Nonequilibrium dynamics in Coulomb glasses near the metal-insulator transition

Dragana Popović

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

Boulder 2009 Summer School

Supported by NSF DMR and NHMFL (NSF and the State of Florida)

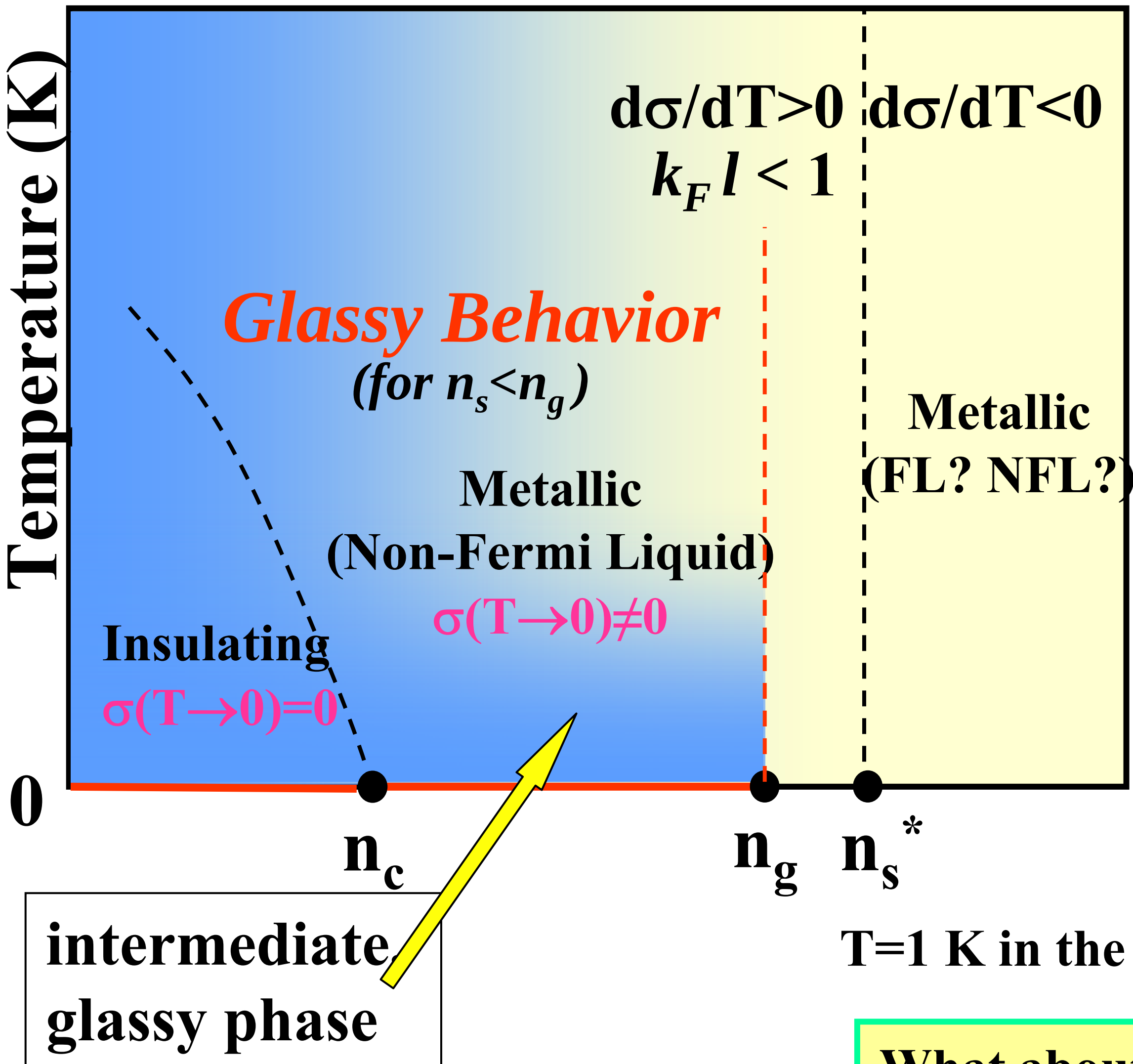
Lecture I: Metal-insulator transition and complexity in electronic systems

Lecture II: Studies of the electron dynamics near the 2D MIT: Relaxations of conductivity

Lecture III: Studies of the electron dynamics near the 2D MIT: Fluctuations of conductivity

- Phase diagram and aging in a 2DES in Si – brief summary
- Noise measurements as a probe of glassiness in low- and high-mobility samples:
  - probability density functions
  - noise power spectrum
  - second spectrum
- Noise measurements in a magnetic field
- Theory, simulations, experiments in other systems

Phase diagram of a 2DES in Si



Glassy regime:

- slow, nonexponential relaxations
- diverging τ_{eq} (T_g=0)
- aging (change at the MIT)

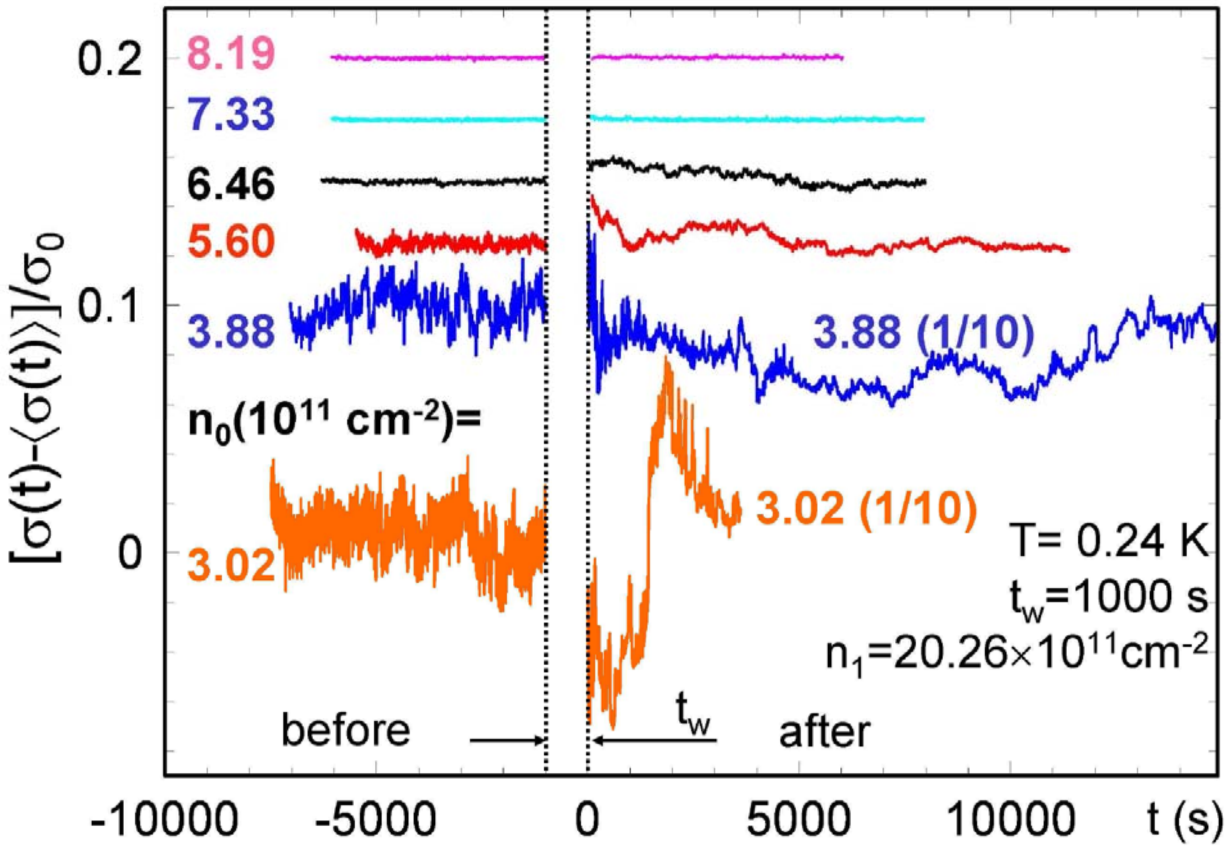
Waiting time protocol for each density n_s:

- fix n_s at 10 K
- cool down to meas. T
- change n_s to a different value during t_w
- back to the initial density and measure $\sigma(t)$
- warm up to 10 K; repeat for different t_w

T=1 K in the waiting time protocol

What about aging at lower T?

Waiting time protocol at T=0.24 K



slowly relaxing <σ(t)> subtracted (only top 3 traces)

Much more noise after t_w (during aging) than before

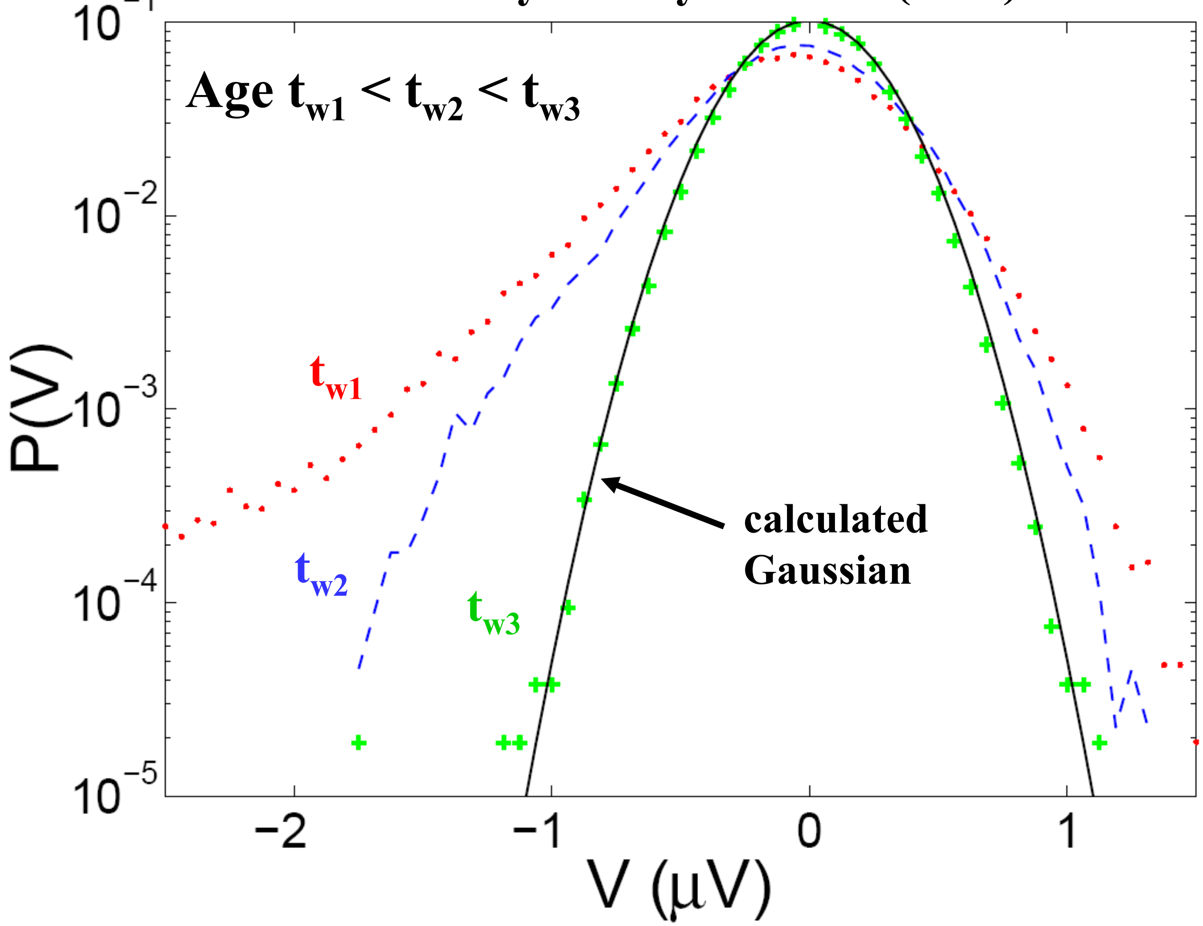
Before: signal noisier at low n_s

Study fluctuations (noise) at low T

provides complementary information; so far, only mean values of conductivity

Noise in Laponite (colloidal suspension)

Probability density function (PDF)



non-Gaussian

↓

Gaussian

as it ages and approaches equilibrium

(Buisson *et al.*, Proc. SPIE 5469, 95 (2004); edited by Popović, Weissman, Rácz)

Noise protocol:

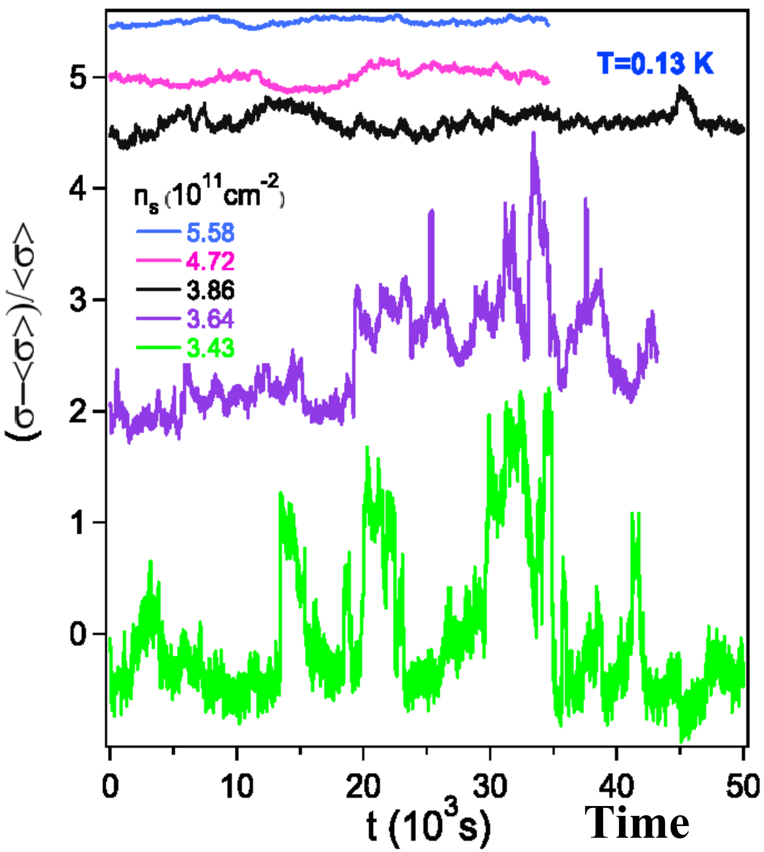
- start from a fixed n_s at high T (*e.g.* 10 K)
- cool down to measurement T (< 1 K)
- measure σ(t)
- warm up to ~1 K;
  change V_g (density n_s) by a small amount – no observable relaxations
- cool down to measurement T (< 1 K)
- measure σ(t) for this new density
- repeat (warm up to ~1 K, change n_s in a small step, cool down, measure σ(t))

Noise protocol: density changed in tiny steps at ~1 K (not at 10 K)

Noise in low-mobility Si MOSFETs

[S. Bogdanovich and D. Popović, PRL 88, 236401 (2002)]

