Taking control of flowing dense suspensions

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UNIVERSITY OF CAMBRIDGE

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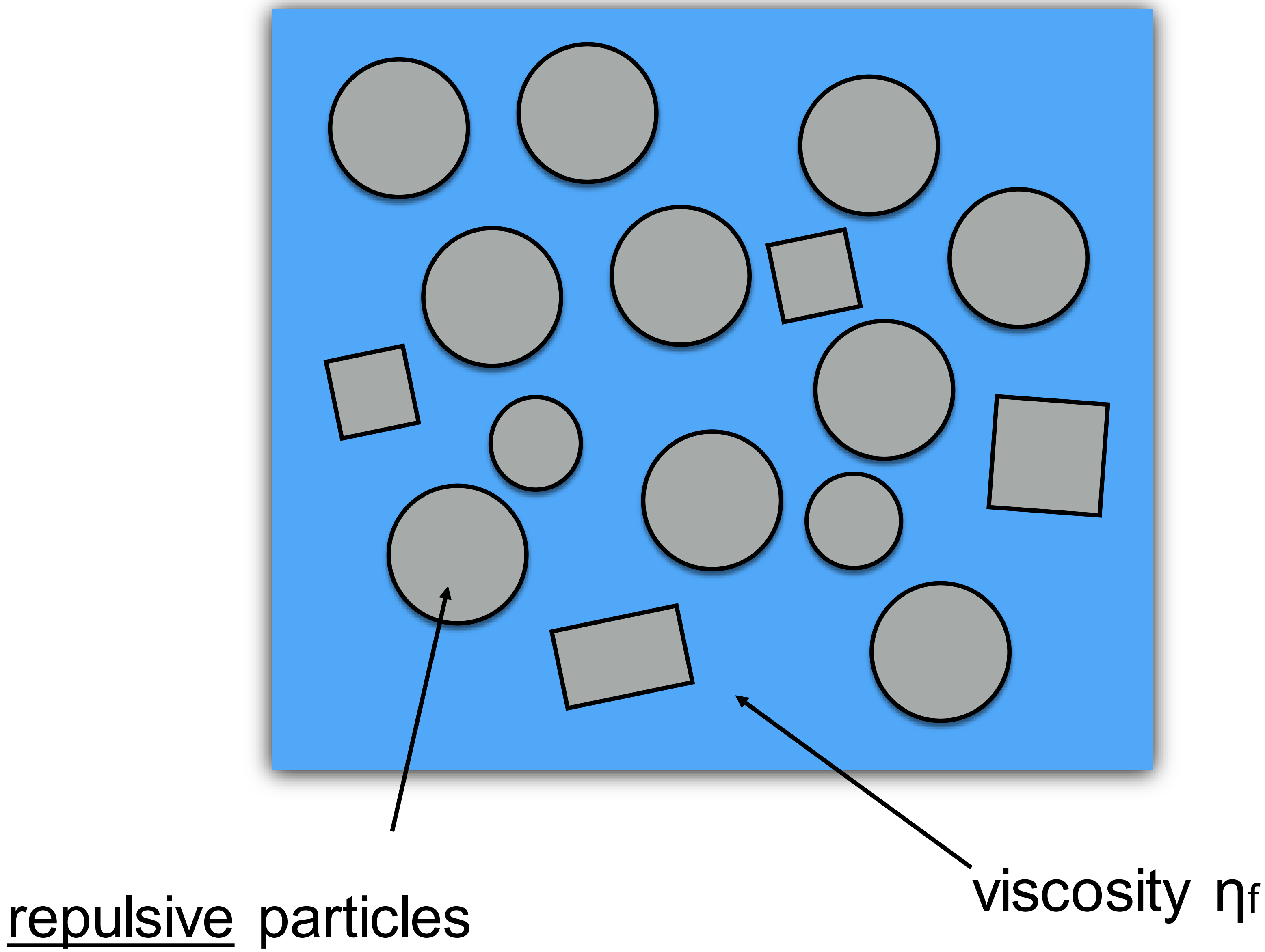
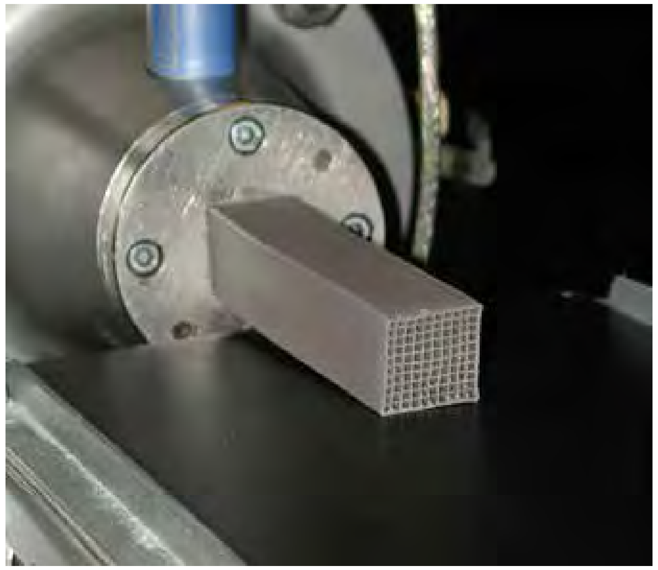
Research interests
Suspension rheology
Self-assembling athermal emulsions
Theory of polymer glasses

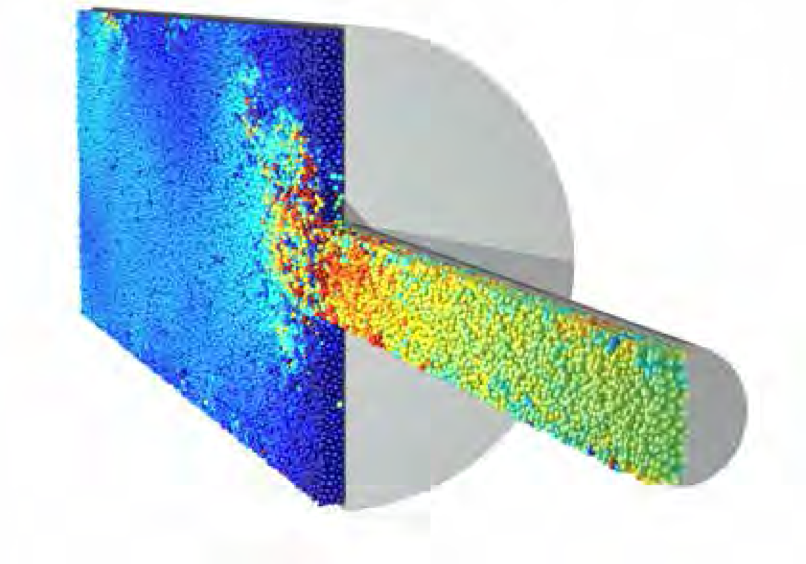
Dense suspensions



volume fraction φ~30-65%

Dense suspensions





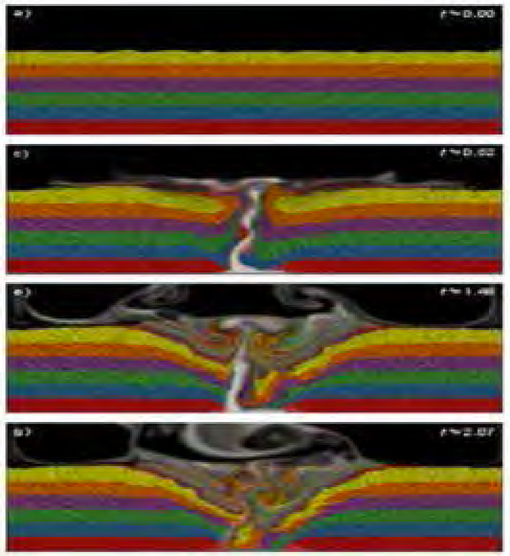
Ness et al, AIChE Journal (2017)

In industry:

Paste extrusion

Cement/concrete handling and transportation

Muds, slurries, wet sands



In nature:

Magma flows

e.g. Bergantz et al, Journal of Geophysical Research (2017)

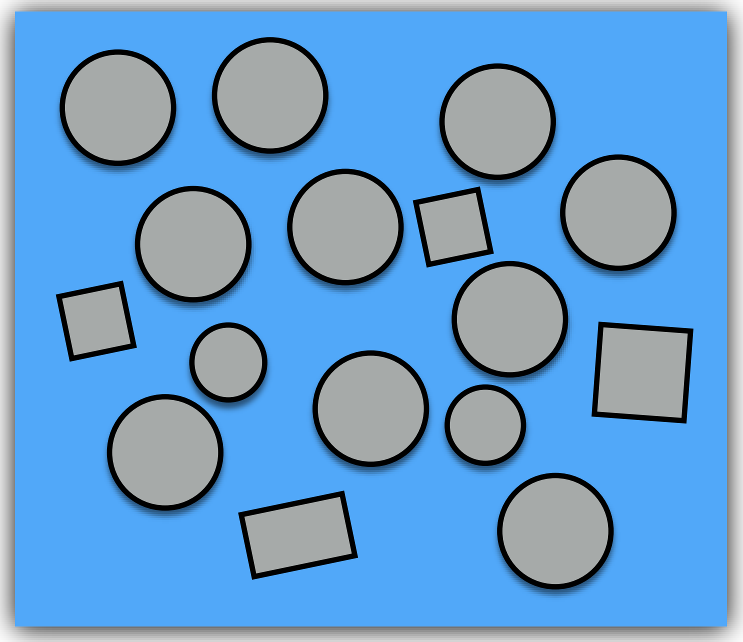
Subsea landslides

In medicine:

Calcium phosphate cement for bone replacement

e.g. Zhang et al, Acta Biomaterialia (2014)

Dense suspensions



10^{-9} 10^{-6} 10^{-3} 10^{0} particle size [m]

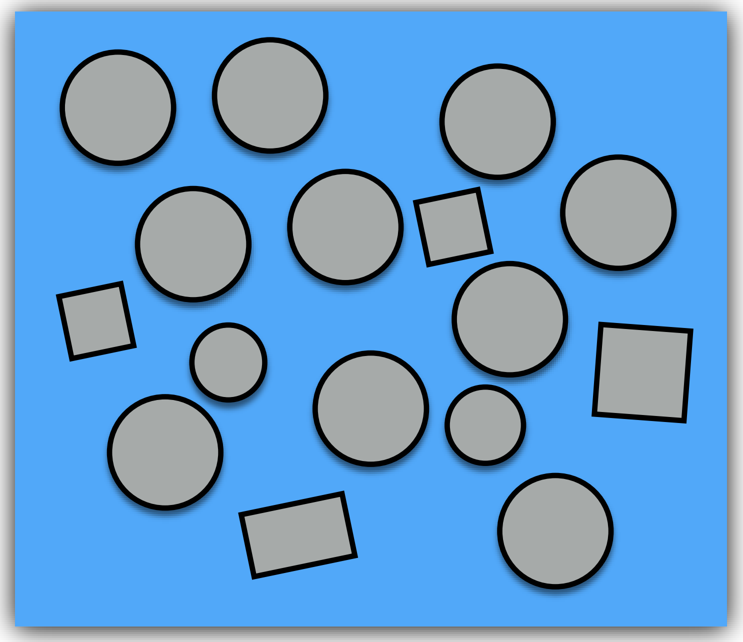
nanoparticle dispersions

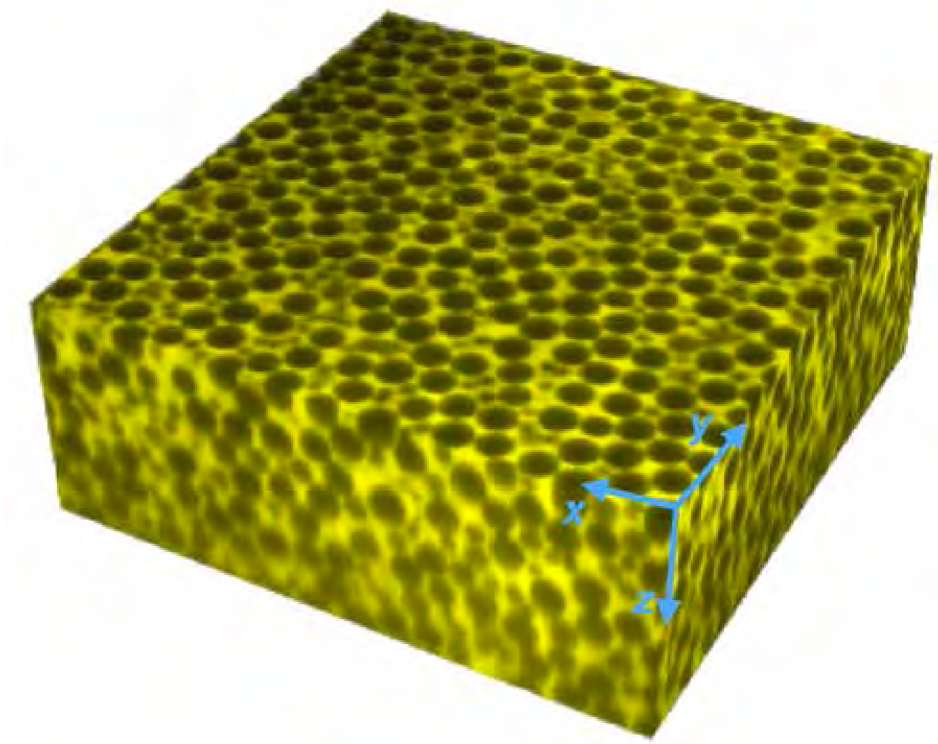
geophysical flows

Brownian motion important

Particle inertia + gravity important

Dense suspensions





10^{-9} 10^{-6} 10^{-3} 10^{0} particle size [m]

nanoparticle dispersions

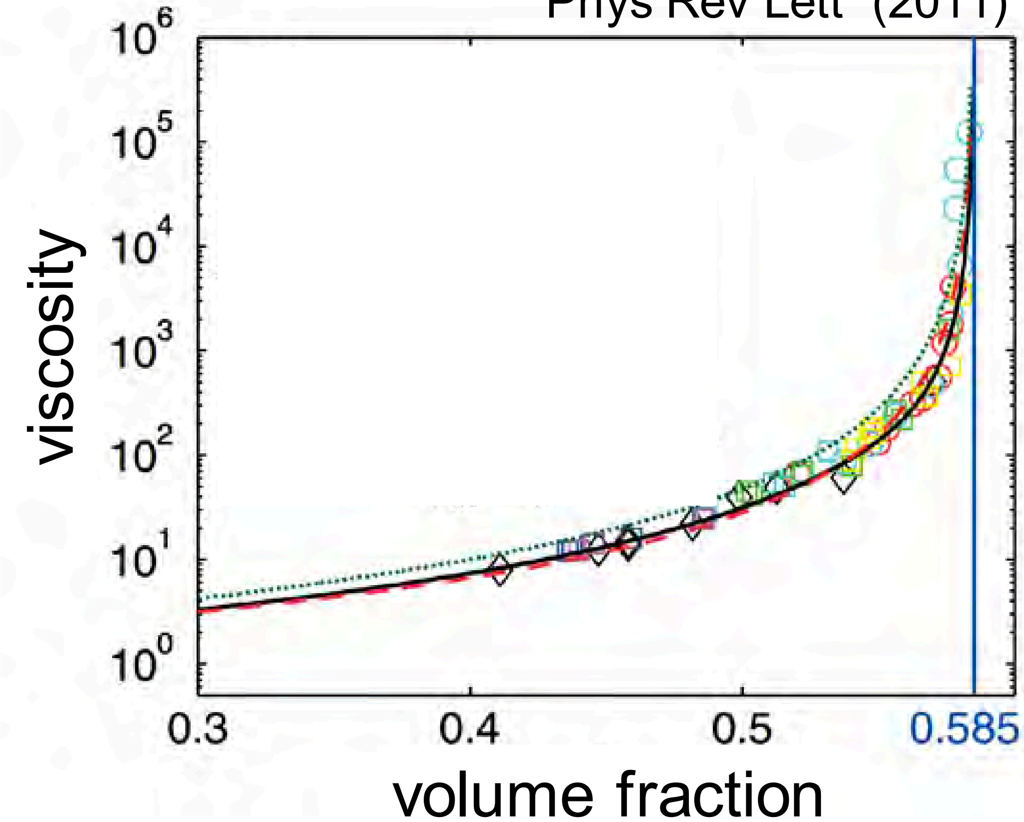
geophysical flows

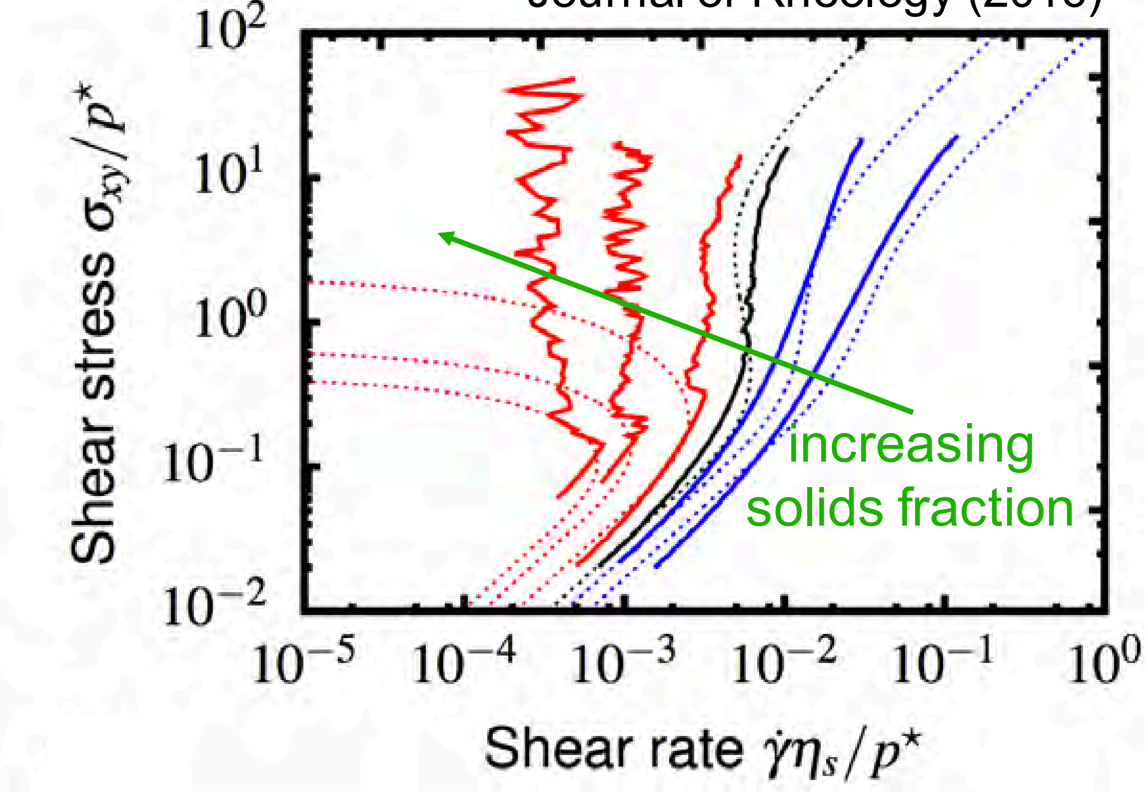
Brownian motion important

Particle inertia + gravity important

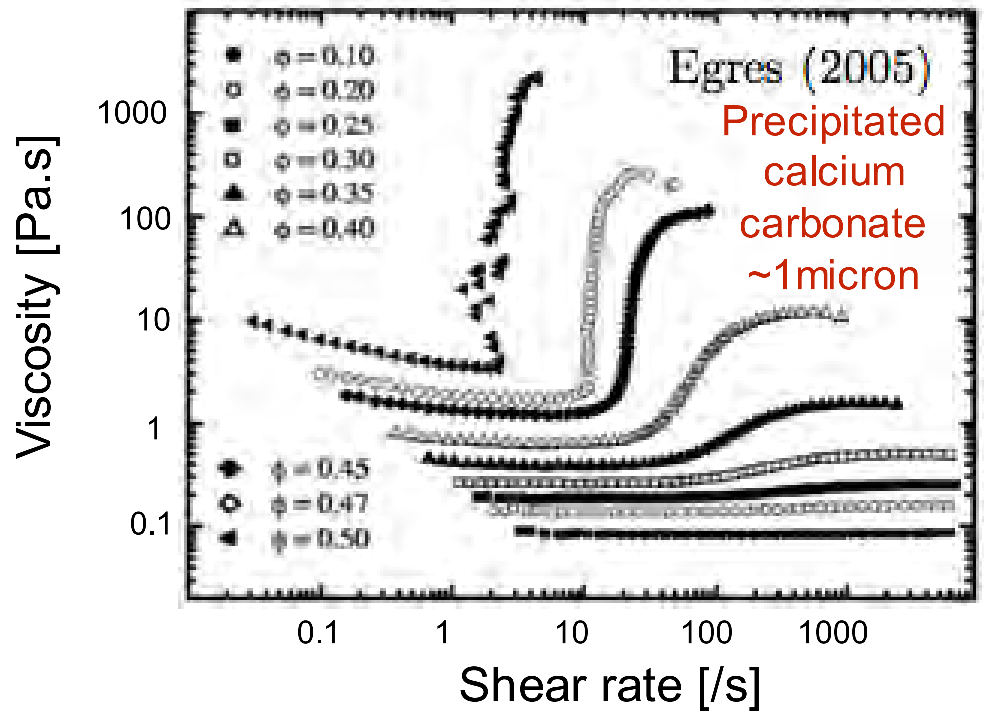
Relevant size range for many industries: wash coats, slurries, food stuffs

