Thinning or thickening? Complex rheology of dense suspensions

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Driven Disordered Systems 2014 – Grenoble, June 5, 2014

Coworkers

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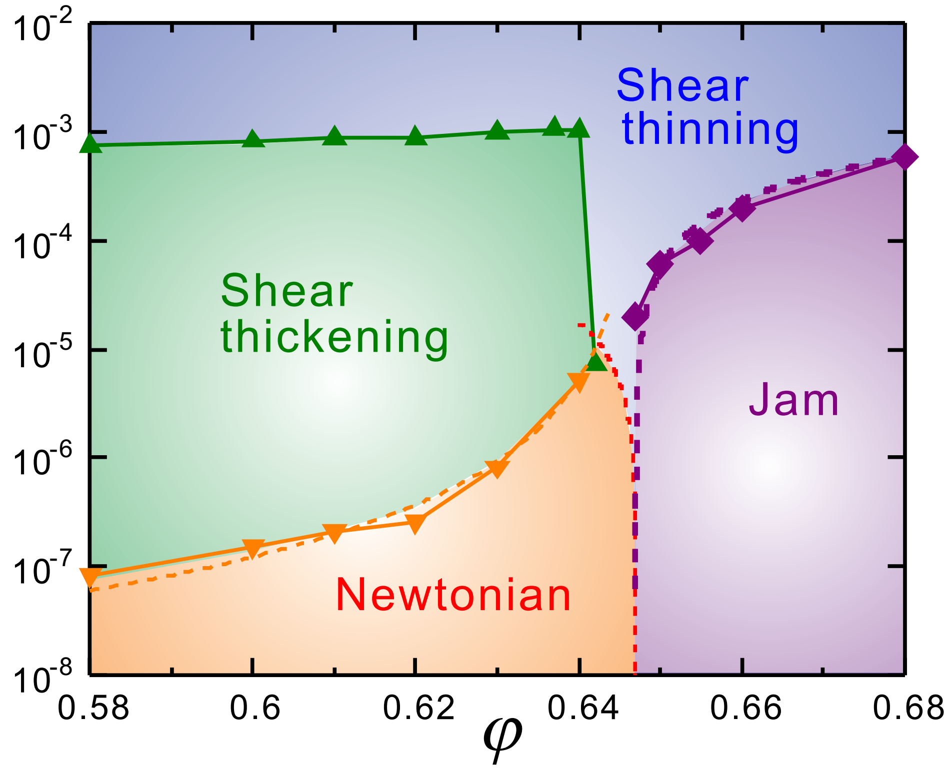
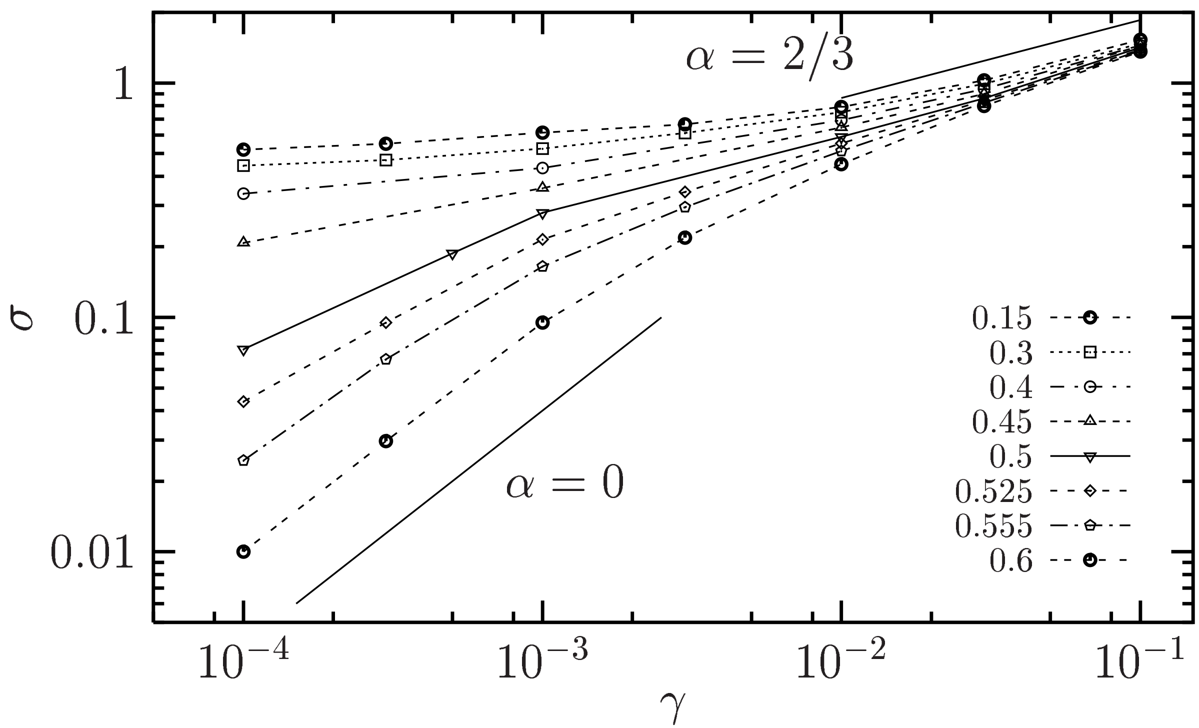


[Kawasaki, Ikeda, Berthier, arXiv:1404.4778]

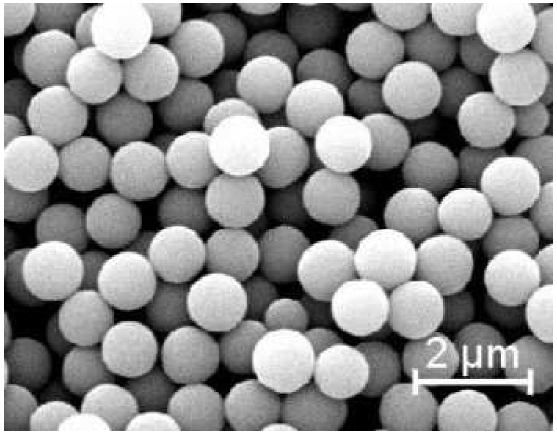
Nonlinear glassy rheology

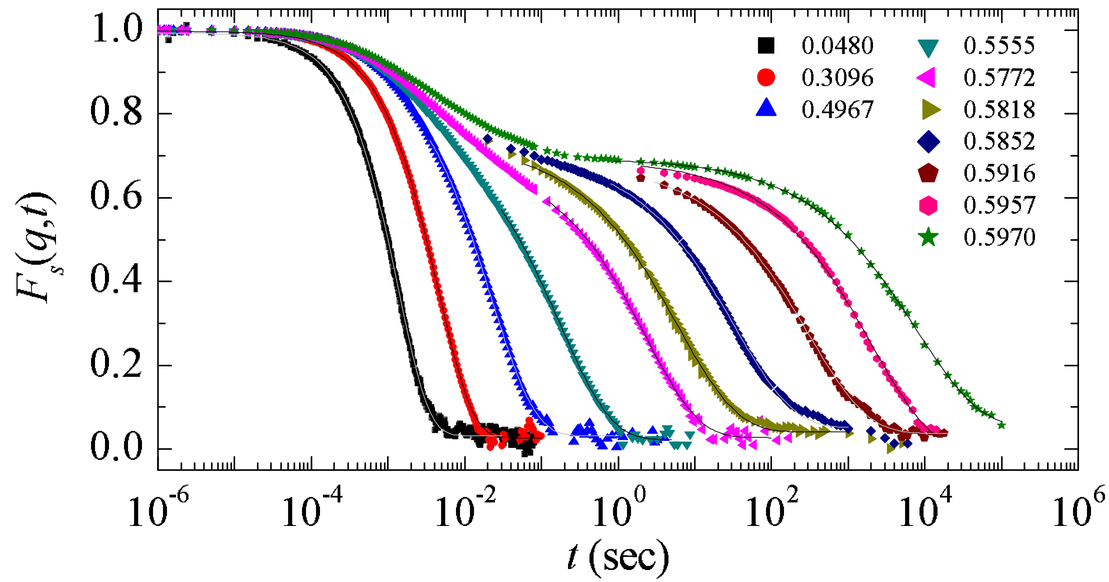
- Decreasing T in supercooled liquids: 'Diverging' viscosity $\eta(T)$.
- Transition from viscous fluid to solid material (finite yield stress).
- Flow curves at finite shear rate $\dot{\gamma}$ in simple shear flow: $\sigma = \sigma(\dot{\gamma}) = \eta(\dot{\gamma})\dot{\gamma}$, in binary LJ mixture. Viscosity is a function.



