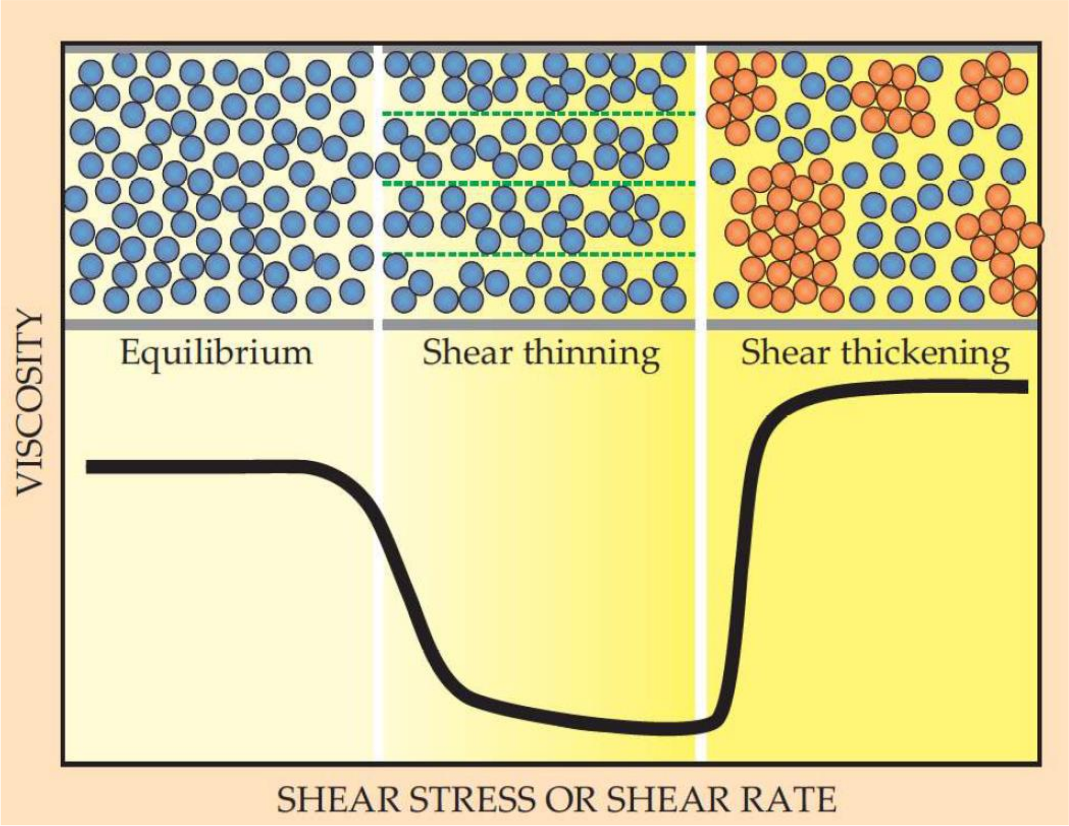
Discontinuous shear thickening of cornstarch suspension: *macroscopic, local, and microscopic analysis*

Guillaume Ovarlez, LOF, CNRS-Solvay-Univ. Bordeaux

with **Abdoulaye Fall & Anaël Lemaître**

Guillaume Chatté, Nicolas Lenoir & Annie Colin

Annals of Shear-thickening



Wagner and Brady, Physics Today 2009.

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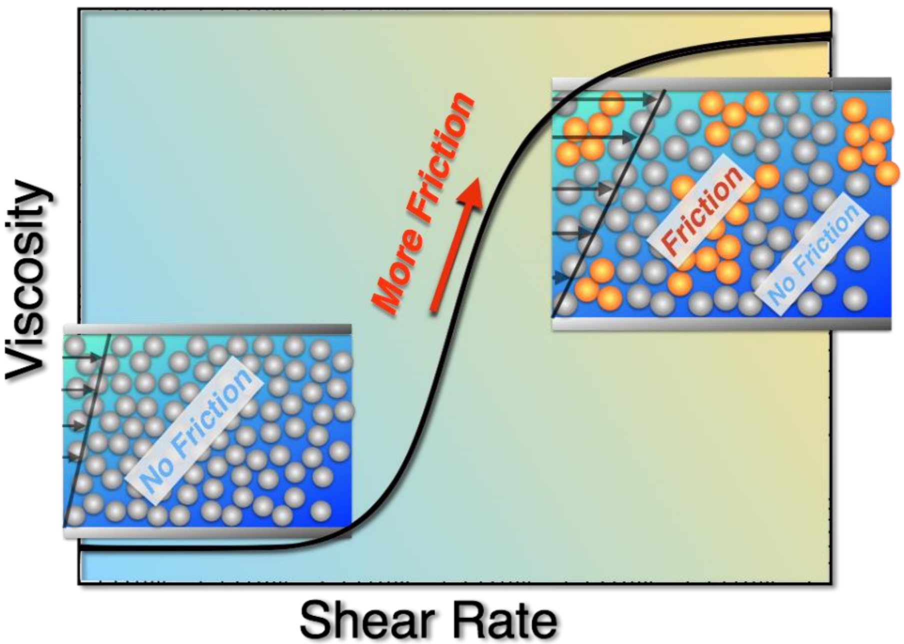
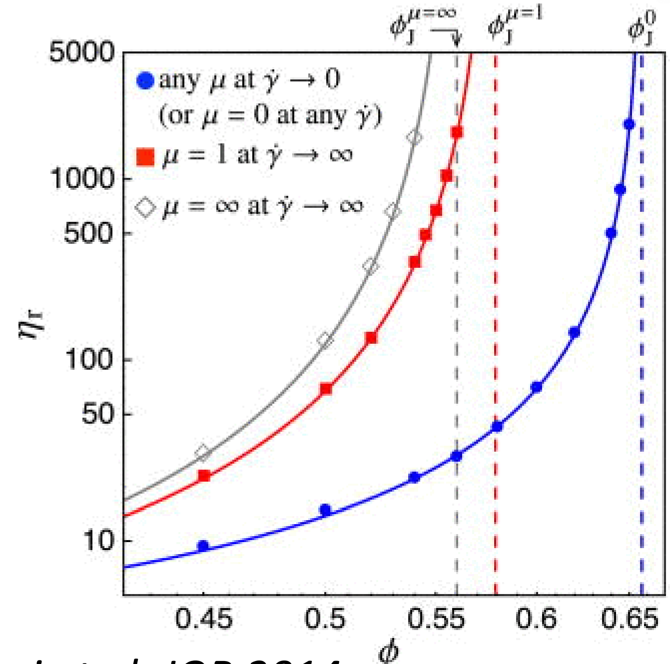
Current Trends in Shear-thickening

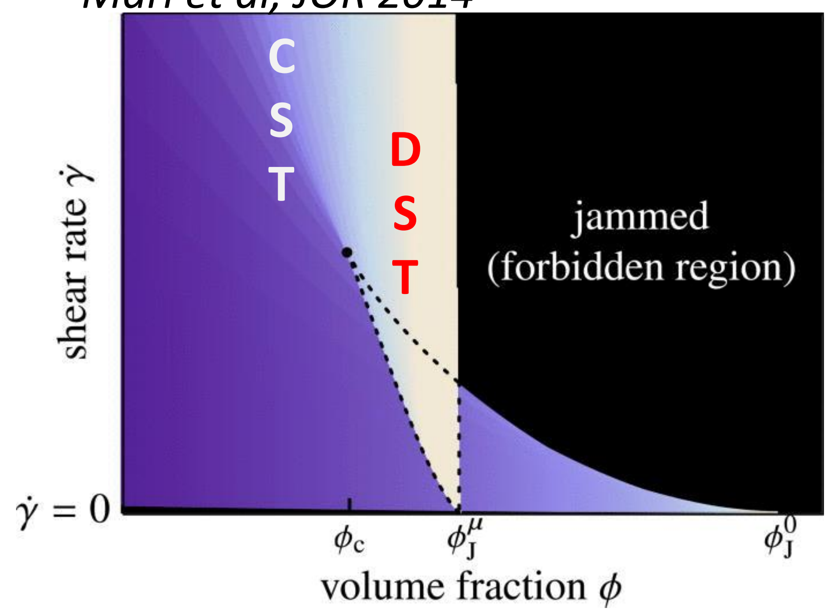
Seto et al., PRL 2013
Wyart and Cates, PRL 2014

