Yielding and fluidization of soft solids

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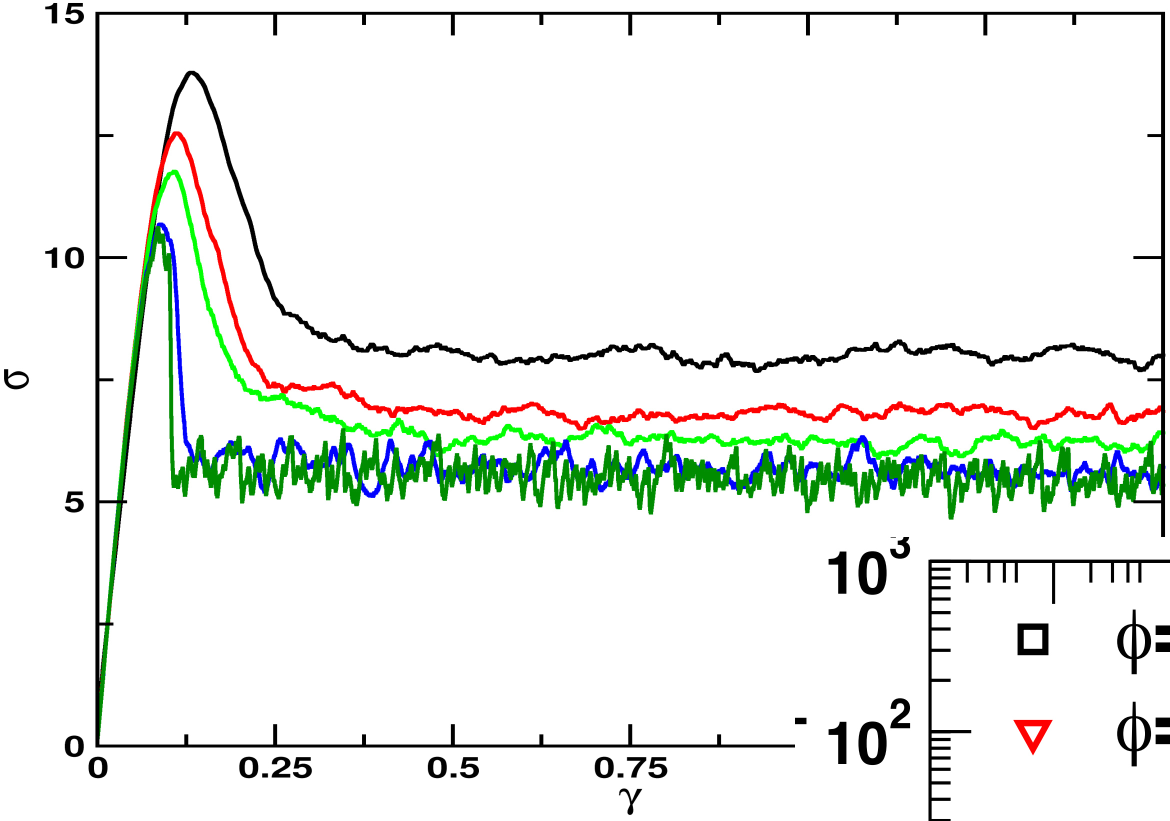
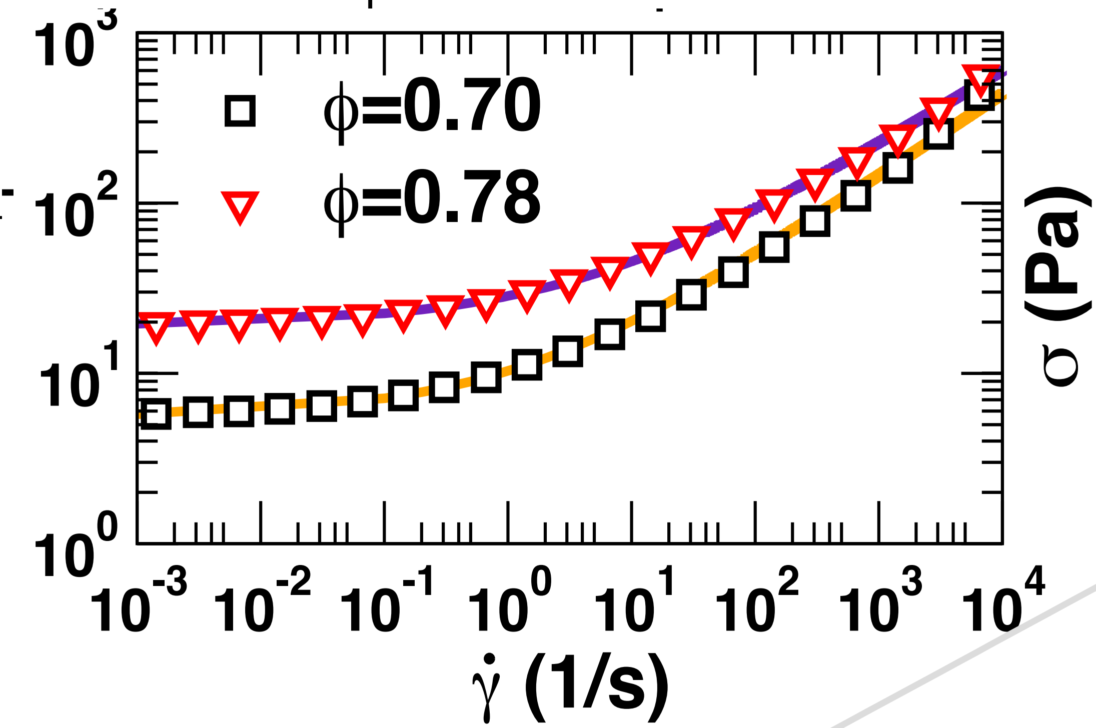
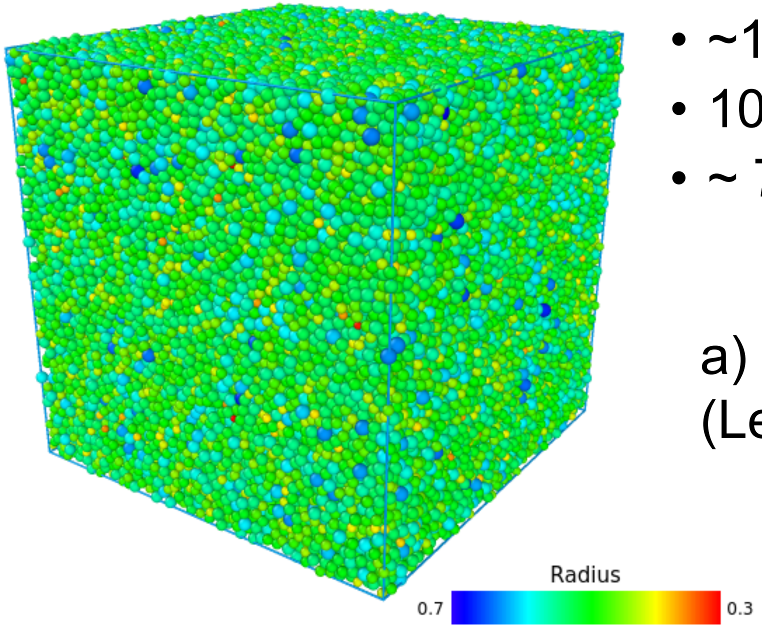
Making jammed soft solids flow



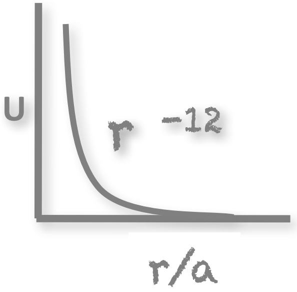


- Local plasticity
- Microscopic dynamics and interplay with flow rate

Numerical simulations



- ~10^5 soft spheres
- 10% size polydispersity
- ~ 70-80% volume fraction



a) periodic boundary conditions (Lees-Edwards)

$$m\frac{d^2\vec{r}_i}{dt^2} = -\zeta\left(\frac{d\vec{r}_i}{dt} - \dot{\gamma} z_i \vec{e}_x\right) - \nabla_{\vec{r}_i} U$$