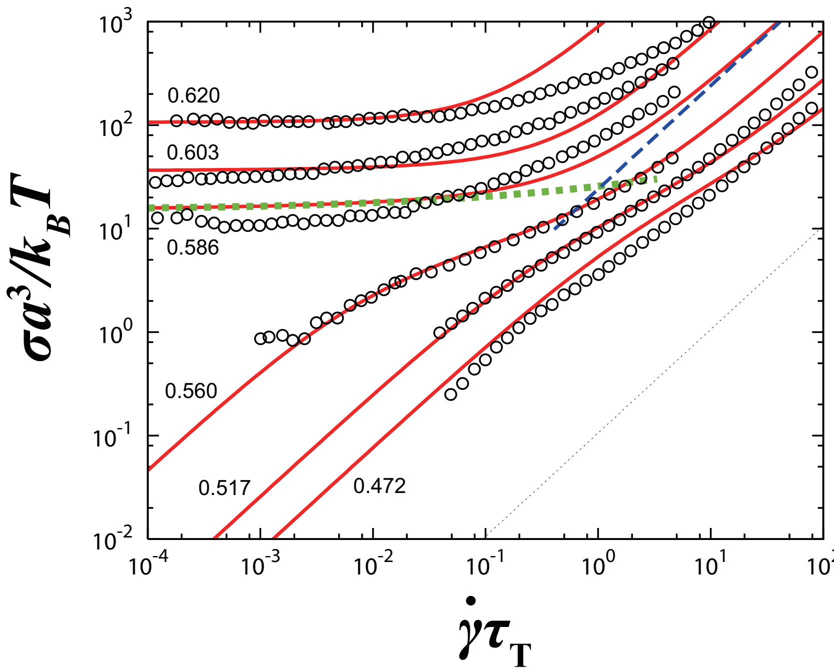
[Berthier & Barrat JCP '01]

Dense colloidal suspensions





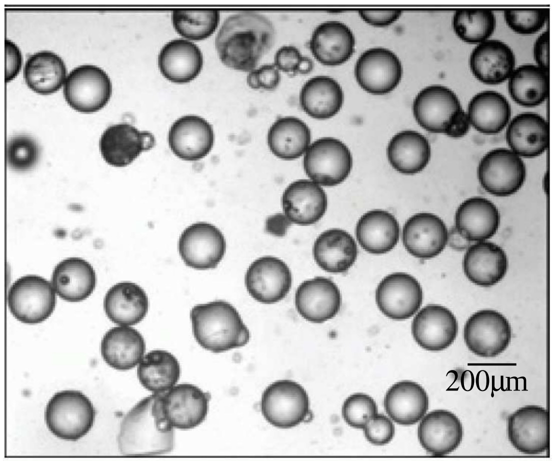
- Colloidal (Brownian) glass transition upon compression.
- 'Diverging' viscosity: $\eta_T(\varphi)$.
- Rheology similar to molecular glasses: $\eta = \eta(\dot{\gamma}, \varphi)$.



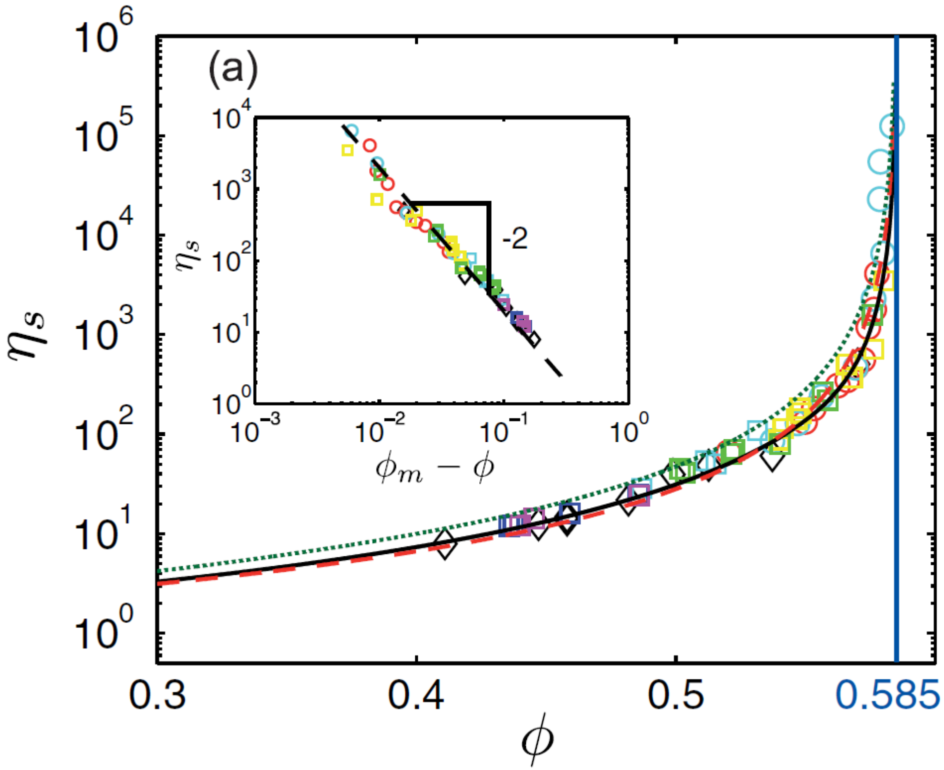
[Brambilla *et al.*, PRL '09]
[Petekidis *et al.*, JPCM '04]

Granular suspensions

- Jamming transition: compressing macroscopic (non-Brownian) particles.
- Example: granular suspensions. 'Diverging' viscosity: $\eta_0(\varphi) \neq \eta_T(\varphi)$.



[Brown & Jaeger, PRL '09]



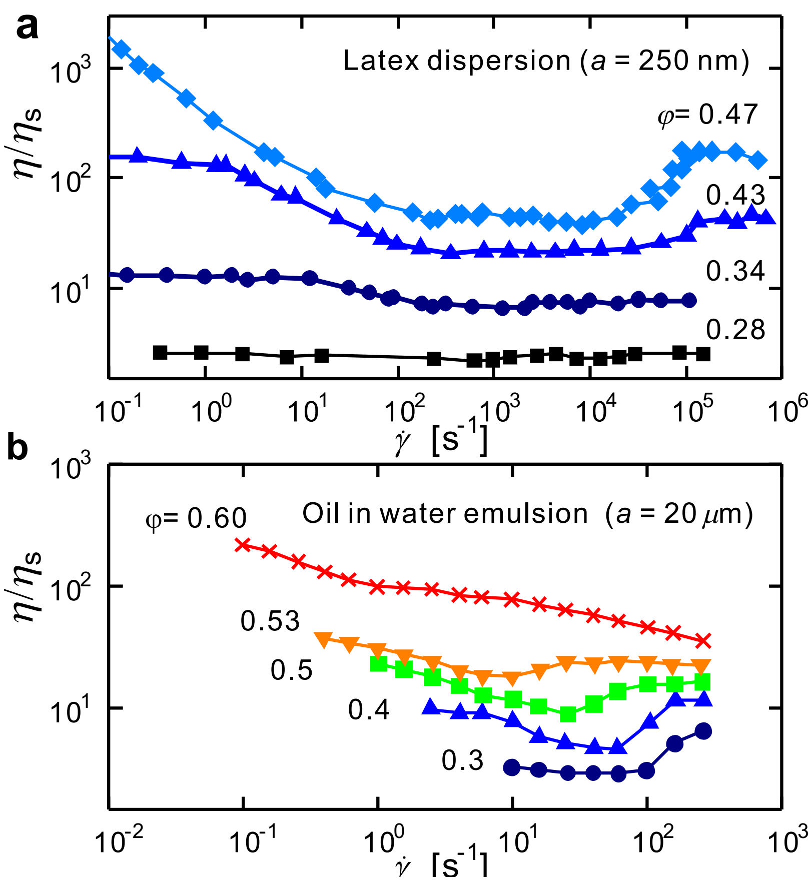
[Boyer & Pouliquen, PRL '10]

- Rigid particles: linear rheology $\eta = \eta_0(\varphi)$.