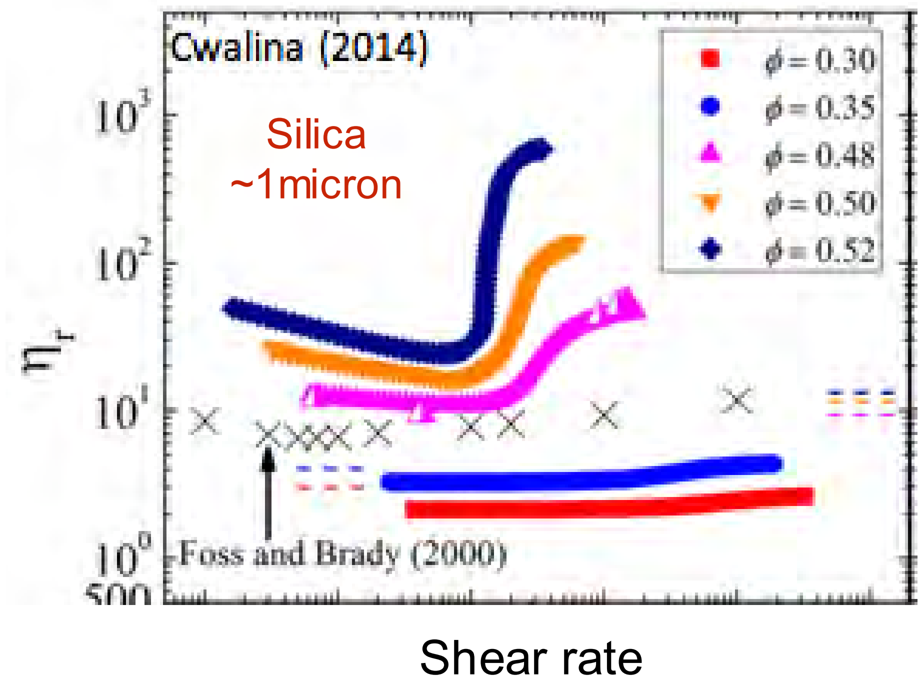
Dense suspensions - *processing challenges*

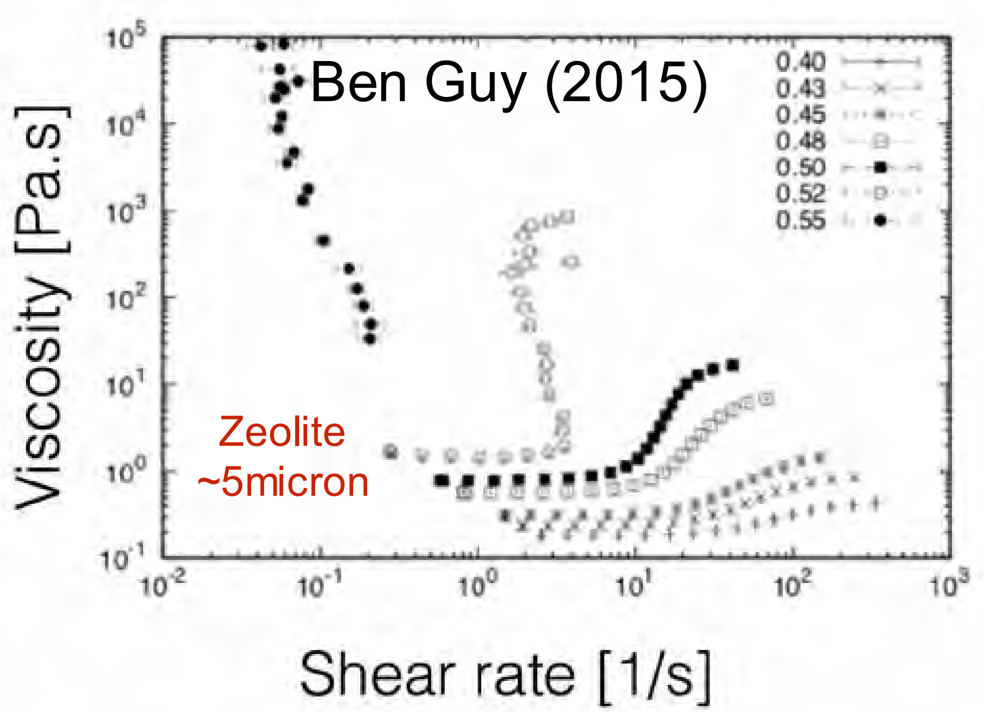


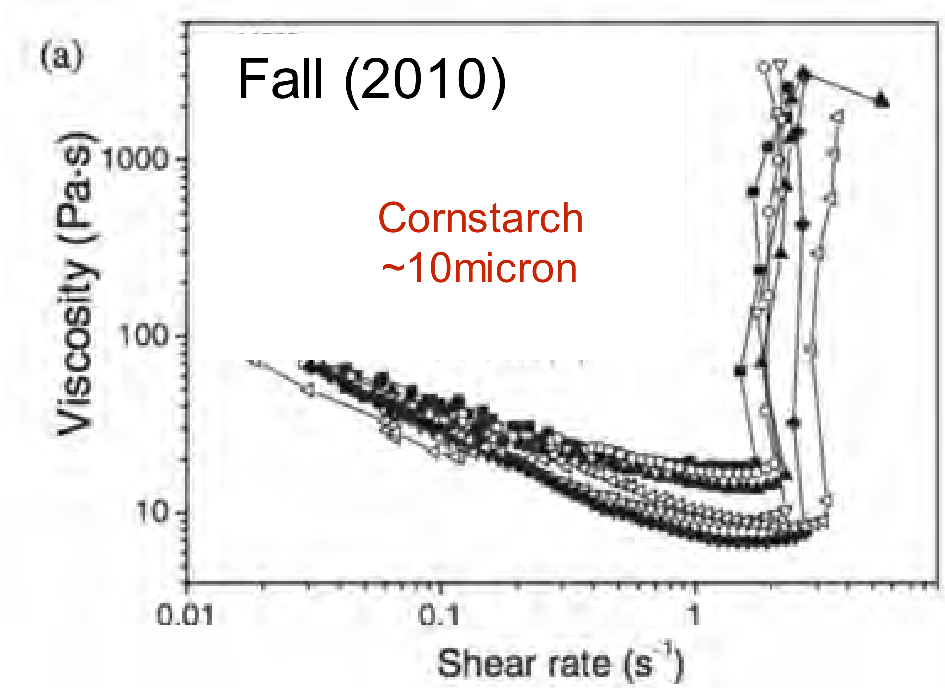


Dense suspensions - *processing challenges*









Diagnosing these rheological features

A key practical question is:

Should we be most worried about the hydrodynamics (i.e. the fluid properties) or the surface contacts (i.e. the particle properties)?

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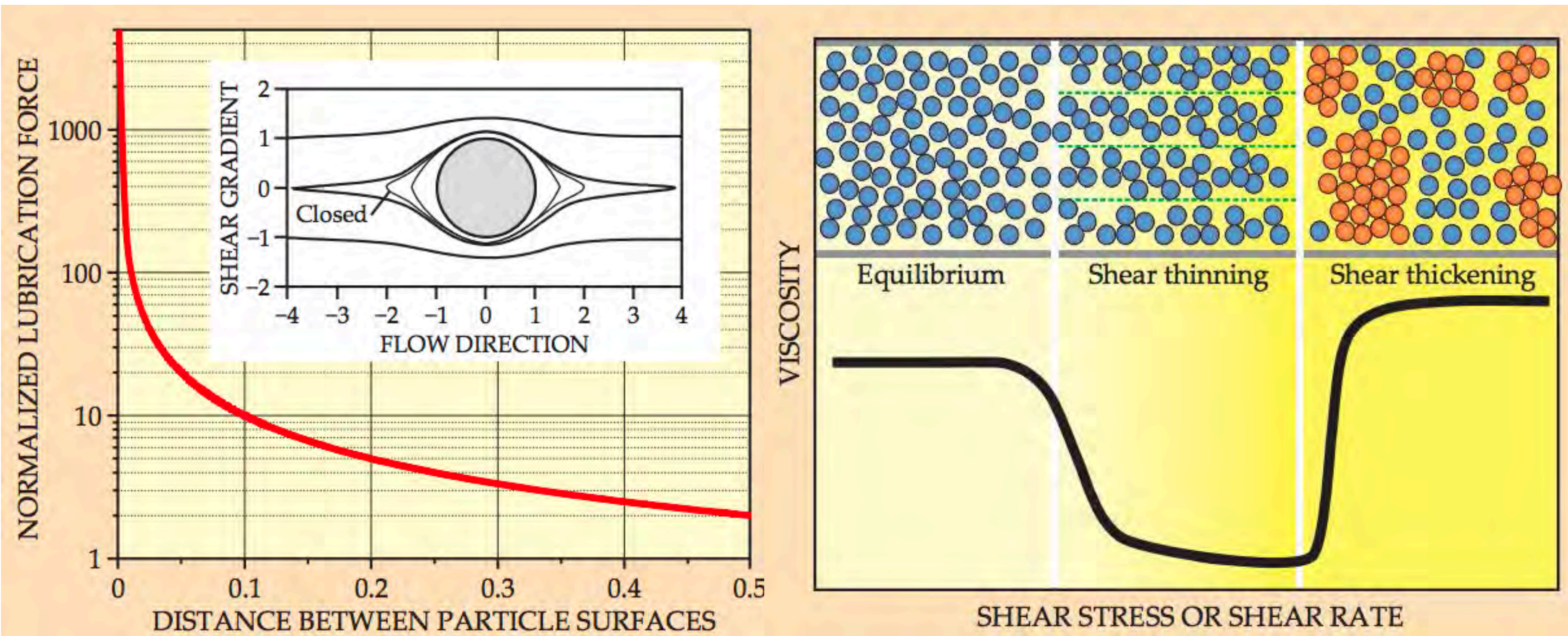
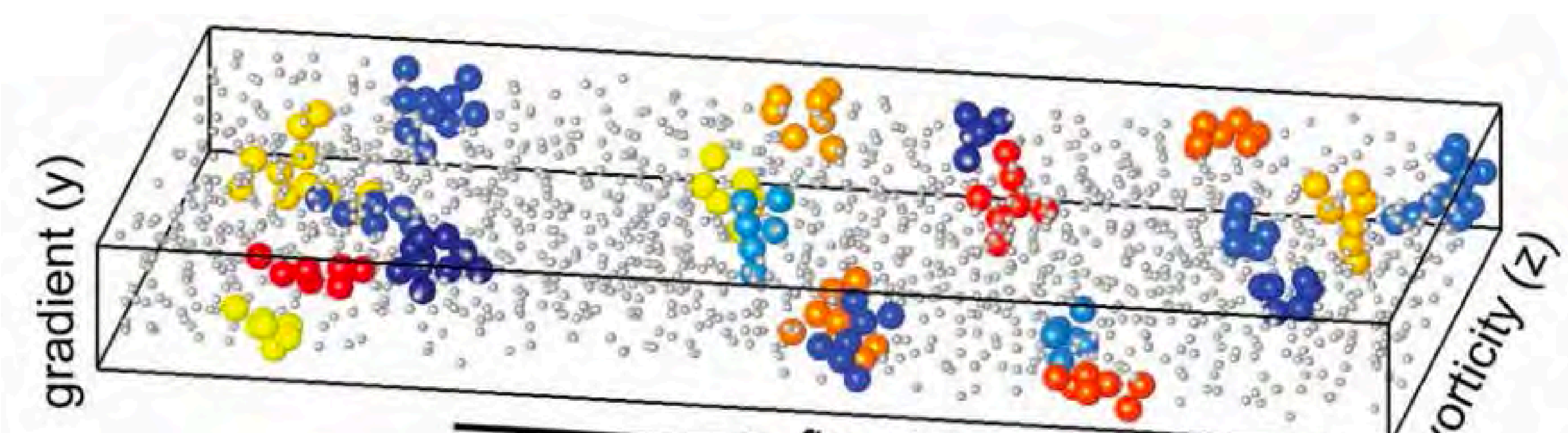


Wagner and Brady, Physics Today (2009):



Cheng et al, Science (2011):

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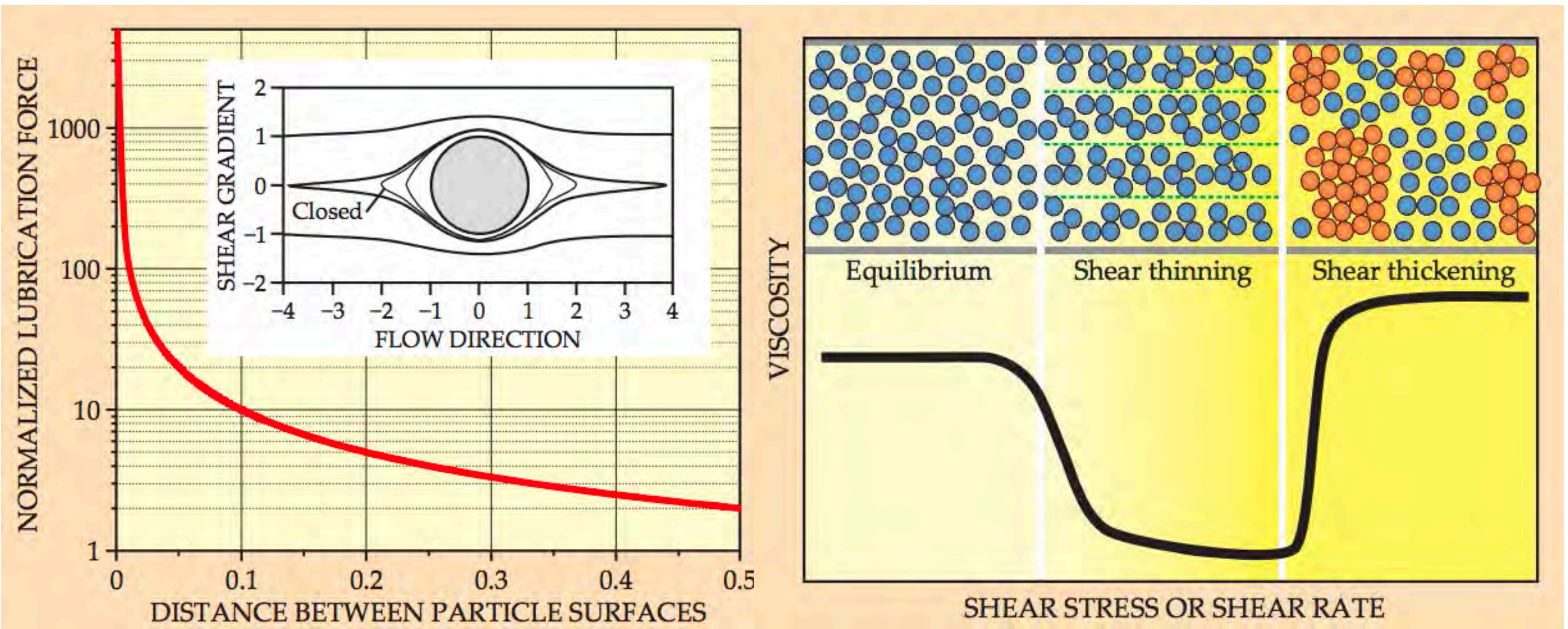

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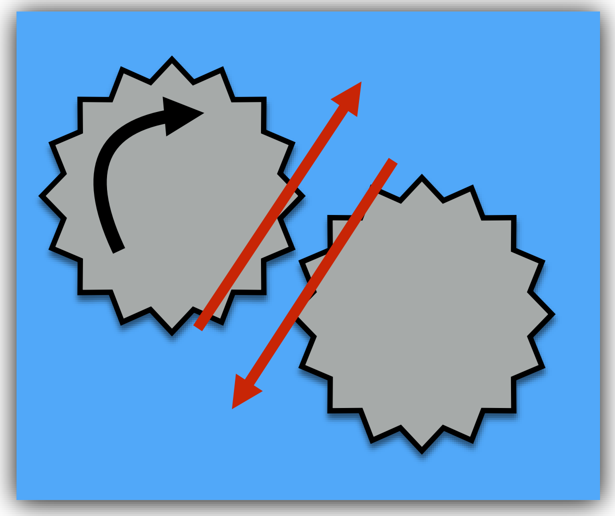
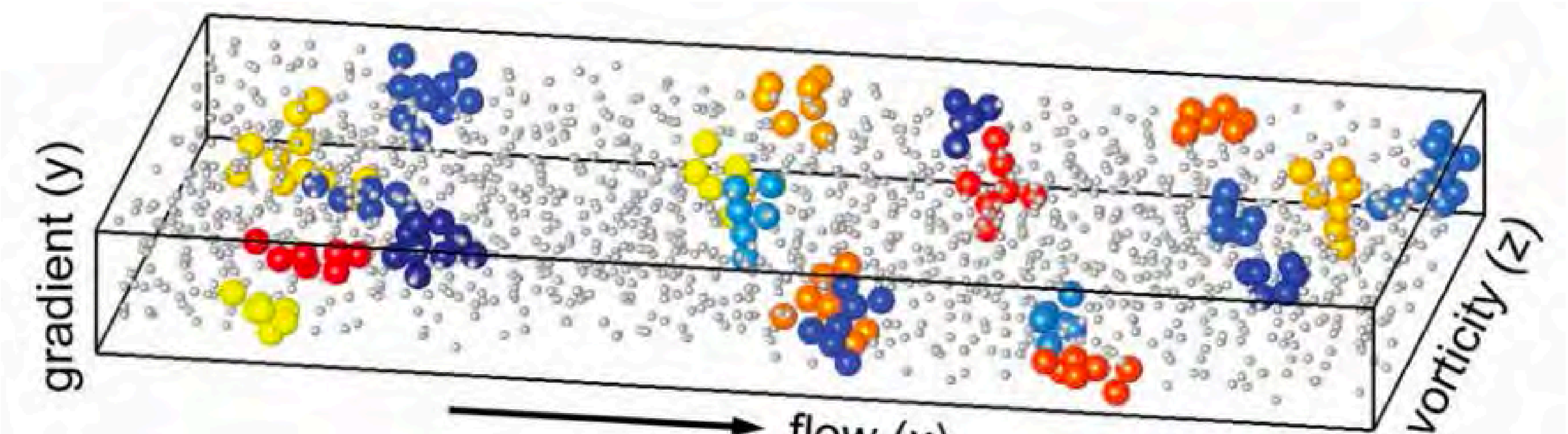


Fernandez et al, PRL (2013)
Seto et al, PRL (2013)
Wyart and Cates, PRL (2014)



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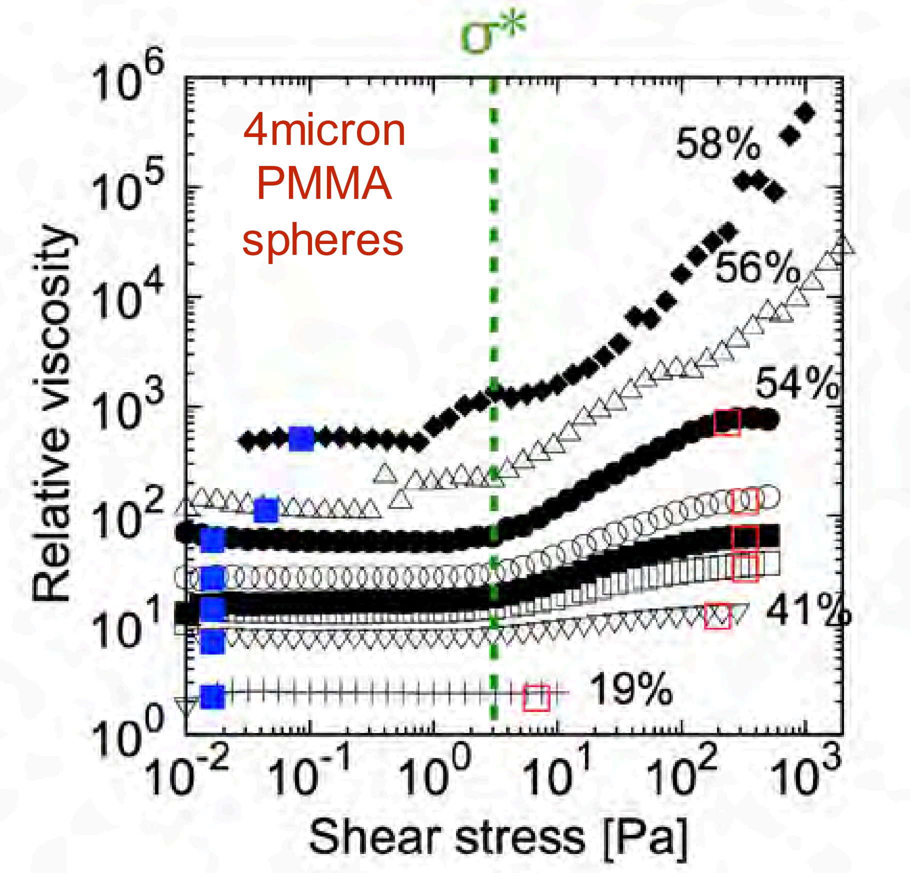
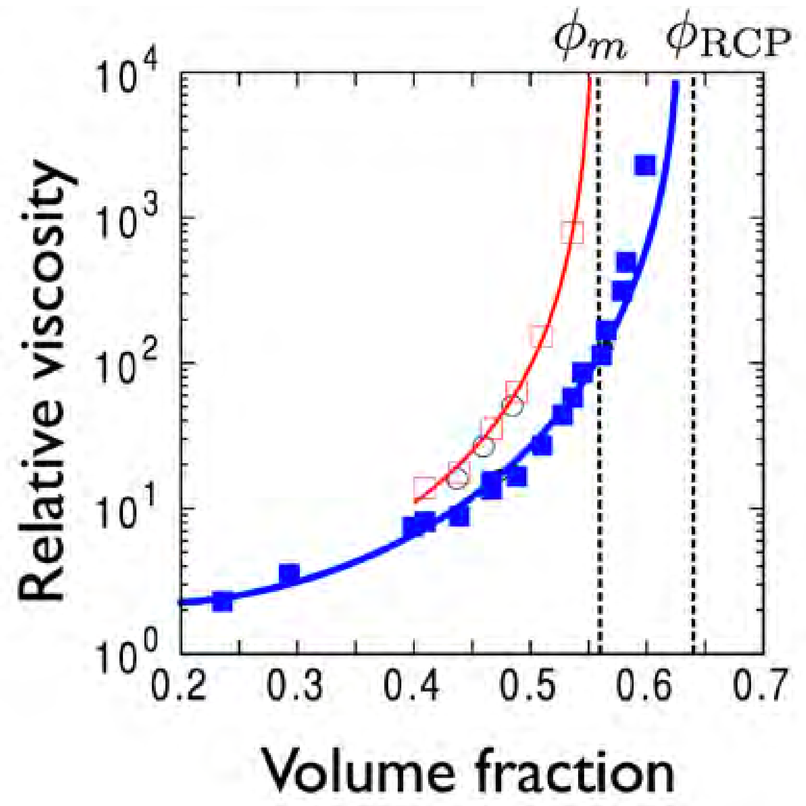
5 key characterisation experiments that suggest particle properties

