Superconductor-Insulator Transitions in Highly Underdoped Cuprates

Dragana Popović

National High Magnetic Field Laboratory
Florida State University, Tallahassee, FL, USA

Support: **NSF grants (DMR-0905843, DMR-1307075 and previous)**
NHMFL (NSF and the State of Florida)

Collaborators:

Experiments at NHMFL/FSU, USA:

Xiaoyan Shi (now at Sandia National Labs, USA → U. Texas at Dallas, USA)
Ivana Raičević (now at FPM Group, USA)
Zhenzhong Shi
Ping V. Lin
Jan Jaroszyński
Paul Baity

Single crystals: **T. Sasagawa,** Tokyo Institute of Technology, Japan

Films (MBE):
- **G. Logvenov,** Brookhaven National Lab., USA (now at MPI Stuttgart, Germany)
- **A. Bollinger,** Brookhaven National Lab., USA
- **I. Božović,** Brookhaven National Lab., USA

C. Panagopoulos, Univ. of Crete and FORTH, Greece; Nanyang Tech. Univ., Singapore

Theory: **V. Dobrosavljević,** Florida State University, USA

L. Benfatto, Sapienza University of Rome, Italy

Questions

1. <u>Strongly correlated 2D systems</u>:

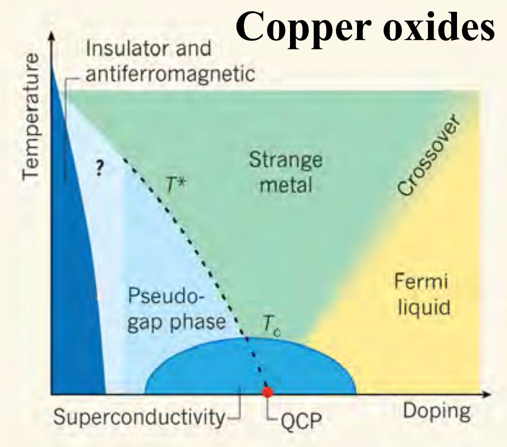
   Nature of the **insulating ground state**?

   Quantum phase transition from an insulator to a superconductor with doping?

2. <u>Cuprates</u>:

   Emergence of high-T_c superconductivity from a doped Mott insulator?

   - Quantum criticality
   - Role of disorder
   - Competing orders
   - Vortex matter physics
   - …

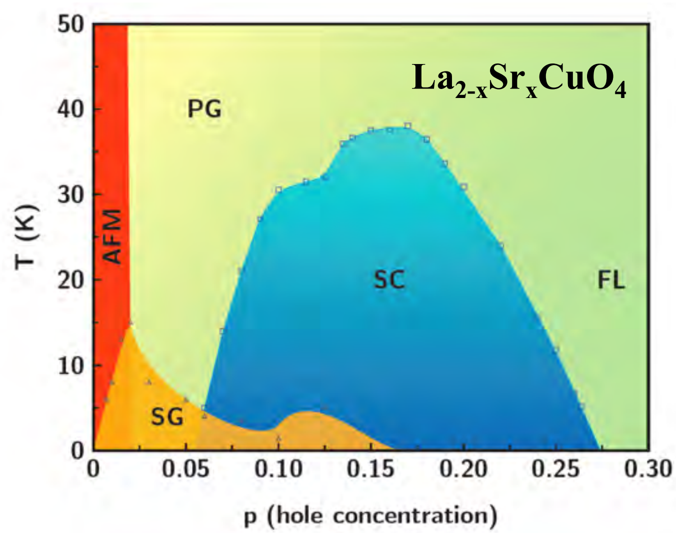


[from C. Varma, Nature 468, 184 (2010)]

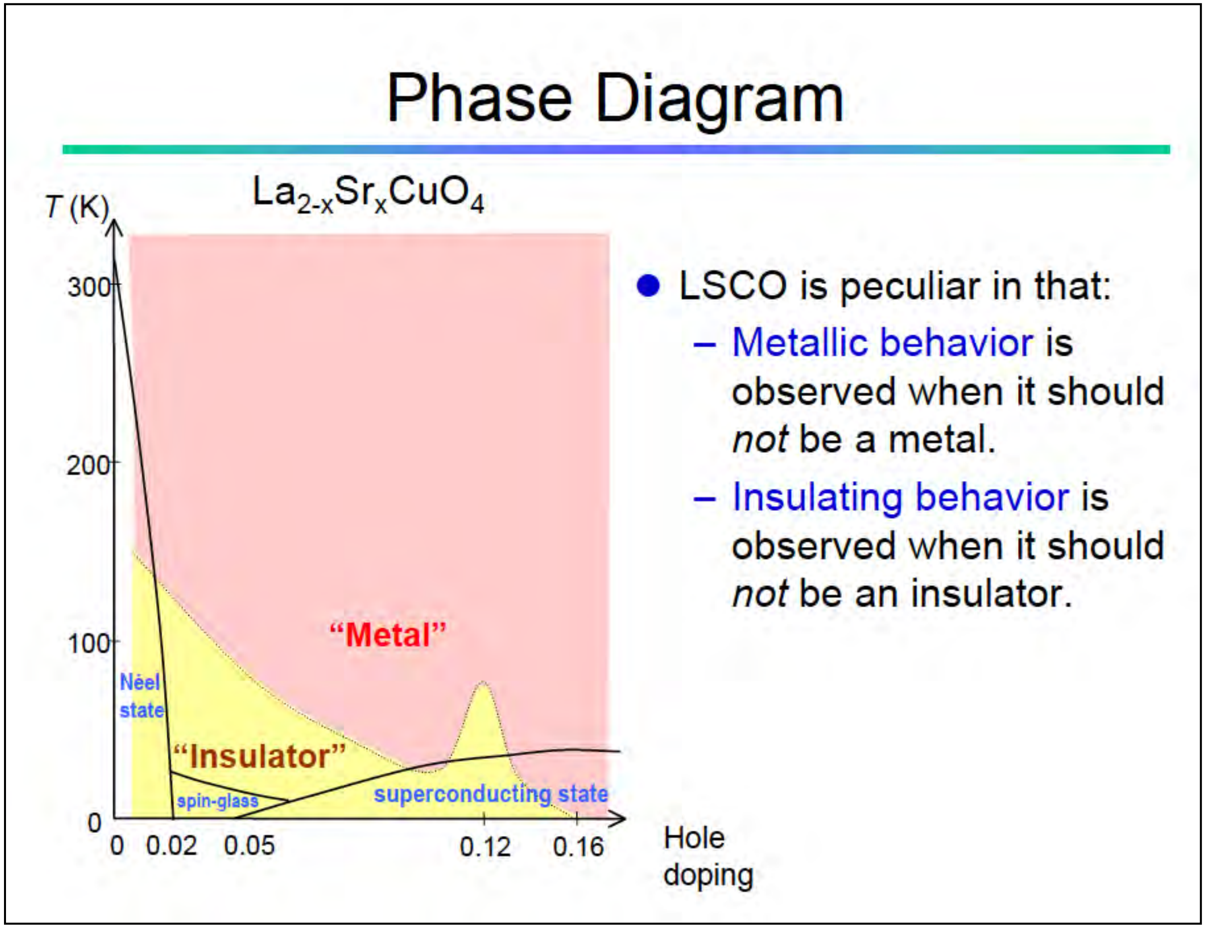
Outline

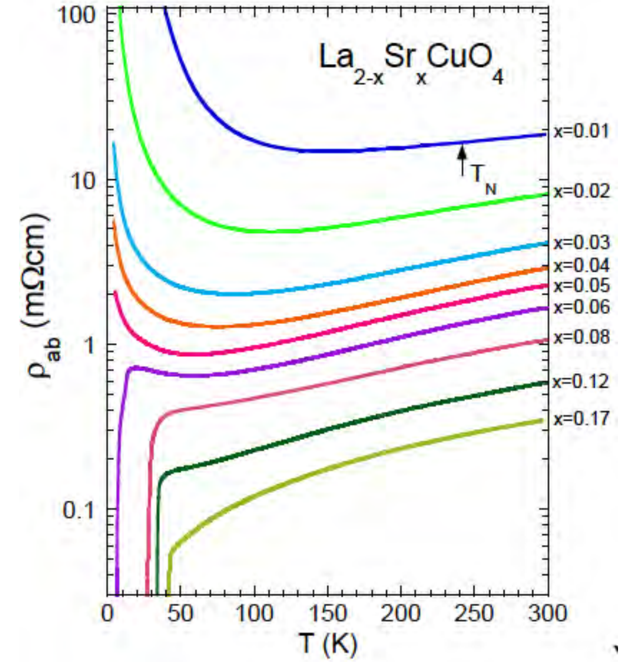
Our experiments on La-based cuprates probe charge order:

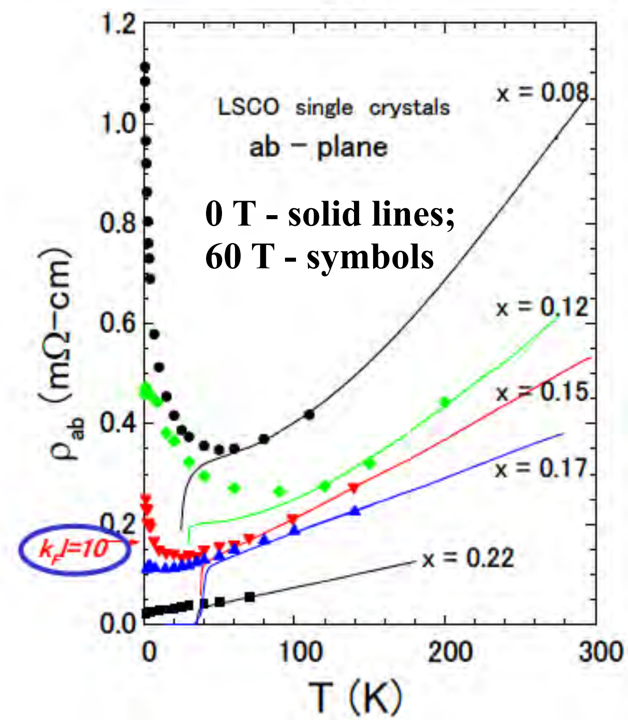
- Nature of the insulating ground state at low doping:
  charge cluster glass
- Doping-driven transition from insulator to superconductor:
  coexistence and competition between different orders
- Magnetic-field-driven superconductor-insulator transition (SIT):
  the interplay of quantum criticality and vortex matter physics
- Dynamics near thermally-driven superconducting transition:
  dynamical heterogeneities



