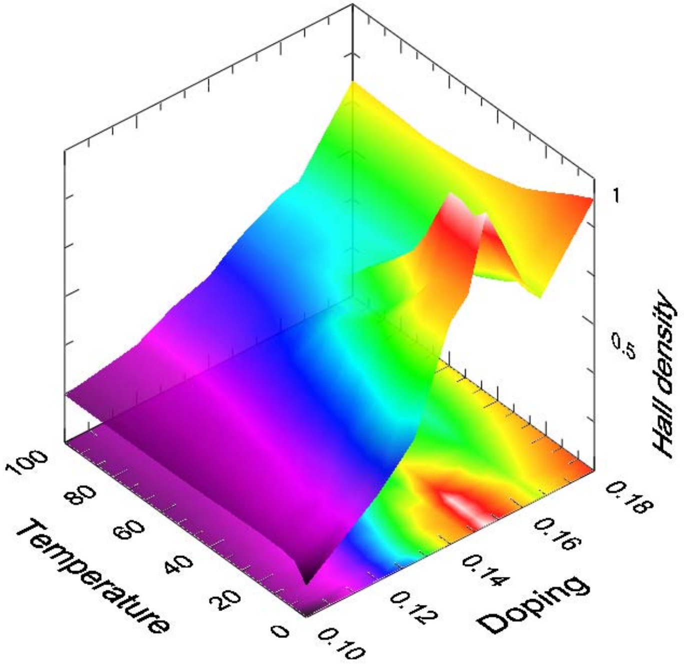
To submit a proposal for magnet time, www.magnet.fsu.edu

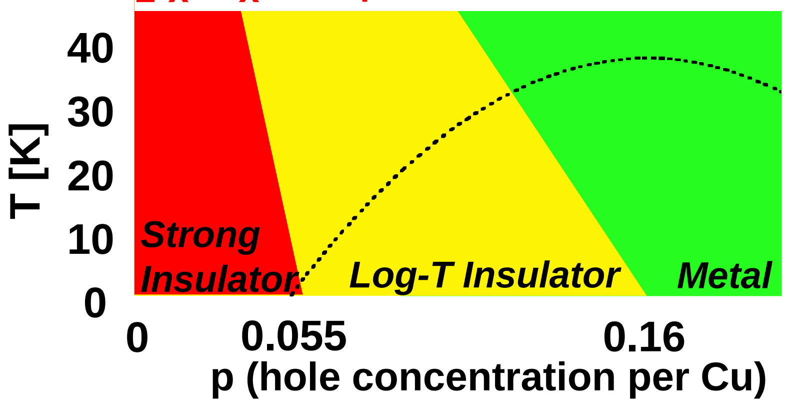
The Abnormal Normal State of the High-*Tc* Superconductors

Using 60 teslas ...
...to suppress the superconducting state
...(undress the electrons)…
…to reveal the low-temperature normal-state phase diagram



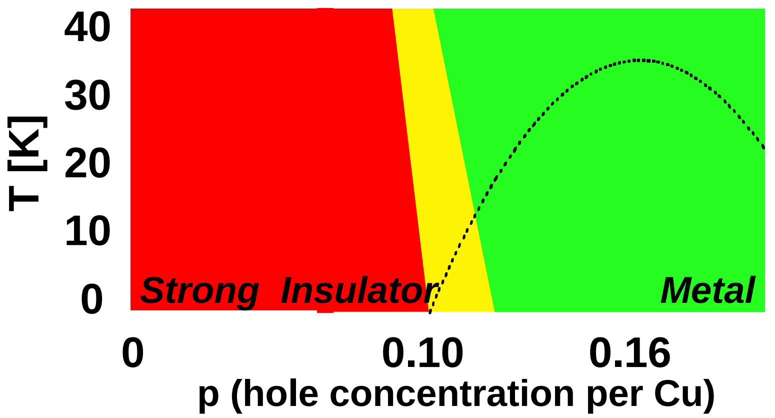
Nature **424**, 912 (2003)
Signature of Optimal Doping in Hall-effect Measurements on a High-Temperature Superconductor

$La_{2-x}Sr_{x}CuO_{4}$



Phys Rev Lett **77**, 5417 (1996)
Insulator-to-metal crossover in the normal state of $La_{2-x}Sr_{x}CuO_{4}$ near optimum doping

$Bi_{2}Sr_{2-x}La_{x}CuO_{6+\delta}$



Phys. Rev. Lett. **85**, 638 (2000)
Metal-to-Insulator Crossover in the Low-Temperature Normal State of $Bi_{2}Sr_{2-x}La_{x}CuO_{6+\delta}$

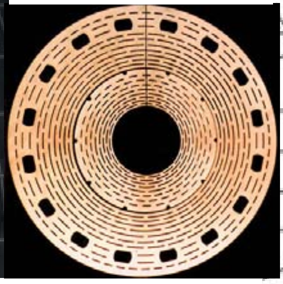
National High Magnetic Field Laboratory

Florida State University

Los Alamos National Laboratory

University of Florida

33T Florida Bitter Magnet

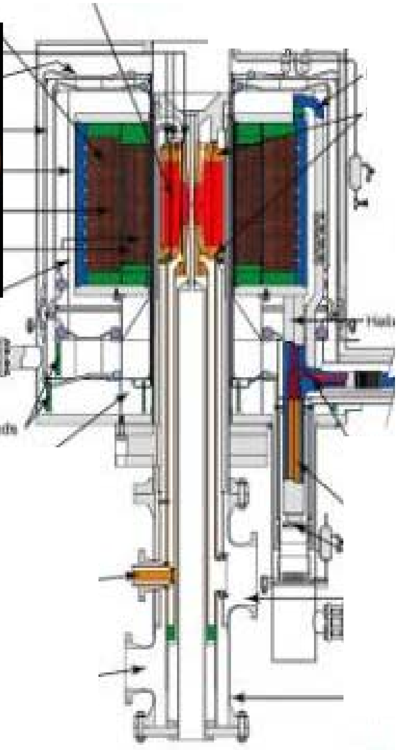


65T Pulse Magnet
15mm bore

11.4T MRI Magnet
400mm warm bore

Advanced Magnetic Resonance Imaging and Spectroscopy Facility

High B/T Facility
17T, 6wks at 1mK



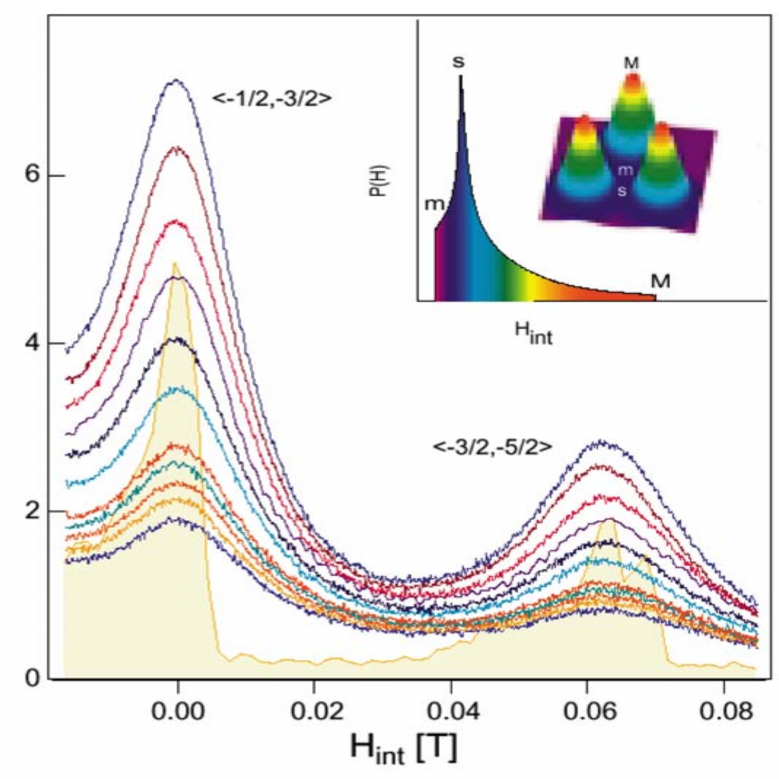
45T Hybrid Magnet

NHMFL – DC Facility

In-house Scientists:

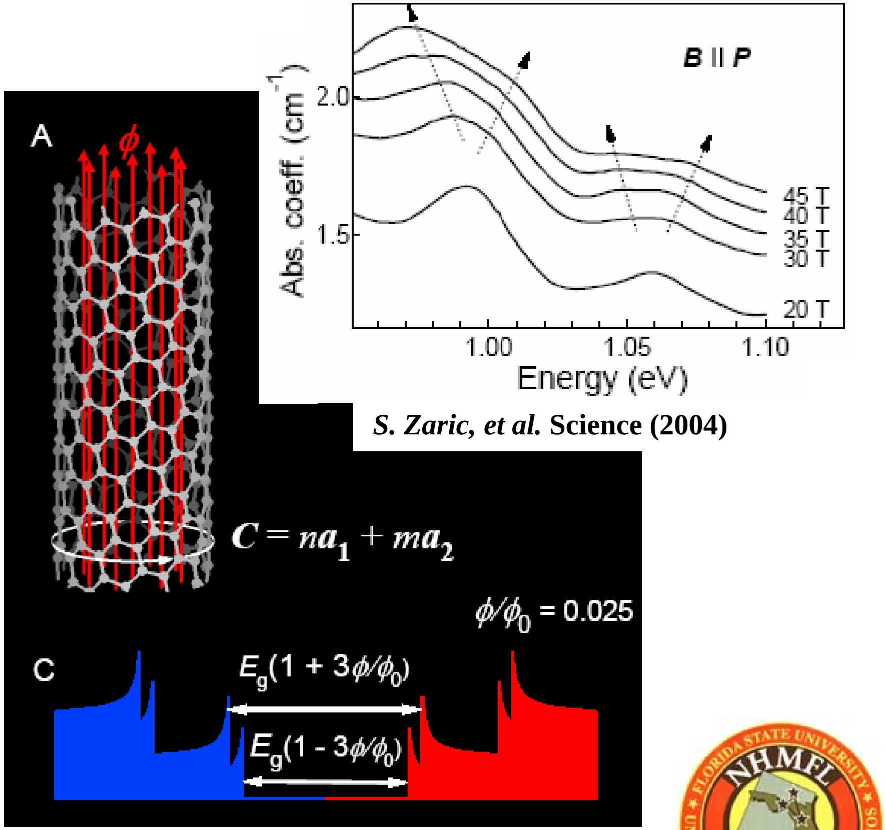
- Luis Balicas (*Magnetism and Transport)*
- Lloyd Engel (*Microwave conductivity)*
- Scott Hannahs (*Transport, Data Acquisition*)
- Phil Kuhns (*Condensed Matter NMR*)
- Tim Murphy (*Low Temp. Physics*)
- Eric Palm (*Low Temperature Physics*)
- Arneil Reyes (*Condensed Matter NMR*)
- Dmitri Smirnov (*FIR & Raman Spectroscopy)*
- Alexei Souslov (*Ultrasound Spectroscopy*)
- Stan Tozer (*High Pressure*)
- Yong-Jie Wang (*Far Infrared Spectroscopy)*
- Xing Wei (*Visible Optical Spectroscopy)*
- Sergei Zvyagin *(Sub/Millimeter Wave Spectroscopy)*

Imaging the Vortex Lattice in High Tc Superconductor



V. Mitrovic, et al. Nature (2001)

Aharonov Bohm Phase in Carbon Nanotubes



S. Zaric, et al. Science (2004)

NHMFL –
Pulsed Facility

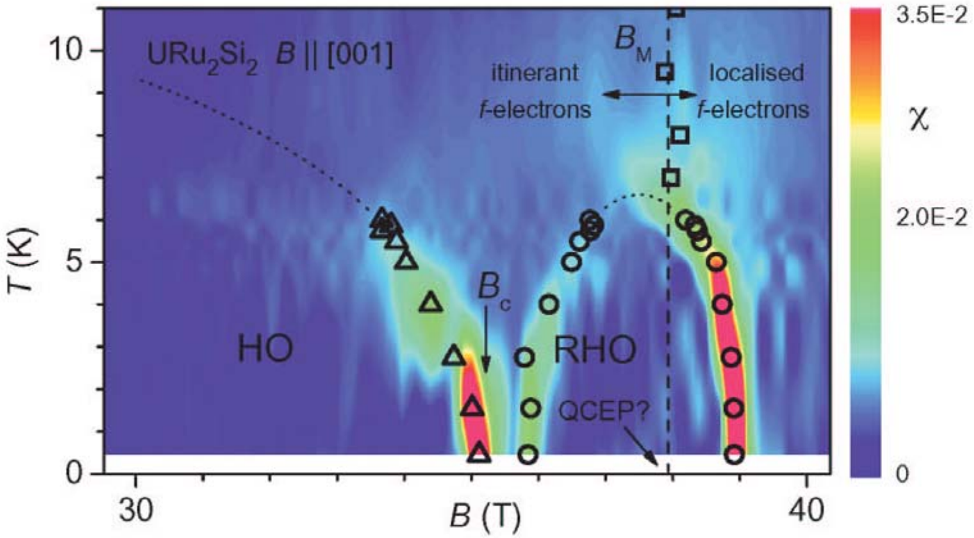
Six fully-multiplexed magnet cells
host 150-200 visiting scientists a year,
20% travel from overseas
to use unique pulsed field capabilities

In-house Scientists:

- **Scott Crooker (*Visible, IR, THz Spectroscopy*)**
- **Marcelo Jaime (*Thermodynamics, esp. Specific Heat*)**
- **Neil Harrison (*Thermodynamics, esp. Magnetization*)**
- **Fedor Balakirev (*Magneto-transport)***
- **John Singleton (*Magnetization, GHz spectroscopy*)**
- **Charles Mielke (*RF Transport & Head of Users Program*)**
- **Albert Migliori (*Thermodynamics, Ultrasound Spectroscopy*)**
- **Dwight Rickel (*Optical Spectroscopy*)**
- **Jason Lashley (*Thermodynamics, esp. Specific Heat*)**

Magnetic Field Driven Phase Transitions and Quantum Criticality

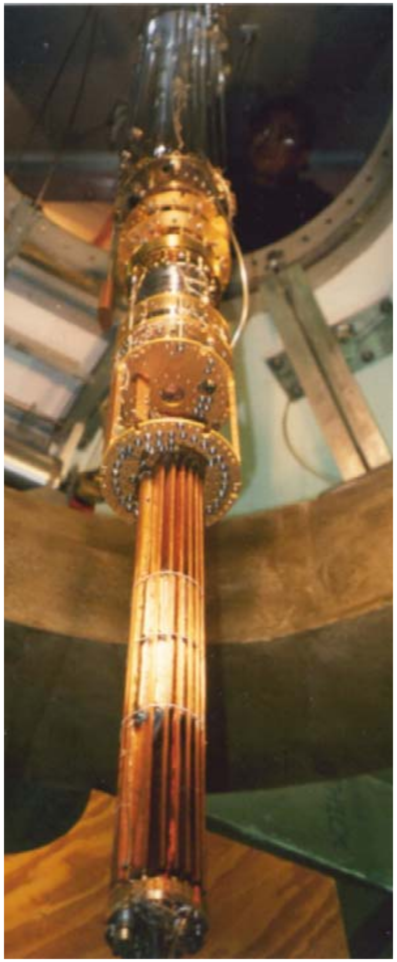
Jaime, et al, PRL 89 (2002) 287201
Harrison, et al, PRL 90 (2003) 096402
Kim, et al, PRL 91 (2003) 256401



Preliminary, unpublished
data removed by request of author.

NHMFL - UF Facilities

High B/T Facility



•High Field:

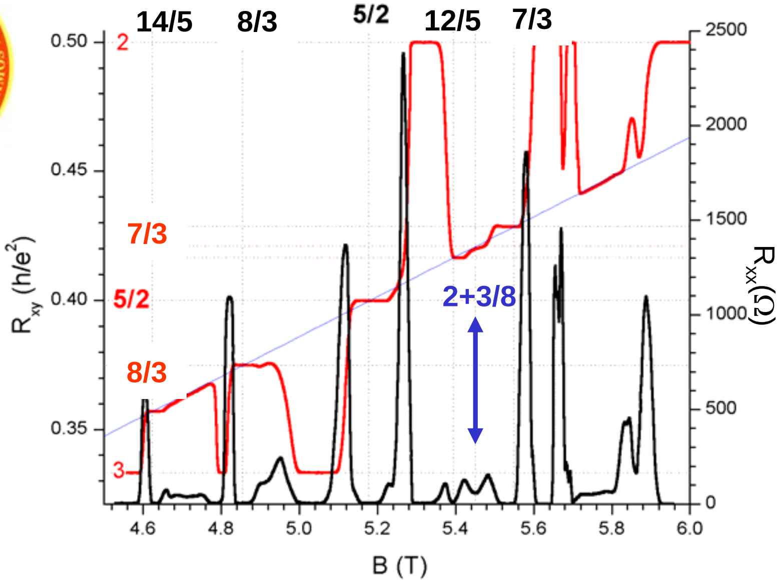
B = 15.5/17 T– 4.2/2.2 K

•Ultra-Low Temperatures

5 mole $PrNi_5$ nuclear demag refrige

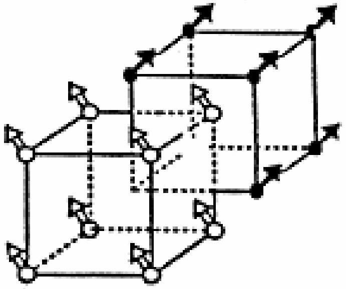
T_{min}< 0.5mK, 8nW cooling power

Maintains 1mK for > 6 wks



Need for High B/T

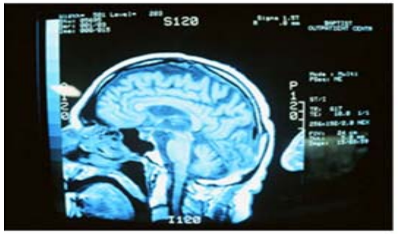
- Small energy gap of FQHE states
- Small energy differences among competing quantum phases
- Quantum phase transitions



Nuclear Magnetic
Ordering

In-house Scientists:

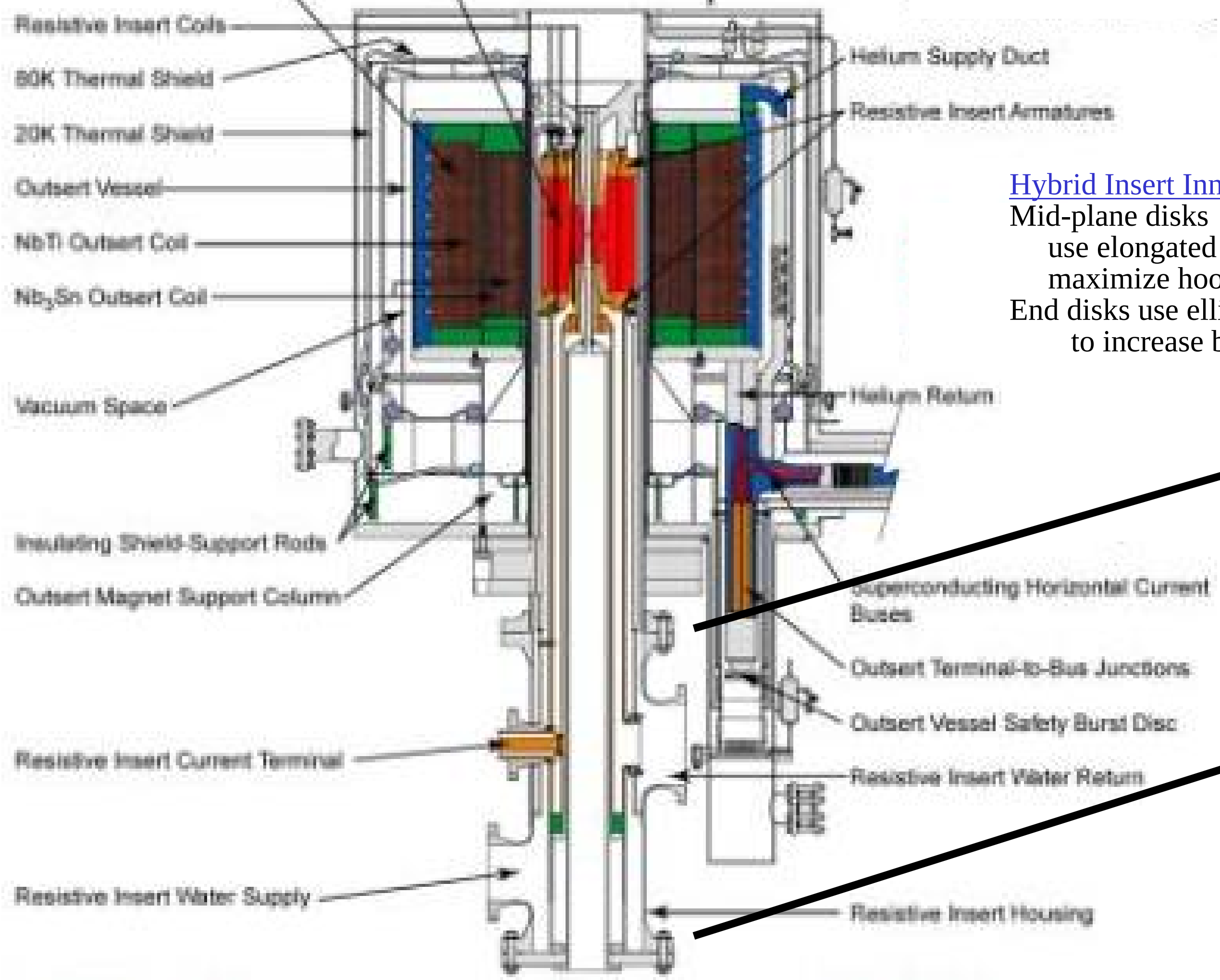
Jian-Sheng Xia (*Low T Physics*)
Dwight Adams (*Low T Physics*)
Yoonseok Lee (*Cond. Matt. Physics*)



