What are the indications for the pseudogap in the frequency and temperature dependence of the optical conductivity ?

D. van der Marel

Collaboration with
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[3]*Universiteit van Amsterdam*
[4]*University of Minnesota*

Optical Conductivity of c Axis Oriented $YBa_2Cu_{6.70}$: Evidence for a Pseudogap

C. C. Homes, T. Timusk, R. Liang, D. A. Bonn, and W. N. Hardy, PRL 71 (1993)

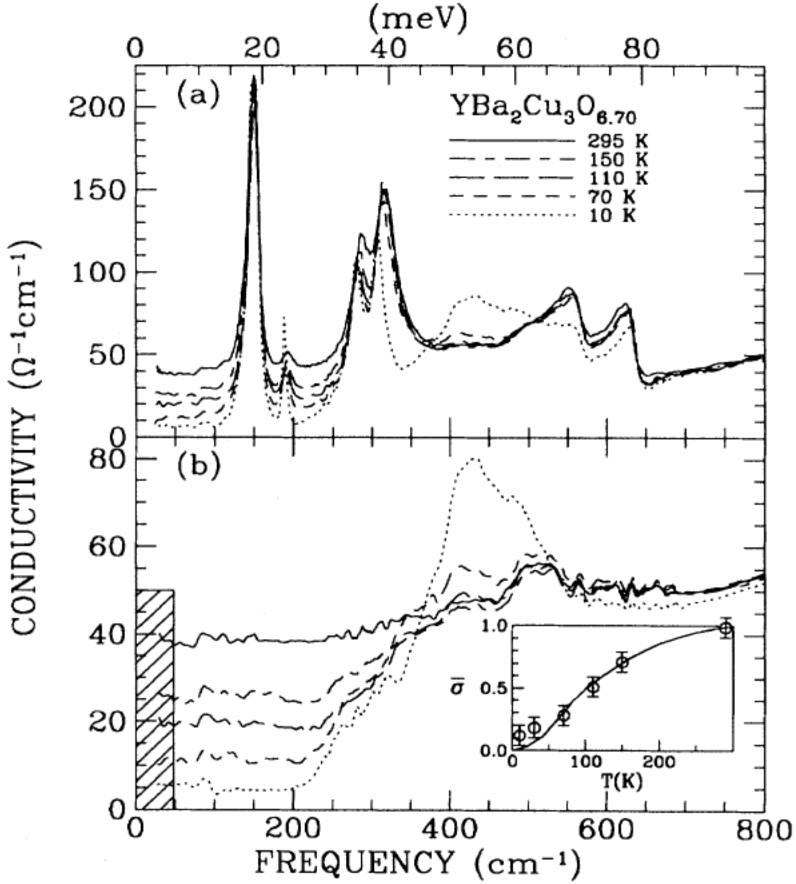
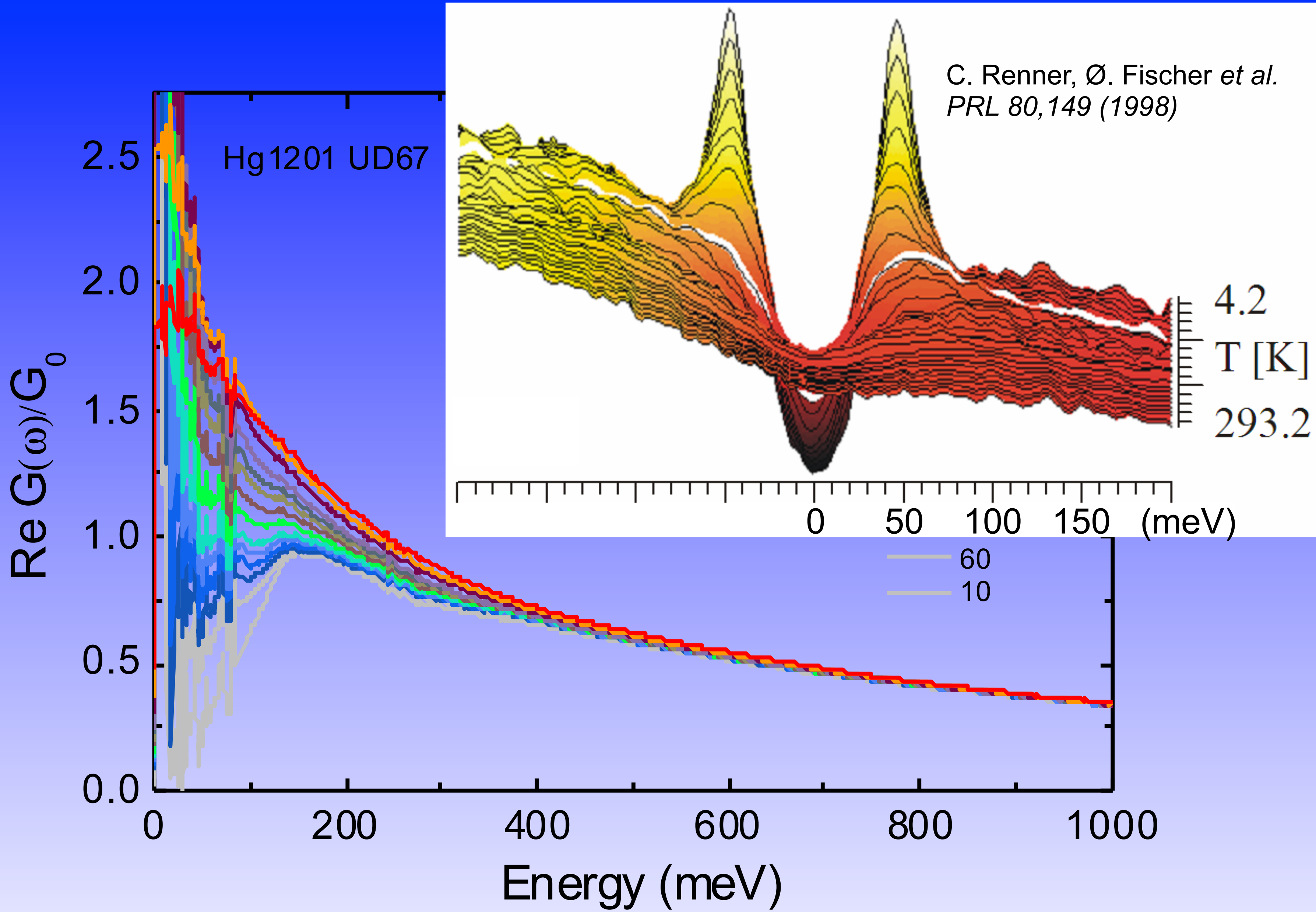
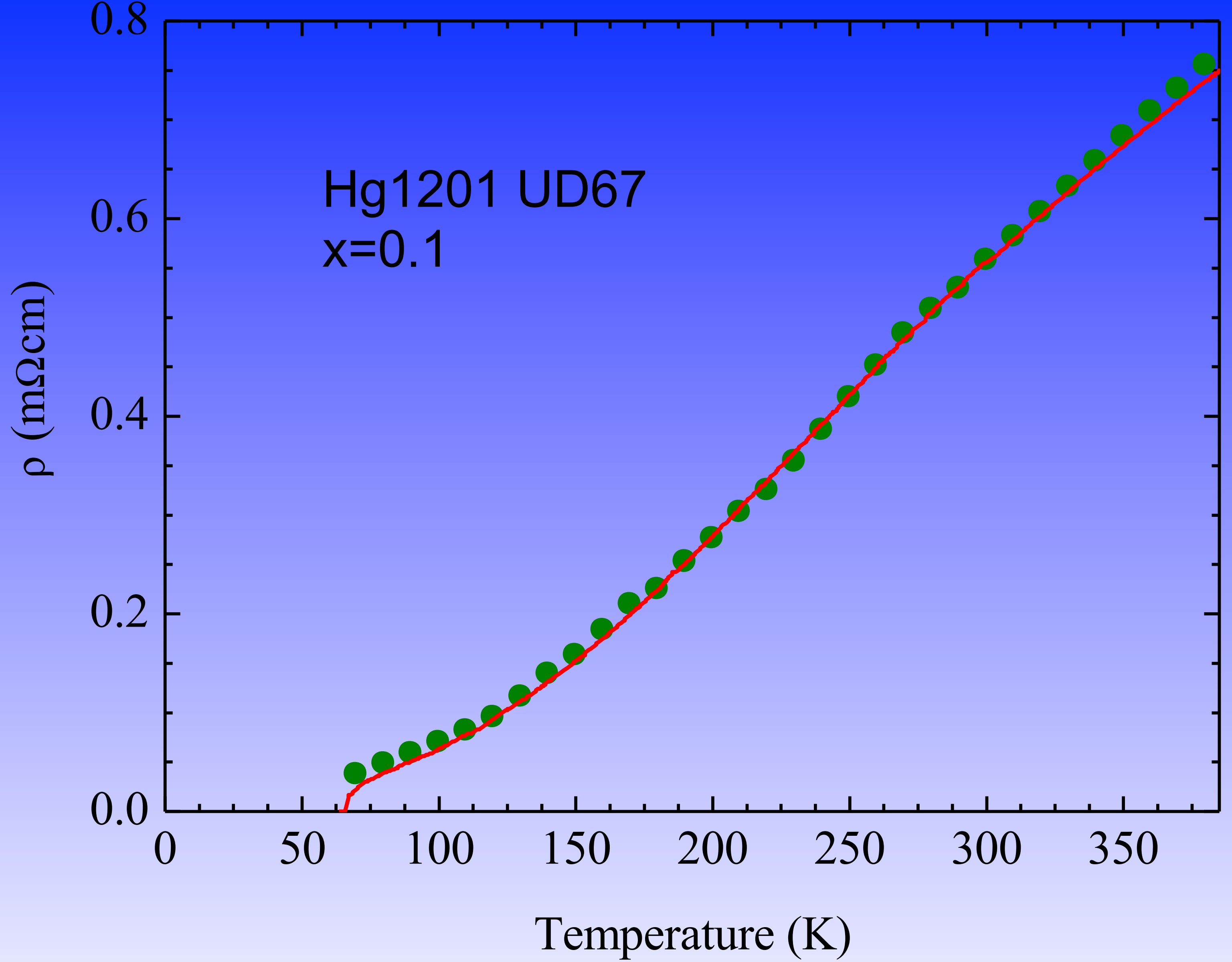


