# National High Magnetic Field Laboratory

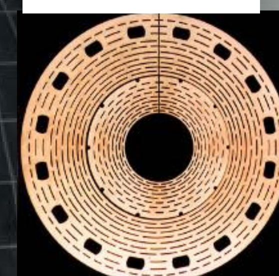
1.4 GW Generator

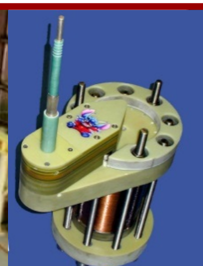
Florida State University

Los Alamos National Laboratory

University of Florida

45T Hybrid DC Magnet

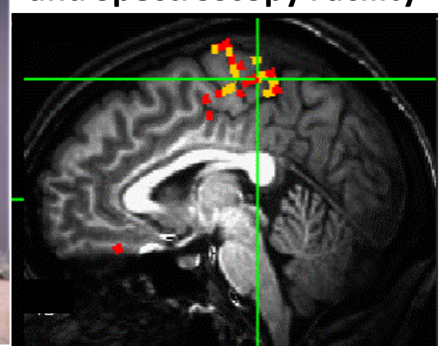


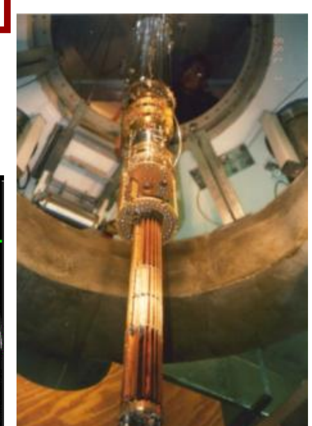


101T Pulse Magnet
10mm bore

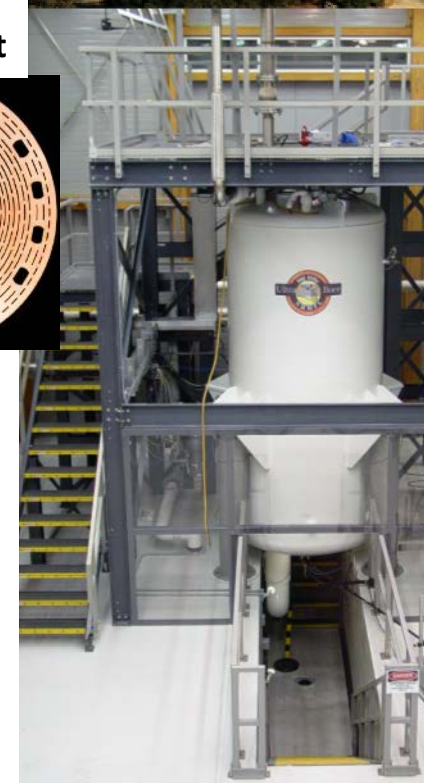
11.4T MRI Magnet
400mm warm bore

Advanced Magnetic Resonance Imaging and Spectroscopy Facility



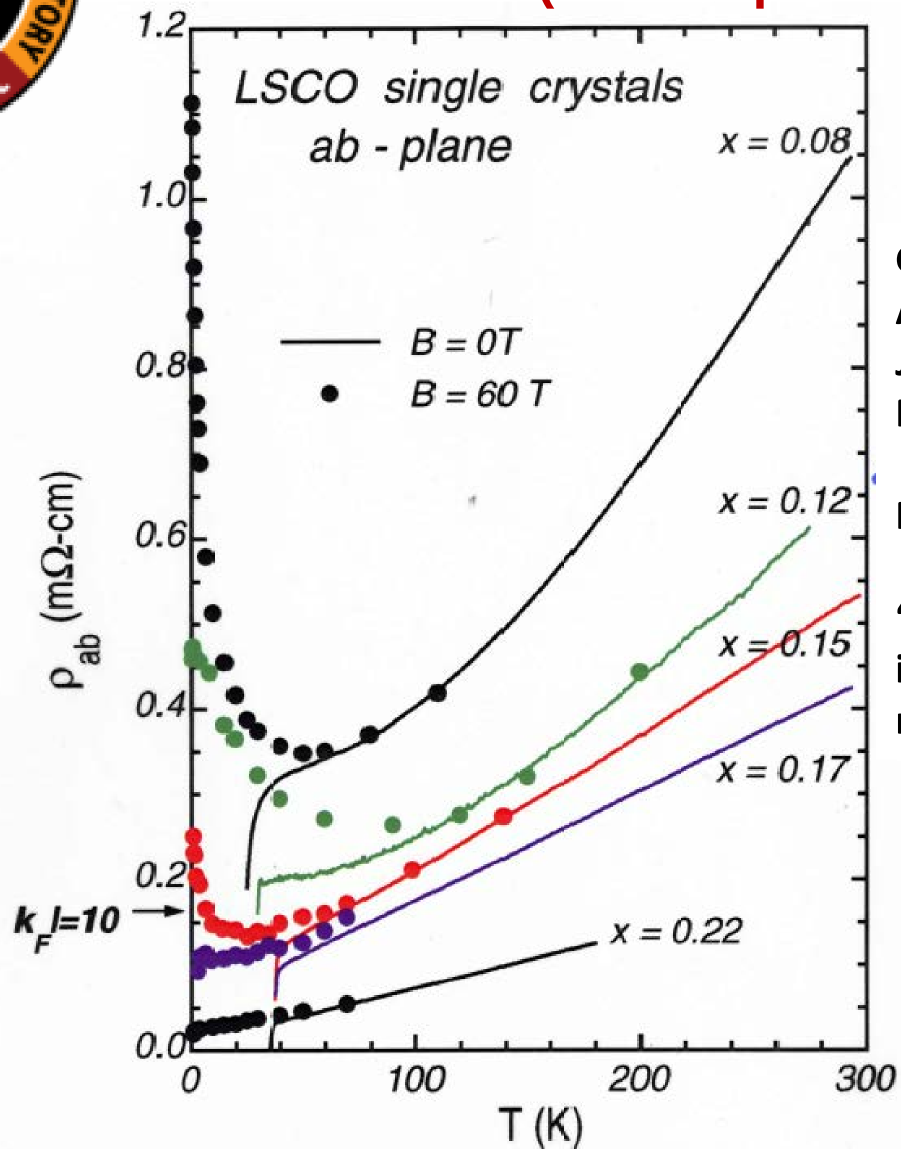


High B/T Facility
17T, 6weeks at 1mK



900MHz, 105mm bore
21T NMR/MRI Magnet

# Evidence for a Phase Transition Near Optimum Doping in the Cuprates (1995 to present)




G.S. Boebinger, Yoichi Ando, A. Passner, T. Kimura, M. Okuya, J. Shimoyama, K. Kishio, K. Tamasaku, N. Ichikawa, and S. Uchida,

Phys. Rev. Lett. 77, 5417 (1996)

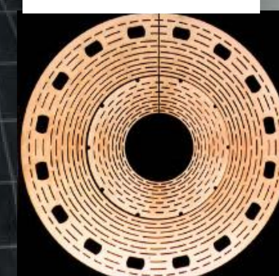
"Insulator-to-metal crossover in the normal state of $La_{2-x}Sr_xCuO_4$ near optimum doping."

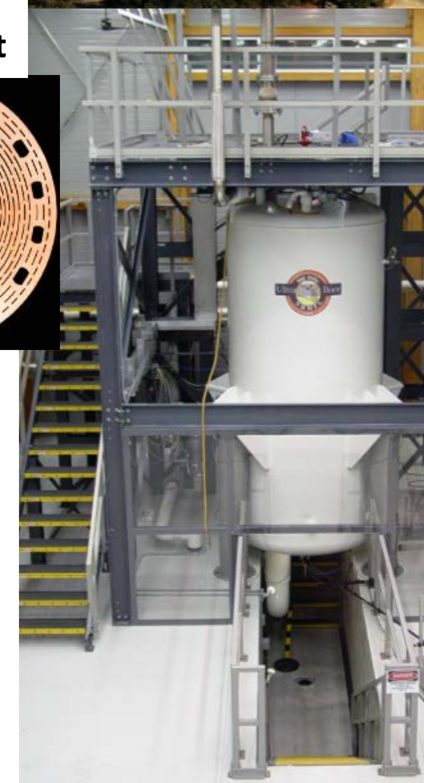
# Overview of the MagLab User Program

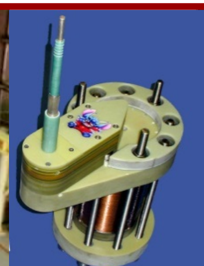
# National High Magnetic Field Laboratory

1.4 GW Generator


45T Hybrid
DC Magnet







101T Pulse Magnet
10mm bore

11.4T MRI Magnet
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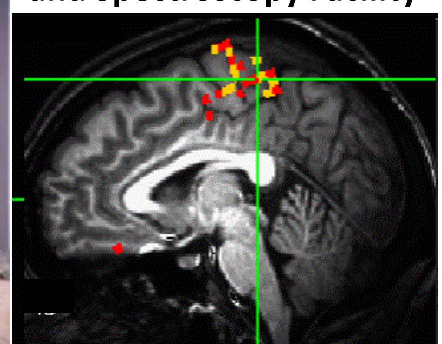
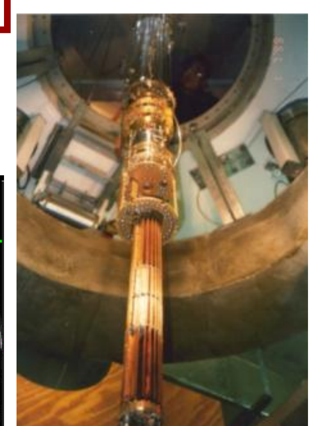
Advanced Magnetic
Resonance Imaging
and Spectroscopy Facility

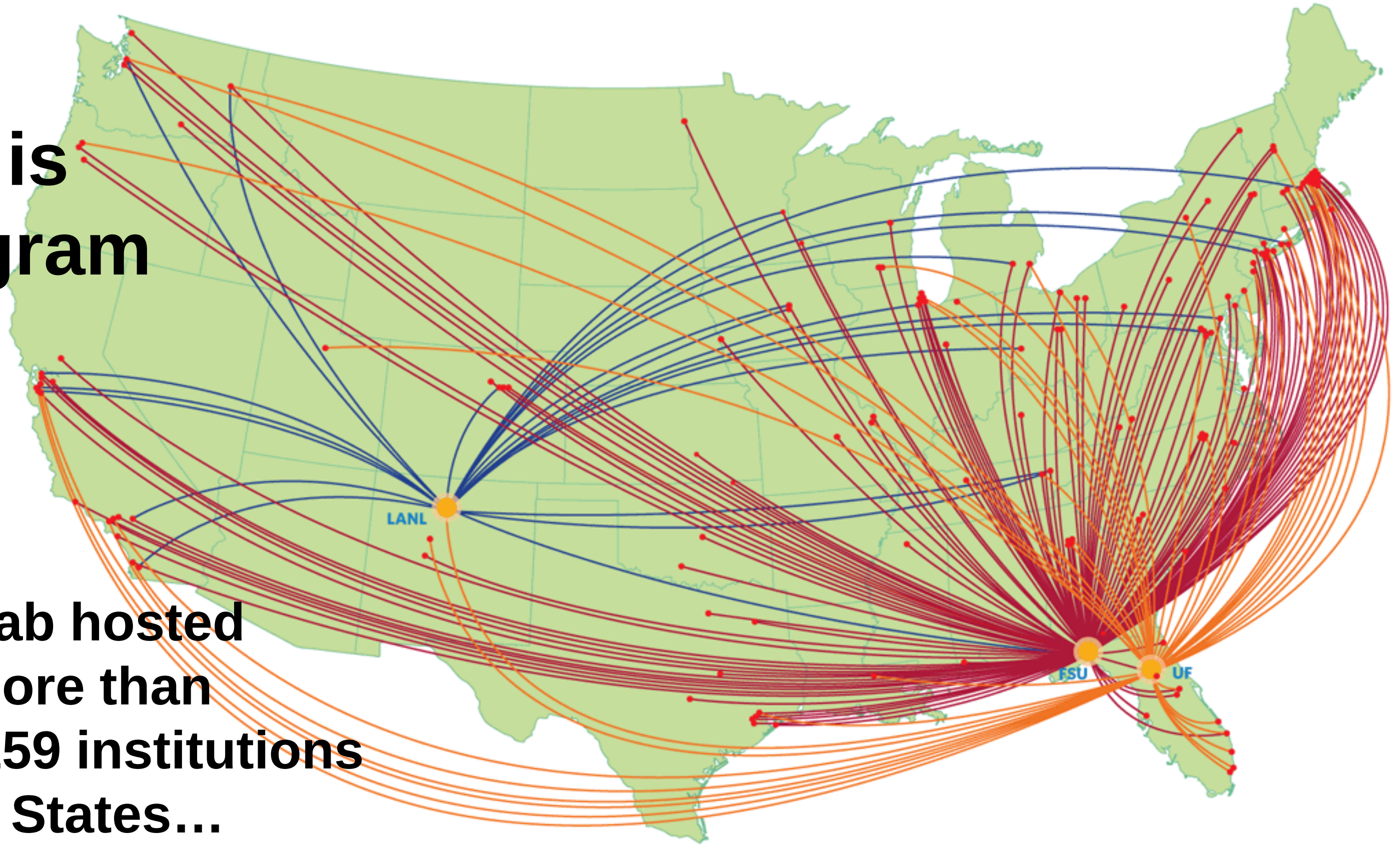




High B/T Facility
17T, 6weeks at 1mK

900MHz, 105mm bore
21T NMR/MRI Magnet

# The MagLab is its User Program

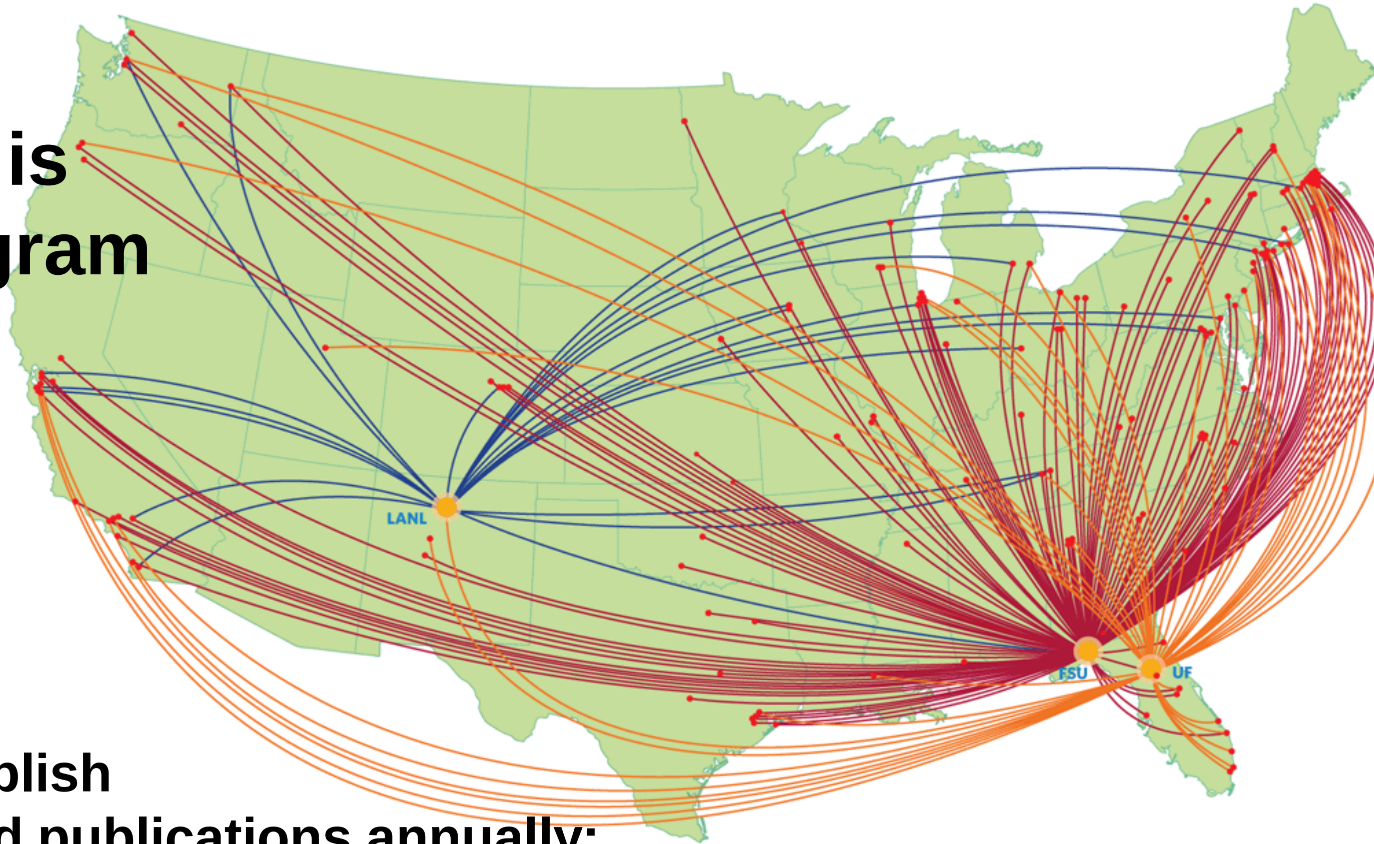



**In 2012, the MagLab hosted experiments by more than 1350 users from 159 institutions across the United States…**

**…and a total of 277 institutions throughout the world.**

NATIONAL HIGH MAGNETIC FIELD LABORATORY
FSU • UF • LANL

# The MagLab is its User Program




**MagLab users publish about 440 refereed publications annually:**

**<u>2009-2013 Publications</u>**

| | |
|---|---|
| **2200** | **Total Publications** |
| ***28*** | ***PNAS*** |
| ***63*** | ***Nature Journals*** |
| ***147*** | ***Physical Review Letters*** |
| ***318*** | ***Physical Review B*** |
| ***47*** | ***PRB (Rapid Comm)*** |
| ***59*** | ***JACS*** |

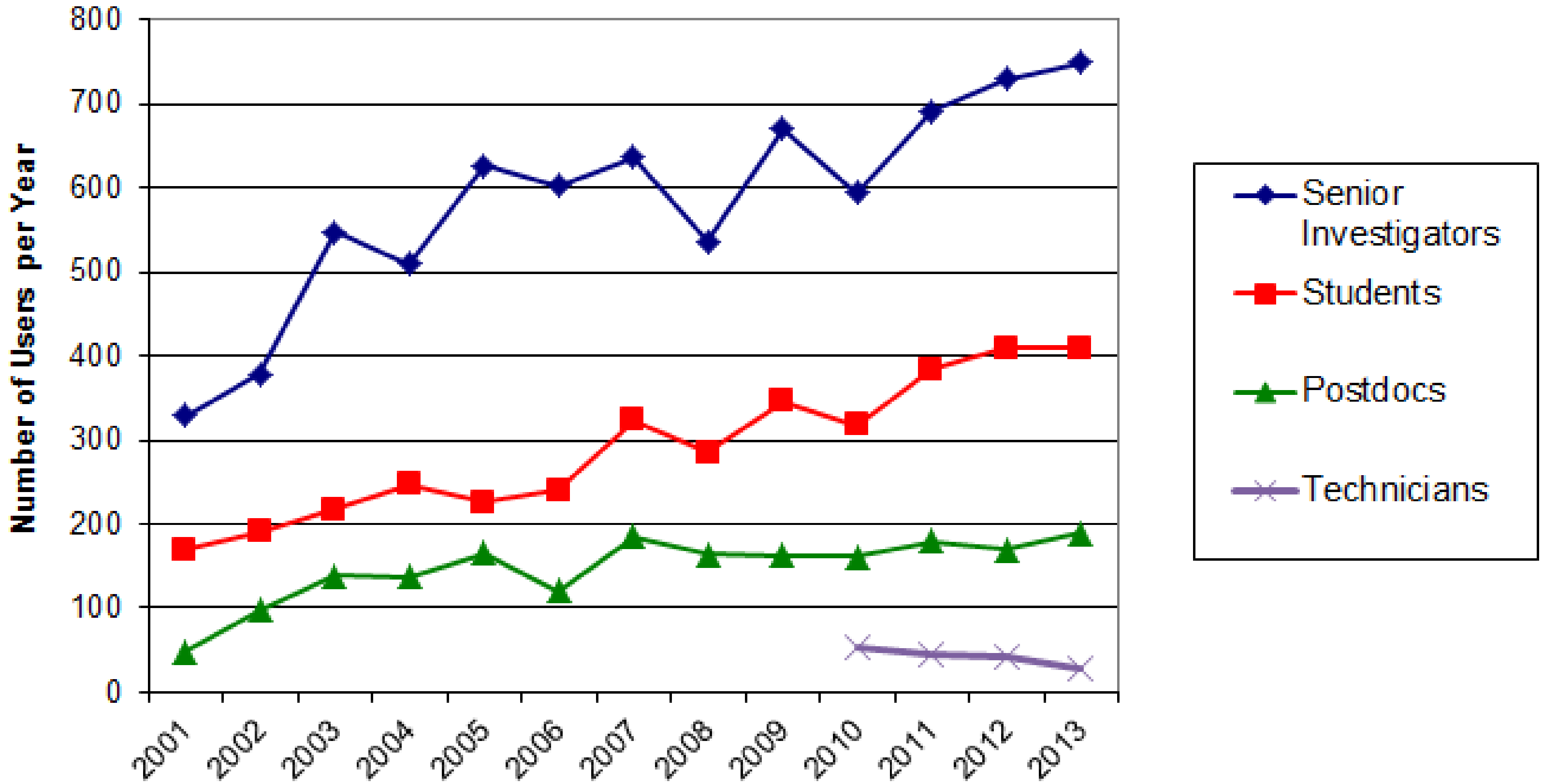
NATIONAL HIGH MAGNETIC FIELD LABORATORY FSU • UF • LANL

FLORIDA STATE UNIVERSITY 1851

Los Alamos NATIONAL LABORATORY

UF UNIVERSITY of FLORIDA

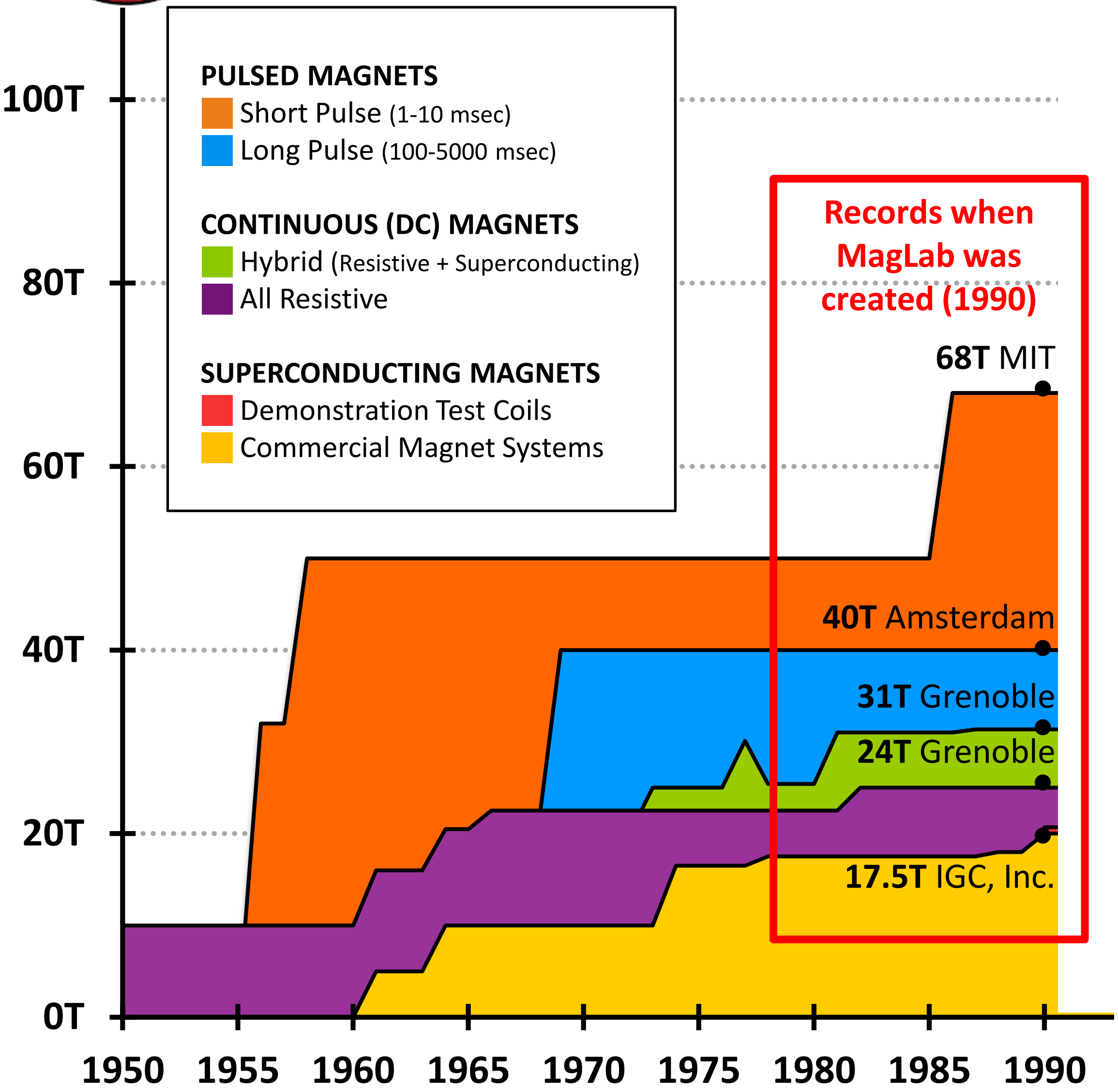
**Magnet Lab User Profile**
**2001-2013**
as of 2/3/2014



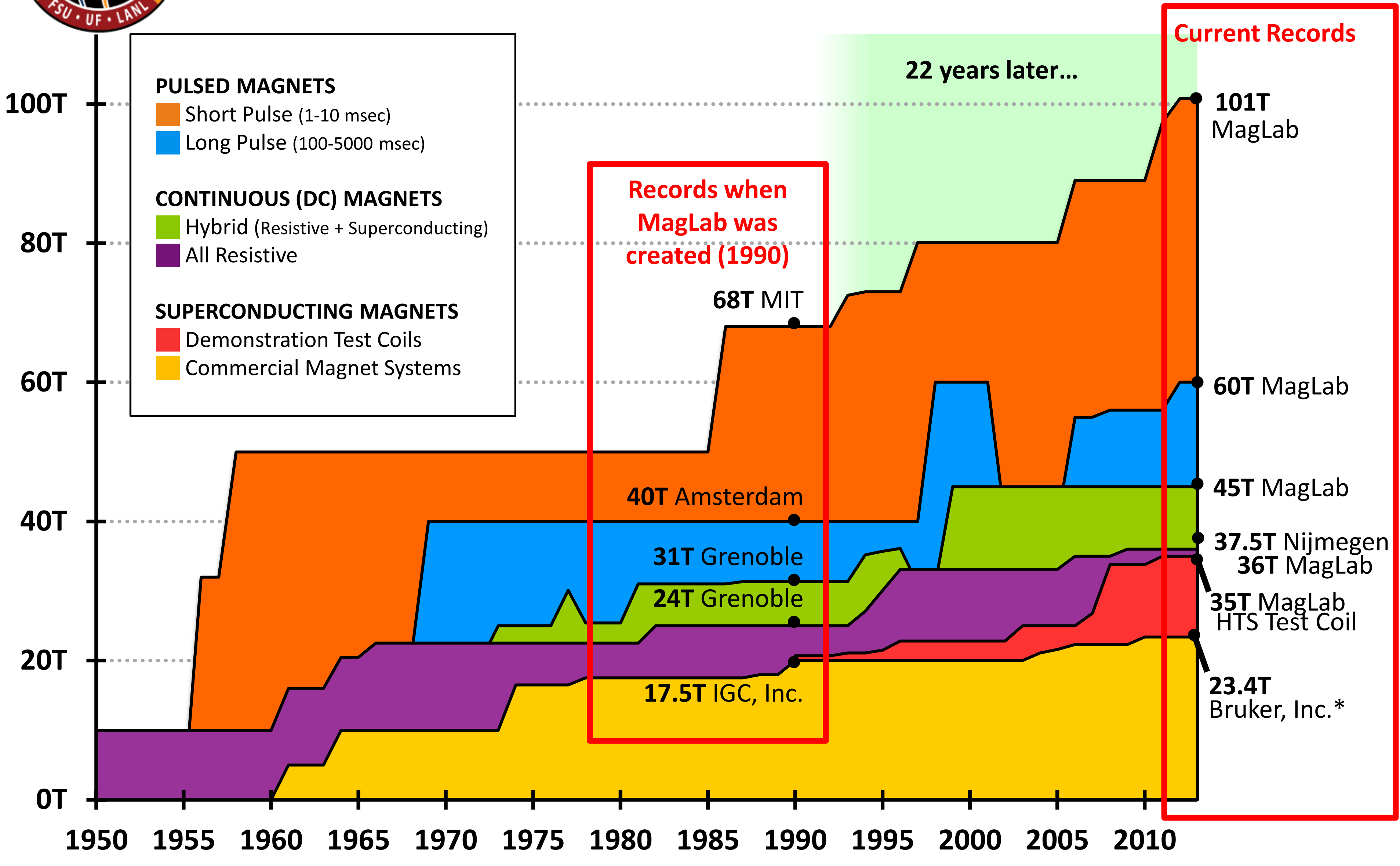

**Hosting ~ 1350 Users annually: 55% senior investigators, 15% postdocs, 30% students**

**Hosting ~ 425 Principal Investigators annually,** <u>**approximately 20% are new every year**</u>

# MagLab Technology  Leads the World



# MagLab Technology  Leads the World




***MagLab Website:***
**magnet.fsu.edu**

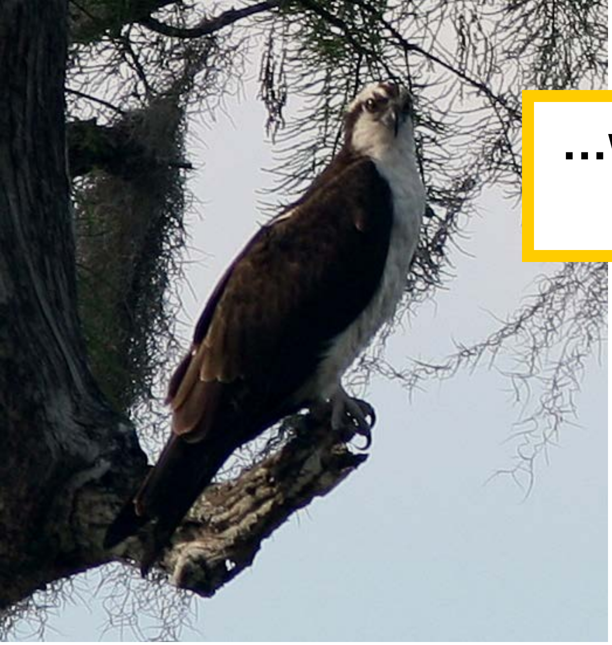
**Click on "Search Pubs" for all refereed publications from the user program**

**Click on "Publications & Reports" for :**

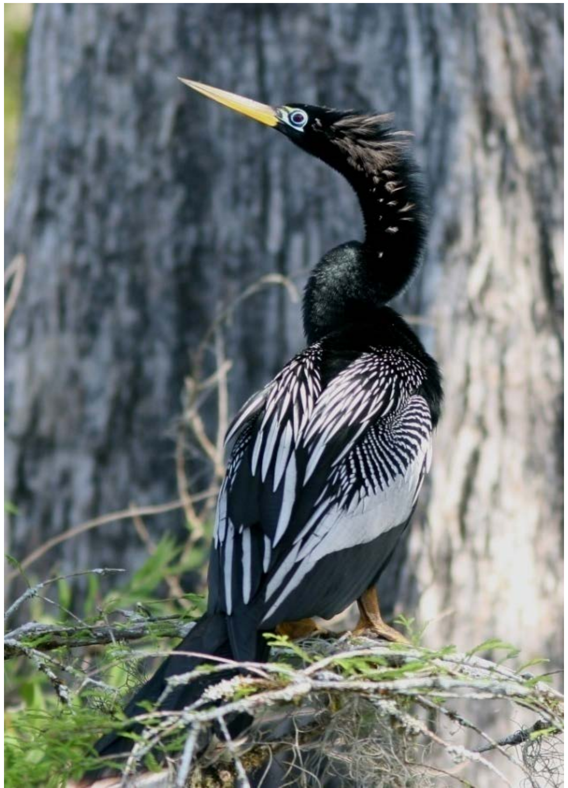
***MagLab Reports*, our scientific outreach magazine**

**and *Flux*, our outreach magazine for the general public**

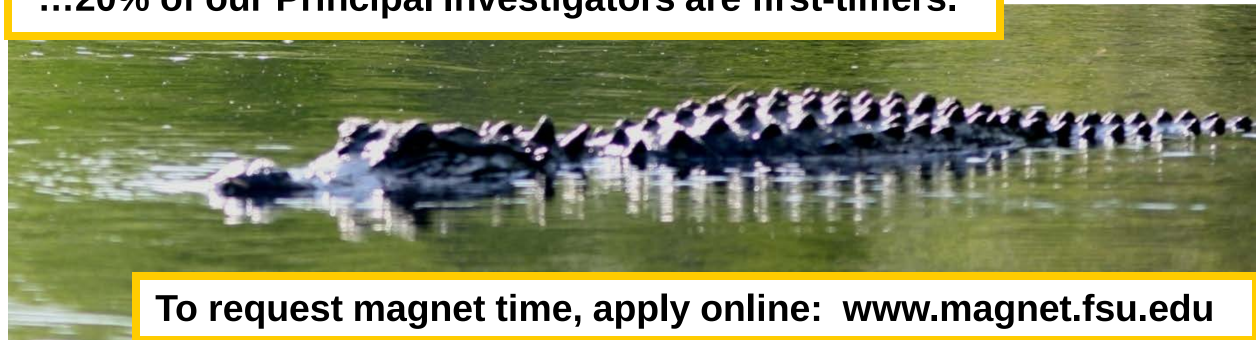
**…we look forward to hosting you at the MagLab**