AMRIS Facility

45T NHMFL hybrid magnet

Cu/Nb_3Sn composite strands around Cu cores inside 10mm x 12mm steel conduit



Mid-Plane / **End Turn**

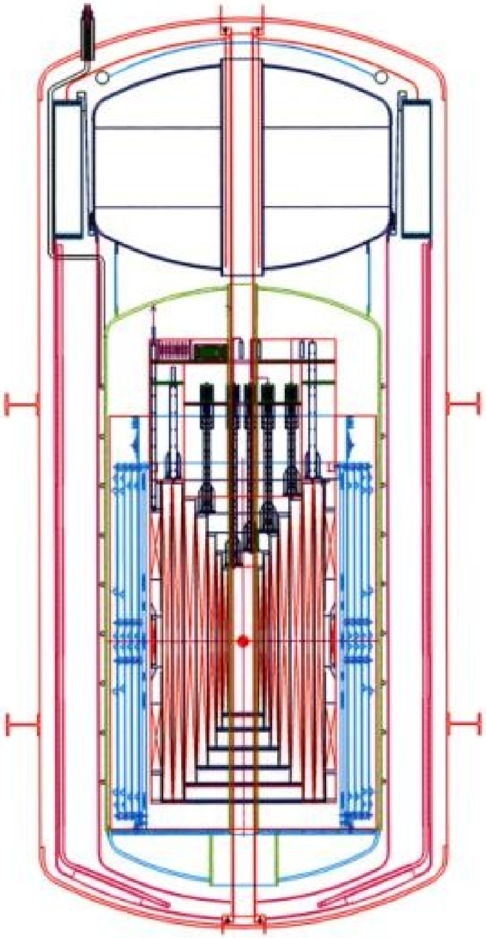
Florida Bitter Plates

Hybrid Insert Innovations

Mid-plane disks
use elongated hole to
maximize hoop strength.

End disks use elliptical holes
to increase bending stiffness.

Superconducting Magnet Development

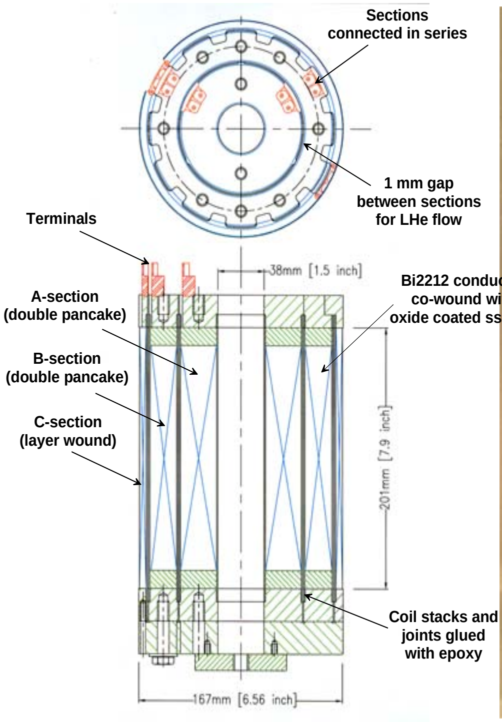


900 MHz NMR magnet

- 21.1 teslas
- 105mm warm bore
- 1 ppb homogeneity

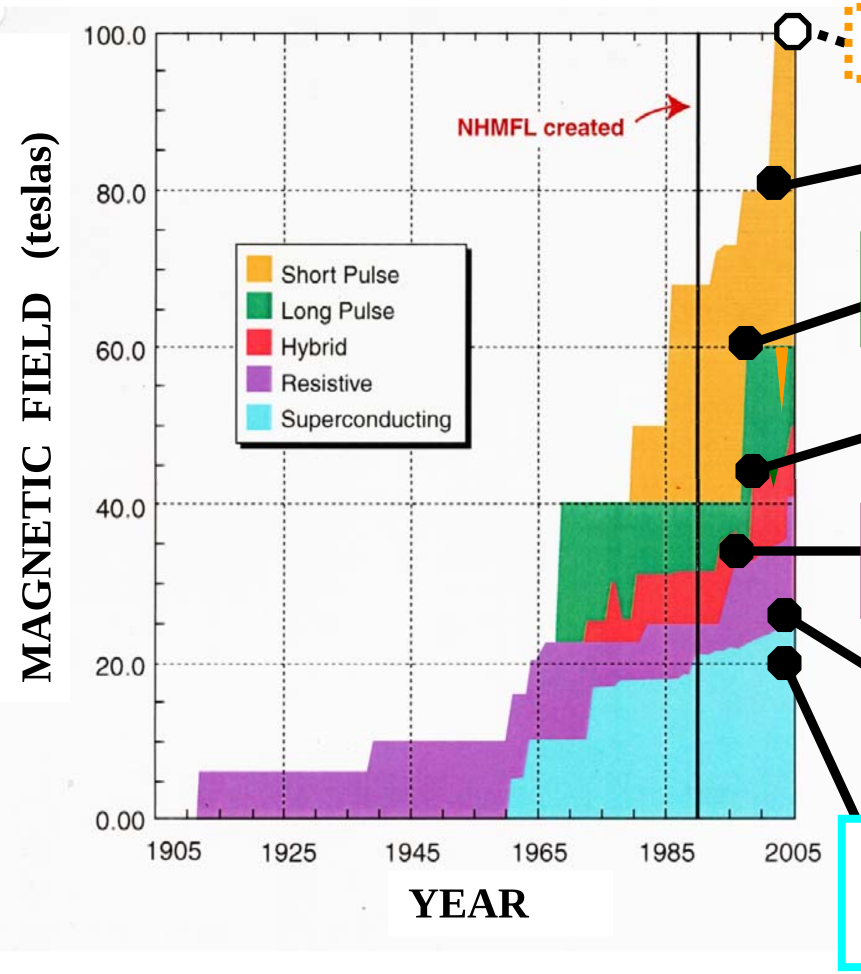
High Tc Insert Coil

- 1999…3T…16mm bore in 19T background field
- 2003…5T…38mm bore in 20T background field



NHMFL: Justin Schwartz, Huub Weijers, Ulf Trociewitz
Industrial Collaborator: Ken Marken, Oxford Instruments

100 YEARS OF NON-DESTRUCTIVE MAGNETS



2006 - 100T Multi-shot Pulsed Magnet

1999: 80T Short-Pulse Magnet
(ties the world record)

1998: 60T Controlled-Pulse Magnet
(world record) (rebuild in 2004)

1999: 45T DC Hybrid Magnet
(world record)

1996: 33T DC Resistive Magnet
(world record)

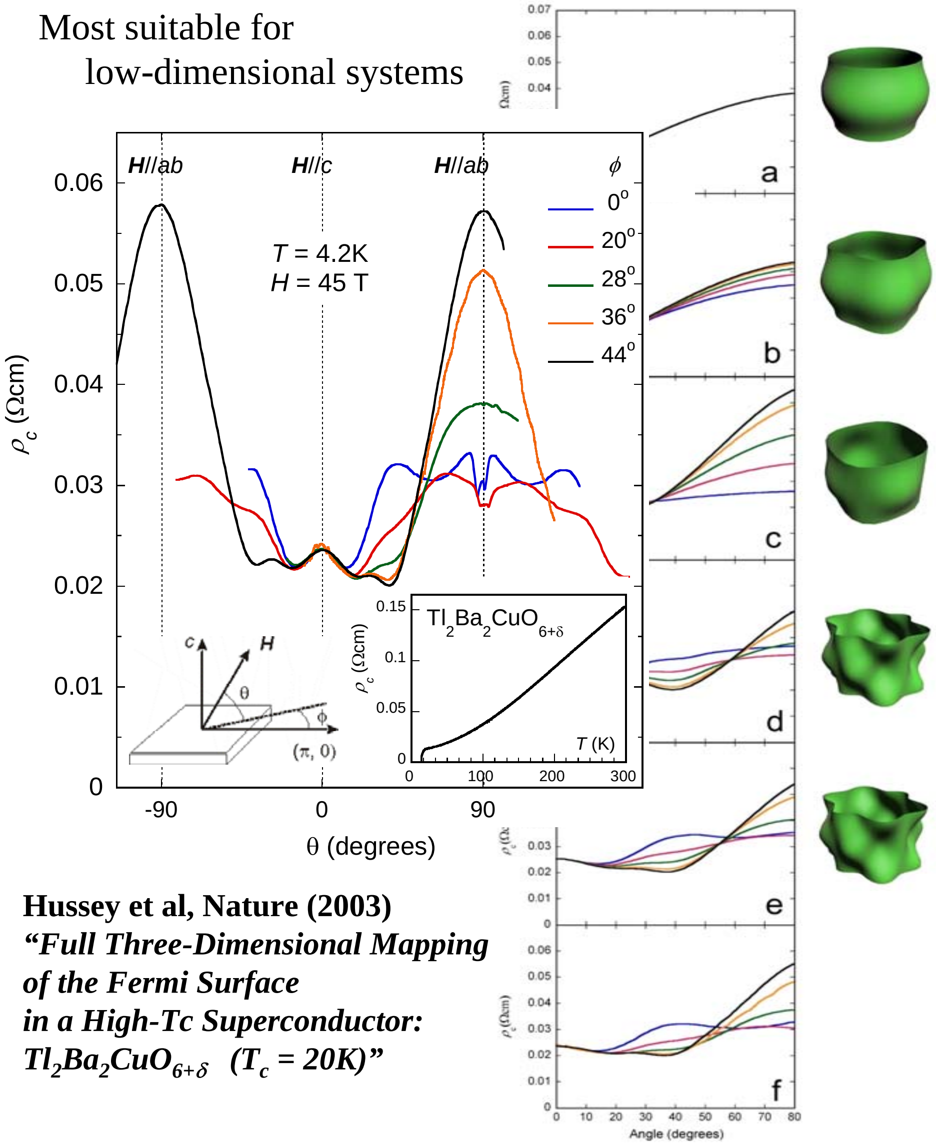
2003: 25T in 38mm bore
using 5T high-Tc insert
(world record)

2004: 900 MHz (21.1T) NMR magnet
(competitive in peak field,
uniquely large 105mm warm bore)

State-of-the-Art Fermi Surface Studies

Sample-Tilting in the Hybrid…

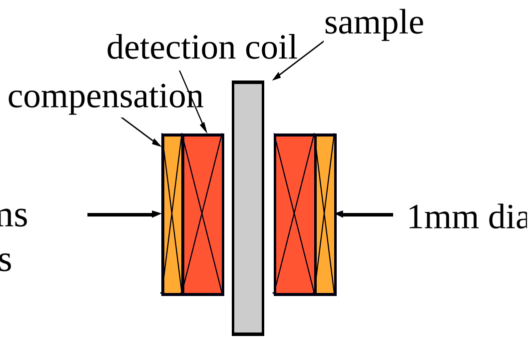
Most suitable for
low-dimensional systems

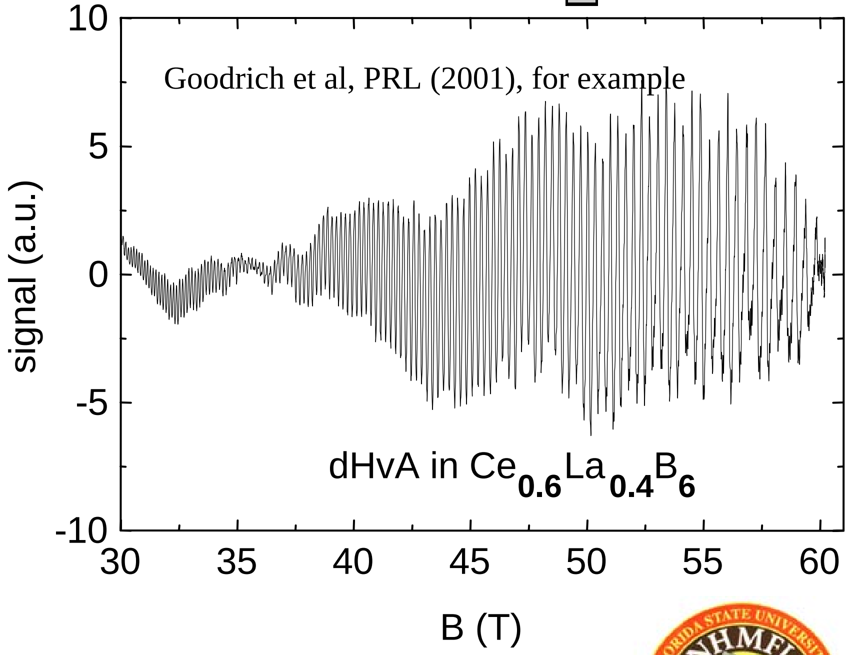


Hussey et al, Nature (2003)
"Full Three-Dimensional Mapping of the Fermi Surface in a High-Tc Superconductor: $Tl_2Ba_2CuO_{6+\delta}$ (T_c = 20K)"

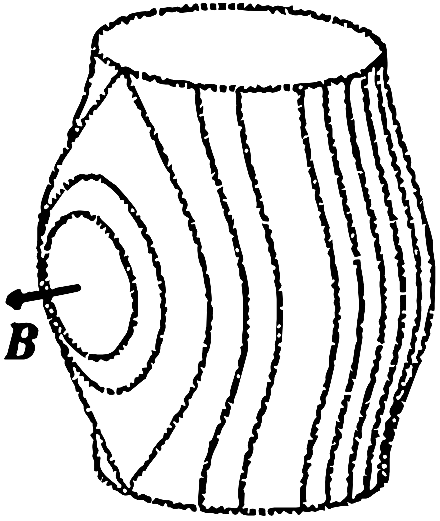
or deHaas-vanAlphen Oscillations in Pulsed Magnetic Fields

Most suitable for:
Heavy mass systems
Disordered systems





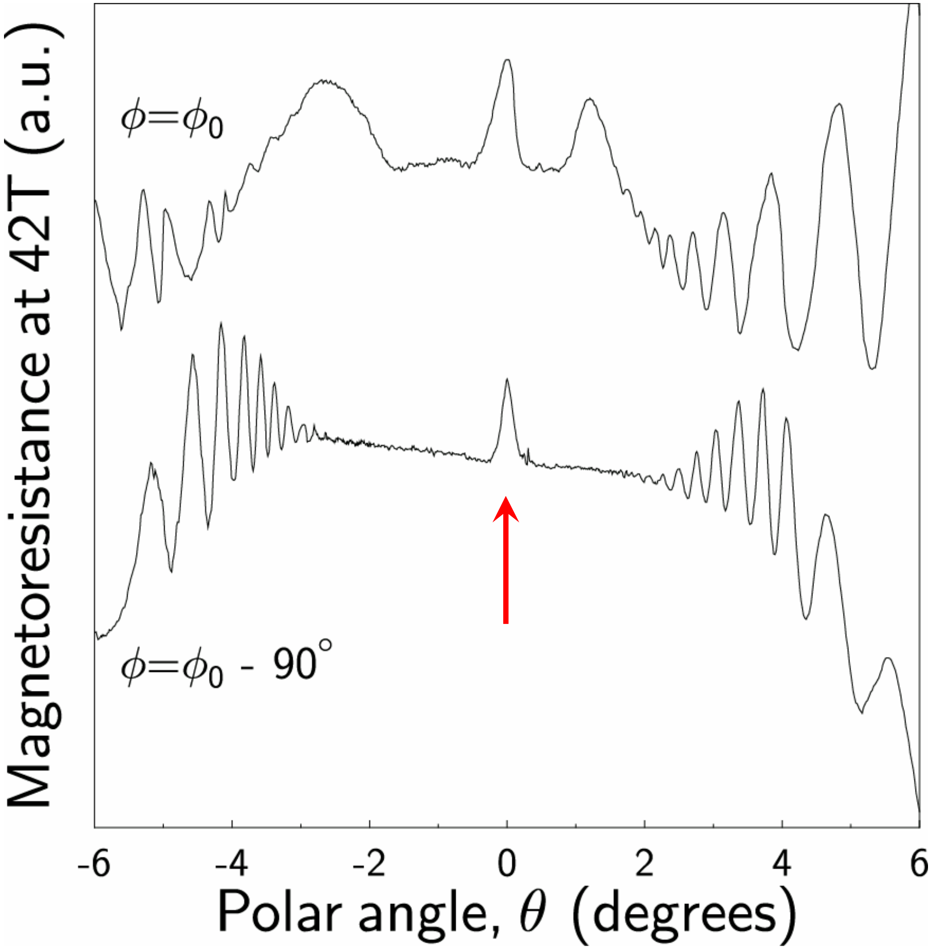
Test for interlayer coherence in a quasi-two-dimensional superconductor



Quasi-2D Fermi Surface of

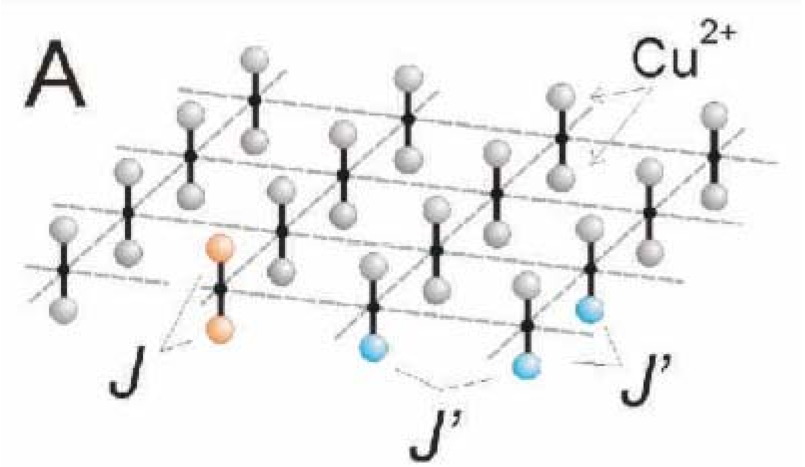
κ-(BEDT-TTF)$_2$Cu(NCS)$_2$.