FIG. 2. The optical conductivity of $YBa_2Cu_3O_{6.70}$ along the c axis from $\approx$25 to 800 cm^{-1} obtained by a Kramers-Kronig analysis of the reflectance with (a) the phonons at 150, 192, 286, 317, 557, and 630 cm^{-1} present and (b) subtracted to yield the electronic background. Note that the formation of a pseudogap is clearly visible well above T_c (63 K). The shaded area represents the spectral weight of the



S.I. Mirzaei, D. Stricker *et al., PNAS 2013*



S.I. Mirzaei, D. Stricker *et al.*, *PNAS 2013*

Optical response of a classical charged fluid

$$\sigma(\omega) = \frac{ne^2 / m}{\tau^{-1} - i\omega}$$

Generalization to interacting electrons in cuprates

$$\frac{G(\omega, T)}{G_0} = \frac{\pi K}{\tau^{-1}(\omega) - i\omega m^*(\omega)}$$

← → K = Integrated spectral weight

W Götze & P Wölfle, PRB 6, 1226 (1972)
JW Allen & JC Mikkelsen, PRB 15, 2952 (1977)

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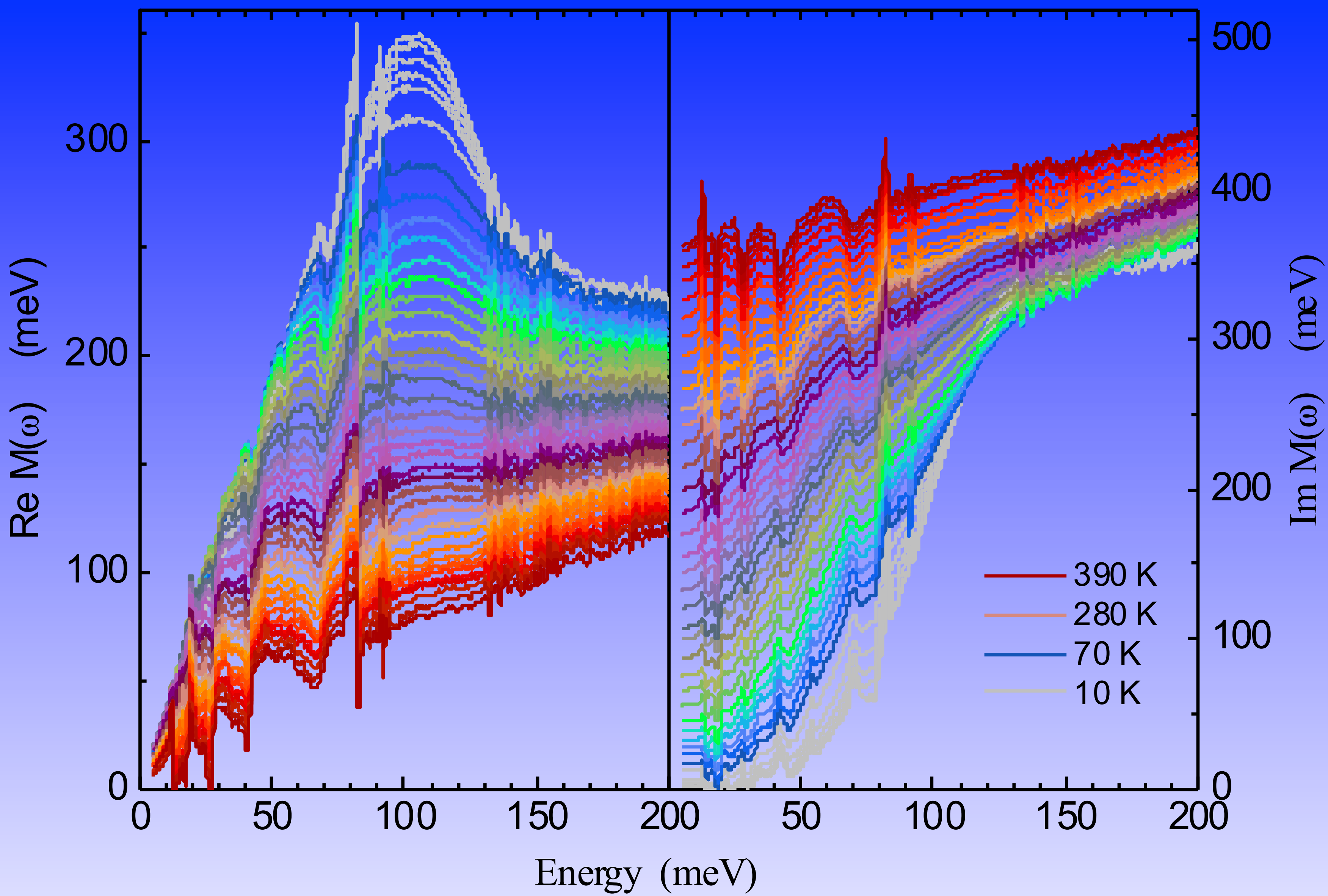
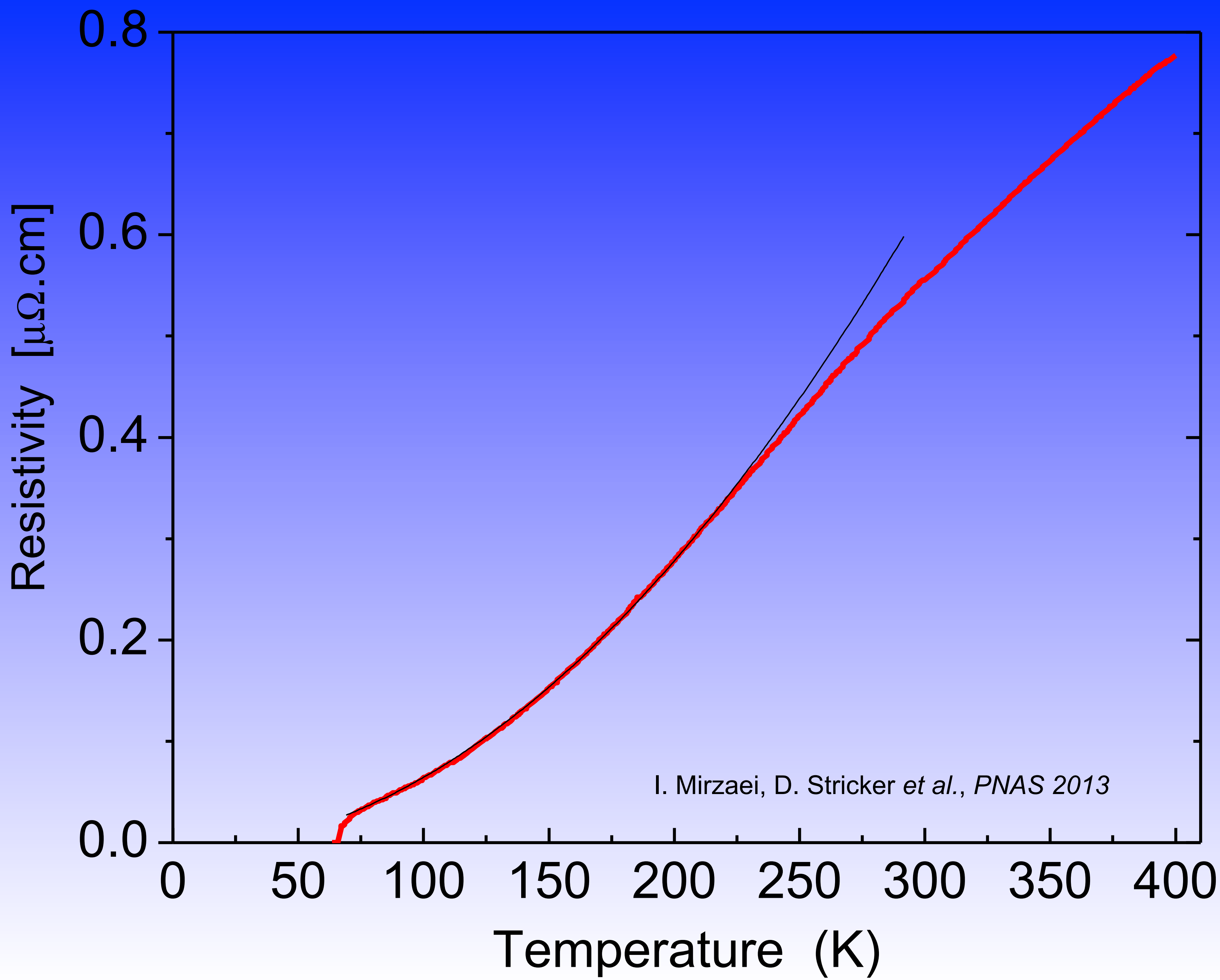
Straightforward inversion of the experimental data:

$$M_2(\omega) = \pi K \cdot \mathrm{Re}\frac{G_0}{G(\omega,T)}$$

W Götze & P Wölfle, PRB 6, 1226 (1972)
JW Allen & JC Mikkelsen, PRB 15, 2952 (1977)



Re M(ω) (meV)
Im M(ω) (meV)
Energy (meV)
390 K
280 K
70 K
10 K
0
100
200
300
400
500
0
50
100
150
200


0.8
0.6
0.4
0.2
0.0
Resistivity [μΩ.cm]
0
50
100
150
200
250
300
350
400
Temperature (K)
I. Mirzaei, D. Stricker *et al.*, *PNAS 2013*

Fermi liquid

Single particle life time: $\tau_{sp}(\varepsilon,T) \propto \left[\varepsilon^2 + \pi^2 \left(k_B T\right)^2\right]^{-1}$

Optical relaxation rate: $\begin{Bmatrix} 1/\tau_{opt}(\omega,T) \propto (\hbar\omega)^2 + (p\pi k_B T)^2 \\ p = 2 \end{Bmatrix}$

