Non-linear mechanics and rheology of dense suspensions – KITP, UCSB Jan. 24th 2018

Avalanche-like fluidization of a non-Brownian particle gel

A. Kurokawa[1], V. Vidal[2], K. Kurita[1], T. Divoux[3,4] & S. Manneville[2]

(1) **Earthquake Research Institute, The University of Tokyo,**
1-1-1 Yayoi, Bunkyo-ku, Tokyo, Japan

(2) **Laboratoire de Physique, Ecole Normale Supérieure de Lyon,**
46 allée d'Italie, 69364 Lyon Cedex 07, France.

(3) **Centre de Recherche Paul Pascal, UPR 8641 CNRS,**
115 av. Dr. Schweitzer, 33600 Pessac, France

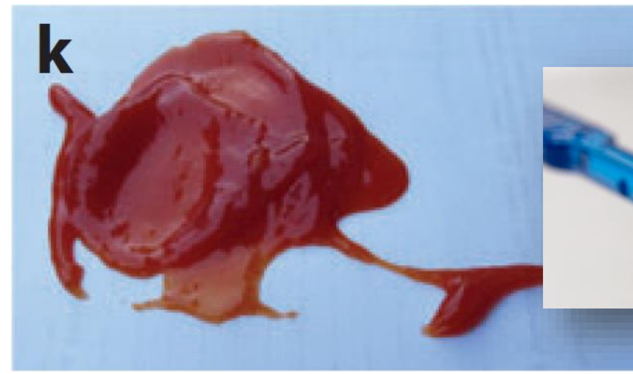
(4) **MultiScale Material Science for Energy and Environment, UMI 3466, CNRS-MIT,**
77 Massachusetts Avenue, Cambridge, Massachusetts 02139, USA

Acknowledging funding from:

http://www.crpp-bordeaux.cnrs.fr/~divoux

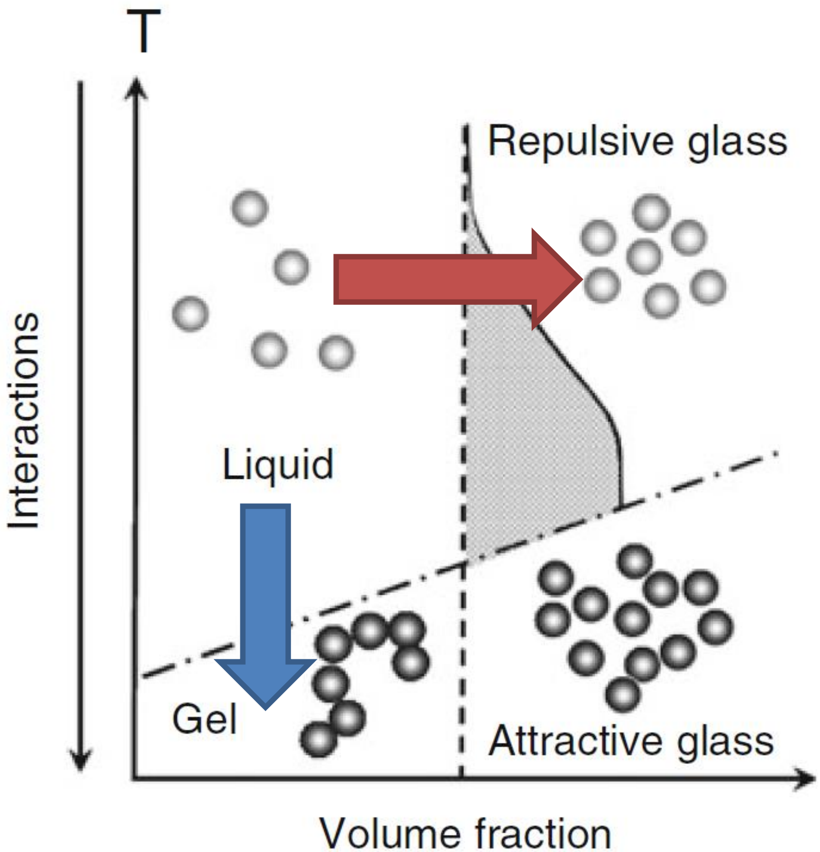
Yield stress fluids

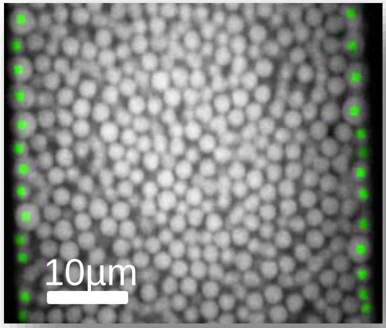
Yield stress fluid = { **solid-like** below σ_c / **liquid-like** above σ_c }



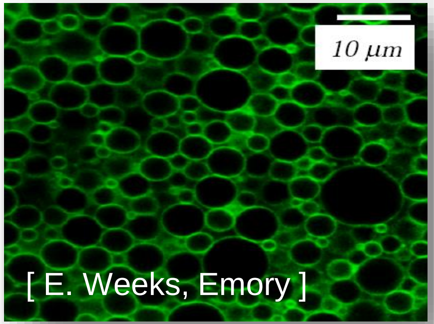
Coussot, J. Non-Newt. Fluid Mech. **211**, 31 (2014)
Balmforth, Frigaard & Ovarlez, Annu. Rev. Fluid Mech. **46**, 121 (2014)
Bonn, Denn, Berthier, Divoux & Manneville, Rev. Mod. Phys. 89, 035005 (2017)

Classifying Yield stress fluids





Close packed colloids

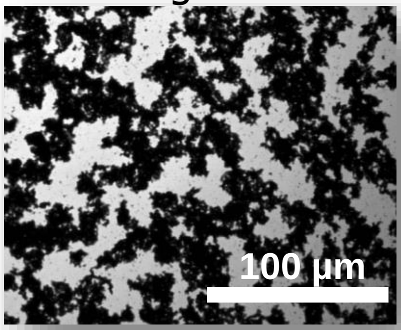


Dense emulsions

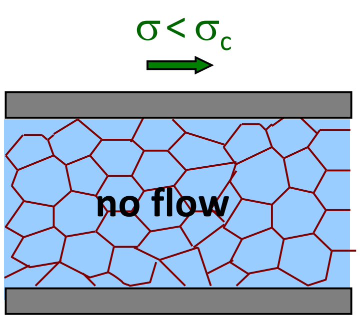
Sciortino, Nature Materials **1**, 1 (2002)
Bonnecaze & Cloitre, Adv. Polym. Sci. **236**, 117 (2010)

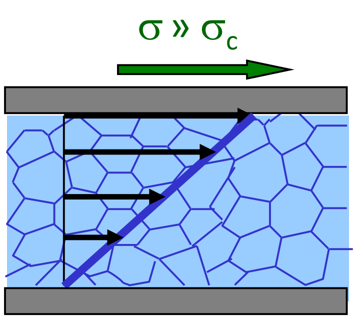
Scenario of the yielding transition?

Colloidal gels

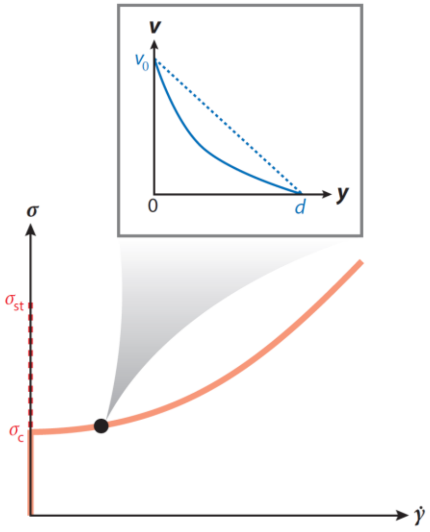


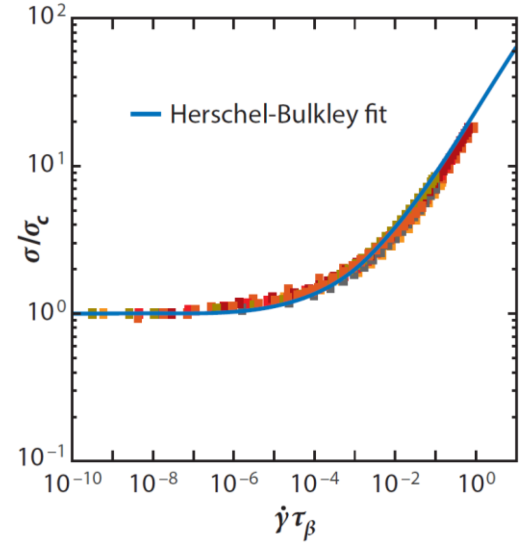
Clays





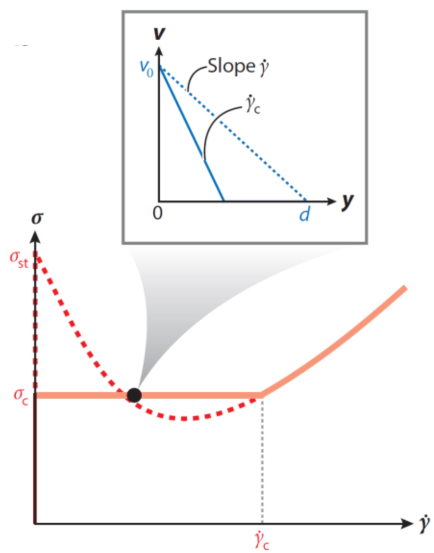
Liquid to solid transition (not the other way around!)

