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H4.SMR/1001-6

IX TRIESTE WORKSHOP ON OPEN PROBLEMS IN STRONGLY CORRELATED SYSTEMS

14 - 25 July 1997

OUT-OF-PLANE CHARGE TRANSPORT IN HIGH-Tc CUPRATES

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

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Out-of-plane charge transport in high-Tc cuprates

- distinct ρ_c behavior in underdoped Y124

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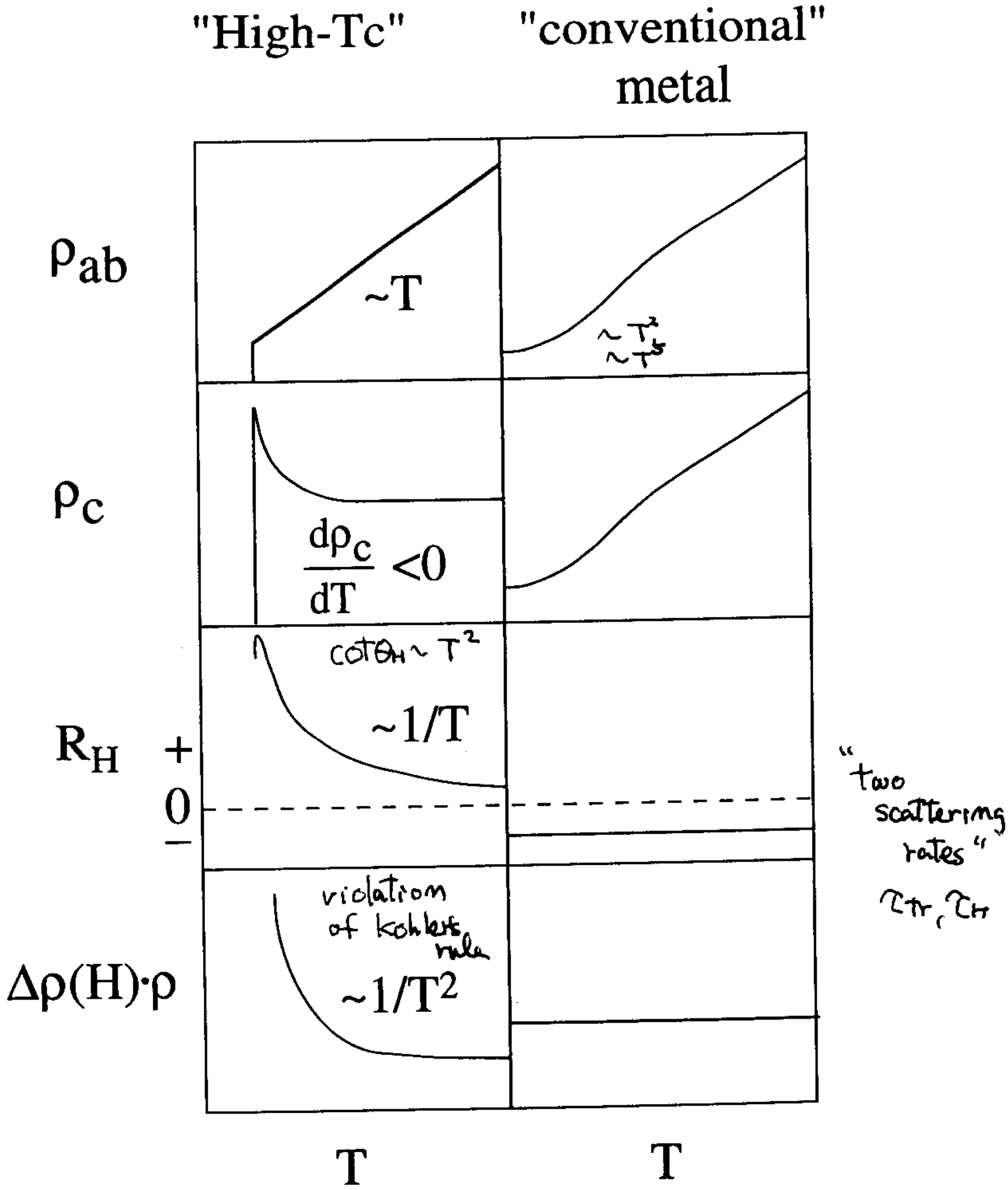
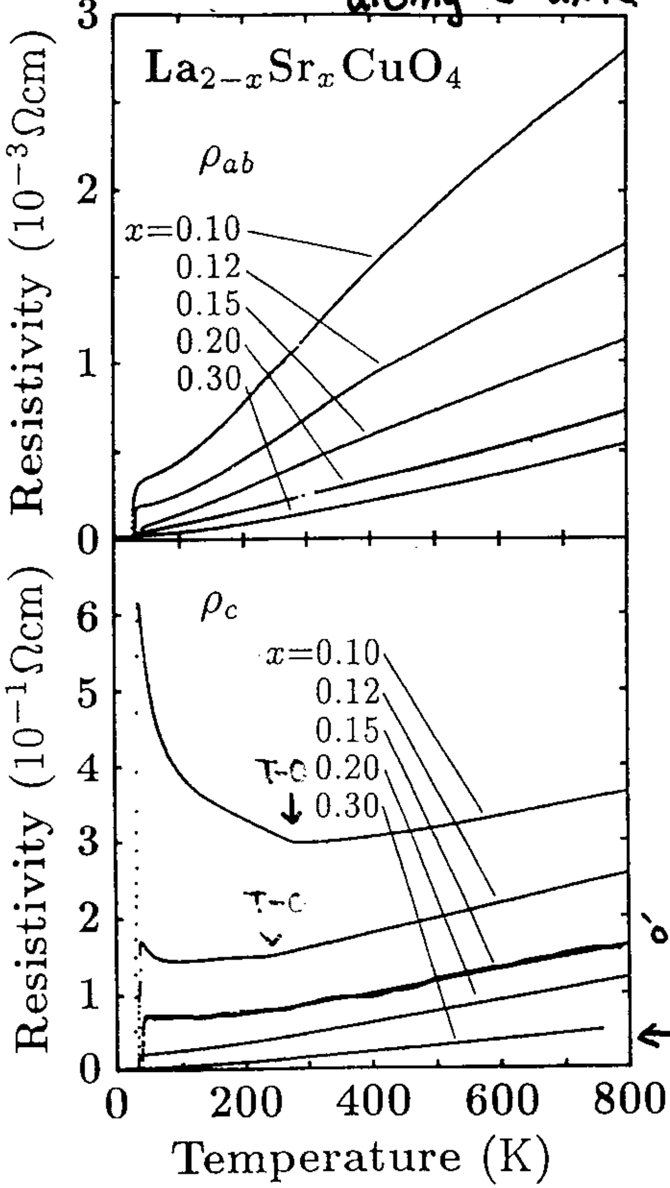
1. overview on out-of-plane transport
2. Y124, underdoped cuprate with spin gap
3. anisotropic 3D transport in Y124
4. field-induced dimensionality control

Hallmarks of Anomalous Charge Transport in High-Tc Cuprates.



Completely different conduction macanism along c-axis



'optimum'

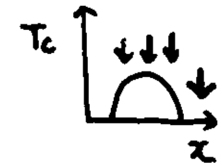
$\leftarrow \frac{1}{\sigma_{min}} \sim$ 10 mΩ·cm.

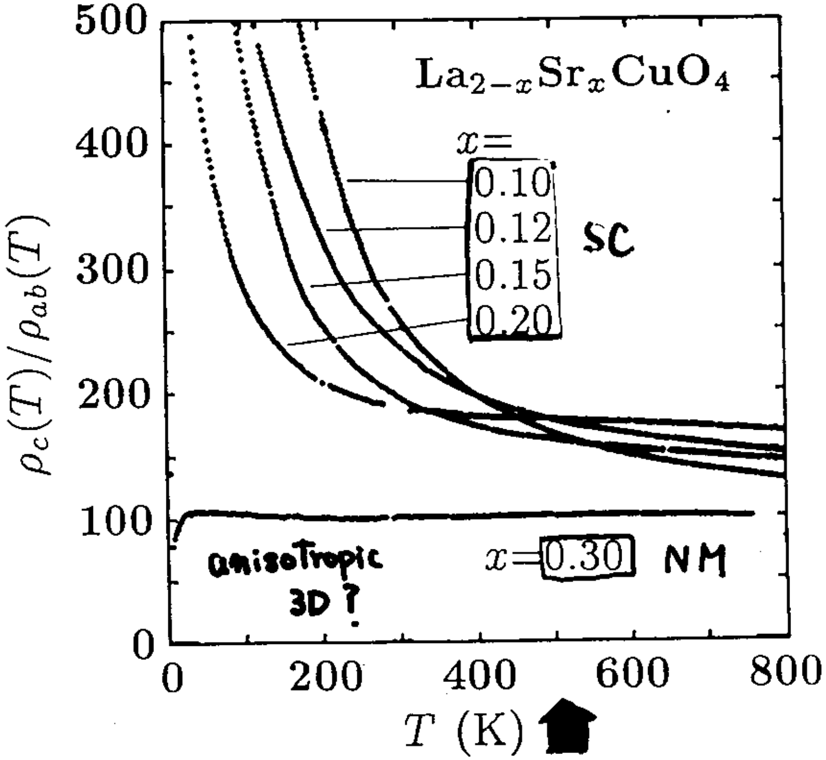
1 Temp dep. completly different from ρ_{ab}

2 underdoped $\rho_c \to \infty$ $T \to 0$

Fig. 2

2D-3D "crossover" ↕ disappearance of SC





ρ_{ab}, R_H anomaly

"anomalous metal"

Fig. 3

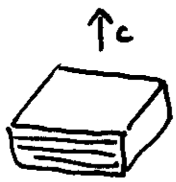
No correlation between ρ_c/ρ_{ab} and T_c

ρ_c strongly

matrials dependent

no correlation with T_c

$\uparrow c$



$\frac{\rho_c}{\rho_{ab}} = 10^2 \sim 10^6$

V

V

band calc.

charge are

strongly

confined

within the plane

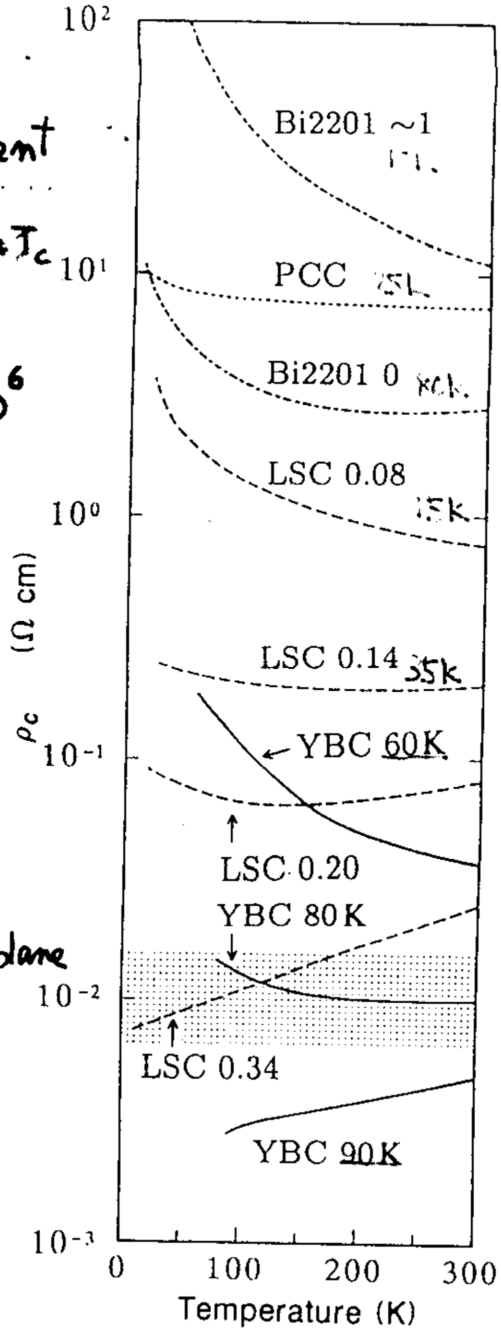


FIG. 2 Temperature dependences of ρ_c for $YBa_2Cu_3O_{7-y}$, $La_{2-x}Sr_xCuO_4$, $Pr_{2-x}Ce_xCuO_{4-y}$ ($x \approx 0.15$) and $Bi_2Sr_{2-x}La_xCuO_6$, abbreviated to YBC, LSC, PCC and Bi2201, respectively. The numbers following LSC and Bi2201 indicate the Sr and La composition x, respectively (the value of $x = 0.14$ for LSC is from ref. 6). The shaded region indicates the critical resistivity along the c axis, which is the extended Mott–Ioffe–Regel limit estimated from the values given in the text.

Recovery of coherent transport in "overdoped" normal metal

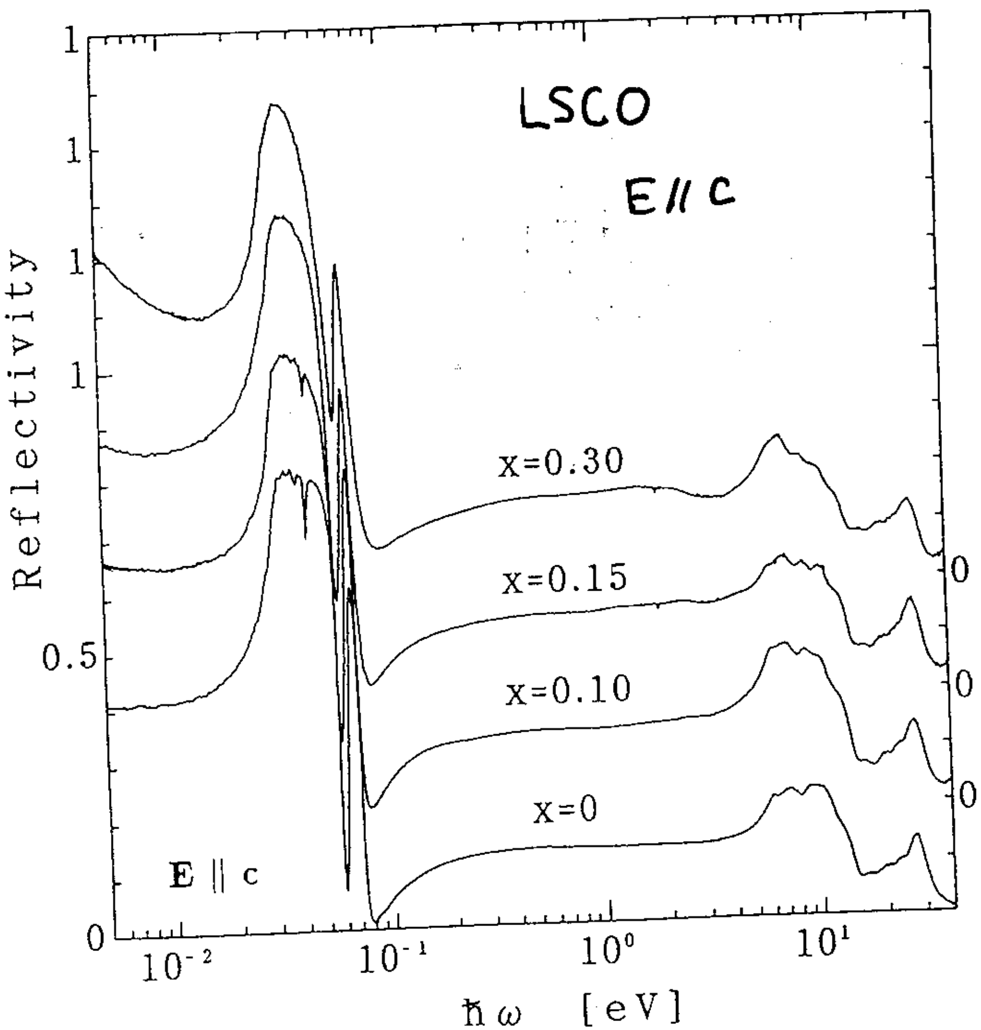
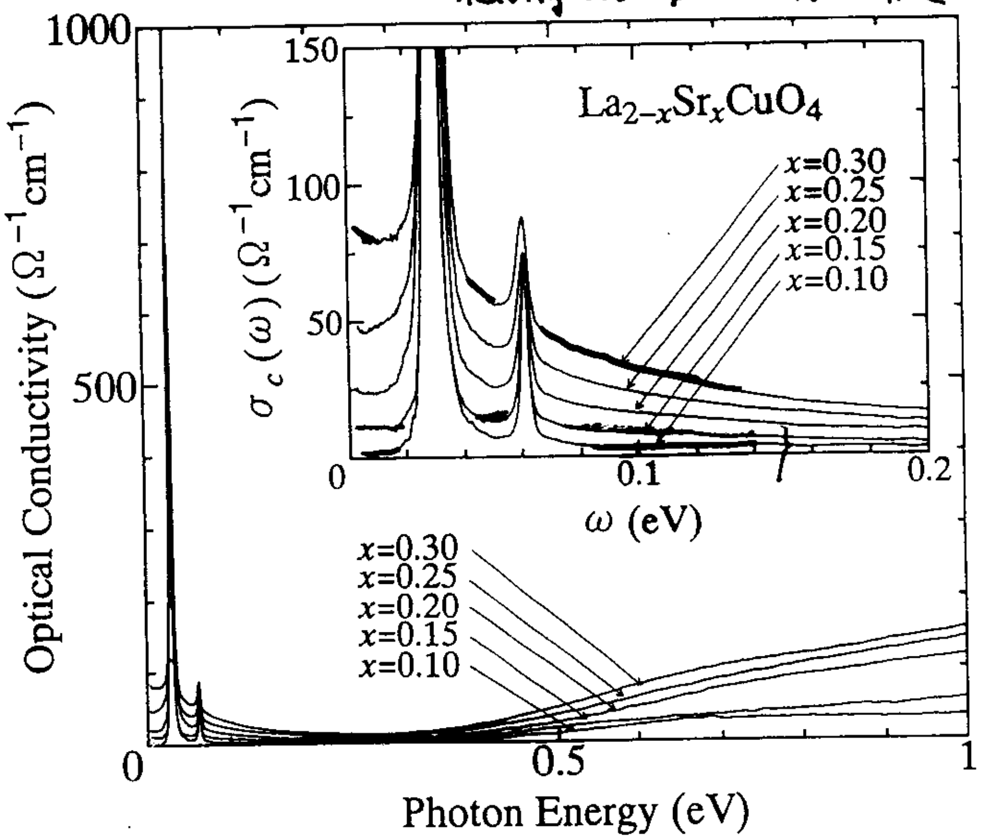


Fig. 1 K. Tamasaku et al.

