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Workshop on Novel States and Phase Transitions in Highly Correlated Matter

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Superconducting-induced spectral weight transfers in $Bi_2Sr_2CaCu_2O8+\delta$: BCS-like to unconventional superconductivity crossover

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These are preliminary lecture notes, intended only for distribution to participants

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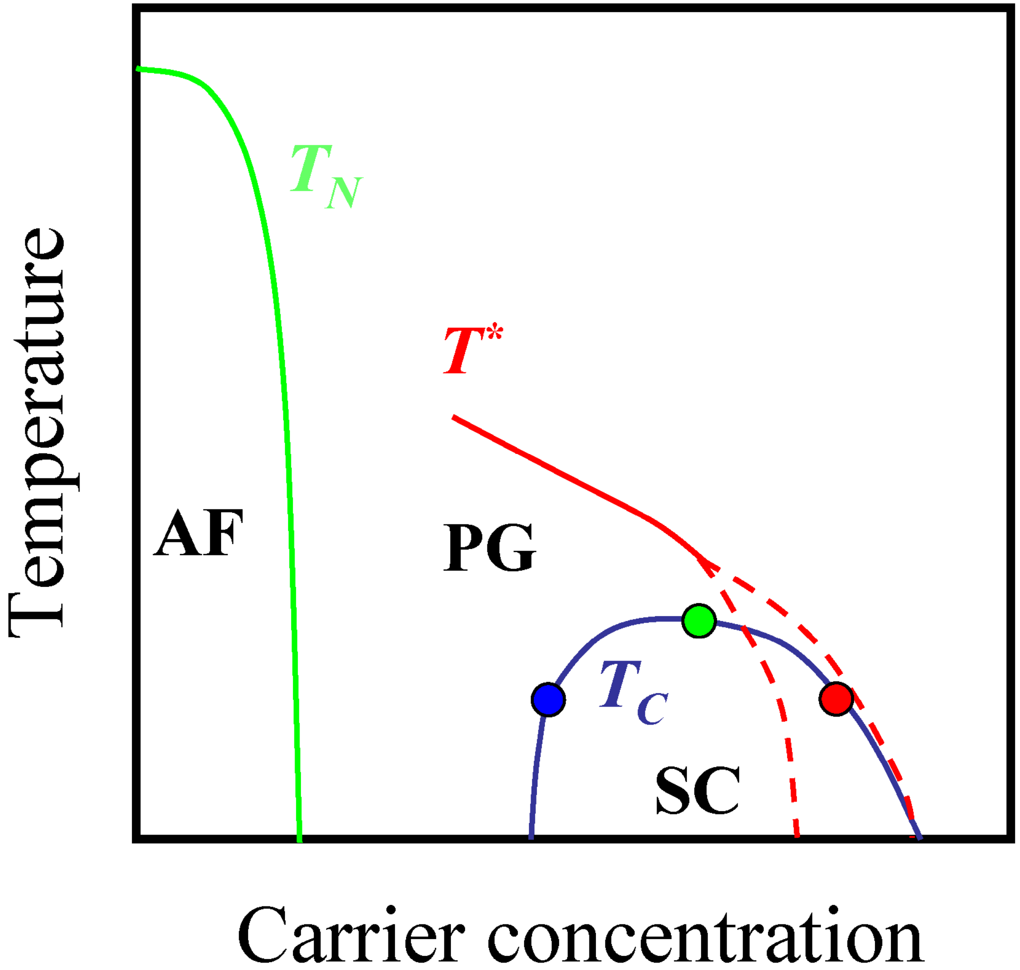
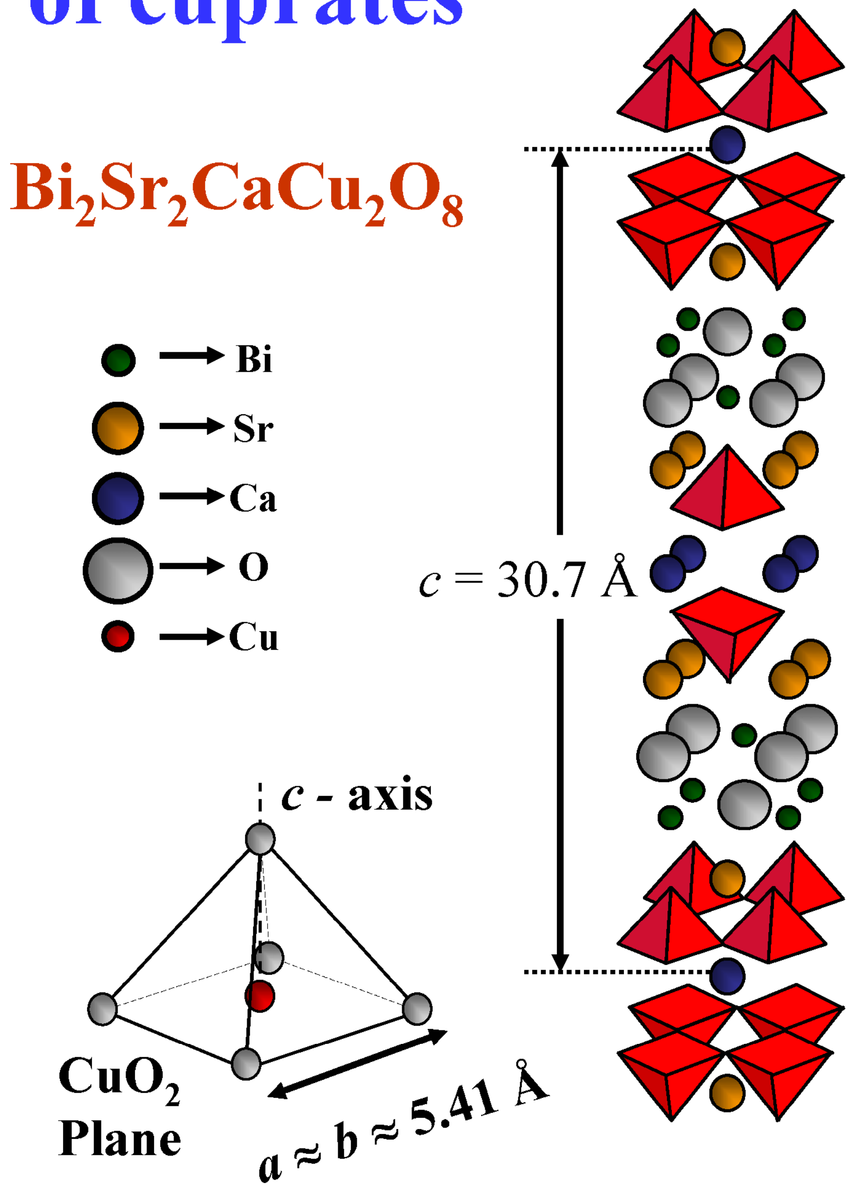
Laboratoire de Physique des Solides - Orsay

