Spatially Heterogeneous Ages in Glassy Dynamics

Horacio E. Castillo — Ohio University, Athens OH

Collaborators:

Claudio Chamon — Boston University
Leticia Cugliandolo — ENS, Paris
Malcolm Kennett — Cambridge University

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Glassy States of Matter and Nonequilibrium Quantum Dynamics Seminar

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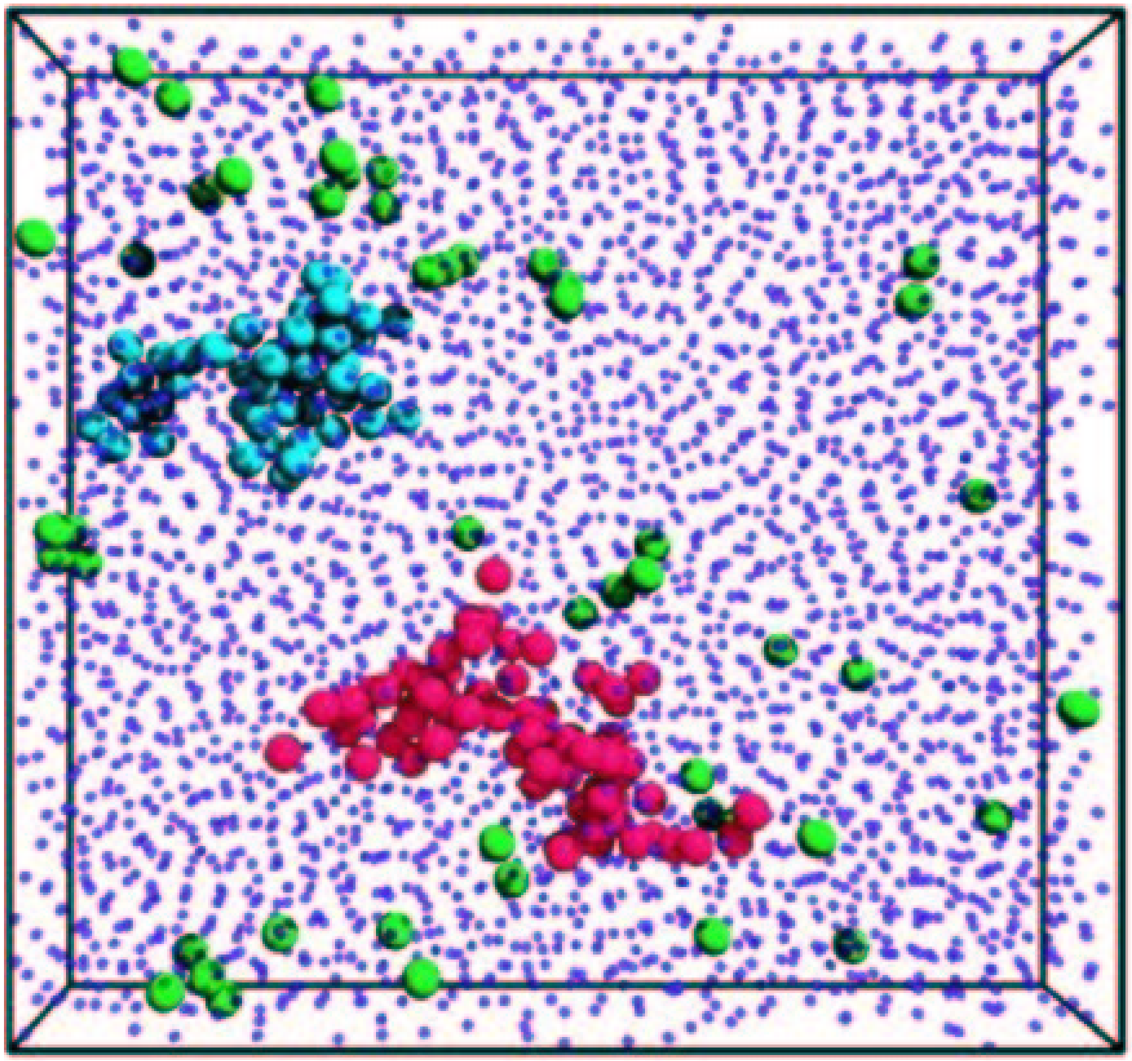
The Problem: Dynamical heterogeneities

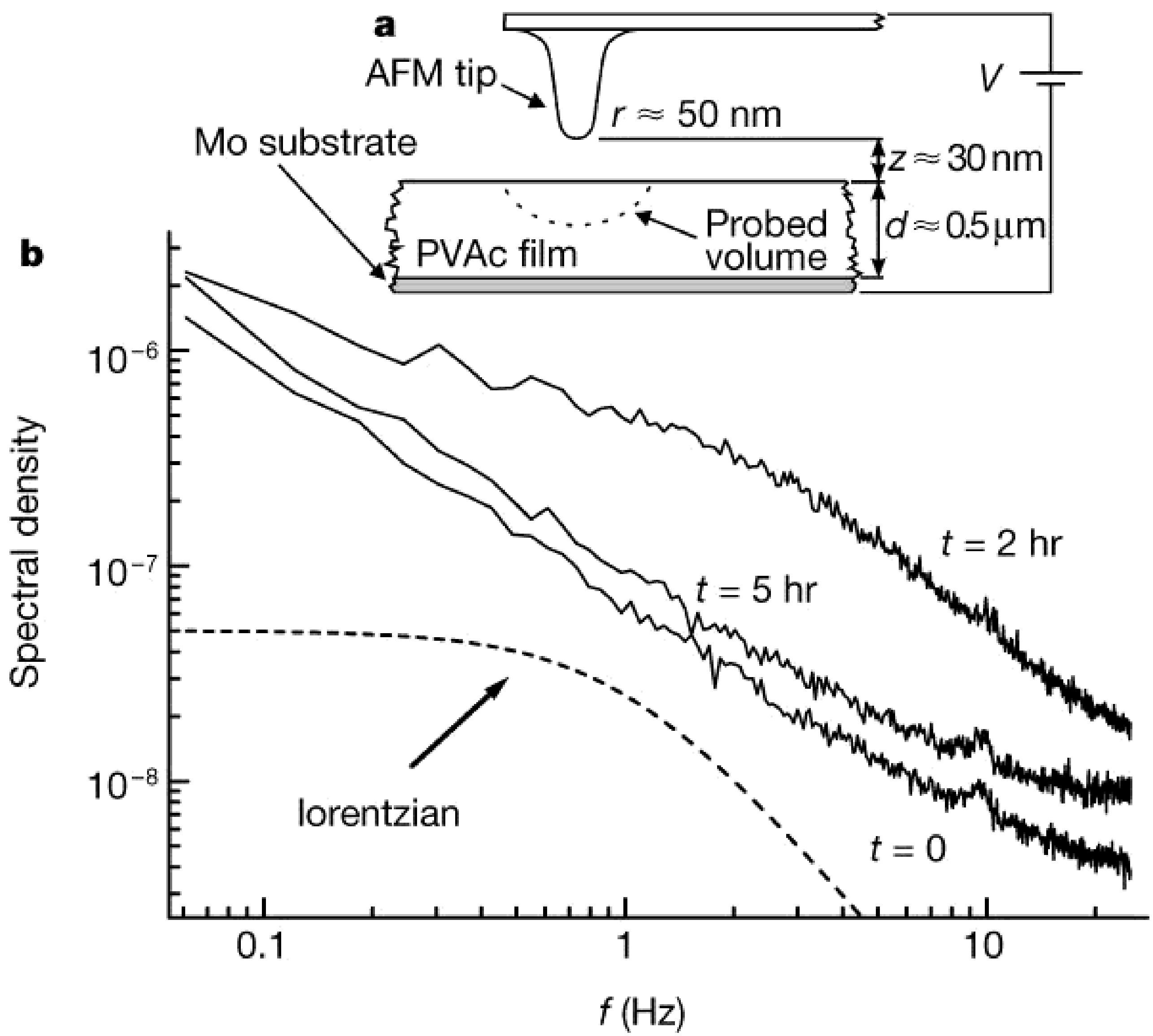
Colloid: confocal microscopy (Weeks et al., Science **287**, 627 (2000))



Supercooled liquid, the fastest 5% of the particles are highlighted

The Problem: Dynamical heterogeneities

PVAc: dielectric fluctuations (Vidal Russell & Israeloff, Nature **408**, 695 (2000))



Polymer glass, $T = T_g - 9K$, transient appearence of strongly fluctuating region under tip

