The Optical Conductivity and the electron-boson spectral functions in cuprates

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Collaborators

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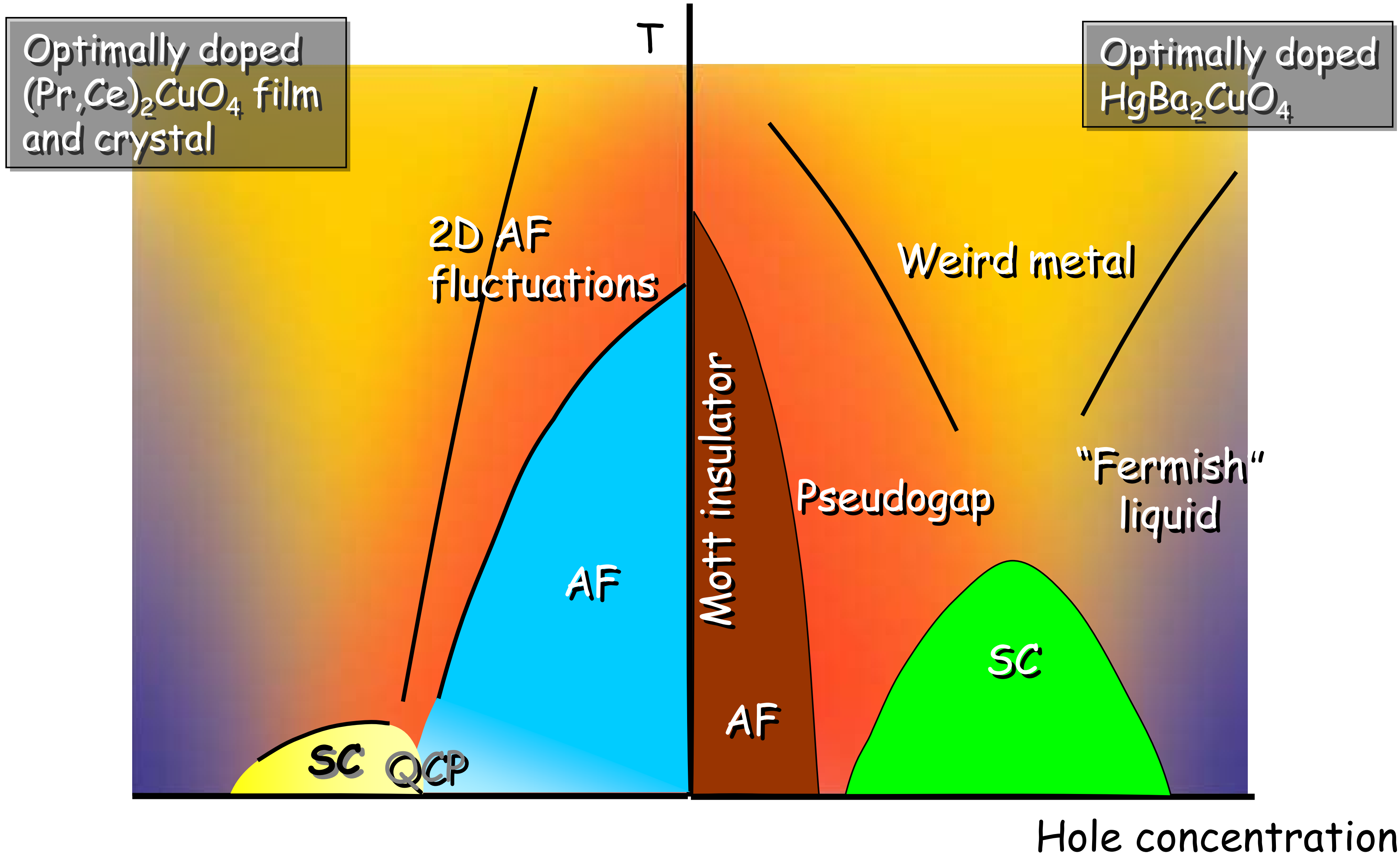
Outline

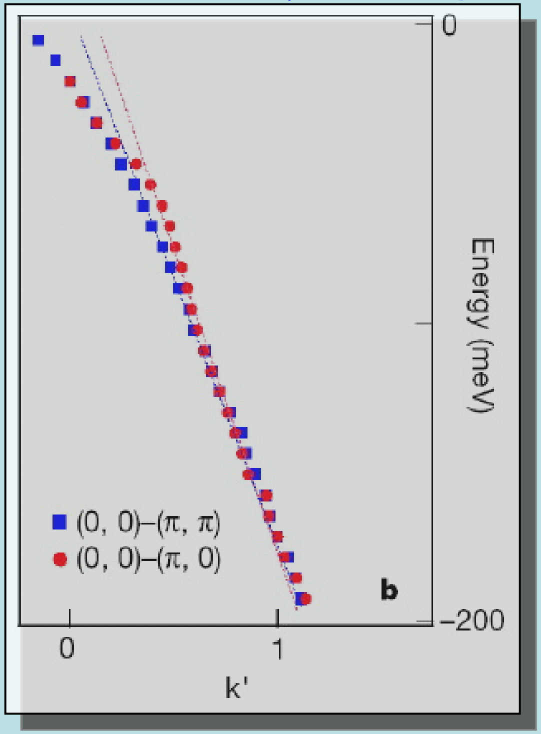
- ✓ Phase diagram
- ✓ The problem of the superconducting glue
- ✓ The electron-boson effective interaction
- ✓ Electron doped $(Pr,Ce)_2CuO_4$
- ✓ Hole doped Hg-1201
- ✓ Optics and Neutrons

The phase diagram of cuprates



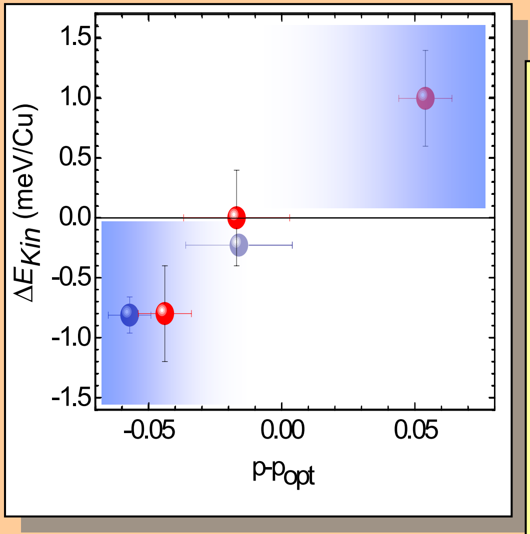
Which glue keeps the pairs together?

Conventional phonon glue



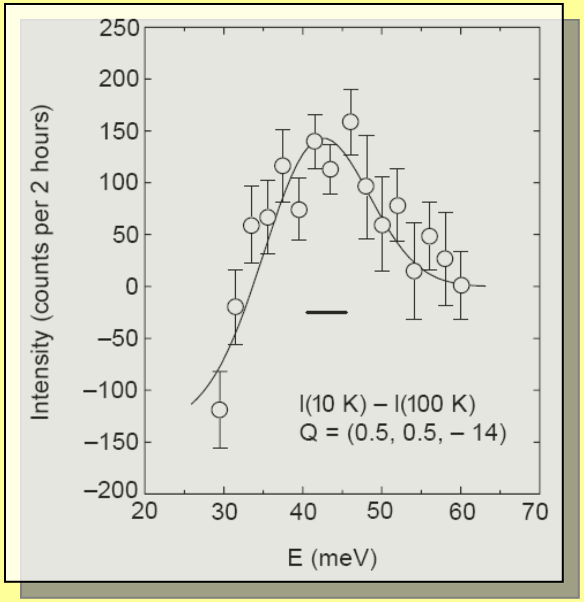
Lanzara et al., Nature **412**, 510 (2001)

Kinetic energy lowering



Deutscher, Santander & Bontemps, PRB 72, 092504 (2005)

Spin fluctuations



Fong et. al, Nature **398**, 588 (1999)