Y. Ando, May 2005 talk in Dresden:



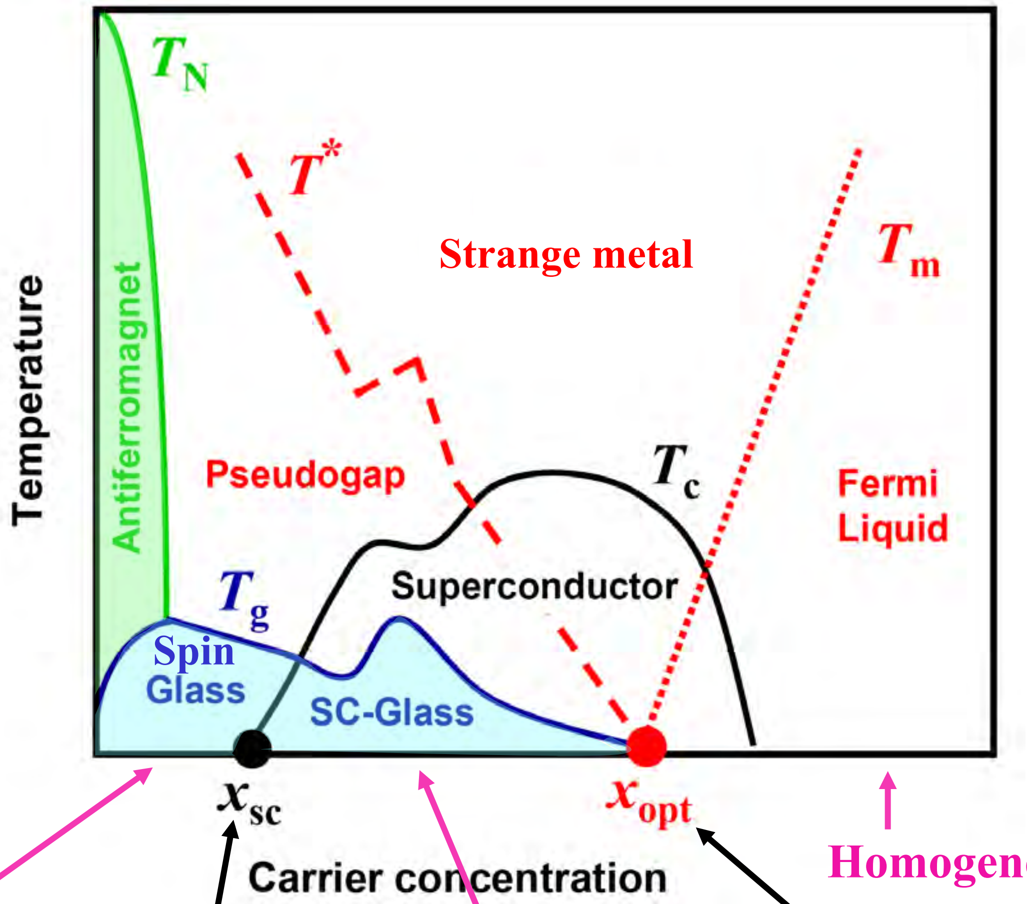




Y.A.: Electron self-organization?

Top right: Ando *et al.*, PRL 87, 017001 (2001);
Bottom right: Boebinger *et al.*, PRL 77, 5417 (1996).

Nature of the ground states and evolution with doping?



[C. Panagopoulos and V. Dobrosavljević, PRB 72, 014536 (2005) and references therein]

Homogeneous metal

Charge glass insulator (insulating cluster or stripe glass)

Superconductor-insulator transition

Inhomogeneous, conducting glassy state – bad metal?

Quantum glass transition?

Lightly doped $La_{2-x}Sr_xCuO_4$: Experimental protocols

A. Resistance noise spectroscopy: Fluctuations

- **PDFs, power spectrum, second spectrum**

[Raičević *et al.*, Proc. SPIE 6600, 660020 (2007); Phys. Rev. Lett. 101, 177004 (2008); Phys. Rev. B 83, 195133 (2011)]

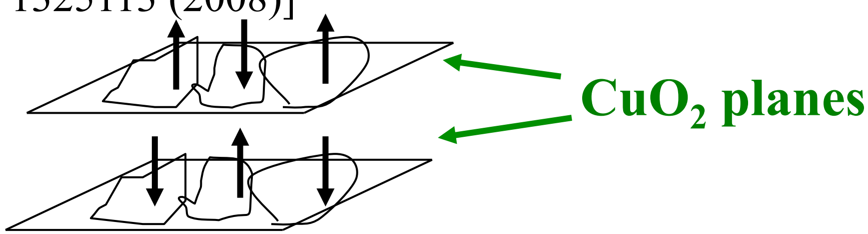
B. History-dependent transport

1) **Zero-field cooled vs. field-cooled resistance**
2) **Hysteretic magnetoresistance**

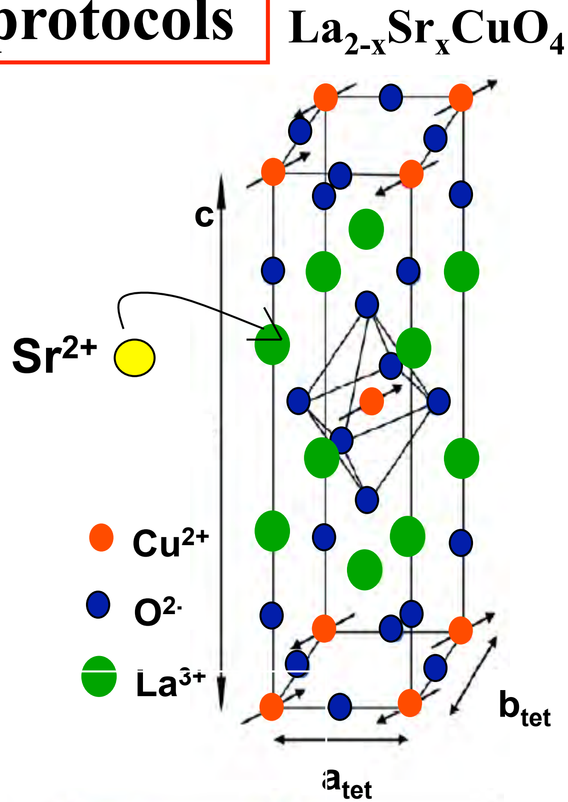
[Raičević *et al.*, Phys. Rev. B 81, 235104 (2010); J. Supercond. Nov. Magn. 25, 1239 (2012); Shi *et al.*, Physica B 86, 155135 (2012); Nature Mater. 12, 47 (2013)]

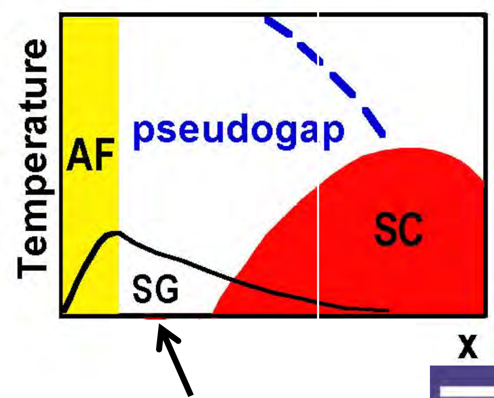
C. Dielectric measurements

[Park *et al.*, Phys. Rev. Lett. 94, 017002 (2005); Jelbert *et al.*, Phys. Rev. B 78, 1325113 (2008)]



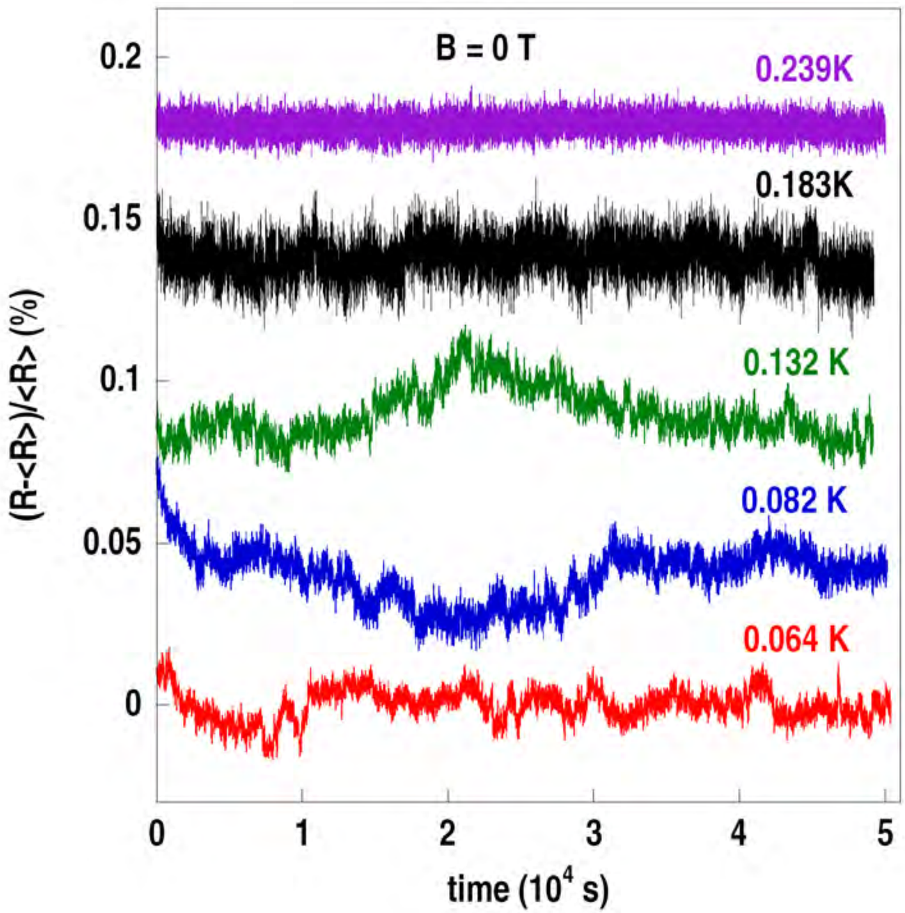
Short-range AF order: in-plane AF domains; holes in domain walls

