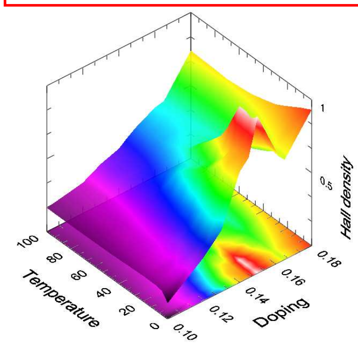
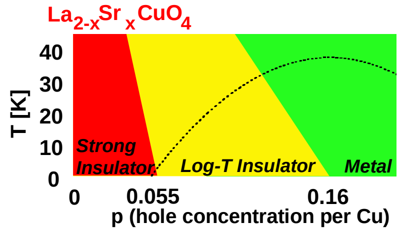
The Abnormal Normal State of the High-*Tc* Superconductors

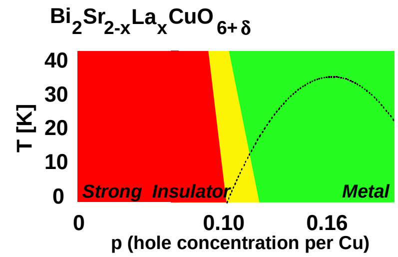
Using 60 teslas ...
...to suppress the superconducting state
...(undress the electrons)…
…to reveal the low-temperature normal-state phase diagram



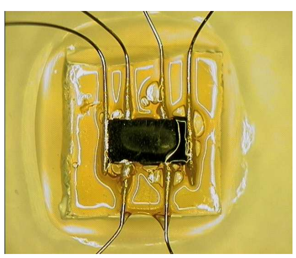
Nature **424**, 912 (2003)
Signature of Optimal Doping in Hall-effect Measurements on a High-Temperature Superconductor



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

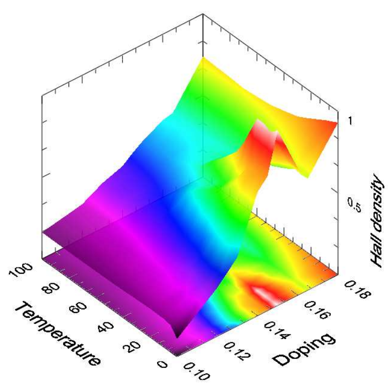


The Cast of Characters

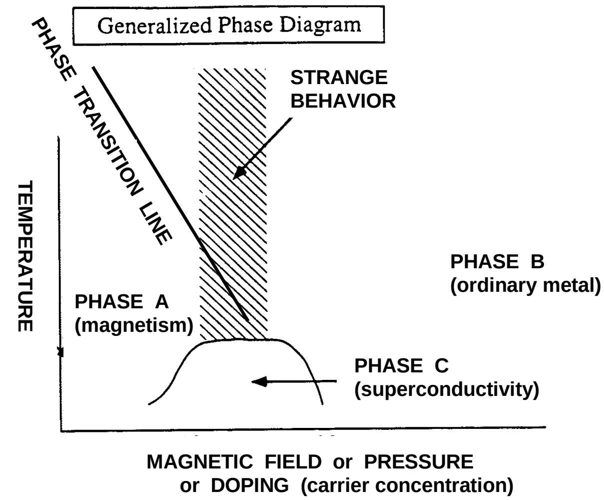
Joze Bevk, Al Passner
Bell Laboratories, Lucent Technologies

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

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



The Hall Number Peaks at Optimal Doping in a High-Tc Cuprate



Tuning to Quantum Critical Points
using Pressure or Magnetic Field

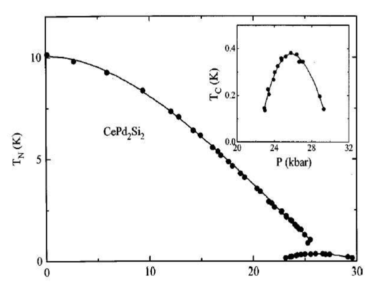
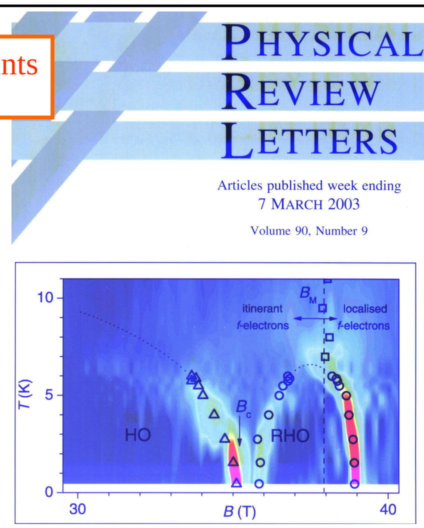


FIG. 25. Phase diagram for the antiferromagnet $CePd_2Si_2$ as a function of pressure, after Julian *et al.* (1998). The superconducting transition induced by pressure at low temperatures and pressures between 23 and 29 kbar shown in the main figure is expanded in the inset.

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



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

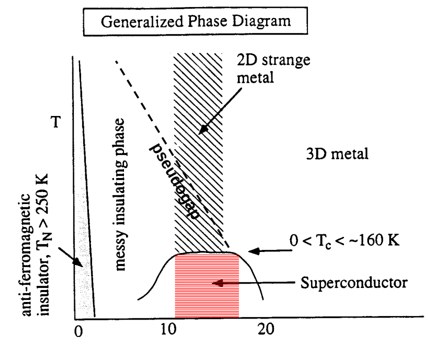


Figure 3.26. "Generalized Phase Diagram" as seen (roughly) in $(La - Sr)CuO_4$.

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

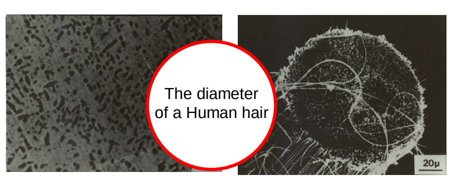
12 feet	**Ears**	**6 pounds per square inch**
2000 feet	**Submarine**	**1000 psi**
12,000 feet	**Ocean Floor**	**6000 psi**

Pressure inside NHMFL Pulsed Magnets

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

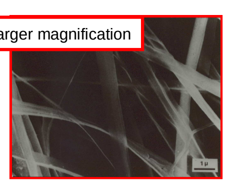
(which equals 1.4GPa or 130 kg per square millimeter)

(which is more pressure than most materials can handle)



