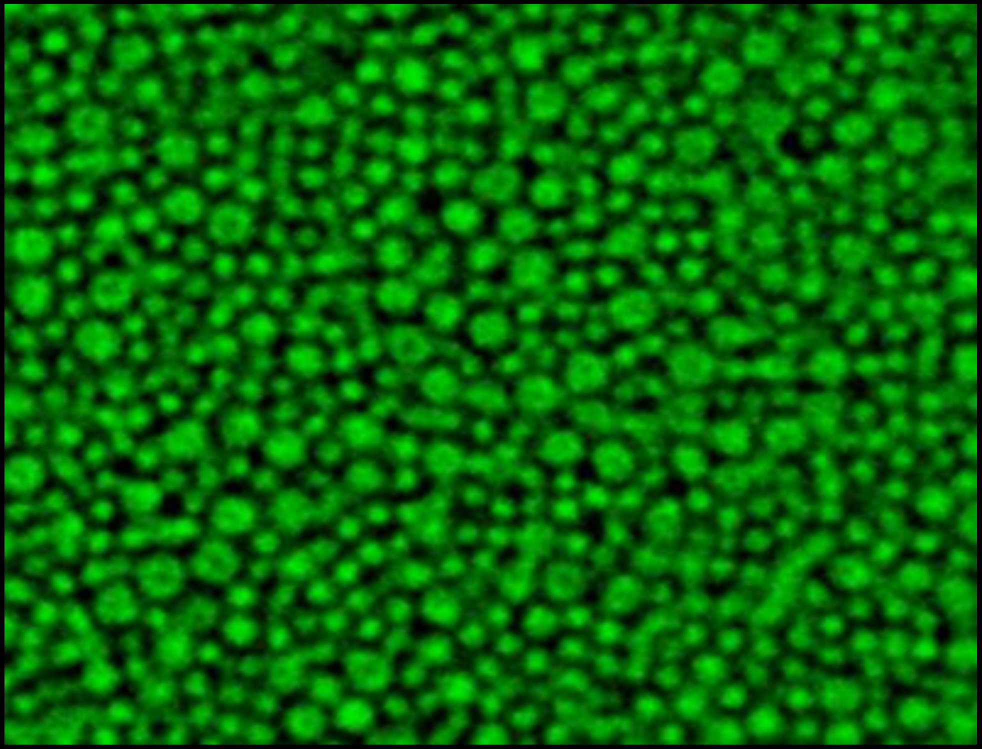
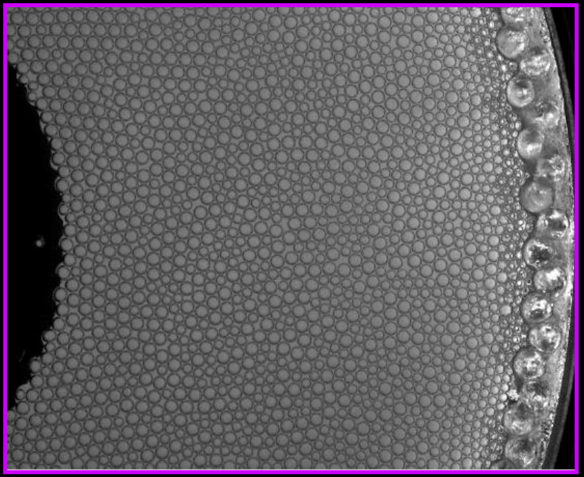
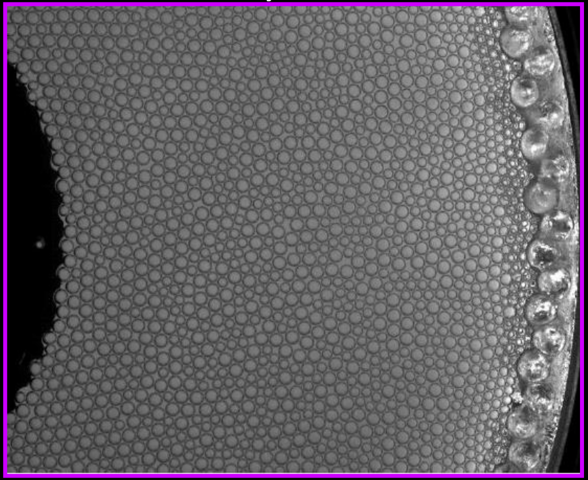
Direct Experimental Evidence of Encoding and Retrieving Mechanical Memory in Sheared Amorphous Solids



No memory encoded



Memory encoded



Ajay Sood
Dept. of Physics
Indian Institute of Science
Bangalore, India

KITP- Memory Formation in Matter 2018

Acknowledgements

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(PhD Student, JNCASR)

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Rajesh Ganapathy
(JNCASR)

Earlier experiments on 3D colloidal glasses Under oscillatory shear:

Dr. Hima Nagamanasa (IBS Seoul)
Dr. Shreyas Gokhale (MIT)
Prof. Rajesh Ganapathy (JNCASR)

Vol 438|15 December 2005|doi:10.1038/nature04380 nature

Nature (2005)

LETTERS

Chaos and threshold for irreversibility in sheared suspensions

D. J. Pine[1,2], J. P. Gollub[1,3], J. F. Brady[4] & A. M. Leshansky[5]

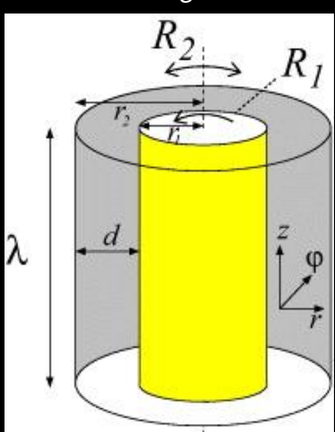
ARTICLES

Random organization in periodically driven systems

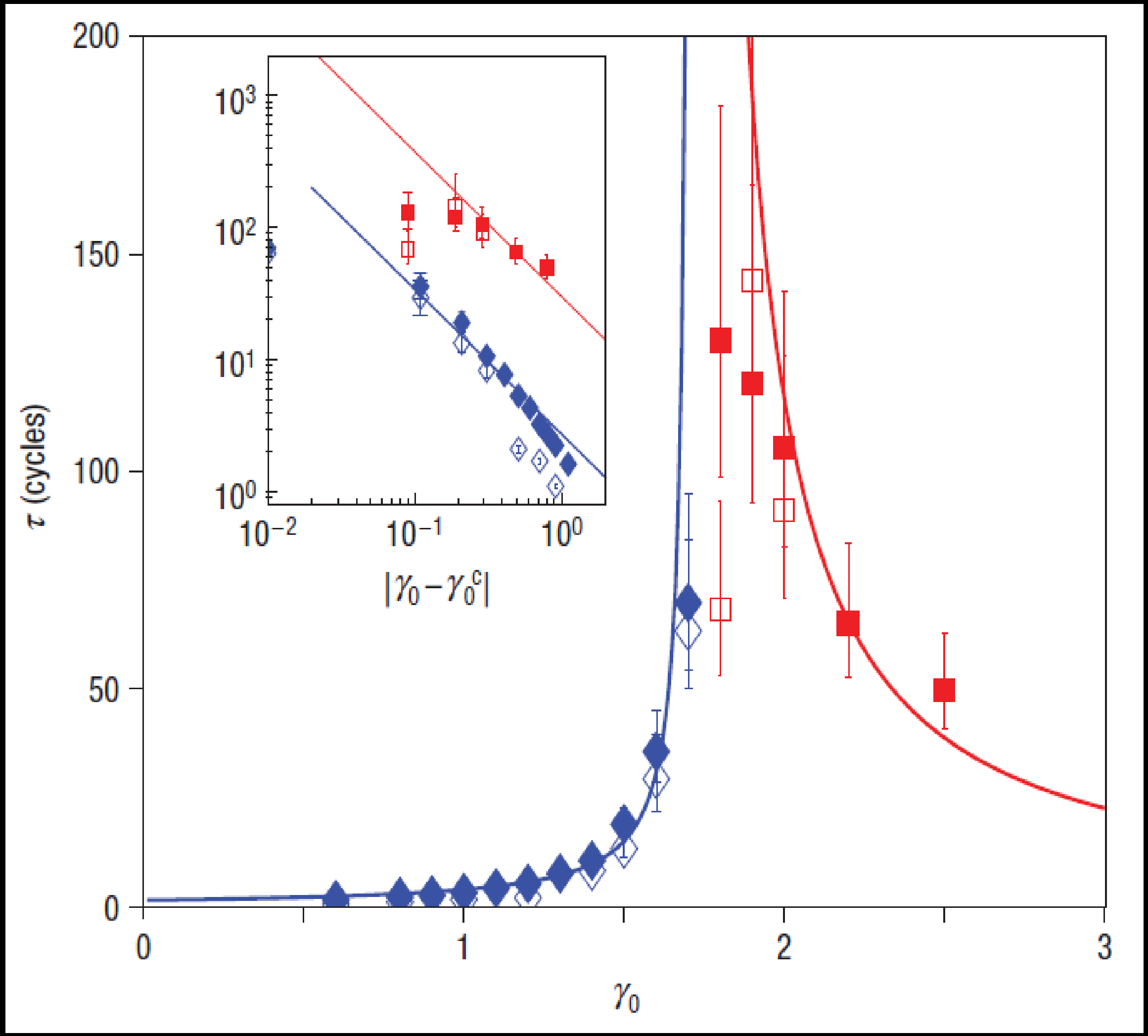
LAURENT CORTÉ[1], P. M. CHAIKIN[1], J. P. GOLLUB[2] AND D. J. PINE[1]*

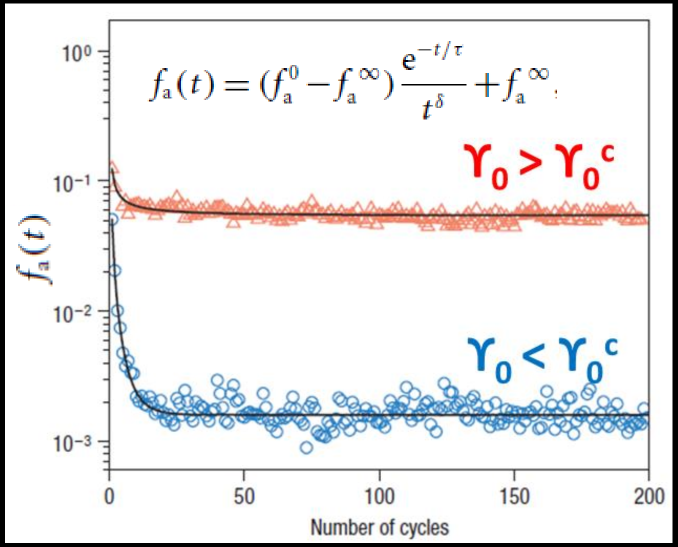
nature physics | VOL 4 | MAY 2008 |

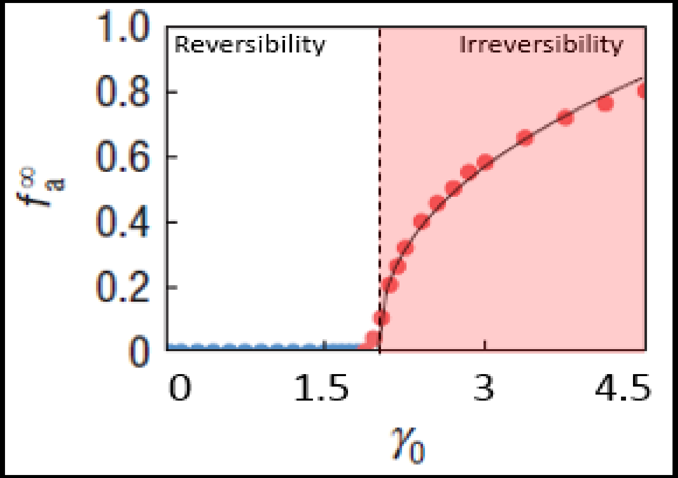
$$\Upsilon(t) = \Upsilon_0 \sin(\omega t)$$



Random Organization & Basis for Mechanical Memory







- Irreversibility onset – Non-equilibrium phase transition from an absorbing state to a fluctuating steady state
- System adapts to a particular strain

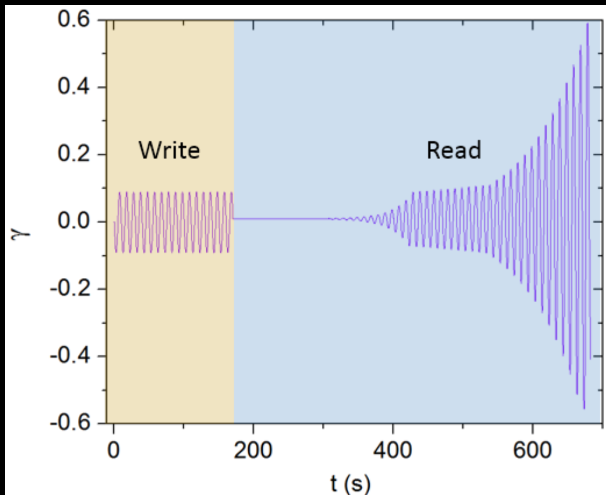
Pine et al., *Nature* 438, *997* (2005)
Corte et al., *Nature Physics* **4**, 420 - 424, (2008)

Mechanical Memory – Dilute Suspensions

PRL **107,** 010603 (2011) PHYSICAL REVIEW LETTERS week ending 1 JULY 2011

Generic Transient Memory Formation in Disordered Systems with Noise

Nathan C. Keim* and Sidney R. Nagel†

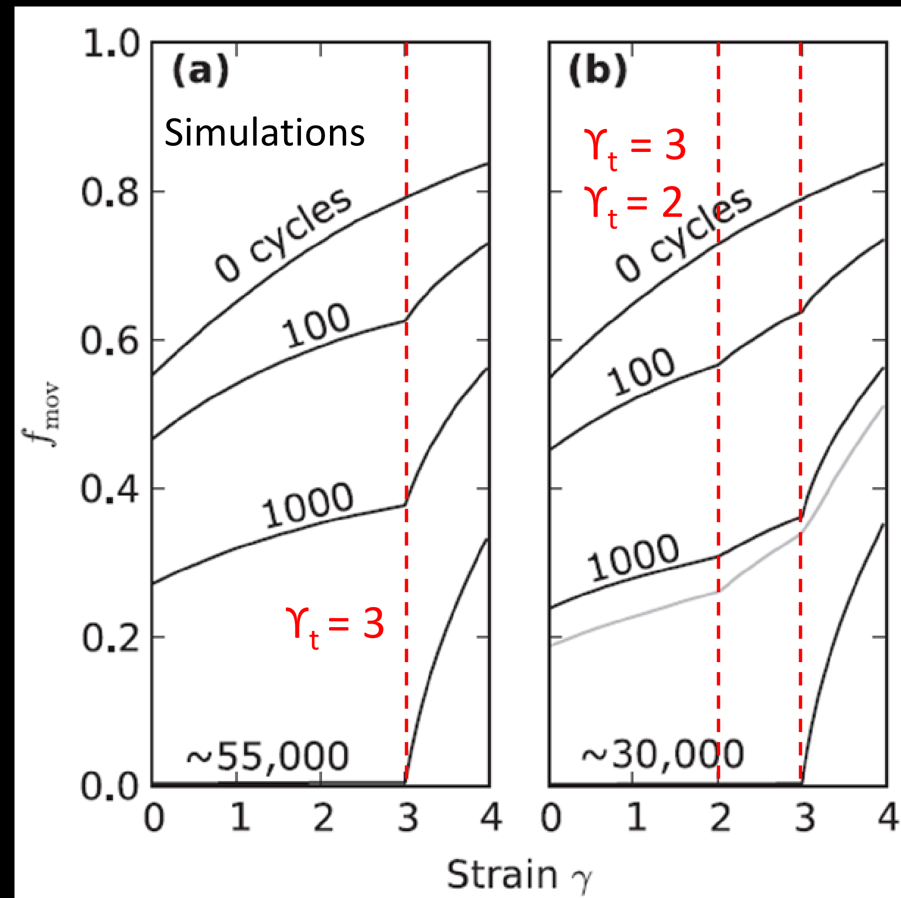


Reading memory

Done by applying one cycle of shear of each strain amplitude across Υ_t

Noise stabbilizes multiple memories.

cycles. Grey line: memory of both values remains after 10^5 cycles when the system is stabilized by noise ($\epsilon_{noise} = 0.006$).



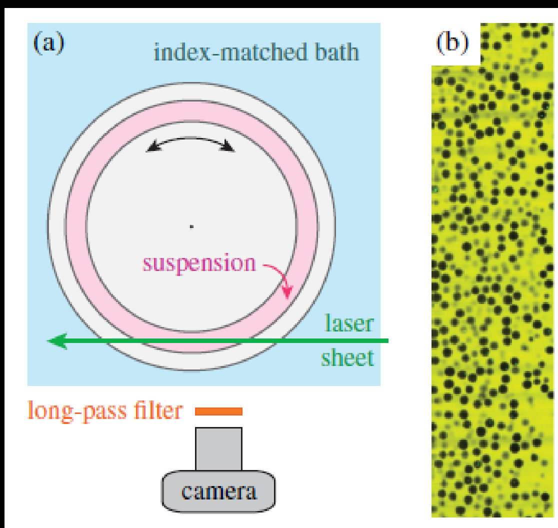
In (b) , Two memories.

