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SMR 1232 - 20

XII WORKSHOP ON
STRONGLY CORRELATED ELECTRON SYSTEMS

17 - 28 July 2000

SUBKELVIN THERMAL CONDUCTIVITY IN CUPRATE AND ORGANIC SUPERCONDUCTORS

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

Subkelvin thermal conductivity in cuprate and organic superconductors

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H. Aubin (Now in Urbana)) Orsay, 97-99
S. Belin
S. Nakamae) Paris, since 01/2000
C. Capan

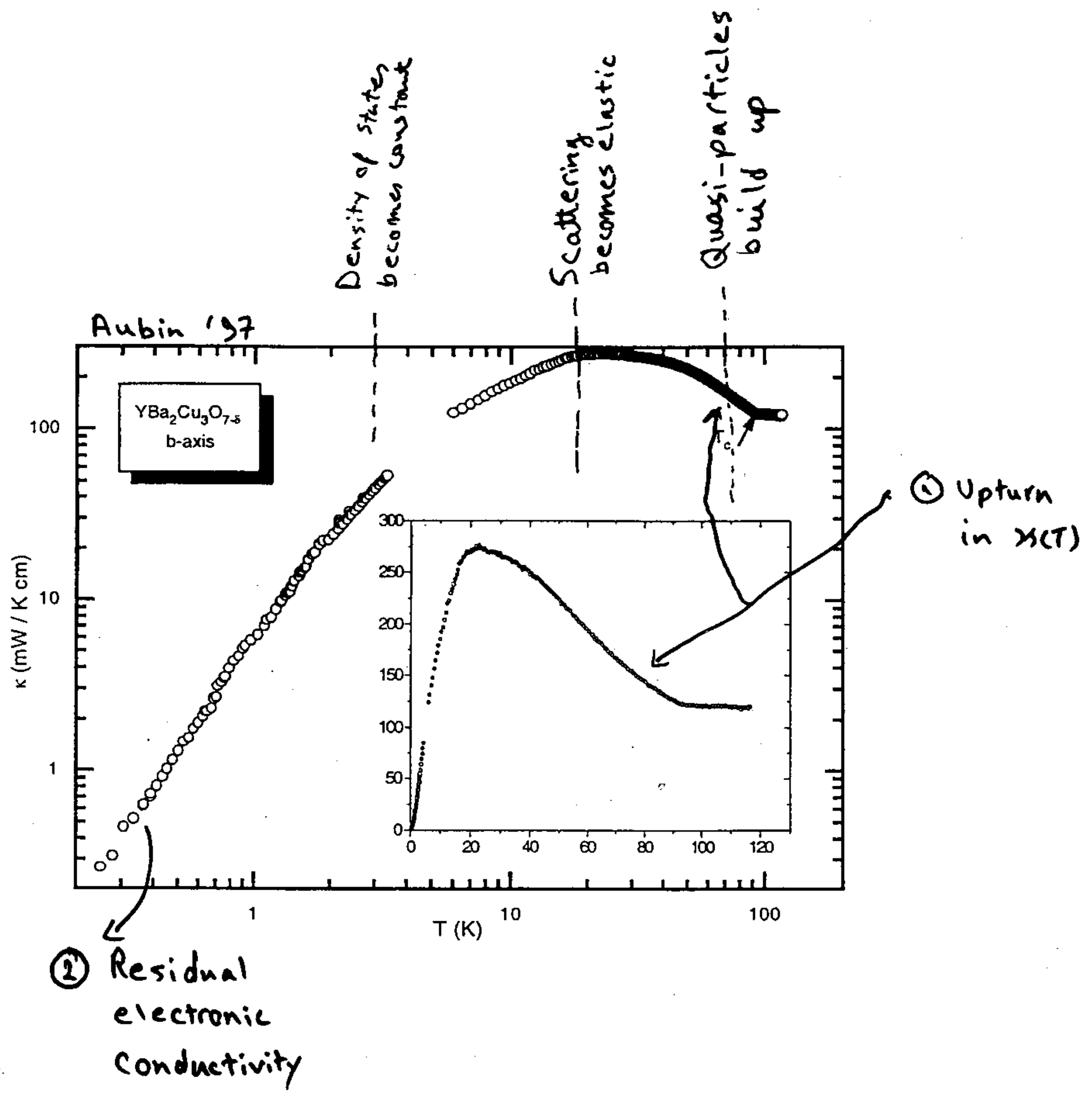
F. Rullier-Albenque, *Orme-les-mérisiers* electron irradiation

T. Tamegai, *Tokyo* Bi2212

N. E. Hussey, *Loughborough*
H. Takagi, *Tokyo*
S. Tajima, *Tokyo* Y124

L. Taillefer, *Toronto*

L. Forro, Lausanne Bi2212



Aubin '97
Density of states becomes constant
Scattering becomes elastic
Quasi-particles build up
YBa2Cu3O7-δ
b-axis
κ (mW / K cm)
T (K)
Tc
① Upturn in κ(T)
② Residual electronic conductivity

Quasi-Particle transport in unconventional superconductors in absence of inelastic scattering

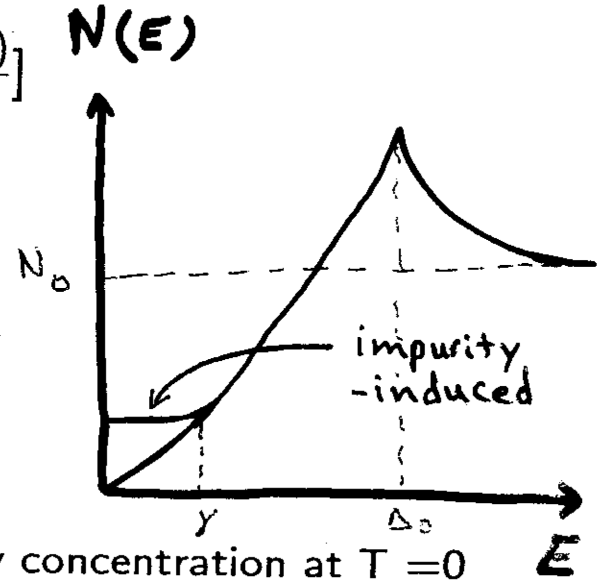
Basic idea: pair breaking by potential scattering produces zero-energy quasi-particles.

Schmitt-Rink et al. , Hirschfeld et al.(1986)

Impurity bandwidth γ :

Unitary: $\gamma \sim (\Gamma\Delta_0)^{1/2}$

Born: $\gamma \sim \Delta_0 \exp[-\Delta_0 \frac{(1+ctg^2\delta)}{\Gamma}]$



Universal Regime

(P. A. Lee 1993)

For d-wave state

$N(0) \propto \gamma$

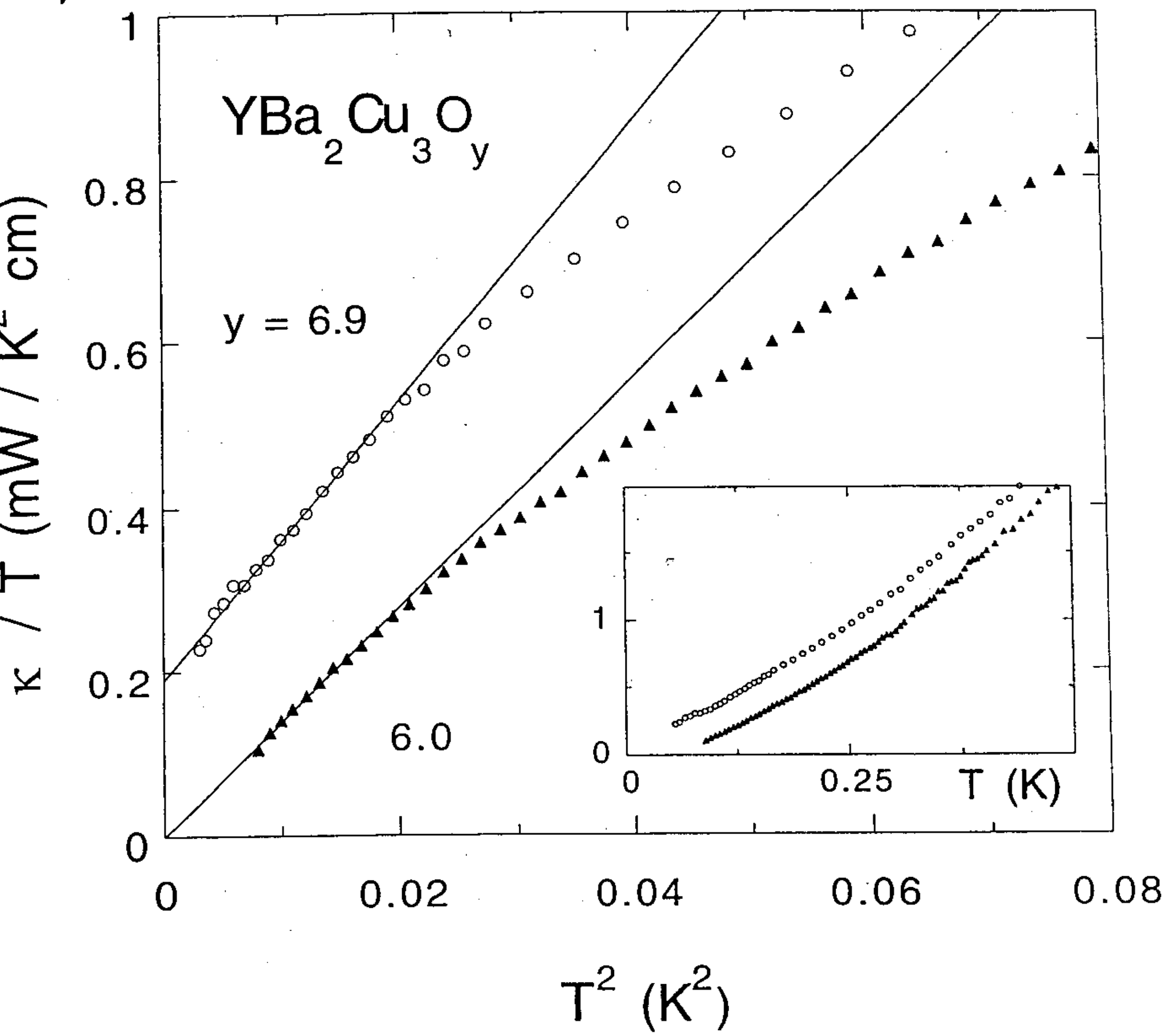
$\frac{1}{\tau} \propto \gamma$

$\frac{\kappa_{00}}{T}$ becomes independent of impurity concentration at T =0

⚠ Both γ and $\tau(\epsilon)$ depend [redacted] on the impurity phase shift.

