Thermal conductivity in cuprates:

High energy gaps from low energy quasiparticles

Robert W. Hill

Exotic Order and Criticality in Quantum Matter, KITP June 7-11 2004

Collaborative Networks – High quality single crystals……

Louis Taillefer

Makariy Tanatar
Shiyan Li
Filip Ronning
Cyril Proust
Andrew Macfarlane
Robert Gagnon

May Chiao
Christian Lupien
Etienne Boaknin
David Hawthorn
Michael Sutherland
Johnpierre Paglione

Harry Zhang

Walter Hardy
Doug Bonn
Ruixing Liang
Darren Peats
Jennifer DeBenedictis

Rick Greene
Patrick Fournier

Andrew Mackenzie
N.N.Koleshnikov

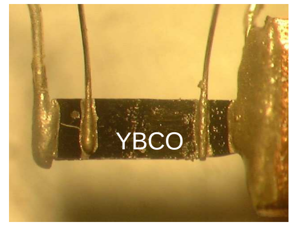
Shuichi Wakimoto
Nigel Hussey

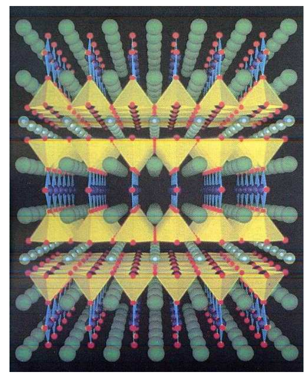
T.Kimura
M.Nohara
H.Takagi

Institute of Solid State Physics
Russian Academy of Sciences

Outline

- Some basics….
  Thermal conductivity: electrons and phonons
  Thermal conductivity in superconductors
- Superconducting State …..
  BCS d-wave superconductivity?
  universal behaviour,
  constant nodal Fermi velocity
- Underdoped (pseudogap) regime……
  YBCO vs LSCO, rewriting the phase diagram
- Normal State ……
  Fermi liquid? (outlook)





Thermal conductivity primer

$\kappa = \kappa_{electrons} + \kappa_{phonons}$

Kinetic theory formulation:

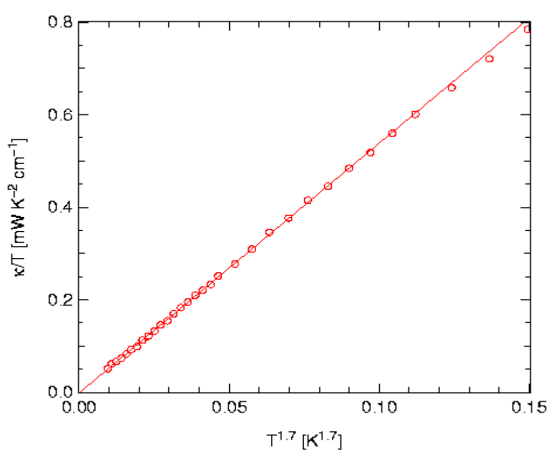
$$\kappa = \tfrac{1}{3} cvl$$

$$\kappa_{ph} = \tfrac{1}{3}\beta T^3 v_s l_0^{ph}$$

$$\kappa_e = \tfrac{1}{3}\gamma T v_F l_0^e$$

Phonons: beyond Casimir T^3 limit

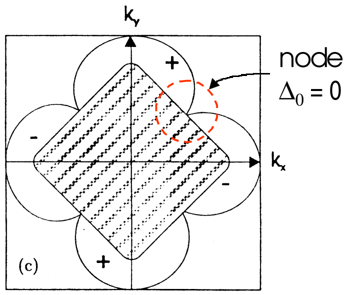
s – wave superconductor : V_3Si



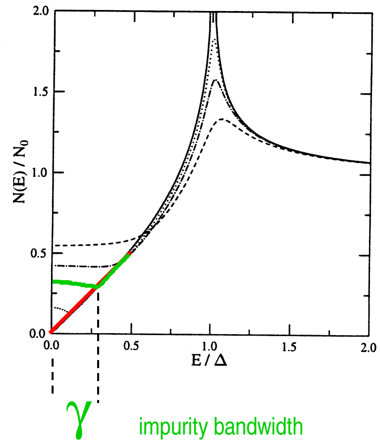
R.O.Pohl and B. Stritzker, Phys.Rev.B. **25**, 3608 (1982).

