Flows of suspensions of particles in yield stress fluids studied by X-ray microtomography

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Motivations

Dense suspensions and rheology

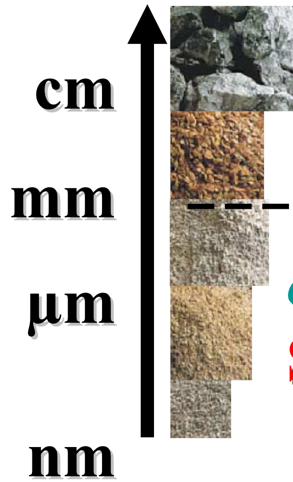
Can be easily shaped

Stands on a wall

Yield stress fluids

Hard to cast…

Suspension of particles in a yield stress fluid



Noncolloidal particles

sand & gravel

Scale Separation

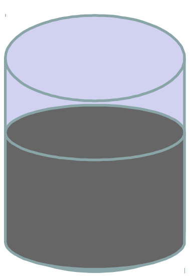
cement paste

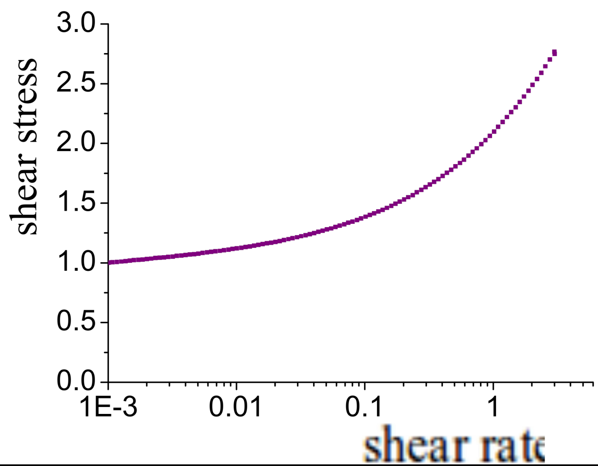
Suspending yield stress fluid

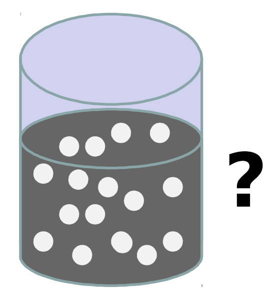
Other examples: debris flow, coal slurries, food industry…

***Composite materials** (reinforced with particles)*

Paste = yield stress fluid





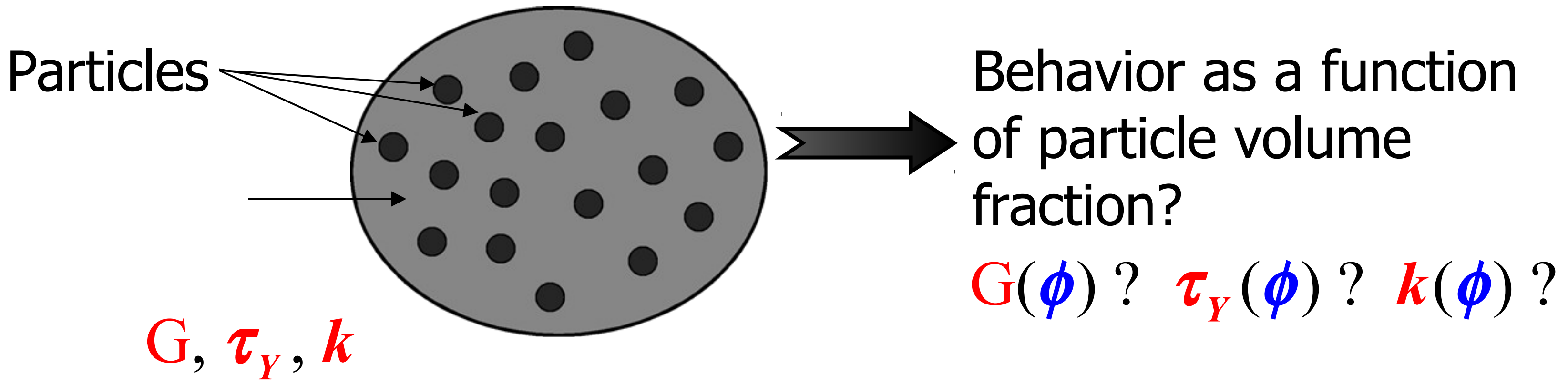


Model materials

Focus on cases where only Mechanical Interactions between particles

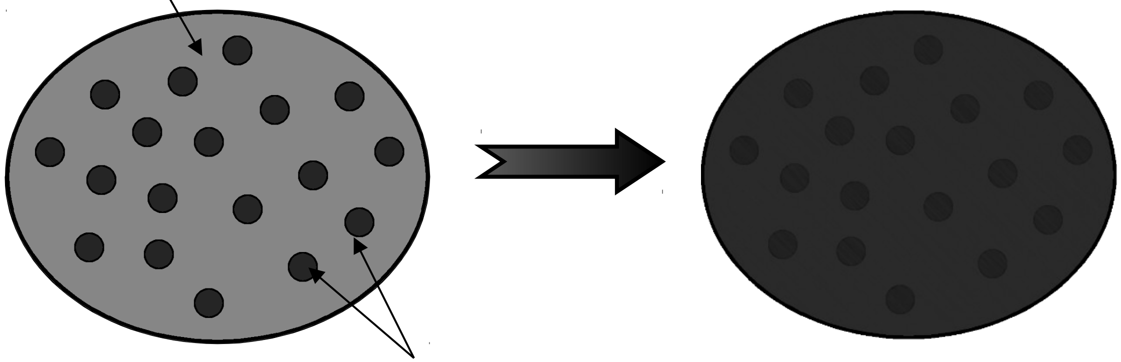
(i.e. no specific physicochemical interactions between materials)

☐ Common framework for **model** and **experiments**



Role of microstructure

Yield stress fluid $\begin{cases} \text{Elastic modulus } G'_0 \\ \text{Yield stress } \tau_{y0} \end{cases}$

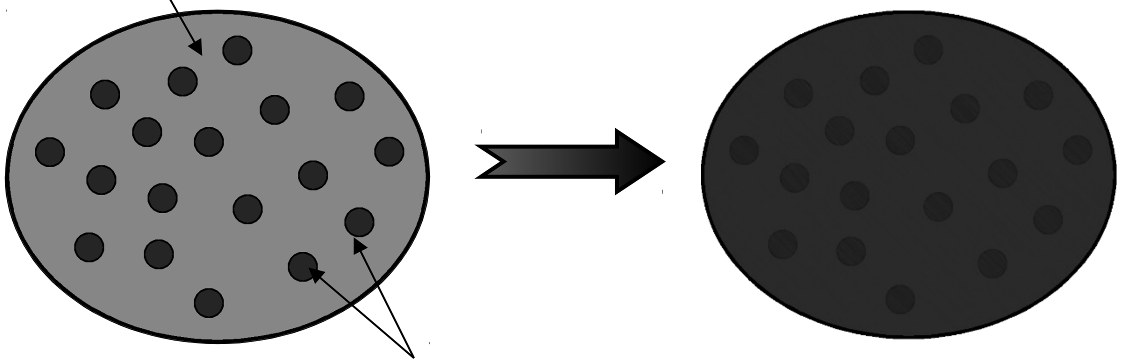


$$G'(\phi) = G'_0 \times f(\phi)$$
$$\tau_y(\phi) = \tau_{y0} \times g(\phi)$$

rigid, monodisperse particles, volume fraction ϕ **ISOTROPIC** distribution of the particles

Role of microstructure

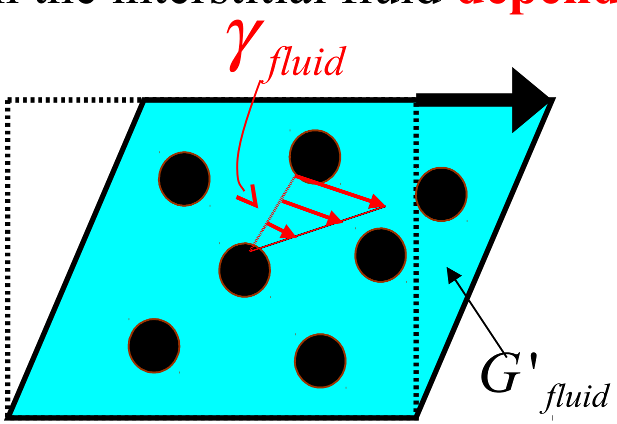
Yield stress fluid
- Elastic modulus G'_0
- Yield stress τ_{y0}