Heterogeneity lifetime ≈ relaxation time

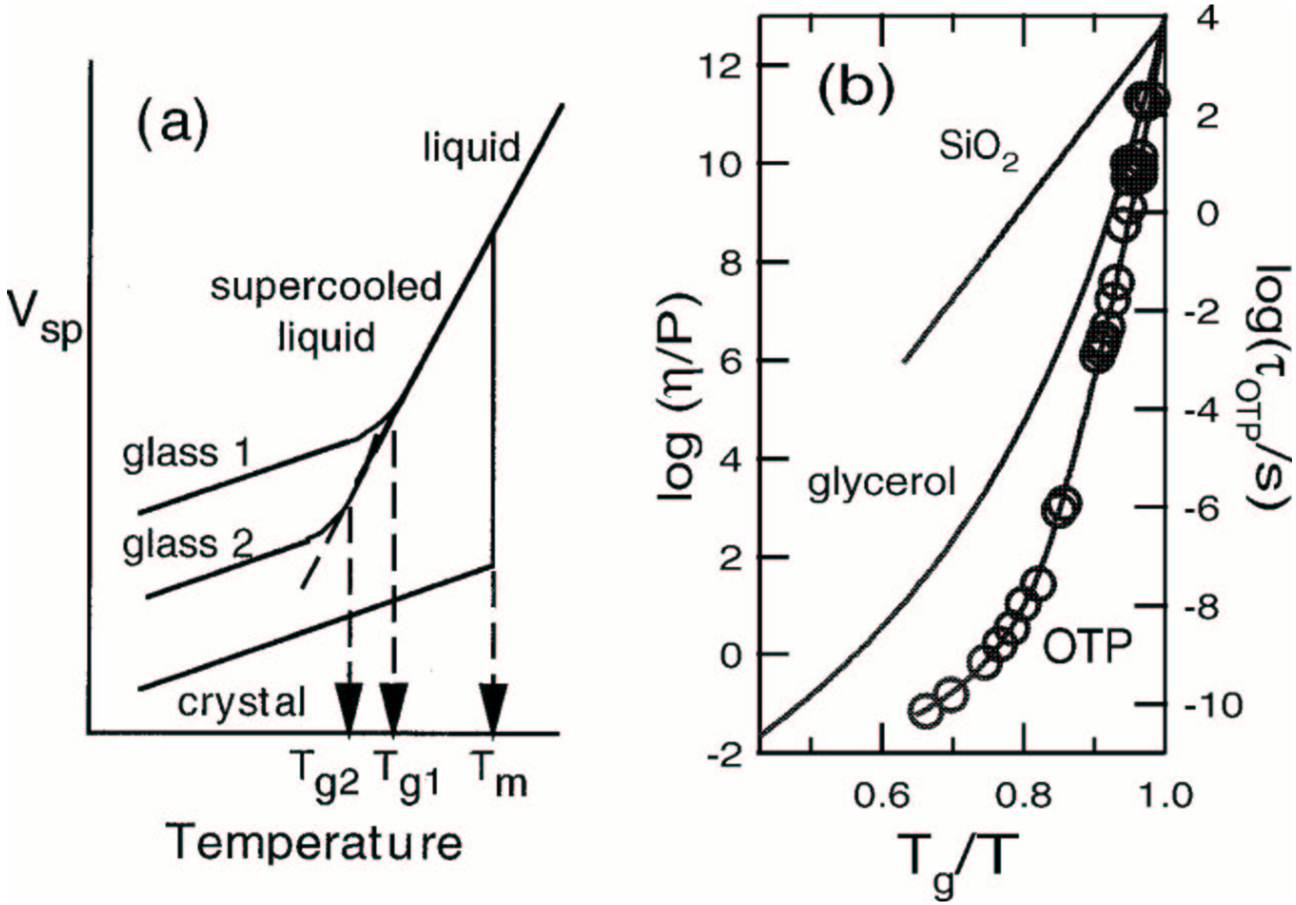
Motivation

- Experiments show spatially heterogeneous dynamics.
- We don't have a theory of spatial fluctuations in glassy dynamics

Outline

1. Experiments show that glasses are out of equilibrium:
   - Age-dependent effects ("Physical aging").
   - "FDT violations".
2. Symmetry under time reparametrization: changing ages is easy (for glasses).
3. Goldstone mode: space dependent ages in glassy systems: numerical evidence and scaling properties.
4. Symmetry breaking terms at finite time: mass of the soft mode.

Slow dynamics in glasses

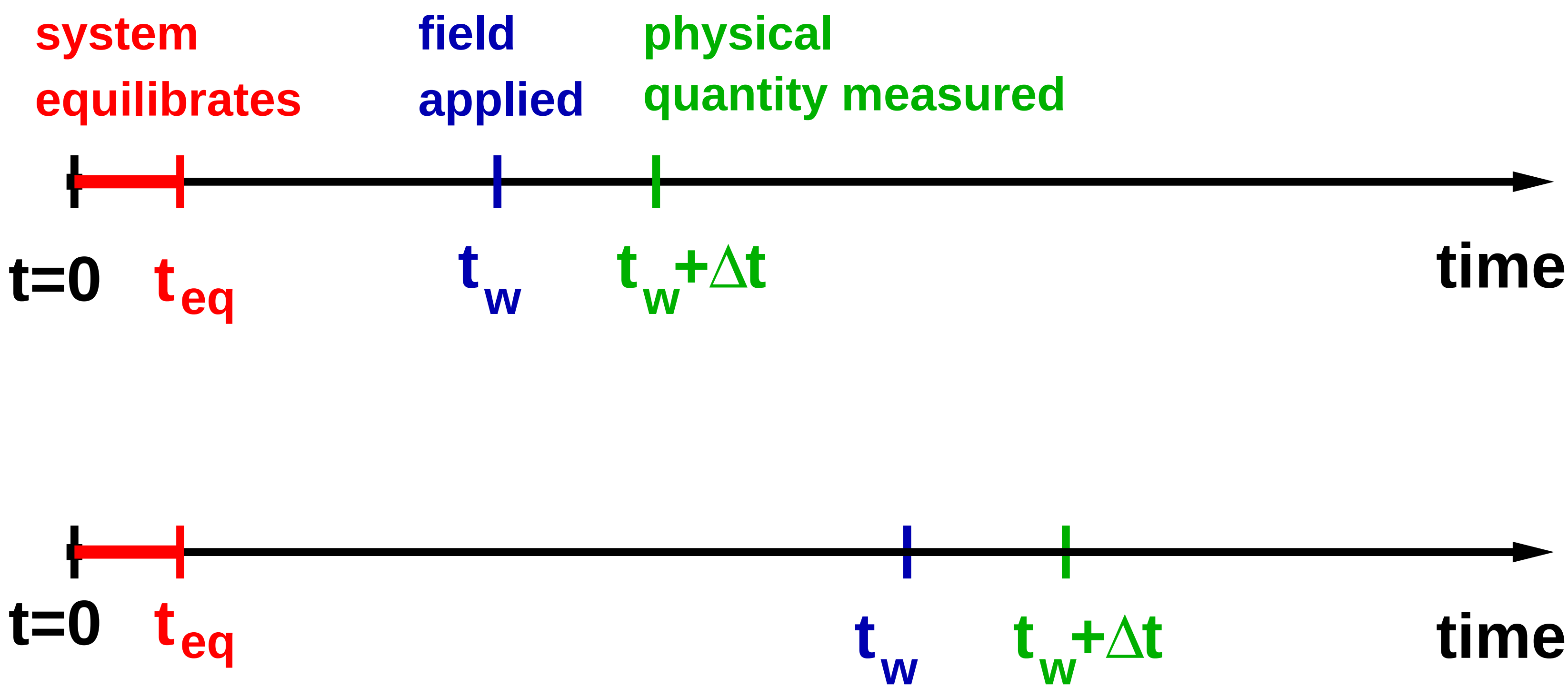


M.D.Ediger (2000)

(a) At the glass transition, the system "falls out" of equilibrium.

(b) Viscosities and relaxation times increase dramatically as a material cools towards T_g.

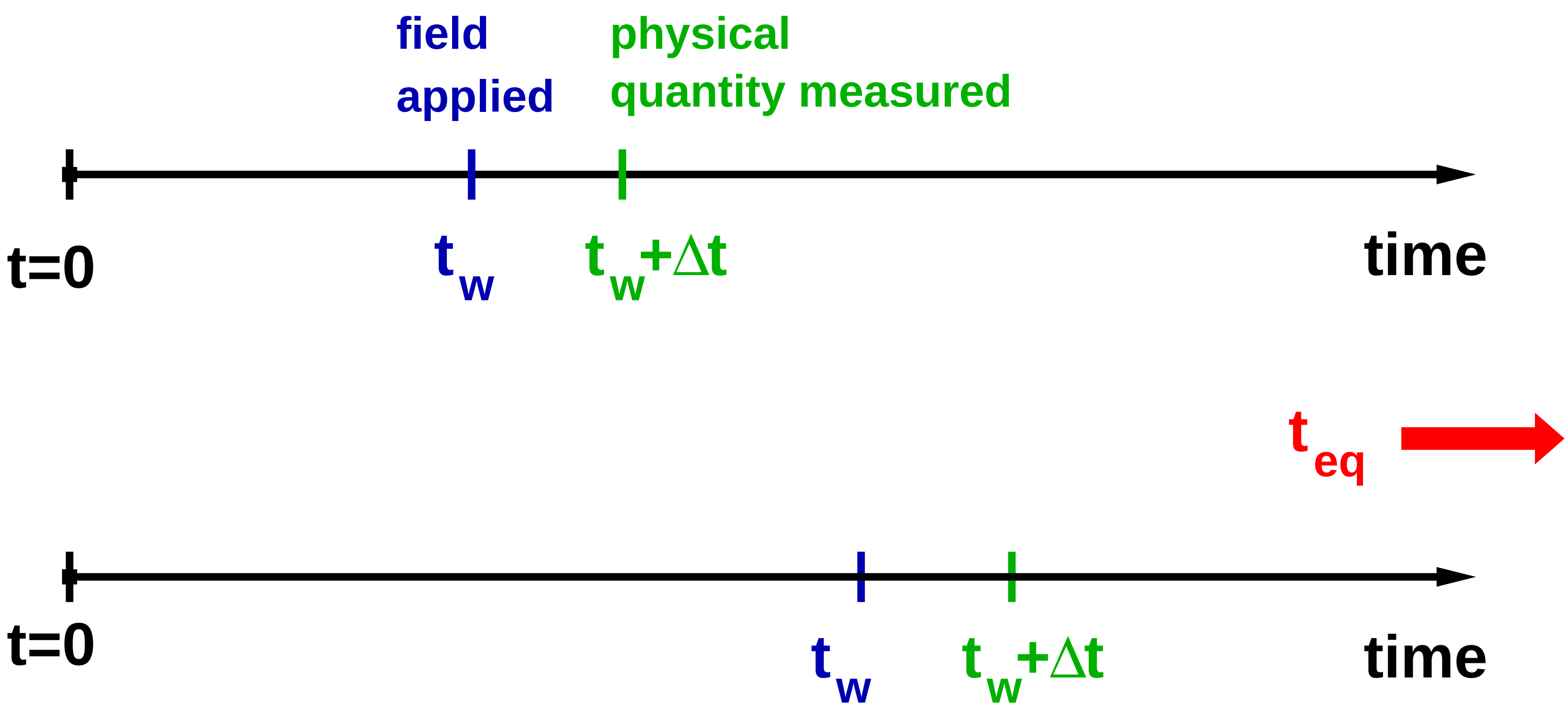
Conventional material



The two experiments give the same result

Time Translation Invariance (TTI)