NATIONAL
HIGH MAGNETIC
FIELD LAB



**We host ~ 1400 magnet users annually**
**…20% of our Principal Investigators are first-timers.**

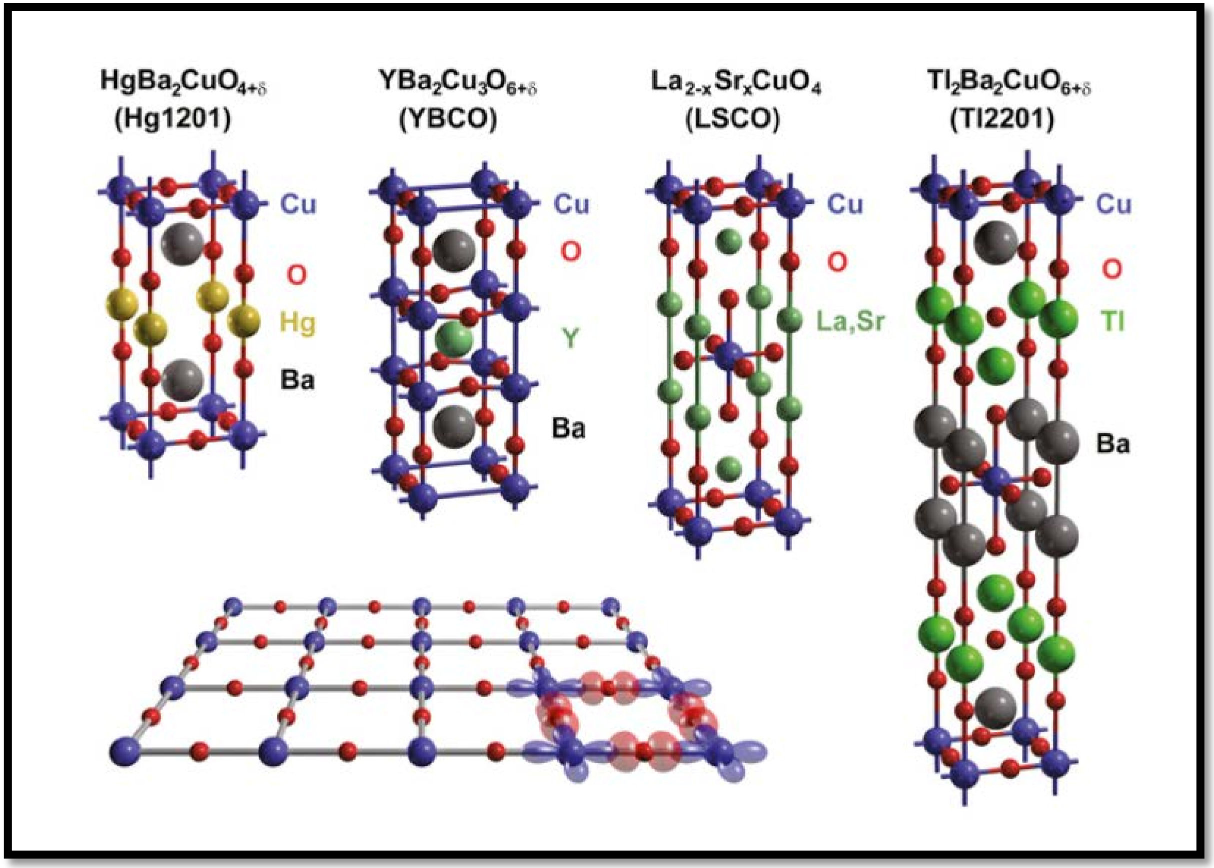


**To request magnet time, apply online: www.magnet.fsu.edu**

# The Cuprates:  The Early Years

# Key Ingredients for Cuprate Supercondutivity

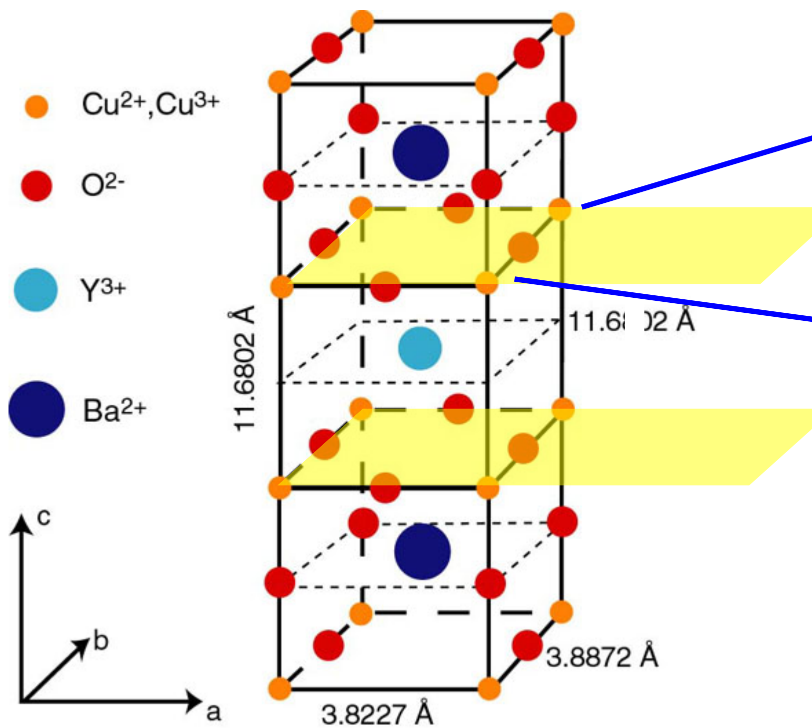
$T_c$=94 K  $T_c$=94 K  $T_c$=39 K  $T_c$=90 K

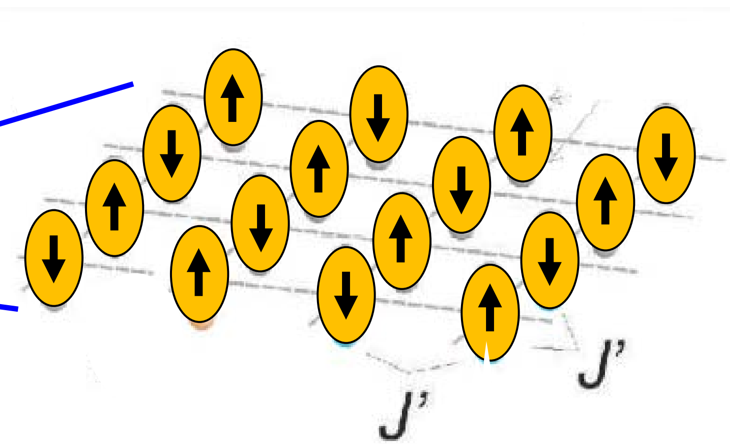



Barisic, N *et al.*, PNAS (2013)

# First Key Ingredient for (‘Cuprate’) High-Temperature Superconductors:

## the Copper – Oxygen Plane



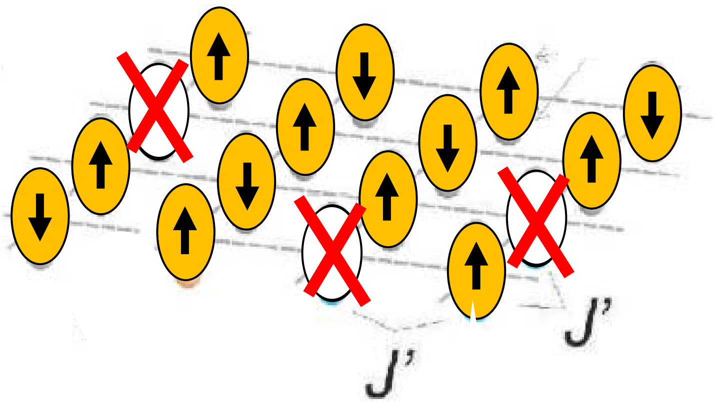




***The 2D Copper-Oxygen Plane…***
*…the playground of high-temperature superconductivity*

***With one electron on each Copper atom, the electrons cannot move …and you have an insulator***

# Second Key Ingredient for ('Cuprate') High-Temperature Superconductors:

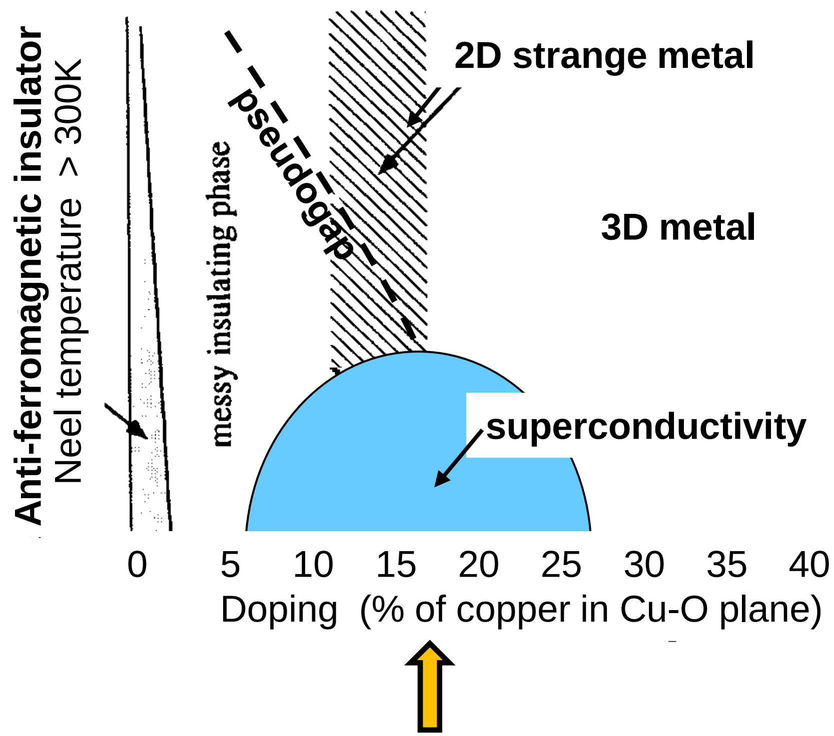
## Removing electrons from the Copper – Oxygen Plane




*With one electron on each Copper atom, the electrons cannot move …and you have an insulator*

***However, remove ~5% to ~27% of the electrons…***

***<u>…and you have a High-Tc Superconductor</u>***



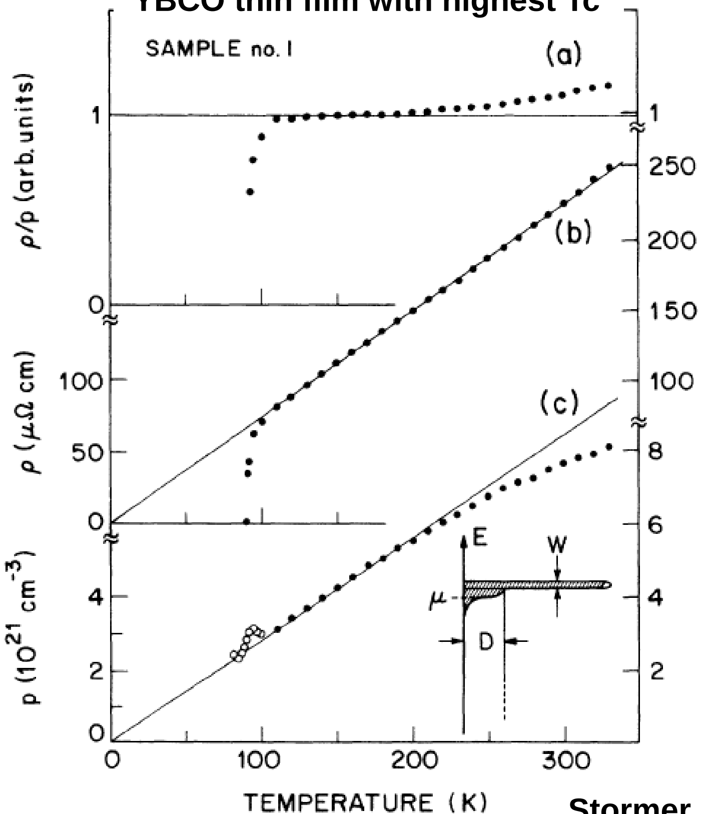

For more than a dozen different materials, the <u>*same*</u> 16% doping

***…optimizes superconductivity (highest transition temperature)***

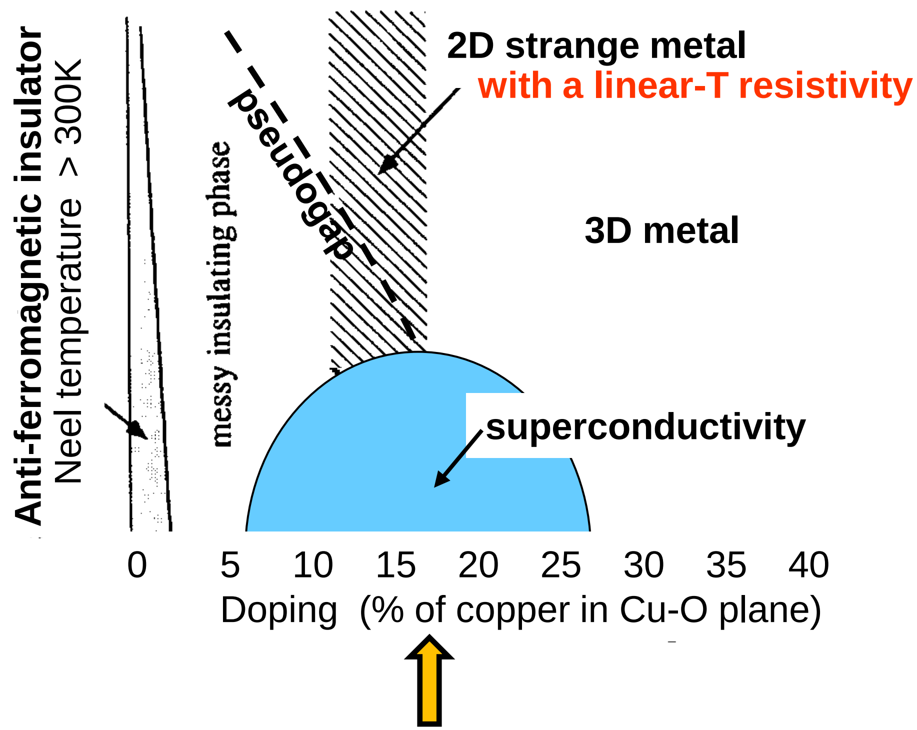
# Second Key Ingredient for ('Cuprate') High-Temperature Superconductors:

## Removing electrons from the Copper – Oxygen Plane

YBCO thin film with highest Tc




Stormer, et al. PR B38, 2472 (1988)




For more than a dozen different materials, the <u>*same*</u> 16% doping

***…optimizes superconductivity (highest transition temperature)***

***…optimizes linear-T resistivity***

# Phase Diagram of the High-*Tc* Superconductors

c. 1988

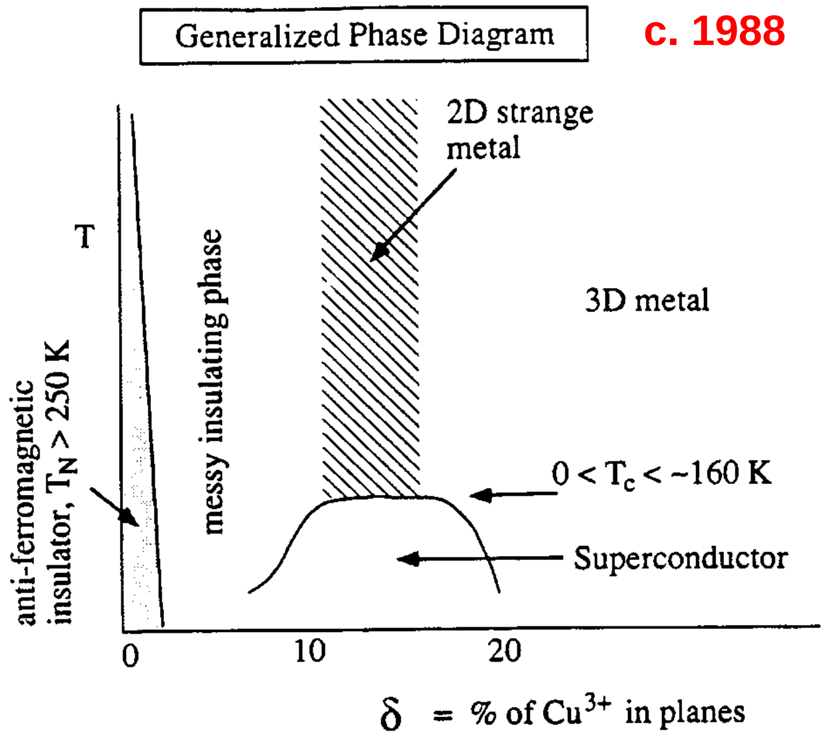
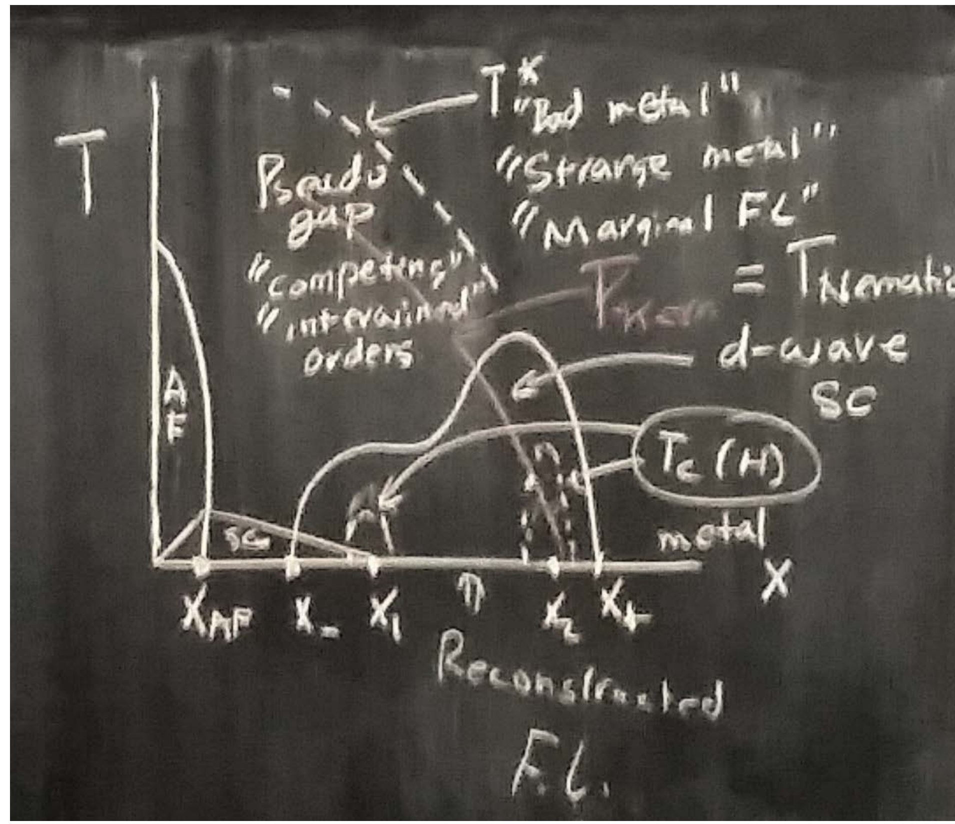



Figure 3.26. "Generalized Phase Diagram" as seen (roughly) in $(La - Sr)CuO_4$.

July 7, 2014, c.9:30am



# Suppressing Superconductivity with Magnetic Fields

# to Probe the Abnormal Normal State in the Zero-Temperature Limit

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

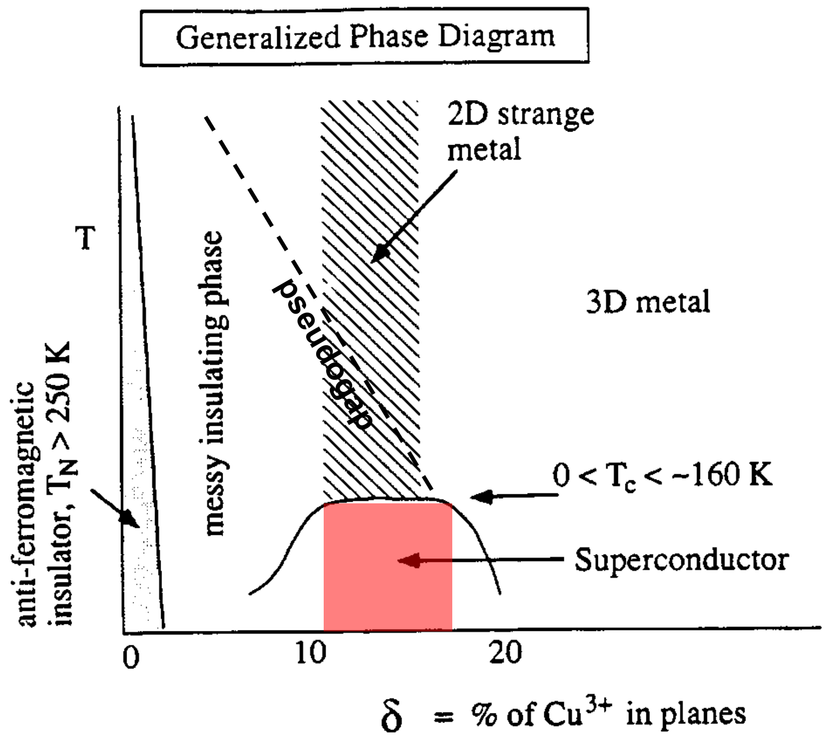



Figure 3.26. "Generalized Phase Diagram" as seen (roughly) in $(La - Sr)CuO_4$.

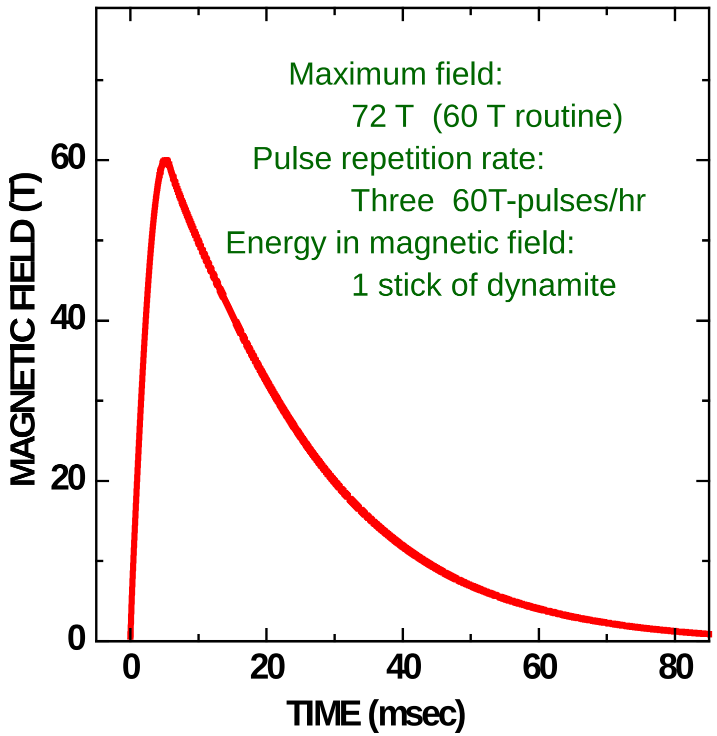
**SUPERCONDUCTORS IN THE NORMAL STATE**

| 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 <u>256</u>, 1526 (1992) and Research News, Science <u>278</u>, 1879 (1997)**

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

# Pulsed Magnet Facility, Bell Laboratories (1990-1998)


**Energy = 1 stick of dynamite**

**Energy = 1 jelly doughnut**

# Challenges in Producing High Magnetic Fields

***Pressure Under Water***

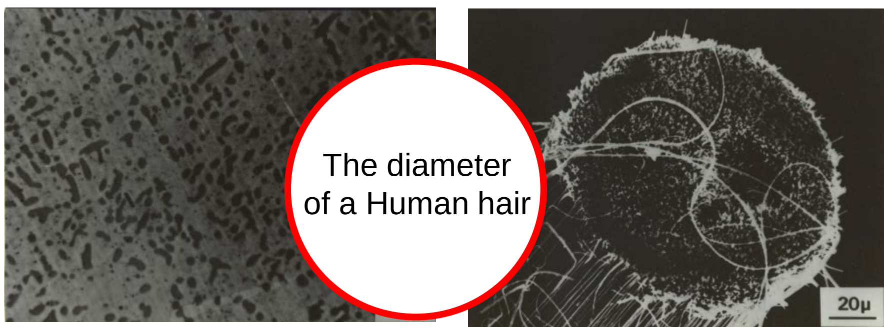
| | | |
|---|---|---|
| **12 feet** | **Ears** | **6 pounds per square inch** |
| **2000 feet** | **Submarine** | **1000 psi** |
| **12,000 feet** | **Ocean Floor** | **6000 psi** |

***Pressure inside NHMFL Pulsed Magnets***

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

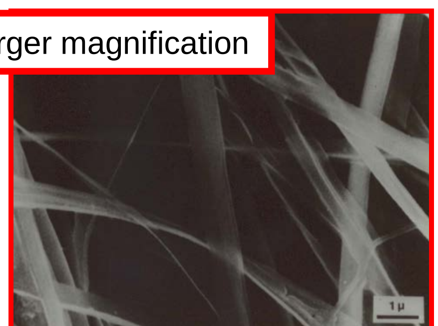
(which equals 1.4GPa or 130 kg per square millimeter)

***(which is more pressure than most materials can handle)***



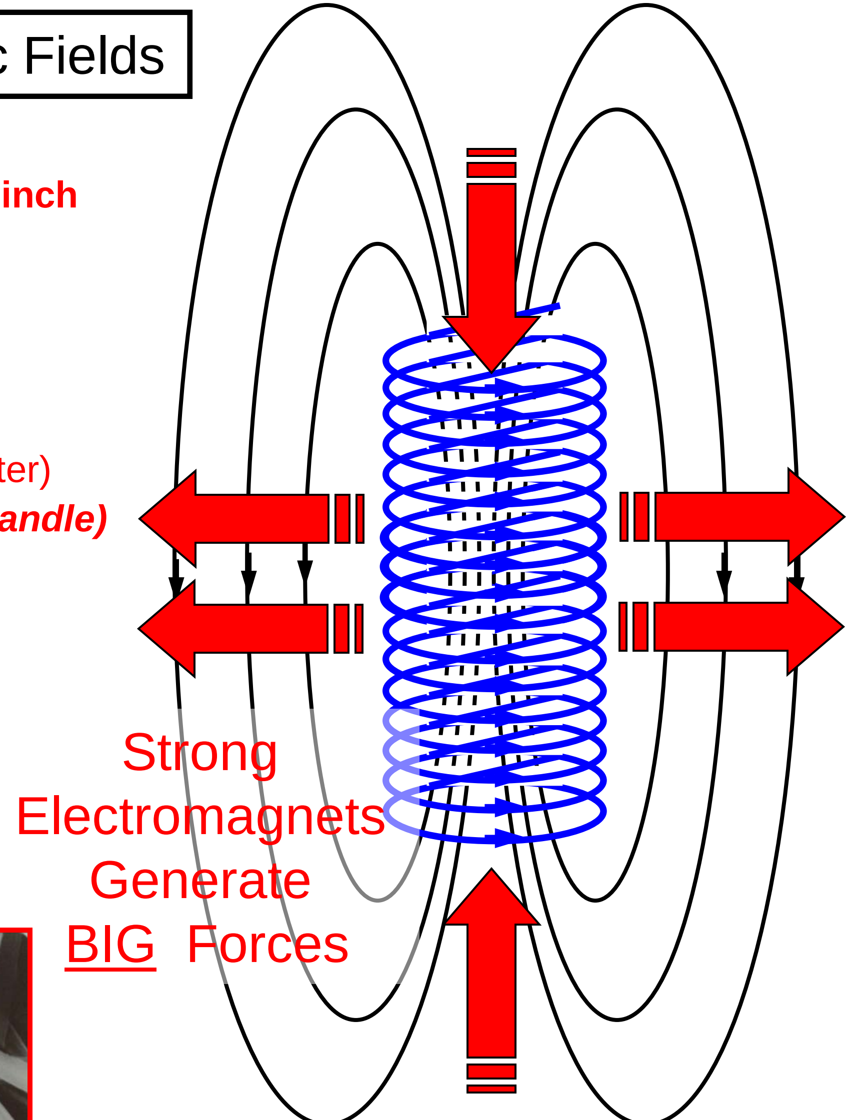

20% Niobium Droplets
in 80% Copper Matrix

20 times larger magnification




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

**…except the nano-composite is five times stronger than either constituent**



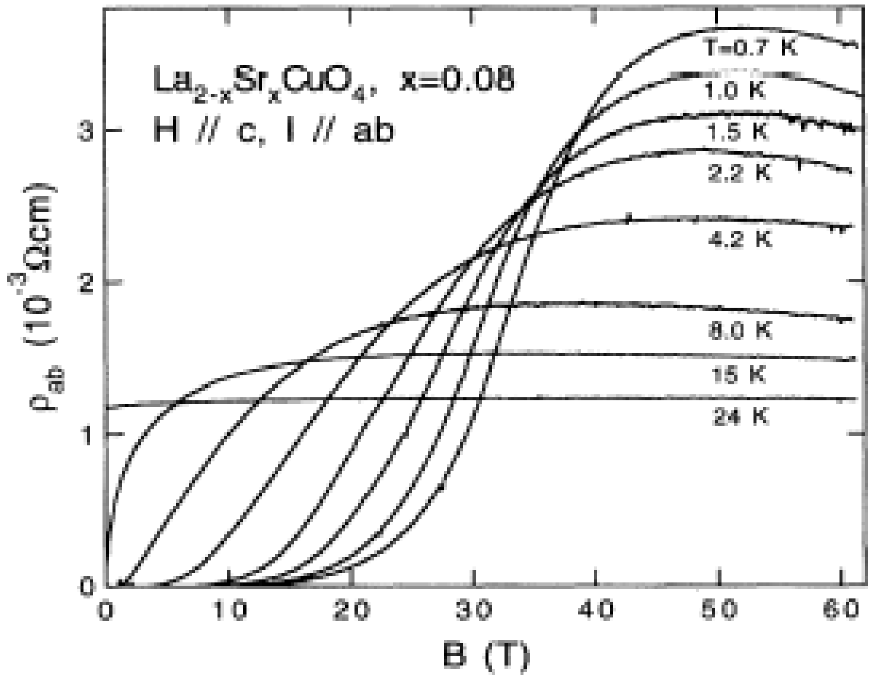
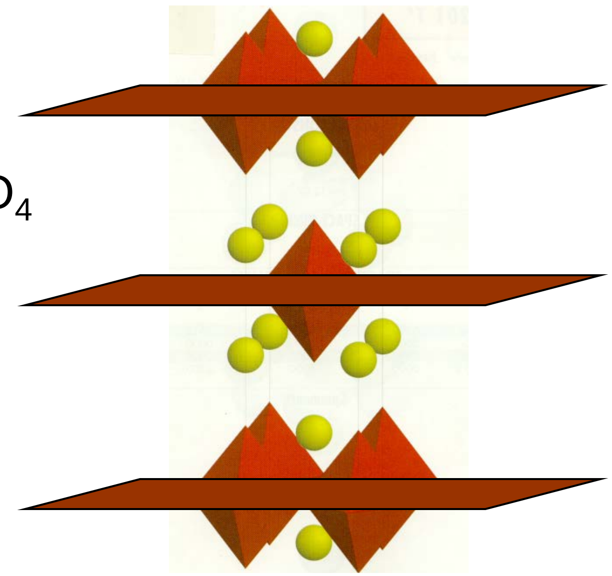



FIG. 1. In-plane resistivity $\rho_{ab}$ versus magnetic field for the $x = 0.08$ La$_{2-x}$Sr$_x$CuO$_4$ single crystal at various temperatures.

$(LaSr)_2\,CuO_4$



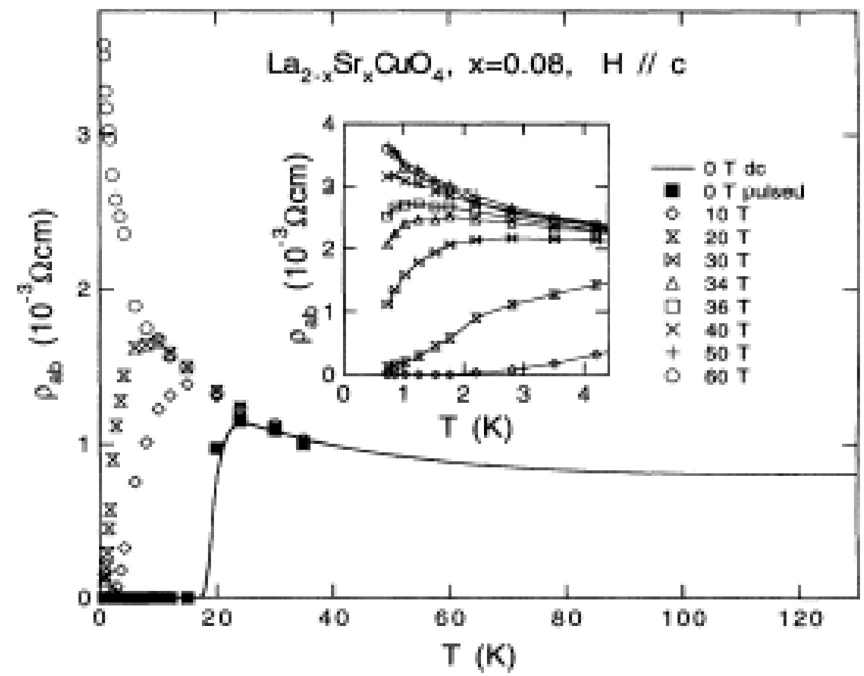



FIG. 2. Temperature dependence of $\rho_{ab}$ in 0, 10, 20, and 60 T, obtained from the pulsed magnetic field data. The solid line shows the zero-field resistive transition. The inset contains the low-temperature data.