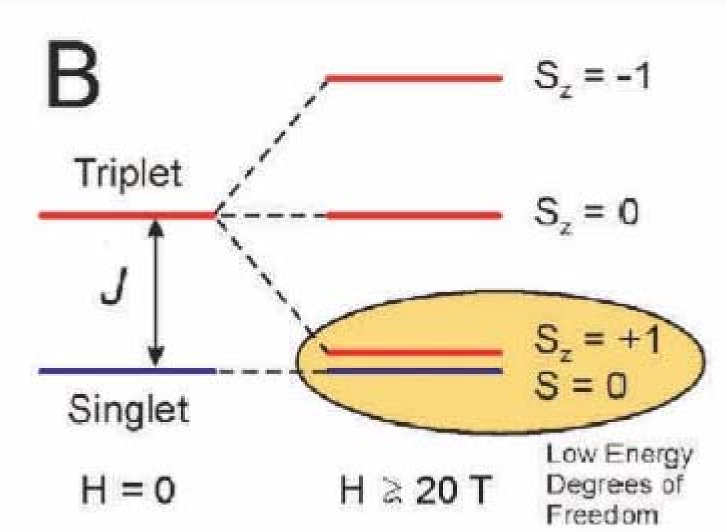
The lines indicate quasiparticle orbits on the Fermi Surface due to the in-plane magnetic field B. Note the closed orbits about the "belly" of the Fermi Surface.



John Singleton, P. A. Goddard, A. Ardavan, N. Harrison, S. J. Blundell, J. A. Schlueter, and A. M. Kini
Phys. Rev. Lett. **88**, 037001 (2002) *“Test for interlayer coherence in a quasi-two-dimensional superconductor”*

Magnetic Field-Induced Condensation of Triplons in Han Purple Pigment $BaCuSi_2O_6$



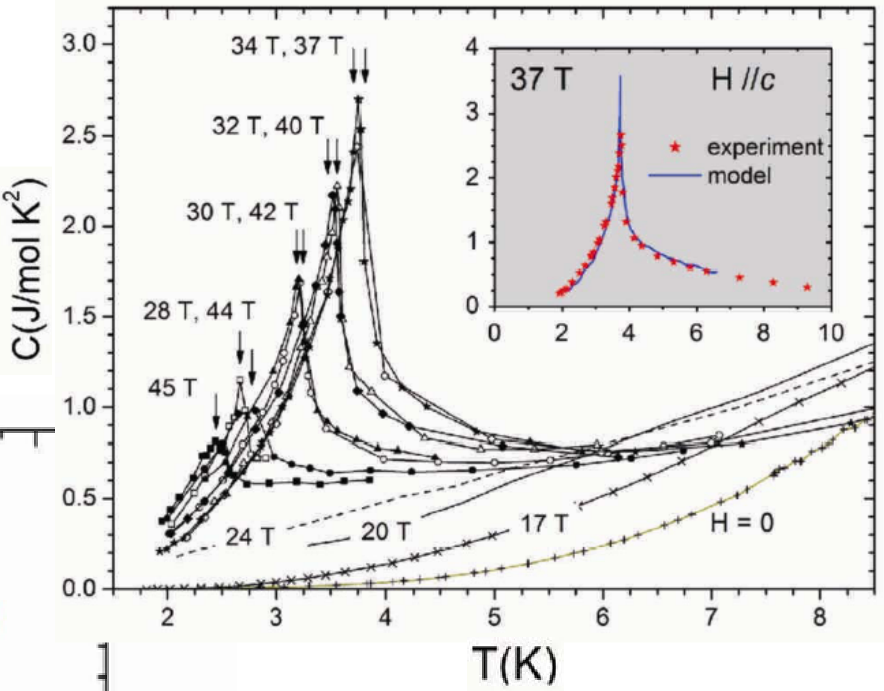


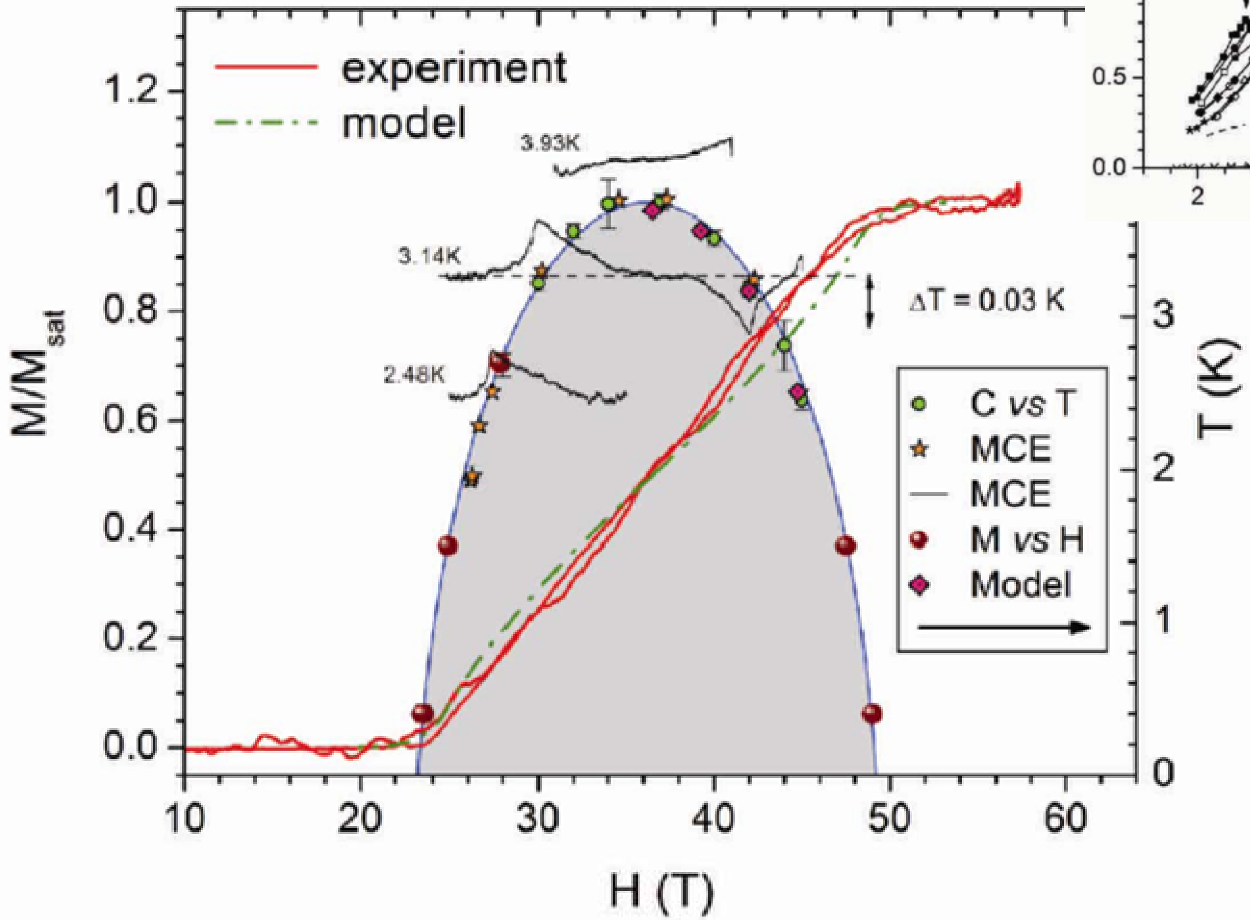
$BaCuSi_2O_6$: An ancient pigment
A quasi-2D magnetic insulator
Gapped spin dimer ground state

Magnetic fields drive a phase transition
to a gas of bosonic spin triplet excitations (triplons)

Magnetic Field-Induced Condensation of Triplons i
in Han Purple Pigment BaCuSi$_2$O$_6$

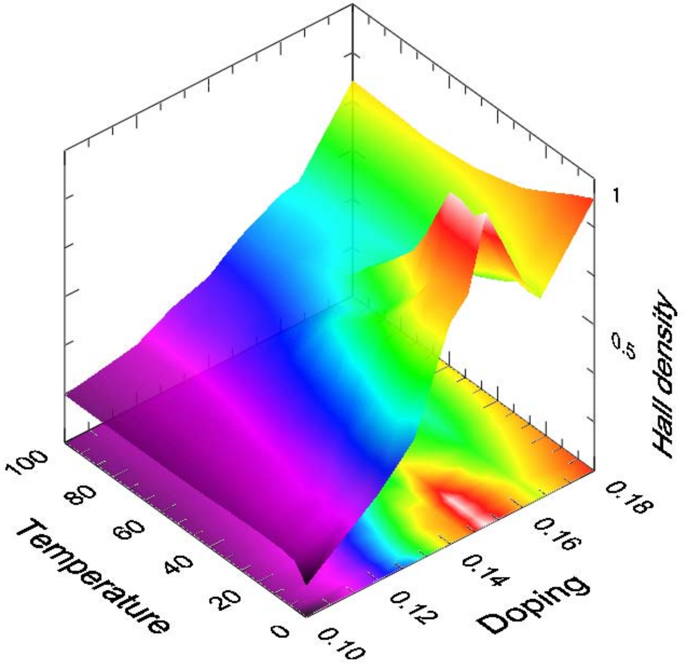
arXiv:cond-mat/0404324 v2 18 Apr 2004



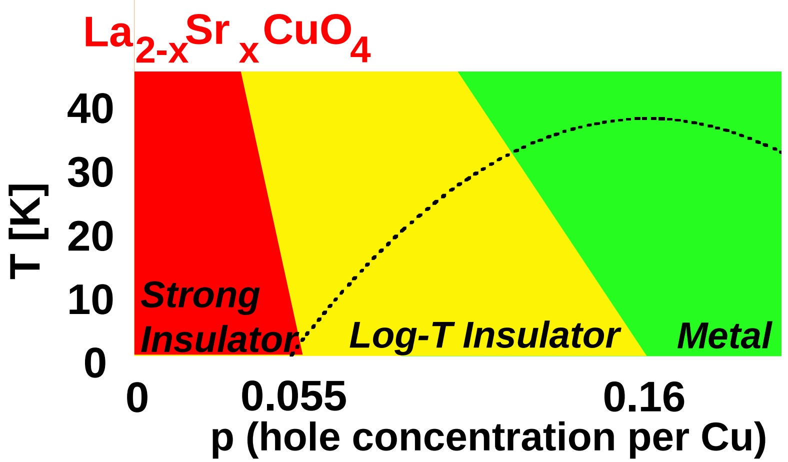


The Abnormal Normal State of the High-*Tc* Superconductors

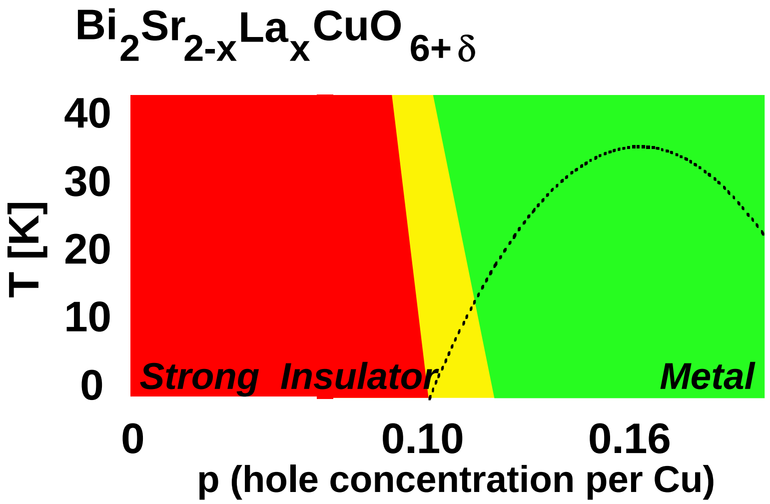
Using 60 teslas ...
...to suppress the superconducting state
...(undress the electrons)…
…to reveal the low-temperature normal-state phase diagram



Nature **424**, 912 (2003)
Signature of Optimal Doping in Hall-effect Measurements on a High-Temperature Superconductor



Phys Rev Lett **77**, 5417 (1996)
Insulator-to-metal crossover in the normal state of $La_{2-x}Sr_xCuO_4$ near optimum doping



Phys. Rev. Lett. **85**, 638 (2000)
Metal-to-Insulator Crossover in the Low-Temperature Normal State of $Bi_2Sr_{2-x}La_xCuO_{6+\delta}$

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...(undress the electrons)…
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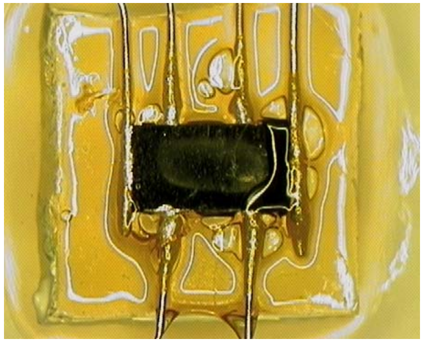
$Bi_2Sr_{2-x}La_xCuO_{6+\delta}$



Joze Bevk, Al Passner
Bell Laboratories

Fedor Balakirev, Jon Betts, Neil Harrison,
Kee Hoon Kim, Albert Migliori
National Magnetic Field Laboratory at Los Alamos

The Cast of Characters

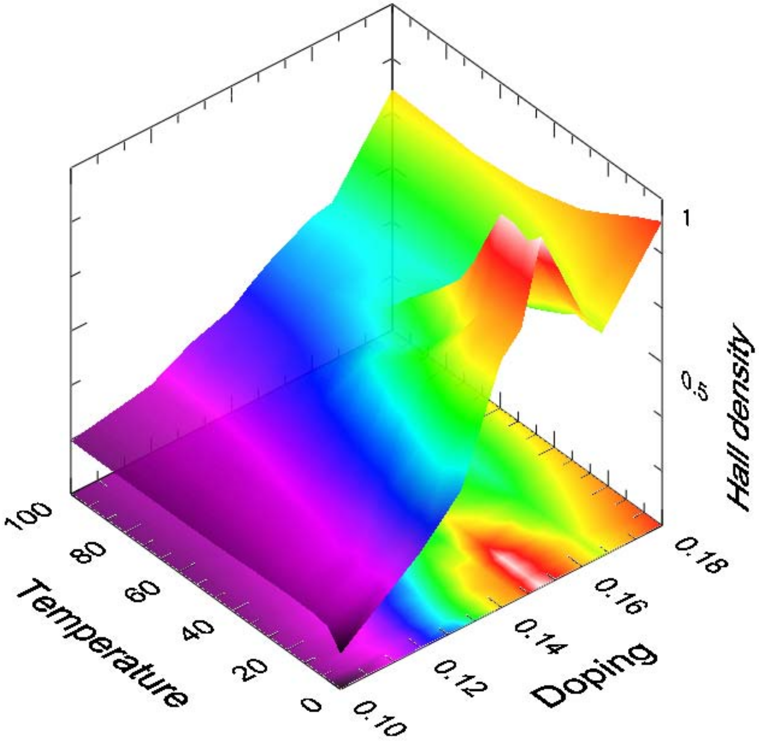
BSLCO
Yoichi Ando, Shimpei Ono, S. Komiya, Kouji Segawa
CRIEPI, Tokyo

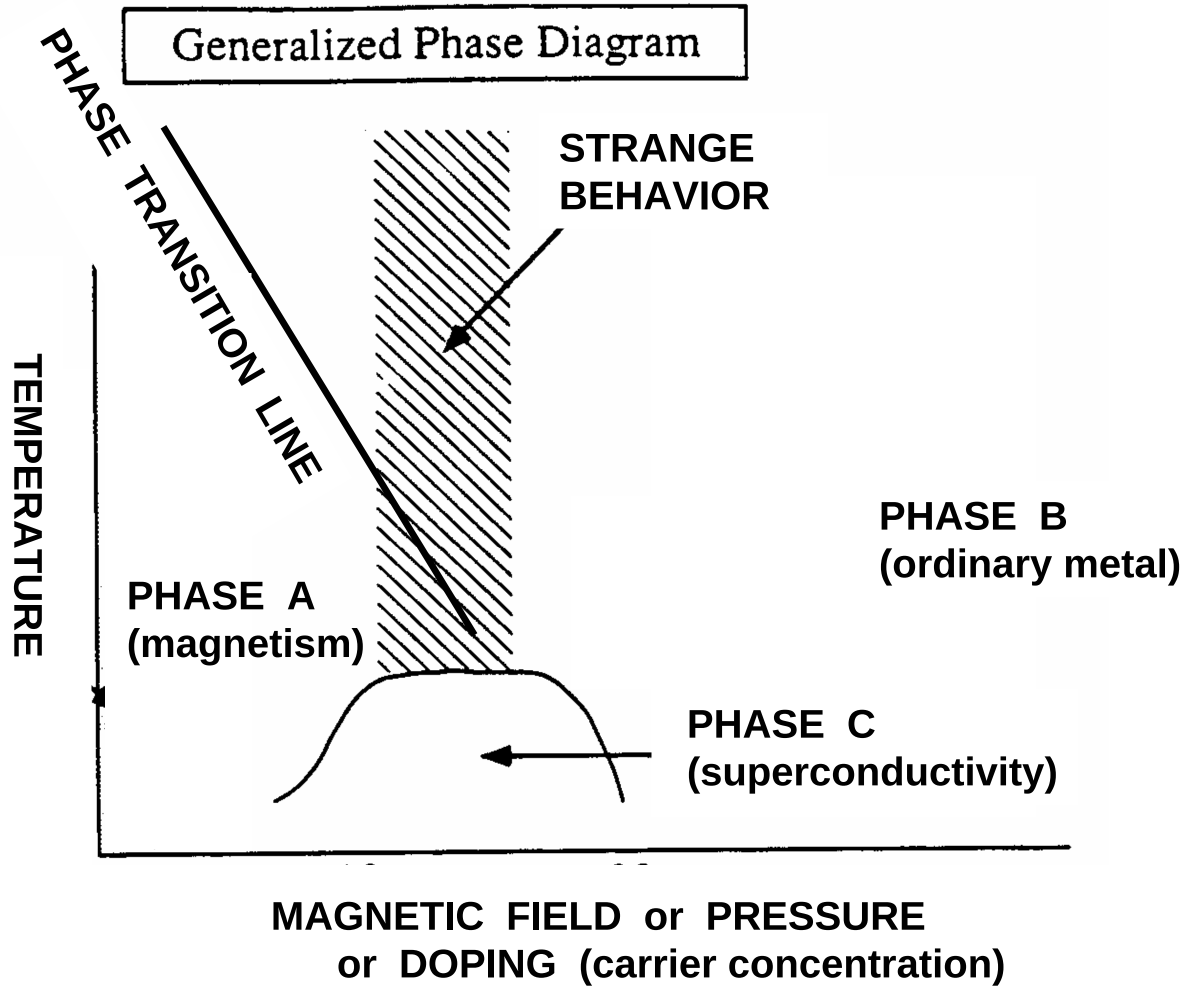
LSCO
Kohji Kishio, Masayuki Okuya, Tsuyoshi Kimura,
Jun-ichi Shimoyama, *University of Tokyo*

LSCO and Ladder Compound
Shin-ichi Uchida, Naoki Motoyama, Kenji Tamasaku,
Noriya Ichikawa, Hiroshi Eisaki, *University of Tokyo*

Tl-2201
Andre Tyler, Andy Mackenzie
Cambridge University and University of St. Andrews

Bi-2201
Nan Lin Wang, Christoph Geibel, Frank Steglich
TH Darmstadt and Max Planck Institute, Dresden





Generalized Phase Diagram

PHASE TRANSITION LINE

STRANGE BEHAVIOR

TEMPERATURE

PHASE A
(magnetism)

PHASE B
(ordinary metal)

PHASE C
(superconductivity)

MAGNETIC FIELD or PRESSURE
or DOPING (carrier concentration)

Tuning to Quantum Critical Points
using Pressure or Magnetic Field

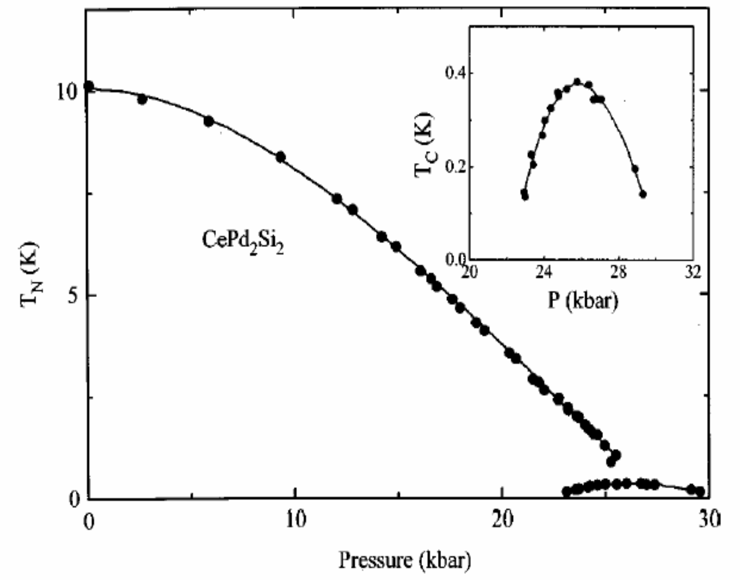


FIG. 25. Phase diagram for the antiferromagnet CePd$_2$Si$_2$ as a function of pressure, after Julian *et al.* (1998). The superconducting transition induced by pressure at low temperatures and pressures between 23 and 29 kbar shown in the main figure is expanded in the inset.

