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Workshop on
Novel States and Phase Transitions in Highly Correlated Matter

12 - 23 July 2004

In-plane charge dynamics and superfluid density in High-Tc superconducting cuprates

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Workshop on Novel States and Phase Transition in Highly Correlated Matter
July, 2004 (Trieste, Italy)

In-plane Charge Dynamics and Superfluid Density in High-T_c Superconducting Cuprates

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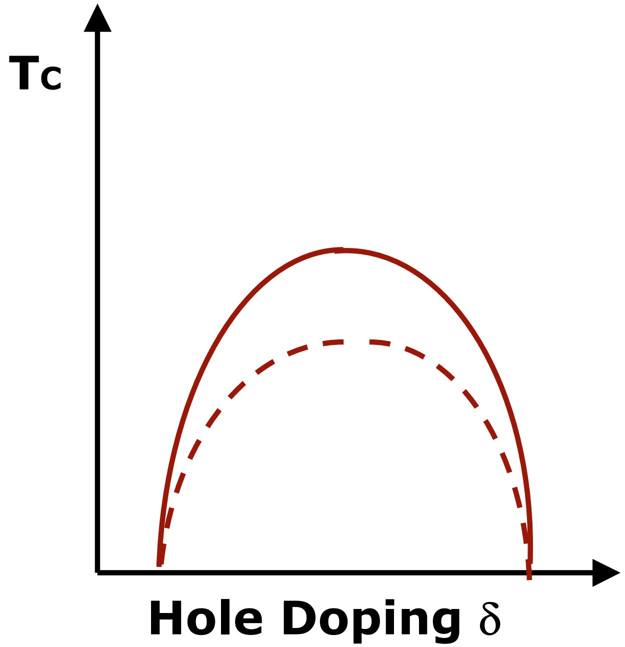
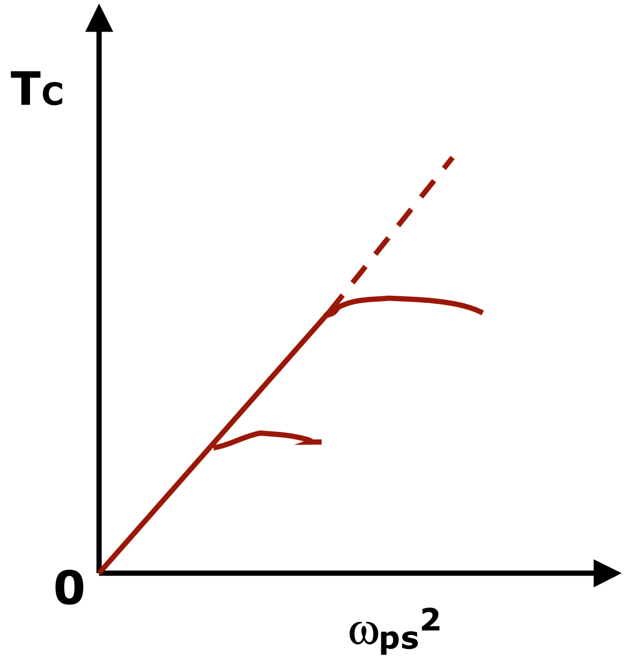
Subject:
(I) : Superfluid Density and Inhomogeneity
(II) : Development of F.S. and Normal State Optical Spectrum

Superfluid Density & Hole Concentration (ω_{ps}^2 and δ)





What determines T_c?
What determines ω_{ps}?

Background and Purpose

- **Superfluid Density** $\omega_{ps}^2 = (2\pi\lambda_L)^{-2}$
  μSR, Microwave, FIR results seem to be different.
  need to be re-examined.
- **Effect of inhomogeneous electronic state?**
  real space & ***k***-space inhomogeneity
  (stripes, pseudo-gap state...)

Purpose

- To measure a pure in-plane spectrum
- To estimate λ_L^{-2} and compare with the μSR data
- To examine the low-ω charge response

→ ***Peculiarity of the electronic state in HTSC***

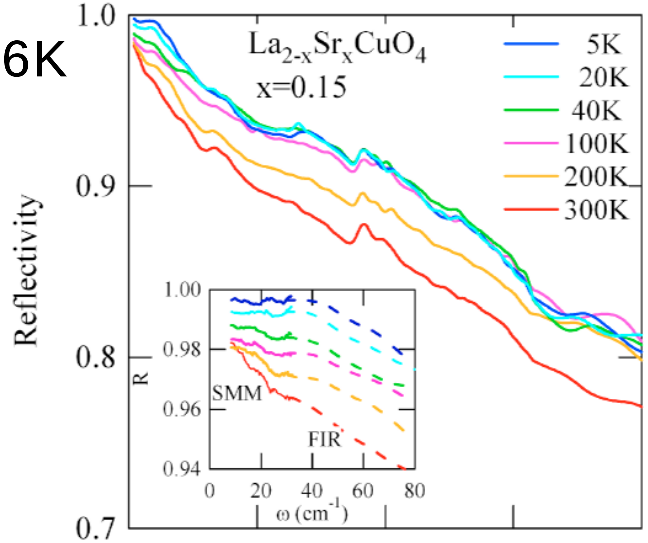
Experiments

Crucial Point

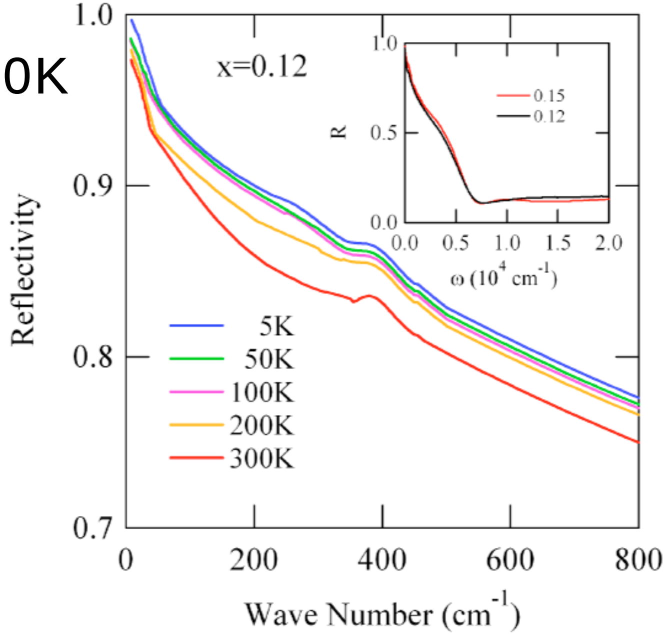
- Extraction of pure in-plane $\sigma(\omega)$
  to avoid the *c*-axis component admixture
  ex. Reflectivity measurement with E//a
  in s-polarized geometry
- Measurement down to the low-ω region
  to evaluate a residual $\sigma(\omega)$
  ex. Measurement in the millimeter- and
  sub-millimeter wavelength region

