Workshop on “Nanoscale Fluctuations in Magnetic and Superconducting Systems”
Max-Planck Institute, Dresden, 14 May 2005

Electron Self-Organization and Insulating Ground State of Cuprate Superconductors

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Outlines

- Brief History of Superconductivity
- Basics of High-Tc Cuprates
- Electron Self-Organization in High-Tc Cuprates inferred through ….
  - Unusual Metallic Transport
  - Peculiar Localization Behavior

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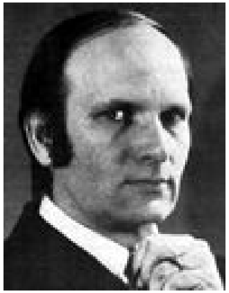
Superconductivity

- 1911: Discovery of zero resistivity in mercury by H. Kamerlingh-Onnes

(1913 Nobel Prize)

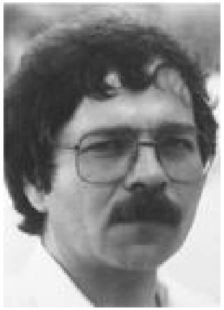
- 1957: Bardeen, Cooper and Schrieffer explained the superconductivity in metals (BCS theory)

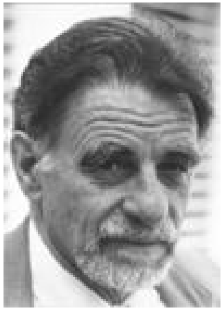


(1972 Nobel Prize)

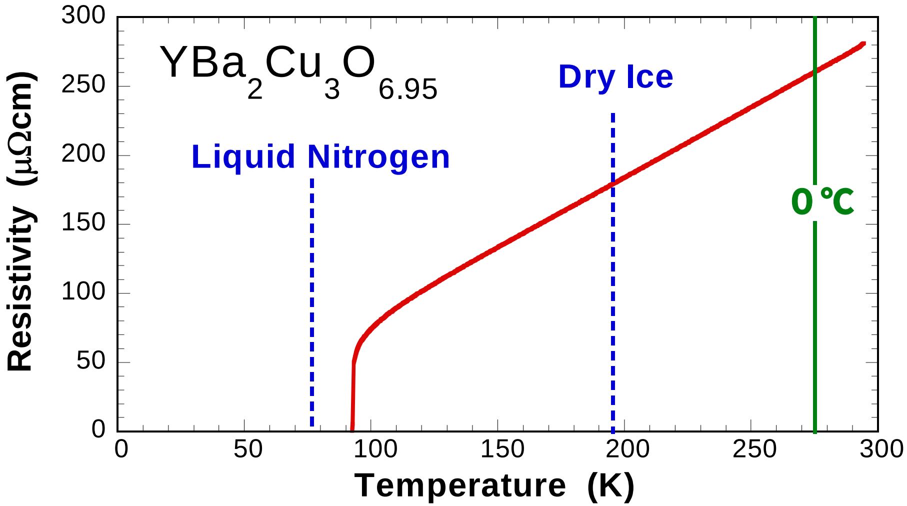
High-Temperature Superconductivity

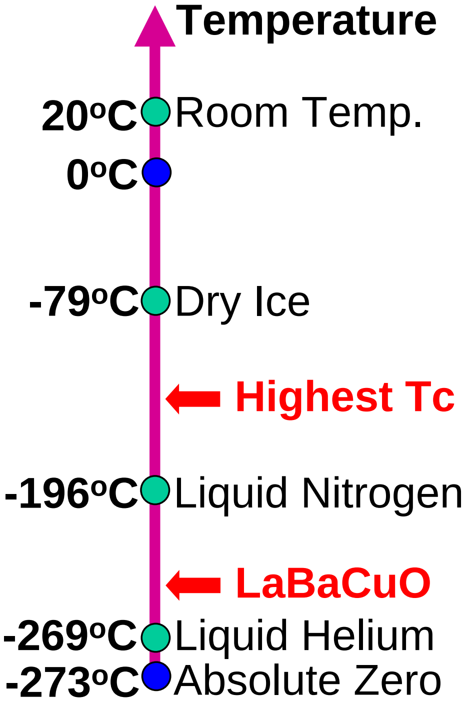
- Discovered by Bednorz and Müller in a copper oxide (cuprate) in 1986





(1987 Nobel Prize)





Transition Temperature T_c

- BCS superconductors

$$k_B T_c = 1.13\hbar\omega_D \cdot e^{-\frac{1}{N(0)|V|}}$$

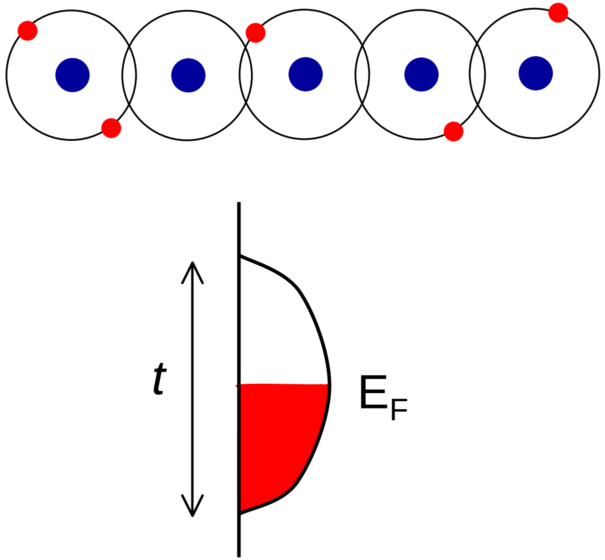
- Higher T_c is achieved with:
  - – Larger ω_D → lighter elements
  - – Larger N(0) → van Hove singularity *etc*.
  - – Larger |V| → stronger electron-phonon int.

- What about copper-oxide superconductors?
  - – ***Need to understand the HTSC mechanism!***

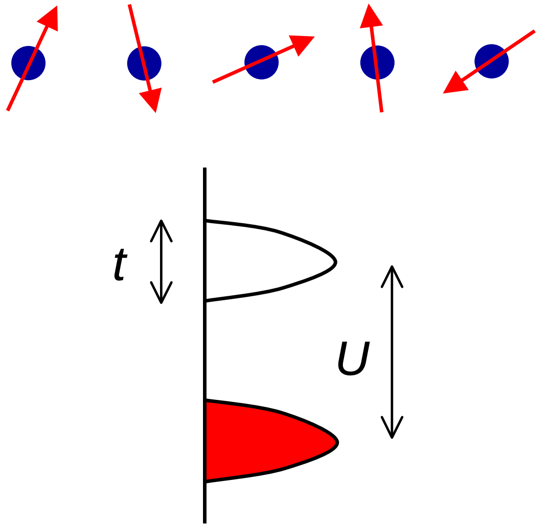
High-Temperature Superconductor

- Parent Cuprate La_2CuO_4 : Mott Insulator

Conventional Metal



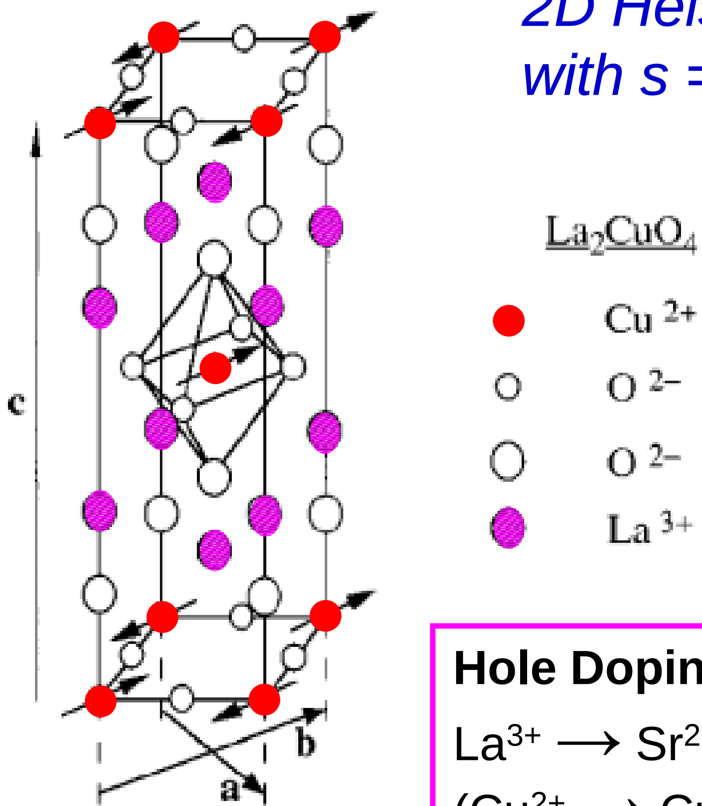
Mott Insulator



High-Temperature Superconductor

- Parent Cuprate La_2CuO_4 : Mott Insulator

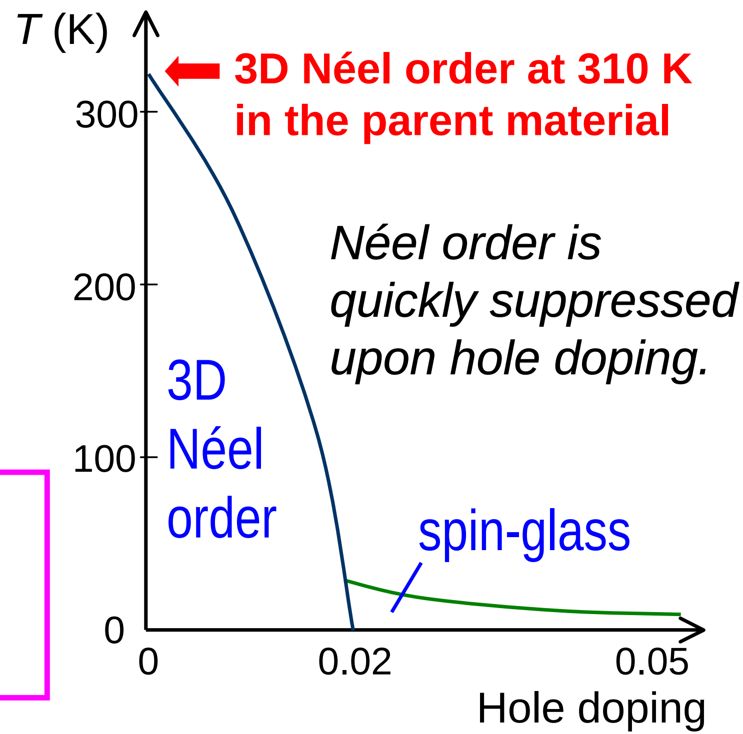
2D Heisenberg Antiferromagnet
with s = 1/2 on a square lattice



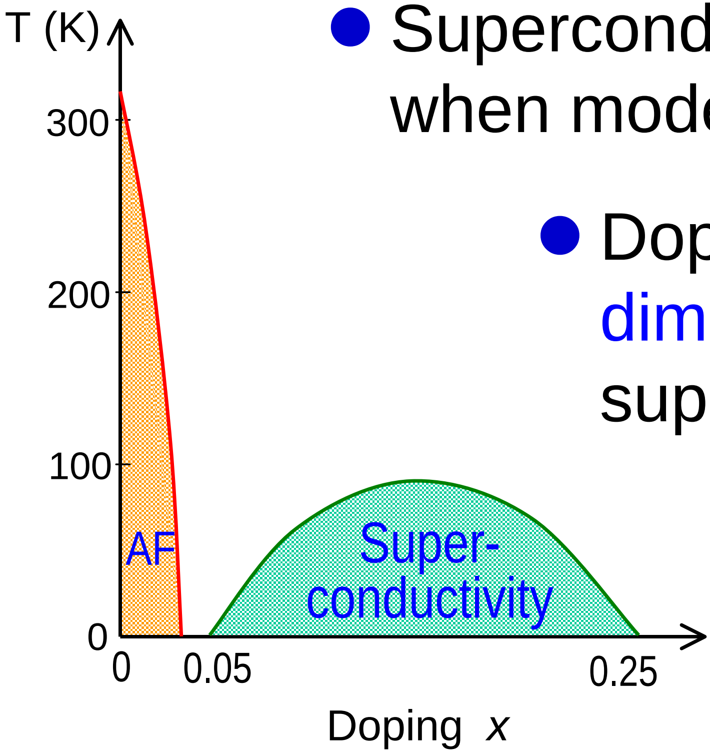
Hole Doping:

$La^{3+} \longrightarrow Sr^{2+}$

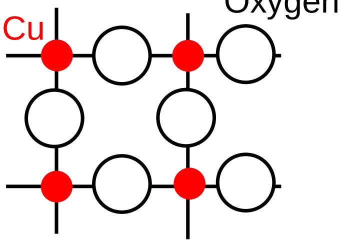
$(Cu^{2+} \longrightarrow Cu^{2+\delta})$



Further Doping



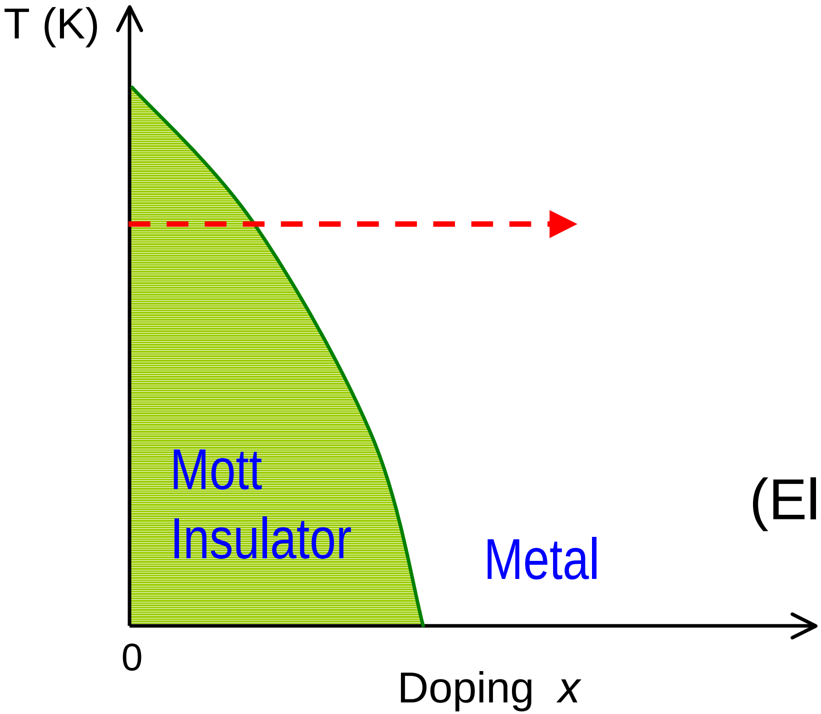
- Superconductivity shows up when moderately doped.
- Doped holes go into the two-dimensional CuO_2 planes, which support metallic transport.