G. R. Stewart, Rev. Mod. Phys. 73, 797 (2001)


PHYSICAL REVIEW LETTERS

Articles published week ending
7 MARCH 2003

Volume 90, Number 9

A. Suslov et al., Phys. Rev. B68, 20406-1-4 (2003).
P. Chandra et al., Nature **417**, 831 (2002).
M. Jaime et al., PRL **89**, 287201 (2002).
N. Harrison et al., PRL **90**, 096402 (2003).
K.H. Kim et al., PRL to be published (2004).

The Abnormal Normal State of the High-*Tc* Superconductors

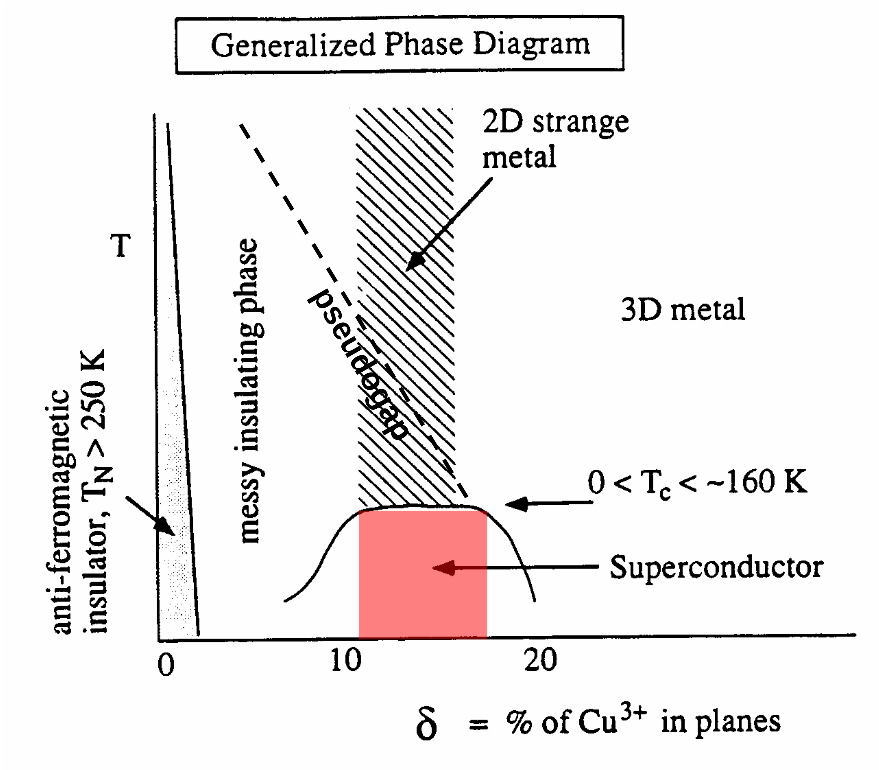
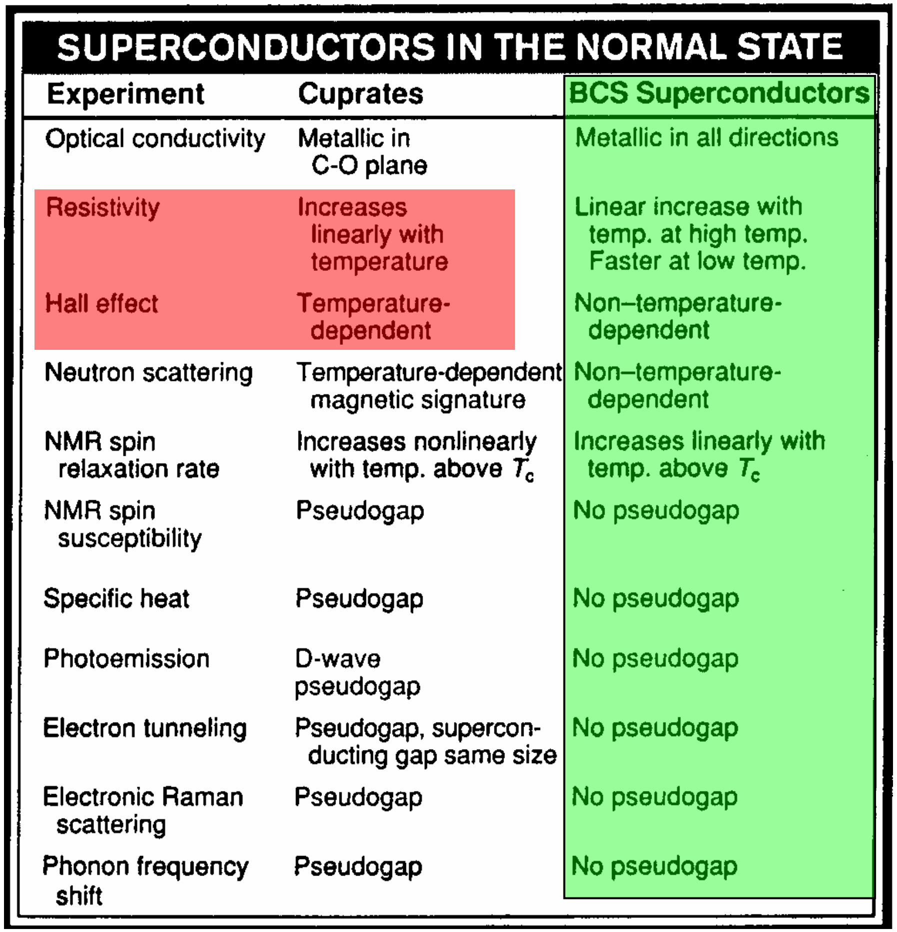


Figure 3.26. "Generalized Phase Diagram" as seen (roughly) in $(La - Sr)CuO_4$.



SUPERCONDUCTORS IN THE NORMAL STATE

Experiment	Cuprates	BCS Superconductors
Optical conductivity	Metallic in C-O plane	Metallic in all directions
Resistivity	Increases linearly with temperature	Linear increase with temp. at high temp. Faster at low temp.
Hall effect	Temperature-dependent	Non–temperature-dependent
Neutron scattering	Temperature-dependent magnetic signature	Non–temperature-dependent
NMR spin relaxation rate	Increases nonlinearly with temp. above T_c	Increases linearly with temp. above T_c
NMR spin susceptibility	Pseudogap	No pseudogap
Specific heat	Pseudogap	No pseudogap
Photoemission	D-wave pseudogap	No pseudogap
Electron tunneling	Pseudogap, superconducting gap same size	No pseudogap
Electronic Raman scattering	Pseudogap	No pseudogap
Phonon frequency shift	Pseudogap	No pseudogap

Anderson, Science 256, 1526 (1992) and Research News, Science 278, 1879 (1997)

Using 60 teslas....to suppress the superconducting state and reveal the normal-state phase diagram

Challenges in Producing High Magnetic Fields

Pressure Under Water

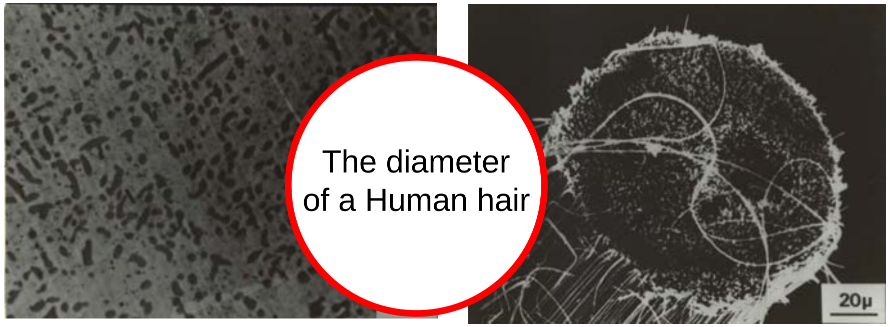
12 feet	**Ears**	**6 pounds per square inch**
2000 feet	**Submarine**	**1000 psi**
12,000 feet	**Ocean Floor**	**6000 psi**

Pressure inside NHMFL Pulsed Magnets

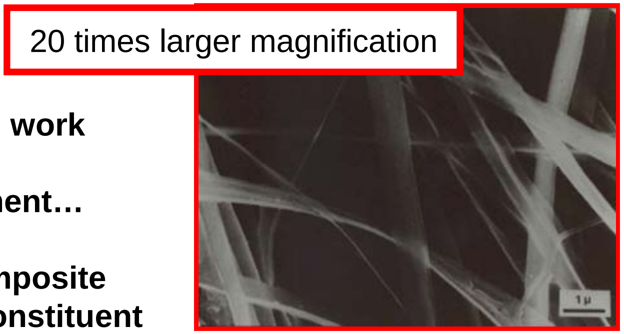
800,000 gauss	**Pulsed Magnet**	**200,000 psi**

(which equals 1.4GPa or 130 kg per square millimeter)

(which is more pressure than most materials can handle)

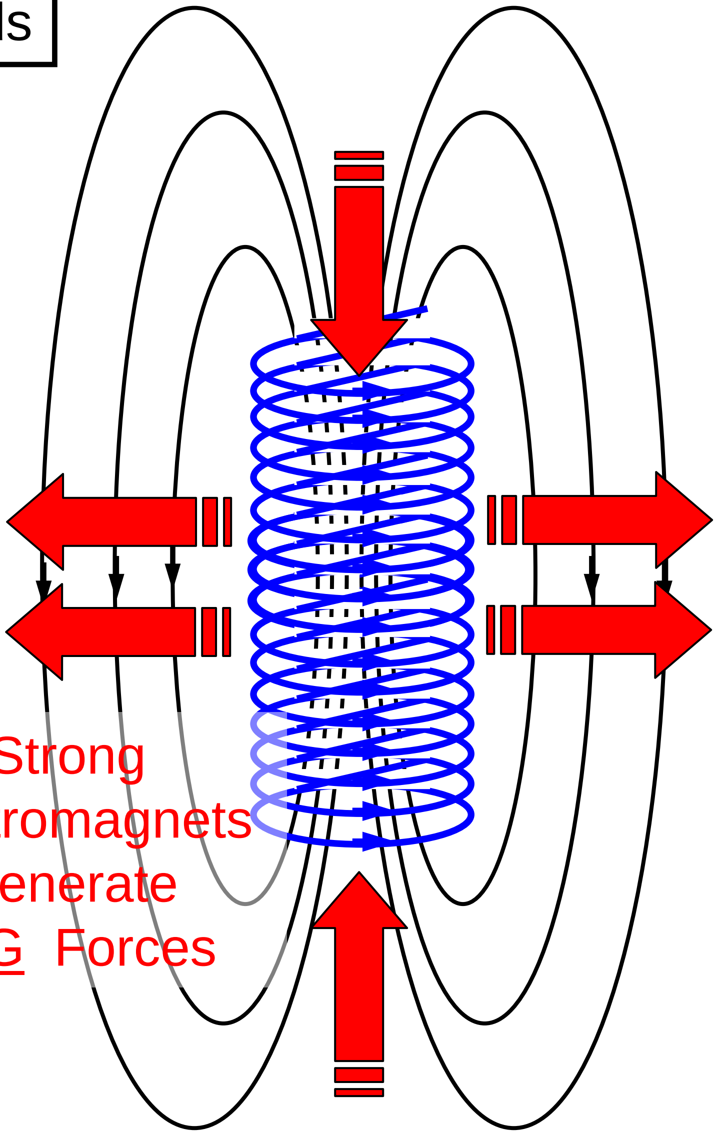


20% Niobium Droplets
in 80% Copper Matrix



The Niobium ribbons work
(sort of)
like steel bars in cement…

…except the nano-composite
is stronger than either constituent

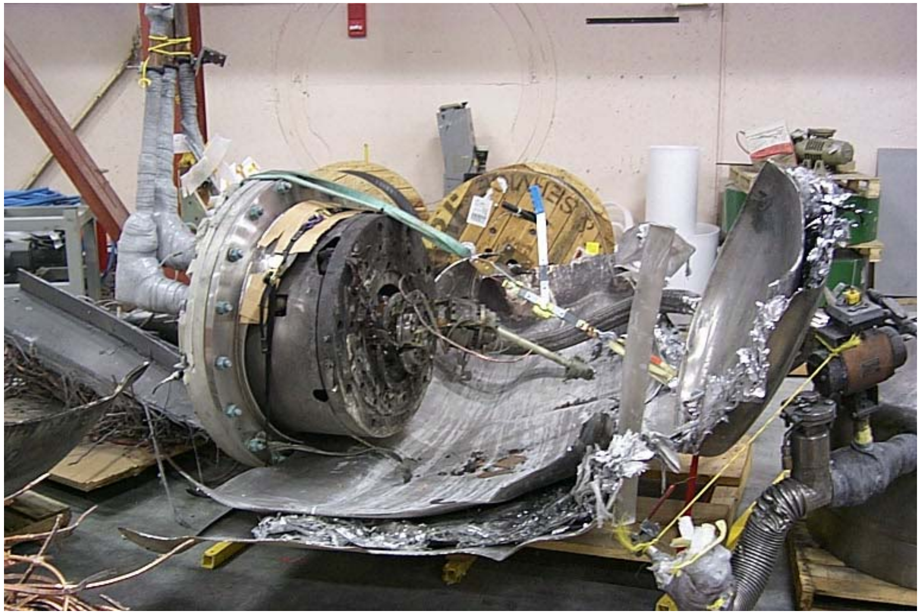


Strong
Electromagnets
Generate
<u>BIG</u> Forces

Pulse 915
July 28,2000

9:15:00 am

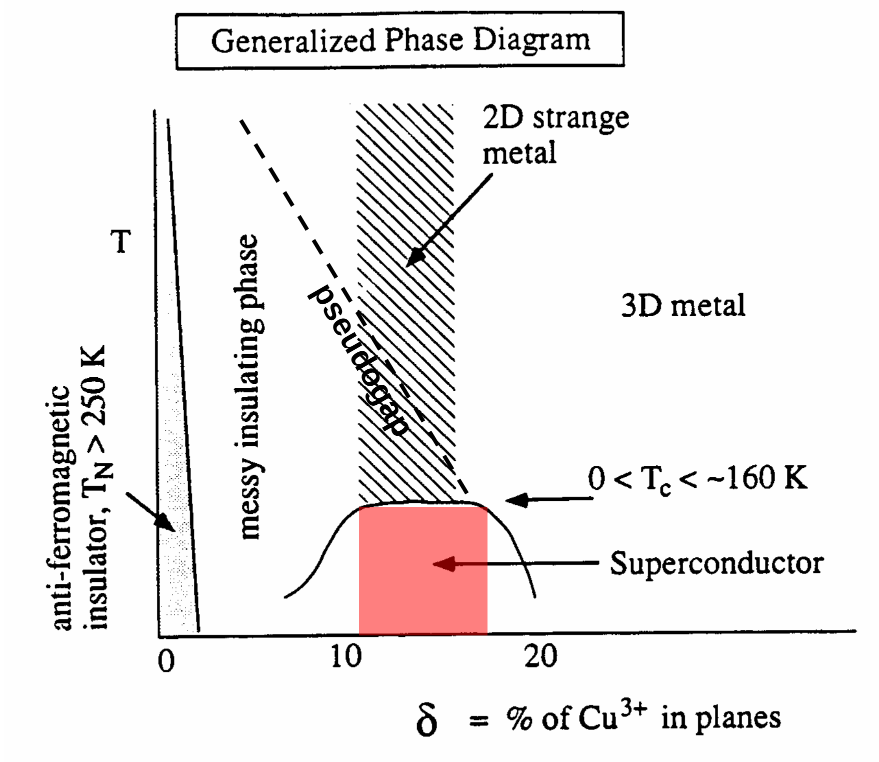
9:15:01 am



Analysis of Debris
until January 2001

Until You Spread Your Wings,
You’ll Have No Idea How Far You Can Walk.

The Abnormal Normal State of the High-*Tc* Superconductors



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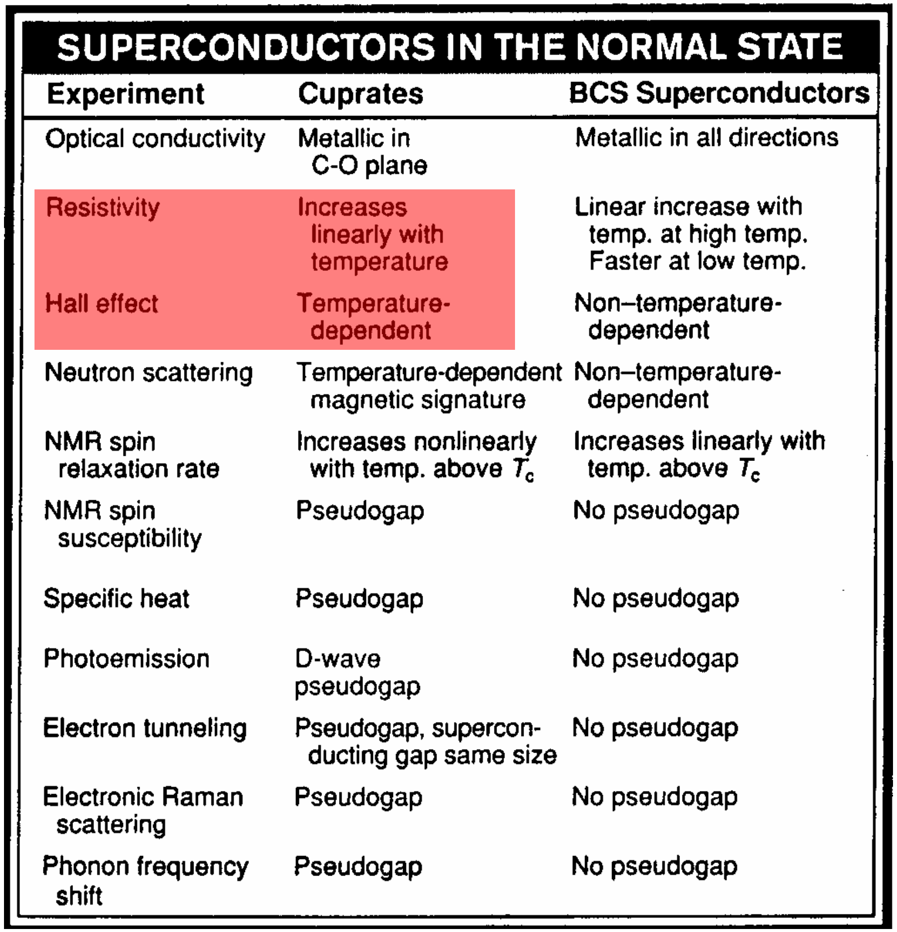