Conductivity



Time

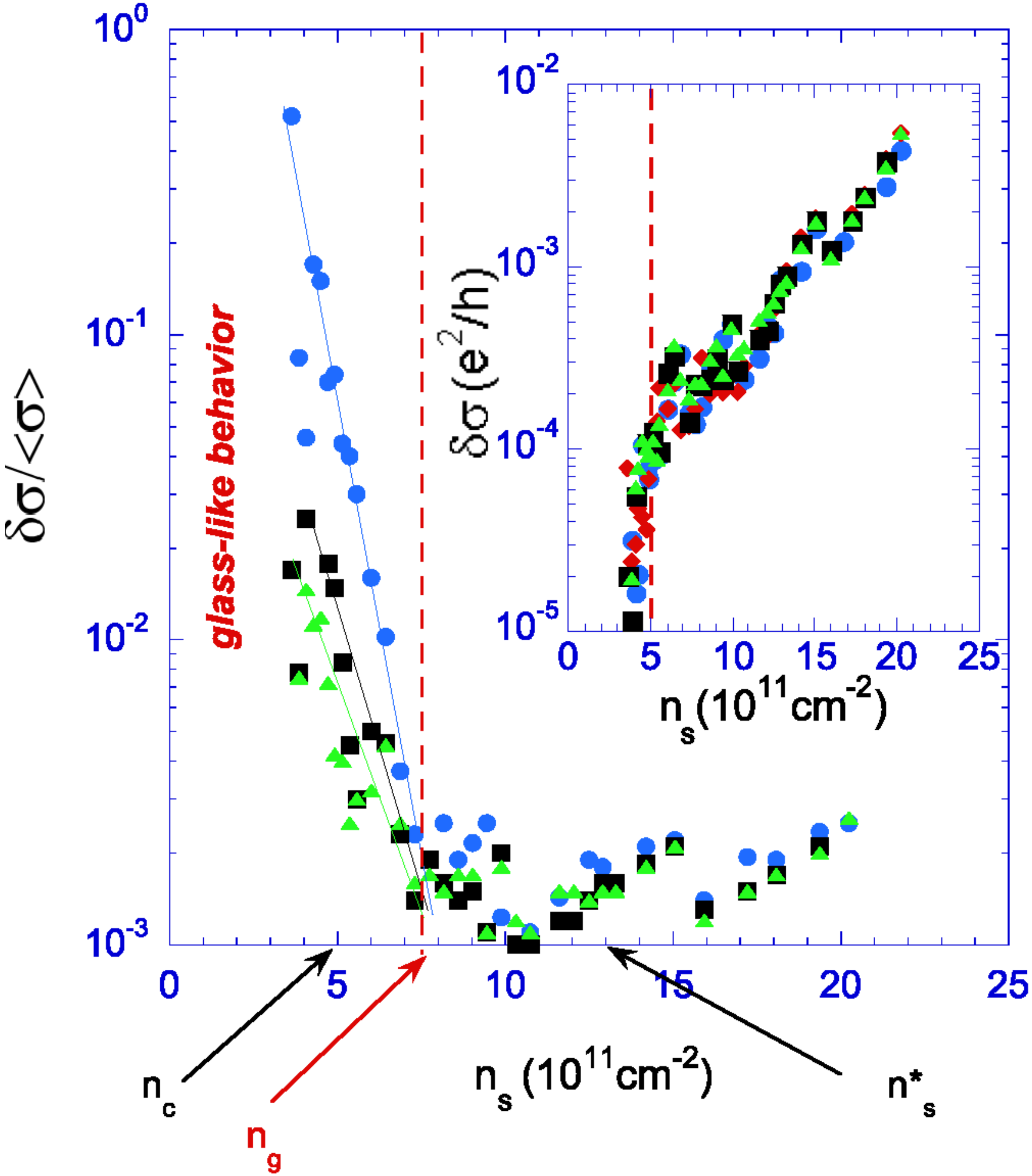
- relative fluctuations are of the order of 100% at low n_s and T
- noise decreases with increasing n_s and T
- non-Gaussian
- the character of the noise changes dramatically as n_s is varied: at high n_s, the variance no longer varies with time

$\langle\sigma\rangle$ - time averaged conductivity

variance:

$\delta\sigma^2 = \langle(\sigma - \langle\sigma\rangle)^2\rangle$

Large, slow, and non-Gaussian at low n_s and T!



T=0.130 K

T=0.196 K

T=0.455 K

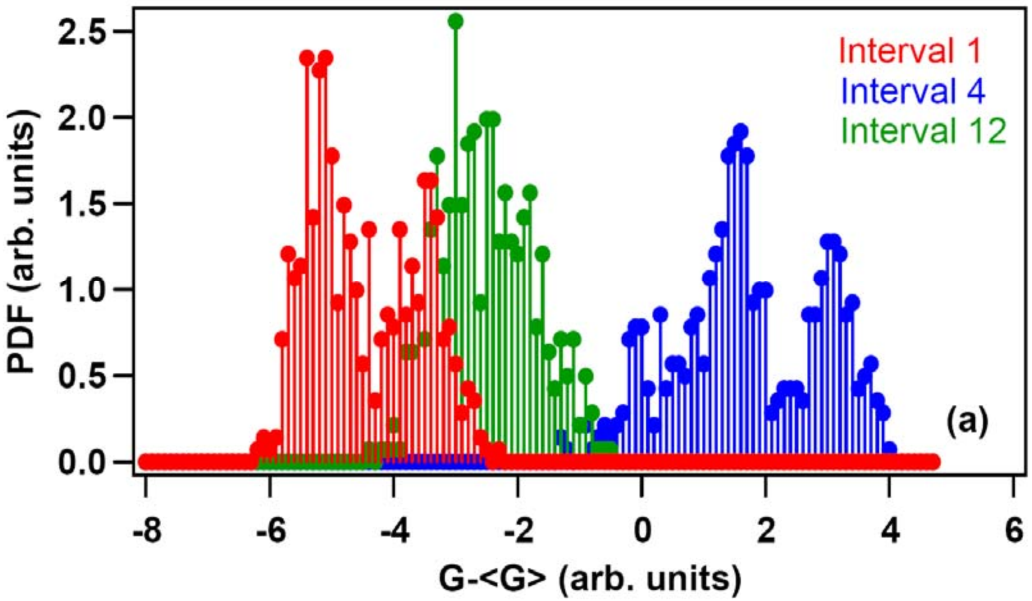
T=0.805 K

$$\delta\sigma = \langle(\sigma - \langle\sigma\rangle)^2\rangle^{1/2}$$

- **a dramatic change of $d(\delta\sigma)/dn_s$ at n_c (2D MIT)**
- **a dramatic increase of noise ($\delta\sigma/\langle\sigma\rangle$) at n_g (glass transition)**
- **glassy phenomena observed below n_g**

Probability density functions (PDF) of fluctuations

- PDF: - Gaussian for $n_s > n_g$
  - non-Gaussian for $n_s < n_g$



Low-mobility sample

T=0.13 K

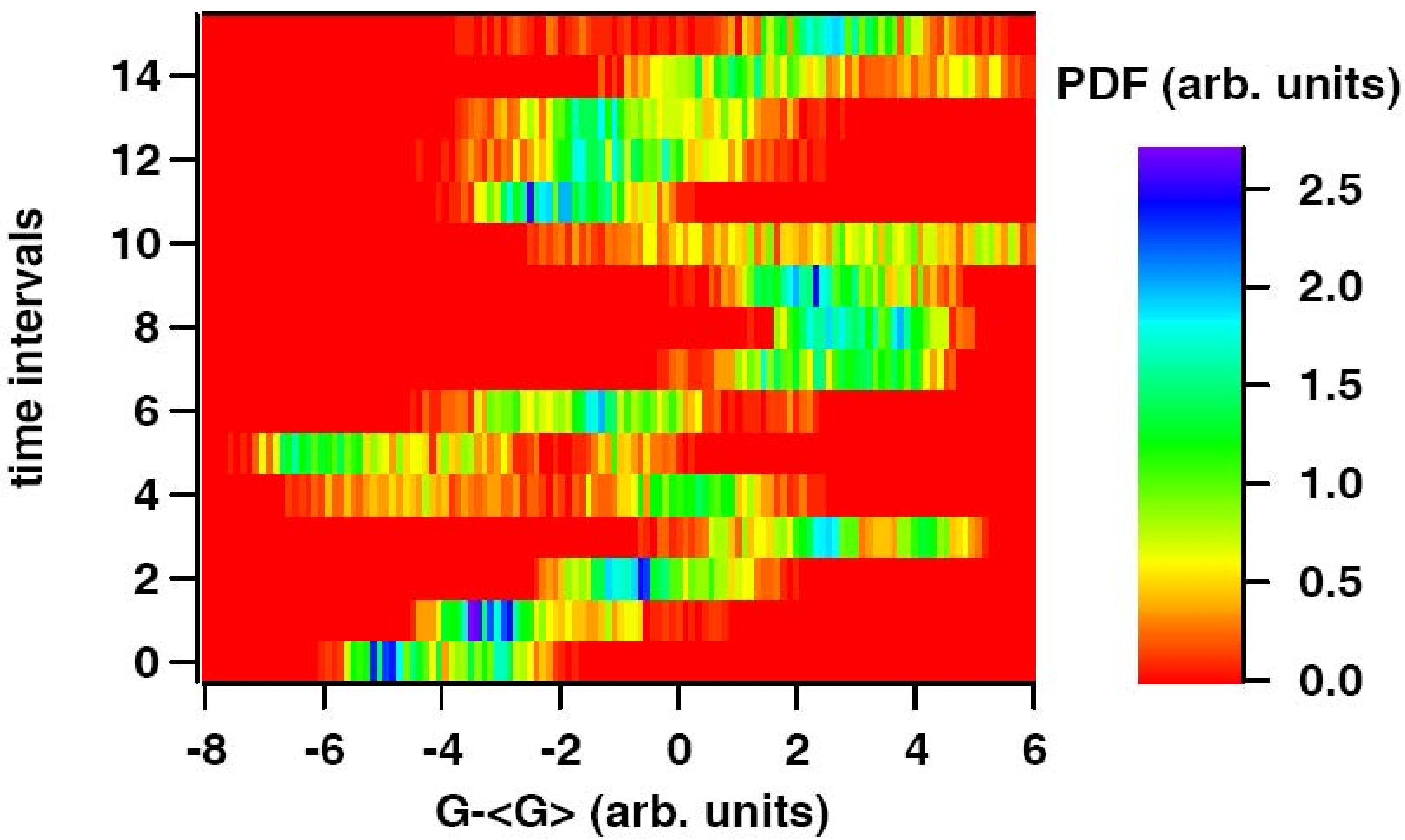
$n_c < n_s(10^{11}\ cm^{-2})=5.58 < n_g$

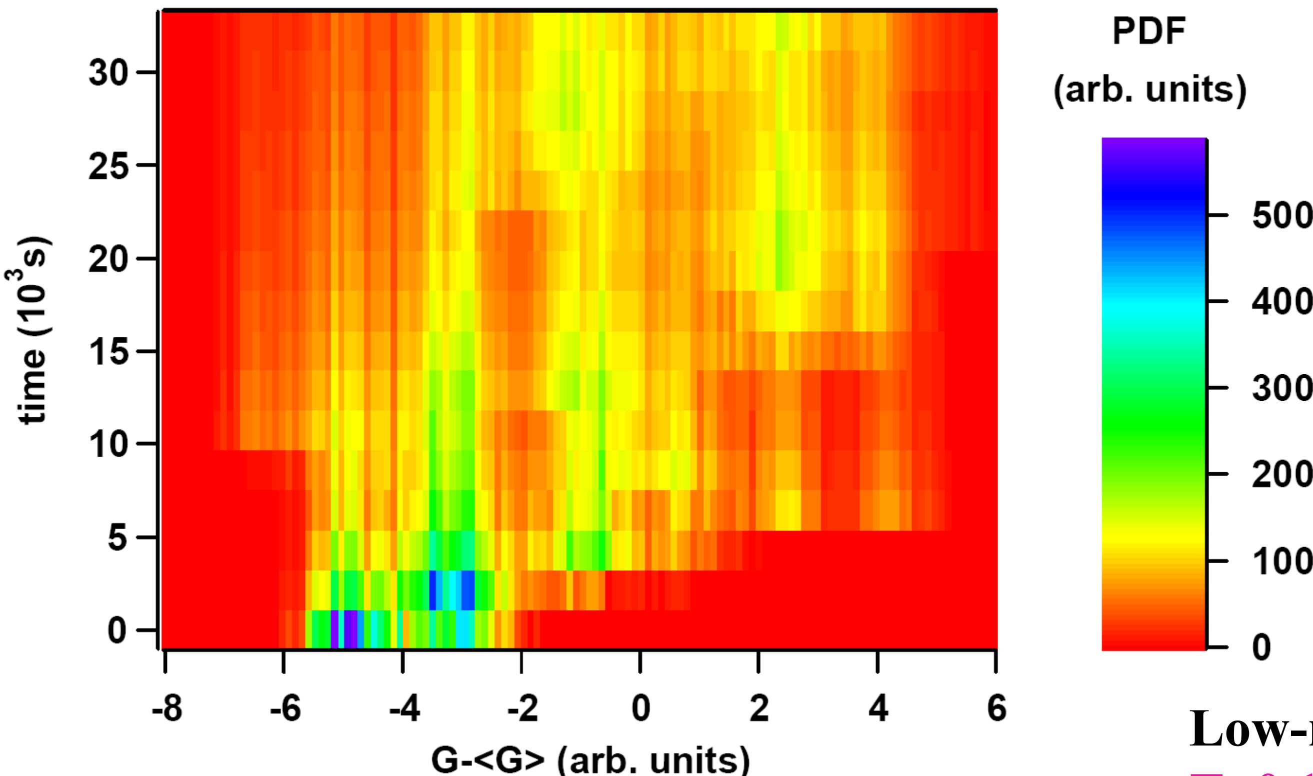
(metallic glassy phase)

Each time interval ≈ 35 minutes

- structure changes with time

PDF for sixteen different 35 minute intervals:





Low-mobility sample

T=0.13 K

$n_c < n_s(10^{11}\ cm^{-2})=5.58 < n_g$

Each time interval ≈ 35 min

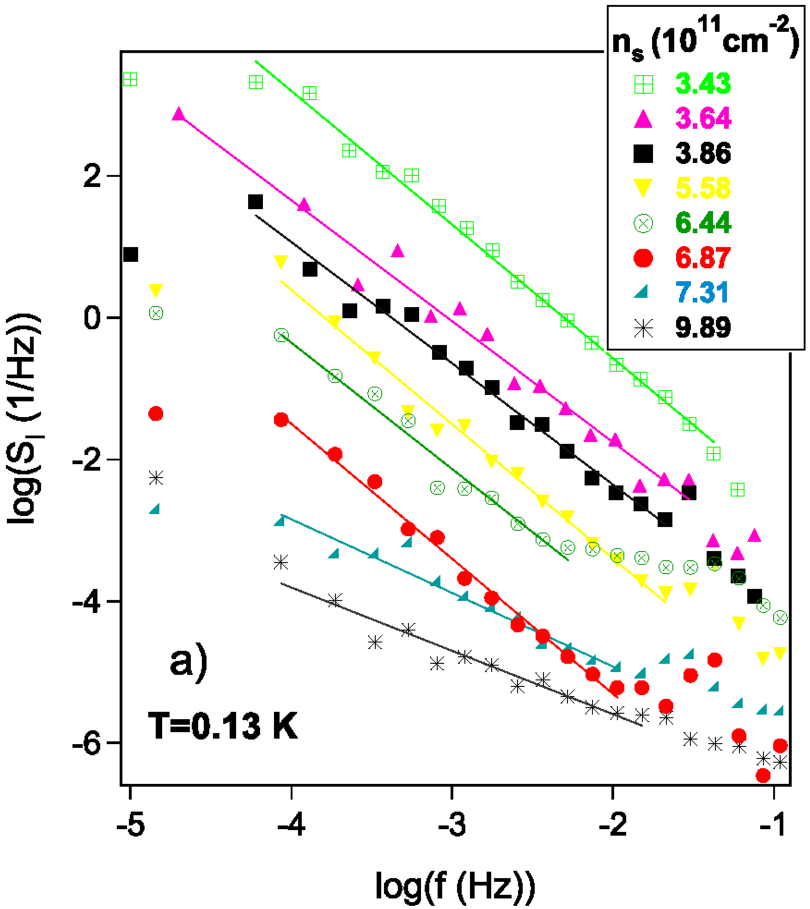
- **broadens with the increasing sampling time but never becomes Gaussian**

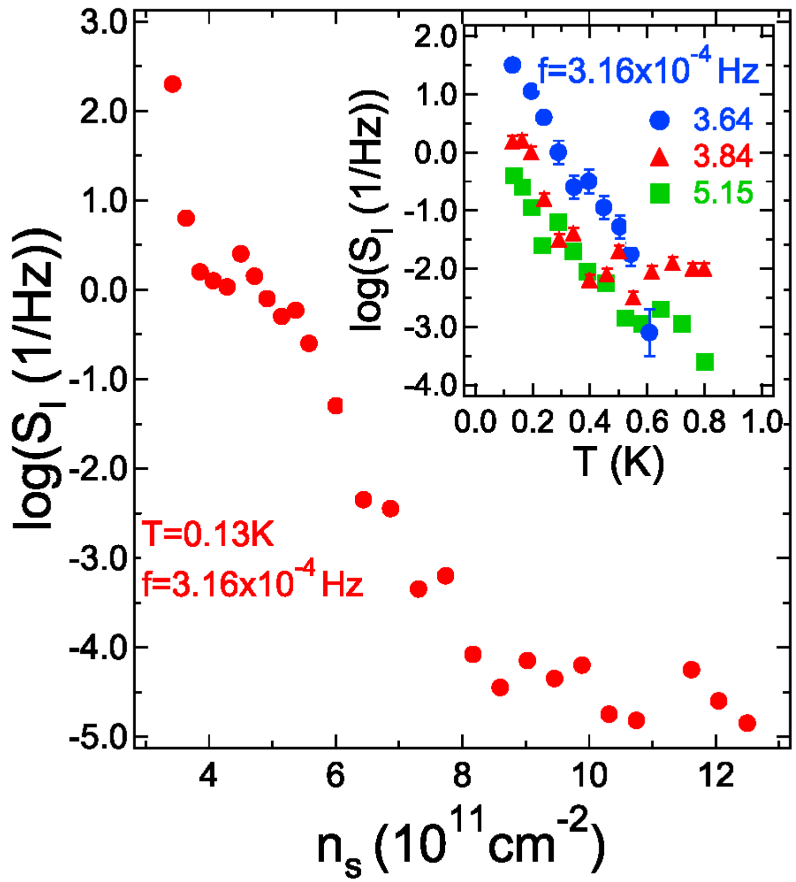
• **nonergodic on experimental time scales**

Noise power spectrum (low-mobility samples):

Power spectrum of [σ(t)-<σ>]/<σ>:

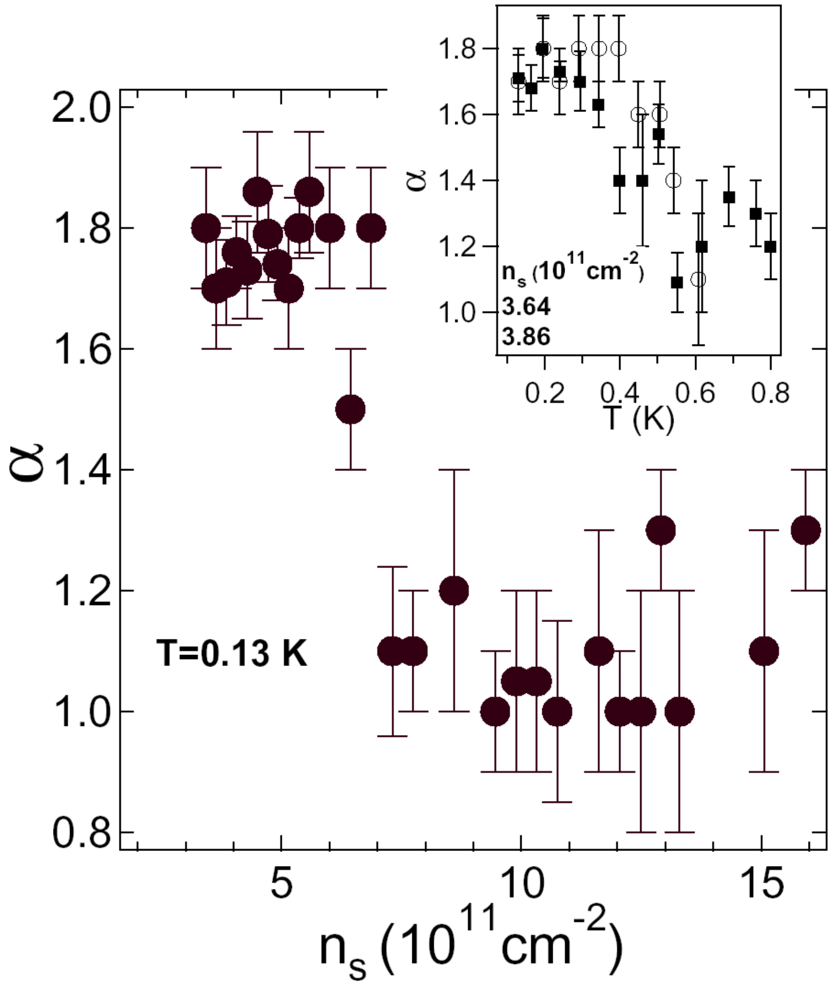
$S_I \propto 1/f^{\alpha}$





- a sudden and dramatic slowing down of the electron dynamics for $n_s < n_g \approx 7.5\times10^{11}$ cm^{-2}

Noise exponent α has a <u>sudden jump</u> at $n_s = n_g$!



$S_I \propto 1/f^{\alpha}$

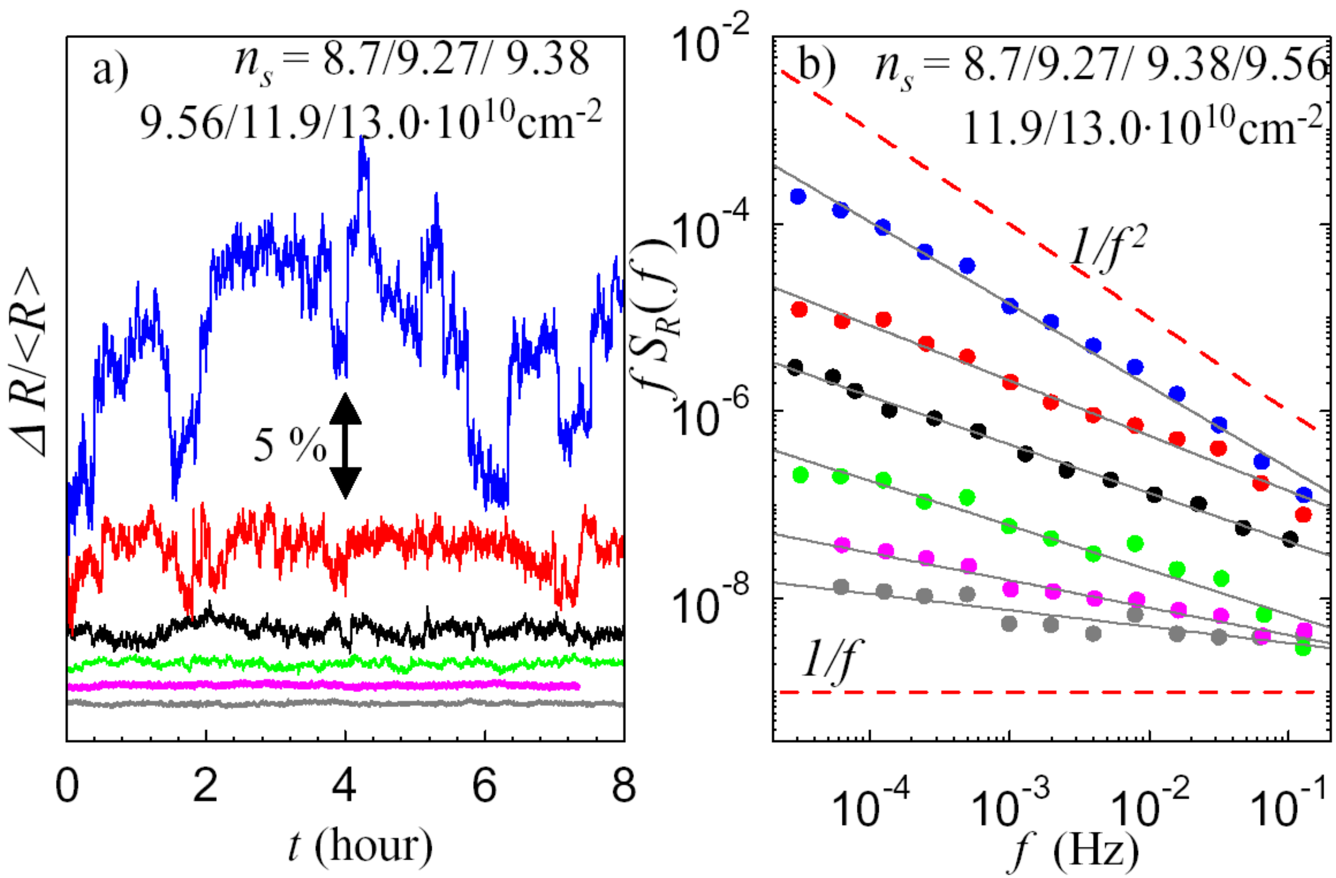
- a sudden shift of the spectral weight towards lower *f* indicates a sudden (sharp) and dramatic slowing down of the electron dynamics at n_g

- observable only at low enough temperatures

Use noise to identify the glass transition!

[Bogdanovich and Popović, PRL 88, 236401 (2002)]

Resistance noise and power spectra in high-mobility (low disorder) Si MOSFETs



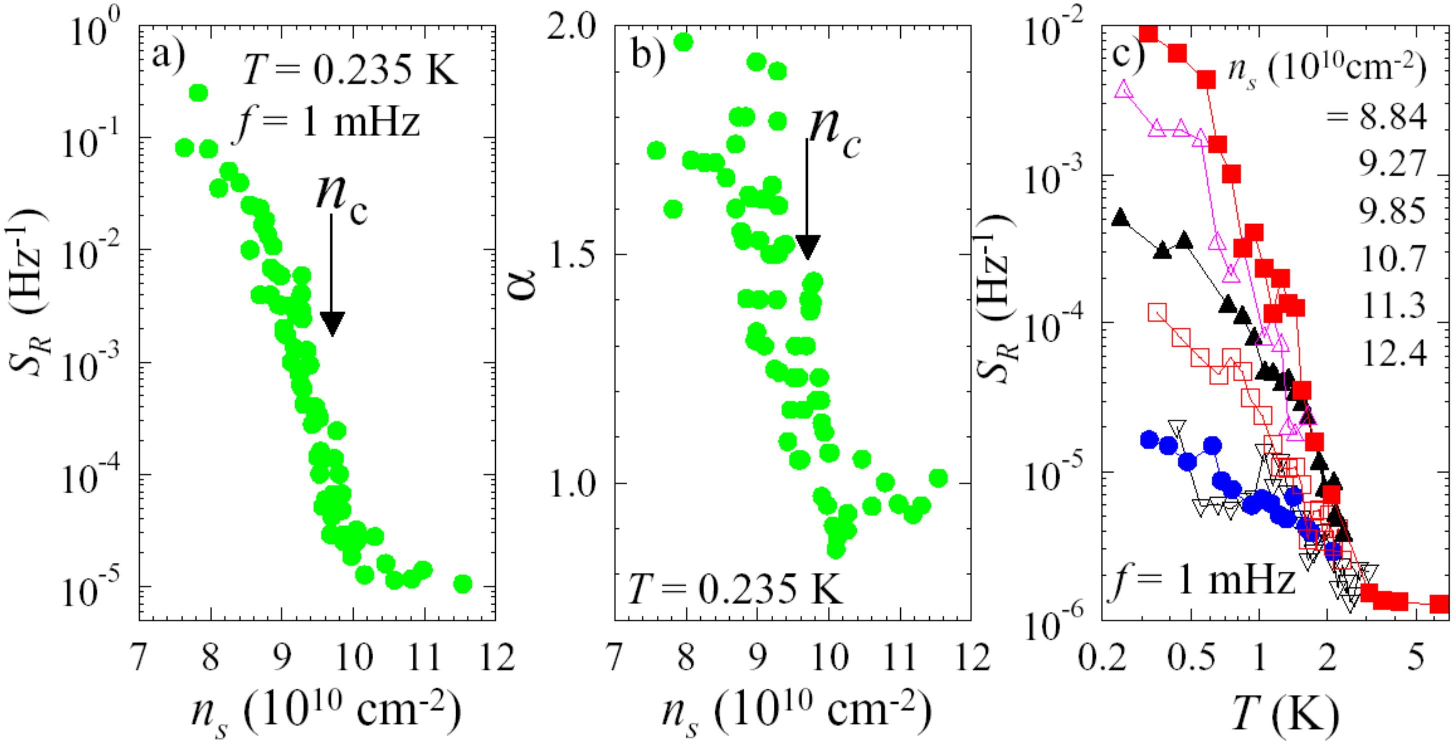
T=0.24 K

$S_R \propto 1/f^{\alpha}$,

$1 \leq \alpha \leq 2$

[Jaroszyński, Popović, Klapwijk, PRL 89, 276401 (2002)]

Noise in samples with <u>low disorder</u>:

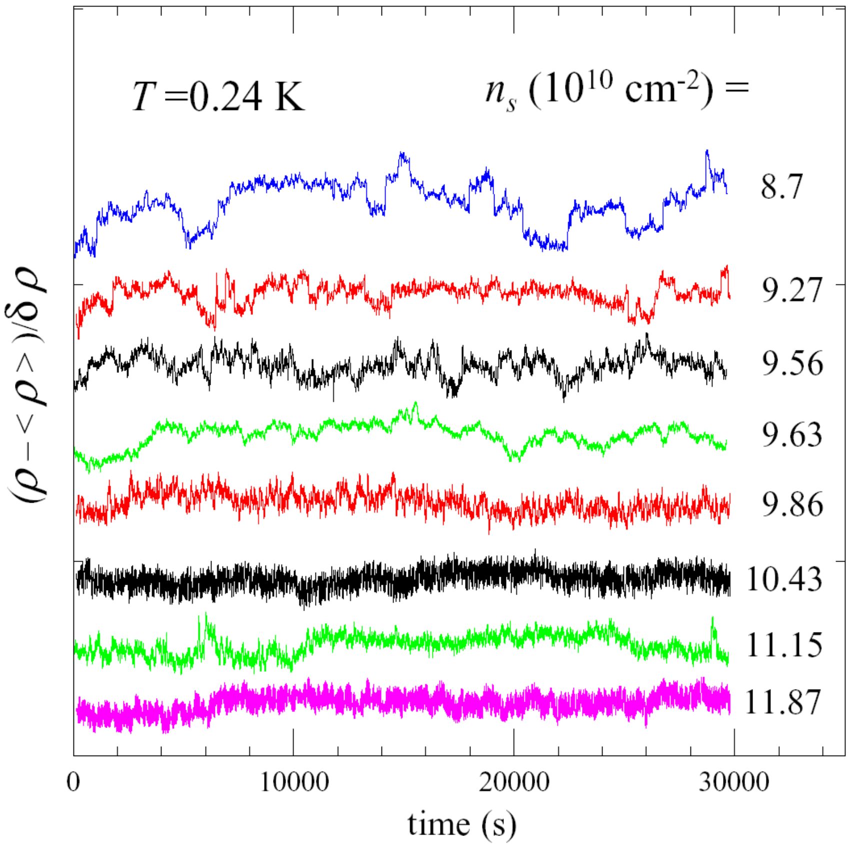


- **a dramatic increase of the low-frequency noise at low n_s and T**
- **a rapid increase of the exponent α with decreasing n_s**

$\Rightarrow$ Glass transition at $n_g \approx 10\times10^{10}$ cm$^{-2} \geq n_c$

Glass transition and the MIT almost coincide – no intermediate phase

Noise in high-mobility Si MOSFETs:



- non-Gaussian at low n_s and T
- variance changes with time

↓

check higher order correlations

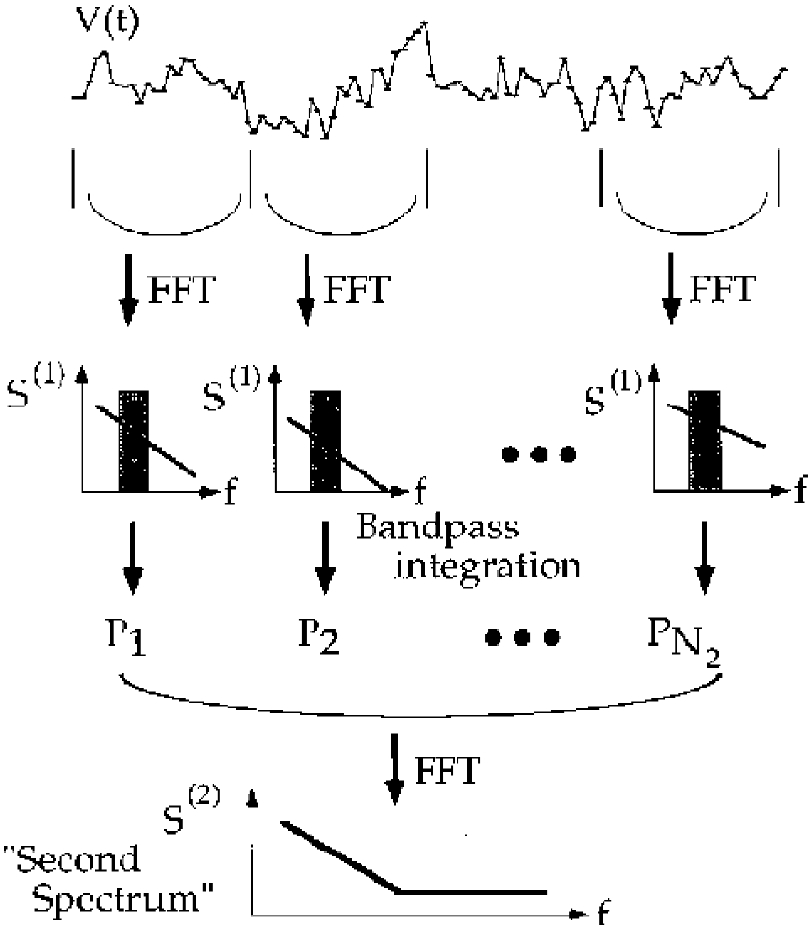
[Weissman:
Rev. Mod. Phys. 60, 537 (1988);
Rev. Mod. Phys. 65, 829 (1993)]

ρ - resistivity
<ρ> - time-averaged resistivity
$\delta\rho^2$ = variance

Second spectrum – “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



[*i.e.* Fourier transform of the autocorrelation function of the time series of $S_R(f)$; fourth-order noise statistic]

- probes correlations between fluctuators:

  uncorrelated fluctuators

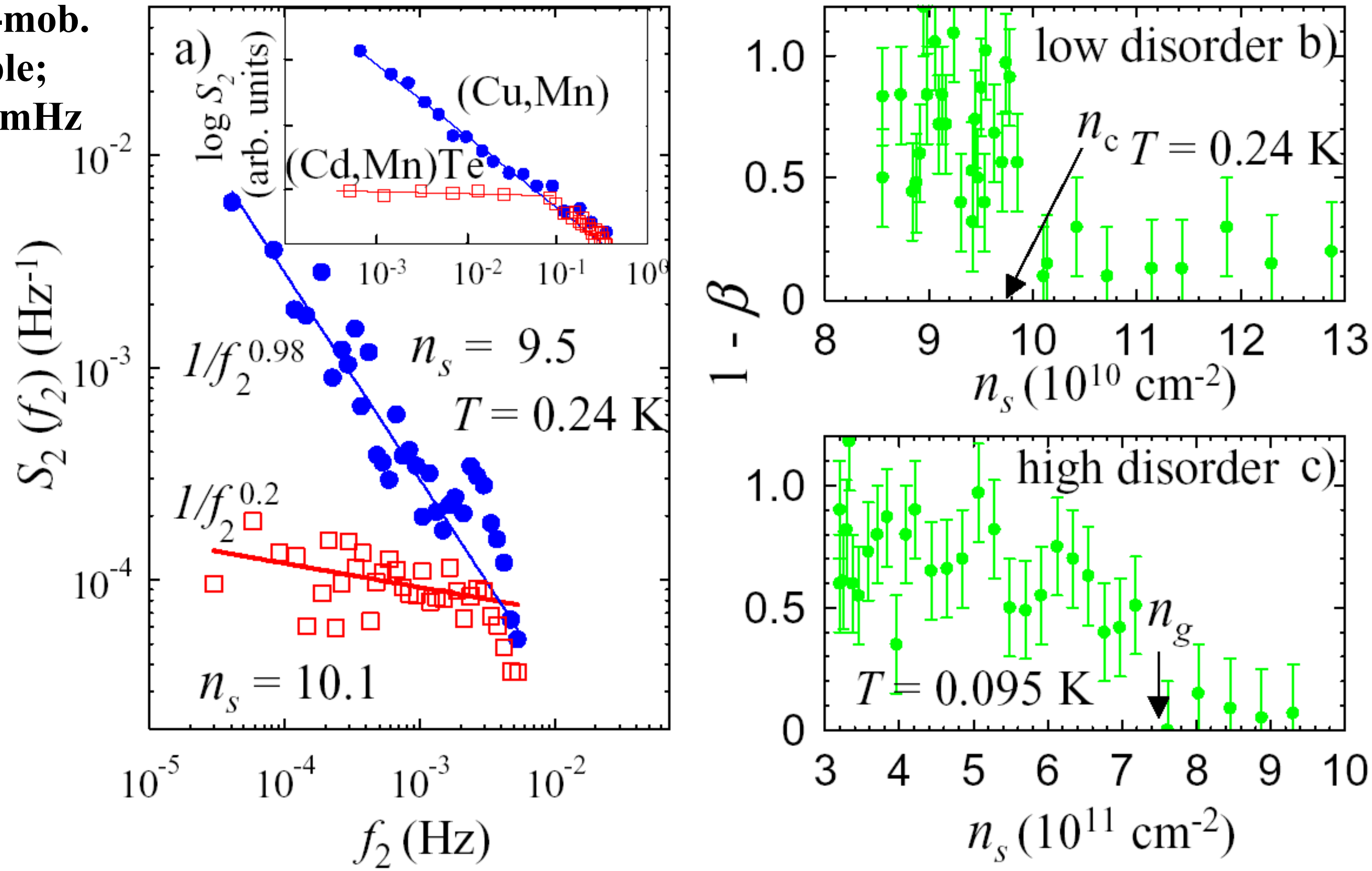
  $\Rightarrow$ $S_2(f_2,f)$ white;

  correlated fluctuators

  $\Rightarrow$ $S_2 \propto 1/f_2^{\,1-\beta}$ (non-Gaussian)

Second spectrum in a 2DES in Si:

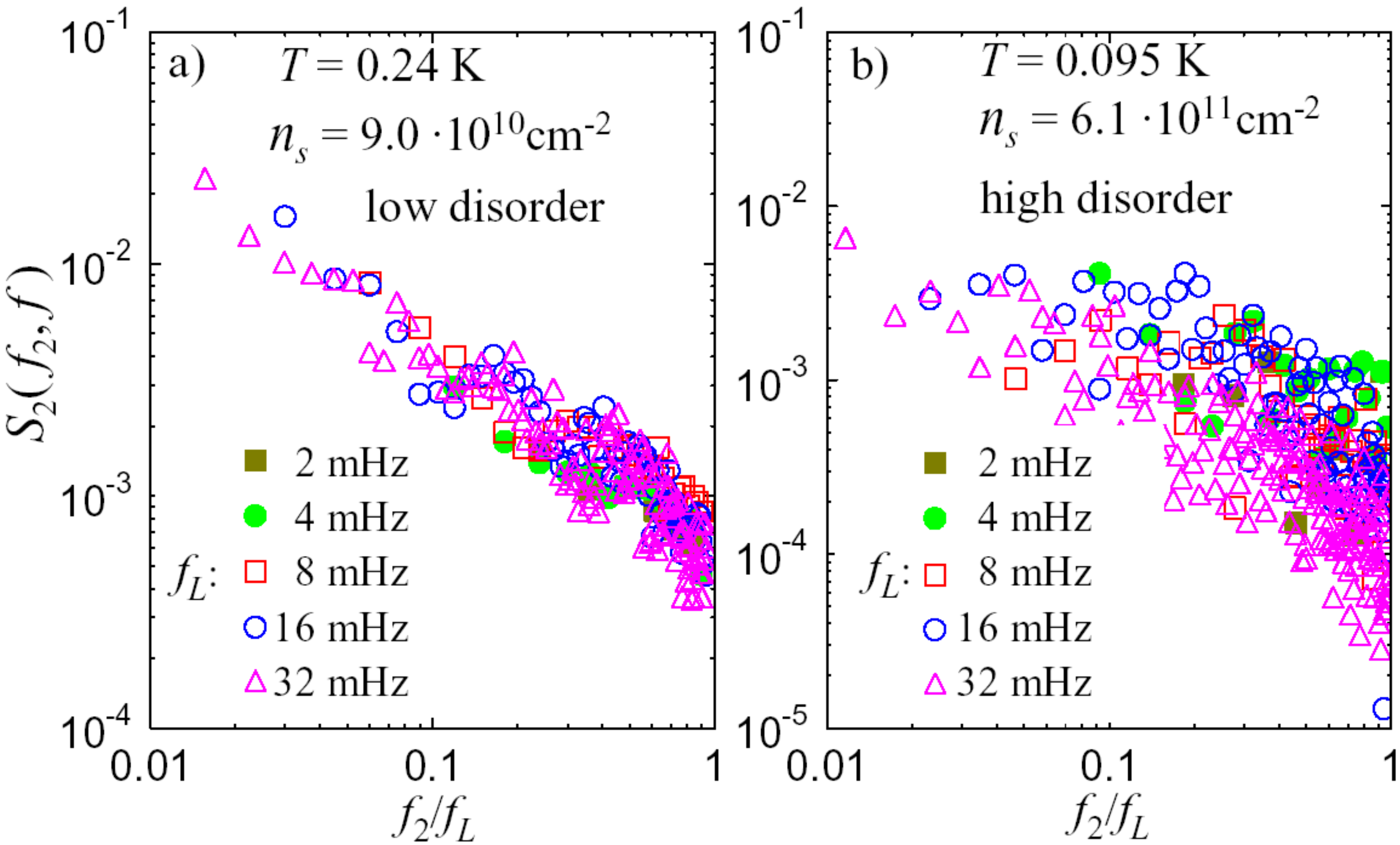
high-mob. sample; f_L=1 mHz



- **a dramatic change in S_2 near n_g: S_2 white – uncorrelated at high n_s, S_2 nonwhite – correlated below n_g**
- **high-mobility samples: $n_c \lesssim n_g \sim n_s^*$ (no intermediate phase)**
- **low-mobility samples: $n_c < n_g \approx 1.5n_c < n_s^*$ (wide intermediate phase)**

Scaling of the second spectra

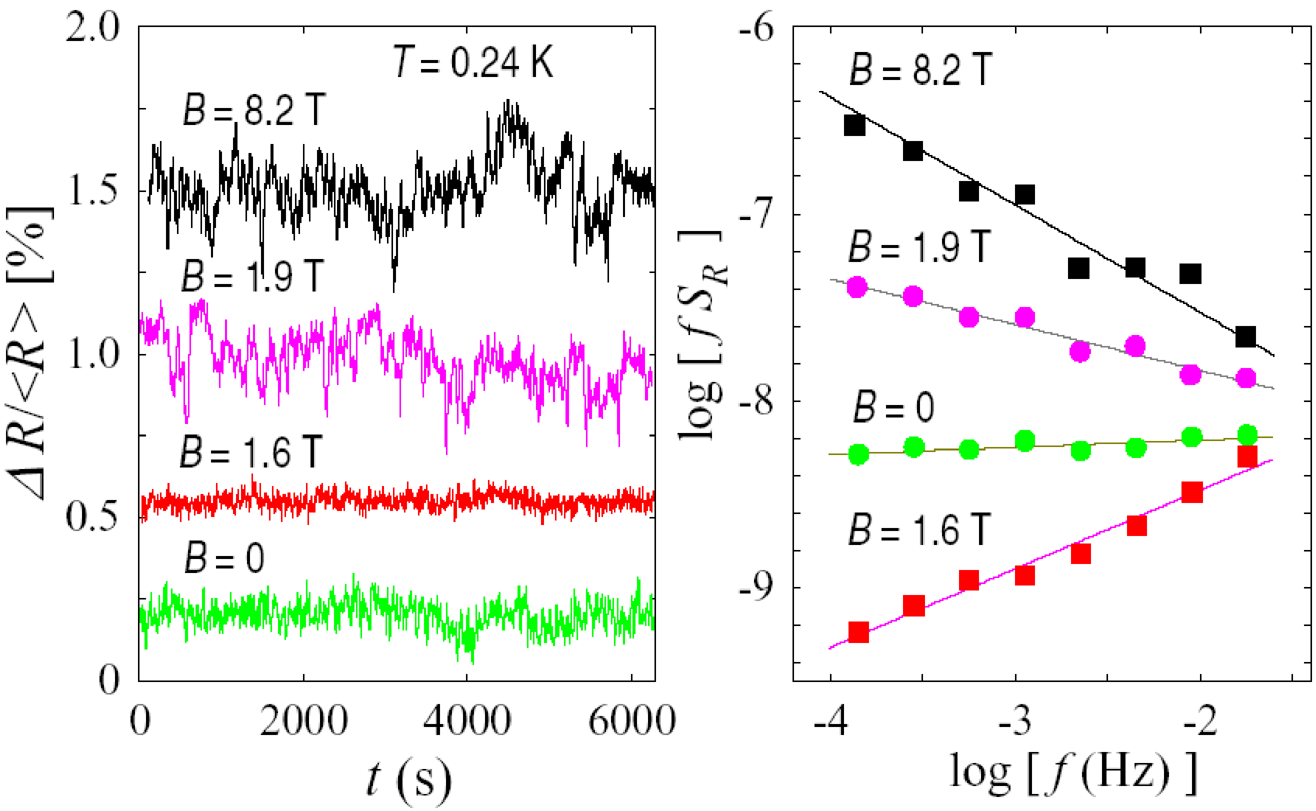
[measured at $f = (f_L, 2 f_L)$]



- **no systematic dependence on f $\Rightarrow$ scale invariance**
- **consistent with the hierarchical picture of glassy dynamics**
- **rules out interacting two-state systems (droplets, clusters, defects, …) as possible sources of noise**

Noise measurements in parallel magnetic fields: spin or charge?