Experiment 1: viscosity divergence





Below σ* Flow arrest occurs at ~64%

Above σ* Flow arrest occurs at ~57%

Guy, Hermes, Poon, PRL (2015)

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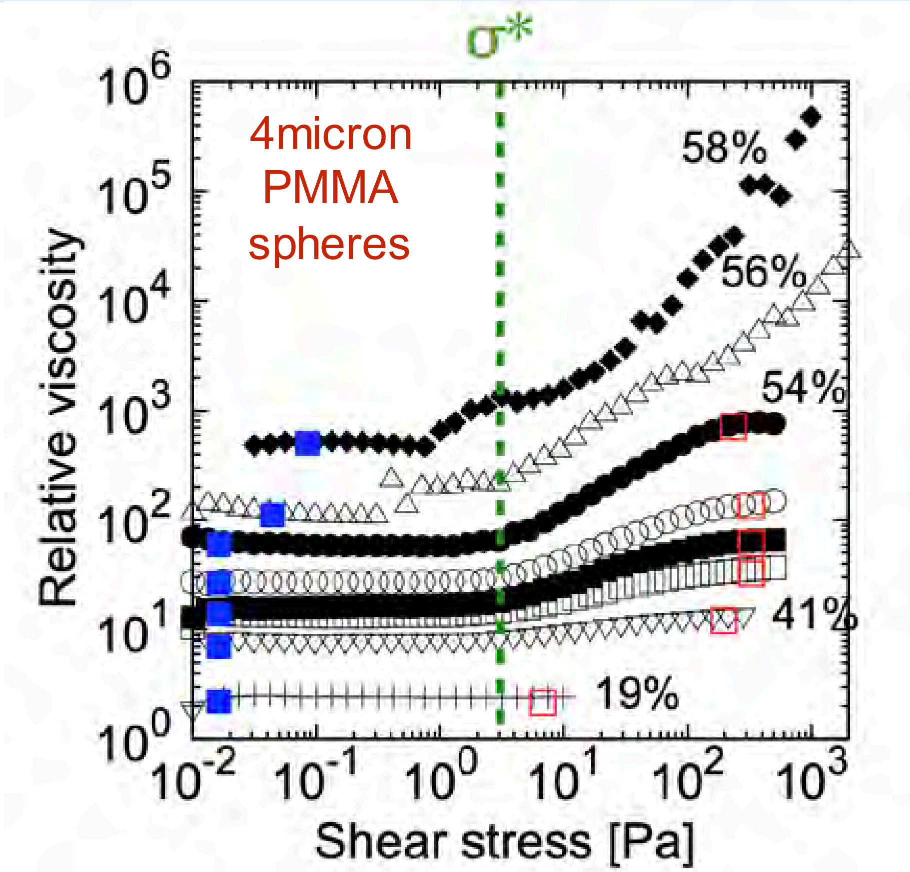
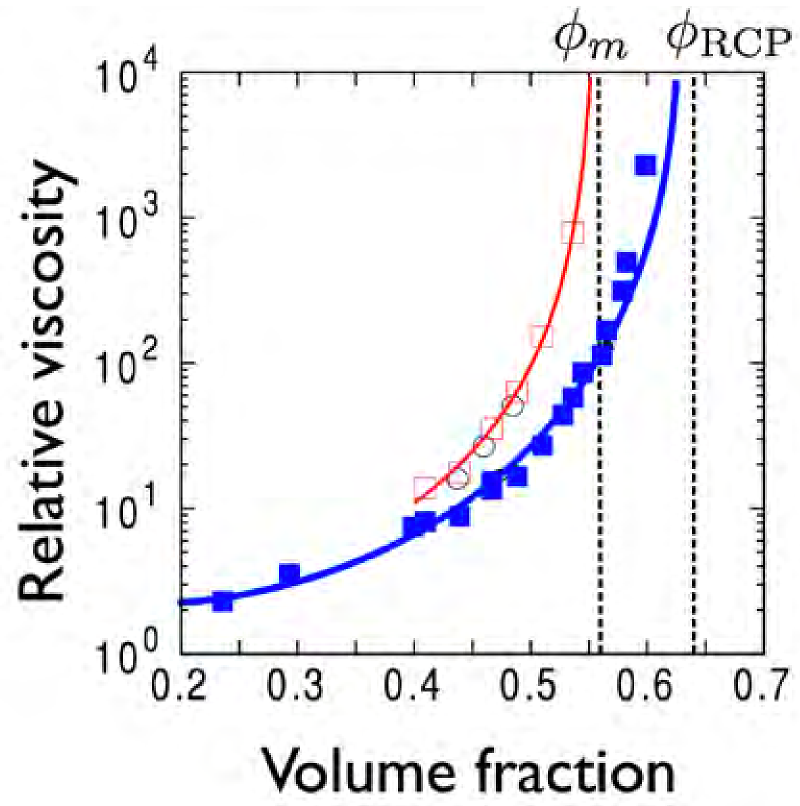


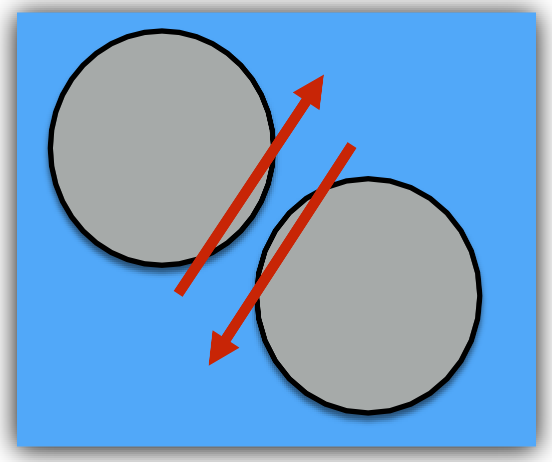


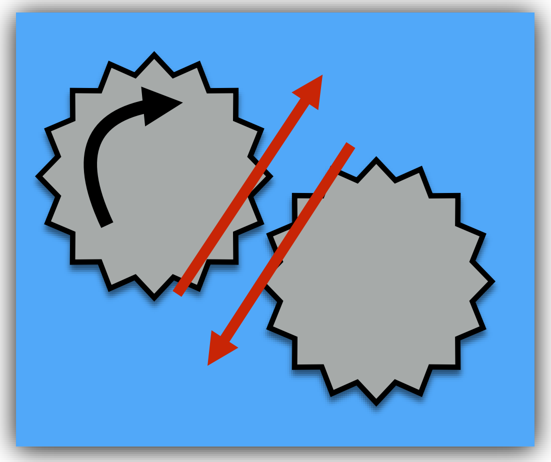
Below σ* Flow arrest occurs at ~64%

Above σ* Flow arrest occurs at ~57%

*Random close packing for **smooth** particles*

*Random loose packing for **rough** particles*





Guy, Hermes, Poon, PRL (2015)

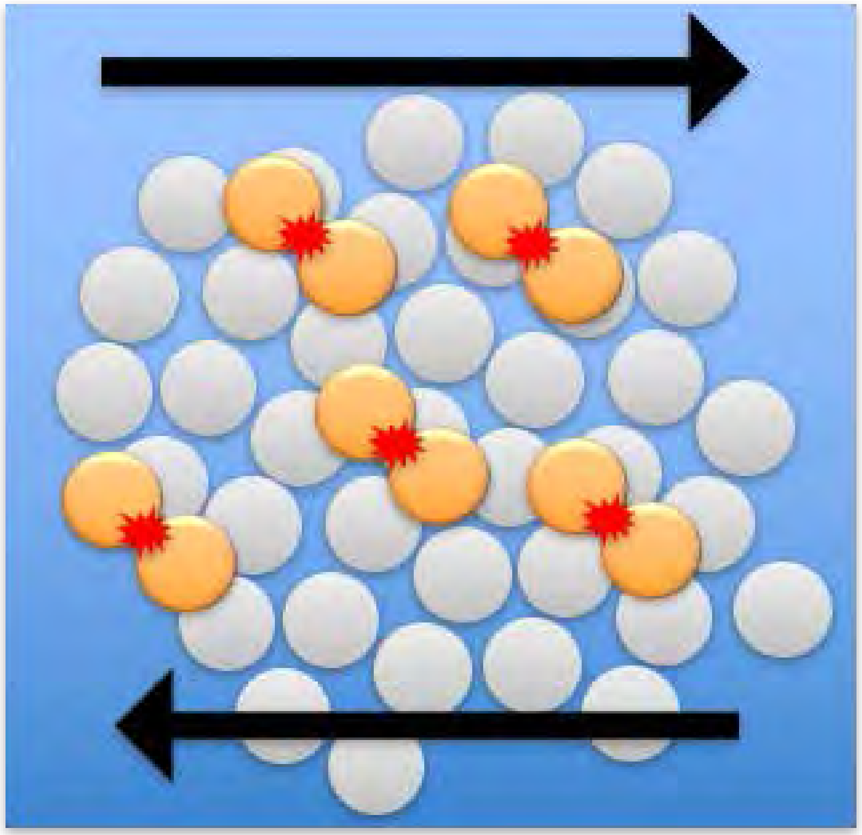
Frictional contacts constrain **translational** and **rotational** degrees of freedom

Experiment 2: shear flow reversal

Suspension stress has **hydrodynamic** and **contact** contributions

Fh ~ relative velocities
reversible

Fc ~ repulsive interaction
irreversible



Lin et al, PRL (2015)

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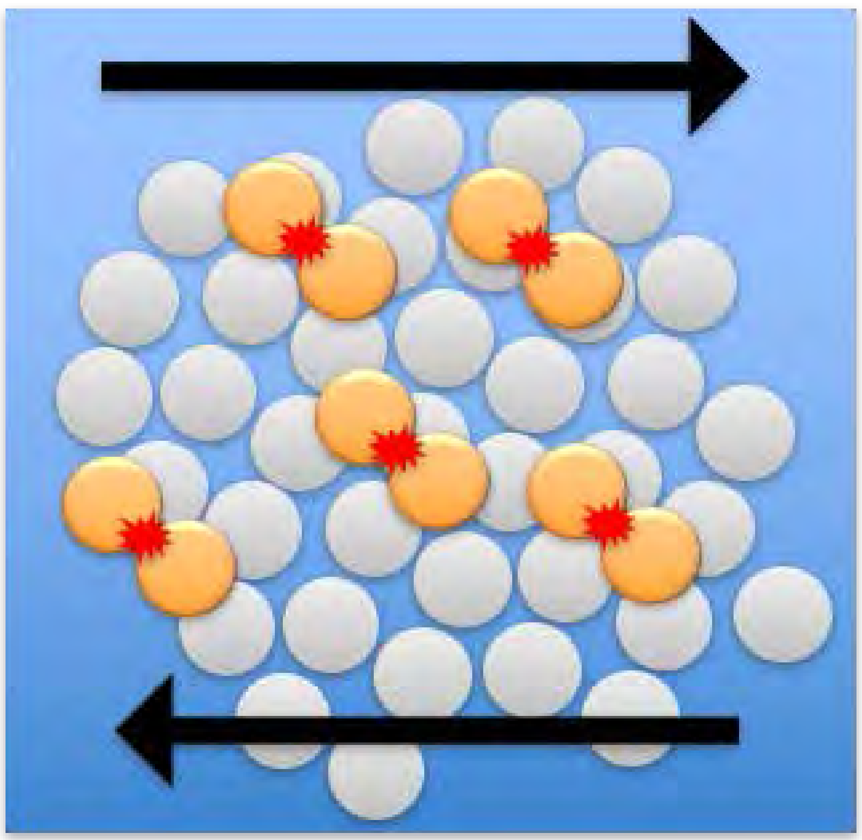

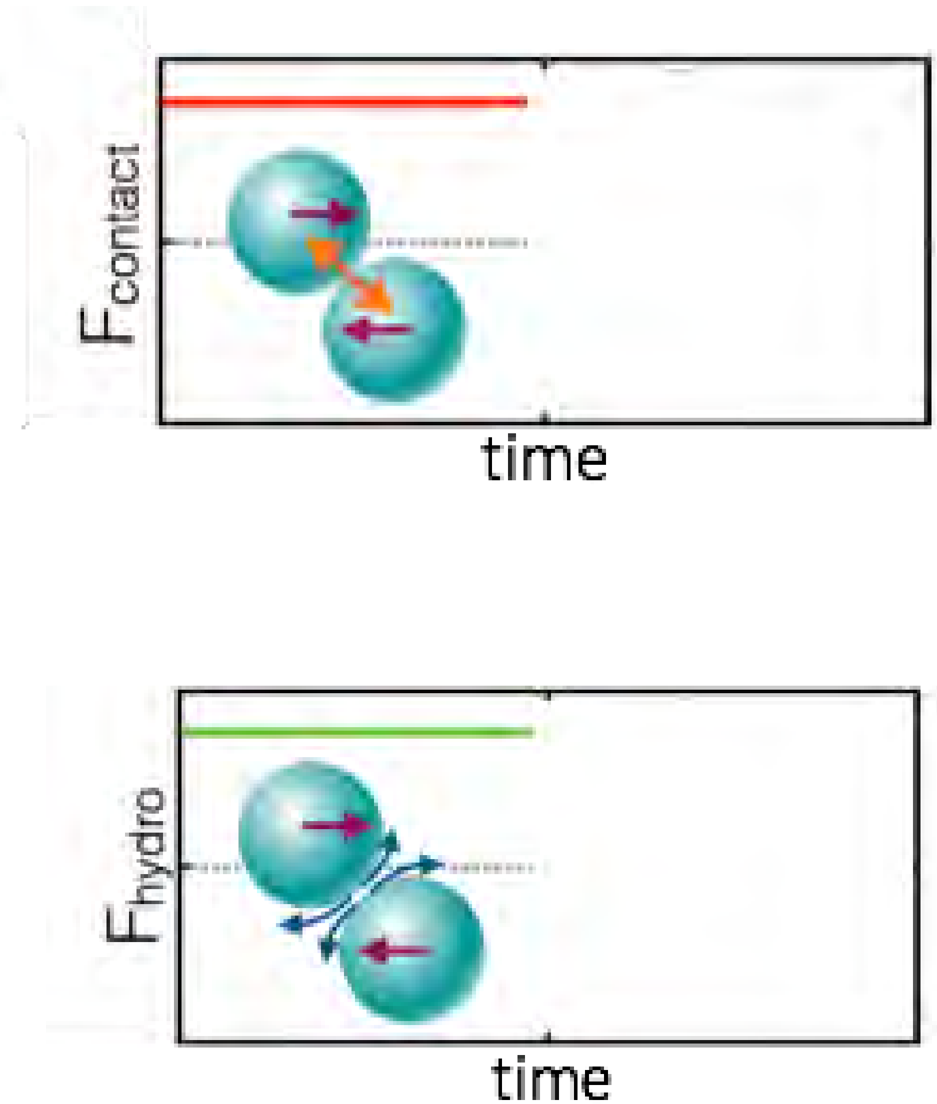

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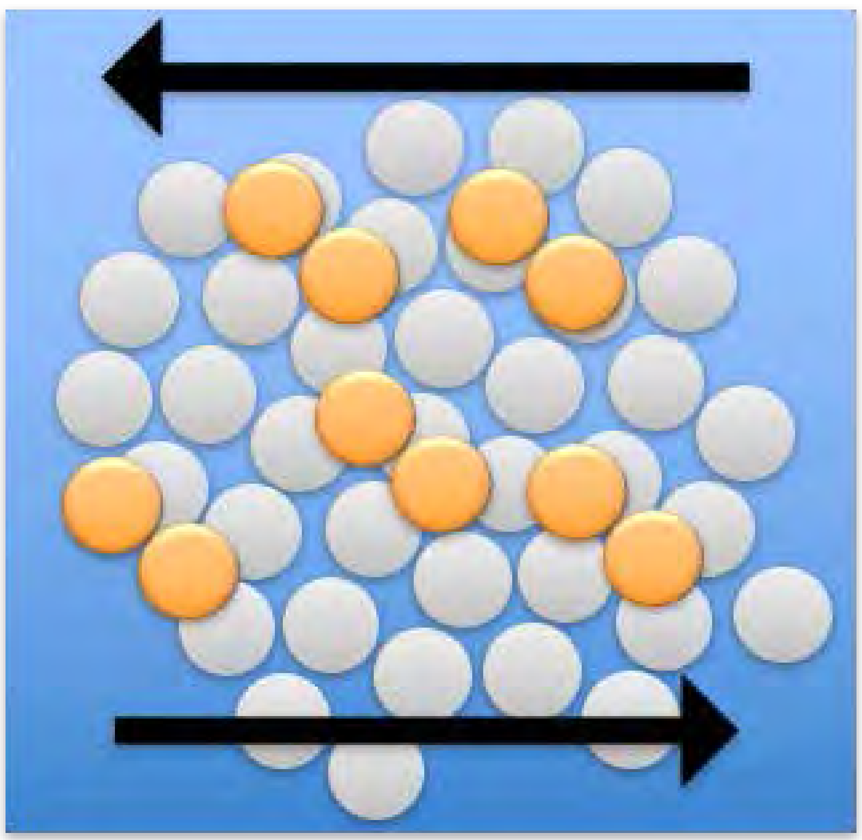

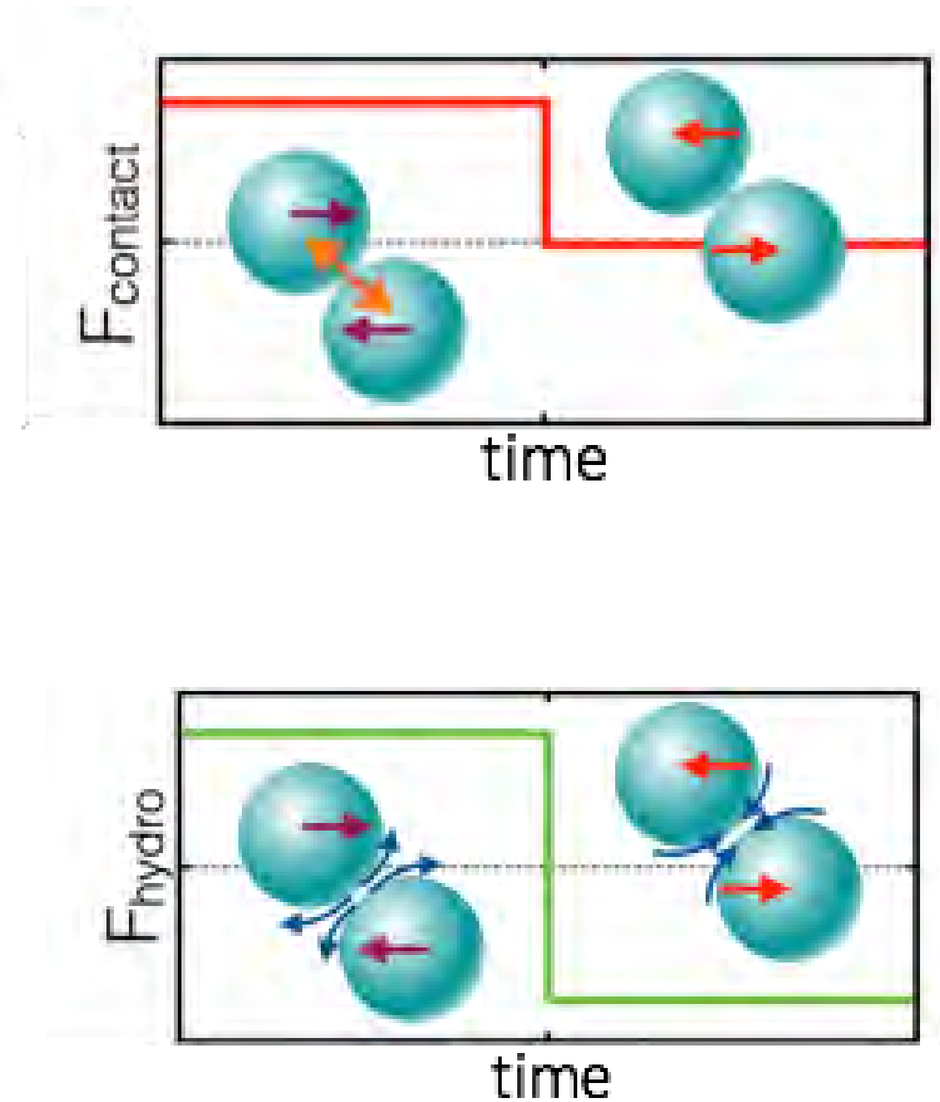

Lin et al, PRL (2015)