http://blairlab.georgetown.edu

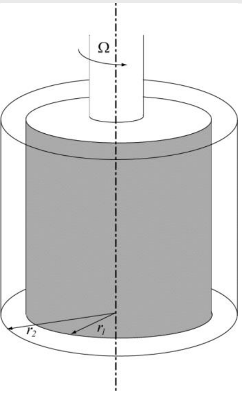




Mari et al, JOR 2014

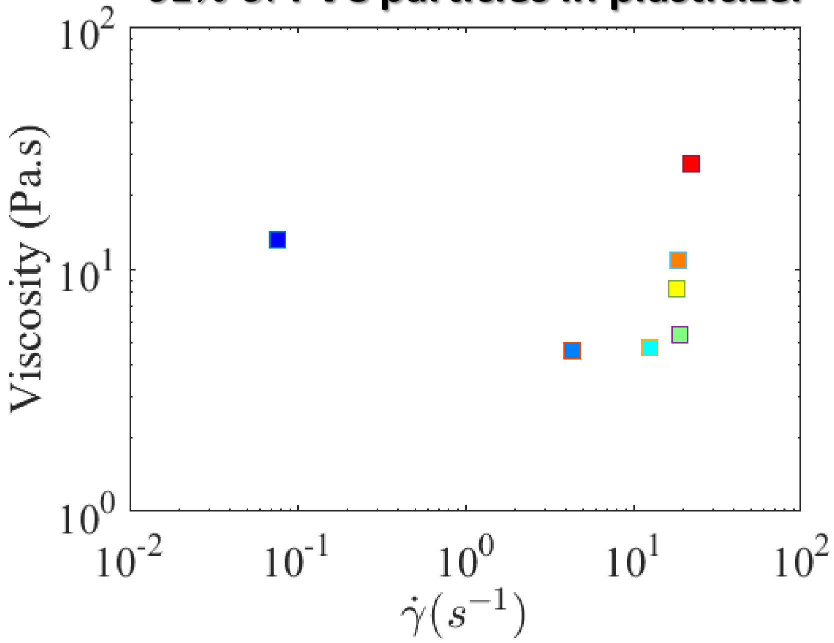


From rheometry to physics…

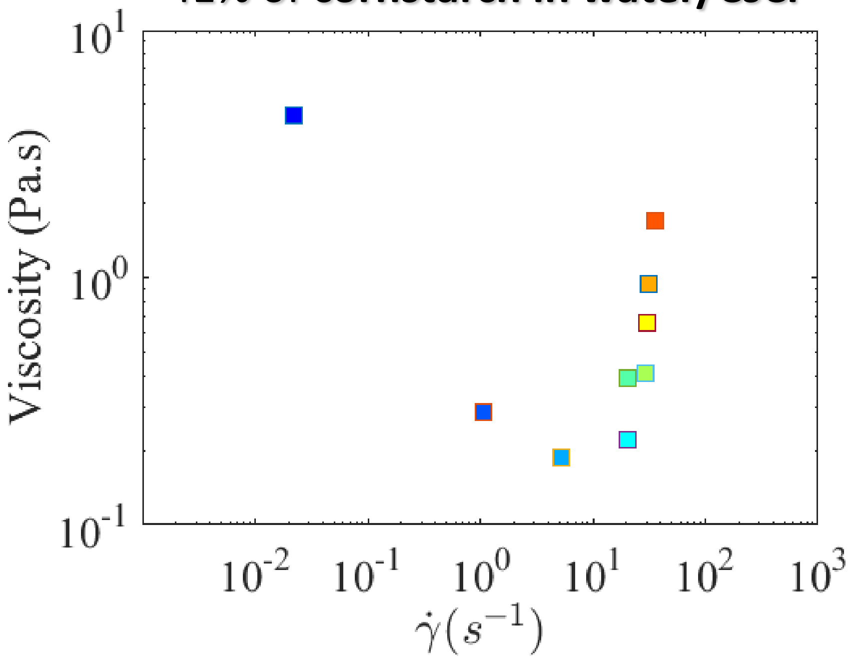


Couette rheometer: rotor radius 24 mm; 1 mm gap
Stress steps

61% of **PVC particles in plasticizer**



41% of **cornstarch in water/CsCl**

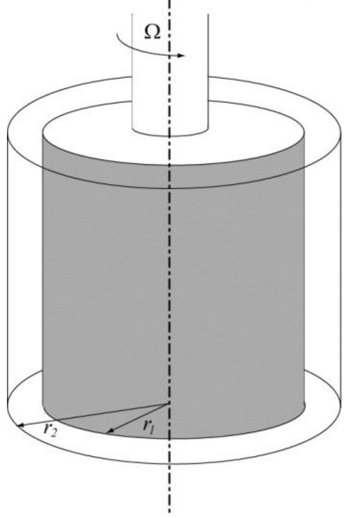


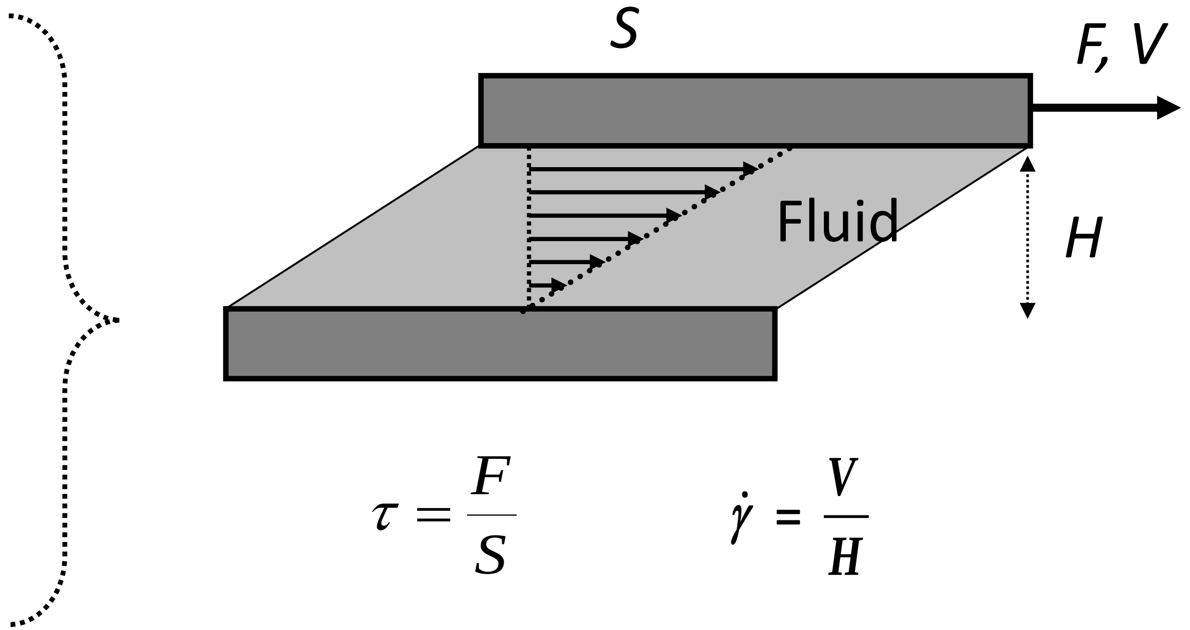
Physicist question: Same physical origin?

Rheologist question: Is that really the same behavior?

From rheometry to physics…

Rheometry





$$\tau = \frac{F}{S} \qquad \dot{\gamma} = \frac{V}{H}$$

***Macroscopic** measurement:*

F(V)

(or T(Ω))

*The **rheologist** question* →

Hypotheses :

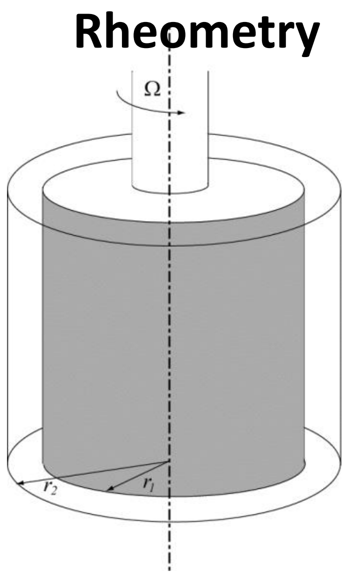
- **homogeneous shear**
- **homogeneous material**

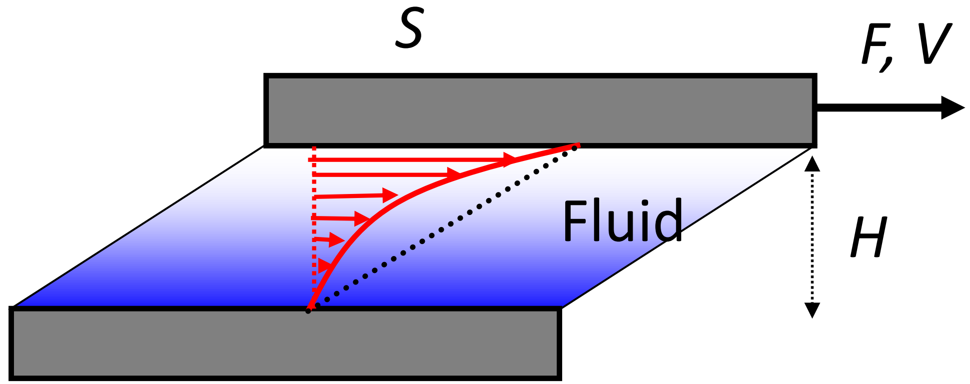
Constitutive law?????

$$\tau(\dot{\gamma})$$

at constant ϕ

From rheometry to physics…





$$\tau = \frac{F}{S} \qquad \cancel{\dot{\gamma} = \frac{V}{H}}$$

Macroscopic *measurement:*

F(V)

(or T(Ω))

The rheologist question →

Hypotheses :

?

- ~~**homogeneous shear**~~
- ~~**homogeneous material**~~

Constitutive *law:*

$$\tau(\dot{\gamma}, x)$$

Bad evaluation of shear rate

Bad knowledge of the material

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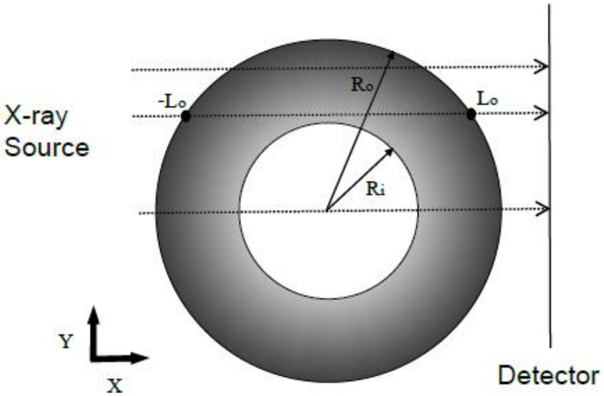
Volume fraction measurements from X-ray imaging

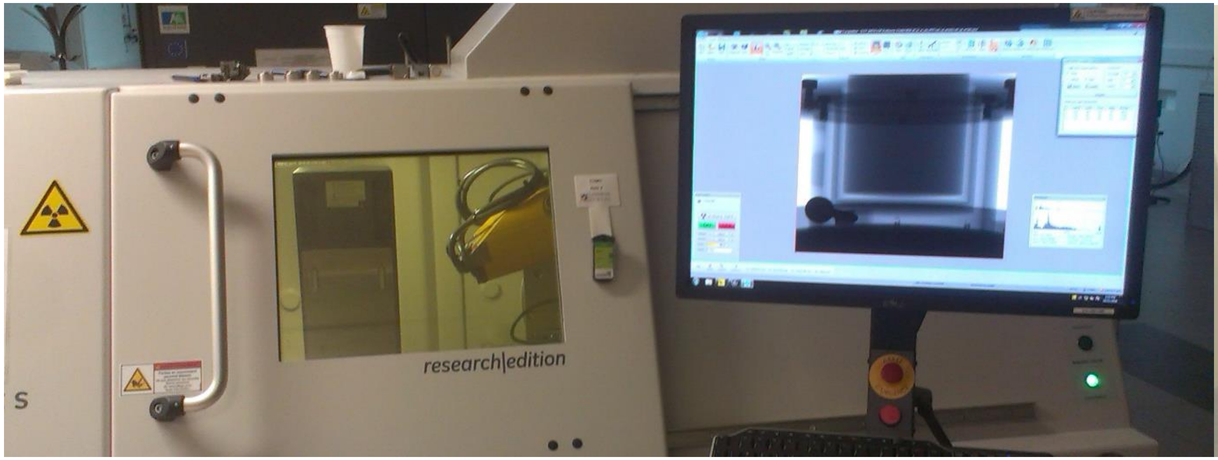


Raw measurement :
Intensity transmitted through the sample
$\boldsymbol{I}(\boldsymbol{y},\boldsymbol{z},\boldsymbol{t})$

⬇

Volume fraction field
$\boldsymbol{\phi}(\boldsymbol{r},\boldsymbol{z},\boldsymbol{t})$

Methodology developed with Sarah Hormozi & Nicolas Lenoir
→ ***Paper by Gholami et al., to be published ?????? in American Journal of Rheology***

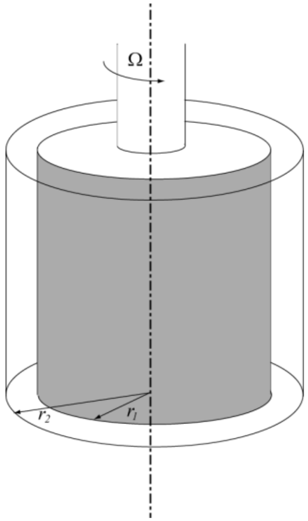


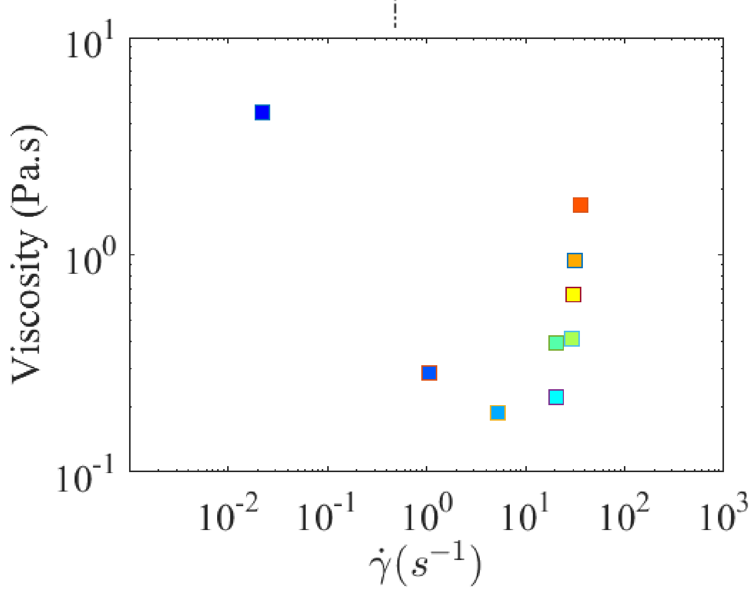
- Real-time measurement (0.1 s)

→ **any** suspension with **contrast** of x-ray absorption between particle and fluid

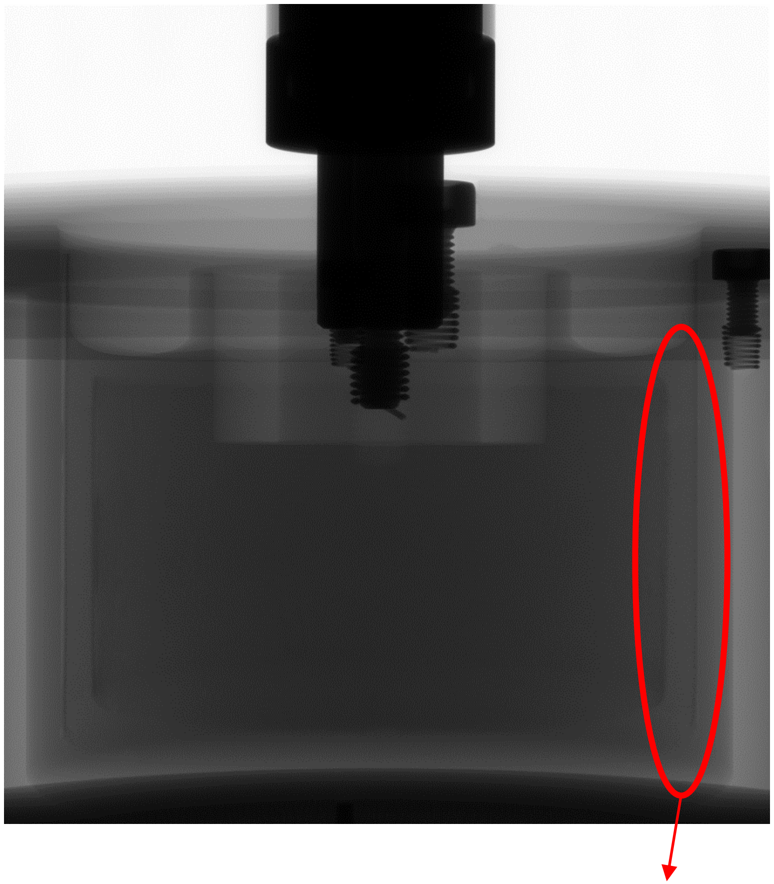
- pixel size: down to gap size / N (for camera of N*N pixel^2)

