Nonequilibrium dynamics in Coulomb glasses near the metal-insulator transition

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

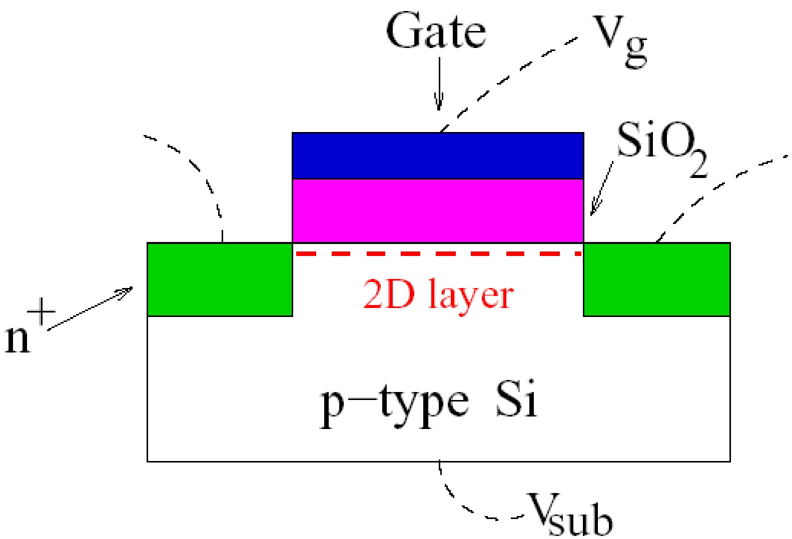
Lecture II: **Studies of the electron dynamics near the 2D MIT: Relaxations of conductivity**

- **2D electron system in Si: temperature dependence of conductivity**
- **Relaxations of conductivity after a rapid change of density**
- **Relaxations after a waiting time protocol: aging and memory**
- **Aging across the 2D MIT**

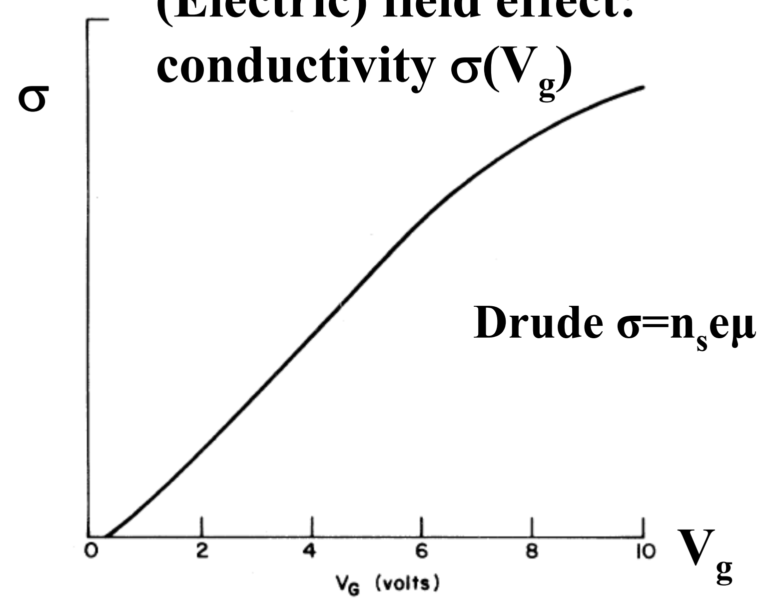
Lecture III: **Studies of the electron dynamics near the 2D MIT: Fluctuations of conductivity**

Studies of the electron dynamics near the 2D MIT

- **Problem: strongly interacting electrons in a random potential**
- **2D electron system in Si MOSFETs; samples with very different amounts of disorder**



(Electric) field effect: conductivity $\sigma(V_g)$



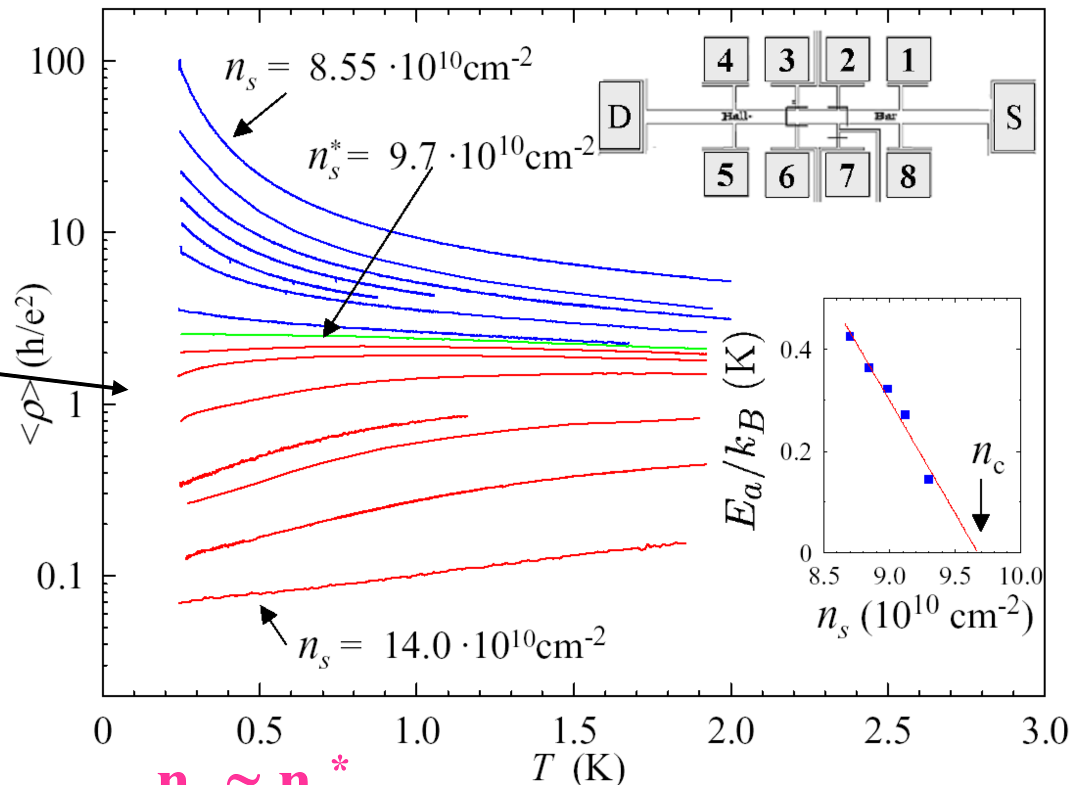
- **"peak mobility" at 4.2 K – rough measure of disorder**
- **vary density n_s using V_g**

Evidence for phase transition(s)? MIT, glass transition?

Resistivity in high-mobility (low disorder) Si MOSFETs

- **high-mobility** (~ 25,000 cm²/Vs) **Si MOSFETs (Groningen/Delft);**
  L=120 μm, W=50 μm
  (d_{0x}=147 nm, Al gates, N_a~10^{14} cm^{-3})

"separatrix" n_s^*



- **lowest n_s and T:**
  $\langle\rho\rangle \propto \exp(E_a/k_BT)$

  $\Rightarrow$ $n_c \approx 9.7\times10^{10}$ cm^{-2}

critical density (where strong localization ends)