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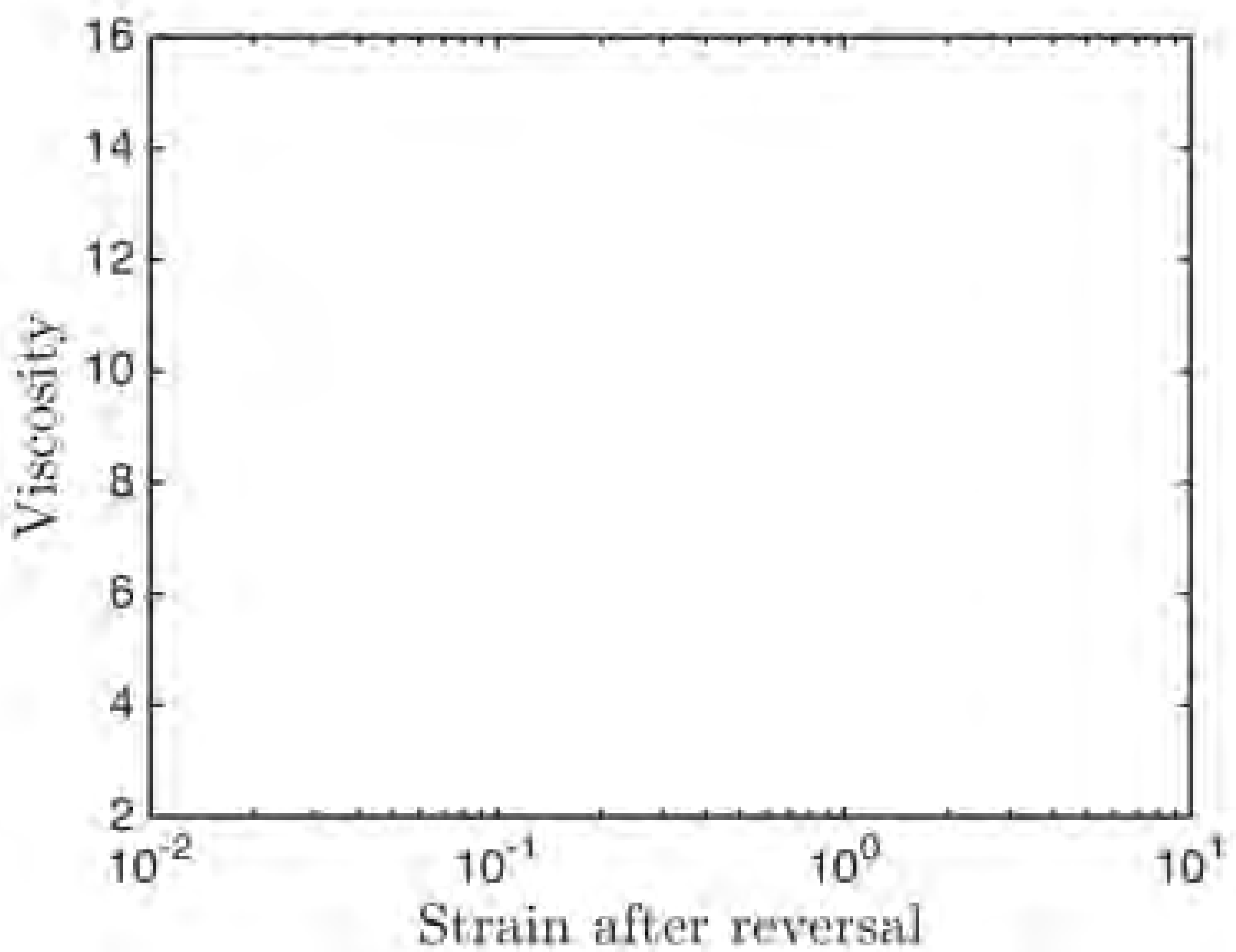

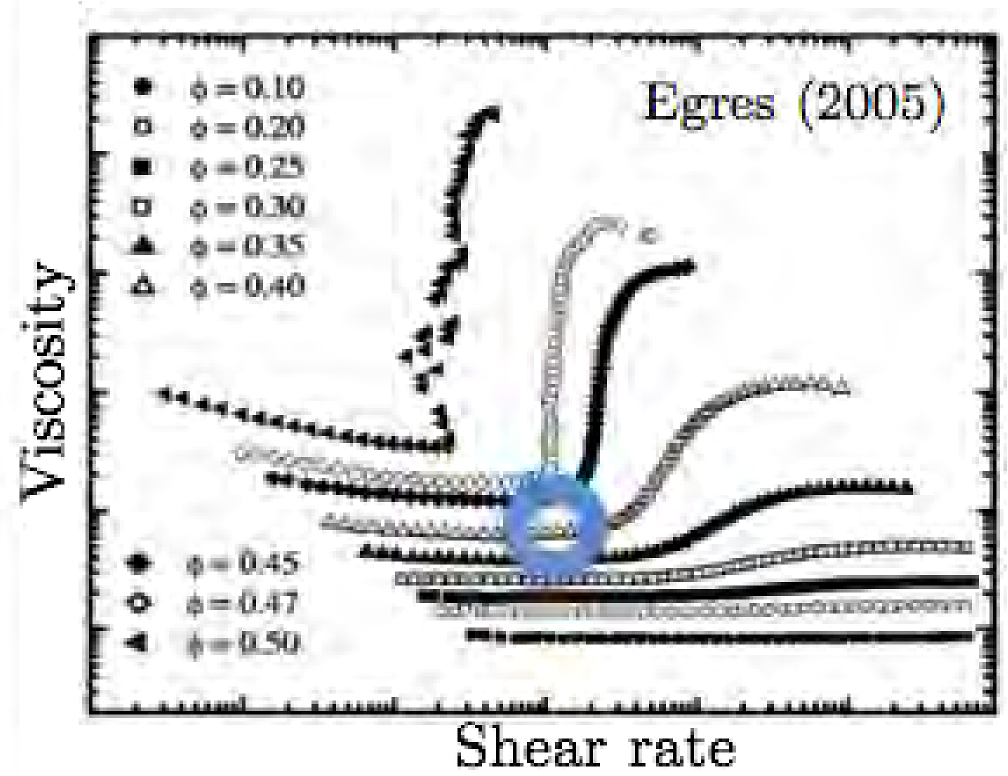

Lin et al, PRL (2015)

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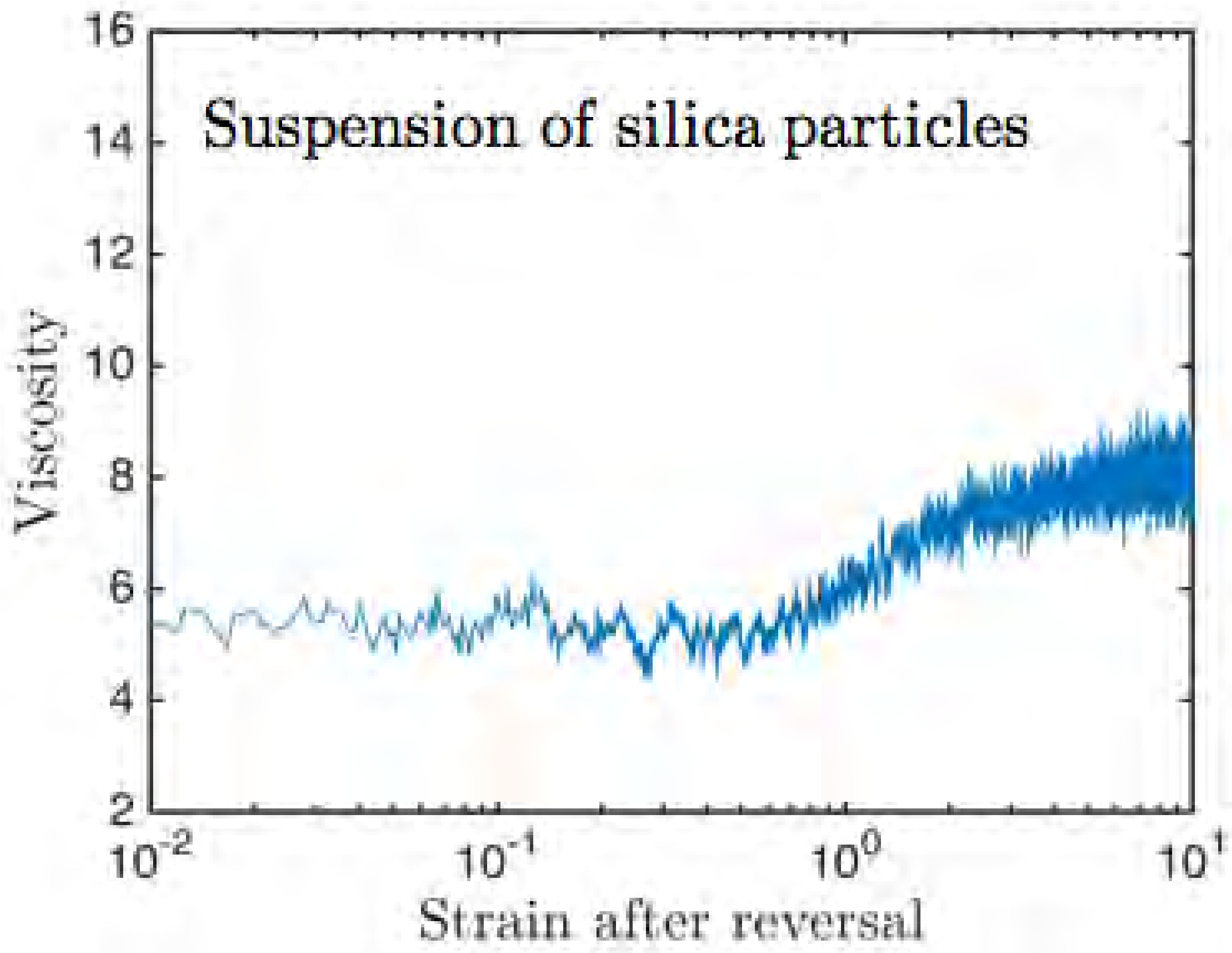

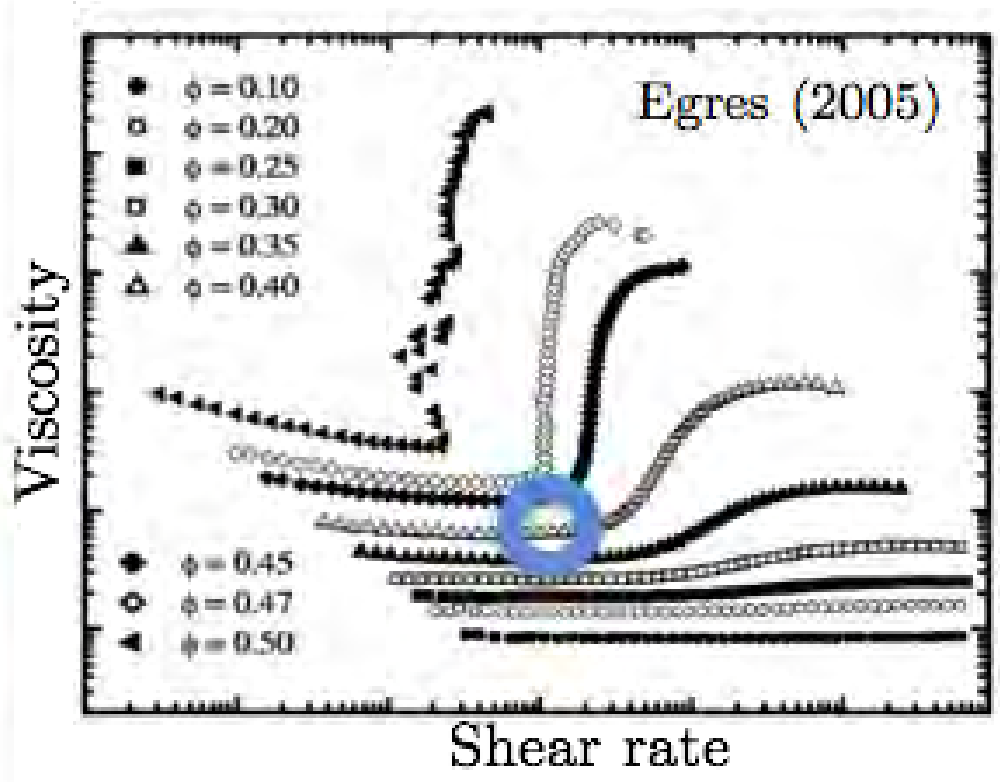

Lin et al, PRL (2015)

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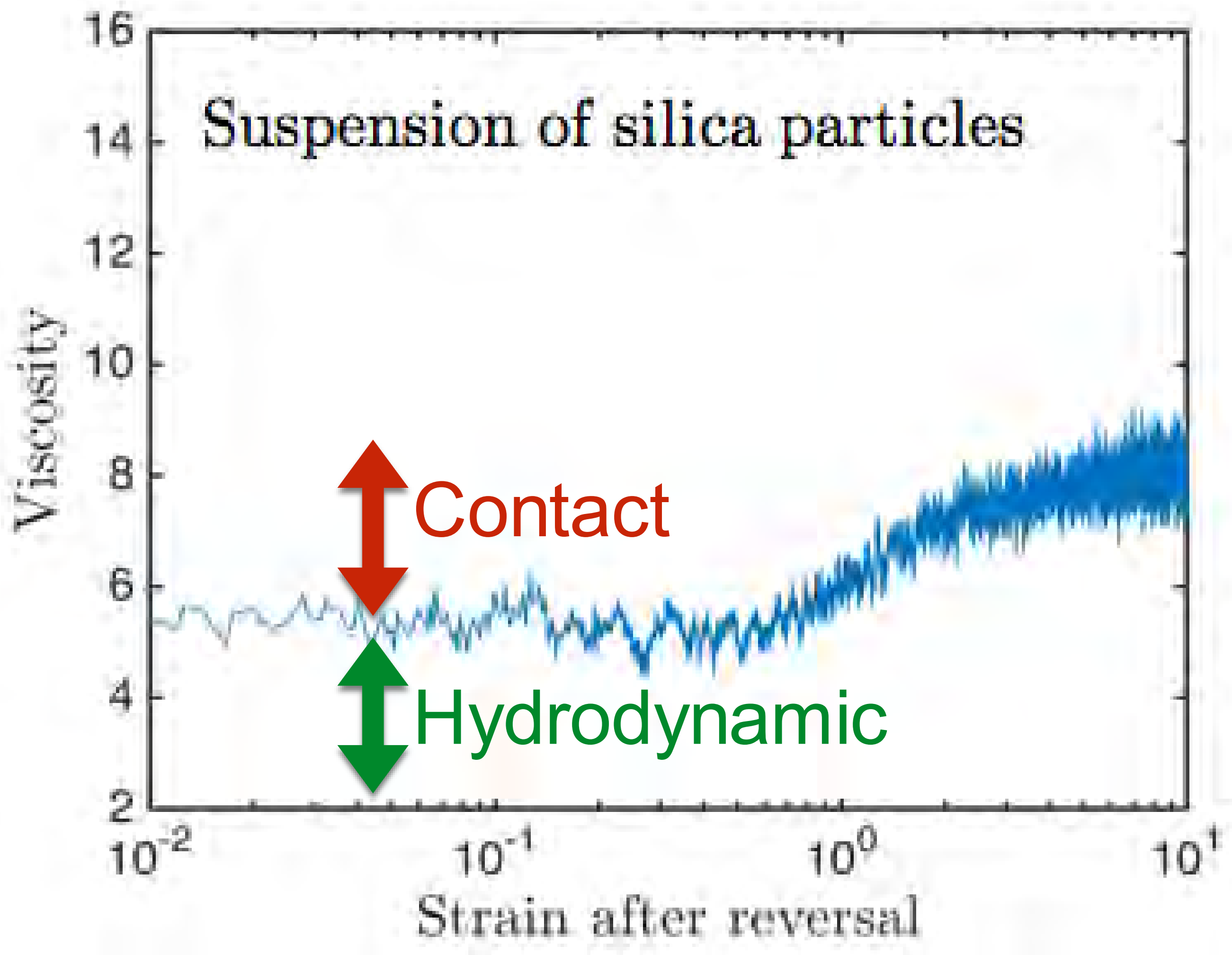

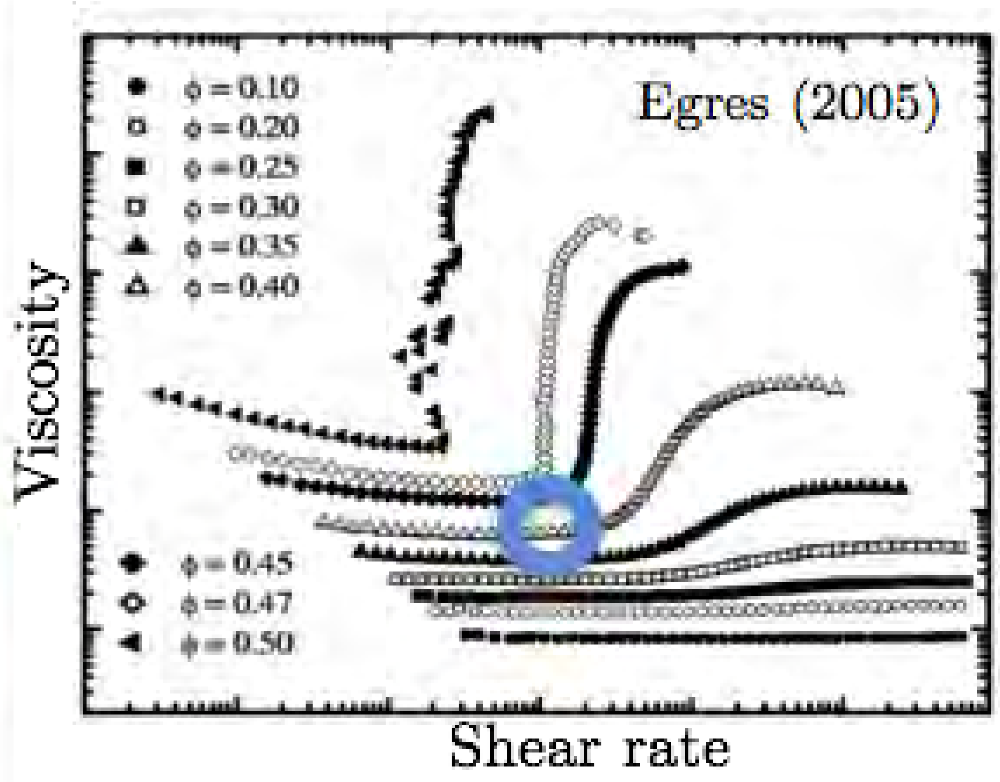

Lin et al, PRL (2015)

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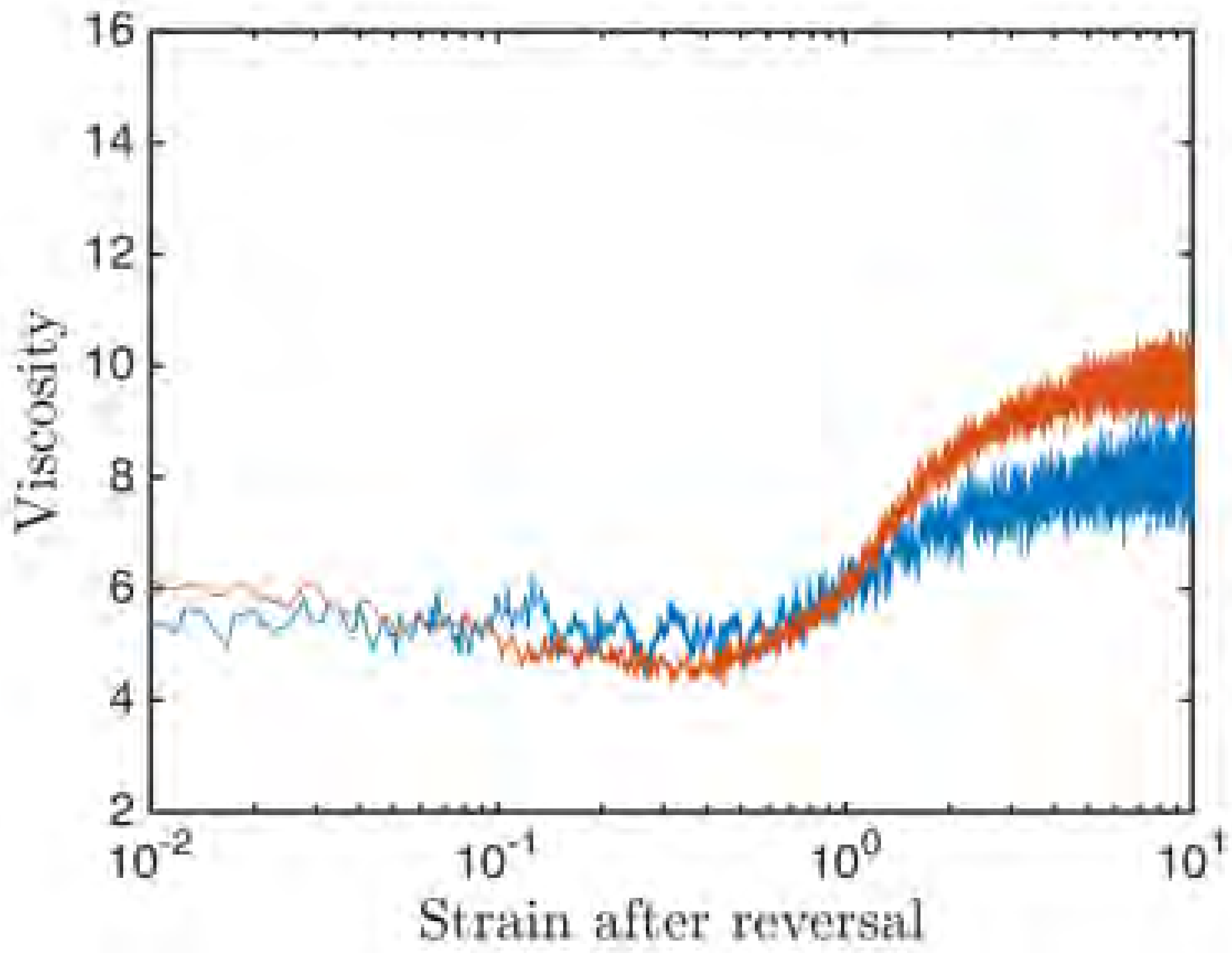

