In-plane optical conductivity study of Bi-2212 at various doping levels: energy scale involved in pairing

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Outline

E*nergy scale* over which the *optical conductivity is modified* in the superconducting state: measure *spectral weight lost* at $T \ll T_c$ and compare it to the *superfluid density*

Introduction: Ferrell-Glover-Tinkham (FGT) sum rule

1. $Bi_2Sr_2CaCu_2O_{8+\delta}$ [Bi-2212] underdoped and overdoped films
2. Reflectivity and conductivity
3. Analysis: violation of the FGT sum rule

Conclusion

Introduction

From reflectivity to conductivity

$$R(\omega) = \frac{I_{ref}}{I_{inc}} = \left| \frac{\eta - 1}{\eta + 1} \right|^2$$

Complex refractive index $\eta(\omega) = [\varepsilon(\omega)]^{1/2} = n + i\,k$

$$e(w) = e_{¥} + i\; s(w) \,/\, e_0\, w$$

$\varepsilon(\omega)$ = dielectric function

$\sigma(\omega)$ = optical conductivity

Sum rule and transfer of spectral weight

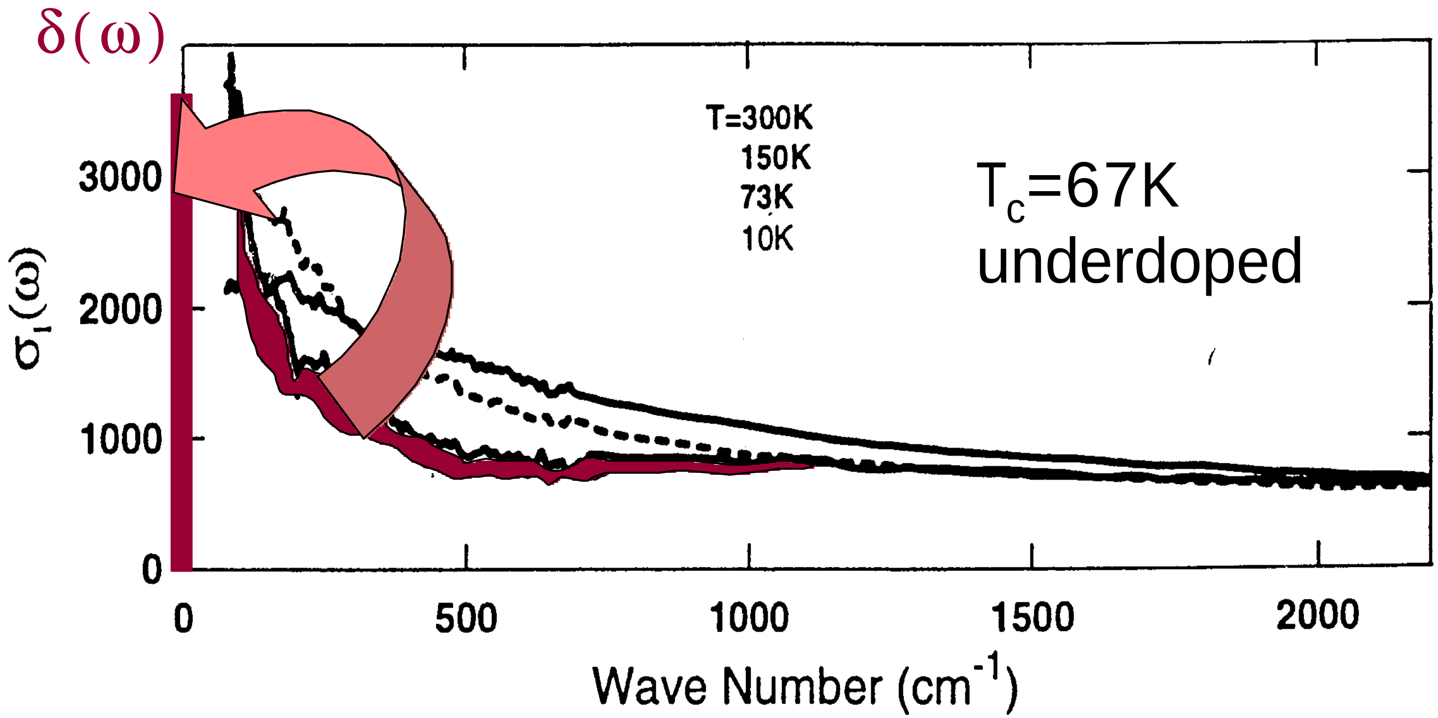
Conservation of the total spectral weight
under the real part $\sigma_1(\omega)$ of the optical conductivity
$\Leftrightarrow$ charge conservation

$$\int_0^{\infty} \sigma_1(\omega, T) d\omega = \frac{\pi}{2} \frac{ne^2}{m}$$

$$W(\omega_M, T) = \int_{0^+}^{\omega_M} \sigma_1(\omega, T) d\omega$$

Monitoring the transfer of spectral weight
as a function of temperature

Transfer of spectral weight into the δ function at T <Tc

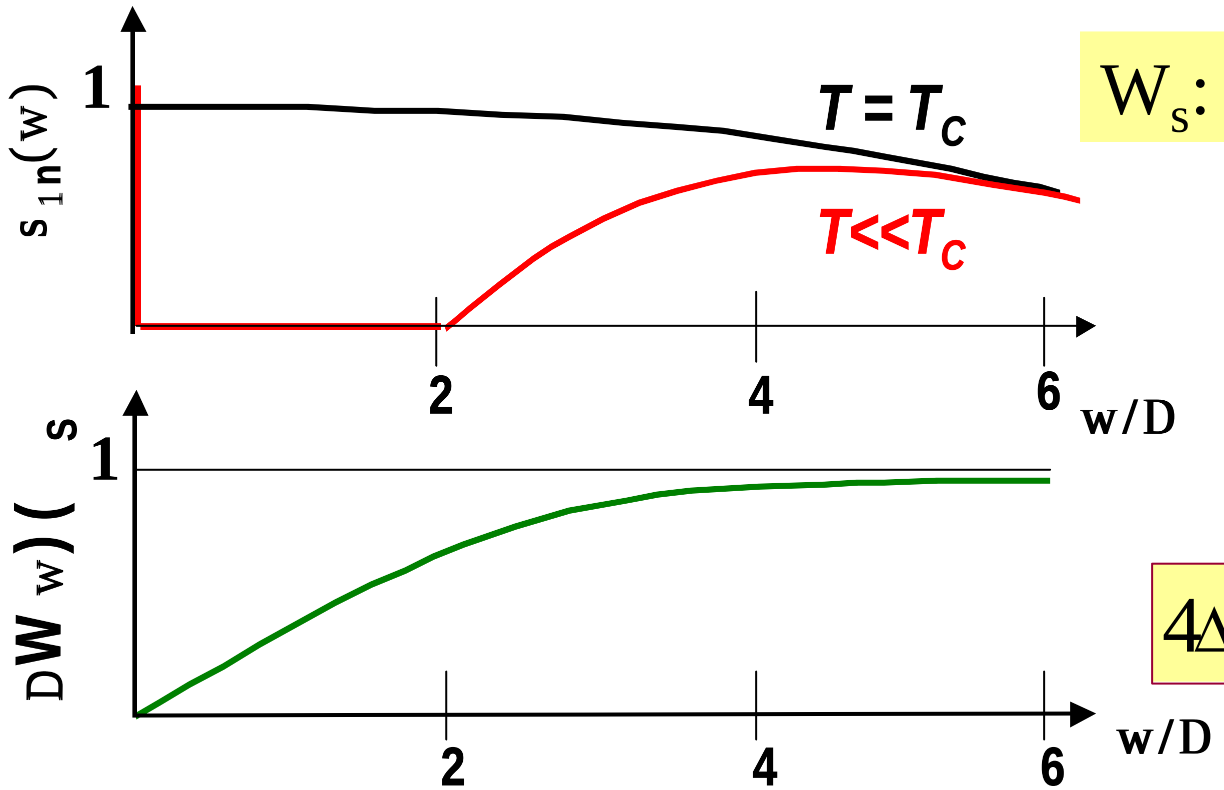


Bi-2212 single crystal

A.V. Puchkov et al, J. Phys. Condens. Matter 8, 10049 (1996)