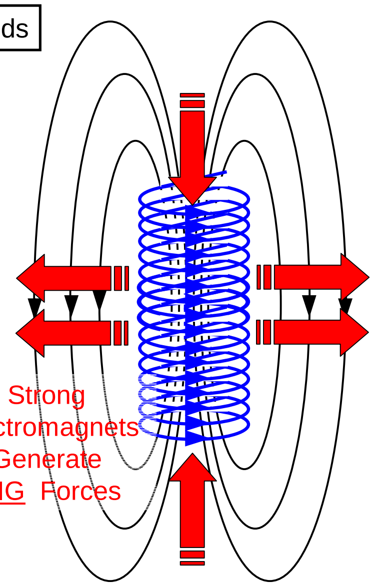
20% Niobium Droplets
in 80% Copper Matrix

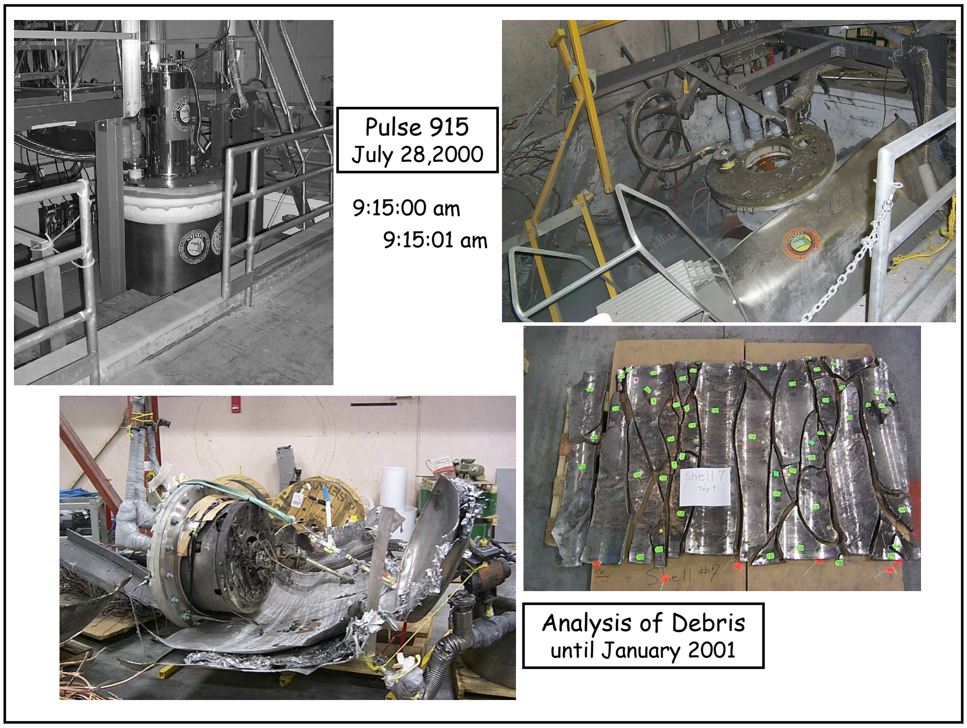
20 times larger magnification

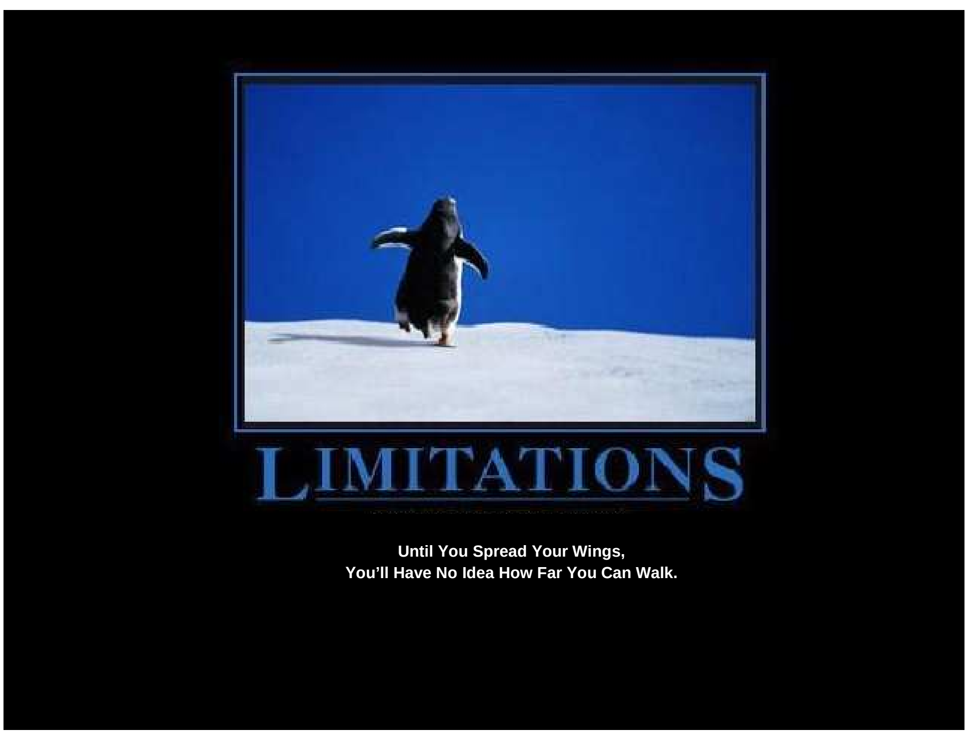


The Niobium ribbons work (sort of) like steel bars in cement…

…except the nano-composite is stronger than either constituent




Pulse 915
July 28,2000
9:15:00 am
9:15:01 am
Analysis of Debris
until January 2001


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

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

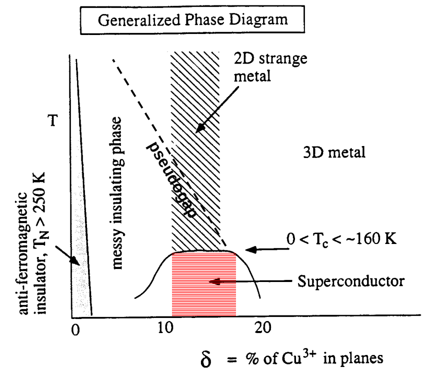


Figure 3.26. "Generalized Phase Diagram" as seen (roughly) in $(La-Sr)CuO_4$.