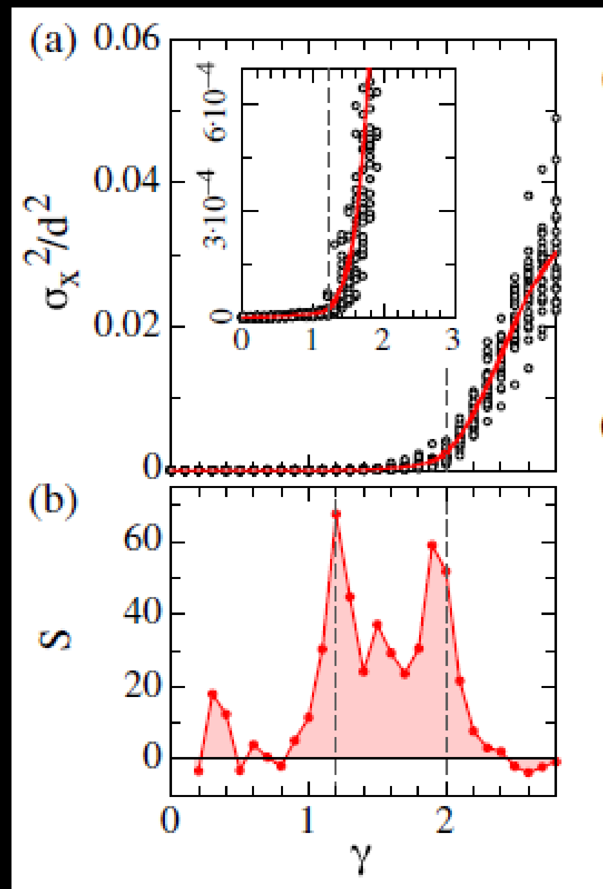
(b) With dual training values, $\gamma_1 = 3.0$ and $\gamma_2 = 2.0$, (pattern: $\gamma_1, \gamma_2, \gamma_2, \gamma_2, \gamma_2, \gamma_2$, repeat ...), both values can be identified at intermediate times. The system completely self-organizes, re-

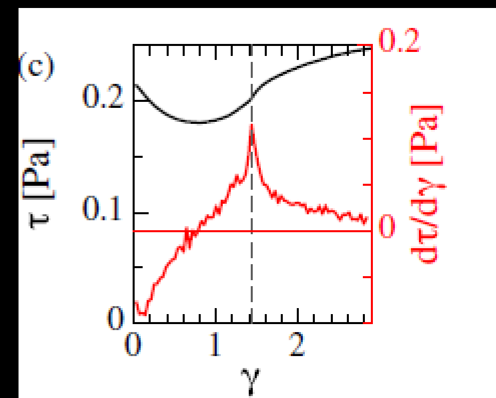
PRL 113, 068301 (2014) PHYSICAL REVIEW LETTERS week ending 8 AUGUST 2014

Multiple Transient Memories in Experiments on Sheared Non-Brownian Suspensions

Joseph D. Paulsen,[1,2,4,*] Nathan C. Keim,[3,4] and Sidney R. Nagel[4]







the particles have diameters, d, between 106 and 125 μm, with volume fraction of ϕ = 0.35.

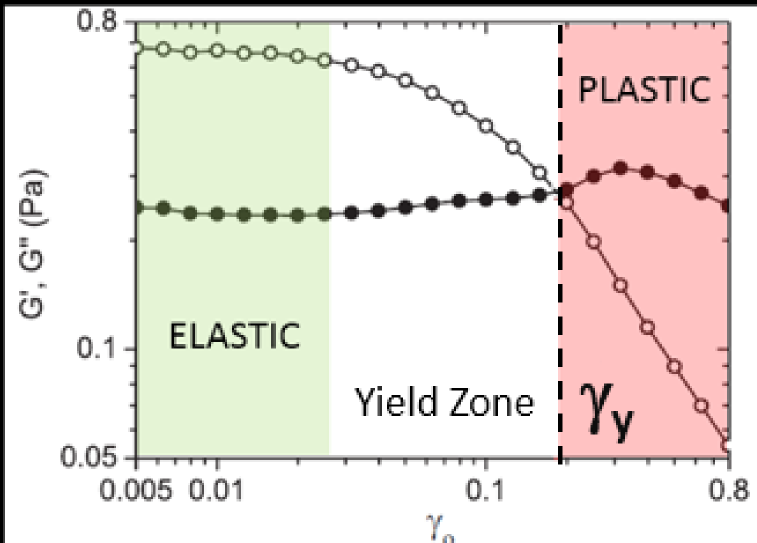
Also see Keim, Paulsen and Nagel, PRE 88,032306(2013)

FIG. 3 (color online). Multiple memories. (a) Readout of 48 independent experiments with the training sequence $\gamma =$ 2.0, 1.2, 1.2, 1.2, 1.2 repeated 4 times. Points: individual runs.

Do concepts carry over to dense suspensions?

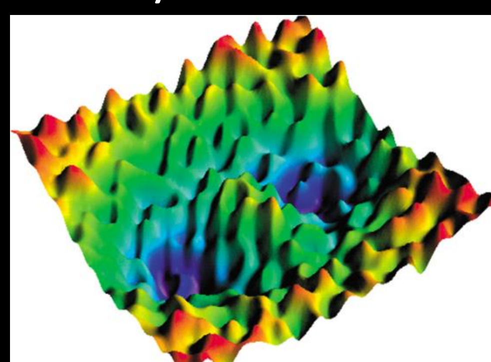
Dense Suspensions
Appearance of a yield stress

Examples: Emulsions, Foams and Suspensions

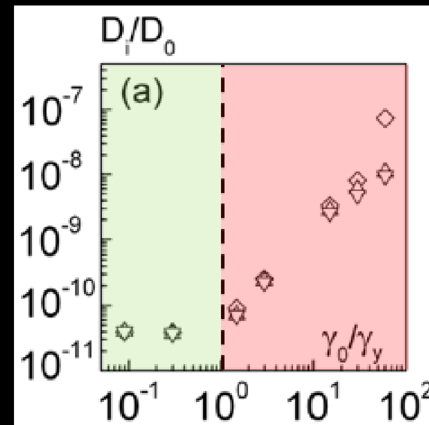


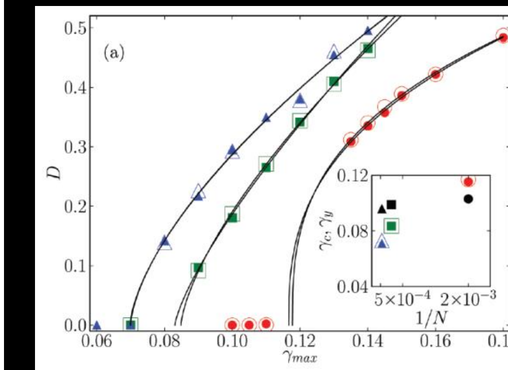
Elastic Regime – Reversible Dynamics
Plastic Regime – Irreversible Dynamics

Roughness of the energy landscape plays the role of noise



Mohan et al., J of Rheology (2013)
Fiocco et al., PRE (2013)

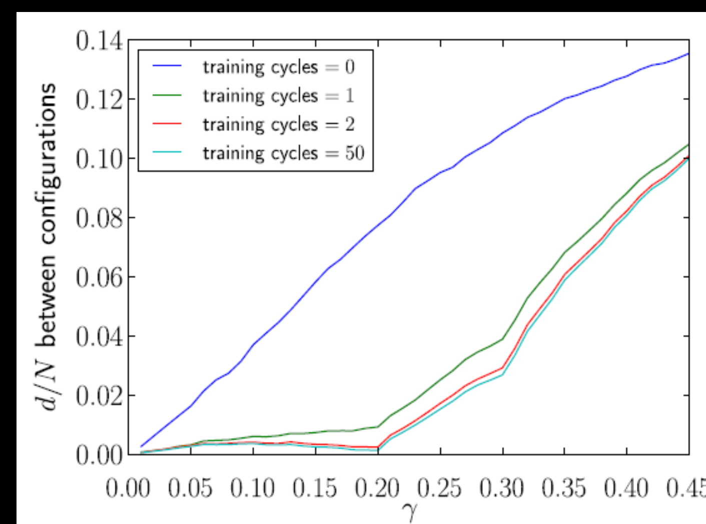




Yielding shares similarities with Random Organization

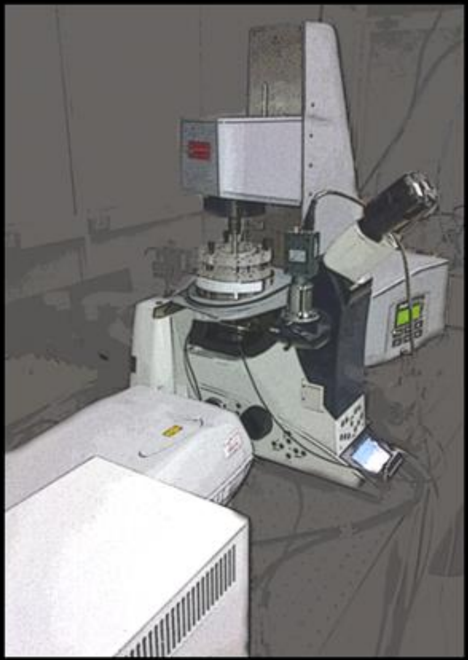
Knowlton et al., Soft Matter (2014)

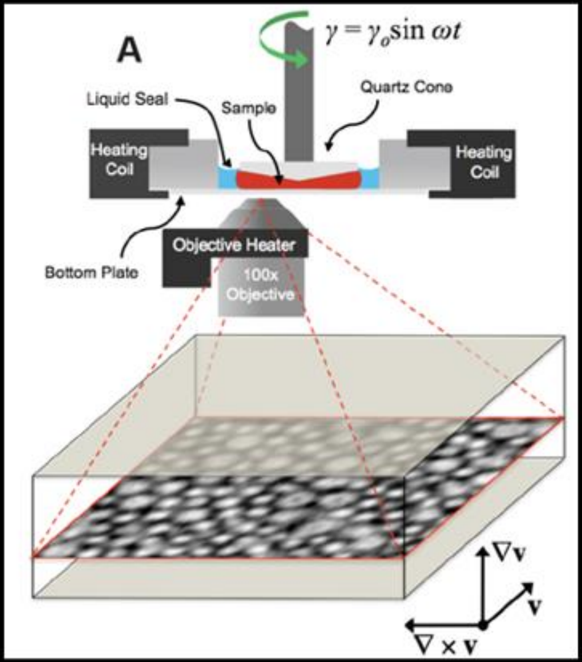
Memory in Simulations



Fiocco ,Fofffi and Sastry, PRL (2014)

Random Organization and Yielding in Colloidal Glasses





K.Hima Nagamanasa, S Gokhale, A K Sood and R Ganapathy,

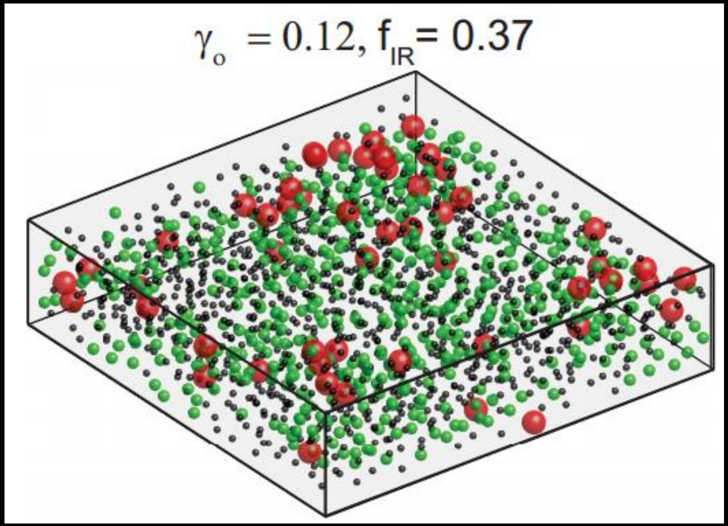
PRE 89, 062308(2014)

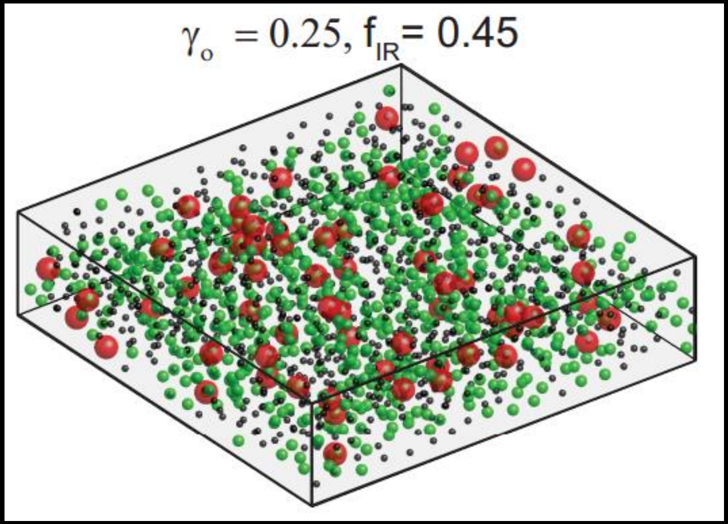
Binary Colloidal Glass made of
Poly N-isopropylacrylamide (PNIPAM) particles
size (~ 1 um)

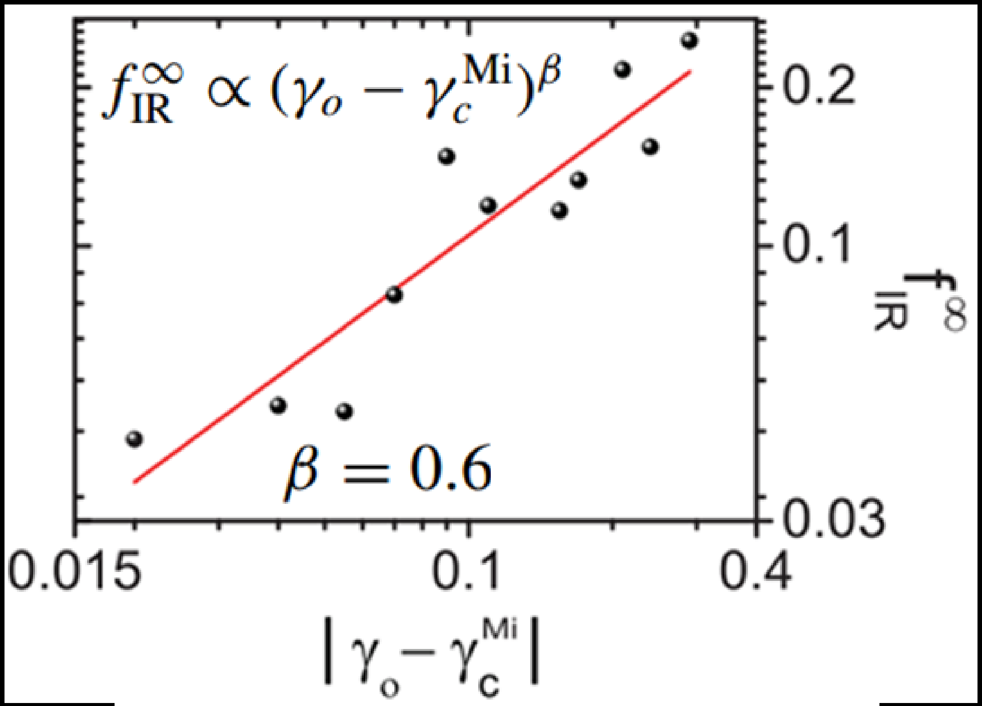
$n_{small} : n_{big} = 3:1$ $R_{small} : R_{big} = 1:2$

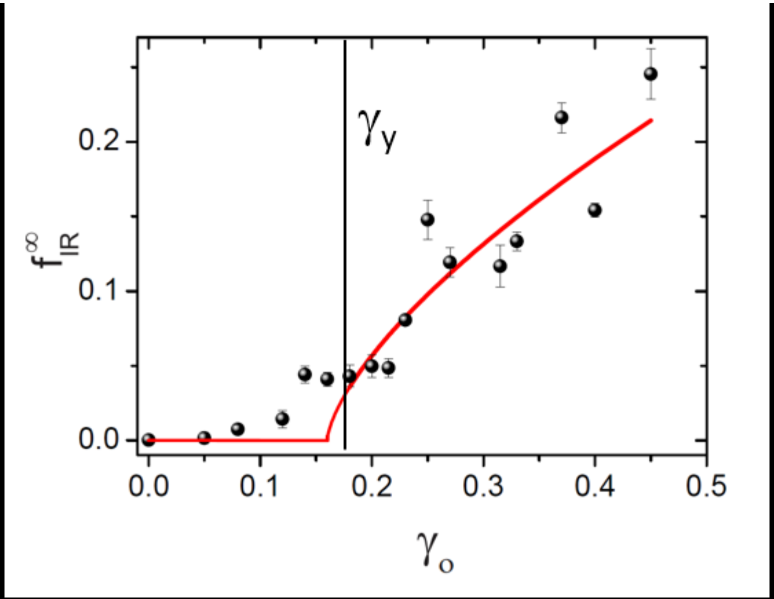
$\phi_{Particle} > \phi_{glass}$ 58% at 27°C

Quantifying Irreversible Yield Events (3D)





