# *Electrostatic Modification of Cuprates*

Allen M. Goldman
School of Physics and Astronomy
University of Minnesota

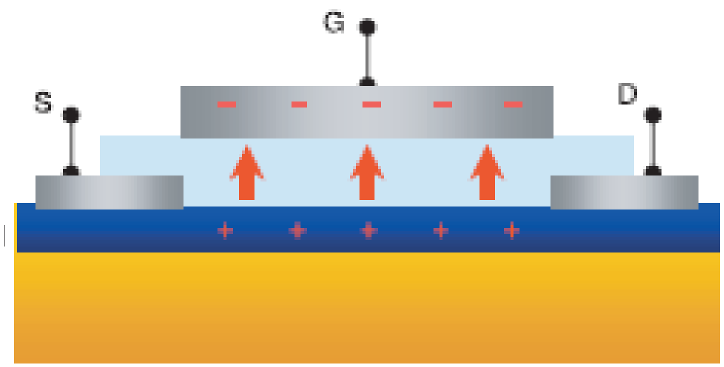
- # Principal Collaborators
- Xiang Leng (BNL)
- Javier Garcia-Barriocanal (Complutense)
- Joseph Kinney
- Boyi Yang
- Yeonbae Lee (LBL/UCB)
- JJ Nelson

Xiang Leng *et al.*, Phys. Rev. Lett. **107**, 027001 (2011).
Xiang Leng et *al.*, Phys. Rev. Lett. **108** 067004 (2012).
Garcia-Barriocanal *et al.*, Phys. Rev. B 87, 024509 (2013)

# How can one modify the electronic properties of a material?

- **Chemical doping** (changes composition, structure,…)
- **Electrostatic charging** (reversible?, continuous, fast,…)

## Field Effect Transistor




Induced carriers:

$$Q = CV_G = \varepsilon \frac{A}{d} V_G$$

$\varepsilon$ : dielectric constant

$d$ : thickness of the gate dielectric

This approach is compatible with—

Complex oxides: **cuprate superconductors**, **Mott insulators**, and colossal magnetoresistive compounds

**Two-dimensional and interfacial superconductors**

Organic and inorganic semiconductors, novel carbon structures, single molecules, graphene, topological insulators.

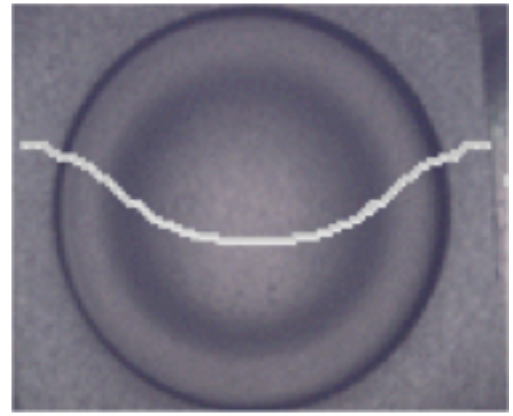
Can provide a tool for studying quantum critical behavior.

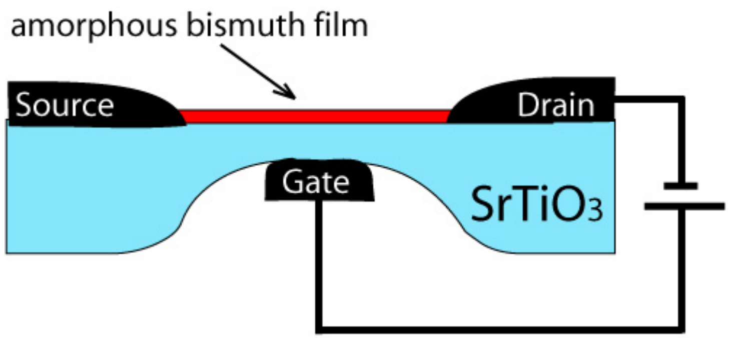
It may be possible to dope into regimes not accessible by chemical doping.

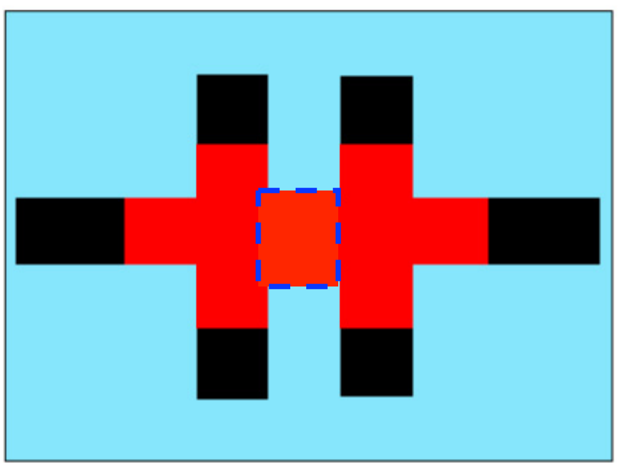
# FET Structure: Combined Substrate and Gate Insulator

Back of a micro-machined substrate.
Height profile is superimposed on the picture.
Thickness in middle can range from 10μm to 100μm
Surface roughness of approximately 1μm.

Diameter of the thinned region is typically 4mm.



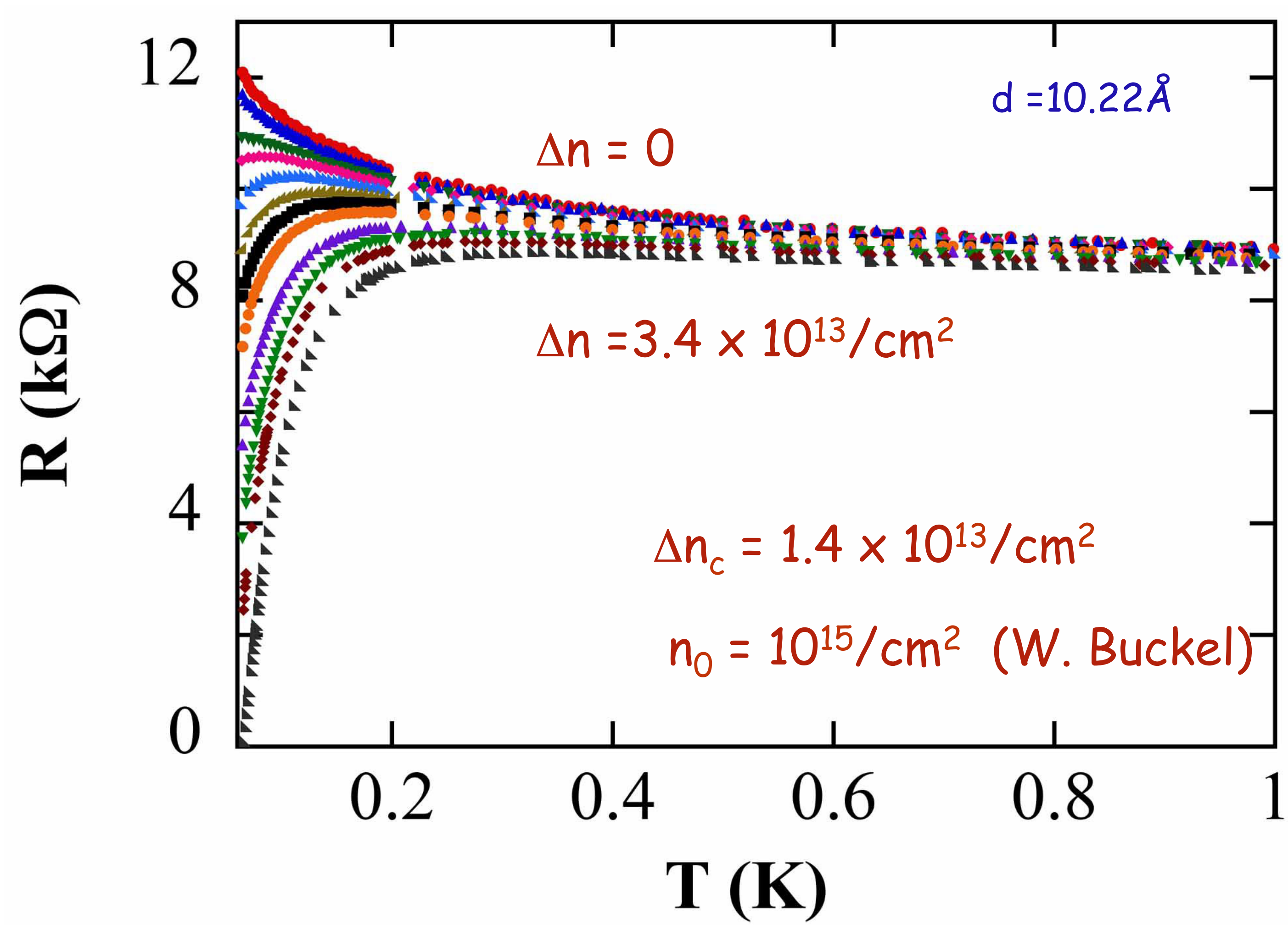


Cartoon of insulating substrate separating a Bi film from the gate Thickness of the film is about 10 Å, and that of the source and drain about 100 Å. Separation between the gate and the film is approximately 50 μm.

A. Bhattacharya, *et al.*, APL **85**, 997 (2004)

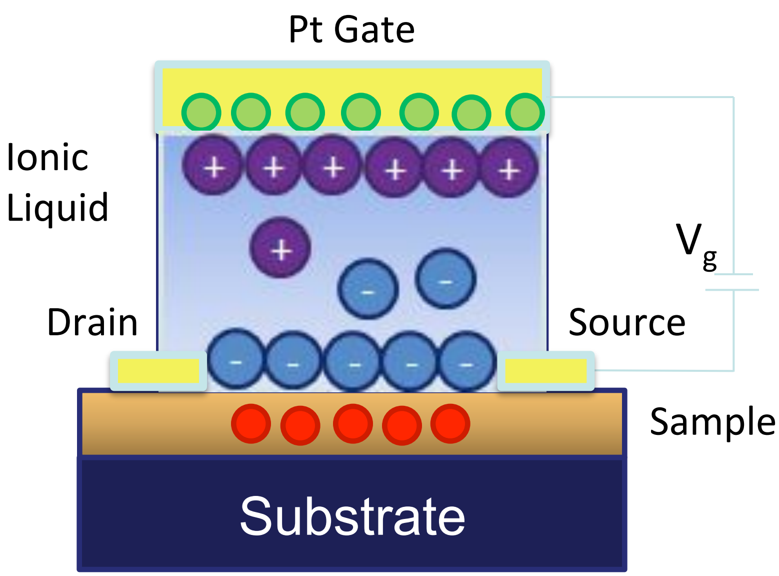
# Electrostatically Tuned S-I Transition

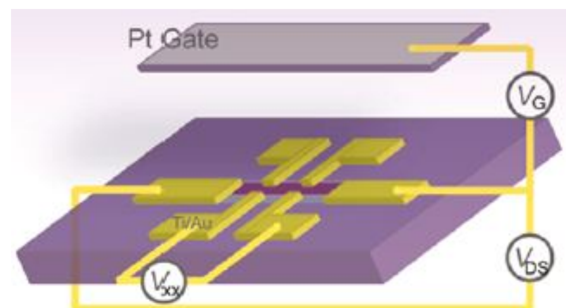


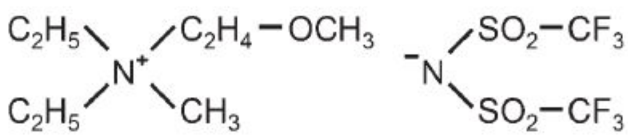

K. Parendo *et al.*, PRL 95, 049902 (2005)

# Electric Double Layer Transistor

## EDLT



[DEME][TFSI]

1853. ANNALEN *No.* 7.
DER PHYSIK UND CHEMIE.
BAND LXXXIX.

# I. *Ueber einige Gesetze der Vertheilung elektrischer Ströme in körperlichen Leitern, mit Anwendung auf die thierisch-elektrischen Versuche;*

*von H. Helmholtz.*

(Schluſs.)

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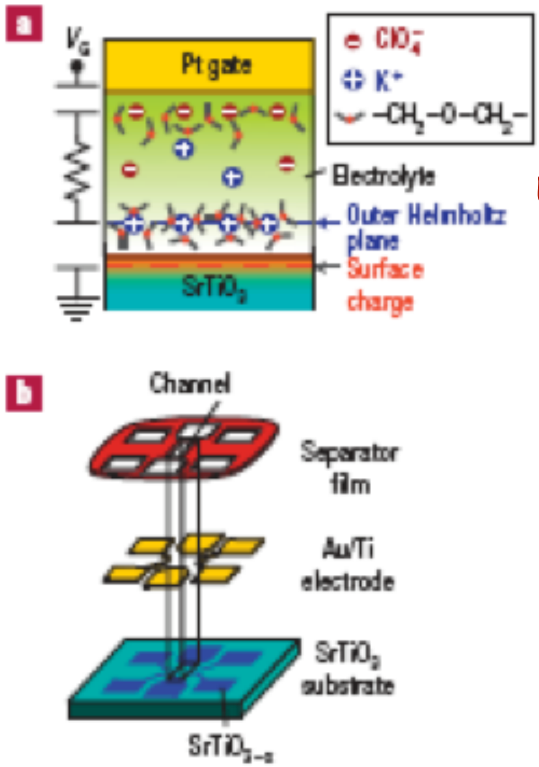
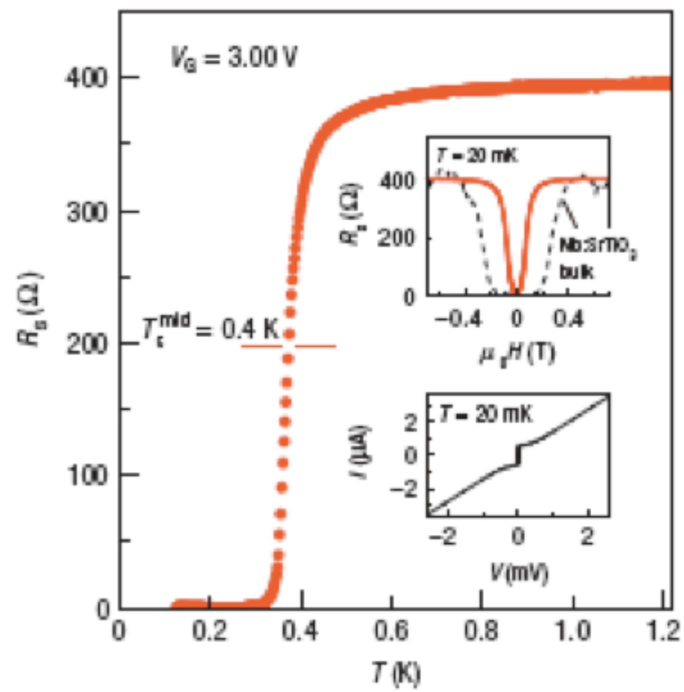
## IV. Theorem von der gleichen gegenseitigen Wirkung zweier elektromotorischen Flächenelemente.

