Glassy charge dynamics and magnetotransport in lightly doped La_2CuO_4

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Support at NHMFL:

NSF DMR-0403491, NHMFL (NSF, State of Florida)

Outline

• High-T_C superconductors: doped Mott insulators

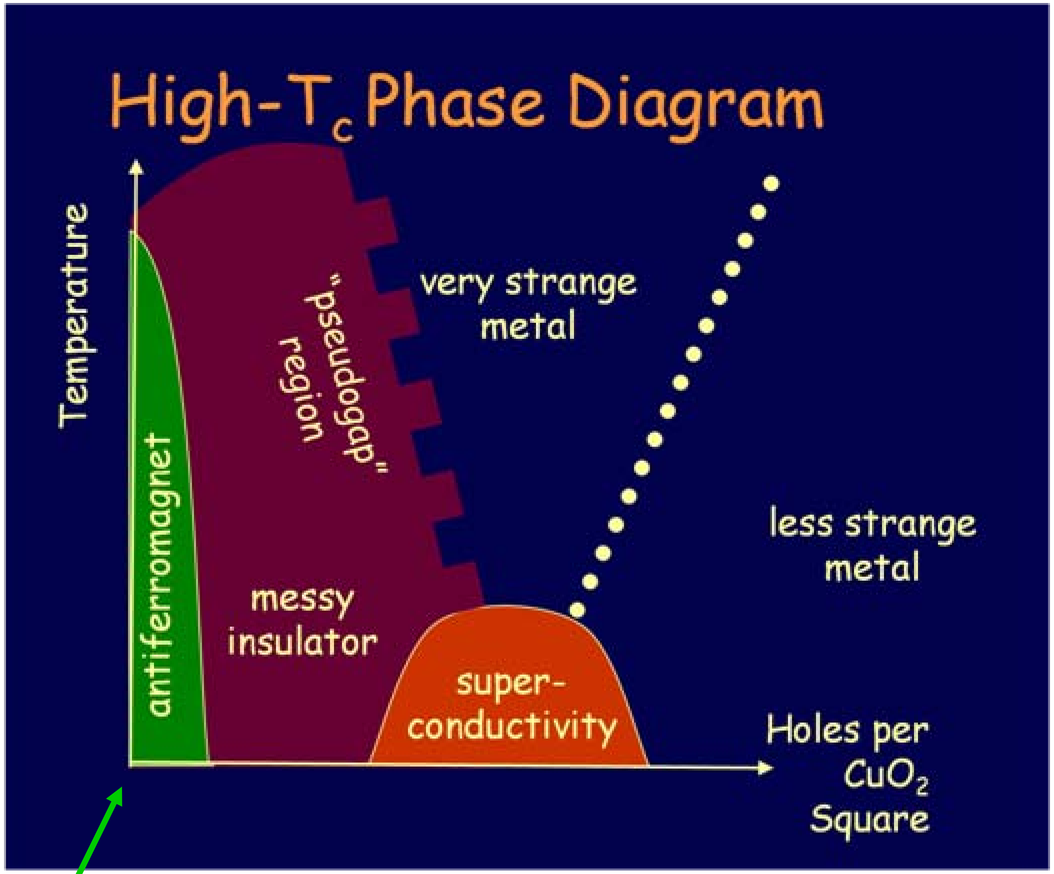
• Metal-insulator transition; Coulomb glass

• Role of inhomogeneities in cuprates - one of the major open issues

• Nature of the ground state in cuprates? Case of La_2CuO_4 at low doping:
- hysteretic and memory effects in magnetotransport
- resistance fluctuations (noise)
- microscopic mechanism

• Conclusions and future work

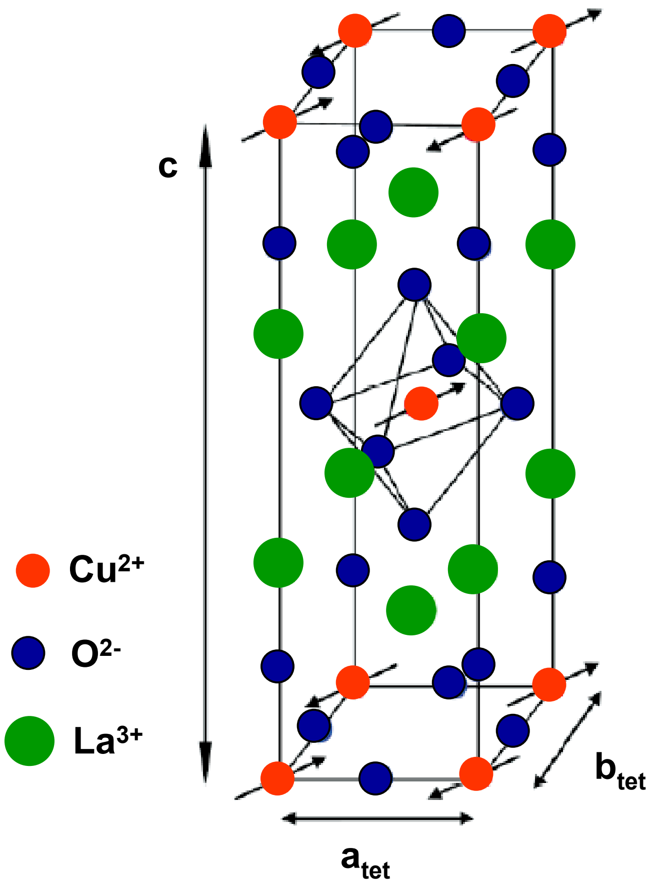
Complex behavior of high-T_C superconductors



- 3D Néel order at 310 K in the parent material
- 3D Néel order suppressed with ≈2-3% doping
- only a few per cent (≈5-6%) of dopants cause a transition from an insulating to a (super) conducting state

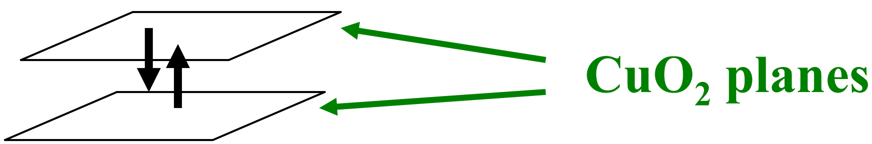
- undoped parent compound (*e.g.* La_2CuO_4): Mott insulator, not a metal
- single-electron band theory of solids fails

Parent cuprate La_2CuO_4



- one hole on each Cu site
  - in-plane AF exchange interaction $J_{\|} \sim 0.1$ eV
  - weak inter-plane interaction ($J_{\|}/J_{\perp} \sim 10^5$)

3D long-range antiferromagnetic (AF) order:

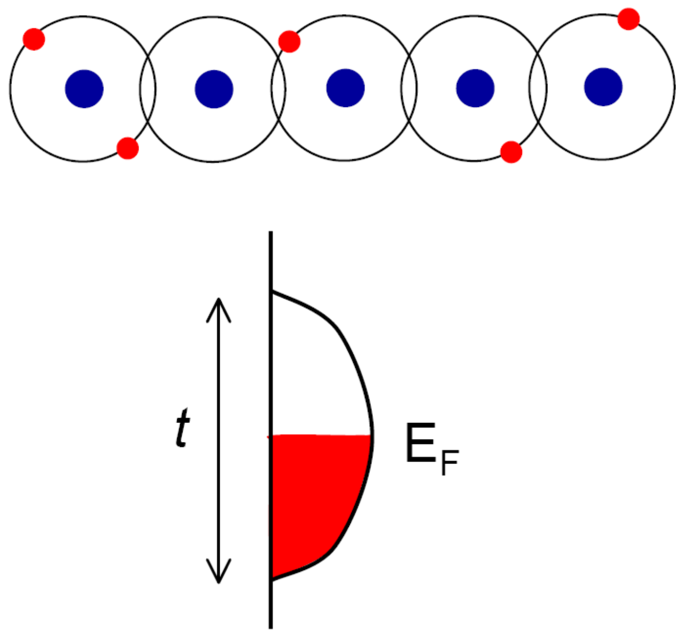


- weak FM moments along c-axis in each ab plane due to spin canting

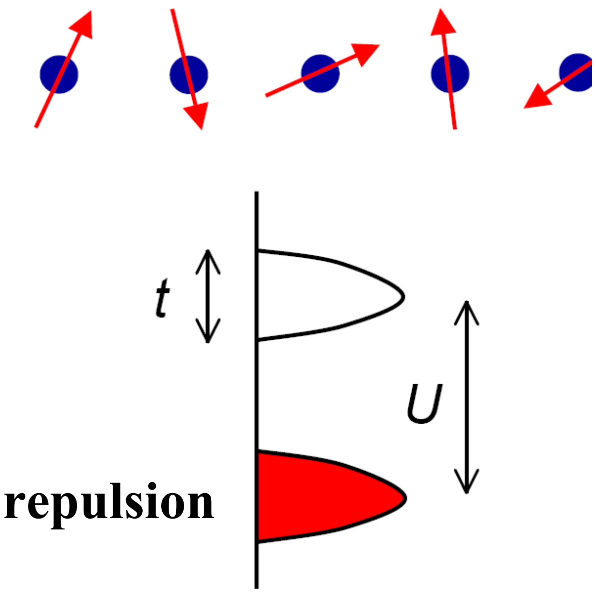
Parent cuprate La_2CuO_4

• **Mott insulator**

Conventional metal



Mott insulator



U: on-site
Coulomb repulsion

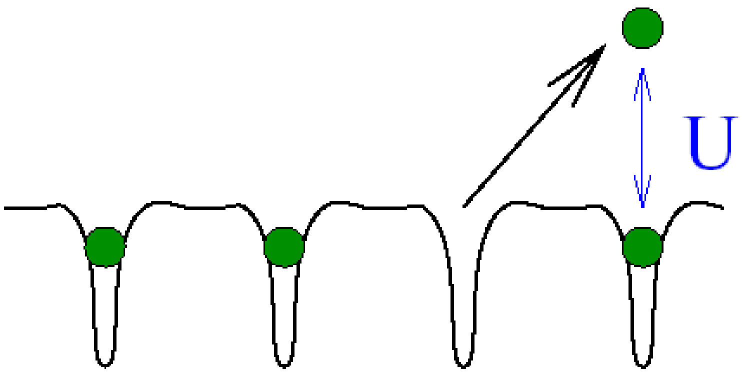
How does a transition from a Mott insulator to a conductor occur as a function of doping?

General problem

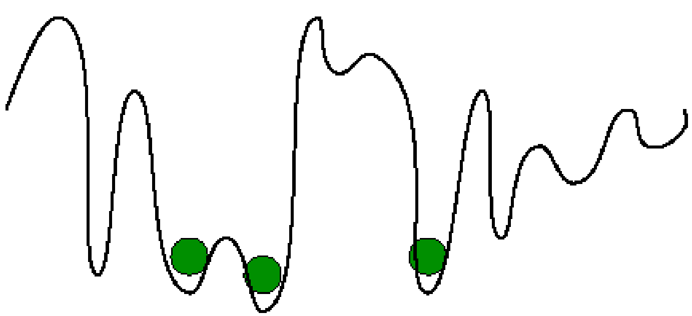
• high density – kinetic energy (Fermi energy) dominates

• low density – potential energy dominates:

➢ electron-electron interactions
(Mott insulator)



➢ disorder due to impurities,
defects (Anderson insulator)



Result: formation of localized (bound) states ⟶ no conduction

Metal-insulator transition: a quantum critical point

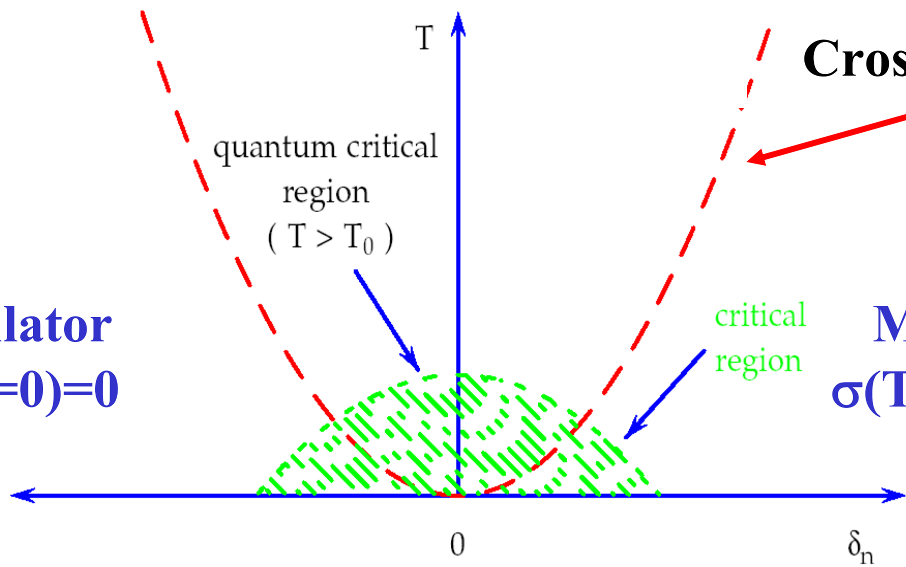
- Experiments: a continuous transition; sharp phase transition at $T=0$

Crossover temperature

$T_0 \sim |\delta_n|^{z\nu}$

Insulator

$\sigma(T=0)=0$



Metal

$\sigma(T=0)\neq 0$

Control parameter

$\delta_n=(n_s-n_c)/n_c$

(n_s- carrier density)

- "dynamical scaling" in the critical region: $\sigma(n_s,T) \propto T^x f(T/\delta_n^{z\nu})$

- power-law critical behavior: $\sigma(n_s,T=0) \propto \delta_n^{\mu}$

Theoretical problems: no broken symmetry; order parameter? No small parameter; elementary excitations? Standard approaches fail