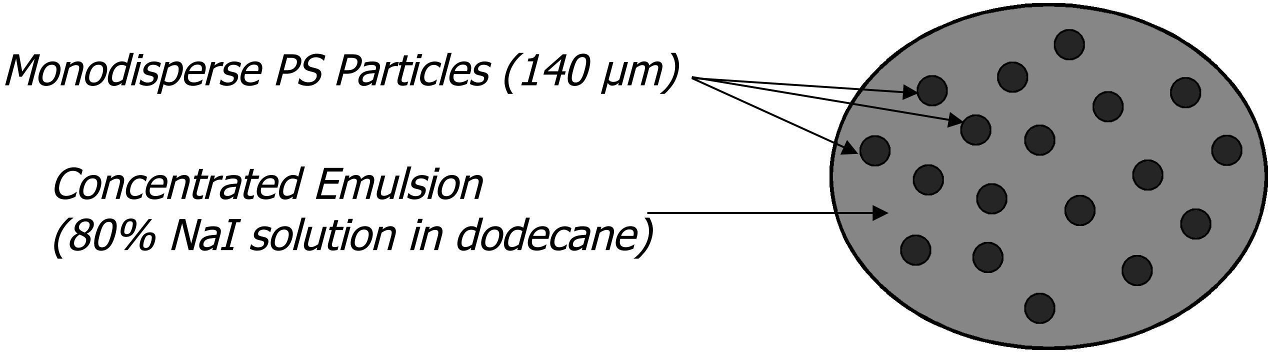
$$G'(\phi) = G'_0 \times f(\phi)$$
$$\tau_y(\phi) = \tau_{y0} \times g(\phi)$$

rigid, monodisperse particles, volume fraction ϕ ~~ISOTROPIC~~ distribution of the particles

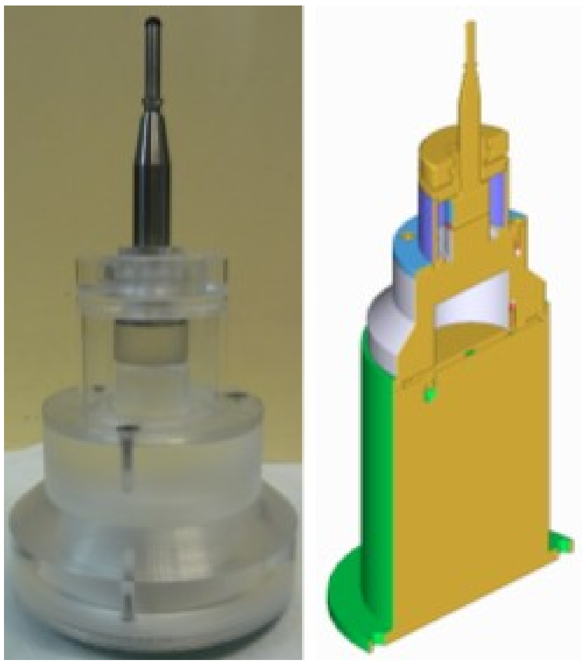
strain in the interstitial fluid **depends on microstructure**



Material & methods

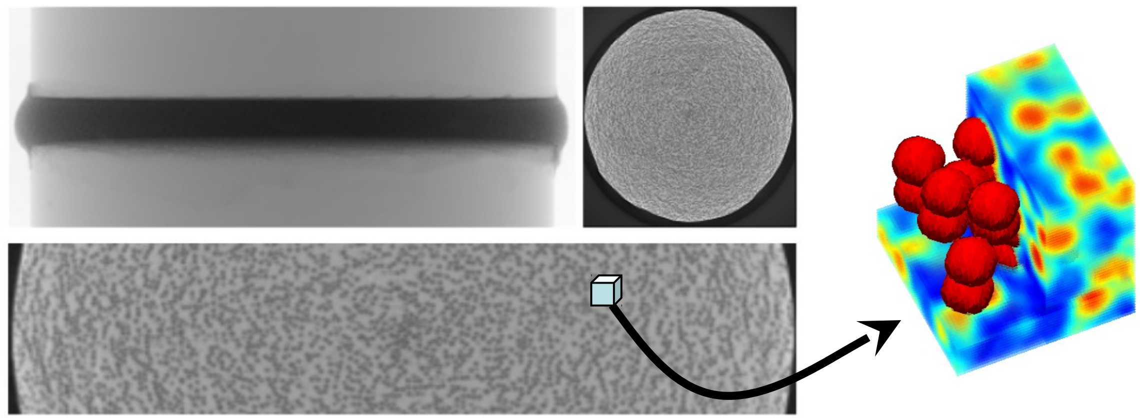


1- finding a good particle/fluid contrast material + stability for 3D scan → dodecane with NaI + PS beads (140µm)



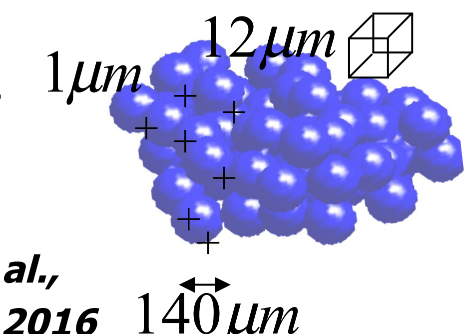
2- loading/shearing done ex-situ with a parallel plate configuration

