Friction and the S-shaped flow curve of shear thickening

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- Friction: Bart Weber, Lars Pastewka, Till Junge
- 'Magical molecules': Tomislav Suhina, Fred Brouwer
- S-shaped flow curve: Zhongcheng Pan, Henri de Cagny
- Simulations: Vishnu Sivadasan, Eric Lorentz, Alfons Hoekstra

Friction in suspensions

PRL 94, 028301 (2005) PHYSICAL REVIEW LETTERS week ending 21 JANUARY 2005

Flow of Wet Granular Materials

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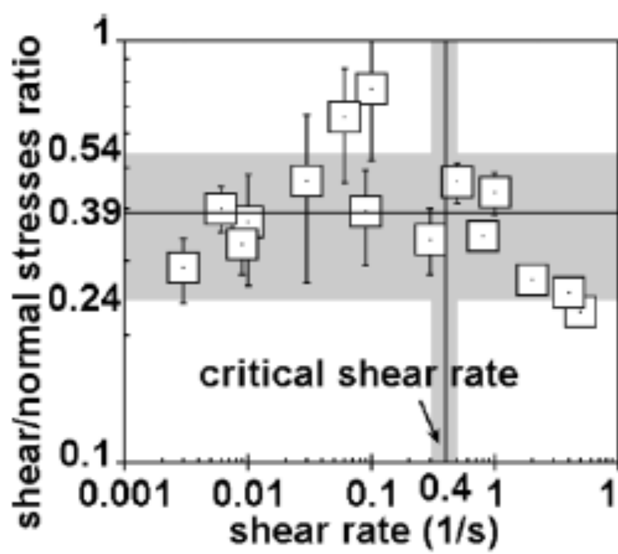
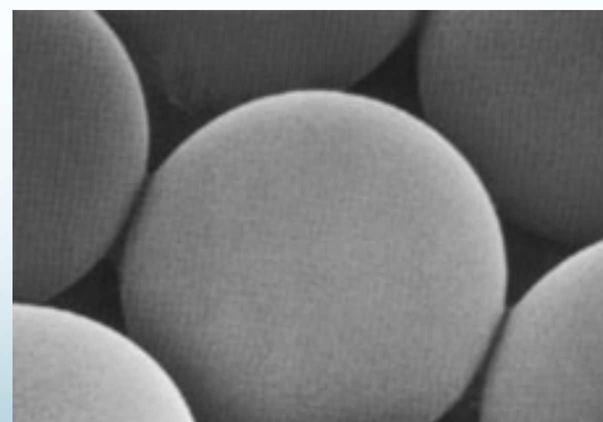
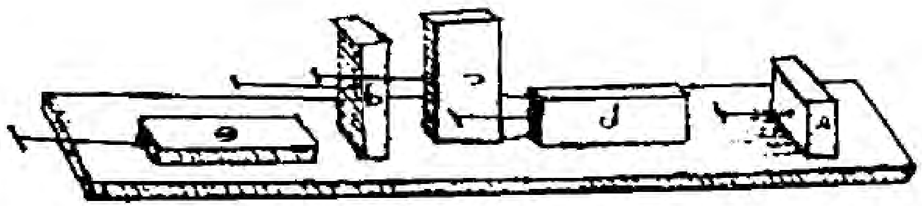
The transition from frictional to lubricated flows of a dense suspension of non-Brownian particles is studied. The pertinent parameter characterizing this transition is the Leighton number Le $= \frac{\eta_s \dot{\gamma}}{\sigma}$, the ratio of lubrication to frictional forces. Le defines a critical shear rate below which no steady flow without





PMMA in salt water

Friction: Amontons' Law



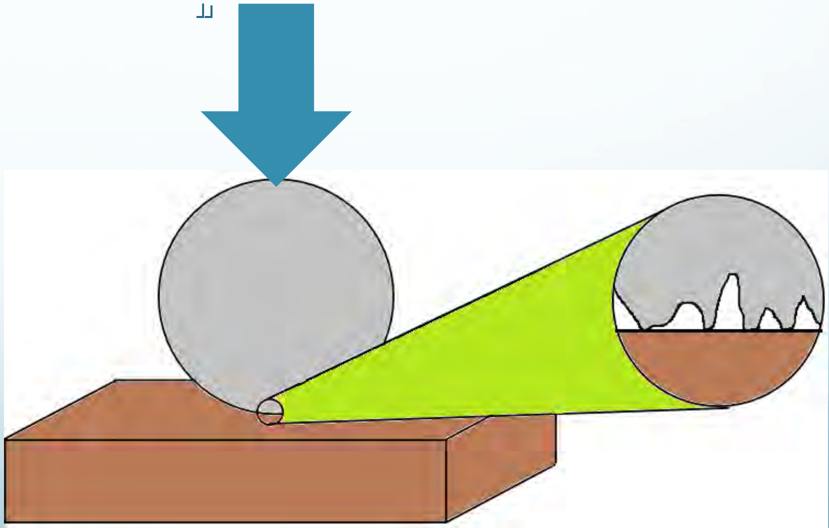
In the Codex Atlanticus and the Codex Madrid, Leonardo da Vinci (1452-1519) documented the first systematic experiments on friction

Amontons Law:

$$F_F = \mu \cdot F_N$$

Friction force is independent of the (apparent) contact area

- Real Contact Area ~ Normal Force?
- Friction Force~ Real Contact Area?

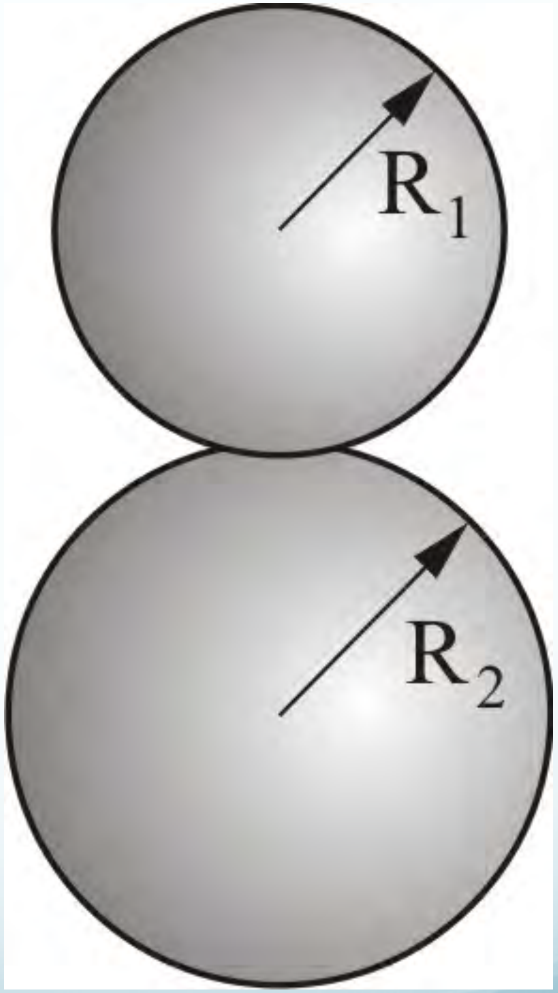


The Hertz Contact is non-linear!

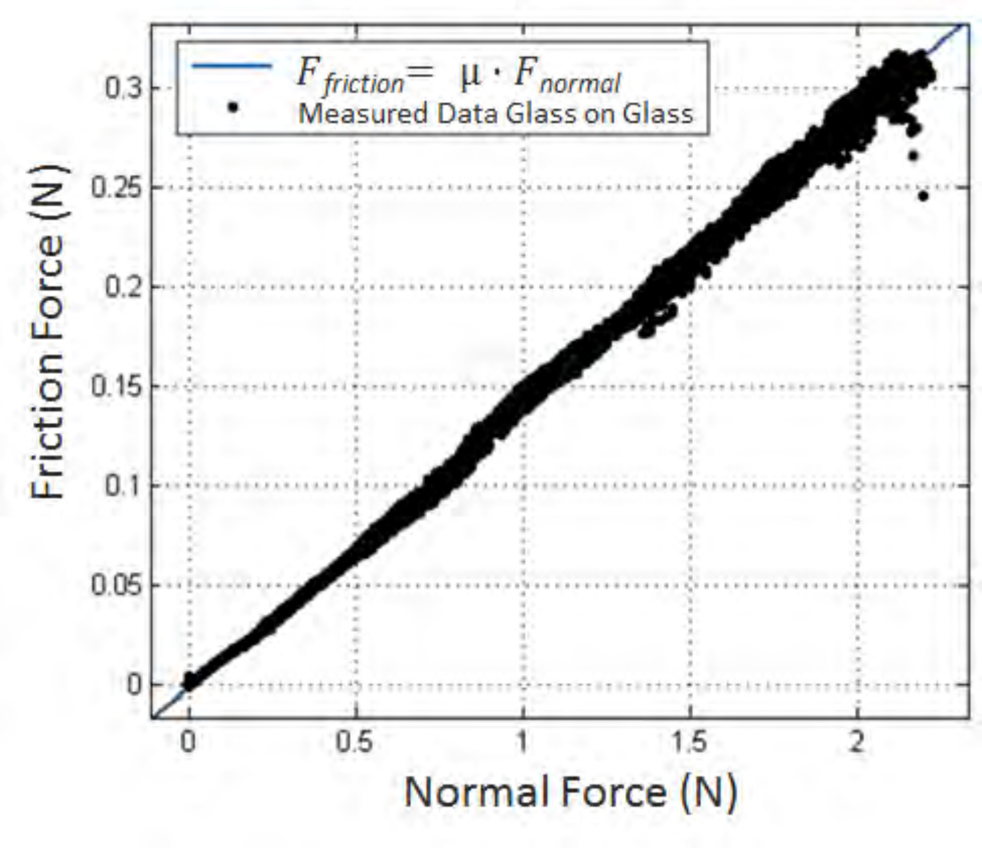
$$A = \pi \cdot \left(\frac{3R}{4E^*}\right)^{2/3} \cdot F_N^{2/3}$$

