Out-of-equilibrium dynamics in a two-dimensional Coulomb glass

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Outline

- **2D system of strongly interacting electrons in a random potential**
- **Electron density n_s varied from the insulating to the metallic regime, *i.e.* through the metal-insulator transition (MIT)**
- **Probing the glassy dynamics:**

1) measure fluctuations of conductivity – information on correlations

⇒ slowing down and correlated statistics for $n_s < n_g$ as $T \rightarrow 0$

2) measure response to a perturbation

⇒ nonexponential relaxations

⇒ diverging equilibration times for $n_s < n_g$ as $T \rightarrow 0$

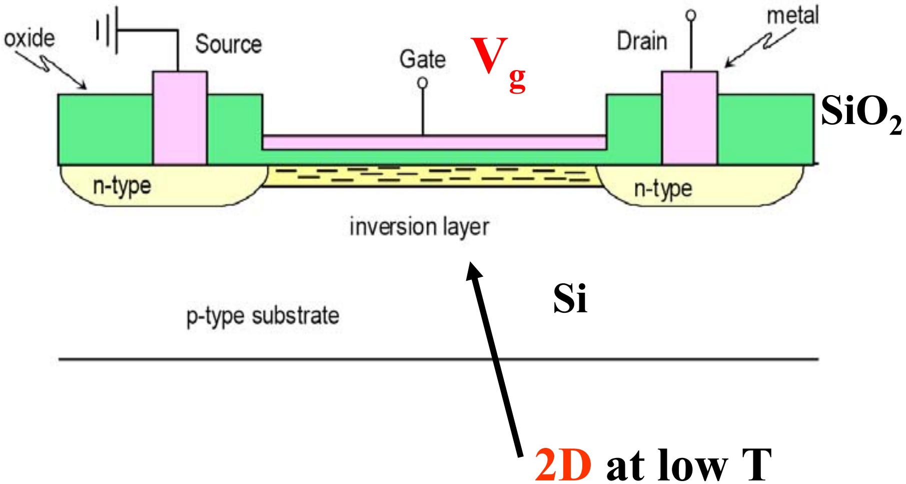
(glass transition $T_g = 0$)

⇒ aging and memory

⇒ abrupt change in aging properties at the 2D MIT (n_c)

Samples: 2D electron system in Si MOSFETs

(metal-oxide-semiconductor field-effect transistor)



Disorder due to:

1) Na+ ions randomly distributed throughout SiO_2 (frozen out below ~100 K)
2) interface roughness

2D electrons move in a smooth random potential

- low densities ($n_s \sim 10^{11}$ cm^{-2})

Fermi energy: $E_F = \pi\hbar^2 n_s/2m^* \approx 0.6$ meV

Electron-electron interaction energy:

$$E_{e\text{-}e} \sim (e^2/\varepsilon)(\pi n_s)^{1/2} \approx 10 \text{ meV}$$

$$\longrightarrow \quad r_s \equiv E_{e\text{-}e}/E_F \propto n_s^{-1/2} \sim 10!$$

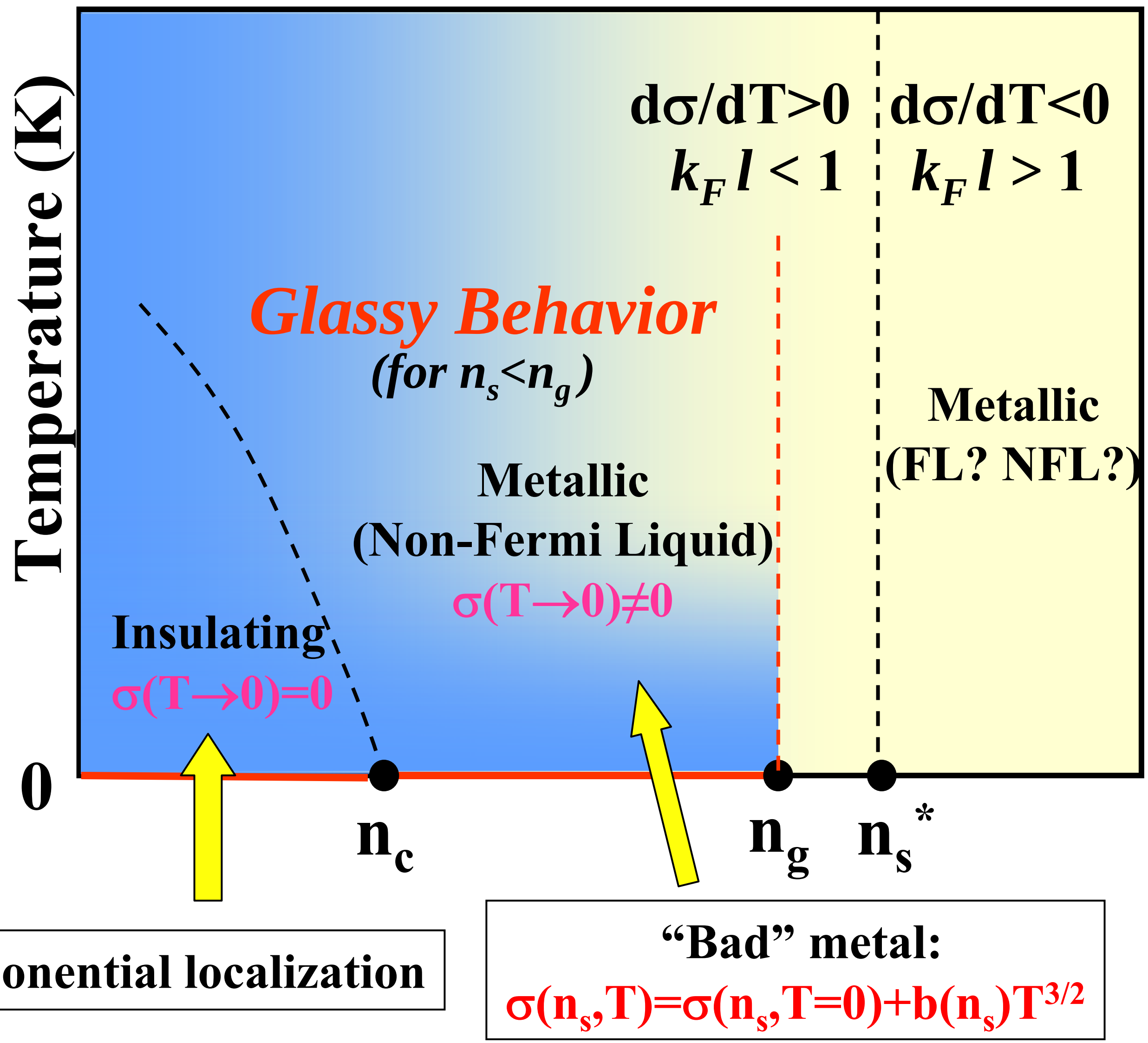
- critical conductivity ~ e^2/h

$\sigma \sim (e^2/h)(k_F l) \Rightarrow k_F l \sim 1$

(l – mean free path; k_F – Fermi wave vector)

⇒ strong Coulomb interactions, strong disorder

Phase diagram of a 2DES in Si



Focus on the $k_F l < 1$ region

(glassiness not observed for $k_F l > 1$)