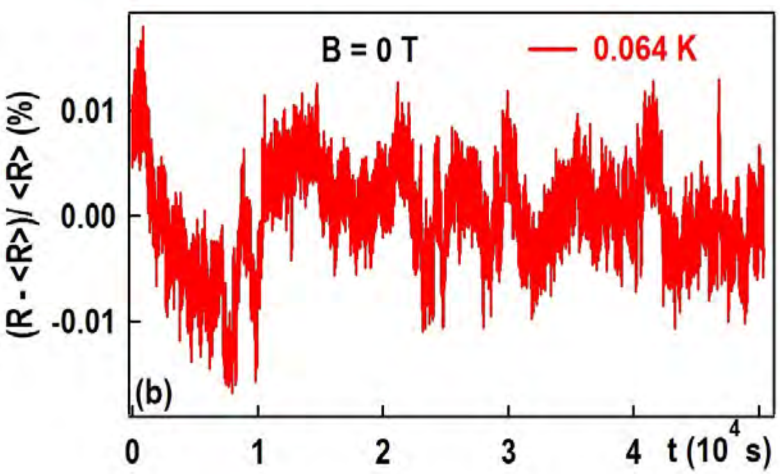




In-plane resistance fluctuations (noise)

- Single crystal $La_{2-x}Sr_xCuO_4$, x=0.03; T_{SG}= 7-8 K
- Variable-range hopping transport at low T





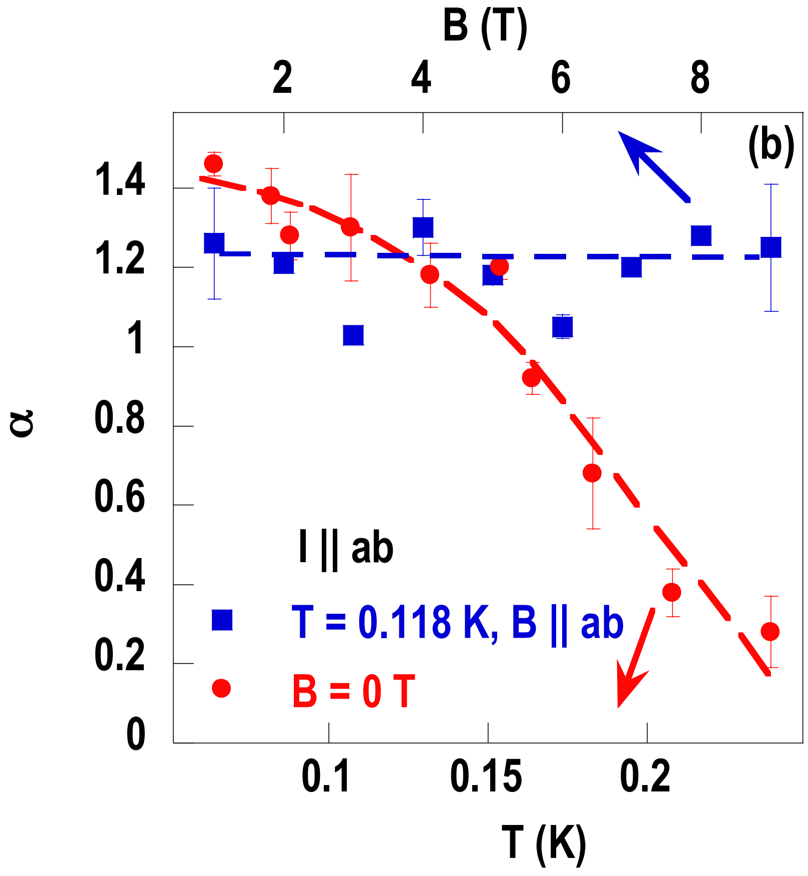
- noise: Gaussian at “high” T
- at low T (<0.2 K), non-Gaussian noise
  metastable states *(out-of-equilibrium)*

Noise statistics

- **Very low T**: **magnetic background frozen**
- **Power spectrum**: $S_R \sim 1/f^{\alpha}$

Slowing down of the dynamics as $T \rightarrow 0$

- **Increasing non-Gaussianity of the noise as $T \rightarrow 0$**



Second spectrum (S_2) – "noise of the noise"

(Voss&Clarke, Restle&Weissman, Seidler&Solin)

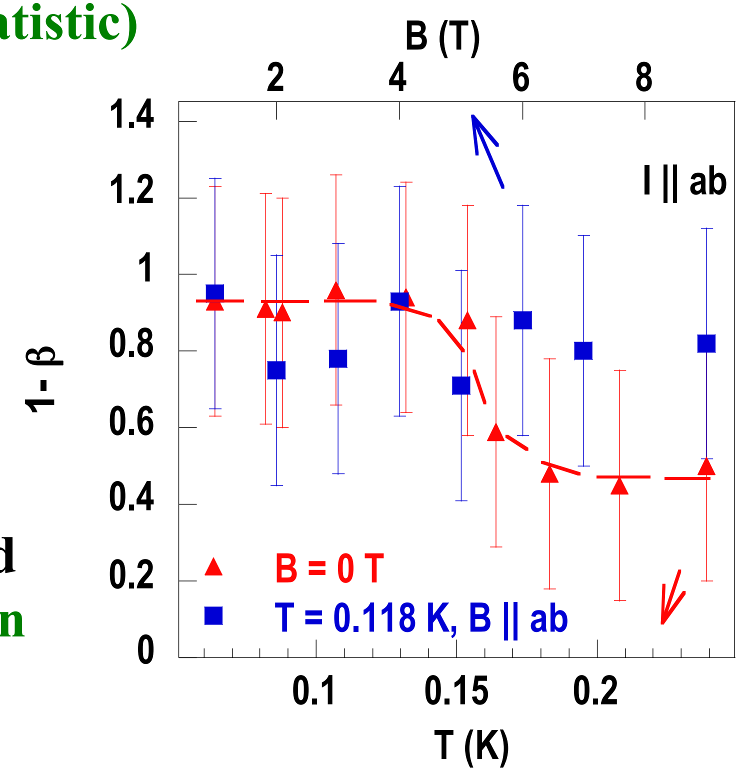
- $S_2(f_2,f)$: power spectrum of the fluctuations of $S_R(f)$ with time (Fourier transform of the autocorrelation function of the time series of $S_R(f)$; fourth-order noise statistic)

$$S_2 \propto 1/f_2^{\ 1-\beta}$$

$1-\beta = 0$ ⟹ Gaussian (uncorrelated)

$1-\beta > 0$ ⟹ non-Gaussian (correlated)

Increase of correlations as $T \rightarrow 0$



- Noise statistics independent of both B and magnetic history (unlike conventional spin glasses, but like a spin-polarized 2DES)

  ⟹ charge, not spin!

$\Rightarrow$ **Charge glass transition $T_{cg}=0$**

Scaling of the second spectra

Measure of correlations

- **can distinguish between different models (Weissman):**

- interacting droplet model

- hierarchical, tree-like model

S_2 decreases with f for a fixed f_2/f,

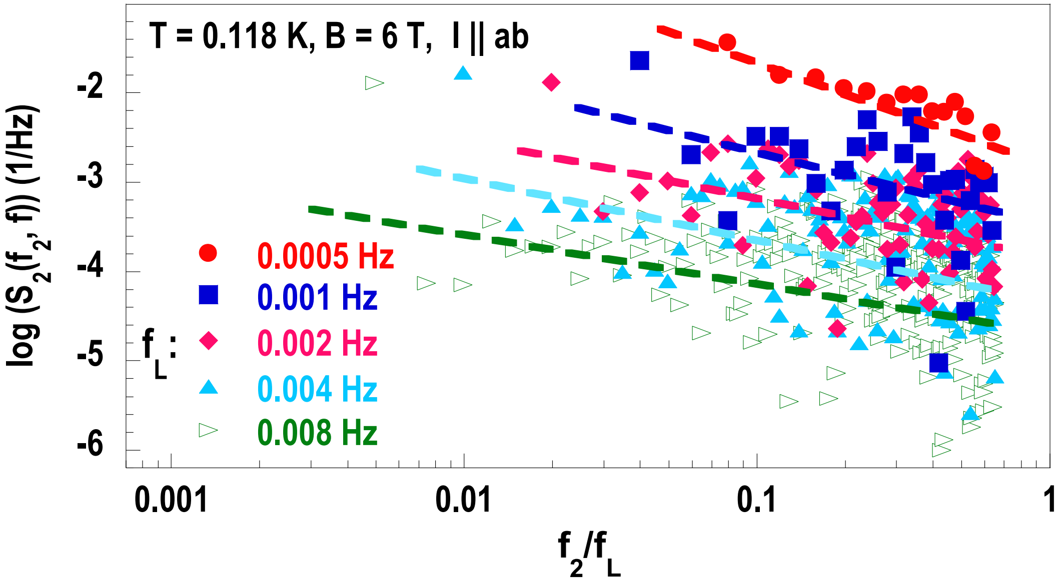
consistent with droplet picture

(short-range interactions)