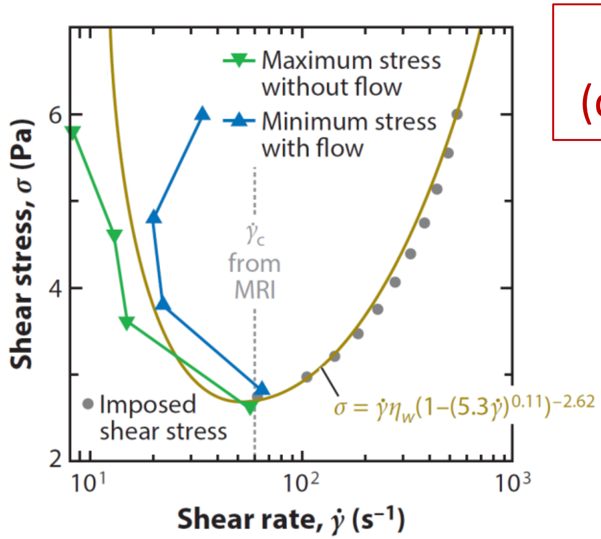




Homogeneous flow at steady state
(microgels, emulsions, foams, etc.)

Cloitre et al. *PRL* 90, 068303 (2003)
Ovarlez et al. *JNNFM* 193, 68–79 (2013)
Dinkgreve et al., *PRE* 92, 012305 (2015)
Etc.





Shear-banded flow below $\dot\gamma_c$
(colloidal gels, clay suspensions, etc.)

Coussot et al. *PRL* 88 218301 (2002)
Moller et al., PRE 77, 041507 (2008)
Etc.

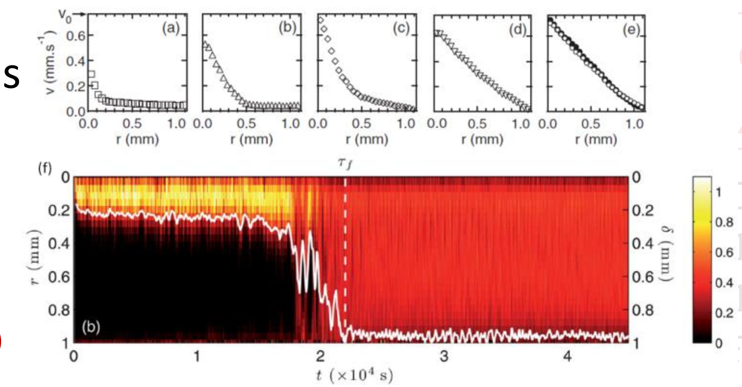
Divoux, Fardin, Manneville & Lerouge, Annu. Rev. Fluid Mech **48**, 81 (2016)

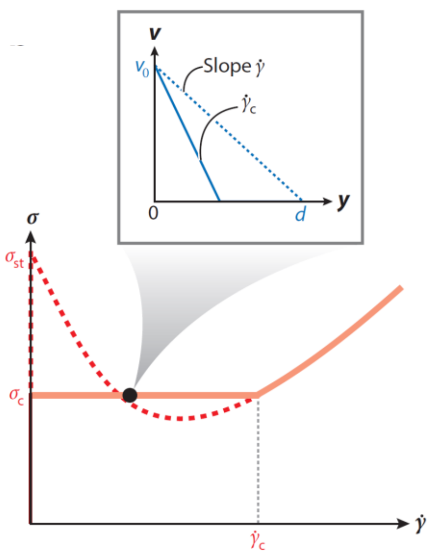
Liquid to solid transition (not the other way around!)

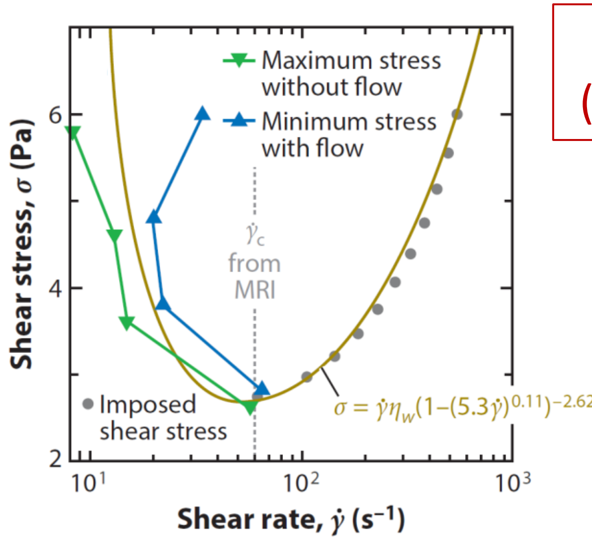
What about the solid to liquid transition ?

- Existence of long lived & yet transient shear bands
- Non-trivial scaling of the band lifespan

T. Divoux, D. Tamarii, C. Barentin & S. Manneville, *PRL* **104**, 208301 (2010)
T. Divoux C. Barentin & S. Manneville, *Soft Matter* **7**, 8409 (2011)
T. Divoux C. Barentin & S. Manneville, *Soft Matter* **7**, 9335 (2011)
T. Divoux D. Tamarii, C. Barentin, S. Teitel & S. Manneville, *Soft Matter* **8**, 4151 (2012)







Shear-banded flow below $\dot\gamma_c$
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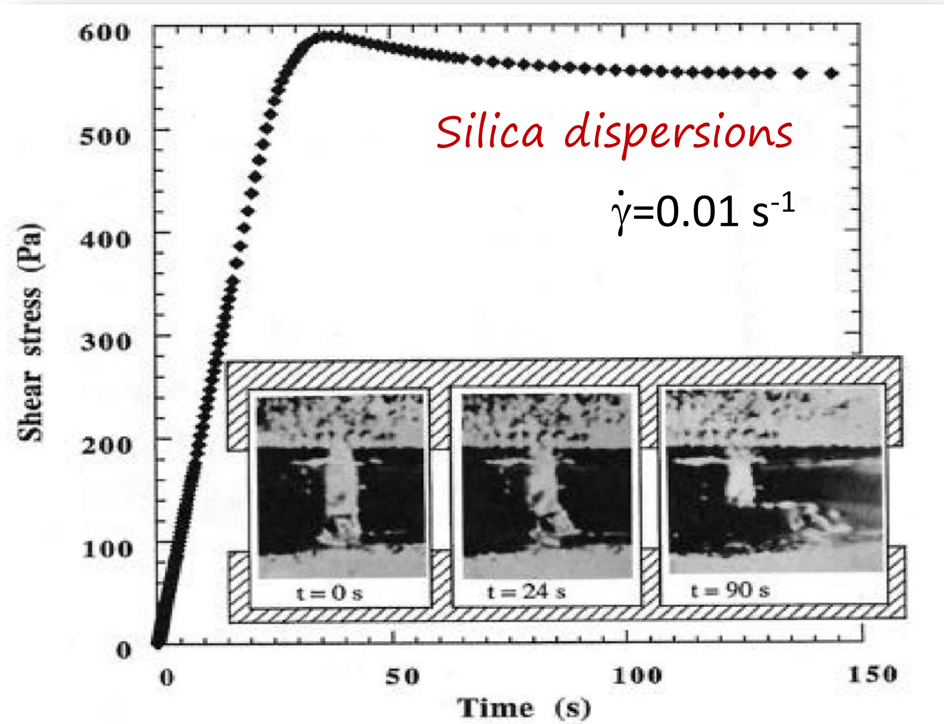
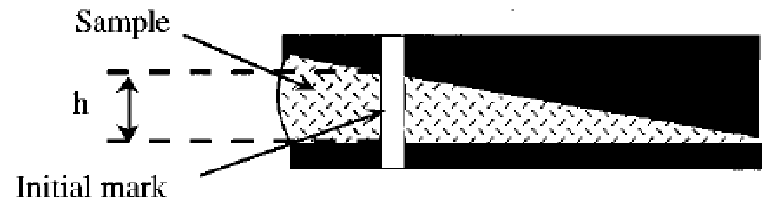
Etc.