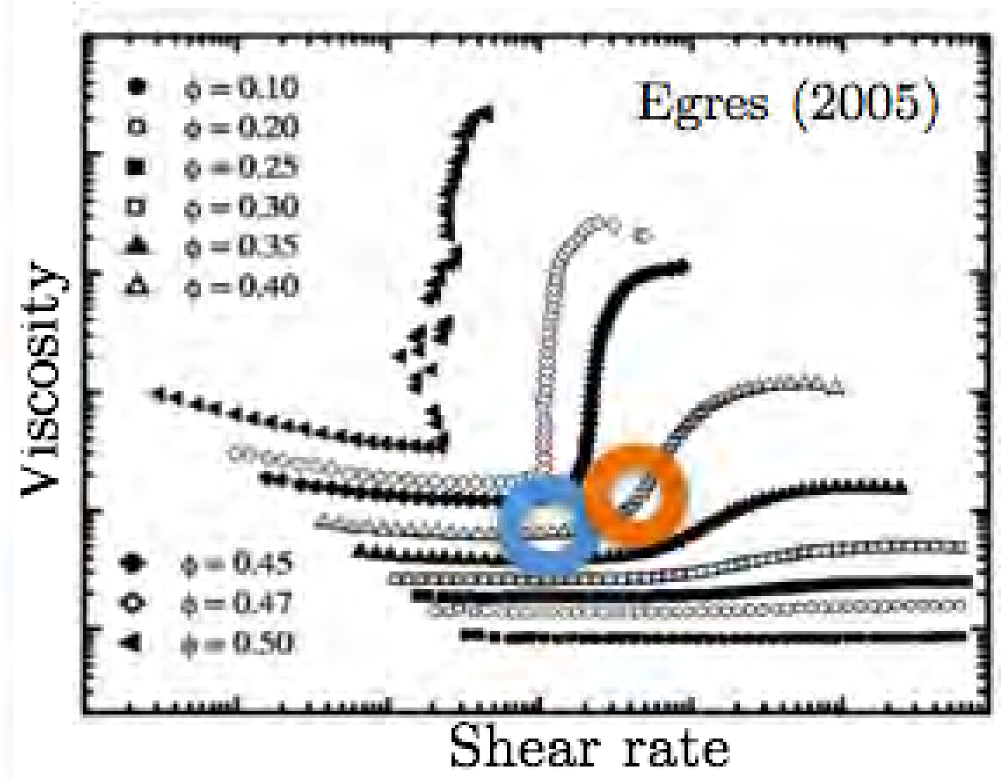

Lin et al, PRL (2015)

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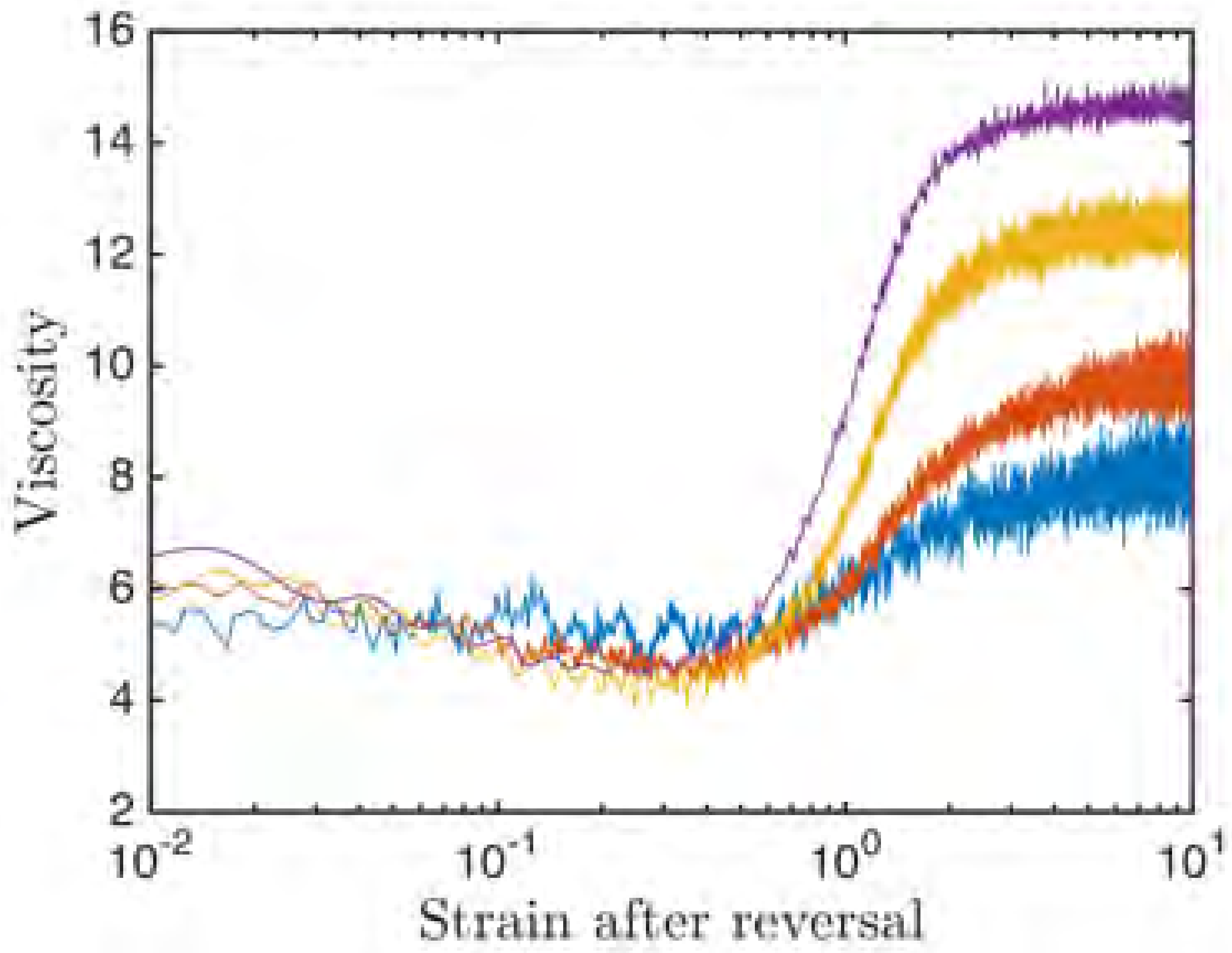

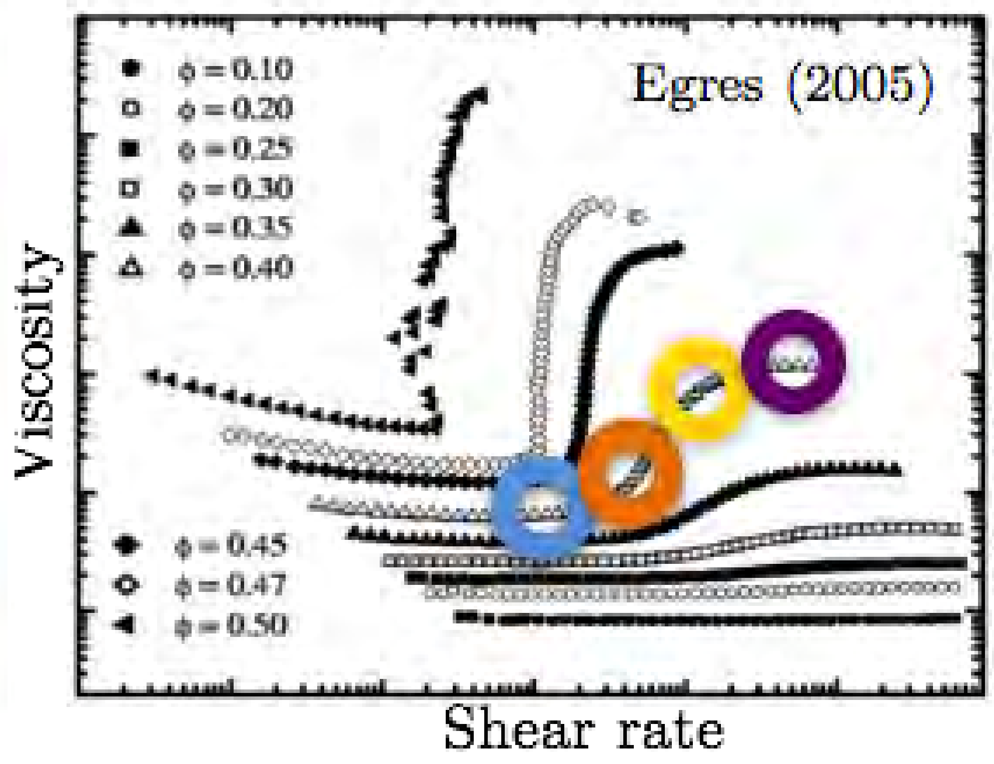

Lin et al, PRL (2015)

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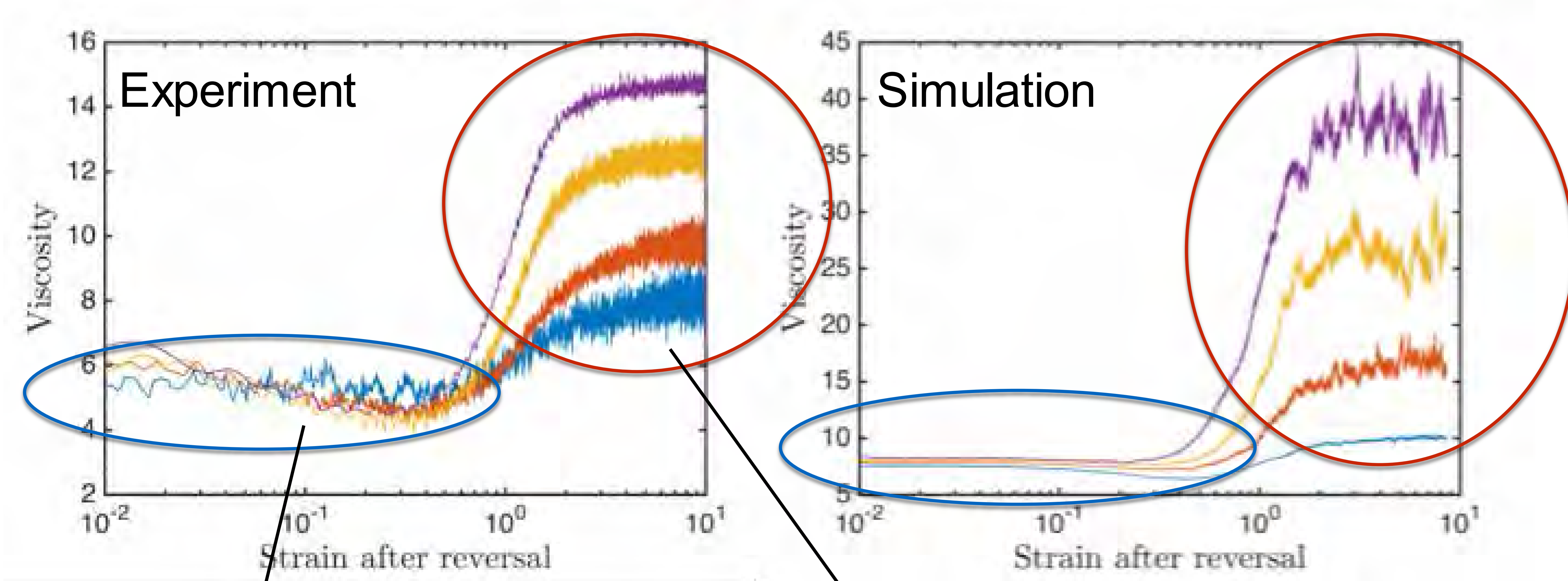


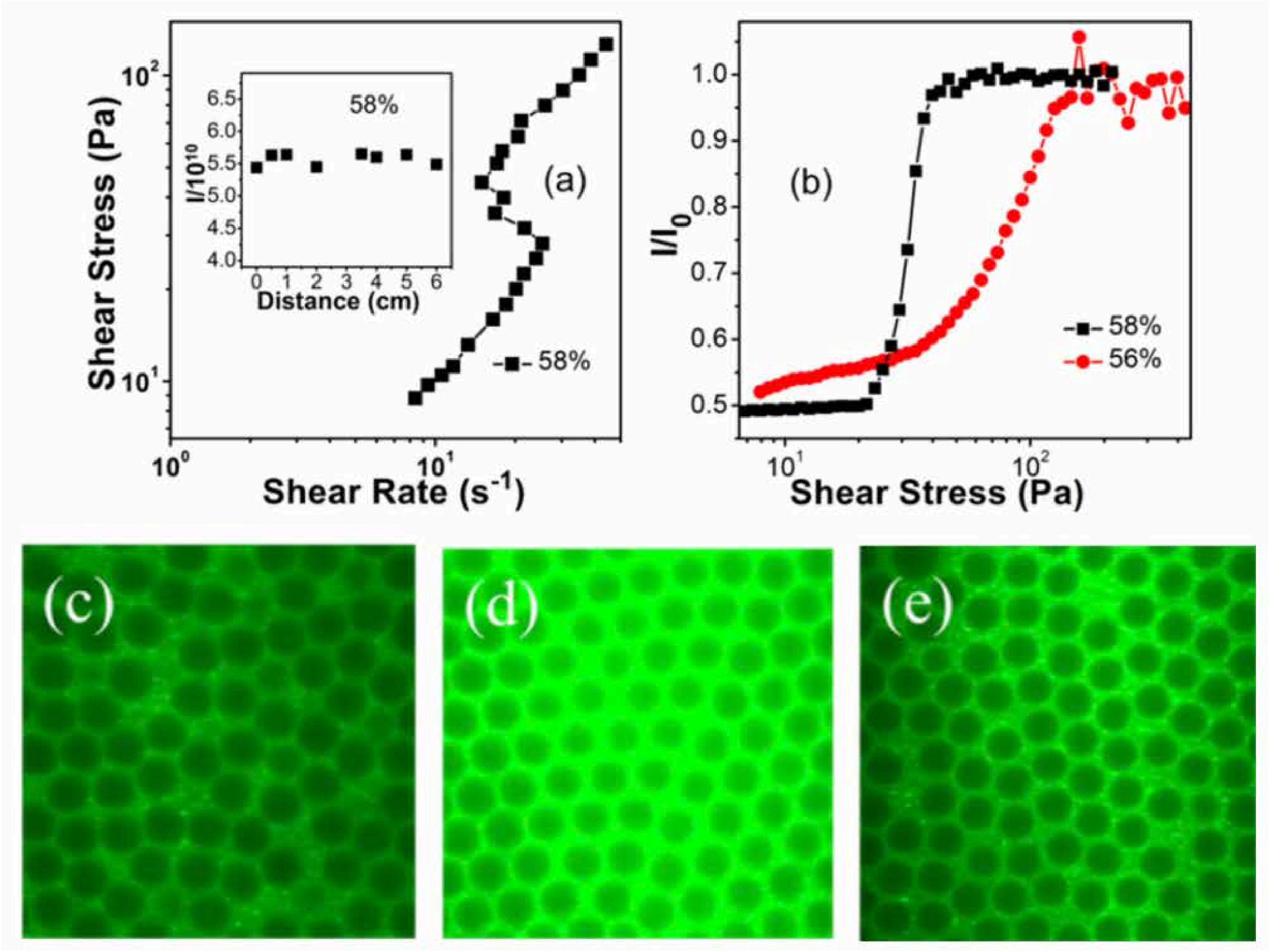
Contact part increases with shear rate

Hydrodynamic part independent of shear rate

Lin et al, PRL (2015)

Experiment 3: direct observation of contacts

Stress-dependent, fluorescent additive to identify contact points?



Pan et al, PRE (2015)

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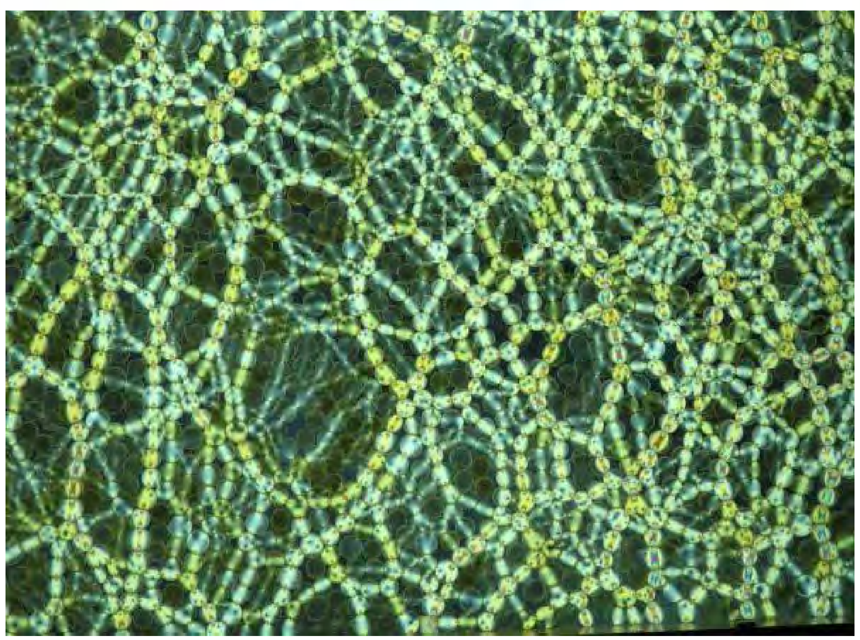
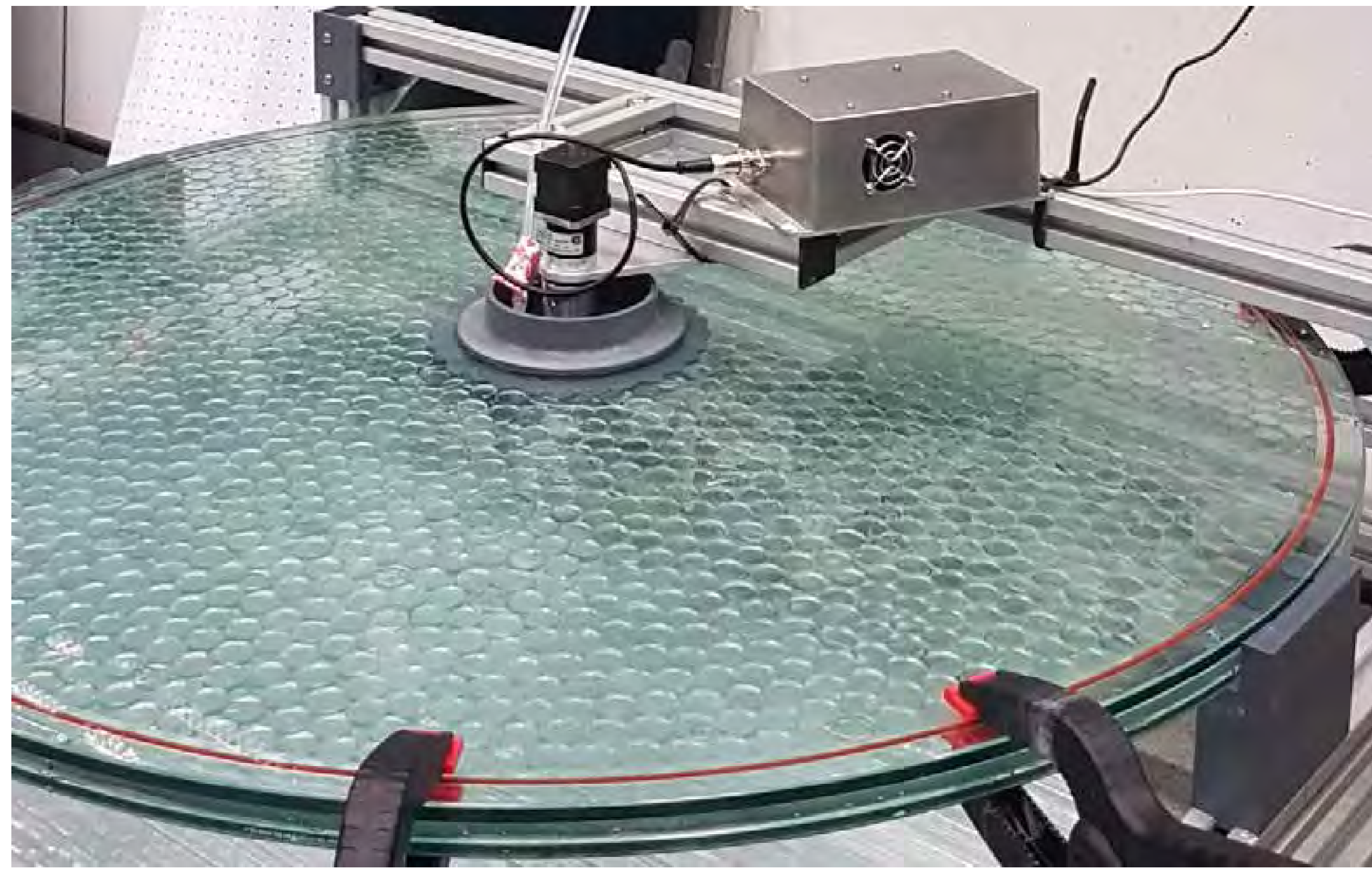


