How do yield stress materials start to flow?

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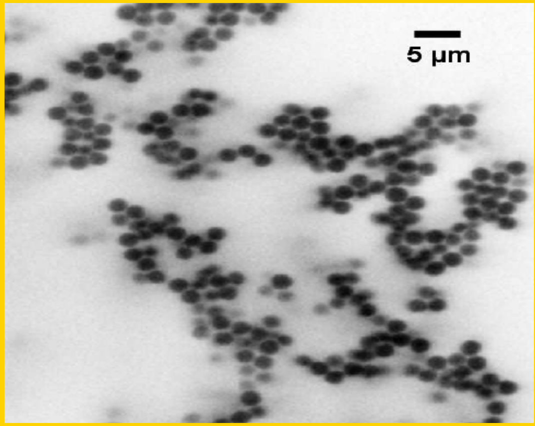
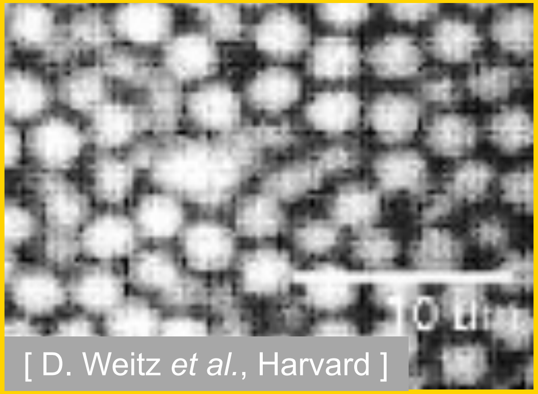
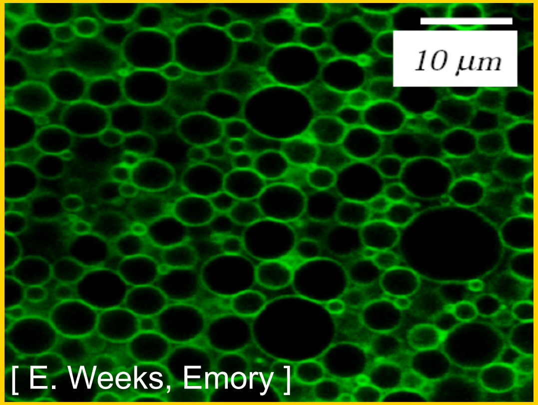
Soft jammed materials are yield stress fluids



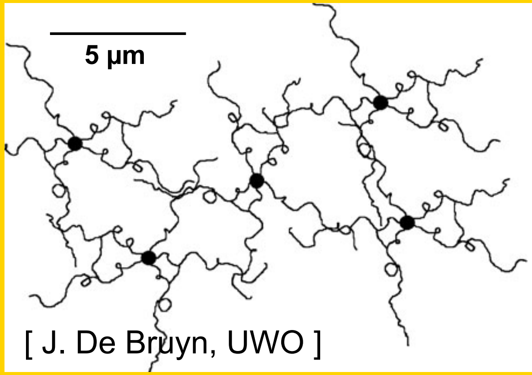
colloidal gels and glasses



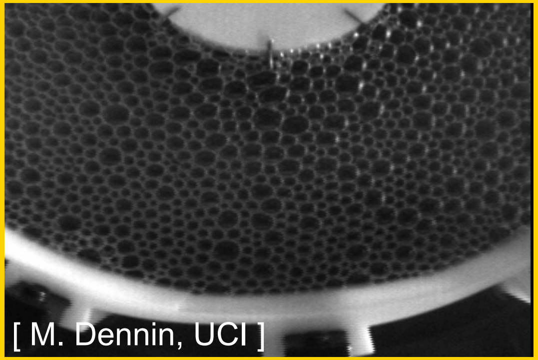
emulsions



carbopol gels



foams



solid-like below σ_c

liquid-like above σ_c

⇨ how does this yielding transition work?

Outline

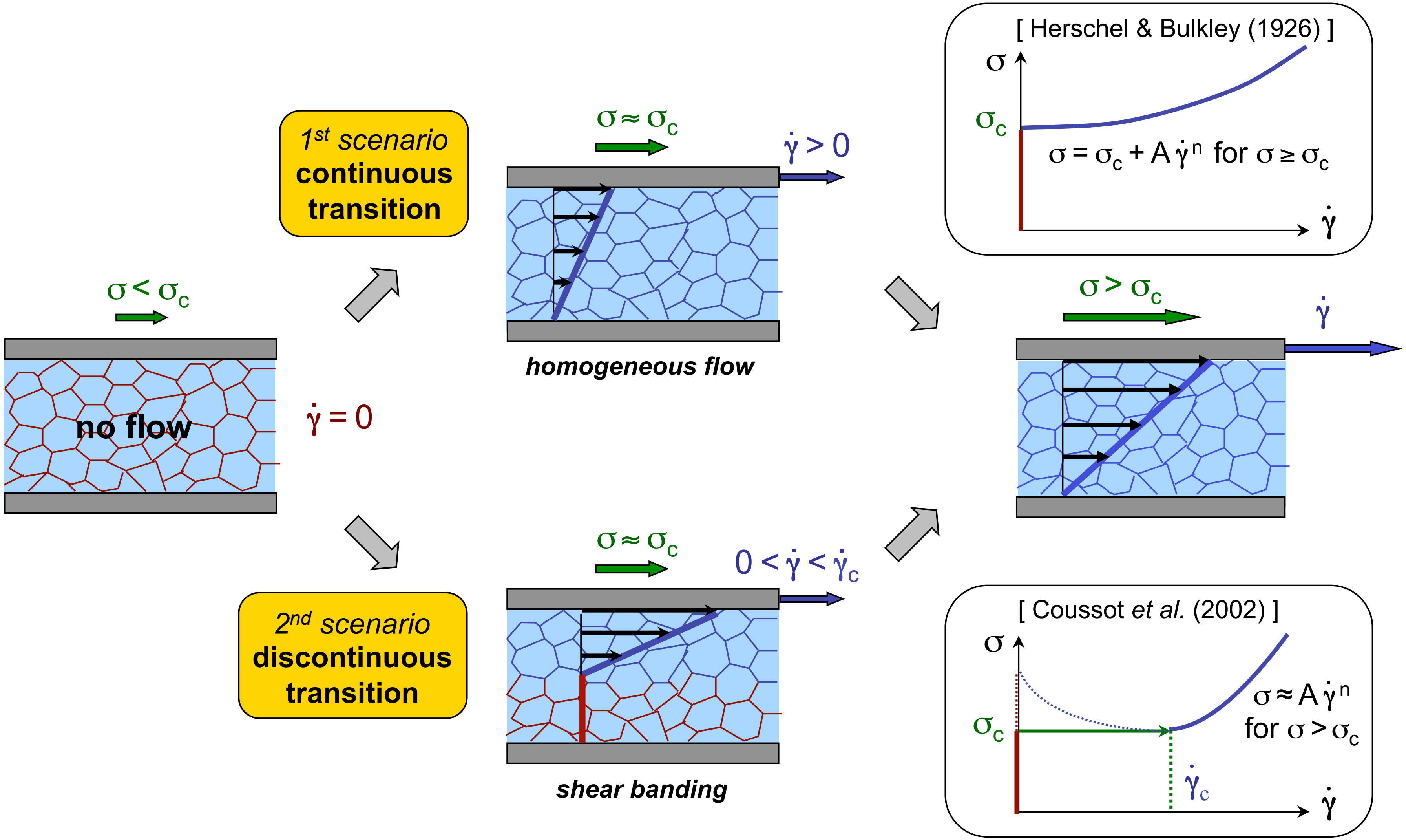
What is the steady-state reached after yielding?

- continuous *vs* discontinuous yielding transition
- a very short review of experimental results
- towards a classification of yield stress materials

How do yield stress materials reach steady state?