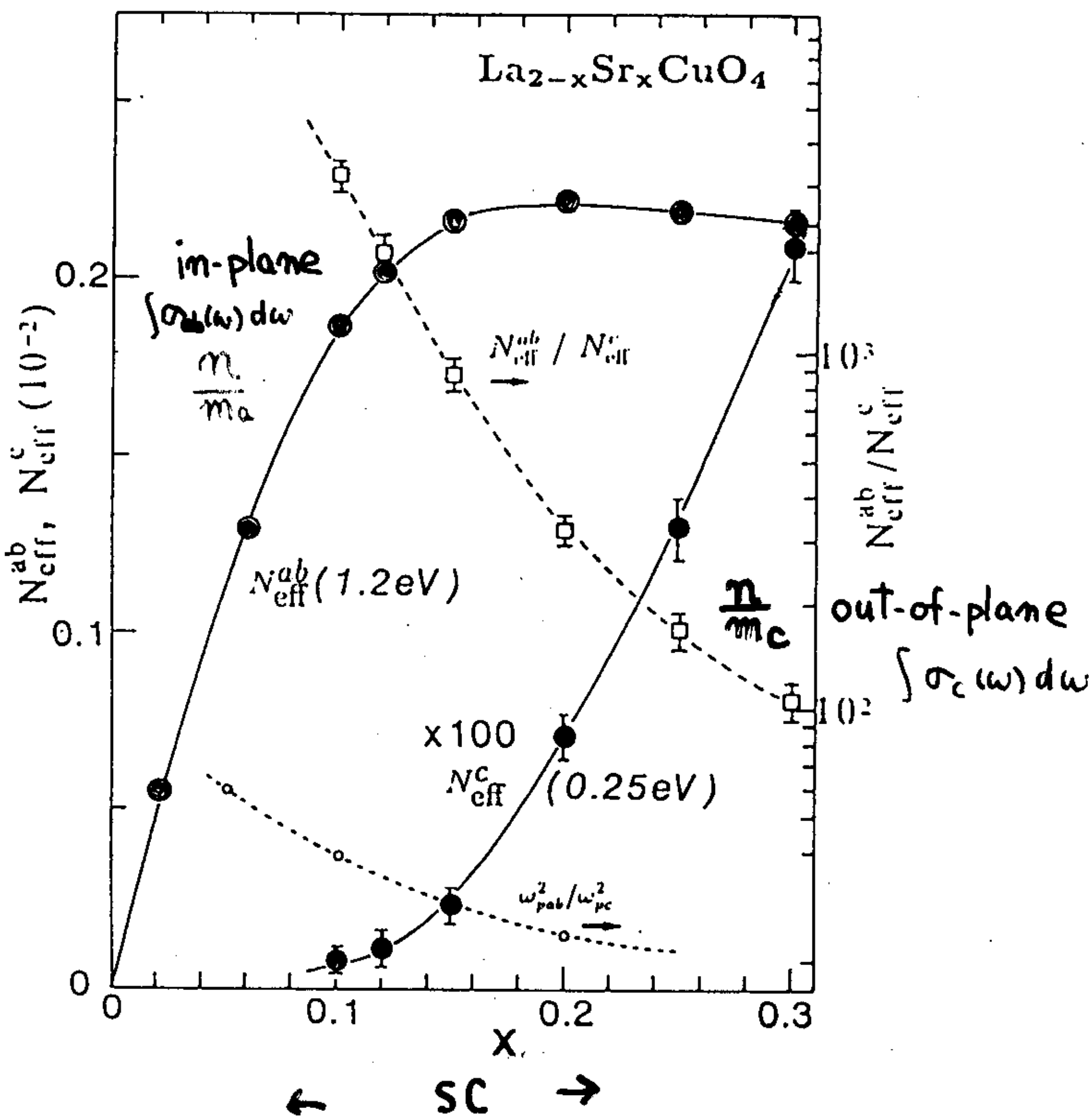
under-optimum σ(ω) ω-indep 'incoherent'

heavily overdoped Drude-like



energy scale ~ T

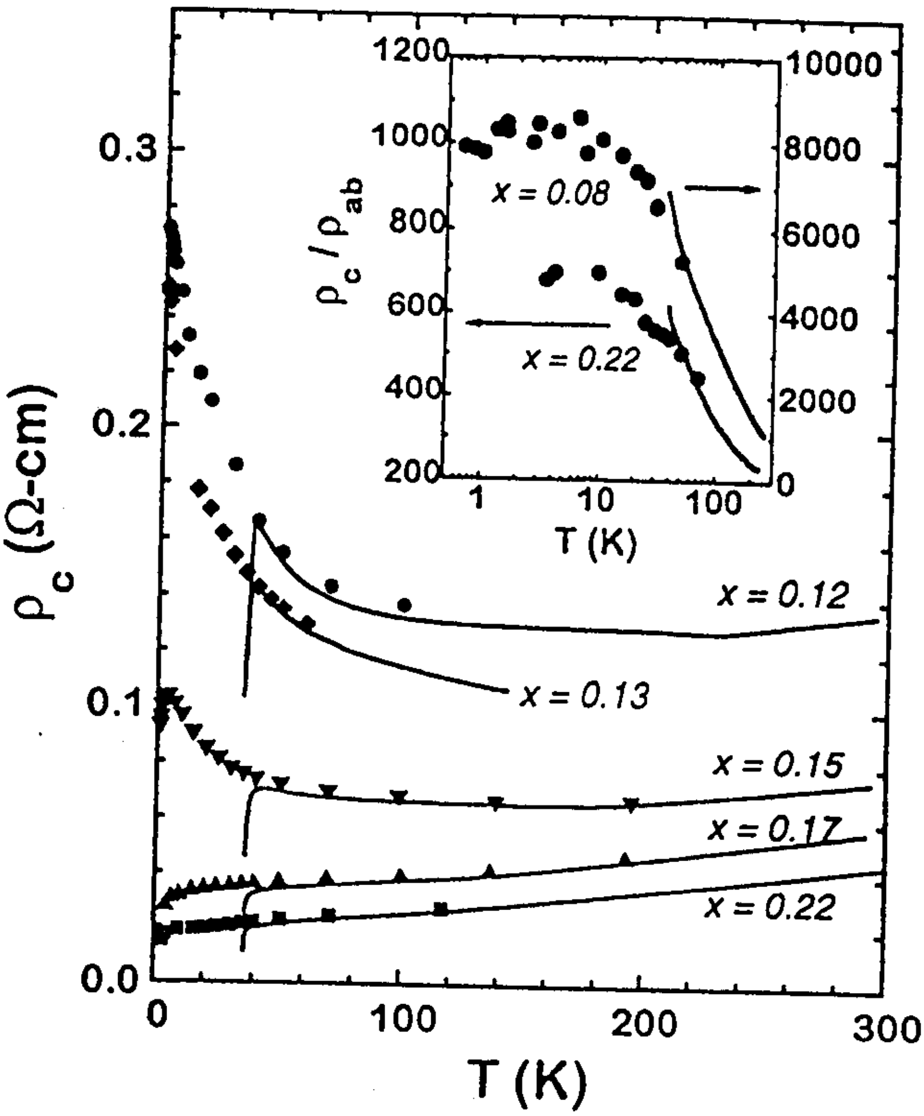
Strong suppression of out of plane spectral weight



T→0 limit Boebinger

underdoped $\rho_c \to \infty$ ($\propto -\ln T$)

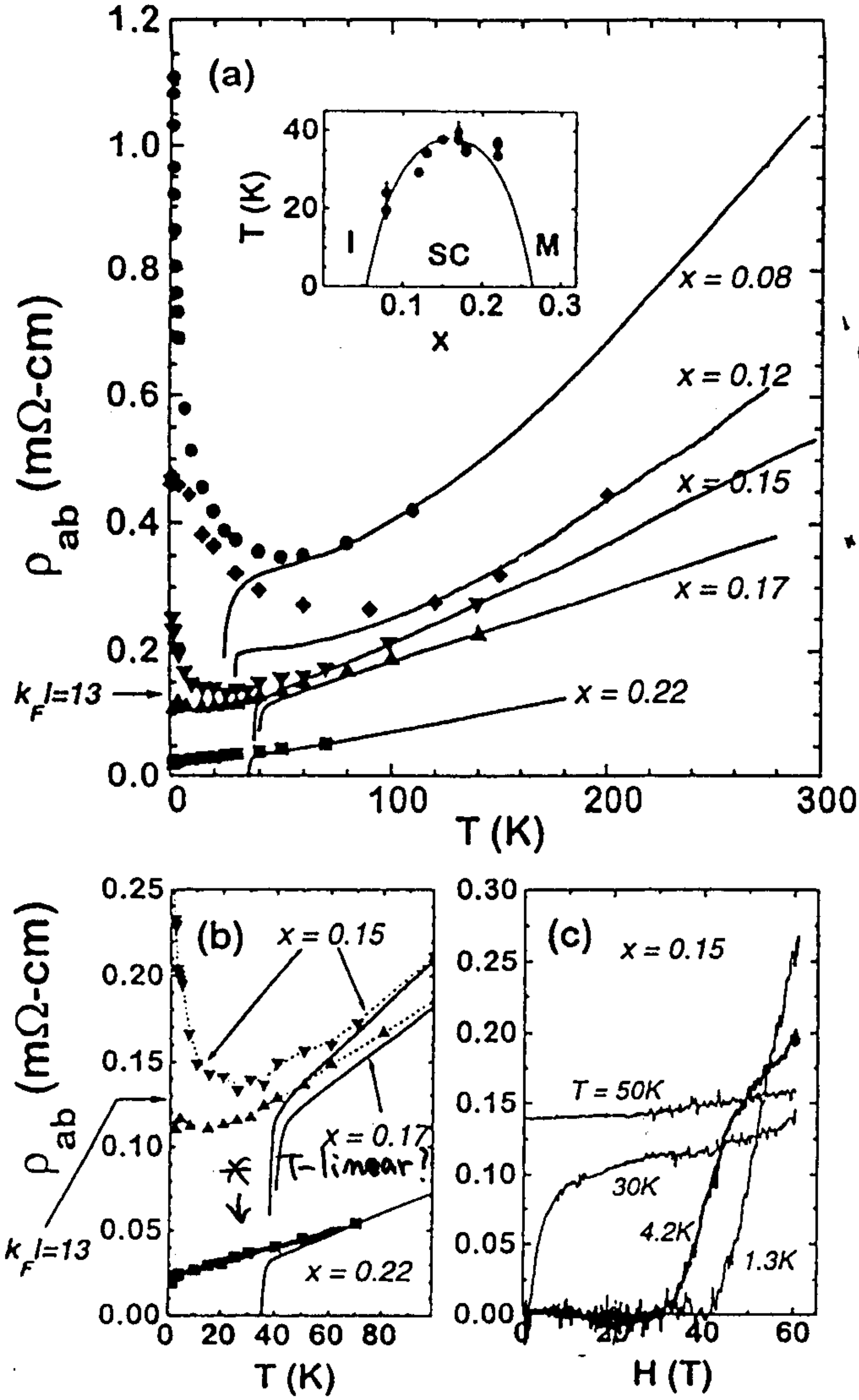
overdoped $\rho_c \to$ const



Boebinger

ρ_c divergence

accompanied with $\log T$ divergence of ρ_a



'underdoped'

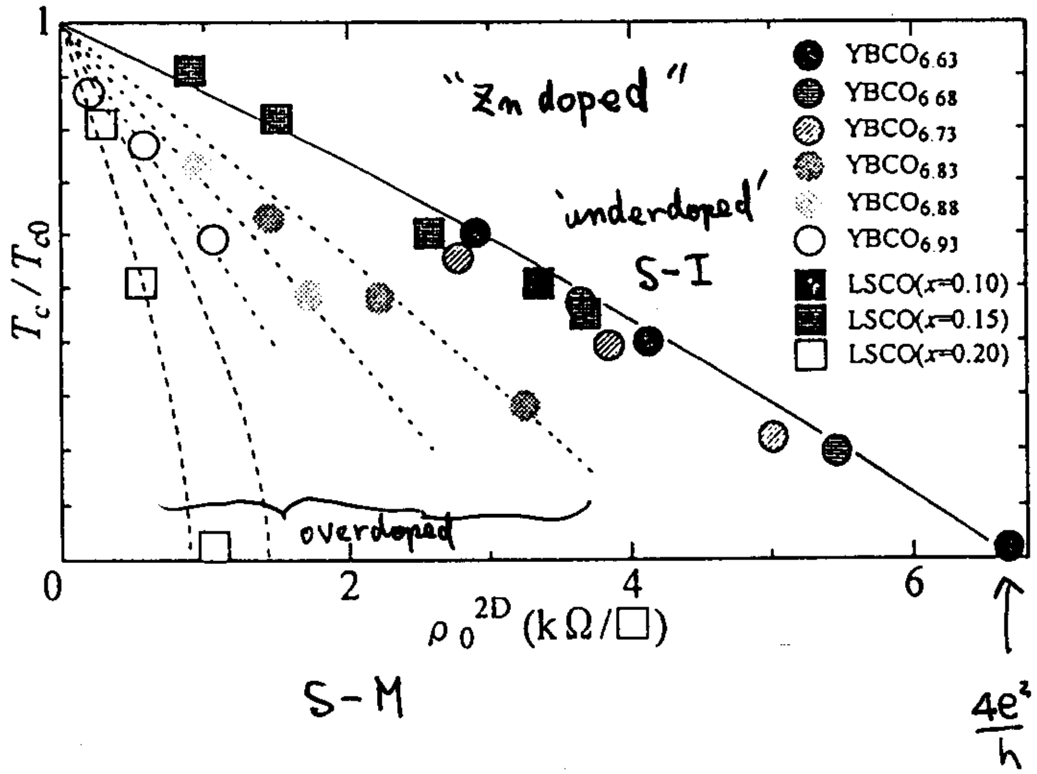
$\rho \propto -\log T$ at low T

"1/8" anomaly

2D S-I transition (disorder induced)

