Self energy spectroscopy of superconductors

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with
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Crystal growers:

UBC
R. Liang
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Genda Gu

Saclay
D. Colson
V. Viallet-Guillen

Chernogolovka
N.N. Kolesnikov

McMaster
H. Dabkowska
B.D. Gaulin
R. Hughes
J. Preston

Ames
N. Ni
P.C. Canfield
S.L. Bud'ko

Westinghouse
J. Talvacchio
M.G. Forrester

Outline

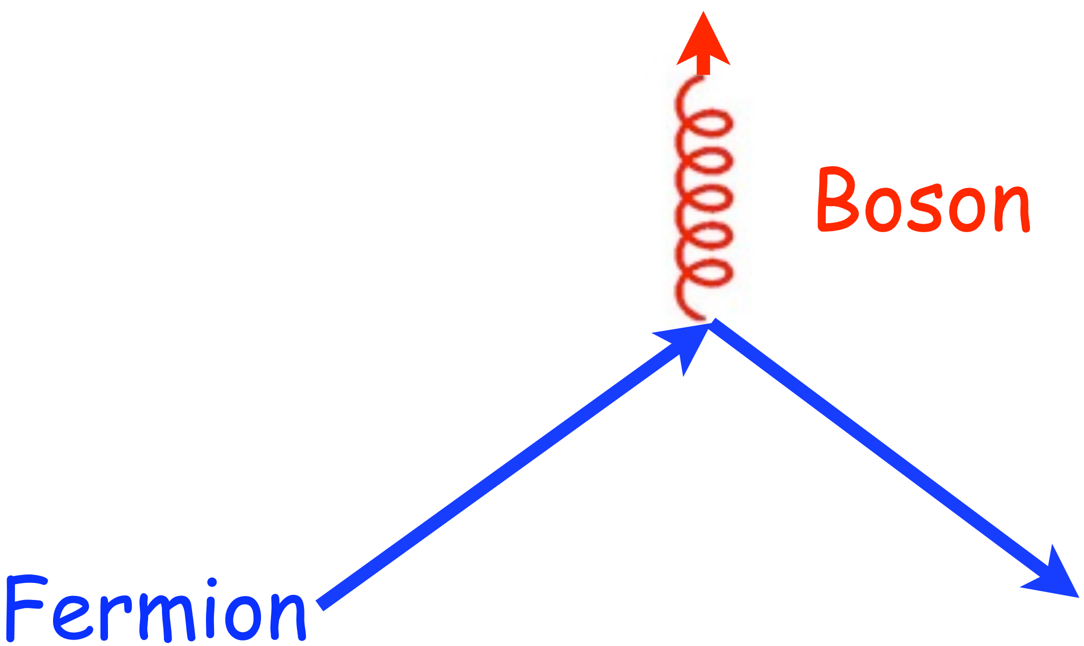
- Finding the glue in the old superconductors, tunneling -> neutrons -> phonons
- New superconductors, new spectroscopy
  - Angle resolved photo emission (ARPES)
  - Optical conductivity
- The glue function in various systems
  - Ortho II YBCO
  - $Ba_{0.35}K_{0.45}Fe_2As_2$
  - Bi-2212
  - LSCO
  - Mercury
- The isotope effect
- Conclusion: Are we there yet?

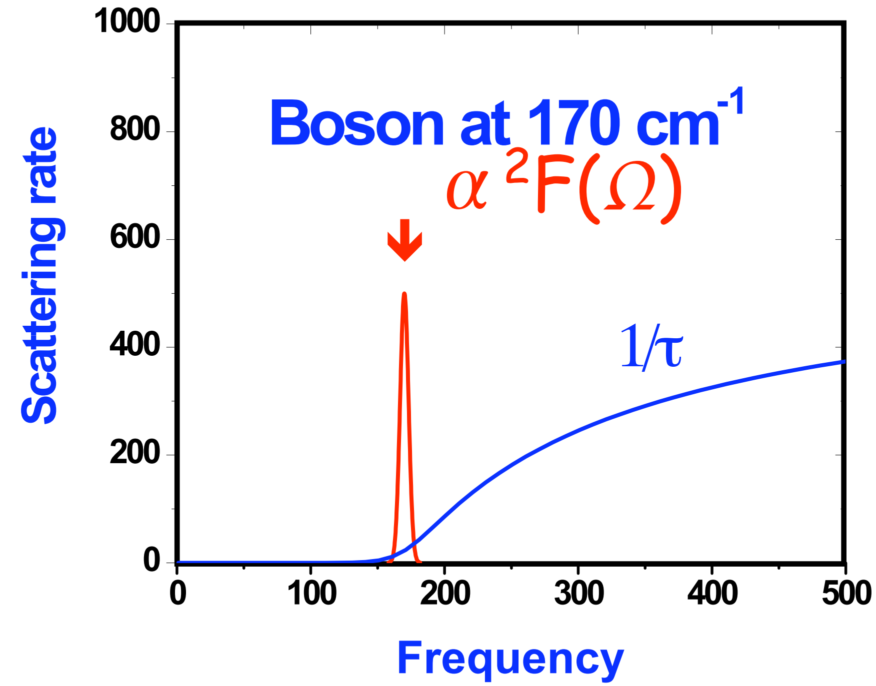
History of glue:

The old superconductors

Self energy from boson exchange

T=0, boson creation





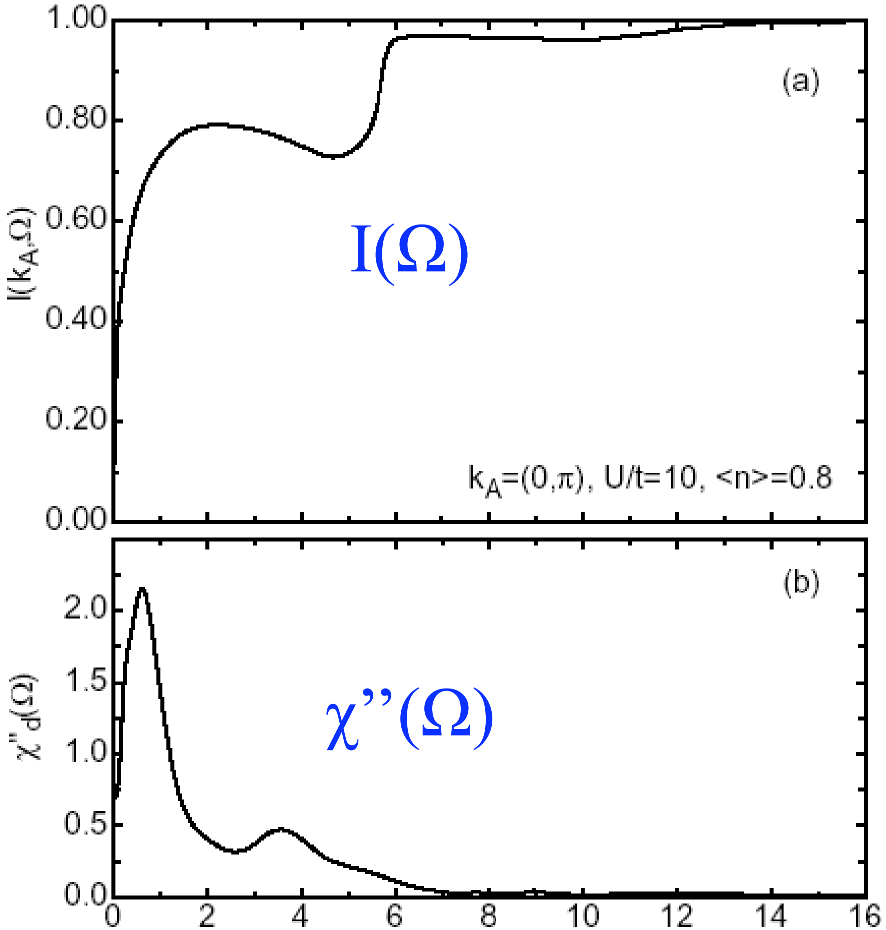
Goal: to determine the bosonic spectral function $\alpha^2F(\Omega)$ by spectroscopy.

Hubbard model DCA calculations

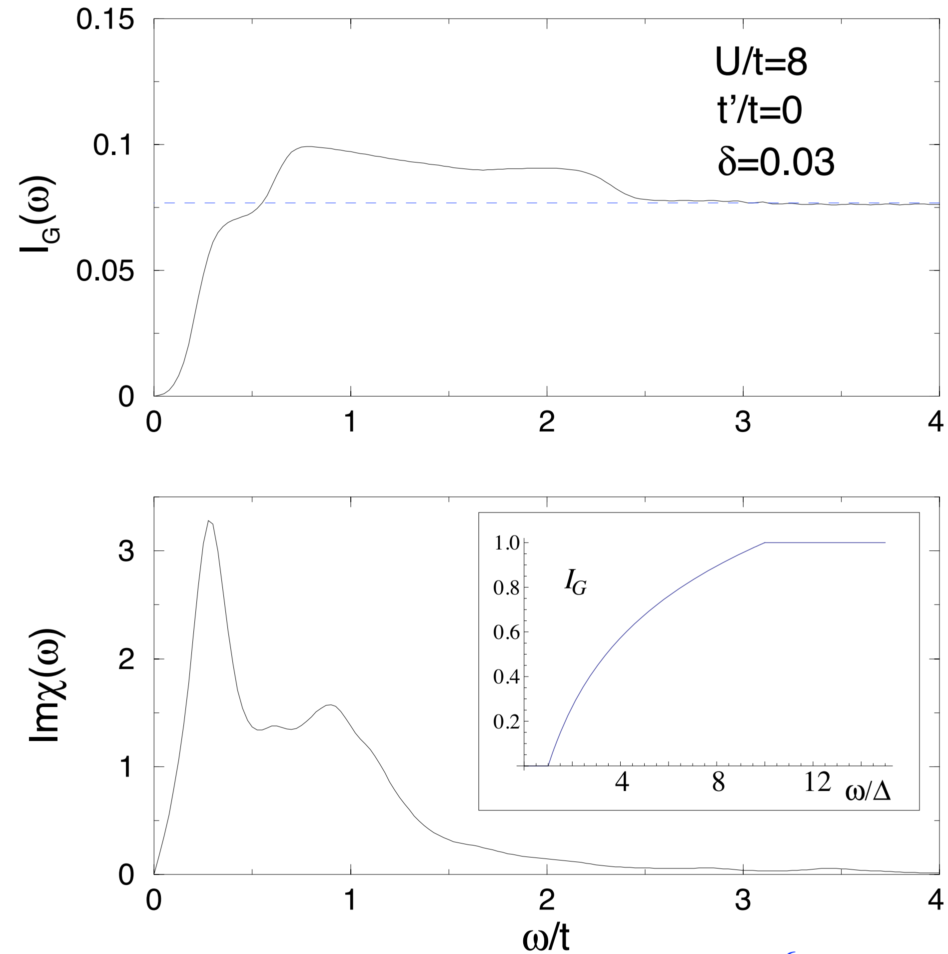
Conribution from spin fluctuations to the gap function I(Ω)

Maier *et al.* cond-mat/801.4506

Kyung *et al.* arXiv: 0812.1228

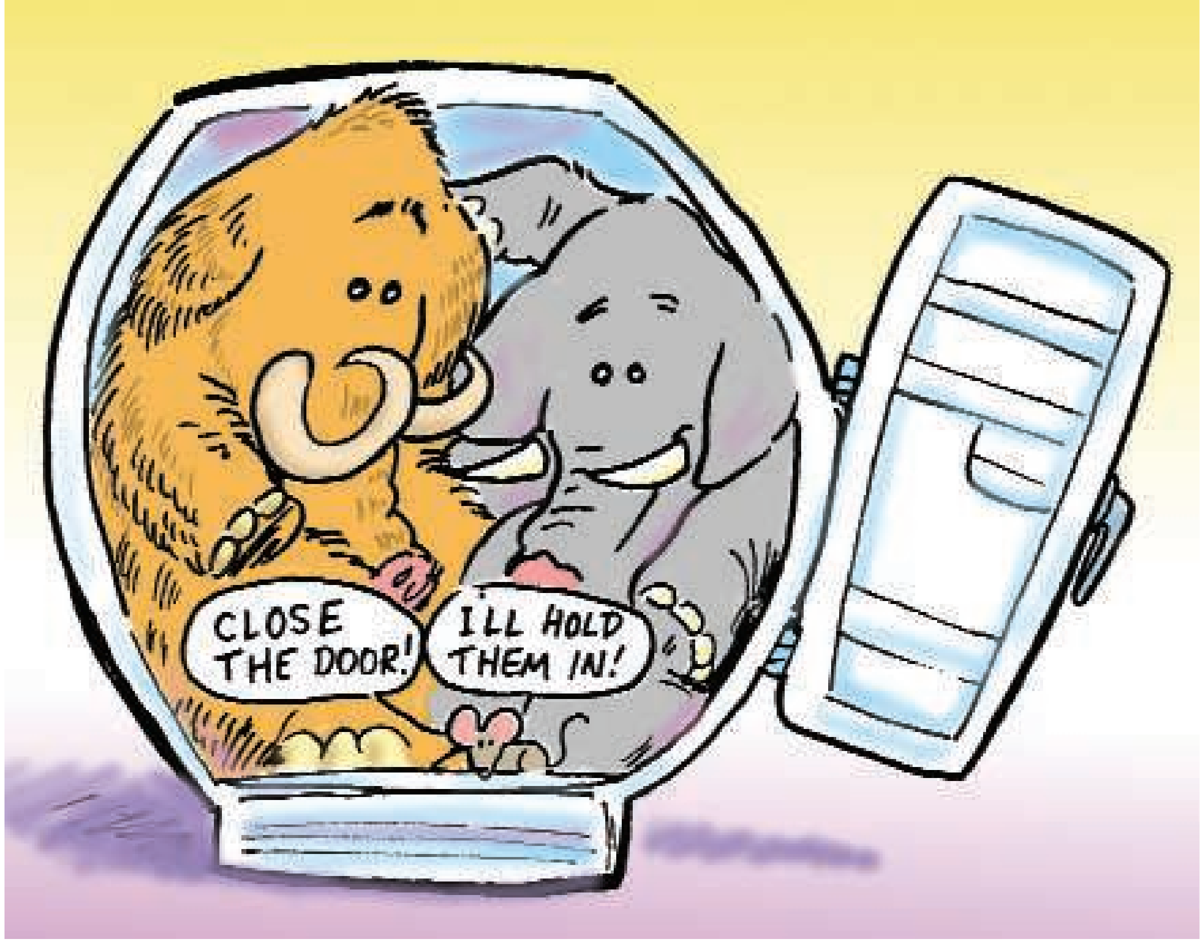


frequency → (Ω/t)



Anderson's view:
The bosonic mouse vs RVB elephant & mammoth

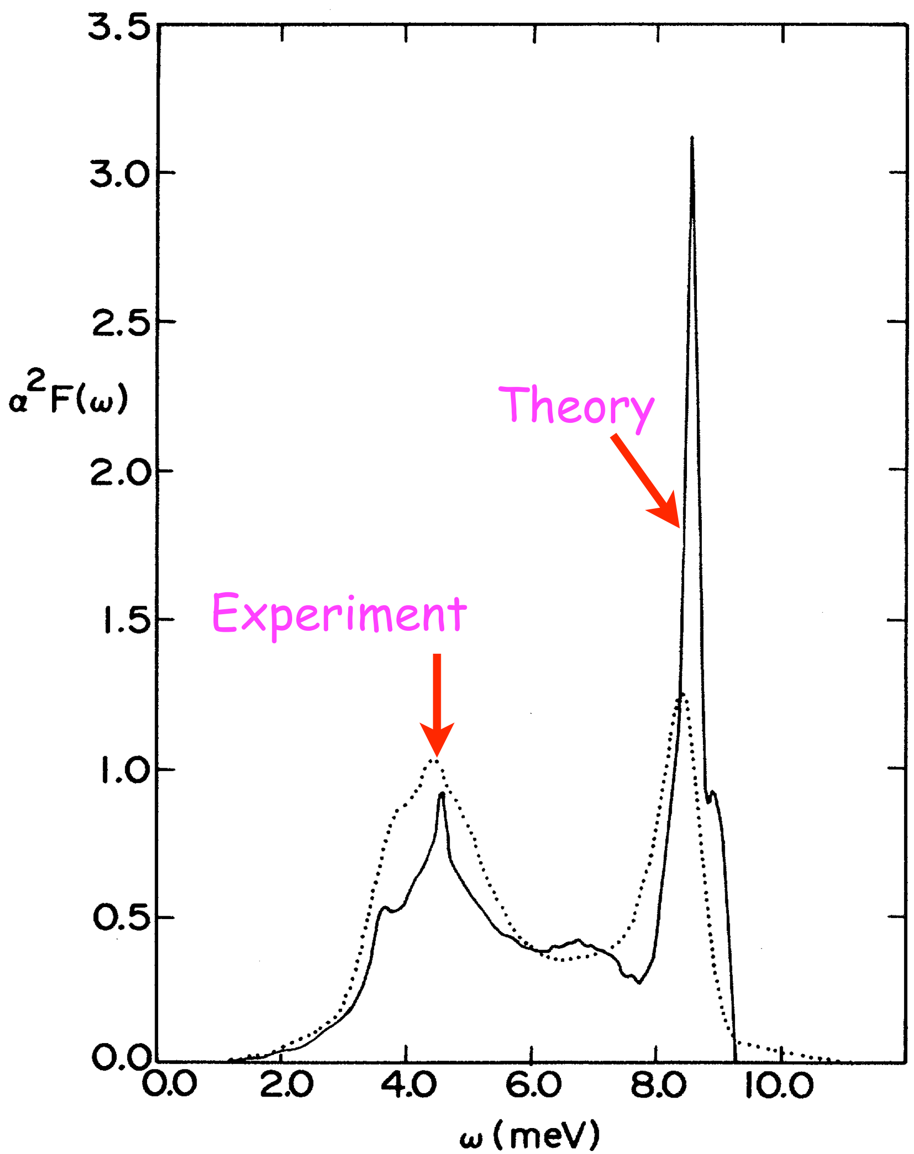
P.W. Anderson, Science **317,** 1705 (2007)



Measuring self energy by spectroscopy

- Tunneling
- Angle resolved photo emission (ARPES)
- Optical reflectance

Tunneling in lead

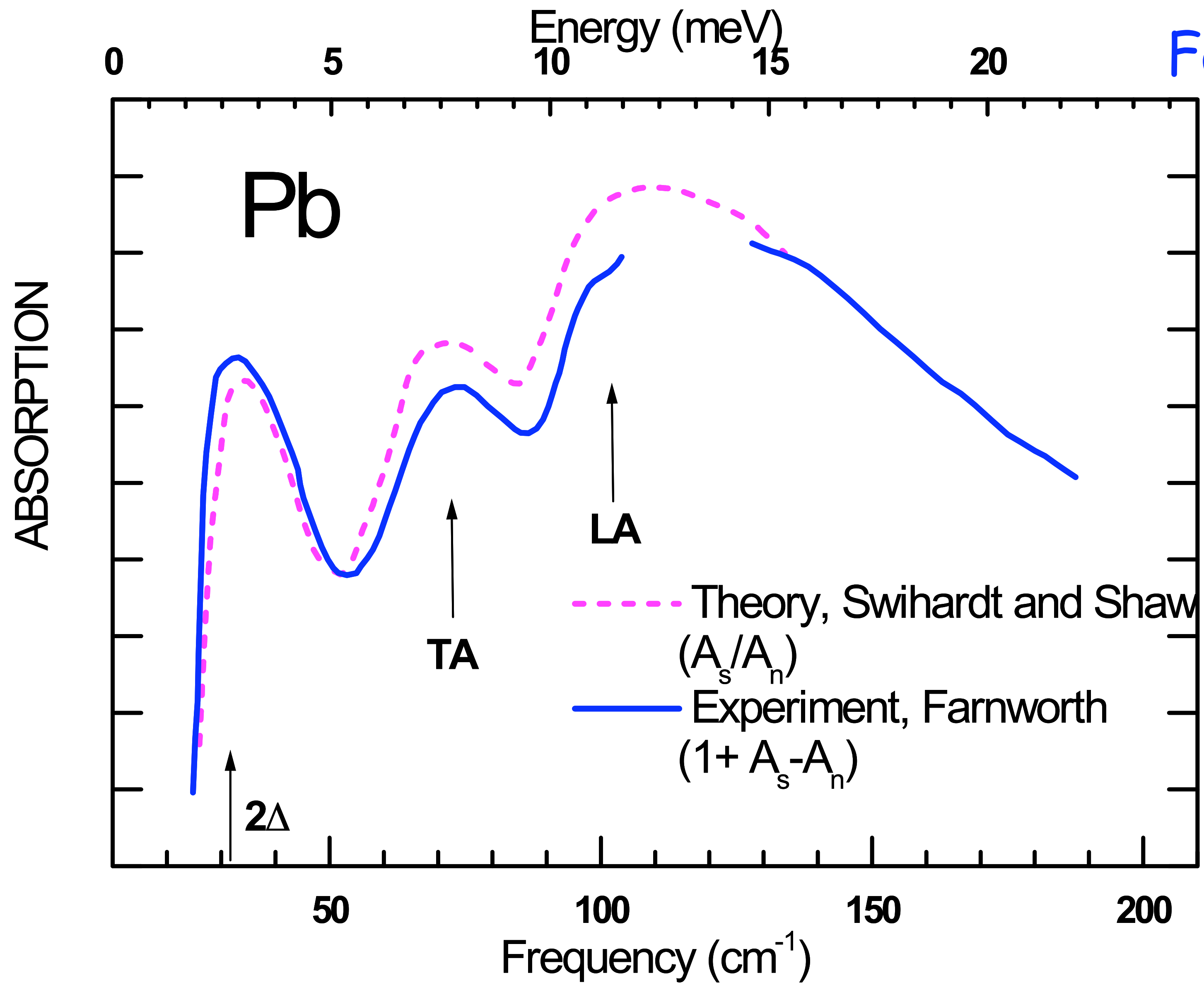


Experiments:
Rowell and McMillan
tunneling
Eliashberg inversion

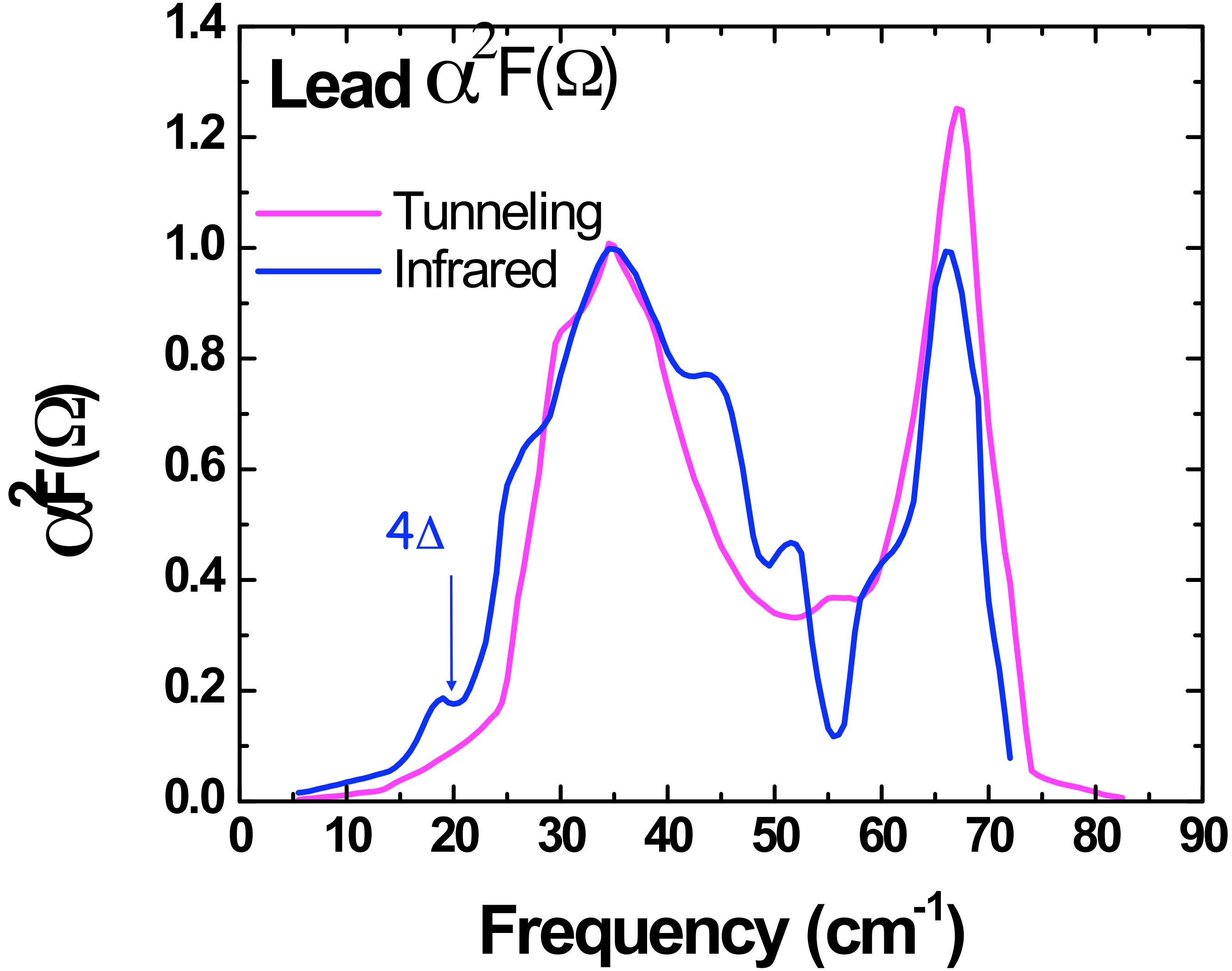
Theory:
Tomlinson Carbotte
Pseudopotential
electron-ion potential
Phonons from neutron
scattering

Optical absorption in Pb

Farnworth et al.