Extended BCS Theory : superconducting gap with nodes

d-wave gap: $\Delta = \Delta_0 \cos(2\phi)$



density of states



impurity bandwidth

clean limit

Linear density of states at low energy
- governs all low temperature properties

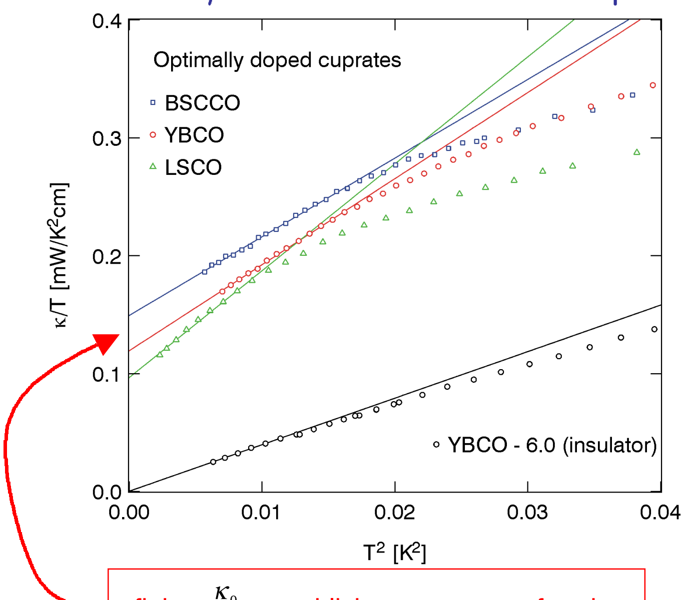
e.g. $C_e \sim T^2$

impurity effects

Finite density of delocalised states at zero energy

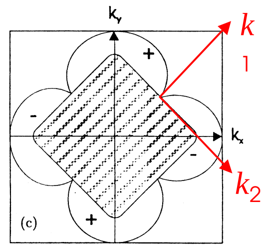
e.g. $C_e \sim T$ and $\kappa_e \sim T$ (metallic conductivity from qp's)

Thermal conductivity in d-wave 'unconventional' superconductor



finite $\frac{\kappa_0}{T}$ establishes presence of nodes

Fermi-liquid theory of nodal quasiparticles



$$E = +\eta\sqrt{v_F^2 k_1^2 + v_2^2 k_2^2}$$

v_F = Fermi velocity

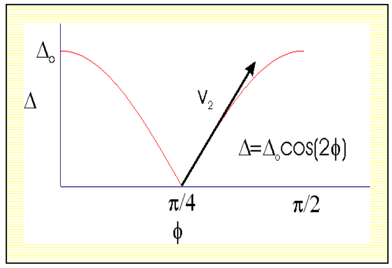
$$v_2 = \frac{1}{\eta k_F}\cdot\frac{\partial\Delta}{\partial\phi}\Big|_{node}$$

thermal transport ($T \to 0$, $T \ll \gamma$)

$$\frac{\kappa_0}{T} = \frac{k_B^2}{3\eta}\frac{n}{d}\left(\frac{v_F}{v_2} + \frac{v_2}{v_F}\right)$$

- universal
- no Fermi-liquid parameters
- no vertex corrections

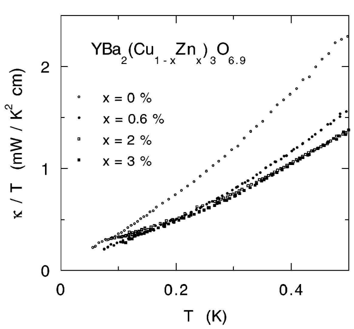
A. Durst and P. A. Lee, Phys. Rev. B **62**, 1270 (2000).
M. J. Graf *et al.*, Phys. Rev. B **53**,15147 (1996).

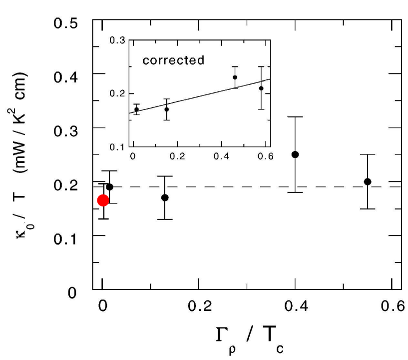


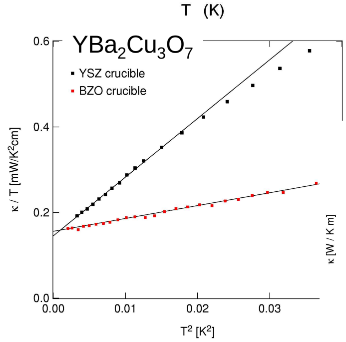
pure d-wave case: $v_2 \sim \Delta_0$

Universal thermal conductivity

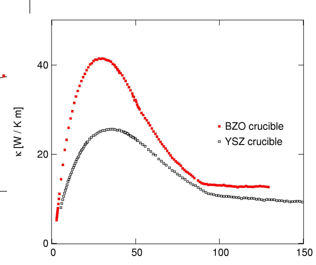
Taillefer *et al.*. Phys. Rev. Lett. **79** 483 (1997)







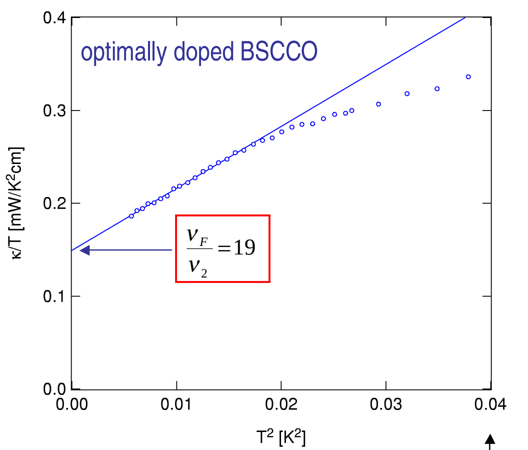
Hill *et al.*. Phys. Rev. Lett. **92** 027001 (2004)



... and Bi-2212 (optimal doping)
Nakamae *et al.*
PRL **63** 184509 (2001)