From BCS to Eliashberg Theory

$\alpha^2F(\omega)$ electron-boson spectral density (effective interaction)

BCS theory

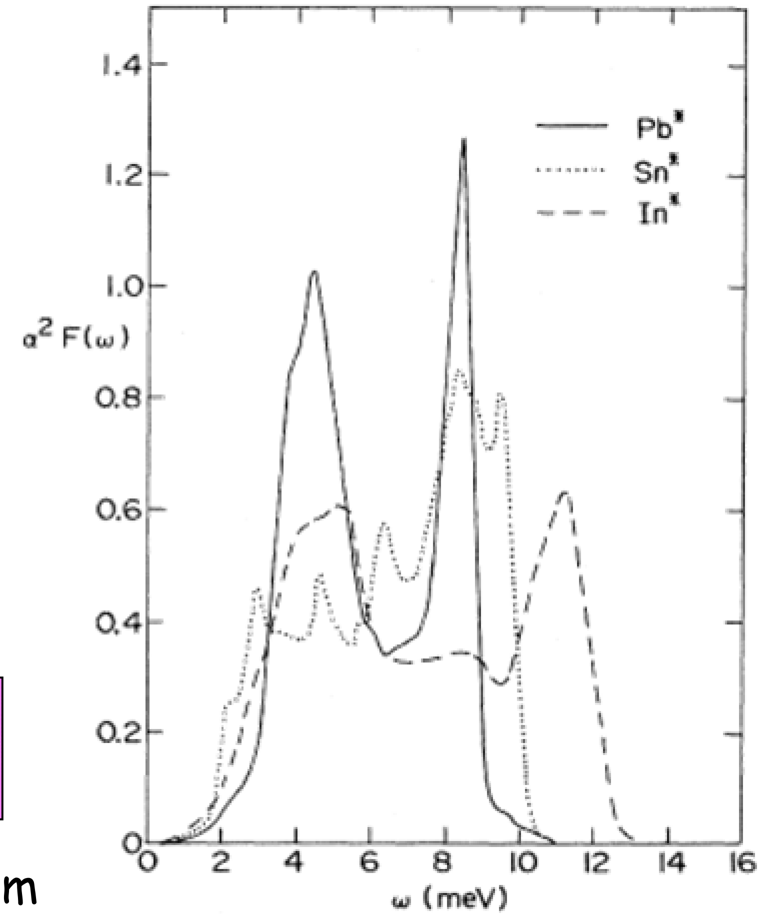
$$k_B T_c = 1.13\hbar\omega_c \exp\left(-\frac{1+\lambda}{\lambda-\mu^\star}\right)$$

$$\lambda = \lambda(0) = \int_0^\infty \frac{2\alpha^2F(\Omega)}{\Omega}d\Omega$$

Eliashberg theory

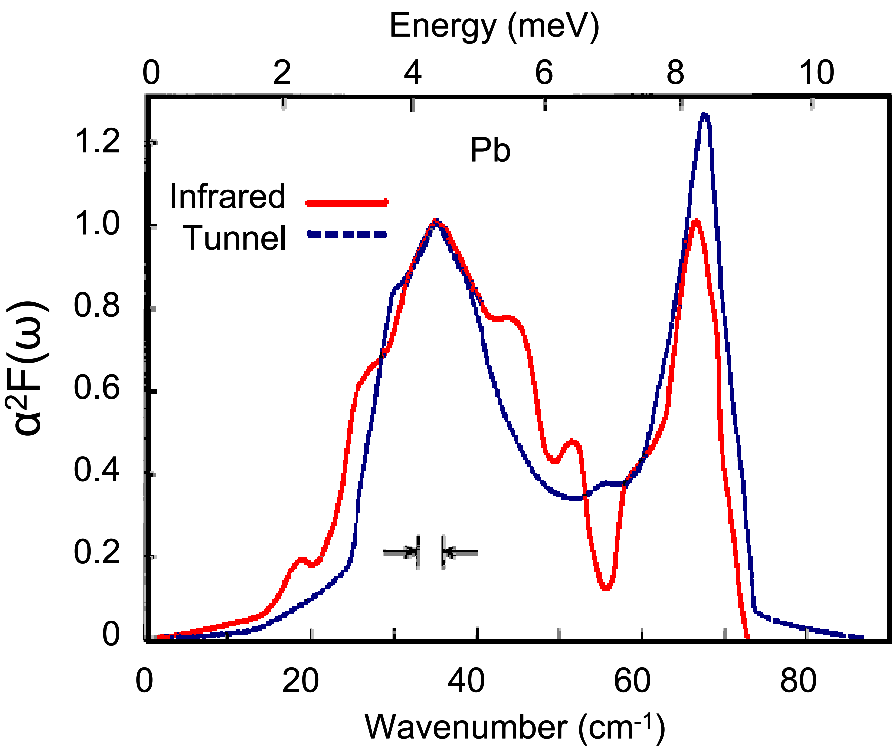
$$\lambda(m-n) = \int_0^\infty \frac{2\,\Omega\,\alpha^2F(\Omega)}{\Omega^2+(\omega_n-\omega_m)^2}d\Omega$$

The gap and T_c are determined from a sum over all couplings λ (mass renormalization).



Carbotte, RMP **82**, 1027 (1990)

The two cents from optics

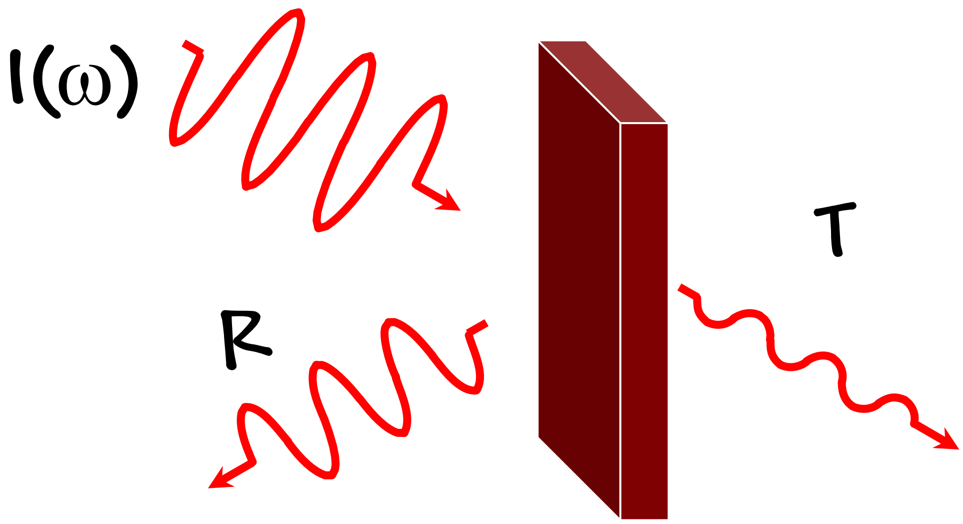


Farnworth and Timusk, PR 14, 5119 (1976)

- ✓Optical Eliashberg bosonic function
- ✓Charge channel excitation spectra
- ✓Average over all q vectors

The "simple" task:
Find the electron-boson spectral density and guess what the boson is…

The Optical Conductivity Measurement



R(ω) and T(ω) ~ $|E|^2$ are real functions.

$$R = \left|\frac{E_R}{E_0}\right|^2 = \left|\frac{1-\sqrt{\varepsilon}}{1+\sqrt{\varepsilon}}\right|^2$$