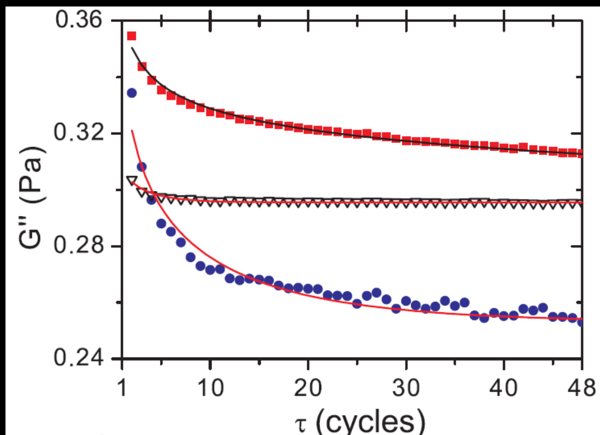




Fraction of particles (f_{IR}) that did not return to their positions after one complete oscillation cycle

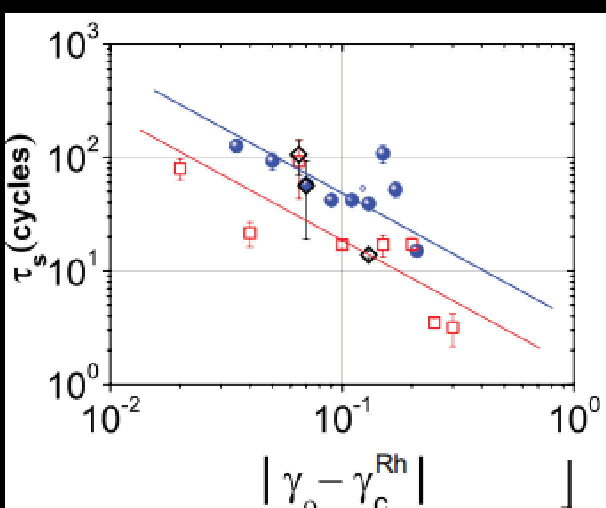
Signatures of Slowing Down Near Yield

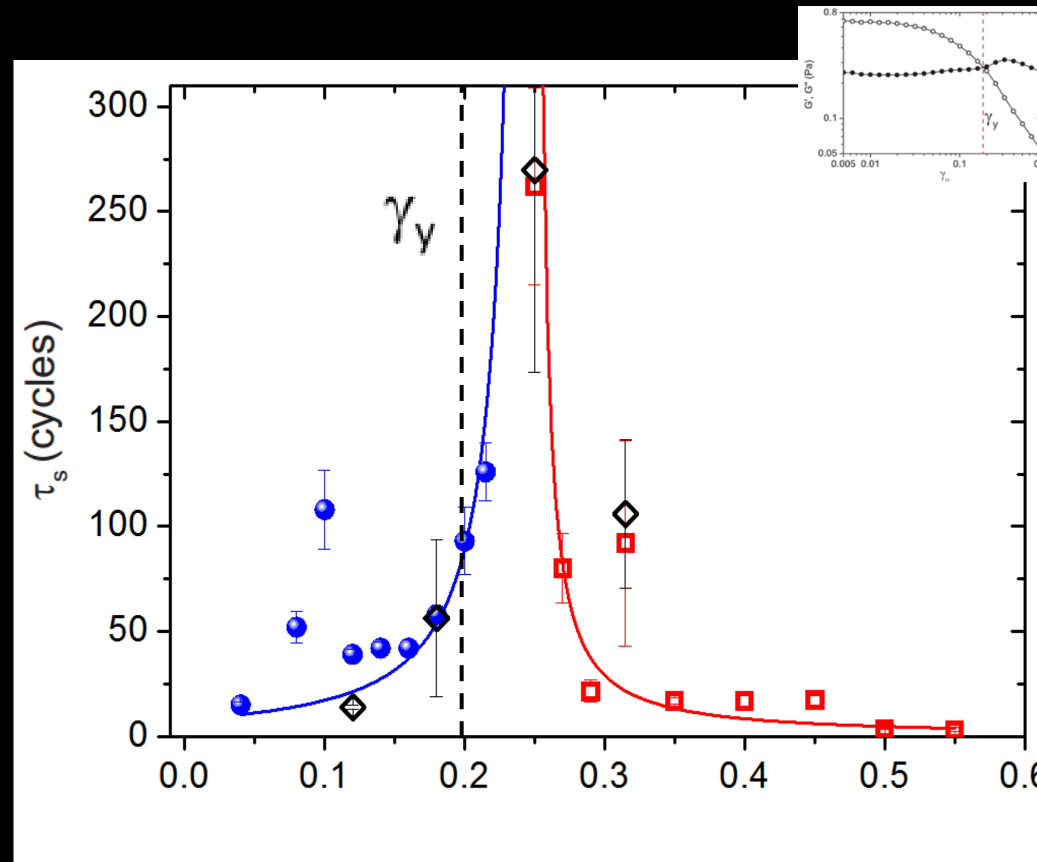
Irreversible events lead to dissipation of energy and should also reflect in the loss modulus G''



$\gamma_o = 0.04$ (●), $\gamma_o = 0.25$ (■) and $\gamma_o = 0.45$ (▽)

$$G''(\tau) = (G''_o - G''_\infty)\frac{e^{-\tau/\tau_s}}{\tau^\delta} + G''_\infty$$





$$\tau_s \propto |\gamma_o - \gamma_c|^{-\alpha}, \text{ with } \alpha = 1.1$$

"Absorbing Phase Transition", CDP Universality Class

Menon and Ramaswamy PRE 79, 061108 (2009)

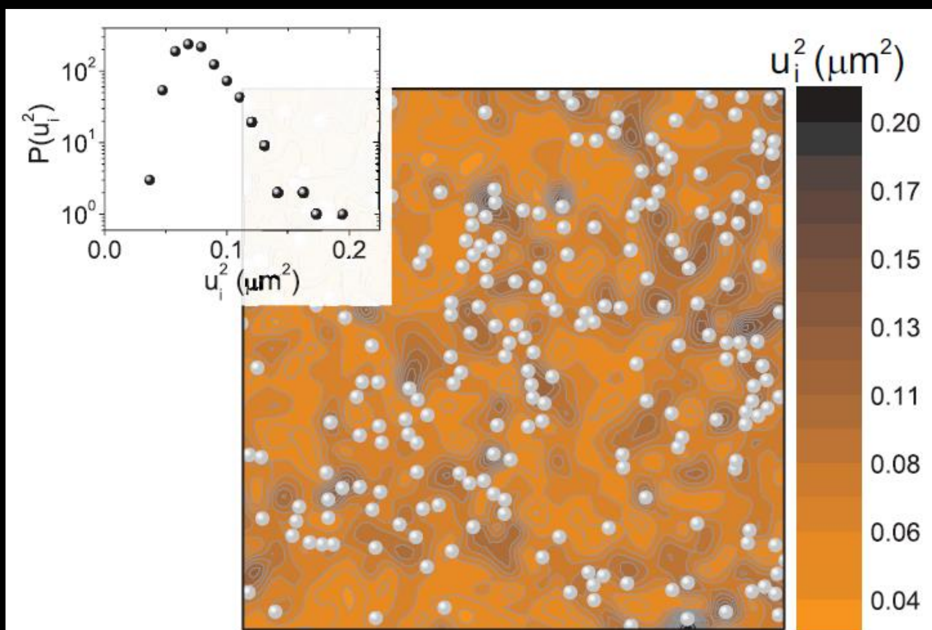
Spatial Cooperativity Near Yielding

Debye-Waller factor: mean squared deviation of a from its mean position

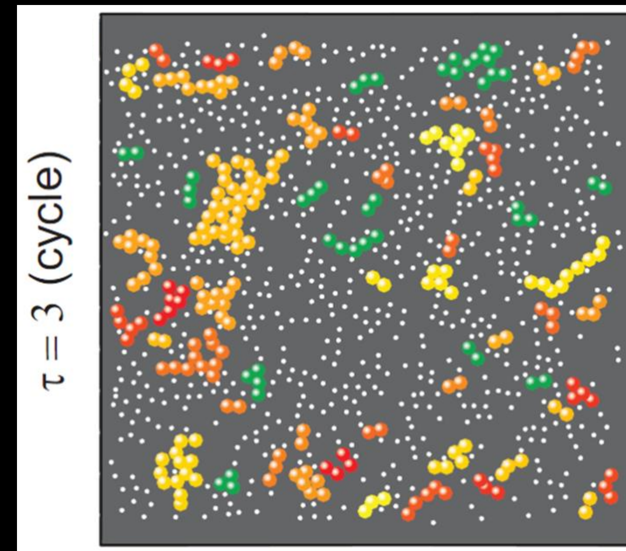
$$DW_i = \left\langle \left(\langle r_i \rangle - r_i(t) \right)^2 \right\rangle_{\text{cycle}}$$

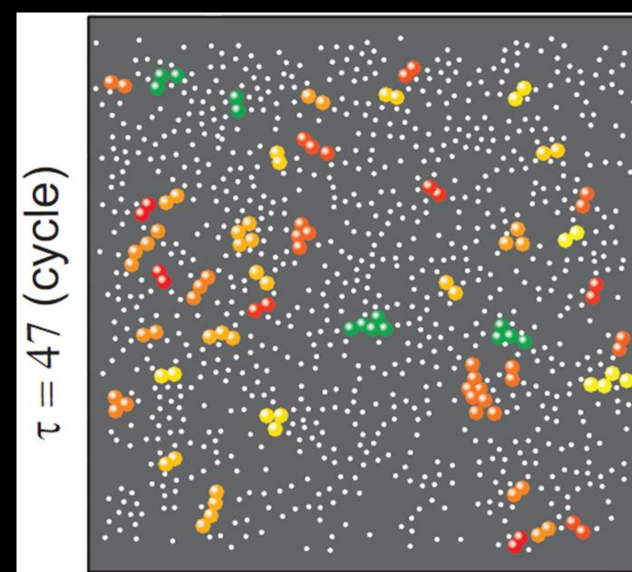
$r_i(t)$ instantaneous displacement

$\langle r_i \rangle$ average position of the particle

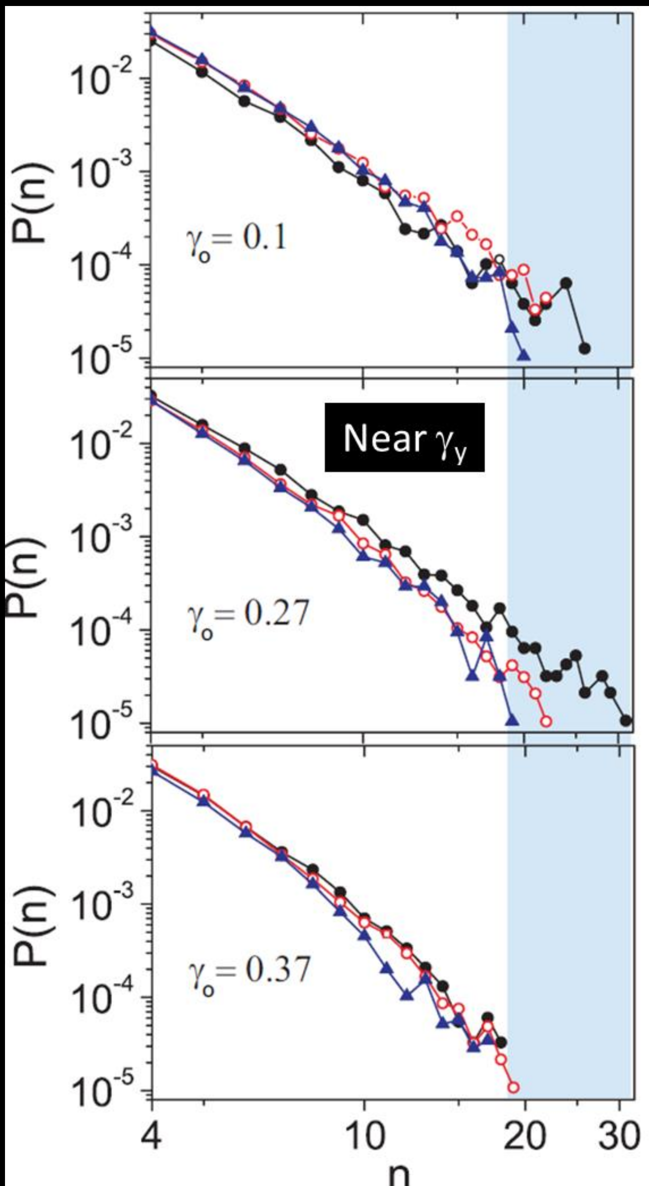


$\gamma_o = 0.27$





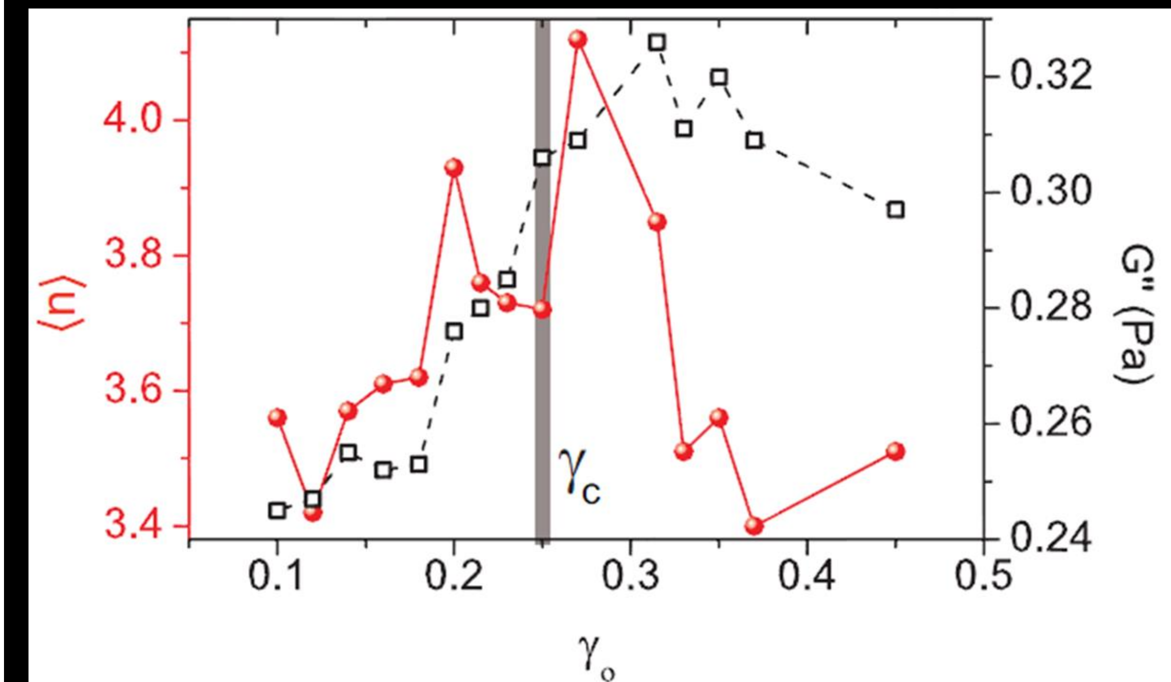
Time Evolution of Spatial Cooperativity



$\tau = 2$ to 10 (●)

$\tau = 20$ to 30 (○)

$\tau = 37$ to 47 (▲)

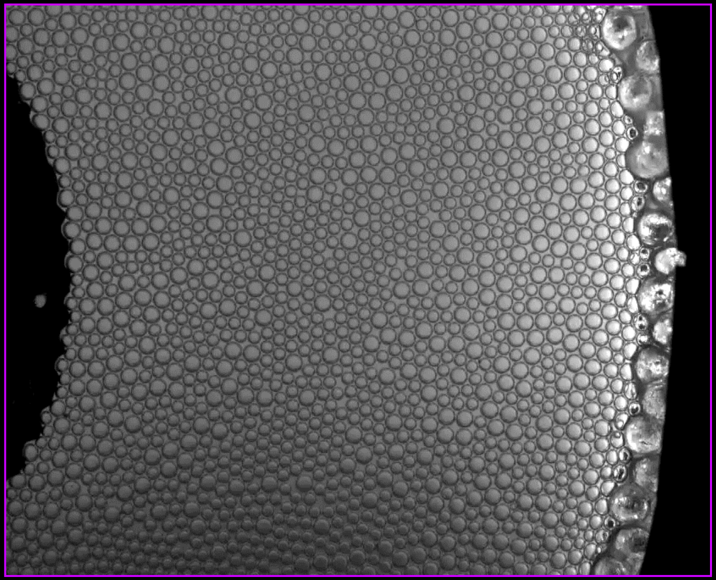


Maximal cooperative dynamics near yielding

Questions

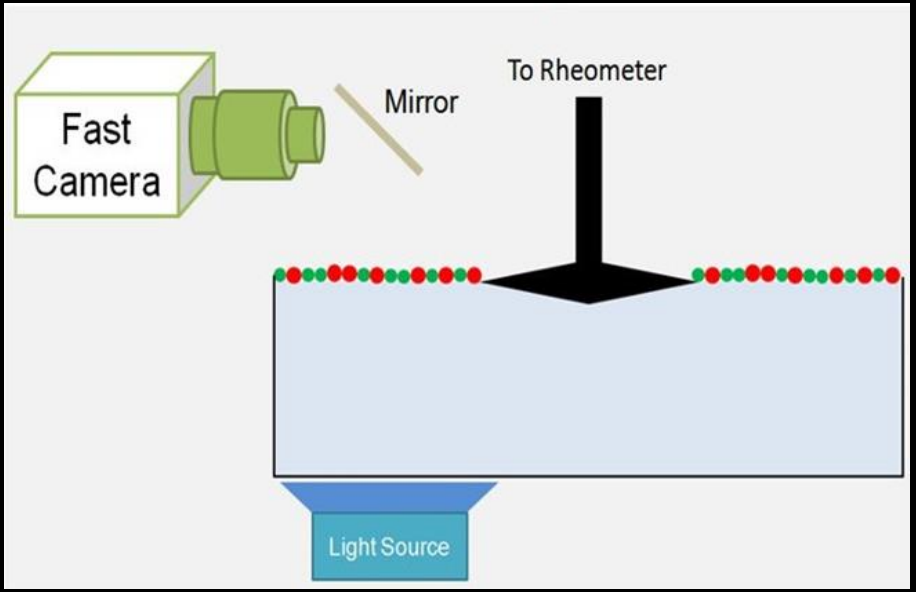
- Experimental system to directly observe memory in amorphous solids?