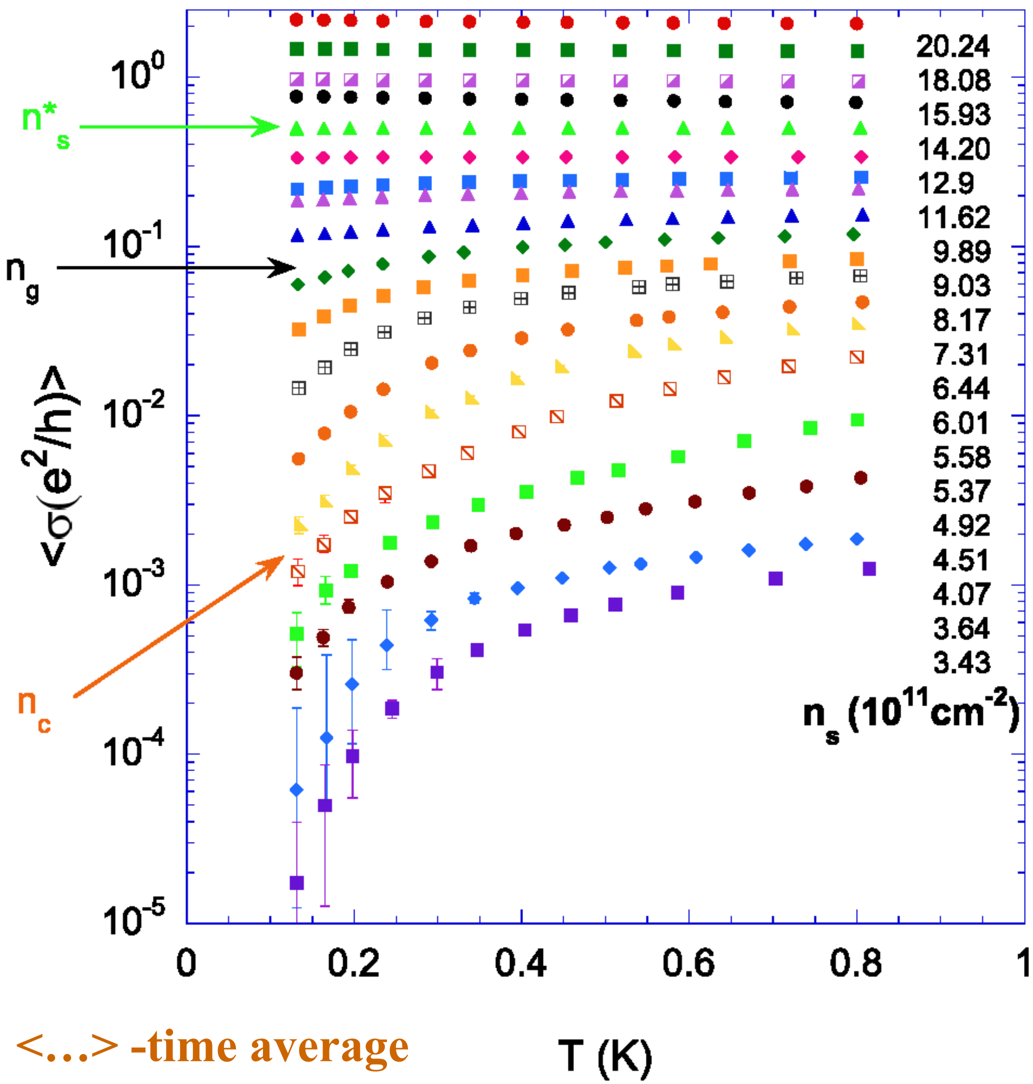
$n_c \approx n_s^*$

$n_c \leq n_g$

glass transition

Will show this later

Conductivity in low-mobility (high disorder) Si MOSFETs

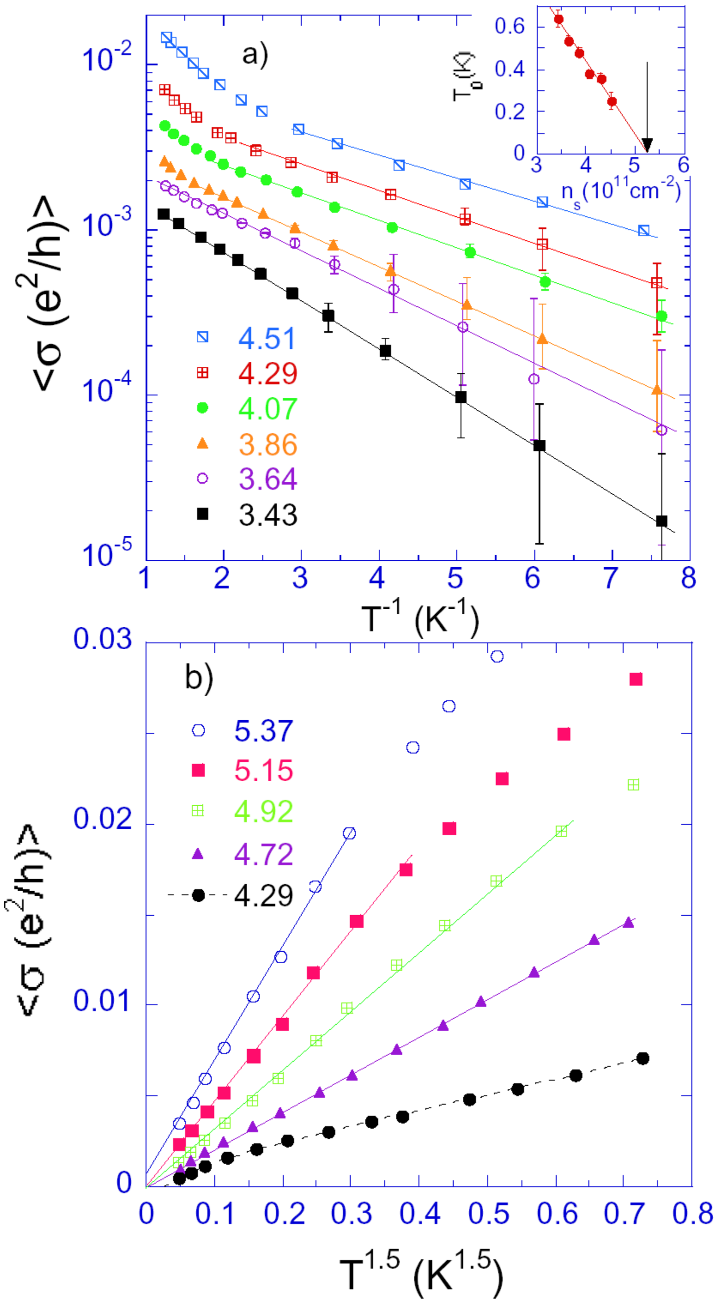


<...> -time average

- <u>low-mobility</u> (~600 cm^2/Vs) Si MOSFETs (IBM); L×W: 1x90 and 2x50 μm^2 (d_{ox}=50 nm, poly-Si gates, N_a~10^{17} cm^{-3})
- metallic $\langle\sigma(T)\rangle$ at high n_s
- $d\langle\sigma\rangle/dT=0$ at $n_s^*=12.9\times10^{11}$ cm^{-2} ("separatrix")
- metal-insulator transition: $n_c=(5.0\pm0.3)\times10^{11}$ cm^{-2}
- glass transition (will show later): $n_g=(7.5\pm0.3)\times10^{11}$ cm^{-2}

→ metallic glass

$k_F l < 1$ ("bad" metal)



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

- at the lowest n_s, strongly localized:

  $\langle\sigma\rangle \propto \exp(-T_o/T)$,

  → $n_c=(5.0\pm0.3)\times10^{11}$ cm^{-2},

  $n_c \ll n_s^*$

- just above n_c (metallic glass):

  $\langle\sigma\rangle=a(n_s) + b(n_s)T^x, \;\; x\approx1.5$

non-Fermi liquid behavior

(not a good metal)

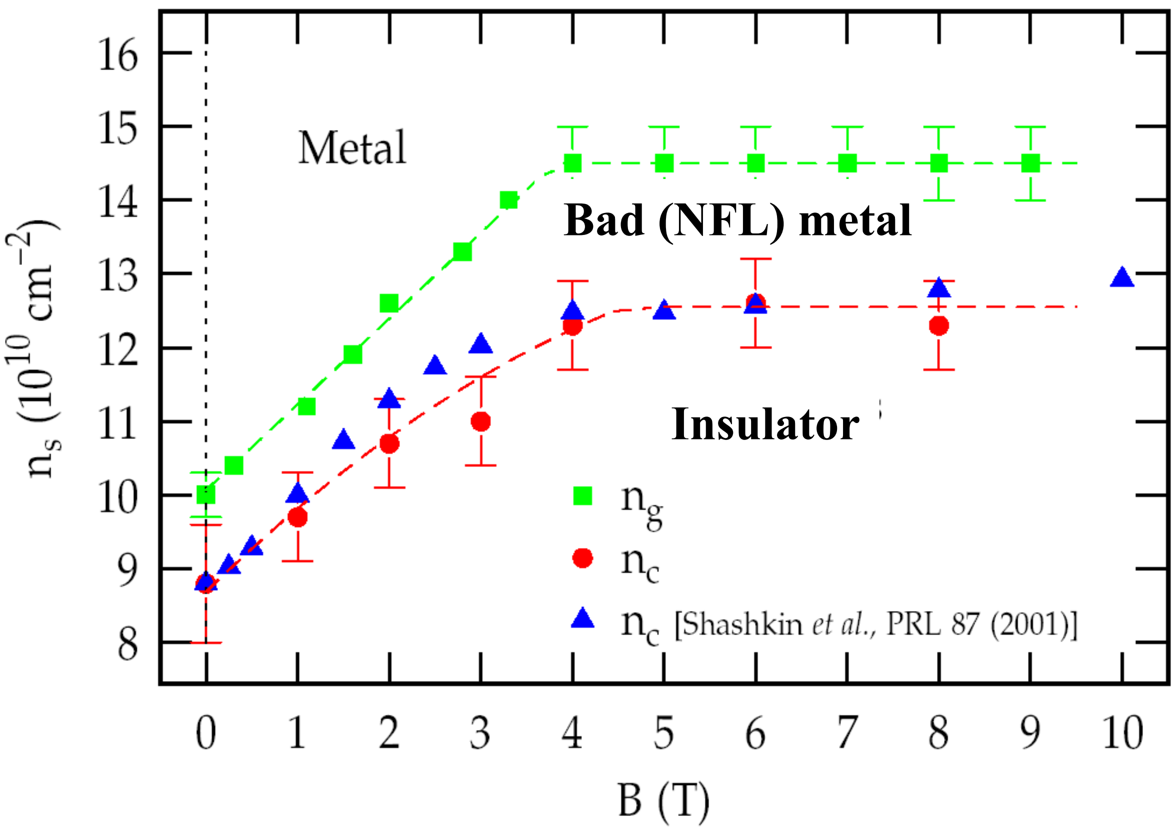
$\langle\sigma(n_c,T)\rangle \propto T^{3/2}$ (a power law, as it should be for the MIT)

(consistent with V. Dalidovich and V. Dobrosavljević, PRB 66, 081107 (2002), for the metallic glass phase)

Back to high-mobility samples; apply parallel magnetic field B

(no orbital effect;
B couples only to spins)

B ⟶ 2DES spin-polarized



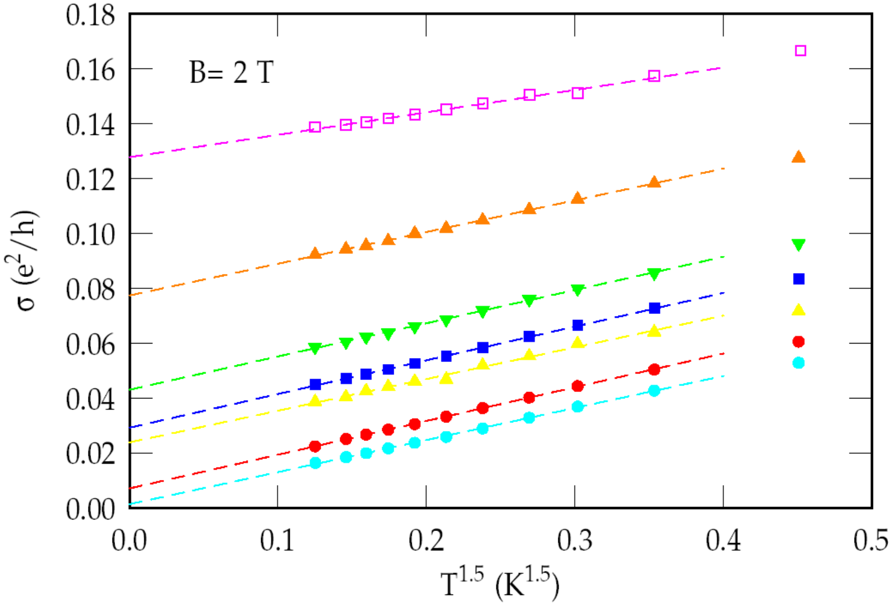
B=0:
(almost) no intermediate phase

Apply B:
emergence of intermediate phase with the same $\sigma(T)$ as in samples with high disorder

(suppression of screening by parallel B ⇒ effective disorder increases)

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

Intermediate metallic phase



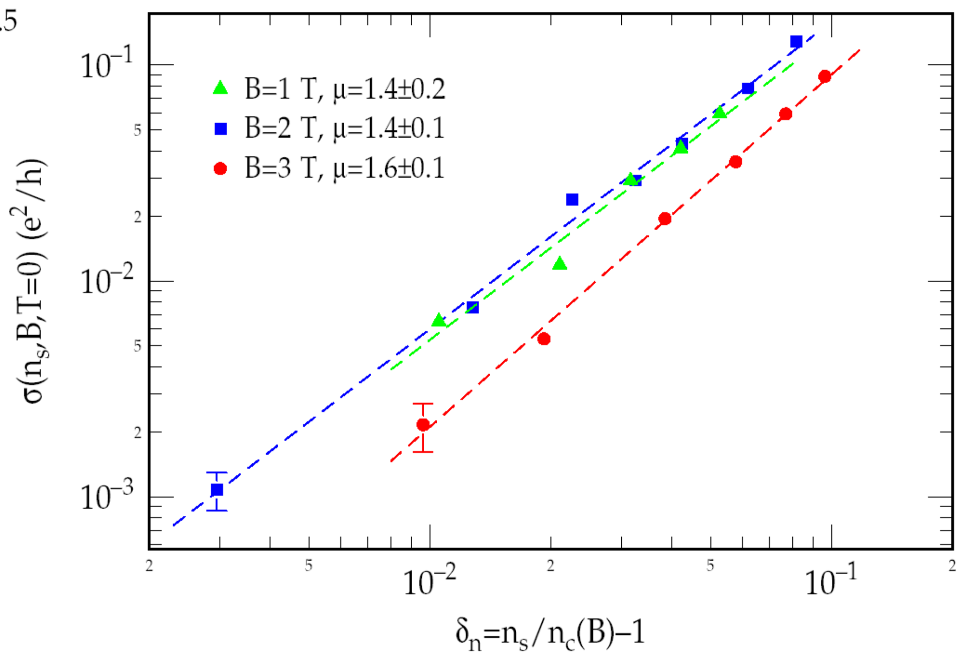
$\sigma(n_s,T,B)=\sigma(n_s,T=0,B)+b(n_s,B)T^{3/2}$!

