Superconductivity induced spectral weight redistribution in cuprate high temperature superconductors

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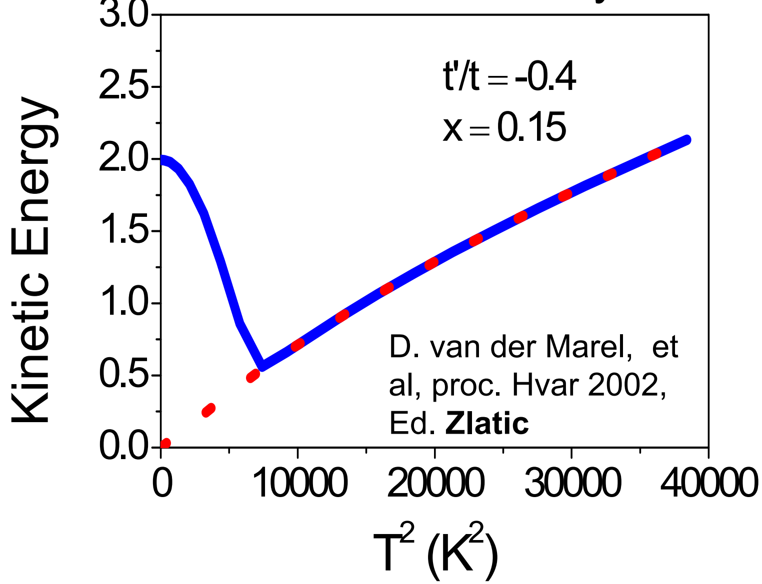
Optical study of spectral weight transfer in relation to the kinetic changes of the normal and the superconducting state.

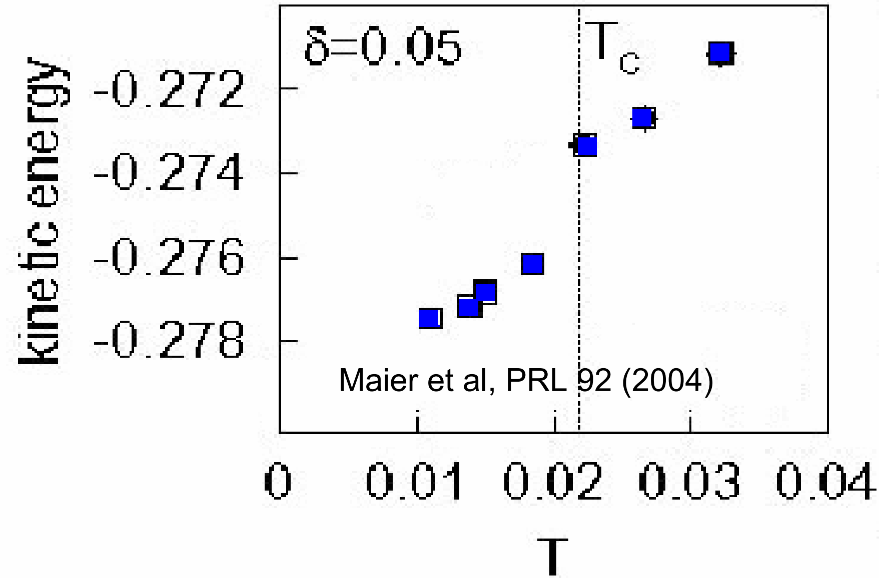
- The pairing mechanism and kinetic energy
- Some relevant details of our experimental methods & equipment
- Spectral weight transfer of the superconducting state
- The relevant energy scales of optical SW transfer
- Doping dependence of the SW transfer