Bob Behringer



https://www.youtube.com/watch?v=R1QUMrjWiDU

Pan et al, PRE (2015)

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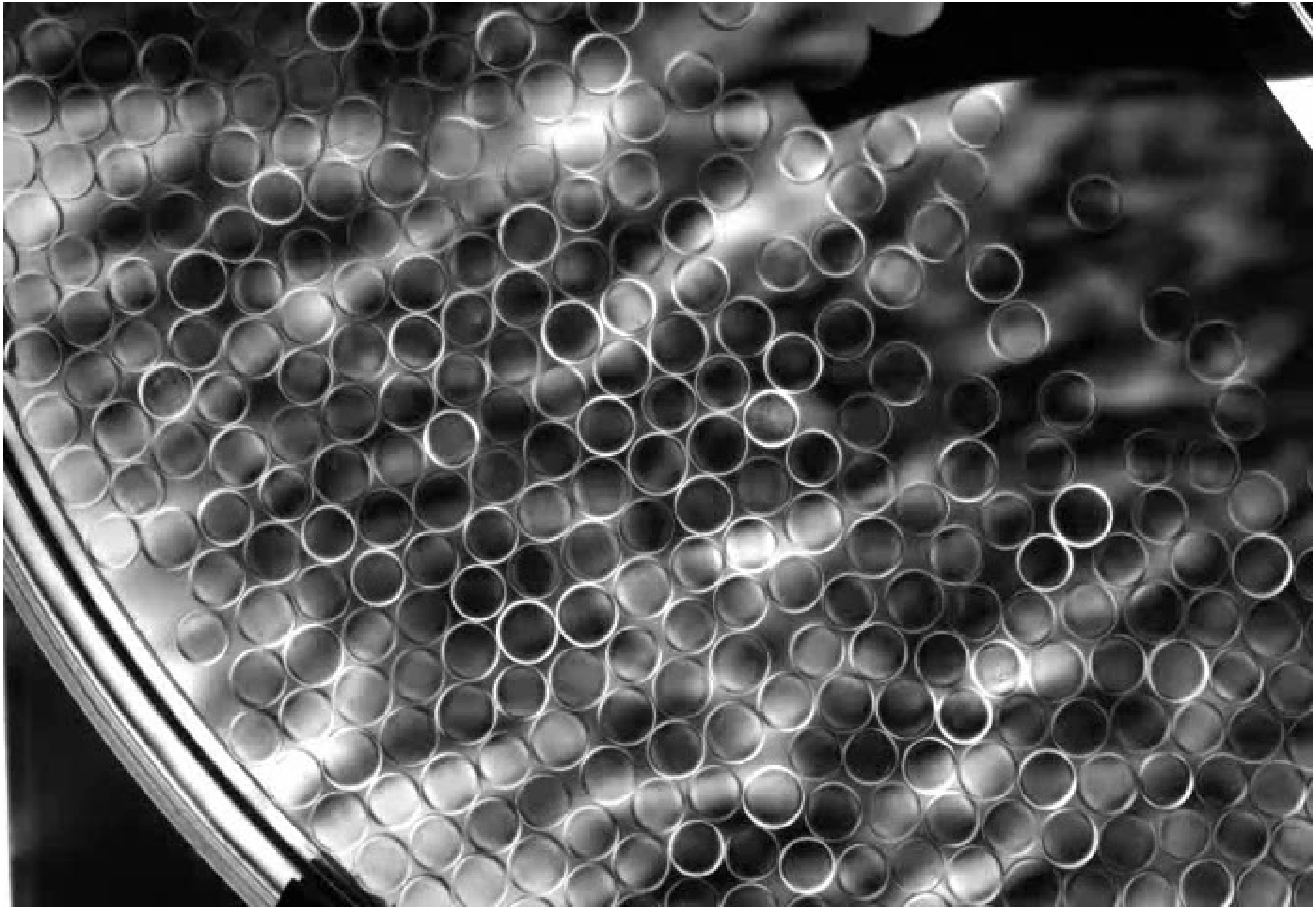
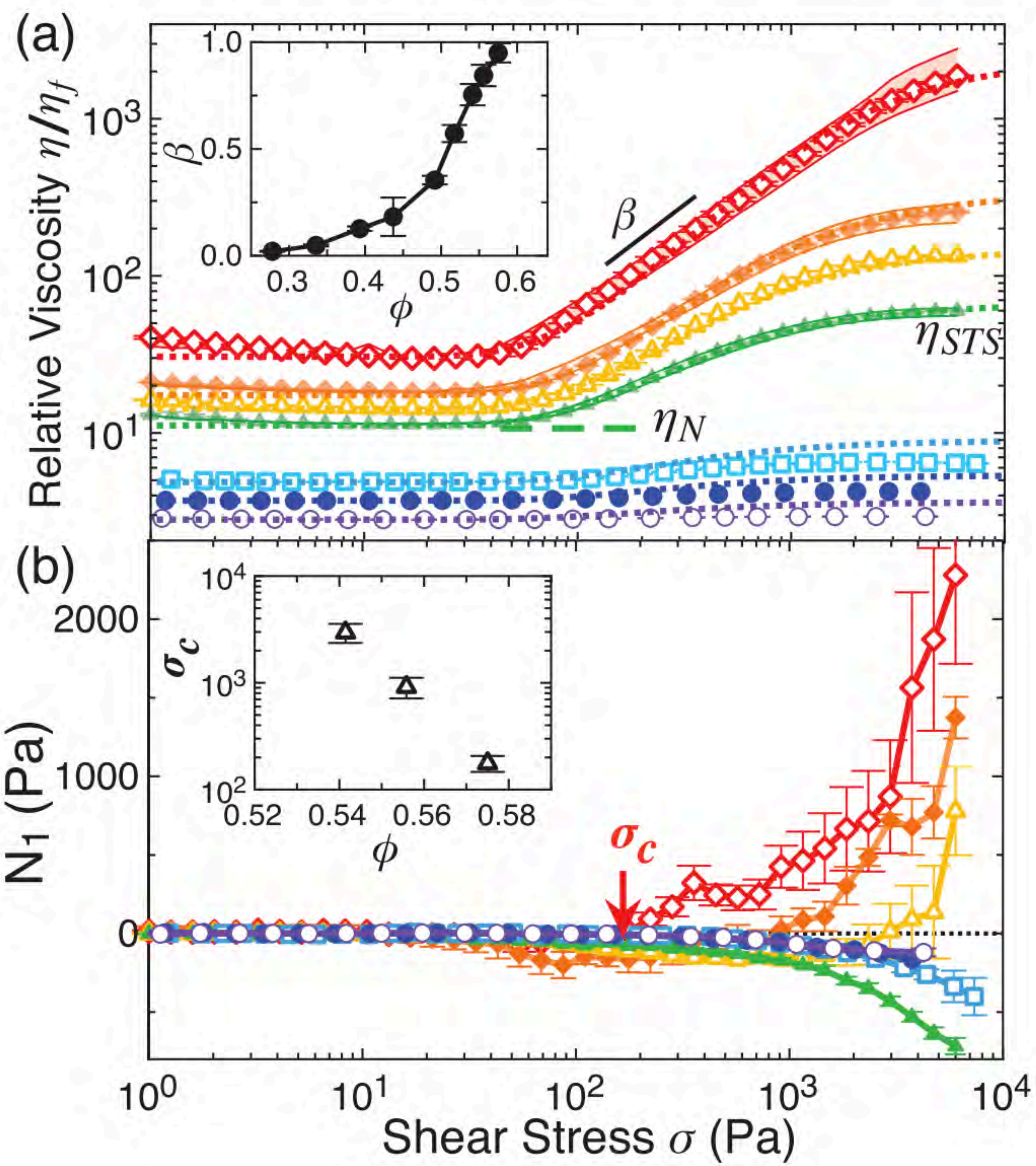
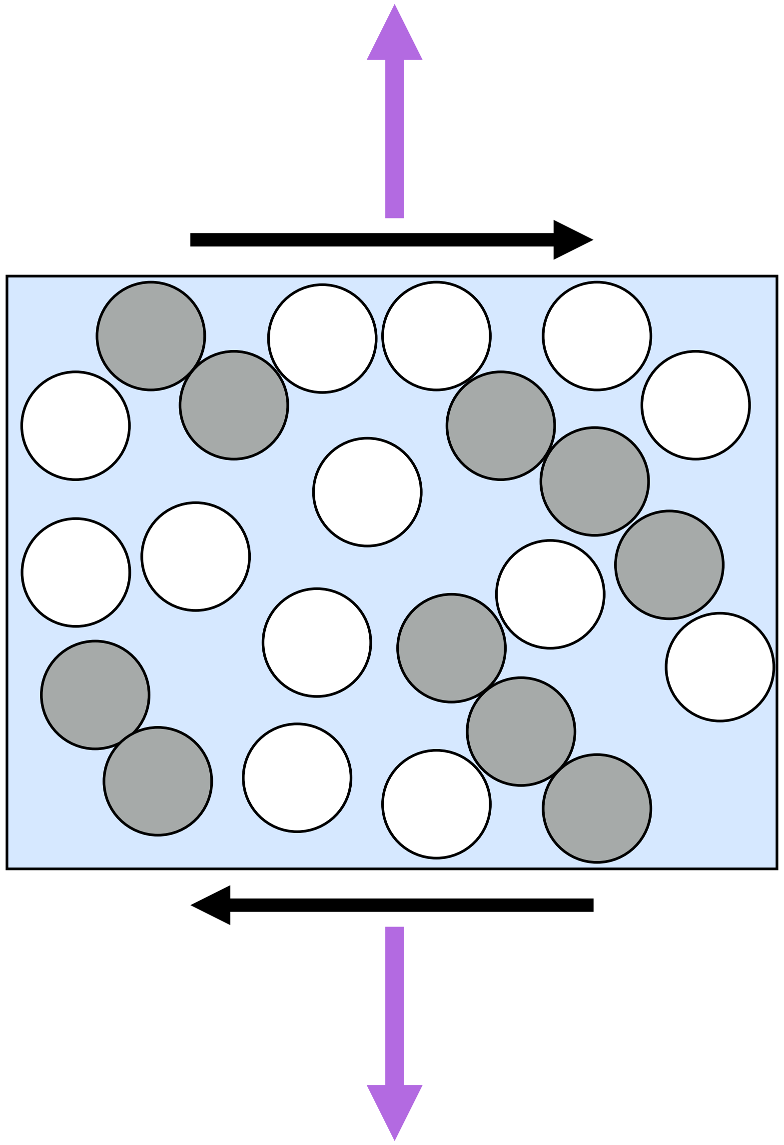


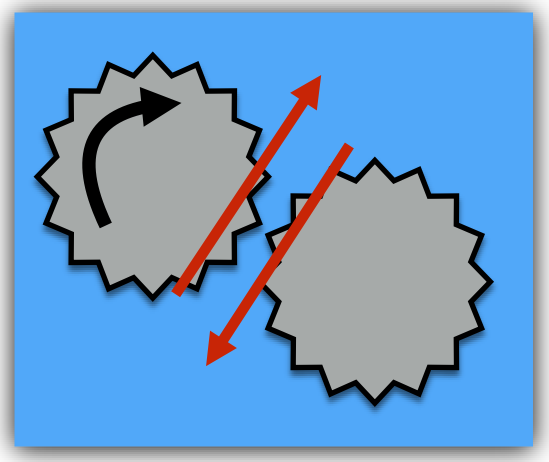
Experiment 4: normal stresses

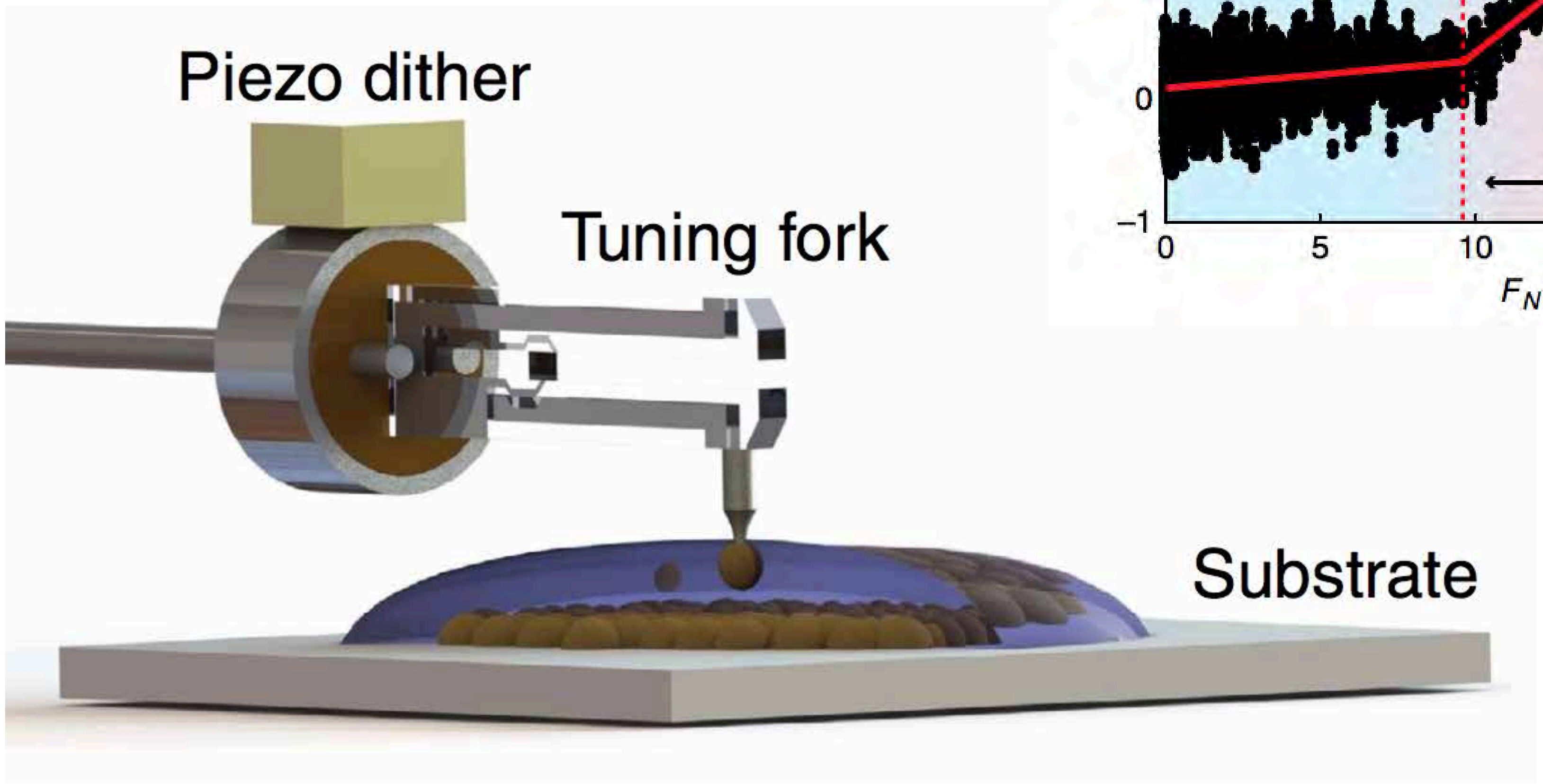


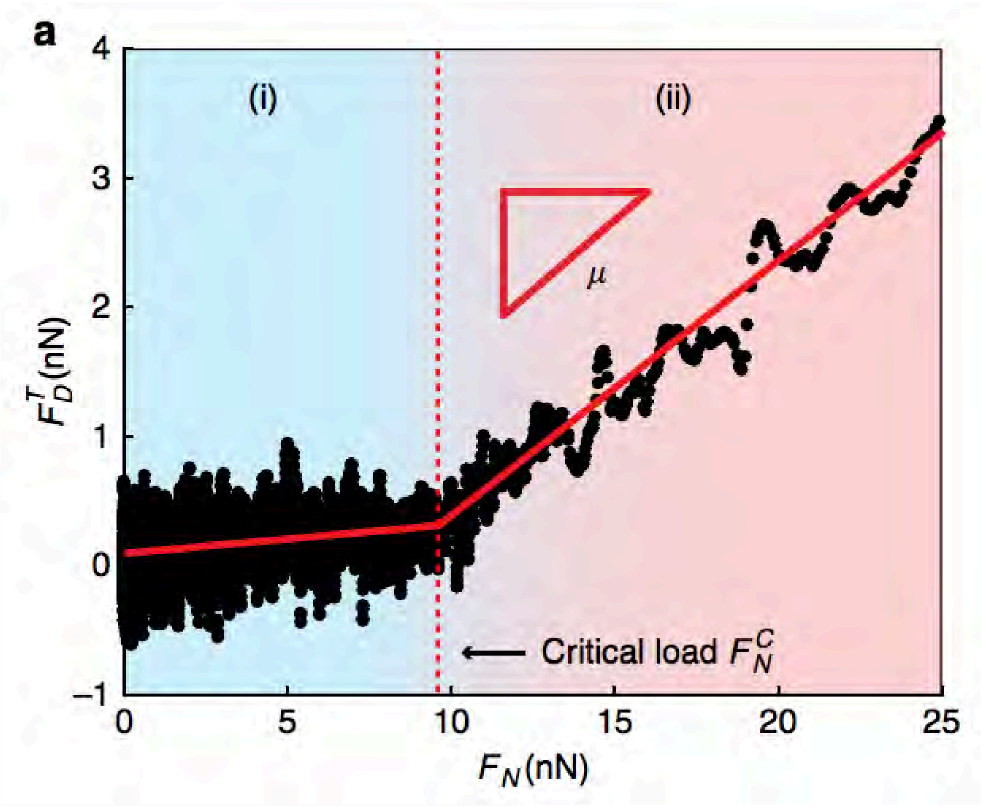


Royer et al, PRL (2016)

Experiment 5: probing the surfaces







Comtet et al, Nat Comms (2017)

Diagnosing these rheological features

A key practical question is:

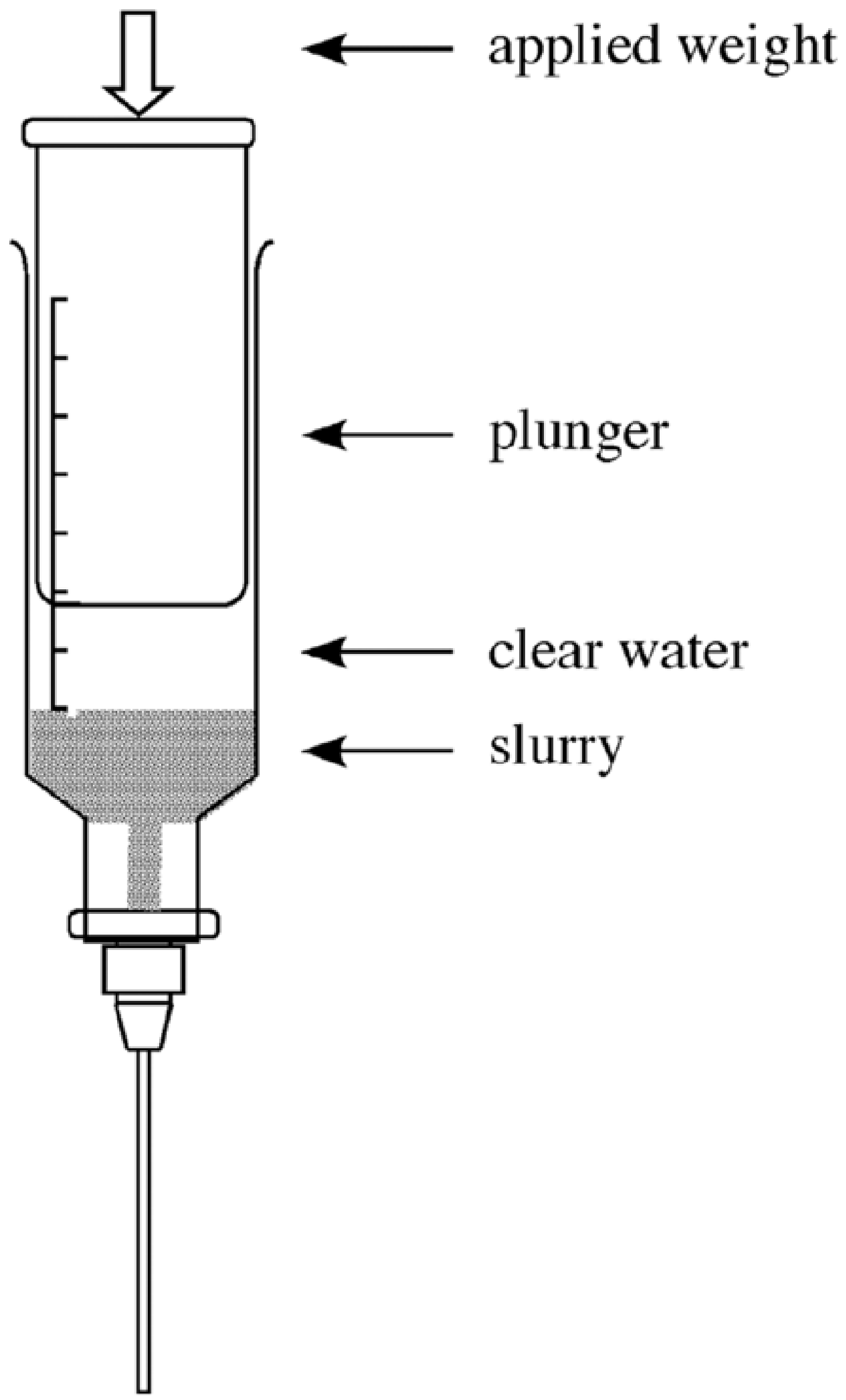
Should we be most worried about the hydrodynamics (i.e. the fluid properties) or the surface contacts (i.e. the particle properties)?