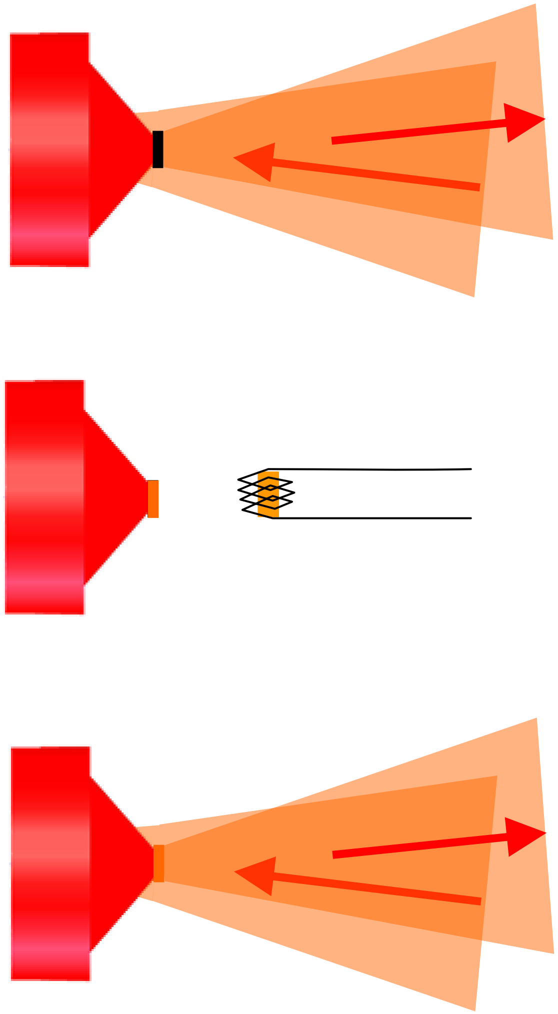
Reflected Power (Real)

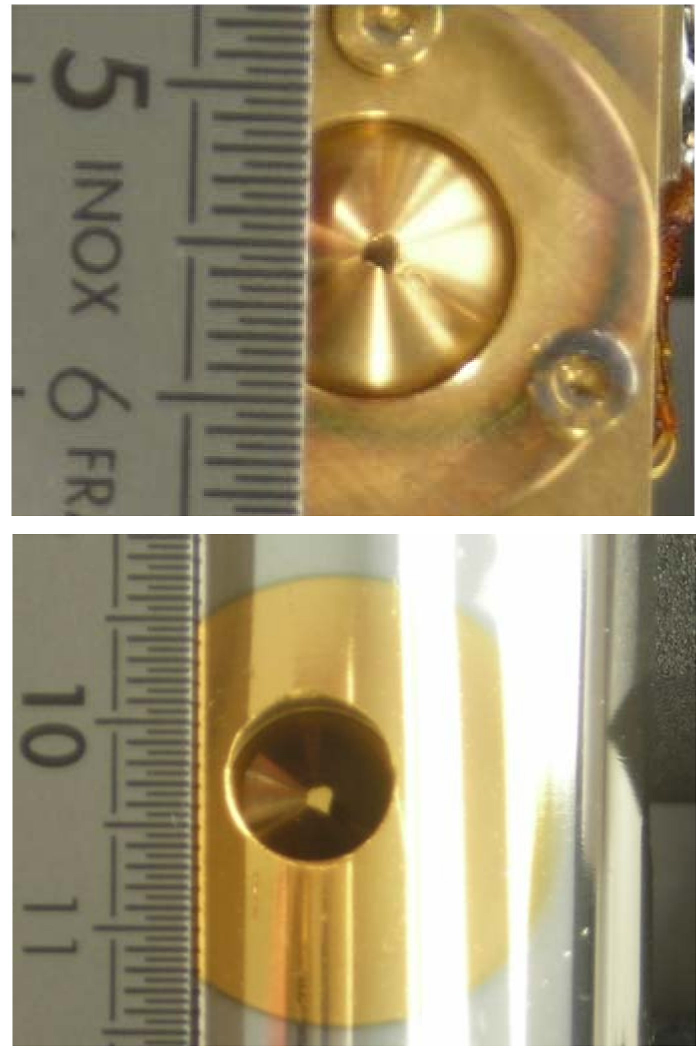
Kramers-Kronig, simulation; fit; R & T inversion...

$$\sigma = \sigma_1 + i\sigma_2 = i\varepsilon_0\omega\left(1-\varepsilon\right)$$