Nodal quasiparticles in Cuprates: optimal doping

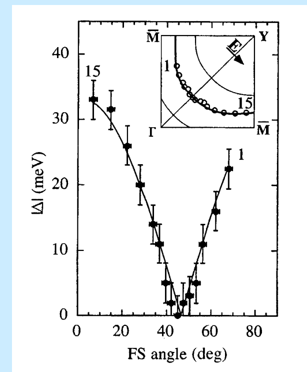
thermal conductivity



j_Q // a axis

$T_c/500$

ARPES: BSCCO $T_c = 90K$



$v_F = 2.5\times10^7$ cm/s

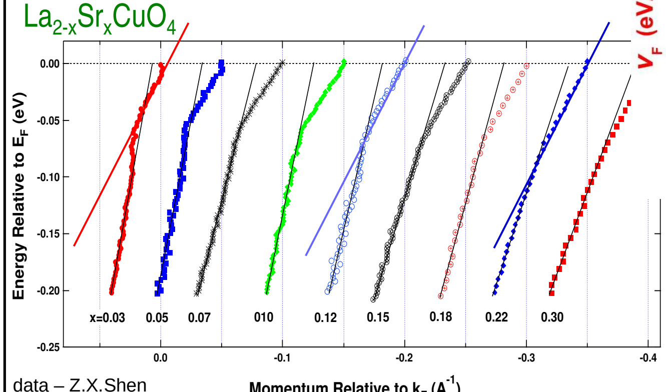
$v_2 = 1.23\times10^6$ cm/s

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

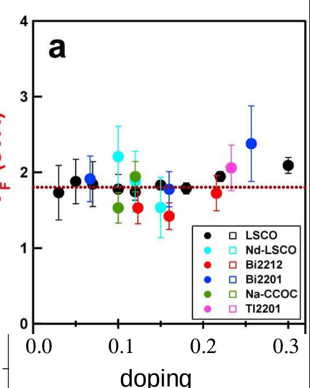
Ding et al. PRB **54** (1996) R9678
Mesot et al. PRL **83** (1999) 840

doping independent Fermi velocity (v_F)

$La_{2-x}Sr_xCuO_4$



data – Z.X.Shen

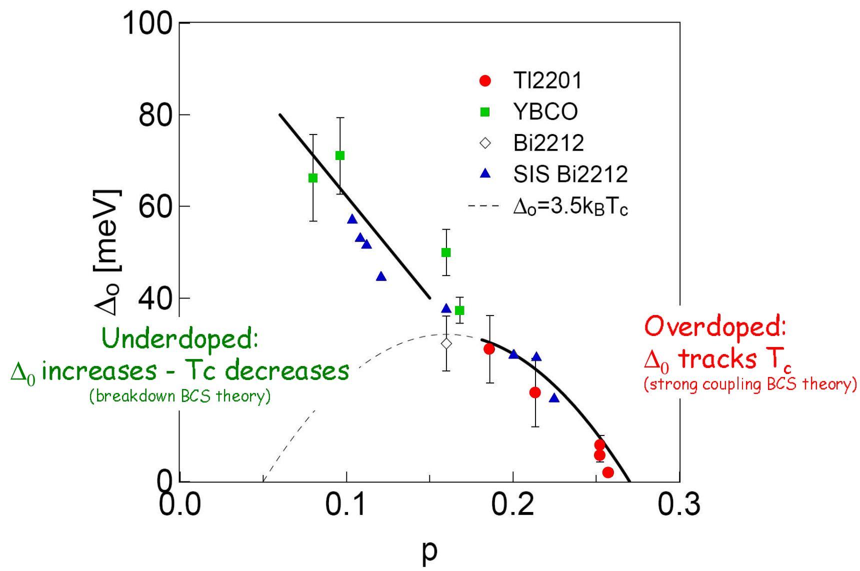


Yoshida et al. Nature **423** 398 (2003)

Consequence
- assuming simplest d-wave gap
$\Delta \sim \Delta_0 \cos(2\phi)$

$$\frac{\kappa_0}{T} \sim \frac{1}{v_2} \sim \frac{1}{\Delta_0}$$

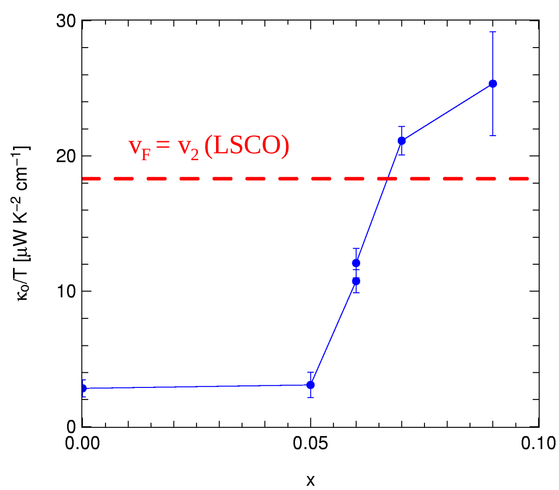
Doping dependence superconducting gap from thermal conductivity



D.G.Hawthorn et al., preprint (2004)
M.Sutherland et al. Phys Rev B 67 174520 (2003)

Thermal transport in $La_{2-x}Sr_xCuO_4$

Nodes exist at all doping levels which are superconducting

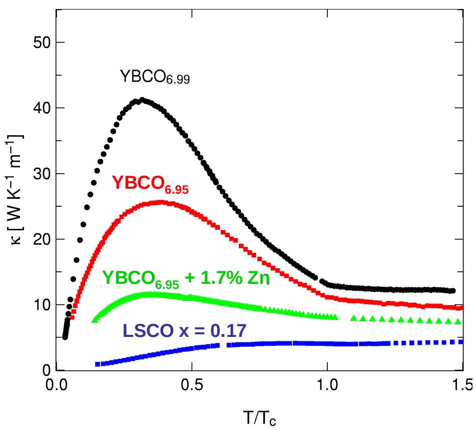


$$\frac{\kappa_0}{T} = \frac{k_B^2}{3\eta}\frac{n}{d}\left(\frac{v_F}{v_2} + \frac{v_2}{v_F}\right)$$

minimum when $v_F = v_2$

.... Non-universal behaviour?