It gets even more complicated…

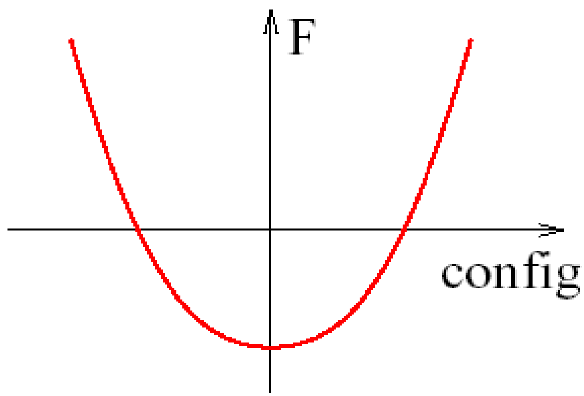
- Coulomb repulsion: keep electrons apart (uniform density)
- Random potential: nonuniform density

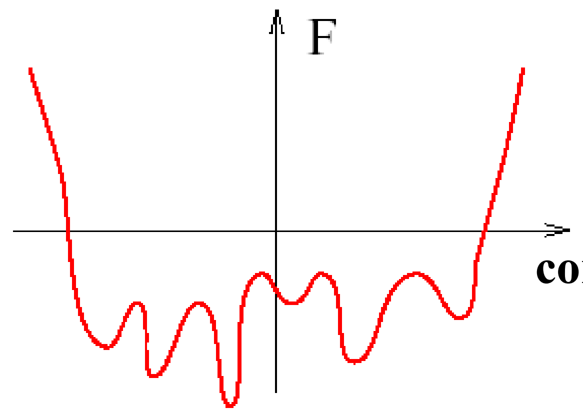
- competition between Coulomb interactions and disorder

→ **Frustration!** (can't make everyone happy)

→ emergence of (exponentially) many metastable states with similar (free) energy

Fluid





Glass

configuration space

Experimental signature: slow, out-of-equilibrium dynamics

Coulomb glass

Coulomb glass

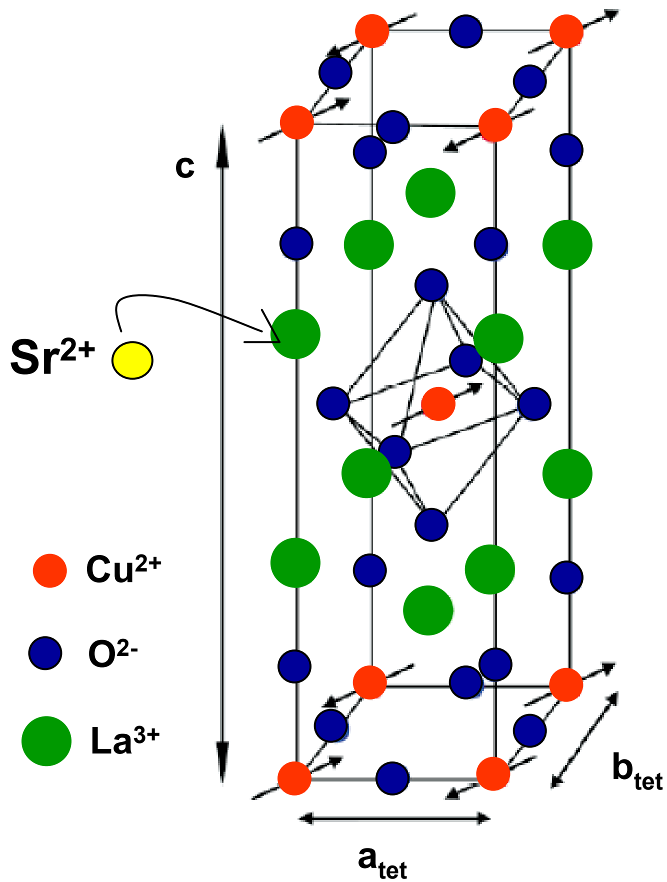
- expected in Anderson insulators with strong electron-electron interactions [M. Pollak (1970); Efros, Shklovskii (1975); Davies, Lee, Rice (1982,84)]

Observations of glassiness in electronic systems – very few:

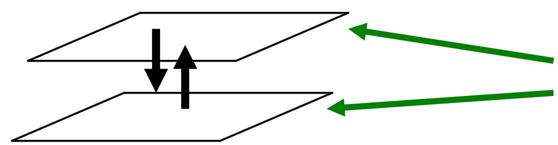
- slow relaxations in GaAs capacitance (Monroe *et al.*)
- slow relaxations and thermal hysteresis in conductivity of granular films (Goldman *et al.*, Wu *et al.*, Frydman *et al.*)
- slow relaxations of photoconductivity in $YH_{3-\delta}$ (Lee *et al.*)
- slow relaxations, aging, memory in conductivity of InO_x (Ovadyahu *et al.*) and granular Al (Grenet *et al.*)
- 2D electrons in Si (DP *et al.*): slow relaxations, aging, memory; slow, correlated dynamics – from insulating to (poorly) metallic
- lightly doped cuprates (DP *et al.)*

my work

Doped La_2CuO_4



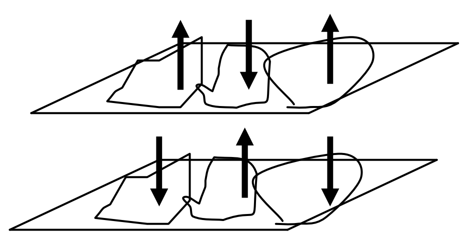
3D long-range antiferromagnetic (AF) order:



- weak FM moments along c-axis in each ab plane due to spin canting

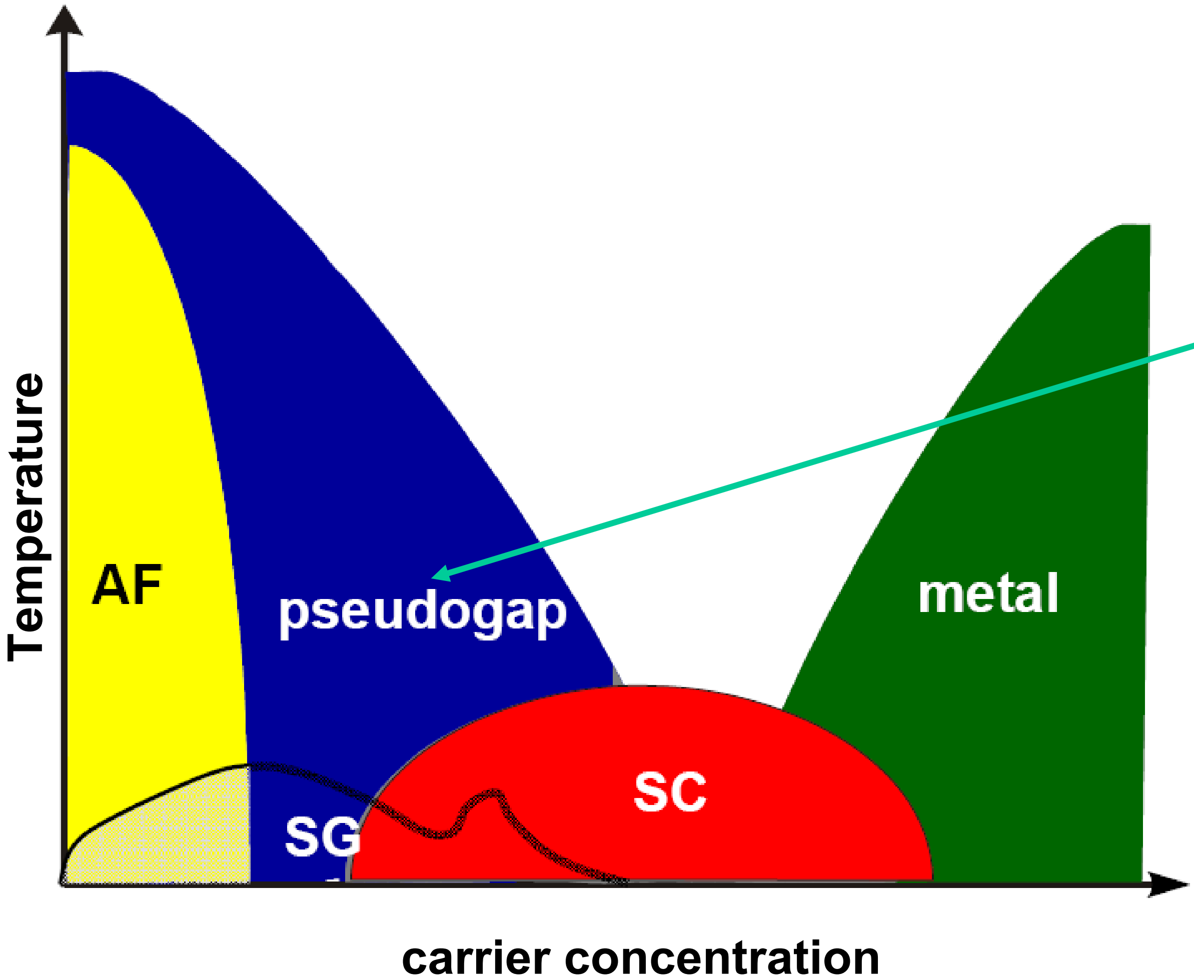
- doped holes go into the 2D CuO_2 planes

$\Rightarrow$ Long-range AF order destroyed for x ≧ 0.02 (Sr), x>0.03 (Li) - short-range magnetic order persists



- AF domains; holes along (antiphase) domain walls?

Complex behavior of high-T_C superconductors



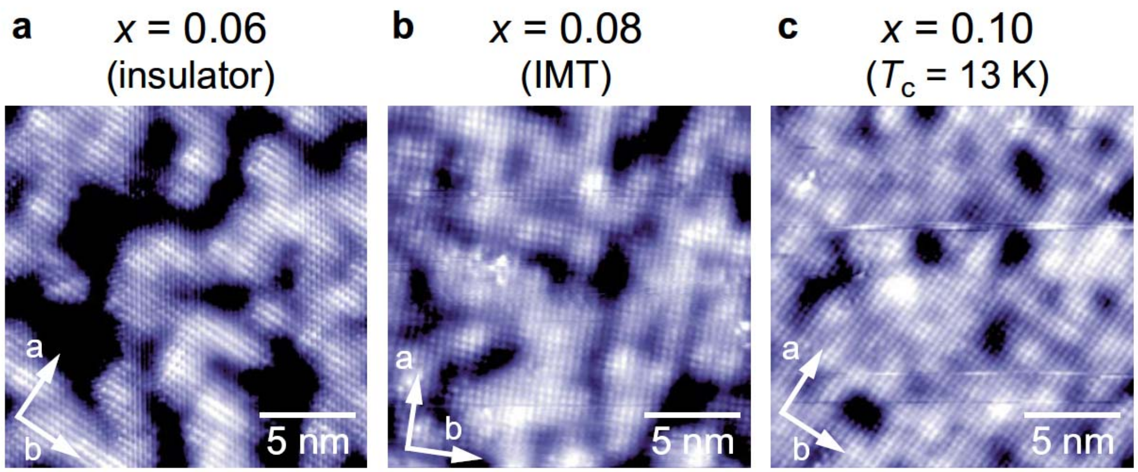
Emergence of nanoscale inhomogeneities!

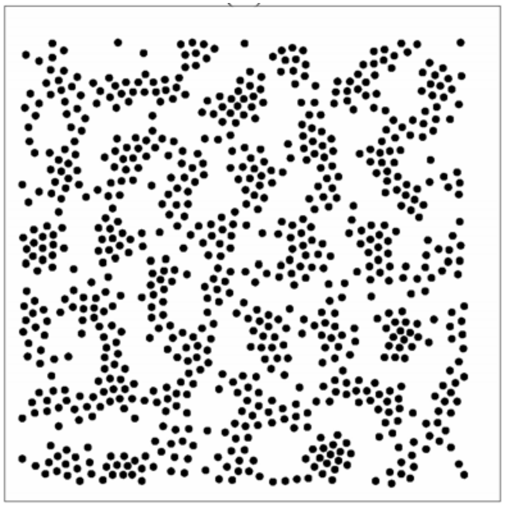
- spin glass behavior well established at low T

Nanoscale charge inhomogeneities

STM images

Computer modeling





$Ca_{2-x}Na_xCuO_2Cl_2$

[Kohsaka *et al.*, Phys. Rev. Lett. 93, 097004 (2004)]

("stripe- and clump-forming systems")

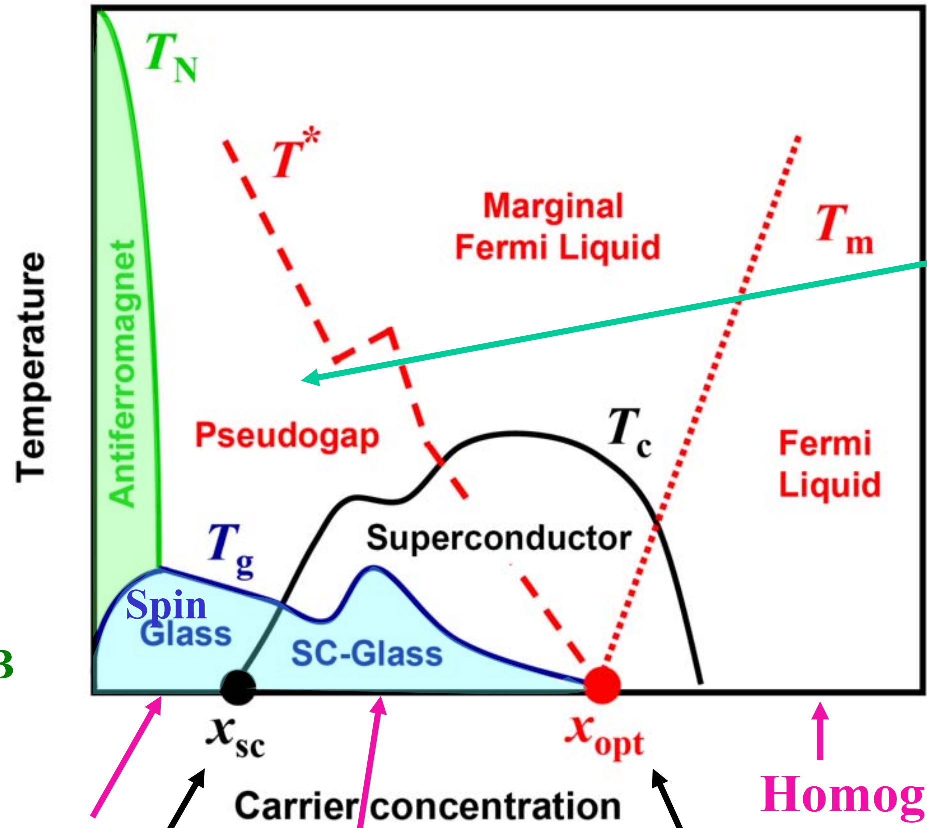
[Reichhardt *et al.*, Europhys. Lett. 72, 444 (2005)]

- **global phase separation not possible because of <u>charge neutrality</u>**

- **(infinitely?) many possible arrangements of nanoscopic ordered regions with comparable energies ⟹ charge (Coulomb) glass?**

Motivation

- Doped Mott insulators
- Insulator to (super) conductor transition?