Dia. 20mm & height 2mm



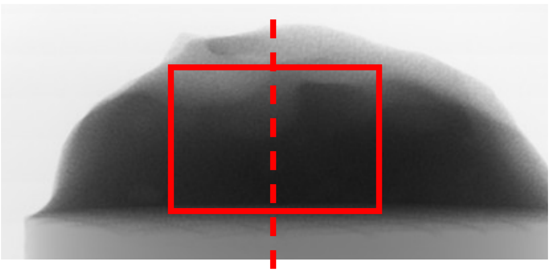
3- scan : 1 hour with a 12µm voxel size

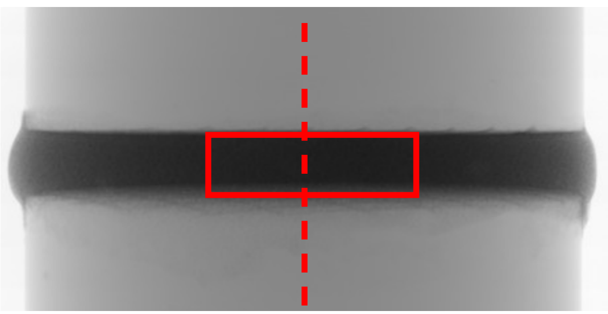
Deboeuf et al., unpublished 2016

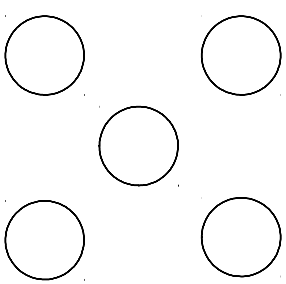


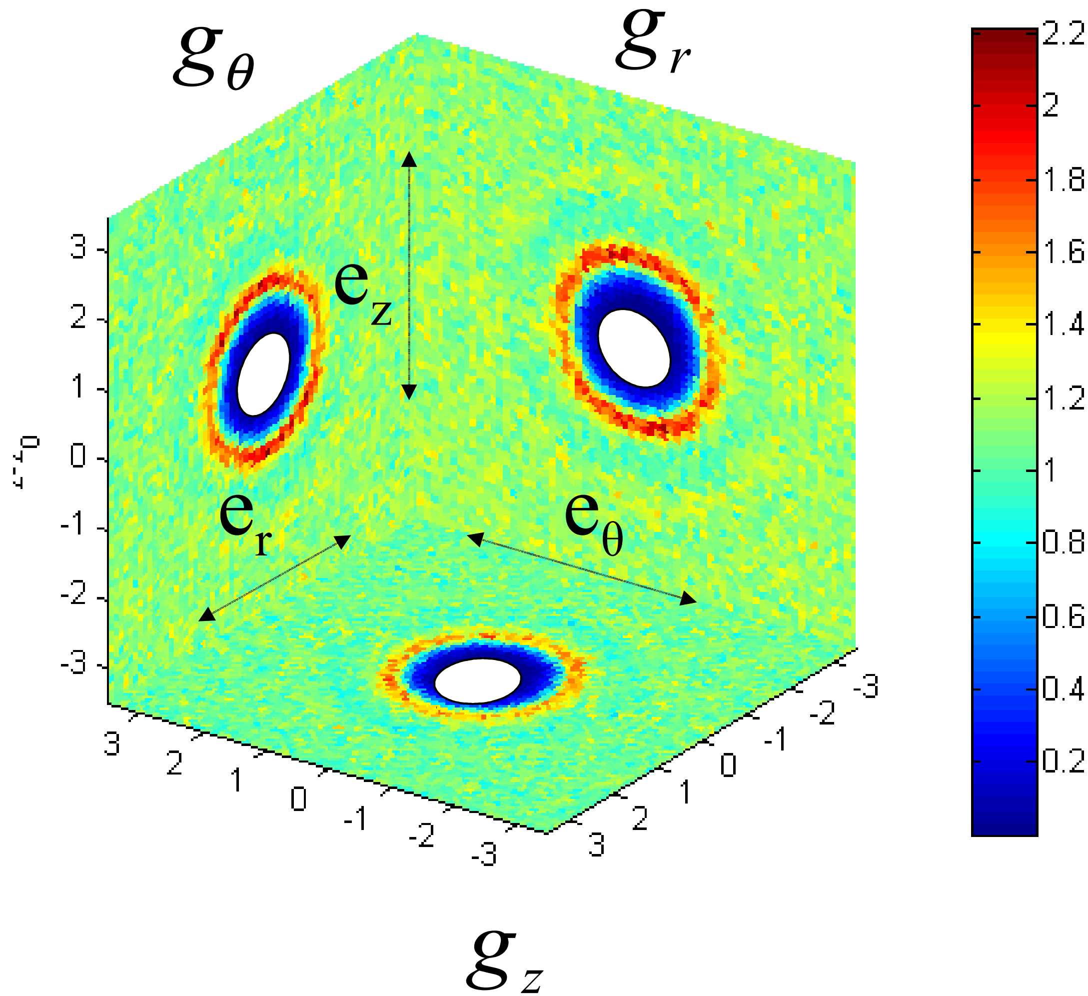
Pair distribution function: prepared suspension

No preshear and load





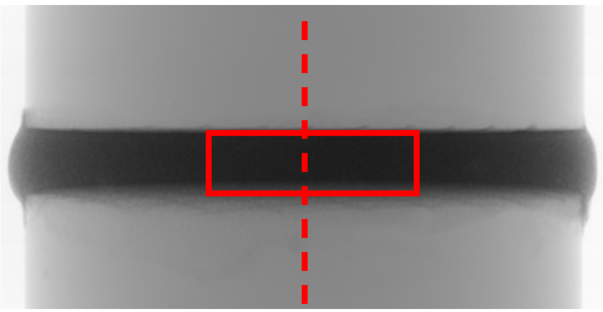


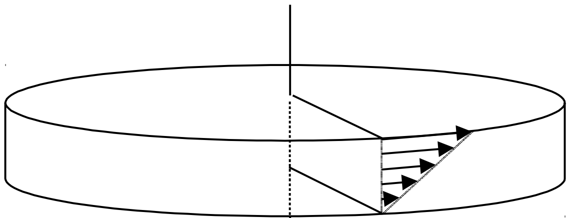


isotropic Microstructure

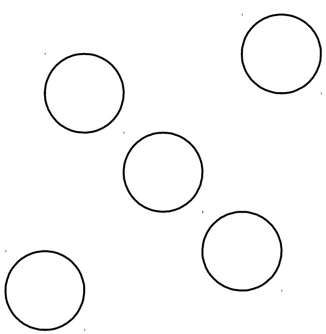
Pair distribution function: sheared suspension

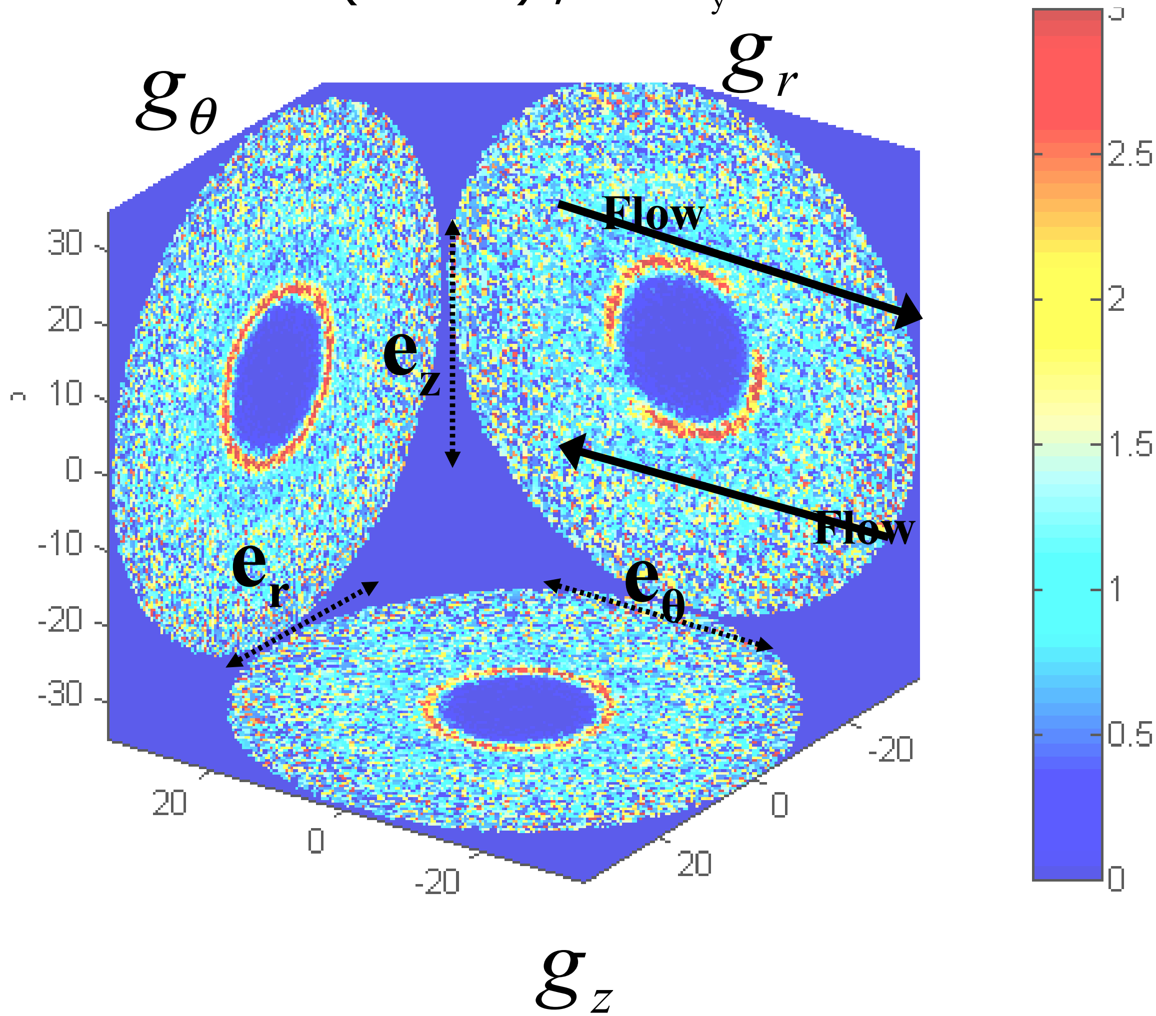
Steady state at low rate (10^{-2} s^{-1}) ; $\tau \approx \tau_y$





Azimuthal flow $v_\theta(r,z)$



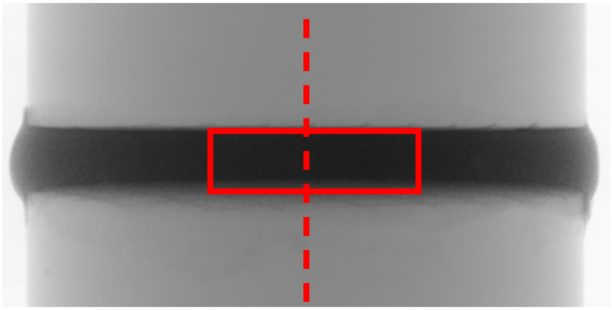


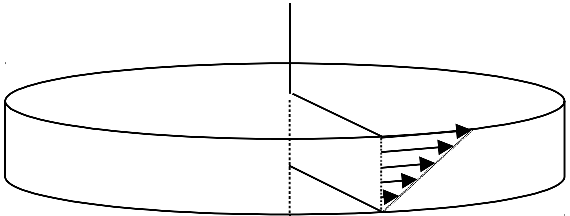
anisotropic in shear plane

isotropic in other planes

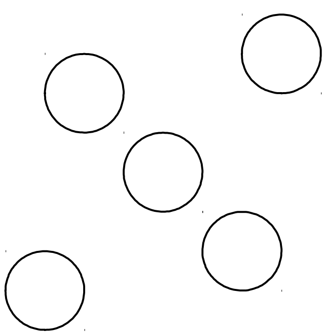
Pair distribution function: sheared suspension