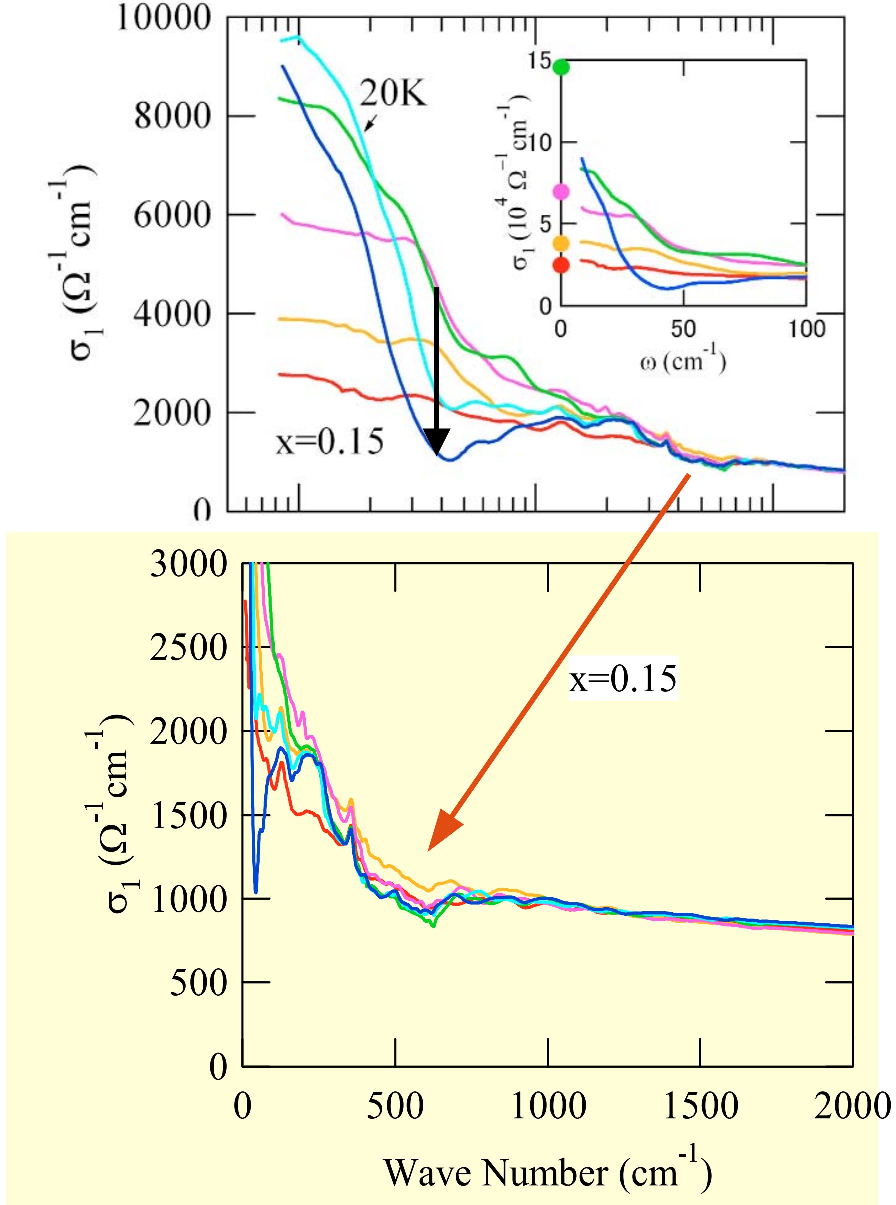
In-plane polarized spectra of $La_{2-x}Sr_xCuO_4$