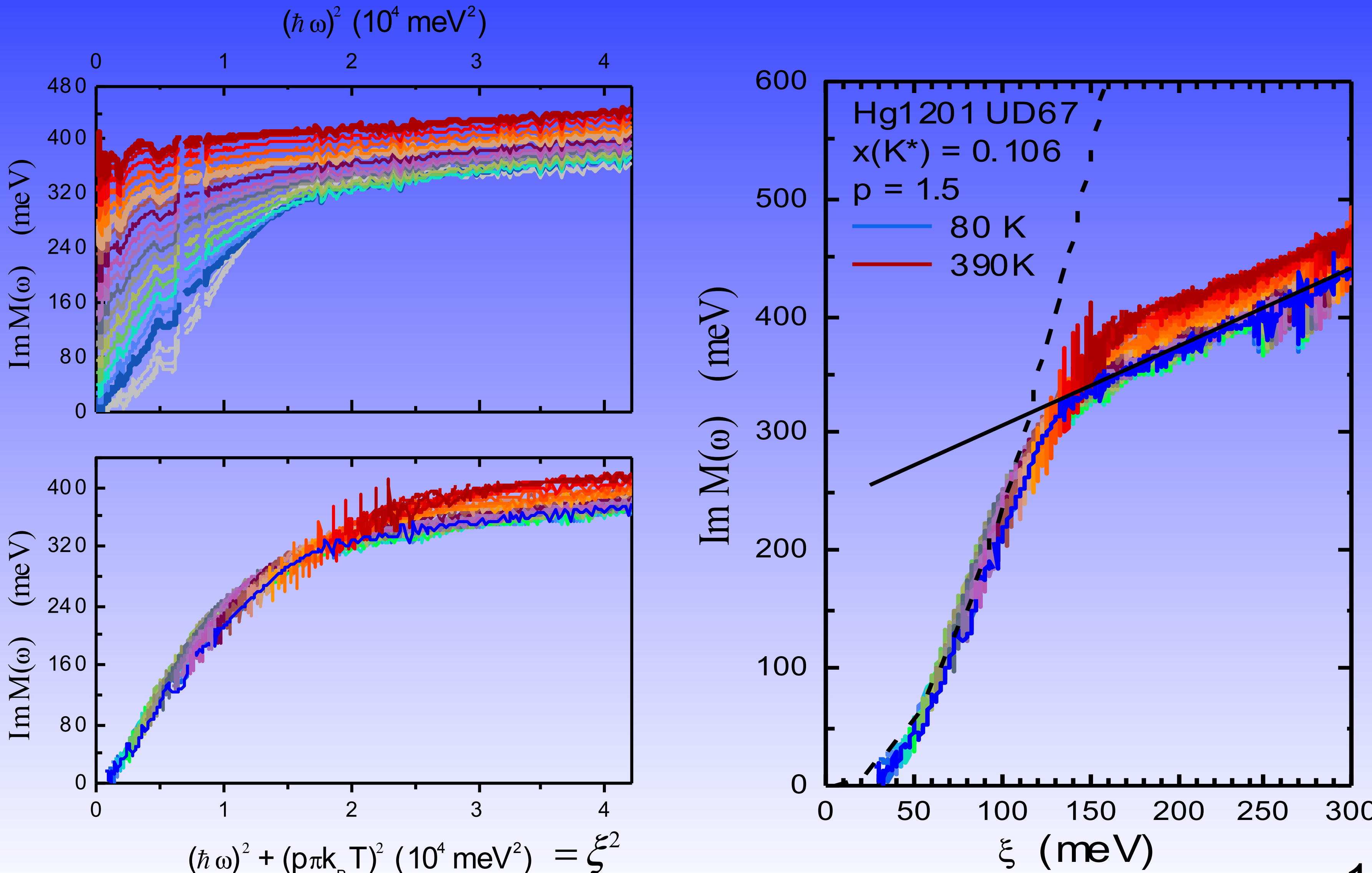
R. N. Gurzhi, Sov. Phys. JETP 35, 673 (1959)

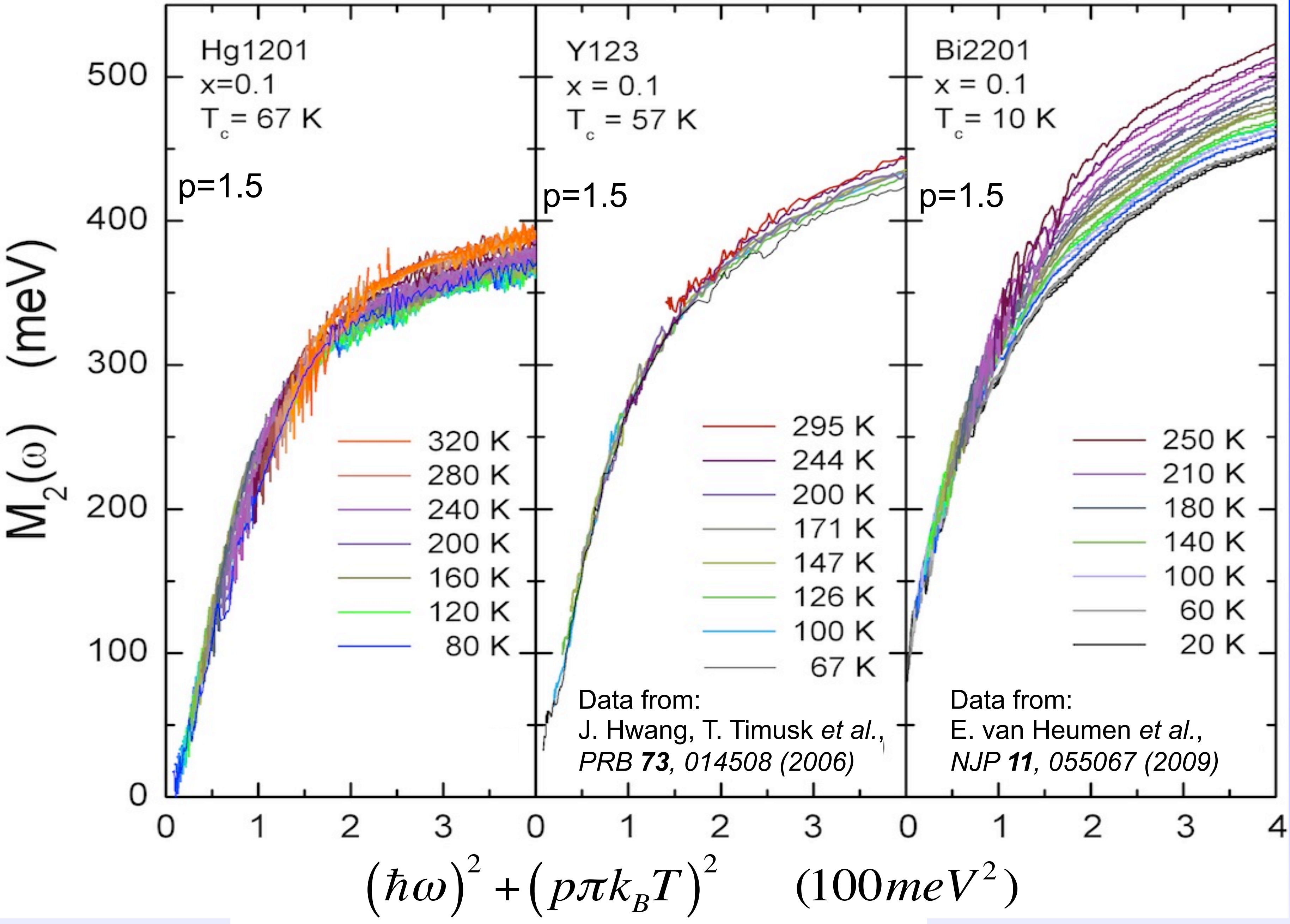
D. L. Maslov & A. V. Chubukov, PRB 86, 155137 (2012)