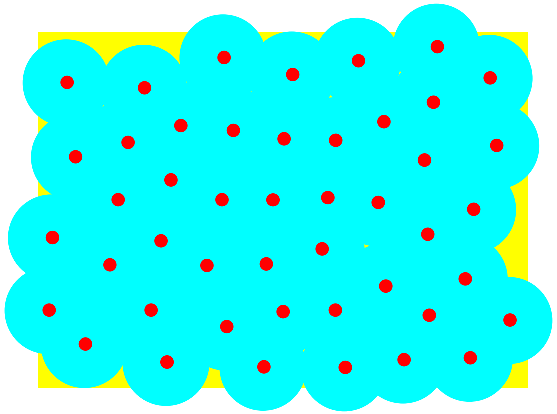


How does the metallic transport emerge in the CuO_2 planes when holes are doped?

Ordinary Insulator-Metal Transition

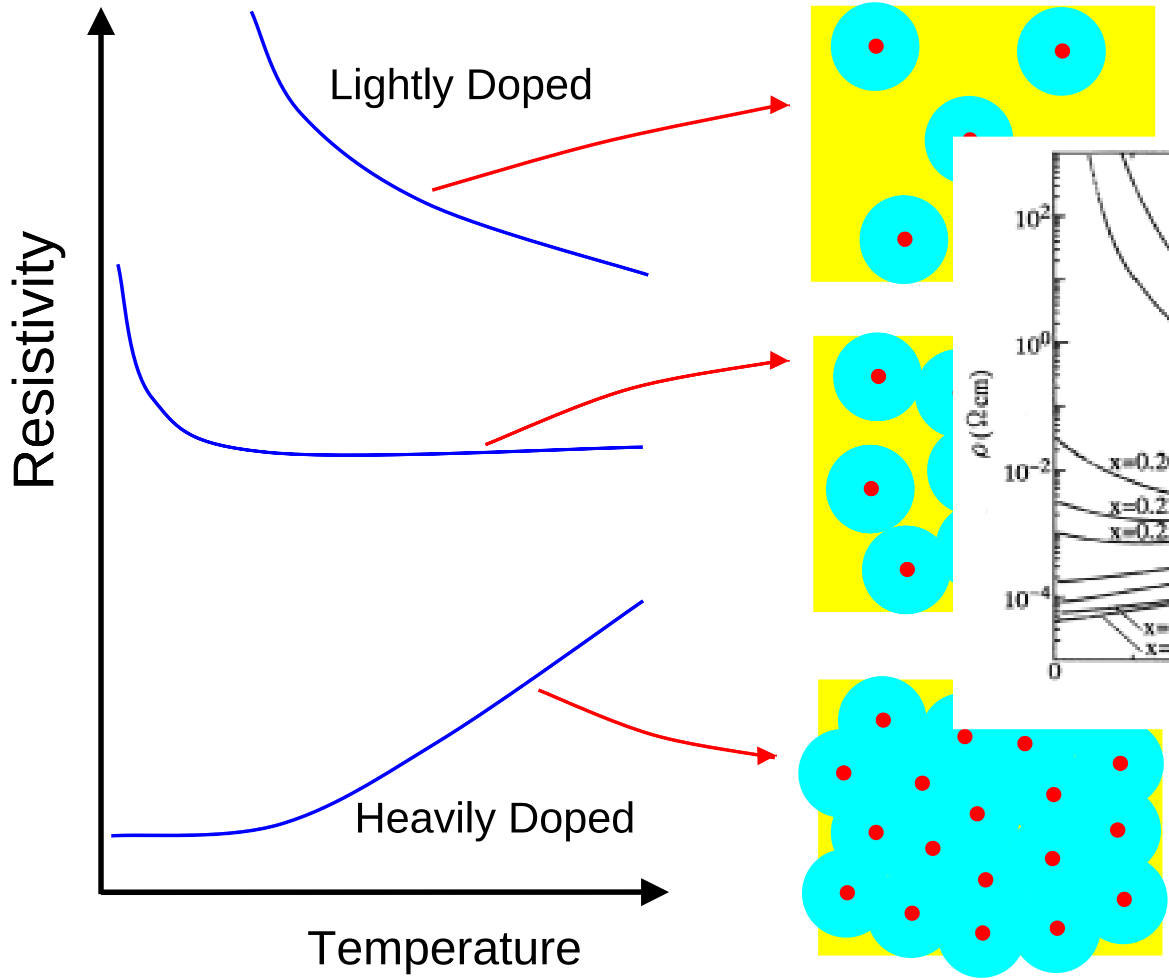
- Carrier Doping to Mott Insulator

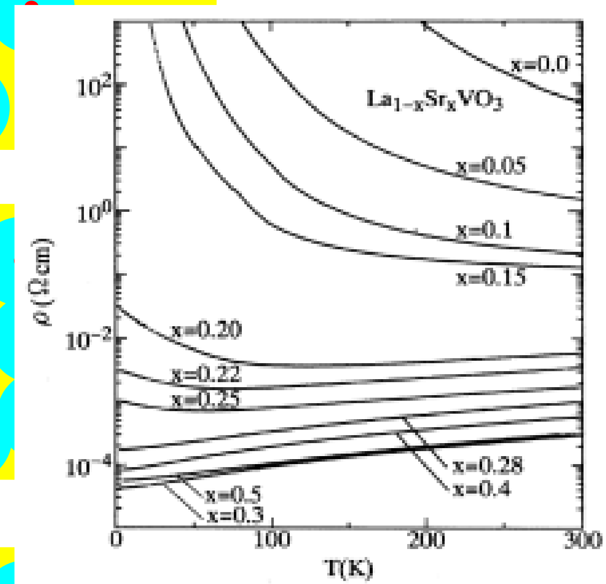




Metallic State
(Electrons form Bloch waves)

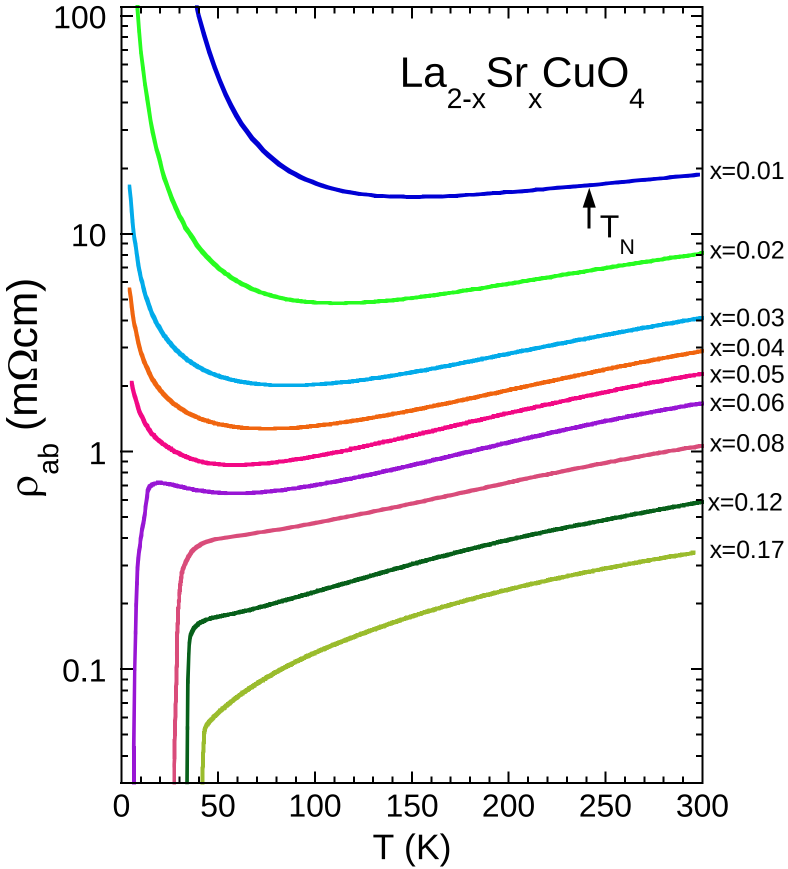
Ordinary Insulator-Metal Transition





Inaba *et al.*, PRB **52**, R2221 (1995)

Unusual Metallic Transport in LSCO

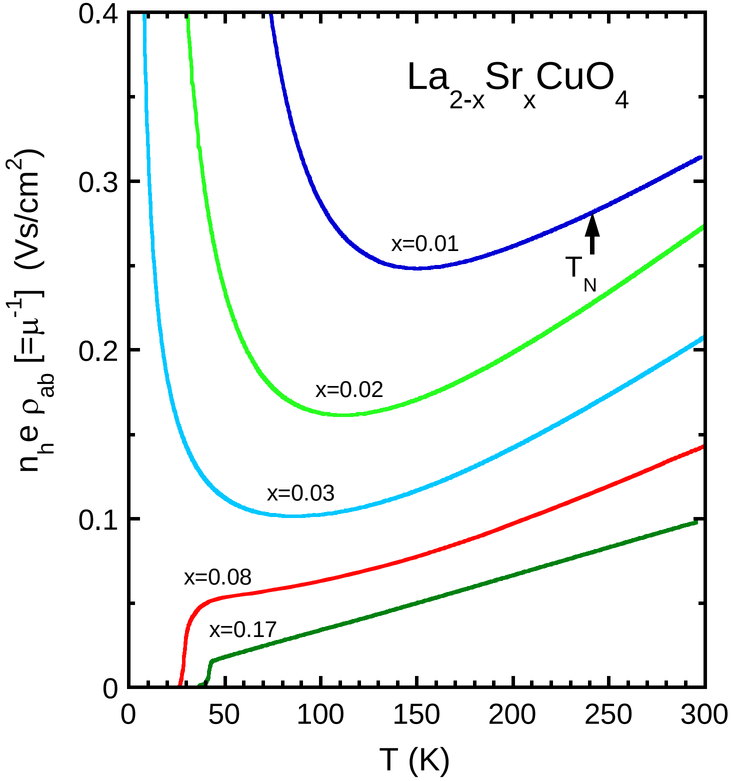


- Metallic behavior is observed at only 1% doping.
- Magnitude of ρ_{ab} at x = 0.01 is *too large* for a 2D metal.

  (Electron mean free path would be *shorter* than their de Broglie wave length.)

Y. Ando *et al.*, PRL **87**, 017001 (2001)

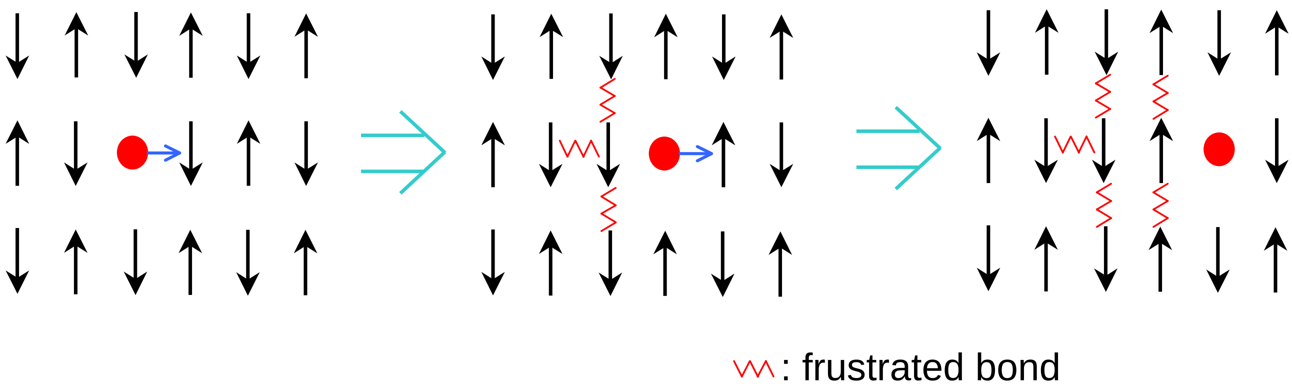
Mobility of Holes



- The mobility of doped holes in the Néel state (at x = 0.01) is not much different from that at optimum doping.

Motion of a Hole in an Antiferromagnet

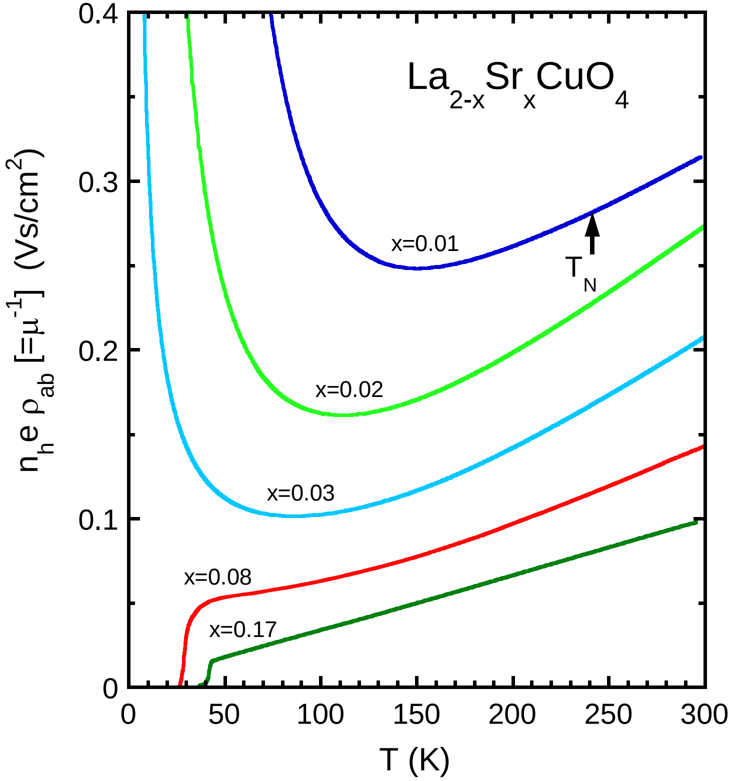
Motion of a single hole frustrates the AF bonds.



⇒ Antiferromagnetic order should impose a large effective mass on doped holes.

cf. E. Dagotto, RMP **66**, 763 (1994)

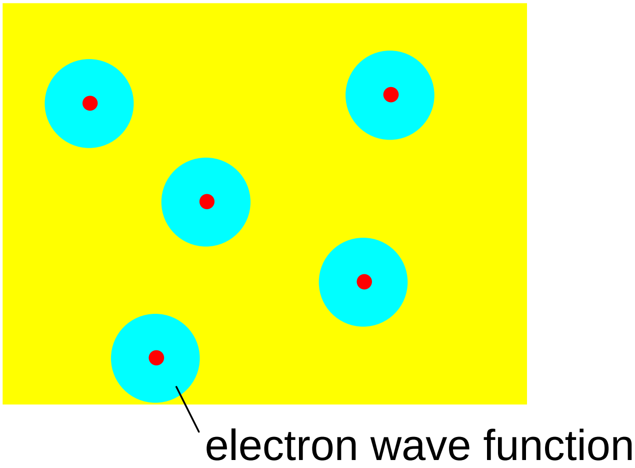
Mobility of Holes



- "High" mobility in the Néel state is unusual.