Complex Optical Conductivity

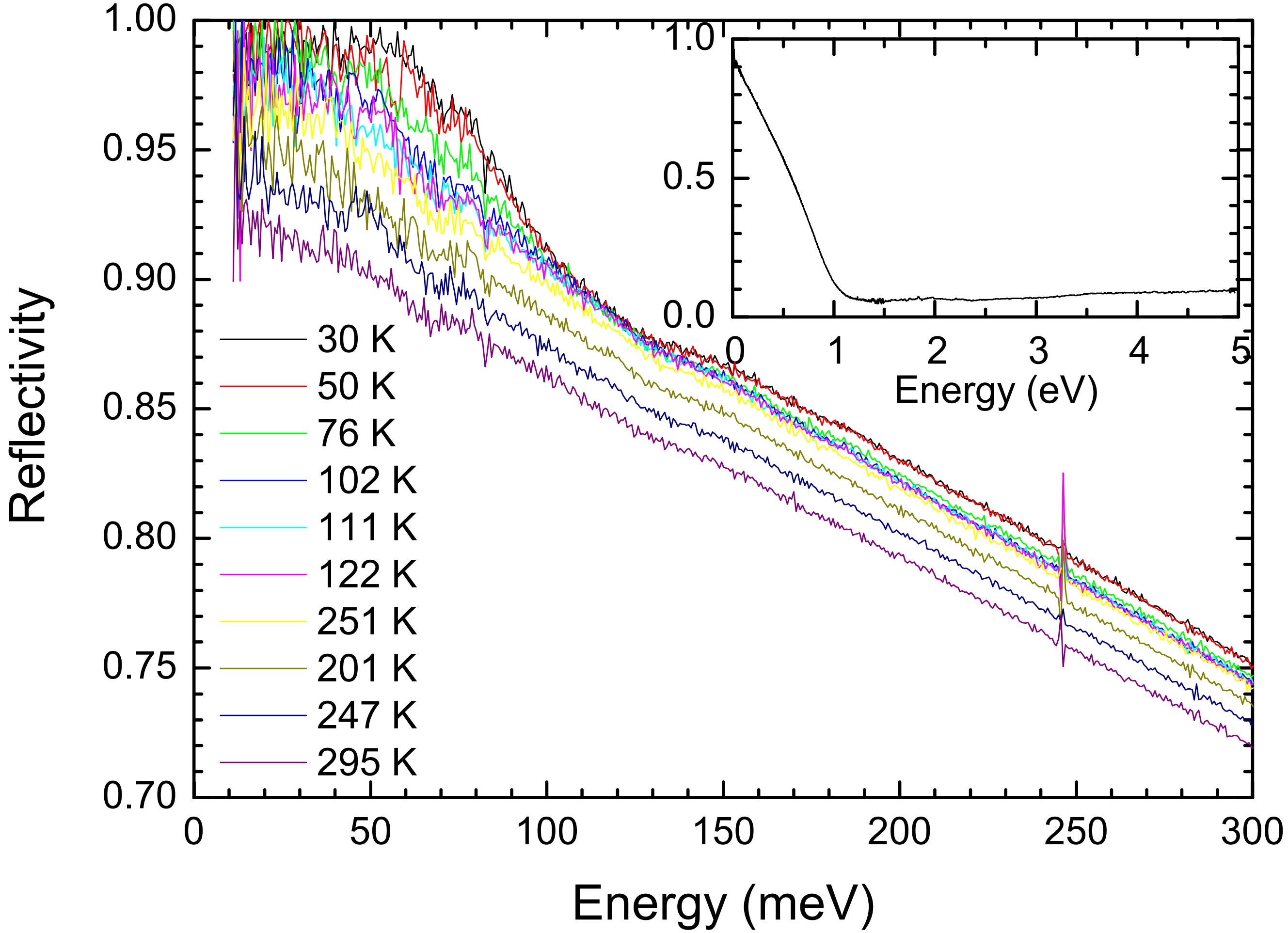
In-situ overfill technique



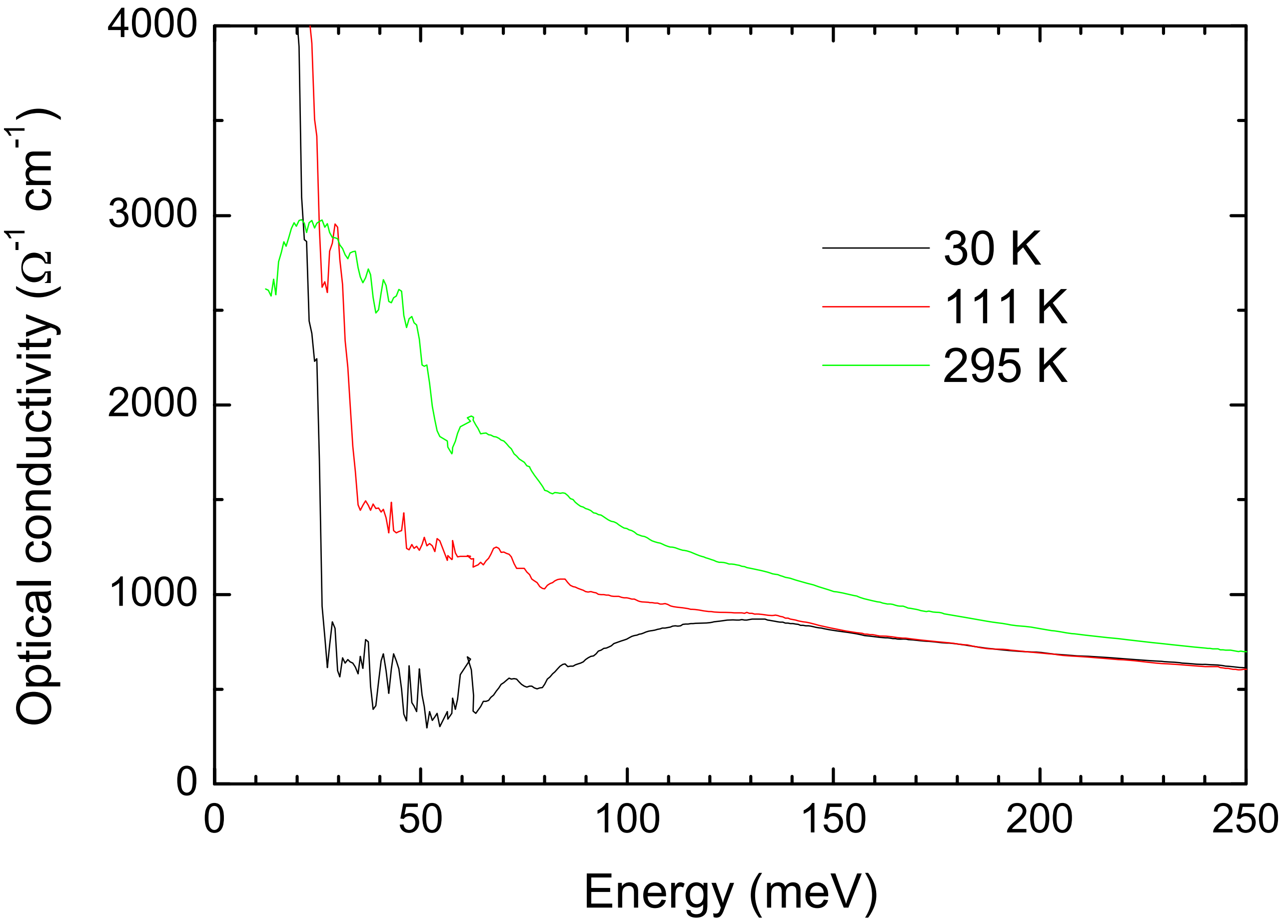


Homes *et al.*, Appl. Opt. **32**, 2976 (1993)

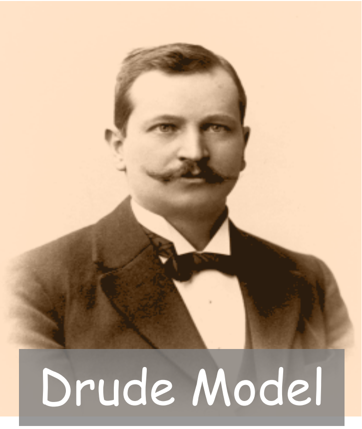
Reflectivity - Hg-1201



Optical Conductivity - Hg-1201

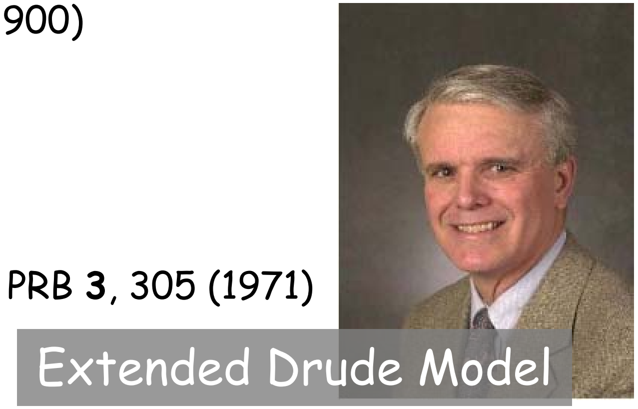


Obtaining the Scattering Rate - Extended Drude Model



Drude, Ann. Physik **306**, 566 (1900)

Allen, PRB **3**, 305 (1971)



$$\sigma(\omega) = \frac{2\pi}{Z_0} \frac{\Omega_p^2}{\tau^{-1} - i\omega}$$

$$\sigma(\omega) = \frac{2\pi}{Z_0} \frac{\Omega_p^2}{\tau^{-1}(\omega) - i\omega\left[1 + \lambda(\omega)\right]}$$

Scattering rate

$$\frac{1}{\tau(\omega)} = \frac{2\pi}{Z_0}\Omega_p^2 \,\mathrm{Re}\left(\frac{1}{\sigma(\omega)}\right)$$

Mass enhancement

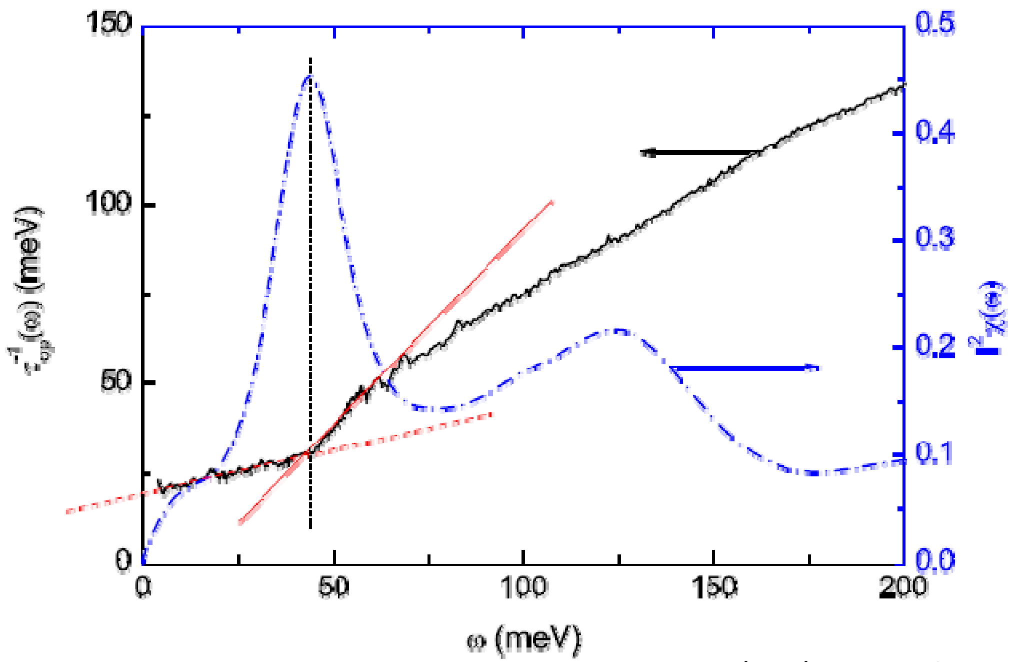
$$\frac{m}{m^\star} = 1 + \lambda(\omega) = \frac{1}{\omega}\frac{2\pi}{Z_0}\Omega_p^2 \,\mathrm{Im}\left(\frac{1}{\sigma(\omega)}\right)$$