The "Universal" linear term

Taillefer '97



– A residual electronic contribution

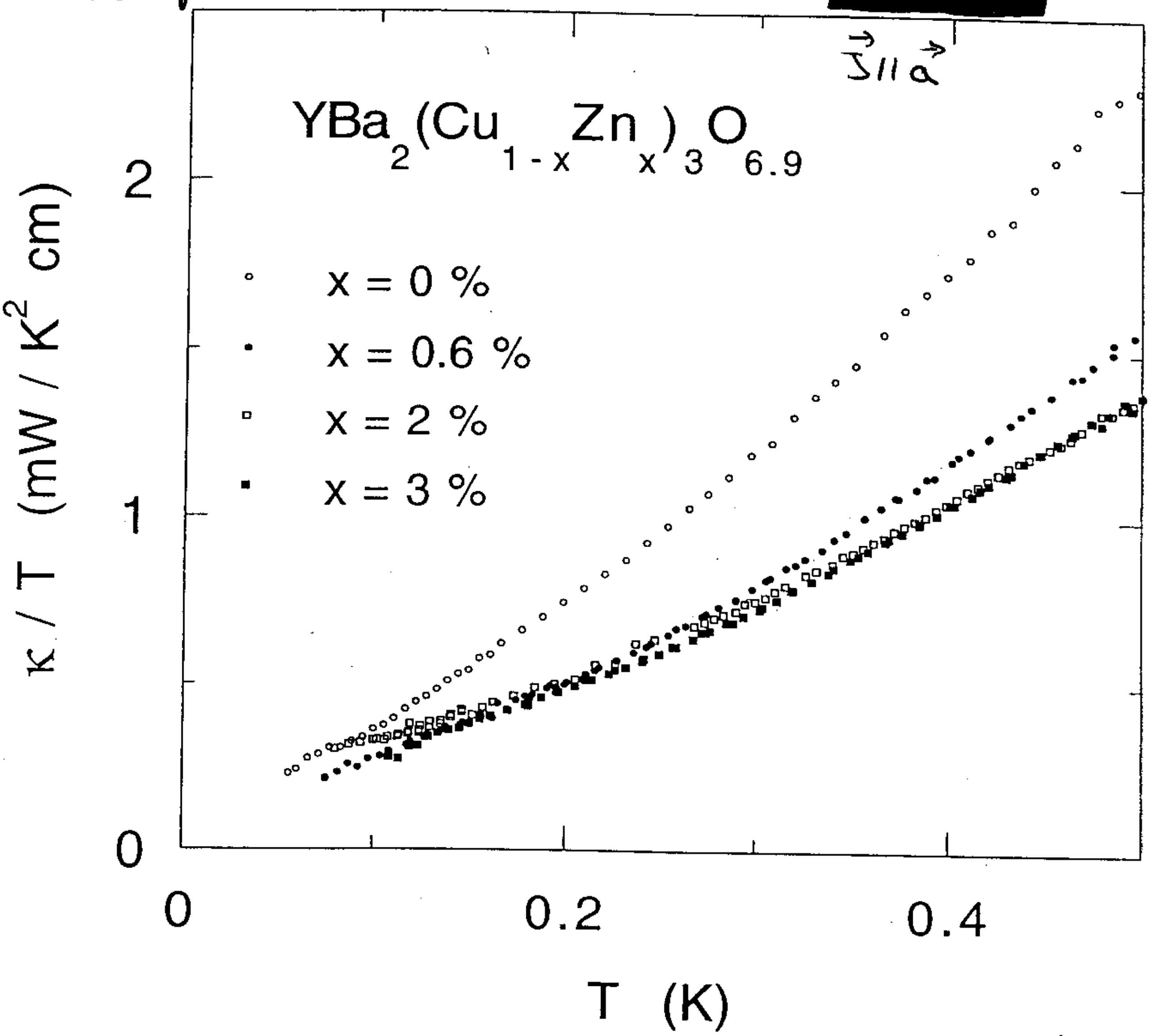
For $T \longrightarrow 0$

$$\frac{\kappa}{T} = \kappa_{00} + A T^2$$

residual electronic ("balistic" Phonon contribution

Effect of Zn-doping on the linear term

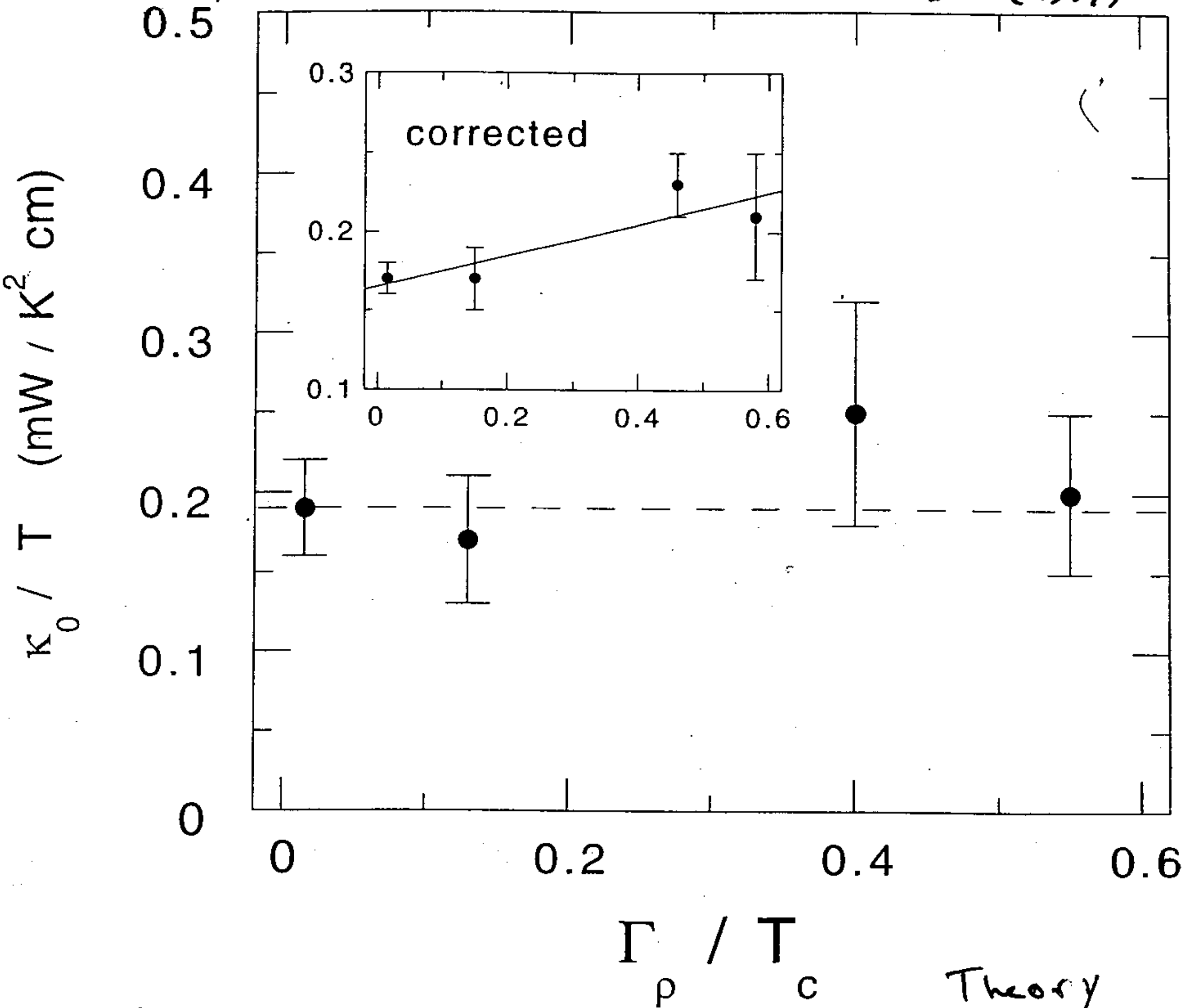
Taillefer '97 [redacted]



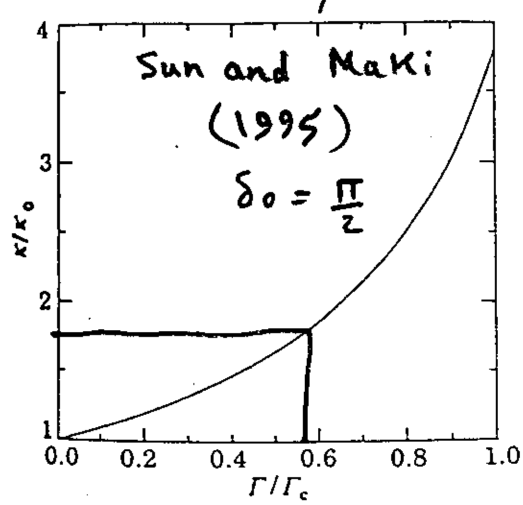
At T=0,1 K, Thermal conductivity is virtually unchanged!

The change in $\frac{\kappa_0}{T}$ with the scattering rate!

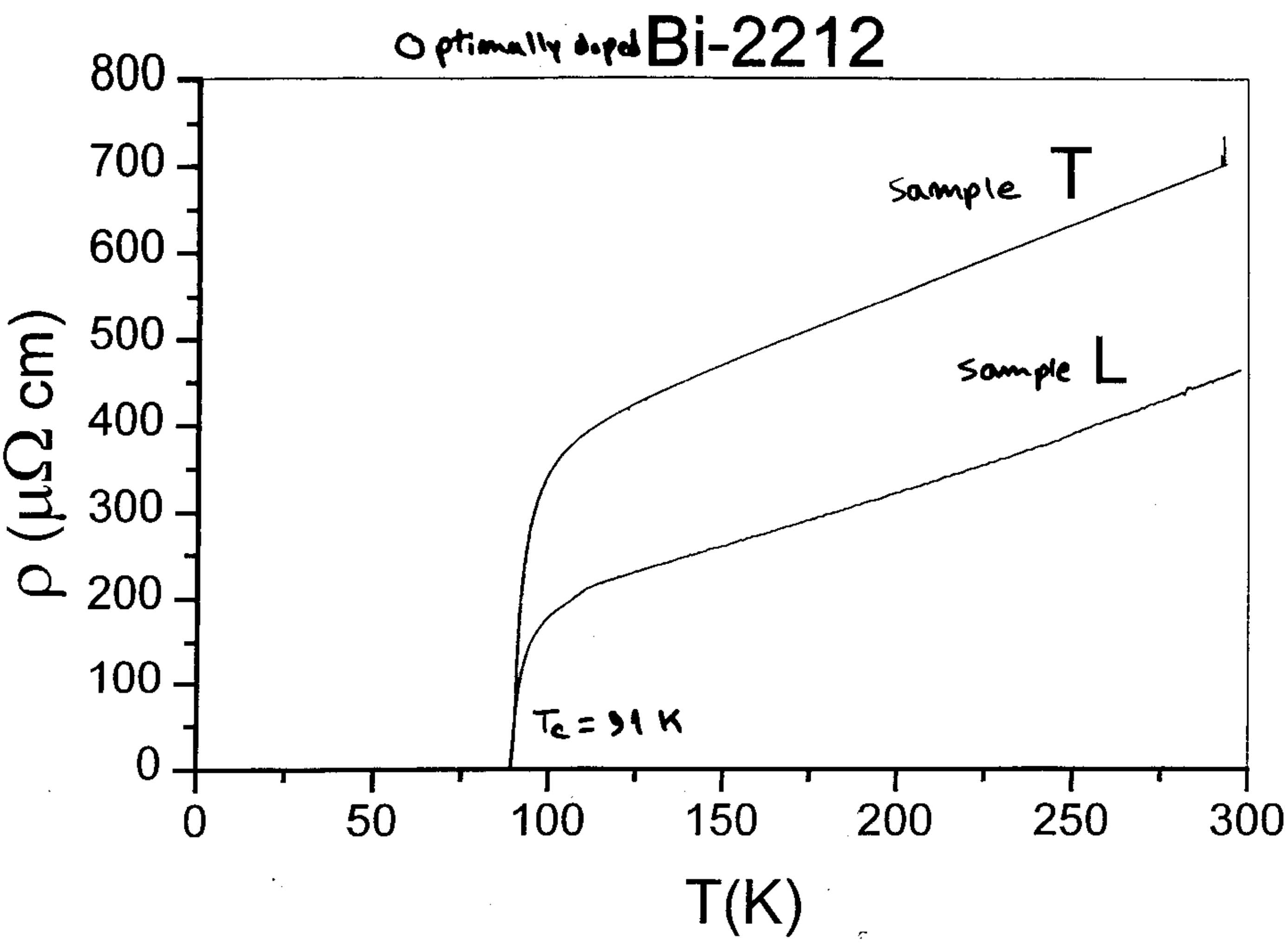
Taillefer '97 [redacted] (1997)