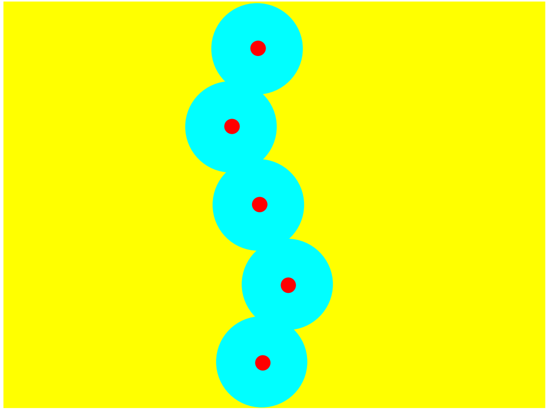
*Mobility in LSCO (3-10 cm^2/Vs) is comparable to that in Pb (2.5 cm^2/Vs) at 300 K.

Transport Mechanism (simple picture)



Random Distribution

⇒ **Localize**



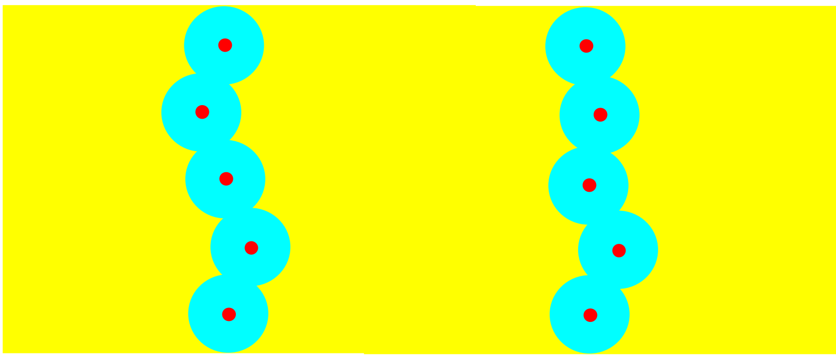
Electron Self-Organization

(Stripe Formation)

⇒ **Metallic Transport**

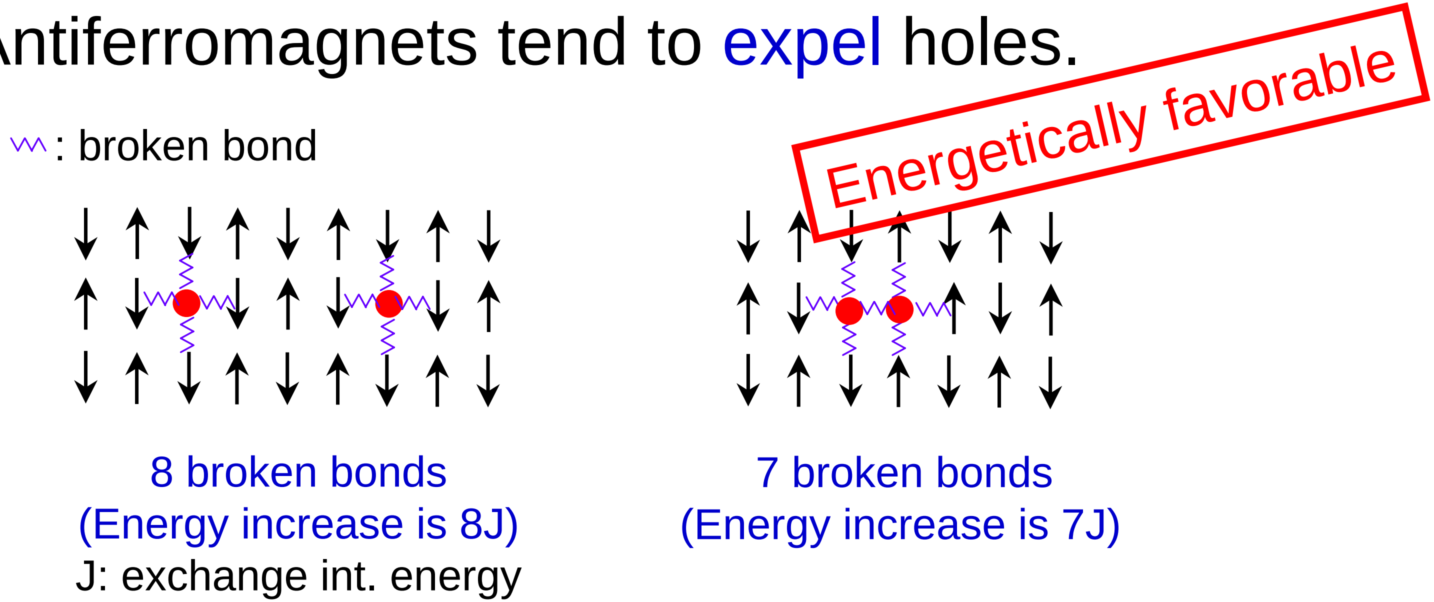
Transport through Stripes

- Self-organization picture naturally explains …
  - Insensitivity of the metallic transport to the Néel ordering
  - Too large bulk resistivity
  - Weak doping-dependence of the mobility



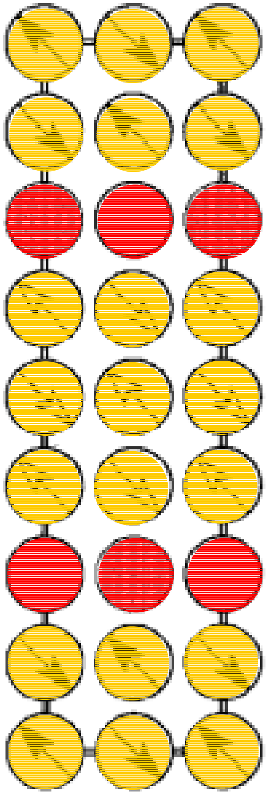
Why Stripes are Formed?

- Antiferromagnets tend to expel holes.



- Holes tend to segregate, but *macroscopic* phase segregation will increase Coulomb energy and is prohibited.
- Kinetic energy can be lowered by forming stripes.

Stripes Seen in LSCO Family

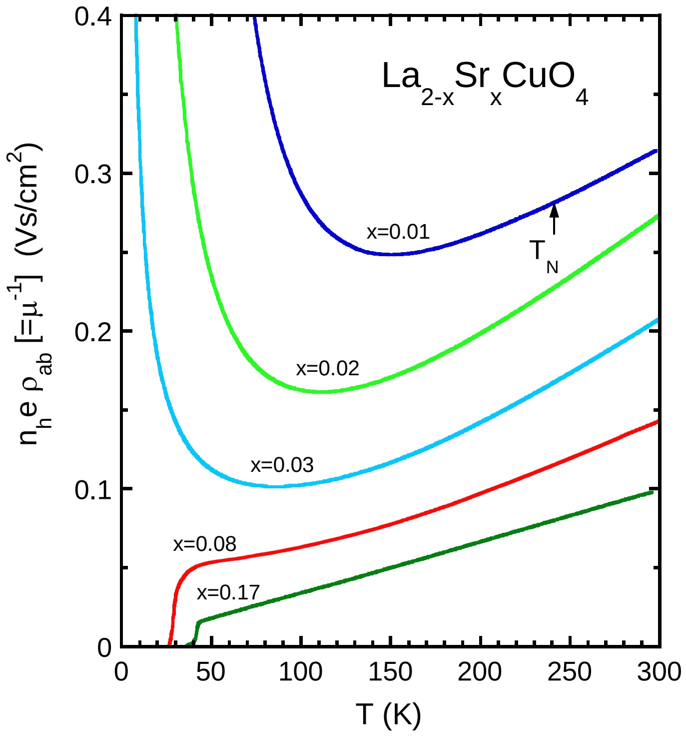


- Stripe order has been actually observed by neutron and X-ray scattering experiments.

J. M. Tranquada *et al.*,
Nature **375**, 561 (1995)

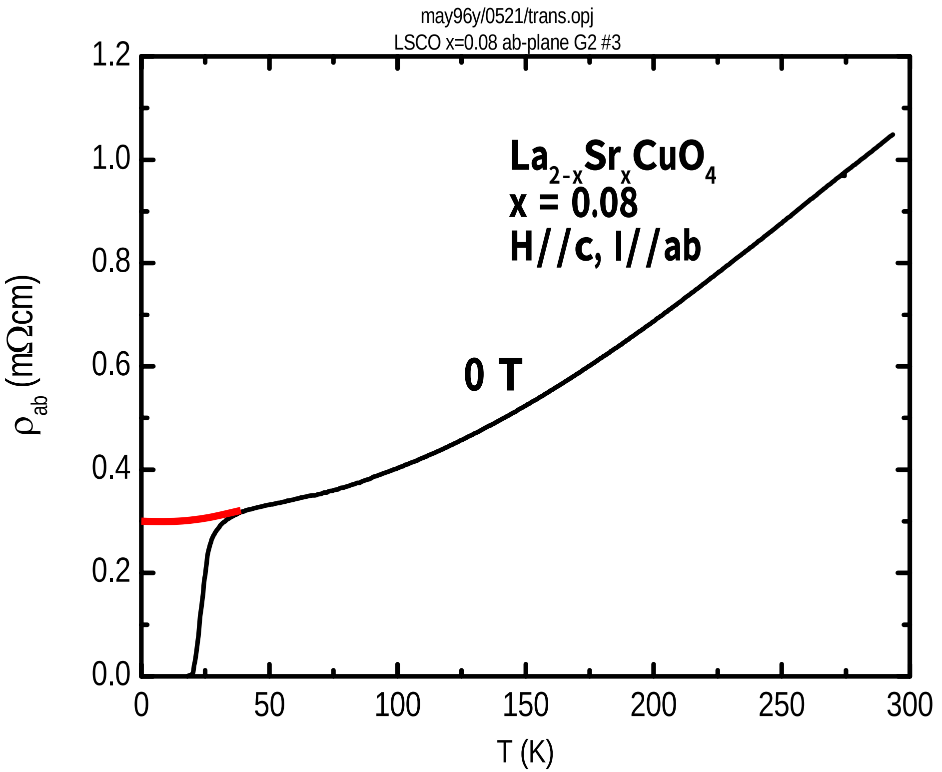
Peculiar Localization

We have seen …

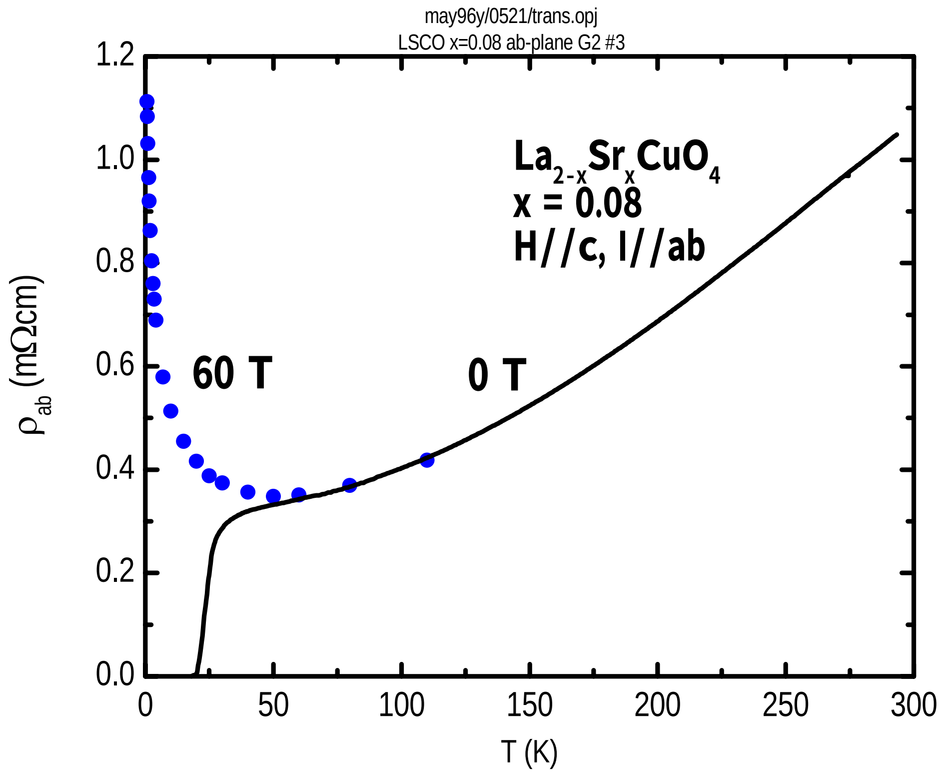


"Anomalous Metal" at moderate temperature down to very low doping.

However, that's not the whole story …



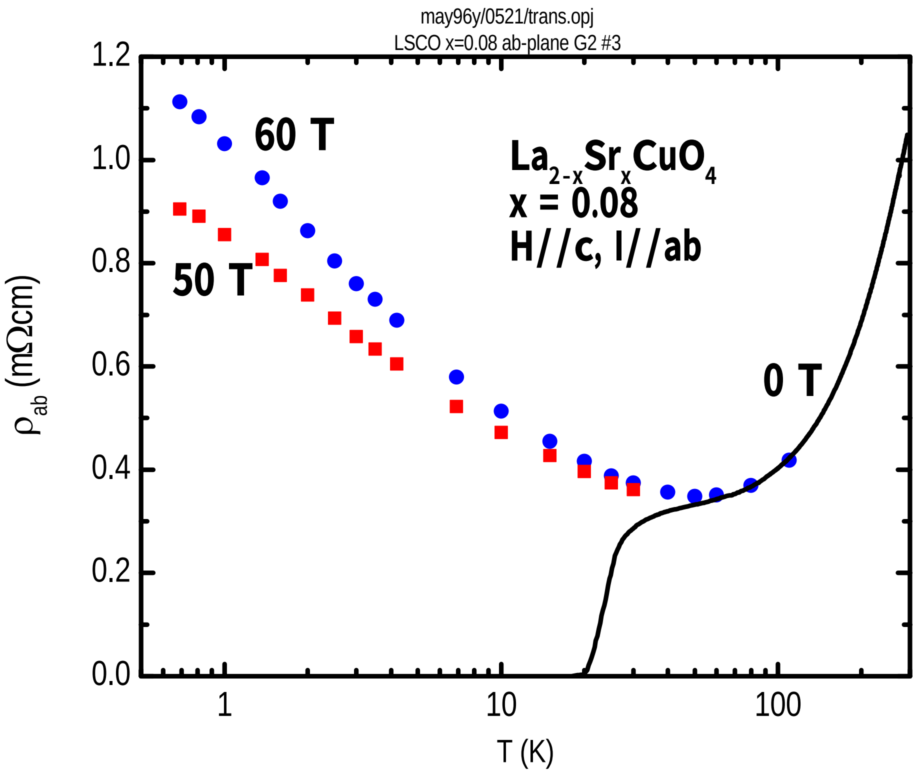
However, that's not the whole story …



Pronounced insulating behavior shows up when supercond-uctivity is suppressed by 60-T pulsed magnetic field.