Steady state at low rate (10^{-2} s^{-1}) ; $\tau \approx \tau_y$

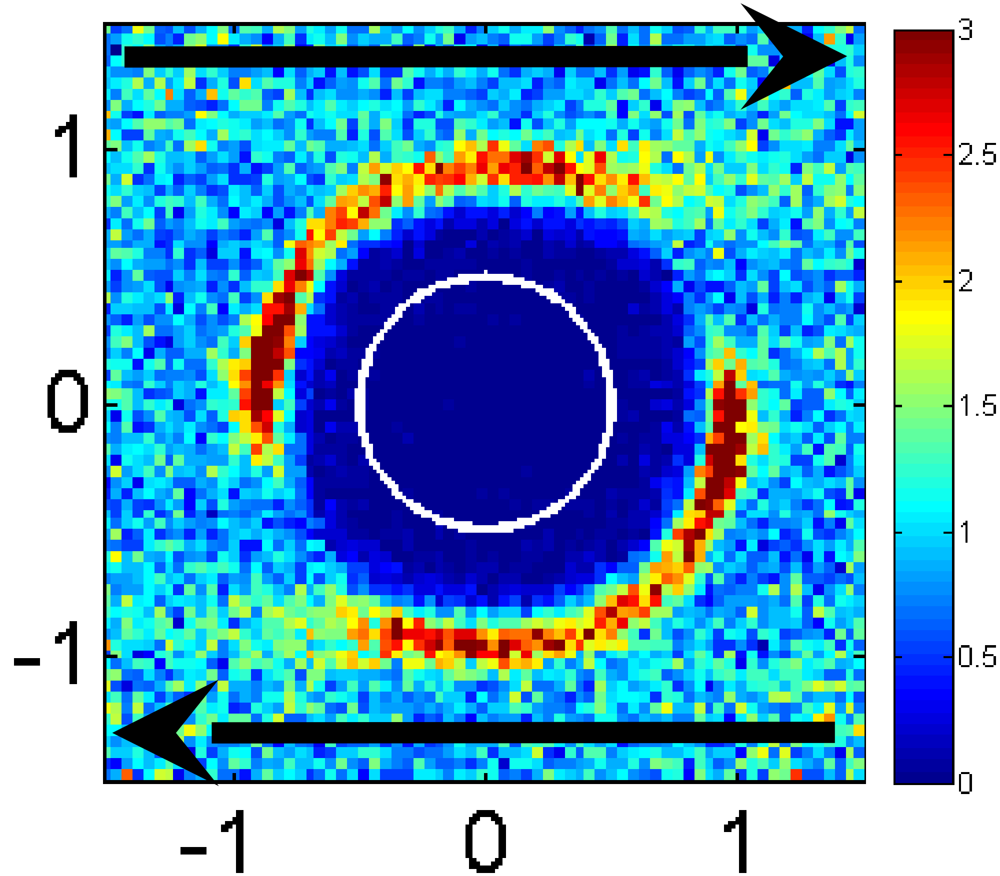




Azimuthal flow $v_\theta(r,z)$



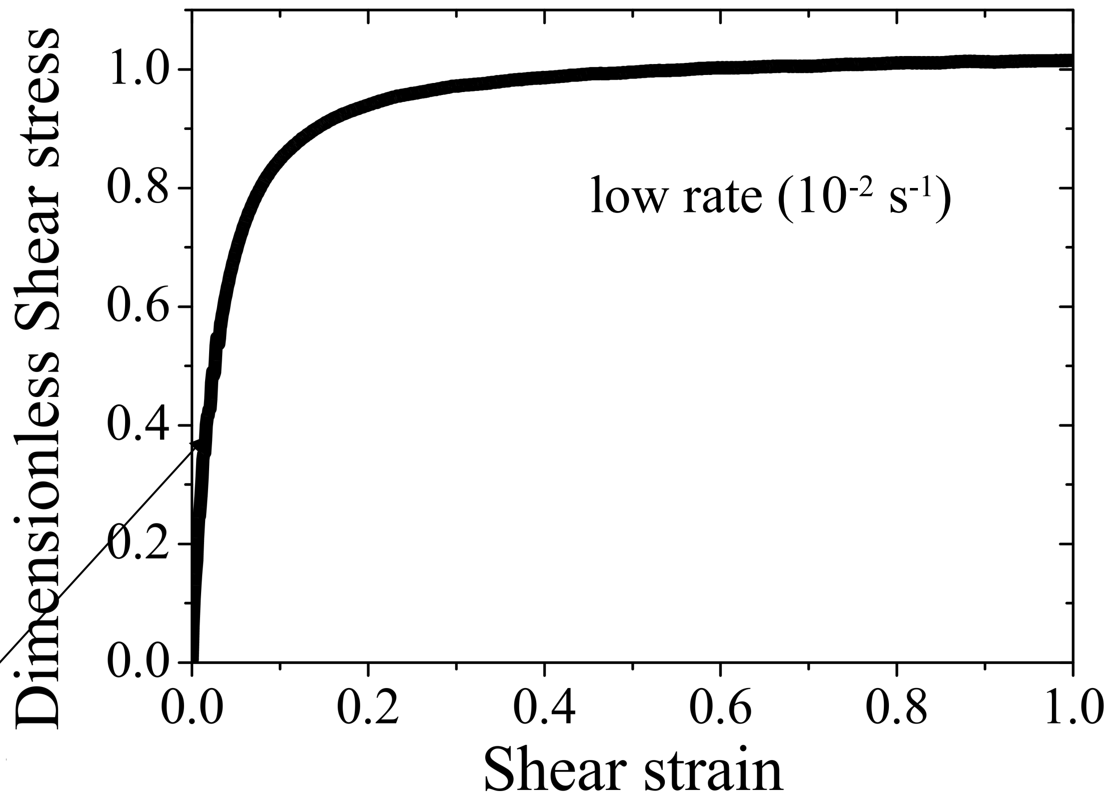
In the shear plane (e_θ, e_z)