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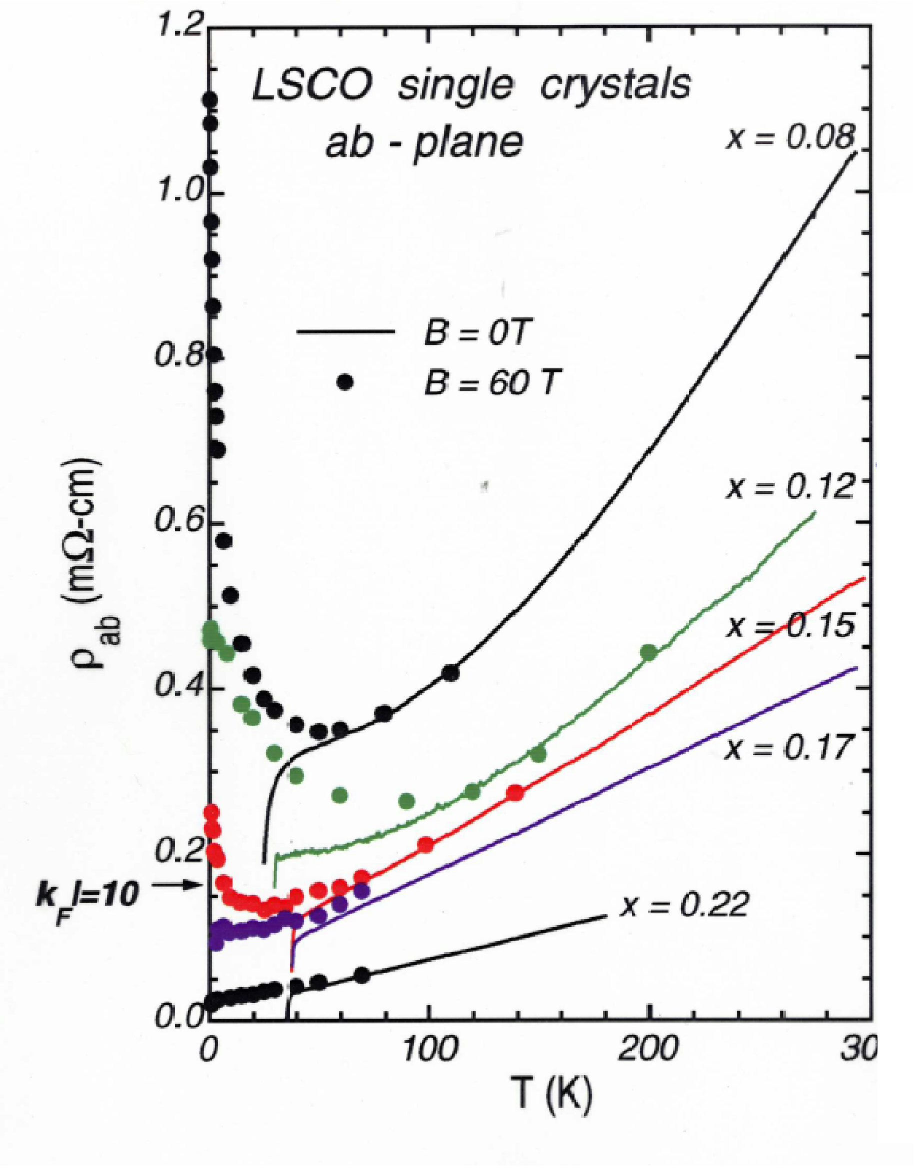
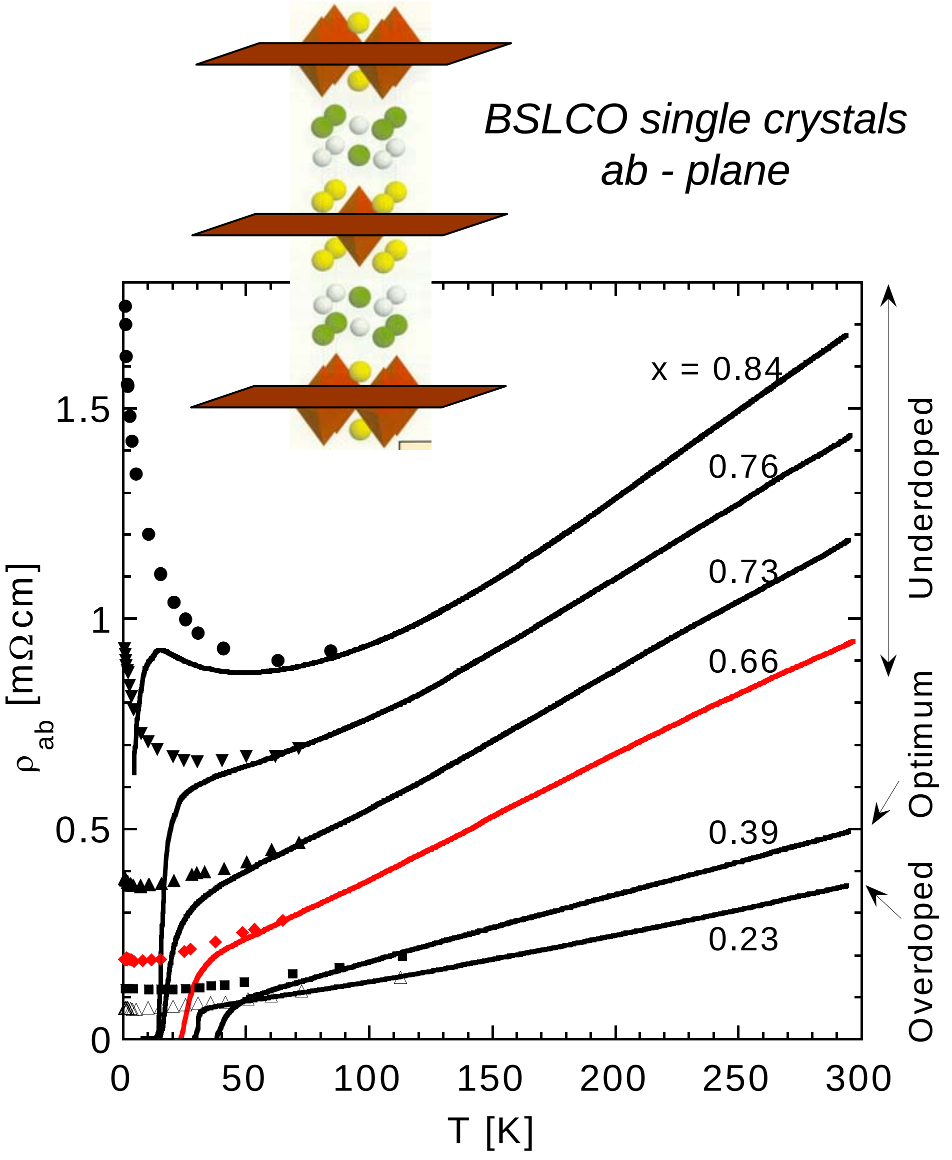
Anderson, Science 256, 1526 (1992) and Research News, Science 278, 1879 (1997)

Using 60 teslas....to suppress the superconducting state and reveal the normal-state phase diagram

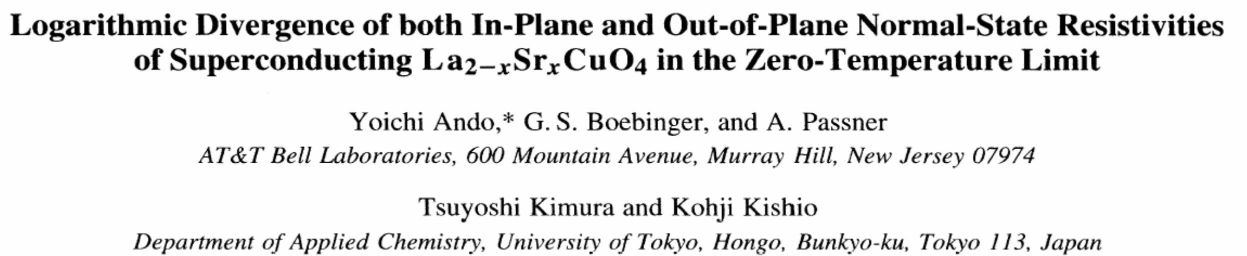


PRL **77**, 5417 (1996)



PRL **85**, 638 (2000)

$La_{1.92}Sr_{0.08}CuO_4$



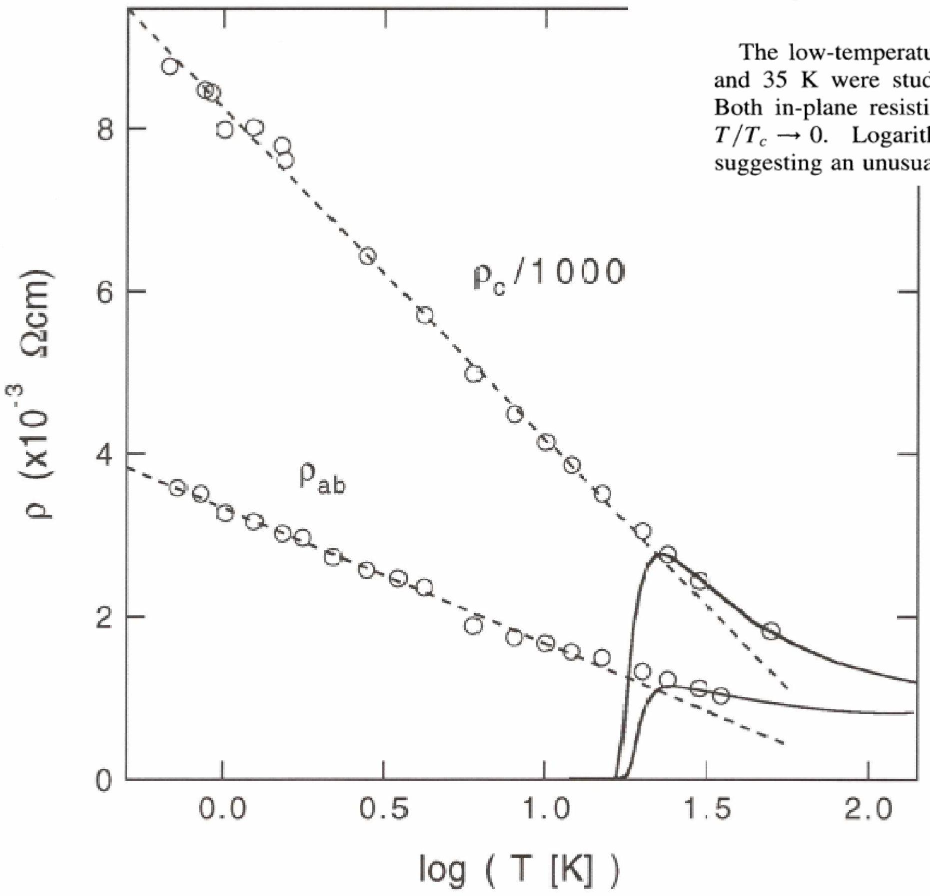
Logarithmic Divergence of both In-Plane and Out-of-Plane Normal-State Resistivities of Superconducting $La_{2-x}Sr_xCuO_4$ in the Zero-Temperature Limit

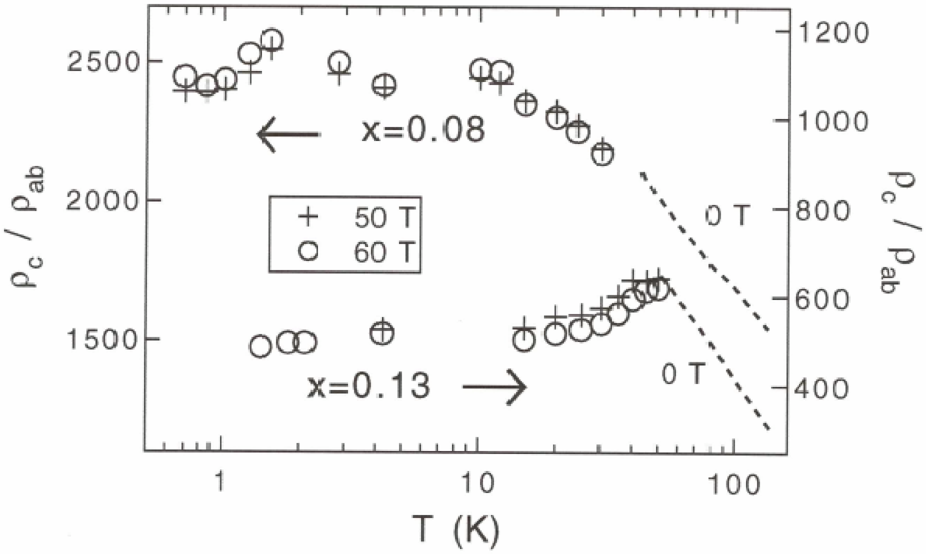
Yoichi Ando,* G. S. Boebinger, and A. Passner
AT&T Bell Laboratories, 600 Mountain Avenue, Murray Hill, New Jersey 07974

Tsuyoshi Kimura and Kohji Kishio
Department of Applied Chemistry, University of Tokyo, Hongo, Bunkyo-ku, Tokyo 113, Japan

(Received 18 August 1995)

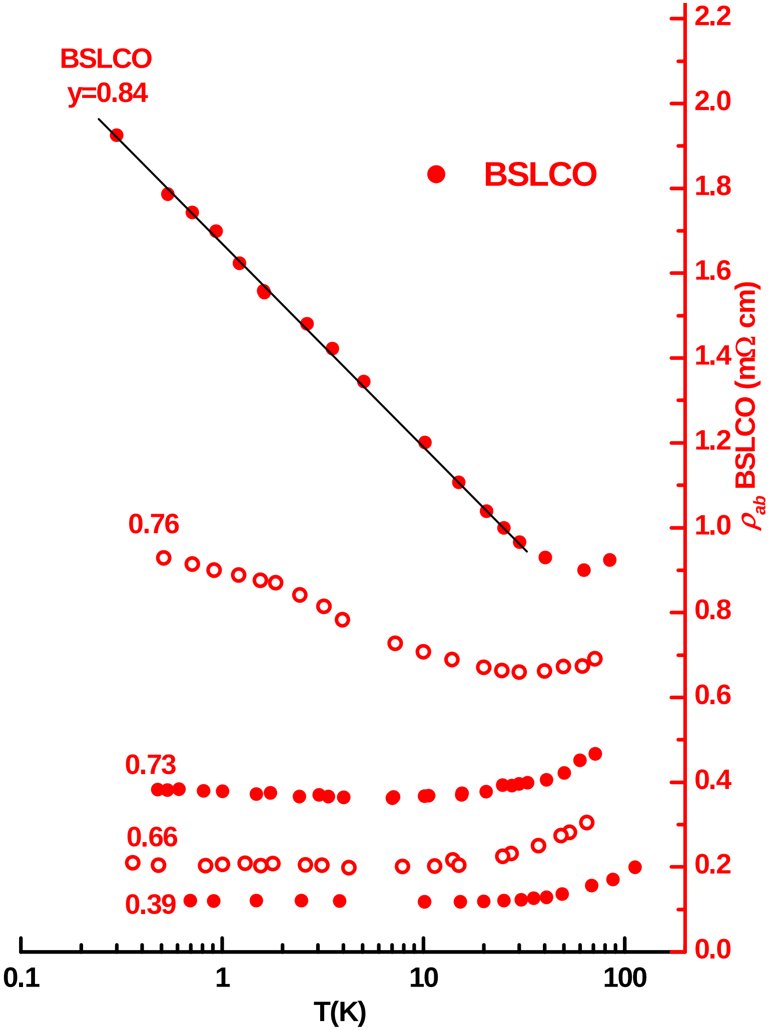
The low-temperature normal-state resistivities of underdoped $La_{2-x}Sr_xCuO_4$ crystals with T_c of 20 and 35 K were studied by suppressing the superconductivity with pulsed magnetic fields of 61 T. Both in-plane resistivity ρ_{ab} and out-of-plane resistivity ρ_c are found to diverge logarithmically as $T/T_c \to 0$. Logarithmic divergence is accompanied by a nearly constant anisotropy ratio, ρ_c/ρ_{ab}, suggesting an unusual three-dimensional insulator.





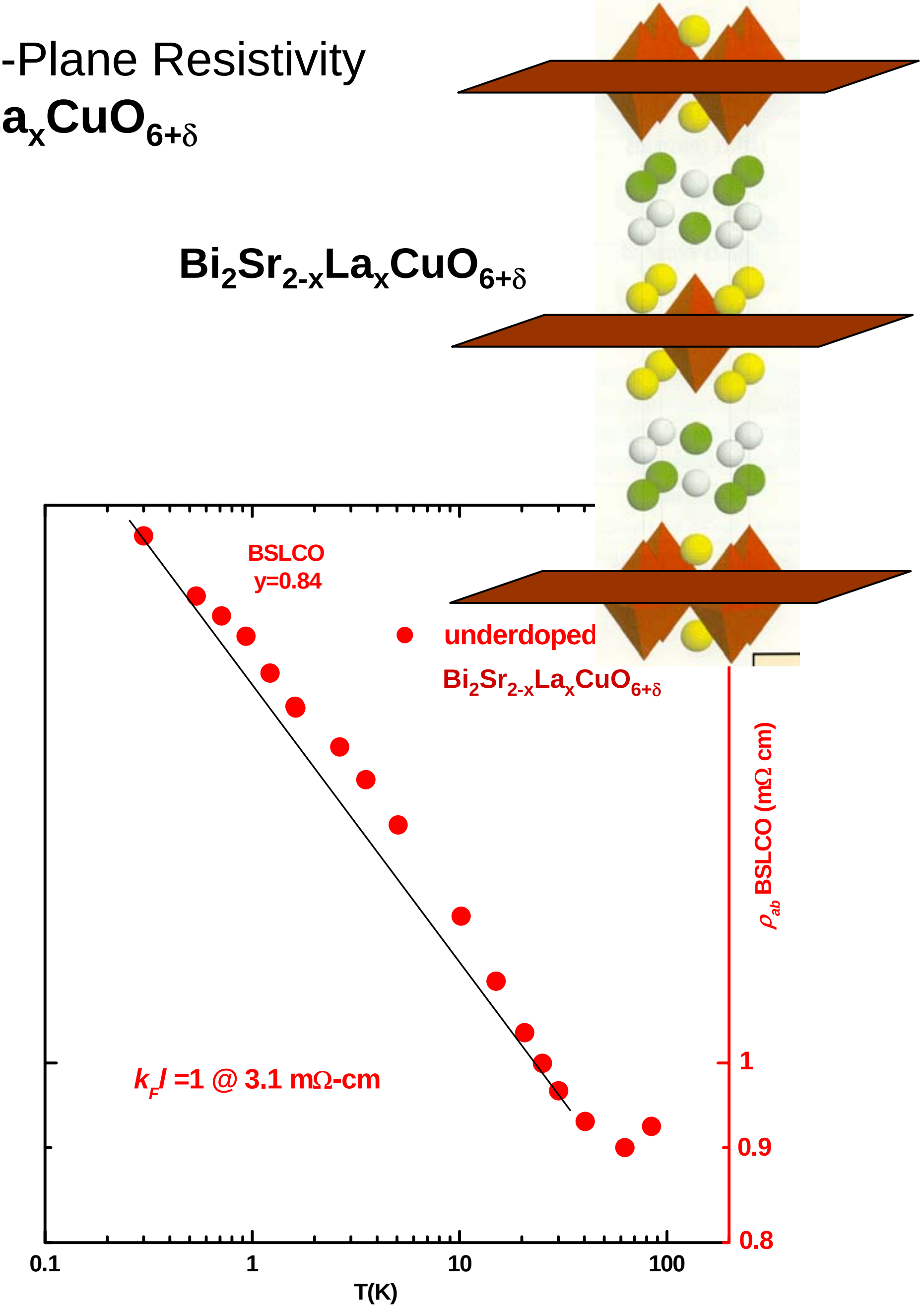
PRL **75**, 4662 (1995)

Logarithmic Divergence of the In-Plane Resistivity of Underdoped **$Bi_2Sr_{2-x}La_xCuO_{6+\delta}$**



Phys. Rev. Lett. **85**, 638 (2000)