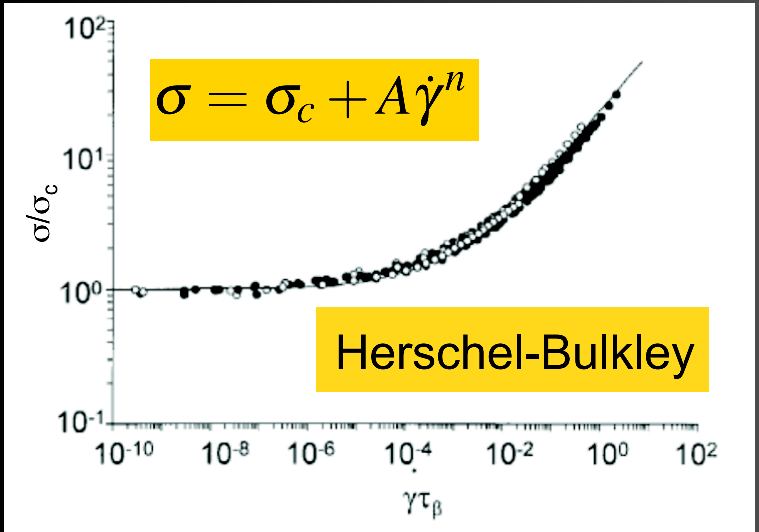
- ultrasonic velocimetry in carbopol microgels
- shear rate-imposed experiments
- stress-imposed experiments
- comparison with other materials

The rheological response of soft jammed materials

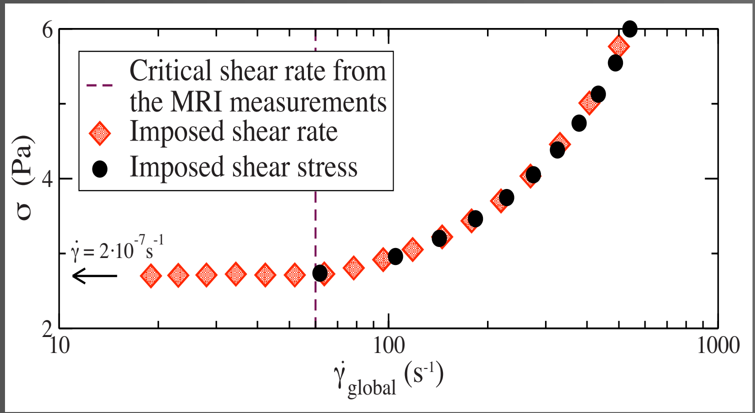


What is the steady-state flow curve?

microgels [Cloitre *et al.* *PRL* (2003)]



ludox colloidal gel [Møller *et al.* *PRE* (2008)]



existence of a critical shear rate

continuous transition

discontinuous transition

⇨ in practice, it may be hard to decide from rheology alone

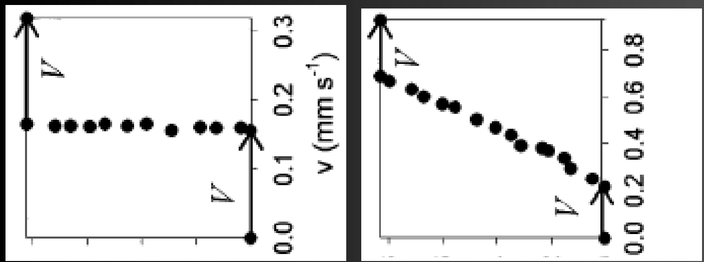
⇨ look at the <u>steady-state local flow field</u> at the macroscale (50 μm)

What is the steady-state local flow field?

continuous transition

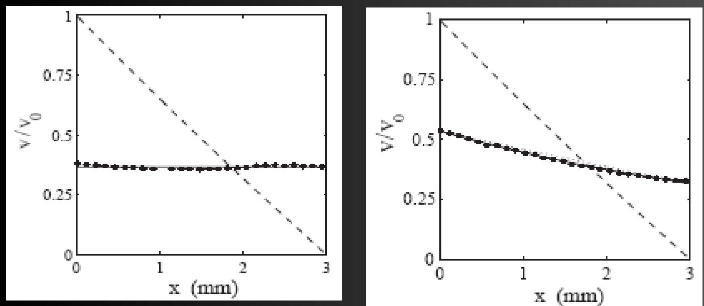
microgels

[Meeker *et al.* *PRL* (2004)]



emulsions

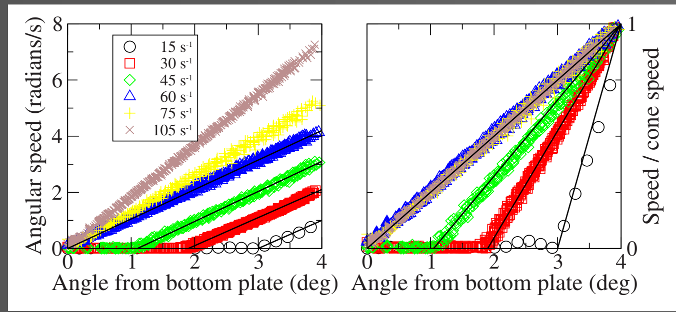
[Salmon *et al.* *EPJE* (2003)]



discontinuous transition

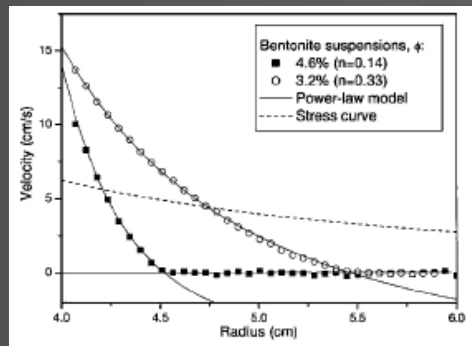
ludox colloidal gel

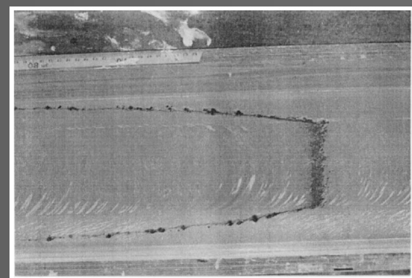
[Møller *et al.* *PRE* (2008)]



clays (bentonite, laponite)

[Coussot *et al.* *PRL* (2002)]





homogeneous steady-state flow *vs* **shear-banded flow**

Towards a classification of yield stress materials

“Simple” yield stress materials

microgels, emulsions, wet foams

- continuous yielding transition
- Herschel-Bulkley flow curve
- homogeneous flow in steady state

“Other” yield stress materials

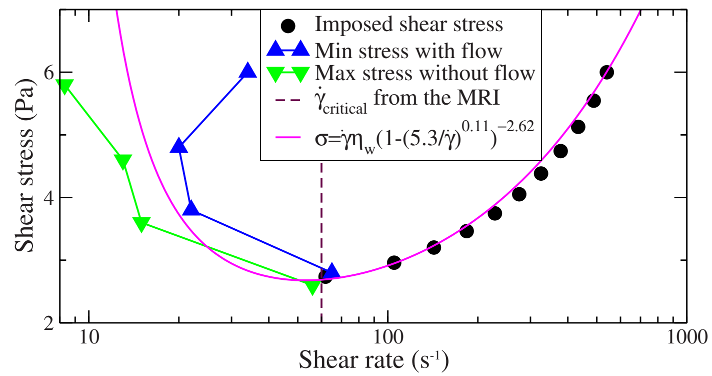
colloidal, granular & clay suspensions

- discontinuous yielding transition
- existence of a critical shear rate $\dot{\gamma}_c$
- shear-banded flow in steady state

What exactly causes steady-state shear banding?

