SHAKEN AND STIRRED:
RANDOM ORGANIZATION, VISCOSITY AND DISSIPATION IN GRANULAR SUSPENSIONS

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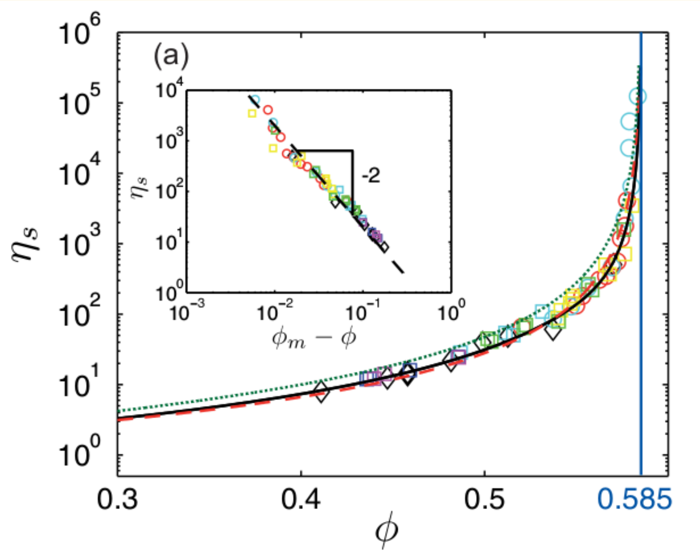
VISCOSITY DIVERGENCE, JAMMING

[Boyer, Guazzelli & Pouliquen, PRL 2011]



MUCEM, Marseille

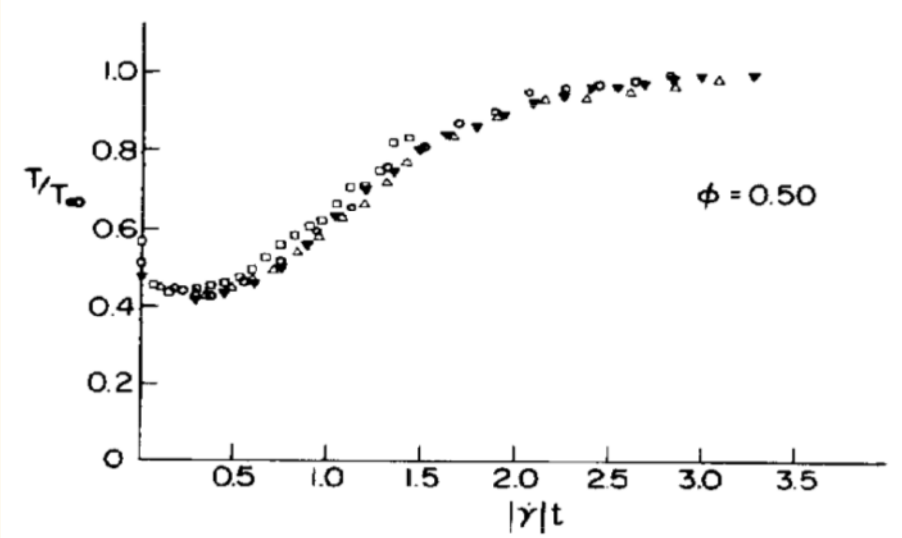
- Ultra-high performance concretes
- Lower water to cement ratio, very thick
- Use of "superplasticizers", i.e. composition tuning

MODEL GRANULAR SUSPENSIONS SHOW "SIMPLE" RHEOLOGY IN *STEADY STATE*.

EPTITOME OF UNSTEADY FLOW: SHEAR REVERSAL

[Gadala-Maria & Acrivos, JOR 1980]

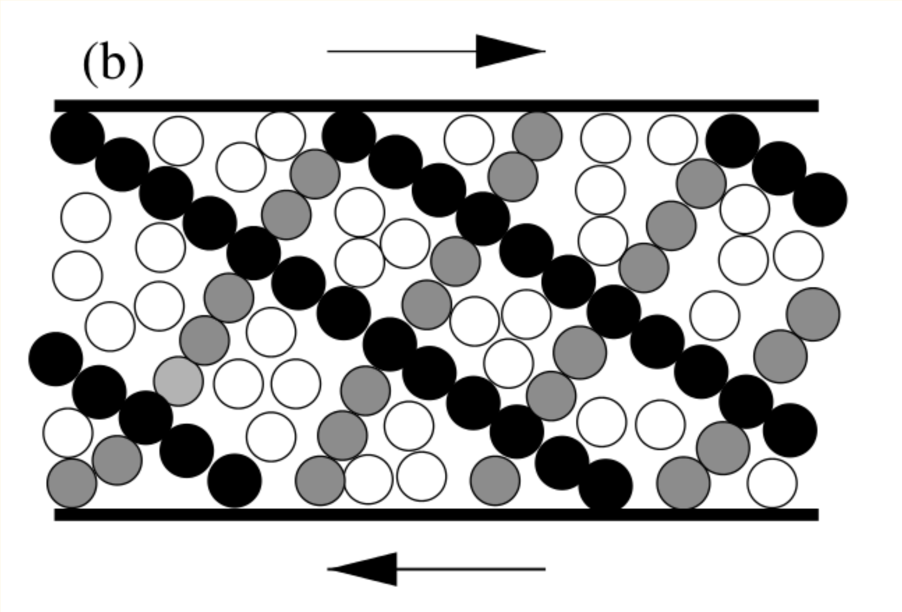
Shear up to steady-state in a given direction, and suddenly apply opposite shear



"Memory" of past applied load

FRAGILITY OF DENSE SUSPENSIONS

[Cates, Wittmer, Bouchaud & Claudin, PRL 1998]



Mechanical response depends strongly on the compatibility of the instantly applied load with respect to the load history.

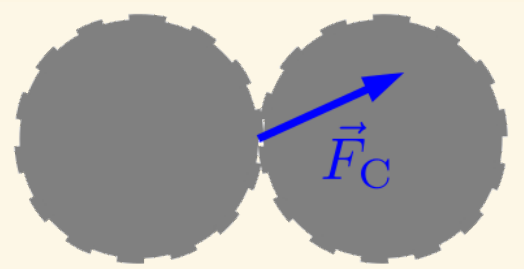
DEM + LUBRICATION SIMULATIONS

[Seto et al, PRL 2013]
[Mari et al, JOR 2014]
[Mari et al, PRE 2015]

Spherical hard particles in a Newtonian fluid in the Stokes regime, short-range hydro (lubrication) + contacts

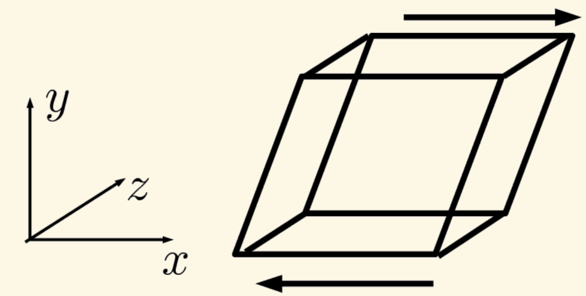
Eq. of motion (force balance)

$$0 = F_{\mathrm{H}}(U) + F_{\mathrm{C}}$$



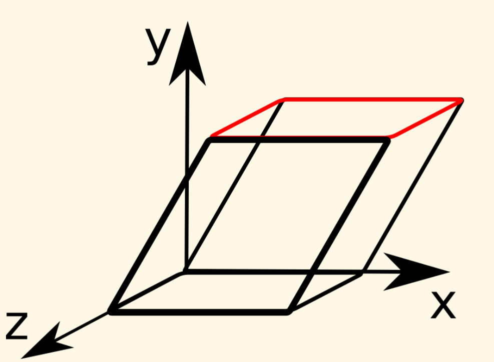
$$|F_{\mathrm{C}}^{\mathrm{t}}| < \mu |F_{\mathrm{C}}^{\mathrm{n}}|$$

Simple shear through Lees-Edwards b.c.



