Instabilities at "zero" Reynolds number: experiments from shear-thinning in surfactant solutions to shear-thickening in dense suspensions

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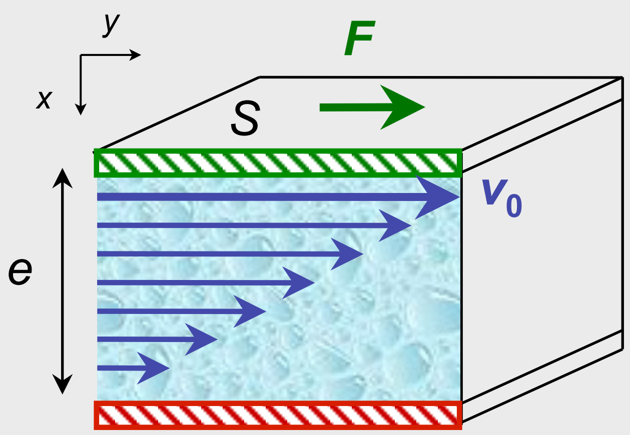
Physics of Dense Supensions, KITP, January 18th 2018

Flow-microstructure coupling

simple shear

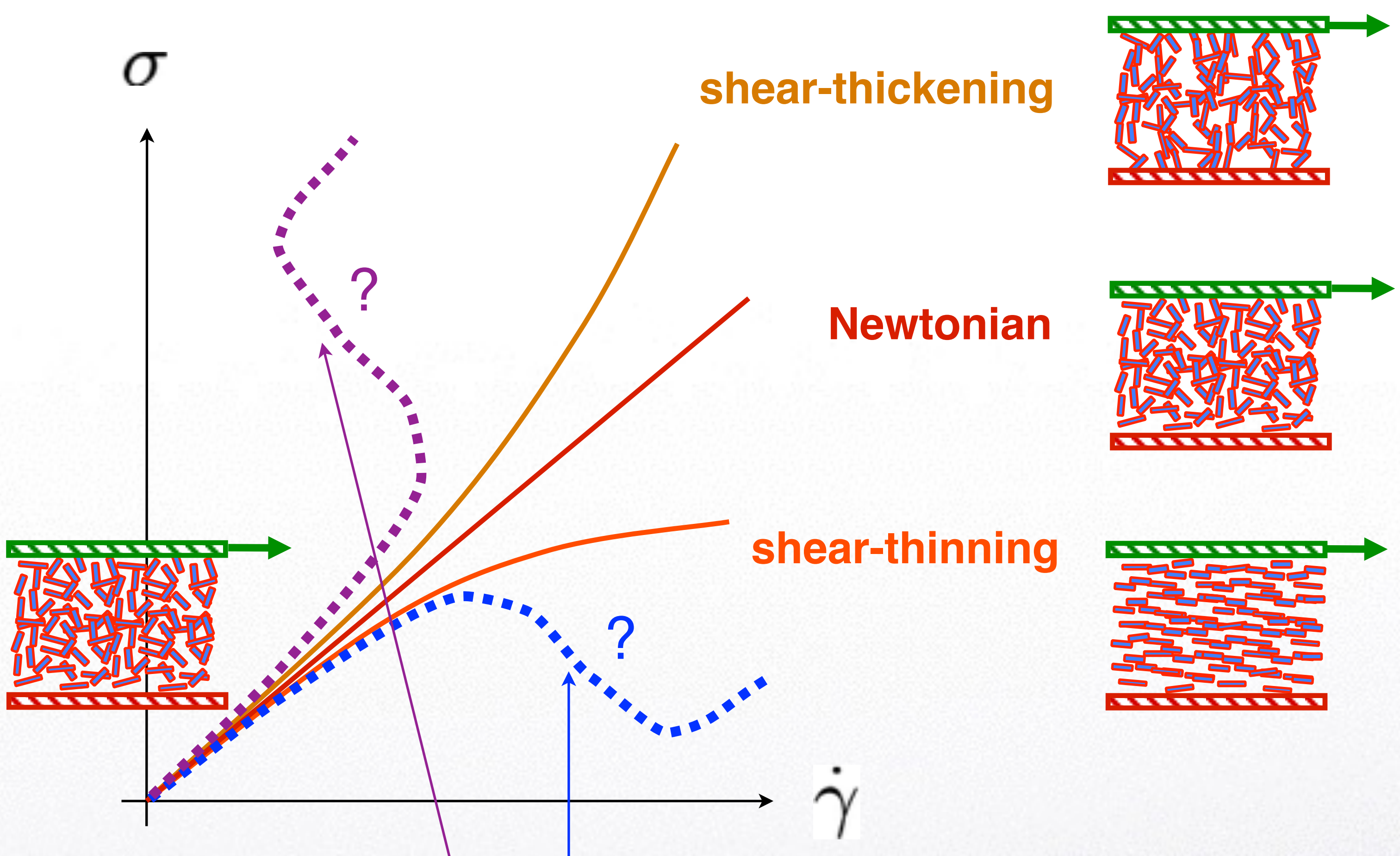


shear stress : $\sigma = \dfrac{\partial F_y}{\partial S_x} \simeq \dfrac{F}{S}$

shear rate : $\dot{\gamma} = \dfrac{\partial v_y}{\partial x} \simeq \dfrac{v_0}{e}$

shear viscosity : $\eta = \dfrac{\sigma}{\dot{\gamma}}$

flow curve : shear stress *vs* shear rate



unstable when $\dfrac{\partial \sigma}{\partial \dot{\gamma}} < 0$

feedback between flow and microstructure

⇒ possibility of mechanical instabilities

Outline

I. Surfactant solutions

from gradient banding to elastic turbulence to vorticity banding

II. Yielding in soft glassy (“squishy”) materials

from steady shear localization to critical-like fluidization dynamics

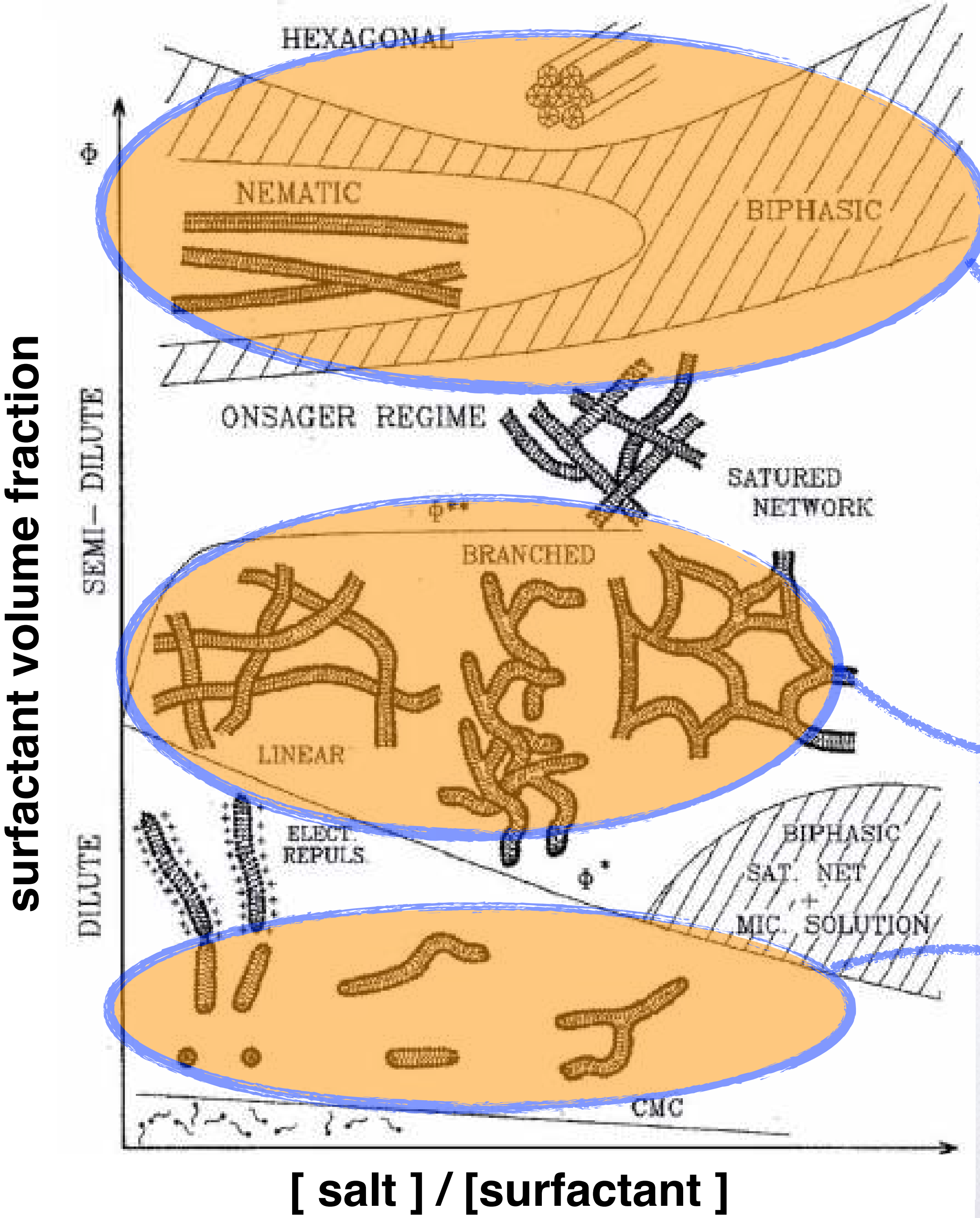
T. Divoux, M.-A. Fardin, SM & S. Lerouge, *Ann. Rev. Fluid Mech.* **48**, 81–103 (2016)

D. Bonn, M. Denn, L. Berthier, T. Divoux & SM, *Rev. Mod. Phys.* **89**, 035005 (2017)

III. What about dense suspensions?

similarities and differences with other complex fluids

Structure and rheology of wormlike micelles

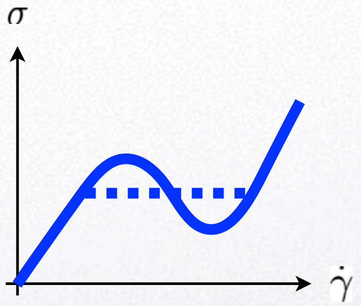


“suspensions” of Brownian “particles”
<u>anisotropic</u>, <u>deformable</u> & <u>breakable</u>
radius ≈ 1 nm & length up to ≈ 1 μm

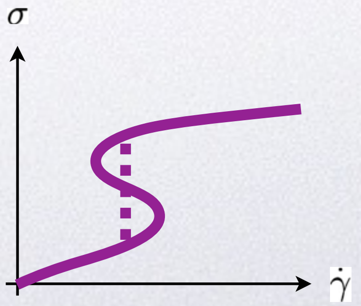
crowding of self-assembled structures
⇒ ***yield stress***

flow-concentration coupling, nematohydrodymics
& elasticity ⇒ ***complications!***

shear-induced ordering
⇒ ***shear-thinning***



shear-induced growth
⇒ ***shear-thickening***



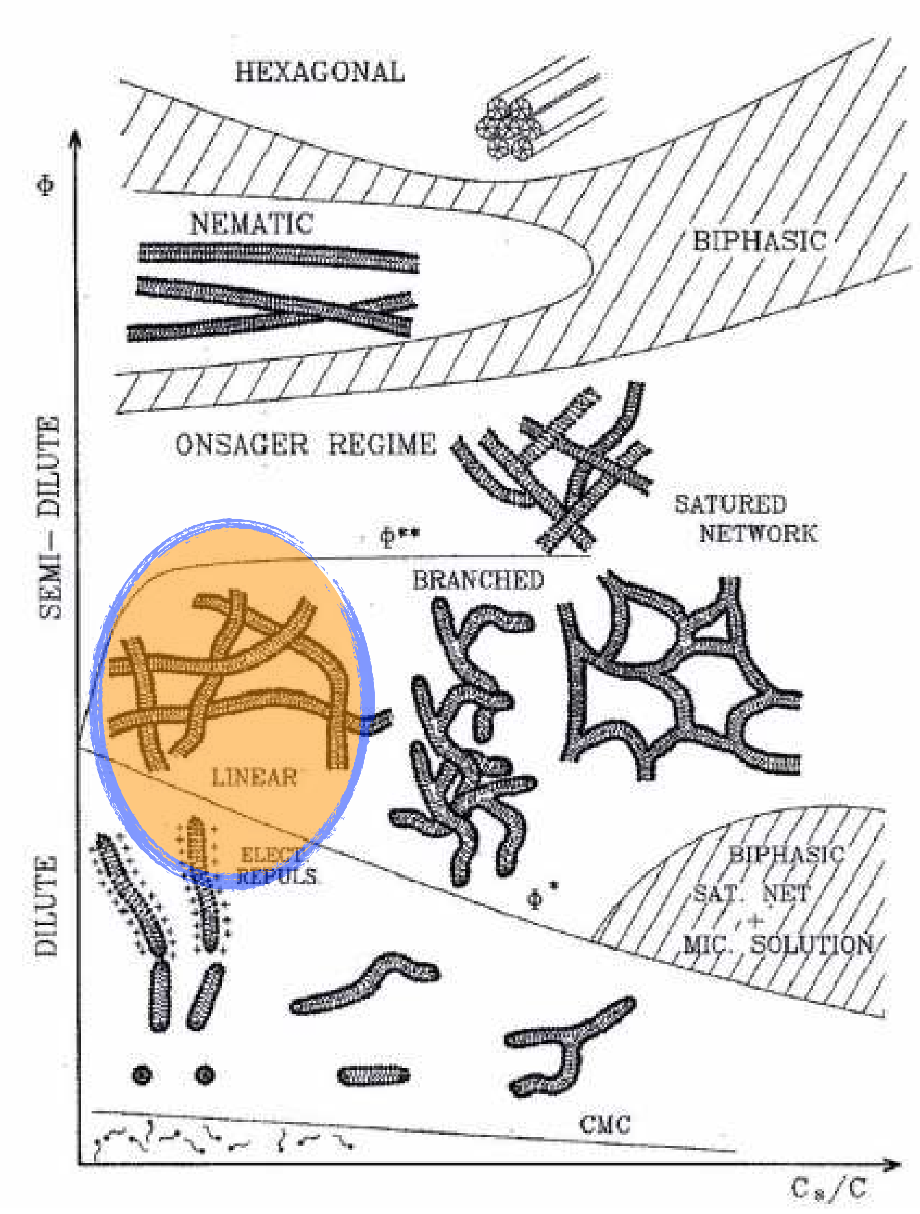
<u>see also</u> Cates & Fielding, *Adv. Phys.* **55**, 799-879 (2006)
Manneville, *Rheol. Acta* **47**, 301-318 (2008) & Olmsted, *ibid.* 283-300
Lerouge & Berret, in *Polymer Characterization*, 1-71 (2009)

⇒ flow behaviour shared
with dense suspensions?

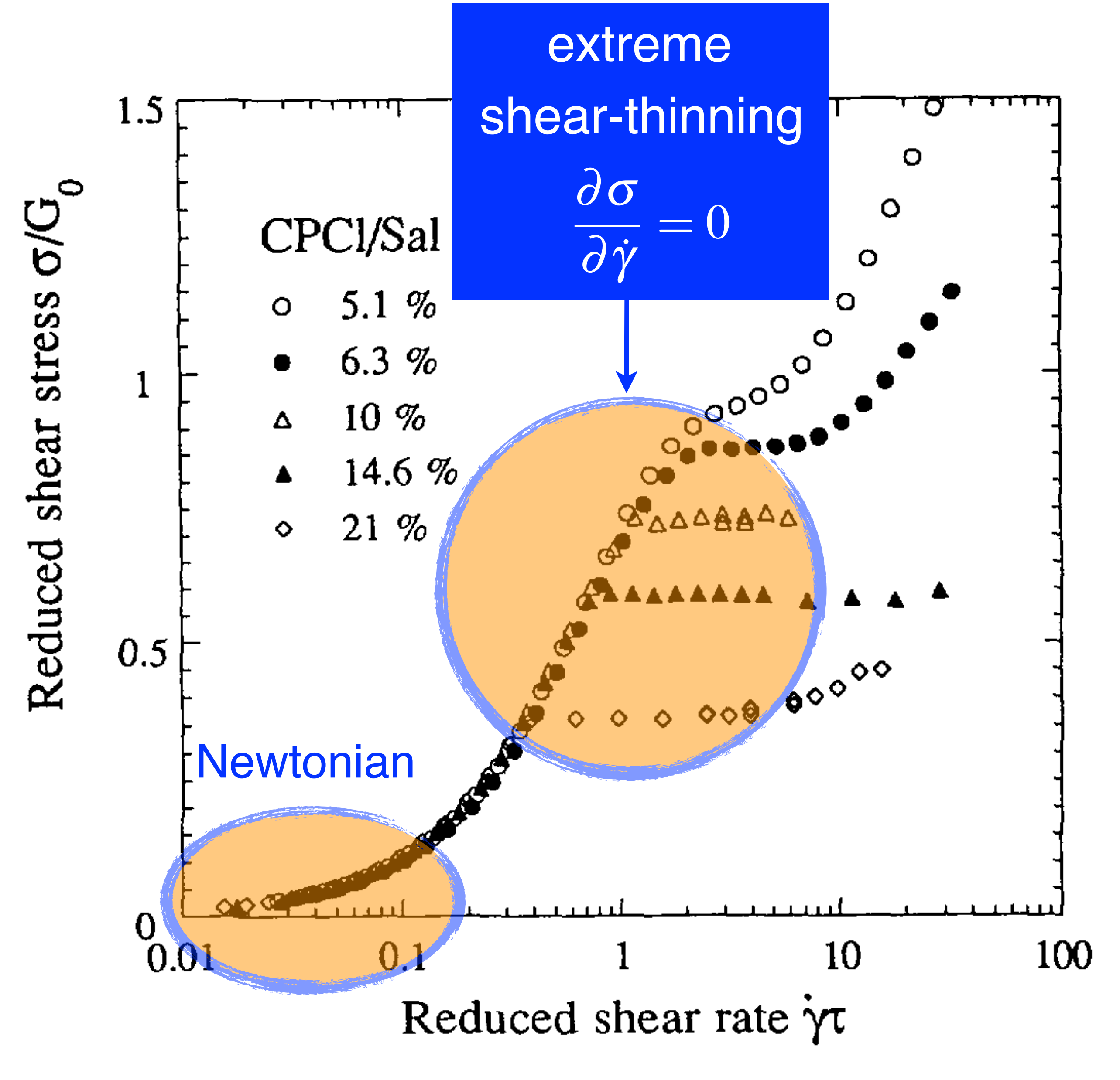
Shear banding in (semidilute) wormlike micelles

a semidilute “suspension” of semi-flexible, breakable cylindrical aggregates

with radius ≈ 1 nm & length up to ≈ 1 µm



Candau & Lequeux, *Rheol. Acta* **12**, 357-373 (1994)



extreme shear-thinning

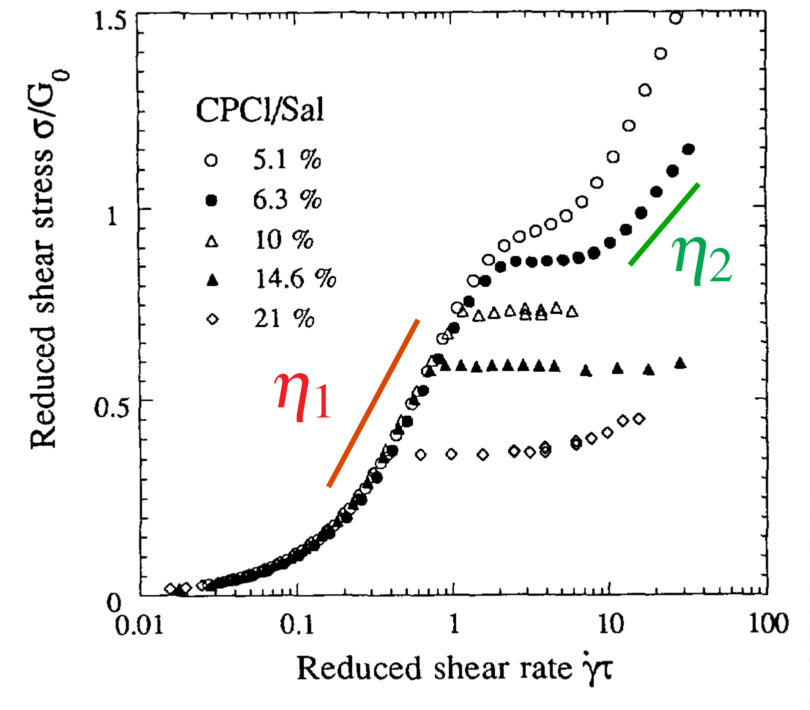
$$\frac{\partial \sigma}{\partial \dot{\gamma}} = 0$$

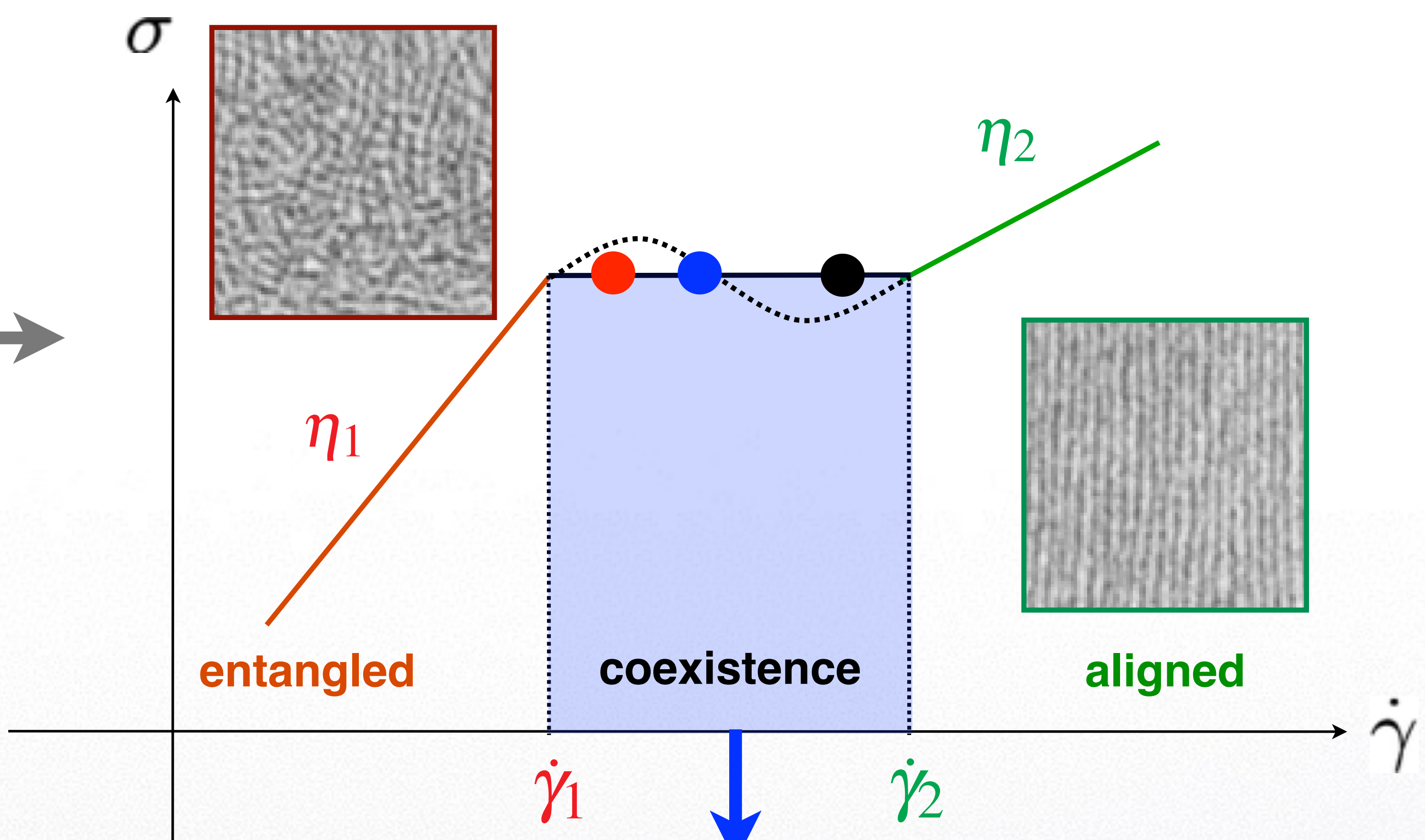
Newtonian

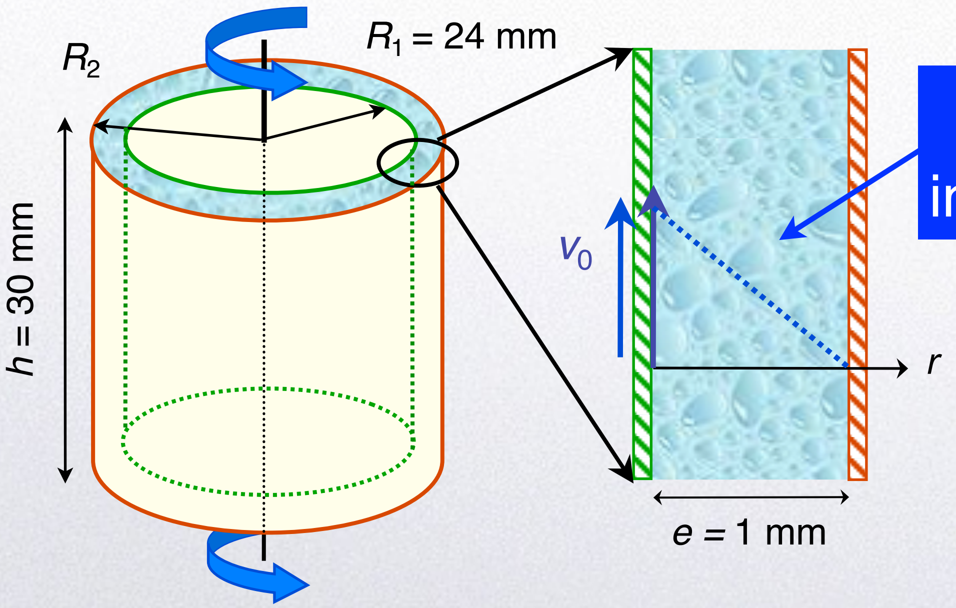
Berret *et al.*, *J. Phys II France* **4**, 1261-1279 (1994)

