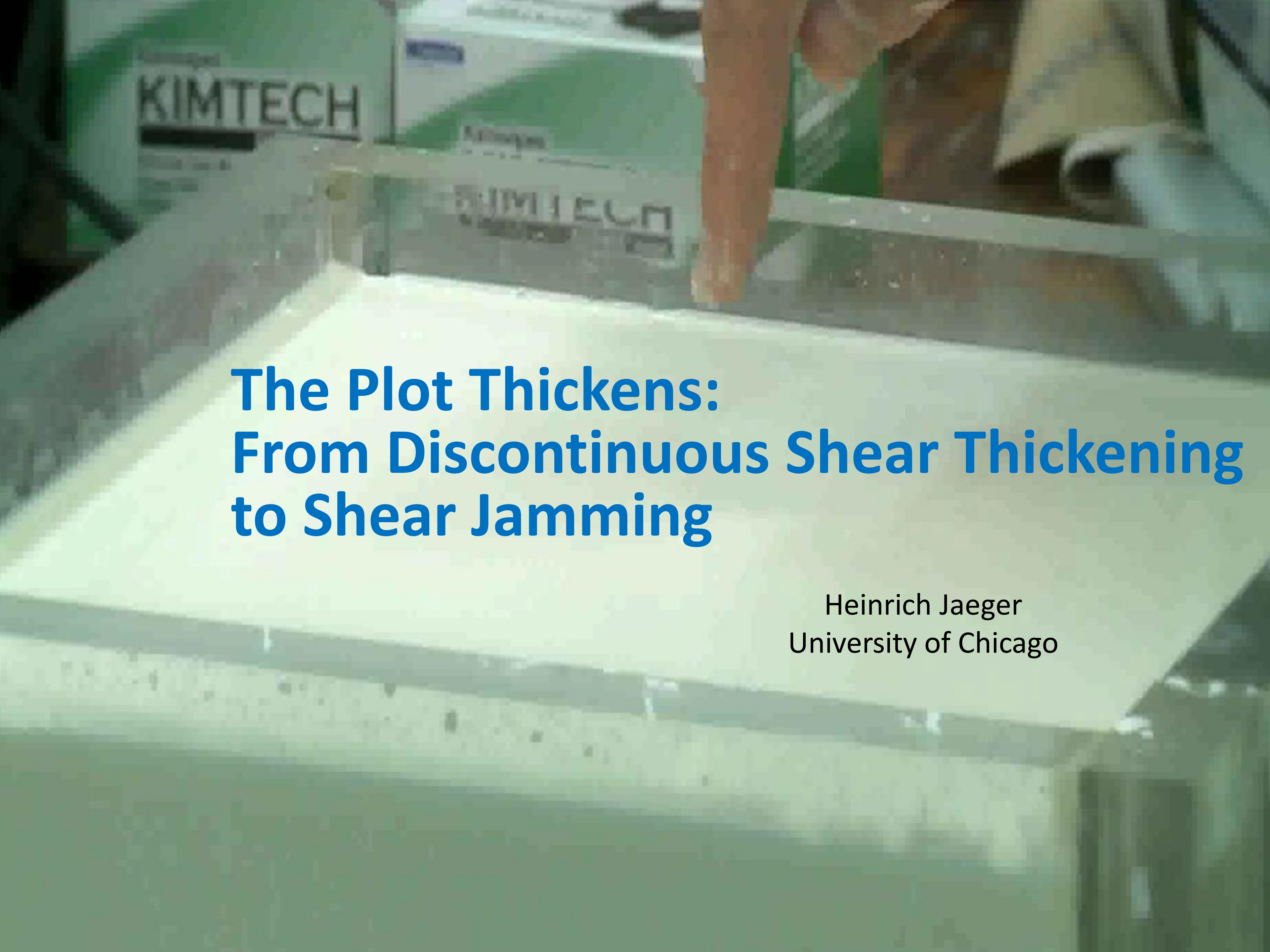
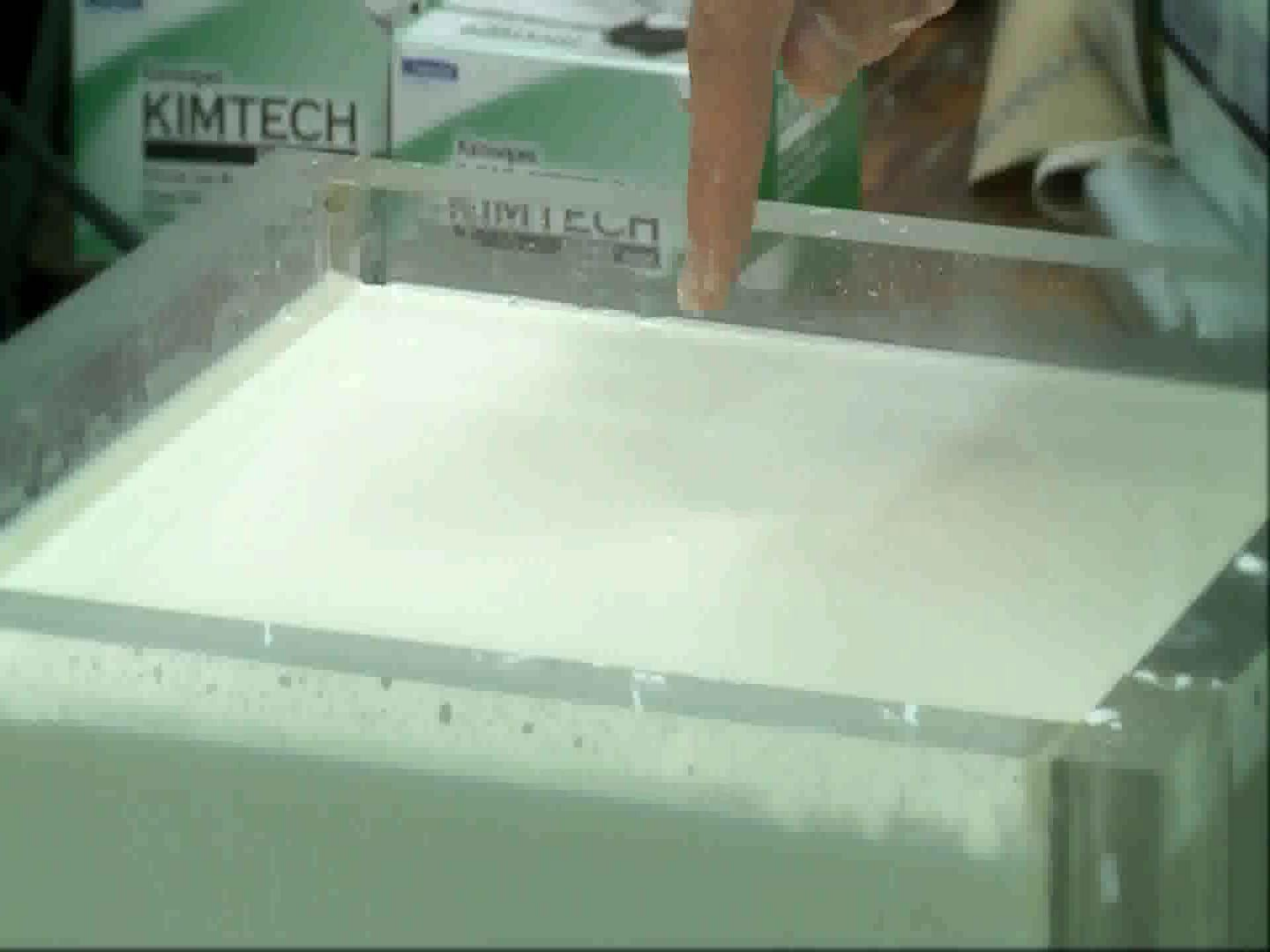
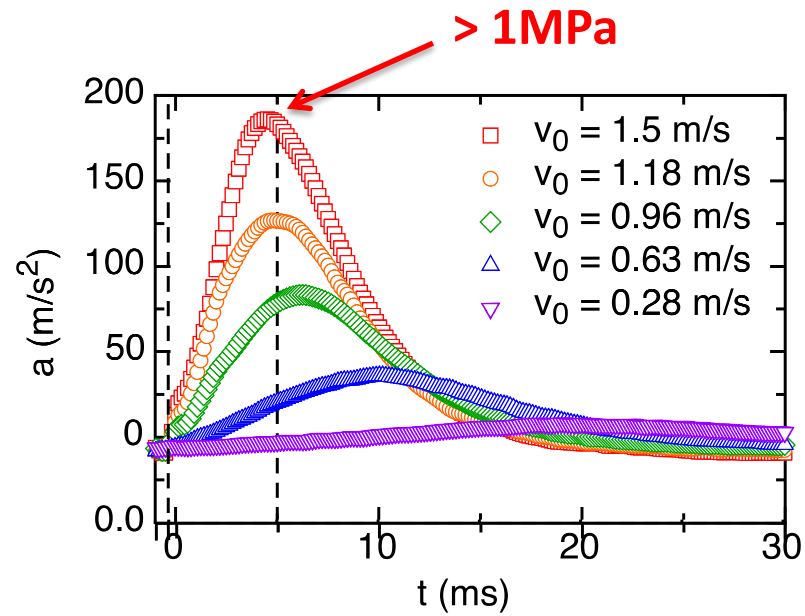


The Plot Thickens: From Discontinuous Shear Thickening to Shear Jamming

Heinrich Jaeger
University of Chicago


KIMTECH

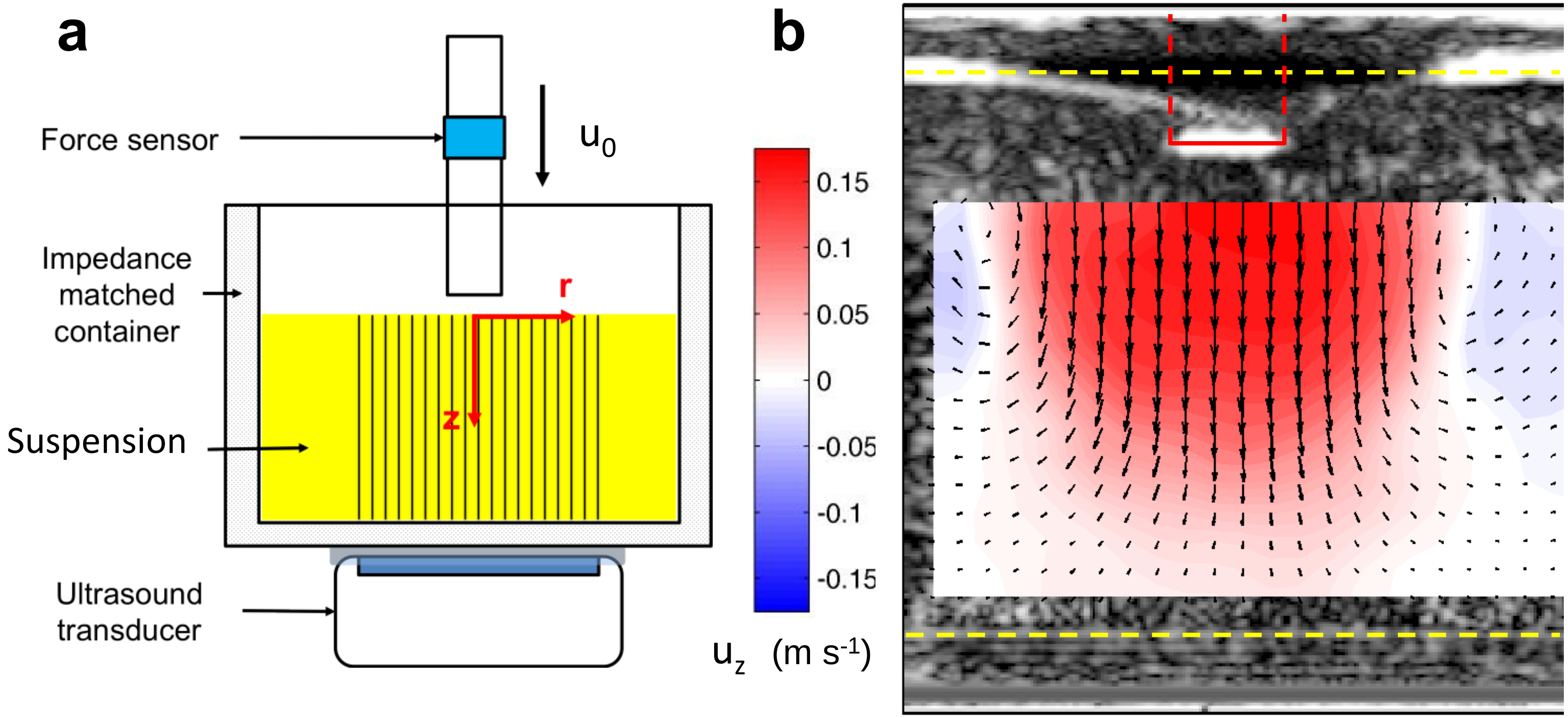
Impact at 4m/s



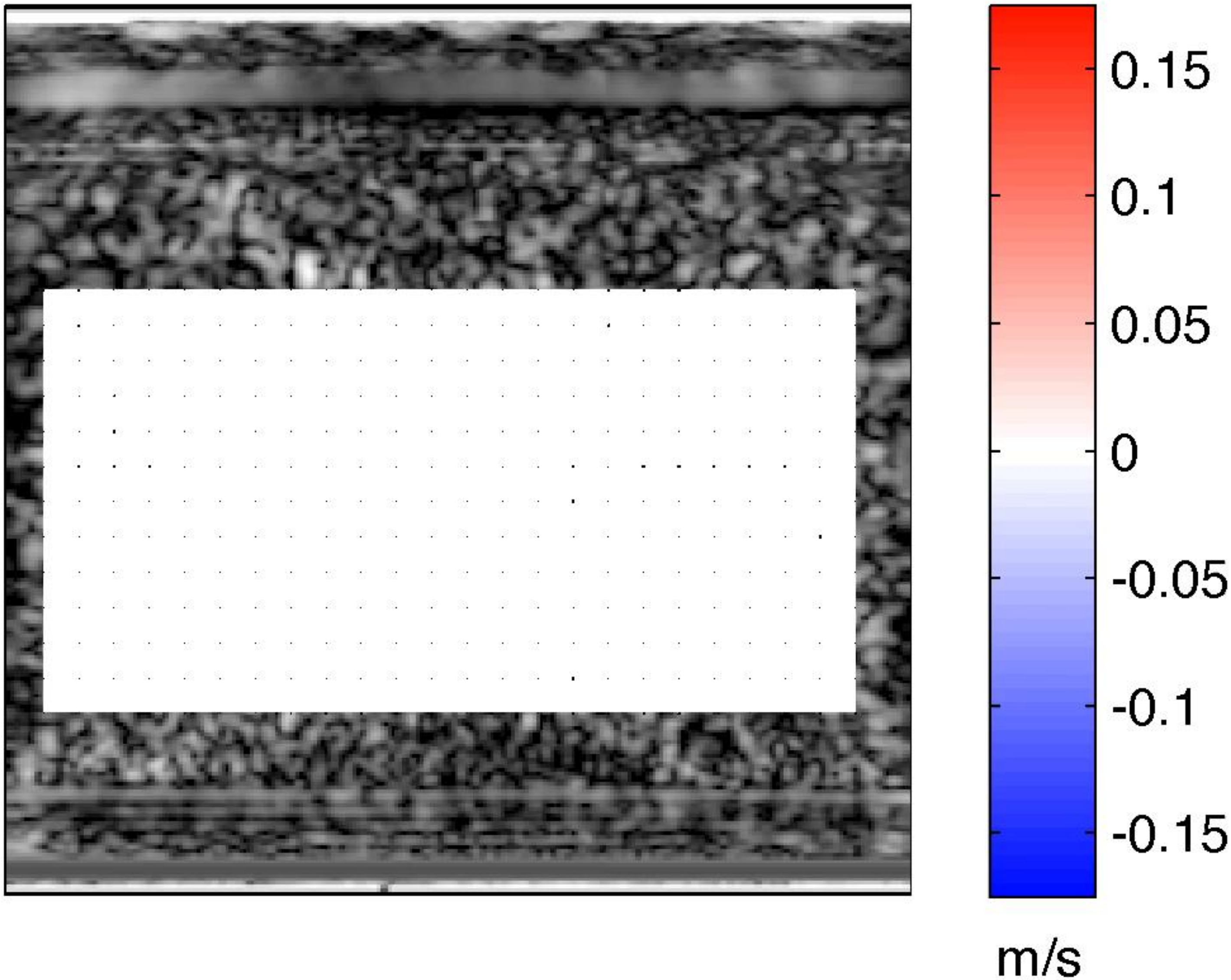
S. Waitukaitis & HMJ,
Nature (2012)