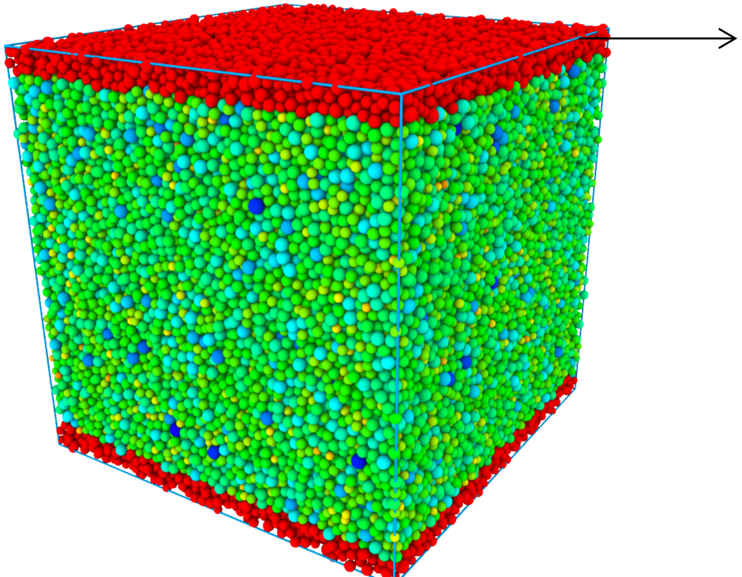
$$\tau_0 = \sqrt{ma^2/\epsilon}$$

b) Wall based simulations:

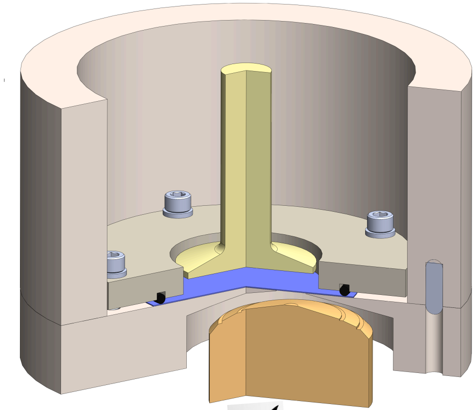
- Roughened walls, deformation applied by moving one of them
- Dissipative Particle Dynamics

$$\vec{F}_i^{DPD}(t) = \vec{F}_i^{int}(t) + \sum_{j(\neq i)} F_{ij}^D$$

$$F_{ij}^D = -\zeta\omega(r_{ij})(\hat{r}_{ij}.v_{ij})\hat{r}_{ij}$$

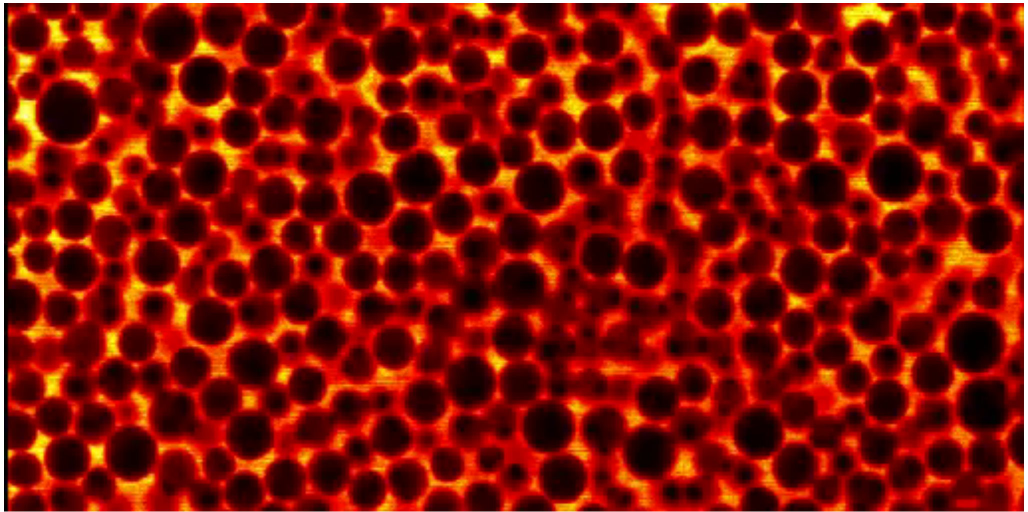


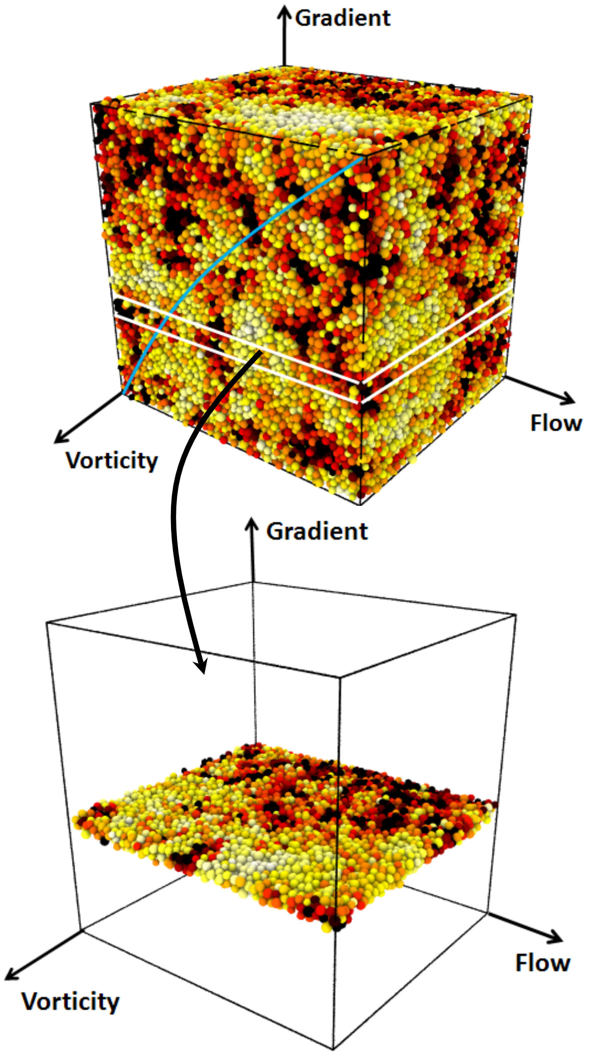
The Con-rheo in Blair’s Lab



- Oil/water-glycerol emulsion (+SDS)
- Droplet size ~6.0μm
- 15% polydispersity
- 70% volume fraction

- Parallel plate rheometer (gap 100μm)
- Roughened bottom plate





Droplet rearrangement analysis

- Time-resolved fluorescence confocal images acquired under shear (continuous rotation at a fixed $\dot{\gamma}$)

- 3D images stacks ($\dot{\gamma} \leq 10^{-2} s^{-1}$); time-resolved spatial cross-correlations between pairs of 2D images at high rate ($\dot{\gamma} > 10^{-2} s^{-1}$)

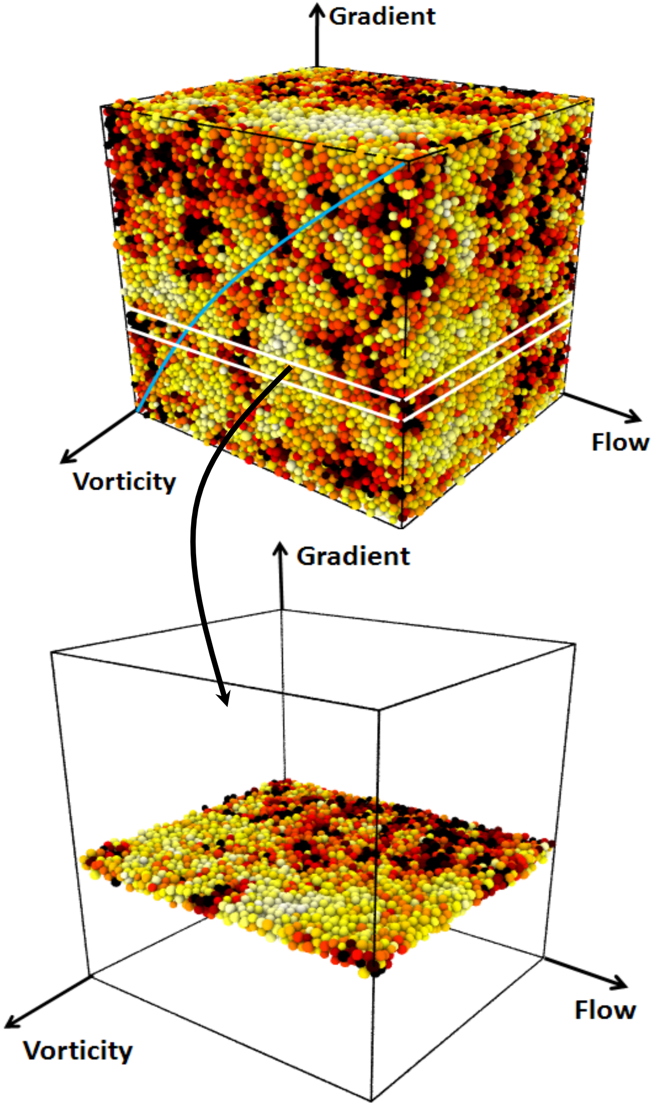
$$v(x,y)|_z \longrightarrow \dot{\gamma}_l = dv_x/dz$$