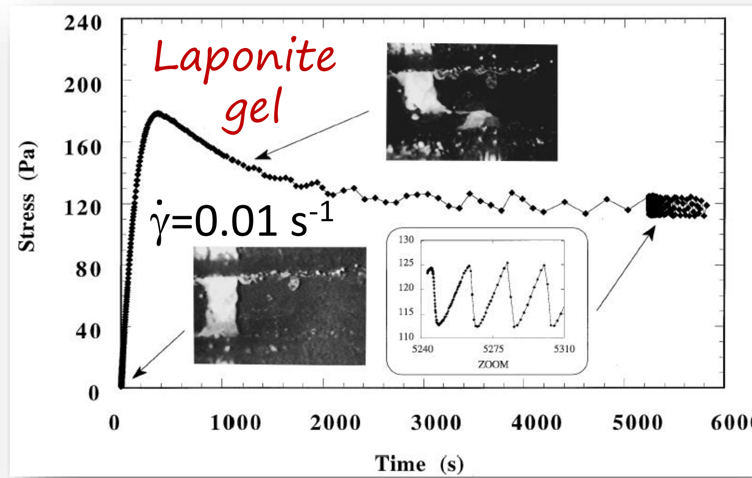
Divoux, Fardin, Manneville & Lerouge, Annu. Rev. Fluid Mech **48**, 81 (2016)

Fluidization scenario during shear start up: <u>short-time behavior</u>



Persello et al., J. Rheol. **38**, 1845 (1994)





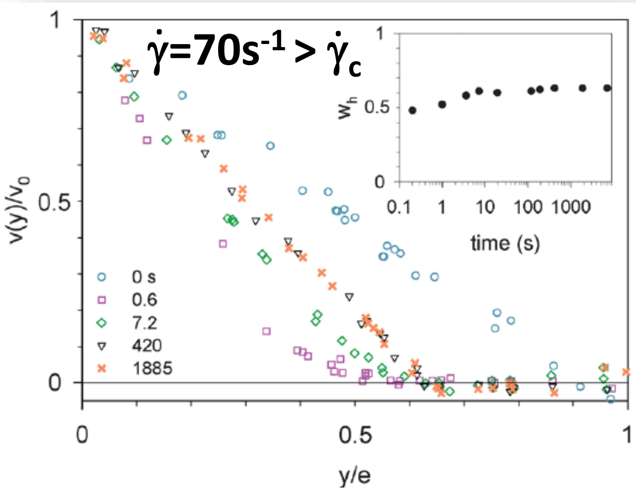
Pignon et al., J. Rheol. **40**, 573 (1996)

Pioneering local measurements unraveled the following fact:

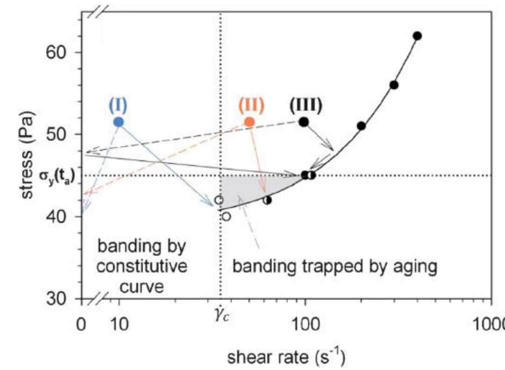
- ✓ Stress overshoot
- ✓ **Heterogeneous yielding dynamics**, which may involve bulk “fracture” and/or slip plane
- ✓ Subtle interplay between bulk deformation & wall slip may lead to stick-slip dynamics

Fluidization scenario during shear start up: long-time behavior

• Influence of the preshear: shear-banding trapped by aging



laponite suspensions



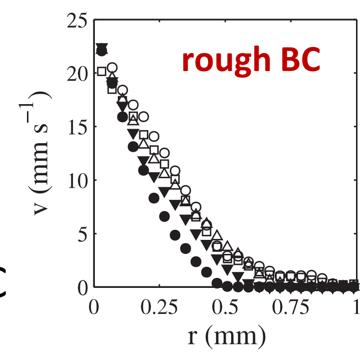
Steady-state shear banding if the time between the latest rejuvation & the shear start up is "long enough"

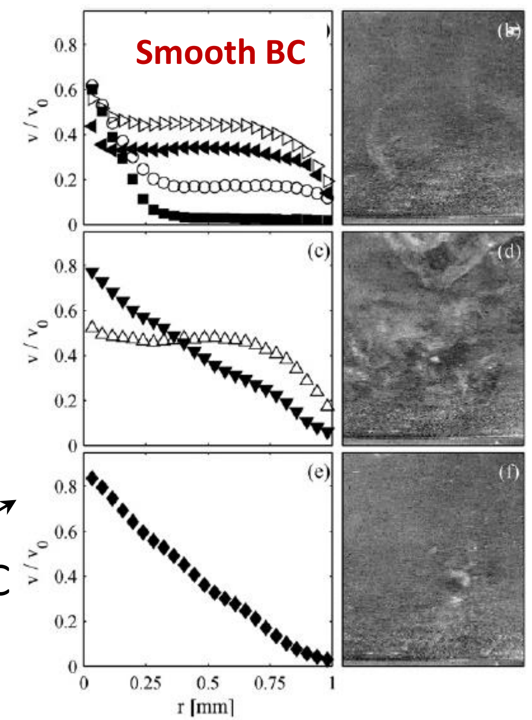
Martin & Hu, Soft Matter (2012)

• Influence of the boundary conditions

laponite suspensions

steady shear-banding under rough BC





but steady homogeneous flow under smooth BC

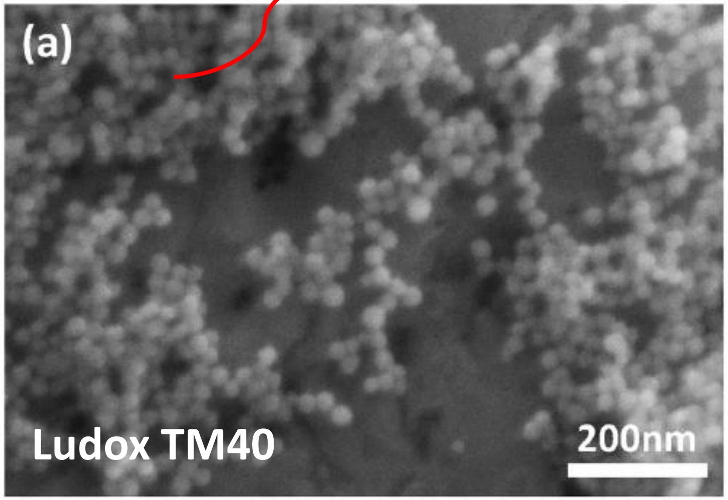
Gibaud et al. Phys. Rev. Lett. (2008), Soft Matter (2009)

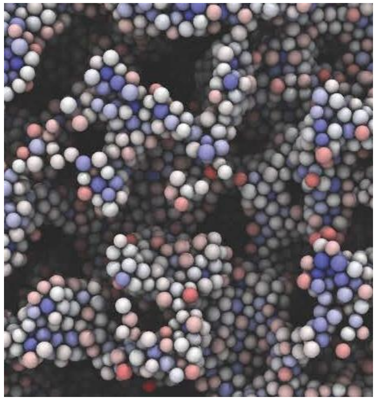
Non-Brownian gel made of fused silica particles

Following the recipe of *Moller et al. Phys. Rev. E (2008)*

+ 1.2M salt (NaCl) → **?**

SEM images





Roseanna N. Zia, Cornell Univ.