Track Flow Field inside 3D Suspension
with ultrasound @ 10,000fps

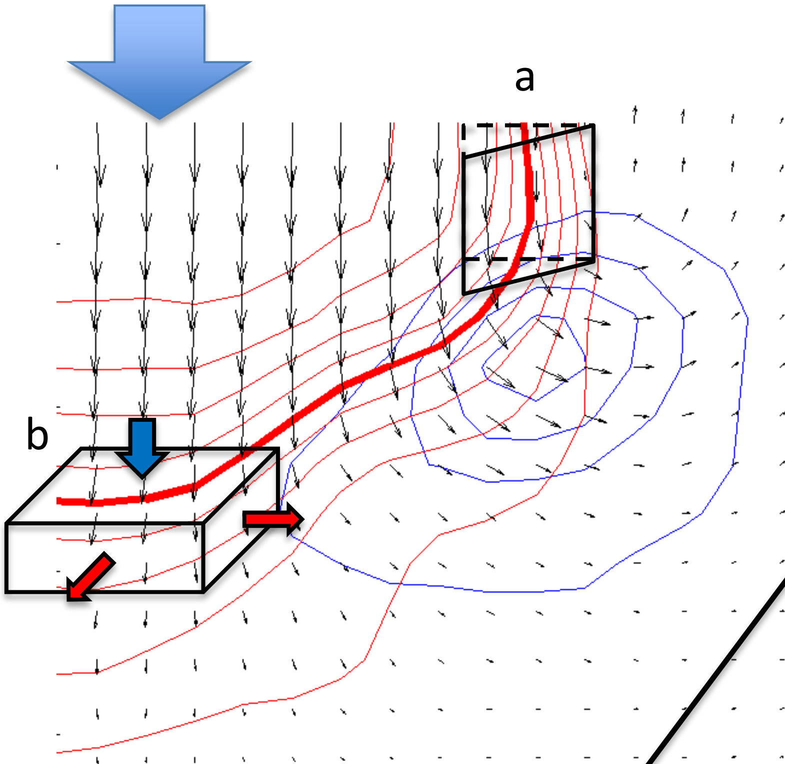
Endao Han



Propagating **Jamming Front** converts fluid into solid

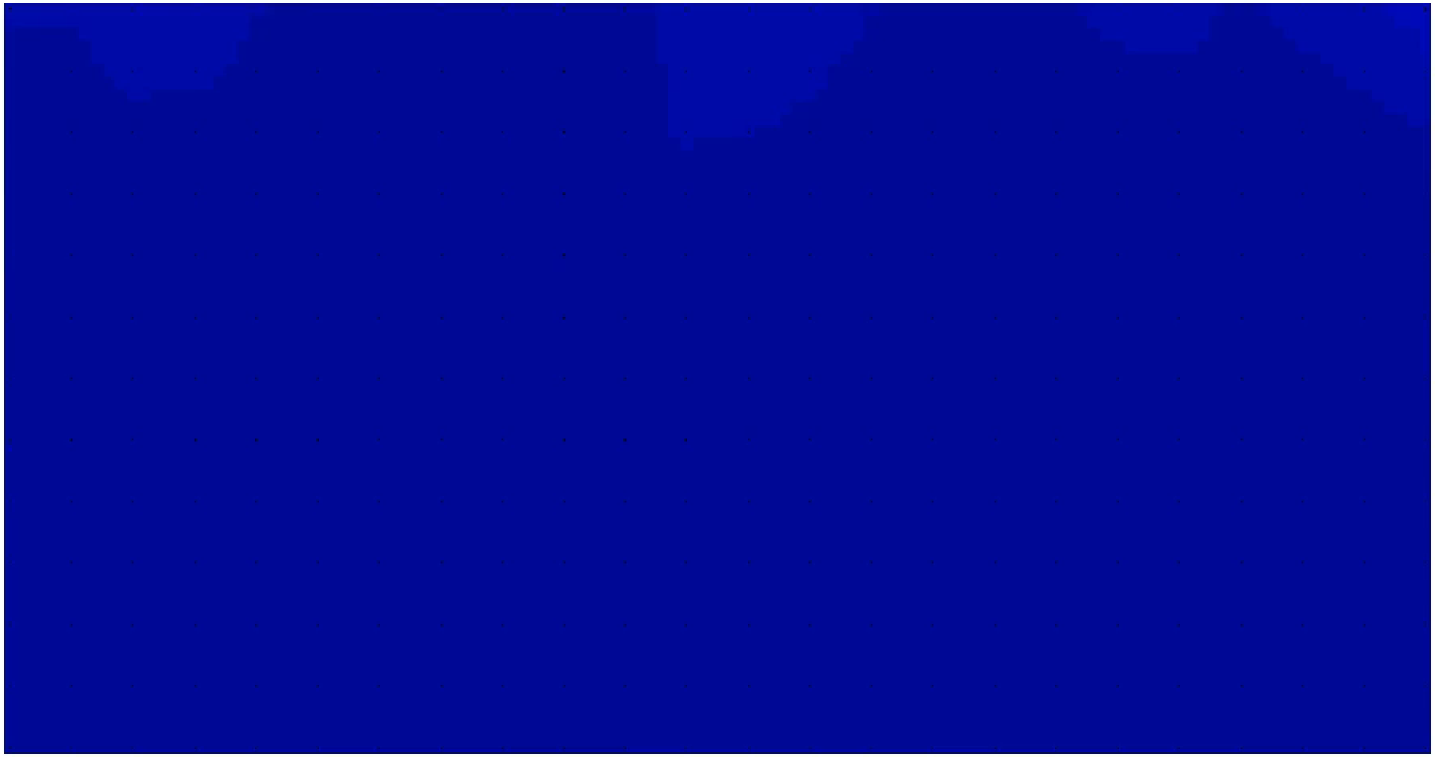


Strain Rate Tensor from Velocity Field



$$
\begin{array}{c} \\ r \\ \theta \\ z \end{array}
\begin{array}{c}
\begin{array}{ccc} \quad r \quad & \quad \theta \quad & \quad z \quad \end{array} \\
\begin{bmatrix}
\frac{\partial u_r}{\partial r} & 0 & \frac{1}{2}\left(\frac{\partial u_r}{\partial z} + \frac{\partial u_z}{\partial r}\right) \\
0 & \frac{u_r}{r} & 0 \\
\frac{1}{2}\left(\frac{\partial u_r}{\partial z} + \frac{\partial u_z}{\partial r}\right) & 0 & \frac{\partial u_z}{\partial z}
\end{bmatrix}
\end{array}
$$

Shear Jamming Front = locus of maximum shear intensity



Front speed $u_f = k u_0$ $k = 1/\varepsilon \gg 1$

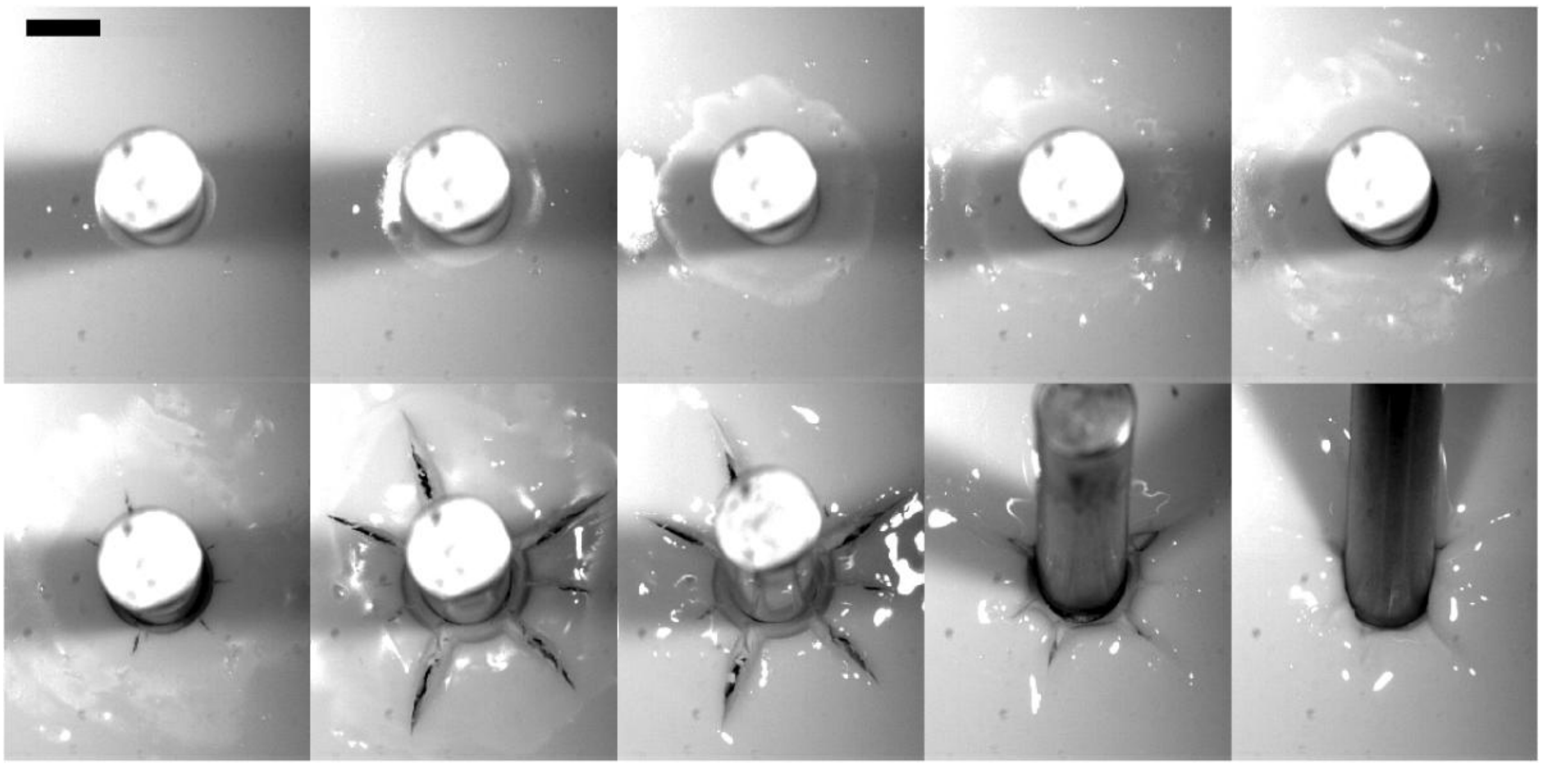
Longitudinal front speed ≈ 2 x transverse front speed

E. Han, I. Peters, HMJ Nature Comm. (2016)

- As jammed region expands into bulk, stress grows ("added mass"); 1D: $\tau \propto k\rho u_0^2$