Emergence of nanoscale inhomogeneities!

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

Glassy insulator?

Homogeneous metal

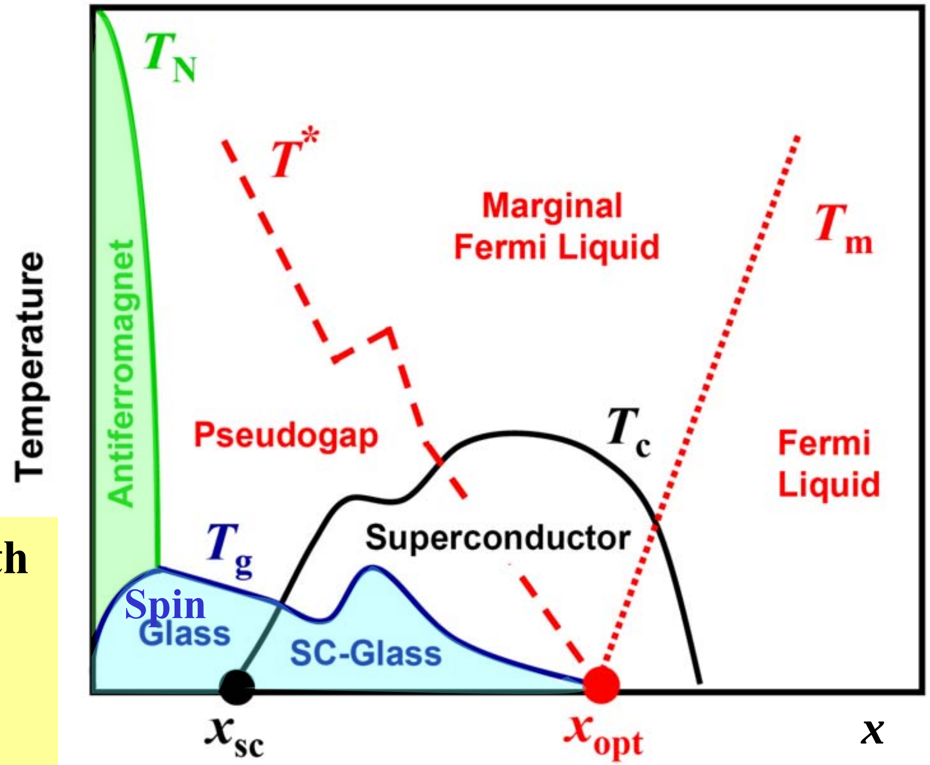
Metal-insulator transition?

Inhomogeneous, conducting glassy state?

Quantum glass transition?

Motivation

- Doped Mott insulators
- Insulator to (super) conductor transition?



Mott transition with disorder – theory: V. Dobrosavljević *et al., PRLs* … (1999-2005)

MIT in a 2DES in Si at T=0
[Popović *et al.*, PRLs from 2002 to 2007; many signatures of glassiness; Coulomb glass; T_g=0]

Glassy insulator | Metallic glassy phase ($k_F l$ < 1; "bad" metal) | Metal

n_c metal-insulator transition

n_g glass transition

carrier density

Glassy charge dynamics in cuprates? Nature of the ground state?

<u>Glasses:</u> - many metastable states
- slow, nonequilibrium dynamics

supercooled water

How to probe glassy dynamics?

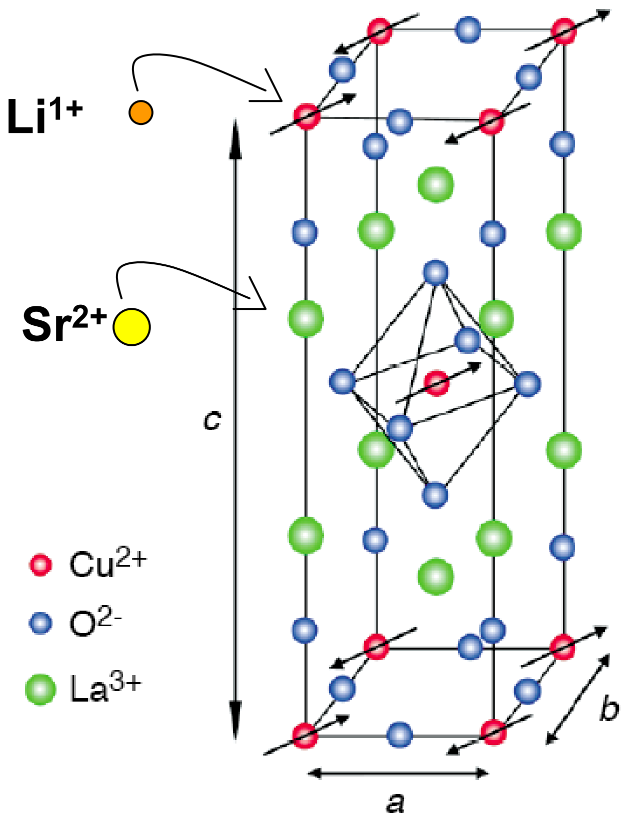
• measure response of the system to some kind of a perturbation ⇒ slow, nonexponential relaxations

• fluctuations – provide complementary information (correlations)

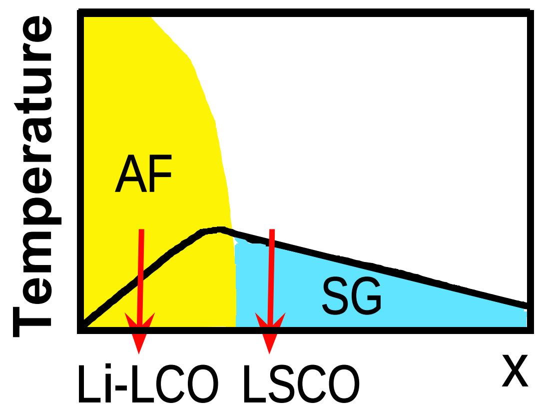
<u>For charge glass:</u> transport (bulk probe; mean values of resistivity) and resistance noise (fluctuations)

Lightly doped La_2CuO_4

- a good candidate (well characterized, disorder)



• Sr and Li (no magnetic moment) doped:
similar magnetic behavior, but no SC in Li-LCO



x=0.03 in this talk:

$La_2Cu_xLi_{1-x}O_4$ in **antiferromagnetic** phase (T_f ~ 7-8 K)

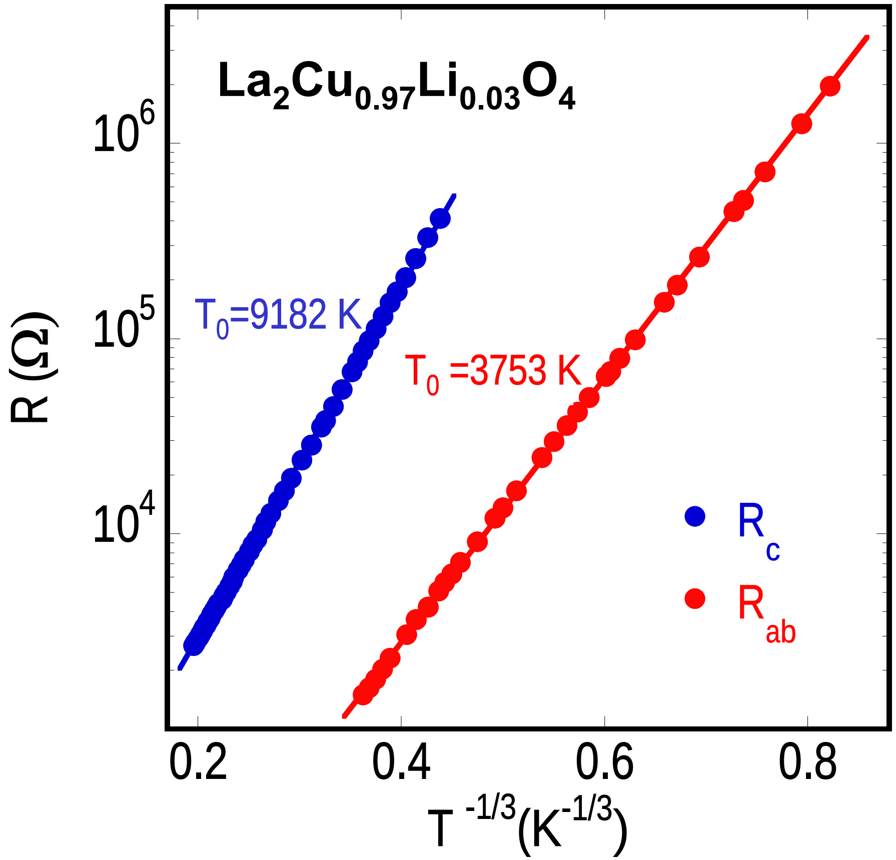
$La_{2-x}Sr_xCuO_4$ in **spin-glass** phase (T_{sg} ~ 7-8 K)

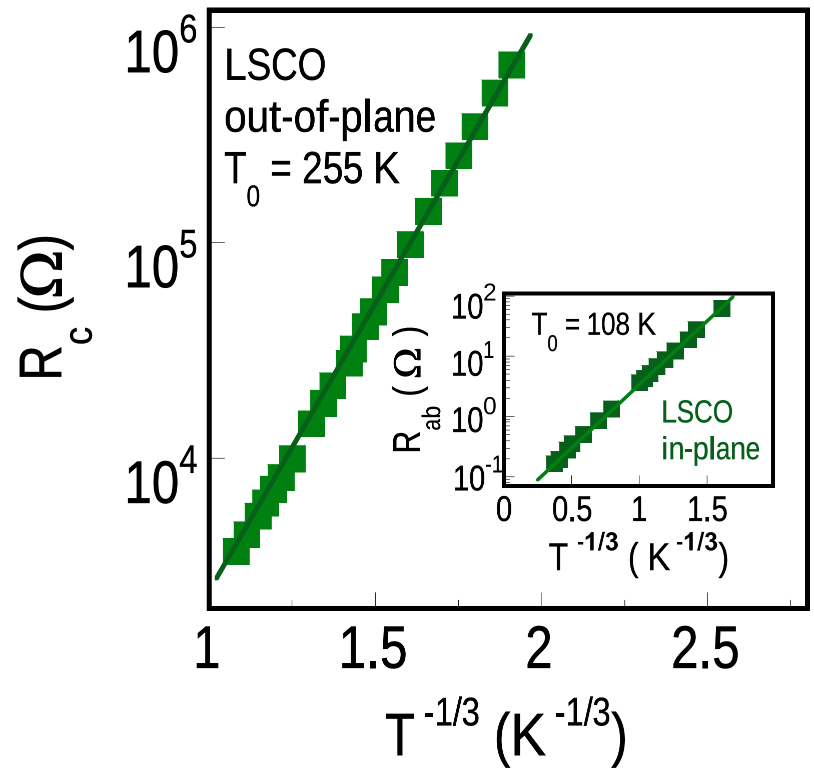
Dielectric measurements: an electronic glass state

AF Li-LCO: Park *et al.*, PRL 94, 017002 (2005);

x=0.03 LSCO: Jelbert *et al.*, PRB 78, 132513 (2008)

Temperature dependence of the resistance



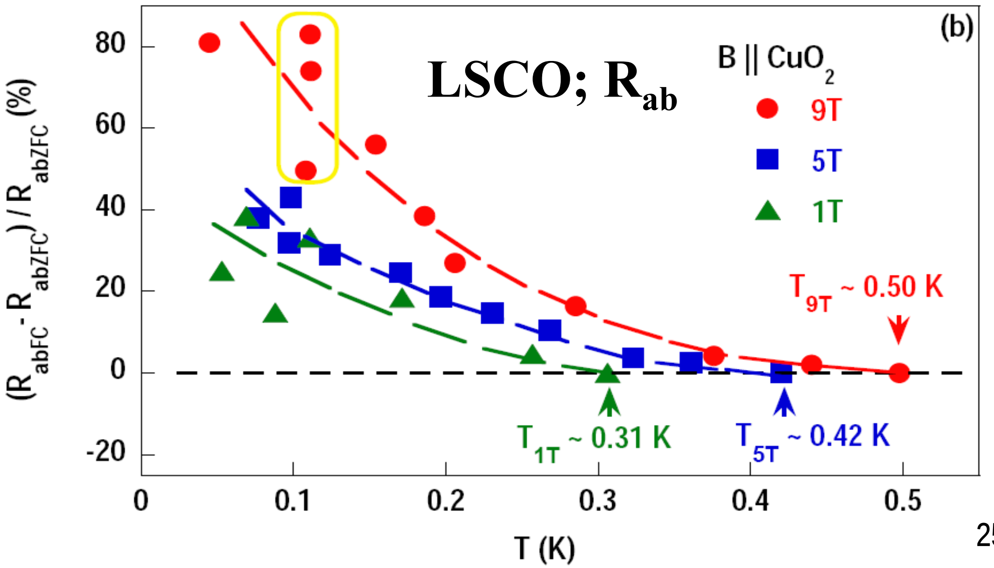


Variable-range hopping (VRH): $R \propto \exp[(T_0/T)^n]$, n=1/3 (2D exponent)