(same as in low-mobility samples at B=0!)

$\sigma(n_s,T=0,B) \propto \delta_n^{\mu}$, $\mu \sim 1.5$

consistent with QPT

$n_s(10^{10}\ cm^{-2})$=11.9, 11.6, 11.3, 11.2, 11.0, 10.9, 10.7 from top; $n_c(B=2T)=10.67\times10^{10}\ cm^{-2}$



- at B=0, $\mu \sim$ 1-1.5 [Fletcher et al., Semicond. Sci. Tech. 16, 386 (2001)]

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T=0 phase diagram

Intermediate phase!

Insulator: $\sigma(T=0)=0$

Strange metal: $\sigma(T=0)\neq 0$

$\sigma(n_s,T)=\sigma(n_s,T=0)+b(n_s)T^{3/2}$

Metal: $\sigma(T=0)\neq 0$;
$d\sigma/dT<0$

n_c n_g n_s^* **density**

will show this is a glass transition

n_s^* – separatrix (from transport)

n_g – glass transition (will show later)

n_c – critical density for the MIT from $\sigma(T)$ on both insulating and metallic sides

High disorder (low-mobility devices): $n_c < n_g < n_s^*$

Low disorder (high-mobility devices): $n_c \approx n_s^* \lesssim n_g$ for B=0,

$n_c < n_s^* \lesssim n_g$ for $B\neq 0$

[Bogdanovich, Popović, PRL 88, 236401 (2002);
Jaroszyński, Popović, Klapwijk, PRL 89, 276401 (2002);
Jaroszyński, Popović, Klapwijk, PRL 92, 226403 (2004)]

How to probe glassy dynamics?

- measure **response** of the system **to** some kind of a **perturbation**
 (*e.g.* after a rapid cooling;
 a spin glass in a magnetic field)

supercooled water

- here, perturbation = change of V_g;
 measure conductivity σ *vs.* time t
 after the perturbation is switched off

[see also papers by Z. Ovadyahu for similar work in InO_x electron glass deep in the insulating regime]

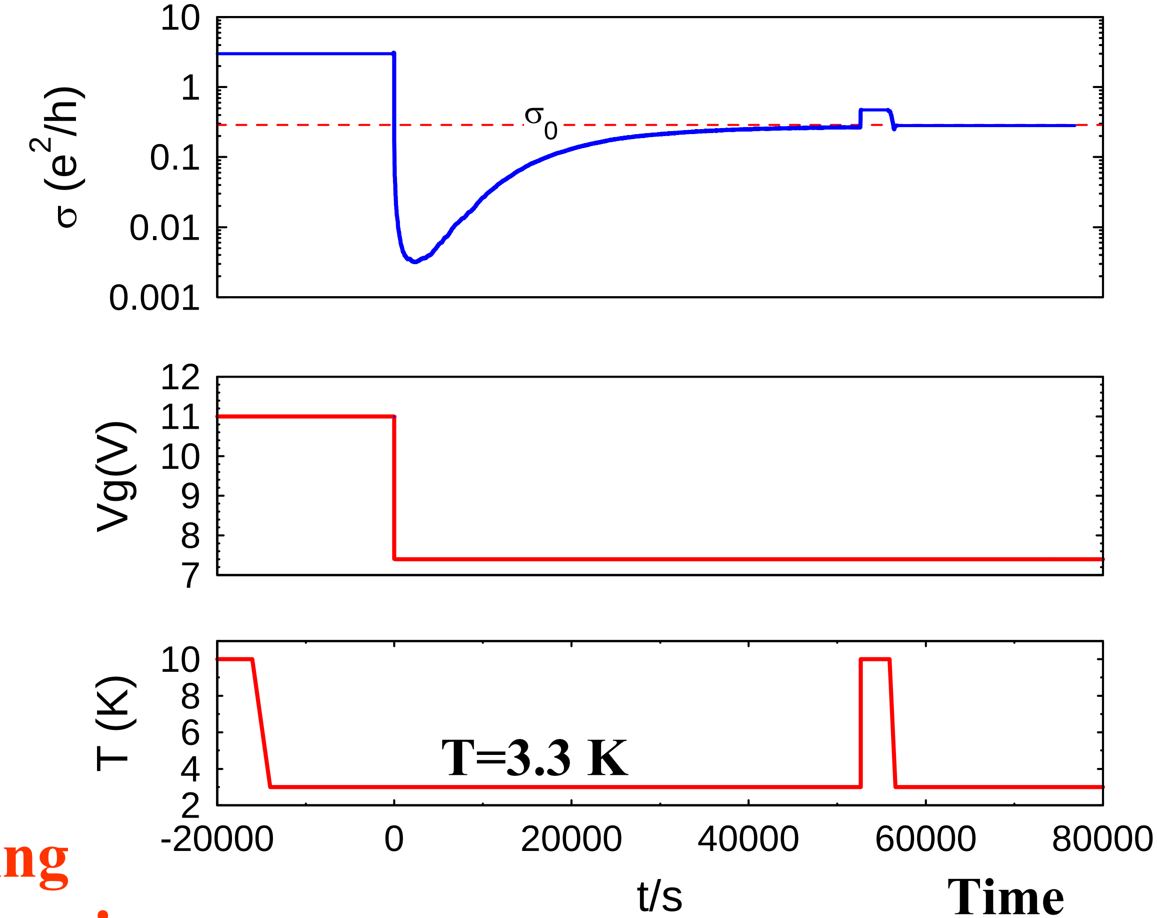
Relaxations of conductivity after a rapid change of n_s

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

Low-mobility samples

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

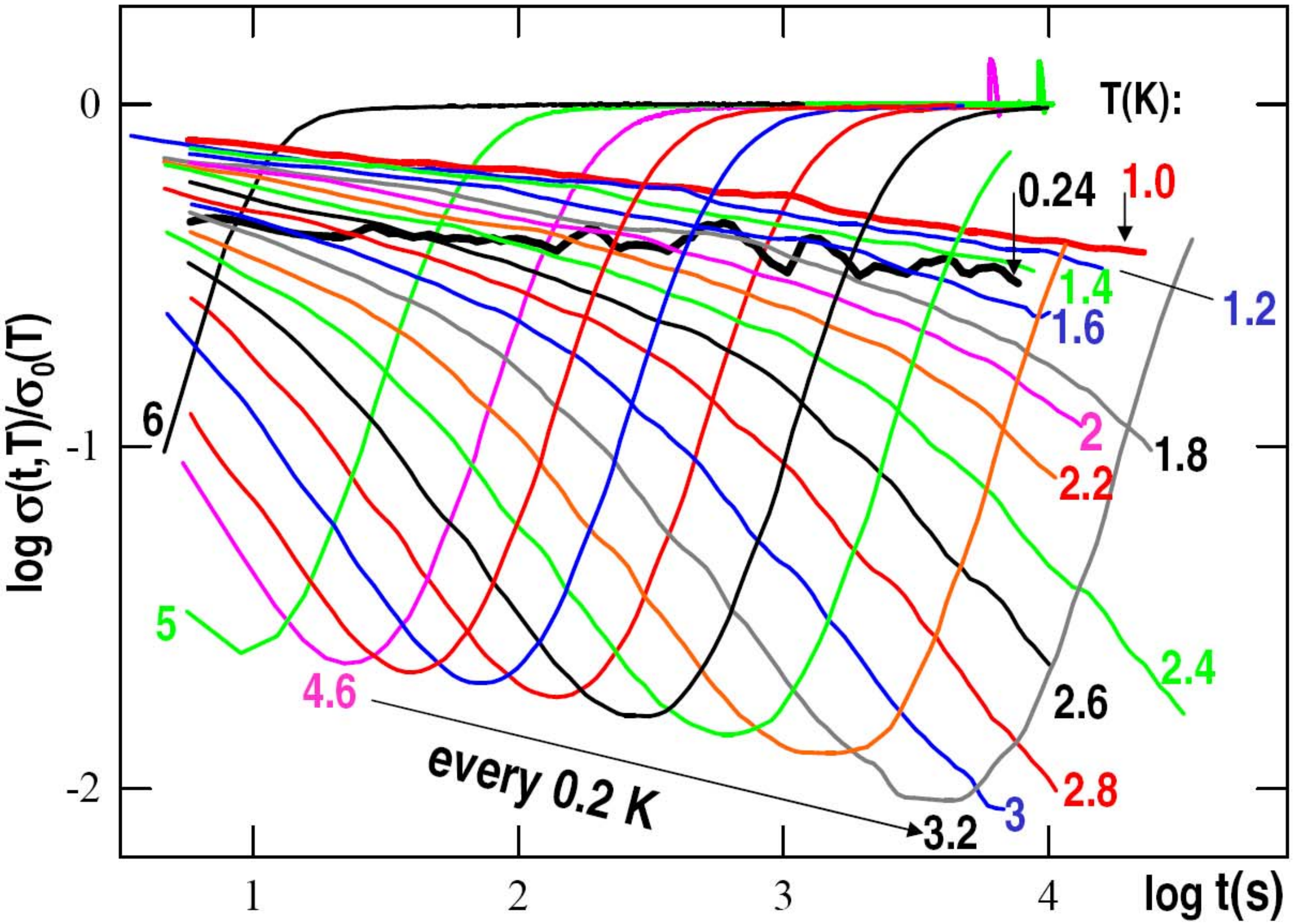
Final
$n_s(10^{11}$cm$^{-2})=$
$=4.74 \geq n_c$

$\Delta E_F \gg k_B T$

Overshooting of equilibrium!