C. Berthod *et al*, PRB 87, 115109 (2013)

Fermi-liquid

Optical signature: scaling collapse





S.I. Mirzaei, D. Stricker *et al.*, *PNAS 2013*

Strong coupling theory

P.B. Allen
PRB 1971

$$\frac{G(\omega,T)}{G_0} = \frac{i\pi K}{\omega + M(\omega,T)}$$

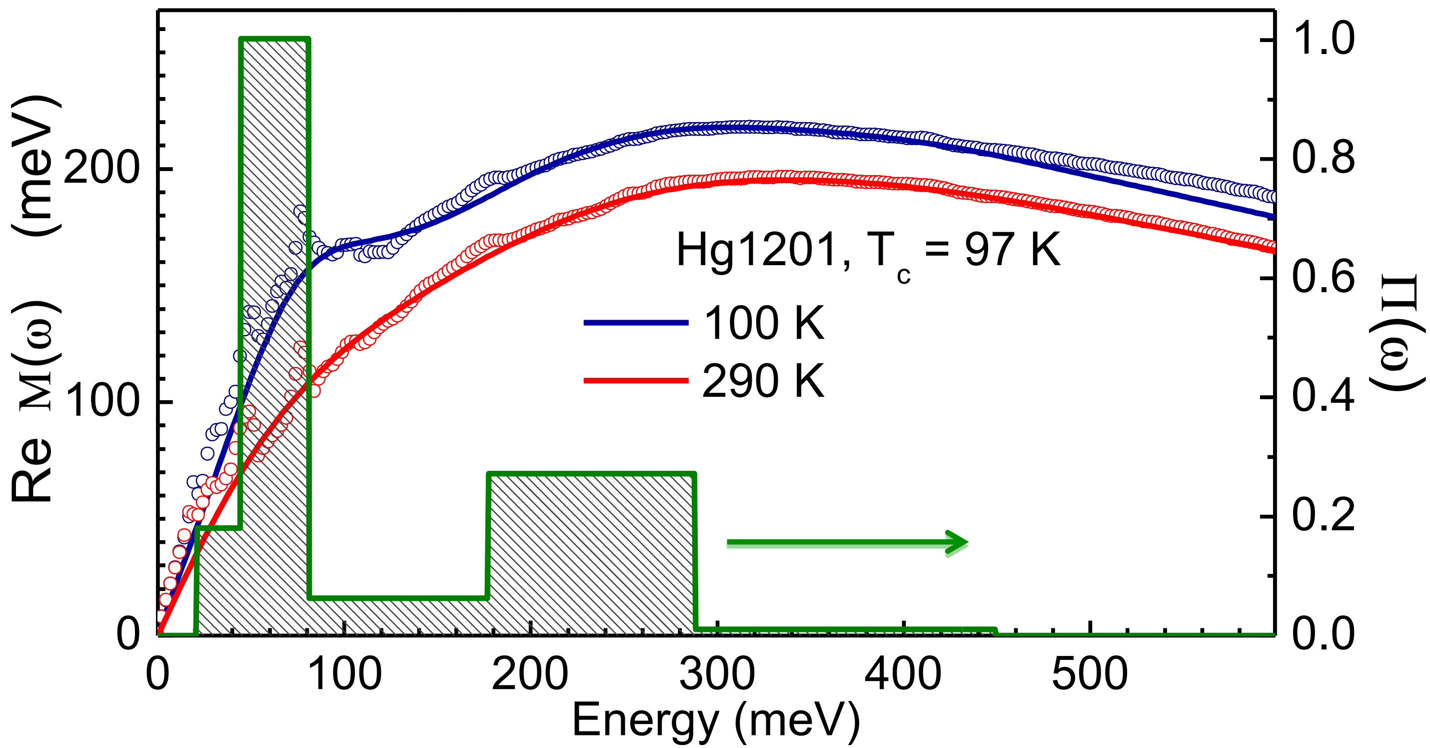
$$M(\omega,T) = \omega\left[\int_{-\infty}^{\infty} \frac{n_F(\omega+\varepsilon,T) - n_F(\varepsilon,T)}{\omega - \Sigma(\omega+\varepsilon,T) + \Sigma^*(\varepsilon,T)} d\varepsilon\right]^{-1} - \omega$$

$$\Sigma(\omega,T) = \int d\varepsilon \int d\omega' \tilde{\Pi}(\omega') \left[\frac{n_B(\omega') + n_F(\varepsilon)}{\omega - \varepsilon + \omega' + i\delta} + \frac{n_B(\omega') + 1 - n_F(\varepsilon)}{\omega - \varepsilon - \omega' - i\delta}\right]$$

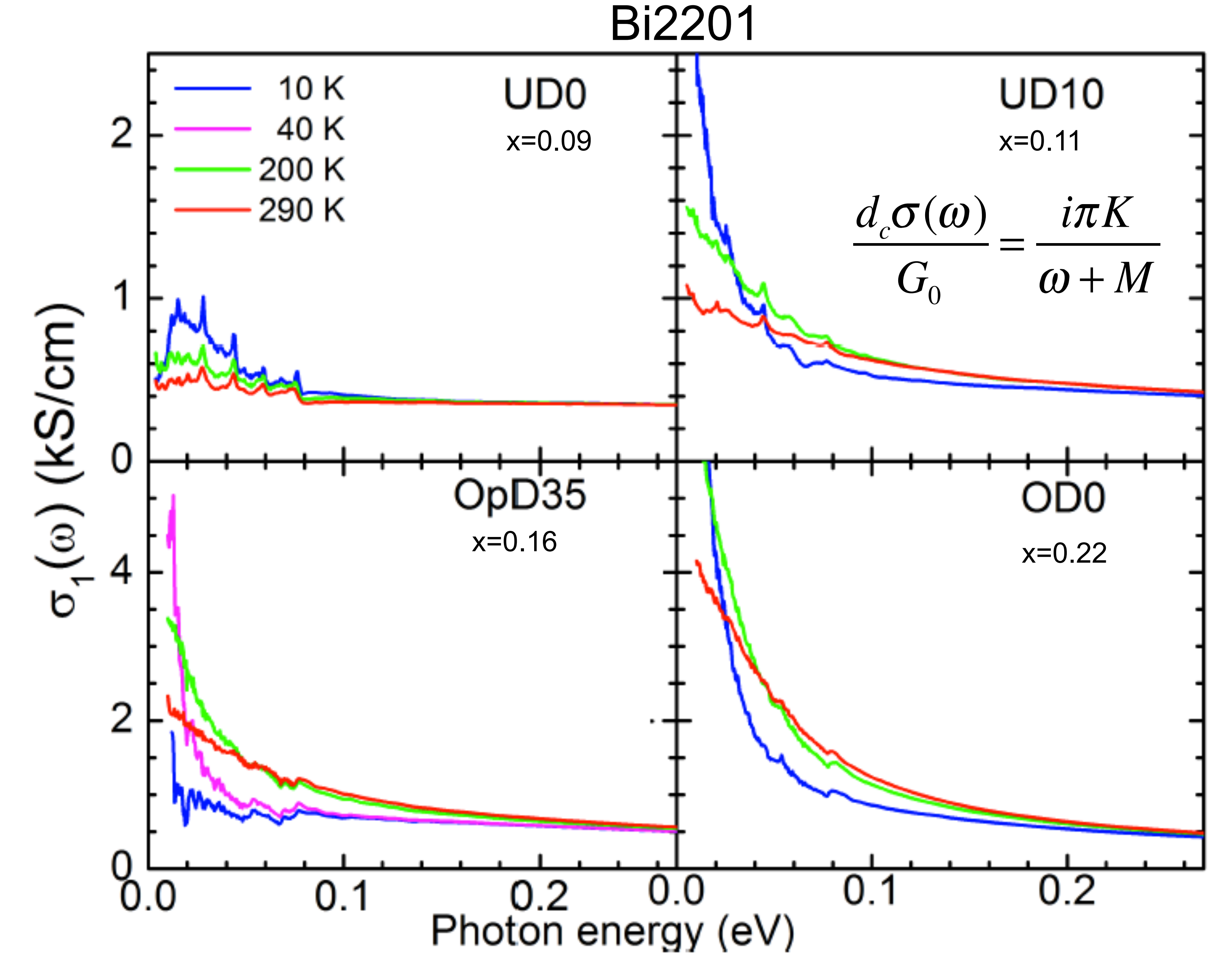
The glue function: $\tilde{\Pi}(x)$ **can be fitted to experimental data**

Optical Memory function

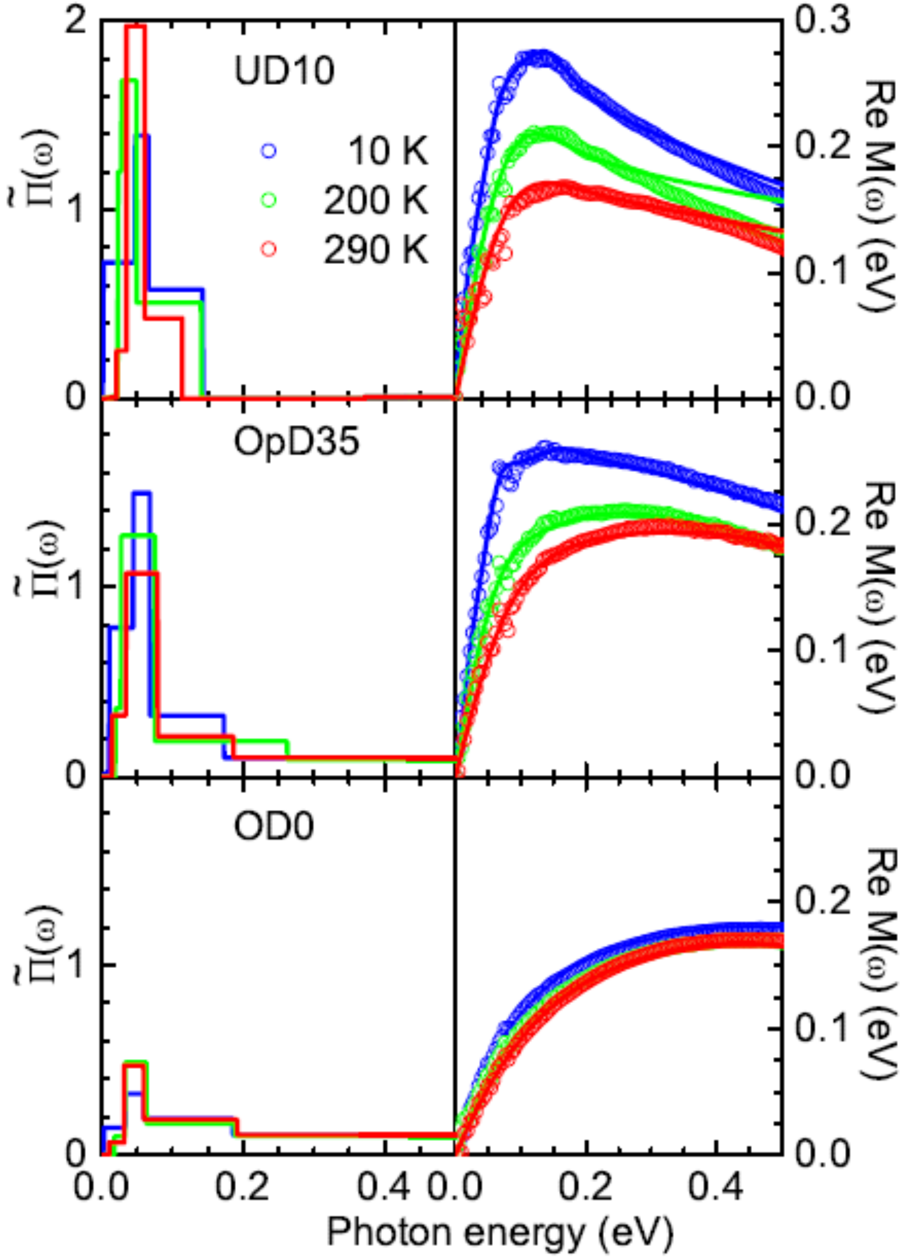
Fit of **Π(ω) to the experimental data at 100 and 290 K simultaneously**