Extracting the Bosonic Function from the Scattering Rate

$$\frac{1}{\tau(\omega)} = \frac{1}{\tau_{imp}} + \int_0^\infty d\nu\, K(\omega, \nu, T)\, I^2\chi(\nu)$$

Dirty limit scattering

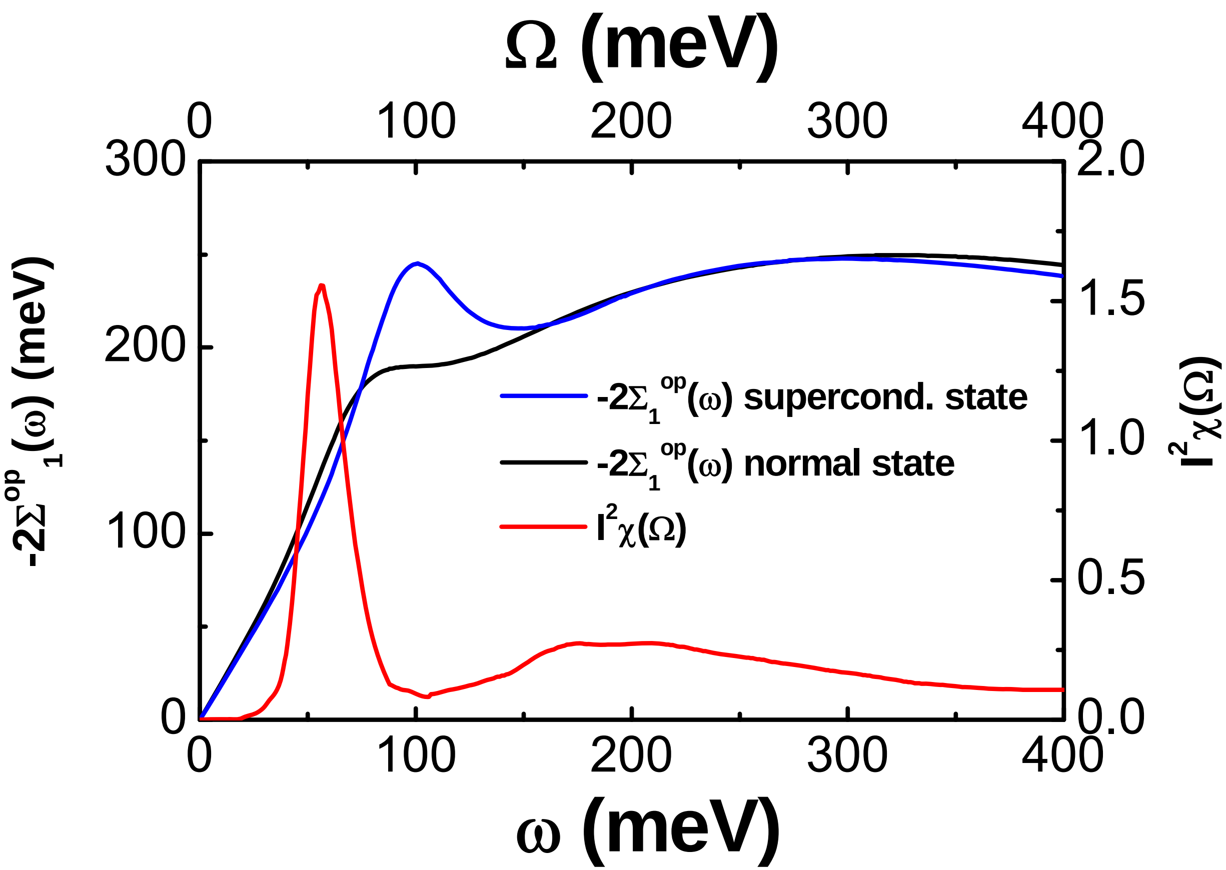
Eliashberg *d*-wave clean limit



- (Pr,Ce)$_2$CuO$_4$ single crystal T_c = 20 K
- Peaks in $I^2\chi$ track slope changes in τ^{-1}

Schachinger, Homes, Lobo, and Carbotte, PRB **78**, 134522 (2008)

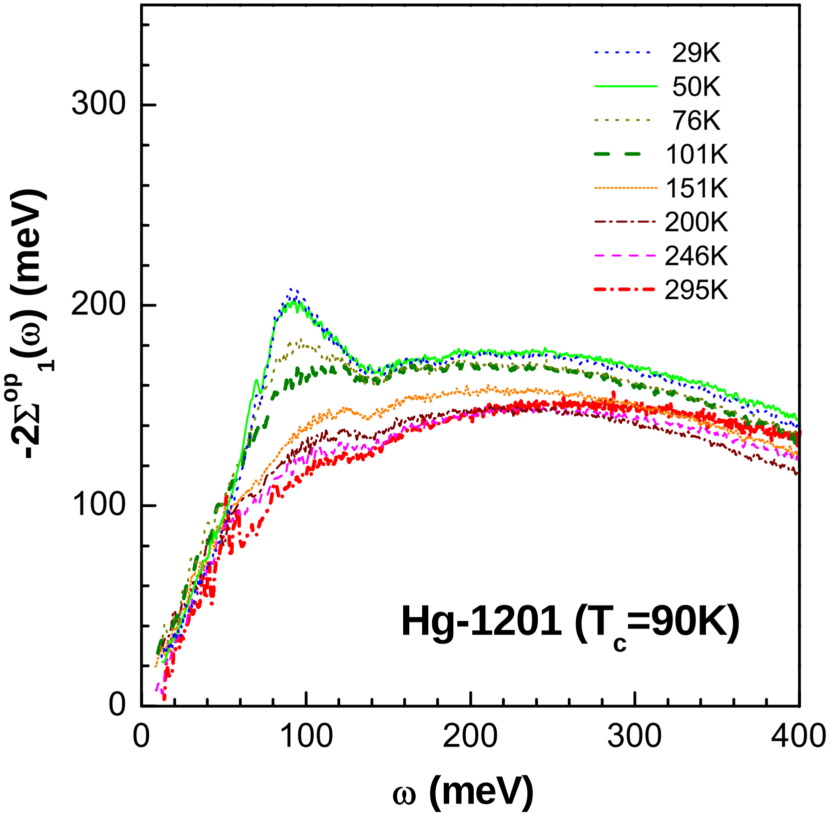
Bosonic Mode and the Mass Enhancement



- ✓ Peak in mass enhancement is shifted by the gap value
- ✓ $I^2\chi$ peak has no clear signature in the mass enhancement
- ✓ Eliashberg kernel kills the signature of the bosonic spectrum in the normal state

Yang et al., submitted 2008.

