The Superconductor-Insulator Transition of Electrostatically Doped $La_2CuO_{4+\delta}$

Javier Garcia Barriocanal

GFMC, Universidad Complutense de Madrid (Spain)
School of Physics and Astronomy, University of Minnesota (USA)

Zaragoza, December 2012

UNIVERSITY OF MINNESOTA
Driven to Discover℠

Universidad Complutense Madrid

GFMC
Grupo de Física de Materiales Complejos

Alexey Kobrinskii, Xiang Leng, Joe Kinney, Boyi Yang, Steve Snyder, Allen M Goldman (UMN)

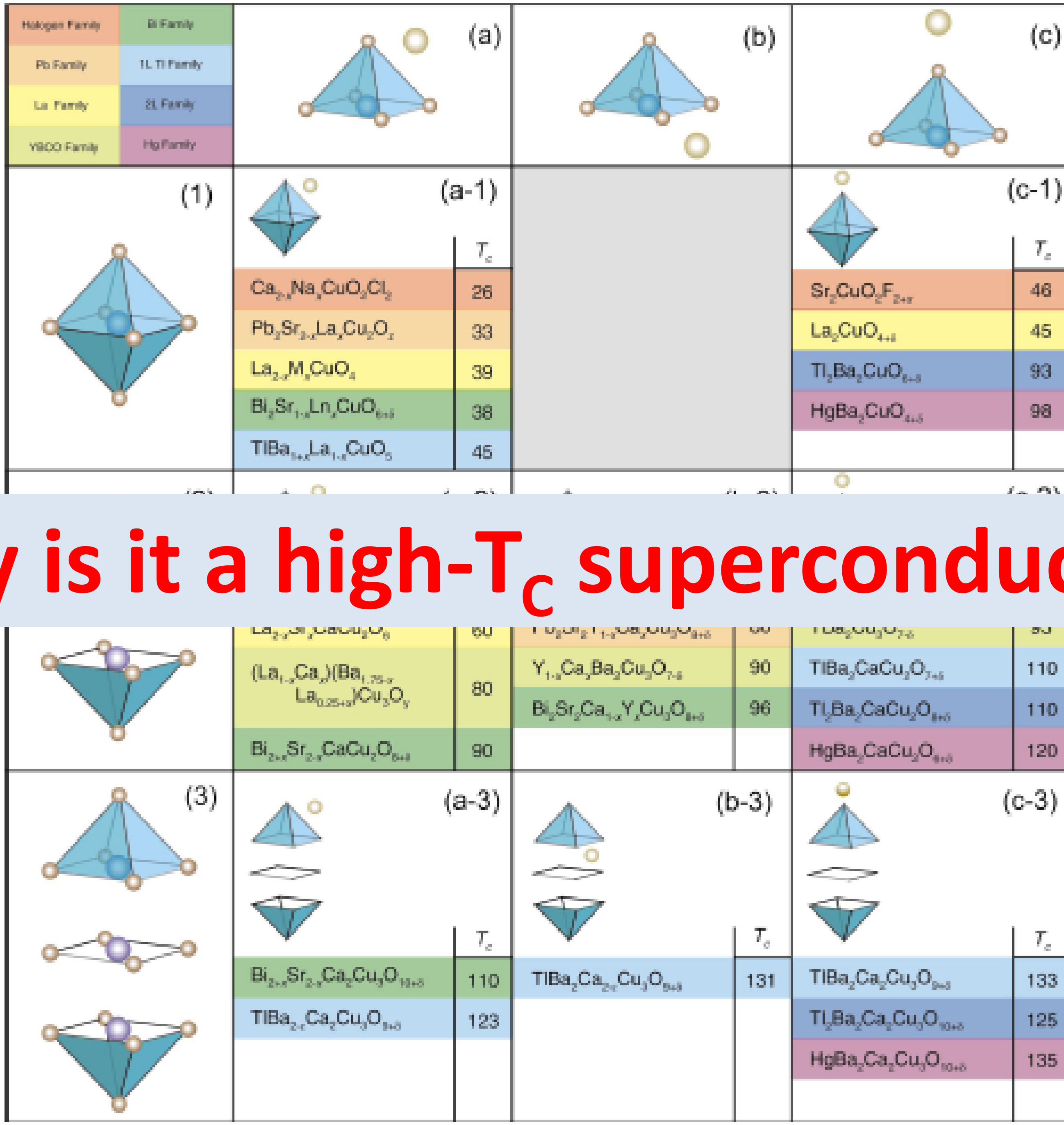
Maria Varela (UCM - ORNL)

In memory of Zlatko Tesanovic

Outline

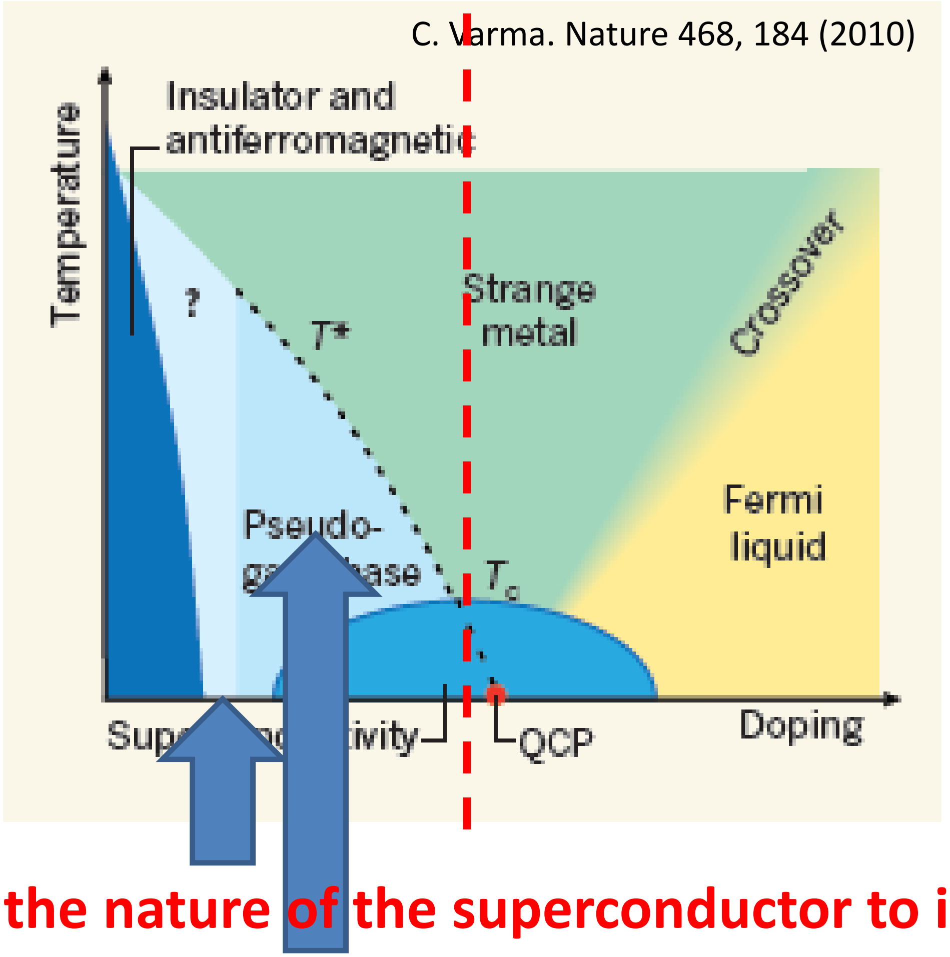
1. Introduction
2. Epitaxial Growth and Structural Characterization
   - Molecular Beam Epitaxy, X-Ray, AFM and STEM experiments
3. Transport and Magneto-Transport Experiment
   - Electronic Double Layer Transistor (EDLT)
   - Results
     - Superconductor Insulator Transition
4. Conclusions

Why is it a high-T_C superconductor?



Eisaki, PRB, 69 (2004)

General phase diagram for HTC



What is the nature of the superconductor to insulator transition?

What happens near the Mott state?

Magnetism and Superconductivity are linked!

AFM correlations are present at the PG and SC regions of the PD

Eisaki, PRB, 69 (2004)

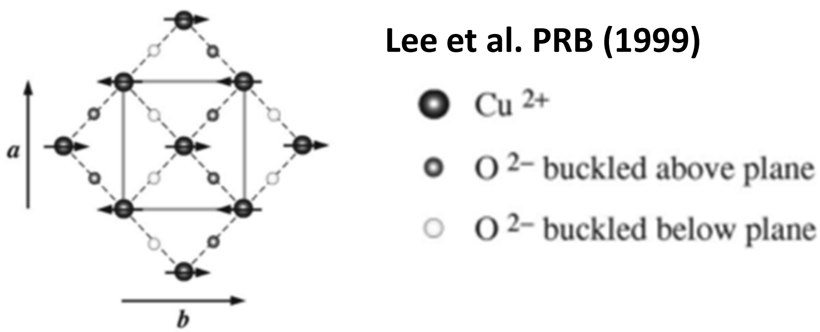
$La_2CuO_{4+\delta}$ (δ-LCO) vs $La_{2-X}M_XCuO_4$ (LMCO)

We ran out of Sr (=M)!!

That was a lucky accident …

$La_2CuO_{4+\delta}$ (δ-LCO) vs $La_{2-X}M_XCuO_4$ (LMCO)

Lee et al. PRB (1999)



LCO **δ-LCO**

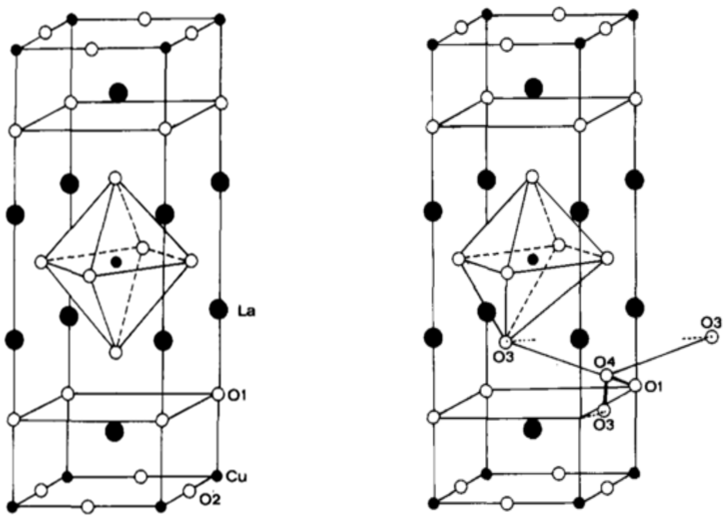


Fig. 1. (a) Three dimensional structural arrangement of La_2CuO_4. One tetragonal unit cell is represented. (b) The position of O4 in the pseudo tetragonal unit cell of $La_2CuO_{4.032}$. The displaced O4 atoms to the O3 positions are indicated.

Chailout et al. Physica C (1989)

δ-LCO is a HTS derived from the antiferromagnetic - Mott insulator La_2CuO_4 (LCO)

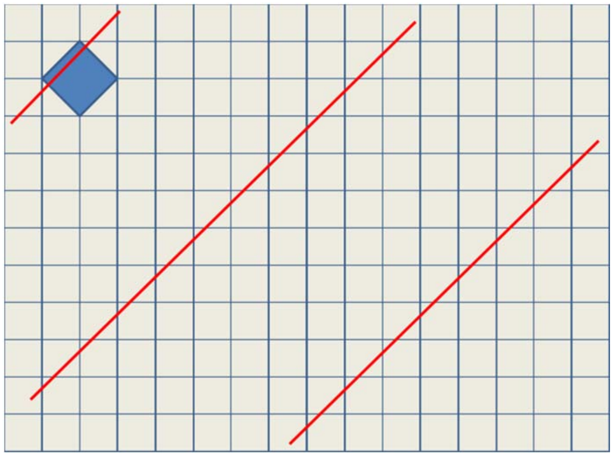
Oxygen interstitials (i-O) are located in between $La_2O_{2+\delta}$ layers, far away from the CuO_2 superconducting planes

Disorder is weak and T_C is the highest of the La 214 family of compounds

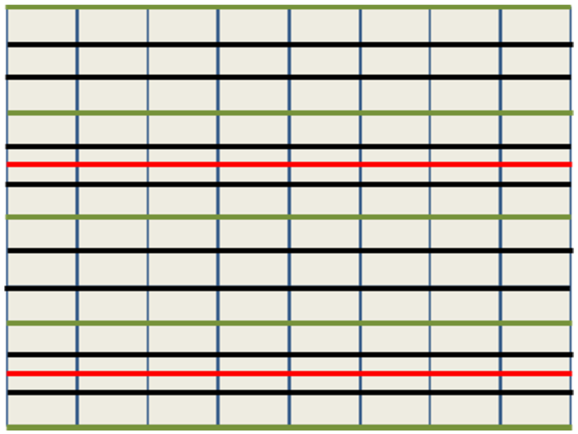
i-O are introduced in specific positions of the crystal structure

$La_2CuO_{4+\delta}$ (δ-LCO) vs $La_{2-X}M_XCuO_4$ (LMCO)

ab plane



ac plane



δ-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

Disorder is weak and T_C is the highest of the La 214 family of compounds

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

Chailout et al. Physica C (1989)

$La_2CuO_{4+\delta}$ (δ-LCO) vs $La_{2-X}M_XCuO_4$ (LMCO)

LMCO | **δ-LCO**

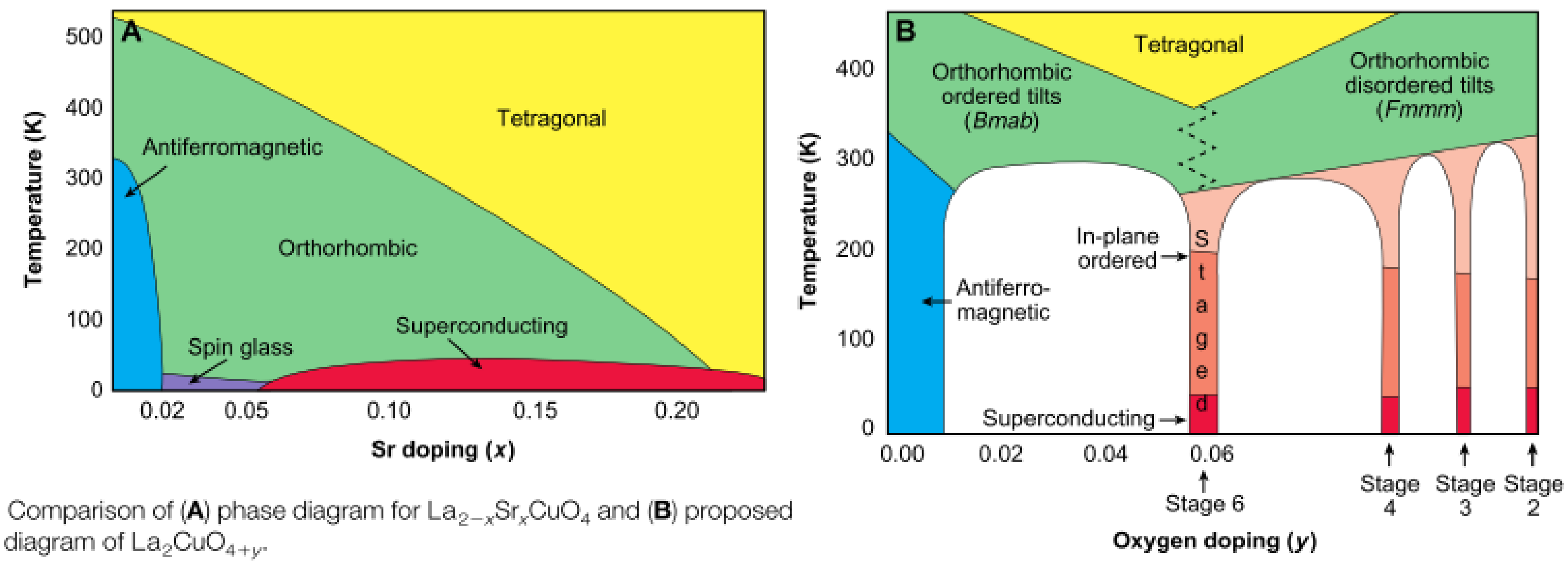


Fig. 1. Comparison of (**A**) phase diagram for $La_{2-x}Sr_xCuO_4$ and (**B**) proposed phase diagram of La_2CuO_{4+y}.