$T_c = 36K$

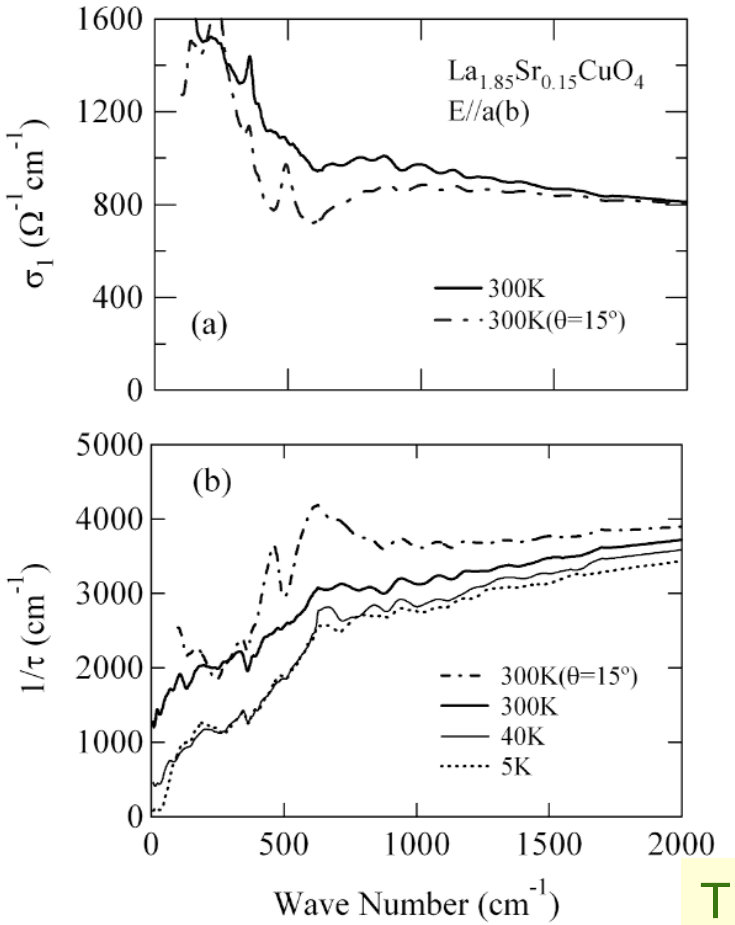


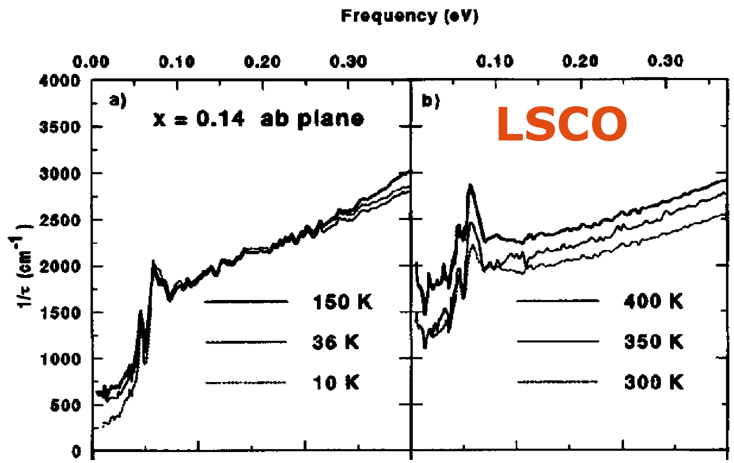
$T_c = 30K$





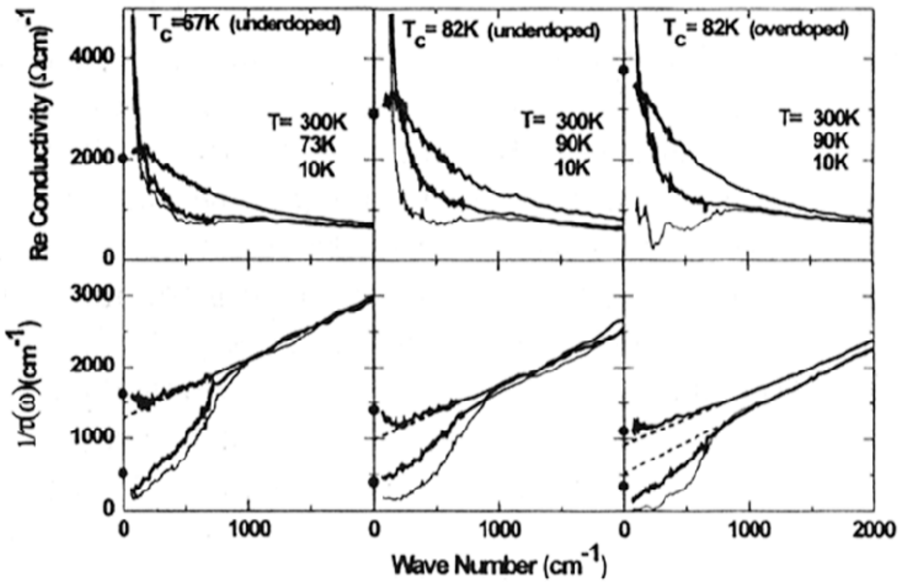
Kink in 1/$\tau(\omega)$





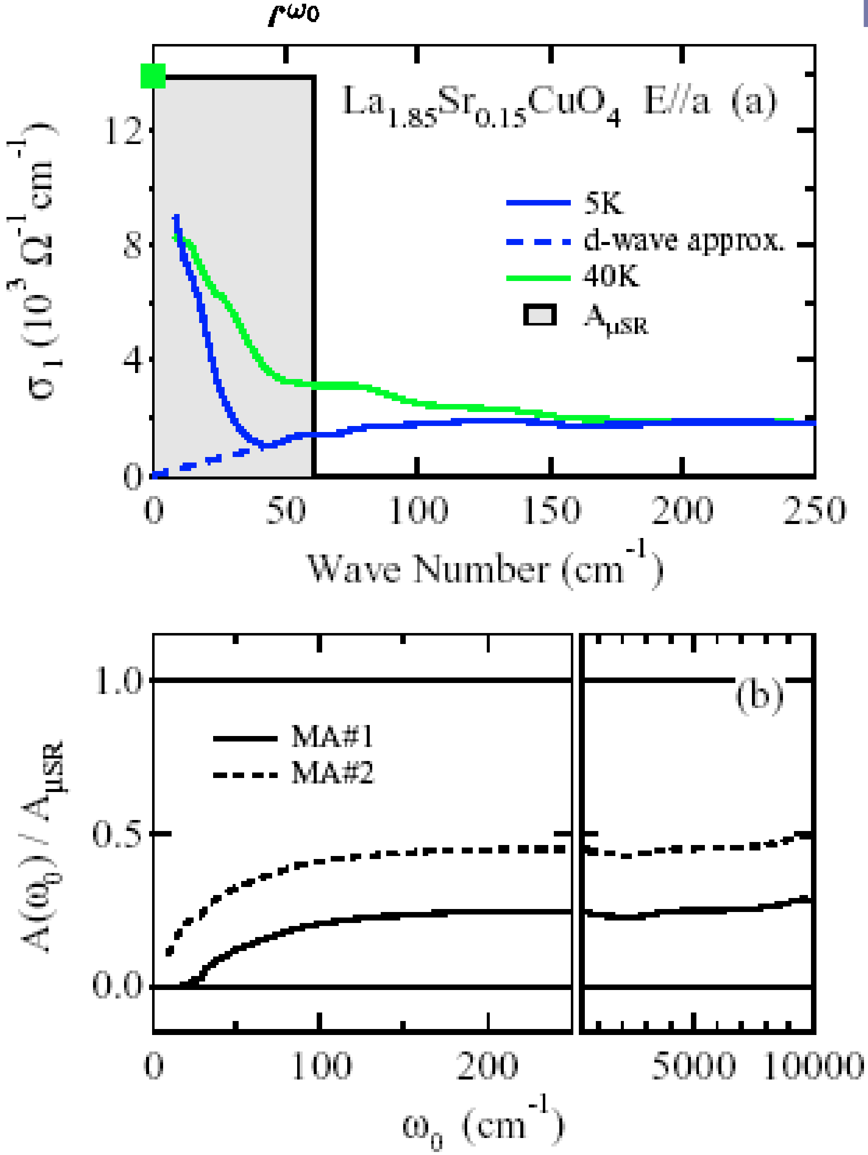
Startseva et al., PRB59, 7184 ('99)

BSCCO



The kink at ω~700cm^{-1} is neither related to a SC gap nor to pseudo-gap.

$$\rho_s = \frac{\omega_{ps}^2}{8} = \int_{0+}^{\omega_0} [\sigma_n(\omega,\ 0) - \sigma_s(\omega,0)]\, d\omega$$



Estimation of ω_{ps} from missing area in $\sigma_1(\omega)$

$A = \omega_{ps}^2/8 = 1/[8(2\pi\lambda_L)^2]$

With and without the low-ω peak:
A/A(μSR) = 0.3~ 0.5

→λ_L($10^4 cm^{-1}$)=400~ 530 nm
cf. λ_L=430 nm *by Somal et al.*
λ_L=400 ±100 nm (10GHz)
by Shibauchi et al.

>> λ_L (μSR) = 280±15nm
(for the same crystal)

For x=0.12
λ_L($10^4 cm^{-1}$)=990 nm
cf. λ_L=630 nm *by Dumm et al.*
(x=0.13? T_c=32K)
>> λ_L (μSR) = 310 nm

Estimation from $\sigma_2 (= \omega_{ps}^2 / 2\pi\omega)$

Large contribution from the residual conductivity

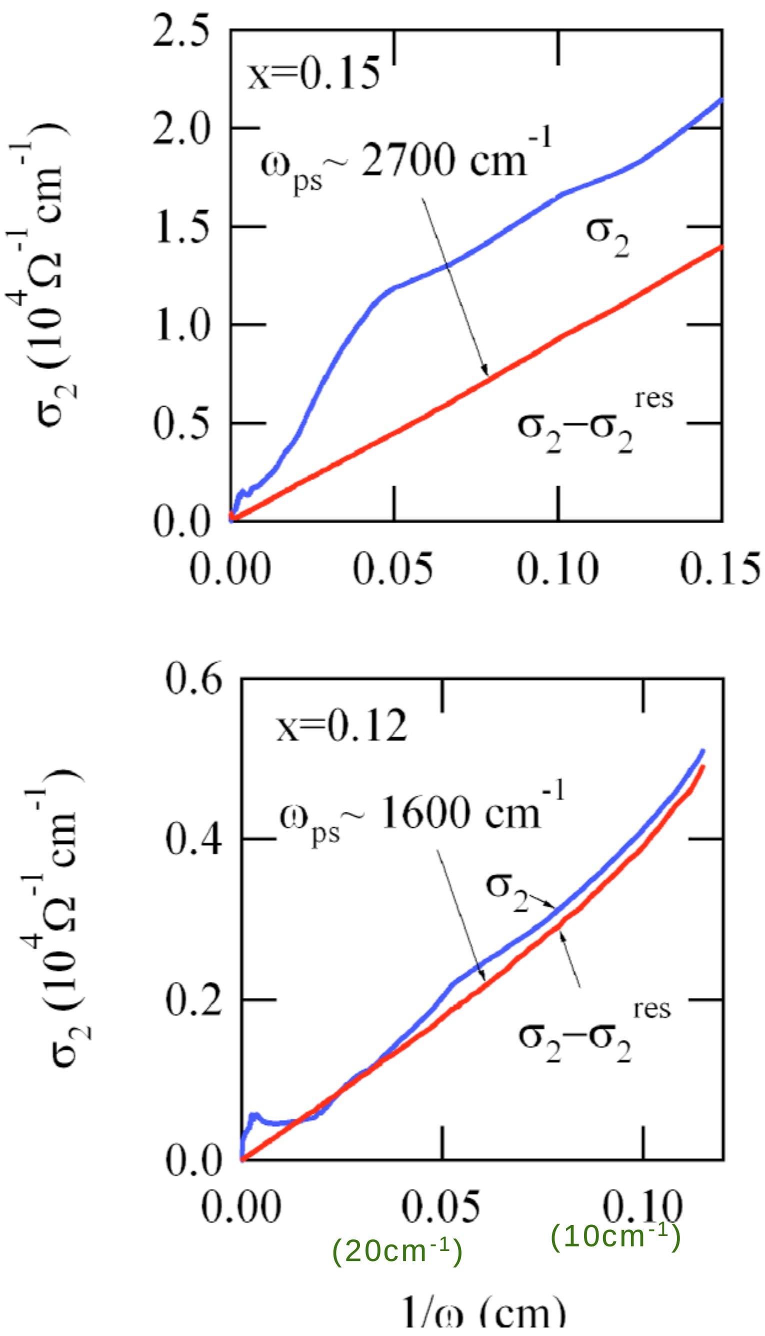
Consistent value of superfluid density

λ_L (x=0.15) =590 nm ↔ 530nm from σ_1

λ_L (x=0.12) =1000 nm ↔ 990nm from σ_1

→No remarkable contribution from high-ω region

FGT-sum rule holds.