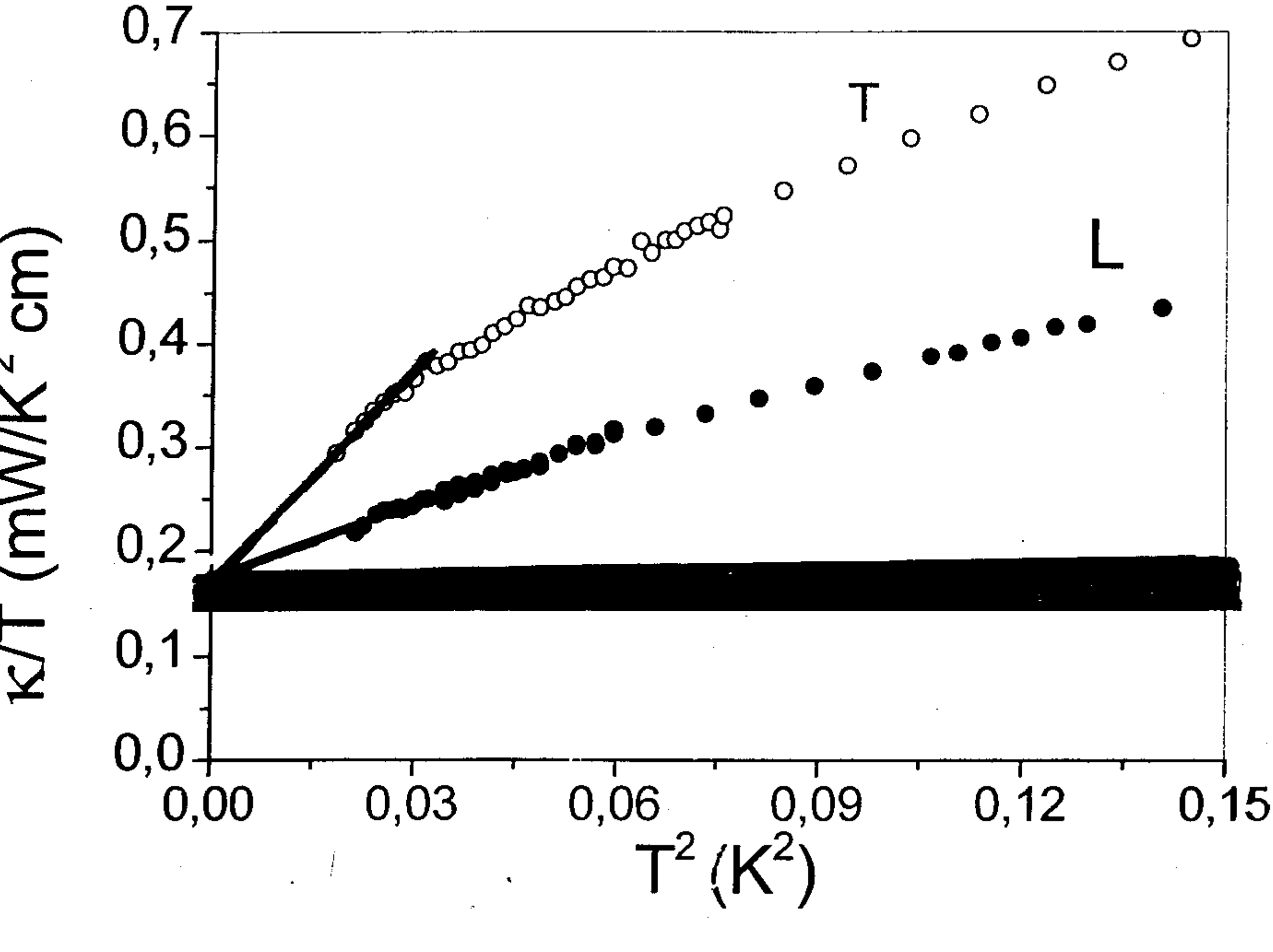


Theory

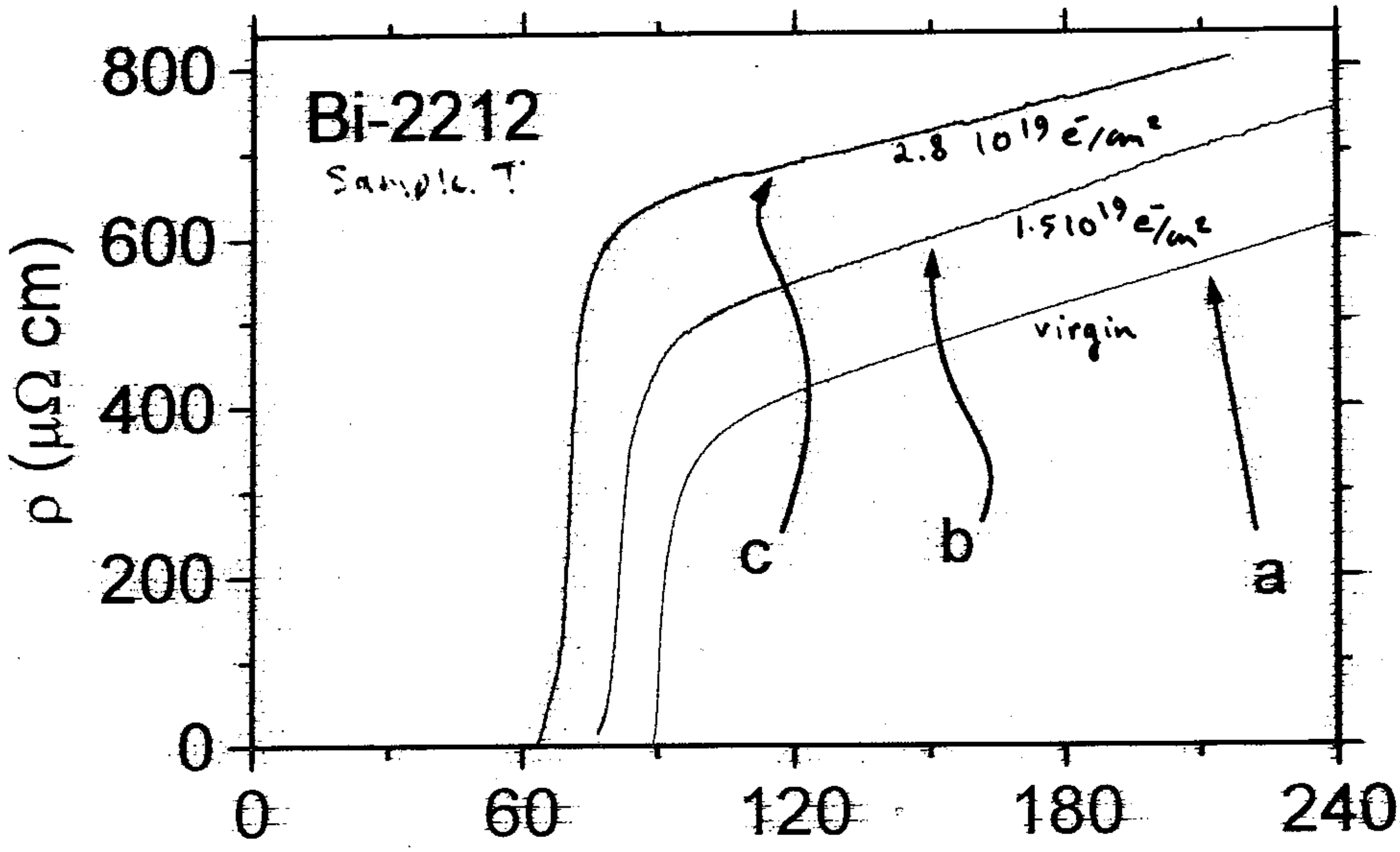


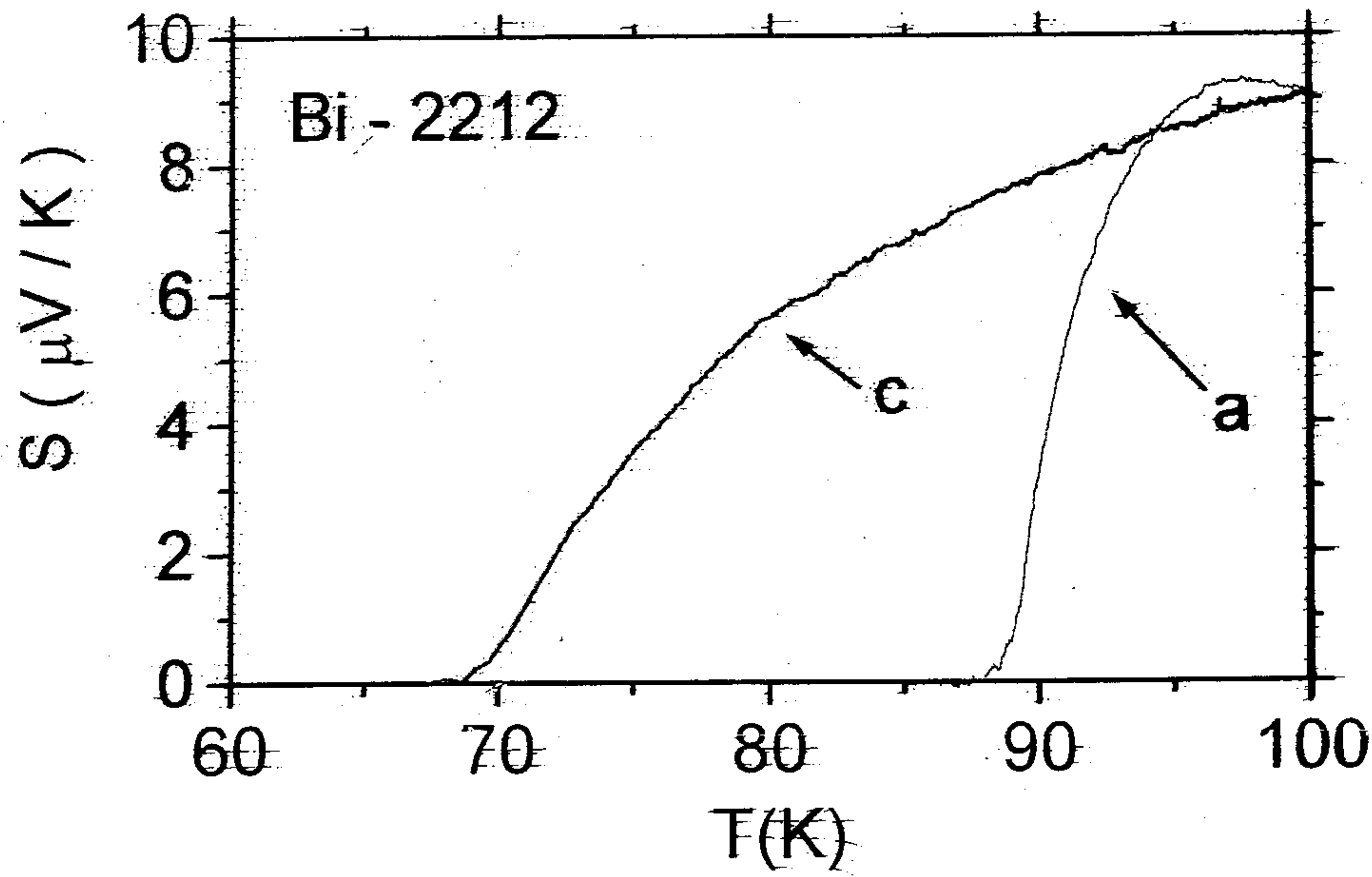
The increase in $\frac{\kappa_0}{T}$ is less than what is expected for resonant ($\delta_0 = \frac{\pi}{2}$) scattering!


Optimally doped Bi-2212
800
700
600
500
400
300
200
100
0
ρ (μΩ cm)
sample T
sample L
T_c = 91 K
0
50
100
150
200
250
300
T(K)