Wells et al. Science (1995)

δ-LCO phase diagrams is characterized by the presence of miscibility gaps

T_C is not continuous depends on the staged number

A continuous phase diagram has never been explored due to phase separation

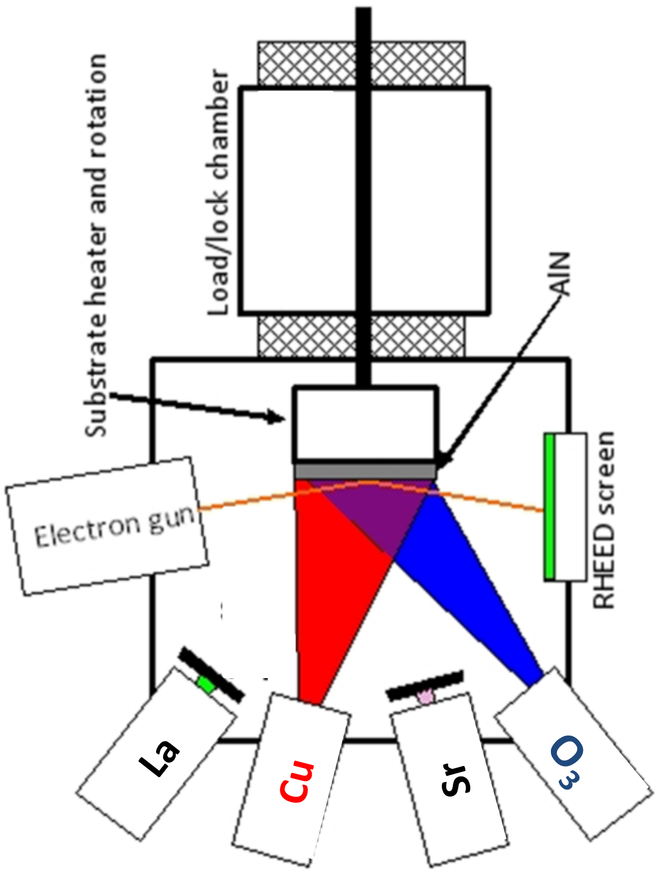
EDLT are different from bulk crystals

Outline

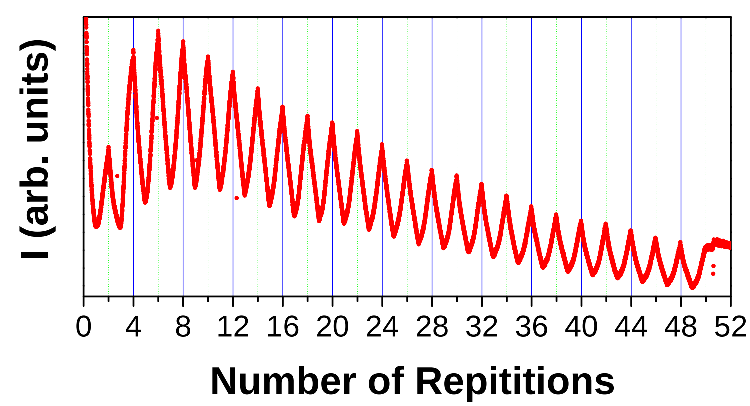
1. Introduction
2. **Epitaxial Growth and Structural Characterization**
   – Molecular Beam Epitaxy, X-Ray, AFM and STEM experiments
3. Transport and Magneto-Transport Experiment
   – EDLT
   – Results
      • Superconductor Insulator Transition
4. Conclusions

Epitaxial growth of δ-LCO thin films

Ozone Assisted Molecular Beam Epitaxy



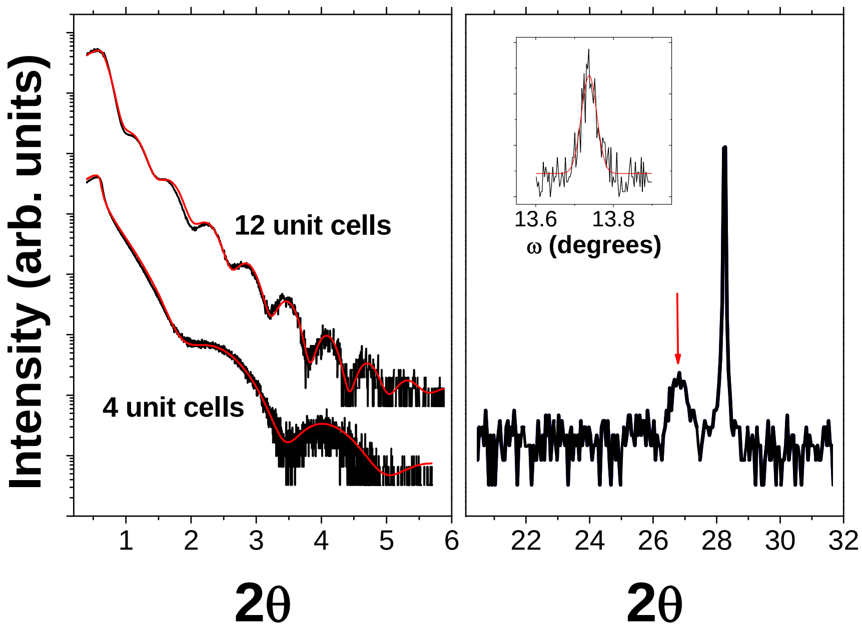
- UHV chamber: 1×10^{-8} Torr- 1×10^{-10} Torr
- Shuttered growth technique
- T_{GROWTH} = 750°C
- On SLAO (0 0 1) substrates
- $P[O_3] = 3 \times 10^{-5}$ Torr
- Reflection High Energy Electron Diffraction (RHEED): ¼ unit cell accuracy



Structural characterization

Specular and off-specular X-Ray Diffraction

Specular: XRR & WAXRD



Flat thin films textured on (001) direction

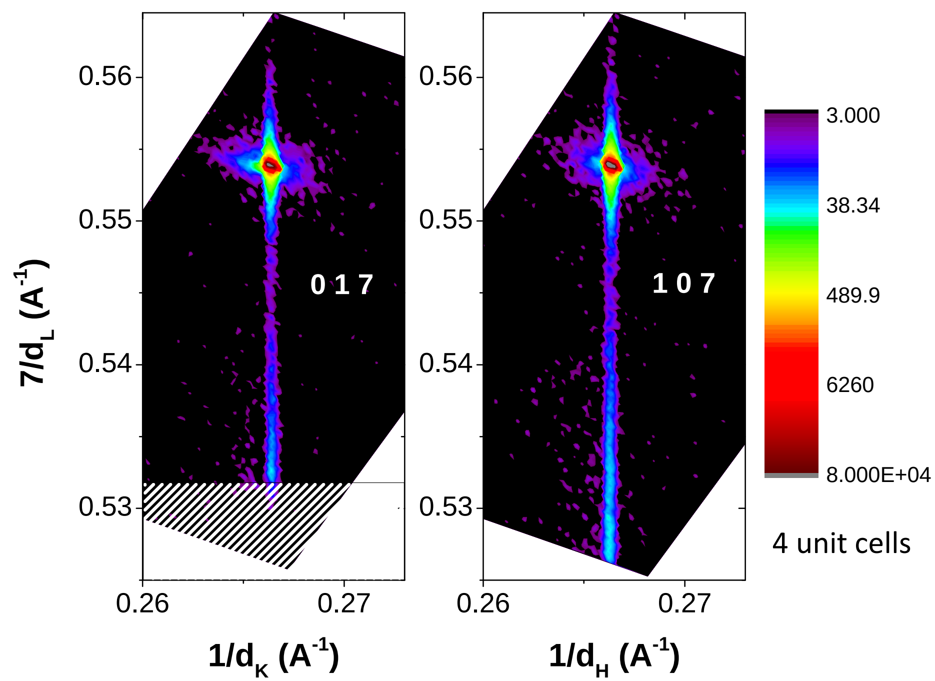
$\sigma_{Substrate}$ = 2 A;

σ_{Film} = 4-6 A;

In plane compression

Out of plane traction

Off-specular: Reciprocal Space Maps



Epitaxial thin films

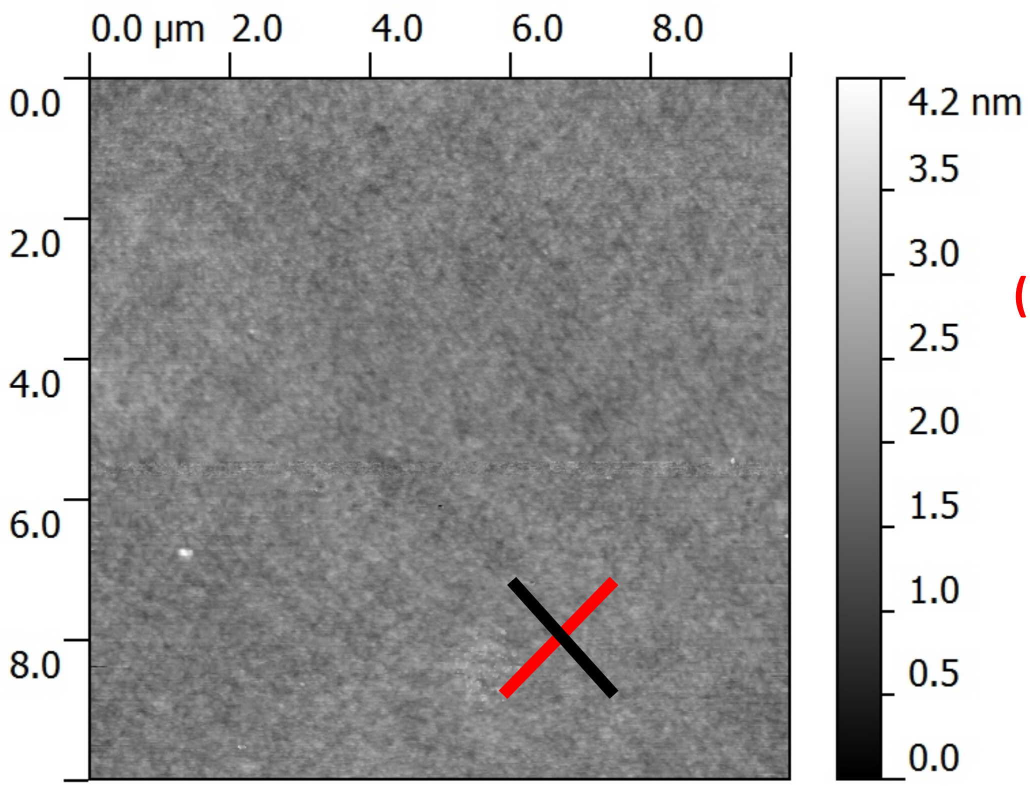
Lateral coherence length limited by the substrate

Out of plane coherence length limited by the film thickness

Structural characterization

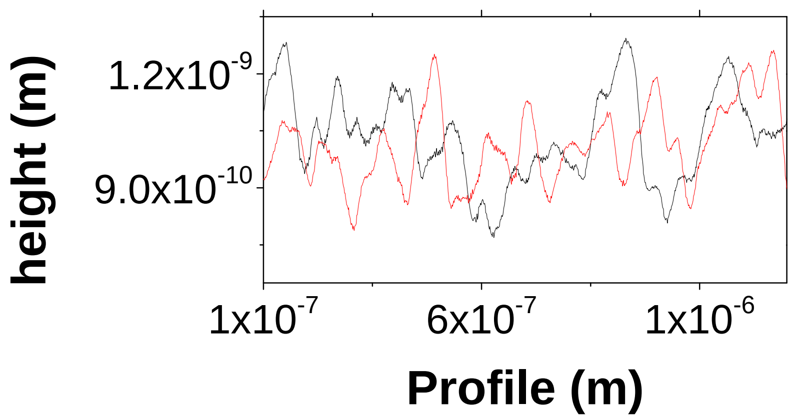
Atomic Force Microscopy and Scanning Transmission Electron Microscopy

AFM



$\sigma_{Surface}$ (RMS) = 2 A;
Δ_{height} = 4 A (1/3 u.c.);

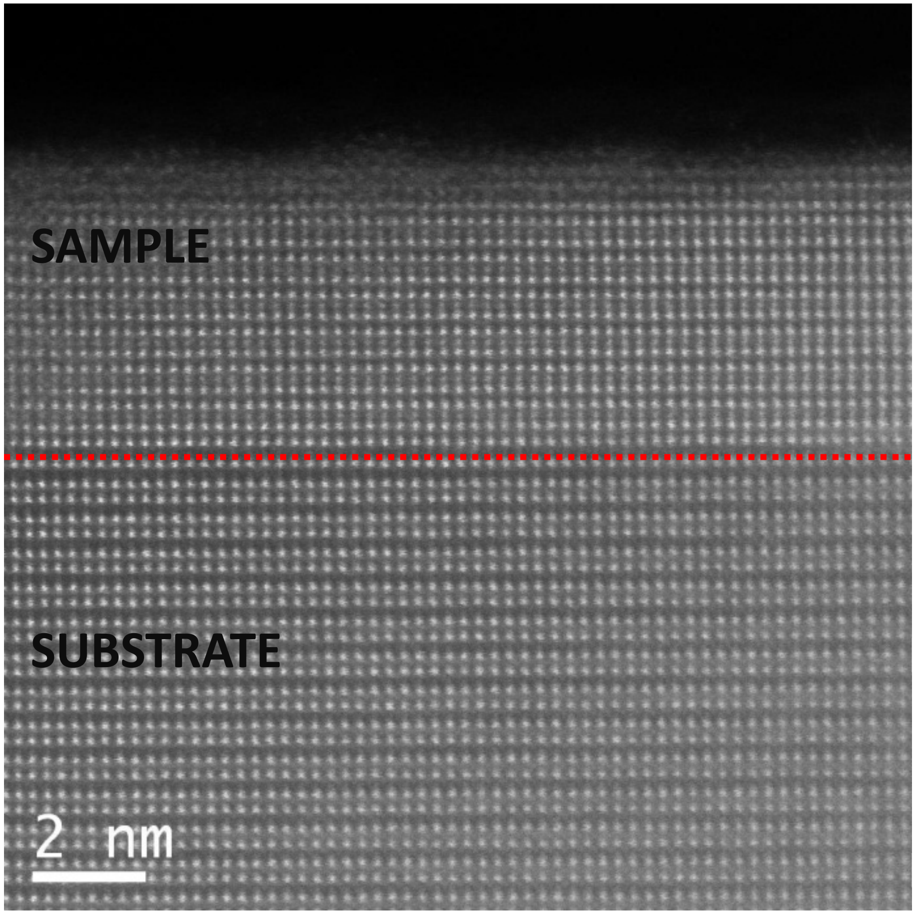
3.75 % thickness variation
(relative to the sample thickness ~5 nm)