R. Lobo, N. Bontemps } ESPCI - Paris
IR spectroscopy

Z. Konstantinovic, Z. Li, H. Raffy } LPS – Orsay
Samples

Some generalities of cuprates



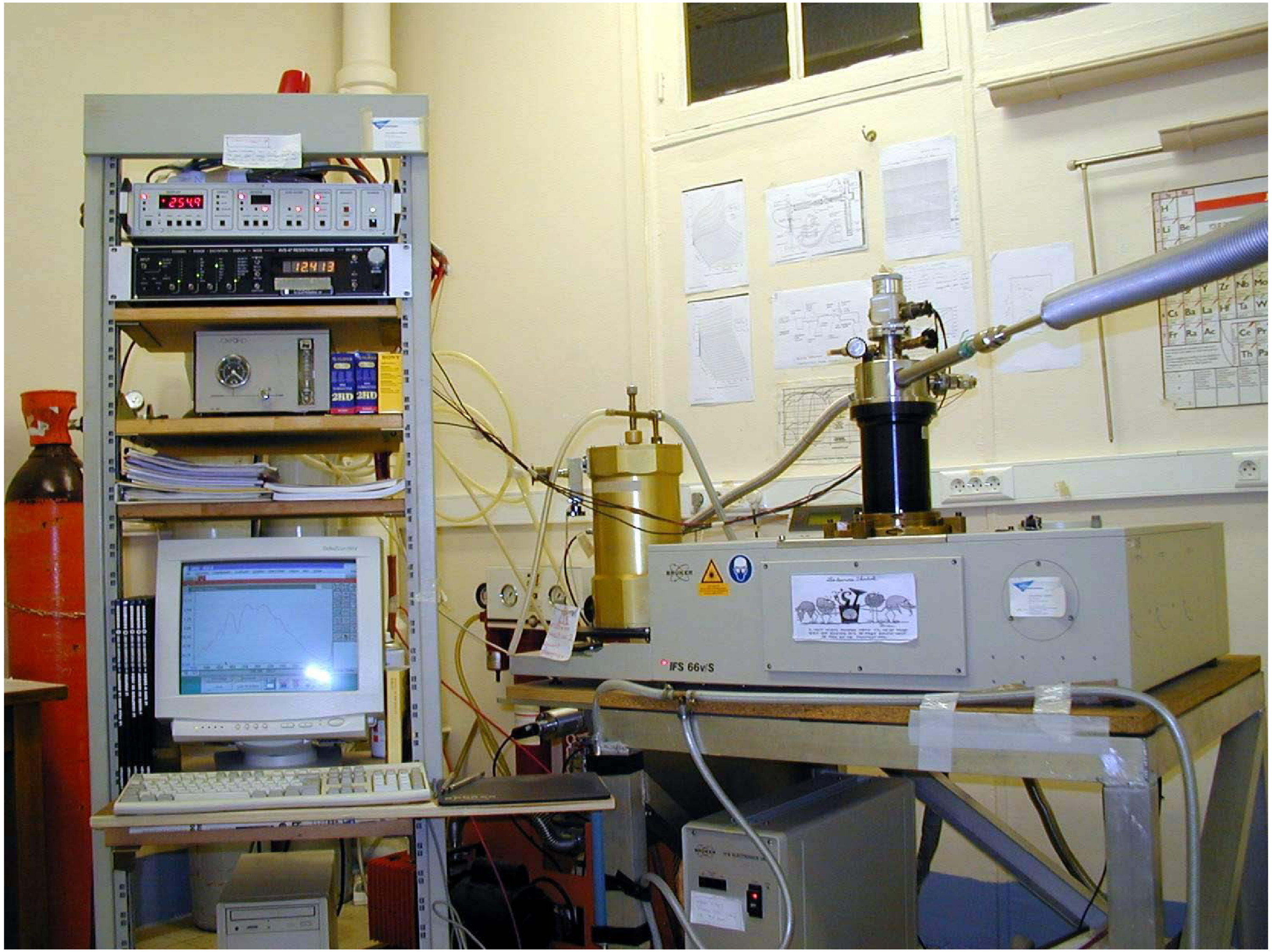


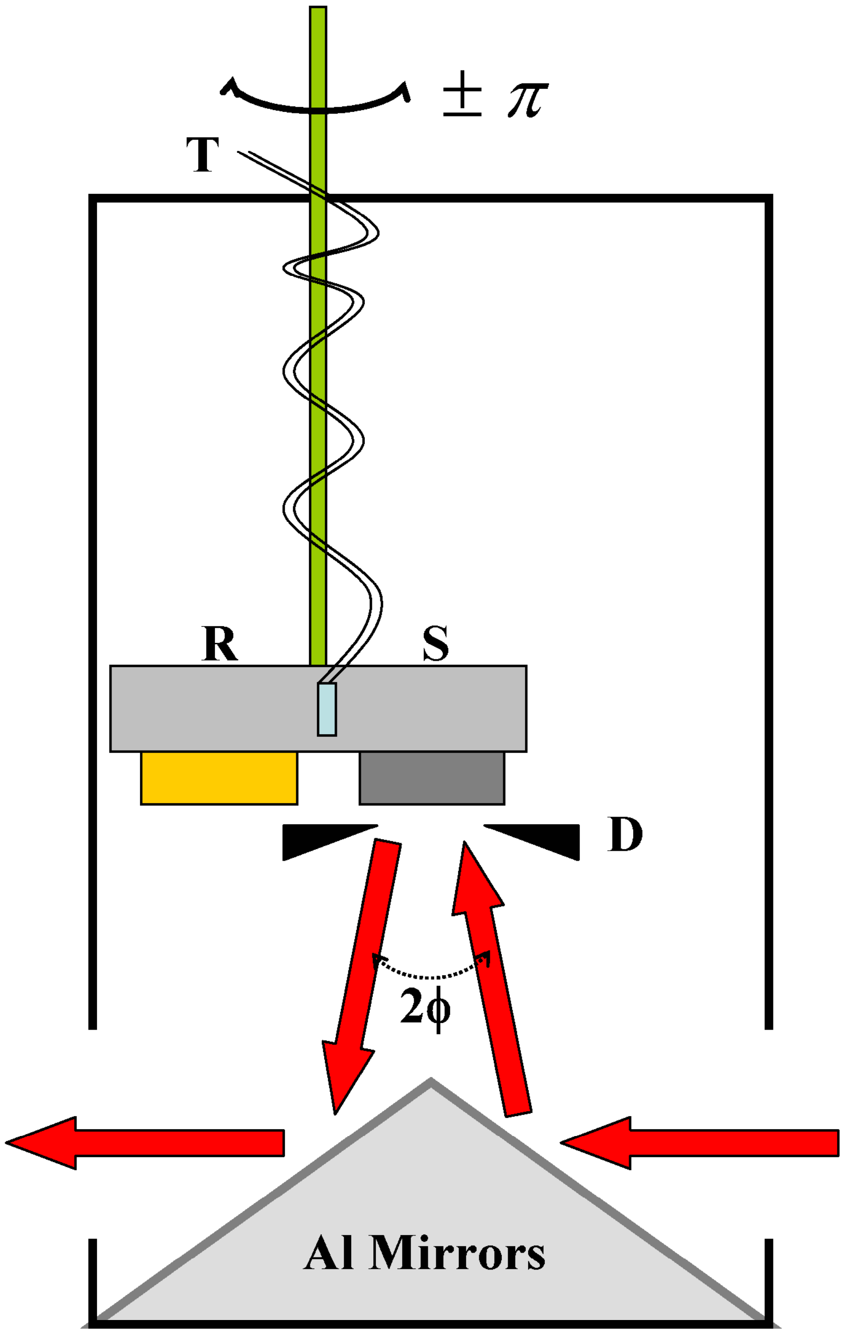
Problems studied

FROM UNDERDOPED TO OVERDOPED

- **Energy scale of the excitations that are modified by the superconducting transition.**
- **Superconducting-induced kinetic energy change of the in-plane charge carriers.**