Comparison with the μSR data

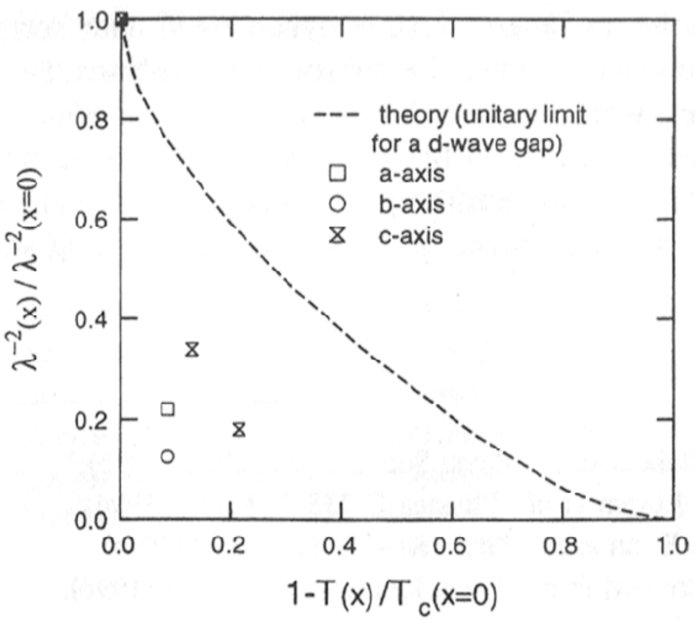
	LSCO x=0.15	LSCO x=0.12	YBCO (T_c=93K)	YBCO (77K)	YBCO (60K)	Bi-2212 (70K)	Tl-2201 (80K)
FIR λ_L (nm)	530	990	$116^{//b}$ $160^{//a}$	$240^{//a}$	280*	680**	240***
μSR λ_L (nm)	280	310	112	190	170-210	190	160

*C. Homes et al., Phys. Rev. B ('04). **Santader-Syro et al., Europhys. Lett. ('03)
***Puchkov et al., Phys. Rev. B ('95).
μSR data: Y. J. Uemura et al.('89), Ch. Niedermeyer et al.('93), J.E. Sonier et al.('97)

λ_L^{-2} (FIR) << λ_L^{-2} (μSR)
Commonly observed in HTSC?

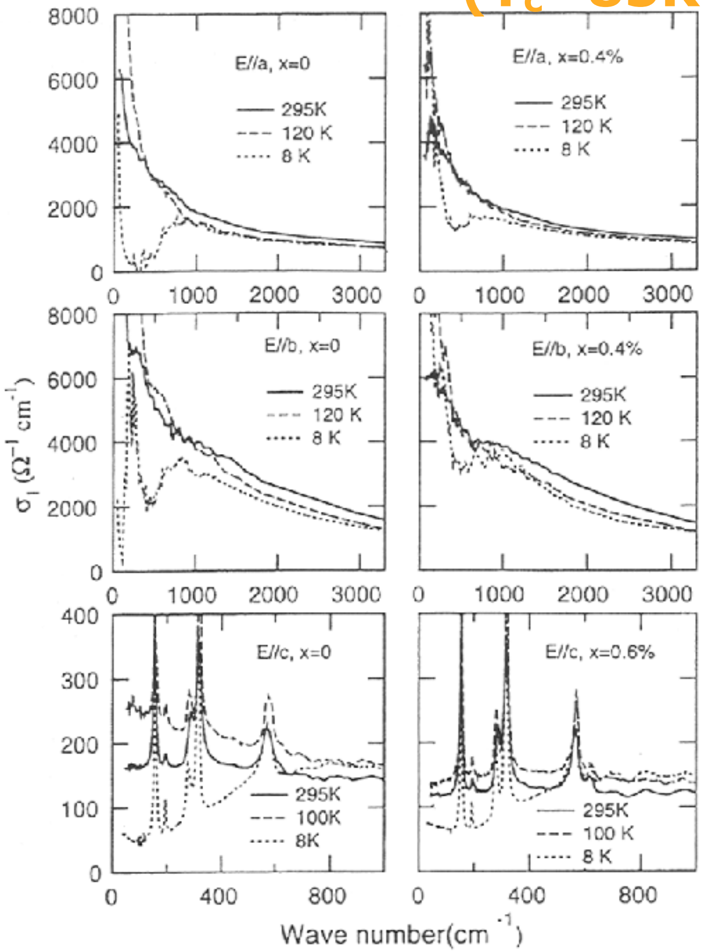
Impurity Effects on λ_L

Rapid suppression of superfluid density



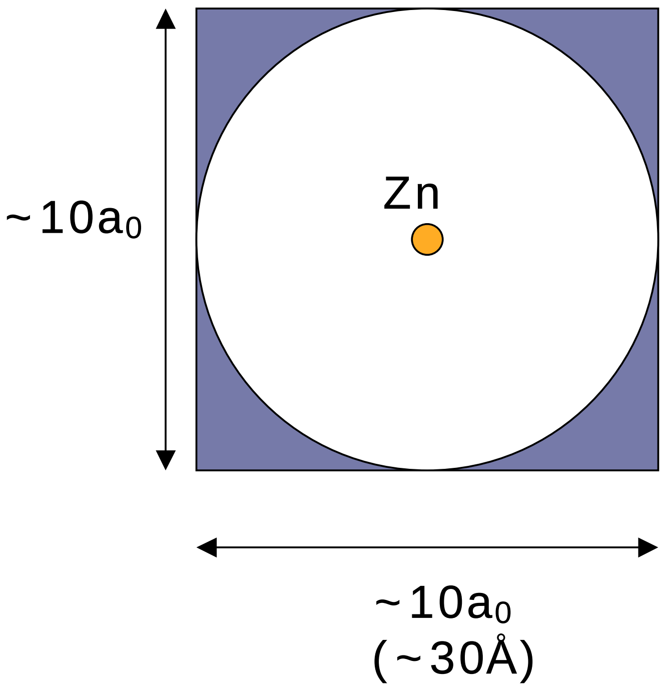
Pure YBCO

Zn0.4% (T_c=85K)



N. L. Wang et al. PRB (1998).

Local pair-breaking picture for short ξ superconductors



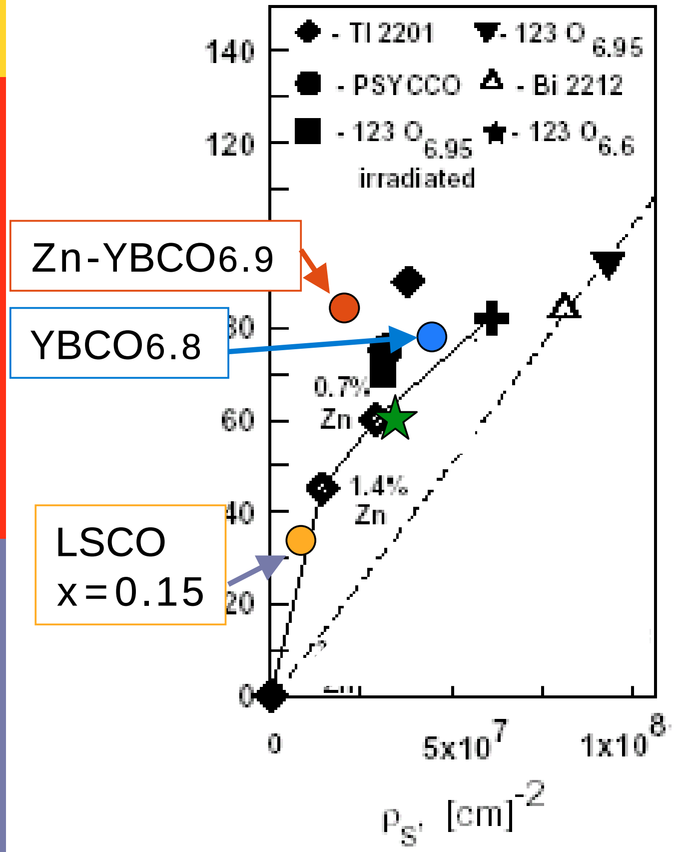
IF one Zn-atom destroys S.C. in the area with a diameter of 30Å,

1% Zn within the CuO_2-plane is enough to suppress S.C. over the whole area.