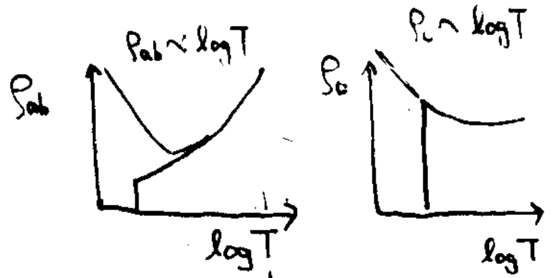
$$R_\square = \frac{4e^2}{h} \sim 6.7\,k\Omega$$

$$\rightarrow \rho_{3d} = R_\square \cdot d \sim 1.6\,m\Omega cm \text{ LSCO}$$



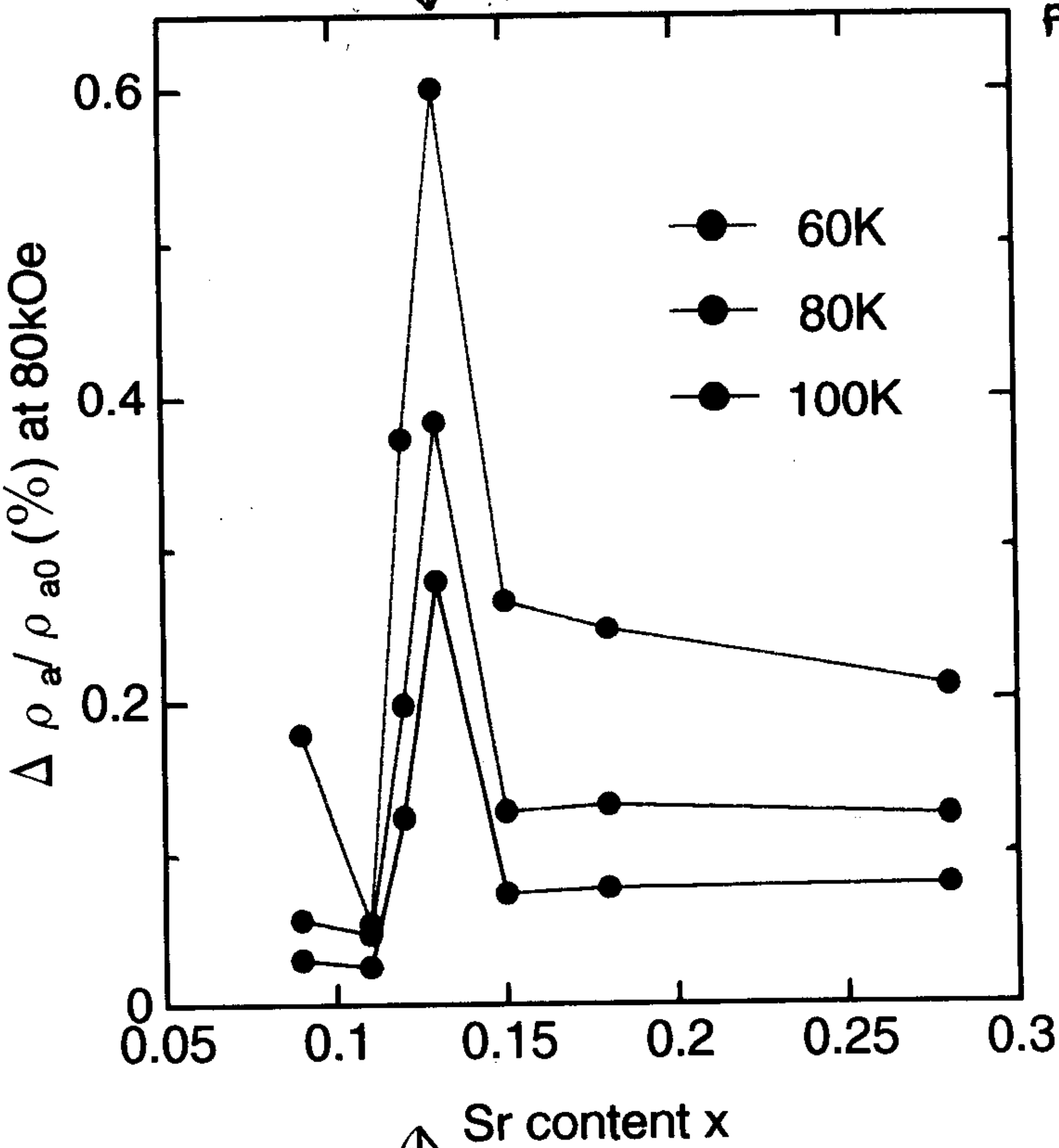
In-plane MR

pronounced anomaly around "1/8"



T. Kimura, H.T

PRB(96)



"1/8"

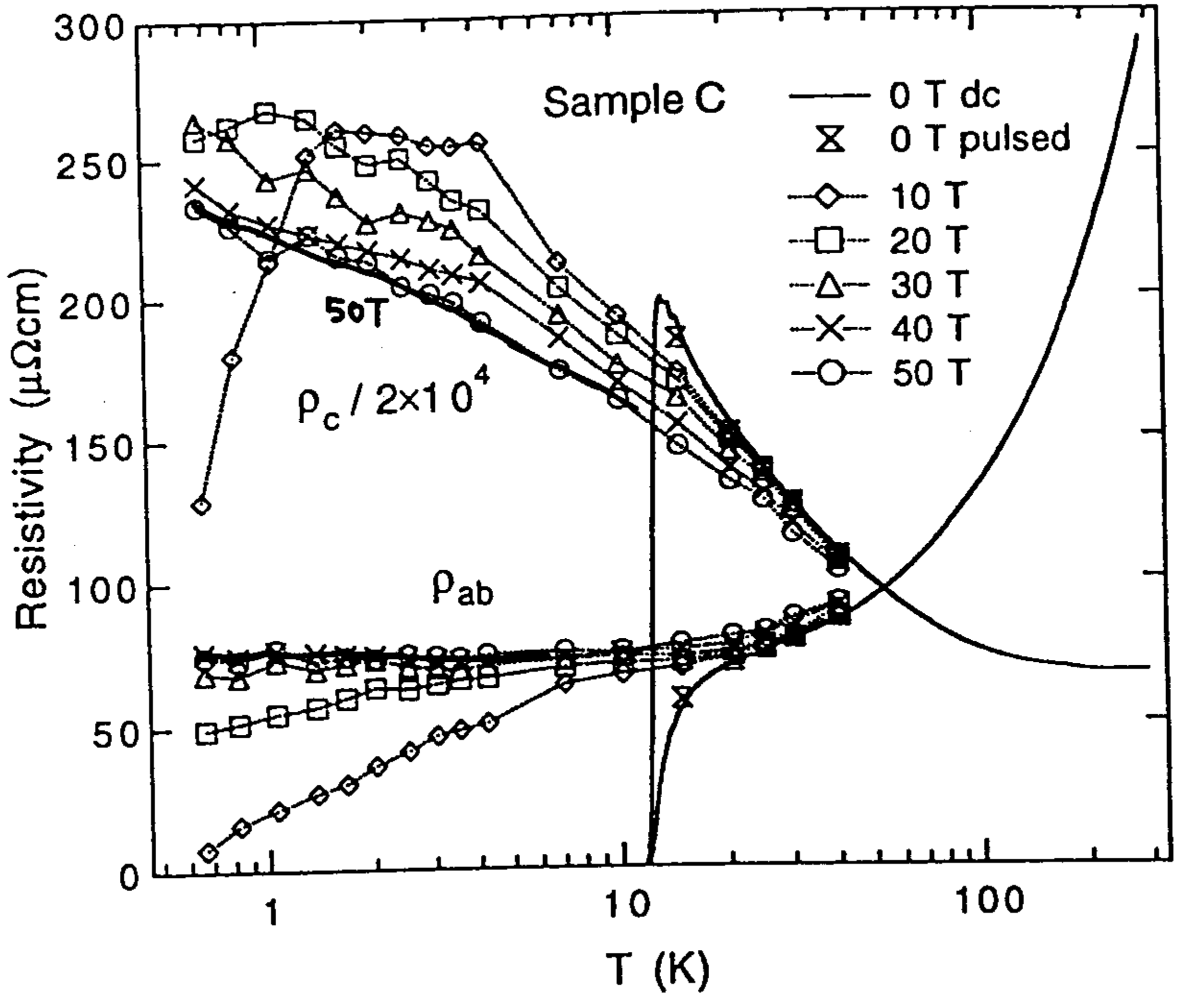
field induced charge ordering?

$Bi_2 Sr_2 CuO_6$ $\rho_c \to \infty$ but $\rho_a \to$ const FL?

$\updownarrow$

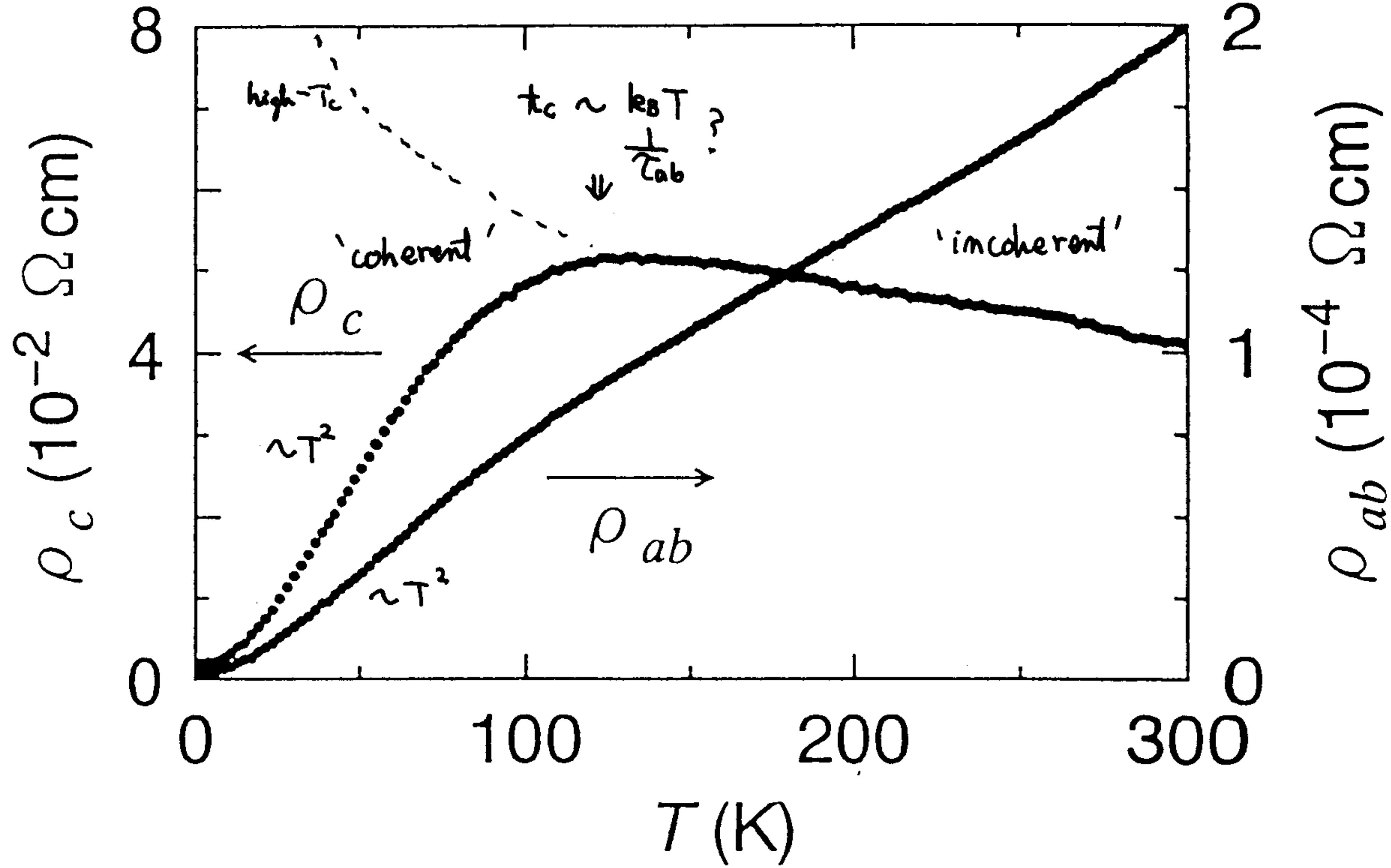
$\rho_a \to \infty$ LSCO

Ando - Boebinger

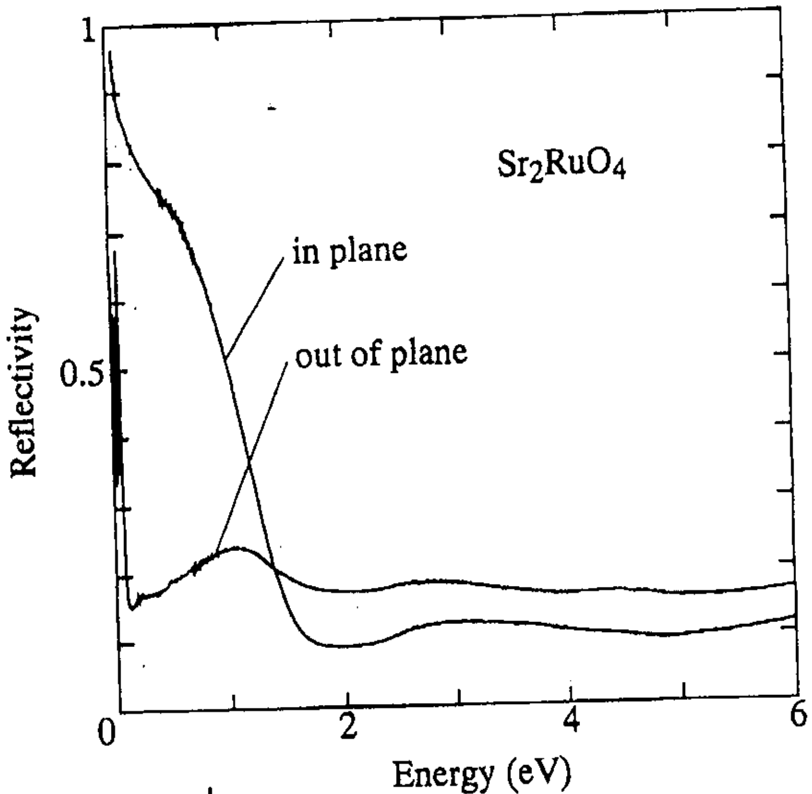


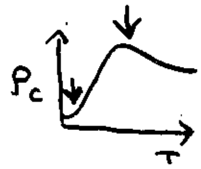
Sr_2RuO_4 (K_2NiF_4 structure)