n_c – critical density for the MIT

n_g – glass transition density

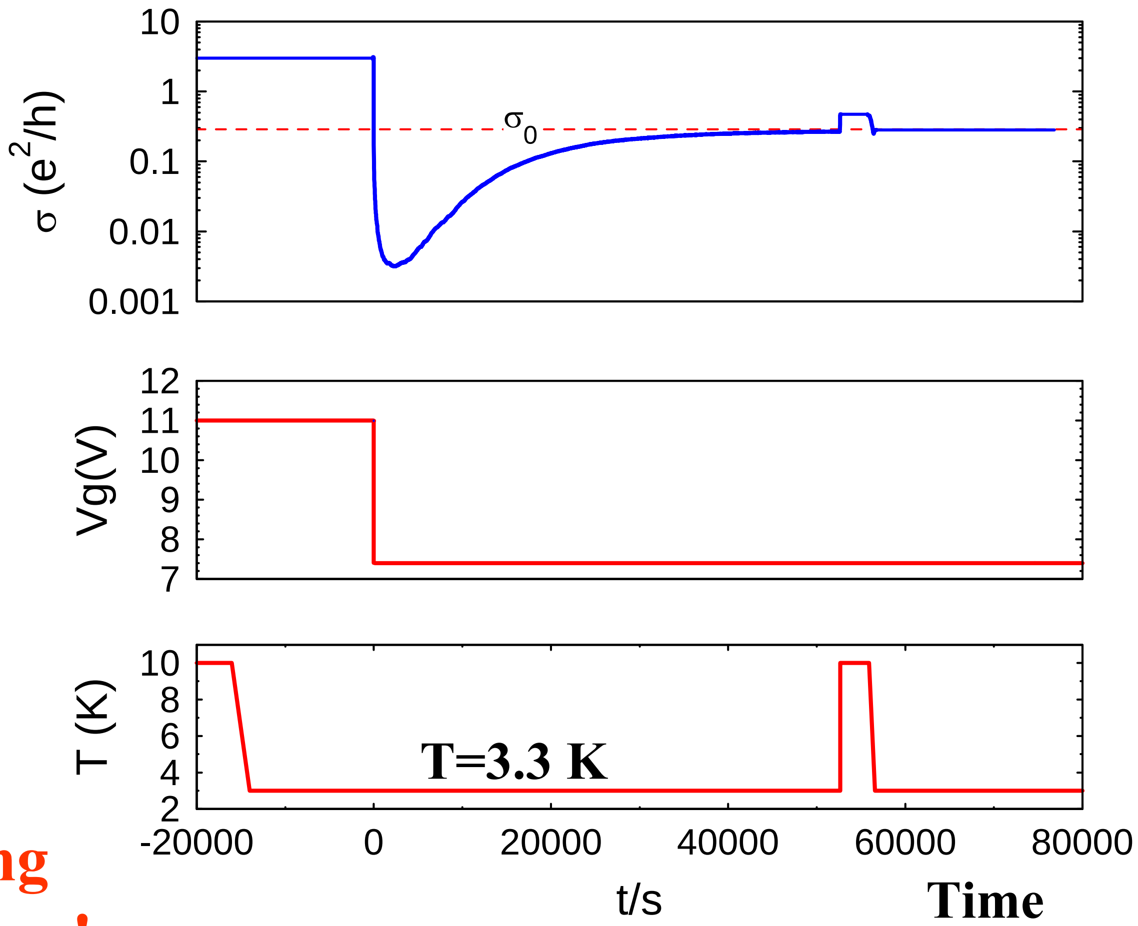
Relaxations of conductivity after a rapid change of n_s

Low-mobility samples

$n_g \approx 7.5\times10^{11}cm^{-2}$, $n_c \approx 4.5\times10^{11}cm^{-2}$

Initial $n_s(10^{11}cm^{-2})$ $=20.26 > n_g$

$k_F l \leq 1$



σ_0 – equilibrium conductivity at T and final n_s

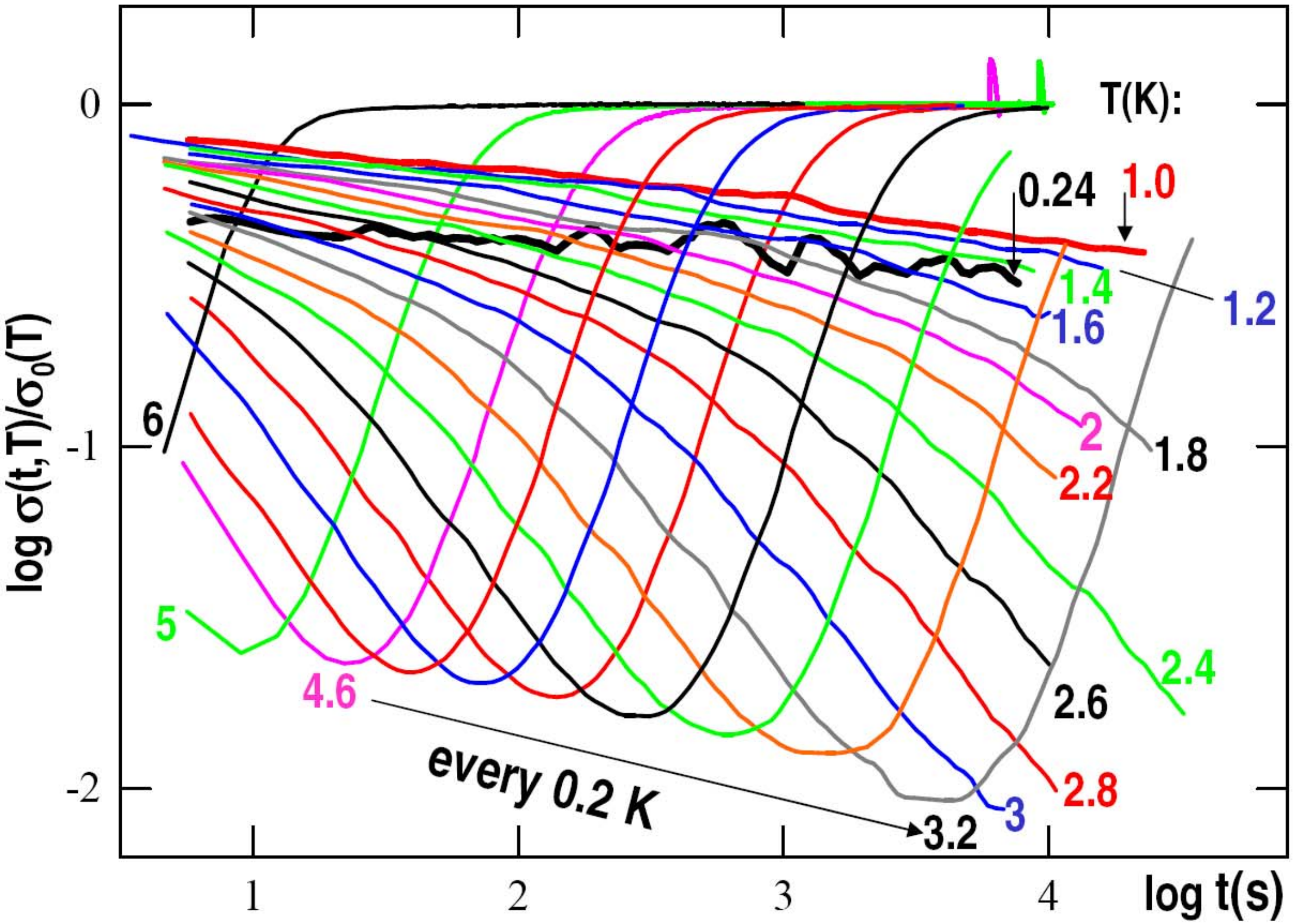
Final $n_s(10^{11}cm^{-2})=$ $=4.74 \geq n_c$

$\Delta E_F \gg k_B T$

Overshooting of equilibrium!

[J. Jaroszyński and D. Popović, PRL 96, 037403 (2006)]