Competing interactions on different length scales

Charge cluster glass

$La_{2-x}Sr_xCuO_4$, x=0.03

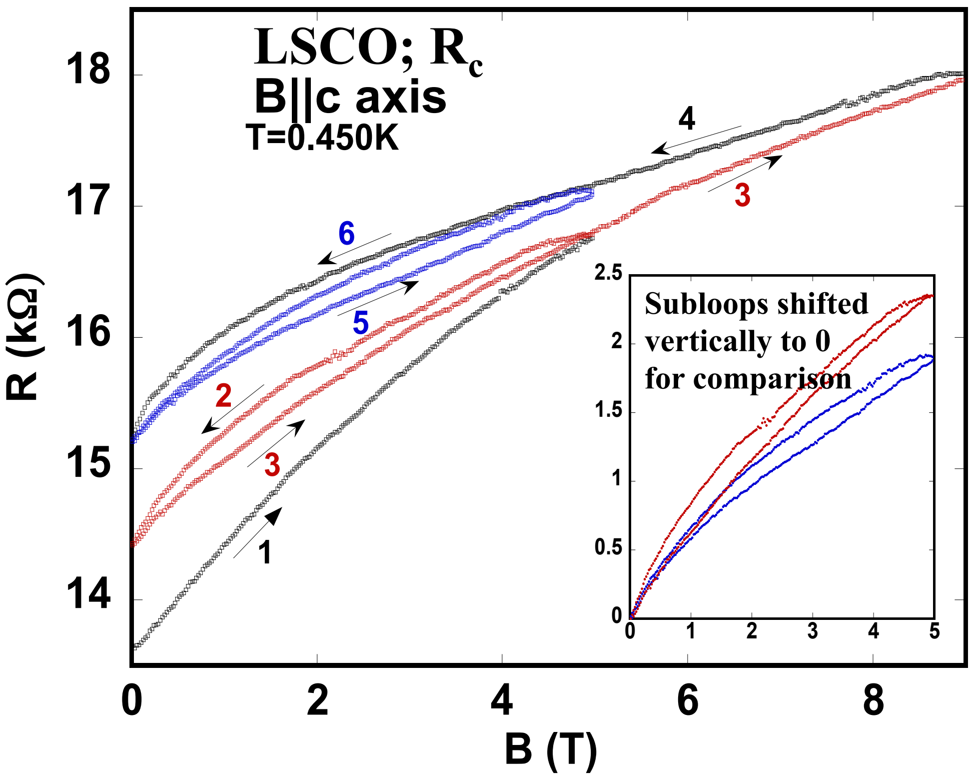


(Schmalian and Wolynes, PRL 85, 836 (2000): **"stripe" glass** in a model with **competing interactions** on different length scales, **NO disorder**)

Different from metallic spin glasses and a 2D Coulomb glass – systems with long-range interactions: hierarchical!

History dependence in transport in non-SC samples: $T_{onset} << T_{sg}$

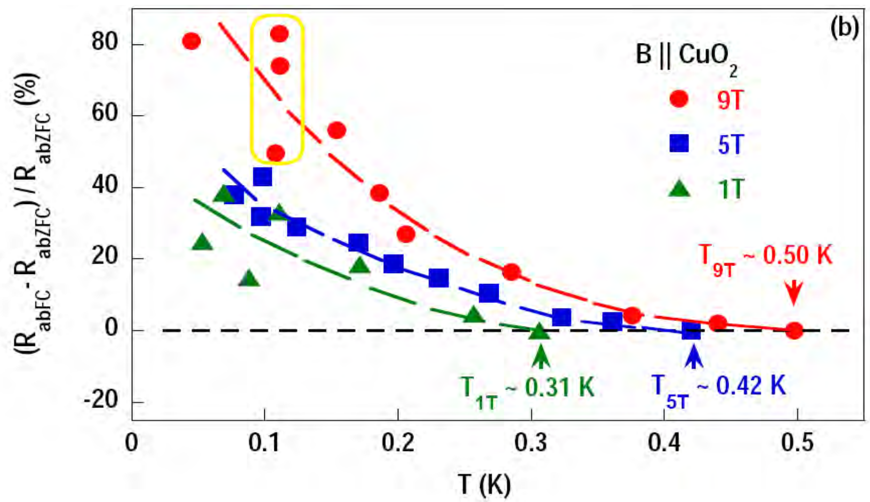
Hysteretic behavior of the low-T positive MR



Memory in R erased for T ≥ 1K, T_{SG} ≈ 7K: holes do not merely “follow” the spins

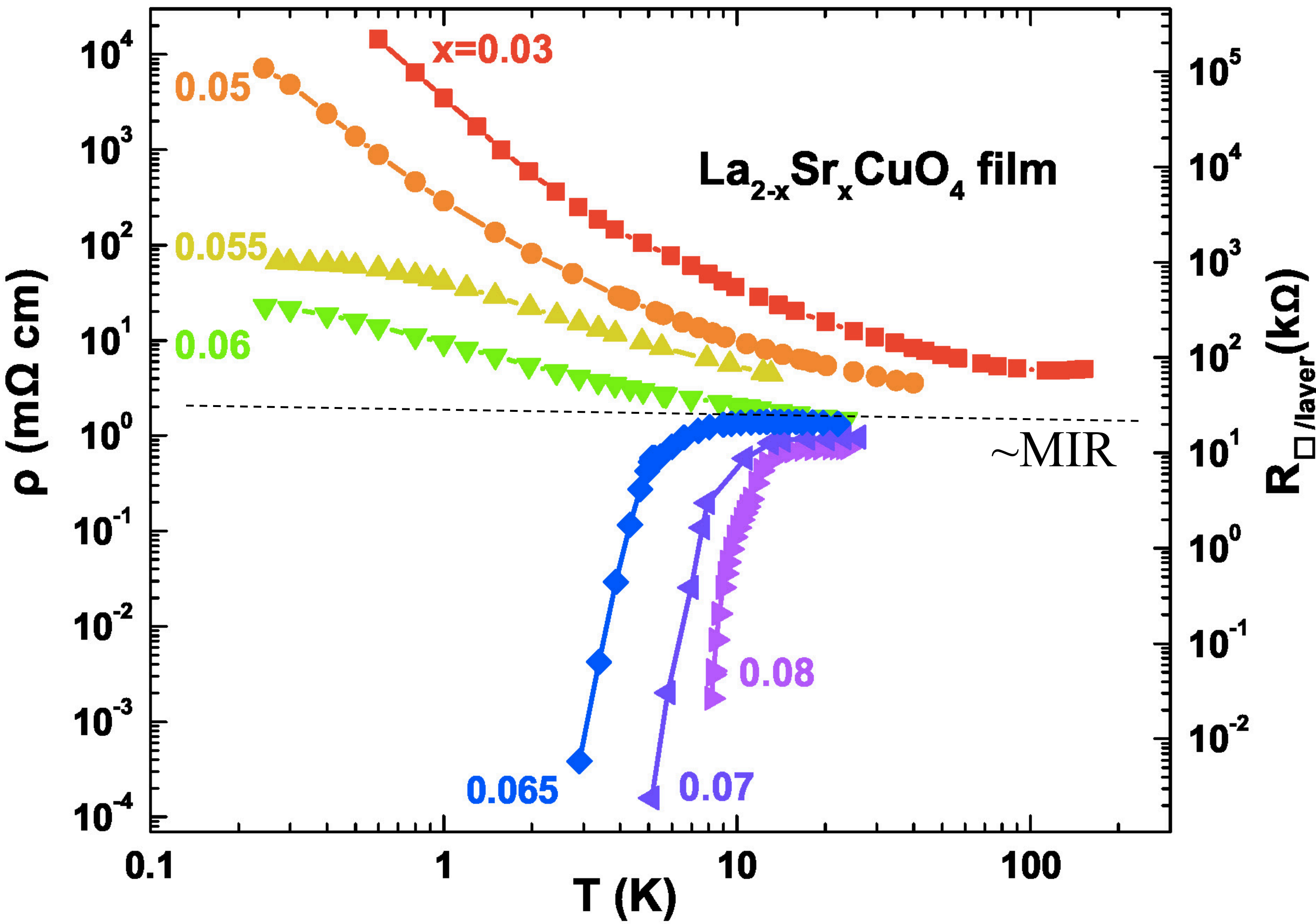
(R_c, R_{ab}; B||c and B||ab)

Difference between field-cooled and zero-field cooled resistance R(B=0)



Use these effects as “easy tools” for detecting charge glassiness as a function of doping.

Temperature dependence of the in-plane resistivity



x	T_c (K) (midpoint)
0.065	6±1
0.07	9±1
0.08	12±1

$R_{\square} = \rho / d$,

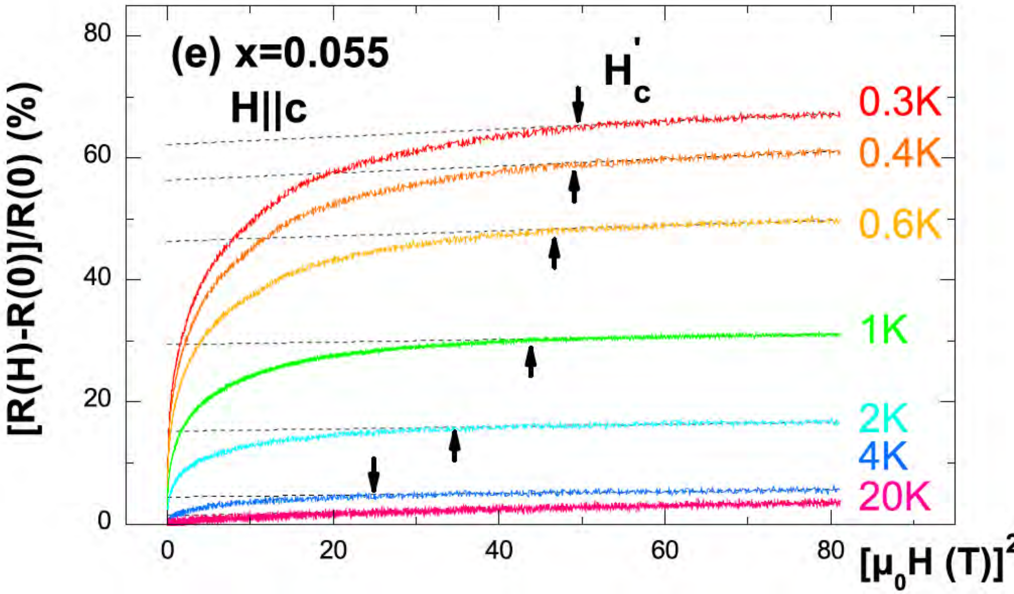
$R_{\square/\mathrm{layer}} = \rho / l$,

d – sample thickness (~100 nm);
d = n*l* ; n - # of layers;
***l* = 6.6 Å – thickness of one layer**

x=0.03 and x=0.05: 2D variable-range hopping
x=0.055 and x=0.06: non-SC; ρ(T) cannot be fitted to any simple form
x≥0.065: SC