Comparing tunneling and optics in Pb



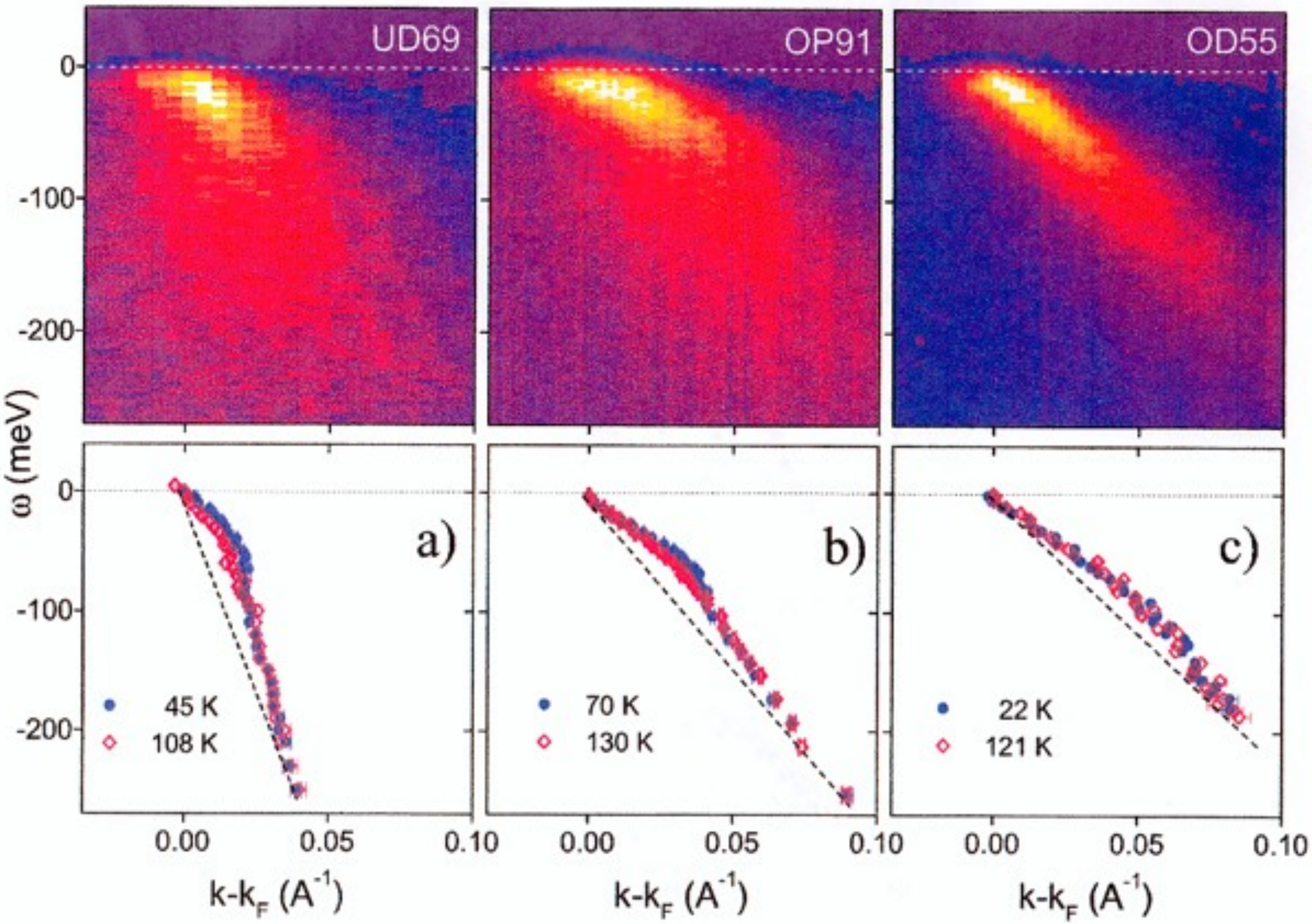
Can we do this in the new superconductors?

Measuring self energy by spectroscopy

- Tunneling
- Angle resolved photo emission (ARPES)
- Optical reflectance

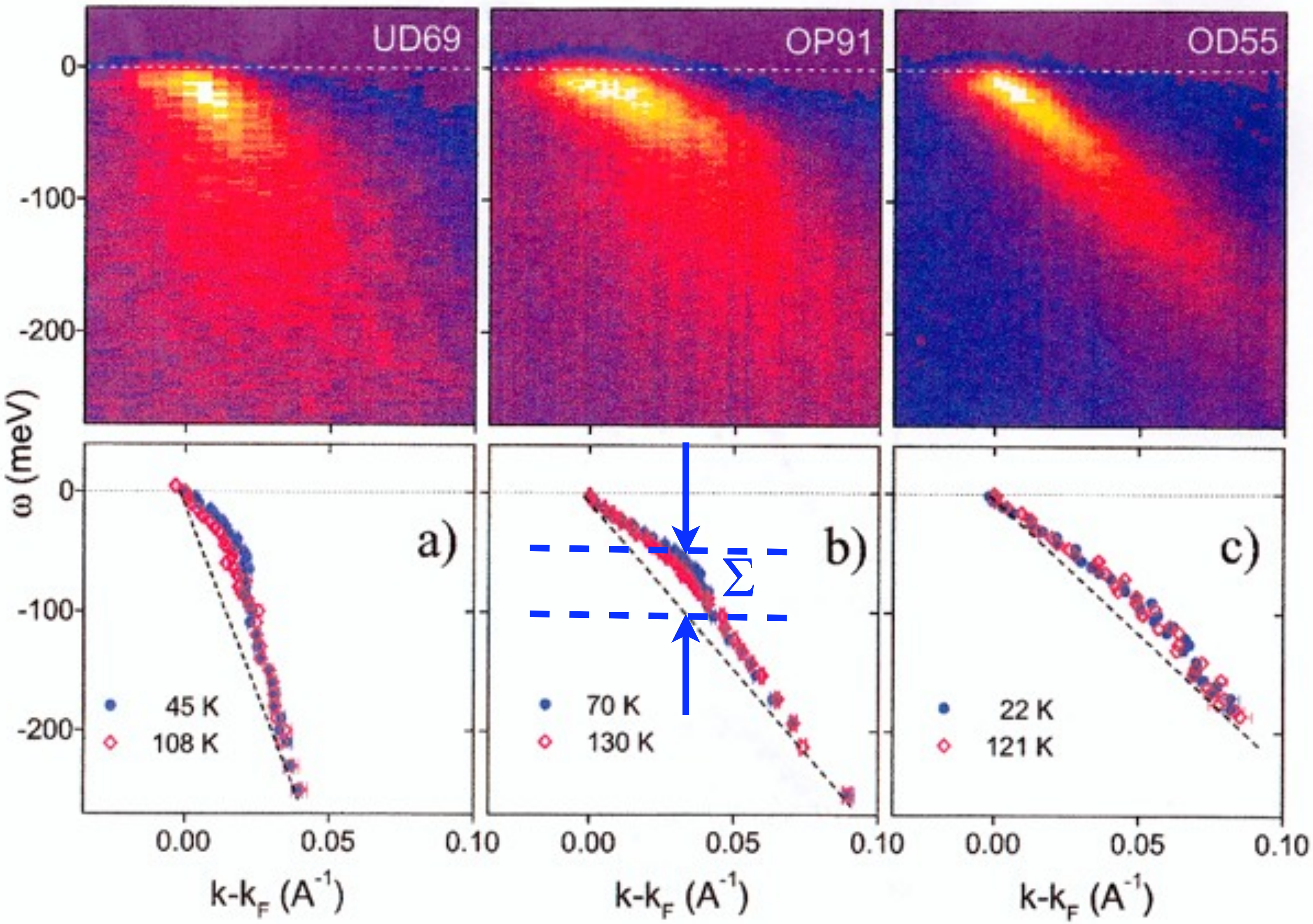
Observing the ARPES "kink"

P.D. Johnson et al.



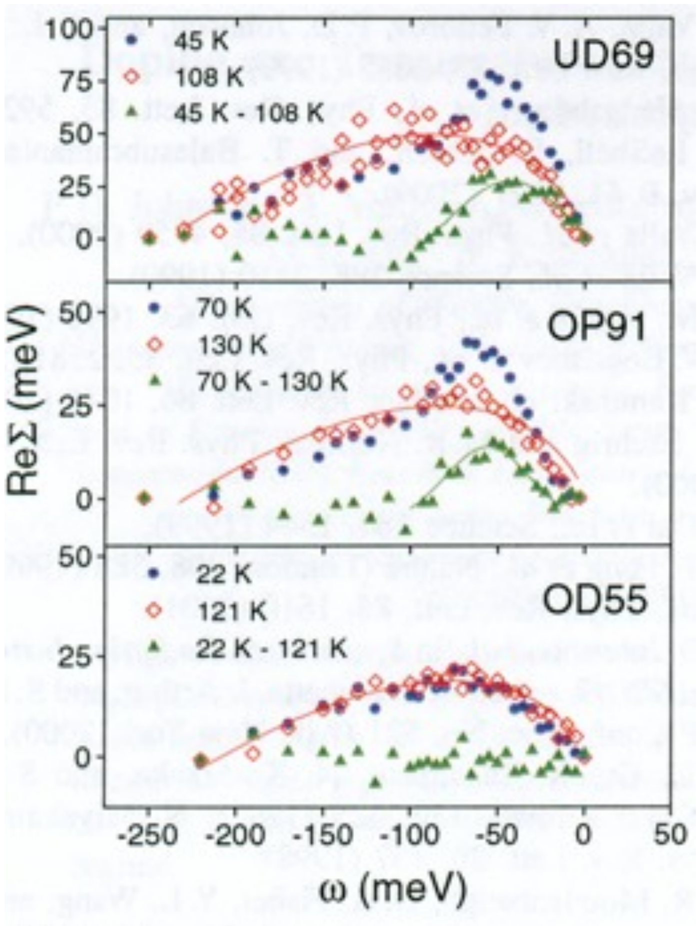
Observing the ARPES "kink"

P.D. Johnson et al.



Self energy Σ observed by ARPES

P.D. Johnson et al.



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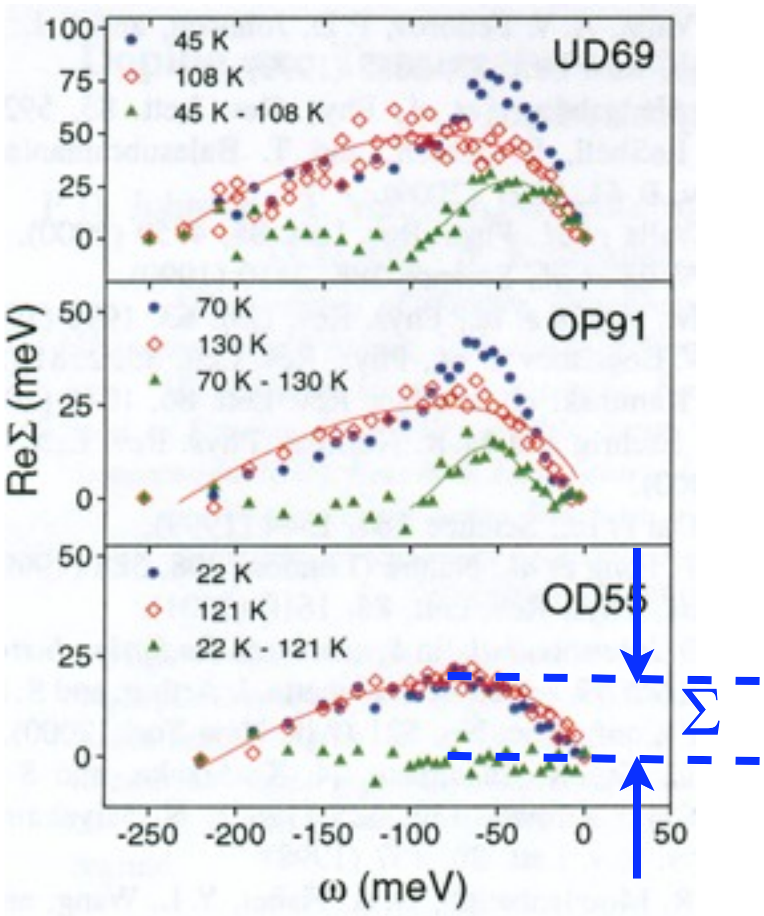

Measuring self energy by spectroscopy

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Measuring self energy by spectroscopy

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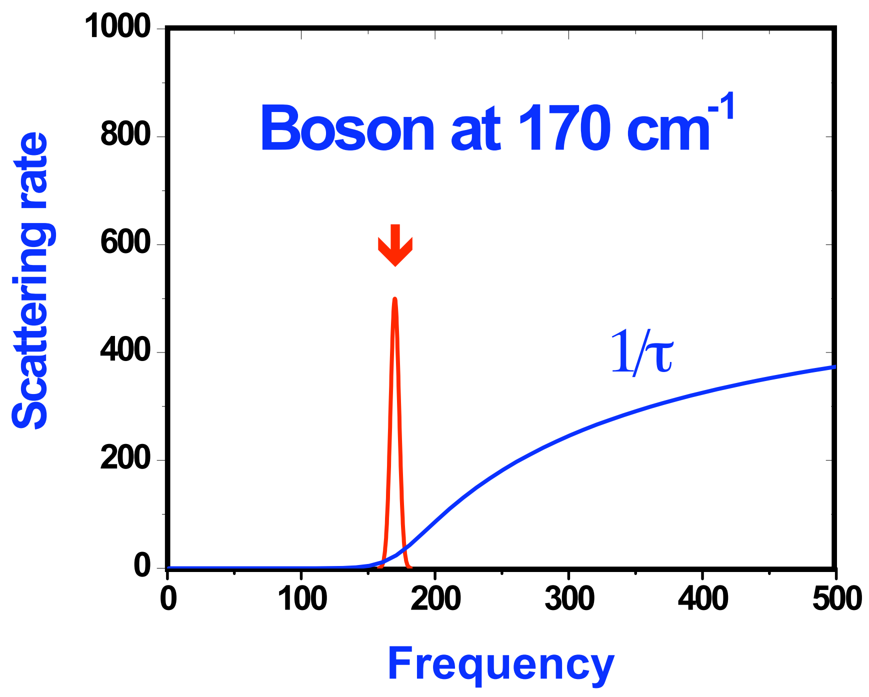
Standard optical formulas:

$r = Re^{i\theta} = (\varepsilon - 1)/(\varepsilon + 1)$

$\omega\,(\varepsilon - \varepsilon_H) = 4\pi\sigma i$

Drude conductivity, extended

$$4\pi\sigma(\omega) = \frac{\omega_p^2}{1/\tau(\omega) - i\omega(1+\lambda(\omega))}$$



Extended Drude Model

$$4\pi\sigma(\omega) = i\omega_p^2 \,/\, (\omega - 2\Sigma^{op}(\omega, T))$$

$\Sigma^{op} = \Sigma_1^{op} + i\Sigma_2^{op}$ Optical self energy

$1/\tau(\omega,T)$ Frequency dependent scattering rate

λ Mass enhancement $m^* = m(1+\lambda)$

$\omega_p = 4\pi ne^2/m$ Plasma frequency

$\Sigma_1(\omega,T) = -\lambda\omega/2$ Real part of self energy

$\Sigma_2(\omega,T) = -1/(2\tau)$ Imaginary part of self energy

The parameters $1/\tau(\omega,T)$ and $\lambda(\omega, T)$ can be obtained from the experimental $\sigma(\omega) = \sigma_1 + i\sigma_2$

$$1/\tau(\omega,T) = ne^2/m \, \mathrm{Re}(1/\sigma(\omega))$$

$$\omega(1+\lambda(\omega)) = ne^2/m \, \mathrm{Im}(1/\sigma(\omega))$$

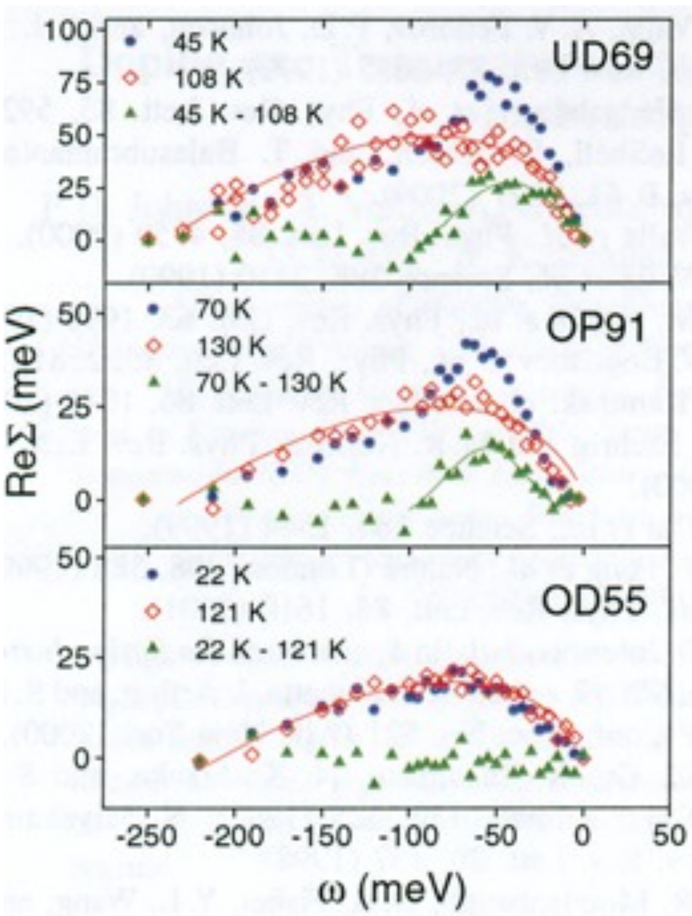
Caveats

- Σ^{op} is not exactly the self energy Σ as measured by ARPES.
  - The optical conductivity is an average over the Fermi surface
  - There is an addtional factor of (1-cos θ) where θ is the scattering angle
- The plasma frequency ω_p must be known
- For the extended Drude formalism there must only be channel of conductivity.
- $\alpha^2_{tr}F(\Omega)$ is not the same as $\alpha^2F(\Omega)$

Comparison of ARPES and infrared $\Sigma(\omega)$

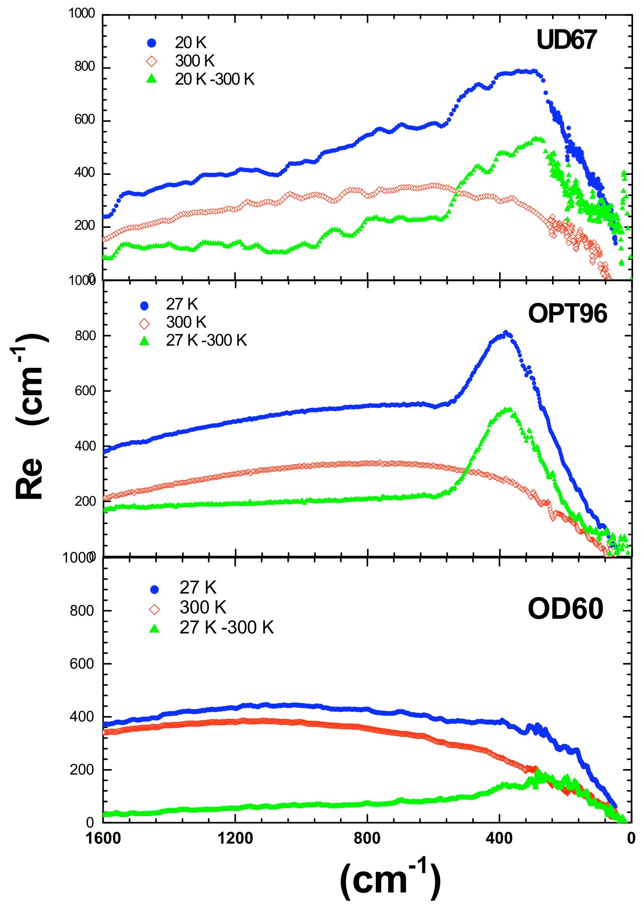
ARPES

P.D. Johnson et al.