Actually, it depends on how the sample is cooled…

History dependence in transport: zero-field cooling (ZFC) *vs.* field cooling (FC)

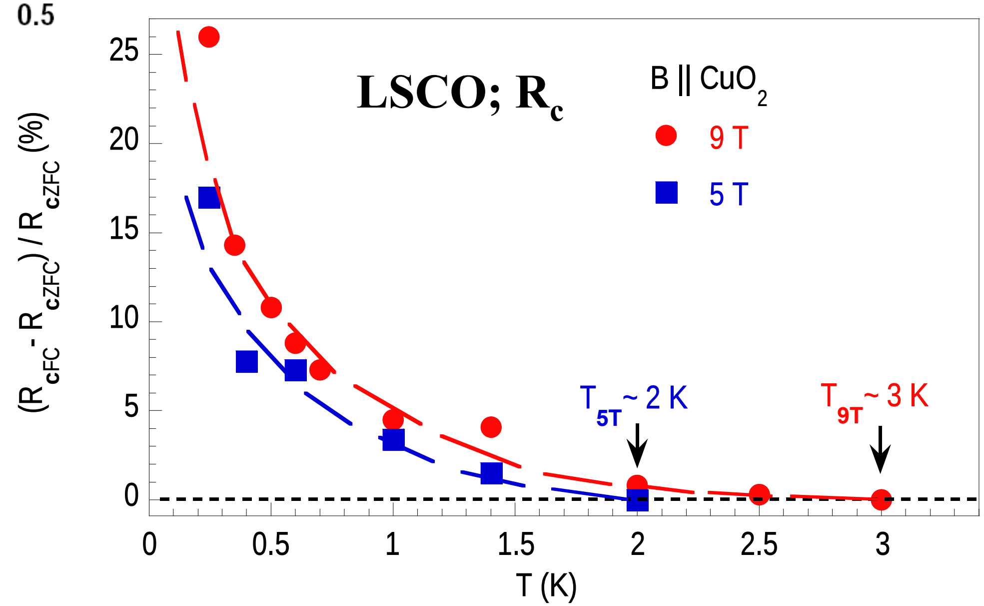
Difference between FC and ZFC resistance R(B=0)



- observed in both R_{ab} and R_c, for both B||ab and B||c
- difference disappears at much lower T in ab sample

Signature of out-of-equilibrium dynamics

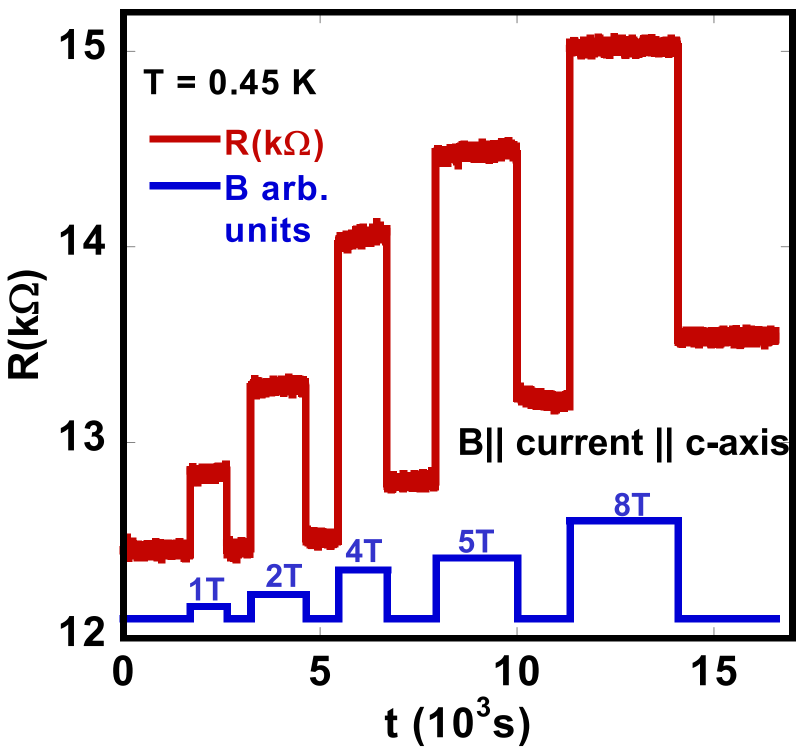
Onset T < $T_{sg} \approx 7$ K



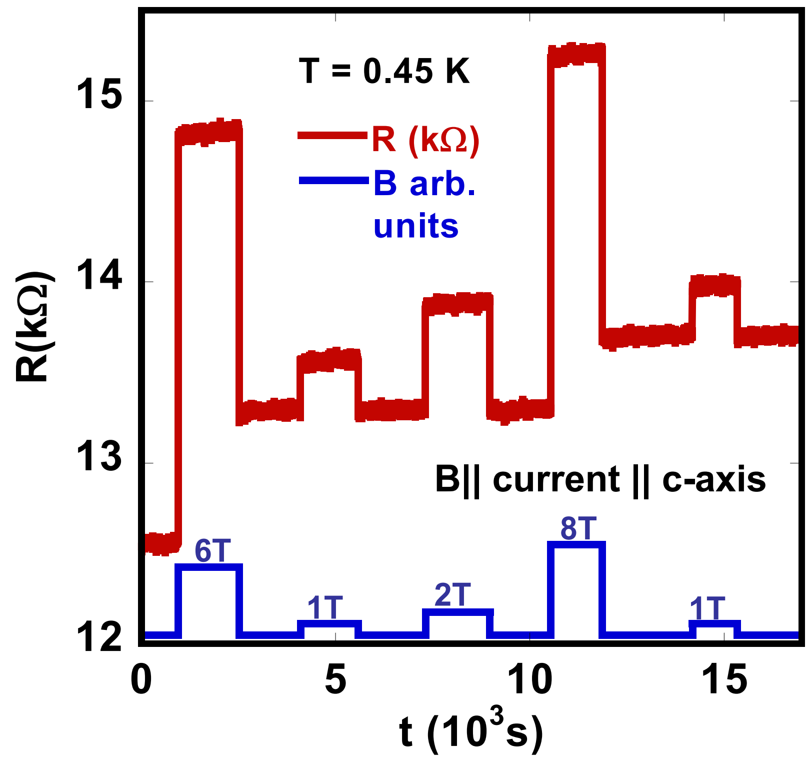
Memory effects

(observed in both R_{ab} and R_c, for both B||c and B||ab)

LSCO; R_c



LSCO; R_c



- higher B enable overcoming higher energy barriers

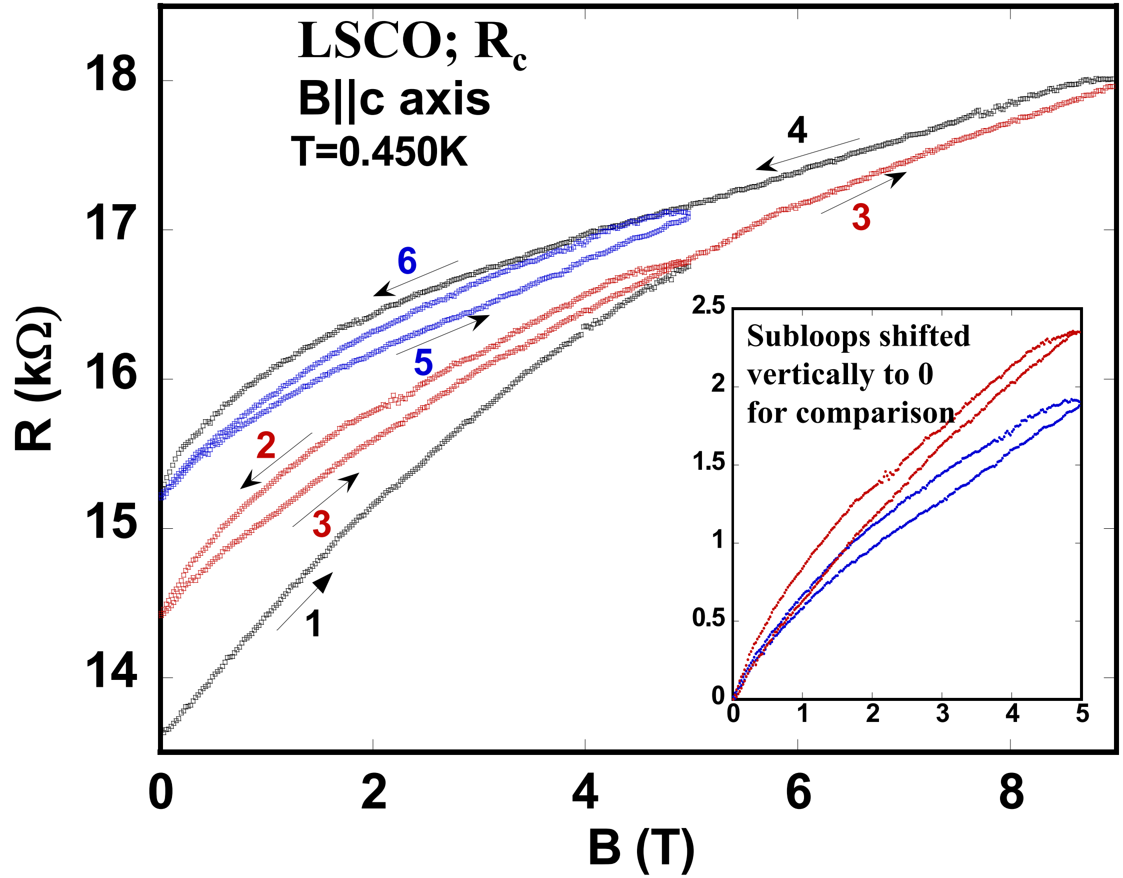
- R(B=0) determined by the highest B previously applied - memory of magnetic history

Also, manganites: Levy et al., PRL 89, 137001 (2002);
YBCO: Ando et al., PRL 83, 2813 (1999)

Hysteretic behavior of the resistance

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

Memory in R wiped out for T ≥ 1K, spin glass transition $T_{SG} \approx 7K$



- hole-rich regions between interacting hole-poor AF domains

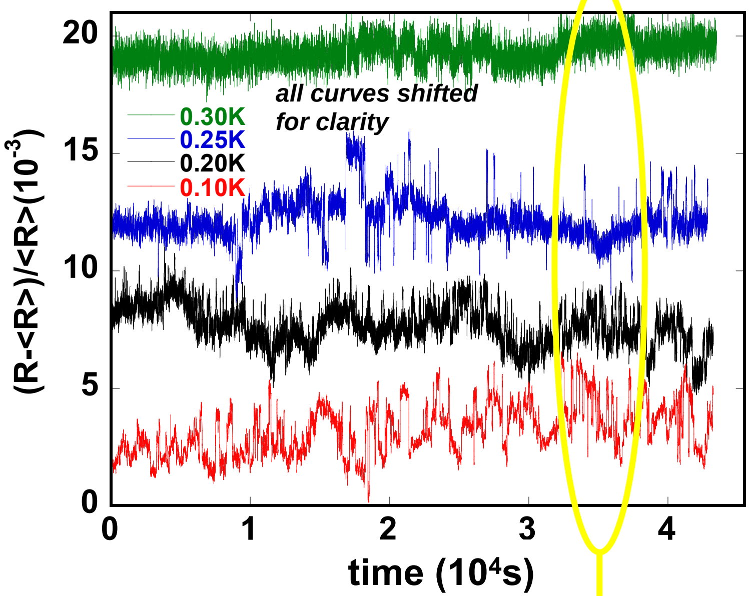
Do the holes merely "follow" the spins?