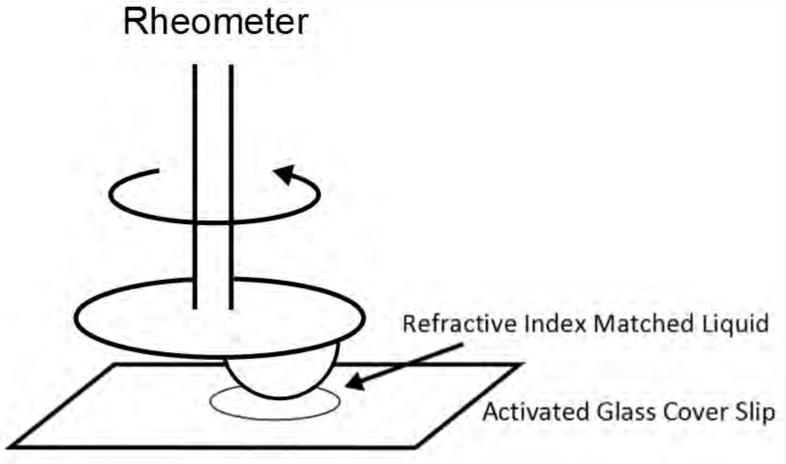
$$R = \frac{1}{1/R_1 + 1/R_2}$$

$$A = constant \cdot F_N^{2/3}$$



Amontons' Law for a single PMMA sphere

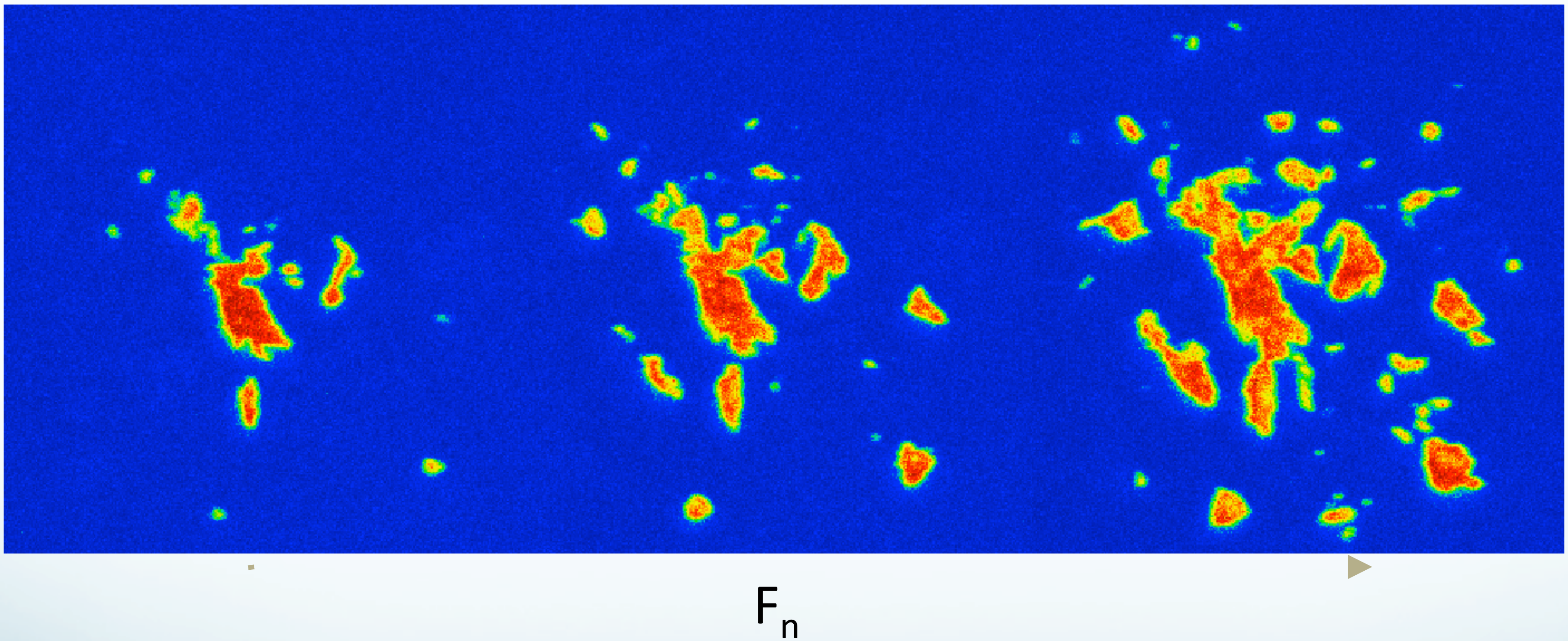




$$A = constant \cdot F_N^{2/3}$$

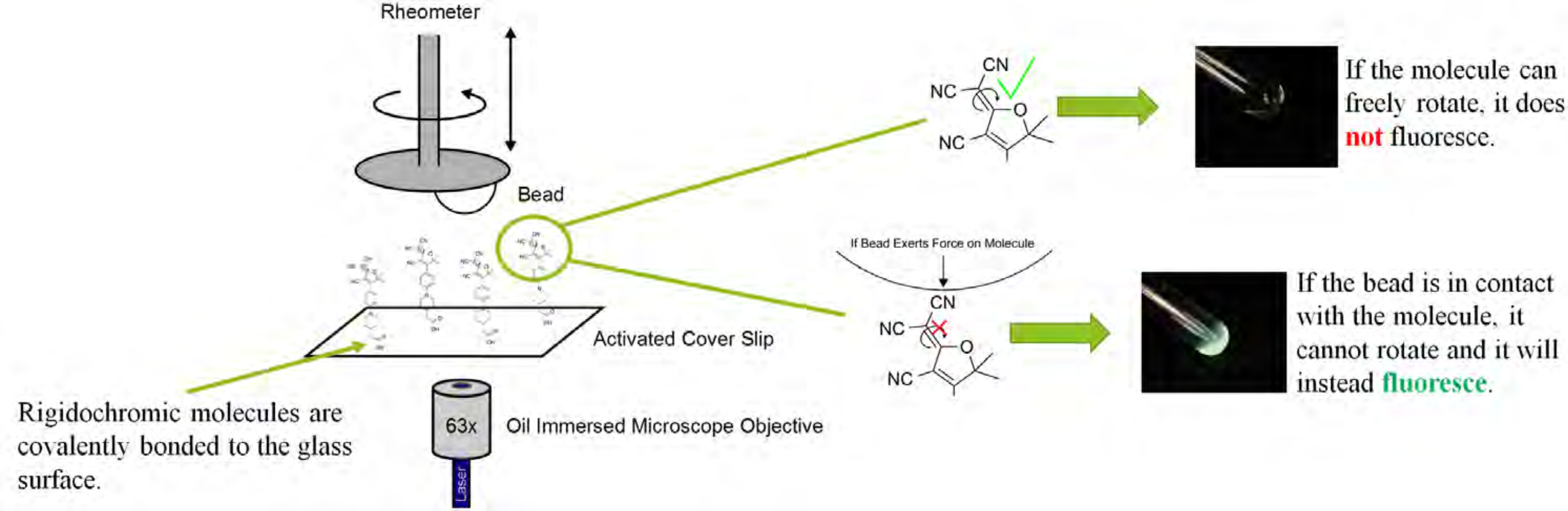
Even though macroscopically it looks like a Hertz contact, Amonton is still obeyed! What is the real contact area?

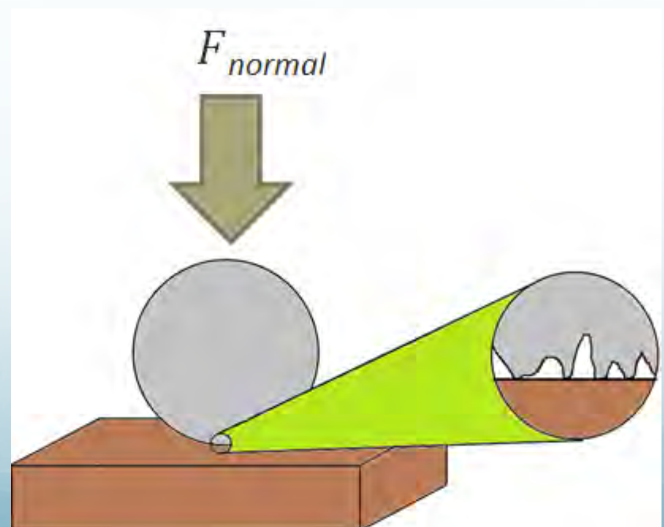
Direct observation of the real contact area in friction



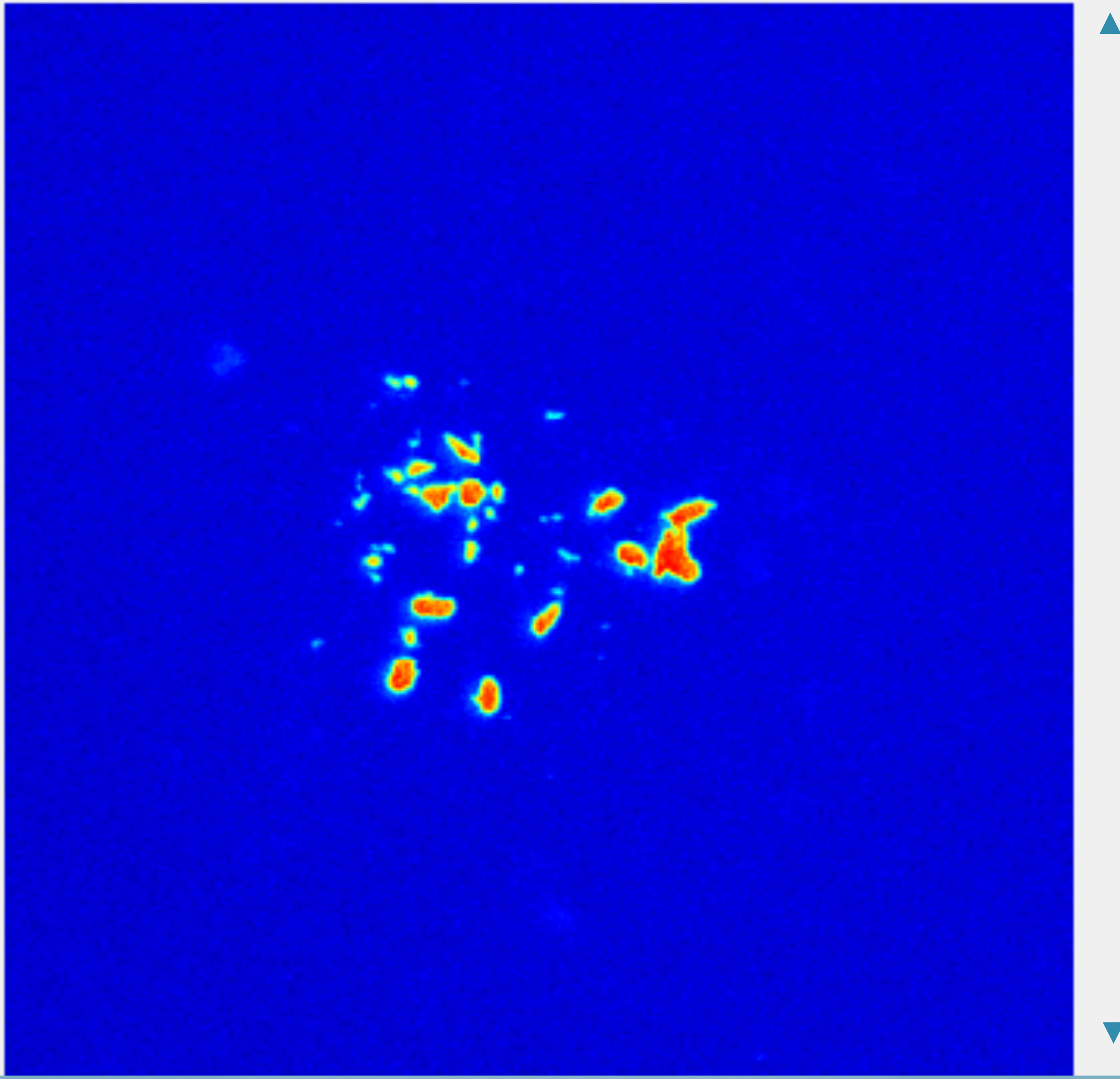
B. Weber et al. Nat. Comms 2018 (in print)