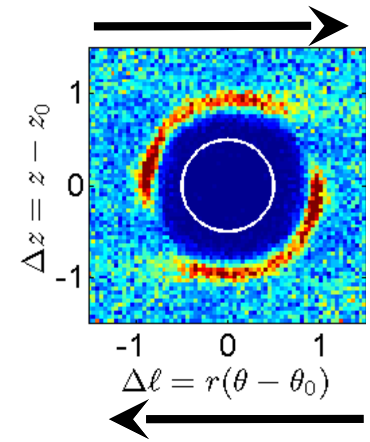


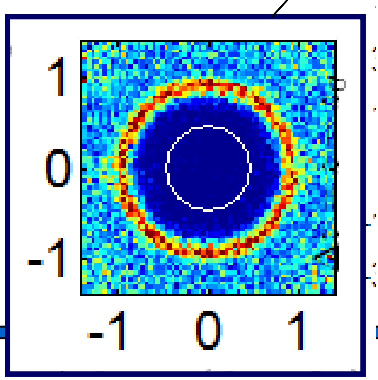
anisotropic in shear plane

isotropic in other planes

Elastoplastic response **from initial state (isotropic)**

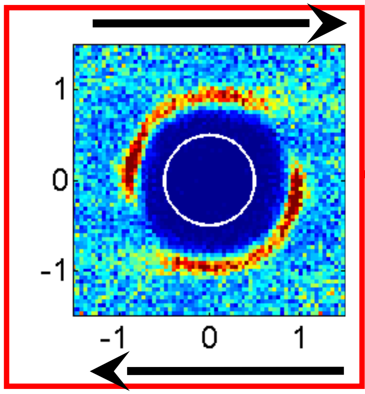


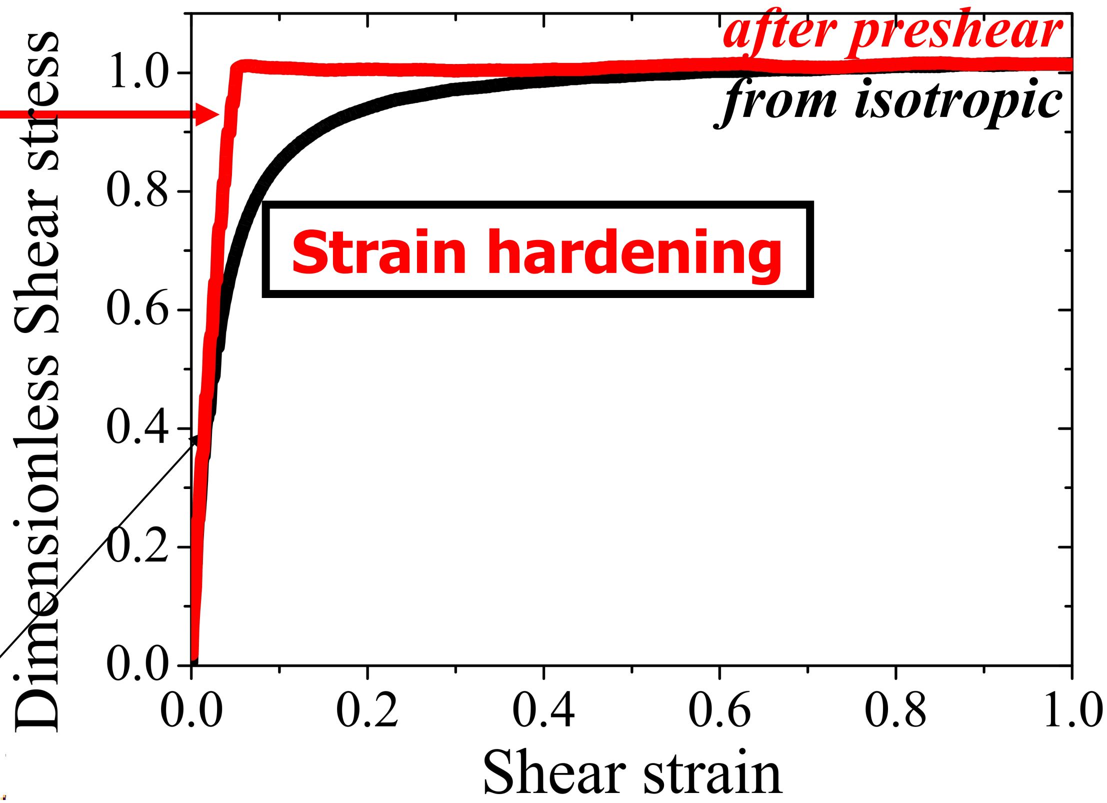


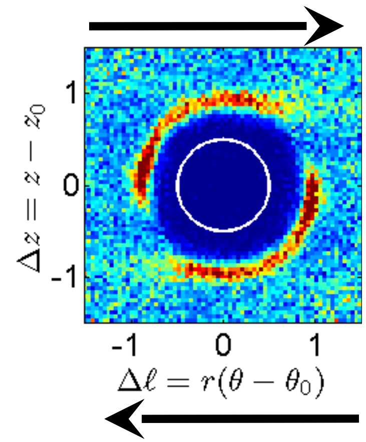


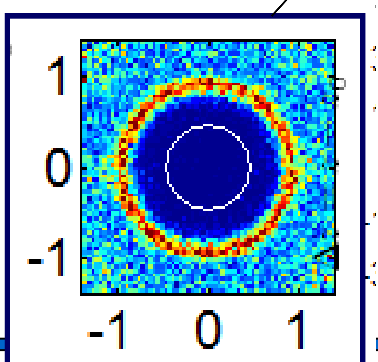
Dependence on shear history

Elastoplastic response **after preshear**



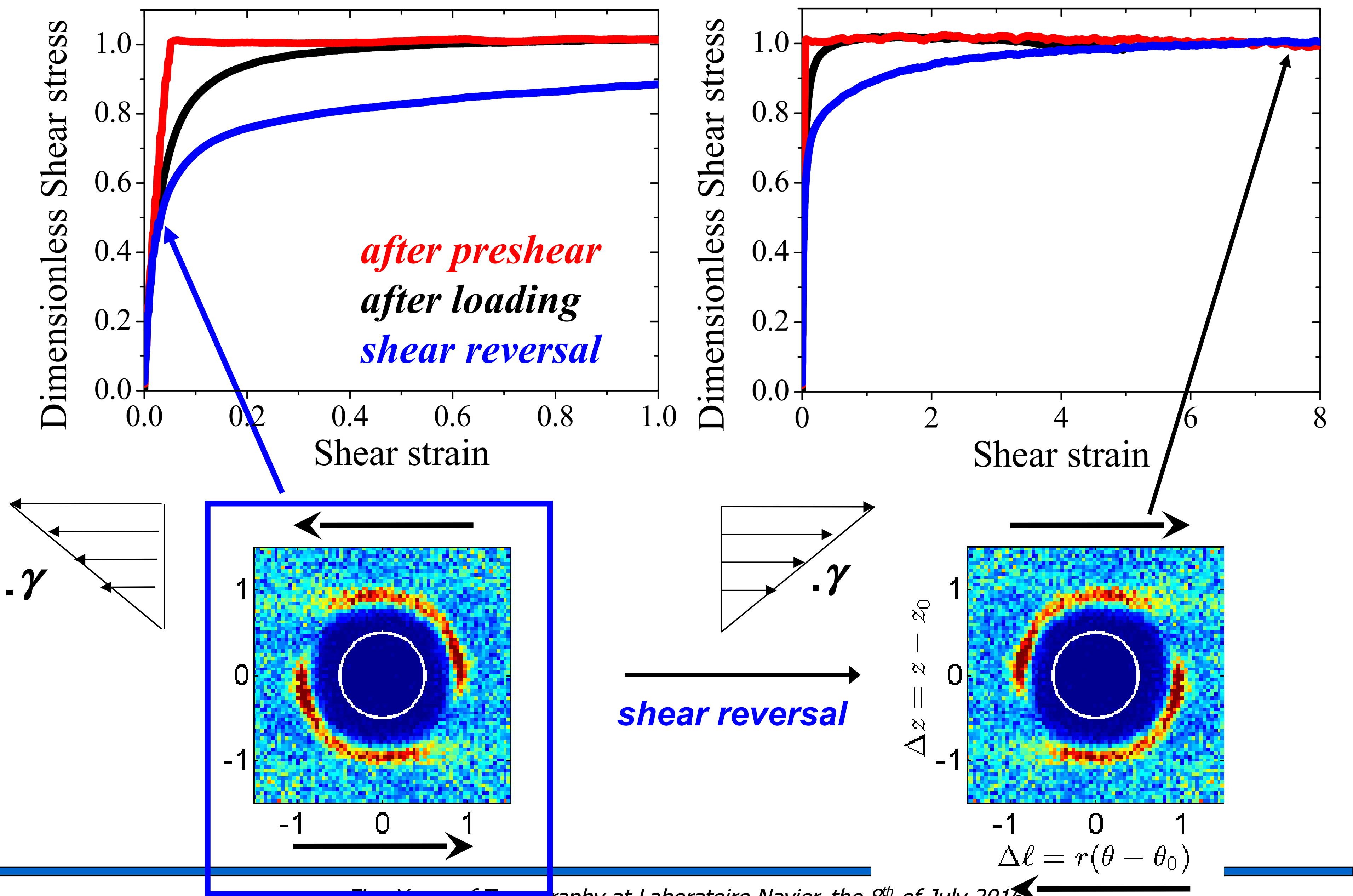




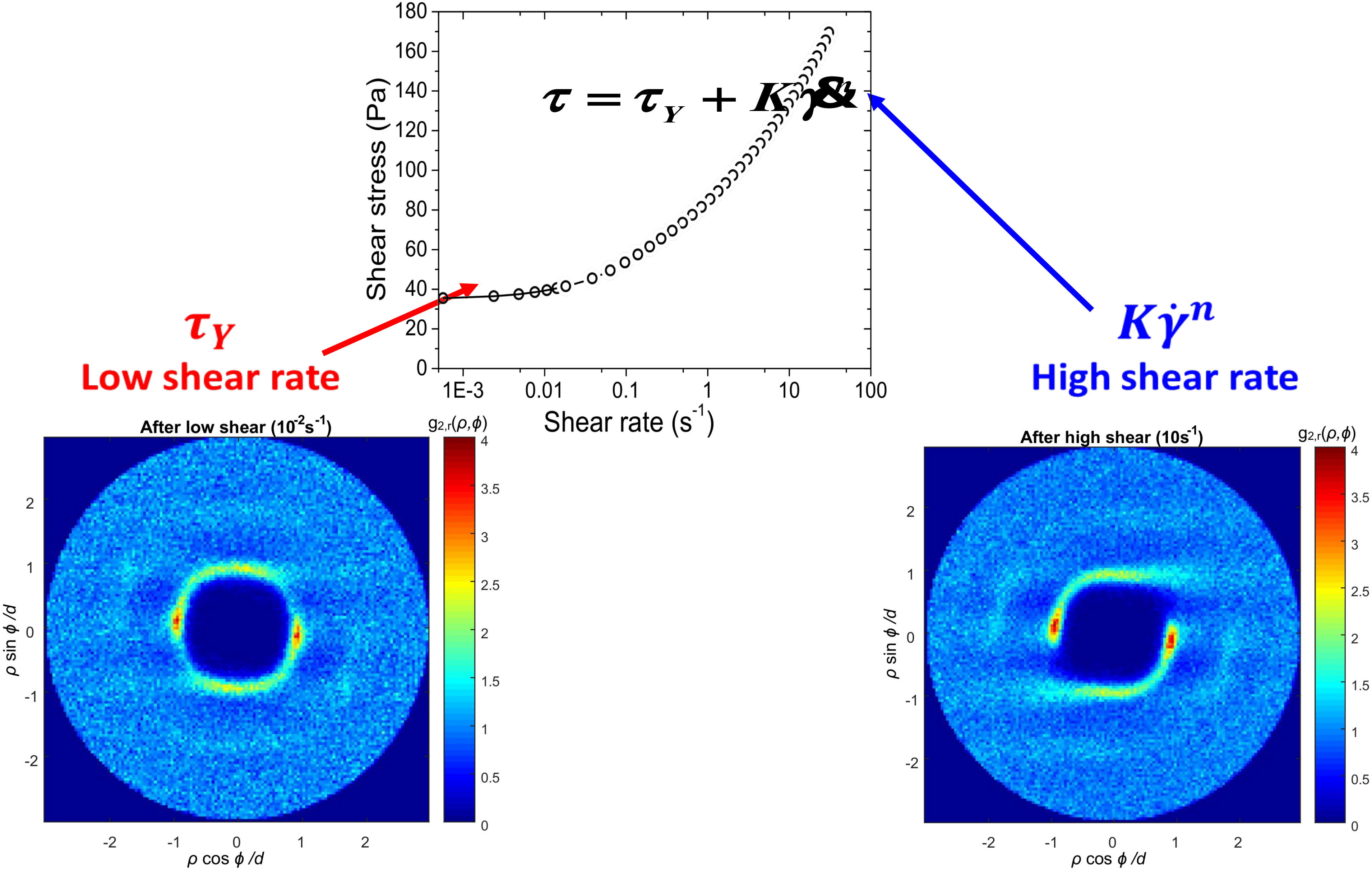


Initial microstructure = final microstructure
Almost perfect elastoplastic behavior

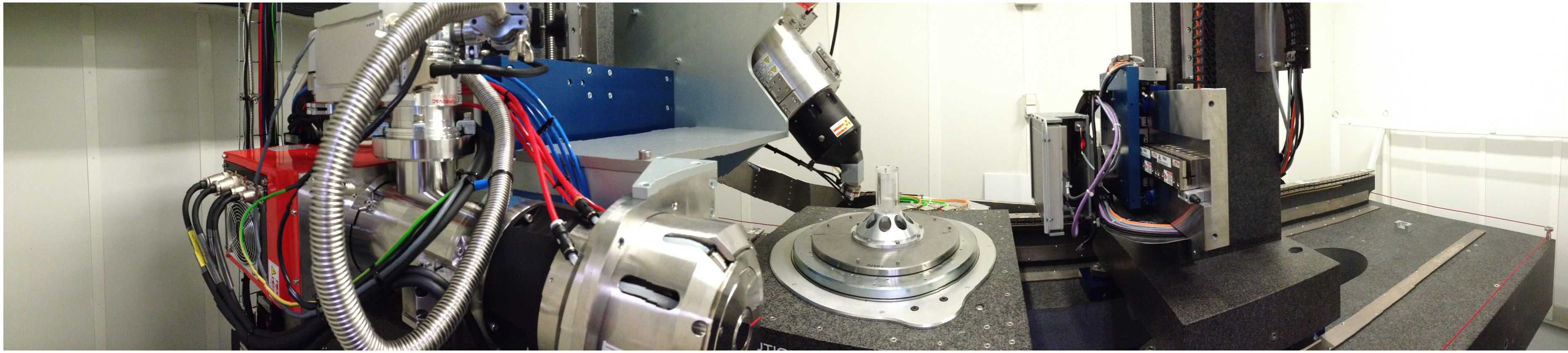
Dependence on shear history



Dependence on shear rate