analogy with a first-order phase transition

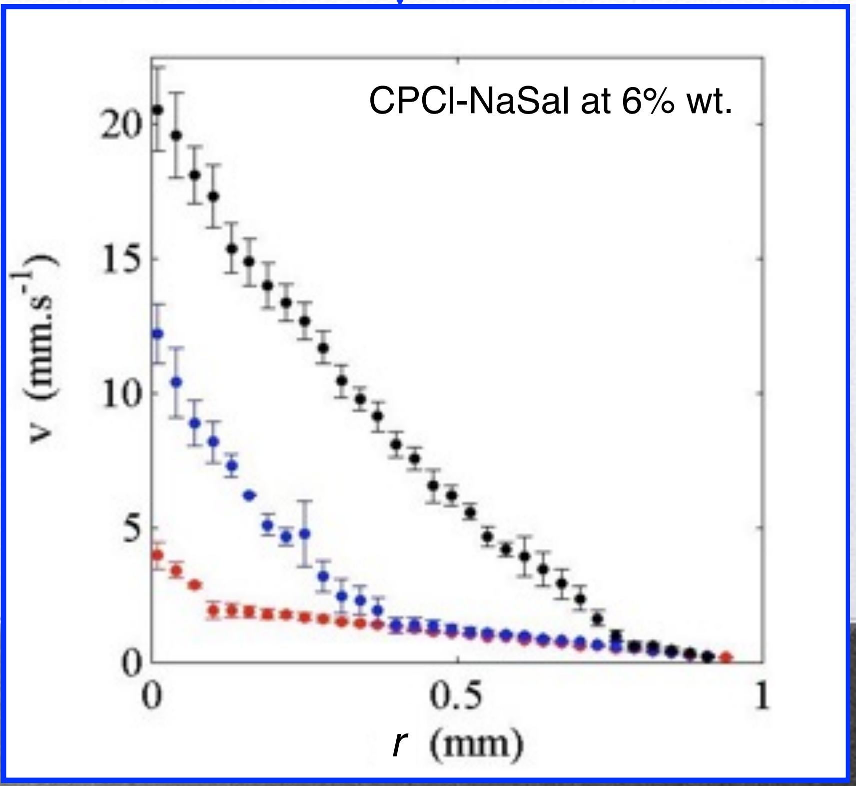
Shear banding in (semidilute) wormlike micelles







velocity profile
in Couette geometry



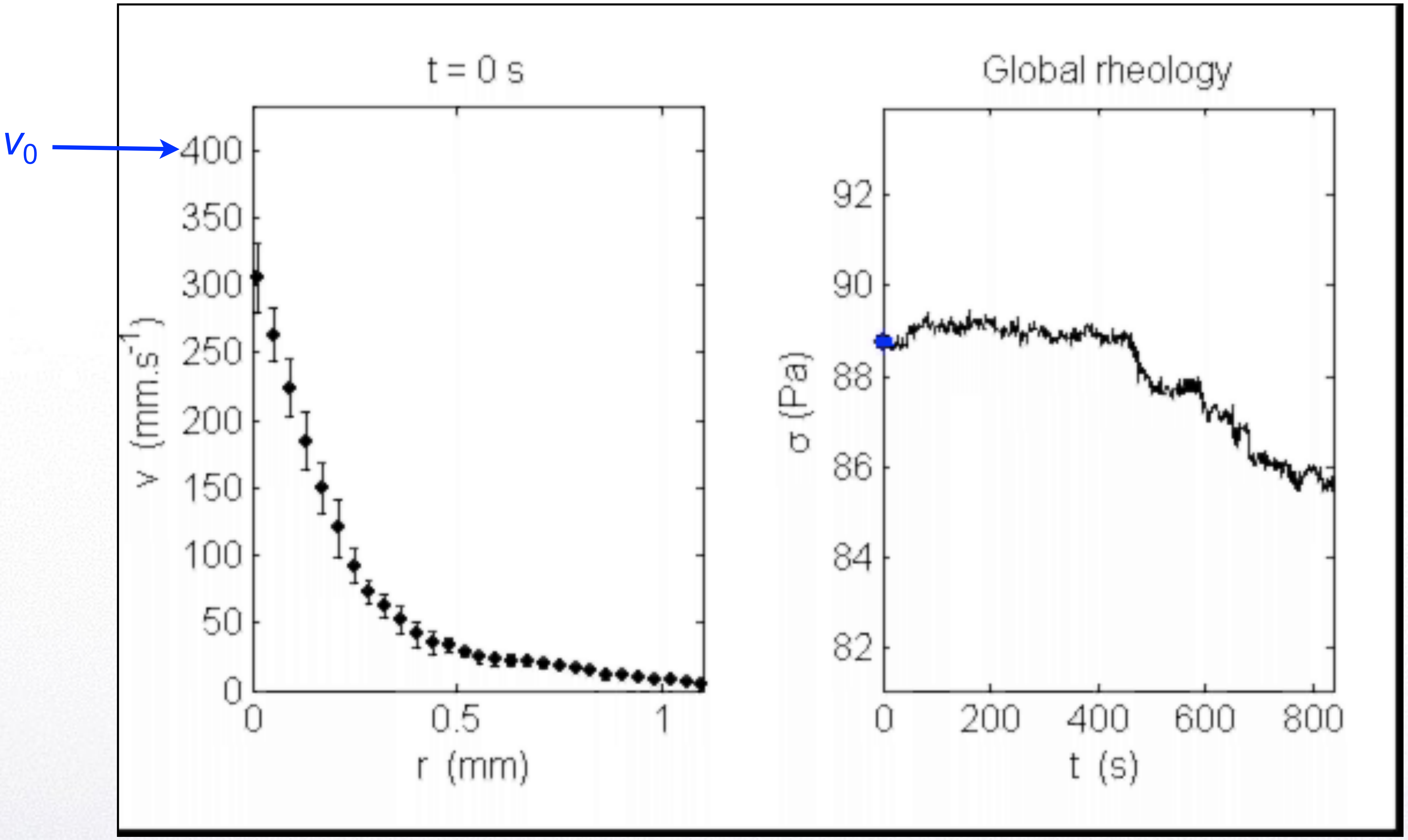
coexistence of two shear bands
along the gradient direction

Salmon *et al.*, *PRL* **90**, 228303 (2003)

Unsteady shear bands

$\dot{\gamma} = 400\ \mathrm{s}^{-1}$ during 900 s

CTAB-D_2O at 20% wt.



Bécu *et al.*, *PRL* **93**, 018301 (2004) & *PRE* **76**, 011503 (2007)

Lettinga & Manneville, *PRL* **103**, 248302 (2009)

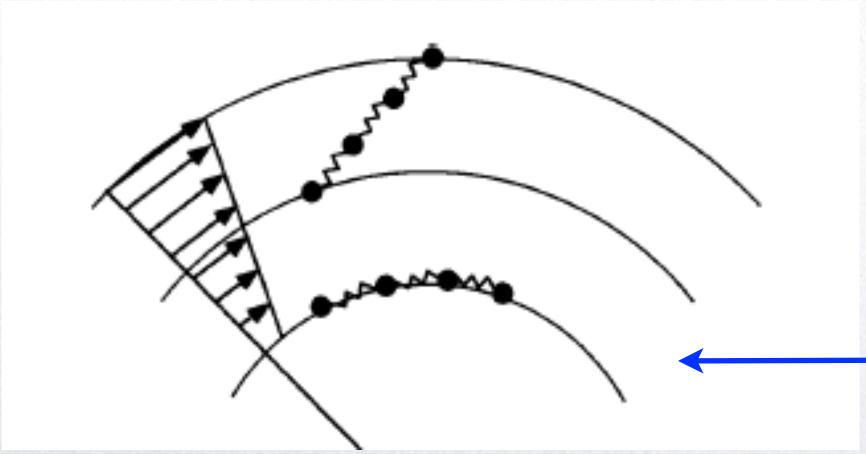
- fluctuations of interface position and of wall slip velocity
- intermittent nucleation of a high-shear band at the stator

⇒ unstable, three-dimensional flow?

Normal forces in viscoelastic fluids

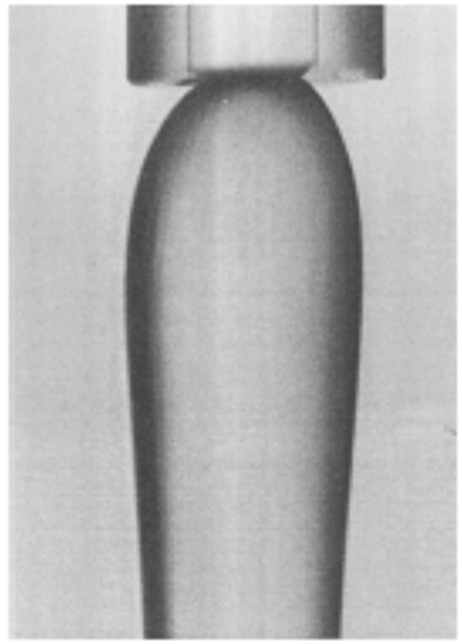
Weissenberg effect (1946)

G. McKinley, MIT

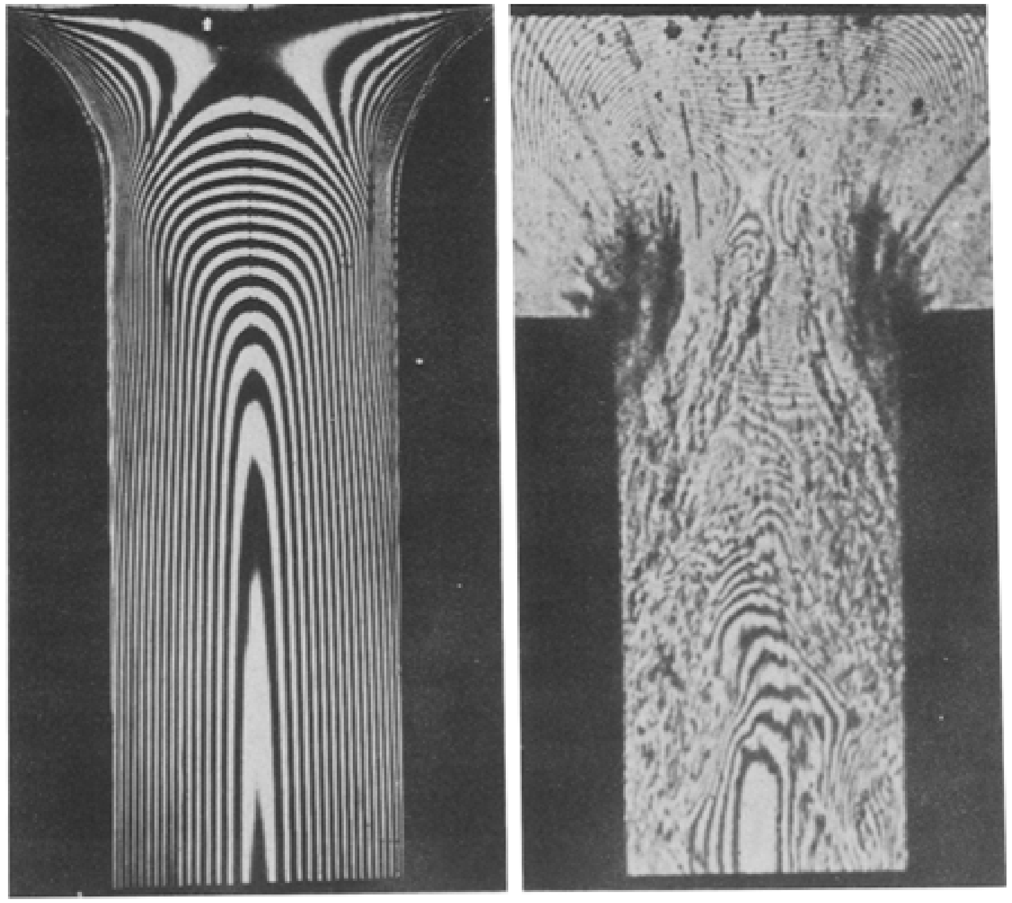


Pakdel & McKinley, *PRL* **77**, 2459-2463 (1996)

die swell



polymer flow birefringence

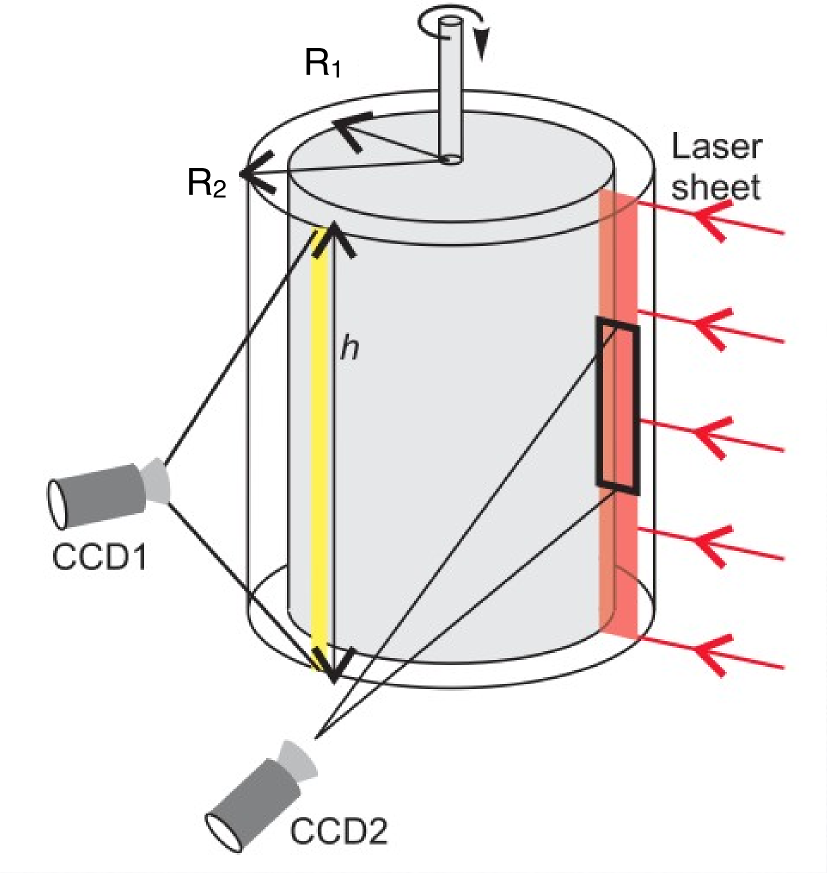


Vinogradov, *Rheol. Acta* **12**, 357-373 (1973)

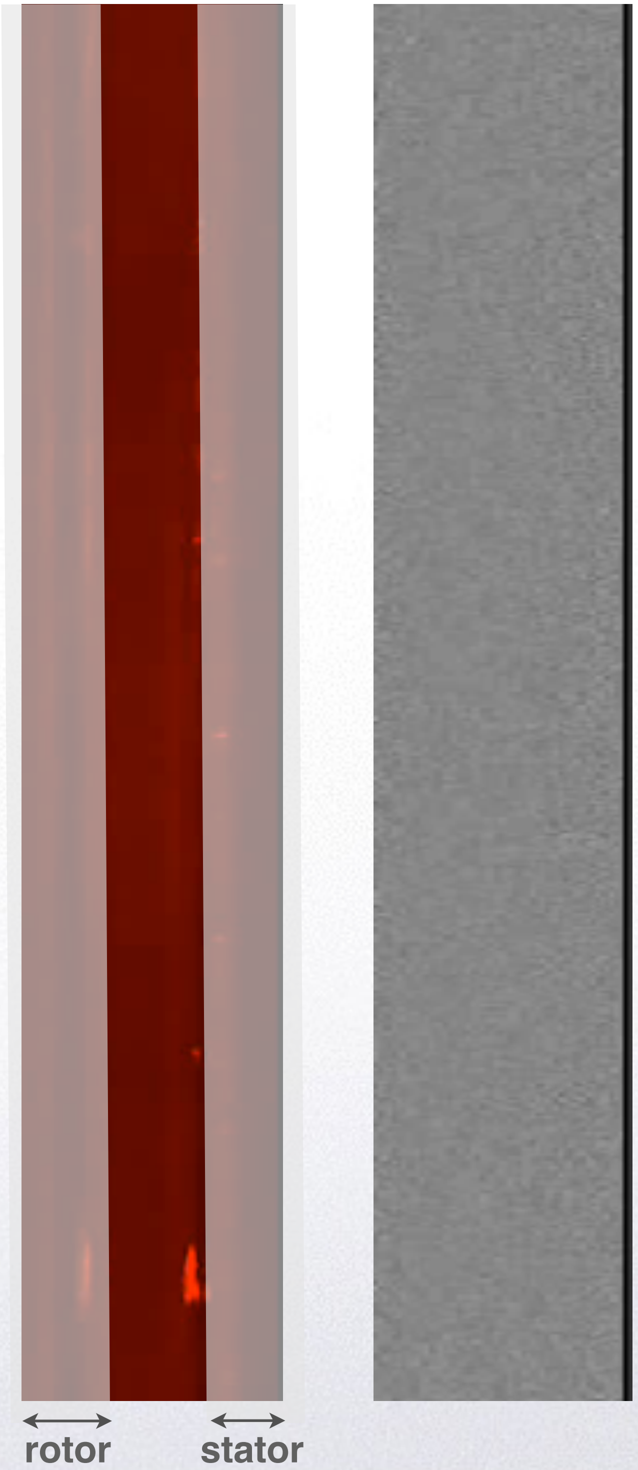
in a cylindrical geometry
curved streamlines ⇒ inward forces

possibility of elasticity-driven instabilities
in the absence of inertia

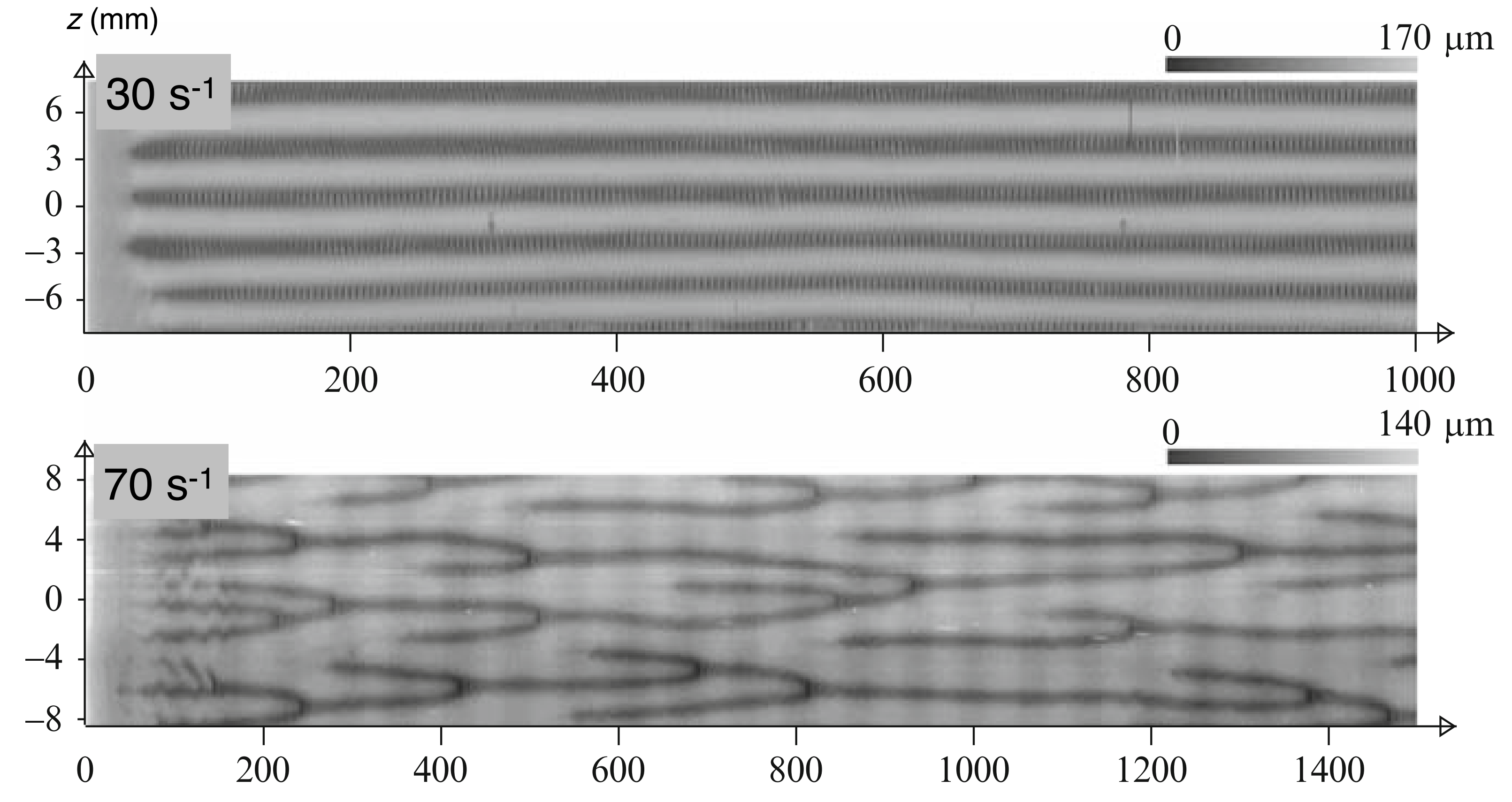
Rheo-optical study of shear banding

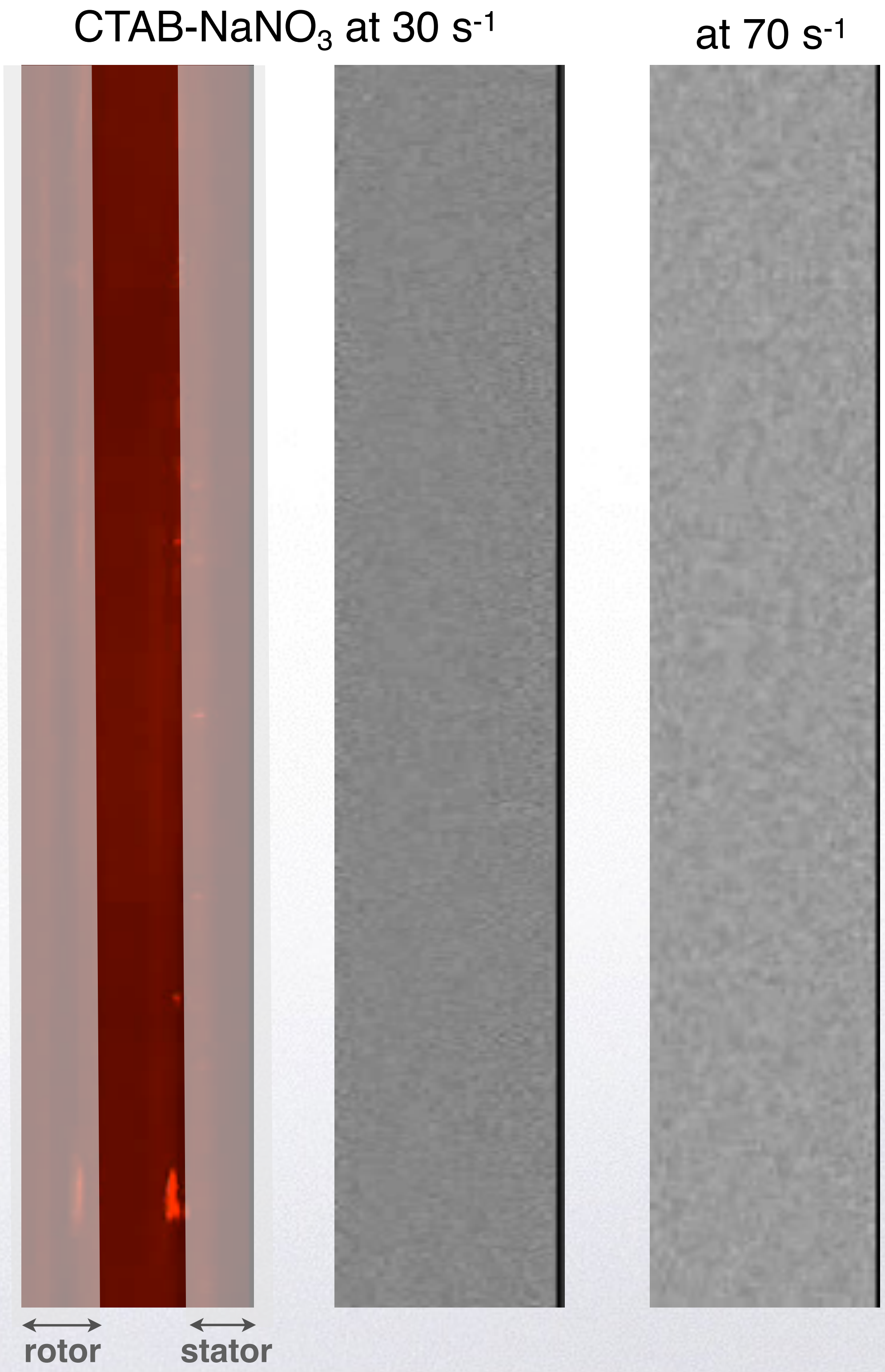


CTAB-$NaNO_3$ at 30 s^{-1}



Rheo-optical study of shear banding




CTAB-$NaNO_3$ at 30 s^{-1}

at 70 s^{-1}

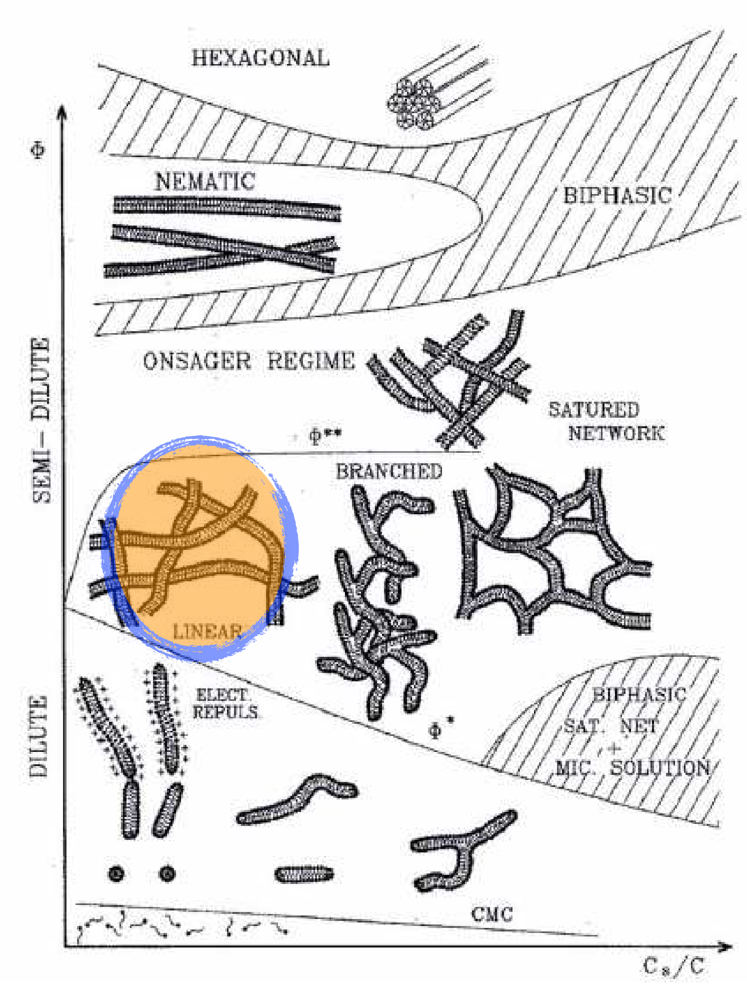
- instability of the interface between shear bands
- pairs of counter-rotating vortices
- creation-annihilation dynamics ⇒ chaotic?