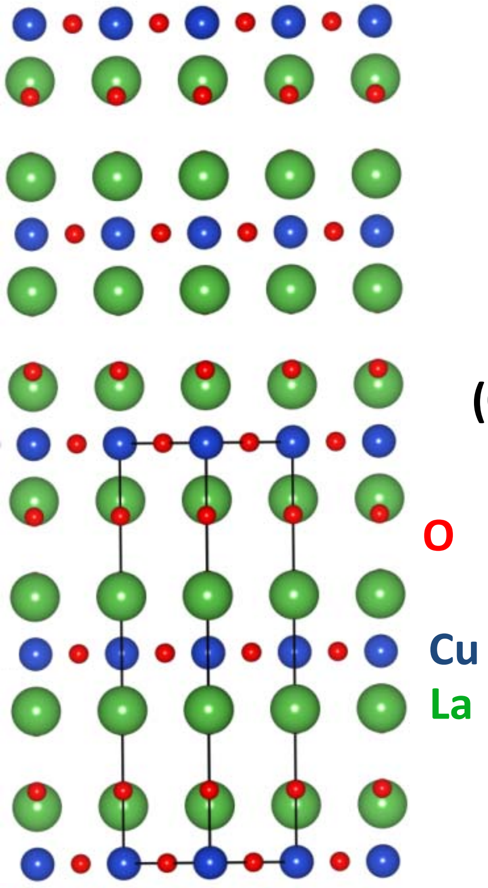


Structural characterization

Atomic Force Microscopy and Scanning Transmission Electron Microscopy

STEM





ADF
Z-Contrast
(011) cross-section

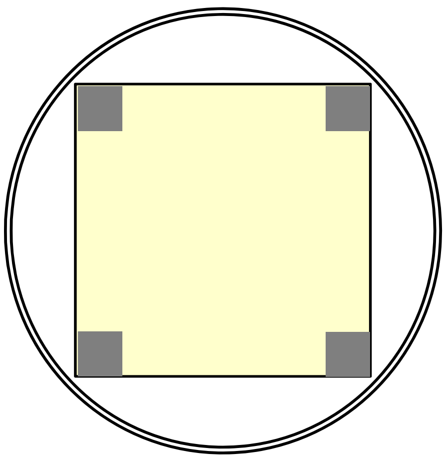
Maria Varela @ ORNL

Outline

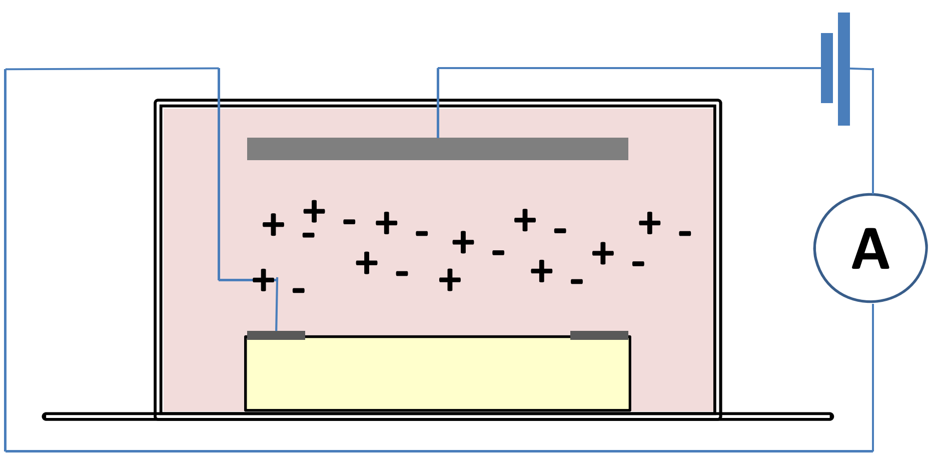
1. Introduction
2. Epitaxial Growth and Structural Characterization
   - Molecular Beam Epitaxy, X-Ray, AFM and STEM experiments
3. **Transport and Magneto-Transport Experiment**
   - EDLT
   - Results
     - Superconductor Insulator Transition
4. Conclusions

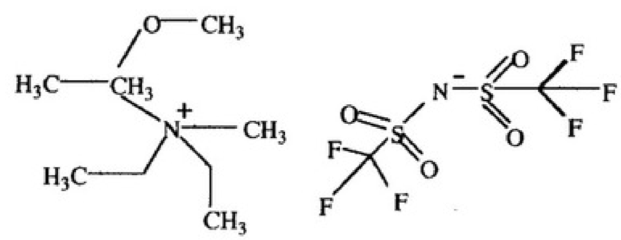
Transport and Magneto Transport Experiment

EDLT



- **O-MBE: 4 u.c. δ-LCO film**
- **Electrode evaporation: Ag / liquid N_2**
- **Glass container**
- **Top gating: Pt coil**
- **DEME TFSI**

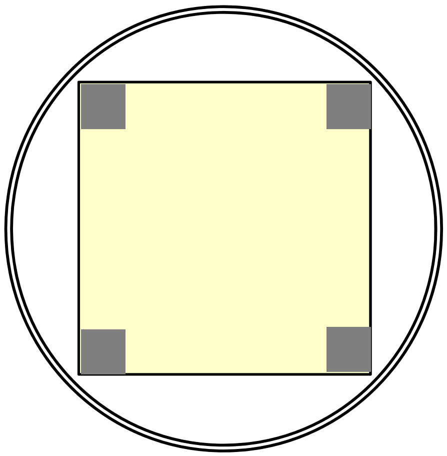




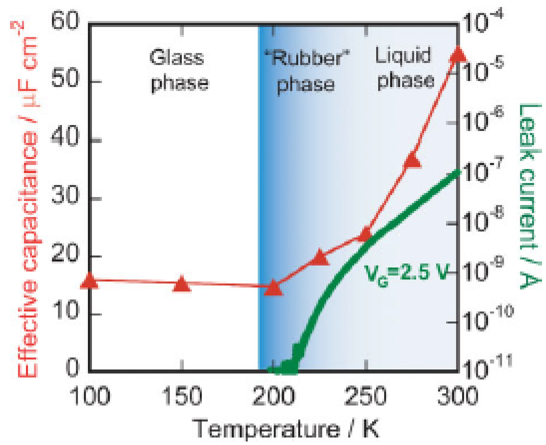
Scheme 2. *N,N*-Diethyl-*N*-methyl-*N*-(2-methoxyethyl)ammonium bis(trifluoromethylsulfonyl)imide ([DEME]TFSI)

Transport and Magneto Transport Experiment

EDLT



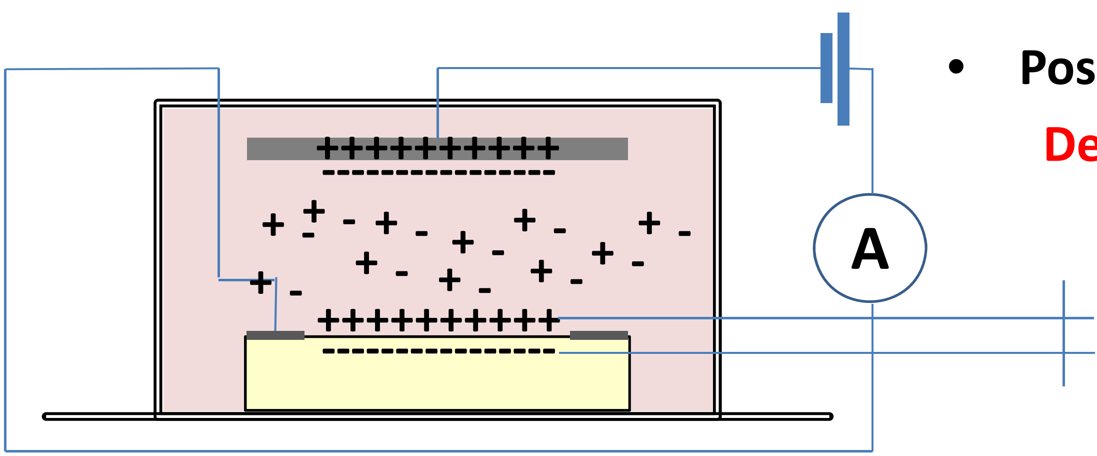
- **Gate voltage changed at 245 K**



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

- **Positive gate voltage:**

  Depletion of holes



d ~ 1 nm

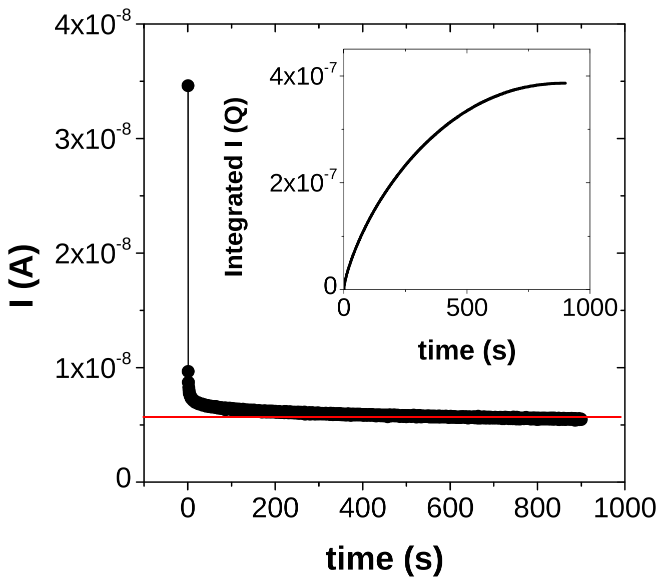
Huge electric field: 10^9 V/m

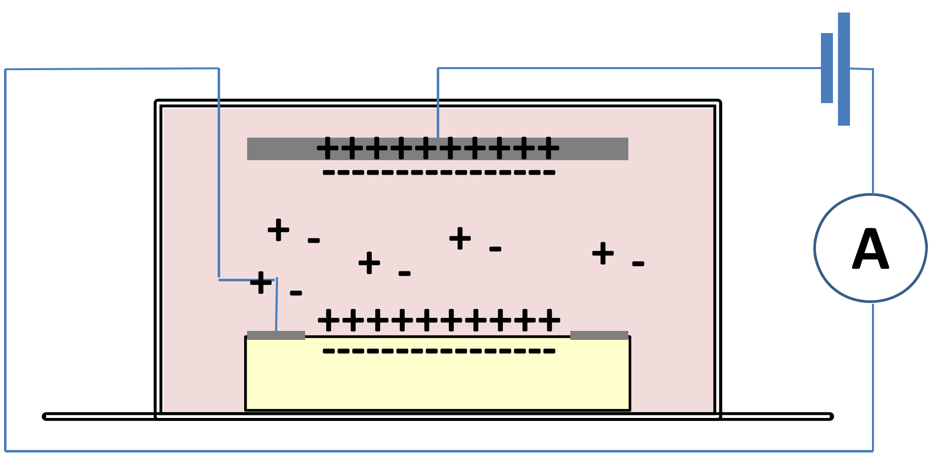
Transport and Magneto Transport Experiment

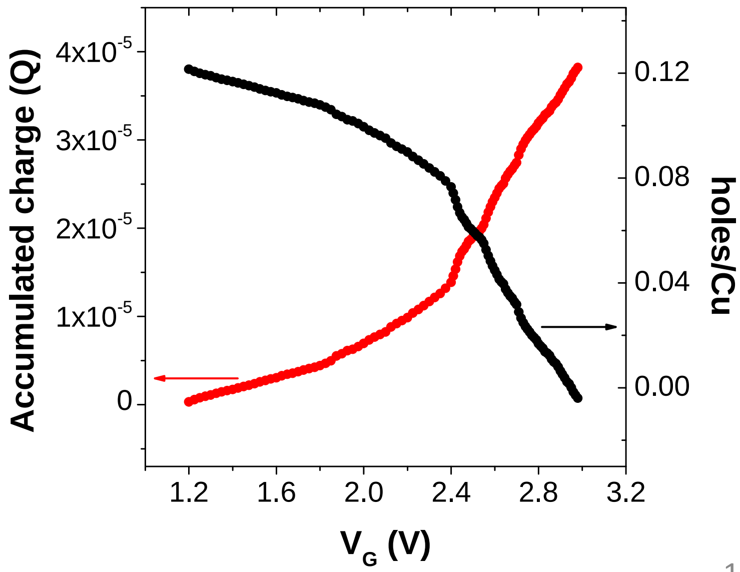
EDLT

Qualitative estimation of holes/Cu from charge leakage measurements

Initial concentration estimated from Hall measurement (180 K; V_G = 0 V)



