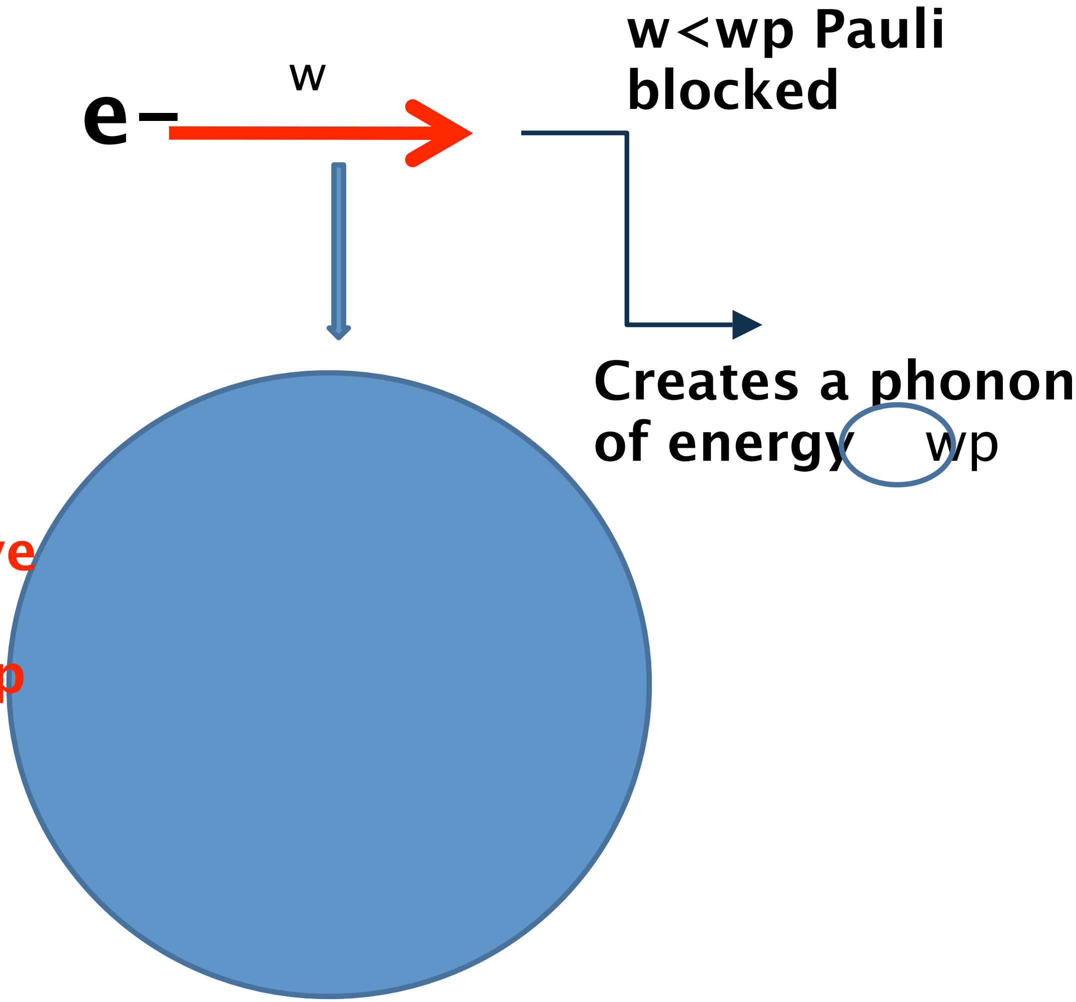
$$A(\mathbf{k},\omega) = \frac{1}{\pi}\frac{\Gamma}{(\omega - E_{\mathbf{k}})^2 + \Gamma^2}$$

New dispersion

Broadening

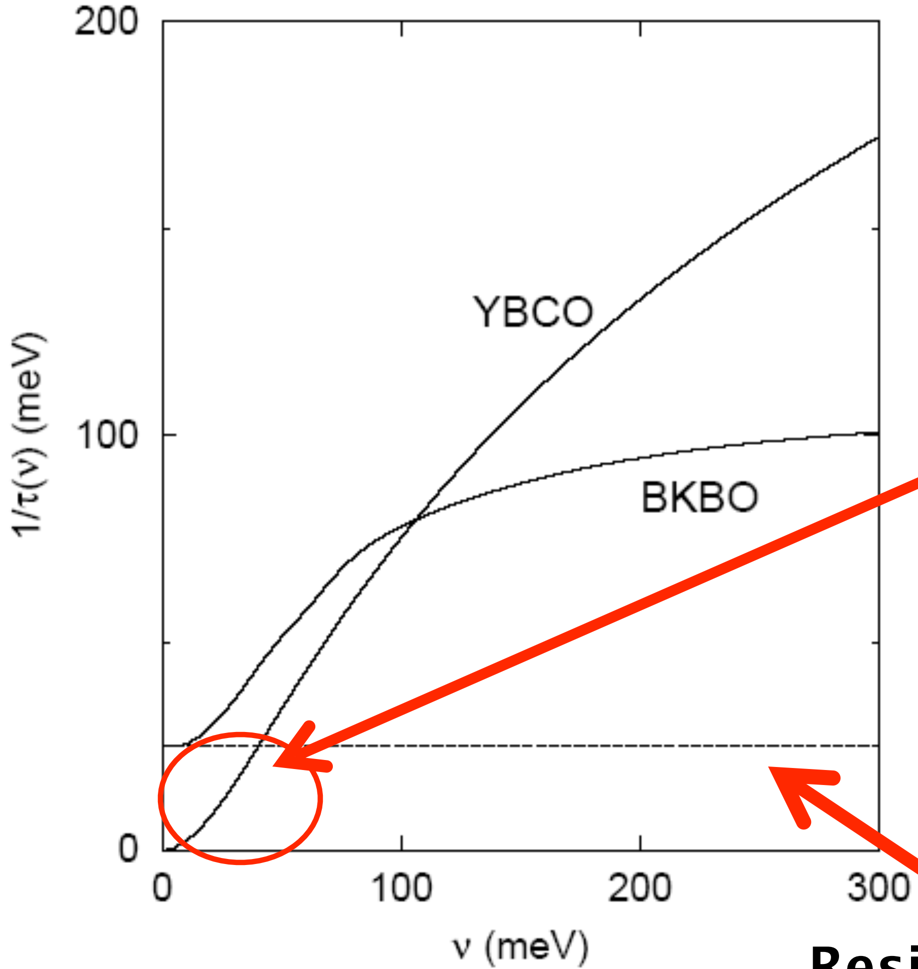
$$E_{\mathbf{k}} = \varepsilon_{\mathbf{k}} + \mathrm{Re}\left[\Sigma(E_{\mathbf{k}})\right]$$

Quasiparticle scattering rate due to phonon creation ,asks how long an electron stays in state |k>

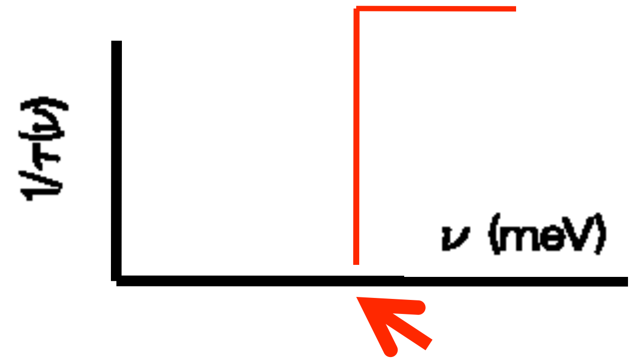


Can only scatter creating a phonon if its energy above the Fermi energy is larger than the phonon energy wp

Scattering rate due to phonon is zero till energy ‘ wp’ at which point it increases out of zero



Profile here reflects pho
frequency distribution



w−phonon

Residual elastic
scatt

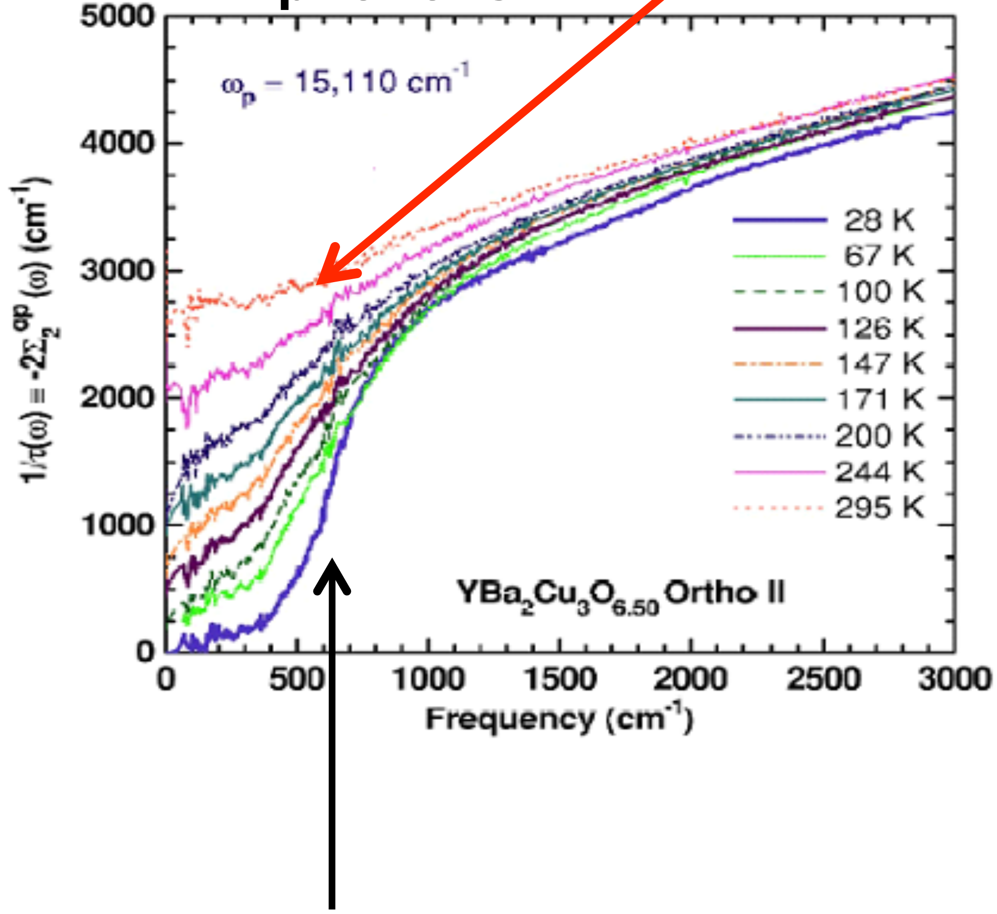
Scattering rate is zero till excitation energy of electron is large enough to create a phonon at which point it rises out of zero.
Rise reflects the available phonon frequency distribution F[w]

The real thing

Blurred with increasing temp . New scattering processes become possible because of thermal population of real phonons

a-axis

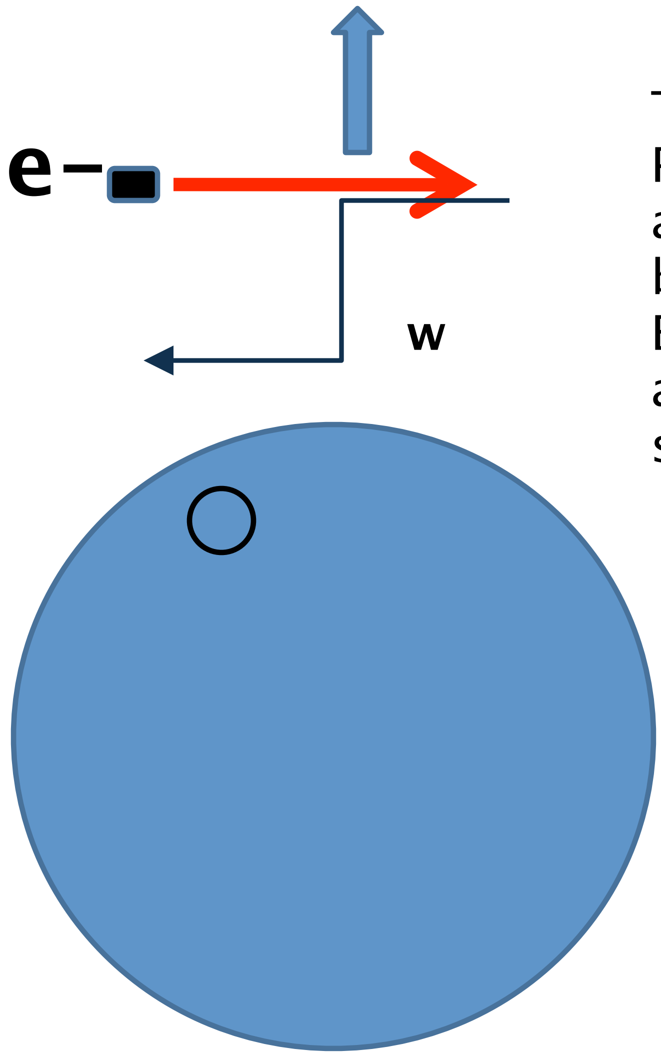
T_c = 59K



The mode in Y123 Ortho-II

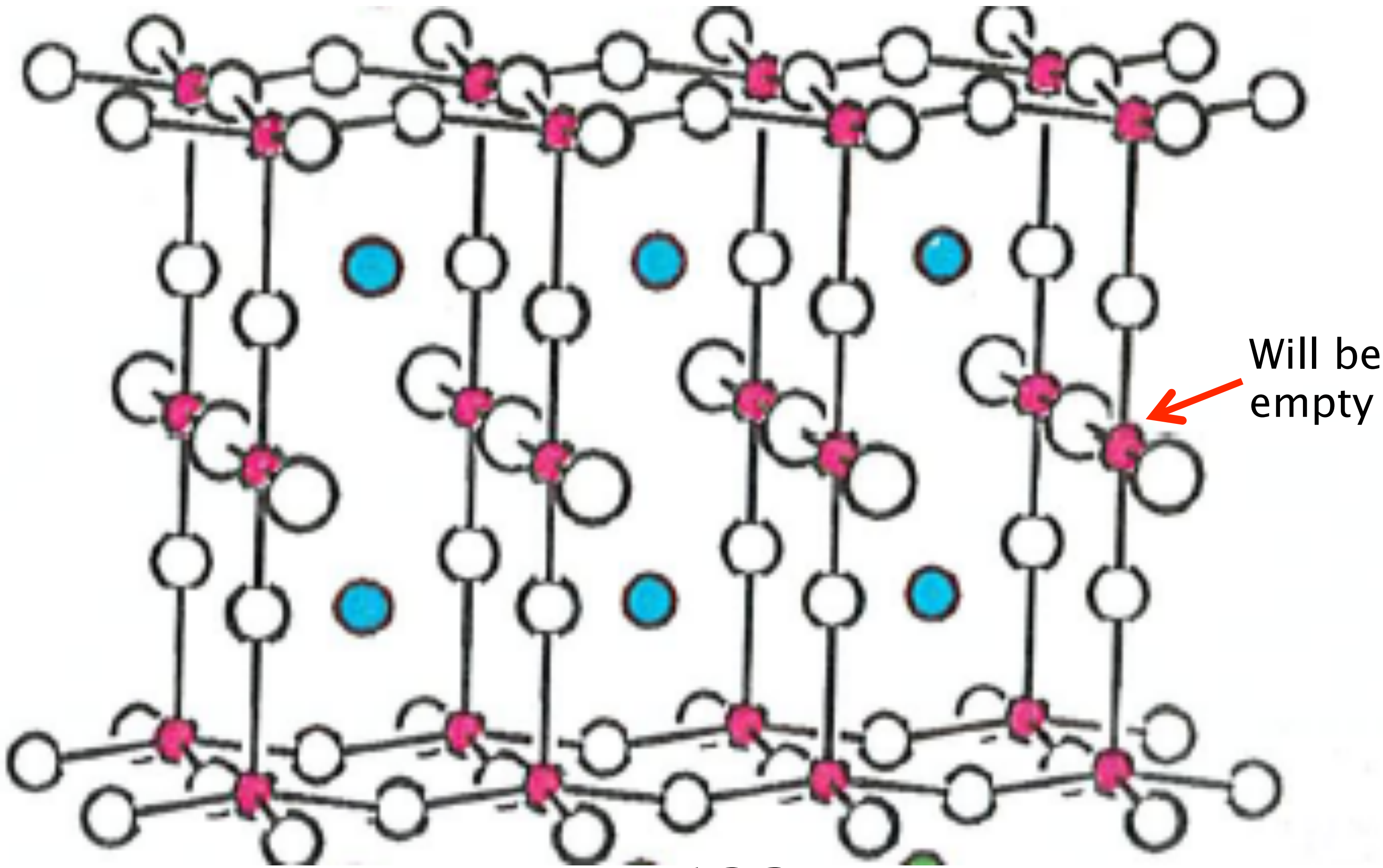
Quasiparticle scattering rate due to absorption of a real thermally created phonon

No threshold for such scattering with real phonons



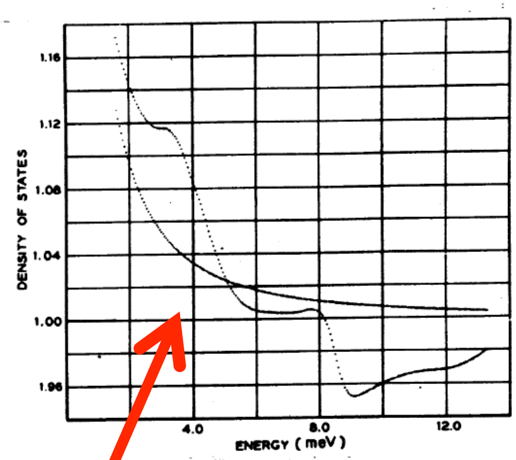
Thermally excited Phonon w is absorbed by electron. Empty states are always available for such scattering