Universal behaviour in the cuprates



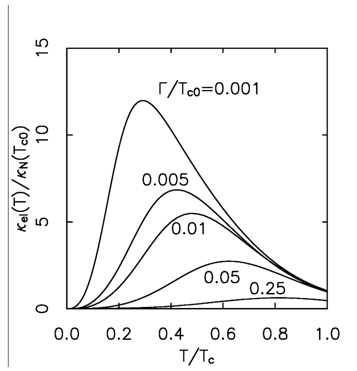
comparative levels of elastic scattering

YBCO(BZO)	:	YBCO(YSZ)	:	LSCO
1		10		100

Established universal behaviour

YBCO (optimal and overdoped)
Taillefer PRL (1997) , Hill PRL (2004)

Bi-2212 (optimal doping)
Nakamae *et al.* PRL **63** 184509 (2001)

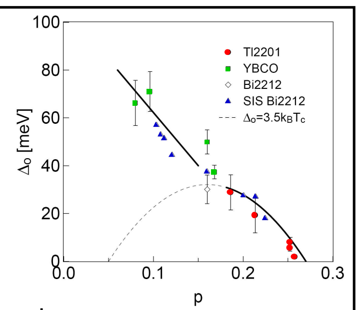


Hirschfeld and Putikka, PRL **77**, 3909 (1996)

Summary and Conclusions - 1

superconducting state is *d*-wave at all dopings
- **no evidence** for additional complex component.

$$\frac{\kappa_0}{T} > 0 \text{ (all } p\text{)}$$



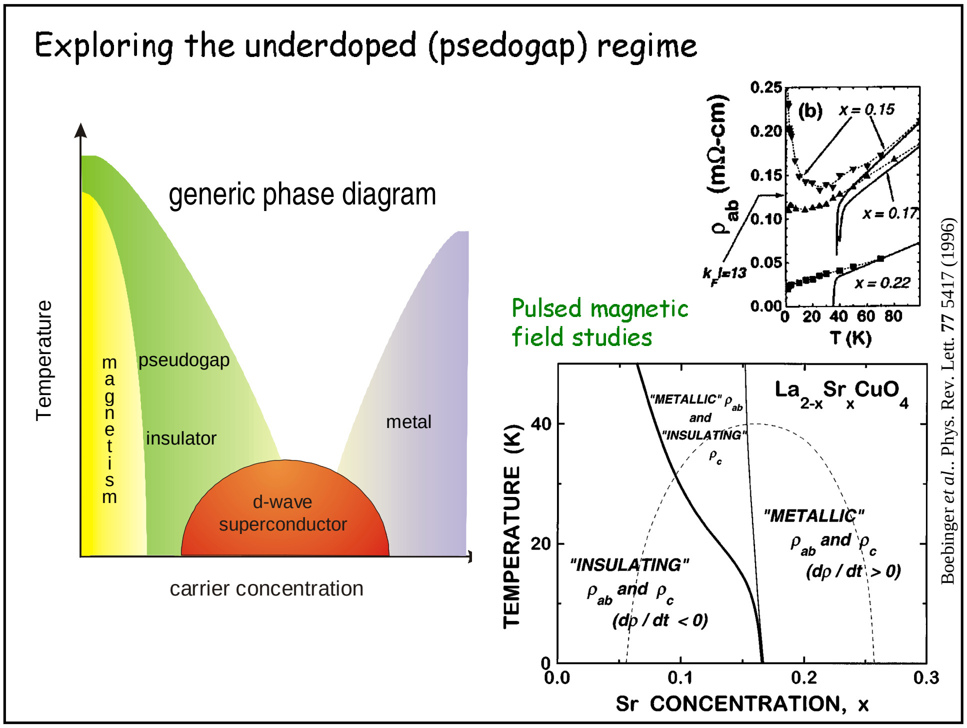
doping dependence of superconducting gap maximum :