E. van Heumen et al., PRB 79, 184512 (2009)



E. van Heumen *et al., New Journal of Physics 11 (2009) 055067*

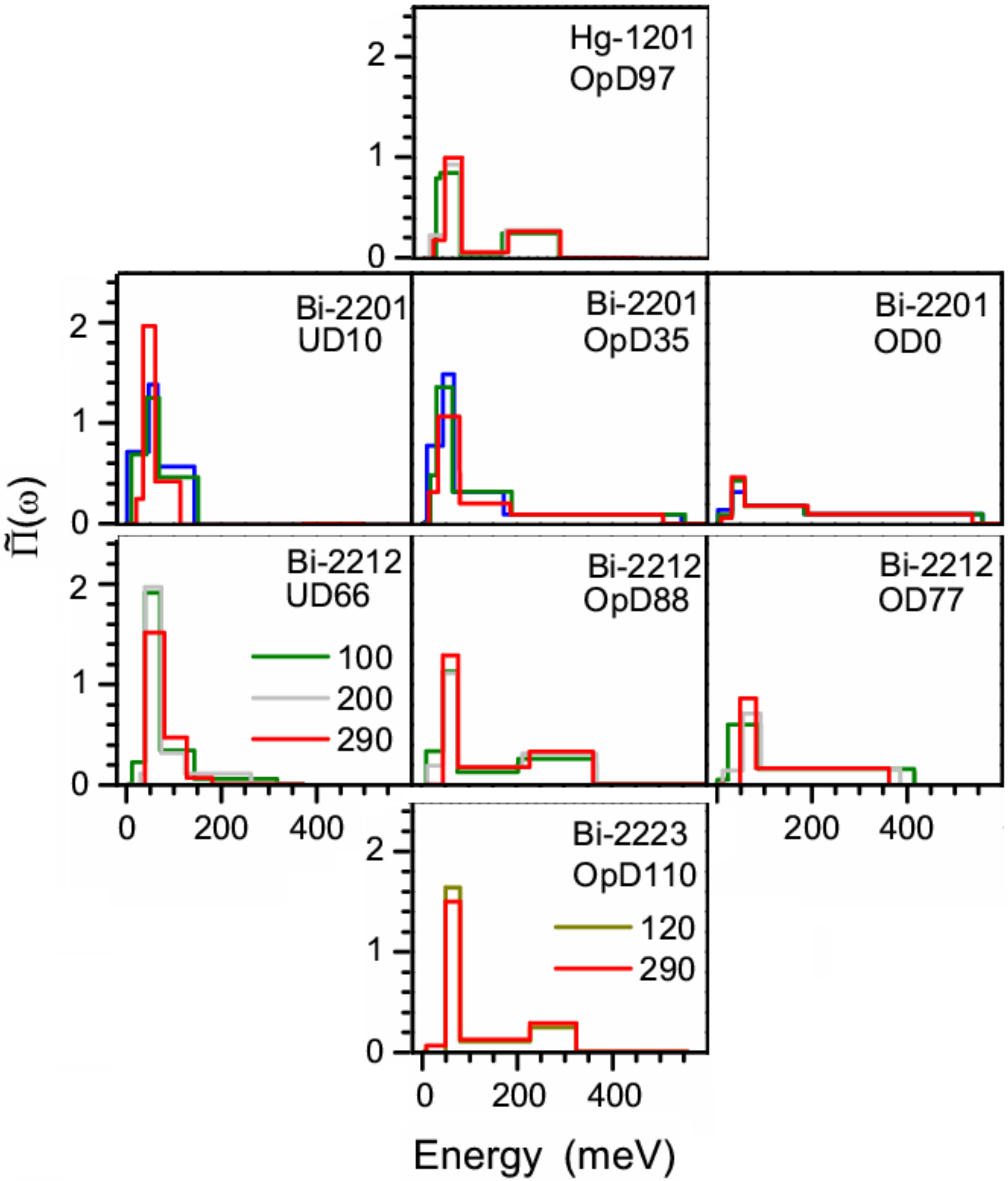


Tc=0 K

Tc=35 K

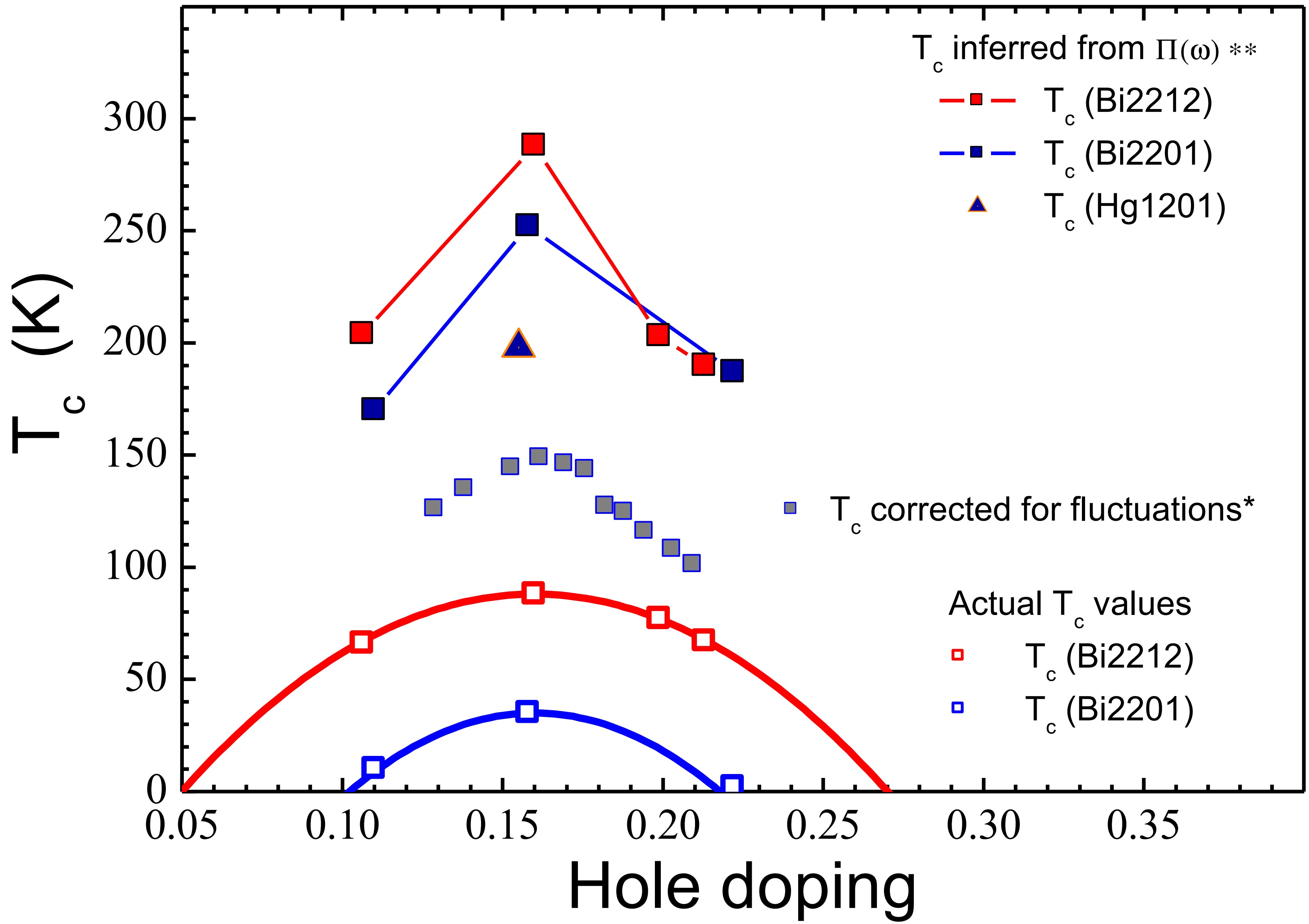
Tc=0 K

E. van Heumen *et al., New Journal of Physics 11 (2009) 055067*