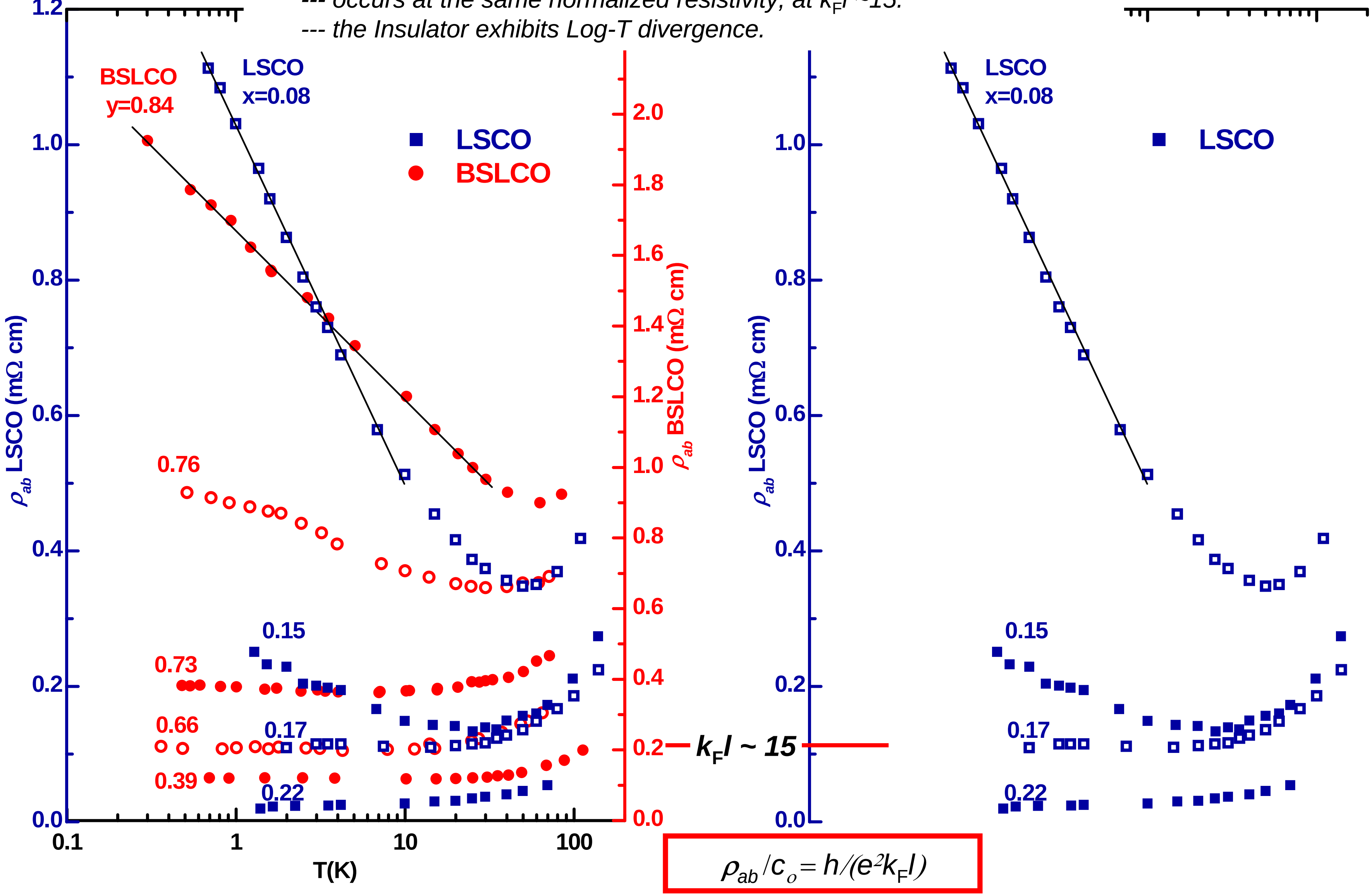
Metal-to-Insulator Crossover in the Low-Temperature Normal State of $Bi_2Sr_{2-x}La_xCuO_{6+\delta}$



Logarithmically Divergent Resistivity in Underdoped Cuprates

***Similarities** between the Insulator-to-Metal crossover in BSLCO and LSCO:*

- *--- occurs under the superconducting ‘dome’*
- *--- occurs at the same normalized resistivity, at $k_F l$ ~15.*
- *--- the Insulator exhibits Log-T divergence.*



$$\boxed{\rho_{ab}/c_o = h/(e^2 k_F l)}$$

LSCO $k_F l$ =1 @ 1.6 mΩ

Bi-2201 $k_F l$ =1 @ 3.1 mΩ

DocumentsData

LSCO $k_F l$ =1 @ 1.6 mΩ

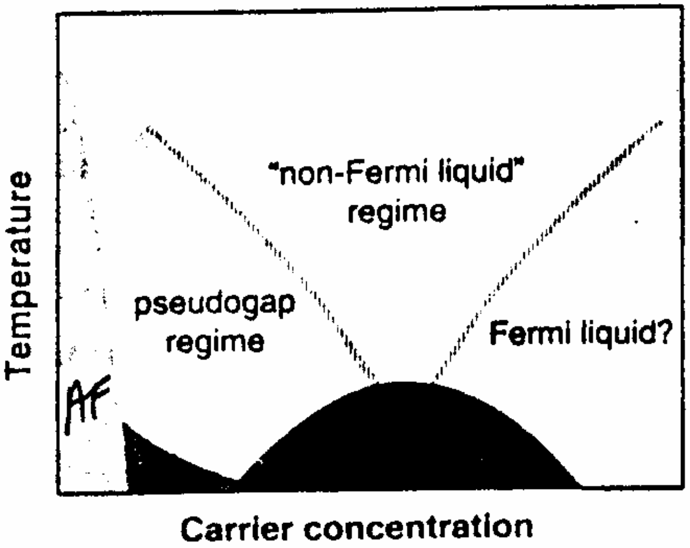
QUANTUM CRITICAL POINT
in the HIGH-Tc CUPRATES ?

--- In the quantum critical region, temperature is the only energy scale controlling the physics.

--- Strong critical fluctuations can mediate singular interactions between quasiparticles.

--- These singular interactions can provide both a strong pairing mechanism and a source of non-Fermi liquid behavior.

--- The observed linear-T resistivity is attributed to Quantum Critical Behavior



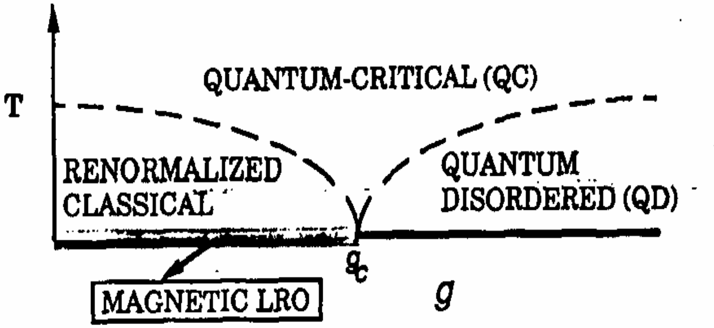


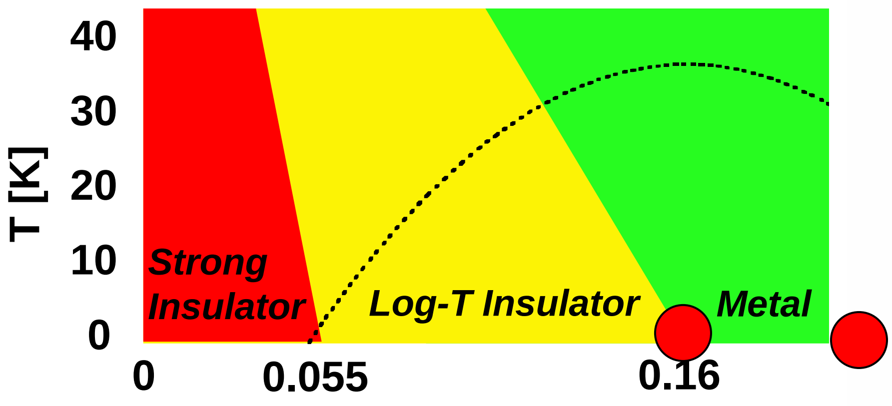
FIG. 1. Phase diagram of $\mathcal{H}$ (after Ref. [4]). The magnetic LRO can be either spin-glass or Néel type, and is present only at $T=0$. The boundaries of the QC region are $T \sim |g - g_c|^{z\nu}$.

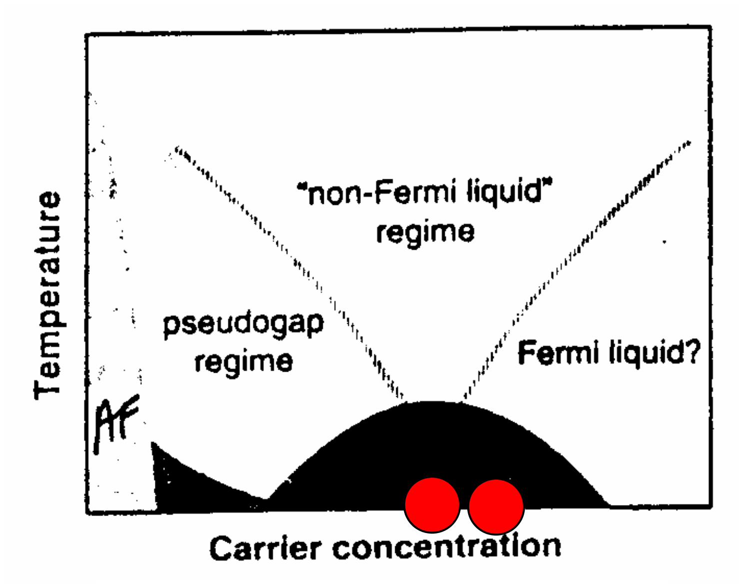
from "Universal Quantum-Critical Dynamics of Two-Dimensional Antiferromagnets"
Subir Sachdev and Jinwu Ye, PRL **69** (1992) 2411

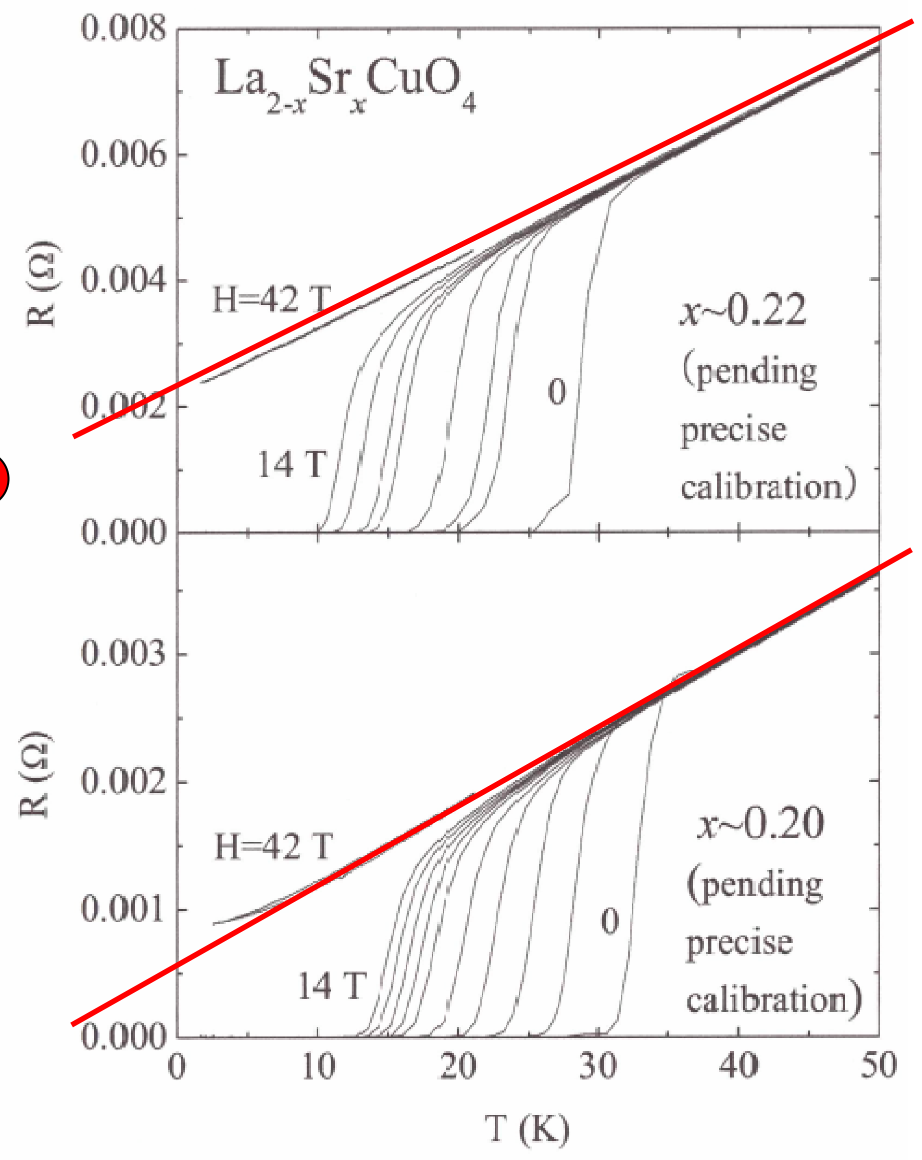
Ref [4] is Chakravarty, Halperin and Nelson, PRL **60** (1988) 1057; PR **B39** (1989) 2344

Searching for evidence of a quantum critical point in the resistivity

$La_{2-x}Sr_xCuO_4$







week ending
7 MAY 2004

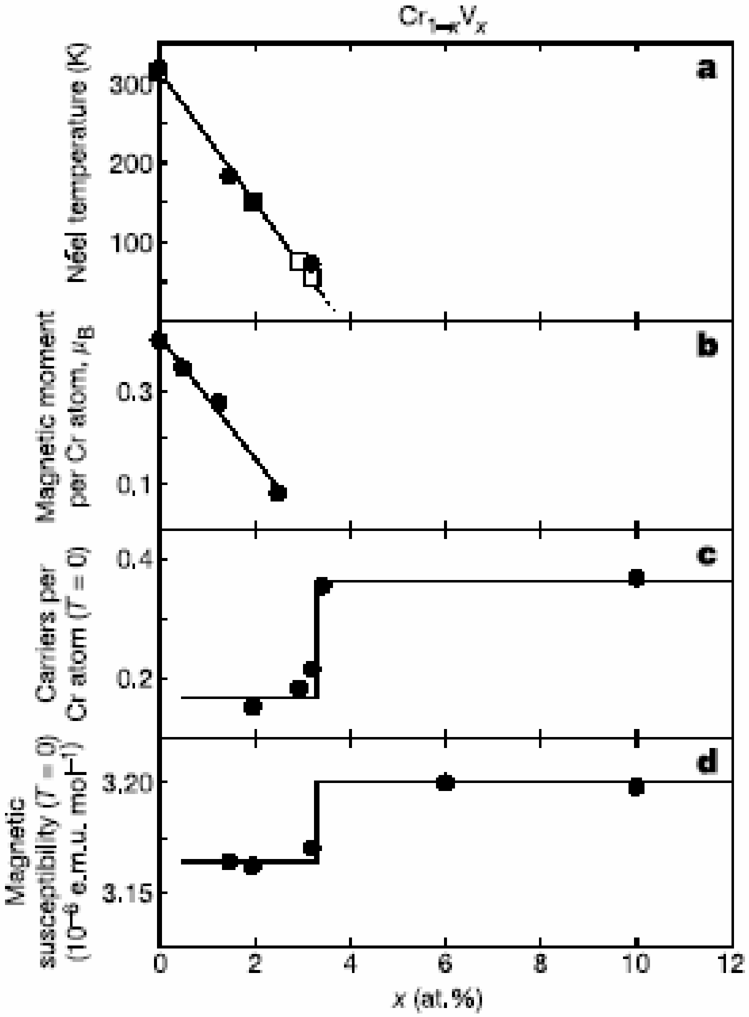
PHYSICAL REVIEW LETTERS

VOLUME 92, NUMBER 18

NATURE | VOL 419 | 3 OCTOBER 2002 |

Quantum phase transition in a common metal

A. Yeh*†, Yeong-Ah Soh*, J. Brooke*†, G. Aeppli*, T. F. Rosenbaum†
& S. M. Hayden‡



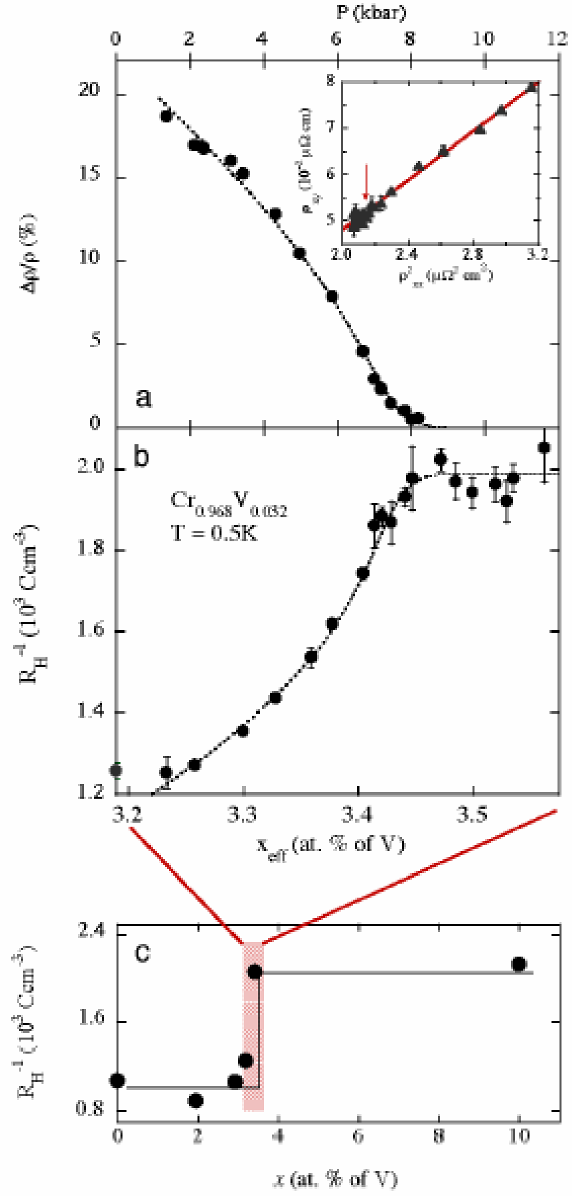
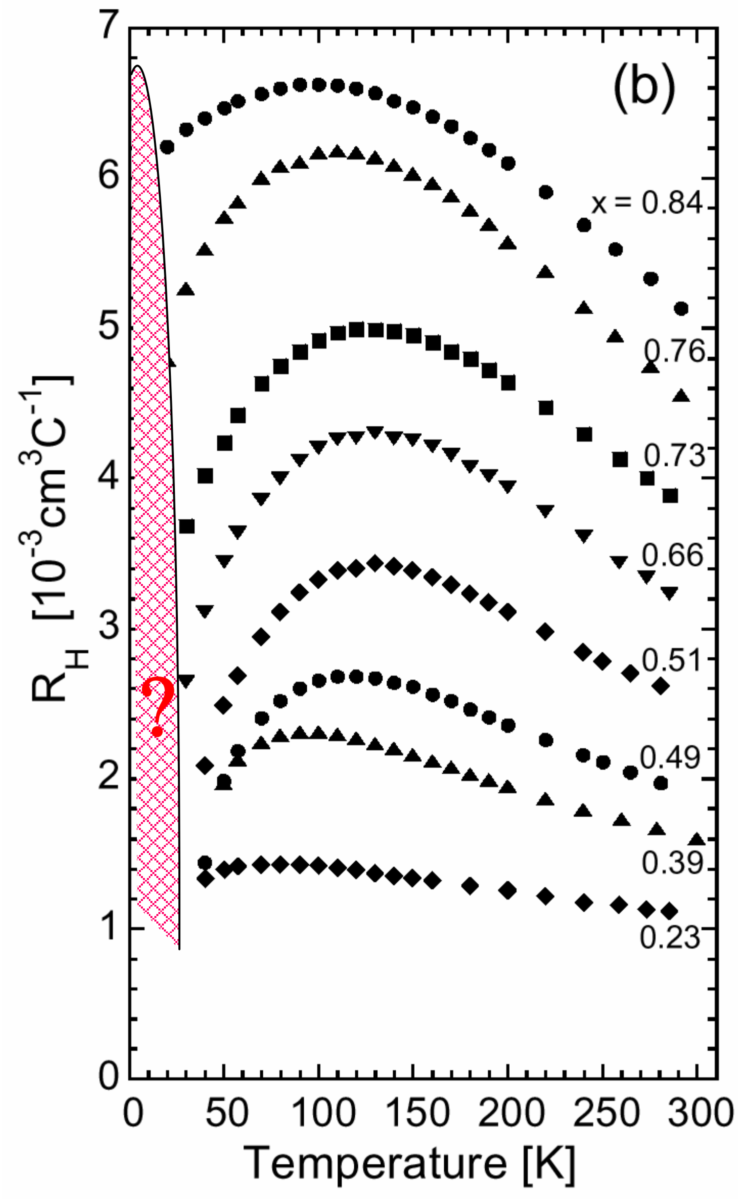
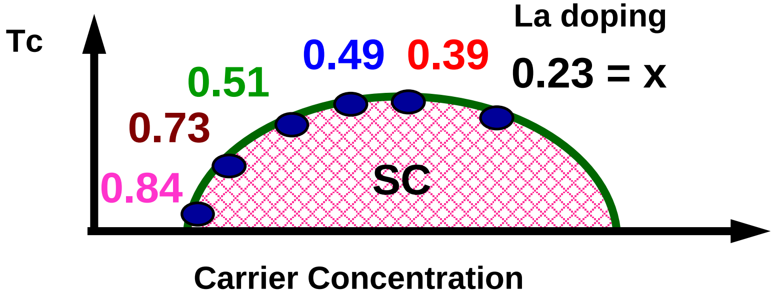