Ferrell-Glover-Tinkham (FGT) sum rule

$$\Delta W = W(\omega, T \geq T_c) - W(\omega, T << T_c)$$

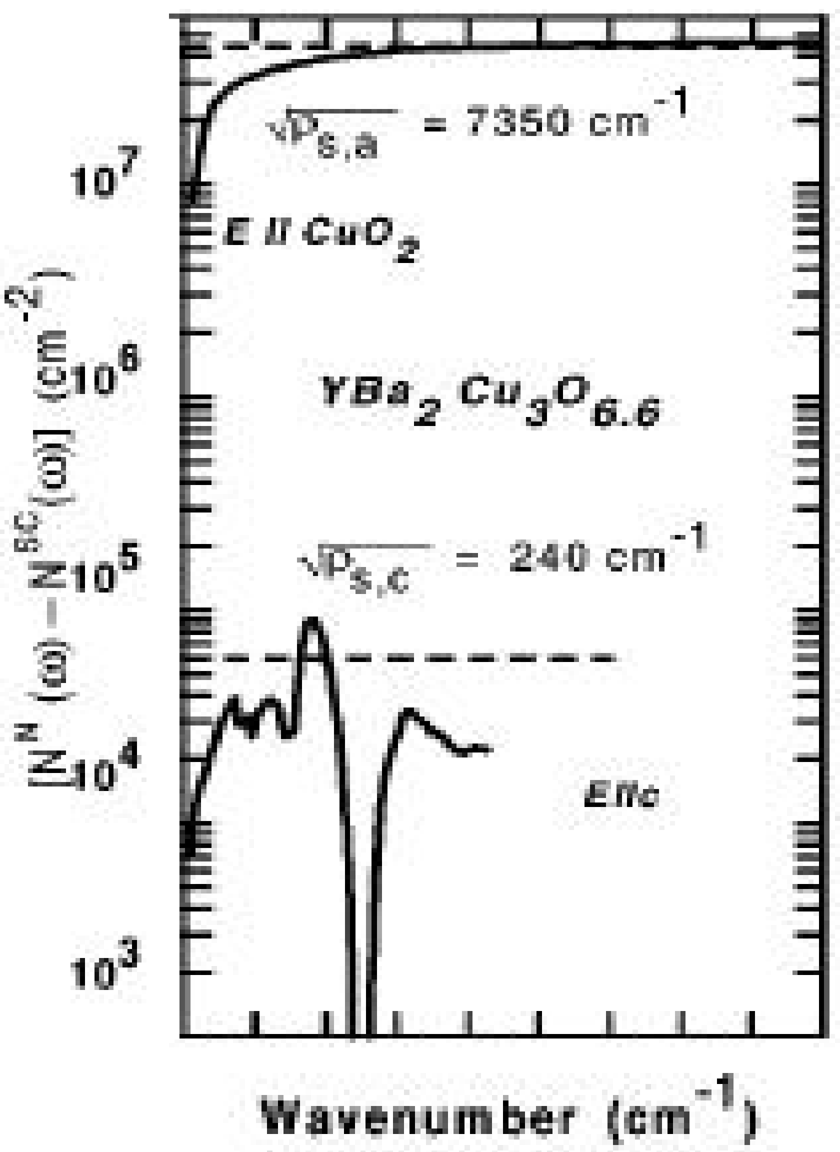


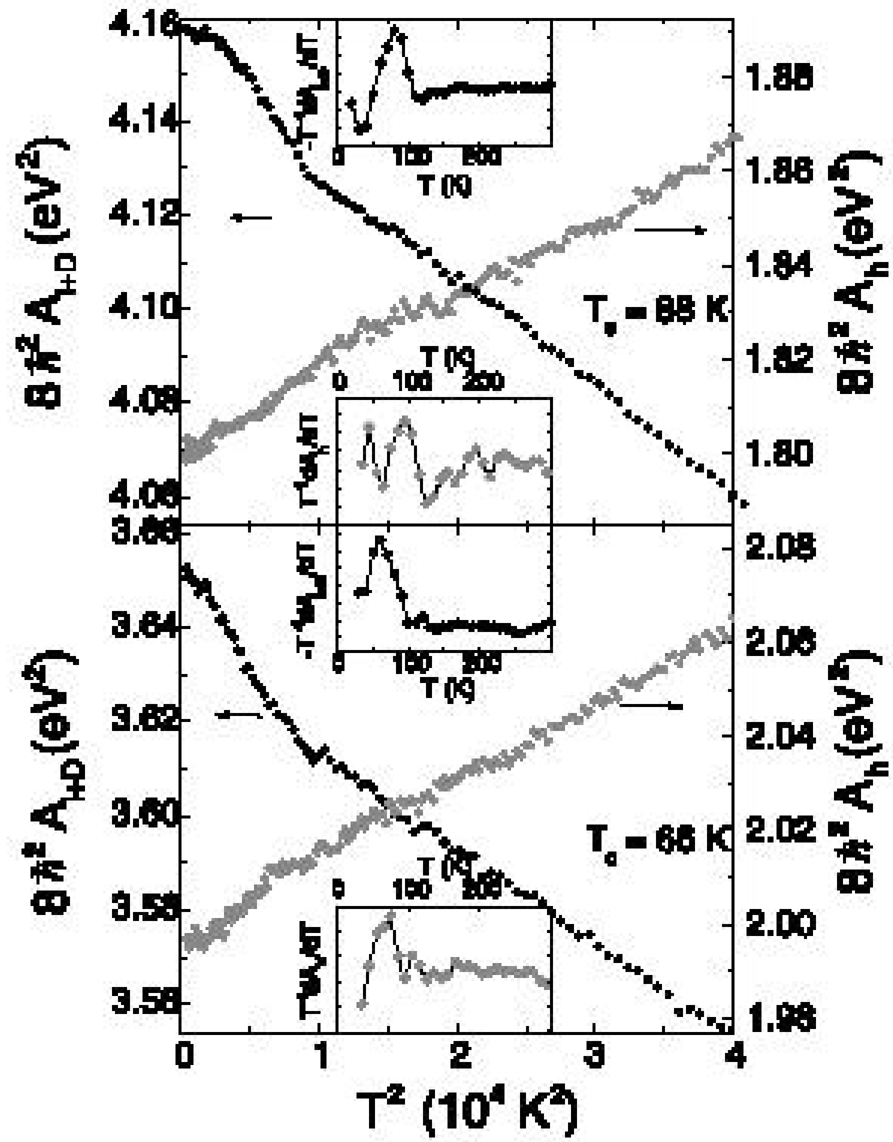
W_s: superfluid weight

cuprates

$$4\Delta_M \approx 0.1\text{eV} = 800\text{cm}^{-1}$$

W/W$_s$ goes to 1 at w/D~4-6





D.N.Basov et al, PRB 63, 134514 ('01) H.J.A.Molegraaf, Science 295, 2239 ('02)