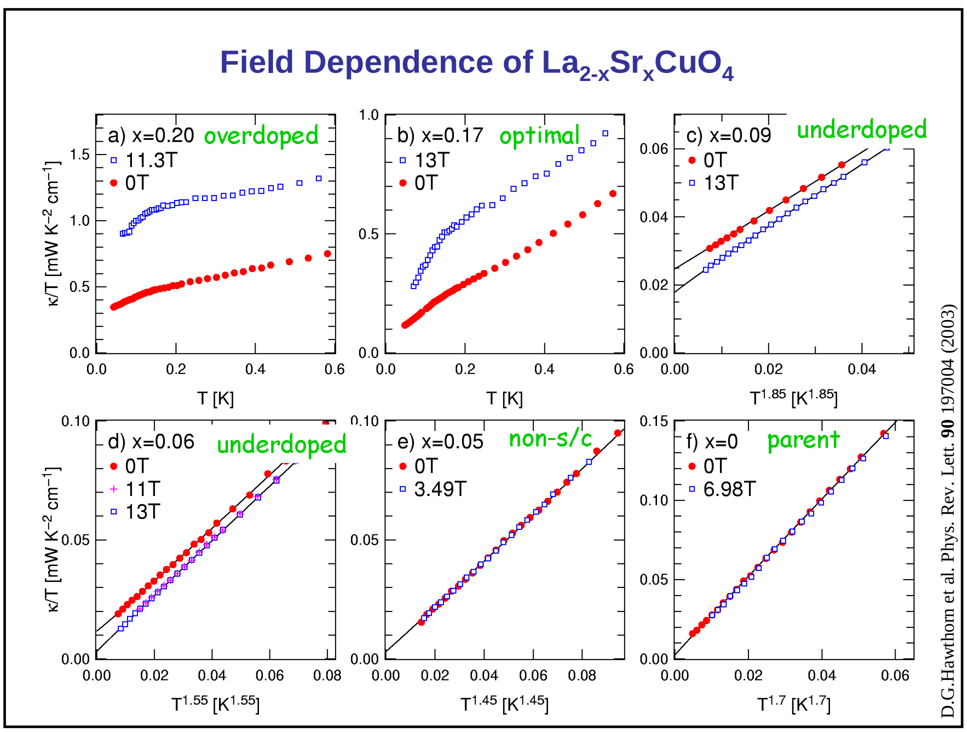
- overdoped – optimal doped: Δ_0 *scales* with T_c (BCS theory)
- optimal doped – underdoped: Δ_0 *increases* while T_c *decreases* (Failure BCS theory)

Δ_0 scales with pseudogap :

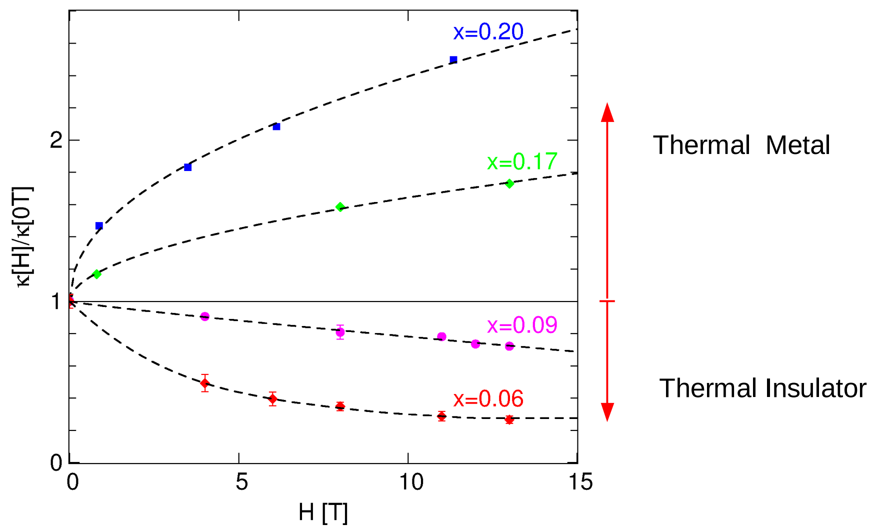
- likely common (superconducting) origin
- pseudogap is : (i) quasiparticle gap
  (ii) must have nodes
  (iii) must have linear dispersion

LSCO is different (non-universal) – disorder or competing order ?


Exploring the underdoped (psedogap) regime
generic phase diagram
Temperature
magnetism
pseudogap
insulator
metal
d-wave superconductor
carrier concentration
Pulsed magnetic field studies
(b) x = 0.15
x = 0.17
x = 0.22
ρab (mΩ-cm)
T (K)
La2-xSrxCuO4
"METALLIC" ρab and "INSULATING" ρc
"METALLIC" ρab and ρc (dρ / dt > 0)
"INSULATING" ρab and ρc (dρ / dt < 0)
TEMPERATURE (K)
Sr CONCENTRATION, x
Boebinger et al., Phys. Rev. Lett. 77 5417 (1996)


Field Dependence of La2-xSrxCuO4
a) x=0.20 overdoped
11.3T
0T
b) x=0.17 optimal
13T
0T
c) x=0.09 underdoped
0T
13T
d) x=0.06 underdoped
0T
11T
13T
e) x=0.05 non-s/c
0T
3.49T
f) x=0 parent
0T
6.98T
κ/T [mW K⁻² cm⁻¹]
T [K]
T^1.85 [K^1.85]
T^1.55 [K^1.55]
T^1.45 [K^1.45]
T^1.7 [K^1.7]
D.G.Hawthorn et al. Phys. Rev. Lett. 90 197004 (2003)

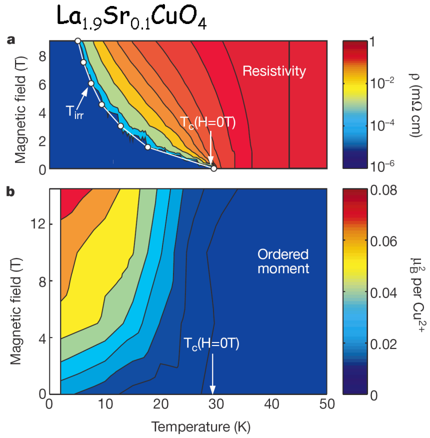
Field Dependence of $La_{2-x}Sr_xCuO_4$



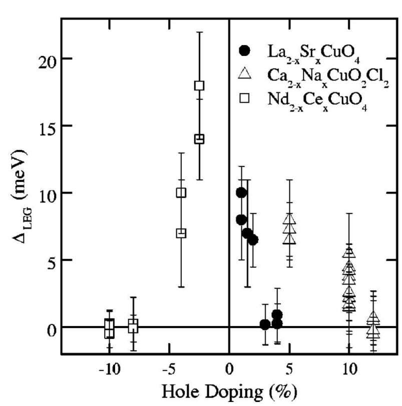
D.G.Hawthorn et al. Phys. Rev. Lett. **90** 197004 (2003)