Lerouge *et al.*, *PRL* **96**, 088301 (2006)
Lerouge *et al.*, *Soft Matter* **4**, 1808-1819 (2008)
Fardin *et al.*, *PRL* **103**, 028302 (2009)

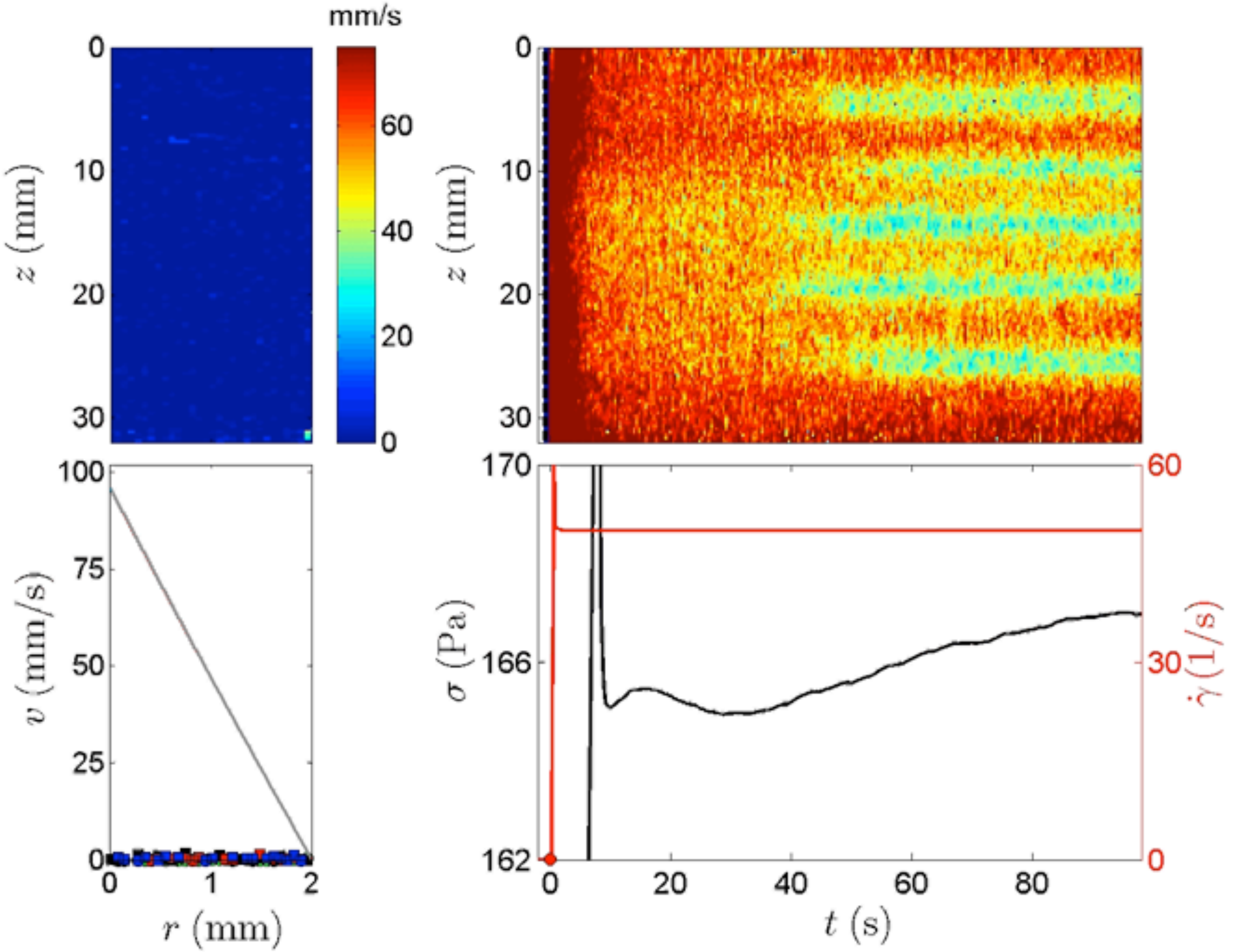
how to quantify these unstable dynamics?

Rheo-ultrasonic imaging of elastic instability

CTAB (0.3 M) - $NaNO_3$ (0.4 M)

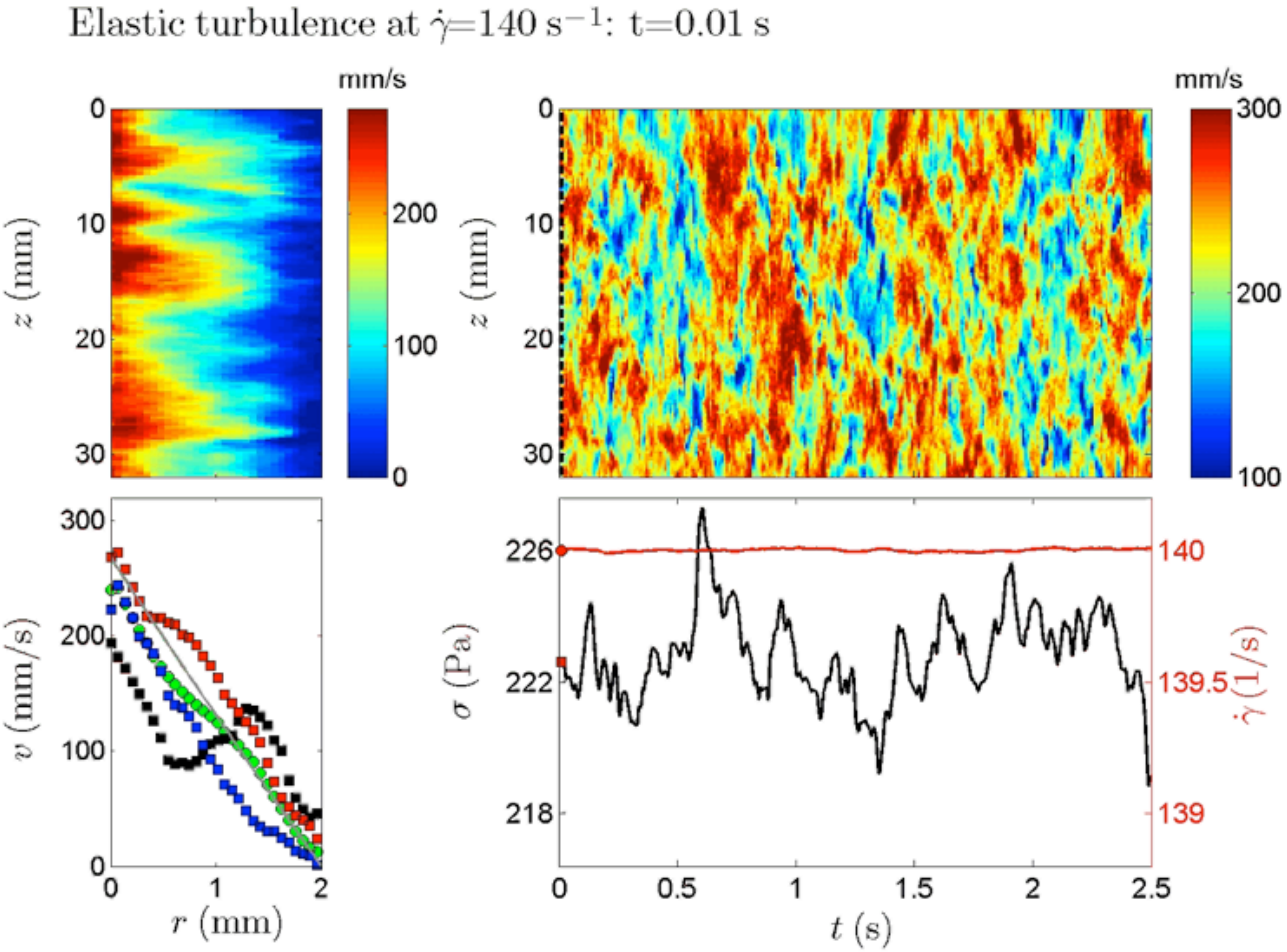


Transition to a shear-banded vortex flow at $\dot{\gamma}$=50 s^{-1}: t=-0.8 s



Perge *et al.*, *Eur. Phys. J* E **37**, 23 (2014) & *Soft Matter* **10**, 1450 (2014)
Fardin *et al.*, *Phys. Rev.* E **89**, 011001(R) (2014)

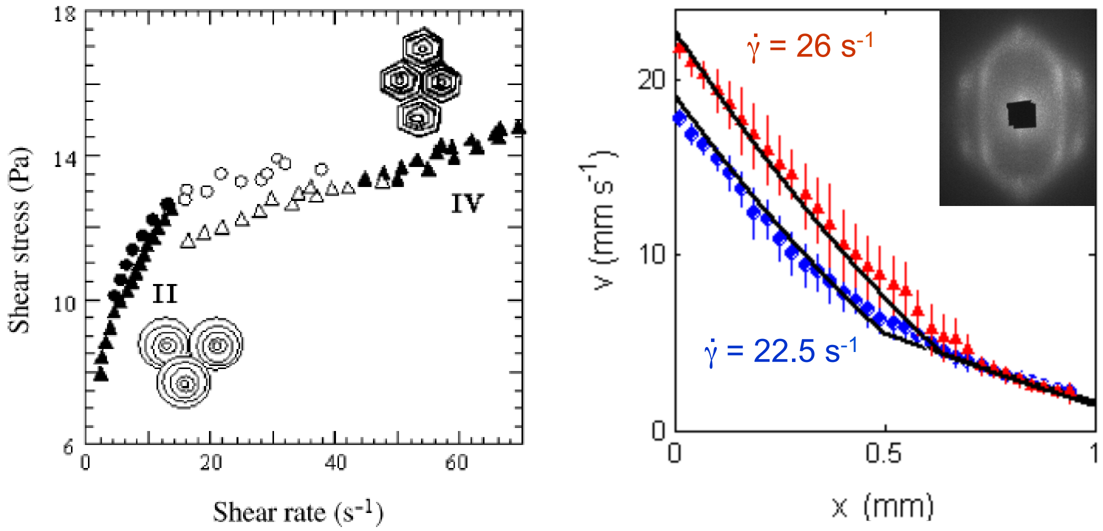
Rheo-ultrasonic imaging of elastic turbulence


Elastic turbulence at $\dot{\gamma}$=140 s^{-1}: t=0.01 s

Perge *et al.*, *Eur. Phys. J* E **37**, 23 (2014) & *Soft Matter* **10**, 1450 (2014)
Fardin *et al.*, *Phys. Rev.* E **89**, 011001(R) (2014)

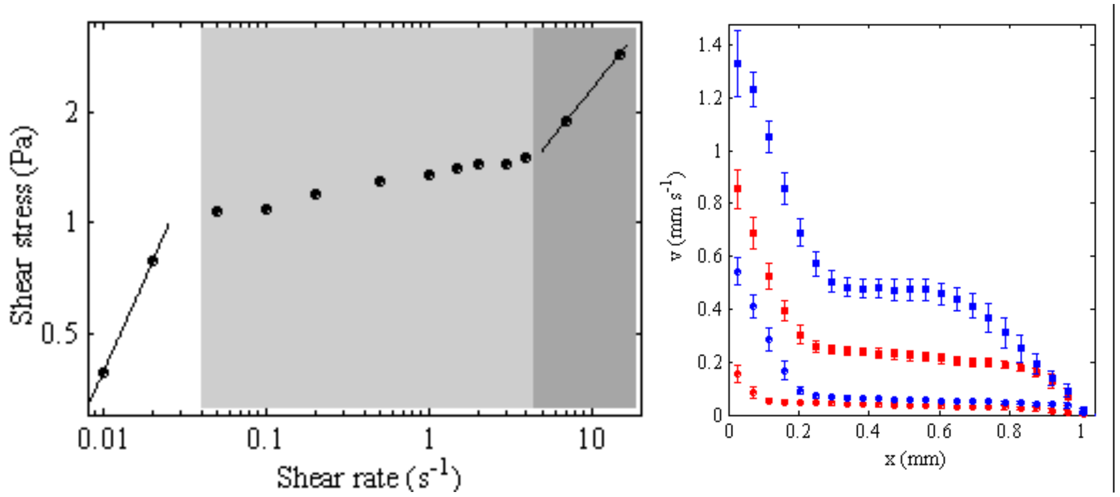
Similar phenomenology in…

surfactant multilamellar vesicles



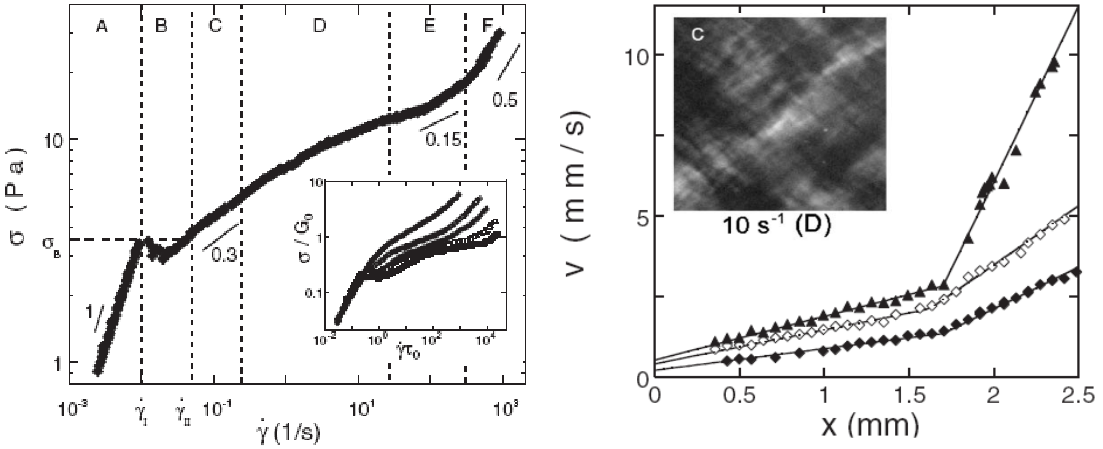
Salmon *et al.*, *PRE* **68**, 051503 (2003)

triblock copolymer micelles



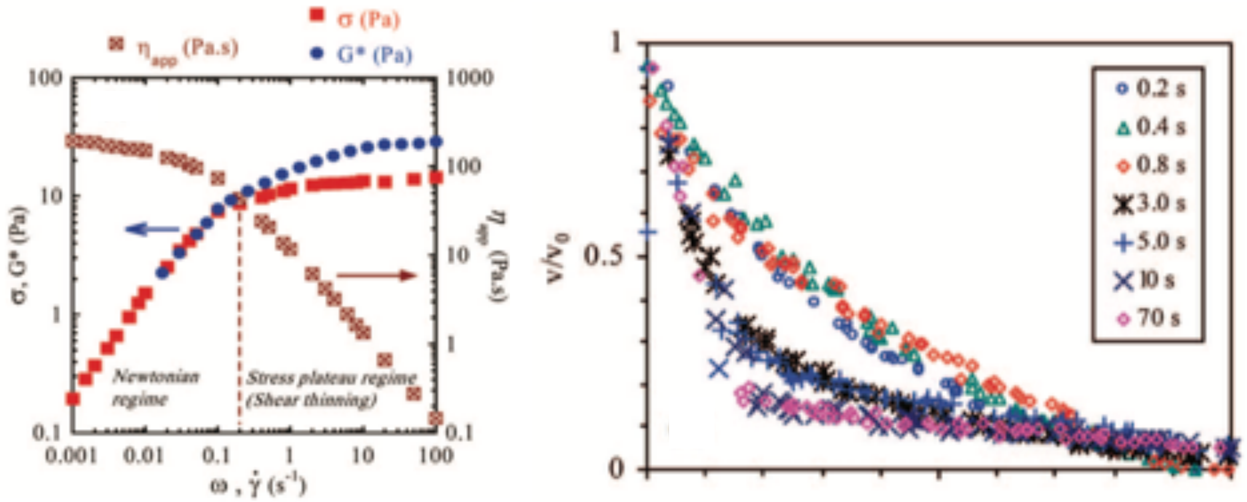
Manneville *et al.*, *PRE* **75**, 061502 (2007)

EHUT supramolecular polymers



van der Gucht *et al.*, *PRL* **75**, 108301 (2006)

entangled DNA solutions

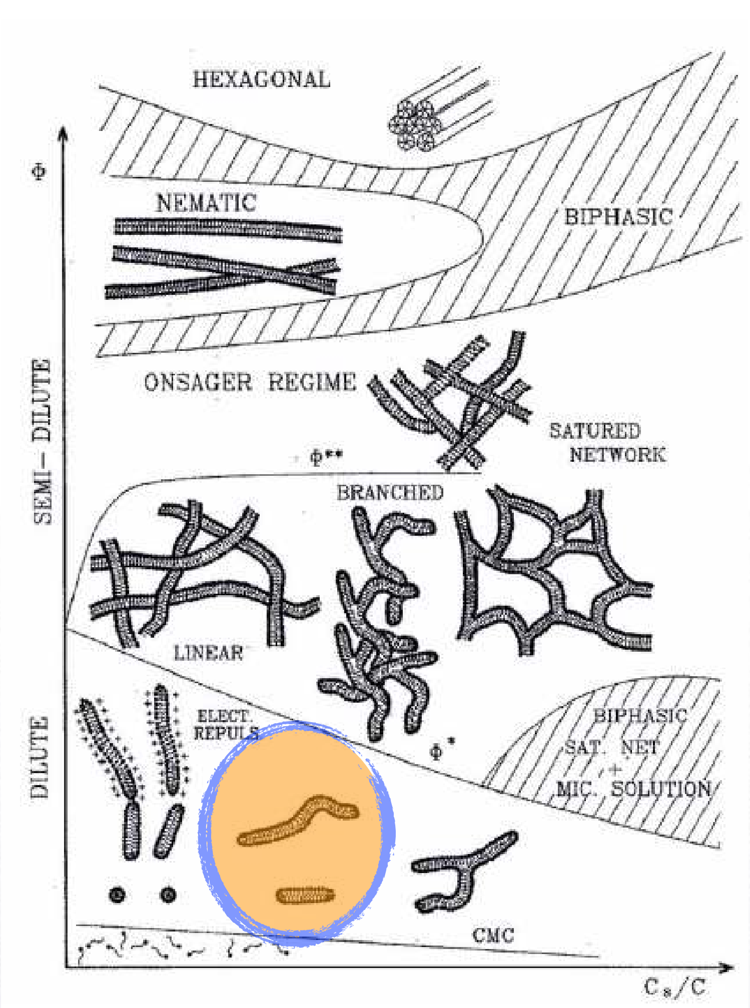


Boukany *et al.*, *Macromol.* **41**, 2644-2650 (2008)

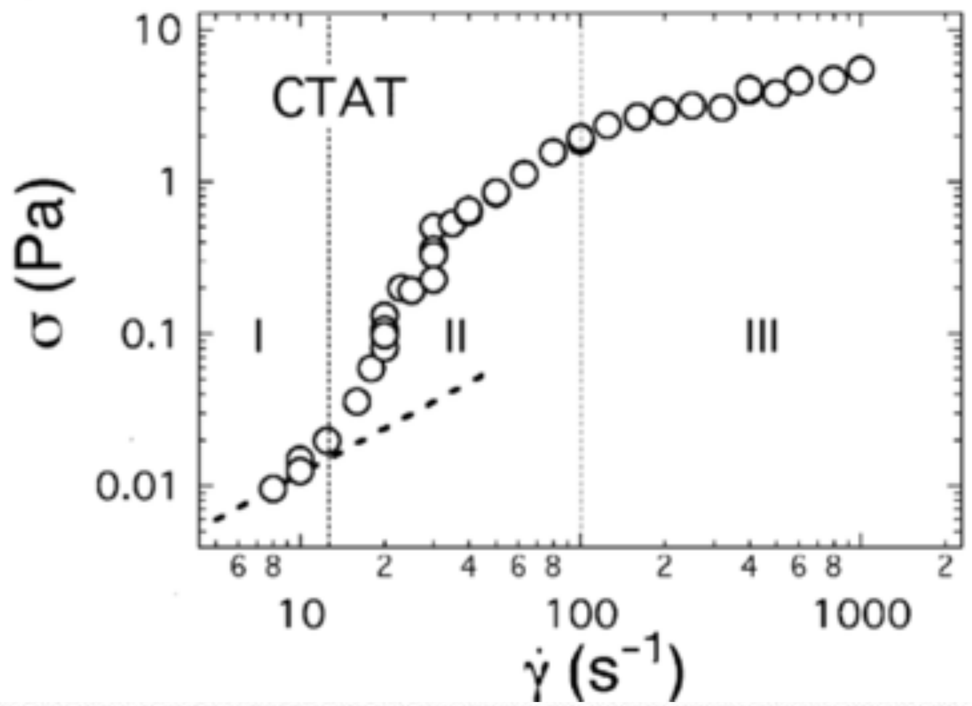
gradient banding is widespread in shear-thinning transitions

+ complications due to elasticity!

Shear-thickening in (dilute) wormlike micelles

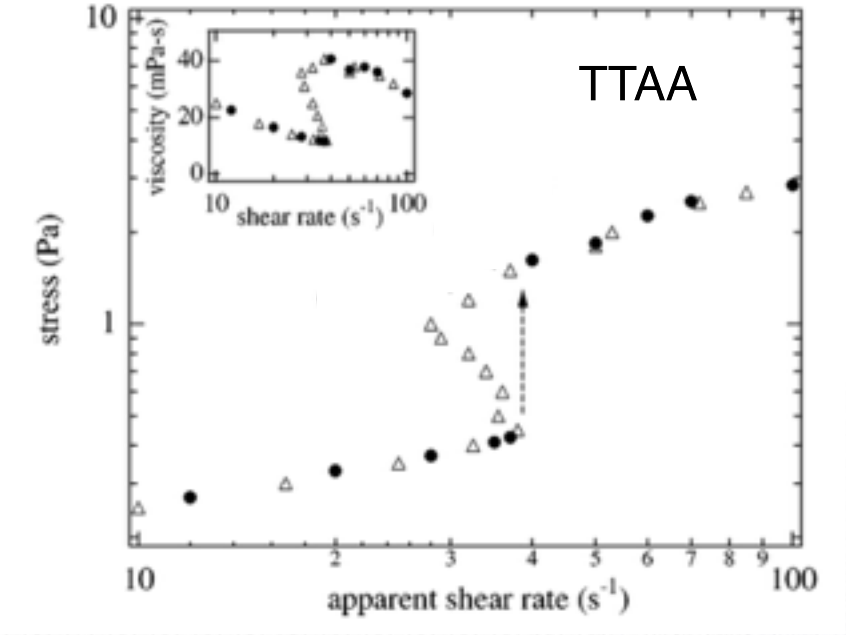


continuous transition

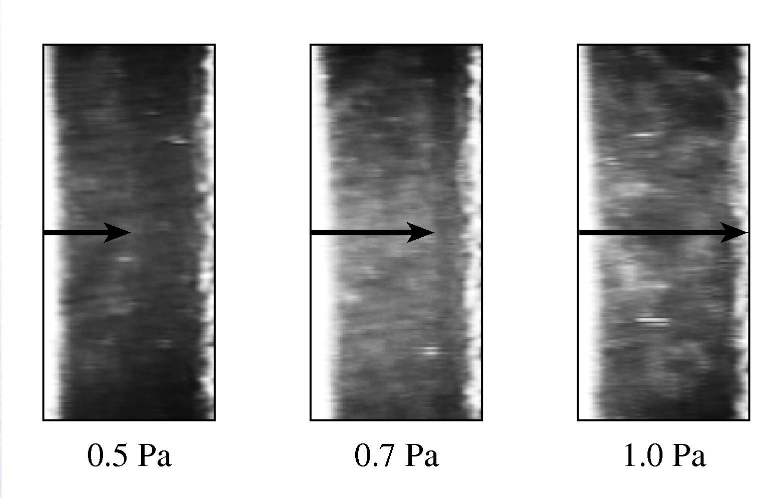


Gamez-Corrales *et al.*, *Langmuir* **79**, 6755-6763 (1999)

discontinuous transition



Boltenhagen *et al.*, *PRL* **79**, 2359 (1997)
Hu *et al.*, *J. Rheol.* **42**, 1185 (1998)

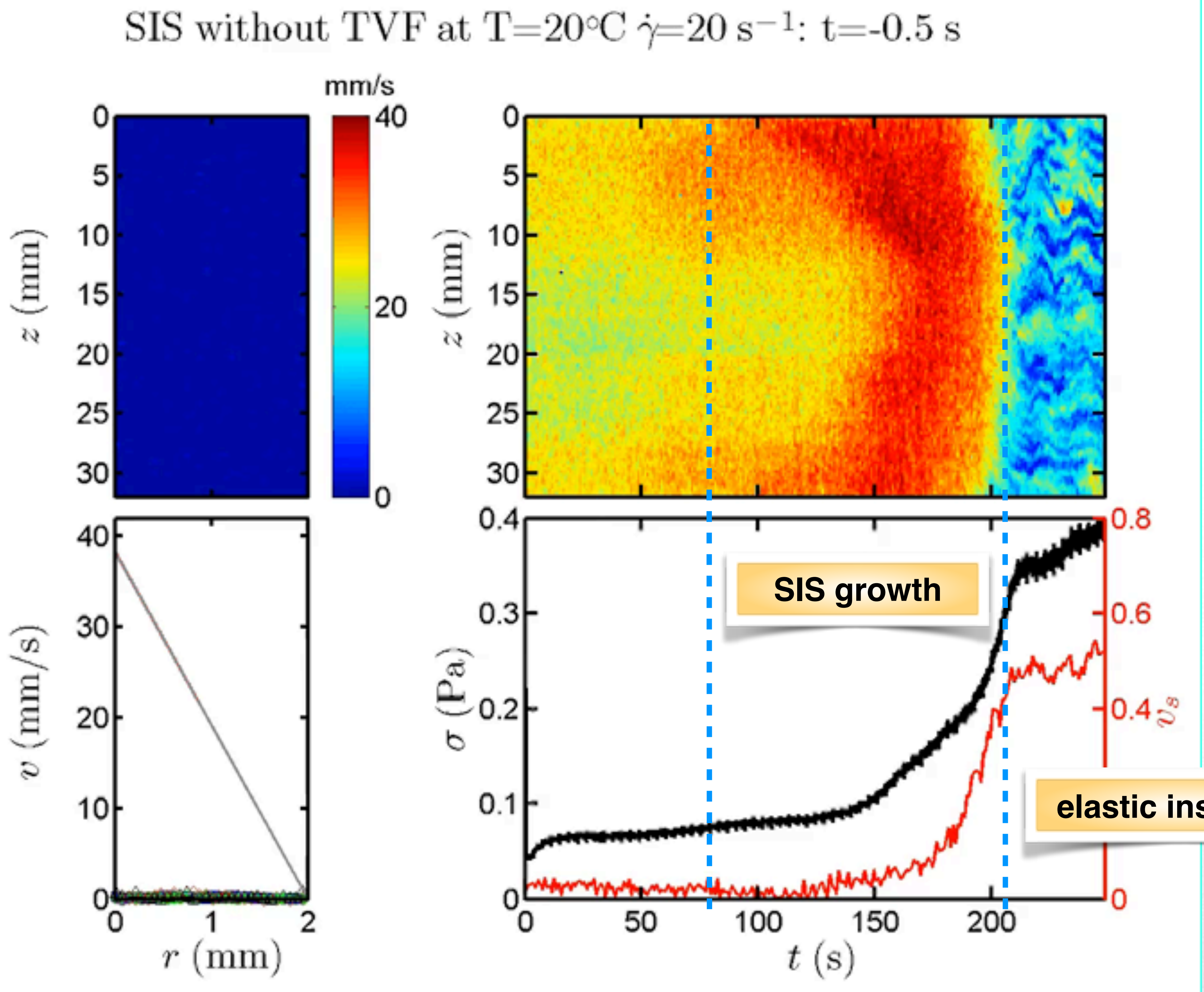


⇒ growth of gel-like shear-induced structures (SIS)

⇒ phase coexistence under imposed stress

Dynamics of shear-thickening wormlike micelles

CTAT
0.16% wt.