1) $Bi_2Sr_2CaCu_2O_{8+\delta}$ samples

thin films

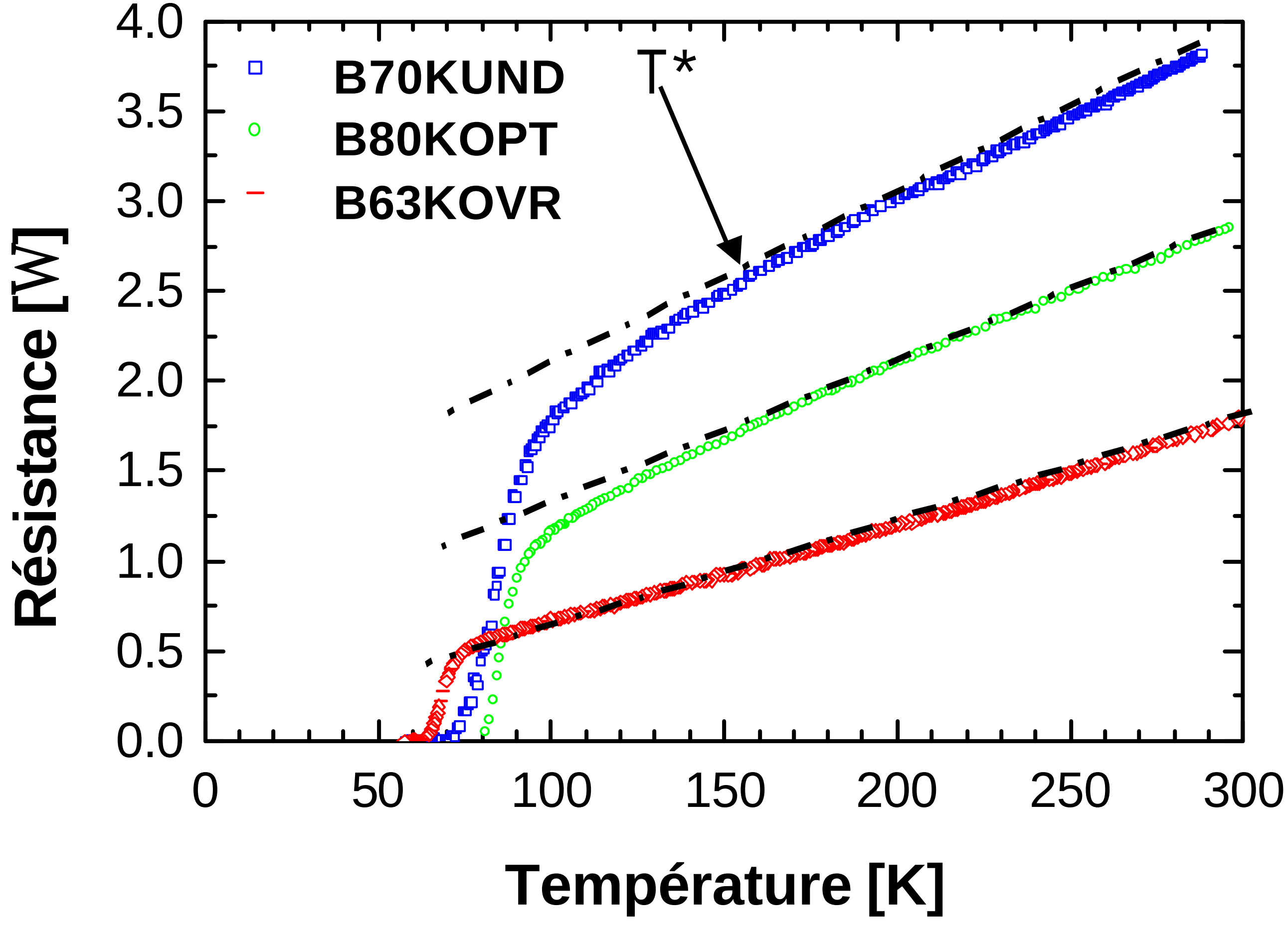
✓RF magnetron sputtering onto $SrTiO_3$

✓Reversible change of doping only by oxygen annealing

✓Thickness 2000-4000 Å

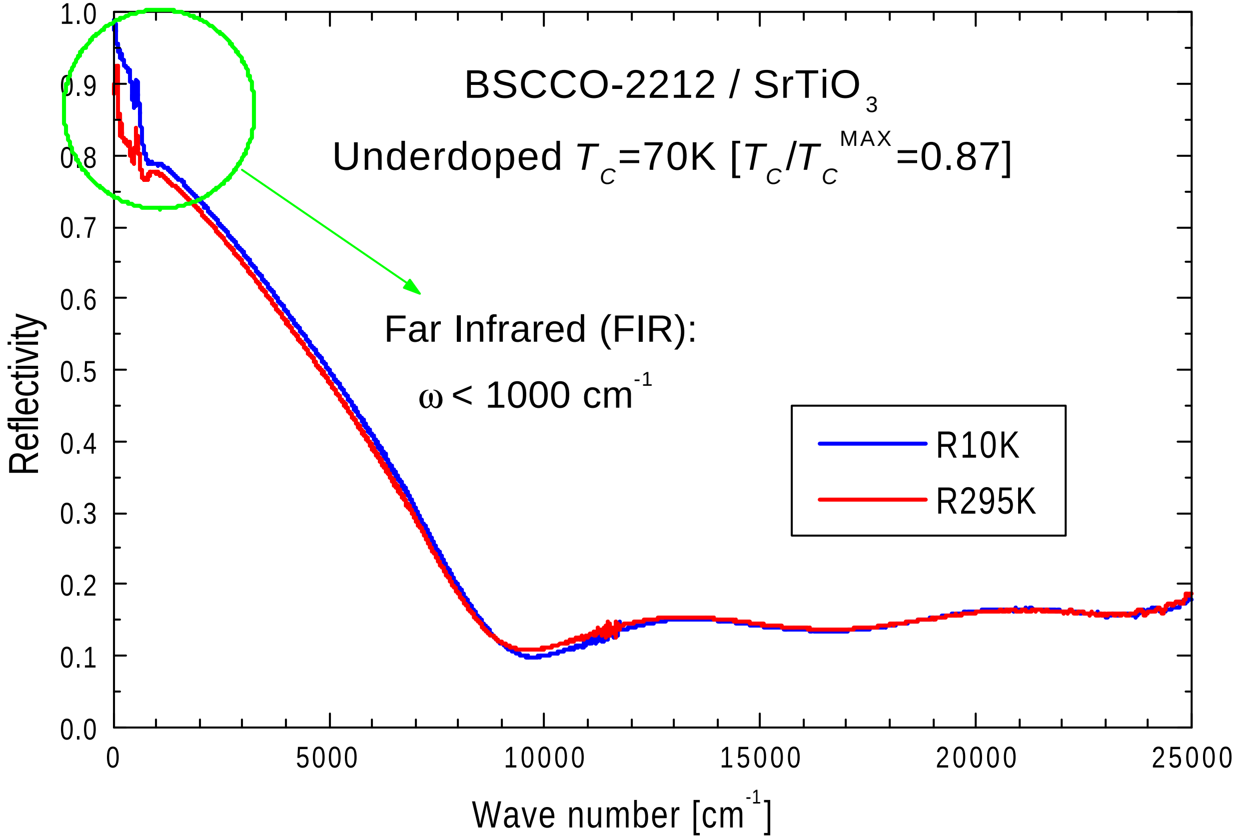
✓*Large area samples for optics: change in reflectivity < 0.2%*