Infrared

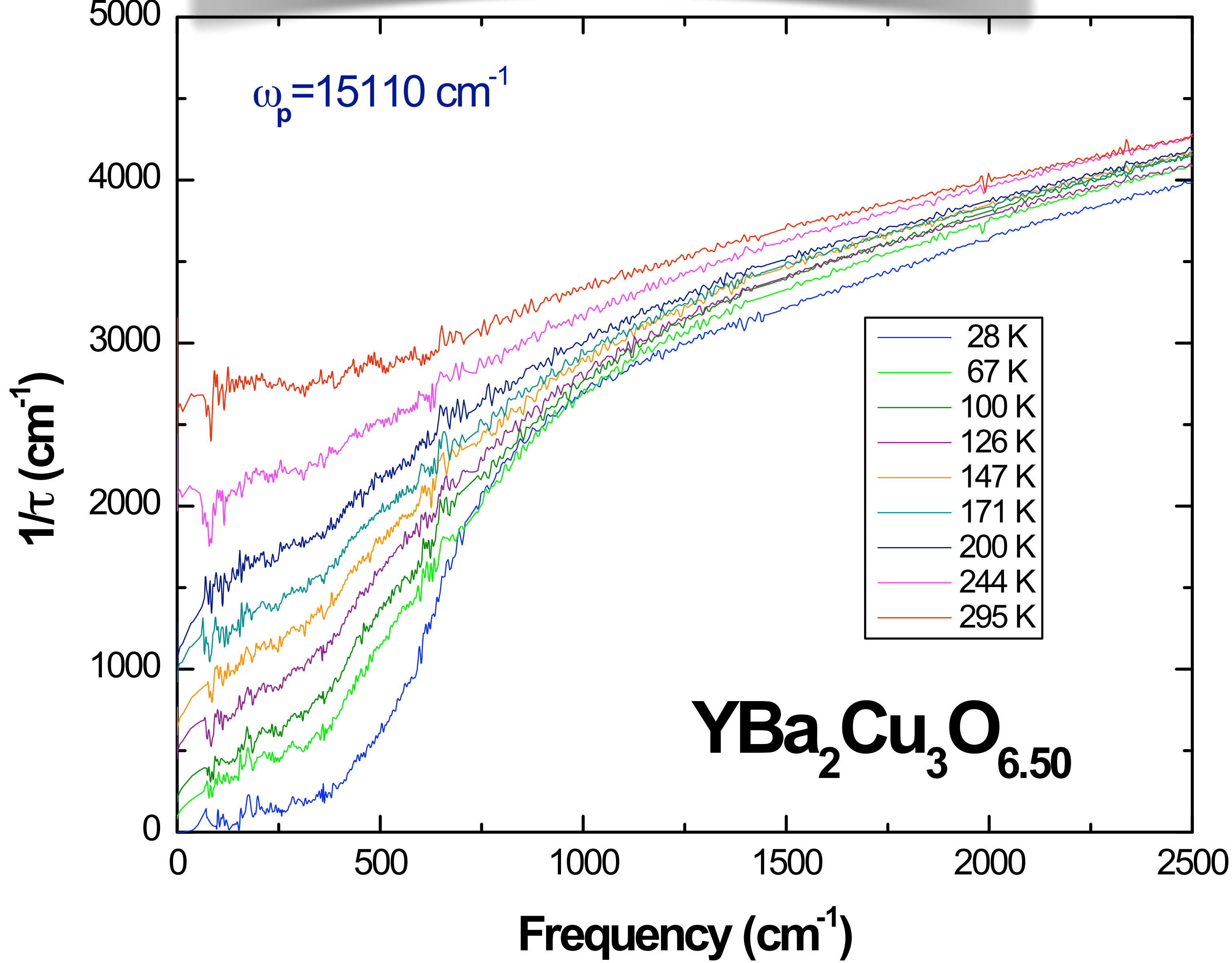
J. Hwang et al.



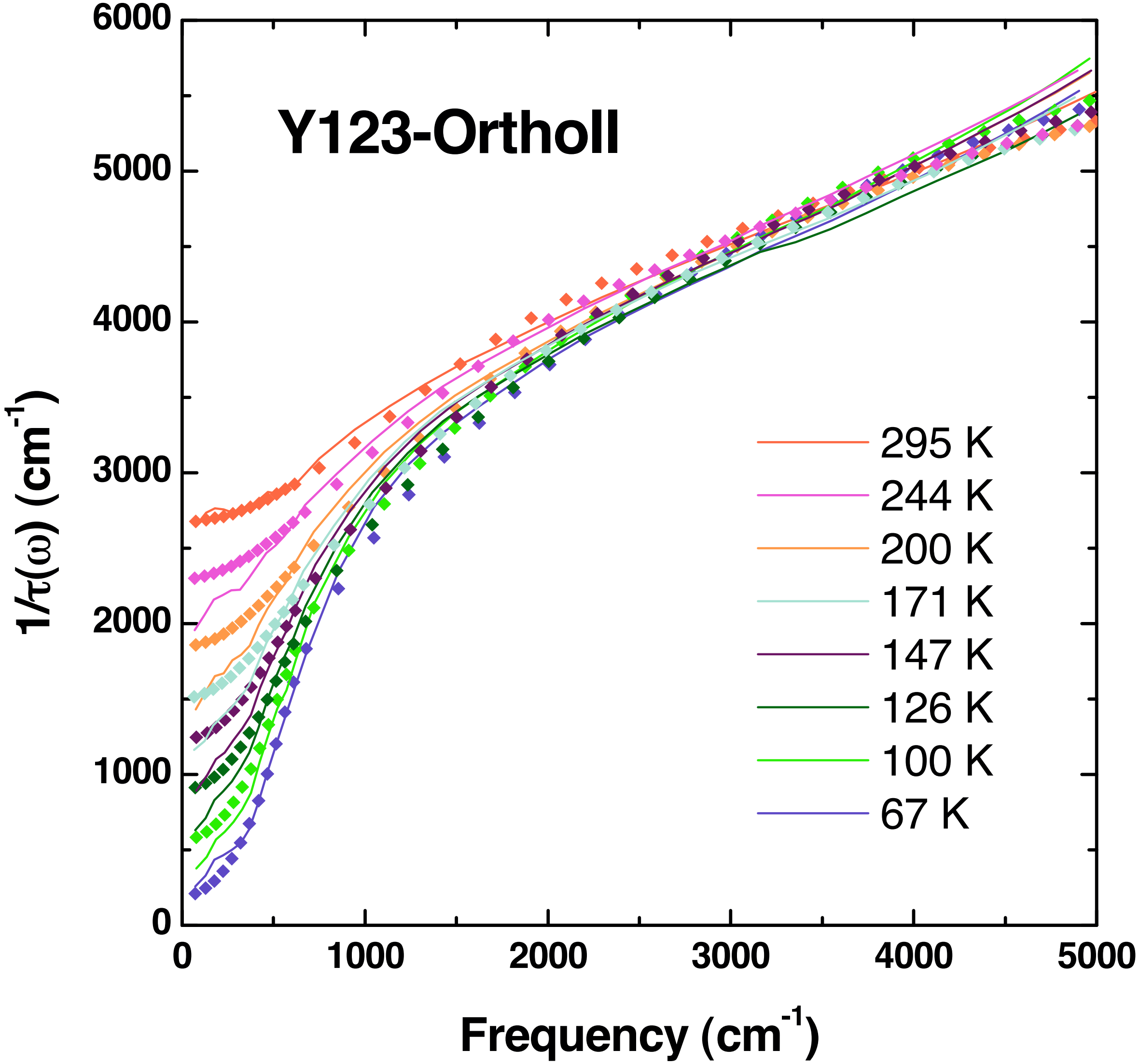
Bosonic modes in YBCO, evidence for magnetic scattering

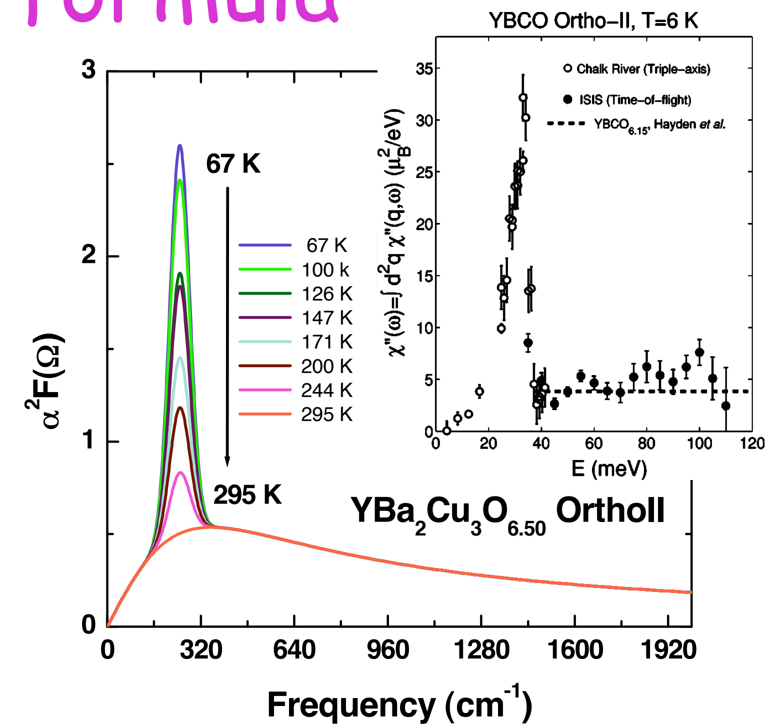
Ortho II YBCO scattering rate

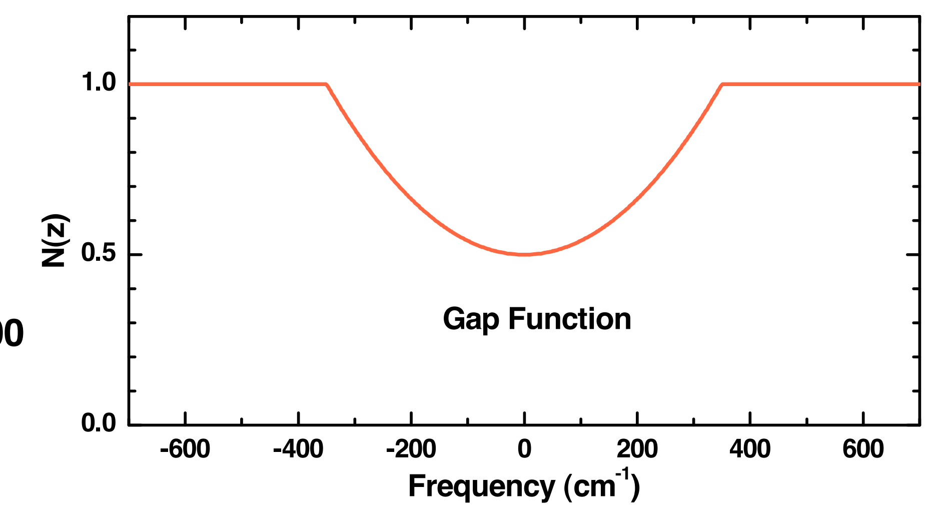
$$1/\tau(\omega,T) = ne^2/m \, \mathrm{Re}(1/\sigma(\omega))$$



Fits to Shulga's formula

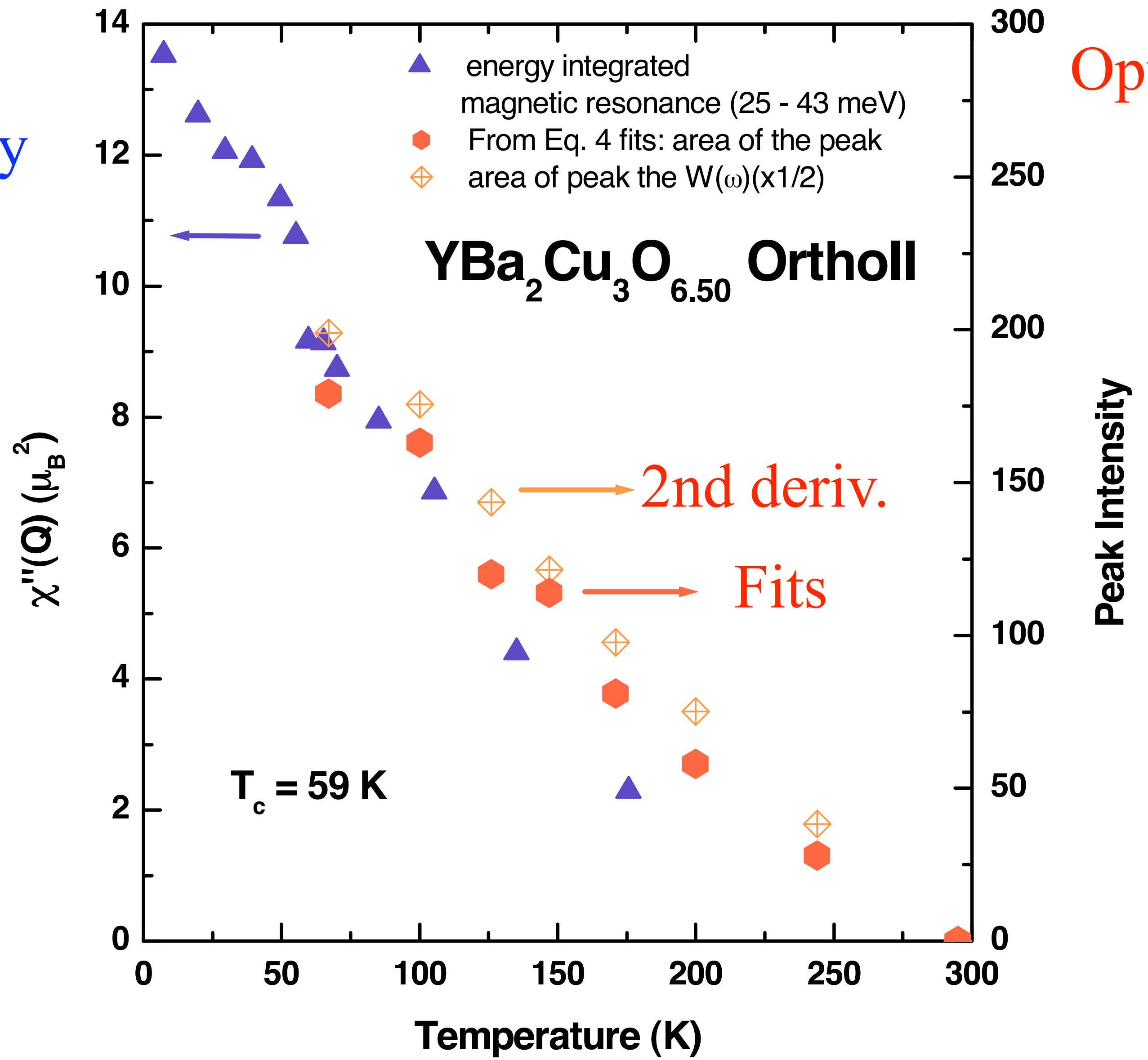






Temperature dependence of the mode spectral weight

Neutron susceptibility



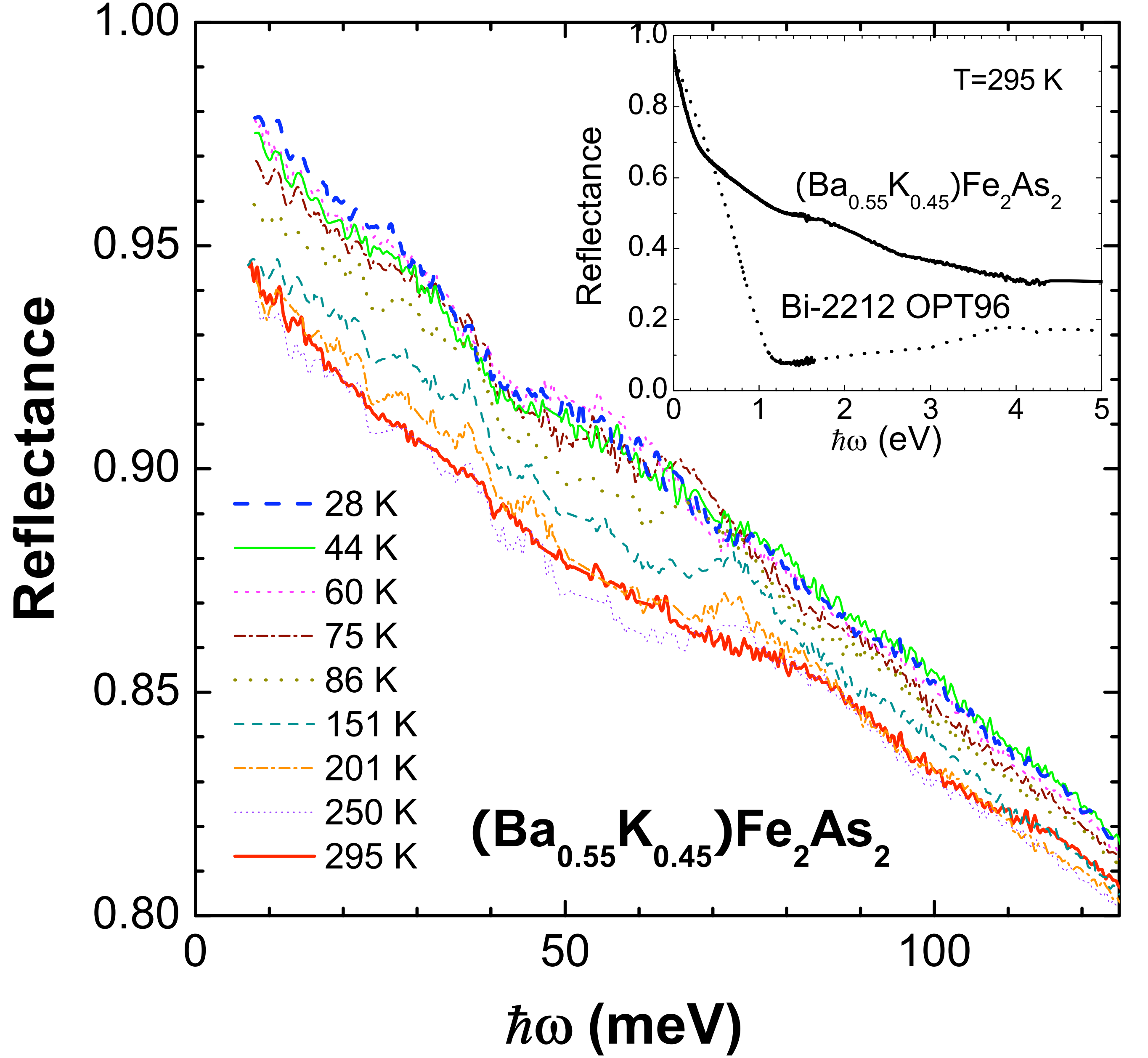
Optical amplitude

Inversion of the $1/\tau$ spectra

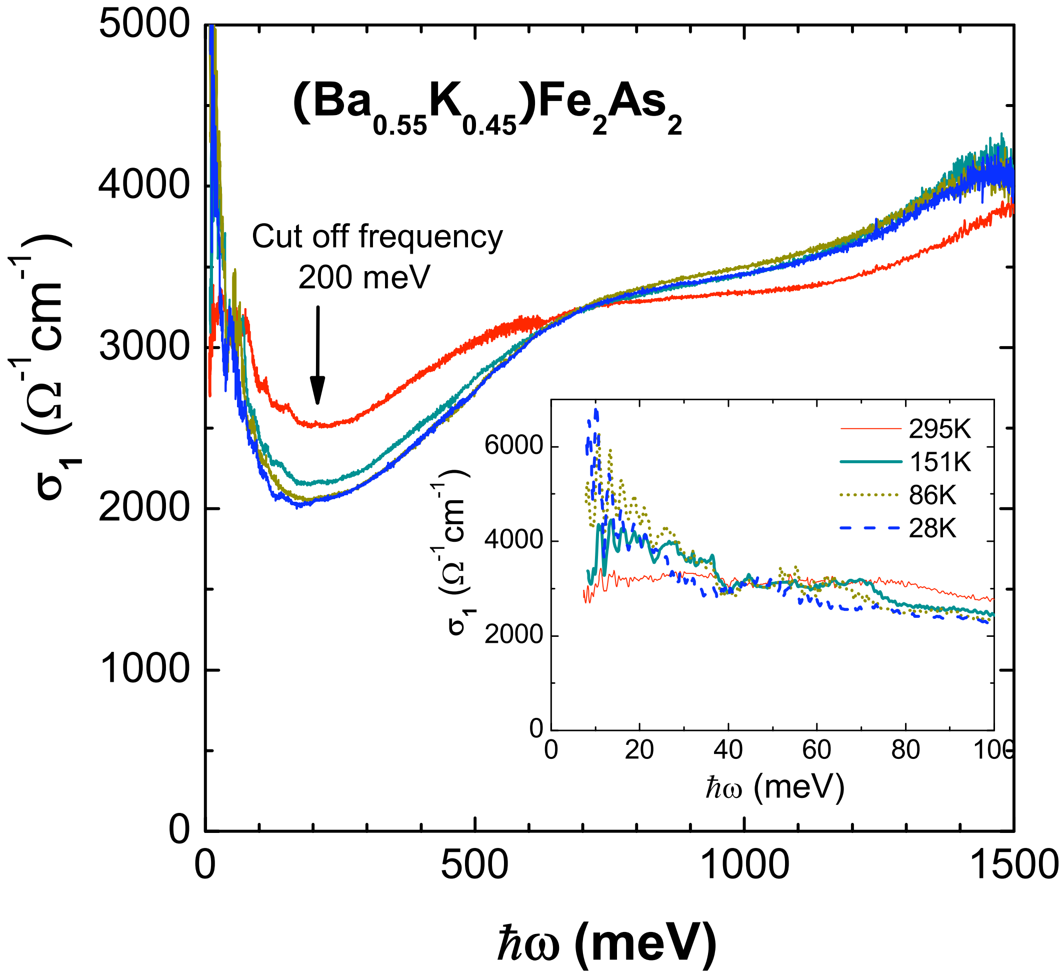
- Allen approximation for $1/\tau$ solved by maximum entropy inversion to give $I^2\chi(\omega)$
- Use Kubo's formula with $I^2\chi(\omega)$ to fit $1/\tau$
- d-wave full Eliashberg inversion gives T_c