The art of infrared reflectivity measurements

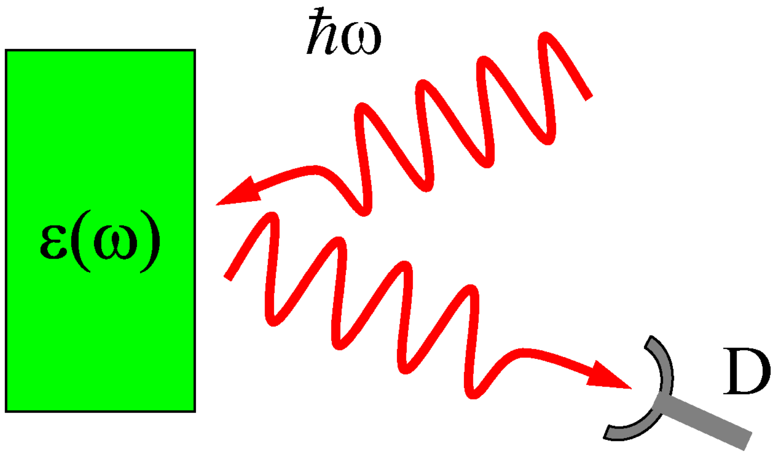

IFS 66v/S



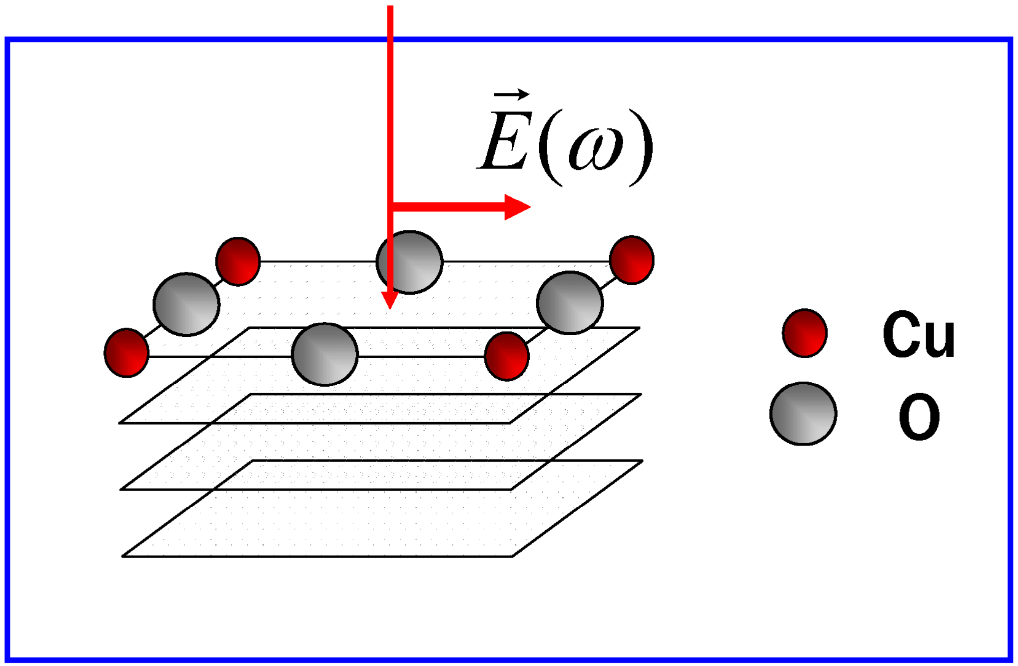
The sample holder

- $\Phi < 8°$
- Alignment S/R better than 10^{-3} rad

From reflectivity to conductivity



Normal incidence



Optical response of the charge carriers

Reflectivity R(ω) → σ(ω) = Complex conductivity

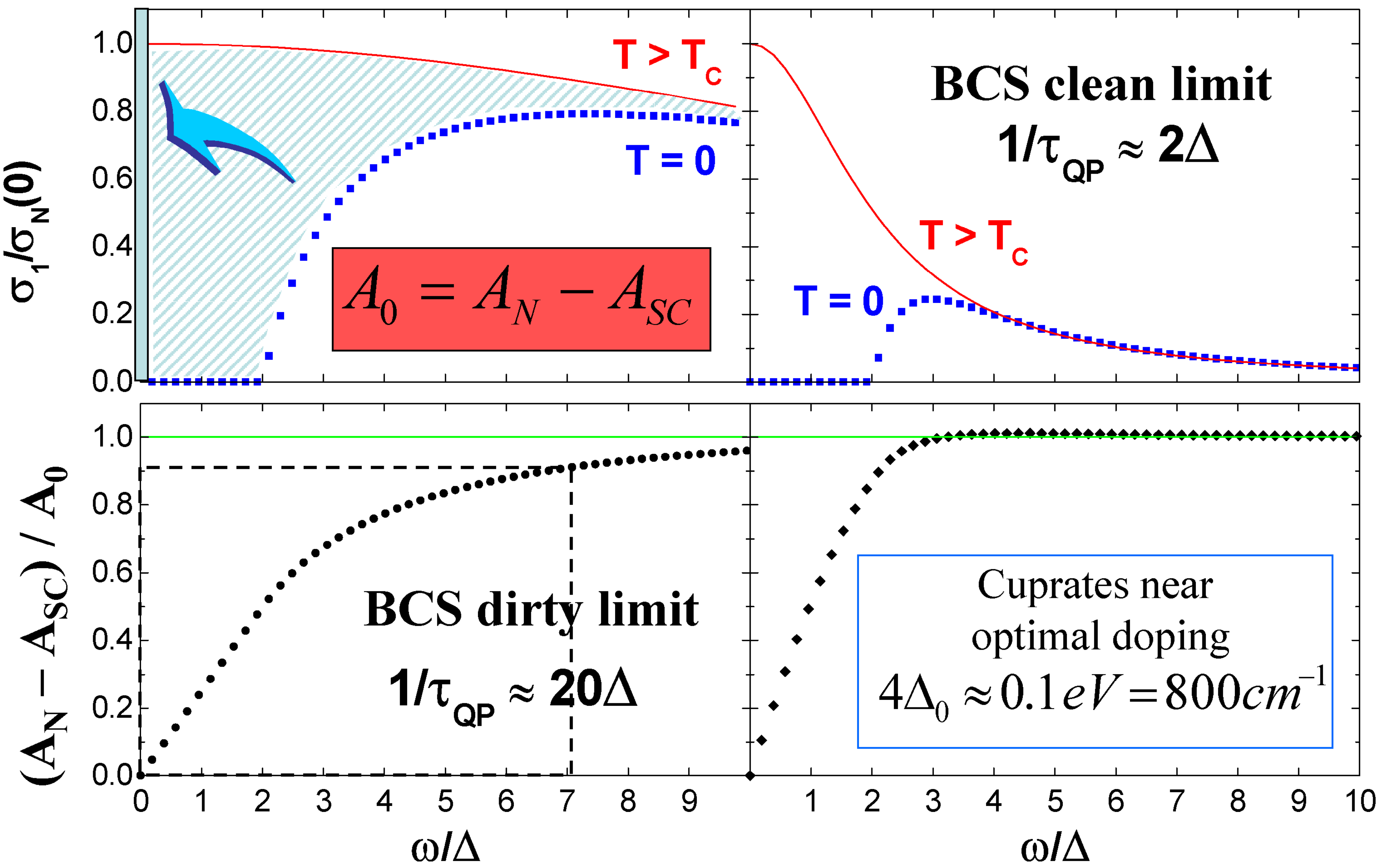
Re [σ(ω)] ~ Rate of electromagnetic energy absorption per unit volume

« OSCILLATOR STRENGTH » SUM RULE

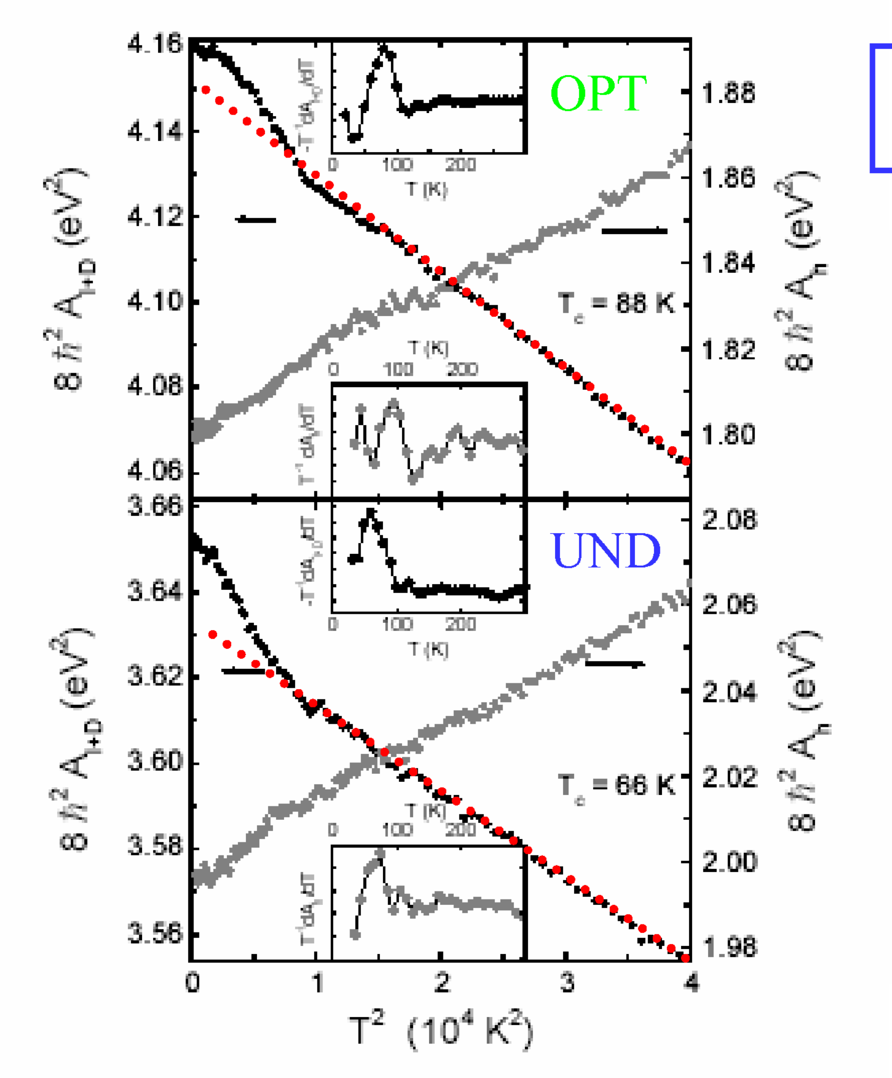
$$\int_0^\infty \mathrm{Re}[\sigma(\omega)]\,d\omega = \frac{\pi}{2}\frac{ne^2}{m_e}$$