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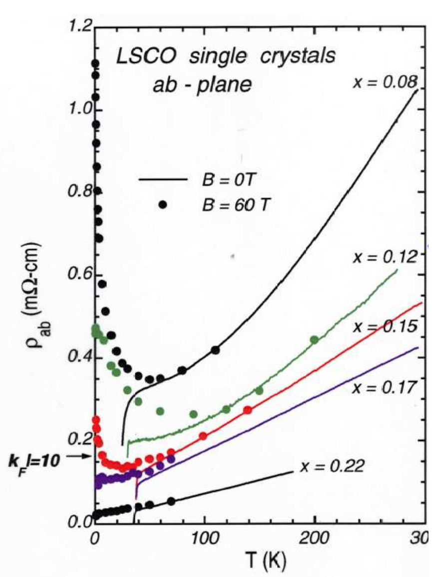
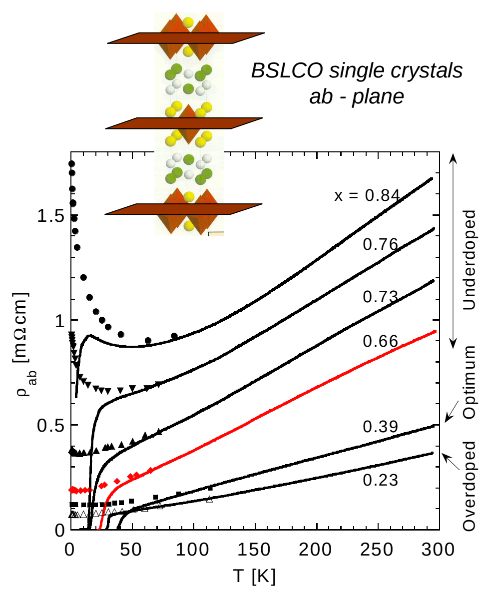
Anderson, Science 256, 1526 (1992) and Research News, Science 278, 1879 (1997)

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

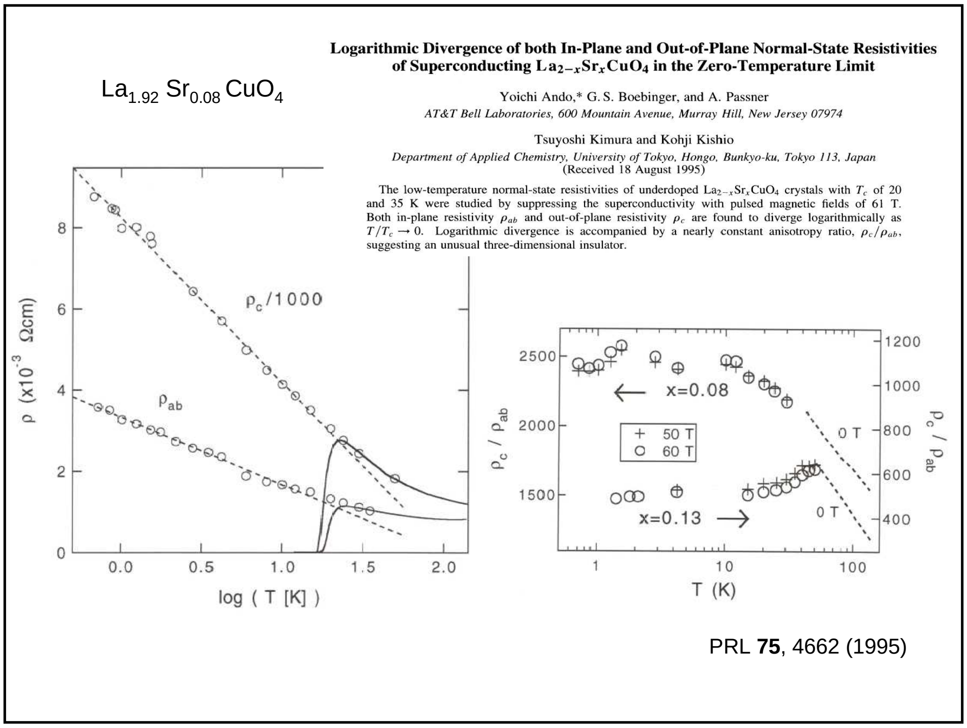


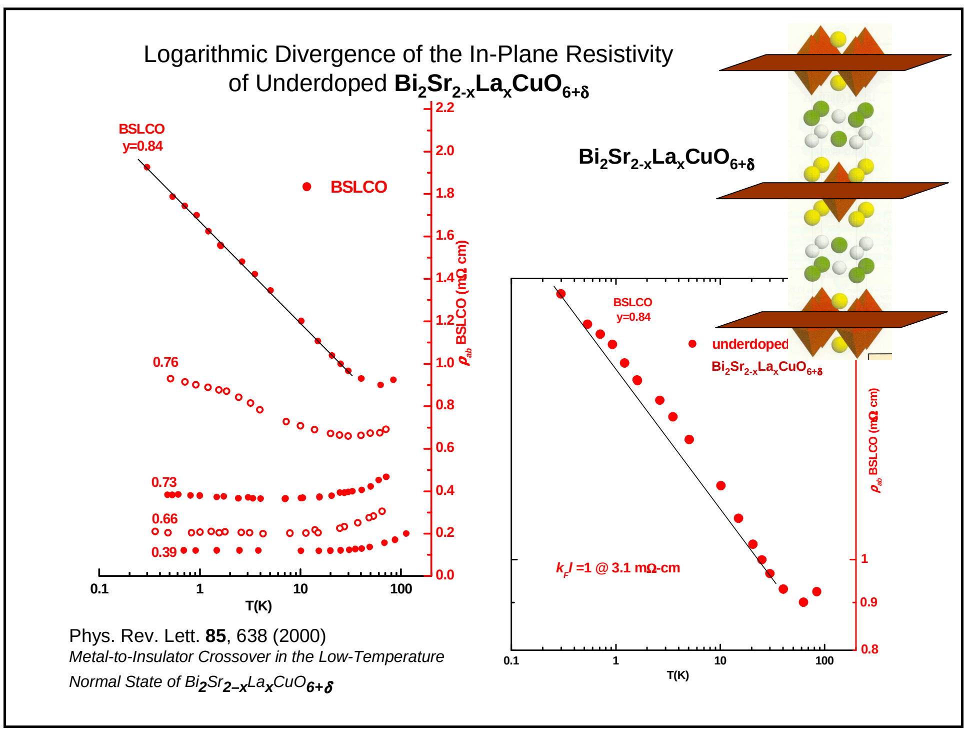
PRL **77**, 5417 (1996)



PRL **85**, 638 (2000)