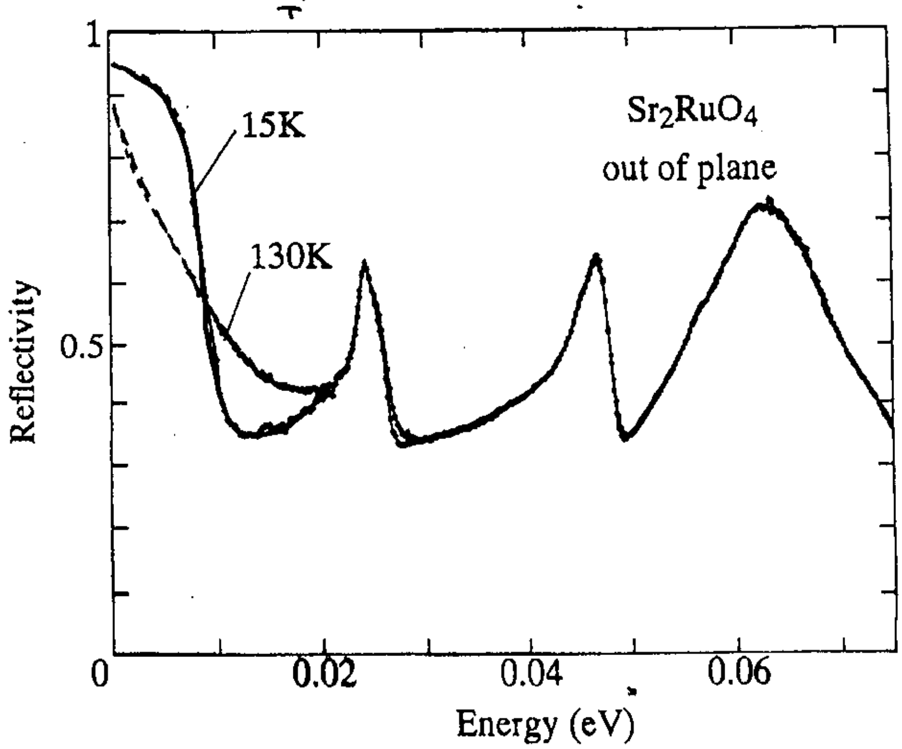
Maeno et al. Nature



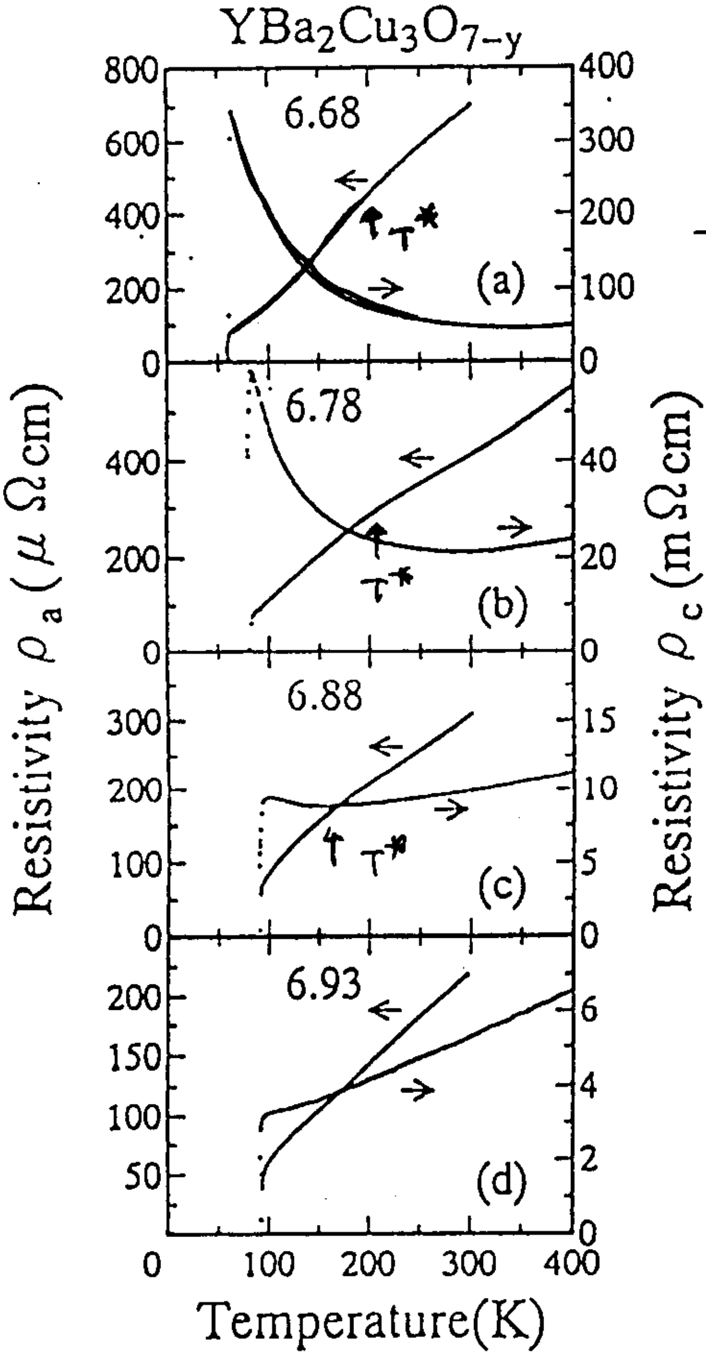
Katsufuji, Kasai, Tokura PRL

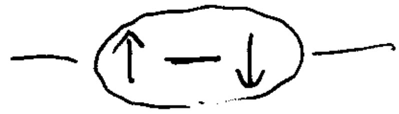






Charge Confinement associated with "spin gap"





insulating ρ_c

↕

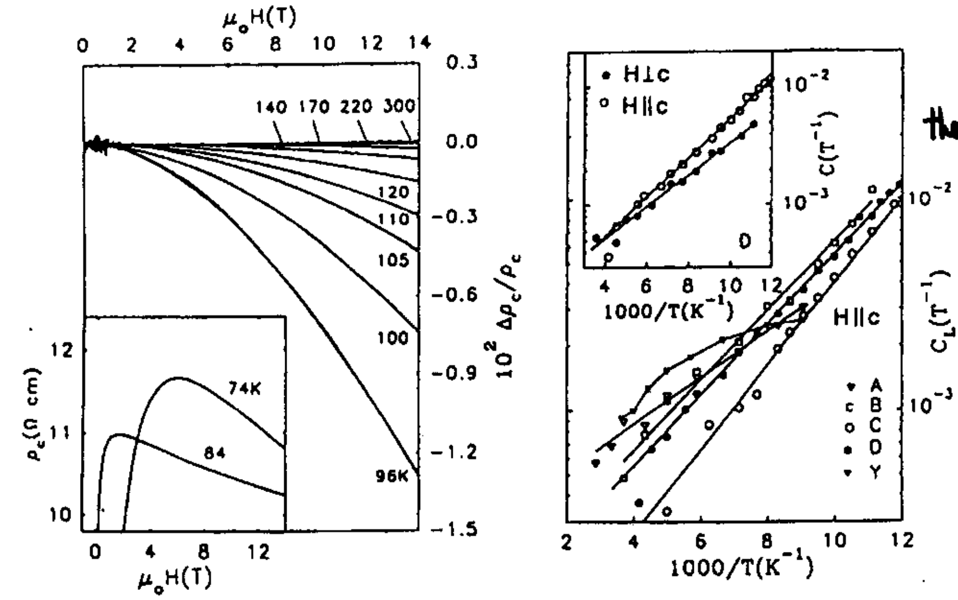
'spin gap'

c-axis Magnetoresistance

UNDERDOPED

Negative isotropic MR proportional to B^2

Effect of pseudogap on $\rho_c(T)$?



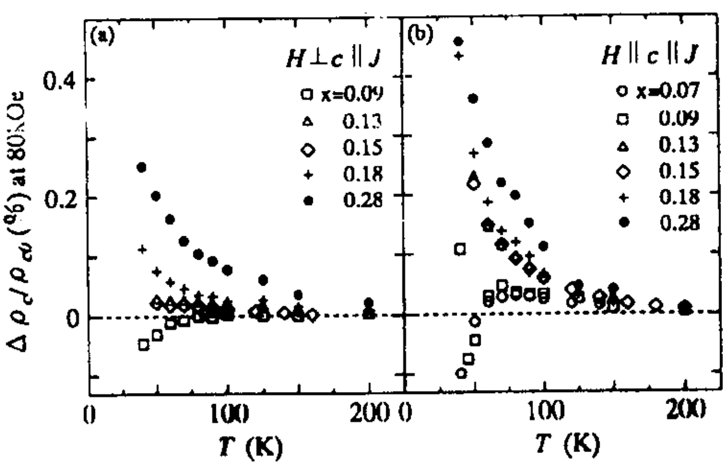
Yan *et al.*
PRB
52 R751
(1995)

OVERDOPED

Crossover to positive orbital B^2 MR

Gradual metalizing of c-axis with increased doping

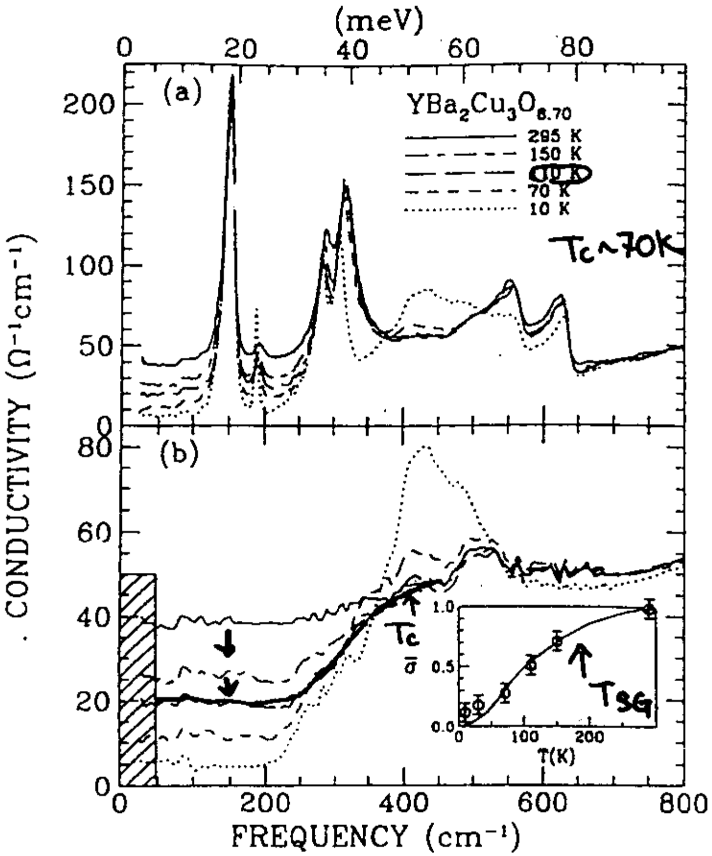
Unusual longitudinal MR



Kimura *et al.*
PRB
53 8733
(1996)

pseudo gap in $\sigma_c(\omega)$ above T_c in underdoped Y123

Homes
Tajima



insulating ρ_c
↕
pseudogap in $\sigma_c(\omega)$
↓
appears to be connected with SC gap smoothly

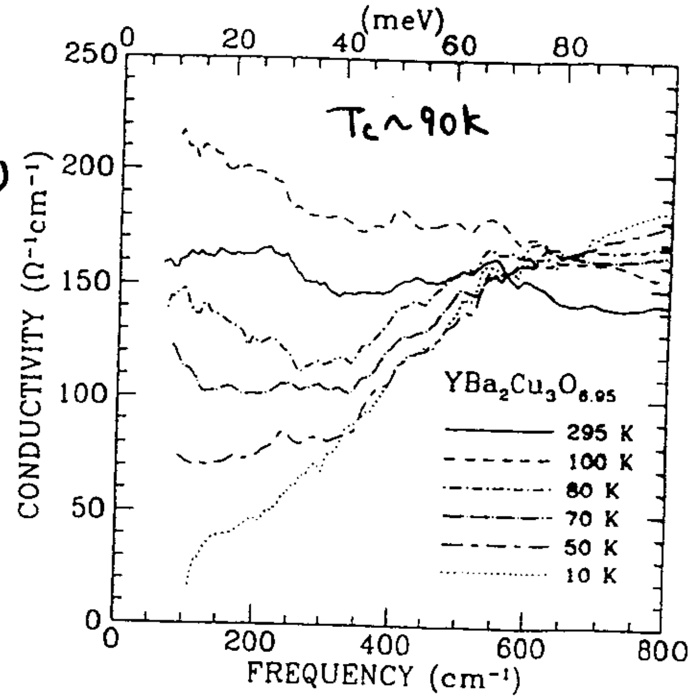


FIG. 2. The optical conductivity of $YBa_2Cu_3O_{6.70}$ along the c axis from ≈25 to 800 cm^{-1} obtained by a Kramers-Kronig analysis of the reflectance with (a) the phonons at 150, 192, 286, 317, 557, and 630 cm^{-1} present and (b) subtracted to yield the electronic background. Note that the formation of a pseudogap is clearly visible well above T_c (63 K). The shaded area represents the spectral weight of the condensate (305 cm^{-1}) for $T \ll T_c$. Inset: The conductivity at 50 cm^{-1} normalized with respect to the room temperature conductivity (open circles), compared to the normalized Knight shift for Cu(2) (solid line) in $YBa_2Cu_3O_{6.63}$ (after Ref. [2]).

FIG. 3. The optical conductivity of $YBa_2Cu_3O_{6.95}$, along the c axis from ≈90 to 800 cm^{-1}, above and below T_c (93 K), with the phonons normally present at 153, 195, 287, 313, and 567 cm^{-1} removed to show the electronic background. The normal-state behavior is metallic. Below T_c a gaplike depression appears in the conductivity, but shifts to zero frequency with decreasing temperature, leaving residual conductivity at ≈10 K (dotted line) down to the lowest measured frequency point ≈ 100 cm^{-1}.

What is generally believed for the out-of-plane transport in high-Tc cuprates

ρ_c/ρ_a by far larger than those predicted by band calculations

temperature dependence distinctly different from ρ_a

no apparent correlation between ρ_c/ρ_a and Tc

insulating behavior pronounced in the underdoped region, in particular when spin gap is developed ($T<T^*$)

Y124 ρ_c distinctly different

- -closely related with pseudo gap in $\sigma_c(\omega)$
- -isotropic negative MR
- -charge confinement associated with the spin gap?
- –T=0 limit

  logarithmic divergence with $T\rightarrow 0$, accompanied by in-plane insulating behavior underdoped LSCO, but unversal?

  ρ_c diverge with $T\rightarrow 0$ (Bi2201) but not for ρ_a

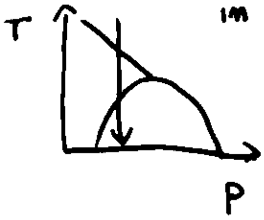
tend to recover coherent behavior when overdoped

- $-\rho_c$ is metallic and appears to stay finite with $T\rightarrow 0$ (LSCO, Y123 90K, Tl)

$YBa_2Cu_4O_8$

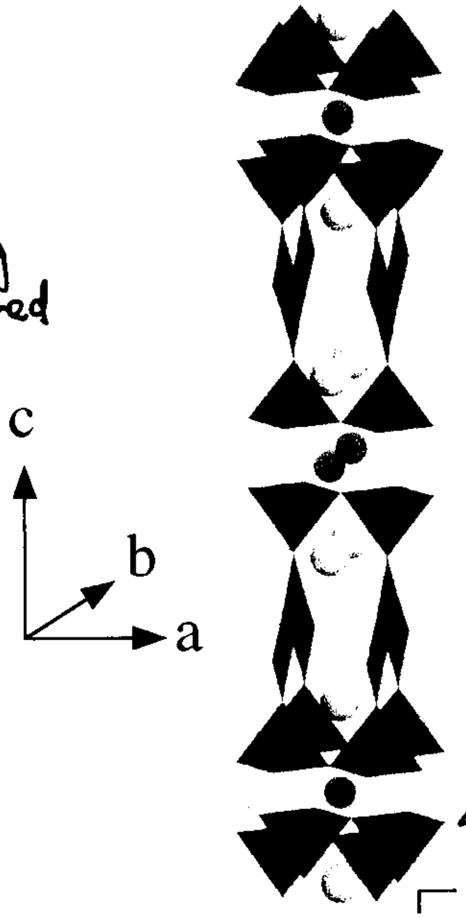
"underdoped" in nature

no doping required



"clean"

superstructure of 2D + 1D



2D CuO_2

1D CuO "metallic"

double chain stable

no O-vacancy

2D CuO_2

1D CuO

2D CuO_2.