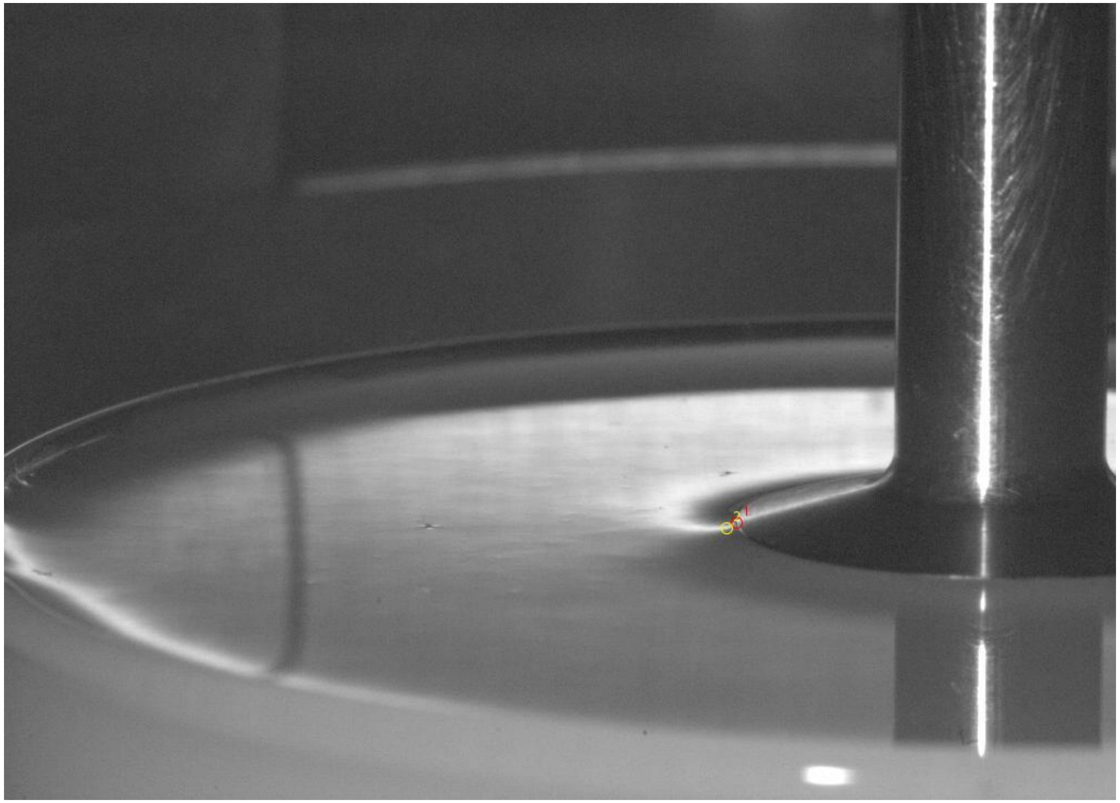
see E. Han's poster

- Once front reaches bottom (or boundaries), solid plug forms

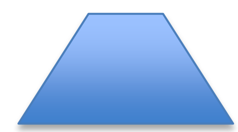


M. Roché *et al.* (2013)

Jamming under extension



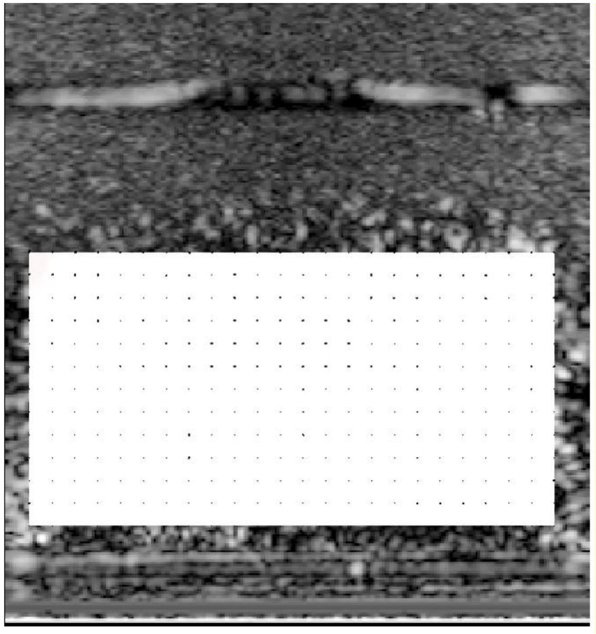
Sayantan



- Solidification instead of necking & snap-off
- Force shoots up when fronts reach boundaries

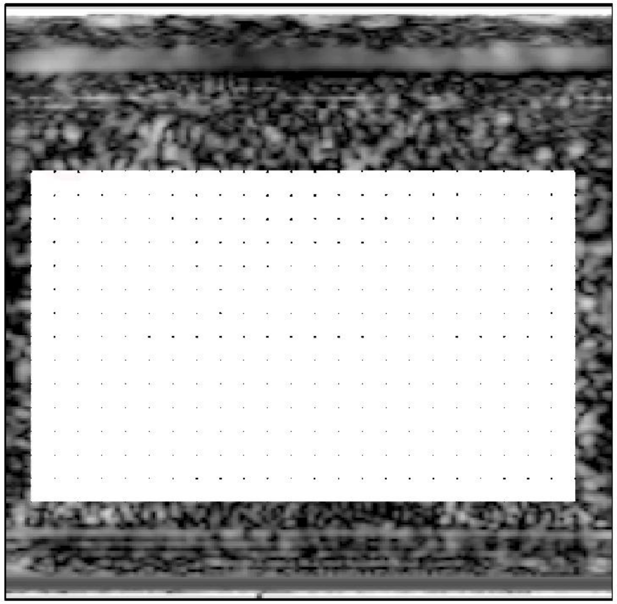
Shear Jamming Fronts
convert unjammed fluid into jammed solid

Extension (3D)



Majumdar *et al.*, PRE (2017)

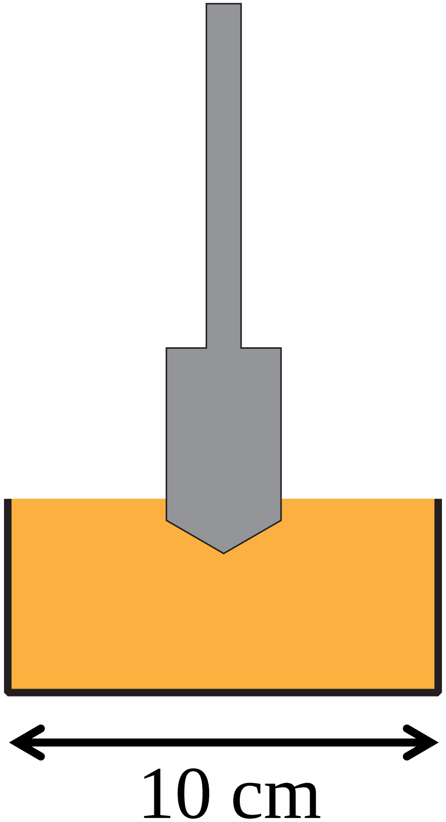
Impact (3D)

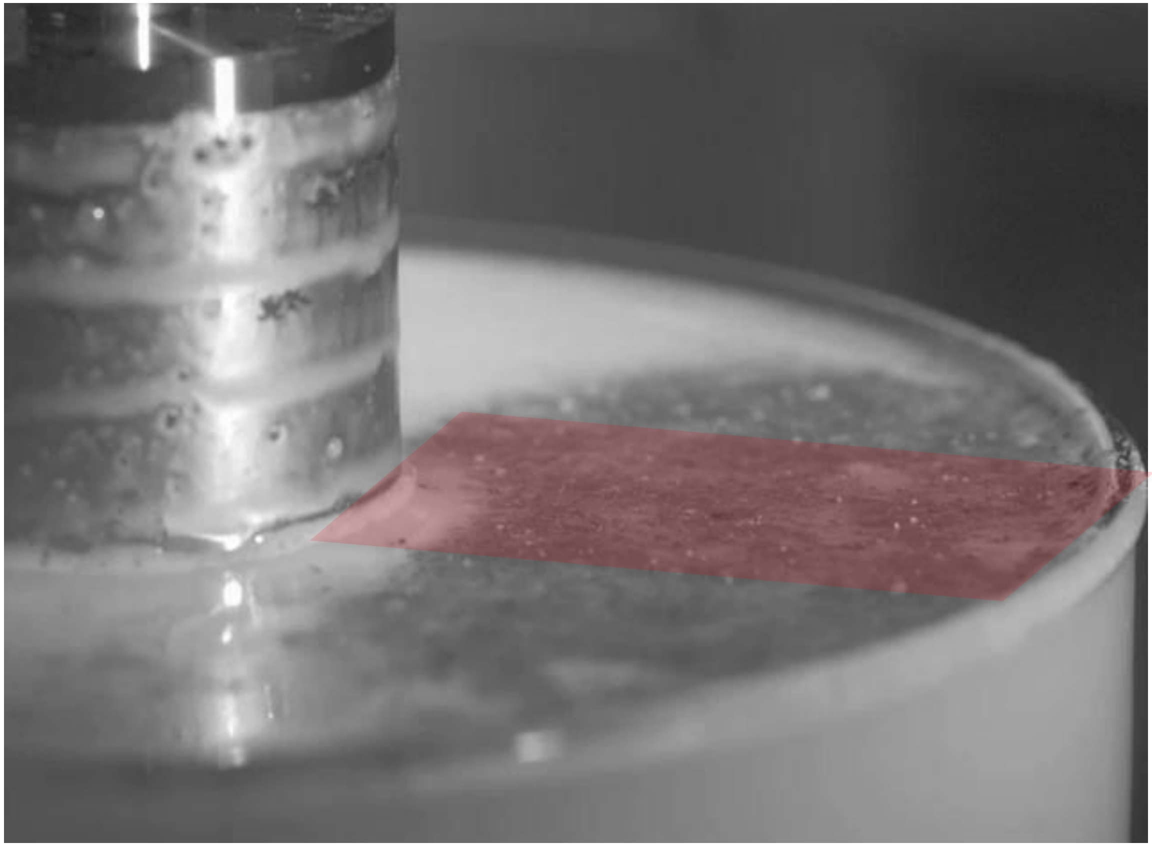


Han *et al.*, Nat. Comm. (2016)

Ivo Peters

Shear jamming in Couette geometry



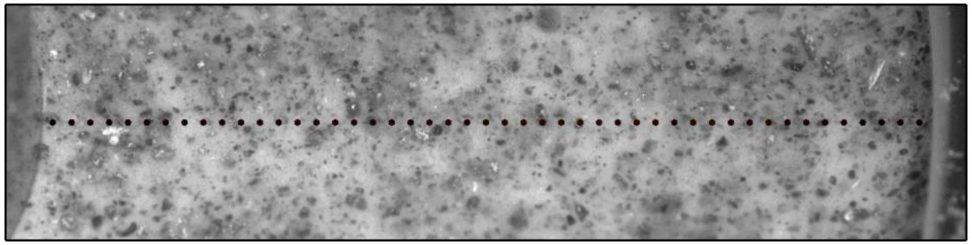


1000 fps

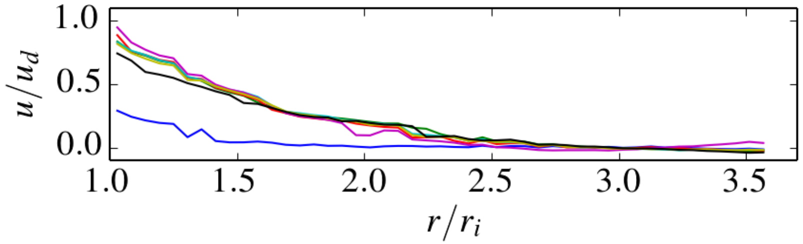
Jamming onset requires minimum shear stress

(= sufficiently fast shearing speed)