Ando-Boebinger Experiment, 1995-1996

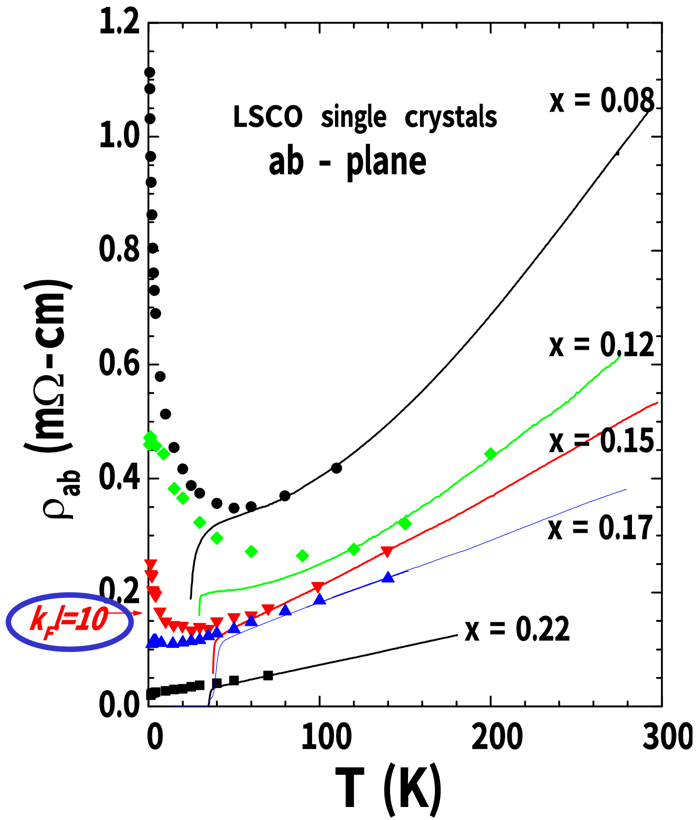
However, that's not the whole story …



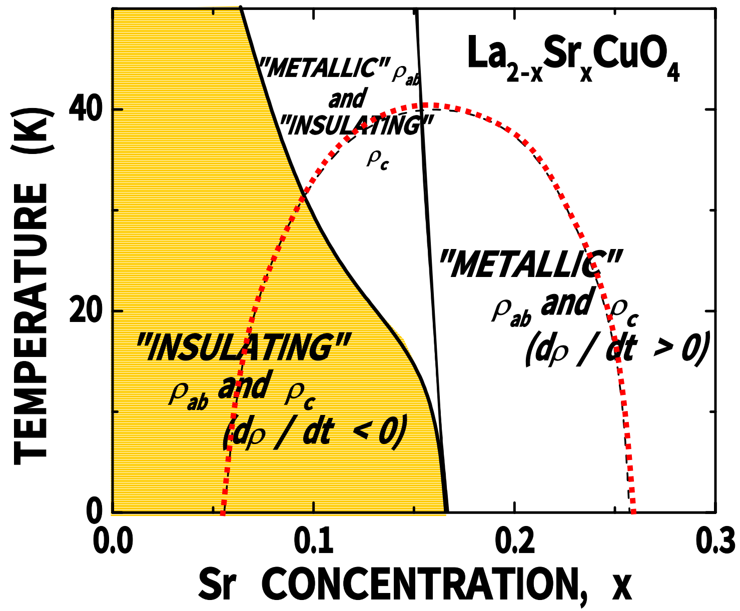
log(1/T) divergence of resistivity at low temperature

Y. Ando *et al.*, PRL **75**, 4662 (1995)

Metal-Insulator Crossover under 60 T

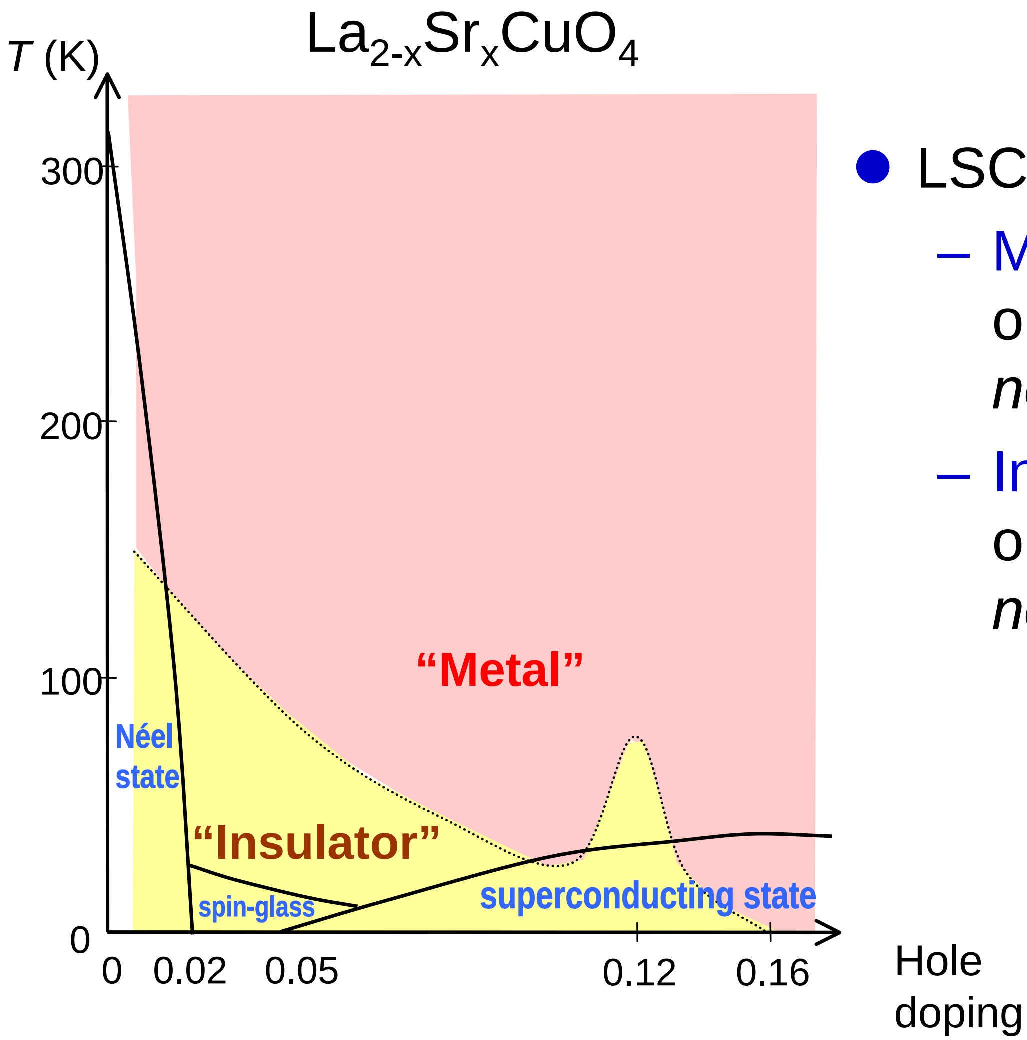


G. S. Boebinger, Y. Ando *et al.*, PRL **77**, 5417 (1996)



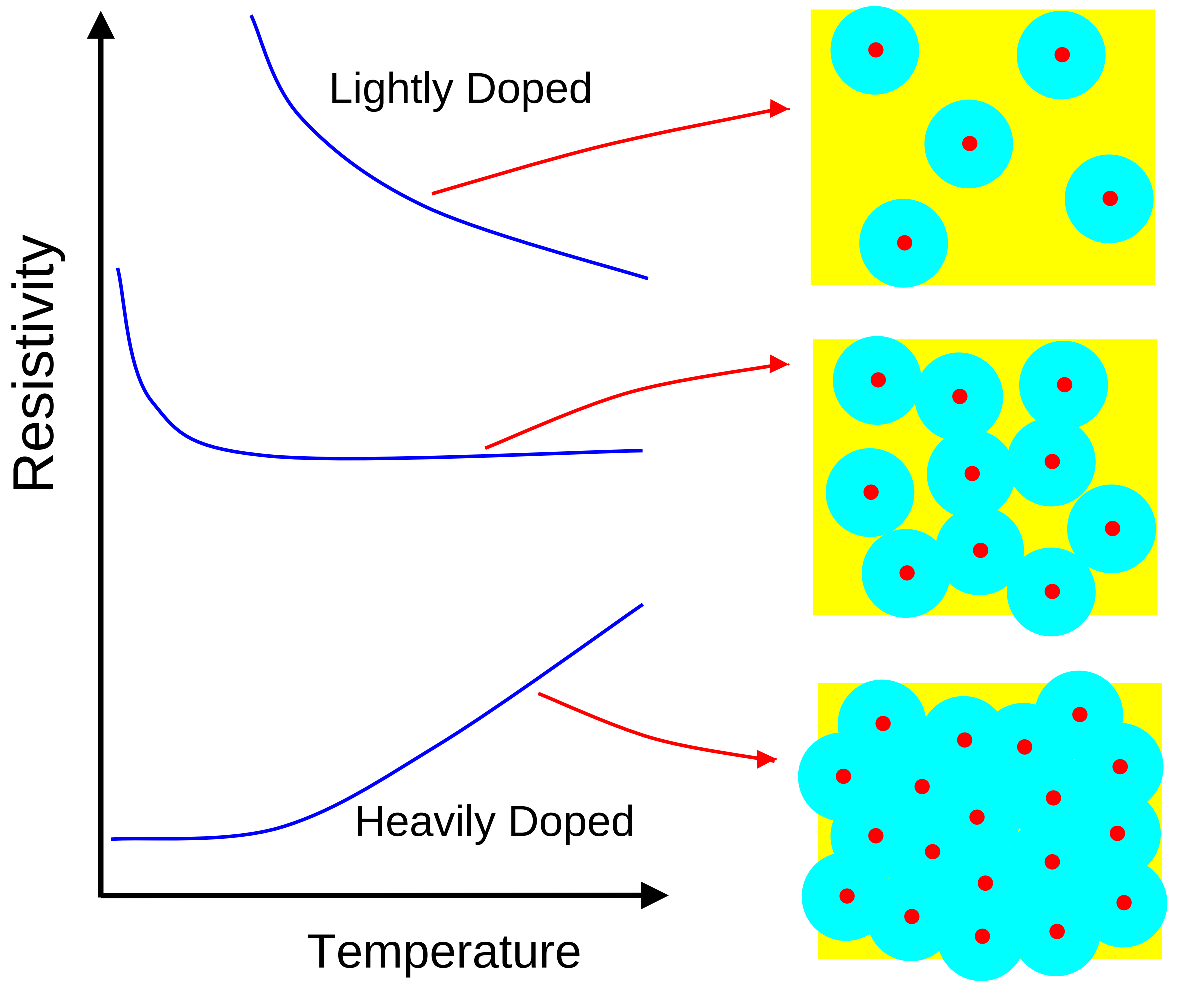
“Anomalous Insulator” at low temperature
(ρ_{ab} is too small for a 2D electron-localized system.)

Phase Diagram

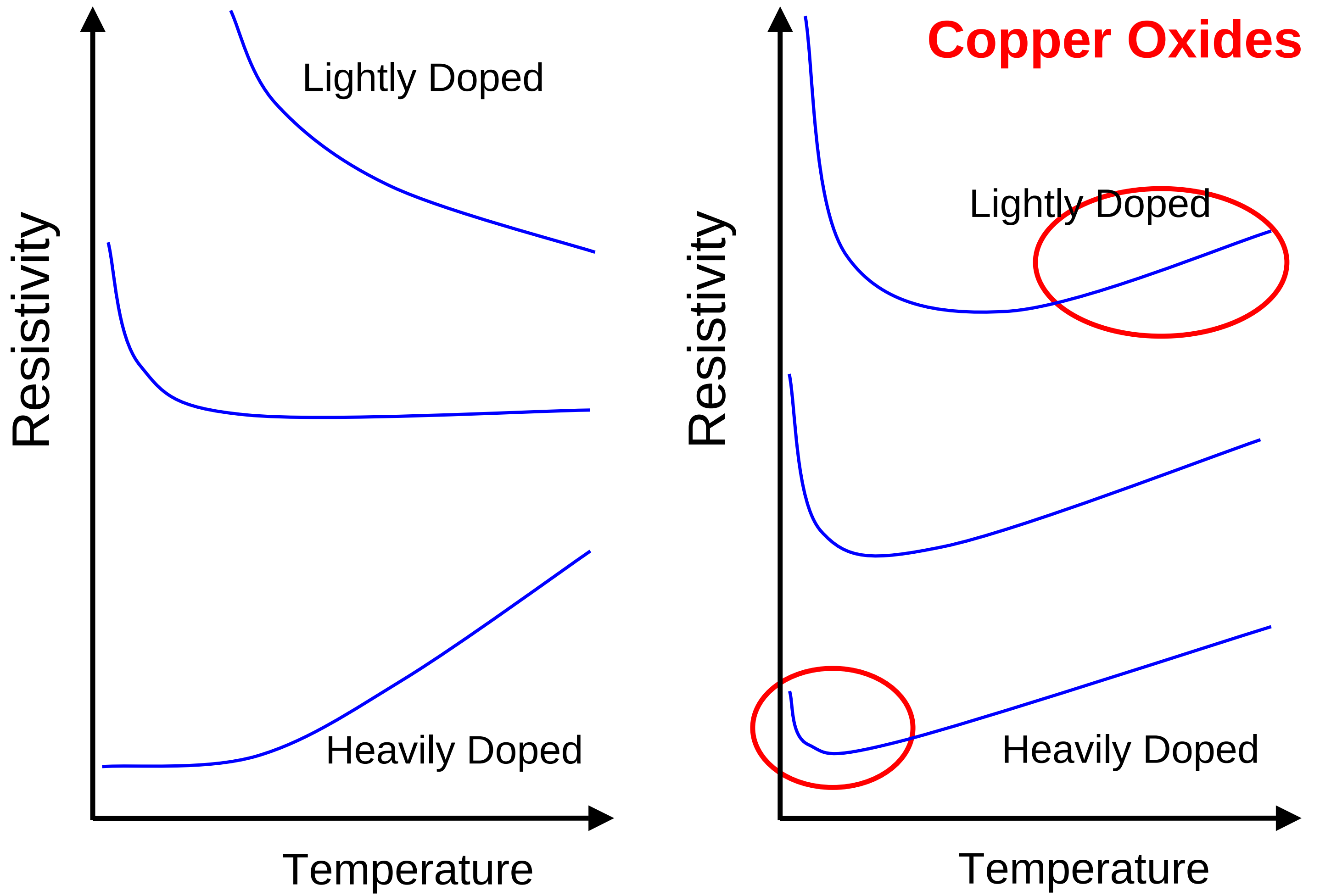


- LSCO is peculiar in that:
  - Metallic behavior is observed when it should *not* be a metal.
  - Insulating behavior is observed when it should *not* be an insulator.