# Electric Double-Layer FET- $SrTiO_3$

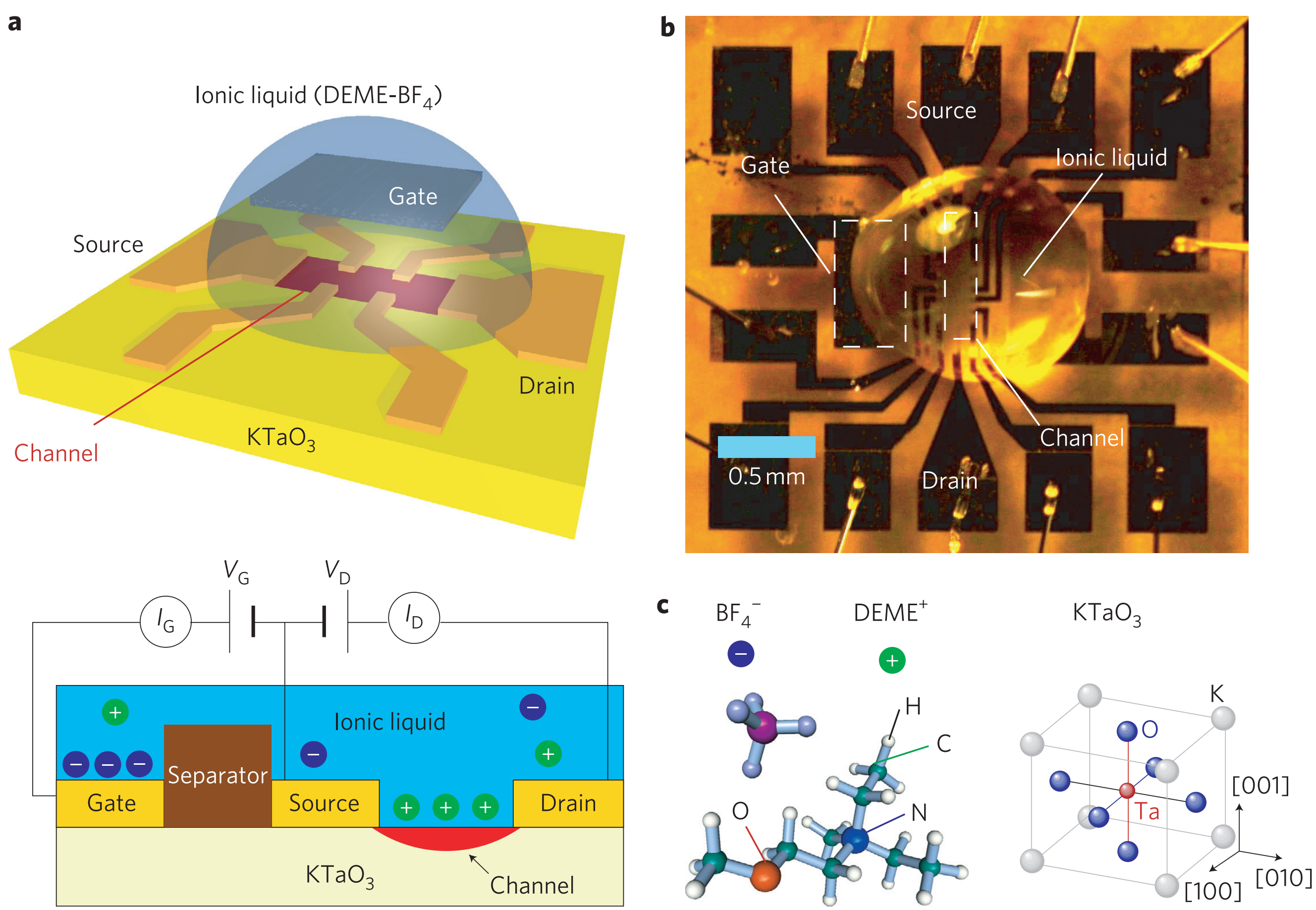



Electrolyte: polyethylene oxide, containing $KClO_4$

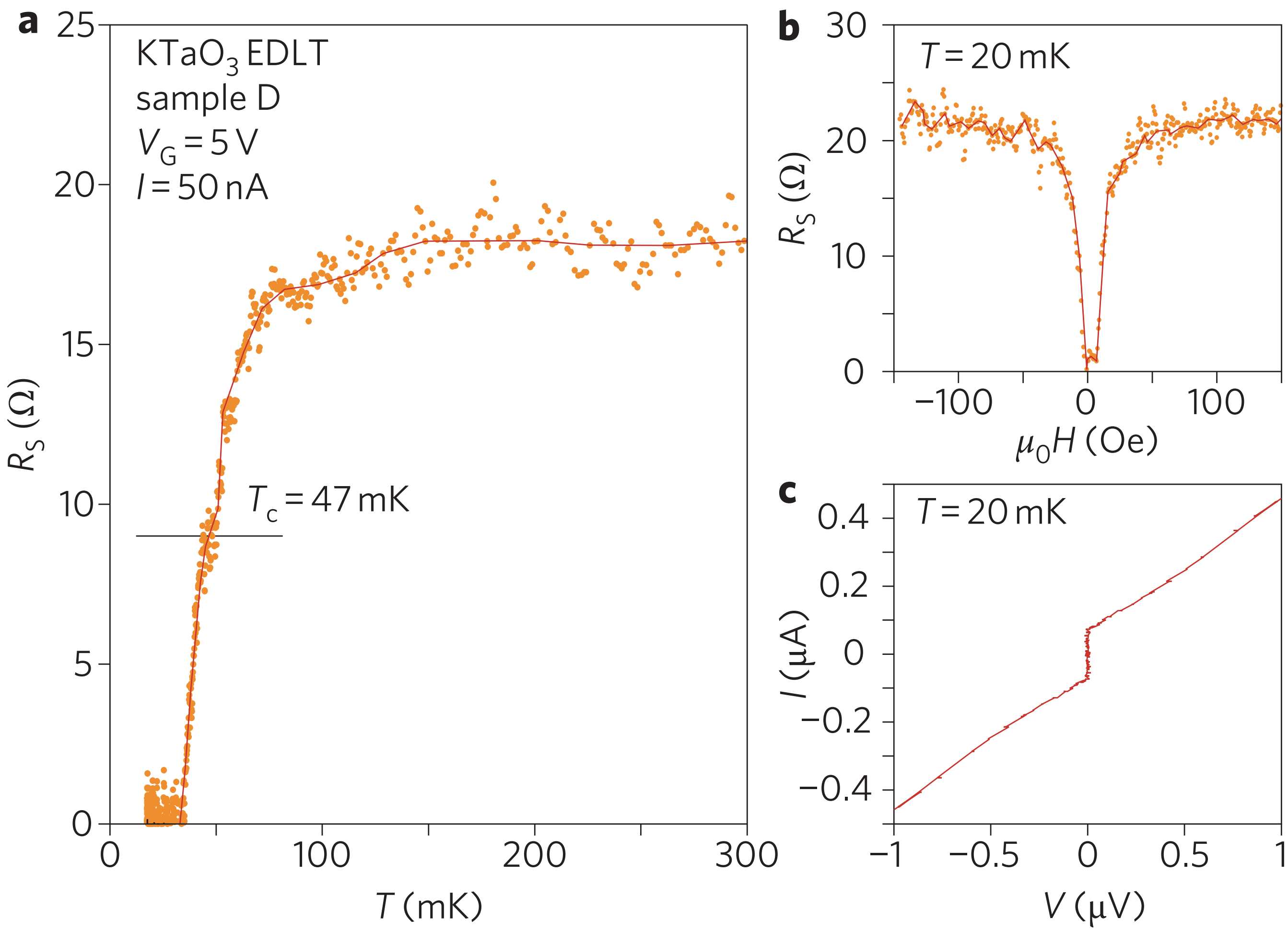



K. Ueno *et al.*, Nature Materials **7**, 855 (2008)

# Search for Superconductivity of $KTaO_3$

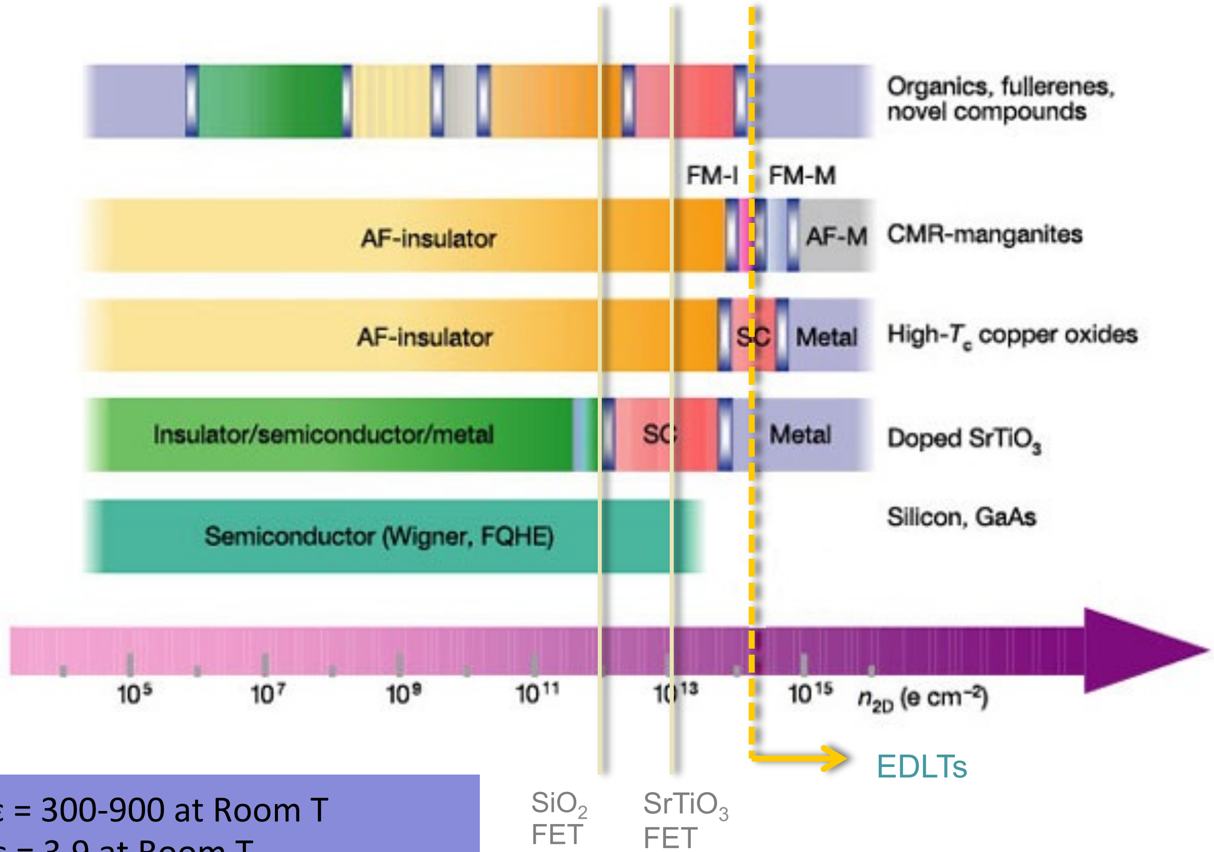



K. Ueno *et al*, Nature Nanotechnology 6 **408 (2011)**




K. Ueno *et al*, Nature Nanotechnology **6** **408** **(2011)**

# Properties of materials as a function of 2D charge density



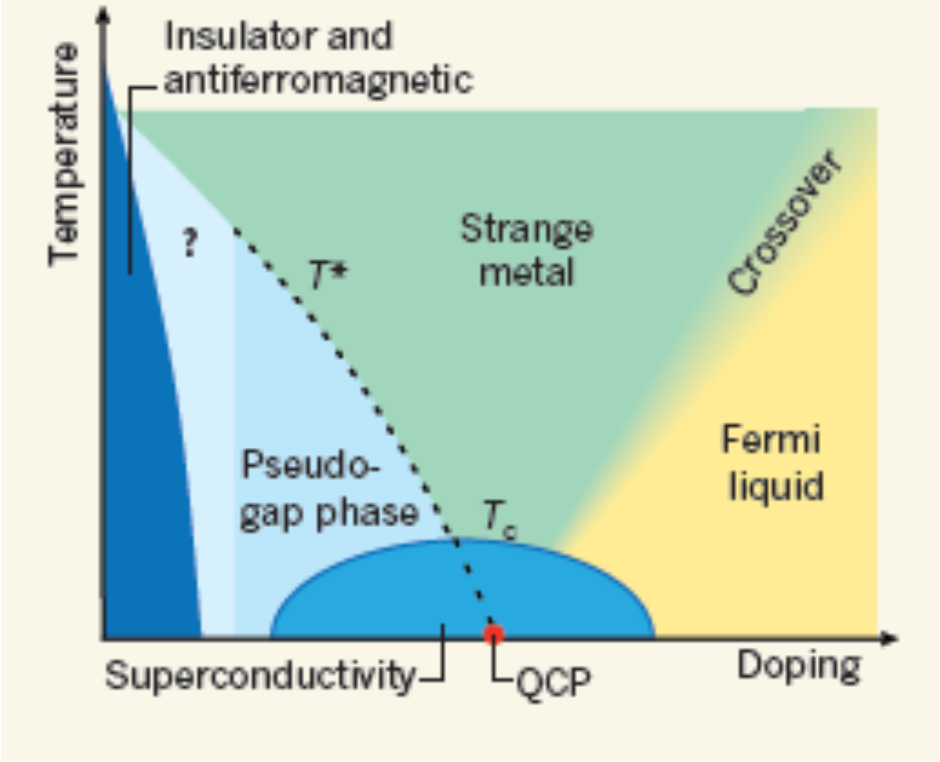

$SrTiO_3$: ε = 300-900 at Room T
$SiO_2$: ε = 3.9 at Room T

From: C.H. Ahn, J.-M. Triscone, J. Mannhart, Nature (2003)

Also see: Ahn et al. Rev. Mod. Phys. (2006).