Bosonic modes in $Ba_{0.35}K_{0.45}Fe_2As_2$

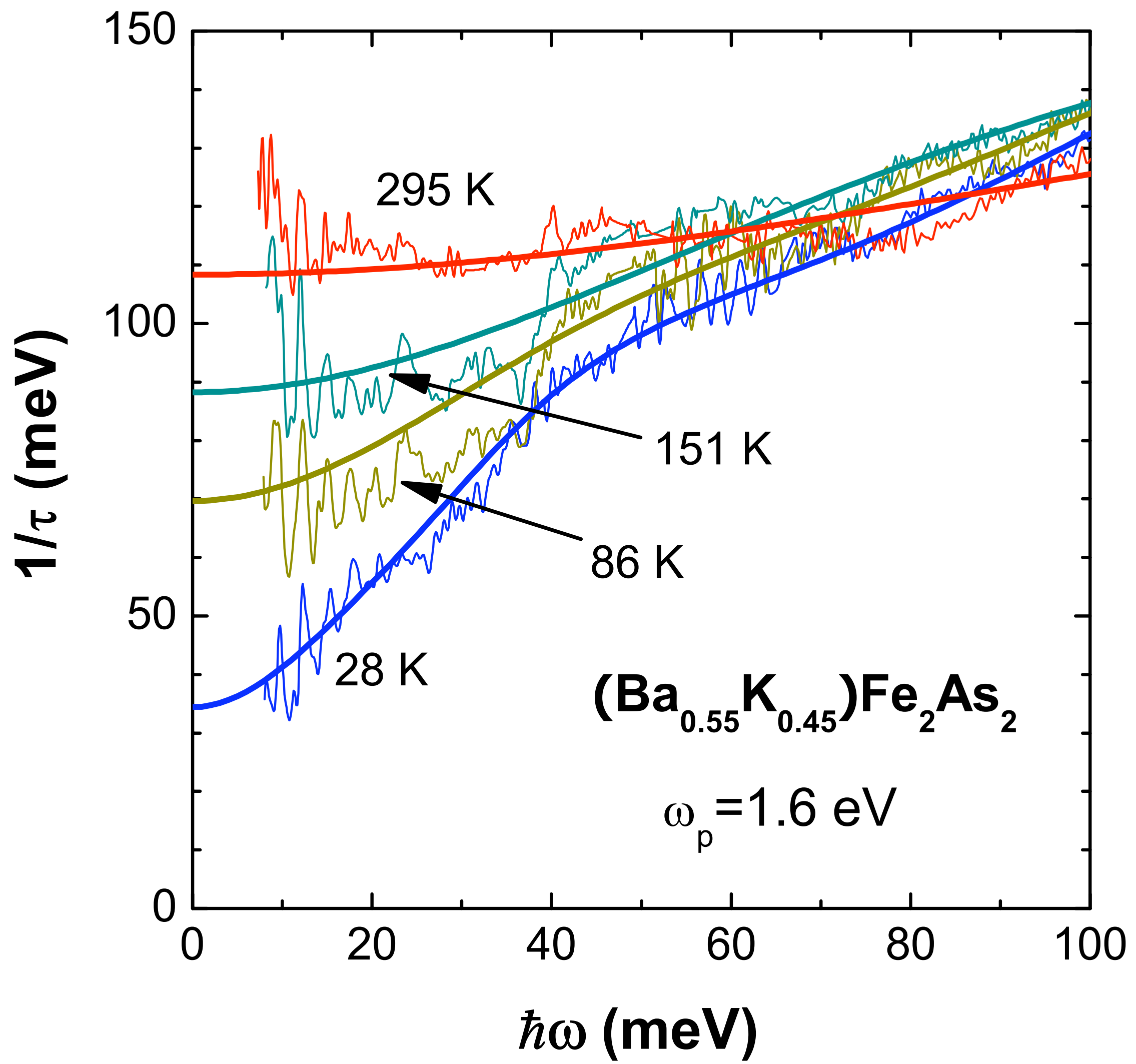
Reflectance of $Ba_{0.35}K_{0.45}Fe_2As_2$



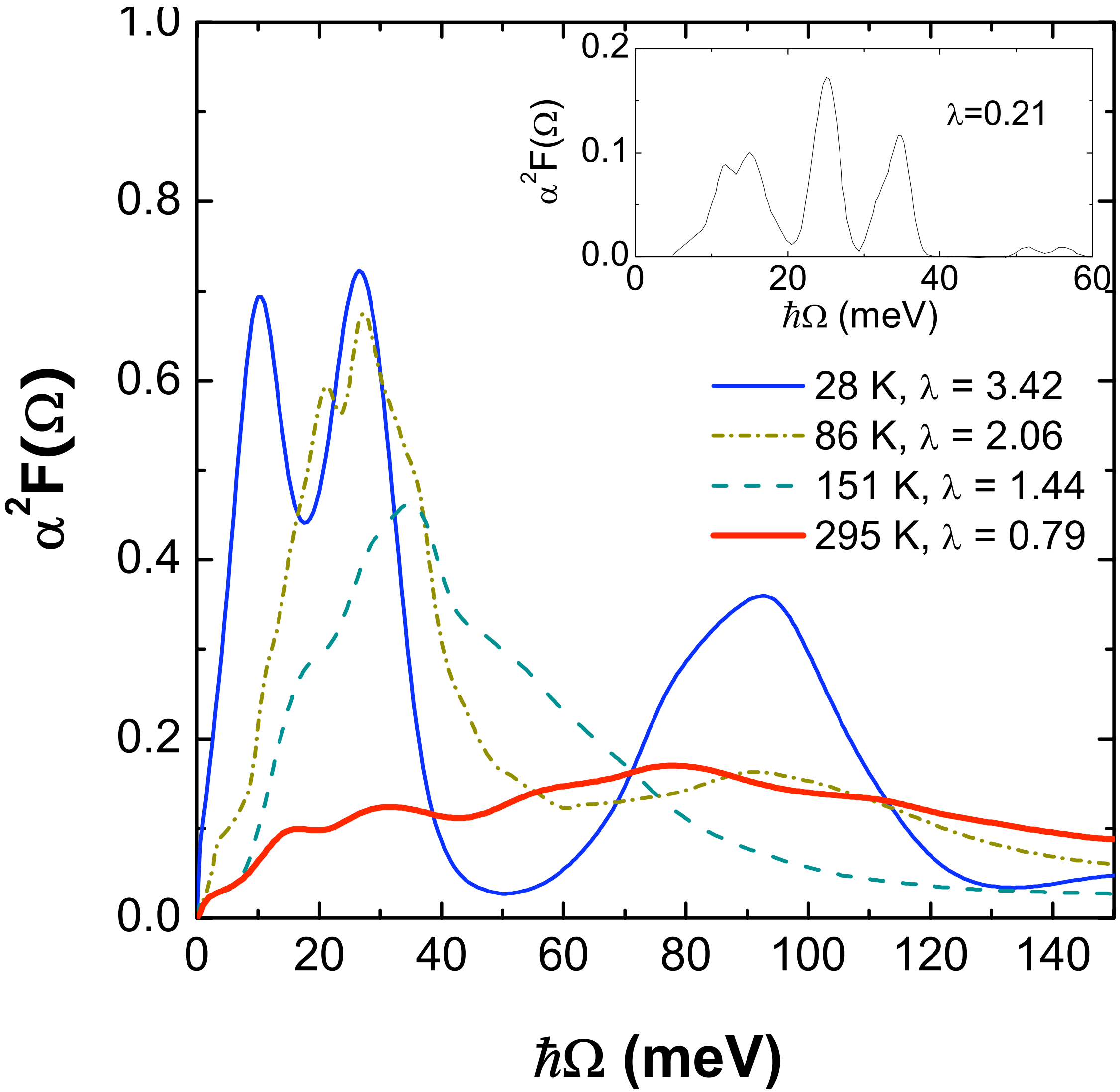
Conductivity

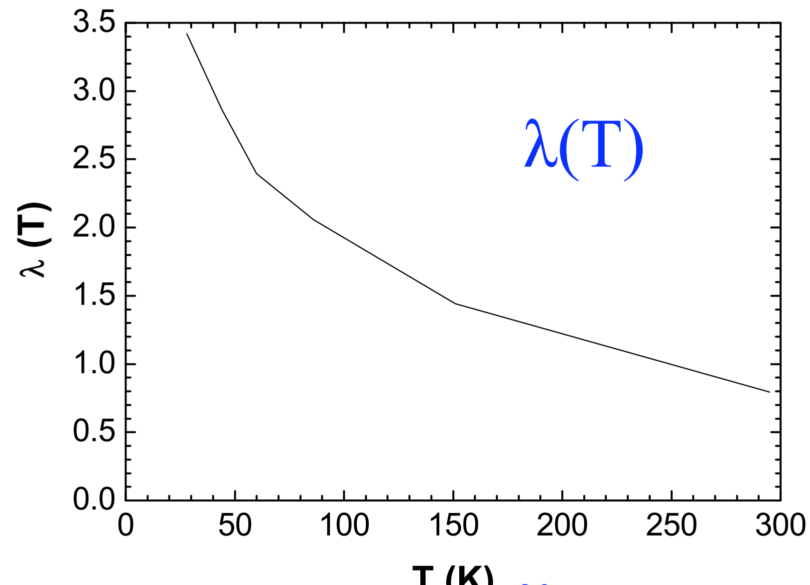


The scattering rate

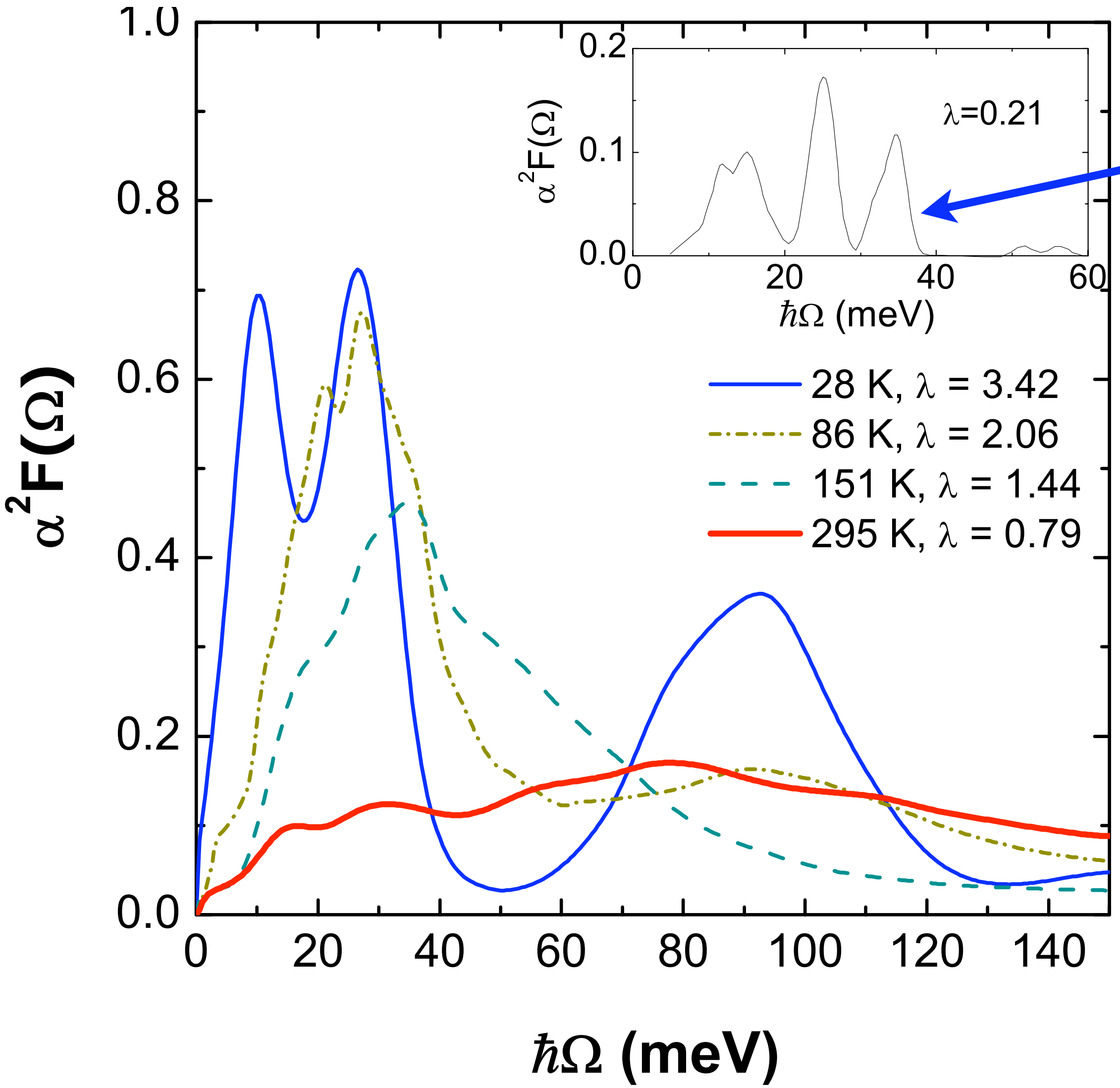


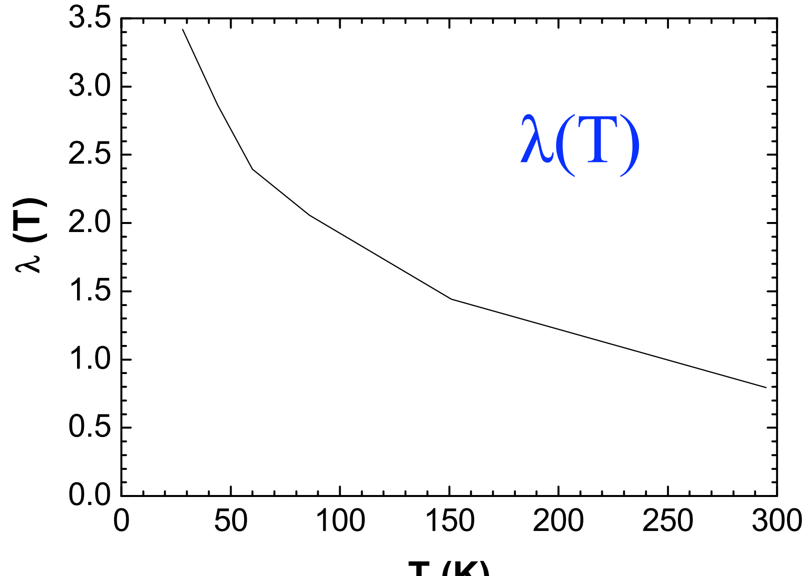
The bosonic spectral function





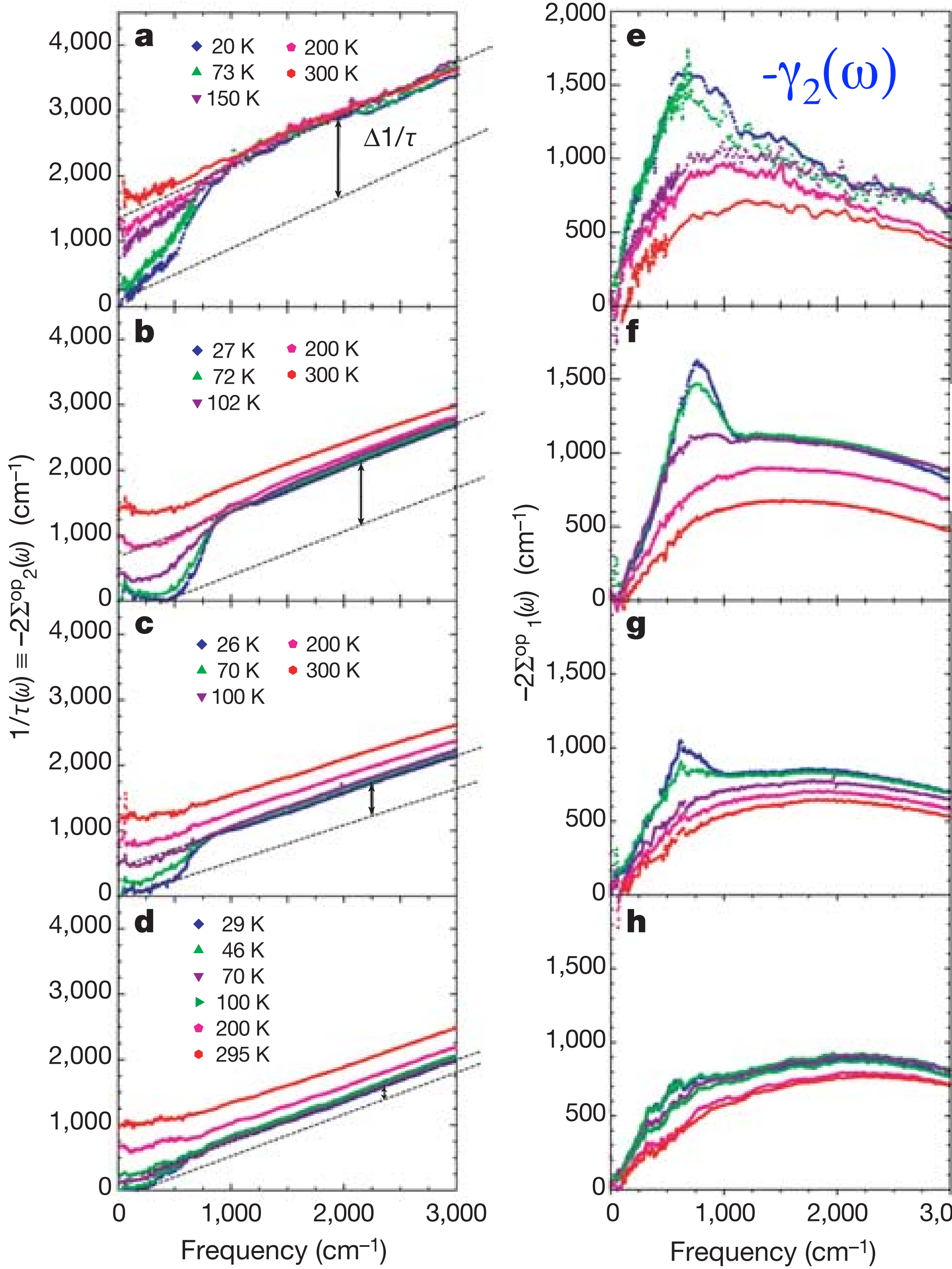
The bosonic spectral function





Bi-2212

- Doping dependence of the self energy
- Comparision with ARPES
- New results on the bosonic spectral function



Real and imaginary parts of the scattering rate in Bi-2212

Hwang et al. 2003

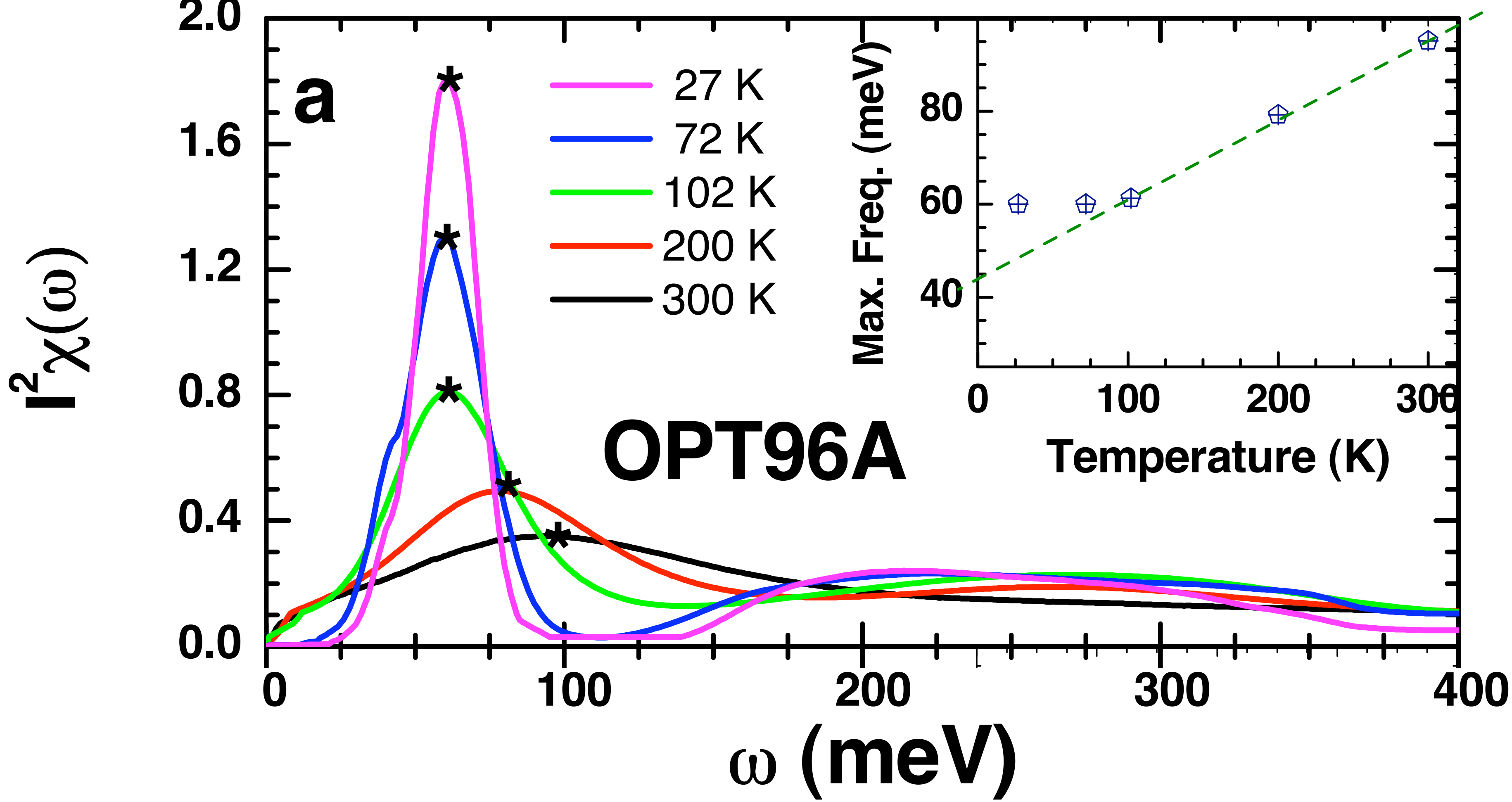
Optical self energy:

$$1/\tau = -2(\Sigma_2^{op}(\omega) + i\Sigma_1^{op}(\omega))$$

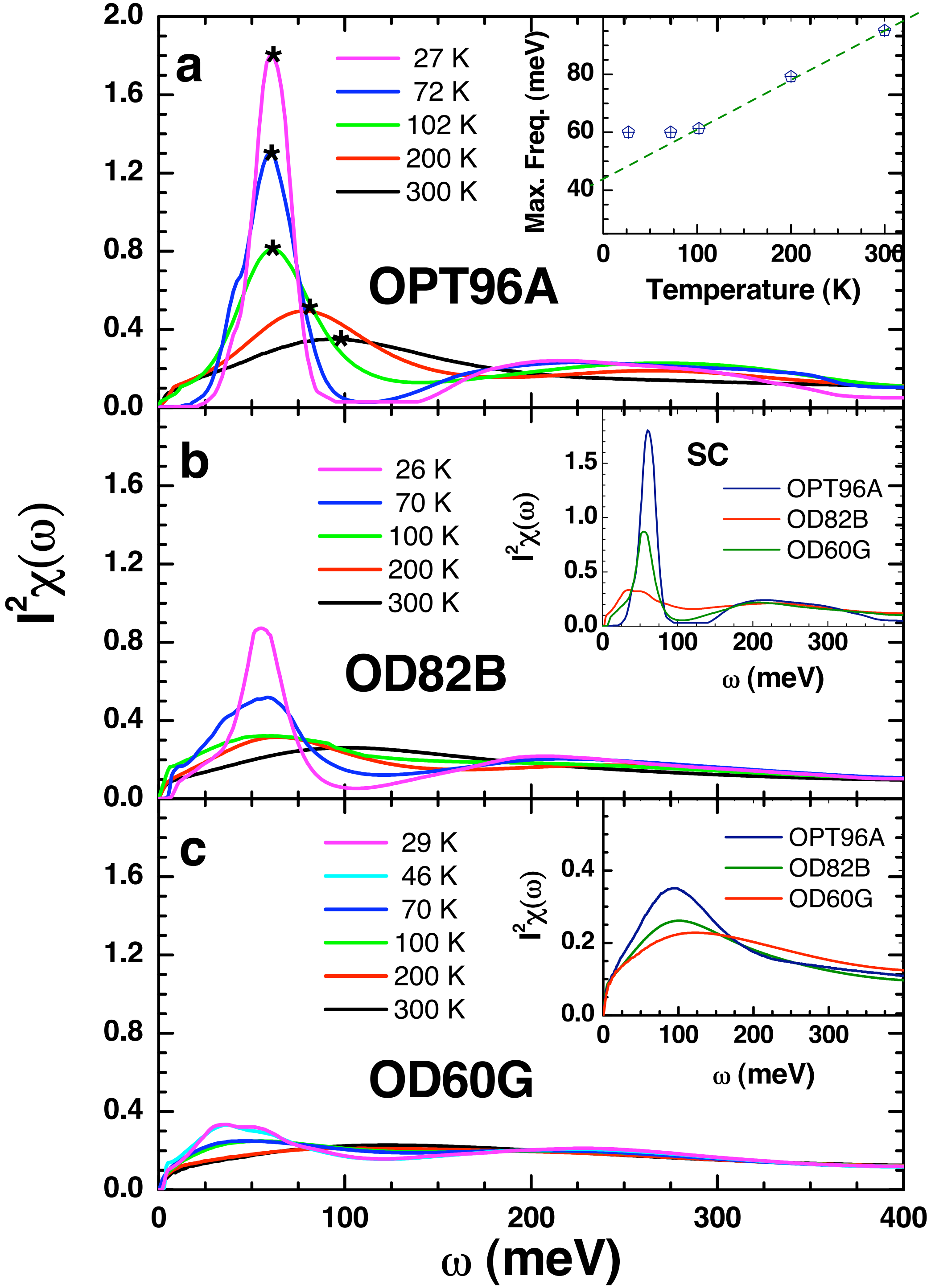
Doping

Bi-2212 Eliashberg inversion

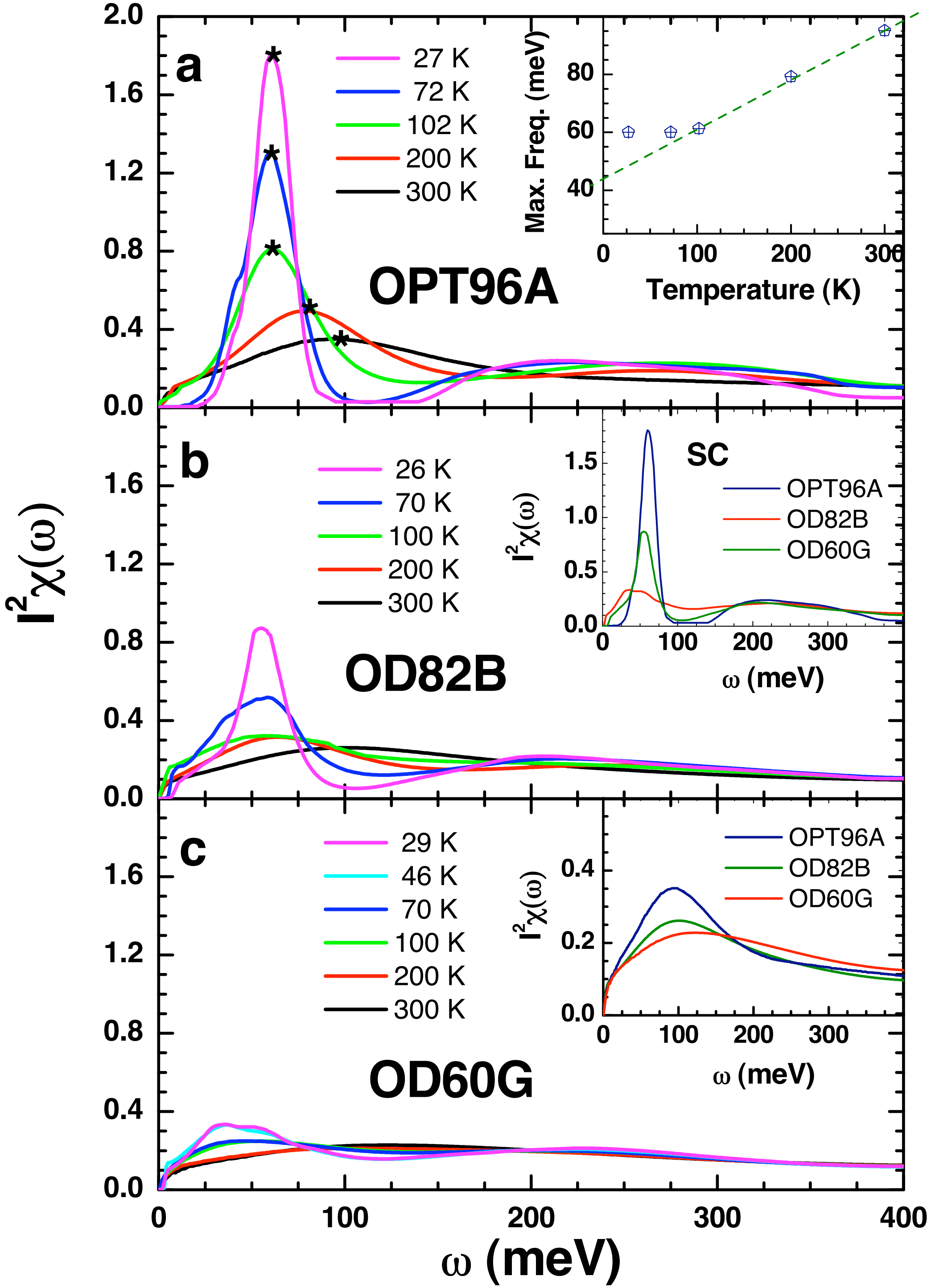
Hwang with Schachinger and Carbotte



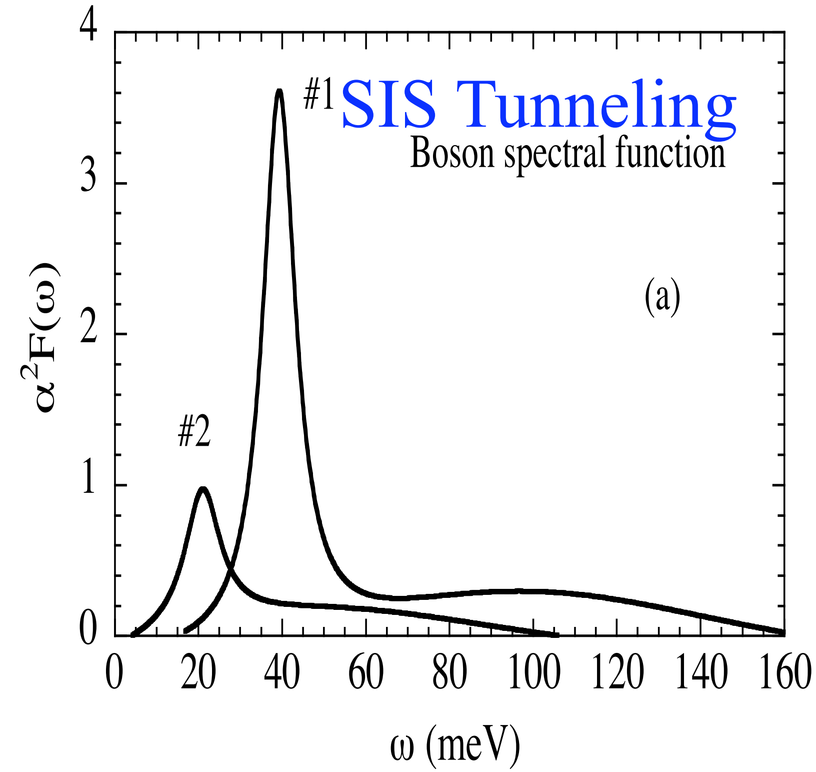
Eliashberg inversion, doping dependence



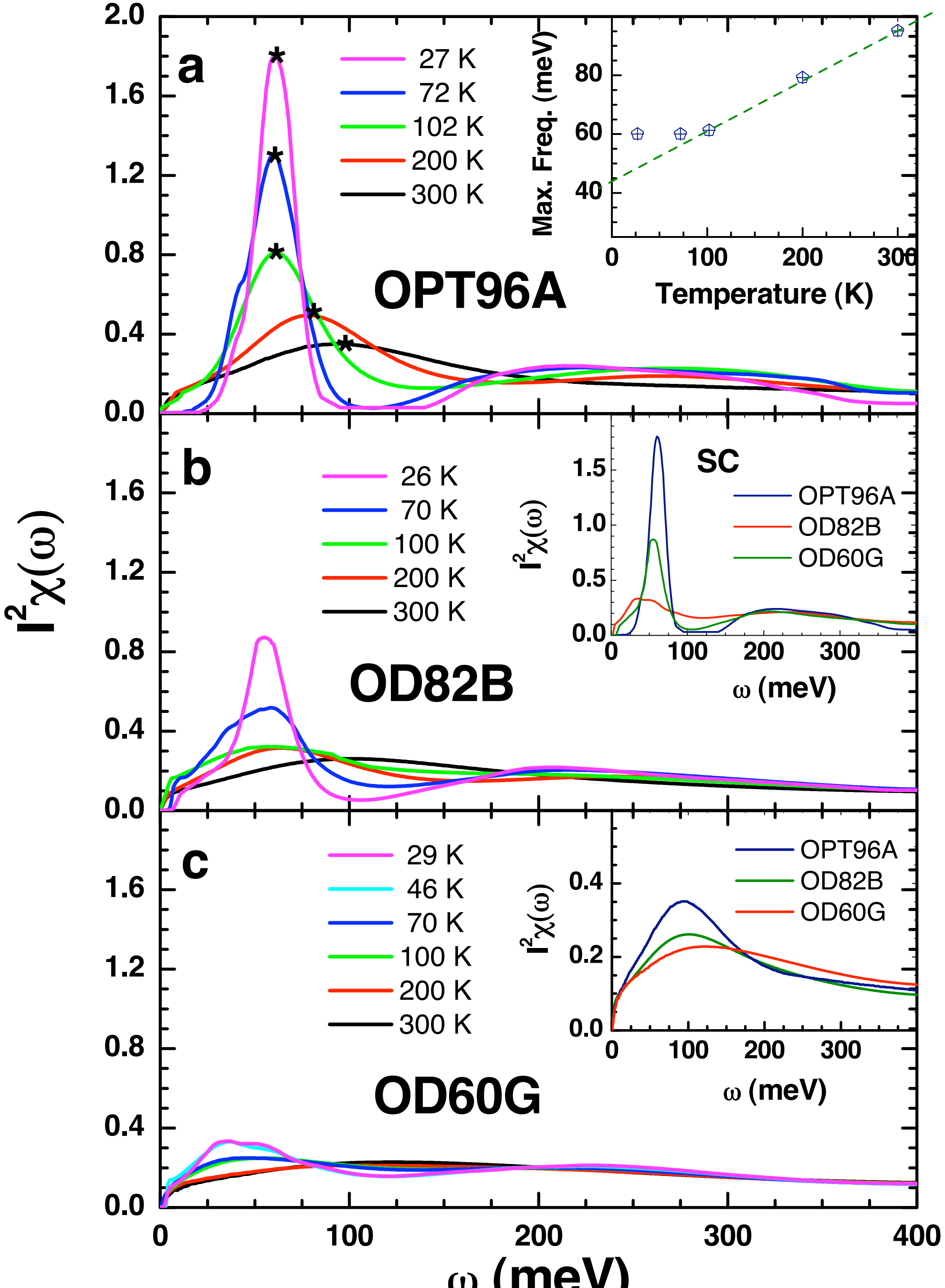
Comparison with tunneling data



Zasadzinski
et al. (2005)

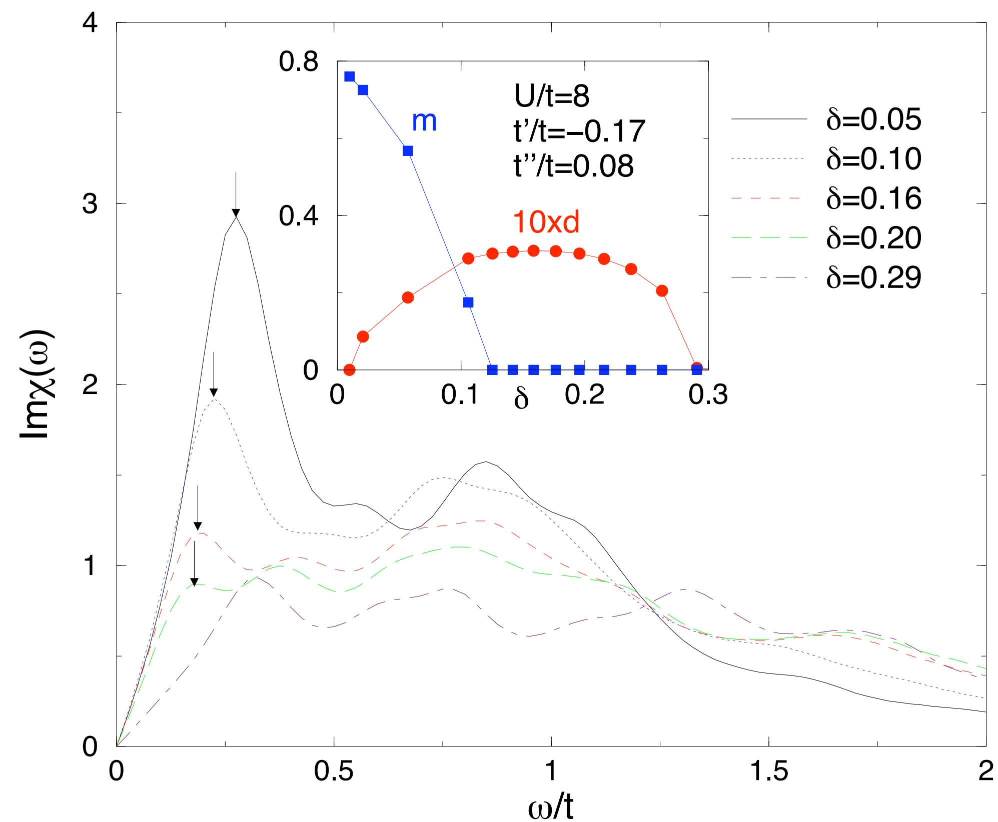


Eliashberg inversion, doping dependence

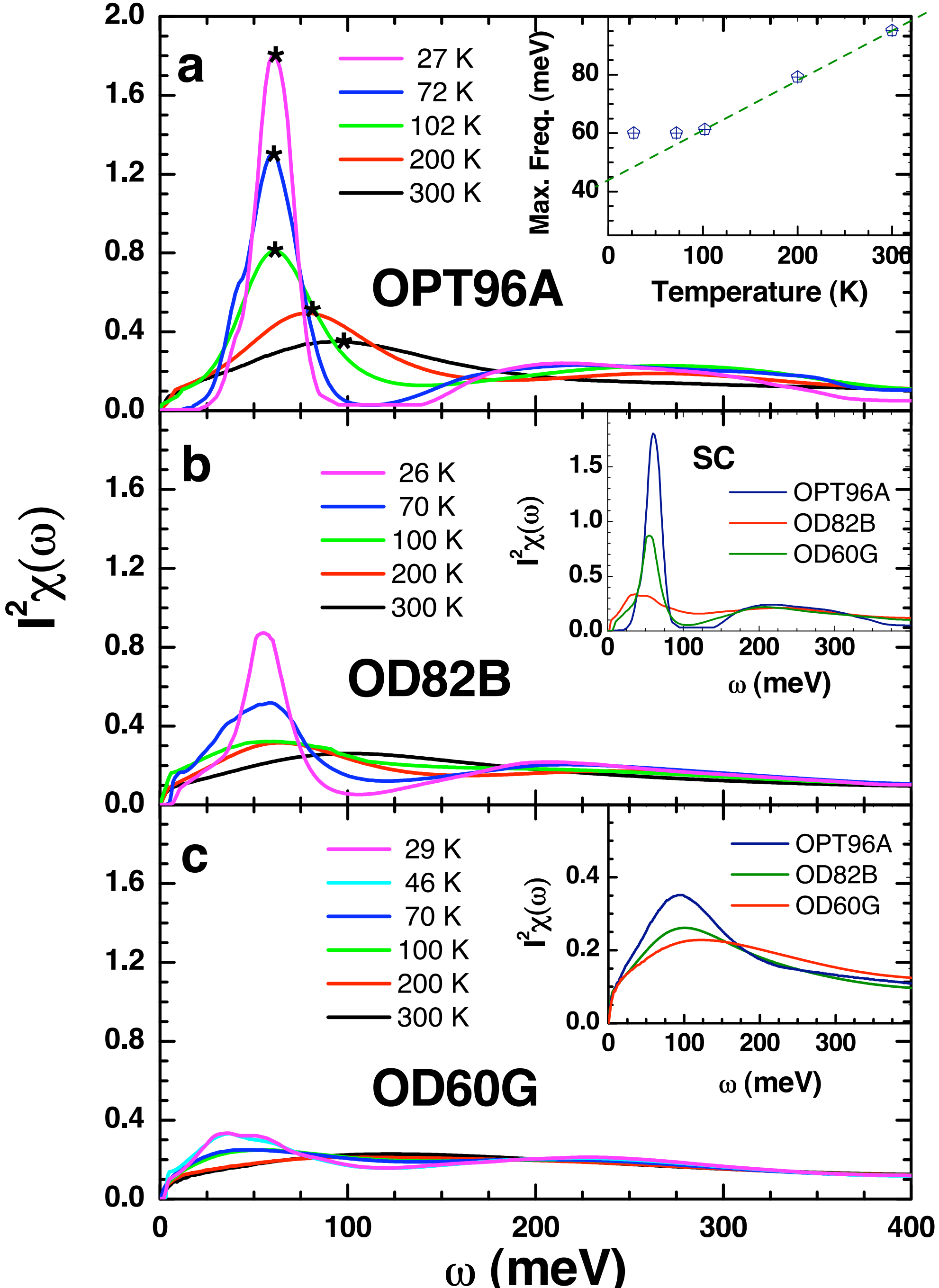


Comparison with DMF theory

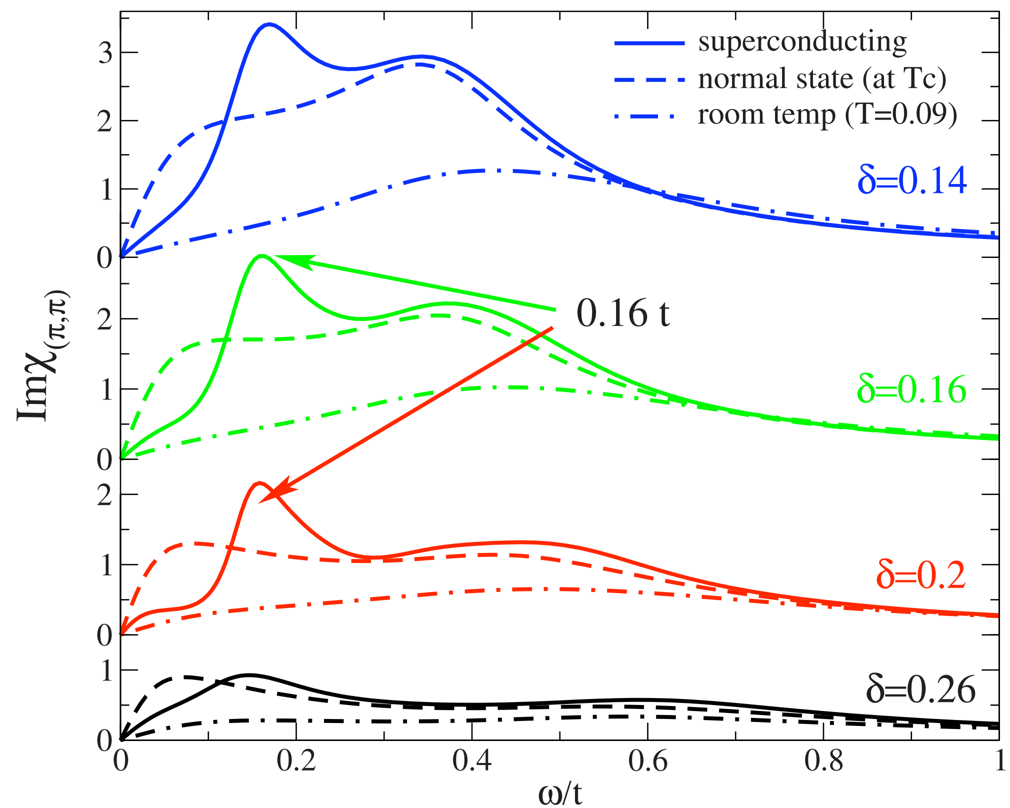
Kyung *et al.* arXiv: 812.1228



Eliashberg inversion, doping dependence



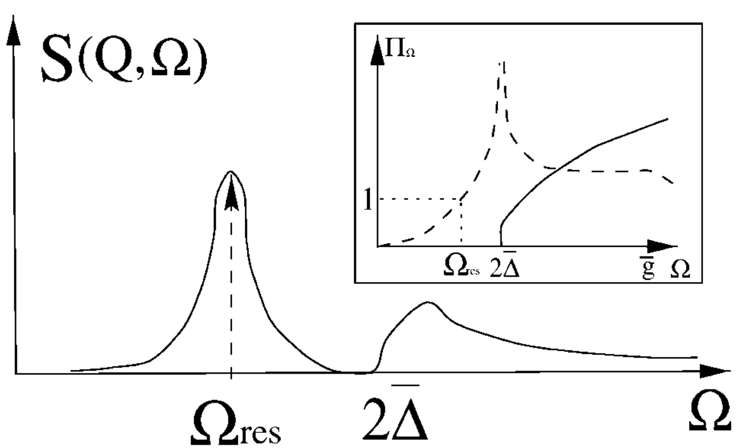
Haule & Kotliar PRB 76, 104509 (2007)