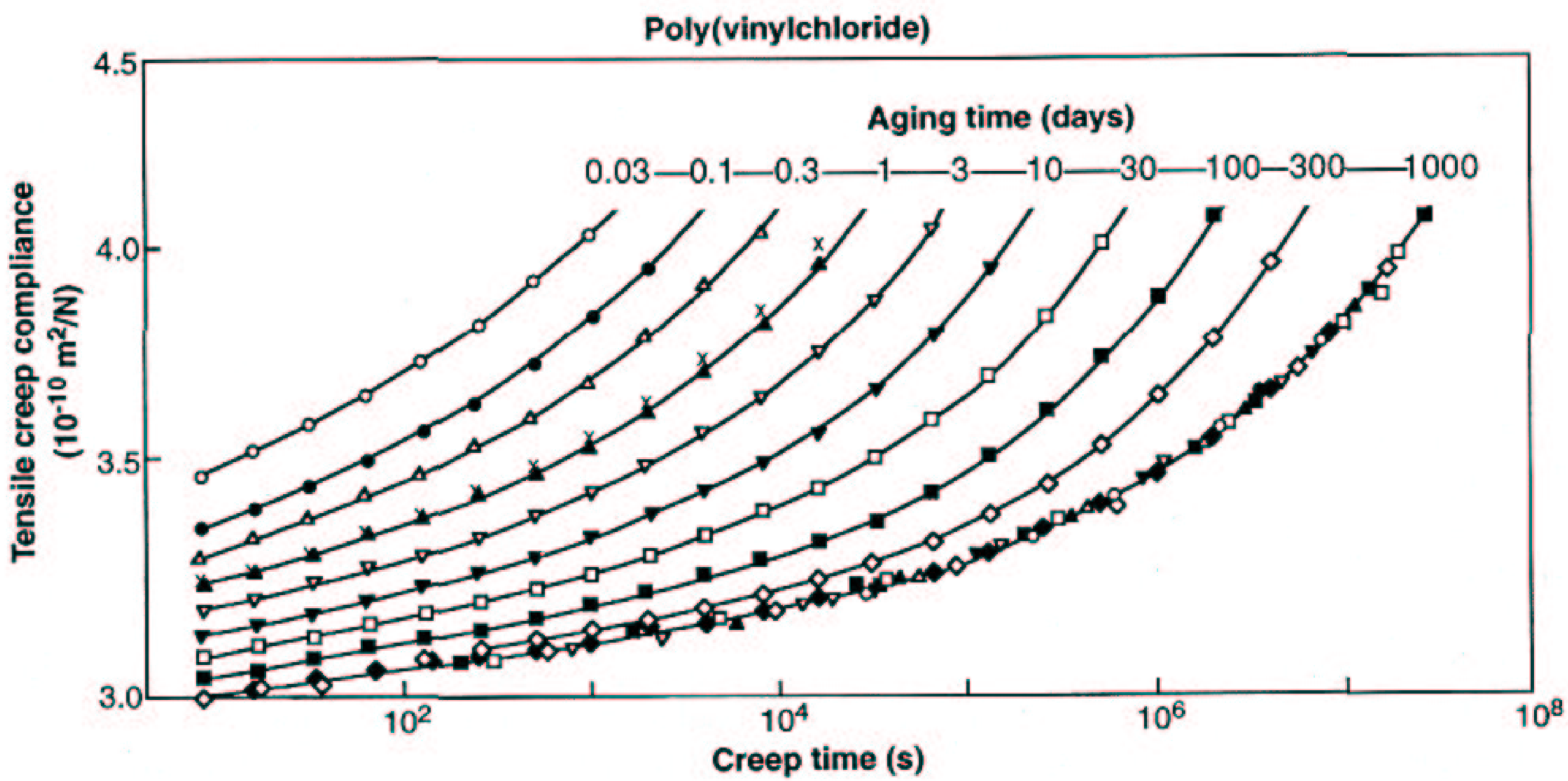
Material in a glassy state



The two experiments give different results

TTI Broken: AGING !!

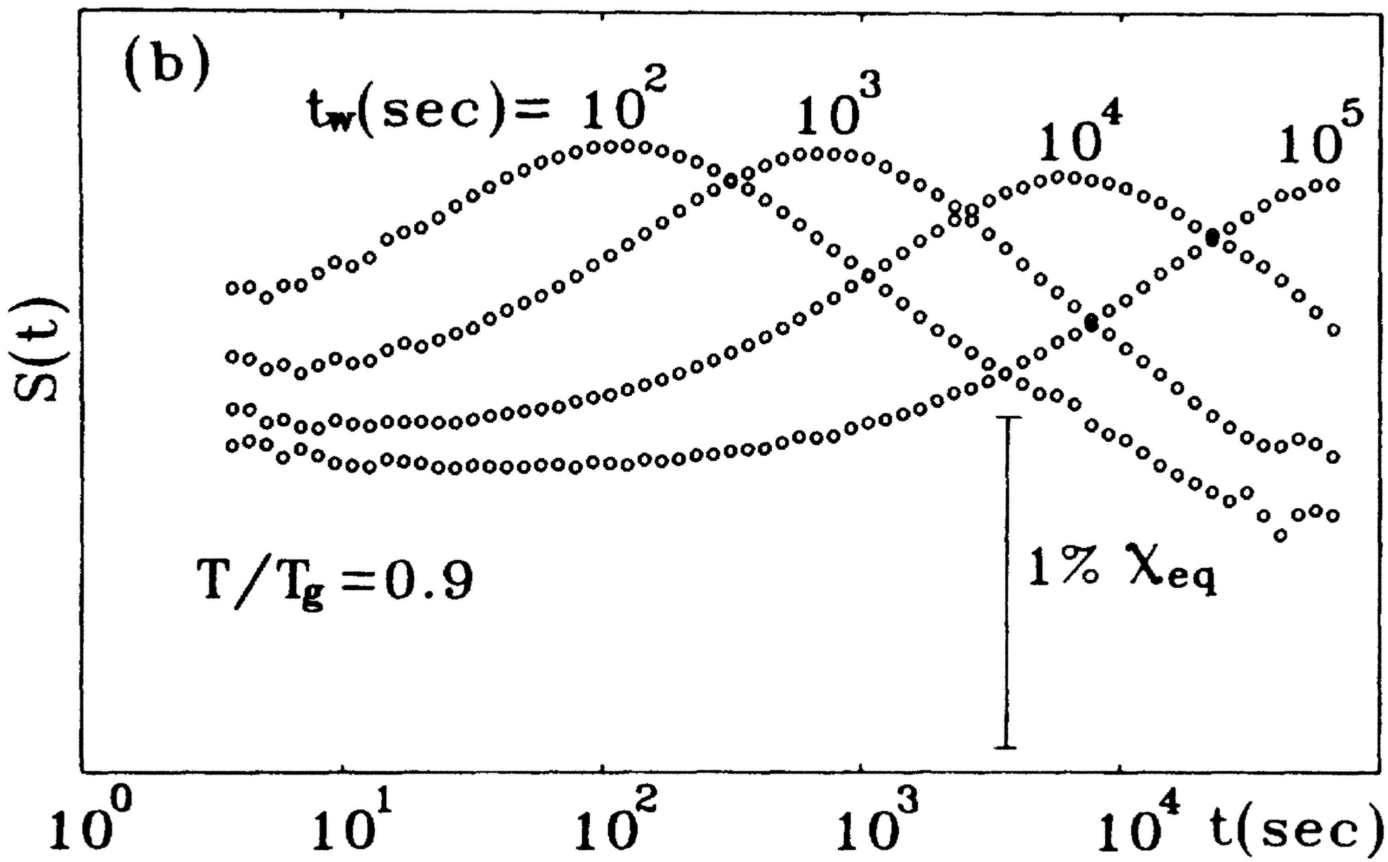
Aging in glasses: mechanical response in PVC (Struik, 1978)



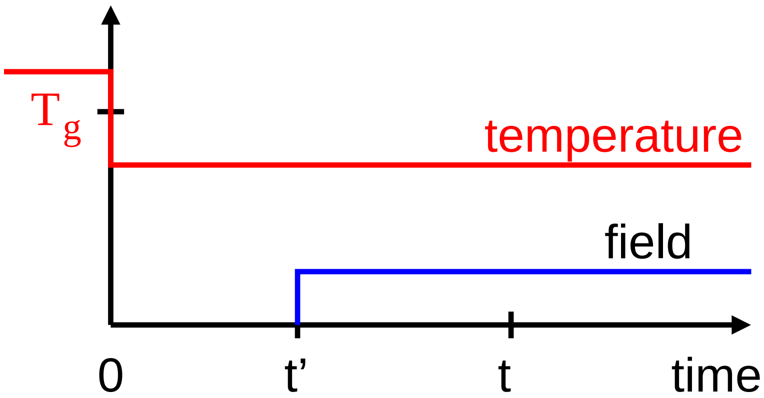
Aging in spin glasses:

ZFC relaxation in $(Fe_{0.15}Ni_{0.85})_{75}P_{16}B_6A1_3$

(Svedlindh et al., PRB **35**, 268 (1987))



Fluctuation - response in spin glasses

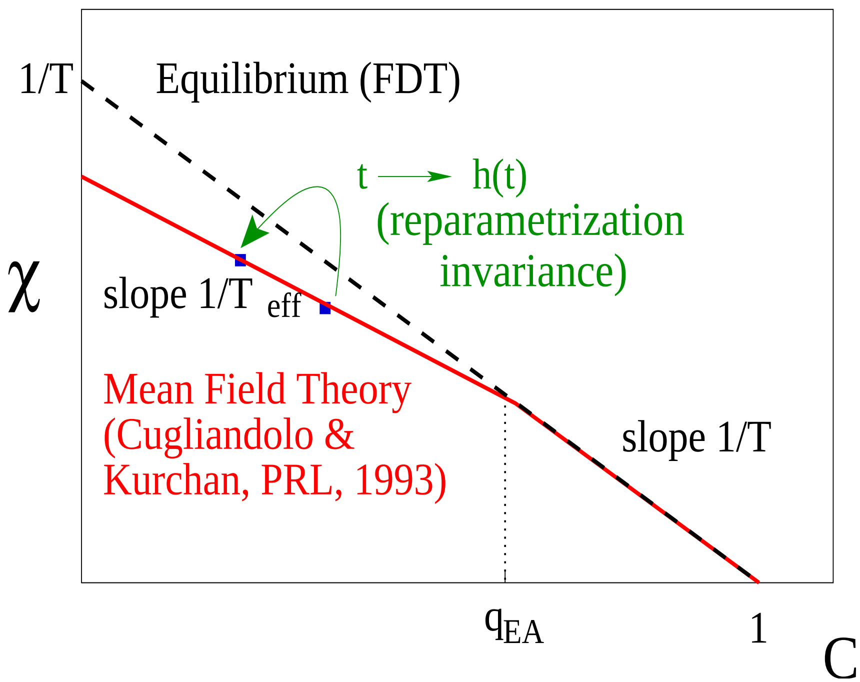


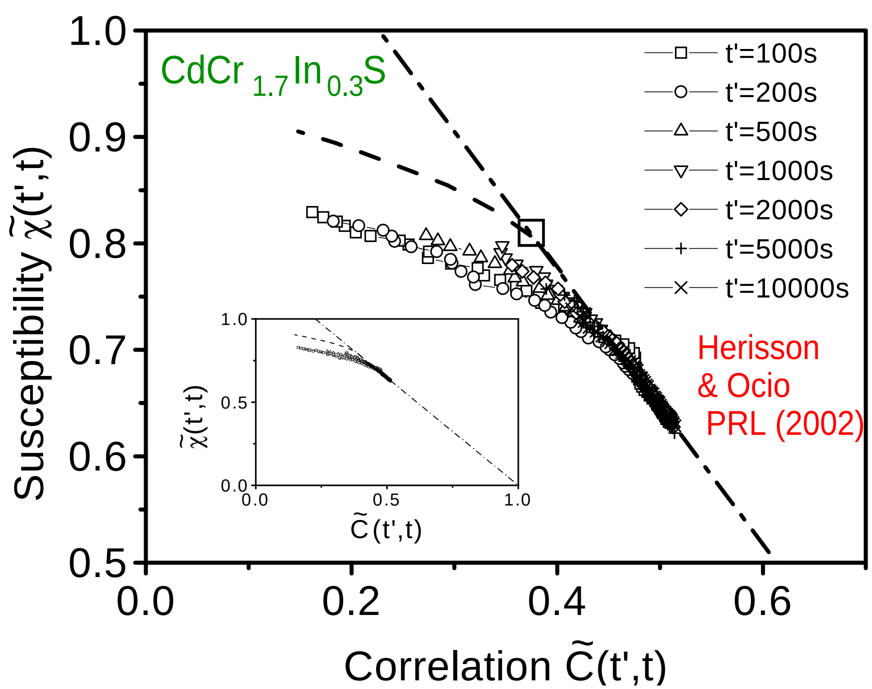
Correlation (noise)

$$C_{\vec r}(t,t') \equiv \frac{1}{V_{\vec r}} \sum_{i\in V_{\vec r}} \langle S_i(t) S_i(t') \rangle$$