Non-Brownian gel made of fused silica particles

Following the recipe of *Moller et al. Phys. Rev. E (2008)*

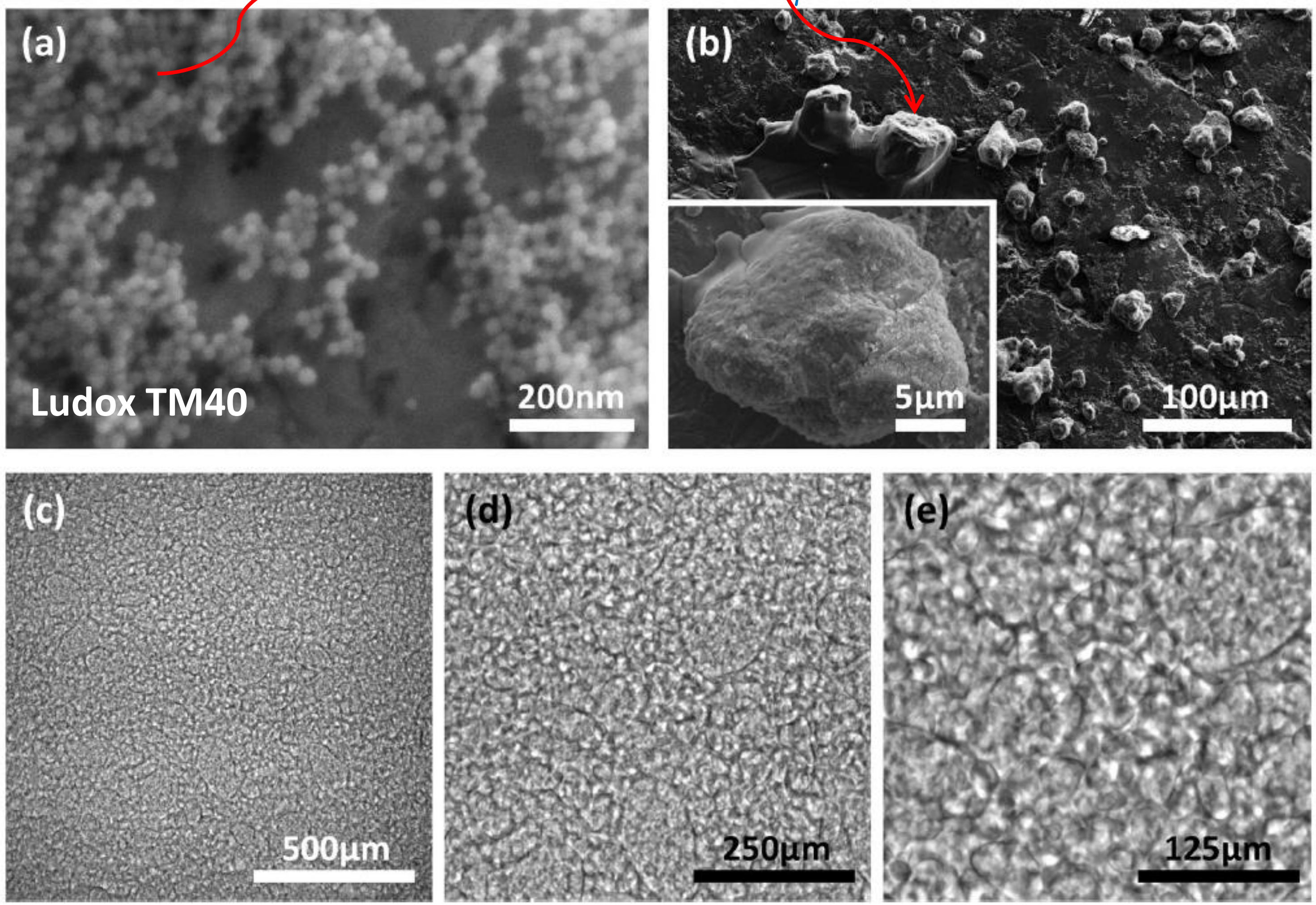
Interparticle siloxane bonds

$$-\mathrm{Si}-\mathrm{OH} + \mathrm{HO}-\mathrm{Si}- \rightarrow -\mathrm{Si}-\mathrm{O}-\mathrm{Si}- + \mathrm{H_2O}$$

Depasse & Watillon, J. Colloid Interface Sci. (1970)

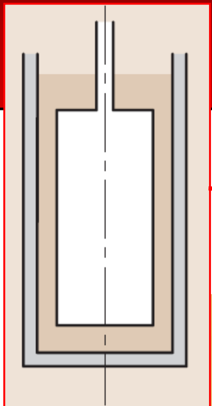
+ 1.2M salt (NaCl) → Non Brownian particles!

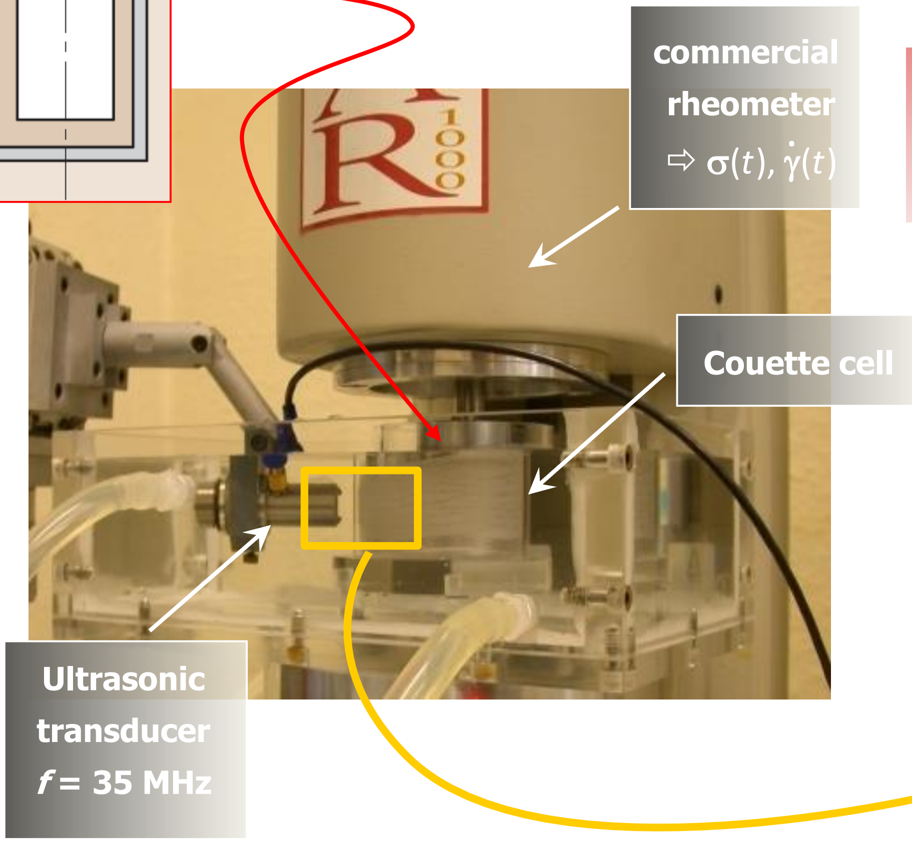
SEM images



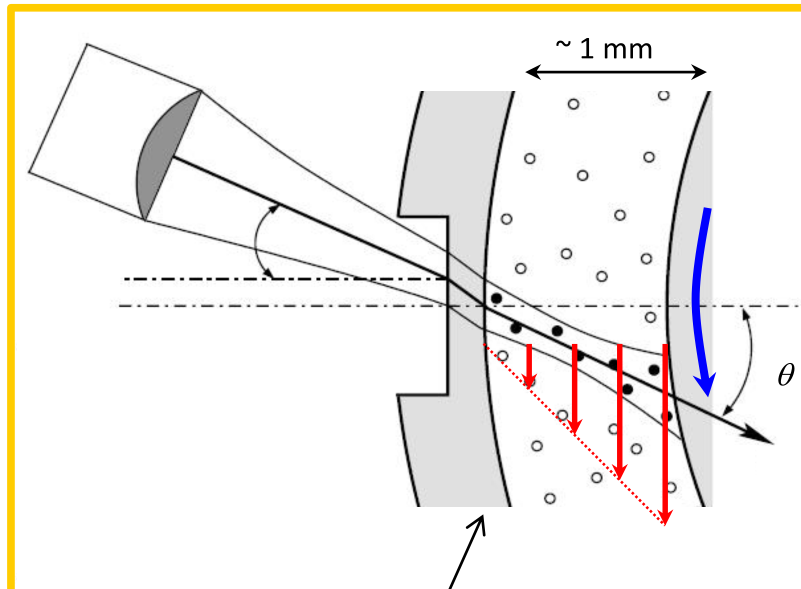
Bright field images microscopy

Rheology & time resolved velocimetry





- Rheometer: AR-G2 (TA Instruments)
- Gap e = 2 mm
- Surface roughness ≈ 15 nm (polished plexiglass)