Disorder or Competing Order in non-superconducting LSCO

$La_{1.9}Sr_{0.1}CuO_4$



Appearance of SDW order as superconductivity is suppressed by magnetic field



ARPES measured gap at nodal point in underdoped LSCO

B.Lake *et al.* Nature **415** 299 (2002)

K.M.Shen *et al.* Phys. Rev. B. **69** 054503 (2004)

Normal State

H > H_{c2}

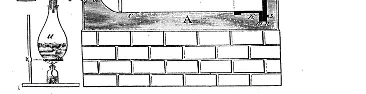
1853. ANNALEN No. 8.
DER PHYSIK UND CHEMIE.
BAND LXXXIX.

I. *Ueber die Wärme-Leitungsfähigkeit der Metalle;*
von G. Wiedemann und R. Franz.

§. 1.

Ueber zwanzig Jahre sind verflossen, seit Hr. Despretz durch seine mühevollen Untersuchungen zuerst einige sichere Zahlenwerthe über die relative Leitungsfähigkeit verschiedener fester Körper für die Wärme aufgefunden hat. —

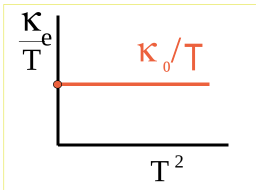
Die grofse Genauigkeit und Sorgfalt, mit welcher die Versuche von Hrn. Despretz angestellt wurden, hat gewifs mit Recht zur Folge gehabt, dafs die von ihm aufgestellten, nach dem damaligen Zustande der Wissenschaft glänzenden Resultate als Grundlage unserer Kenntnifs in dem bearbeiteten Felde dienen mufsten.

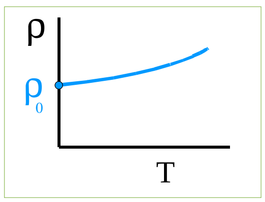


In den Tubulus *d* war ein Messingrohr *ee* eingekittet. In dieses Rohr war bei *ff* ein zweites Rohr *gg* eingeschliffen, welches durch aufgelegte Gummiringe luftdicht daran

Wiedemann-Franz law (low T)

Wiedemann & Franz, Ann. Phys. **89** 497 (1853)





Fundamental property of a Fermi Liquid

ratio $\frac{\text{heat}}{\text{charge}}$ transport coefficients

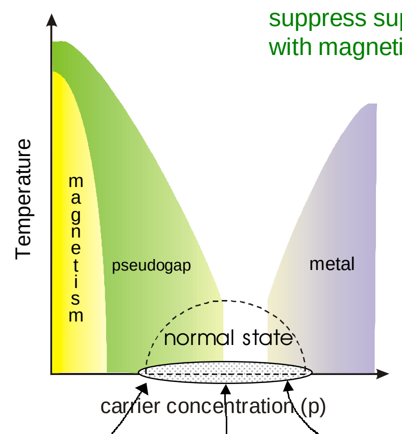
$$\frac{\kappa_0}{\sigma_0 T} = L_0 = \frac{\pi^2}{3}\left(\frac{k_B}{e}\right)^2$$

Nature of excitations ?

heat carriers = charge carriers
= charge *e* fermions (Landau qp)

What are normal state, low energy excitation in cuprates ?

suppress superconductivity
with magnetic field

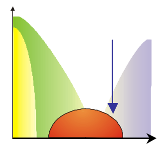


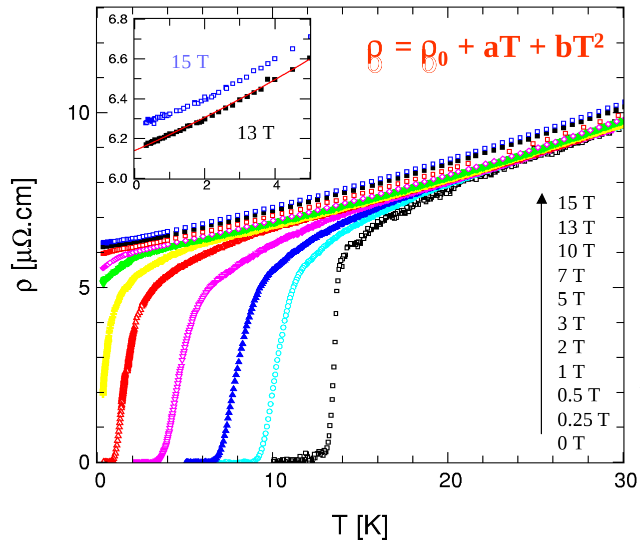
underdoped
$La_{1.94}Sr_{0.06}CuO_4$
T_c ~ 8K
p = 0.06