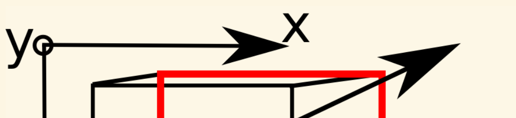
PROTOCOL

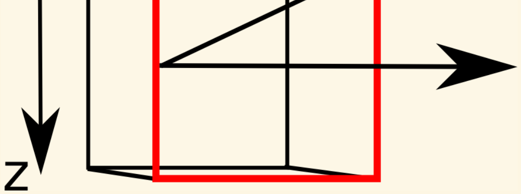
1. Shear at constant stress in the x direction
(with gradient along y), up to steady-state



2. Shear in a new direction making an angle θ with x
(keeping the gradient along y)

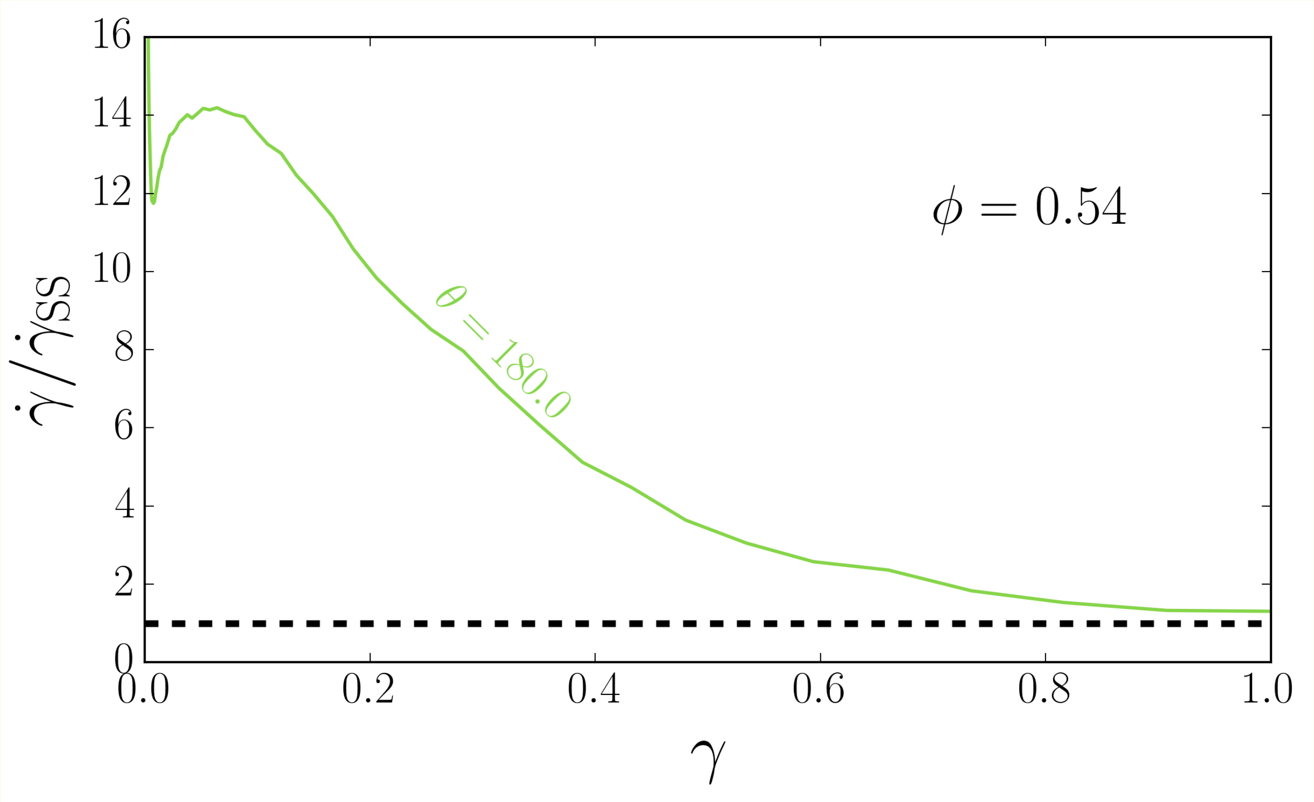
θ




z

SHEAR RATE RESPONSE

$\theta = 180$ is shear reversal



SHEAR RATE RESPONSE