n [m^{-3}] = Total density of carriers
$\boldsymbol{m_e}$ [Kg] = Carrier bare mass
e [C] = Electron charge

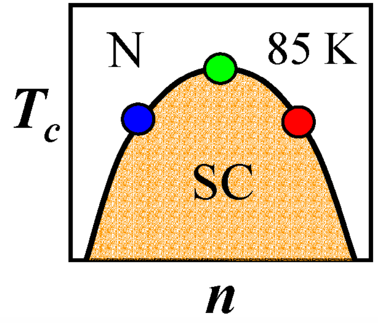
BCS superconductors: the Ferrel-Glover-Tinkham sum rule

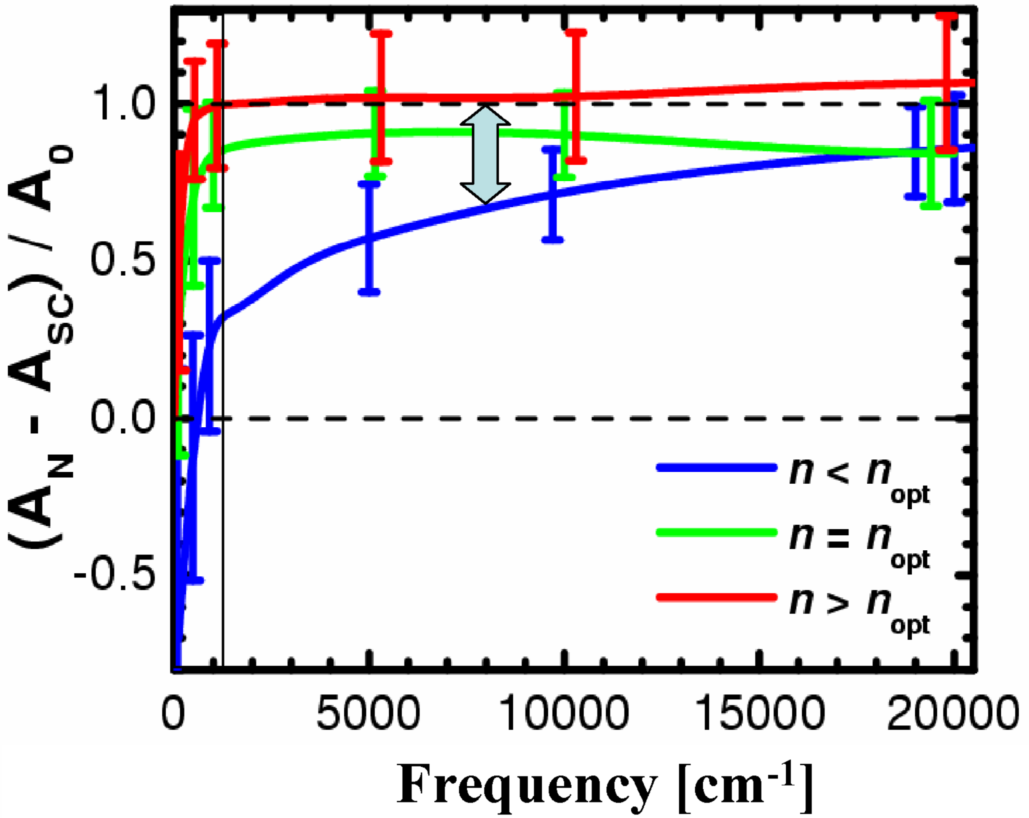


Previous results on underdoped to optimally-doped Bi-2212…



$\Delta E_{kin} \approx 1$ meV

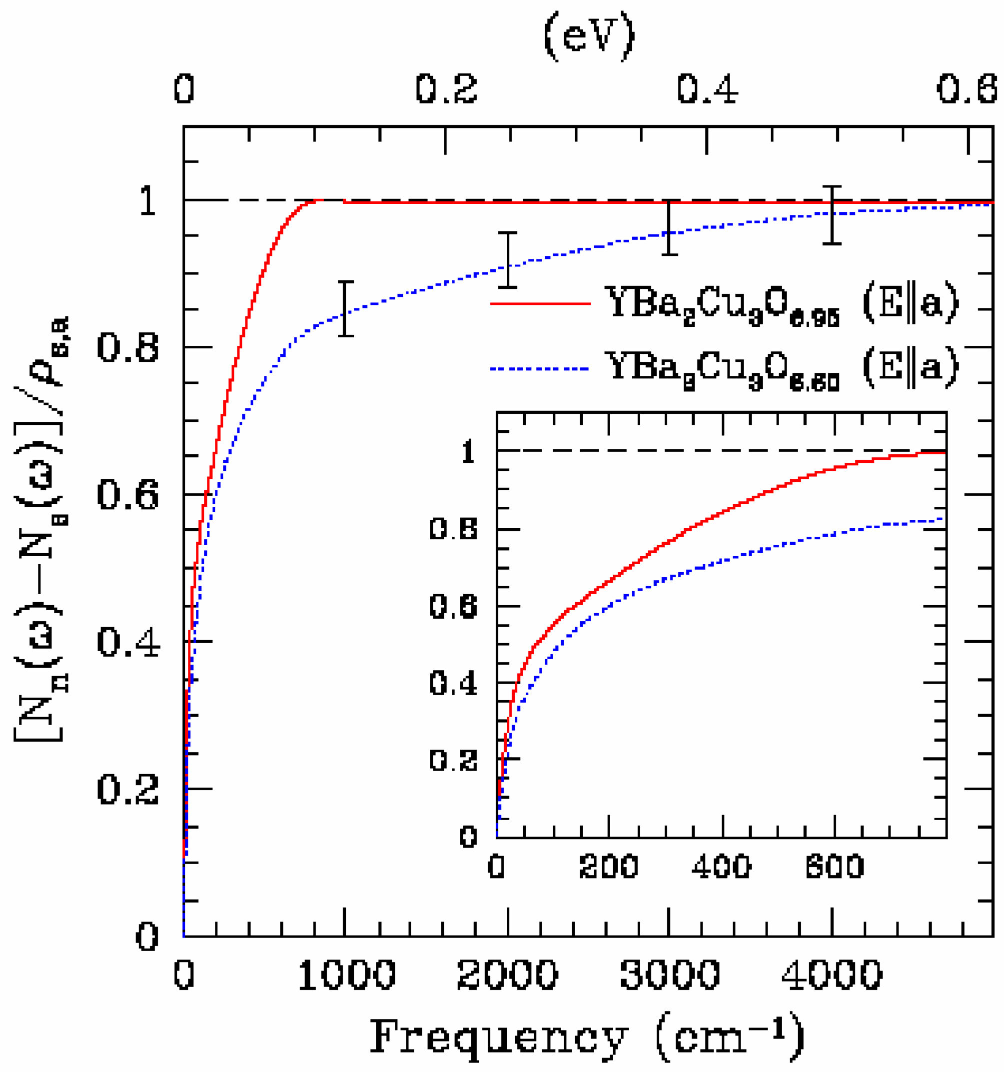




H. Molegraaf *et al.*, Science **295**, 2239 (2002)