$La_{1.92}Sr_{0.08}CuO_4$

**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**

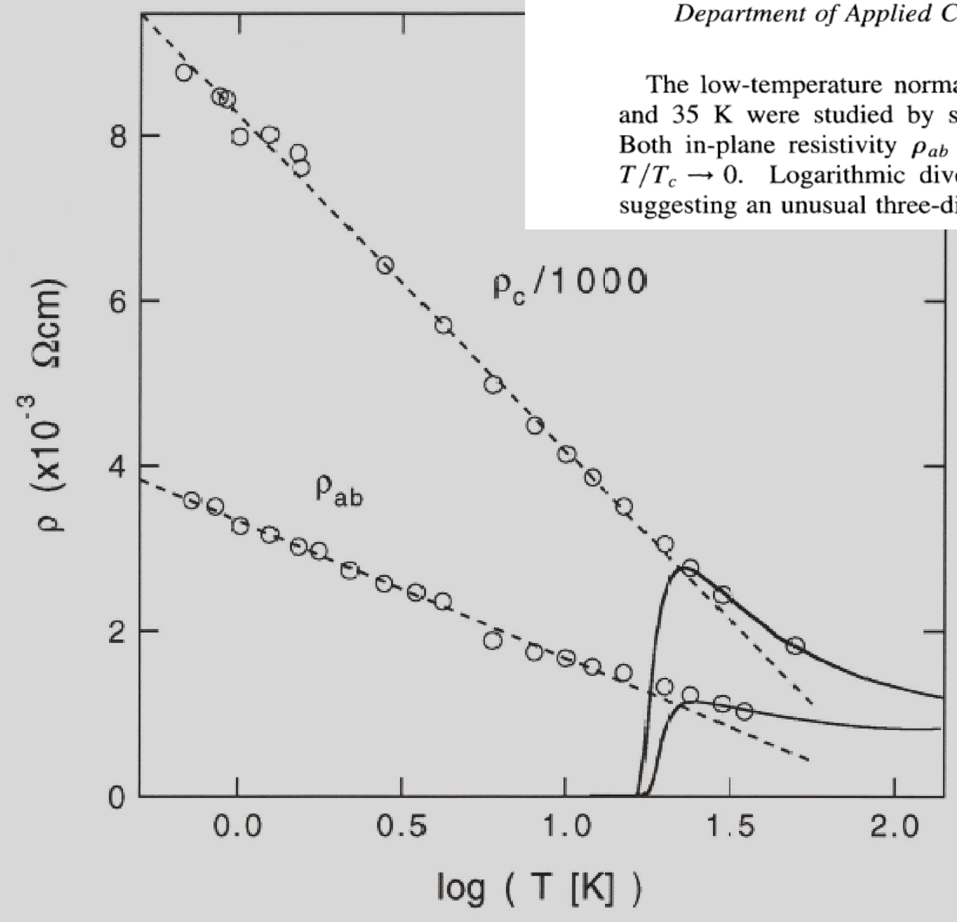

Yoichi Ando,* G. S. Boebinger, and A. Passner
*AT&T Bell Laboratories, 600 Mountain Avenue, Murray Hill, New Jersey 07974*

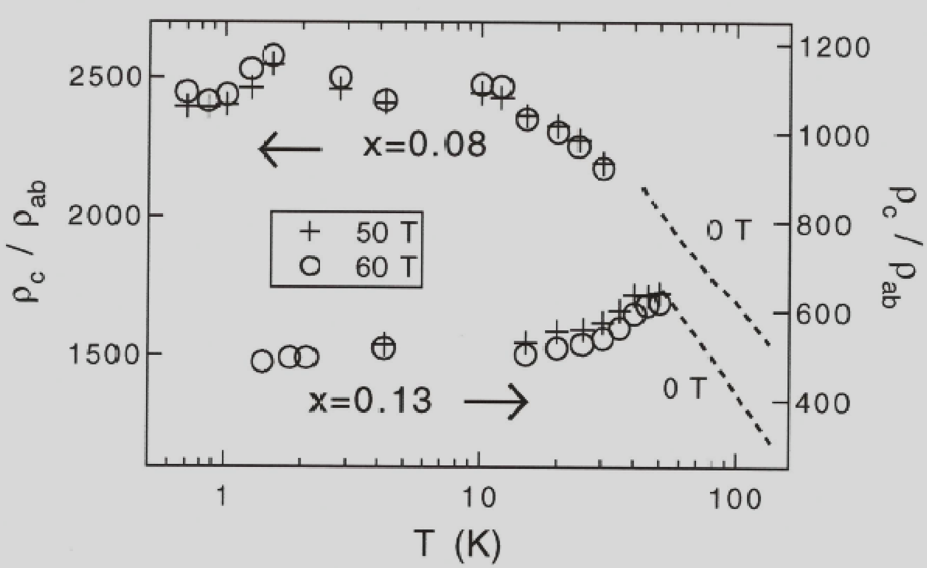
Tsuyoshi Kimura and Kohji Kishio
*Department of Applied Chemistry, University of Tokyo, Hongo, Bunkyo-ku, Tokyo 113, Japan*


(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 $\rho_{ab}$ and out-of-plane resistivity $\rho_c$ are found to diverge logarithmically as $T/T_c \to 0$. Logarithmic divergence is accompanied by a nearly constant anisotropy ratio, $\rho_c/\rho_{ab}$, suggesting an unusual three-dimensional insulator.

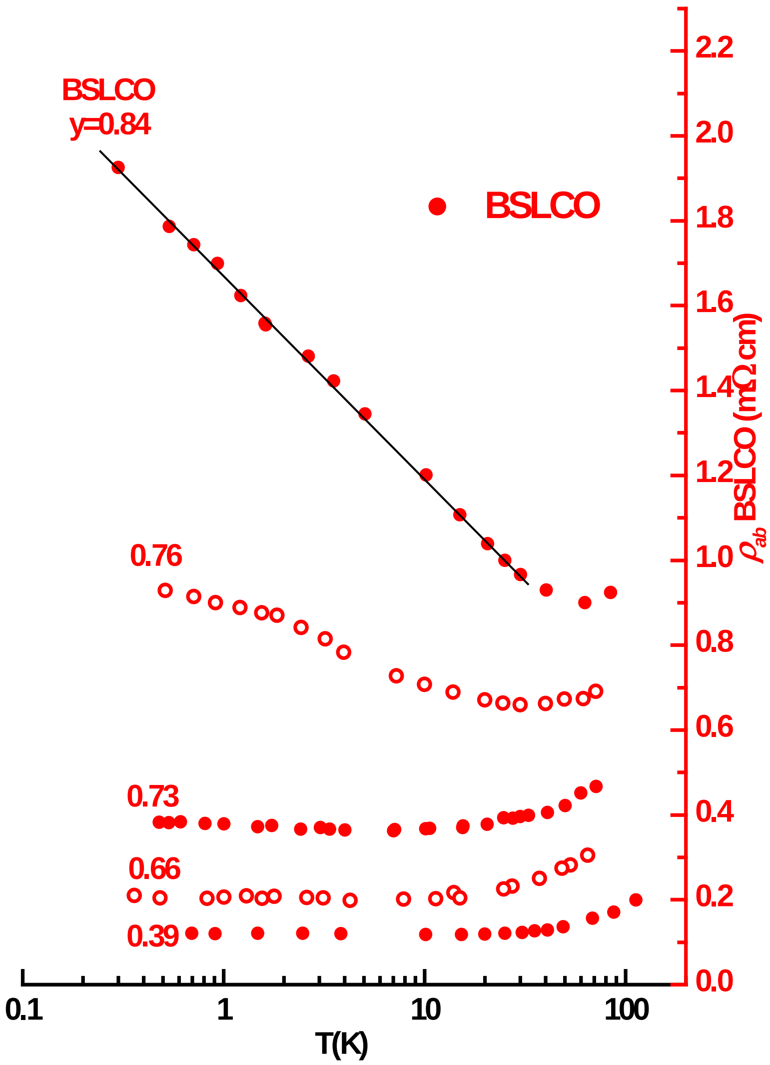



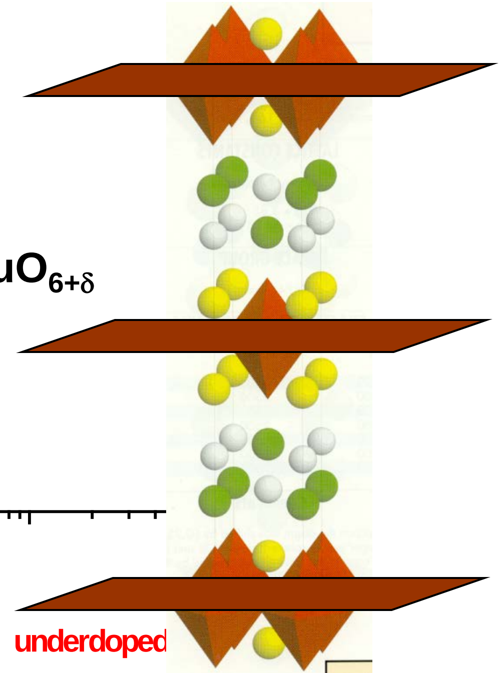



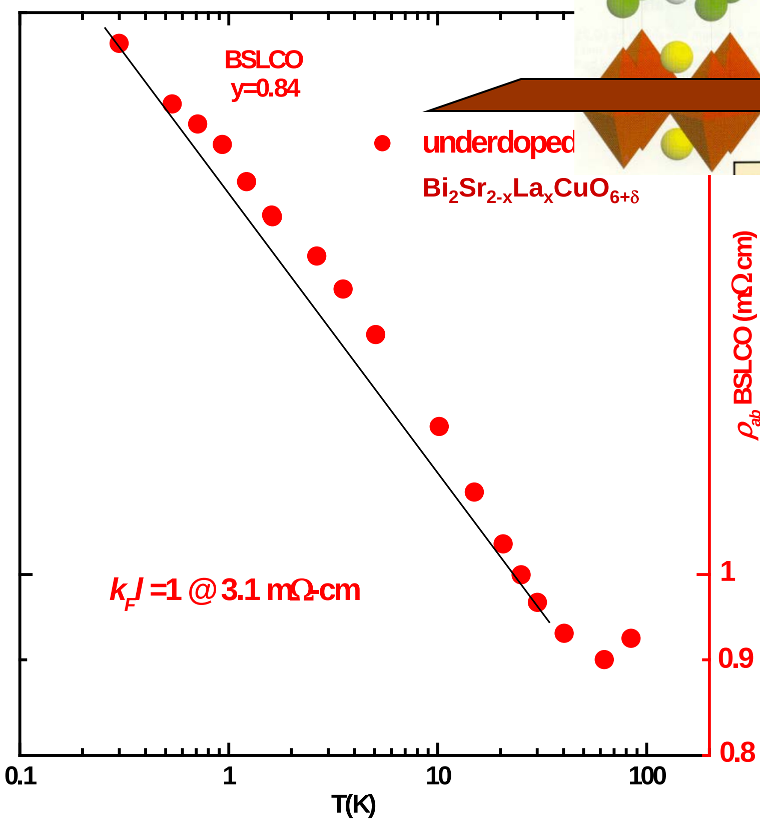


PRL **75**, 4662 (1995)

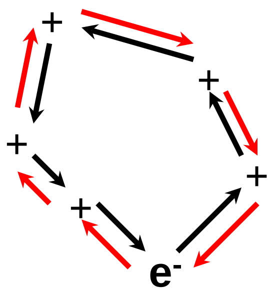
# Logarithmic Divergence of the In-Plane Resistivity of Underdoped $\mathbf{Bi_2Sr_{2-x}La_xCuO_{6+\delta}}$



# LOGARITHMIC DIVERGENCES….WHAT THIS IS NOT



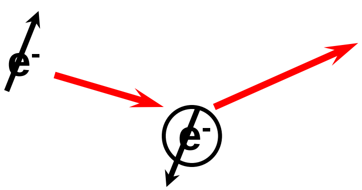
## Weak Anderson Localization

*Time-reversed scattering sequences give rise to coherent backscattering*

*Small logarithmic decrease in conductivity in two dimensional systems.*

***NOT LIKELY, because...***

**Large effect seen in resistivity. Persists even in 60T magnetic field.**



## Kondo Scattering

*Spin-flip scattering of conduction electrons from local magnetic moments*

*Logarithmic increase in resistivity in three dimensions*

***NOT LIKELY, because...***

**Persists in 60T magnetic field even for temperatures $k_BT < g\mu_BH$**

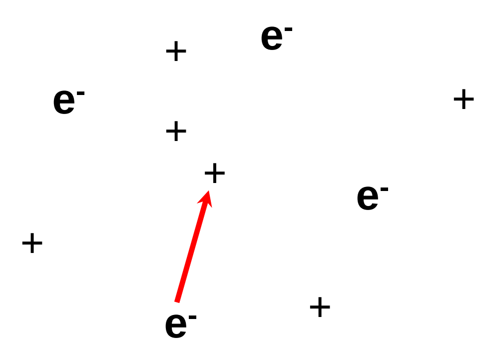
## Enhanced Localization due to Electron Interactions

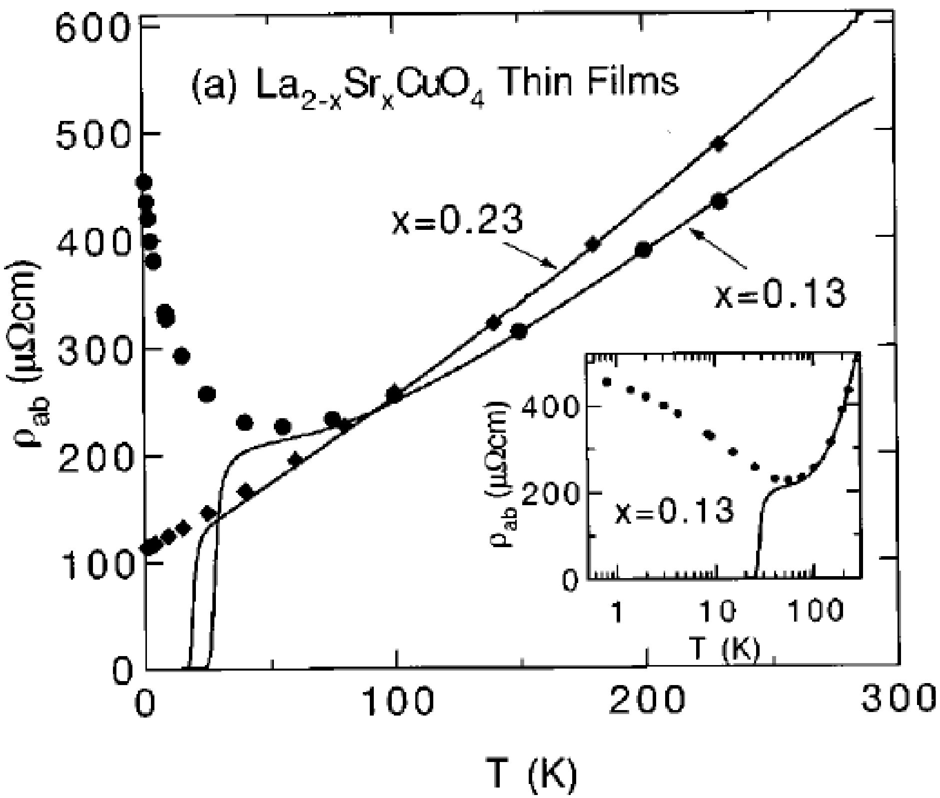
*Logarithmic decrease in the density of states near the Fermi energy*

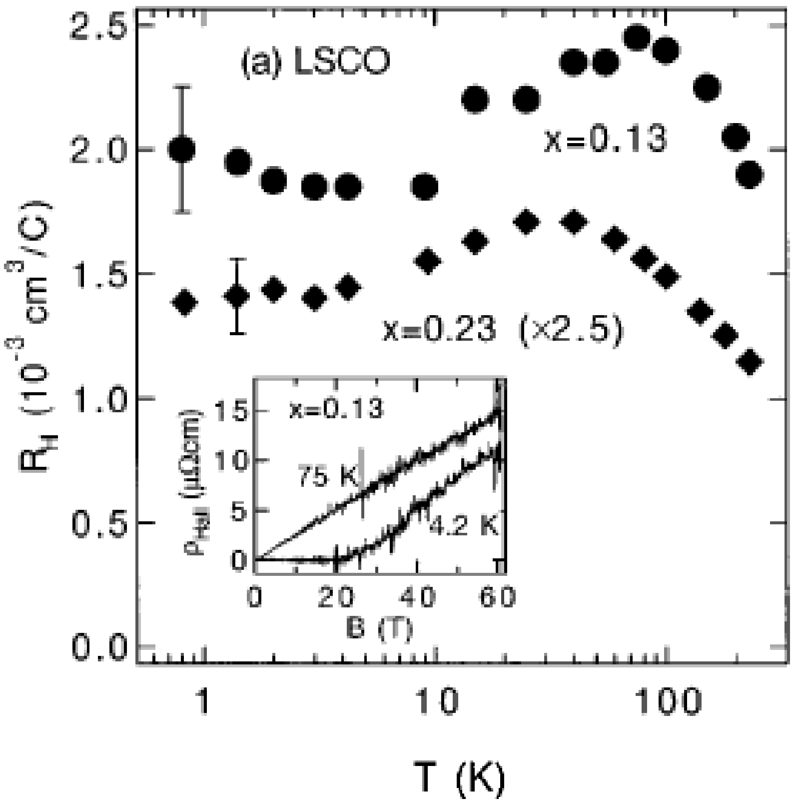
*Logarithmically suppressed conductivity in two-dimensional systems and carrier concentration due to reduced density of states*

***NOT LIKELY, because...***

**Large effect seen in resistivity. No divergence seen in Hall effect.**



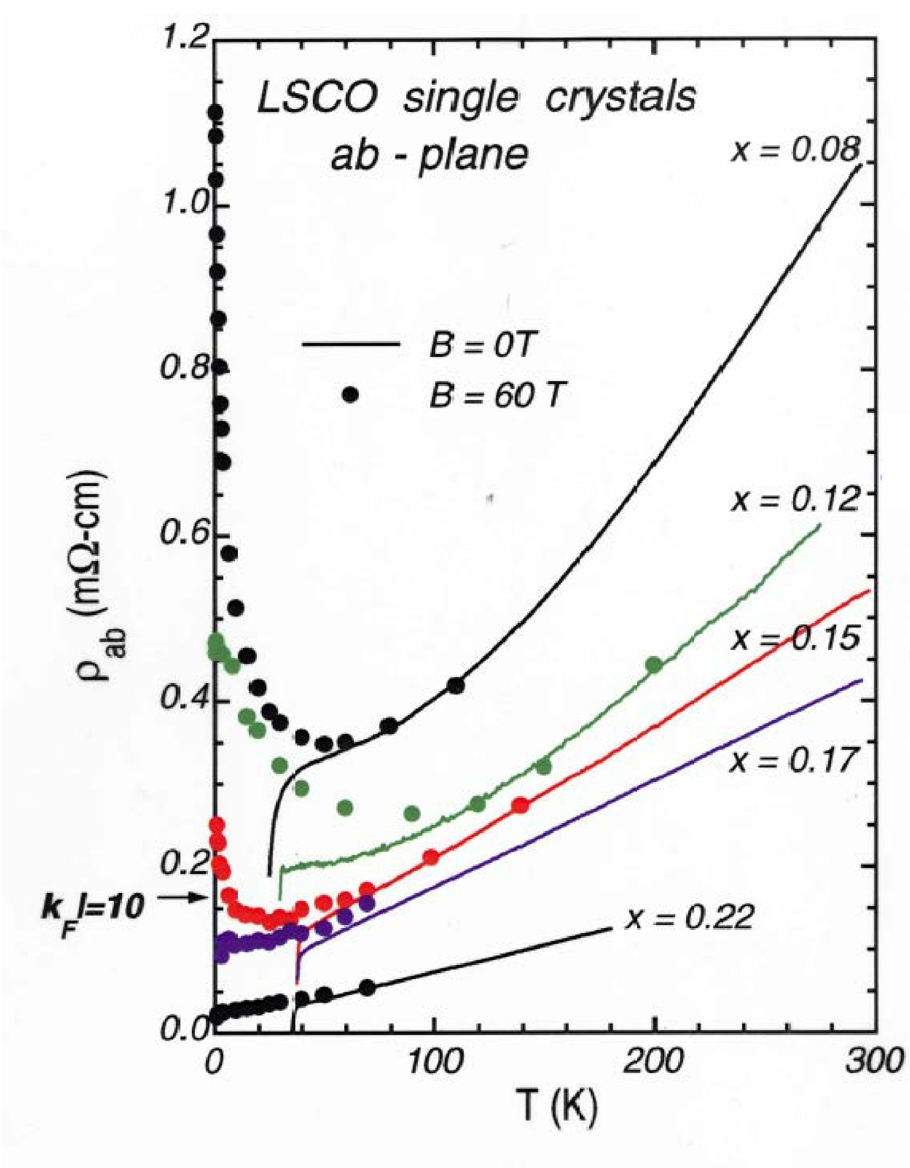


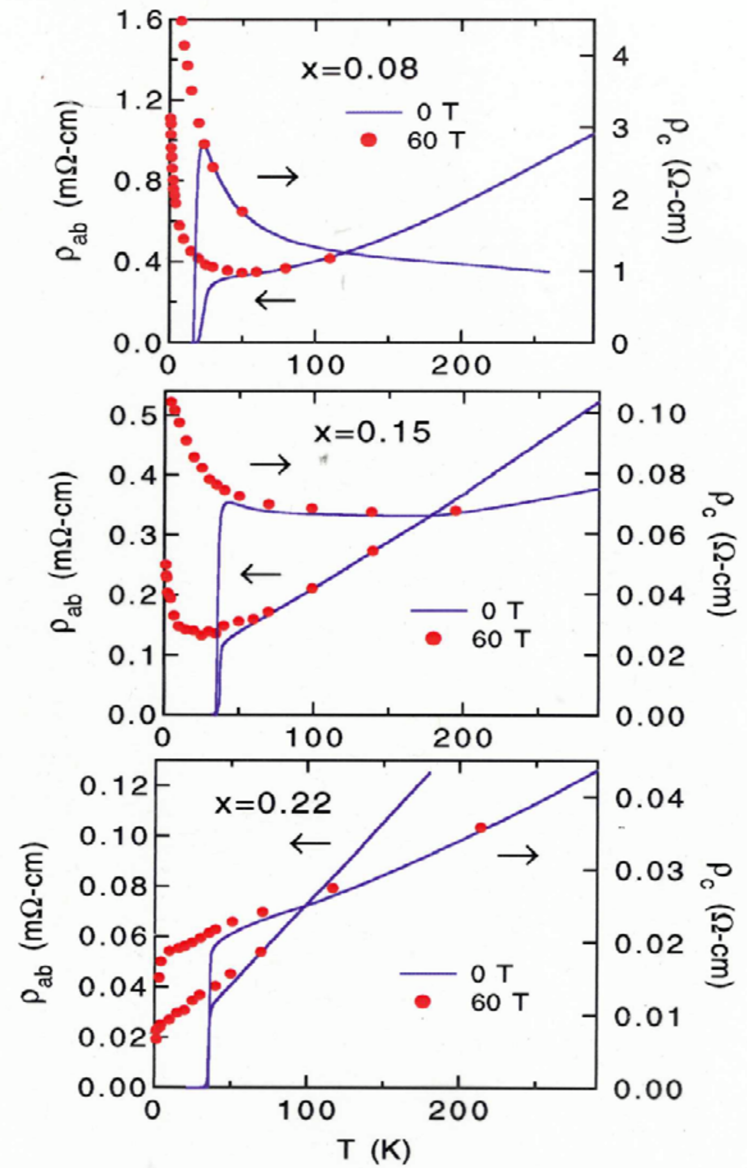



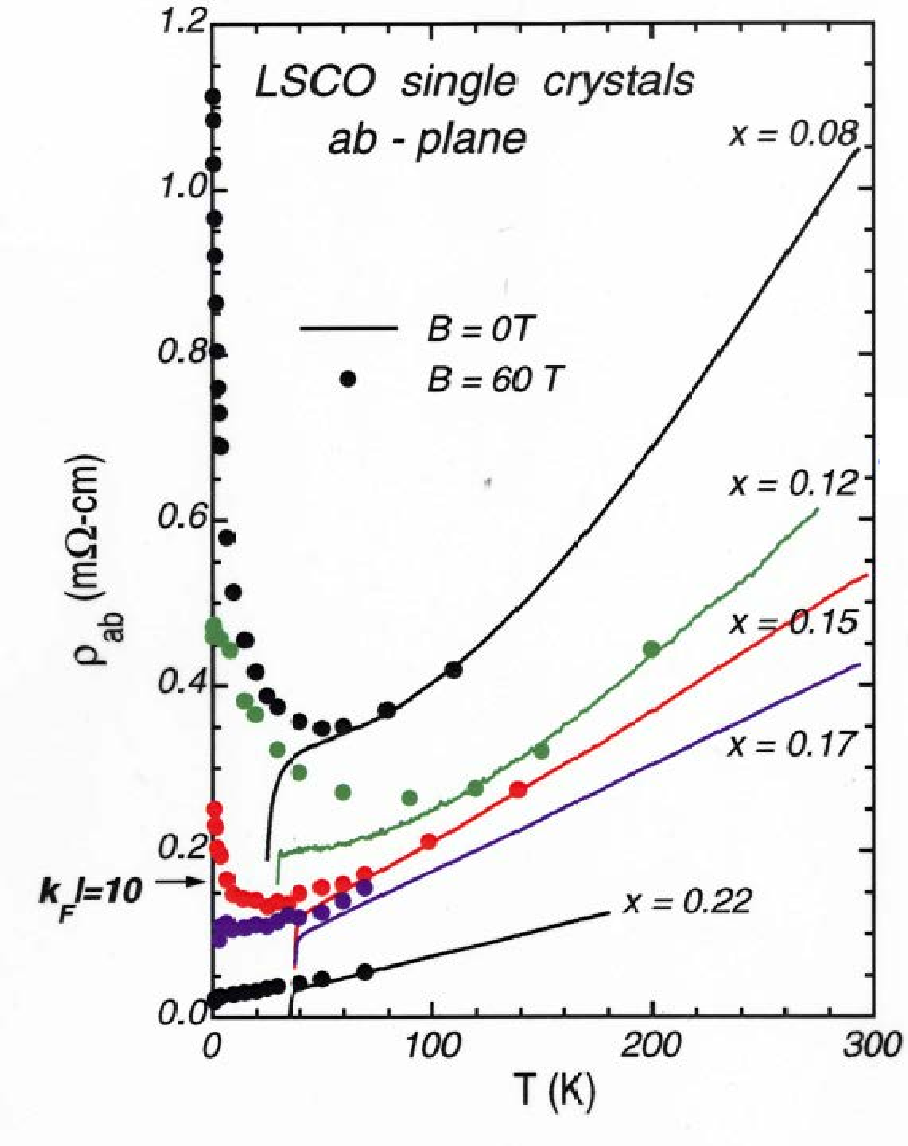

**Ando, Boebinger, et al. PRB 56 R8530 (1997)**

# “Insulator-to-metal crossover in the normal state of $La_{2-x}Sr_xCuO_4$ near optimum doping.”

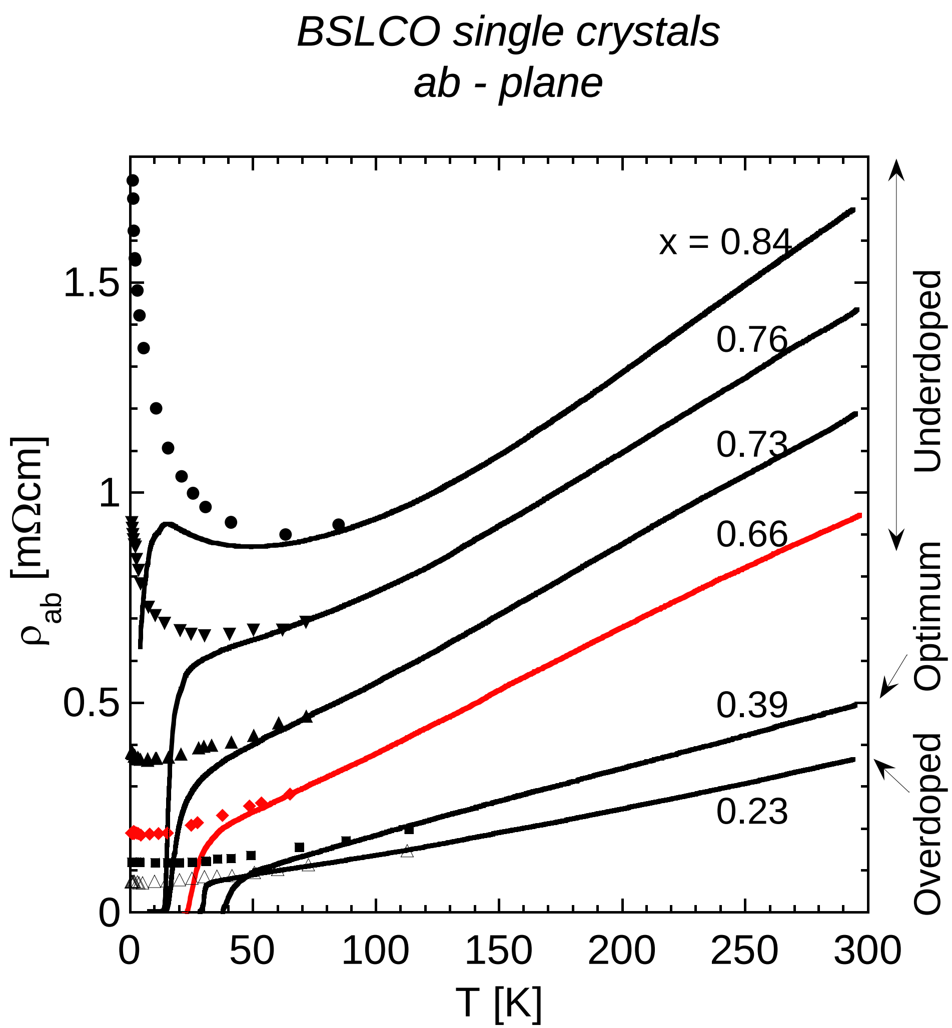
**G.S. Boebinger, Yoichi Ando, A. Passner, T. Kimura, M. Okuya,
J. Shimoyama, K. Kishio, K. Tamasaku, N. Ichikawa, and S. Uchida,** **Phys. Rev. Lett. 77, 5417 (1996).**






PRL **77**, 5417 (1996)



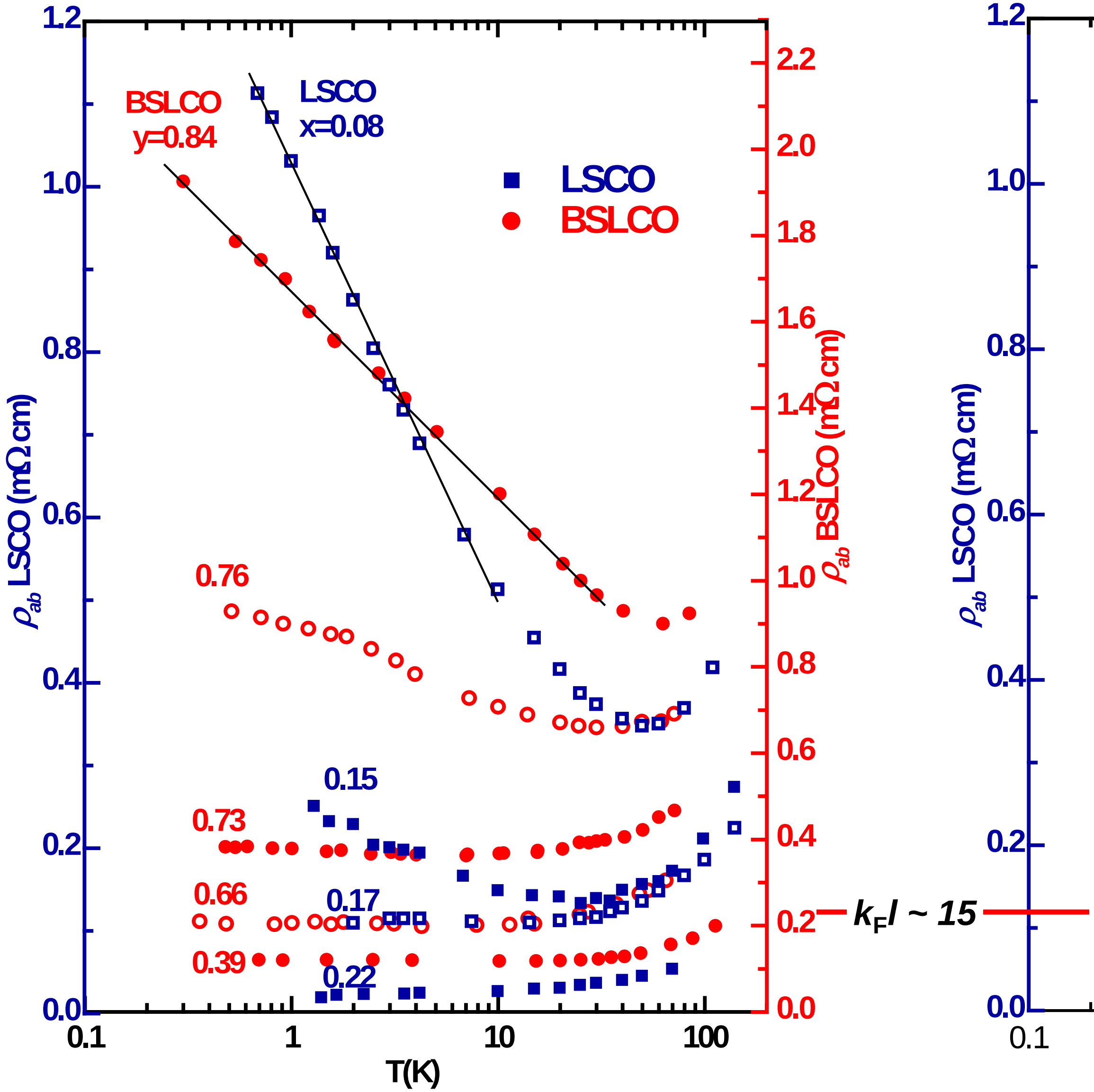

PRL **85**, 638 (2000)

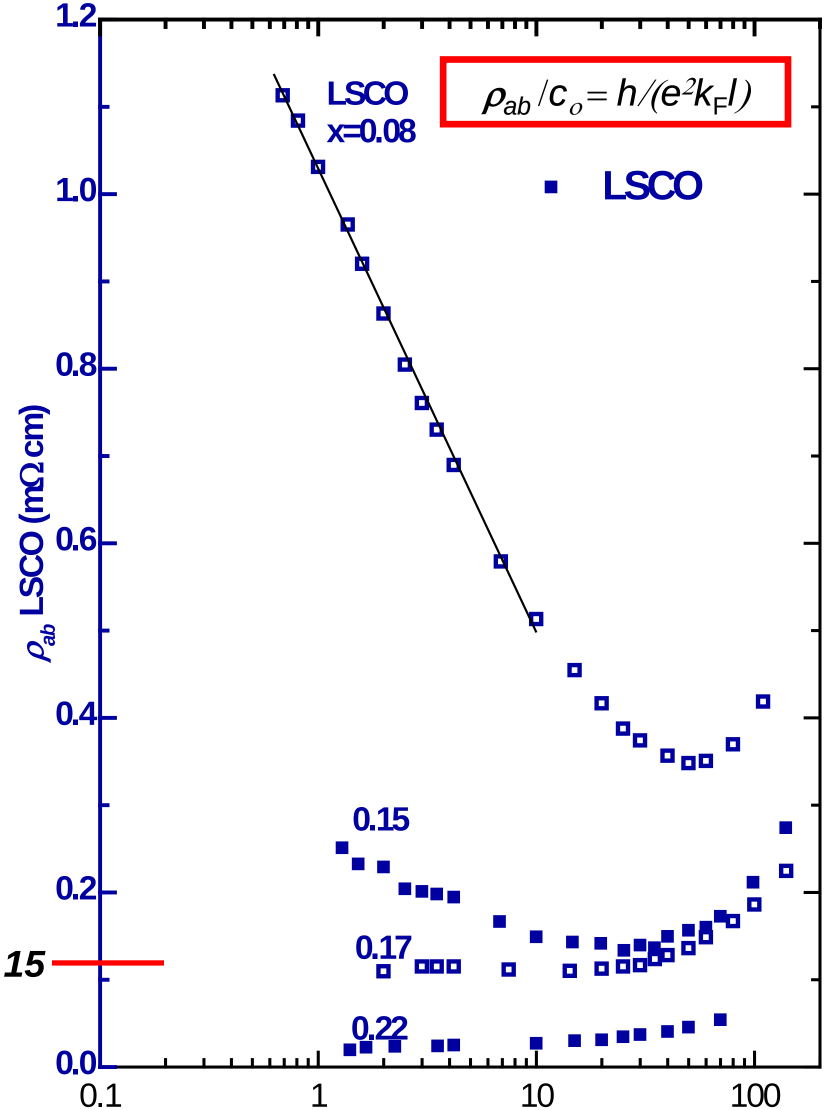
# Logarithmically Divergent Resistivity in Underdoped Cuprates