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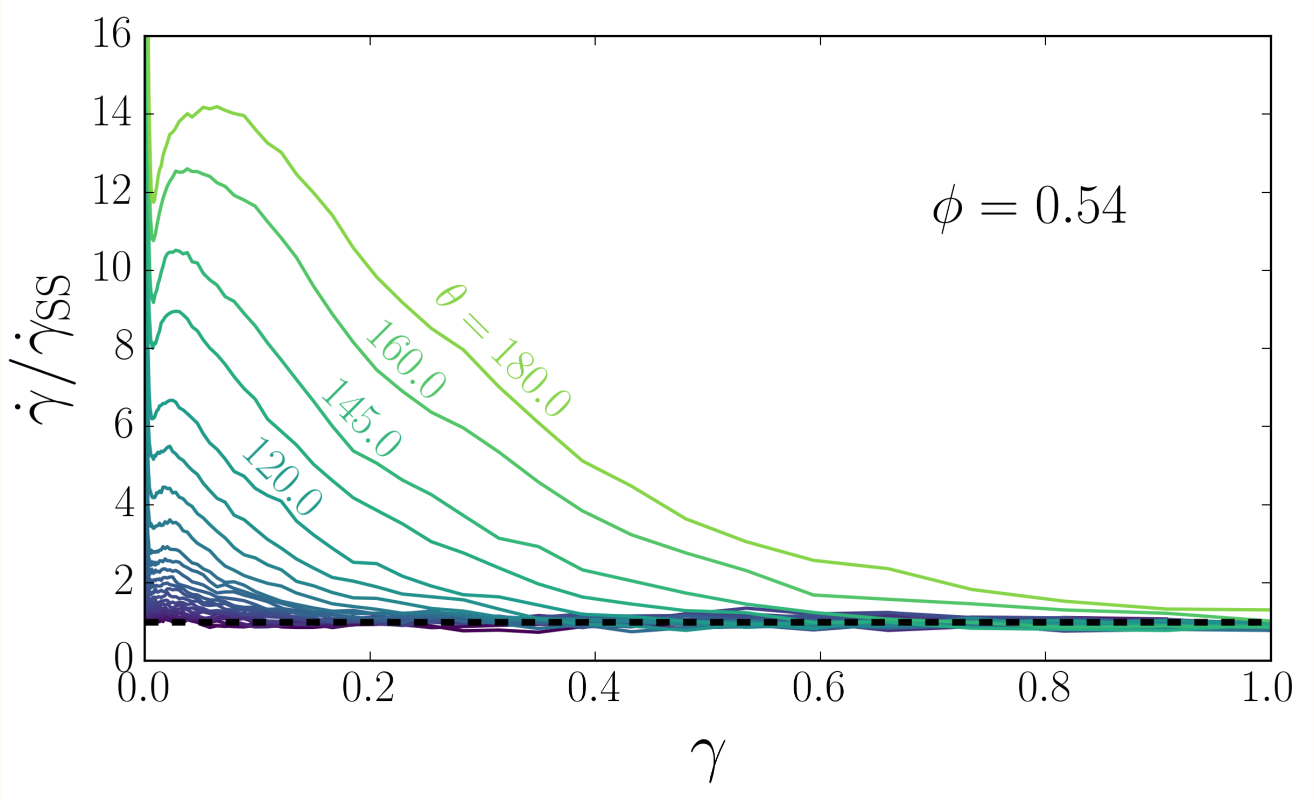
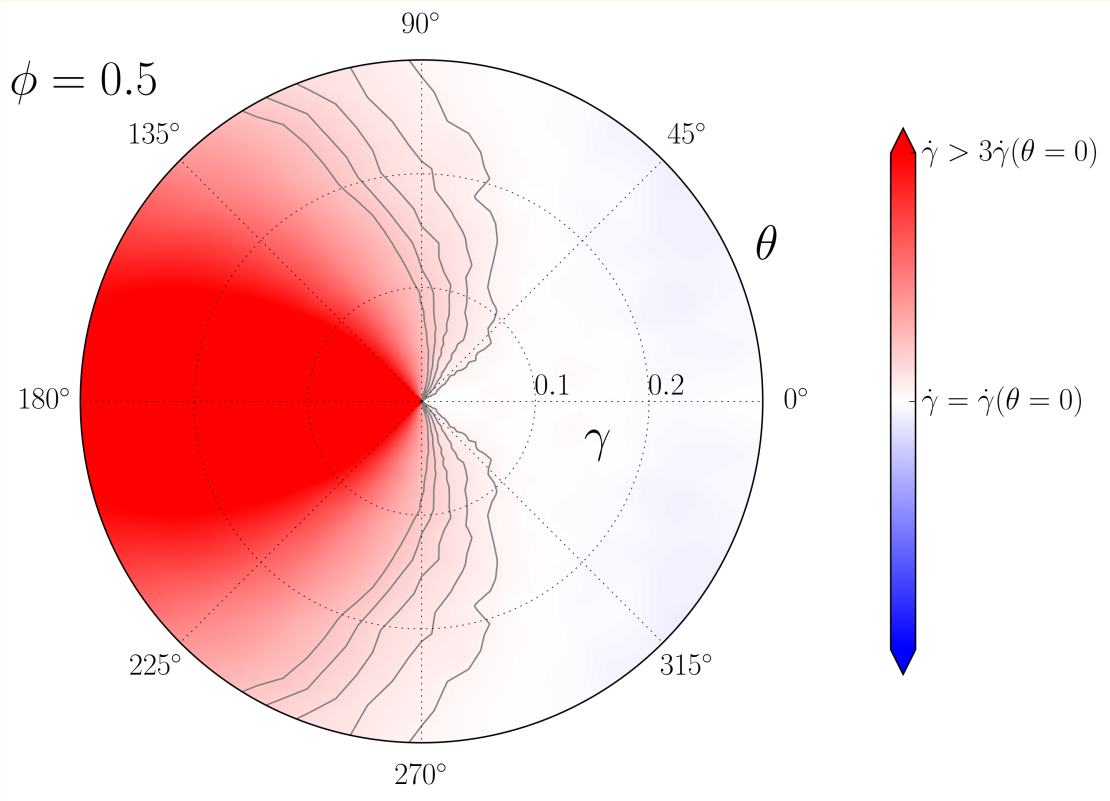
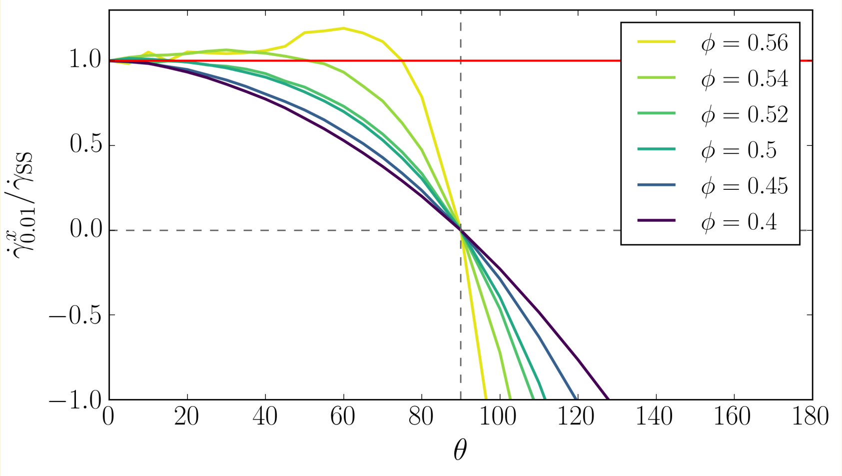


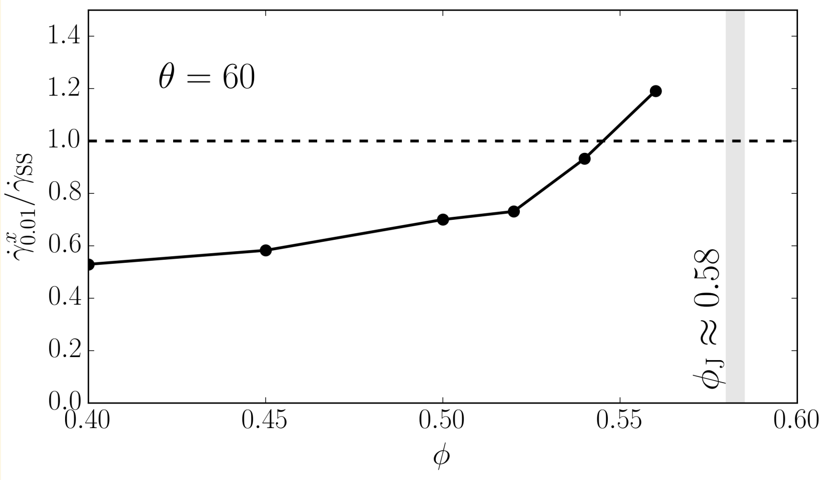
SHEAR RATE MAPS



SHEAR RATE GAIN

Maximum rate projected on the x direction



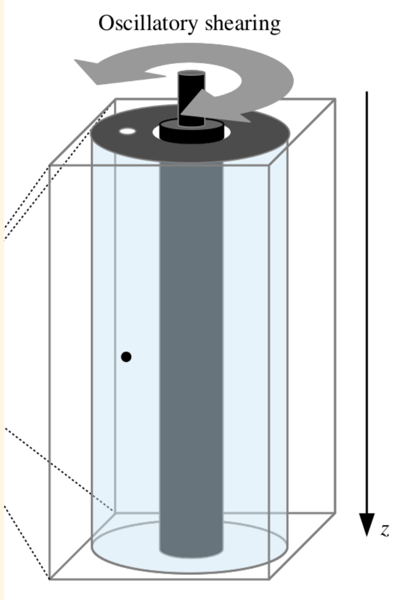


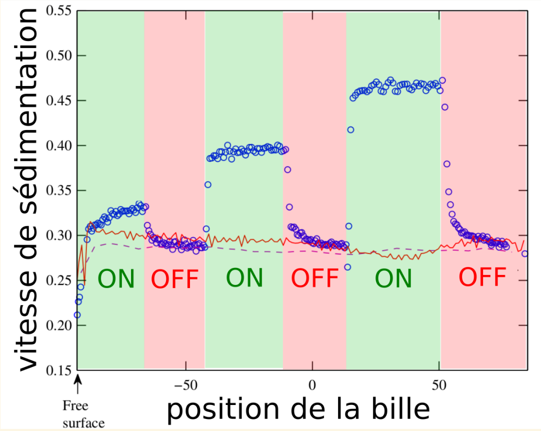
Can we use it and flow at lower viscosity
for more than a transient time?