Resistance of the $Bi_2Sr_2CaCu_2O_{8+\delta}$ samples

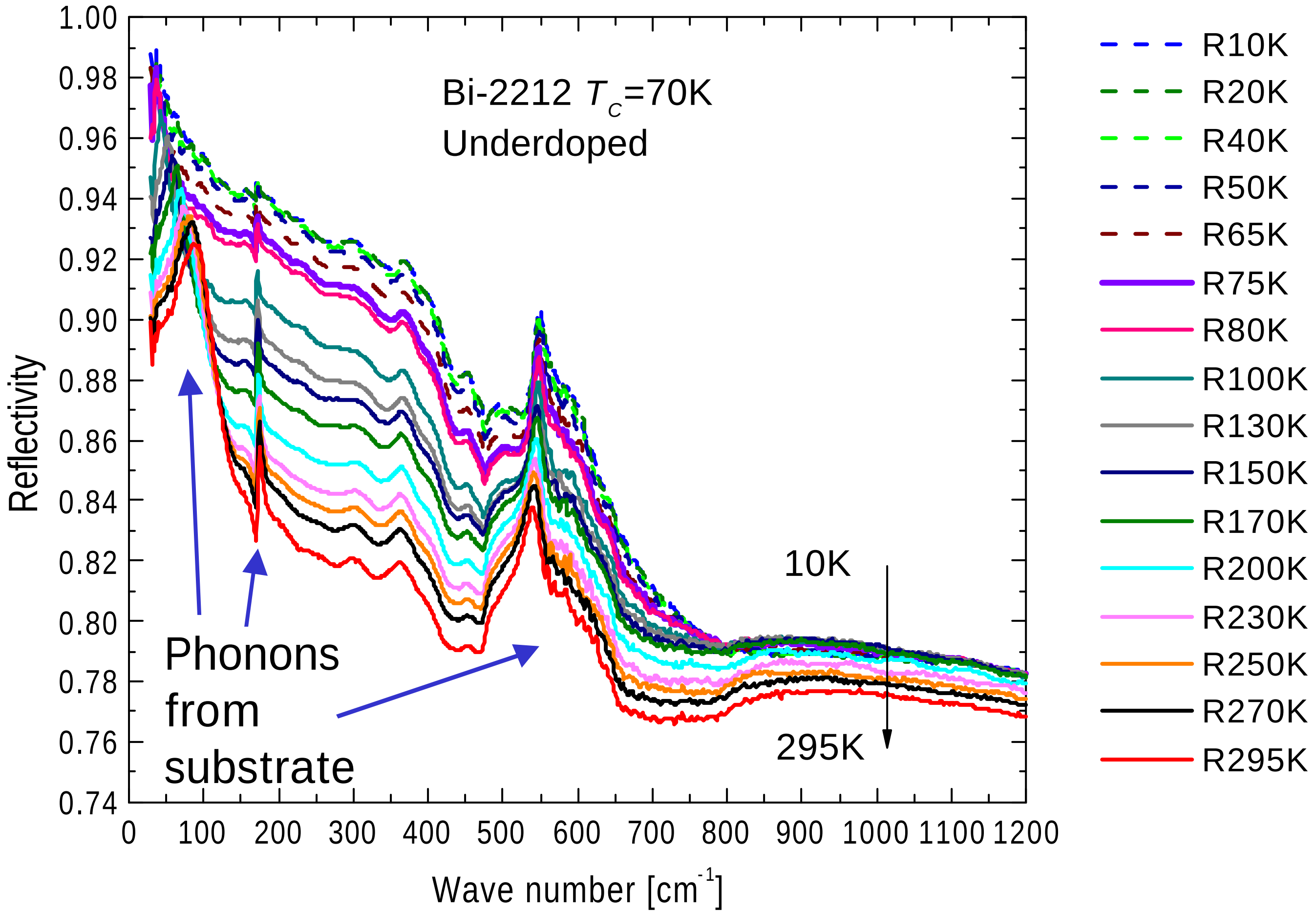


2) Reflectivity and conductivity

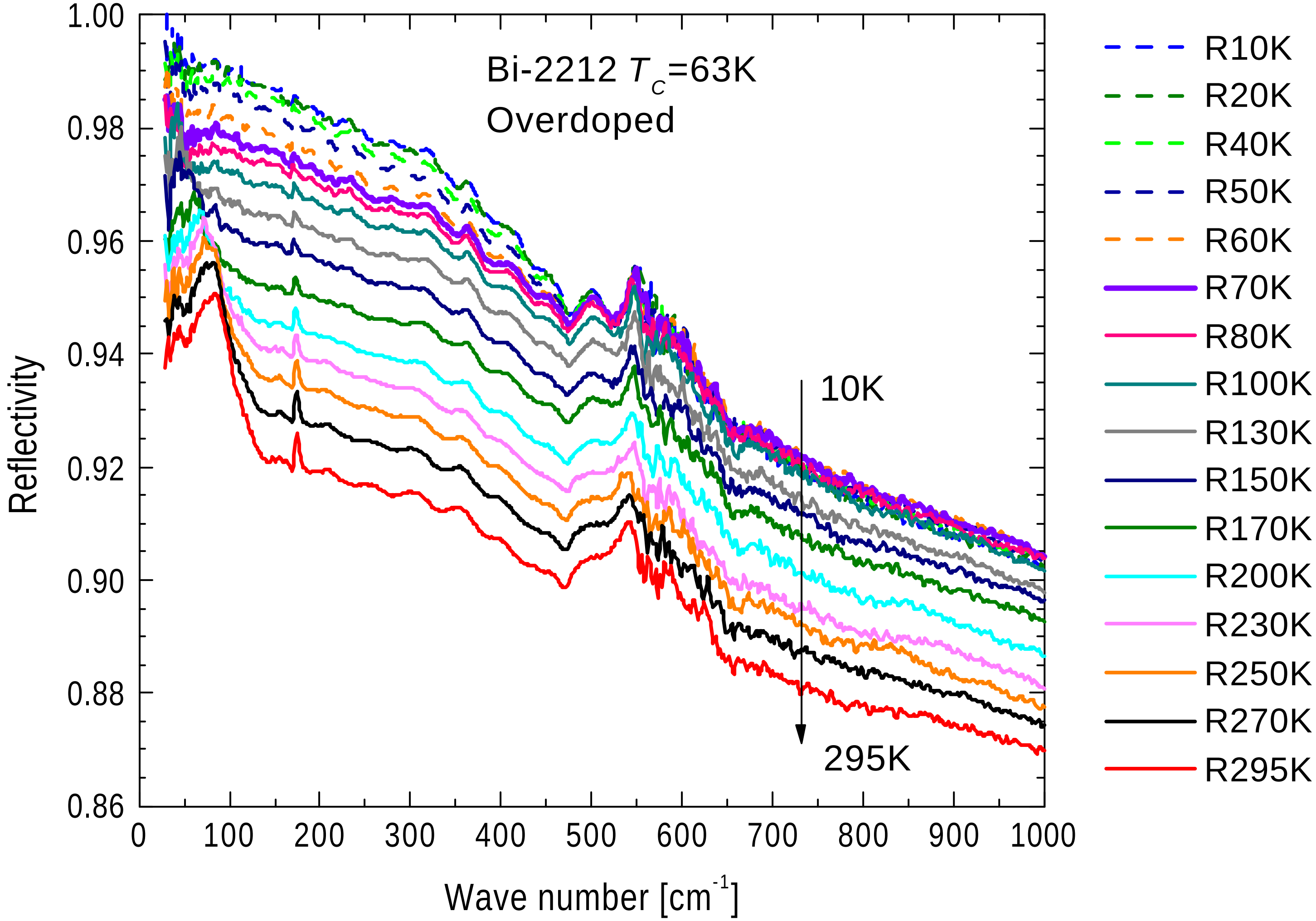
Reflectivity 30-25000 cm^{-1}



Far infrared reflectivity spectrum



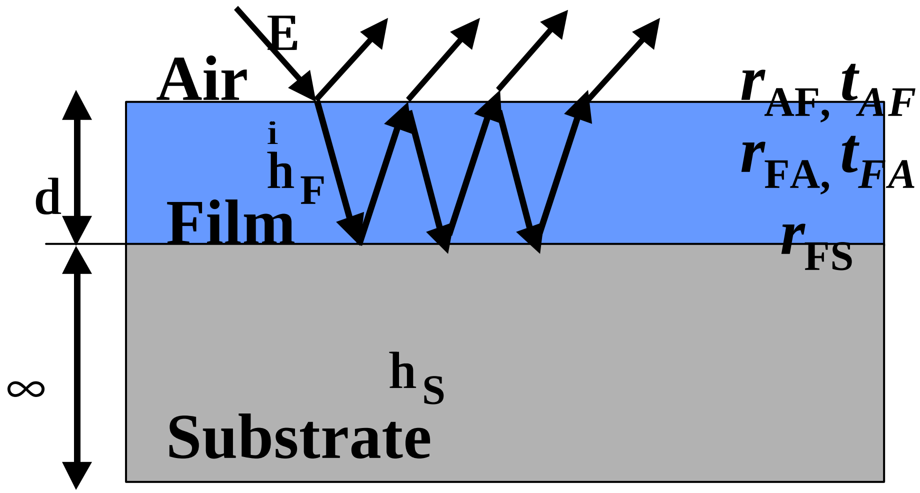
$8000\ cm^{-1} = 1\ eV$



Bi-2212 T_c=63K
Overdoped
10K
295K
Reflectivity
Wave number [cm^{-1}]
1.00
0.98
0.96
0.94
0.92
0.90
0.88
0.86
0
100
200
300
400
500
600
700
800
900
1000
R10K
R20K
R40K
R50K
R60K
R70K
R80K
R100K
R130K
R150K
R170K
R200K
R230K
R250K
R270K
R295K

8000 cm^{-1} = 1 eV

Reflectivity of a thin film on a substrate



$e_{SrTiO3}(\omega,T)$ (known at each T)

$e_{Bi}(\omega,T)$ dielectric function warranting causality

$$\rho = r_{AF} + \frac{t_{AF} t_{FA} r_{FS} r_{FA} A_F}{r_{FA}(1 - r_{FS} r_{FA} A_F)}$$