High-field magnetoresistance and superconducting fluctuations

Non-SC sample



Normal-state resistivity (dashed lines) at low fields:

$$\rho_n(H) = \rho_n(H\!=\!0) + \alpha H^2$$

(Max $\omega_c\tau \approx 0.01$ at ~10 T)

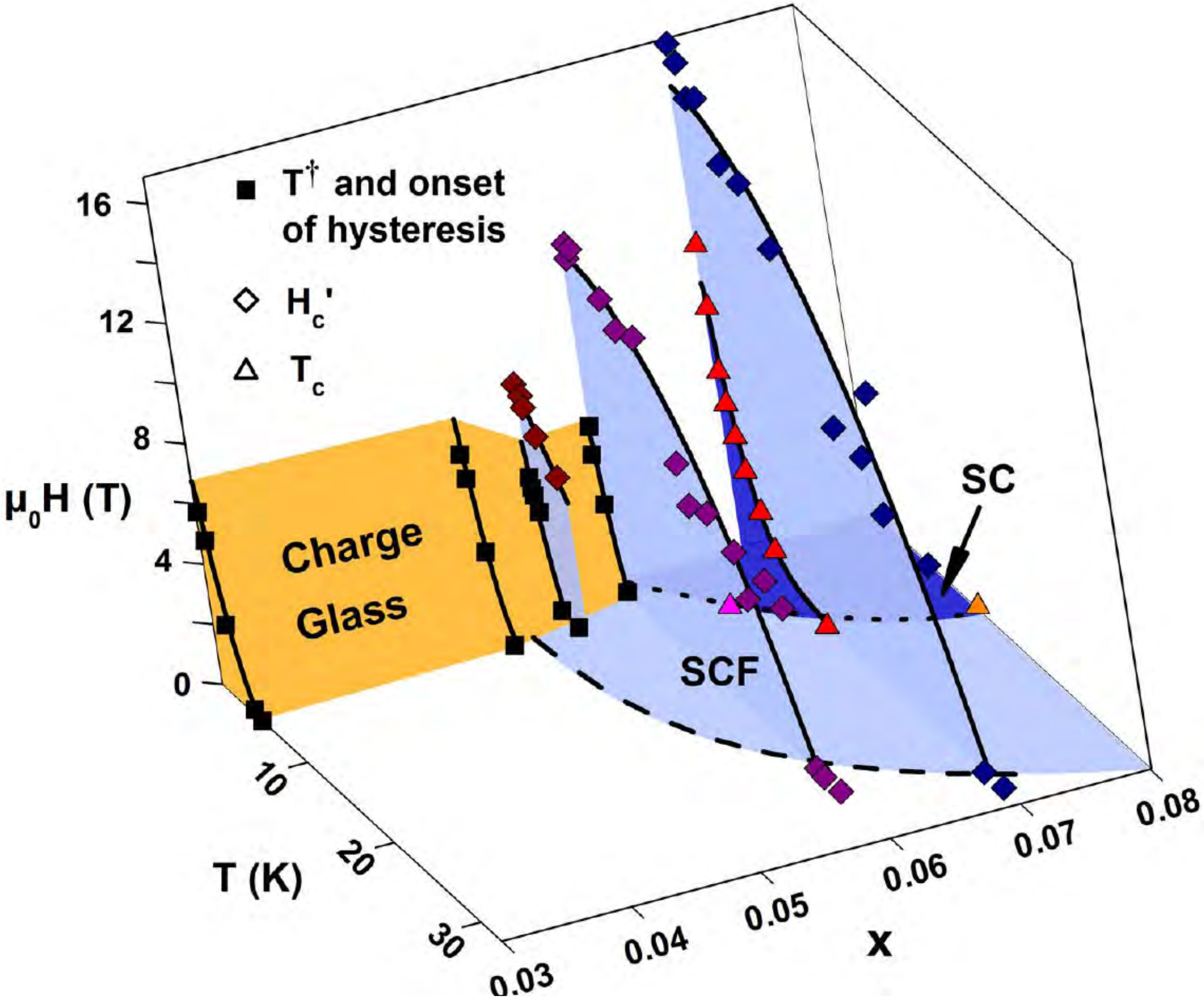
$H_c'(T)$ – field above which SCFs are suppressed and normal state is restored

Contribution to conductivity from SCFs:

$$\Delta\sigma_{SCF}(T,H) = \rho^{-1}(T,H) - \rho_n^{-1}(T,H)$$

<u>LSCO</u>: Harris *et al.*, PRL 75, 1391 (1995), Rourke *et al.*, Nature Phys. 7, 455 (2011); Shi *et al.*, Nature Mater. 12, 47 (2013); Shi *et al.*, Nature Phys. 10, 437 (2014)
<u>YBCO</u>: Rullier-Albenque *et al.*, PRL 99, 027003 (2007); PRB 84, 014522 (2011)

Doping-driven superconductor-insulator transition in $La_{2-x}Sr_xCuO_4$



- Charge glass in the insulating regime at low doping

- Suppression of charge glassiness with doping

- Coexistence and competition of charge glass with superconducting fluctuations (SCFs) on the insulating side of the superconductor-insulator transition (SIT)

Onset of SIT influenced by charge glass order

[X. Shi *et al.*, Nature Mater. 12, 47 (2013)]

H-field-driven superconductor-insulator transition in cuprates

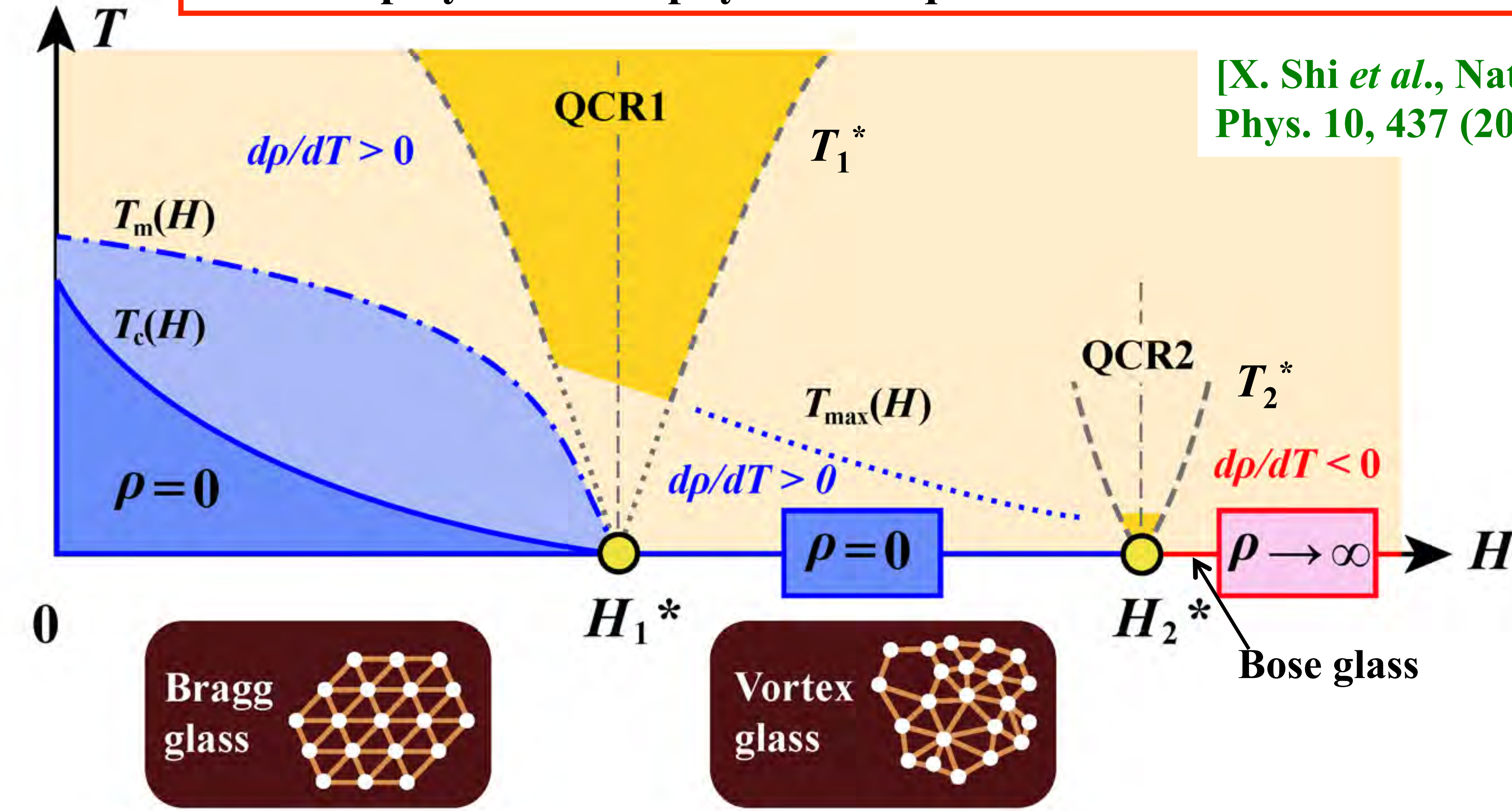
- **Questions:**
  - **Zero-temperature *H*-field-driven superconductor-insulator transition (SIT) in 2D? Quantum criticality? (scaling)**

    (See "Conductor-Insulator Quantum Phase Transitions", ed. by Dobrosavljević, Trivedi, Valles; Oxford University Press, 2012, for review and open questions)
  - **Nature of the field-induced resistive state?**
  - **Interplay of quantum criticality and vortex matter physics?**

- **Experiments:**
  - **Magnetoresistance over a wide range of *H* and *T* (down to 0.09 K)**
  - **Low-T_c (~ 4 K) $La_{2-x}Sr_xCuO_4$ samples grown using different methods**

- **Conclusions:**
  - **<u>Three</u> distinct phases as $T \rightarrow 0$; <u>two</u> quantum critical points**

Sketch of the (*T, H*) phase diagram in underdoped $La_{2-x}Sr_xCuO_4$: Interplay of vortex physics and quantum critical behavior



[X. Shi *et al*., Nature Phys. 10, 437 (2014)]