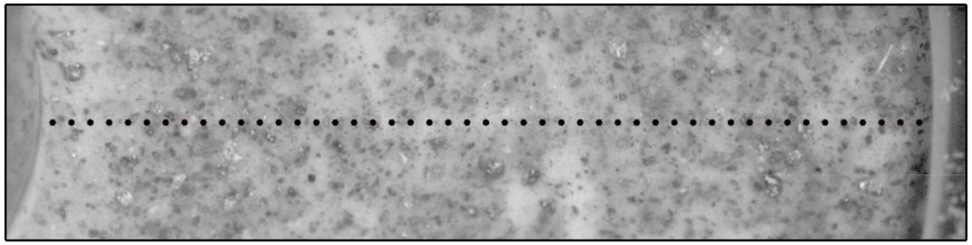
$u_d = 0.008$ m/s



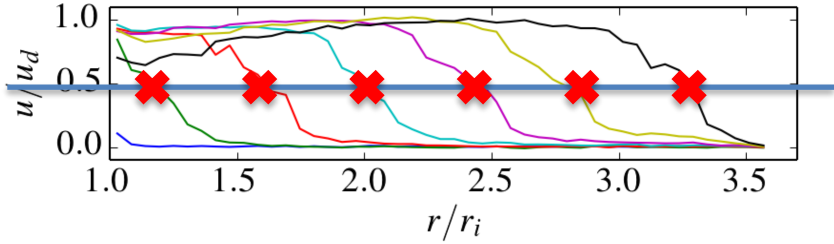
30 fps

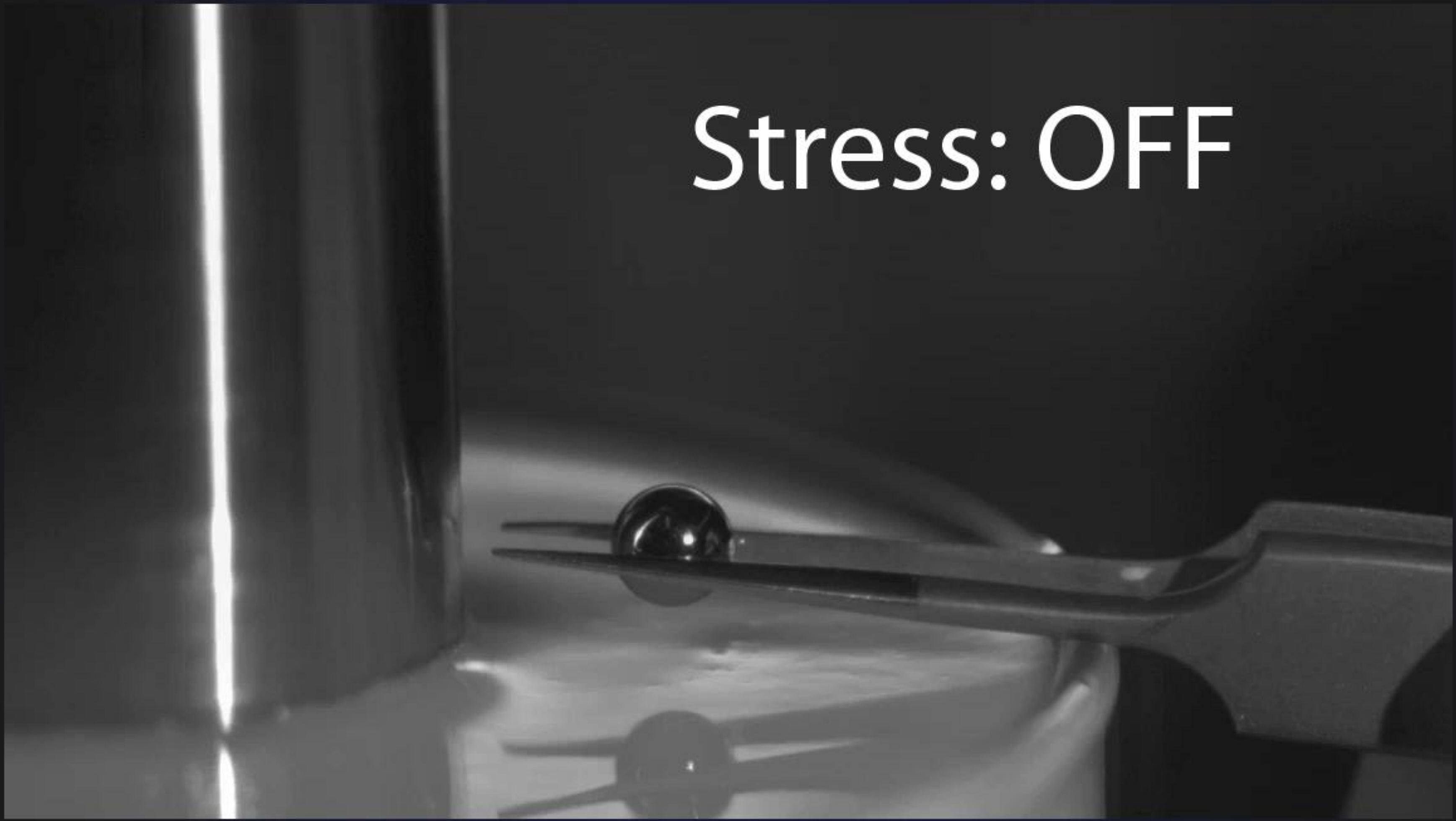


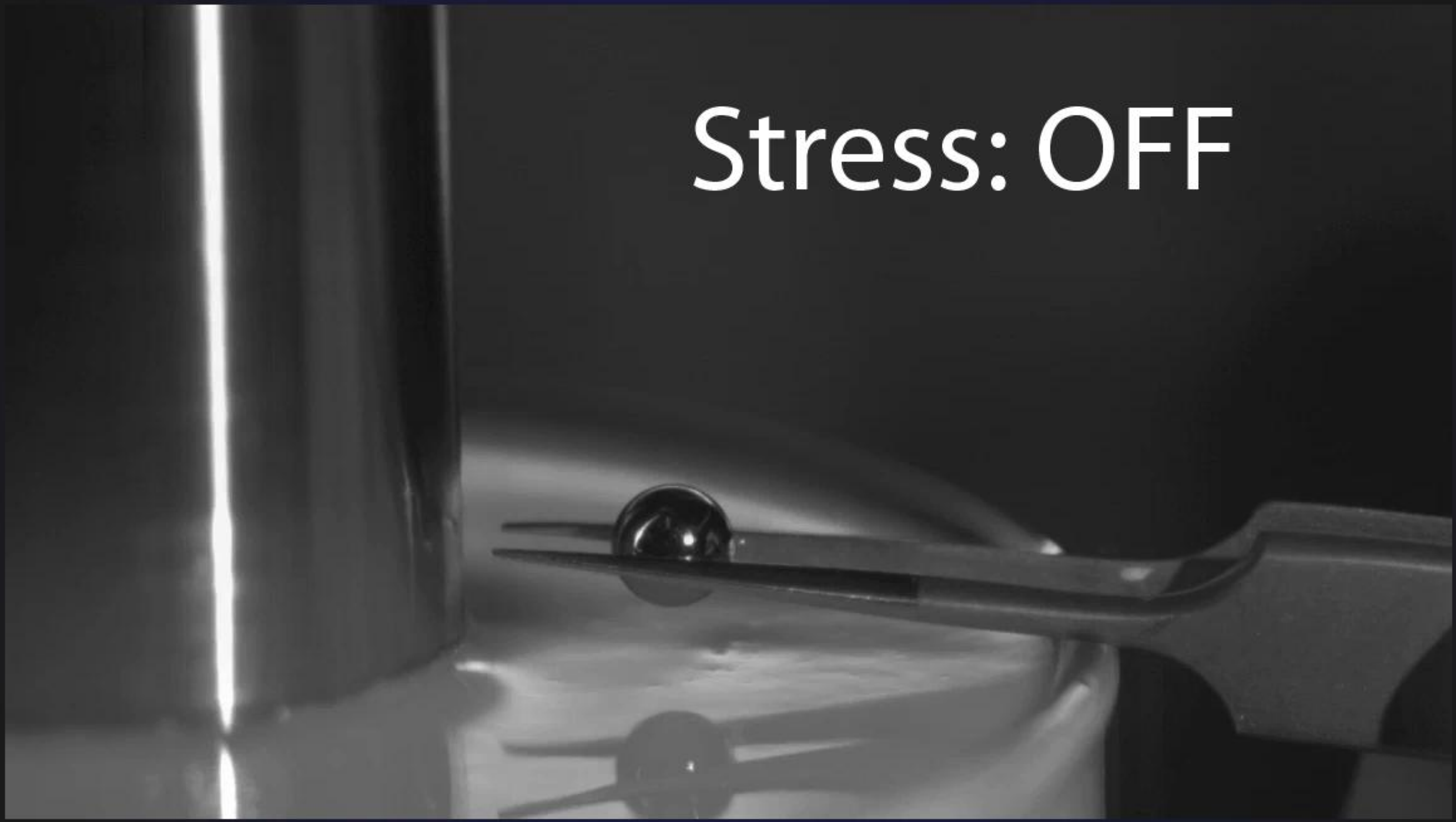
$u_d = 0.8$ m/s



3000 fps

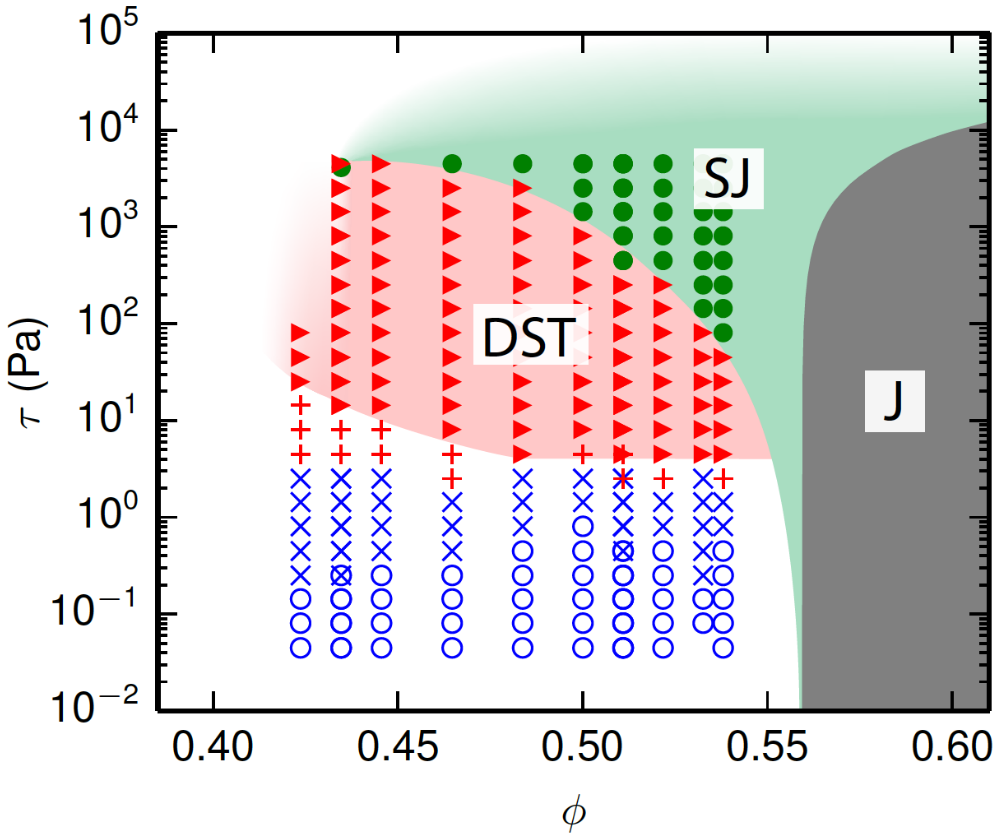



Stress: OFF


Stress: OFF

State Diagram

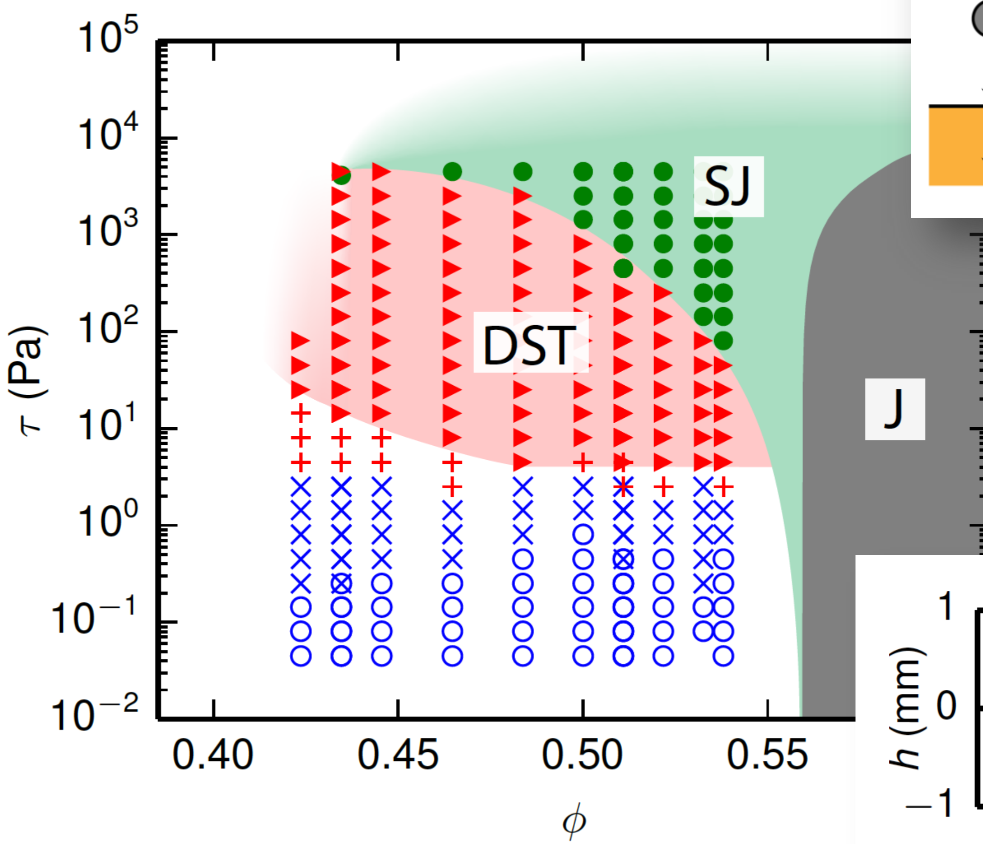
based on Couette experiments

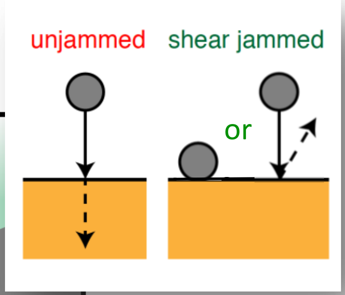


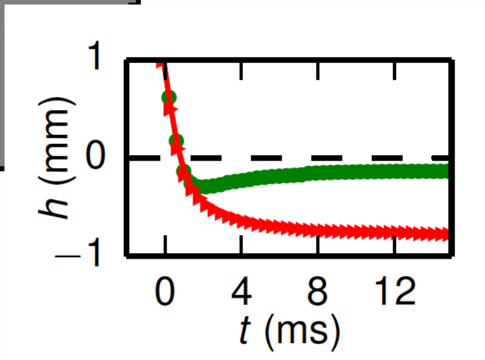
I. Peters, S. Majumdar, HMJ, Nature (2016)