Experiment

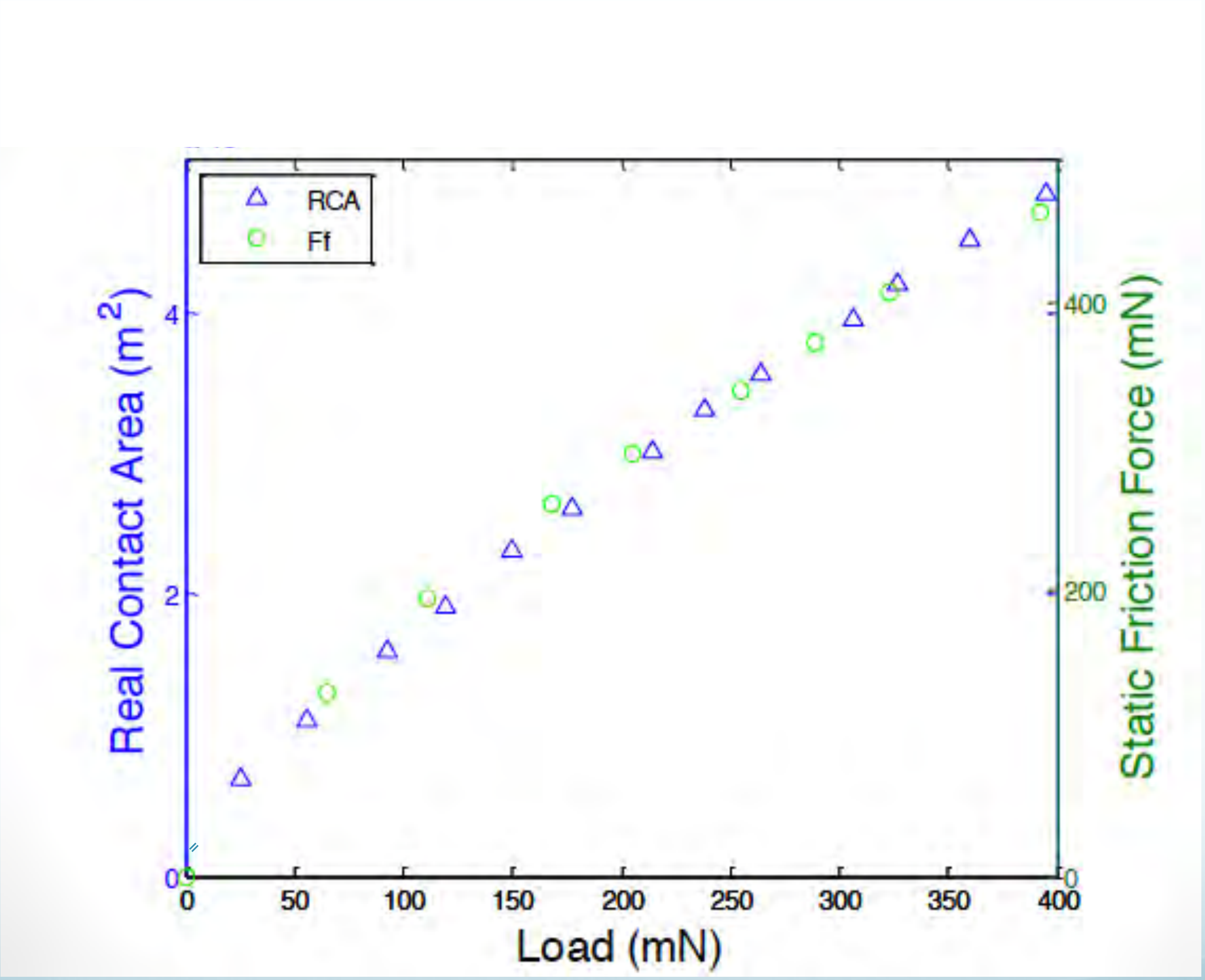




T. Suhina et al.
Angew. Chem. 2014

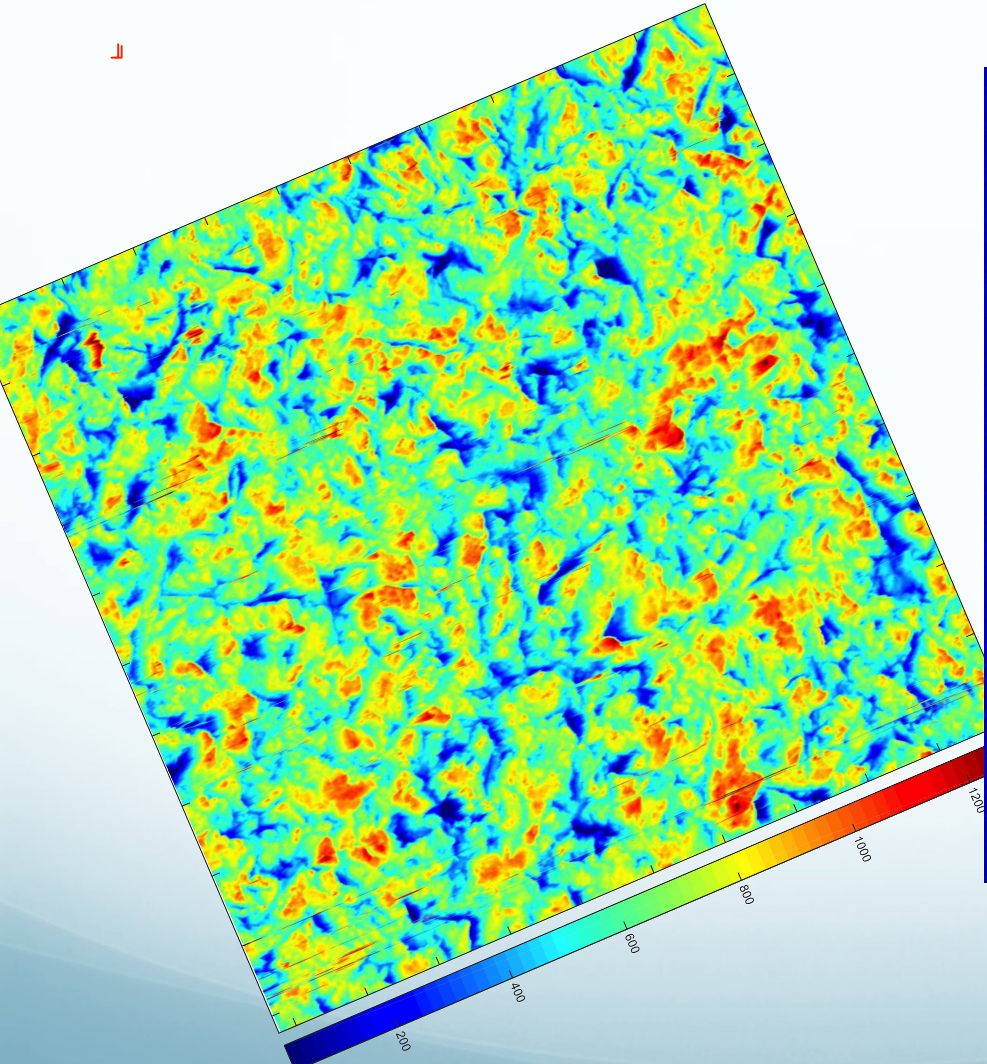

65 µm

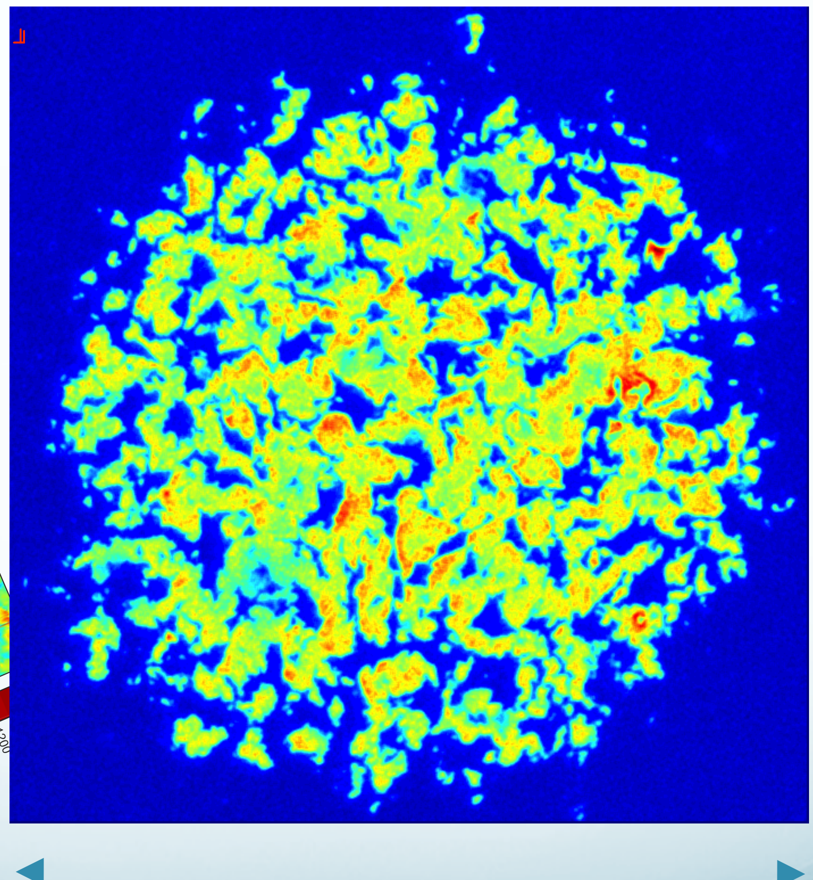
PMMA sphere



Not at all Amontons!

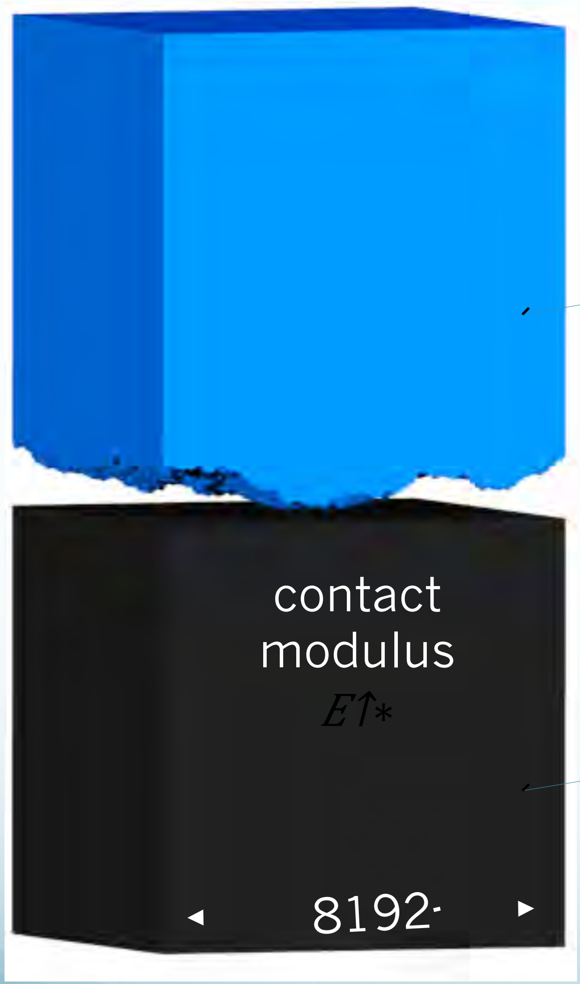
AFM and Microscopy on the same surface





65 µm

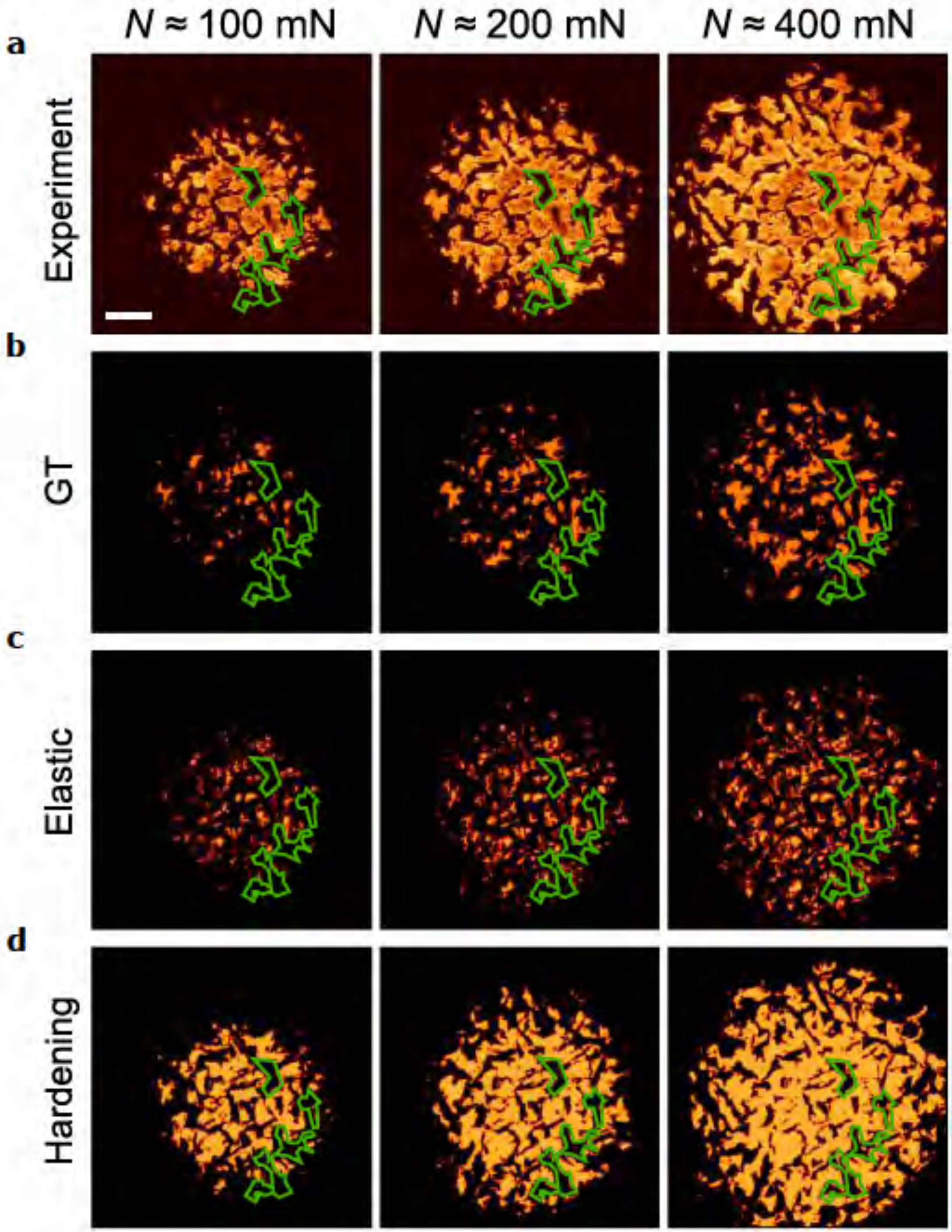
Simulations (Pastewka, Junge)



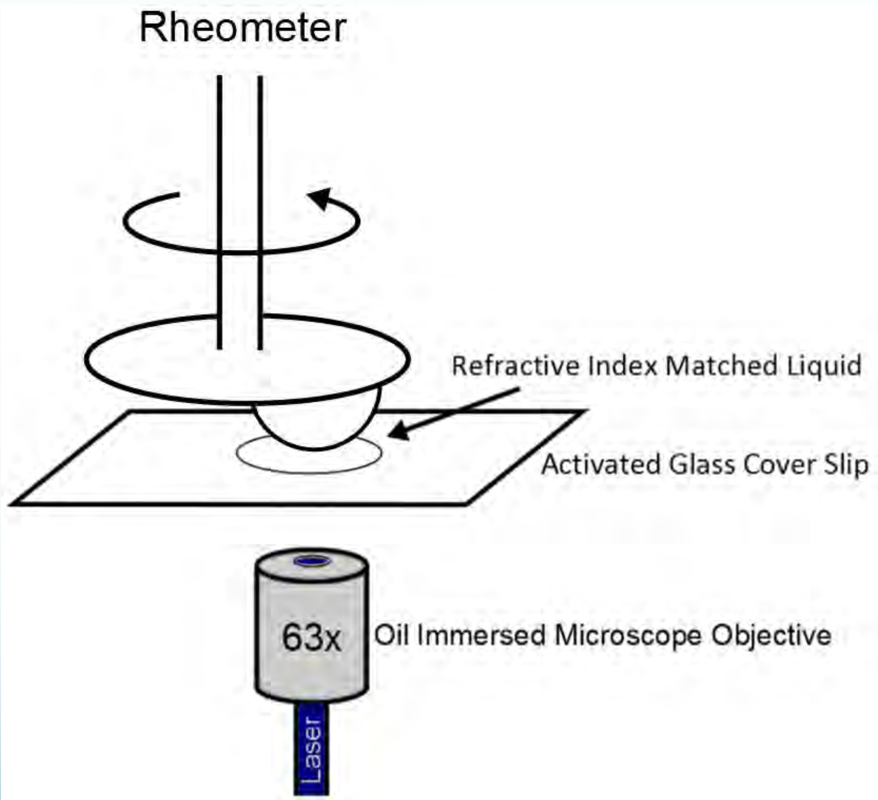
- Contact of two elastic bodies can be *exactly* mapped onto a rigid object contact and elastic flat with effective modulus
- FFT for elastic deformation (up to 8k x 8k surface grid)
- Contact of spheres: Free space Green's function + de-couple periodic images through a padding region
- Hard-wall boundary conditions
- Simple plasticity model: Upper bound for surface pressure

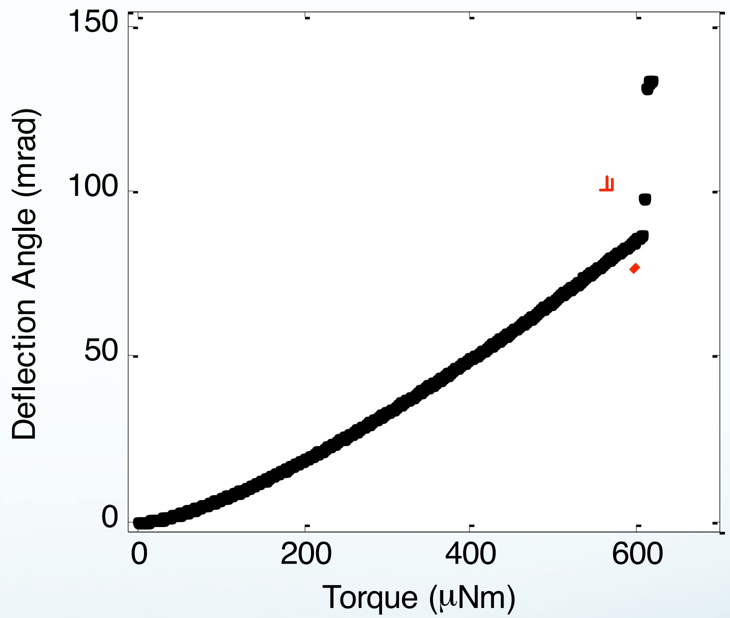
FFT: Stanley, Kato, *J. Tribol.* 119, 481 (1997)
De-coupling images: Hockney, Methods in Comput. Phys. 9, 135 (1970)
Hard-wall: Polonsky, Keer, *Wear* 231, 206 (1999)
Atomistic derivation: Campaña, Müser, *Phys. Rev. B* 74, 075420 (2006)
Pastewka, Sharp, Robbins, *Phys. Rev. B* 86, 075459 (2012)