- Soft particles: Jamming transition from viscous to solid suspension (yield stress) with non-linear rheology: $\eta = \eta(\dot{\gamma}, \varphi)$, at $T = 0$.

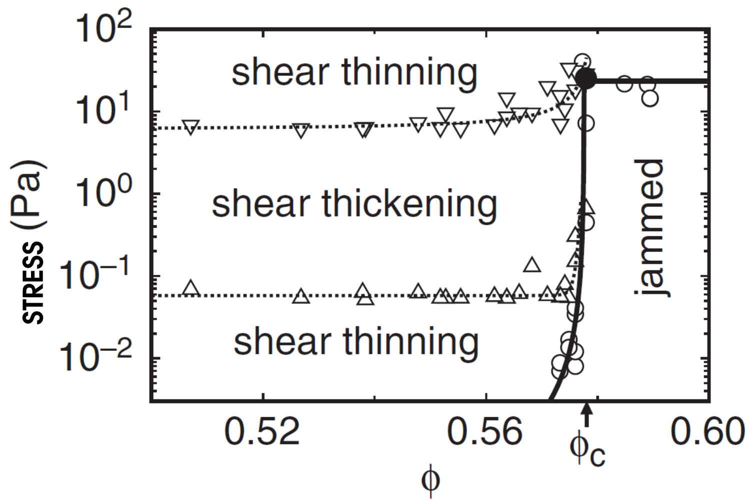
Shear-thickening

- Observed in large variety of systems: soft/hard, large/small... Multiple ‘complex’ explanations: hydrodynamics, micro-structure...



[Wagner, Brady, Phys. Today ’09]

[Otsubo, Rheol. Acta ’94]



[Brown, Jaeger PRL ’09]

- Thickening coexists with other regimes.
- Strong interplay with jamming.
- Role of friction for macroscopic particles: discontinuous thickening.

Simple numerical model

- To understand complex systems, one must understand simple ones...

- Langevin dynamics for soft harmonic spheres with shear and temperature in $d = 3$:

$$m \frac{d\mathbf{v}_i}{dt} + \xi(\mathbf{v}_i - \dot{\gamma} y_i \mathbf{e}_x) + \sum_j \frac{dV(|\mathbf{r}_i - \mathbf{r}_j|)}{d\mathbf{r}_i} + \eta_i = 0,$$

with $\langle \eta_i(t) \eta_j(t') \rangle = 2k_B T \xi \mathbf{1} \delta(t - t')$ and $V(r \leq a) = \epsilon(1 - r/a)^2$.

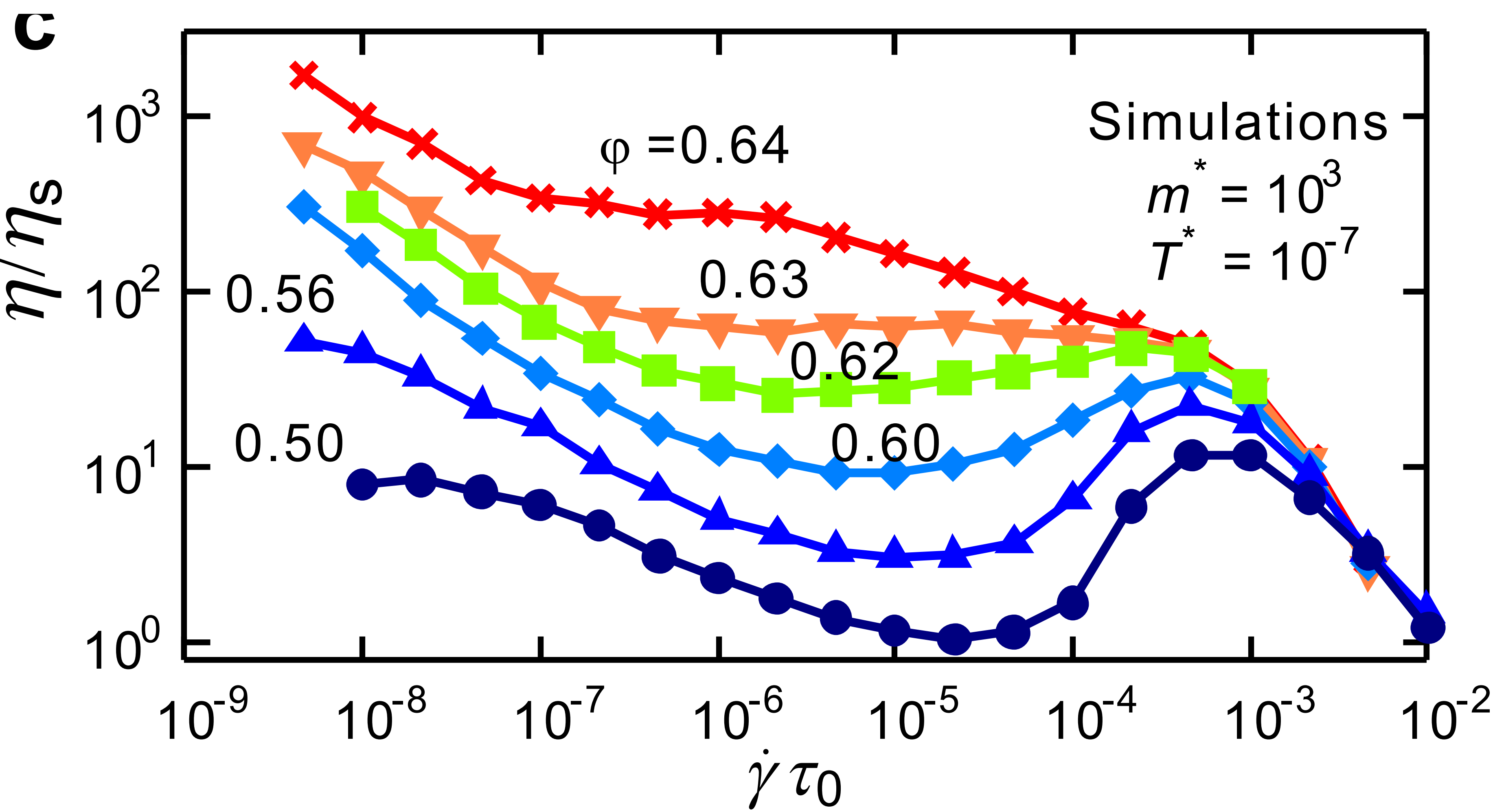
- Four microscopic timescales:

(i) dissipation: $\tau_0 = \xi a^2/\epsilon = 1$, our time unit.
(ii) thermal time: $\tau_D = \xi a^2/(k_B T) \to \infty$ when $T \to 0$.
(iii) velocity damping: $\tau_v = m/\xi$.
(iv) shear rate: $\dot{\gamma}$, competes with (i)-(iii).

- We can study both finite and zero temperature, both overdamped and inertial regimes within single model. Vary $\dot{\gamma}$ at constant (T, m).