Ordinary Materials

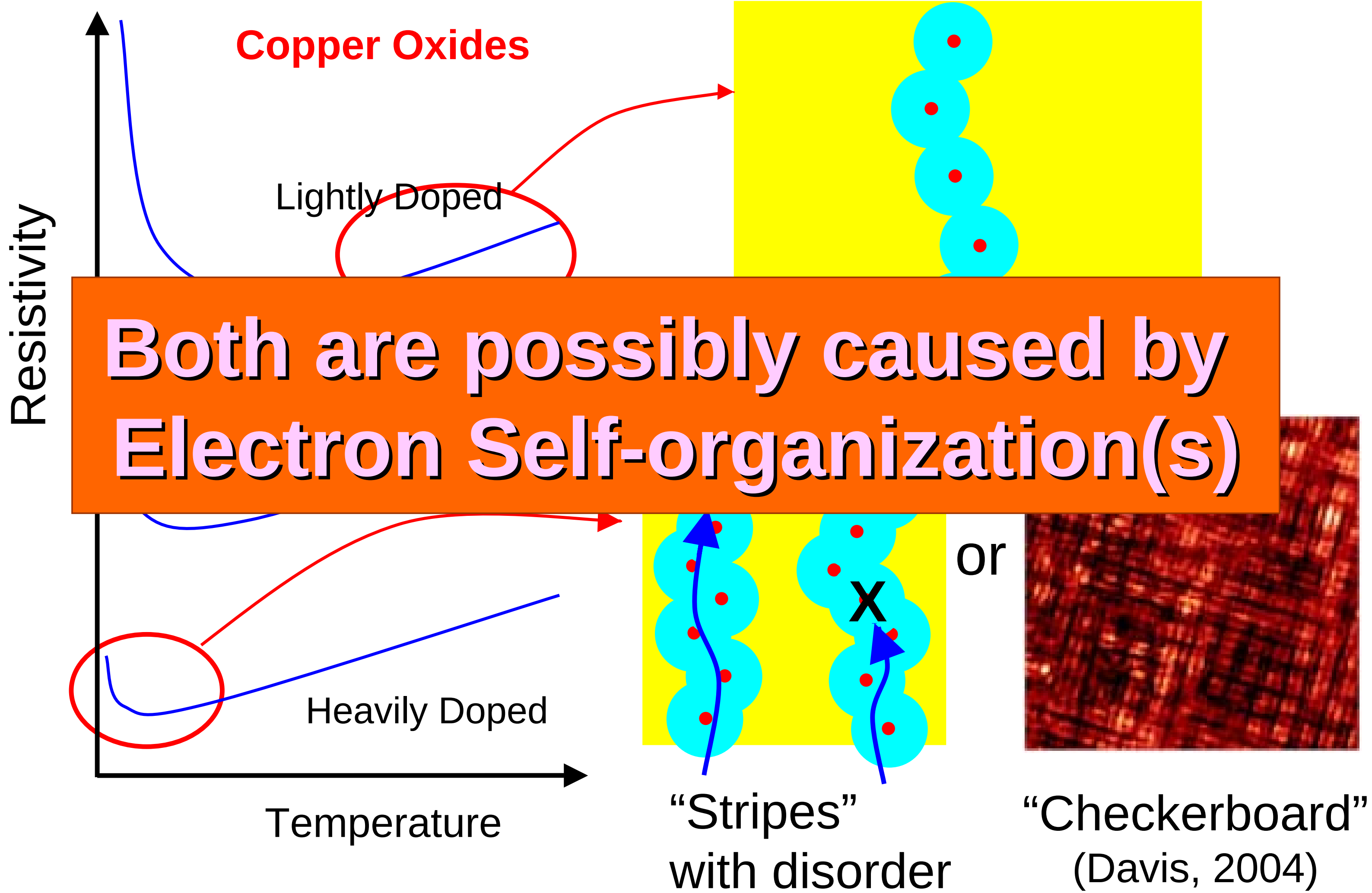


Comparison



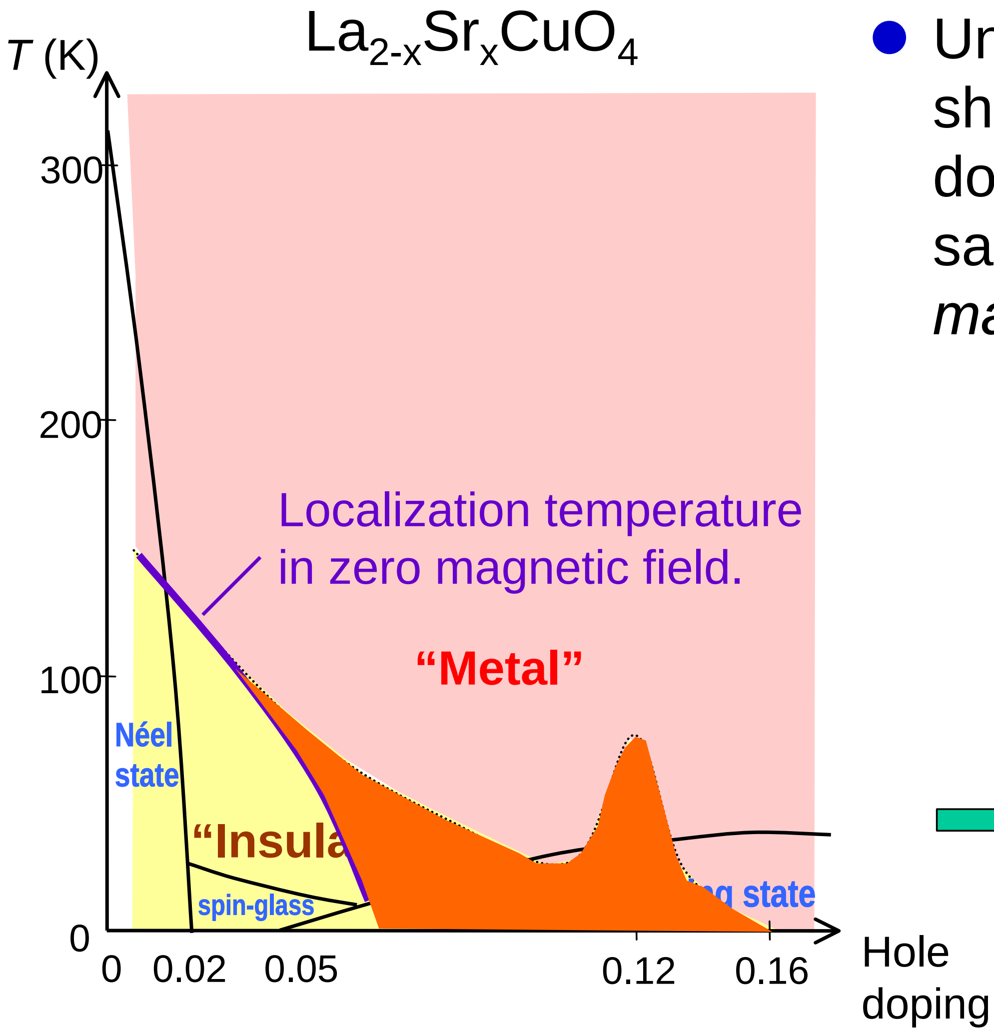
Resistivity
Lightly Doped
Heavily Doped
Temperature
Copper Oxides
Resistivity
Lightly Doped
Heavily Doped
Temperature

Copper Oxides

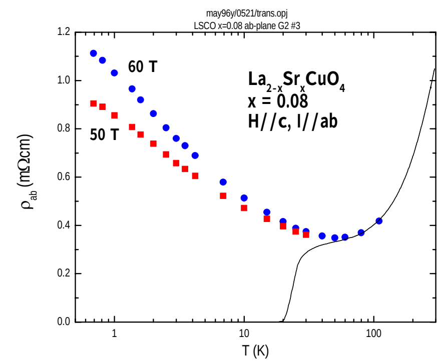


Both are possibly caused by Electron Self-organization(s)

Phase Diagram (reprise)

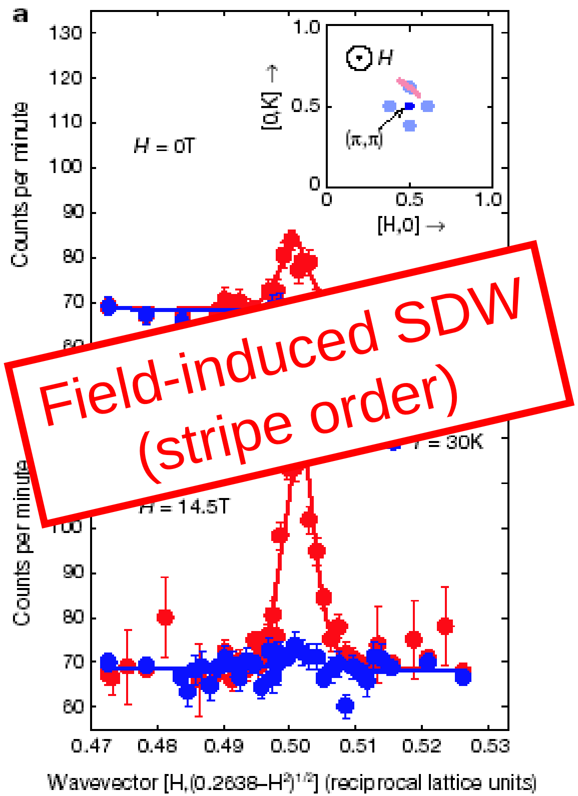


- Unusual Insulating state shows up under the SC dome in underdoped samples *when the magnetic field is applied*.

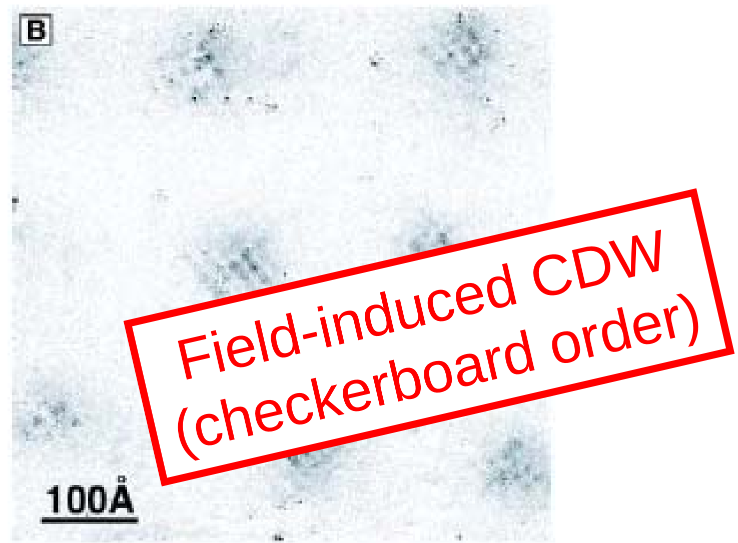


"Insulating State" is *caused* by the magnetic field?

Magnetic-Field-Induced SDW/CDW



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



J. E. Hoffman *et al.*, Science **295**, 466 (2002)

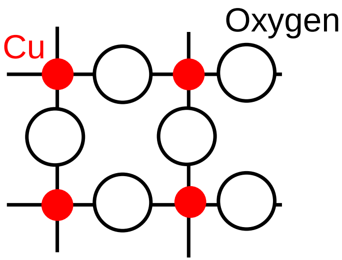
It is possible that these orders in the SC state are responsible for the localized state under 60 T.

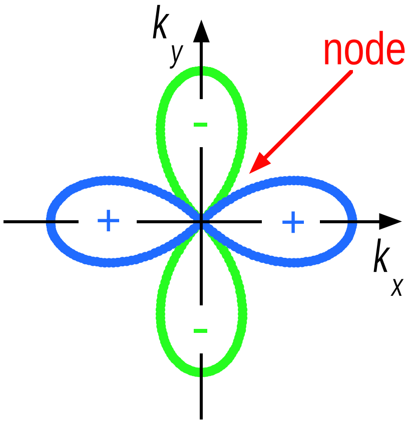
Let’s sort out the magnetic-field effect

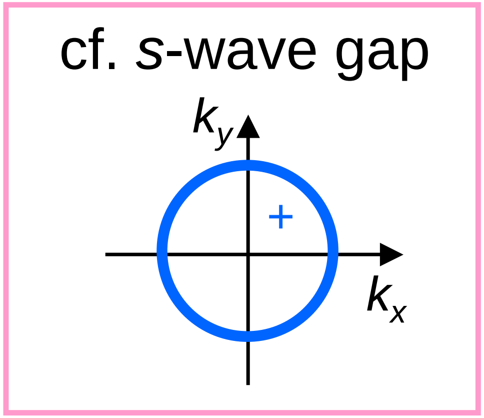
in the superconducting state.

Heat Transport in the SC State

- Cuprates have a “*d*-wave” superconducting gap.

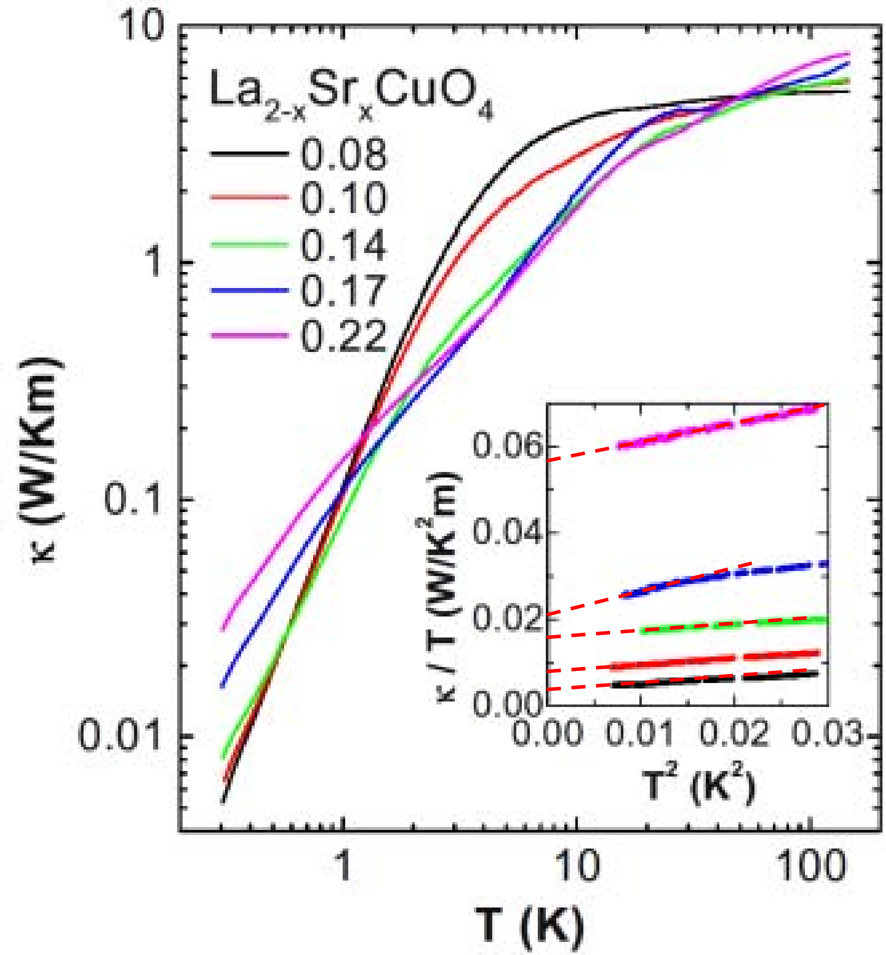


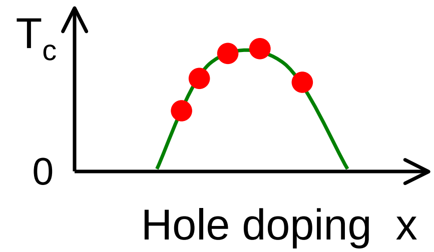




- Zero-energy quasiparticles exists near the nodes and carry heat in the *d*-wave SC state down to low T.