VISCOSITY REDUCTION: NEW IDEA, MECHANICAL DRIVING

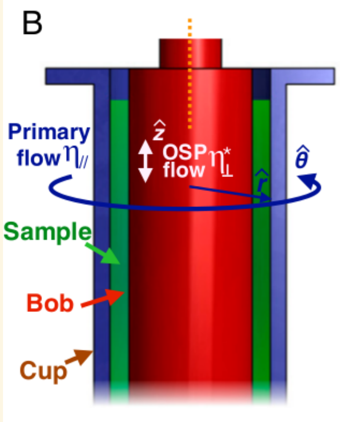
Primary flows with oscillatory cross shear

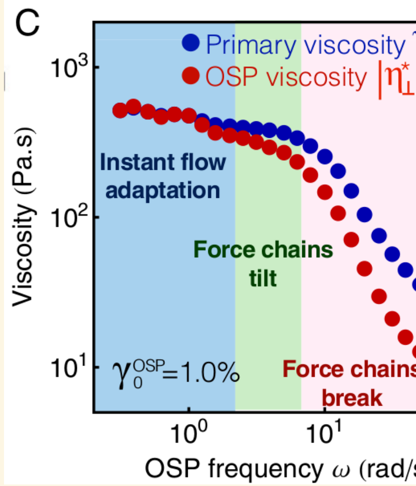
Speeding sedimentation of a large intruder
[Blanc, Lemaire & Peters, JFM, 2014]





"Unthickening" of cornstarch
[Lin et al, PNAS, 2016]



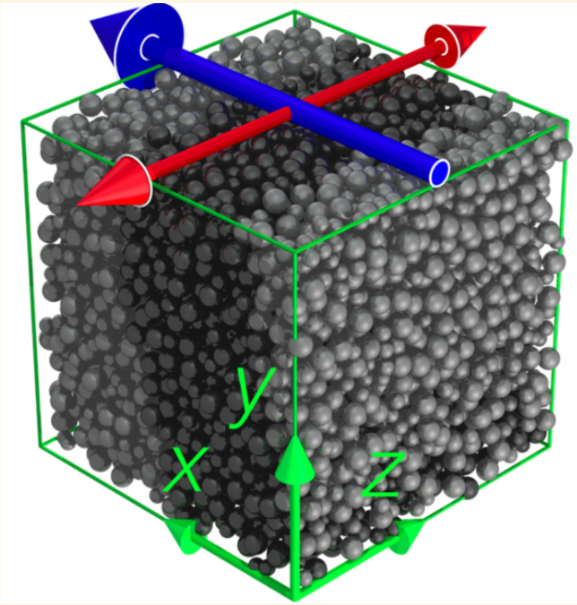


Viscosity drop generic?

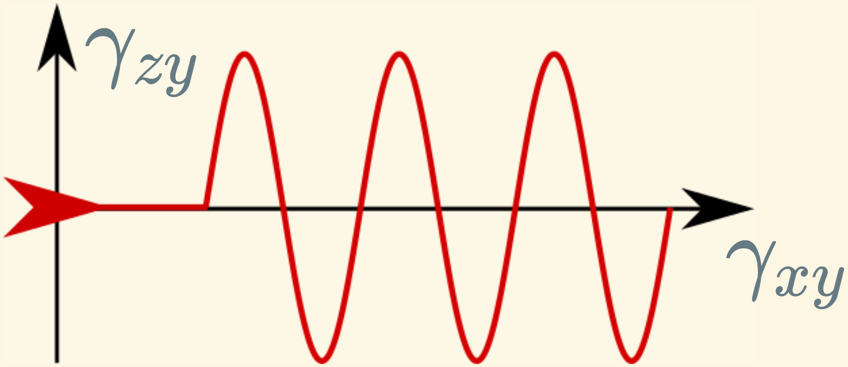
Dependent on thickening? Works only for frictional systems?

SIMULATIONS

Rate-independent suspension of particles with only lubrication and frictional contacts



$$\dot{\gamma}_{xy} = \dot{\gamma}$$
$$\dot{\gamma}_{zy} = \dot{\gamma}_{\perp} \cos(\omega t)$$

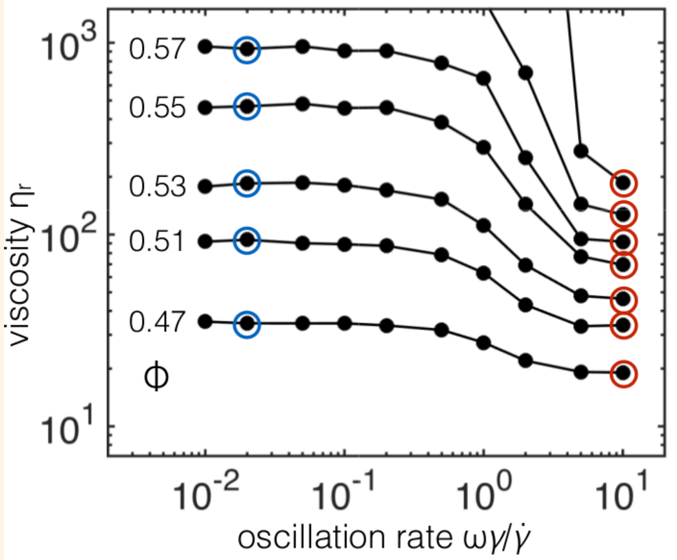


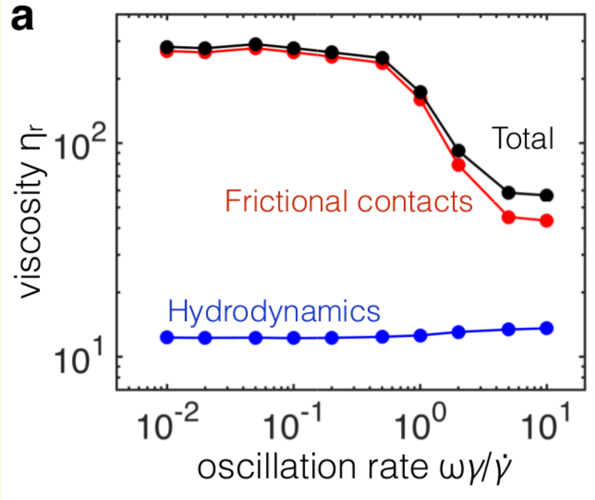
Viscosity:

$\eta = \sigma_{xy}/\dot{\gamma}_{xy}$

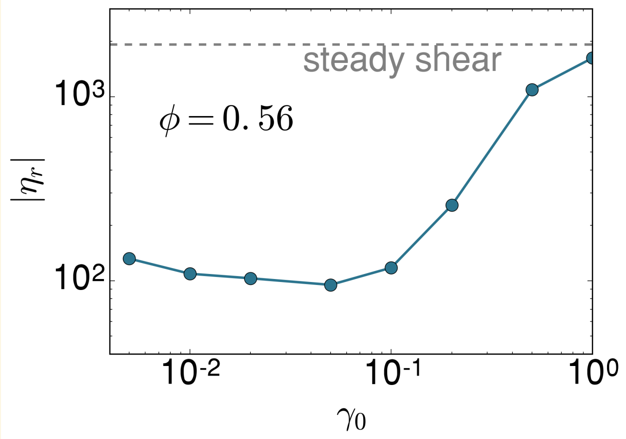
VISCOSITY REDUCTION WITHOUT THICKENING

When $\gamma = 1\% - 5\%$,
strong viscosity drop.