***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.*



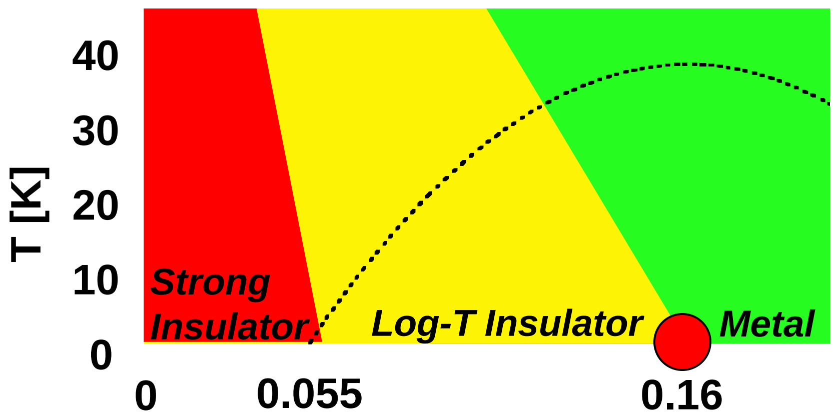

LSCO $k_F l$ =1 @ 1.6 mΩ

DocumentsData

LSCO $k_F l$ =1 @ 1.6 mΩ

**Questions:** Metal-Insulator Crossover in the Low-Temperature Normal State

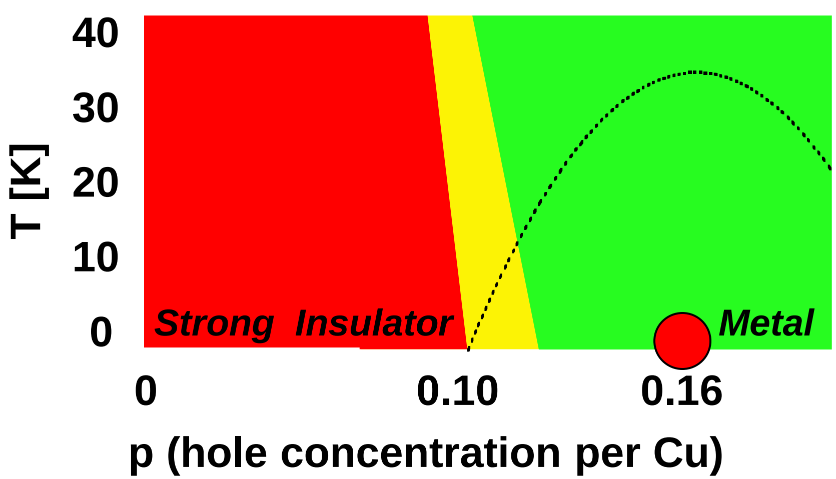
$La_{2-x}Sr_xCuO_4$




*Sharp Insulator-to-Metal Crossover*
*---at optimum doping*

*Evidence of a Quantum Critical Point ?*
*---near optimum doping*
*---where linear-T resistivity*
*has been attributed to critical behavior*

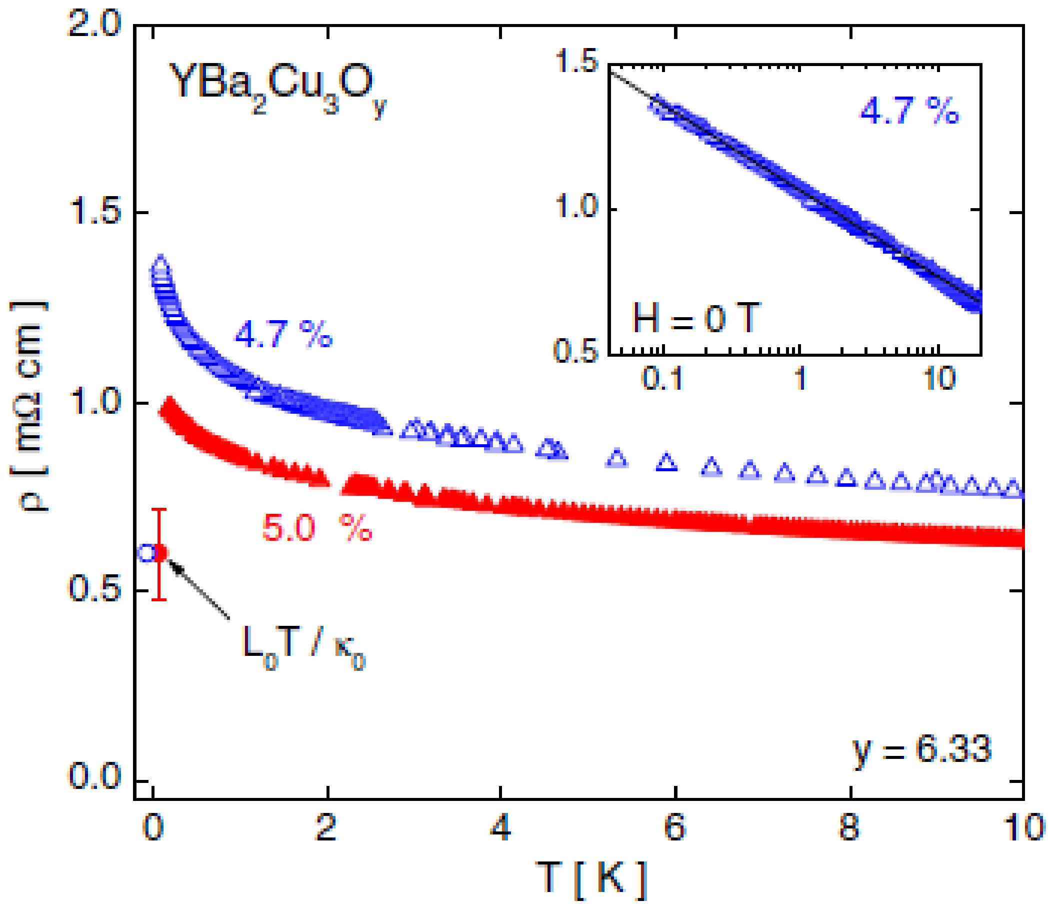
$Bi_2Sr_{2-x}La_xCuO_{6+\delta}$

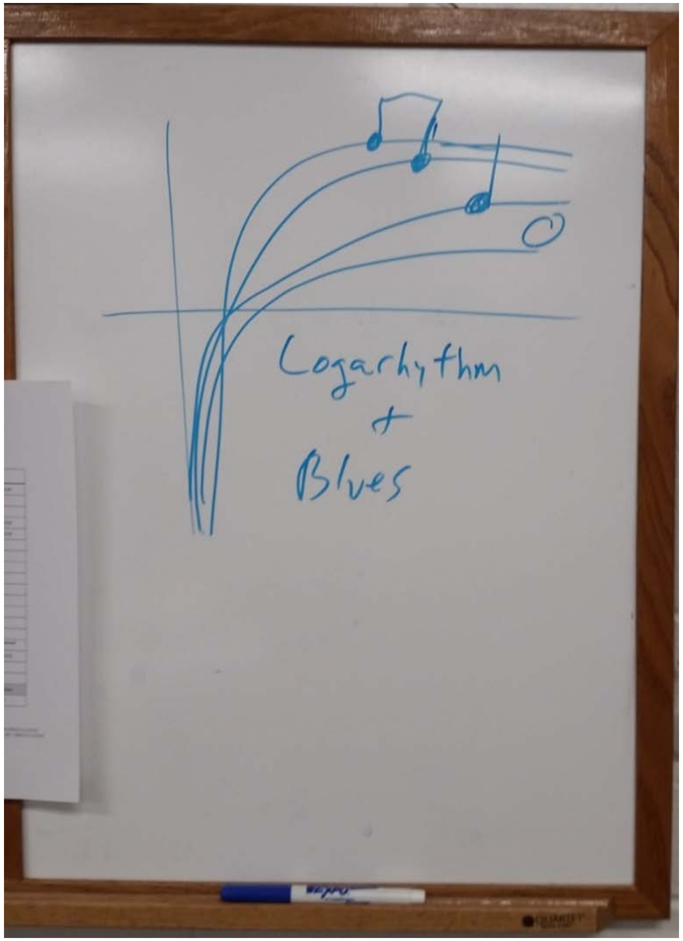



*No evidence of weird resistivity behavior*
*at optimum doping in BSLCO...*
*other than the usual linear-T resistivity.*

*If there were a Quantum Critical Point*
*at optimum doping in BSLCO ....*
*---between two metallic states.*
*---underdoped metal exhibits*
*unusual scattering or localization.*
*---would like to find experimental evidence*
*in transport.*

Logarithmic upturn in resistivity in underdoped, non-superconducting YBCO

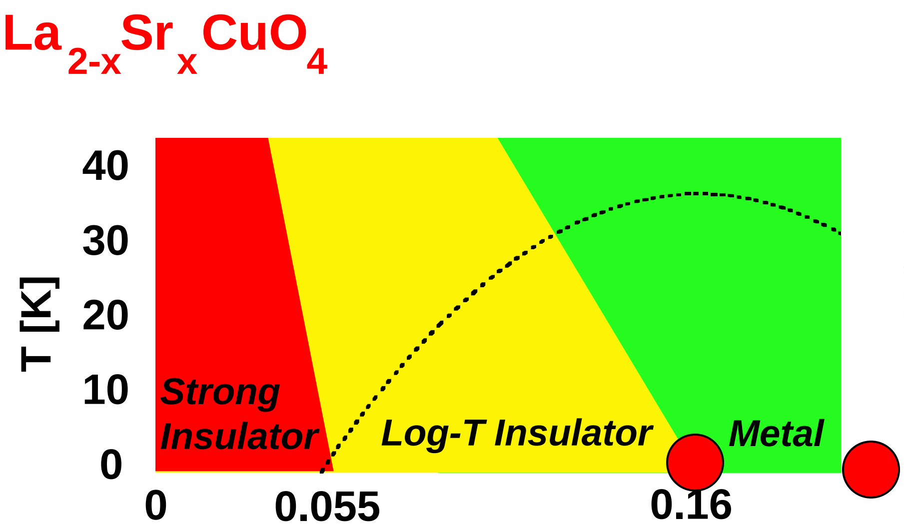


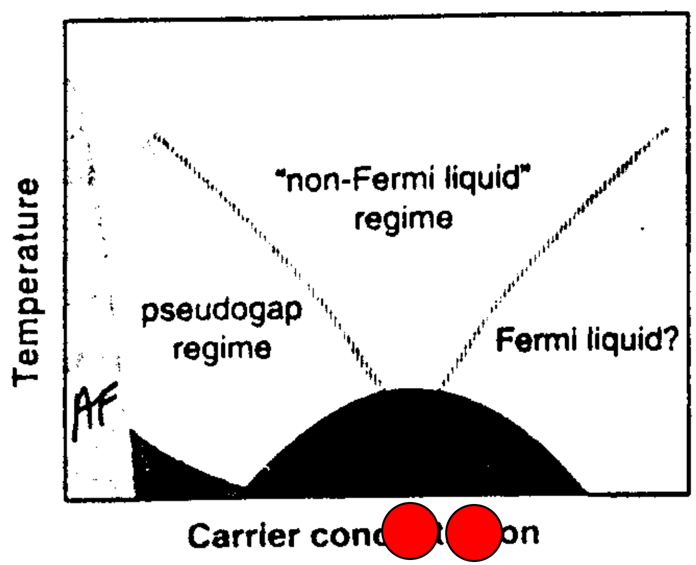



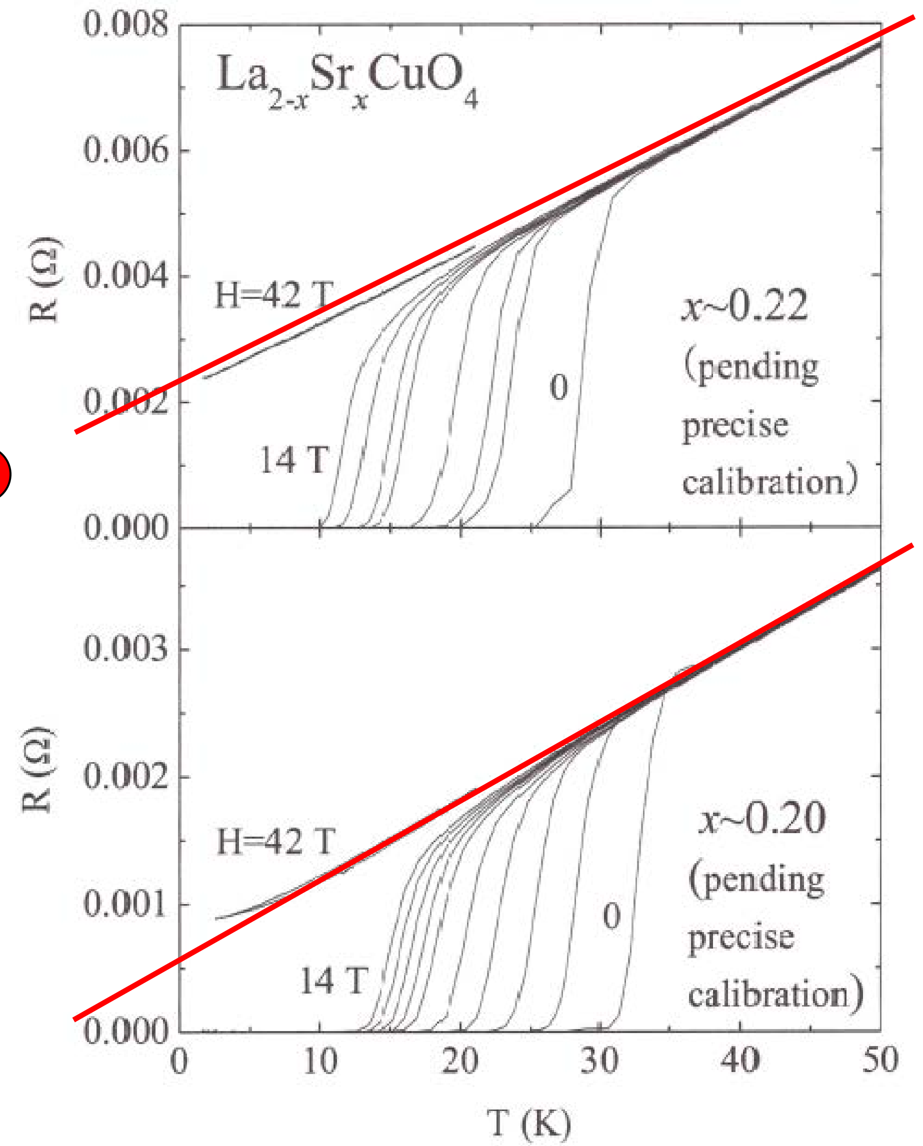

Nicolas Doiron-Leyraud,[1] Mike Sutherland,[2] S. Y. Li,[1] Louis Taillefer,[1,3,*] Ruixing Liang,[4,3] D. A. Bonn,[4,3] and W. N. Hardy[4,3]

PRL 97, 207001 (2006)

# Linear-T to zero temperature as evidence of a quantum critical point



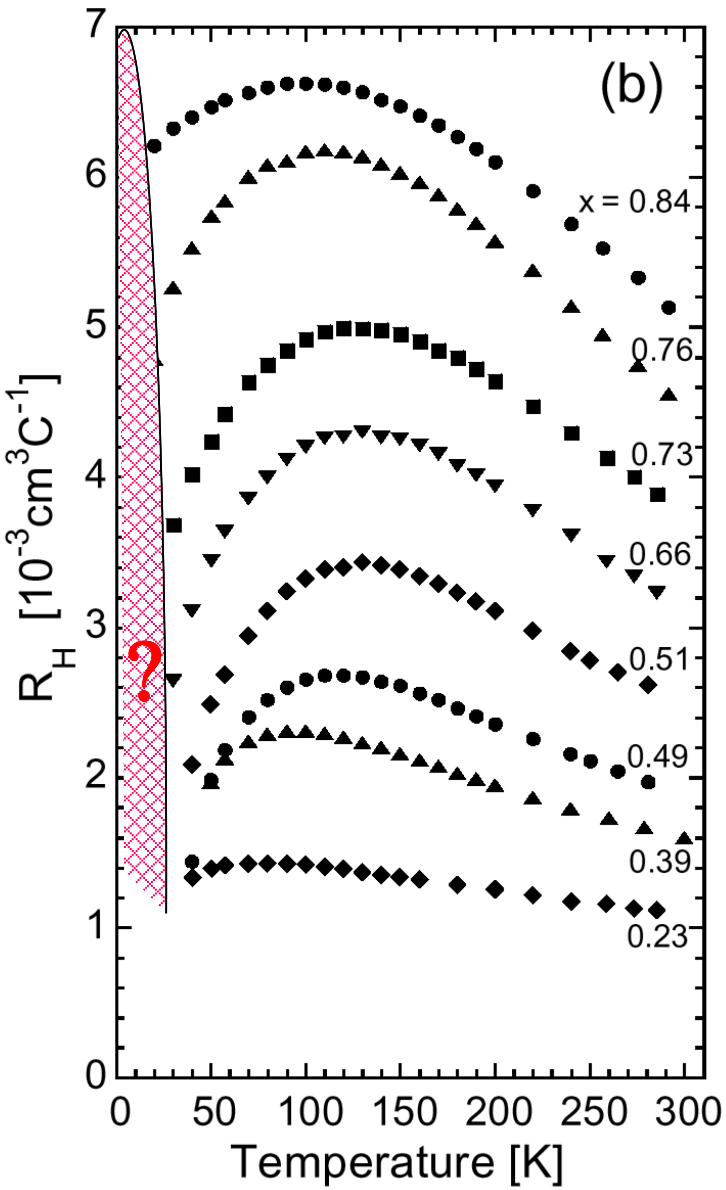




K.H. Kim, N. Harrison, G.S. Boebinger (Los Alamos);
S. Komiya, S. Ono, Y. Ando (CRIEPI) (unpublished 2003)

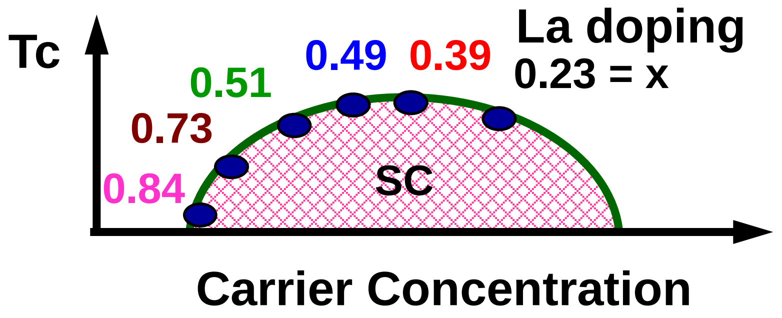
# Switching from Resistivity

# to Hall Measurements

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



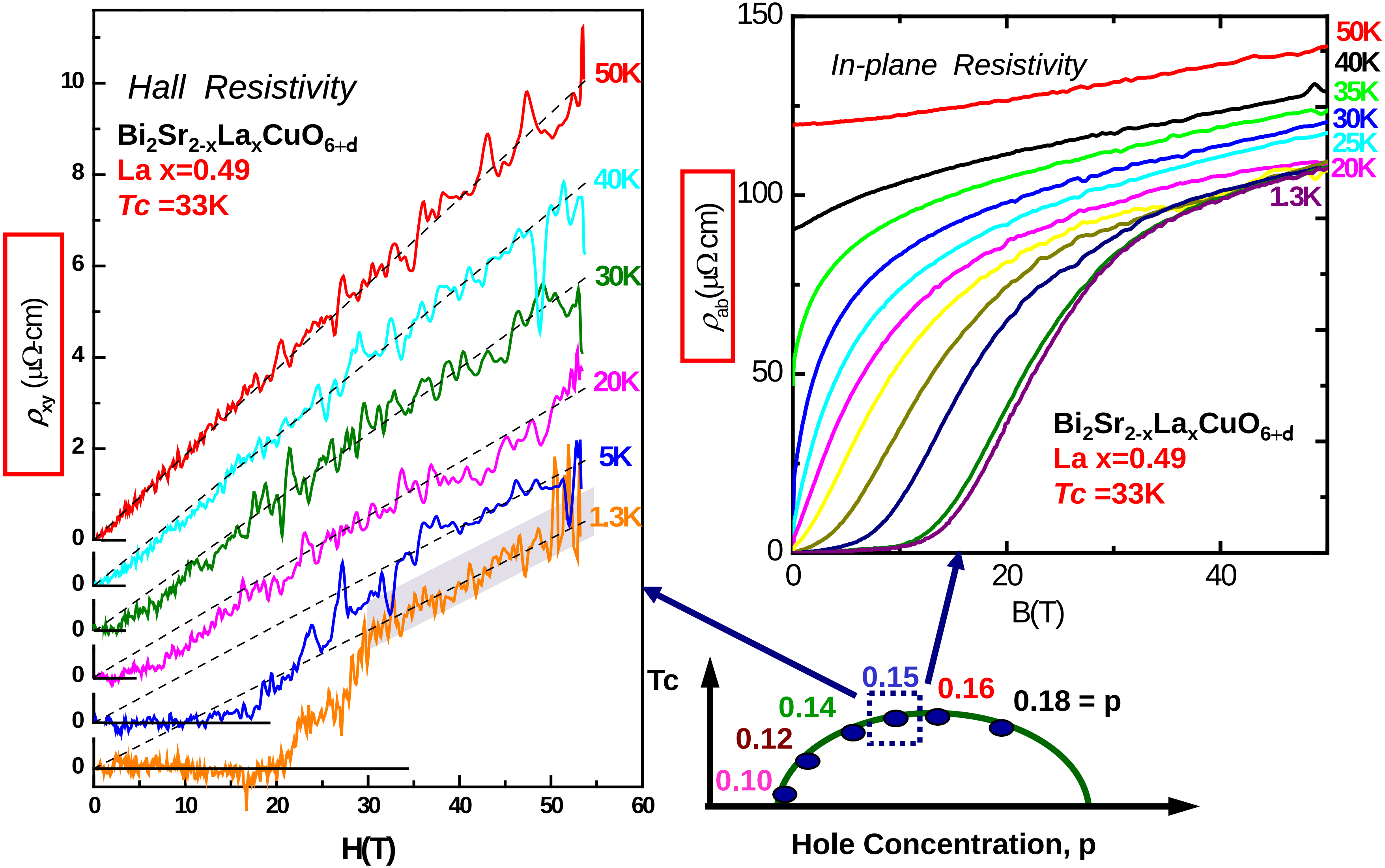

## Hall Effect in $Bi_2Sr_{2-x}La_xCuO_{6+d}$




- Unusual Temperature-dependence of Hall coefficient not understood

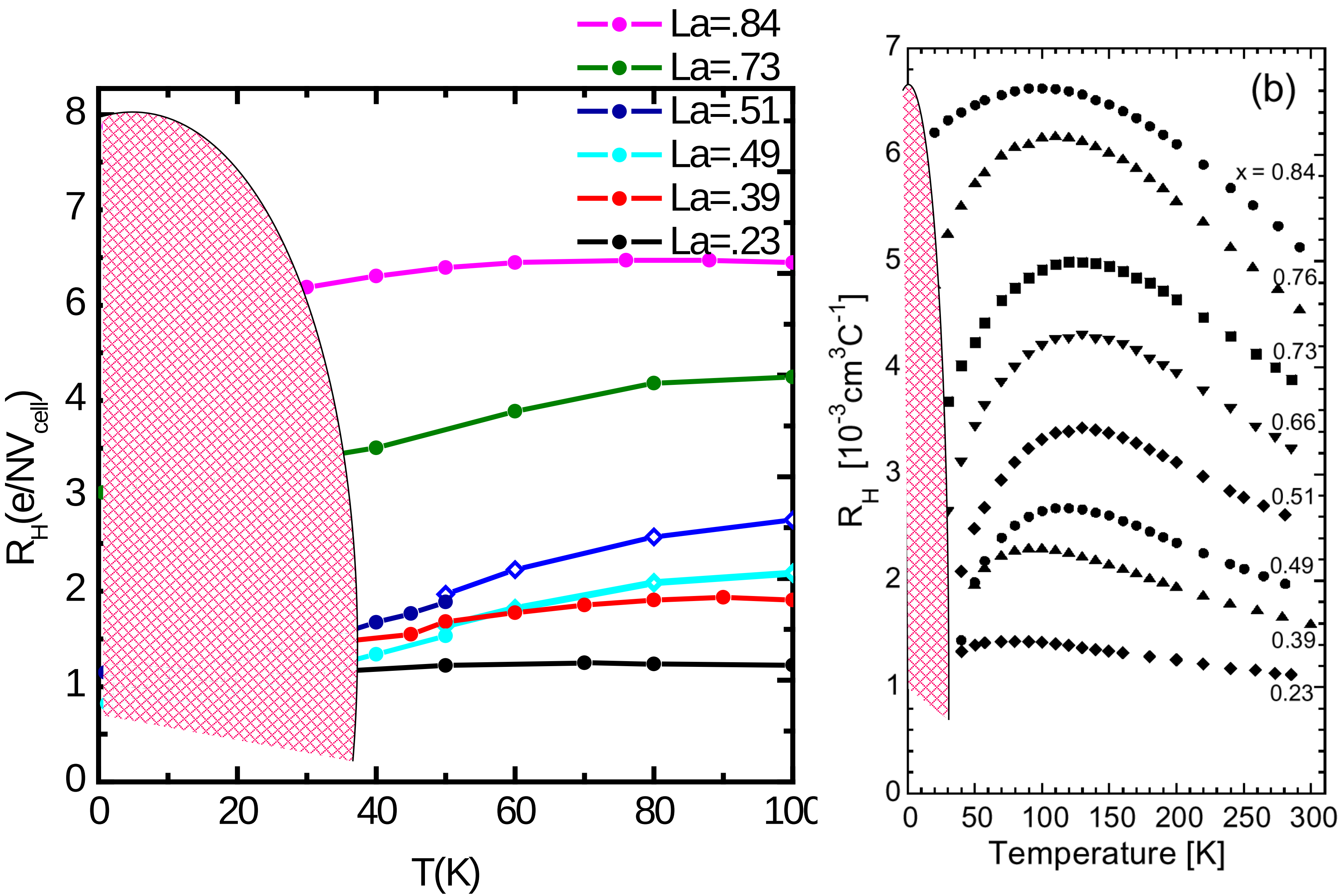
**- What happens below $T_c$ ?**

# Low Temperature Normal State Hall Effect

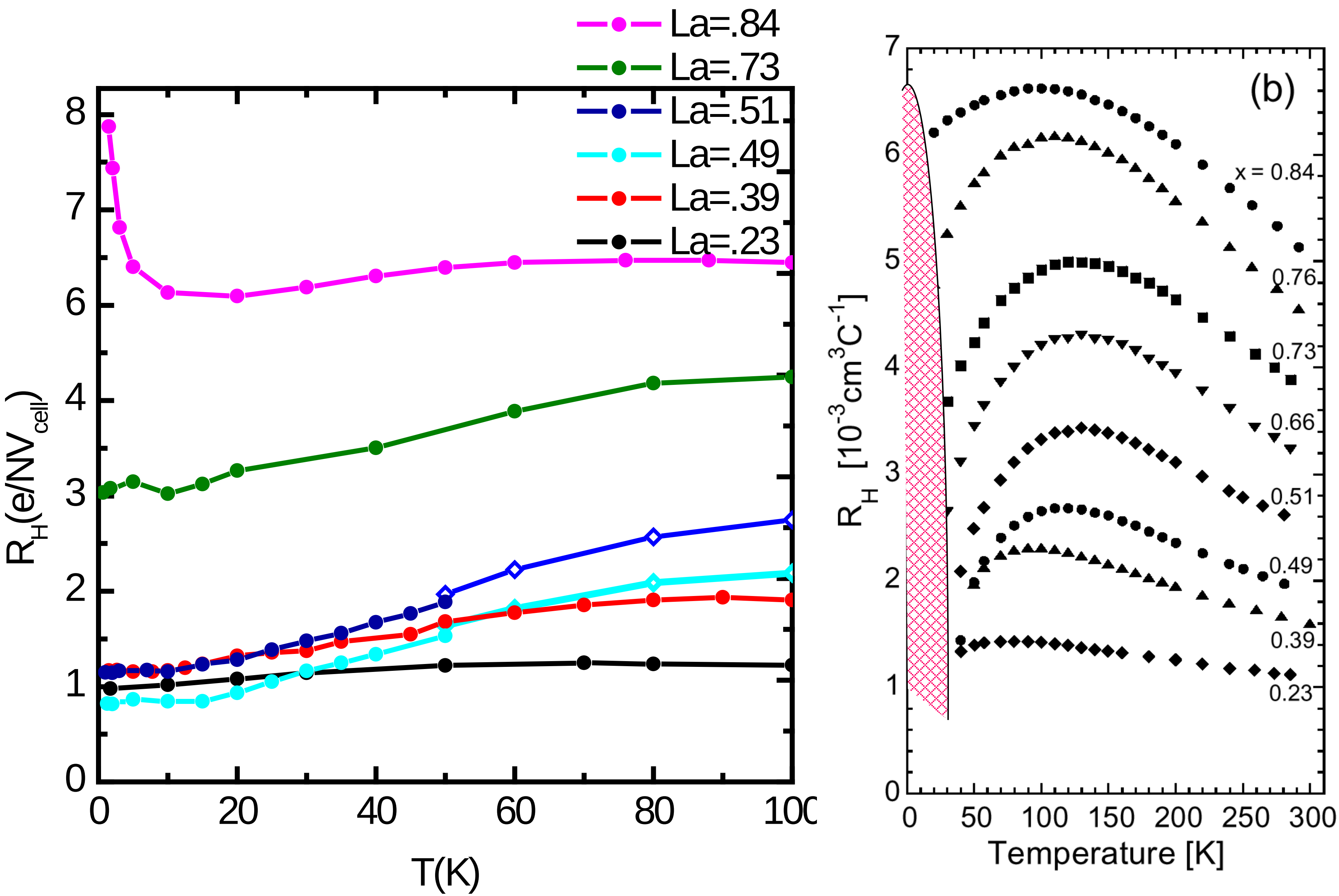



*High-field Hall voltage is linear in field*

# Low Temperature Hall Effect

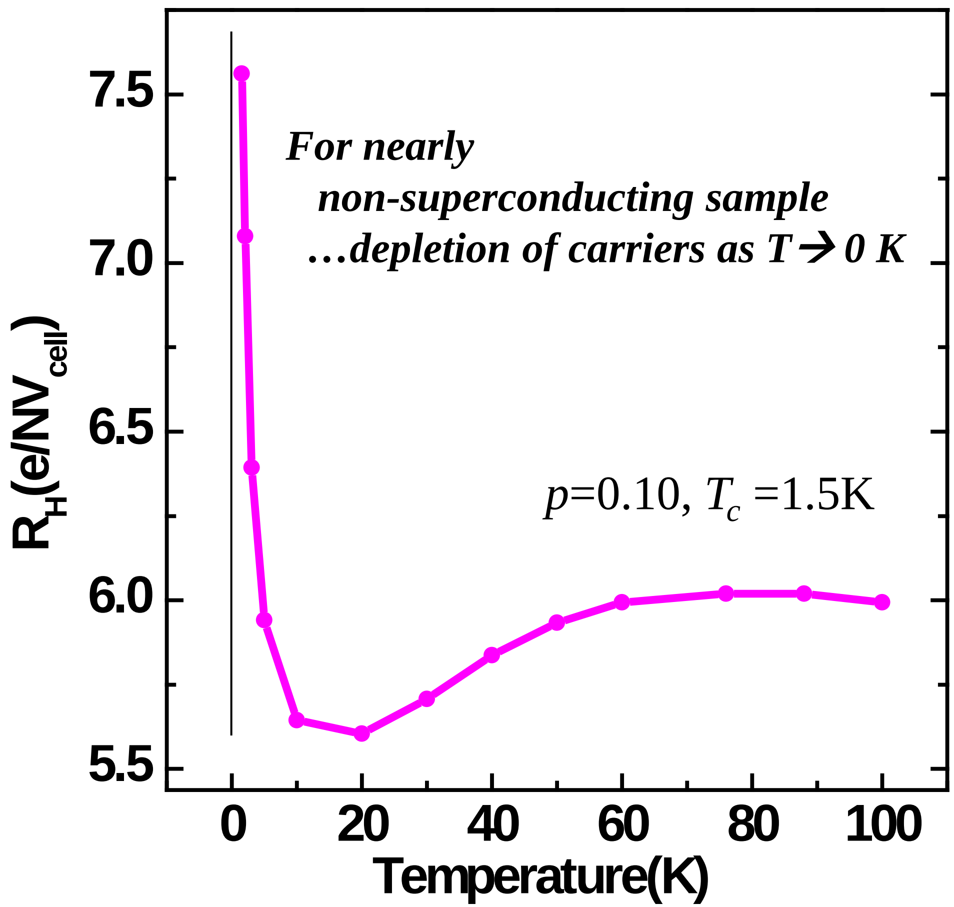


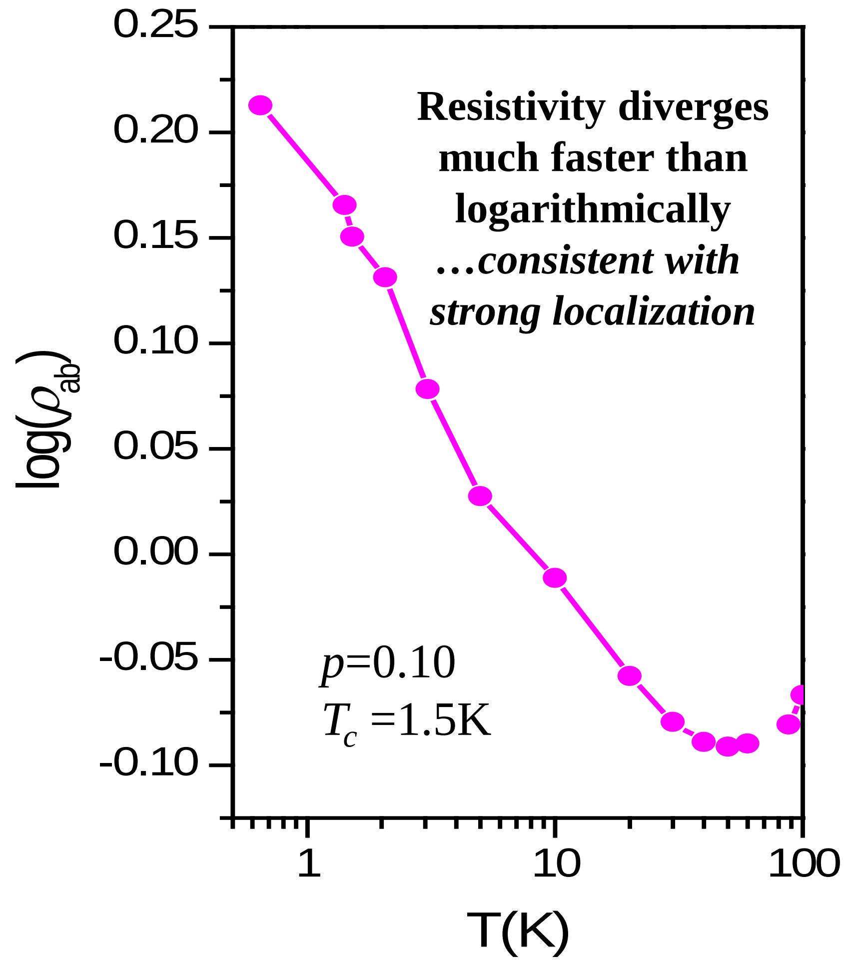
# Low Temperature Hall Effect



# Insulator-to-Superconductor boundary
# (the Underdoped Side of the Superconducting Dome)

**$Bi_2Sr_{2-x}La_xCuO_{6+d}$**



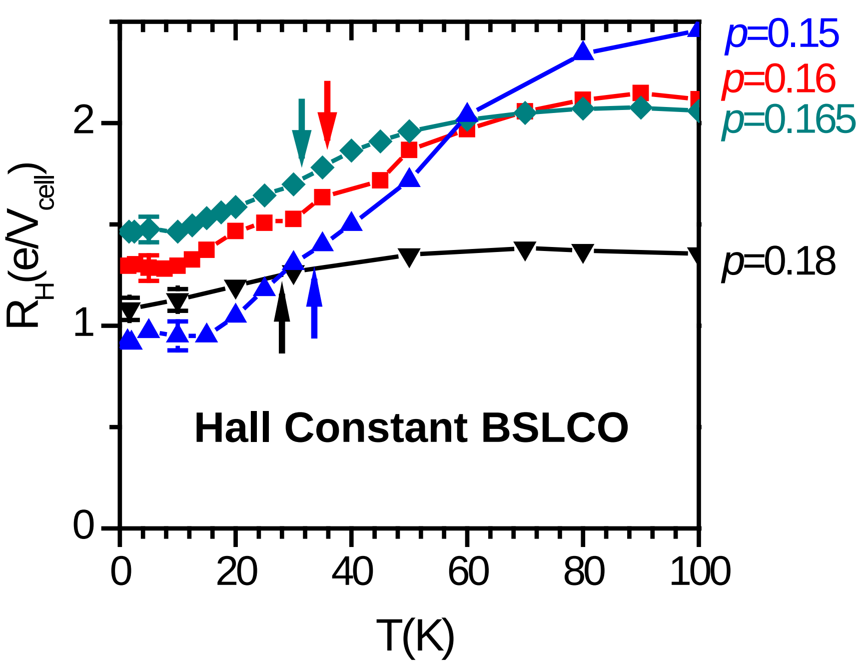
*“Signature of optimal doping in Hall-effect measurements on a high-temperature superconductor”*