SIS growth

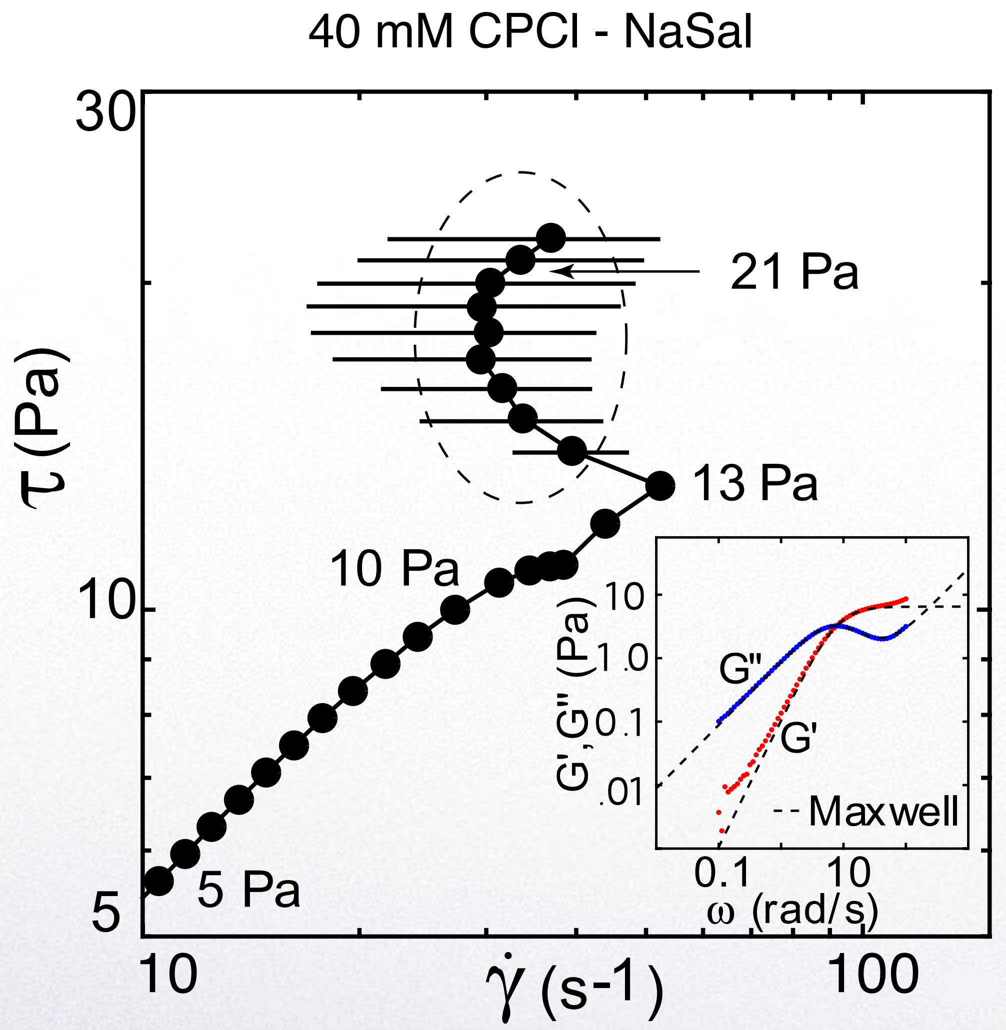
elastic instability

⇒ long induction phase and subsequent elastic instability of the SIS

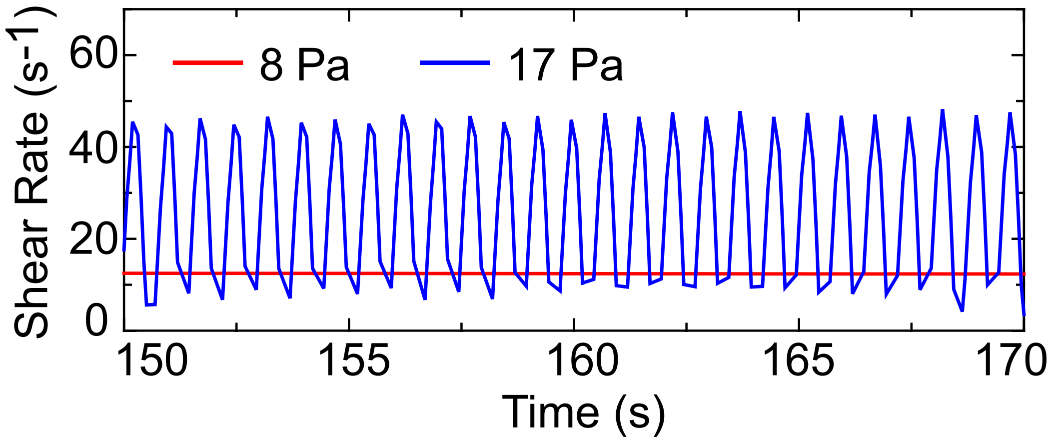
Fardin *et al.*, *Phys. Rev.* E **89**, 011001(R) (2014)

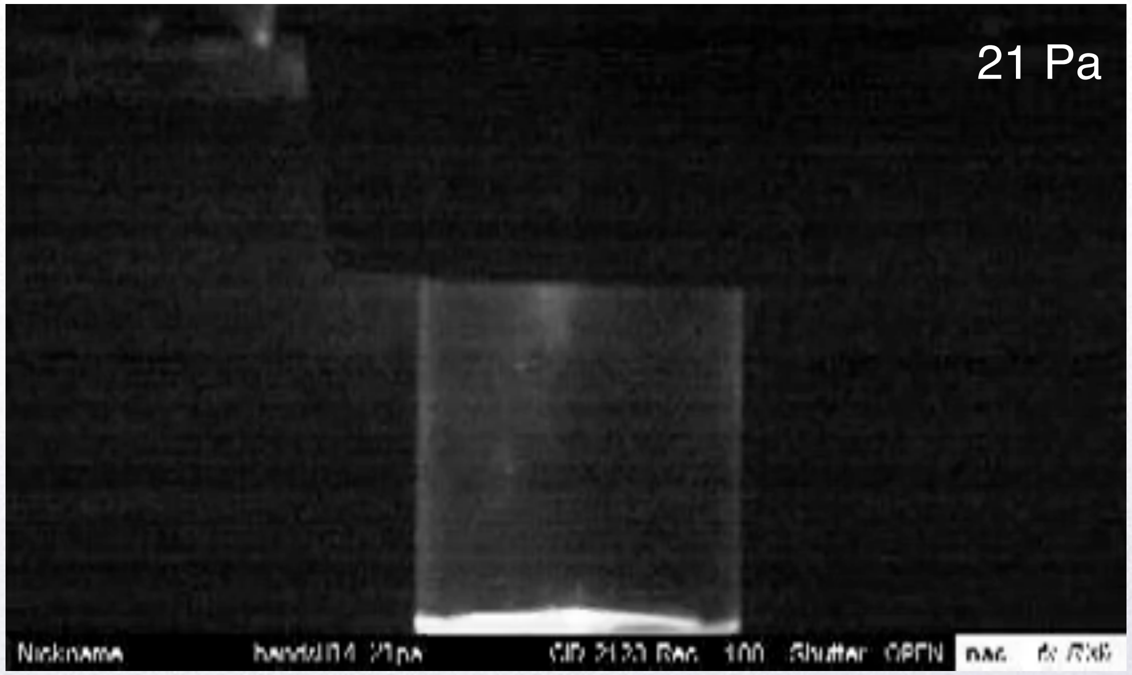
Vorticity banding in wormlike micelles

shear-thinning <u>followed by</u> shear-thickening !



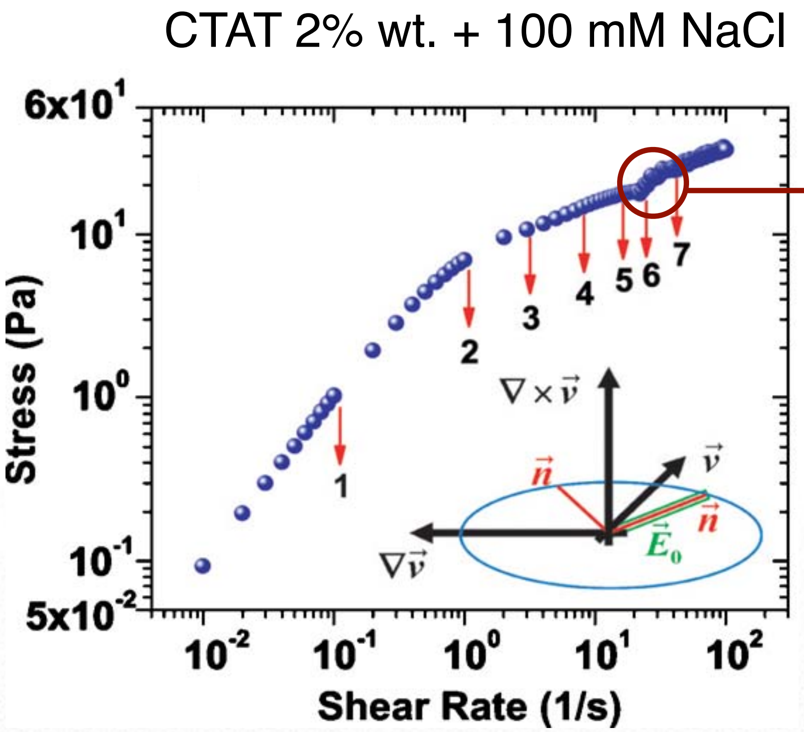
Herle *et al.*, *PRL* **99**, 158302 (2007) &
Eur. Phys. J. E **26**, 3-12 (2008)

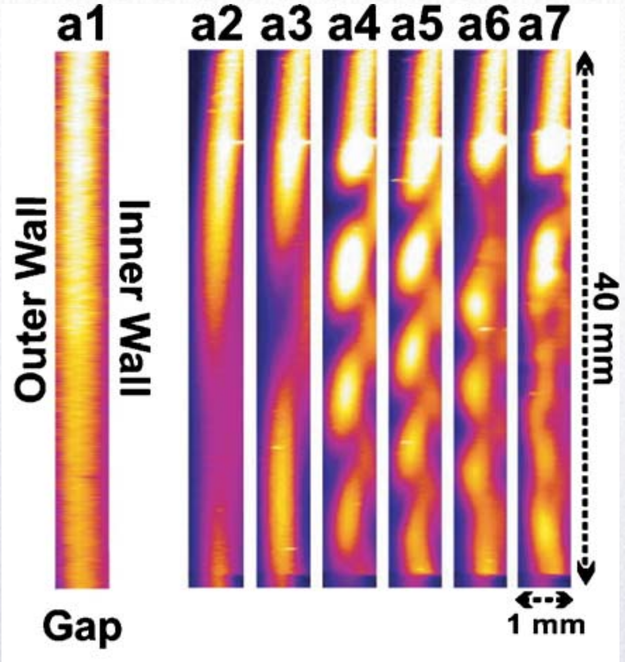


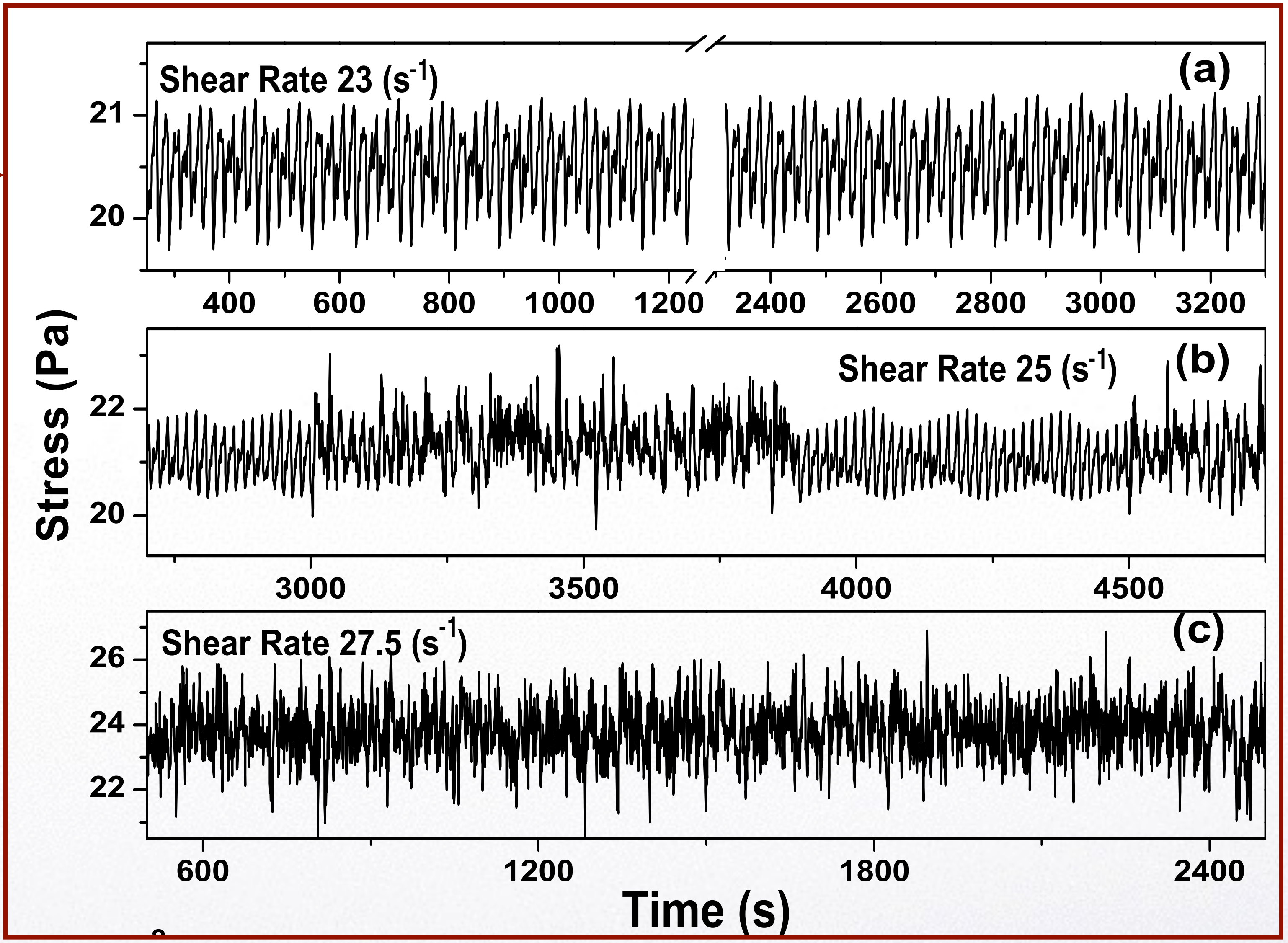


periodic oscillations of the shear rate & alternating vorticity bands
⇒ interplay between alignment/concentration & viscoelasticity

Rheochaos in wormlike micelles







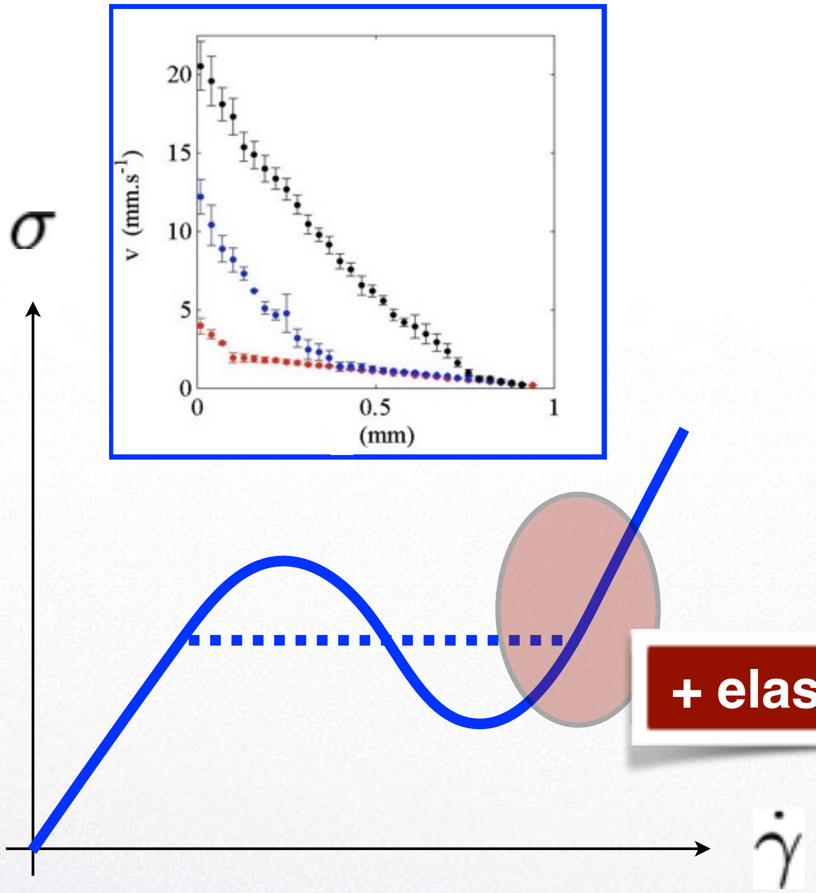
Ganapathy & Sood, *PRL* **96**, 108301 (2006) & *PRE* **78**, 021504 (2008)

⇒ evidence for type-II intermittency (via quasiperiodicity)

⇒ flow-concentration coupling and/or elastic instability?

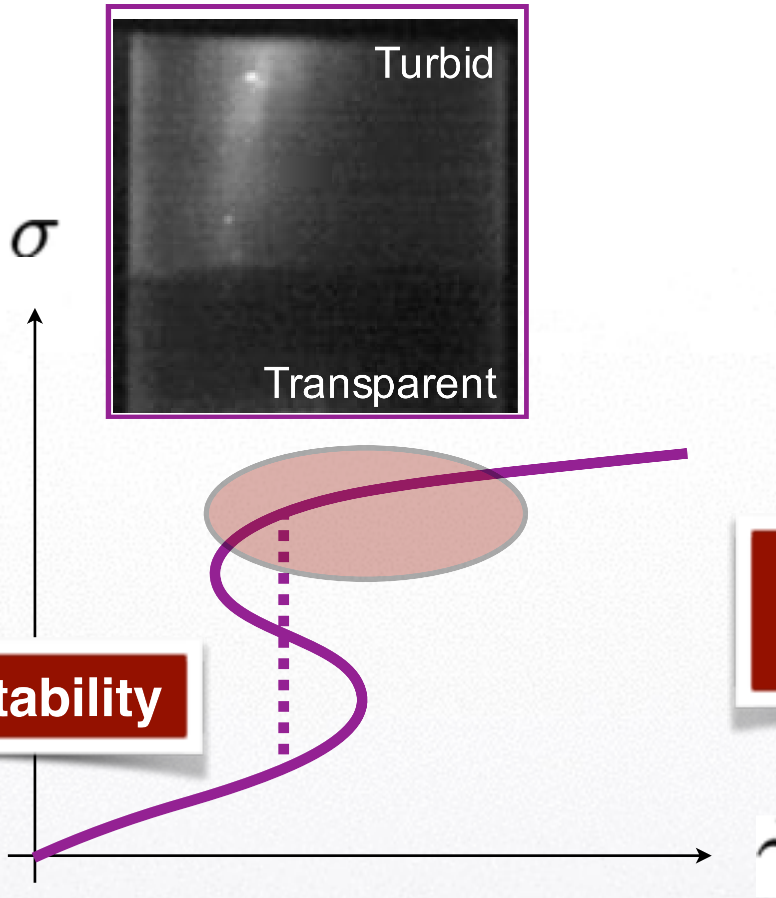
Wormlike micelles summary

shear-thinning
⇒ gradient banding

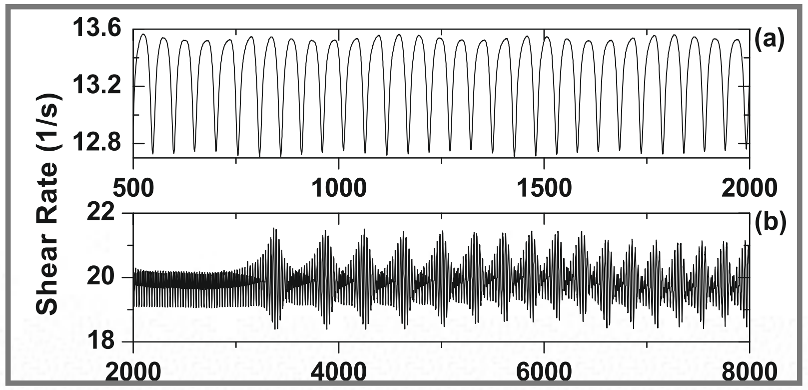


+ elastic instability

shear-thickening
⇒ vorticity banding



… or both?