Response (susceptibility)

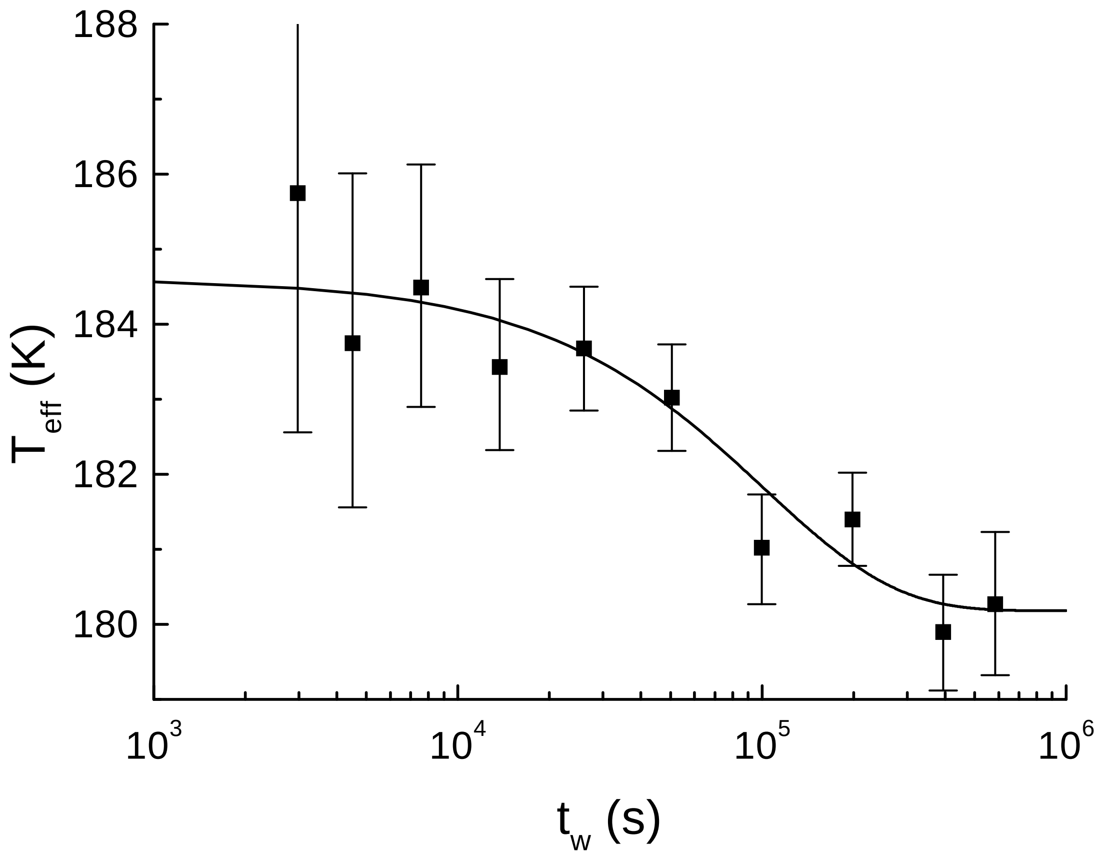
$$\chi_{\vec r}(t,t') \equiv \frac{1}{V_{\vec r}} \sum_{i\in V_{\vec r}} \partial \langle S_i(t) \rangle / \partial h_i$$





"FDT violation" (noise vs $Z(\omega)$ expts.)

Glicerol (Grigera and Israeloff, PRL **83**, 5038 (1999))



$T_g \approx 196K$,

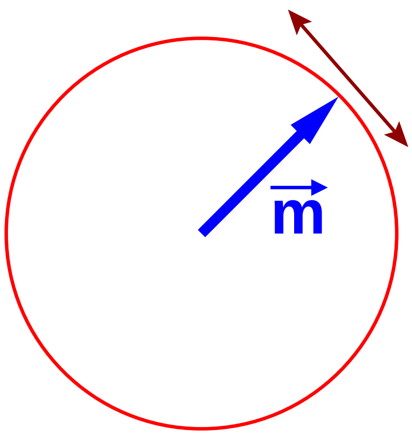
$T_{\text{env}} = 179.8K$

Can we understand dynamical heterogeneities?

A possible explanation: the glassy material is aging, but the ages are fluctuating in space.

Can we understand dynamical heterogeneities?

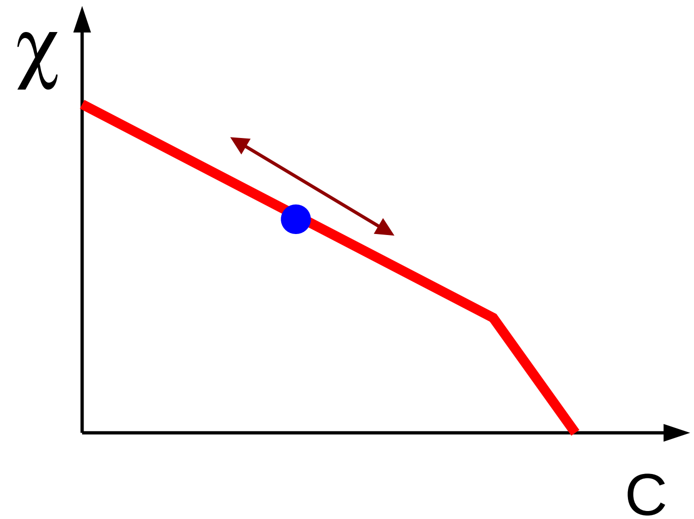
Equilibrium state
of ferromagnet



Rotations $\mathcal{R}_\theta$ leave
free energy $\mathcal{F}$
unchanged

Minimization of $\mathcal{F}[\vec{m}(\vec{r})]$
selects the (mean field
approx.) physical
magnetization

Nonquilibrium dynamics of spin glass



RG in time: reparametrizations $t \to h(t)$
leave "dynamical action" $\mathcal{S}$ unchanged
(irrelevant terms break symmetry at finite times)

(C.Chamon, M.P.Kennett, H.E.C.,
L.F.Cugliandolo, PRL **89**, 217201 (2002))

Minimization of $\mathcal{S}[(C_{\vec{r}}(t,t_w), \chi_{\vec{r}}(t,t_w))]$ selects the
(mean field approx.) physical evolution of (C, χ)

Can we understand dynamical heterogeneities?

Equilibrium state
of ferromagnet

Fluctuations with high
probability (small $\delta\mathcal{F}$):

$\mathcal{R}_{\theta(\vec{r})}$

(direction of the
magnetization varies
smoothly in space)
"magnons"

Nonquilibrium dynamics
of spin glass

Fluctuations with high
probability (small $\delta\mathcal{S}$):

$t \to h_{\vec{r}}(t)$

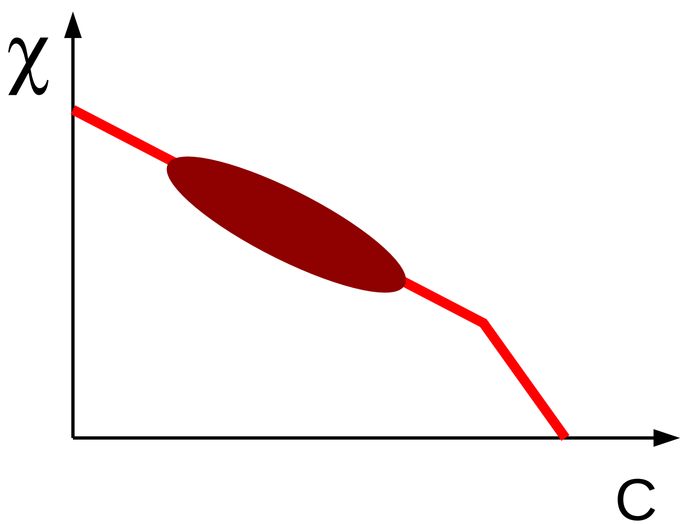
(age of the material varies
smoothly in space)

(H.E.C., C.Chamon,
L.F.Cugliandolo, M.P.Kennett,
PRL **88**, 237201 (2002))

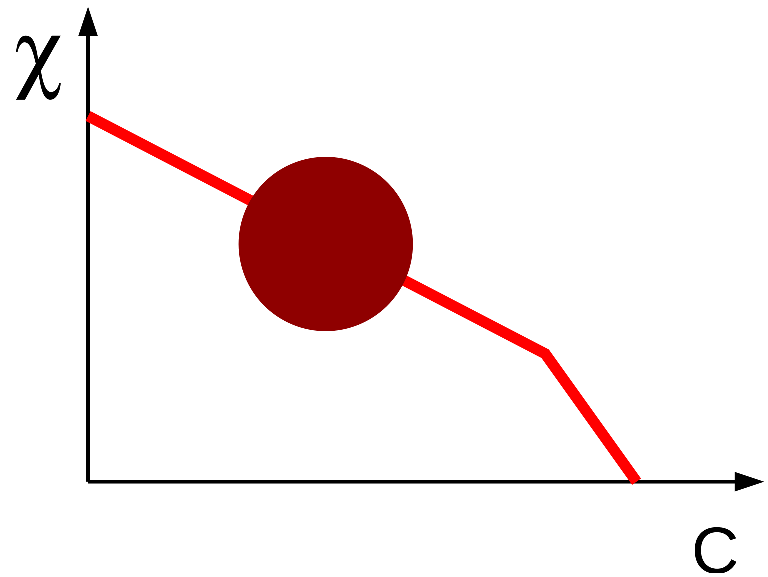
How do we test this theoretical framework?