Ortho II, alternating full and empty Cu–O chain



YBaCuO 123

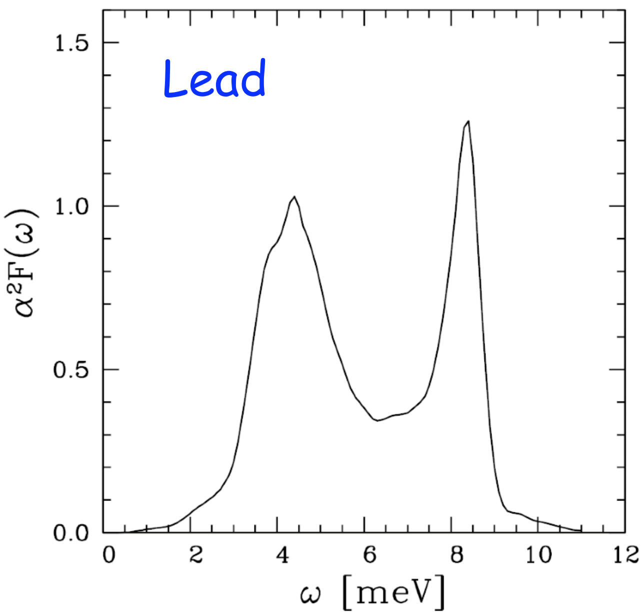
Can invert I-V characteristics to get electron-phonon spectral density through Eliashberg equations



$$dI/dV = N_S(\omega)$$

$$N_S(\omega) = G\,[\alpha^2 F(\omega);\, \mu*]$$

Details matter!
Image of phonon spectra



McMillan and Rowell, Phys. Rev. Lett. **14**, 108 (1965)

Electron-phonon spectral density in Pb

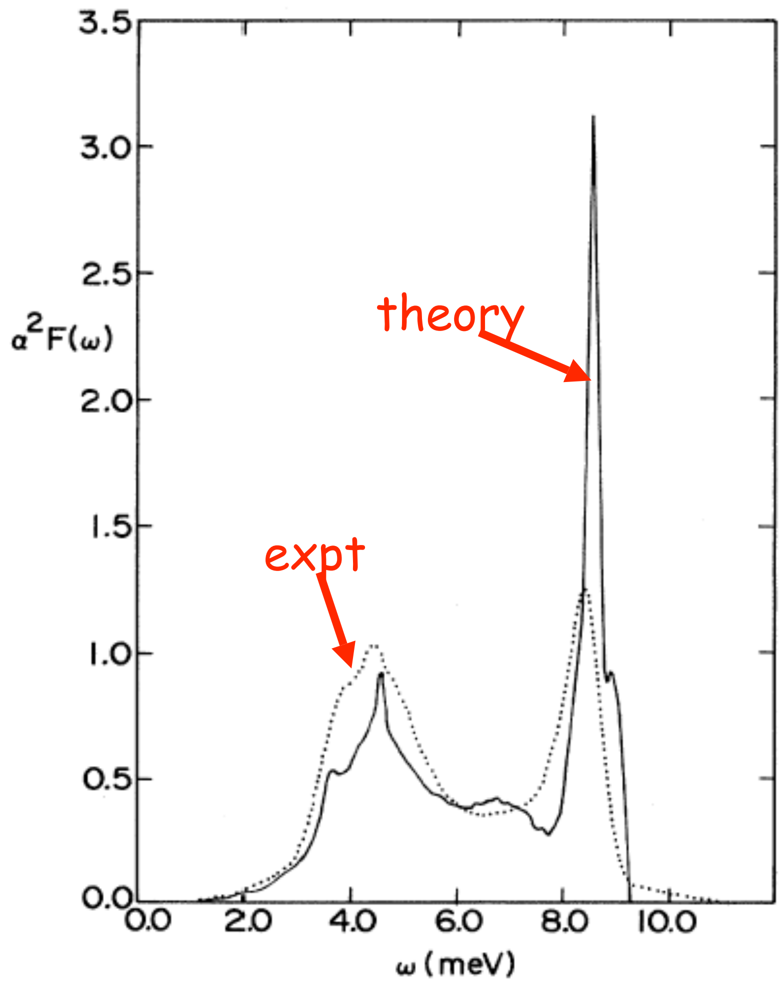
Tunneling:

McMillan and Rowell, Phys. Rev. Lett. **14**, 108 (1965).

Calculations:

Tomlinson and Carbotte, Phys. Rev. B **13**, 4738 (1976).

This function contains all of the complicated information on electron and phonon dynamics and the coupling between them that enters superconductivity.



Remarkable condensation of required information!

Inversion of optical data

How to get information on mechanism from optics

Can get distribution of bosons that scatter electrons from an
analyses of scattering rates

What is recovered is a weighted boson distribution i.e.
weighted by appropriate electron –boson coupling

In conventional superconductors, tunneling has been method of choice to get information on gap and phonons

Optics has been hard, good metals reflectance near 1

In poor metals such as oxides, optics has been great!

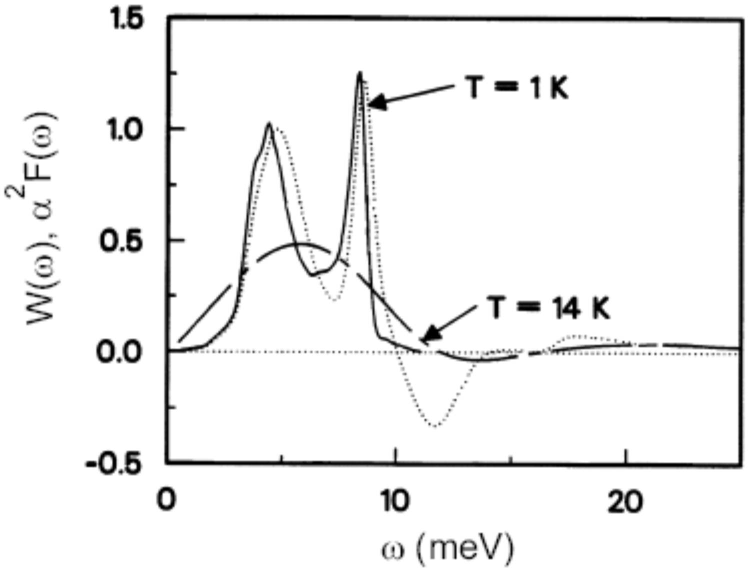
INVERSION

$$\alpha^2 F(\nu) \sim W(\omega) = \frac{1}{2\pi}\frac{\omega_p^2}{4\pi}\frac{d^2}{d\nu^2}\left\{\nu \,\mathrm{Re}\frac{1}{\sigma(\nu)}\right\}$$

- Calculation of conductivity from Pb
- Electron–phonon spectral density and differentiation to get it back

Normal state only

Solid curve is input and others are output at two temperatures

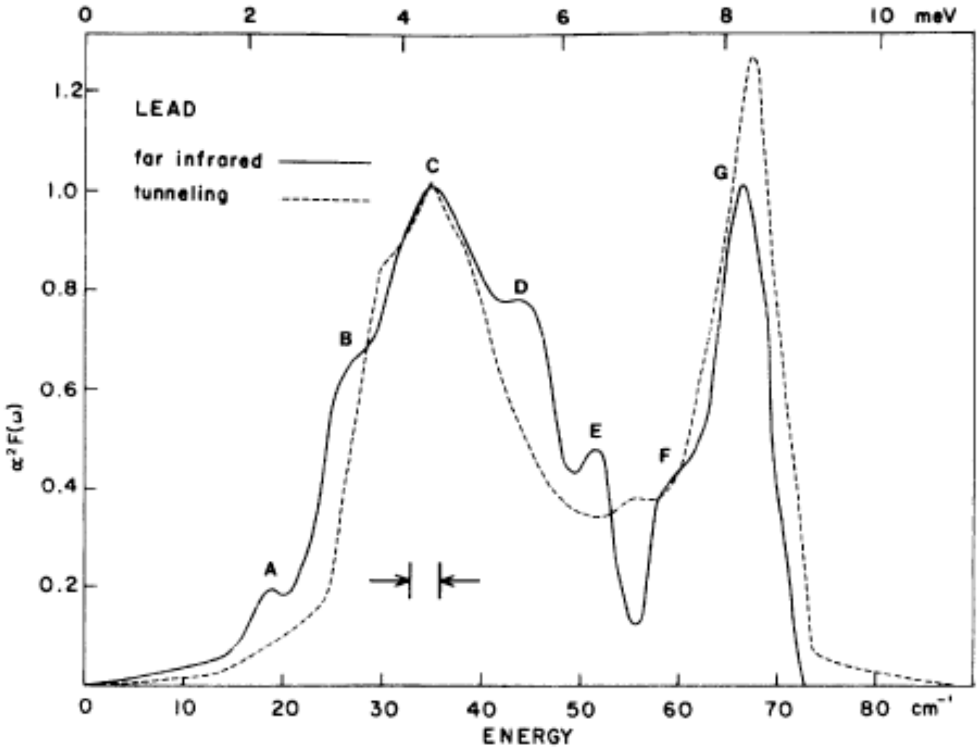


In theory!

F. Marsiglio, T. Startseva and J.P. Carbotte, Phys. Lett. A **245**, 172 (1998)

Electron-phonon spectral density from optics

Old data for Pb
good agreement
with tunneling



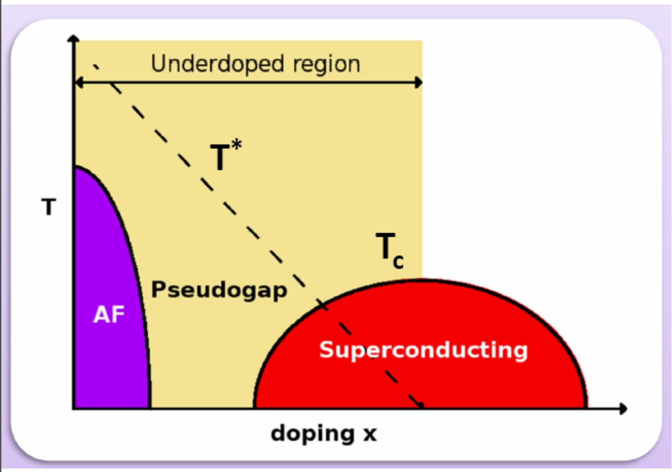
It works beautifully!

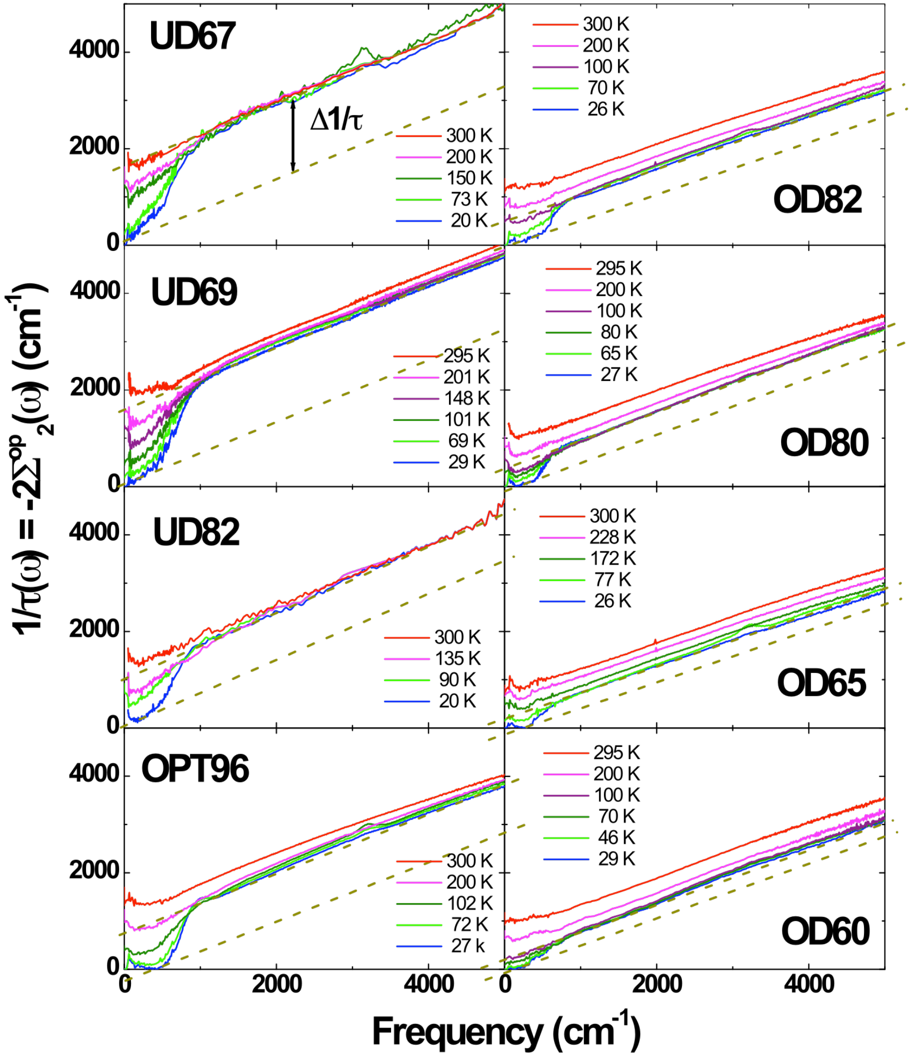
B. Farnworth and T. Timusk, Phys. Rev. B **10**, 2799 (1974); ibid **14**, 5119 (1976).

Hwang et. al. [Timusk-group] Nature,427,714 [2004]

Optical scattering rate in Bi2212 across the doping range

from underdoped to





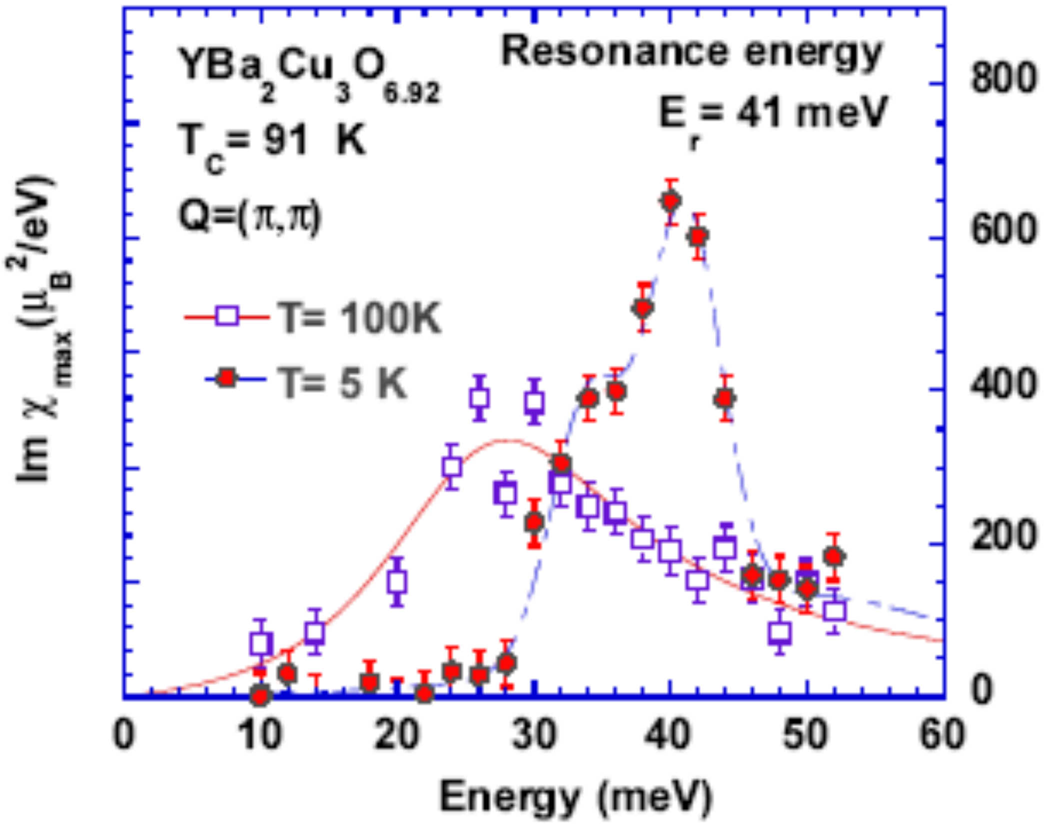
What should we see if its spin fluctuation exchange ?