Quasiparticle Heat Transport at low T





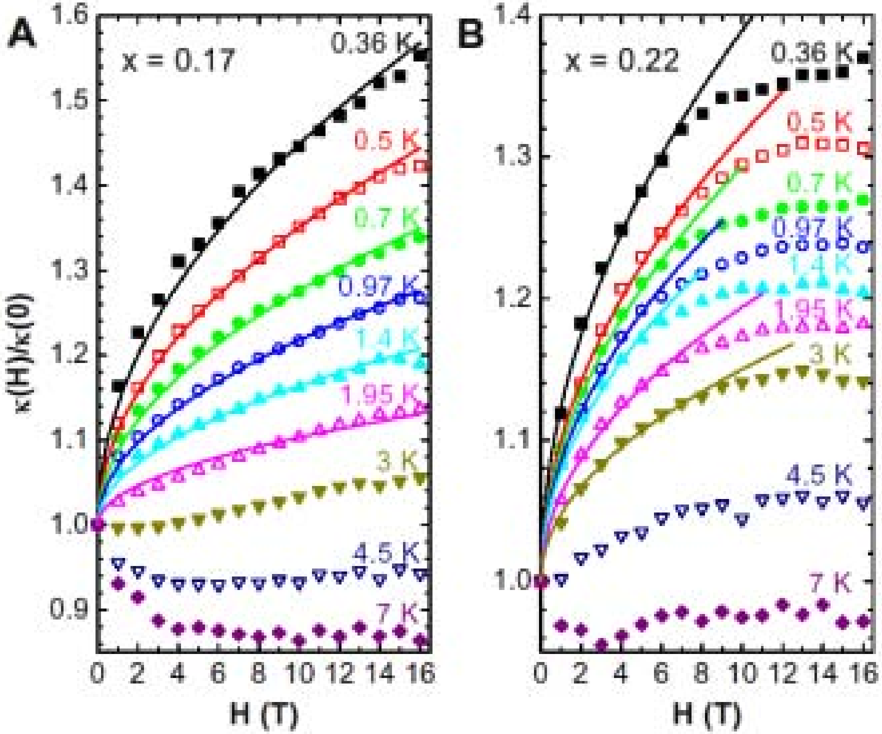
Zero intercept of the κ/T vs. T^2 plot gives a measure of the QP transport at 0 K.

⇒ In all these samples, there are delocalized QPs that carry heat.

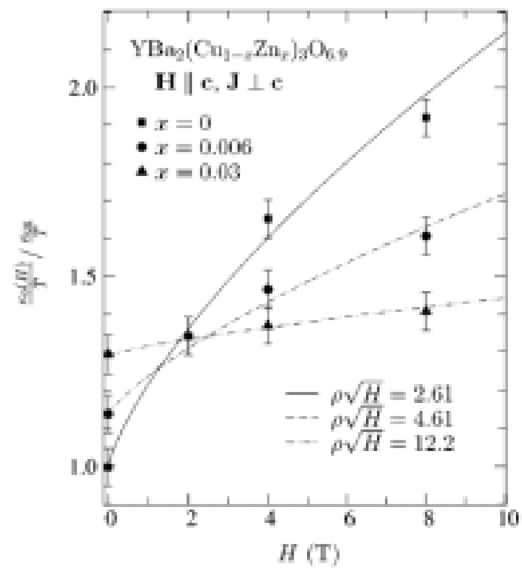
⇒ All the samples are "conductive" in 0 T.

Magnetic-Field Dependence (1)

Optimum and Overdoped



cf. $YBa_2Cu_3O_{6.9}$



M. Chiao *et al.*, PRL **82**, 2943 (1999)

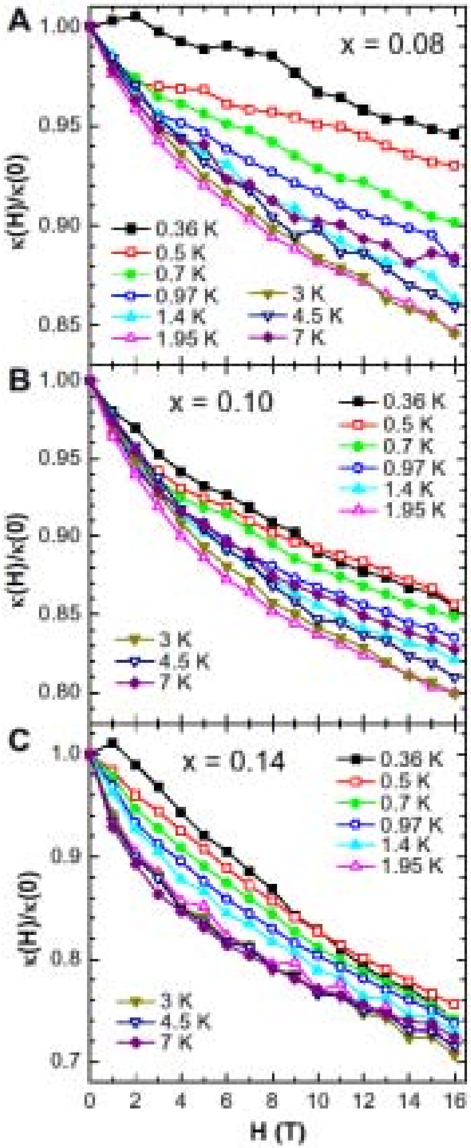
Magnetic-Field Dependence (2)

Underdoped LSCO

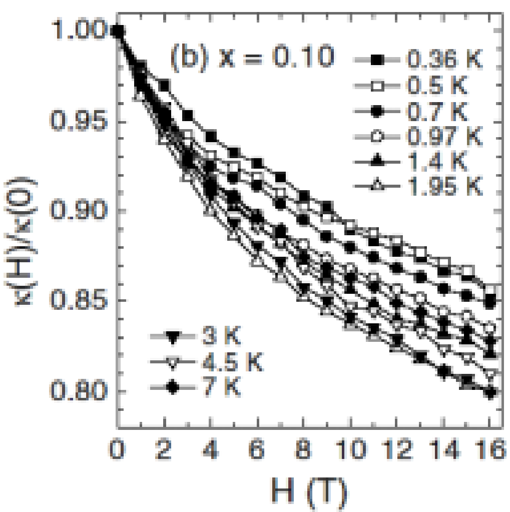
➡ No increase in κ with magnetic field

Specific heat shows QPs are created with magnetic field.

➡ QPs do *not* contribute to the transport, which means they are **localized.**

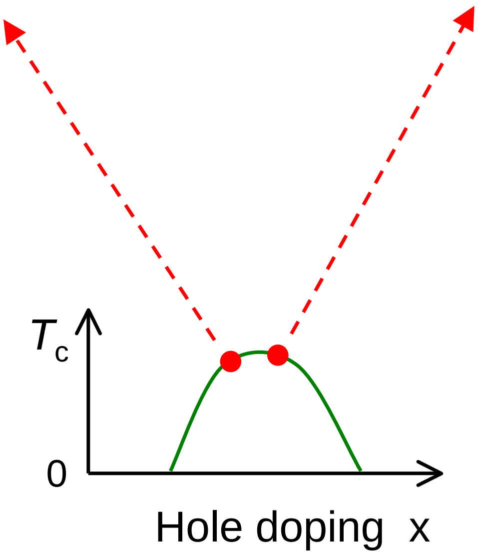


Magnetic-Field Dependence of κ

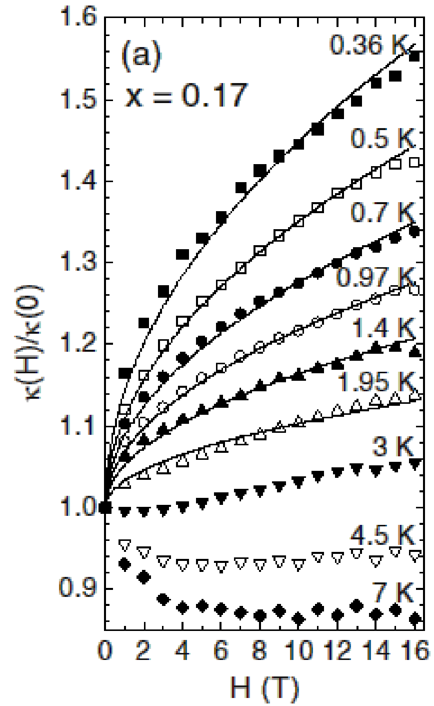


localized

under-doped



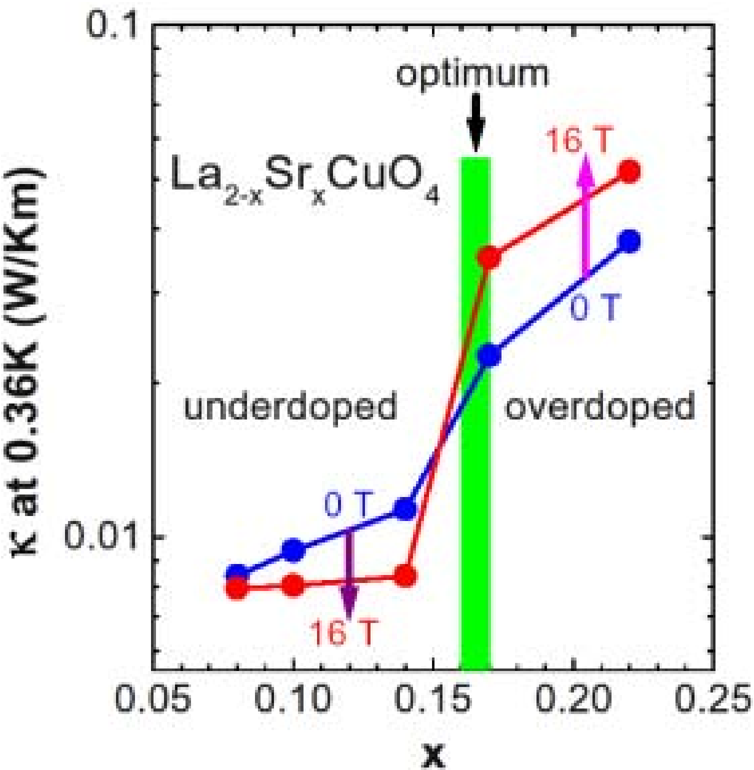
optimally-doped



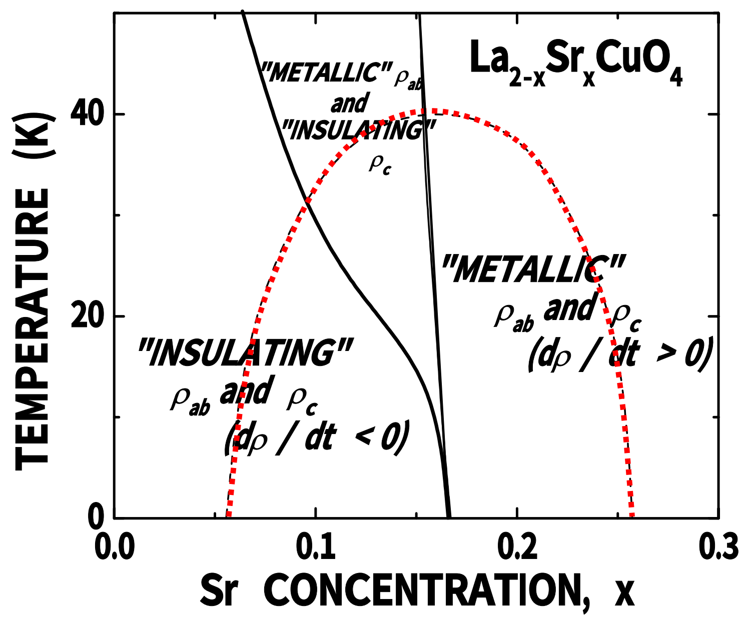
conductive

X. F. Sun *et al.*, PRL **90**, 117004 (2003)

Magnetic-Field-Induced Localization



X. F. Sun *et al.*,
PRL **90**, 117004 (2003)



G. S. Boebinger *et al.*,
PRL **77**, 5417 (1996)

Thus, magnetic field is actually causing a

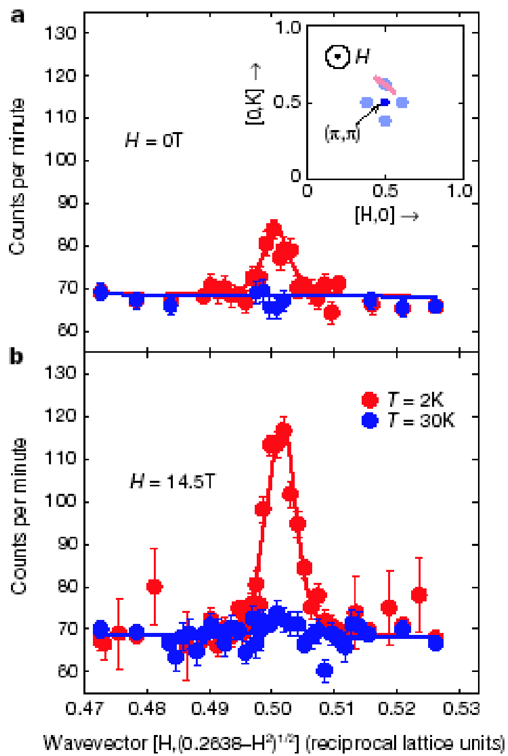
quasiparticle localization

in the underdoped SC state.