FIG. 2 (color). Critical behavior of the (a) normalized resistivity and (b) the inverse Hall coefficient in the $T \rightarrow 0$ limit as a function of pressure P. The resistivity and the inverse Hall

Y. Ando et al., Physica ***C341****, 1913(2000)*



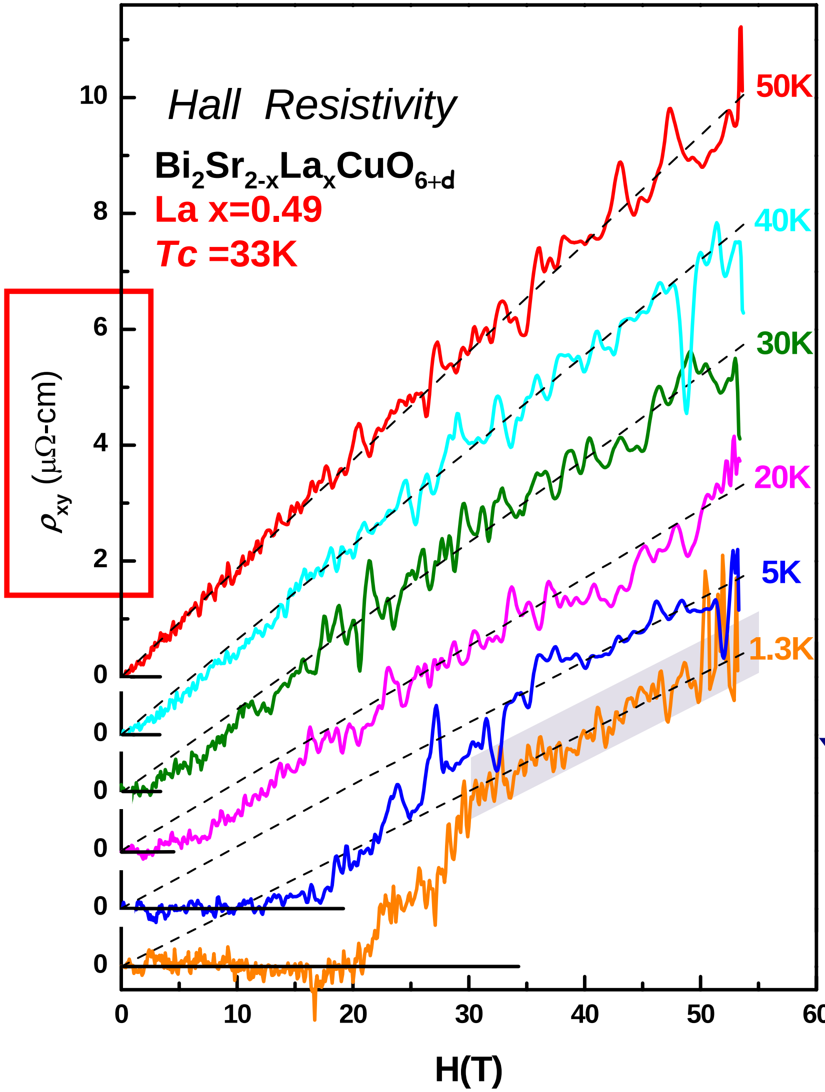
Hall Effect in $Bi_2Sr_{2-x}La_xCuO_{6+d}$

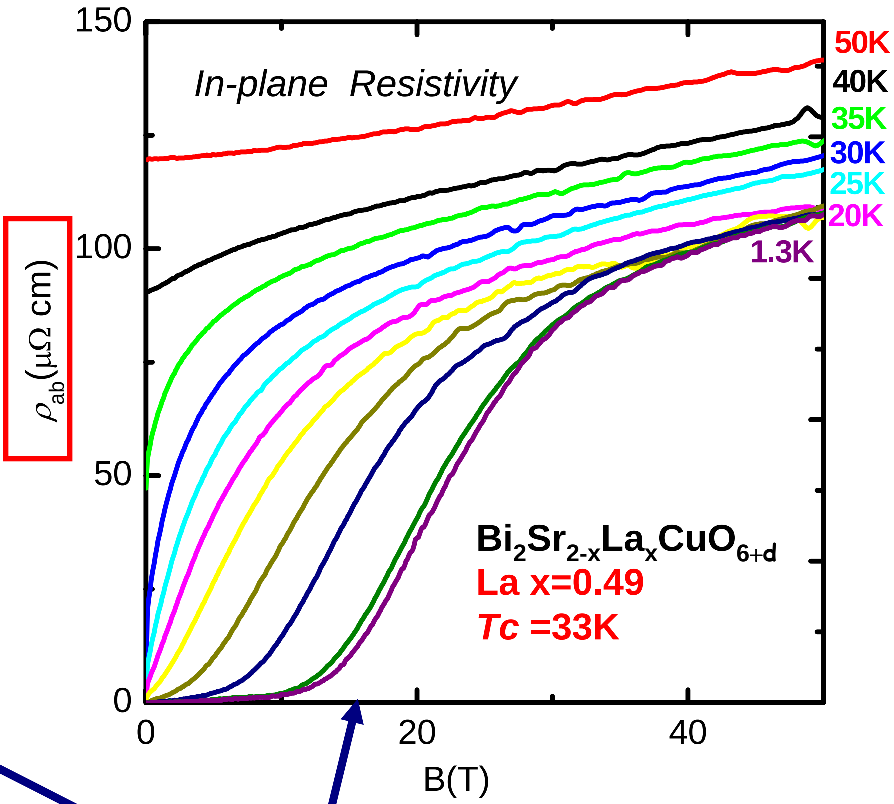


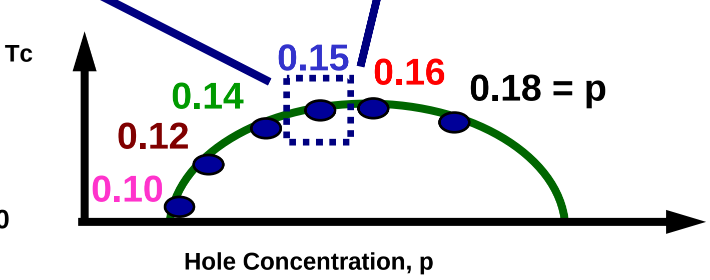
- Unusual Temperature-dependence of Hall coefficient not understood

- What happens below *T_c* ?

Low Temperature Normal State Hall Effect



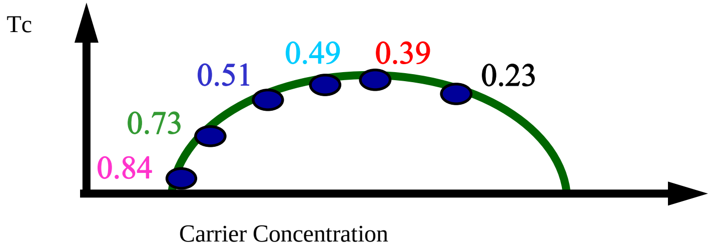


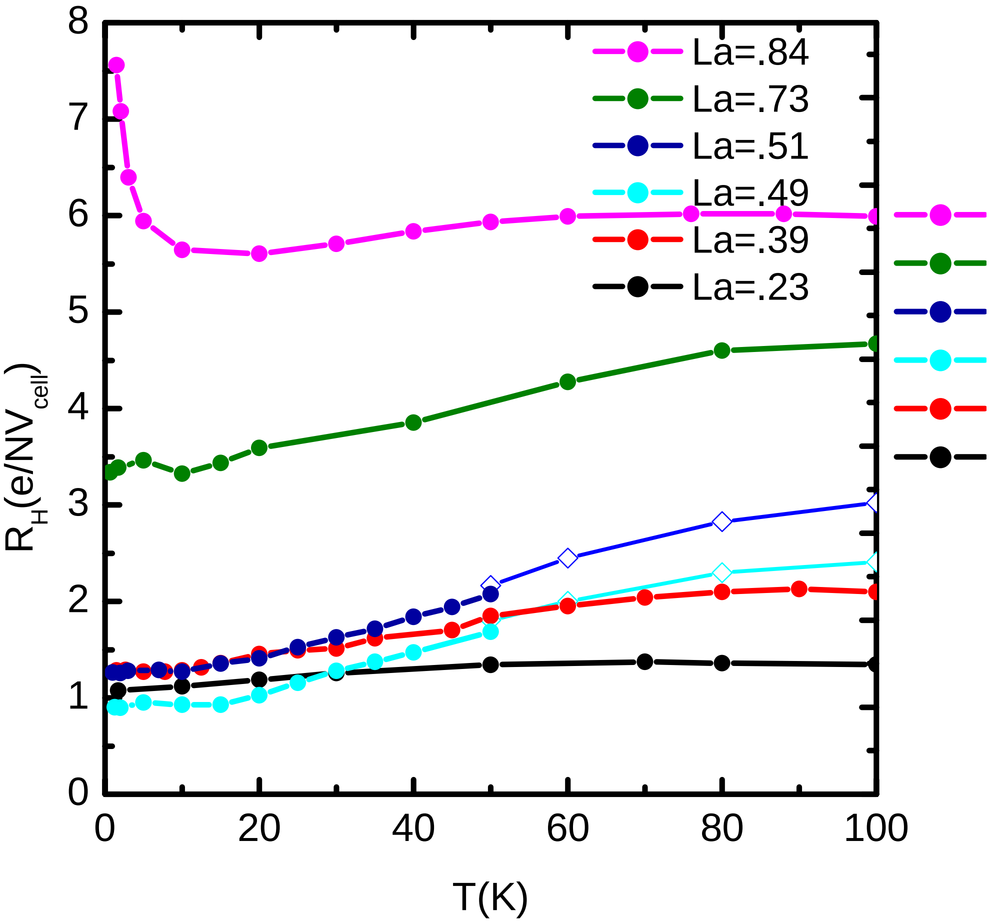


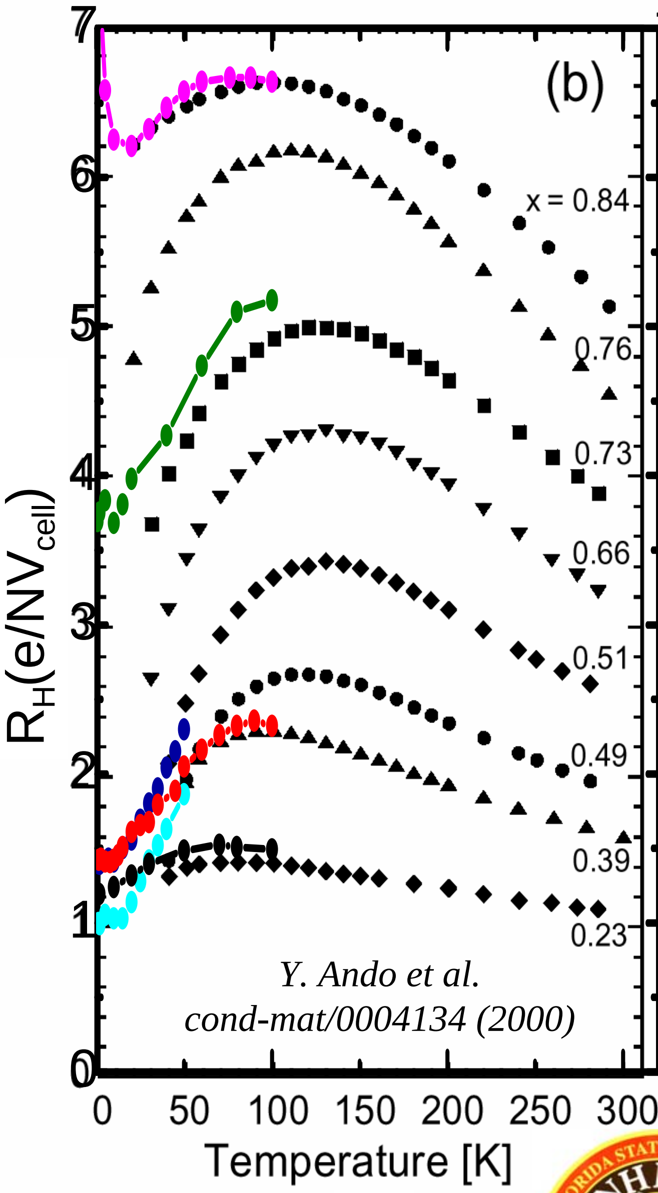
High-field Hall voltage is linear in field

Low-T Hall Effect in BSLCO

(two years to develop technique)



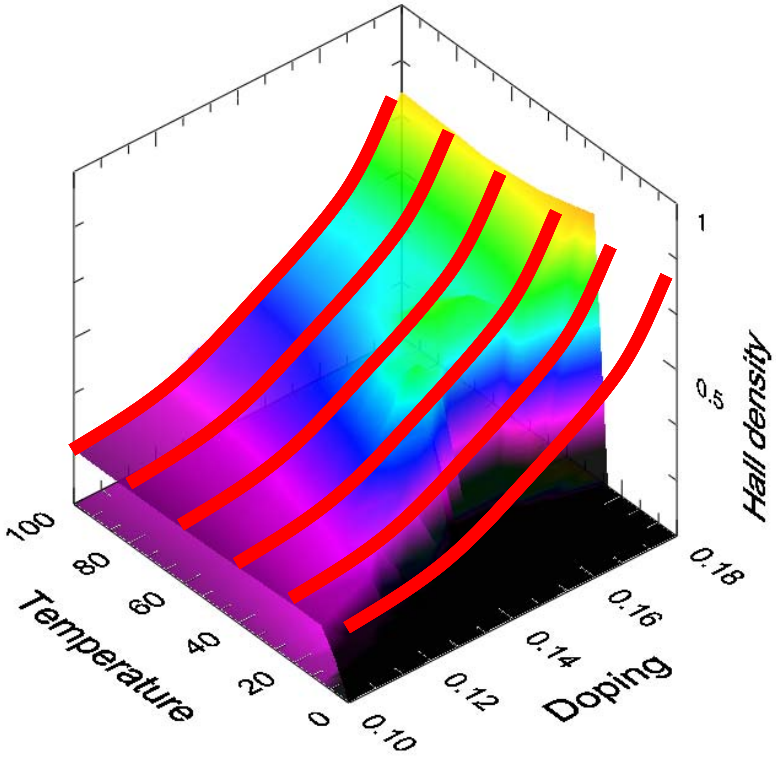




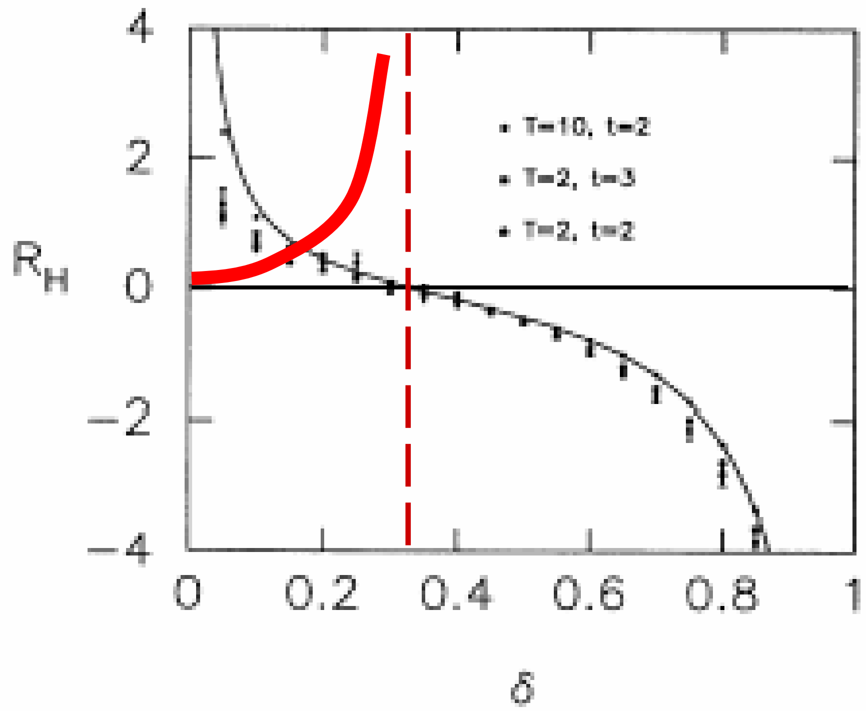
Y. Ando et al.
cond-mat/0004134 (2000)

BSLCO Hall Effect
in DC Magnet

Measured Evolution of Hall Density upon Doping

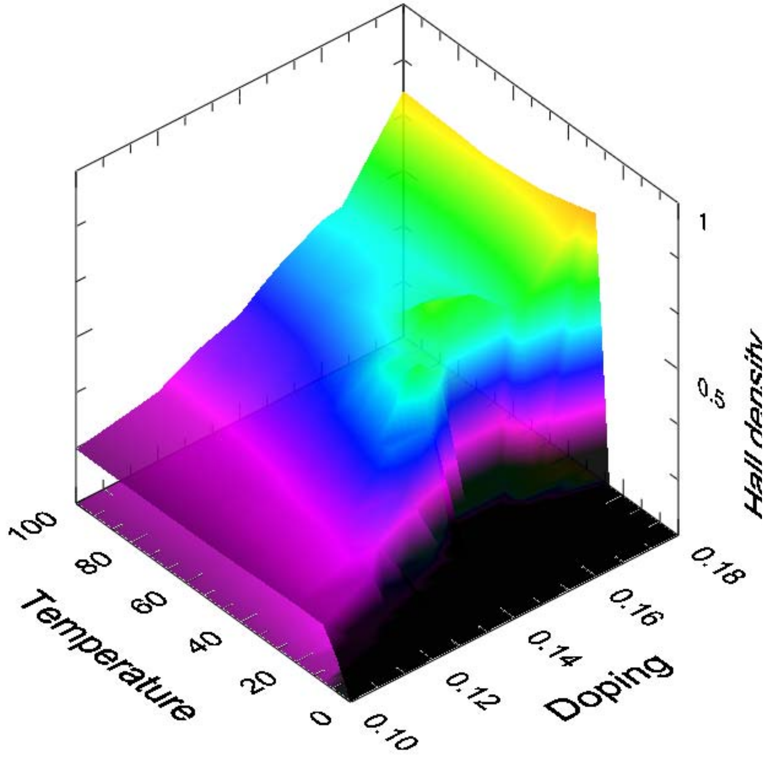


Calculated Evolution of Hall Coefficient (= 1/Hall density) upon Doping



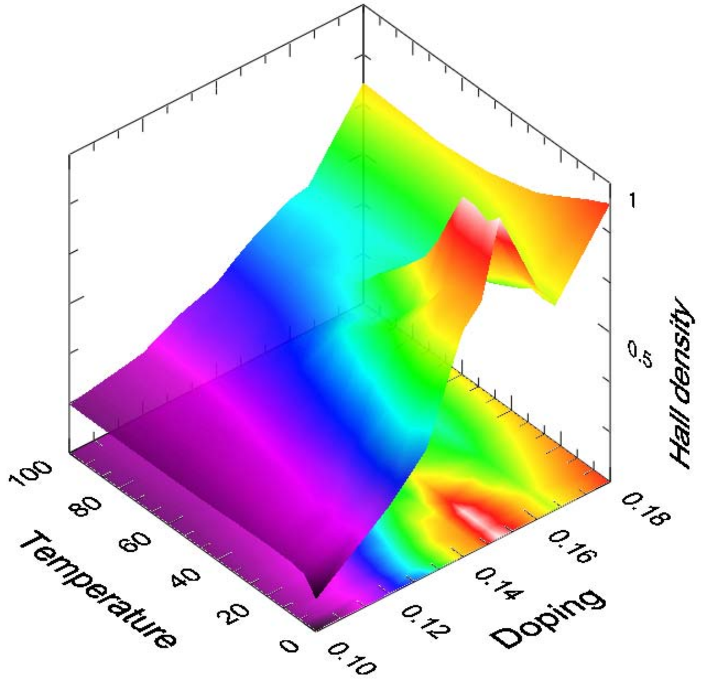
Shastry, Shraiman, Singh
PRL **70**, 2004 (1993)