(Greenwood-Tripp)



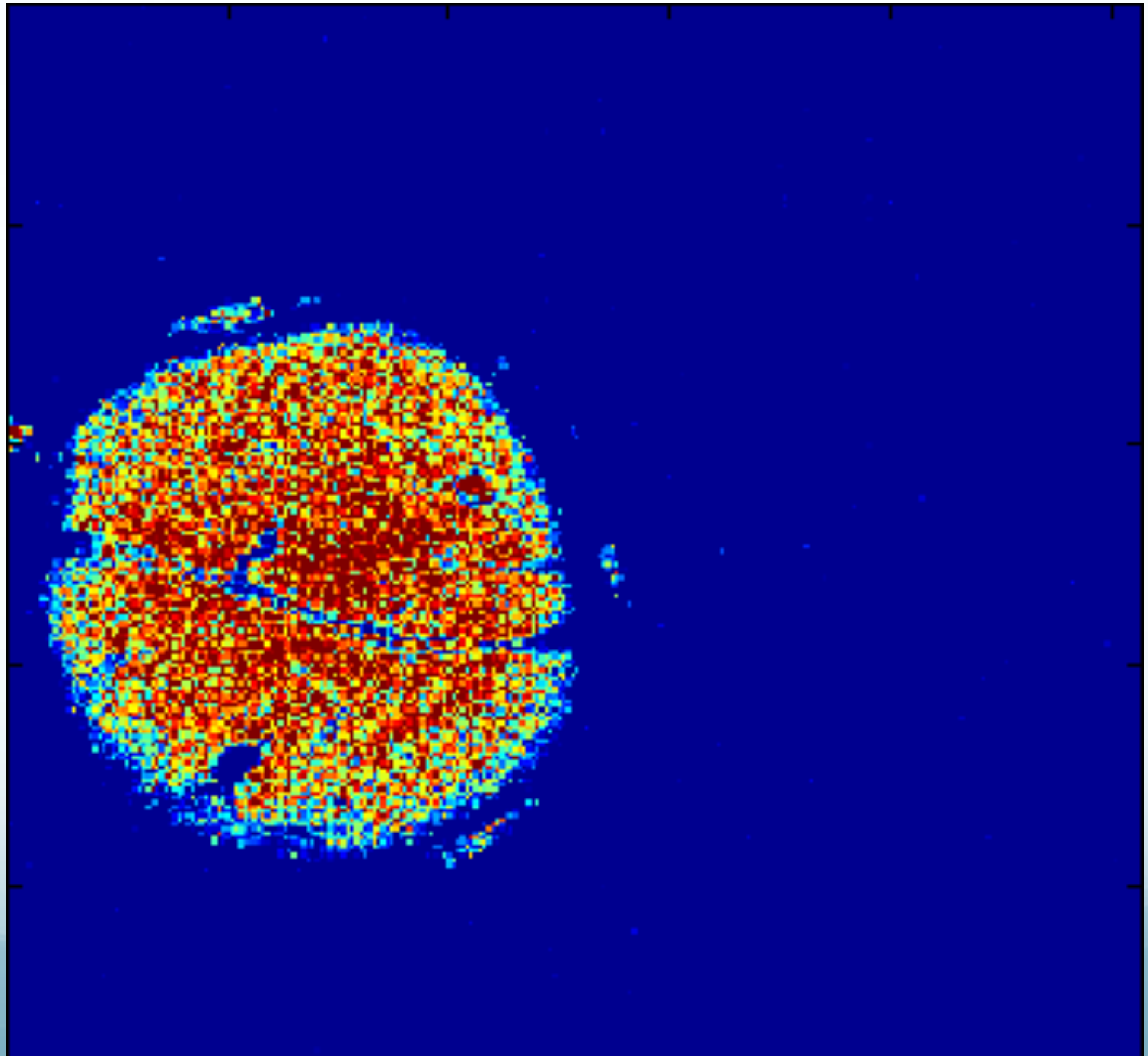
Friction Measurements

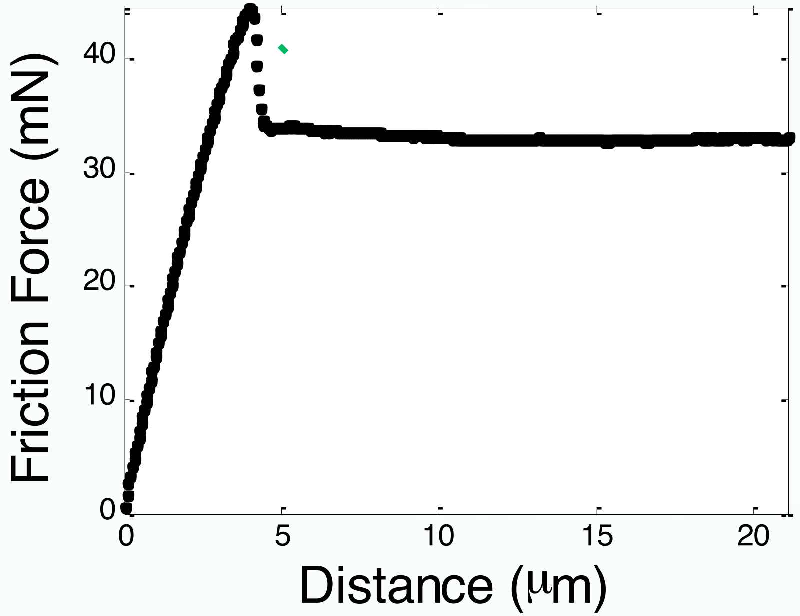




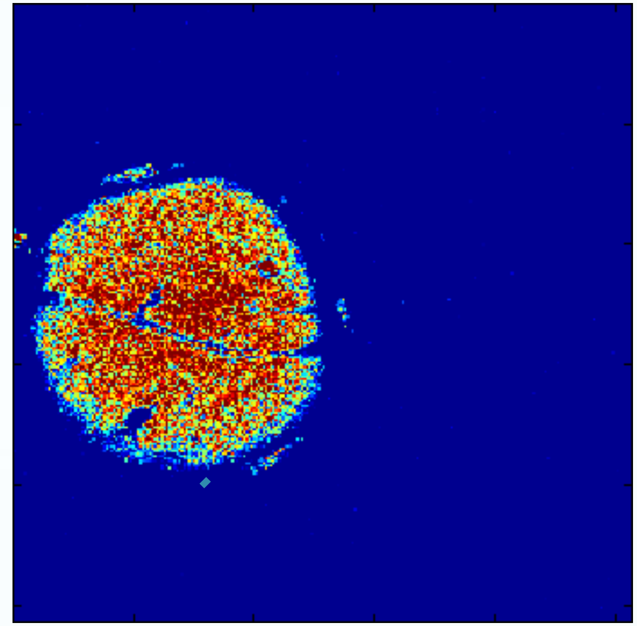
Static Friction Force

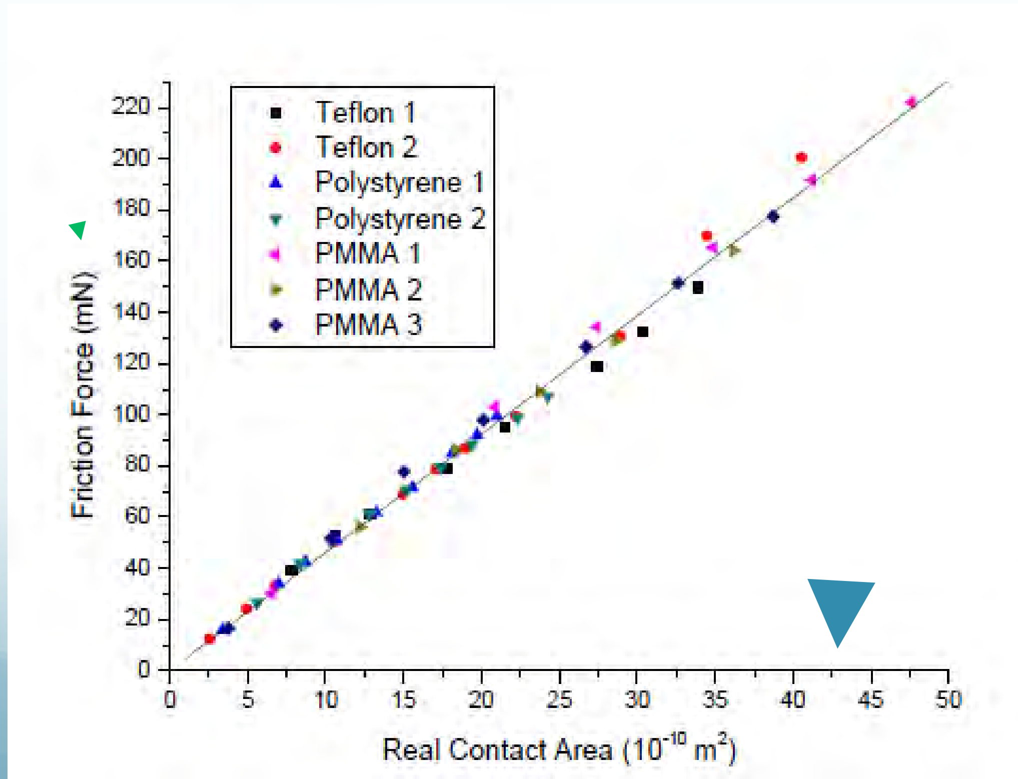
Sliding Experiment





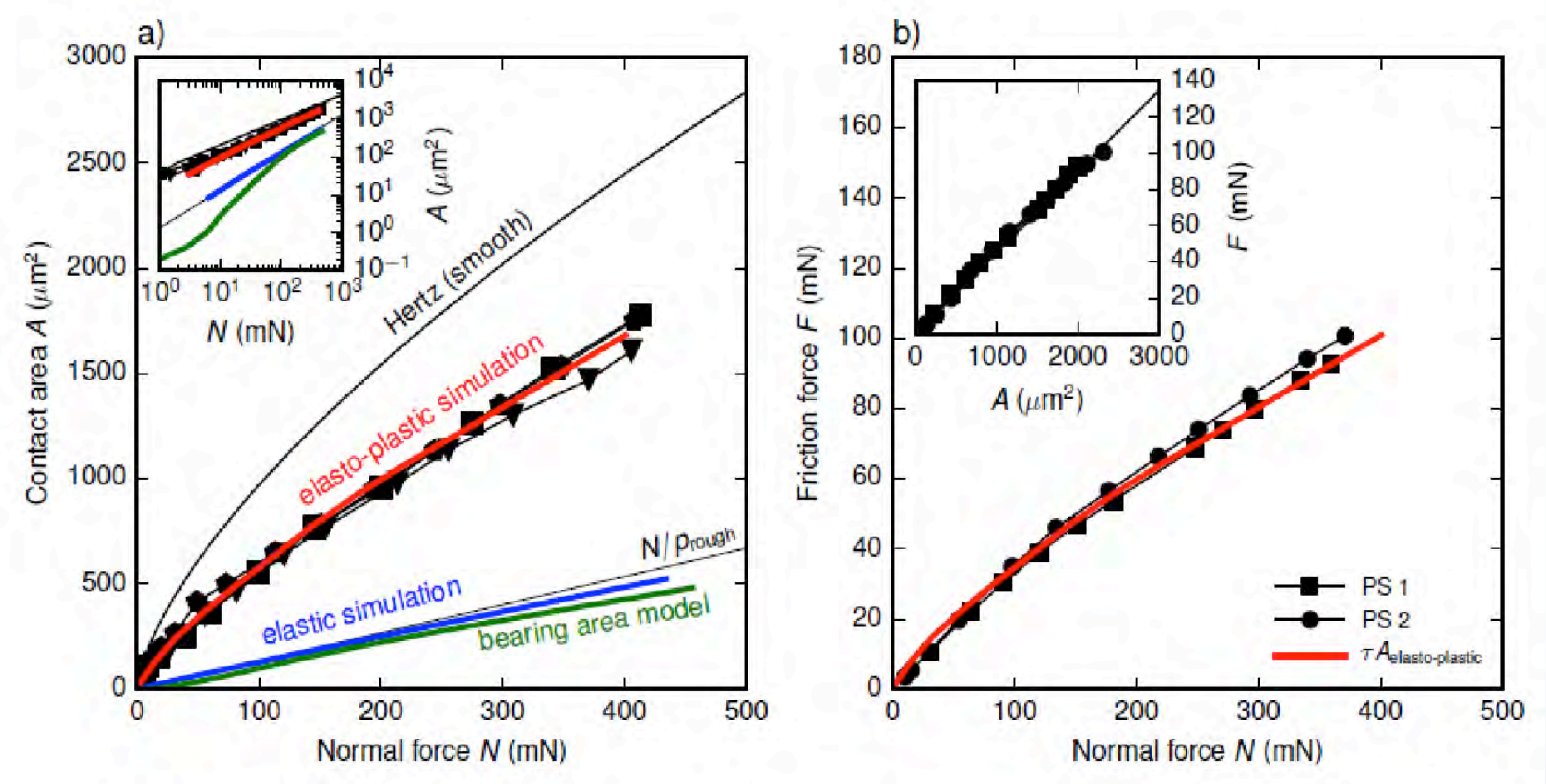
Friction Force (mN)
0
10
20
30
40
0
5
10
15
20
Distance (μm)