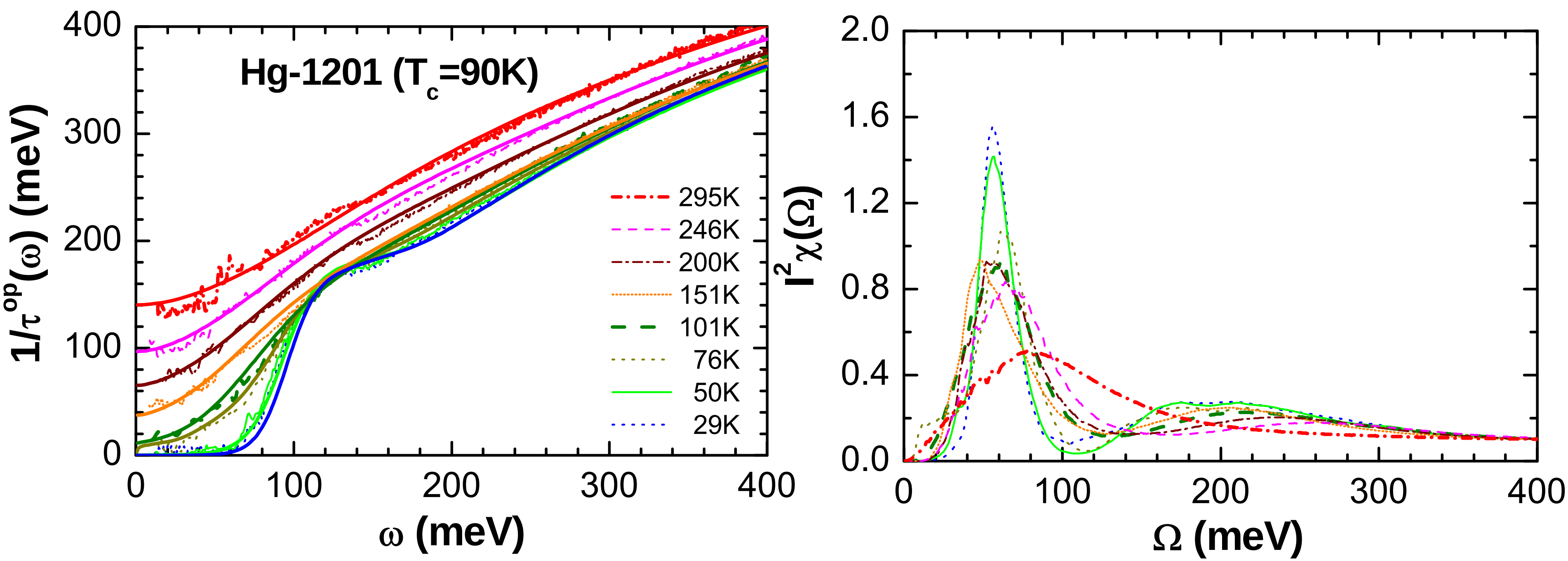
Hg-1201 - Effective Mass



- ✓ Mass enhancement shows a peak at 100 meV in the superconducting state
- ✓ 100 meV peak vanishes very close to Tc
- ✓ Expected gap around 20 meV predicts that bosonic peak should be at 60 meV

Yang et al., submitted 2008.

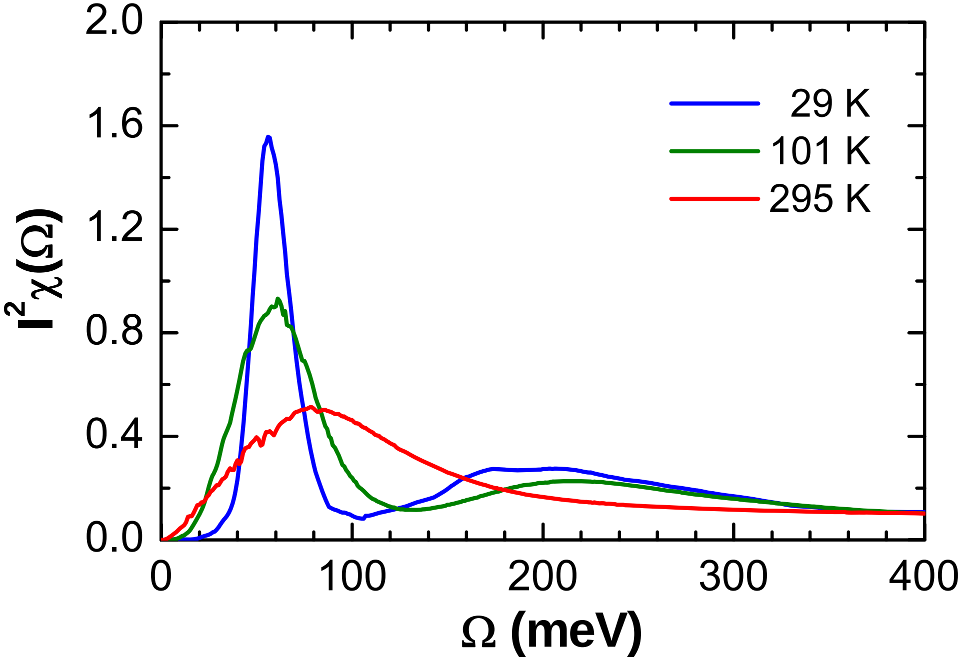
Hg1201 - Scattering Rate and $I^2\chi$ Inversion



Yang et al., submitted 2008.

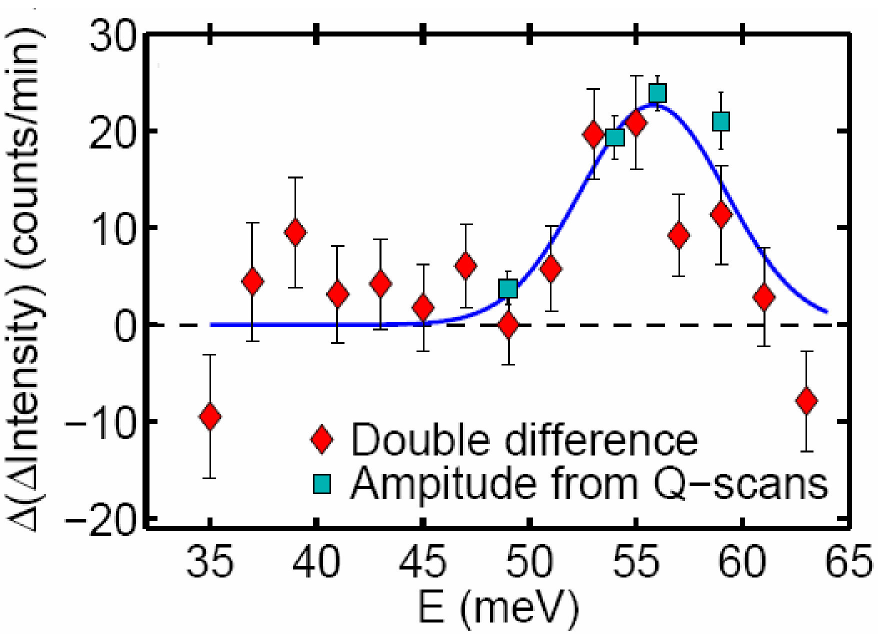
Charge and Spin spectral functions on Hg-1201

Optics



Yang et al., submitted 2008.