$T_1^* \sim |\delta|^{z\nu}$, $z\nu \sim 0.7$

2D SIT in the clean limit

$(R_{\square/\text{layer}} \approx 18\ \text{k}\Omega)$

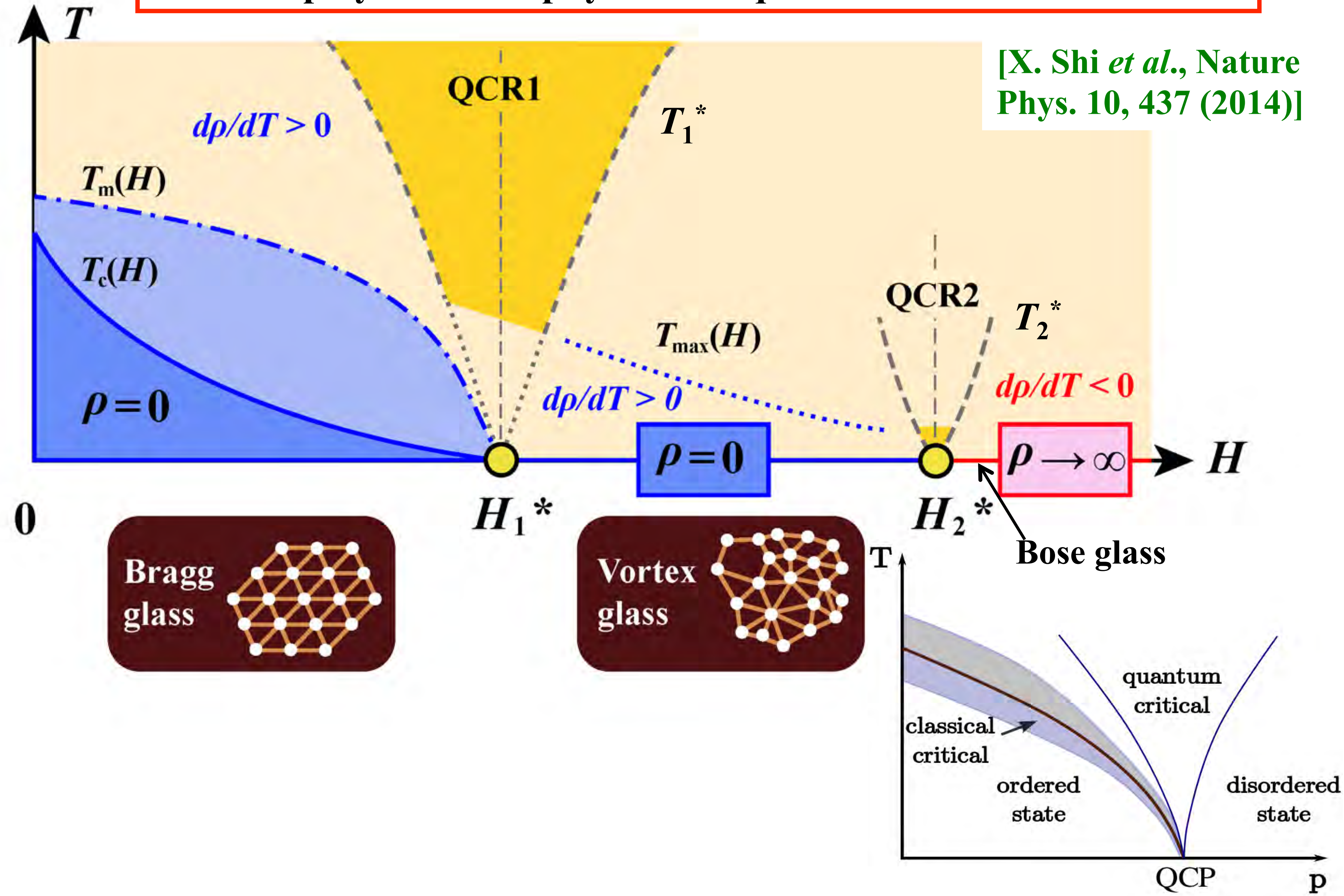
$T_2^* \sim |\delta|^{z\nu}$, $z\nu \approx 1.15$

2D SIT in the dirty limit

$(R_{\square/\text{layer}} \approx 97\ \text{k}\Omega)$

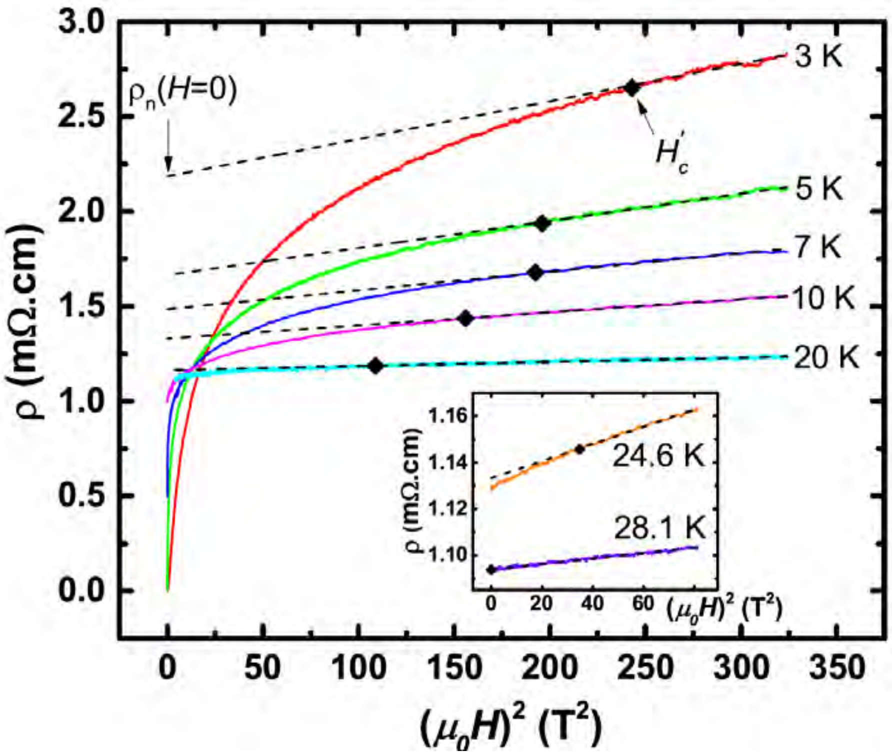
Sketch of the (*T, H*) phase diagram in underdoped $La_{2-x}Sr_xCuO_4$: Interplay of vortex physics and quantum critical behavior

[X. Shi *et al.*, Nature Phys. 10, 437 (2014)]



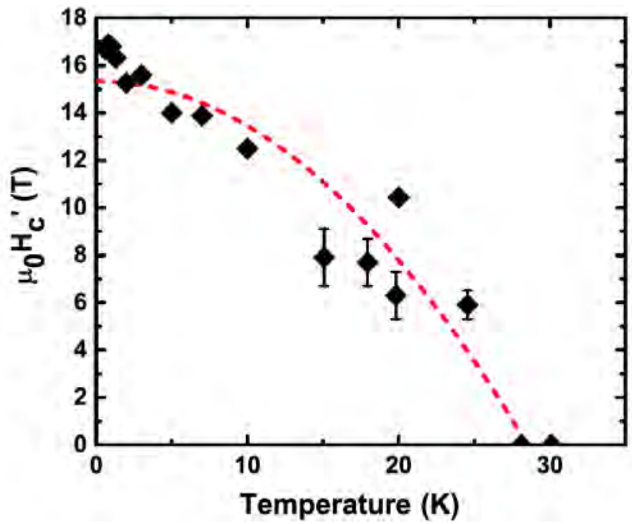
H=0 thermally-driven superconducting transition in a highly underdoped $La_{2-x}Sr_xCuO_4$

Extent of SCFs from MR:

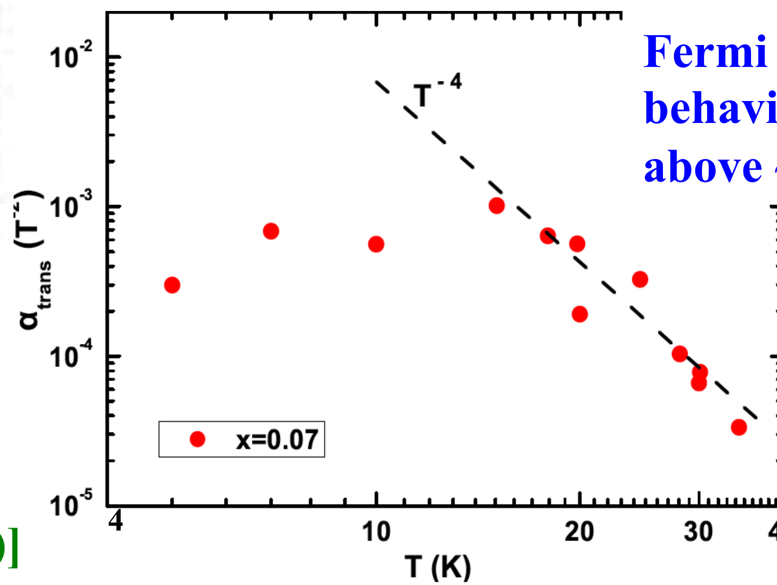


$$[\rho_n(H) - \rho_n(0)]/\rho_n(0) = \alpha_{trans} H^2$$

[X. Shi *et al*. (unpublished)]