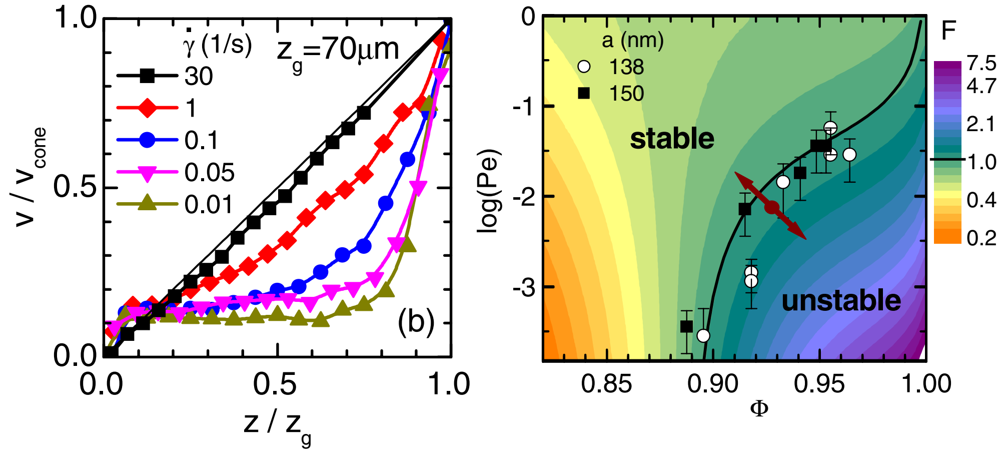
- aging *vs* shear rejuvenation ➤ link with thixotropy
  - structural parameter(s) : λ model, fluidity model
    [Coussot *et al.* (2002), Picard *et al.* (2002), Rogers *et al.* (2008)]
  - aggregation & breakup of fractal clusters [Møller *et al.* (2008)]

  ➪ *see P. Coussot's talk*

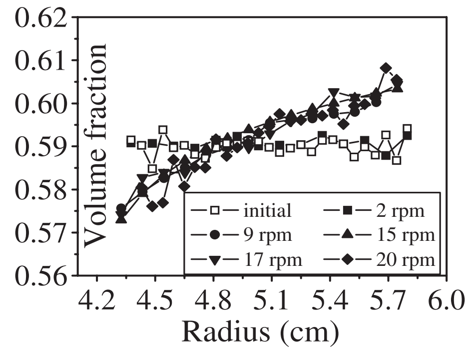


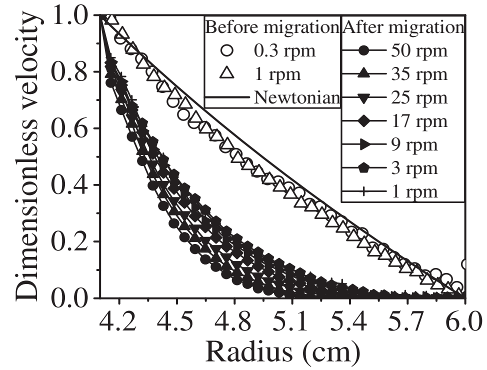
- flow-concentration coupling / particle migration

colloidal glasses [Besseling *et al. PRL* (2010)]



granular suspensions
[Fall *et al. PRL* (2010)]





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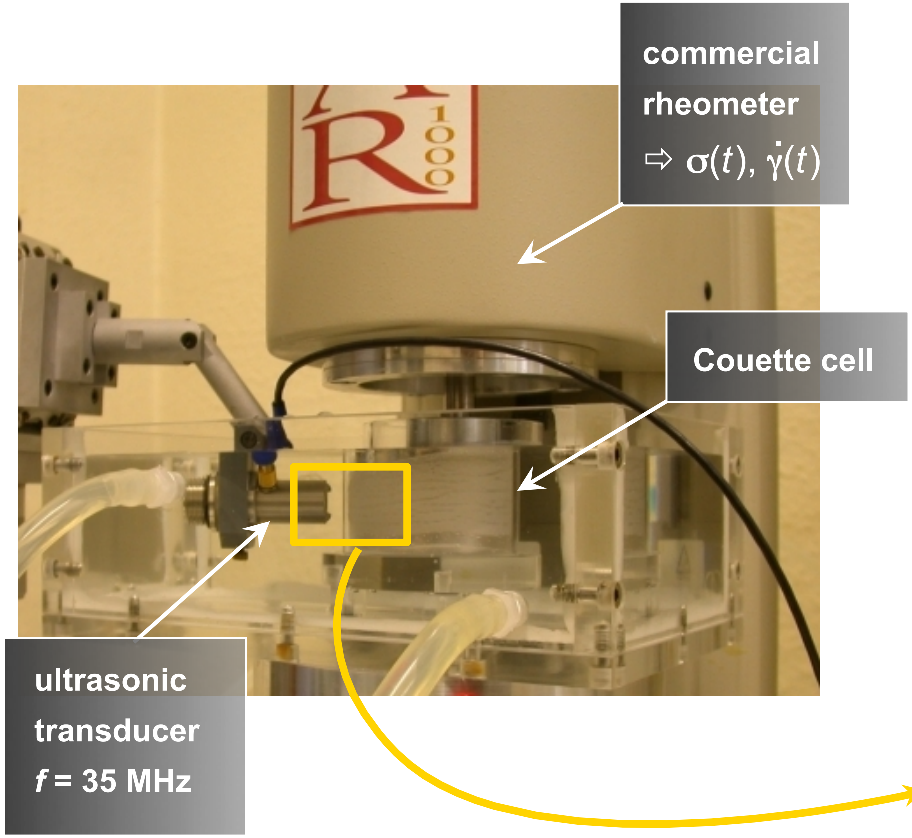
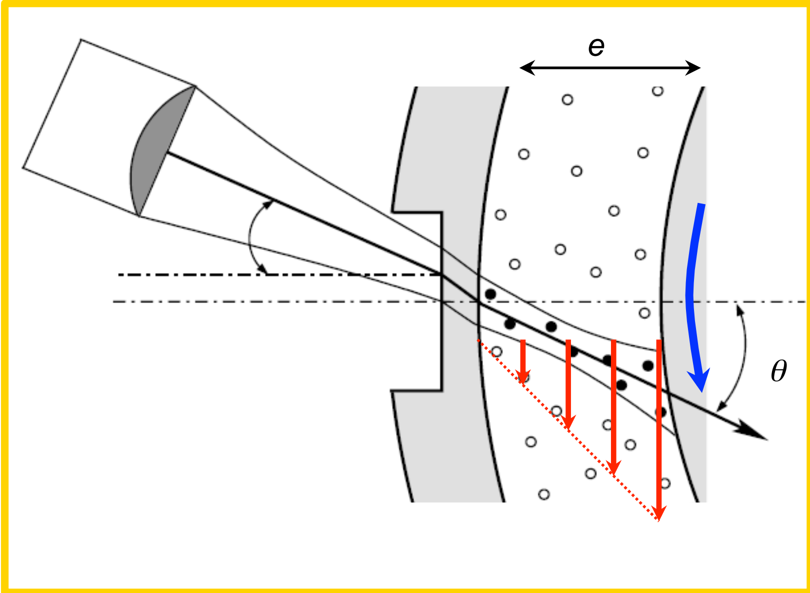
Ultrasonic velocimetry



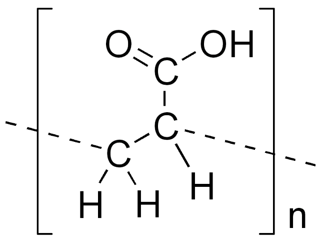
rheometer	Anton Paar MCR 301
gap	e = 0.45 – 3 mm
surface	polished Plexiglas or sandpaper



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

[Manneville *et al.*, *Eur. Phys. J.* AP **28**, 361 (2004)]