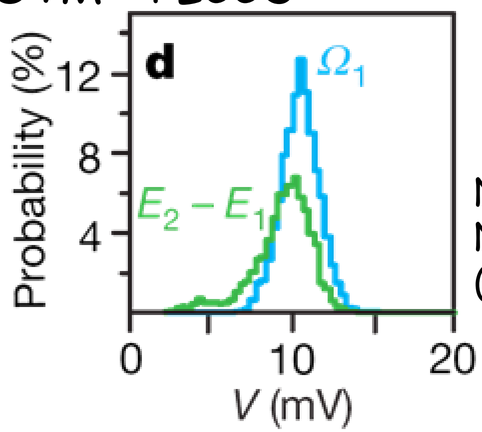
Neutron scattering



Yu et al., condmat 0810.5759

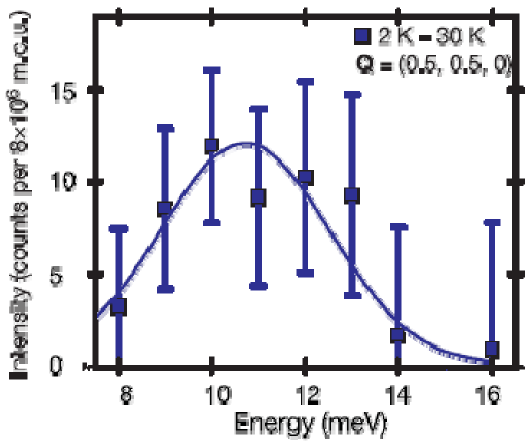
Optical Bosonic Spectra in PCCO

STM - PLCCO

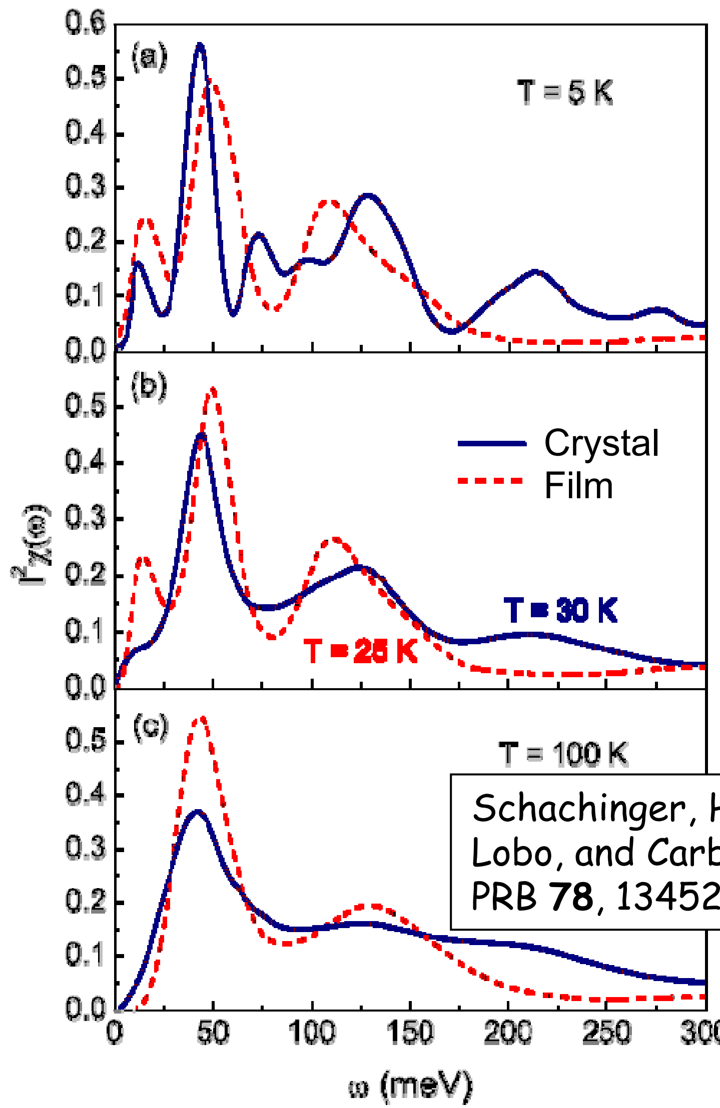


Niestemski et al. Nature **450**, 1058 (2007).

Neutrons - PLCCO

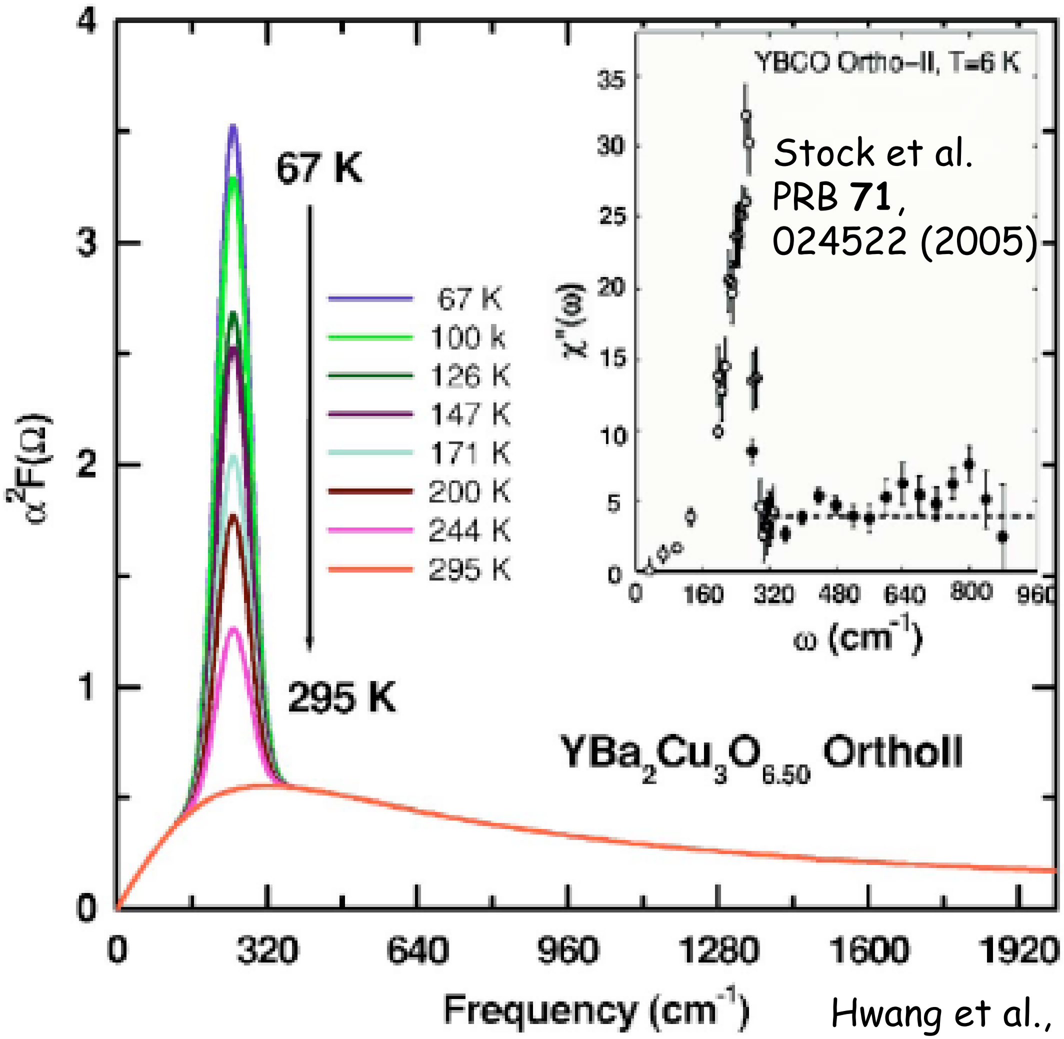


Wilson et al., Nature 442, 59 (2006)



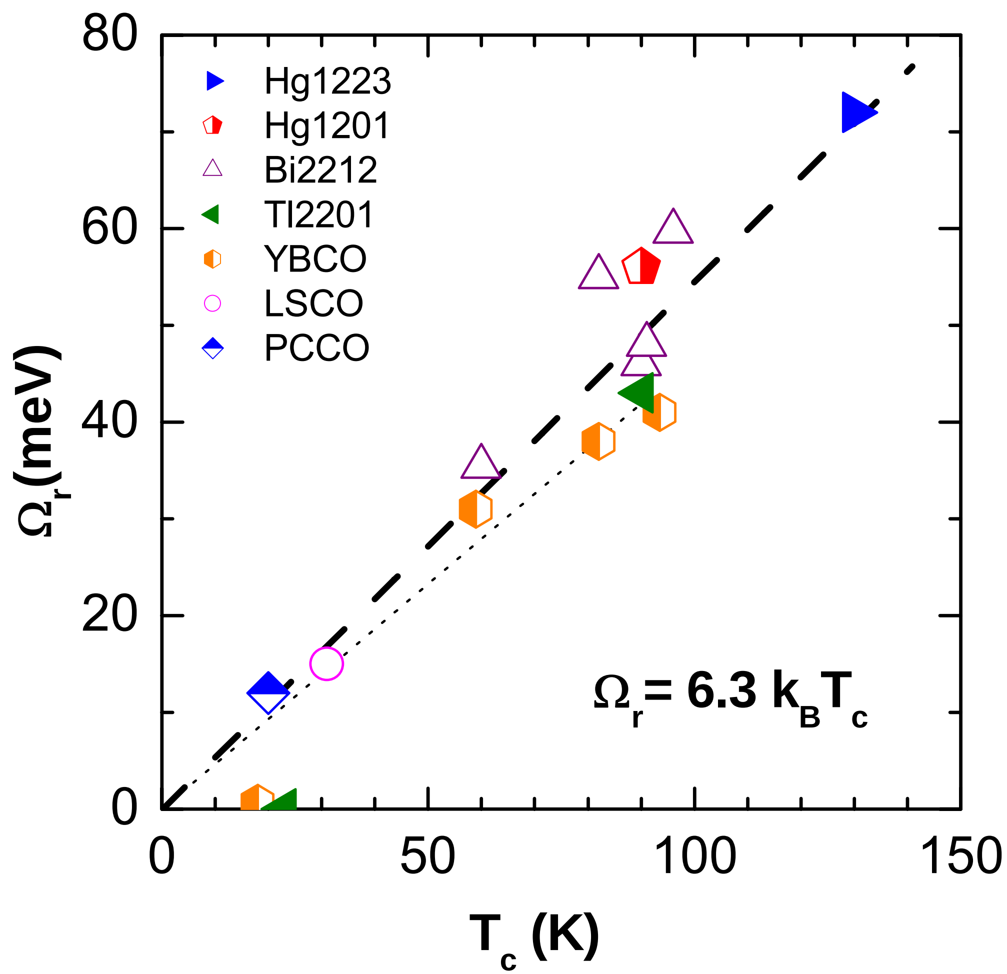
Schachinger, Homes, Lobo, and Carbotte, PRB **78**, 134522 (2008)