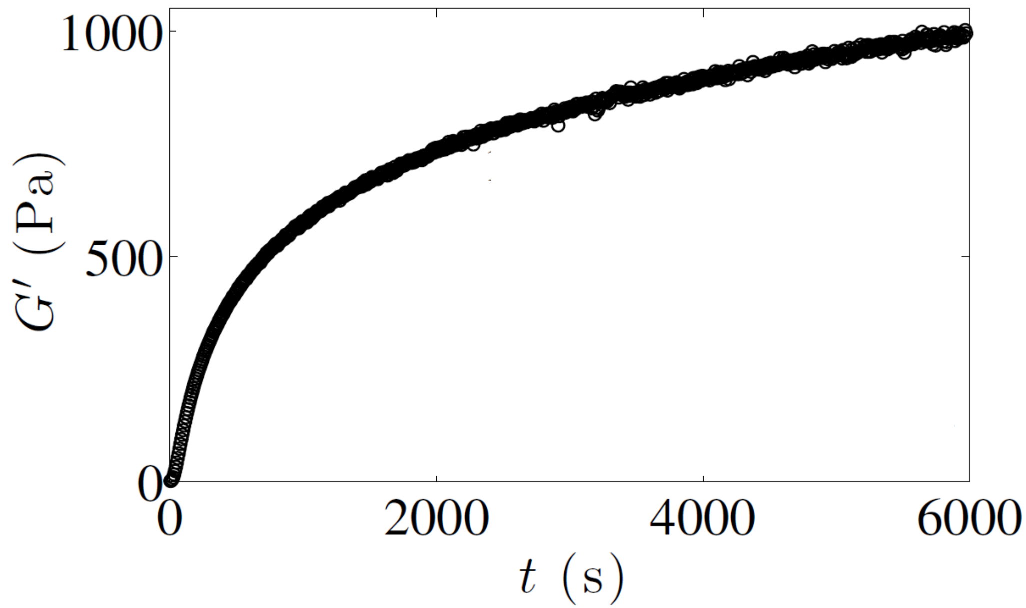


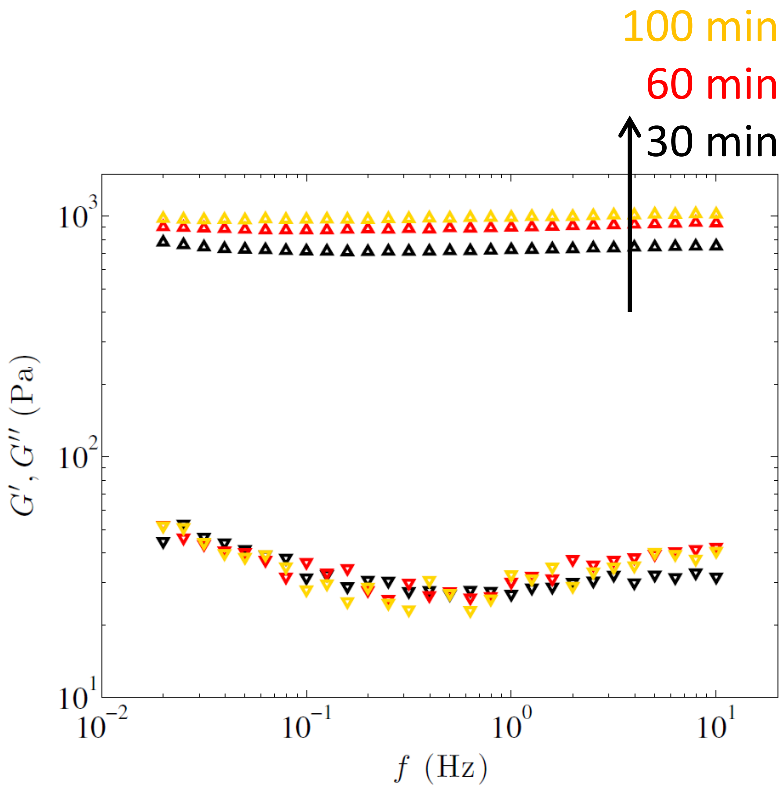
Acoustic tracers = sample's microstructure
- non invasive technique -

- speckle tracking algorithm ⇨ $v(r,t)\sin\theta$
- spatial resolution ~ 40 µm
- temporal resolution ~ 0.1 s per velocity profile

S. Manneville et al., Eur. Phys. J. AP (2004)

Gel build up & linear rheology





Logarithmic increase of the elastic modulus after a preshear (2min @500s^{-1}).

Common feature of attractive gels:

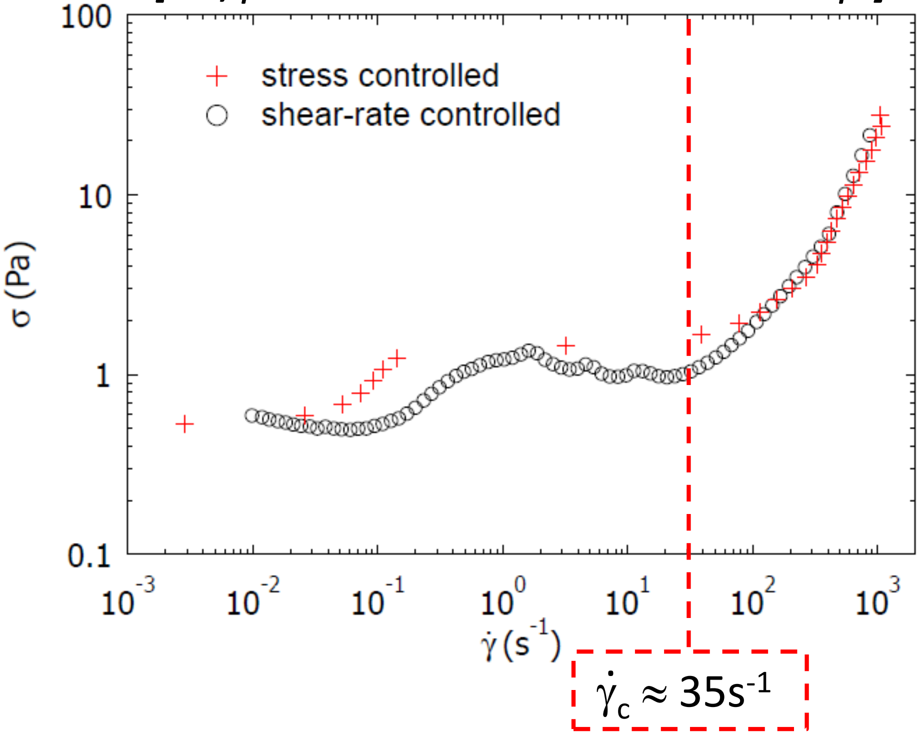
- Coated silica particles *Derec et al., Phys. Rev. E. (2003)*
- Clays *Ovarlez & Chateau, Phys. Rev. E. (2008)*
- Carbon black *Grenard et al., Soft Matter (2014)*

Soft Glassy rheology

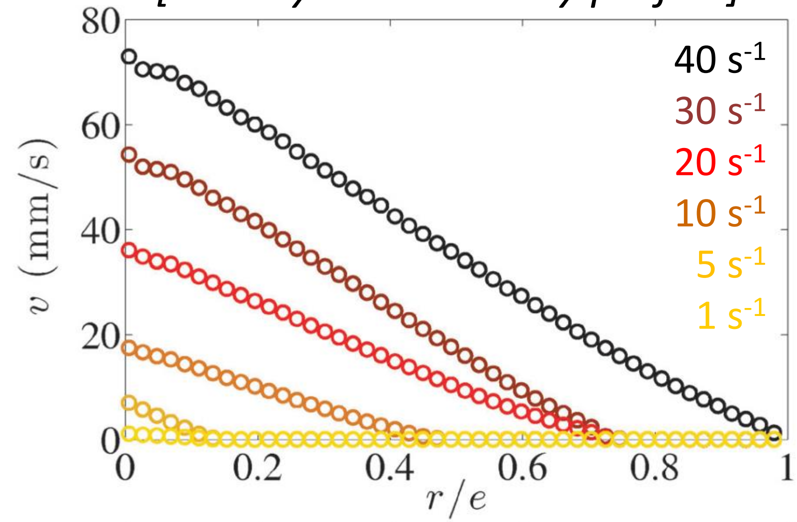
$G'(\omega) \approx constant \gg G''(\omega)$

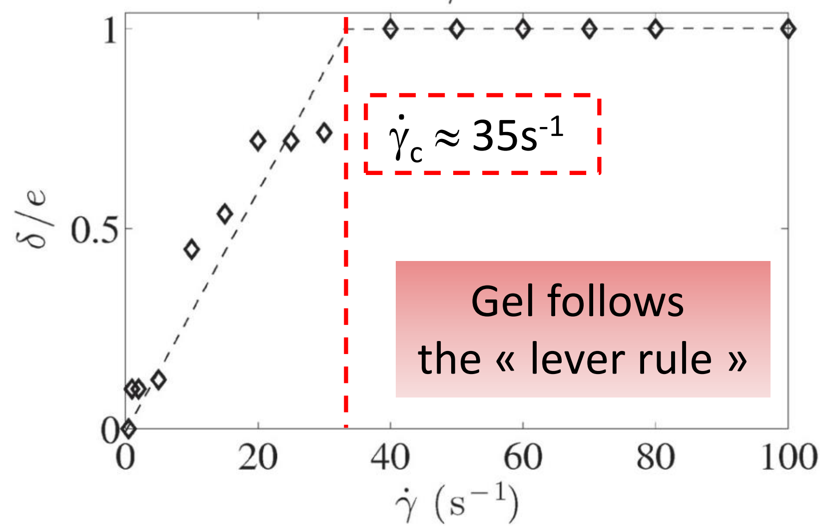
Steady-state rheology – “classic” shear-banding scenario

[8s/point – 10min downward sweep]



[Steady state velocity profile]