Expect to see a picture of local spin susceptibility i e BZ average

In cuprates see a broad background and sometimes a prominent spin one resonance in magnetic susceptibility
at specific momentum [pi,pi]

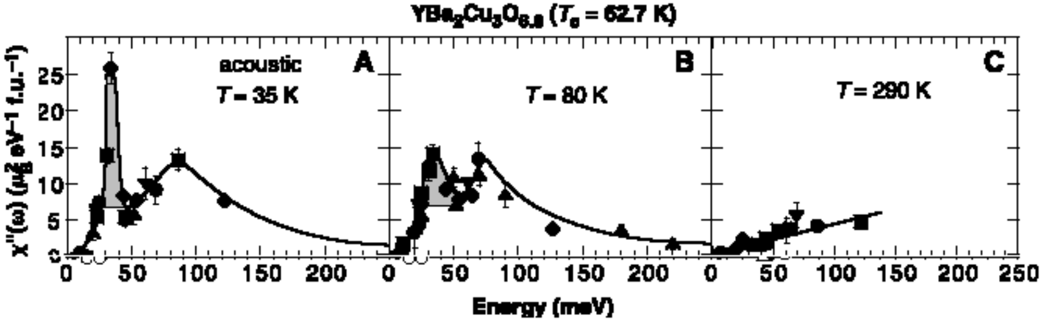
great ,easier to see

Famous 41 mev spin one resonance



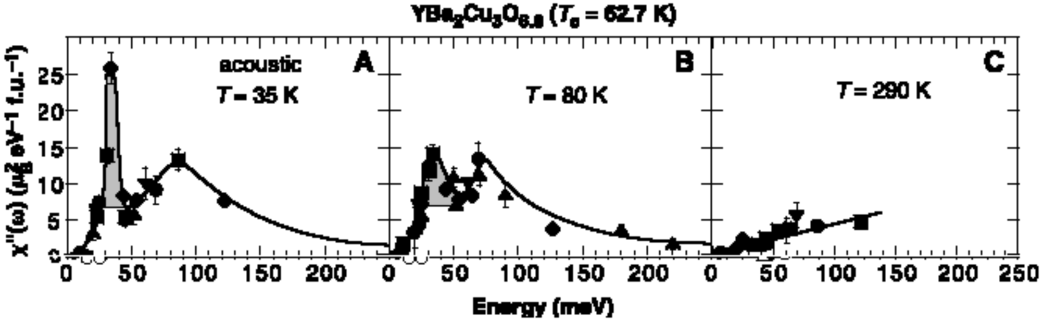
Ph. Bourges, Y. Sidis, H.F. Fong, B. Keimer, L.P. Regnault, J. Bossy, A.S. Ivanov, D.L. Lilius, and I.A. Aksay, in High Temperature Superconductivity, eds. S.E. Barnes, *et al.*, CP483 (American Institute of Physics, Amsterdam, 1999), p. 207.

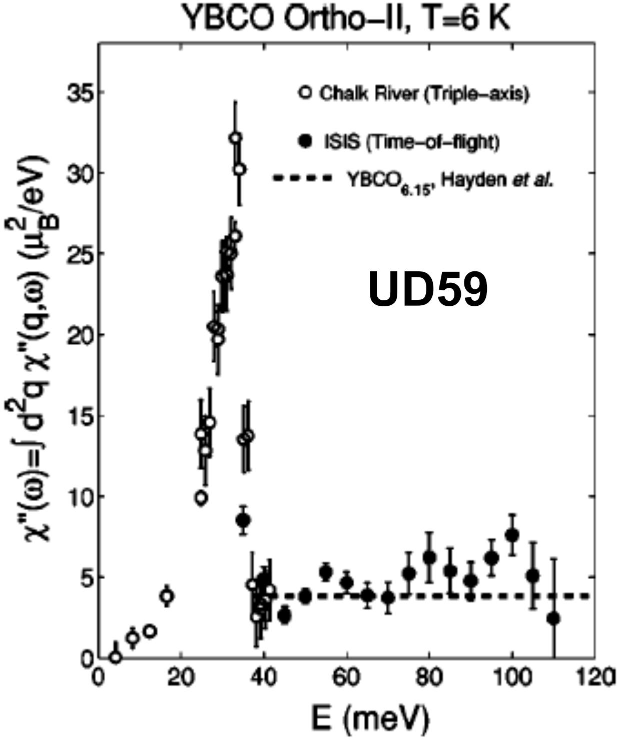
The neutron resonance mode



Hayden et. Al. PRL 76,1344 [1996]
Stock et.al. PRB 71,024522 [2005]
Bourges et.al. PRB 53,876 [1996]
and other Bourges references

The neutron resonance mode





Hayden et. Al. PRL 76,1344 [1996]
Stock et.al. PRB 71,024522 [2005]
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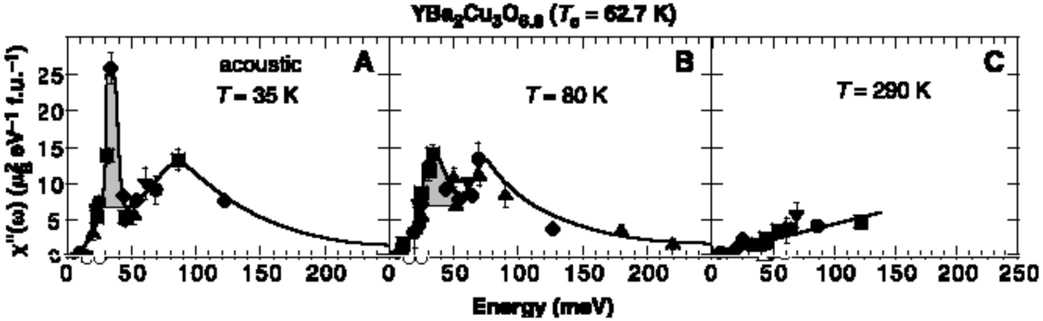
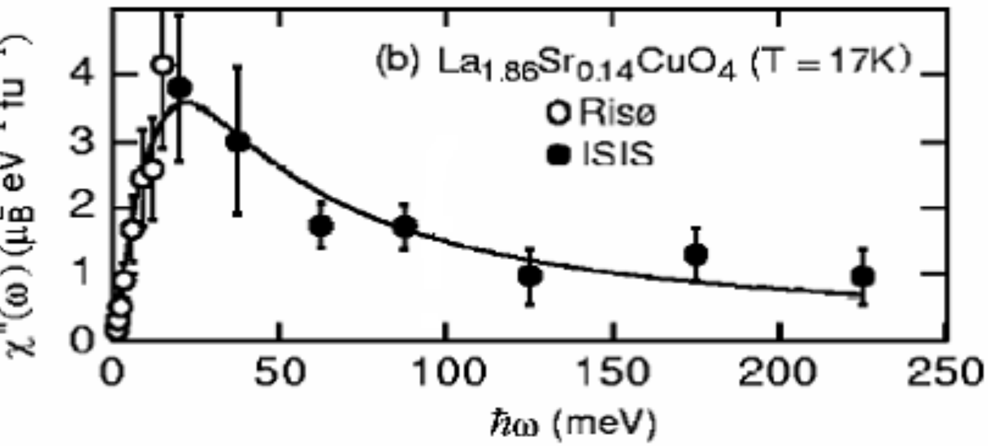
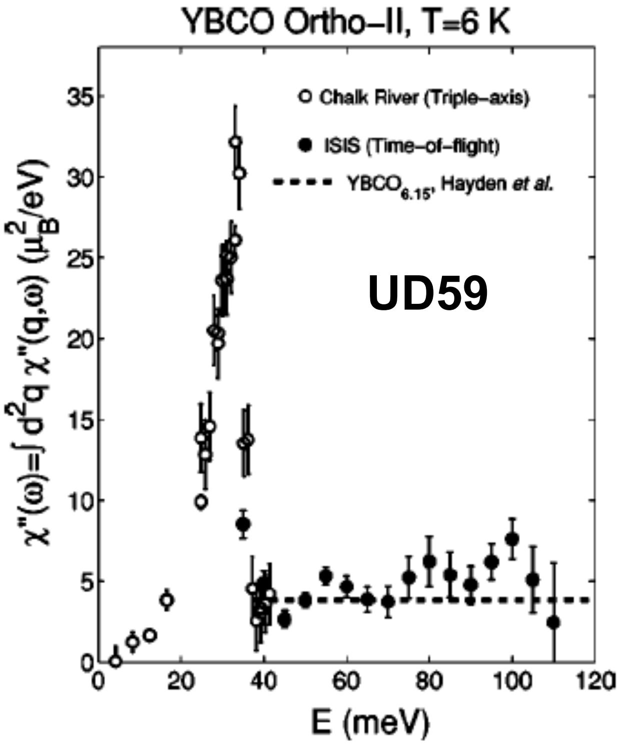
The neutron resonance mode





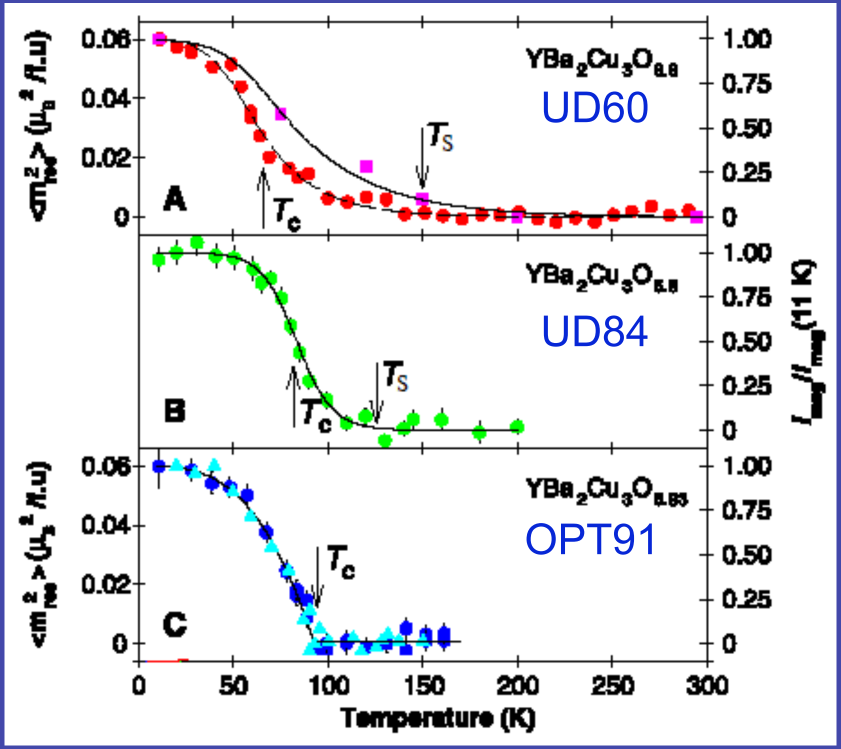


Hayden et. Al. PRL 76,1344 [1996]
Stock et.al. PRB 71,024522 [2005]
Bourges et.al. PRB 53,876 [1996]
and other Bourges references

Temperature and doping dependence …

Temperature

Y123

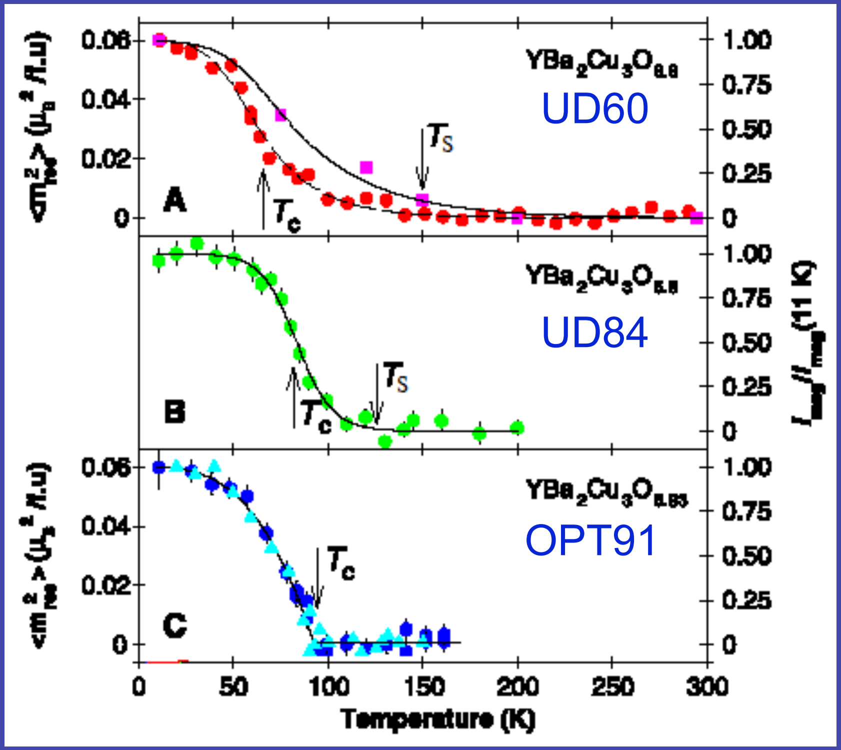


Dai *et al.*, Science **284**, 1344 (1999)

Temperature and doping dependence …

Temperature

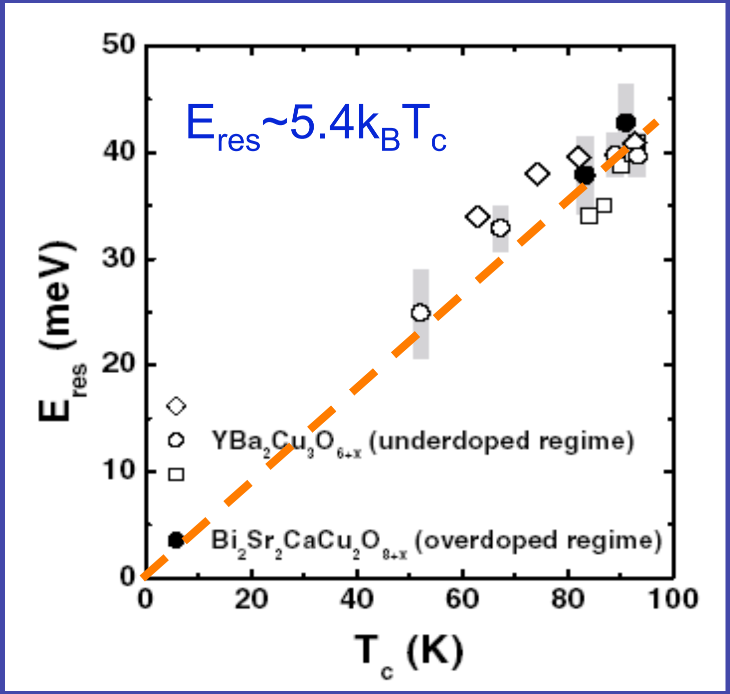
Y123



Dai *et al.*, Science **284**, 1344 (1999)

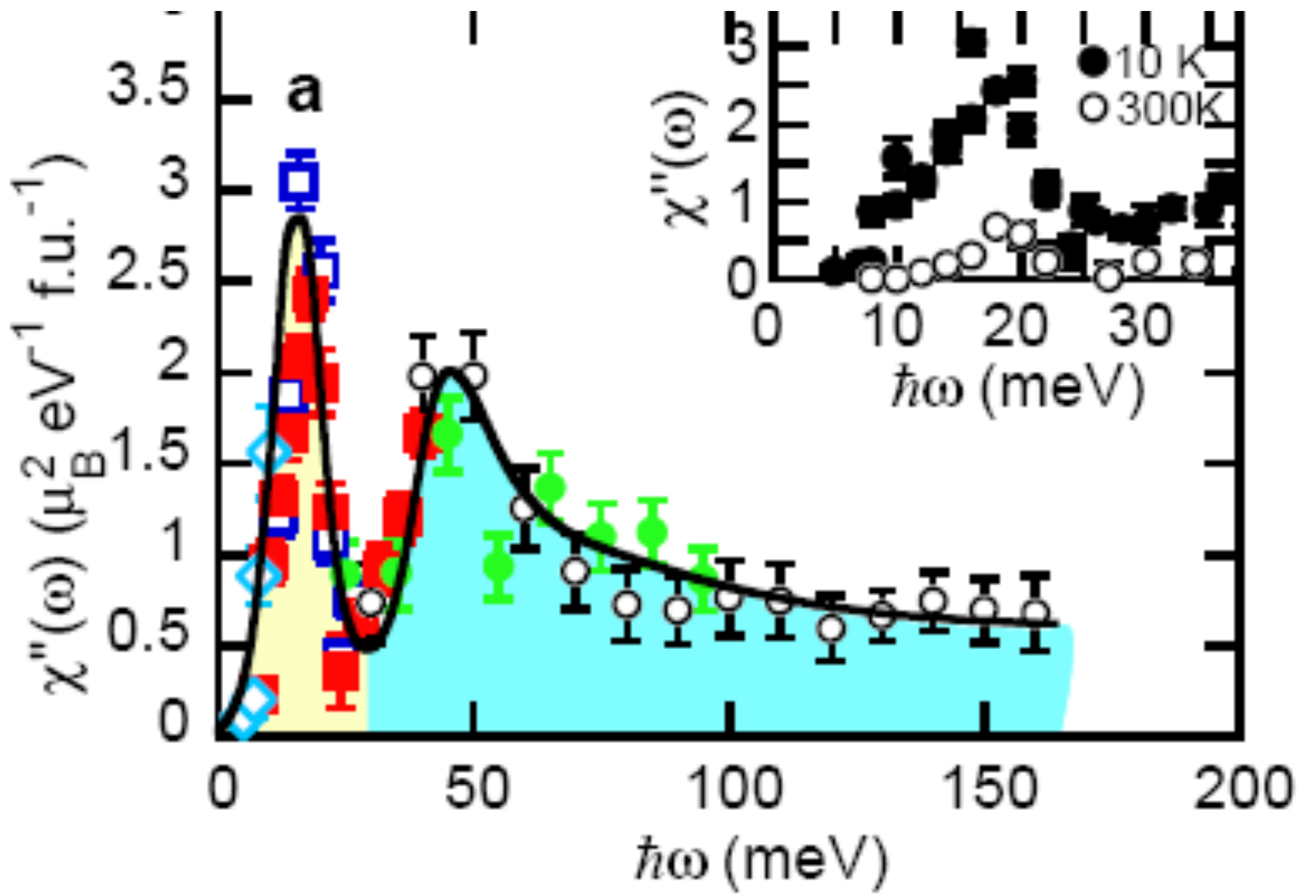
Doping

Y123 & Bi-2212



He *et al.*, PRL **86**, 1610 (2001)