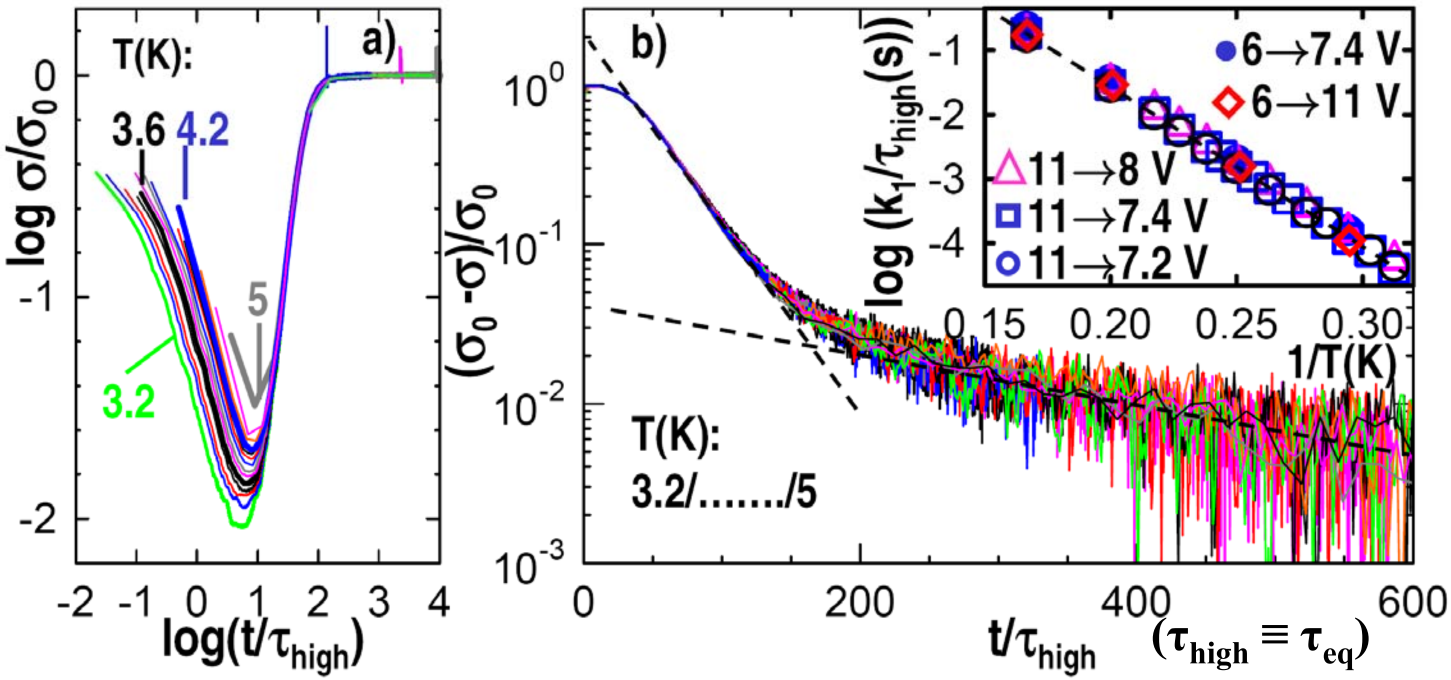
Repeat measurement at (many) different T (after warm-up to 10 K):



- minimum moves to longer times as T decreases – slower relaxations

Approach to equilibrium:

data (for different T) collapse for times after the minimum



- **Relaxations exponential**

- **The system reaches equilibrium after a long enough t**
- **Characteristic (equilibration) time $\tau_{eq} \propto \exp(E_A/T)$, $E_A \approx 57$ K**

$\tau_{eq} \to \infty$ as $T \to 0$, *i.e.* glass transition $T_g = 0$

[see Grempel, Europhys. Lett. 66, 854 (2004) for a 2D Coulomb glass; also showed aging]

Initial relaxation:

data (for different T) collapse for times before the minimum:

- **for short enough $t < \tau_{eq}$,**

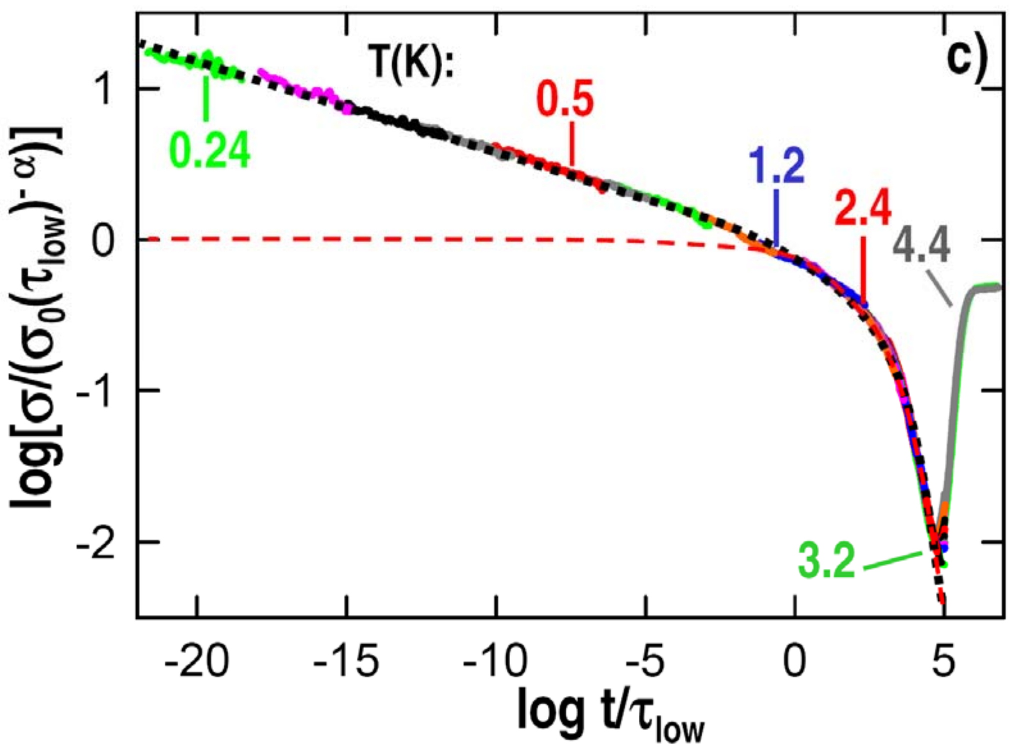
$$\sigma(t,T)/\sigma_0 \propto t^{-\alpha(n)} \exp\{-[t/\tau_{low}(n_s,T)]^{\beta(n)}\}$$

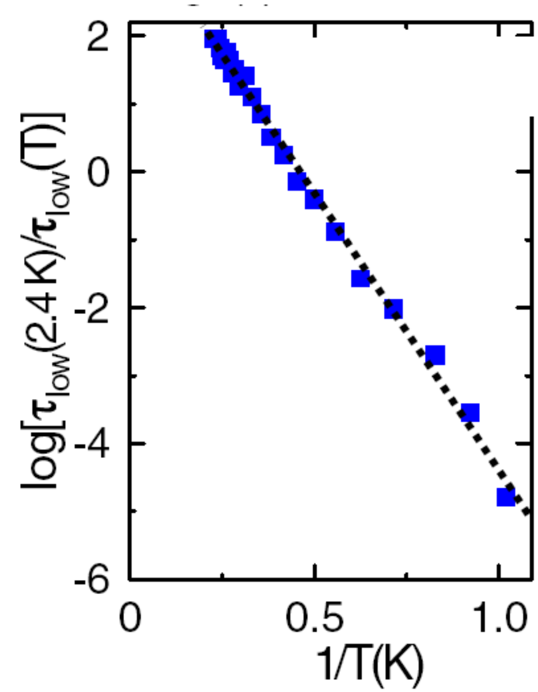
(α=0.07, β<0.3 for this n_s)

($n \equiv n_s$)

glassy relaxation

$\tau_{low} \propto f(n_s) \exp(E_a/T)$, $E_a \approx 20$ K





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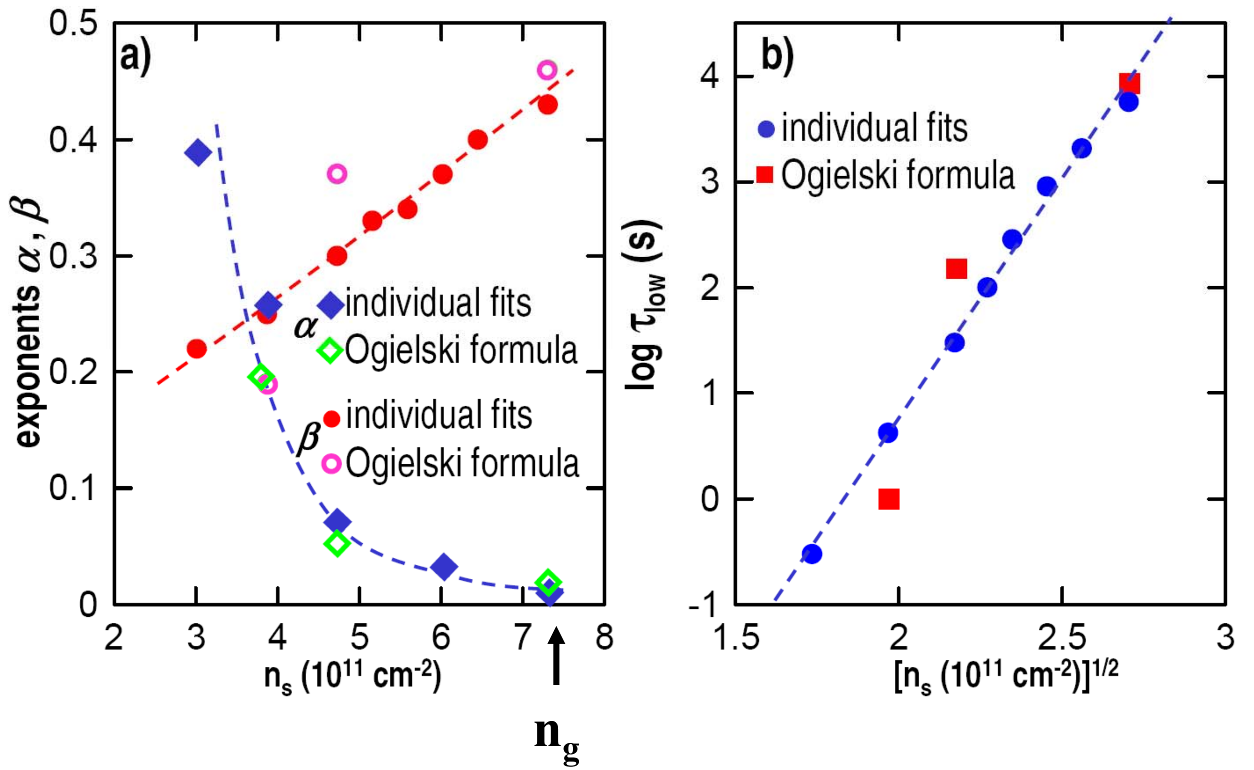
Repeat everything for many different n_s