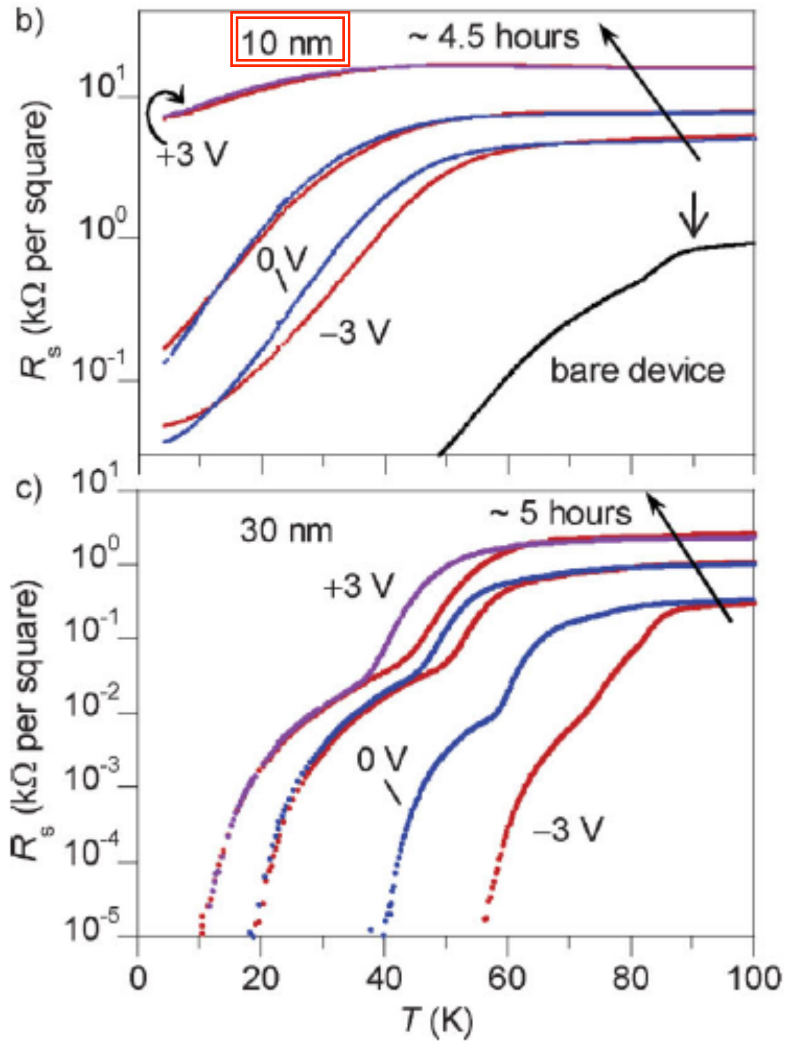
# Generic phase diagram for HTS

C. Varma. Nature 468, 184 (2010)



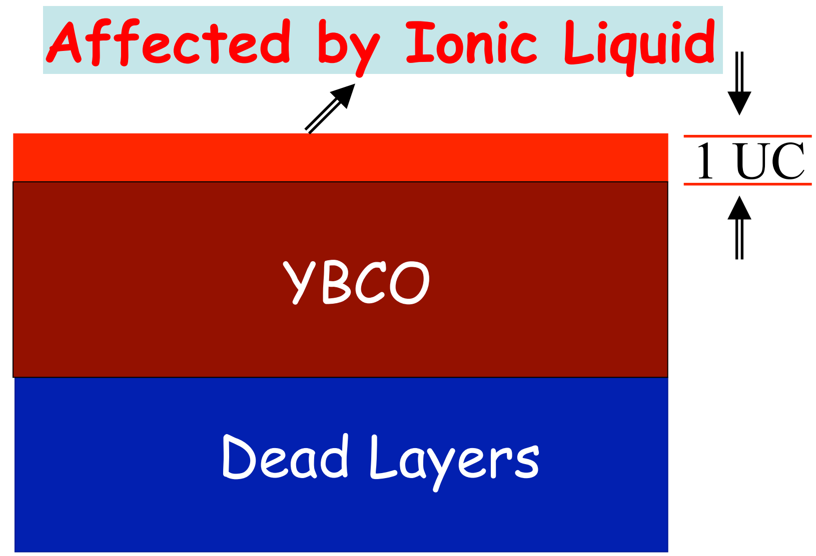

Superconductivity starts at x ~ 0.03,corresponding to 3.5 x $10^{13}$ carriers per plane

# Ionic liquid-gated cuprates




Large $\Delta T_c$ in YBCO

- 10 nm may be too thick;
- Thomas-Fermi screening length < 1 nm (1 UC~1.1nm);



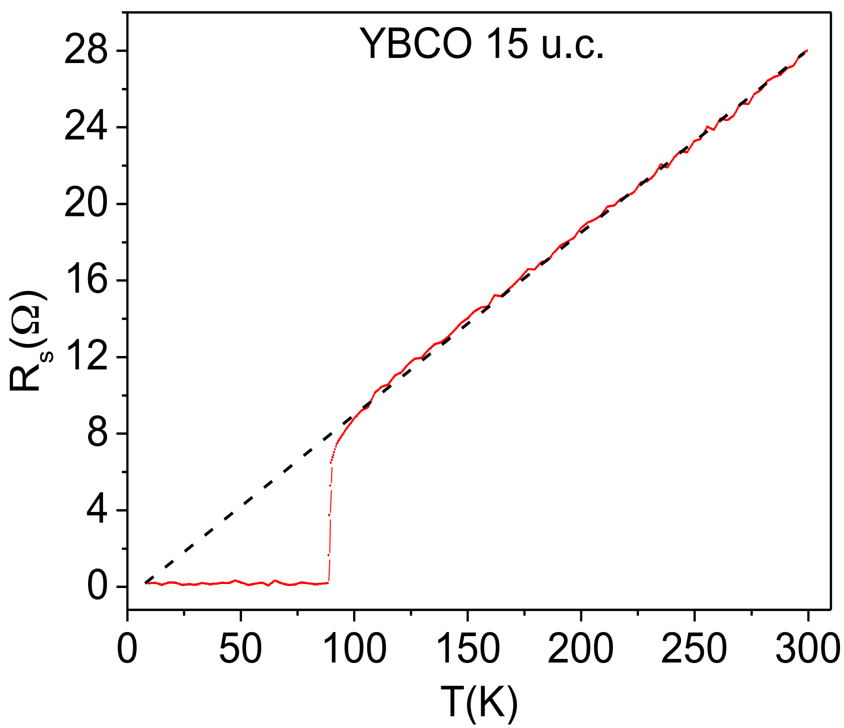

**Need ultrathin YBCO films!**

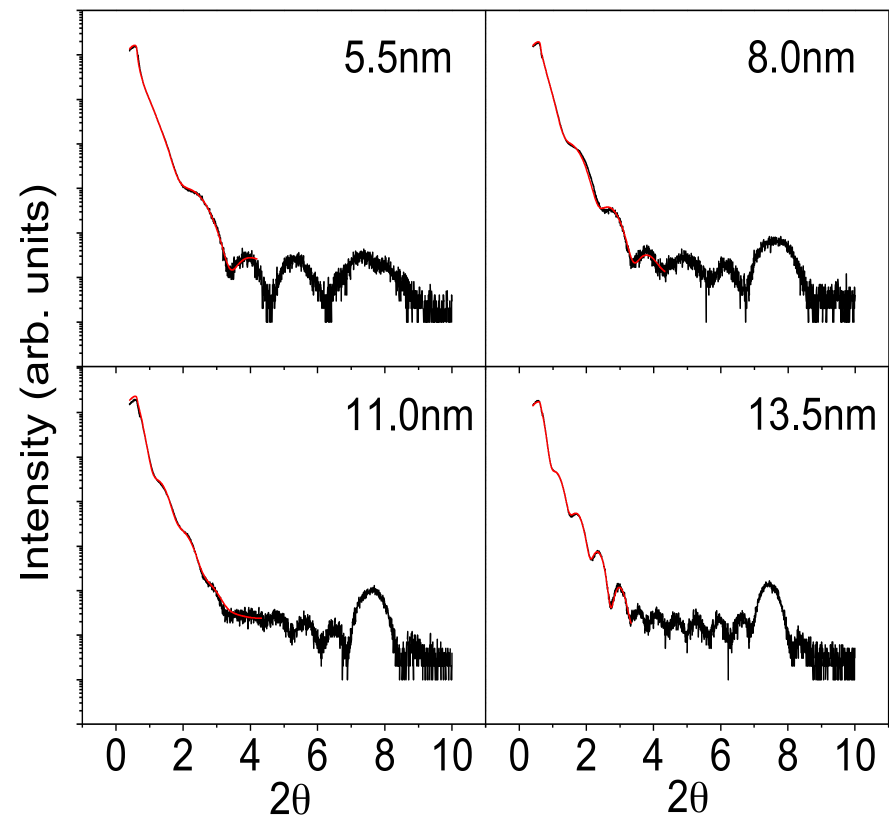
*A.S. Dhoot et al., Adv. Mater. 22, 2529 (2010)*

# Film deposition and characterization

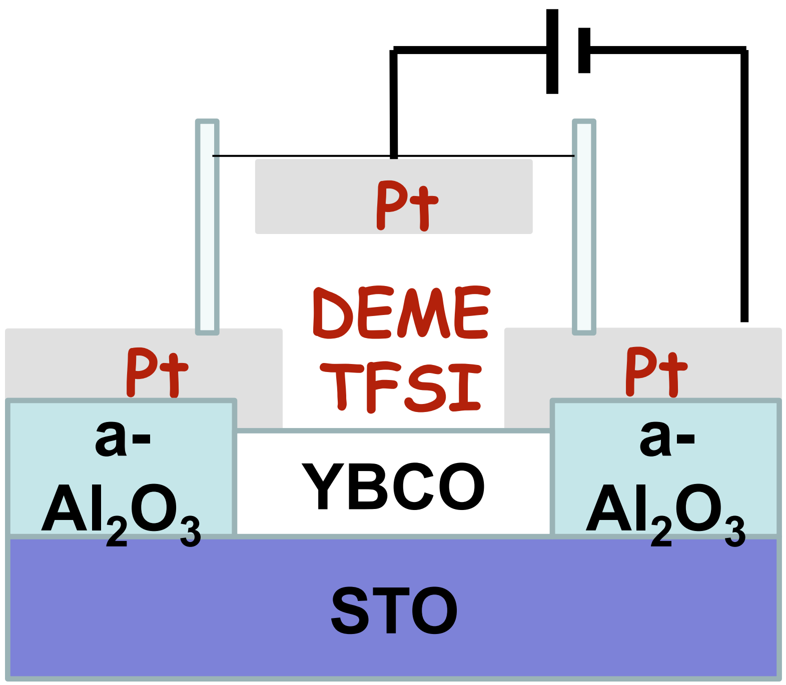
- High pressure oxygen sputtering system;
- Deposition rate ~1UC/minute (1 UC ~1.1 nm)

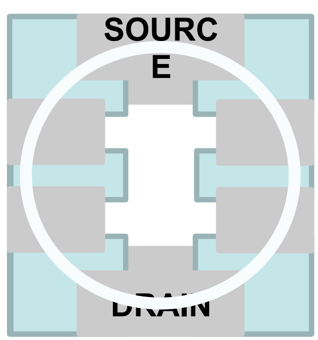
- Thicknesses determined from X-ray reflectivity data;
- Roughness ~0.5 nm;
- Control thickness of nm scale.



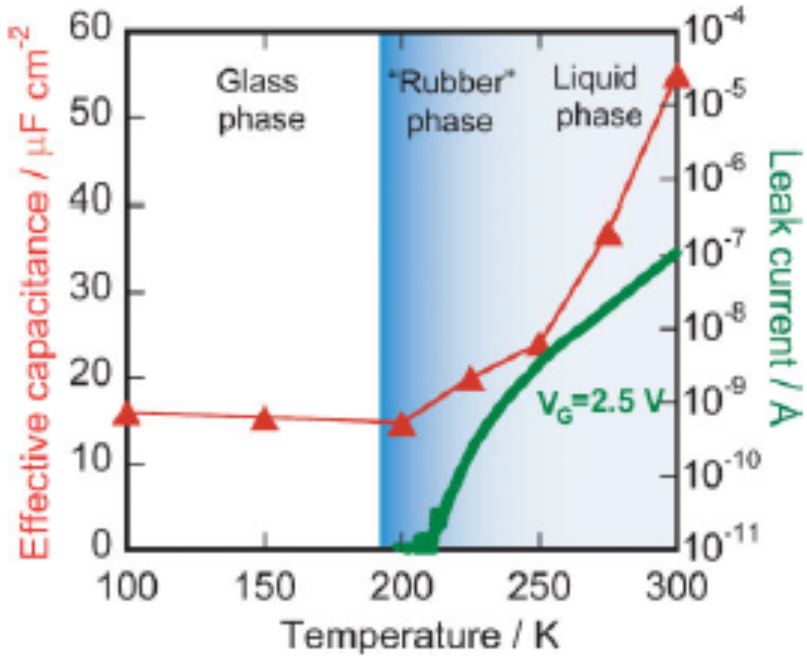



# EDLT fabrication

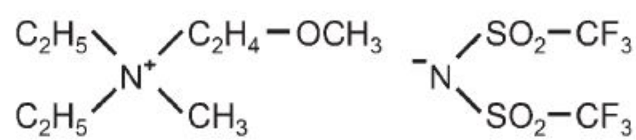



- YBCO very sensitive, reacts with most chemicals
- Pre-pattern: Deposition of a-$Al_2O_3$
- STO surface treatment: $TiO_2$ termination
- YBCO deposition
- Electrode evaporation: Pt
- Glue glass cylinder
- DEME TFSI
- Top gating: Pt coil