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

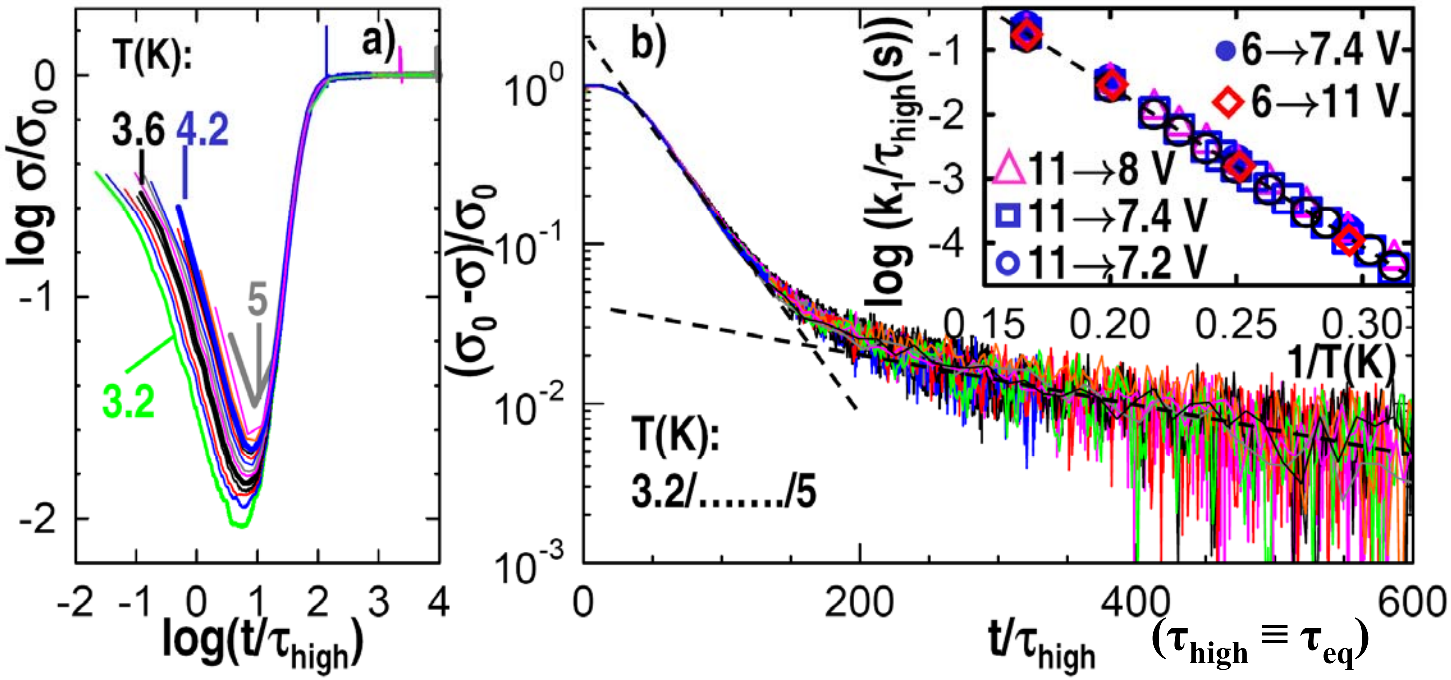
Repeat measurement at (many) different T (after warm-up to 10 K):



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

Approach to equilibrium:

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



$(\tau_{high} \equiv \tau_{eq})$

- Relaxations exponential

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

$\tau_{eq} \to \infty$ 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 $t < \tau_{eq}$,**

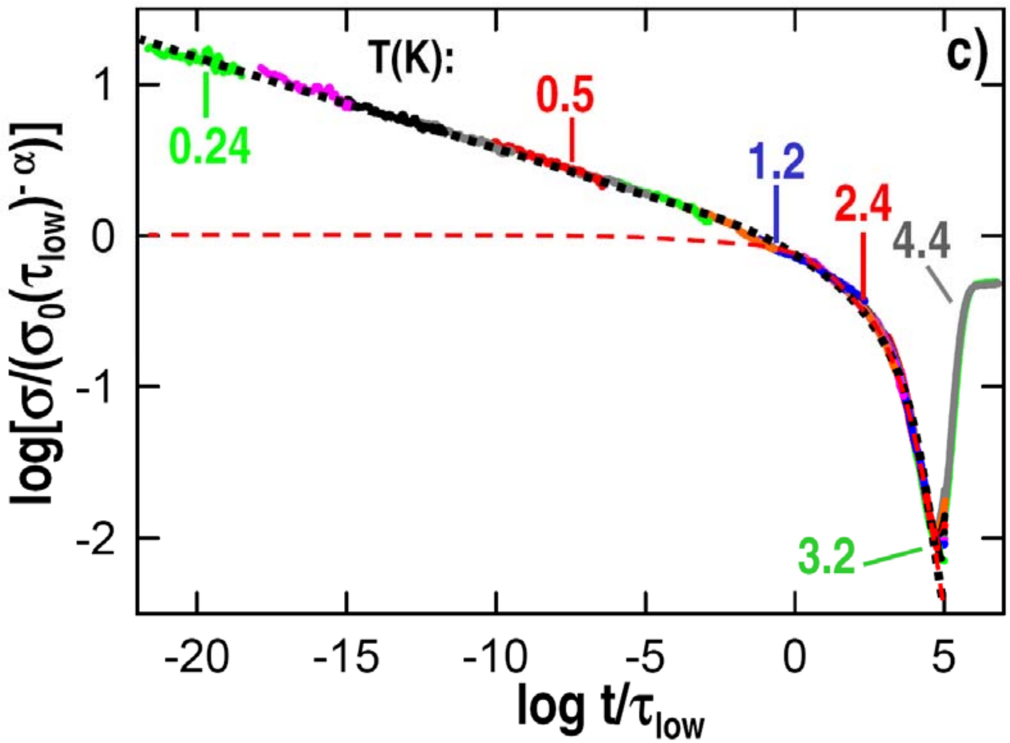
$$\underbrace{\sigma(t,T)/\sigma_0 \propto t^{-\alpha(n)} \exp\{-[t/\tau_{low}(n_s,T)]^{\beta(n)}\}}_{\text{glassy relaxation}}$$

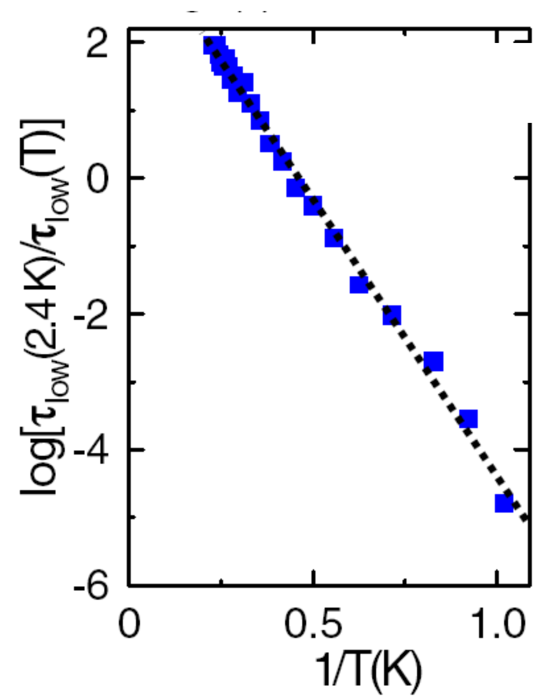
(α=0.07, β<0.3 for this n_s)

($n \equiv n_s$)

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

$E_a \approx 20$ K





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

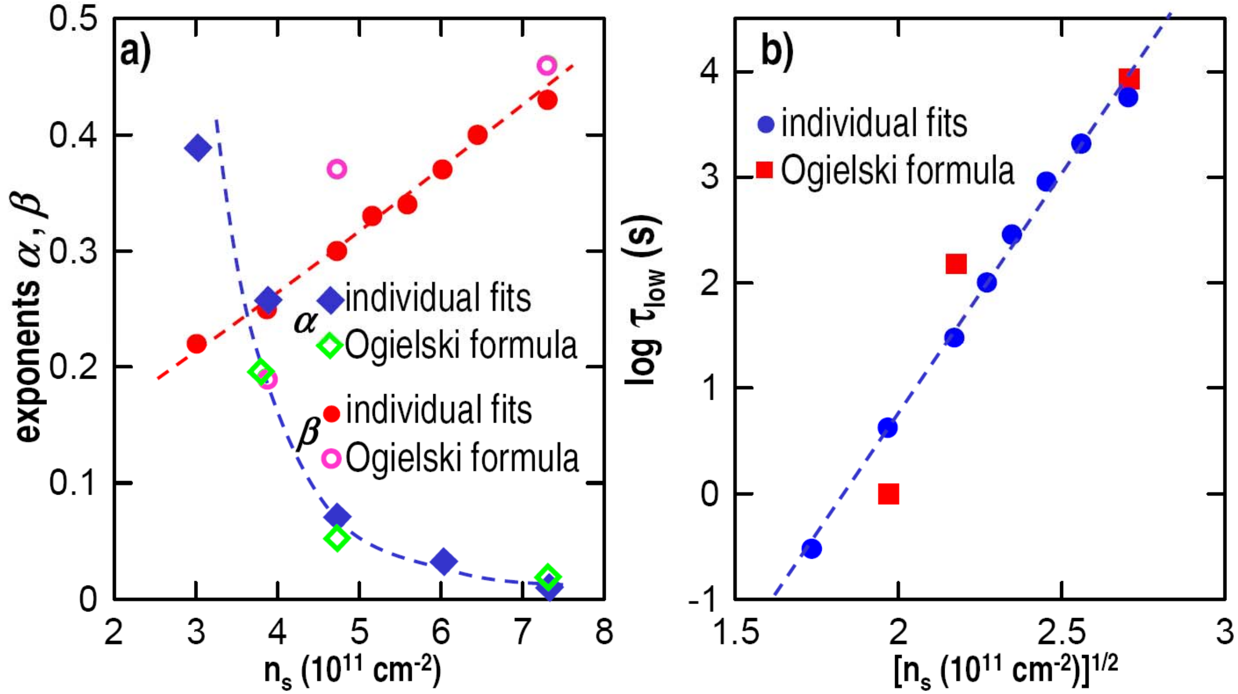
- **<u>$T \rightarrow 0$:</u>**

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

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

$\alpha(n_s) \rightarrow 0$ as $n_s \rightarrow n_g^-$

(no slow relaxation for $n_s > n_g$)



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

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 $T \to 0 \Rightarrow T_g = 0$; 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!