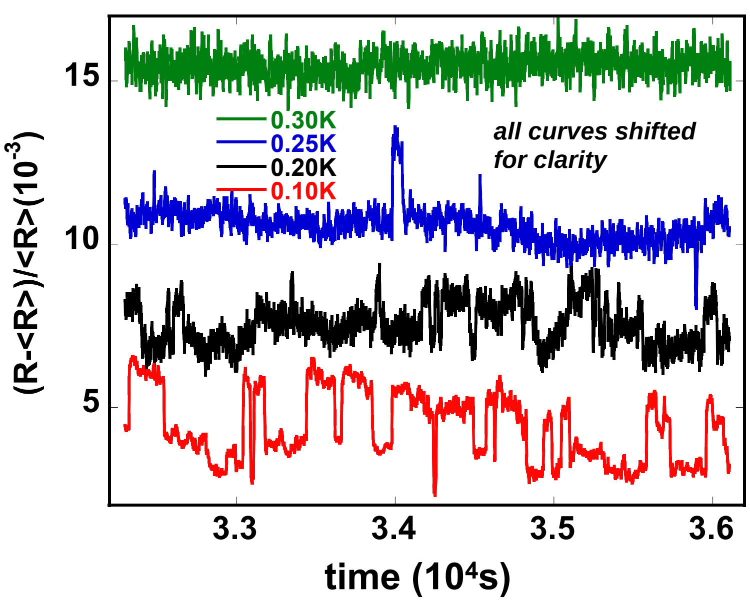
$T_{onset} < T_{sg}$

- return point memory
- incongruent subloops ⇒ interactions between domains

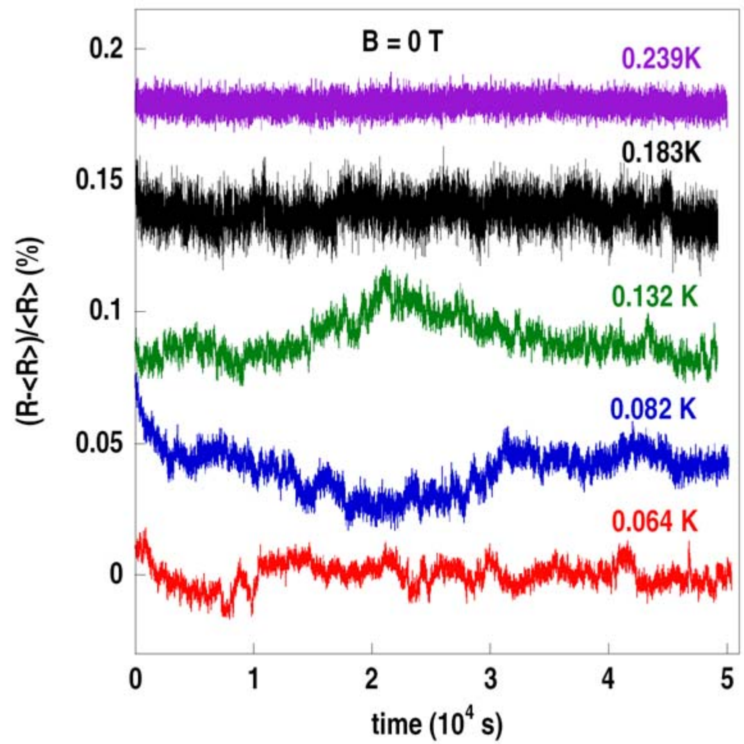
Resistance fluctuations (noise); LSCO

R_c





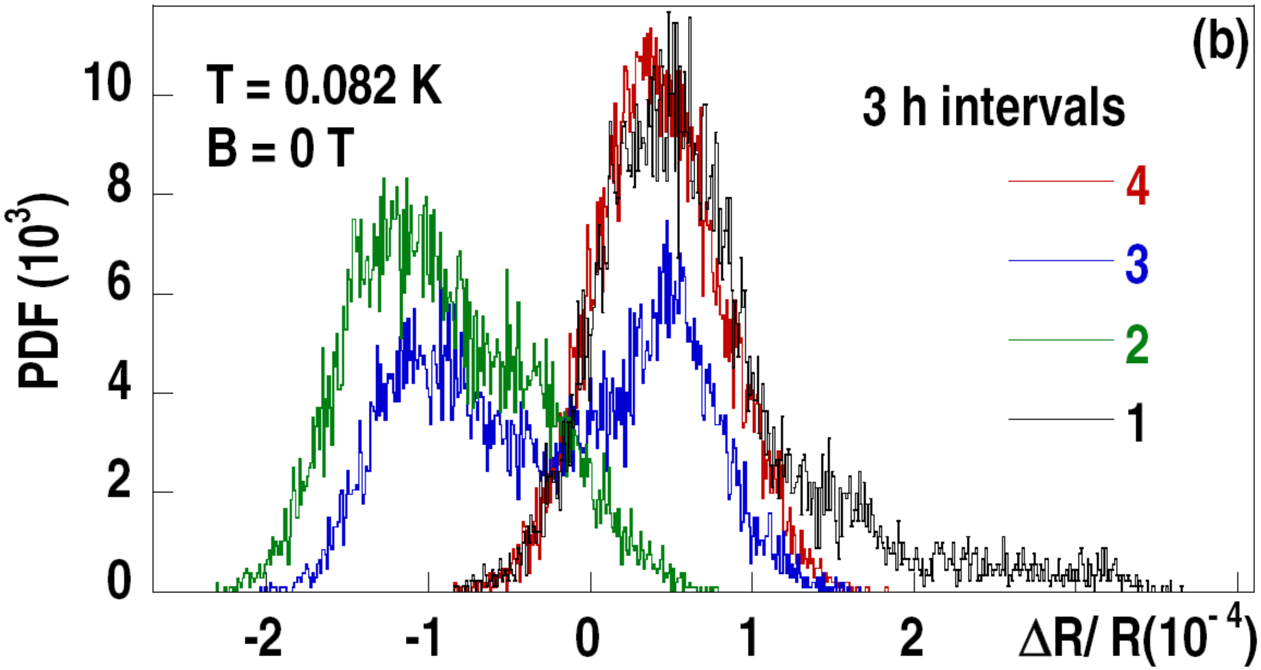
R_{ab}



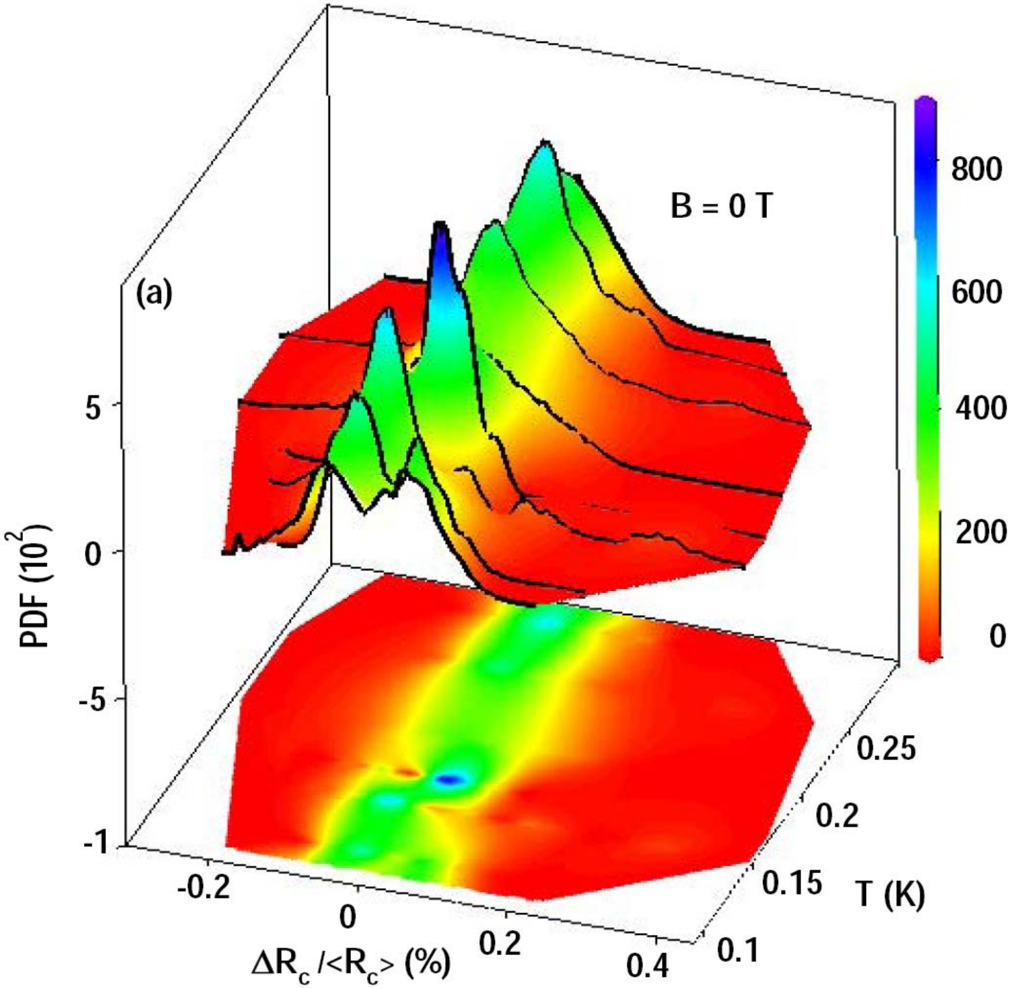
- **noise Gaussian at “high” T**
  (*e.g.* T > 0.18 K for R_{ab} noise)
- **at low T, non-Gaussian noise**
  metastable states *(out-of-equilibrium)*

Probability density functions (PDF) of fluctuations

Noise in R_{ab}



• structure depends on the observation time – different states contribute ⇒ nonergodic



- increase sampling time to 12 hours, but never becomes Gaussian at low T

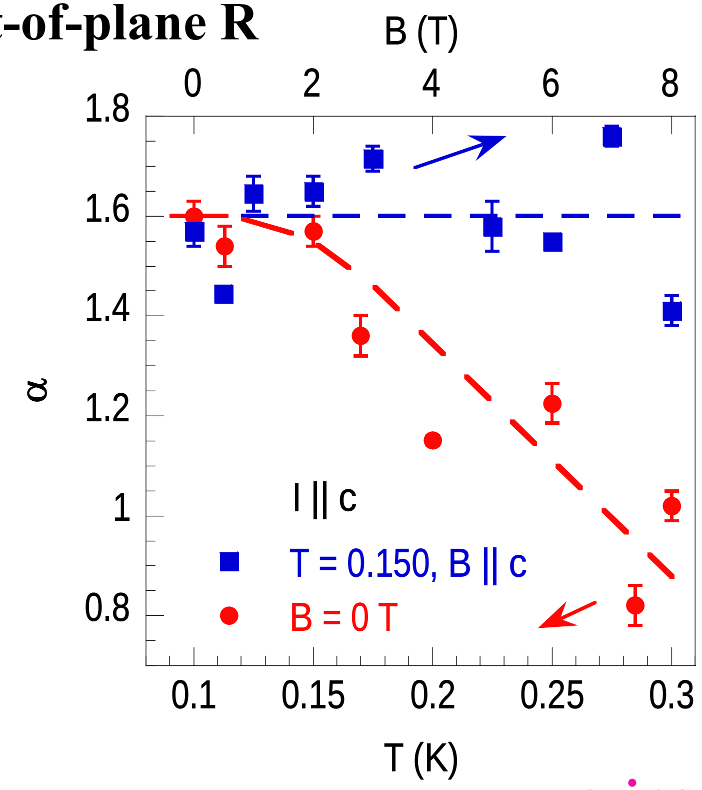
• nonergodic, does not reach equilibrium on experimental time scales at low T

Onset of glassiness in transport at T<< T_{SG}: suggests spin and charge glass not directly related