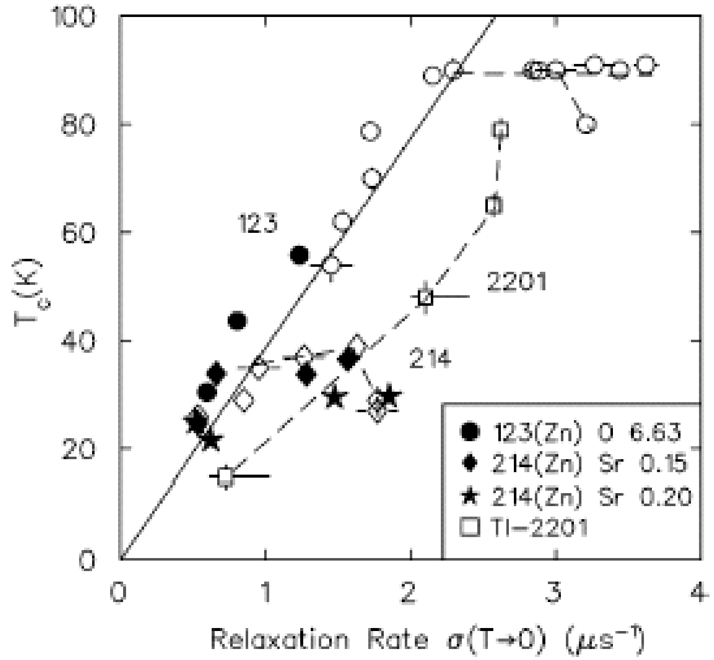
$YBa_2(Cu_{1-x}Zn_x)_3O_y$

x=0.66% → ~1% Zn in the plane

Deviation from the linear plot of $T_c \sim \rho_s$



D.N. Basov et al., PRL ('98).



B. Nachumi et al., PRL ('96).

Origin of discrepancy between FIR and μSR

Inhomogeneity

SC order parameter is not uniform in a crystal?

FIR: Average information of SC & non-SC area

μSR: More sensitive to the SC area

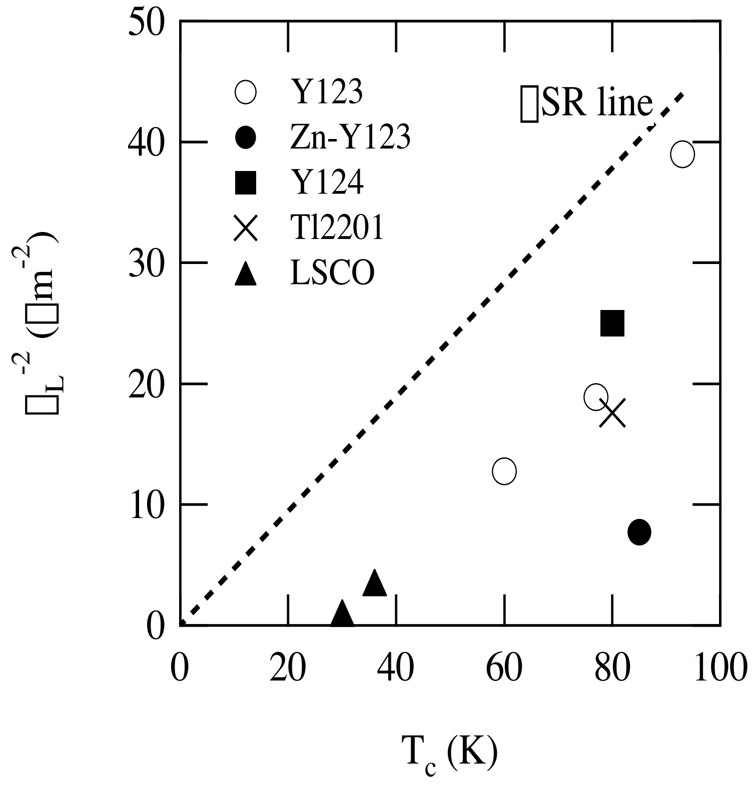
Possible case for inhomogeneity

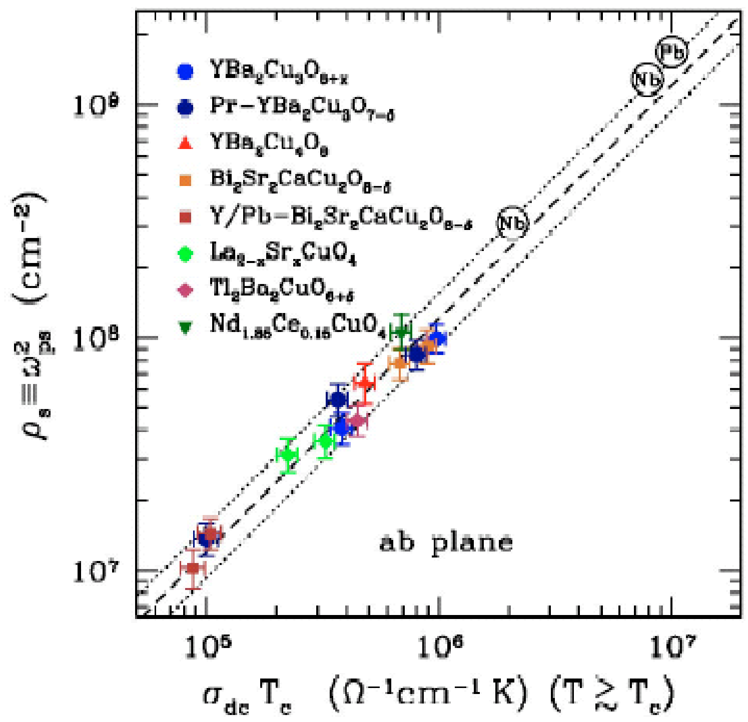
(i)pseudo-gap area + SC area *ex. Underdoped YBCO & BSCCO*