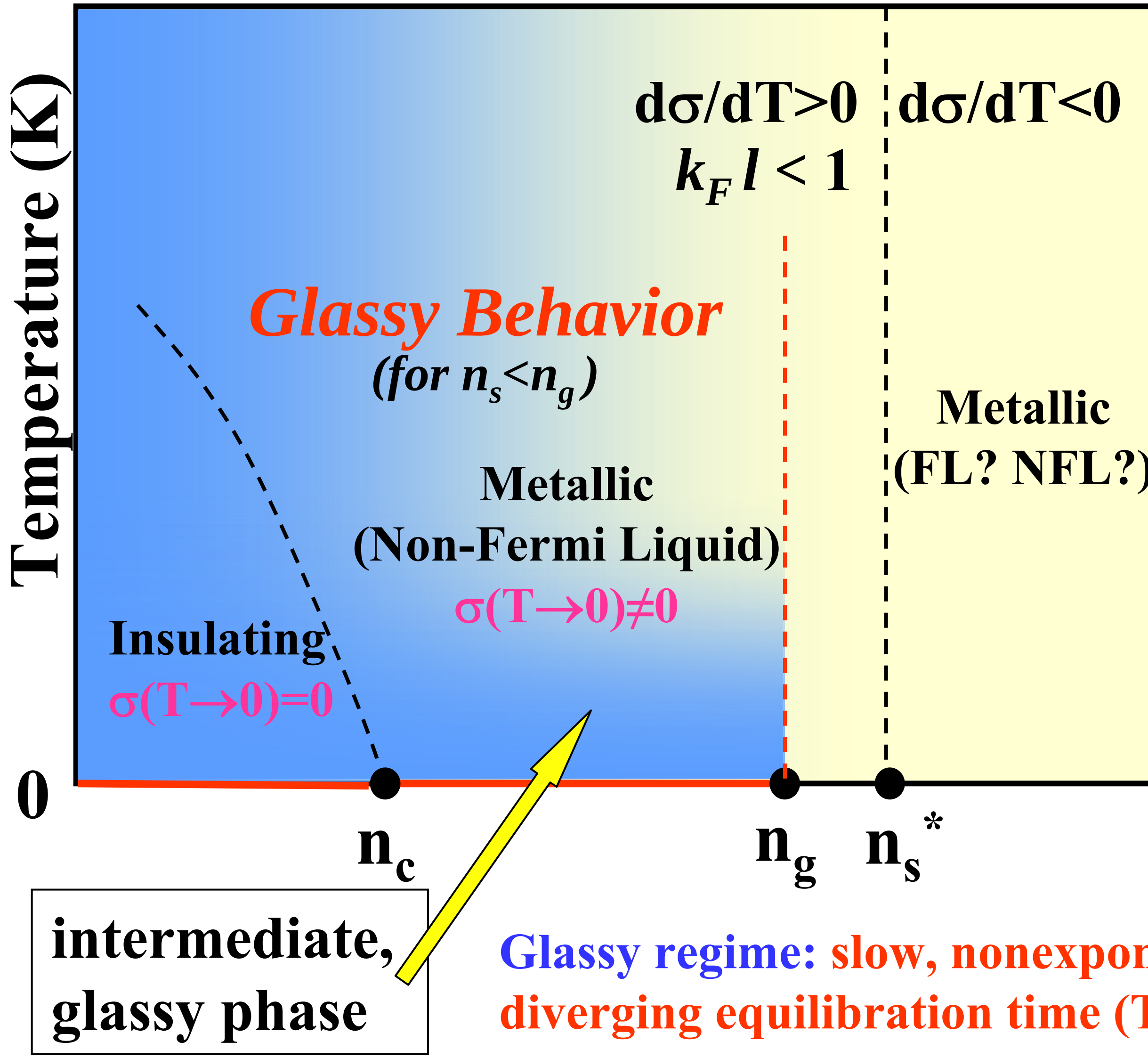
  age of the Universe ~ 10^{10} years)

- Coulomb interactions between 2D electrons – a dominant role in the out-of-equilibrium dynamics

- as $T \to 0$, no relaxations for $n_s > n_g$; no relaxations for $k_F l > 1$

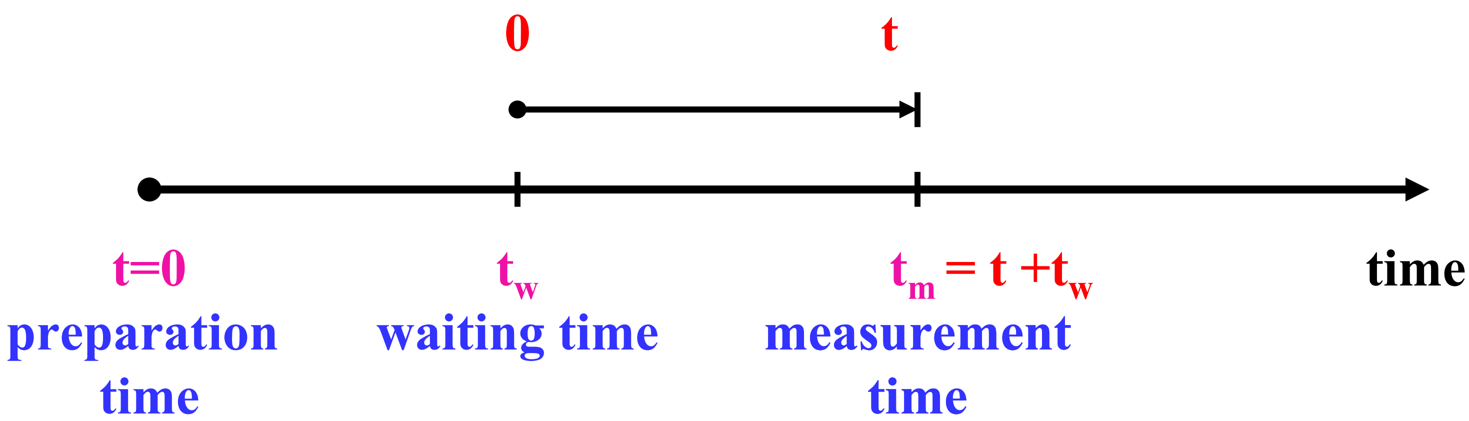
Note: system equilibrates only after it first goes farther away from equilibrium!

Phase diagram of a 2DES in Si



Glassy regime: slow, nonexponential relaxations, diverging equilibration time (T_g=0)

Times



In equilibrium $\tau_{eq} < t_m$

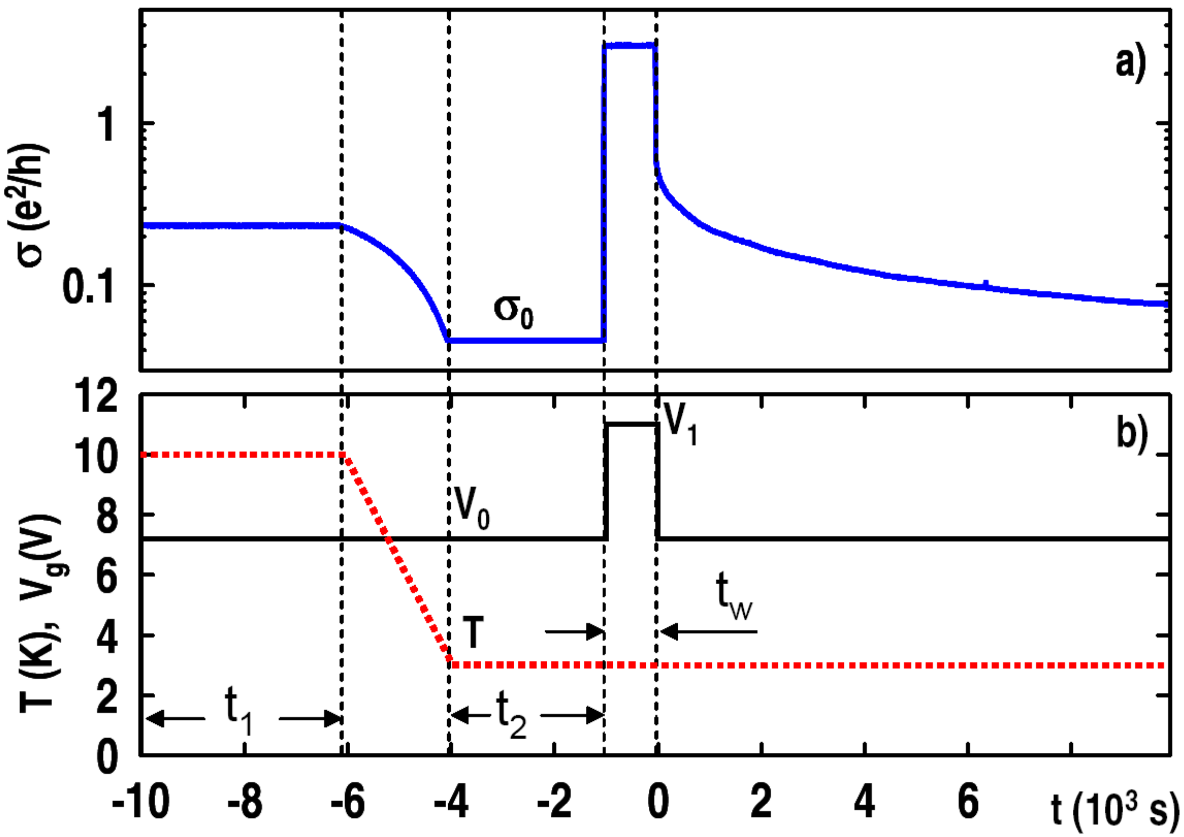
Out of equilibrium $\tau_{eq} > t_m$

Out of equilibrium:

responses and correlations depend on two times, t and t_w (age) - aging

- *Slow Relaxations and Nonequilibrium Dynamics in Condensed Matter,* edited by J.-L. Barrat, M.V. Feigelman, J. Kurchan, J. Dalibard (Springer, New York, 2003) - Les Houches summer school
- *Ageing and the Glass Transition,* edited by M. Henkel, M. Pleimling, R. Sanctuary (Lecture Notes in Physics, Springer, 2007) – Univ. of Luxemburg summer school