$\tau_{low} \propto \exp(a n_s^{1/2}) \exp(E_a/T)$, $E_a \approx 20$ K

- **T→0:**

  $\sigma/\sigma_0 \propto t^{-\alpha}$

  as expected for a phase transition at T=0 (previous slide: scaling as T→0)



- Coulomb interactions in 2D: $E_F/U \sim n_s^{1/2}$

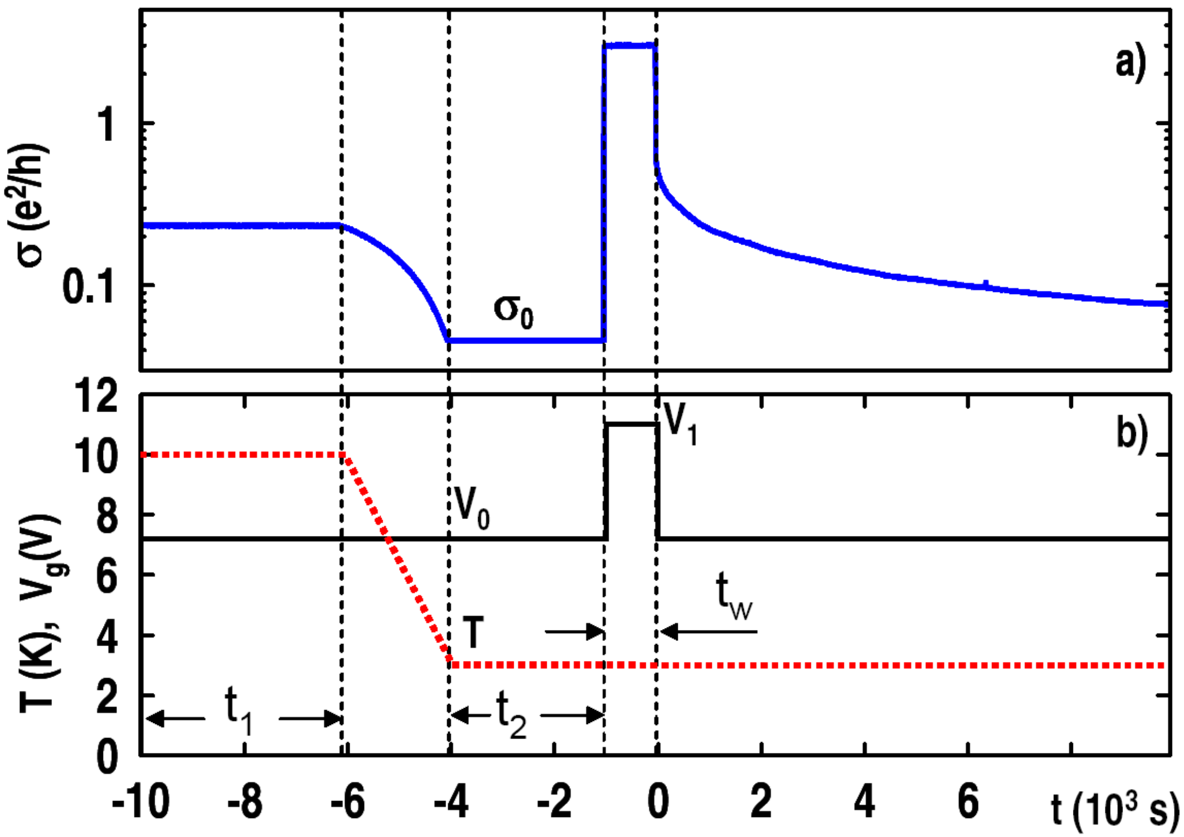
β grows with n_s: relaxations faster with increasing n_s

What have we learned from relaxations?

- data strongly suggest $T_g = 0$ for $n_s \leq n_g$ in a 2DES in Si
  (diverging equilibration time, scaling of nonexponential relaxations, power law as $T \rightarrow 0 \Rightarrow T_g = 0$; similar behavior in spin glasses, where $T_g \neq 0$)
- at finite T, the system appears glassy for short enough t
  (*e.g.* at T= 1 K, equilibration time ~ 10^{13} years!
  age of the Universe ~ 10^{10} years)
- Coulomb interactions between 2D electrons – a dominant role in the out-of-equilibrium dynamics
- as $T \rightarrow 0$, no relaxations for $n_s > n_g$; no relaxations for $k_F l > 1$

Note: system equilibrates only after it first goes farther away from equilibrium!