State Diagram

based on Couette experiments



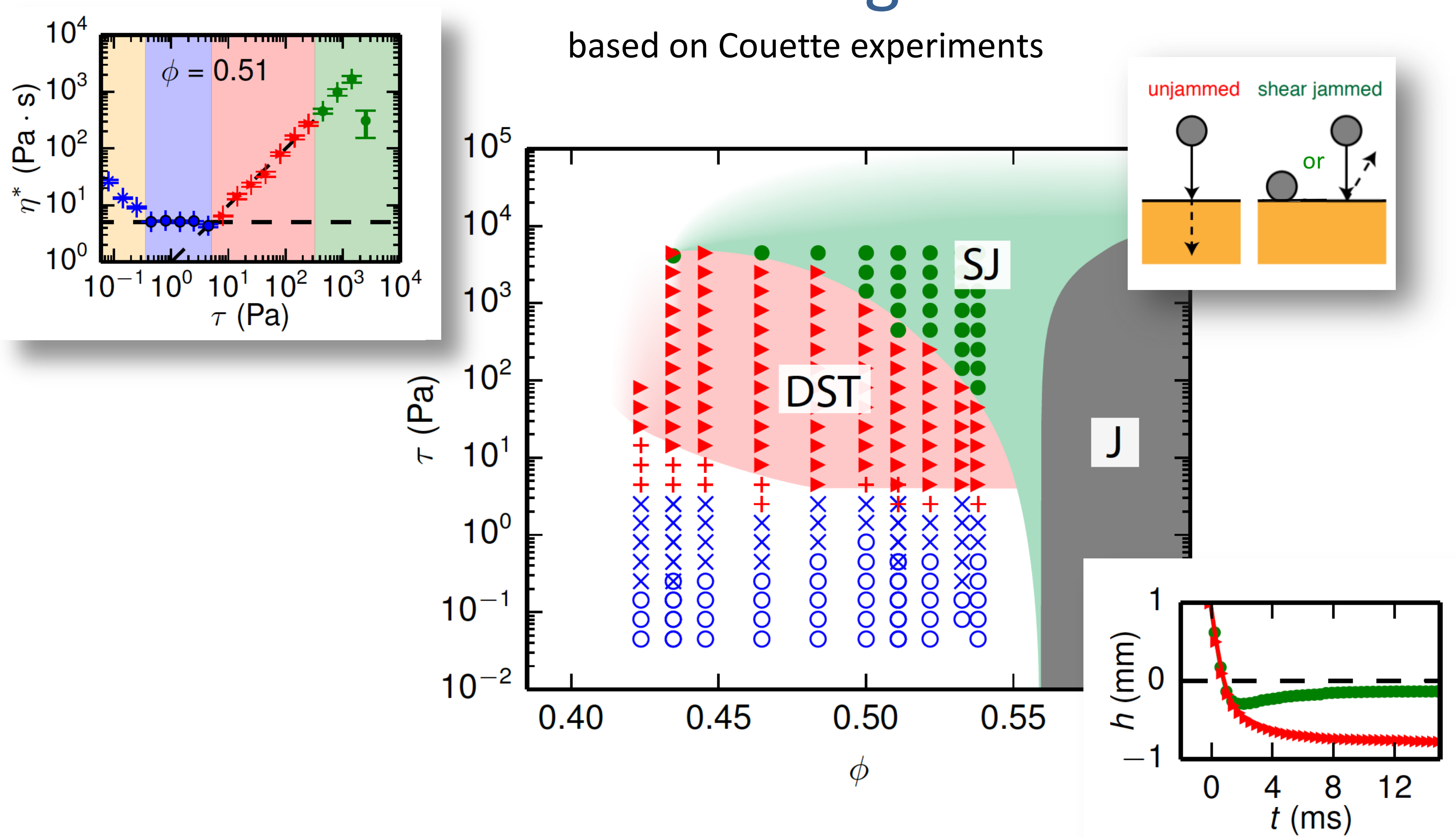




I. Peters, S. Majumdar, HMJ, Nature (2016)

State Diagram

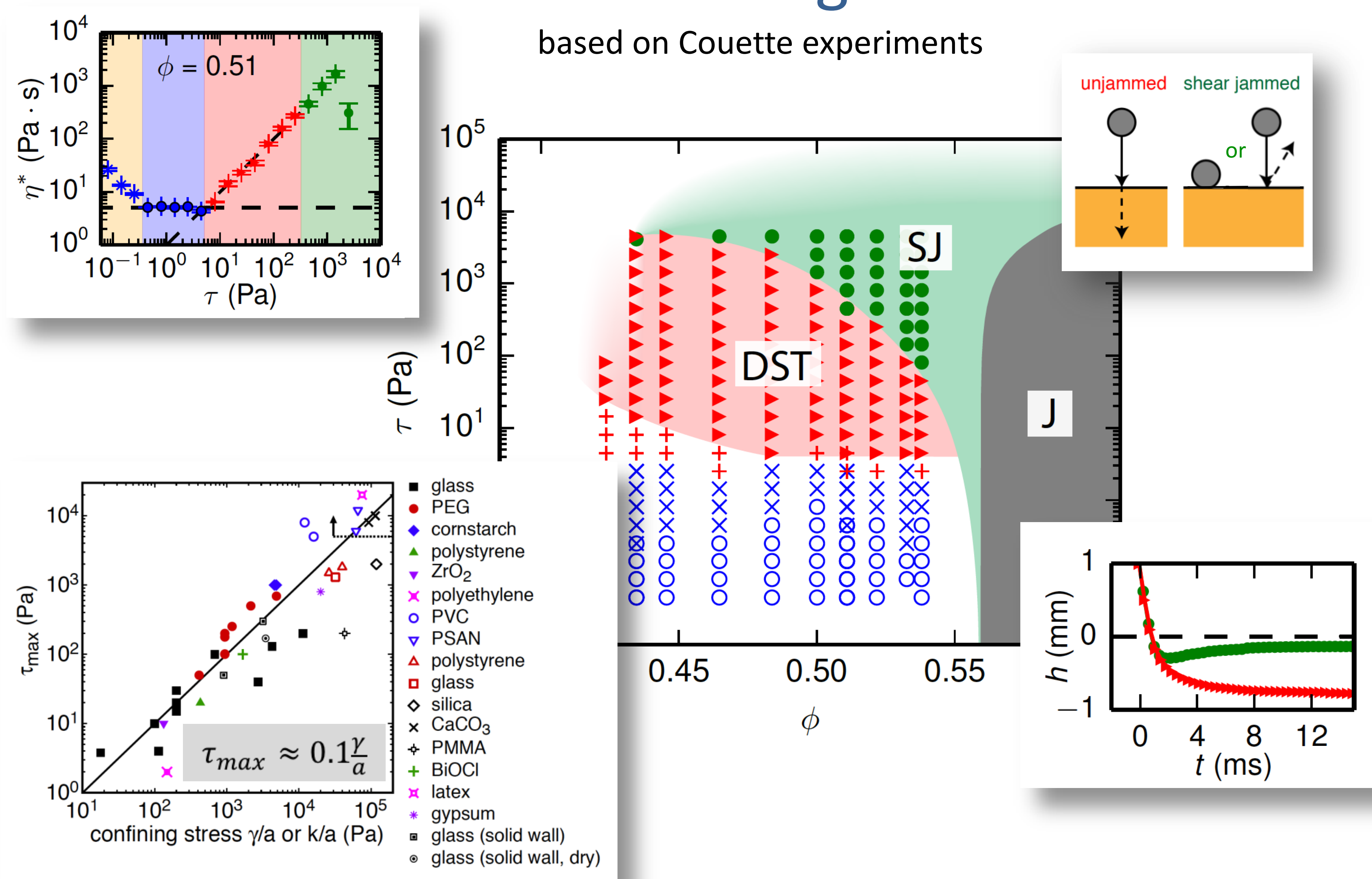
based on Couette experiments



I. Peters, S. Majumdar, HMJ, Nature (2016)

State Diagram

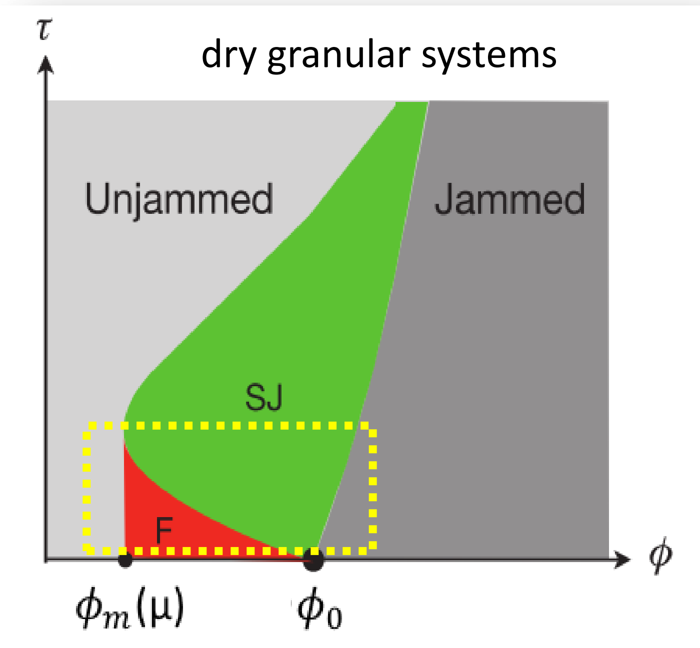
based on Couette experiments



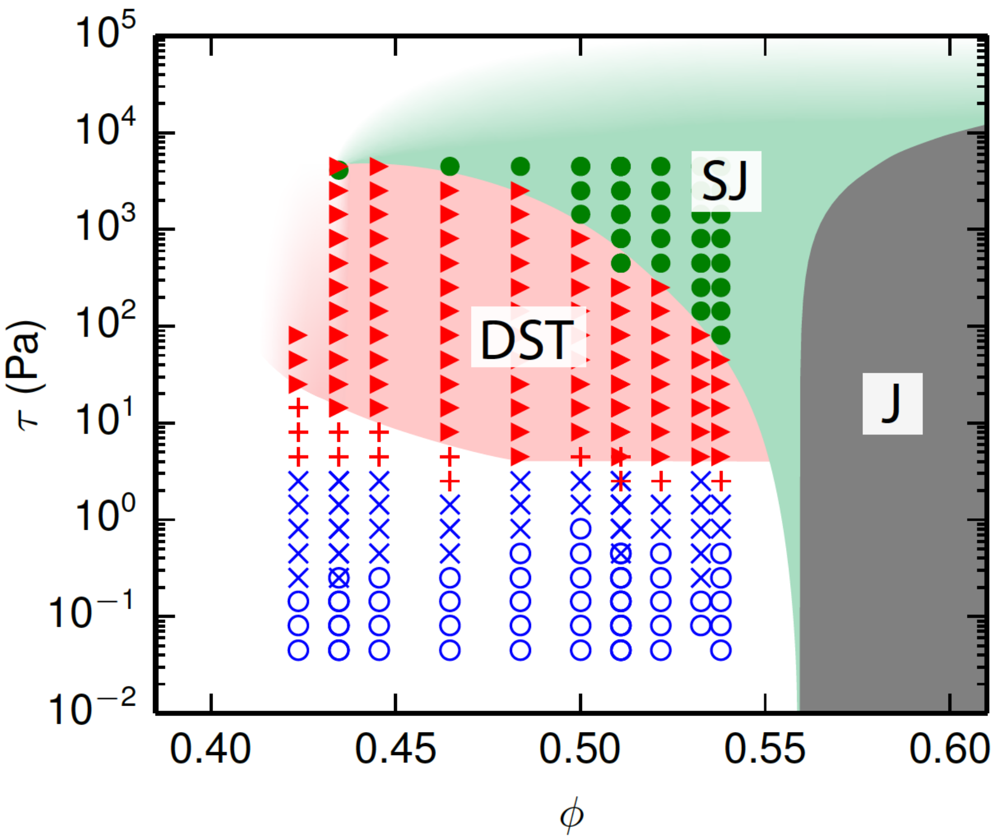
E. Brown & HMJ, JOR (2012)

I. Peters, S. Majumdar, HMJ, Nature (2016)

State Diagrams

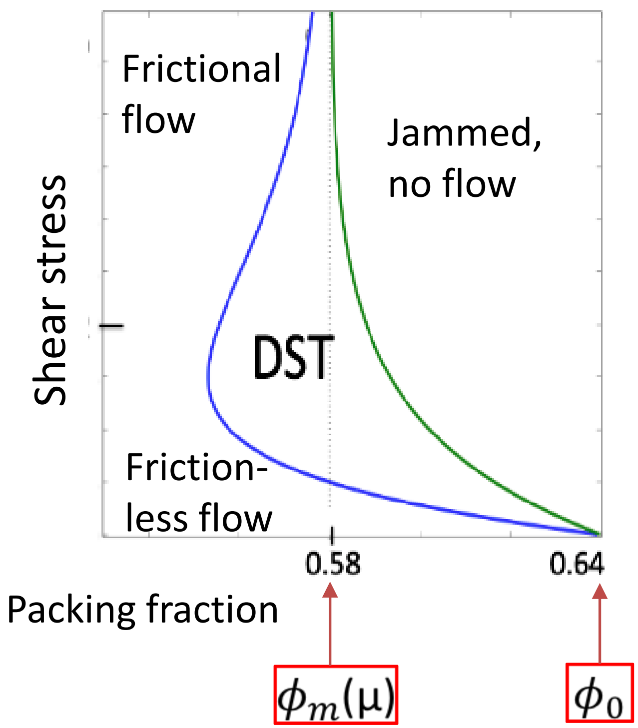


Bi *et al.*, Nature (2011)



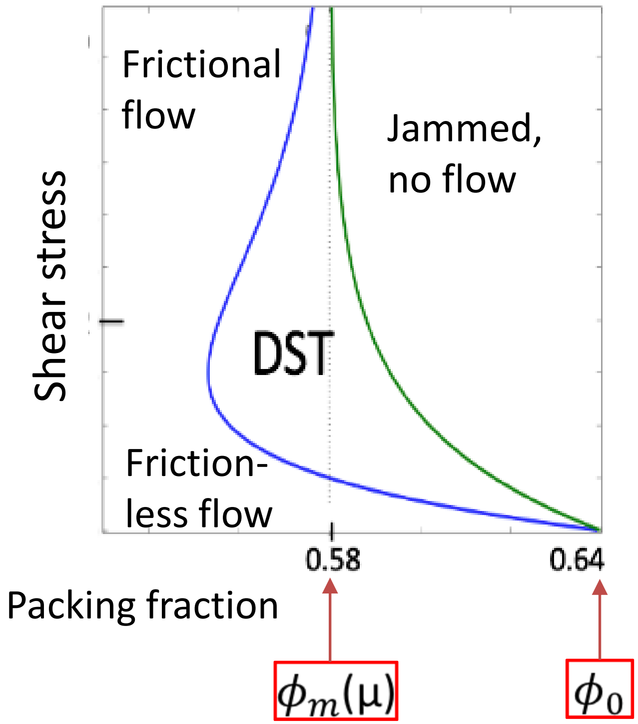
State Diagrams

Wyart & Cates (2014)

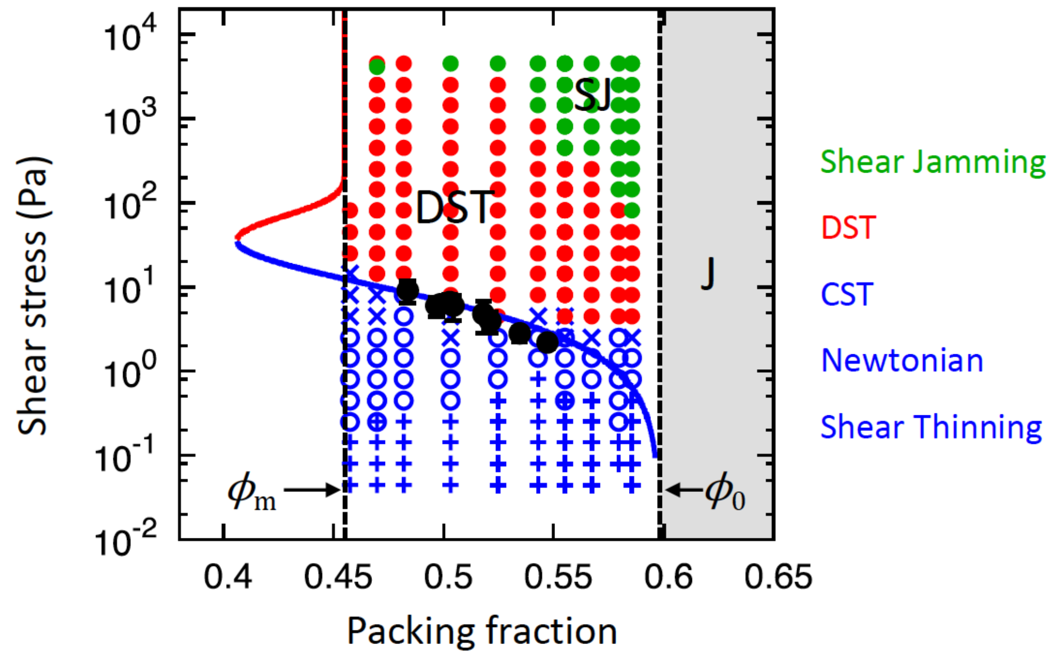


State Diagrams

Wyart & Cates (2014)