Two energy scales in spin susceptibility of La1.64Sr0.16CuO4



Averaged over the B Z

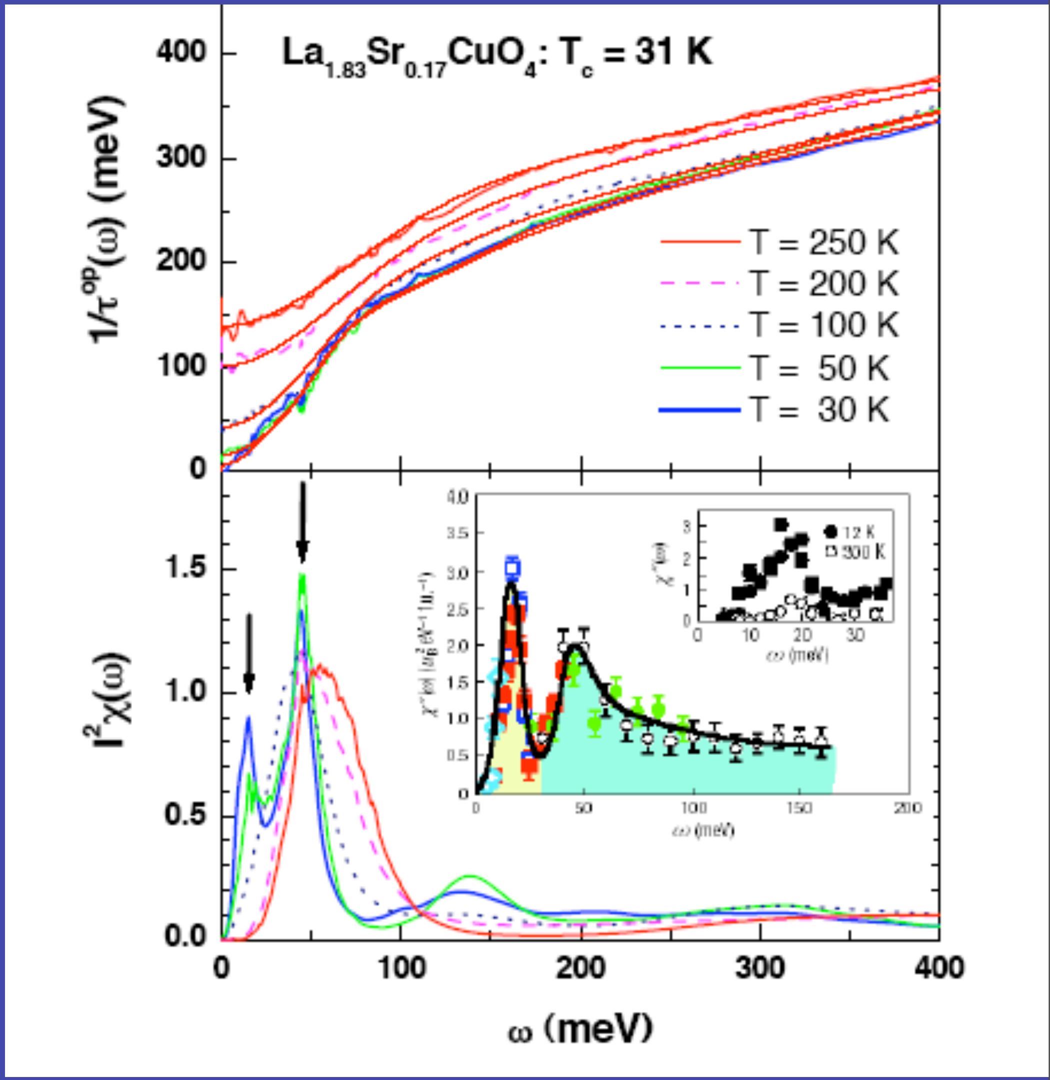
B Vignolle et al Nature Phys 3,163 [2007]

What does optics see?

Phonons
Spin fluctuations
Both? [most likely case]?

Listen carefully and tell me what you think

Inversion in LSCO



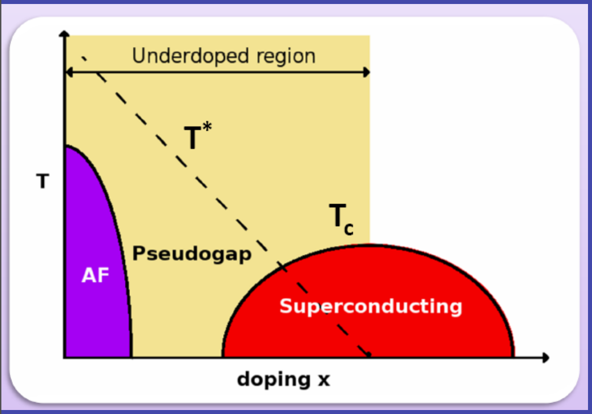
Get two peak structure at low T
And evolution to single peak at room temp
Good agreement with neutrons

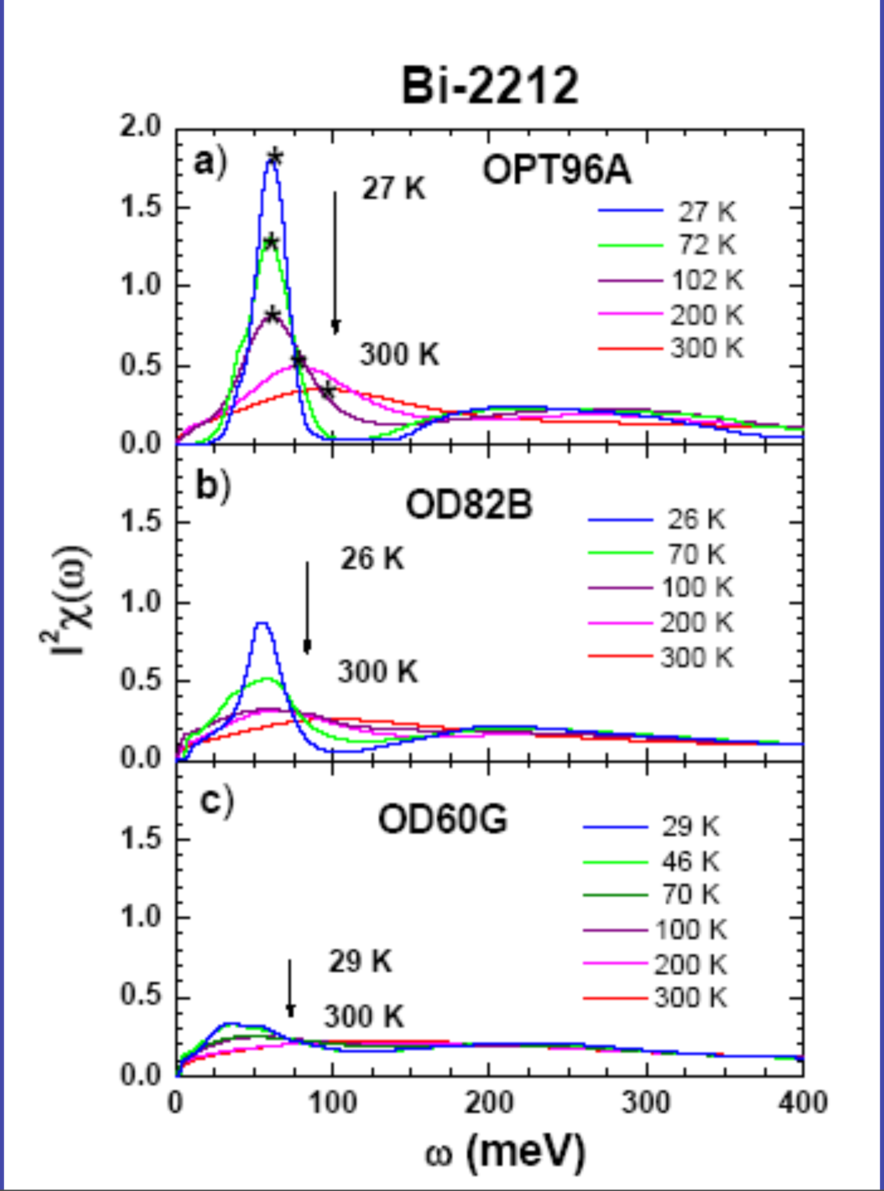
Looks real good !

Hwang et. al. Phys. Rev. Lett.,100,137005 [2008]

Temperature and Doping evolution of Electron-Boson Spectral Function

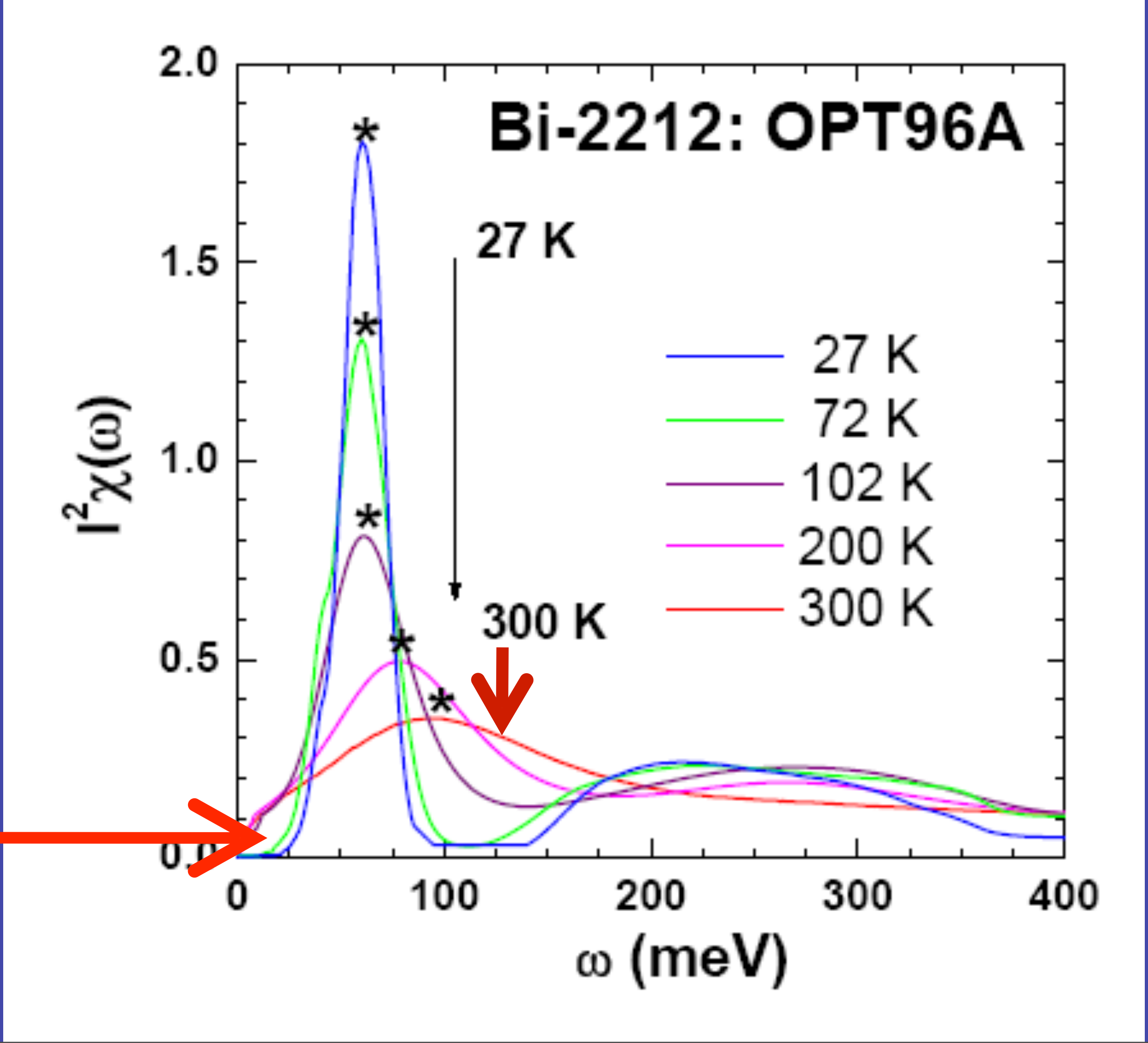
Sharp peak goes away with increasing temperature and doping





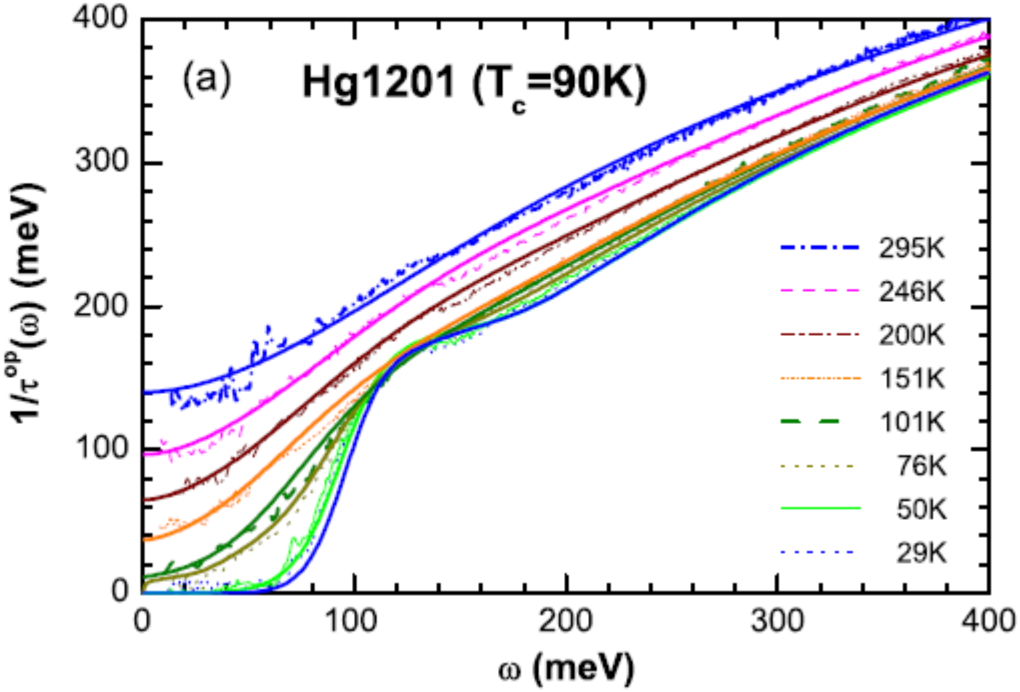
Hwang et al ,PRB 75, 144506 [2007]