The Pairing mechanism and the electronic Kinetic Energy

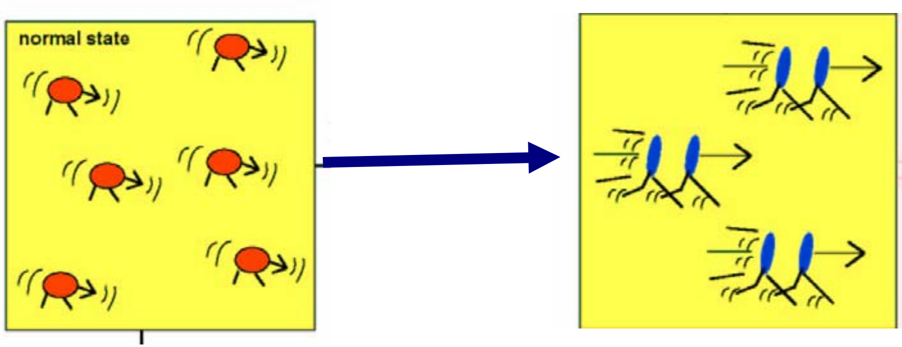
BCS theory



Hubbard model, DMFT

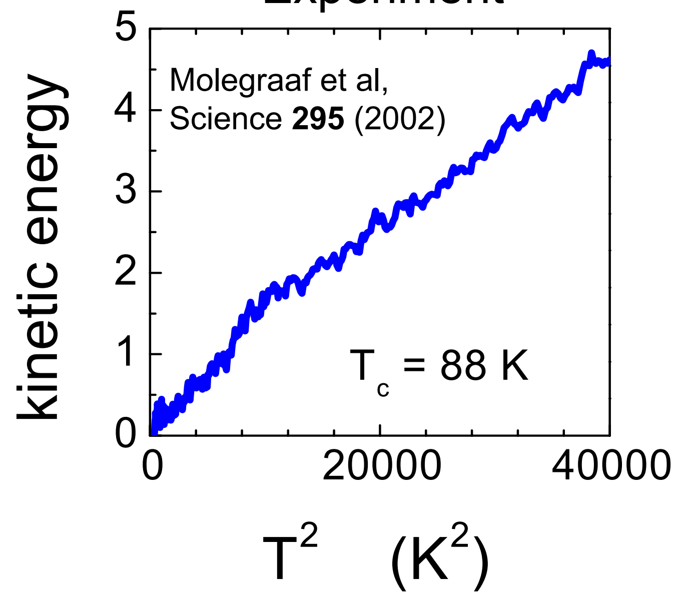


Theoretical Prediction by Hirsch

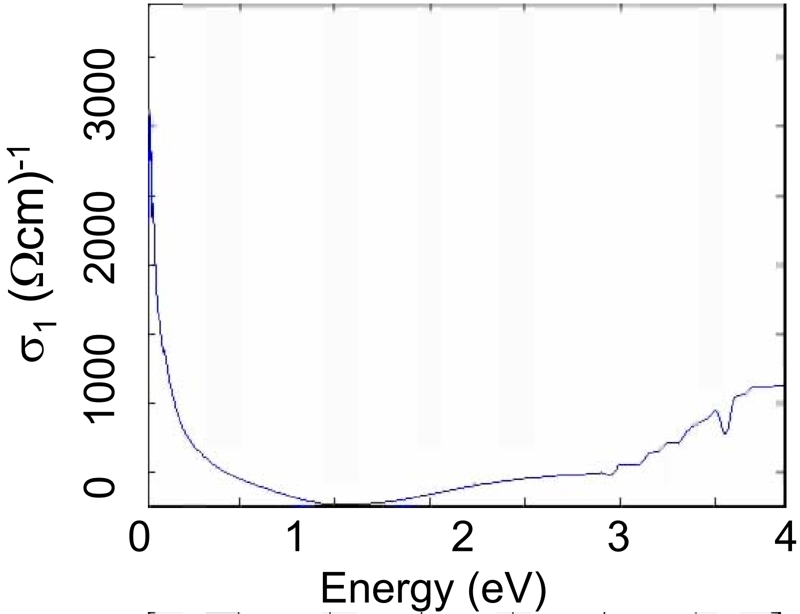


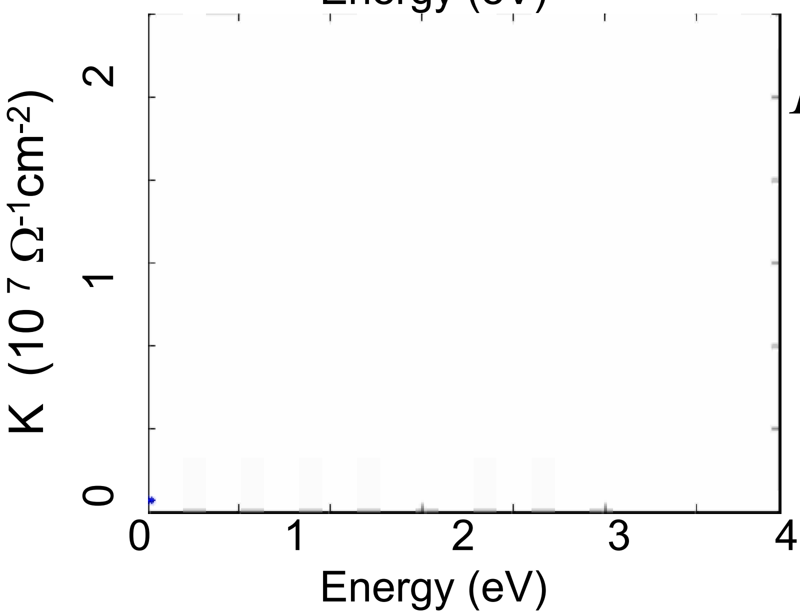
J.E. Hirsch, Physica C **201**, 347 (1992)
J. E. Hirsch, and F. Marsiglio, Physica C **331** (1999)
J.E. Hirsch, Science **295** (2002).

Experiment



The SW and the Kinetic Energy

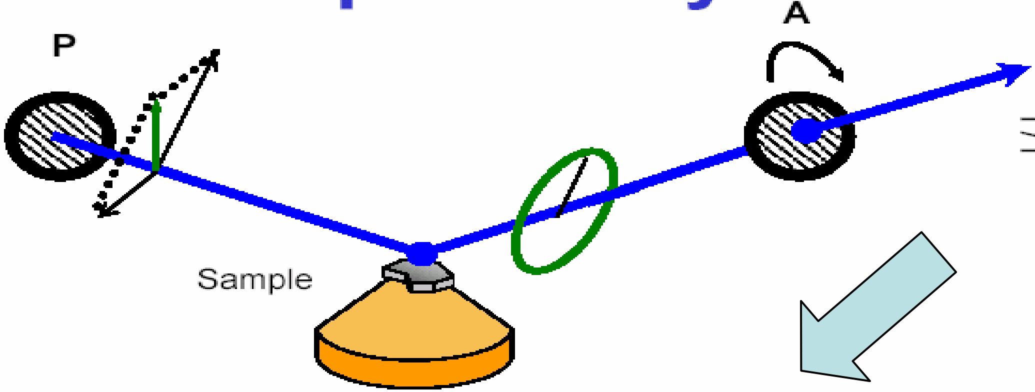


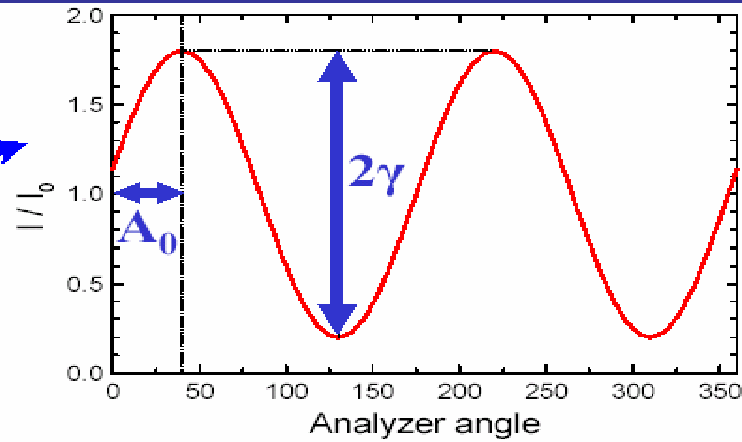


$$K(T) \equiv \frac{2d\hbar^2}{\pi e^2}\int_0^{\Omega_c}\sigma_1(\omega)d\omega = -\left\langle \hat{H}_{\text{kinetic}} \right\rangle$$

Experimental determination of σ_1 σ_2

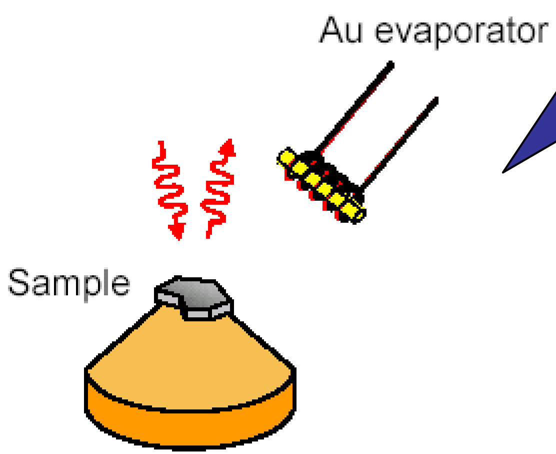
Ellipsometry





$$\varepsilon(\omega) = \varepsilon_1(\omega) + 4\pi \mathbf{i}\, \sigma_1(\omega)/\omega$$

Reflectivity



Multioscillators variational Routine

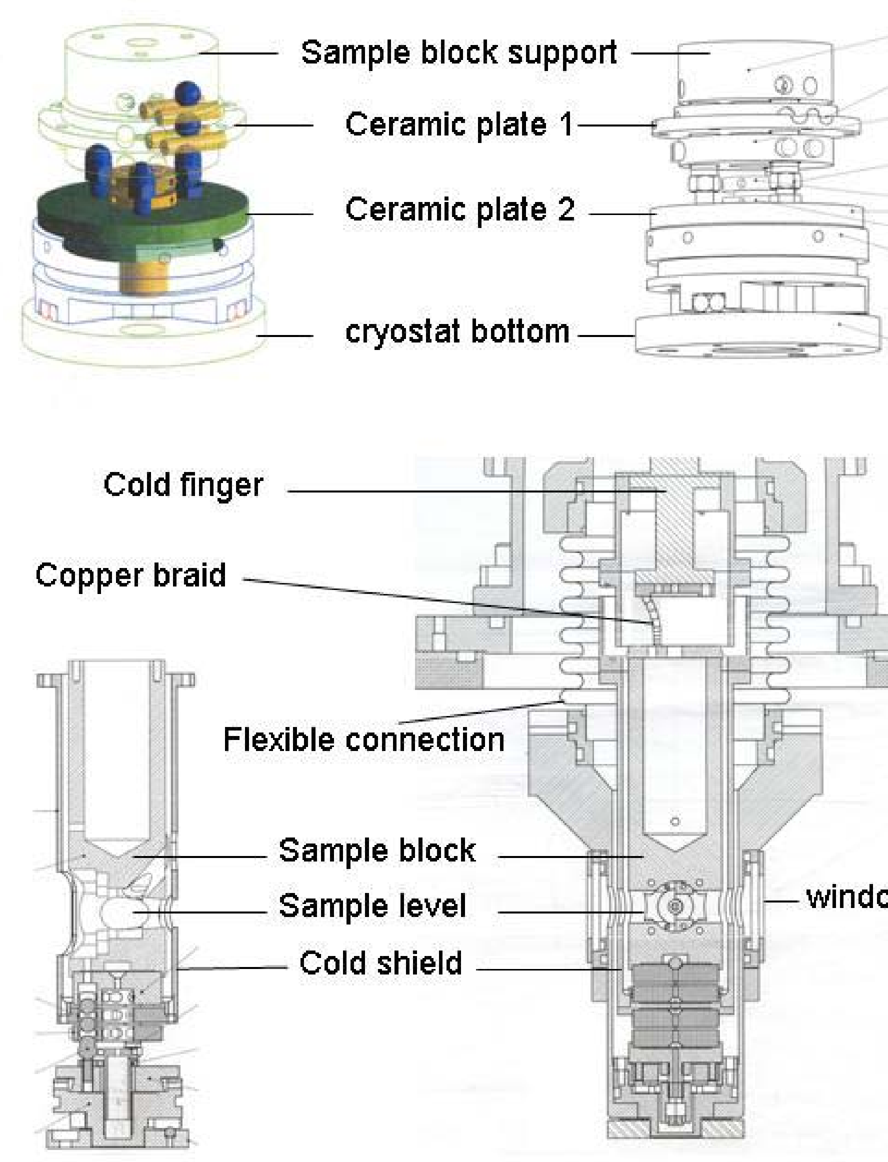
Kuzmenko, Rev. Sci. Instr. (2005)

$$\sigma(\omega),\ \varepsilon(\omega)$$

3d generation optical cryostats:

- ultra-stable alignment
- signal stability~0.1 %
- UH vacuum < 10^{-9}Torr

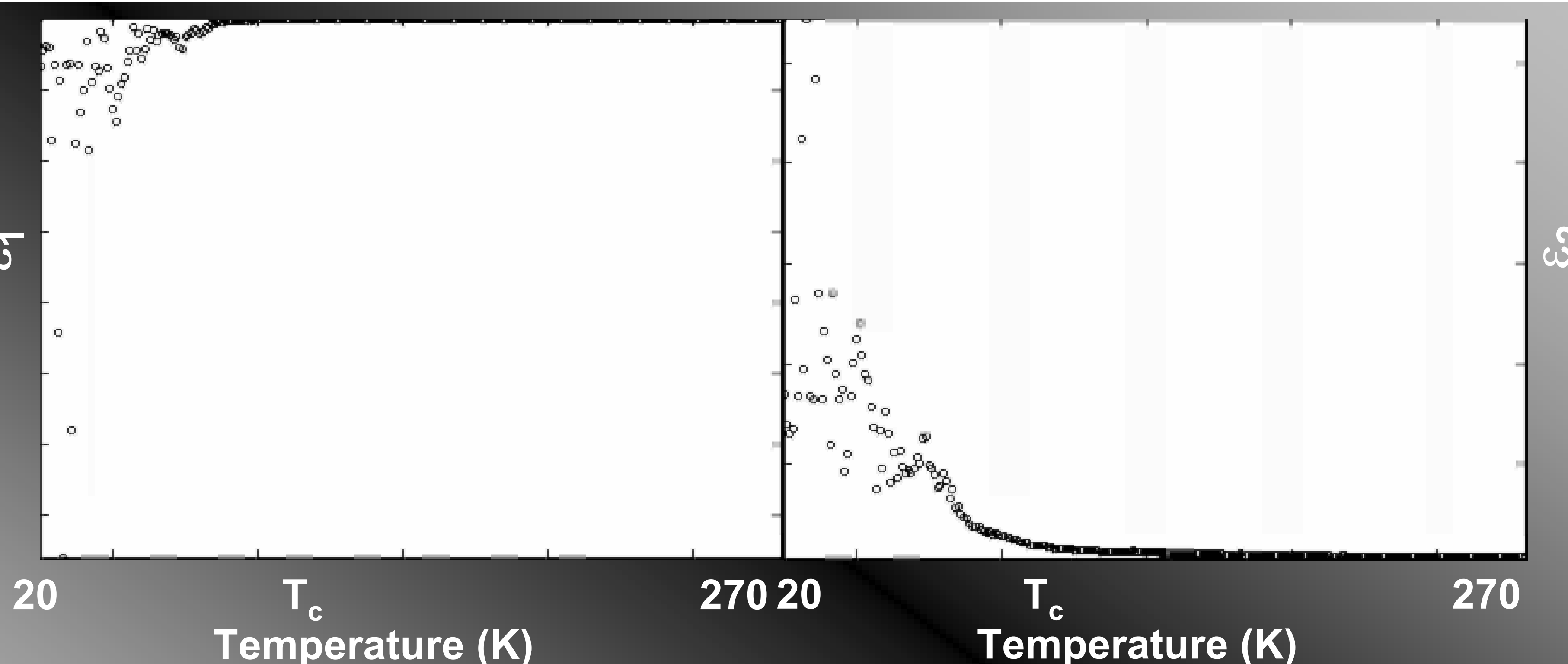
Experimental Procedure:
1 spectrum/ K
4K <T< 300 K