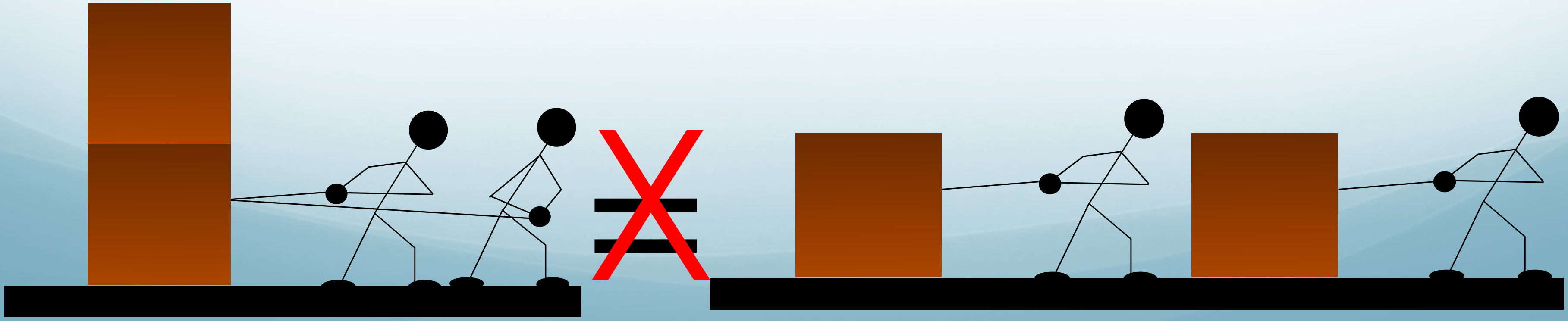




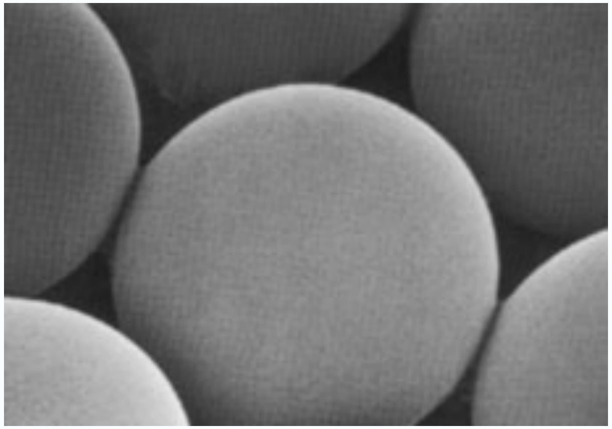
Teflon 1
Teflon 2
Polystyrene 1
Polystyrene 2
PMMA 1
PMMA 2
PMMA 3
Friction Force (mN)
0
20
40
60
80
100
120
140
160
180
200
220
0
5
10
15
20
25
30
35
40
45
50
Real Contact Area (10^{-10} m^2)

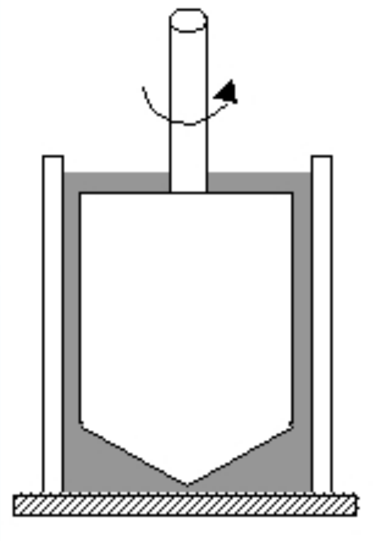
Amontons' (f)law





Back to Granular Suspensions

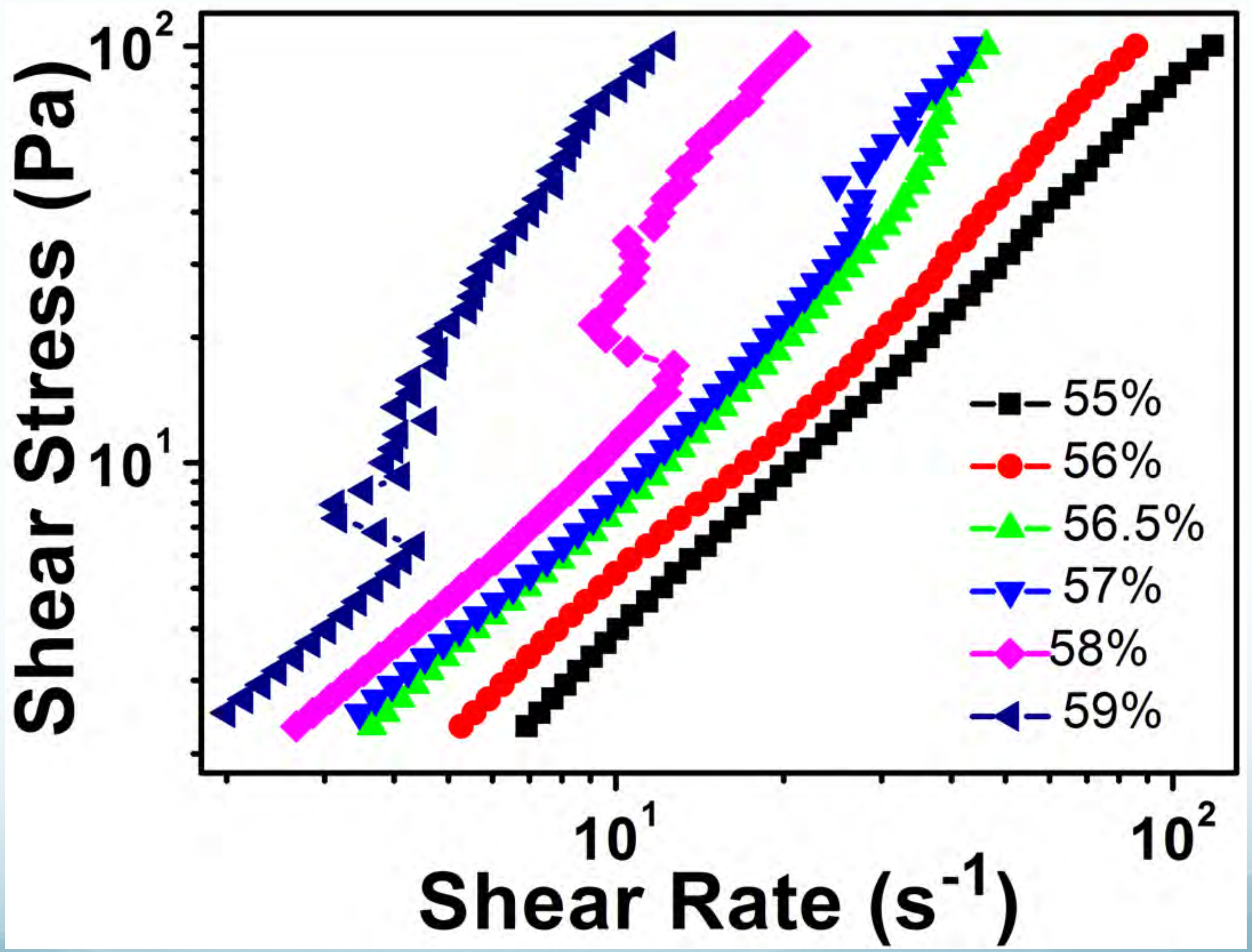




- PMMA, $d = 6\ \mu m$; H_2O/NaI
- Couette, *gap = 1mm.*
- CSR & CSS

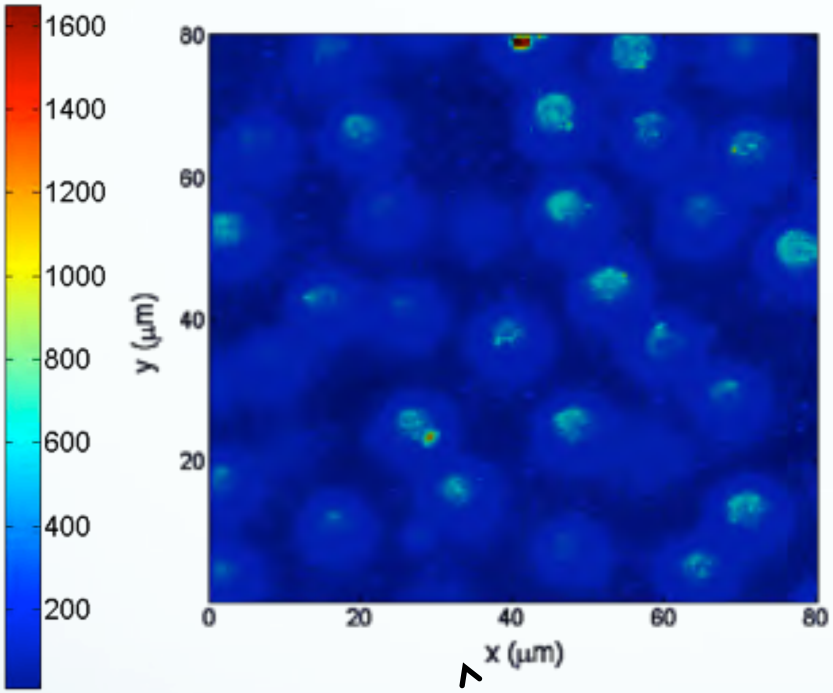
S-Shaped Flow Curve

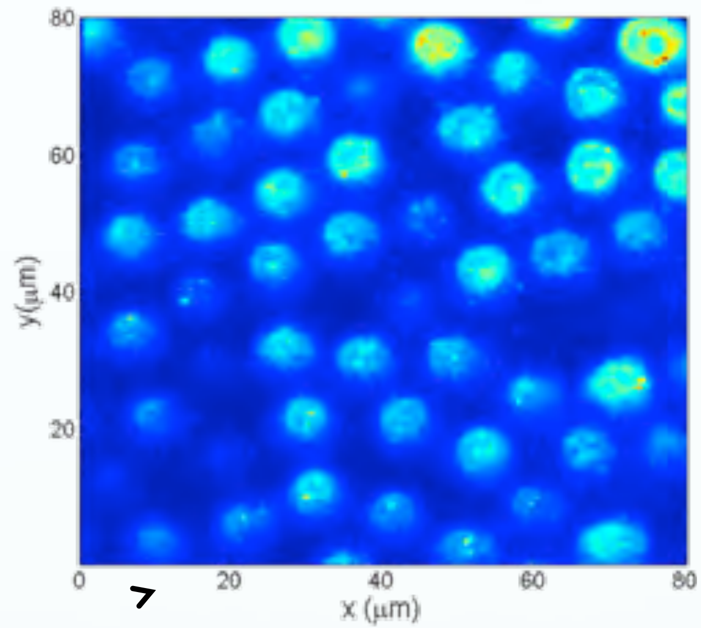
CSS:
1-100 Pa



Z. Pan et al., PRE 2015

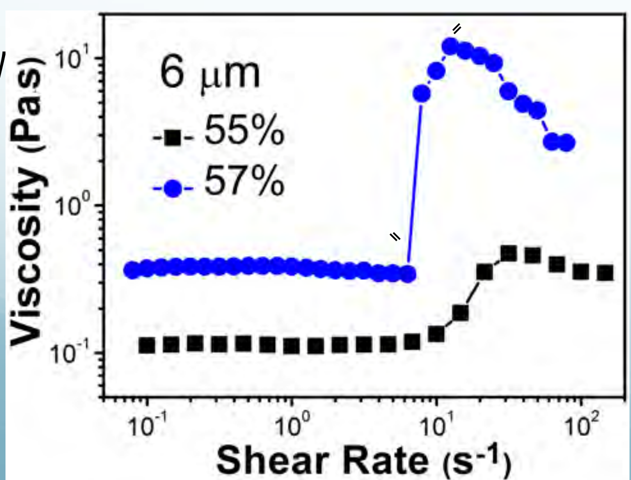
Effect of shear

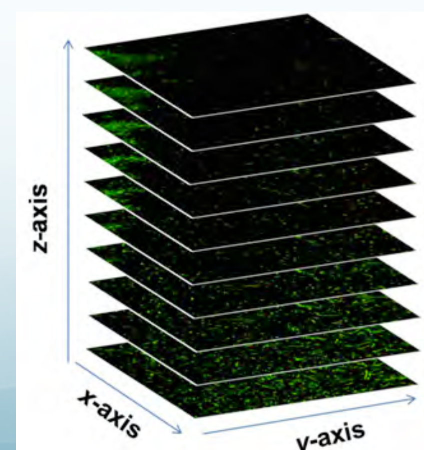




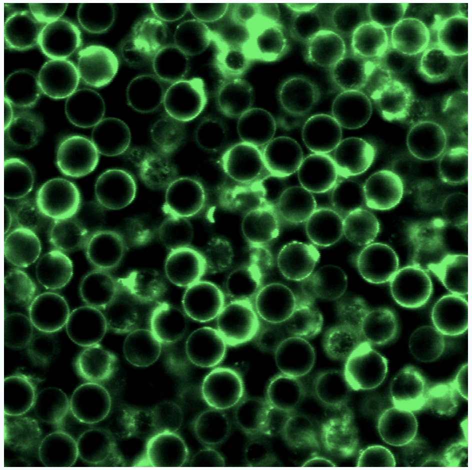
Velocity

intensity/
a.u.