+ flow-concentration coupling
+ nematohydrodynamics

surfactant wormlike micelles show a wide range of heterogeneous flows & dynamical behaviours (that are interesting to keep in mind for dense suspensions)

Outline

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from gradient banding to elastic turbulence to vorticity banding

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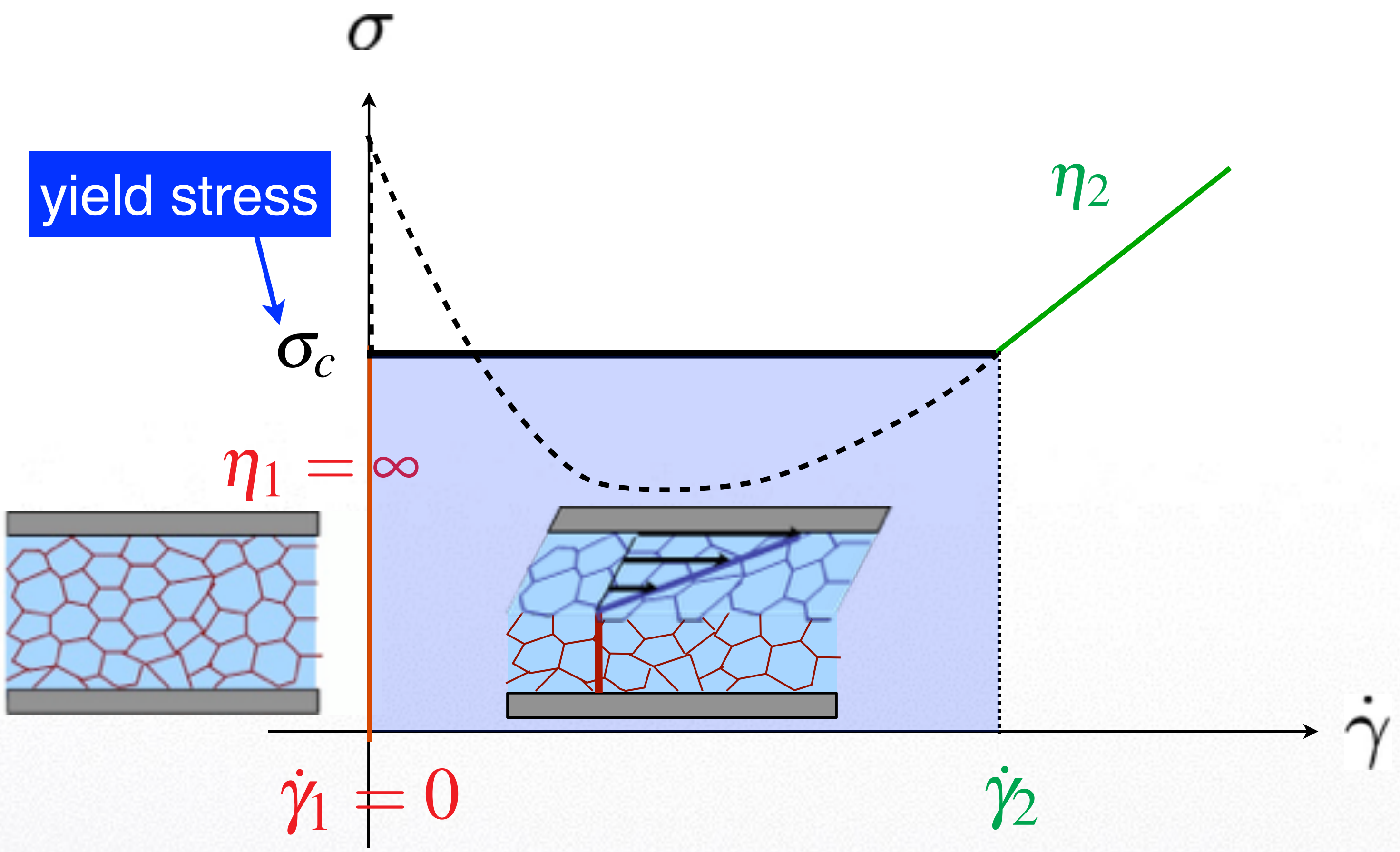
T. Divoux, M.-A. Fardin, SM & S. Lerouge, *Ann. Rev. Fluid Mech.* **48**, 81–103 (2016)

D. Bonn, M. Denn, L. Berthier, T. Divoux & SM, *Rev. Mod. Phys.* **89**, 035005 (2017)

III. What about dense suspensions?

similarities and differences with other complex fluids

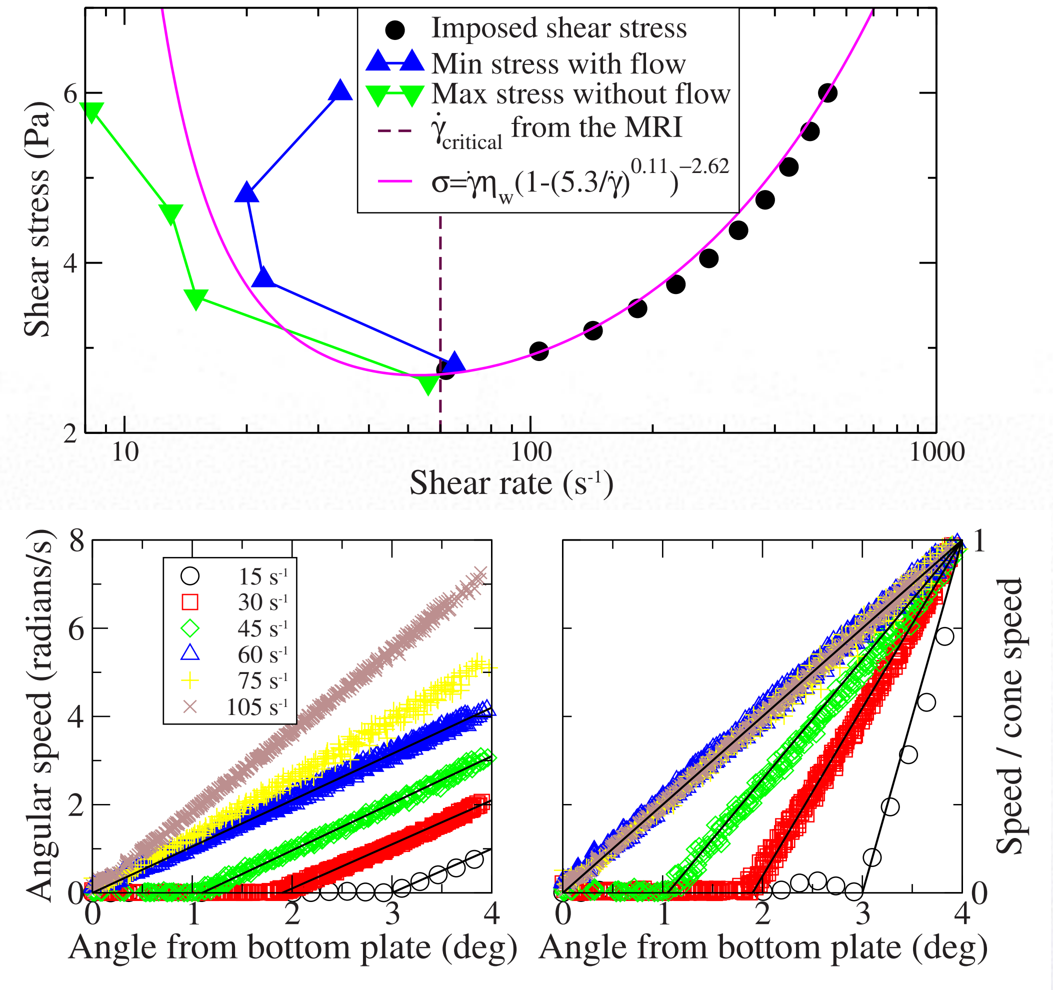
Shear banding in yield stress fluids



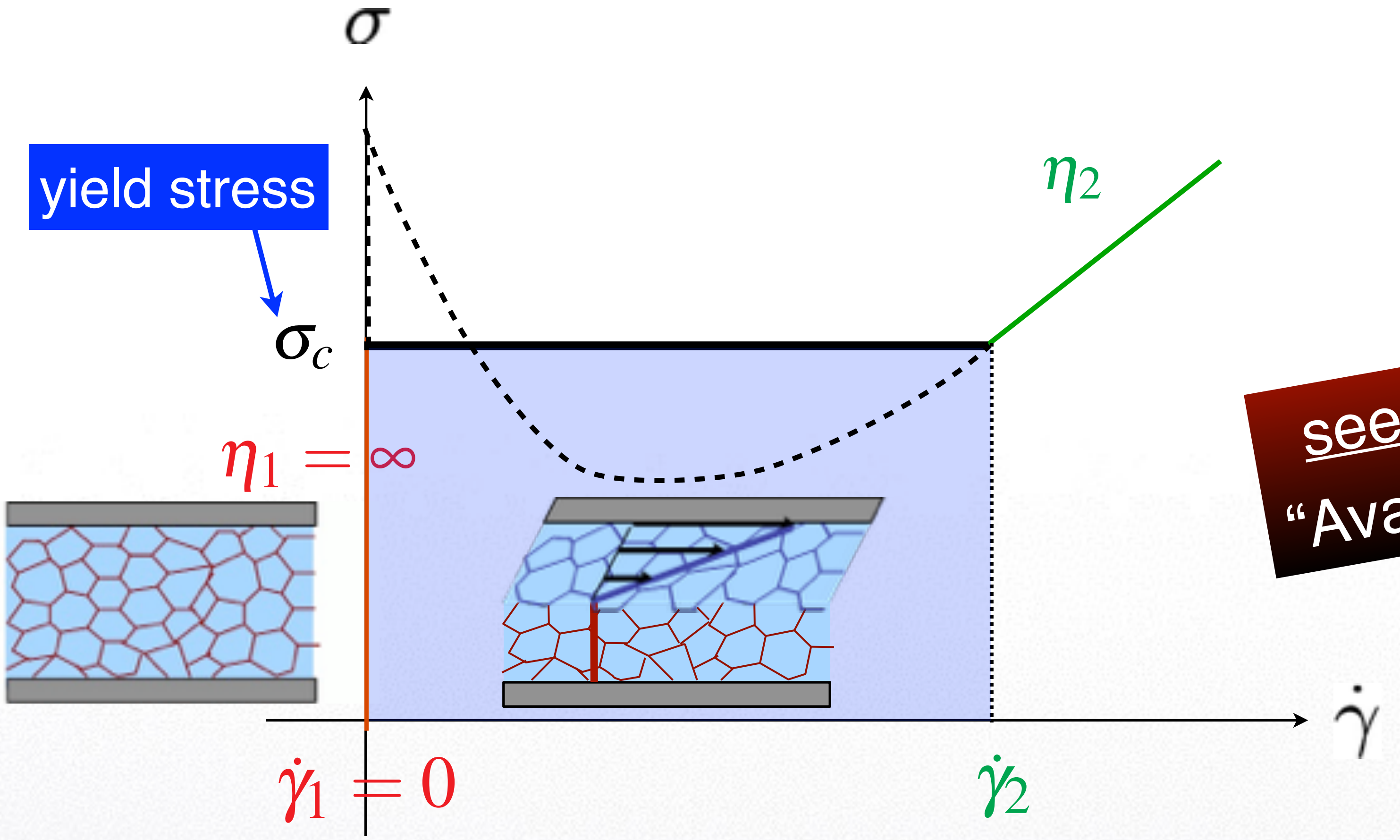
- “1st order” shear-induced solid-liquid transition
- coexistence = shear localization in a fluidized region

ludox colloidal gel

Møller *et al.*, *PRE* **77**, 041507 (2008)

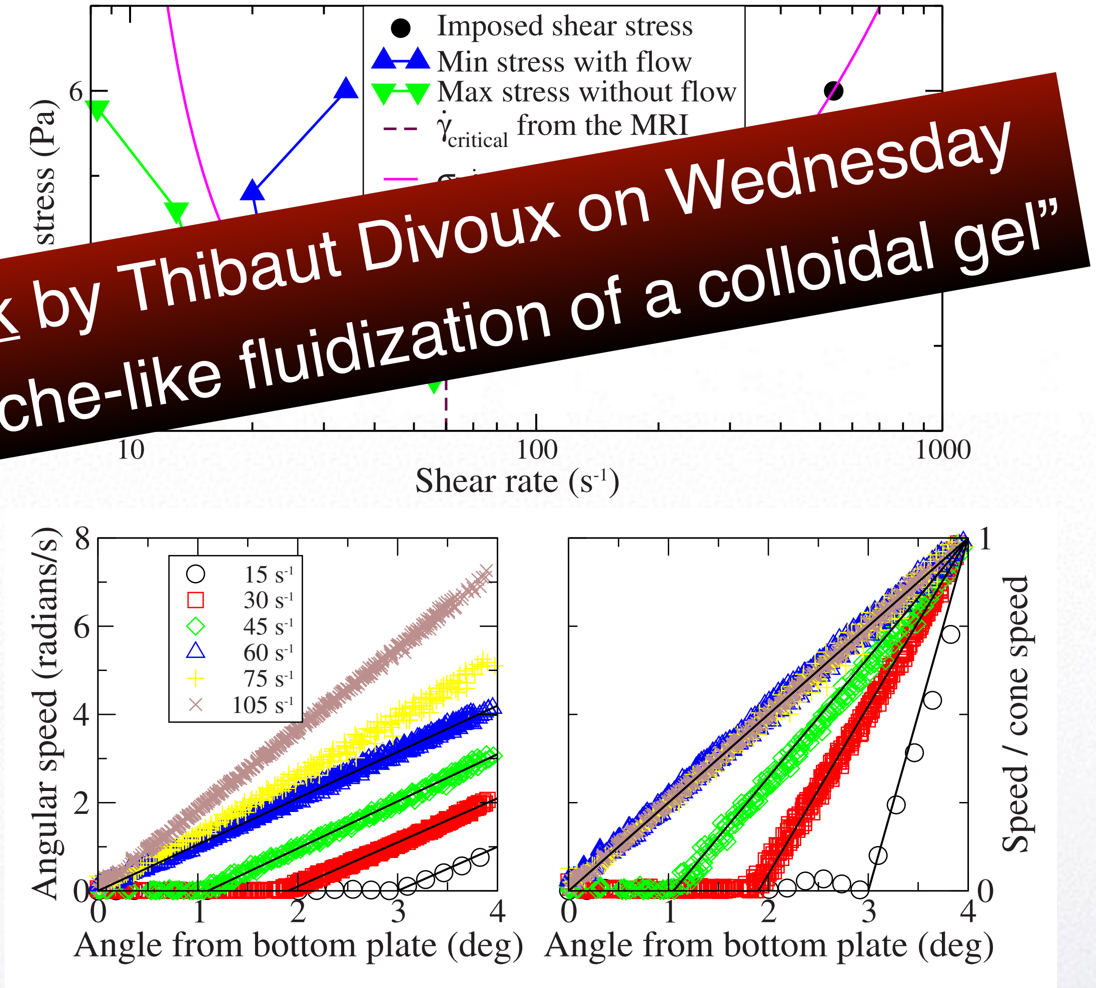


Shear banding in yield stress fluids



ludox colloidal gel

Møller *et al.*, *PRE* **77**, 041507 (2008)



see talk by Thibaut Divoux on Wednesday
“Avalanche-like fluidization of a colloidal gel”

- “1st order” shear-induced solid-liquid transition
- coexistence = shear localization in a fluidized region

Seen in :
colloidal gels

pastes

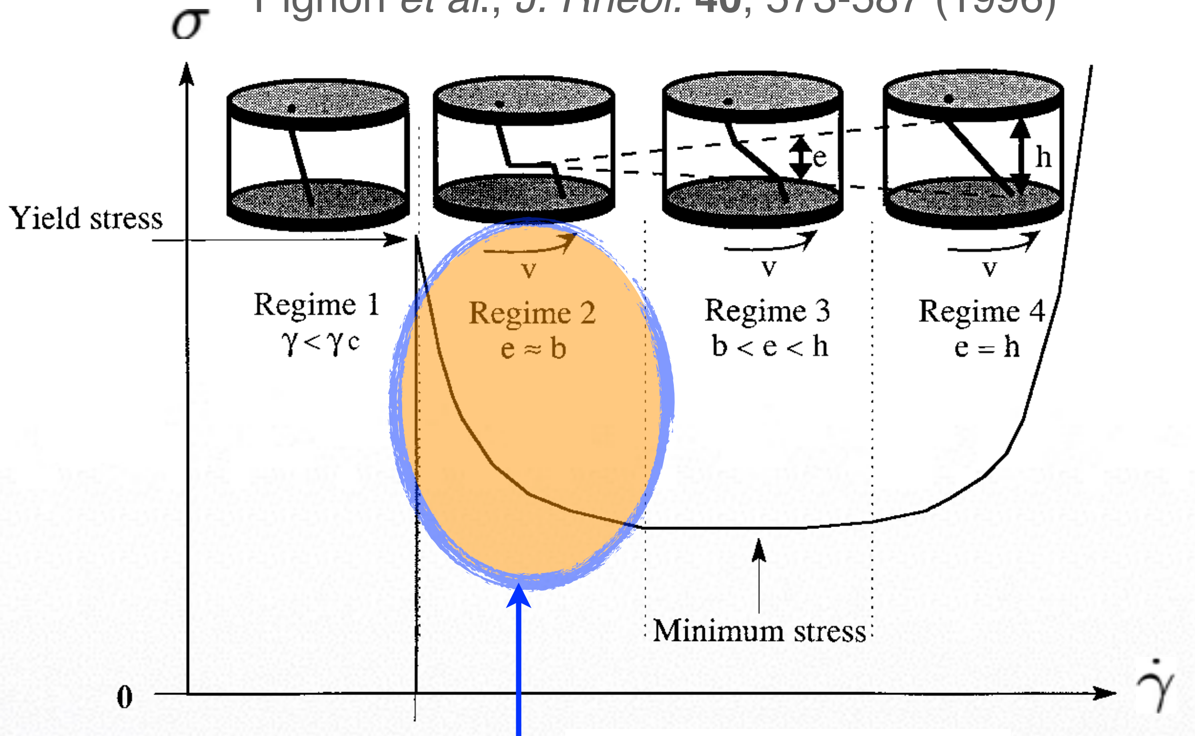
and clay suspensions

⇒ interplay between aging and shear rejuvenation

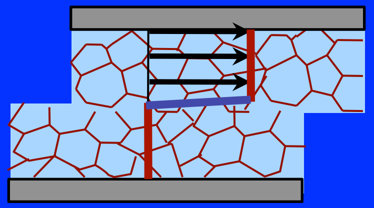
Other instability modes

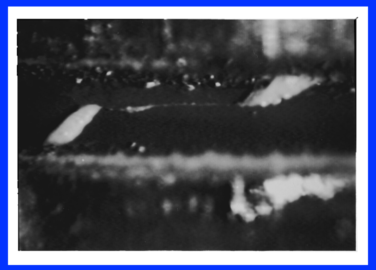
laponite suspensions

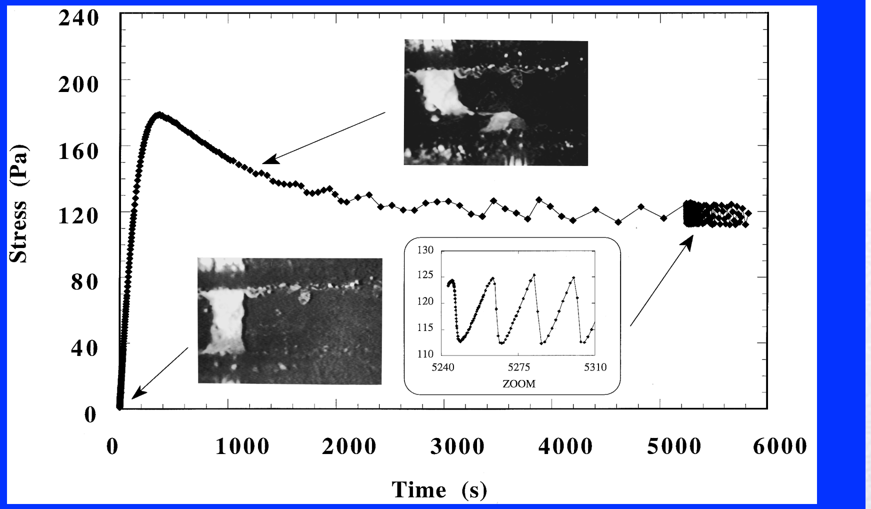
Pignon *et al.*, *J. Rheol.* **40**, 573-587 (1996)



<u>no steady flow</u>: fractures and stick-slip







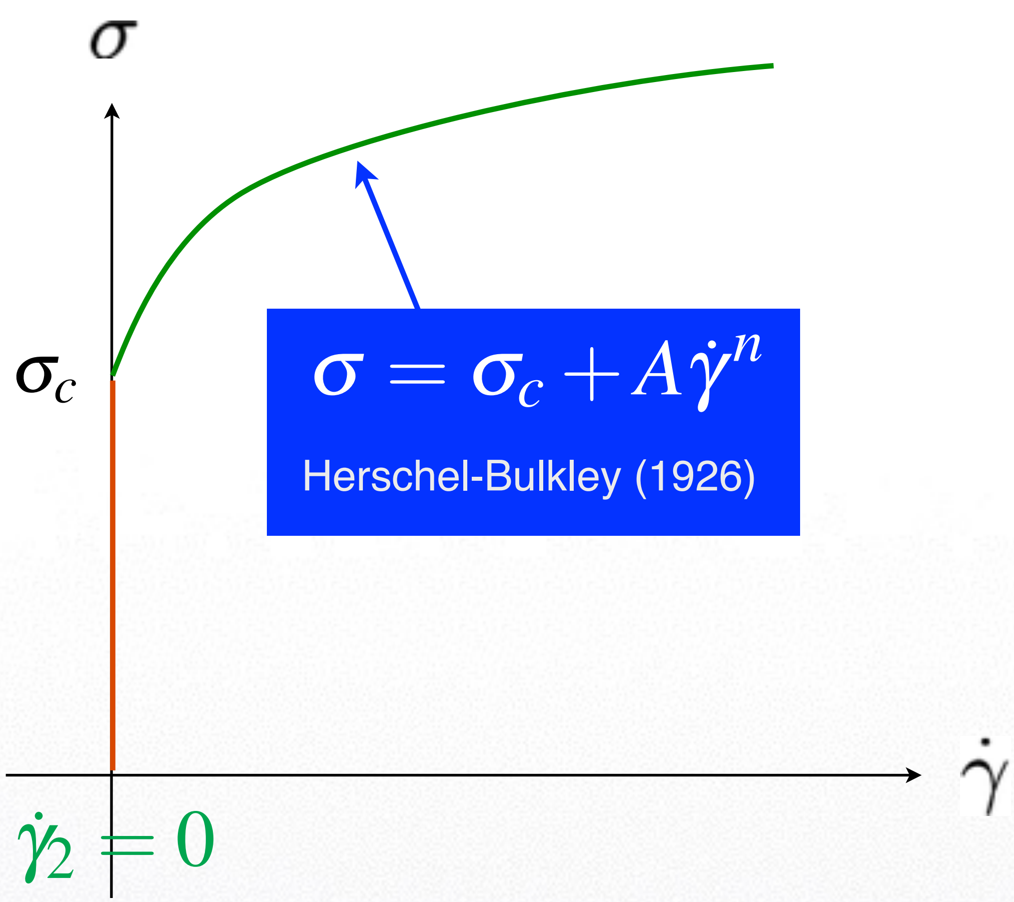
casein gels

Leocmach *et al.*, *PRL* **113**, 038303 (2014)

- irreversible fluidization
- fracture growth
- well-defined wavelength
- macroscopic phase separation

⇒ does homogeneous, continuous yielding exist at all?

Simple yield stress fluids

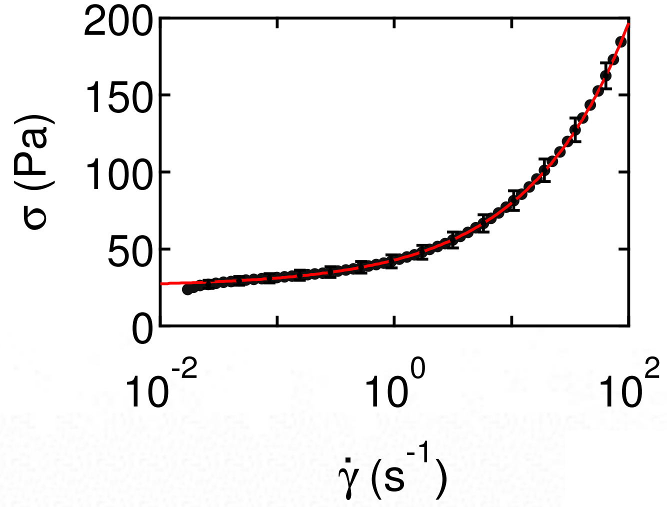


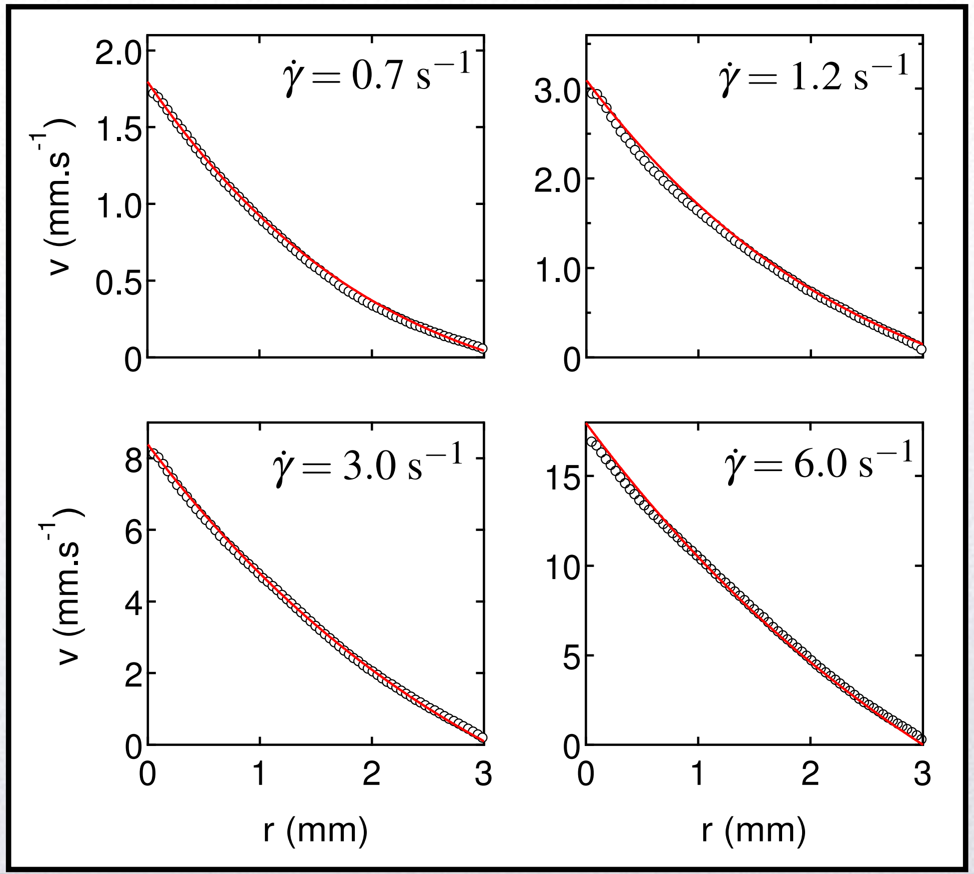
$$\sigma = \sigma_c + A\dot{\gamma}^n$$

Herschel-Bulkley (1926)

carbopol microgel (ETD 2050)

Divoux *et al.*, *Soft Matter* **8**, 4151-4164 (2012)





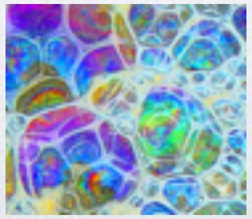
- “2^{nd} order” shear-induced solid-liquid transition
- homogeneously sheared flow