Redistribution of spectral weight with temperature in OP doped Bi2212



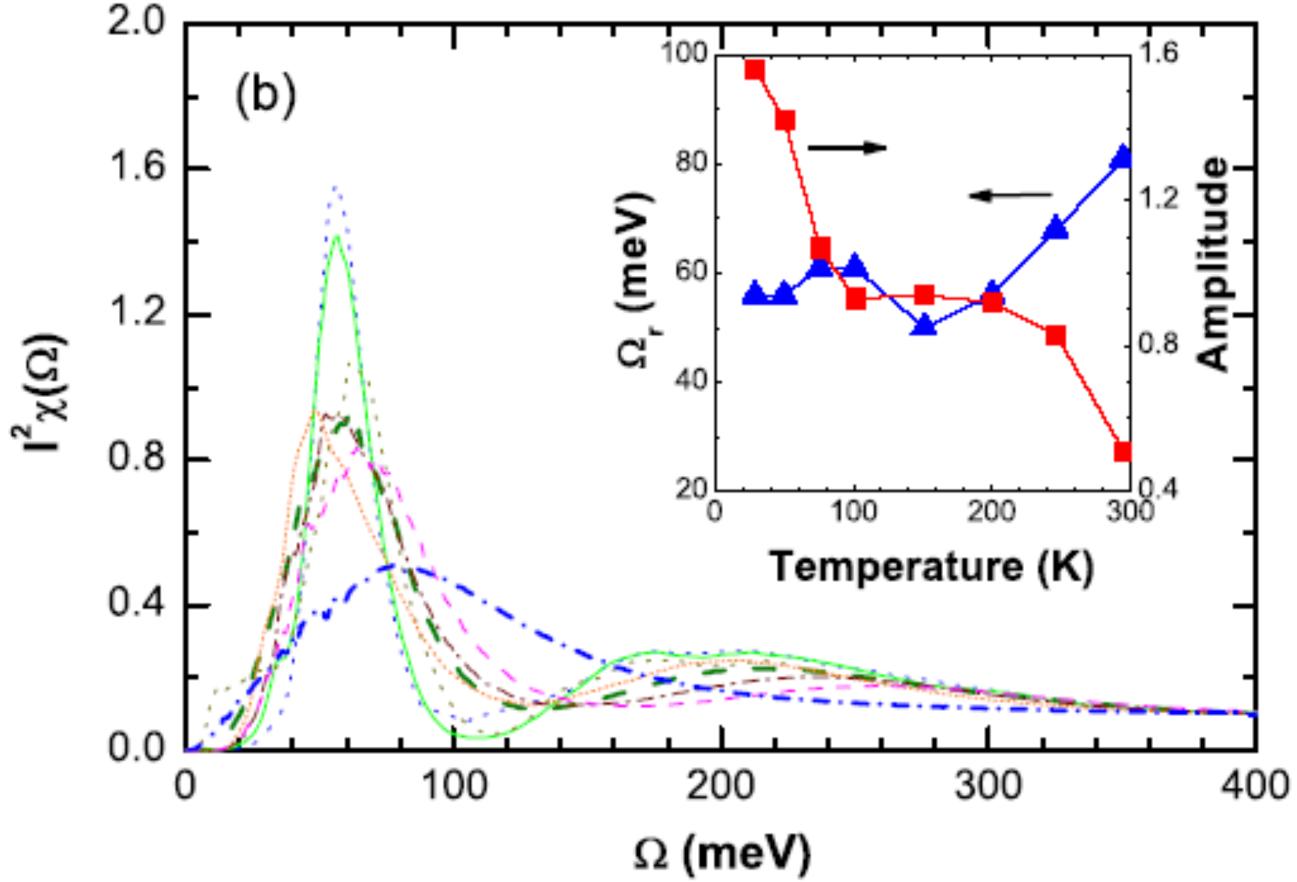
Spin gap

J. Hwang et. al. Phys. Rev. Lett. 102 , 027003 [2009]   **Hg Ba2 Cu O4+, Tc=90K**



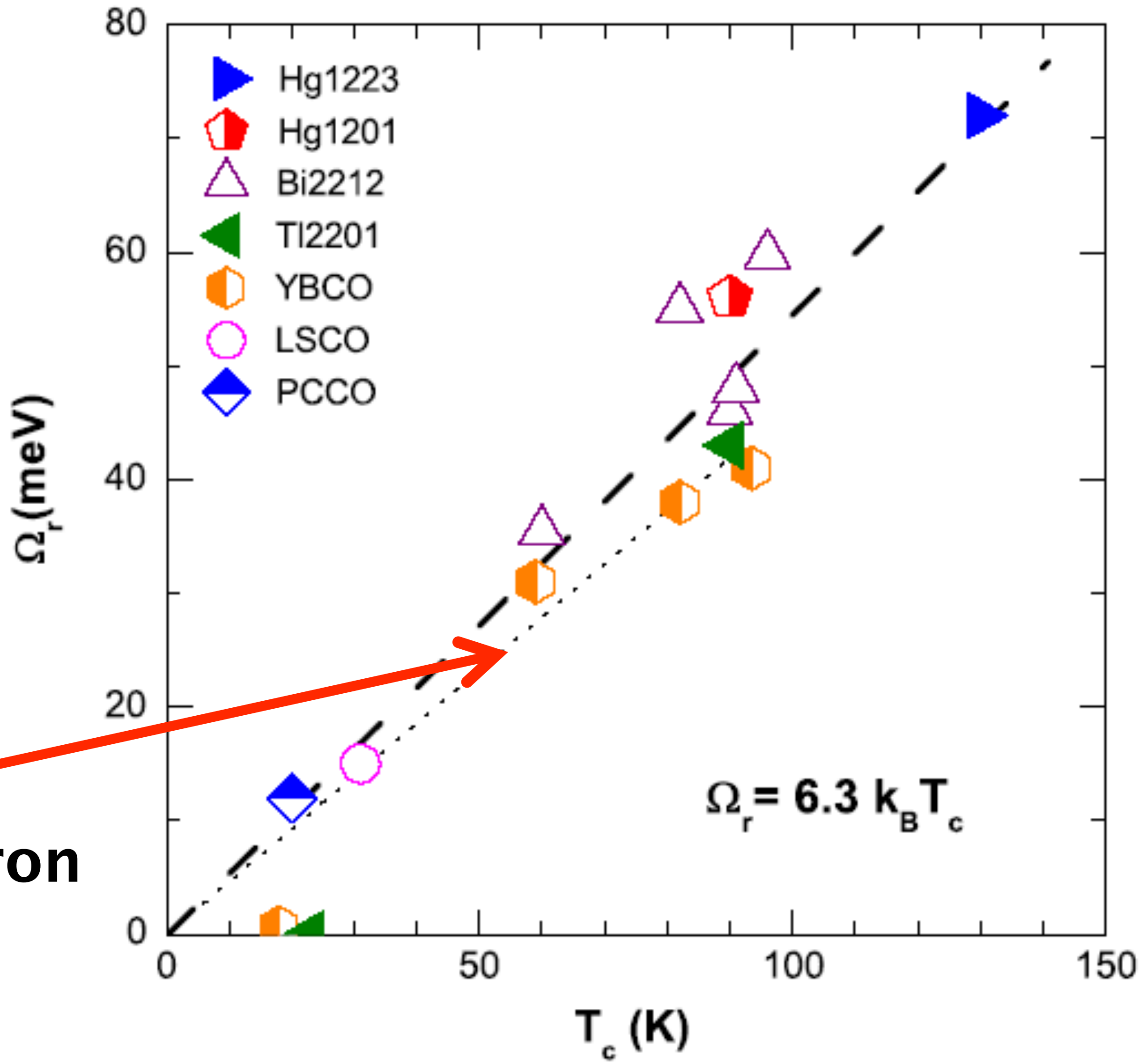
Optical scattering rate

Same temperature evolution as Bi2212 Resonance energy moves up and amplitude is reduced with increasing temperature



Spectral density extends to high energy and evolves with temperature

Summary of optical resonance energy vs Tc



From neutron scattering

Angular resolved photo emission

ARPES

Electron spectral density

$$A(\mathbf{k},\omega) = \frac{1}{\pi}\frac{\Sigma''(\mathbf{k},\omega)}{[\omega - \varepsilon_{\mathbf{k}} - \Sigma'(\mathbf{k},\omega)]^2 + [\Sigma''(\mathbf{k},\omega)]^2}$$

Real part self energy

Imaginary part self energy

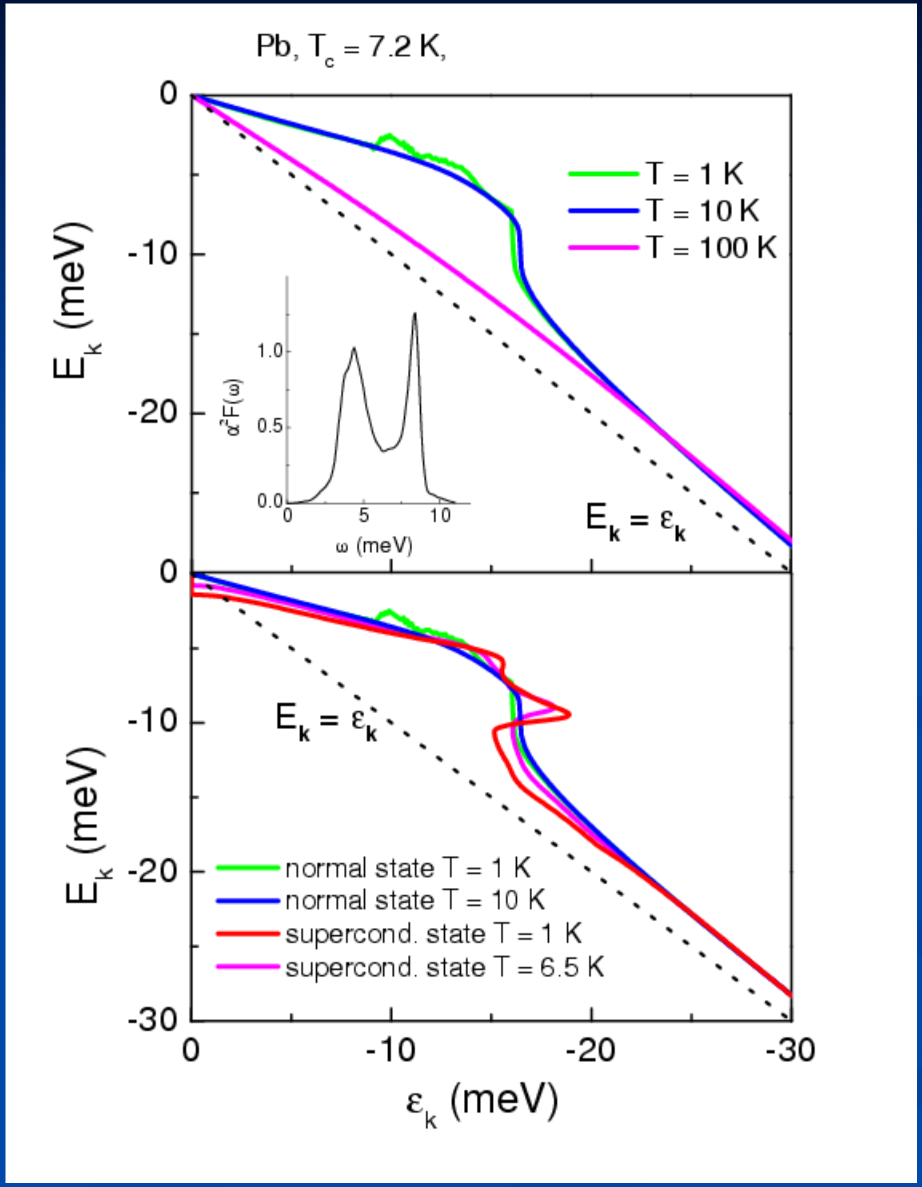
ARPES measures this function at negative energy only

Self energy $\Sigma(k,\omega)$ gives renormalizations

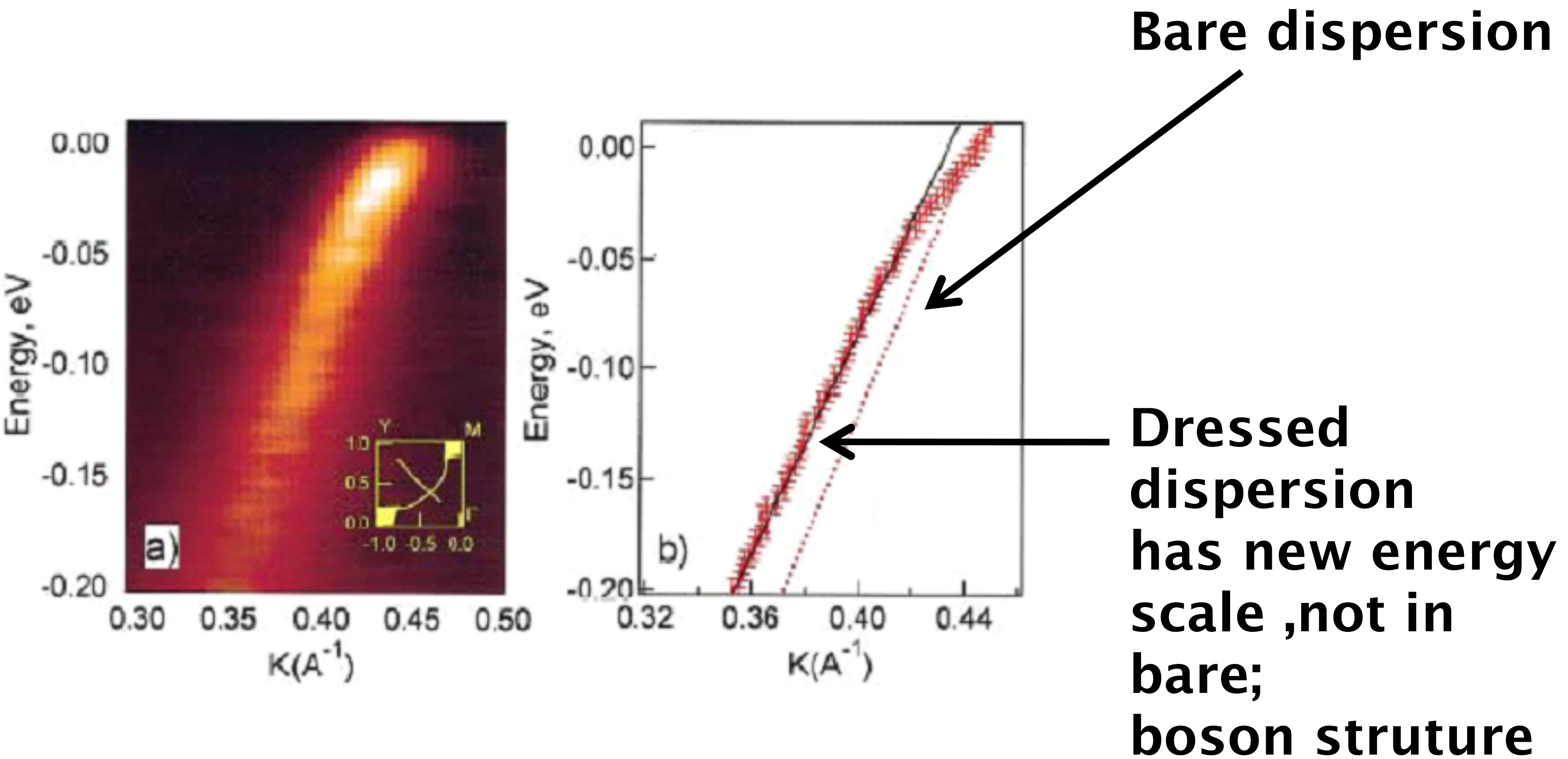
Renormalized dispersion in Pb: Electron-phonon interaction

$$E_{\mathbf{k}} = \varepsilon_{\mathbf{k}} + \mathrm{Re}\left[\Sigma(E_{\mathbf{k}})\right]$$

Schachinger et al PRB 67, 214508 [2003]

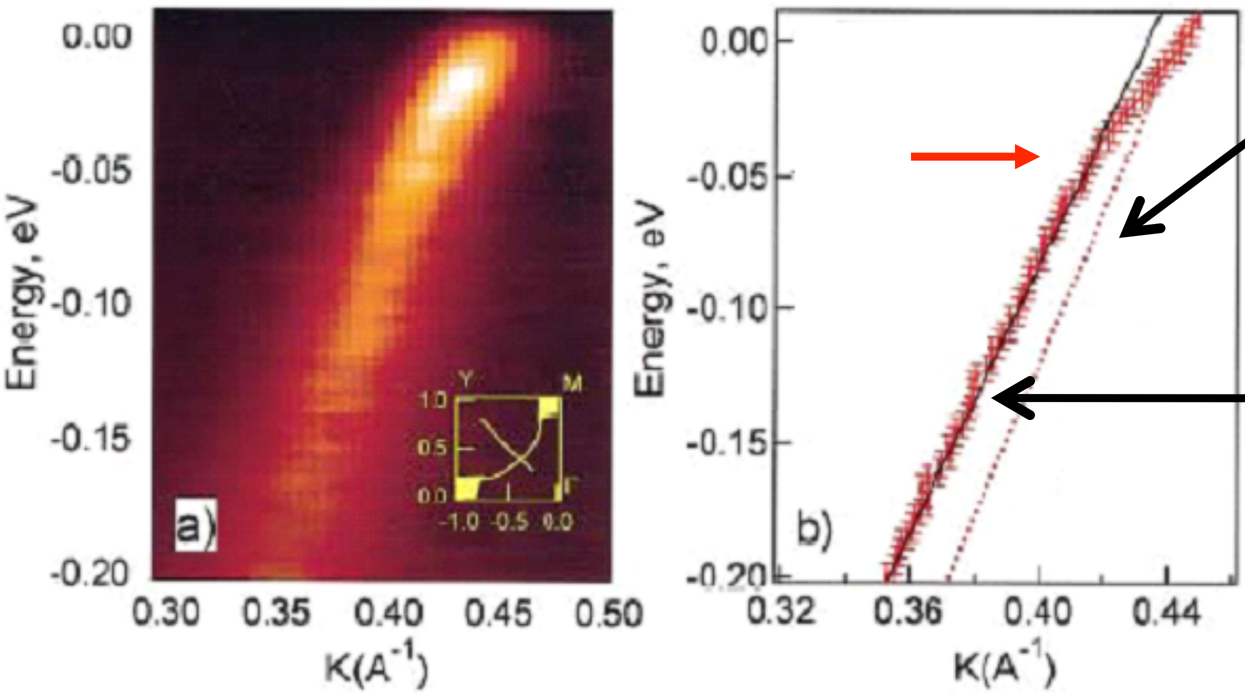


The Kink in ARPES



Bogdanov, Lanzara et. al. Phys. Rev. Lett. 85,2581 [2000]