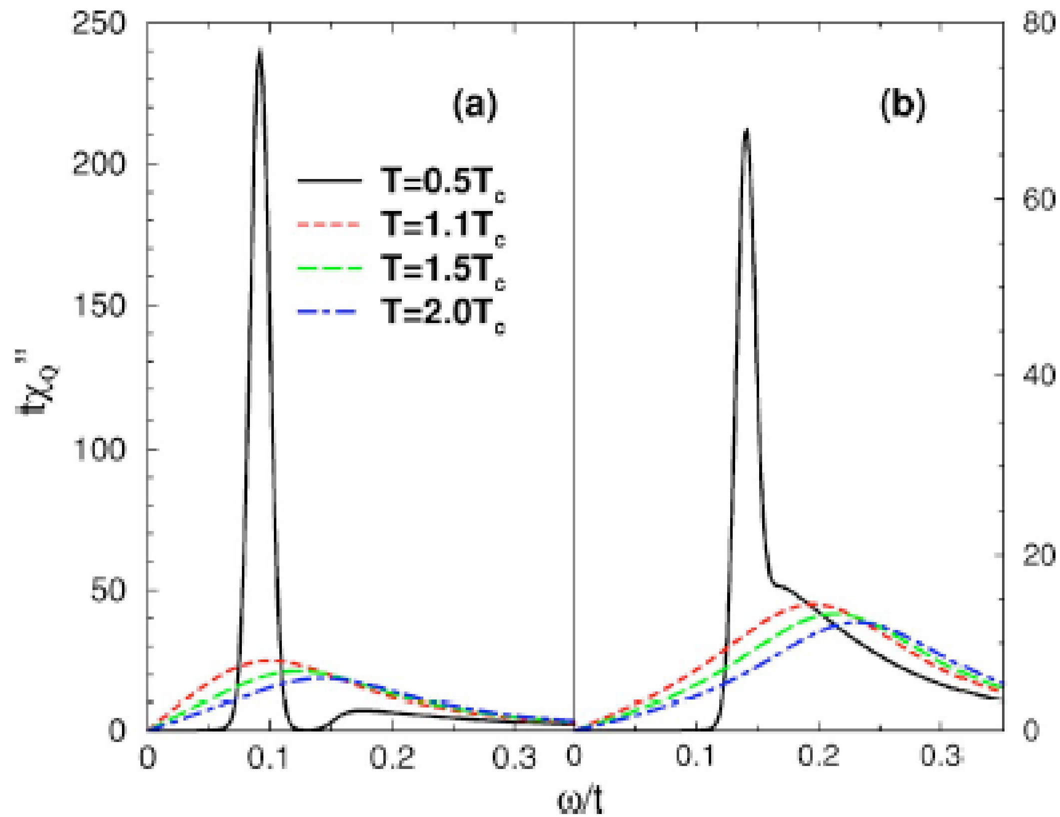
Other theoretical ideas for the magnetic susceptiblity

Exciton model

Eschrig & Norman
Abanov & Chubukov



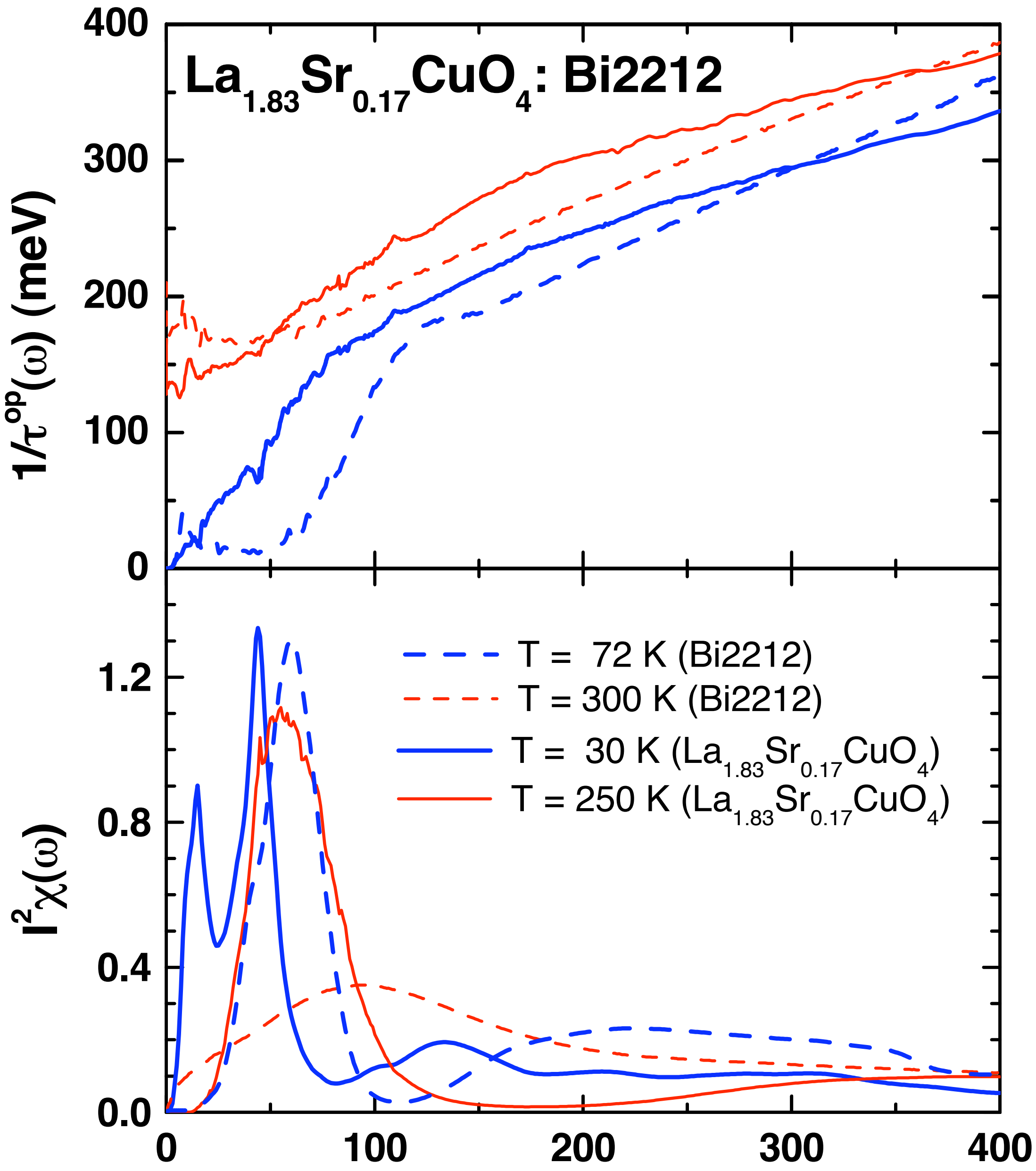
Memory function
Prelovsek & Sega



LSCO

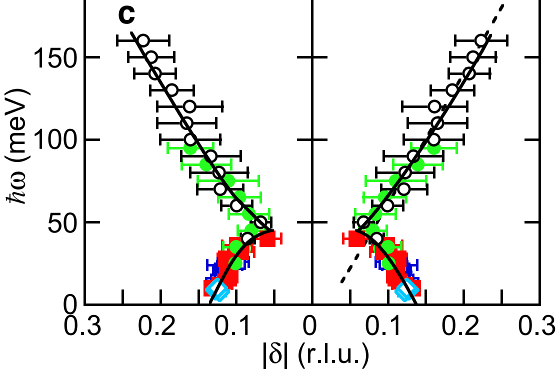
- Odd material, $T_c = 30$ K
- Comparision with neutron scattering
- "Prediction of T_c"

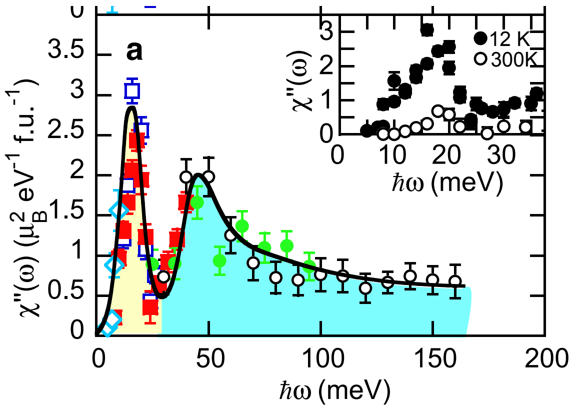
LSCO self energy

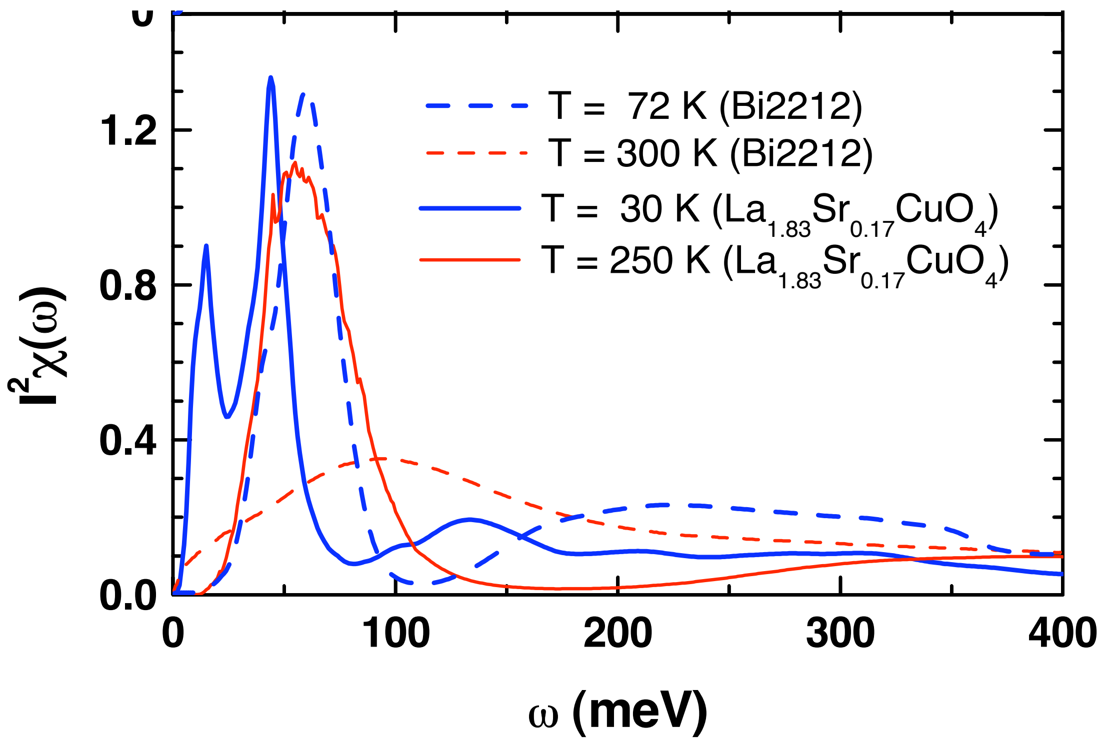


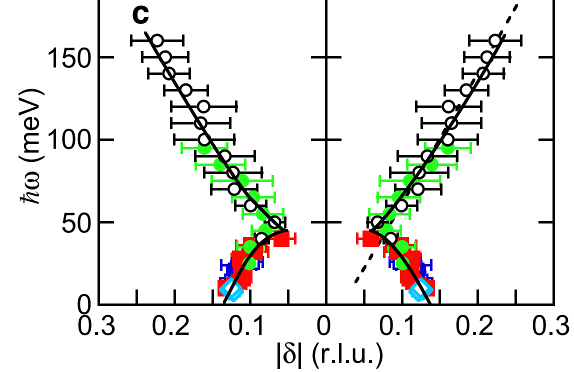
LSCO neutron scattering

Vignolle *et al.*



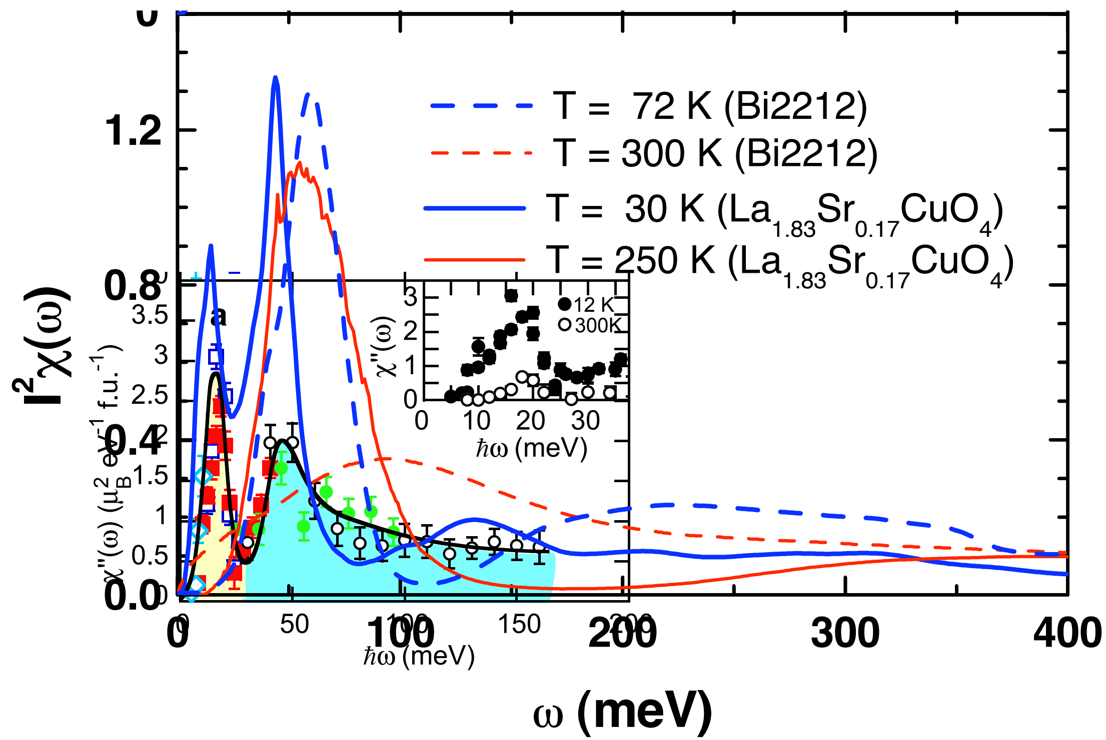






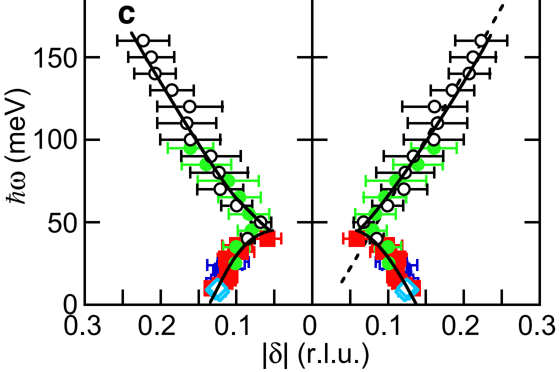
LSCO neutron scattering

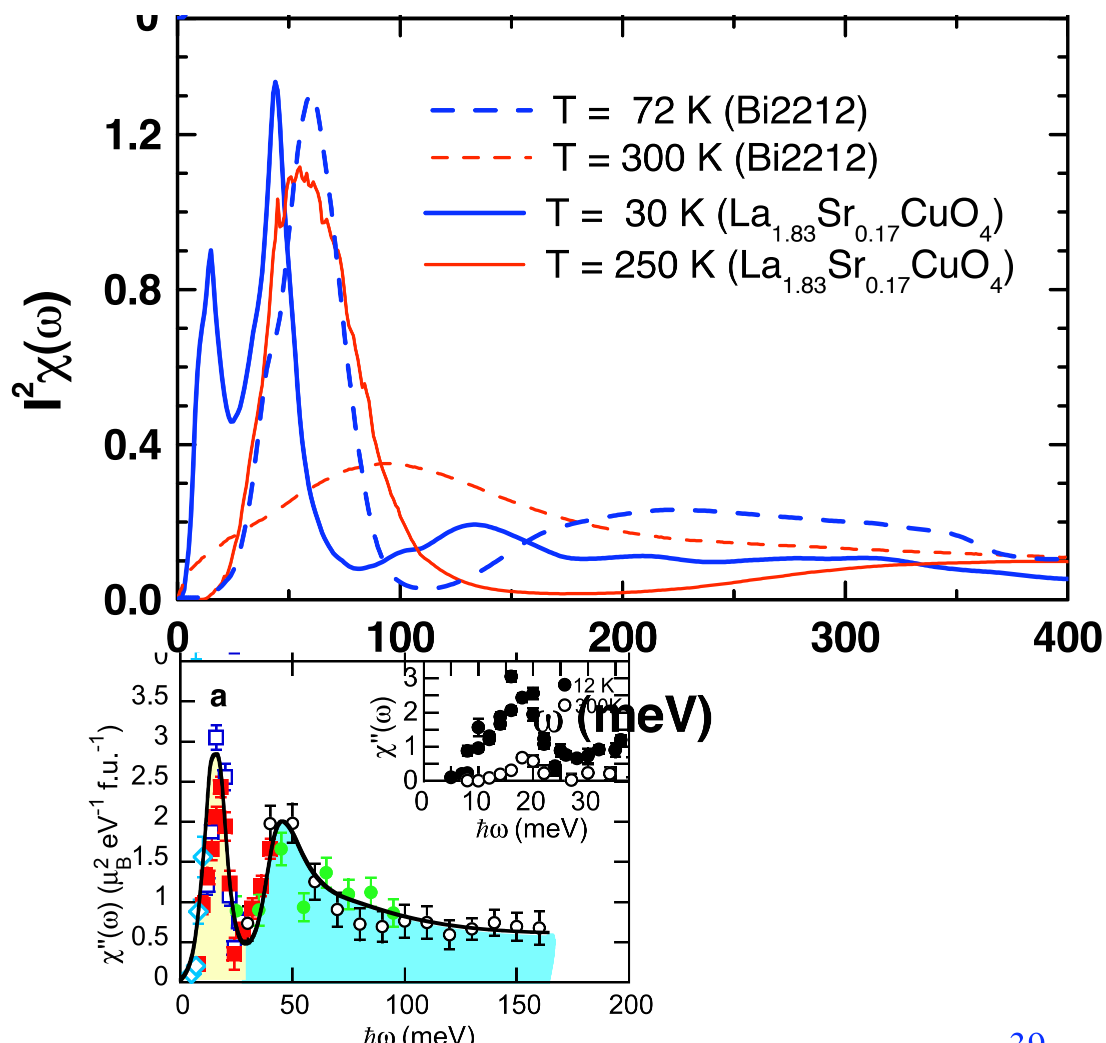
Vignolle *et al.*



LSCO neutron scattering

Vignolle *et al.*





Why is LSCO T_c so low?

McMillan equation for T_c:

$$k_B T_c \cong \hbar\, \omega_{ln} \exp\left[- \frac{1+\lambda^s}{\lambda^d} \right]$$

	LSCO	Bi-2212
λ_d	1.90	1.85
λ_s	3.40	2.50
ω_{ln}	25	50 meV
T_c	29	89 K

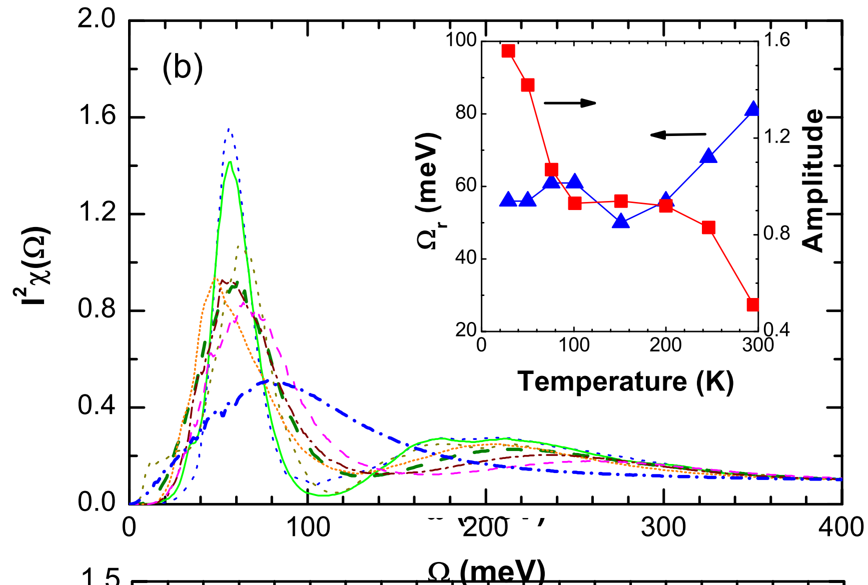
where

$$\omega_{ln} \equiv \exp\left[\frac{2}{\lambda} \int_0^\infty \ln\omega\, \frac{I^2\chi(\omega)}{\omega}\, d\omega \right]$$

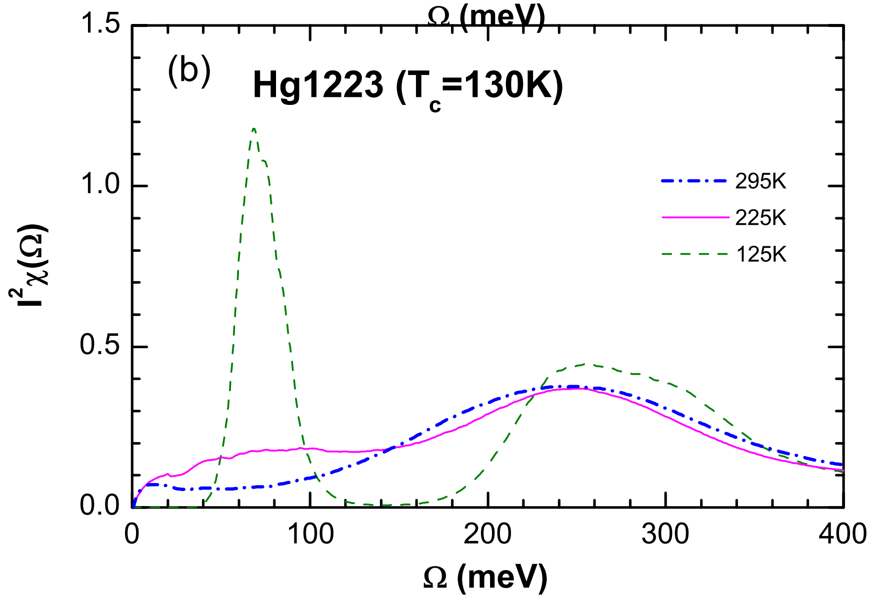
$$\lambda^{(s,d)} = 2 \int_0^{\omega_c} \bar{I}^2_{(s,d)} \chi(\omega)/\omega\, d\omega$$