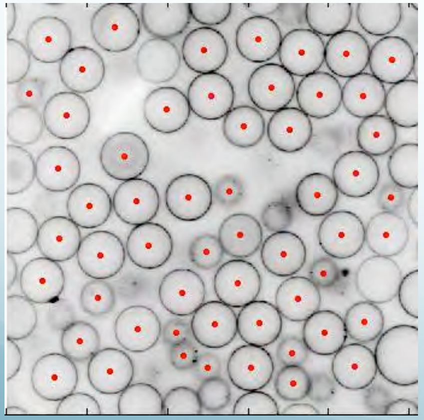




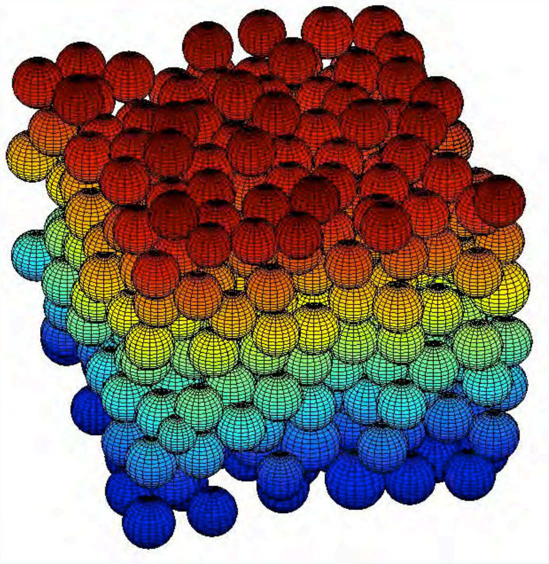
Frictional contact networks



2D images
Confocal microscopy (xy plane)

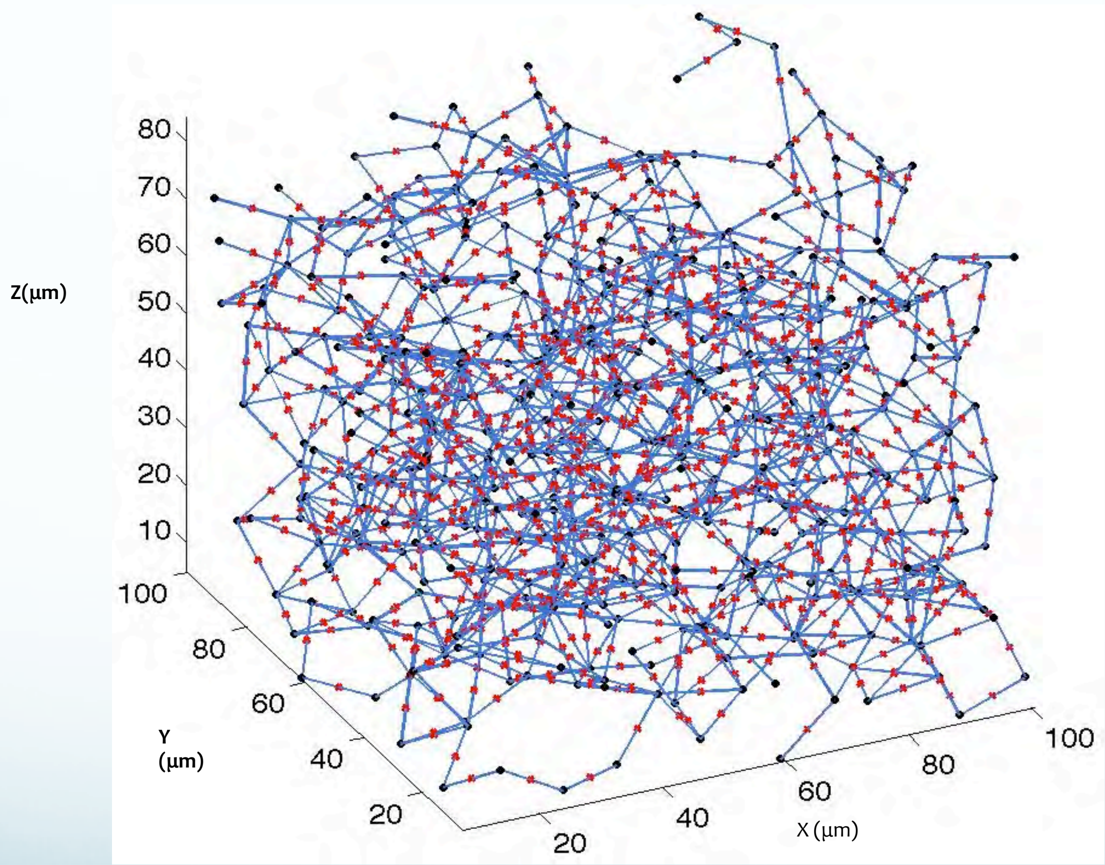


The centers of the particles are calculated



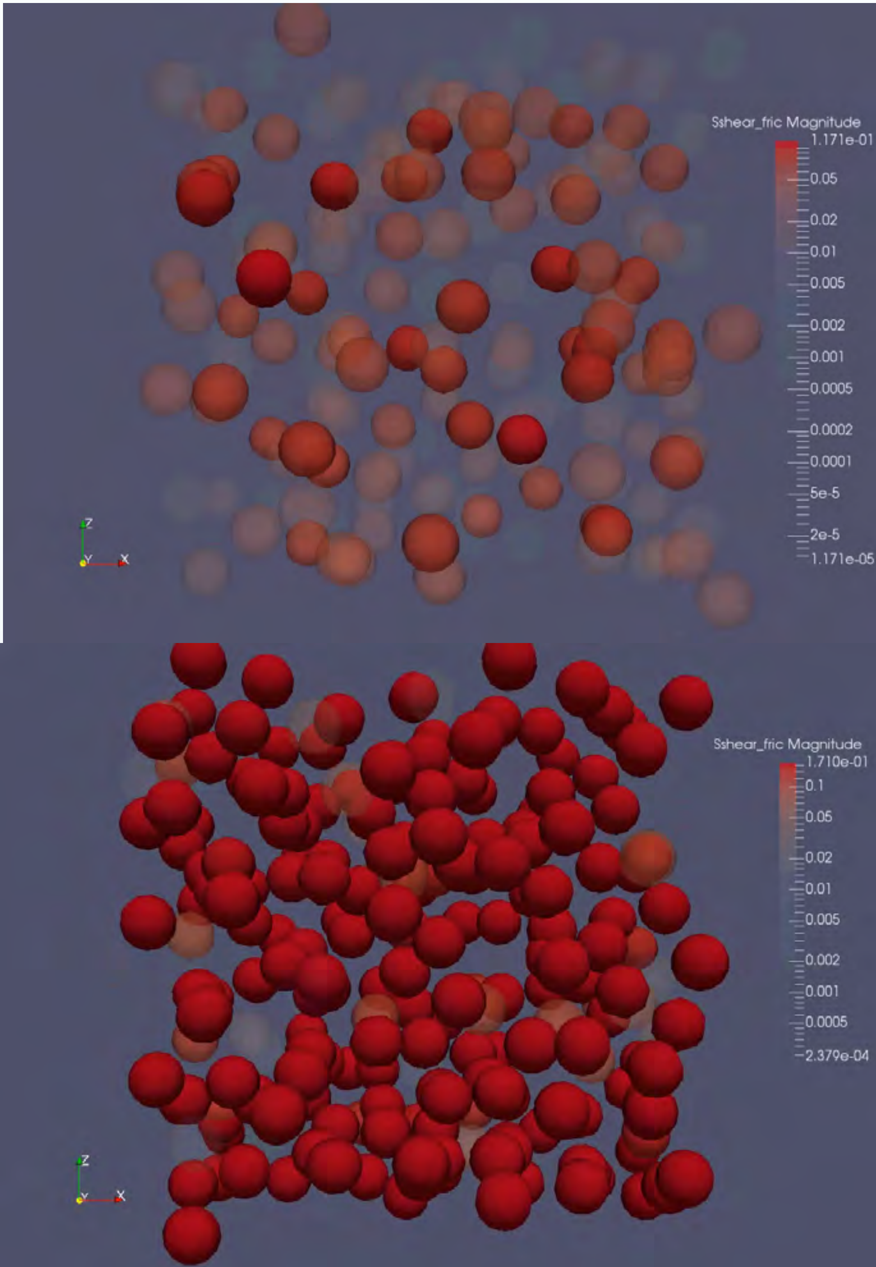
3D model

From this we can construct the frictional contact network



(just after flow cesssation,in a very concentrated thickened suspension)

Next: compare this to LBM simulations



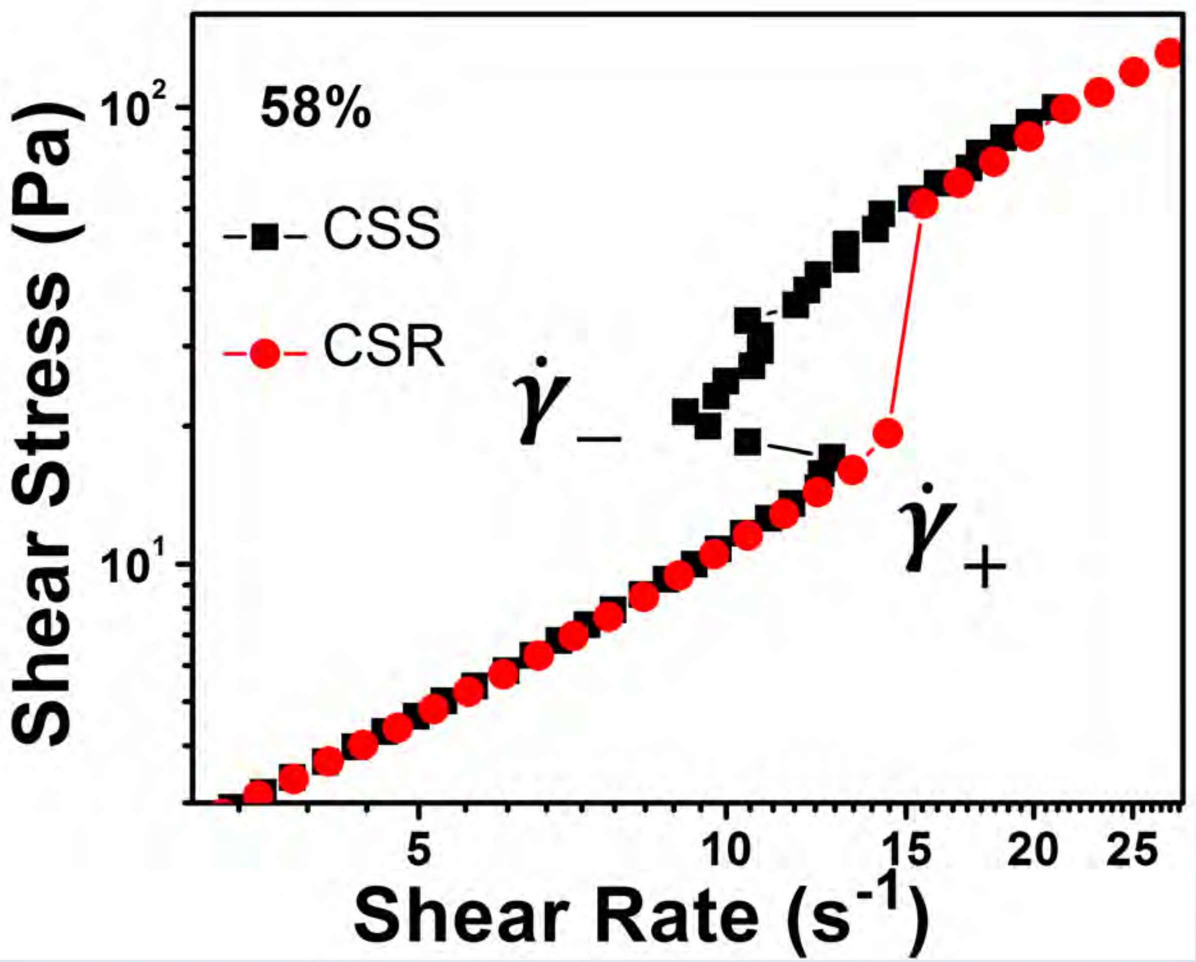
CST
f~0.5

DST
f~1

Vishnu

Computers and Fluids, in press

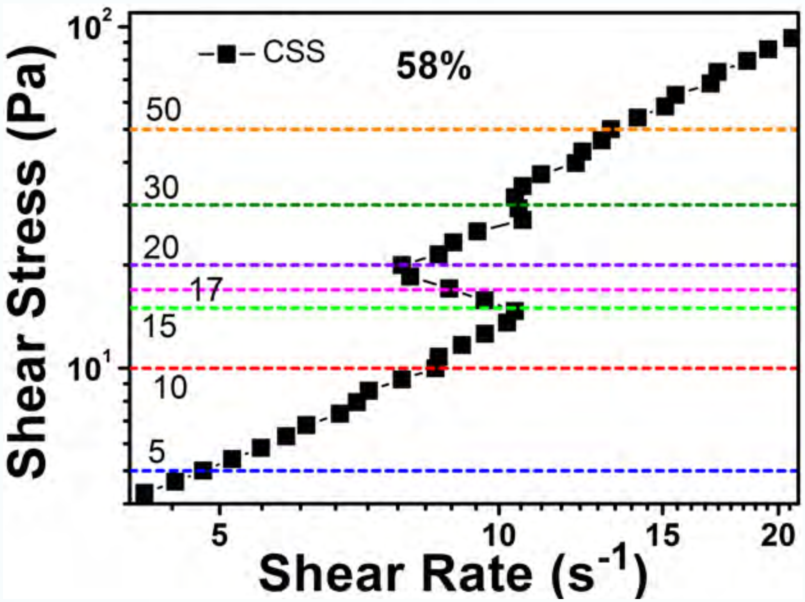
Back to DST: what about the flow stability?