Relaxations of conductivity after a waiting time protocol: aging and memory

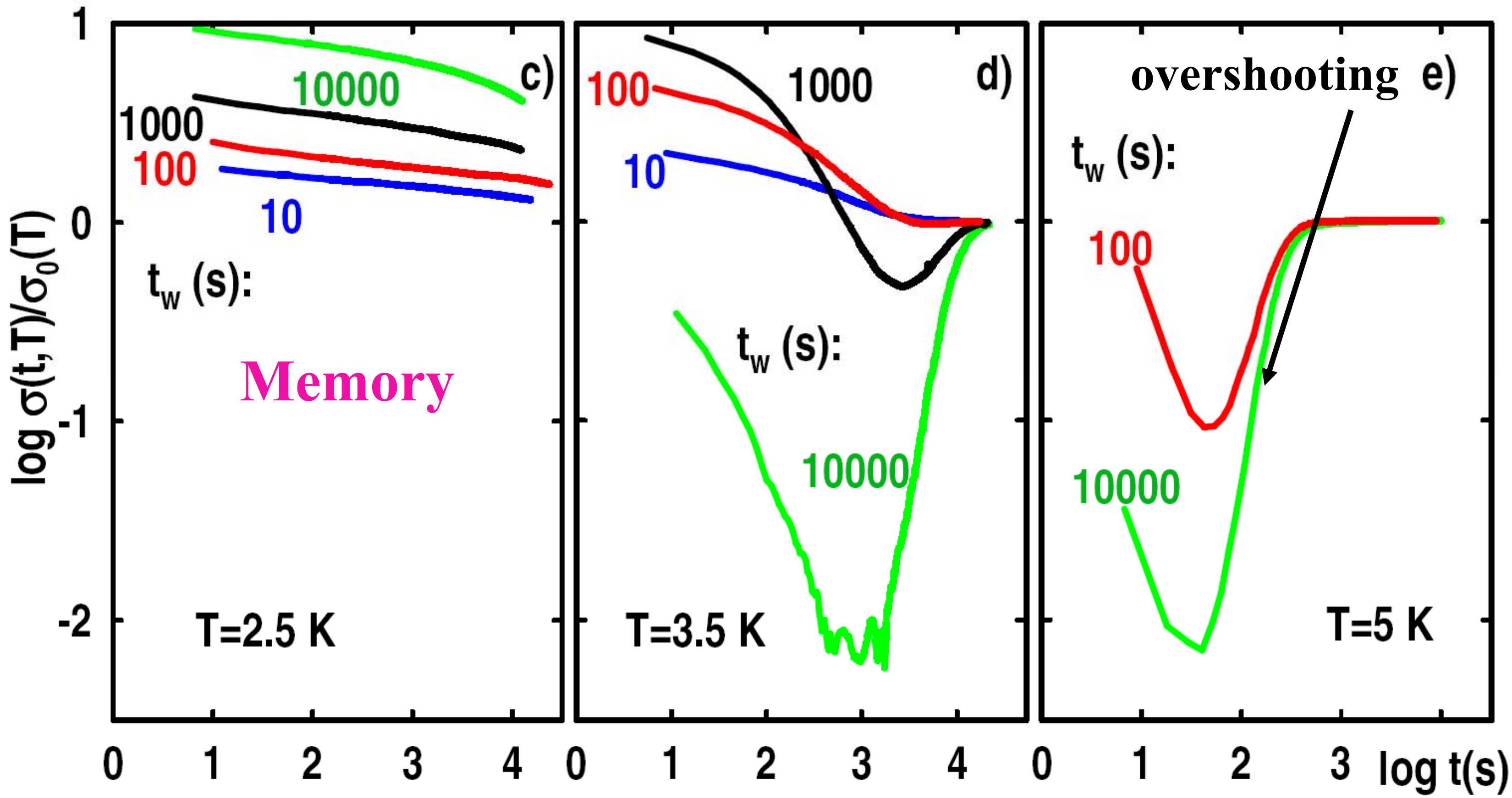


Initial and final $n_s(10^{11} cm^{-2})=3.88 < n_c$; density during t_w=1000 s: $n_s(10^{11} cm^{-2})=20.26 > n_g$

- **change history by varying T and t_w**

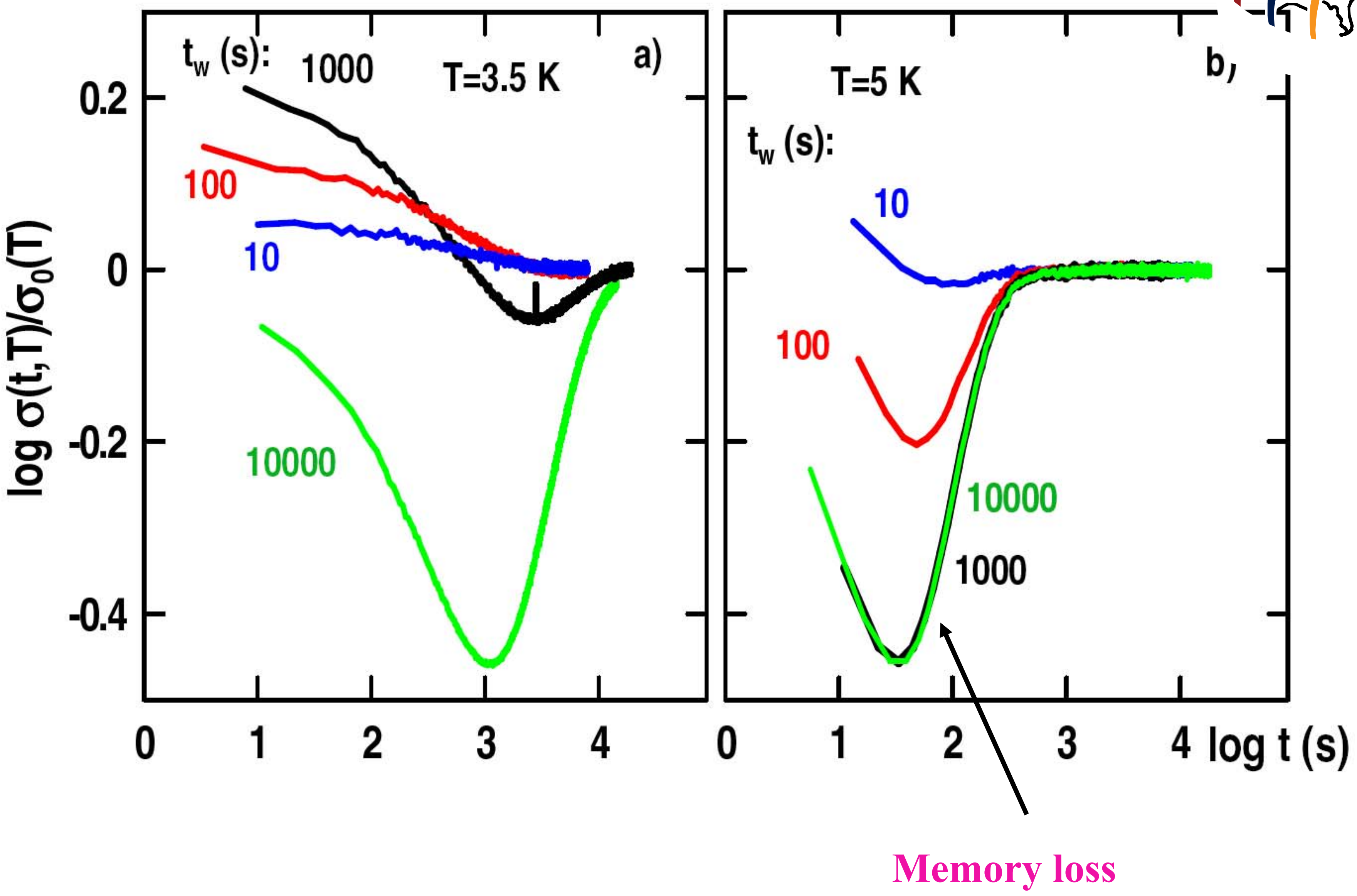
[J. Jaroszyński and D. Popović, Phys. Rev. Lett. 99, 046405 (2007)]

Relaxations for a few different T and t_w:

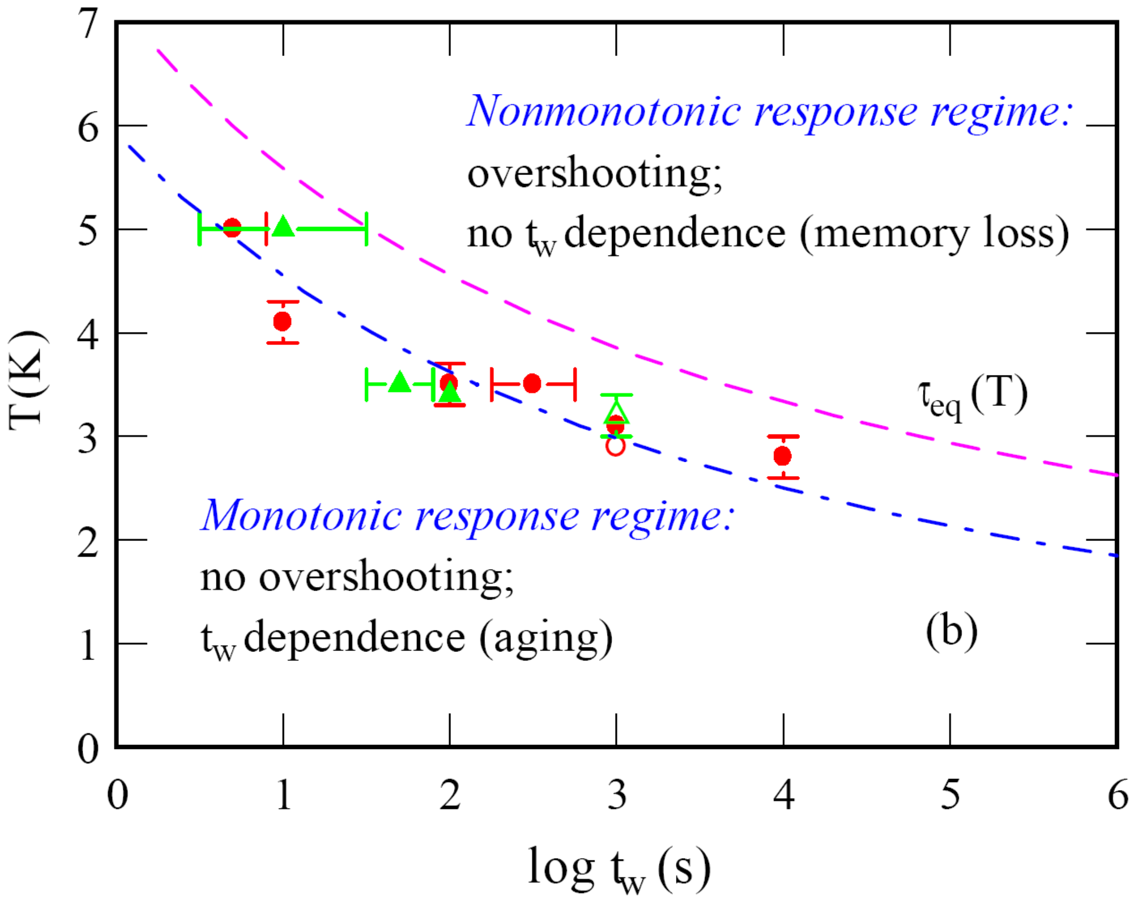


Response (conductivity) depends on the system history (t_w and T) in addition to the time t – *aging* – a key characteristic of relaxing glassy systems.