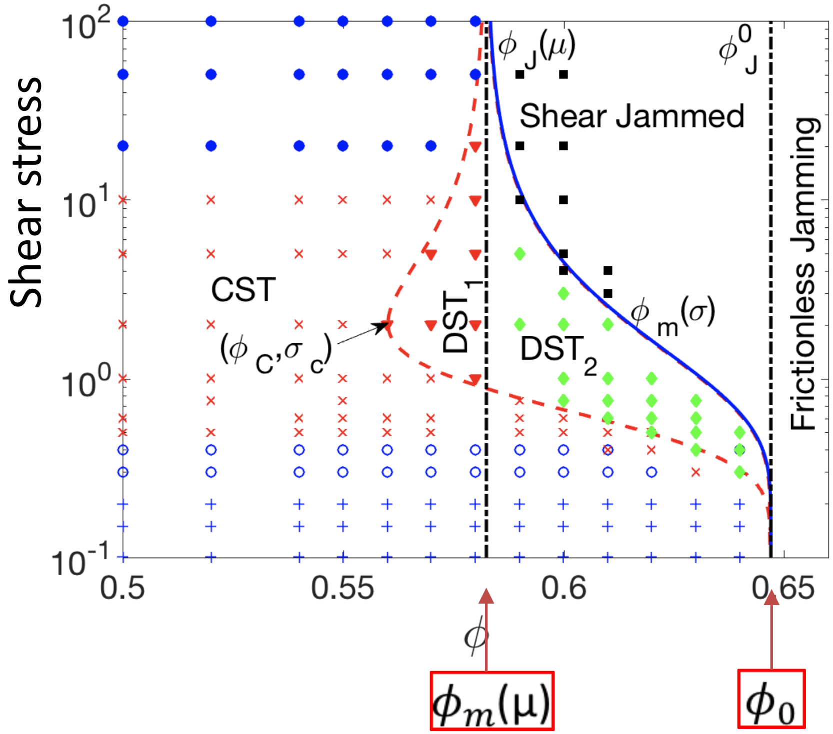


- Couette data [Peters et al., 2016]
- parallel plate data (black) [unpubl.]
- Wyart-Cates DST boundary

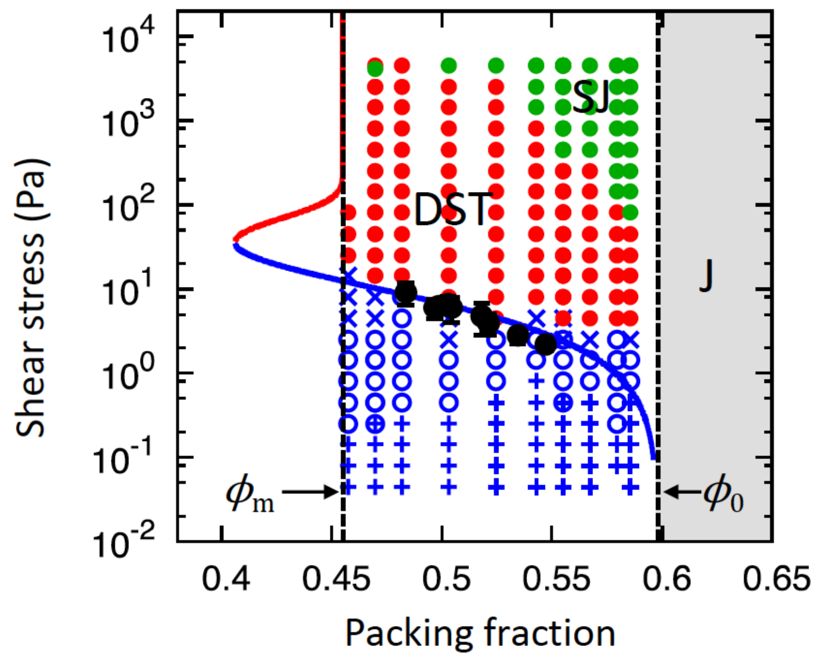


State Diagrams

Singh, Mari, Denn, Morris (in press)

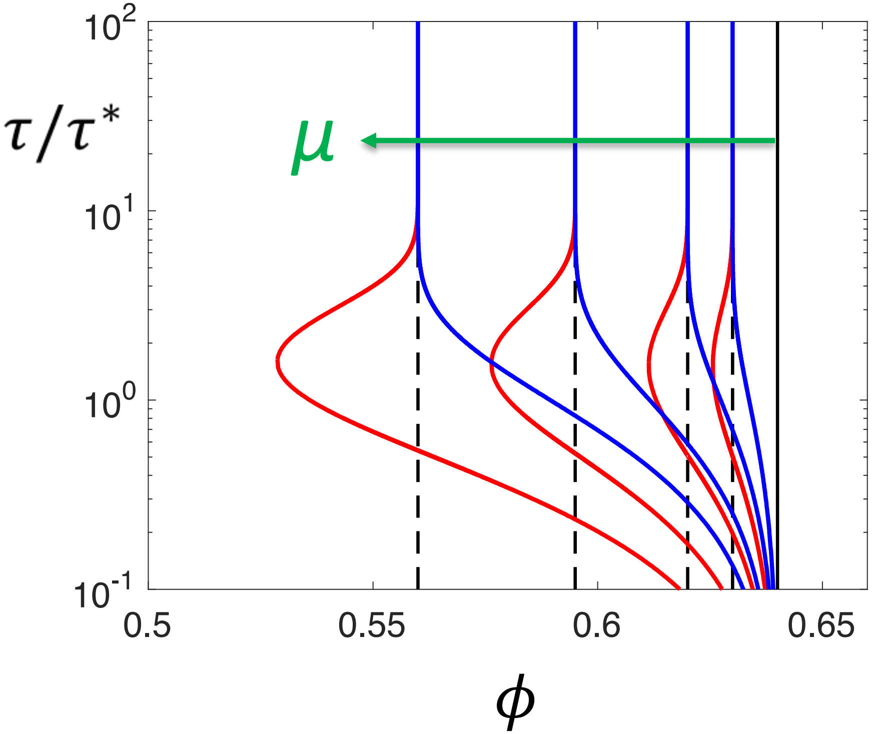


- Couette data [Peters et al., 2016]
- parallel plate data (black) [unpubl.]
- Wyart-Cates DST boundary

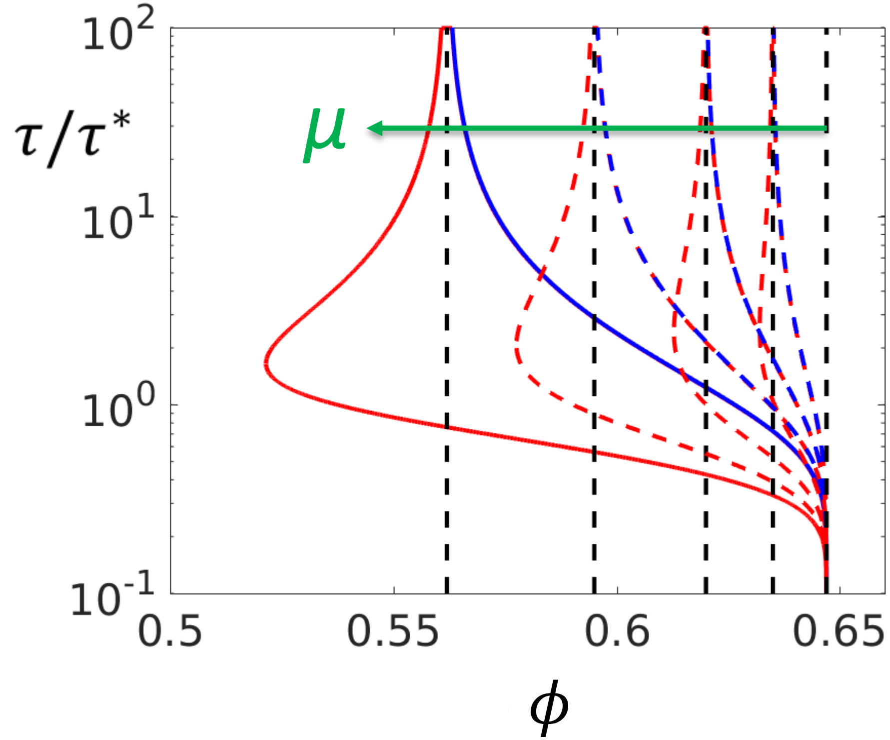


Boundaries shift with $\phi_m(\mu)$

Based on Wyart & Cates (2014)



Based on Singh, Mari, Denn, Morris (in press)



Abhi Singh (private comm.)

➔ Need large μ to obtain significant shear jamming region below ϕ_0

Which particle-scale properties control μ?

- Particle size and geometry
- Particle surface roughness
- Particle surface chemistry

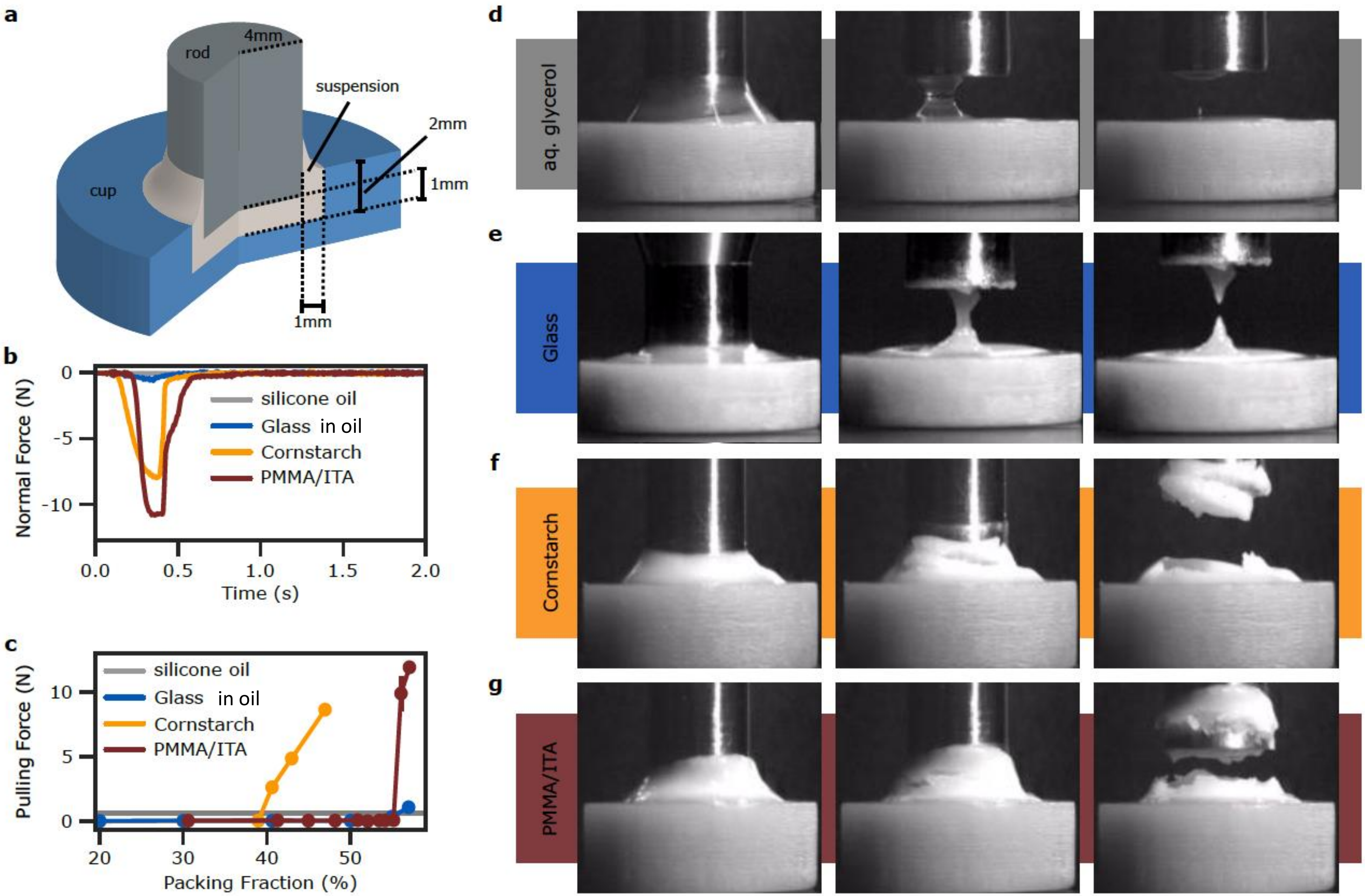
Which particle-scale properties control μ?

- Particle size and geometry
- Particle surface roughness
- Particle surface chemistry

➔ Tailor capacity for hydrogen bonding to elicit, or suppress, shear jamming

Nicole James

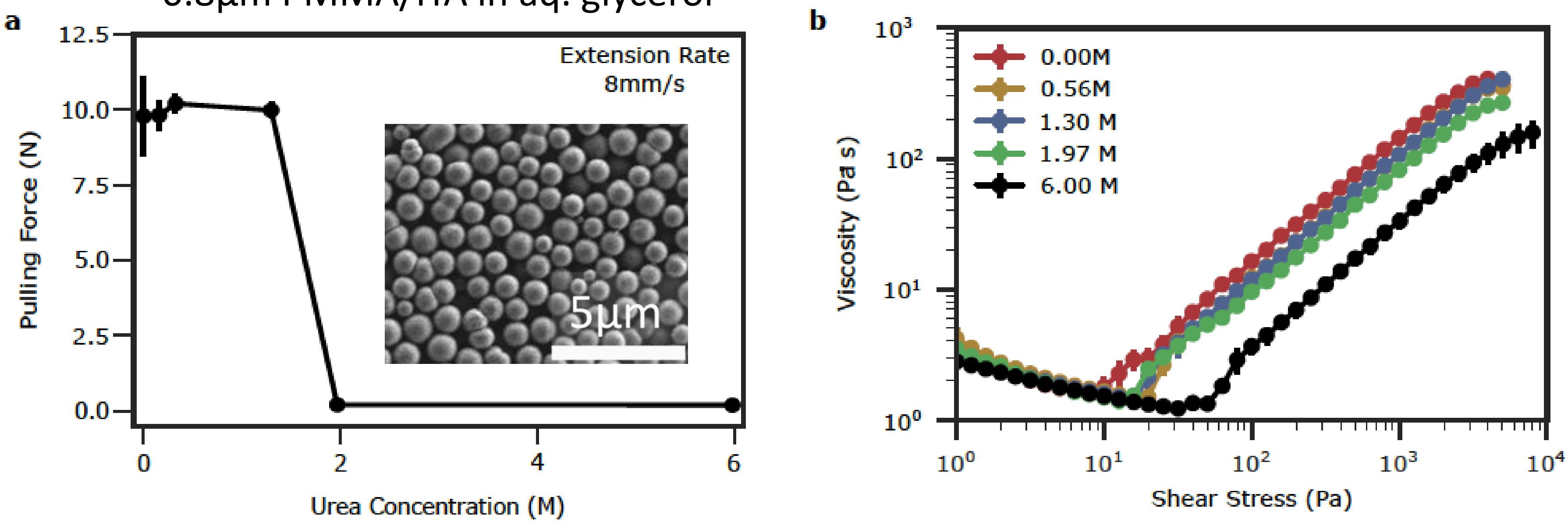
Pull test for shear jamming



Adding urea suppresses shear jamming…

…but not DST!