A. F. Santander-Syro *et al.*, EuroPhys. Lett. **62**, 568 (2003)

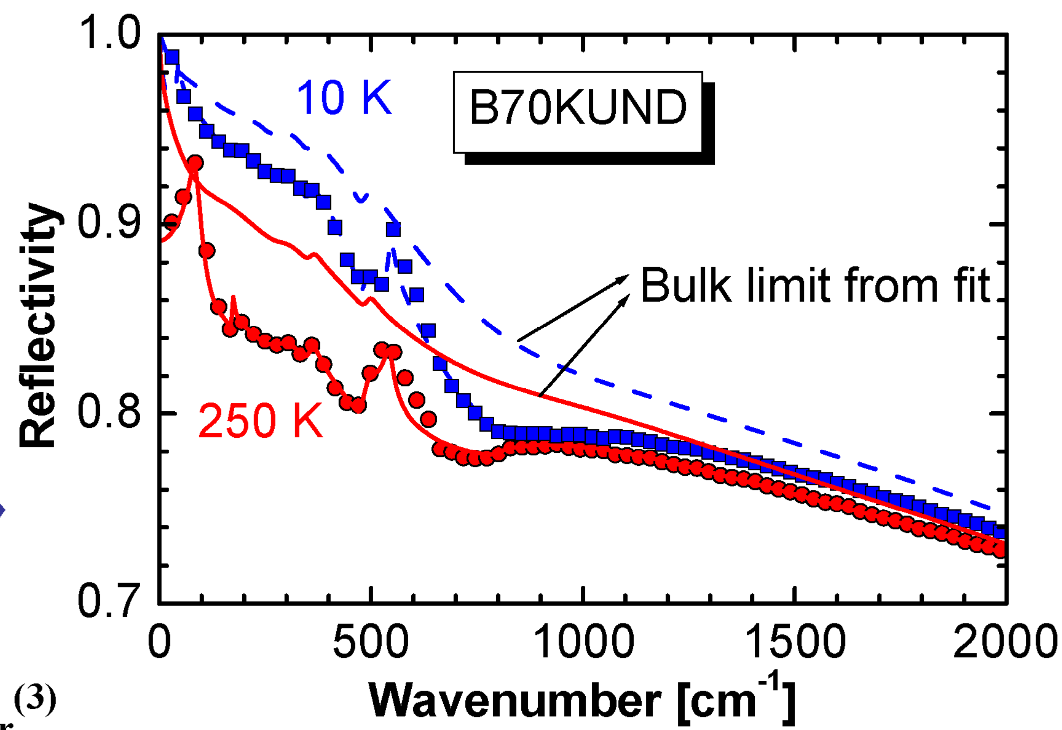
Consistent results in clean-limit underdoped YBCO-6.6

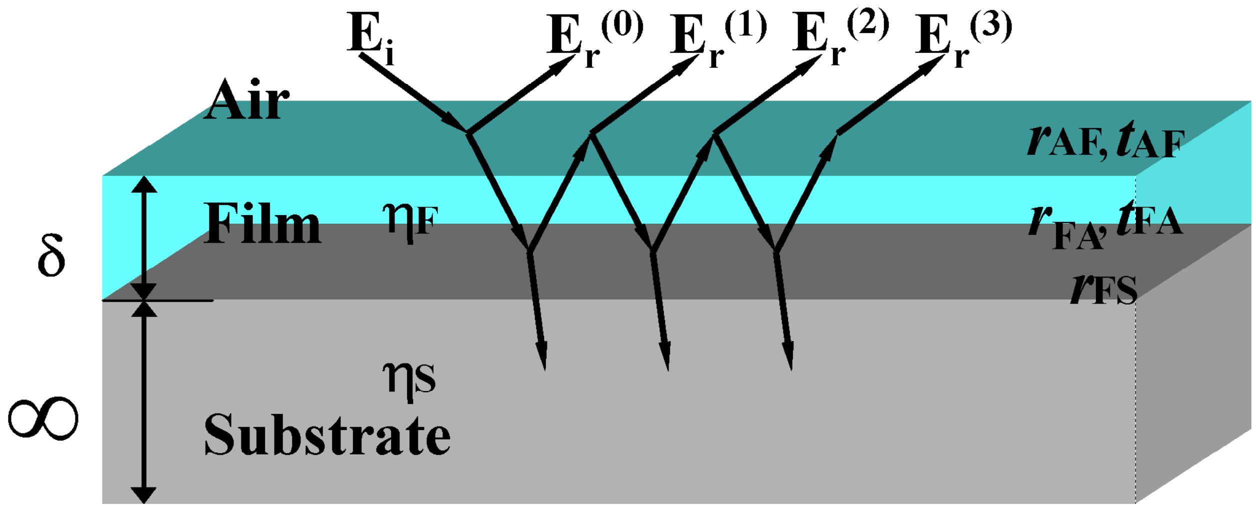


C. Homes *et al.*, PRB **69**, 0024514 (2004).

Temperature dependencies require unprecedented accuracy

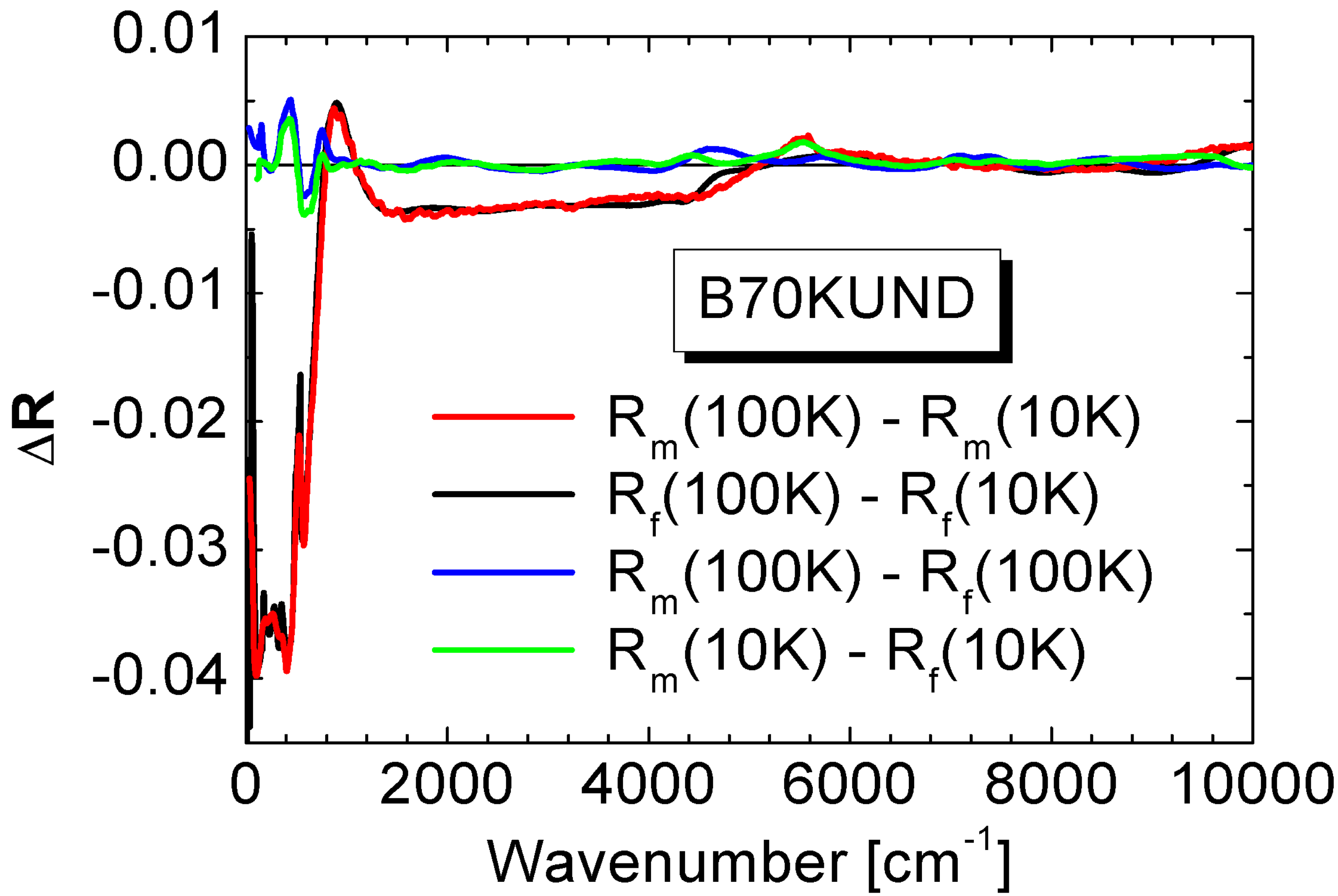
→ State of the art thin-films
Epitaxial
Large surface (36 mm²)
No intergrowth phases
Stoichiometry 2212