[Ikeda et al., PRL '12, Soft Matter '13, Kawasaki et al., arXiv'14]

Multiple rheological regimes

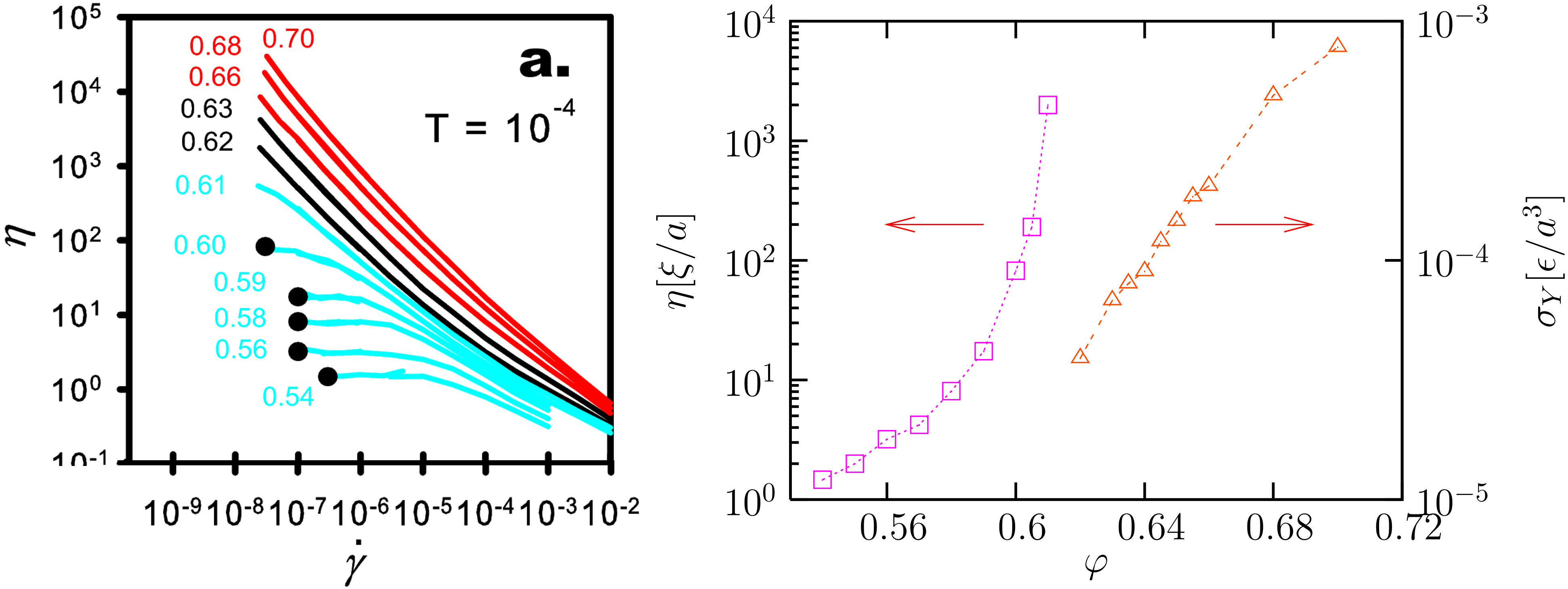


- Complex patterns of Newtonian, shear-thinning, and shear-thickening regimes, with nontrivial density dependence.

- Qualitatively similar to experimental data.

Soft glassy rheology

• Steady state rheology at $(T = 10^{-4}, m = 0)$. Diverging Newtonian viscosity and emerging yield stress as φ increases.

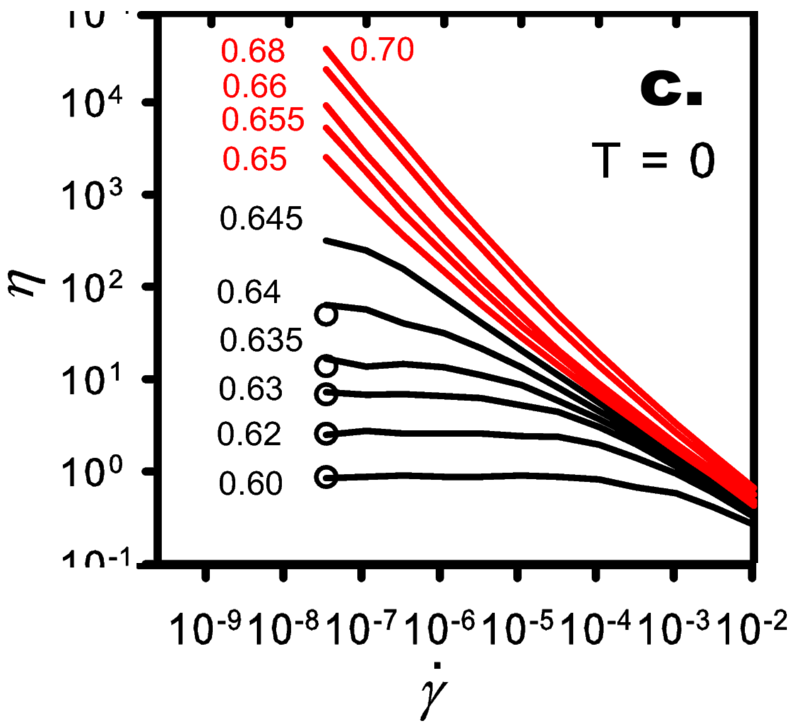


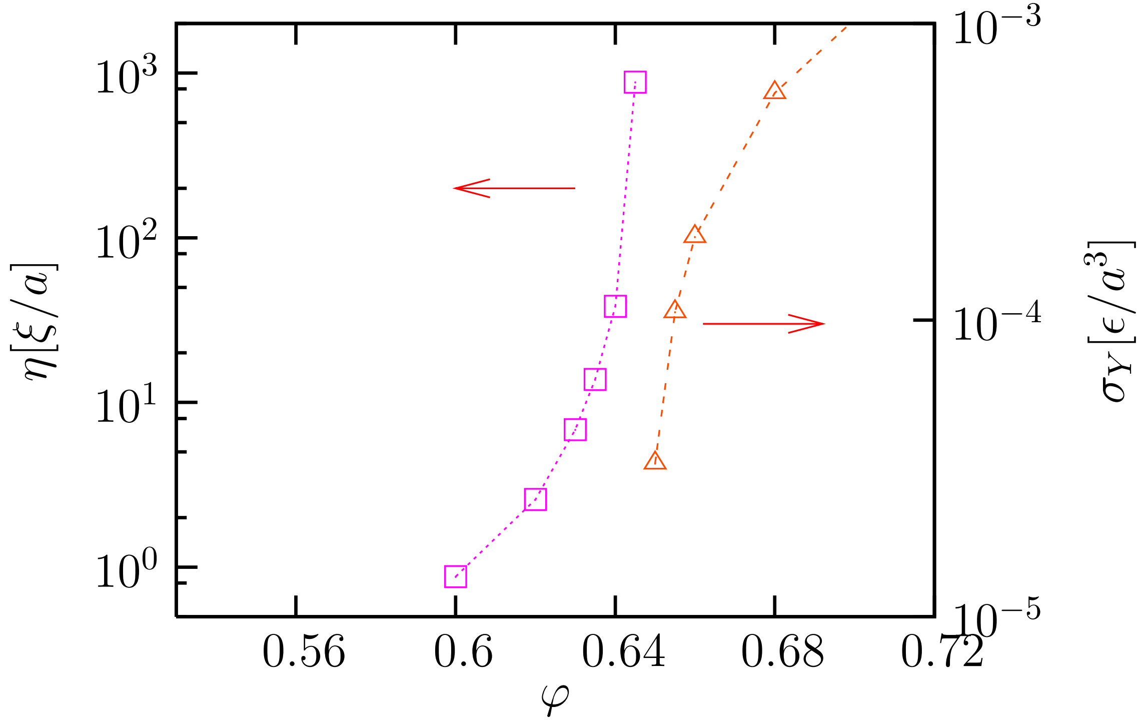
• Glassy rheology, as seen in colloidal particles, star polymers, microgels, simple supercooled liquids: $\dot\gamma\tau_D \ll 1$.

• Theories of driven glasses capture competition between slow glassy dynamics and shear flow (reasonably) well.

Non-Brownian suspension rheology

- Rheology at $(T = 0, m = 0)$. Diverging Newtonian viscosity and emerging yield stress as φ increases.