And a few more… [for $n_s(10^{11}cm^{-2}) = 7.33 \le n_g$]:



When is the overshooting observed?



- overshooting only when the system is excited out of a thermal equilibrium ($t_w \gg \tau_{eq}$); no memory

- no OS when excited out of a relaxing (nonequil.) state ($t_w \ll \tau_{eq}$): aging and memory

What is the origin of overshooting???

- **observed in a variety of systems (*e.g.* insulating granular metals, manganites, biological systems)**

- **some theoretical models**
  [Morita *et al.*, PRL 94, 087203 (2005); Mauro *et al.*, PRL 102, 155506 (2009)]

- **large perturbations out of equilibrium?**

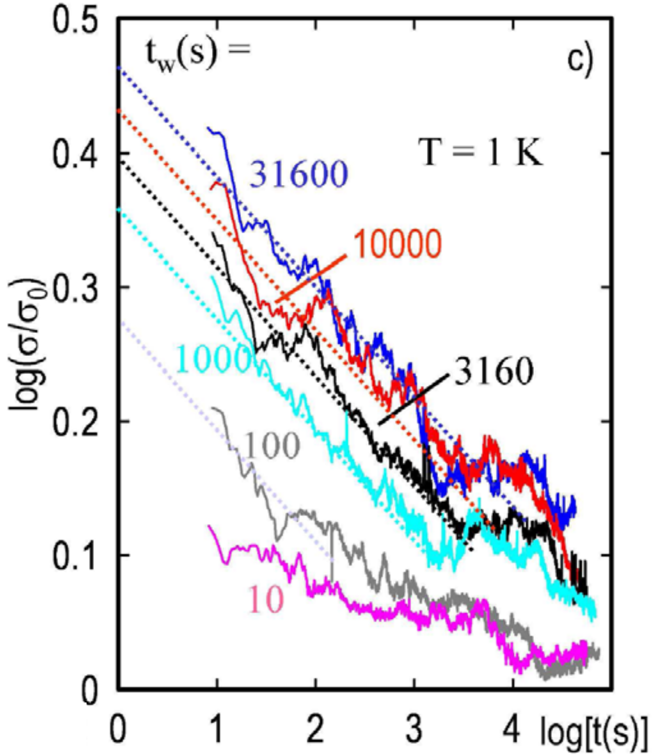
- **here $\Delta E_F >> T$ should trigger major charge rearrangements**
  (n_s changed up to a factor of 7; in InO_x, density change ~ 1%)

Aging regime (no OS, T=1 K)

[J. Jaroszyński and D. Popović, Phys. Rev. Lett. 99, 216401 (2007)]

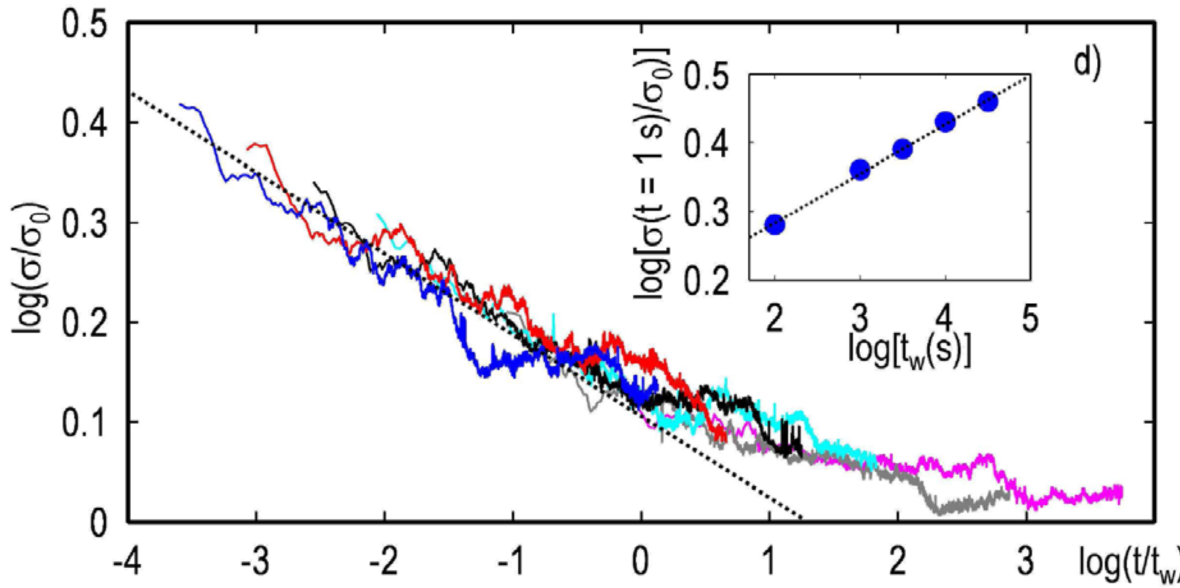
(T= 1 K: $\tau_{eq} \sim 10^{13}$ years!

Age of the Universe ~ 10^{10} years)



$n_0 < n_c$

Full (simple) aging: $\sigma(t/t_w)$



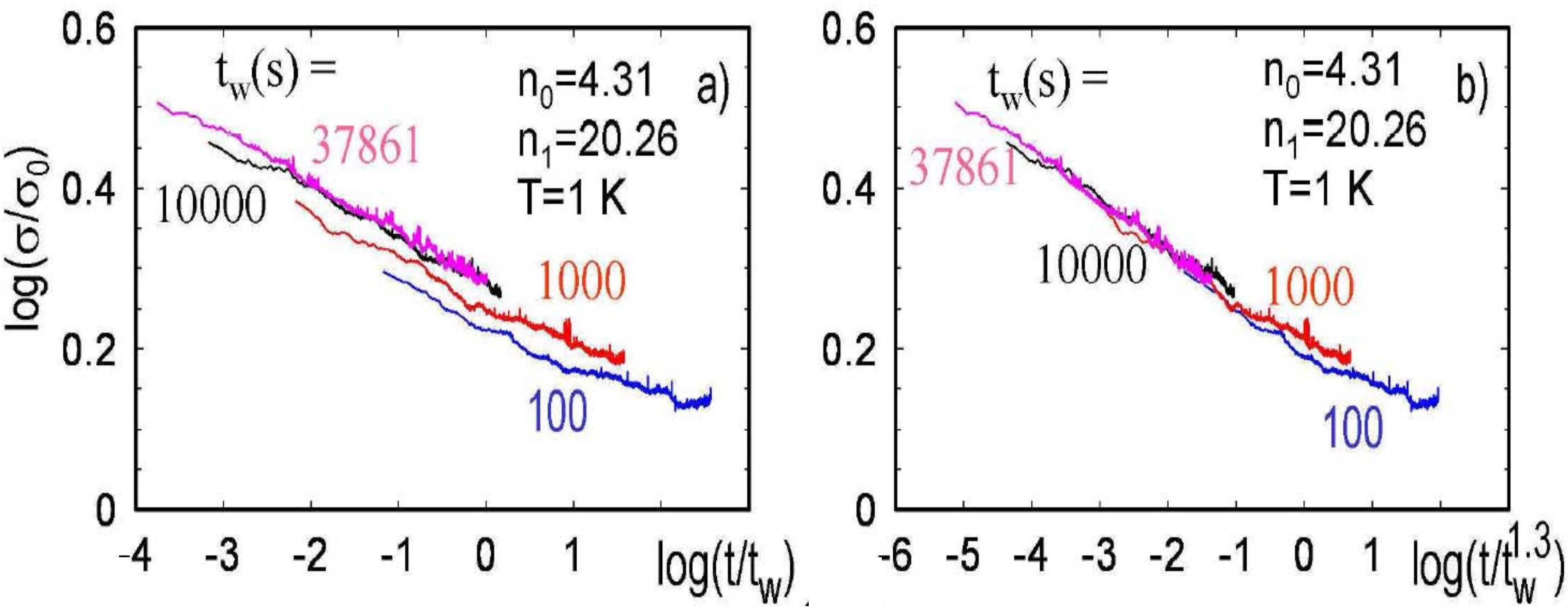
$\sigma(t)/\sigma_0 \propto (t/t_w)^{-\alpha}$ for $t \leq t_w$