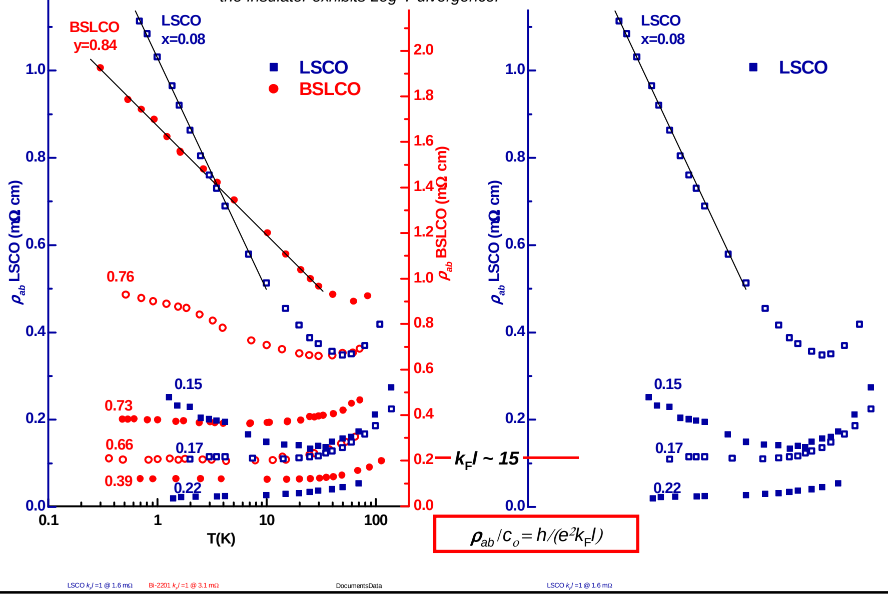
The Hall Number Peaks at Optimal Doping in a High-Tc Cuprate





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.



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

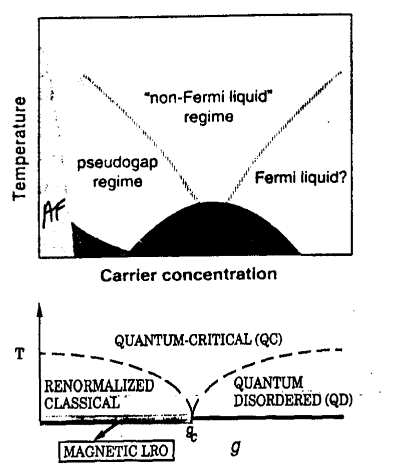
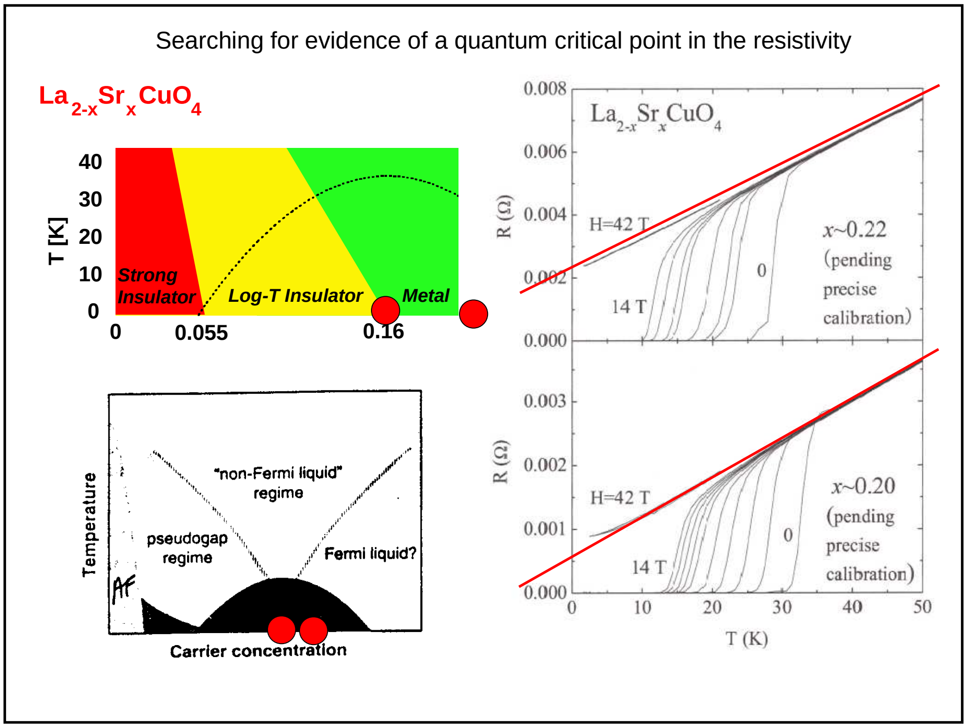


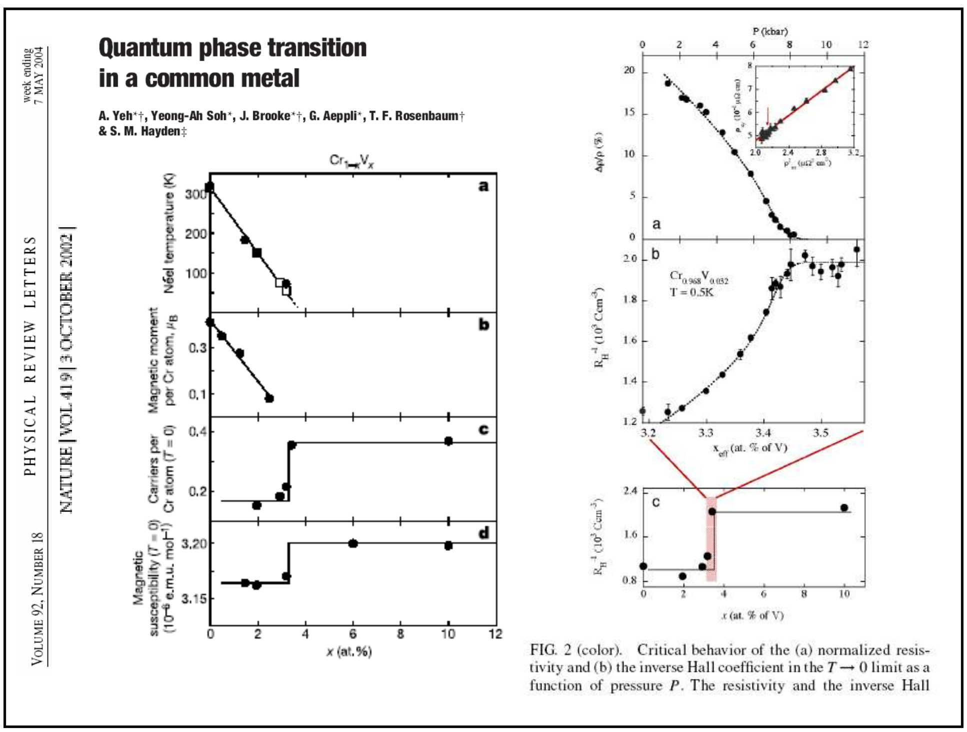
FIG. 1. Phase diagram of $\mathcal{H}$ (after Ref. [4]). The magnetic LRO can be either spin-glass or Néel type, and is present only at $T=0$. The boundaries of the QC region are $T \sim |g-g_c|^{z\nu}$.