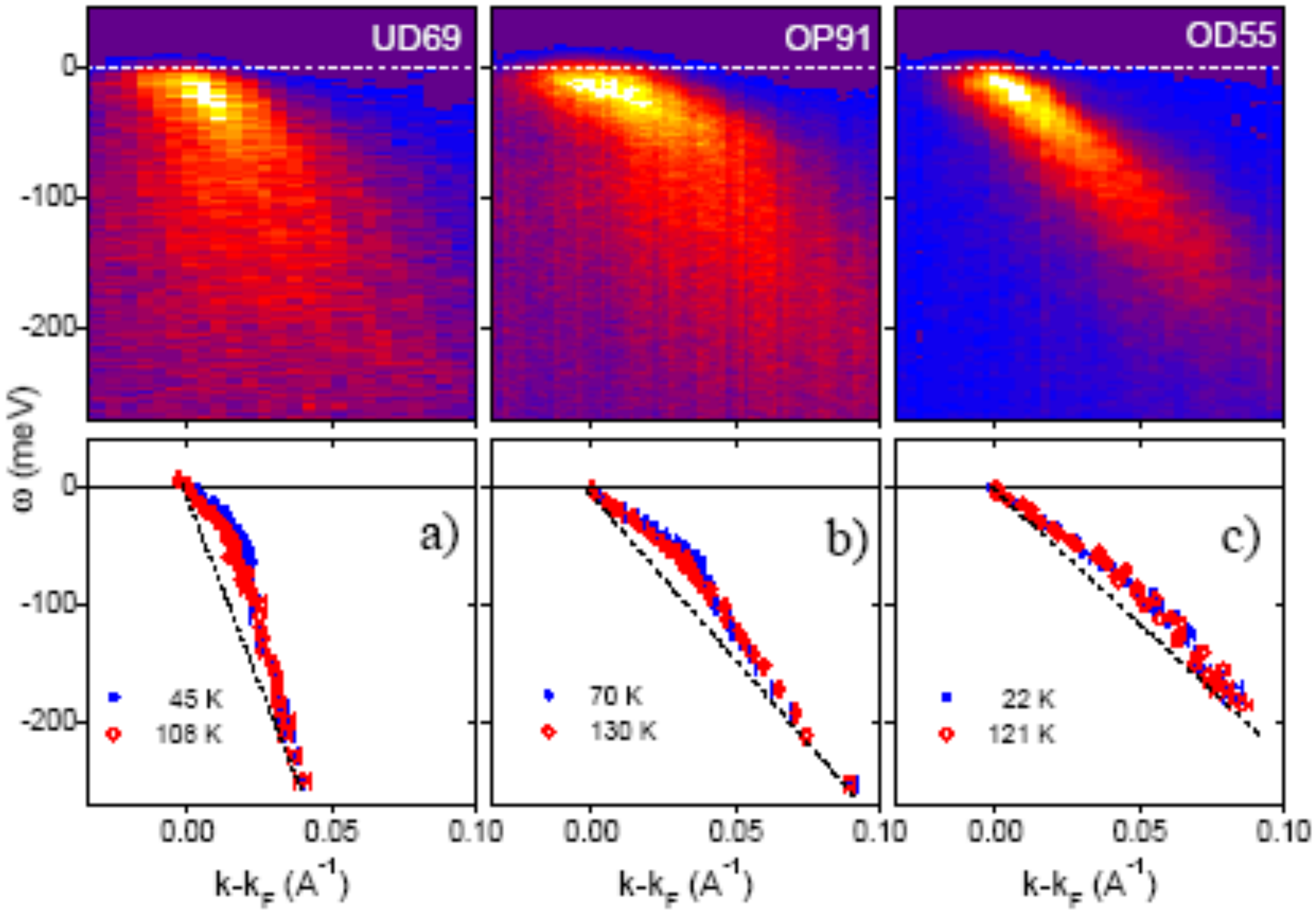
The Kink in ARPES



Bare dispersion

Dressed dispersion has new energy scale ,not in bare; boson struture

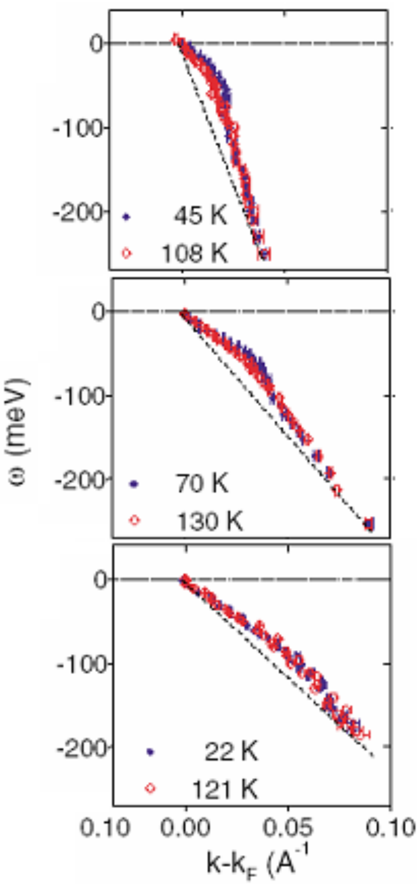
Bogdanov, Lanzara et. al. Phys. Rev. Lett. 85,2581 [2000]

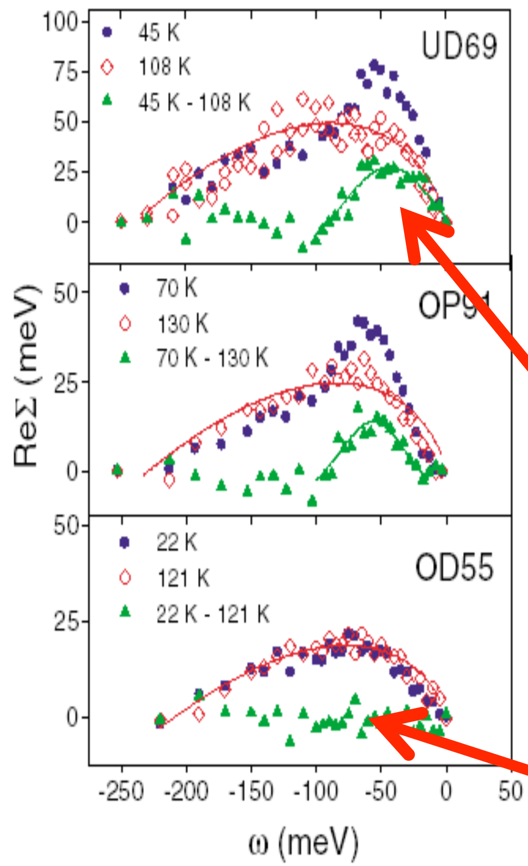


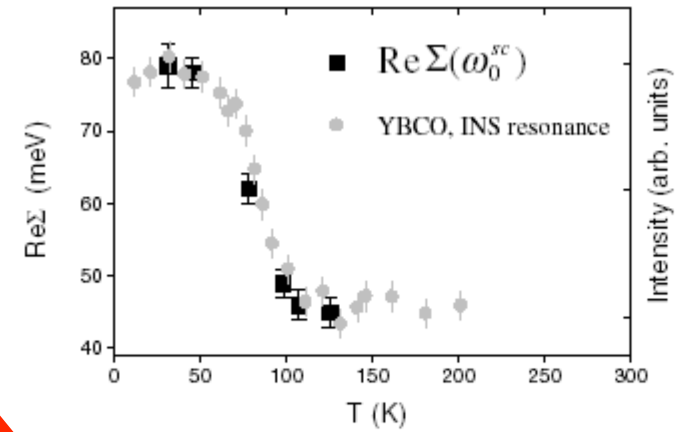
Johnson et. al. PRL 87,177007 [2001]

Bi-2212 near the nodal region

$\Sigma^{qp}{}_1(\omega)$ Quasiparticle self energy







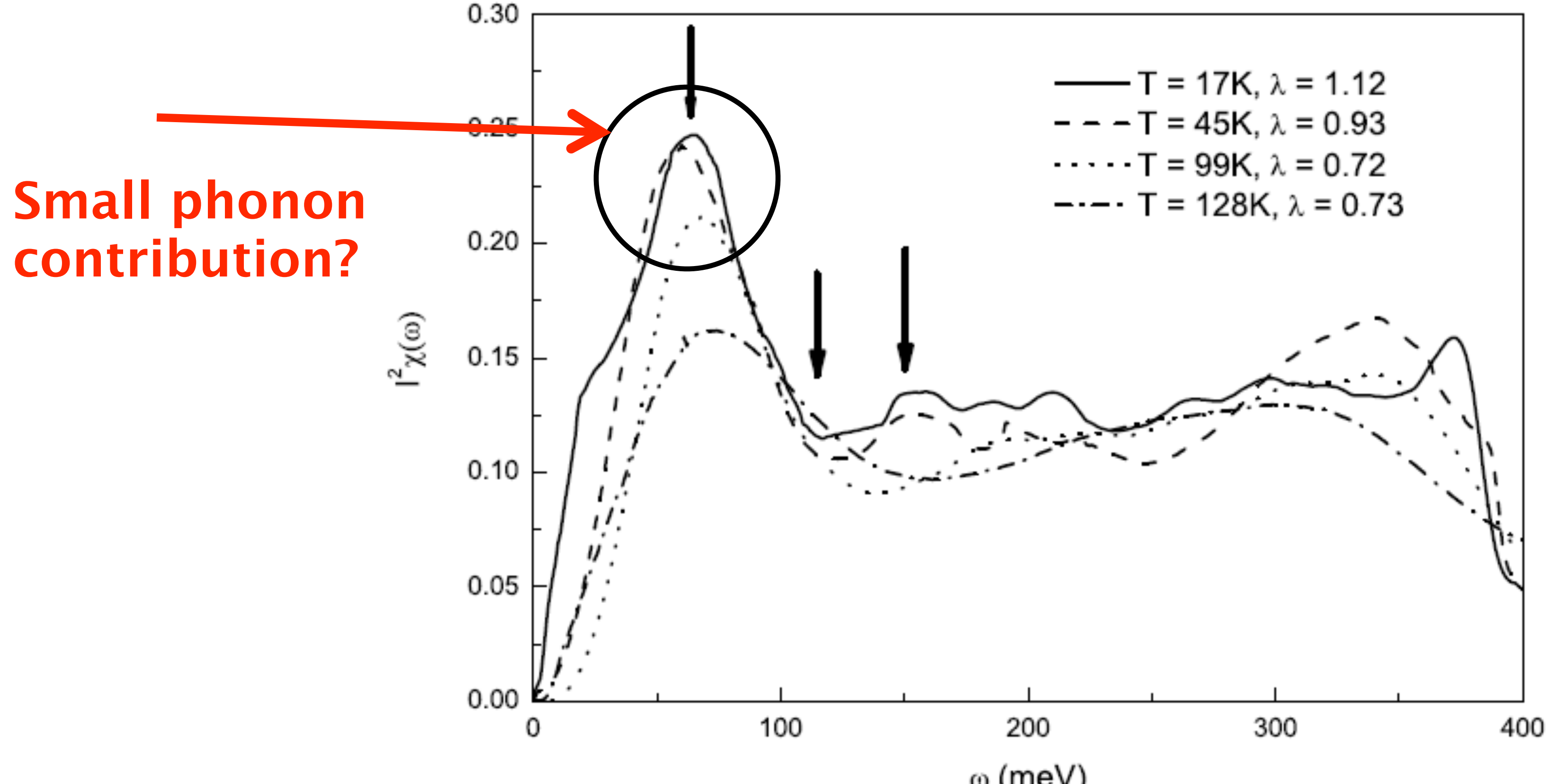
Ω ~$6.0k_BT_c$

peak

no peak

$$E_{\mathbf{k}} = \varepsilon_{\mathbf{k}} + \mathrm{Re}\left[\Sigma(E_{\mathbf{k}})\right]$$

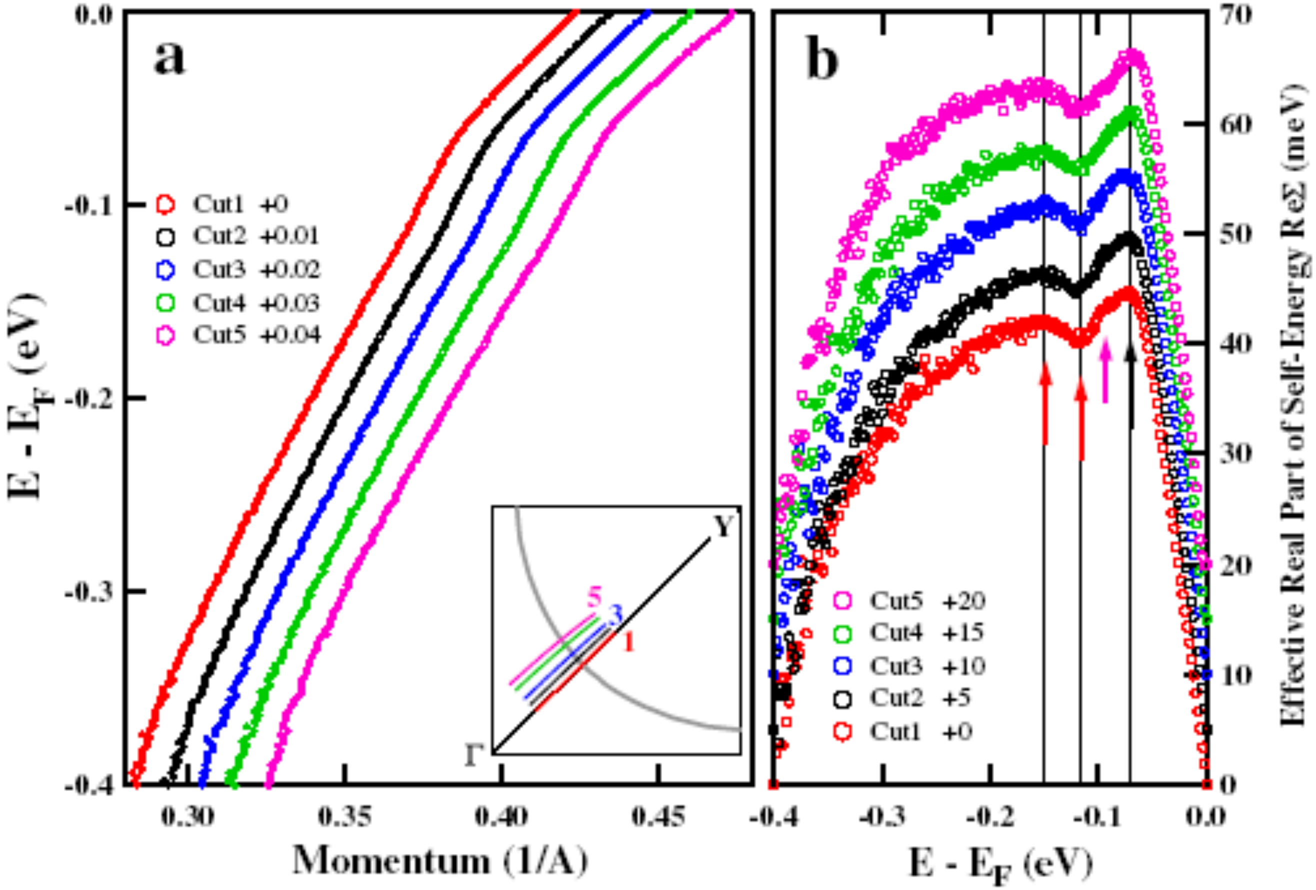
Schachinger - Carbotte , inversion [PRB 77,094524 [2008] of nodal direction ARPES data in Bi2212 by X. J. Zhou-gr



Spectrum extends to high energy and evolves with temperature

W. Zhang et. al. [X. J. Zhou-group] PRL 100,107002 [2008] :Bi2212

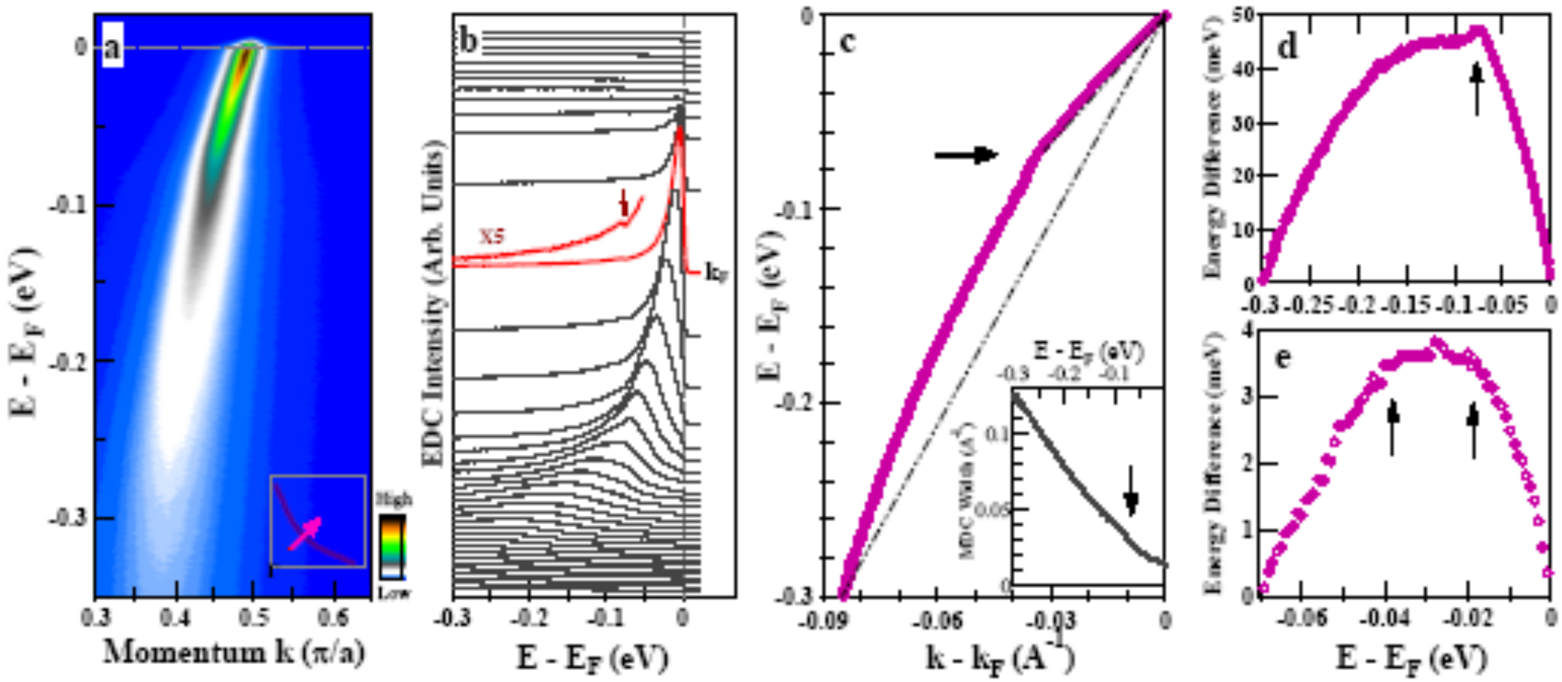
Features at 70,115,150 meV interpreted by authors as not phonons