Field-Induced Incommensurability

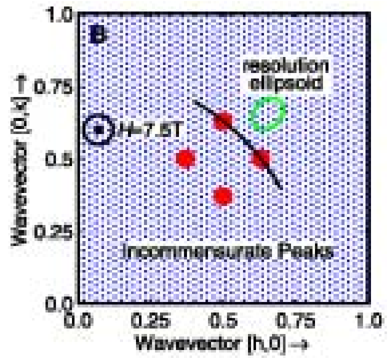
x = 0.10 (underdoped)

x = 0.16 (optimally-doped)

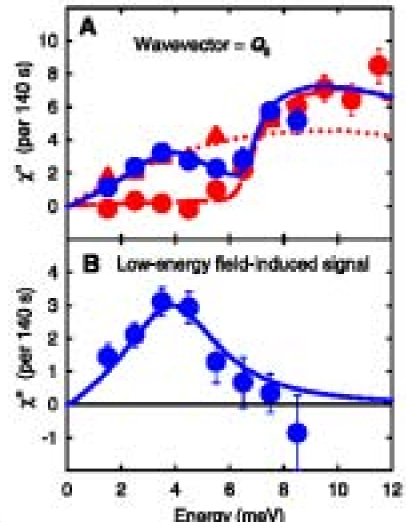


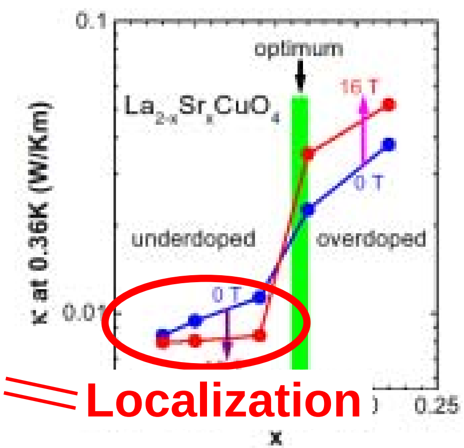
B. Lake *et al.*, Nature **415**, 299 (2002)

Field-induced *static* stripes



B. Lake *et al.*, Science **291**, 1759 (2001)





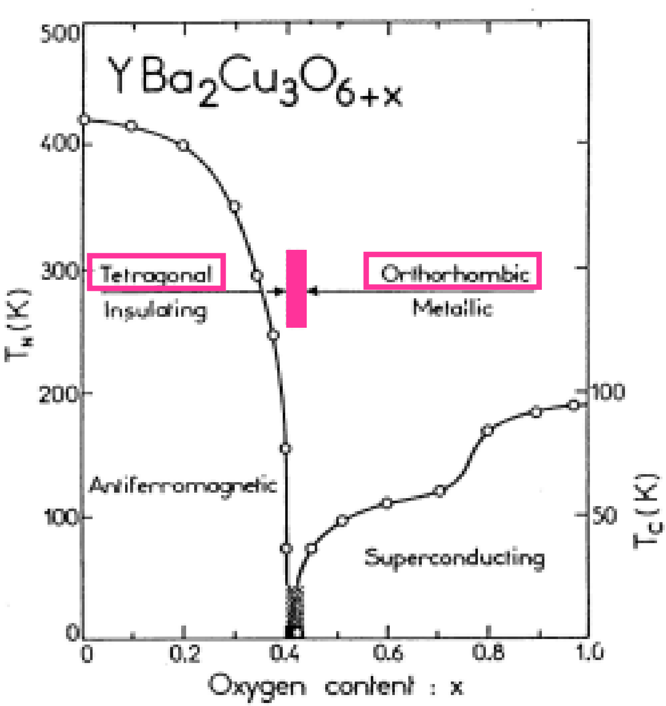
Localization

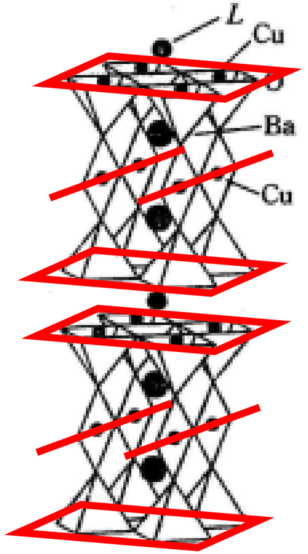
No static stripes, only *dynamical* stripes

How about the cleanest cuprate, YBCO?

$YBa_2Cu_3O_y$

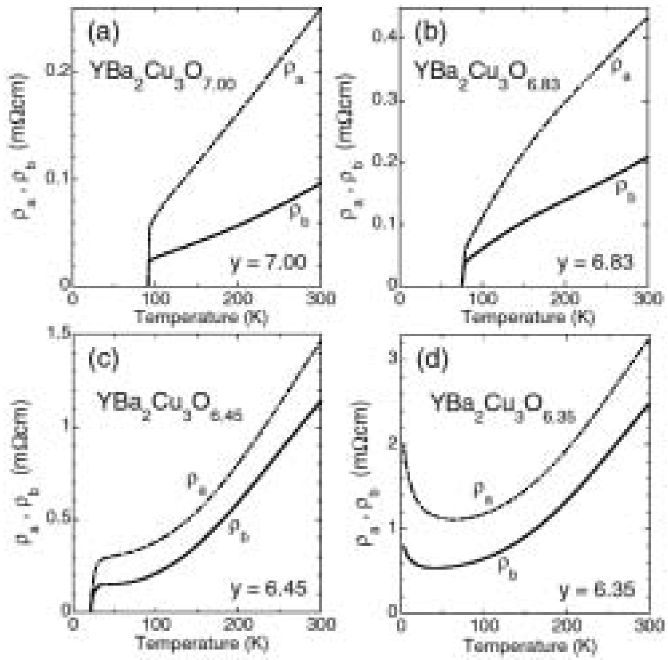
- Phase diagram of YBCO



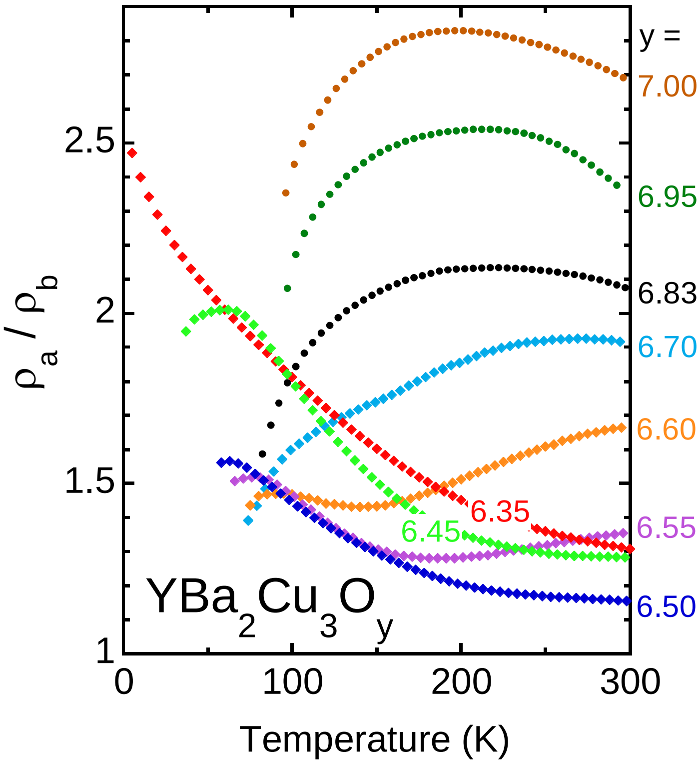


J. Rossat-Mignod *et al.*, Physica B **169**, 58 (1991)

Resistivity Anisotropy in YBCO

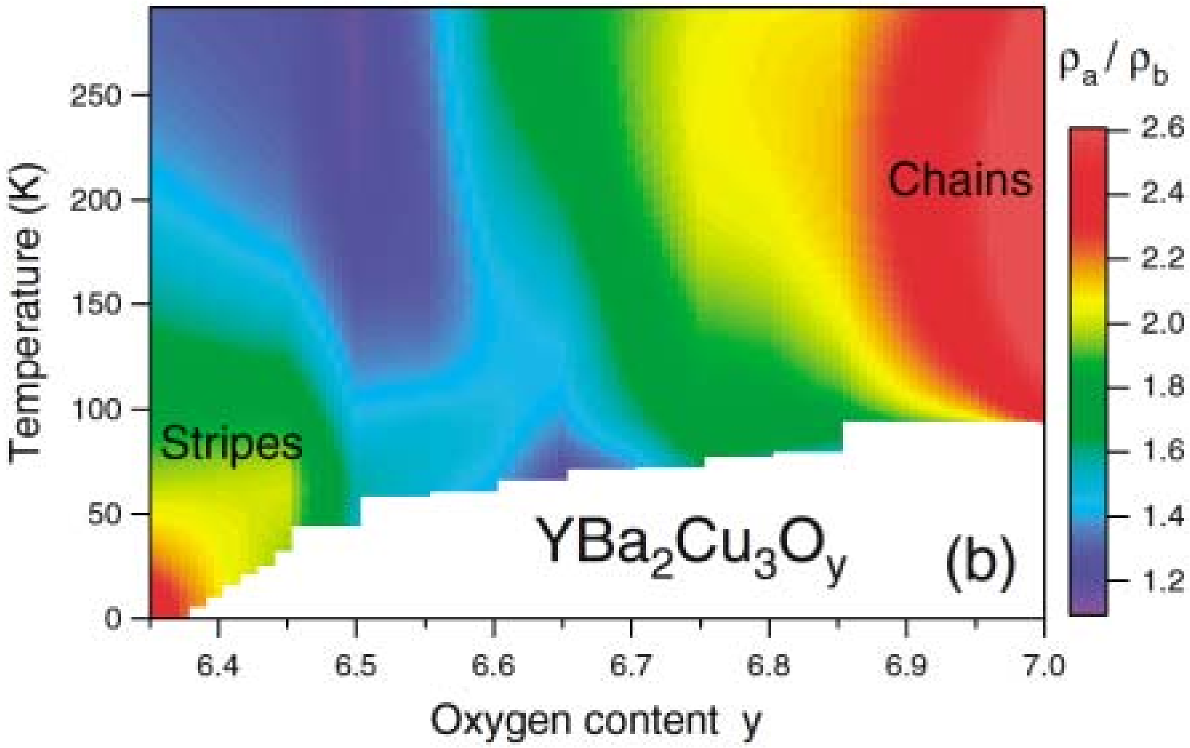


Y. Ando *et al.*, PRL **88**, 137005 (2002)



- At low doping, anisotropy tends to grow with lowering T.

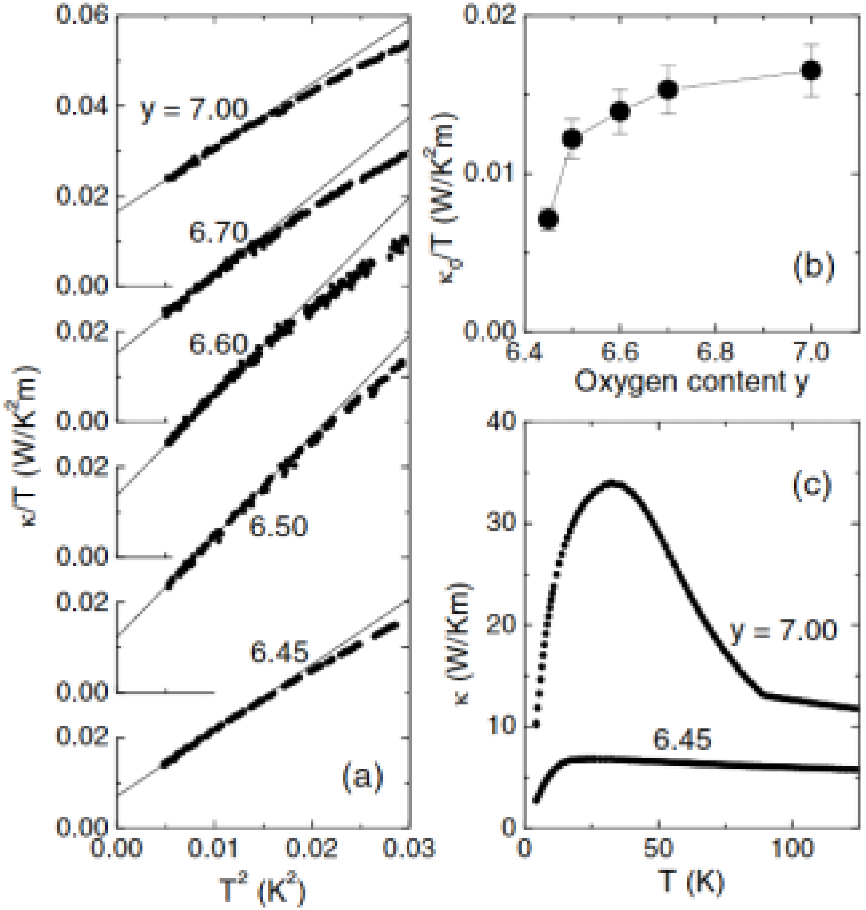
Resistivity Anisotropy Mapping for YBCO



Clear sign of electron self-organization for y < 6.55

Y. Ando *et al.*, PRL **88**, 137005 (2002)

QP Heat Transport in YBCO at *H* = 0

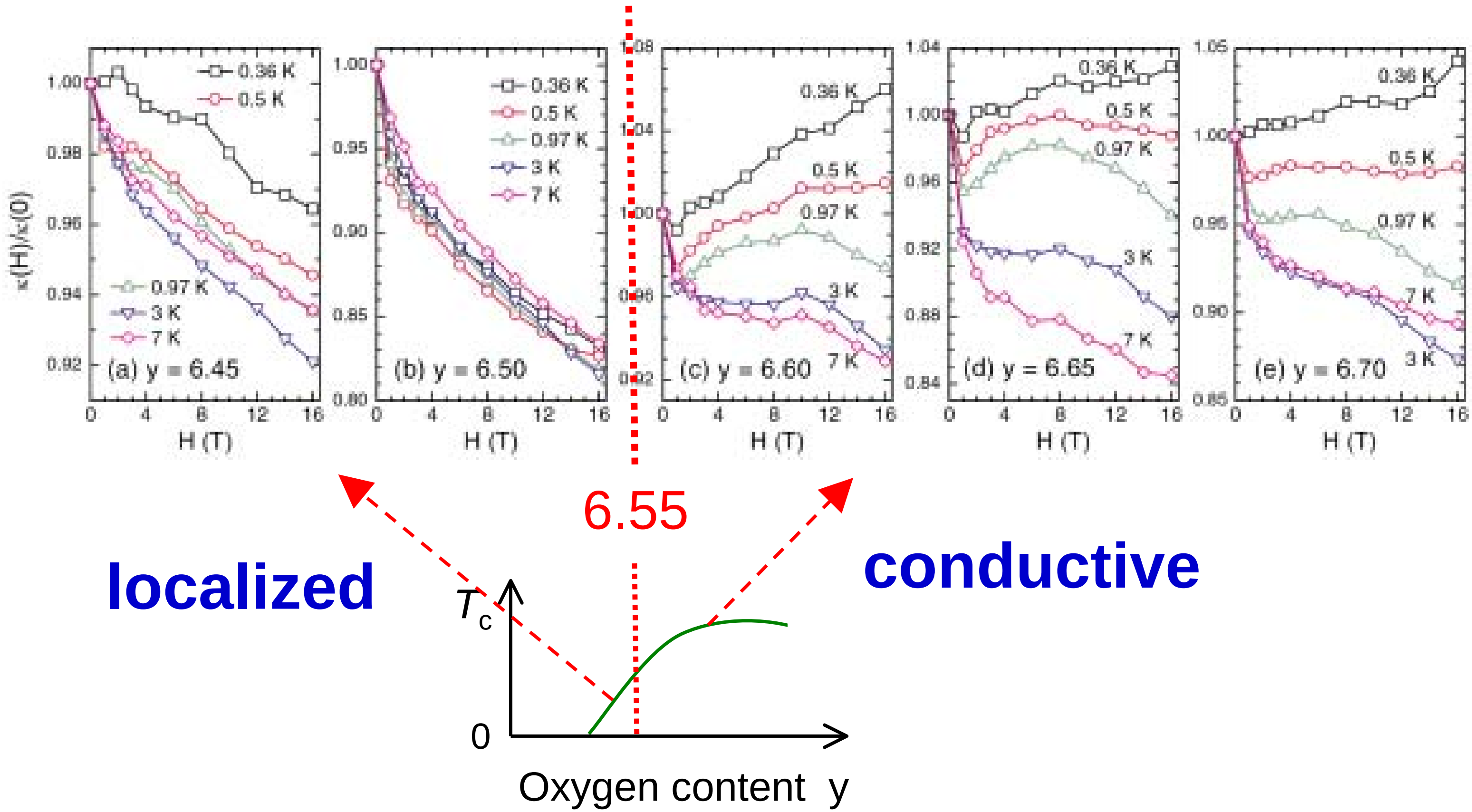


⇒ As in LSCO, there are delocalized QPs in all the SC samples.