Development of an in situ rheometer



Multi-configurations : Couette & parallel plates

Couette : ext dia. 20mm, int. dia. 10mm, height 30mm

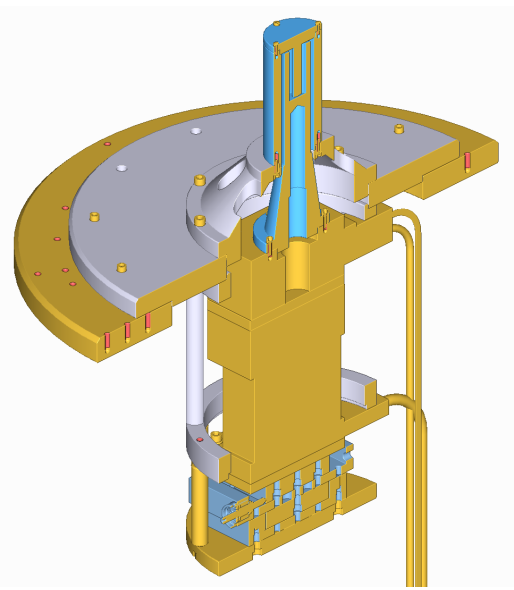
Parallel : dia. 20mm, heigth 2mm

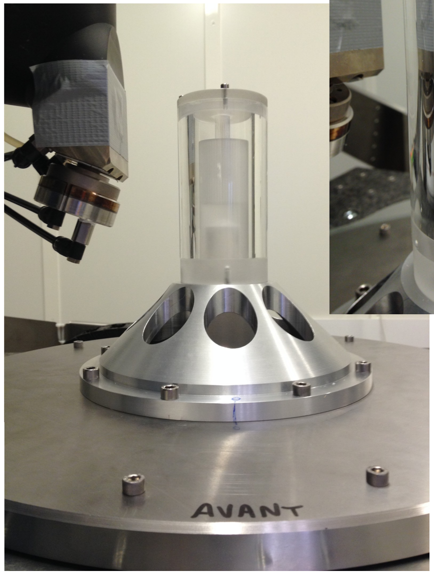
Load capacity : 14N

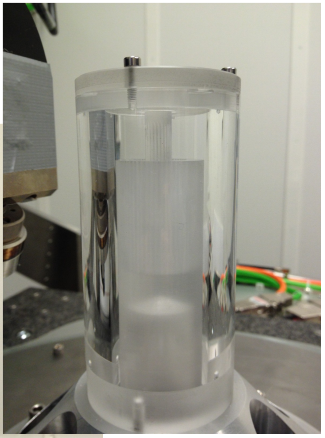
Displacement : range 30mm, rate 10 mm/s, resolution 50µm

Rotation: max rate 720°/s , max torque 0.42Nm at 0°/s, load 100N, repetability 0.2 µm, concentricity +- 1.5µm

David Hautemayou (Navier)



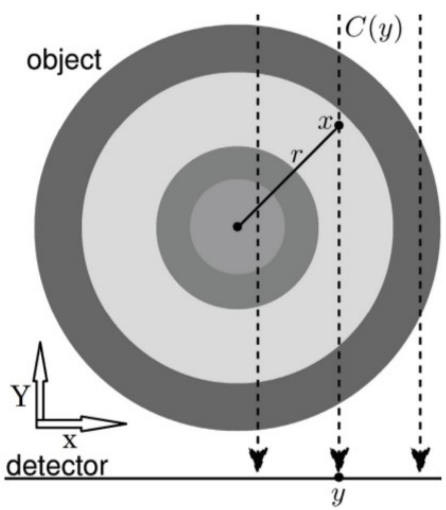


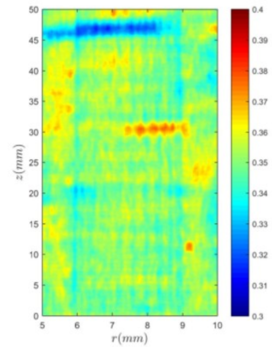


2D/3D validation

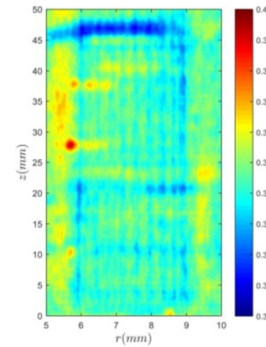
Same material with reference radiographs and then, a radiograph every 0.5s