Rheology with X-ray imaging





@Placamat, Bordeaux



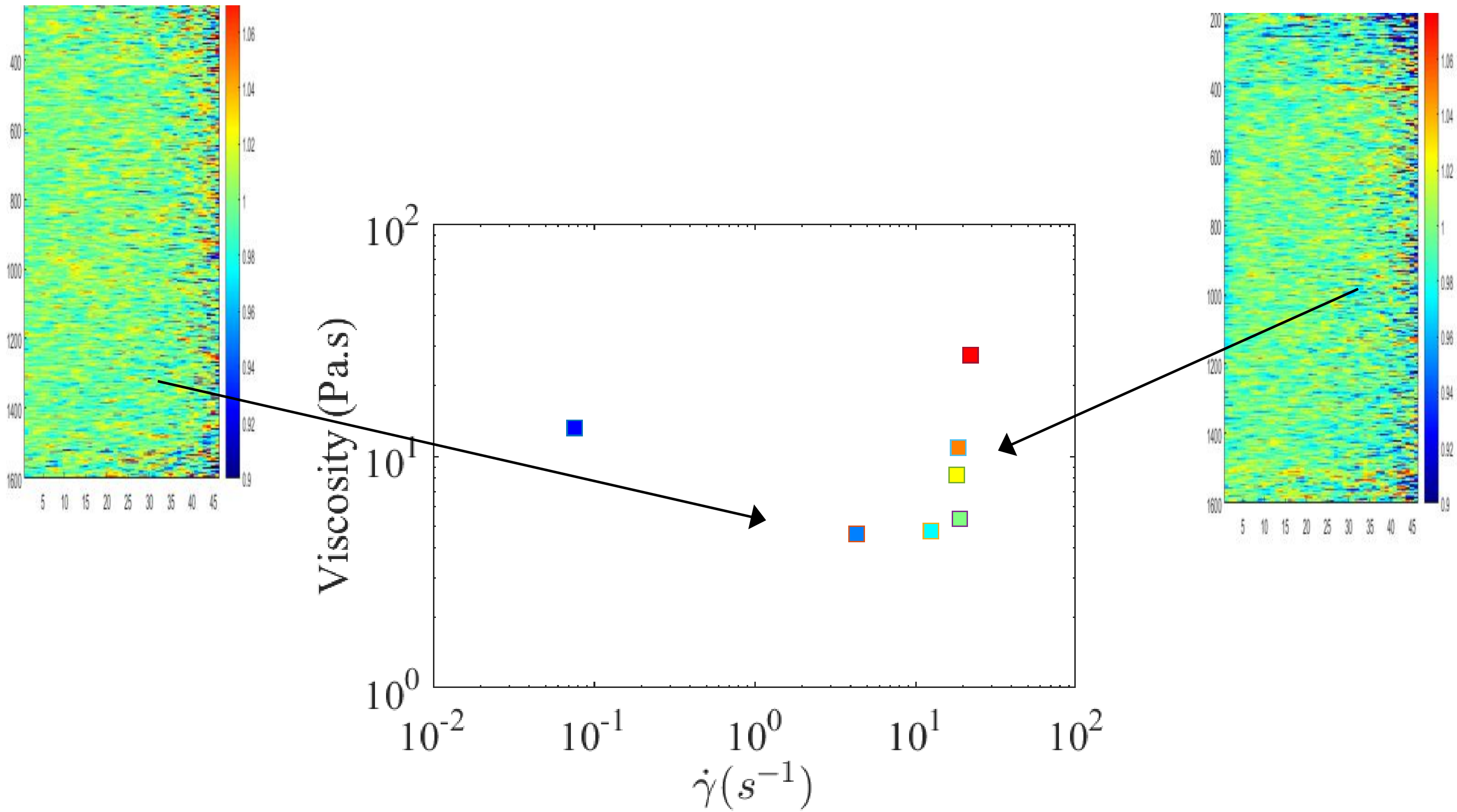
Volume fraction field $\boldsymbol{\phi(r,z,t)}$ extracted

Real-time measurement during rheology experiment

X-ray imaging: application to shear thickening

61% of **PVC particles in plasticizer** 1mm gap Couette *(stress inhomogeneity : 8%)*

Volume fraction fields in the gap of the Couette cell remain **constant**



Discontinuous Shear Thickening is a viscosity jump
in the constitutive behavior of the homogeneous material

X-ray imaging: application to shear thickening

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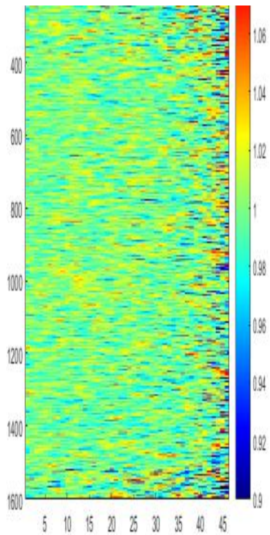
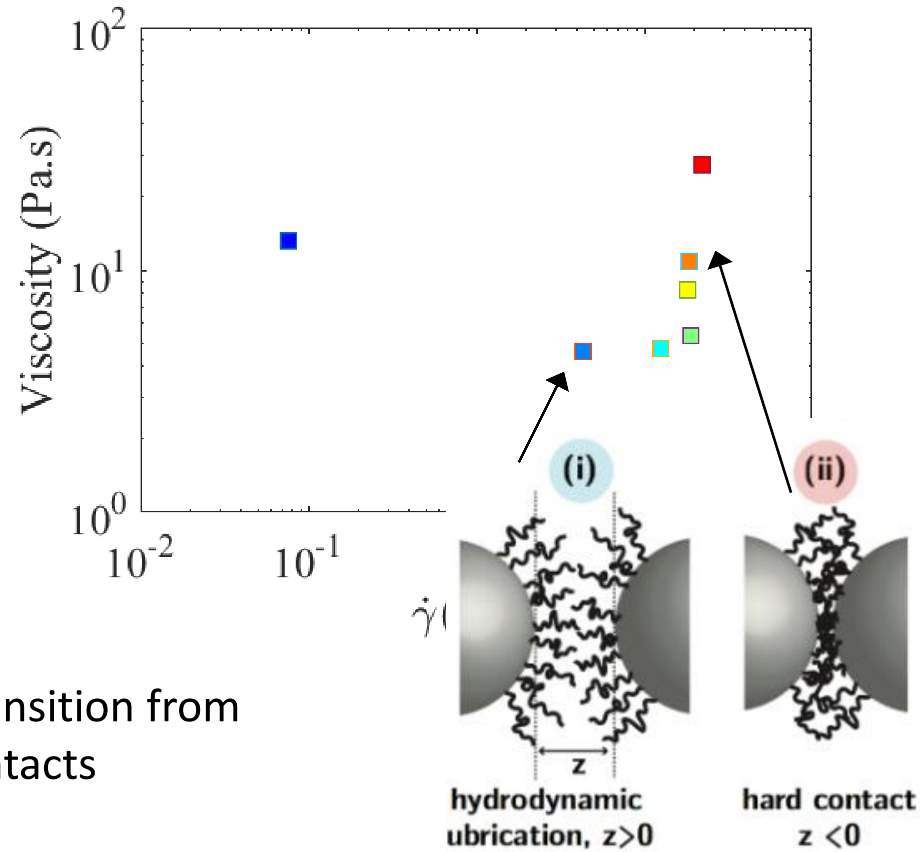
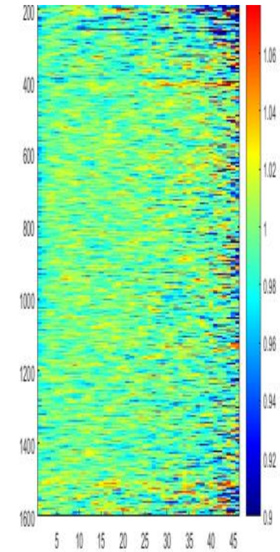


SEE **TALK by ANNIE COLIN**
SEE **POSTER by JEAN COMTET**





Interpreted as transition from lubrication to contacts

Consistent with *Seto et al, PRL 2013*

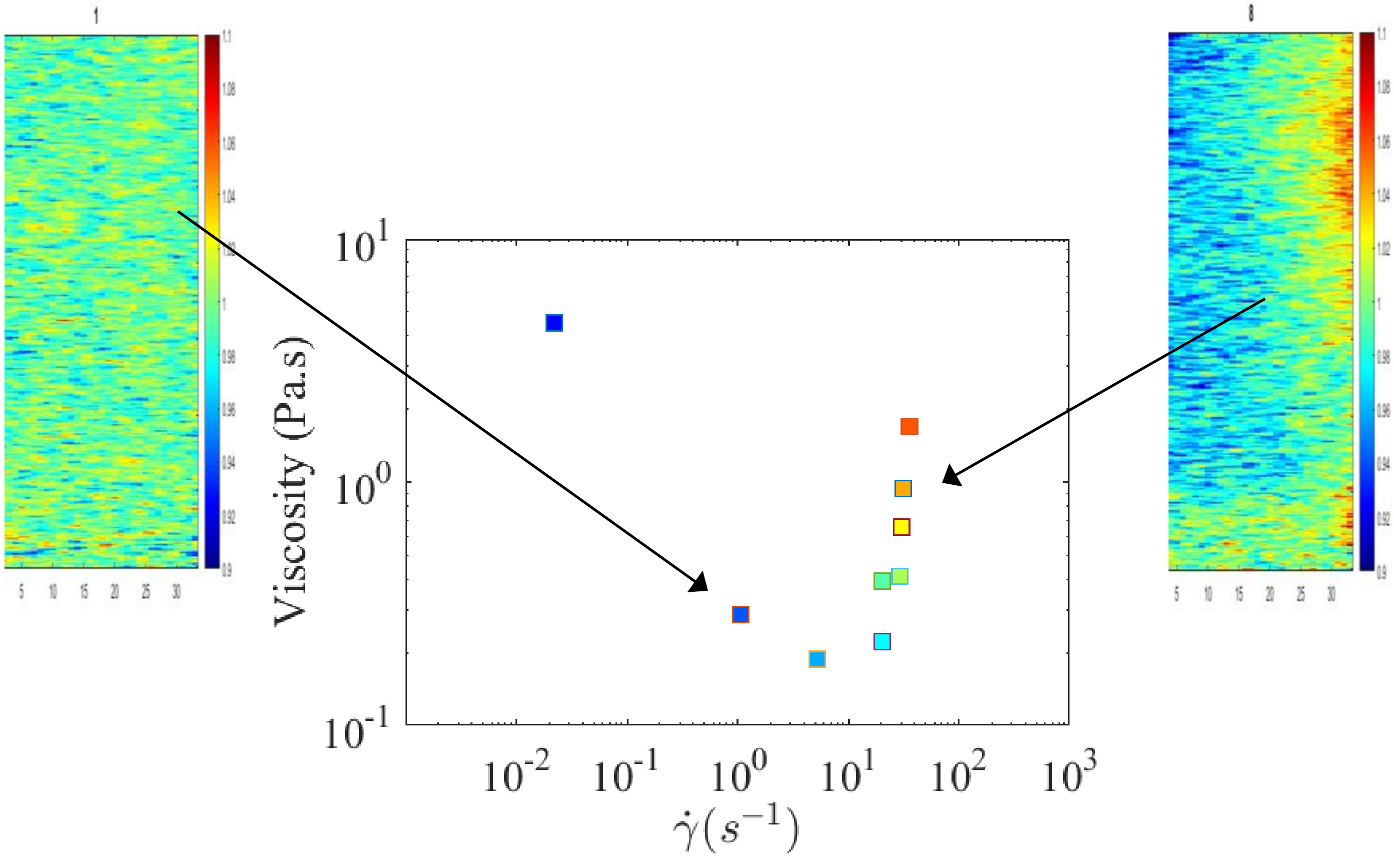
Comtet et al., Nature communication 2017

X-ray imaging: application to shear thickening

41% of **cornstarch in water/CsCl** in 1mm gap Couette *(stress inhomogeneity : 8%)*

Volume fraction field abruptly changes in the thickening regime

Homo geneous



±5% variation in the gap

X-ray imaging: application to shear thickening

41% of **cornstarch in water/CsCl** in 1mm gap Couette *(stress inhomogeneity : 8%)*

