

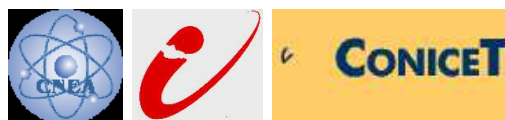
Off-equilibrium dynamics of the vortex glass

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Vortex Glass Transition

- Fisher, Fisher, Huse, PRB 1991; V. Glass Scaling theory;
 $\rho \sim |T - T_g|^{\nu(z-1)}$ $\nu = 0.9 - 1.7, z = 4 - 6$
- Gauge glass model & frustrated disordered XY model:
 - ★ Finite T_c in 3d for $\kappa = \infty$
 - ★ $T_c = 0$ for $\kappa < \infty$ in 3d (Bokil & Young 1995)
- London Langevin model, van Otterlo et al, PRL 1998, Reichhardt et al, PRL 2000:

Window glass behavior?
Volger-Fulcher law : $\rho \sim e^{-1/(T-T_g)}$
- Experiments, YBCO:
 - ★ A. Petrean et al, PRL 2000, V. Glass scaling in $\rho(T)$
 - ★ Strachan et al, PRL 2001, No IV scaling.



LONDON-LANGEVIN model

London Langevin model: van Otterlo et al, PRL 1998, Reichhardt et al, PRL 2000.

$$\underbrace{\eta \frac{\partial \mathbf{r}_{lz}(t)}{\partial t}}_{\text{friction}} = \underbrace{\mathbf{f}_{lz}^{int}(t) + \mathbf{f}_{lz}^{elast}(t)}_{\text{interactions}} + \underbrace{\mathbf{f}_{lz}^P(t)}_{\text{randompinning}} + \underbrace{\mathbf{f}_{lz}^T(t)}_{\text{thermalnoise}}, \quad (1)$$

- \mathbf{r}_{lz} : 2D position of l -th vortex in z -th plane.
- In-plane interaction force: $\mathbf{f}_{lz}^{int} = -\nabla_{\mathbf{r}_{lz}} U^p[\{\mathbf{r}_{lz}(t)\}]$ with

$$U^p[\{\mathbf{r}_{lz}(t)\}] = \sum_{l' \neq l} U\left(\frac{|\mathbf{r}_{lz'} - \mathbf{r}_{lz}|}{\lambda}\right), \quad \text{with}$$

$$U(x) = \frac{\Phi_0}{8\pi^2 \lambda^2} K_0(x),$$
- Elastic (inter-plane) force: $\mathbf{f}_{lz}^{elast} = -\nabla_{\mathbf{r}_{lz}} U^e[\{\mathbf{r}_{lz}(t)\}]$ with

$$U^e[\{\mathbf{r}_{lz}(t)\}] = V\left(\frac{|\mathbf{r}_{(z+1)l} - \mathbf{r}_{lz}|}{2r_g}\right) + V\left(\frac{|\mathbf{r}_{(z-1)l} - \mathbf{r}_{lz}|}{2r_g}\right), \quad (2)$$

$$V(|\mathbf{x}|) = \begin{cases} 2c_j(|\mathbf{x}| - 1) & \text{for } |\mathbf{x}| \geq 1 \\ c_j(|\mathbf{x}|^2 - 1) & \text{for } |\mathbf{x}| < 1, \end{cases} \quad (3)$$

with $\mathbf{x} = |\mathbf{r}_{z'l} - \mathbf{r}_{lz}|/2r_g$, $z' = z \pm 1$,



- Random pinning force:

$$\mathbf{f}_{lz}^P = -\nabla_{\mathbf{r}_{lz}} \int d^2\mathbf{r}' u(\mathbf{r}', z) p(|\mathbf{r}_{lz} - \mathbf{r}'|), \quad (4)$$

$$\langle u(\mathbf{r}, z) u(\mathbf{r}', z') \rangle = \gamma \delta(\mathbf{r} - \mathbf{r}') \delta_{zz'},$$