optimal doped
$Pr_{1.85}Ce_{0.15}CuO_4$
T_c ~ 20K
p = 0.15

overdoped
$Tl_2Ba_2CuO_{6+\delta}$
T_c ~ 15K
p = 0.26

overdoped $Tl_2Ba_2CuO_{6+\delta}$: charge transport





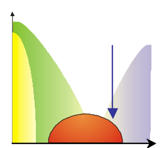
H=13 T

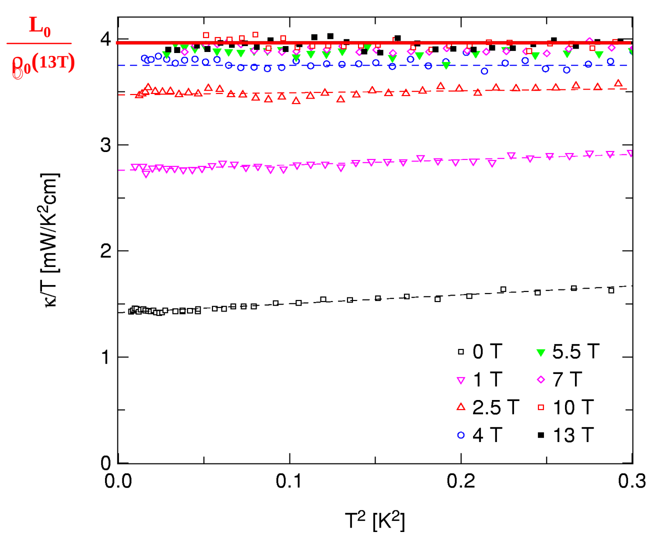
ρ_0=6.15 μΩ.cm

$\frac{L_0}{\rho_0} = 3.98\ \mathrm{mW.cm^{-1}.K^{-2}}$

Proust et al. Phys.Rev.Lett. **89** 147003 (2002)

overdoped $Tl_2Ba_2CuO_{6+\delta}$: heat transport

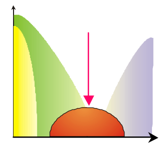


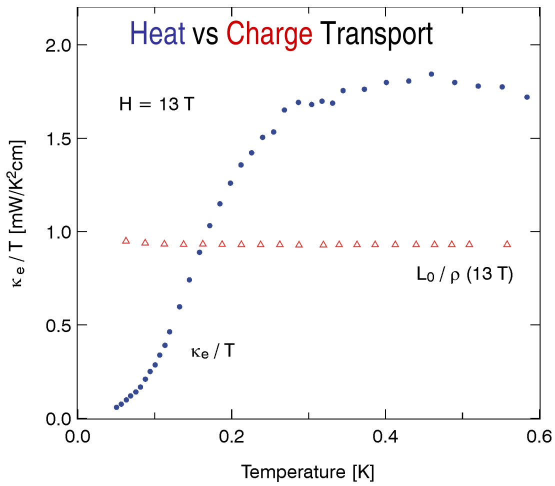


Wiedemann-Franz law: perfectly obeyed

Proust et al. Phys.Rev.Lett. **89** 147003 (2002)

$Pr_{1.85}Ce_{0.15}CuO_4$ – optimally doped cuprate





Violation of Wiedemann-Franz law

nature

NATURE | VOL 414 | 13 DECEMBER 2001 |

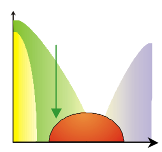
articles

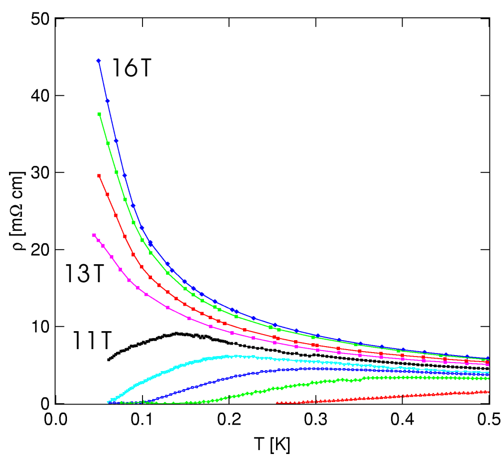
Breakdown of Fermi-liquid theory in a copper-oxide superconductor

R. W. Hill, Cyril Proust, Louis Taillefer, P. Fournier & R. L. Greene

underdoped $La_{1.94}Sr_{0.06}CuO_4$

charge transport





Normal state is charge and thermal insulator

D.G.Hawthorn et al. Phys. Rev. Lett. **90** 197004 (2003)

normal state: Wiedemann-Franz law study summary

Tl2201 (p=0.26)

perfect agreement with WF law

….. Fermi liquid physics

PCCO (p=0.15)

- T < 0.25 K : $\kappa_e \sim T^{3.6}$
- T > 0.25 K : $\frac{\kappa_e}{T} \sim 2\frac{L_0}{\rho_0}$

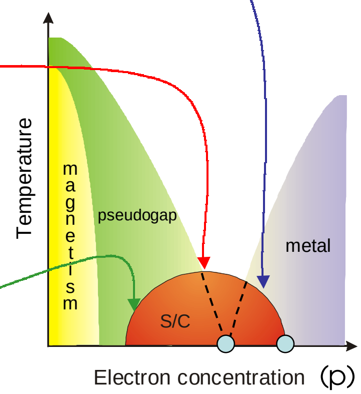
Complete violation of Wiedemann-Franz law….

……Fermi liquid physics is not appropriate.