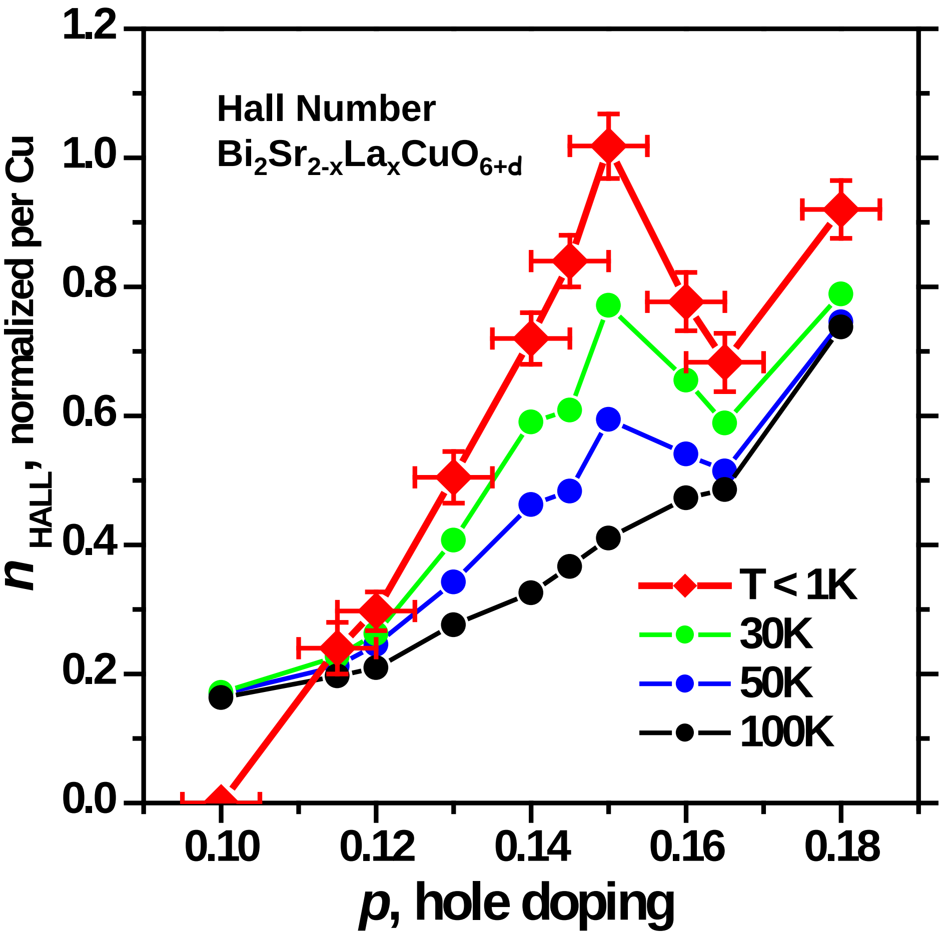
**Fedor F. Balakirev, Jonathan B. Betts, Albert Migliori, S. Ono, Yoichi Ando & Gregory S. Boebinger,** **Nature 424, 912 (2003).**

***Change in T-dependence***

***…no feature at zero-field Tc***

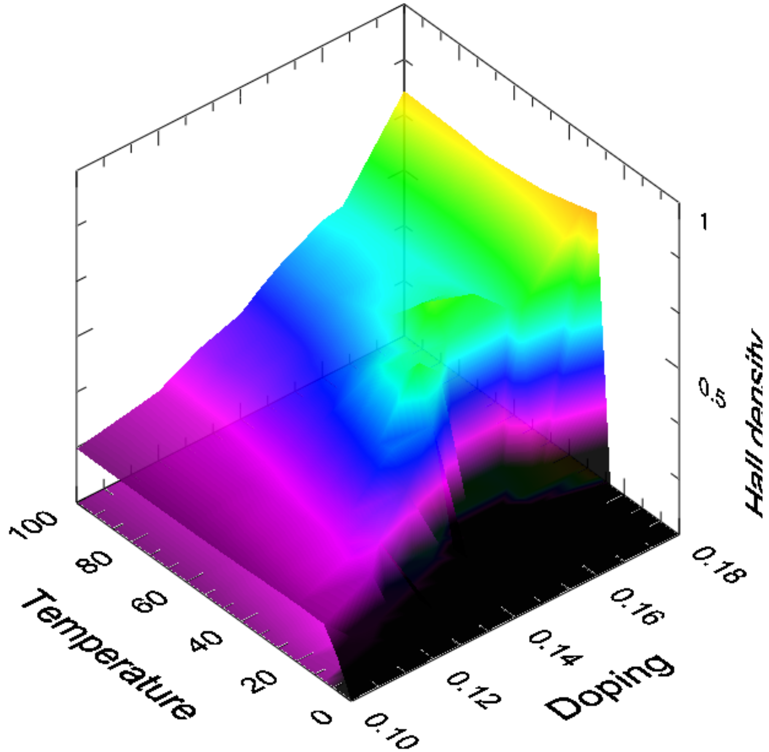
***…lose temperature dependence as T→ 0***



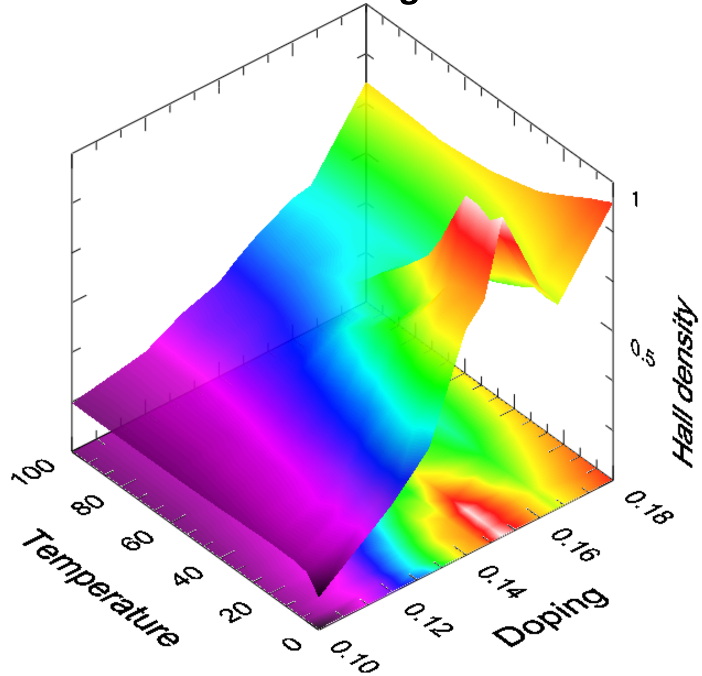

**…gives an anomaly at doping corresponding to the at highest Tc**

***We may understand the high-temperature behavior of the Hall number…***




***…but not the peak at low temperatures***

***…at temperatures below Tc***
***…and centered on the sample with the highest Tc***

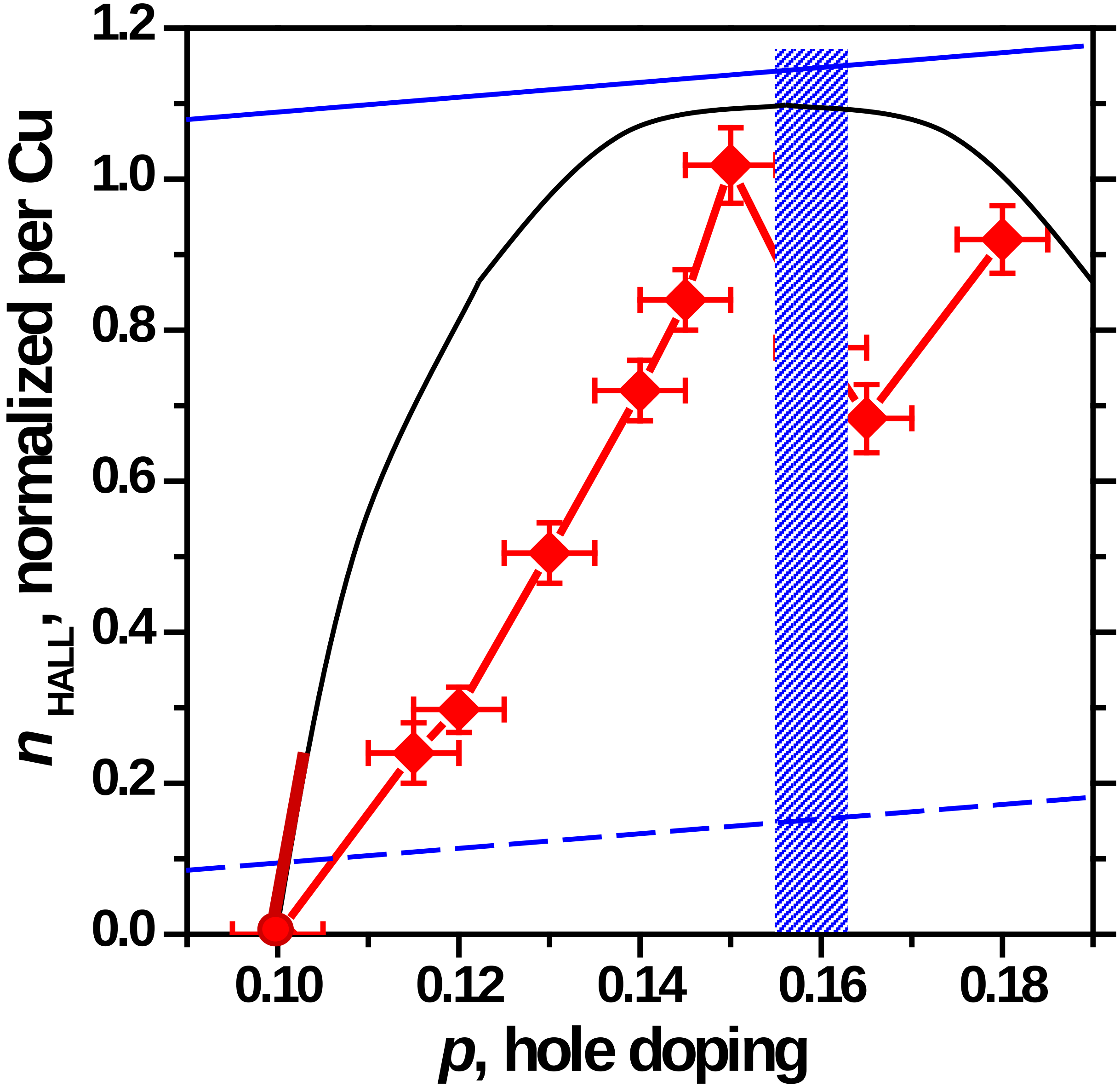



**Fedor F. Balakirev, et al, Nature 424, 912 (2003).**

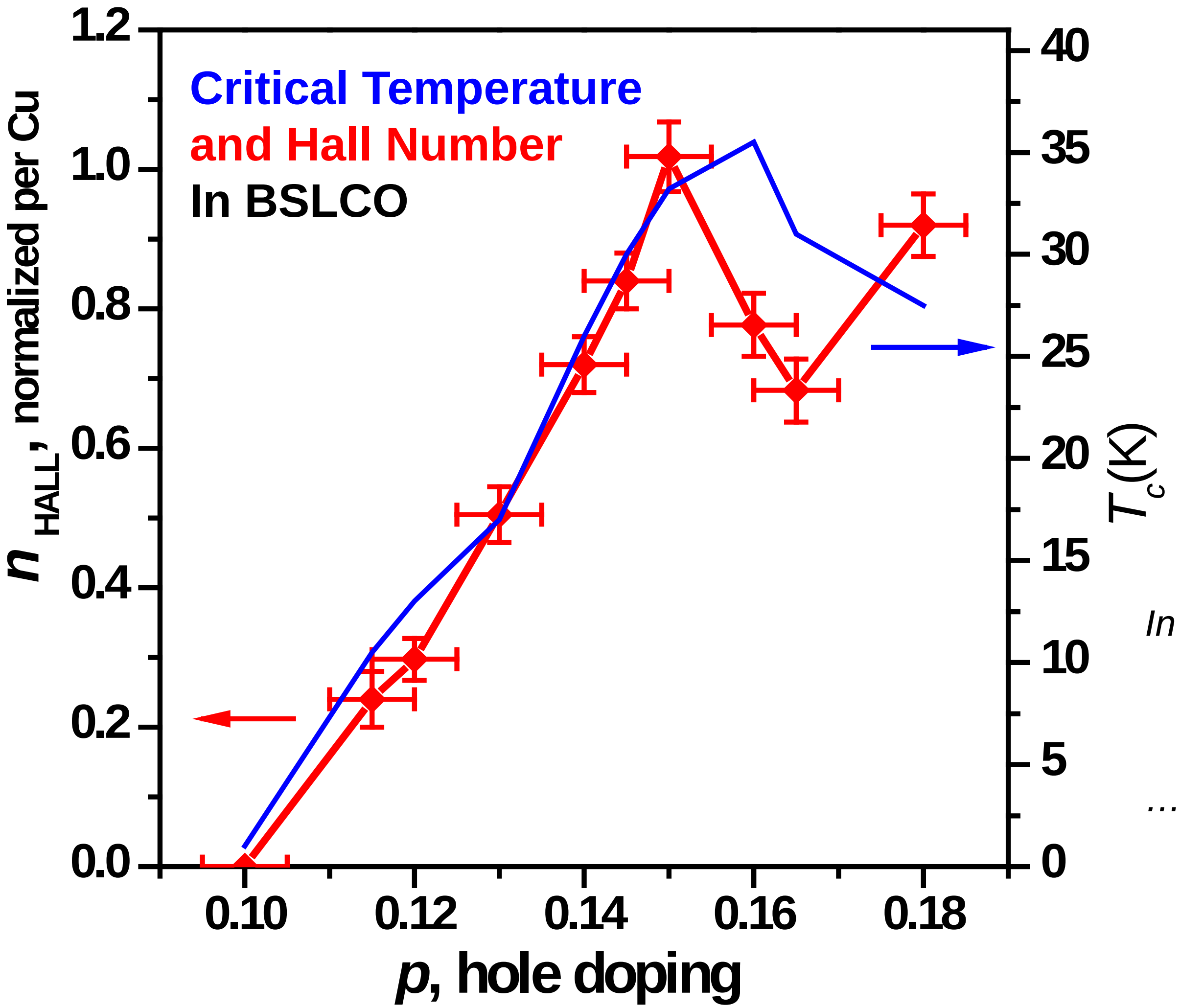
Low-Temperature
Hall Number
in $Bi_2Sr_{2-x}La_xCuO_{6+d}$

Onset of carriers
yields onset of
superconducting phase

Jump at doping
with Highest Tc



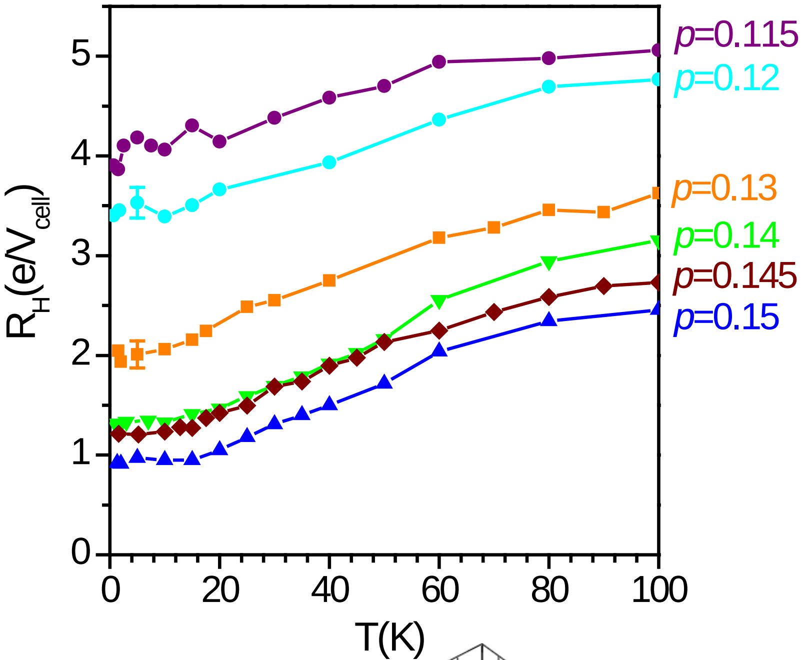
# Hall Number is correlated with $T_c$



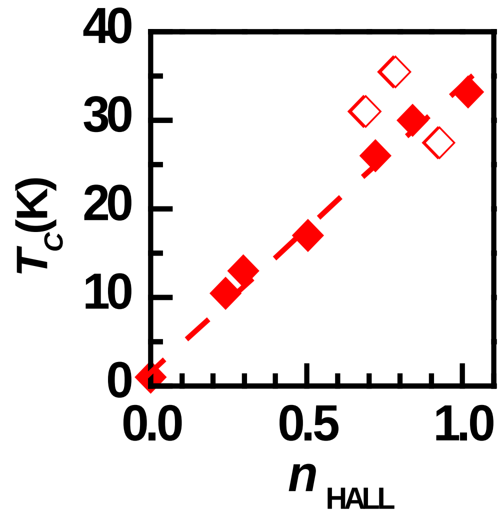

*In the underdoped regime…*

*$n_{Hall}$ shows remarkably linear correlation with $T_c$*

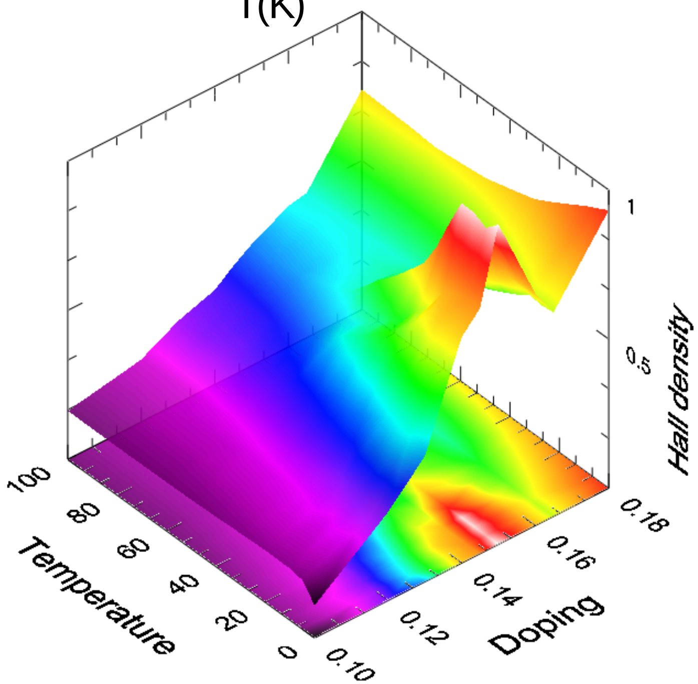
*…but not in the overdoped regime…*




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 underdoped samples*




Sharp anomaly in doping dependence of the Hall number at optimum doping
*---suggesting change in the Fermi Surface*

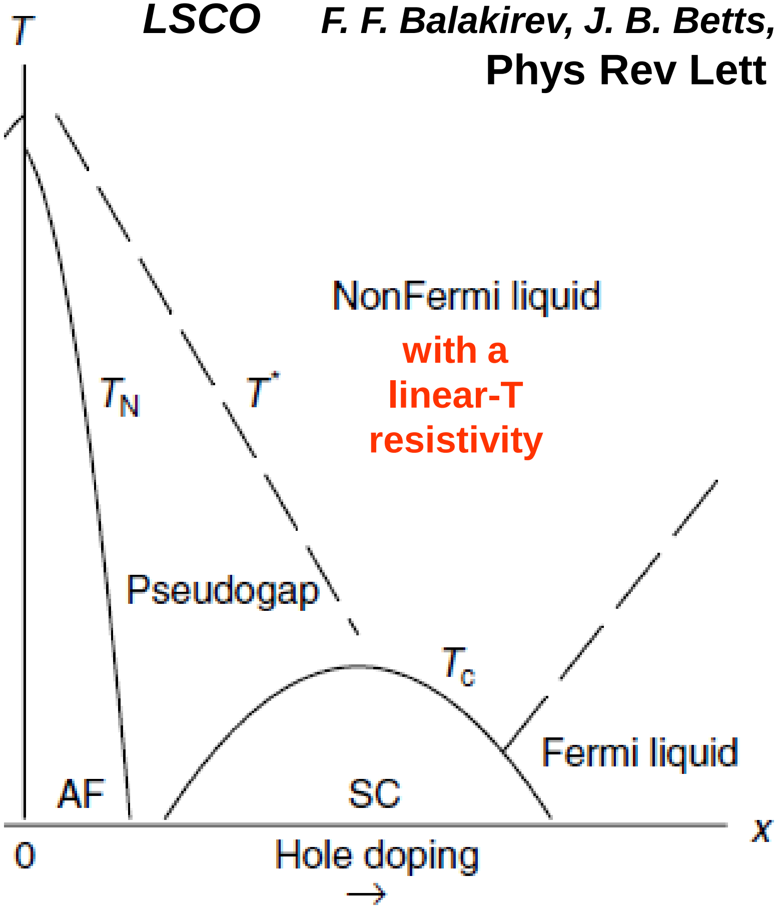
**…suggests a Quantum Critical Point governs High-Tc Superconductivity**

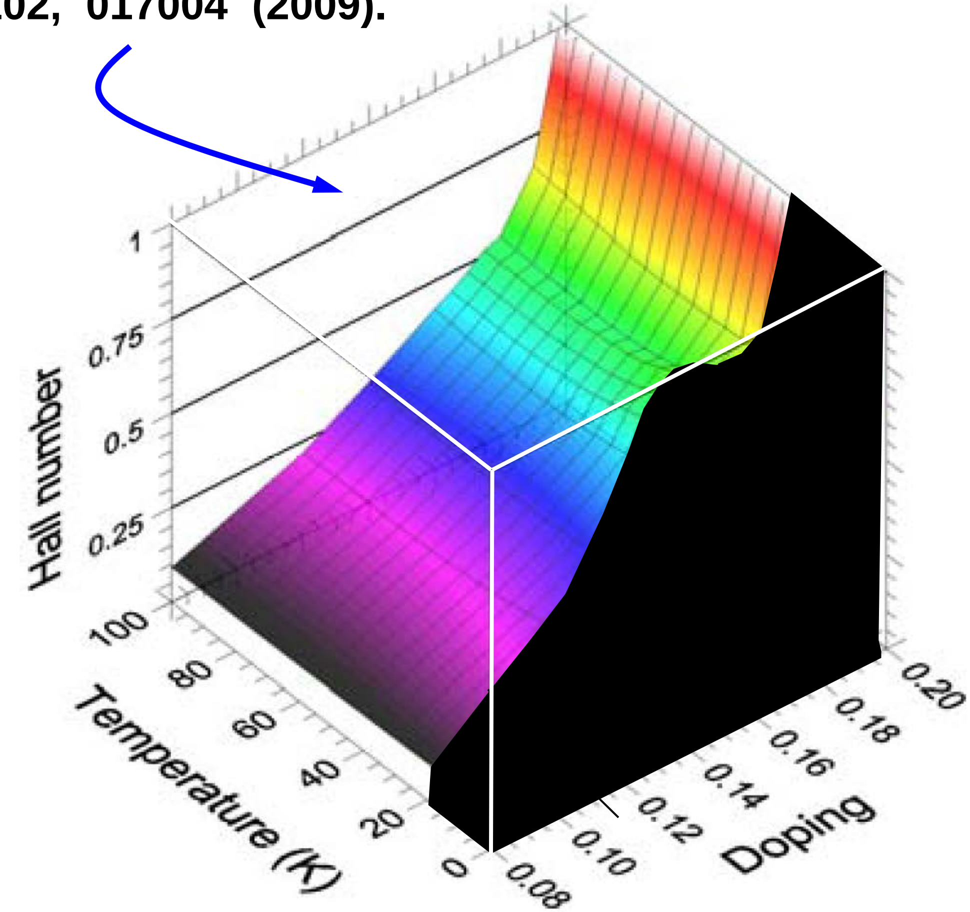
**Fedor F. Balakirev, et al, Nature 424, 912 (2003).**

# *Quantum Phase Transition at Optimum-Doping: Peak in Hall number also seen in LSCO*

***LSCO*** ***F. F. Balakirev, J. B. Betts, A. Migliori, I. Tsukada, Yoichi Ando & GSB***

**Phys Rev Lett 102, 017004 (2009).**

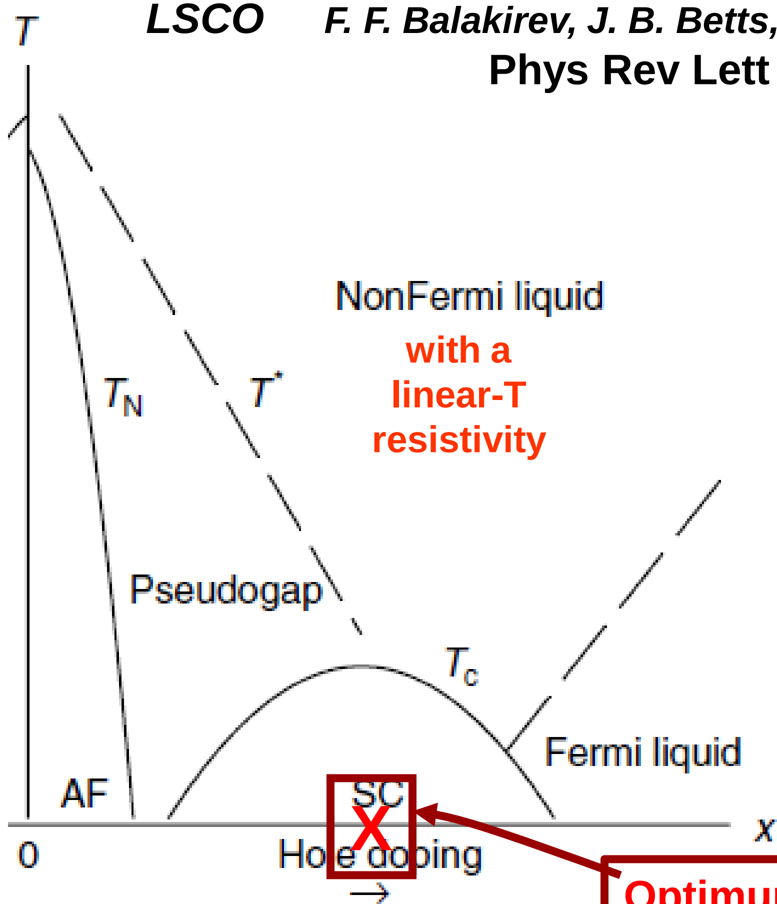


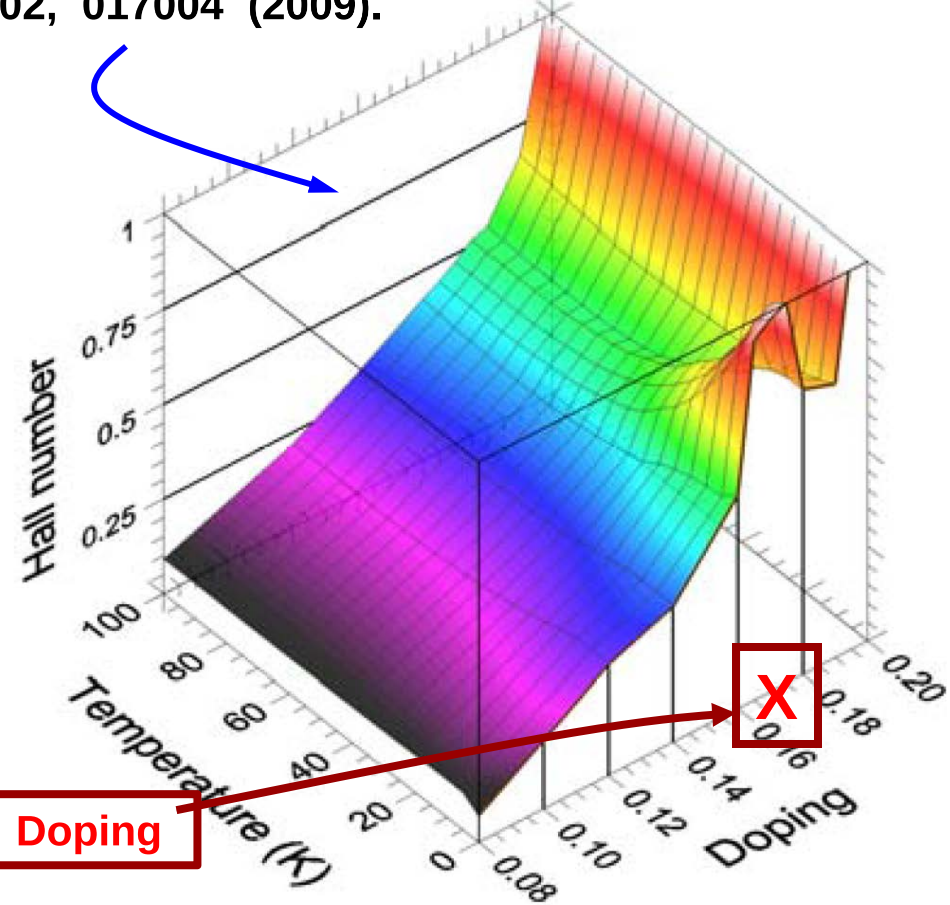



# *Quantum Phase Transition at Optimum-Doping: Peak in Hall number also seen in LSCO*

***LSCO*** ***F. F. Balakirev, J. B. Betts, A. Migliori, I. Tsukada, Yoichi Ando & GSB***

**Phys Rev Lett 102, 017004 (2009).**



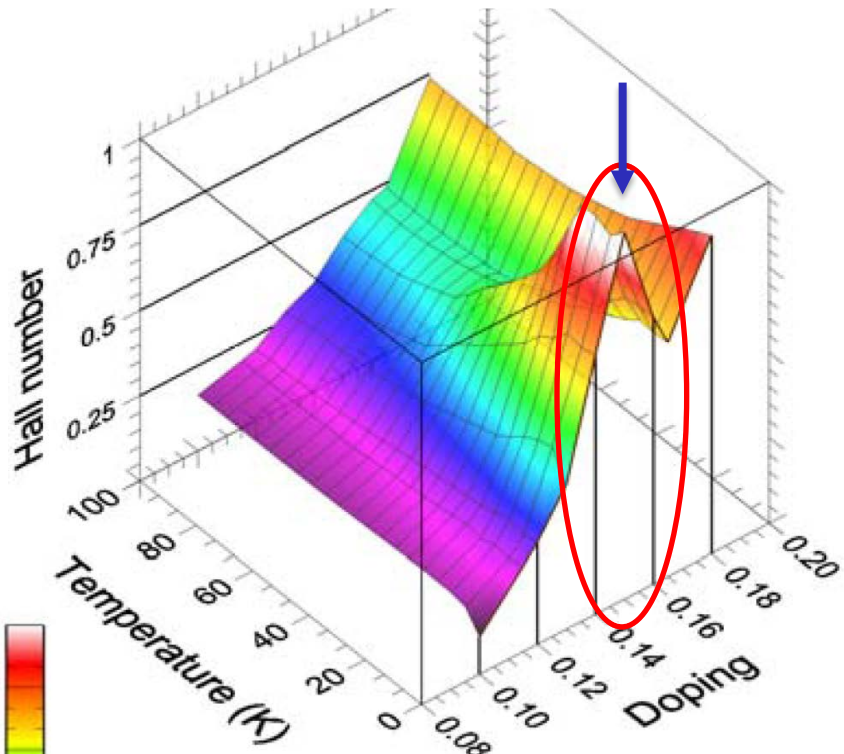




**Optimum Doping**

# *Quantum Phase Transition at Optimum-Doping: Peaks in Hall number seen in two systems*

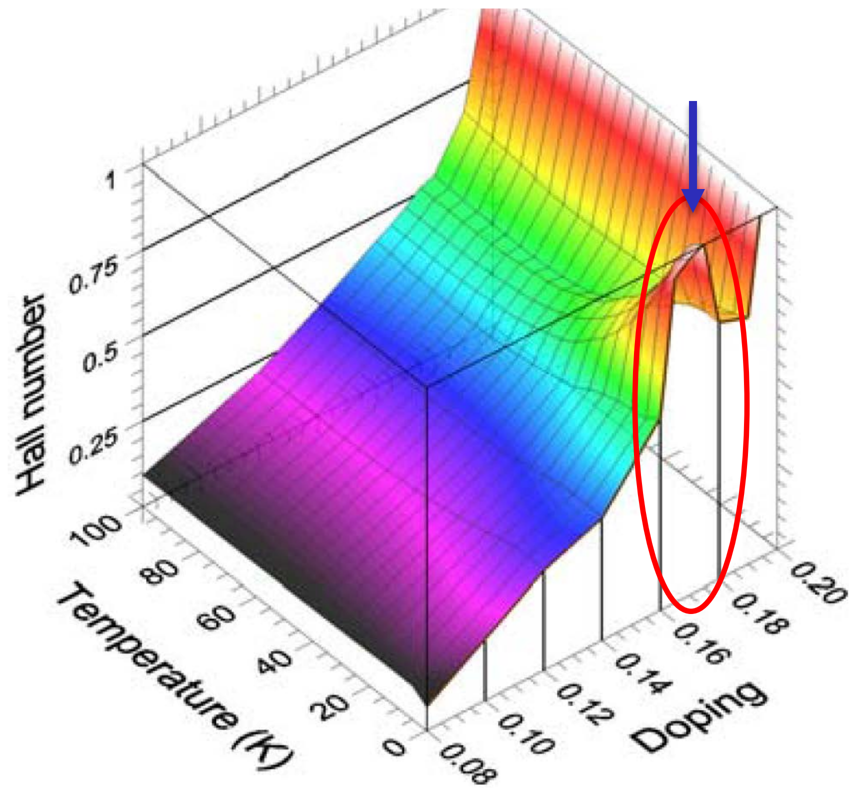
First observed in Bi-2201 in 2003

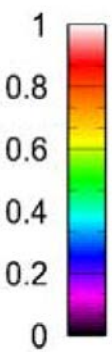
**Fedor F. Balakirev, Jonathan B. Betts, Albert Migliori, S. Ono, Yoichi Ando & Gregory S. Boebinger, Nature 424, 912 (2003). "Signature of optimal doping in Hall-effect measurements on a high-temperature superconductor"**