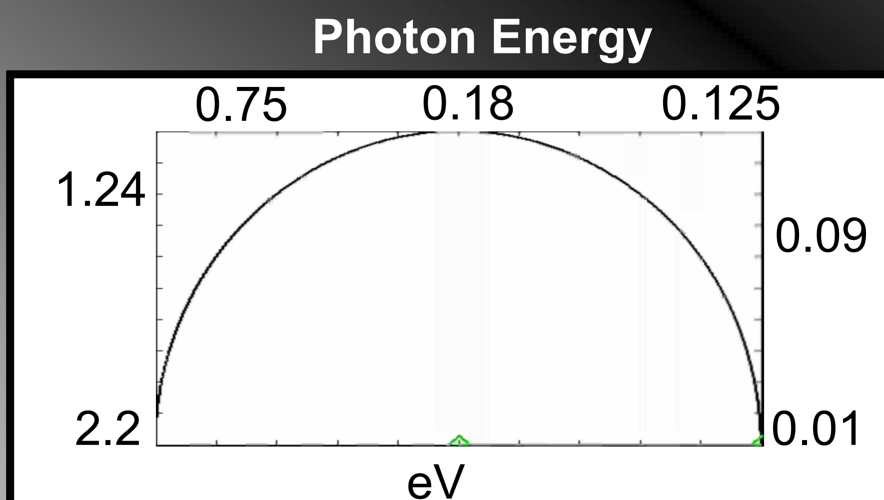


HV cryostat without outer crystat walls

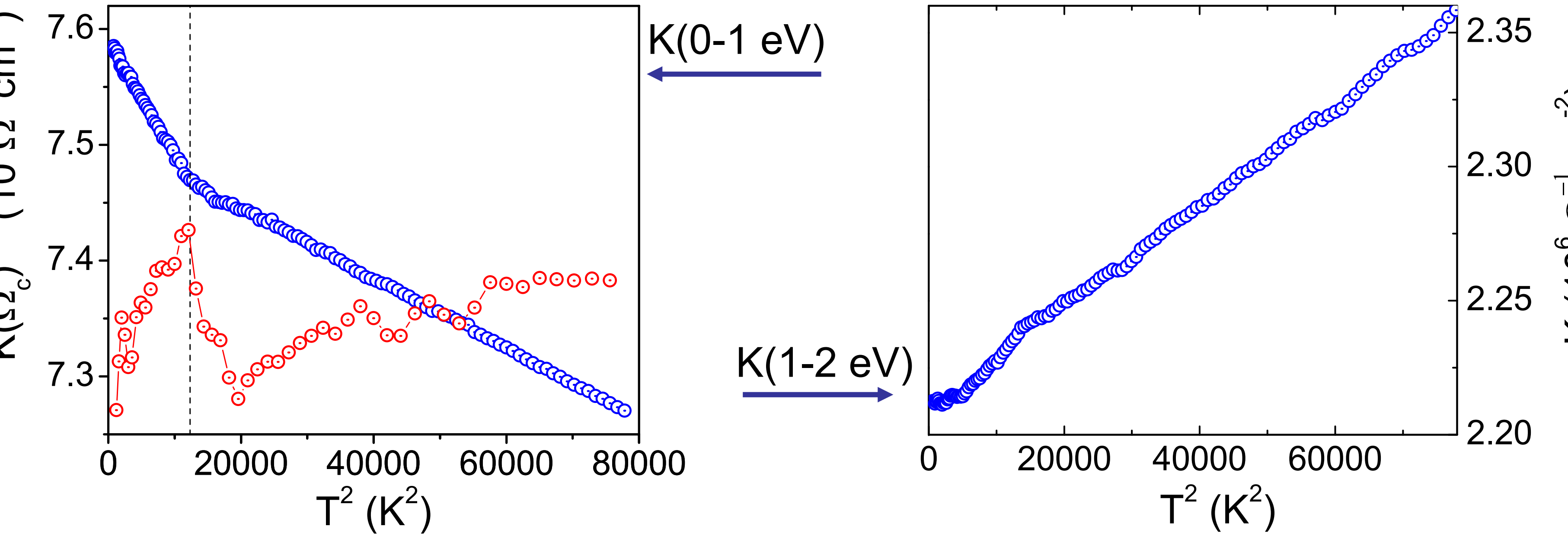
UHV cryostat

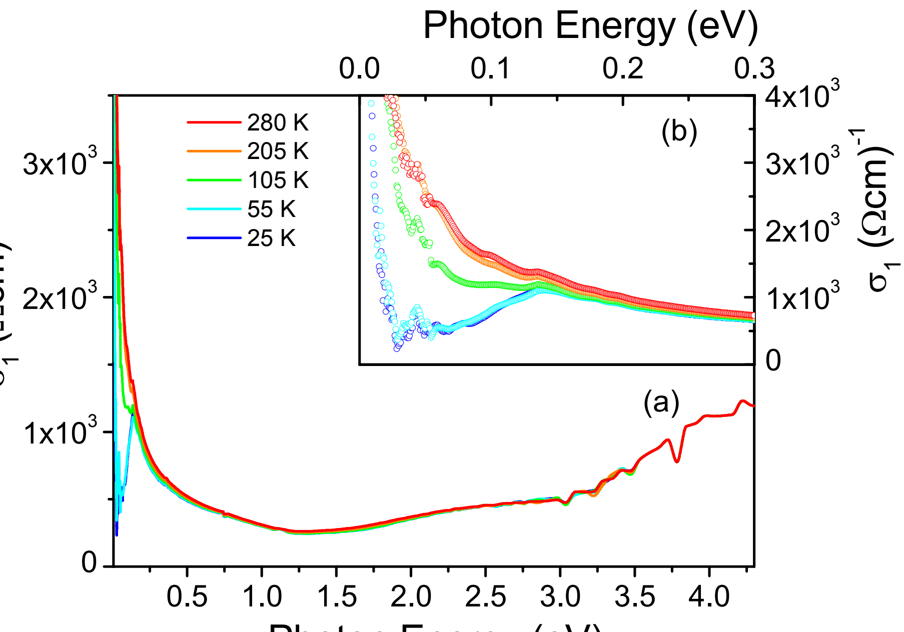
$E \| ab$ Bi2223 $T_c = 111$ K, $\sigma_1 \approx \varepsilon_2 * \omega$





SW in optimally doped Bi2223, Tc = 111 K





$E \| ab$

otal
pectral weight

$$\frac{2\hbar^2}{\pi e^2}\int_0^\infty \sigma_1(\omega)d\omega = \frac{\hbar^2 n_e}{m_e} = \sum_{k,\sigma} n_{k\sigma}\frac{\hbar^2}{m_e}$$ **(f-sum rule)**

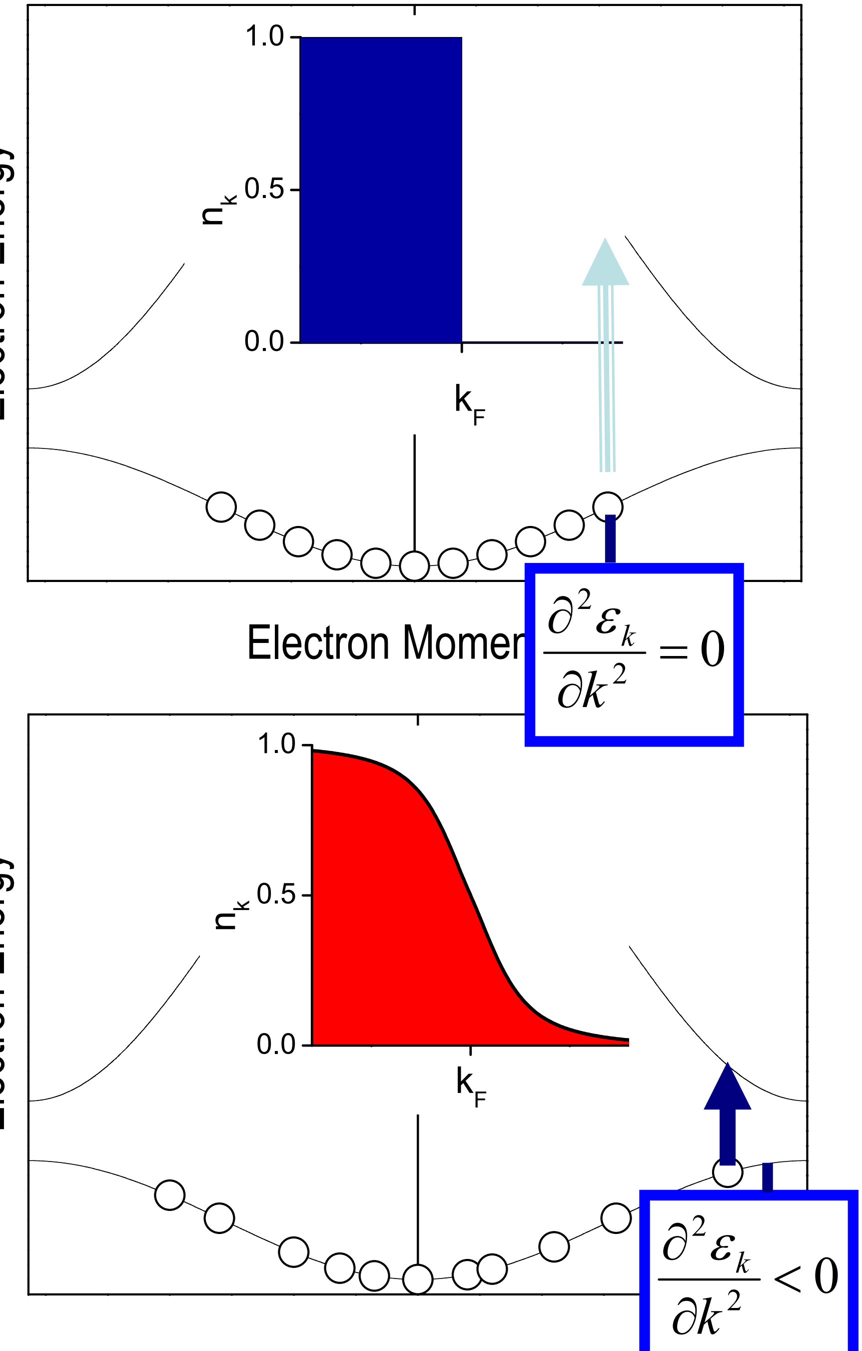
ree charge
pectral weight

$$K \equiv \frac{2d\hbar^2}{\pi e^2}\int_0^{\Omega_c} \sigma_1(\omega)d\omega = \sum_{k,\sigma} n_{k\sigma}\frac{\partial^2 \varepsilon_k}{\partial k^2}$$ **(Kubo, 1957**

$$= -\langle H_{\text{kinetic}}\rangle \quad \text{(exact for nearest neighbor tightbinding}$$