$\Rightarrow$ a memory of t_w is imprinted on each $\sigma(t)$

- $\sigma(t, t_w)$ exhibit full aging for $n_s < n_c$
- for $n_s > n_c$, an increasingly strong departure from full aging

aging function: $\sigma(t/t_w^{\mu})$

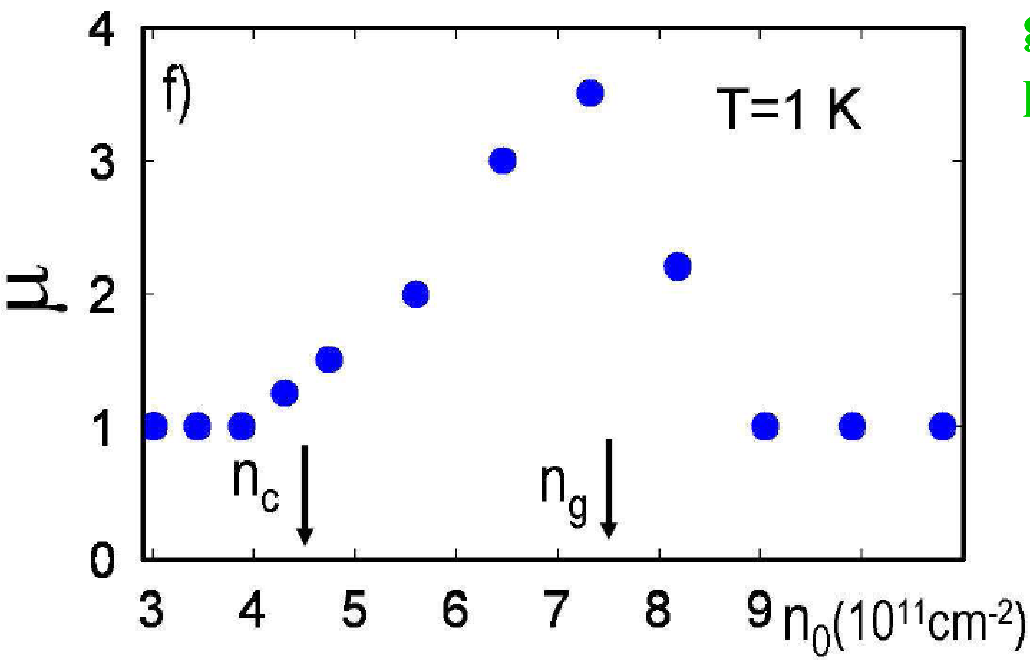
(μ-scaling useful in studies of other glasses; may not have a clear physical meaning)



- $\sigma(t, t_w)$ exhibit full aging for $n_s < n_c$
- for $n_s > n_c$, an increasingly strong departure from full aging that reaches maximum at n_g

aging function: $\sigma(t/t_w^{\mu})$

(μ-scaling useful in studies of other glasses; may not have a clear physical meaning)

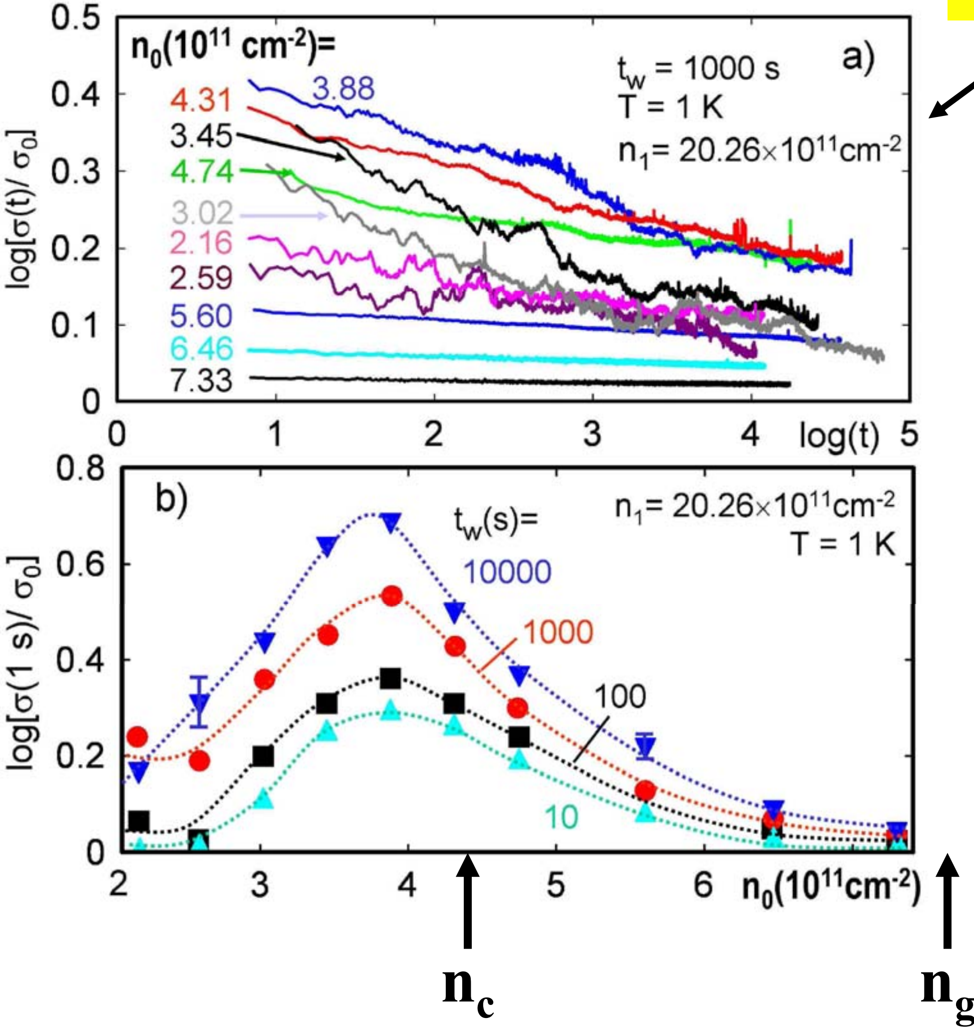


full aging: μ=1

- an abrupt change in aging at the 2D MIT (n_c)
- insulating glassy phase and metallic glassy phase are different!

NOTE: mean-field models of glasses, for example, include both those that show full aging and those where no t/t_w scaling is expected.