Carbopol microgels, a "simple" yield stress material

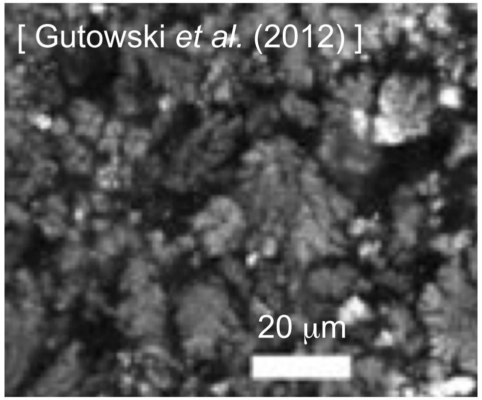


poly(acrylic acid) polymer

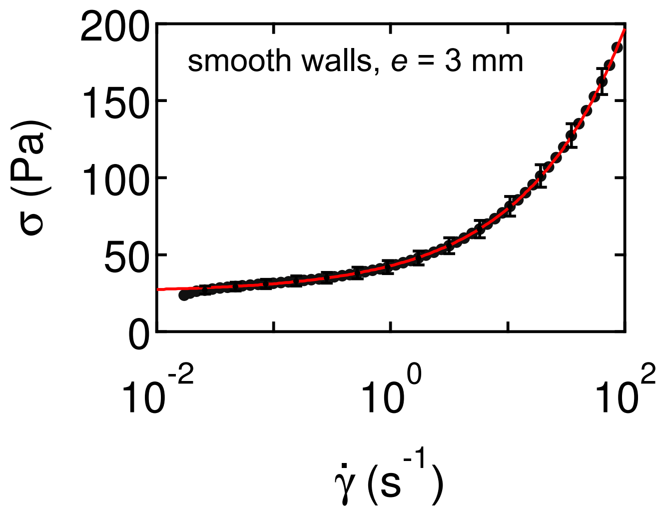
- 1% wt carbopol ETD 2050
- 0.5% wt hollow glass spheres

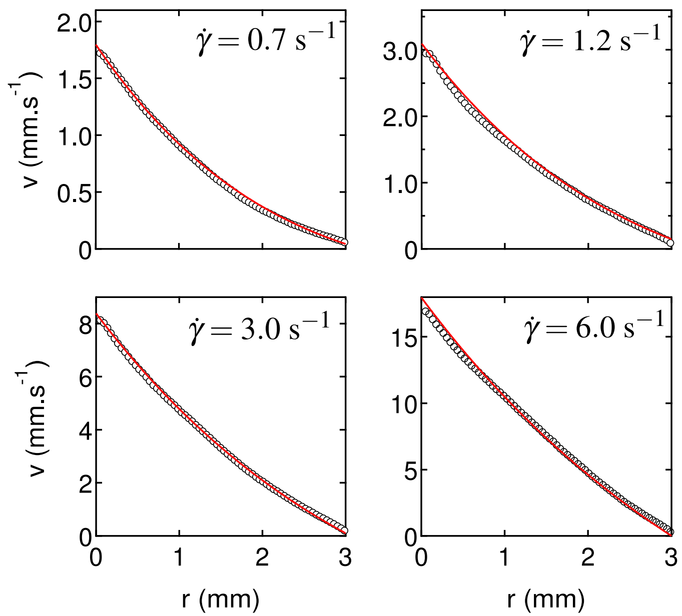
G' = 100 ± 10 Pa
G" = 12 ± 2 Pa

[Ketz *et al.* (1988), Baudonnet *et al.* (2004), Oppong *et al.* (2006), Lee (2011)]



➪ a jammed assembly of soft microgel particles with highly crosslinked cores

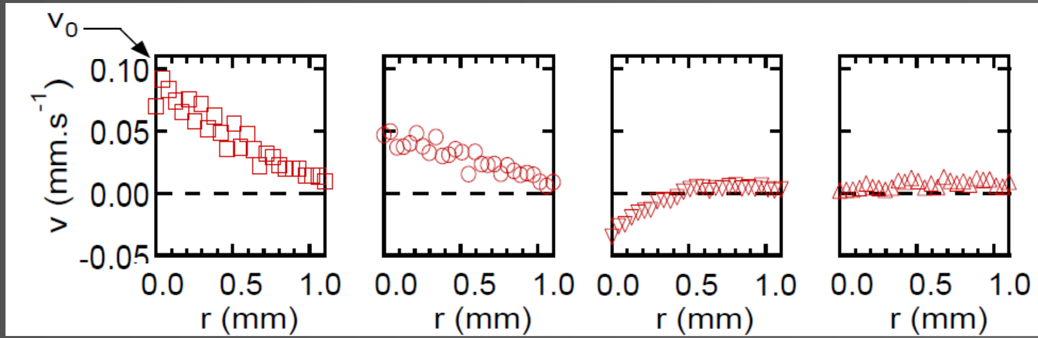




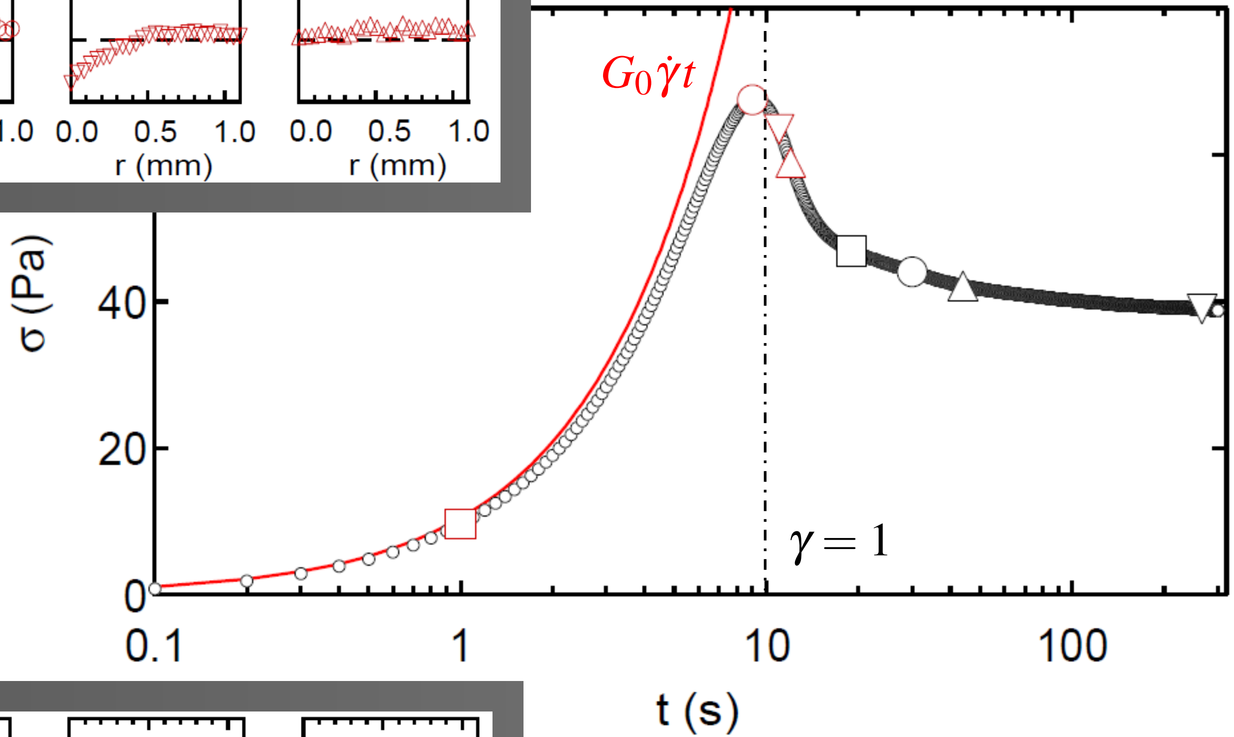
➪ perfect Herschel-Bulkley & "simple" yielding

Shear rate-imposed experiment

[$\dot{\gamma}$ = 0.1 s^{-1}, rough walls, e = 1.1 mm]