(ii)AF-stripes + SC stripes *ex. (La,Nd)214*

(iii)pair-breaking area + SC area *ex. Zn-doped YBCO*

Comment on the relation of ω_{ps}^2 & T_c





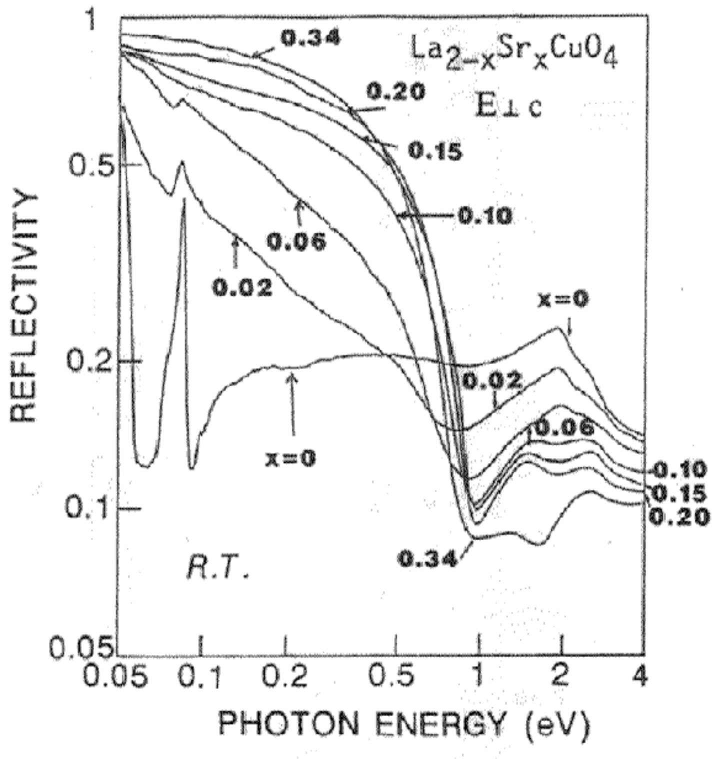
C.C. Homes et al. cond-mat/0404216

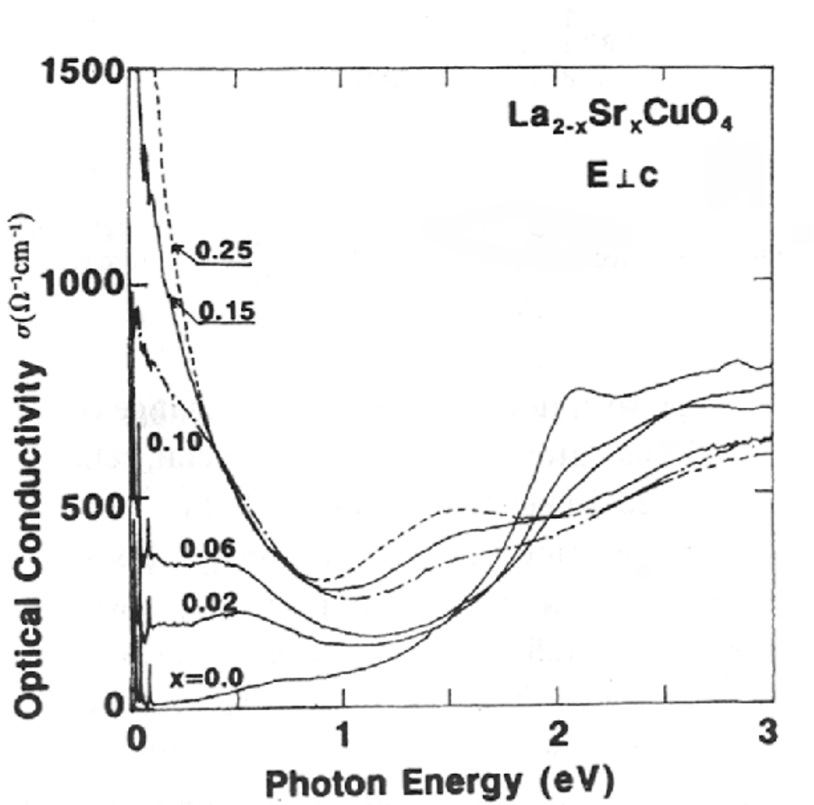
Summary (I)

- The estimated λ_L^{-2}(FIR) is much smaller than λ_L^{-2}(μRS).
- There remains a substantial Drude-like conductivity at low ω.

This may be a characteristic property of inhomogenous electronic system.

Normal State Charge Dynamics : Evolution of F.S. & Optical Spectrum





S. Uchida et al., PRB (1991).
S. Tajima et al., Advances in Superconductivity III (1991).

Extended Drude model
: one component model

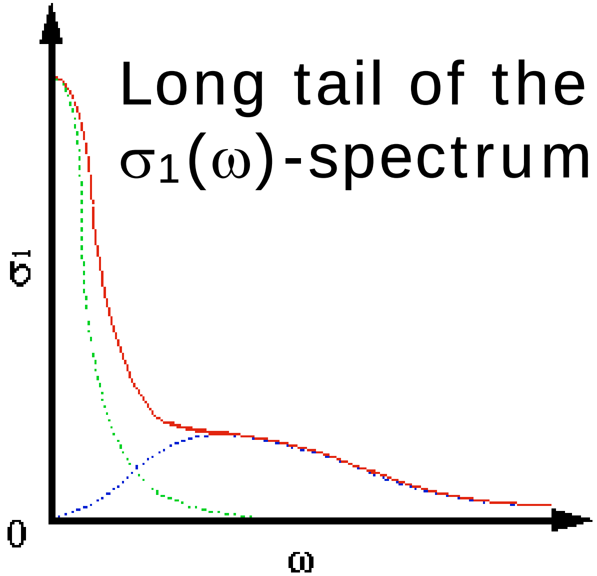
Standard Drude model:
ω-independent m and τ

Extended Drude model:

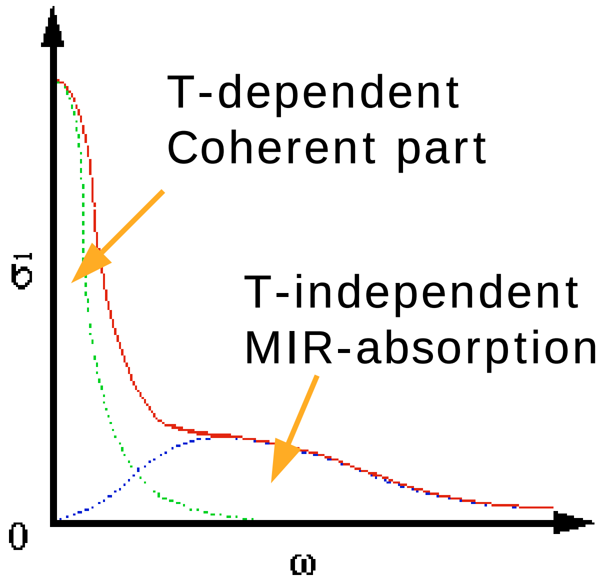
$$\sigma(\omega) = \frac{ne^2\tau^*(\omega)}{m^*(\omega)[1-i\omega\tau^*(\omega)]}$$

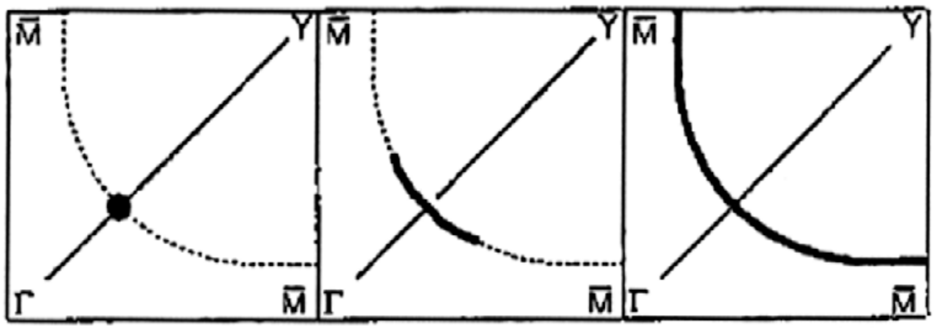
using renormalized mass and scattering rate

$$m^*(\omega) = m_b[1+\lambda(\omega)]$$
$$1/\tau^*(\omega) = 1/\tau[1+\lambda(\omega)]$$



Development of F. S.





Low T ⟷ High T

Small δ ⟷ Large δ

High T or High doping → Large F.S.
Low T or Low doping → Small F.S.