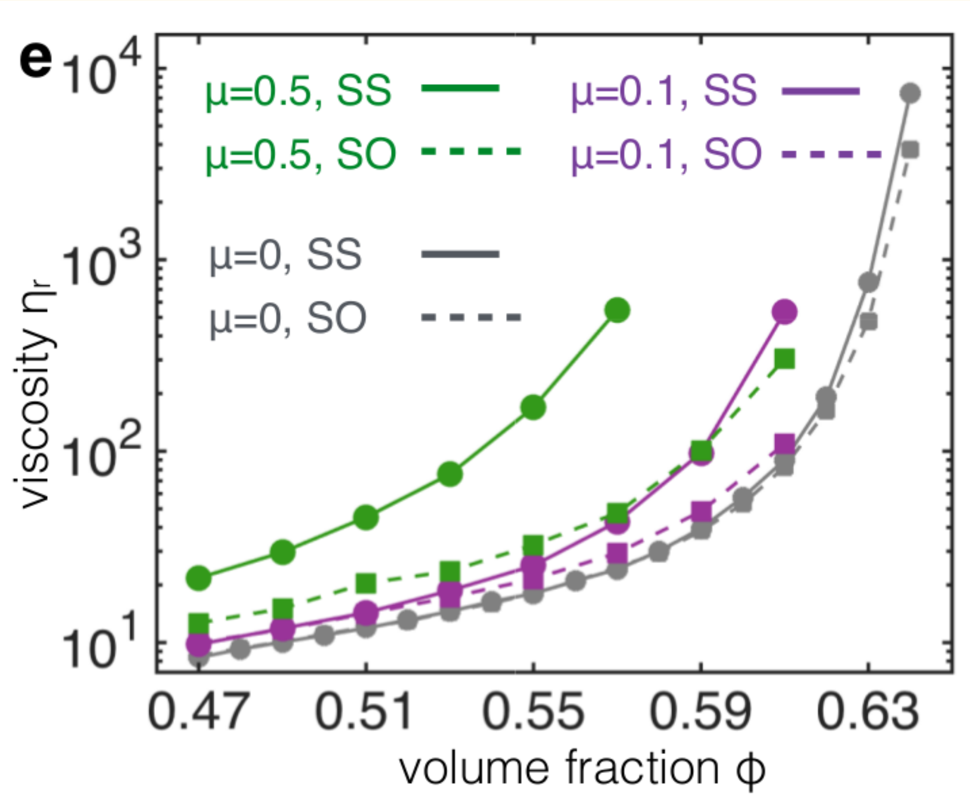




Dependence on γ



VISCOSITY REDUCTION

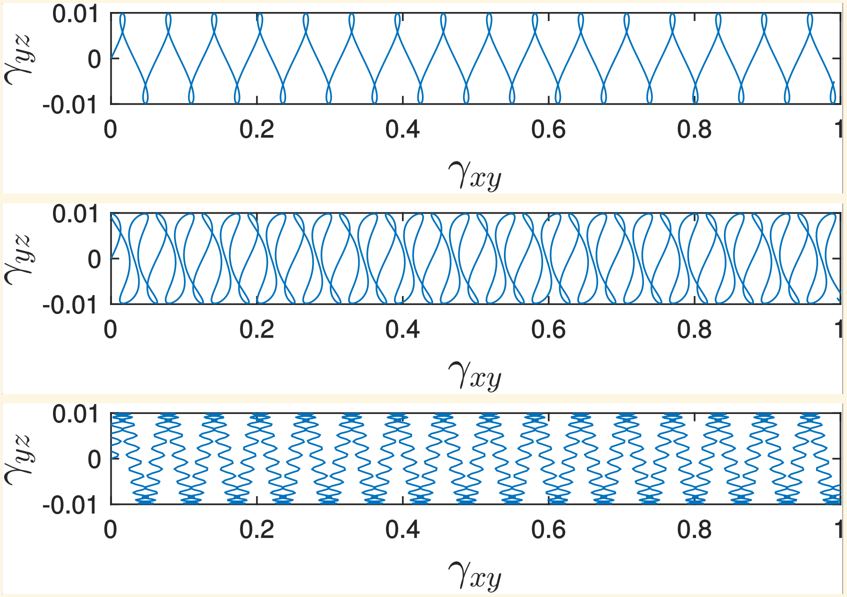


Arbitrary large gain close to jamming

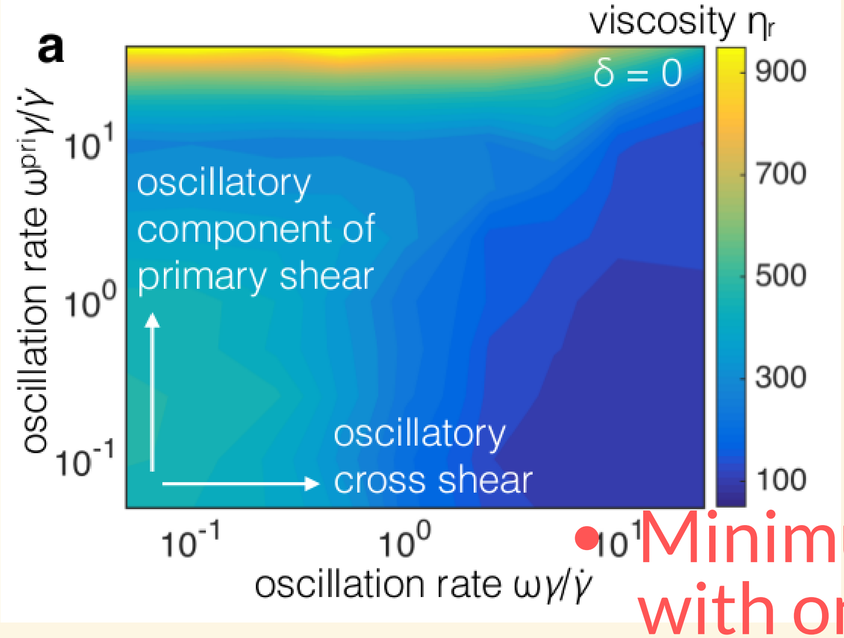
Works for frictional suspensions!

IS ANY OSCILLATION HELPING?

$$\dot{\gamma}_{xy} = \dot{\gamma} + \omega^{\mathrm{pri}}\gamma\cos(\omega^{\mathrm{pri}}t + \delta)$$
$$\dot{\gamma}_{zy} = \omega\gamma\cos(\omega t)$$