Fixed t_w and n_1; vary n_0

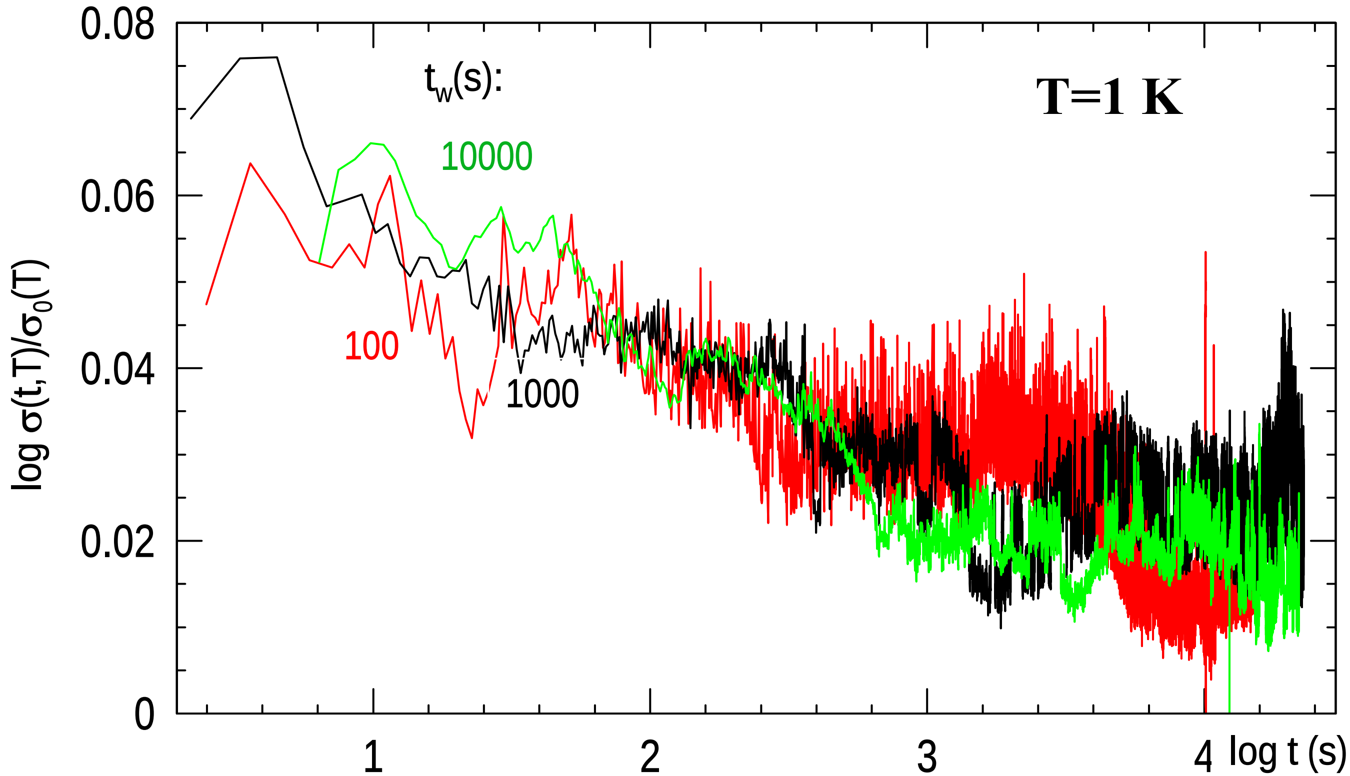


$$\sigma(t)/\sigma_0 = [\sigma(t=1s)/\sigma_0]\ t^{-\alpha}$$

- both relaxation amplitudes $\sigma(t=1s)/\sigma_0$ and slopes α depend nonmonotonically on n_0
- another change in aging properties at $n_s \approx n_c$

Relaxation amplitudes peak just below n_c, and they are suppressed in the insulating regime!

Remove all 2D electrons from the inversion layer during t_w ($V_1<V_T$):



No t_w dependence, *i.e.* no memory!

⇒ Glassiness from 2DES, not from background charges

Summary: 2D Coulomb glass

- Emergence of an intermediate, (NFL) metallic phase ($n_c < n_g$) between the metal and the insulator

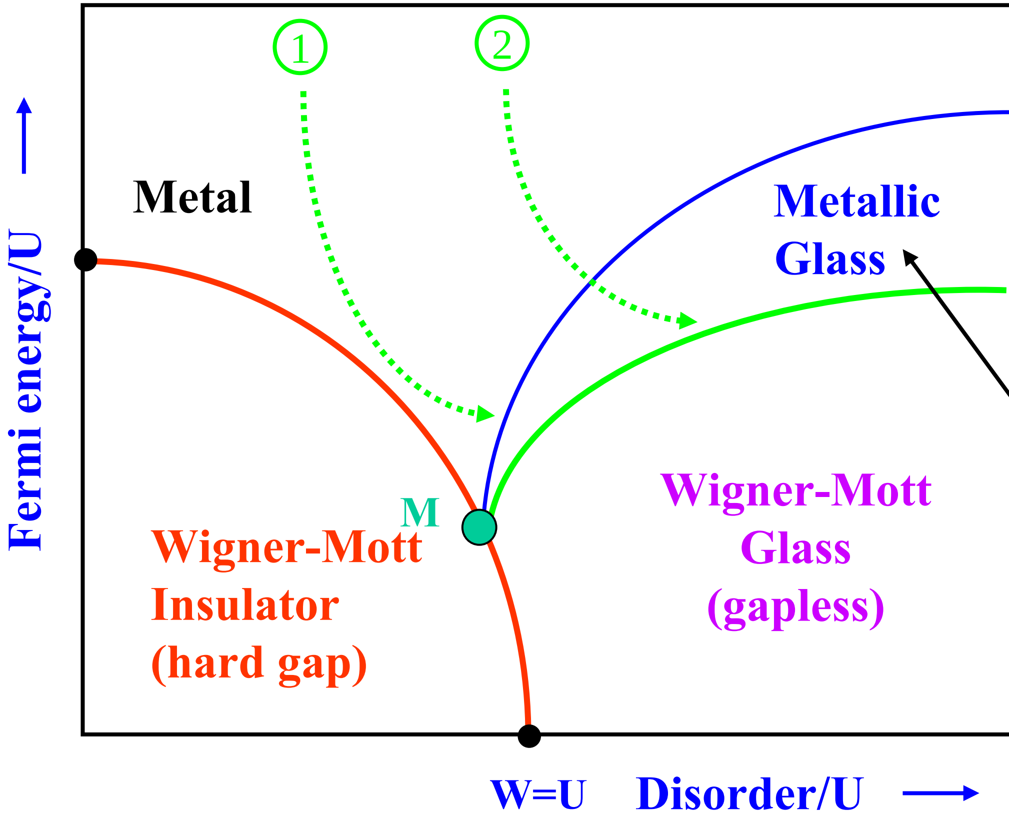
- Glassy behavior for $n_s < n_g$ (in the insulator and in the intermediate phase) – glassy ordering as a precursor of the MIT in a 2DES in Si

- Manifestations of glassiness:
  nonexponential relaxations, diverging equilibration times (T_g=0),
  aging and memory (abrupt changes in aging at the MIT)

- 2DES in Si:
  - similarities to other glassy systems (*e.g.* spin glasses)
  - a "simple", model system for exploring the dynamics of strongly correlated systems (free of complications associated with changes in magnetic or structural symmetry)

[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)



- **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

Trajectories change with time: dynamical inhomogeneities

Noise power and α maximum

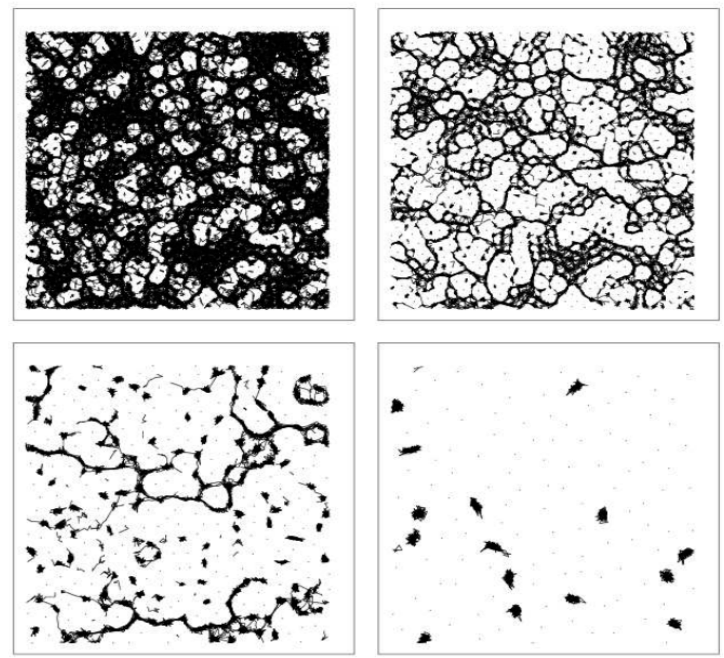


FIG. 5. Electron trajectories for a fixed period of time for fixed $T = 0.09$ at (a)$N_s/N_p = 1.67$, (b) 1.37, (c)0.5, and (d) 0.3.

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

Monte Carlo – aging in a 2D Coulomb glass:

- Grempel, Europhys. Lett. 66, 854 (2004)

- Shimer, Täuber, Pleimling, arXiv: 1007.1929 (2010) –
  density autocorrelation function

The aging function obeys power-law scaling

$$\sim t_w^{-b} (t/t_w)^{-\alpha}$$

where the exponents depend on the density and T