Seen in :

emulsions

microgels

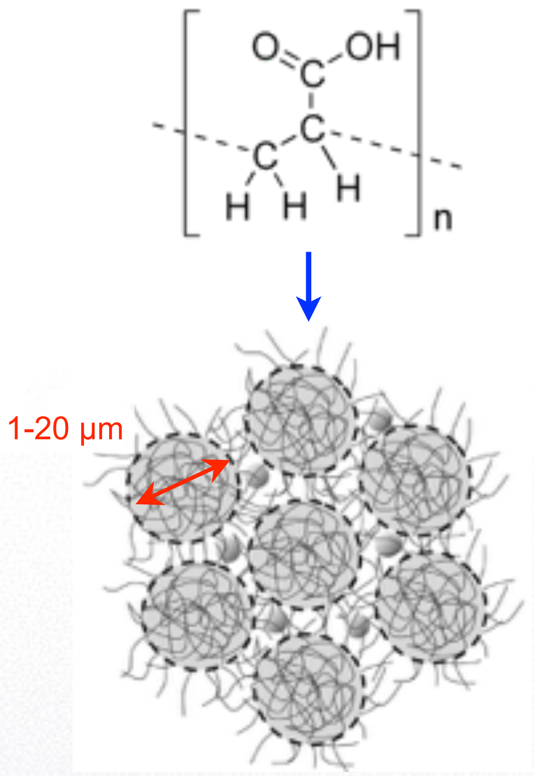
and foams

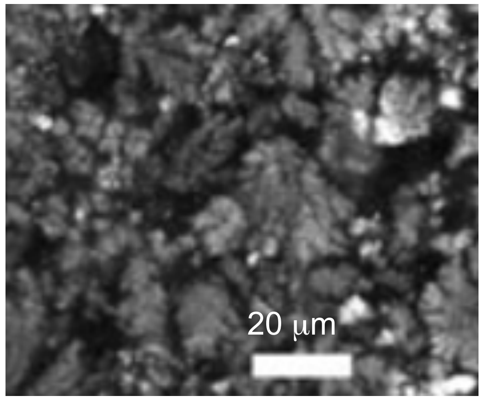


⇒ focus on fluidization dynamics in simple YSF

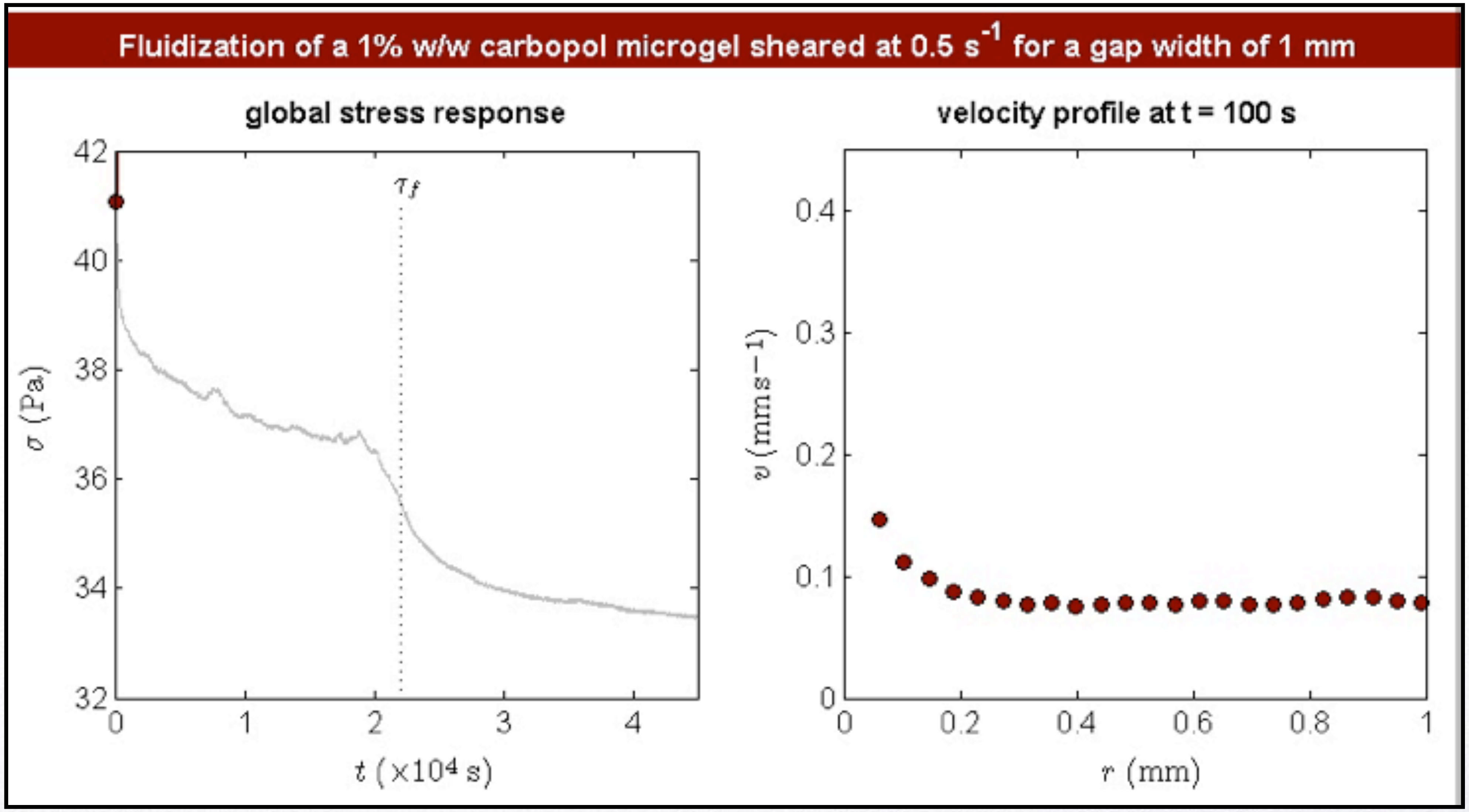
Slow fluidization dynamics in carbopol

poly(acrylic acid) polymer





Gutowski *et al.*, *Rheol. Acta* **51**, 441-450 (2012)


Fluidization of a 1% w/w carbopol microgel sheared at 0.5 s^{-1} for a gap width of 1 mm

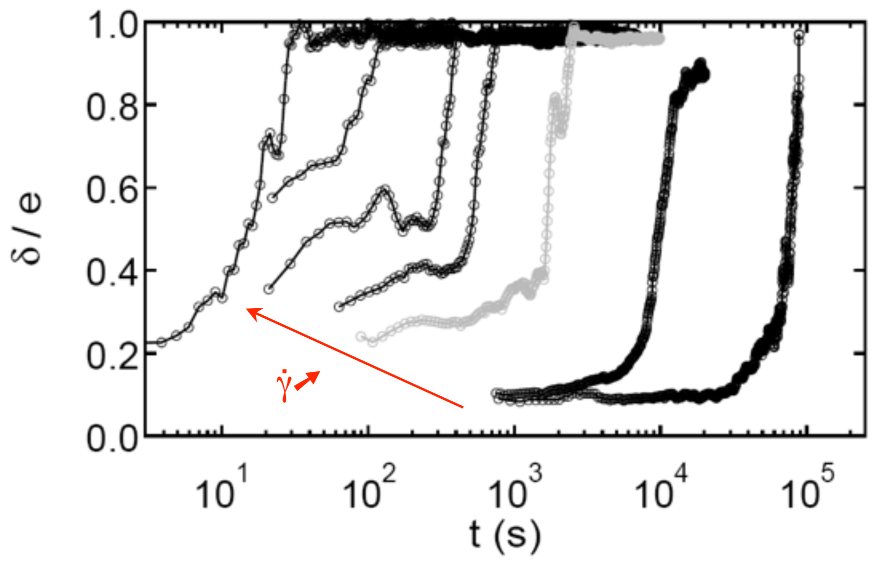
Divoux *et al.*, *PRL* **104**, 208301 (2010) & *Soft Matter* **8**, 4151-4164 (2012)

⇒ long-lasting transient shear-banding

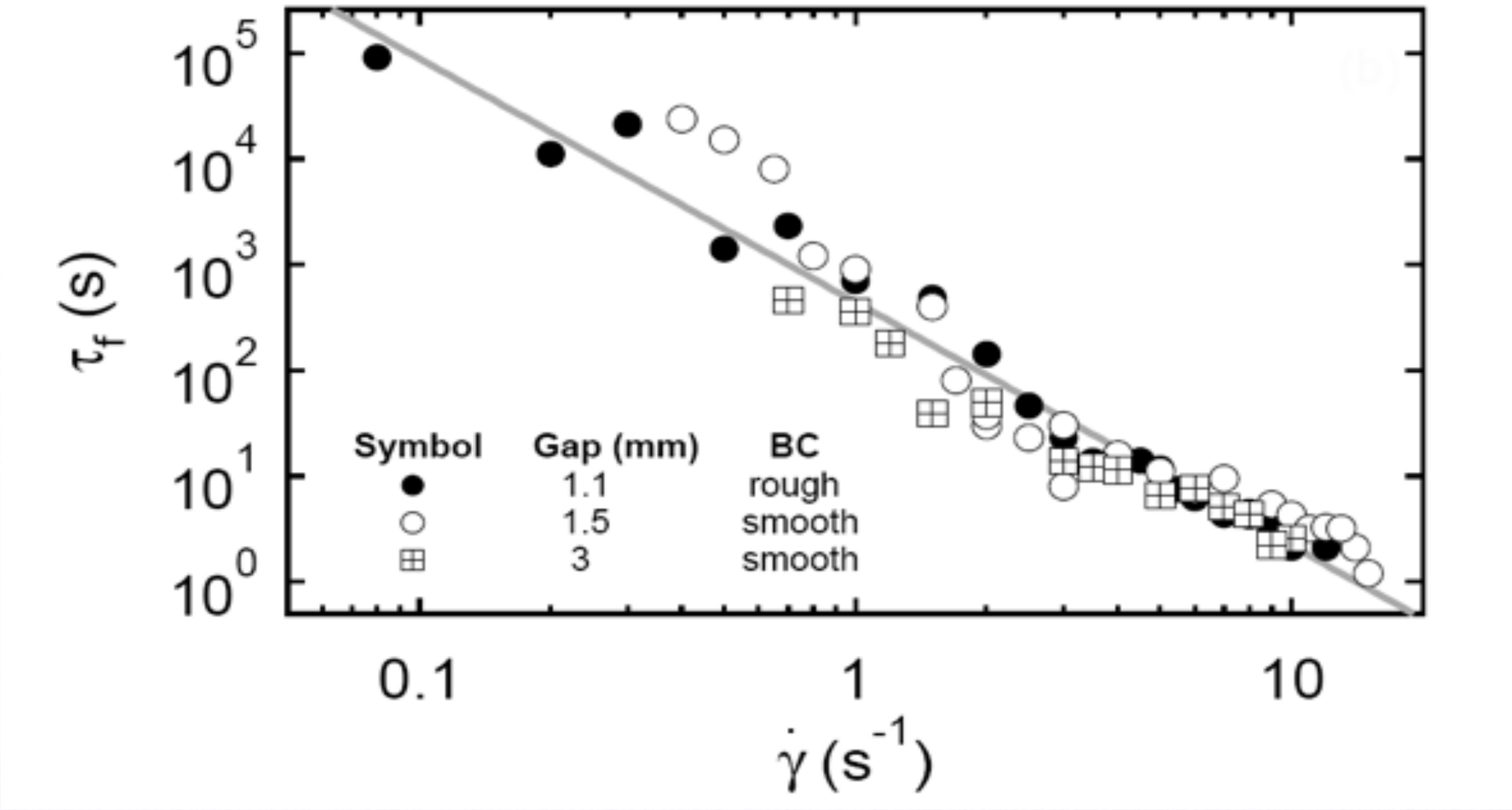
⇒ fluctuations and “sudden” fluidization at τ_f

⇒ rheological signature : “kink” around τ_f

Shear-rate controlled experiments



$$\delta(\tau_f) = 0.9e$$



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

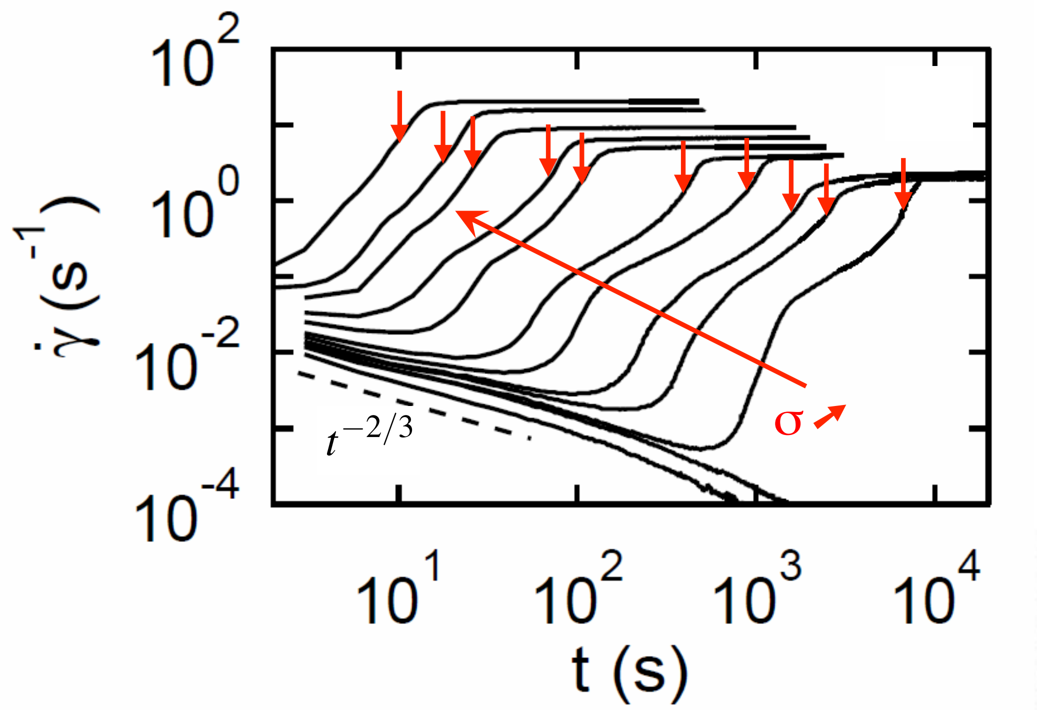
with

$$\alpha = 2.3 \pm 0.1$$

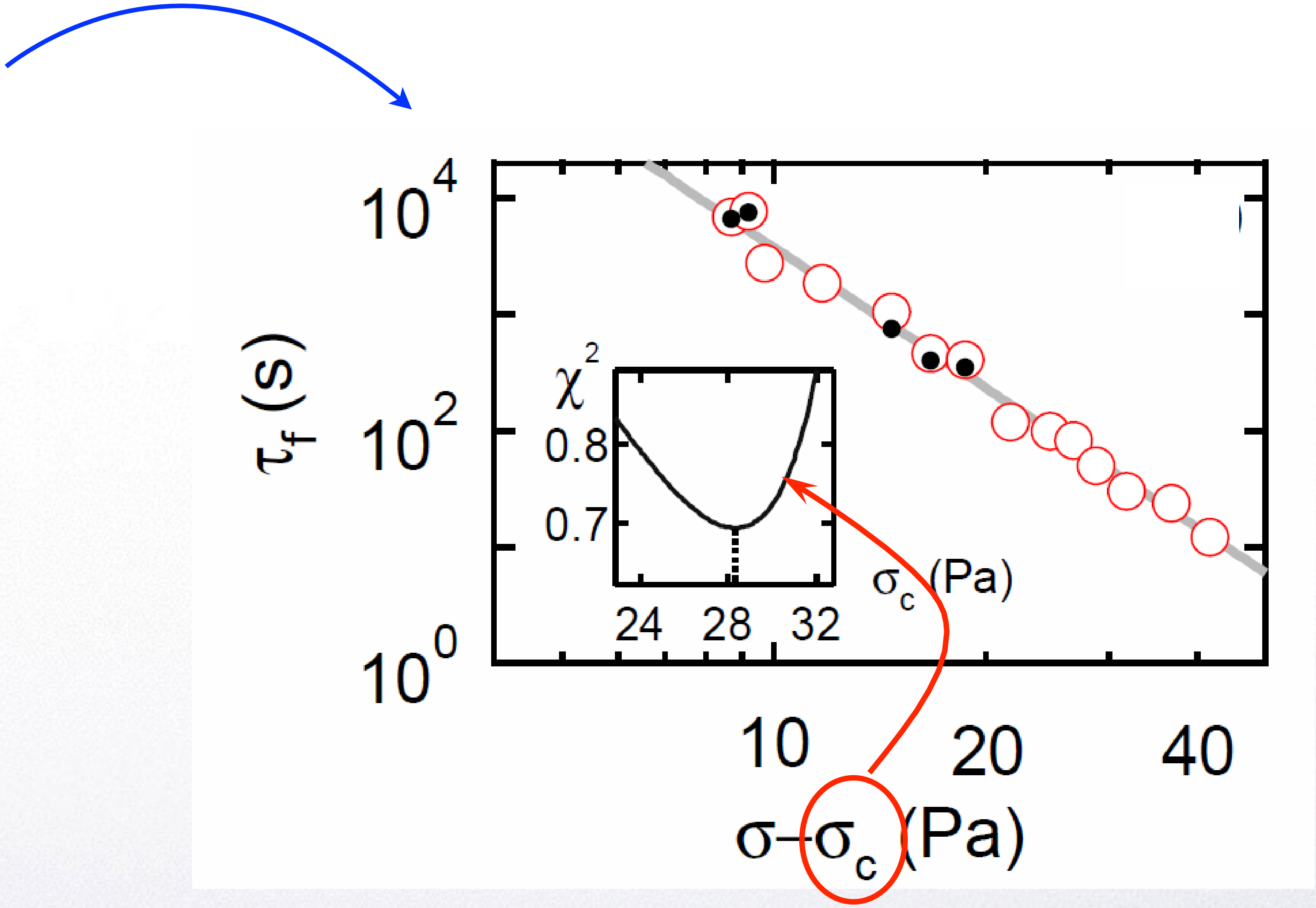
- independent of gap width and wall roughness
- dependent on carbopol batch (preparation, concentration)

⇒ what about imposing the shear stress (creep)?

Stress-controlled experiments



τ_f : second inflexion point

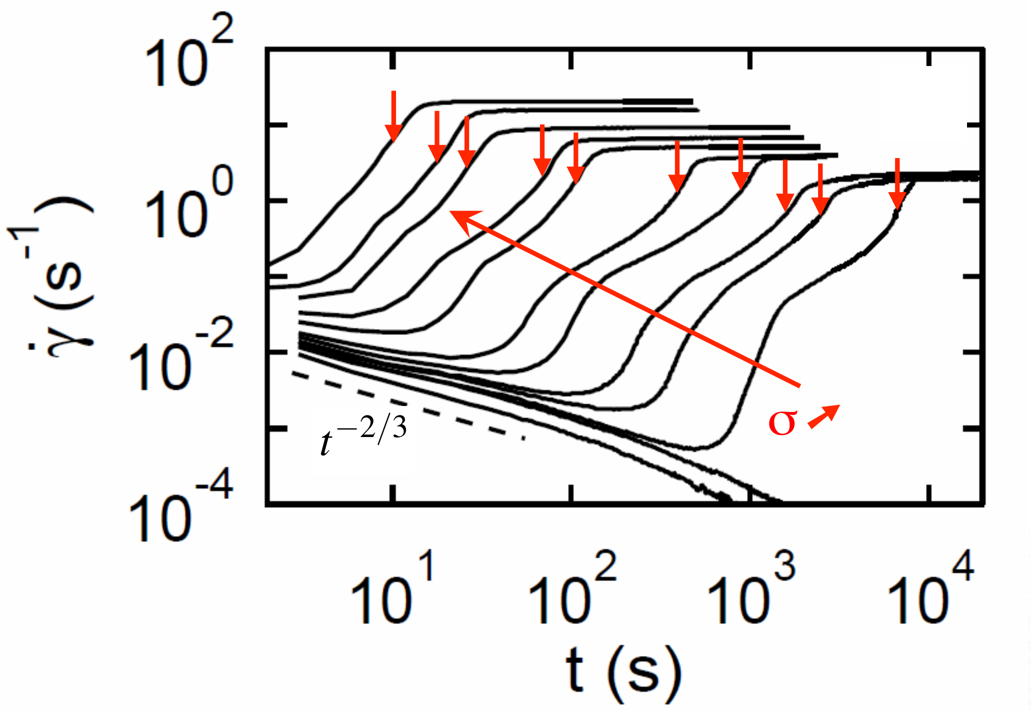


$$\tau_f \sim (\sigma - \sigma_c)^{-\beta}$$

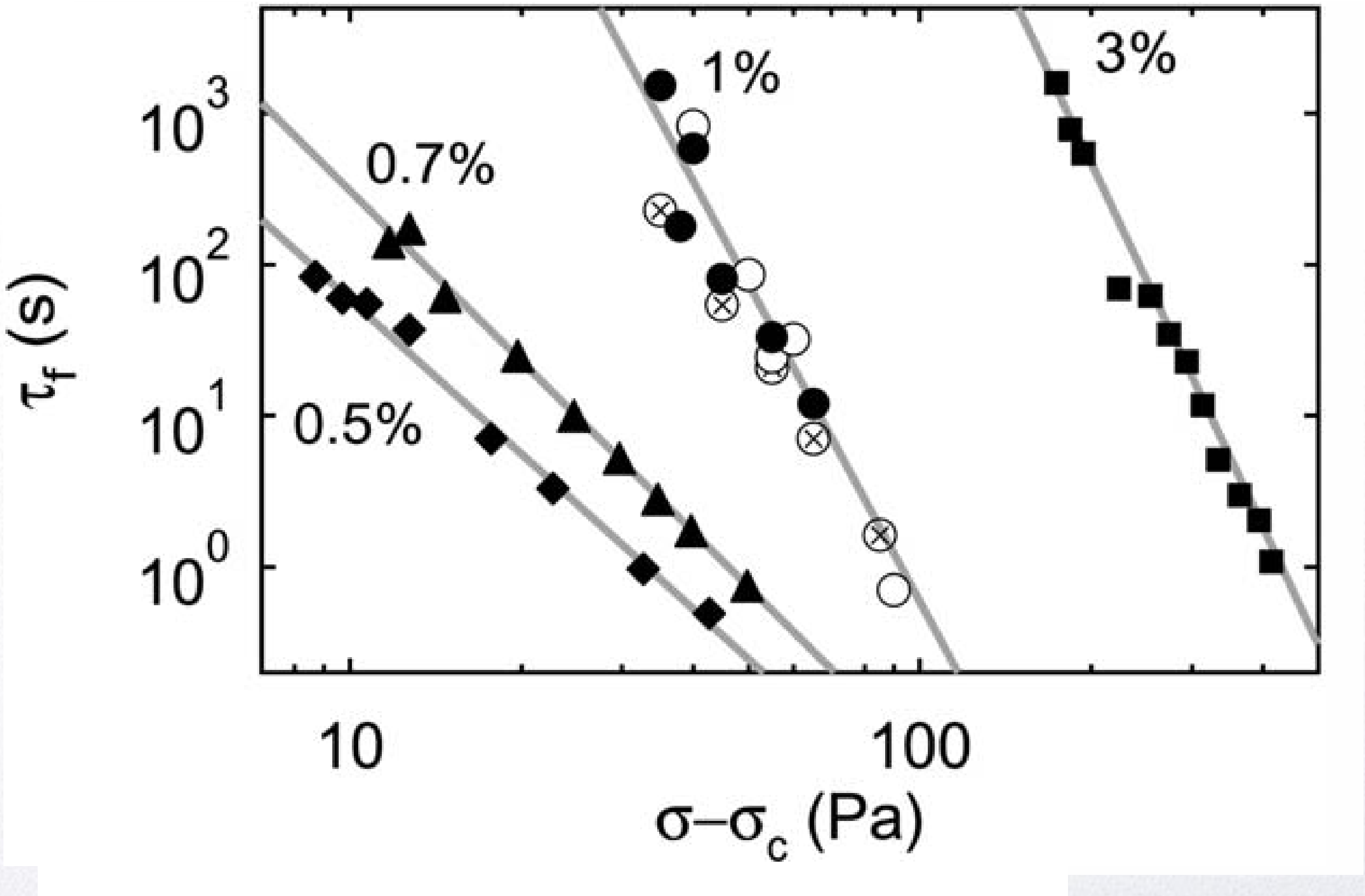
with

$$\beta = 4.0 \pm 0.1$$

Stress-controlled experiments



τ_f : second inflexion point



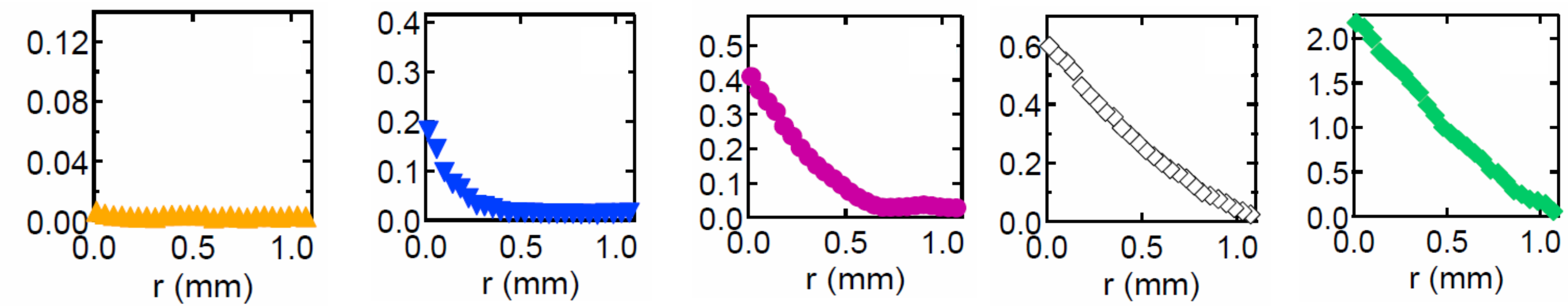
$$\tau_f \sim (\sigma - \sigma_c)^{-\beta}$$

with

$$\beta = 4.0 \pm 0.1$$

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

Link between transients and steady-state



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

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

let us assume

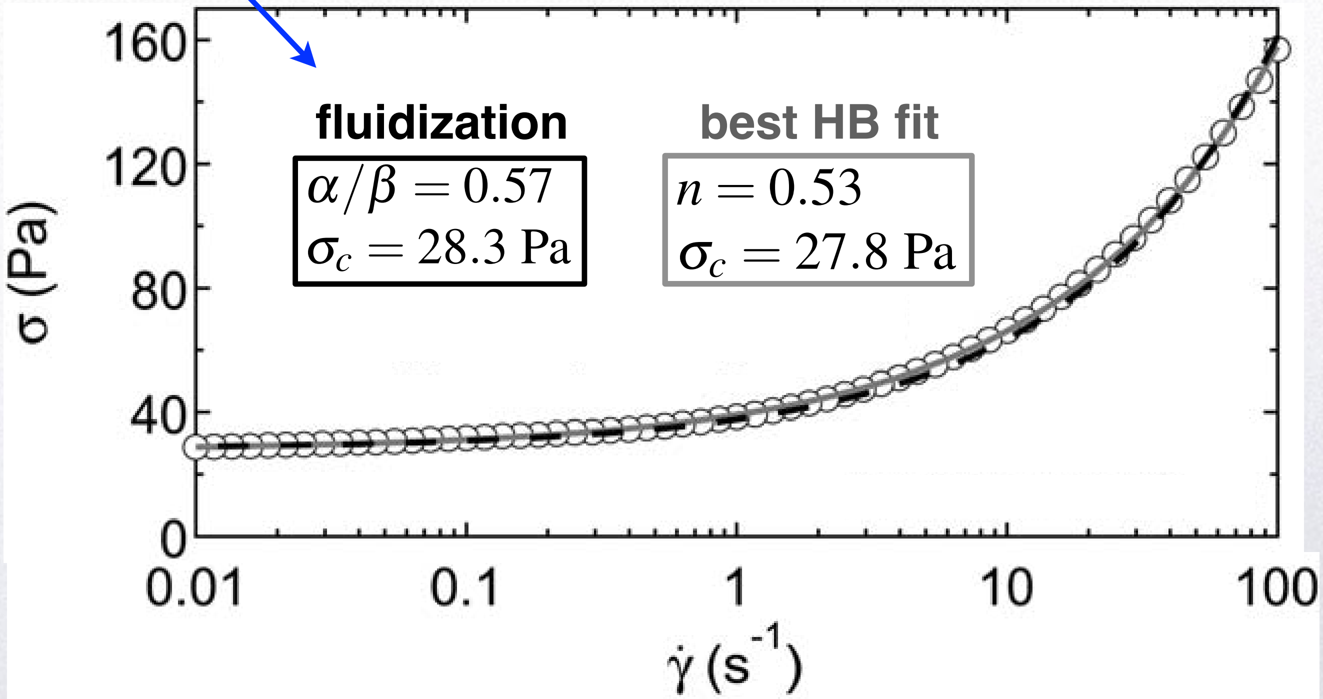
$$\tau_f^{(\sigma)} = \lambda \tau_f^{(\dot{\gamma})} \Rightarrow \boxed{\sigma = \sigma_c + A\dot{\gamma}^n}$$

$$\boxed{n = \alpha/\beta}$$

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

one free parameter: λ≈10

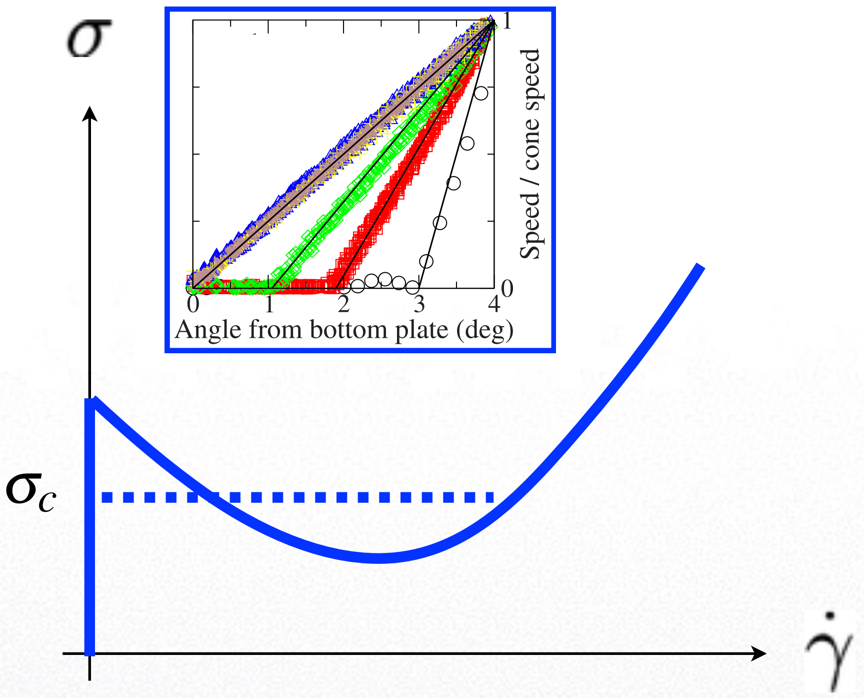
transient shear-banding
with
critical-like dynamics
⇓
Herschel-Bulkley rheology
in
steady state