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

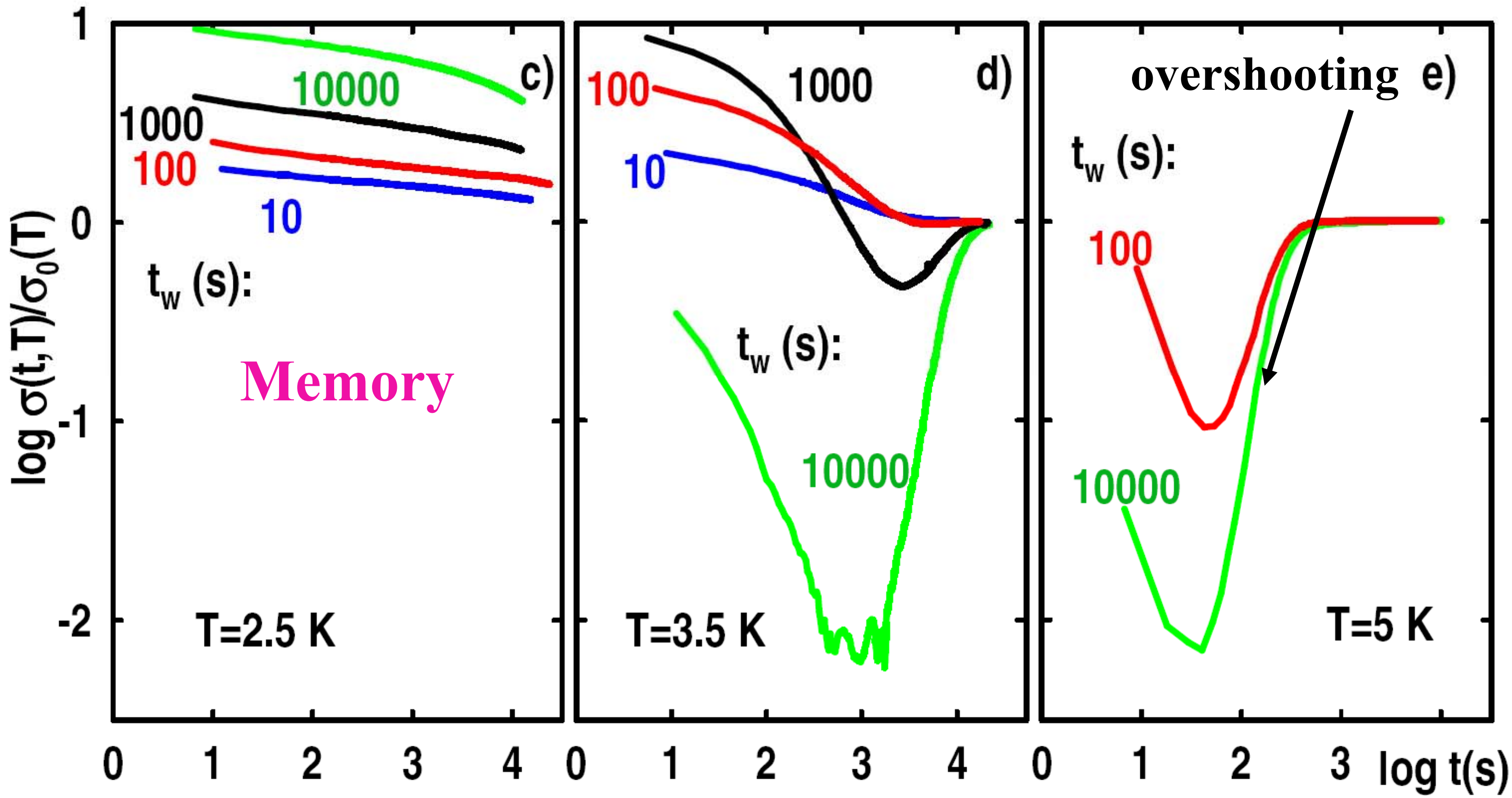


Initial and final $n_s(10^{11}cm^{-2})=3.88 < n_c$; density during t_w=1000 s: $n_s(10^{11}cm^{-2})=20.26 > n_g$

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

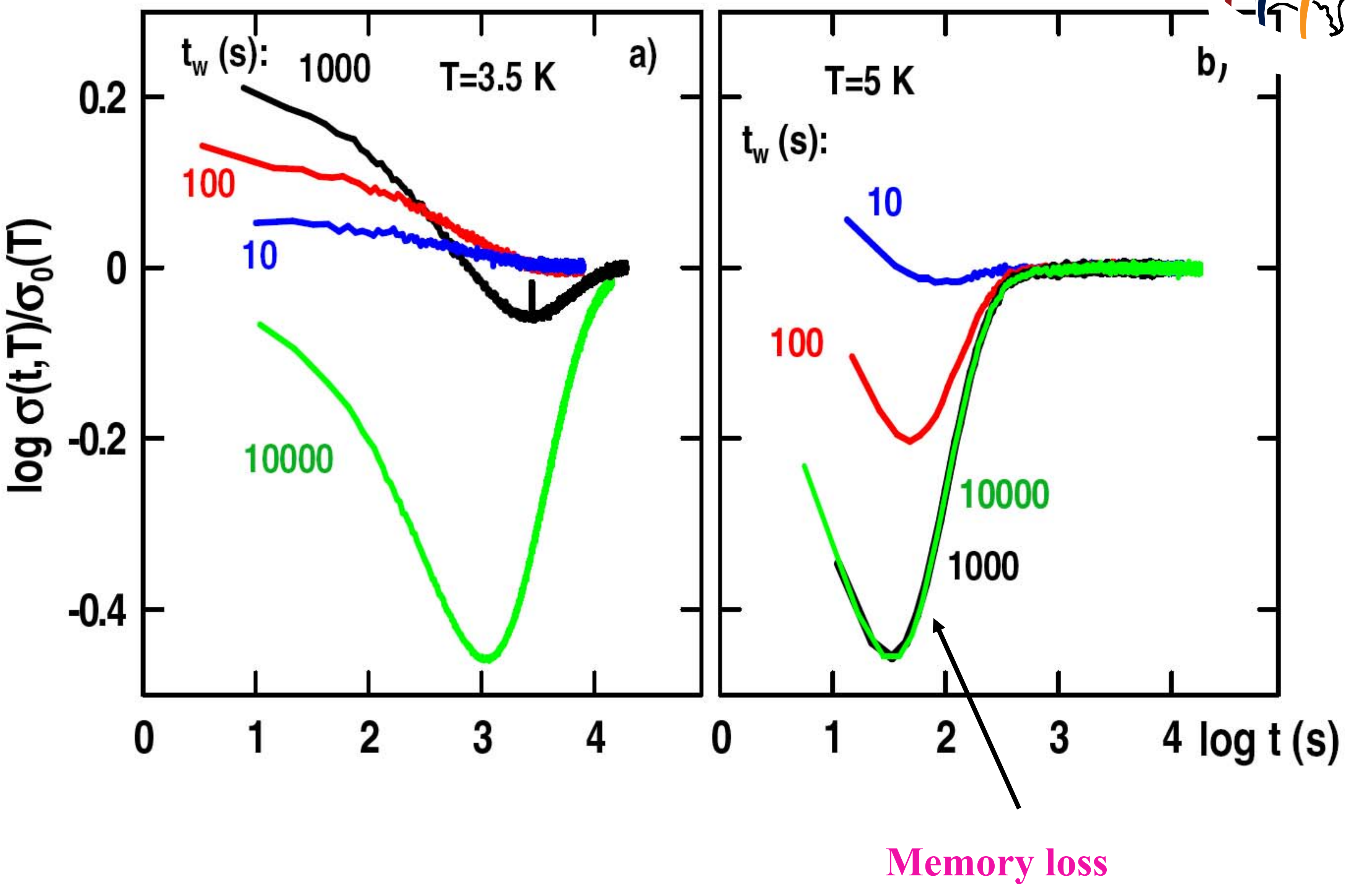
[J. Jaroszyński and D. Popović, Phys. Rev. Lett. 99, 046405 (2007)]

Relaxations for a few different T and t_w:

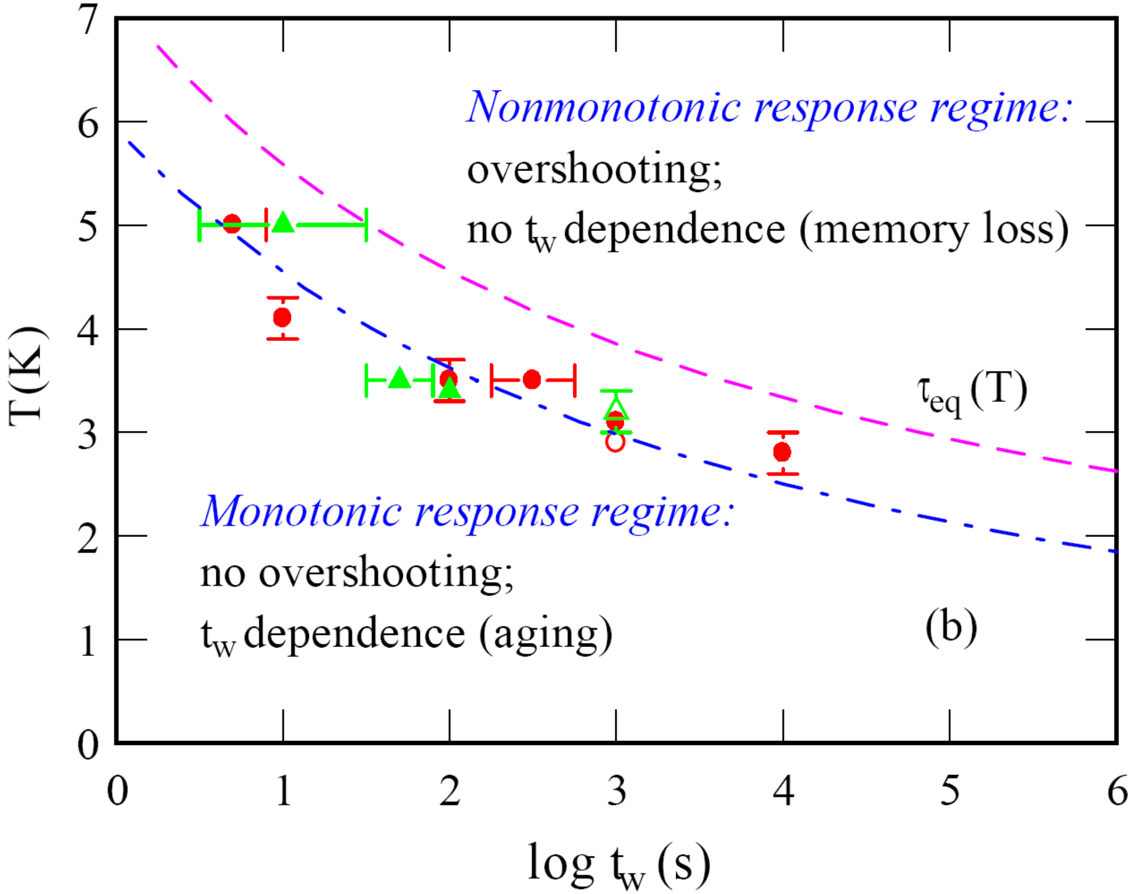


Response (conductivity) depends on the system history (t_w and T) in addition to the time t – *aging* – <u>a key characteristic of relaxing glassy systems.</u>

And a few more… :



When is 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???