local shear rate

local fluctuations in the shear frame $\Delta x, \Delta y$

$\Delta\gamma = \dot{\gamma}_l \Delta t$ accumulated strain

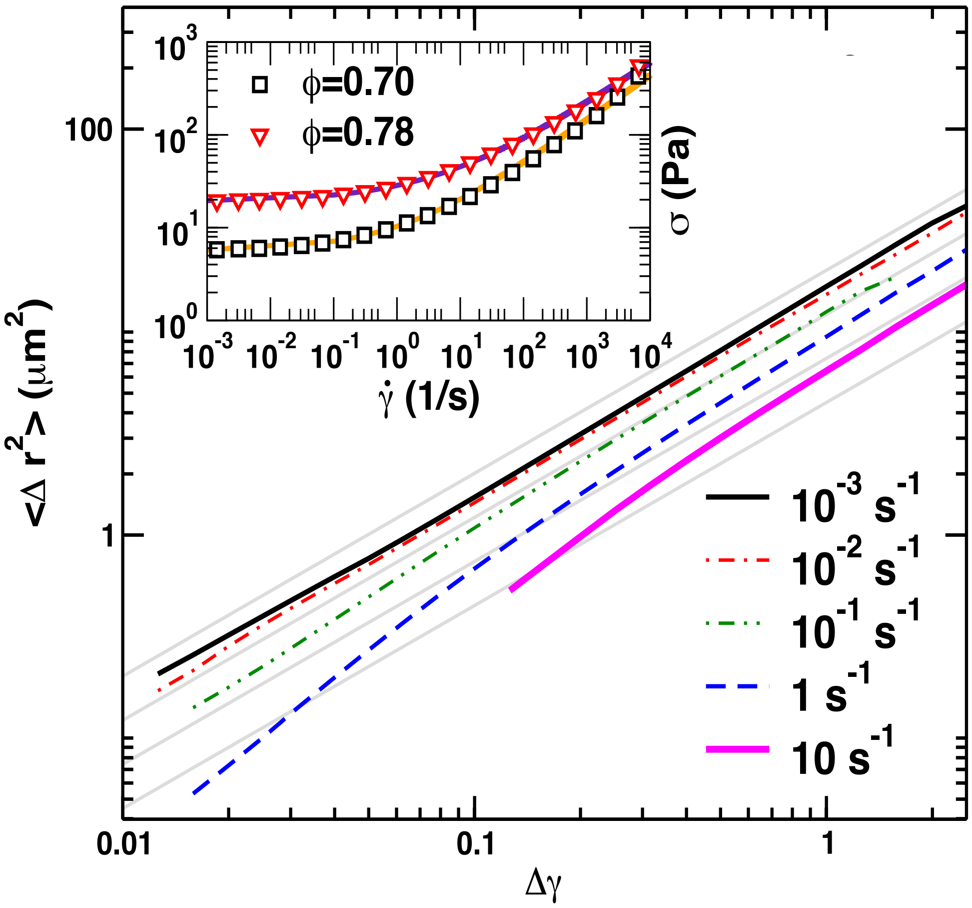
$$\langle \Delta r^2 \rangle = \langle \Delta x^2 + \Delta y^2 \rangle$$

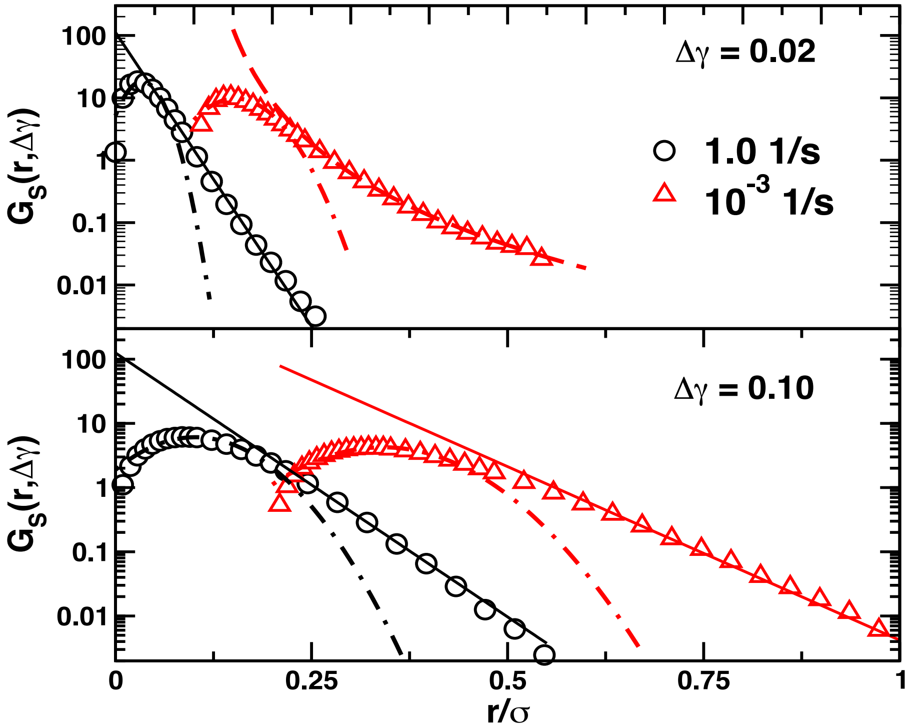


Flow curve and non-affine motion

$$\sigma \simeq \sigma_Y + K\dot{\gamma}^{0.5}$$

experiments





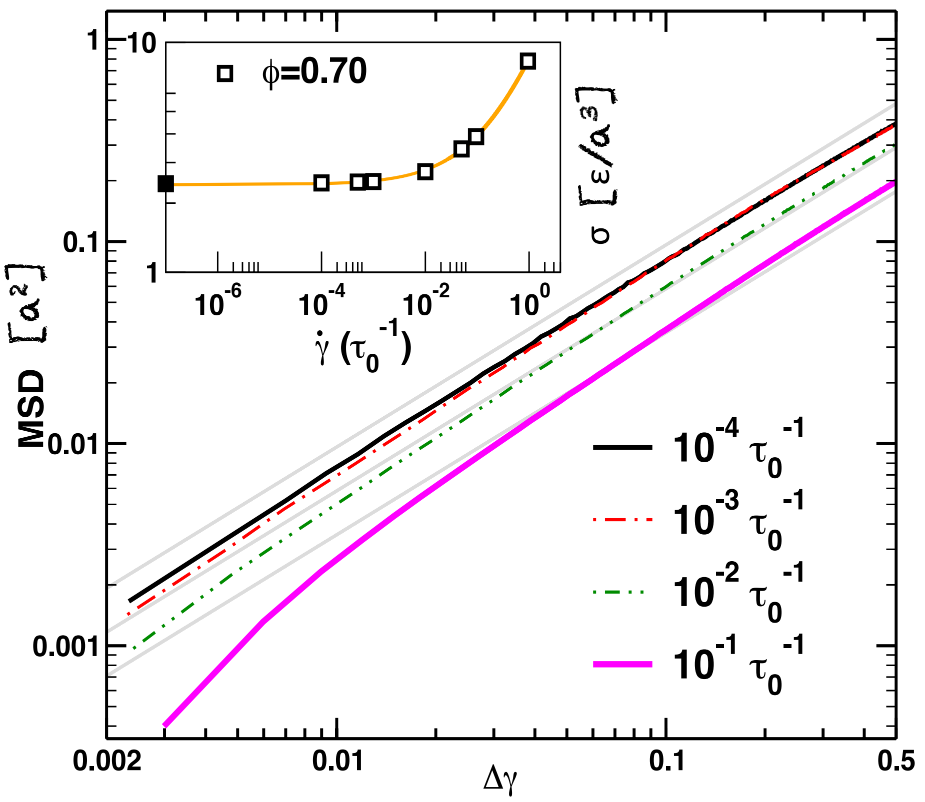
- Shear-rate dependence of elementary flow events