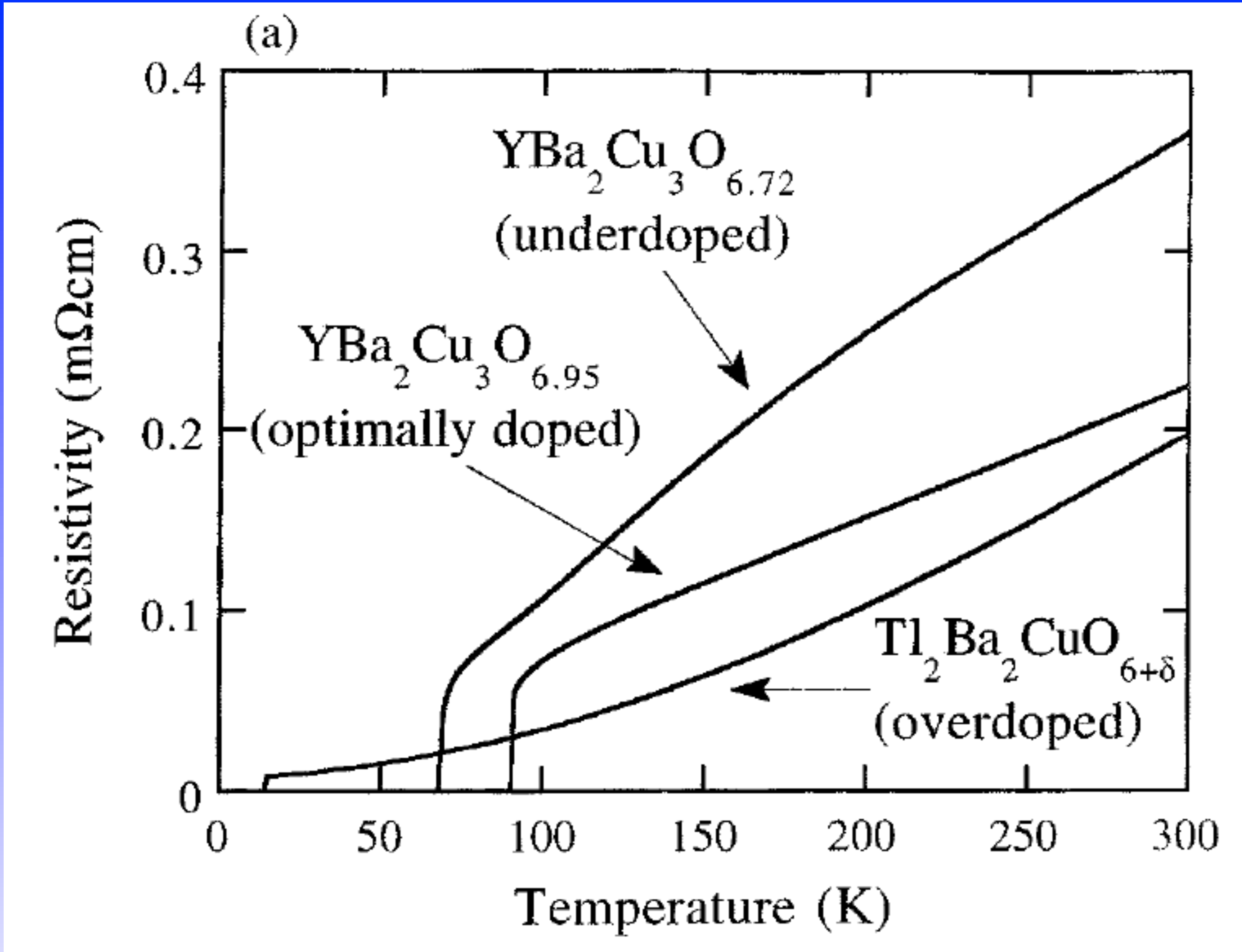


E. van Heumen et al., PRB 79, 184512 (2009)

Possible relation of fluctuation spectrum to T_c

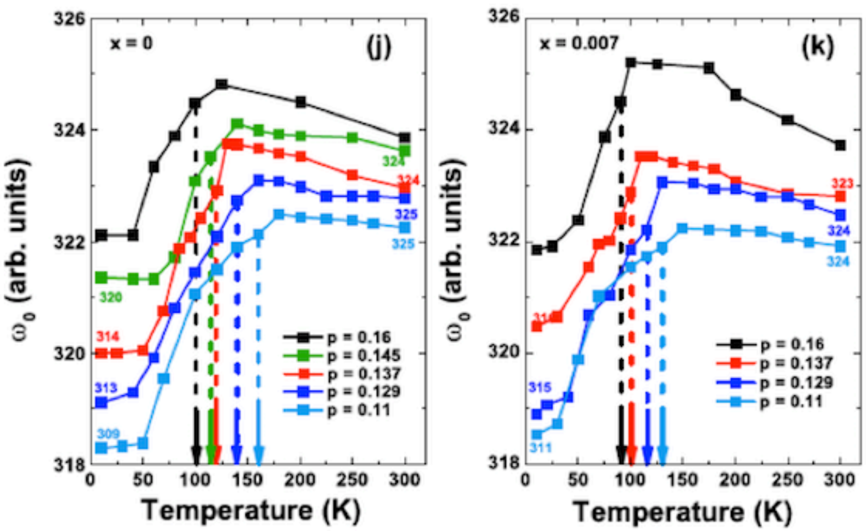


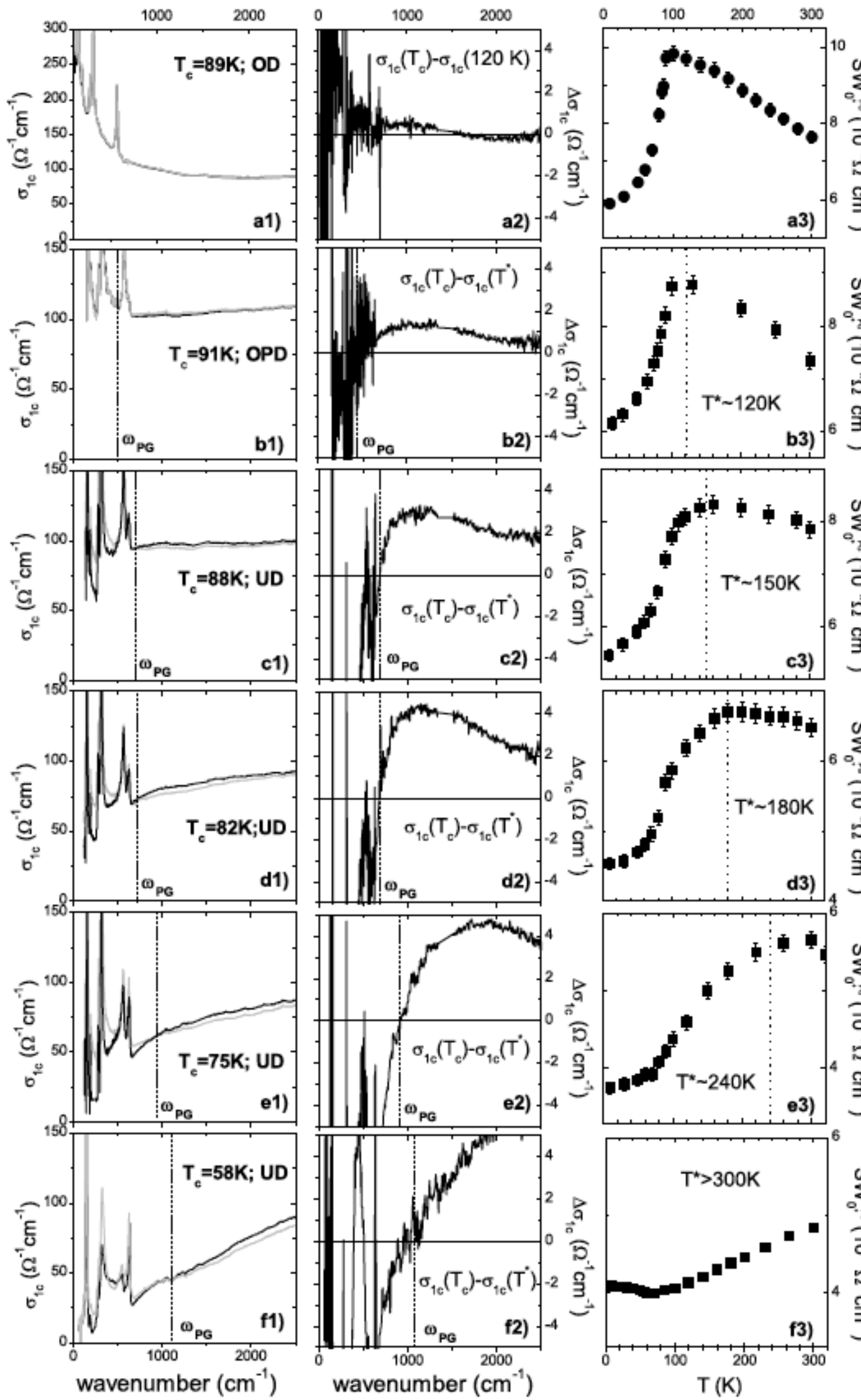
** E. van Heumen et al., PRB 79, 184512 (2009)
* J. Tallon et al., PRB 83, 092502 (2011)