$$\sigma_{bulk}(\omega)$$

Resolving 0.1% in reflectivity



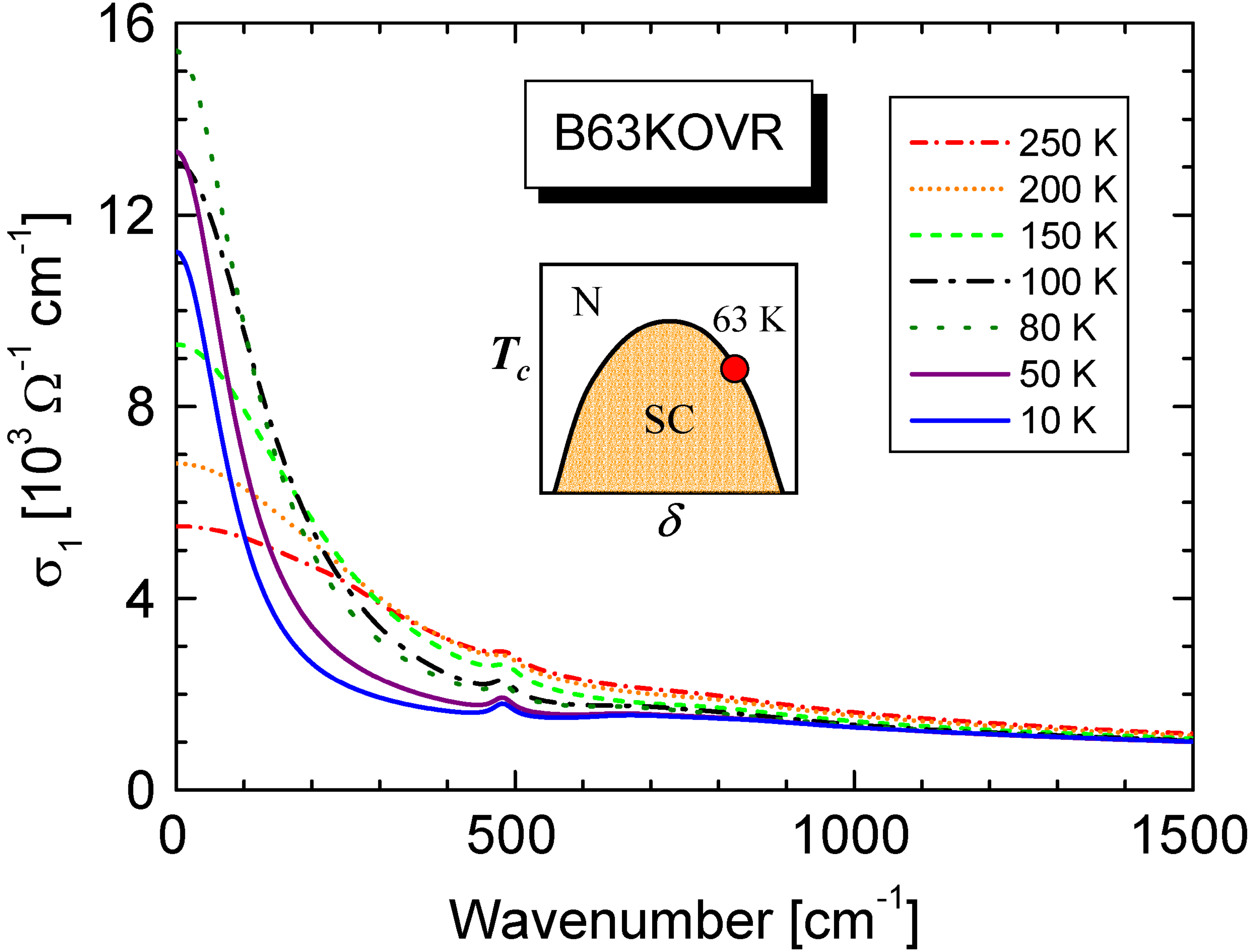
Underdoped material:

$R_N - R_{SC} \sim 0.4\%$ in the mid-infrared

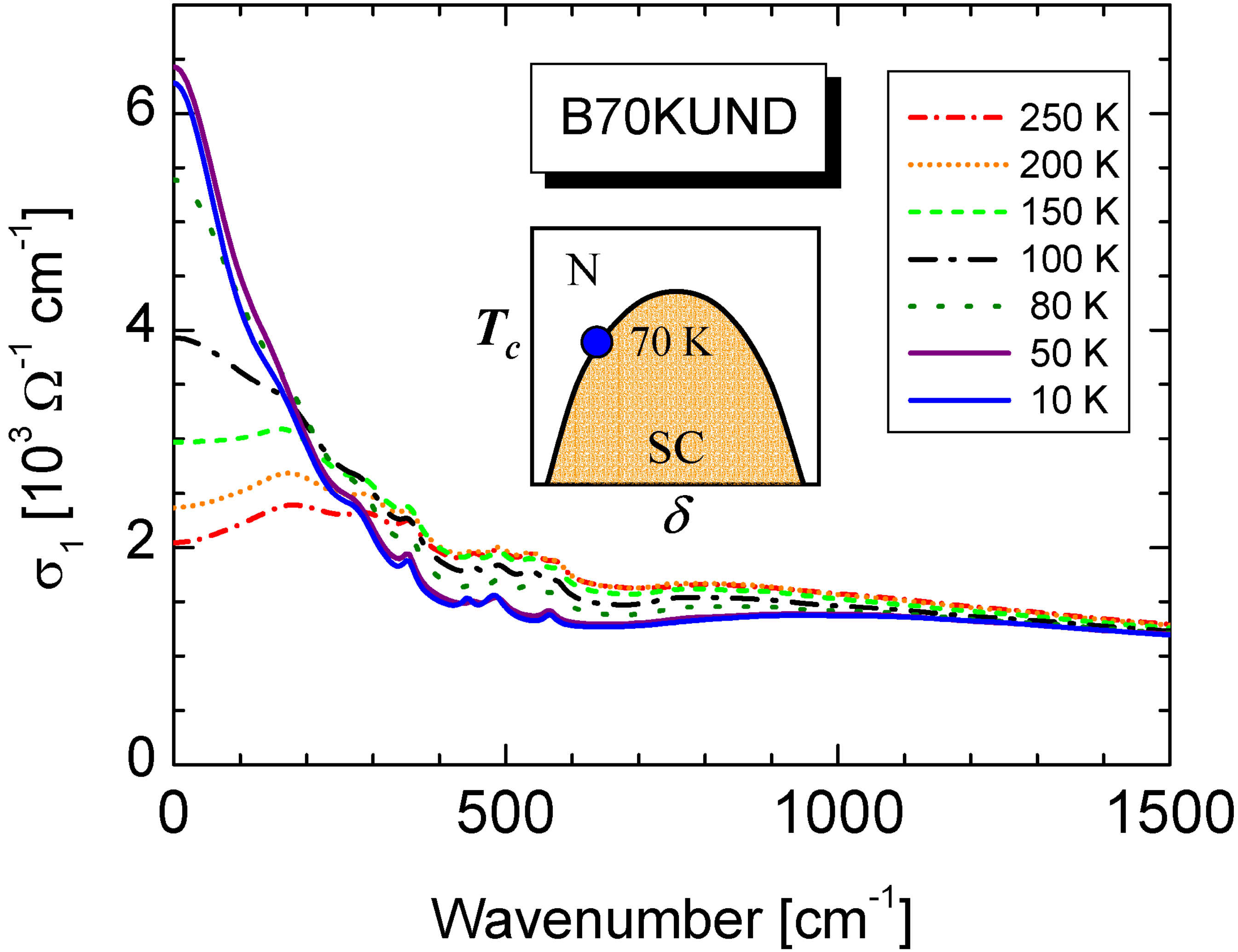
→Spectral weight redistribution up to ~ 1.5 eV

Overdoped material: $\Delta R < 0.1\%$ (not shown)

Conductivity of CuO_2 planes in overdoped Bi-2212



Conductivity of CuO_2 planes in underdoped Bi-2212



Significant residual «free carrier» contribution in the SC state: a rather general characteristic of underdoped samples?