H. Yuan, Adv. Funct. Mater. 19, 1046 (2009)



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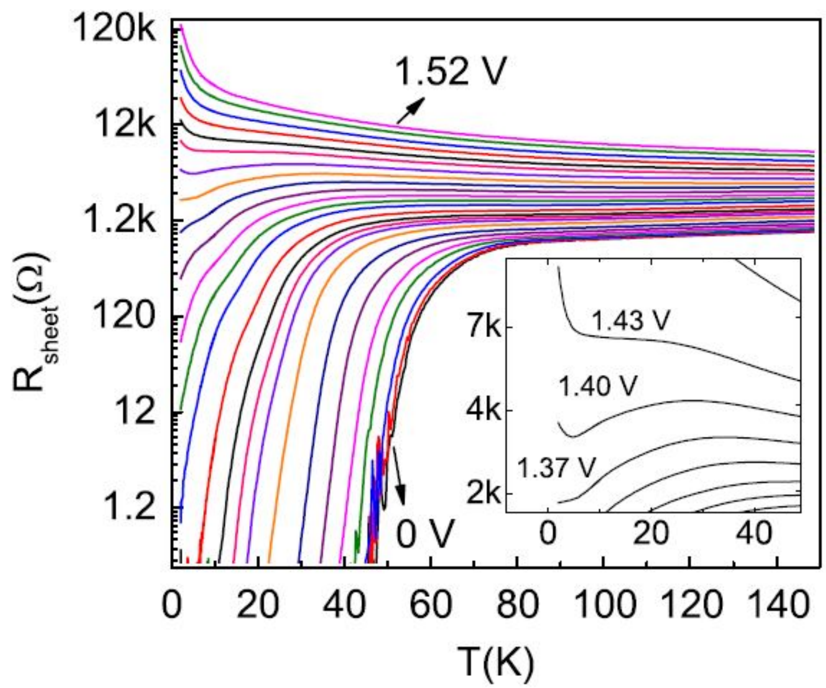
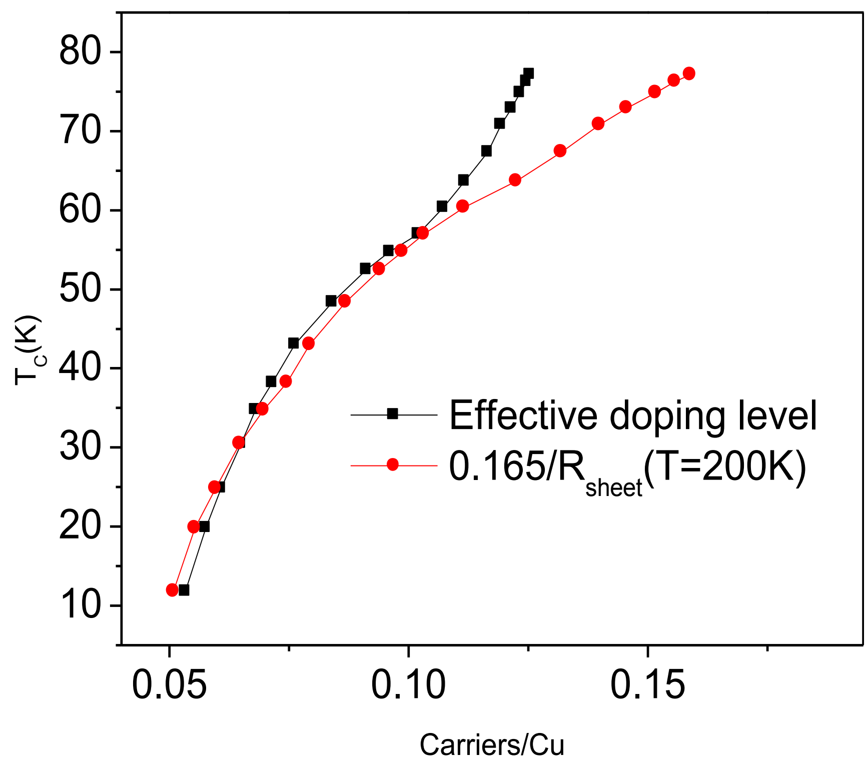
**Gate voltage changed at 240 K**

# 7 UC thick YBCO film



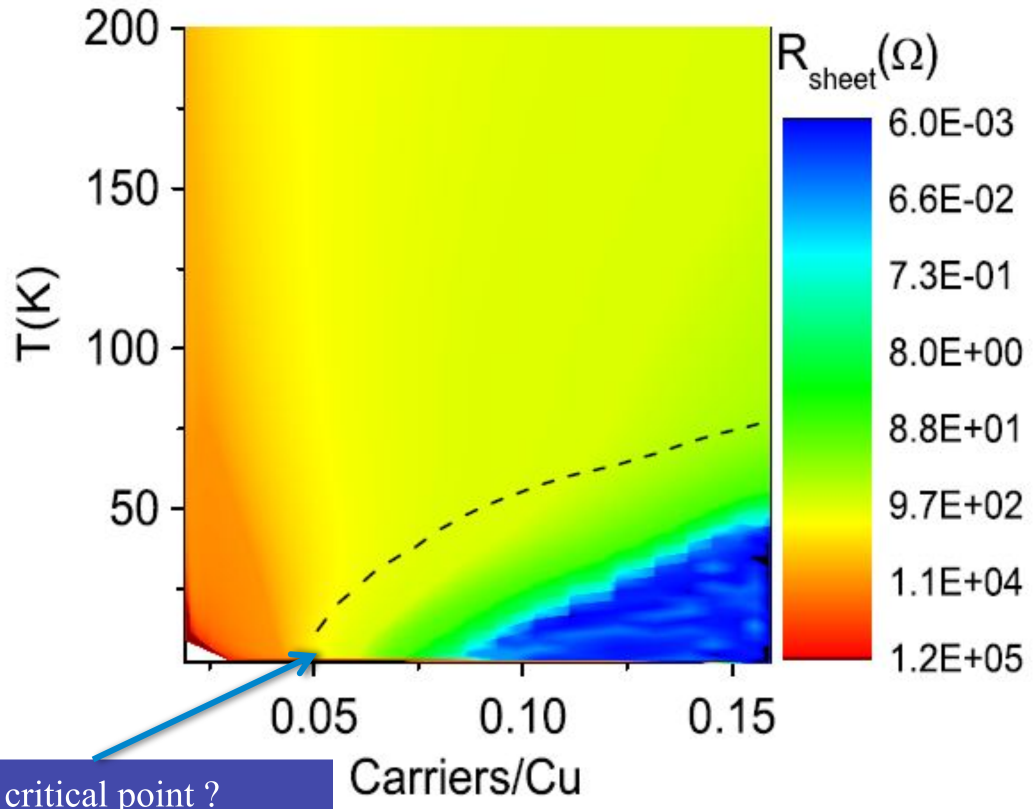

Good match in the SI transition regime

Not good in the optimal doping regime

*X. Leng et al., PRL **107**, 027001 (2011)*

# 7 UC thick YBCO film

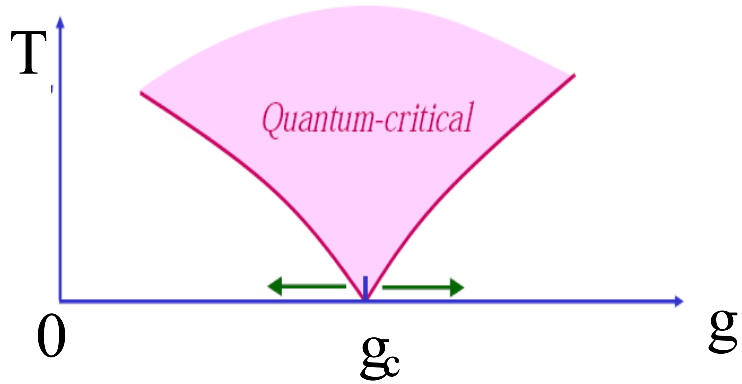
Phase diagram derived from R(T) curves




Quantum critical point ?

*X. Leng et al., PRL* ***107****, 027001 (2011)*

# SI transition: Quantum phase transitions




- QPT can only be accessed by varying a tuning parameter (g) in the limit of zero temperature.
- The tuning parameter may be thickness, magnetic field, disorder, doping, etc.
- Quantum critical region exhibits universal power-law behaviors.
- Spatial correlation length: $\xi \sim |\delta|^{-\nu}$, $\delta = g - g_c$
- Characteristic frequency: $\Omega \sim \xi^{-z}$
- At finite temperature, $\Omega$ is cut off by $k_B T$, leading to a scaling relation:

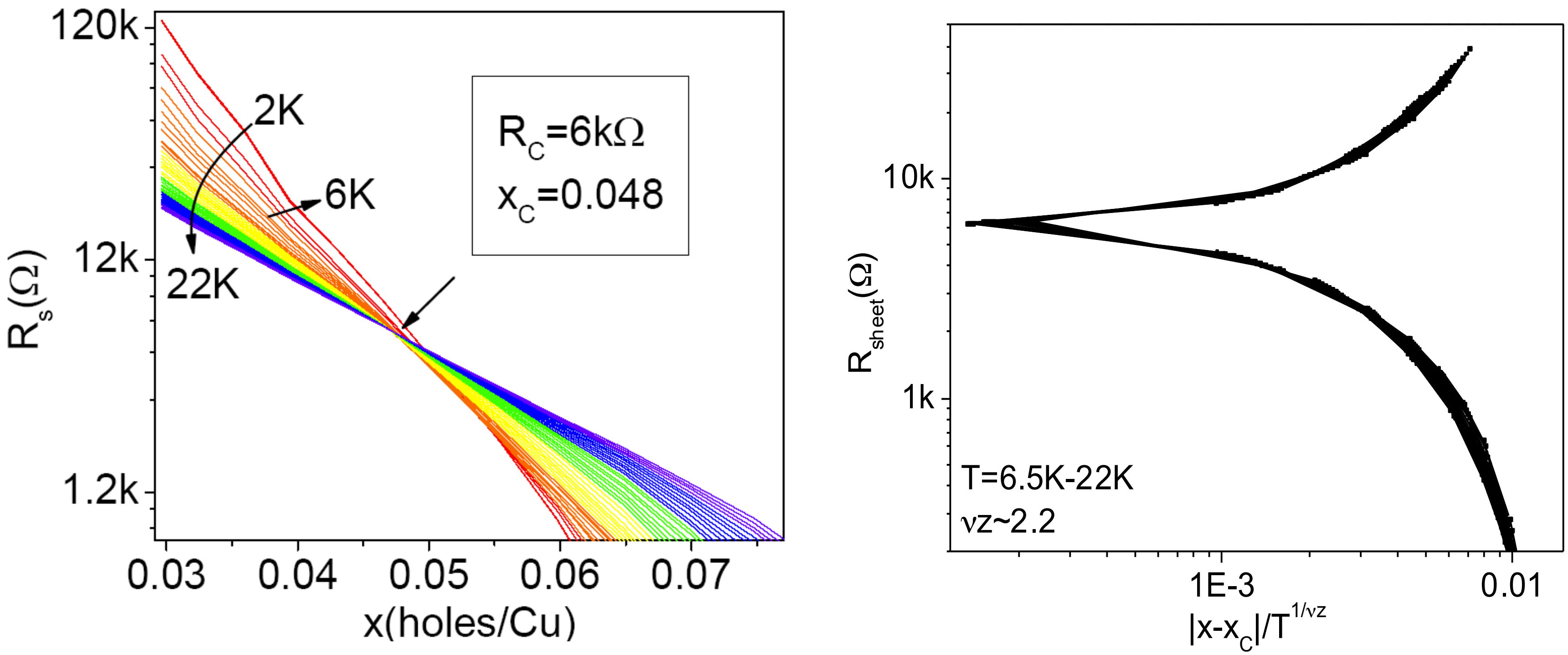
$$R_S = R_C\, f(\delta/T^{1/\nu z})$$

**The critical resistance $R_C$ and the critical exponent product $\nu z$ determine the universality class of the QPT**

M. P. A. Fisher, PRL (1990)

# 7 UC thick YBCO film

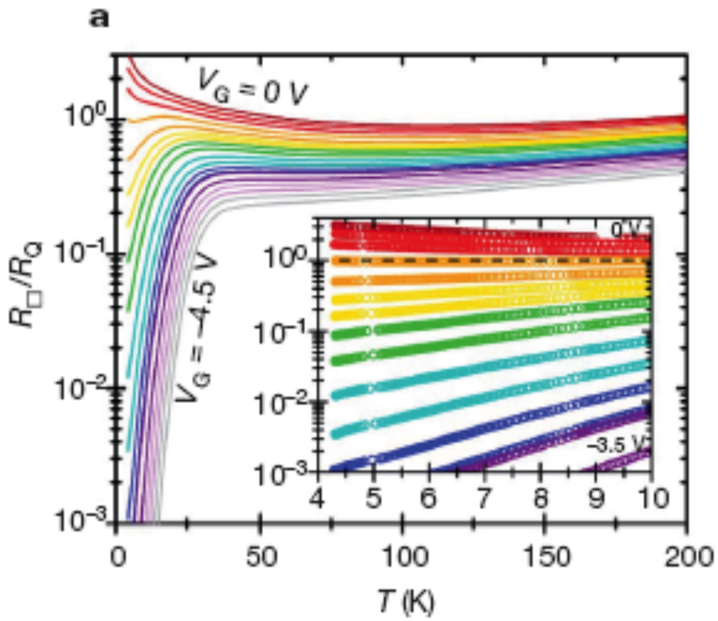
Finite size scaling analysis

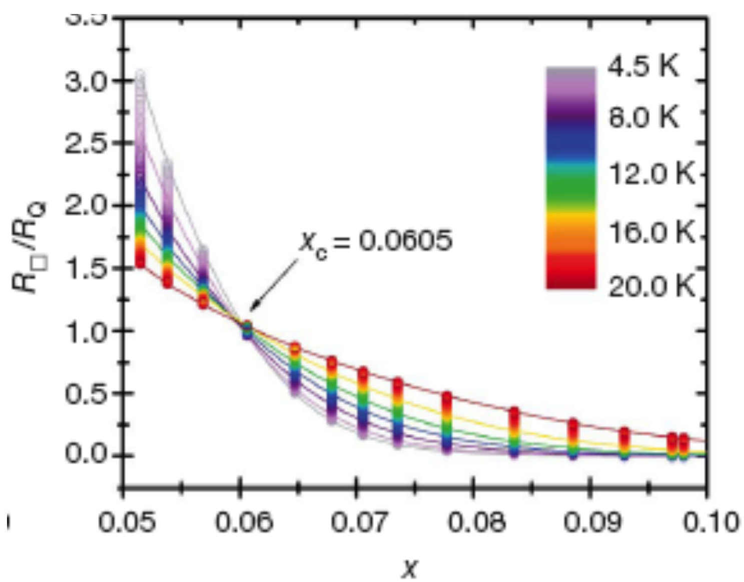


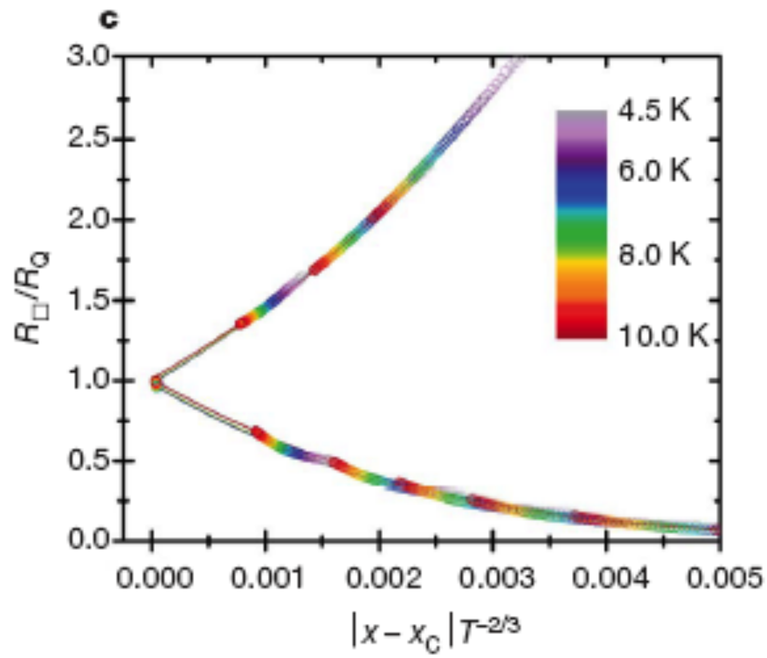

**Breakdown at low temperature**

*X. Leng et al., PRL **107**, 027001 (2011)*

# SI transition in $La_{2-x}Sr_xCuO_4$ film



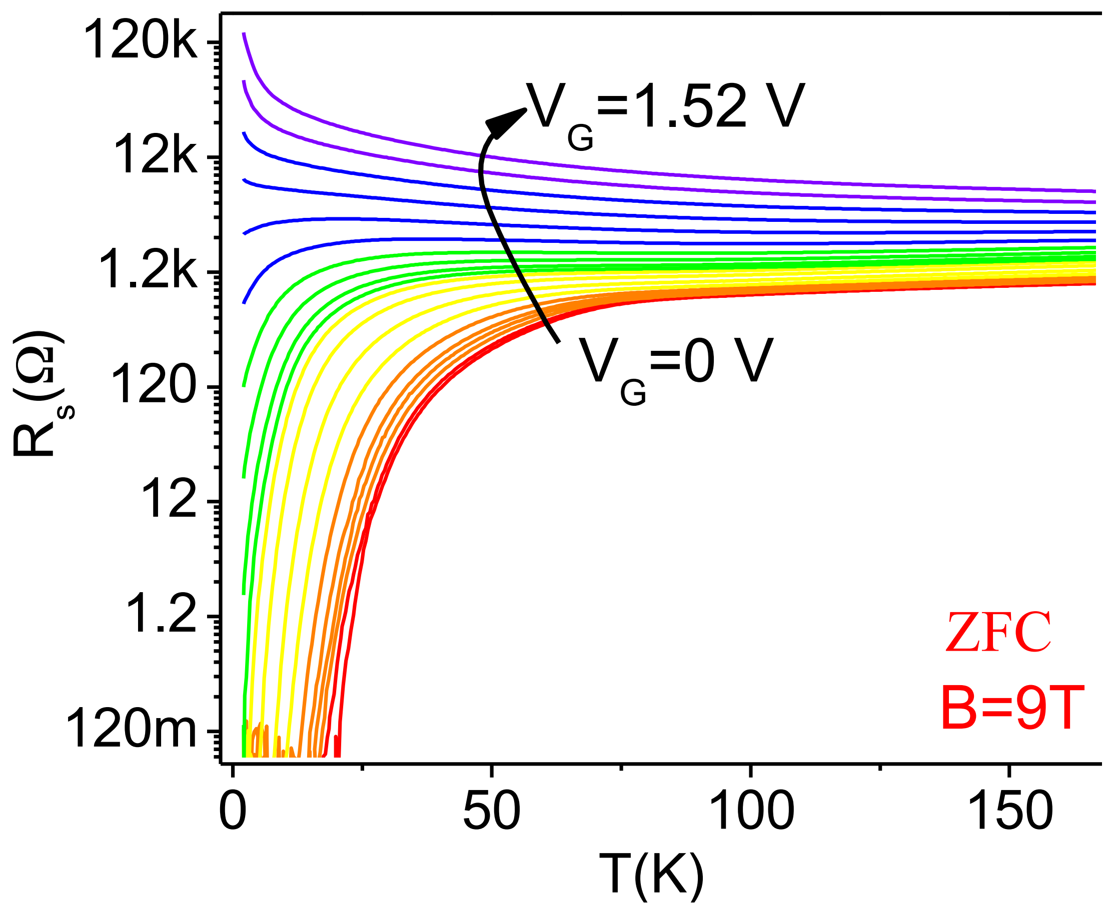




- Scaling analysis from 4.5 K to 20 K;
- $R_C$=6.45kΩ, νz =1.5

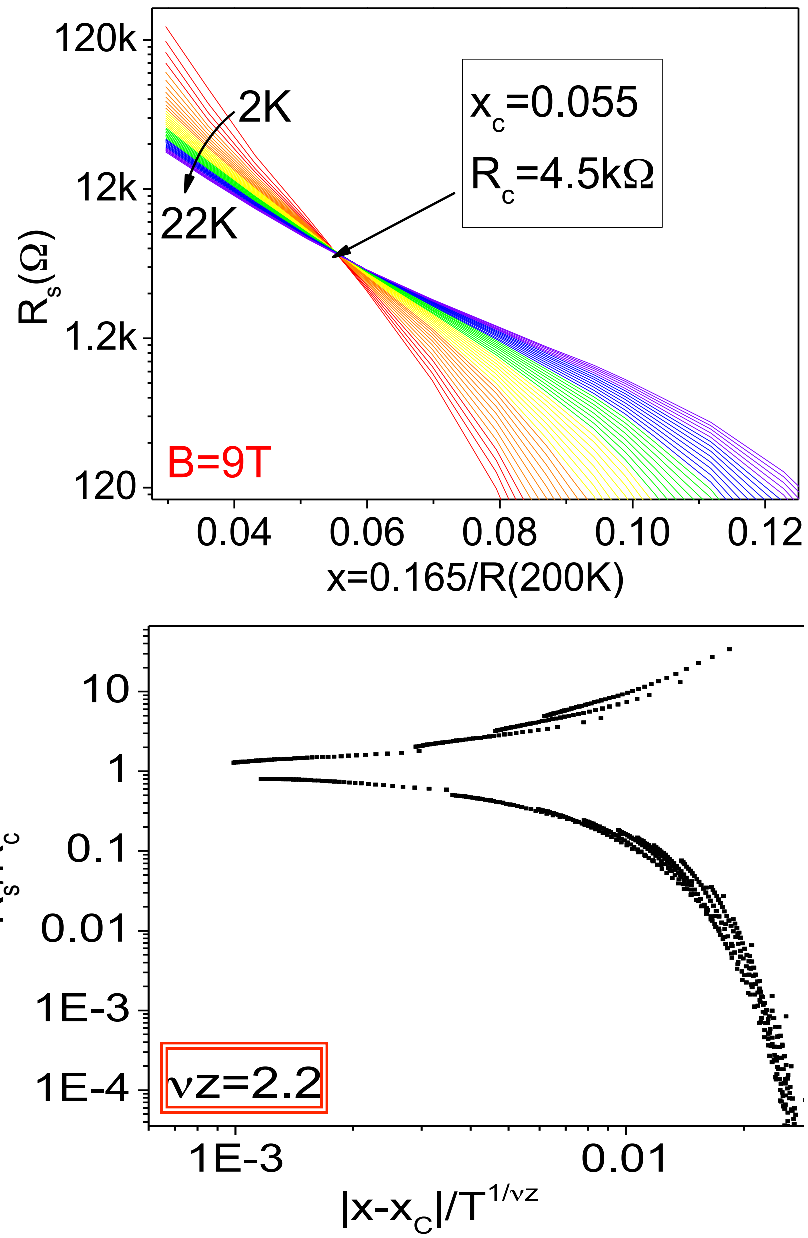
*A. T. Bollinger et al., Nature **472**, 458 (2011)*

# 7 UC thick YBCO film
# In the presence of magnetic field



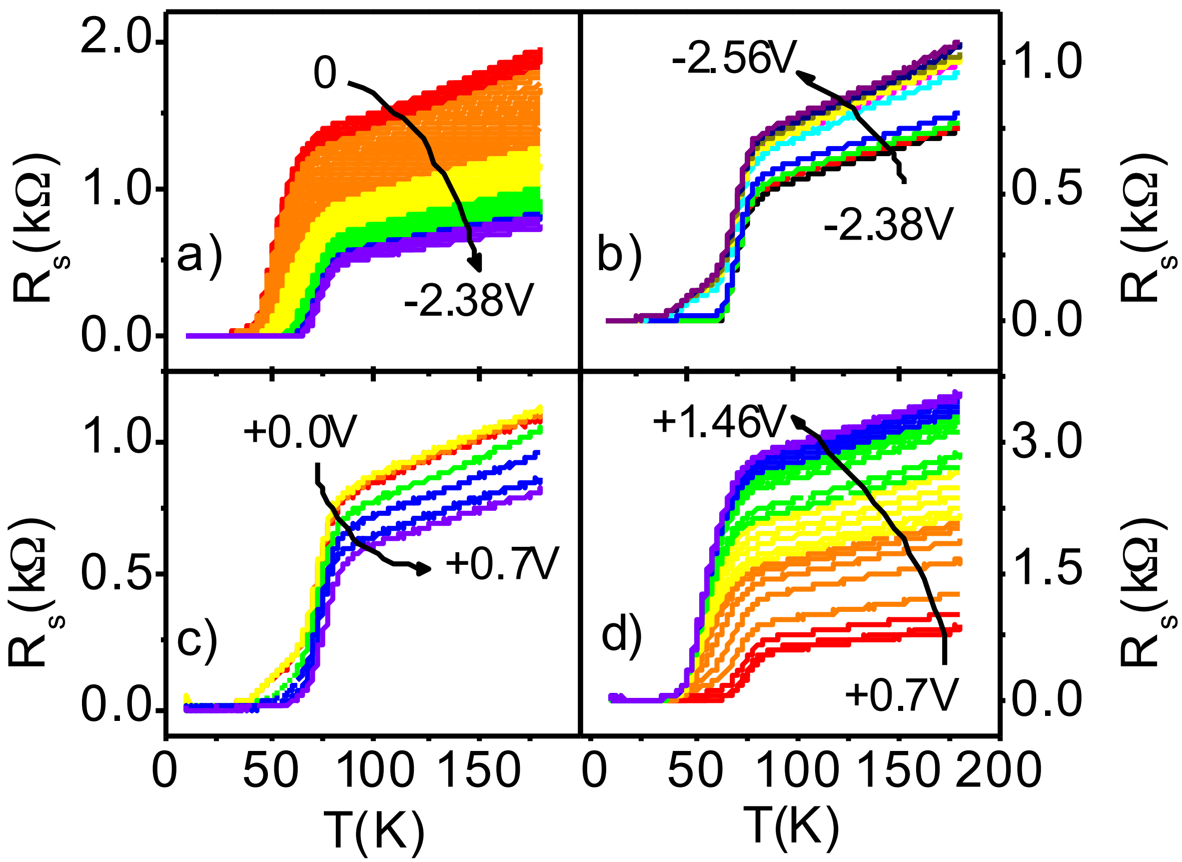

- A cleaner SI transition.
- Inhomogeneity has been suppressed.
- Measurements down to 2K only

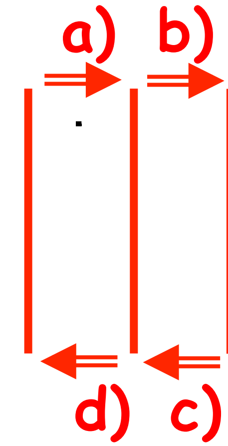
# Finite size scaling analysis




- $x_c$ changed to higher doping level
- νz remains the same;
- Critical resistance is not universal

# Underdoped to Overdoped Transition



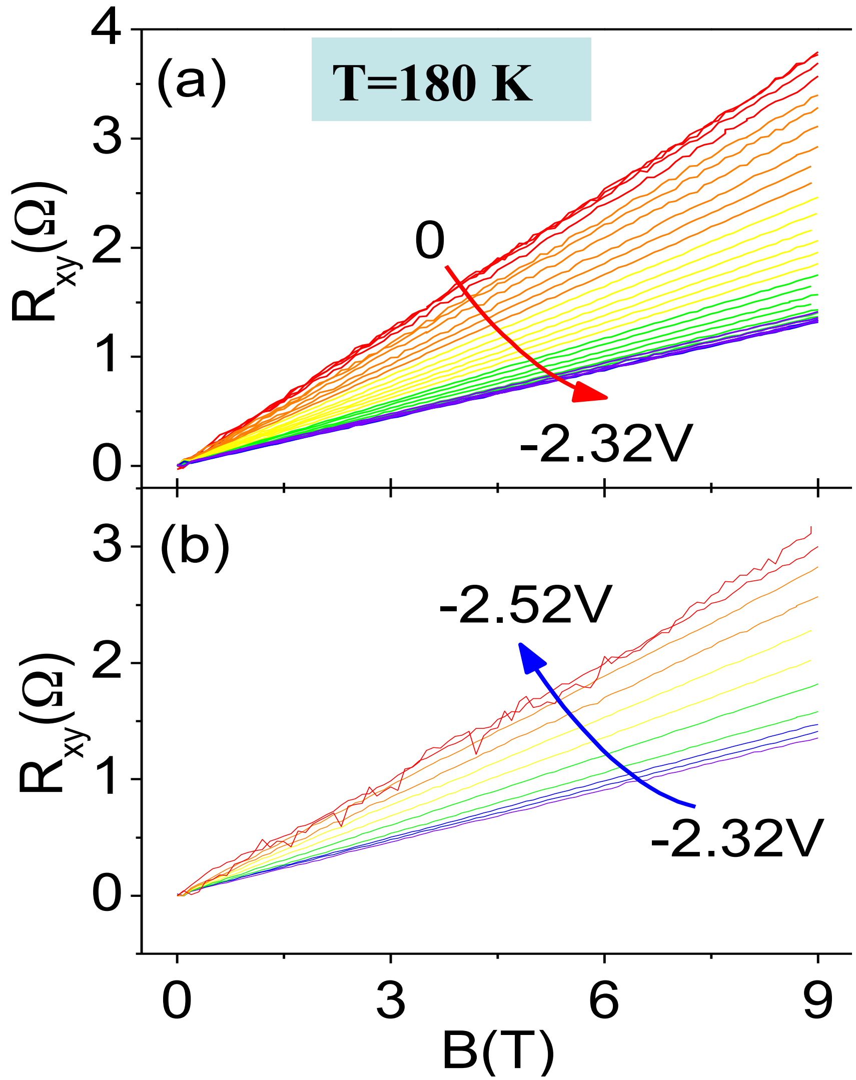




a) Holes injected, $R_{norm}$ drops and $T_C$ increases then saturates

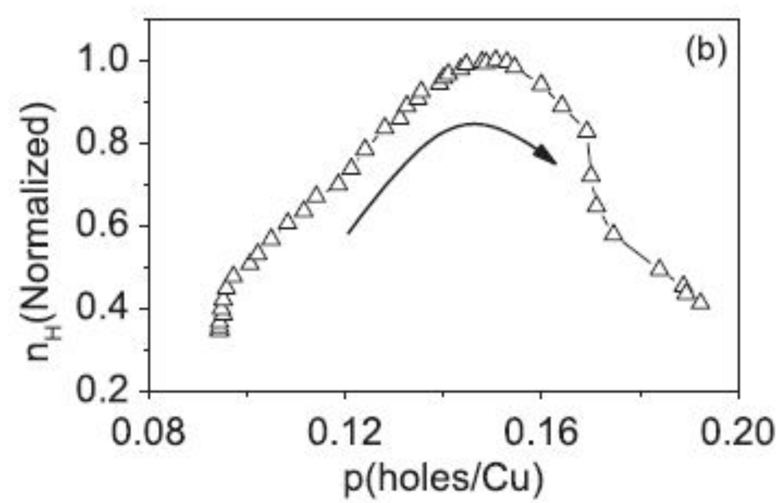
b) Further injection of holes, $T_C$ drops and $R_{norm}$ increases