Volume fraction field abruptly changes in the thickening regime

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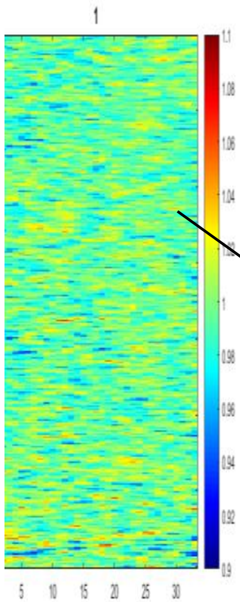
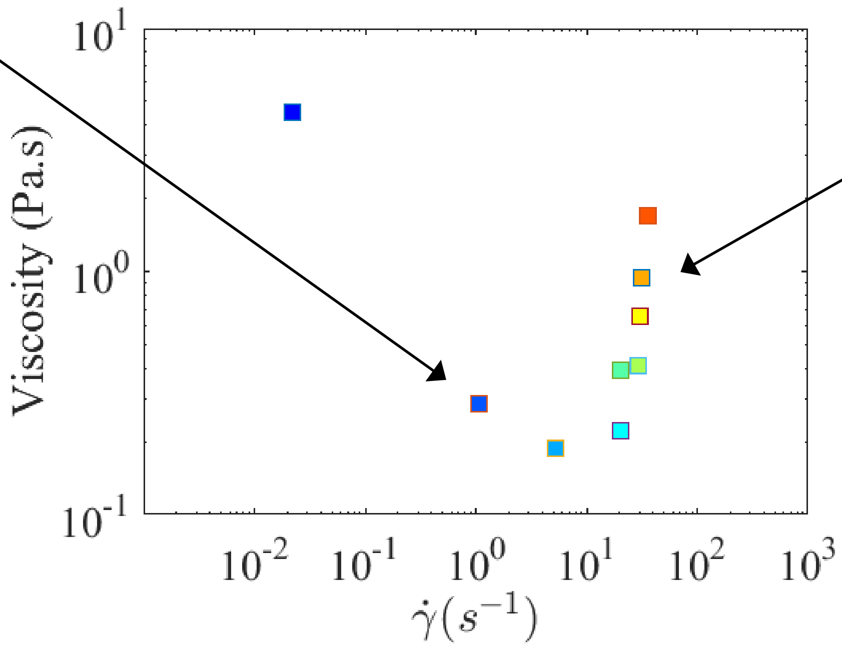
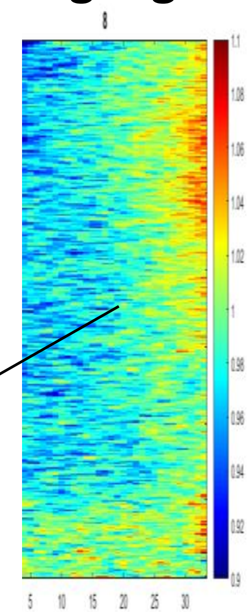
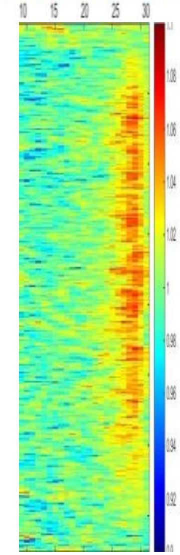






$\pm 5\%$ **variation in the gap**



Same feature and magnitude in a $500\mu m$ gap, with smooth/rough boundaries

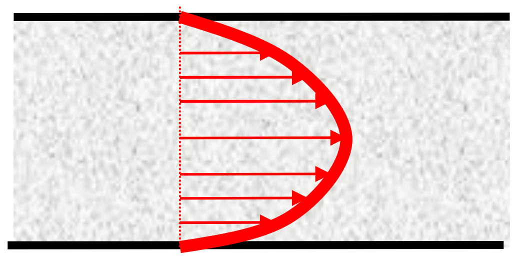
Discontinuous Shear Thickening is ????????????????

Digression: Shear-induced migration in nonBrownian suspensions

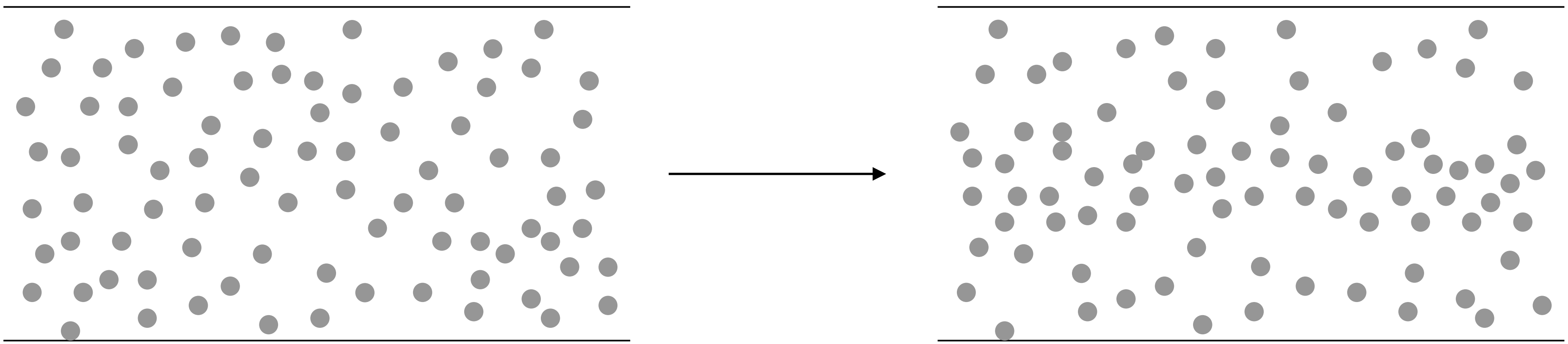
Shear-induced migration in nonBrownian suspensions

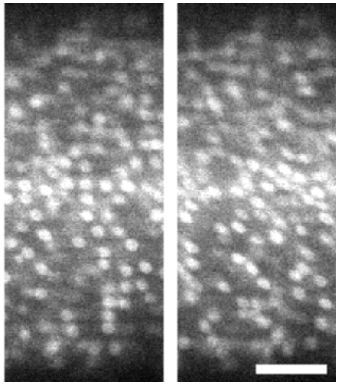
Leighton & Acrivos (1987), Phillips et al. (1992), …

Ex: pipe flow



Migration towards zones of low shear rate





Frank et al. (2003)

⇒ Need for a **diphasic description**

Shear-induced migration and normal stresses

suspension *fluid* *particles*

diphasic description: $\Sigma_{ij} = \sigma_{ij}^{f} + \sigma_{ij}^{p}$

> *Lhuillier (2009):*
> the relevant stress driving migration is the **contact stress**

stress equilibrium on the **particle phase**:

if $\nabla \sigma^{p} \neq \mathbf{0} \rightarrow$ fluid filtration ; $\nabla \sigma^{p}$ balanced by drag force

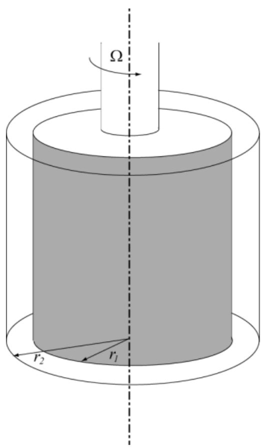
mass conservation $\rightarrow$ kinetic equation for the particle volume fraction

Nott and Brady, JFM (1994)
Mills and Snabre, J. Phys. II (1995)
Morris and Boulay, J. Rheol. (1999)
Lhuillier, Phys. Fluids (2009)
Nott et al., Phys. Fluids (2011)

Steady-state: volume fraction in a wide gap Couette

Ex : viscous suspension ($\Sigma \propto \dot{\gamma}$)

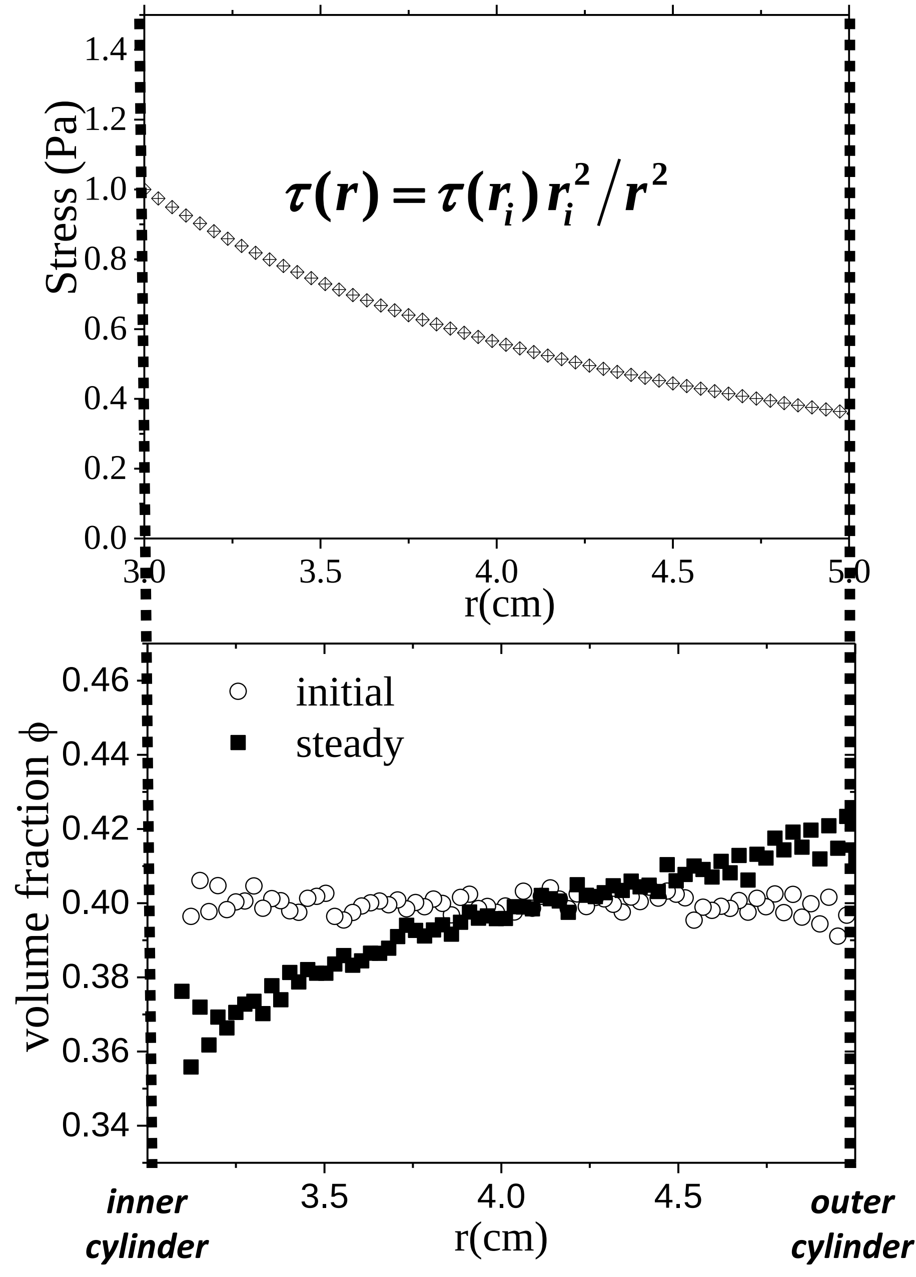
40% of PS beads



In a Couette cell:

$\phi(r)$ and $\dot{\gamma}(r)$ are solution of

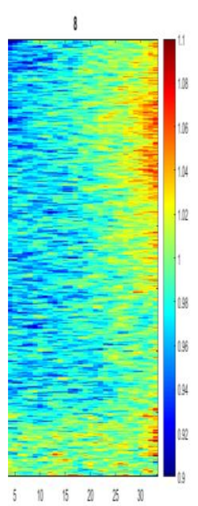
$$\begin{cases} \partial_{\mathrm{r}}\left(\Sigma_{r\theta}(\dot{\gamma}(r),\phi(r))\, r^2\right) = 0 \\ \partial_{\mathrm{r}}\left(\sigma^p{}_{rr}(\dot{\gamma}(r),\phi(r))\, r\right) = \sigma^p{}_{\theta\theta}(\dot{\gamma}(r),\phi(r)) \end{cases}$$