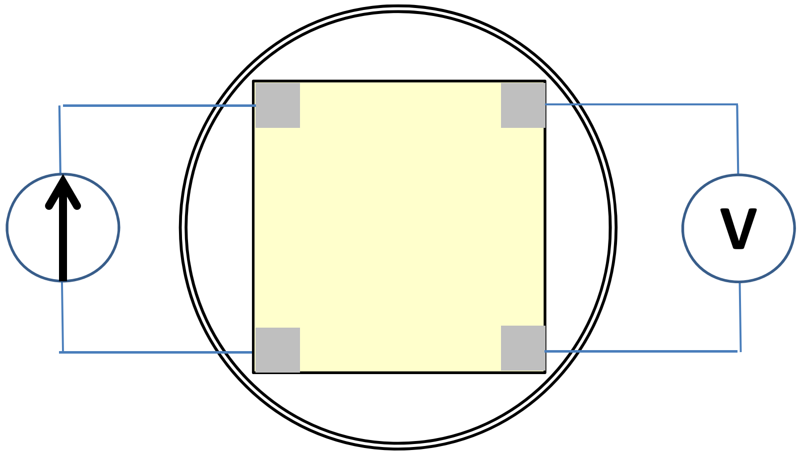


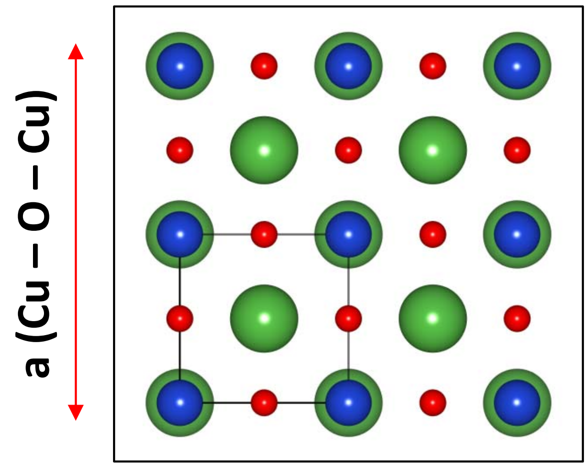


Transport and Magneto Transport Experiment

EDLT

Magneto-transport characterization: T < 200 K - *R(T), IV, R(H)*





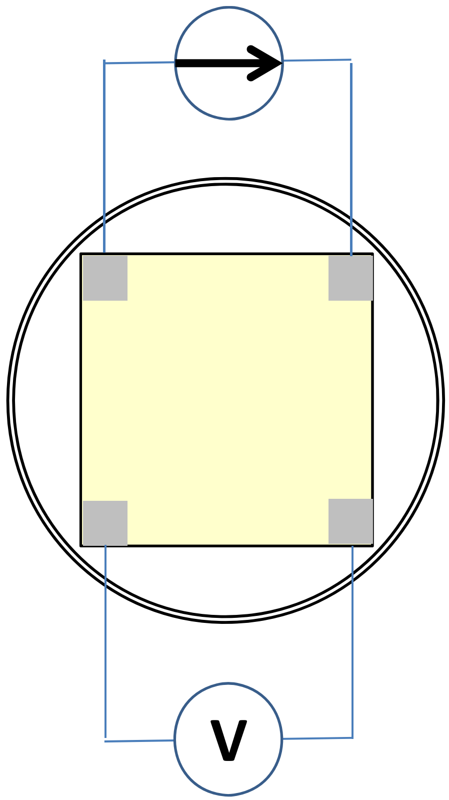
Rs1

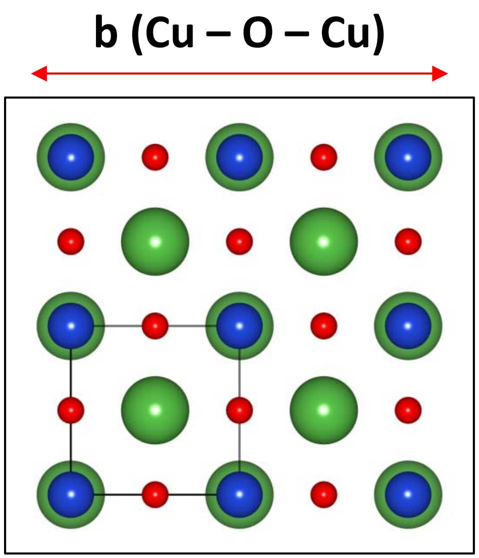
The components of the sheet resistance tensor are calculated using the Montgomery method

Montgomery JAP 1971. Dos Santos et al. JAP 2011

Transport and Magneto Transport Experiment

EDLT



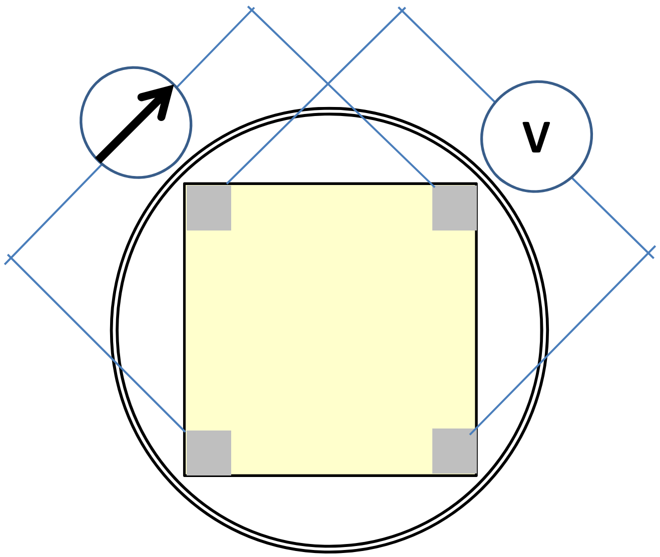


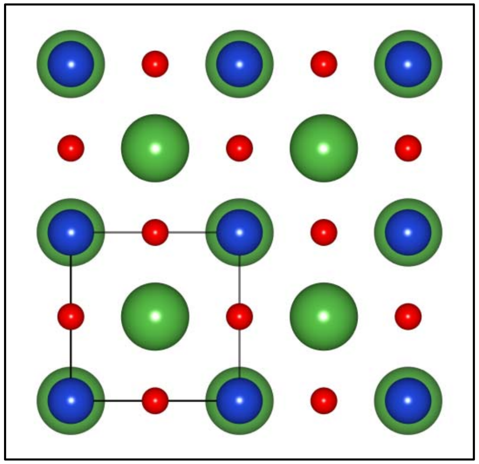
Rs2

We didn't expect any anisotropy, the films are tetragonal and the sample is a square