Experimental System – Bubble Rafts



Amorphous Solid: Bi-disperse Bubble Raft

Soft - Frictionless - Athermal Particles

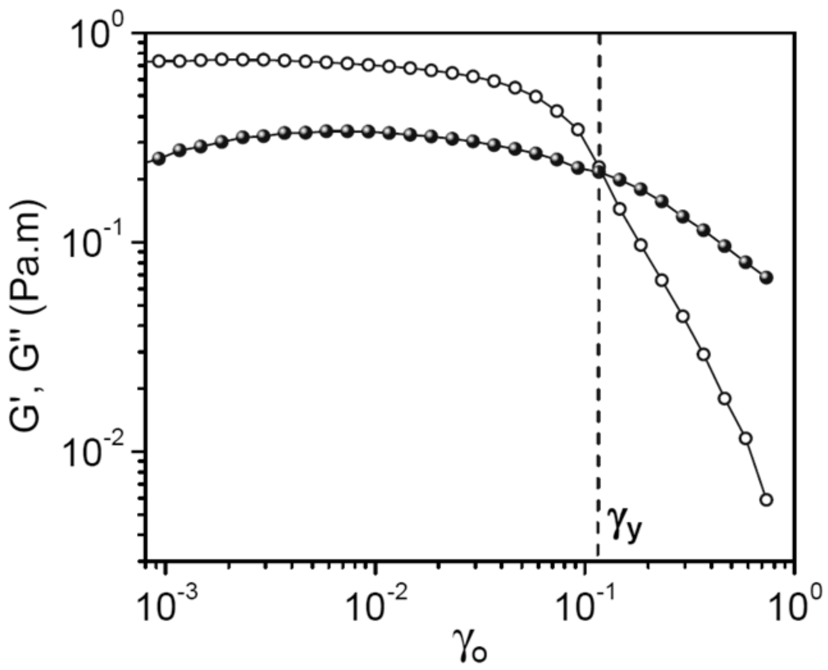


2D Couette Geometry

Area fraction – $\phi > 0.8$

Experimental Details – Bubble Rafts

$\omega = 0.5$ rad/s



Basic characterization:

Couette geometry

Area fraction: $\phi > 0.8$

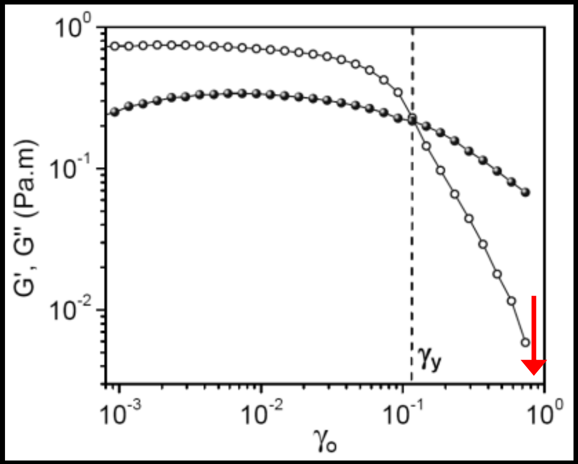
Type of raft: Bidisperse amorphous with some polydispersity

Number ratio of bubbles used: On an average for every 8 big bubbles there are 11 small bubbles in this raft.

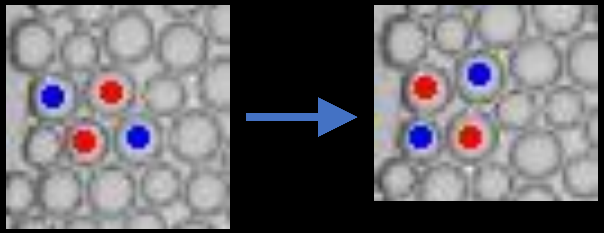
Size of bubbles: Between 1mm and 2.5mm in diameter.

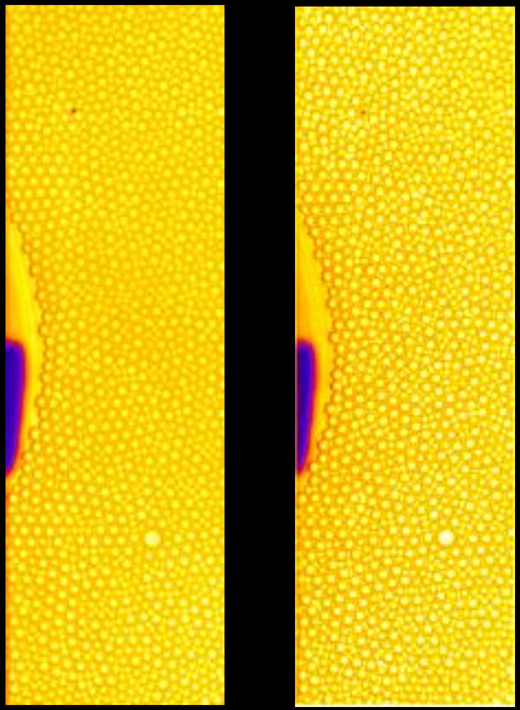
Number of bubbles in the field of view: ~1300 .

Random Organization – Athermal Amorphous Solids



Irreversible T1 Event

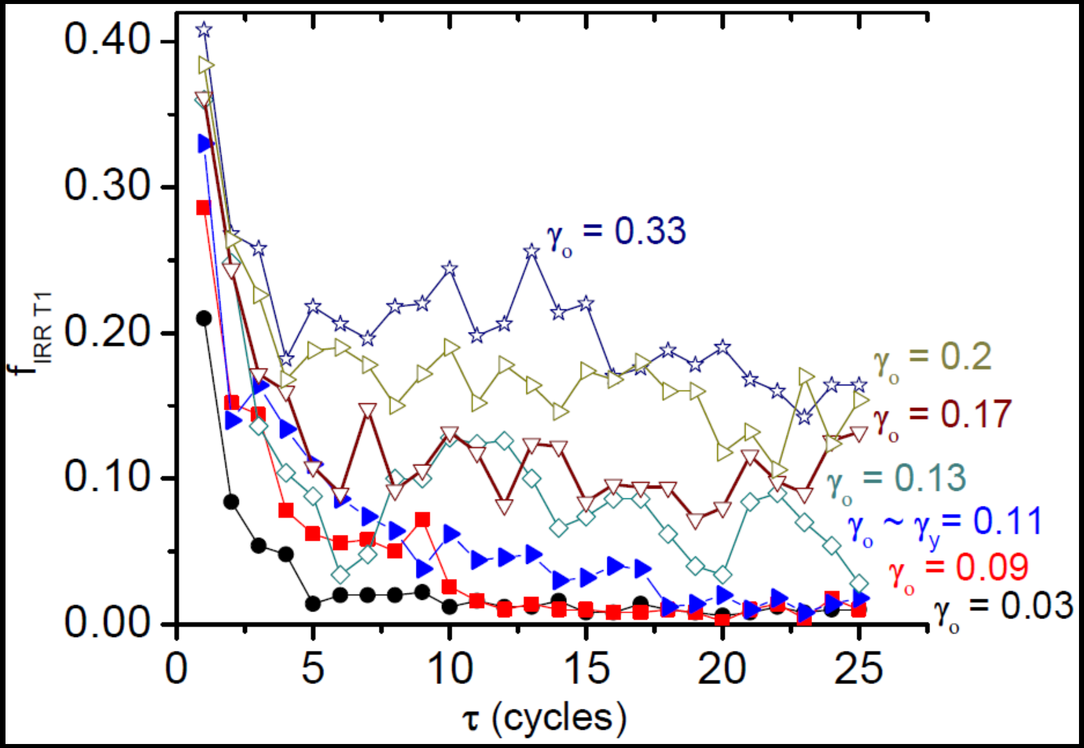


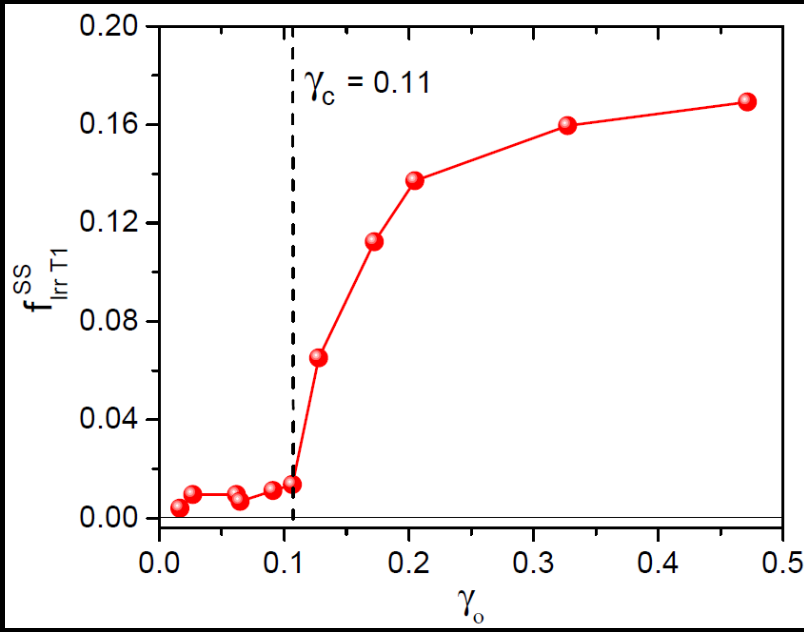


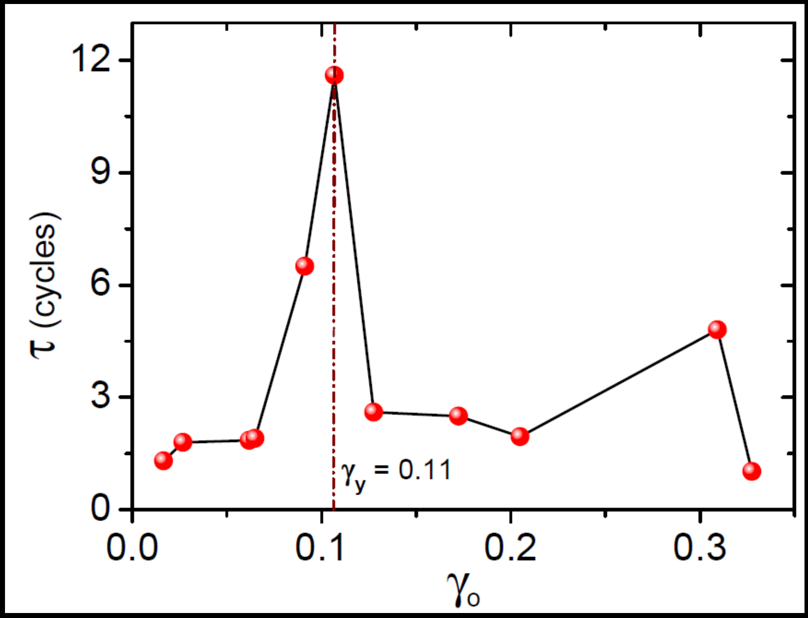
T1 events correspond to a neighbor switching event in which two neighboring bubbles lose contact, and two next nearest neighbors become neighbors .

A True "Absorbing/Reversible State" below Yield

Time Evolution of Irreversibility







Encoding and Retrieving Memory

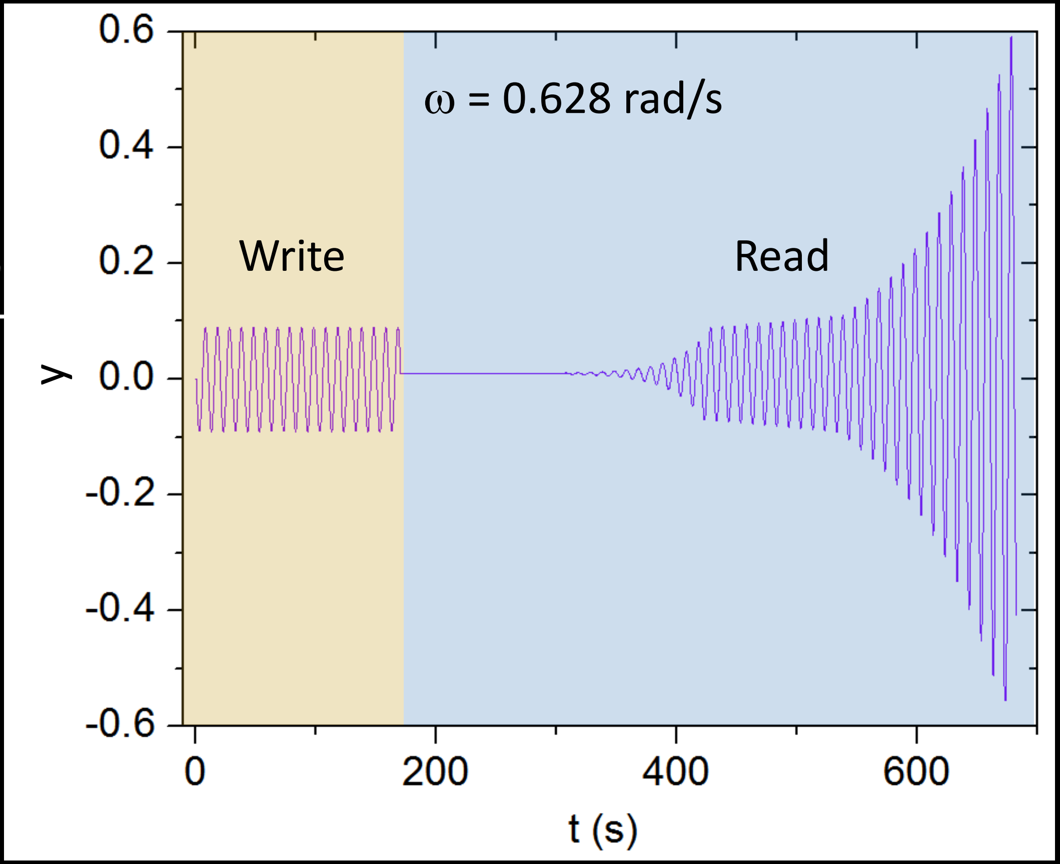
Writing Memory

Done by applying repeated cycles of shear of the same strain amplitude Υ_t

$$\mathrm{MSD}(n) = \frac{\sum_{i=1}^{i=N} |\mathbf{R_i}(n) - \mathbf{R_i}(n-1)|^2}{N}$$

i: particle index
n: step number

MSD ∝ fraction of particles that did not return at the end of a cycle



Reading memory

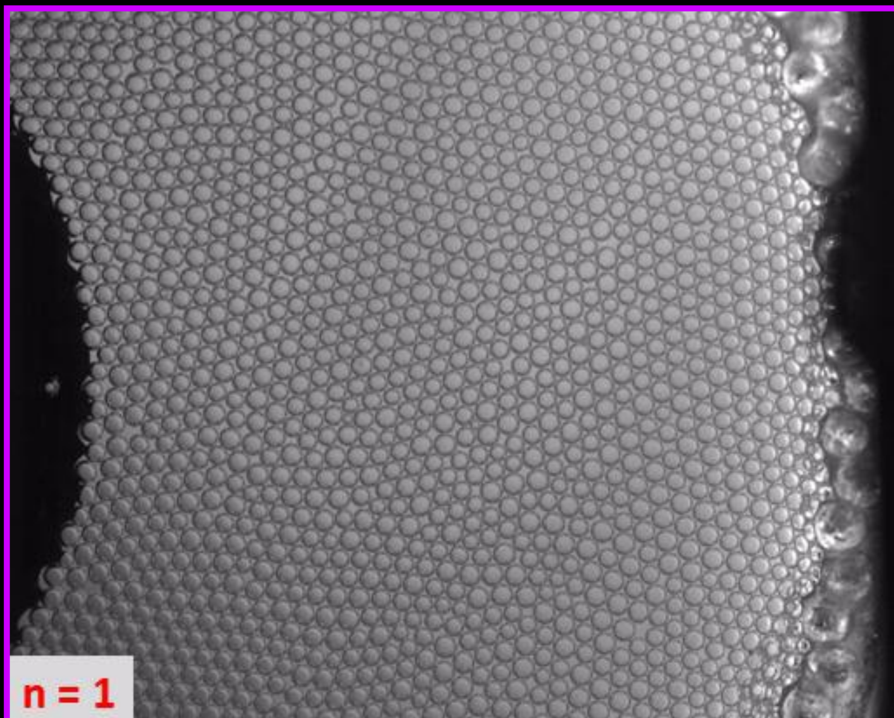
Done by applying one cycle of shear of each strain amplitude across Υ_t