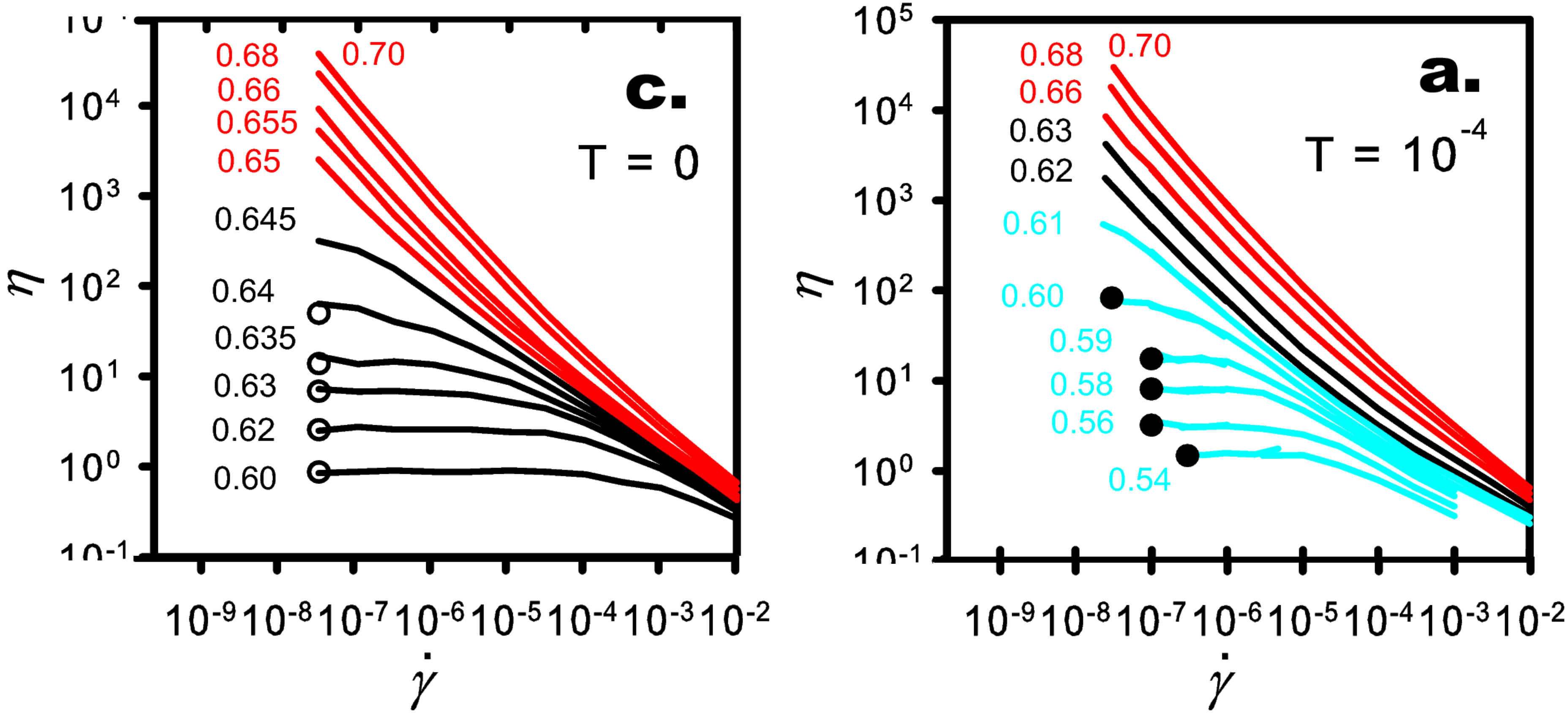




- Rheological signature of $T = 0$ jamming transition: $\dot{\gamma}\tau_D \gg 1$.

- No microscopic theory for rheology. Driven dynamics at $T = 0$ is difficult to attack from first principles, subtle structural changes under shear.

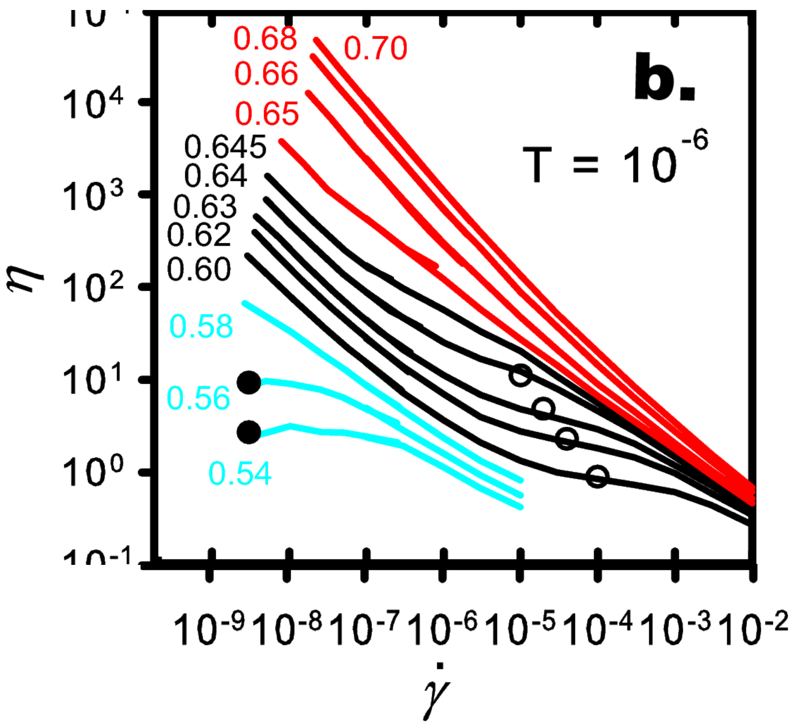
How confusing...

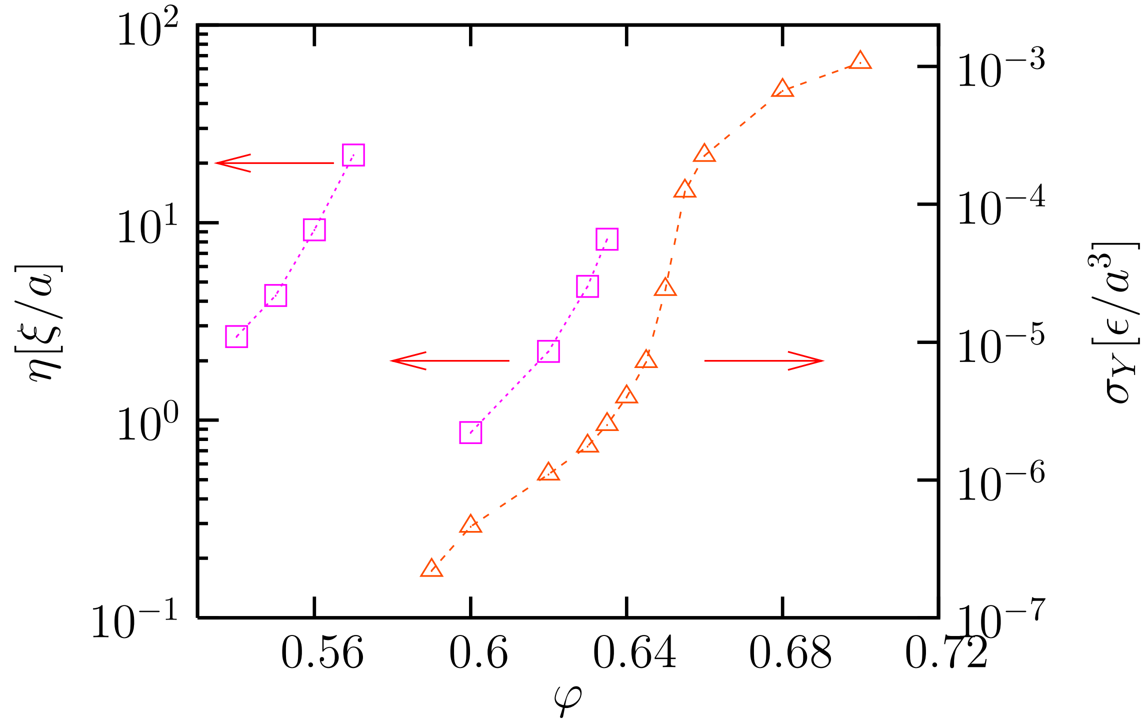


- It is crucial to understand stress & time scales, rather than the shape of the flow curves, in particular $\dot{\gamma}\tau_D \gg 1$ or $\dot{\gamma}\tau_D \ll 1$ makes a dramatic difference (from jamming to glass transitions).