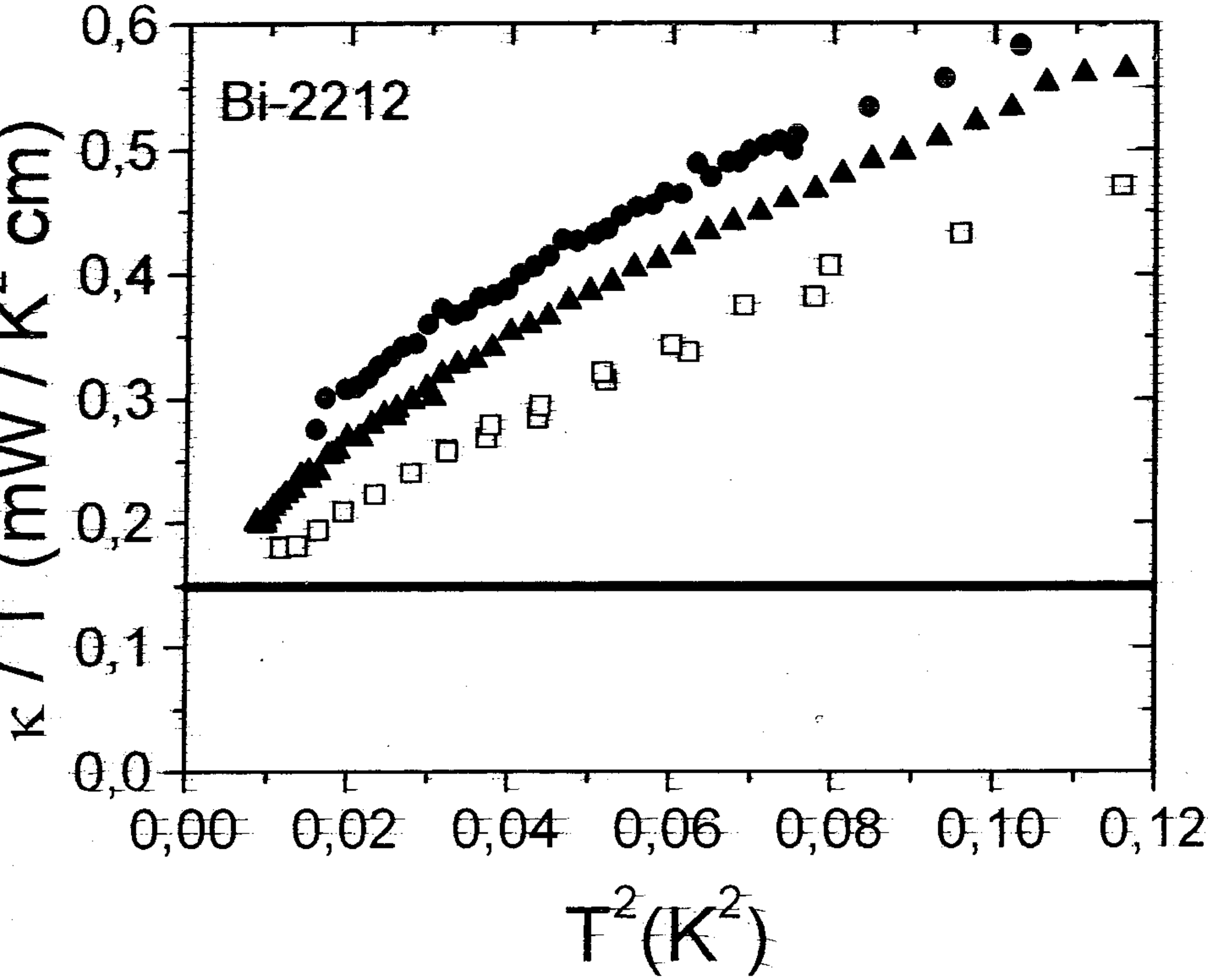

0,7
0,6
0,5
0,4
0,3
0,2
0,1
0,0
κ/T (mW/K² cm)
T
L
0,00
0,03
0,06
0,09
0,12
0,15
T² (K²)

Effect of electron irradiation on optimally-doped Bi2212





Sample T

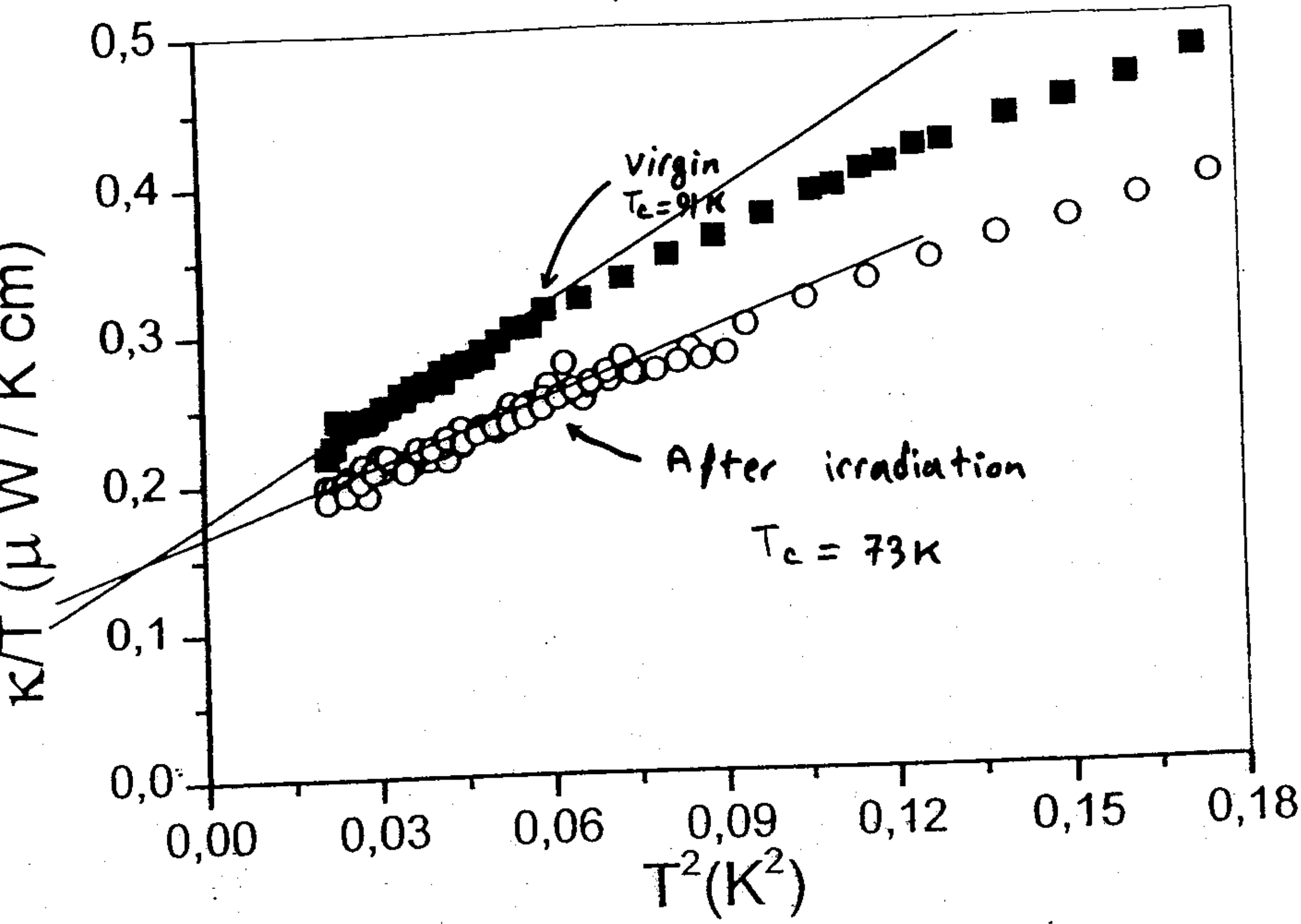


- Decrease in κ with increasing disorder

- "Unmodified" κ_{00}/T ~ 0,15 – 0,17 $\frac{mW}{K cm^2}$

$\frac{v_F}{v_2} = 20 \pm 3$

Sample L



Introduction of disorder:

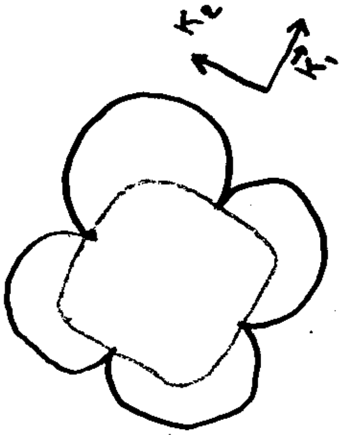
- does not modify κ_{00}
- reduces κ at finite T $\Rightarrow$ $\gamma < 0.2\,K$!!

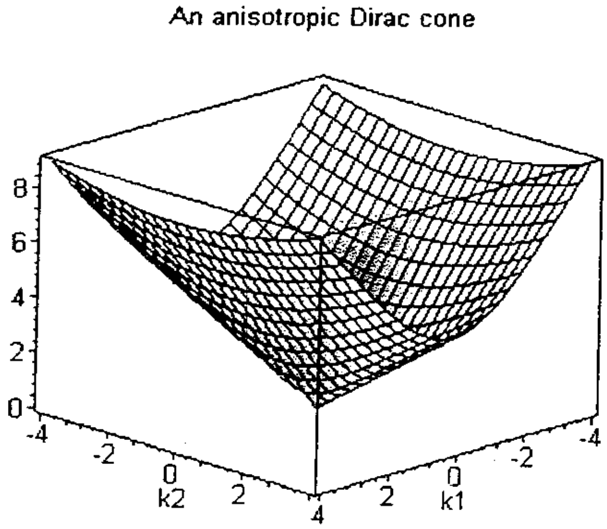
In Unitary limit $\gamma \sim \sqrt{(\Gamma \Delta_0)}$

[redacted] $\sim$ 10 K

Mystery: Why the energy scale is so low?

A TALE OF TWO VELOCITIES!





Durst, Lee 1999

Figure 1: Excitation spectrum in the vicinity of a node.

$$E(k) = ({\epsilon_K}^2 + \Delta_K^2)^{1/2} = (v_F^2 k_1^2 + v_2^2 k_2^2)^{1/2}$$

Fermi velocity: $\overrightarrow{v_F} = \frac{\partial \epsilon_K}{\partial k_1} = v_F \widehat{k_1}$

Gap velocity: $\overrightarrow{v_2} = \frac{\partial \Delta_K}{\partial k_2} = v_2 \widehat{k_2}$

$$\frac{\kappa_{00}}{T} = k_B^2 \frac{v_F^2 + v_2^2}{v_F v_2} \frac{n}{3\hbar}$$

← n: stack density of CuO_2 planes

$\frac{v_F}{v_2}$ determines various low energy properties!

Superconducting Gap Anisotropy and Quasiparticle Interactions: A Doping Dependent Photoemission Study

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(Received 23 December 1998)

Comparing photoemission measurements on Bi2212 with penetration depth data, we show that a description of the nodal excitations of the d-wave superconducting state in terms of noninteracting quasiparticles is inadequate, and we estimate the magnitude and doping dependence of the Landau interaction parameter which renormalizes the linear T contribution to the superfluid density. Furthermore, although consistent with d-wave symmetry, the gap with underdoping cannot be fit by the simple $\cos k_x - \cos k_y$ form, which suggests an increasing importance of long range interactions as the insulator is approached.

PACS numbers: 74.25.Jb, 71.18.+y, 74.72.Hs, 79.60.Bm

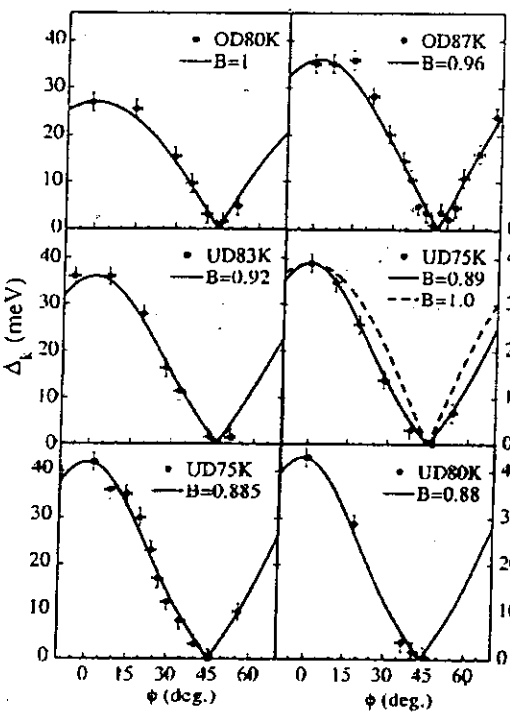


FIG. 2. Values of the superconducting gap as a function of the Fermi surface angle ϕ obtained for a series of Bi2212 samples with varying doping. Note two different UD75K samples were measured, and the UD83K sample has a larger doping due to aging [16]. The solid lines represent the best fit using the gap function: $\Delta_k = \Delta_{max}[B\cos(2\phi) + (1 - B)\cos(6\phi)]$ as explained in the text. The dashed line in the panel of an UD75K sample represents the gap function with $B = 1$.