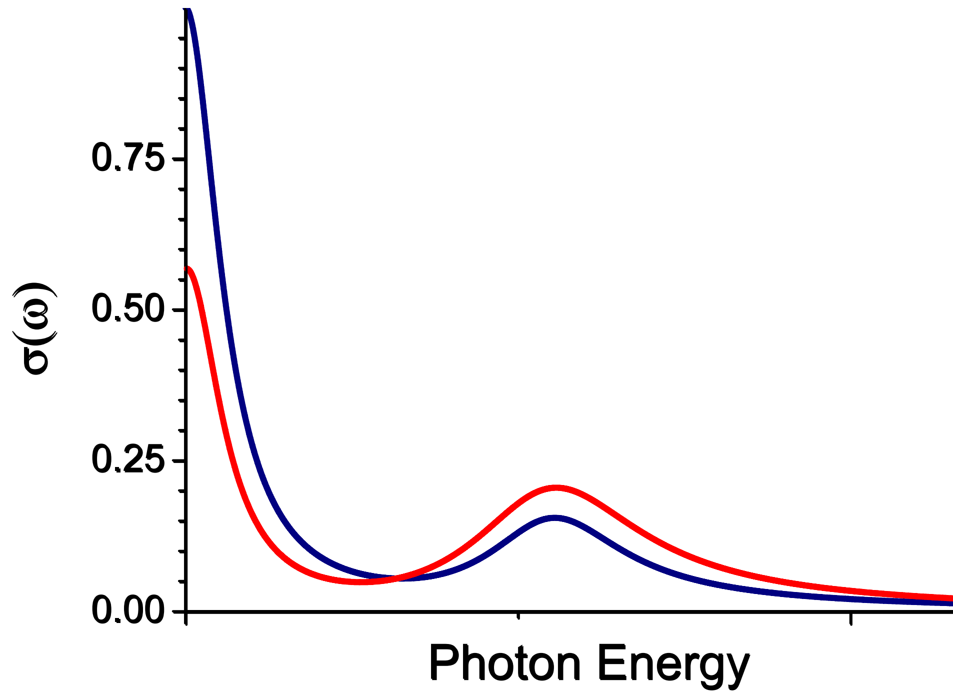
ound charge
=inter-band)
pectral weight

$$\frac{2\hbar^2}{\pi e^2}\int_{\Omega_c}^\infty \sigma_1(\omega)d\omega = \frac{\hbar^2 n_e}{m_e} - K = \sum_{k,\sigma} n_{k\sigma}\left\{\frac{\hbar^2}{m_e} - \frac{\partial^2 \varepsilon_k}{\partial k^2}\right.$$

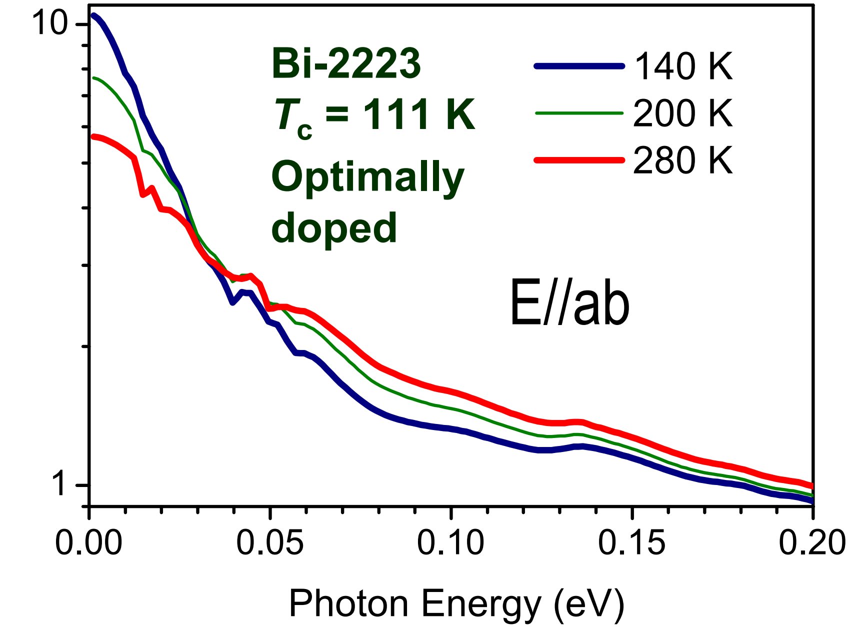


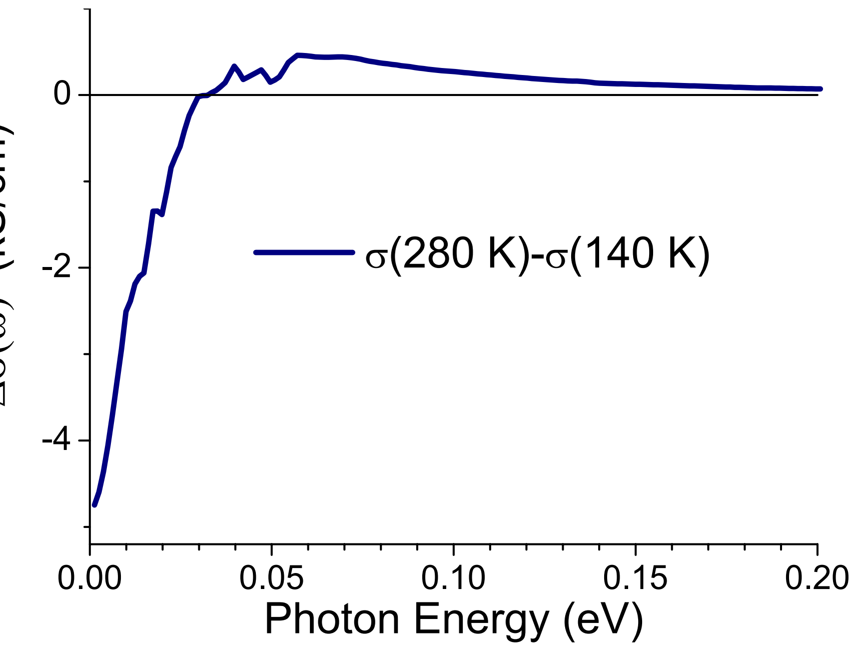
$$\frac{\partial^2 \varepsilon_k}{\partial k^2} = 0$$

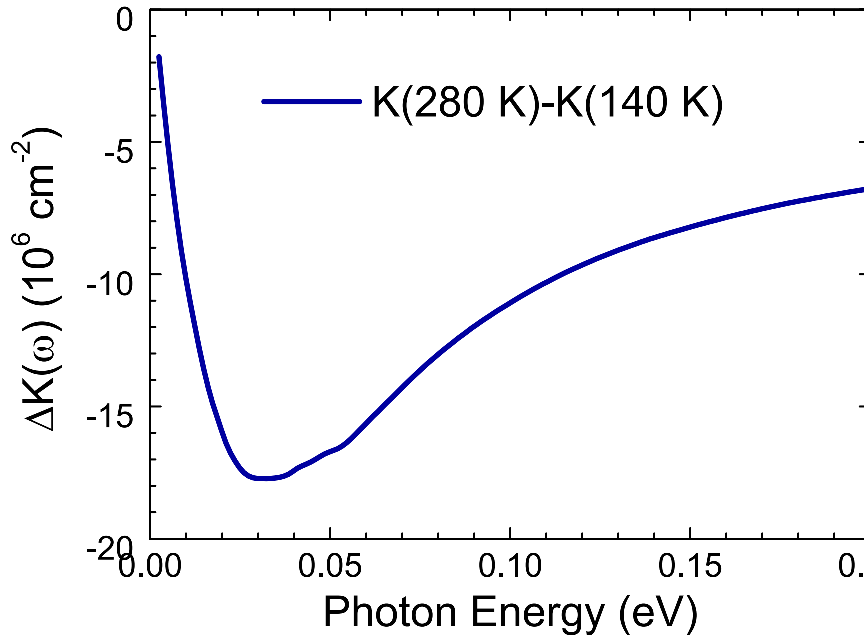
$$\frac{\partial^2 \varepsilon_k}{\partial k^2} < 0$$