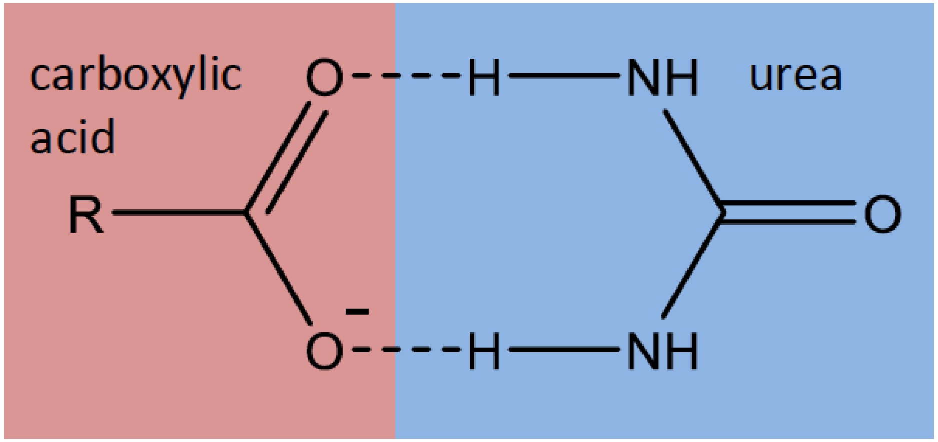
0.8μm PMMA/ITA in aq. glycerol



N. James *et al.*, arXiv:1707.09401

Urea = chaotrope = chemical agent that disrupts hydrogen bonding

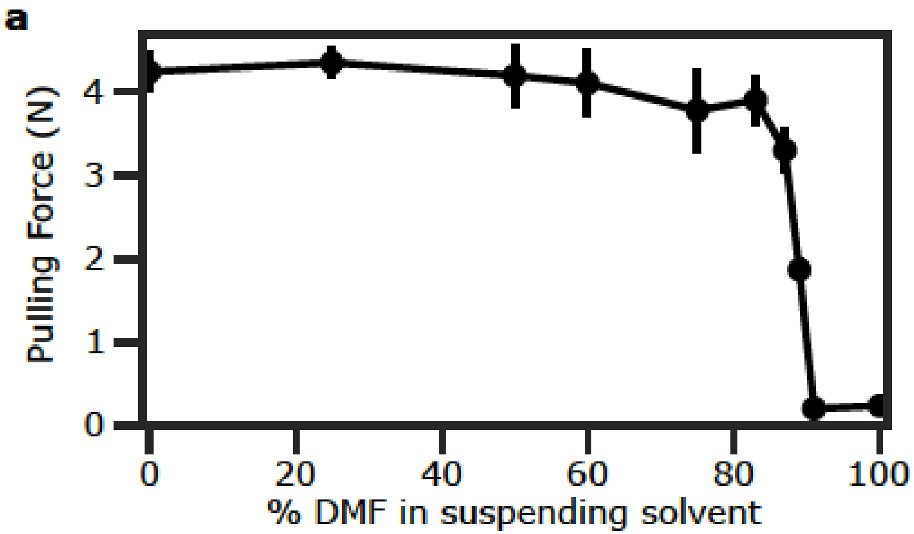
PMMA/ITA particles specifically designed to have surface terminated with COOH groups

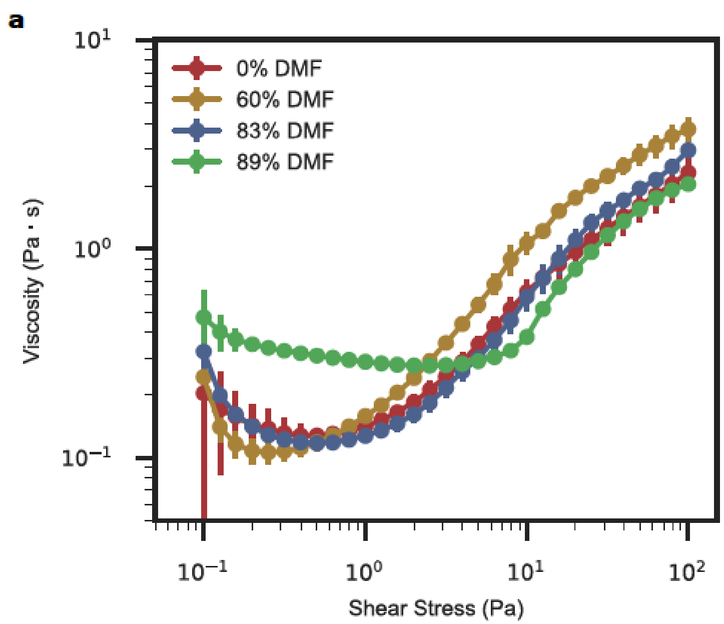


Urea couples to COOH ➔ interferes with hydrogen bonding capacity

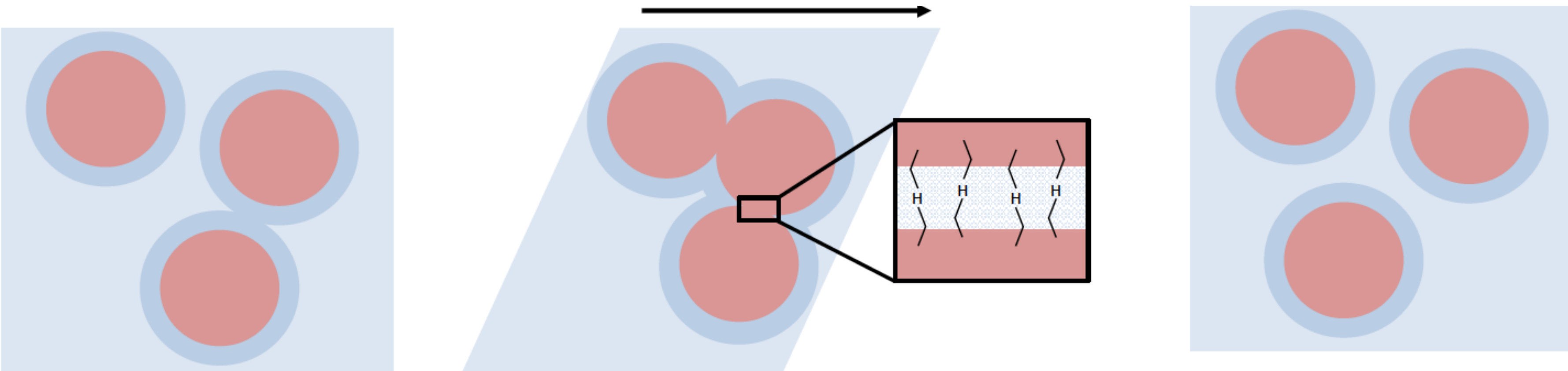
Deplete hydrogen bonding capacity in cornstarch suspensions

➔ *SJ no longer observed…but DST alive & well*





Proposed Scenario



Lubricated contacts
low stresses or rates
ϕ_0 is key

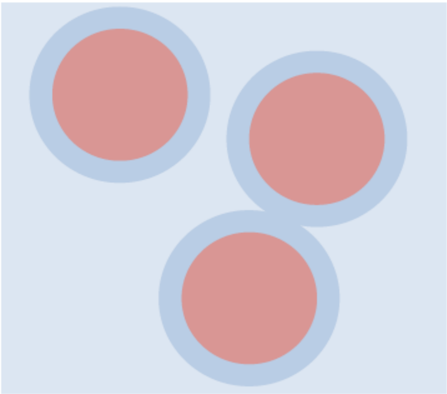
Frictional contact
Lubrication layer is broken
ϕ_m is key

H-bonding
enhances friction between particles

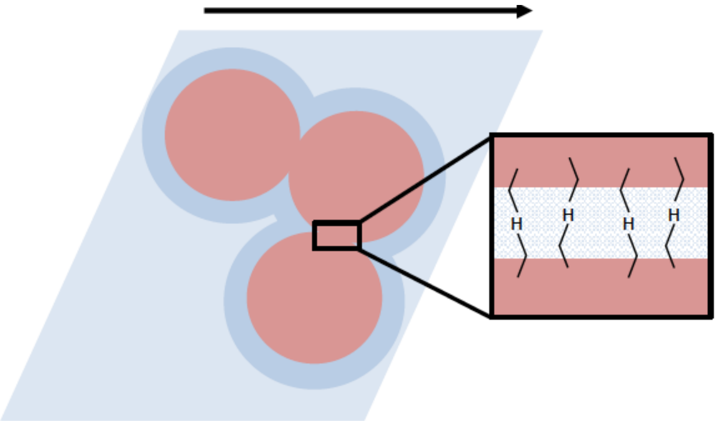
Relaxation
Stress is removed; particle-particle H-bonds may be replaced by solvent-particle bonds

Important: H-bonding is reversible in protic solvents like water

Proposed Scenario

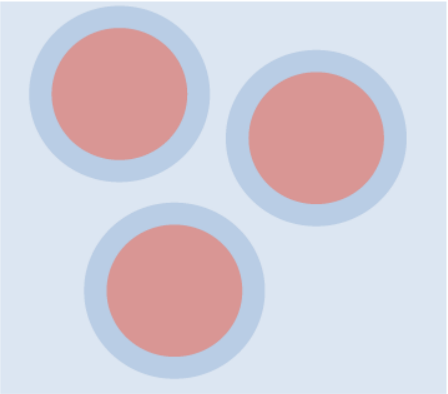


Lubricated contacts
low stresses or rates
ϕ_0 is key



Frictional contact
Lubrication layer is broken
ϕ_m is key

H-bonding
enhances friction
between particles



Relaxation
Stress is removed; particle-particle H-bonds may be replaced by solvent-particle bonds

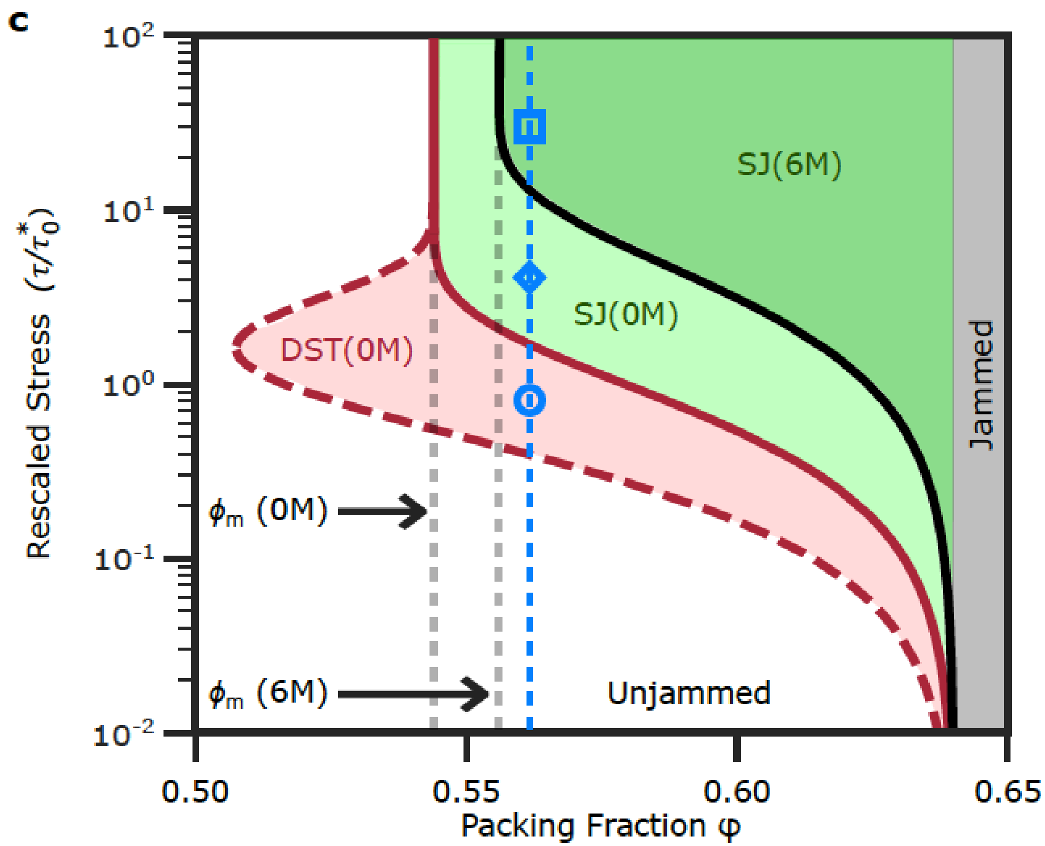
- Inter-particle hydrogen bonding enhances contact friction
- This decreases $\phi_m(\mu)$ & enlarges SJ regime

Conversely:
Reduced hydrogen bonding capacity ➔ smaller μ, larger $\phi_m(\mu)$

↓

reduced SJ regime

Move DST-SJ boundary by controlling μ via hydrogen bonding capacity

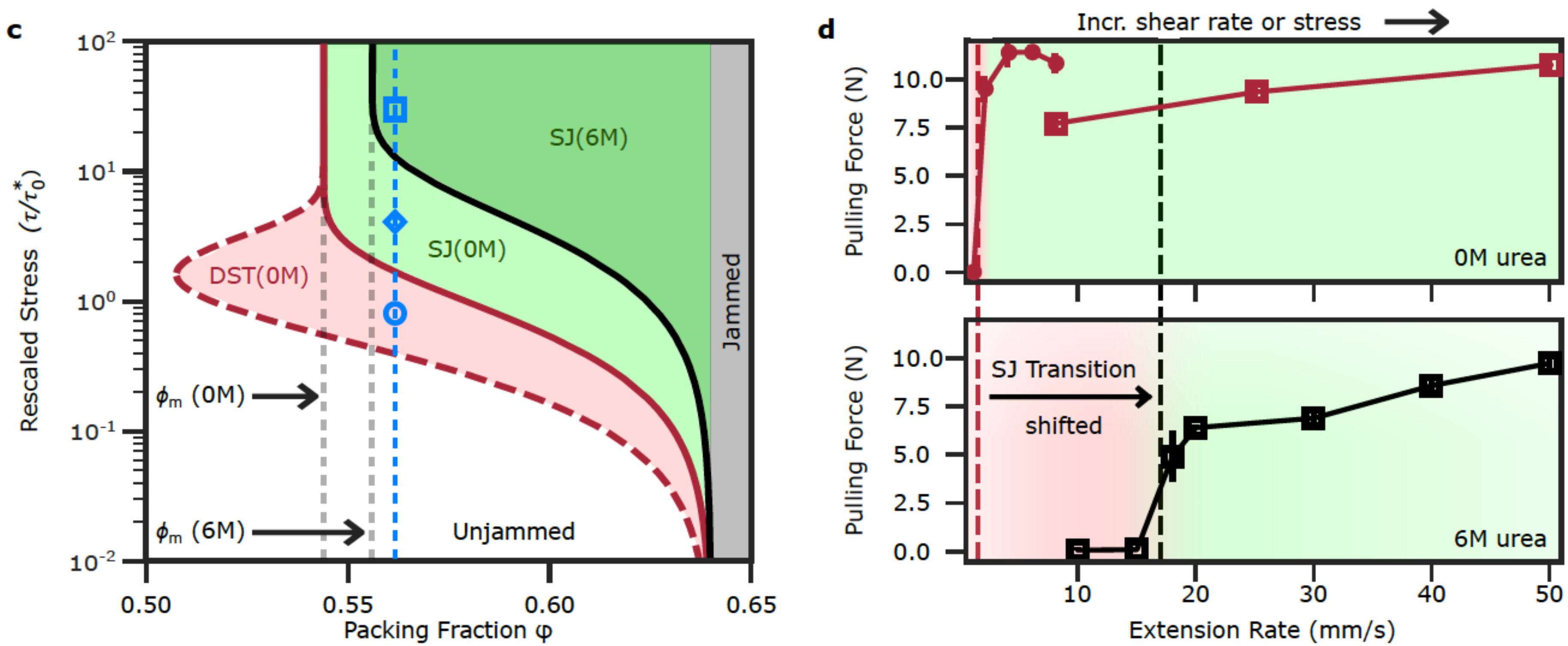


Get ϕ_m , ϕ_0, and τ^* from steady-state rheometry!