MIR-abs. Part :
Carriers excited above Pseudogap

Nodal direction F.S. → σ_{dc}

Anti-nodal direction F.S.
→ $\sigma_c(\omega)$

Gap Energy can be determined from $\sigma_c(\omega)$.

T-linear $\rho(T)$ and ω-linear $1/\tau(\omega)$

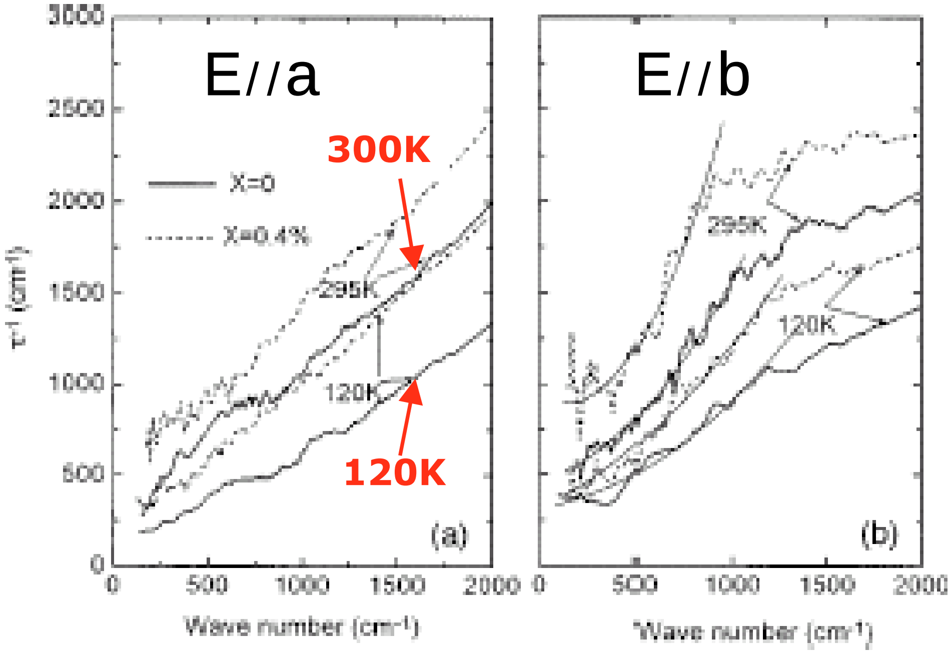
For highly doped case without pseudogap…

E//a
$1/\tau(\omega)$ ~ ω ~ T
$\rho(T)$ ~T

E//b
A kink at ω~1000cm^{-1} due to the chain-related absorption

Extended Drude model inappropriate
for the 2-channel system

Optimally doped YBCO



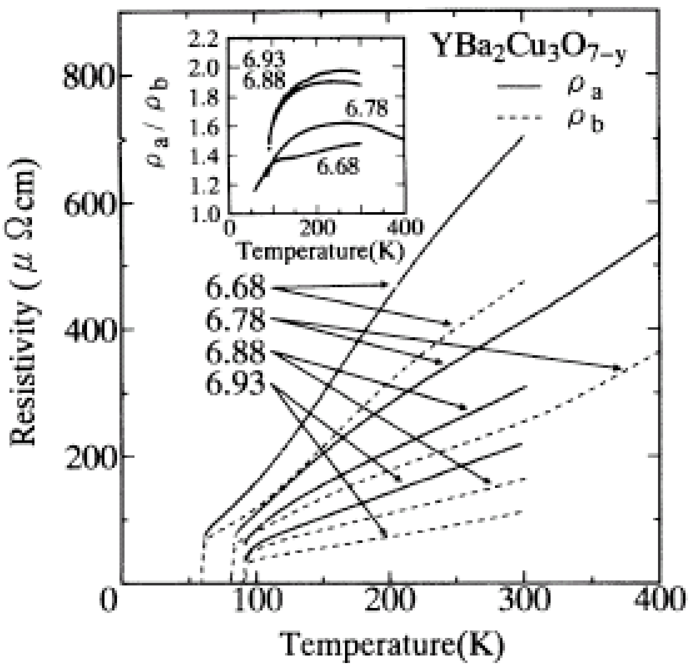
N. L. Wang et al.,
Phys. Rev.B 57, R11081('98)

T-linear ρ(T) and ω-linear 1/τ(ω)

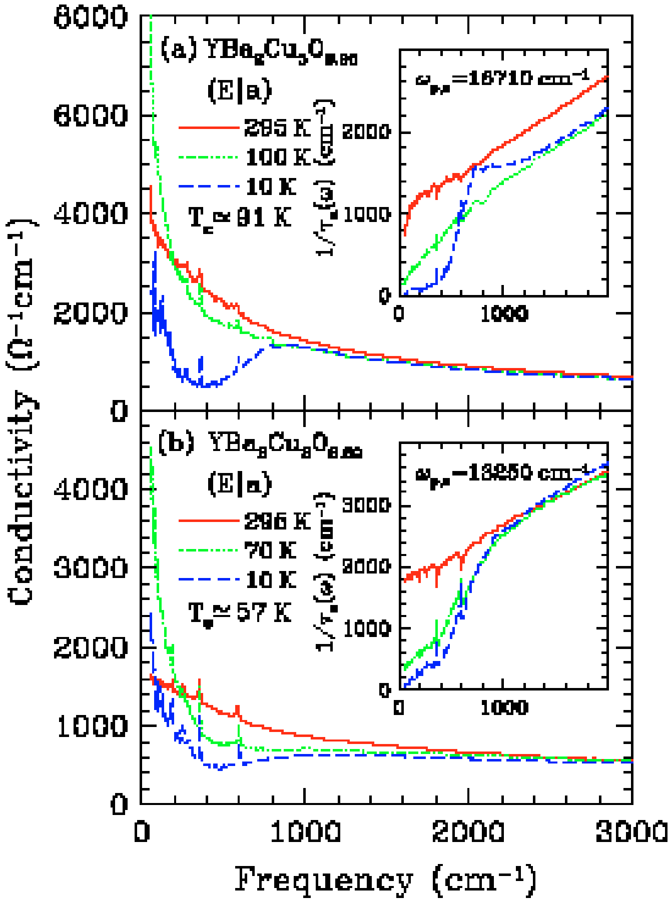
For underdoped case

Deviate from the linear behavior in ρ(T) and 1/τ(ω) simultaneously?

→ NO!



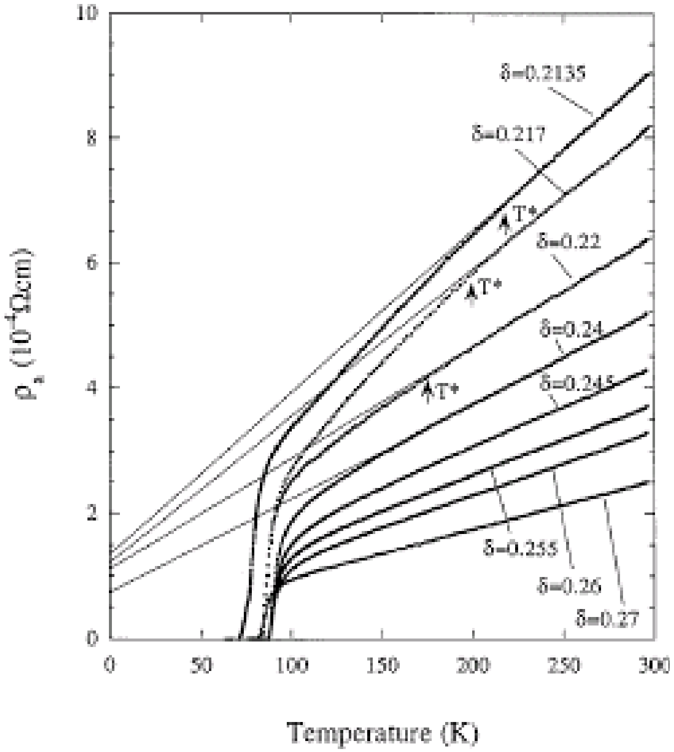
K.Takenaka et al., PRB ('94).