Now confirmed in another high-$T_c$ (LSCO)

**F. F. Balakirev, J. B. Betts, A. Migliori, I. Tsukada, Yoichi Ando, G. S. Boebinger, Phys.Rev.Lett. 102, 017004 (2009). "*Quantum Phase Transition in the Normal State of High-Tc Cuprates at Optimum Doping.*"**

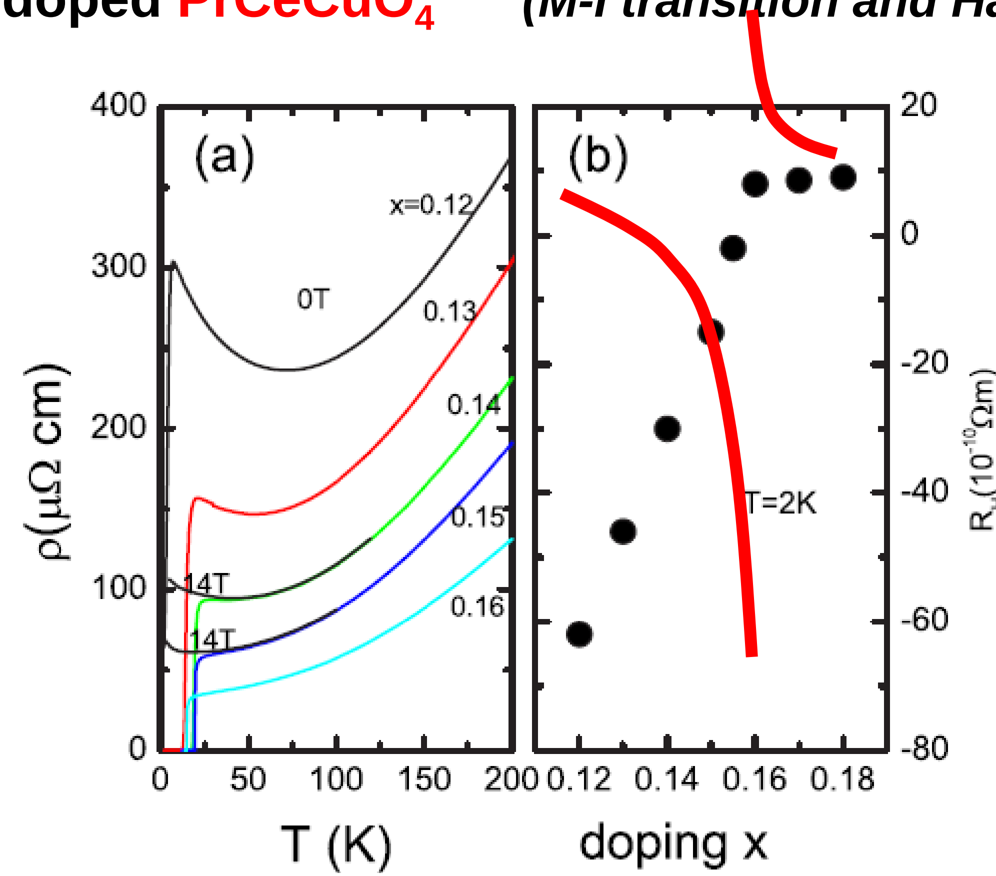



"Hall number"
( ≡ $1/R_{hall}$)
in carriers per
Cu atom

***Evidence of phase transition (but no peak) also reported in electron doped PrCeCuO4*** *W. Yu, J.S. Higgins, P. Vach & R.L. Greene,* **PRB (RC) 020503® (2007).**

**Evidence of phase transition at optimum doping also reported in electron doped $PrCeCuO_4$** ***(M-I transition and Hall changes sign)***




**RED LINES**
**~ 1/R_H**
**~ "n_Hall"**

**i.e. one gets a divergence in electron-doped samples…**

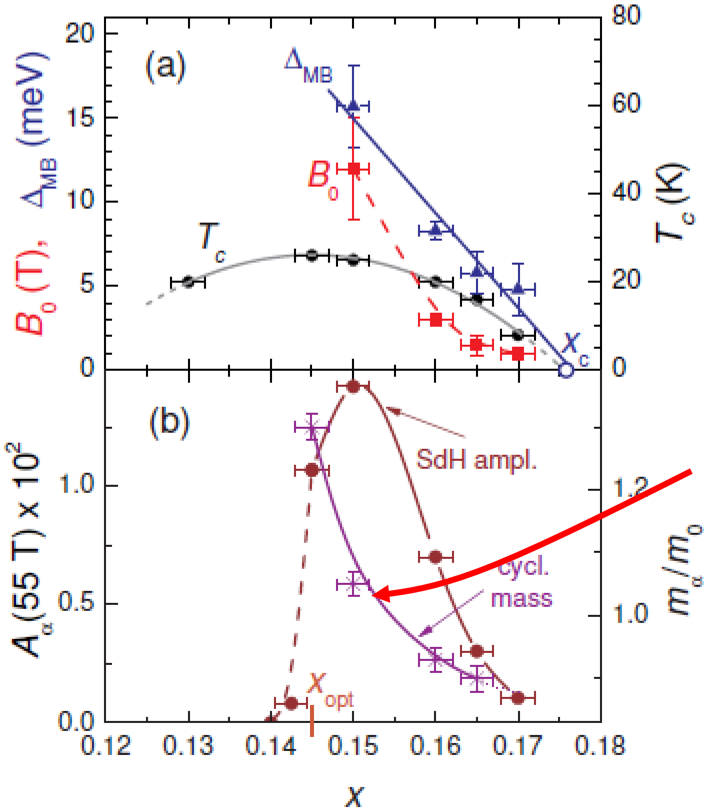
**whereas we see a peak in the hole doped samples.**

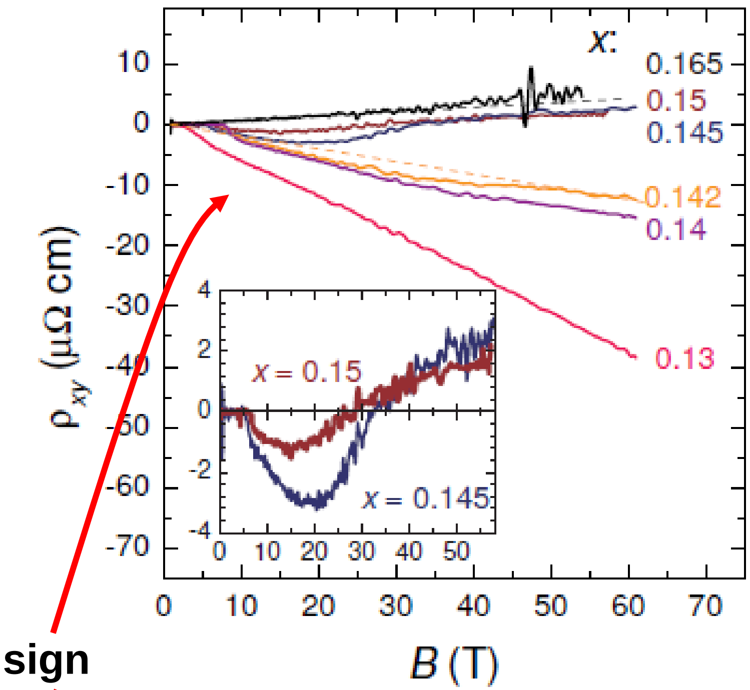
FIG. 2. (Color online) (a) The resistivity of $x=0.12$, 0.13, 0.14, 0.15, and 0.16 films at zero field and at $\mu_0 H=14T \| c$ axis. (b) The Hall coefficient of $0.12 \leqslant x \leqslant 0.18$ films ($T=2$ K).


**Transport evidence of a magnetic quantum phase transition in electron-doped high-temperature superconductors**
***W. Yu, J.S. Higgins, P. Vach & R.L. Greene,*** **PRB 76, 020503(R) (2007).**

# Evidence of phase transition at optimum doping also reported in electron doped $Nd2\text{-}xCexCuO_4$

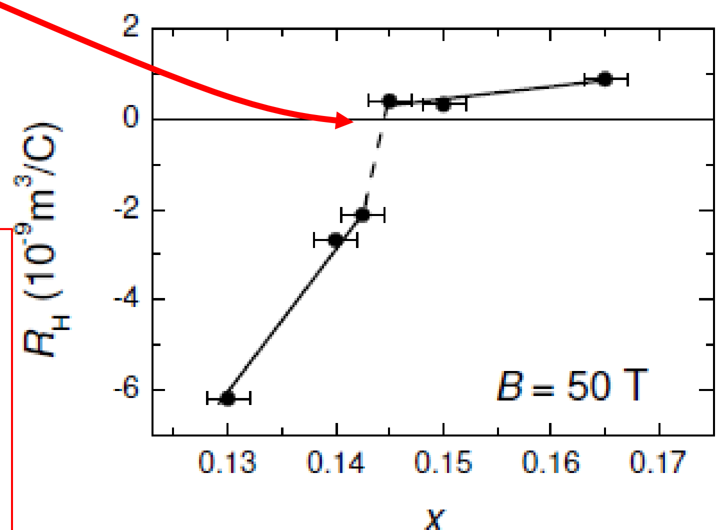
***(M-I transition and Hall changes sign)***




**Mass divergence**

**and Hall changes sign**




**Correlation between Fermi surface transformations and superconductivity in the electron-doped high-Tc superconductor** **Nd2−xCexCuO4**

T. Helm, M.V. Kartsovnik, C. Proust, B. Vignolle, C. Putzke, E. Kampert, I. Sheikin, E.-S. Choi, J.S. Brooks, N. Bittner, W. Biberacher, A. Erb, J. Wosnitza, and R. Gross

arXiv:1403.7398v1

# Back to Zero Magnetic Fields...

# (or at least <30T)

# The Signatures of the Onset of the Pseudogap

# The doping dependence of T* - what is the real high-Tc phase diagram?

**Knight Shift**

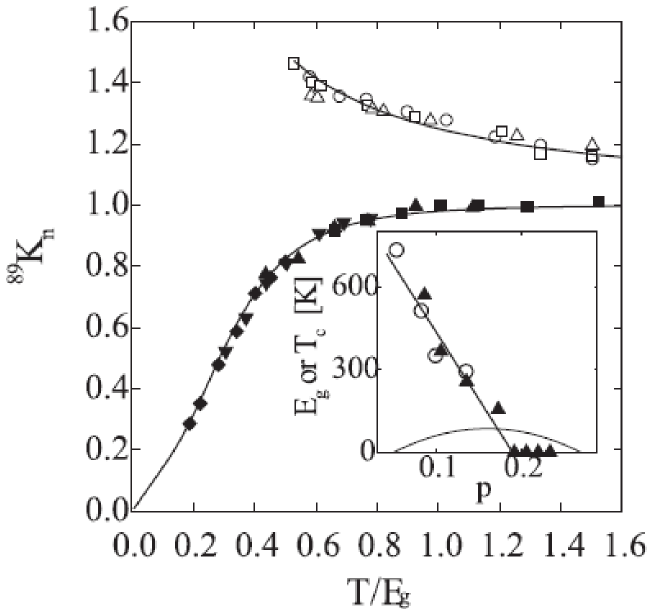



Fig. 3. The $^{89}$Y Knight shift for $Y_{0.8}Ca_{0.2}Ba_2Cu_3O_{7-\delta}$ with different $\delta$ values scaled as a function of $T/E_g$ (◆) $T_c = 47.5$, $p = 0.086$; (▼) $T_c = 65.8$, $p = 0.107$; (▲) $T_c = 83.2$ K, $p = 0.140$; (■) $T_c = 86$ K, $p = 0.160$; (△) $T_c = 72.1$ K, $p = 0.204$; (□) $T_c = 60$ K, $p = 0.221$; (○) $T_c = 47.5$ K, $p = 0.234$). Inset: $E_g$ values obtained from the scaling, 0.1 Ca (○) and 0.2 Ca (▲).

**Specific Heat**

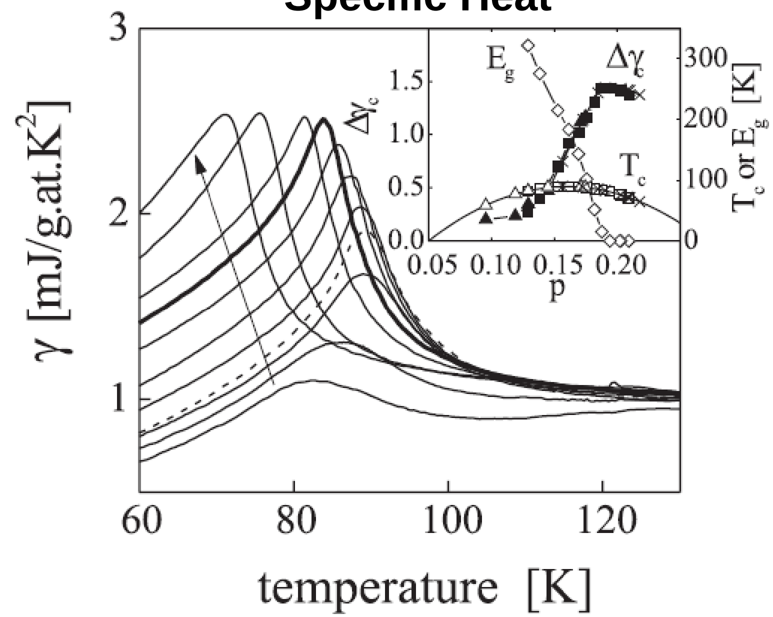



Fig. 5. The $T$-dependence of $\gamma \equiv C_p/T$ for Bi-2212 with different oxygen contents spanning from underdoped to overdoped (indicated by direction of arrow). The curves for critical and optimal doping are indicated by the bold and dashed curves, respectively. Inset: the doping dependence of the increment in $\gamma$ for $Bi_{2.1}Sr_{1.9}CaCu_2O_{8+\delta}$ (■), $Bi_{1.9}Pb_{0.2}Sr_{1.9}CaCu_2O_{8+\delta}$ (×) and $Bi_{2.1}Sr_{1.9}Ca_{0.7}Y_{0.3}Cu_2O_{8+\delta}$ (▲). In each case, $\Delta\gamma_c$ falls abruptly at $p = 0.19$ with the opening of the pseudogap. $E_g$ values obtained from a scaling analysis are shown by the diamonds.

*J.L. Tallon, J.W. Loram / Physica C 349 (2001) 53–68*

# The doping dependence of T* - what is the real high-Tc phase diagram?

**Knight Shift, Resistivity, Specific Heat**

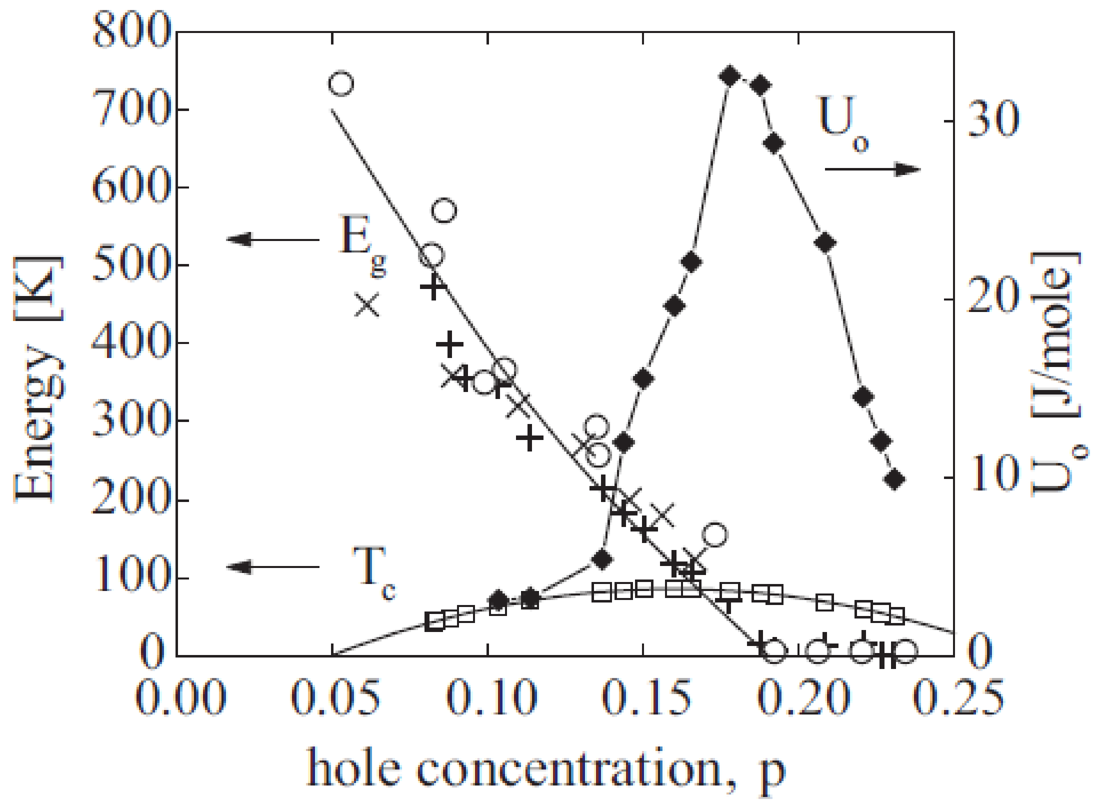
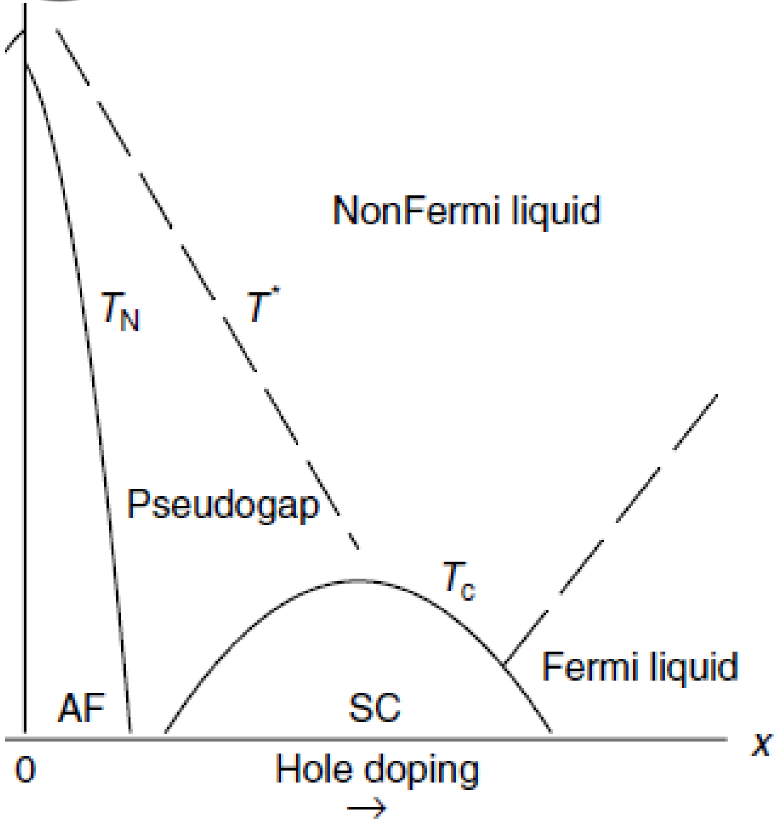



Fig. 4. The doping dependence of $E_g$ for $Y_{0.8}Ca_{0.2}Ba_2Cu_3O_{7-\delta}$ from $^{89}K_s$ (○), from heat capacity (+) and from scaling of the resistivity (×), of the condensation energy $U_0$ (◆) and of $T_c$ (□).

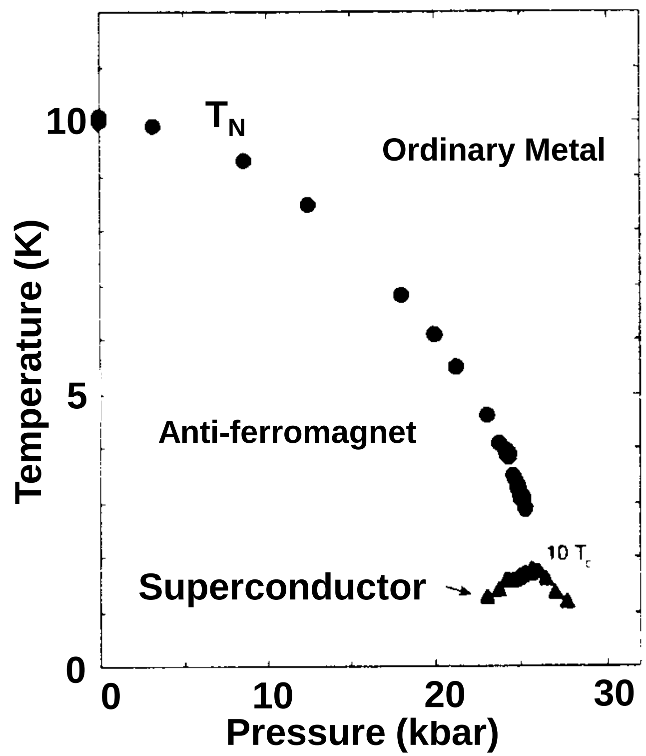
*J.L. Tallon, J.W. Loram / Physica C 349 (2001) 53–68*

# Superconductivity is Stabilized Near Quantum Critical Points, ***but no one knows why.***



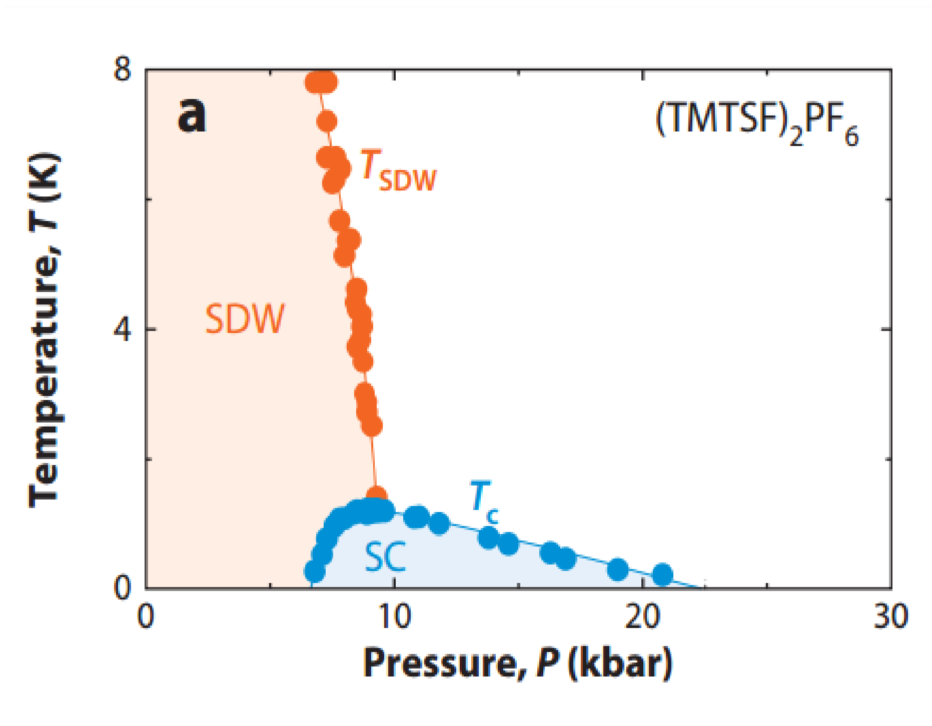

**Hole-doped High-Temperature Superconducting Cuprate Maximum Tc ~ 40-150K**

N.D. Mathur et al., Nature **394**, 39 (1998)

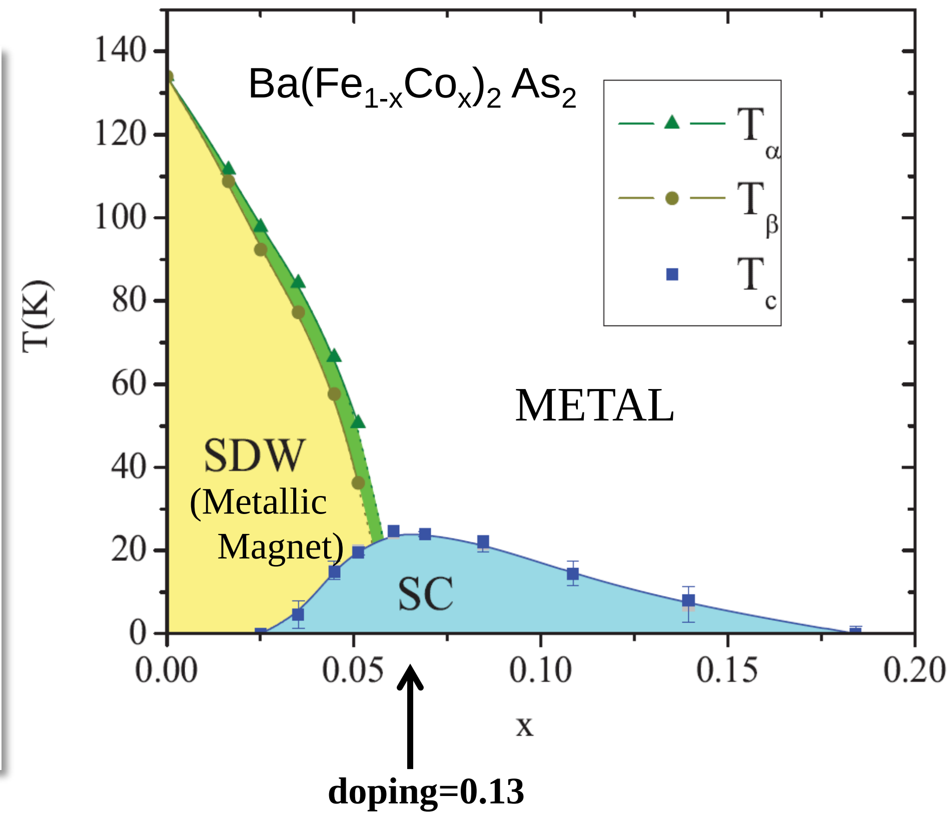



**$CeIn_3$ a Heavy Fermion Compound with Superconducting Tc < 1 K**

**Superconductivity is Stabilized**
**Near Quantum Critical Points,**
***but no one knows why.***

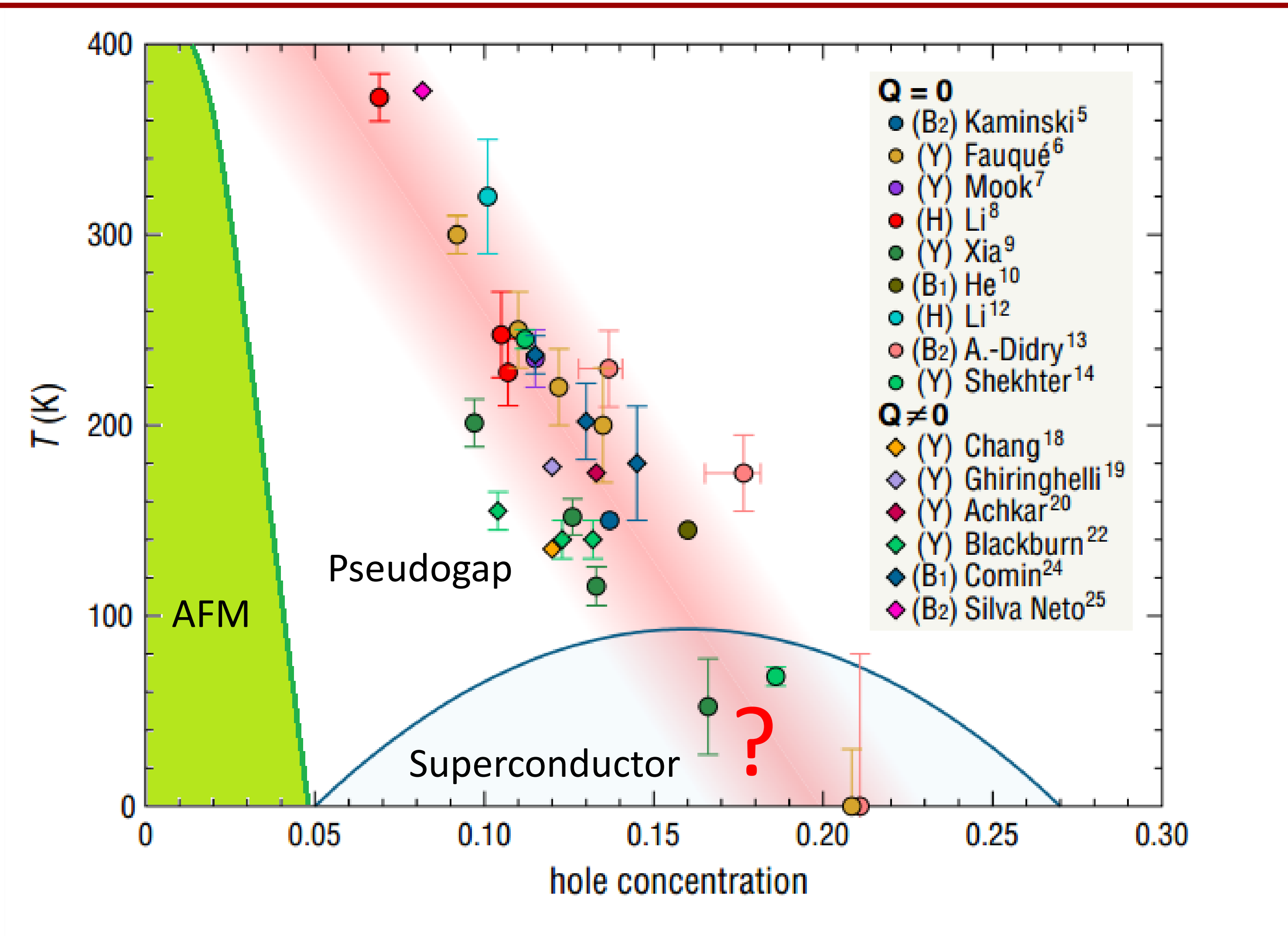



L. Taillefer, Annual Review of Condensed Matter Physics (2010)




Jiun-Haw Chu, James G. Analytis, Chris Kucharczyk, Ian R. Fisher, Phys. Rev. **B 79**, 014506 (2009)
*Determination of the phase diagram of the electron doped superconductor Ba(Fe$_{1-x}$Co$_x$)$_2$ As$_2$*

***As the years go by….***
***Many Broken Symmetries Discovered at the Pseudogap Onset***




K. Fujita *et al.*, Science 344, 612 (2014)

# Is the Onset of the Pseudogap

# a Thermodynamic Transition?

Los Alamos NATIONAL LABORATORY EST. 1943

# “Ultrasound sees all” -Albert Migliori

- Sound speeds depend on compressibility, a thermodynamic susceptibility.
- Any phase transition has a signature in the compressibility.
- Let’s see what a superconductor does (theory by an experimentalist).

energy $$\Delta F\big|_{Tc} = H_c^2\left(T_c, B, P\right) = 0$$

$$H_c(T_c) = 0$$

volume $$\left.\frac{\partial \Delta F}{\partial P}\right|_{Tc} = \Delta V\big|_{Tc} = H_c \left.\frac{\partial H_c}{\partial P}\right|_{Tc} = 0$$

This term never zero

stiffness $$\left.\frac{\partial^2 \Delta F}{\partial P^2}\right|_{Tc} = \left.\frac{\partial \Delta V}{\partial P}\right|_{Tc} = \frac{1}{c_{ij}} = H_c \left.\frac{\partial^2 H_c}{\partial P^2}\right|_{Tc} + \left.\left(\frac{\partial H_c}{\partial P}\right)^2\right|_{Tc}$$

There is *always* a step discontinuity at the superconducting transition in elastic stiffness.