Viscosity map

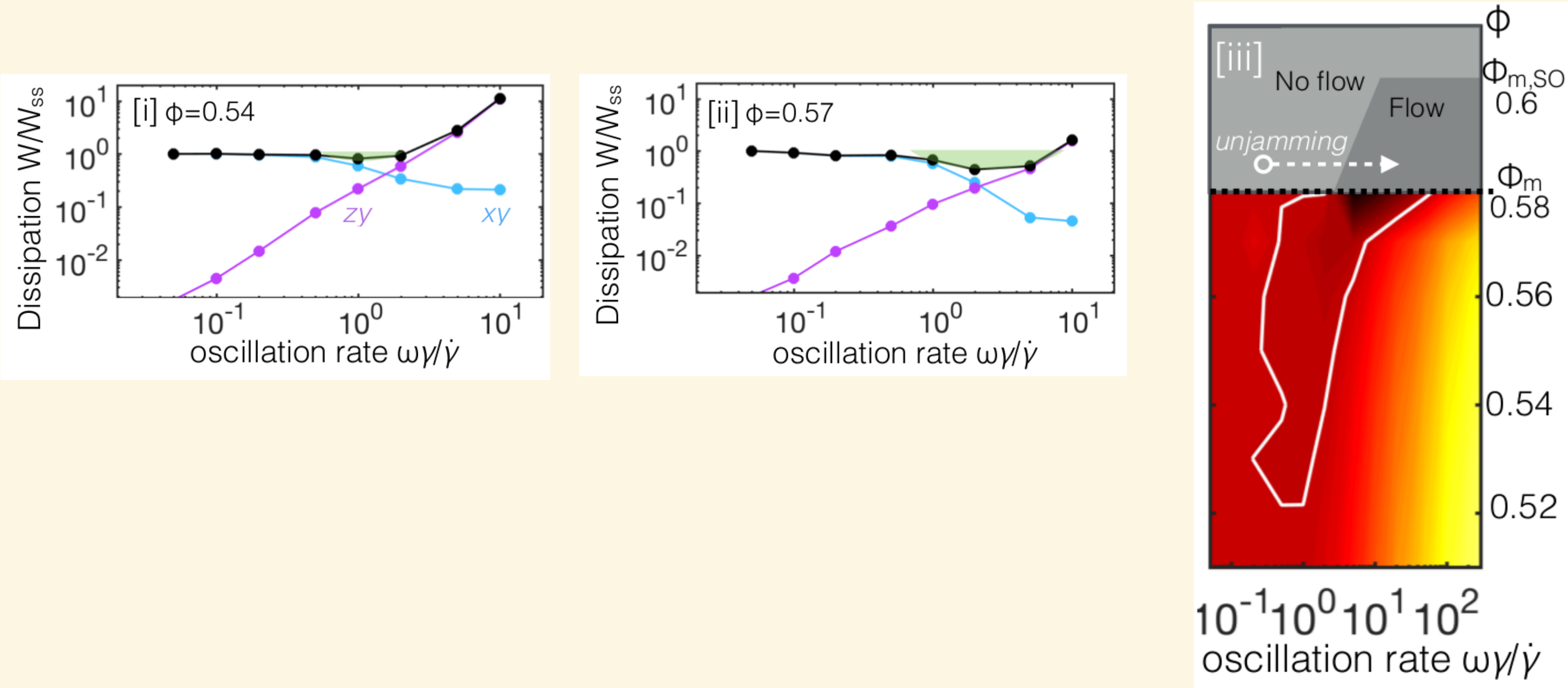


Minimum with only crosswise oscillatio

HOWEVER… DISSIPATION

Dissipation per unit strain $W = \dfrac{\int \Sigma : \dot{\Gamma}\, \mathrm{d}t}{\int \dot{\gamma}_{xy} \mathrm{d}t}$

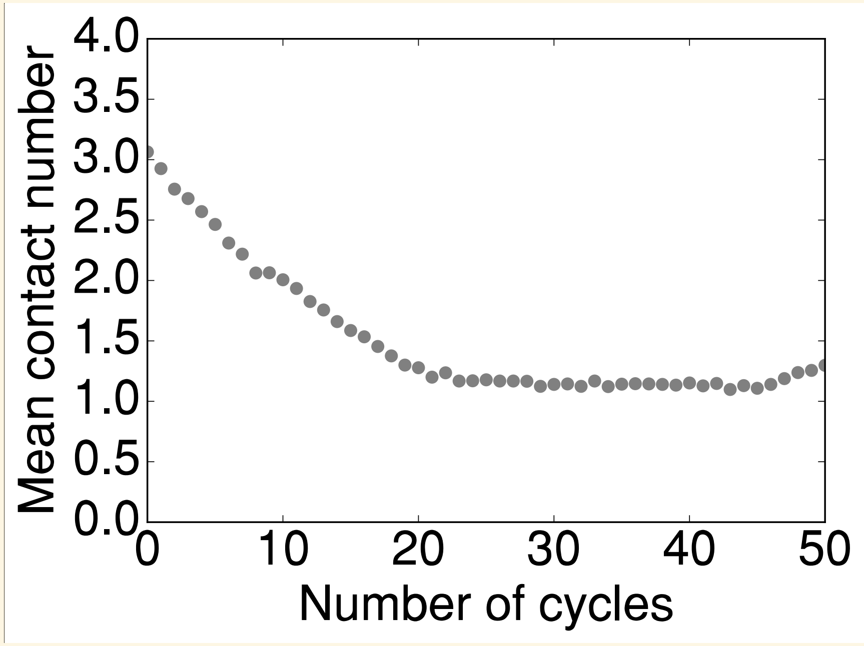
$\dot{\gamma}_{zy} \sim \omega$, $\Sigma_{zy} \sim \omega$, so $W_{zy} \sim \omega^2$.



Can we do better?

ORIGIN OF THE VISCOSITY DROP

Contact drop, that is, *room making*

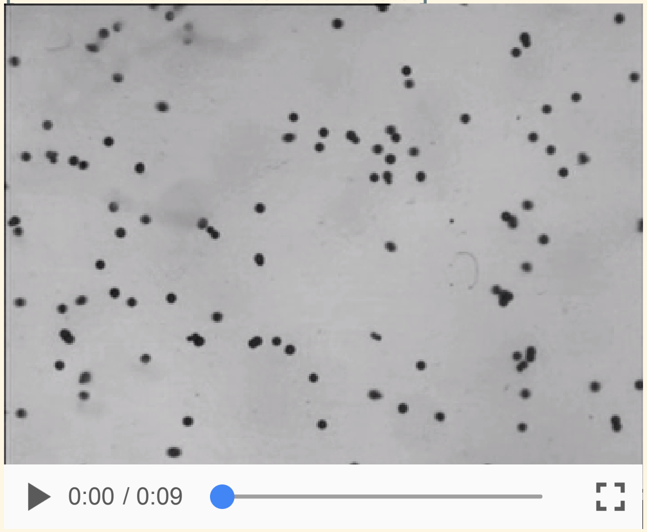


Room-making is slow

"ECHO" EXPERIMENT, RANDOM ORGANIZATION

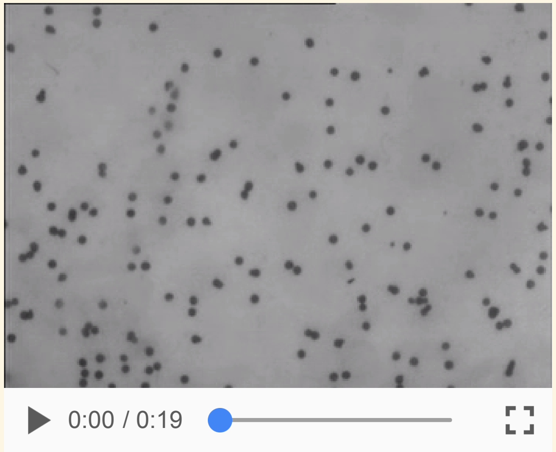
Self-organization, absorbing phase transition

[Pine et al. Nature 2005]



$\phi > \phi_c$

$\phi < \phi_c$

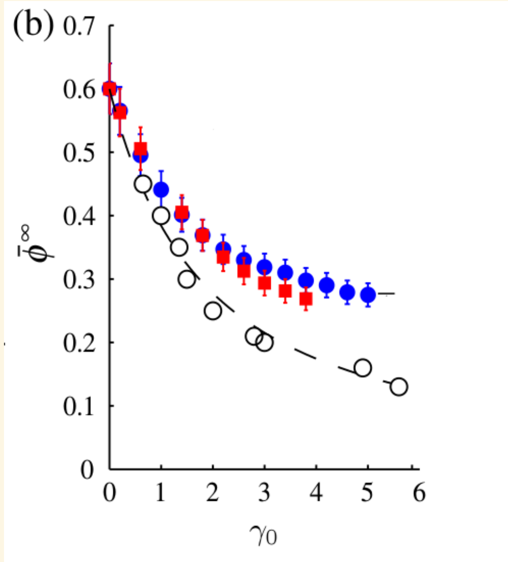


WHERE IS THE ABSORBING PHASE TRANSITION?