- a sufficiently strong magnetic field is expected to destroy the spin glass order; 2DES fully spin polarized for B≈2-4 T



$S_R \propto 1/f^{\alpha}$

α=1.58

α=1.24

α=0.96

α=0.58

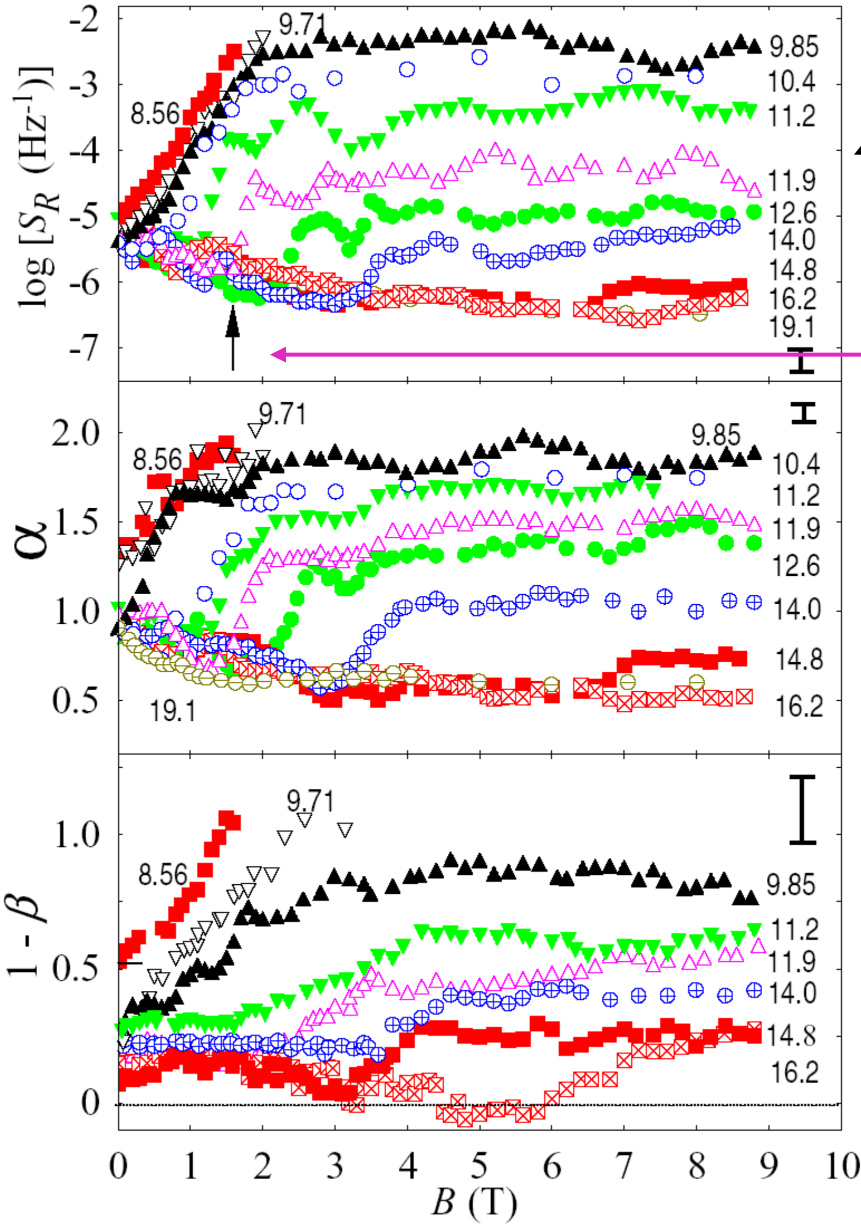
(high-mobility samples)

n_s=11.9×10^{11} cm^{-2} > n_c(B=0)

Same analysis as before:

f=1 mHz

$n_s(10^{10}\ cm^{-2})$



B_g for $n_s=11.9\times10^{10}\ cm^{-2}$

$S_R \propto 1/f^{\alpha}$

$S_2 \propto 1/f^{\,1-\beta}$

The same criteria for glass transition:

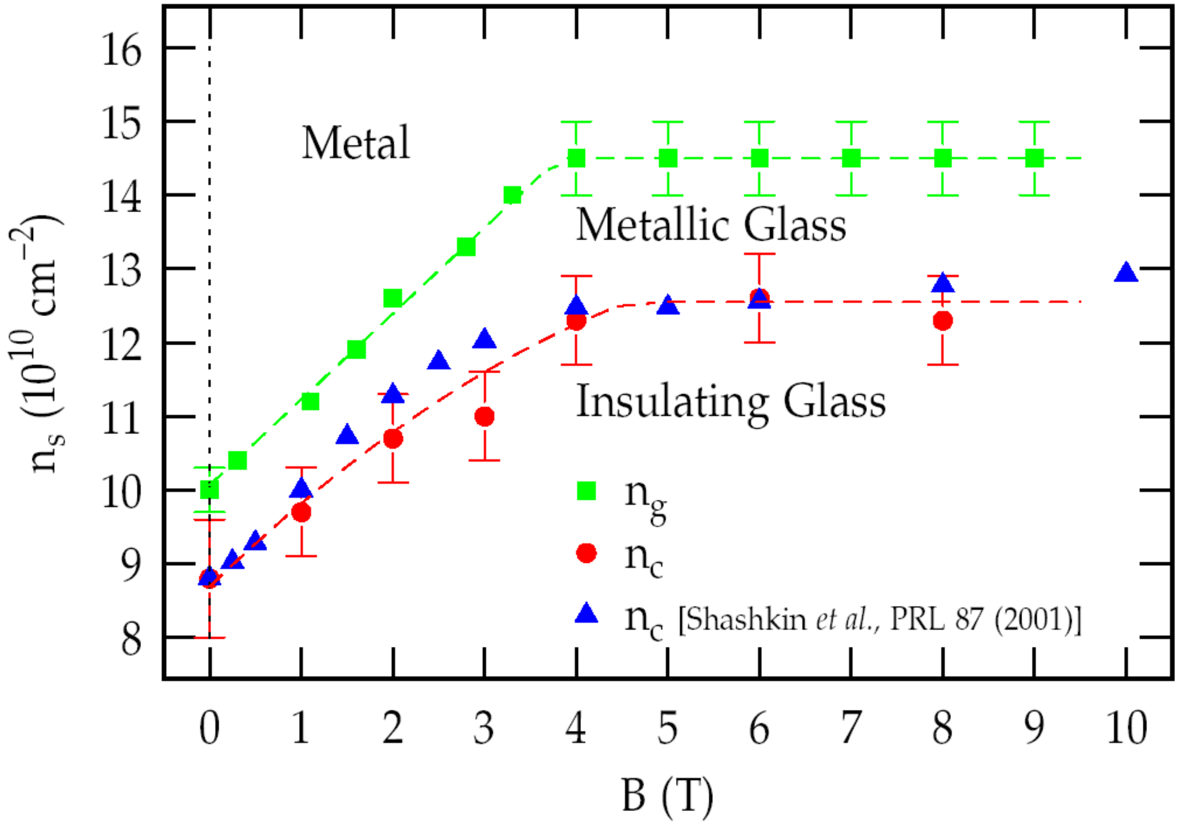
- **a sudden and dramatic increase of S_R, a rapid rise of α, and a change of $(1-\beta)$ at $B_g(n_s)$ at low B and $n_g(B)$ at high B**

glass transition at $B_g(n_s)$ and $n_g(B)$

Phase diagram in B

[Jaroszyński, Popović, Klapwijk, PRL 92, 226403 (2004)]

B ⟶ 2DES spin-polarized



n_g – glass transition

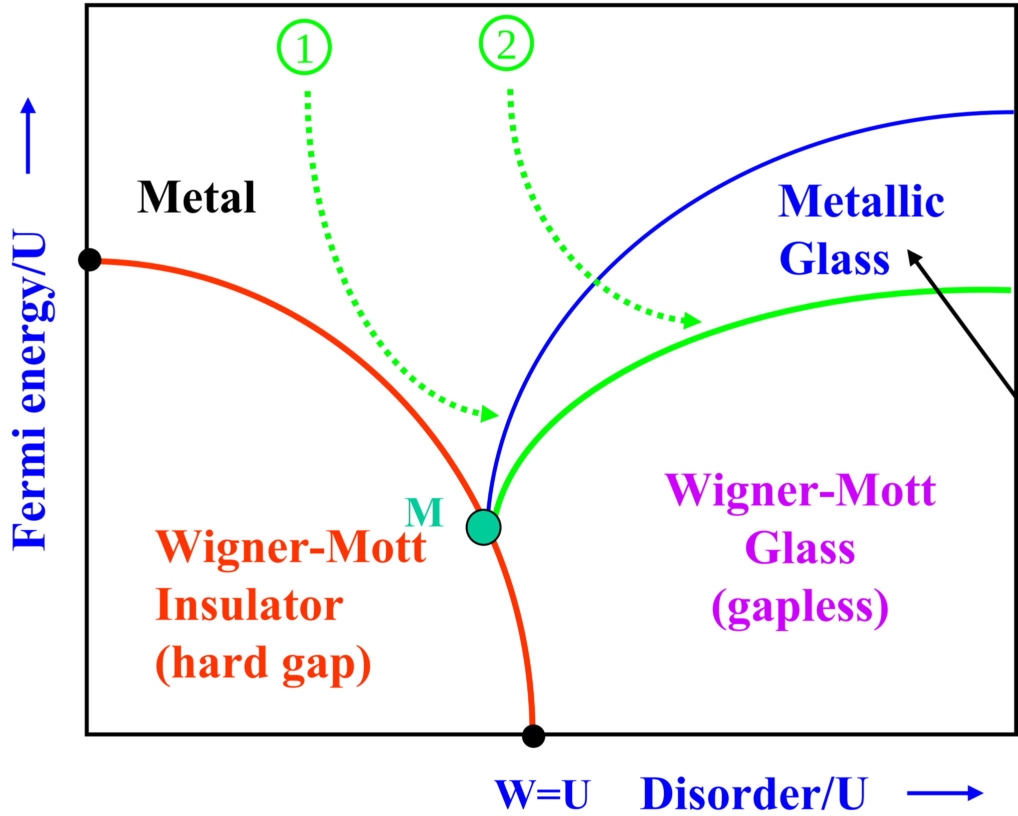
- glass transition persists in high parallel B, where the 2DES is spin polarized

⟹ charge, as opposed to spin, responsible for glassy ordering

Coulomb glass

[V. Dobrosavljevic *et* al.: PRL 83, 4642 (1999); PRB 66, 081107 (2002); PRL 90, 016402 (2003); PRL 91, 066603 (2003); EPL 67, 226 (2003);PRL 94, 046402 (2005)]

Global phase diagram (theory)



- (2D) MIT as a Mott transition with disorder (DMFT picture)
- glass as a precursor of MIT
- melting of glass even at T=0 (by quantum fluctuations)
- Metallic glass phase:

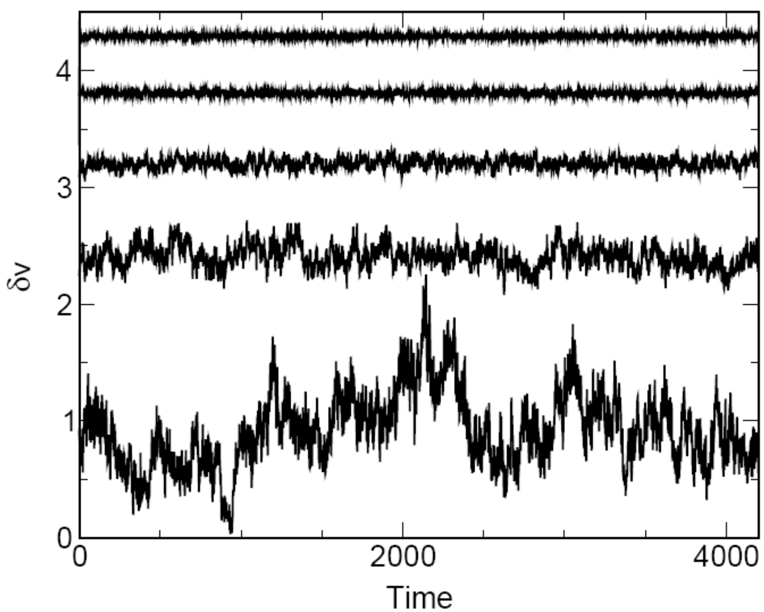
  $\sigma(T) - \sigma(0) \sim T^{3/2}$
- hierarchical, correlated dynamics