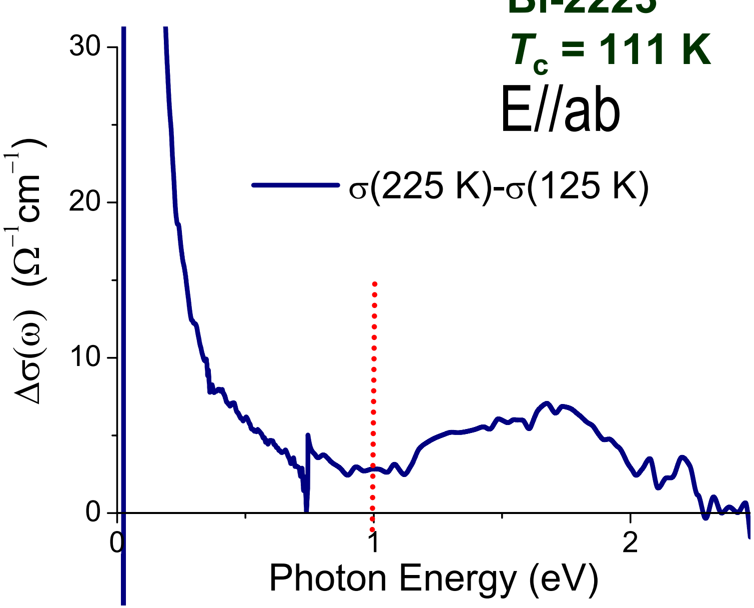


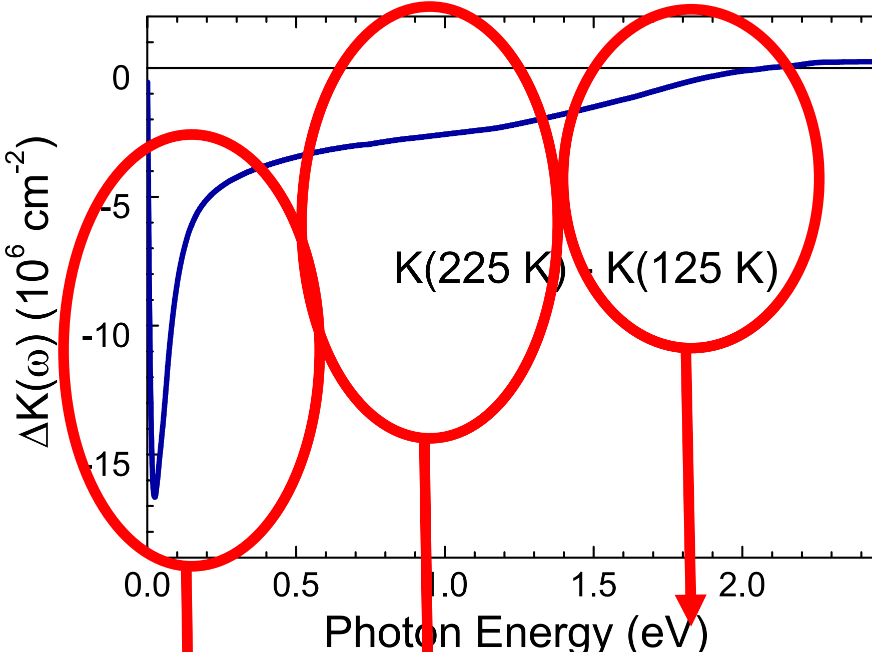
-K(T) and $\langle H_{kin} \rangle_T$ follow the same trend
-exceptions are possible

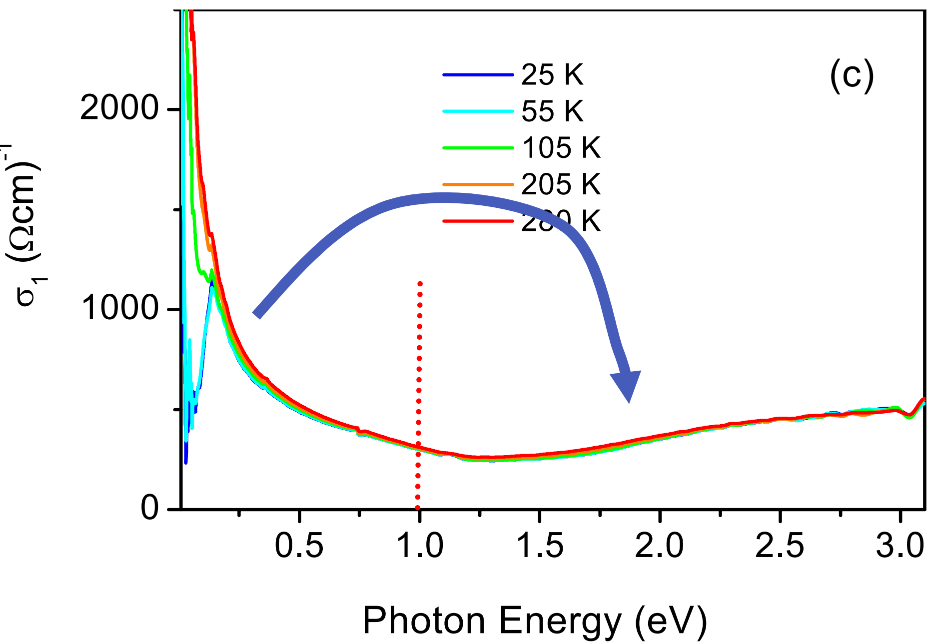

Bi-2223
T_c = 111 K
Optimally
doped
140 K
200 K
280 K
E//ab
10
1
0.00
0.05
0.10
0.15
0.20
Photon Energy (eV)


0
-2
-4
σ(280 K)-σ(140 K)
0.00
0.05
0.10
0.15
0.20
Photon Energy (eV)


0
-5
-10
-15
-20
ΔK(ω) (10^6 cm^{-2})
K(280 K)-K(140 K)
0.00
0.05
0.10
0.15
Photon Energy (eV)