Glass – jamming crossover

• Simulations at $(T = 10^{-6}, m = 0)$. Crossover from glassy physics when $\dot{\gamma}\tau_D \ll 1$ to athermal jamming physics when $\dot{\gamma}\tau_D \gg 1$.

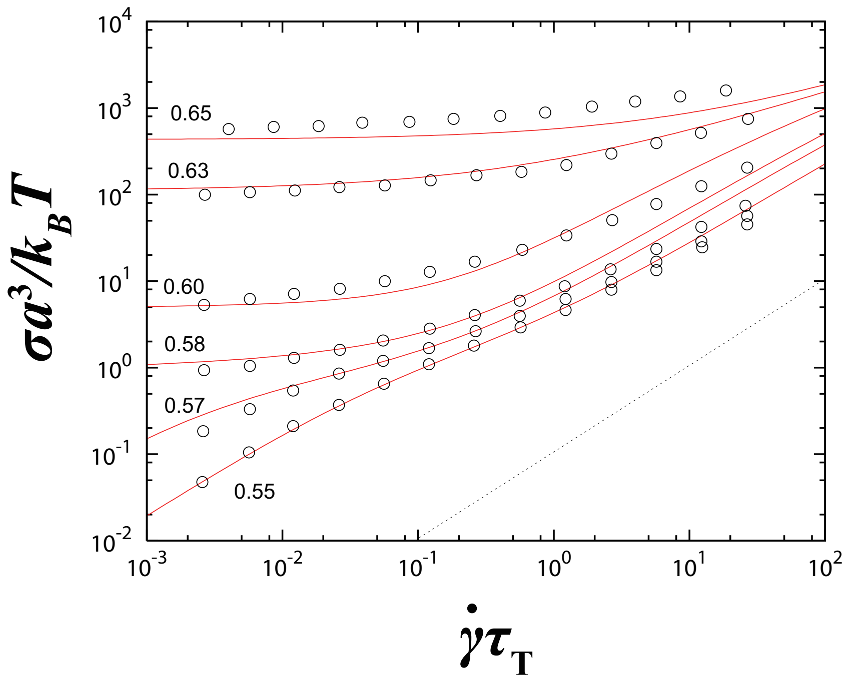


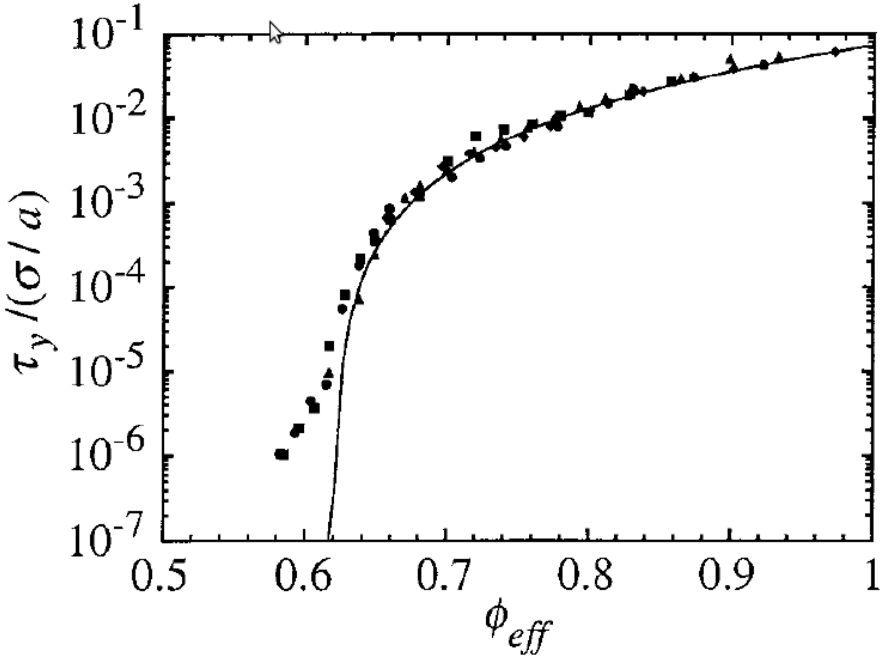


• Two Newtonian regimes, two distinct viscosities, emergence of yield stress (when $\dot{\gamma} \to 0$), with strange density dependence. Complex rheology... even without inertia.

Crossover in experiments

• Microemulsions ideal to observe the crossover: right size, right softness. Both glass and jamming contributions needed to describe rheology.