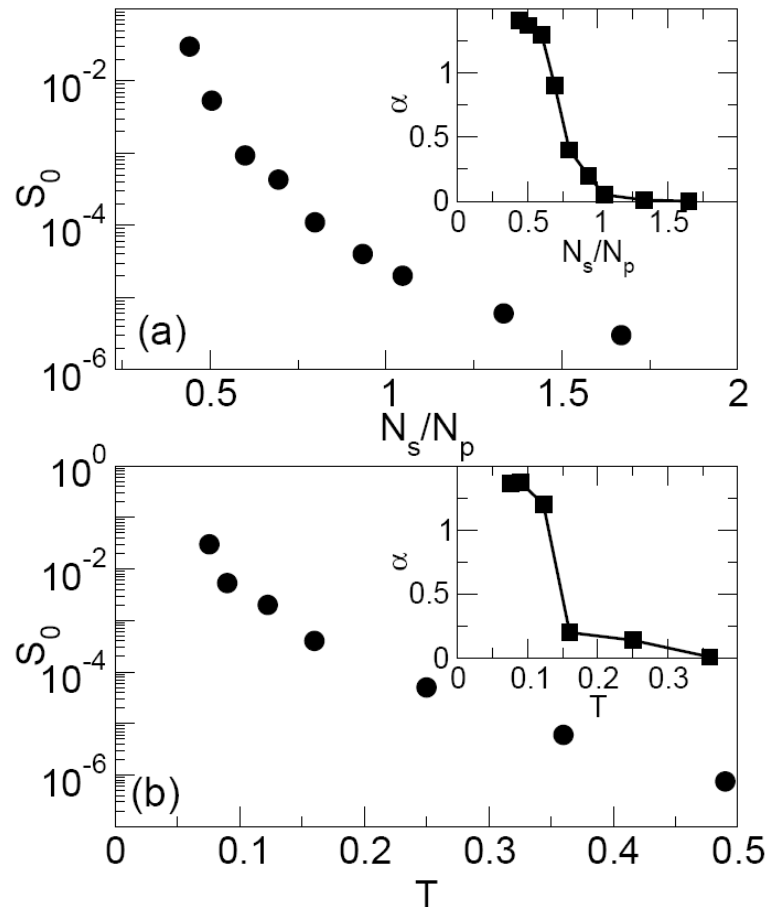
Physical trajectory: $E_F \sim n_s$; $U \sim n_s^{1/2}$; $W \sim$ const. ⇒ $(E_F/U) \sim (W/U)^{-1}$

1 High-mobility samples, 2 Low-mobility samples

Simulations

- **Molecular Dynamics** [C. Reichhardt and C. J. Olson Reichhardt, PRL 93, 176405 (2004)]: **a classical model of interacting electrons in 2D with disorder**
- **increase of noise power and α with decreasing density and T**
- **non-Gaussianity at low n_s and T**





Similar to experiments in 2DES in Si

Noise power and α maximum

Trajectories change with time:
dynamical inhomogeneities

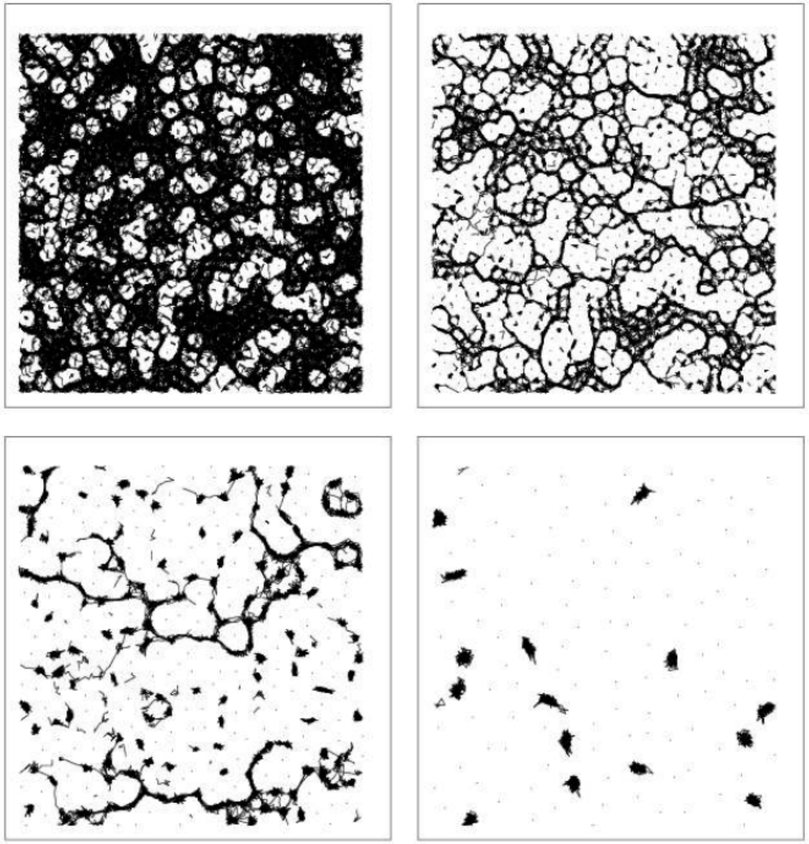


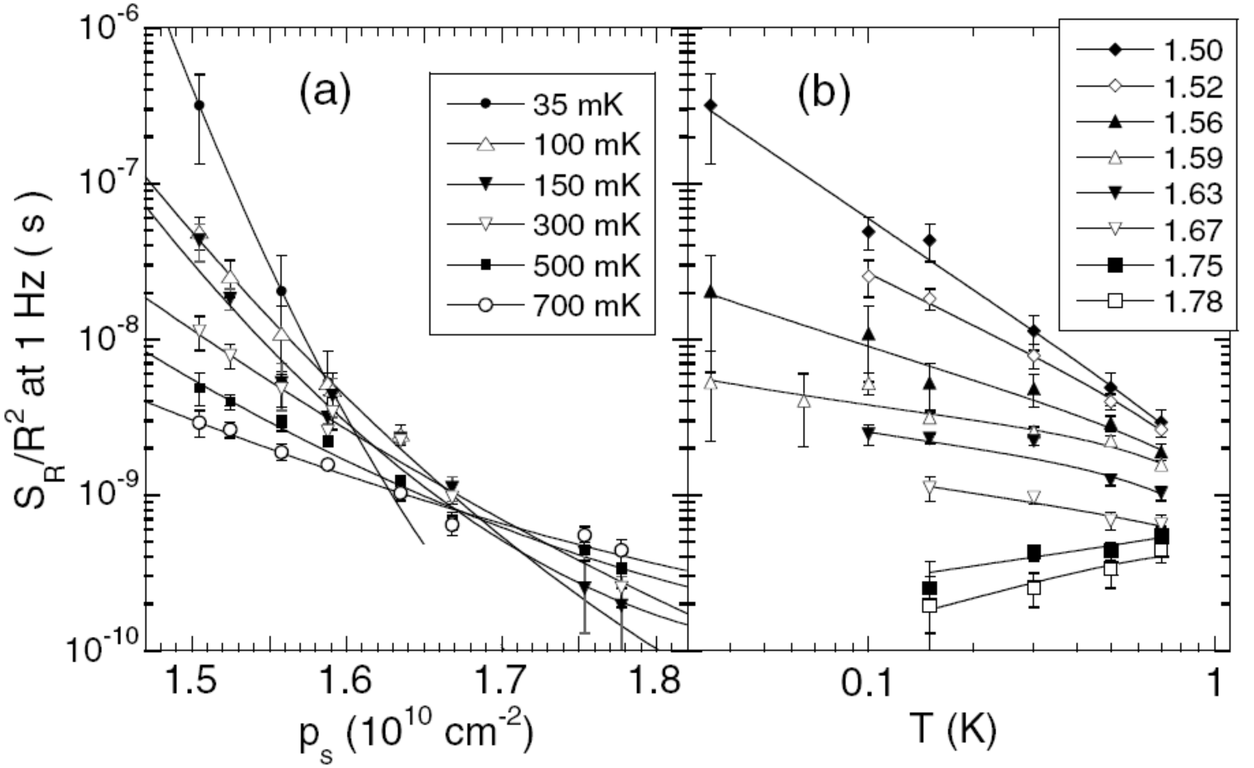
FIG. 5. Electron trajectories for a fixed period of time for fixed $T = 0.09$ at (a)$N_s/N_p = 1.67$, (b) 1.37, (c)0.5, and (d) 0.3.

- Monte Carlo [Kolton, Grempel, Dominguez, PRB 71, 024206 (2005)]:
  3D Coulomb glass - heterogeneous dynamics

Experiments in other systems

- $1/f^{\alpha}$ noise in **2D holes in GaAs** (much less disorder than in Si) – some similarities, but no changes in α (≈1) and (1-β) (≈0)
- not low enough p_s, T, f, or disorder?

[Leturcq, L'Hôte, Tourbot, Mellor, Henini, PRL 90, 076402 (2003)]

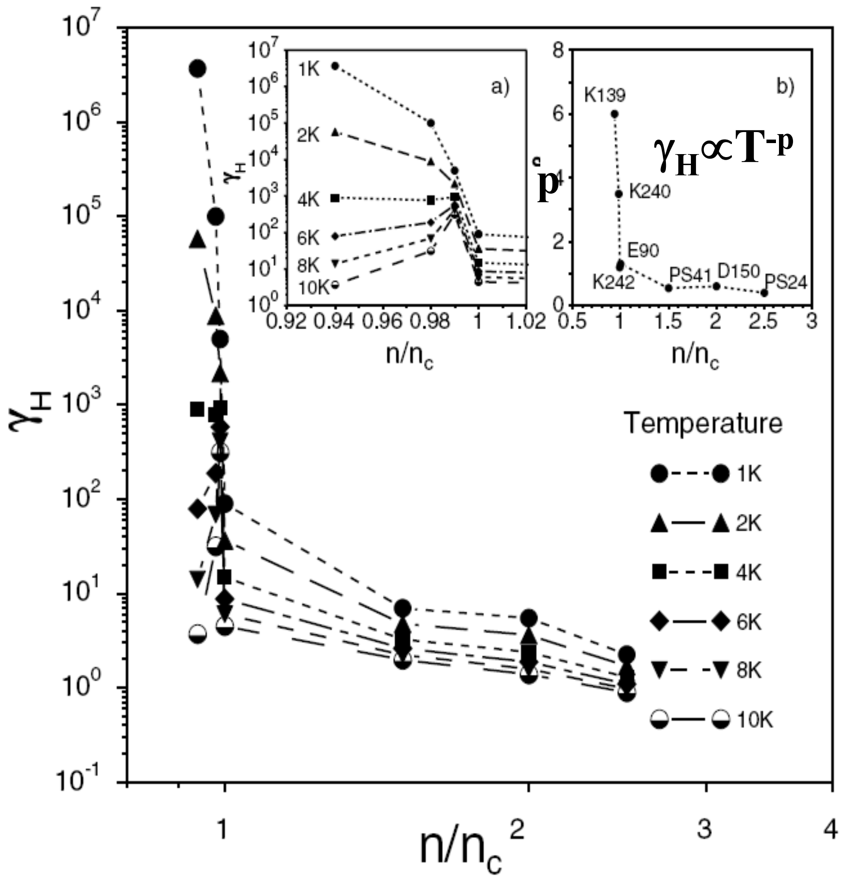


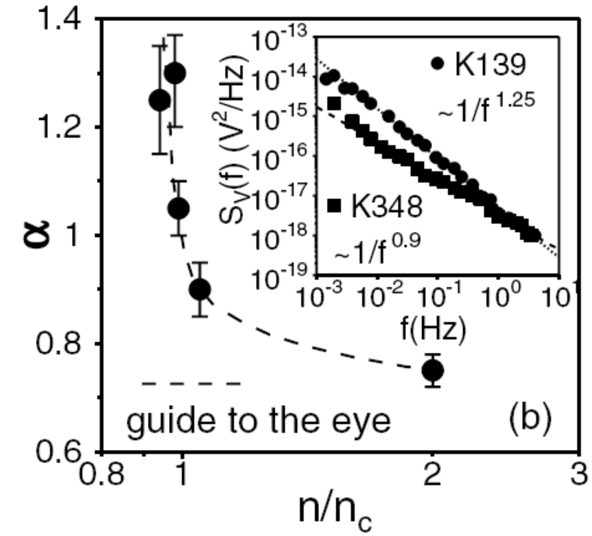
$p_c = 1.44\times10^{10}$cm^{-2}
$p_s^* = 1.57\times10^{10}$cm^{-2}

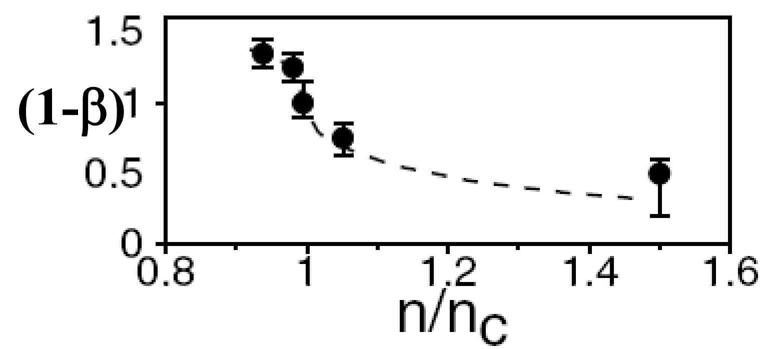
Bulk Si:P(B)

•$1/f^{\alpha}$ noise in bulk Si:P(B) - a huge increase of noise and the onset of non-Gaussianity at the MIT!!! Similar to 2DES in Si!

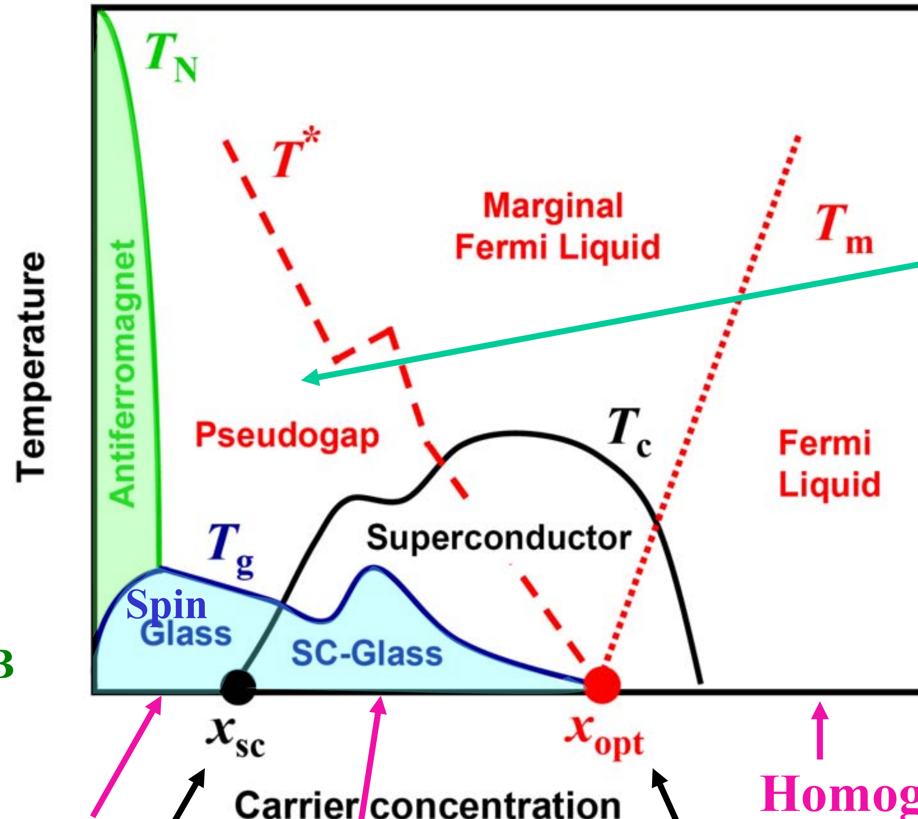
[Kar, Raychaudhuri, Ghosh, v. Löhneysen, Weiss, PRL 91, 216603 (2003)]







High temperature superconductors



Emergence of nanoscale inhomogeneities!