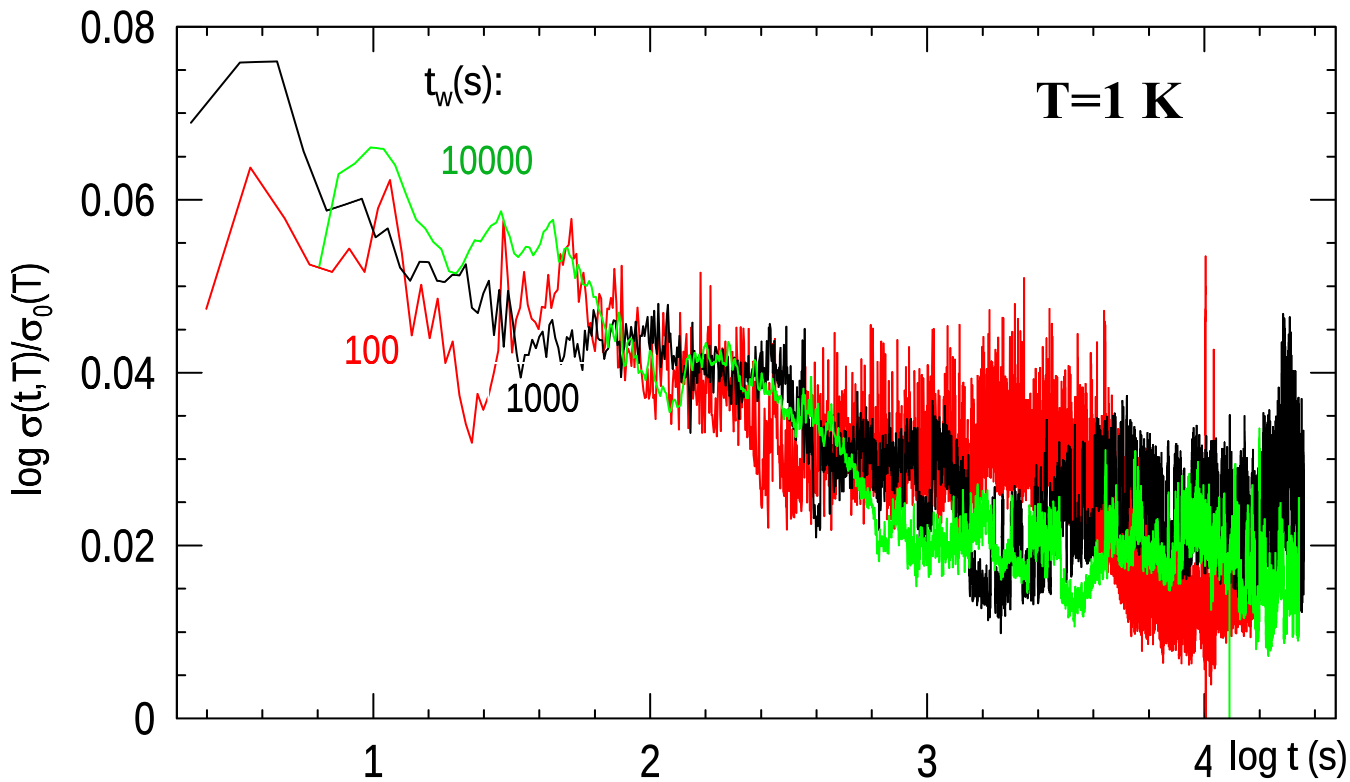
- observed in a variety of systems (e.g. insulating granular metals, manganites, biological systems)

- 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%)

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



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

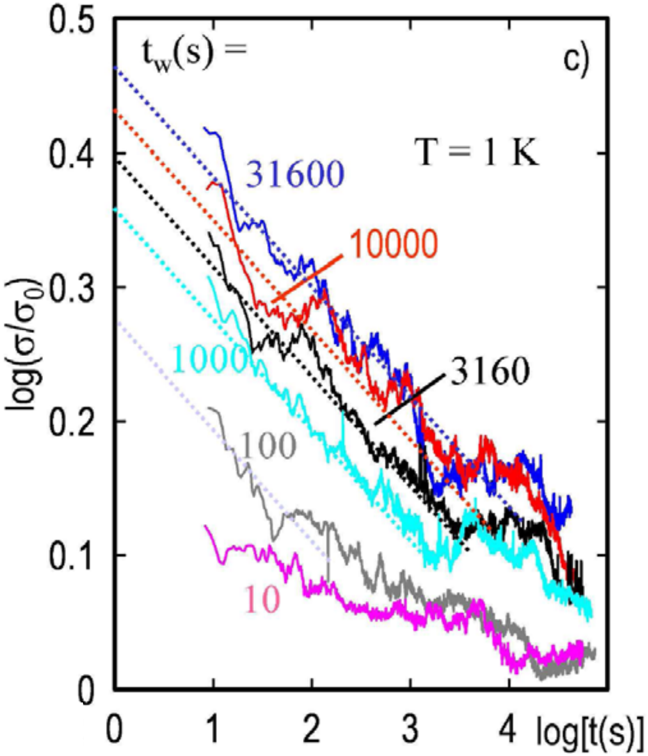
⇒ Glassiness from 2DES, not from background charges

Aging regime (no OS, T=1 K)

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

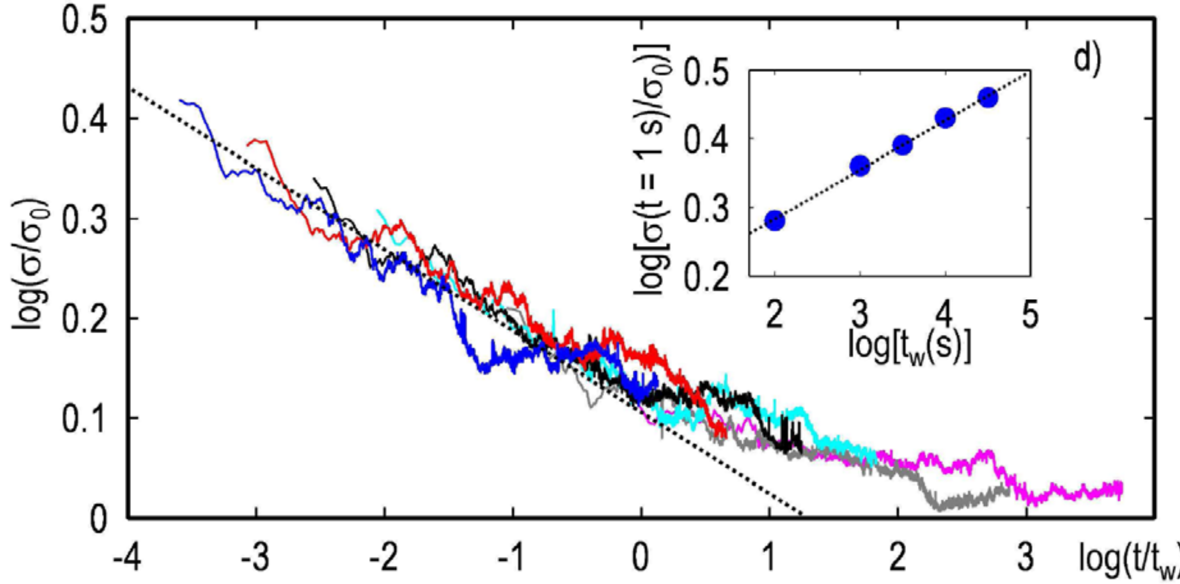
(T= 1 K: $\tau_{eq} \sim 10^{13}$ years!

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 $t \leq t_w$

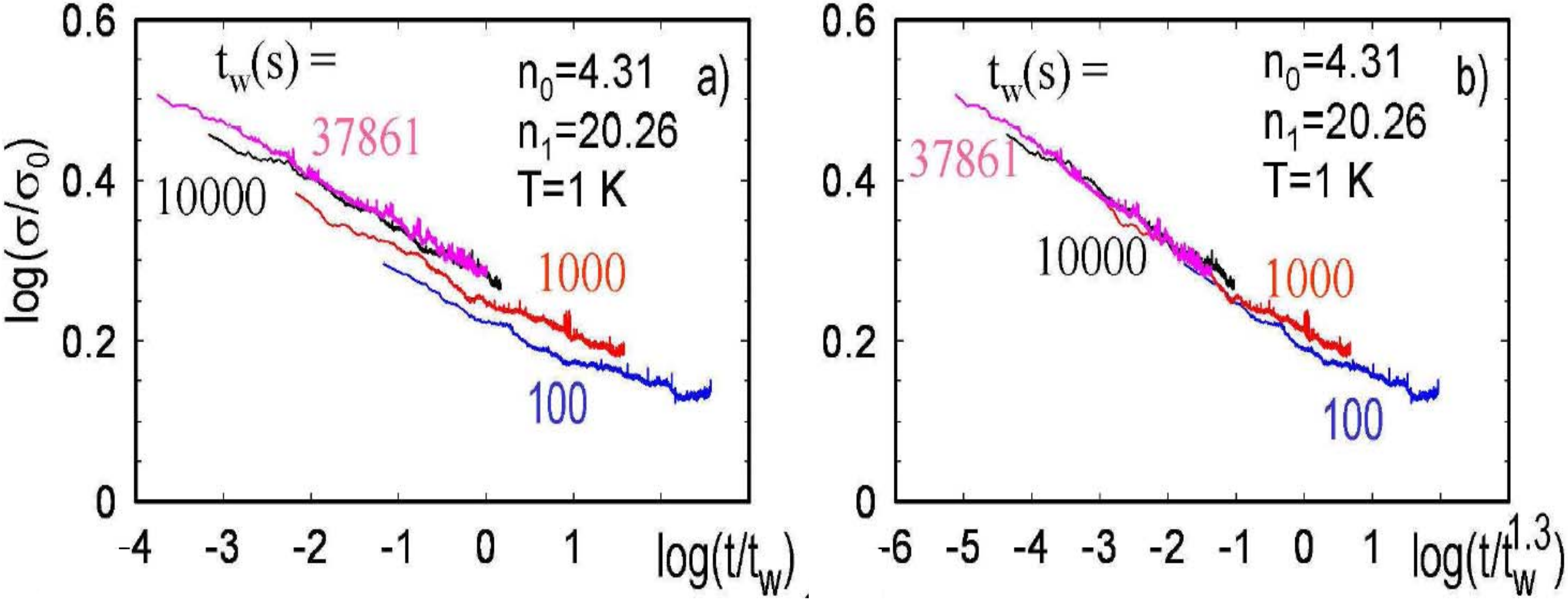
$\Rightarrow$ a memory of t_w is imprinted on each $\sigma(t)$