Mercury based superconductors

The mercury based superconductors



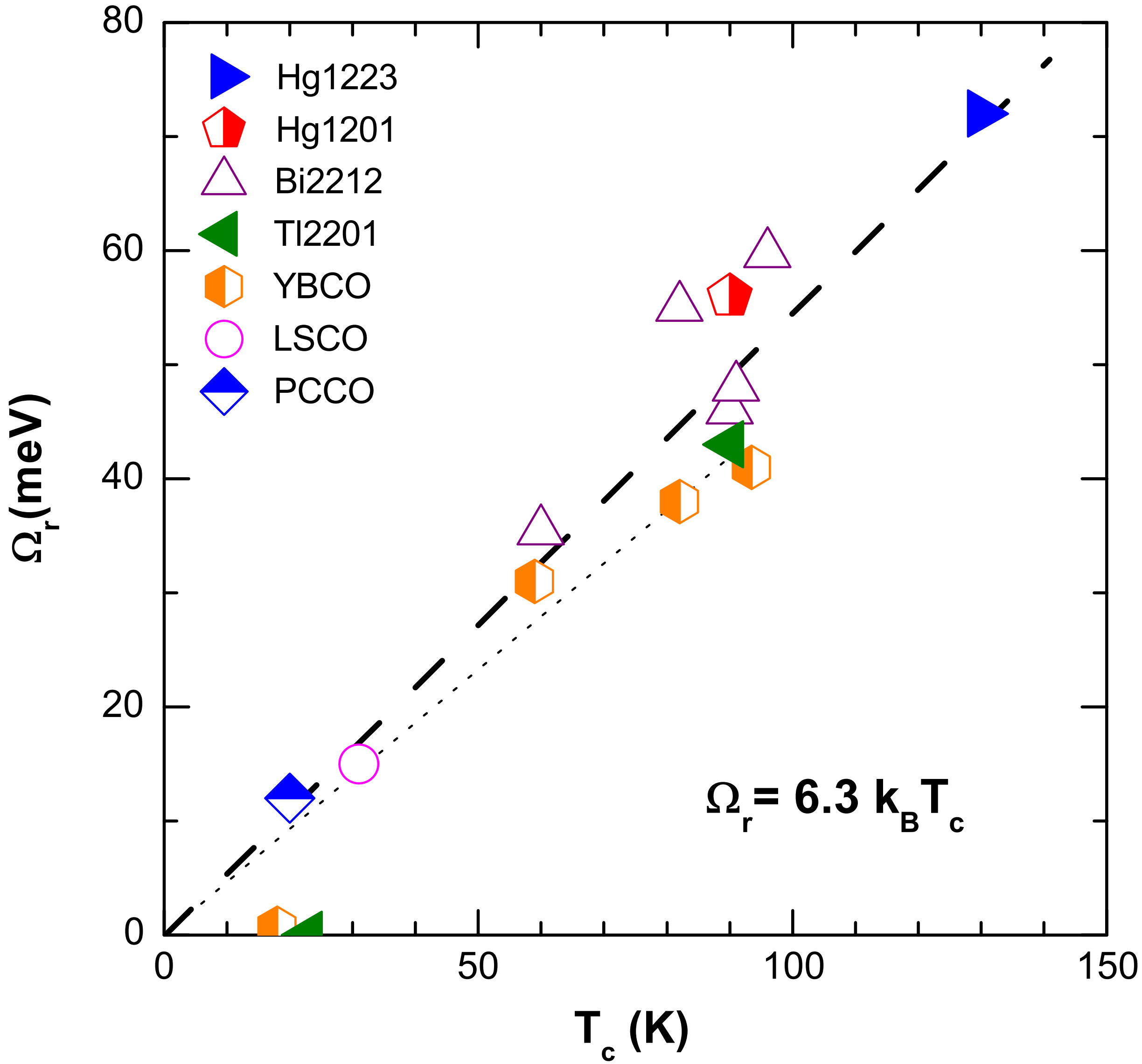
One layer T_c = 90 K



Three layer T_c = 130 K

A “new” scaling law

The peak of the bosonic spectral function scales with 6.6 $k_B T_c$.



A "new" scaling law

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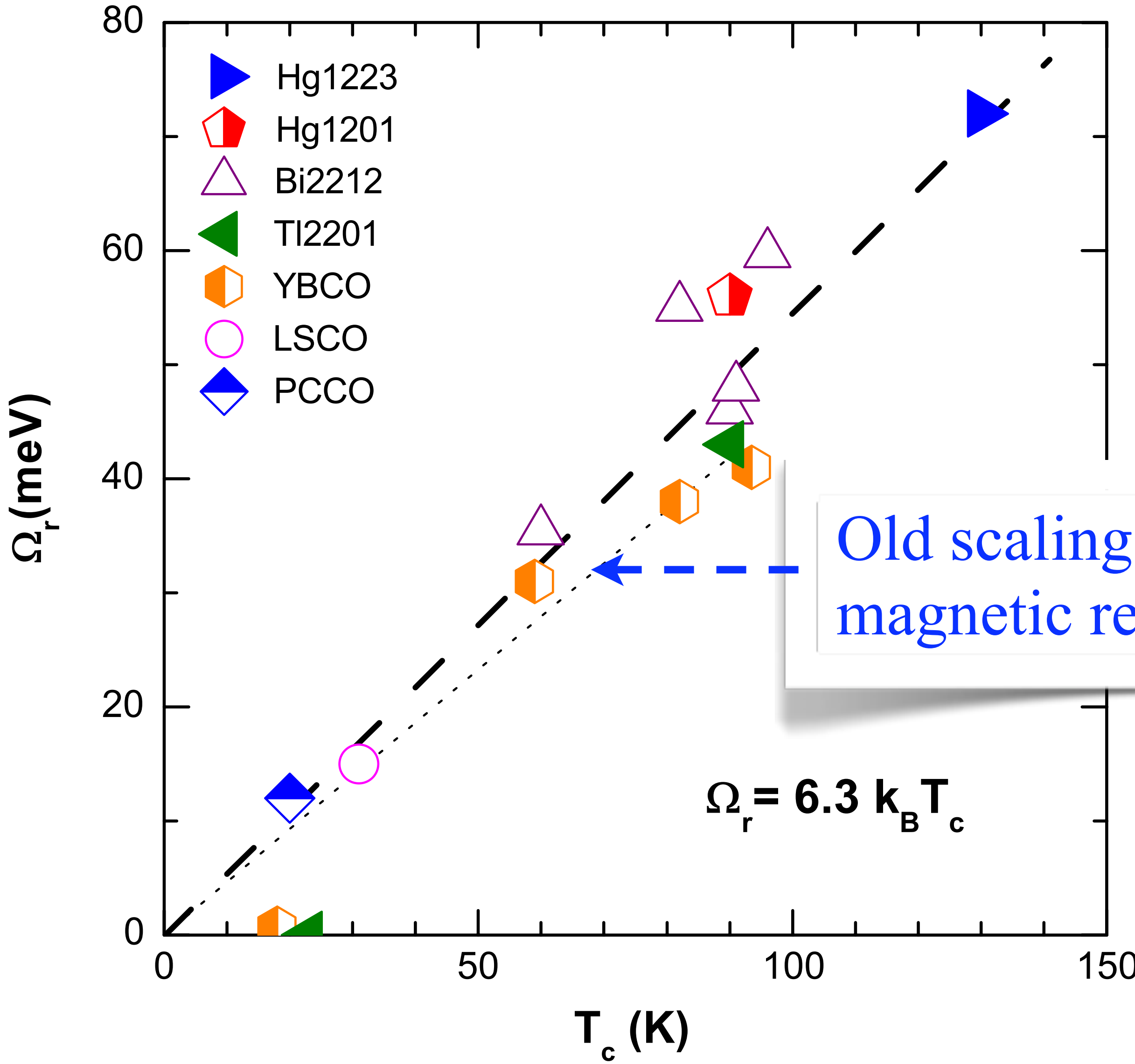
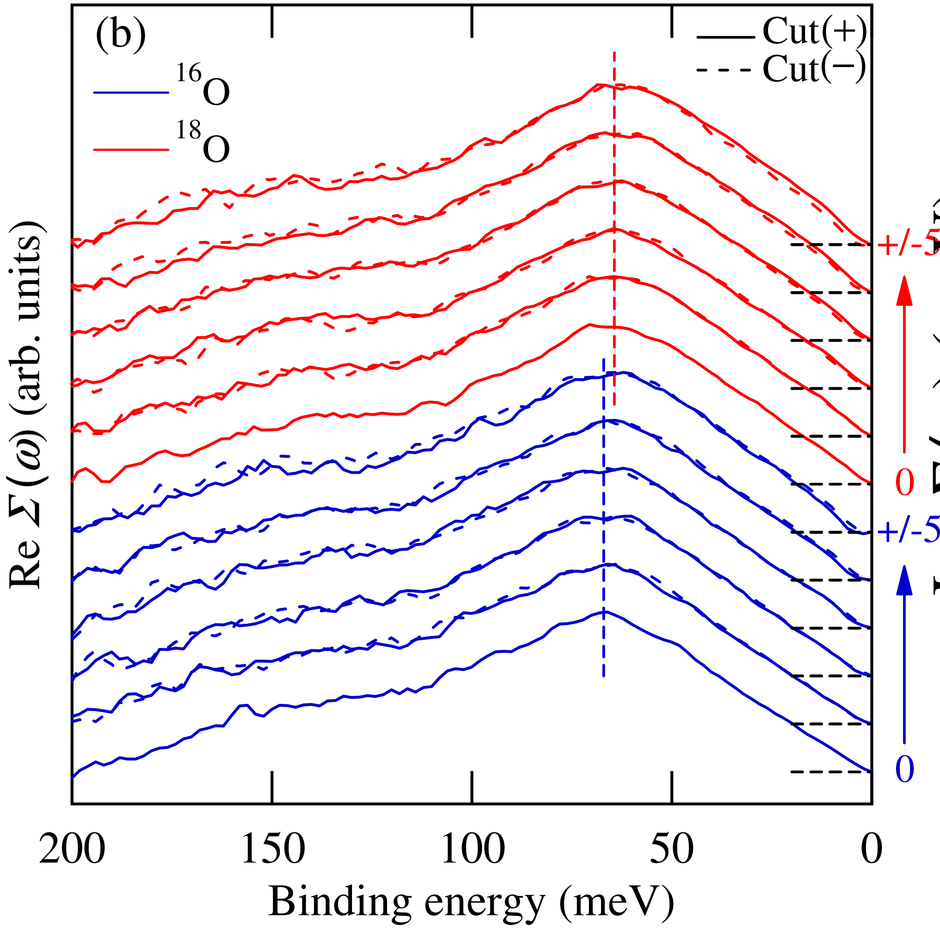


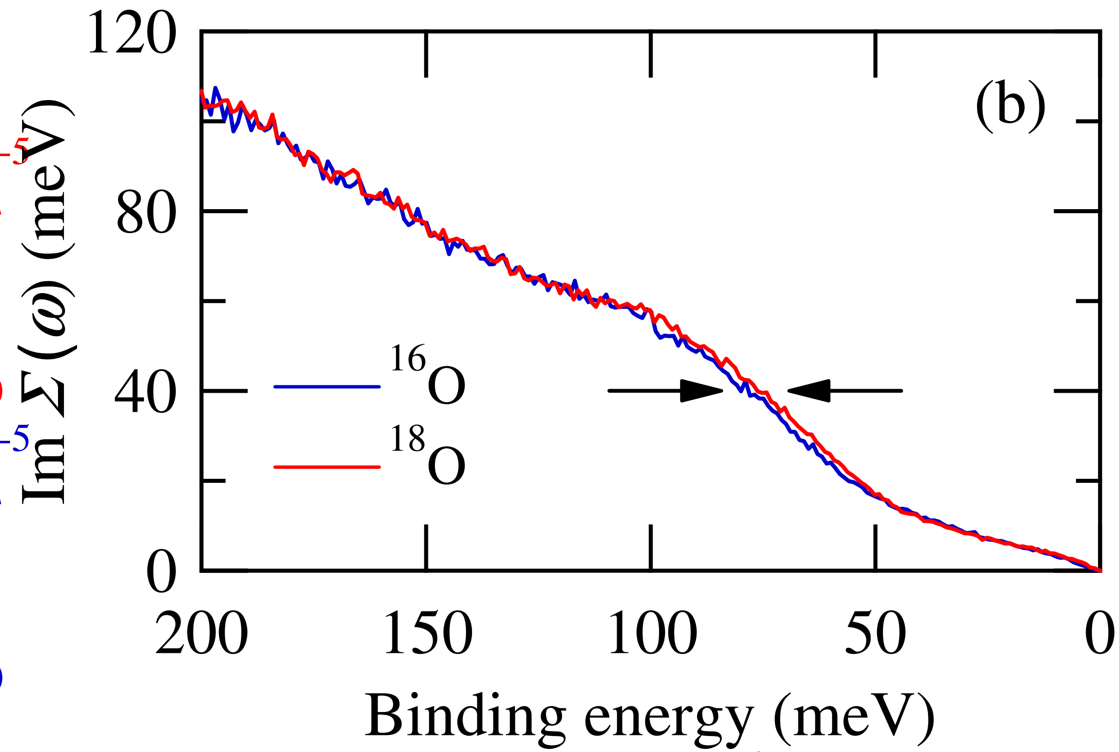
Old scaling law for the magnetic resonance 5.4 $k_B T_c$.

The isotope effect

The isotope effect: new ARPES data

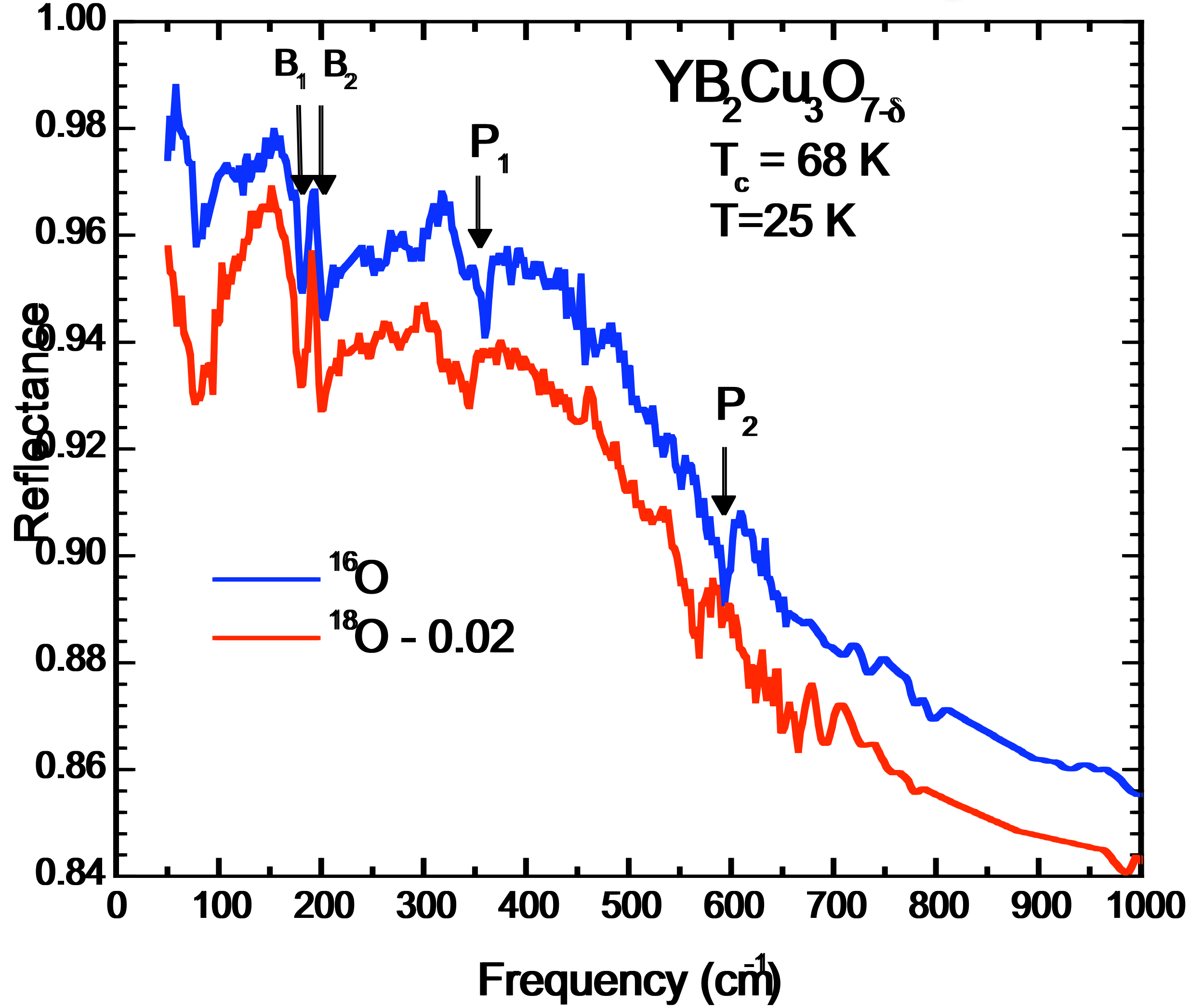
Iwasawa *et al.* PRL 101, 157005 (2008).



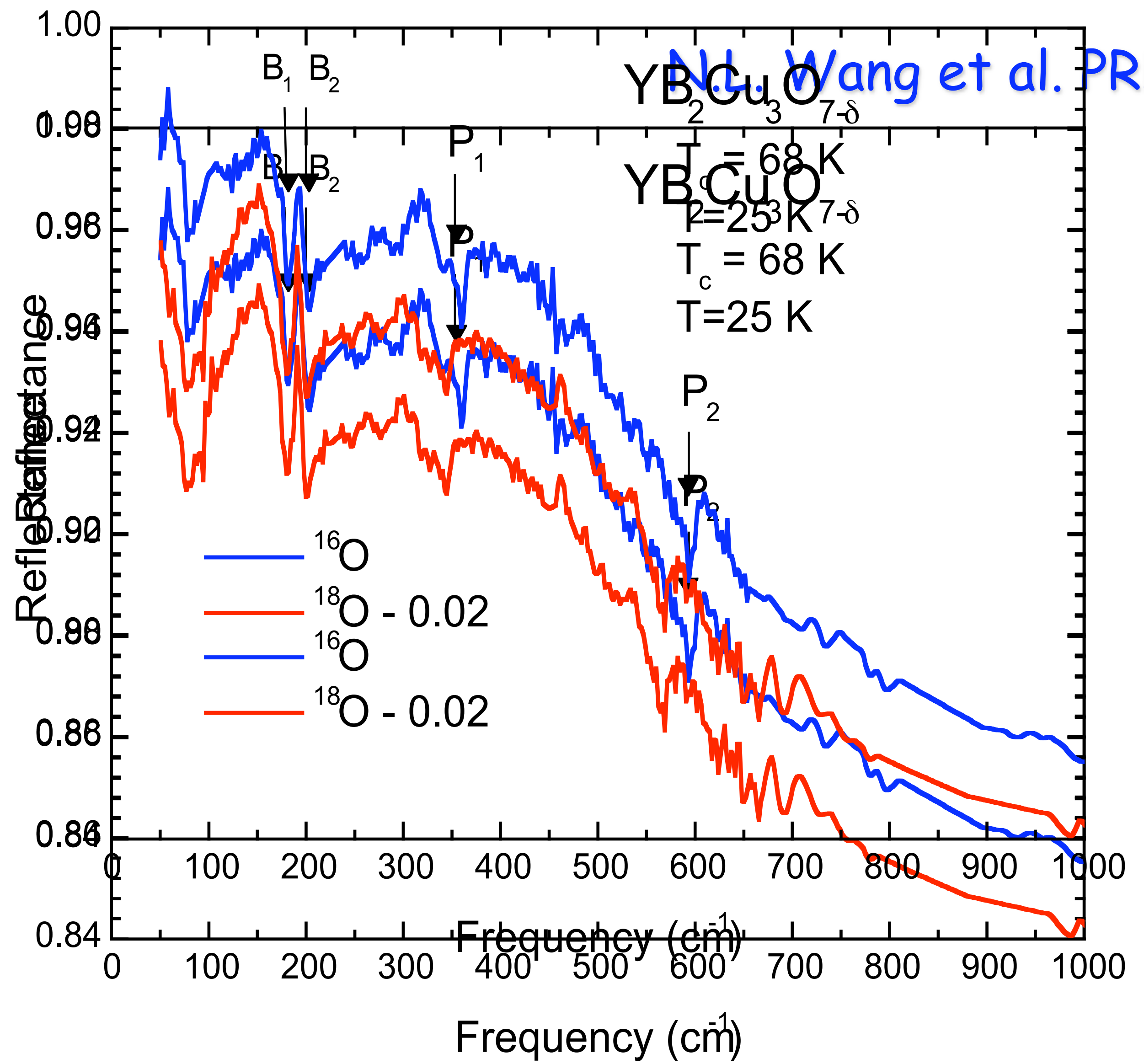


Isotope effect in YBCO from optics

N.L. Wang et al. PRL 2002



Isotope effect in YBCO from optics



N.L. Wang et al. PRL 2002

Isotope effect in YBCO

N.L. Wang et al. PRL (2002).