underdoped, spin gap

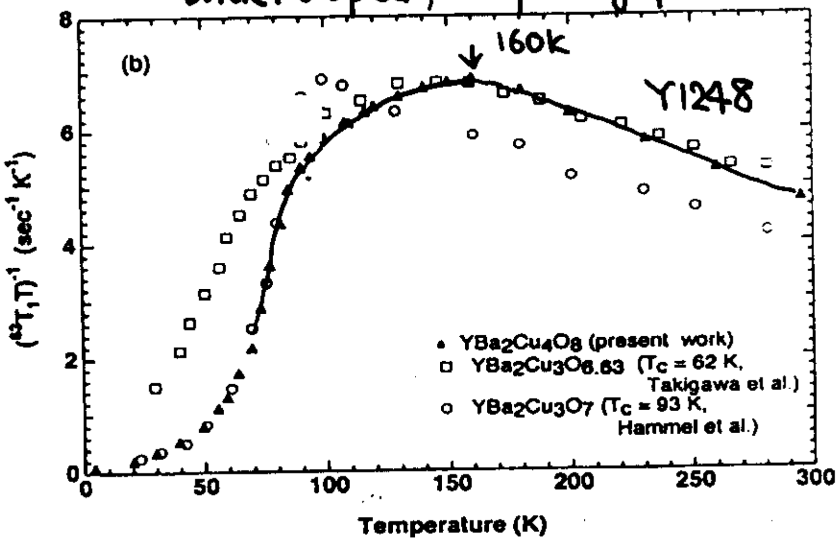
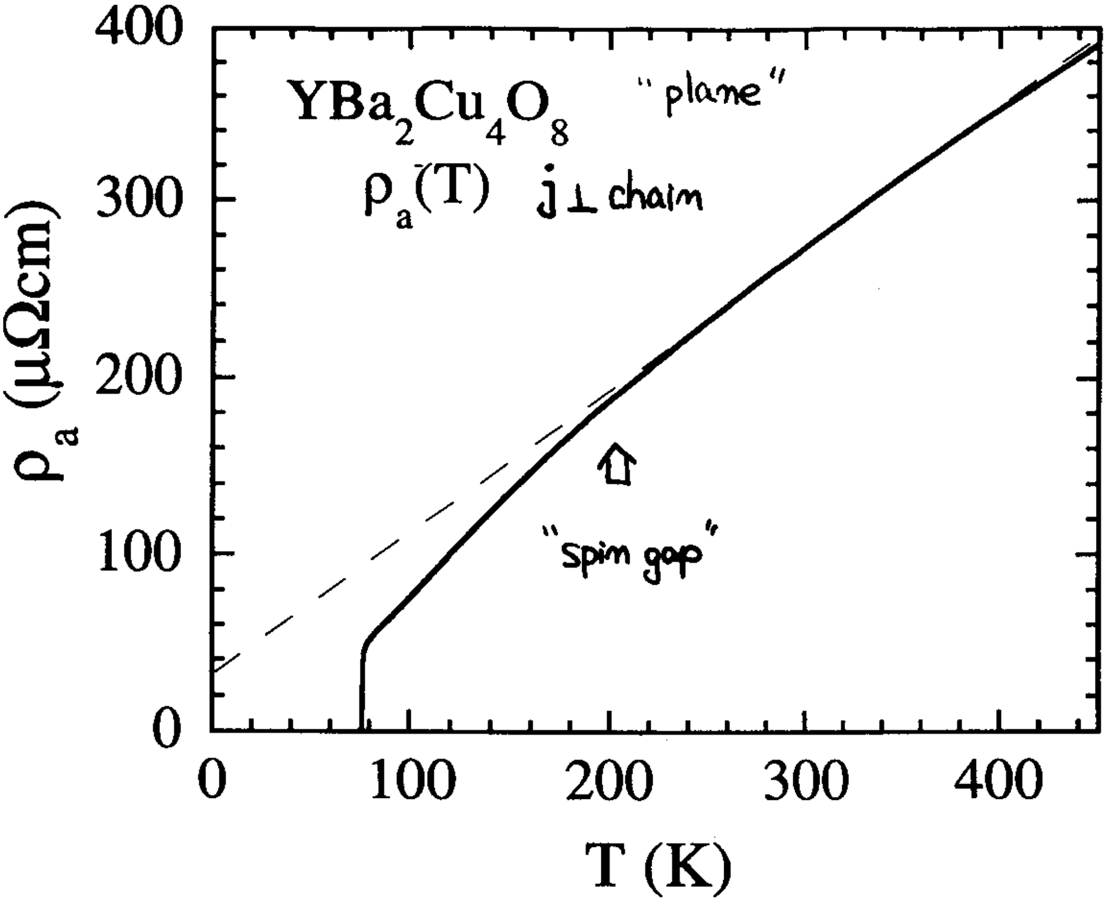


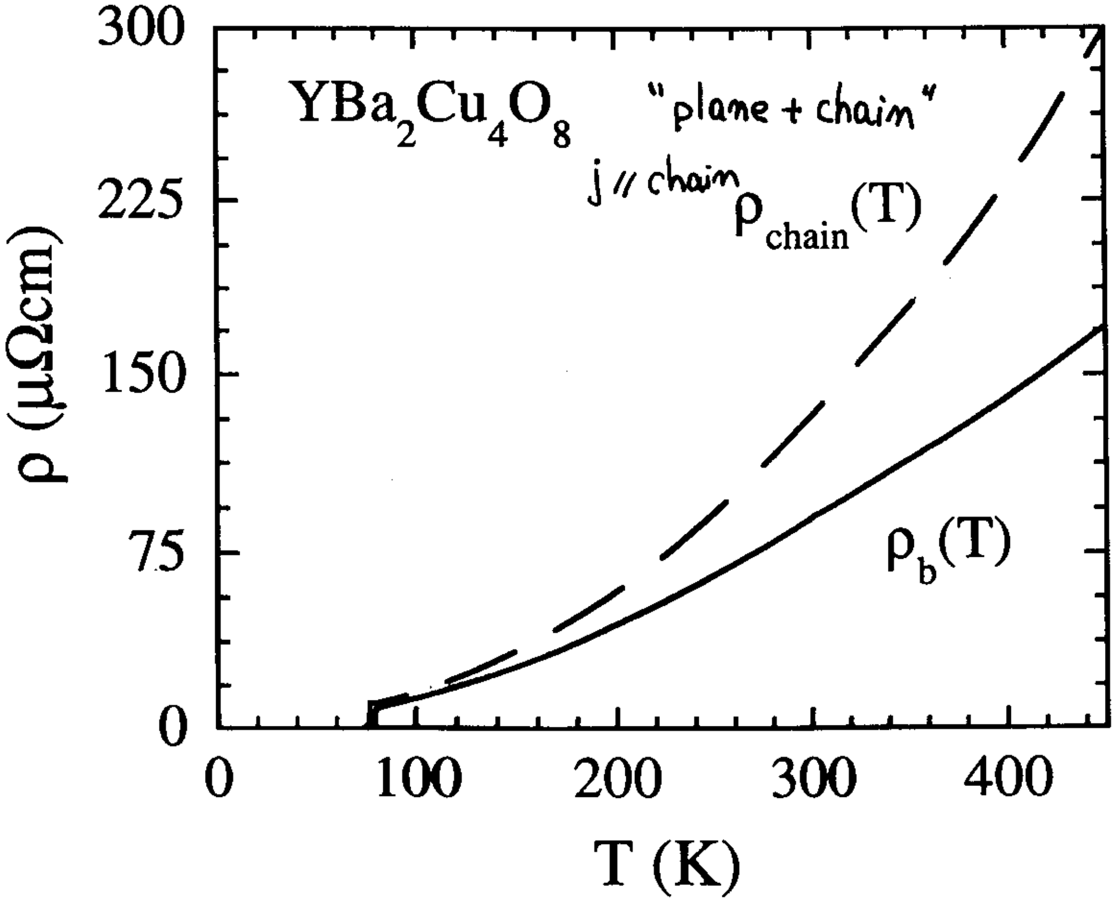
FIG. 8. Comparison of present $(^{\alpha}T_1T)^{-1}$ data for $YBa_2Cu_4O_8$ (triangles) with those for $YBa_2Cu_3O_{6+x}$. The data for the 90-K phase (circles) and the 60-K phase (squares) of $YBa_2Cu_3O_{6+x}$ were taken from Hammel *et al.* (Ref. 2) and Takigawa *et al.* (Ref. 3), respectively. (a) $(^{17}T_1T)^{-1}$ at the O(2,3) site. (b) $(^{63}T_1T)^{-1}$ at the Cu(2) site.

I. Tomeno, etal., *PRB*., **49**, 15327(1994).

In-Plane resistivity

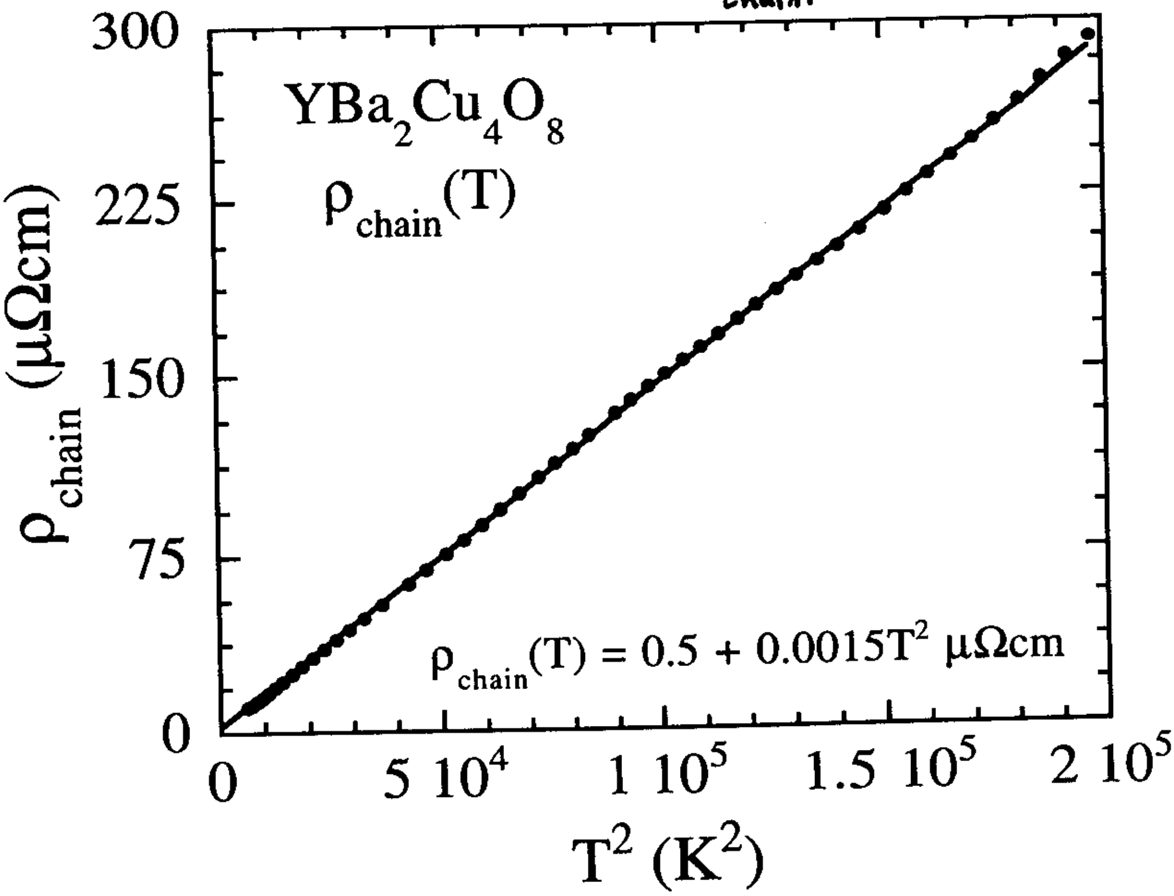


Bucher



$$1/\rho_{chain} = 1/\rho_b - 1/\rho_a$$

(ρ_b: plane + chain; ρ_a: plane)



spin gap effect not clear in ρ_{chain}

1 $\rho_{chain} \sim 5\,\mu\Omega\cdot cm$

$\longrightarrow$ 700 Å at 80 K !

2 $\rho = \rho_0 + AT^2$

$\rho_0 \sim 0.5\,\mu\Omega\cdot cm$

3. T^2 behavior like conventional FL

3D coupling of chains through 2D CuO_2 sheets.

Out-of-plane ρ_c

metallic at low-T
though underdoped
with spin gap.

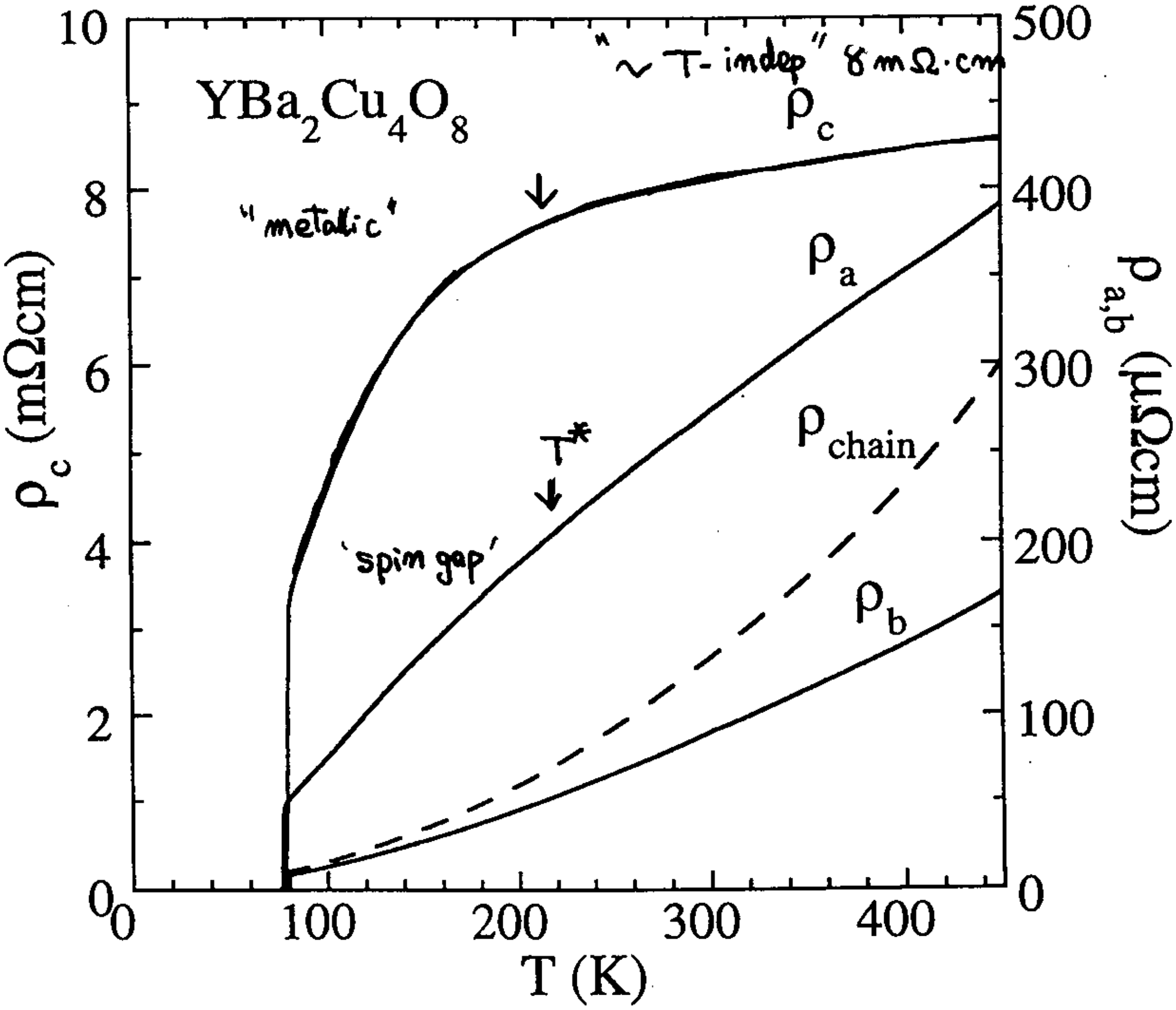
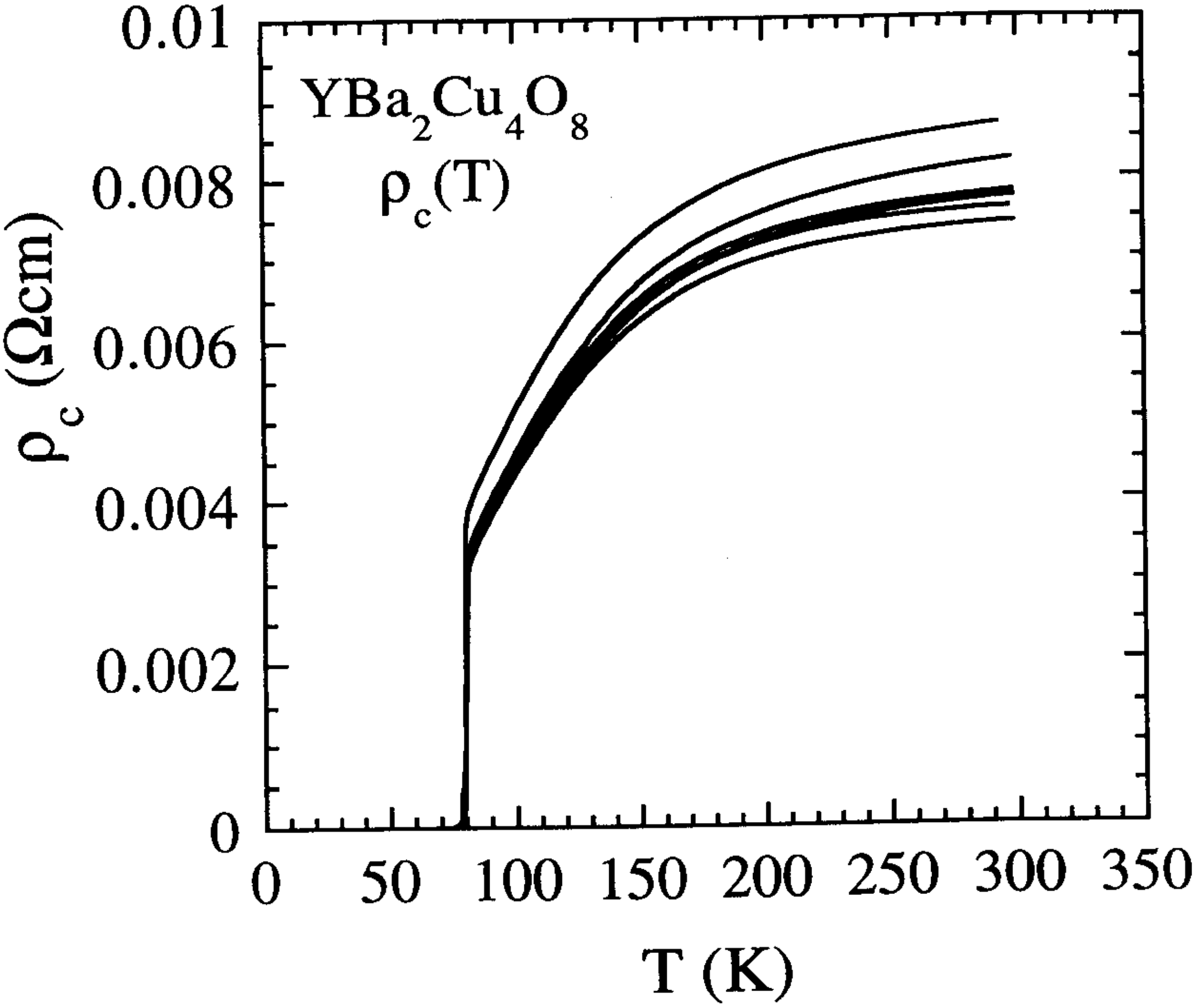
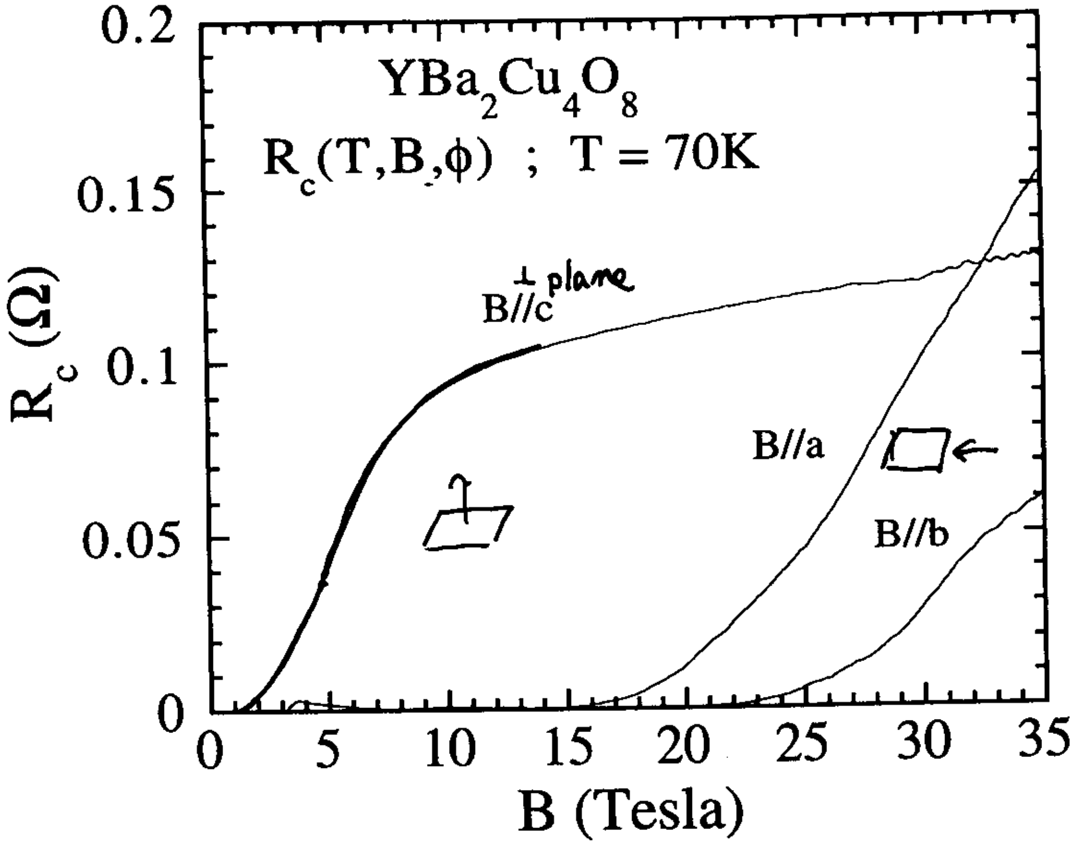