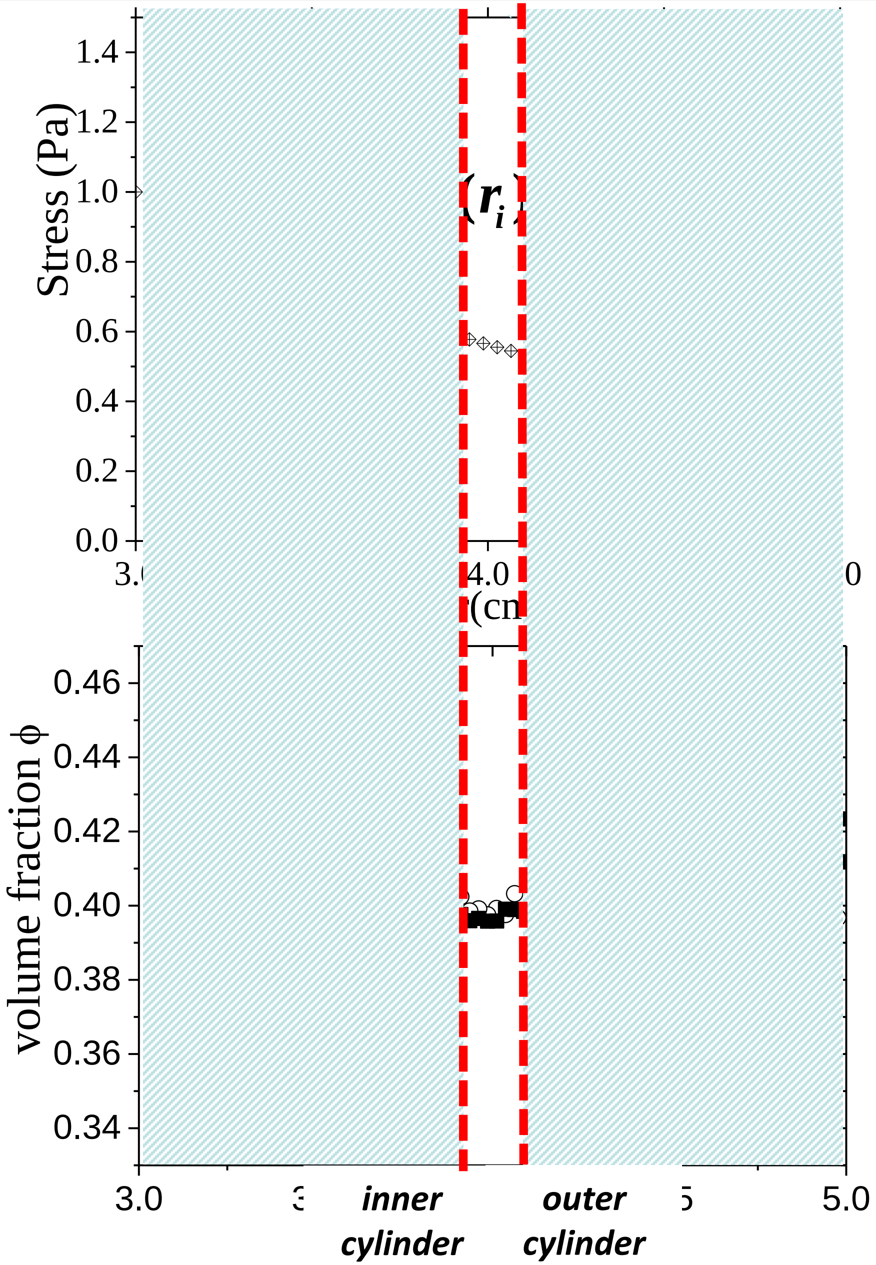
Steady-state: volume fraction in a thin gap Couette

Ex : viscous suspension ($\Sigma \propto \dot{\gamma}$)
40% of PS beads

For a 8% stress inhomogeneity
(case for the thickening suspensions investigated)
$\pm 0.25\%$ relative vol. fraction expected



$\pm 5\%$ variation observed in cornstarch !



Shear-induced migration: strainscale

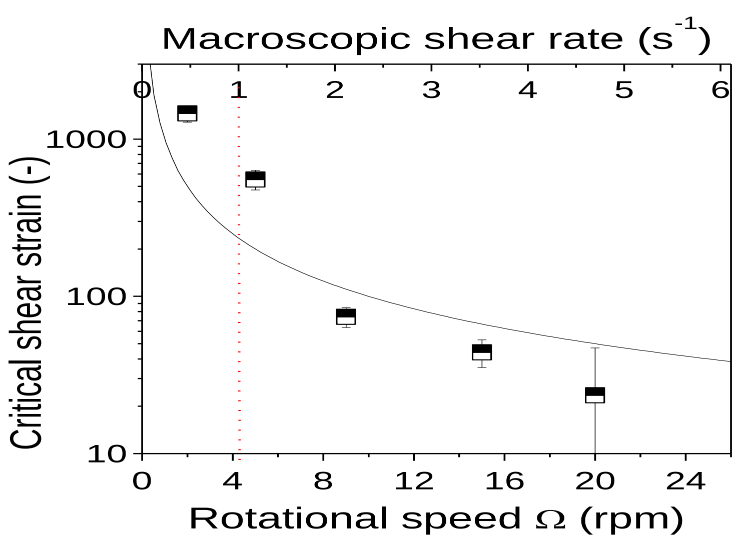
For a viscous suspension, strainscale= $f(\phi)$

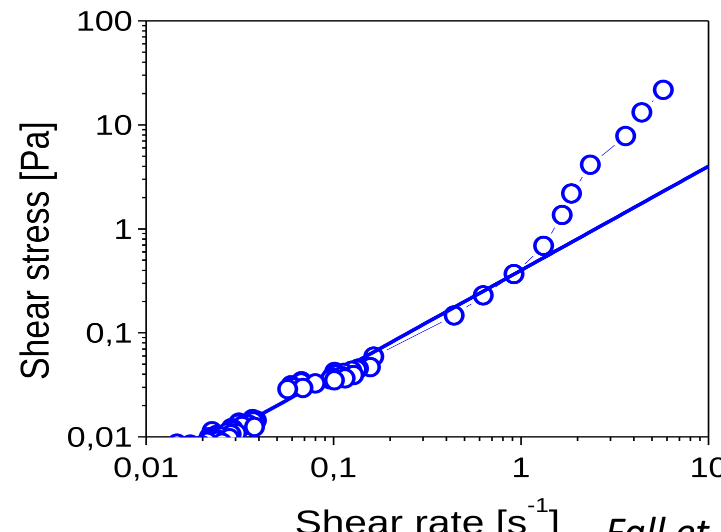
ϕ / ϕ_m	strainscale
0.15	100 000
0.5	10 000
0.85	2 000
0.96	50

case *investigated:*
100 particles in the gap

Strain scale seems to decrease down to 0 near jamming
→ unavoidable…

CST suspension: strainscale= $f(\phi, \dot{\gamma})$; "instantaneous" in thickening regime



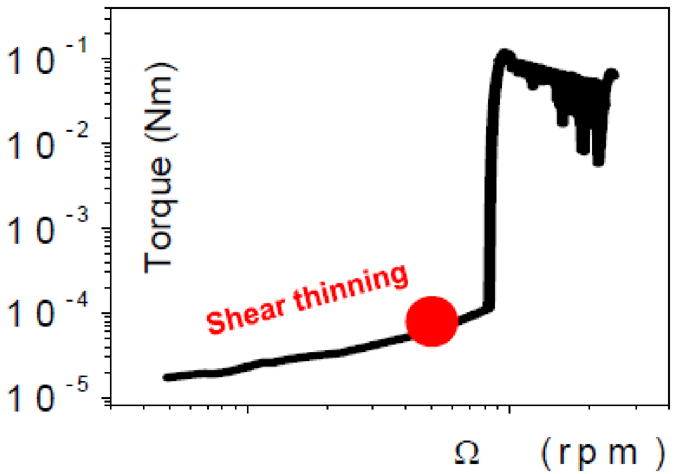


Fall et al., PRL (2010)

Back to cornstarch suspensions

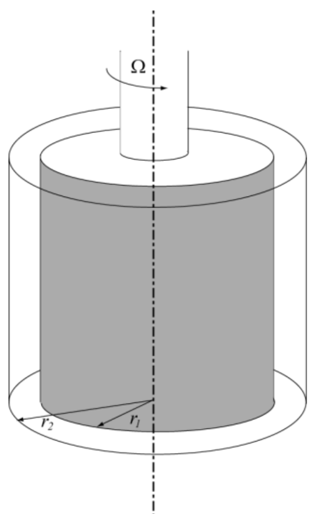
Cornstarch suspension in a wide gap Couette

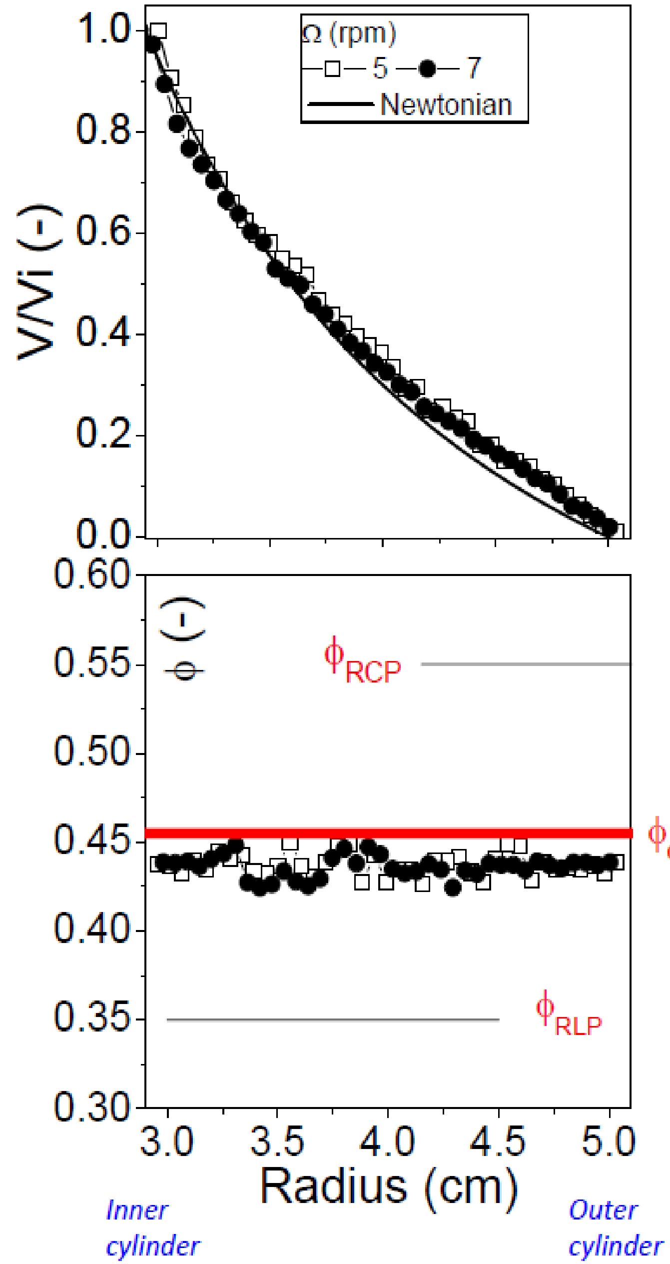
For a 43.9% mean volume fraction



- $\Omega < \Omega_c$ → Shear thinning

  - Homogeneous flow





Cornstarch suspension in a wide gap Couette

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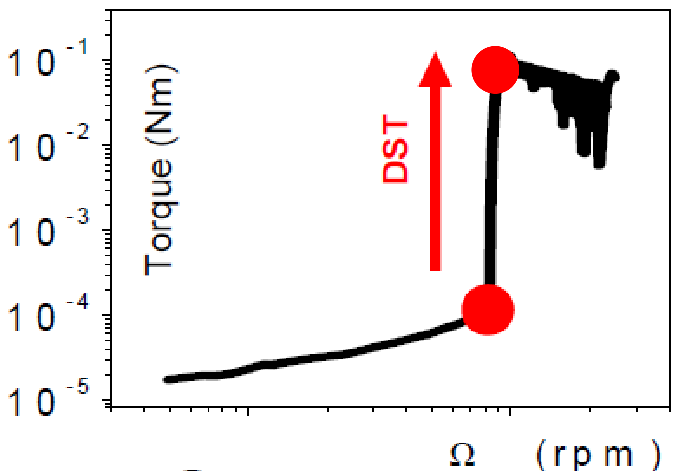
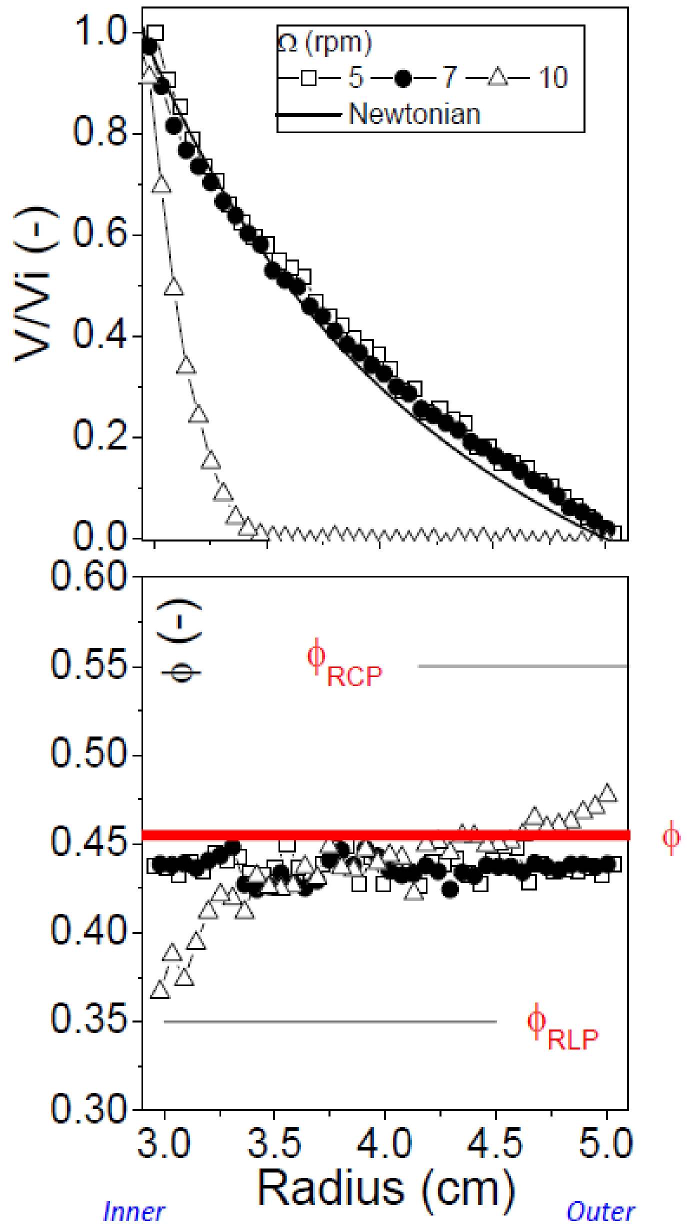