Transport and Magneto Transport Experiment

EDLT

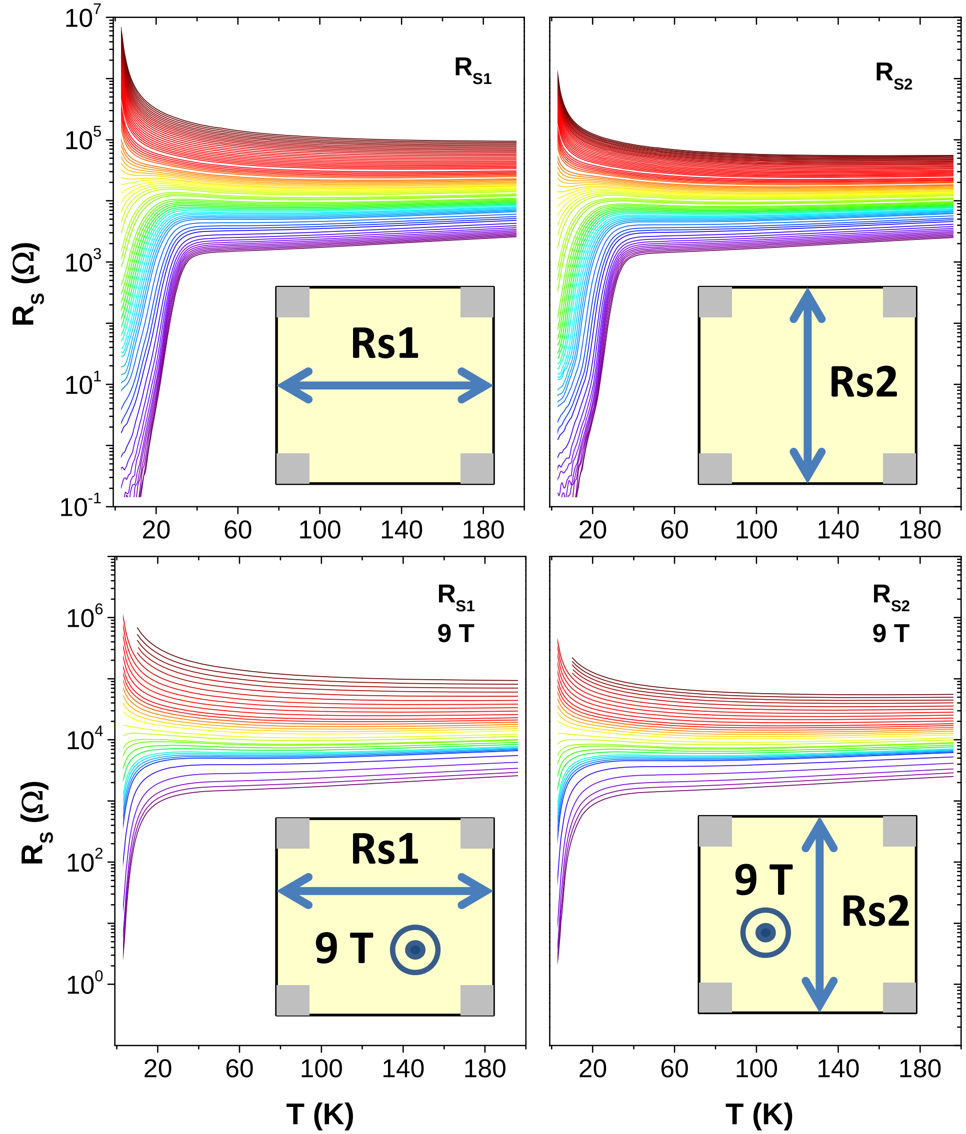




Rxy

Transport and Magneto Transport Experiment

Results



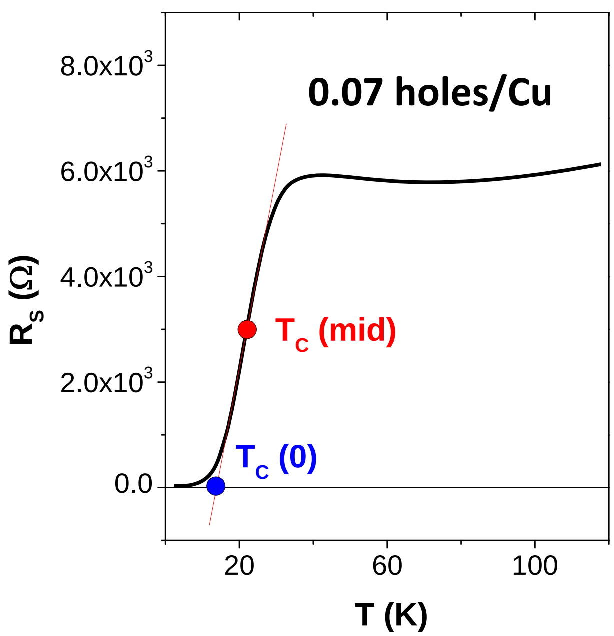
75 levels of charge doping

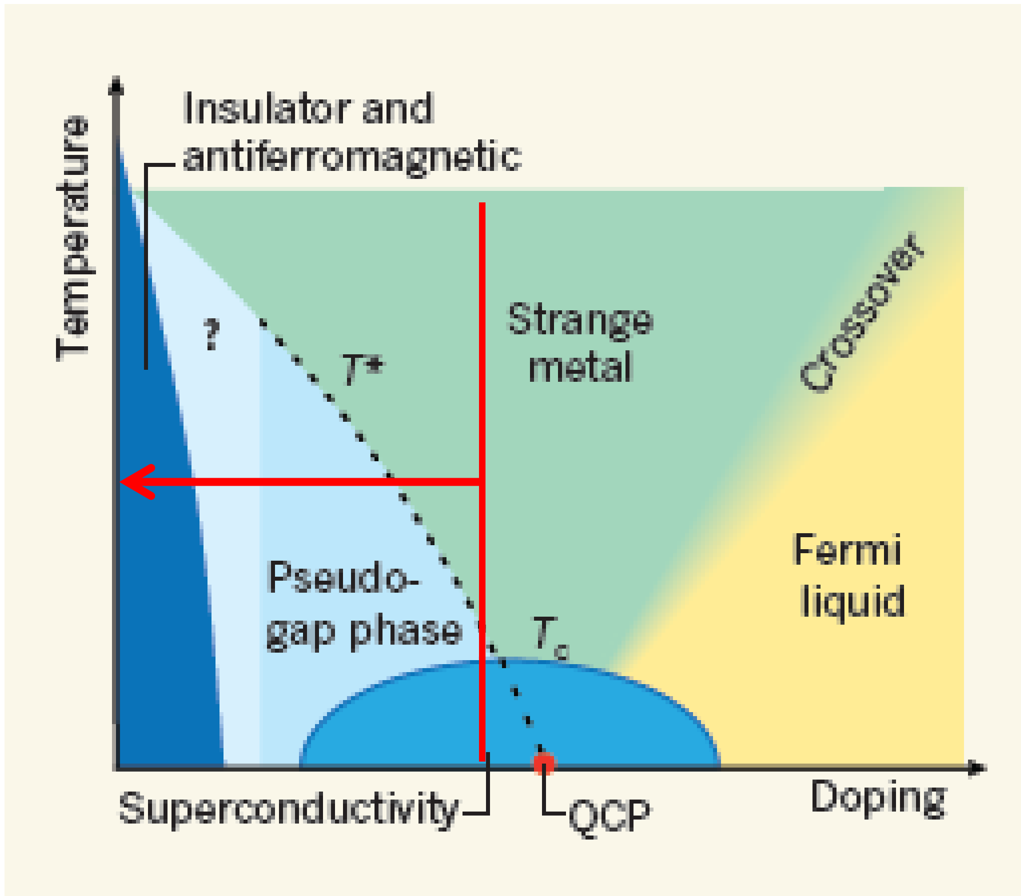
$0.1215 \geq p$ (holes/Cu) ≥ -0.00625

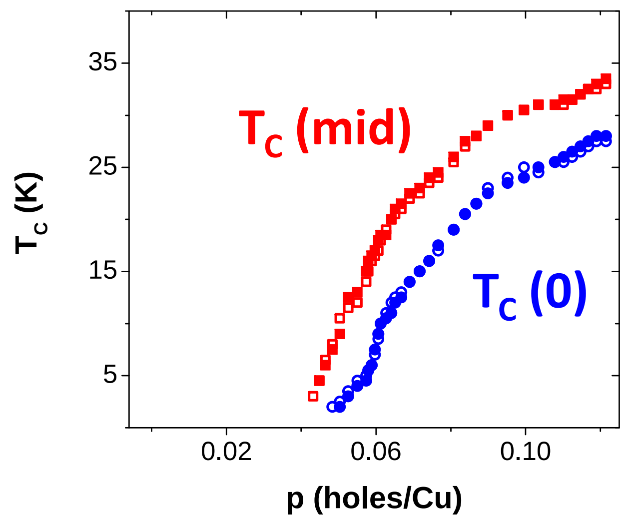
33 levels of charge doping

Transport and Magneto Transport Experiment

Results



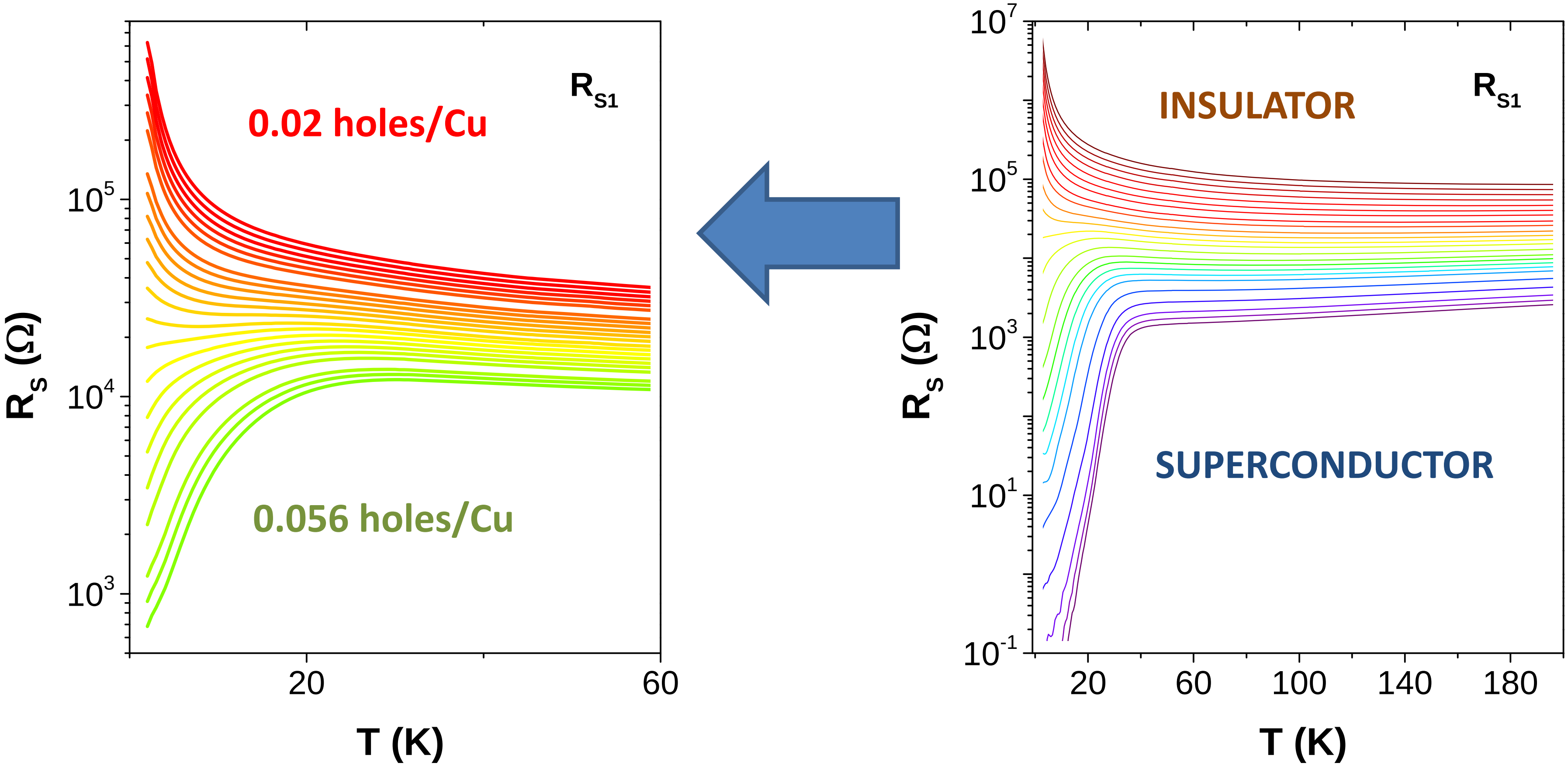




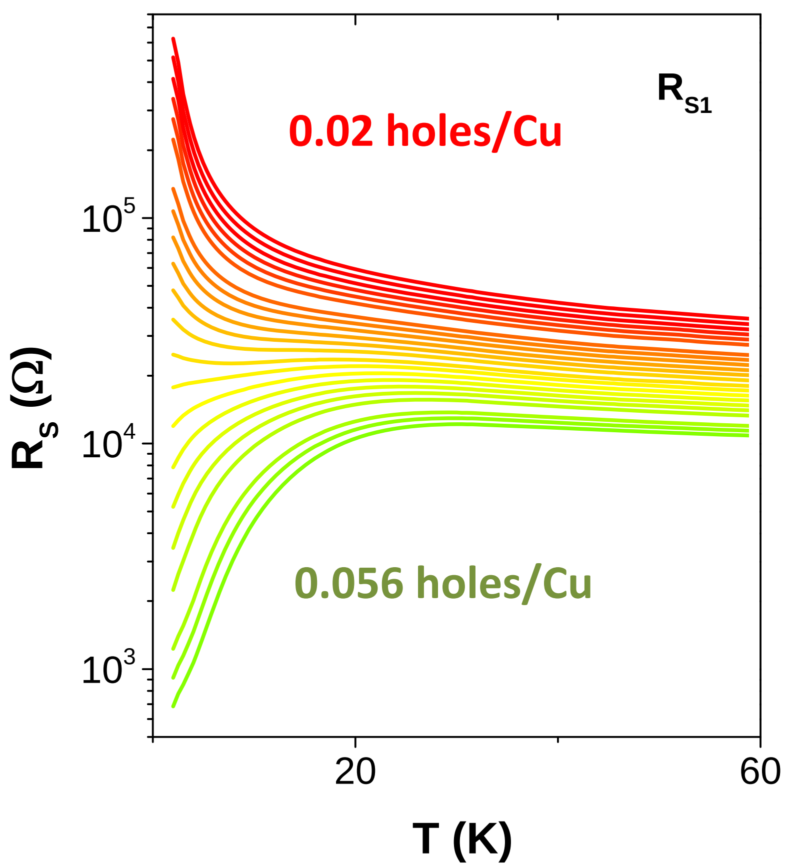
Outline

1. Introduction
2. Epitaxial Growth and Structural Characterization
   - Molecular Beam Epitaxy
   - X-Ray, AFM and STEM experiments
3. Transport and Magneto-Transport Experiment
   - EDLT
   - Results
     - **Superconductor Insulator Transition**
4. Conclusions

Superconductor Insulator Transition

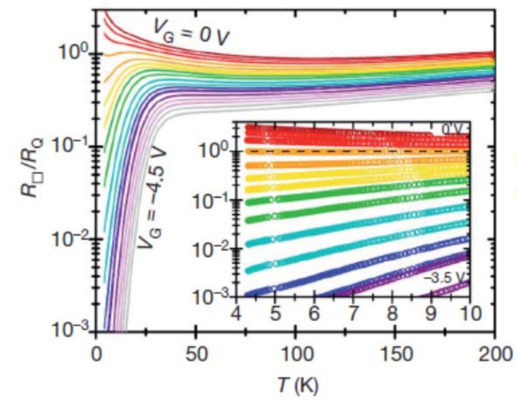


Superconductor Insulator Transition



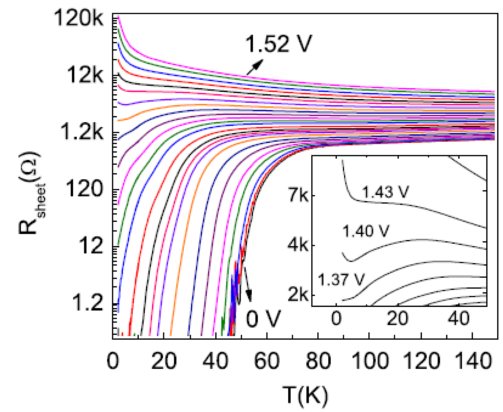
$La_{1-x}Sr_xCuO_4$

Bollinger et al.
Nature 472, 458 (2011)



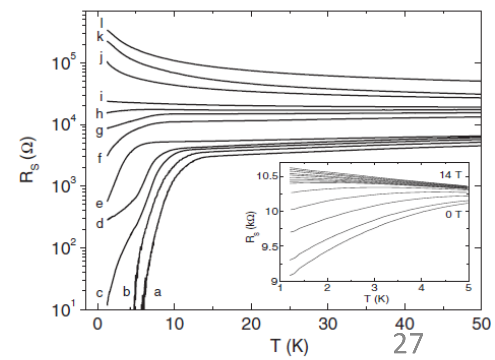
$YBa_2Cu_3O_{7-x}$

XL, JGB et al.
PRL 107, 027001 (2011)



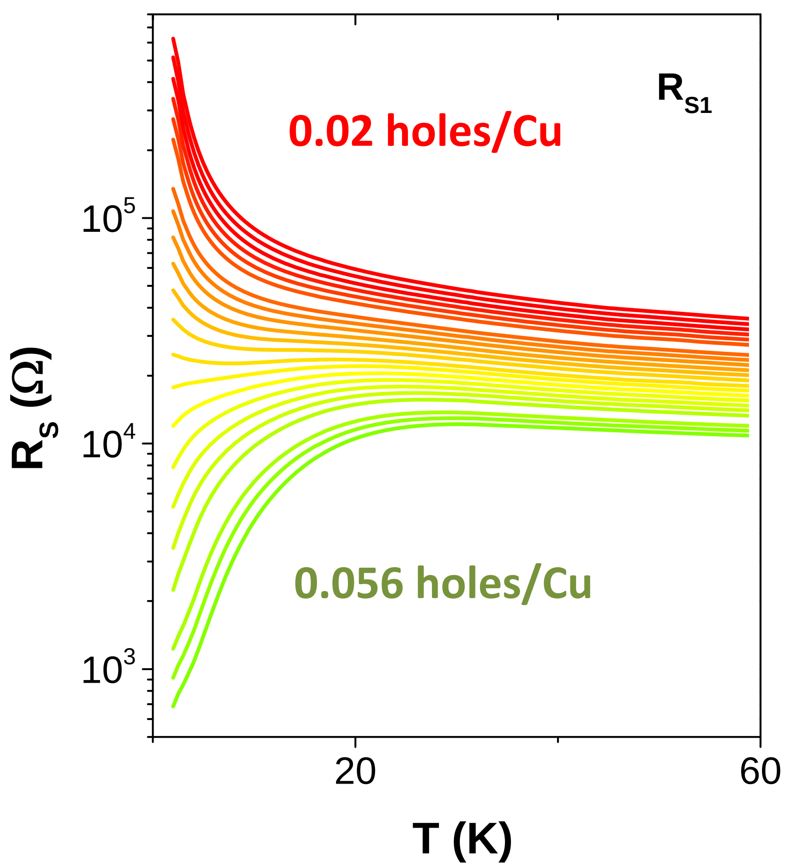
FeSe

Schneider et al.
PRL 108, 257003 (2012)

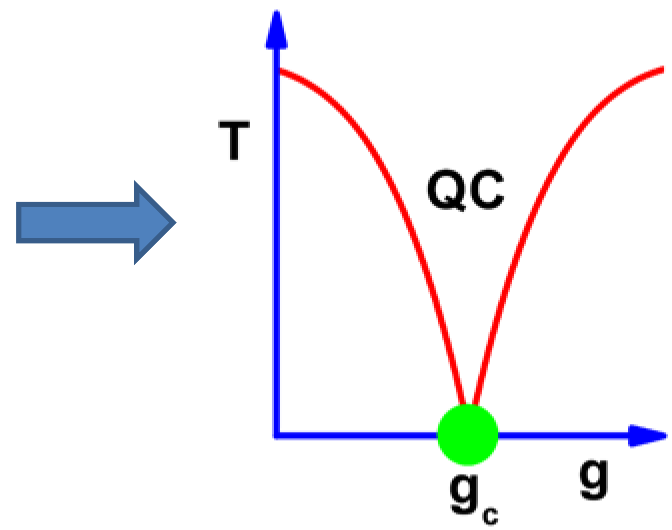


Superconductor Insulator Transition

QPT: finite size scaling analysis



QPT



$g \Rightarrow p$ (holes/Cu)

Scaling function:

$$Rs\,(p, T) = Rs_c f(\,|p-p_c|\; T^{-1/\nu z})$$

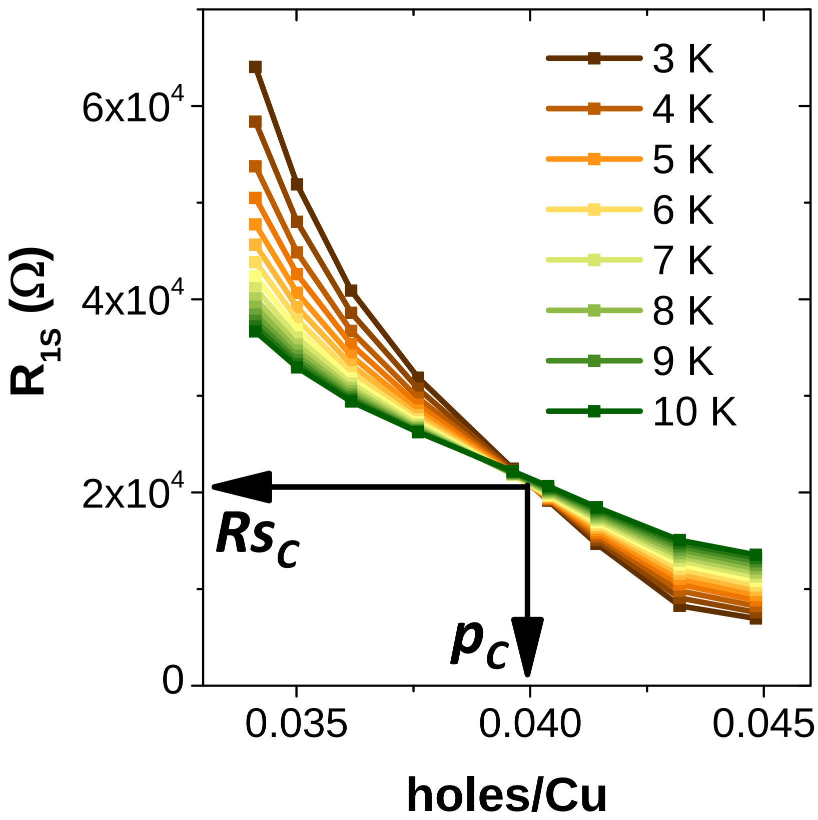
Rs_c p_c νz

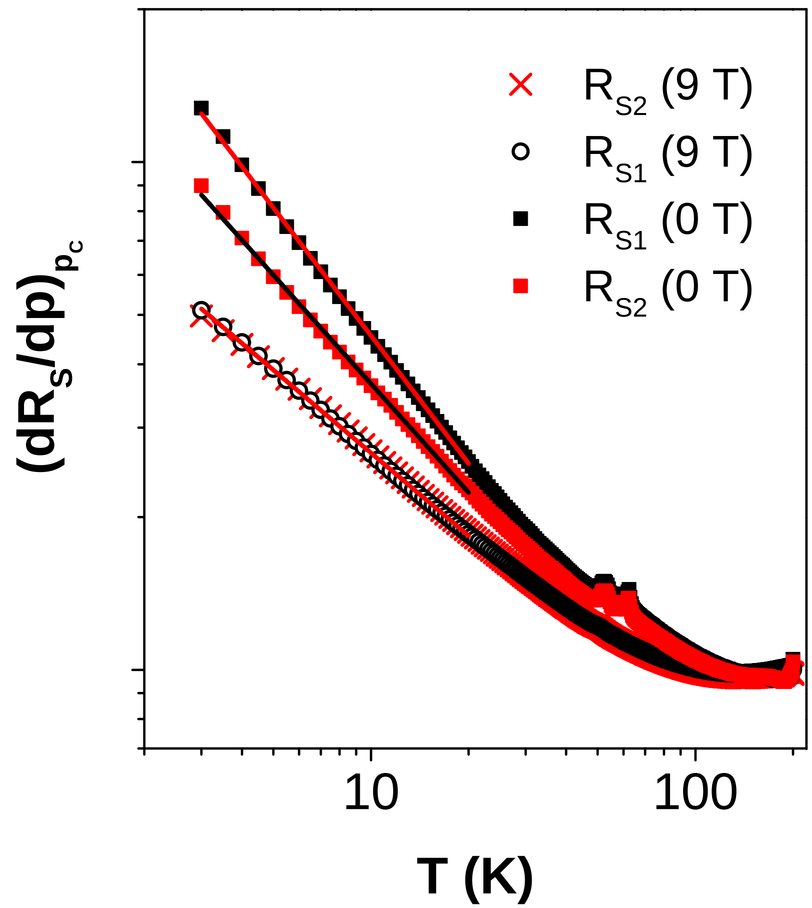
M. P. A. Fisher, PRL (1990)