LSCO (p=0.06)

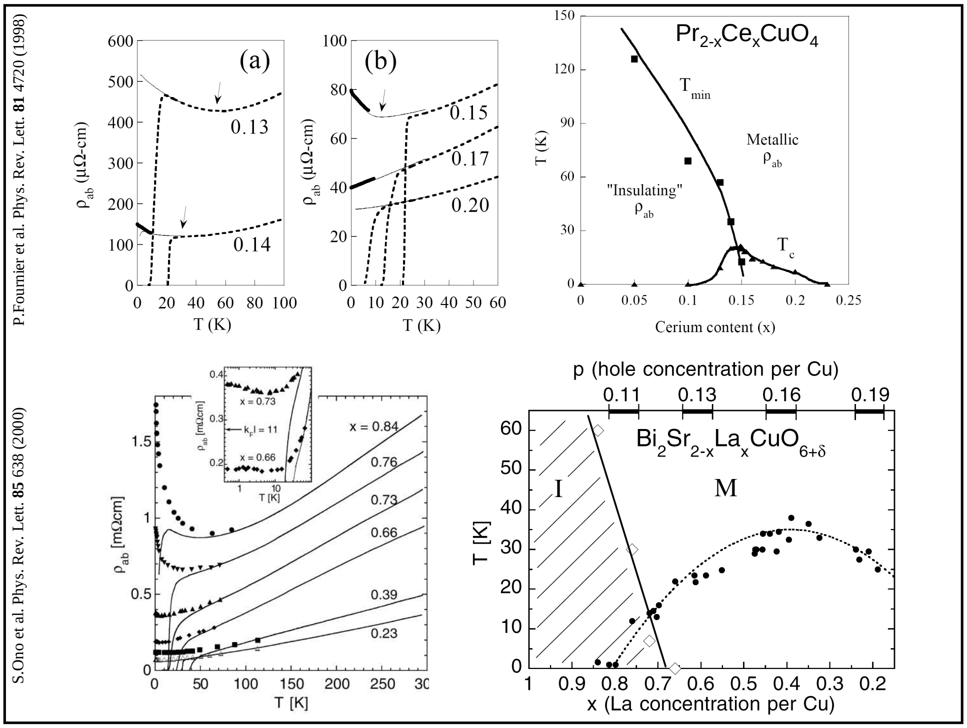
Wiedemann-Franz law inconclusive……

although

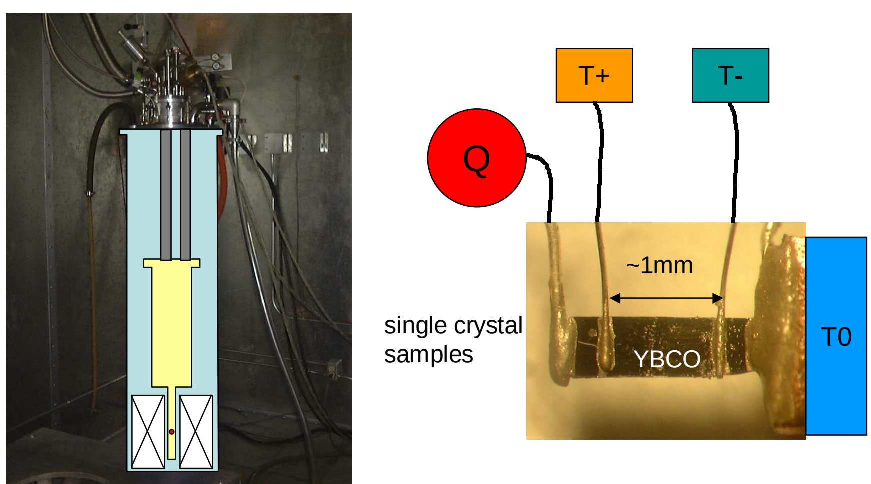


….. YBCO charge transport measurements can address this issue

Extra slides follow this one……



Making thermal conductivity measurements

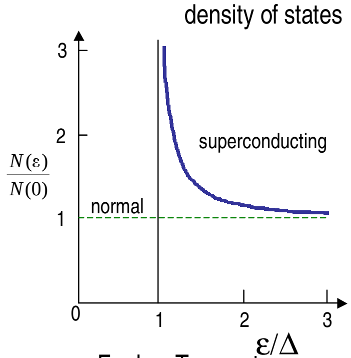


dilution refrigerator: 40mK – 4K
(2 decades in temperature)

magnetic field up to 15 T

$$\kappa = \frac{Q}{\left(T^+ - T^-\right)} \frac{l}{A}$$

Thermal conductivity in fully gapped 'conventional' superconductor



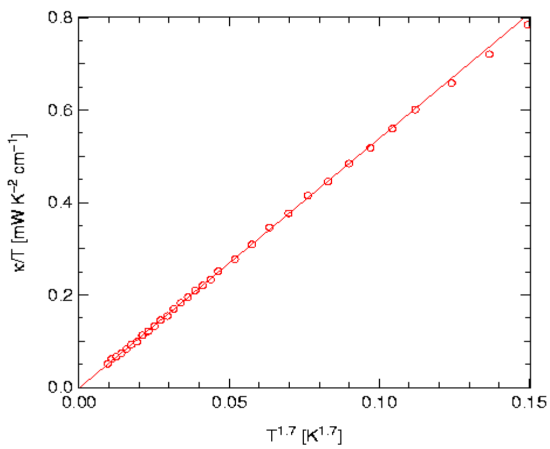
For low T expect
Activated behaviour

e.g. $C_e \sim \exp\left(-\frac{\Delta}{k_B T}\right)$

Minimal effect of impurities unless magnetic

Thermal conductivity

s – wave superconductor : V_3Si



Satterthwaite, Phys. Rev. **125** 873 (1962)

+ phonons!