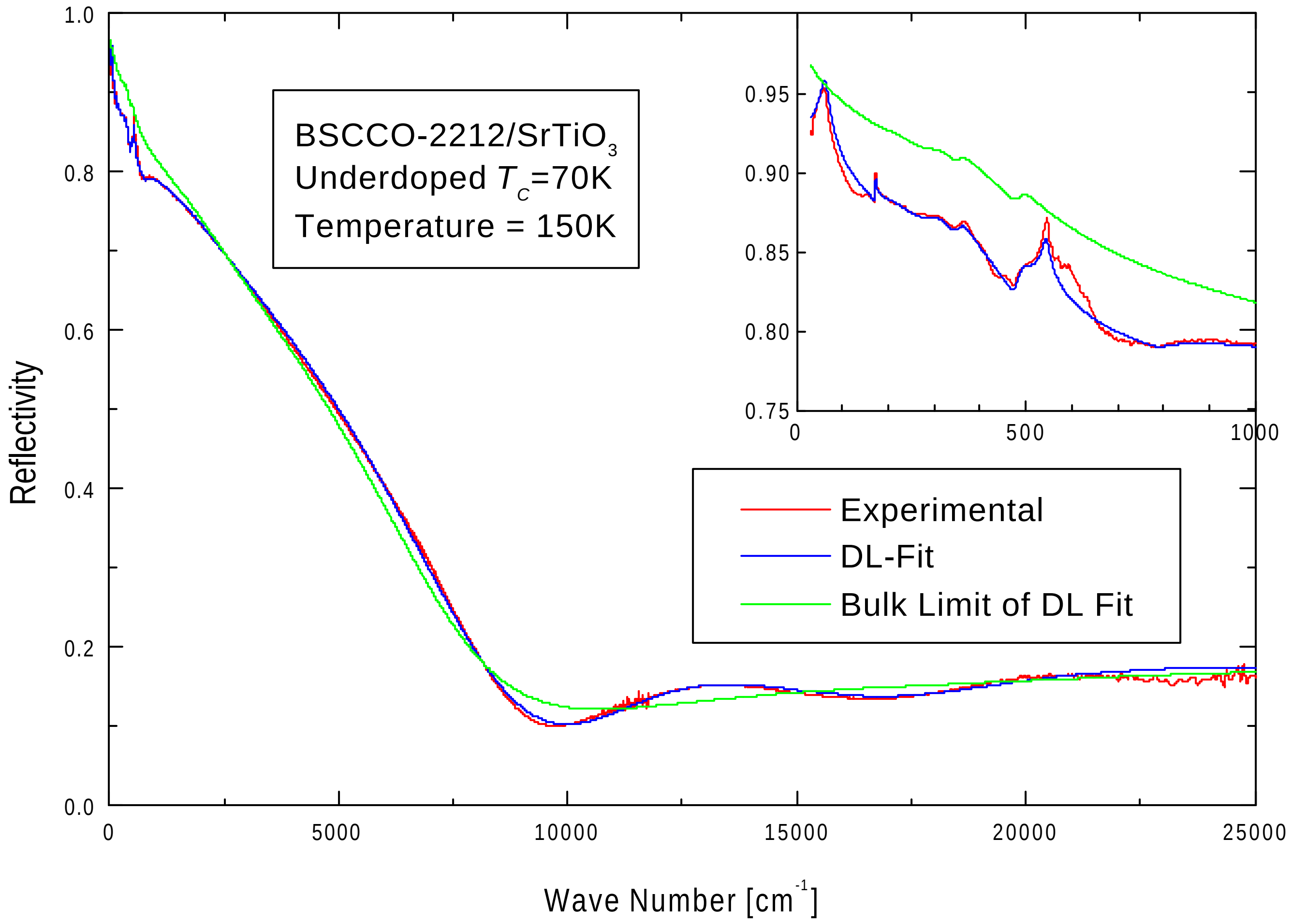
$$\tilde{\varepsilon}_{Bi}(\omega) \Rightarrow \tilde{\sigma}_{Bi}(\omega)$$