and

$$p(r) = \frac{2\xi^2}{r^2 + 2\xi^2}.$$

- Thermal (Langevin) force:

$$\langle f_{lz,\mu}^T(t) \rangle = 0,$$

$$\langle f_{lz,\mu}^T(t) f_{z'l',\mu}^T(t') \rangle = 2\eta k_B T \delta(t - t') \delta_{zz'} \delta_{ll'} \delta_{\mu\mu'},$$

$$\mu, \mu' = x, y$$



Out of equilibrium dynamics of structural glasses

- Two-time correlation functions:

$$C(t_w, t_w + \tau) = \langle O(t_w)O(\tau + t_w) \rangle, \langle O(t) \rangle = 0$$

- Response: $\chi(t_w, t_w + \tau) = \lim_{\epsilon \rightarrow 0} \frac{\langle O(t) \rangle_\epsilon - \langle O(t) \rangle_0}{\epsilon}$,
($H_\epsilon = H - \epsilon(t)O$), $t = t_w + \tau$

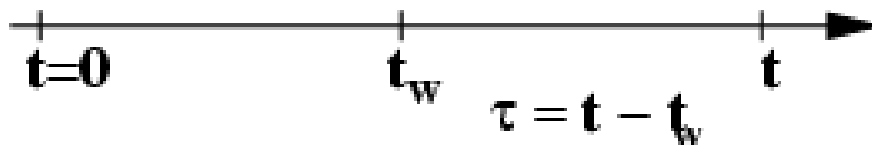
- AGING: dependence on t_w .

- Non-trivial violation of fluctuacion-dissipation relation:

$$\chi(t_w, t) = \frac{y(t_w, t)}{T} C(t_w, t)$$

$$\lim_{t_w \rightarrow \infty} \lim_{t \rightarrow \infty} y(t_w, t) \neq 1$$

relaxation time $\tau_R(t_w) \rightarrow \infty$ for $t_w \rightarrow \infty$





Simulation: Structural glasses

- FDT $\chi = \Delta/2T$

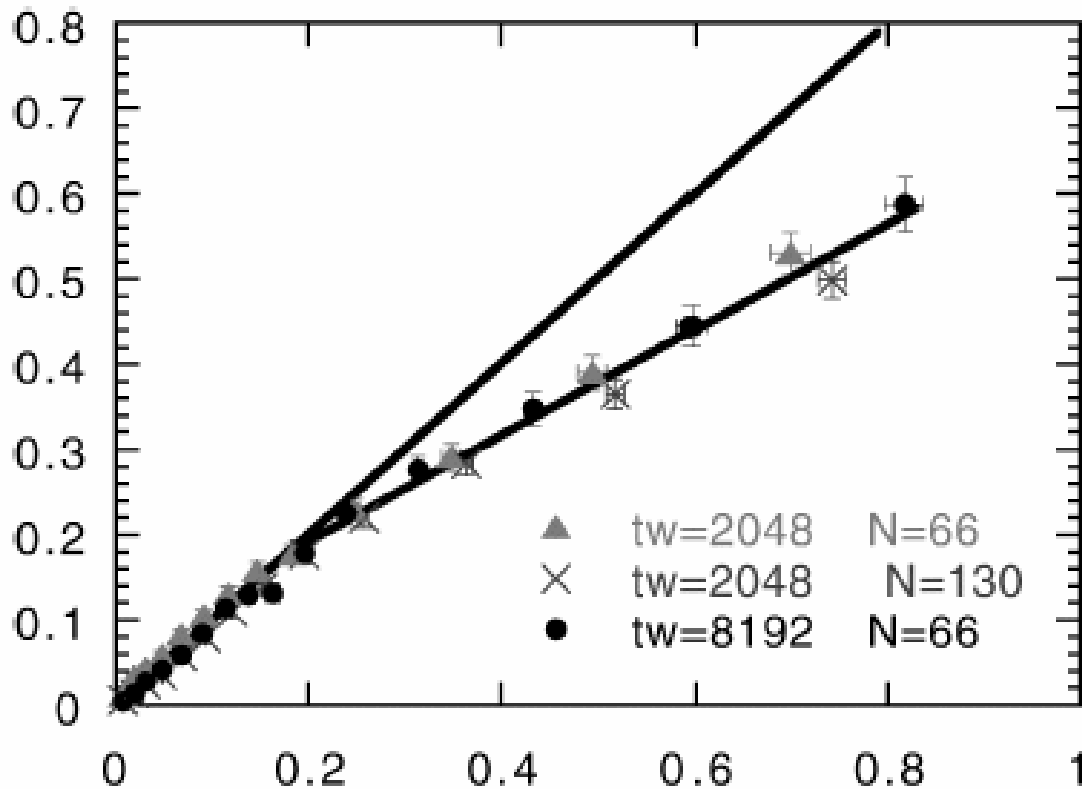
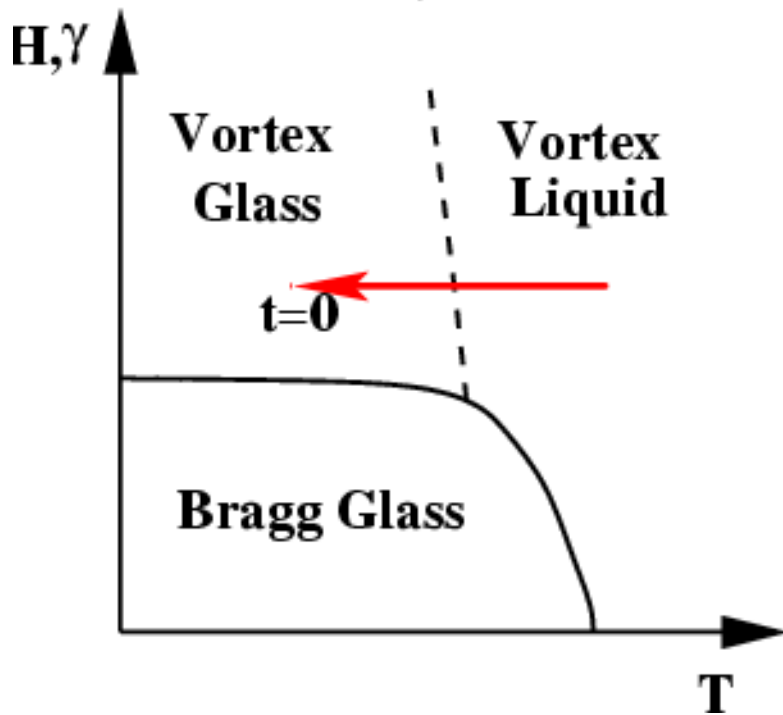


FIG. 2. R versus $\beta\Delta$ at $\Gamma = 1.6$ for $t_w = 8192$ and $t_w = 2048$ at $N = 66$ and for $t_w = 2048$ at $N = 130$. The two straight lines have slope 1 and 0.62, respectively.

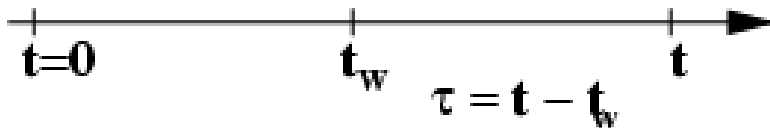
Parisi, PRL 1997



Simulations



- 56 pancakes per plane
- 50 planes
- Quench from $T_{start} = 0.3 > T_g$ to T





Correlation functions measured

- Dynamic wandering

$$W(z, t, t_w) =$$

$$\left\langle \frac{1}{N_{xy}} \sum_l |[\mathbf{r}_{lz}(t) - \mathbf{r}_{l0}(t)] - [\mathbf{r}_{lz}(t_w) - \mathbf{r}_{l0}(t_w)]|^2 \right\rangle$$