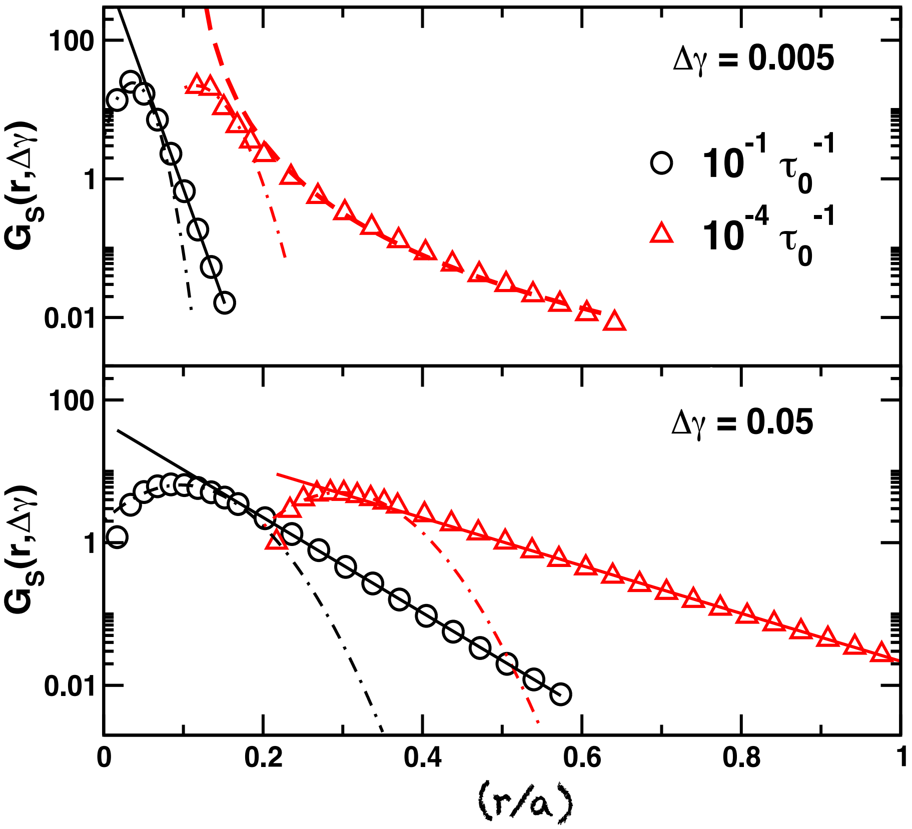
V.V. Vasisht, S. Dutta, EDG and D.L. Blair, PRL 2018