$$\Downarrow$$

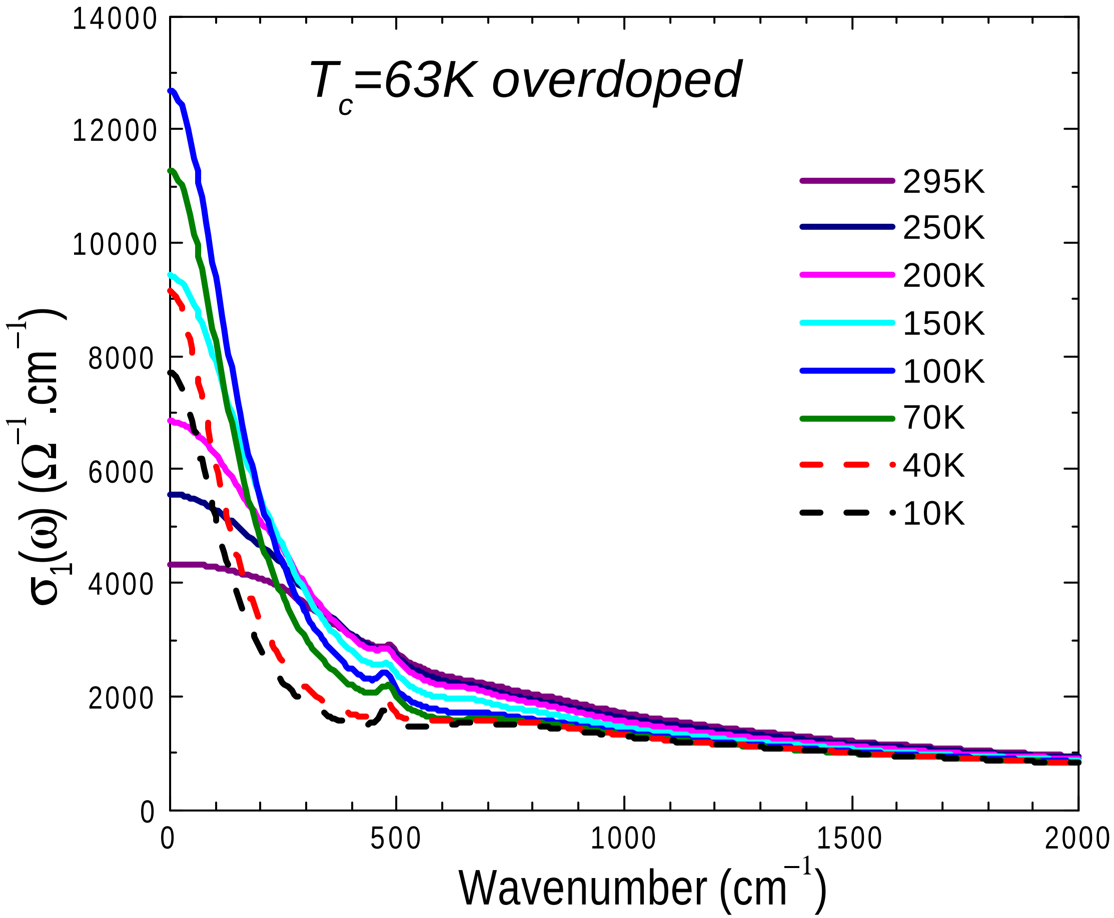
$$\sigma_1(\omega, T)$$

$$R = |\rho|^2$$

Example of a fit



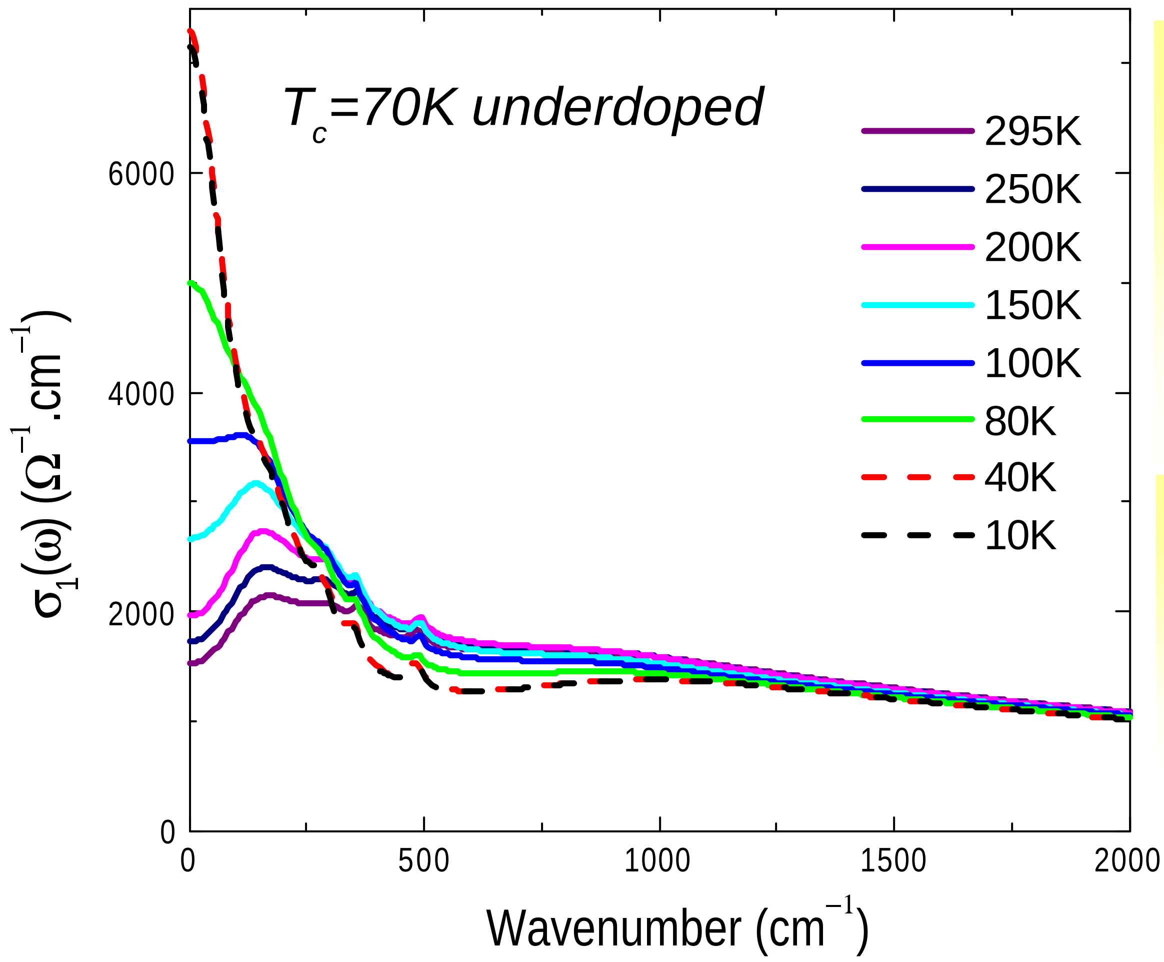
Real part of the optical conductivity – 0VR sample



✓ Transfer of spectral weight at $T>T_c$ from ~300-1500 cm^{-1}, to low frequency

✓Clear loss of spectral weight in the **SC state**

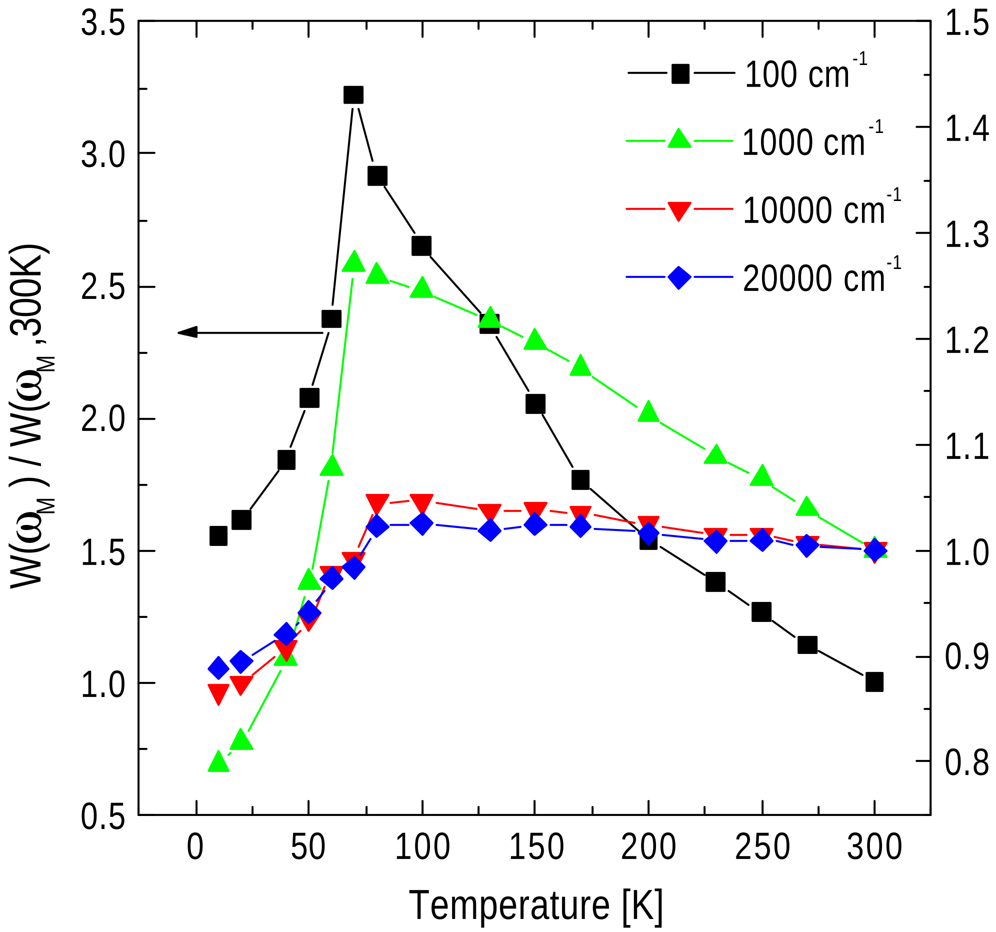
Real part of the optical conductivity – UND sample



✓ As T ↘, narrowing of the low frequency conductivity peak, even ***in the SC state***

✓ No clear loss of spectral weight in the **SC state**

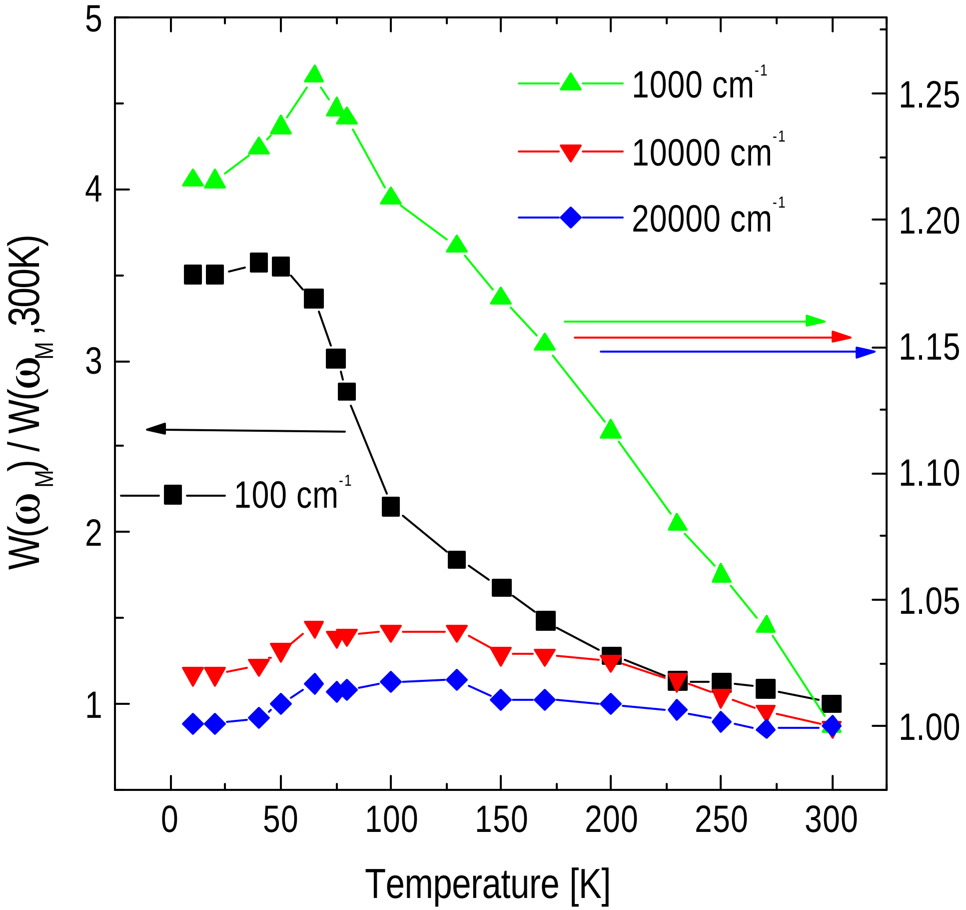
$W_n(\omega,T) = W(\omega_M,T) / W(\omega_M,300K)$ - OVR sample



Spectral weight is continuously collected towards low energies as T ↘

Note the large spectral weight lost (® superfluid)