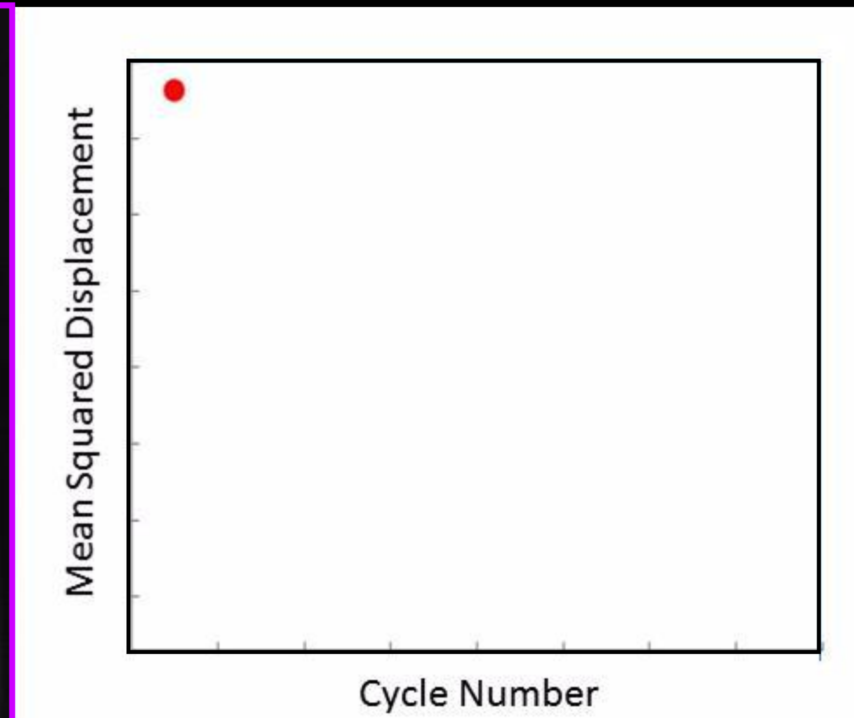
$$\mathrm{MSD}(\gamma_0) = \frac{\sum_{i=1}^{i=N} |\mathbf{R}_\mathrm{i}(\gamma_0 + \delta\gamma_0) - \mathbf{R}_\mathrm{i}(\gamma_0)|^2}{N}$$

Writing Memory

$\Upsilon_y = 0.06$

Stroboscopically Viewed



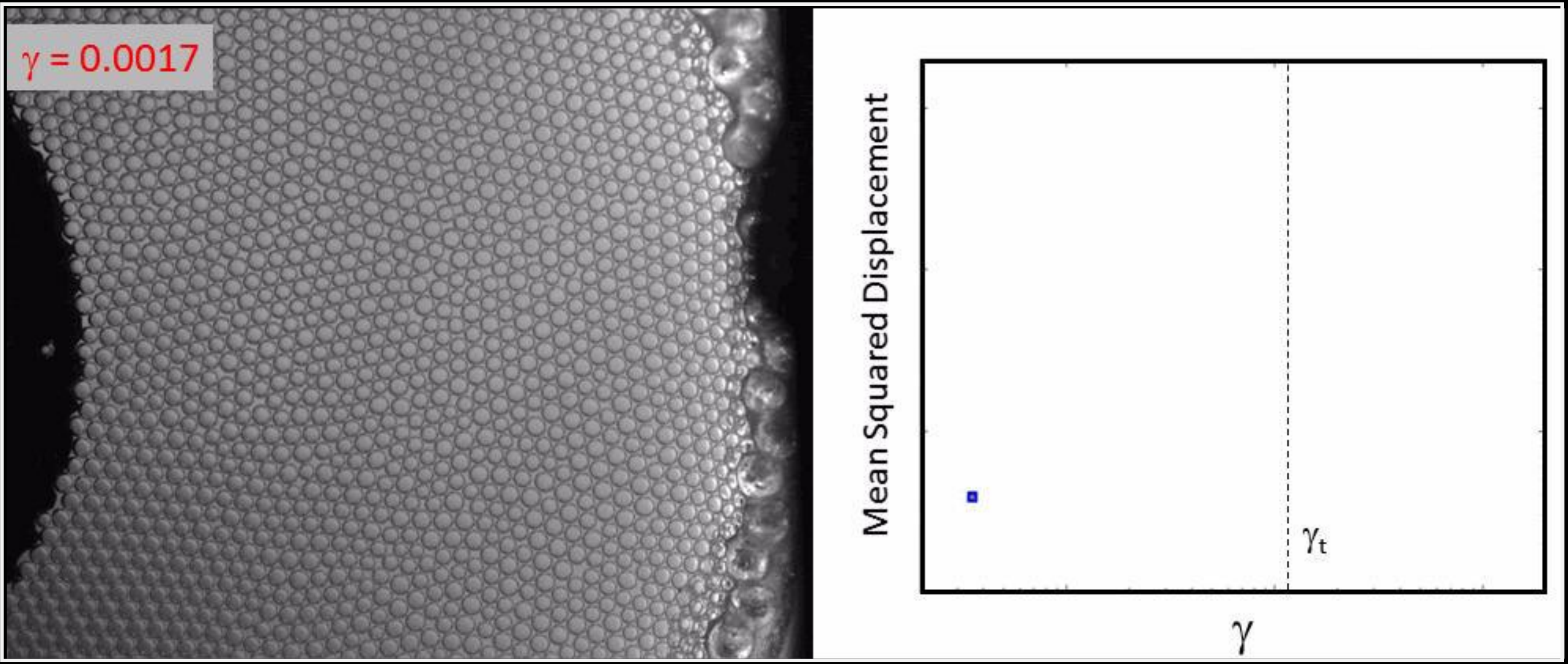


$\Upsilon_t = 0.06$, $\omega = 0.628$ rad/s

$$\mathrm{MSD}(n) = \frac{\sum_{i=1}^{i=N} |\mathbf{R_i}(n) - \mathbf{R_i}(n-1)|^2}{N}$$

Reading Memory

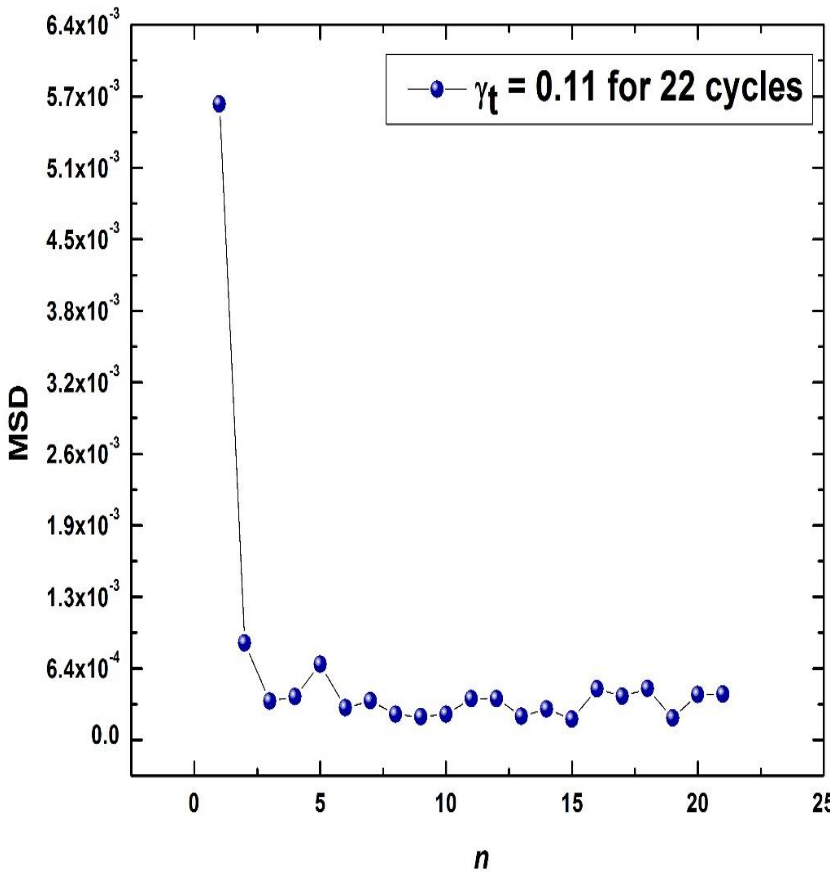
Stroboscopically Viewed

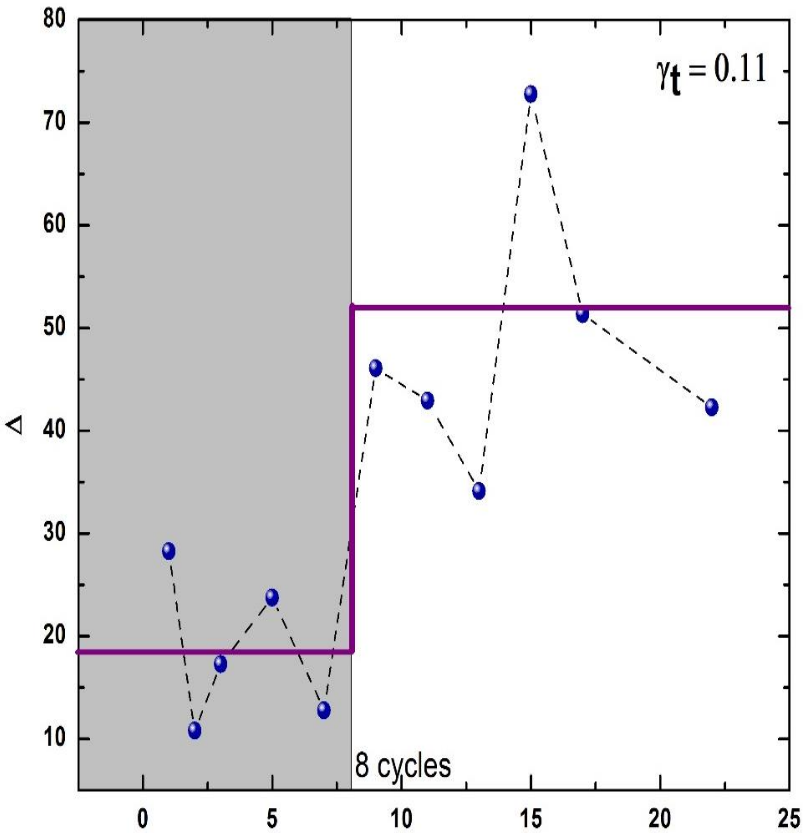


Reading memory after training at $\Upsilon_t = 0.06$

$$\mathrm{MSD}(\gamma_0) = \frac{\sum_{i=1}^{i=N} |\mathbf{R}_\mathrm{i}(\gamma_0 + \delta\gamma_0) - \mathbf{R}_\mathrm{i}(\gamma_0)|^2}{N}$$

Memory as a function of training extent





For every run, pre-shear at 5 s-1for 180s.

In encoding of memory, MSD decays within 2-3 cycles.

Is memory writing complete at the end of 2-3 cycles?

Likely that though MSD has reached steady state, force chains have not ?(BB talk).

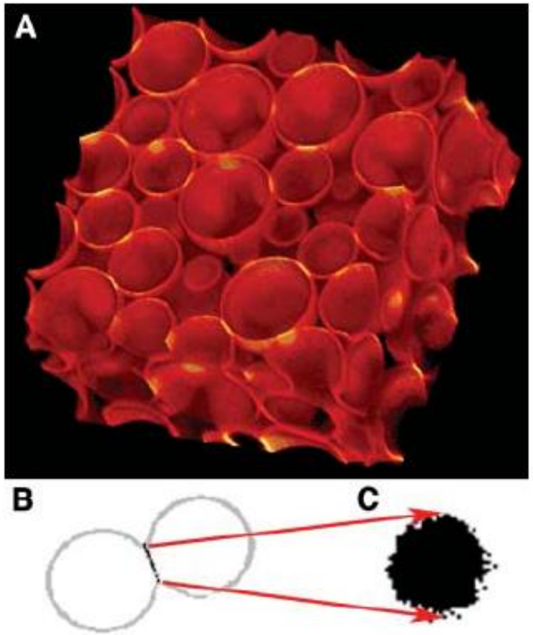


Fig. 1. (**A**) The projection of a 3D image of a small part (80 μm by 80 μm by 30 μm) of a pile shows the fluorescence from the surfaces of the liquid droplets. Droplets of a mixture of perfluorodecalin and α,α,α-trifluorotoluene were formed in refractive-index–matched K-phosphate–aqueous buffer with fluorescent TMR-CPMV particles. Droplets were piled in a 5.7-mm-diameter cylindrical tube to a depth of 6 mm and imaged with a confocal microscope (Zeiss Laser Scan Microscope model 510, 40× objective with a numerical aperture of 1.3). (**B**) A cross section shows the surfaces of two adjacent droplets in the pile. The surfaces were isolated by means of intensity gradients in the 3D image. (**C**) Voxels shared by two adjacent droplets were identified (black); a projection of the contact area defines a circular shape of area *A*.

Measurement of Forces Inside a Three-Dimensional Pile of Frictionless Droplets

J. Zhou,[1] S. Long,[2] Q. Wang,[2] A. D. Dinsmore[1*]

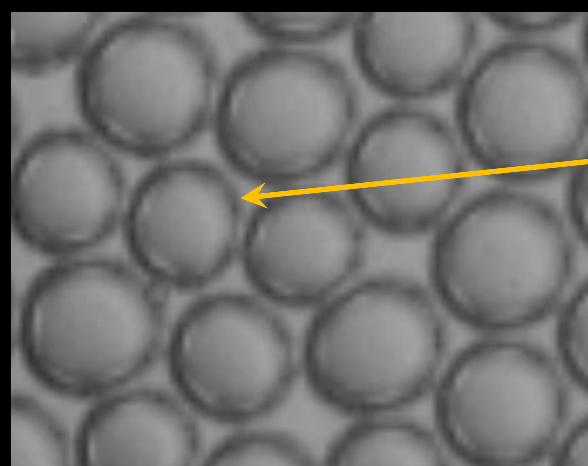
SCIENCE VOL 312 16 JUNE 2006 1631

Force of between two droplets of radius R_i & R_j

$$f_{ij} = \gamma A_{ij} \frac{(R_i + R_j)}{(R_i R_j)}$$

A_{ij} - Contact area
γ - Surface tension

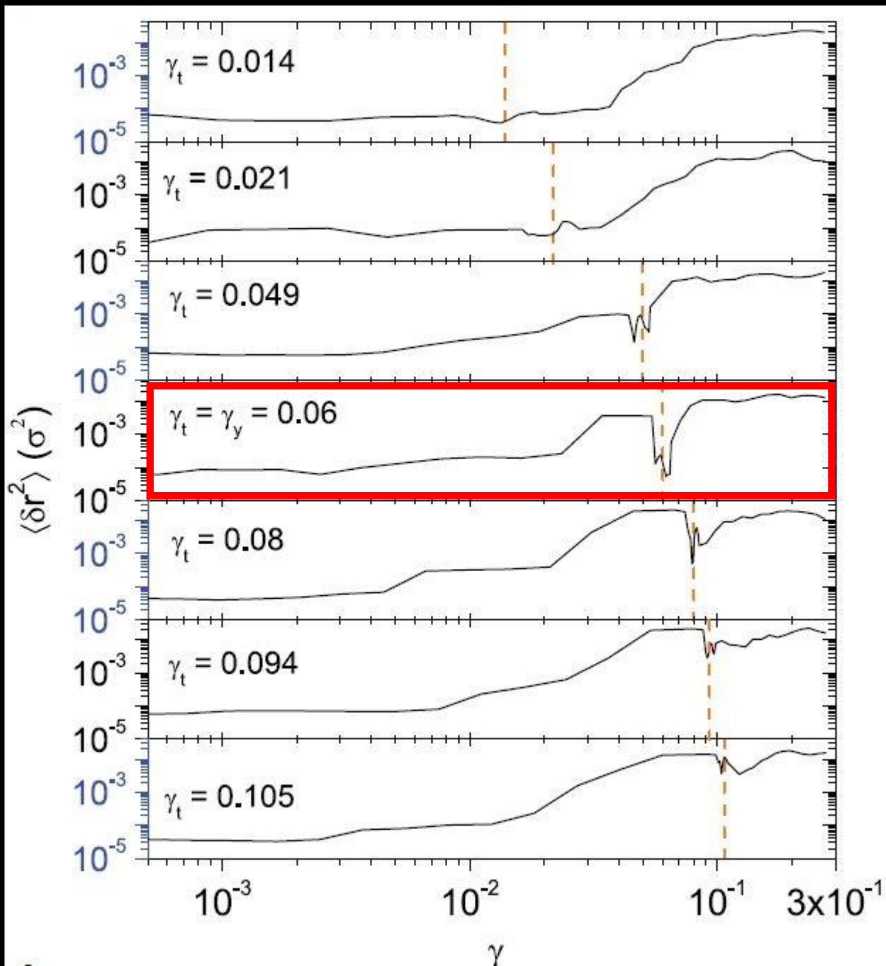
Bubble Rafts

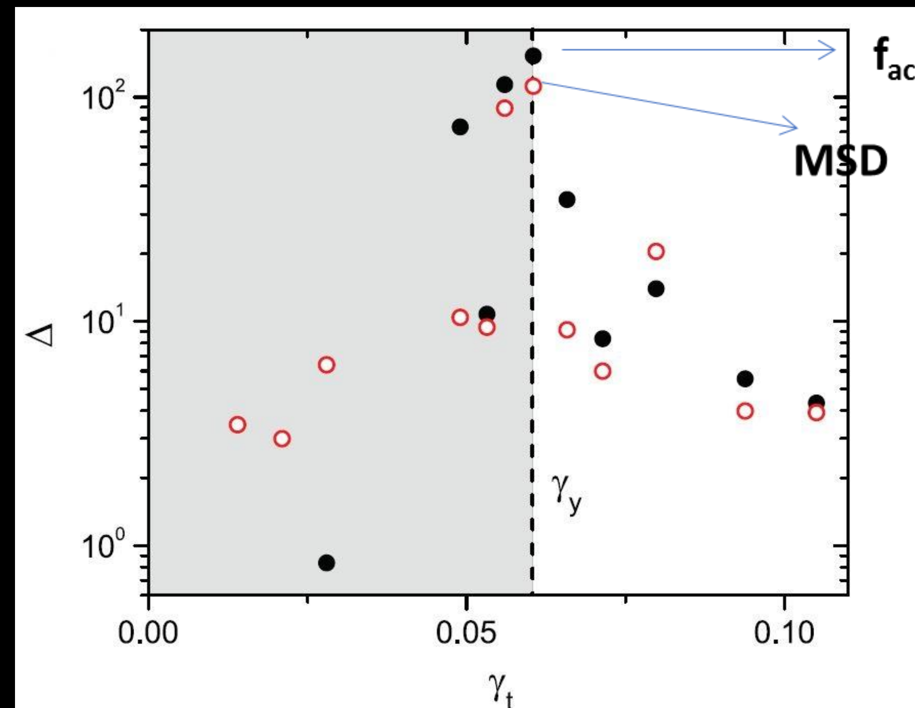


Distortion of bubble perimeters from a circle contains information of forces

For us , this is " to do next"