See:

- **Bi-2212**: A. V. Puchkov *et al.*, PRL **77**, 3212 (1996).
- **YBCO 6.6**: C. Homes *et al.*, PRB **69**, 0024514 (2004).
- **YBCO 6.9**: A. V. Boris et al., Science **304**, 708 (2004) (supplementary material)

Partial spectral weight

$$W(\omega_c, T) = \int_0^{\omega_c} \sigma_1(\omega, T)\, d\omega$$

→ In the normal state, integration starts at 0^+

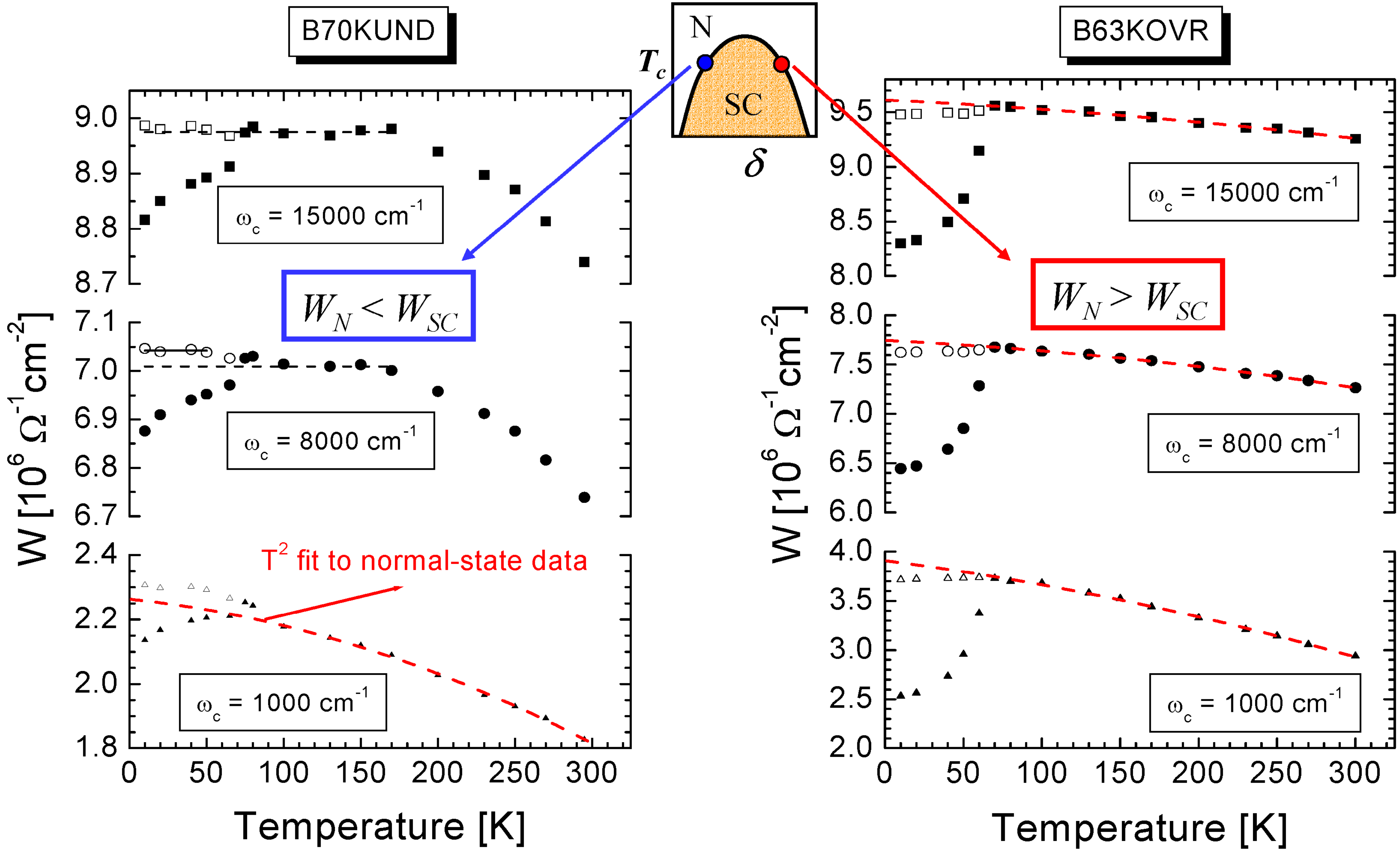
→ In the SC state, W includes the superfluid at $\omega = 0$

The evaluation of W requires:

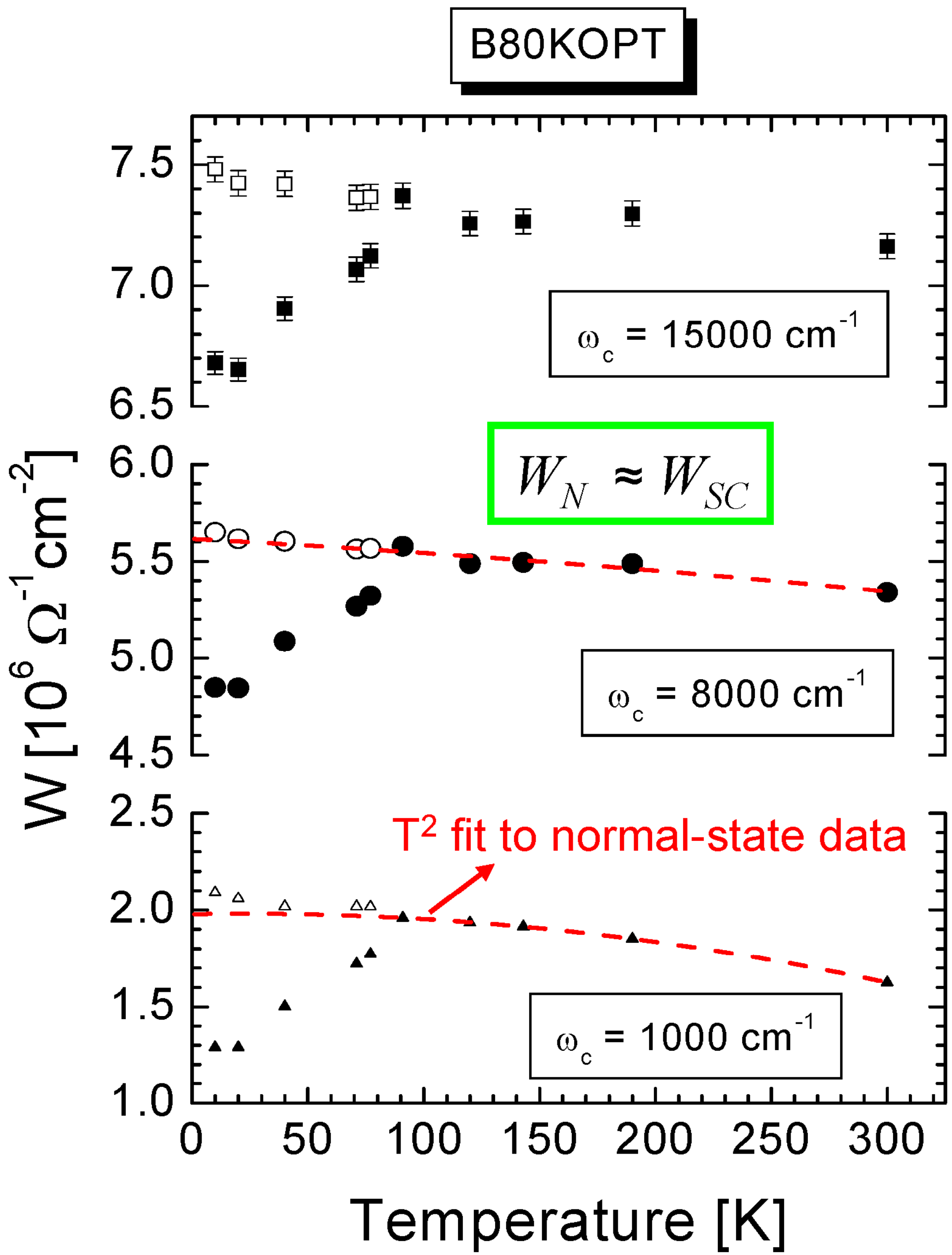
→ A good extrapolation of σ_1 from the first measured frequency to $\omega = 0^+$ ⇒ Cross-check with DC resistivity