Divoux *et al.*, *Soft Matter* **7**, 8409-8418 (2011)

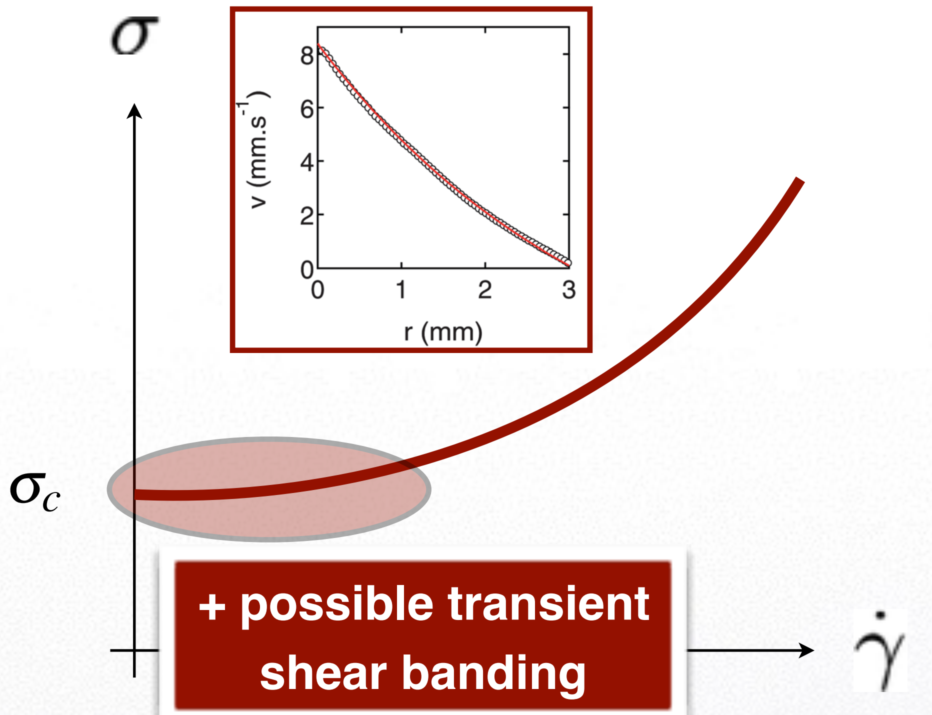
“Squishy” materials summary

heterogeneous flow



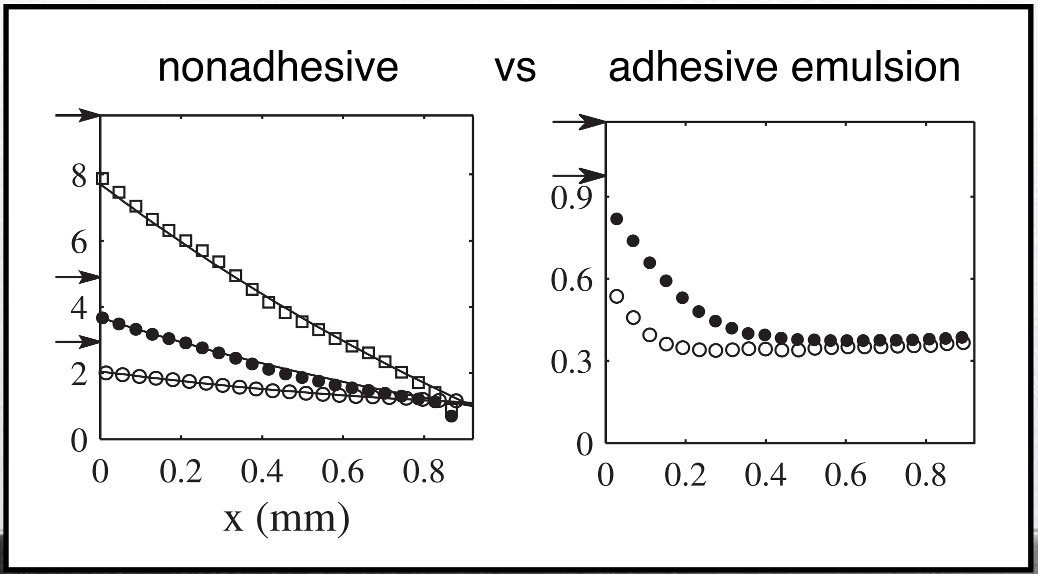
how to tune the system to go from a simple to “thixotropic” yield stress fluid?

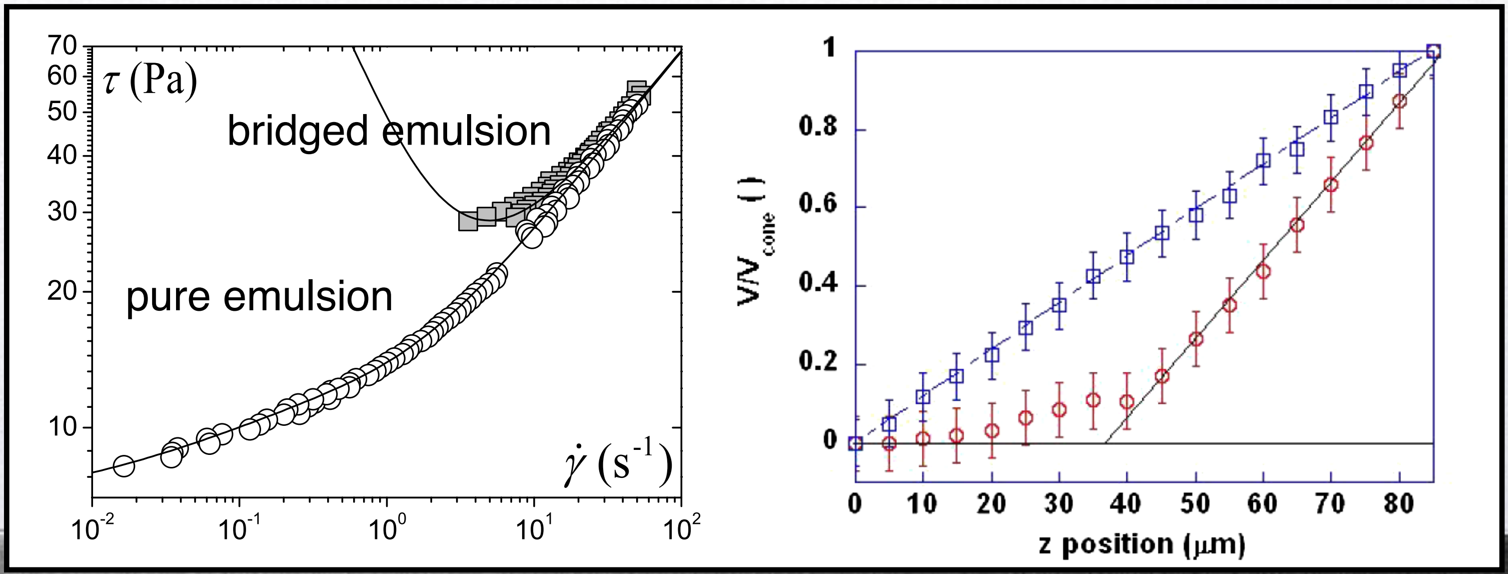
homogeneous flow



+ possible transient shear banding

by playing with interactions





Bécu *et al.*, *PRL* **96**, 138302 (2006)

Coussot & Ovarlez, *Eur. Phys. J* E **33**, 183-188 (2010)
Fall *et al.*, *PRL* **105**, 225502 (2010)

Outline

I. Surfactant solutions

from gradient banding to elastic turbulence to vorticity banding

II. Yielding in soft glassy ("squishy") materials

from steady shear localization to critical-like fluidization dynamics

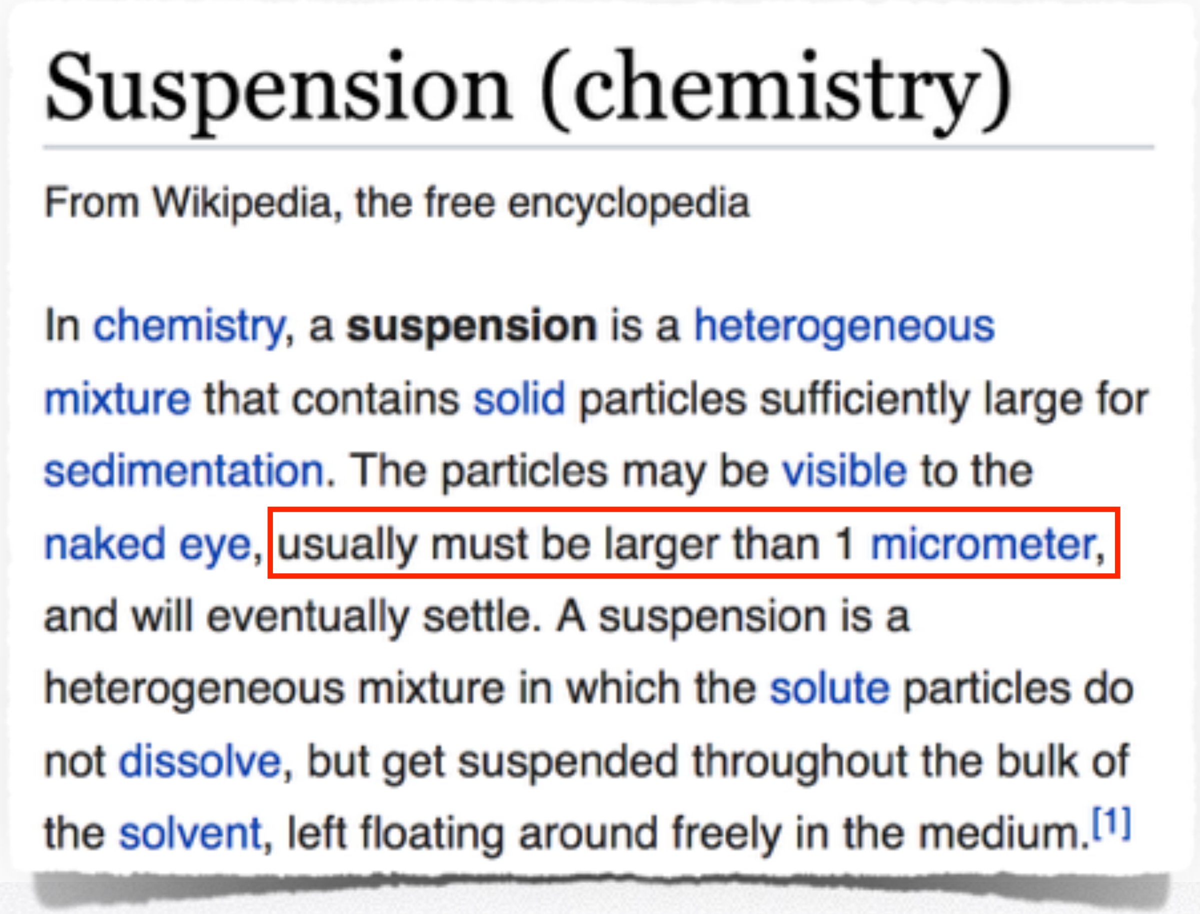
T. Divoux, M.-A. Fardin, SM & S. Lerouge, *Ann. Rev. Fluid Mech.* **48**, 81–103 (2016)

D. Bonn, M. Denn, L. Berthier, T. Divoux & SM, *Rev. Mod. Phys.* **89**, 035005 (2017)

III. What about dense suspensions?

similarities and differences with other complex fluids

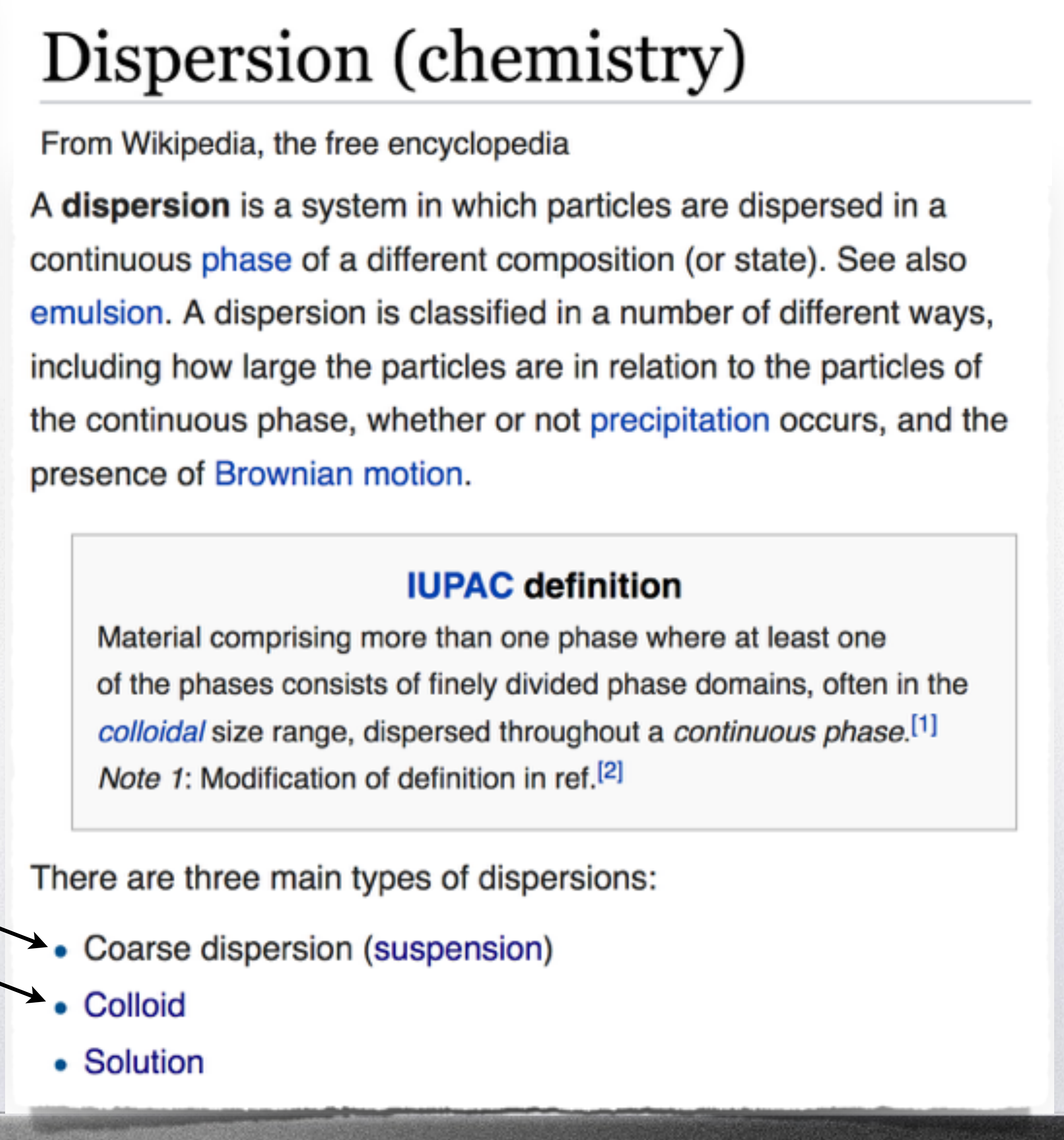
What is a "dense suspension"?



Suspension (chemistry)

From Wikipedia, the free encyclopedia

In chemistry, a **suspension** is a heterogeneous mixture that contains solid particles sufficiently large for sedimentation. The particles may be visible to the naked eye, usually must be larger than 1 micrometer, and will eventually settle. A suspension is a heterogeneous mixture in which the solute particles do not dissolve, but get suspended throughout the bulk of the solvent, left floating around freely in the medium.[1]



Dispersion (chemistry)

From Wikipedia, the free encyclopedia

A **dispersion** is a system in which particles are dispersed in a continuous phase of a different composition (or state). See also emulsion. A dispersion is classified in a number of different ways, including how large the particles are in relation to the particles of the continuous phase, whether or not precipitation occurs, and the presence of Brownian motion.

IUPAC definition

Material comprising more than one phase where at least one of the phases consists of finely divided phase domains, often in the *colloidal* size range, dispersed throughout a *continuous phase*.[1]

Note 1: Modification of definition in ref.[2]

There are three main types of dispersions:

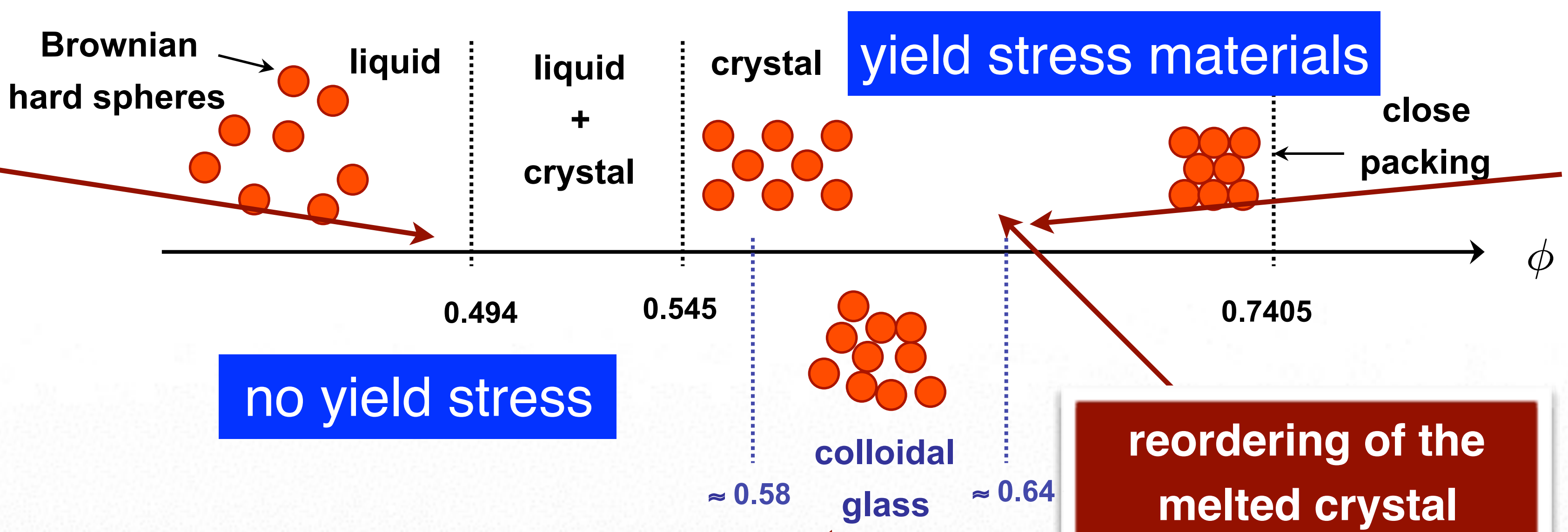
- Coarse dispersion (suspension)
- Colloid
- Solution

suspensions involve non-Brownian particles (?)

"dense" = concentrated enough to lead to non-Newtonian behaviour (?)