1. Measure $C_{\vec{r}}(t, t_w)$ and $\chi_{\vec{r}}(t, t_w)$ at fixed, large (t, t_w).

2. See where the points accumulate in the (C, χ) plane.

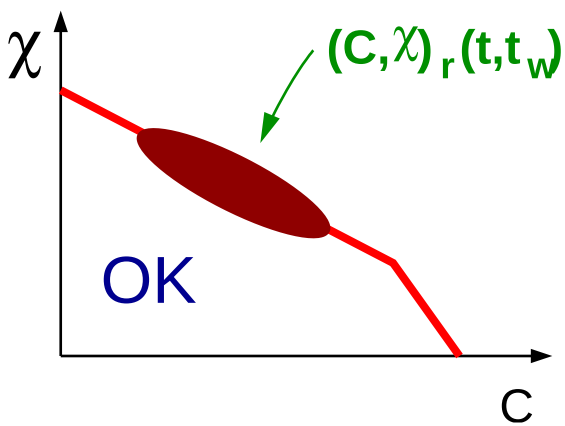


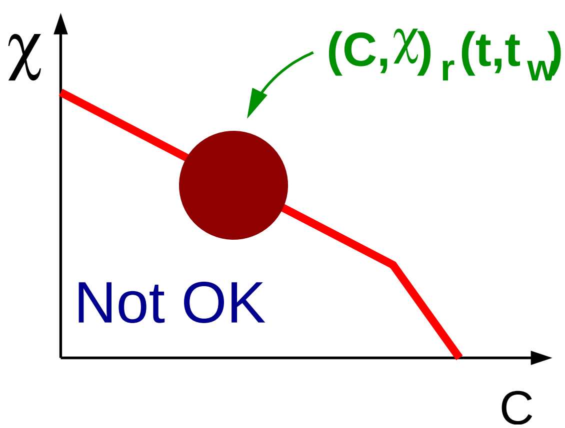
OK!!

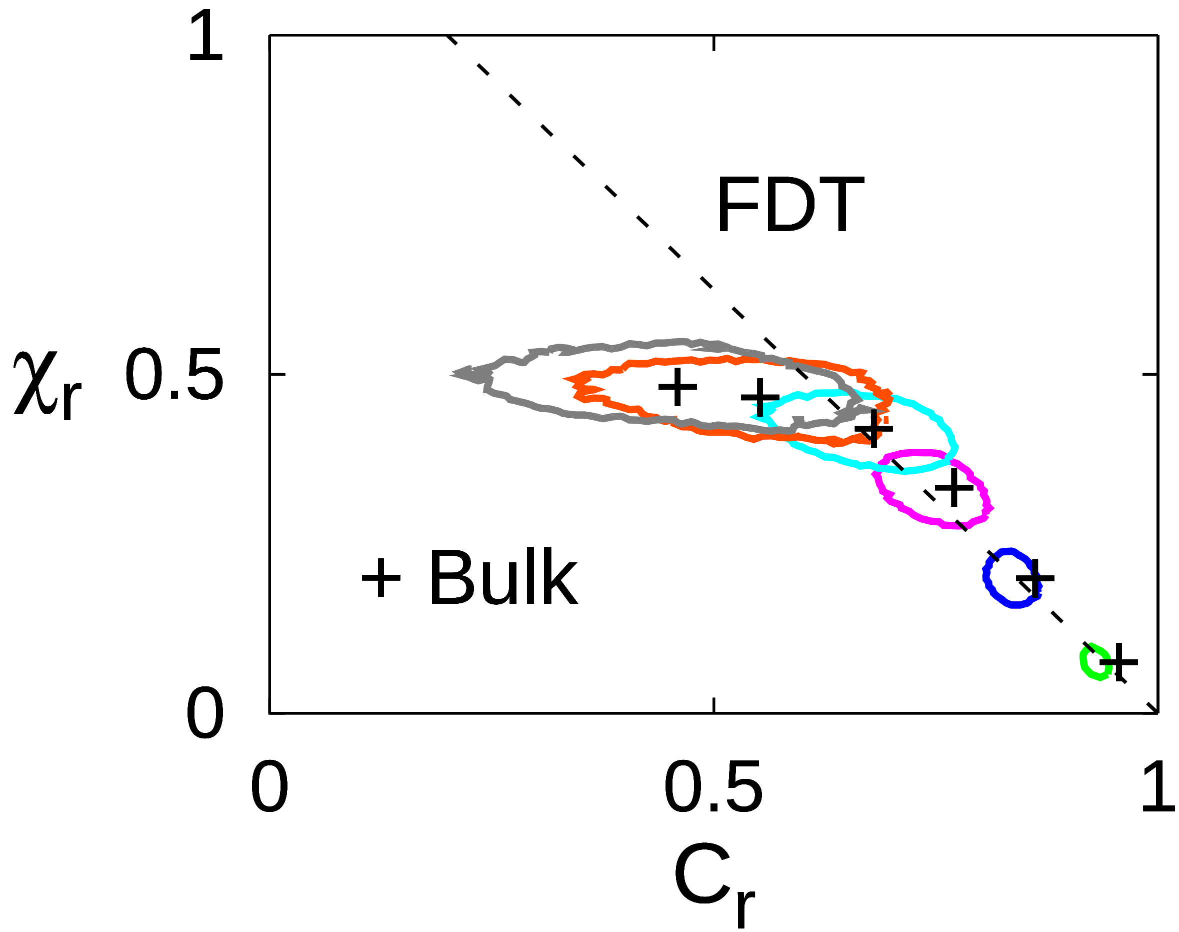


Doesn't work!!

Testing the theoretical framework





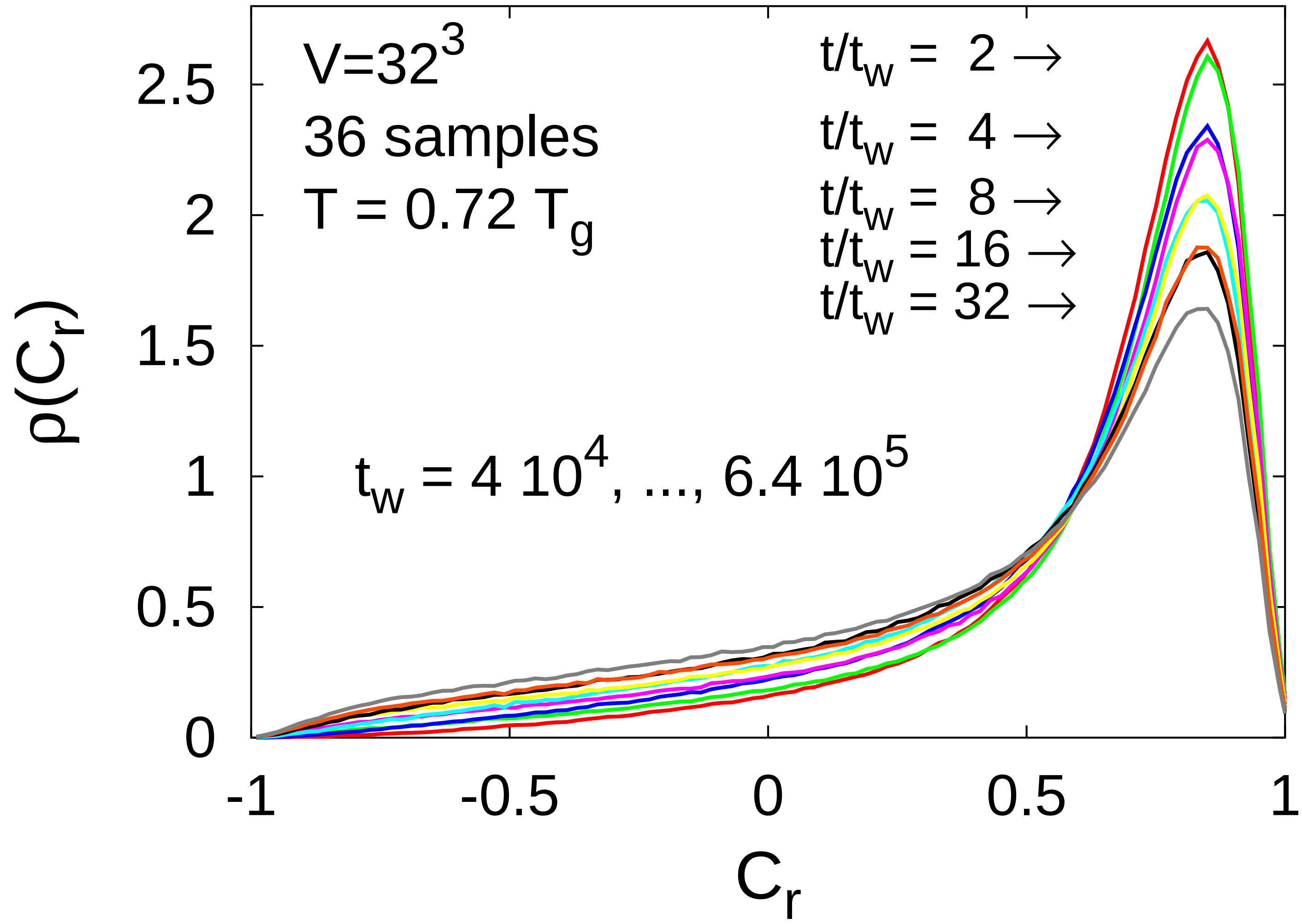


3D short-range $\pm J$ spin glass Monte Carlo

$V = 64^3$, $T = 0.72 T_g$, $t_w = 4 \times 10^4$ MCs

$t/t_w = 1.00005, 1.001, 1.06, 2, 8, 32$

$\rho(C_{\vec{r}})$ collapses with t/t_w

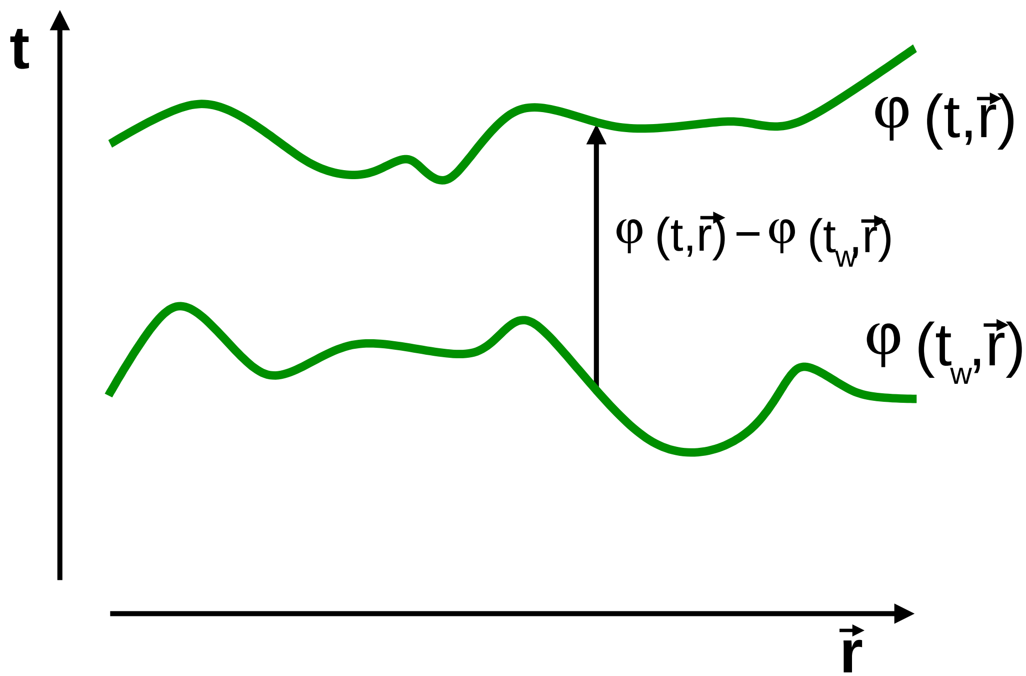


Why does $\rho(C_{\vec{r}})$ collapse with t/t_w?