Superconductor Insulator Transition

QPT: finite size scaling analysis

$Rs\,(p, T) = Rs_C f(\,|p-p_C|\,T^{-1/\nu z}\,)$ $\qquad$ $(dRs/dp)_{Pc} \propto Rs_C\,T^{-1/\nu z} f'(0)$





Crossover between SI regimes
All the isotherms cross at the same point

Superconductor Insulator Transition

QPT: finite size scaling analysis

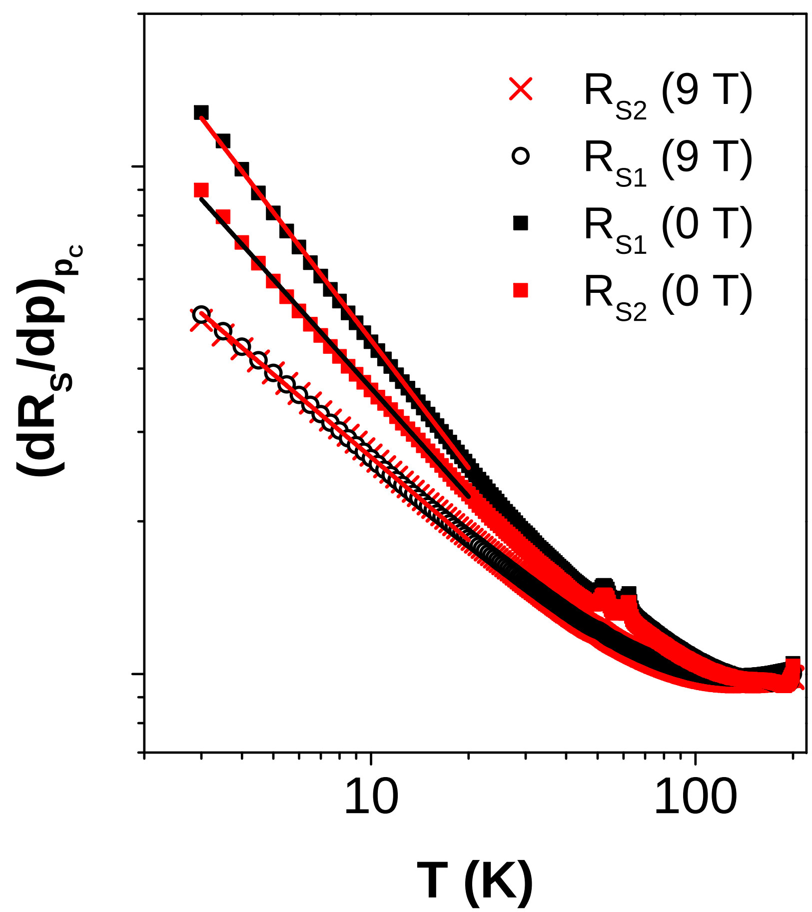
	0 T		9 T	
Direction	1	2	1	2
p_C	0.04	0.04	0.055	0.055
Rs_C (kΩ)	21.5	15	13.5	12.5
νz	1.2	1.4	1.8	1.8

ANISOTROPIC? **ISOTROPIC**

Finite size scaling analysis suggest the presence of a quantum critical point separating the superconducting and insulating regimes.

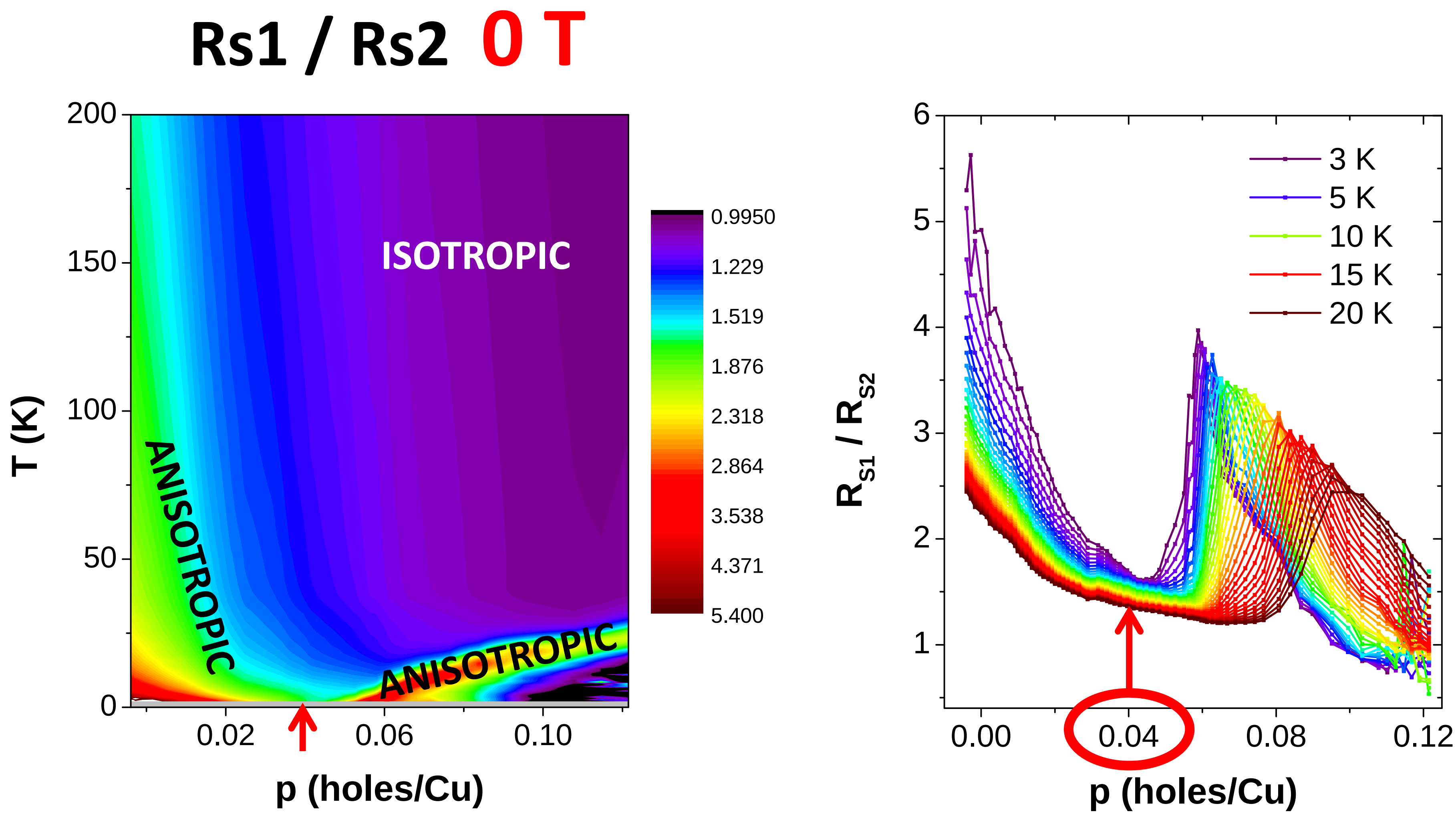
This result should be confirmed at T < 3K

$$(dRs/dp)_{Pc} \propto Rs_C\, T^{-1/\nu z} f'(0)$$



Superconductor Insulator Transition

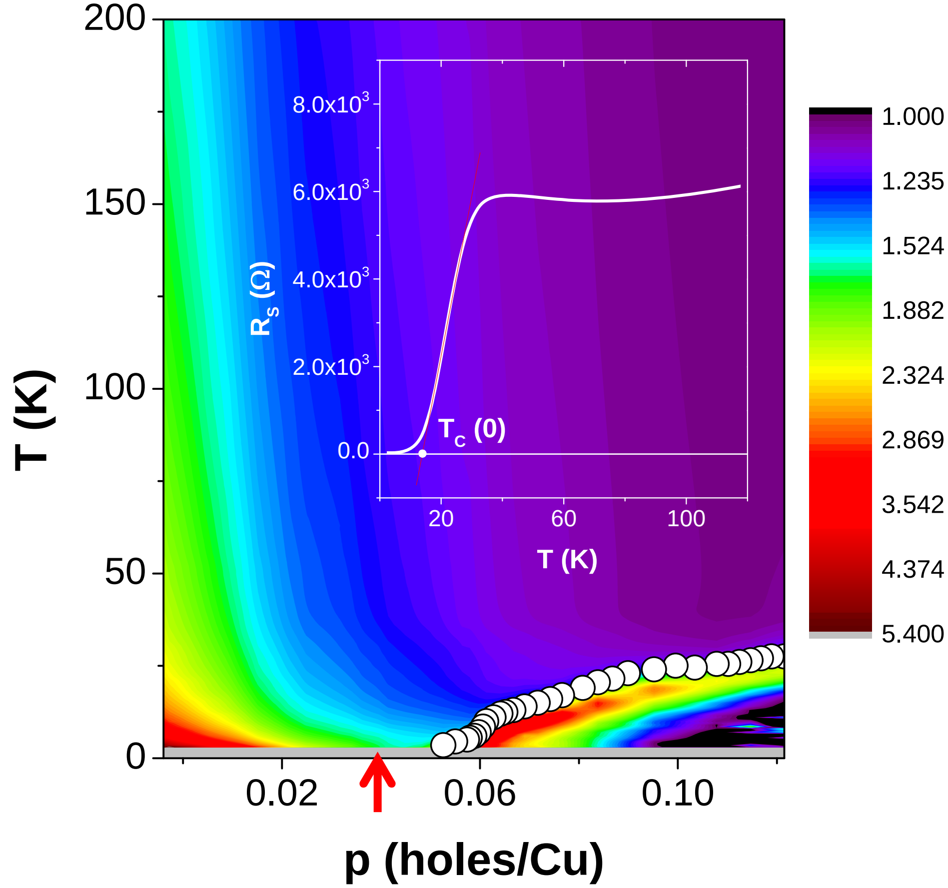
QPT: Anisotropy analysis



Superconductor Insulator Transition

QPT: Anisotropy analysis

Rs1 / Rs2 0 T



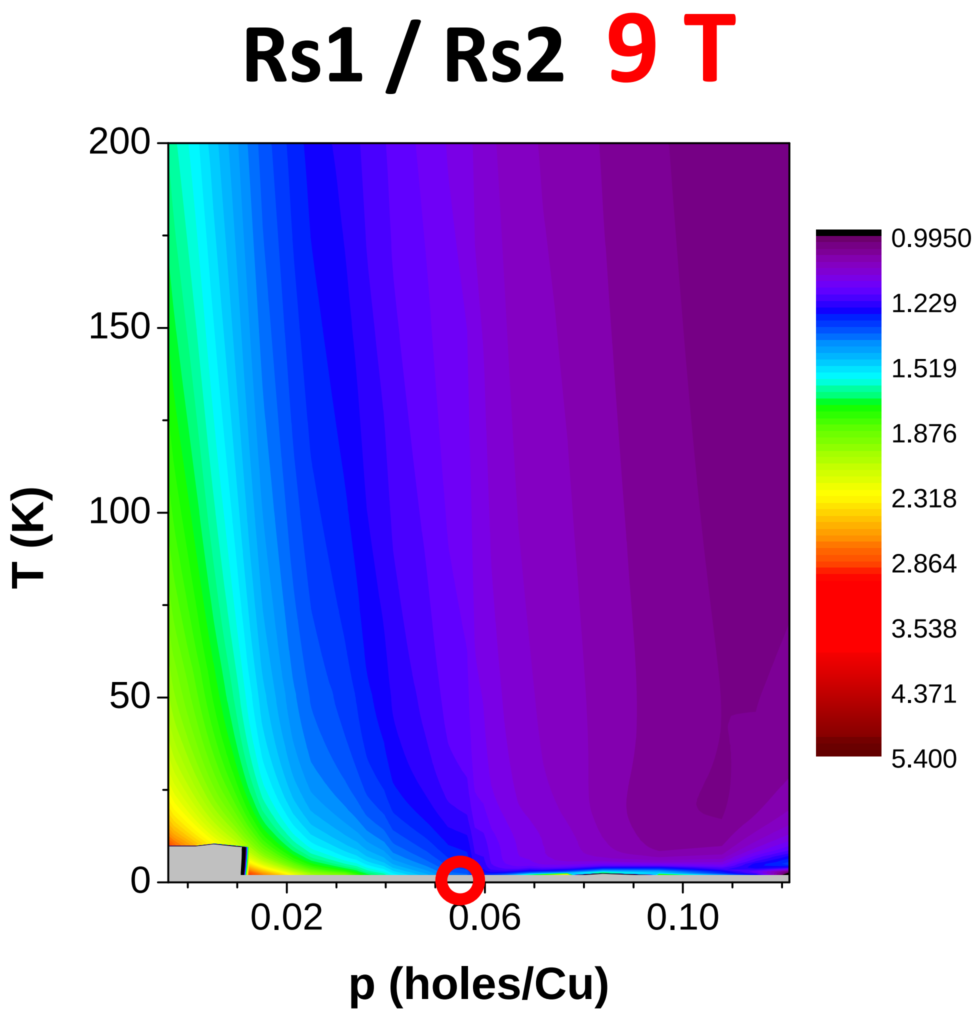
An electronic anisotropy is suggested by the finite size scaling analysis and characterized by the coefficient Rs1/Rs2

The presence of the superconducting transition could be enhancing the detectability of the electronic anisotropy

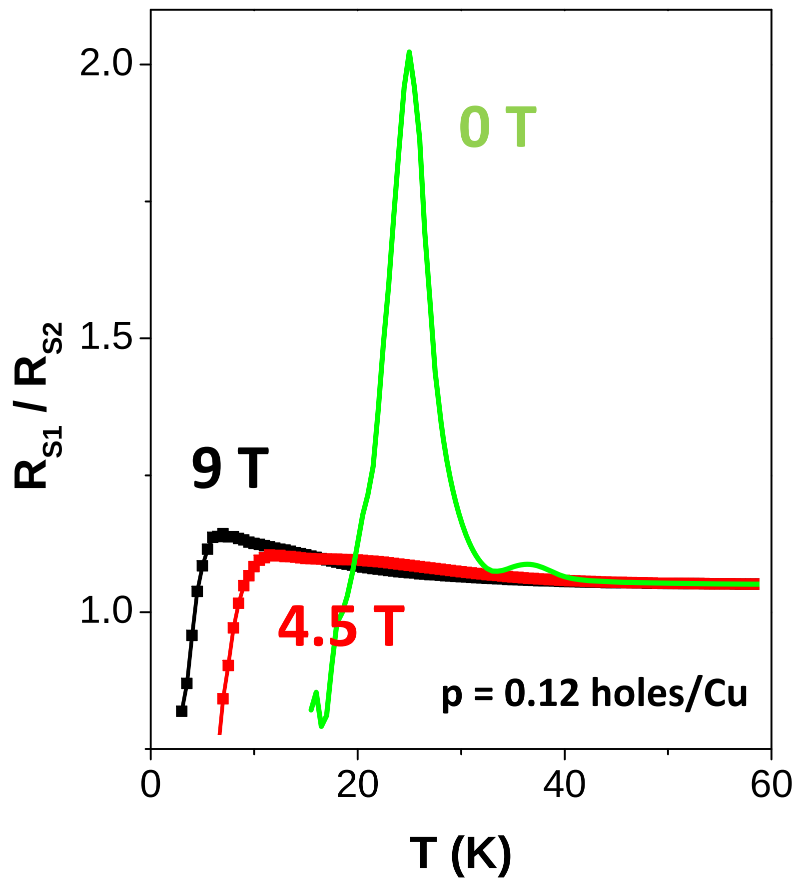
Is this an extrinsic anisotropy?