c) and d) The process is reversible

# Hall effect measurement

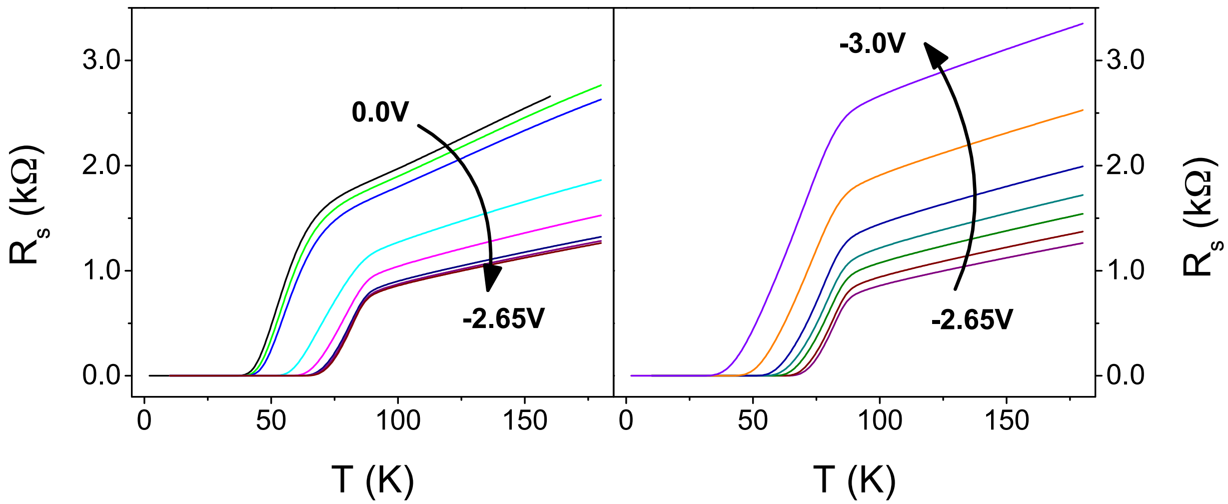


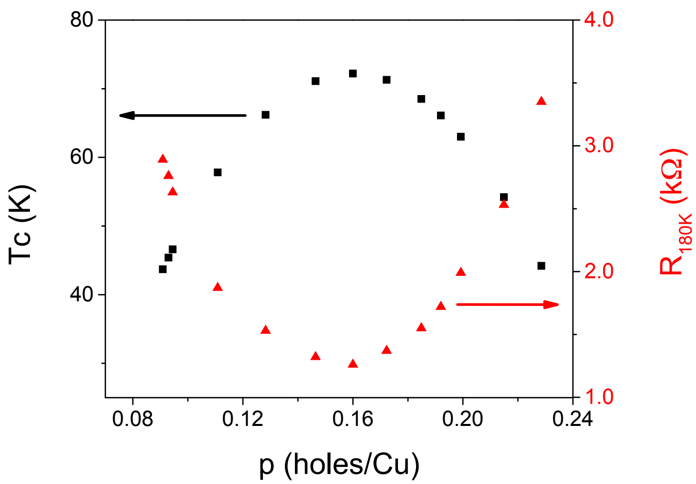

$$n_H = 1/(R_H\,e)$$




A peak around the optimal doping point

*X. Leng et al., PRL **108**, 067004 (2012)*

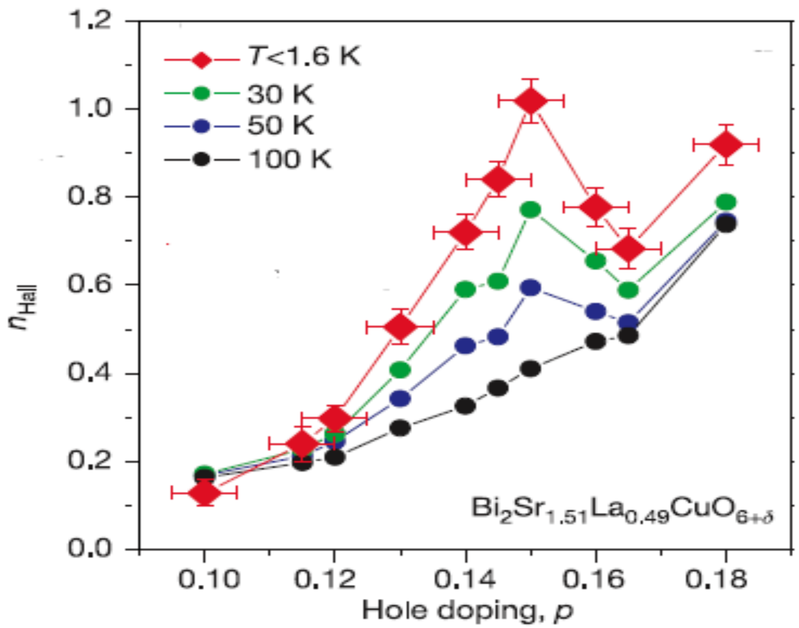


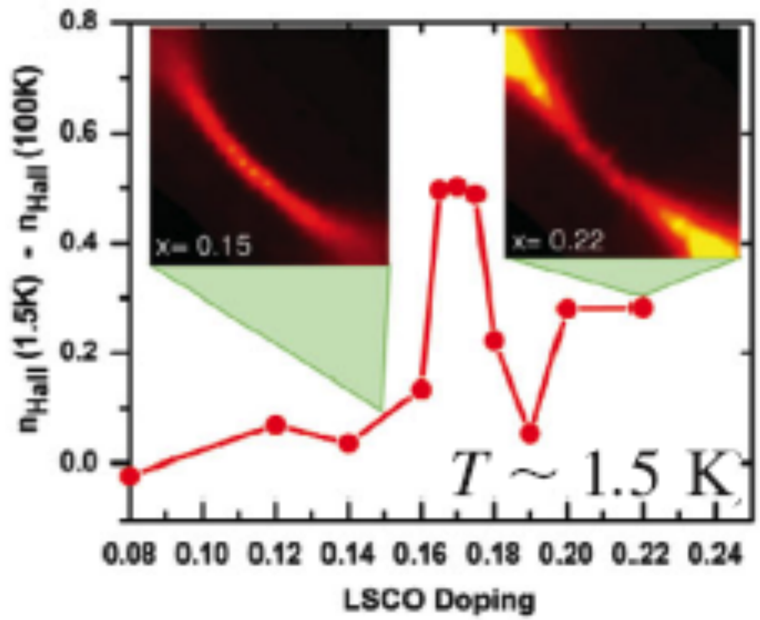





# A 5.5 Unit Cell Thick Film of YBCO

# Hall effect in cuprates

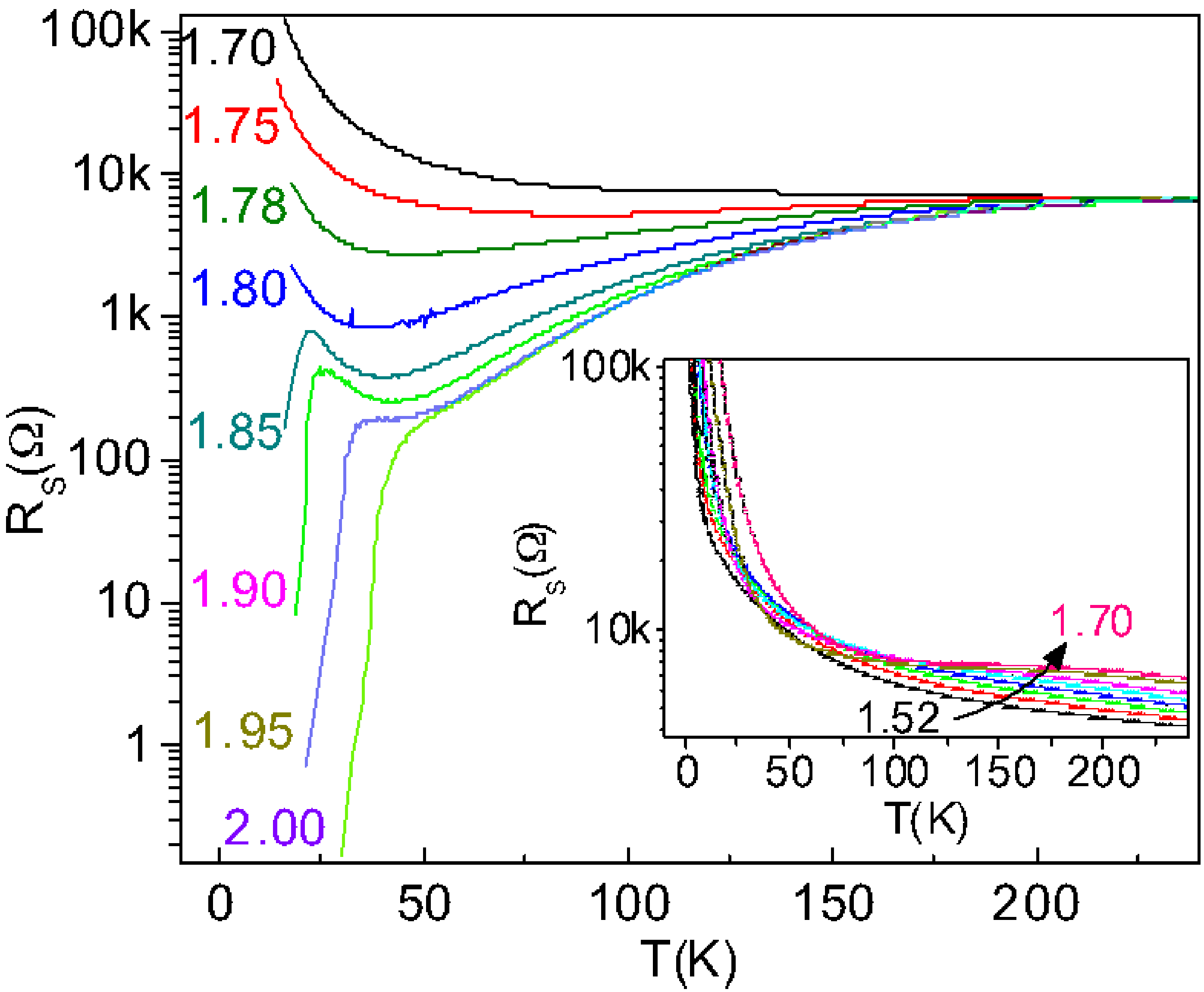


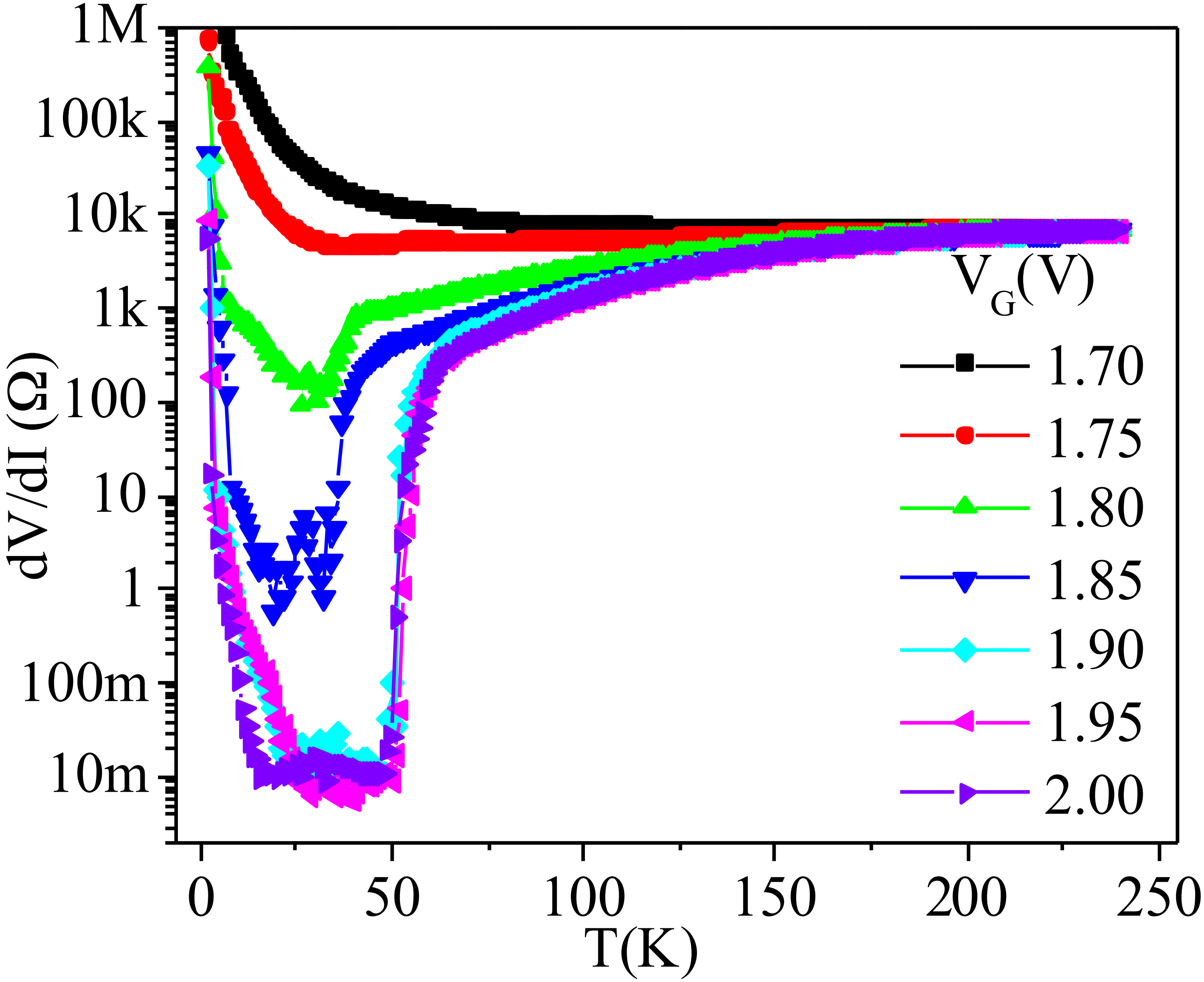

*F. Balakirev et al., Nature 424,912(2003)*

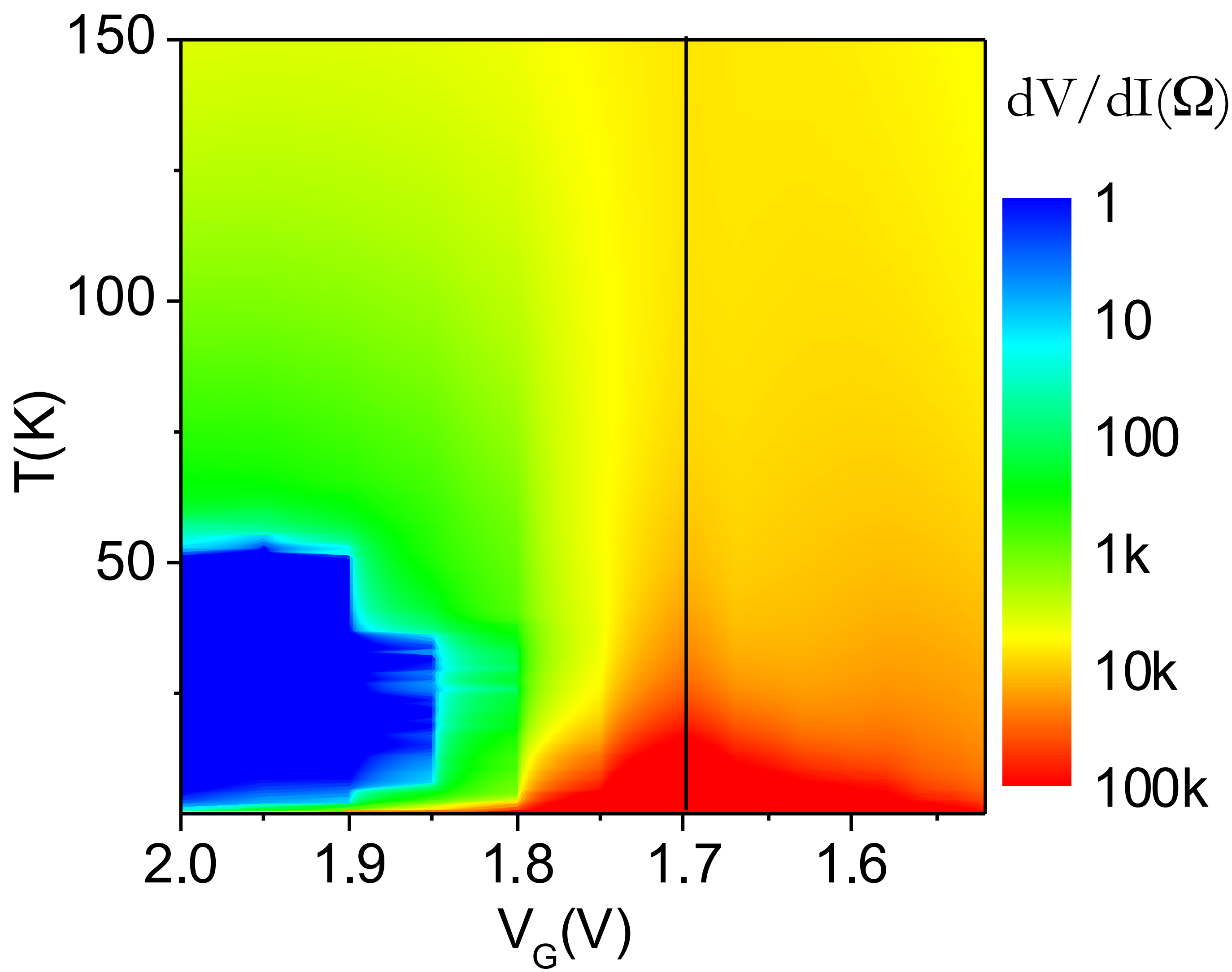
*F. Balakirev et al., PRL* ***102****, 017004(2009)*

# Electron Doping of YBCO

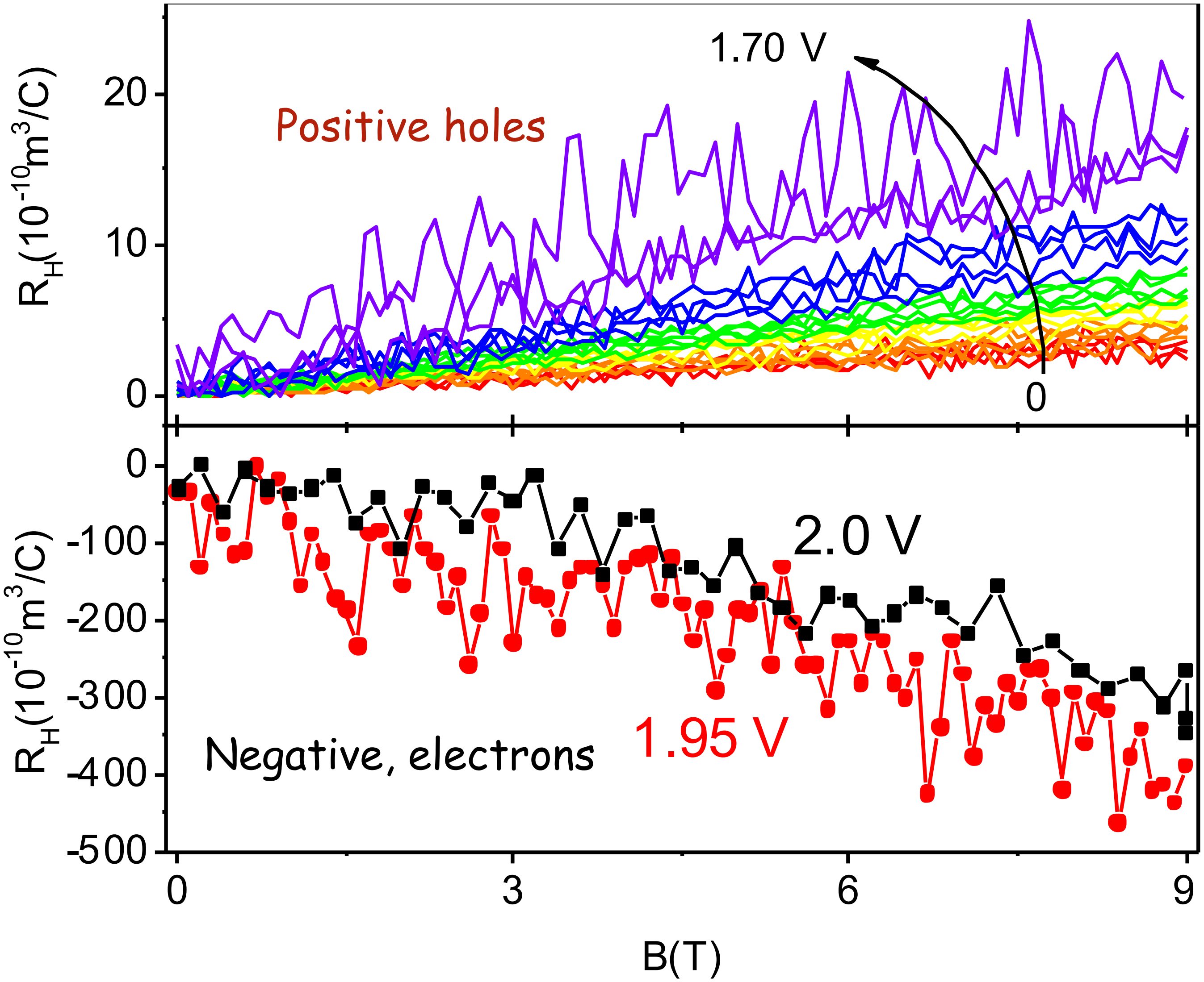


dV/dI at the lowest current (<0.01 nA)





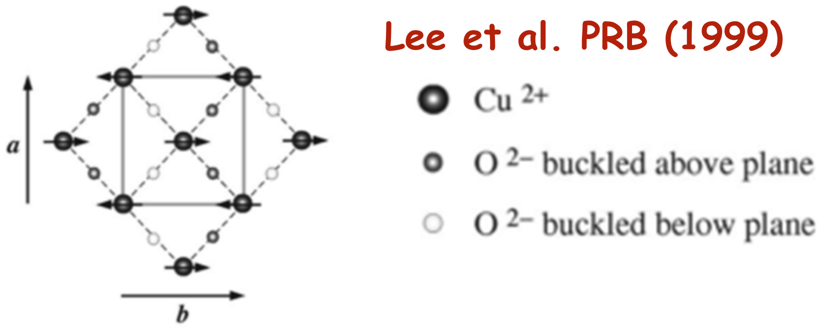
150
100
50
T(K)
2.0
1.9
1.8
1.7
1.6
$V_G$(V)
dV/dI(Ω)
1
10
100
1k
10k
100k



$R_H(10^{-10}m^3/C)$
1.70 V