Momentum resolution 0.004 A-1 Tc=91K, energy resolution 0.56 meV

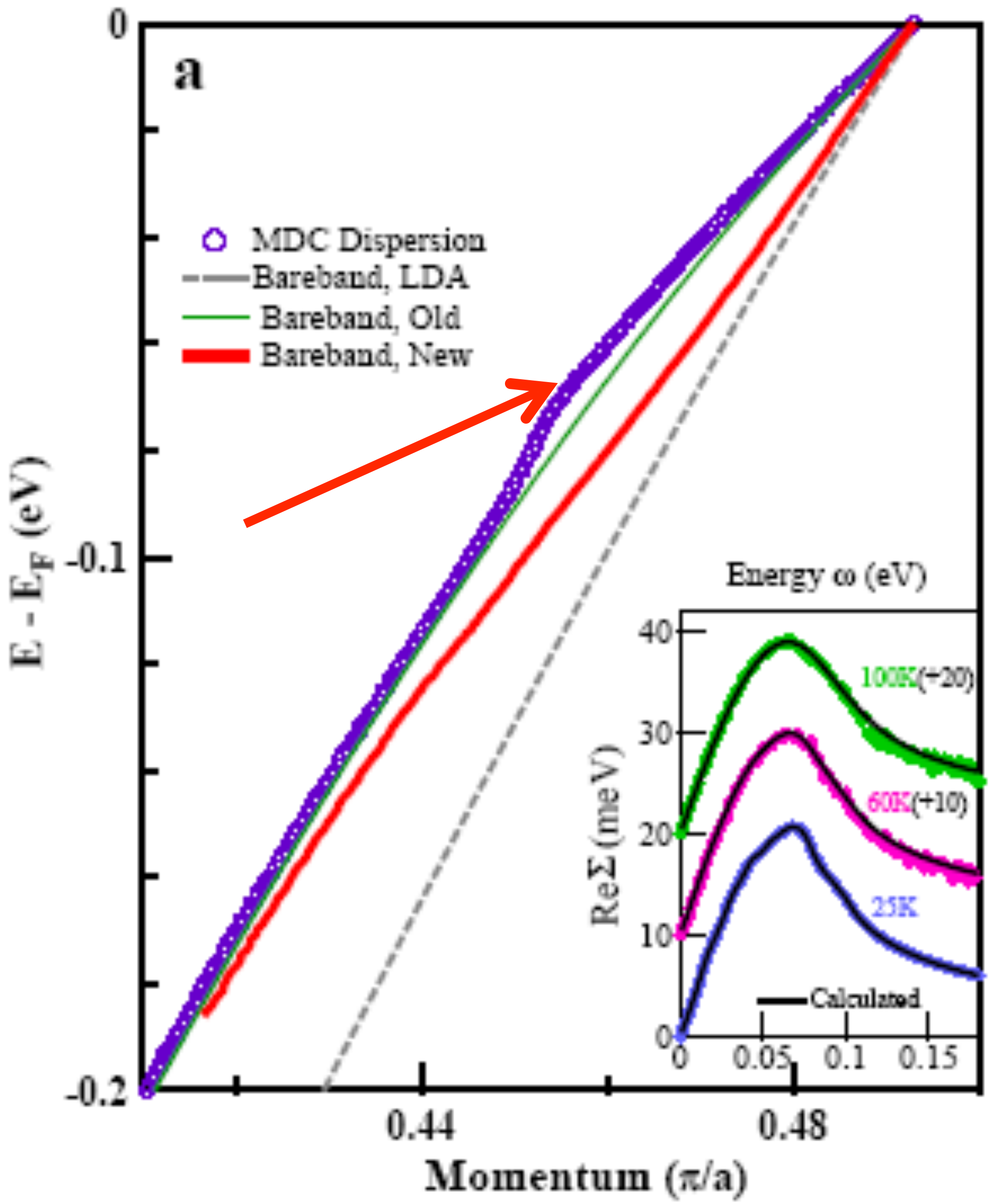
On the other hand

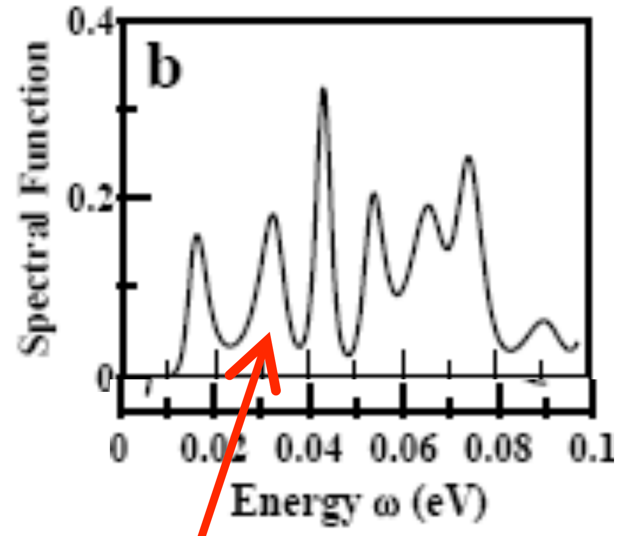
L. Zhao et. al. [X. J. Zhou-group] APS Portland 2010



heavily over-doped [BI PB] 2SR 2CU O6+ ,Tc=5 K

Coupling to multiple phon
modes at 70 meV, lamda=





?

Heavily over-dope
[Bi Pb] Sr Cu O

Interpreted by authors as Phonons

Tunneling Spectroscopy

SIS

Tunneling measures the electron density of states N[ω] DoS

For superconducting-normal junction it is N[ω] that enters

For superconductor-superconductor junctions it's a convolution of the two DoS

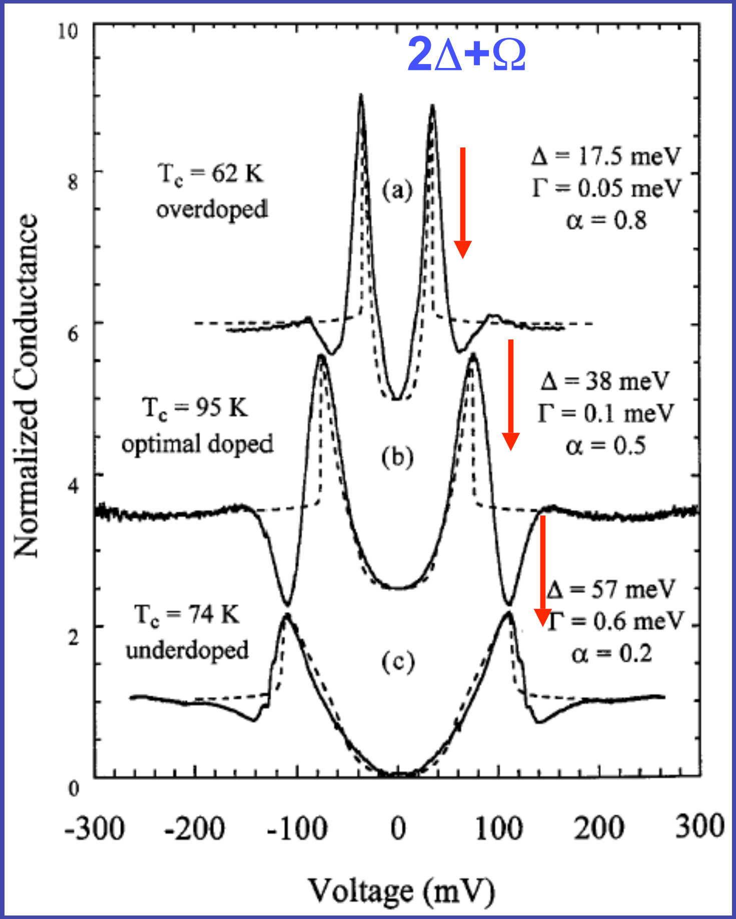
peak-dip-hump in Tunneling

Bi-2212 (SIS junction)

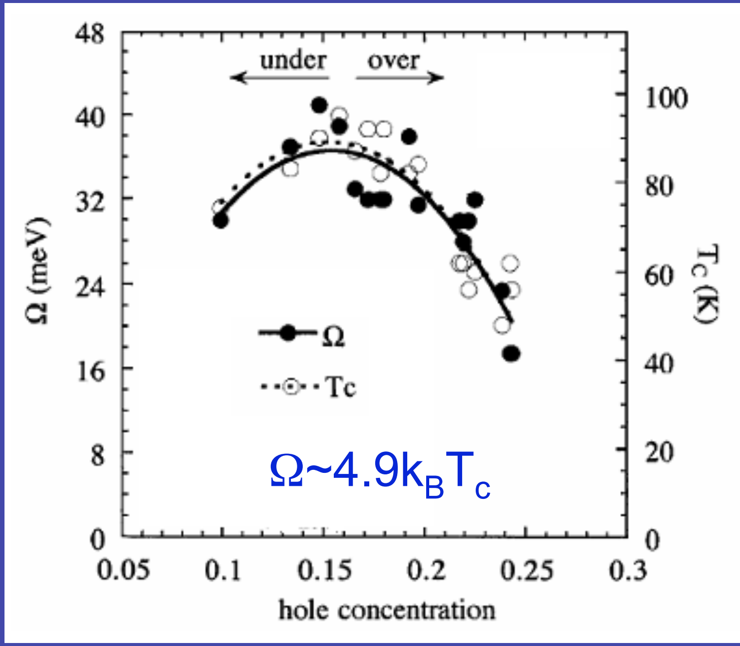
OD62

OPT95

UD74



Tunneling ←→ INS



Zasadzinski *et al.* Phys. Rev. Lett. **87,** 067005 (2001)

Four different techniques give very similar results for the energy of boson peak

ARPES gives about	6
Tunneling gives about	5
Optics gives about 8/1.43= about	5.5
Neutron gives about	5.4

All in units of the critical temperature

Good agreement about resonance but its origin remains controversial

Extent to high energy of spectral density and its evolution with temperature indicate spin fluctuations

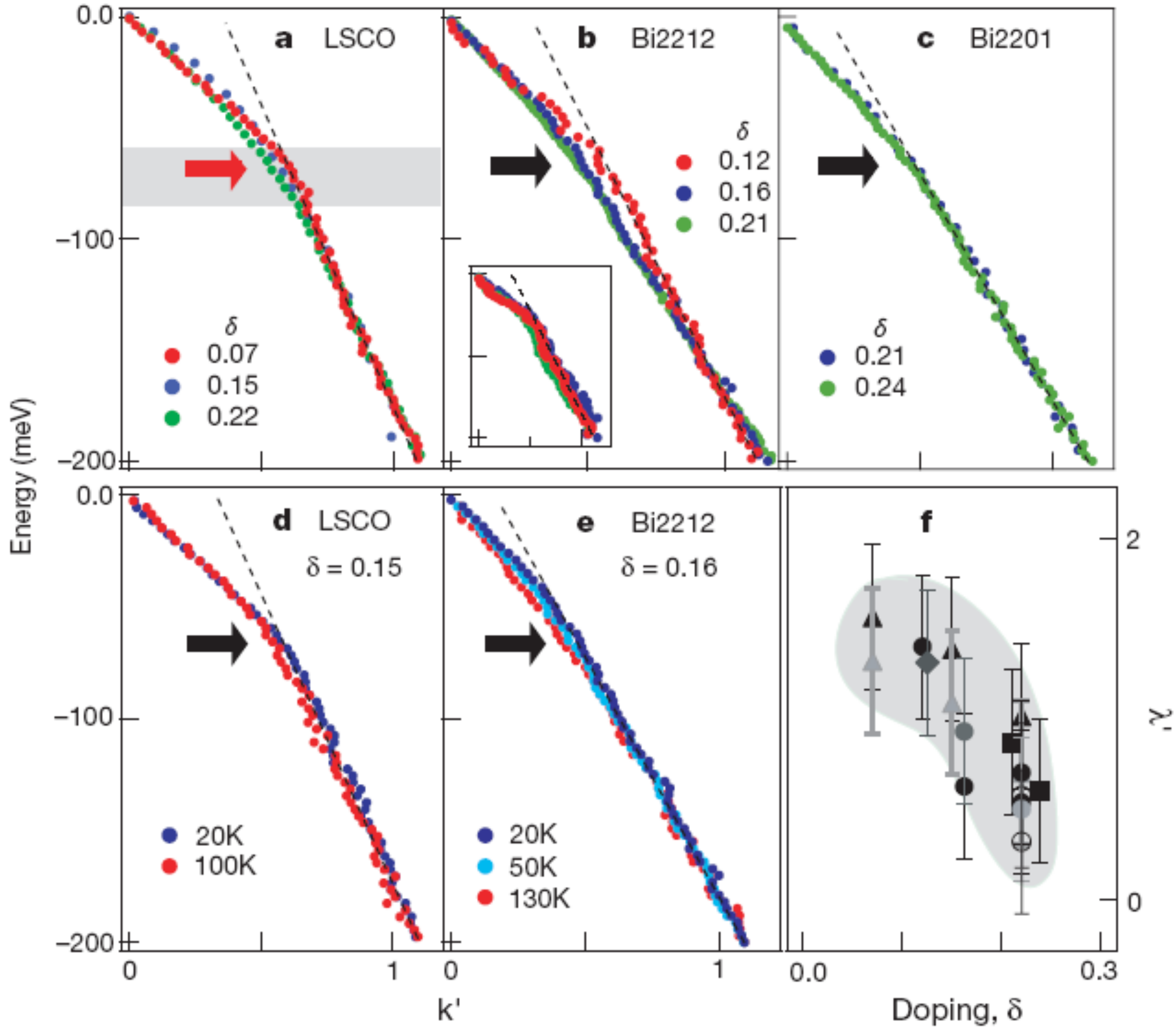
Probably both are involved
What do you think?

We have come a long way!
wonderful journey of discoveries

BUT it is not over yet

END

Lanzara et. al. Nature ,421, 510 [2001]