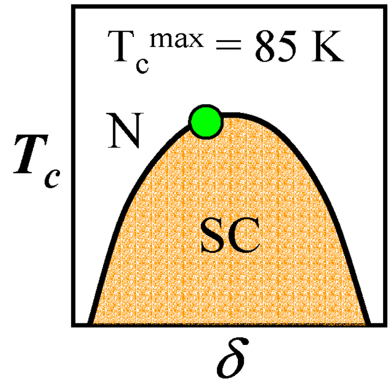
→ The knowledge of the superfluid density ρ_S in the SC state ⇒ Directly from σ_2 at low frequencies (London model)

SC-induced changes of intraband spectral weight: BCS-like to unconventional SC crossover



At the crossover vicinity: spectral weight changes at near-optimal doping





Single-band Hubbard model and kinetic energy change (in the CuO_2 plane)

$$W_{band} = \int_0^{\Omega_P} \sigma_1(\omega) d\omega = \frac{\pi \varepsilon_V}{2} \frac{e^2}{\hbar^2} \frac{a^2}{V} \left(-E_{kin}\right)$$

$$E_{kin}^{N} - E_{kin}^{SC} = \frac{2}{\pi} \frac{\hbar^2}{e^2} \frac{V}{a^2} \left[W_{band}^{SC} - W_{band}^{N}\right]$$

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

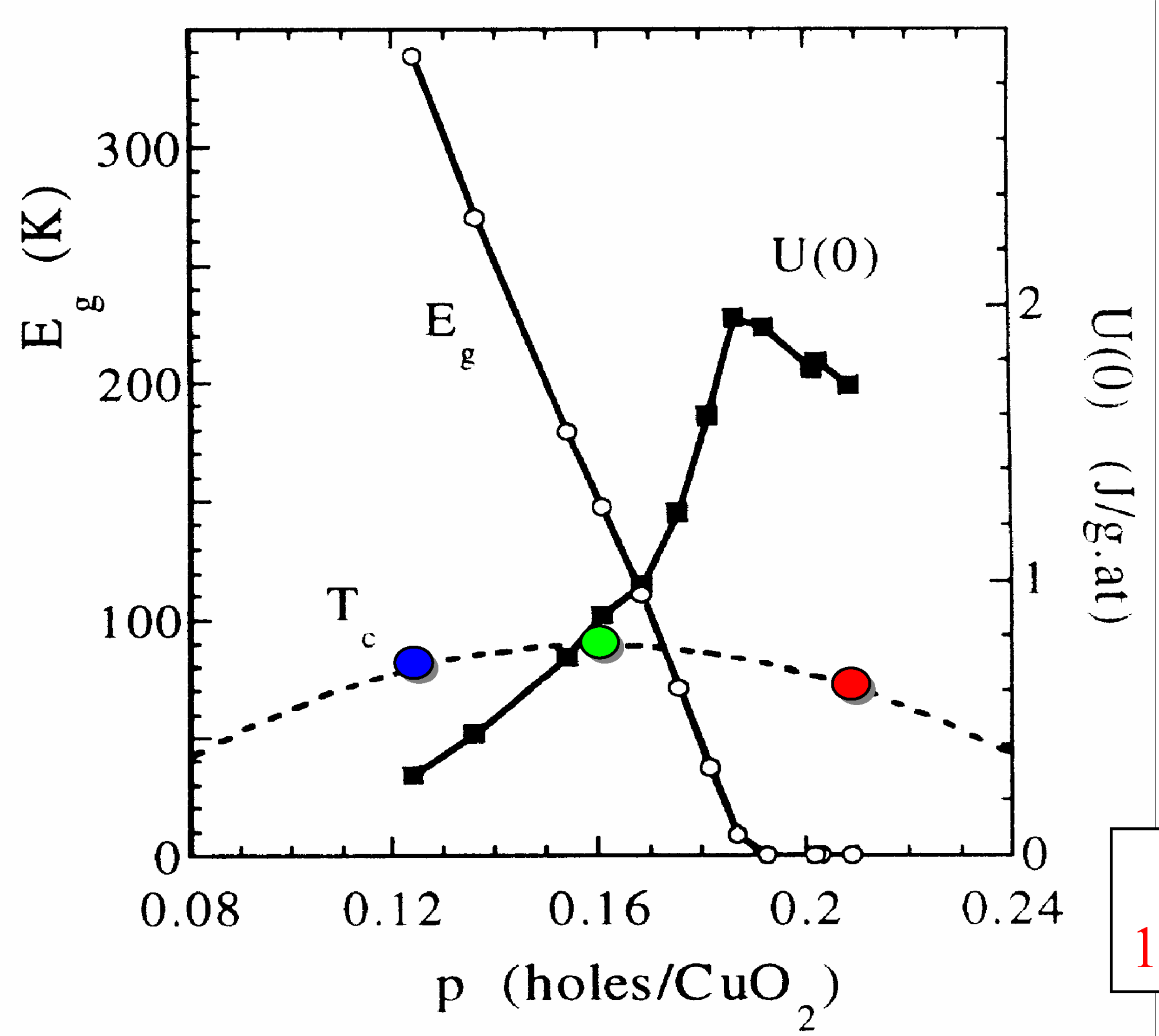
BCS superconductors: kinetic energy change

$$\underbrace{E^{N}_{total} - E^{SC}_{total}}_{} = \underbrace{\left[\overbrace{\frac{1}{2}N(0)\Delta^2}^{U_{cond}} - \frac{\Delta^2}{V_{int}}\right]}_{\Delta E_{kin}} + \underbrace{\frac{\Delta^2}{V_{int}}}_{\Delta E_{pot}}$$

$$N(0)V_{int} < 1 \quad \Rightarrow \quad \boxed{E^{N}_{kin} < E^{SC}_{kin} \text{ in BCS}}$$

- **P. G. de Gennes**, Superconductivity of Metals and Alloys, Addison-Wesley, 1989

Bi-2212: Condensation energy



Bi-2212
1 J/g-at = 0.08 meV per Cu

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

Bi-2212: kinetic energy changes

Underdoped Bi-2212

$$E_{kin}^{N} - E_{kin}^{SC} \approx 0.8 \pm 0.2 \,\text{meV per Cu}$$

Compare to condensation energy:

$$U_{o} < 0.08 \text{ meV/Cu}$$

Overdoped Bi-2212

$$E_{kin}^{N} - E_{kin}^{SC} \approx -(1.2 \pm 0.3)\,\text{meV per Cu}$$

$$\Rightarrow N(0)\mathrm{V}_{\mathrm{int}} \approx 0.2$$

CONCLUSIONS

UNDERDOPED Bi-2212

- **The formation of the superfluid condensate modifies the electronic excitations up to energies beyond 1 eV.**
- **This phenomenon can be assigned to a *decrease* of the carriers kinetic energy.**
- **The decrease in kinetic energy is large enough to account for the condensation energy.**

OVERDOPED Bi-2212

The electronic kinetic energy *increases* at the superconducting transition, displaying a BCS-like behavior.