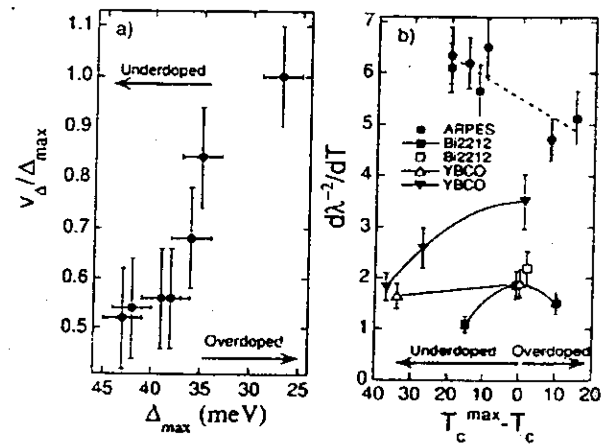
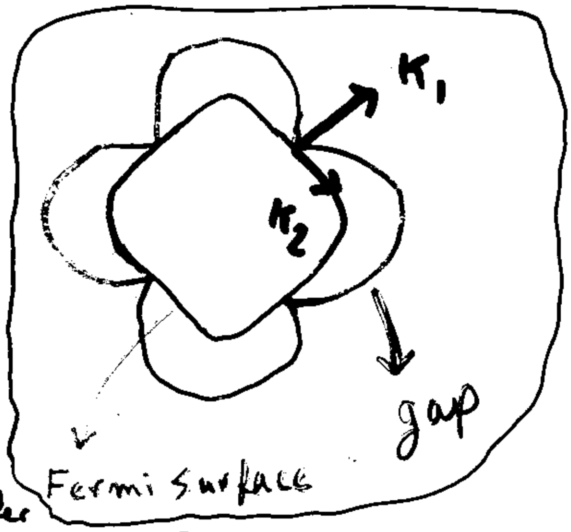


FIG. 3. (a) Normalized slope of the gap at the node (v_Δ/Δ_{max}) vs gap maximum Δ_{max}. Note the clear drop from unity as one enters the underdoped regime. (b) Slope of the superfluid density (in units of 10^{-9} Å^{-2} K^{-1}) vs $T_c^{max} - T_c$ estimated from ARPES measurements based on noninteracting quasiparticles in Bi2212 (filled circles) compared with direct penetration depth measurements in YBCO (open [12] and filled [15] triangles, $T_c^{max} = 92$ K) and Bi2212 (open [13] and filled [14] squares, $T_c^{max} = 95$ K). The error bars for the latter values were ±15% based on ±5% error bars for $\lambda(0)$ [14]. The lines are guides to the eye.

Fine structure of the superconducting gap in optimally-doped Bi2212

$E(k) = (v_F^2 k_1^2 + v_2^2 k_2^2)^{1/2}$
(P. A. Lee '97)



1)Thermal conductivity

$\frac{\kappa_{00}}{T} = \frac{k_B^2}{3\hbar}\frac{v_F}{v_2}n$

$\frac{\kappa_{00}}{T} = 0.14 mW cm^{-1} K^{-2}$

$\frac{v_F}{v_2} \sim 19$

[See also M. Chiao, L. Taillefer et al. PRB August '00]

2)photoemission

(Mesot et al. 1998)

$\frac{v_F}{v_2} \sim 20$

3) Penetration depth

$\frac{1}{\lambda^3}\frac{d\lambda}{dT} = 4 \ln 2 \frac{k_B e^2}{\hbar^2 c^2}\frac{n}{d}\frac{v_F}{v_2}$

with $\lambda(0) = 2100$Å

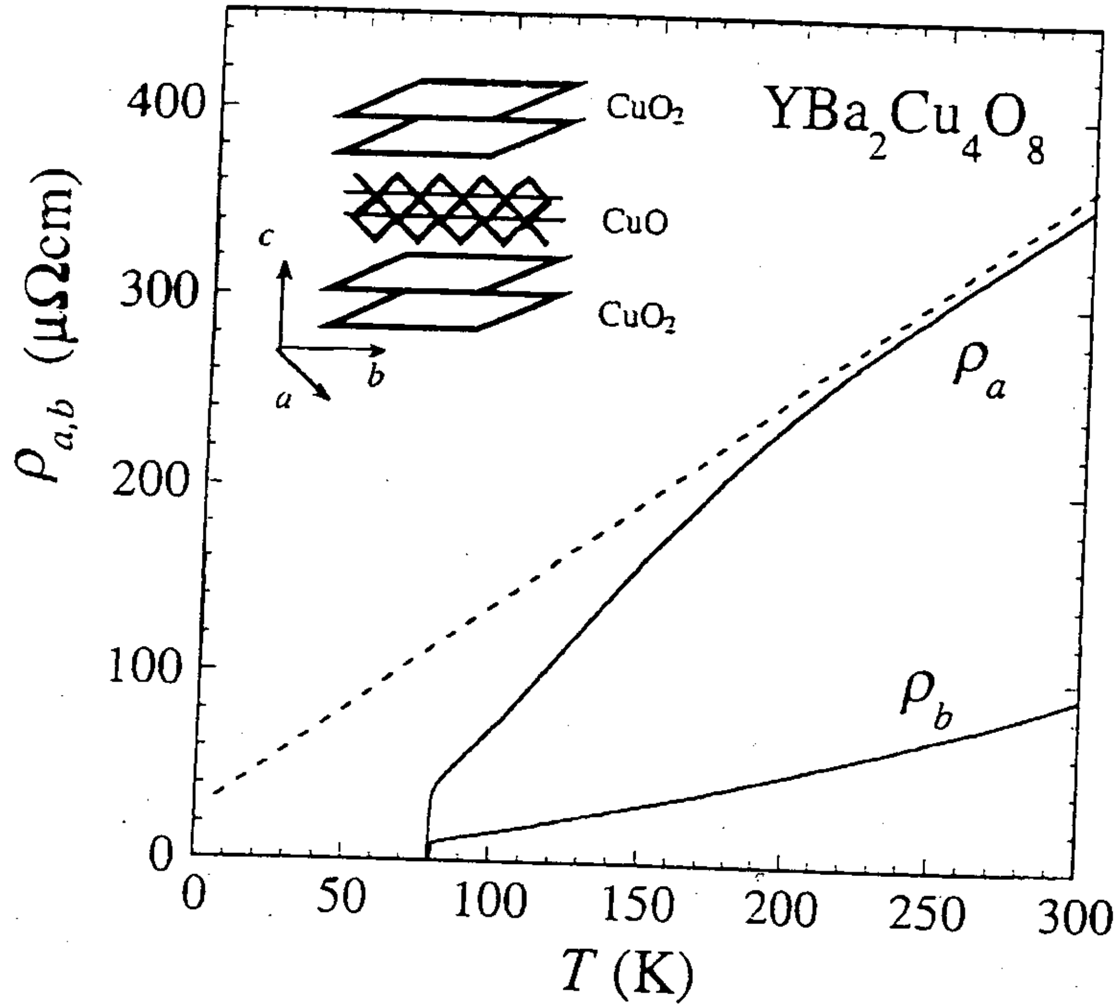
$\frac{d\lambda}{dT} = 10.2$Å$/K$

(Waldmann et al. 1996)

$\frac{v_F}{v_2} \sim 10$

Renormalisation due to QP interactions?

See Durst & Lee, cond-mat/9908182



$YBa_2Cu_4O_8$

Naturally untwinned!

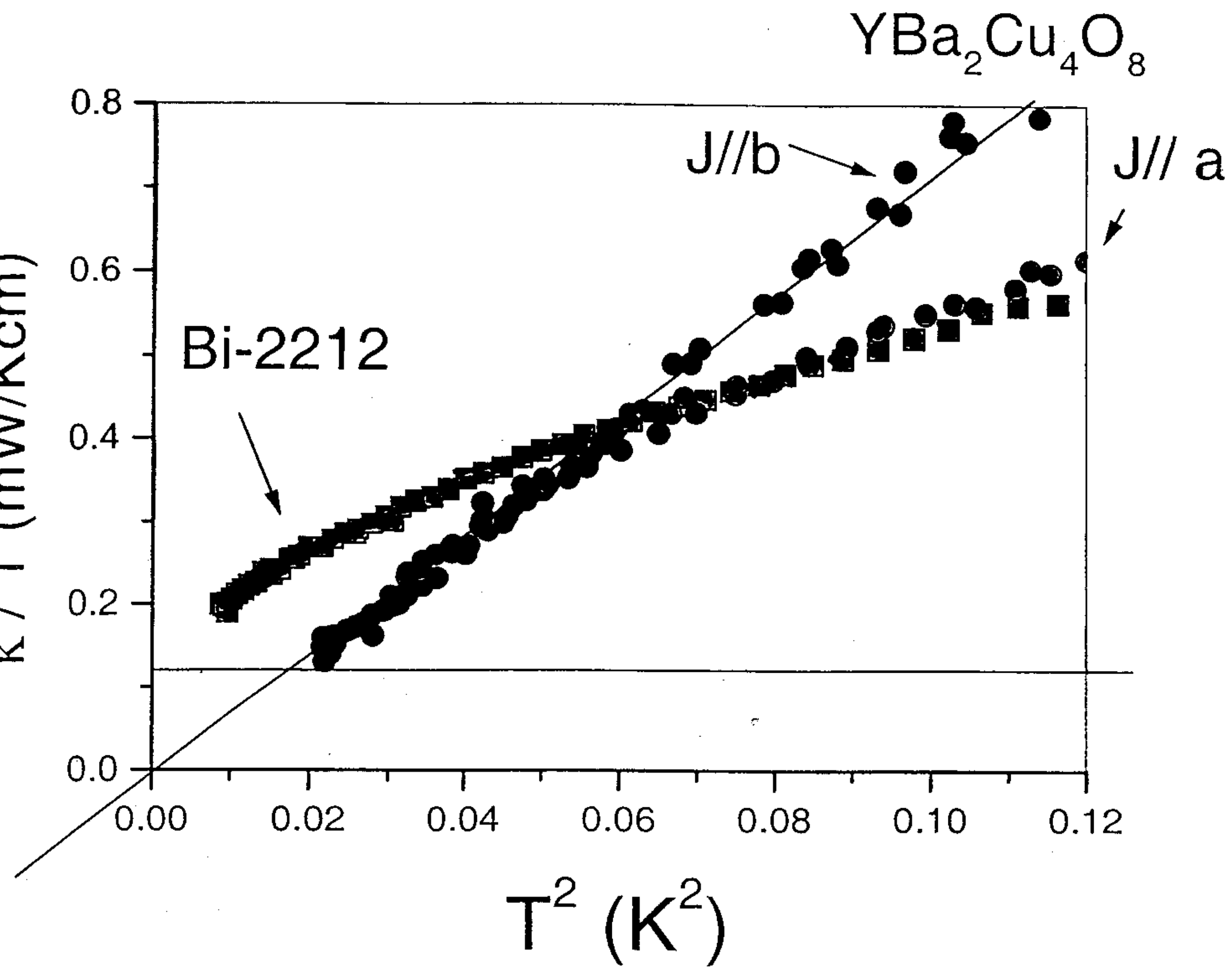
Stochiometric yet underdoped!

Very clean!