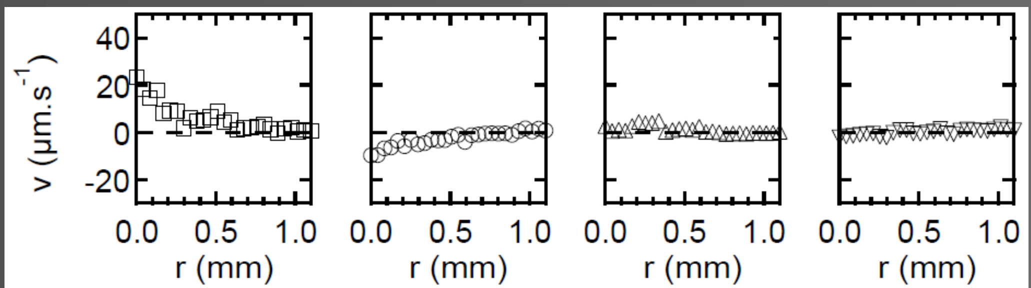
- presence of a stress overshoot at $\gamma \approx 1$
- plasticity before the overshoot



➪ elastic deformation

➪ failure at the rotor

➪ elastic recoil



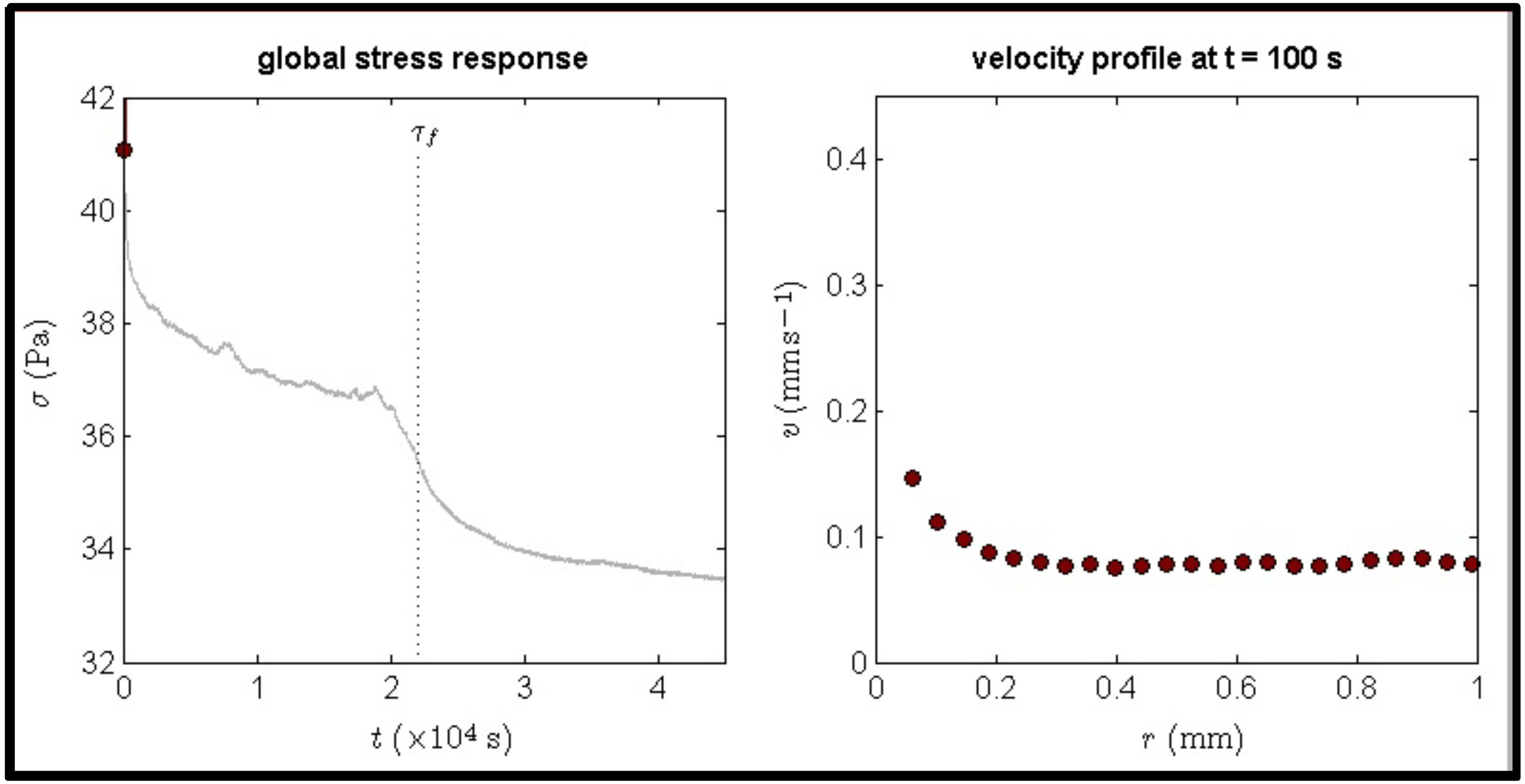
➪ damped oscillations

➪ total slippage at the rotor

Shear rate-imposed experiment

[$\dot{\gamma}$ = 0.5 s^{-1}, smooth walls, e = 1 mm]

- long-time stress response



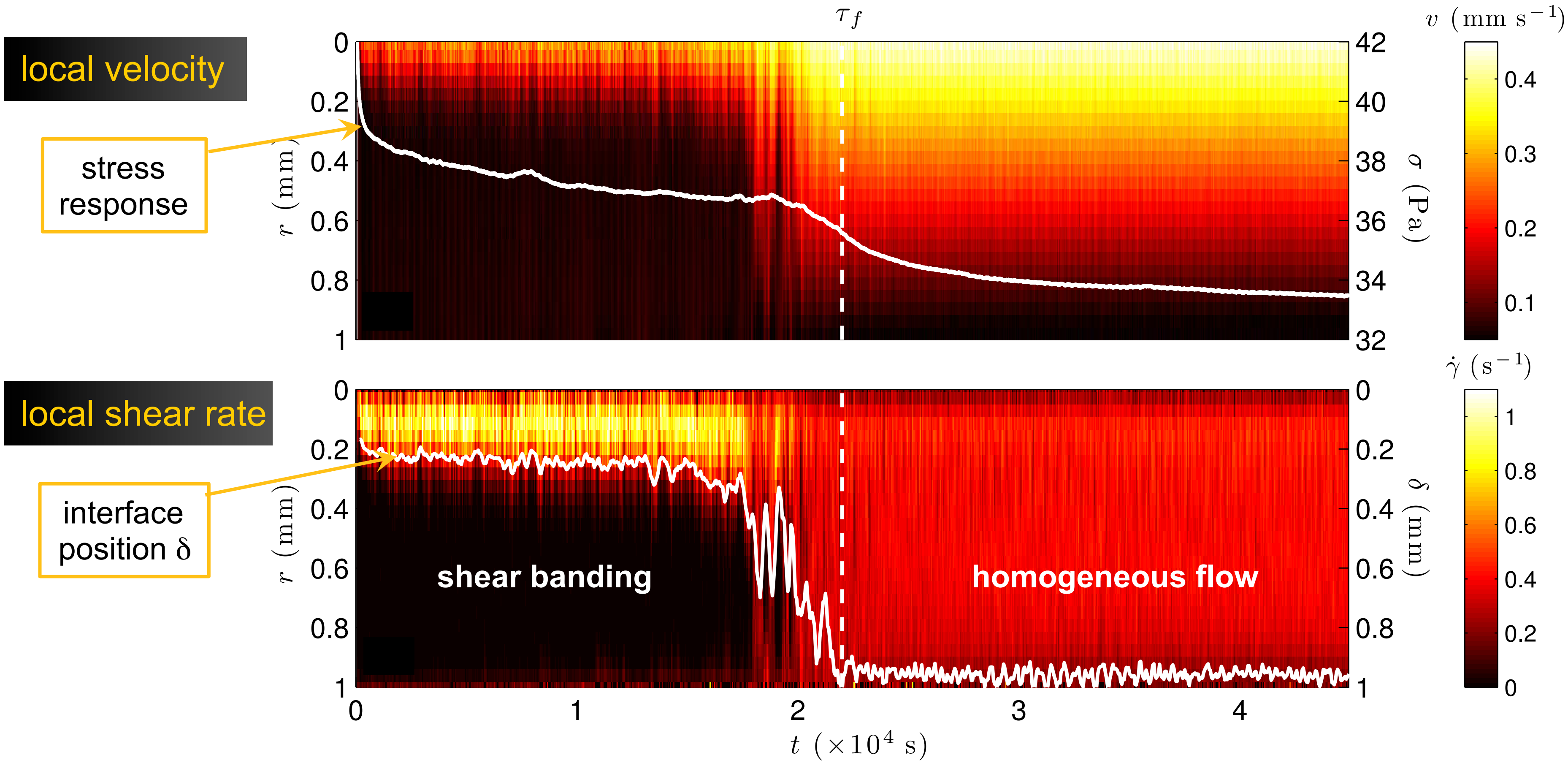
➪ **growth of a shear band & long-lasting shear-banding regime**