If $C_0(t, t_w) \approx C_0(t/t_w)$ (for example, in 3DEA) **then**:

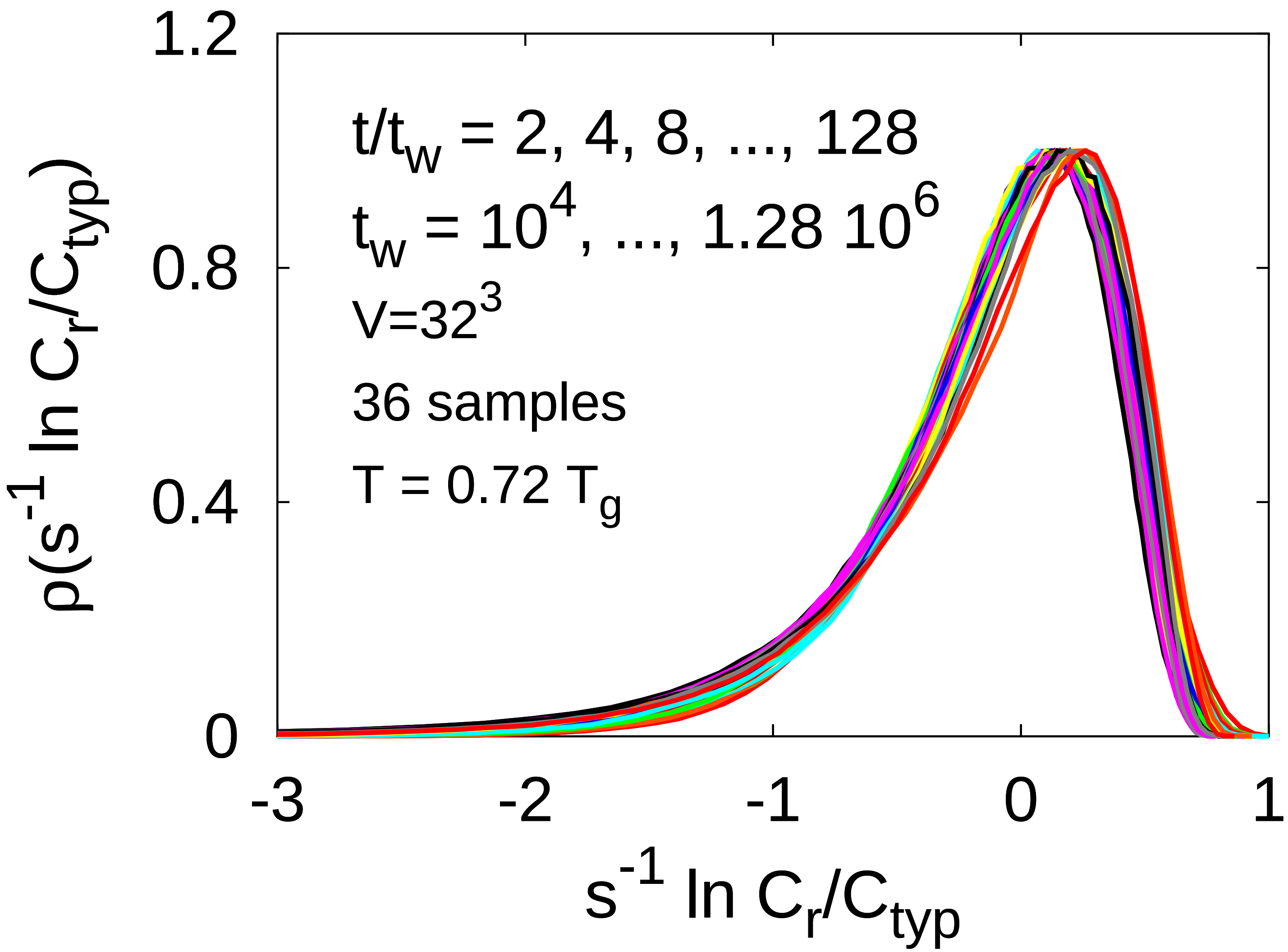
$$t \to h_{\vec{r}}(t) = e^{\varphi_{\vec{r}}(t)}$$

$$C_{\vec{r}}(t, t_w) = C_0(h_{\vec{r}}(t)/h_{\vec{r}}(t_w)) = C_0(\exp(\varphi_{\vec{r}}(t) - \varphi_{\vec{r}}(t_w)))$$



Approximate scaling with time

$$\varphi_{\vec{r}}(t) - \varphi_{\vec{r}}(t_w) \simeq \ln(t/t_w) + \sqrt{a + b\,\ln(t/t_w)}\; X_{\vec{r}}$$



Spatial correlation of the noise:
(Is this mode really a Goldstone mode?)

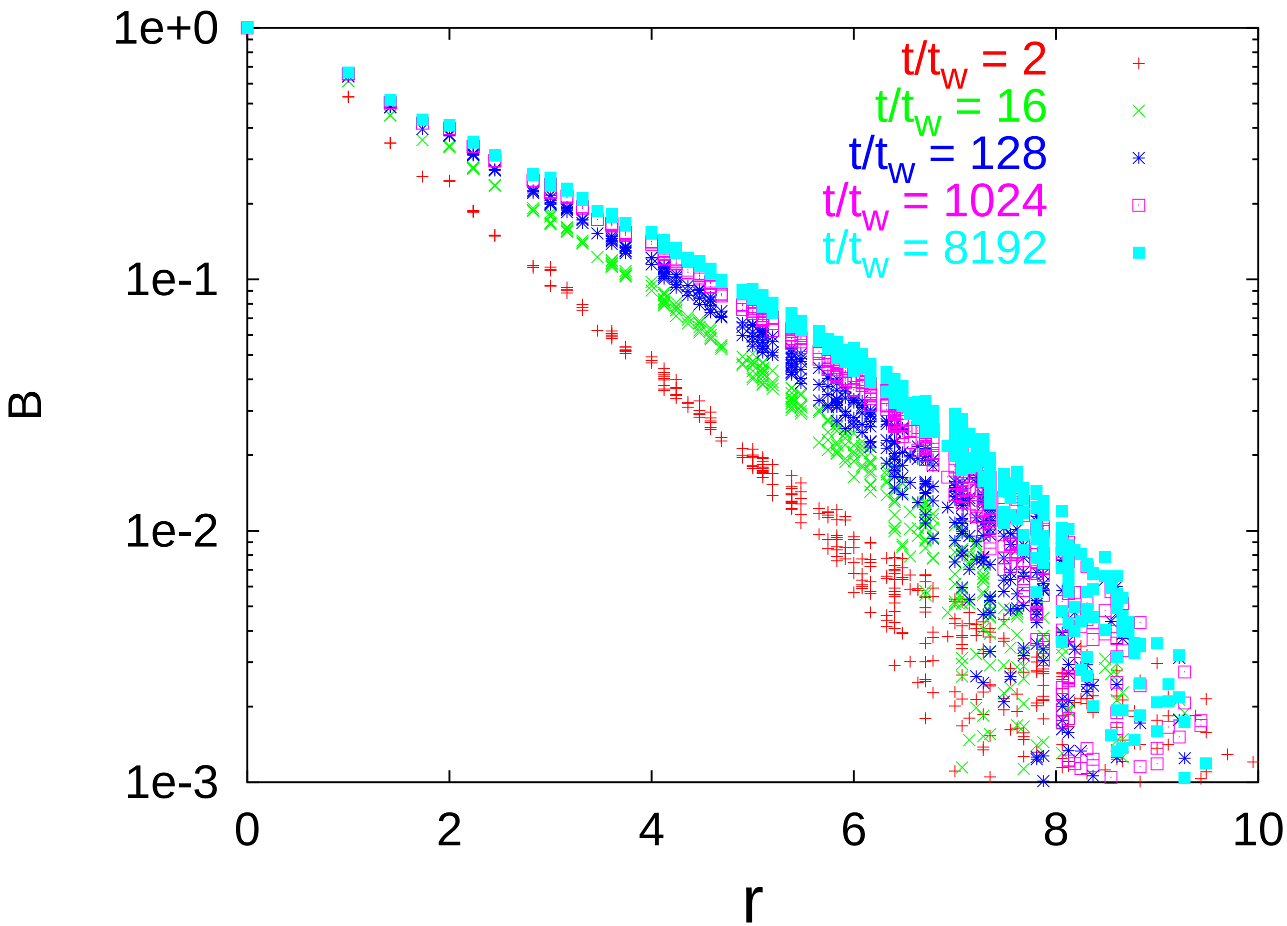
- Up to here, simulation results are consistent with the presence of a soft mode, but we haven't explored any space dependence.

- The theoretical prediction of zero mass for this mode (i.e. power-law spatial correlations in the noise) neglects symmetry breaking terms that go to zero when $t \to \infty$.

- At any finite time, these terms should produce a nonzero mass for the soft mode, (i.e. finite spatial correlation length in the noise). The mass should go to zero and the correlation length should diverge as $t \to \infty$.