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

Glassy insulator?

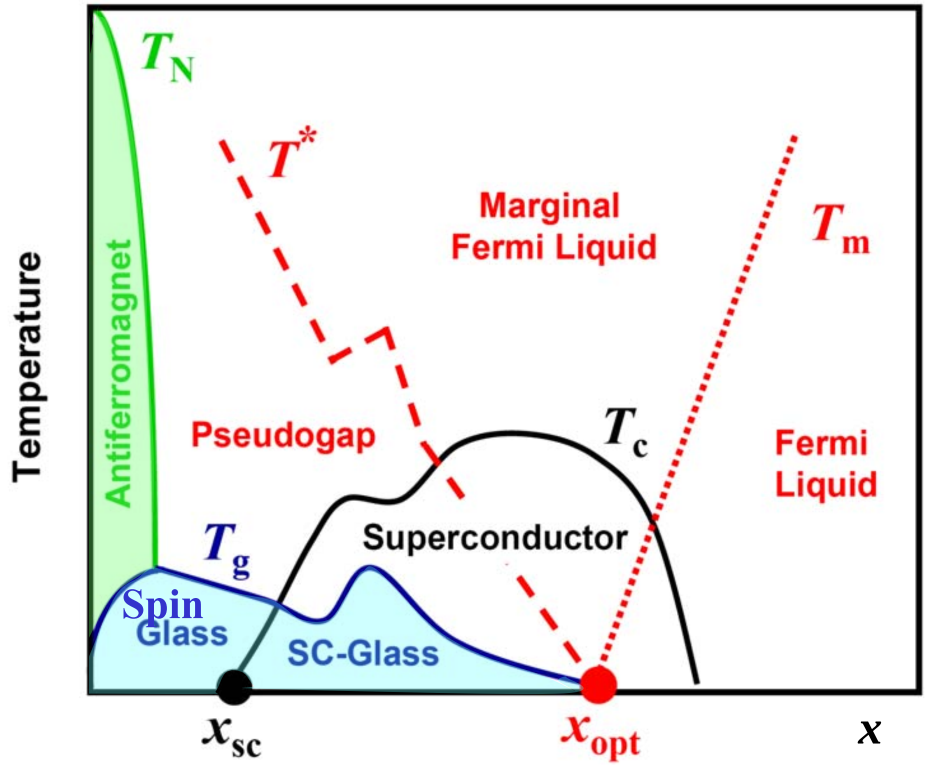
Homogeneous metal

Metal-insulator transition?

Inhomogeneous, conducting glassy state?

Quantum glass transition?

High temperature superconductors



MIT in a 2DES in Si at T=0
[Coulomb glass; T_g=0]

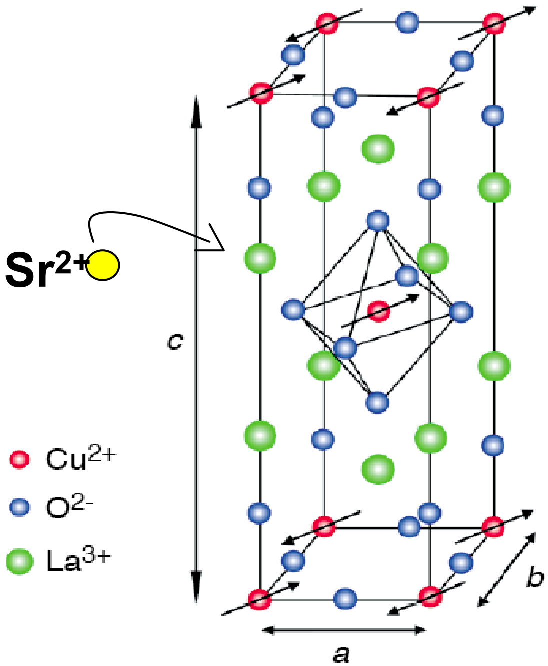
Glassy insulator | **Metallic glassy phase ($k_F l$ < 1; "bad" metal)** | **Metal**

n_c — **metal-insulator transition**

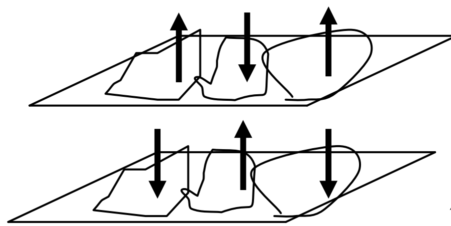
n_g — **glass transition**

carrier density

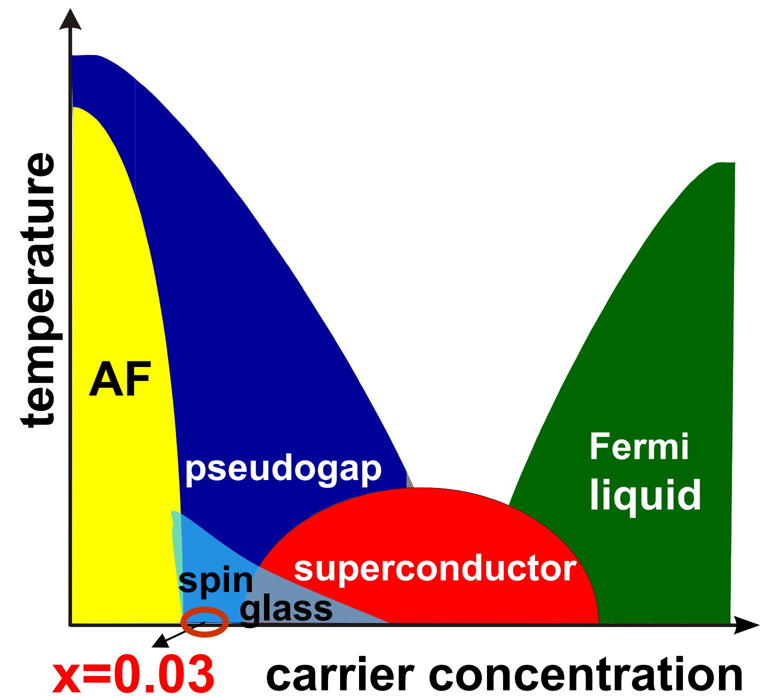
Lightly doped $La_{2-x}Sr_xCuO_4$



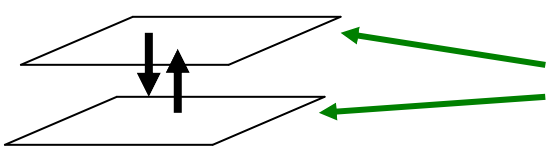
x ≧ 0.02: short-range magnetic order for T> T_{sg}
(T_{sg} - spin glass transition)



• AF domains; holes along domain walls

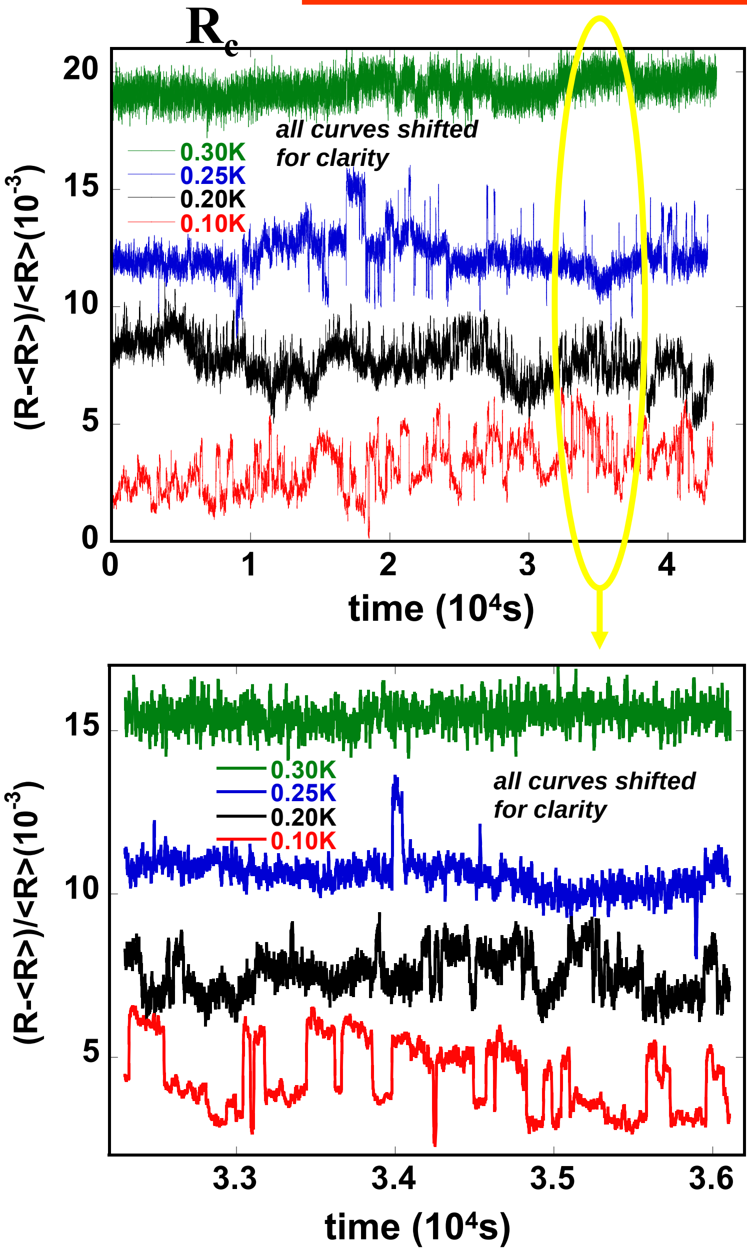


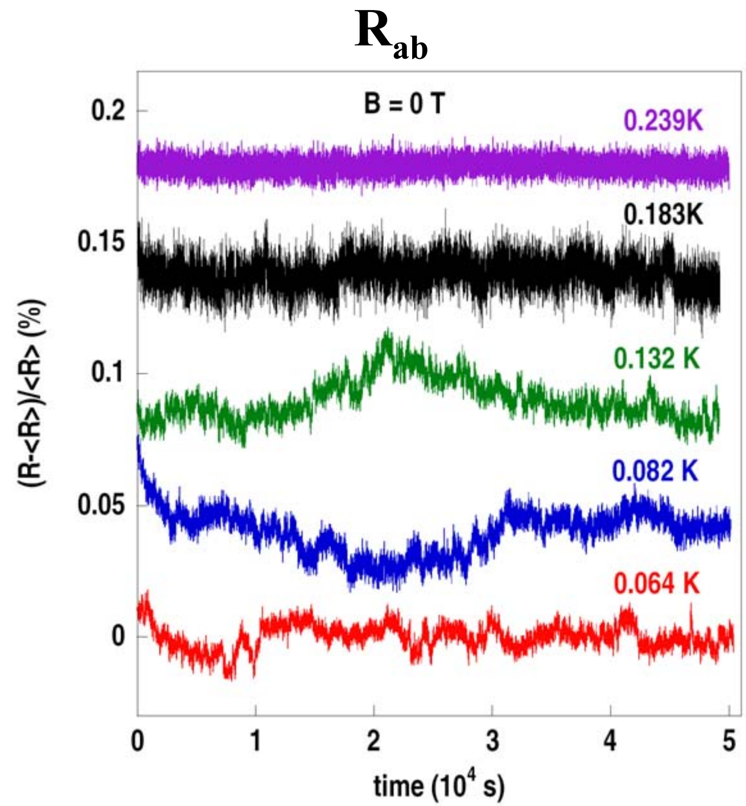
3D long-range antiferromagnetic (AF) order:



T_{sg} ~ 7-8 K

Resistance fluctuations (noise); LSCO



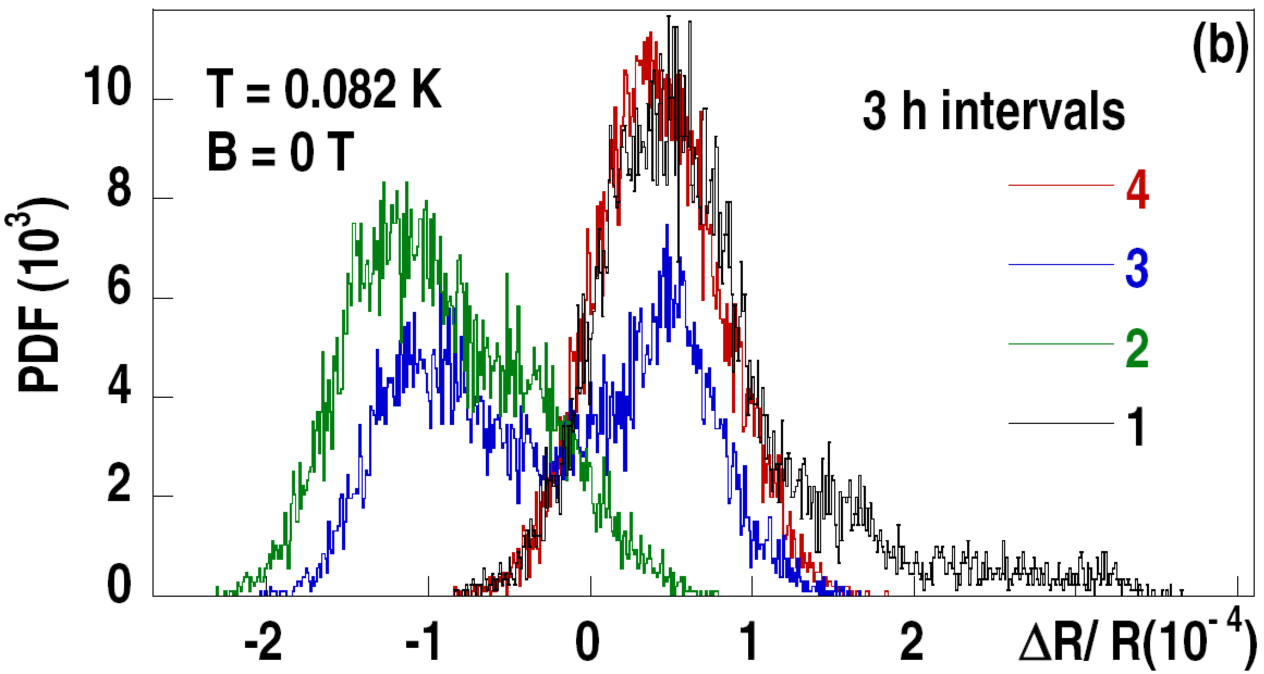


- **noise Gaussian at "high" T** **(*e.g.* T > 0.18 K for R_{ab} noise)**
- **at low T, non-Gaussian noise**