• $\sigma(t, t_w)$ exhibit full aging for $n_s < n_c$

• for $n_s > n_c$, an increasingly strong departure from full aging that reaches maximum at n_g

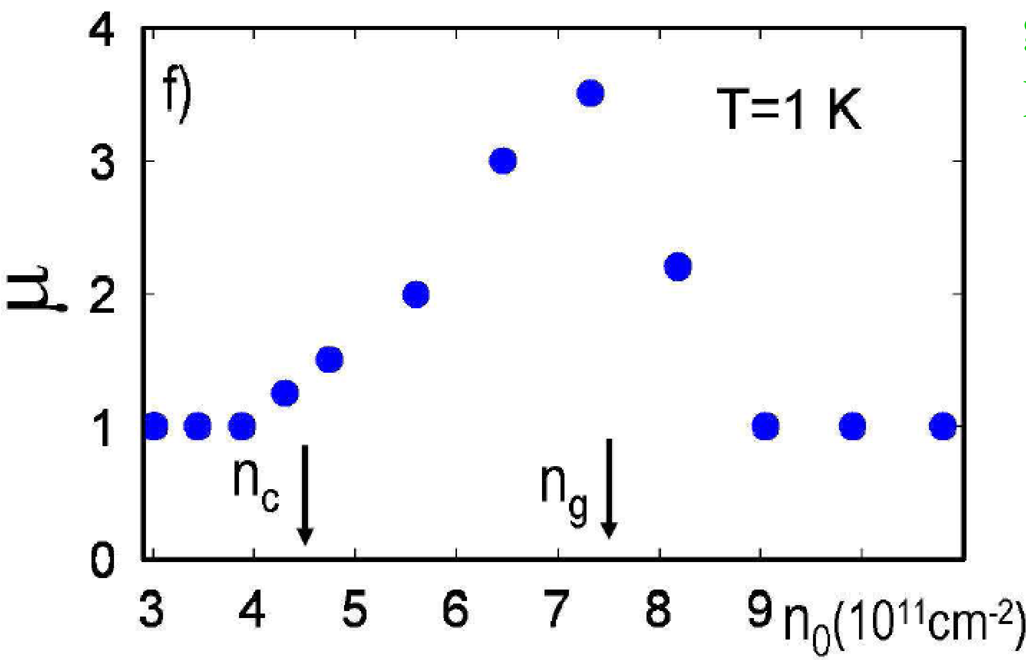
aging function: $\sigma(t/t_w^{\mu})$

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



• $\sigma(t, t_w)$ 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: $\sigma(t/t_w^{\mu})$



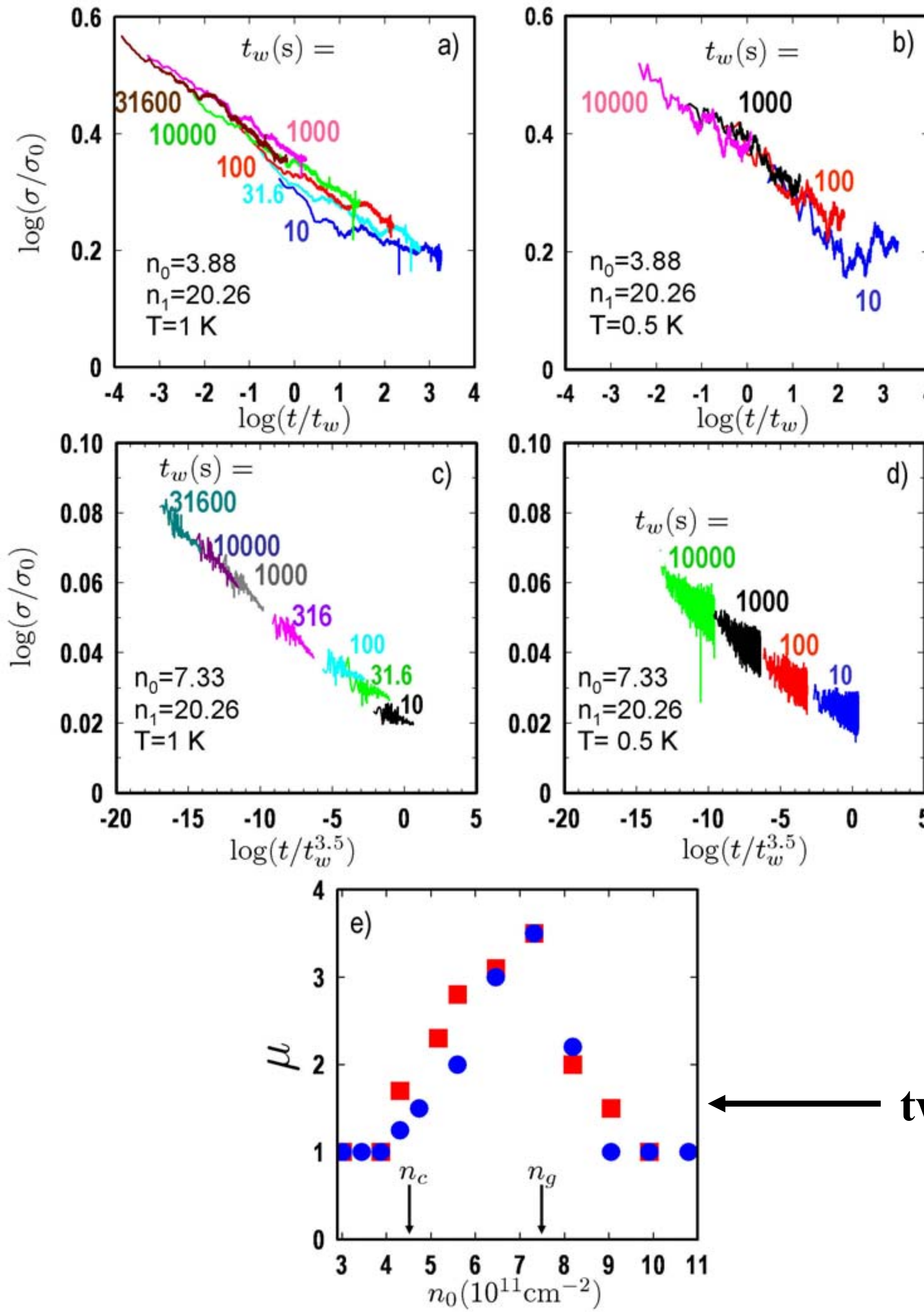
(μ-scaling useful in studies of other glasses; may not have a clear physical meaning)

full aging: μ=1

• an abrupt change in aging at the 2D MIT (n_c)

• insulating glassy phase and metallic glassy phase are different!

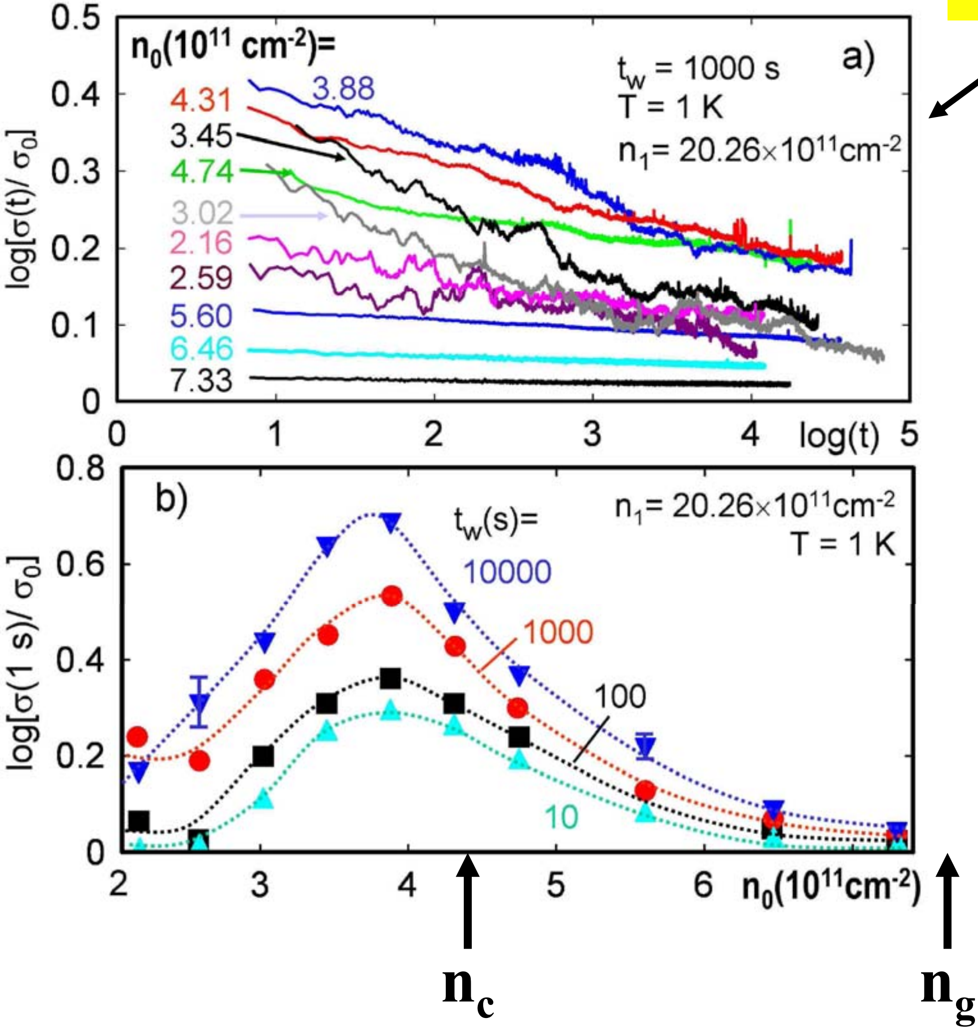
NOTE: mean-field models of glasses include both those that show full aging and those where no t/t_w scaling is expected.



μ does not depend on temperature

two different samples

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!

Summary of Lecture II

- 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
- 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)

<u>Lecture III:</u> other probes of the electron dynamics – fluctuations of σ