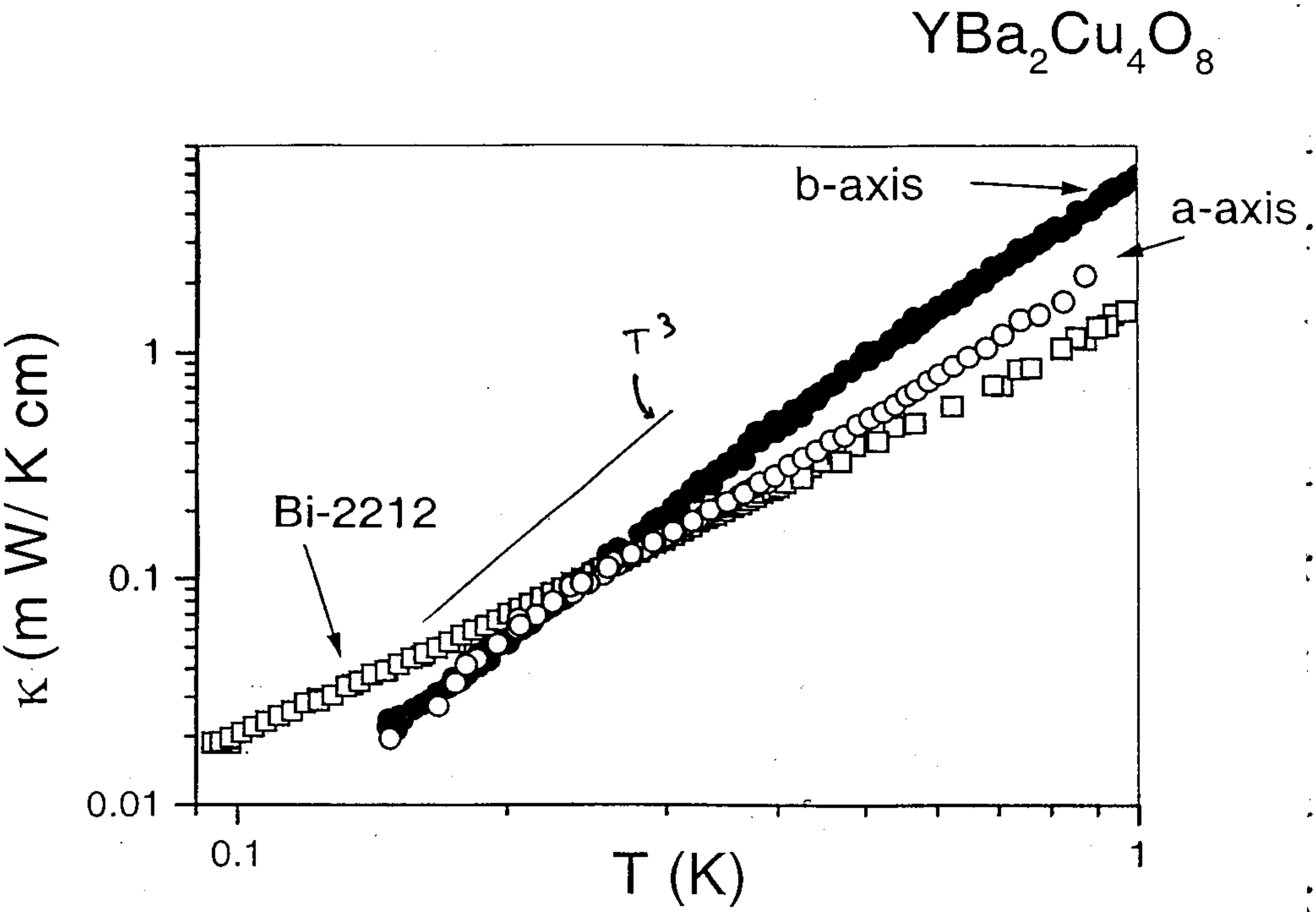
$[\rho_{chain} = \rho_0 + AT^2]$

$\rho_0 \sim 0{,}5\,\mu\Omega cm$

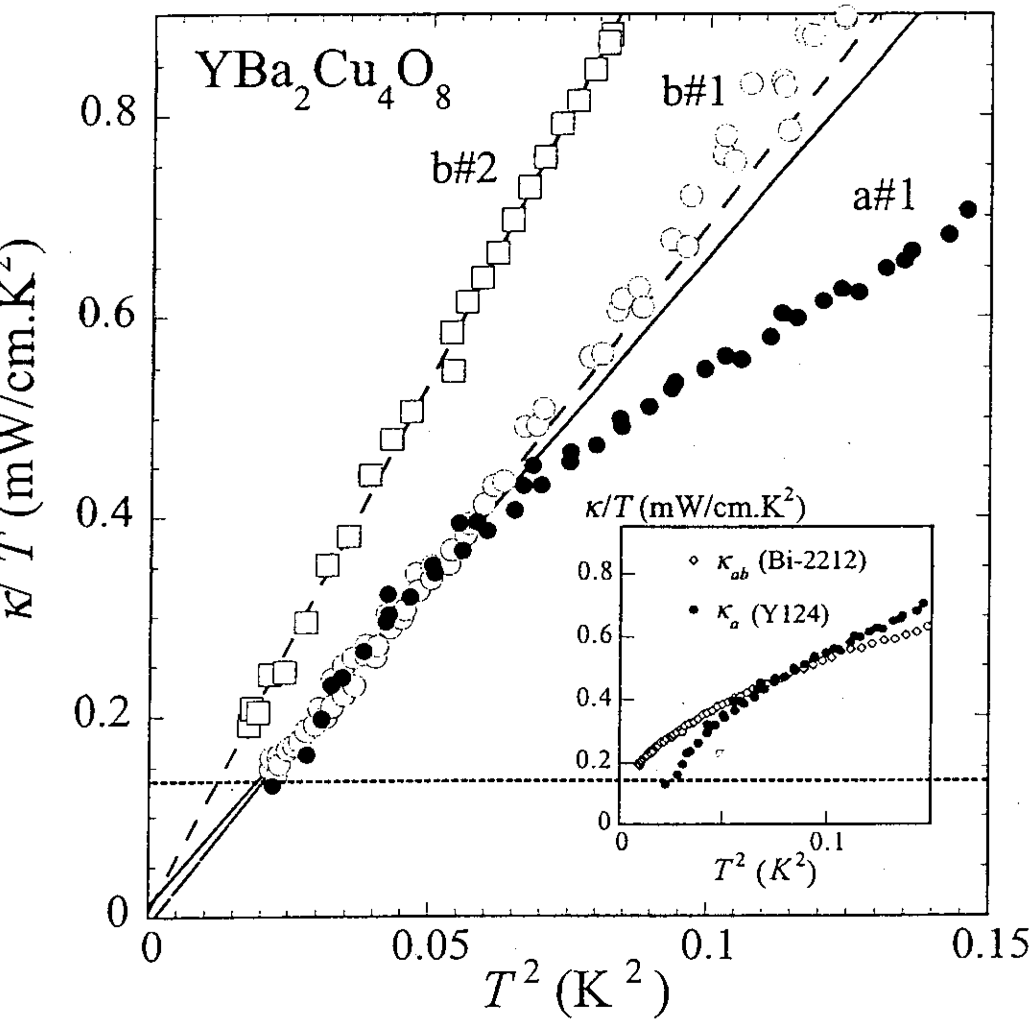
$[100\,\mu\Omega cm$ in $YBa_2Cu_3O_{6.9}]$



No detectable $\frac{\kappa_s}{T}\Big|_{T\to 0}$ in $YBa_2Cu_4O_8$!



YBa$_2$Cu$_4$O$_8$
b-axis
a-axis
T^3
Bi-2212
κ (m W/ K cm)
1
0.1
0.01
0.1
1
T (K)



YBa$_2$Cu$_4$O$_8$
b#2
b#1
a#1
κ/T (mW/cm.K^2)
T^2 (K^2)
0
0.2
0.4
0.6
0.8
0
0.05
0.1
0.15
κ/T (mW/cm.K^2)
κ_{ab} (Bi-2212)
κ_a (Y124)
T^2 (K^2)

Possible reasons for the absence of a linear term in thermal conductivity of $YBa_2Cu_4O_8$

- Absence of nodes?
  No! (See penetation depth for example!)

- Sample too clean and γ too low to be attained?
  Perhaps, but $\frac{d\lambda}{dT}$ yields: $(1+\frac{F_{1s}}{2})^2(\frac{v_F}{v_2})=11.9$ (compared to 8.0 for Bi2212)
  (D. Broun , private communication) .

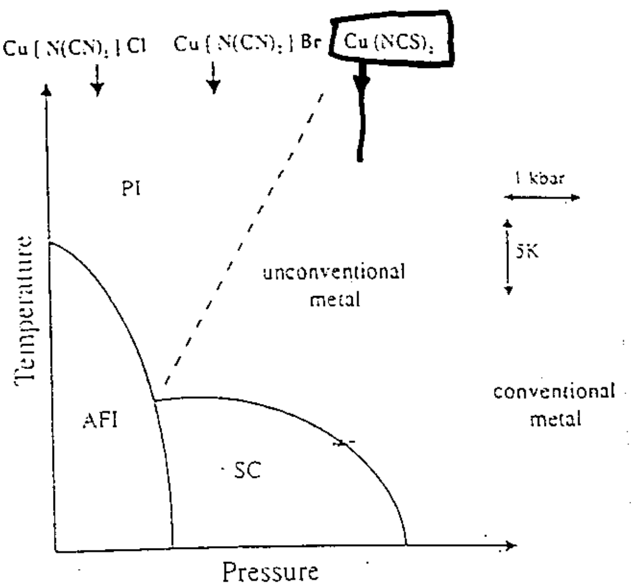
  [For $(1+\frac{F_{1s}}{2})^2 \sim 0,4$ it would give $\frac{v_F}{v_2} \simeq 29$
  $\frac{K_{00}}{T} \simeq 0,2 \frac{mW}{Kcm}$

- Quasiparticle localisation?
  (σ_{1plane} becomes very small below the 60K peak)
  (D. Broun , private communication)
  [redacted]

Work in progress:
Effect of magnetic field
Effect of disorder

κ-$(ET)_2X$ family of organic superconductors

Layered superconductors close to an insulating AF state



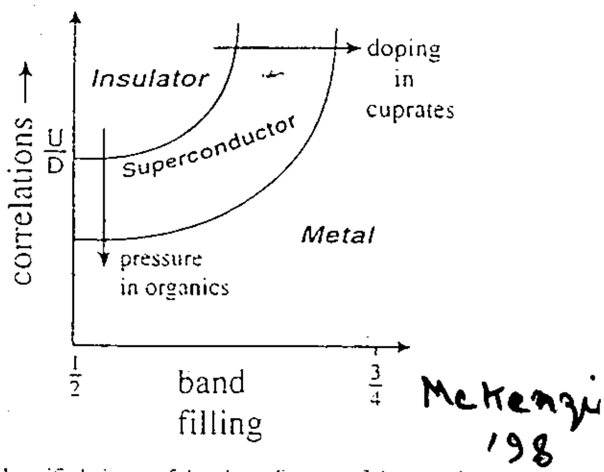


FIGURE 8 A simple unified picture of the phase diagram of the organics and cuprates low-temperatures. The organic superconductors κ-(BEDT-TTF)$_2$X are always at half-filling and one tunes through the insulator-superconductor-metal transition by applying pressure. In the cuprates this transition is passed through by varying the band filling

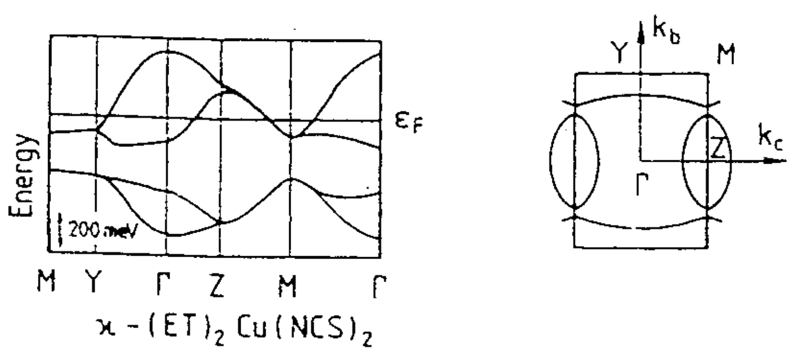
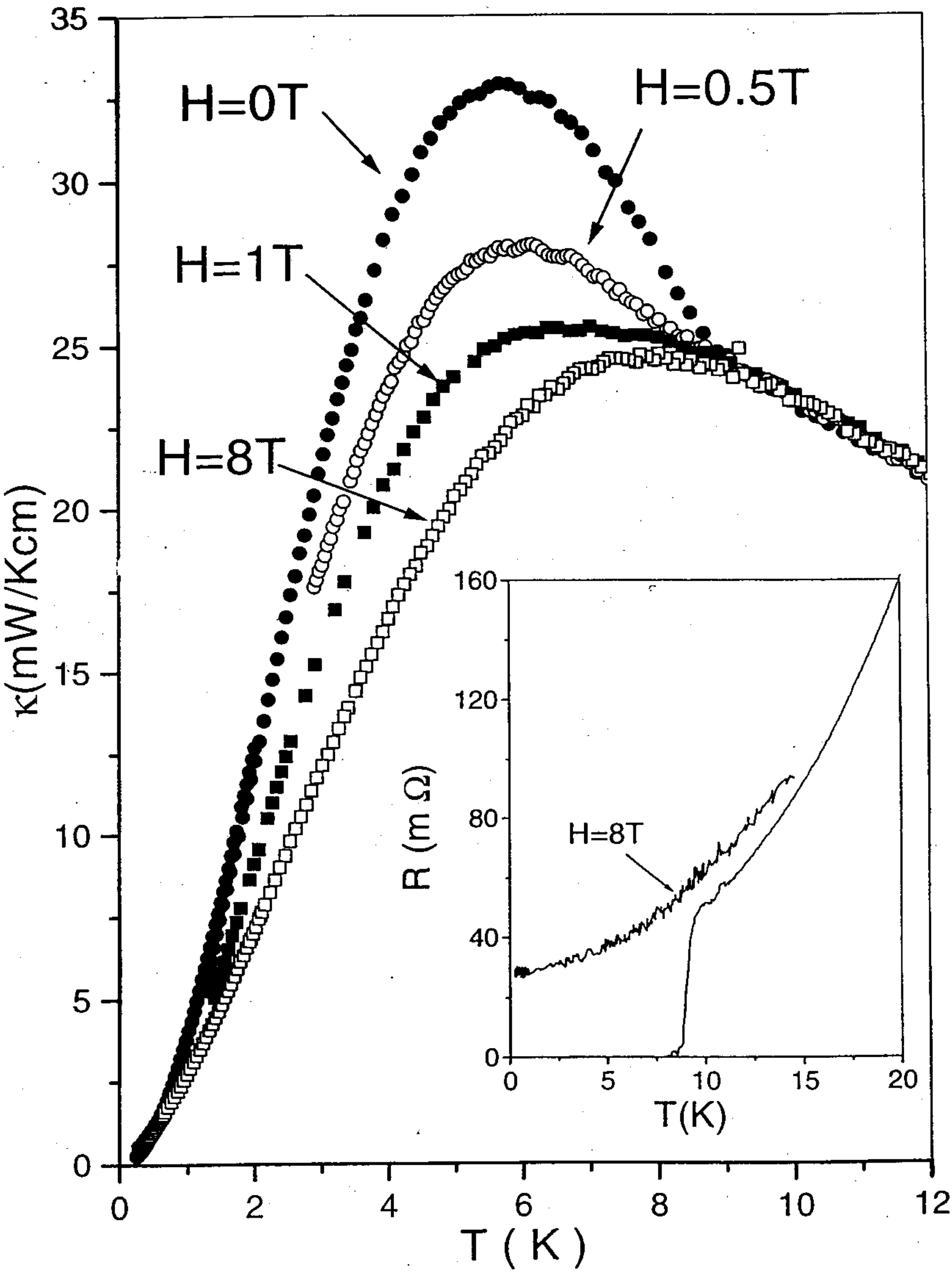