➪ **strong fluctuations & "sudden" fluidization at τ_f**

➪ **rheological signature: "kink" around τ_f**

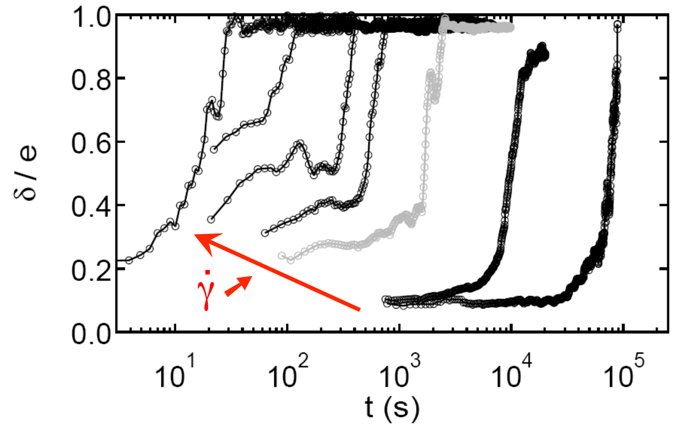
Data analysis

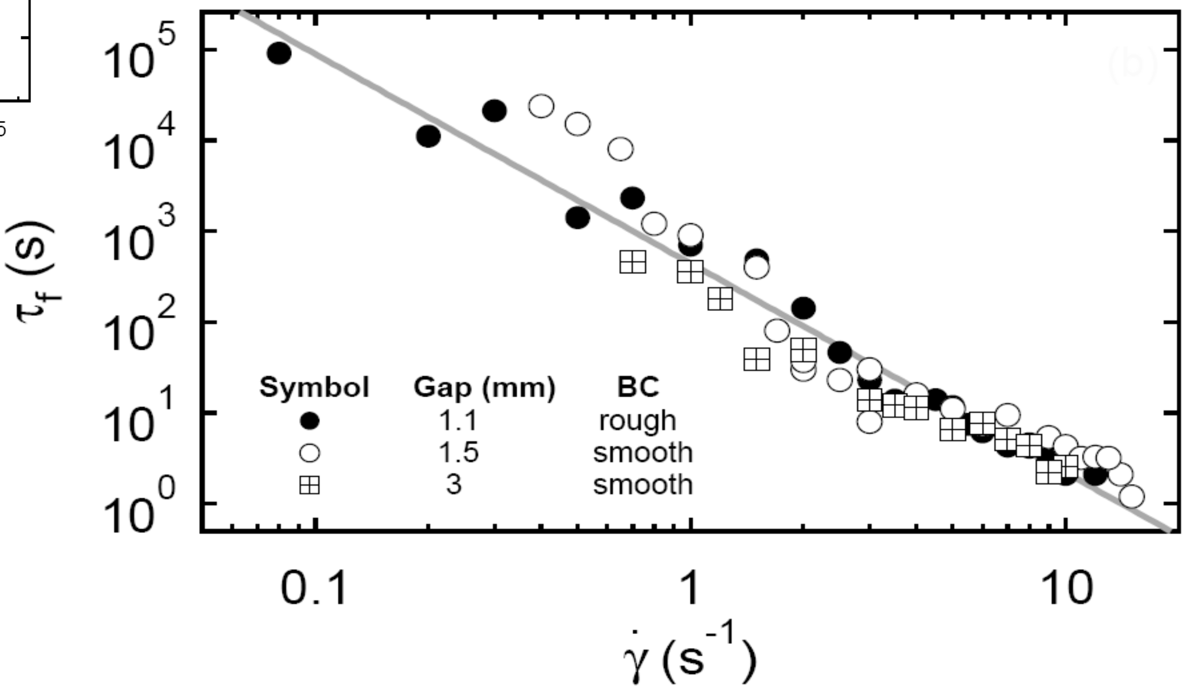
[$\dot{\gamma}$ = 0.5 s^{-1}, smooth walls, e = 1 mm]



➪ well-defined fluidization time τ_f

Shear rate-imposed experiments





$$\tau_f \sim \dot{\gamma}^{-\alpha}$$

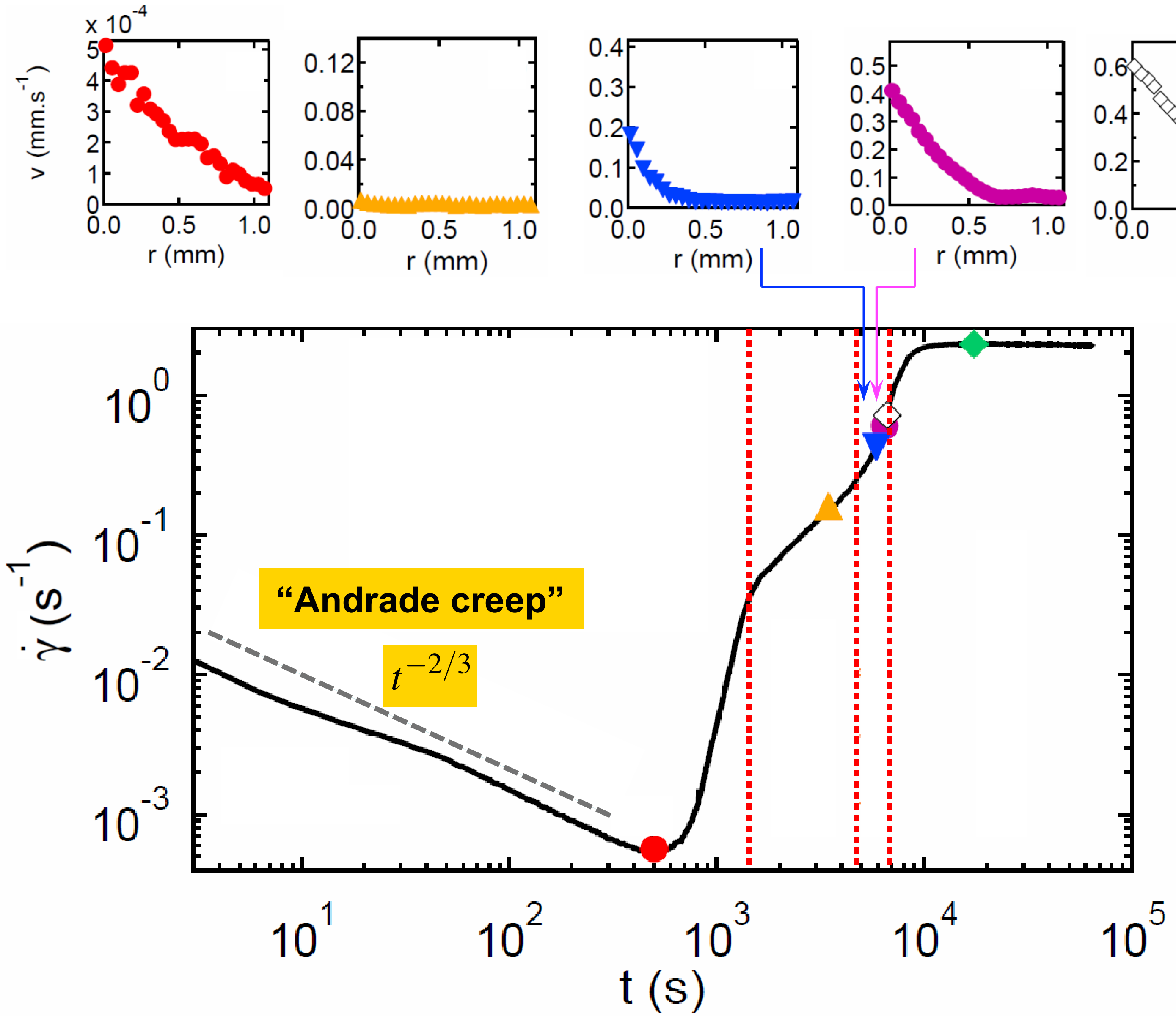
with

$$\alpha = 2.3 \pm 0.1$$

- independent of gap width and wall roughness
- dependent on carbopol batch (preparation, concentration)