Positive holes
0
20
10
0
-100
-200
-300
-400
-500
2.0 V
1.95 V
Negative, electrons
0
3
6
9
B(T)

# $La_2CuO_{4+\delta}$ ($\delta$-LCO) vs $La_{2-x}M_xCuO_4$ (LMCO)

Lee et al. PRB (1999)




LCO

δ-LCO

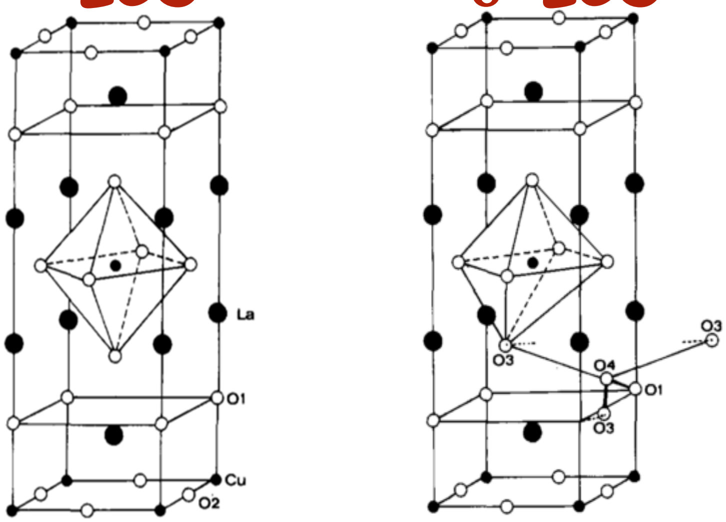



Fig. 1. (a) Three dimensional structural arrangement of $La_2CuO_4$. One tetragonal unit cell is represented. (b) The position of O4 in the pseudo tetragonal unit cell of $La_2CuO_{4.032}$. The displaced O4 atoms to the O3 positions are indicated.

Chailout et al. Physica C (1989)

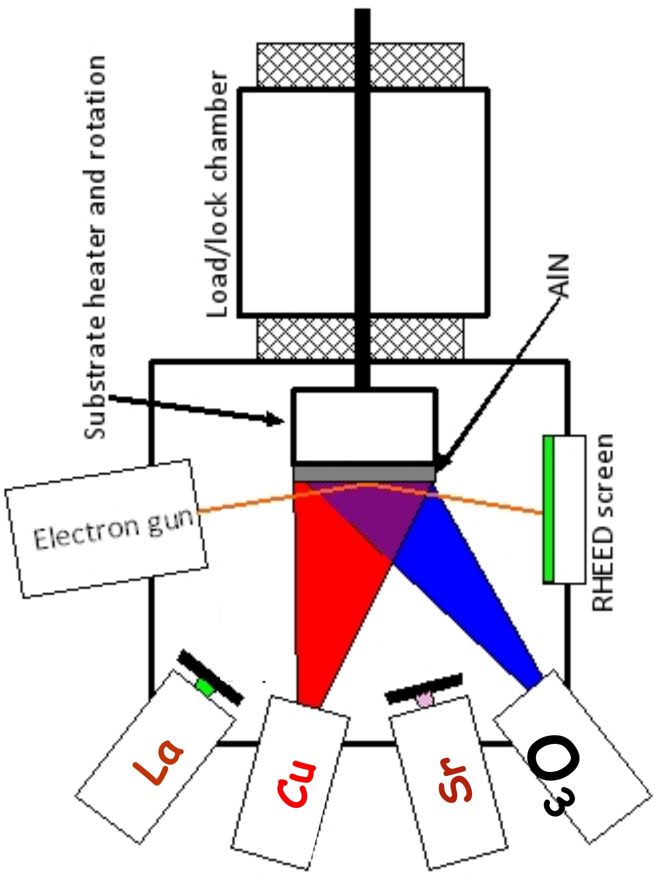
$\delta$-LCO is a HTS derived from the antiferromagnetic - Mott insulator $La_2CuO_4$ (LCO)

Oxygen interstitials (i-O) are located in between $La_2O_{2+\delta}$ layers, far away from the $CuO_2$ superconducting planes

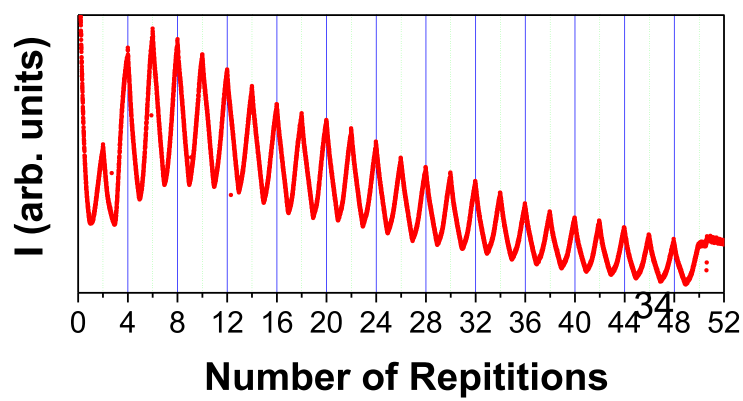
i-O are introduced in specific positions of the crystal structure