A. Mackenzie et al. , *PRB 53, 5848 (1996)*

A. Dubroka et al.
Eur Phys J 188,73 (2

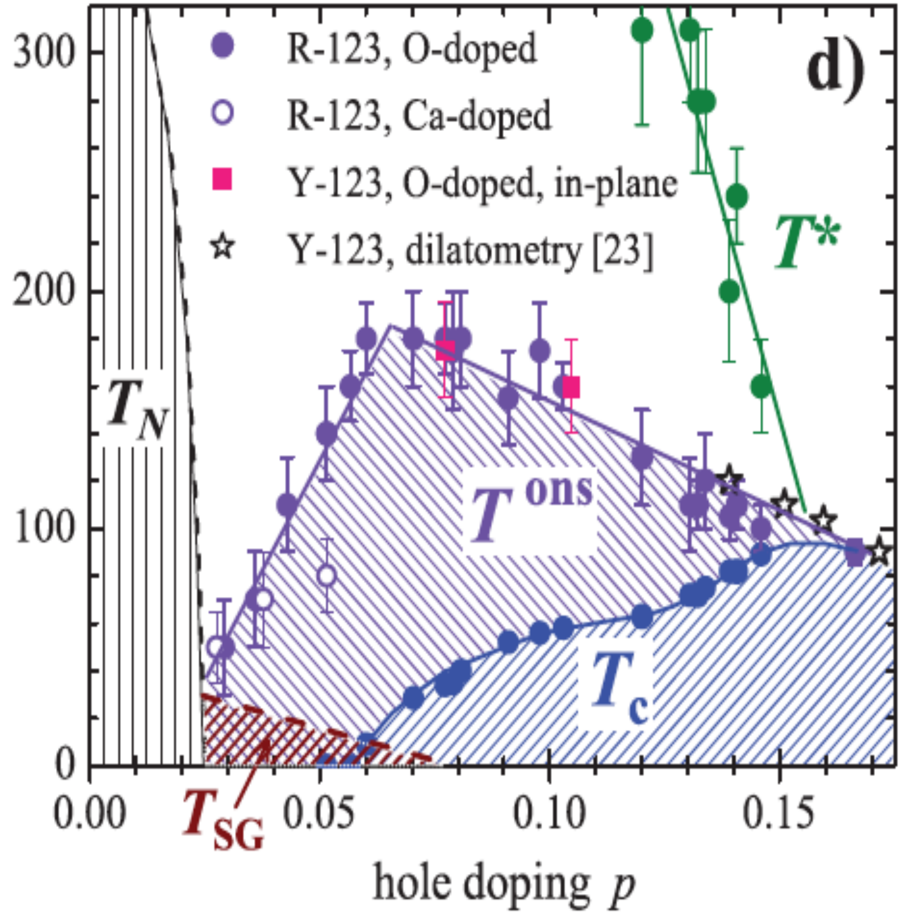


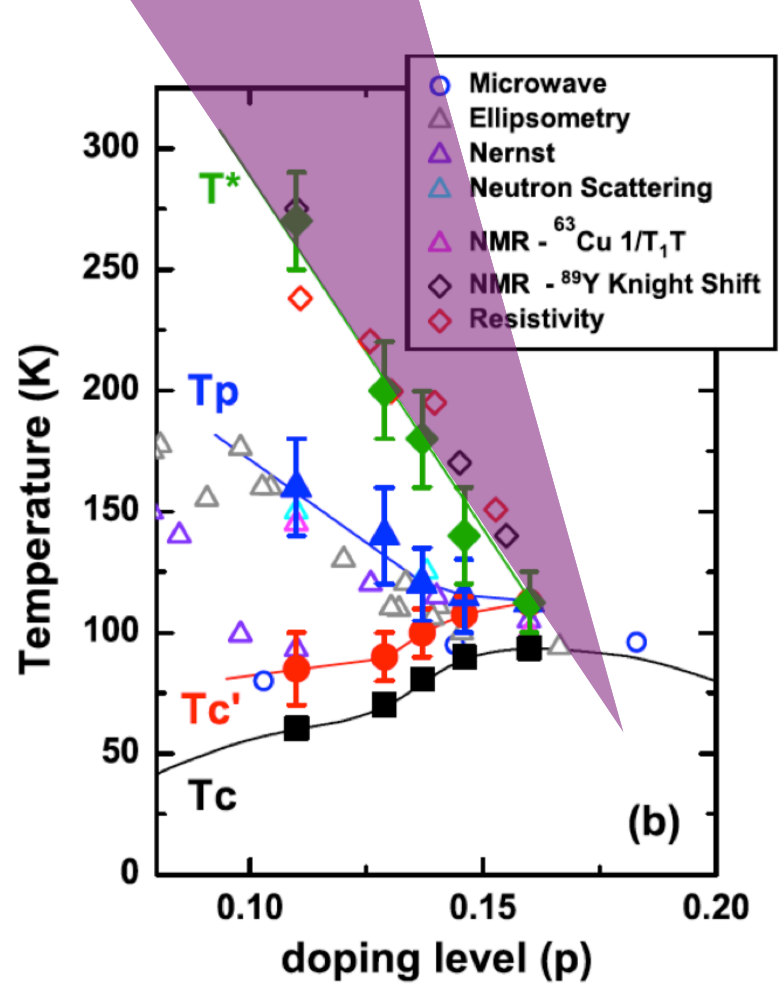


Persistence of the Superconducting Condensate Far above the Critical Temperature

Ece Uykur, Kiyohisa Tanaka, Takahiko Masui, Shigeki Miyasaka, and Setsuko Tajima,

PRL 112, 127003 (2014)



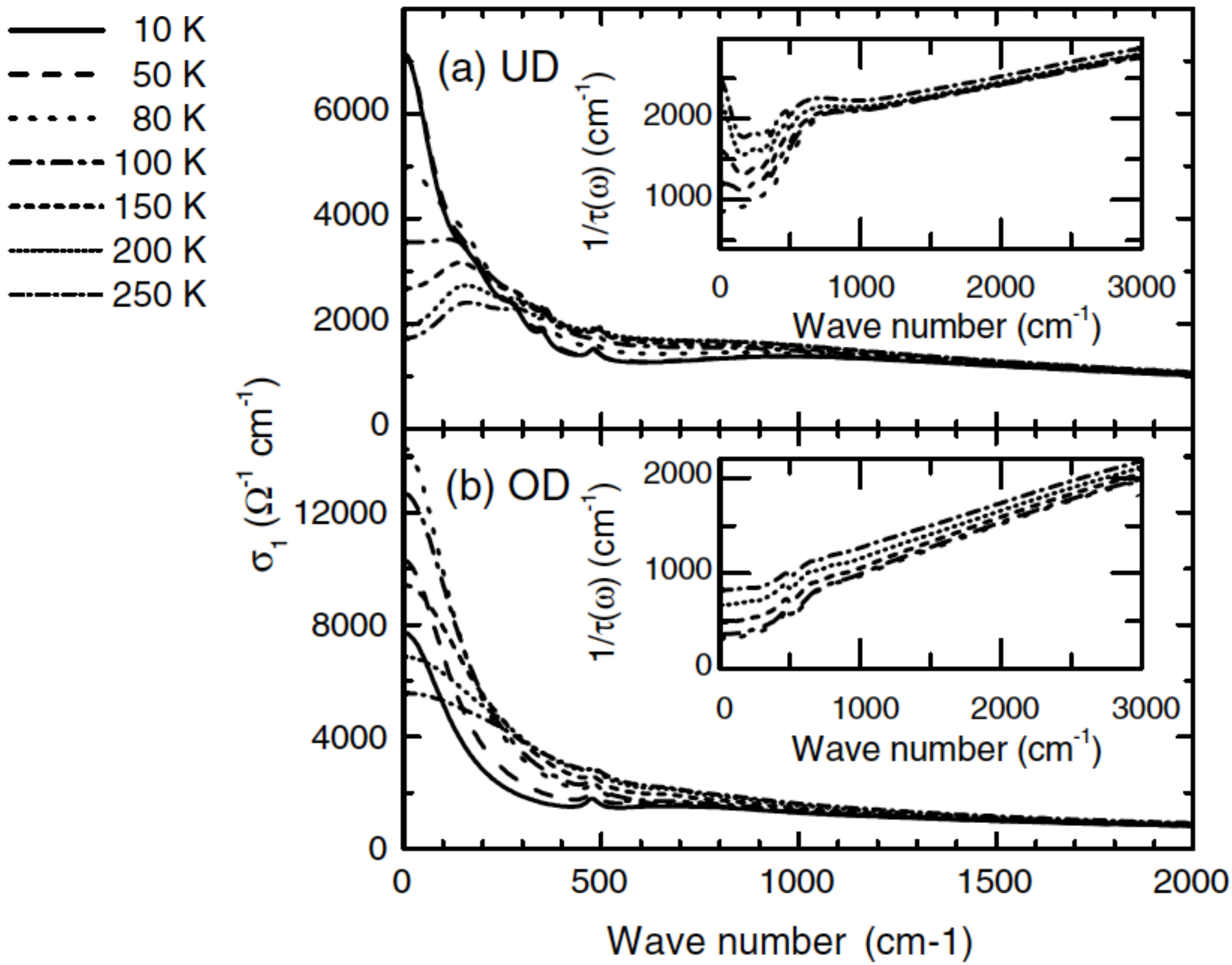


A Dubroka, M Rossle, KW Kim, VK Malik, D Munzar, DN Basov, AA Schafgans, SJ Moon, CT Lin, D Haug, V Hinkov, B Keimer, Th Wolf, JG Storey, JL Tallon, C Bernhard *PRL* **106**, 047006 (2011)

Ece Uykur, Kiyohisa Tanaka, Takahiko Masui, Shigeki Miyasaka, Setsuko Tajima, PRL 112, 127003 (2014)

Absence of a Loss of In-Plane Infrared Spectral Weight in the Pseudogap Regime of Bi-2212

AF Santander-Syro, RPSM Lobo, N Bontemps, Z Konstantinovic, Z Li, and H Raffy, PRL 88 (2002)