Stress-imposed experiment

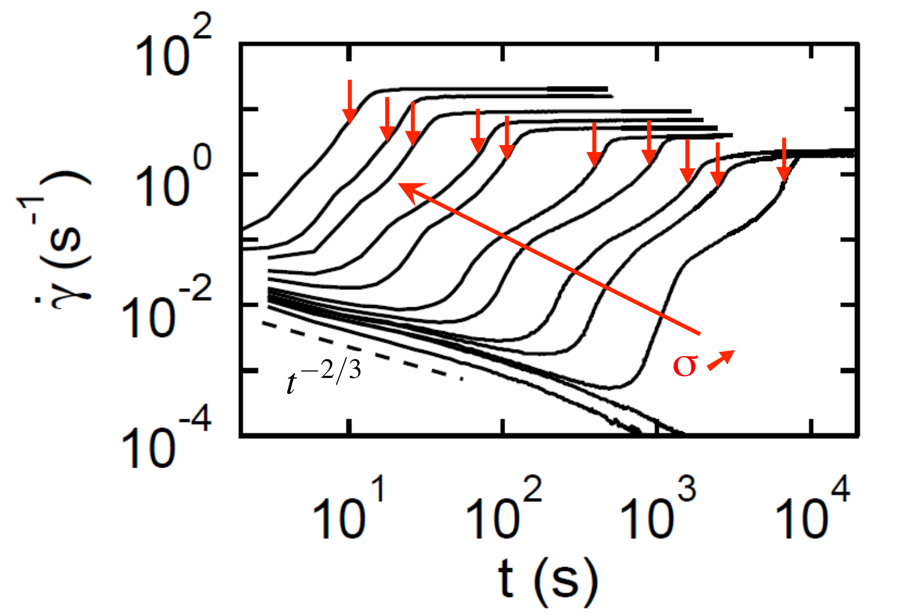
[σ = 37 Pa, rough walls, e = 1.1 mm]

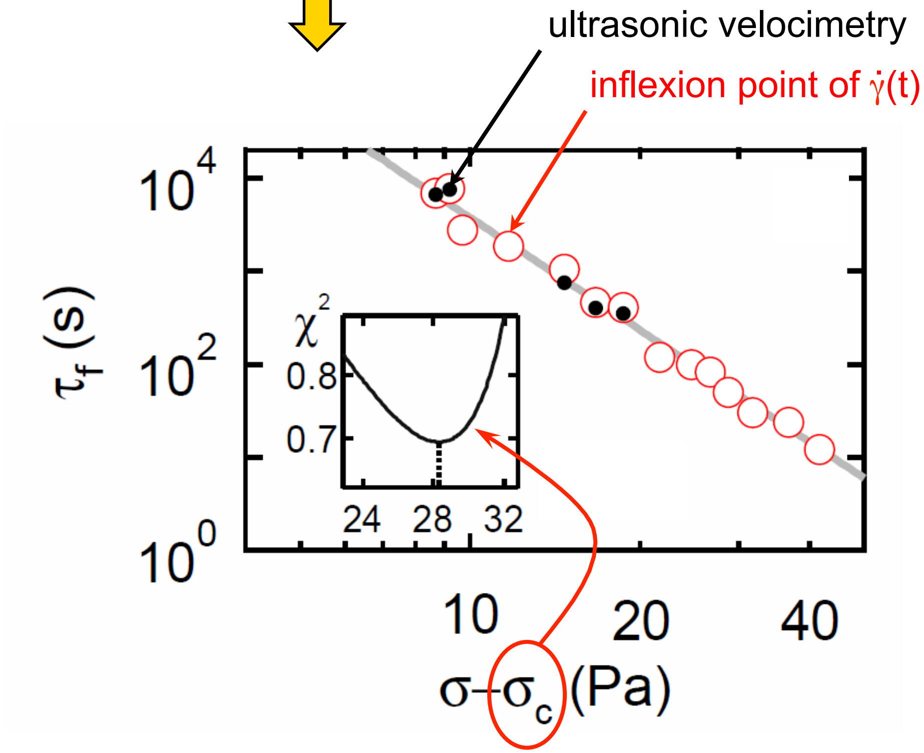


➪ **transient shear banding**

➪ **well-defined fluidization time**

Stress-imposed experiments





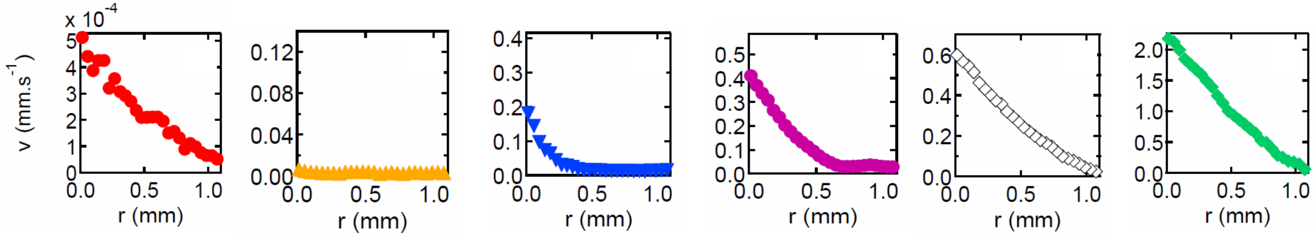
$$\tau_f \sim (\sigma - \sigma_c)^{-\beta}$$

with

$$\beta = 4.0 \pm 0.1$$

- <u>independent</u> of gap width and wall roughness
- <u>dependent</u> on carbopol batch (preparation, concentration)
- estimate of σ_c consistent with steady-state flow curve

Link between transient regime and steady state



- a similar fluidization scenario under imposed $\dot{\gamma}$ and σ

$$\boxed{\tau_f^{(\dot{\gamma})} = a/\dot{\gamma}^{\alpha}}$$

$$\boxed{\tau_f^{(\sigma)} = b/(\sigma - \sigma_c)^{\beta}}$$

let us assume

$$\tau_f^{(\sigma)} = \lambda \tau_f^{(\dot{\gamma})}$$

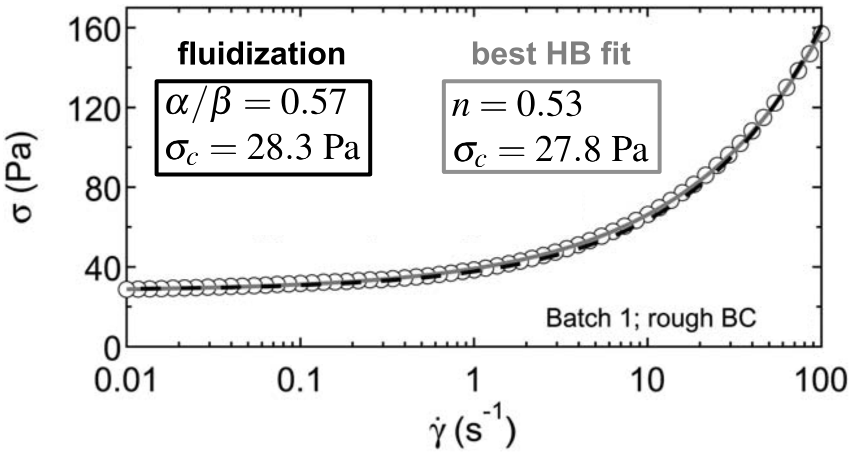
$$\Rightarrow \quad \sigma = \sigma_c + A\dot{\gamma}^n$$