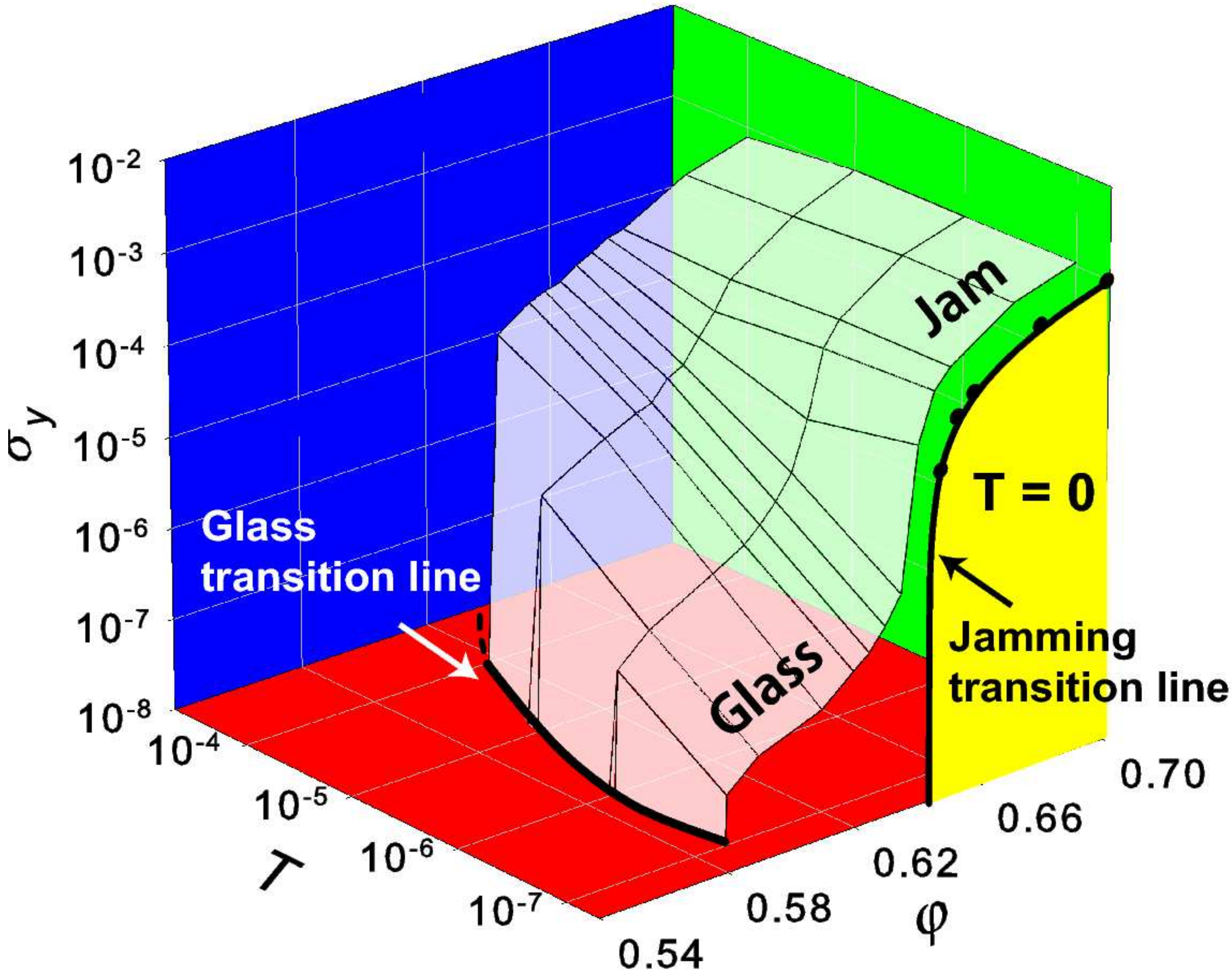




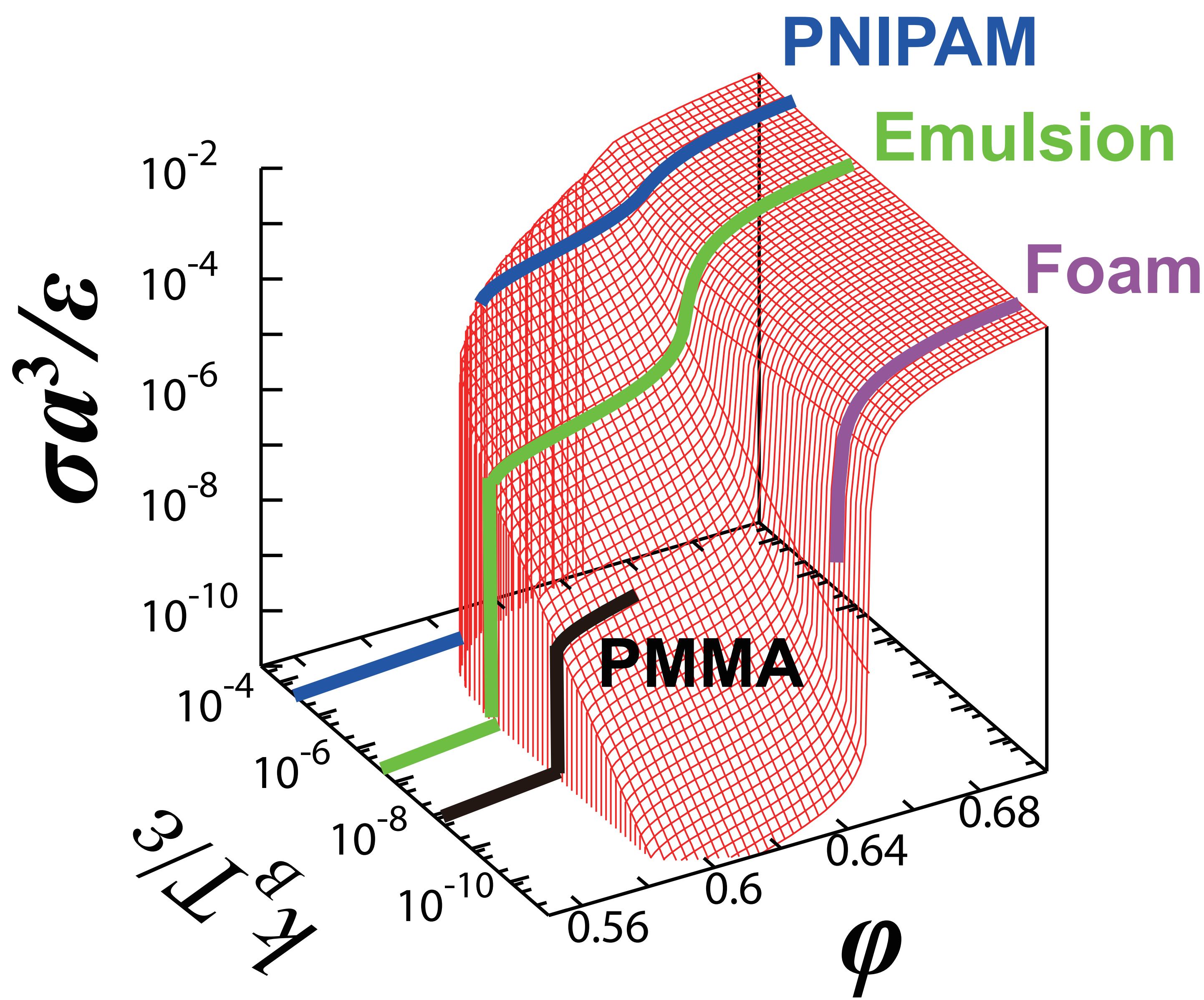
[from Mason, Bibette, Weitz, 1996]

• Star polymers and pnipam microgels are too soft, grains/foams are too large. Either glass or jamming, but one must choose the right one...

‘Jamming phase diagram’

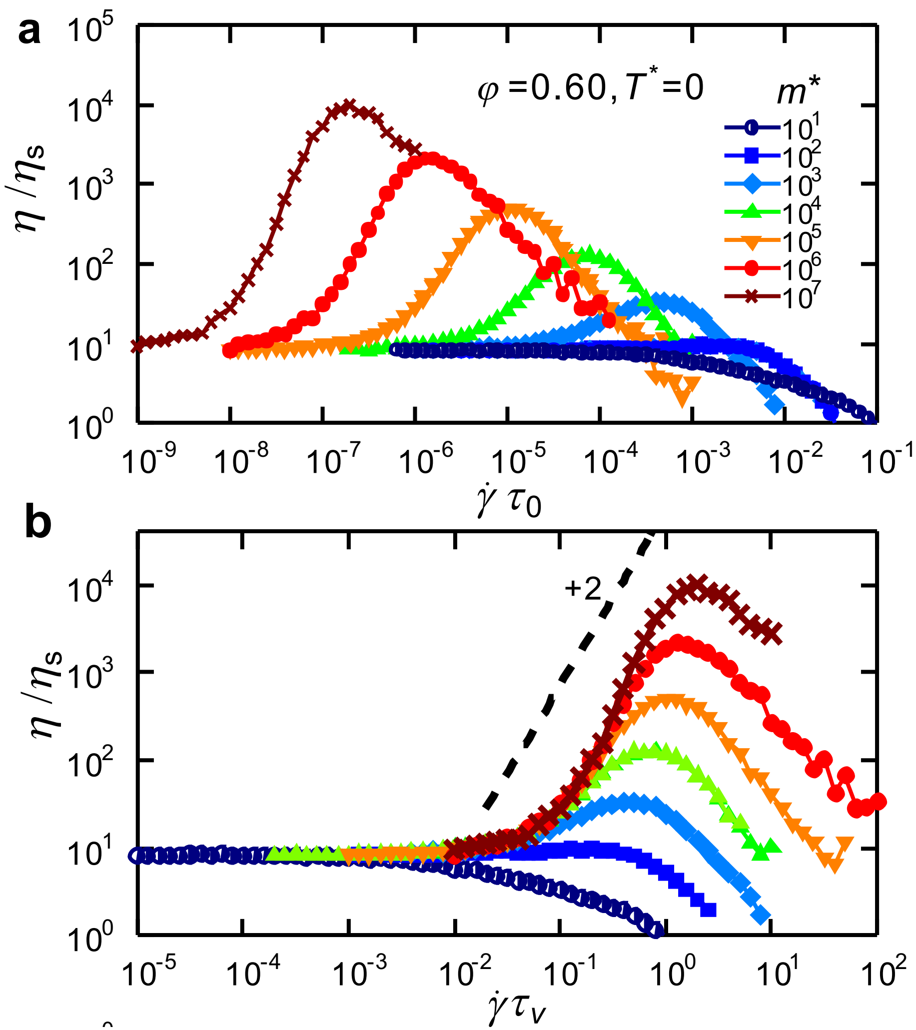


‘Jamming phase diagram’



Inertia adds a 3rd timescale

- Rheology for $(T = 0, \varphi = 0.60)$ and increasing m.



- Crossover from Newtonian to shear-thickening flow when $\dot\gamma \propto 1/\tau_v = \xi/m$ (prefactor ≈ 0.01).

- (i) Energy balance: $\sigma\dot\gamma \approx \rho L^3 \xi \bar{v}^2 / L^3$.