Flow curve and non-affine motion

$$\sigma \simeq \sigma_Y + K\dot{\gamma}^{0.6}$$

simulations





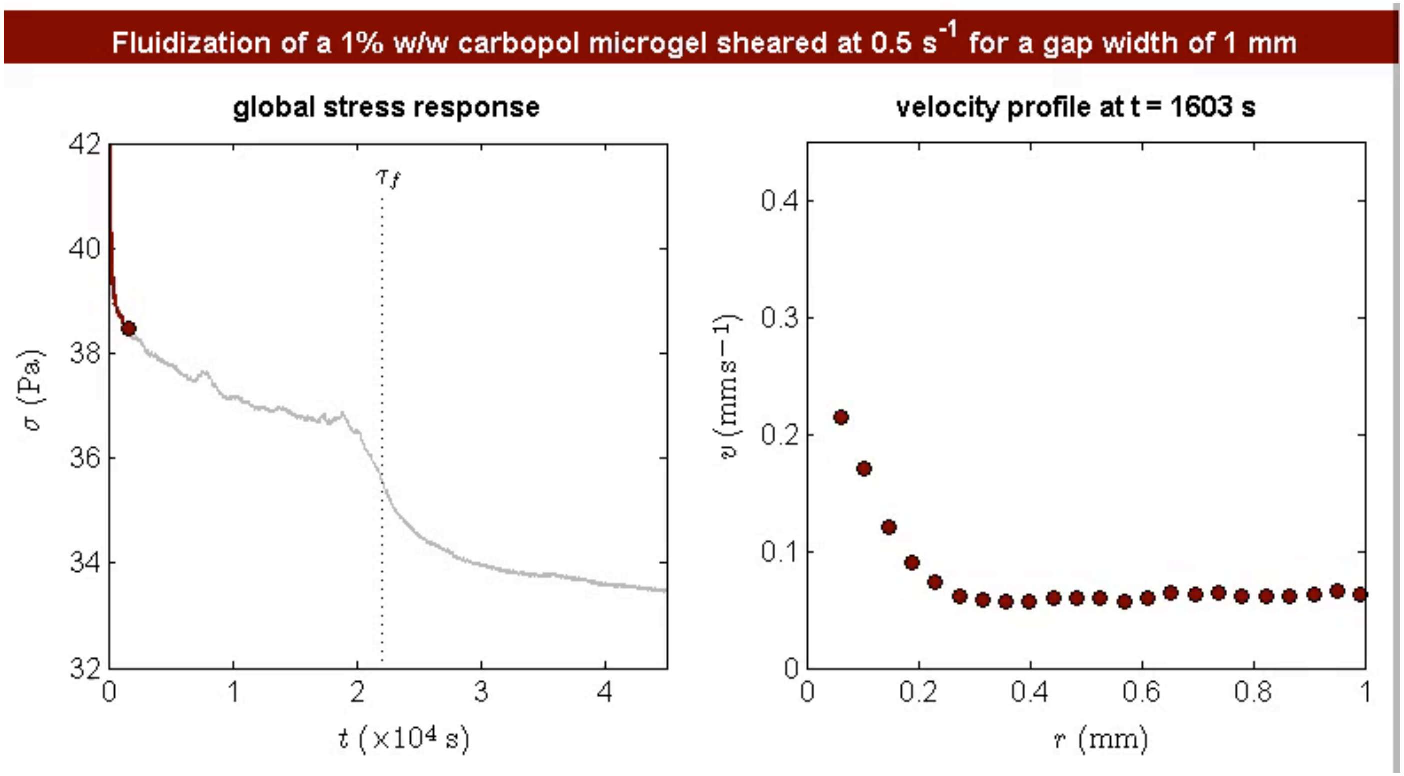
$$U^i = U^i_x \hat{x} + U^i_y \hat{y}$$

$$\delta U^i = |U^i - \langle U \rangle|$$

V.V. Vasisht, S. Dutta, EDG and D.L. Blair, PRL 2018

A complex fluidization – flow inhomogeneities

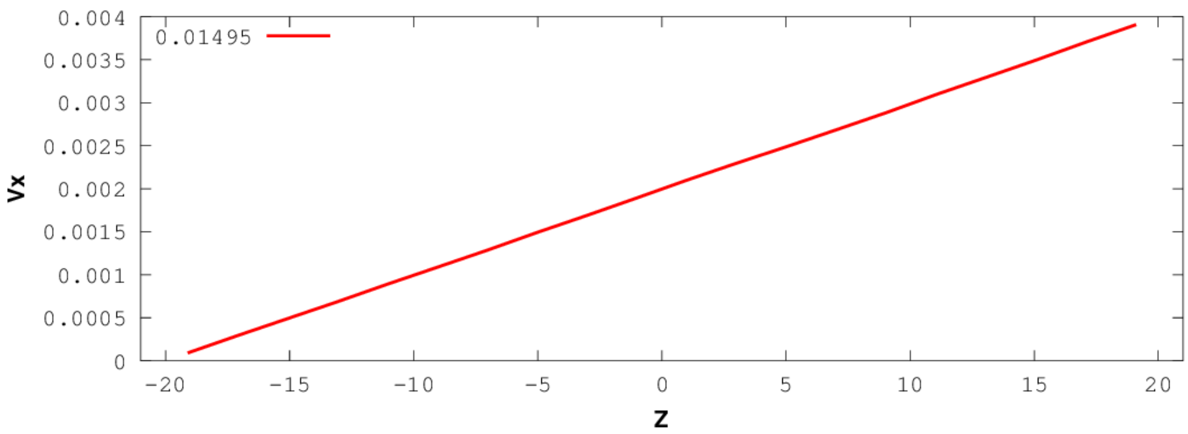
Divoux et al. PRL 2010

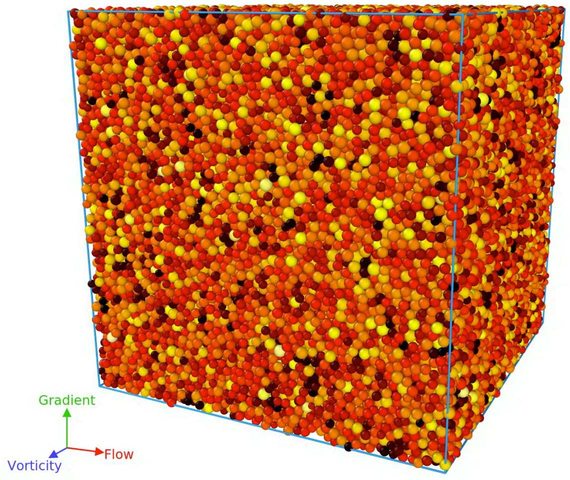


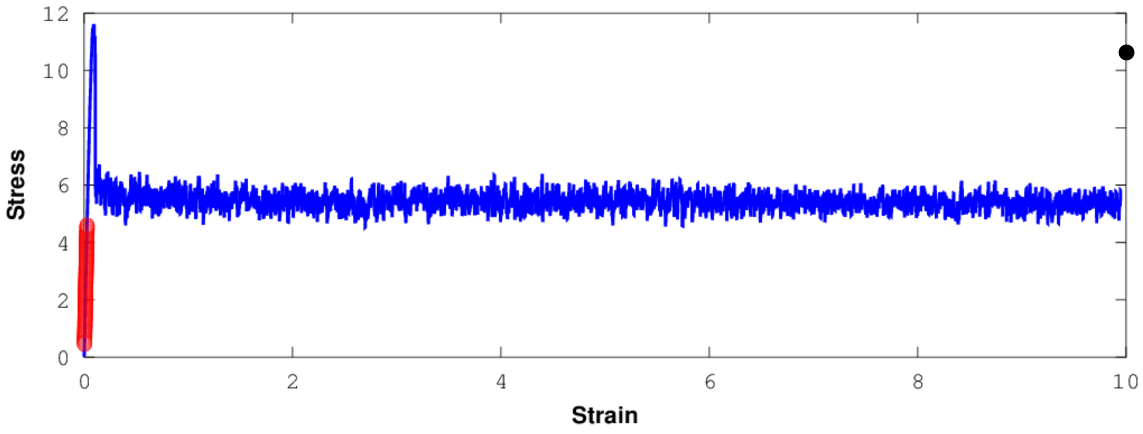
Part of the material is stuck, only part of it flows. No apparent difference in density or in structure between the two parts.

Fielding, Rep. Prog. Phys. 2014; Bonn et al Rev. Mod. Phys. 2017; Divoux et al, Ann. Rev. Fl. Mech. 2016; Shrivastav et al. JOR 2016; Olmsted, Rheol. Acta 2008; Coussot & Ovarlez EPJE 2010; Adams & Olmsted PRL 2009; Manning et al. PRE 2009; Divoux et al. Soft Matter 2012

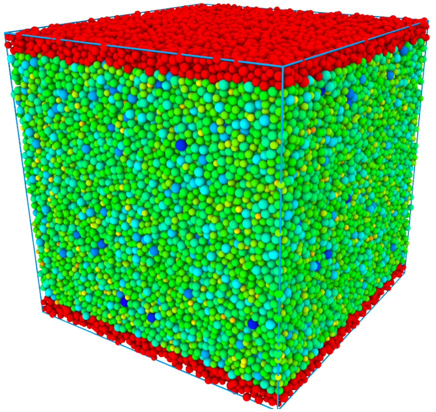
Reconstructing the velocity profile





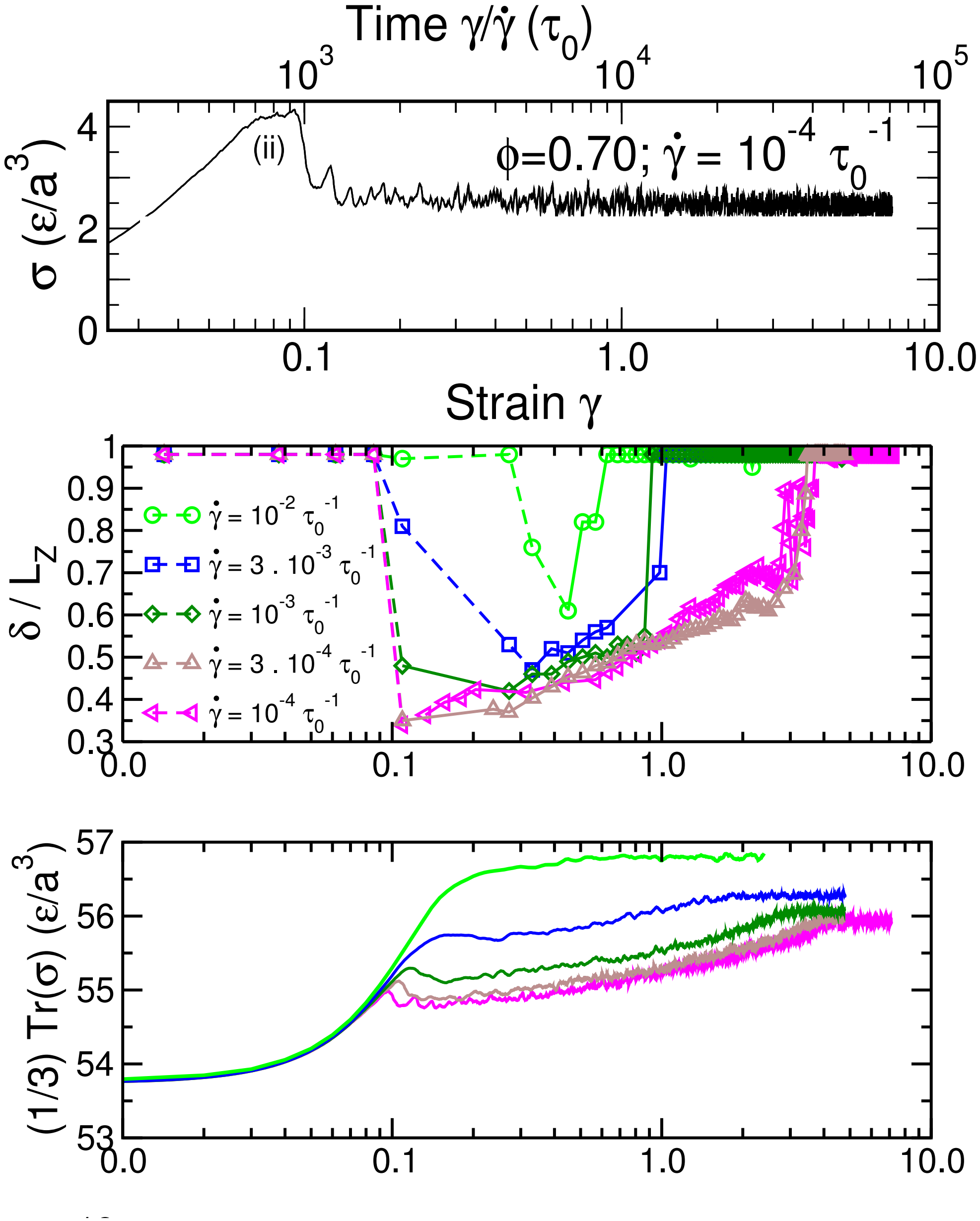


- By the time the stress starts decaying, part of the material forms a non-flowing band.



Wall geometry enhances localization, which tends to happen next to the fixed wall