+ some 3D scans time to time

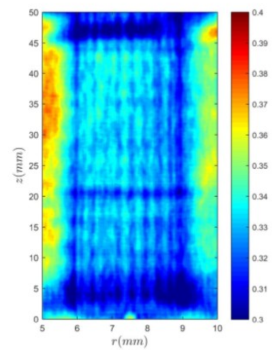




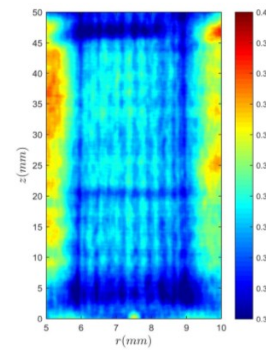
(a) Image number 314



(b) Image number 491



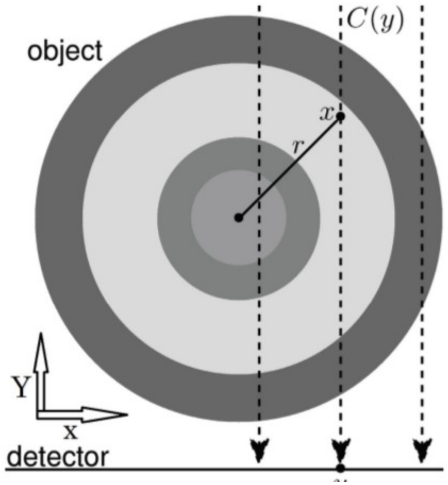
(c) Image number 608



(d) Image number 71999

Average particle concentration

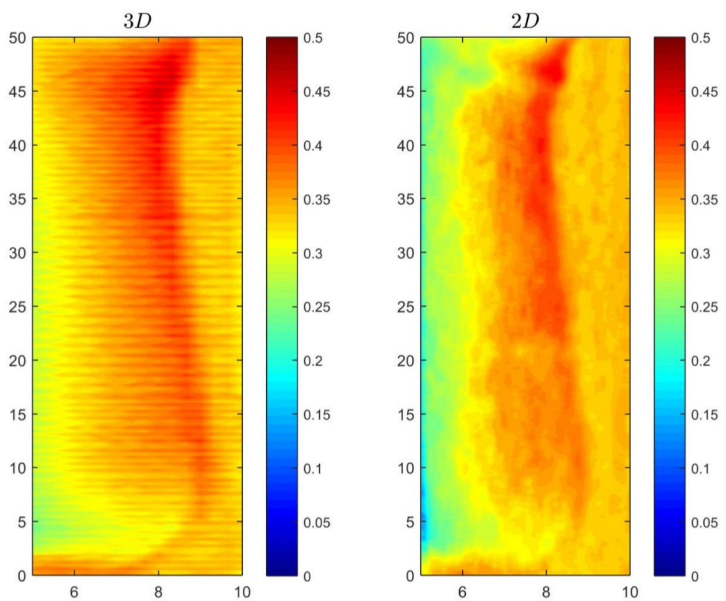
2D/3D validation

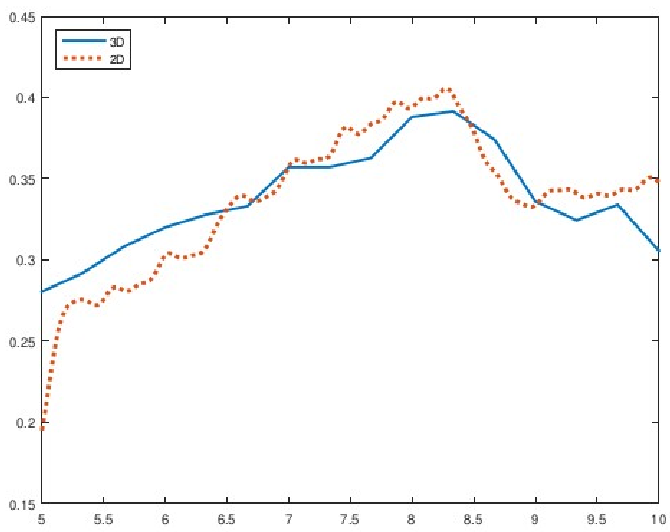


Work by Mohammad Gholami (Ohio University)

Using Abel transformation, calculating the volume fraction from the 2D radiograph)

Done in Matlab





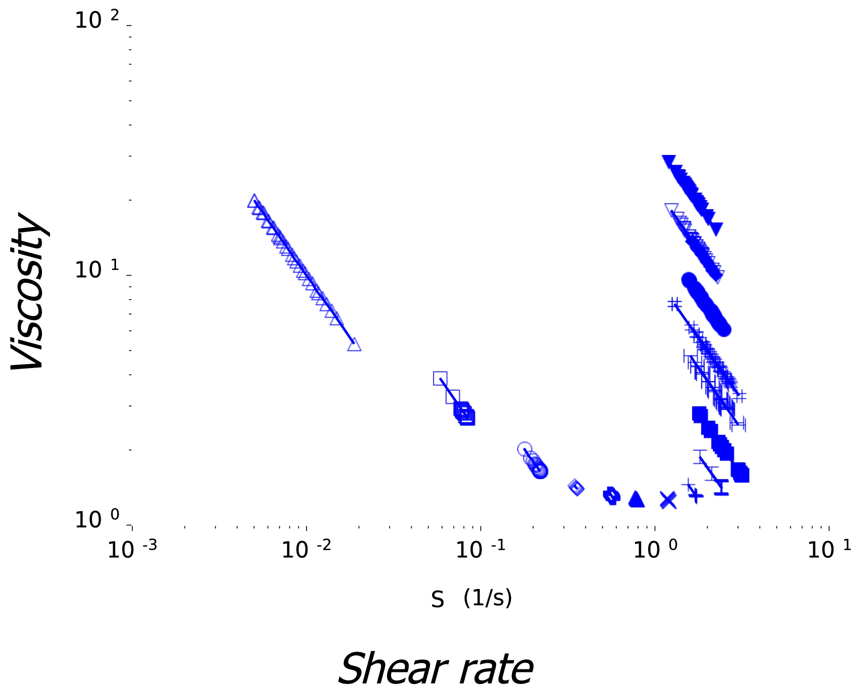
2D/3D comparison of the volume fraction

Time-resolved shear thickening

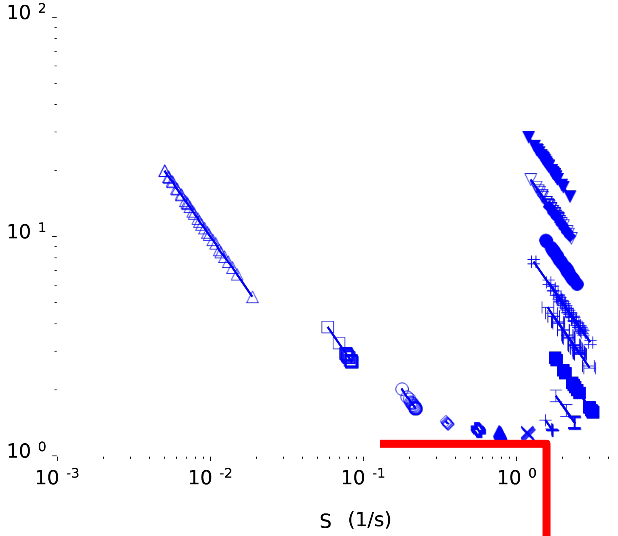
41% of cornstarch in water/CsCl/glycerol, small gap Couette, stress controlled