Signatures of underlying Electron Boson spectrum seen in

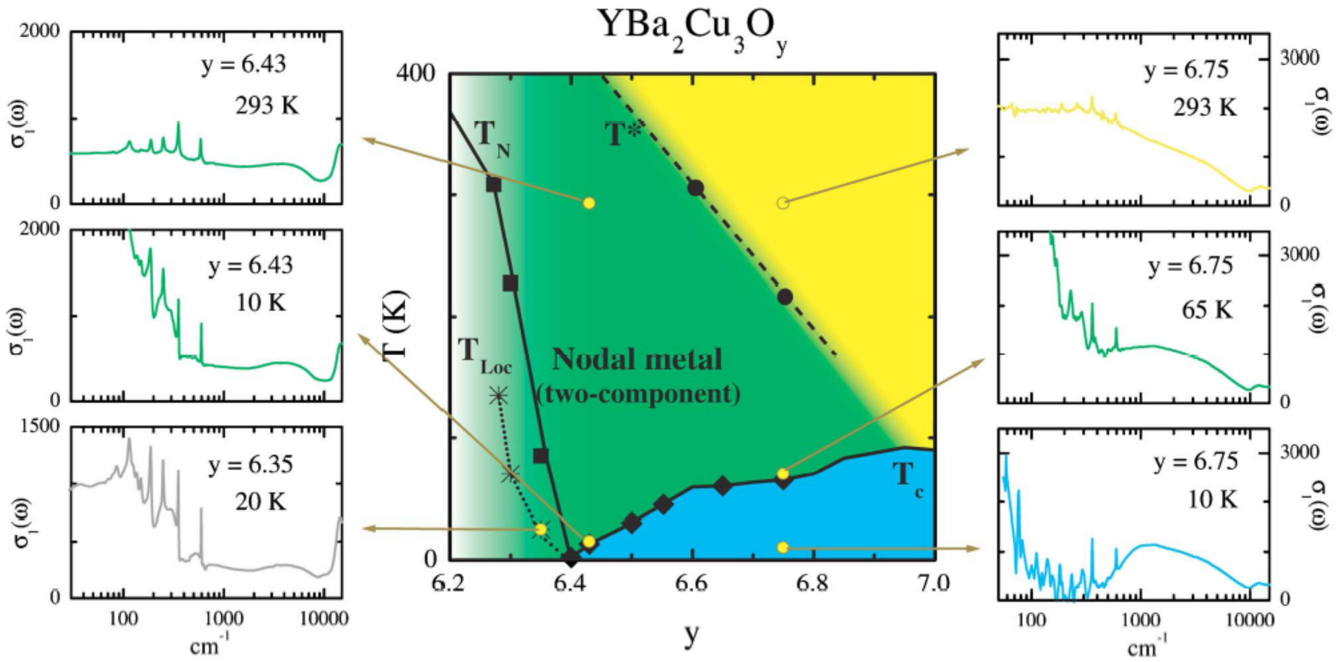
Neutron scattering **INS**

Angular resolved photo emission ARPES

Tunneling SIS junctions

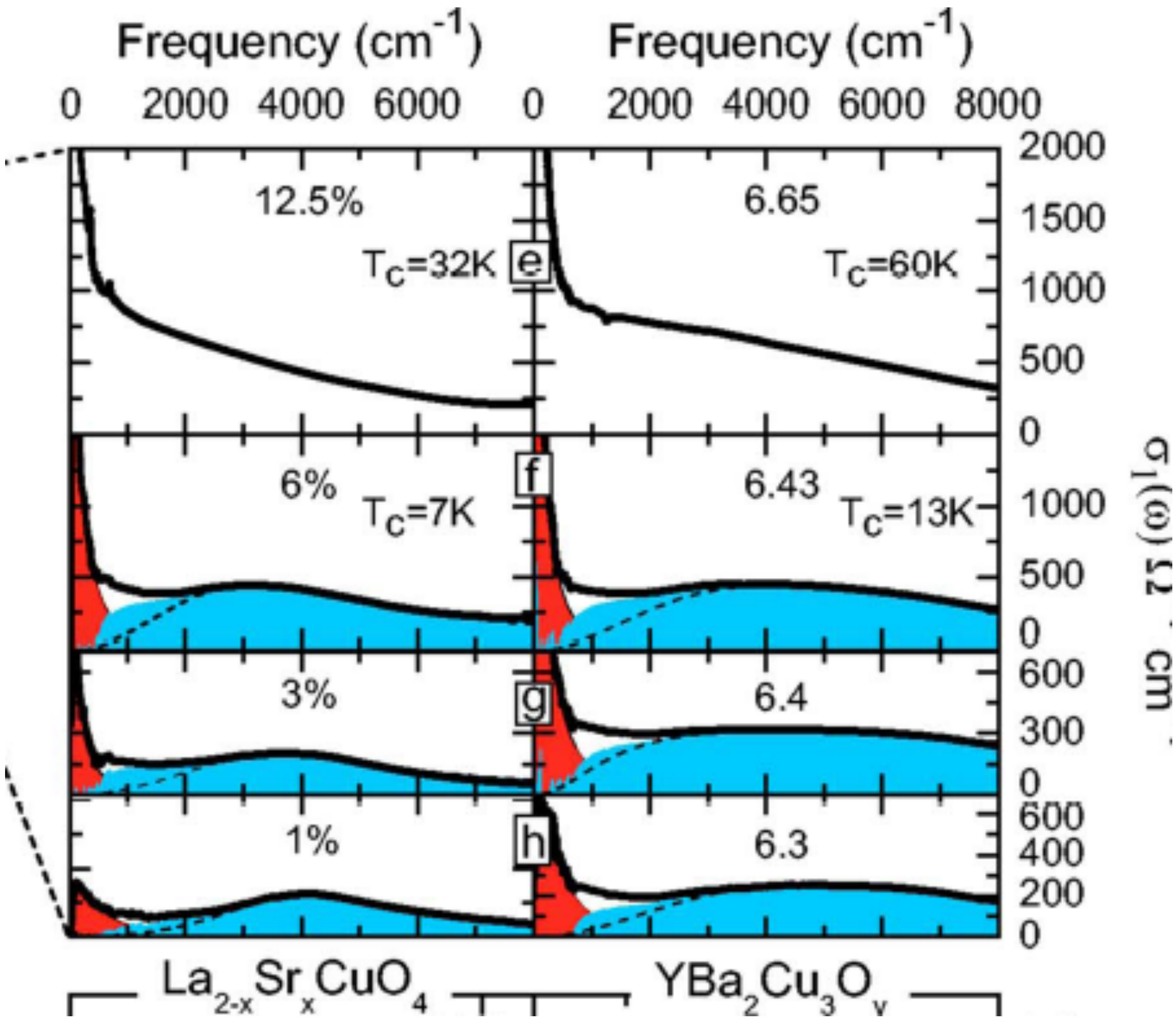
Optics IR-spectroscopy

Coherence in underdoped state and beyond



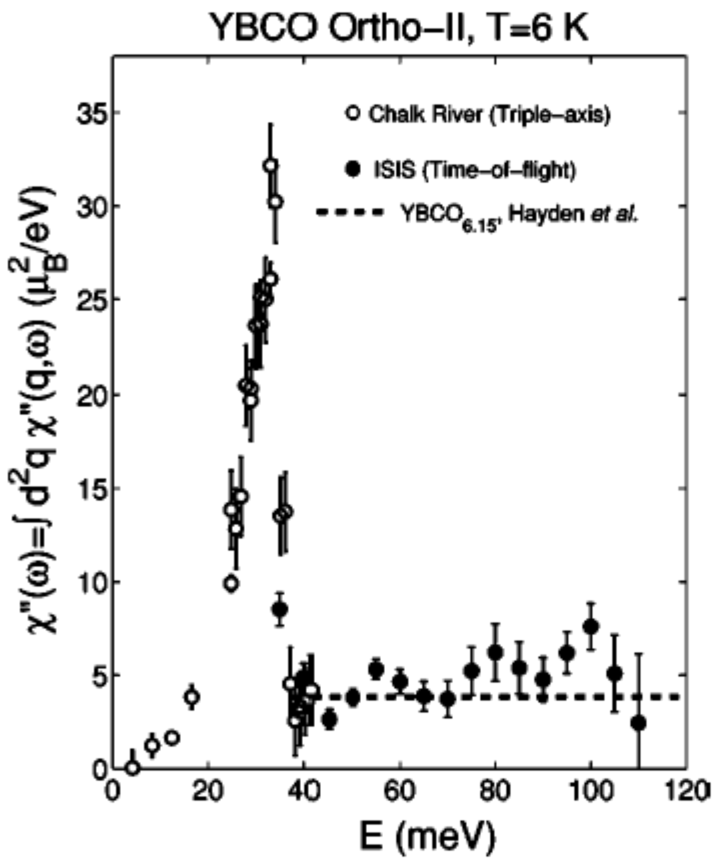
Y. S. Lee et. al. [Basov-group] PRB 72,054529 [2005]

Padilla et. al. [Basov-group] PRB 72,060511 [2005]



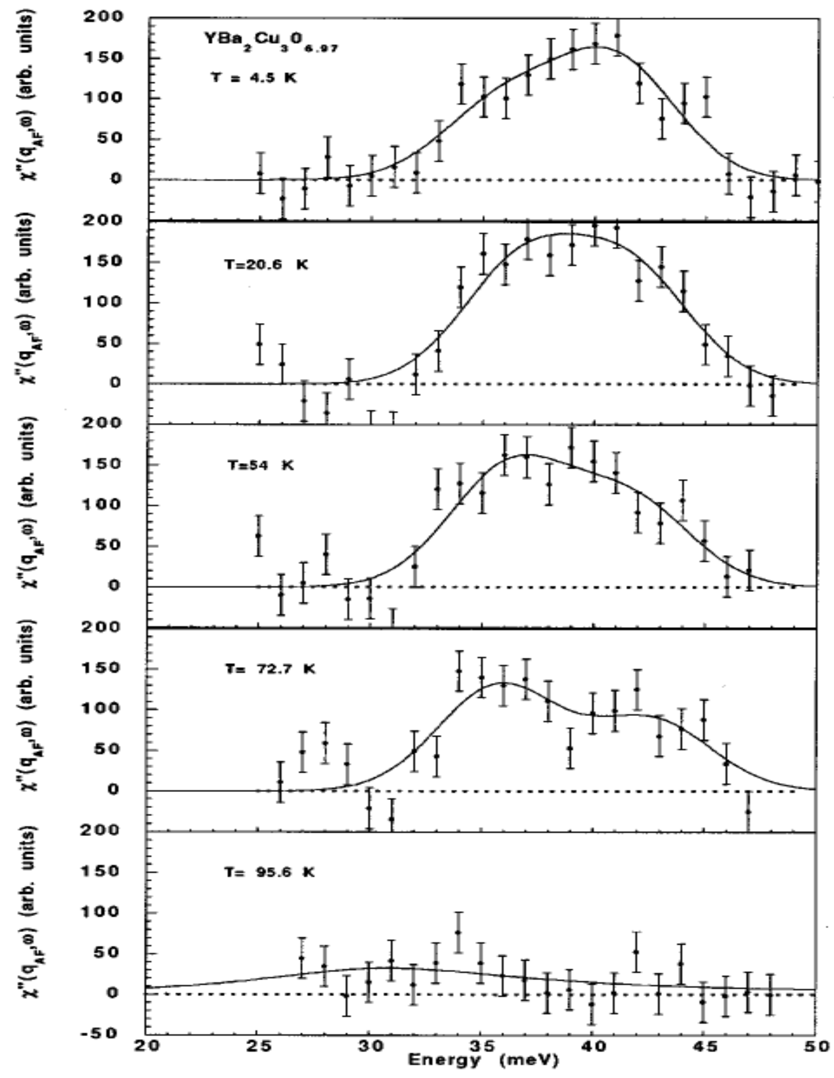
Stock et.al. PRB 71,024522 [2005]

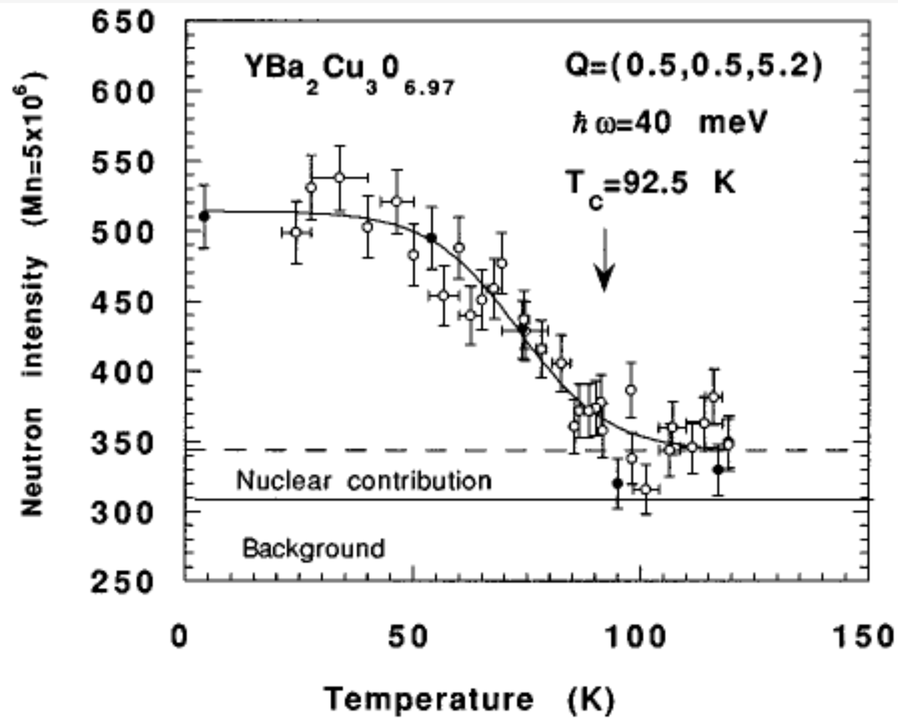
Full and empty chains alternate



Local spin susceptibility from spin polarized neutron scattering

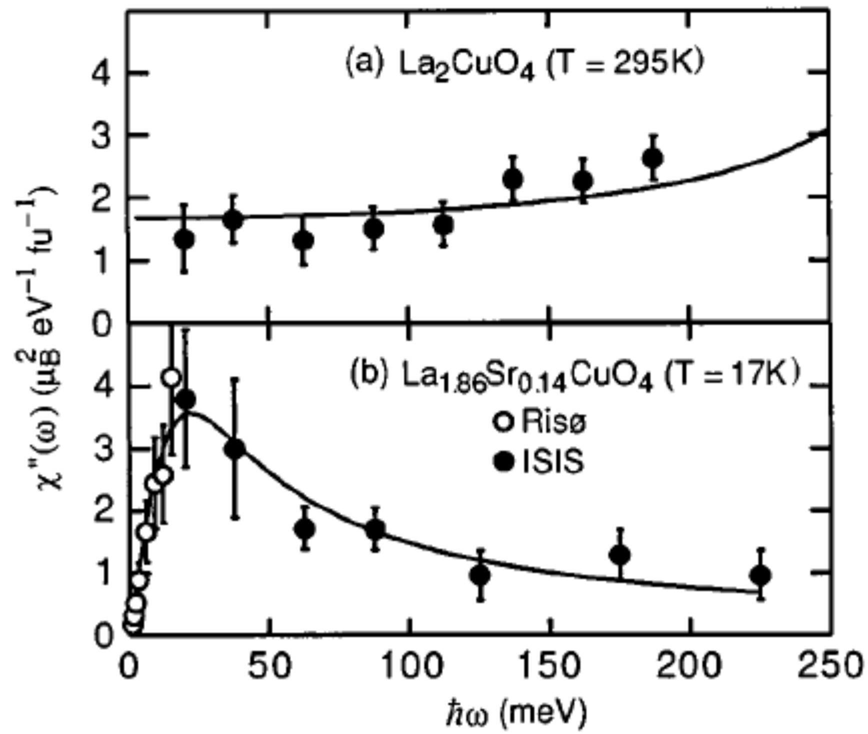
Bourges PRB
53,876 [1996]





YBa2Cu3O6.97
Q=(0.5,0.5,5.2)
ħω=40 meV
Tc=92.5 K
Nuclear contribution
Background
Neutron intensity (Mn=5x10^6)
Temperature (K)
650
600
550
500
450
400
350
300
250
0
50
100
150

Hayden et.al. <PRL 76,1344 [1996]



Local spin susceptibility from polarized spin neutron scattering

Electron-phonon spectral density in Pb

Tunneling:

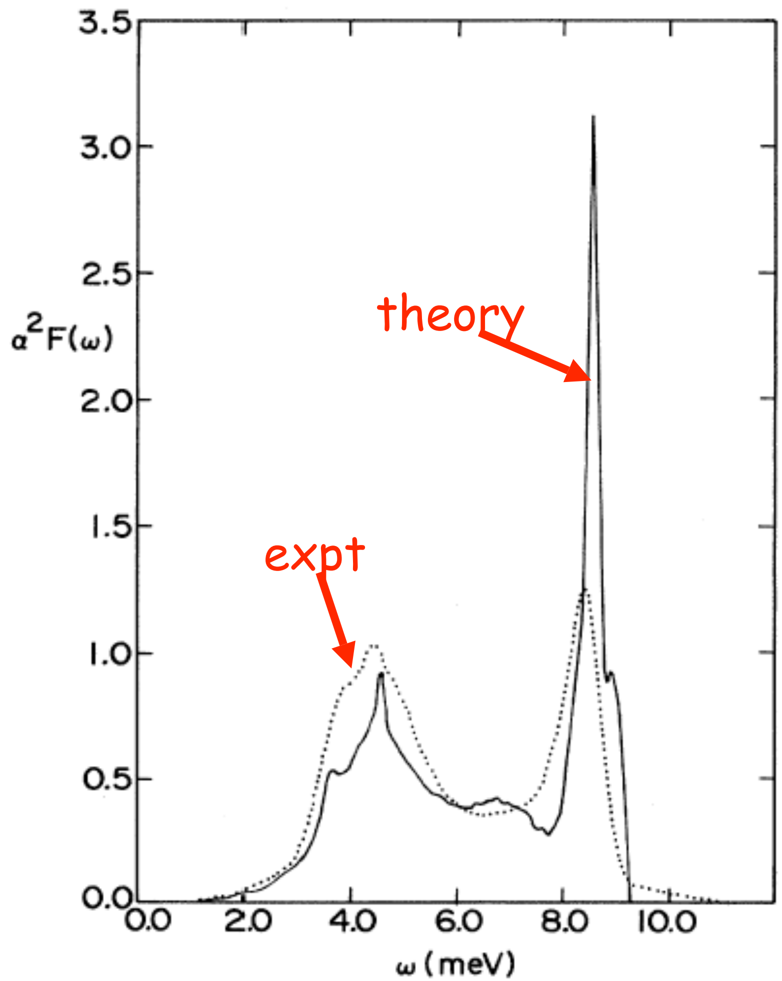
McMillan and Rowell, Phys. Rev. Lett. **14**, 108 (1965).

Calculations:

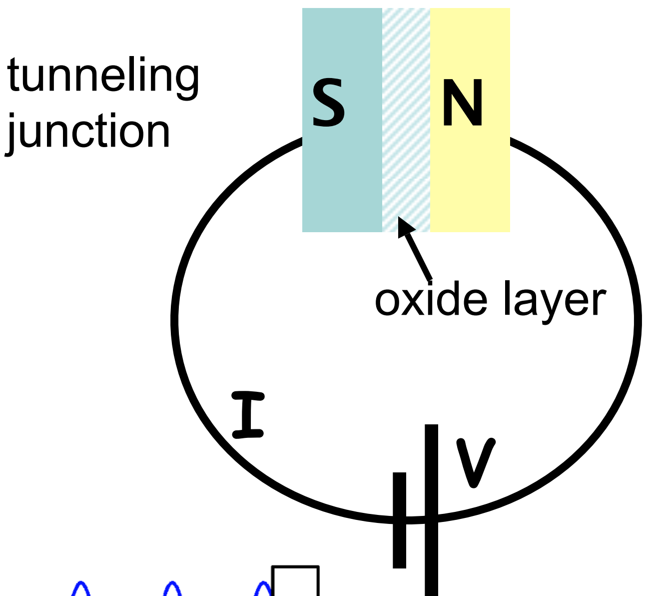
Tomlinson and Carbotte, Phys. Rev. B **13**, 4738 (1976).

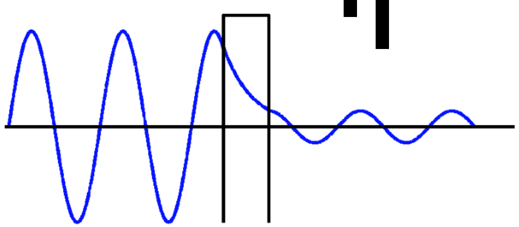
This function contains all of the complicated information on electron and phonon dynamics and the coupling between them that enters superconductivity.

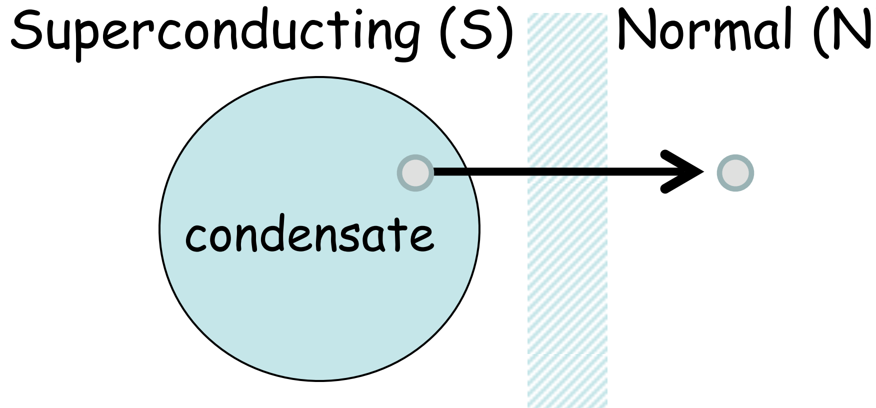
Remarkable condensation of required information!



I-V characteristics of a tunneling junction







Takes energy Δ

Gap in superconducting state means no current till V is equal or greater than Δ