Evolution of the flowing band

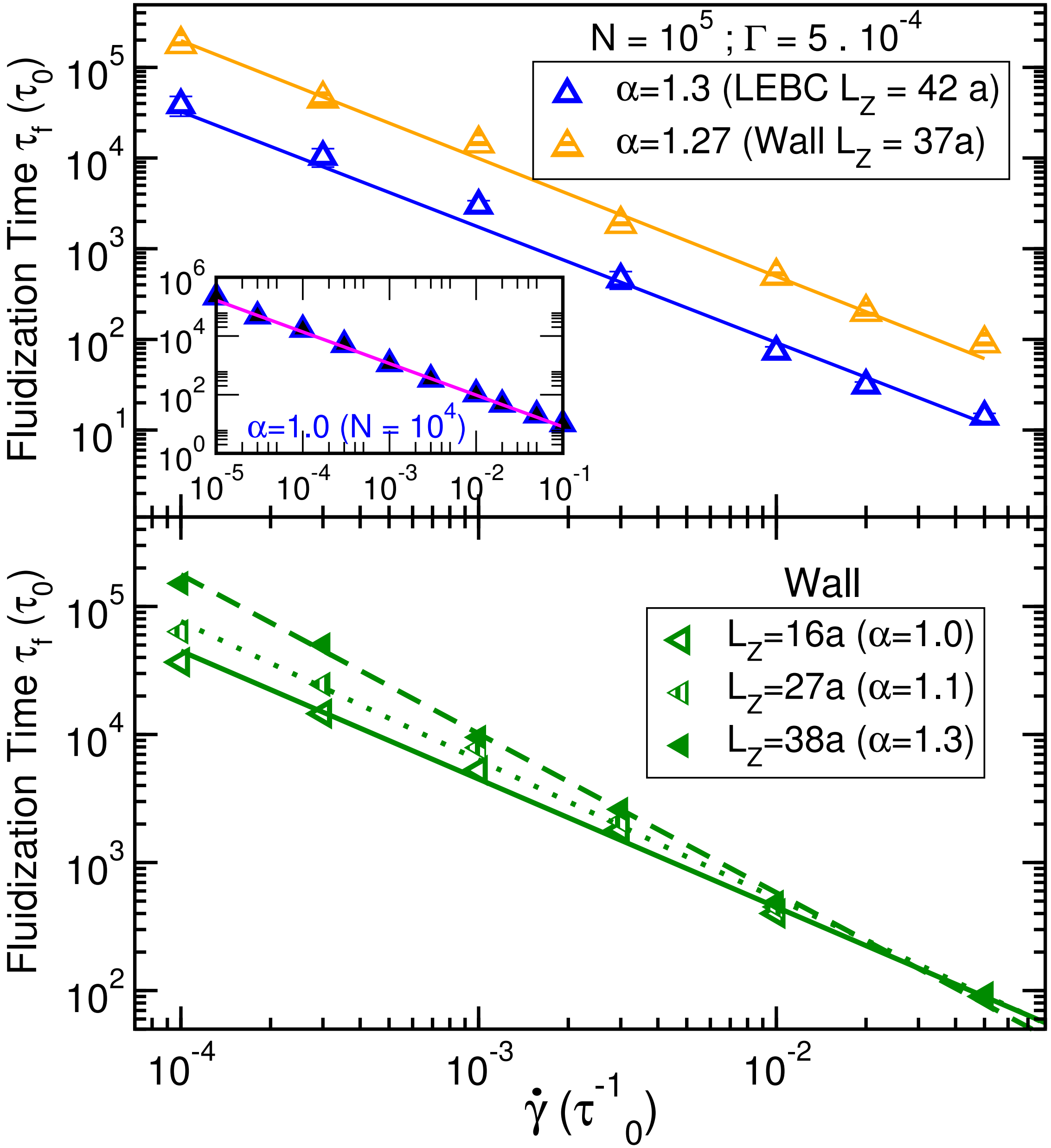


- Small strain response is elastic, but the width of the flowing band depends on the shear rate (see experiments and theory).

- Complete fluidization (onset of homogeneous flow) signaled by the evolution of normal stresses.

See Adams & Olmsted PRL 2009
Divoux et al. PRL 2010
Fielding, RPP 2014

Non-trivial dependence of the fluidization time

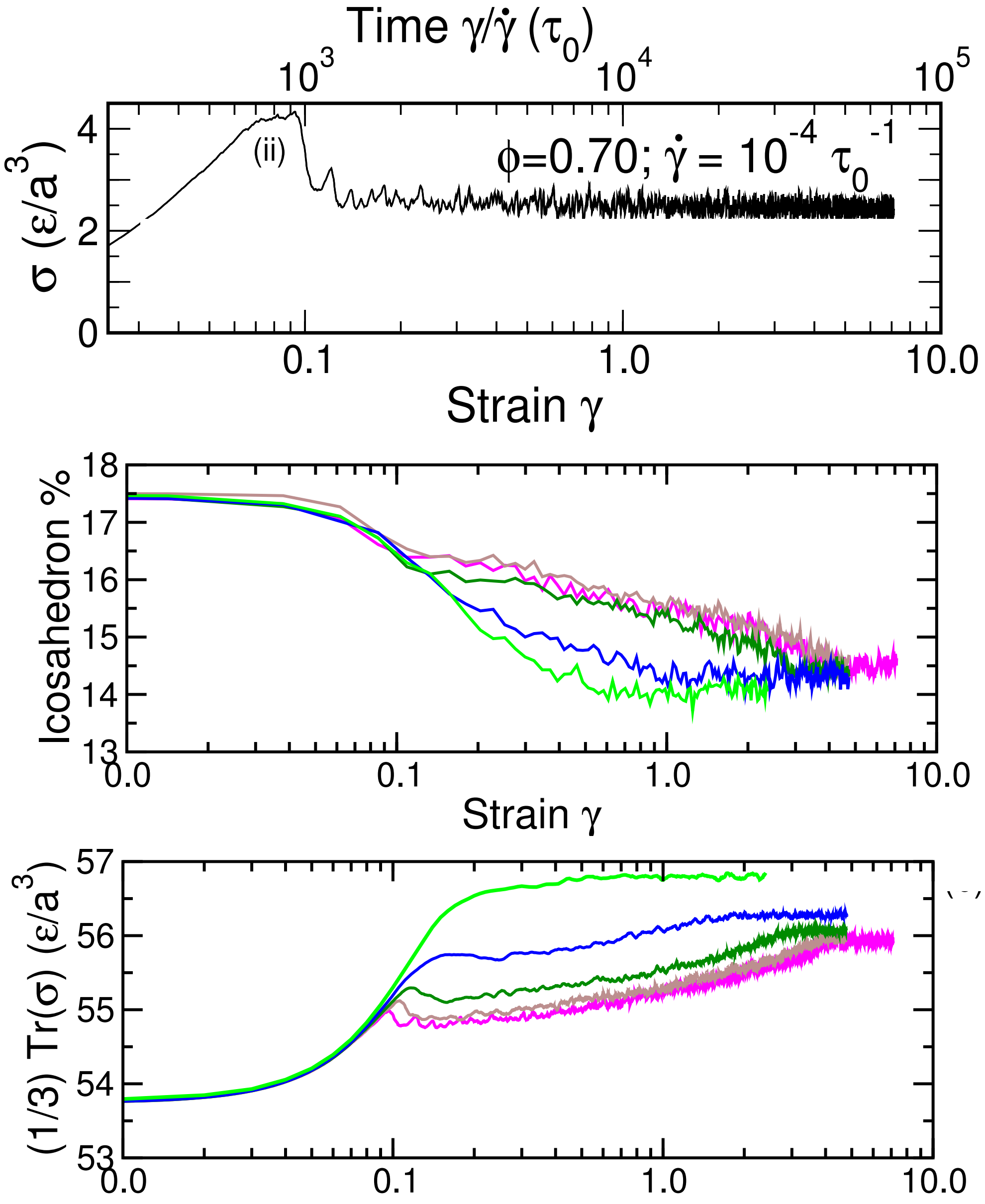


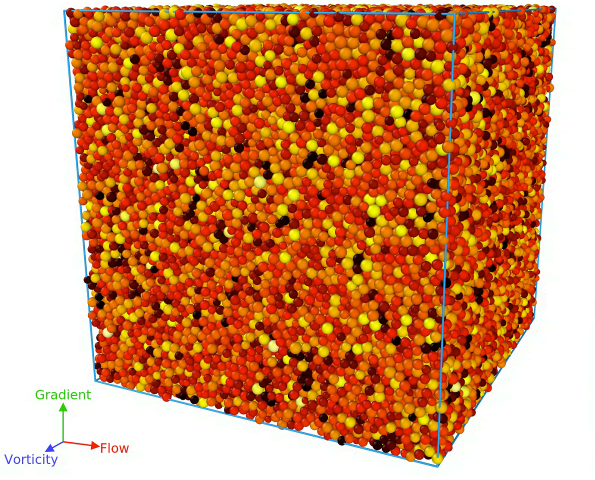
- Small systems: the fluidization time simply set by the imposed shear rate.

- Large systems: microscopic dynamical processes not just slaved to the shear rate.
- Spatial correlations over large distances that increase with the sample size.