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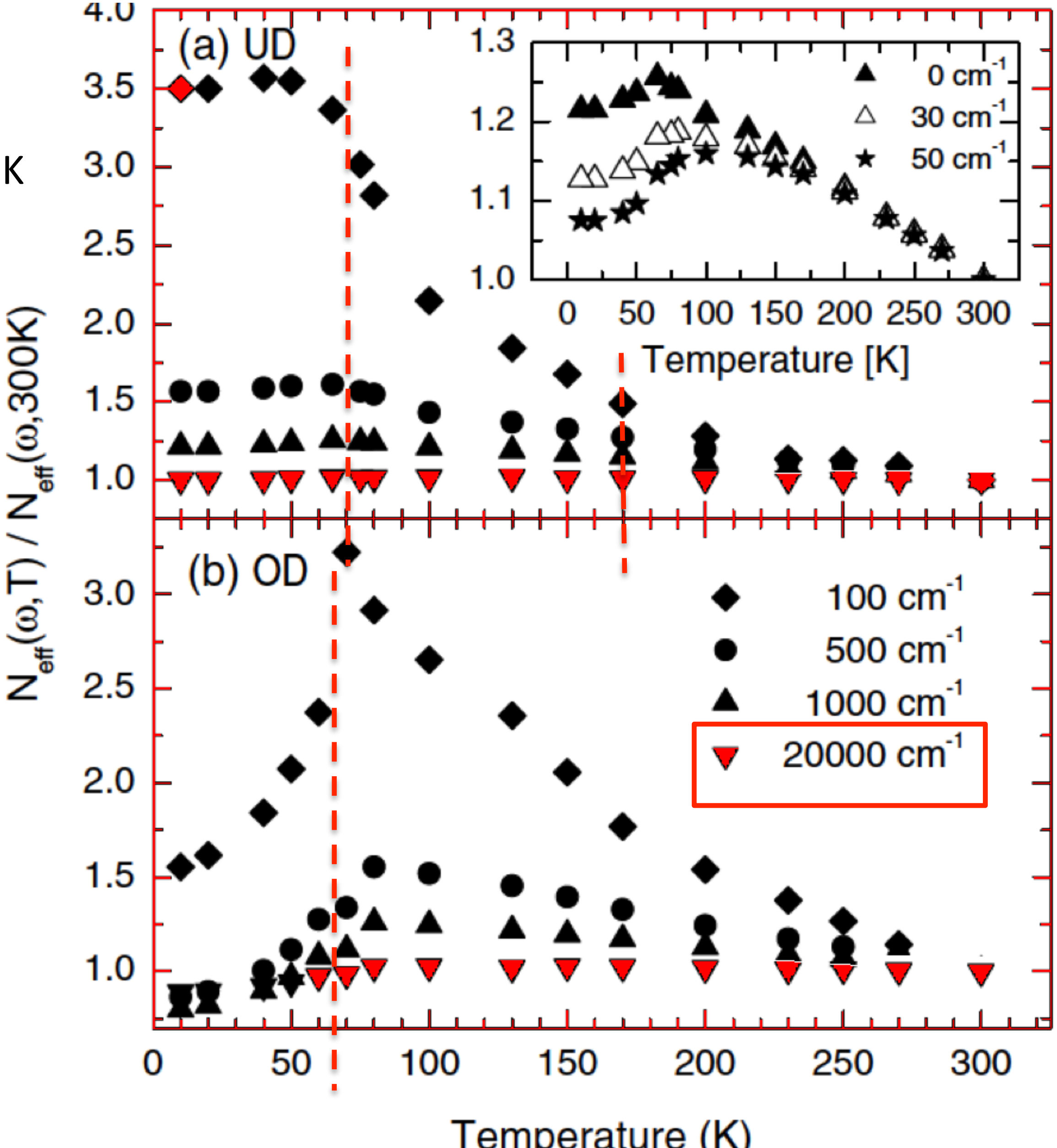
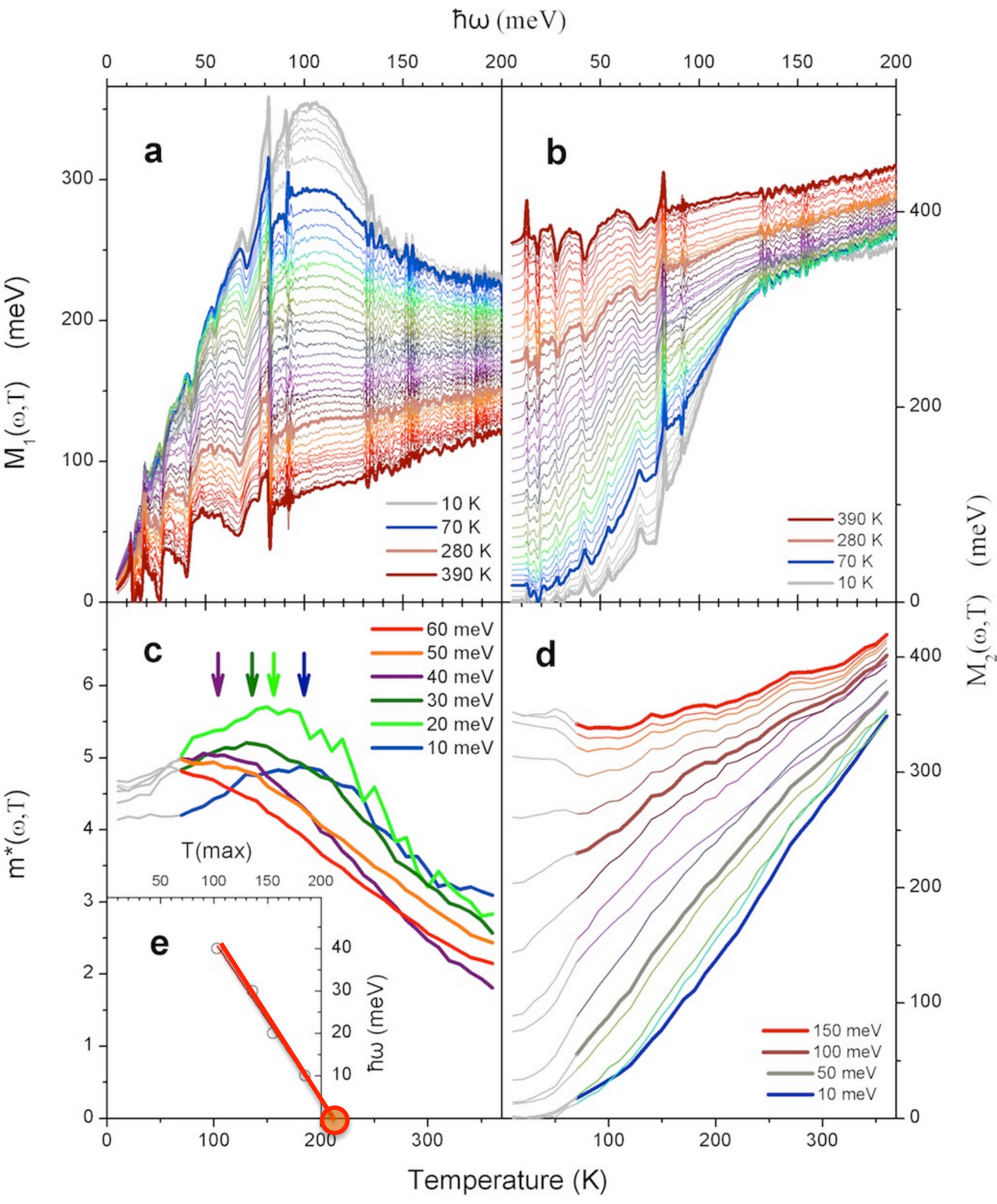
Tc = 70 K, T*=170 K

Tc = 63 K





$$\frac{G(\omega,T)}{G_0} = \frac{i\pi K}{\omega + M(\omega,T)}$$

$$\tau^{-1}(\omega,T) = M_2(\omega,T)$$

$$m^*(\omega,T) = 1 + M_1(\omega,T)/\omega$$

Maximum of m*(ω,T) for ω→0 gives:

T(crossover) = 220 K

(T* = 350 K)

Conclusions

- Pseudogap shows up clearly in frequency dependence along a and c-axis
- An important part of the pseudogap spectral features have to do with the incoherent part of the optical response function and…. consistency with T_c !
- Temperature dependence: *T(cross-over)* shows up in the relaxation rate and in the c-axis conductivity.
- No discernable effects at higher frequencies.
- Yet, the effects of the superconducting T_c are quite visible for energies as high as 1 eV.

sumrules

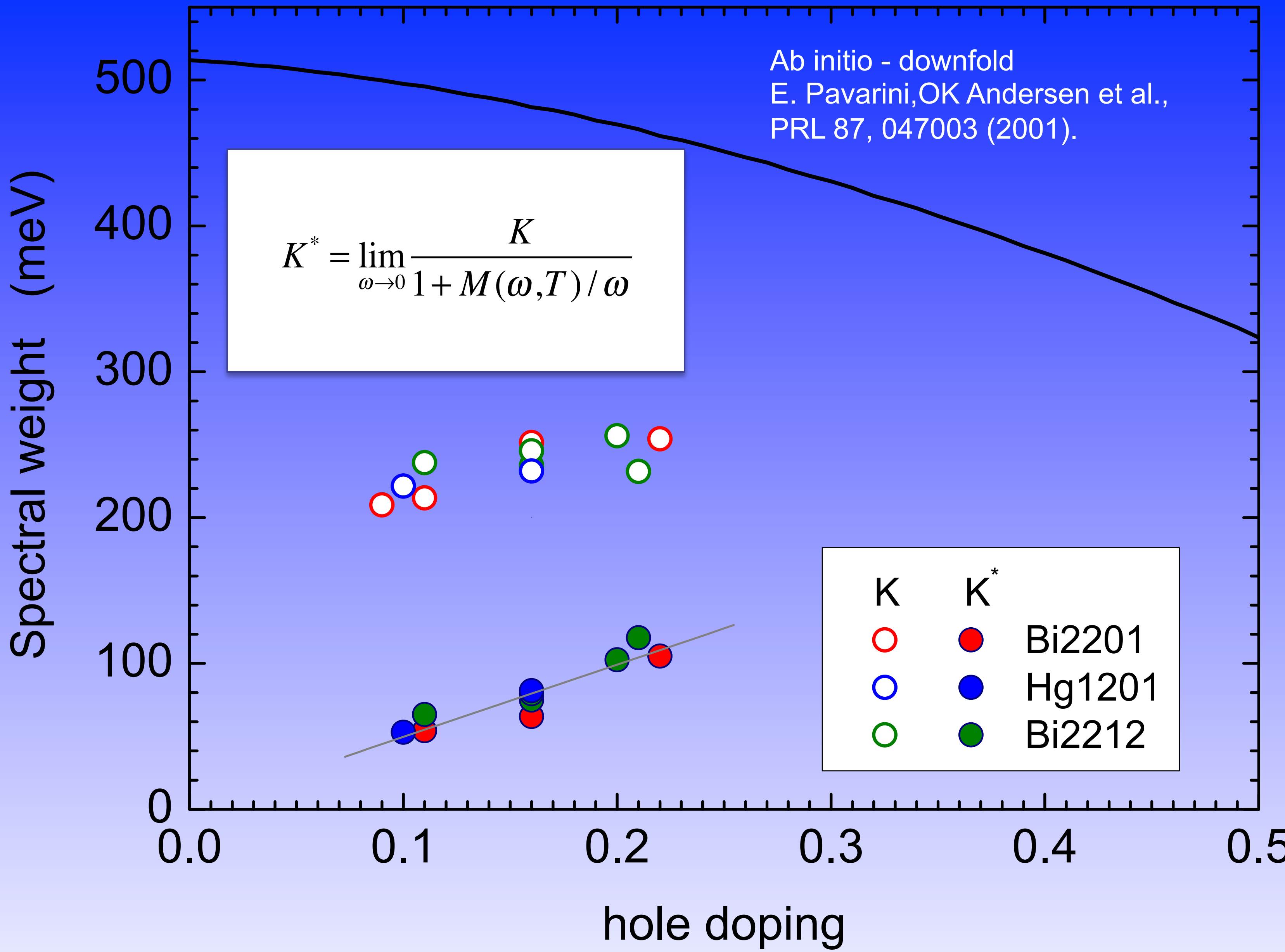
$$\int_0^\infty \omega^{-1} L(q,\omega)\, d\omega = \frac{\pi}{2}$$

$$\int_0^\infty L(q,\omega)\, d\omega = 2\pi E_C(q)$$

$$\int_0^\infty \omega L(q,\omega)\, d\omega = \frac{2\pi^2 n e^2}{m}$$

$$\int_0^\infty \omega^3 L(q,\omega)\, d\omega = \frac{2\pi^2}{m^2} \sum_G G^2 U_G \langle \rho_{-G} \rangle$$

$$\int_0^\infty \operatorname{Im} \omega\varepsilon(\omega)\, d\omega = -\pi^2 e^2 a^2 \sum_{\langle i,j \rangle} t \left\langle c_i^t c_j \right\rangle$$



S.I. Mirzaei, D. Stricker *et al.*, *PNAS, 2013*