Goal of the present talk: solid → liquid

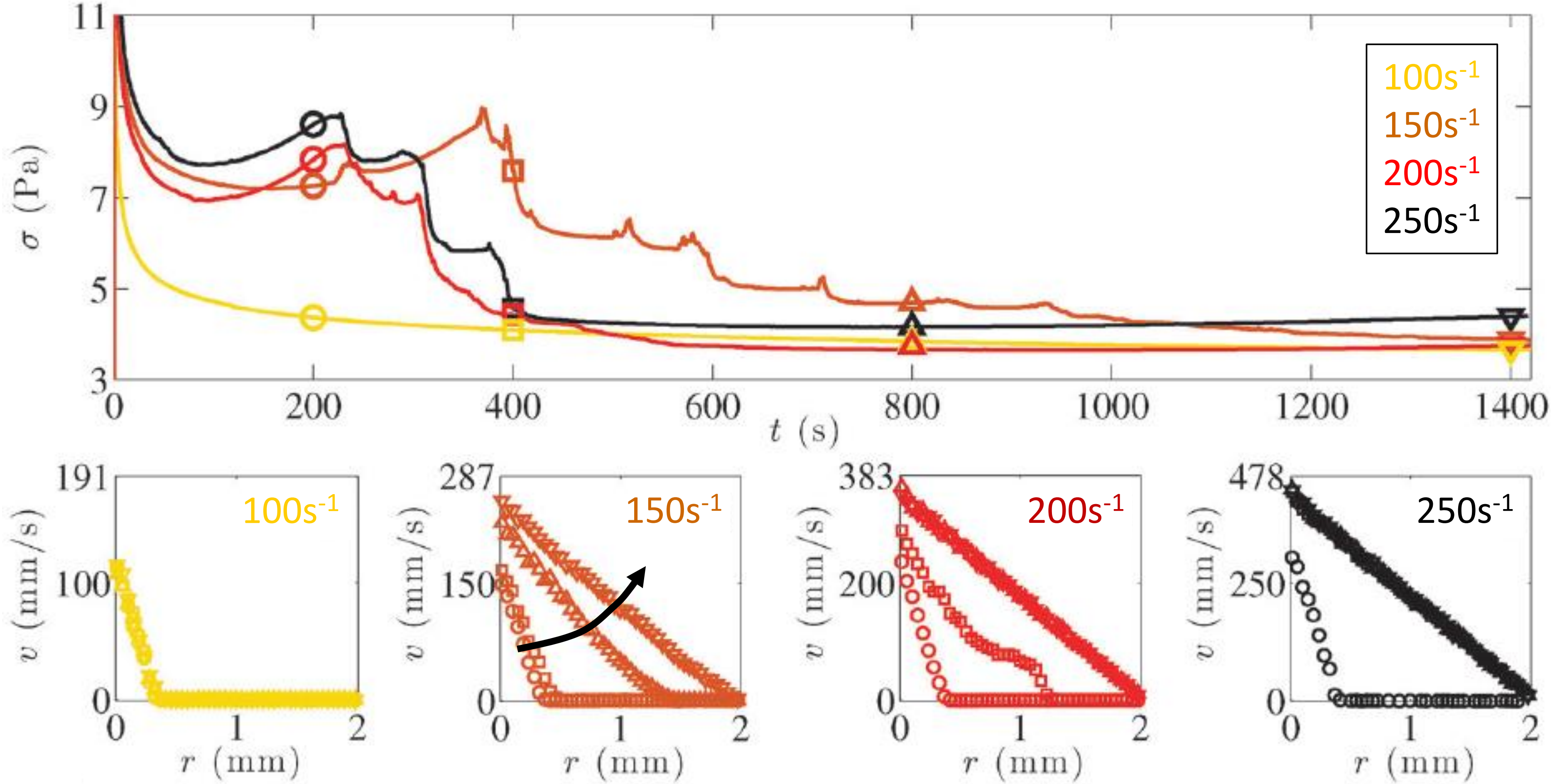
- Local fluidization scenario associated with shear startup experiments ?
- Influence of the “sample age” vs. shear rate ?

In agreement with:

Moller et al. Phys. Rev. E (2008)

Response to shear start up

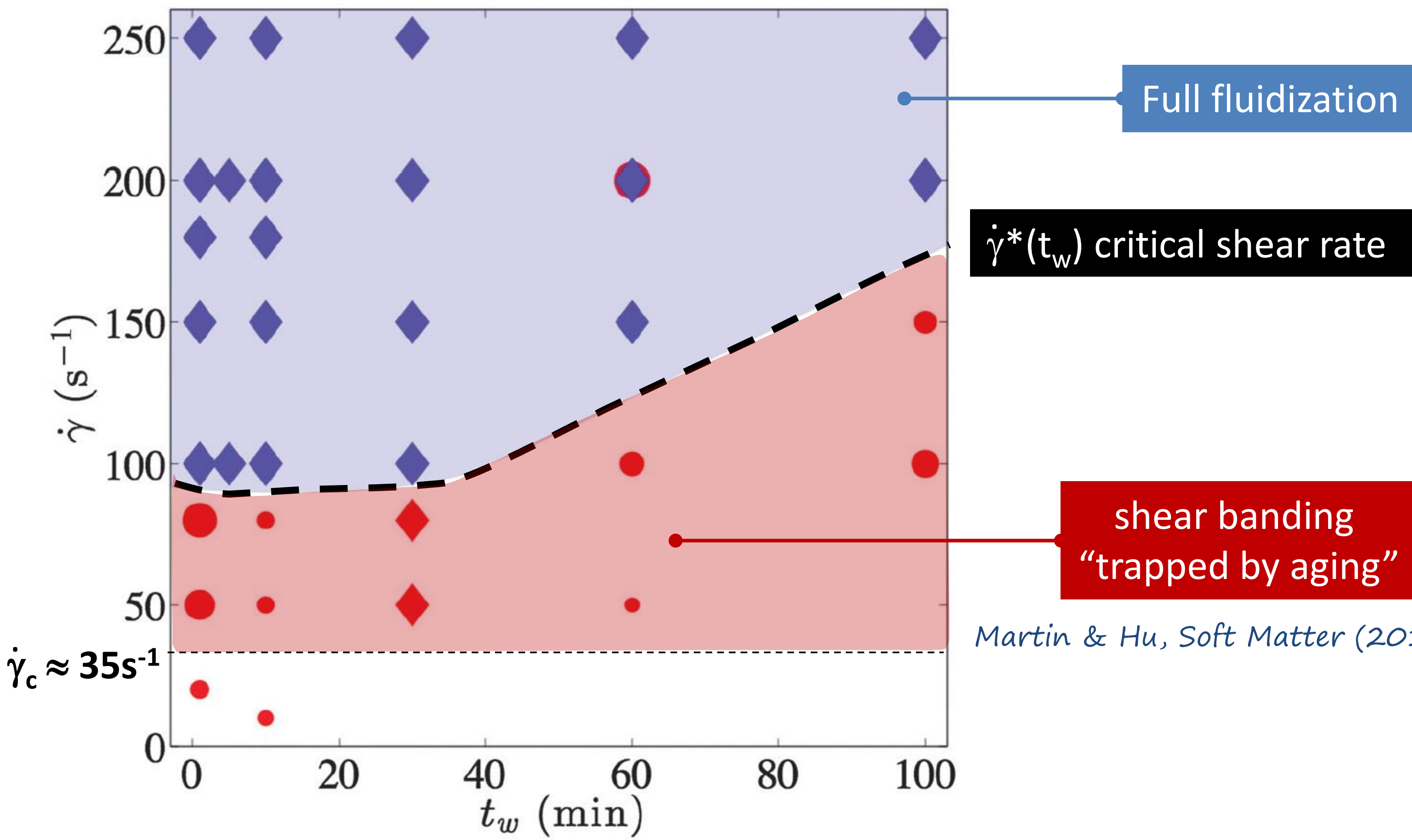
Fixed duration of t_w= **60min** between the preshear ($500s^{-1}$) and the start of the experiment



✓ Existence of a critical shear rate $\dot{\gamma}^* \approx 125s^{-1}$: - for $\dot{\gamma} < \dot{\gamma}^*$, steady state shear-banding
- for $\dot{\gamma} > \dot{\gamma}^*$, complete fluidization

✓ Series of successive stress relaxations associated with the complete fluidization