Arkady Shekhter, B.J. Ramshaw, Ruixing Liang, W.N. Hardy, D.A. Bonn, Fedor F. Balakirev, Ross McDonald, Jon B. Betts, Scott C. Riggs, Albert Migliori, Nature 498, 75 (2013) doi:10.1038/nature12165

Los Alamos NATIONAL LABORATORY EST 1943

# Resonant Ultrasound Spectroscopy is simple

**Resonant ultrasound spectroscopy (RUS) uses the mechanical resonances of small samples to extract all the components of the elastic tensor at the same time.**

**RUS and other ultrasound techniques measure the *adiabatic* moduli-typically within 1% of isothermal moduli in solids.**

**Only RUS measures the true thermodynamic attenuation, independent of defects and scattering, transducer misalignment.**

PROOF COPY 232512RSI

REVIEW OF SCIENTIFIC INSTRUMENTS **76**, 1 (2005)

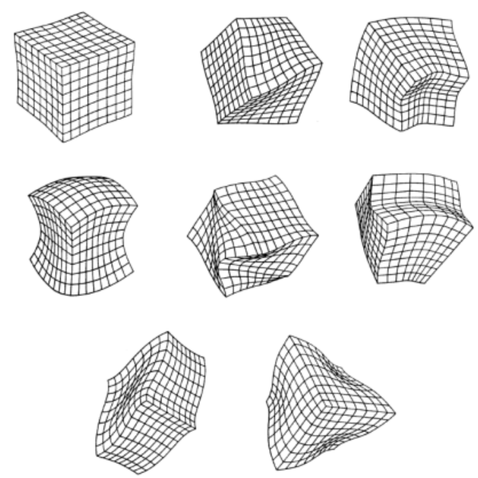
**Implementation of a modern resonant ultrasound spectroscopy system for the measurement of the elastic moduli of small solid specimens**

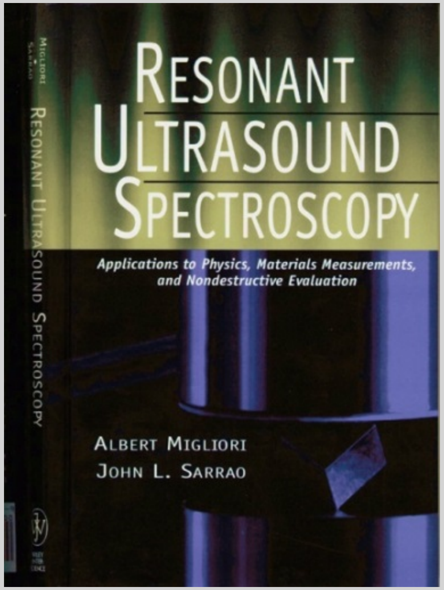
Albert Migliori
*National High Magnetic Field Laboratory of the Los Alamos National Laboratory, Los Alamos, New Mexico 87545*

J. D. Maynard
*The Pennsylvania State University, University Park, Pennsylvania 16802*

(Received 8 August 2005; accepted 24 October 2005)

The use of mechanical resonances to determine the elastic moduli of materials of interest to condensed-matter physics, engineering, materials science and more is a steadily evolving process. With the advent of massive computing capability in an ordinary personal computer, it is now possible to find all the elastic moduli of low-symmetry solids using sophisticated analysis of a set of the lowest resonances. This process, dubbed "resonant ultrasound spectroscopy" or RUS, provides the highest absolute accuracy of any routine elastic modulus measurement technique, and it does this quickly on small samples. RUS has been reviewed extensively elsewhere, but still lacking is a complete description of how to make such measurements with hardware and software easily available to the general science community. In this article, we describe how to implement realistically a useful RUS system. © *2005 American Institute of Physics.*
[DOI: 10.1063/1.2140494]





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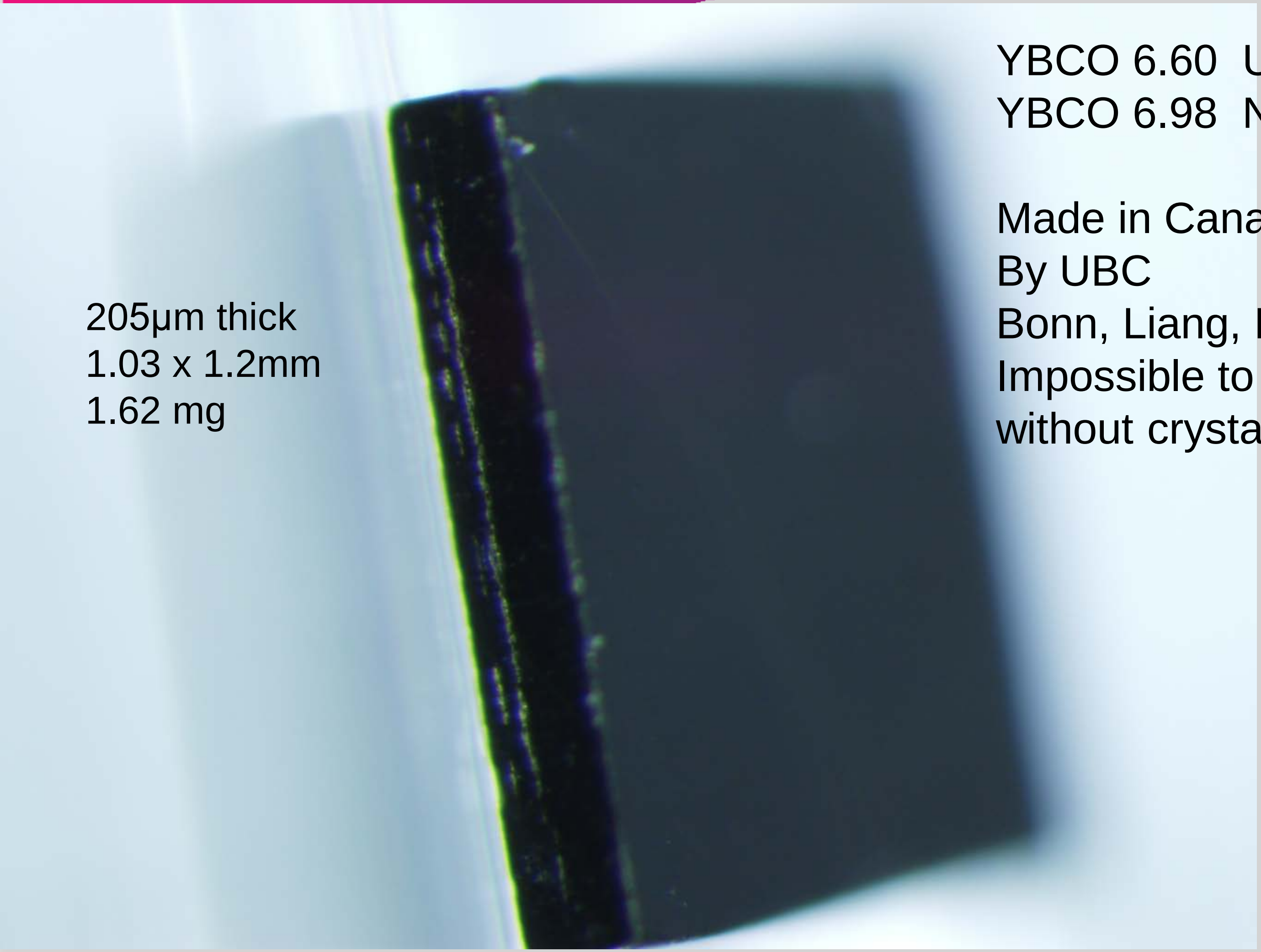
# Tiny single detwinned crystals are *required*

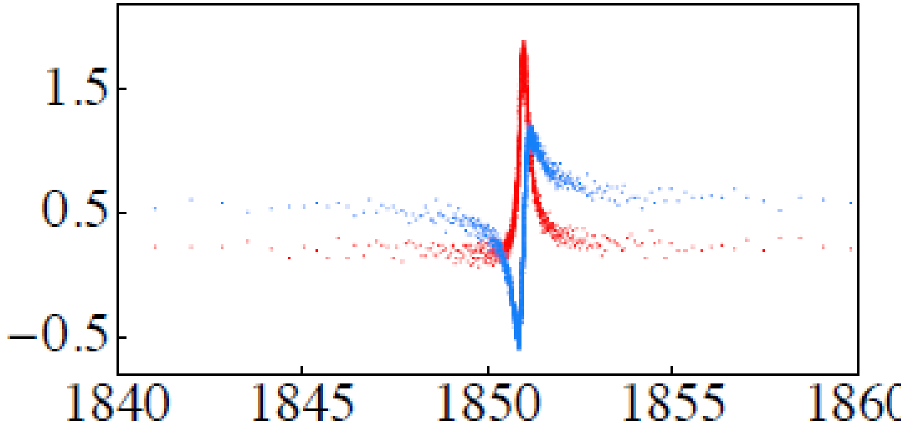


205µm thick
1.03 x 1.2mm
1.62 mg

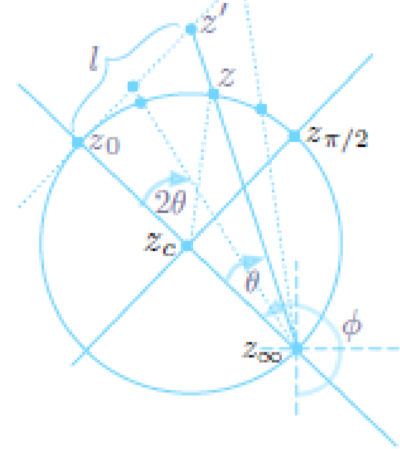
YBCO 6.60 Underdoped $T_c$=61.6K
YBCO 6.98 Near optimal $T_c$=88.0K

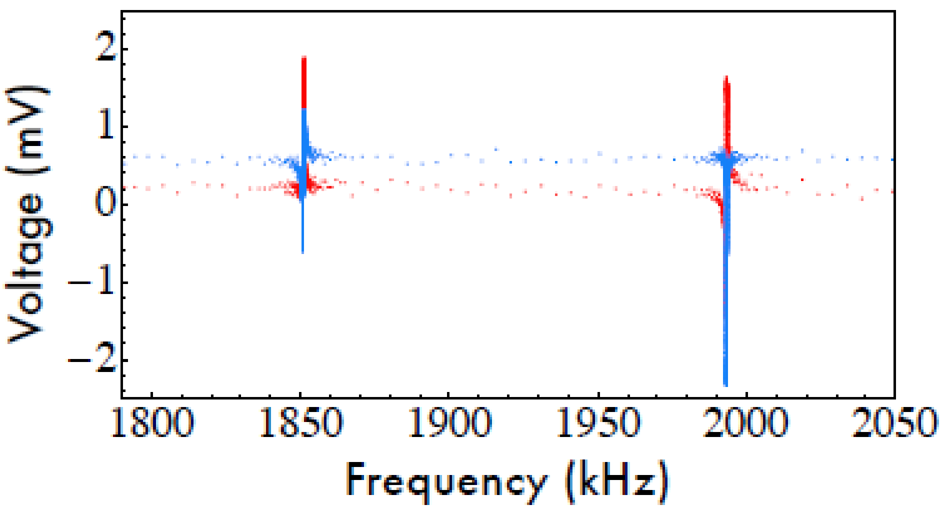
Made in Canada
By UBC
Bonn, Liang, Hardy
Impossible to do what we did without crystals of this quality

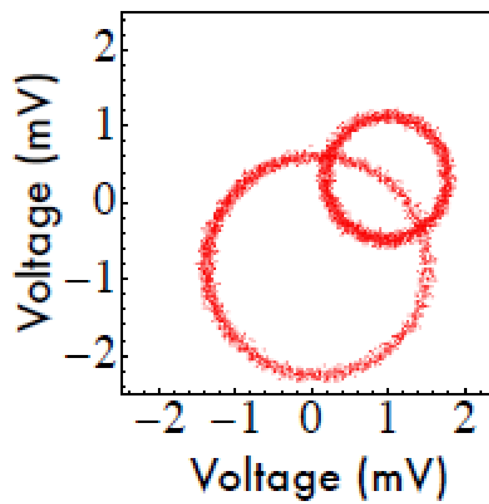
# Resonant Ultrasound Spectroscopy — technique



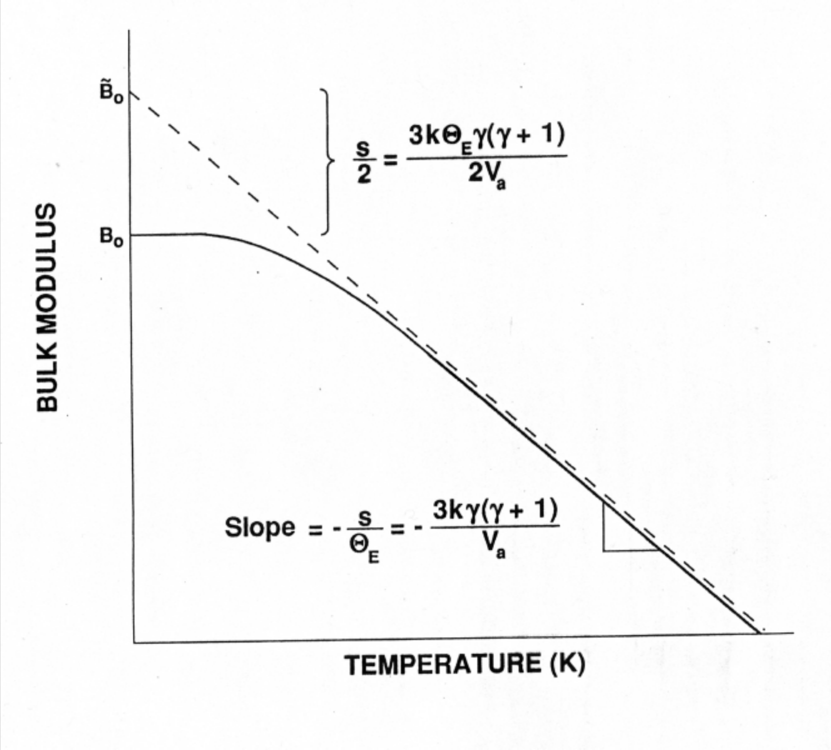

$$z = z_\infty + \frac{Ae^{i\phi}}{\omega - \omega_0 + \frac{i\Gamma}{2}}$$

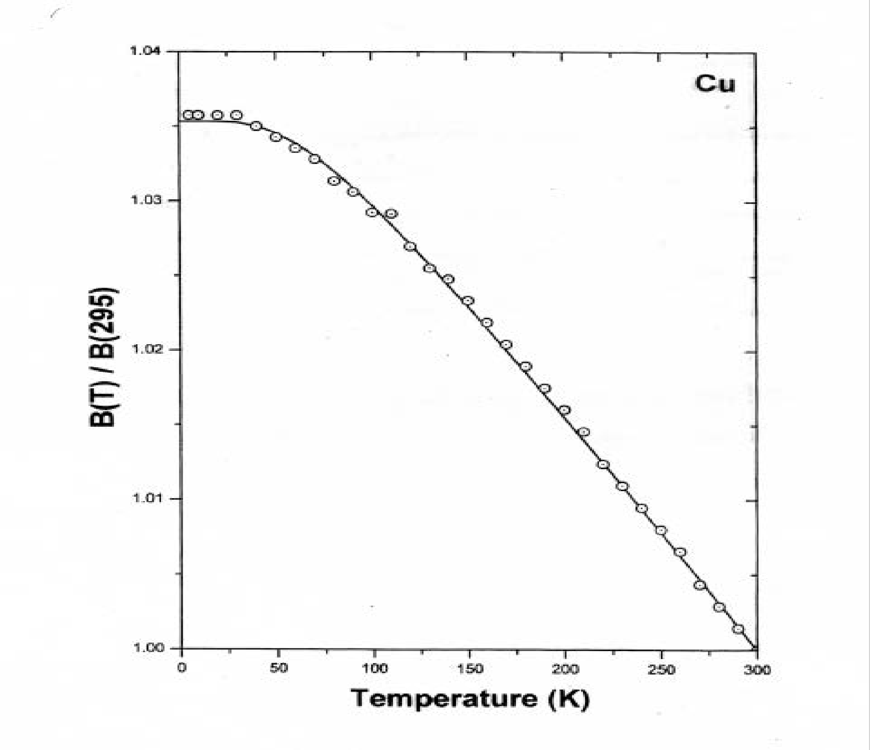


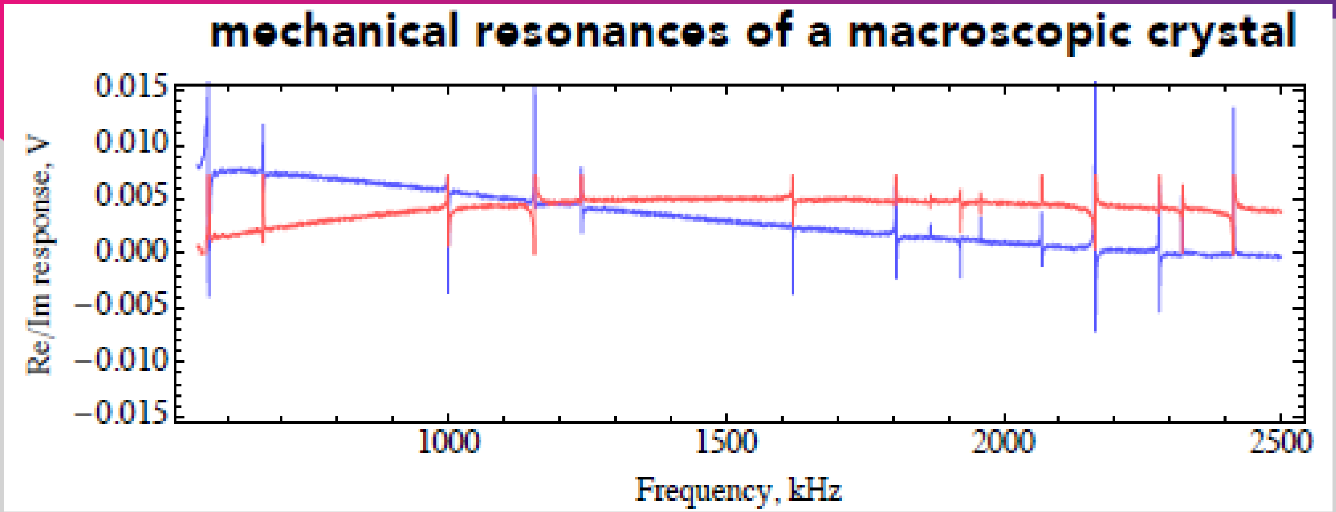



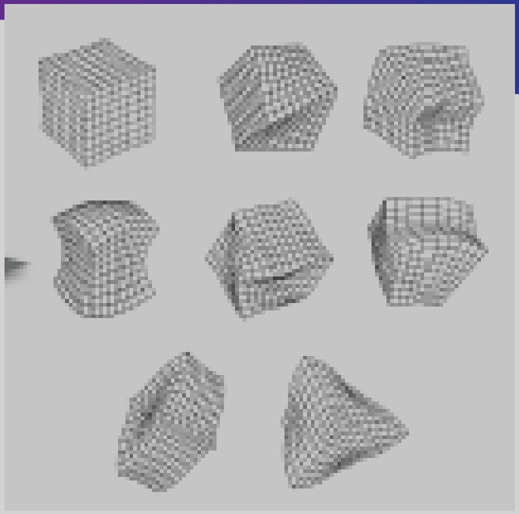
# What is normal?

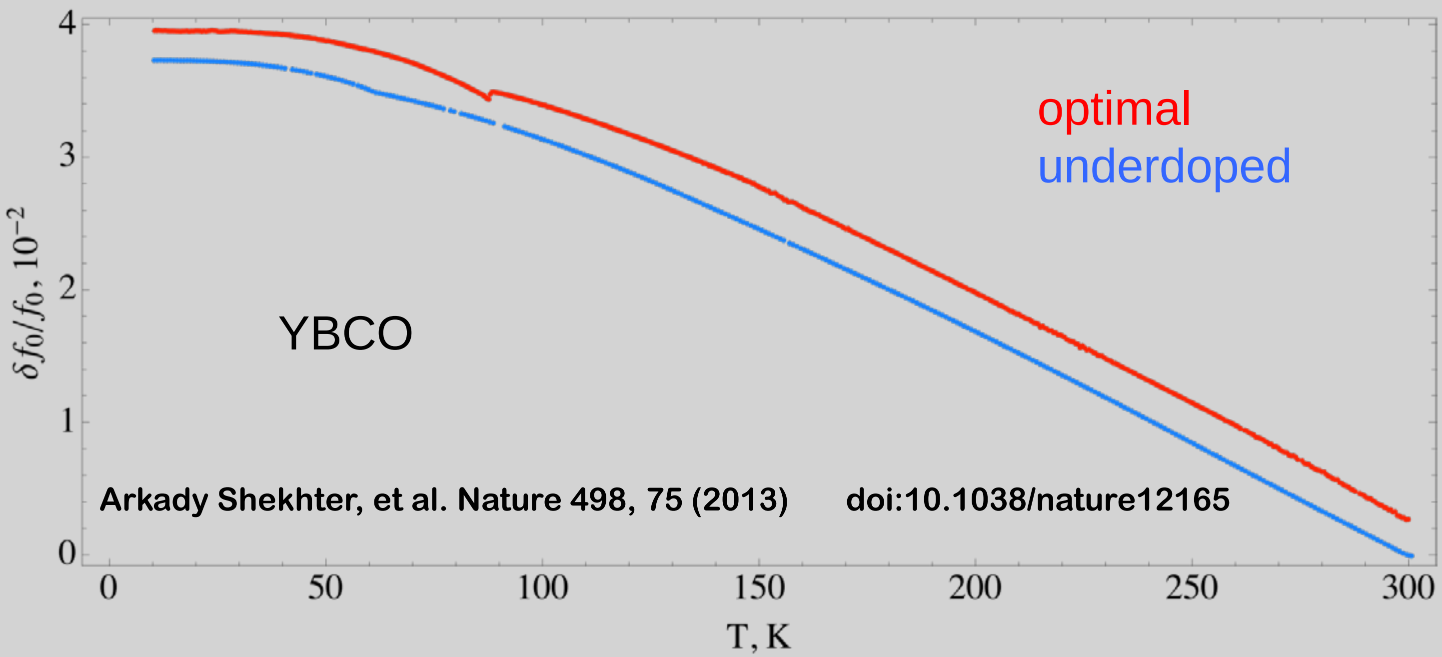


# Overall smoothness and normal behavior






Arkady Shekhter, et al. Nature 498, 75 (2013) doi:10.1038/nature12165

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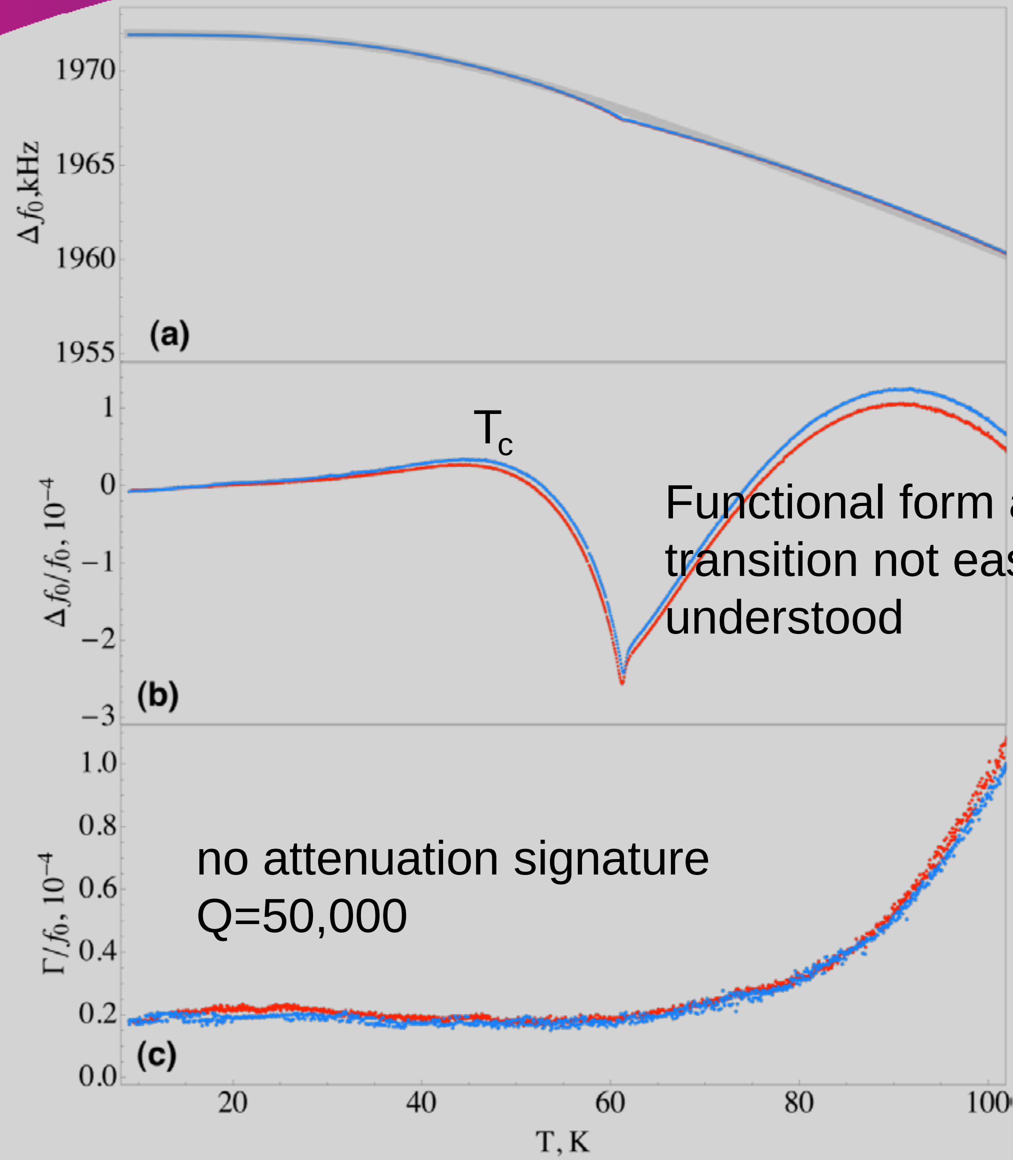
# Elastic moduli and attenuation in underdoped YBCO at superconducting transition through the looking glass




Functional form around transition not easily understood

no attenuation signature
Q=50,000

**Arkady Shekhter, et al.**
**Nature 498, 75 (2013)**
**doi:10.1038/nature12165**

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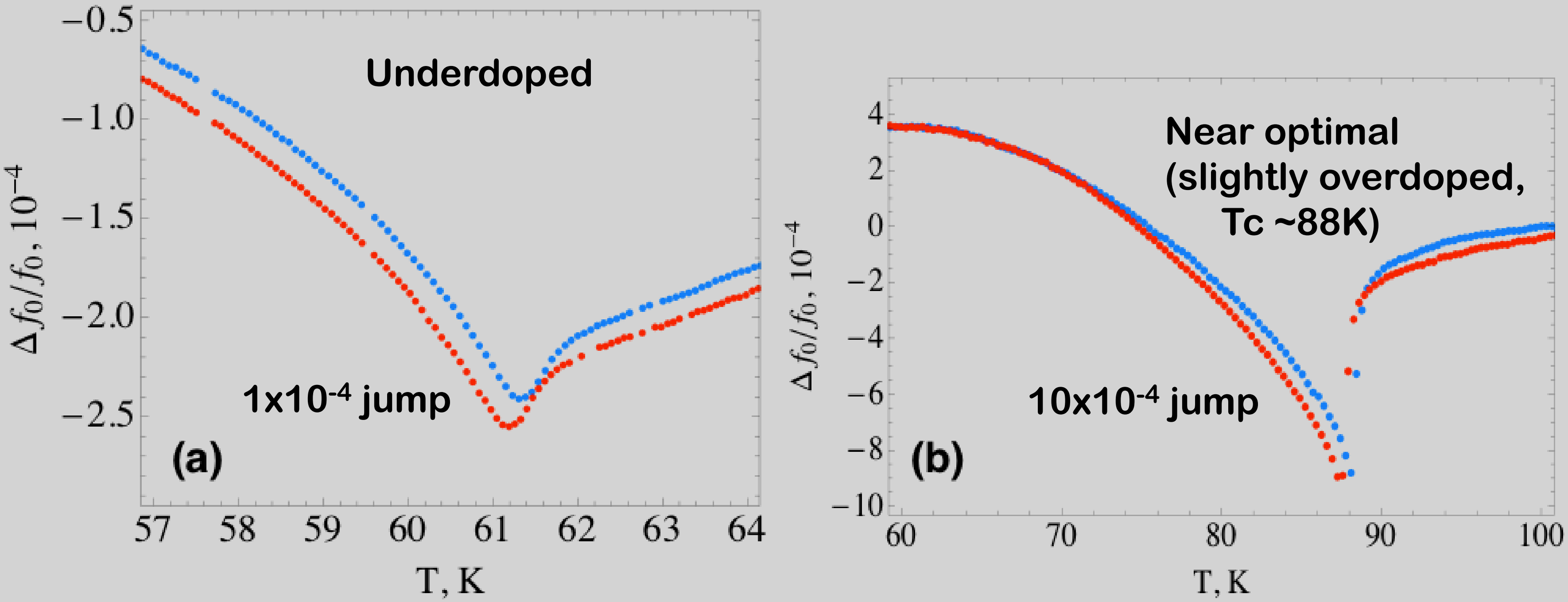
# Detail of the superconducting transition seen through even stronger looking glass

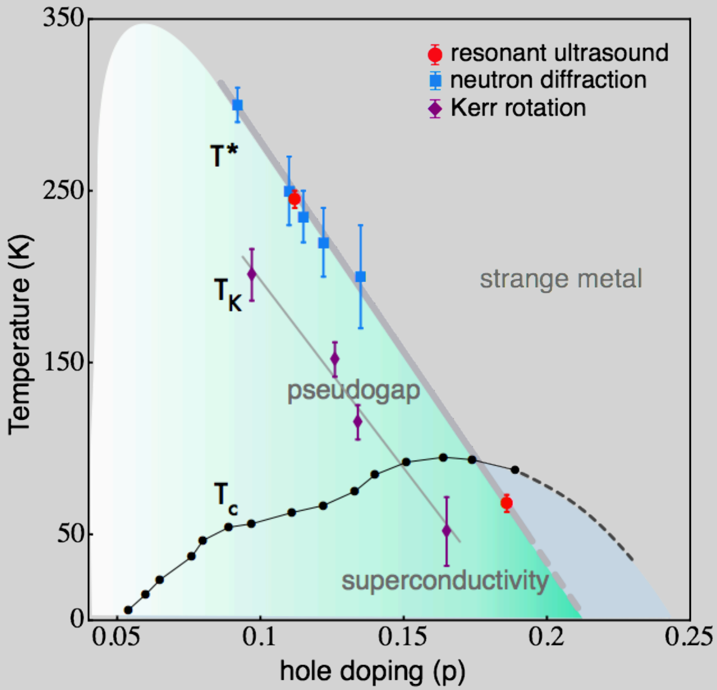
- Step size depends on superconducting fraction.
- Transition width is sharper than most observations of YBCO.
- Size of jump makes sense if we observed full thermodynamic signature: $(T_c/T_f)^2$ (no preformed pairs).



LA-UR-14-20864 64

# Pseudogap boundary in YBCO 6.98 (overdoped) Tc=88.0K

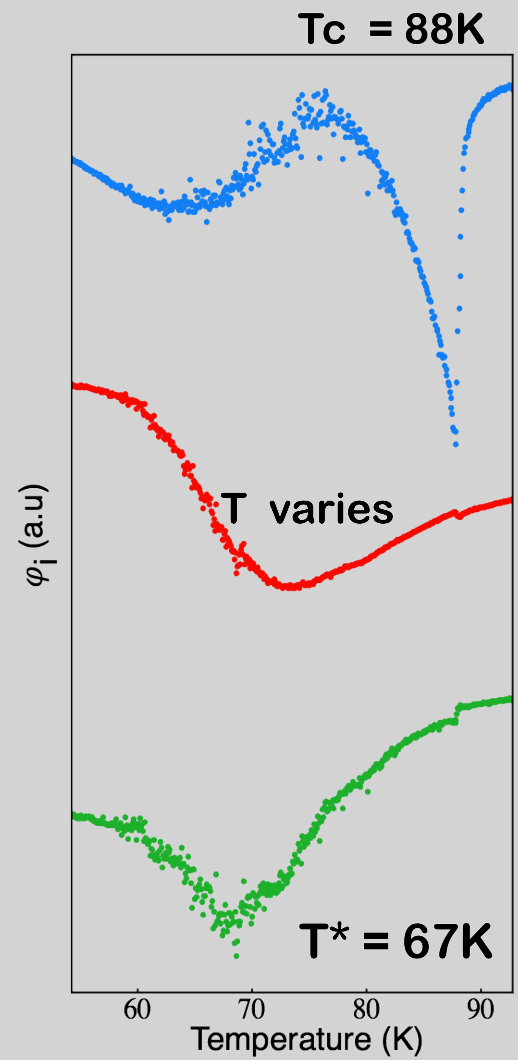
**Perform a linear component analysis of the temperature dependence of multiple resonances**




Superconductivity (this feature appears at the same temperature for all resonances)

Dissipation feature at temperatures that track frequency of each resonance (thus not a phase transition)

Pseudogap (this feature appears at the same temperature for all resonances)




- Each resonance is a combination of the thermal response of several elastic moduli.
- Deconvolution produces the three types of thermal responses shown at right.

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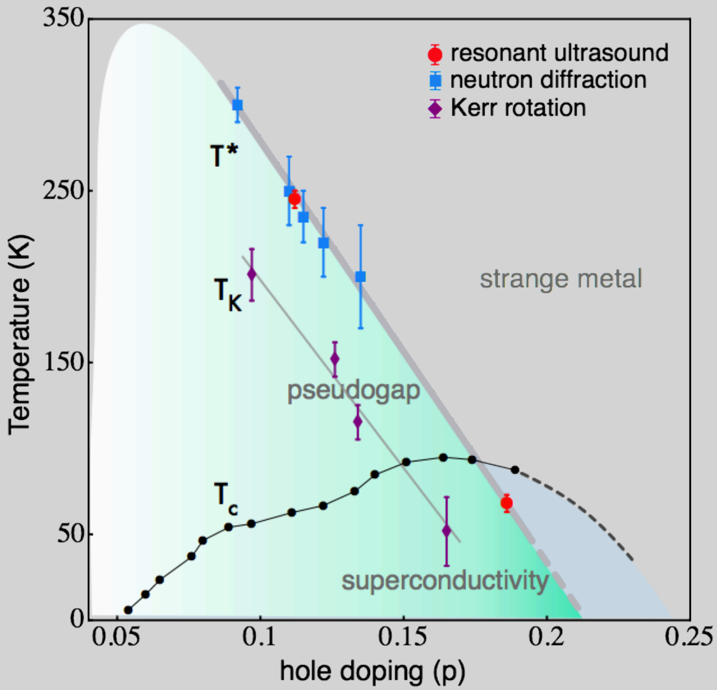


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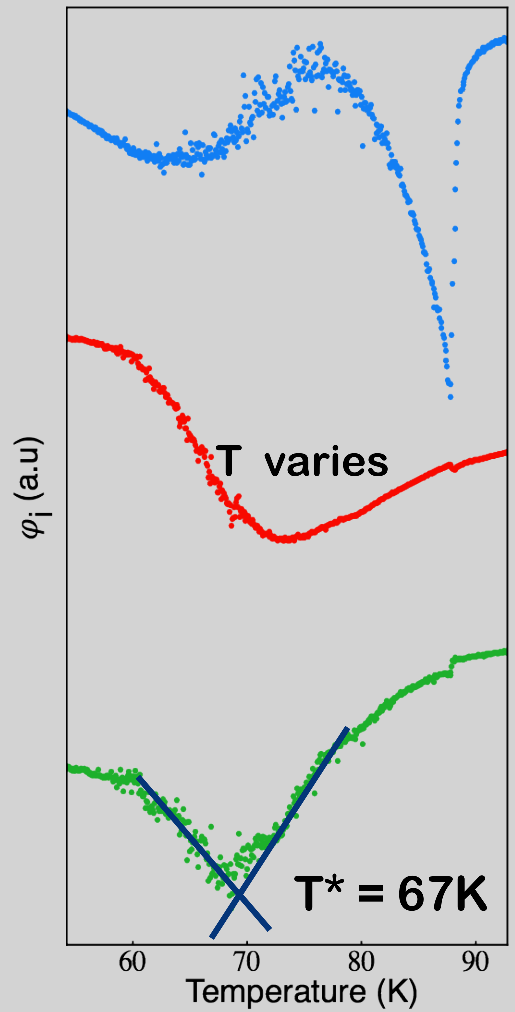
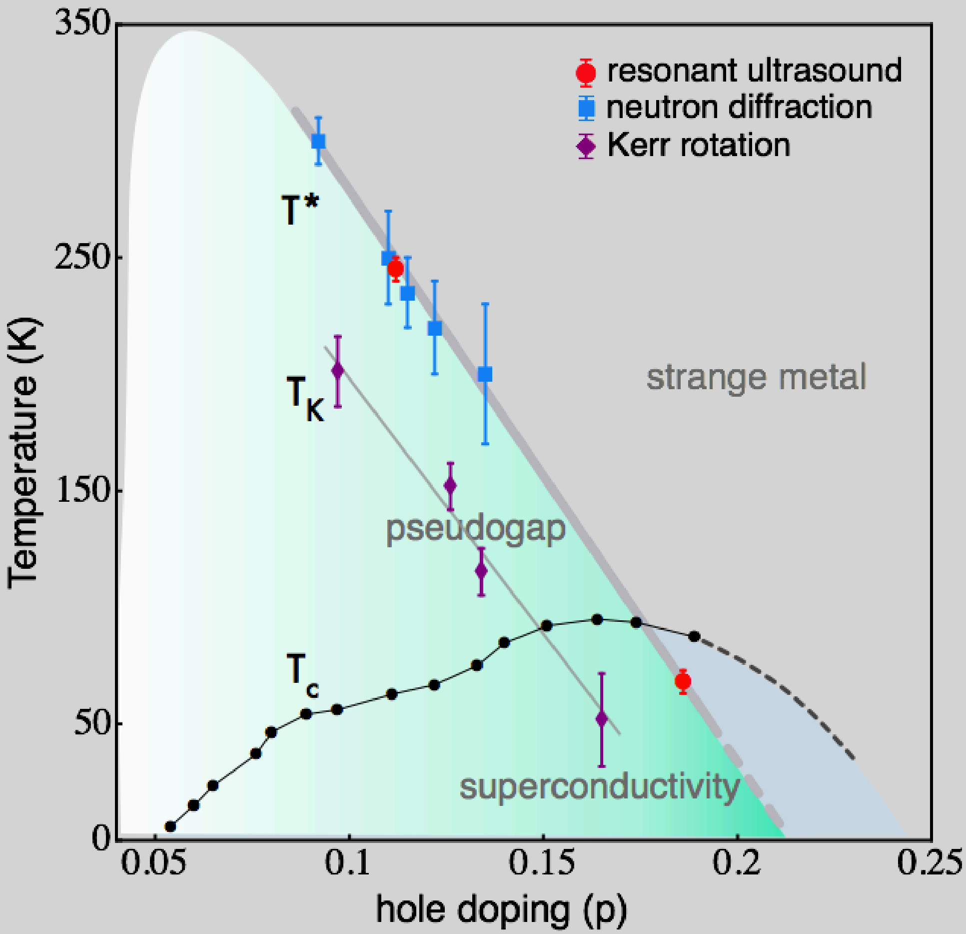



- Each resonance is a combination of the thermal response of several elastic moduli.
- Deconvolution produces the three types of thermal responses shown at right.