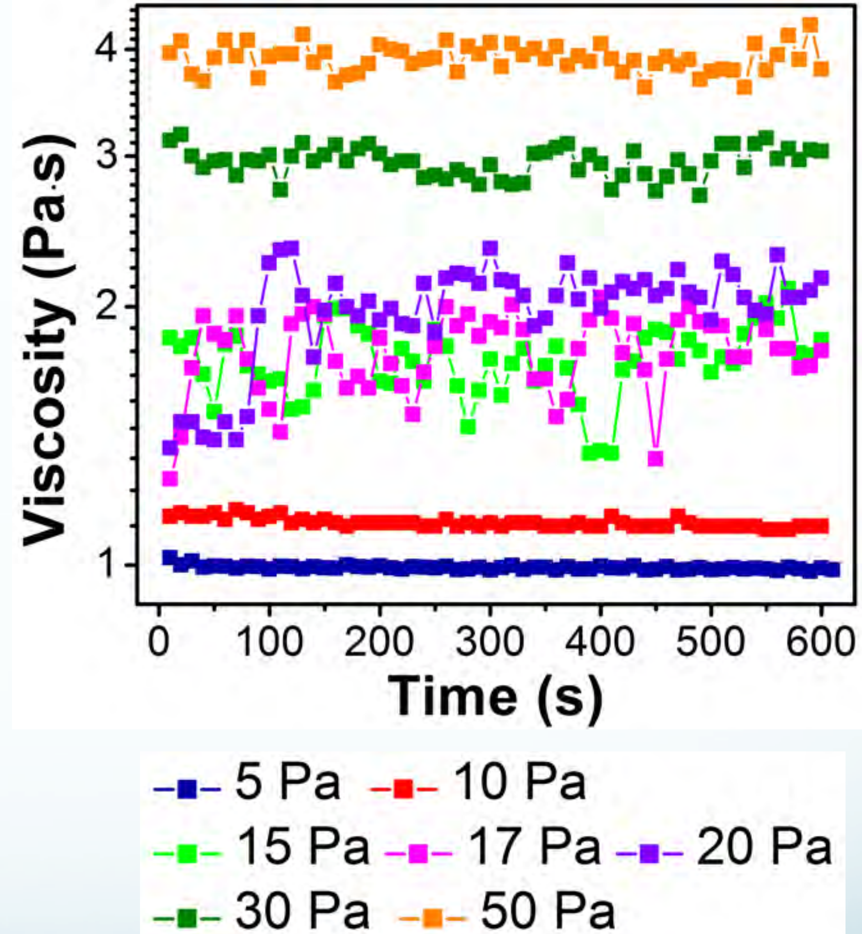


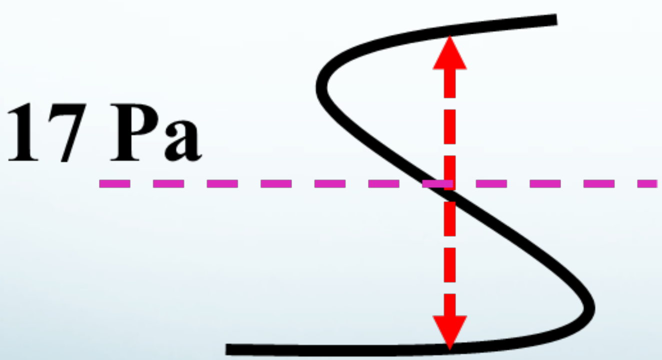
Controlled Stress or Shear Rate

Z. Pan et al., PRE 2015

Constant Shear Stress



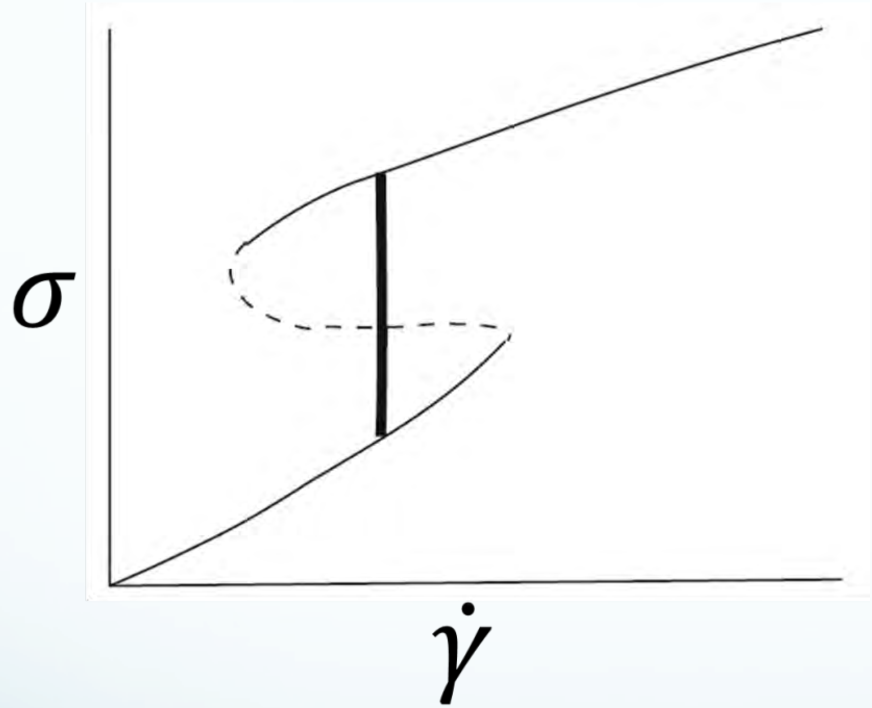




Unstable branch: viscosity roughly fluctuates between two values on the stable branches.

Vorticity Banding ?

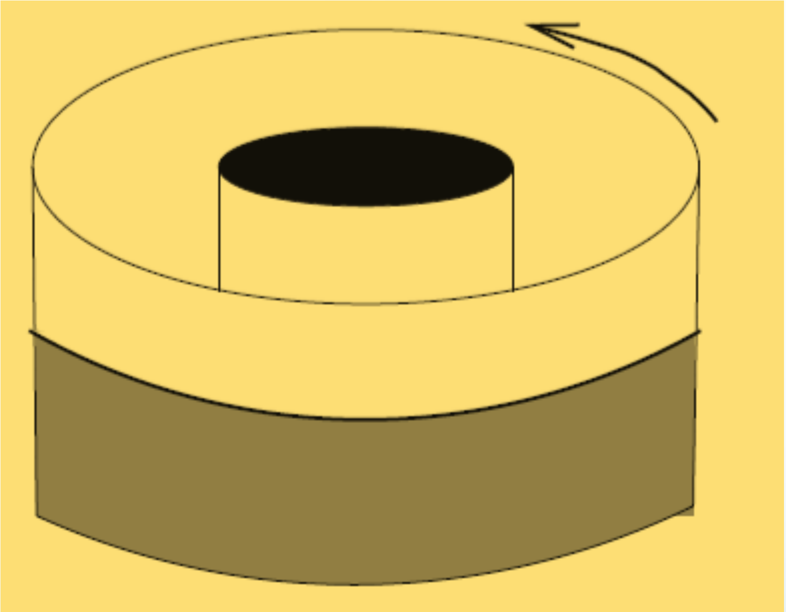
- S-Shaped Flow curve



$$\frac{\partial \Sigma}{\partial t} = f(\dot{\gamma}, \Sigma) + D\frac{\partial^2 \Sigma}{\partial y^2} = 0$$

- **Different Stresses**

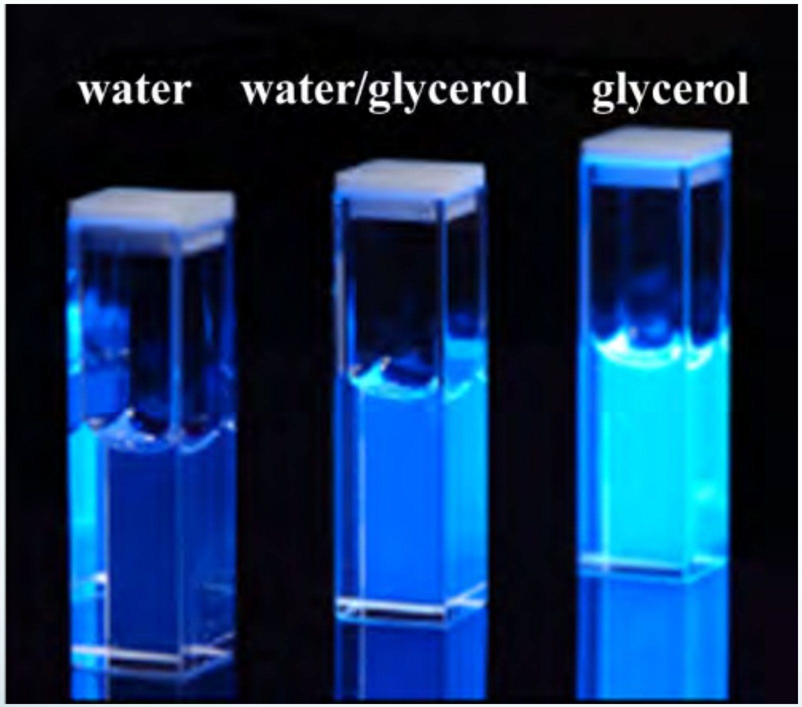
-along the vorticity direction

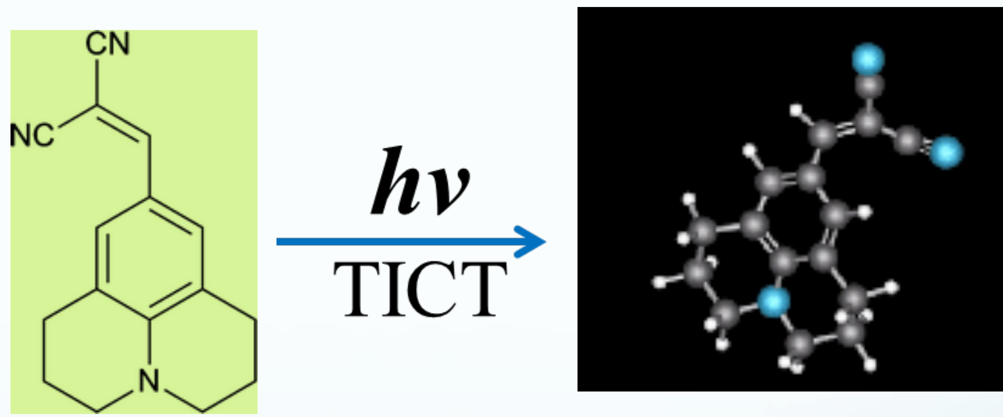


P.D. Olmsted, Rheol Acta 2008.

Coexistence of two states with different viscosities?

Measuring different viscosities
Probe: DCVJ



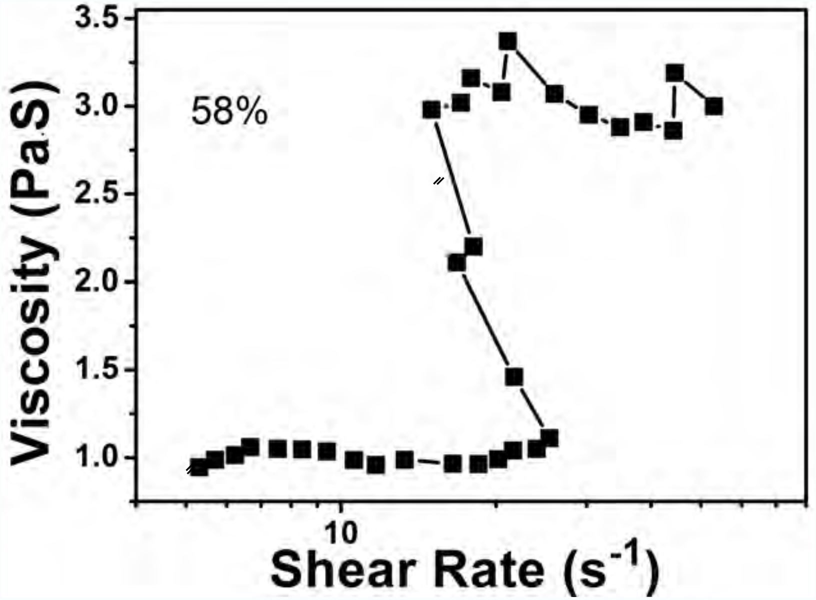


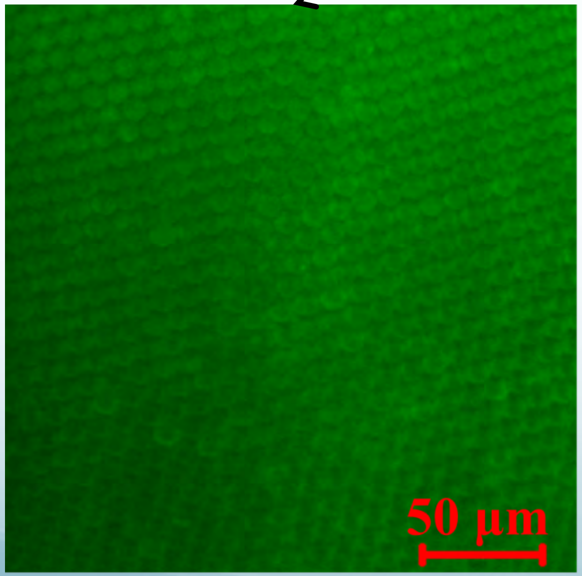
- Twisted Intramolecular Charger Transfer, reacts to viscosity (and pressure!)

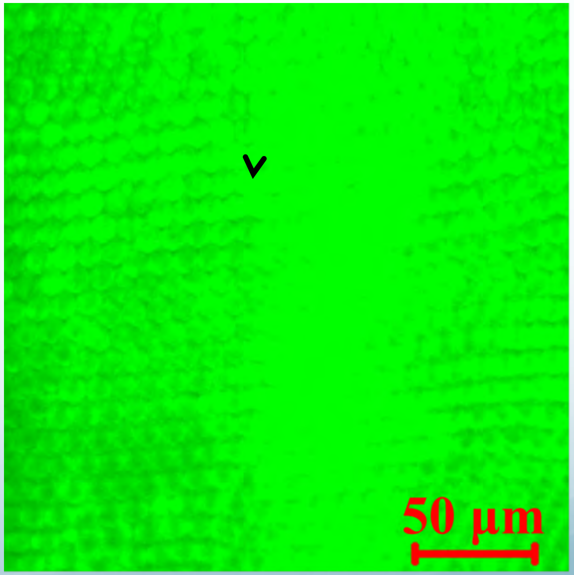
No Vorticity Bands Found!