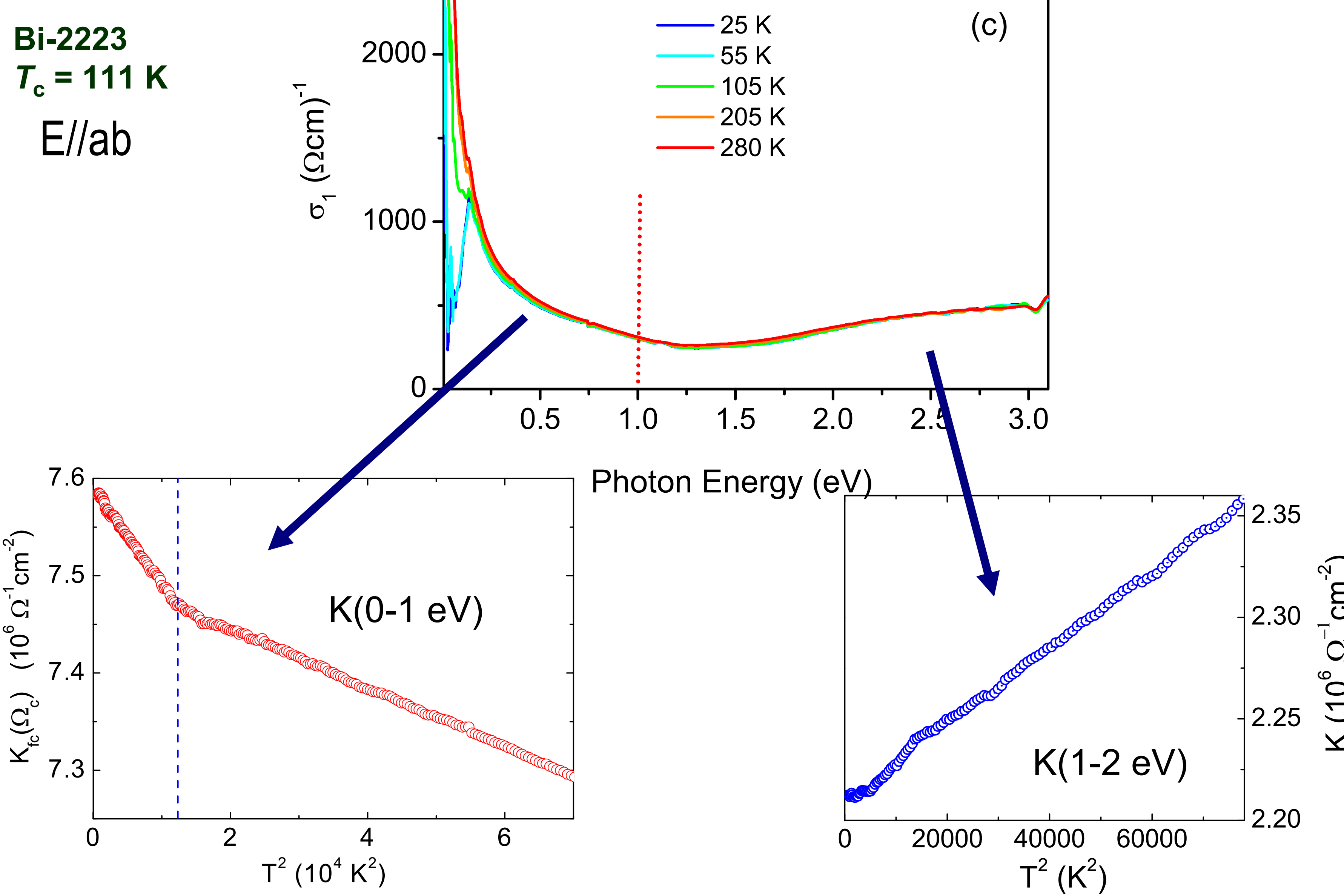


Spectral weigh
recovery

Spectral weight
deficit

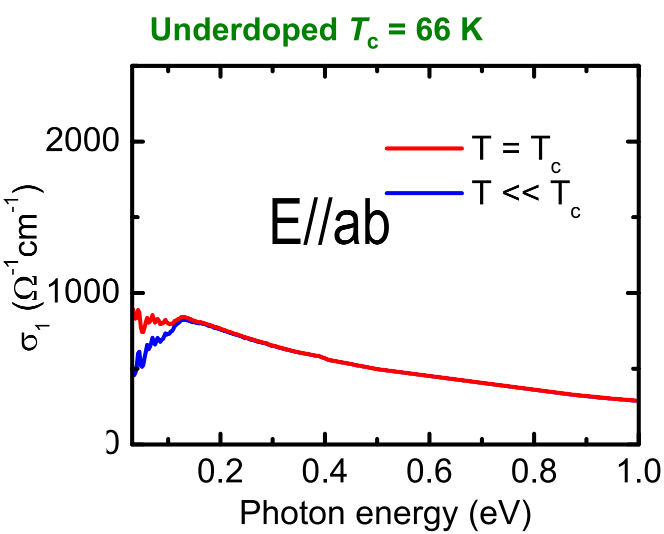
Drude broadening

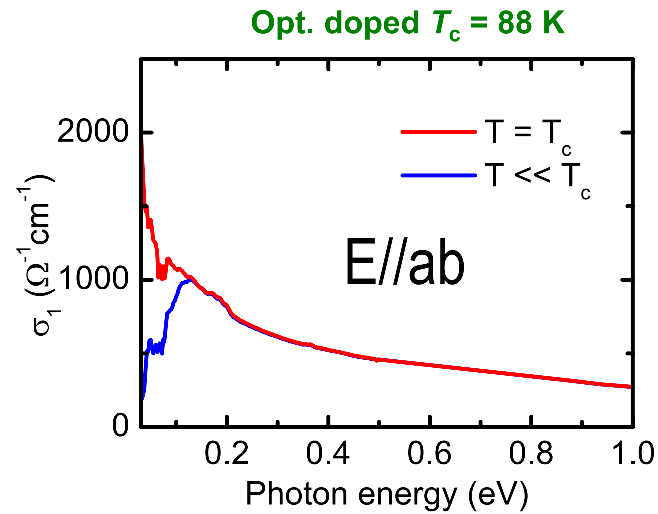
Wrobel, Eder, Fulde, JPC 15 (2003):
0.125 eV ~J < Ω_c < t ~0.4 eV
should provide kinetic energy in t-J mode

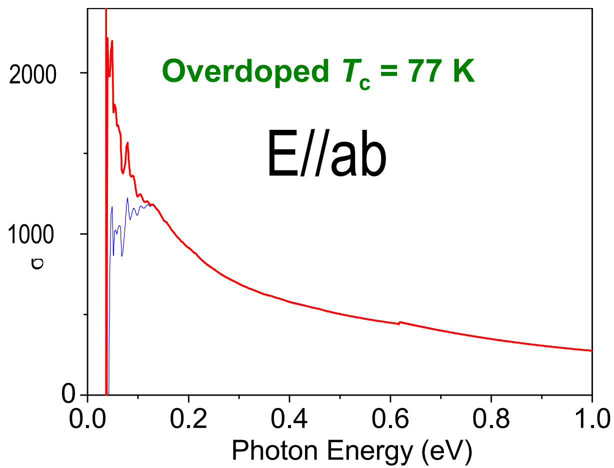


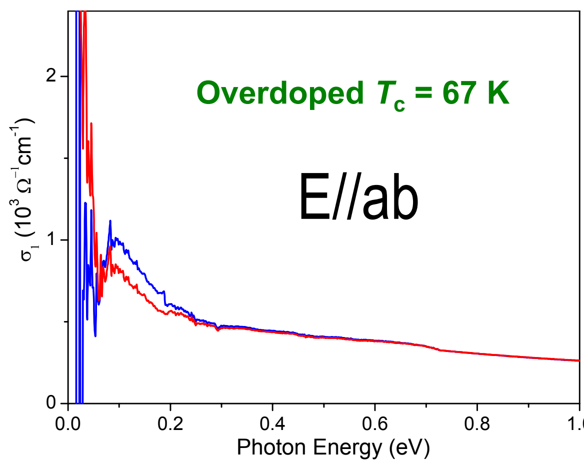
$$K_{fc}(T)_{\exp} / K_0 = 1 - \eta\left(k_B T / K_0\right)^2 + \ldots$$