$W_n(\omega,T) = W(\omega_M,T) / W(\omega_M,300K)$ - UND sample



Spectral weight is continuously collected towards low energies as T ↘

Note the loss of spectral weight only above 1000 cm^{-1}

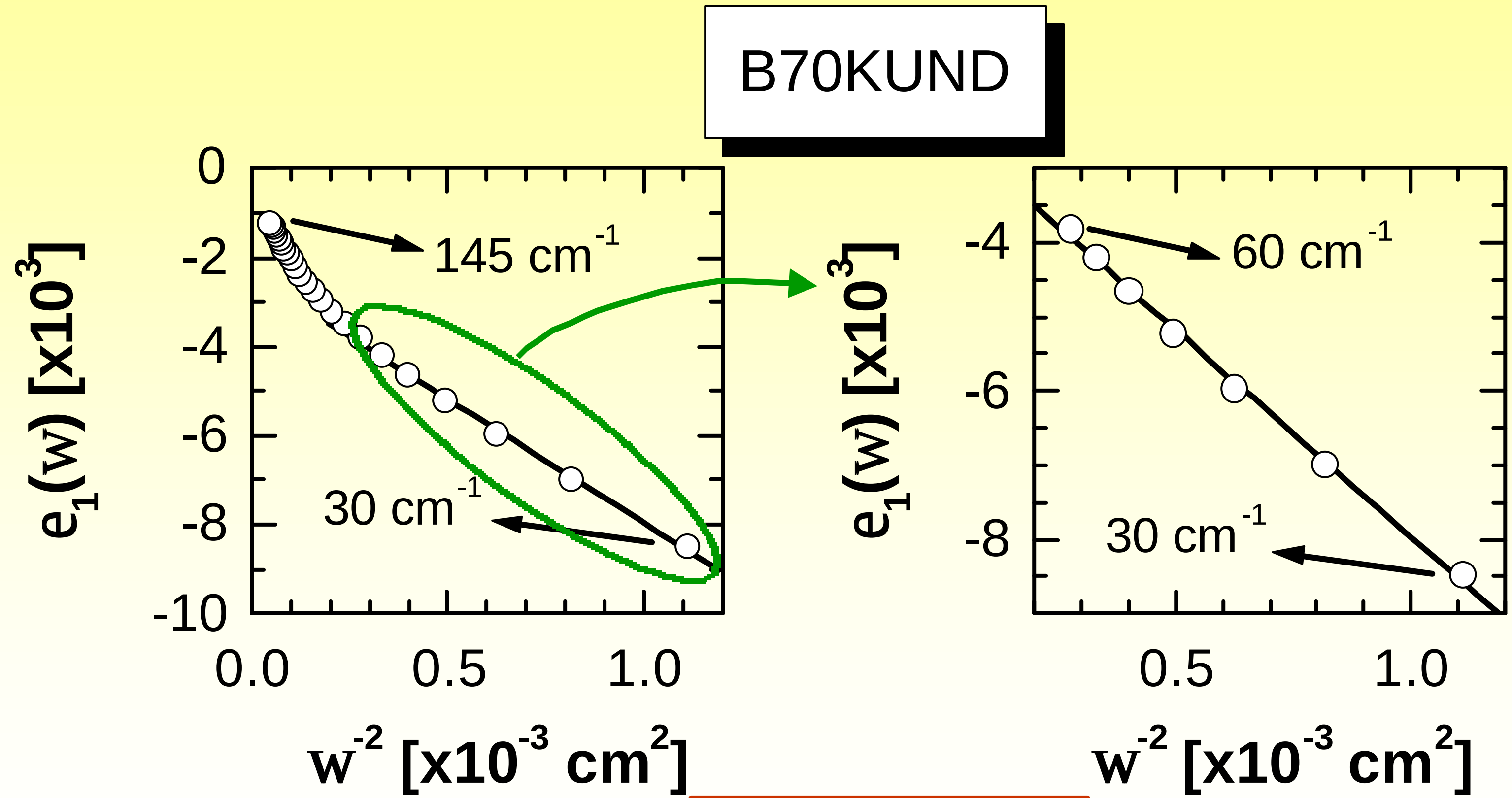
A. F. Santander-Syro et al., PRL 88, 097005 (2002))

Experimental determination of the superfluid density

$$\varepsilon_s(\omega) = \left[\varepsilon_\infty - \frac{\Omega_s^2}{\omega^2}\right] + i\frac{\pi}{4}\frac{\Omega_s^2}{\omega}\delta(\omega)$$

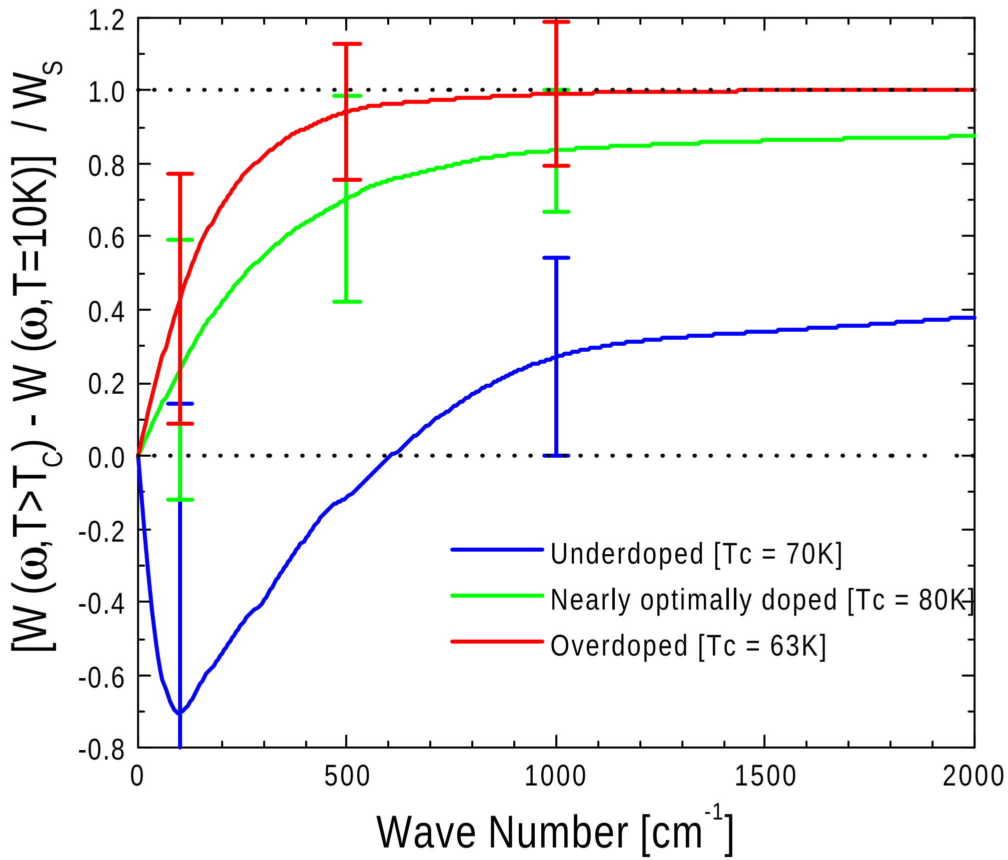
$$\rho_s \equiv \Omega_s^2$$

London approximation



$\lambda_L^{ab} \approx 7115$ Å

In-plane sum rule at various doping levels (low-energy behavior)