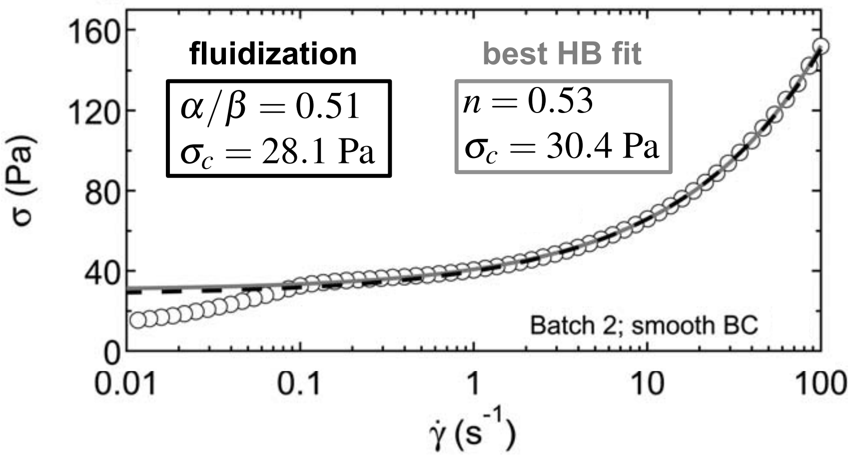
$$n = \alpha/\beta$$

$$A = (b/\lambda a)^{1/\beta}$$

one free parameter: λ ≈ 10

- steady-state Herschel-Bulkley rheology is recovered



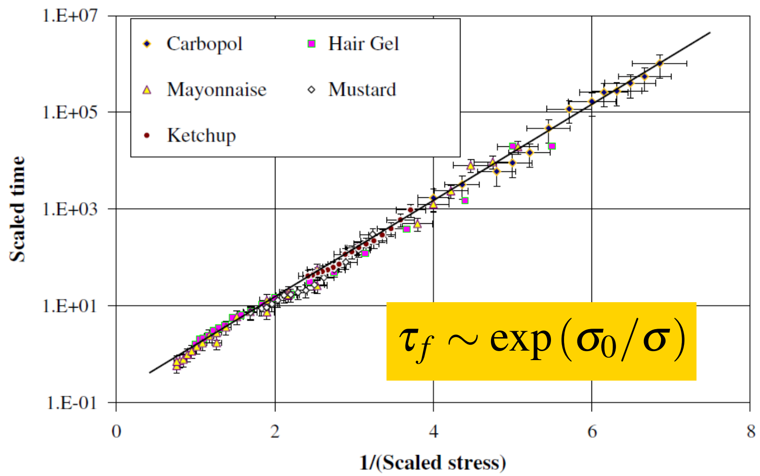


What about other soft jammed materials?

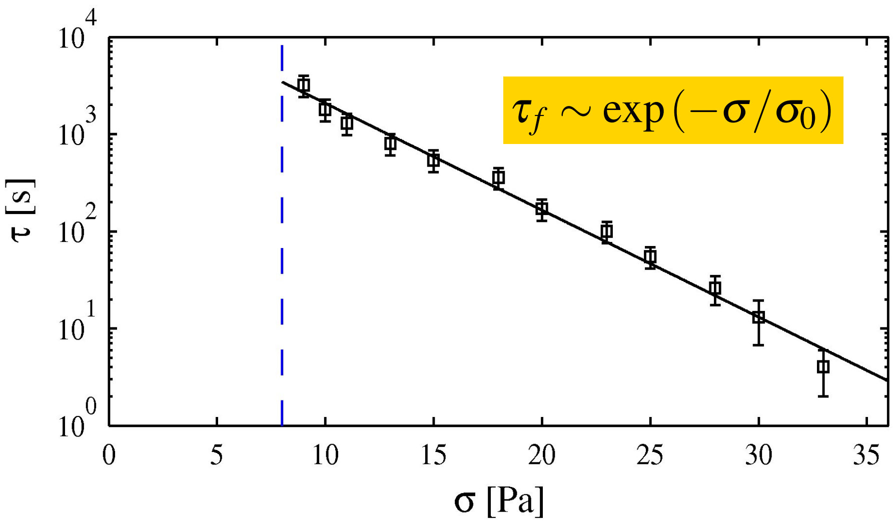
- fractures in yield stress fluids?

  - Taylor model for fracture in elastic solids
  - but no local measurements

  [Caton & Baravian, *Rheol. Acta* **47**, 601-607 (2008)]

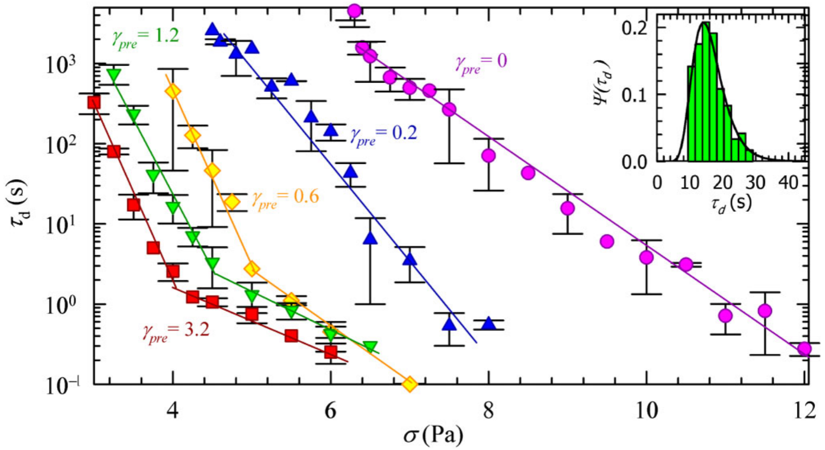


- activated processes in colloidal gels?



  - carbon black particles in mineral oil
  - Kramer's law with $E(\sigma) = E_a - \sigma v$

  [Gibaud *et al.*, *Soft Matter* **4**, 3482-3486 (2010)]



  - gels of stearylated silica
  - bond-breaking models

  [Sprakel *et al.*, *PRL* **106**, 248303 (2011)]
  [Mora, *Soft Matter* **7**, 4908-4917 (2011)]

Conclusions and outlook

Critical-like dynamics of a "simple" yield stress material

- long-lasting transient shear banding
- link with steady-state rheology

$$\boxed{\tau_f^{(\dot{\gamma})} = a/\dot{\gamma}^{\alpha} \text{ \& } \tau_f^{(\sigma)} = b/(\sigma - \sigma_c)^{\beta}} \leftrightarrow \boxed{\sigma = \sigma_c + A\dot{\gamma}^n \text{ with } n = \alpha/\beta}$$

➪ close to the yield point, check carefully that steady-state is achieved

➪ "critical" exponents that remain to be fully understood

➪ a behaviour that is certainly <u>not</u> general

- need for space-resolved structural measurements in the two bands
- what time-resolved models to describe fluidization dynamics?
- how far does the analogy with creep in solids go?

The cement slide

T. Gibaud *et al.*	*PRL* **101**, 258302 (2008)
	Soft Matter **5**, 3026-3037 (2009)
	Soft Matter **6**, 3482-3488 (2010)
T. Divoux *et al.*	*PRL* **104**, 208301 (2010)
	Soft Matter **7**, 8409-8418 (2011)
	Soft Matter **7**, 9335-9349 (2011)
	Soft Matter **8**, 4151-4164 (2012)