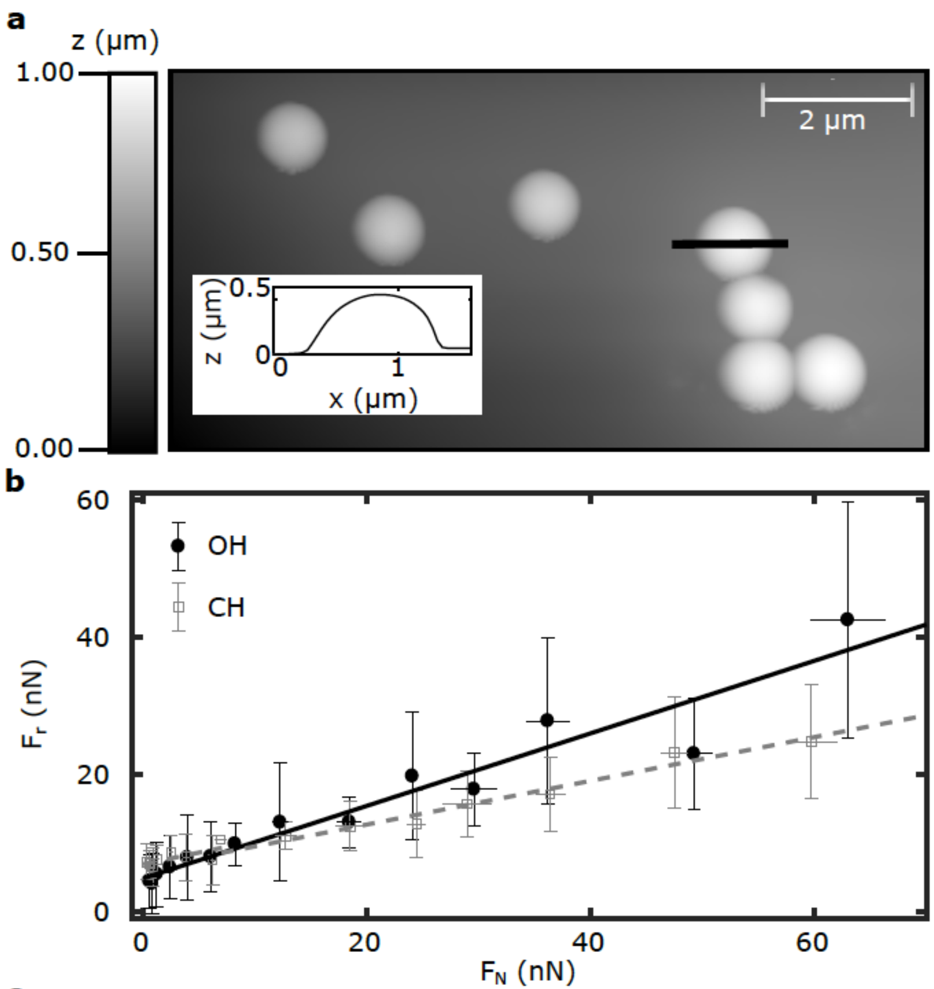
➔ See Nicole James preprint & poster

- At fixed packing fraction: Onset stress for SJ (and also DST) shifts

Pull test = facile method for detecting shift in SJ onset



Measure frictional interactions directly



μ = 0.53

μ = 0.3

Extract friction from lateral deflection force during slow, 100nm AFM scans near apex
>> scale of molecular interactions

Comtet et al. (Nature Comm 8, 2017):
fast oscillatory probe, few nm amplitude

To sum up:

- A shear-jammed state has a yield stress and acts like a solid
- A shear-thickening state, incl. DST, is still flowing…thus not jammed
- The transition from unjammed to jammed state occurs via rapidly propagating fronts that are the locus of intense shear: they transform isotropically amorphous, unjammed fluid into anisotropic, shear-jammed solid

To sum up:

- A shear-jammed state has a yield stress and acts like a solid
- A shear-thickening state, incl. DST, is still flowing…thus not jammed

- The transition from unjammed to jammed state occurs via rapidly propagating fronts that are the locus of intense shear: they transform isotropically amorphous, unjammed fluid into anisotropic, shear-jammed solid

- At fixed packing fraction, the different states of a suspension of hard particles (shear thinning, Newtonian, shear thickening, shear jammed) appear to be delineated by stress ➔ *can construct unifying state diagram*

To sum up:

- A shear-jammed state has a yield stress and acts like a solid
- A shear-thickening state, incl. DST, is still flowing…thus not jammed

- The transition from unjammed to jammed state occurs via rapidly propagating fronts that are the locus of intense shear: they transform isotropically amorphous, unjammed fluid into anisotropic, shear-jammed solid

- At fixed packing fraction, the different states of a suspension of hard particles (shear thinning, Newtonian, shear thickening, shear jammed) appear to be delineated by stress ➔ *can construct unifying state diagram*

- Dense suspensions generically exhibit DST (see Brown et al., Nature Mat., 2010)….but few show shear jamming. Scenario based on recent models: ϕ_m too close to ϕ_0, i.e., friction coefficient μ too small.

- Reversible interparticle hydrogen bonding acts to increase effective friction & elicit shear jamming

To sum up:

- A shear-jammed state has a yield stress and acts like a solid
- A shear-thickening state, incl. DST, is still flowing...thus not jammed
- The transition from unjammed to jammed state occurs via rapidly propagating fronts that are the locus of intense shear: they transform isotropically amorphous, unjammed fluid into anisotropic, shear-jammed solid
- At fixed packing fraction, the different states of a suspension of hard particles (shear thinning, Newtonian, shear thickening, shear jammed) appear to be delineated by stress ➔ *can construct unifying state diagram*
- Dense suspensions generically exhibit DST (see Brown et al., Nature Mat., 2010)....but few show shear jamming. Scenario based on recent models: ϕ_m too close to ϕ_0, i.e., friction coefficient μ too small.
- Reversible interparticle hydrogen bonding acts to increase effective friction & elicit shear jamming

When exactly are particles in contact, i.e., experience contact friction?

What micro-scale properties set $\phi_m(\mu)$?

To sum up:

- A shear-jammed state has a yield stress and acts like a solid
- A shear-thickening state, incl. DST, is still flowing...thus not jammed

- The transition from unjammed to jammed state occurs via rapidly propagating fronts that are the locus of intense shear: they transform isotropically amorphous, unjammed fluid into anisotropic, shear-jammed solid

- At fixed packing fraction, the different states of a suspension of hard particles (shear thinning, Newtonian, shear thickening, shear jammed) appear to be delineated by stress ➔ *can construct unifying state diagram*

- Dense suspensions generically exhibit DST (see Brown et al., Nature Mat., 2010)....but few show shear jamming. Scenario based on recent models: ϕ_m too close to ϕ_0, i.e., friction coefficient μ too small.

- Reversible interparticle hydrogen bonding acts to increase effective friction & elicit shear jamming

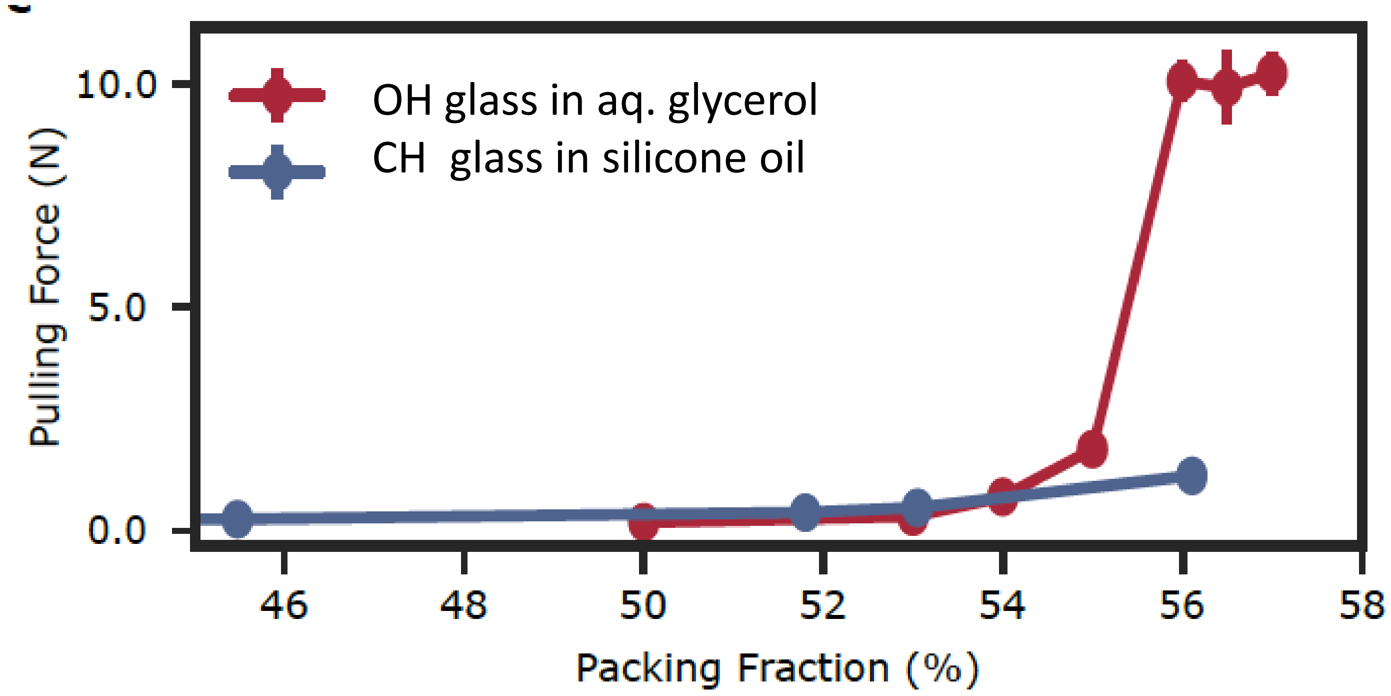
When exactly are particles in contact, i.e., experience contact friction?

What micro-scale properties set $\phi_m(\mu)$?

Particle surfaces / surface chemistry

Solvent properties

Opportunities:
Design surface chemistry & solvent to elicit shear jamming



To sum up:

- A shear-jammed state has a yield stress and acts like a solid
- A shear-thickening state, incl. DST, is still flowing...thus not jammed

- The transition from unjammed to jammed state occurs via rapidly propagating fronts that are the locus of intense shear: they transform isotropically amorphous, unjammed fluid into anisotropic, shear-jammed solid

- At fixed packing fraction, the different states of a suspension of hard particles (shear thinning, Newtonian, shear thickening, shear jammed) appear to be delineated by stress ➔ *can construct unifying state diagram*

- Dense suspensions generically exhibit DST (see Brown et al., Nature Mat., 2010)....but few show shear jamming. Scenario based on recent models: ϕ_m too close to ϕ_0, i.e., friction coefficient μ too small.

- Reversible interparticle hydrogen bonding acts to increase effective friction & elicit shear jamming

When exactly are particles in contact, i.e., experience contact friction?

What micro-scale properties set $\phi_m(\mu)$?

Models & state diagram so far only for steady-state behavior.

What about transient or start-up behavior? Impact, jamming fronts?

To sum up:

- A shear-jammed state has a yield stress and acts like a solid
- A shear-thickening state, incl. DST, is still flowing…thus not jammed
- The transition from unjammed to jammed state occurs via rapidly propagating fronts that are the locus of intense shear: they transform isotropically amorphous, unjammed fluid into anisotropic, shear-jammed solid
- At fixed packing fraction, the different states of a suspension of hard particles (shear thinning, Newtonian, shear thickening, shear jammed) appear to be delineated by stress ➔ *can construct unifying state diagram*
- Dense suspensions generically exhibit DST (see Brown et al., Nature Mat., 2010)….but few show shear jamming. Scenario based on recent models: ϕ_m too close to ϕ_0, i.e., friction coefficient μ too small.
- Reversible interparticle hydrogen bonding acts to increase effective friction & elicit shear jamming

When exactly are particles in contact, i.e., experience contact frict

What micro-scale prop

Collaboration with Matthieu Wyart
➔ extended model
➔ poster by Endao Han

Models & state diagram so far only for steady-state behavior.

What about transient or start-up behavior? Impact, jamming fronts?

To sum up:

- A shear-jammed state has a yield stress and acts like a solid
- A shear-thickening state, incl. DST, is still flowing…thus not jammed

- The transition from unjammed to jammed state occurs via rapidly propagating fronts that are the locus of intense shear: they transform isotropically amorphous, unjammed fluid into anisotropic, shear-jammed solid

- At fixed packing fraction, the different states of a suspension of hard particles (shear thinning, Newtonian, shear thickening, shear jammed) appear to be delineated by stress ➔ *can construct unifying state diagram*

- Dense suspensions generically exhibit DST (see Brown et al., Nature Mat., 2010)….but few show shear jamming. Scenario based on recent models: ϕ_m too close to ϕ_0, i.e., friction coefficient μ too small.

- Reversible interparticle hydrogen bonding acts to increase effective friction & elicit shear jamming

When exactly are particles in contact, i.e., experience contact friction?

What micro-scale properties set $\phi_m(\mu)$?

Models & state diagram so far only for steady-state behavior.

What about transient or start-up behavior? Impact, jamming fronts?