Figure 2
N.E. Hussey et al

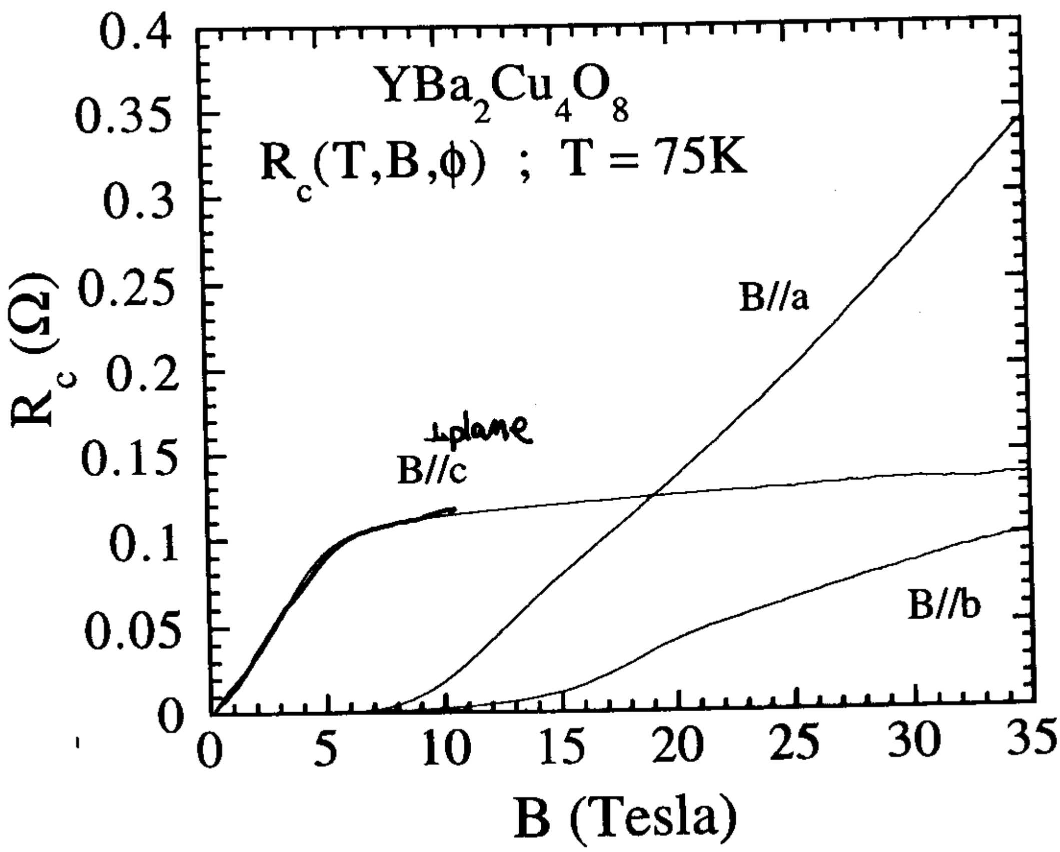
Shorted out due to misoriented domain!

"reproducibility"





Rc dominated by c-axis current
↓
SC supressed significantly when H // c



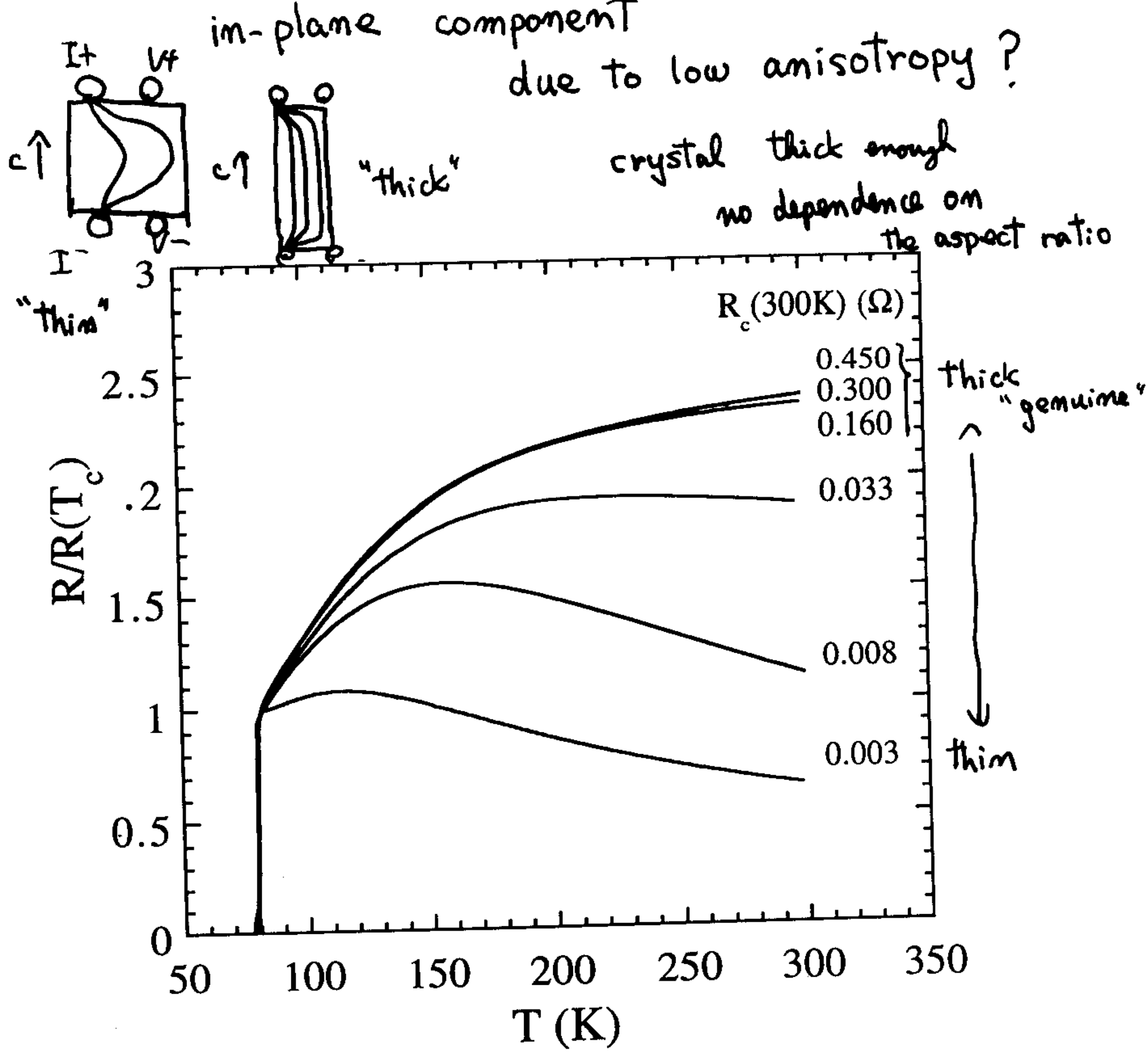


Figure 1
N.E. Hussey et al.

Zhou et al. PRL 97.

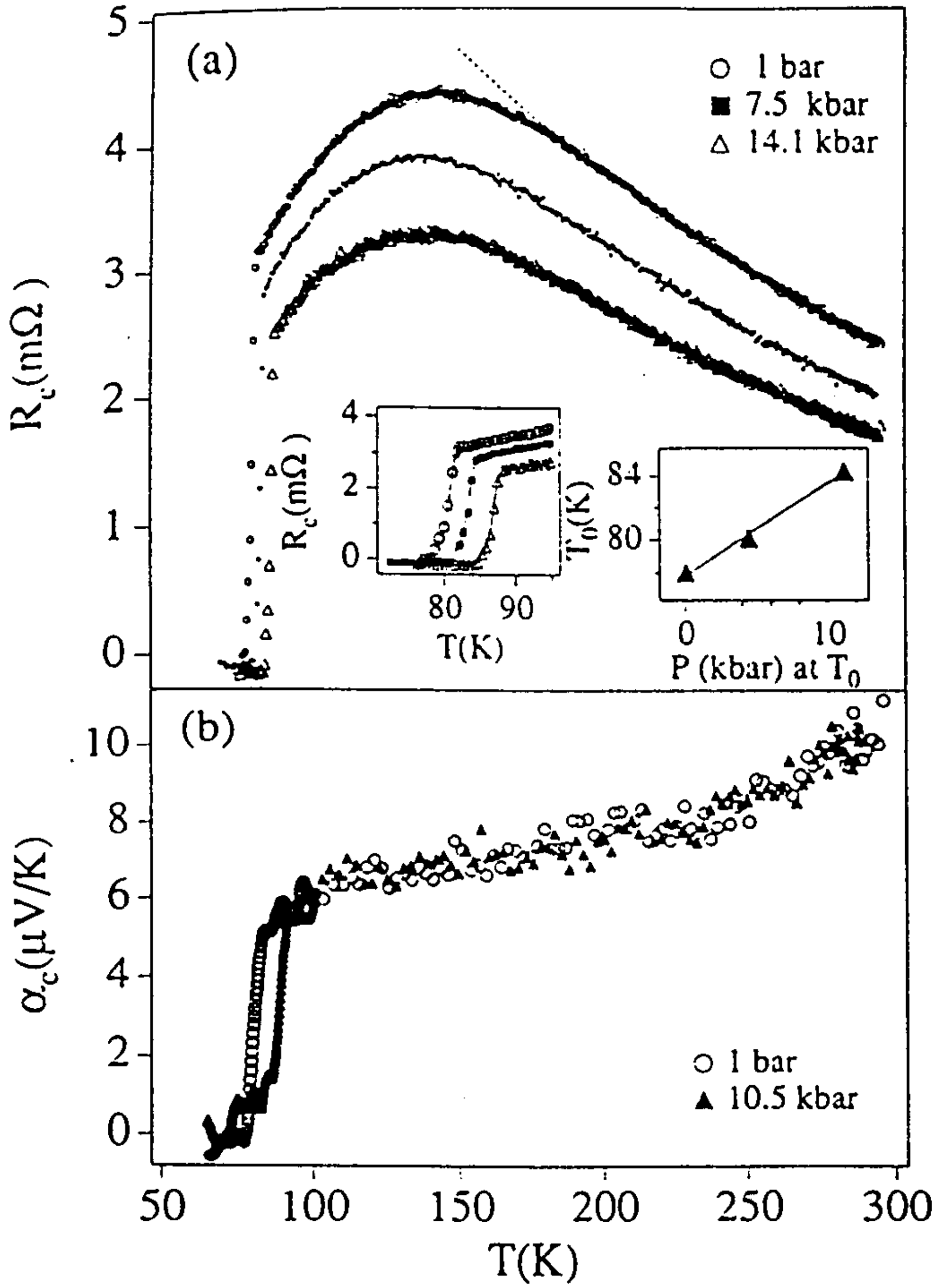
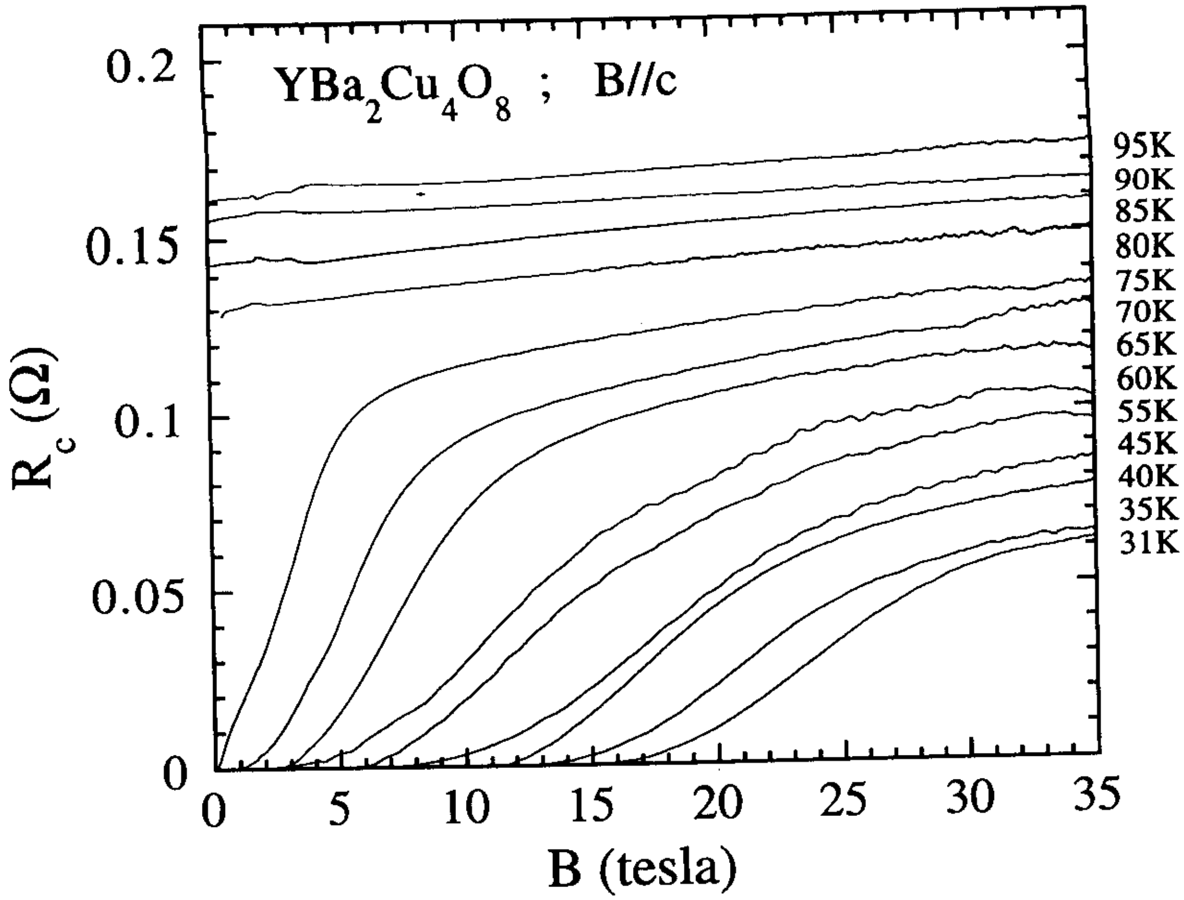