We may understand the high-temperature behavior of the Hall number from the t-J model…



…but not the peak that develops…

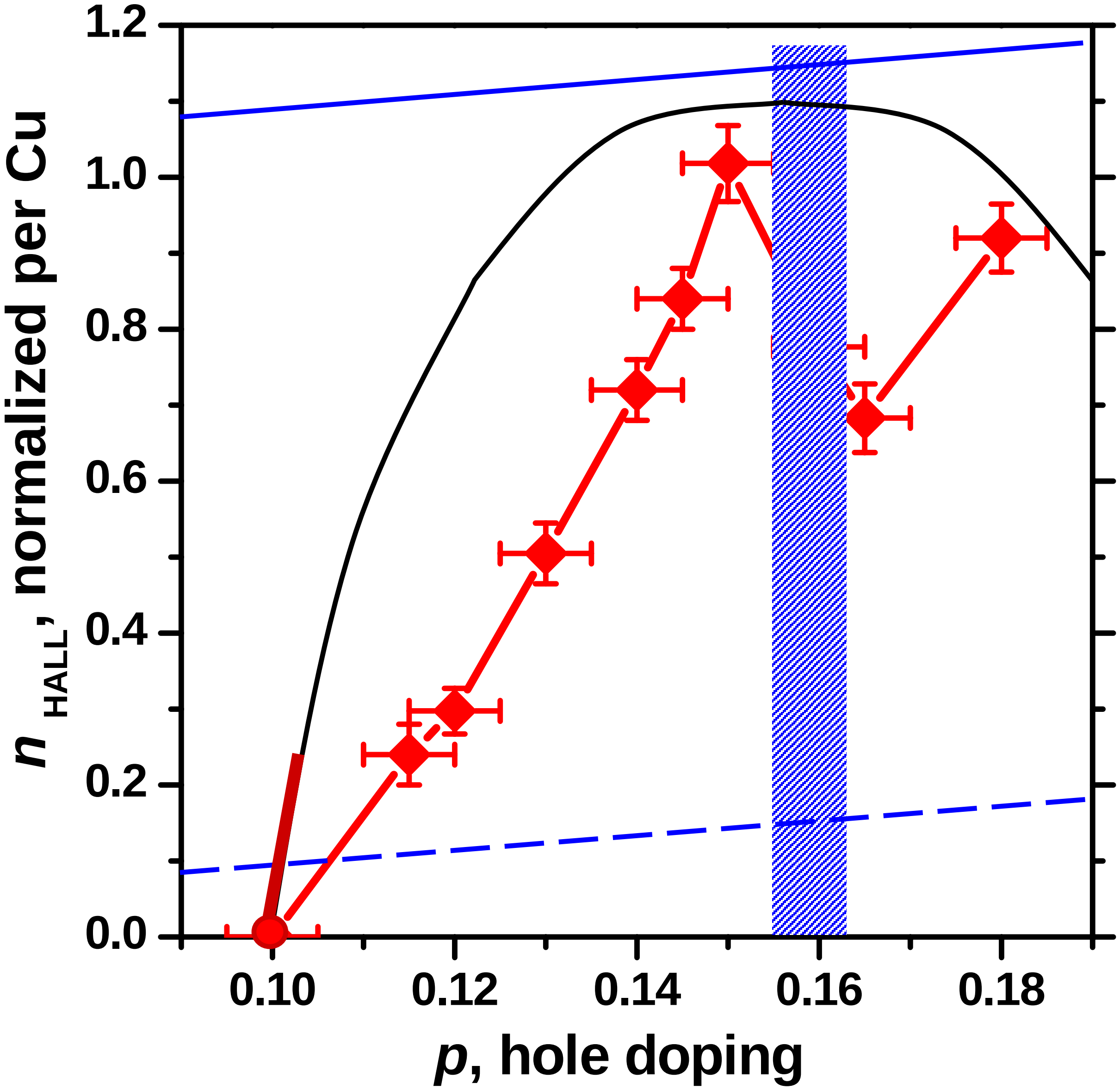
…at temperatures below Tc
…and centered on optimum doping



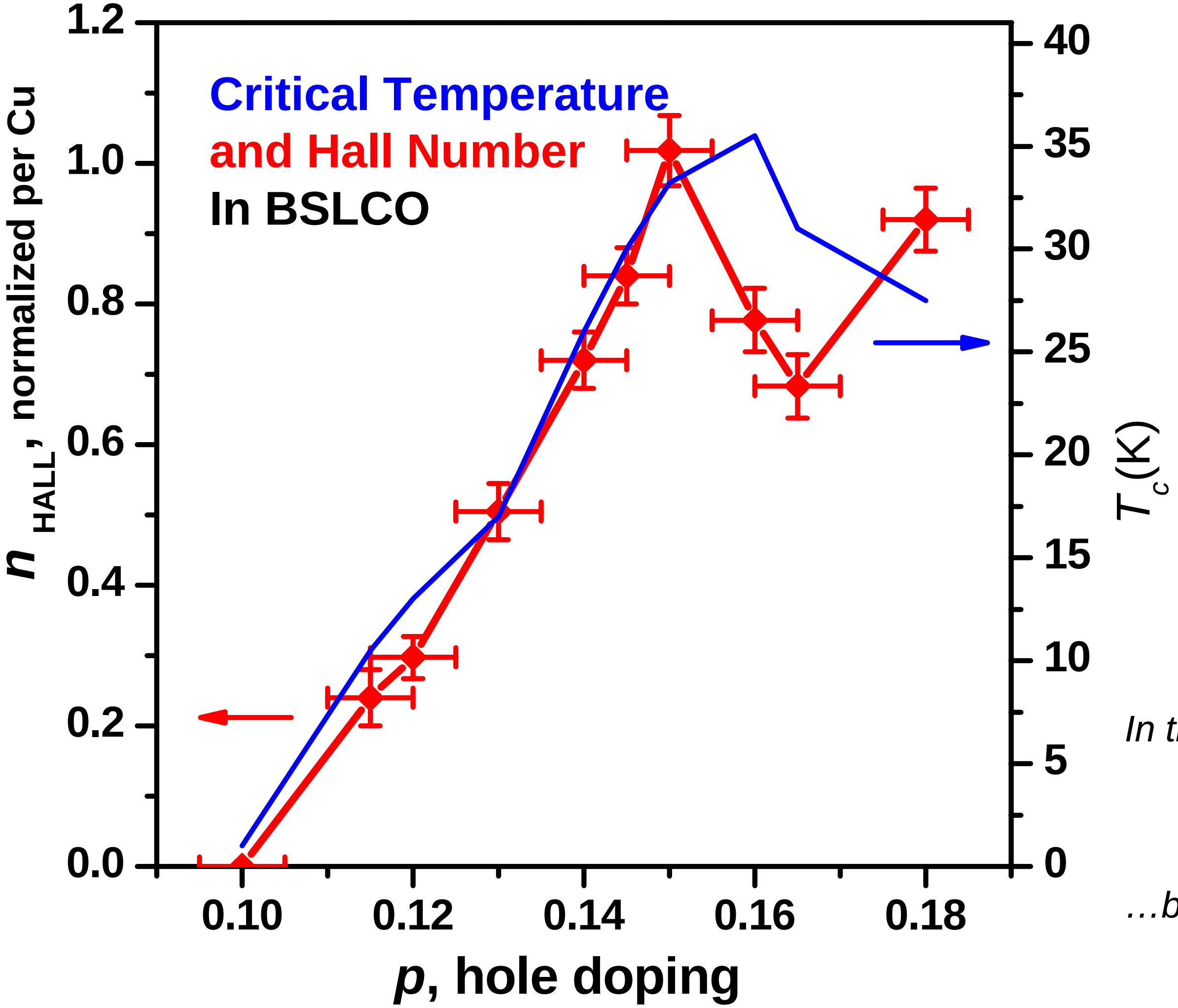
Low-Temperature Hall Number in $Bi_2Sr_{2-x}La_xCuO_{6+d}$

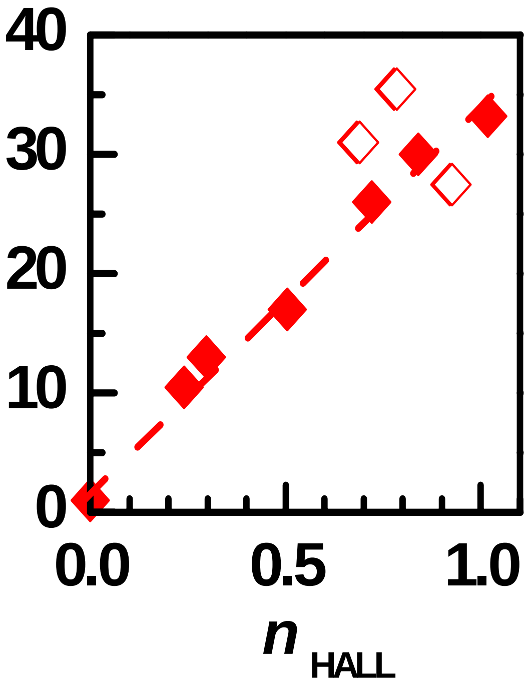
Onset of carriers yields onset of superconducting phase

Peak or Jump near Optimal Doping



Hall Number is correlated with T_c



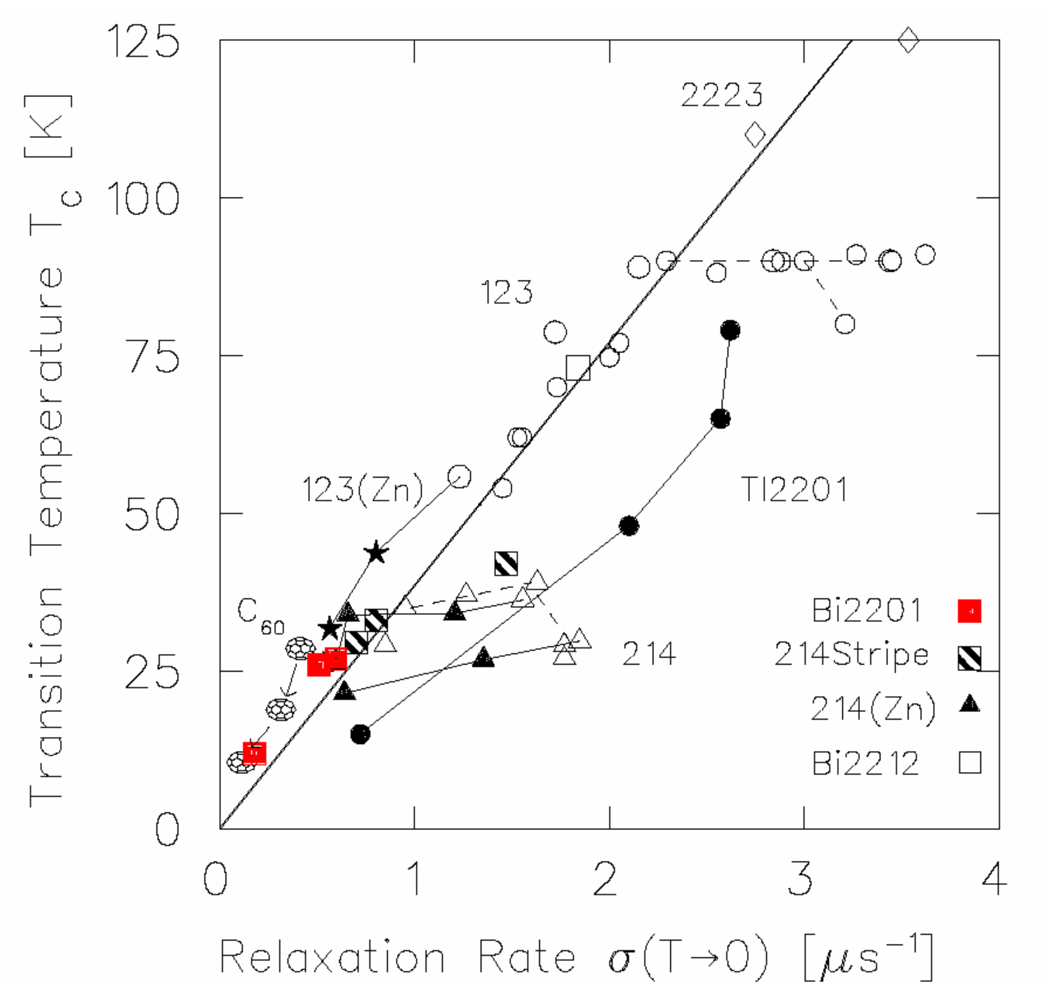


In the underdoped regime…

n_{Hall} shows remarkably linear correlation with T_c

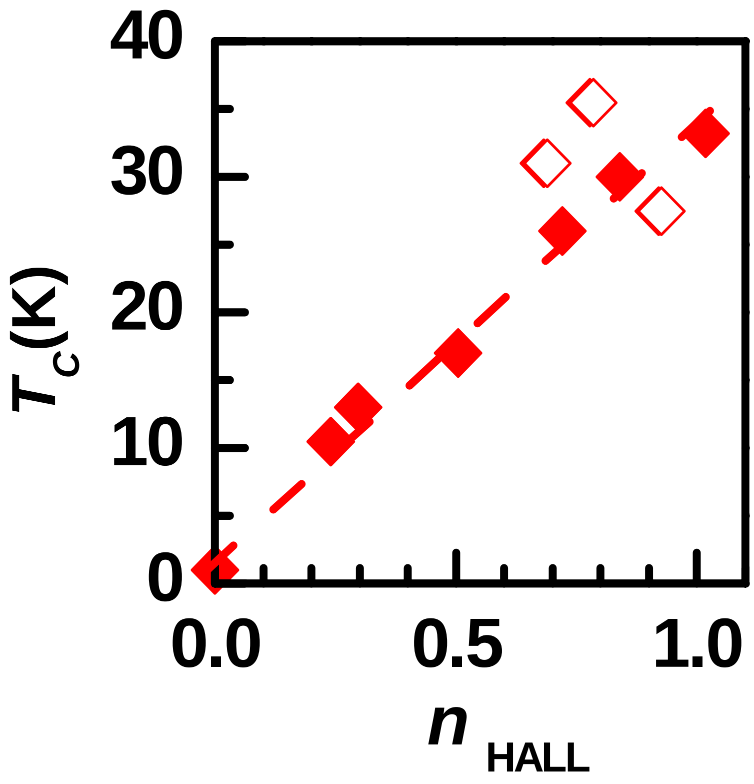
…but not in the overdoped regime…

Evidence that the superconducting transition is governed by phase stiffness (superfluid density) in the underdoped regime

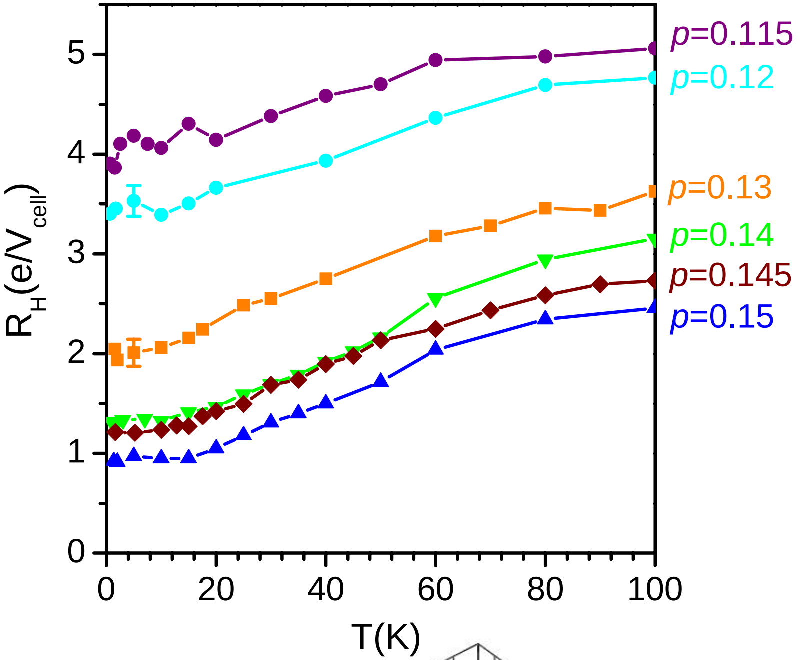


*Y. J. Uemura et al., PRL **62**, 2317(1989)*

…and so is the Hall number…

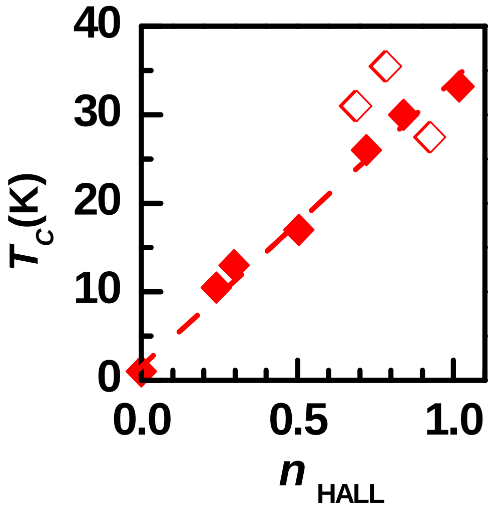


Superfluid density in the superconducting state corresponds to the Hall density throughout the underdoped regime



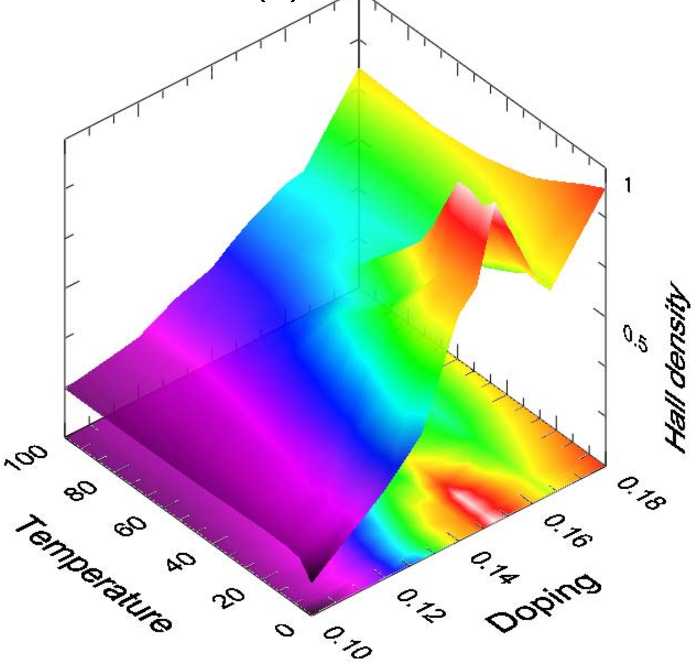
Hall coefficient becomes T-independent at low-T near optimum doping in BSLCO

---suggesting a measurement of the Hall number.



Linear relation between Tc
and the low-T Hall number

---suggests phase stiffness
governs superconducting transition
in the underdoped regime



Sharp anomaly in doping dependence
of the Hall number at optimum doping

---suggesting change in the Fermi Surface

…suggests a Quantum Critical Point governs High-Tc Superconductivity

To submit a proposal for magnet time, www.magnet.fsu.edu

ENΔ OΦ TAΛK