Strength of Memory

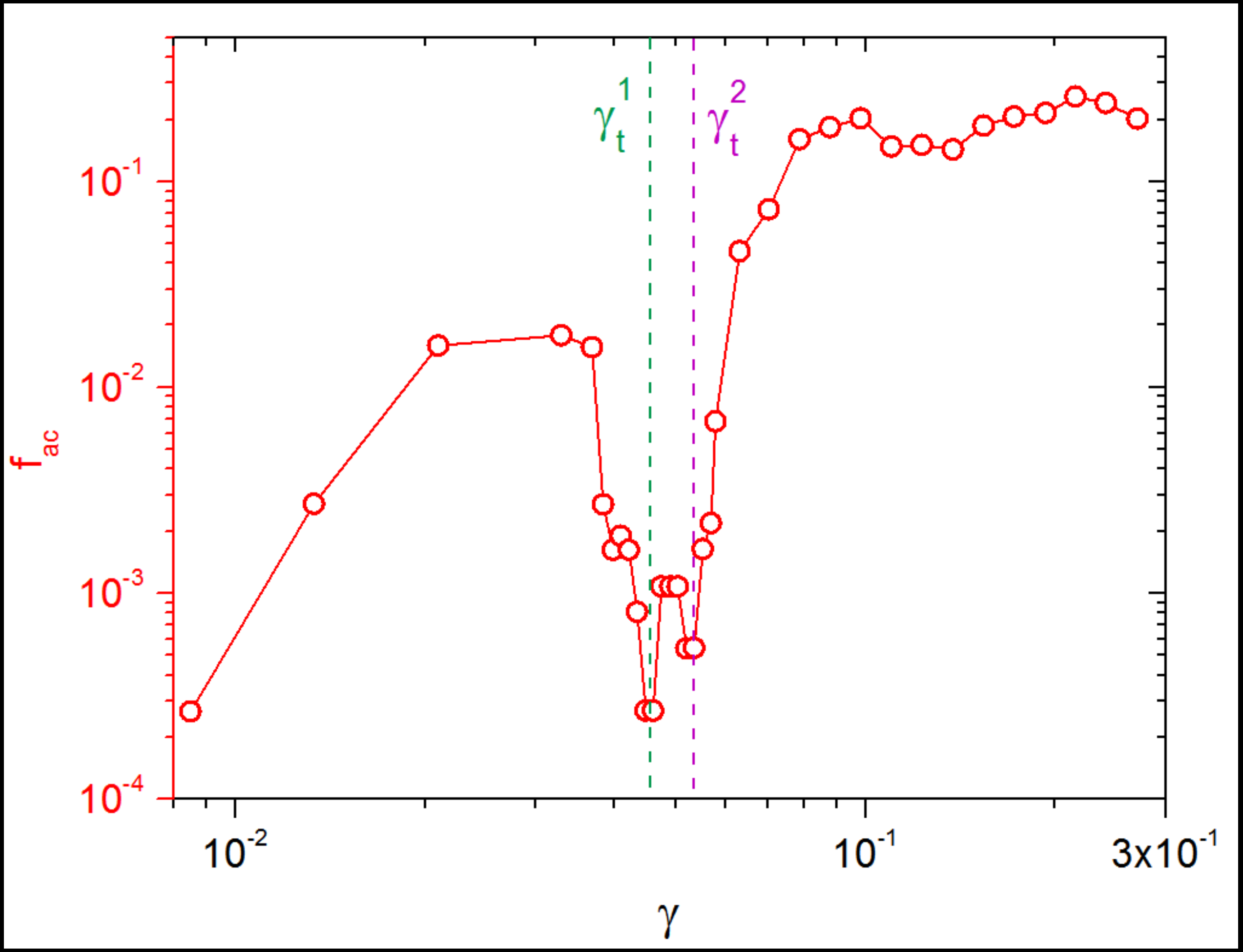




Δ maximum at yield!

Why??

Experimental Evidence for Multiple Memories in Amorphous Solids



$\gamma_t^1 = 0.042$; $\gamma_t^2 = 0.053$

Training sequence – $\gamma_t^2 \gamma_t^1 \gamma_t^1 \ \gamma_t^2 \gamma_t^1 \gamma_t^1$, 11 cycles of each

Dilute non-Brownian suspensions -- noise required for persistent multiple memories.

Athermal amorphous solids - experiments confirm-persistent multiple memories –achieved without external noise due to complex landscape.

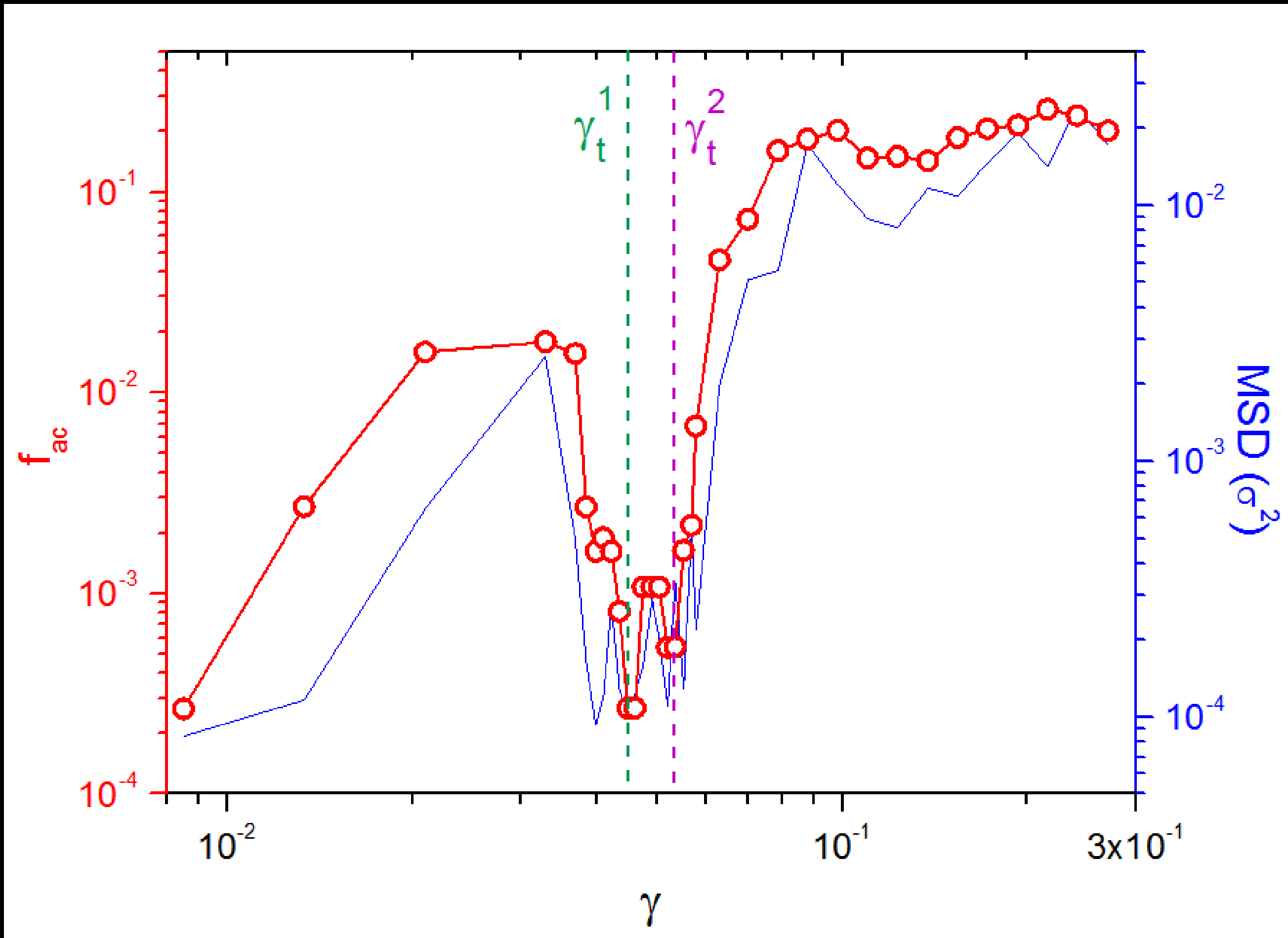
Two read outs for Multiple Memories…….

$\gamma_t^1 = 0.042$; $\gamma_t^2 = 0.053$

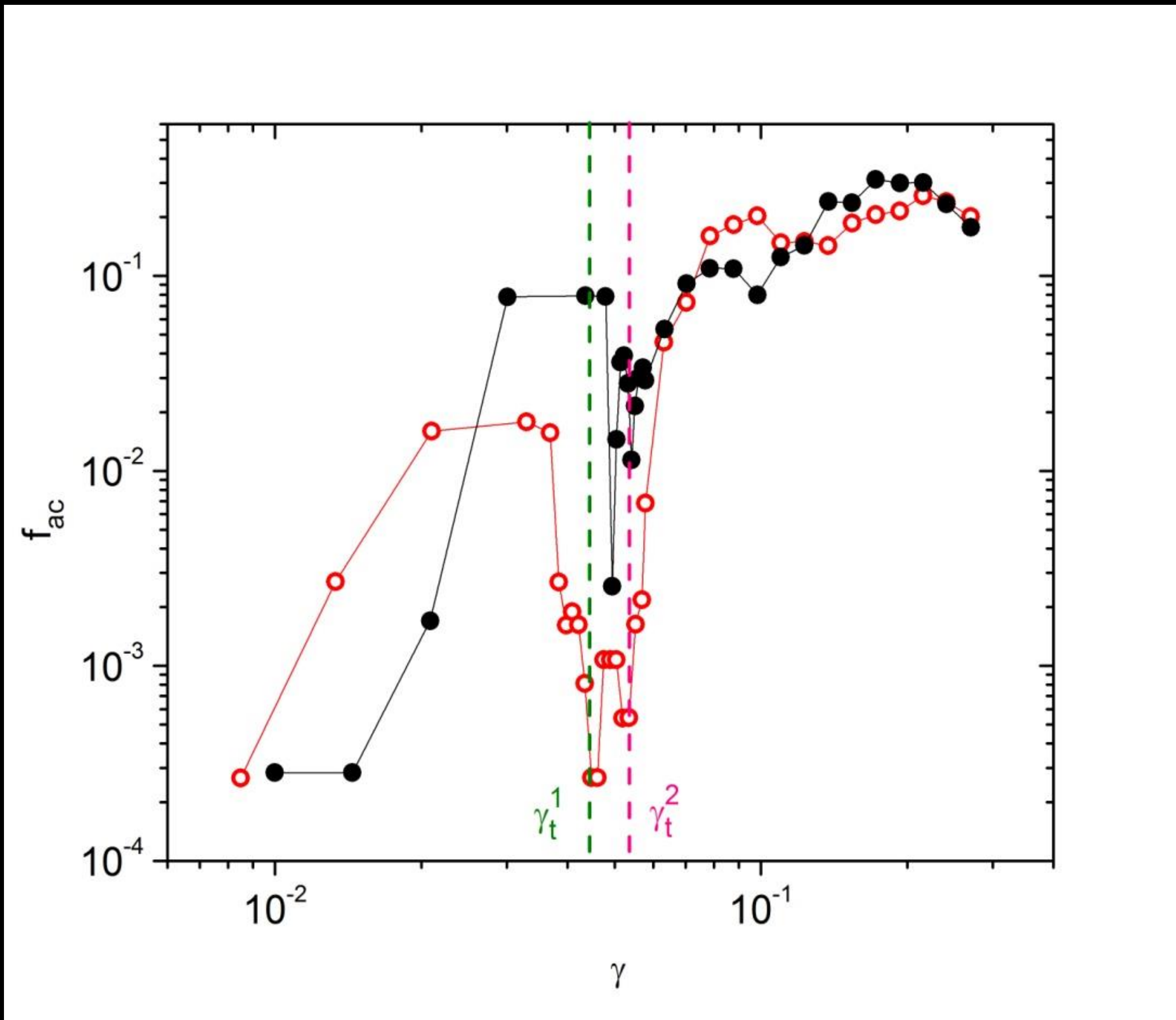
Training sequence –

$\gamma_t^2 \gamma_t^1 \gamma_t^1 \ \gamma_t^2 \gamma_t^1 \gamma_t^1$,

11 cycles of each



Comparing Single and multiple memories



$\gamma_t^1 = 0.042$

$\gamma_t^2 = 0.053$

Training sequence – $\gamma_t^2 \gamma_t^1 \gamma_t^1$ $\gamma_t^2 \gamma_t^1 \gamma_t^1$,
11 cycles of each

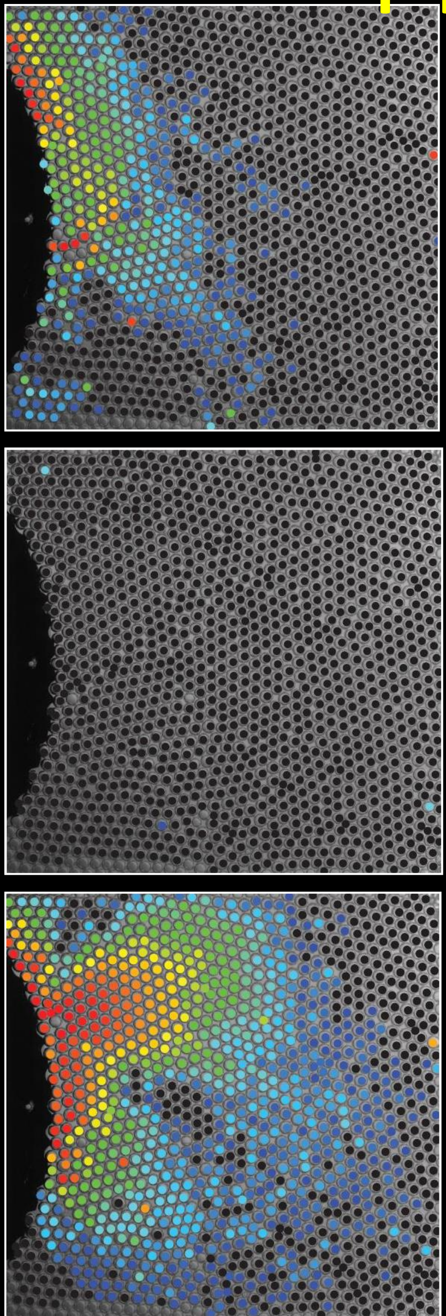
What happens during READ?