Inner cylinder

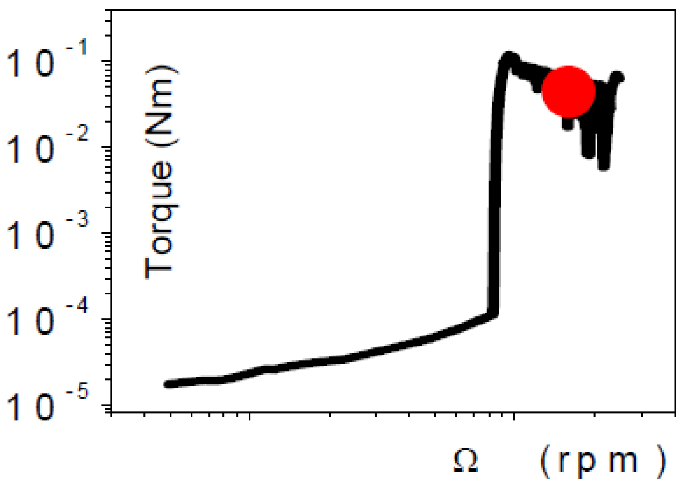
Outer cylinder

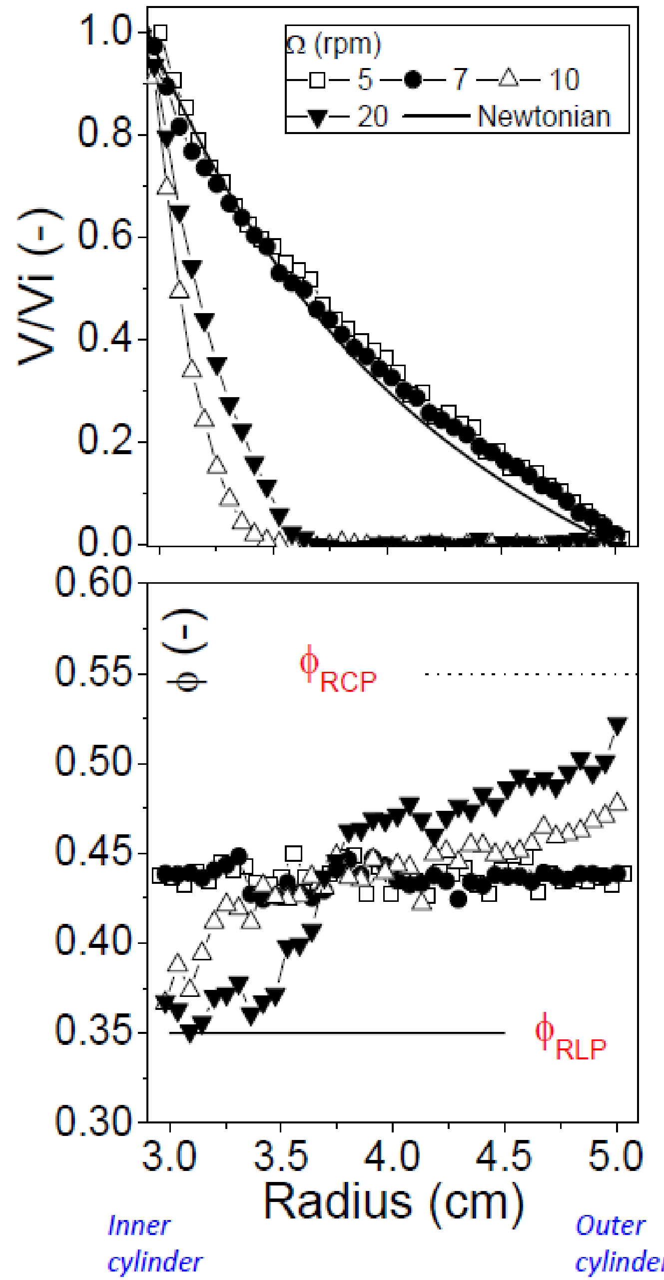
Sudden **shear localization** (creation of a **dead zone**)

Link with emergence of volume fraction **inhomogeneities**

Shear-thickening in cornstarch: local measurements

For a 43.9% mean volume fraction

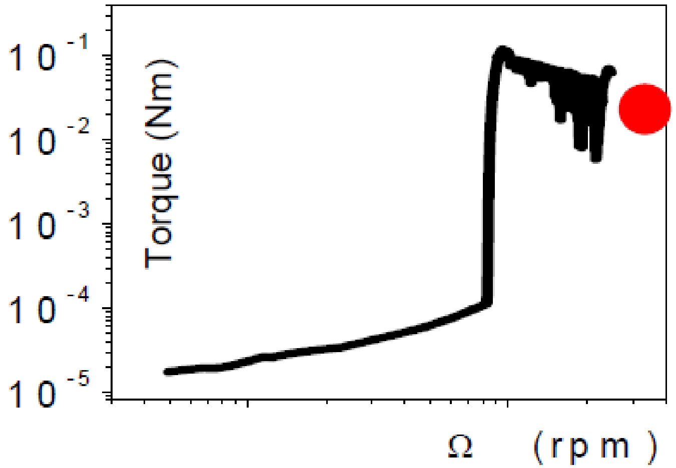




- The sheared region grows up with Ω
- Broadening of the low-density region
- Compaction of the Jammed region towards ϕ_{RCP}

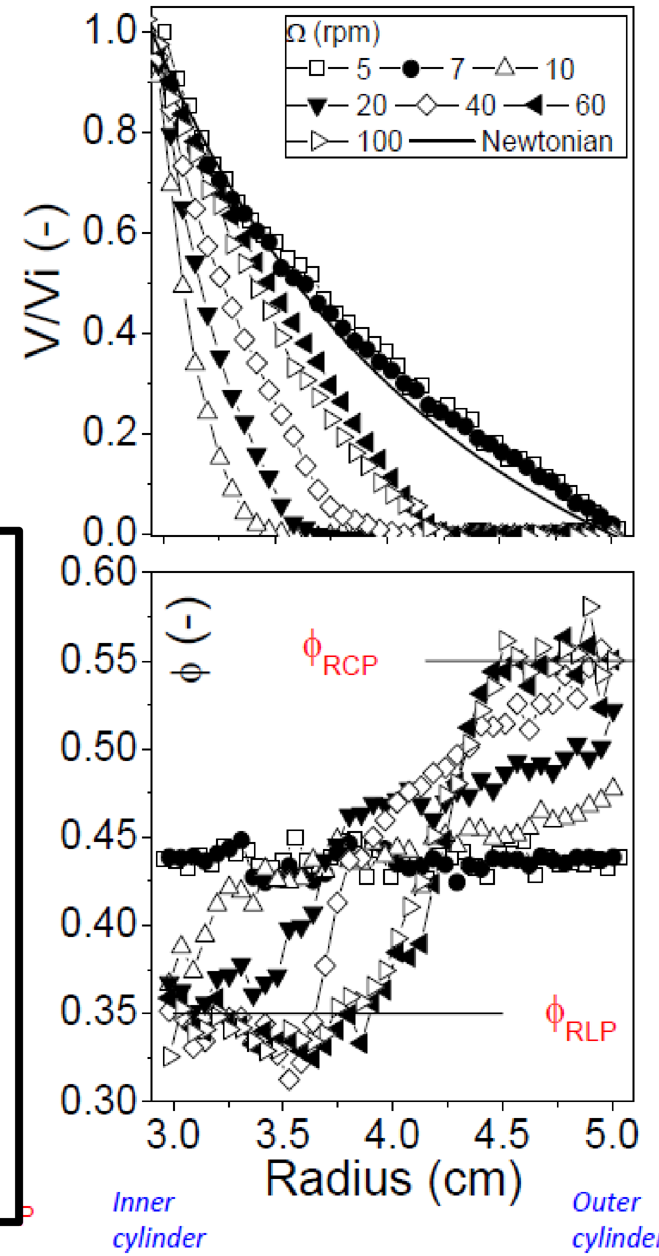
Shear-thickening in cornstarch: local measurements

For a 43.9% mean volume fraction



What can we learn on the local behavior from all this mess???

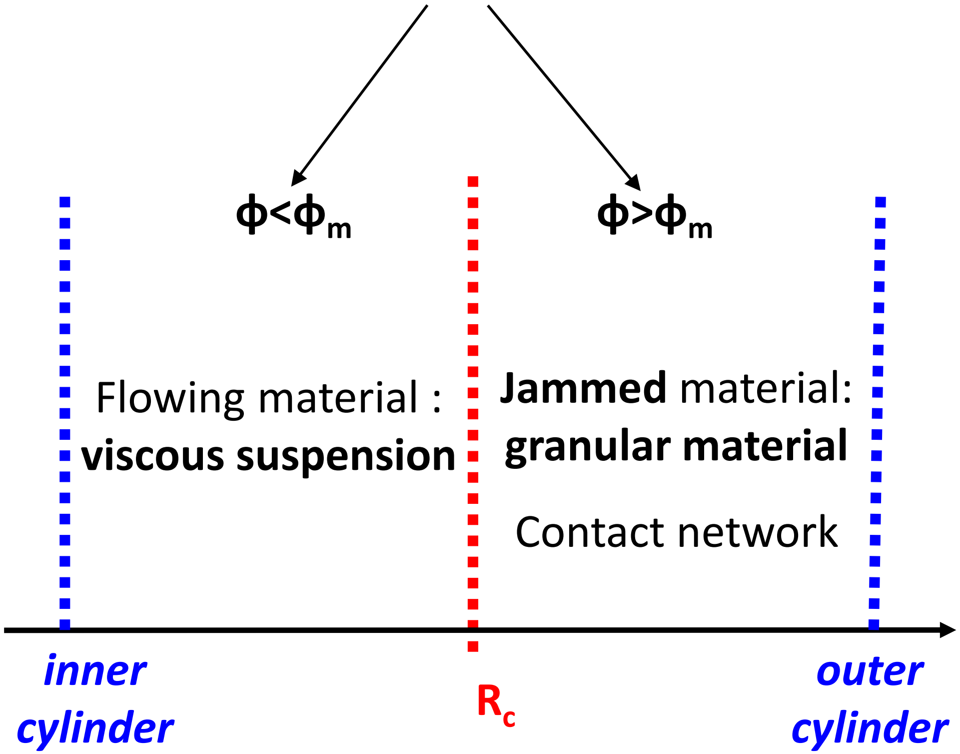
→ Extract all $(\phi, \dot{\gamma}(\phi))$ to build a « state diagram »