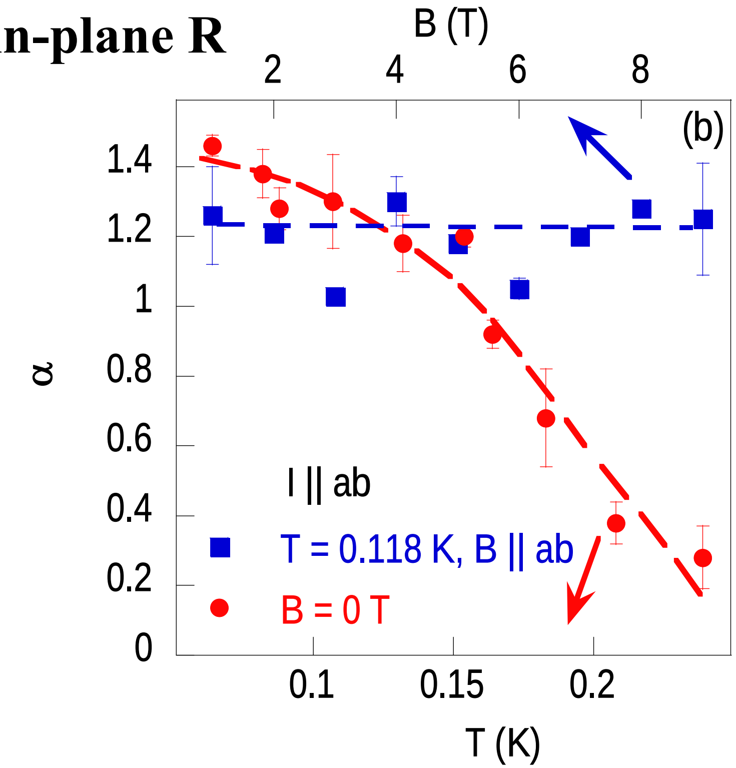
Noise statistics: T and B dependence

- Power spectrum: $S_R \sim 1/f^{\alpha}$

out-of-plane R



in-plane R



- α increases as T is reduced; <u>no effect of B!</u>

$\underbrace{\qquad\qquad\qquad\qquad}$

fewer metastable states that dominate
at low T in the exp. time window

Slowing down of the dynamics as T→0

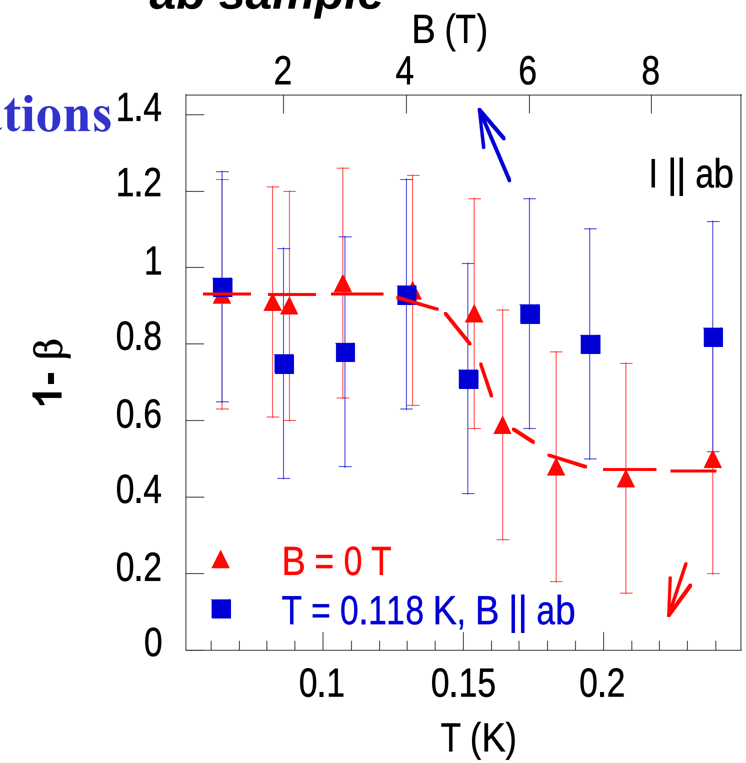
Second spectrum $S_2(f_2, f)$

- the power spectrum of the **fluctuations of S_R (f)** with time

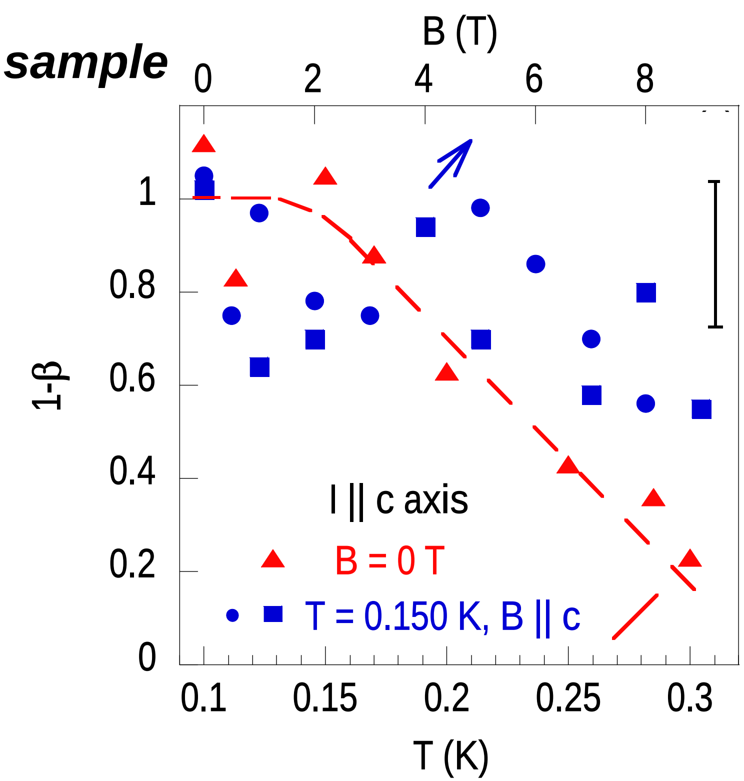
1) white ($1-\beta = 0$) for uncorrelated fluctuators (Gaussian)

2) $S_2(f_2, f) \propto 1/f_2^{1-\beta}$ for interacting fluctuators (non-Gaussian)

ab sample



c sample



Increase of correlations as T → 0

Noise statistics independent of both B and magnetic history

(Partial) summary of noise results

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

- **Increase of correlations as $T \rightarrow 0$**

Glass transition at T=0

- **Noise statistics independent of both B and magnetic history (unlike conventional spin glasses) ⇒ charge, not spin!**

- **Onset of hysteretic and memory effects in magnetoresistance:**

$$T_{onset} << T_{sg}$$

⇒ Charge glass transition $T_{cg}=0$

[I. Raičević *et al.*, PRL101, 177004 (2008)]

Scaling of the second spectra

- can distinguish between different models:

- droplet approach
- hierarchical, tree-like model

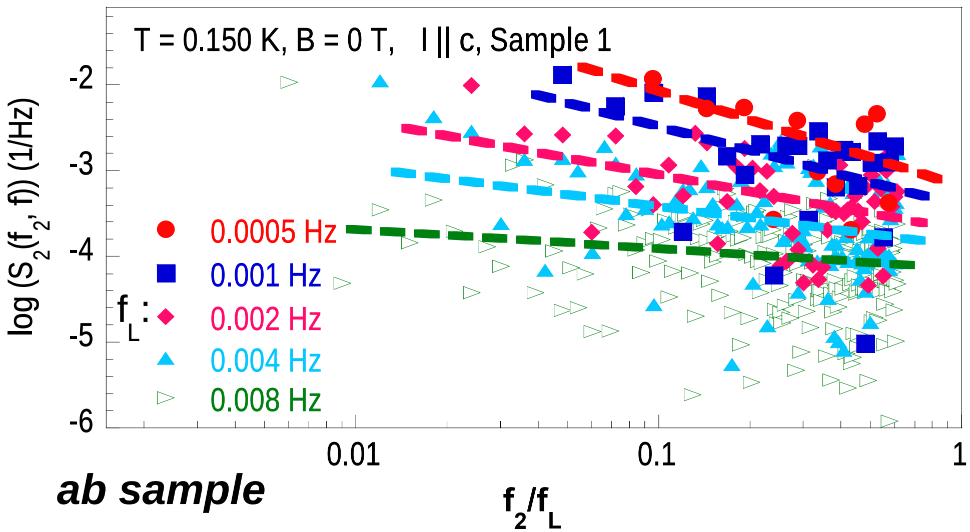
S_2 decreases with f for a fixed f_2/f, consistent with droplet picture (short-range interactions)

⇓

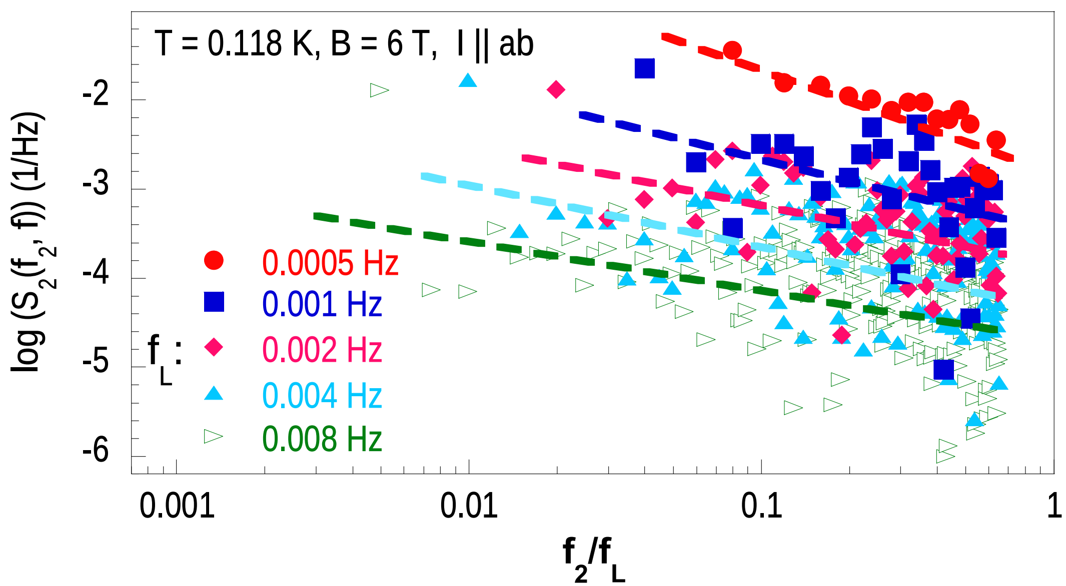
Spatial segregation of holes as a result of competing interactions on different length scales

Cluster charge glass

c sample

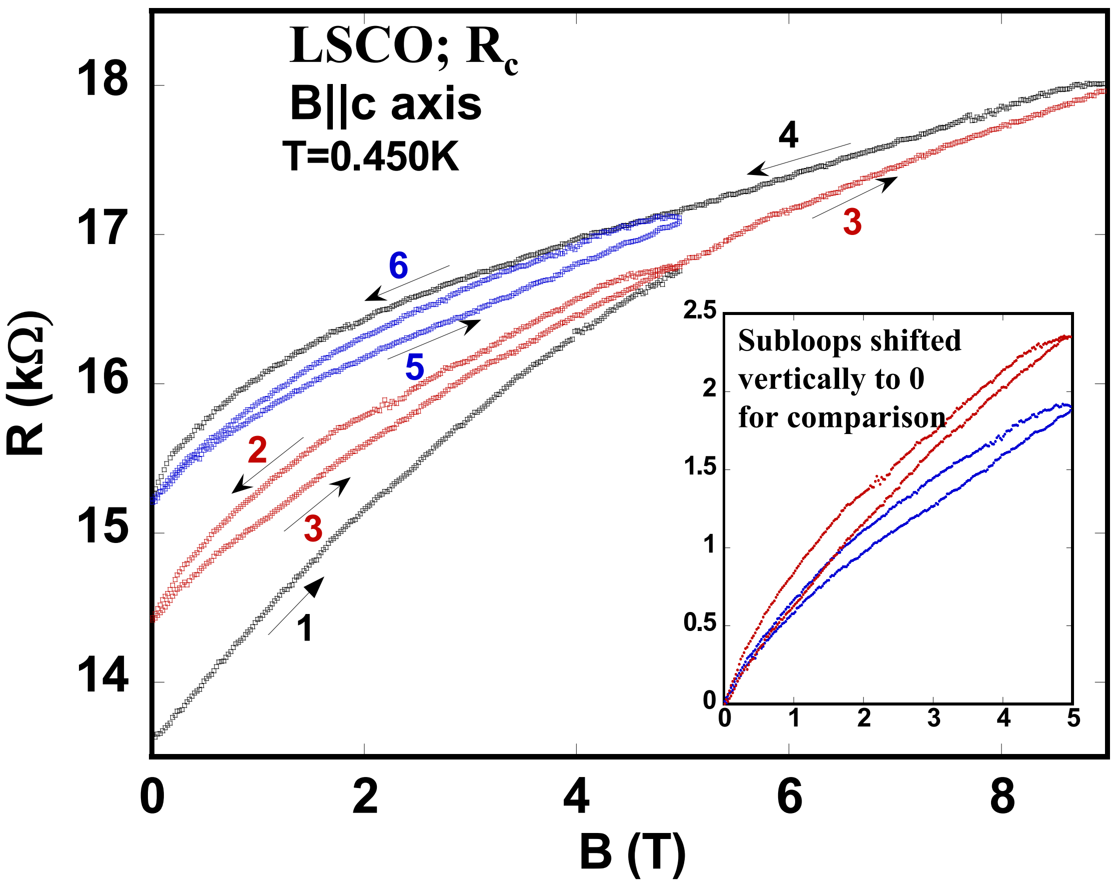


ab sample



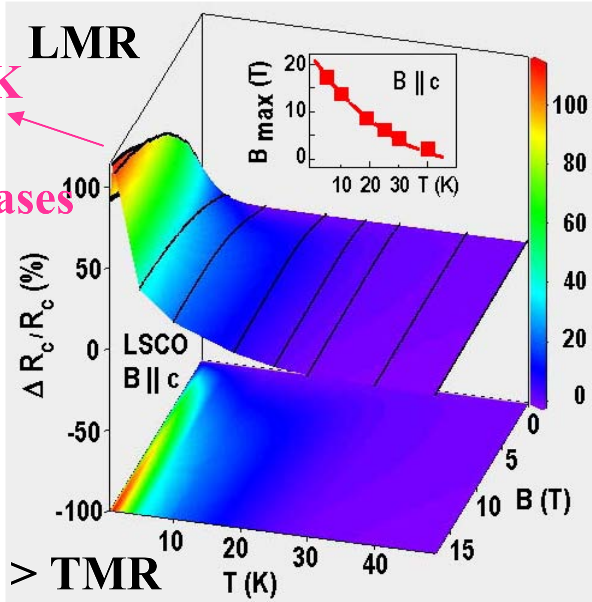
Origin of large positive magnetoresistance at low T???

out-of-plane



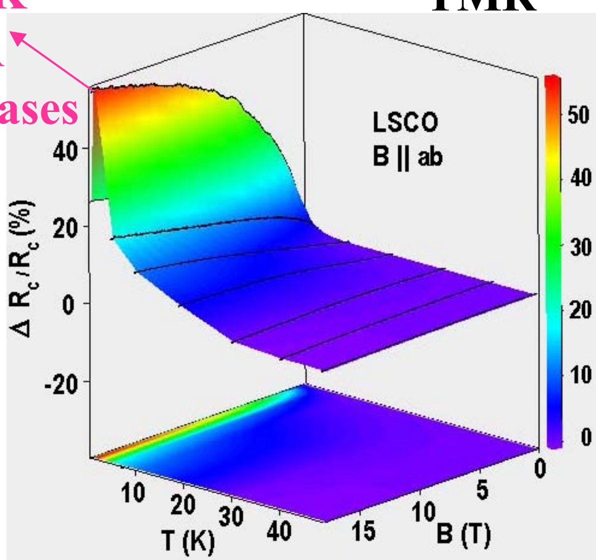
Out-of-plane MR - LSCO

T ~ 1K
+ MR
decreases

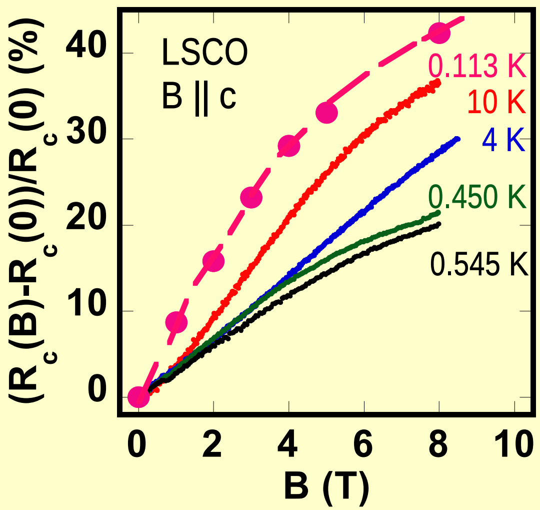


LMR > TMR

T ~ 1K
+ MR
decreases



different sample, fridge



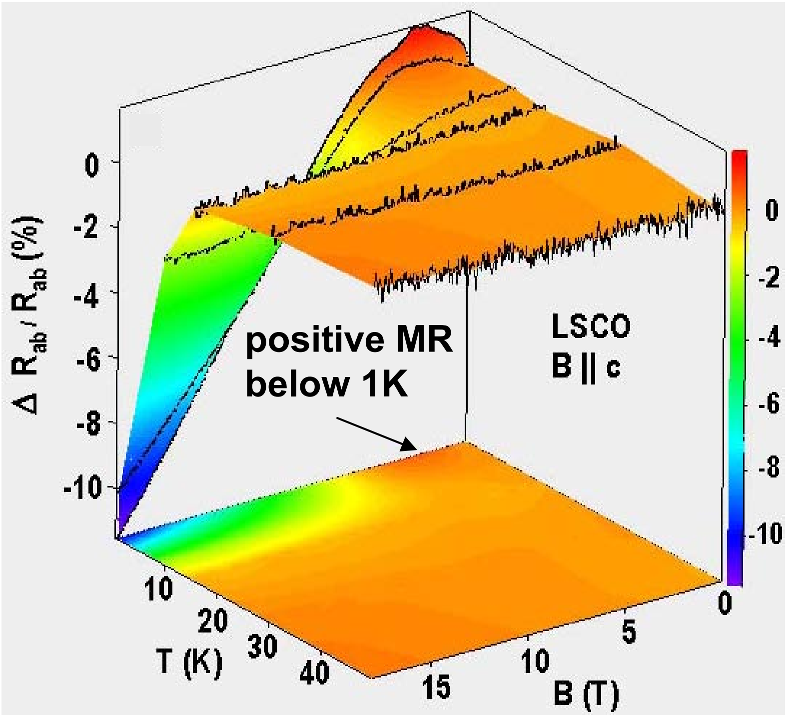
- **Positive MR increases in magnitude again below ~1 K.**
- **Same sample: onset of charge glassiness below ~ 1K**