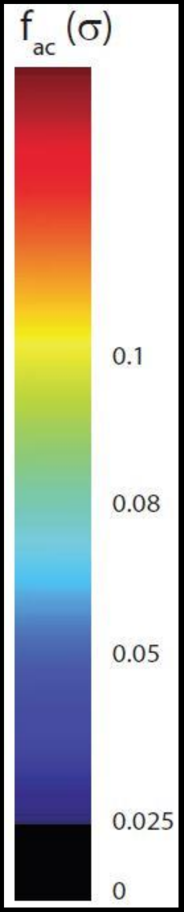
ϒ = 0.05

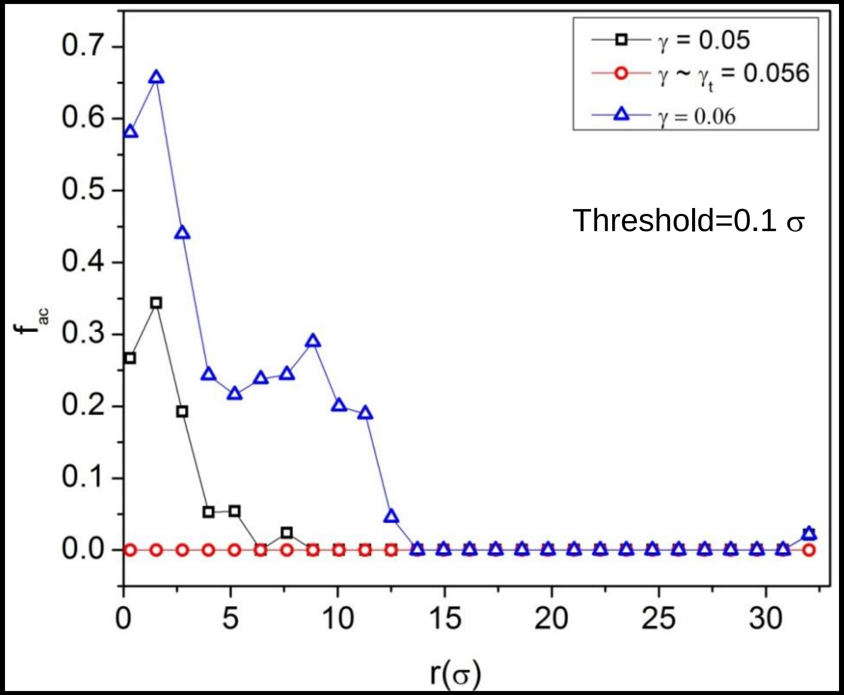
Small hole in spindle to measure strain

$ϒ \sim ϒ_t = 0.056$

ϒ = 0.06



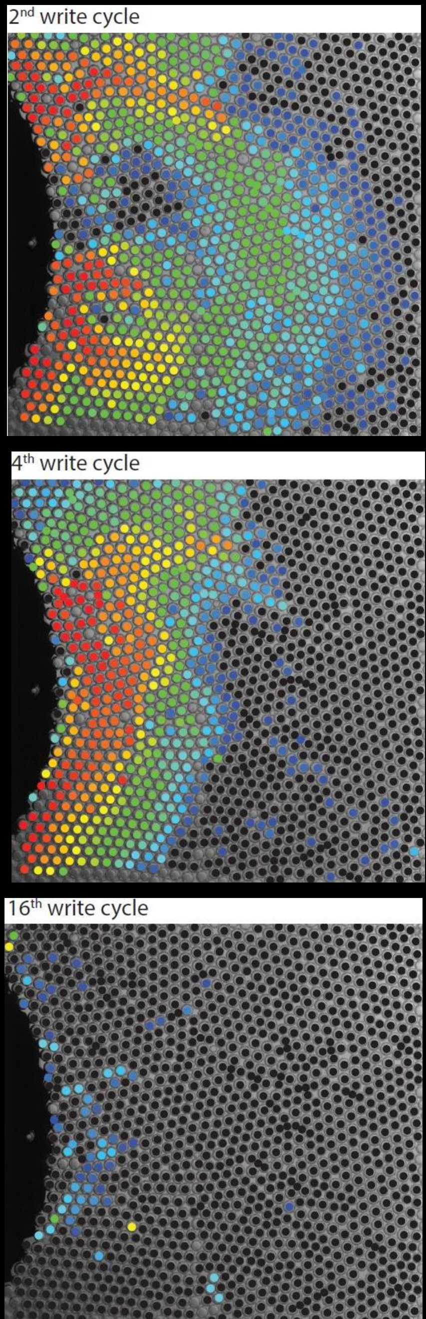


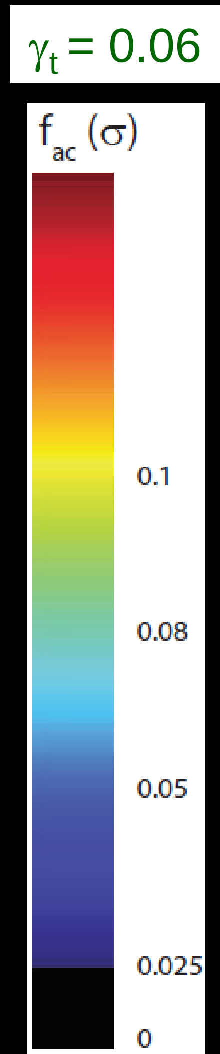


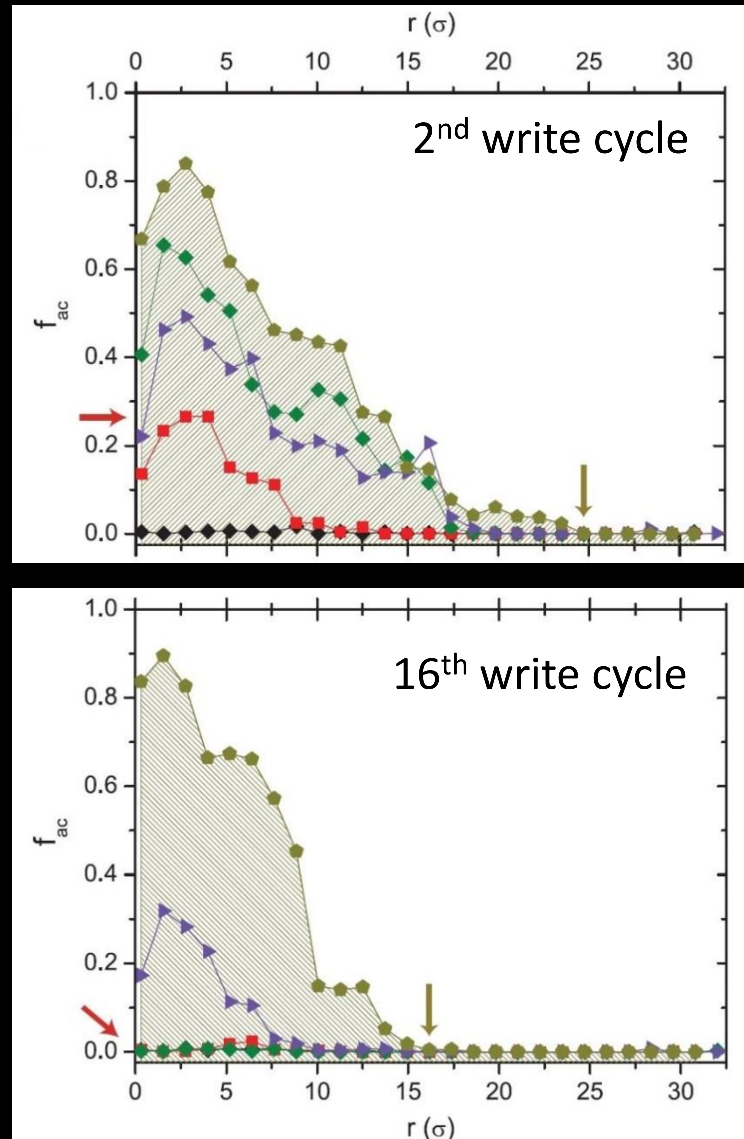
Over a short span of strain amplitudes across $ϒ_t$ a large shift in the band-edge is observed.

Not just a linear change in profile-height

What happens during WRITE?



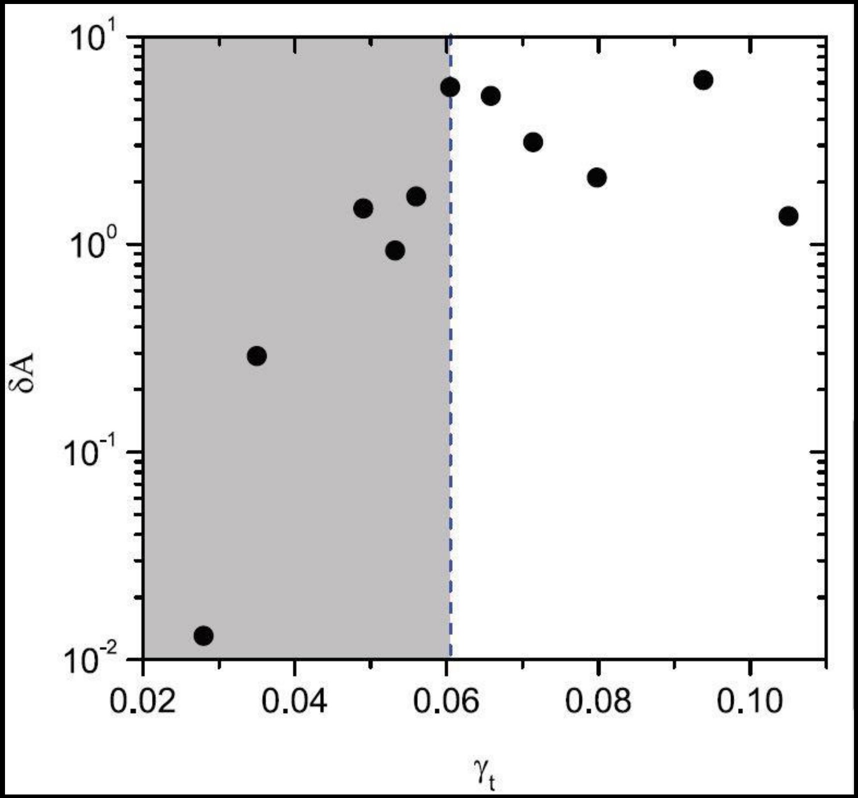


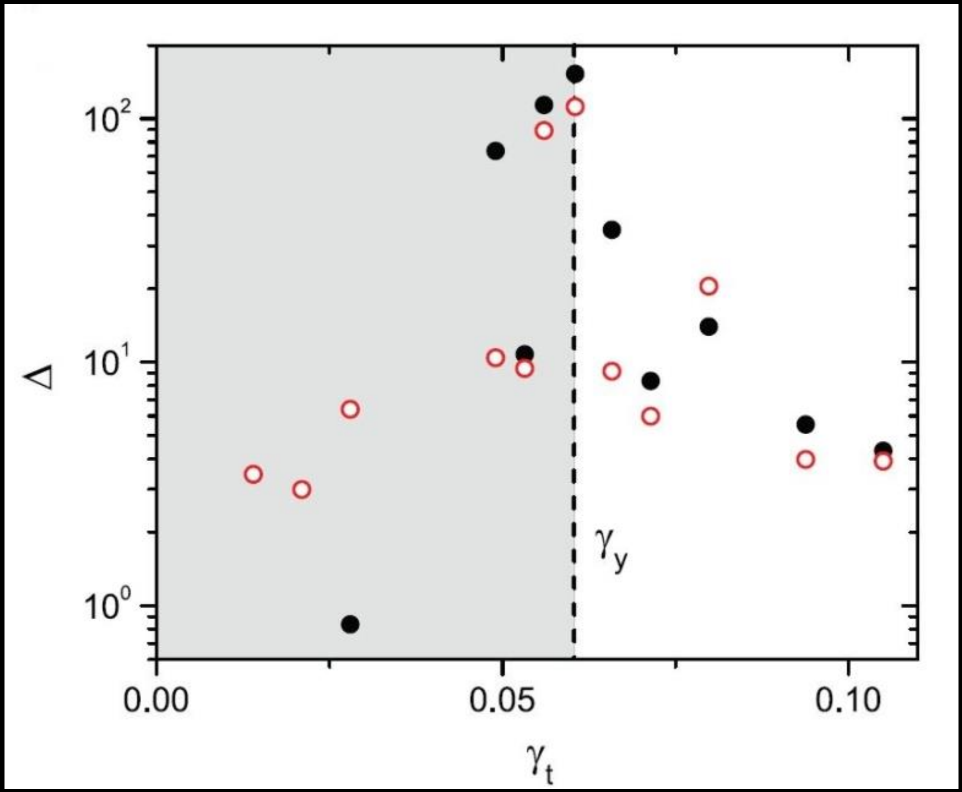


$\gamma_t = 0.014$
$\gamma_t = 0.049$
$\gamma_t = \gamma_y = 0.06$
$\gamma_t = 0.08$
$\gamma_t = 0.105$

- As a function of training cycle, a clear shift in band edge is visible.

Origin of a Maximum in Δ at Yield





Pre-yield: Active particle band edge **does not** reach out during initial write cycles, but **collapses completey** by the end of write

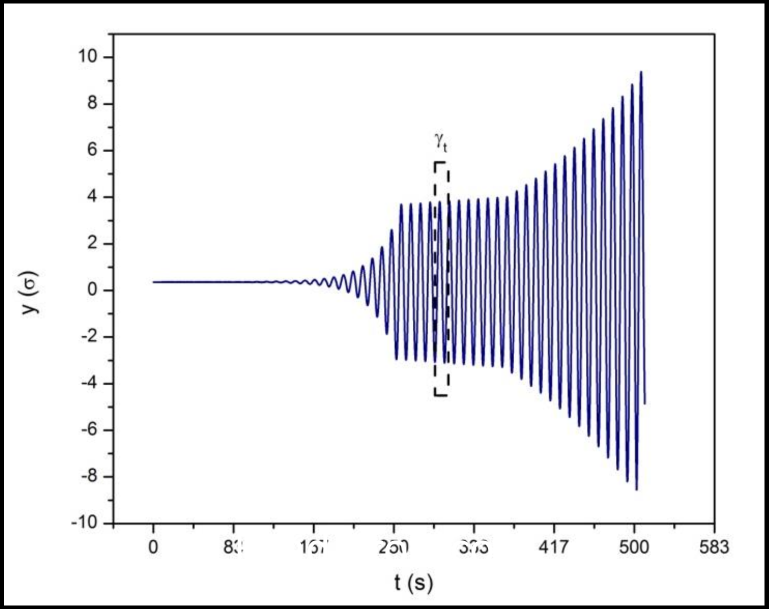
Post-yield: Active particle band edge **reaches out** farthest during initial write cycles, but **does not collapse** completey by the end of write

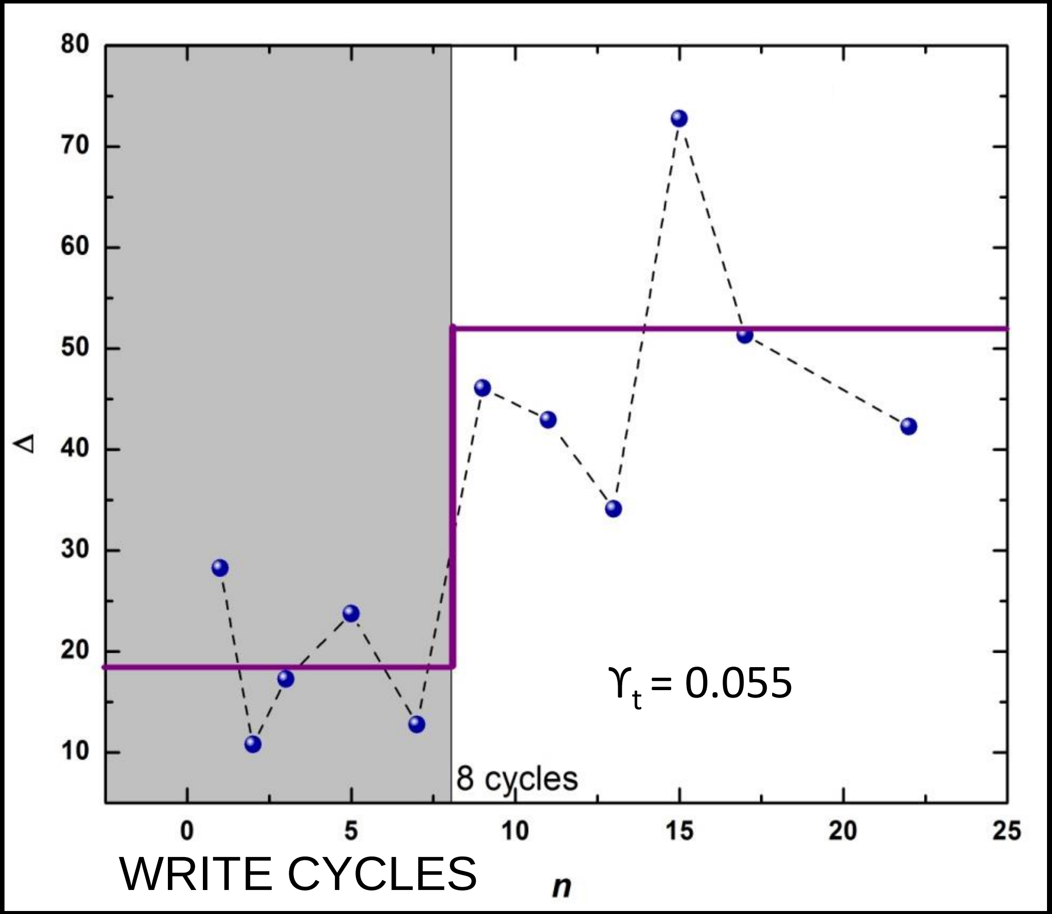
At Yield: ***Maximum motion of the active particle band edge***

Is the act of reading creating memory?