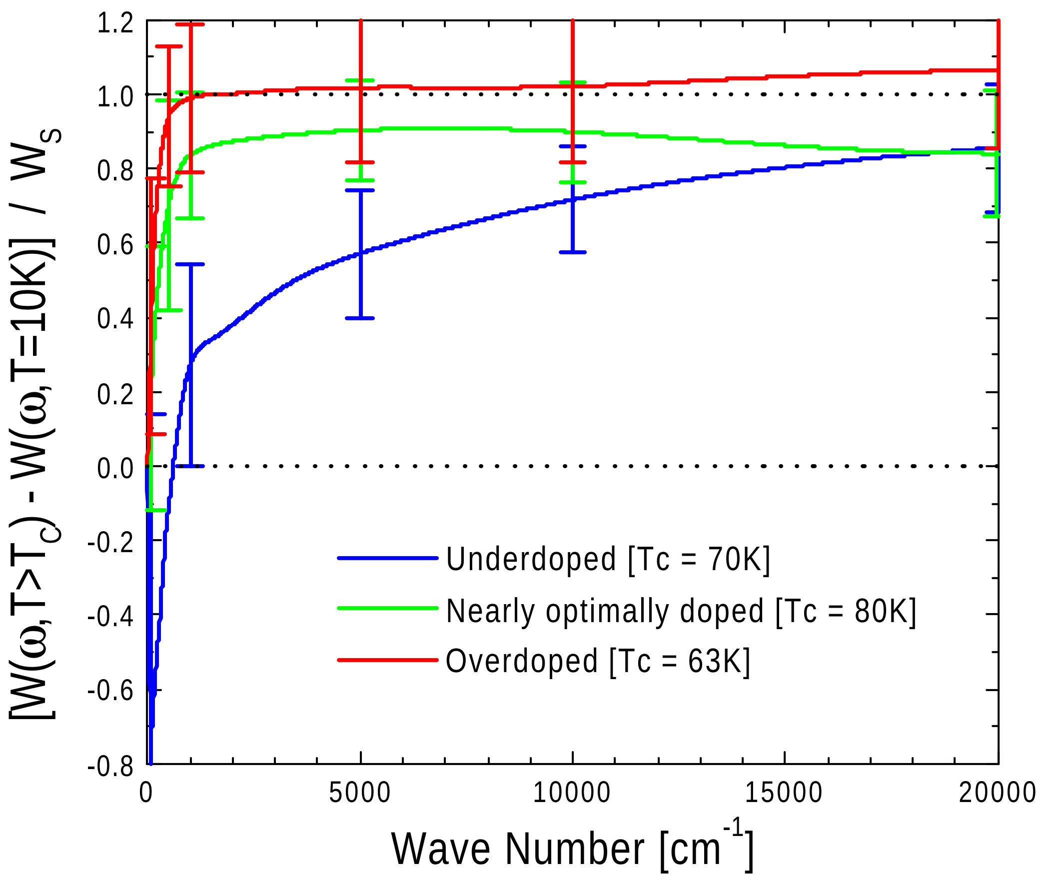


OVR, OPT samples: within the error bars, the FGT sum rule is exhausted at a conventional energy i.e. 1000 cm^{-1}

UND sample

Violation of the FGT sum rule

In-plane sum rule at various doping levels (high-energy behavior)



UD sample: sum rule exhausted at ~2 eV

"color changes" when becoming SC

3) Interpretations ?

Change of kinetic energy ?

$$E^{N}_{kin} - E^{S}_{kin} \propto \int_{\omega_B}^{\infty} [\sigma_{NS}(\omega, T_0 < T_c) - \sigma_S(\omega, T_0 < T_c)]\, d\omega$$

D. J. Hirsch, Physica C 199, 305-310 (1992) and van der Marel. "Strong correlation in the high-T_C era ". Trieste, 17-28 July 2000.

$$\frac{\Delta_{NS} W(1eV)}{W_S} = 1 - \frac{1}{W_S} \frac{\pi e^2}{2\hbar^2} \frac{a^2}{V} [E^{N}_{kin} - E^{S}_{kin}] \quad \text{SI units}$$

For our under-doped Bi-2212:

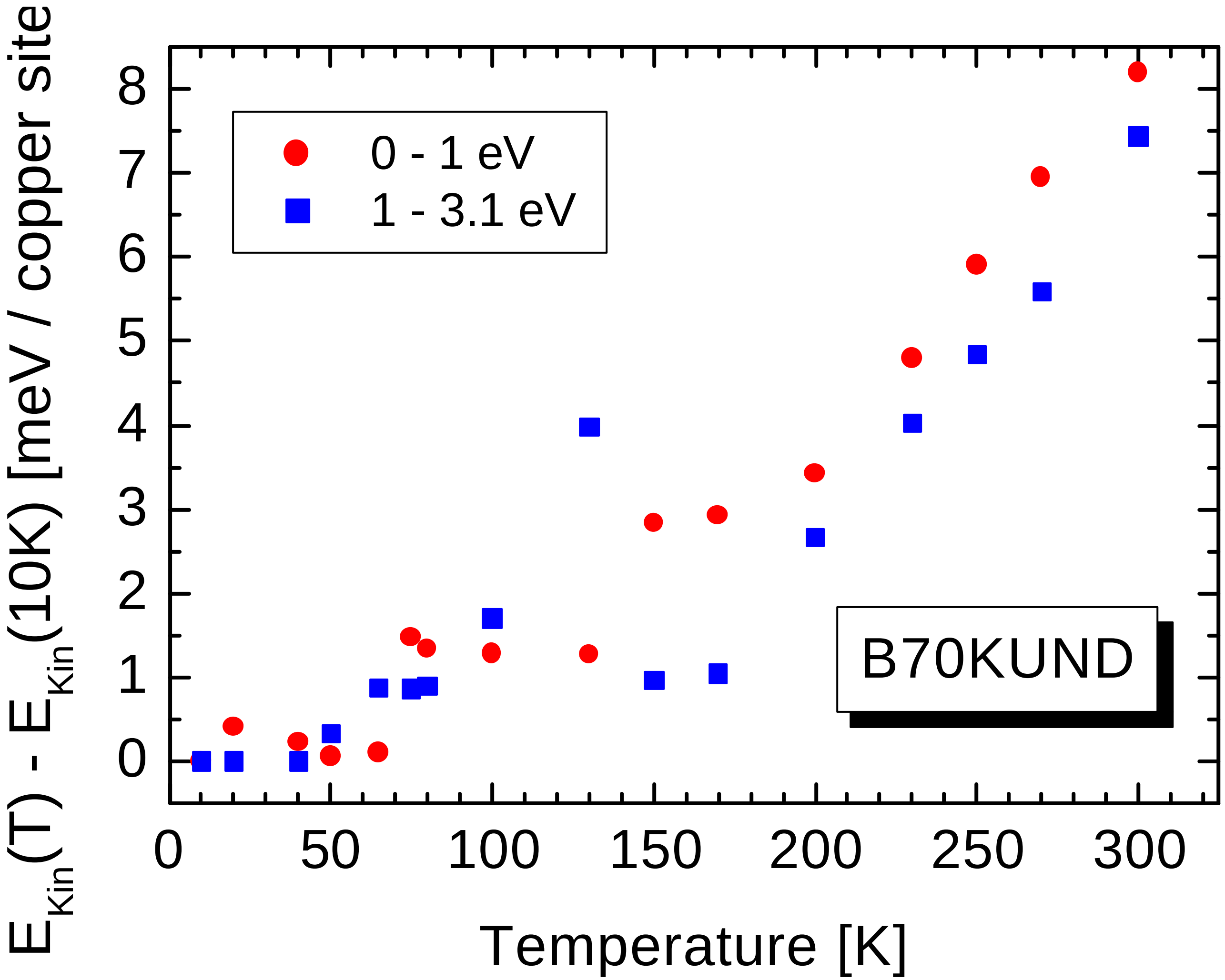
$$\frac{\Delta_{NS} W}{W_S} \approx 0.65 \pm 0.18 \text{ at } 1\text{eV} \Rightarrow \quad \Delta E_{kin} \approx 1.1 \pm 0.3 \text{meV} \quad /\text{Cu}$$

Condensation energy: $U_o \sim 0.08$ meV for optimal T_c

J. W. Loram et al., Physica C ***341-348****, 831-834 (2000).*

Checking the self-consistency of the data: comparison of the changes of spectral weight in the IR (0 to w_B) and the VIS-UV (w_B to 3eV)

$$\frac{2\hbar^2}{\pi e^2}\frac{V}{a^2}\int_{\omega_B}^{\infty}\left[\sigma_1(\omega, T > T_c) - \sigma_1(\omega, 10K)\right] d\omega = \Delta E_k$$



$$E_K = \frac{2}{a^2 N} \sum_k \frac{\partial^2 \varepsilon}{\partial k_x^2} n_k$$

Change in mass tensor: « hole undressing »

J. Hirsch, Physica C 199, 305 (1992), PRB 62, 1487 (2000)

Change in n_k

NS: non Fermi liquid → SC state: Fermi liquid

P.W. Anderson

M.Norman, C. Pépin Condmat/02011415

In both models:

✓ the sum rule violation is larger as doping decreases

✓ ΔE_k ~1-2 meV > condensation energy

Conclusion

- The FGT sum rule is exhausted at ~ 2 eV for the underdoped sample, corresponding to a decrease of kinetic energy in the SC state

$$\Delta E_k \sim 1 \text{ meV}$$

- Pairing from high energy states