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

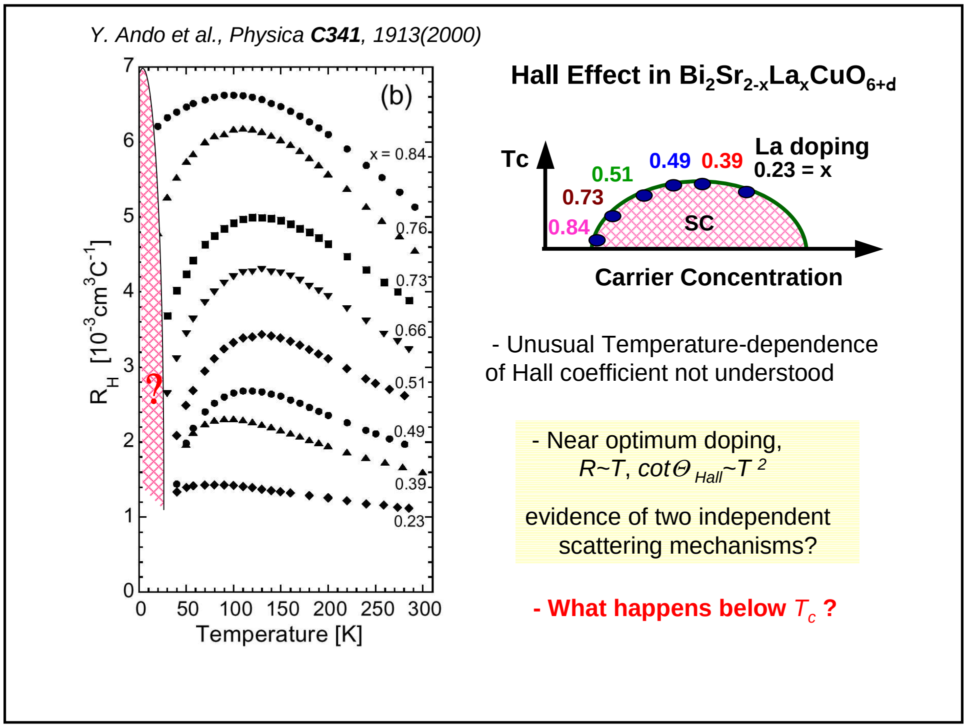
Ref [4] is Chakravarty, Halperin and Nelson, PRL **60** (1988) 1057; PR **B39** (1989) 2344

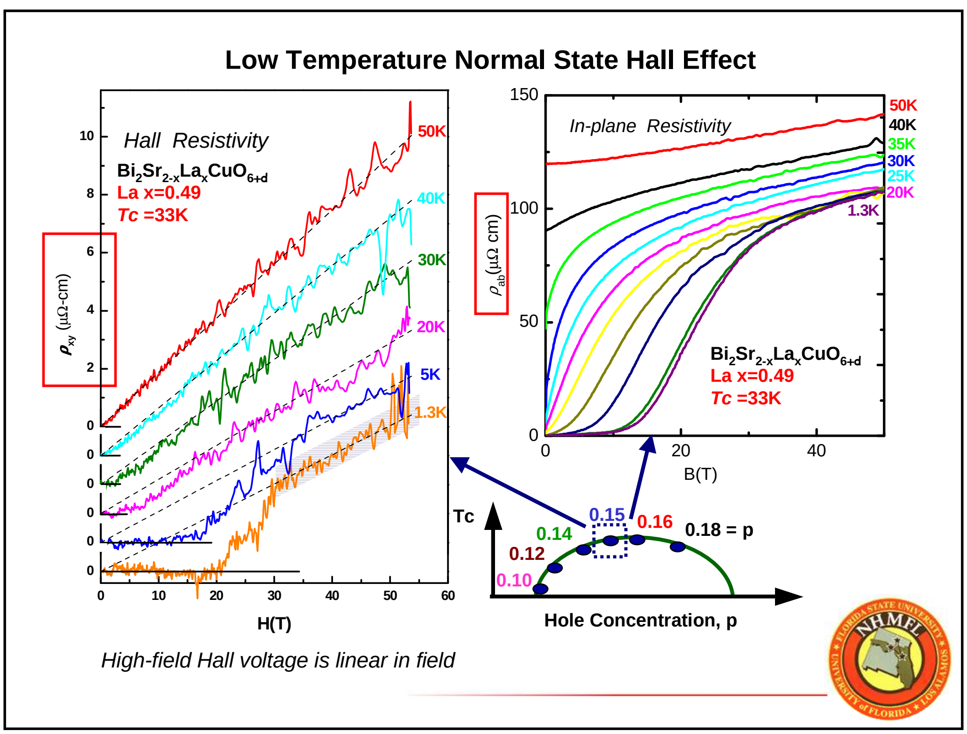
The Hall Number Peaks at Optimal Doping in a High-Tc Cuprate