S-Shaped Curve

Cone-Plate





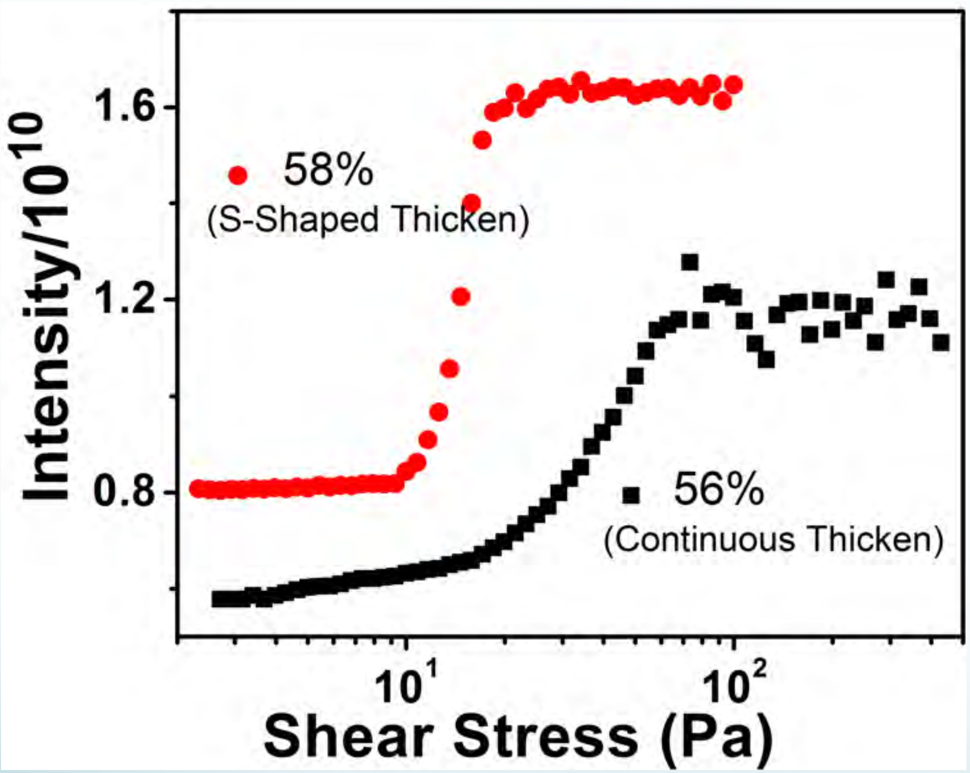


@1 Pa.s

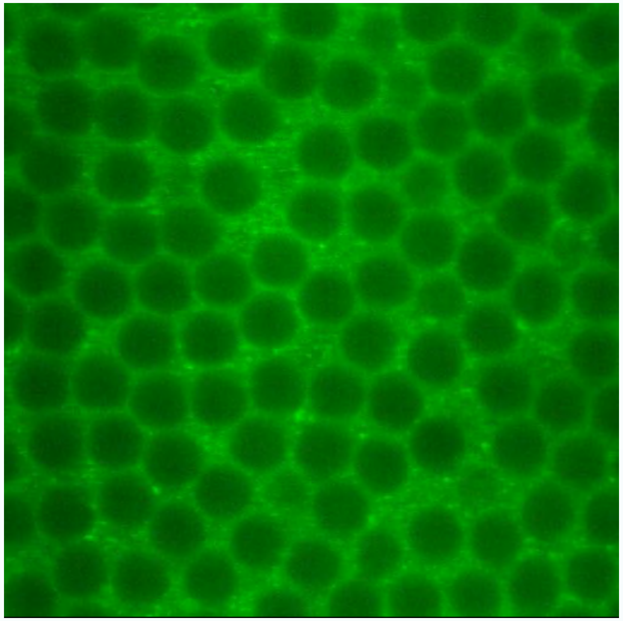
@2.5 Pa.s

Z. Pan et al., PRE 2015

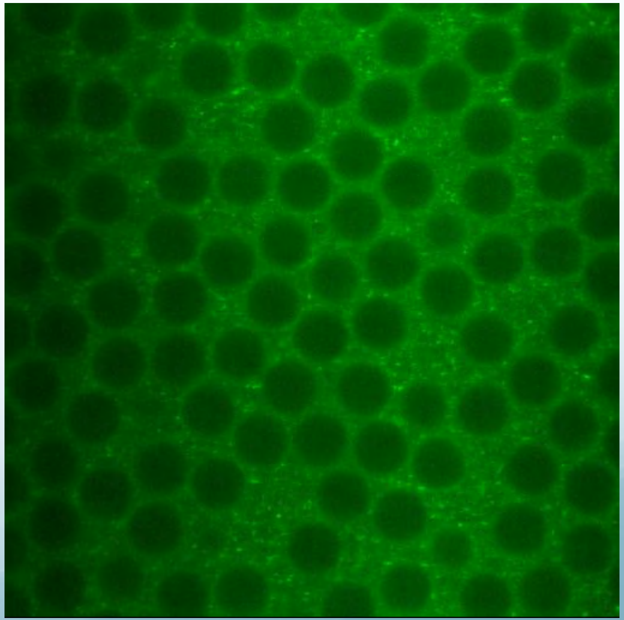
Continuous & discontinuous thickening



58%



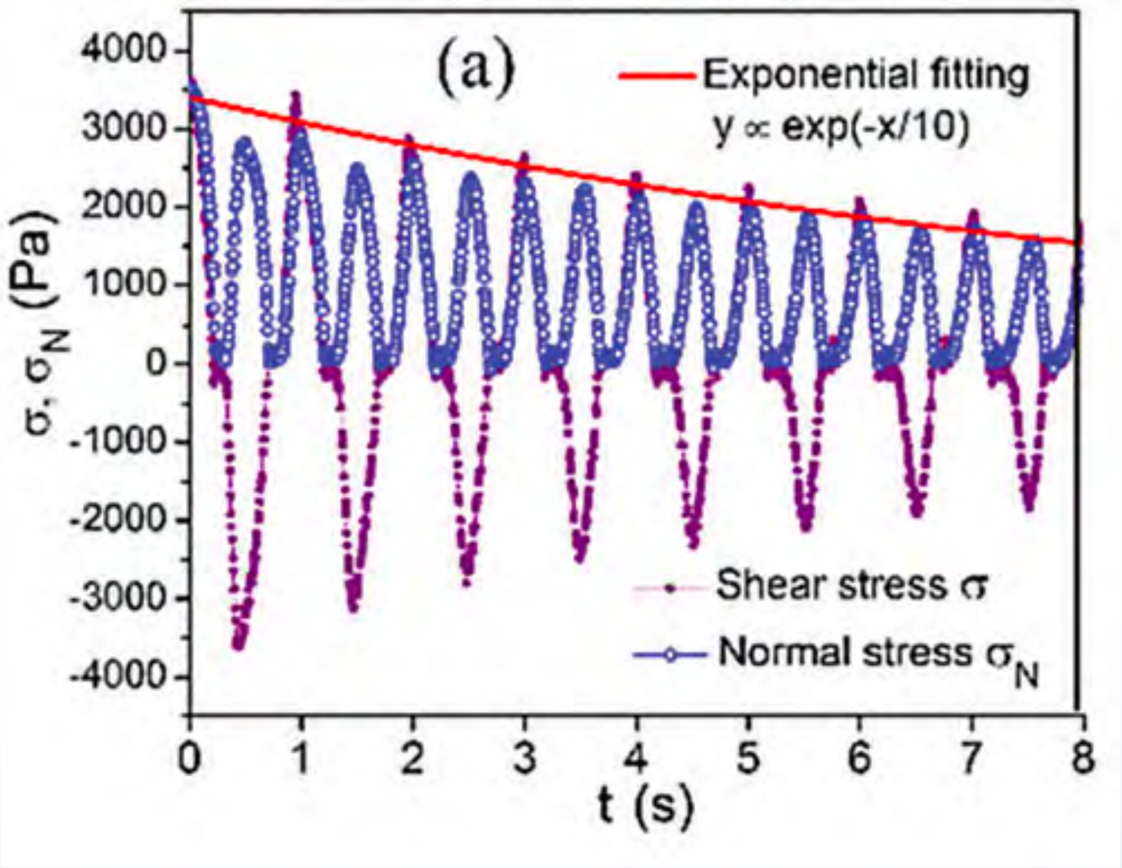
56%



Z. Pan et al., PRE 2015

Increase in the liquid homogeneously throughout the sample. Increase in pressure?

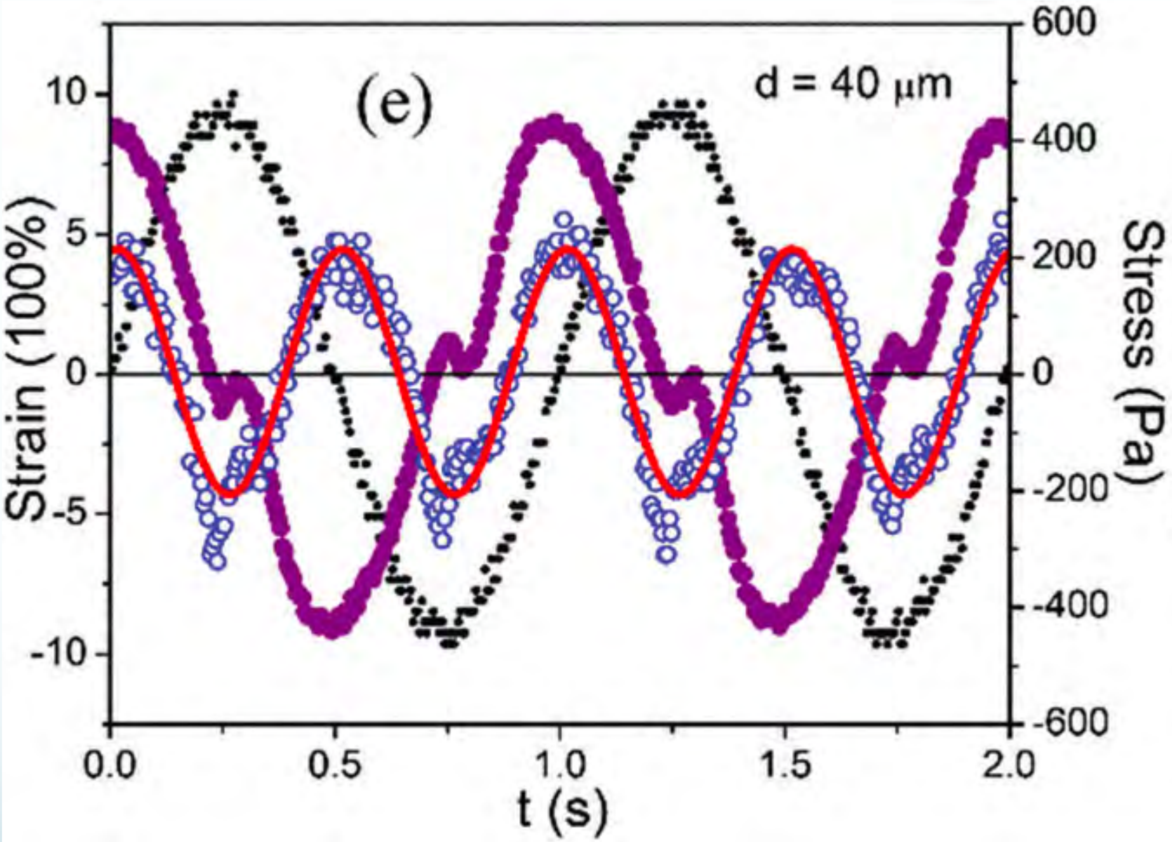
Why is the pressure high? Flow of solvent through the granular packing

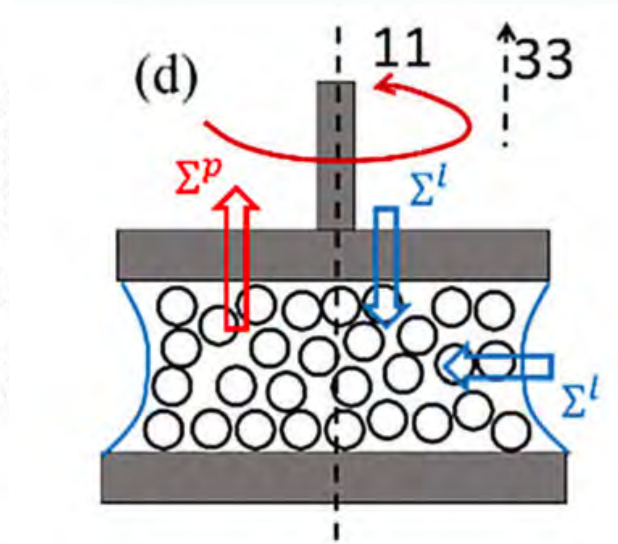


Measurement of the normal stress shows long-time stress decrease in shear and normal stress

Z. Pan et al., Soft Matter 2017

LAOS: phase shift between strain and normal stress: Darcy flow through the granular assembly





Z. Pan et al., Soft Matter 2017

Porosity governs normal stresses in polymer gels
Physical Review Letters 117 (21), 217802 (2016)

Conclusions

- A new probe for studying friction and shear thickening;
- Contact mechanics is subtle, and system-specific
- Shear thickening is due to the emergence of frictional rheology, however fluid transport is also important *(frictional hydroclusters?)*

Shear thickening in concentrated suspensions of smooth spheres in Newtonian suspending fluids
MM Denn, JF Morris, D Bonn
Soft matter 14 (2), 170-184 (2018)