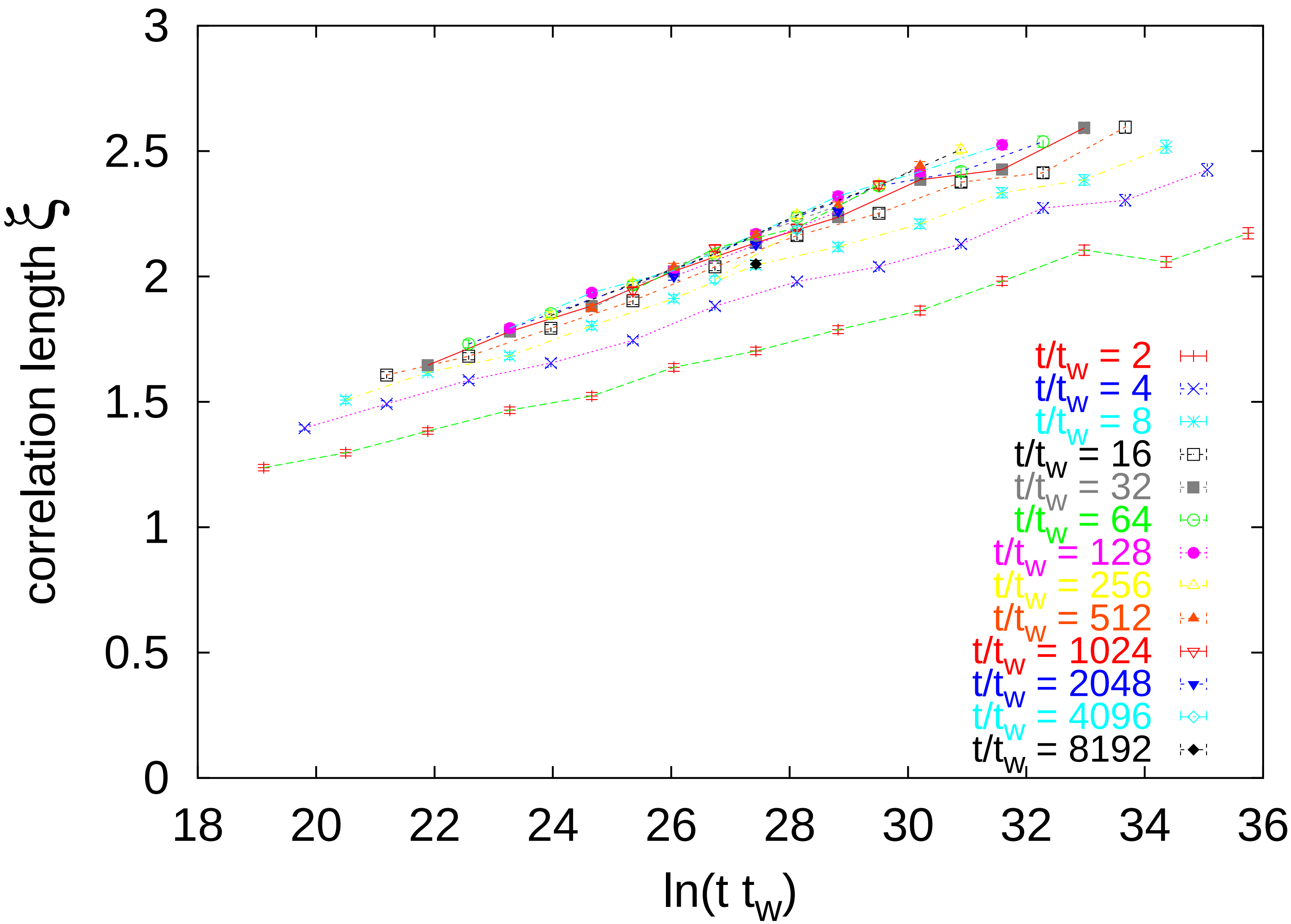
Noise-noise spatial correlations: exponential decay

$$B(\vec{r}, t, t_w) \equiv \langle \delta C_{\vec{r}_i}(t, t_w)\ \delta C_{\vec{r}_i+\vec{r}}(t, t_w) \rangle_{\vec{r}_i}$$



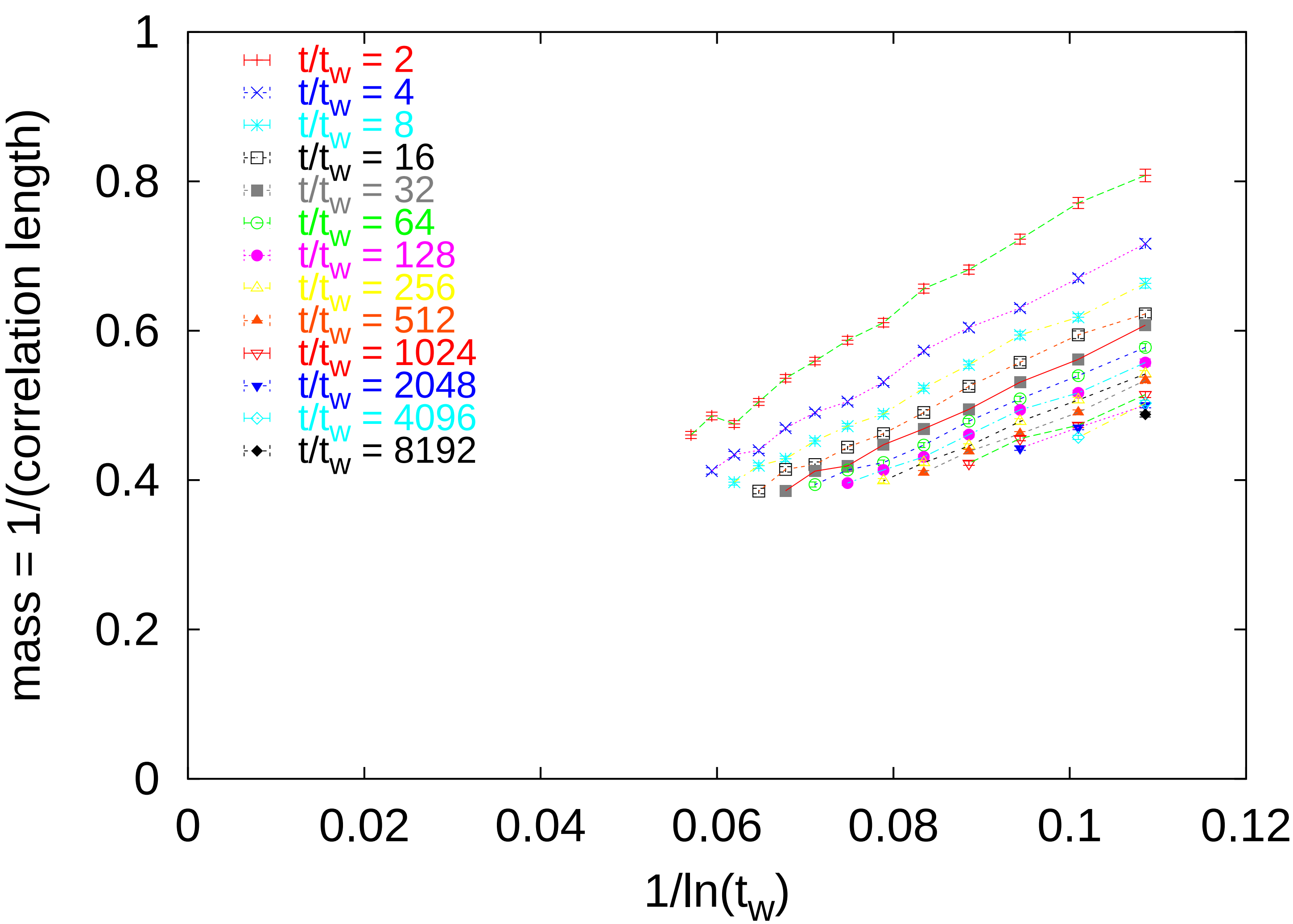
$t_w = 10^4$ MCs, $V = 32^3$, $T = 0.72T_g$, 64 disorder realizations

Correlation length $\xi(t, t_w) \to \xi(t t_w)$



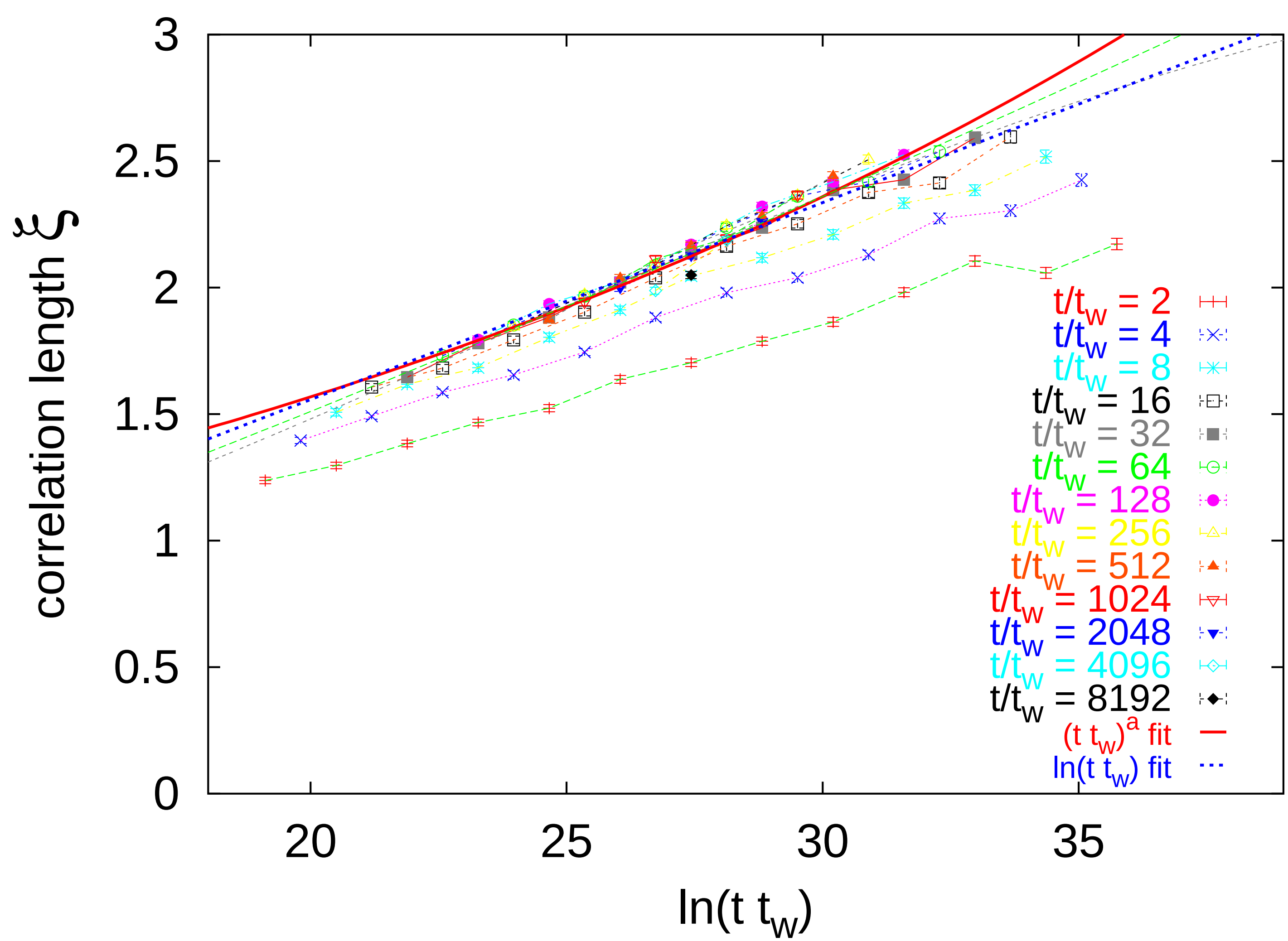
$V = 32^3$, $T = 0.72 T_g$, 64 disorder realizations