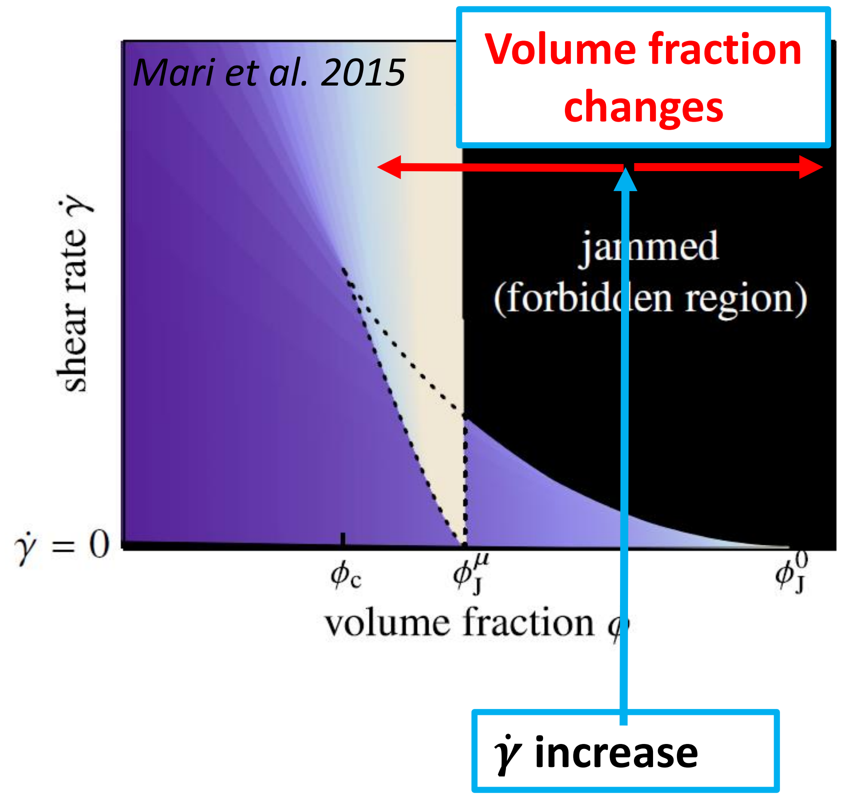


Fall et al., PRL (2015)

Shear induced migration and Shear induced jamming

Shear-induced migration can generate 2 different zones



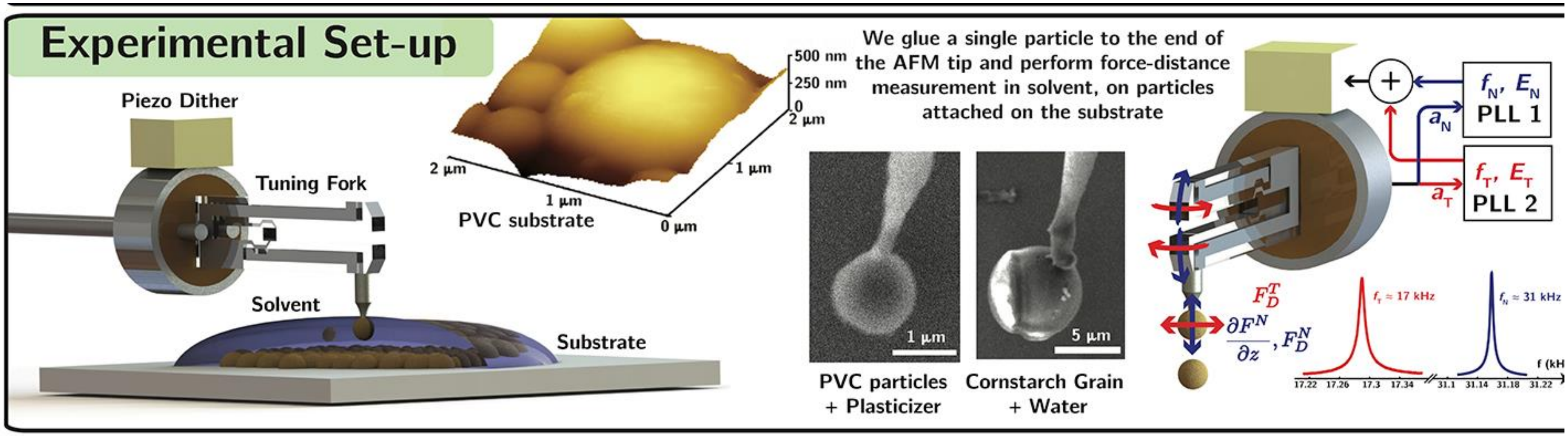


Discontinuous shear thickening = (shear-?) jamming.

ϕ decreases locally to allow for flow near the moving boundary

Now, physics can be discussed…

Force measurements between cornstarch particles



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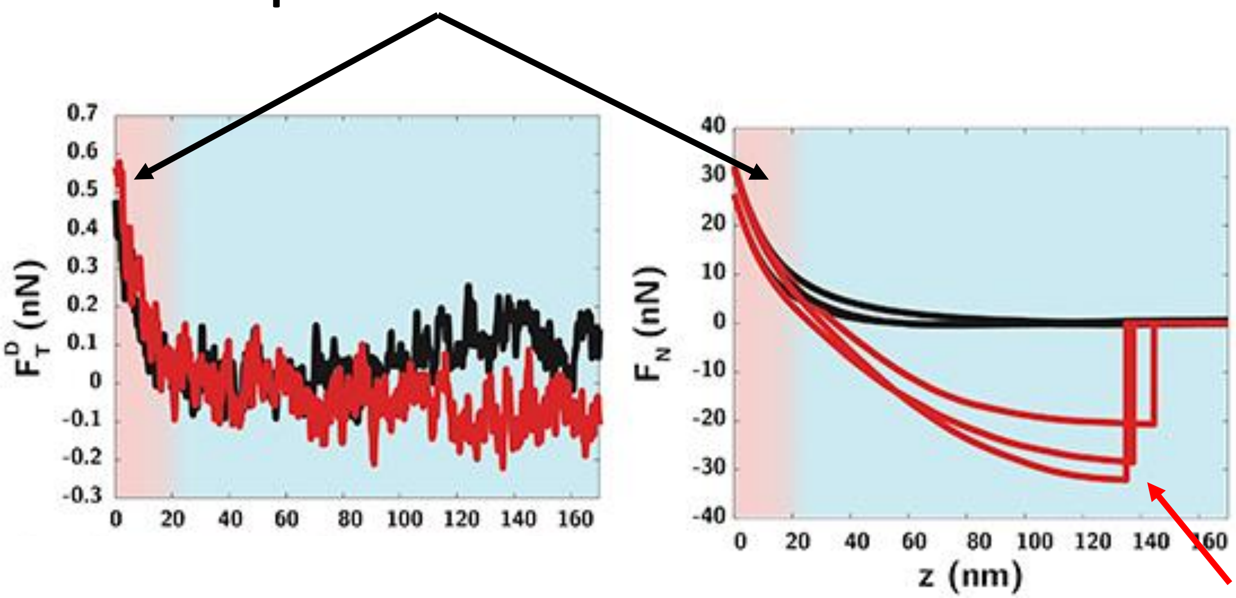
Repulsion with friction



Hysteresis: adhesion force

Proposed mechanism

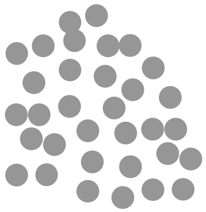
Not a revolution!…

…same idea as
Seto et al., PRL 2013
Wyart and Cates, PRL 2014…
… with adhesion

Transition from

Low stress / shear rate **:**
repulsion, frictionless particles

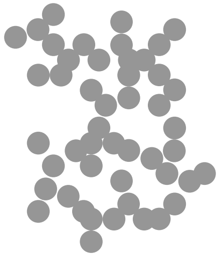
→ suspension of frictionless spheres with **viscous behaviour**



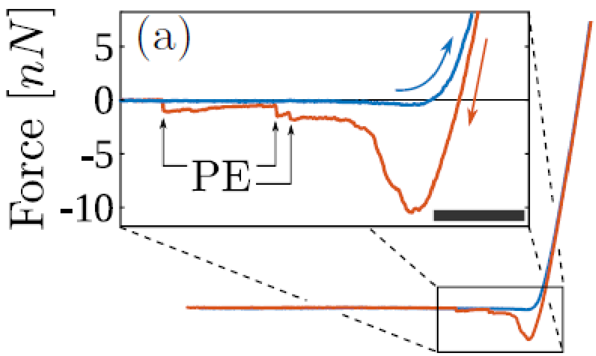
to

High stress/shear rate:
<u>shear-induced adhesion</u>

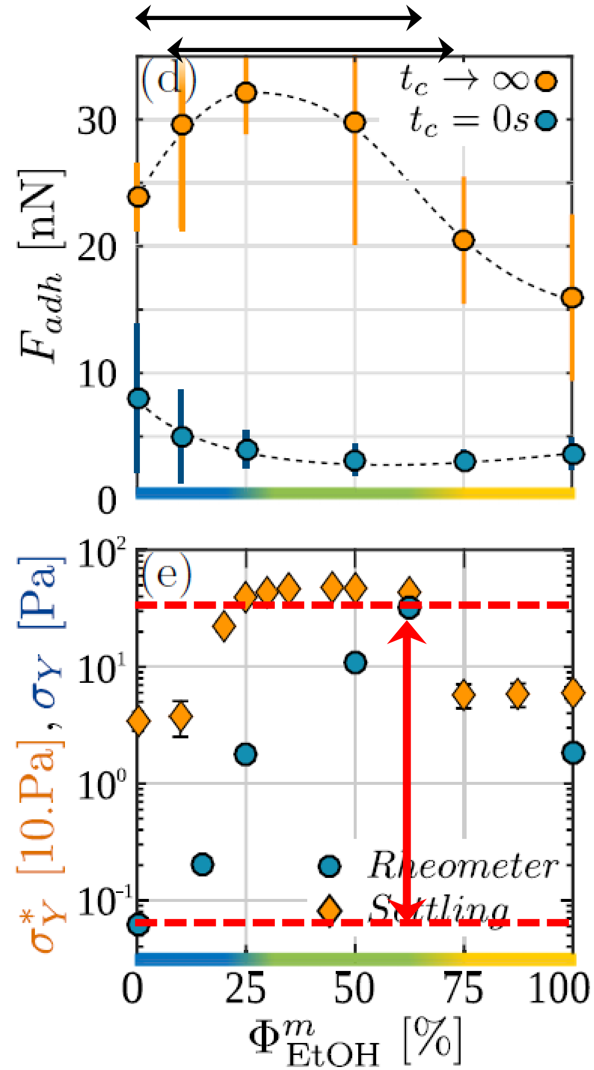
→ **cohesive granular material** (or colloidal gel) **with yield stress**



Linking adhesion force/yield stress



Adhesion force does not vary much with composition

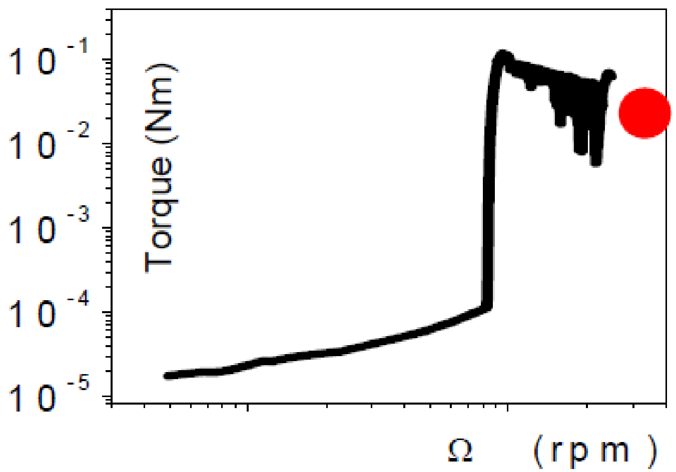


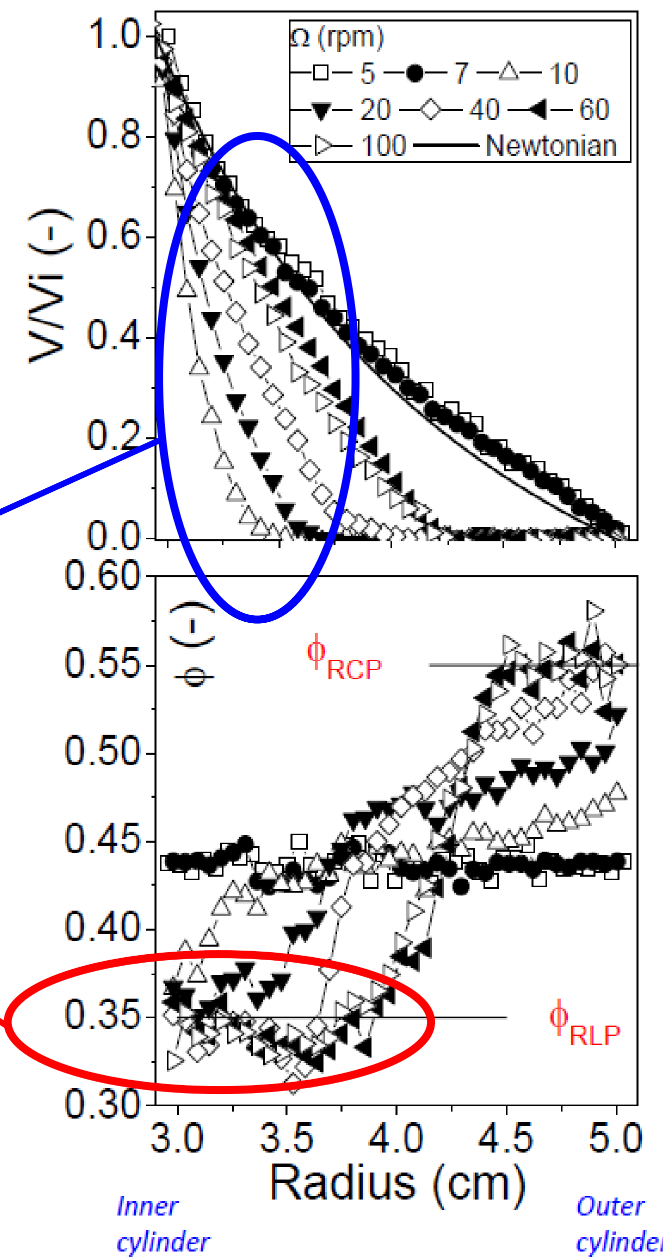
Yield stress increase by 3 orders of magnitude similar to increase during shear thickening!