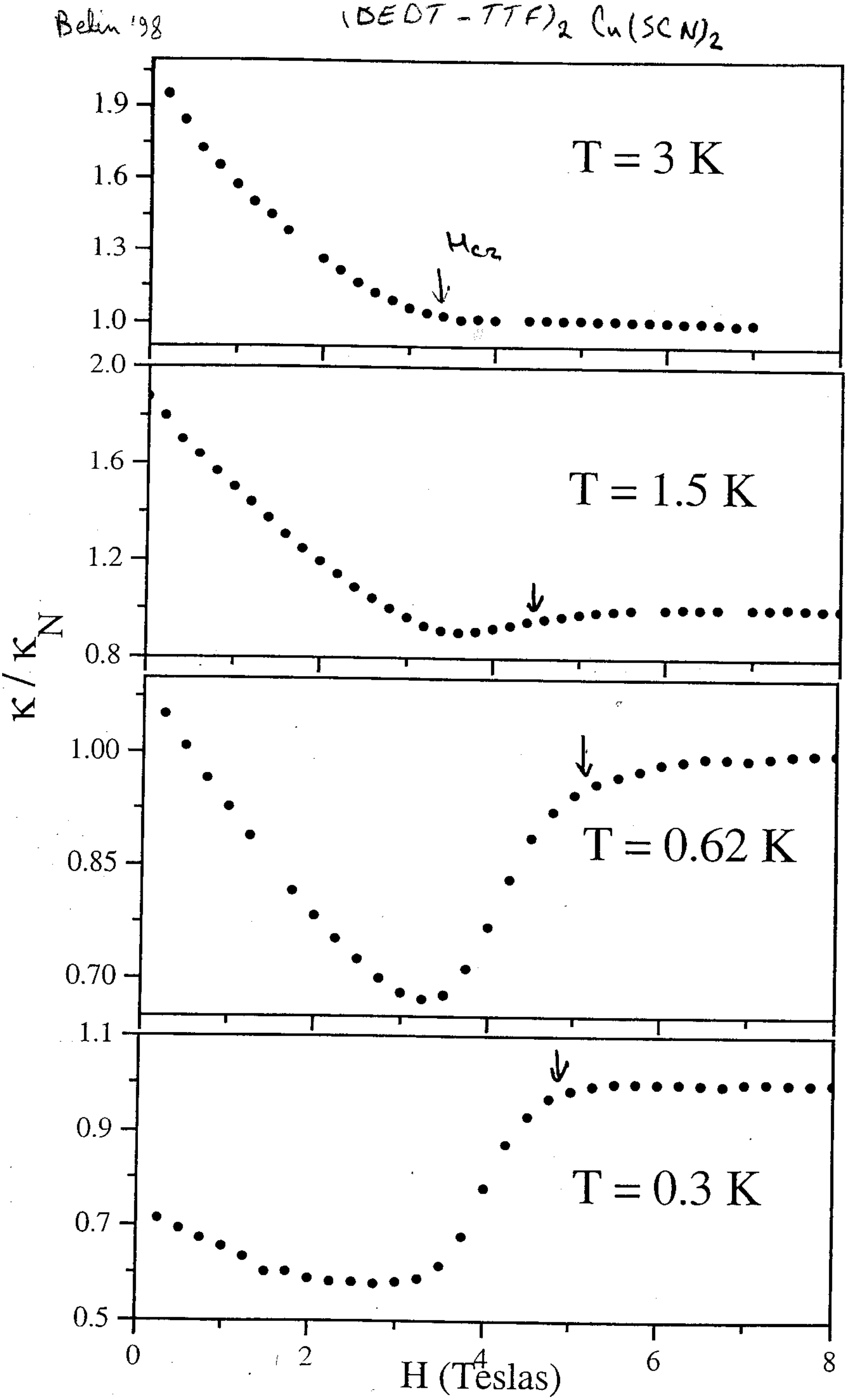
FIGURE 8 Energy band structure and Fermi surface of (a) α-(ET)$_2$KHg(SCN)$_4$ from [78] (b) β-(ET)$_2$IBr$_2$ [74] and (c) κ-(ET)$_2$Cu(NCS)$_2$ [79].

- A well-characterised Fermi Liquid!
- Shubnikov de Hass Oscillations!

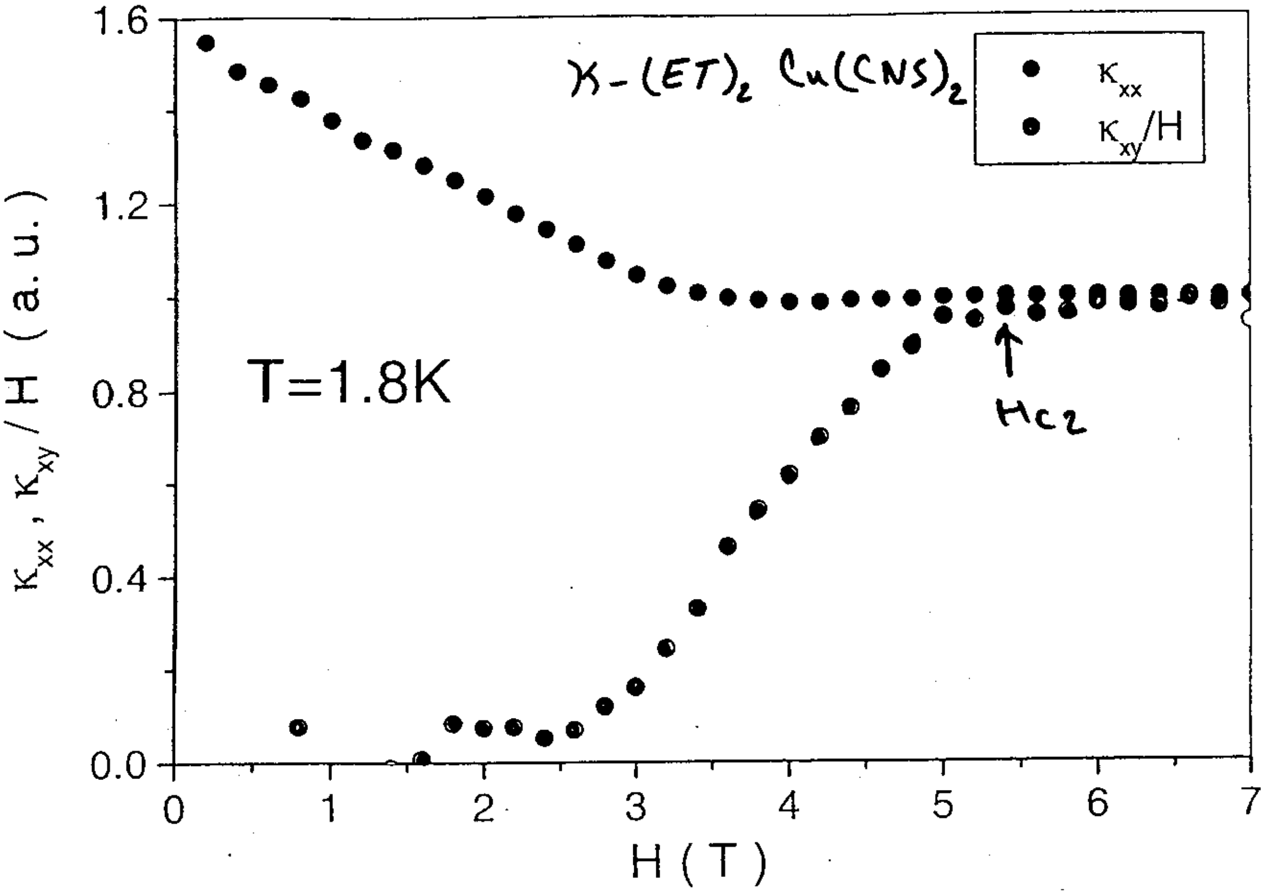
Belin '98

κ-(BEDT-TTF)$_2$ Cu(NCS)$_2$




Belin '98
(BEDT-TTF)2 Cu(SCN)2
Hc2
T = 3 K
T = 1.5 K
T = 0.62 K
T = 0.3 K
1.9
1.6
1.3
1.0
2.0
1.6
1.2
0.8
1.00
0.85
0.70
1.1
0.9
0.7
0.5
0
2
4
6
8
K / KN
H (Teslas)

Comparison of transverse and longitudinal thermal conductivit



κ_{xy} reflects the conductivity of charged (i.e. electronic) carriers!

The essential part of the peak in $\kappa_{xx}(T)$ is due to phonons!

Separation of Quasiparticle and Phononic Heat Currents in $YBa_2Cu_3O_{7-\delta}$

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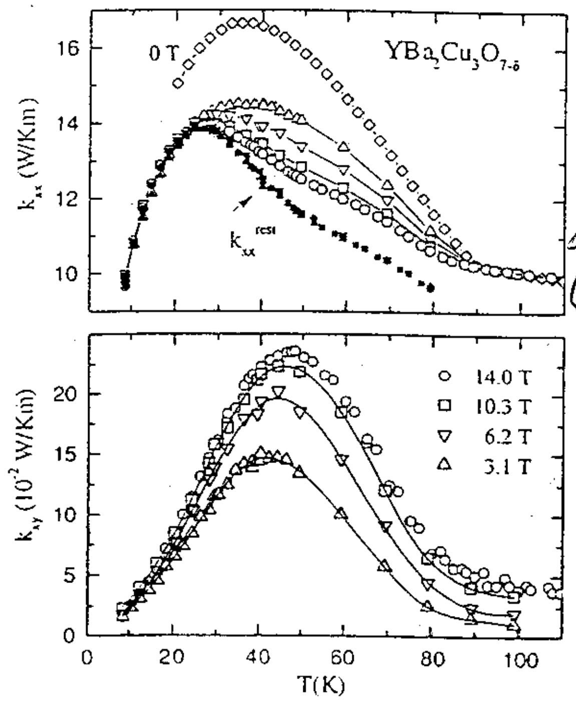
(Received 9 February 1998)

Measurements of the transverse (k_{xy}) and longitudinal (k_{xx}) thermal conductivity in high magnetic fields are used to separate the quasiparticle thermal conductivity (k_{xx}^{el}) of the CuO_2-planes from the phononic thermal conductivity in $YBa_2Cu_3O_{7-\delta}$. k_{xx}^{el} is found to display a pronounced maximum below T_c. Our data analysis reveals distinct transport (τ) and Hall (τ_H) relaxation times below T_c: Whereas τ is strongly enhanced, τ_H follows the same temperature dependence as above T_c.
[S0031-9007(99)08592-0]



G. 1. Open symbols: k_{xx} (upper panel) and k_{xy} (lower nel) of $YBa_2pCu_3O_{7-\delta}$ as a function of temperature T for rious fixed magnetic fields as indicated in the figure. Full mbols: k_{xx}^{rest} as obtained from our data analysis (see text).