Superconductor Insulator Transition

QPT: Anisotropy analysis

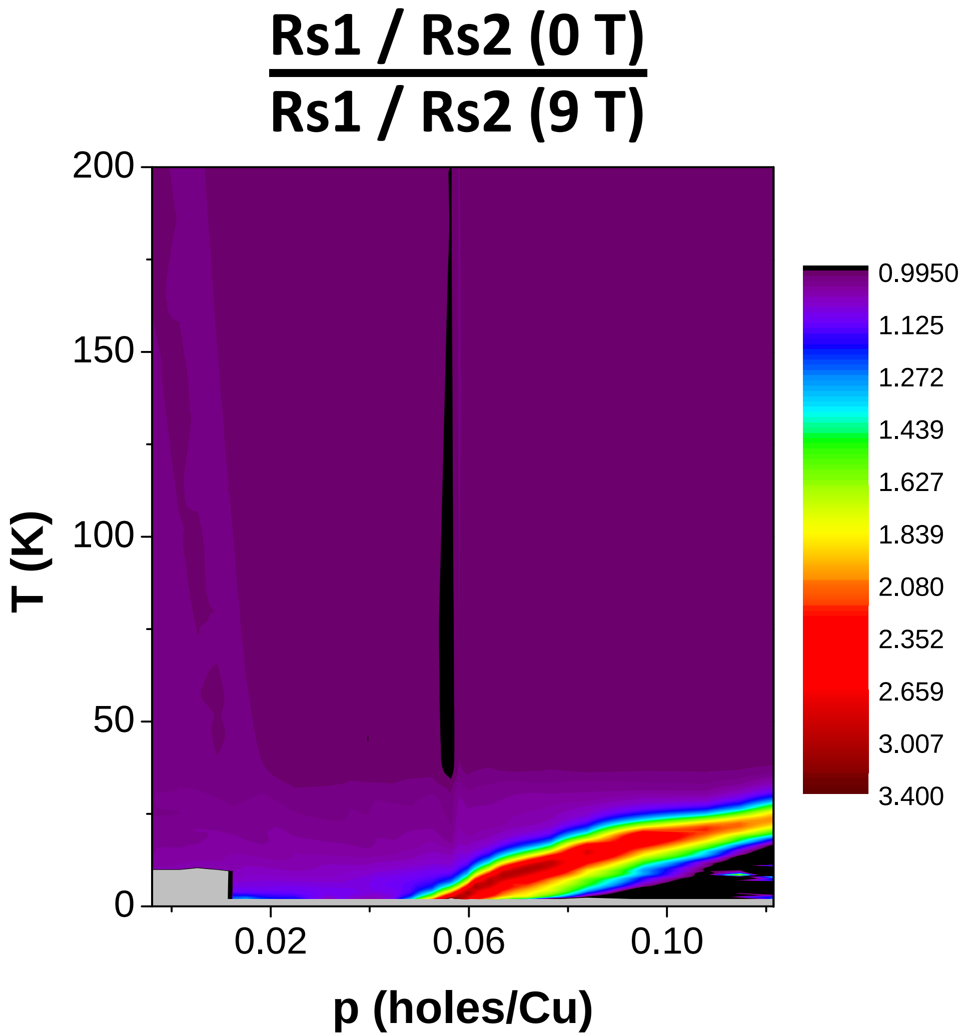


The anisotropy goes away in magnetic field



Superconductor Insulator Transition

QPT: Anisotropy analysis



The electronic anisotropy at the insulating side is magnetic field independent

The electronic anisotropy at the superconducting side goes away with magnetic field (4.5 T and 9 T)

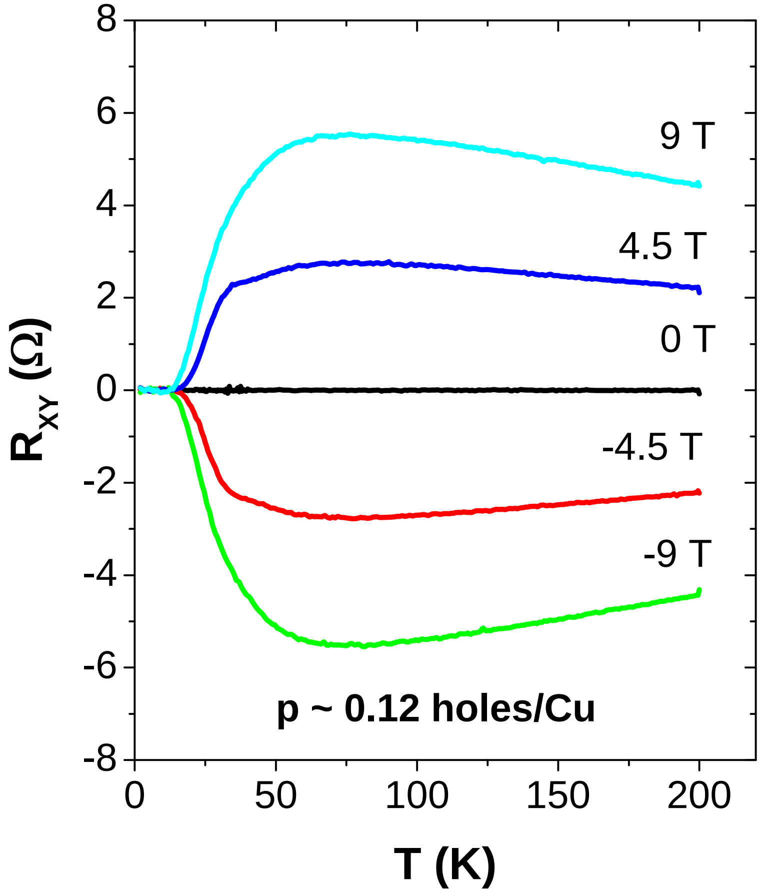
In plane symmetry breaking due to interstitial oxygen stripes

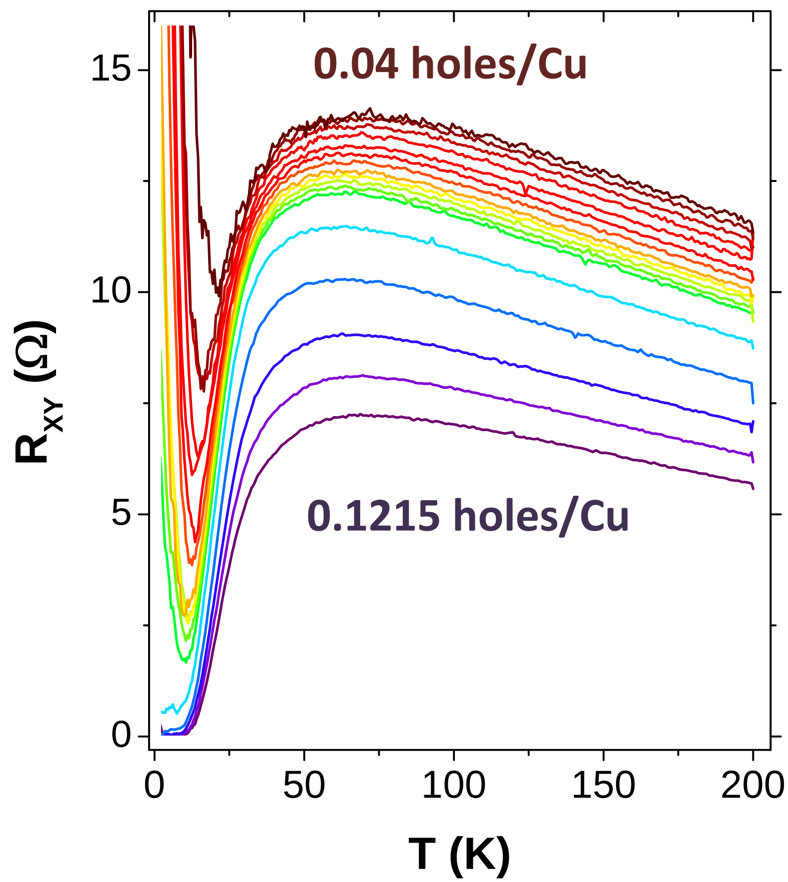
Strong spin-orbit coupling in a 2D system could give rise to the magnetic response of the electronic anisotropy at the superconducting side
(Caviglia et al. PRL 2010)

The anisotropy could arise from the presence of charge or spin density waves, stripes …
(Kivelson et al. Nature 1998)