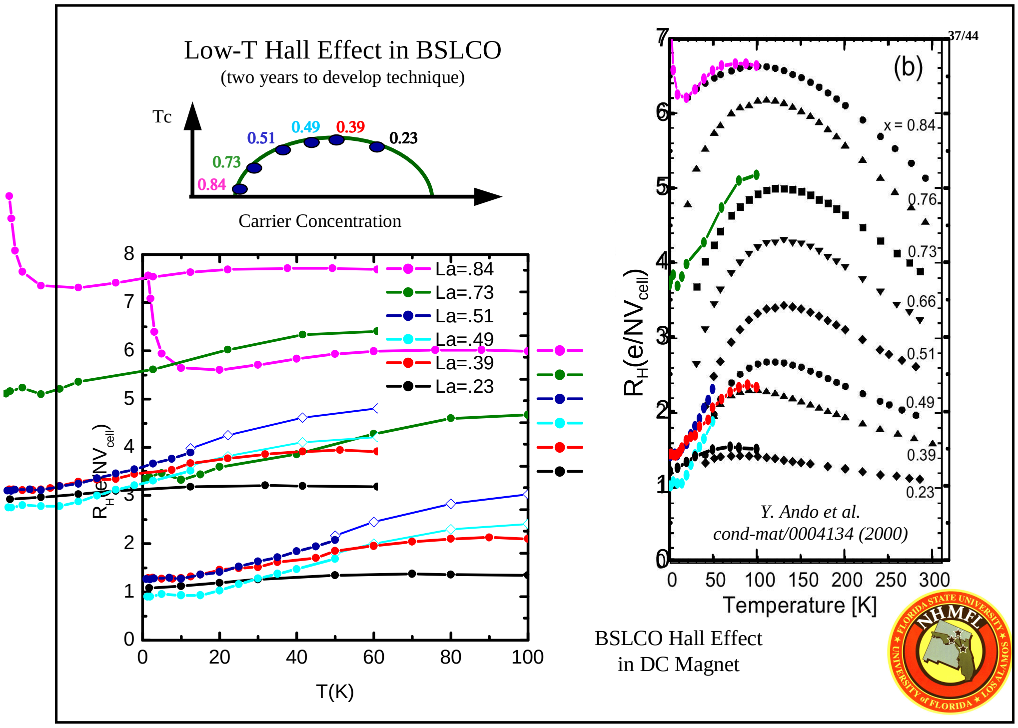


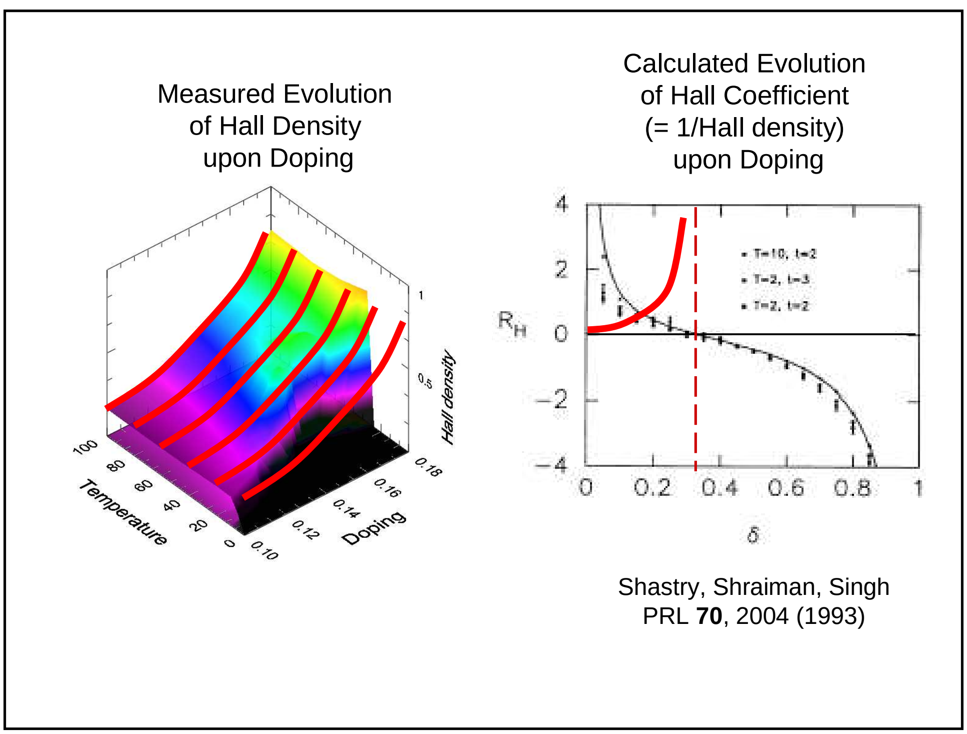
The Hall Number Peaks at Optimal Doping in a High-Tc Cuprate