⇒ All these samples are "conductive" in 0 T.

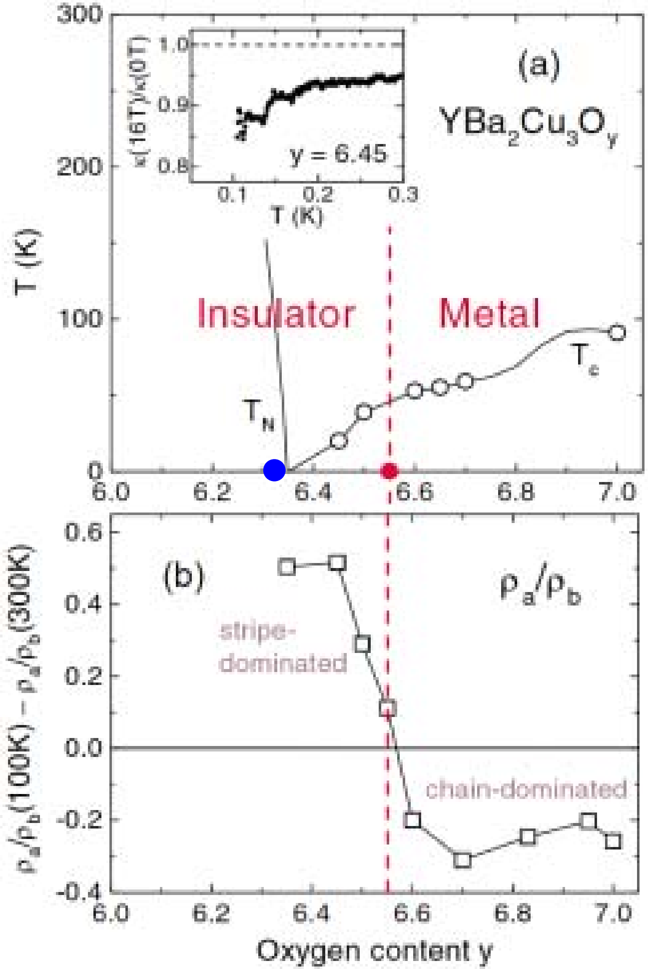
X. F. Sun *et al.*, PRL **93**, 107001 (2004)

Magnetic-Field Dependence of κ

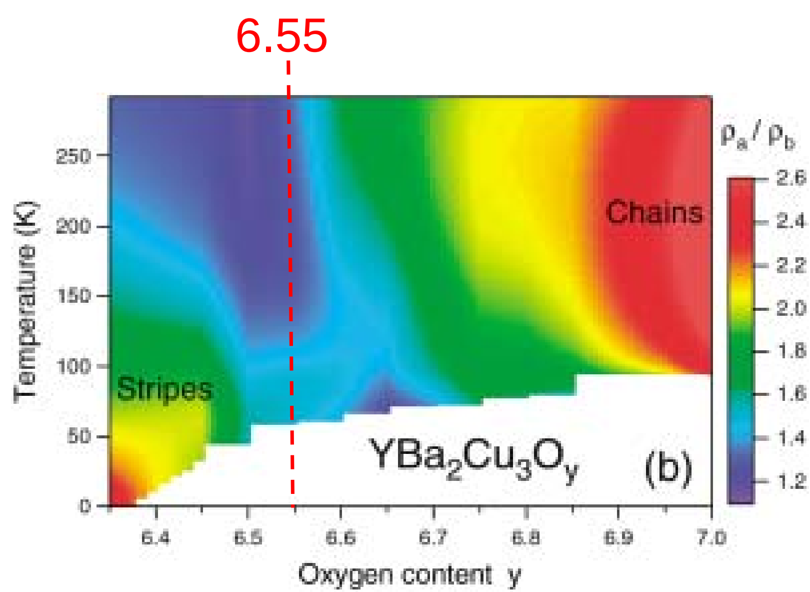


X. F. Sun *et al.*, PRL **93**, 107001 (2004)

Localization and Self-Organization



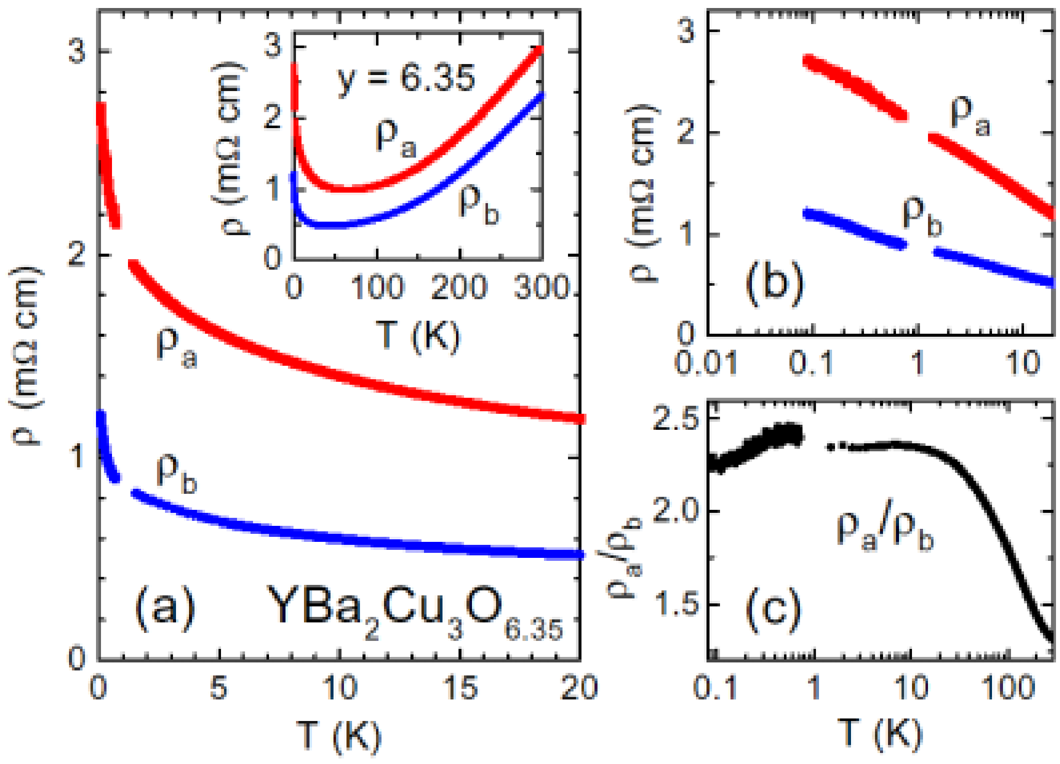
X. F. Sun *et al.*,
PRL **93**, 107001 (2004)



Y. Ando *et al.*, PRL **88**, 137005 (2002)

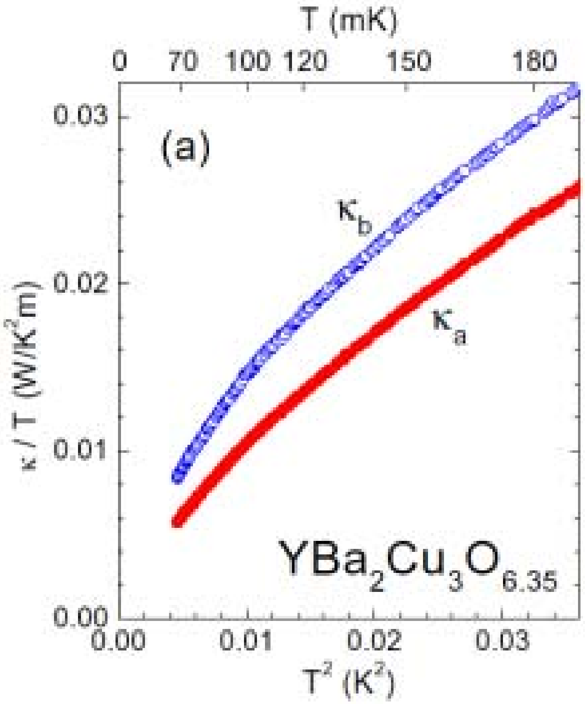
Non-superconducting YBCO

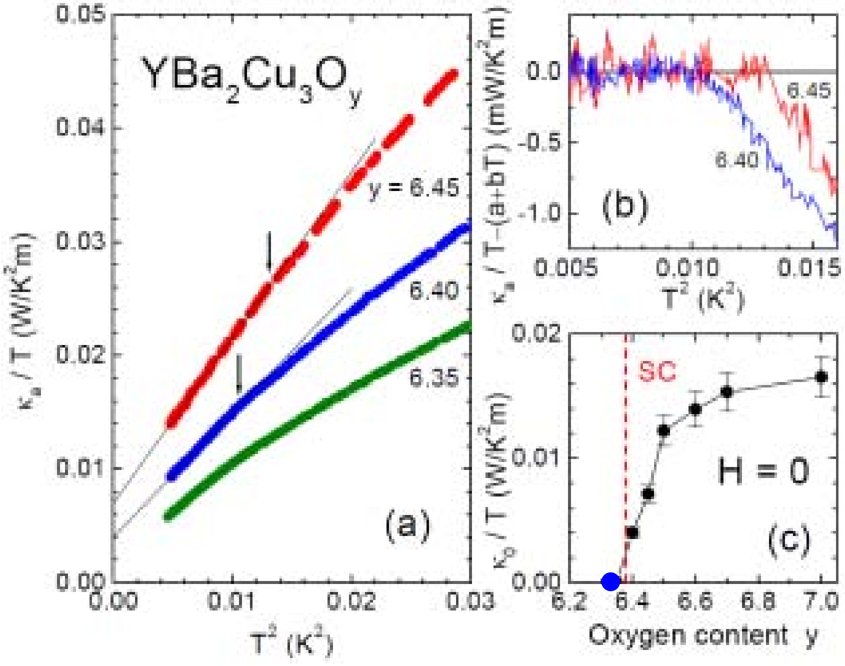
In-Plane Resistivity for y = 6.35



Non-superconducting YBCO

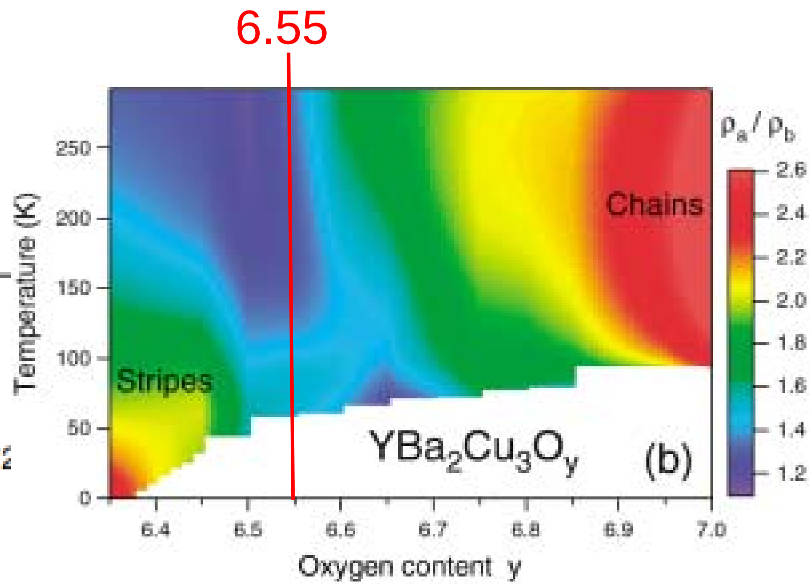
In-Plane Thermal Conductivity



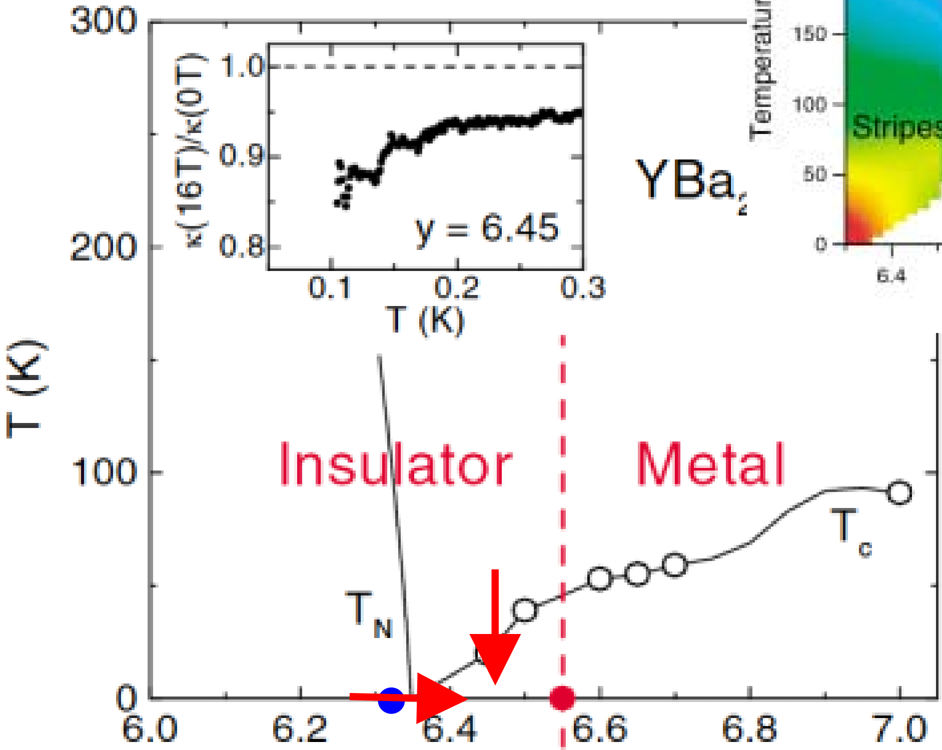


Quasiparticles are localized for T → 0 in the *absence* of SC even in the cleanest cuprate, YBCO, at H = 0.

Kinetic-Energy-Driven Superconductivity?



Y. Ando *et al.*,
PRL **88**, 137005 (2002)



X. F. Sun *et al.*,
PRL **93**, 107001 (2004)

Conclusions

- Self-organization of electrons in high-Tc cuprates seems to be responsible for the emergence of a metallic transport.
- At the same time, the electron self-organization seems to be responsible for the unusual localization behavior that is not well understood.
- Relevance of the electron self-organization to the occurrence of HTSC is obviously a key issue.

Key Issues (in my opinion)

- Electron Self-Organizations
- Insulating Normal State under the SC Dome
- Pseudogap and "Fermi arc" in the Normal State (*d*-wave SC and the Associated Nodal Structure)
- Peculiar Spin Dynamics and the Resonance Mode
- Unusual Roles of Phonons
- Quantum Phase Transition and Criticality

Thank you !