Superconductor Insulator Transition

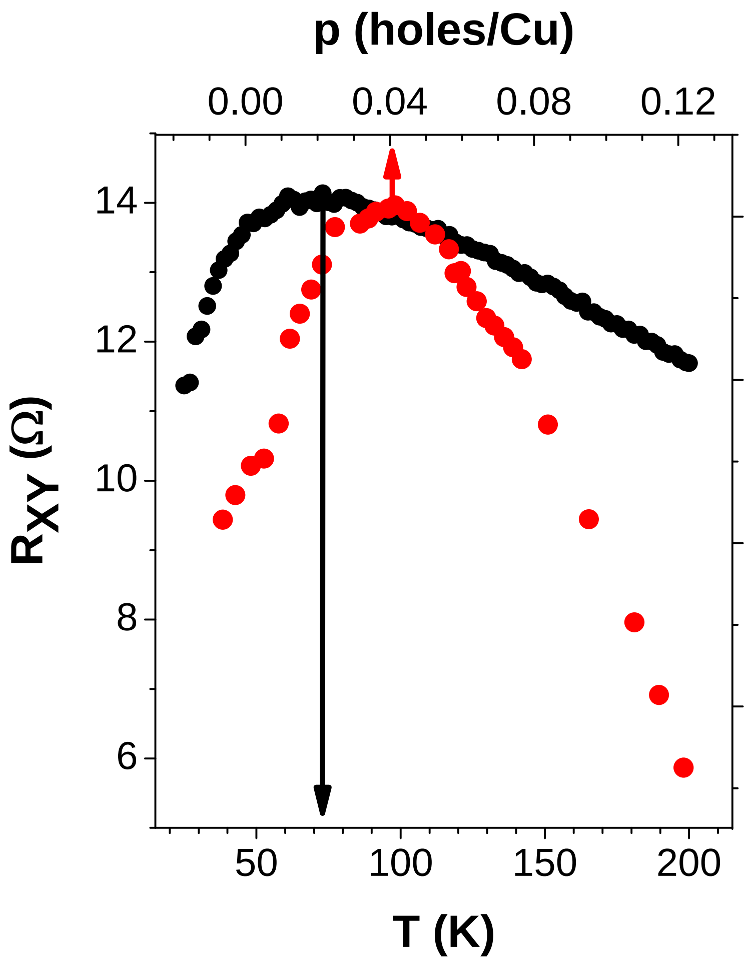
Hall resistance

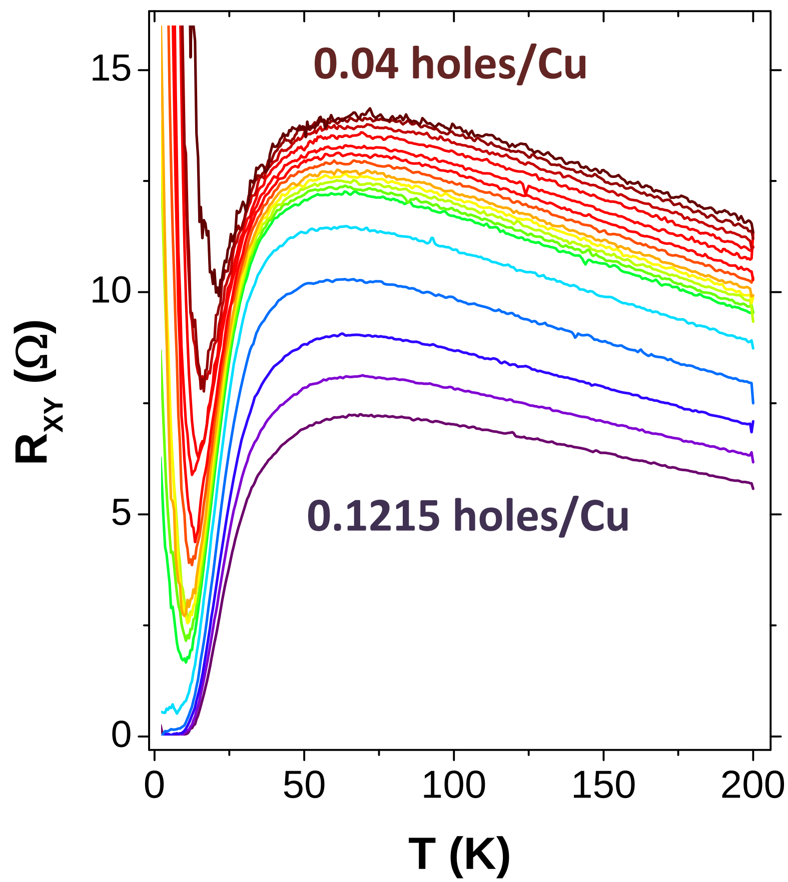




Superconductor Insulator Transition

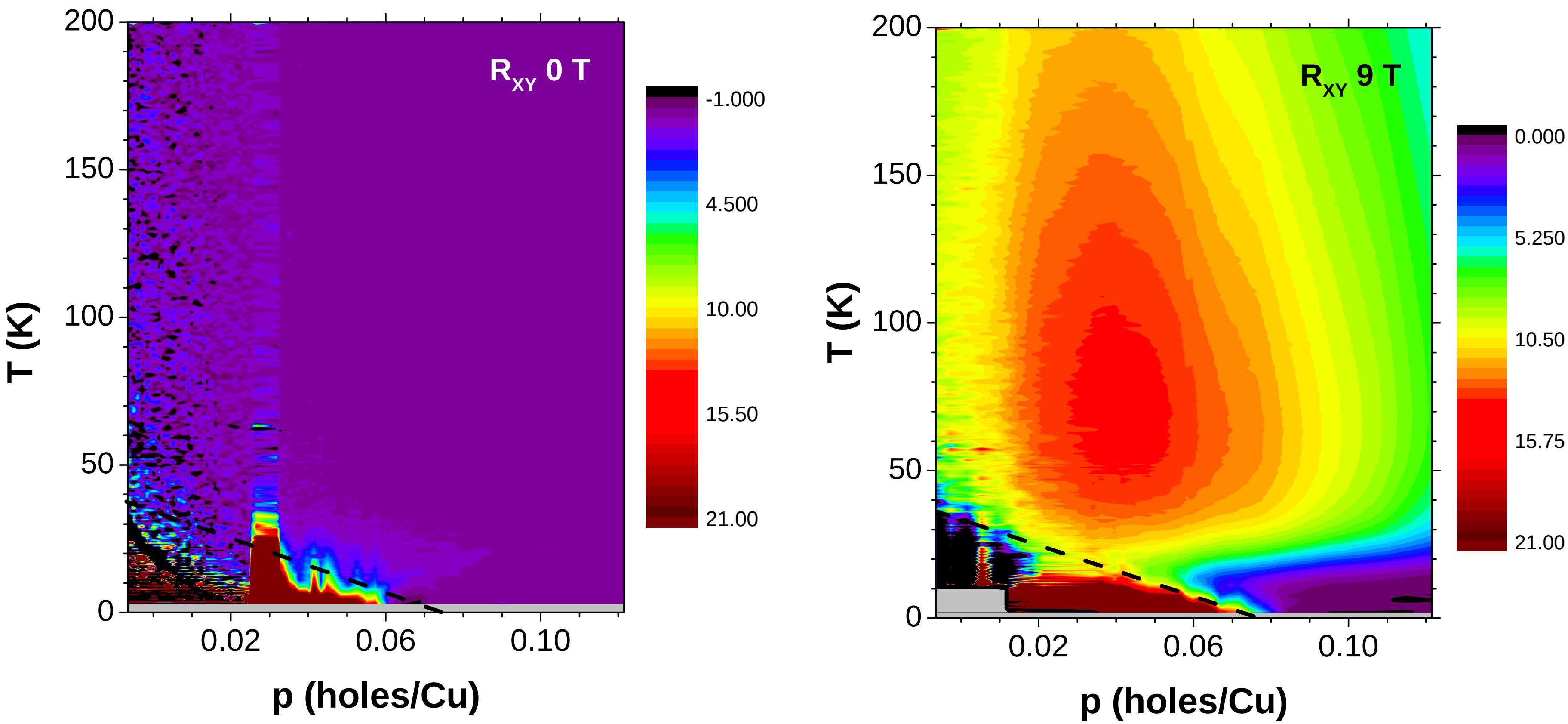
Hall resistance





Superconductor Insulator Transition

Hall resistance



Superconductor Insulator Transition

Hall resistance

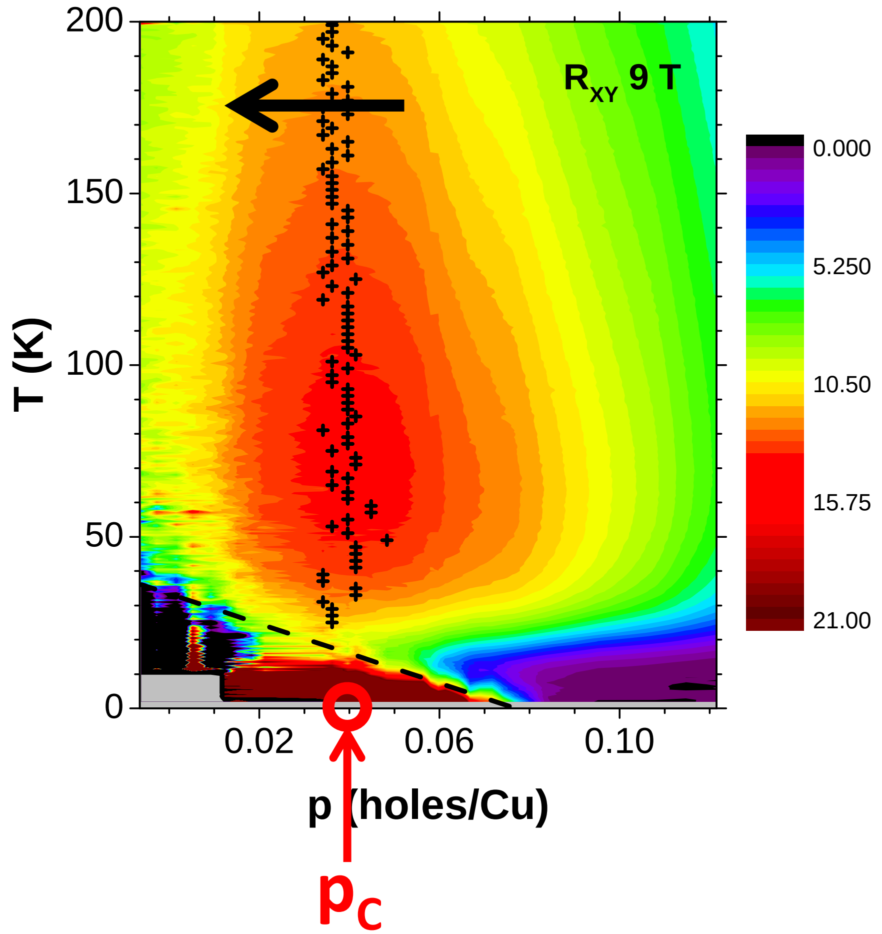
The presence of a maximum in the R_{XY} could be revealing an electronic phase transition

(XL, JGB et al. PRL 2012; Balakirev et al. Nature 2003; LeBoeuf et al. PRB 2011)

Rs measured with 0 T and 9 T are the same in the temperature range where the maximum has been found

Is the QPT at zero temperature promoted by the high temperature changes in R_{XY}??

ROLE OF ELECTRONIC INTERACTIONS IN THE SIT



Superconductor Insulator Transition

Hall resistance

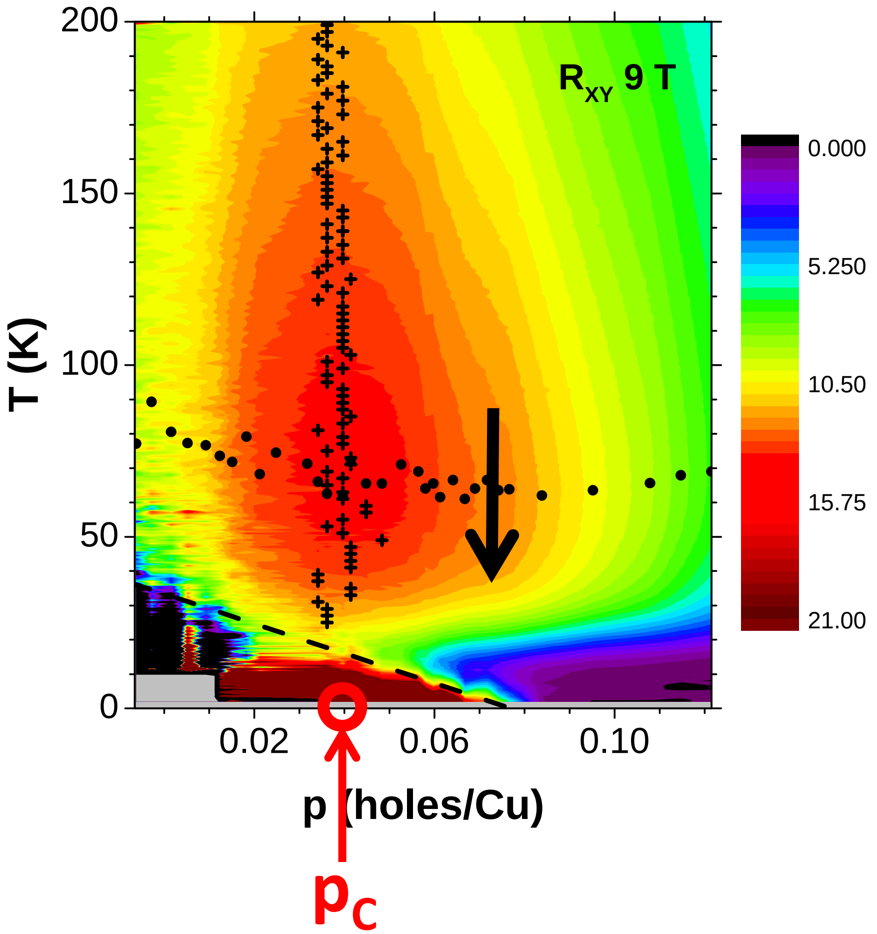
The presence of a maximum in the R_{XY} could be revealing an electronic phase transition

Rs measured with 0 T and 9 T are the same in the temperature range where the maximum has been found

Is the QPT at zero temperature promoted by the high temperature changes in R_{XY}??

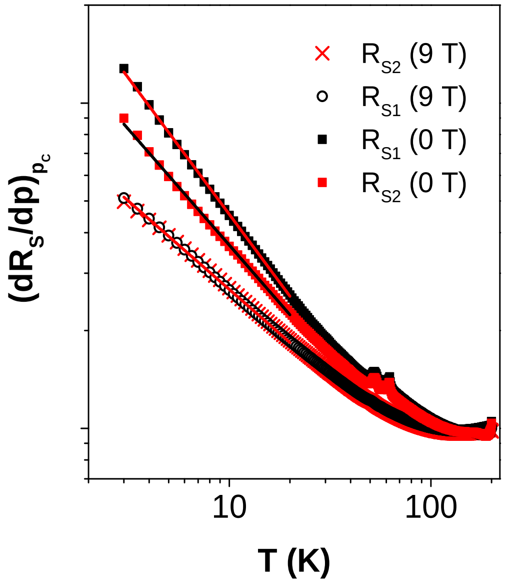
ROLE OF ELECTRONIC INTERACTIONS IN THE SIT

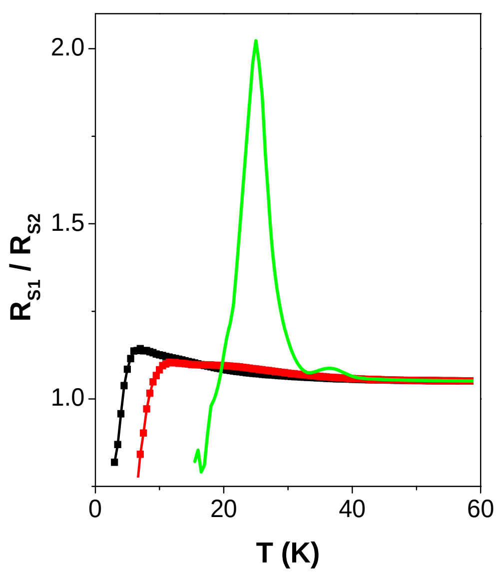
IS THERE ANOTHER TRANSITION IN T?

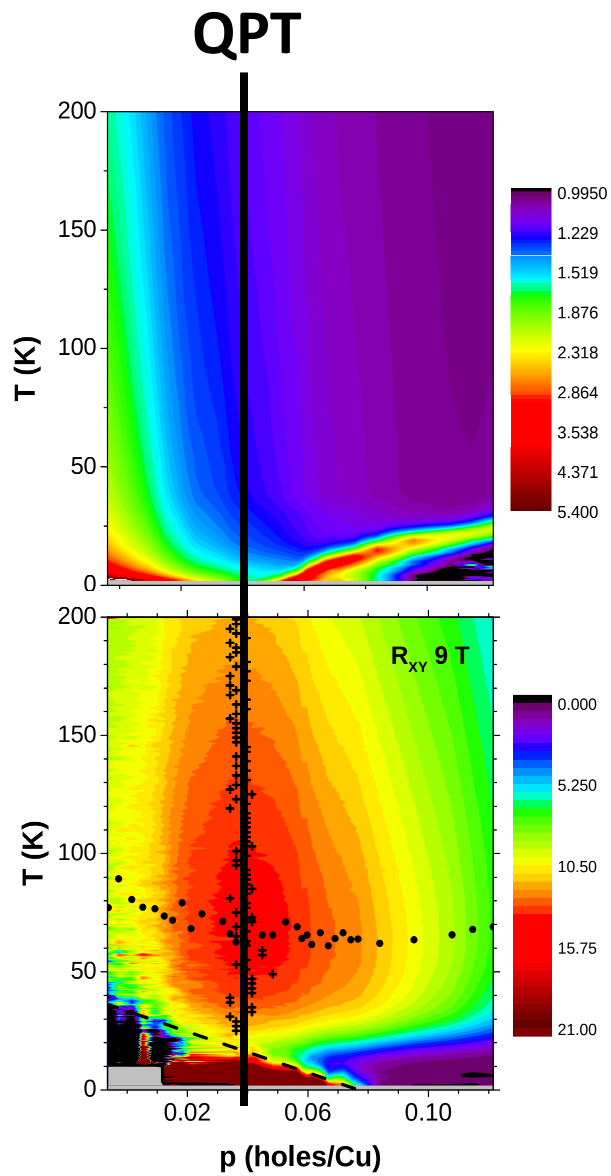


Outline

1. Introduction
2. Epitaxial Growth and Structural Characterization
   – Molecular Beam Epitaxy
   – X-Ray, AFM and STEM experiments
3. Transport and Magneto-Transport Experiment
   – EDLT
   – Results
     • Superconductor Insulator Transition
4. **Conclusions**







QPT separating insulating and superconducting regimes:

Anisotropic?? in 0 T

Isotropic in 9 T

Insulating regime is anisotropic and $\neq$ *f(H)*

Superconducting regime = *f(H)*

Anisotropy is minimized at the SIT

The SIT is promoted at higher temperatures by a change in the electronic ground state that is revealed by Rxy