**The precision in determining T* is determined by the sharpness of the change in slope**

# Conclusions from Resonant Ultrasound Spectroscopy




- Pseudogap onset IS a thermodynamic phase transition, conjectured to be second order with a magnetic order parameter.
- Observed evolution of the pseudogap phase boundary from underdoped to overdoped establishes the presence of a quantum critical point inside the superconducting dome.
- This suggests a quantum-critical origin for both the strange metallic behavior and the glue mechanism of superconducting pairing.

Arkady Shekhter, et al.
Nature 498, 75 (2013)
doi:10.1038/nature12165

# Back to High Magnetic Fields...

# (up to 60T)

# to see Quantum Oscillations

# Large Fermi Surface in Tl-2201 in the overdoped regime

**Original measurement using Angle-Dependent Magneto-resistance Oscillations:**
**N.E. Hussey, M. Abdel-Jawad, A. Carrington, A.P. Mackenzie, L. Balicas,**
***"A coherent three-dimensional Fermi surface in a high-transition-temperature superconductor"*** **Nature 425, 814 (2003)**

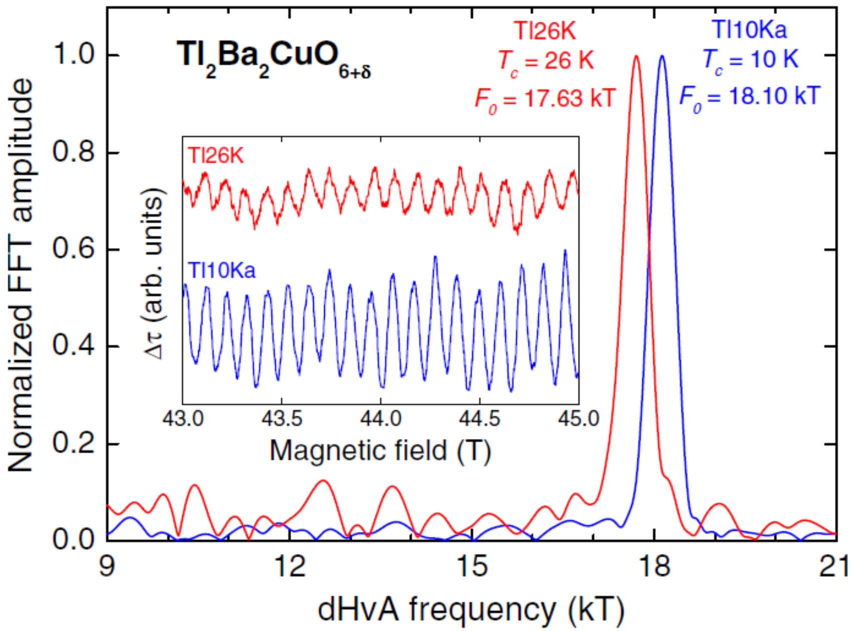
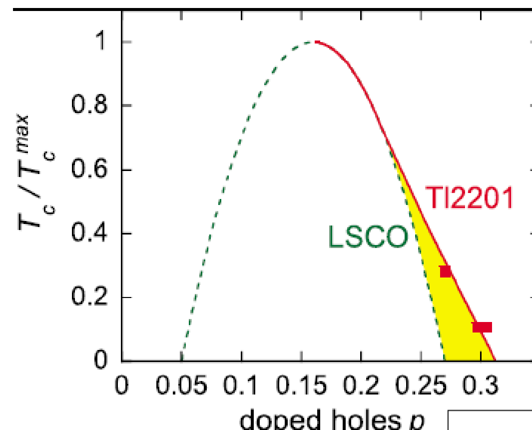
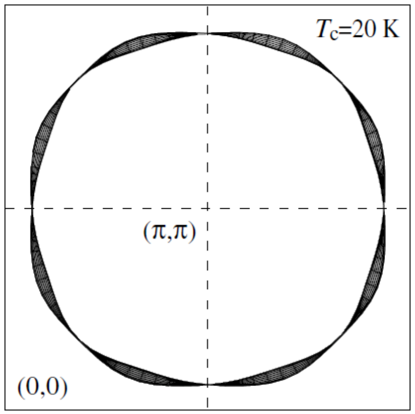


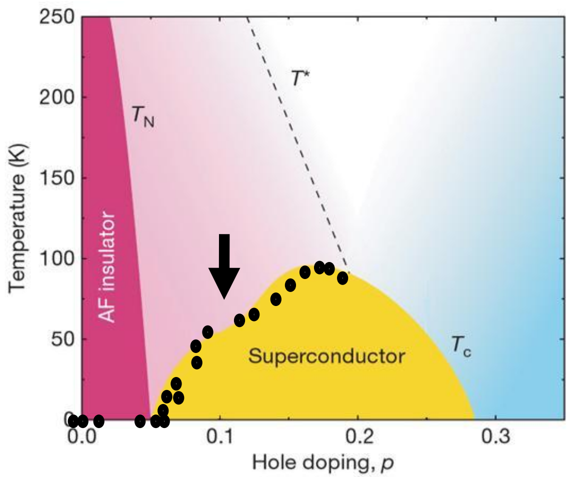

FIG. 1. (Color online) Fast Fourier transform of torque data between 38 and 45 T for Tl26K (red) and Tl10Ka (blue) samples. The data were taken at $T$=0.35 K. The inset shows the raw data for the two samples.

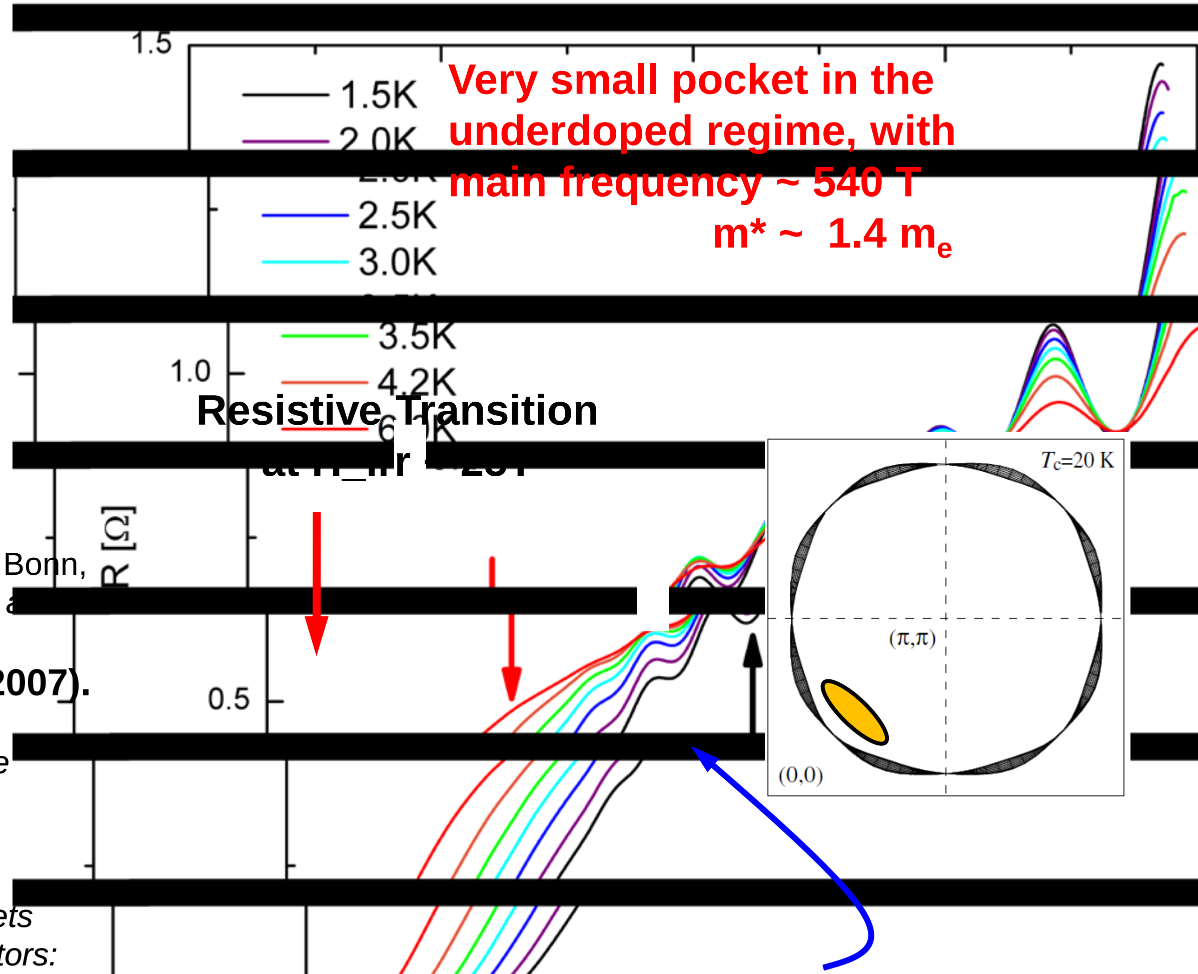



**A.F. Bangura, P.M.C. Rourke, T.M. Benseman, M. Matusiak, J.R. Cooper, N.E. Hussey, and A. Carrington**
***Fermiology and electronic homogeneity of the superconducting overdoped cuprate $Tl_2Ba_2CuO_{6+delta}$ revealed by quantum oscillations*** **Phys. Rev. B 82, 140501(R) (2010)**

# 2007: Small Fermi Surface in the Underdoped YBCO – The Pseudogap State Looks like an Ordinary Fermi Liquid !




N. Doiron-Leyraud, C. Proust, D. LeBoeuf, J. Levallois, J-B Bonnemaison, R. Liang, D.A. Bonn, W.N. Hardy, L. Taillefer, "*Quantum oscillations a*[redacted] *the Fermi surface in an underdoped high-Tc superconductor.*" **Nature 447, 565-568 (2007).**

Yelland, E. A. *et al. Quantum oscillations in the underdoped cuprate YBa2Cu4O8.* **Phys. Rev. Lett. 100, 047003 (2008).**

Bangura A. F. *et al. Small Fermi surface pockets in underdoped high temperature superconductors: observation of Shubnikov-de Haas oscillations in YBa2Cu4O8.* **Phys. Rev. Lett. 100, 047004 (2008).**

Jaudet C. *et al., de Haas–van Alphen oscillations in the underdoped high-temperature superconductor YBa2Cu3O6.5.* **Phys. Rev. Lett. 100, 187005 (2008).**

B.J.Ramshaw, B. Vignolle, J. Day, R. Liang, W.N. Hardy, C. Proust, D.A. Bonn, *Angle dependence of quantum oscillations in YBa2Cu3O6.59 shows free spin behavior of quasiparticles* **Nature Physics 7, 234 (2010)**

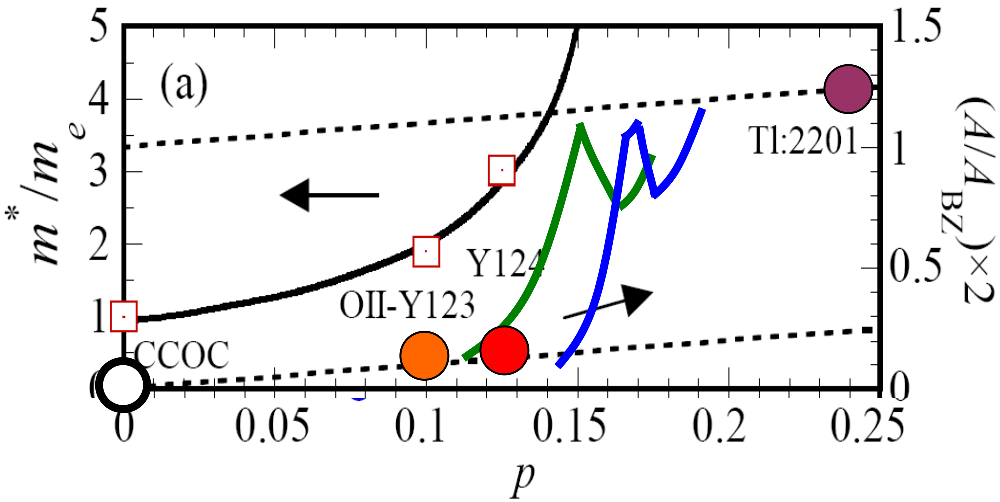
Suchitra E. Sebastian *et al. A multi-component Fermi surface in the vortex state of an underdoped high-Tc superconductor.* **Nature 454 200 (2008)**

# Doping Dependence of Quasiparticle Number

**Hall Effect in Single Layer BSLCO**
F. F. Balakirev, J. B. Betts, A. Migliori,
S. Ono, Y. Ando, and G S. Boebinger,
Nature **424,** 912 (2003).

**Hall Effect in Single Layer LSCO**
F. F. Balakirev, J. B. Betts, A. Migliori,
I. Tsukada, Yoichi Ando, G.S. Boebinger
*Phys.Rev.Lett.* **102**, 017004 (2009)

Effective Mass and Quasiparticle Number




Hussey et al, Nature **425,** 814 (2003)

Doiron-Leyraud, et al Nature **447** 565 (2007)

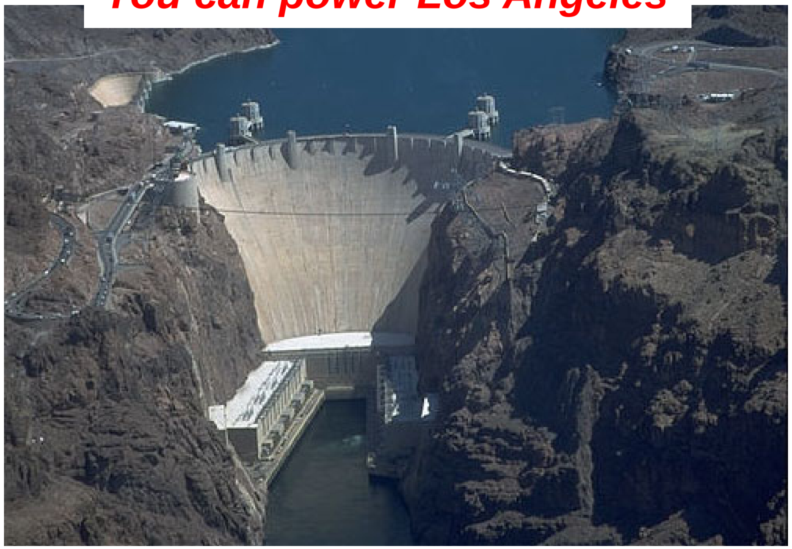
Yelland *et al*., PRL **100**, 047003 (2008)

**Turning it up to "11"...**

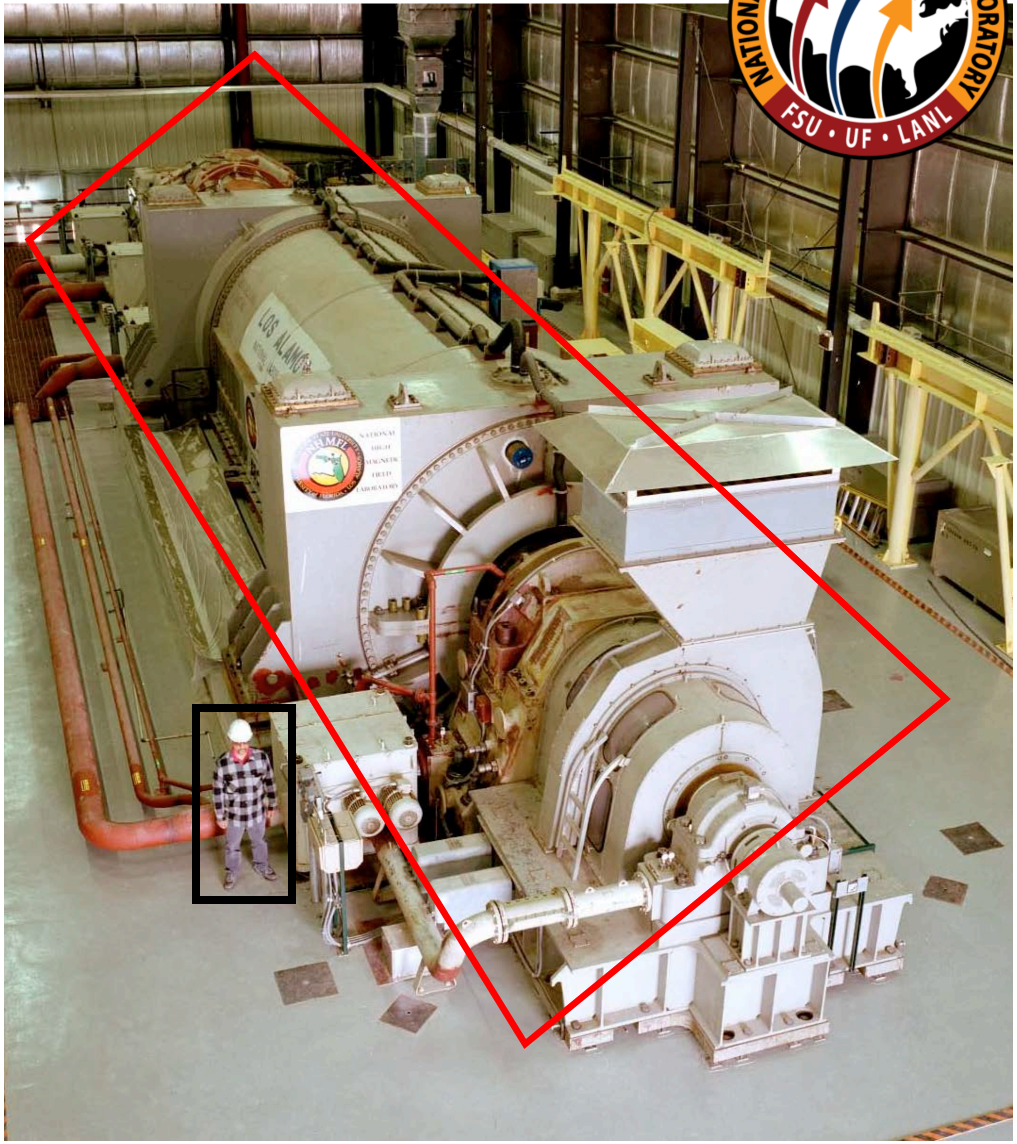
**(Achieved 100T in 2012 for the first time without blowing something up)**

# What can you do with 1,400,000,000 Watts ?

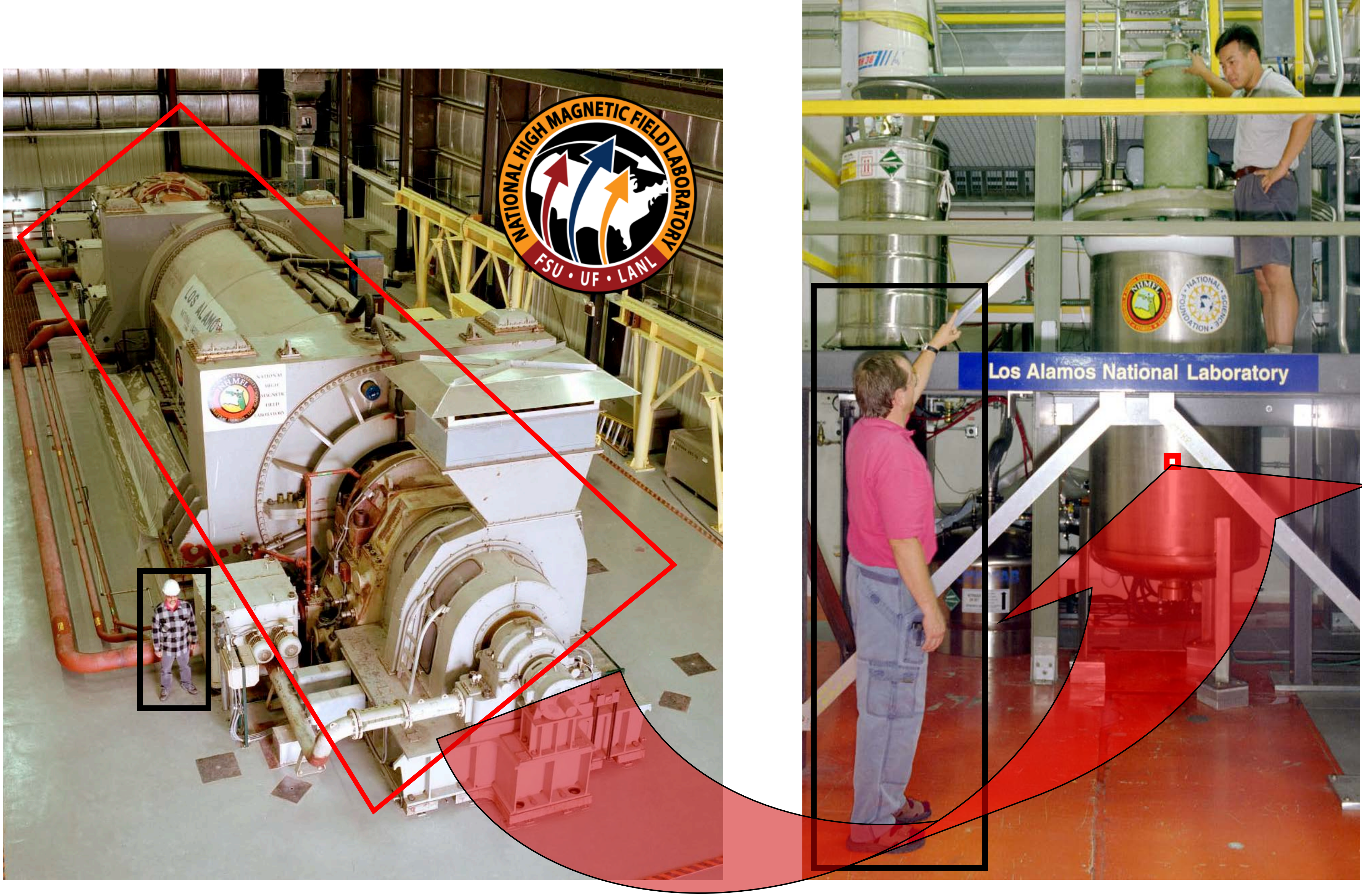
You can power Los Angeles



You can go…

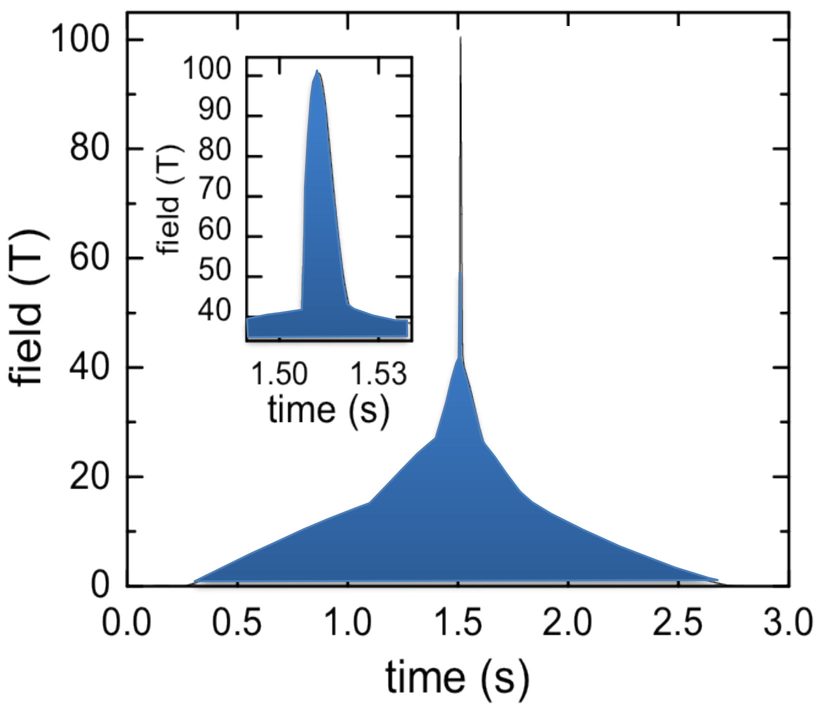



…or you can pulse one magnet

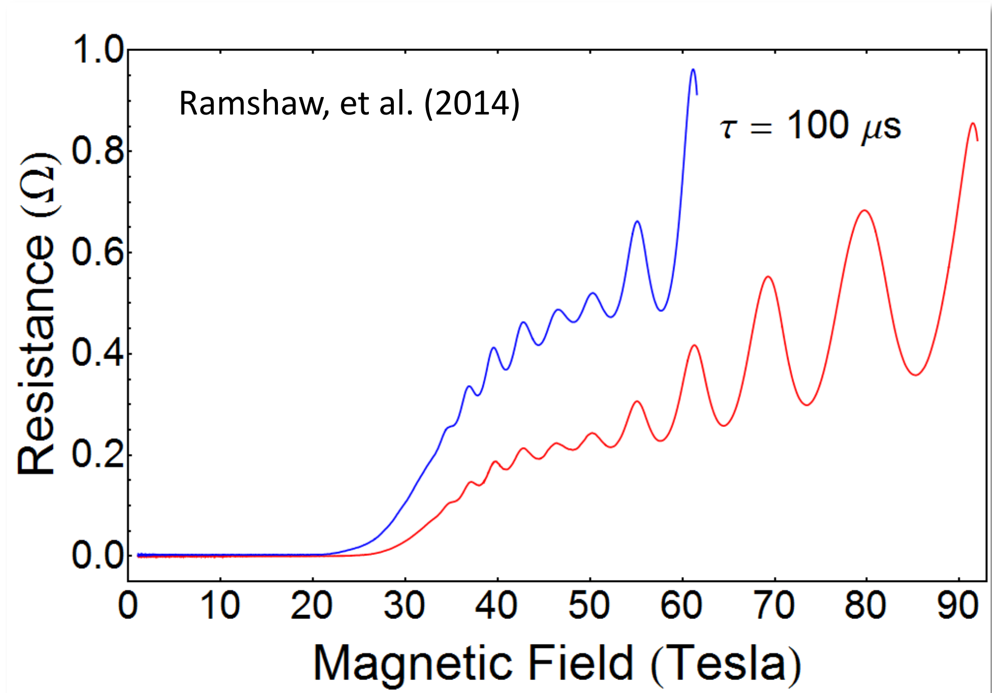



250 Mega Joules = 500 STICKS OF DYNAMITE

# March 22, 2012: 100.7T Pulse
# (Non-destructively!)

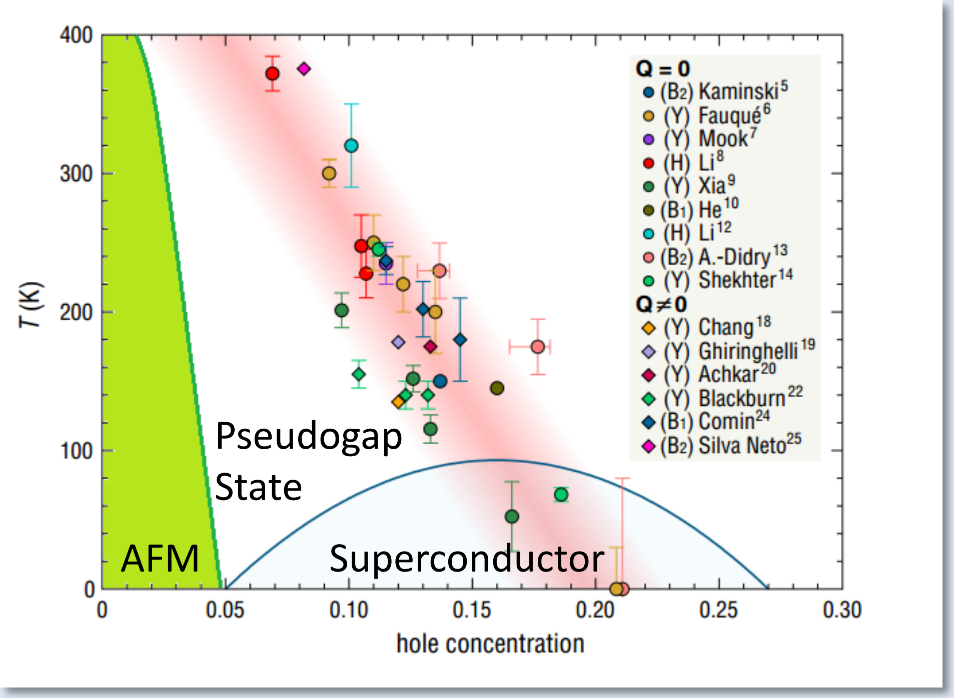



Many groups have used the 100T magnet to study quantum oscillations in cuprates. We will focus on recent unpublished work by Ramshaw, et al. that is relevant to the question of a critical point at optimum doping.




YouTube: Search for "100 tesla magnet"

# There IS a Quantum Critical Point Near Optimum Doping




K. Fujita *et al.*, arXiv (2014)

***IN THE UNDERDOPED REGIME:***

***Magneto-transport finds a low-density metal … with logarithmic scattering or localization.***

***ARPES finds arcs.***

***THE ONSET OF THE PSEUDOGAP :***

***… is a thermodynamic phase transition, from Resonant Ultrasound Spectroscopy***

***… is accompanied by many symmetry-breaking phenomena***

***AT THE TERMINATION OF THE PSEUDOGAP LINE NEAR OPTIMUM DOPING,***

***The linear-T resistivity persists to lowest temperatures***

***There are anomalies in the Hall number.***

***The quasiparticle mass appears to diverge… evidencing enhanced electron interactions***

***IN THE OVERDOPED REGIME:***

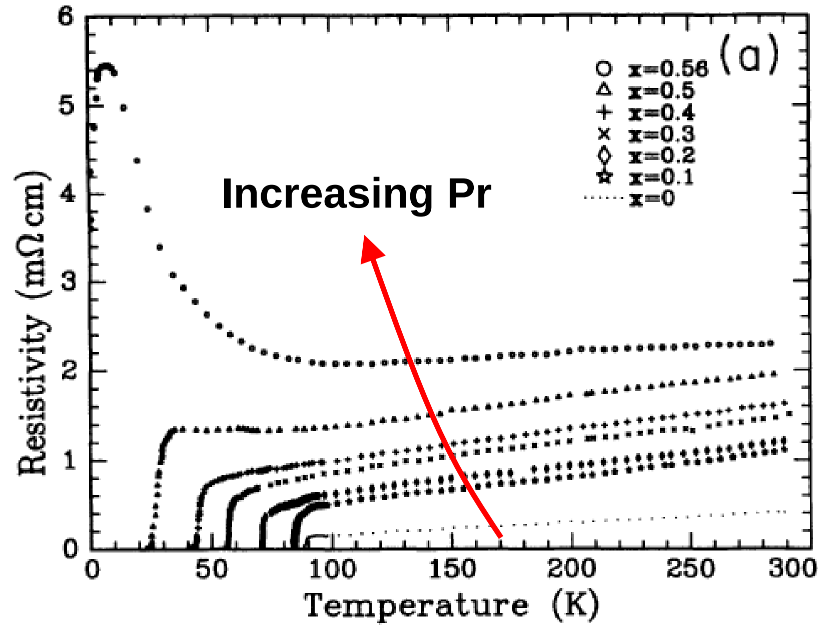
***Magneto-transport finds a high-density metal.***

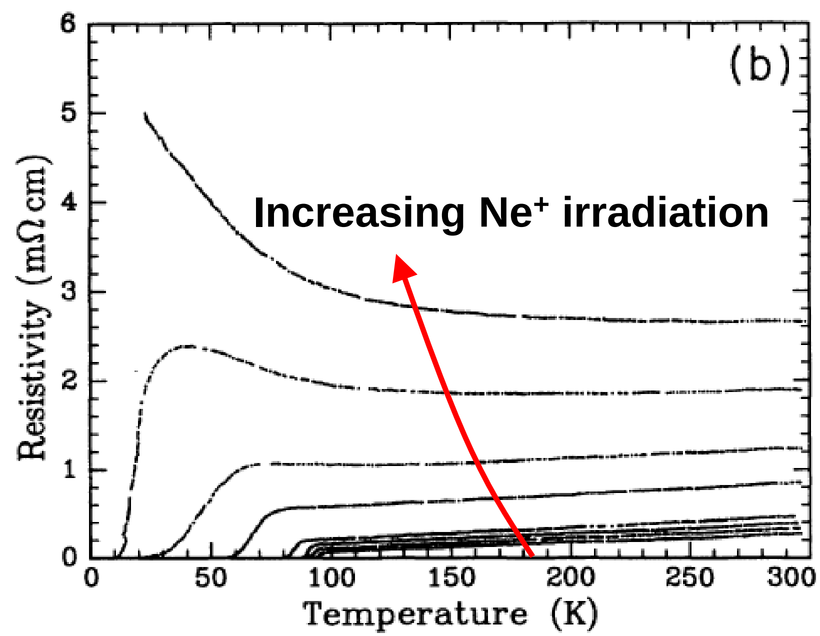
***ARPES finds a complete Fermi surface.***

Thank You !

**Inducing insulating behavior in optimally doped $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ by increasing disorder.**
**(Don't know if this will be log-T)**

Resistivity vs T for (a) $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$. For increasing Pr the Tc drops and the residual resistivity increases,
(b) Ion damaged $YBa_2Cu_3O_{7-\delta}$. After bombardment of 1-MeV $Ne^+$ ions at fluences of (0, 0.1, 2.5, 4.0, 10.0, 15.0, 20.0, and 22.0) X$10^{13}$ ions/$cm^2$. For increasing ion damage the behavior is similar for increasing Pr in (a).




**Electron tunneling and transport in the high-Tc superconductor $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$**

**PHYSICAL REVIEW B 50, 3266 (1994)**
**A. G. Sun, L. M. Paulius, D. A. Gajewski, M. B.Maple, and R. C. Dynes**