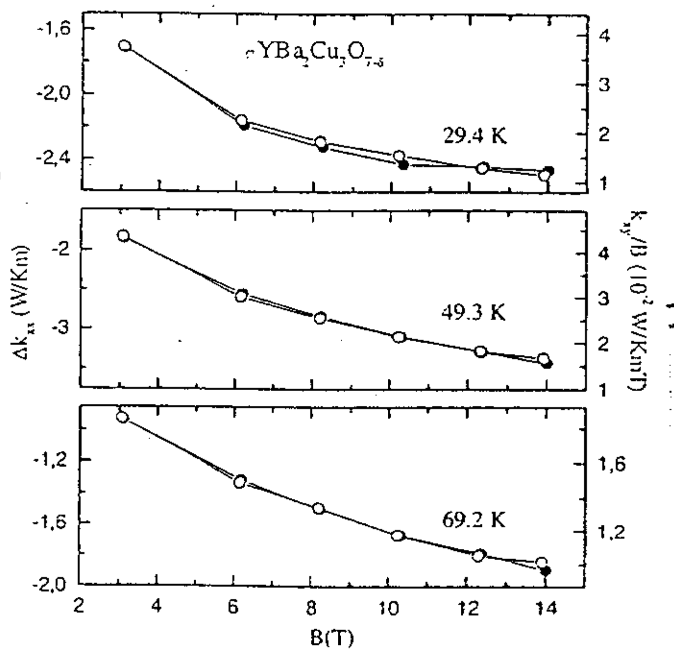
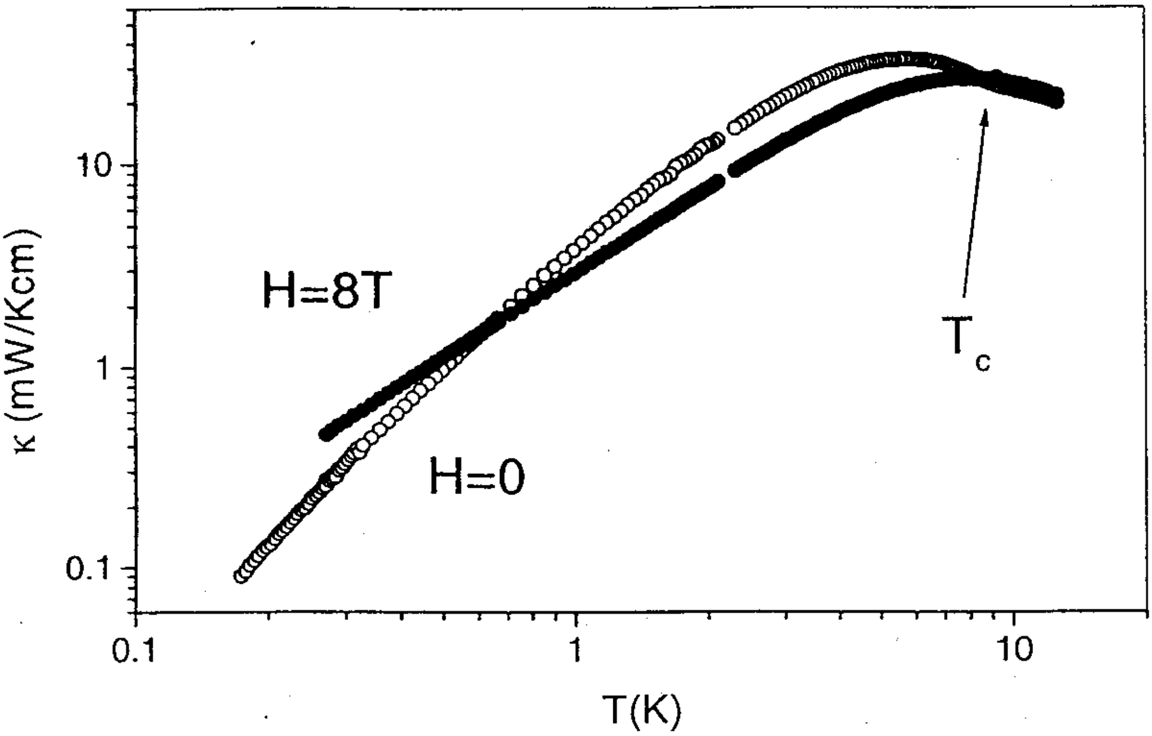


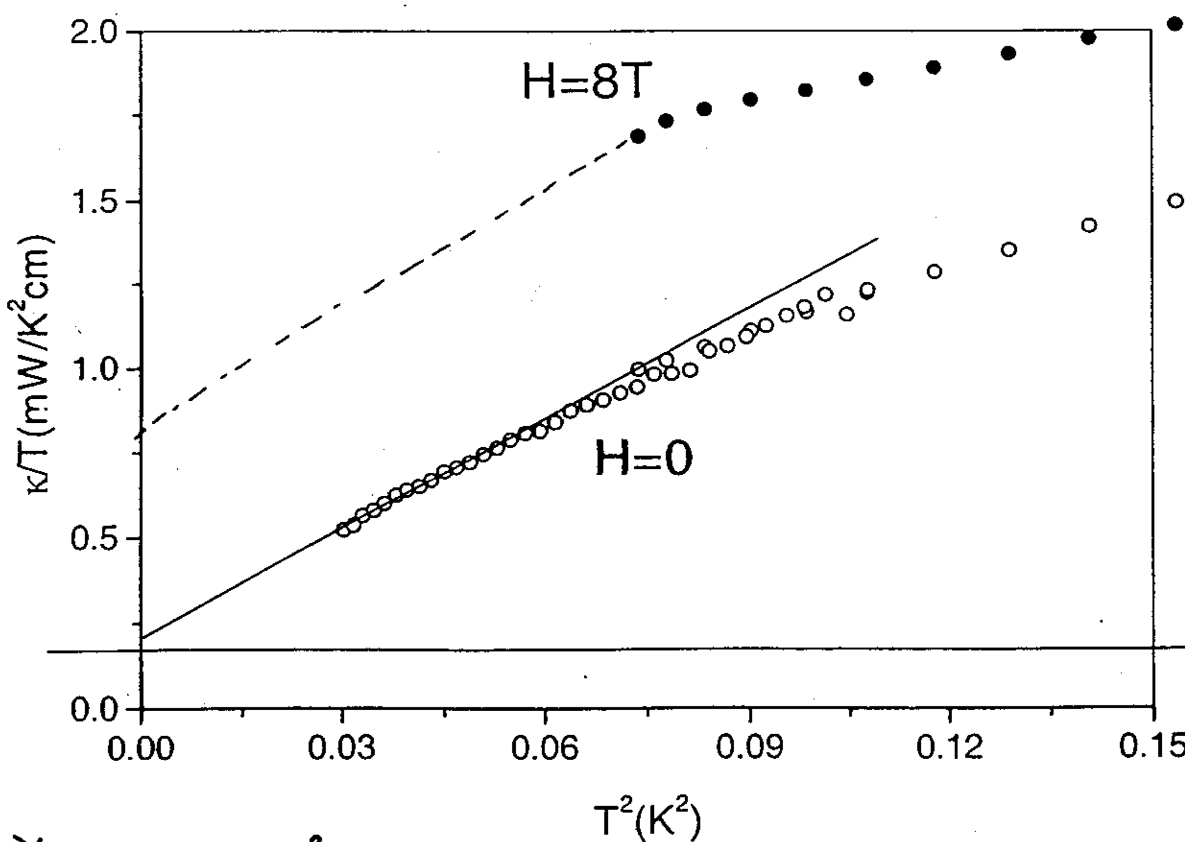
FIG. 2. $\Delta k_{xx} = k_{xx}(B) - k_{xx}(B = 0)$ (•) and k_{xy}/B (∘) versus magnetic field B at fixed temperatures given in the figure.

The upturn in K_{xx} identified as electronic in origin!

κ-(ET)$_2$ Cu (CNS)$_2$

Residual electronic conductivity



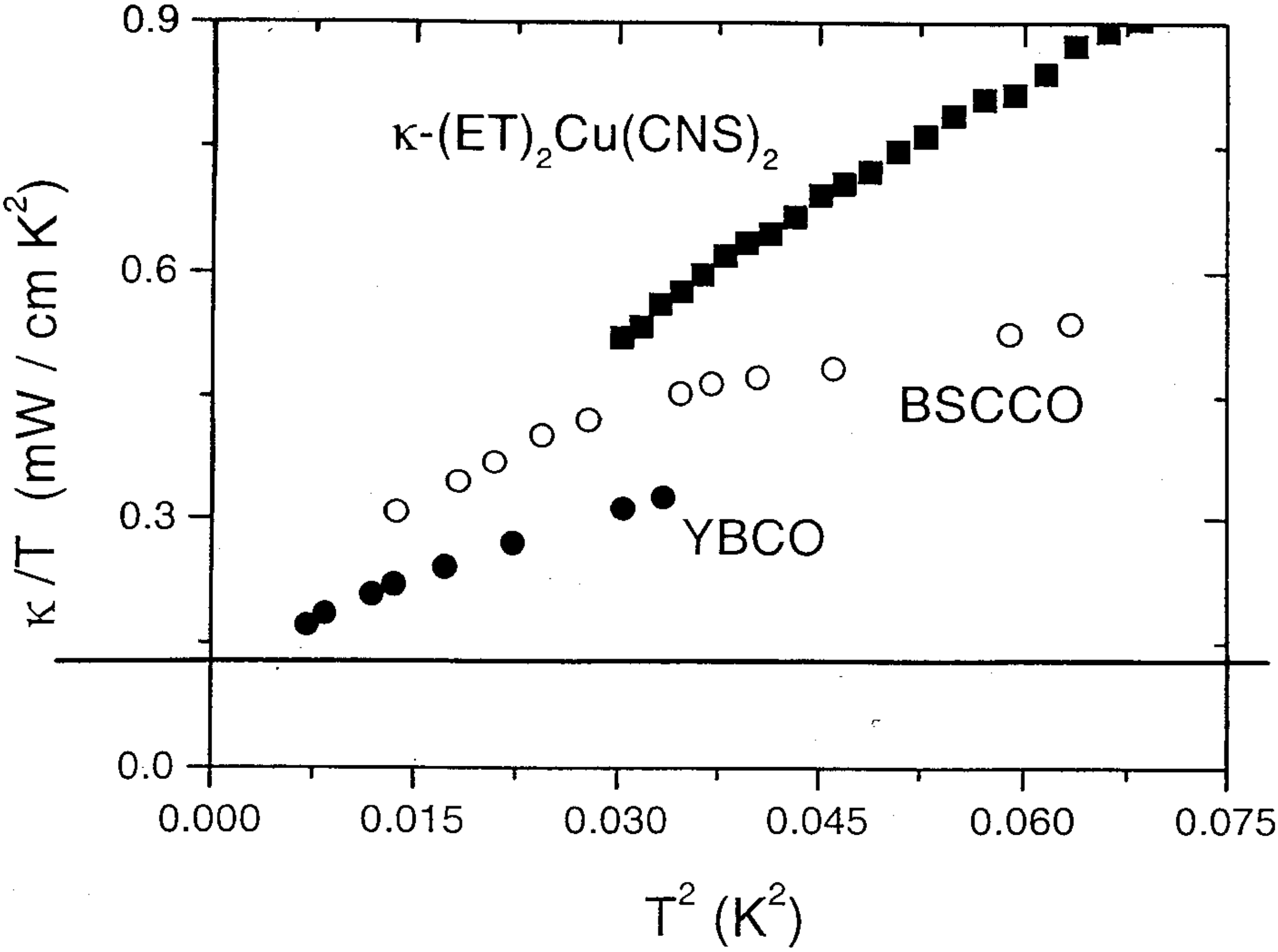


$$\frac{\kappa^{00}}{\kappa_0^n} = \frac{\xi}{l_e} \simeq 5\text{-}10$$

$$\frac{\kappa_{00}}{T} = \frac{\hbar K_\beta^2}{6e^2S}\omega_p^2$$

If $S = |d\Delta_0| = 2\Delta_0$ $\Longrightarrow$ $\frac{\kappa_{00}}{T} \sim 0{,}16 \ \frac{mW}{K^2cm}$

Comparison of residual electronic conductivities



UEMURA RELATION:

$T_c \propto n_s/m^*$ in unconventional superconductors

$\kappa_{00}/T \sim n_s/(m^* \Delta_0)$