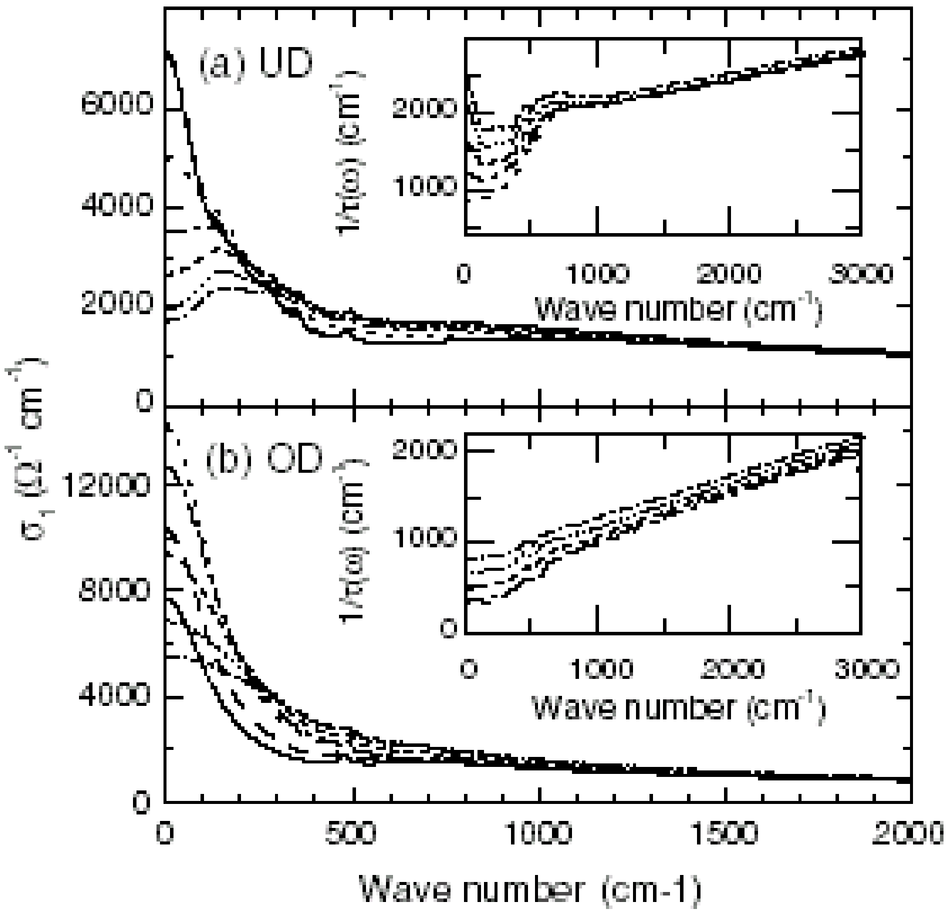
C. Homes et al., PRB('04)

$1/\tau(\omega)$ at T>T* is ω-linear and T-independent?

BSCCO



T.Watanabe et al. PRL79, 2113 (1997).

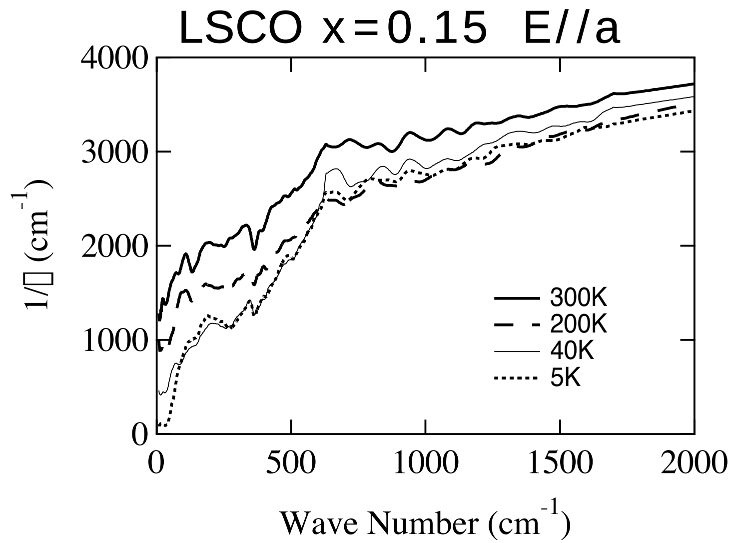


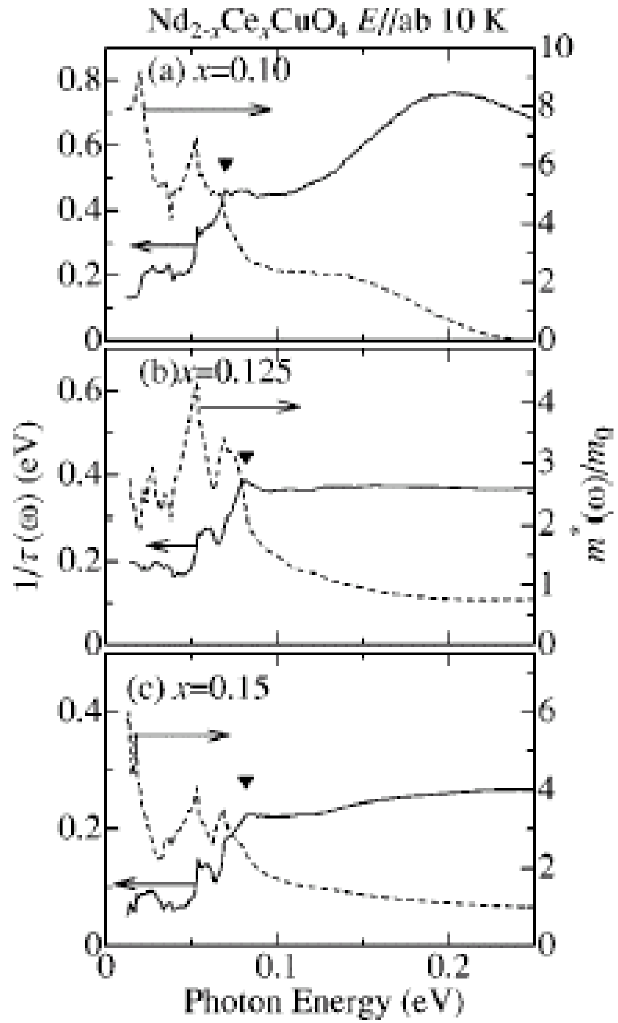
Santander-Syro et al., PRL88, 097005 (2002).

Comment on the kink in $1/\tau(\omega)$

Irrelevant to the pseudo-gap

Y. Onose et al. PRB69 024504('04).





Pseudogap energy should not be determined from $\sigma_{ab}(\omega)$ or $1/\tau_{ab}(\omega)$

99)

Summary (II)

- Only in the optimally/over-doped regime with fully formed F.S., marginal FL-like charge dynamics with T-linear ρ & ω-linear $1/\tau$

For underdoped regime,

- ω-linear $1/\tau$ at R.T. is accidental?
- Mobile charge response (T-dependent spectrum) is limited to the low-ω region. →The ω-linear $1/\tau$ is no longer meaningful?
- The partially gapped F.S. gives the MIR-absorption band.

The kink in $1/\tau$ at ~800cm^{-1} appears in many cases…

>LSCO & NCCO at all temperatures

>The chain contribution for E//b in YBCO

>The c-axis component admixture enhances the kink-structure.

End