- Mean square displacement (MSD)

$$B(t, t_w) = \left\langle \frac{1}{N} \sum_{lz} [x_{lz}(t) - x_{lz}(t_w)]^2 \right\rangle$$



Finite Size effect

$$\tau = t - t_w$$

$$W(z, \tau) \sim \begin{cases} \tau & \tau < t_{1,(z)} \\ z^{2\zeta_T} & \tau > t_{1,(z)} \end{cases}$$

$\zeta = \zeta_T = 1/2$ (thermal line wandering)

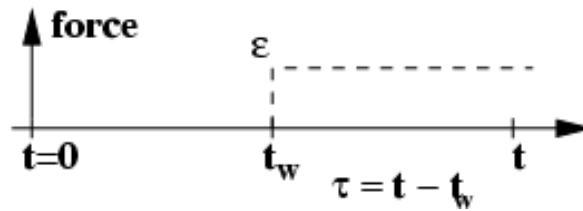
For $t > t_{1,(z=N_z)}$ finite size effect

$$B(\tau) \sim \begin{cases} \tau & \tau < t_{1,(z=1)} \\ \tau^{1/2} & t_{1,(z=1)} < \tau < t_{1,(z=N_z)} \\ \tau & t_{1,(z=N_z)} < \tau \end{cases} \begin{array}{l} \text{single pancake} \\ \text{elastic line} \\ \text{center of mass} \end{array}$$



Response Function

- Integrated Response



Random force for $t \geq t_w$: $\mathbf{f}_{lz} = \epsilon s_{lz} \hat{\mathbf{x}}$,

ϵ : perturbation strength, $s_{lz} = \pm 1$, random

$$\chi(t, t_w) = \frac{\langle \frac{1}{N} \sum_{lz} s_{lz} x_{lz}(t) \rangle_{\epsilon} - \langle \frac{1}{N} \sum_{lz} s_{lz} x_{lz}(t) \rangle_{\epsilon=0}}{\epsilon}$$

x_{lz} , x -component of vortex position,



Multiplicative Scaling

Yoshino, PRL 1998, Directed Polymer in Random Media (1+1)

Define

$$\begin{aligned} B(t, t_w) &= \tilde{B}(\tilde{t})t^\alpha \\ 2kT\chi(t, t_w) &= \tilde{\chi}(\tilde{t})t^\alpha \end{aligned}$$

with $\tilde{t} = t/t_w$ and

$$\tilde{B}(\tilde{t}) = \begin{cases} c_1(T)(\tilde{t} - 1)^{-\alpha(T)} & \tilde{t} \ll 1 \\ c_2(T)(\tilde{t} - 1)^{-\alpha(T)} & \tilde{t} \gg 1 \end{cases}$$
$$\tilde{\chi}(\tilde{t}) = \begin{cases} c_1(T)(\tilde{t} - 1)^{-\alpha(T)} & \tilde{t} \ll 1 \\ y(T)c_2(T)(\tilde{t} - 1)^{-\alpha(T)} & \tilde{t} \gg 1 \end{cases}$$



Violation of FDT

$$\chi(t, t_w) = \frac{y(t, t_w)}{2T} B(t, t_w)$$

with $y(t, t_w) = \frac{T}{T_{\text{ef}}(t, t_w)}$

- for $t < t_w$,

$$\tilde{\chi} = \tilde{B}$$

- for $t > t_w$

$$\tilde{\chi} = y(T) \tilde{B}$$

- Effective temperature:

$$y(T) = \frac{T}{T_{\text{eff}}}$$



Conclusions

- Slow dynamics dominated by elastic line relaxation
- Aging : multiplicative scaling (as polymers in random media)
- Violation of FDT after a quench to the vortex glass

Does the vortex glass freeze like an structural glass??

Yes and No

- Yes
 - ★ Aging
 - ★ Single violation of FDT
 - ★ T_{eff} independent of T
- No
 - ★ Multiplicative aging
 - ★ Similar to polymers in random media