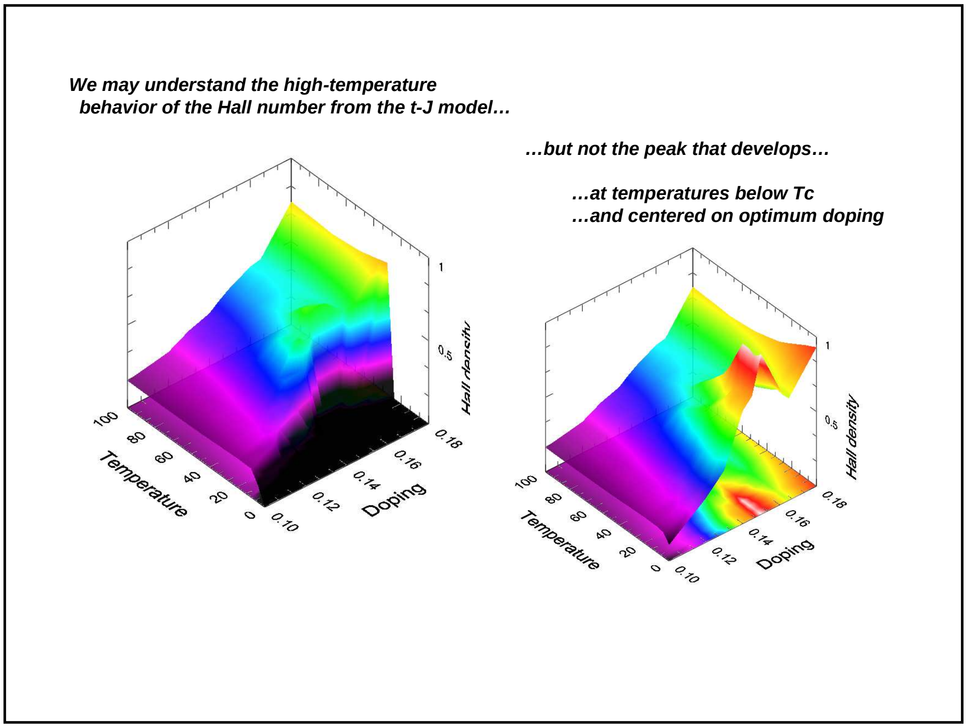


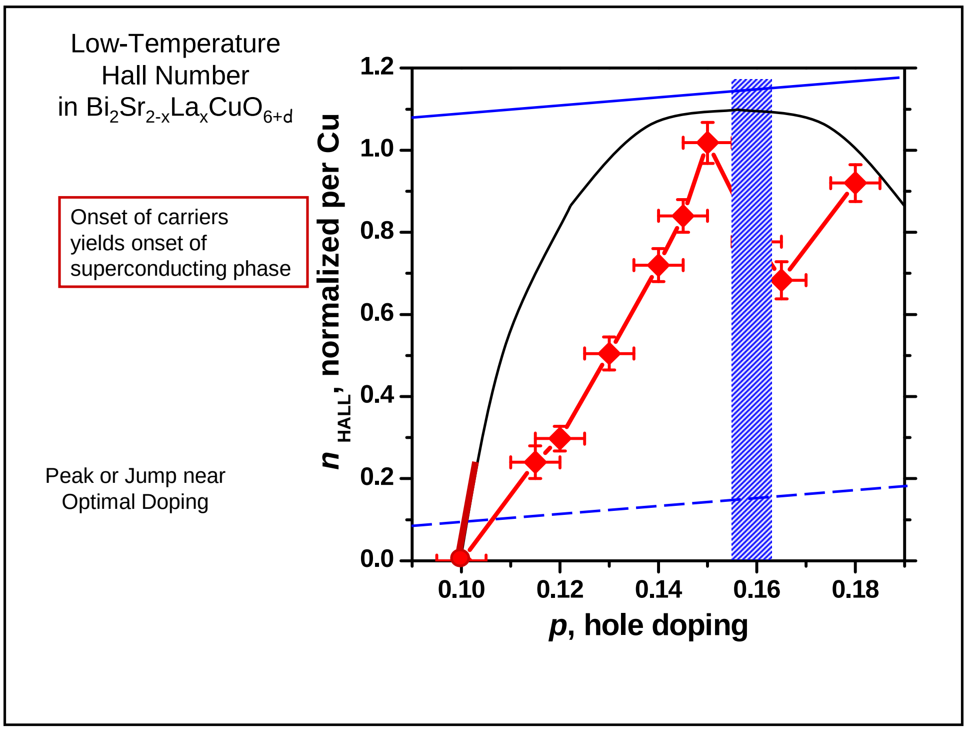
The Hall Number Peaks at Optimal Doping in a High-Tc Cuprate





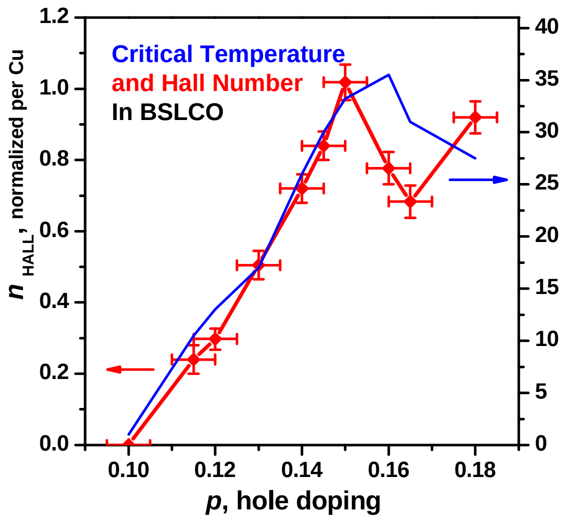
The Hall Number Peaks at Optimal Doping in a High-Tc Cuprate

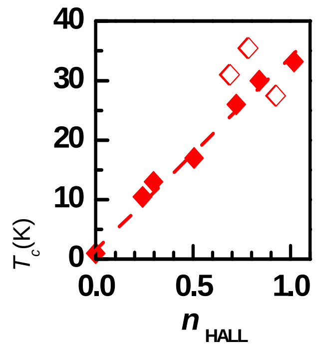




The Hall Number Peaks at Optimal Doping in a High-Tc Cuprate

Hall Number is correlated with T_c

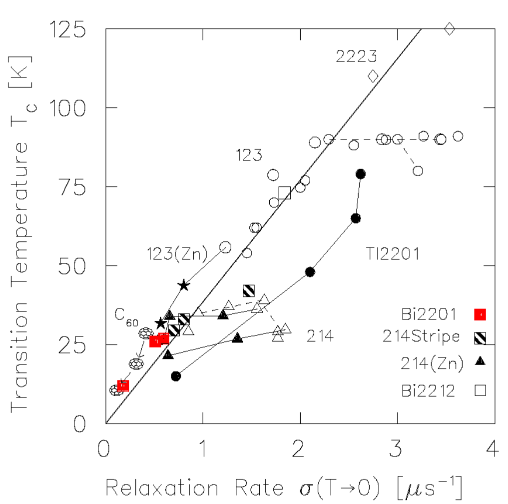




In the underdoped regime…
n_{Hall} shows remarkably linear correlation with T_c

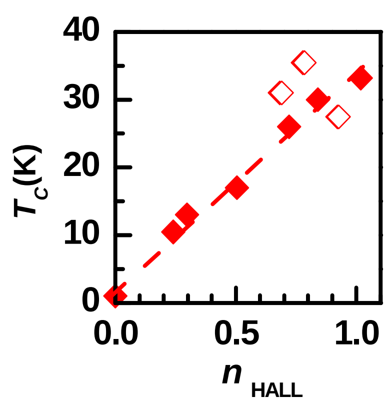
…but not in the overdoped regime…

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



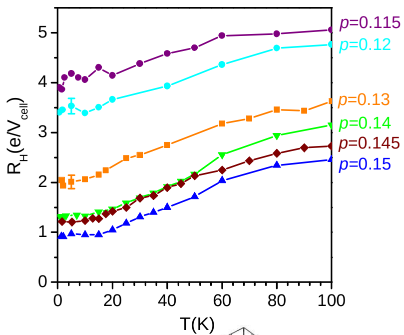
*Y. J. Uemura et al., PRL **62**, 2317(1989)*

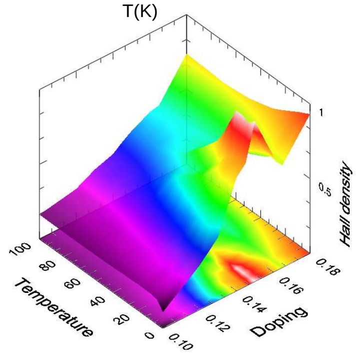
…and so is the Hall number…



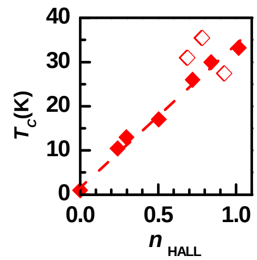
Superfluid density in the superconducting state corresponds to the Hall density throughout the underdoped regime

The Hall Number Peaks at Optimal Doping in a High-Tc Cuprate





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

ENΔ OΦ TAΛK

NewScientist

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

M. Jaime[1*], V. F. Correa[1], N. Harrison[1], C. D. Batista[2], N. Kawashima[3], Y. Kazuma[3], G. A. Jorge[1,4], R. Stern[5], I. Heinmaa[5], S. A. Zvyagin[6], Y. Sasago[7†], K. Uchinokura[7††]