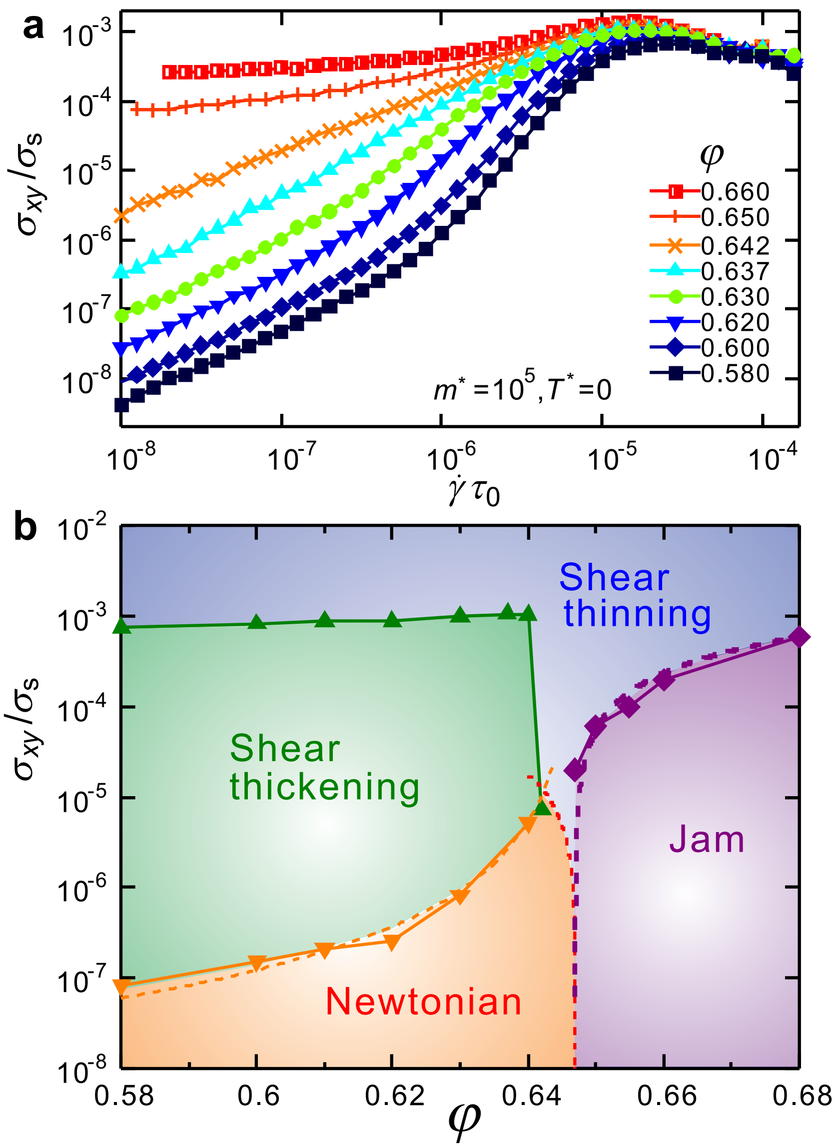
  (ii) Momentum exchange via collisions: $\sigma \approx \rho L^2 \bar{v} m \dot\gamma a / L^2$

  (i) + (ii) $\rightarrow$ 'Bagnold' scaling: $\sigma \approx (\rho m^2 a^2/\xi)\dot\gamma^3$, i.e. $\eta \propto (\dot\gamma\tau_v)^2$.

- Softness controls viscosity maximum: $m\bar{v}^2/2 \approx \epsilon$.

[Kawasaki, Ikeda, Berthier, arXiv:1404.4778]

Dynamic 'phase diagram'



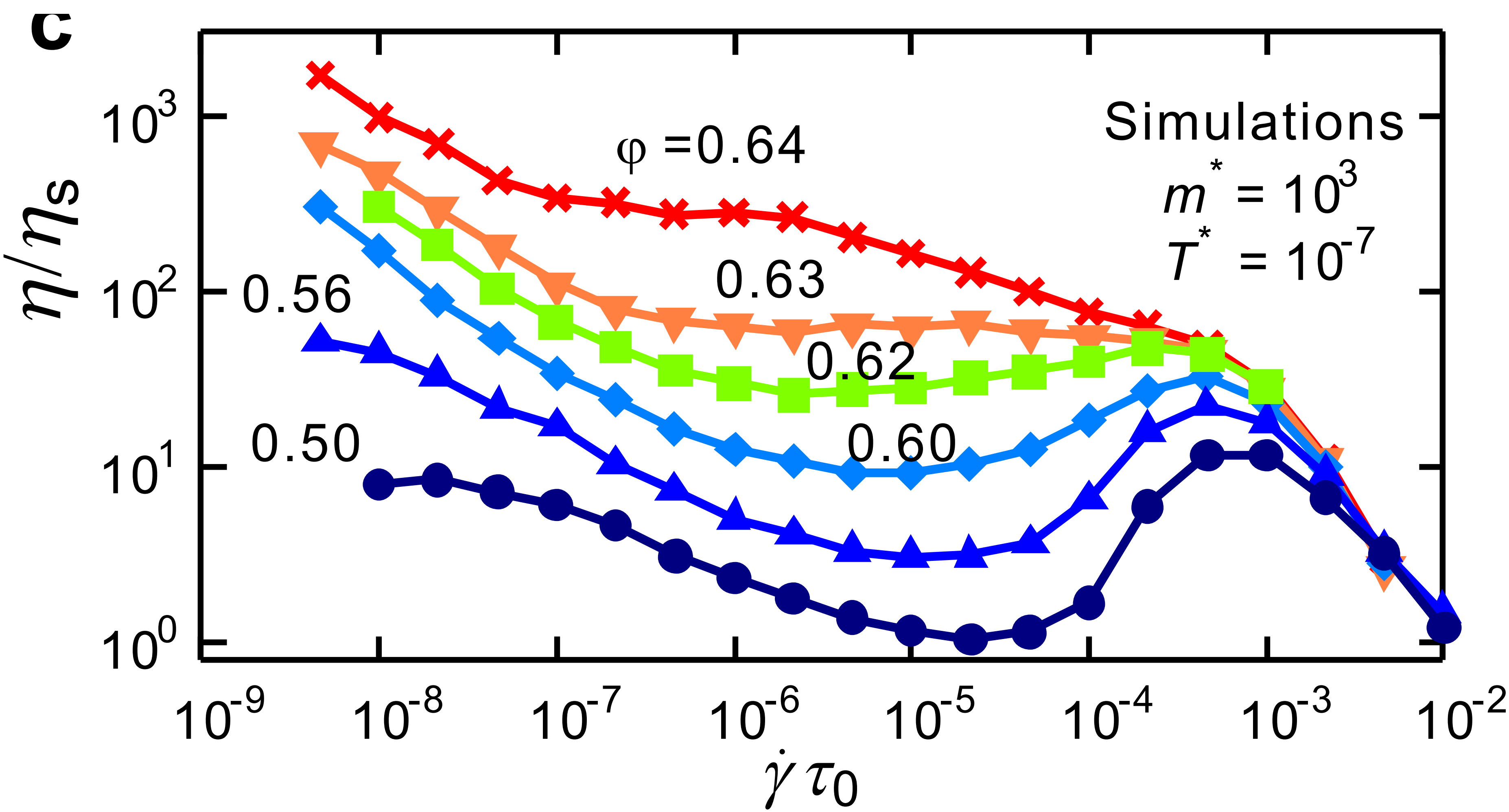
- Shear-thickening observed when $\tau_v^{-1} \ll \dot{\gamma} \ll \dot{\gamma}_c$, and if no additional stress scale.

- Above jamming at $T = 0$, yield stress $\sigma_Y > 0 \rightarrow$ shear-thinning.

- At finite temperature, thermal yield stress develops: $\rightarrow$ shear-thinning.

- Onset of thickening: $\dot{\gamma} \approx 0.01/\tau_v$. Good agreement for some systems (large emulsions, latex), only qualitative agreement for others (macroscopic hard grains).

Jigsaw falling into place



- Thermal glassy regime: $\dot{\gamma} < 10^{-7}$, athermal overdamped: $10^{-7} < \dot{\gamma} < 10^{-5}$, inertial $\dot{\gamma} > 10^{-5}$, softness maximum: $\dot{\gamma} \approx 10^{-3}$, jamming above $\phi = 0.64$. All in a simple model evolving with Langevin dynamics.