- Underdoped samples with ^{16}O and ^{18}O
- Isotope effect: $\Delta\omega/\omega = -\alpha\,\Delta m/m$
- The phonon lines show isotope effect with $\alpha = -0.5$
- The normal state shoulder shows $\alpha = -0.1 \pm 0.1$
- The superconducting state shoulder $\alpha = -0.23 \pm 0.1$

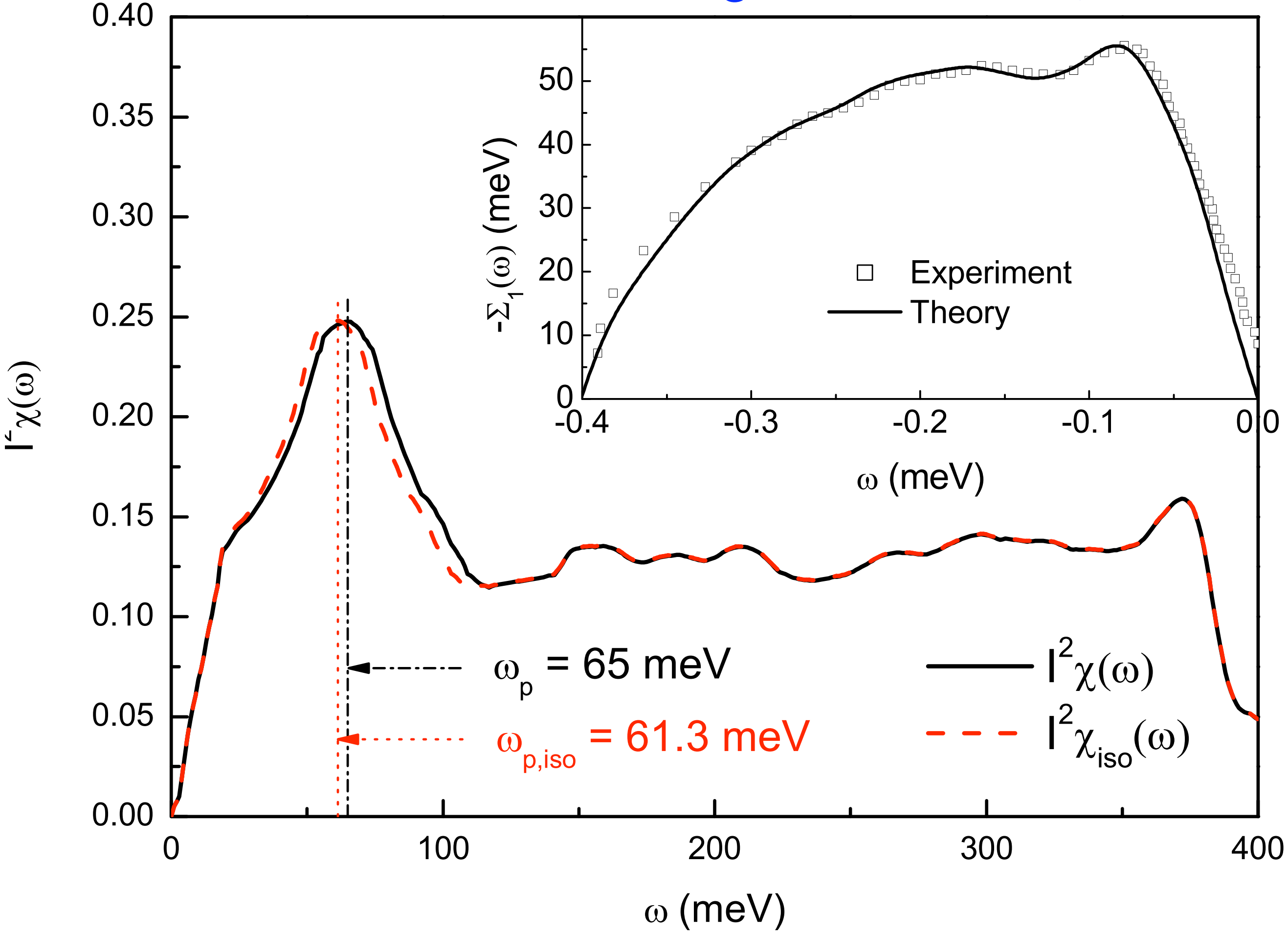
The mode giving rise to the shoulder
is unlikely to be of phonon origin.

Contradiction !

- ARPES finds $\alpha = -0.5$ for nodal kink
- Optics finds $\alpha = -0.1$ Fermi surface average kink

Maximum entropy inversion of nodal ARPES

Wentao Zhang *et al.* PRL **101**, 107002 (2008).



Bi-2212 nodal Σ_1

O^{16} spectral function

O^{18} spectral function

Model: Shift peak of bosonic function by 6 % and calculate Σ_1 change

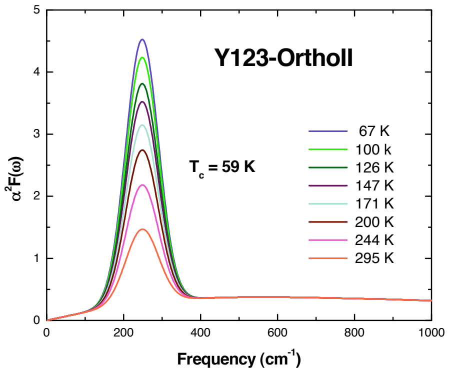
$\lambda_{ep} = 0.2$ Predicted shift 4.5%

$\lambda_{mag} = 0.8$ Observed shift of 5 ± 0.8 %

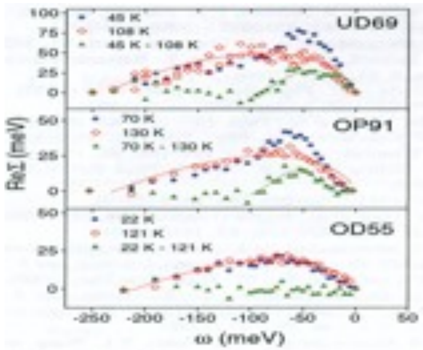
Controversy resolved

Both optics and ARPES are consistent with a 10 to 20 % self energy contributions from phonons.

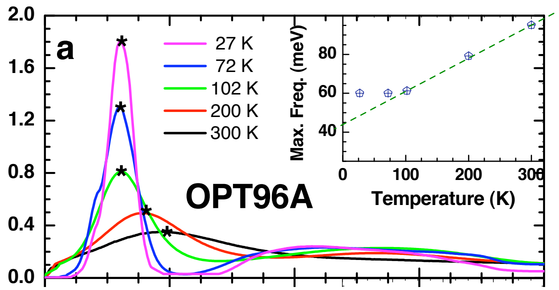
Summary of self energy spectroscopy



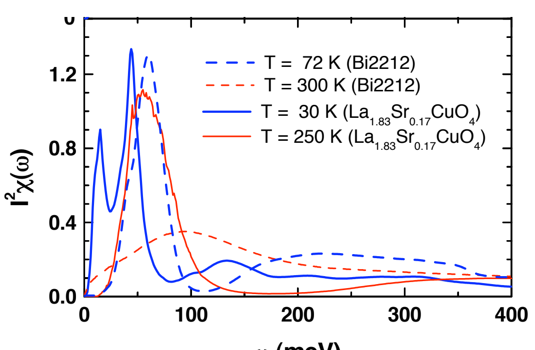
A bosonic peak and a background peak depends on temperature



Bi-2212 cf. ARPES

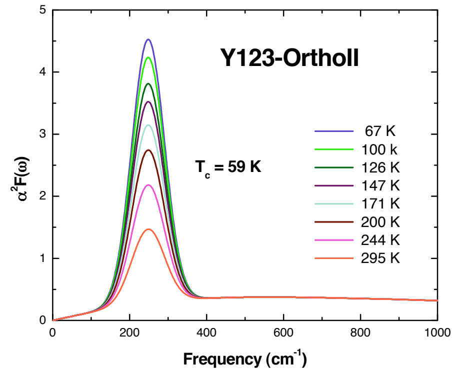


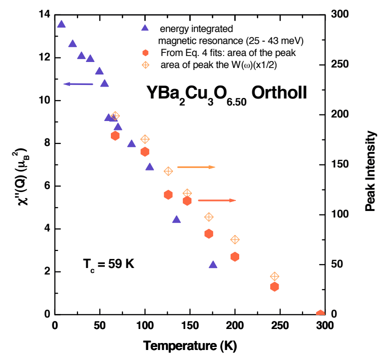
Bi-2212 Shift of spectral weight cf. tunneling



LSCO cf. magnetic neutron scattering

Summary of self energy spectroscopy





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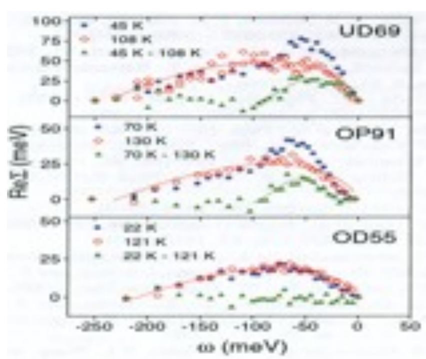
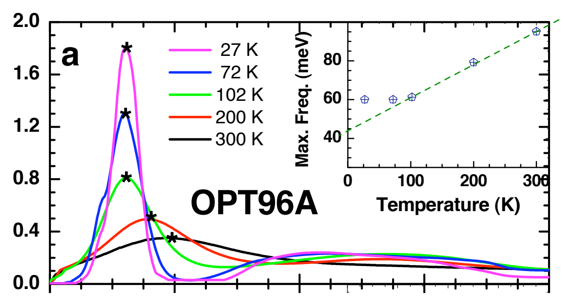


Bi-2212 cf. ARPES



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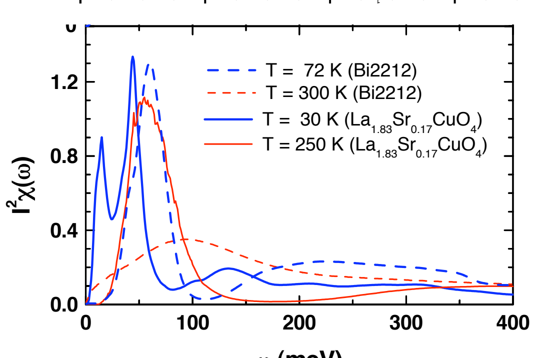

LSCO cf. magnetic neutron scattering

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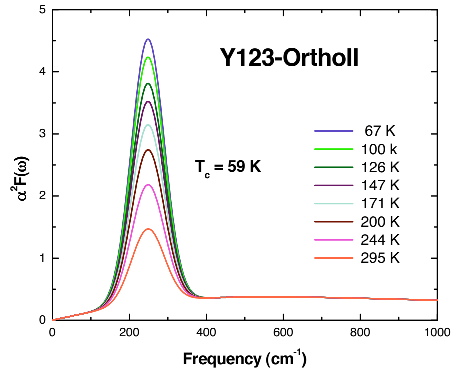

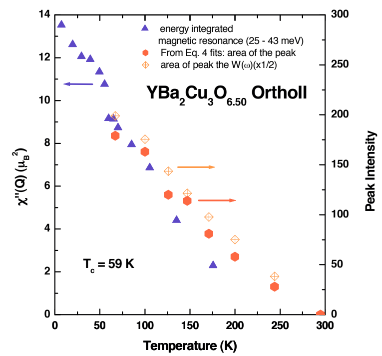

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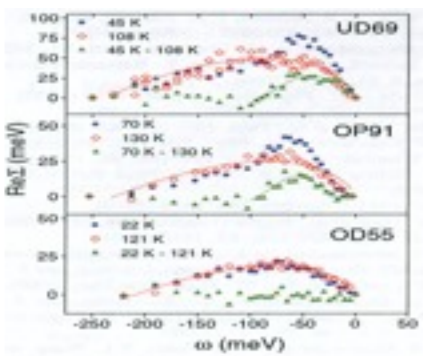

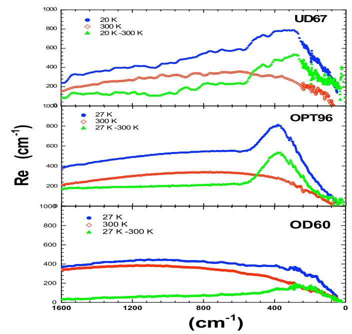

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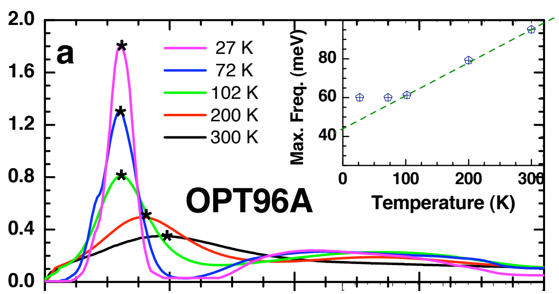

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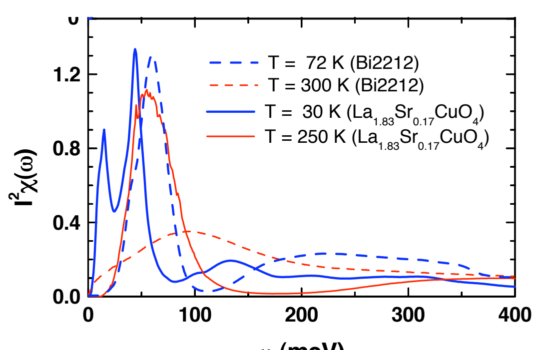
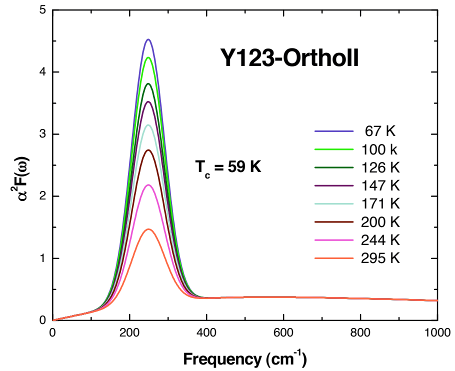
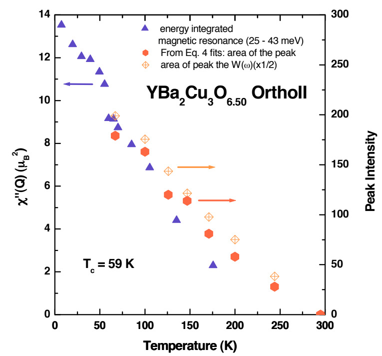


LSCO cf. magnetic neutron scattering

Summary of self energy spectroscopy





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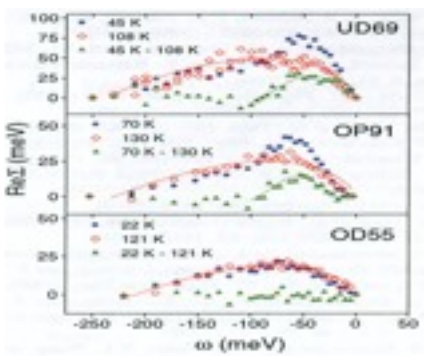
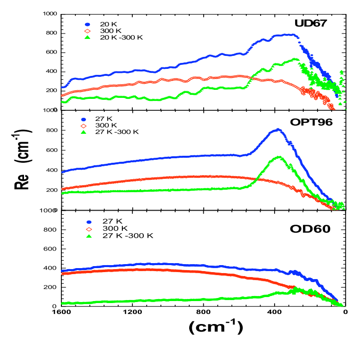
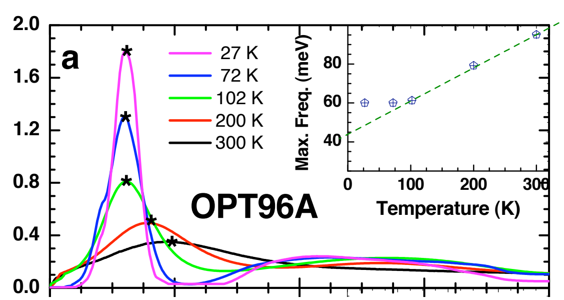
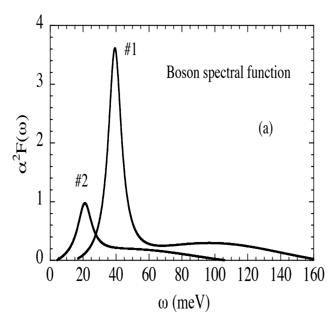




Bi-2212 cf. ARPES





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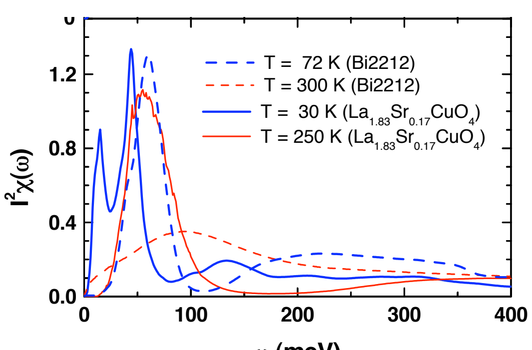
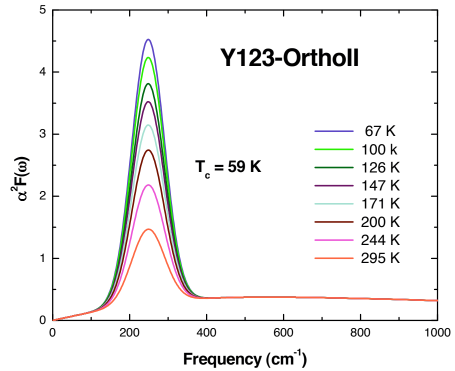
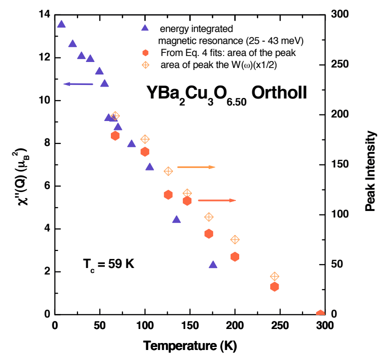


LSCO cf. magnetic neutron scattering

Summary of self energy spectroscopy





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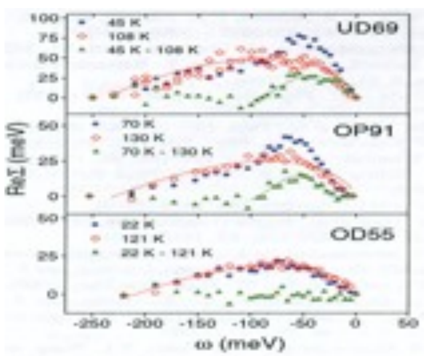

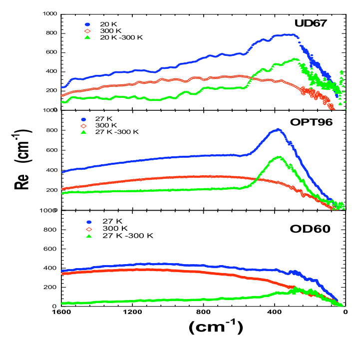

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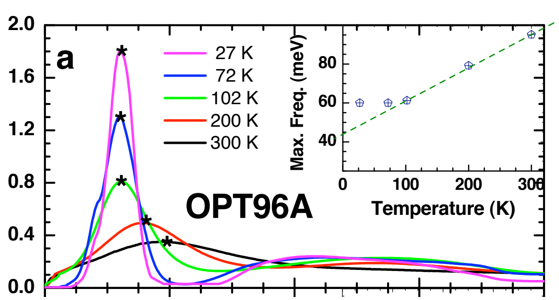

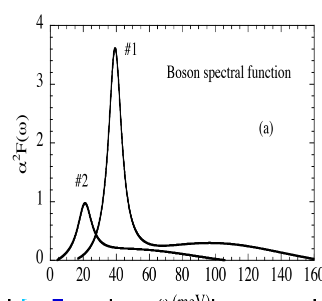

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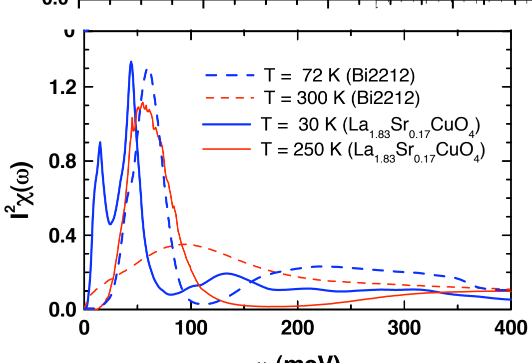

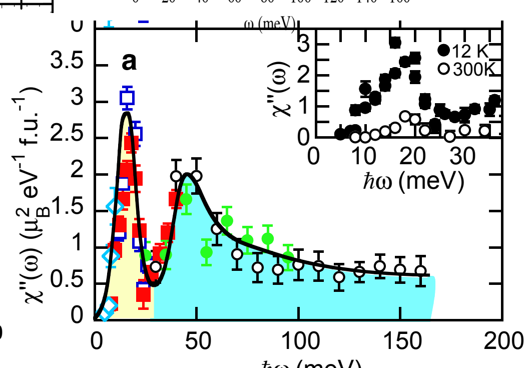

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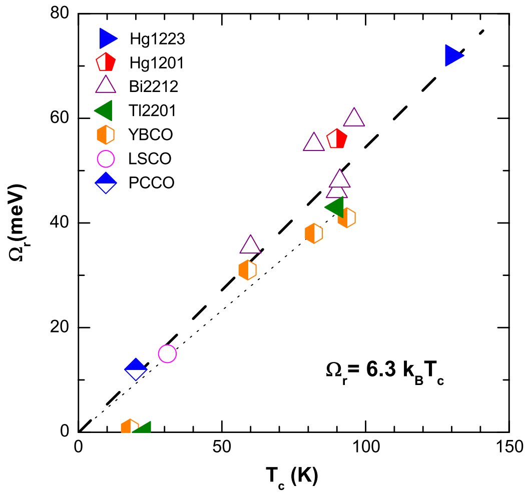
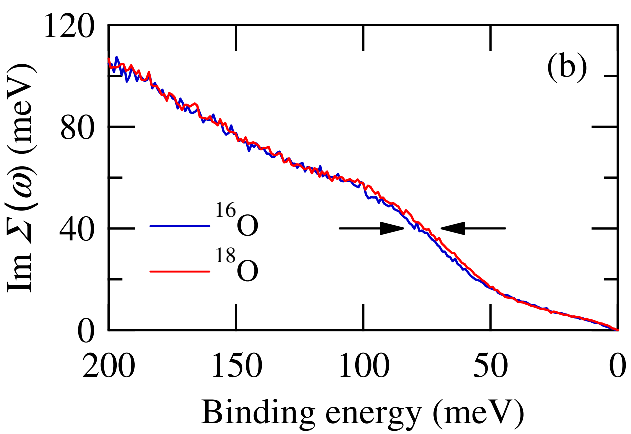
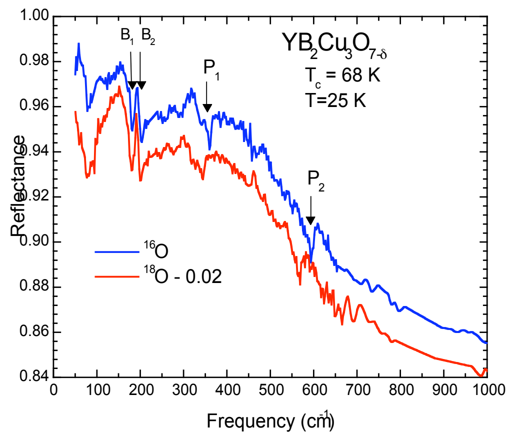


A scaling law $\Omega_{res} \propto 6.3\ k_B T_c$

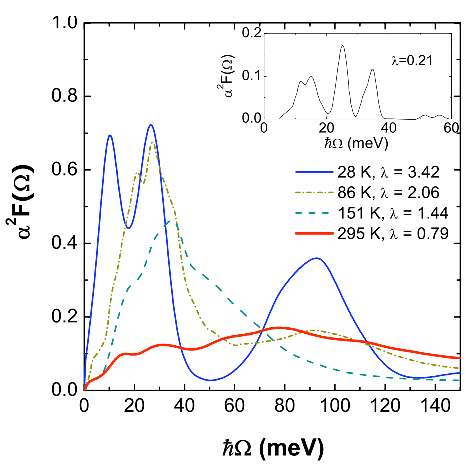




Phonons vs. magnetism

$\lambda_{ep} = 0.2$

$\lambda_{mag} = 0.8$



$Ba_{0.35}K_{0.45}Fe_2As_2$

Remaining tests:

No magnetic mode in:

- Highly underdoped YBCO
- $LSCO_{0.22}$

Remaining problems:

- Origin of magnetic susceptibility
- Materials differences
- Pseudogap, friend or foe?

Thank you