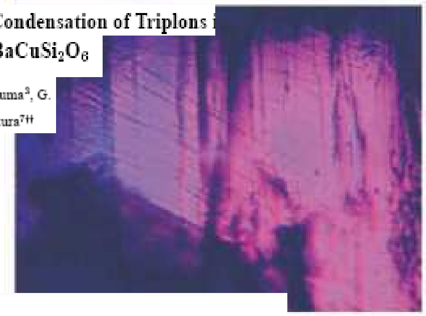
arXiv:cond-mat/0404324 v2 18 Apr 2004

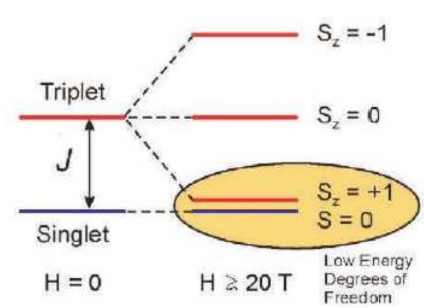
Purple in a spin

A RARE quantum state has been discovered in a pigment first made in China 2000 years ago.

Among the highest chemical achievements of the Han dynasty was the creation of the valuable dye now called Han purple. It contains barium, copper and silicon and has the formula $BaCuSi_2O_6$. Last week, an international team of researchers announced the pigment has a strange property (www.arxiv.org/abs/condmat/0404324): at temperatures near absolute zero, it turns into a state of matter known as a Bose-Einstein condensate, in which every particle shares a single quantum state.

Only one quantum property of the atoms in Han purple condenses – their spin. Physicists toying with spintronic devices, which use spin to process information, could put this to use, says team member Marcelo Jaime of the Los Alamos National Laboratory in New Mexico. "It may lead to an entirely new type of spintronics," he says.





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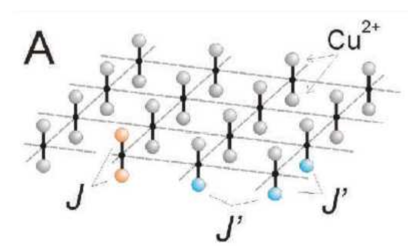
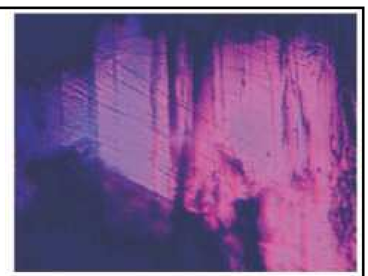
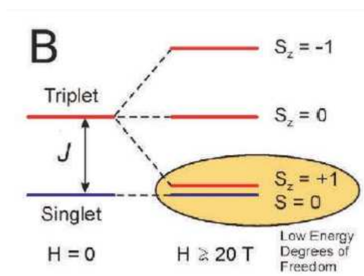




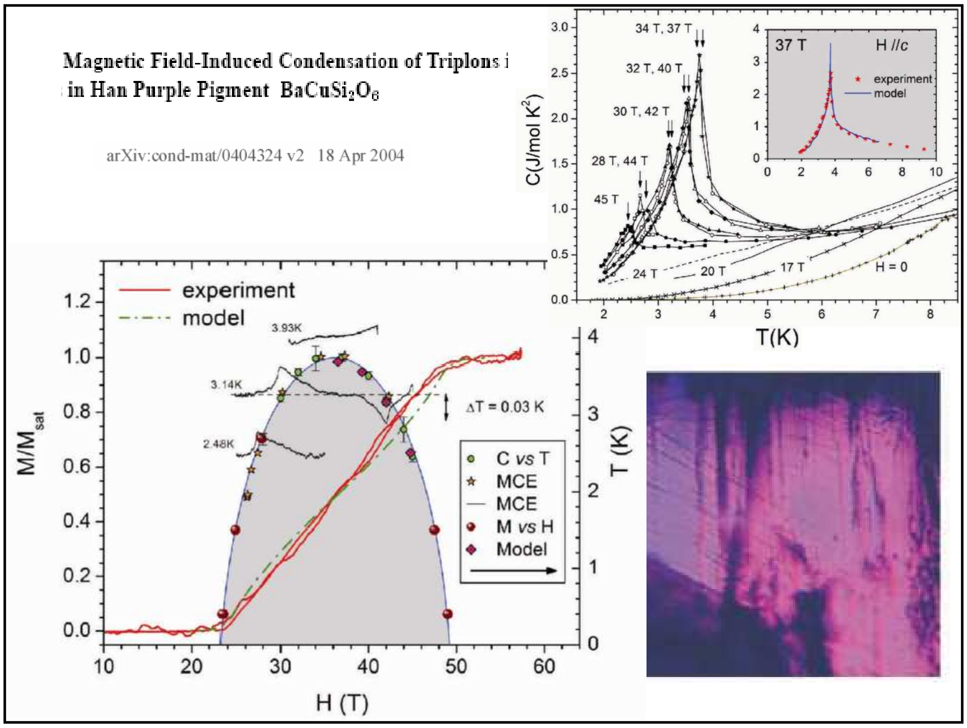


$BaCuSi_2O_6$: An ancient pigment
A quasi-2D magnetic insulator
Gapped spin dimer ground state

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

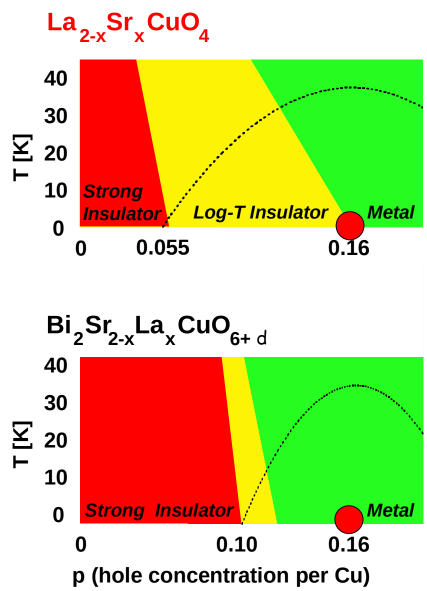
Transition to a coherent state marked by
- Quasi-linear increase in magnetization
- Distinct lambda-anomaly in specific heat
- Maximum in magnetic susceptibility

The Hall Number Peaks at Optimal Doping in a High-Tc Cuprate



The Hall Number Peaks at Optimal Doping in a High-Tc Cuprate

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



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

Linear-in-Temperature Resistivity
---near optimal doping

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

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 localization.
---would like to have some
scrap of experimental evidence.