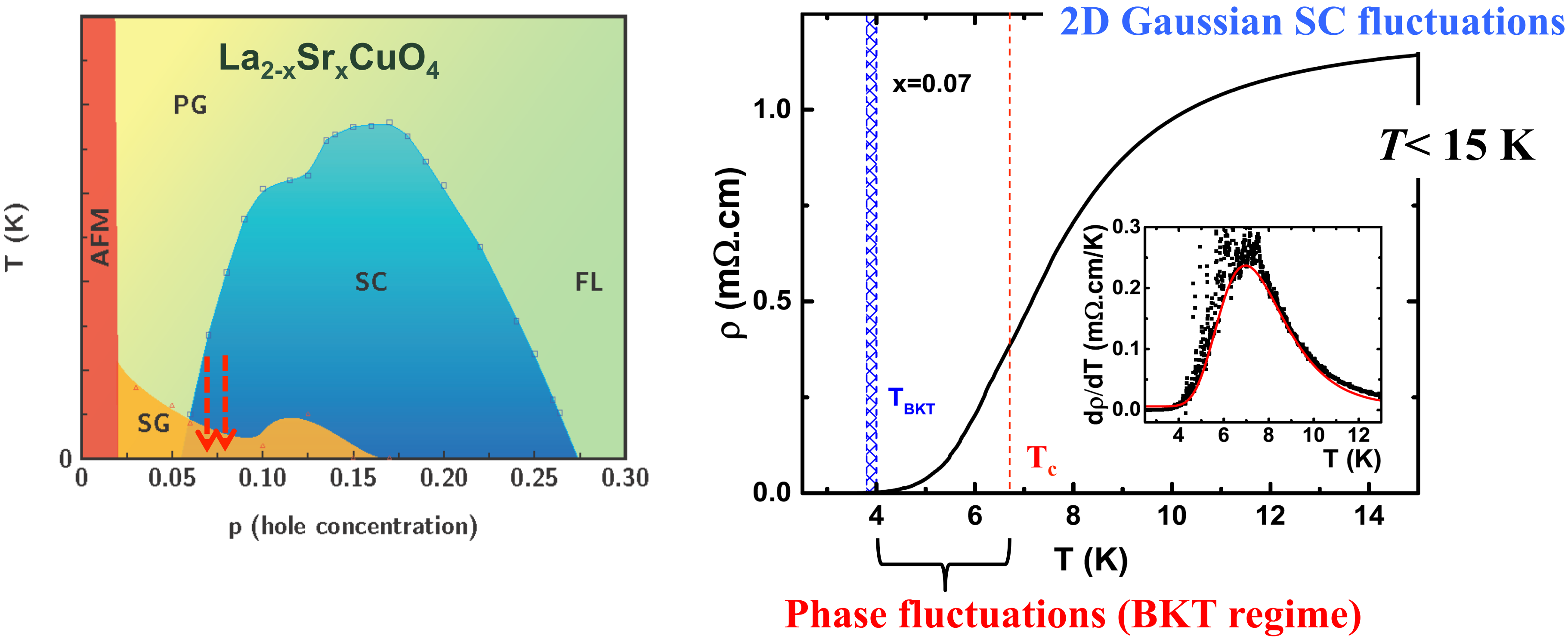


x=0.07
$T_{R=0} \approx 4$ **K**



Fermi liquid behavior above ~15 K

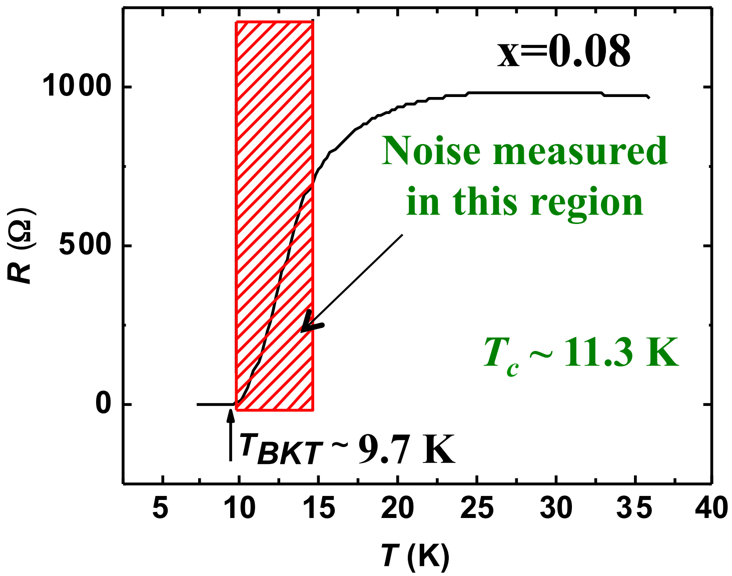
H=0 thermally-driven superconducting transition in a highly underdoped $La_{2-x}Sr_xCuO_4$

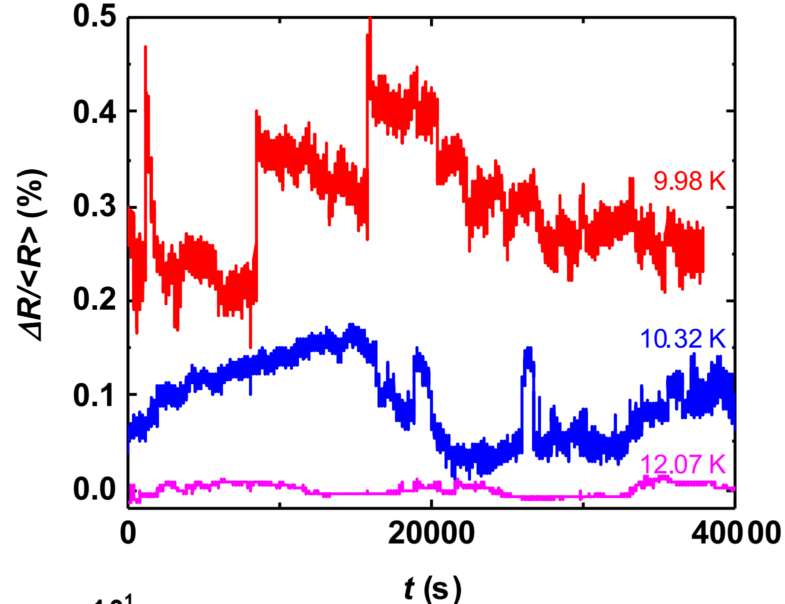


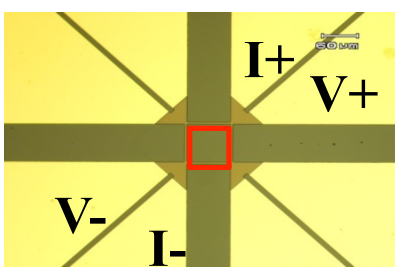
- Signatures of the 2D, Berezinskii-Kosterlitz-Thouless (BKT) transition (thermal unbinding of vortex-antivortex pairs) in bulk samples: paraconductivity, current-voltage characteristics
- Good agreement with theory by Benfatto, Castellani, Giamarchi (PRLs, PRBs since 2007)

[P. Baity *et al*. (unpublished)]

Time-domain spectroscopy of the BKT transition in a highly underdoped $La_{2-x}Sr_xCuO_4$



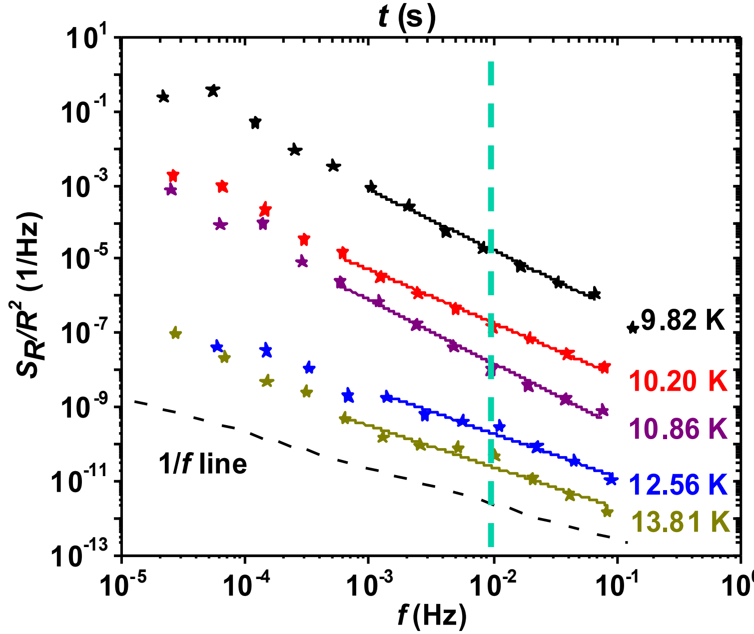




Arm size: 20 µm x 200 µm

Power spectral density:

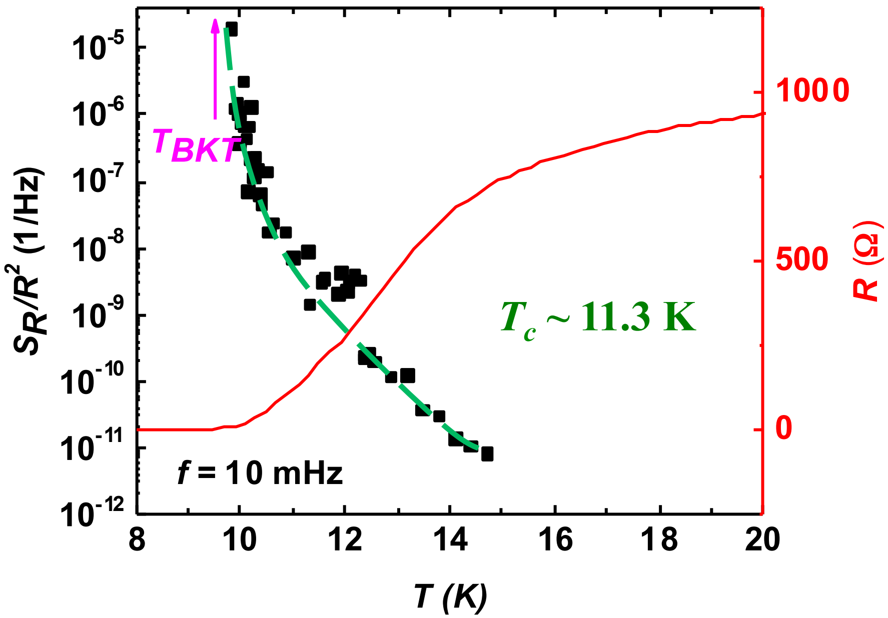
$$\frac{S_R}{R^2} \propto 1/f^{\alpha}$$