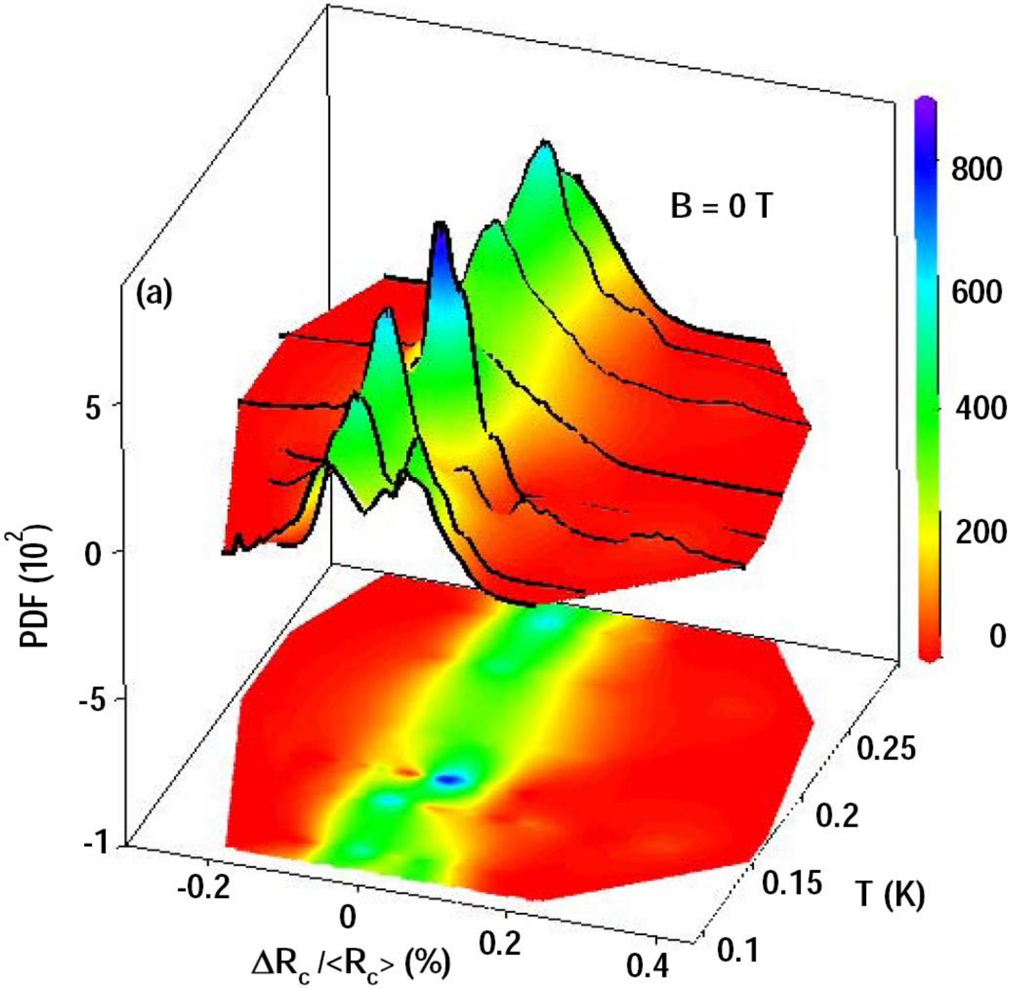
metastable states *(out-of-equilibrium)*

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

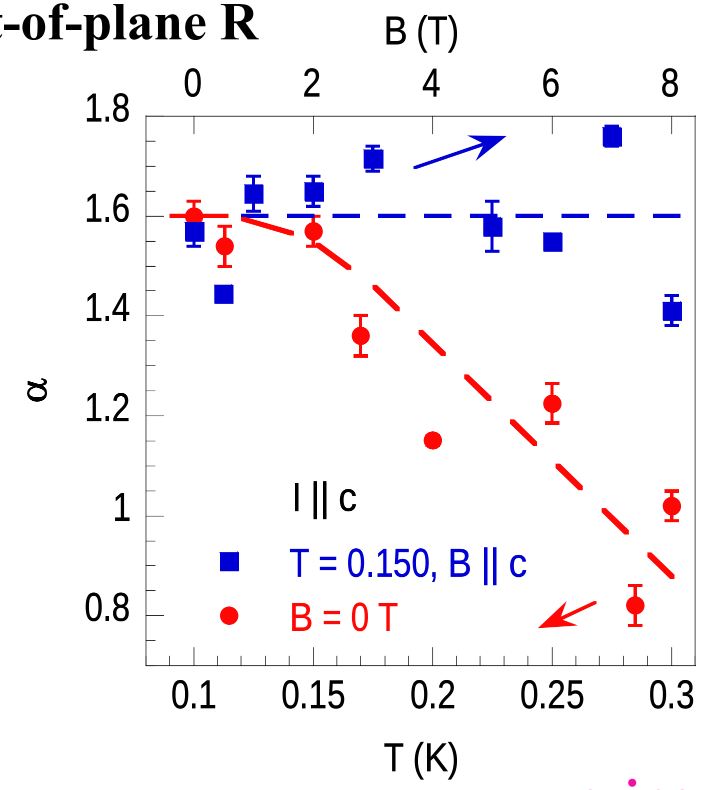
- **nonergodic, does not reach equilibrium** on experimental time scales at low T

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

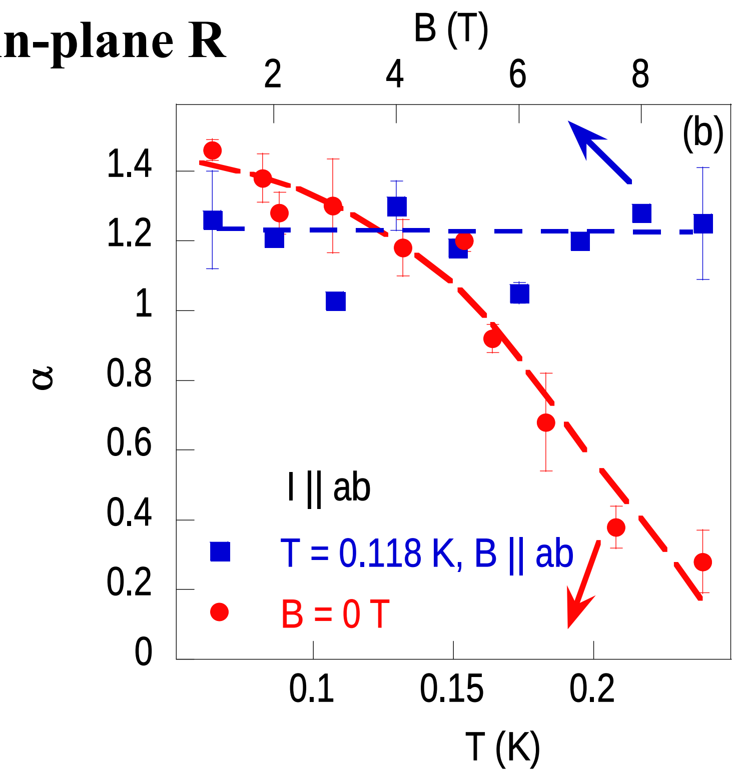
Noise statistics: T and B dependence

• 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>

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

Slowing down of the dynamics as T→0

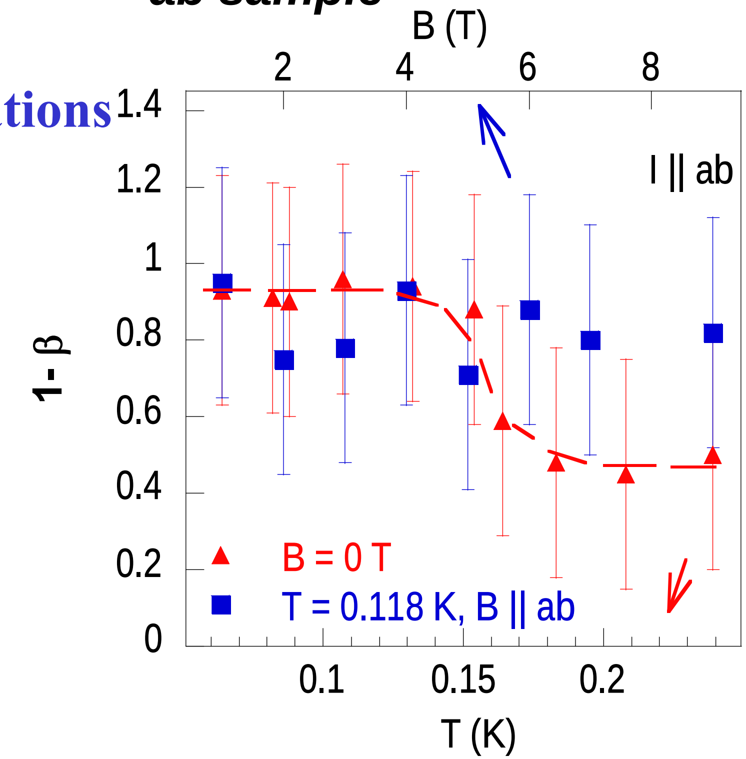
Second spectrum $S_2(f_2, f)$

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

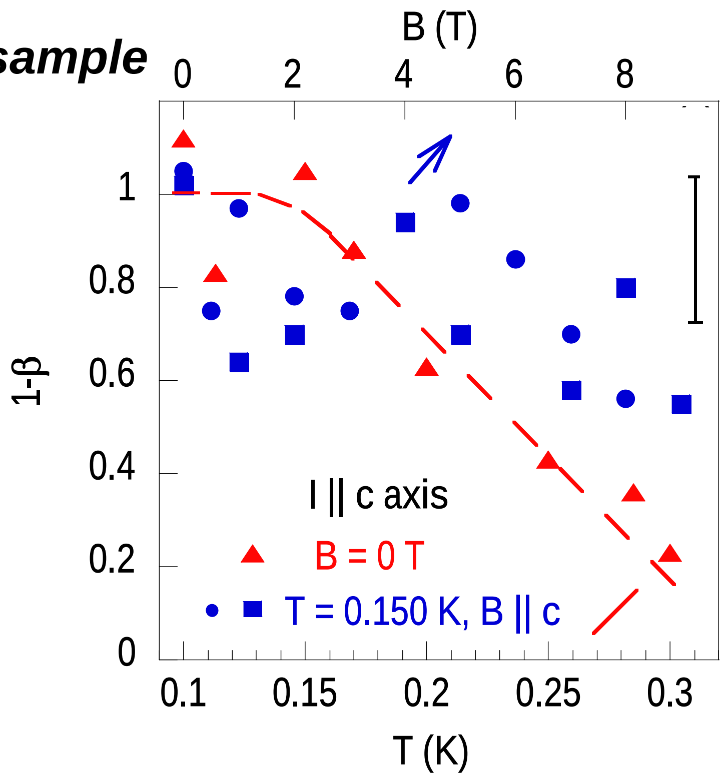
1) white ($1-\beta = 0$) for uncorrelated fluctuators (Gaussian)

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 in LSCO

- 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) $\Rightarrow$ charge, not spin!

- Onset of hysteretic and memory effects in magnetoresistance:

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

$\Rightarrow$ **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

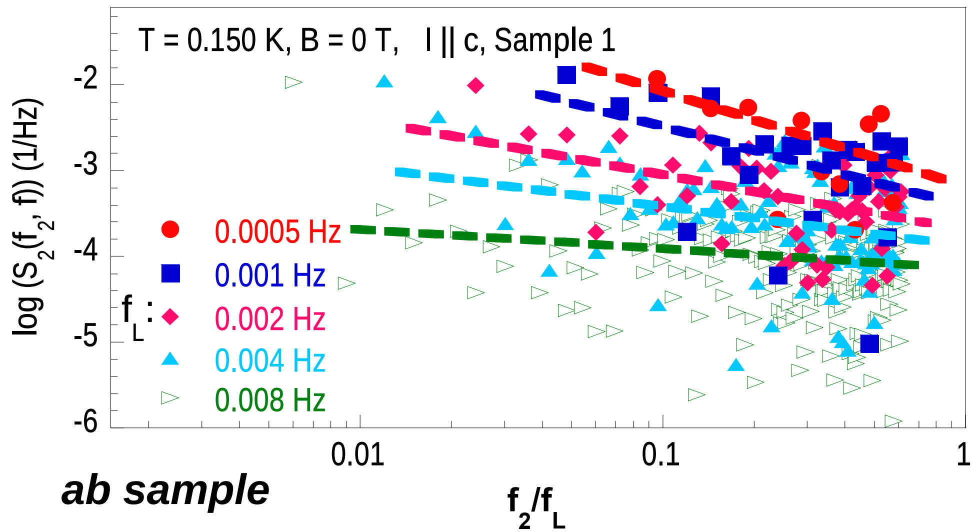
S_2 decreases with f for a fixed f_2/f, consistent with droplet picture (short-range interactions)

⇓

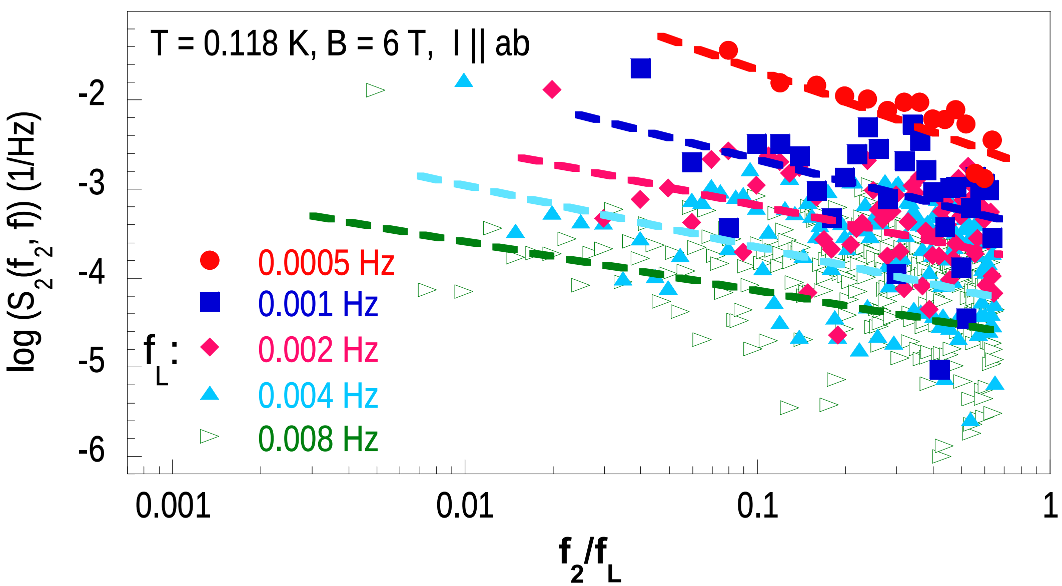
Spatial segregation of holes as a result of competing interactions on different length scales

Cluster charge glass

c sample



ab sample



Summary of Lecture III

- Noise study in a 2DES in Si:
  - sharp transition to a glassy phase as a function of density
  - glass transition at T=0
  - glassy phase: slow, correlated, <u>hierarchical</u> dynamics
  - glassy ordering due to charge, not spin $\Rightarrow$ Coulomb glass

- Noise study in lightly doped $La_{2-x}Sr_xCuO_4$:
  - transition to a glassy phase at T=0
  - glassy phase: slow, correlated dynamics; <u>clusters</u>
  - glassy ordering due to charge, not spin $\Rightarrow$ Coulomb glass

- Noise as a probe of glassy dynamics in other systems (*e.g.* doped Si)

Glasses everywhere…