Flow state diagram

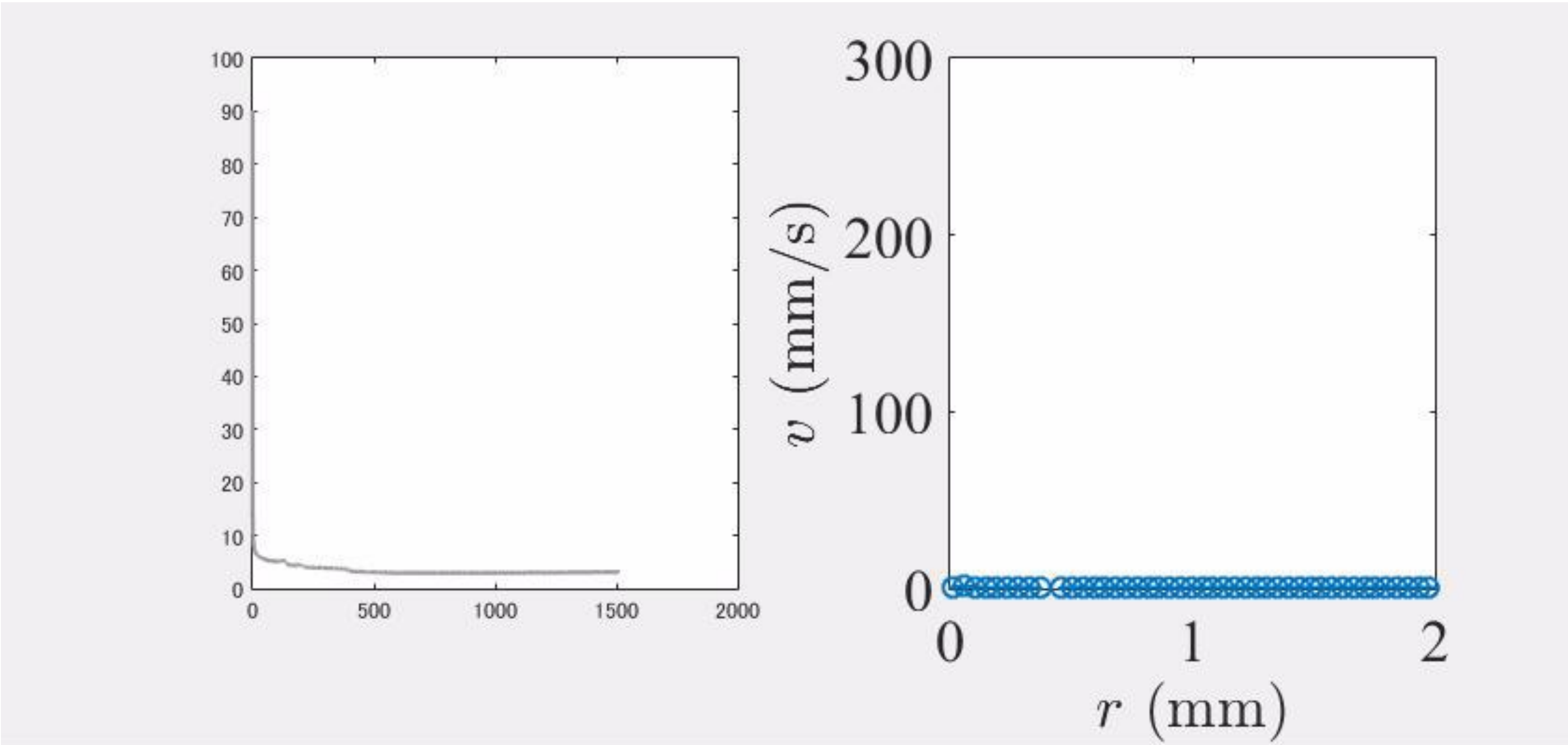


Martin & Hu, Soft Matter (2012)

- γ^* (t_w) separates shear banding trapped by aging from complete fluidization
- Avalanche-like dynamics (♦) leads either to partial or to complete fluidization of the sample

Complete fluidization with “avalanche-like” dynamics

Experimental conditions: t_w=30 min & $\dot{\gamma}$ = 150s^{-1}

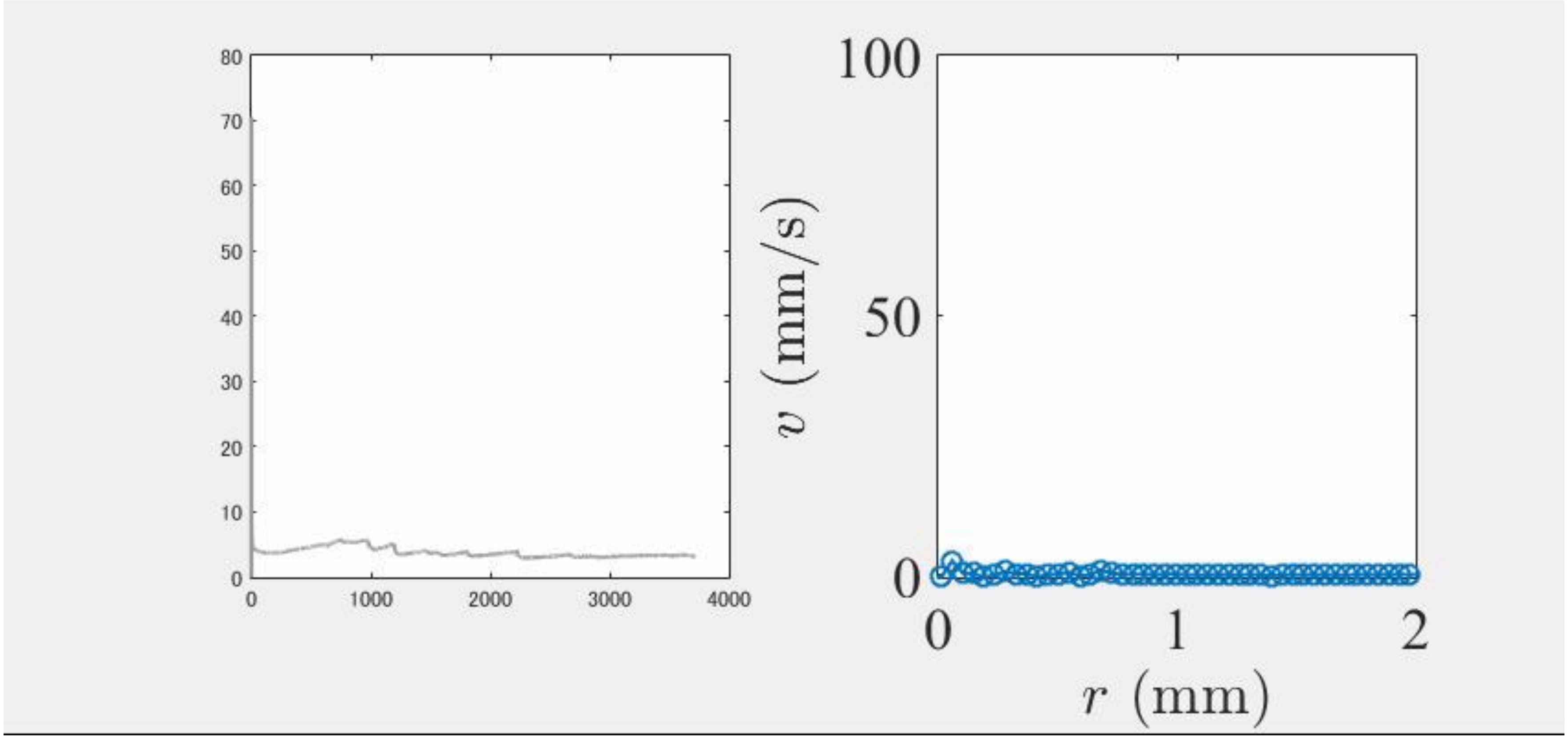


Complete fluidization

- sample is fluidized by successive “spatial avalanches” correlated to stress drops
- wall slip decreases towards negligible values in steady state