Disorder is weak and $T_c$ is the highest of the La 214 family of compounds

# Epitaxial growth of δ-LCO thin films
## Ozone Assisted Molecular Beam Epitaxy



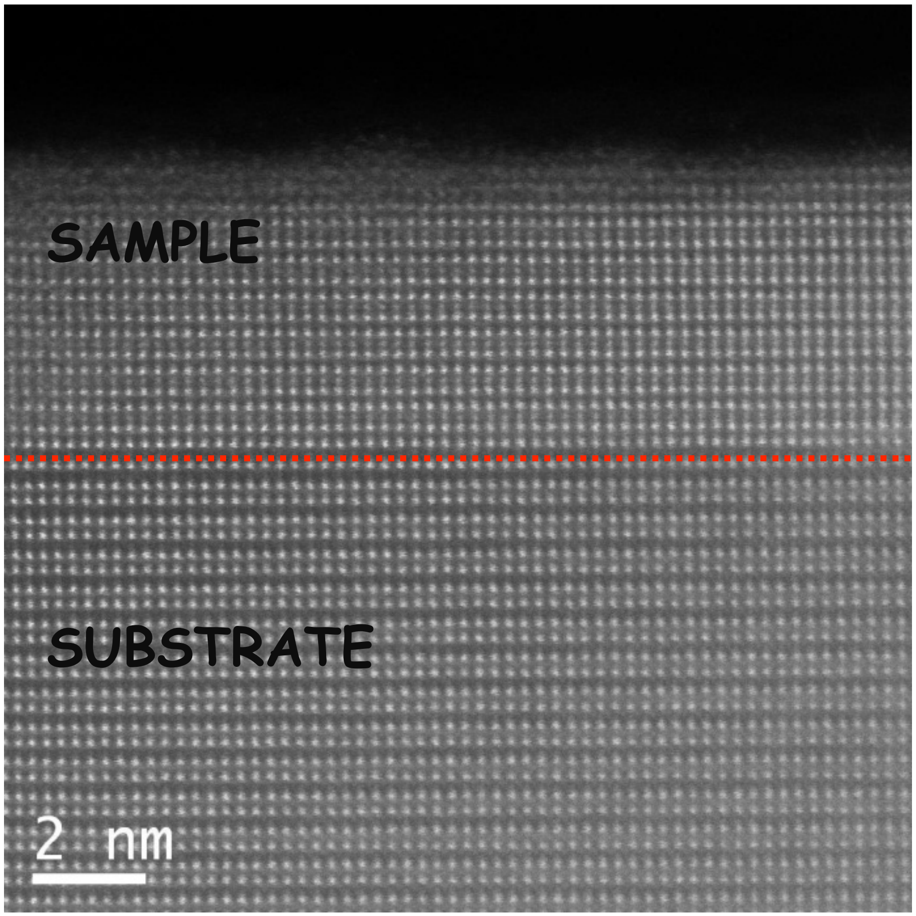

- UHV chamber: $1 \times 10^{-8}$ Torr-$1\times10^{-10}$ Torr
- Shuttered growth technique
- $T_{GROWTH}$ = 750°C
- On SLAO (0 0 1) substrates
- $P[O_3] = 3 \times 10^{-5}$ Torr
- Reflection High Energy Electron Diffraction (RHEED): ½ unit cell accuracy

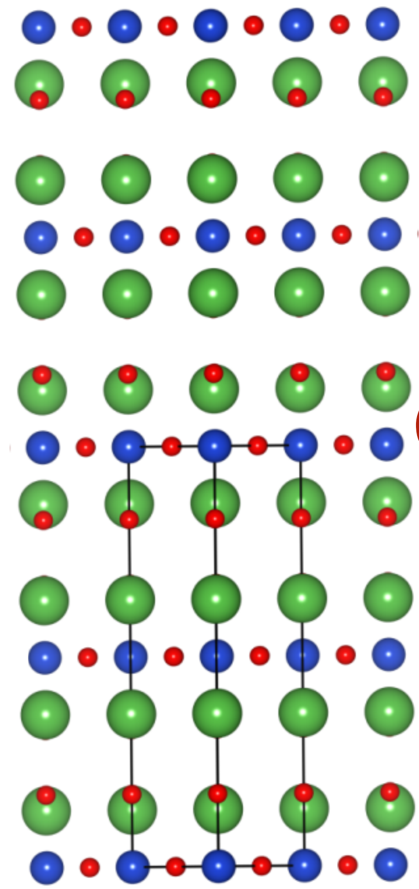


# Structural characterization

## Atomic Force Microscopy and Scanning Transmission Electron Microscopy

STEM



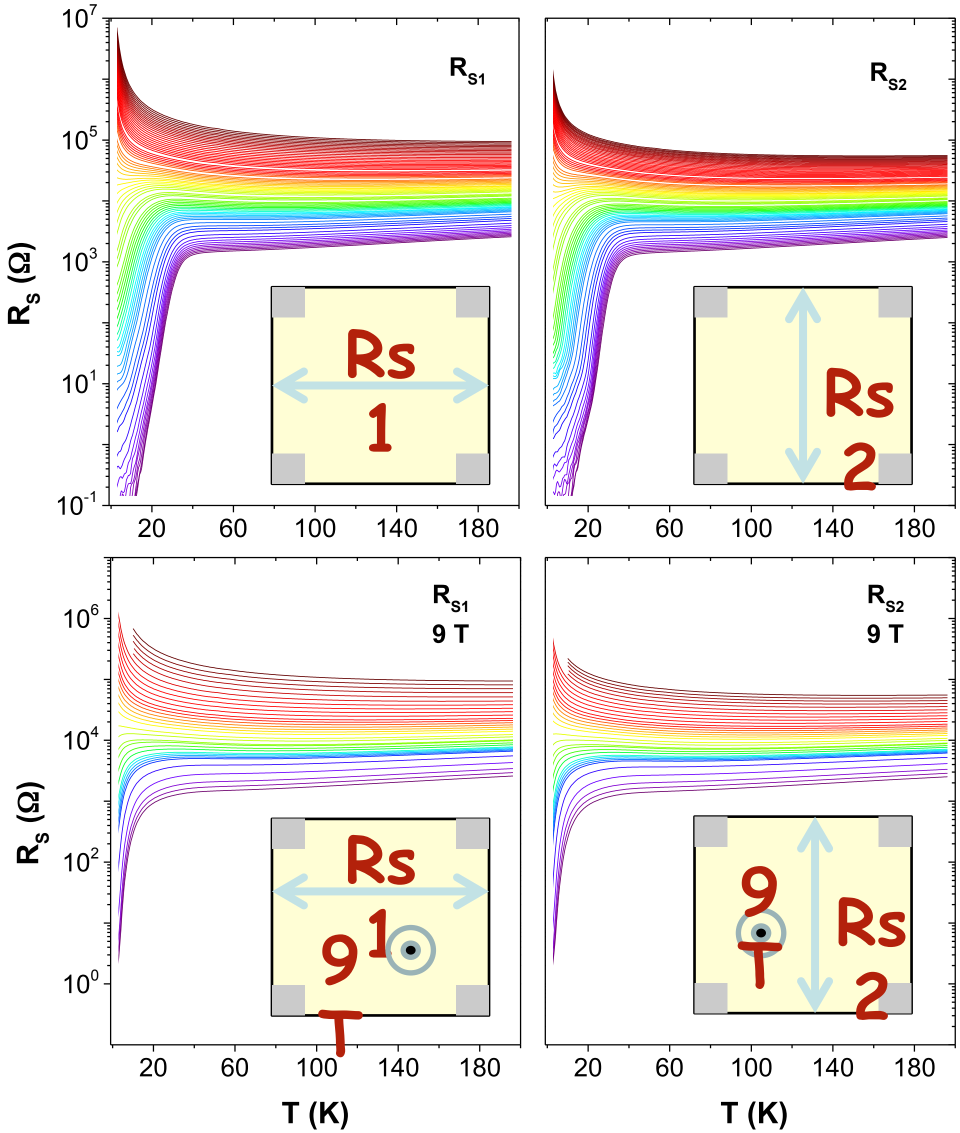
ADF
Z-Contrast
(011) cross-section

Cu O
La

Maria Varela @ ORNL

# Transport and Magneto Transport Experiment

## Results




75 levels of charge doping

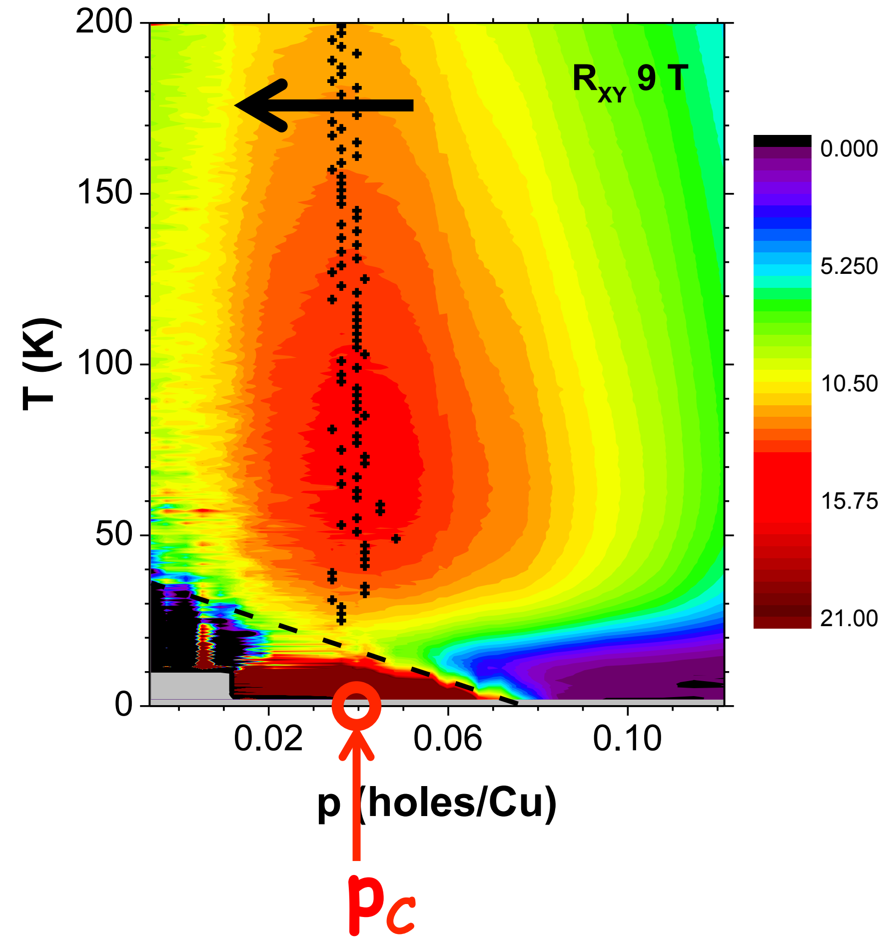
0.1215 ≥ p (holes/Cu) ≥ -0.00625

33 levels of charge doping

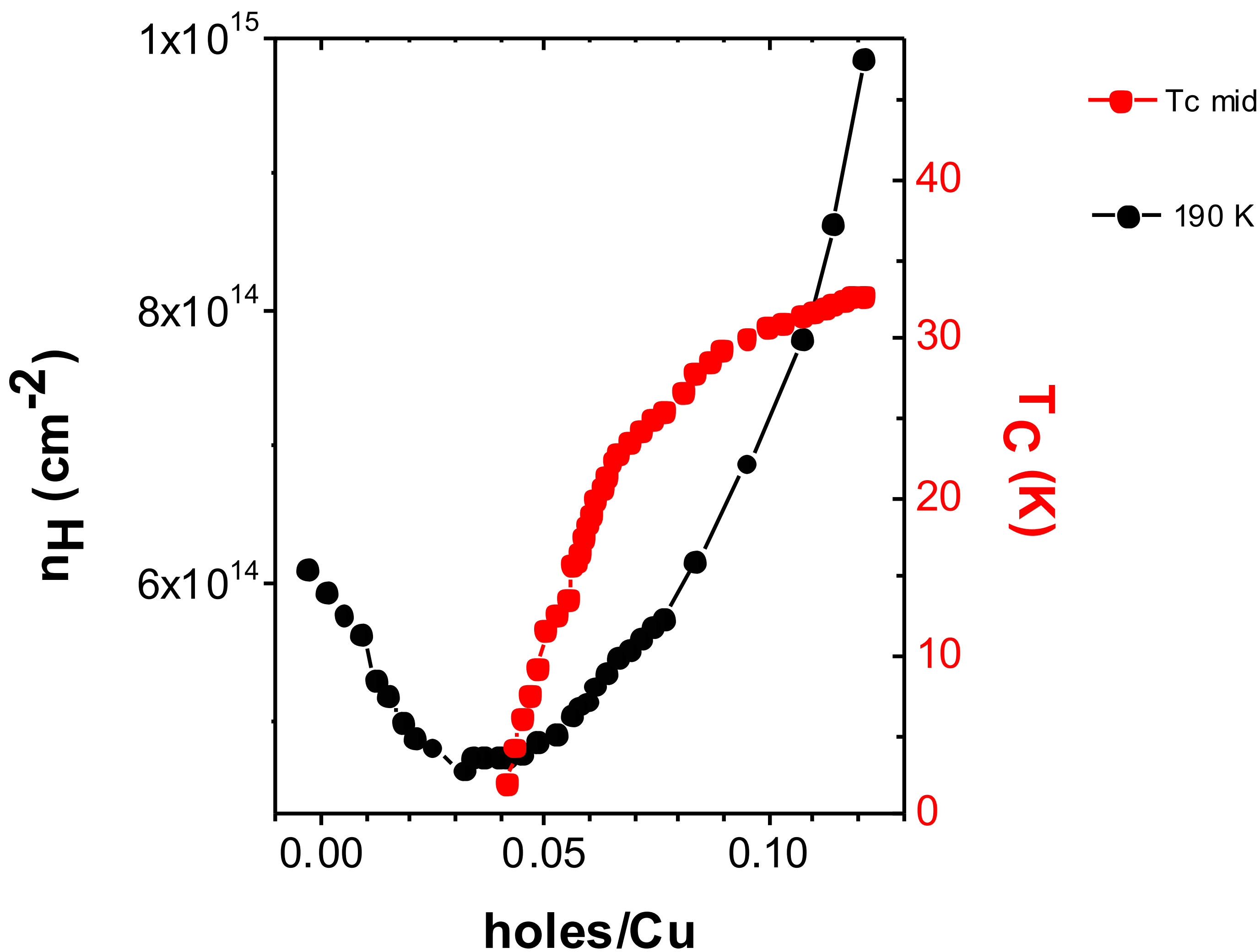
# Superconductor Insulator Transition
## Hall resistance

The presence of a maximum in the $R_{XY}$ could again be revealing an electronic phase transition

*Is the QPT at zero temperature related to the high temperature changes in $R_{XY}$??*



# Minimum in $n_H$ near the edge of the SC dome in δ−LCO



# Summary and Future Prospects

Electronic Double Layer Transistors employing Ionic Liquids can be used to tune the properties of novel materials such as the Cuprates.

We have emphasized the study of YBCO and are now investigating LCO. One can tune through the phase diagram with some surprises.

Currently the measurement of the Hall effect is the major complement to the study of resistance and magnetoresistance. There is evidence from this work of electronic transitions in YBCO near the maximum of the dome of the transition temperature vs. doping, and in LCO near the SI transition.

We plan X-ray spectroscopy and kinetic inductance measurements.

An open question is whether this approach can be efficiently used to search for new superconductors.

Caveats: don't know the actual depth of charge pentratiion
failures—interaction of the ionic liquid with the sample chemistry or physics, movement of oxygen