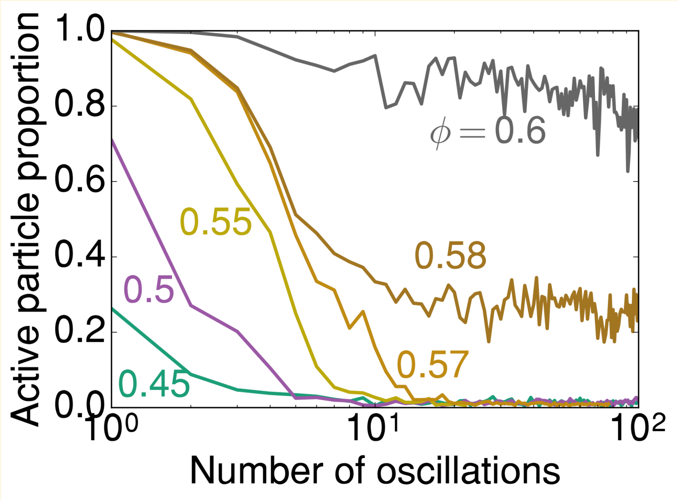
For large $\gamma \approx 1$, phase transition at $\phi_c \approx 0.3$

But in our case $\gamma \approx 1\% \ll 1$!

[Corté et al, PRL, 2009]



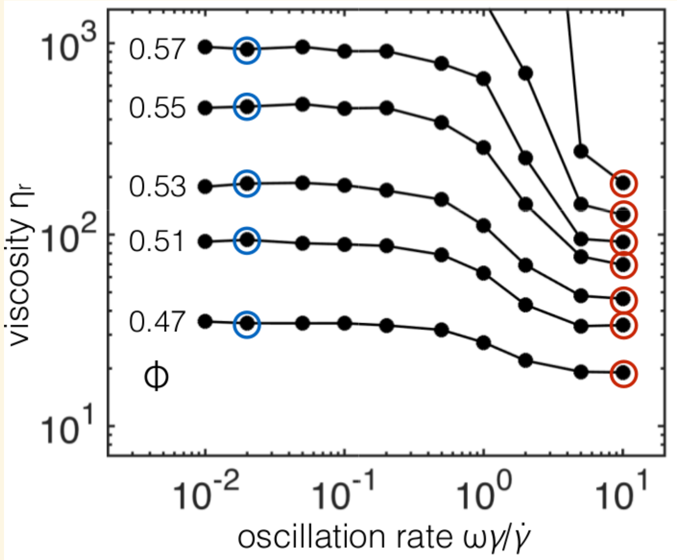
Our system, oscillatory shear only, $\gamma = 2\%$:



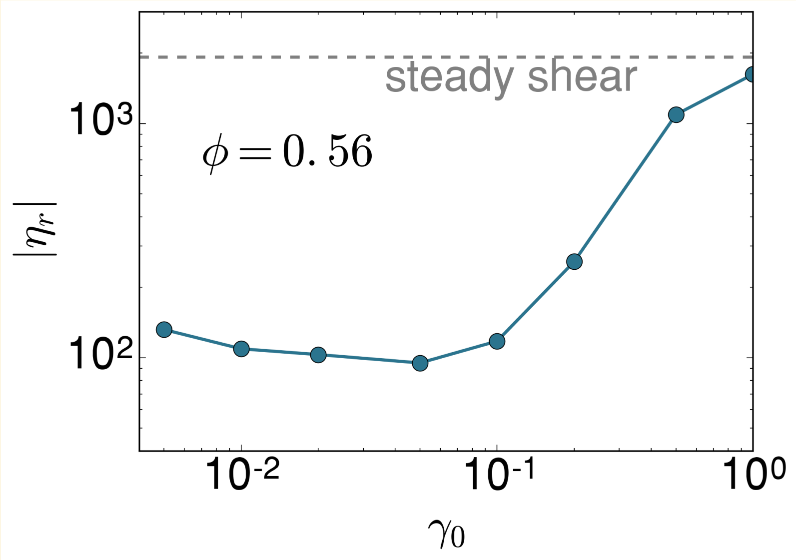
Transition very close to jamming

VISCOSITY REDUCTION AND RANDOM ORGANIZATION

Dependence on frequency



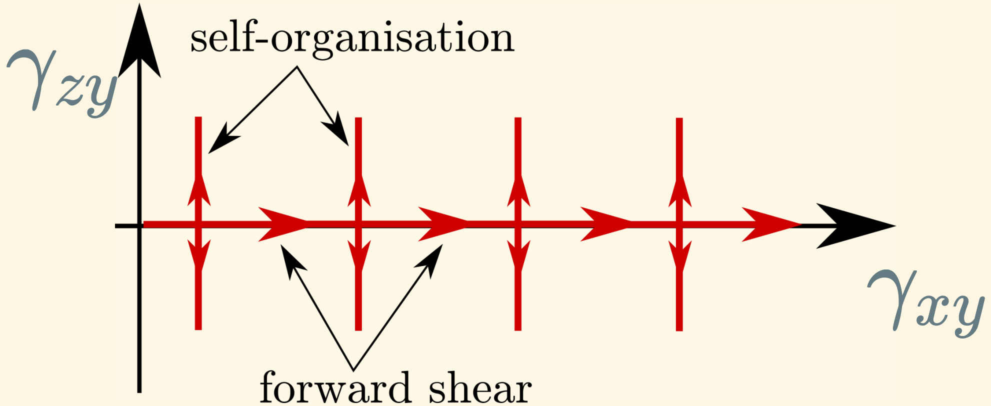
Dependence on amplitude



OCS is using random organization to improve flowability

AN ALTERNATIVE PROTOCOL

Decouple self-organization from primary shear

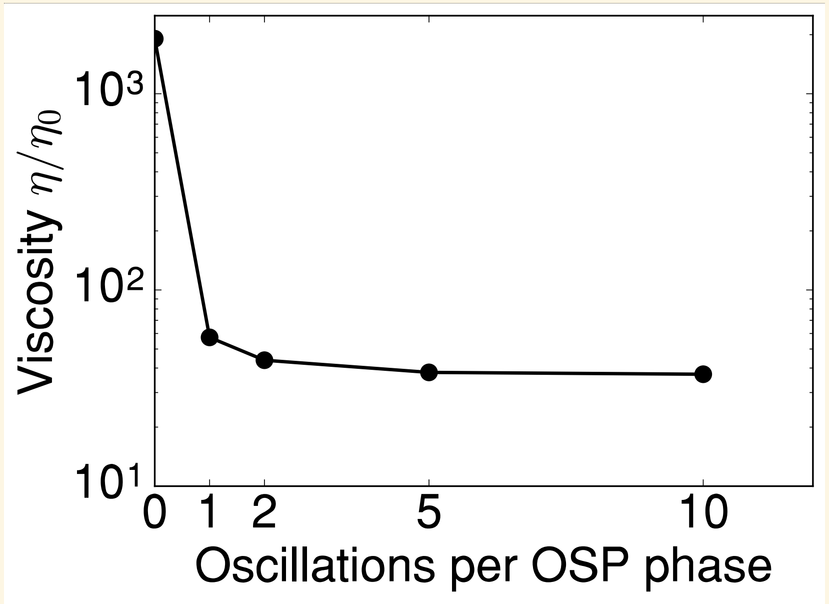


Parameters:

- Strain in the primary direction Γ
- Amplitude of the oscillations γ
- Number of oscillations per period n
- [Proportion of time in oscillations α]

ALTERNATING RANDOM ORGANIZATION AND SHEAR

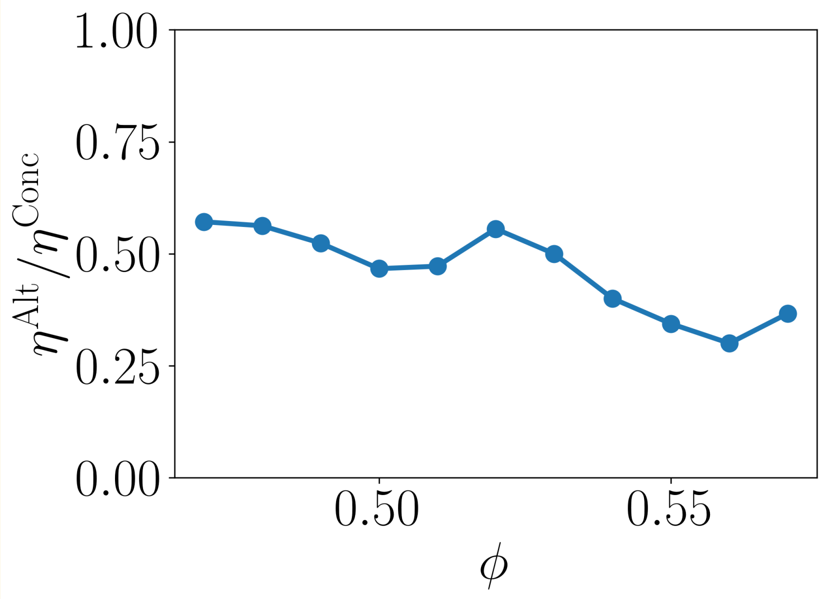
For $\gamma = 2\%$ and $\phi = 0.56$:



Few oscillations are enough

ALTERNATING VS CONCURRENT OCS

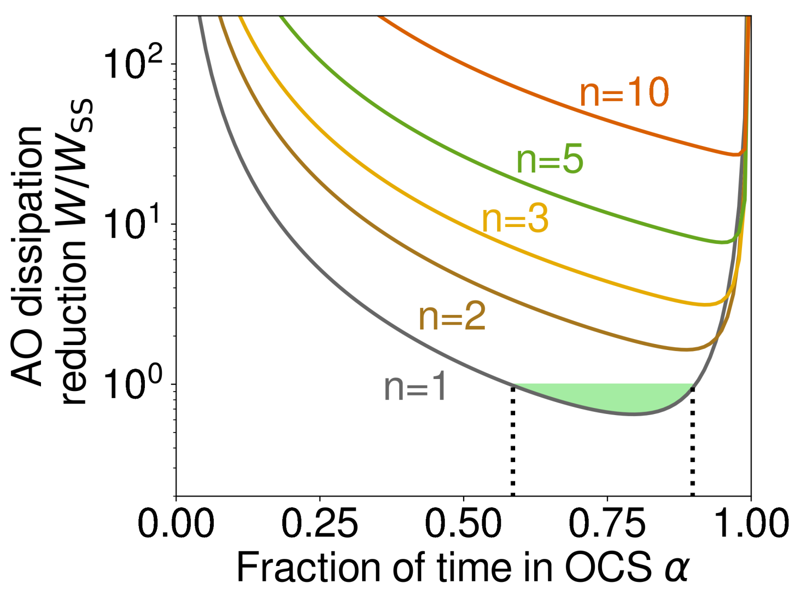
Viscosity obtained for alternating OCS with $n = 1$ and $\gamma = 1\%$ compared to high ω viscosity for concurrent OSP with same γ.



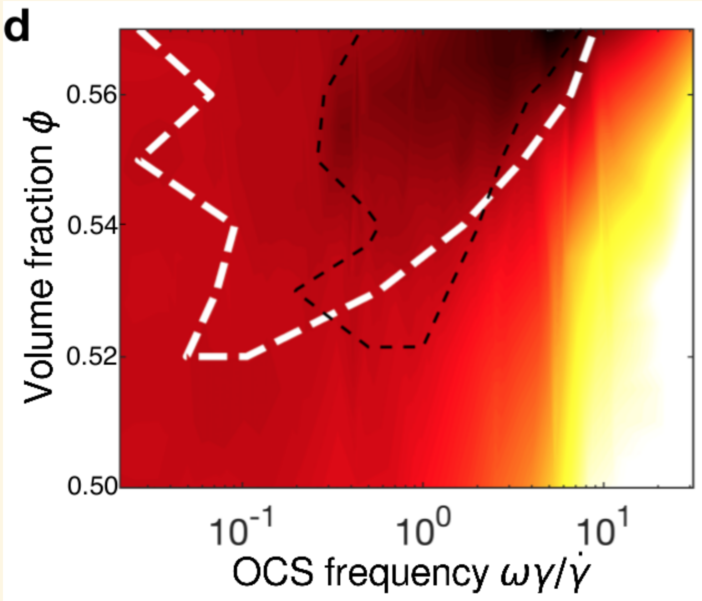
BACK TO DISSIPATION

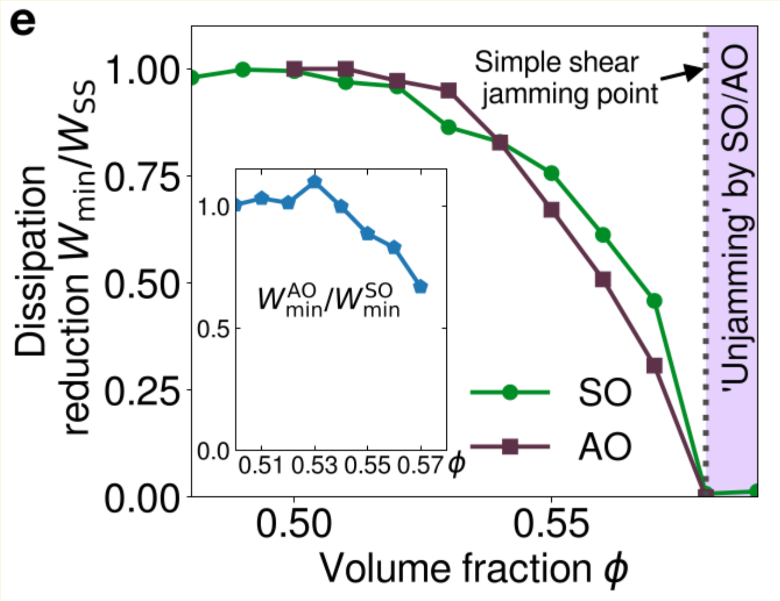
Depends on the time proportion spent in self-organization α!

For $\gamma = 1\%$ and $\phi = 0.56$:



BACK TO DISSIPATION





CONCLUSION

- Powerful tool for viscosity/dissipation reduction *without* composition tuning
- Generic to granular suspensions
- Use of a nonequilibrium phase transition in a rheological context
- Adaptable for industrial devices?