Starting from a given trained microstate,
only sequential READ is possible in experiments

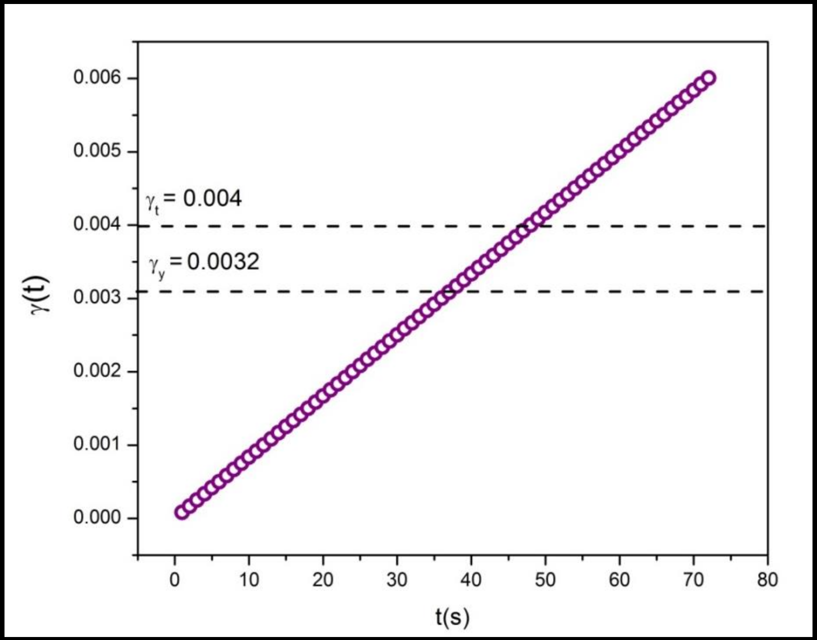
Same Υ_t and same read protocol but different number of write cycles



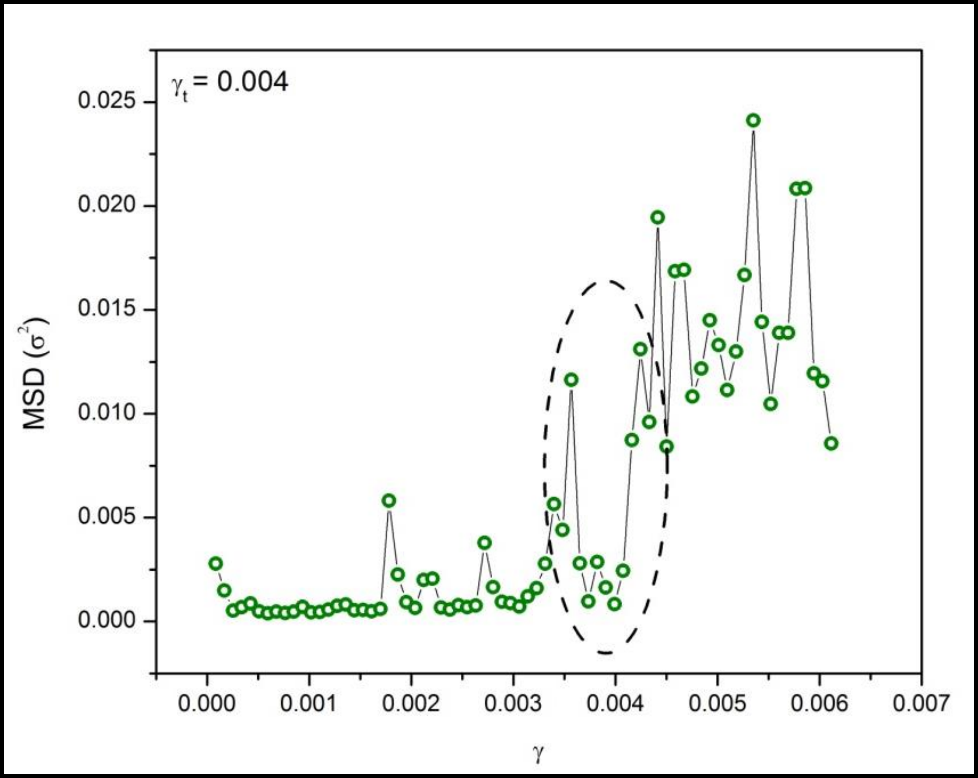


Is the act of reading creating memory?

Linear read

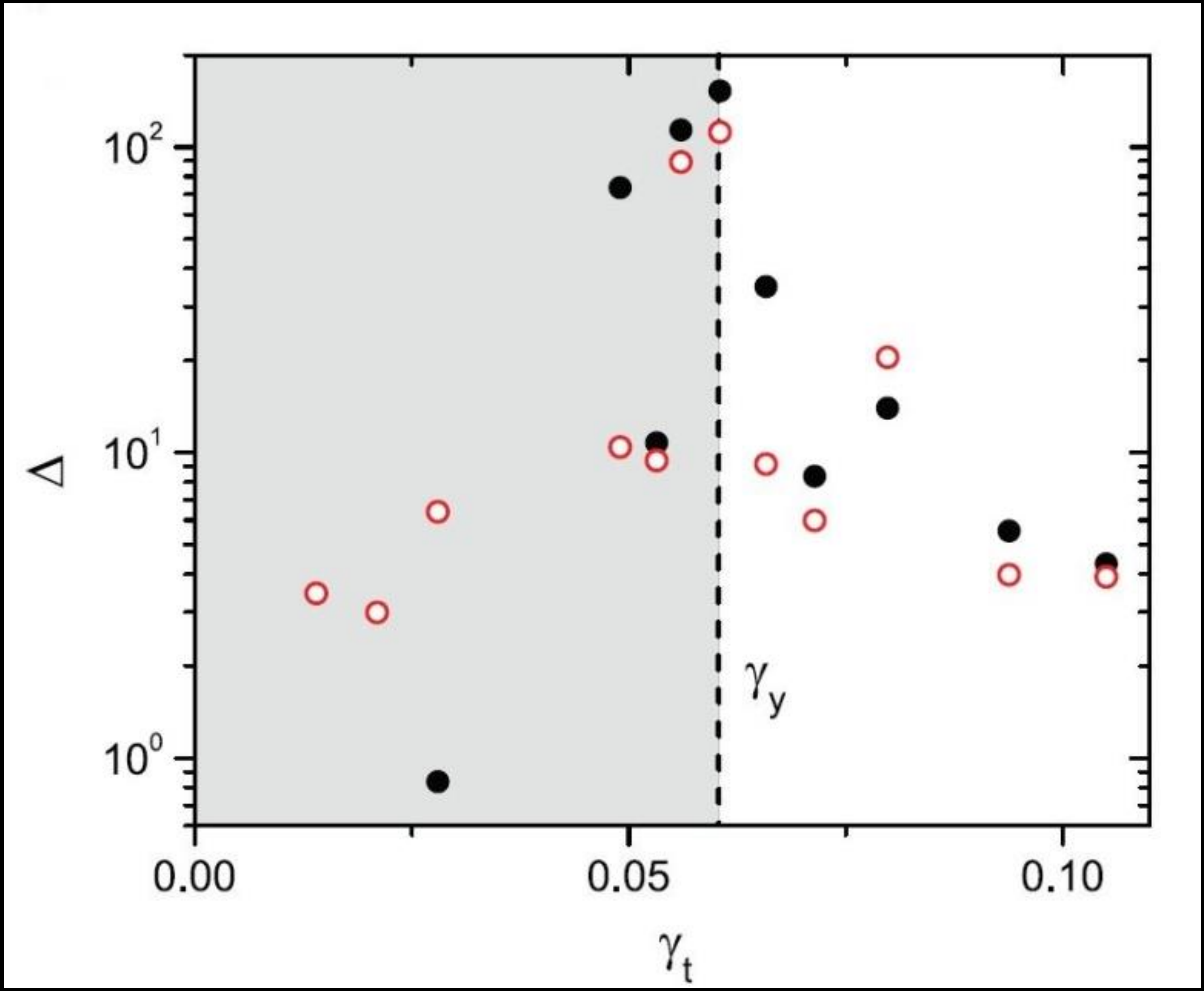


Read protocol 2



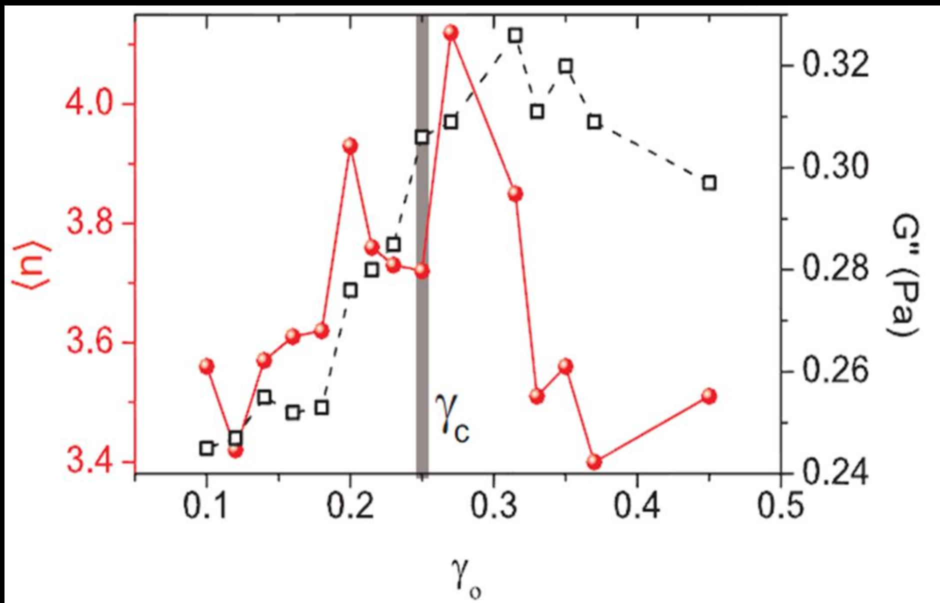
The act of reading memory may reinforce memory but it is not the reason for observing memory

Origin of a Maximum in Δ at Yield



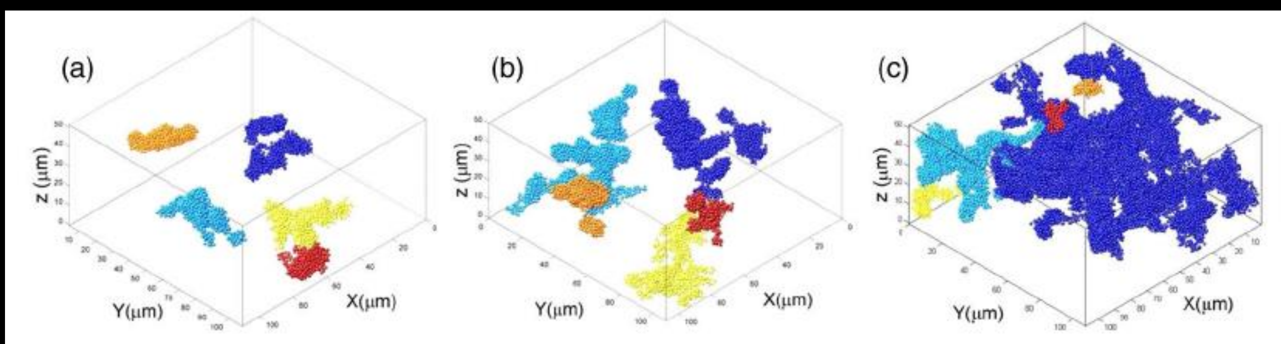
At Yield*: *Maximum motion of the active particle band edge

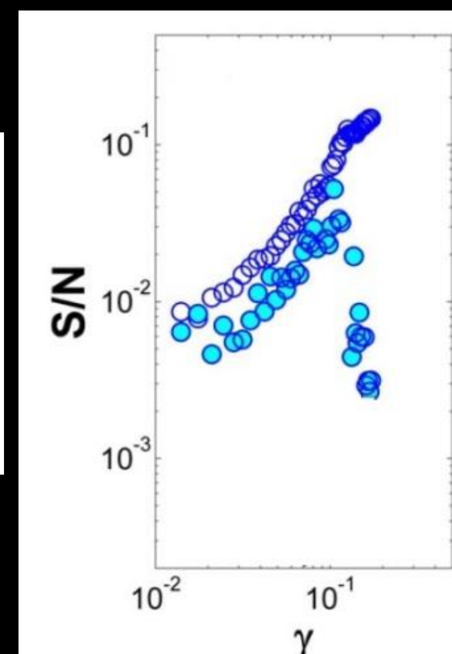
Origin of a Maximum in Δ at Yield



Size of most-mobile particle clusters maximal at yield

Nagamanasa et al., PRE (2014)





At yield size of percolating clusters is maximal

Schall et. al., PRL (2017)

Percolation of largest active cluster. Normalized size of the largest and second-largest nonaffine cluster

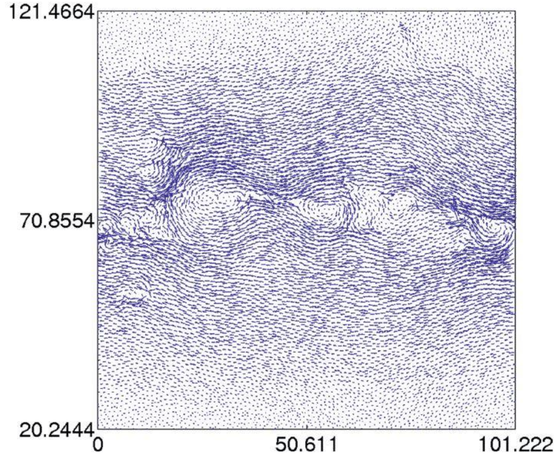
PNAS

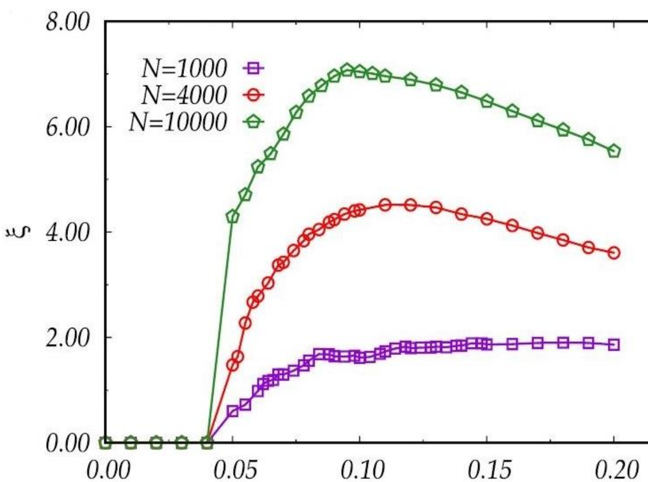
Shear bands as manifestation of a criticality in yielding amorphous solids

Giorgio Parisi[a,1], Itamar Procaccia[b,1], Corrado Rainone[b], and Murari Singh[b]

[a]Dipartimento di Fisica, Sapienza Universitá di Roma, Istituto Nazionale di Fisica Nucleare, Sezione di Roma I, Istituto per i Processi Chimico-Fisici (IPCF)–Consiglio Nazionale delle Ricerche, I-00185 Rome, Italy; and [b]Department of Chemical Physics, The Weizmann Institute of Science, Rehovot 76100, Israel

Contributed by Giorgio Parisi, April 19, 2017 (sent for review February 6, 2017; reviewed by Antonio Coniglio and Olivier Dauchot)





Shear band length scale maximal at yield in steady shear

ARTICLE

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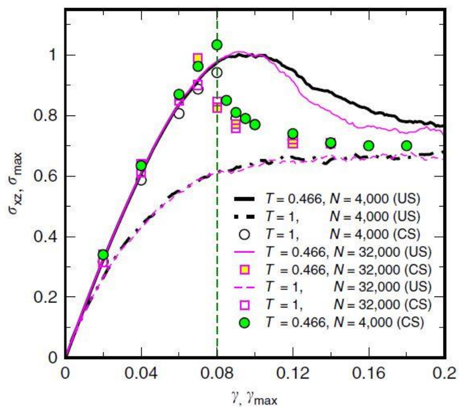
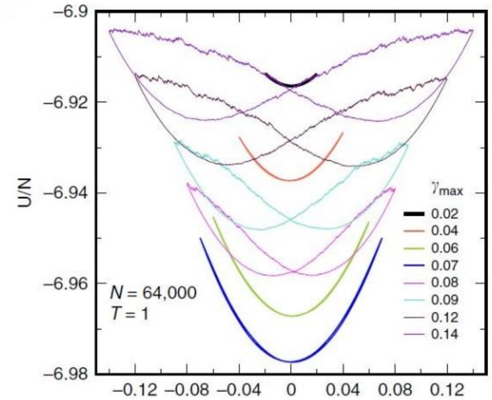
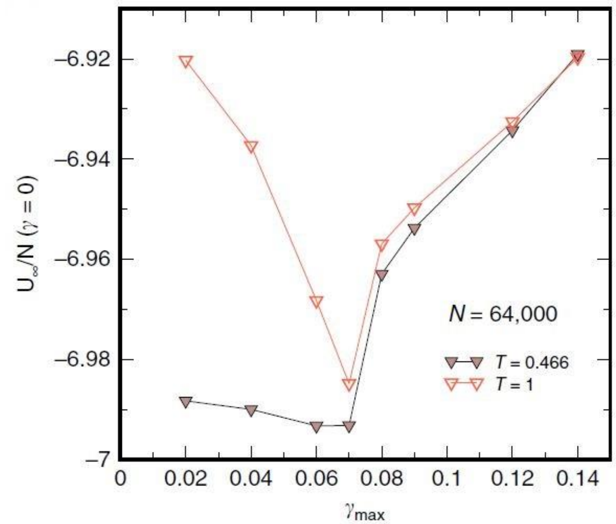
The yielding transition in amorphous solids under oscillatory shear deformation

Premkumar Leishangthem[1], Anshul D.S. Parmar[1,2] & Srikanth Sastry[1]







Subjecting amorphous solids to repeated yield strains makes well-annealed glasses

Summary

- *First experimental observation of memory in amorphous solids.*
- *Memory is maximal at the onset of yield and is correlated with spatial motion of active particle band edge.*
- *Is noise at yield strain self-optimized to result in a maximum in Δ?*
- *Is Δ a read-out for ultrastability of glasses?*
- *System appears to remember similar strain amplitudes – is this a form of associative memory?*