FIG. 4. The resistance (a) and TEP (b) along the c axis versus temperature under several pressures. The dashed line is an exponential fitting to the resistance at 1 bar. Inset: detail of the resistivity near transition temperature and superconductive transition temperature T_0 versus pressure.

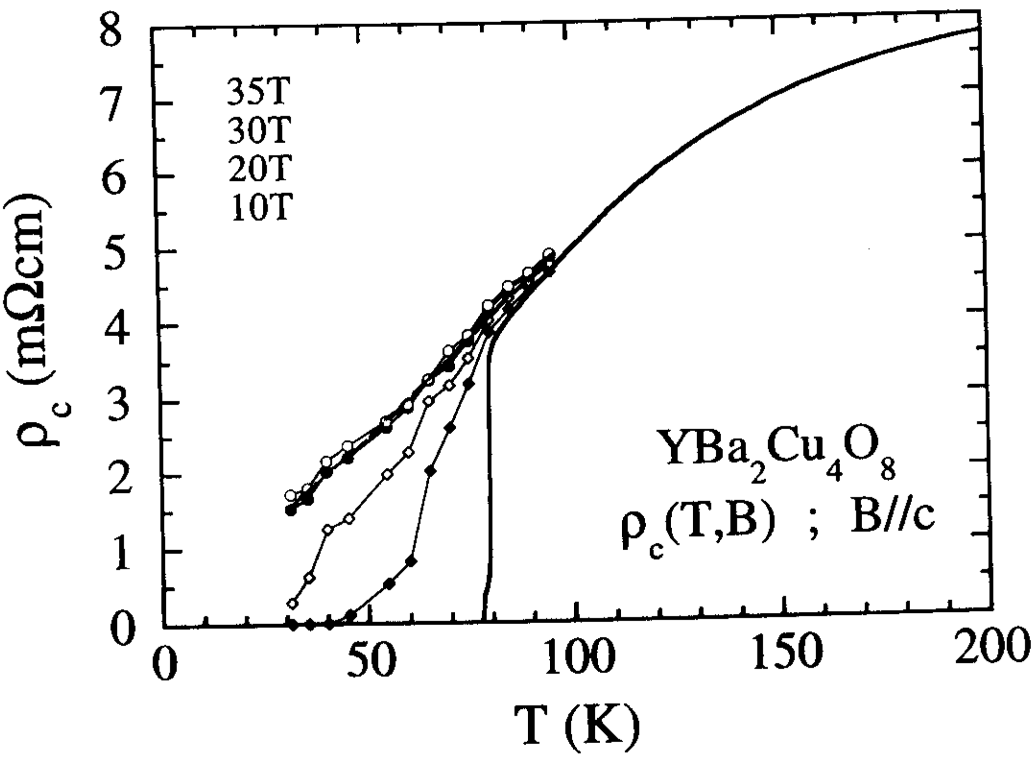
[1 cu da to at H by al pr sh to dr wl sh is lo vs sa ox sli

ha by ha ca fo su di

#2



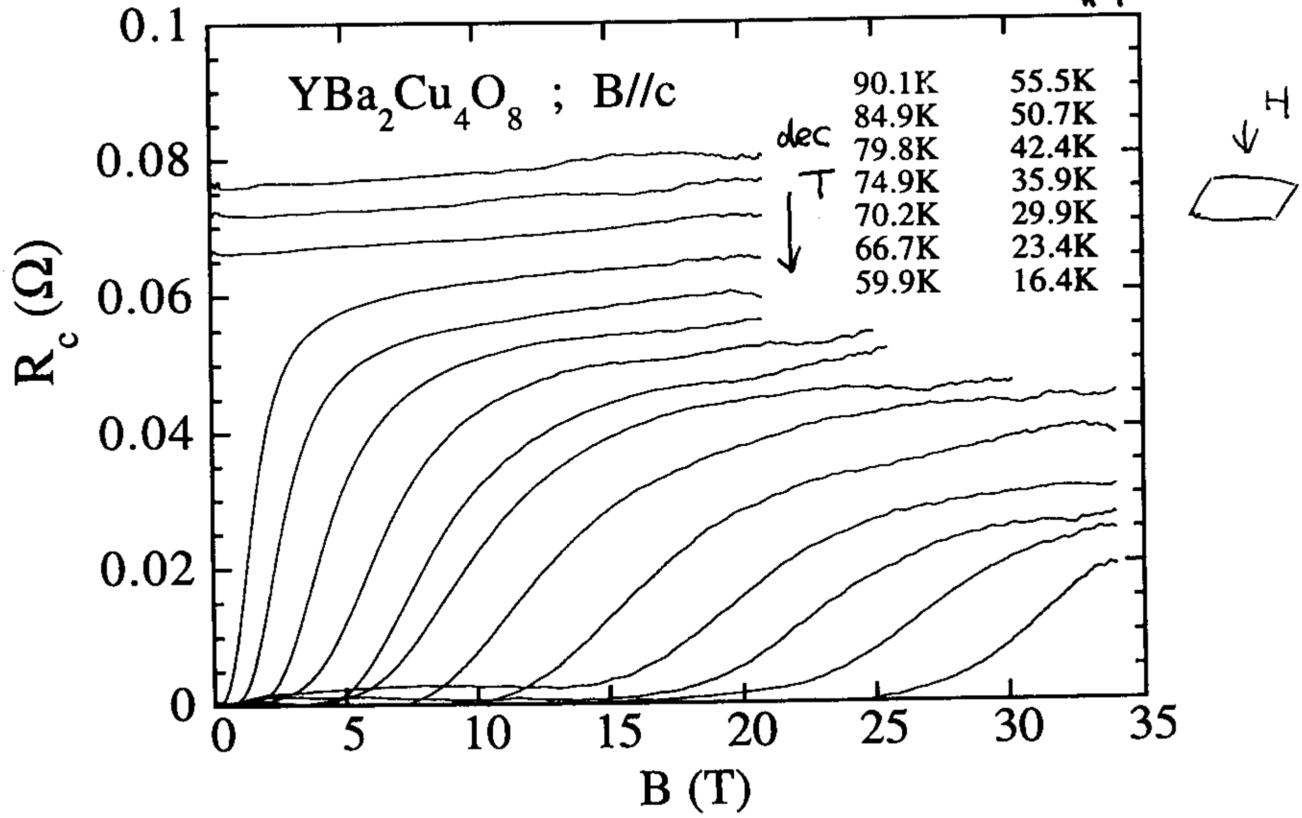
0.2
0.15
0.1
0.05
0
R_c (Ω)
$YBa_2Cu_4O_8$; B//c
95K
90K
85K
80K
75K
70K
65K
60K
55K
45K
40K
35K
31K
0
5
10
15
20
25
30
35
B (tesla)

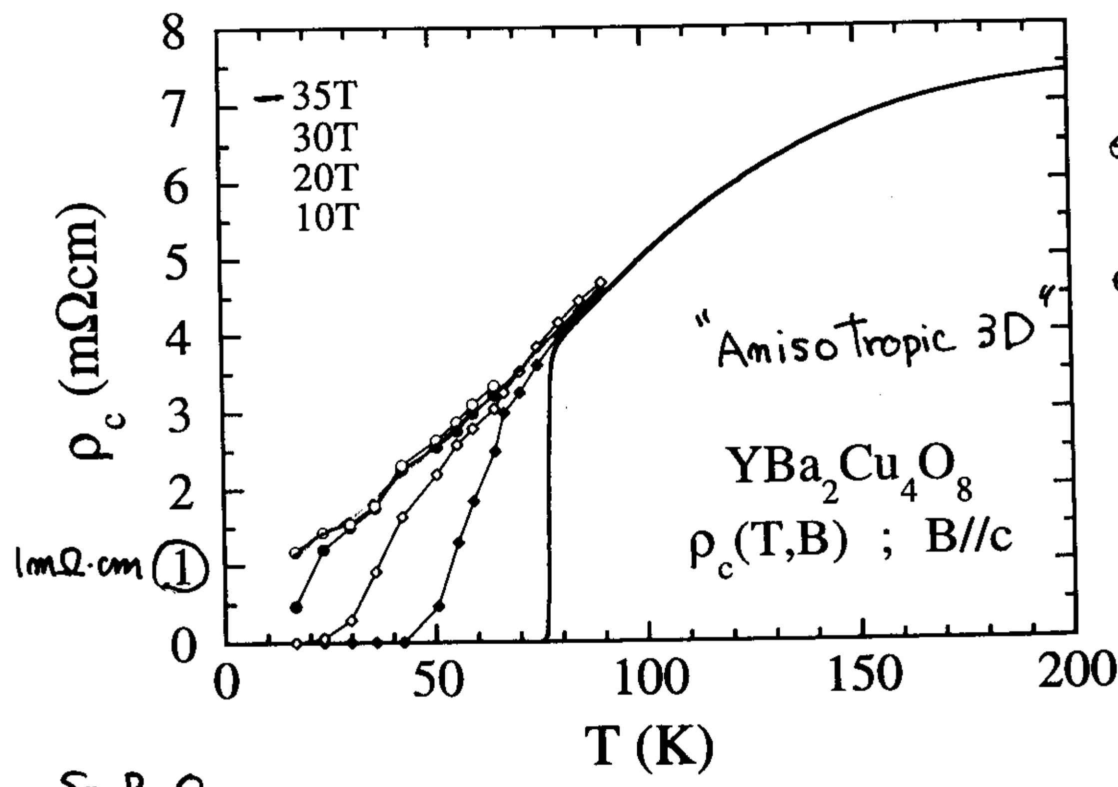


8
7
6
5
4
3
2
1
0
ρ_c (mΩcm)
35T
30T
20T
10T
$YBa_2Cu_4O_8$
ρ_c(T,B) ; B//c
0
50
100
150
200
T (K)

ρc(T) at low T pulsed field

\#1





coherent c-axis transport even in underdoped cuprate with spingap

however close to coherent-incoherent border

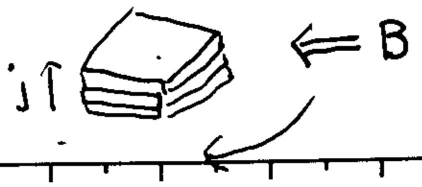
Sr_2RuO_4

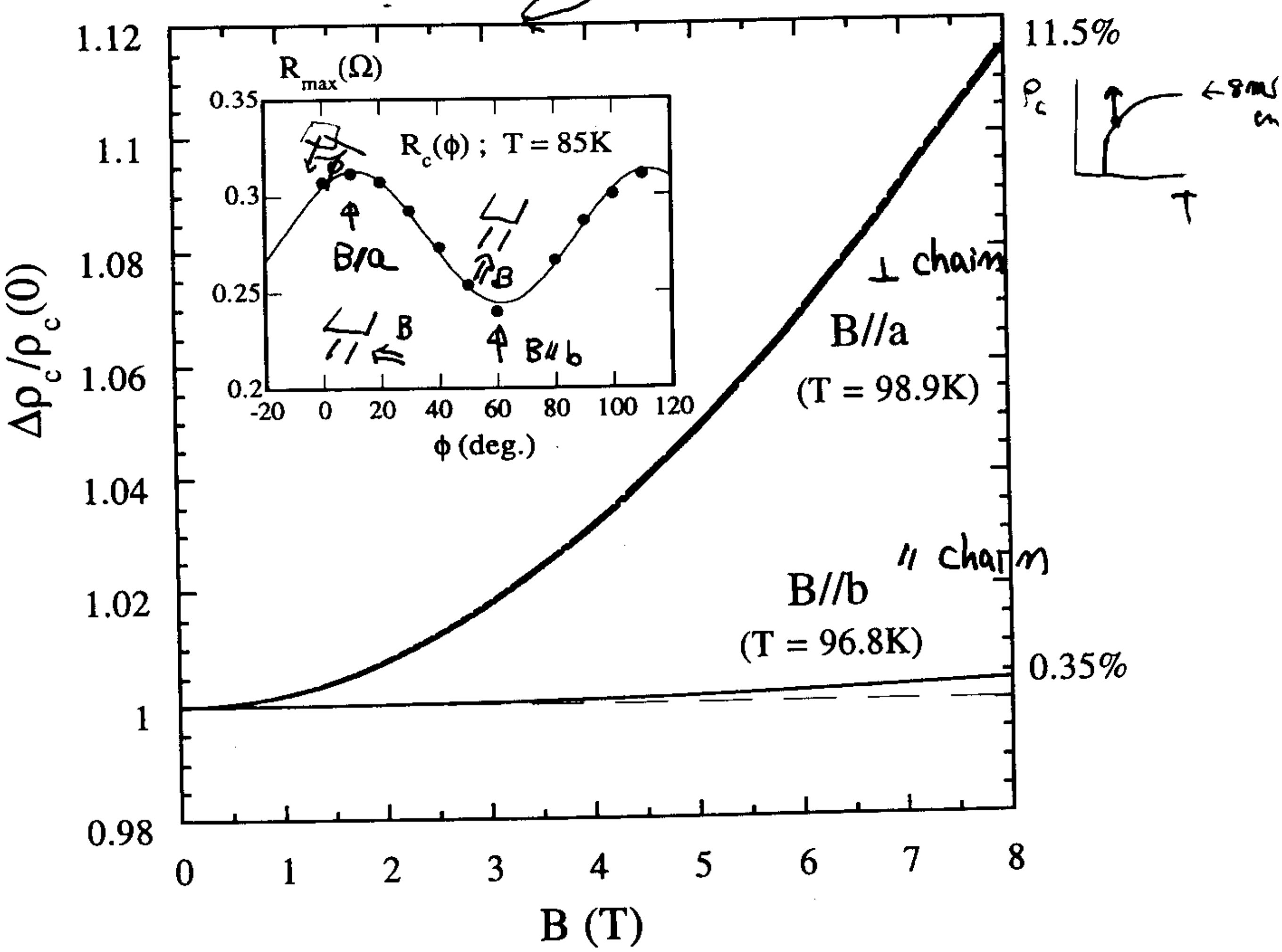
$\rho_c(0) \gtrsim 1\,m\Omega cm$

below 3D Mott limit.