Partial fluidization with “avalanche-like” dynamics

Experimental conditions: t_w=30 min & $\dot{\gamma}$ = $50s^{-1}$

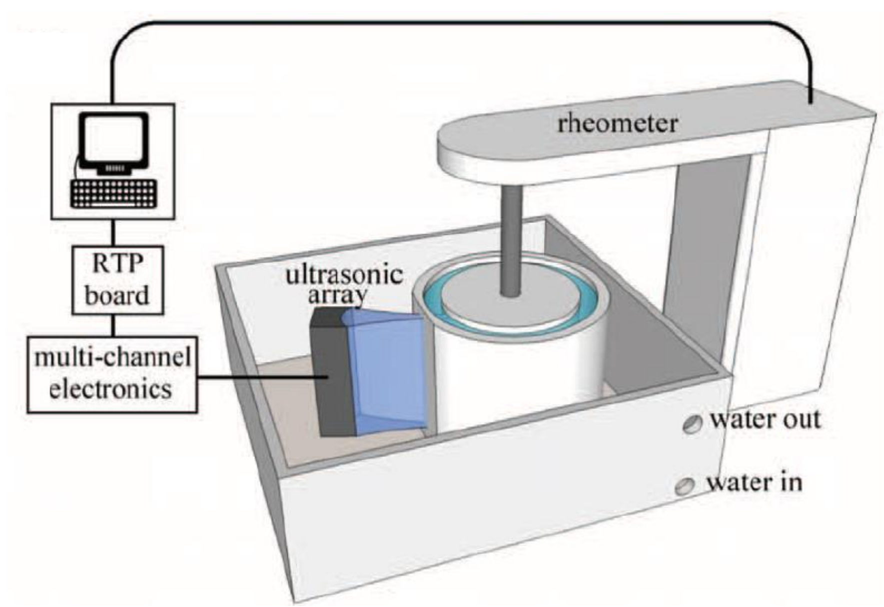


Partial fluidization

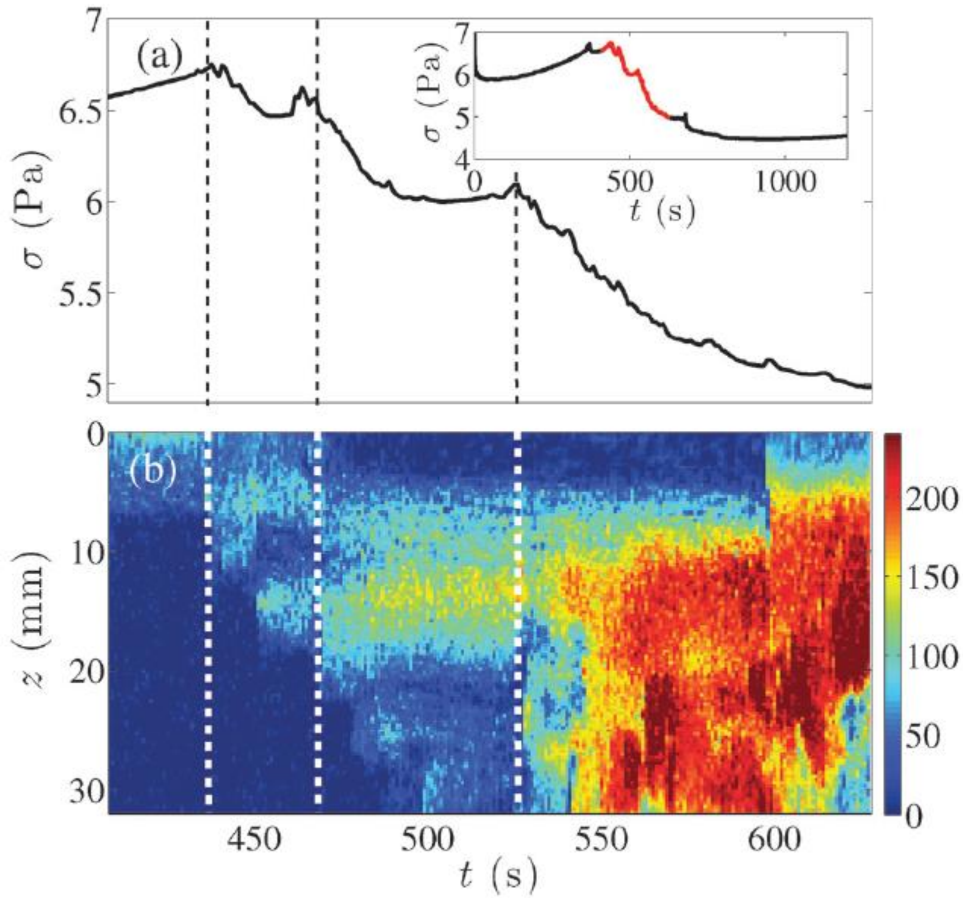
- correlation btw stress evolution & velocity profiles is less marked → **3D events ?**
- wall slip decreases **<u>but</u>** remains at level of about 20%

Local scenario within an avalanche: 2D measurements

Experimental conditions: t_w=1 min & $\dot{\gamma}$ = 200s^{-1}



Gallot et al. Rev. Sci. Instrum. (2013)

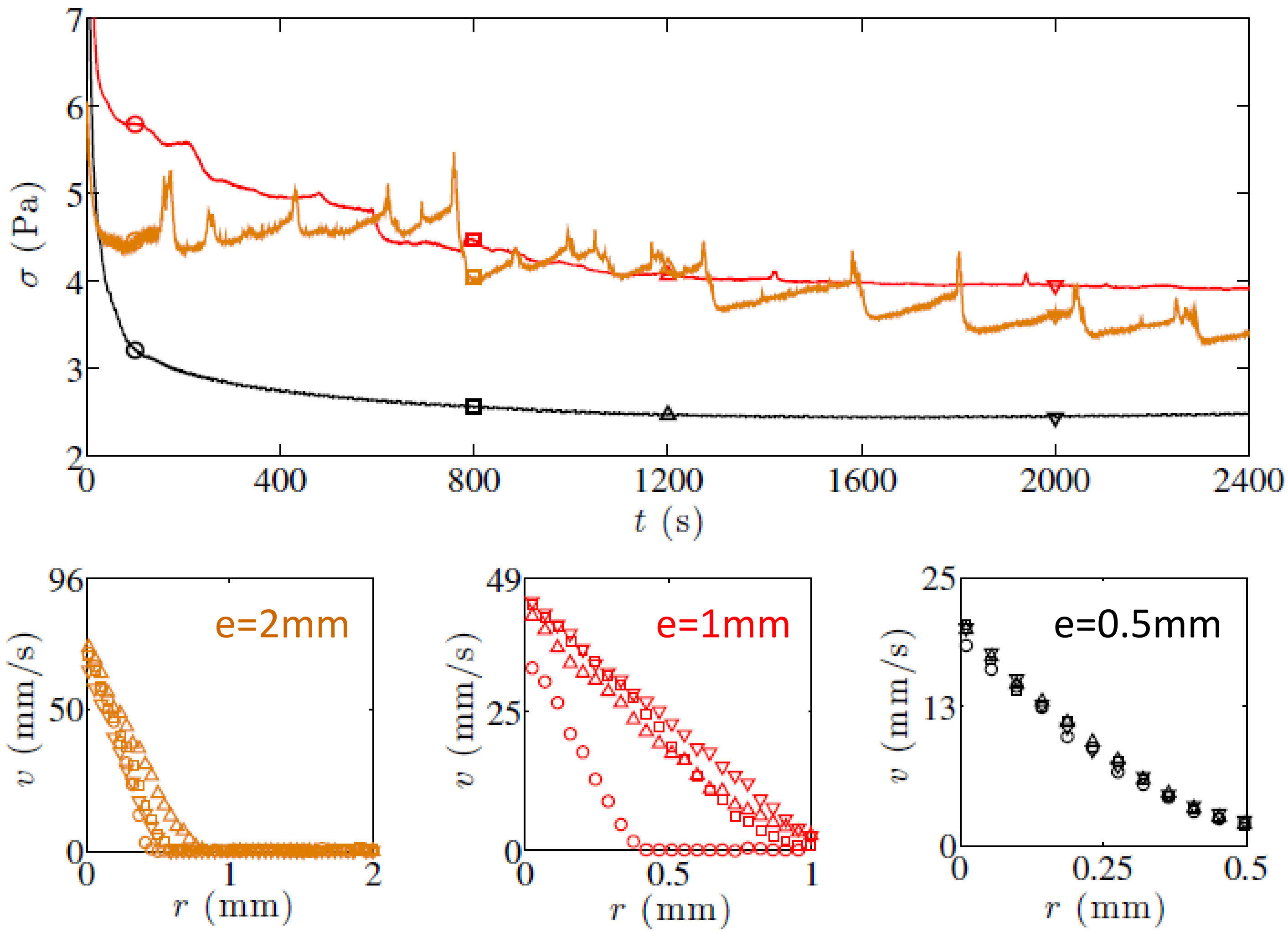


Complete fluidization

- heterogeneous dynamics along the vorticity direction correlated to stress drops
- yielding scenario is not universal: strongly depends on the applied shear rate

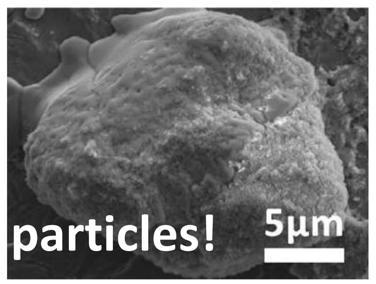
Confinement: influence of the gap width

Experimental conditions: t_w=10 min & $\dot{\gamma}$ = 50s^{-1}



The avalanche-like fluidization scenario is not due to confinement

Take home messages



Conclusions:

- Silica colloids + concentrated amount of salt = **non-Brownian particles!**
- **Existence of a "second" critical shear rate $\dot{\gamma}^*$:**
  - For $\dot{\gamma}_c < \dot{\gamma} < \dot{\gamma}^*$ (steady-state) shear banding trapped by aging
  - $\dot{\gamma}^*$ is not intrinsic to the material but depends on the sample age, the geometry, the boundary conditions, etc.
- **Avalanche-like dynamics:**
  - Heterogeneous dynamics along the vorticity direction, which is observed both during partial & complete fluidization of the sample

Outlooks:

- **Challenge for spatially-resolved models!** (Fluidity model, MD simulations…)
  - What sets $\dot{\gamma}^*$? Scaling with sample age?
  - Minimal ingredients needed to stabilize a transient shear-band?
  - Coupling between avalanche dynamics & wall slip (slip velocity)?
- **Statistics associated with the avalanches**

A. Kurokawa, V. Vidal, K. Kurita, T. Divoux & S. Manneville, Soft Matter **11**, 9016 (2015)

Partial vs. complete fluidization