The flow of dense colloidal “dispersions”

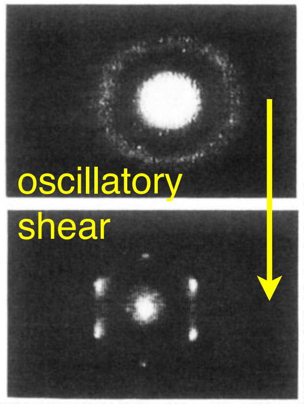
hard-sphere-like dispersions (e.g. stabilized PMMA particles ⌀ < 1µm)



yield stress materials

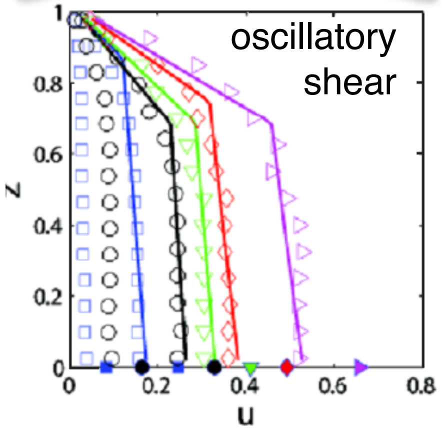
no yield stress

shear-induced ordering



Ackerson & Pusey, *PRL* **61**, 1033-1036 (1988)

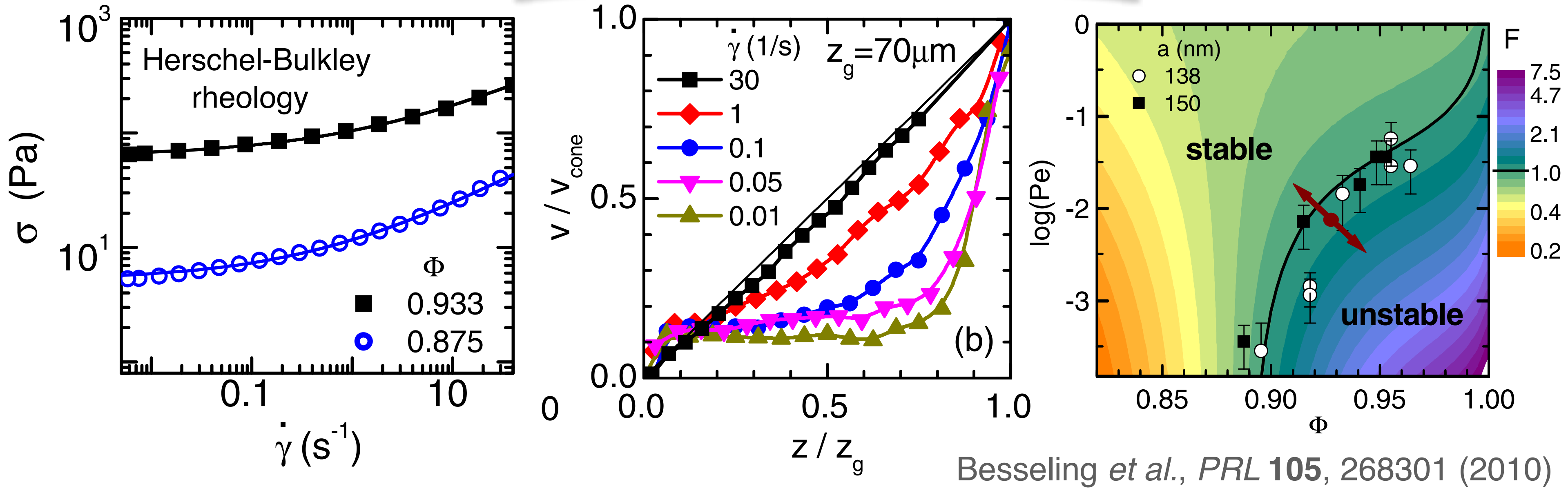
shear melting: slip & bands



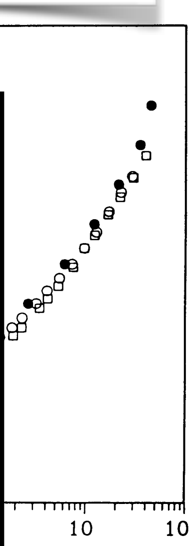
Cohen *et al.*, *PRL* **97**, 215502 (2006)

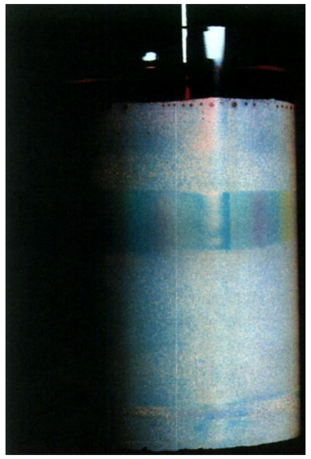
reordering of the melted crystal through phase coexistence

shear banding due to flow-concentration coupling



Besseling *et al.*, *PRL* **105**, 268301 (2010)





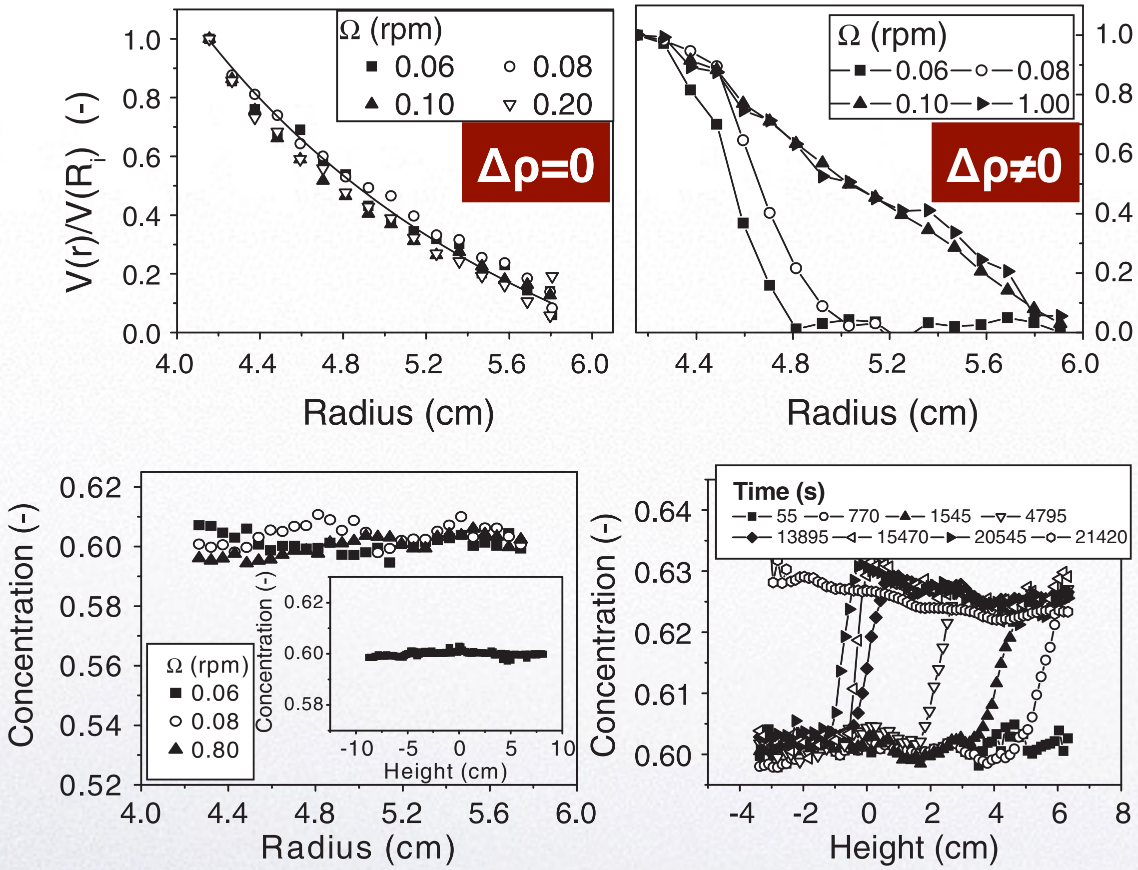
Chen *et al.*, *PRL* **69**, 688-691 (1992)

see also Schall & van Hecke, *Annu. Rev. Fluid Mech.* **42**, 67-88 (2010)

What about dense non-Brownian “suspensions”?

<u>no</u> Brownian motion
⇒ <u>no</u> yield stress

PS spheres ∅ 40 µm



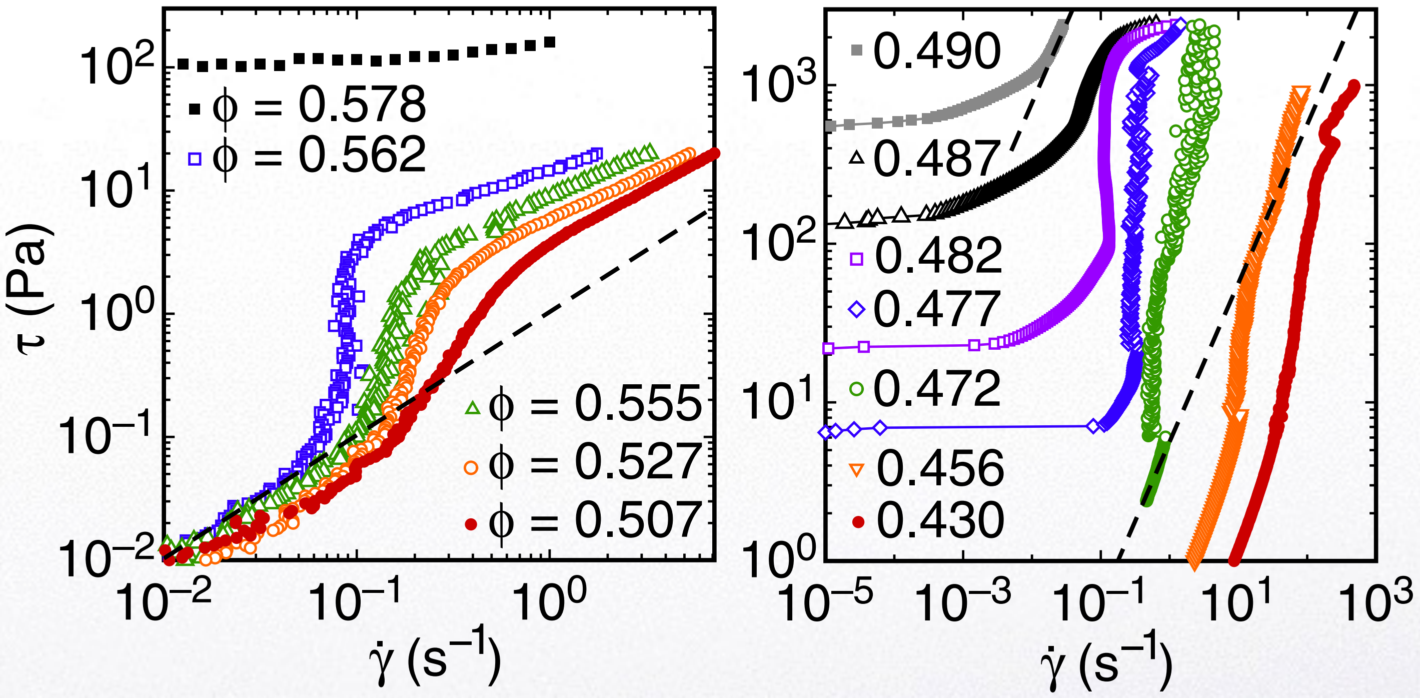
Fall *et al.*, *PRL* **103**, 178301 (2009)

yield stress due to sedimentation

shear-thickening
is ubiquitous in dense suspensions

glass spheres ∅ 88-125 µm

cornstarch



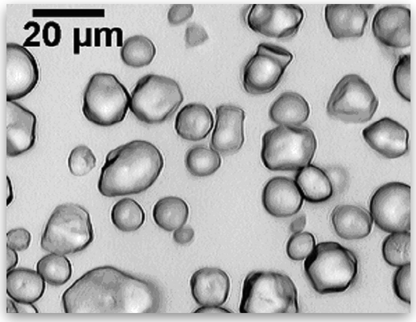
Brown & Jaeger, *PRL* **103**, 086001 (2009)

continuous transition *vs* discontinuous transition

<u>see also</u> Brown & Jaeger, *Rep. Prog. Phys.* **77**, 046602 (2014)
Denn *et al.* *Soft Matter* **14**, 170-184 (2018)

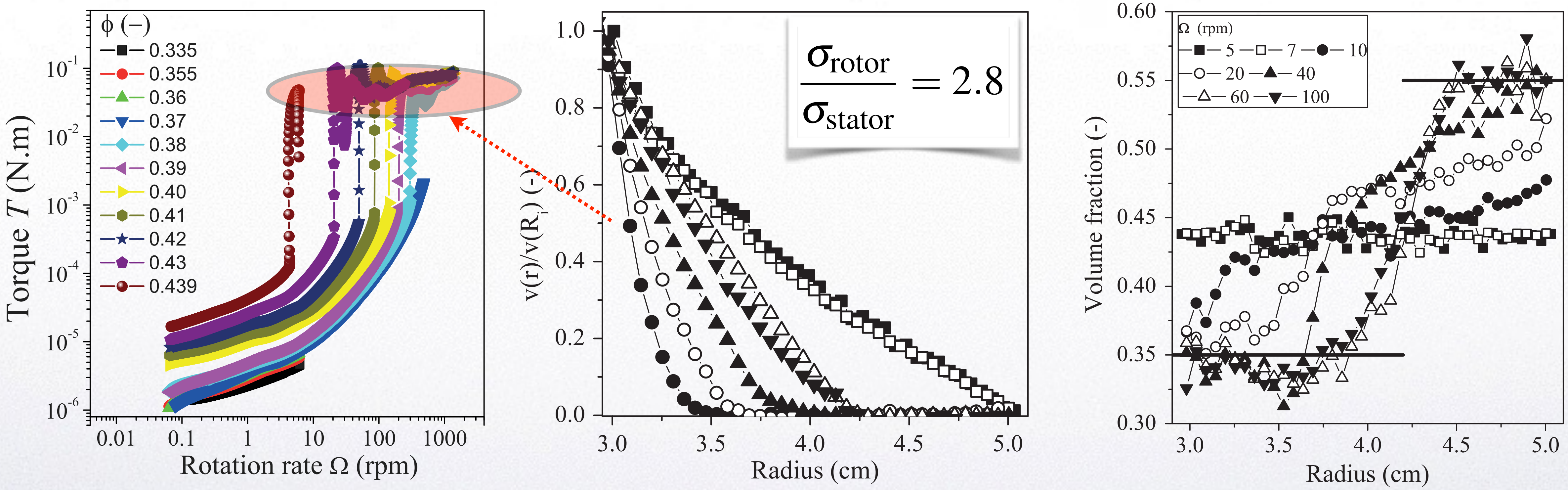
Heterogeneous flows in shear-thickening

cornstarch



shear banding in DST
associated with migration
(in wide-gap Couette geometry)

Fall *et al.*, *PRL* **114**, 098301 (2015)



$$\frac{\sigma_{\text{rotor}}}{\sigma_{\text{stator}}} = 2.8$$

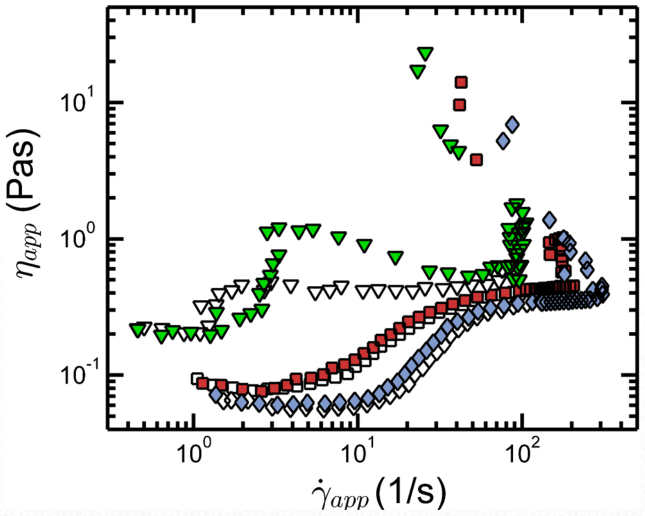
⇒ is migration inherent to the flow of dense suspensions?

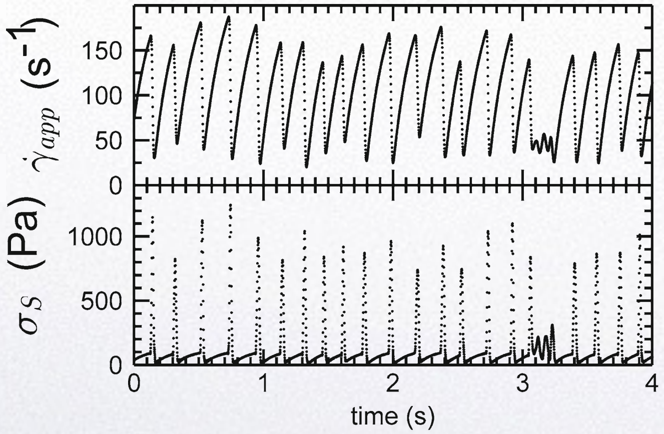
see talk by Guillaume Ovarlez
on Monday

Stick-slip-like oscillations in shear-thickening

PS particles ∅ 5.8 µm

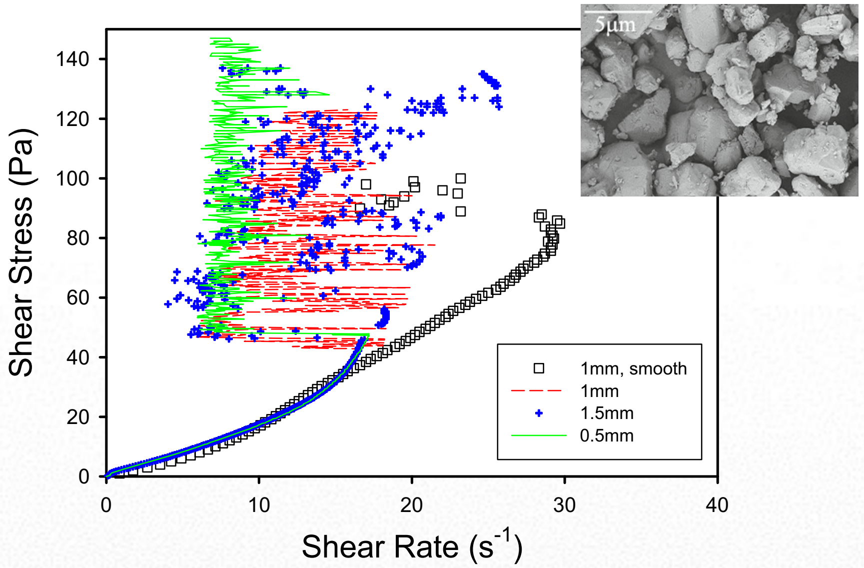
Larsen *et al.*, *Rheol. Acta* **53**, 333-347 (2014)

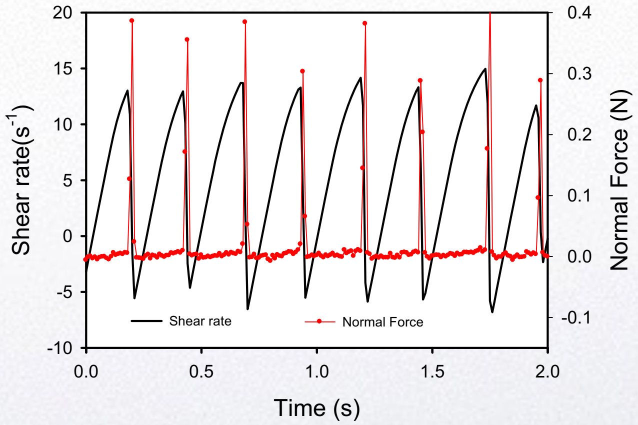




calcium carbonate ∅ 5.5 µm

Bossis *et al.*, *Rheol. Acta* **56**, 415-430 (2017)





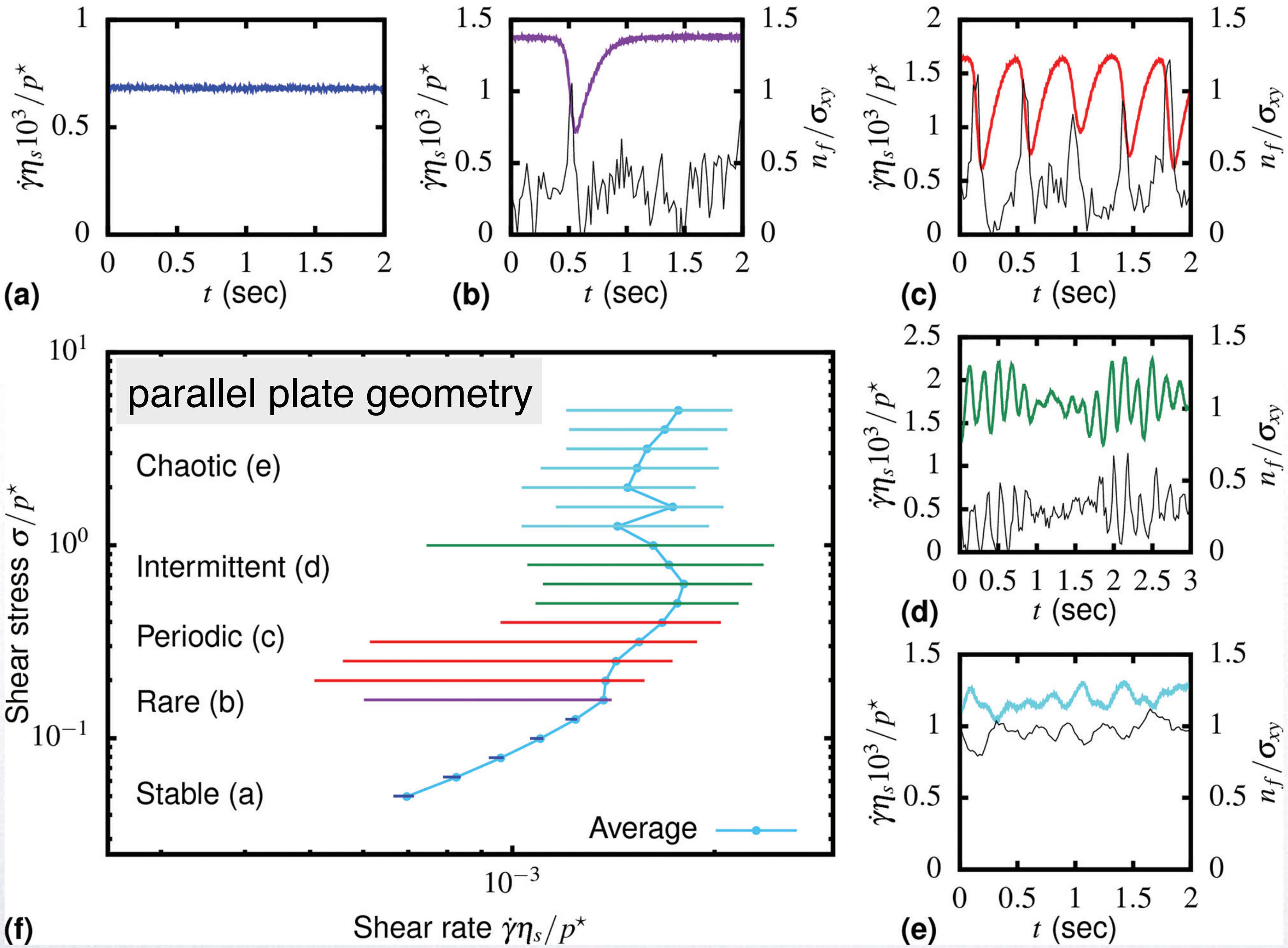
competition between dilatancy and wall slip through flow-concentration coupling

coupling between elasticity of the frictional particle network and instrument inertia

Unstable dynamics during shear-thickening

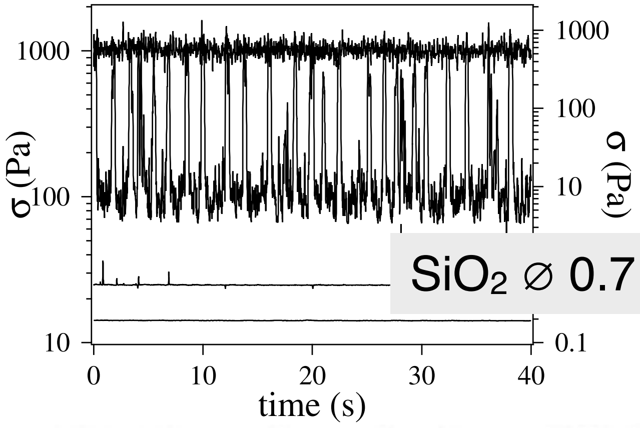
cornstarch

rheochaos?



Hermes *et al.*, *J. Rheol.* **60**, 905-916 (2016)

giant stress fluctuations

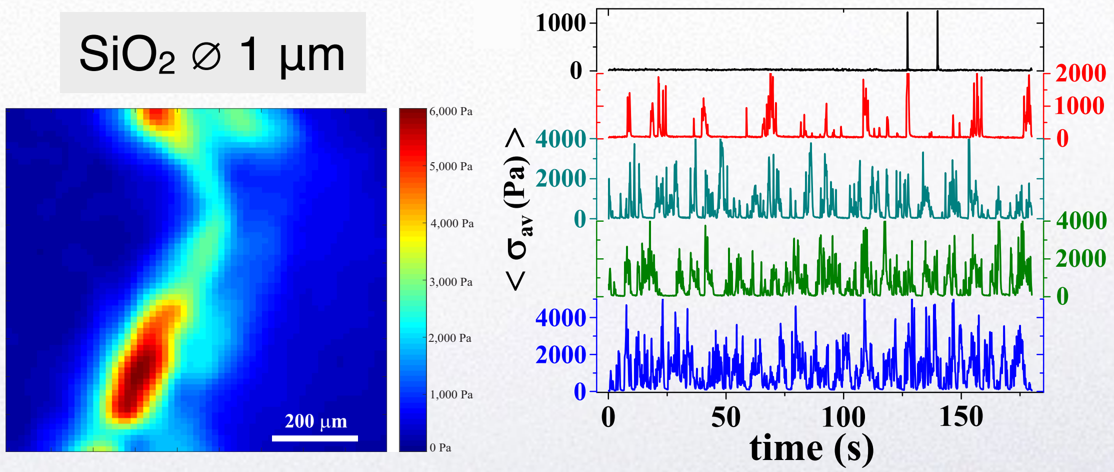


SiO$_2$ ∅ 0.7 µm

Lootens *et al.*, *PRL* **90**, 178301 (2003)

localized stress fluctuations

SiO$_2$ ∅ 1 µm



Rathee *et al.*, *PNAS* **114**, 8740-8745 (2017)

⇒ is unsteadiness inherent to the flow of dense suspensions?

see my talk
on Wednesday

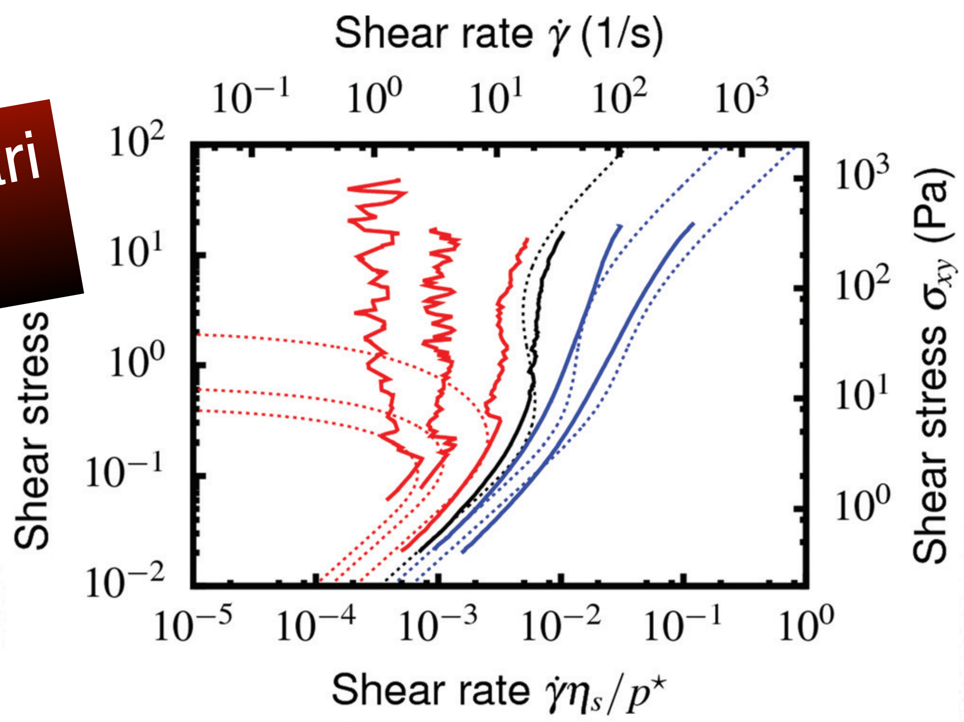
More questions about dense suspensions

⇒ do dense suspensions show vorticity banding?

so far, no experimental evidence
for steady vorticity bands

Pan *et al.*, *PRE* **92**, 032202 (2015)

see talk by Romain Mari
on Tuesday



⇒ can "full jamming" be observed in experiments?

Cates *et al.*, *J. Phys.: Condens. Matter* **17**, S2517 (2005)
Wyart & Cates, *PRL* **112**, 098302 (2014)

⇒ back to colloids: role of attractive interactions? link with yield stress?

non-glassy hard-sphere colloids also show shear-thickening — Frith *et al.*, *J. Rheol.* **40**, 531-548 (1996)

but shear-thickening is lost when a yield stress builds up due to attraction

Gopalakrishnan & Zukoski *et al.*, *J. Rheol.* **48**, 1321-1344 (2004)
Pednekar *et al.*, *Soft Matter* **13**, 1773-1779 (2017)

⇒ role of particle-particle interactions and particle-surface interactions?

need for microscopic friction measurements

Clavaud *et al.*, *PNAS* **114**, 5147-5152 (2017)
Comtet *et al.*, *Nat. Comm.* **8**, 15633 (2017)

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