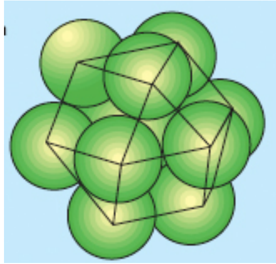
See Divoux et al. PRL 2010

A structural signature





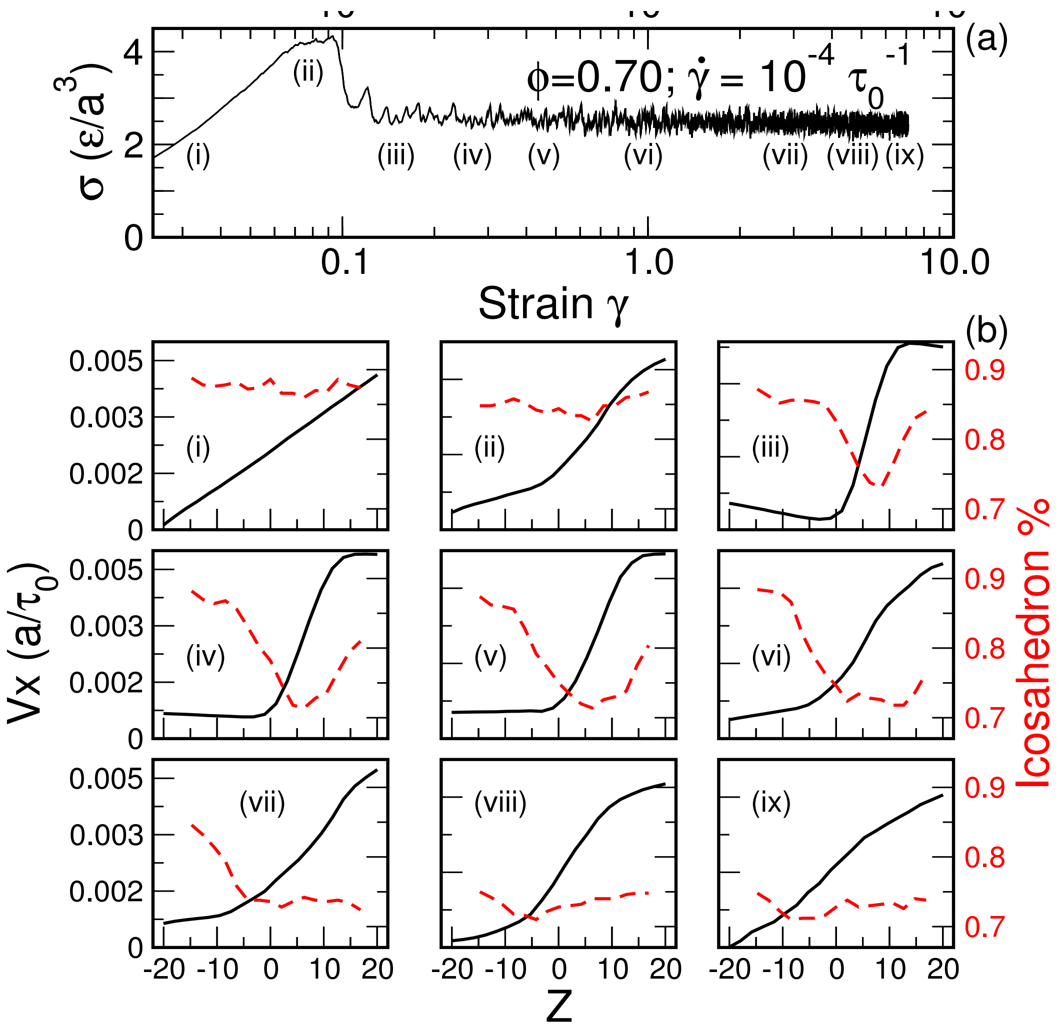
- Time evolution of icosahedral particle packing is correlated to the shear banding.

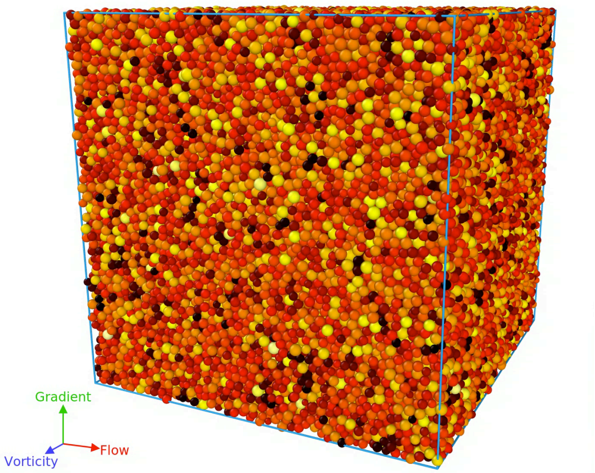


- Prevalence of icosahedral local order in supercooled liquids and glasses is known

Steinhardt, Nelson & Ronchetti PRL 1981; Pinney et al. JCP 2016; Royall & Williams Phys. Rep. 2015

A structural signature





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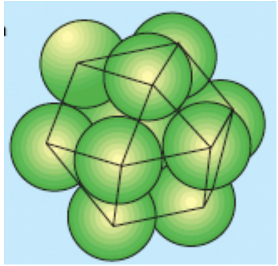

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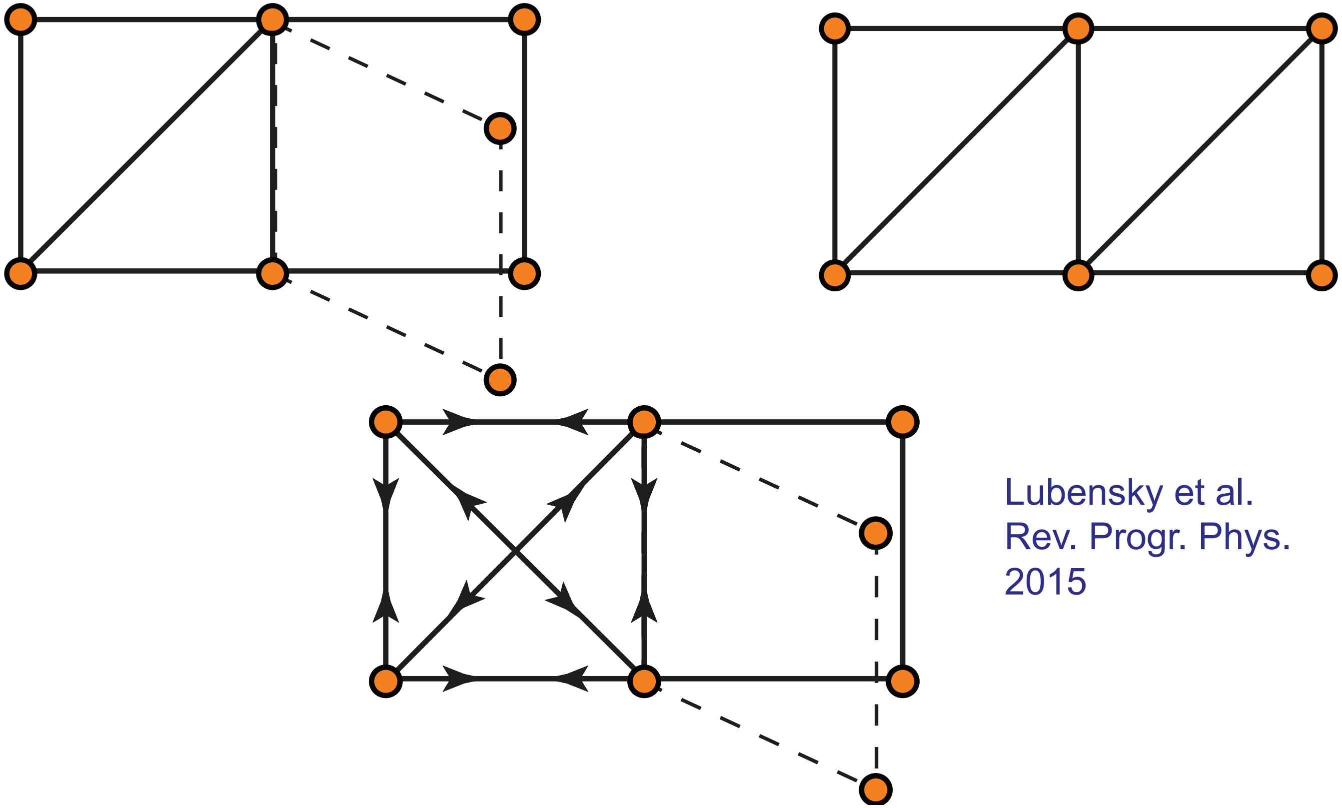
A micromechanical picture