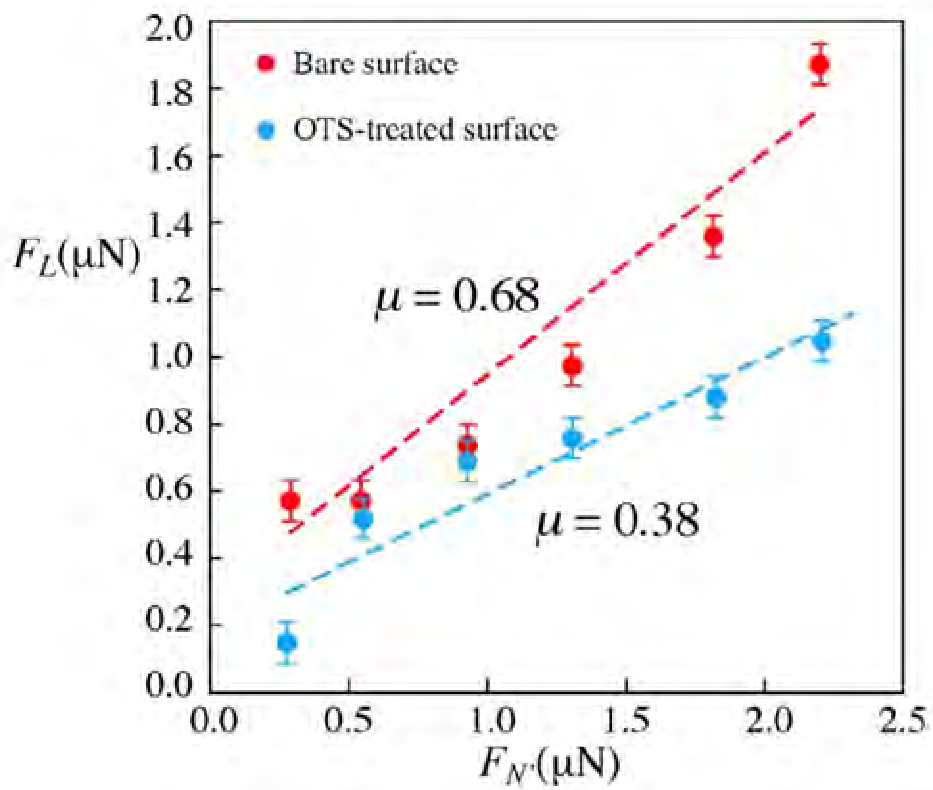
5 key characterisation experiments that suggest particle properties

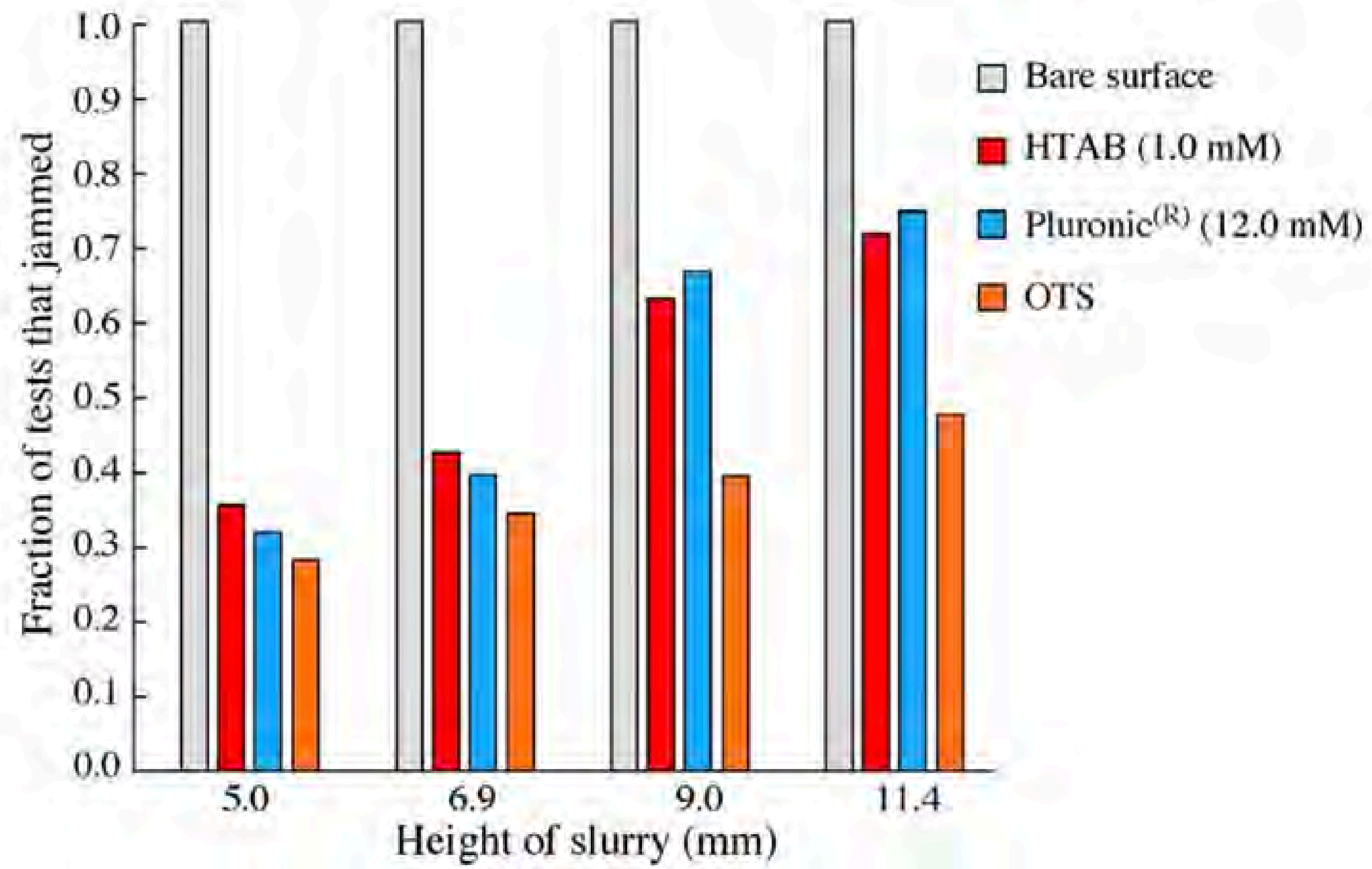
so…

What can we do differently in formulation?

Formulation: particle friction

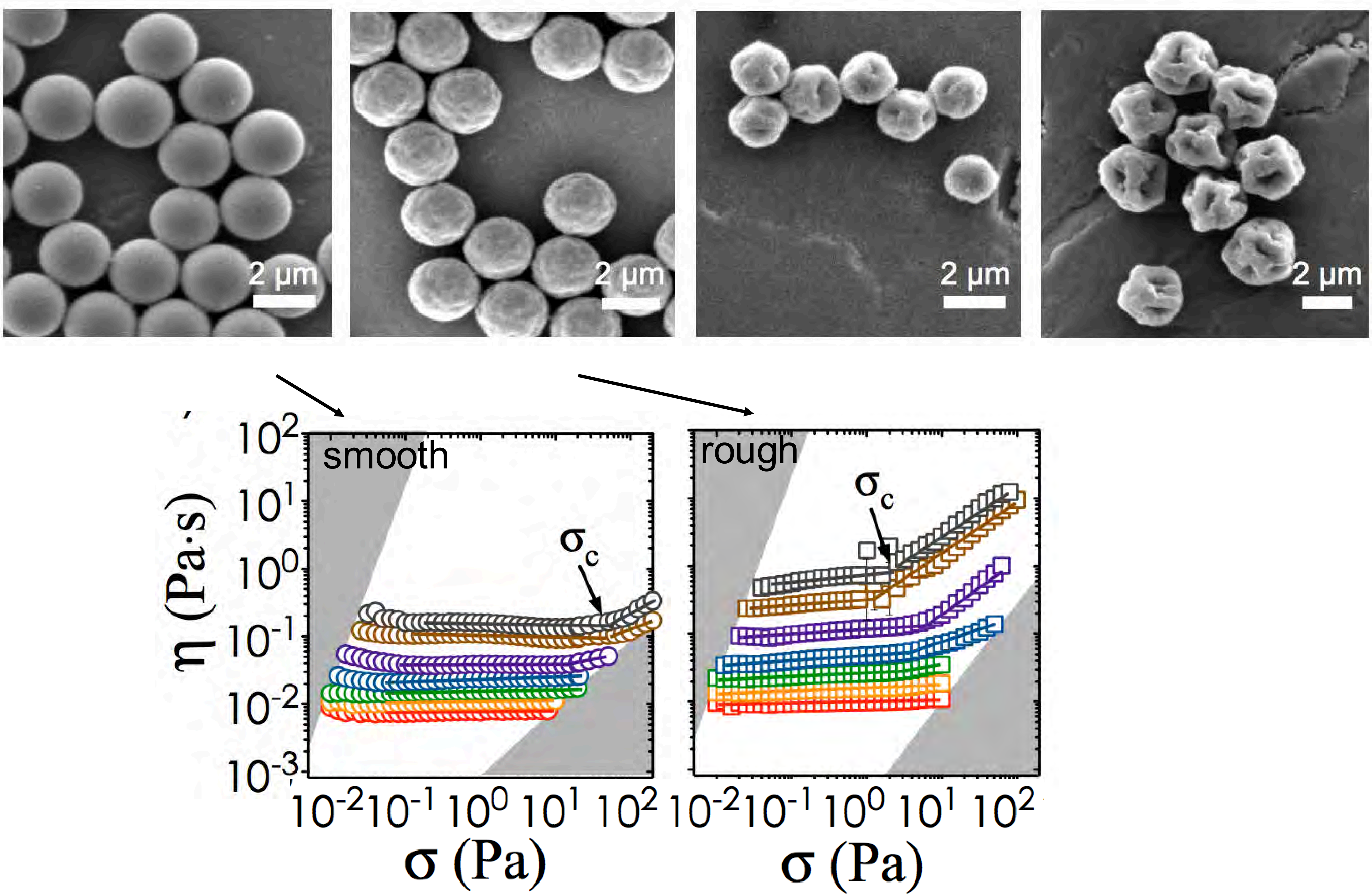






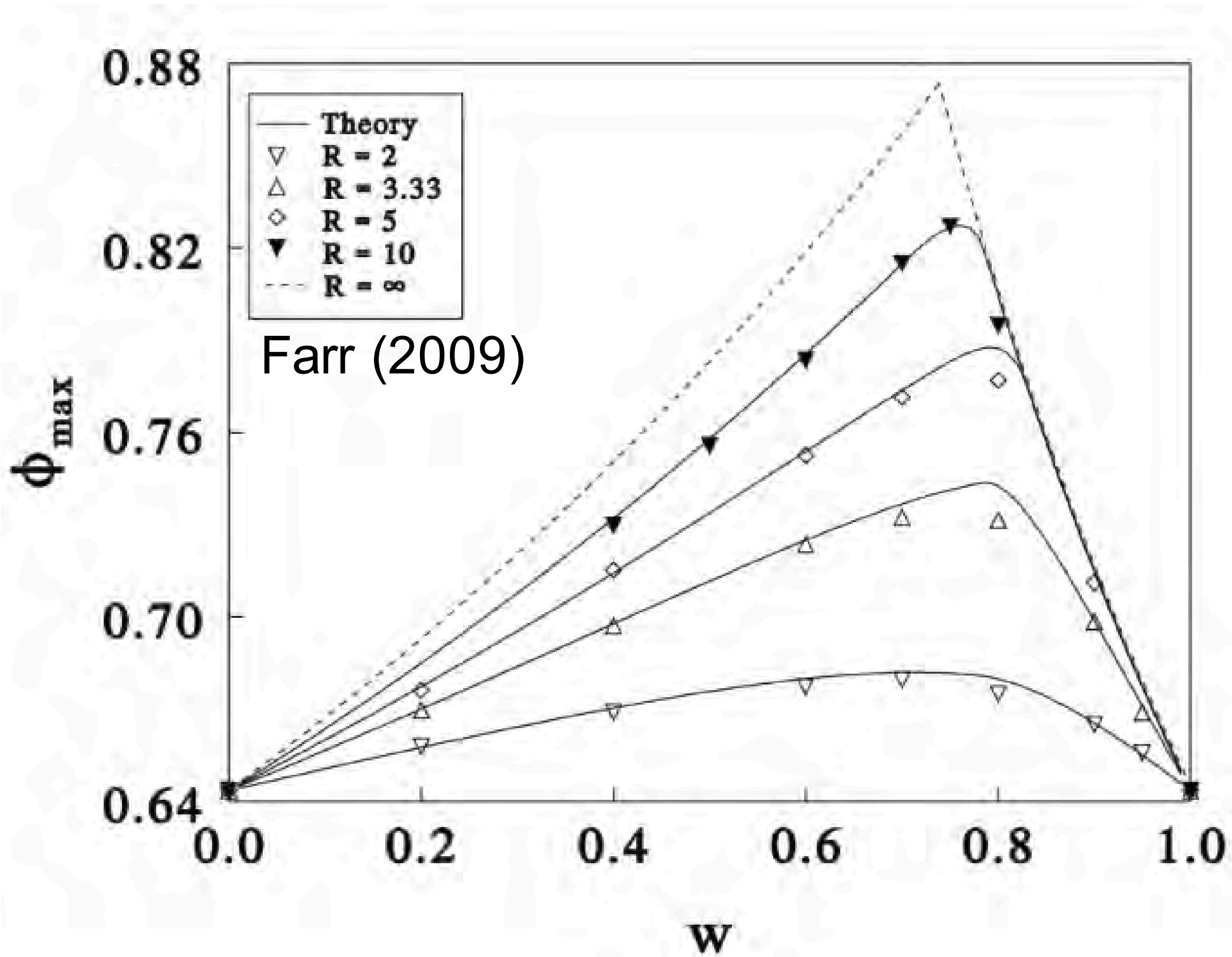
Salunkhe et al, Colloids and Surfaces A 537 (2018) 13–19

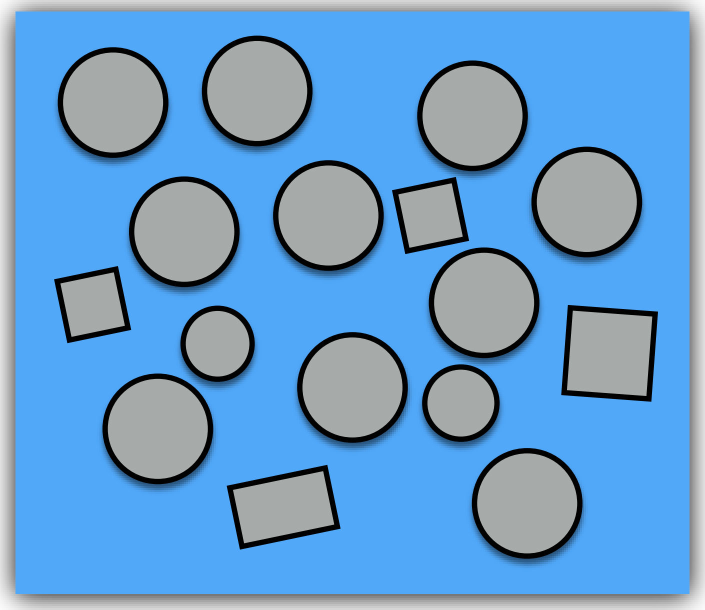
Formulation: particle friction

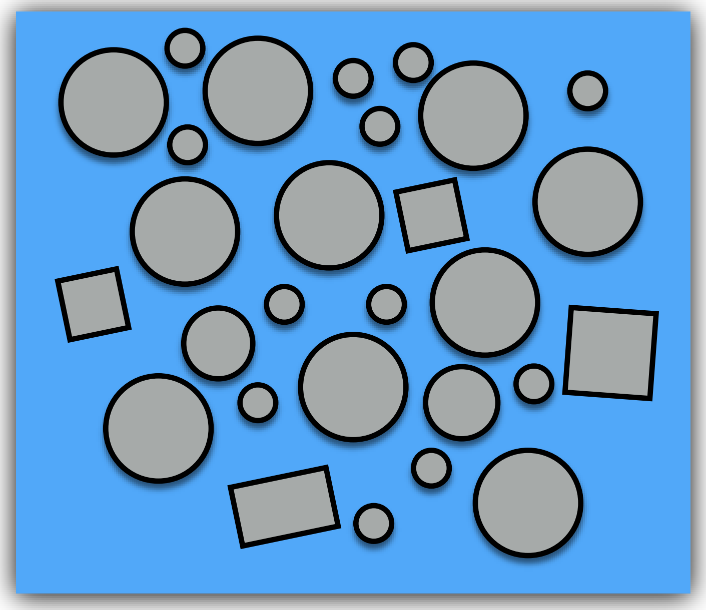


Hsiao et al, PRL 119, 158001 (2017)

Formulation: particle size distribution

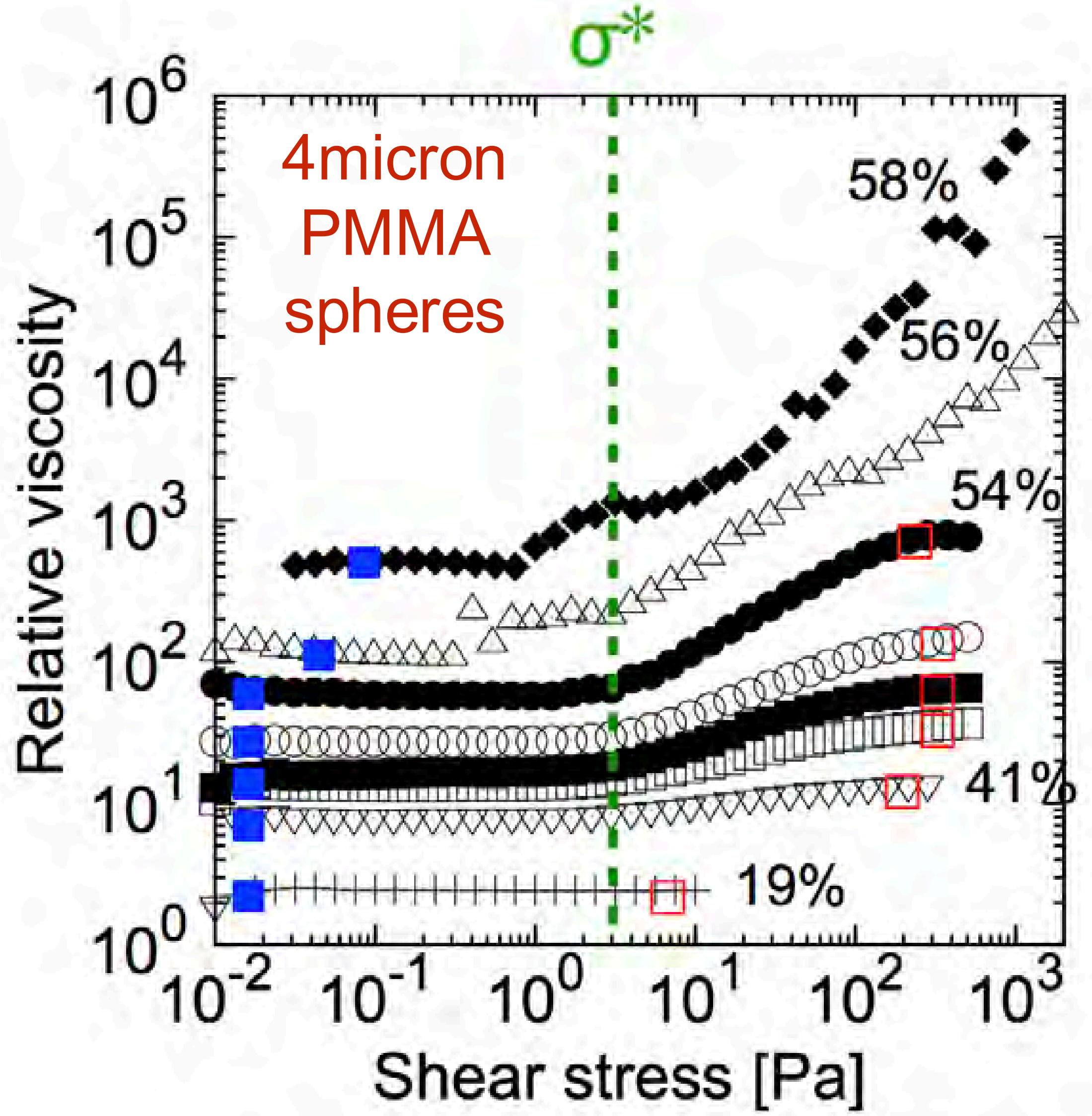


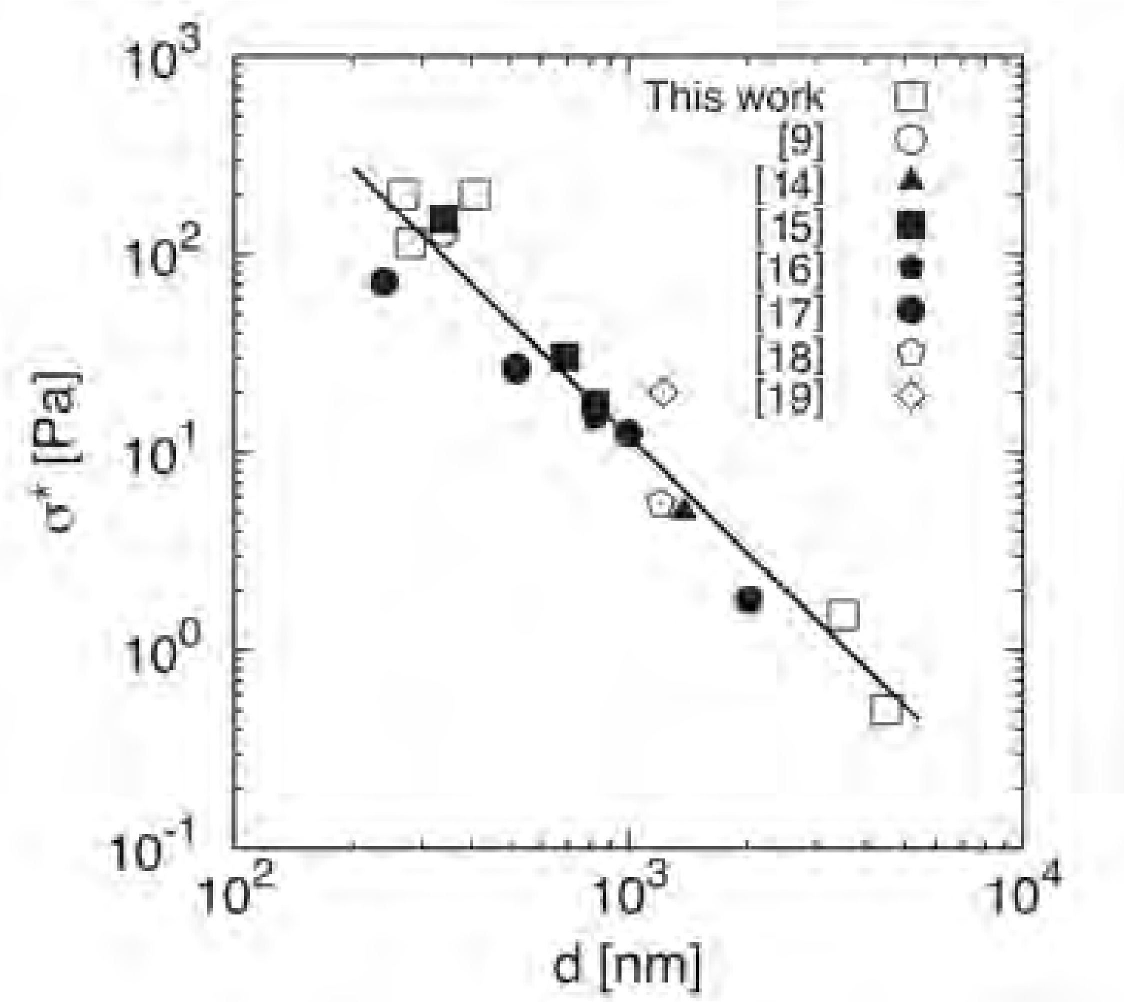




$$\eta = a(\varphi - \varphi_c)^{-2}$$

Formulation: particle size distribution





Guy, Hermes, Poon, PRL (2015)