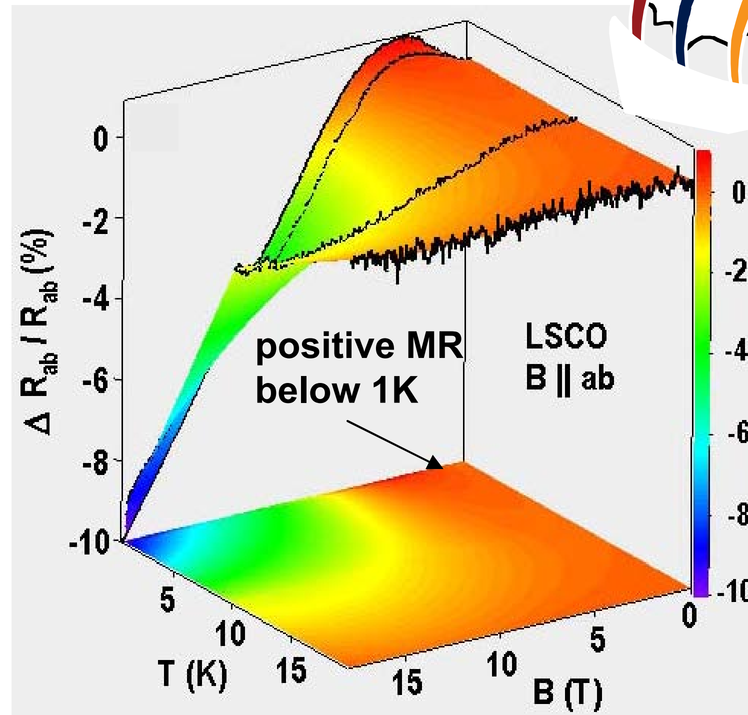
The pMR mechanism changes below ~ 1 K:

***Low T* positive MR closely related to the onset of charge glassiness**

***High T* – crossover to negative MR**

In-plane MR - LSCO





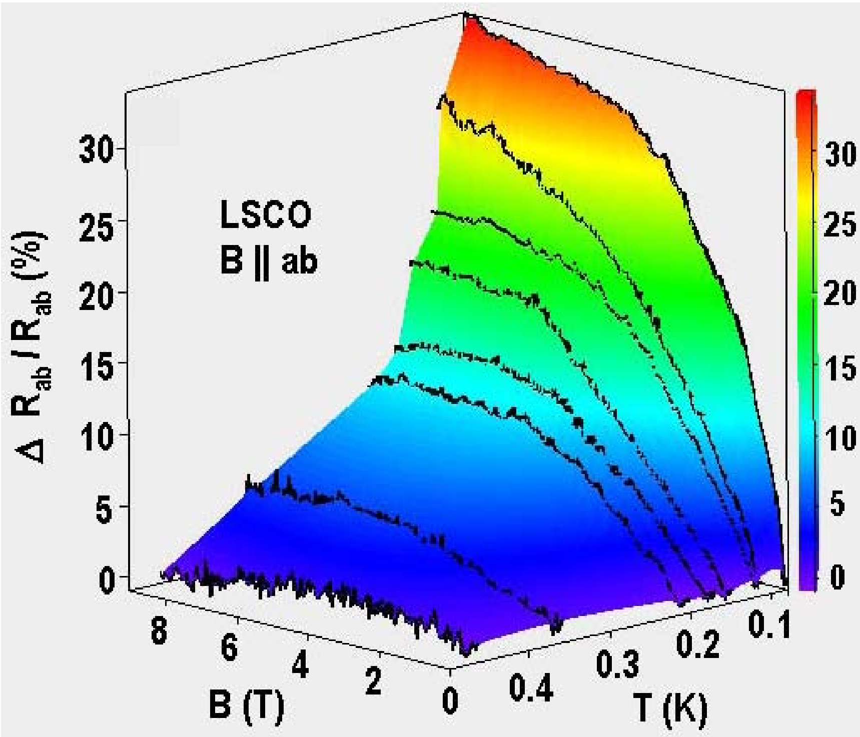
High T **– MR negligible**

- **negative below 10K**
  (onset of spin glass order)
- **isotropic**
- **reorientation of weak FM moments**

Low T

Emergence of low-field positive MR at $T < 1K$

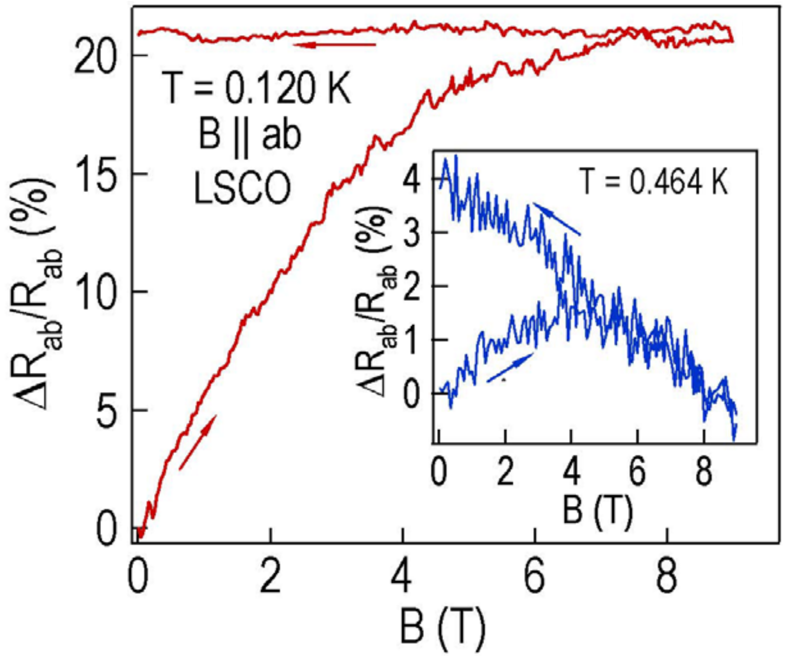
In-plane MR – LSCO, low T



Strong positive MR at low T
(below 0.5 K)

Low-T positive MR coincides with the onset of charge glassiness

Only positive MR exhibits hysteresis

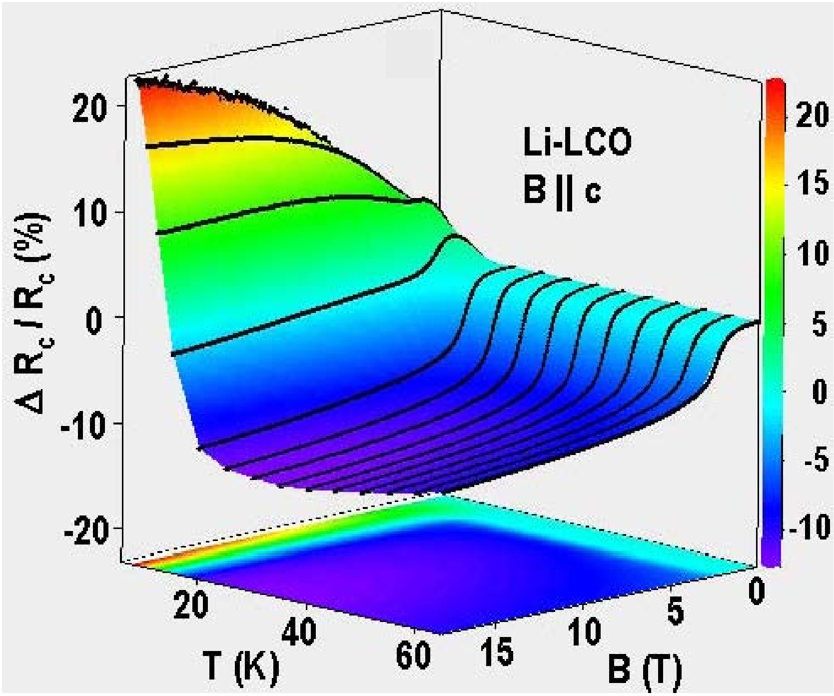


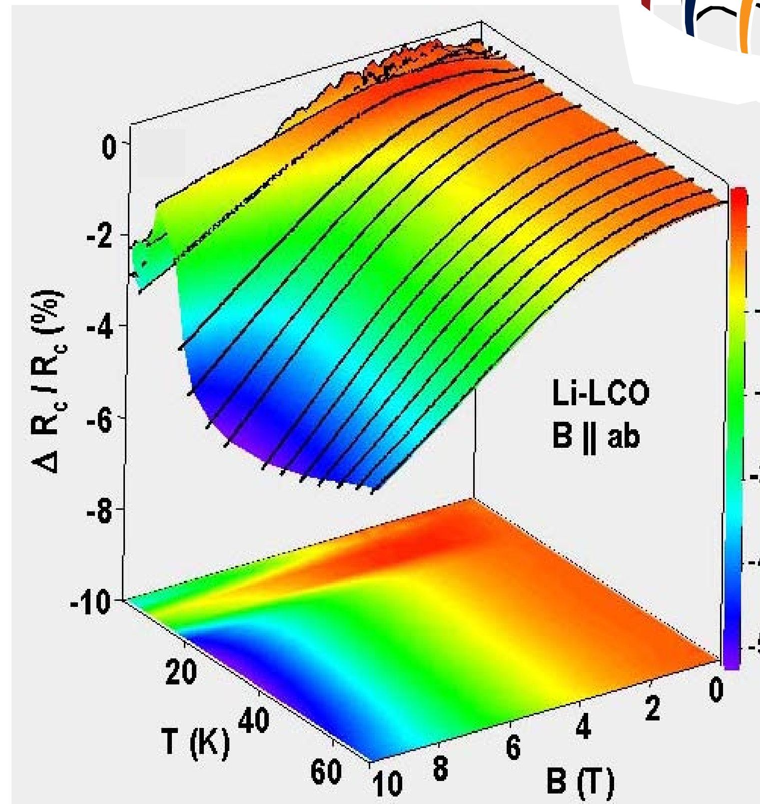
Positive MR - glassy features:
- History dependence
- Memory
- Hysteresis

In the same regime:
- Noise – glassy dynamics as T → 0

Out-of-plane MR – Li-LCO

[Similar to AF (x=0.01) LSCO: Ando *et al.*, PRL 90, 247003 (2003)]