c-axis MR reflects the symmetry of chains

— Importance of clean and metallic chain for the coherent c-axis transport





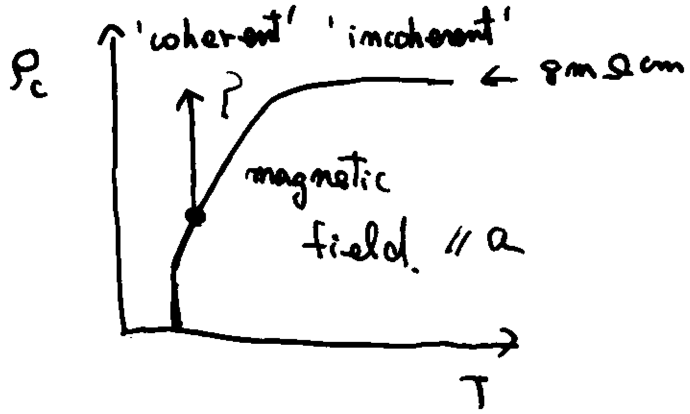
metallic $\rho_c(T)$

⟷ metallic chain

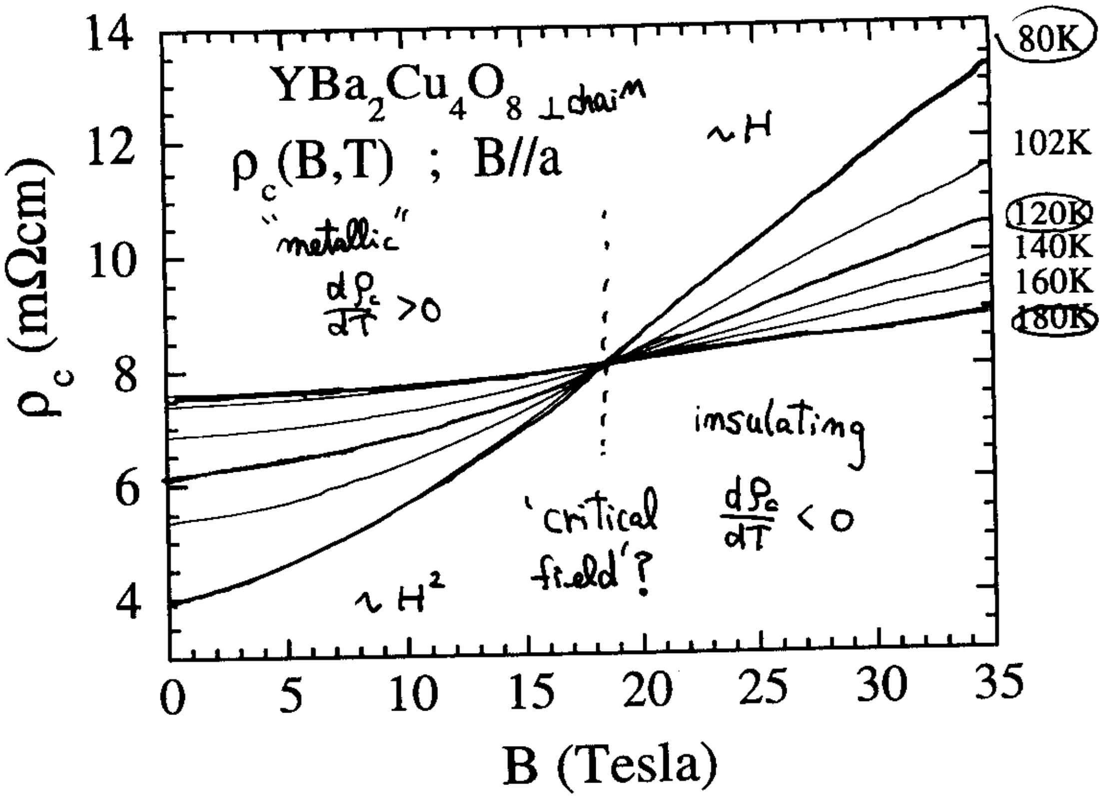
chain carries alone
can lead the coherent c-axis transport ??

→ to achieve coherent c-axis transport,
chain carries must be coupled with
plane carriers

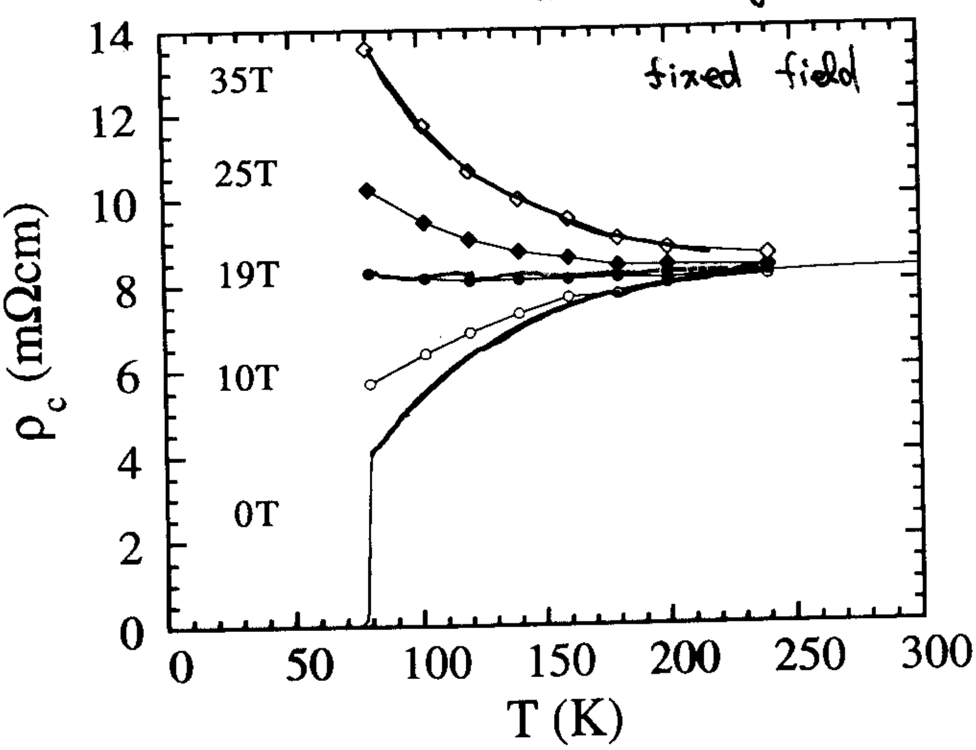
What will happen if $\rho_c \to 8\,m\Omega cm$ with high magnetic field.



High-field normal state c-axis MR



magnetic field induced dimensionality control



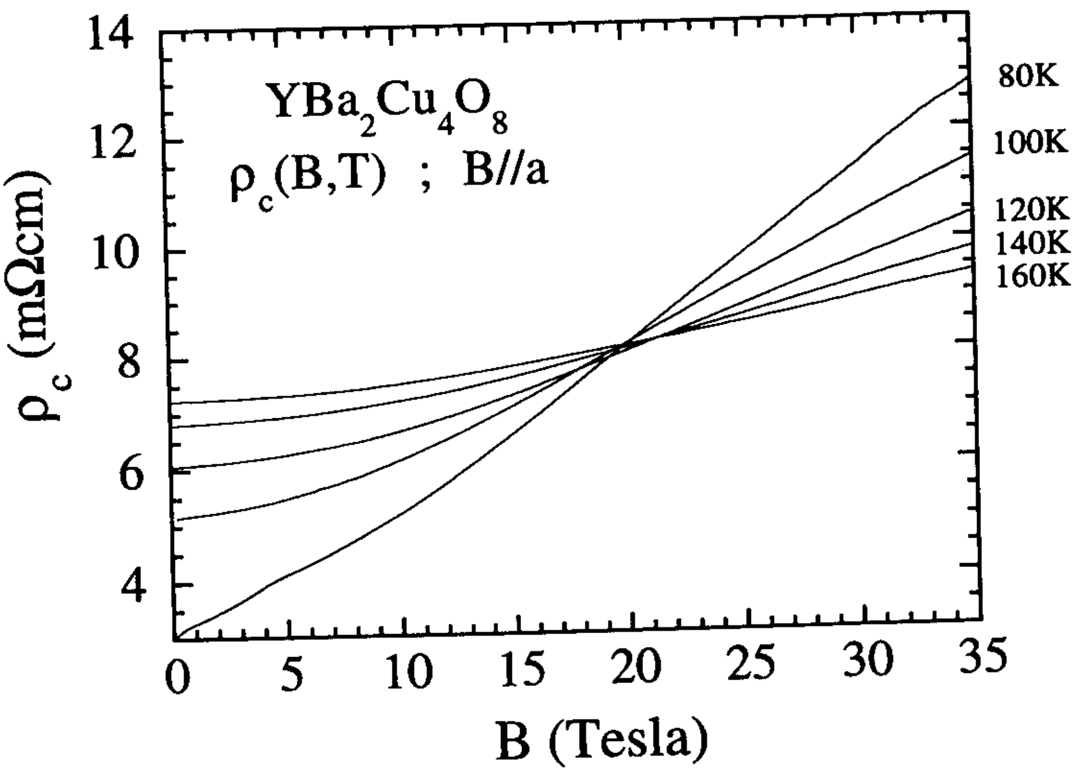
$d_c \sim \frac{4t_c}{V_F eB}$

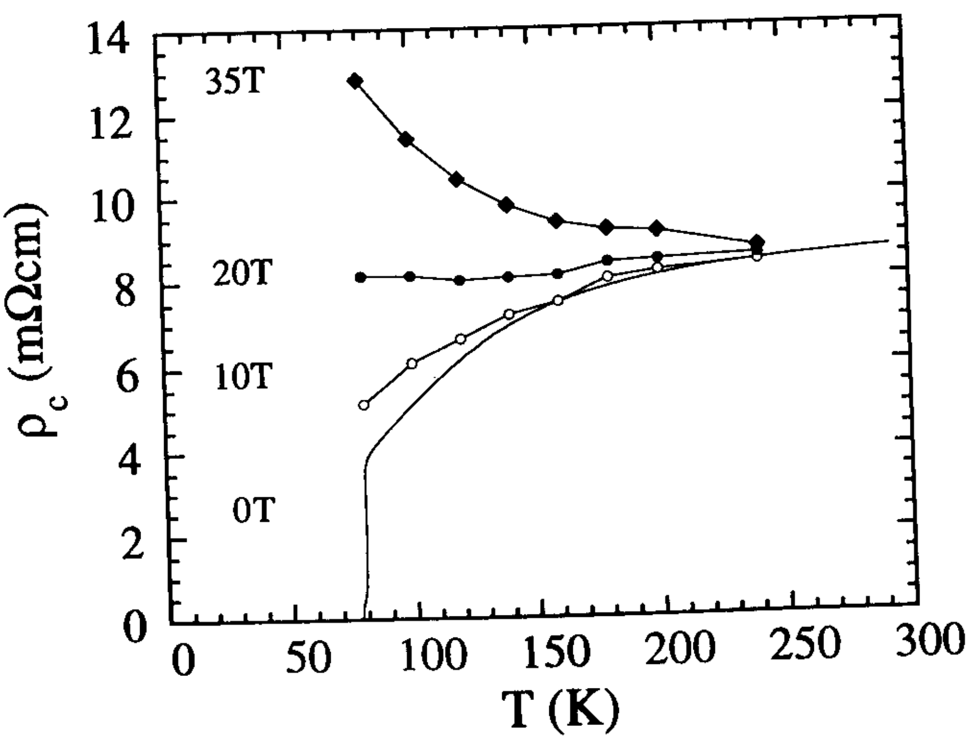
B = 20T

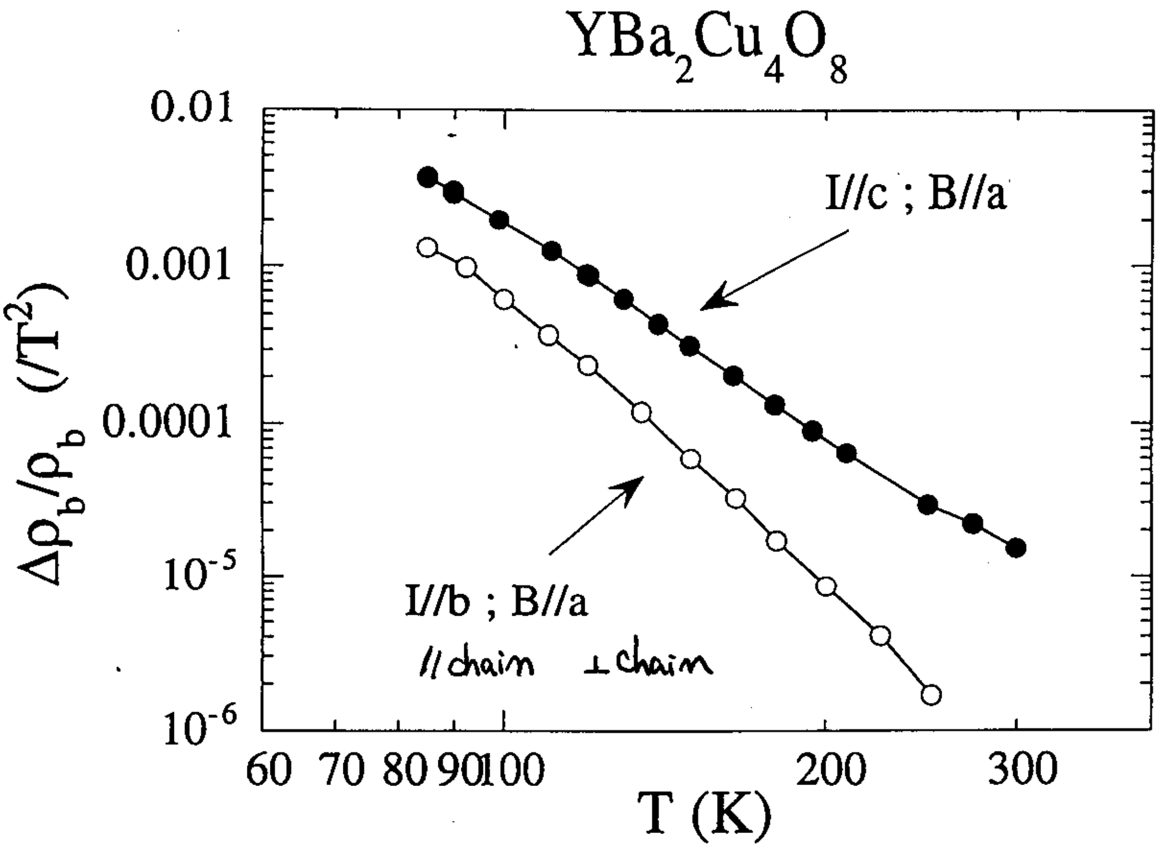
↓

$t_c \sim 5$ meV

sample #2.


YBa2Cu4O8
ρc(B,T) ; B//a
ρc (mΩcm)
B (Tesla)
80K
100K
120K
140K
160K
14
12
10
8
6
4
0
5
10
15
20
25
30
35


35T
20T
10T
0T
ρc (mΩcm)
T (K)
14
12
10
8
6
4
2
0
0
50
100
150
200
250
300



B⊥ chain

$$\frac{\Delta\rho_b}{\rho_b} \sim \frac{1}{3} \frac{\Delta\rho_c}{\rho_c}$$

Y124 summary

Although Y124 is underdoped with a spin gap, ρ_c shows a incoherent to coherent crossover with decreasing temperature

- ρ_c at low temperatures falls below Mott resistivity
- anisotropic 3D transport

Can charge still be confined within the plane?

clean and surprisingly metallic double CuO chains is very likely responsible for the coherent out-of-plane transport

magnetic field can decouple planes and chains

-possible field induced dimensionality change

coherent but close to coherent - incoherent crossover

What is generally believed for the out-of-plane transport in high-Tc cuprates

ρ_c/ρ_a by far larger than those predicted by band calculations

temperature dependence distinctly different from ρ_a

no apparent correlation between ρ_c/ρ_a and Tc

insulating behavior pronounced in the underdoped region, in particular when spin gap is developed ($T<T^*$) ?

- -closely related with pseudo gap in $\sigma_c(\omega)$
- -isotropic negative MR
- -charge confinement associated with the spin gap?
- –T=0 limit

logarithmic divergence with $T\rightarrow0$, accompanied by in-plane insulating behavior underdoped LSCO, but unversal?

ρ_c diverge with $T\rightarrow0$ (Bi2201) but not for ρ_a

tend to recover coherent behavior when overdoped

–ρ_c is metallic and appears to stay finite with $T\rightarrow0$ (LSCO, Y123 90K, Tl)