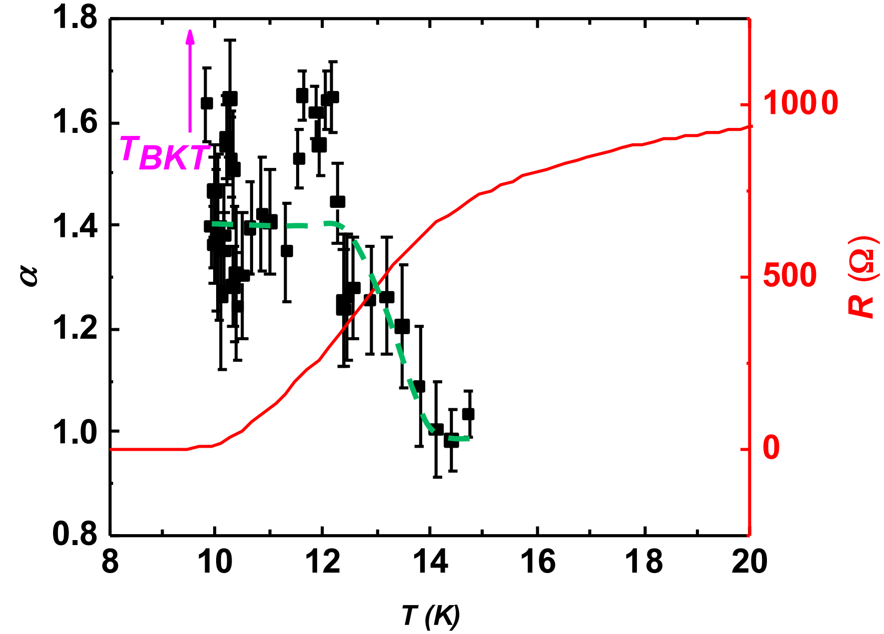


Power spectrum *vs.* temperature

$$\frac{S_R}{R^2} \propto 1/f^{\alpha}$$

Magnitude of the resistance noise

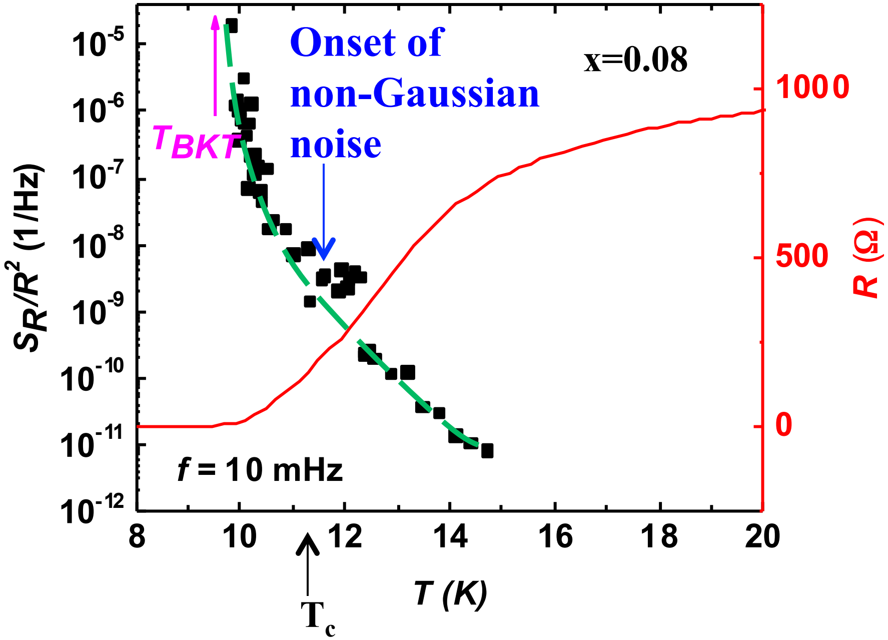




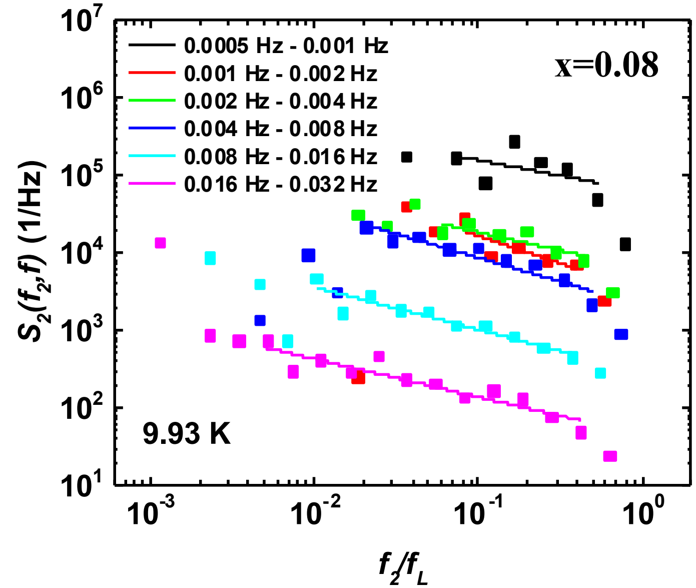
- **Normalized power spectral density increases by several orders of magnitude as $T \rightarrow T_{BKT}$**
- **Below ~14 K, α increases from ~ 1.0 and reaches ~ 1.4 at ~12 K: slowing down of the dynamics**

Time-domain spectroscopy of the BKT transition in a highly underdoped $La_{2-x}Sr_xCuO_4$

Magnitude of the resistance noise



Scaling of the second spectra



In the BKT regime ($T_{BKT} < T < T_c$):

- Exponential increase of noise as $T \to T_{BKT}$
- Slow, correlated dynamics for $T < T_c$
- Interacting domains/clusters
- Non-Gaussian noise suppressed in x=0.07 sample → not due to disorder

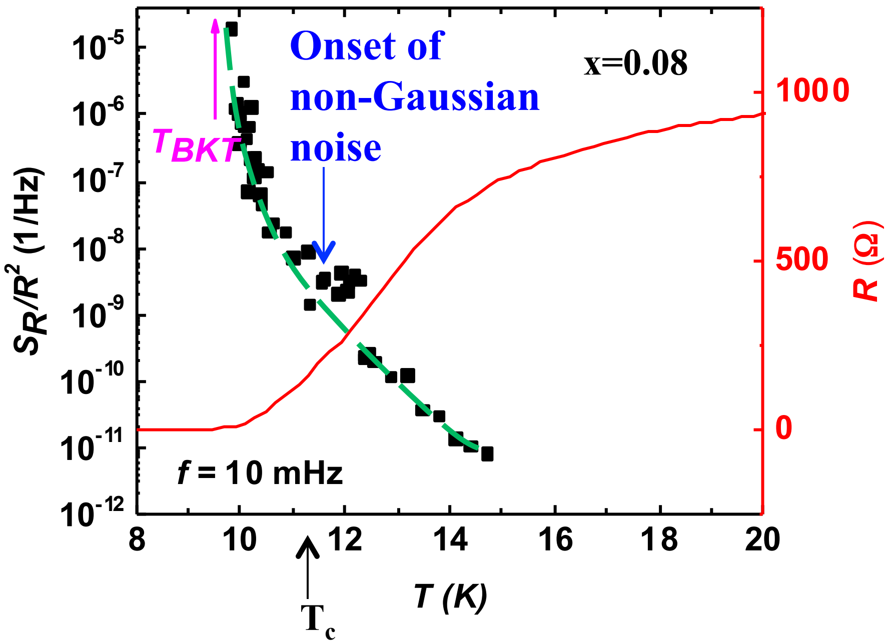
Cluster/stripe glass: competing interactions on different length scales?

Dynamic stripes?

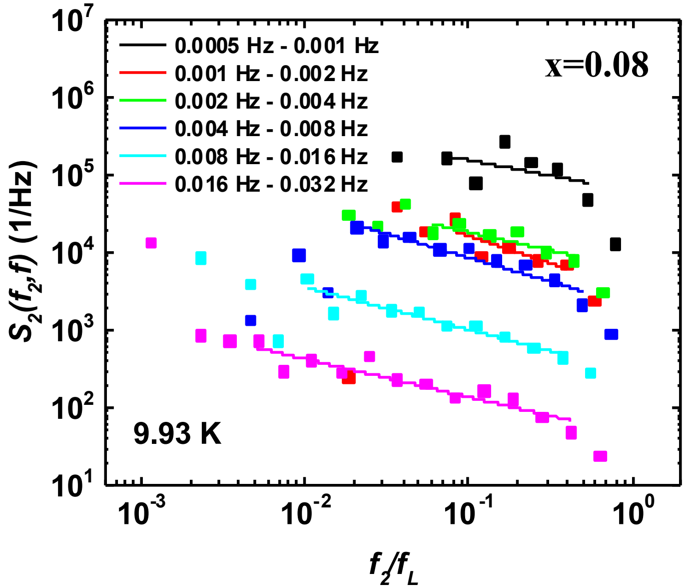
[Z. Shi *et al*. (unpublished)]

Time-domain spectroscopy of the BKT transition in a highly underdoped $La_{2-x}Sr_xCuO_4$

Magnitude of the resistance noise



Scaling of the second spectra



In the BKT regime ($T_{BKT} < T < T_c$):

- **Exponential increase of noise as $T \rightarrow T_{BKT}$**
- **Slow, correlated dynamics for $T < T_c$**
- **Interacting domains/clusters**
- **Non-Gaussian noise suppressed in x=0.07 sample → not due to disorder**

Cluster/stripe glass: competing interactions on different length scales?

Intermediate, bad metal phase?

[Z. Shi *et al*. (unpublished)]

Conclusions

1) Nature of the insulating ground state in $La_{2-x}Sr_xCuO_4$ at low doping

- **Doped holes form charge cluster glass (dynamic charge heterogeneities) in CuO_2 planes**

2) Doping-driven SIT (*H*=0) in LSCO

- **Formation of localized Cooper pairs within the insulating, charge glass state**
- **Onset of SIT influenced by a competing charge order**

3) Thermally-driven (*H*=0) SC transition

- **BKT transition**
- **Fluctuating, interacting clusters/domains; dynamical heterogeneities**

4) *H*-field-driven SIT

- **Three distinct phases at T=0 in underdoped $La_{2-x}Sr_xCuO_4$:**
  - **superconductor with $T_c(H) \neq 0$ (pinned vortex solid/Bragg glass)**
  - **superconductor with $T_c = 0$ (vortex glass)**
  - **high-field insulator (Mott hopping)**