Bi-2212: doping dependence





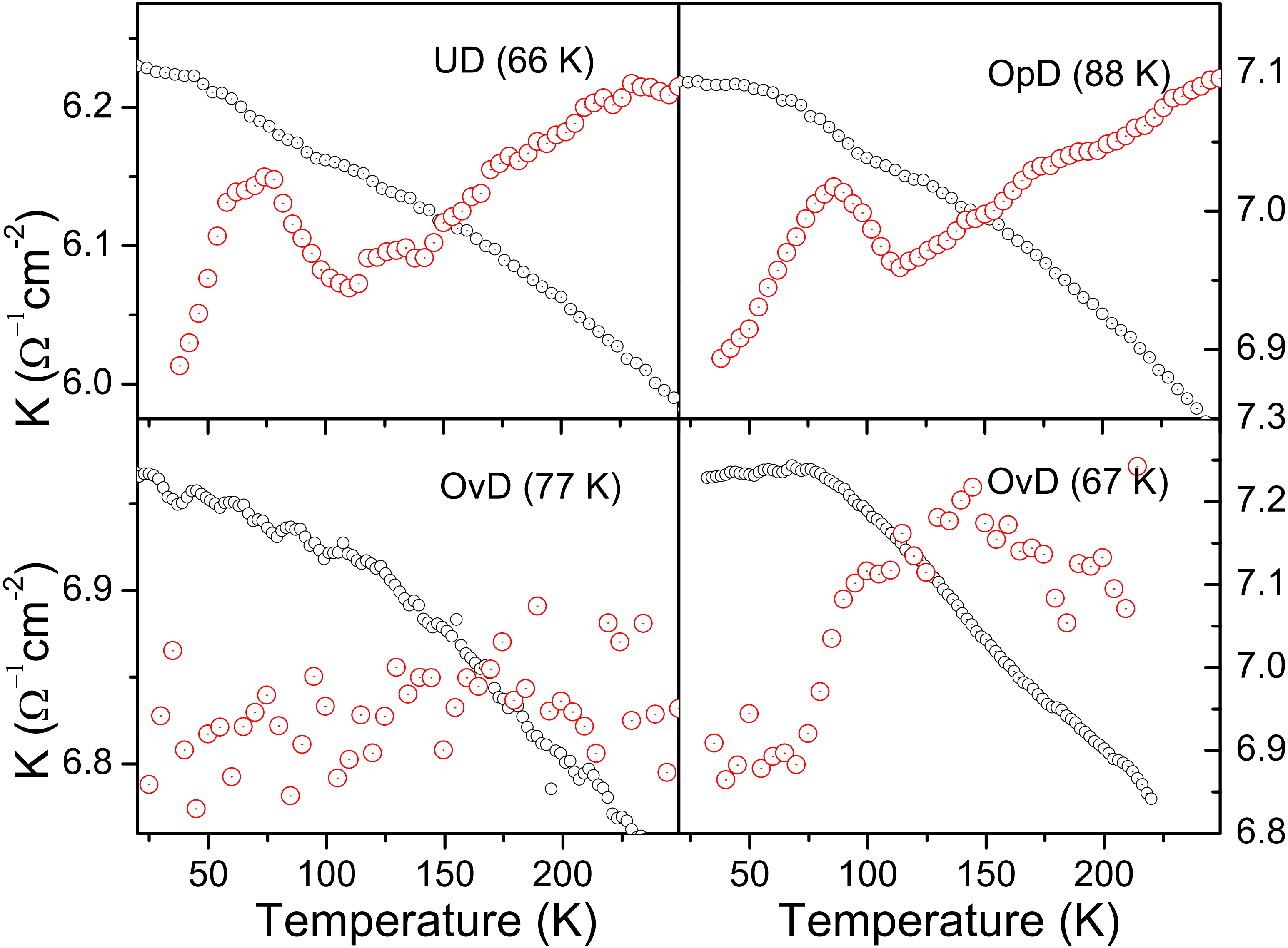


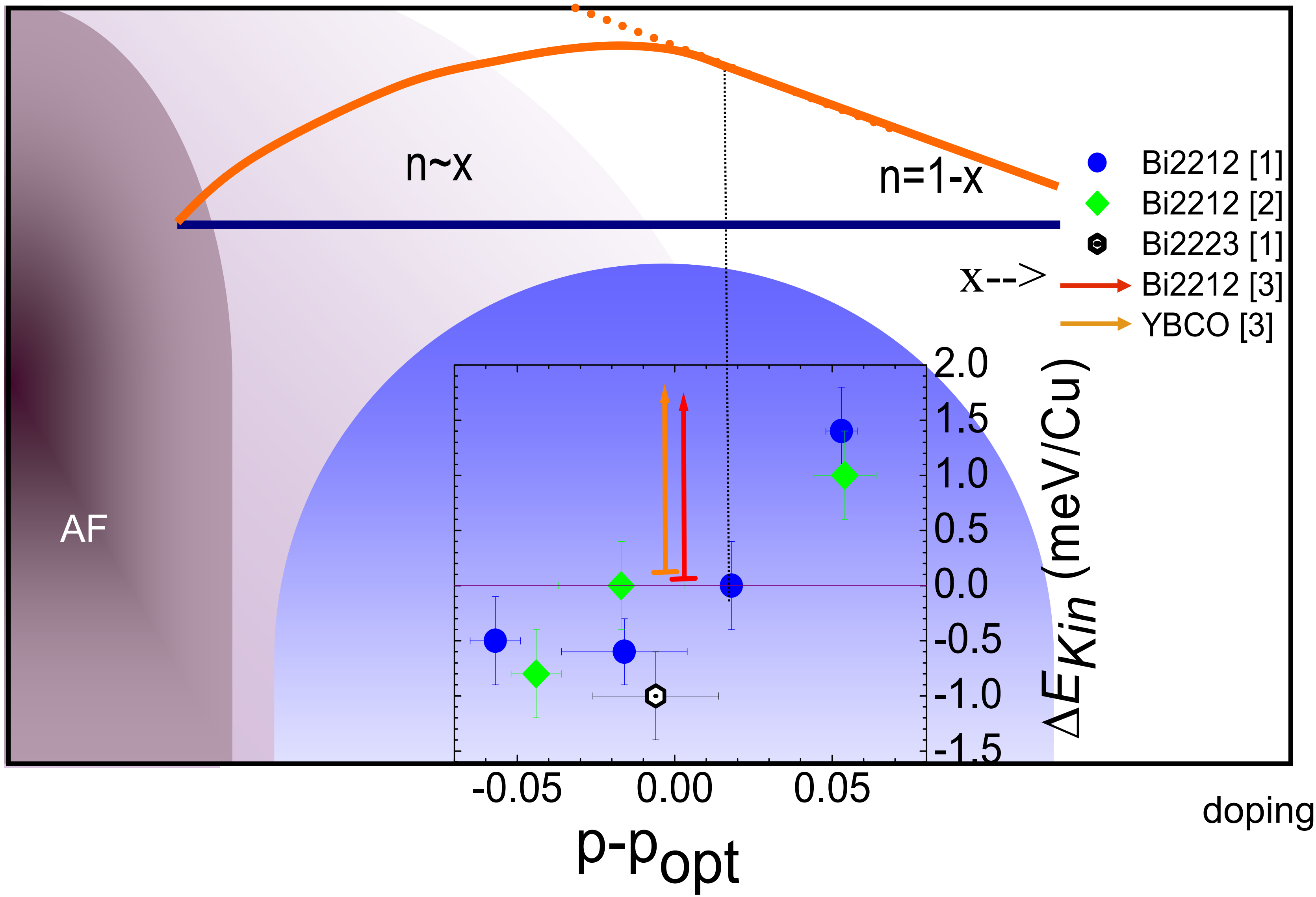


H.J.A.Molegraaf *et al*, Science **295**, 2239 (2002)
A.B.Kuzmenko *et al*, cond-mat/0503768, subm. to PRB

F. Carbone *et al*, to be published,

The doping dependence of the SW in Bi2212

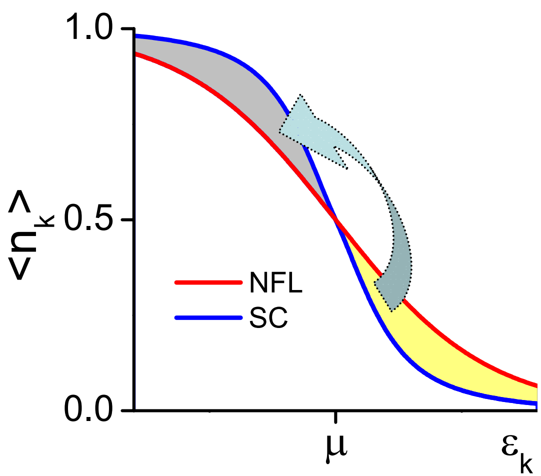




[1] Molegraaf et al, Science 295, 2239 (2002), Carbone et al, submitted to Phys. Rev. Lett. (2005)
[2] Santander-Syro et al, Europhys. Lett 62, 568 (2003), Deutscher et al cond-mat 0503073

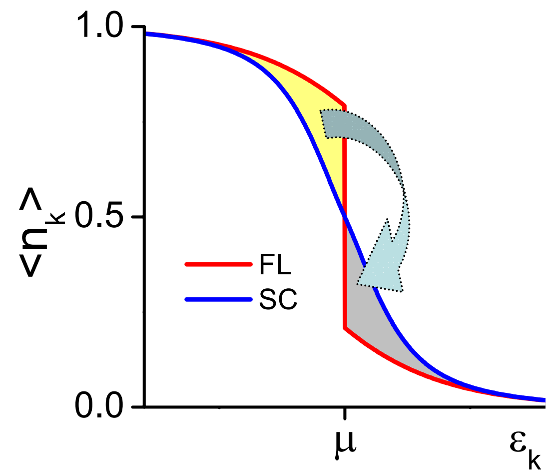
SC-induced change of $\langle n_k \rangle$

Non-FL scenario
(kinetic energy lowering)



Superconducting state more normal than the normal state

Fermi-liquid BCS scenario
(potential energy lowering)



Normal state more normal than the superconducting state

CONCLUSIONS

The low frequency SW in the optimally and under-doped samples increases, in agreement with the calculations base on the Hubbard and t-J models

The SW redistribution changes sign in the overdoped regio

Normal state SW temperature dependence:

$$K_{fc}(T) = K_{fc}(0) - \eta\left(k_B T\right)^2 / K_{fc}(0)$$

Strong renormalization of the temperature coefficient

$$\eta_{\exp} \approx 5 * \eta_{\text{non-correlated}}$$