The mass is not just a function of t_w



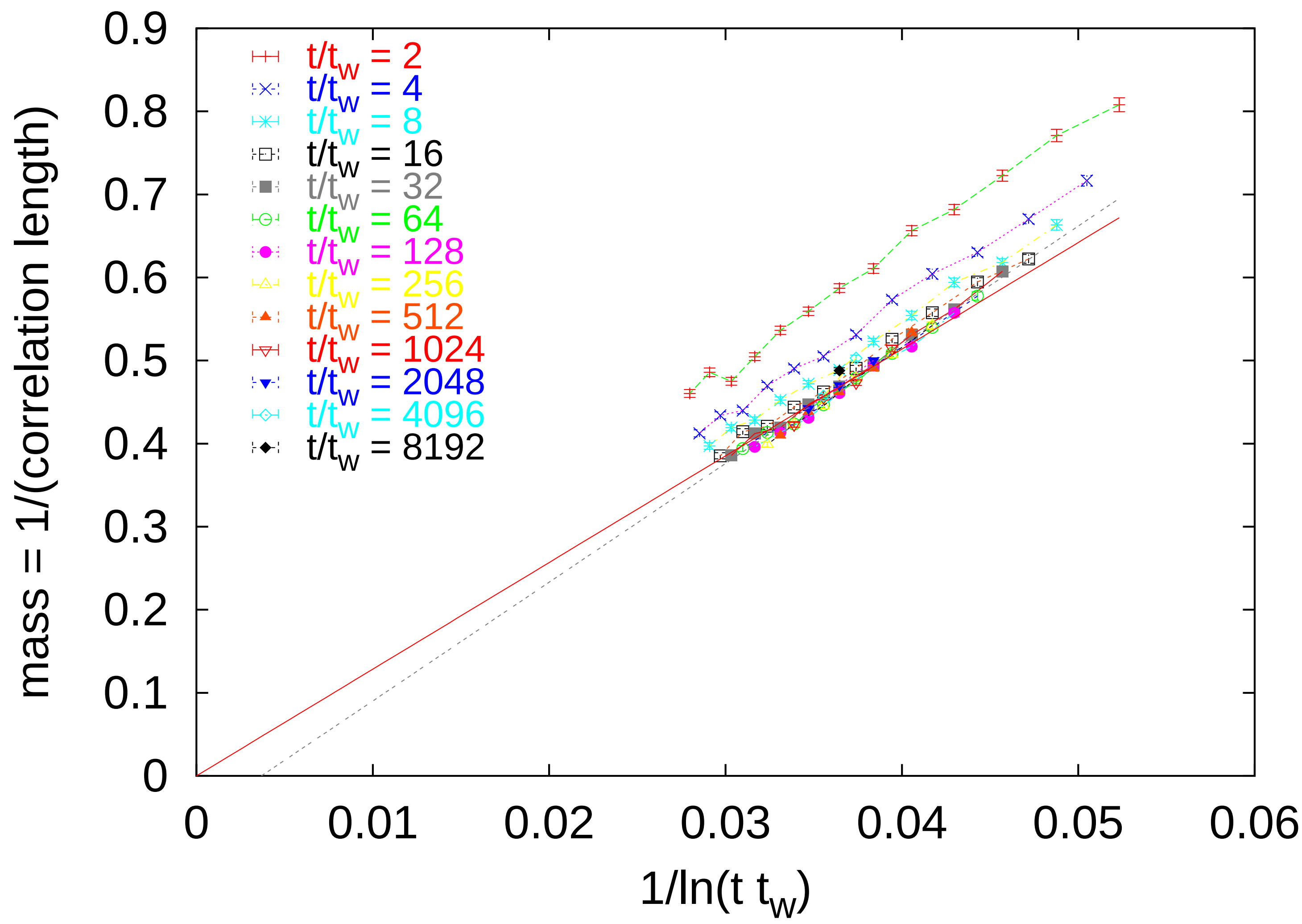
$V = 32^3$, $T = 0.72T_g$, 64 disorder realizations

Slowly growing correlation length $\xi(tt_w)$



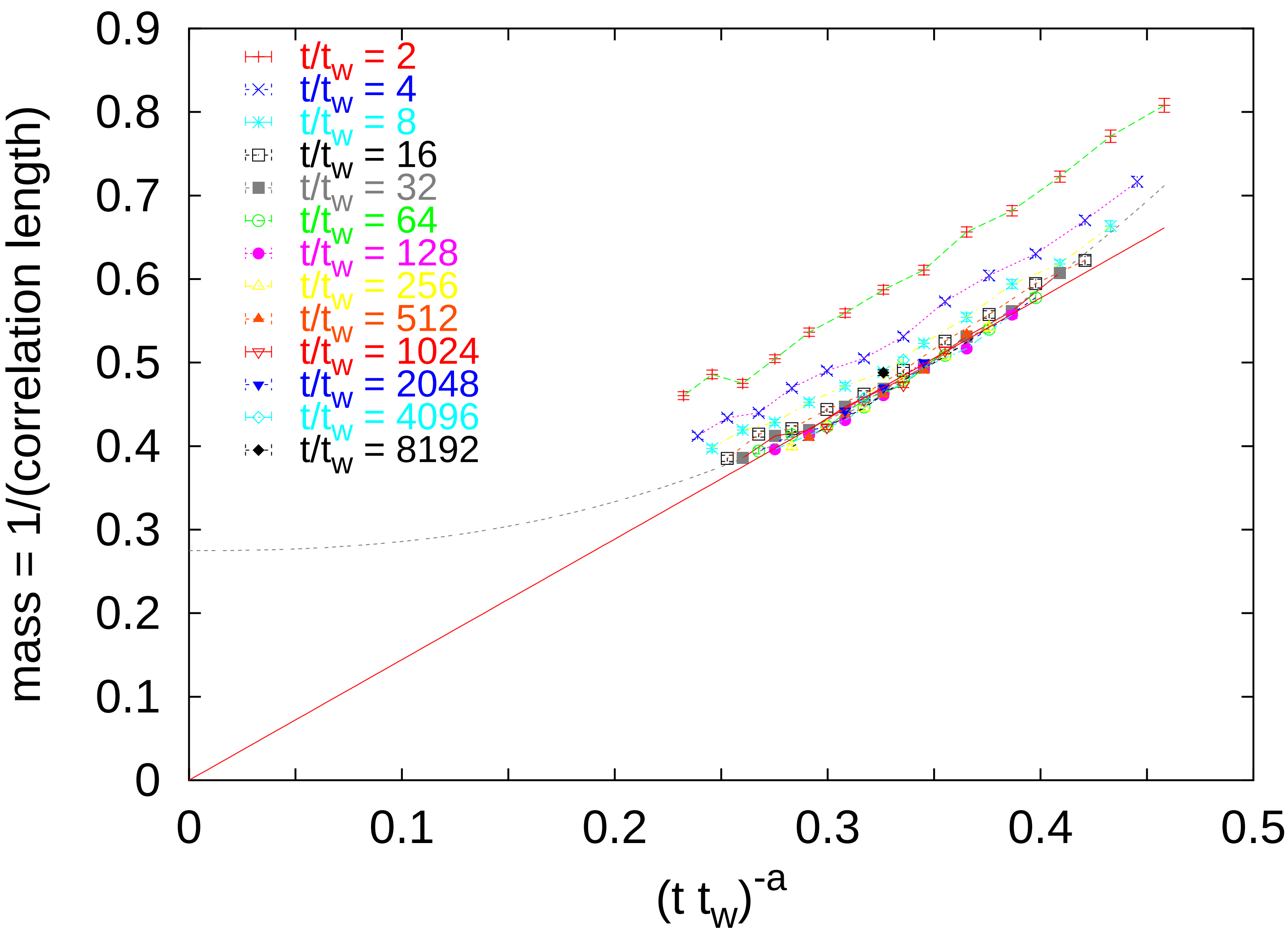
$V = 32^3$, $T = 0.72T_g$, 64 disorder realizations

Mass of the soft mode



$V = 32^3$, $T = 0.72T_g$, 64 disorder realizations

Mass of the soft mode



$a = 0.04$, $V = 32^3$, $T = 0.72T_g$, 64 disorder realizations

Summary

- RG in **time** : In short-range spin glasses, the dynamical action is invariant under *global time reparametrizations* $(t \to h(t))$ at long times.
- Goldstone modes *(age fluctuations)* are high probability modes These modes control the aging dynamics, giving rise to:
  - The distribution of $(C_{\vec{r}}, \chi_{\vec{r}})$ is concentrated on a fixed $\chi(C)$ curve.
  - If $C_0(t, t_w) \approx C_0(t/t_w)$: i) the distributions of $C_{\vec{r}}$ collapse for fixed t/t_w and ii) the distributions for all t and t_w can be rescaled onto a universal curve.
- Irrelevant terms weakly break invariance at finite times: "Goldstone modes" acquire mass $m(t, t_w)$.Numerics show:
  - For accessible timescales ($\leq 10^8$ MCs) $\xi = 1/m \sim 3 - 5$.
  - $\xi(t, t_w) \to \xi(tt_w)$ for large t/t_w.
  - $\xi(tt_w)$ grows slowly with times.
  - $m(tt_w)$ decays slowly: $m \sim 1/\ln(tt_w)$ or $m \sim (tt_w)^{-a}$ $(a \sim 0.04)$.

Perspectives

- Can this framework be applied to analize other glassy systems, including those without explicit disorder?: coarsening in ferrromagnets, dynamics of structural glasses
- Any experiment that probes local fluctuations and responses in glassy systems is a candidate to test these ideas