Oyarte Galvez et al., PRE 2017

Linking yield stress behavior/local behavior

For a 43.9% mean volume fraction





Velocity profiles
of the material
@ local vol. fraction ≃ 35%
consistent with
yield stress fluid behavior
(Herschel-Bulkley)
Yield stress ≃ tens of Pa

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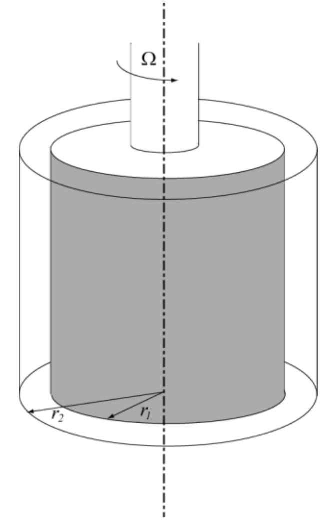
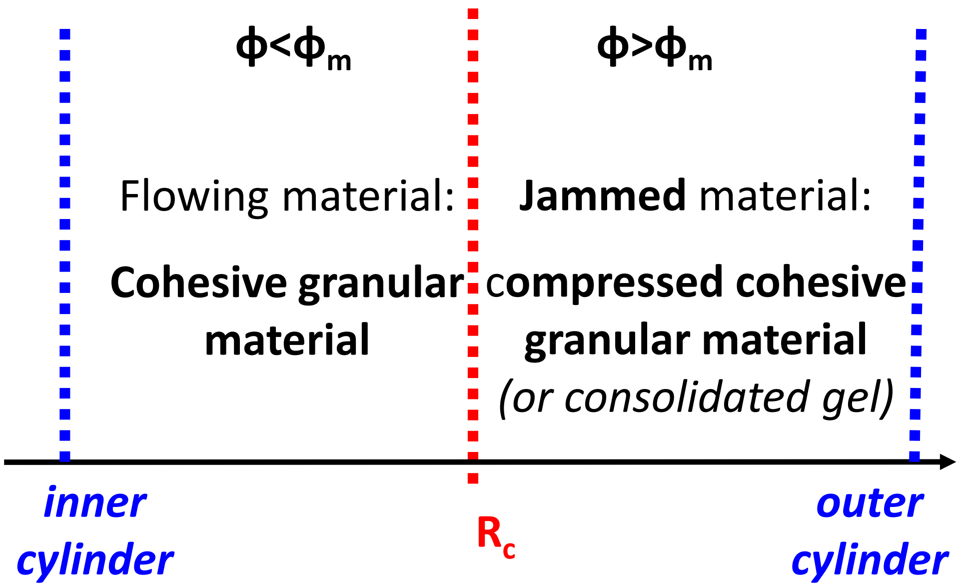
Fall et al., PRL (2015)

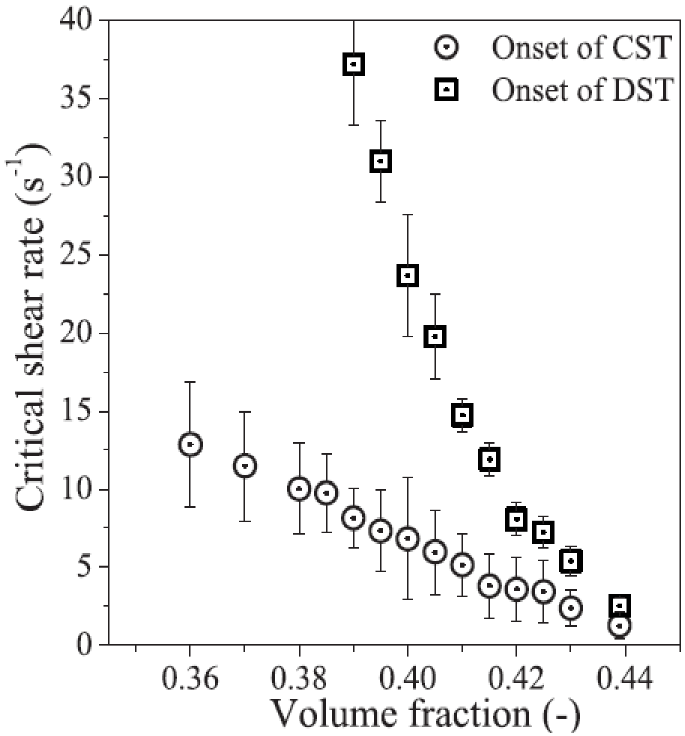
Linking shear-induced inhomogeneities/adhesion

- shear-thickening = shear-induced adhesion
- the cohesive granular material is irreversibly compressible up to ϕ_{rcp}





Accessible volume fractions



Jammed states

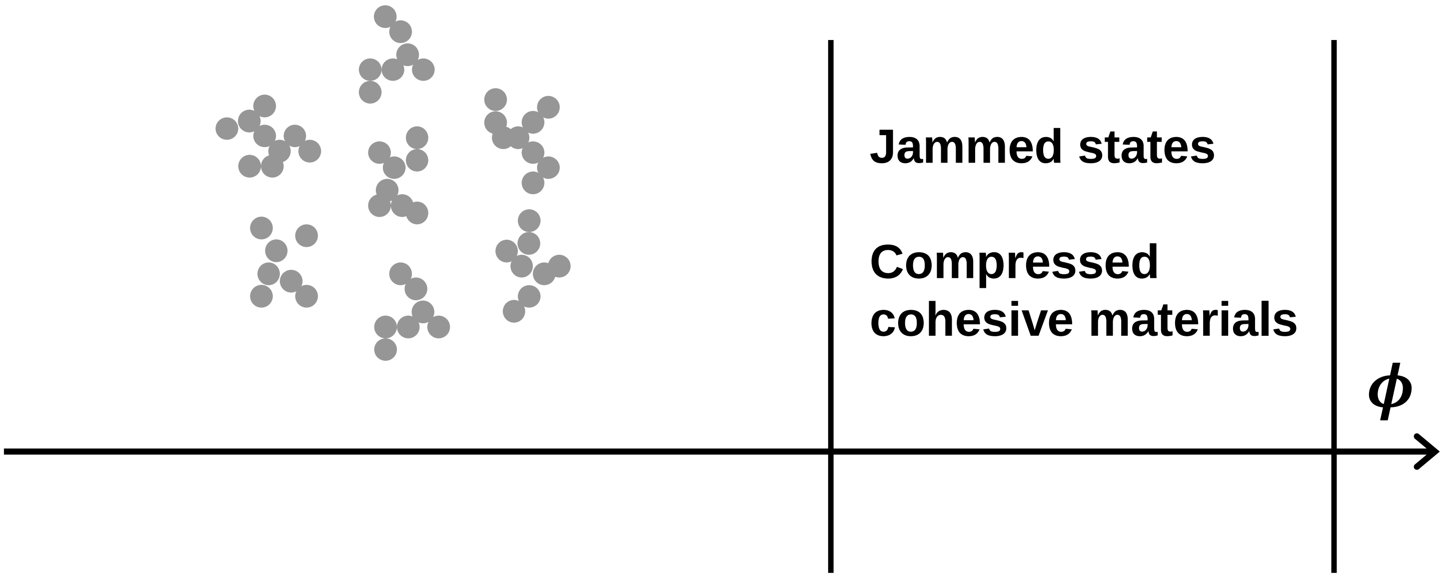
Compressed cohesive materials

ϕ

$\phi_0 = 45\% \neq \phi_{rcp} = 55\%$

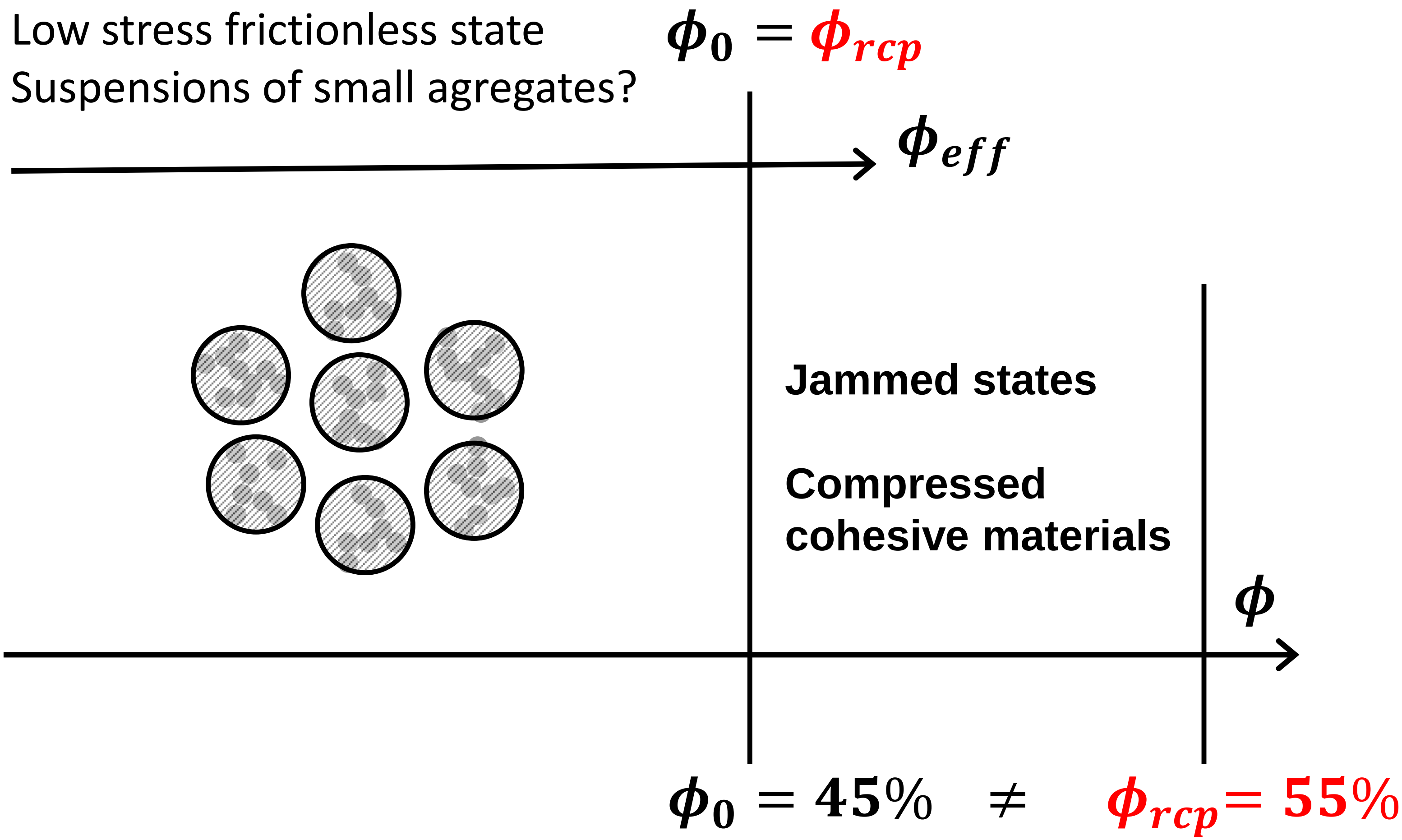
Accessible volume fractions

Low stress frictionless state
Suspensions of small agregates?



$$\phi_0 = 45\% \neq \phi_{rcp} = 55\%$$

Accessible volume fractions



Other explanation? → ask Eric Clément!

Conclusion

Strong interplay between migration / shear thickening / (Shear-) jamming

« Discontinuous shear-thickening »

jump in viscosity OR shear-induced yield stress OR shear jamming…

depends on interparticle forces

hard to know from only macroscopic measurements

Need for volume fraction measurements

Conclusion

Cornstarch:

- Revisit the origin of the **s-shape?**
  In which range of local vol. fraction does s-shape exist?
- Impacts on the surface of a Couette cell (*Peters et al., Nature 2016*)
  → **which volume fractions are truly investigated?**

Other systems investigated:

- **PMMA suspensions** → **inhomogeneous** at DST…
- **Silica suspensions** → **inhomogeneous** at DST…

} To be studied in more depth

- **PVC suspensions** (Comtet et al., Nature. Comm 2016) :
  « THE » canonical system!