...and also in ortho-II YBCO



Hwang et al., PRB **73**, 014508 (2006)

Optics, Neutrons and T_c Scale

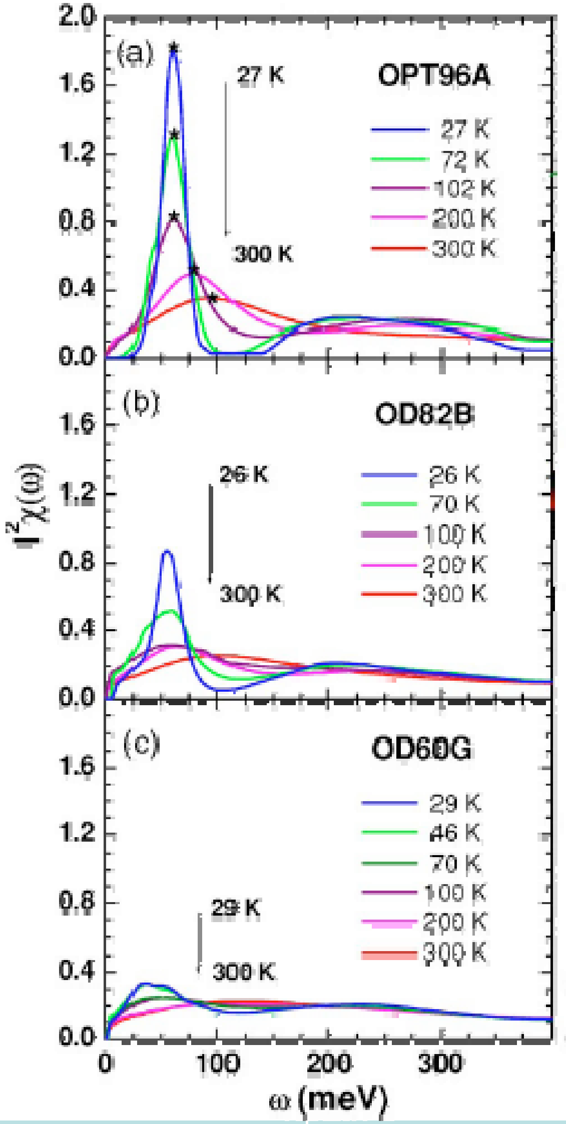


Yang et al., submitted 2008.

Summary & Conclusions

- ✓ Generalized Drude formula defines a frequency dependent scattering rate.
- ✓ Inversion of scattering rate allows for the determination of the Eliashberg optical bosonic spectrum.
- ✓ Optical bosonic spectrum shows a resonance peak that scales with T_c.
- ✓ Correlation between optics and neutron scattering data indicate that carriers are coupled to spin fluctuations.

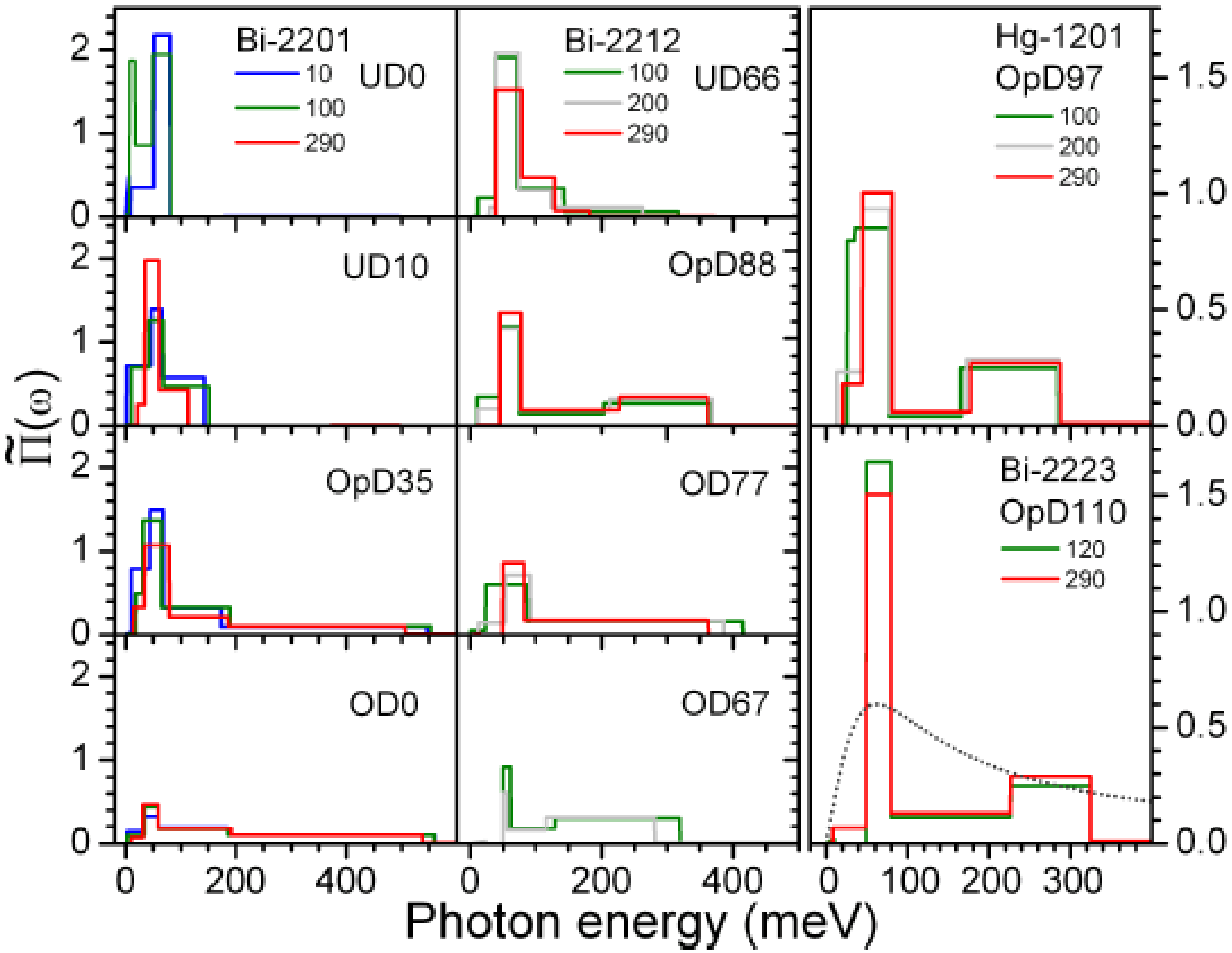
Electron-boson spectral density in BSCCO



- ✓Optical Eliashberg bosonic function
- ✓Charge channel excitation spectra
- ✓Average over all q vectors

Hwang et al., PRB 75, 144508 (2007)

Coupling to Spins or to Phonons?



van Heuman et al., arXiv 0807.1730