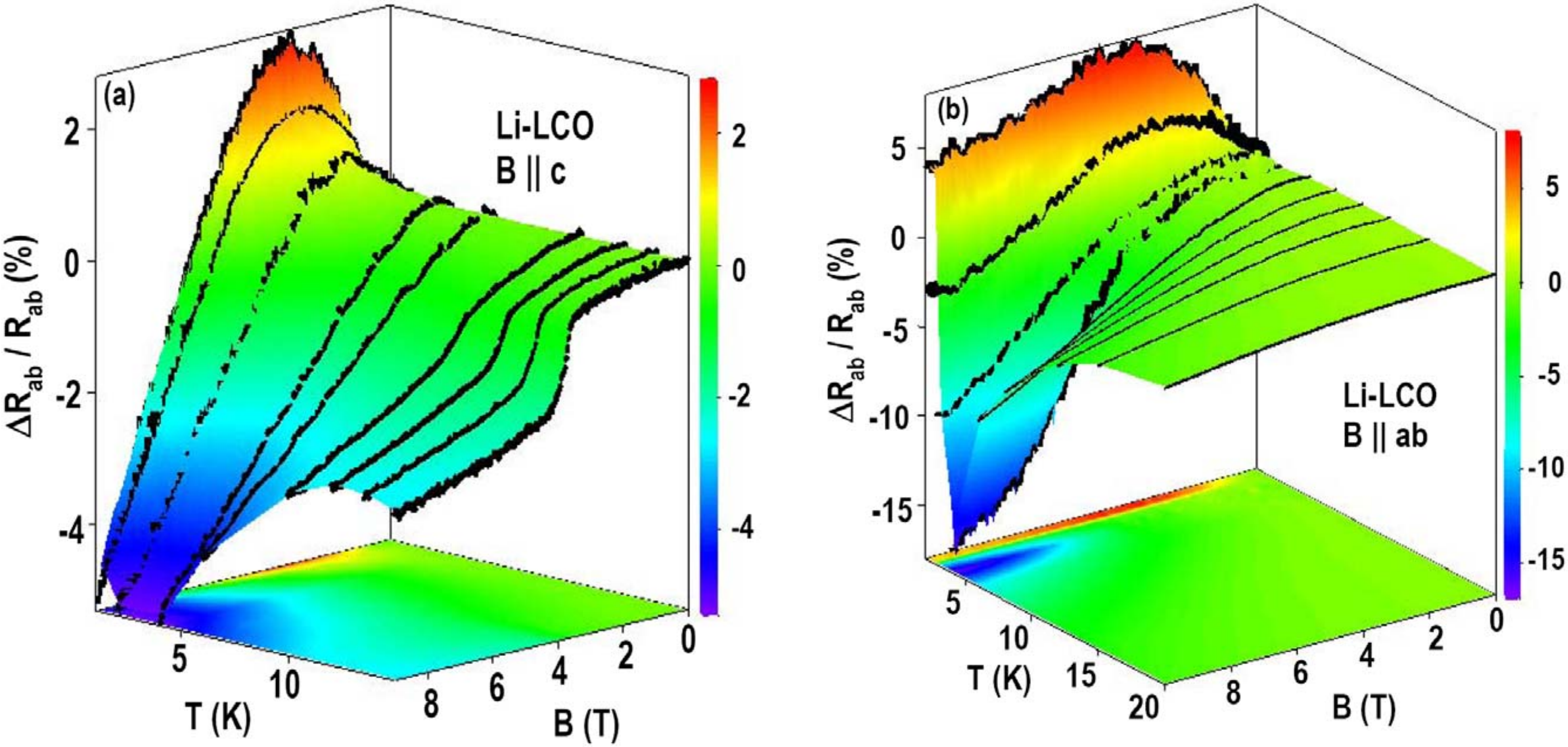
High T

- B || c
  - negative - steplike decrease (spin flop)
  - strong positive below ~ 12 K
- B || ab
  - negative ($\propto B^2$; smooth rotation of weak FM moments)

Low T

- B || ab: low-field positive MR below 3 K

In-plane MR – Li-LCO



<u>High T</u> **– negative MR**

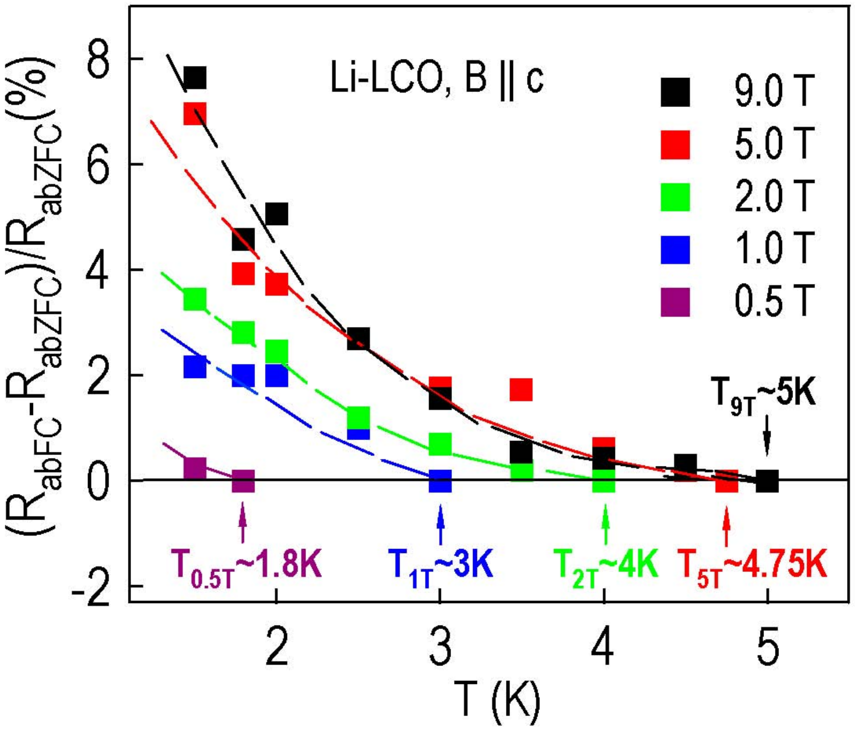
- **B || c – steplike decrease**
- **B || ab – B^2 dependence**

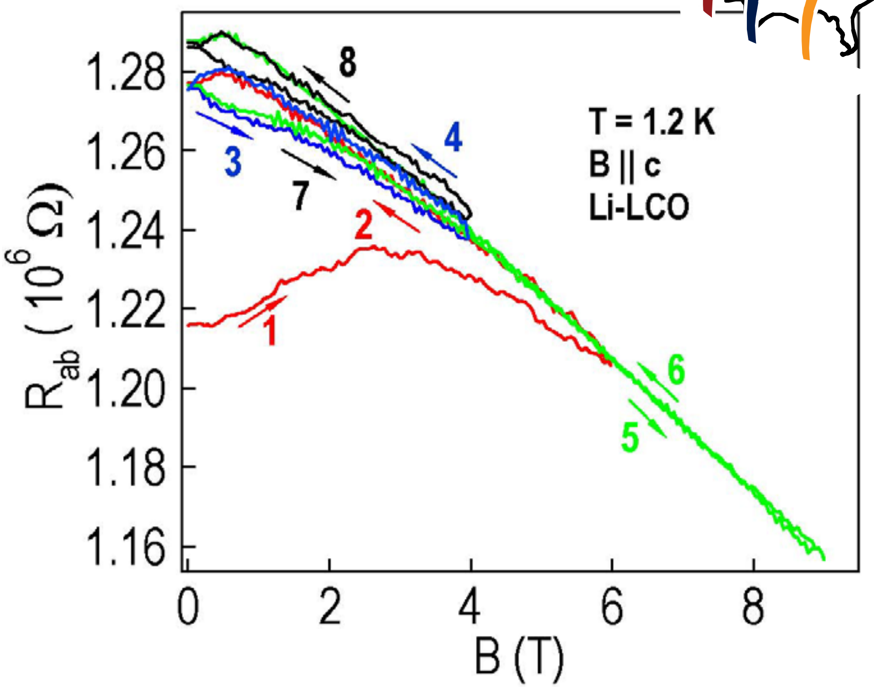
<u>Low T</u>

- **low-field positive MR below ~ 4K**

Li-LCO: glassy features in transport

• Same as in LSCO





History dependent behavior

$R_{FC} - R_{ZFC}$ decreases with increasing T and vanishes at a B-dependent T

• Memory – the highest applied field determines R(B=0)

• Hysteresis only in the region of (initial) positive MR

• Return point memory

Origin of the positive magnetoresistance

Li-LCO – insulating for all x ⟹ **superconducting fluctuations not the origin**

Exponential enhancement

$$R(B,T) = R(0,T)\exp\left(\frac{B^2}{B_0{}^2}\right)$$

not observed

hole localization length much smaller than the magnetic length

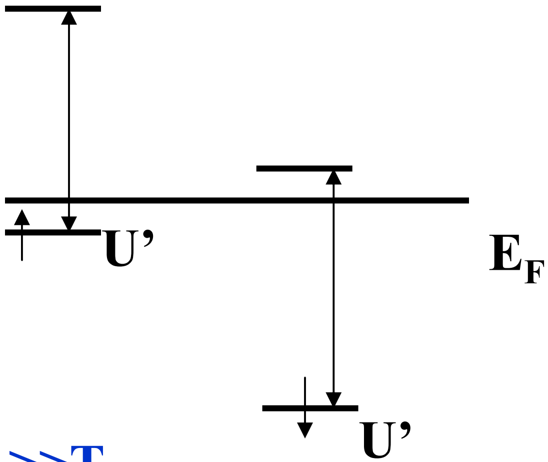
Orbital effects not the origin

Must be a spin related effect!!

Reorientation of weak ferromagnetic moments leads to **Negative, not positive MR**

Remaining possibility: **coupling of B** **to the** **spins of holes** **which populate localized states** **within Mott-Hubbard gap** **U**

Strongly disordered materials with Mott VRH and intra-state correlations (Coulomb repulsion U' between two holes in the same disorder-localized state)



U' >>T

- Spins of singly occupied states become parallel in strong enough B

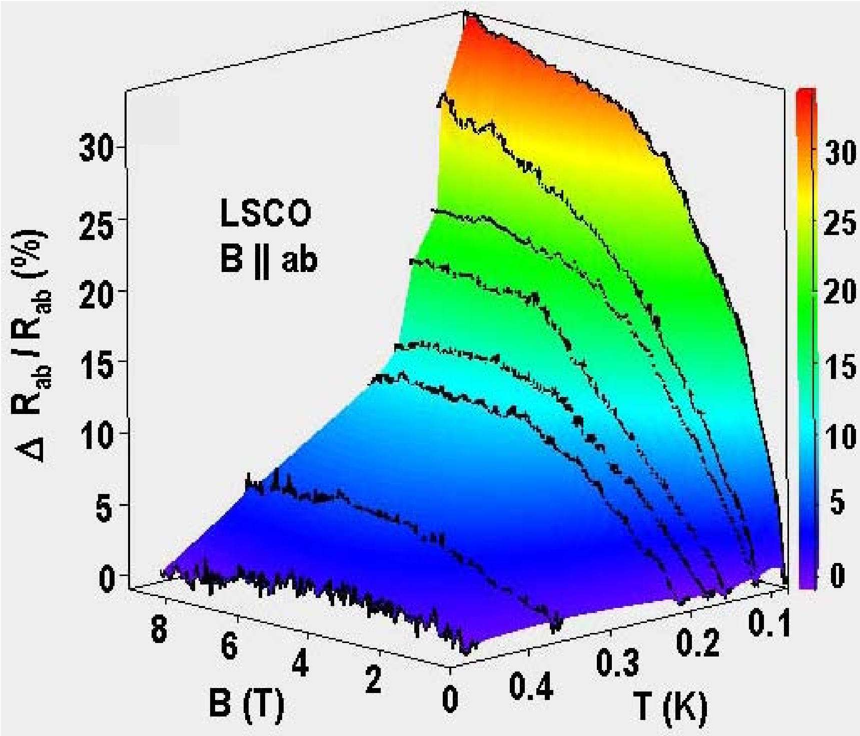
⇓

Zeeman splitting blocks some hopping channels ⇒ positive MR

[Kurobe, Kamimura, J. Phys. Soc. Jpn. 51, 1904 (1982)]

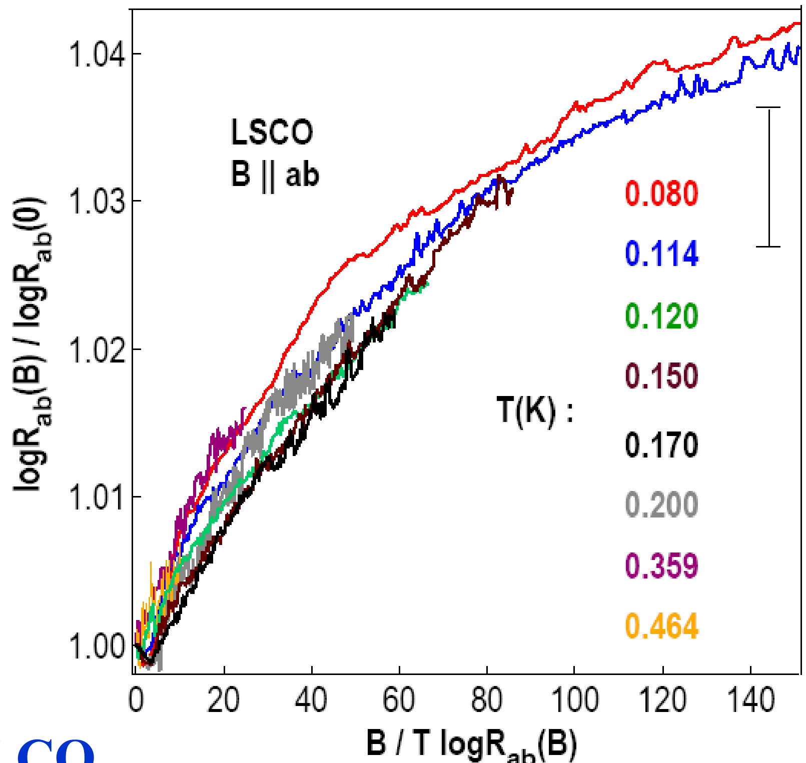
Positive MR in various nonmagnetic, disordered materials with strong Coulomb interactions attributed to this effect

Meir, Europhys. Lett. 33, 471 (1996): Positive MR due to Zeeman splitting - universal function of B/T log R



Test this prediction:

same data replotted



All data in the regime of positive MR collapse onto one function of a single scaling parameter!

- Scaling works for both LSCO and Li-LCO
- It appears that the magnetic background remains inactive in this regime of T and B (frozen spins/AF domains; holes that "live" in domain walls – analogous to other disordered, interacting systems)

Conclusions

Lightly doped La_2CuO_4 : two different transport regimes within the spin glass phase

1) <u>"High T"</u> < T_{sg}: - magnetic structure important ⇒ negative MR

2) <u>Low T,</u> T → 0 limit (*i.e.* T < 1 K in practice):

- **glassy charge dynamics (noise); charge cluster glass, $T_{cg}=0$**
- **positive MR with hysteresis and memory**
- **magnetic structure not important, to leading order**
- **U' on disorder-localized state important (U'~20 K in LSCO)**

As T→0, behavior characteristic of systems that are far from any magnetic ordering

Use hysteretic, positive MR as an easy tool for detecting charge glassiness confined to the domain walls: intrinsic or driven by disorder?

Хвала!