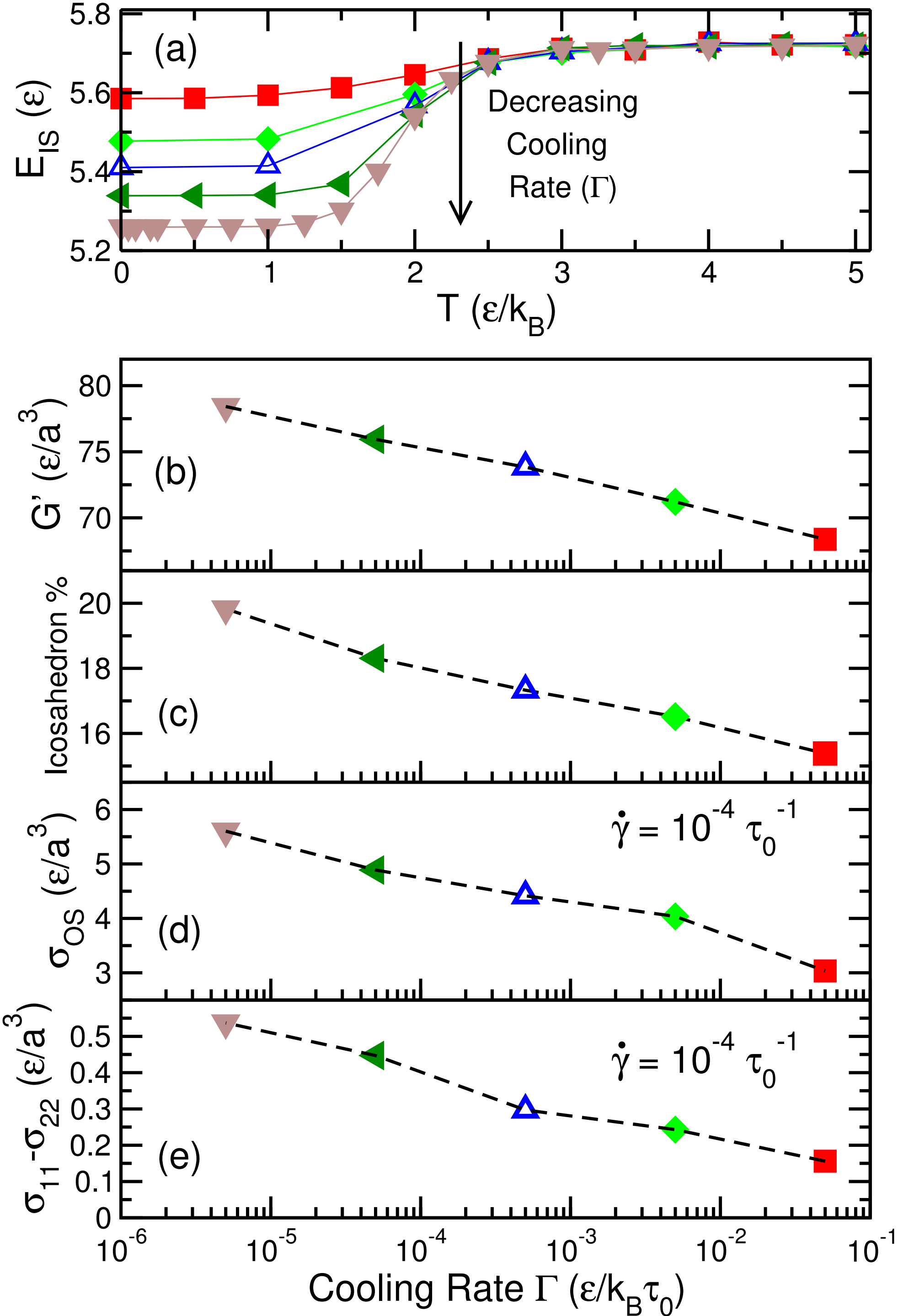
Lubensky et al.
Rev. Progr. Phys.
2015

Overconstrained domains allow for local compression or tension with no net force under load = self-stress states

Icosahedrally packed domains signal overcoordinated (and hence overconstrained) regions, where stresses tend to accumulate under load, e akin to self-stress states

Testing the hypothesis

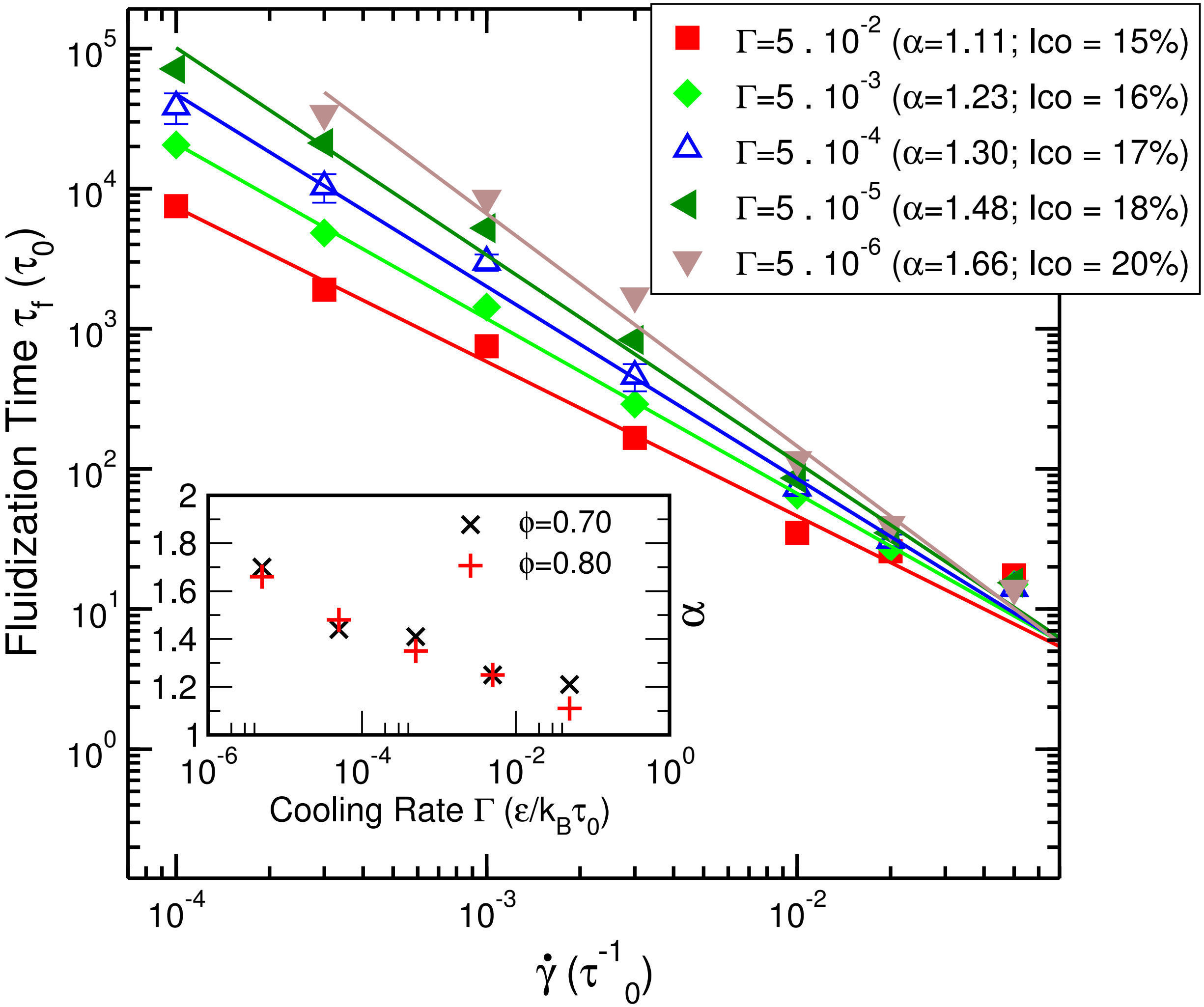
- Changing the cooling rate in preparing the initially solid samples.
- Deeper minima = higher percentage of icosahedrally packed domains; higher mechanical strength; higher overshoot; stronger tendency to dilate



Effect on fluidization time

- The fluidization exponent α increases with the increasing icosahedral packing percentage in the initially solid sample.

- Redistribution of the mechanical constraints under shear introduce a characteristic time that interferes with the imposed shear rate and strongly affects the timescale over which fluidization occurs.



Summary

- Over-constrained domains favor stress storage (and a stress overshoot) in dense soft solids under shear, by concentrating stresses in self-stress states that are mainly compressive and that self-organize into a non-flowing band in the material.

A general mechanism for the emergence and persistence of flow inhomogeneities in dense soft solids

V.V. Vasisht, G. Roberts and EDG, arXiv:1709.08717

V.V. Vasisht, S. Dutta, EDG and D.L. Blair, PRL 2018