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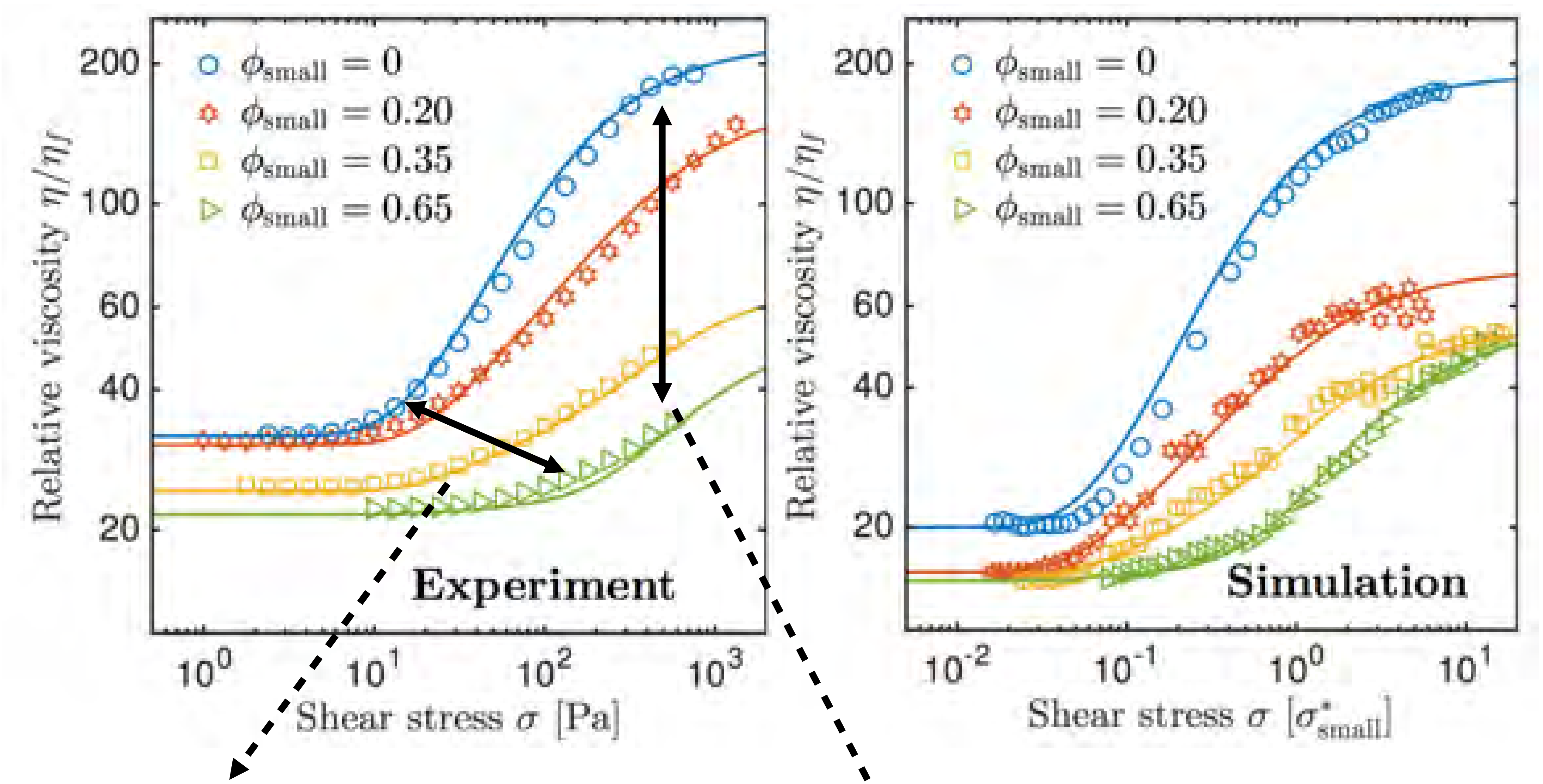
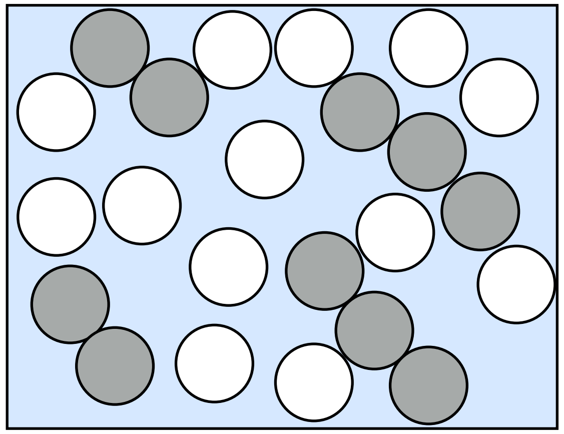


Order of magnitude shift in onset stress

Order of magnitude reduction in viscosity

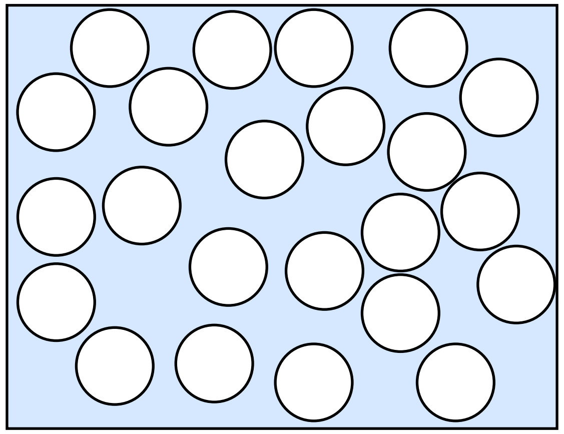
Formulation: rethinking processing



Reversible hydrodynamics
+
irreversible contacts

Self-organisation under
oscillatory flow

Pine, Nature (2005)



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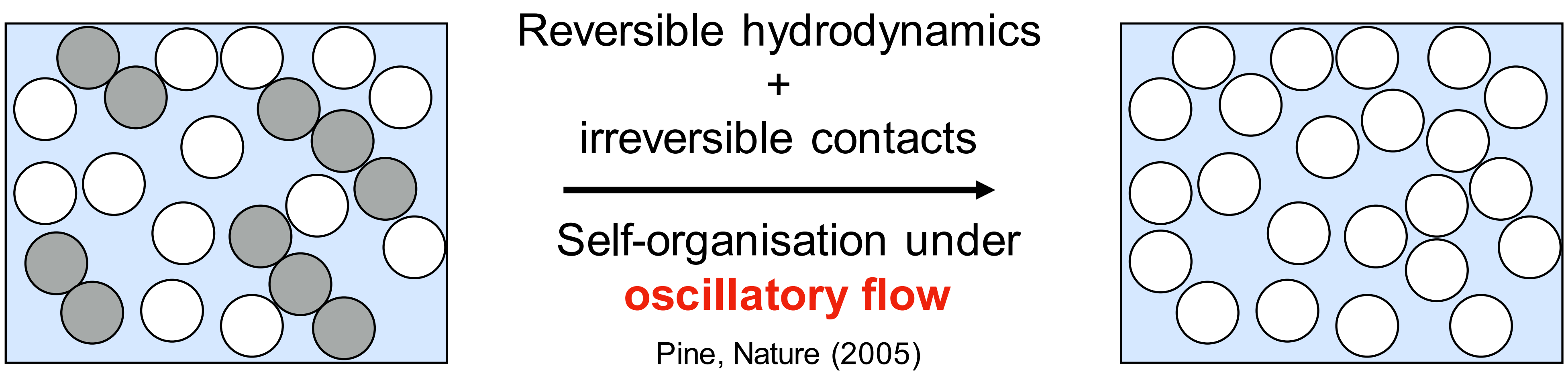
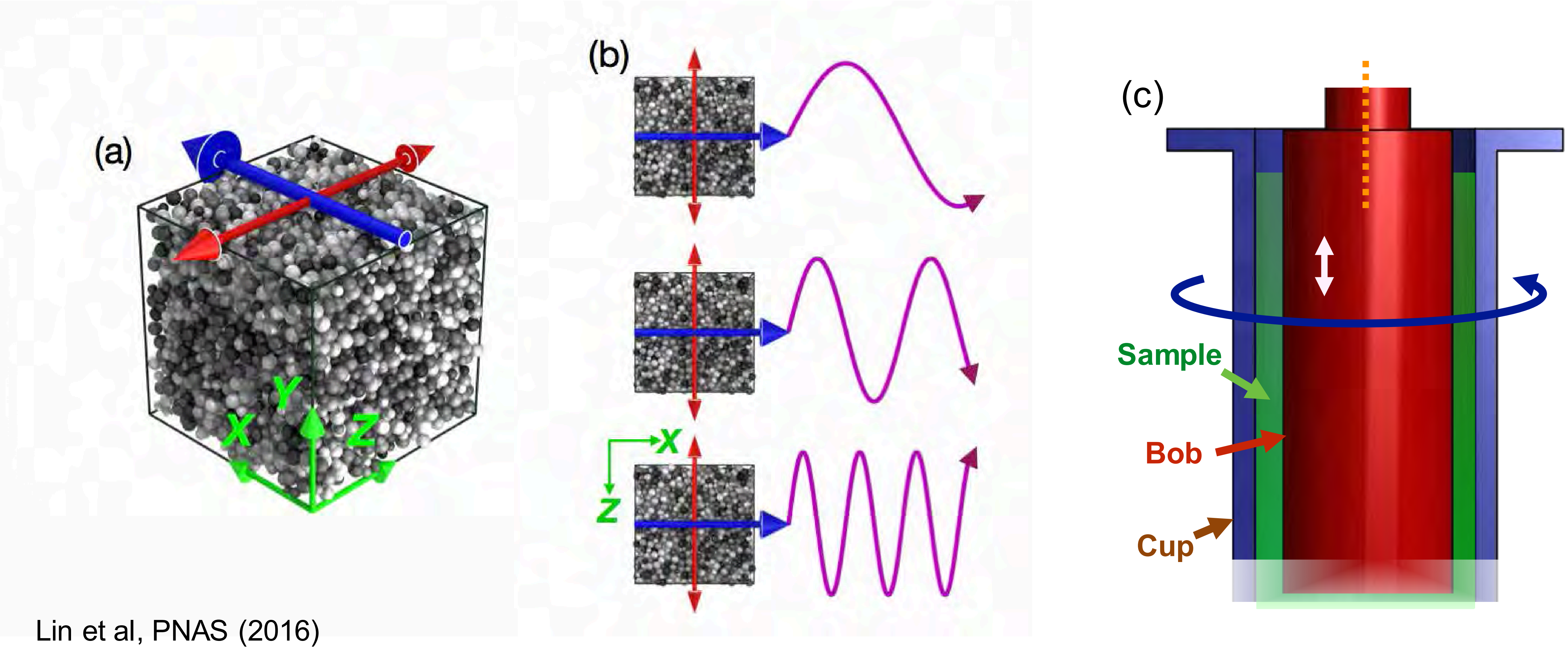
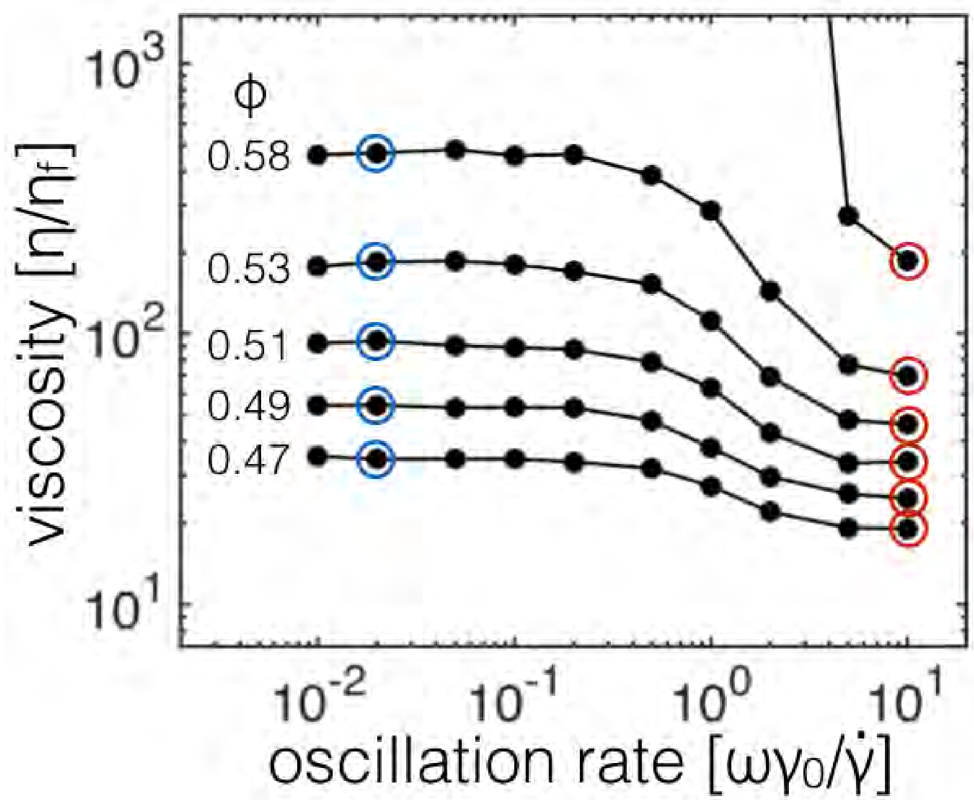


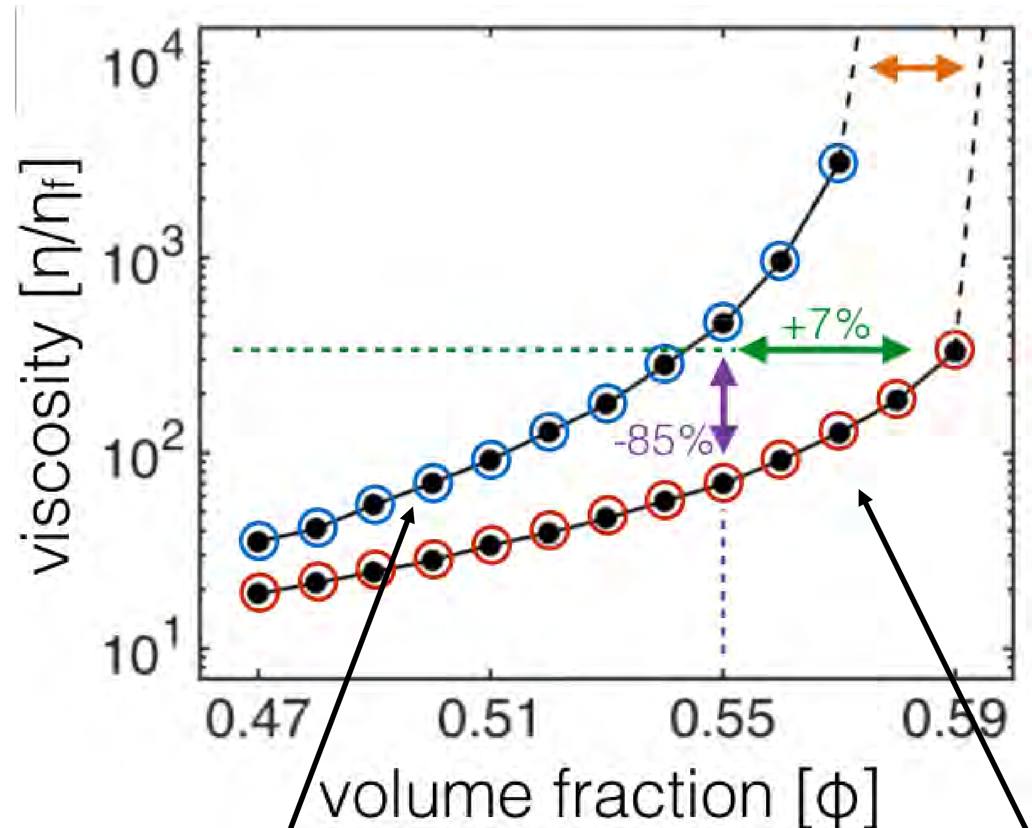
Pine, Nature (2005)



Lin et al, PNAS (2016)

Formulation: rethinking processing





Simple shear flow

Simple shear flow + Oscillatory cross shear

Summary

Evidence for the importance of particle-particle contacts:

1. Viscosity divergences at low and high stress
2. Transient shear reveals irreversible stresses
3. Photoelasticity reveals direct contacts
4. Normal stress analysis
5. AFM measurements reveal static friction coefficient

What we can do to take control:

1. Tune the surface chemistry and particle topology
2. Optimise the particle size distribution
3. Implement flow protocols with complex histories

Outlook and potential future directions

1- Can subsidiary flows be applied widely in practice?

2- What about attractive particles? Is friction still important?

3- We can isolate contacts and hydrodynamics - can we infer specific contact forces from rheology?

Observing and quantifying force transmission in dense suspensions

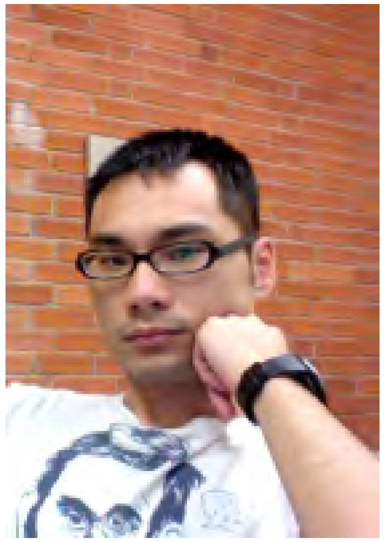
1. *Measuring the stresses in* ***suspensions of coarse and fine particles***
2. *Understanding the forces on* ***particles in non-Newtonian suspending fluids***

Implementing active flow control in industrial scenarios

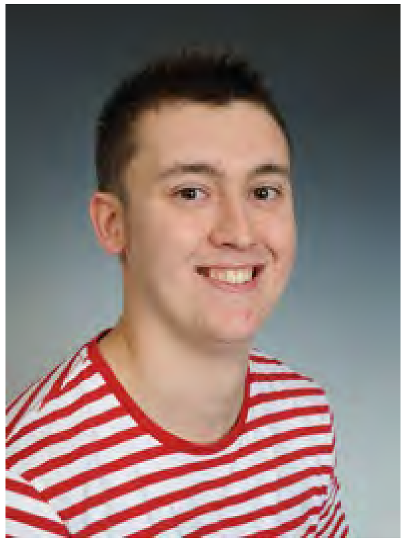
1. *Viscosity and dissipation with* ***non-Newtonian suspending fluids***
2. ***Mitigating*** *flow* ***instabilities*** *and flow rate fluctuations*

Coire Gabhail, Glencoe, 22 October 2015

Romain Mari



Neil Lin



Ben Guy

Michiel Hermes

Ness & Sun, *PRE* (2016)
Ness & Sun, *Soft Matter* (2016)
Lin, **Ness**, Cates, Sun and Cohen, *PNAS* (2016)
Lin, Guy, Hermes, **Ness**, Sun, Poon and Cohen, *PRL* (2015)
Guy, Hermes, Poon, *PRL* (2015)
Ness, Mari and Cates, *submitted*
Khan, Thomas, Vriend and **Ness**, *in prep*

Thank you!

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