2D X-ray imaging

2D volume fraction profiles

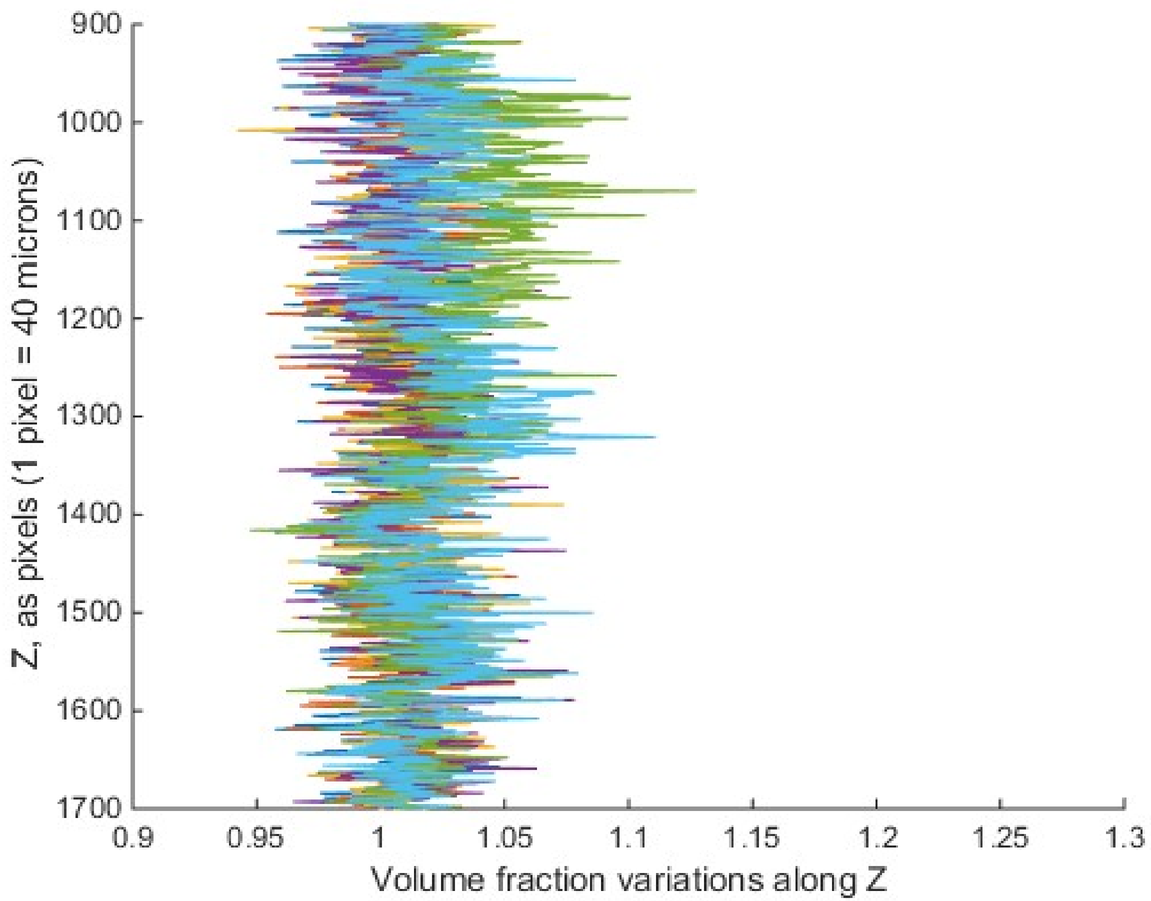


Time-resolved shear thickening

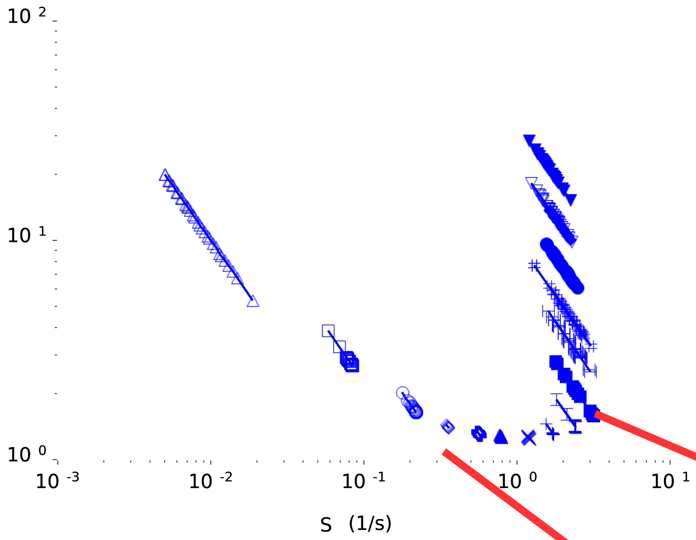


Before DST: homogeneous

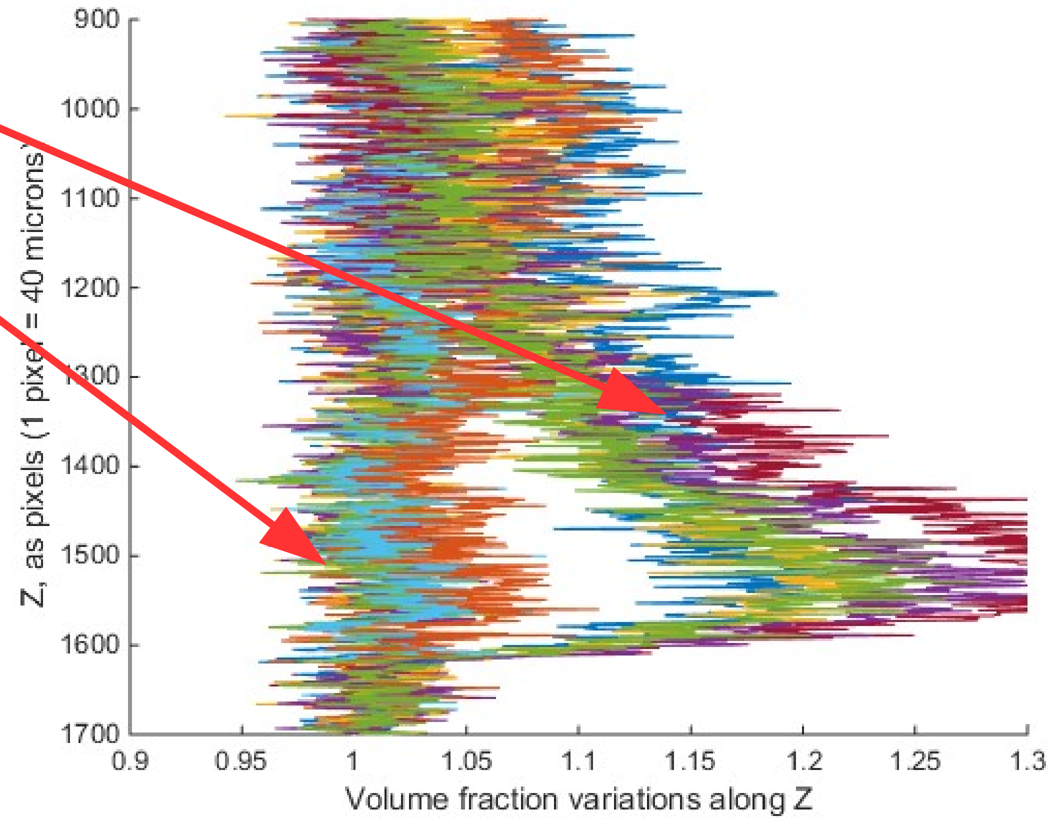
Vertical volume fraction profile, near the rotor



Time-resolved shear thickening



Vertical volume fraction profile, near the rotor



Formation of a jammed (close to RCP) **granular material block near the rotor, at the bottom** balanced by **decrease near stator**

How can anything be interpreted on the intrinsic behavior????

Conclusions

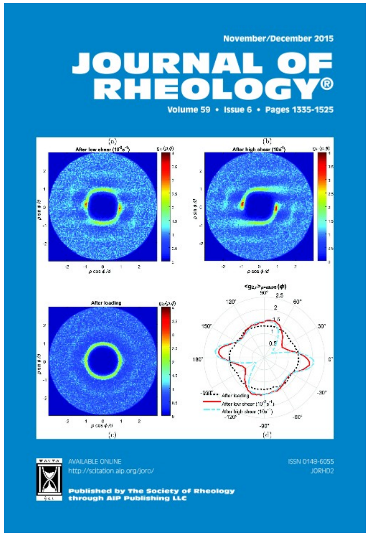
- Development of new experimental methods for yield stress fluids with non-colloidal particles

- 2D validated by 3D → in some cases, no need of a special in situ rheometer

- Not so simple behaviour

- New experimental perspectives for many different materials (both models and real materials)→ if you've got a good candidate you're interested on, send it !!

Ovarlez et al. (2015), *Flows of suspensions of particles in yield stress fluids*, Journal of Rheology.



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Programme ANR : Sciences de l'information, de la matière et de l'ingénierie : Sciences de l'ingénierie, matériaux, procédés, énergie (JCJC SIMI 9) 2010 : projet SUSPASEUIL

Référence projet : ANR-10-JCJC-0905

THANKS FOR YOUR ATTENTION!!