Non-linear mechanics and rheology of dense suspensions – KITP, UCSB Feb. 5th 2018

Wall slip in flows of Soft Glassy Materials

A short review & some perspective

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Acknowledging funding from:

Outline

- What is wall-slip?
  Macroscopic approach & observable: slip velocity

- How to measure slip velocities?
  Direct & indirect methods

- How does wall slip impact steady-state flows ?
  Flow curves measurements

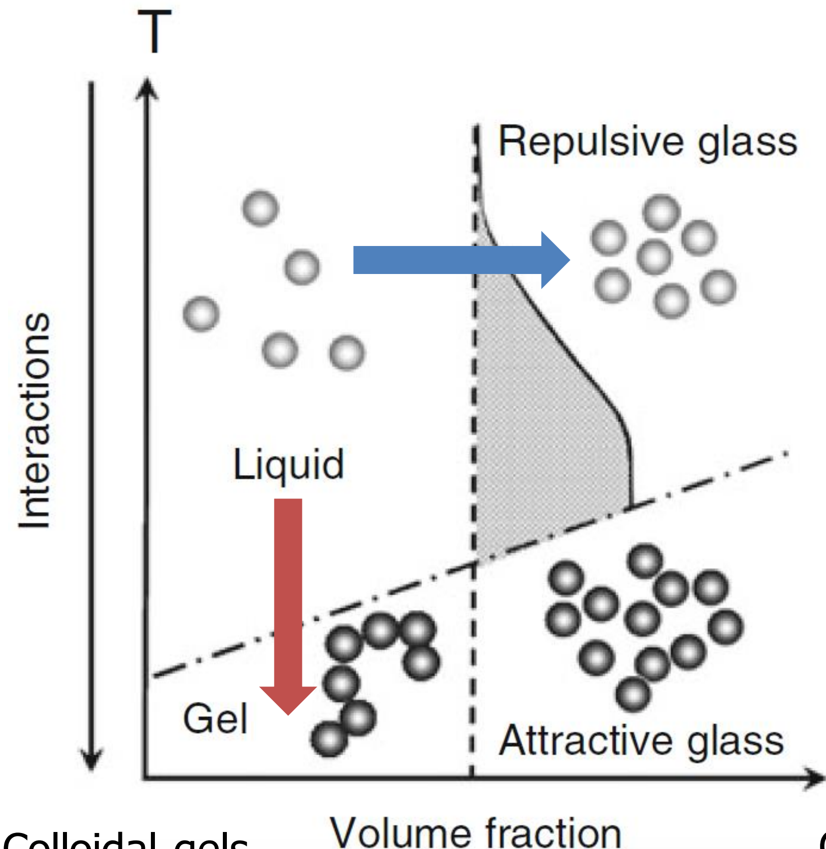
  - ✓ Results for (dense) suspensions of hard particles
    Hard sphere-like or attractive interactions

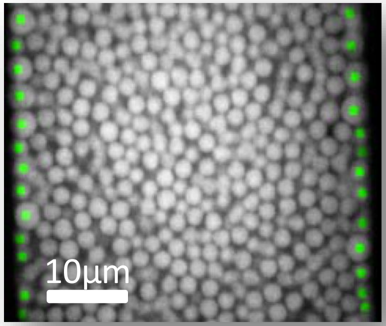
  - ✓ Results for jammed assemblies of soft particles
    Discrepancies in the scaling of the slip velocity

  - ✓ Results on a system of soft particles of tunable size
    Scaling of slip velocities in p-NIPAM for different temperatures

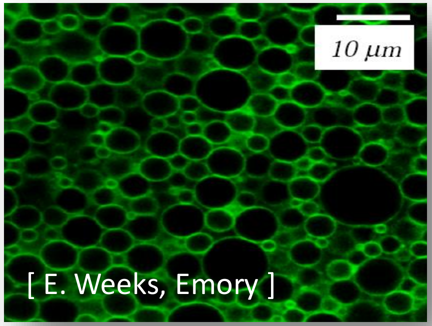
- How does wall slip impact transient flows… (and steady-state)?
  Wall slip associated with shear-start up flows & yielding transition

From dilute suspensions… to soft glassy materials

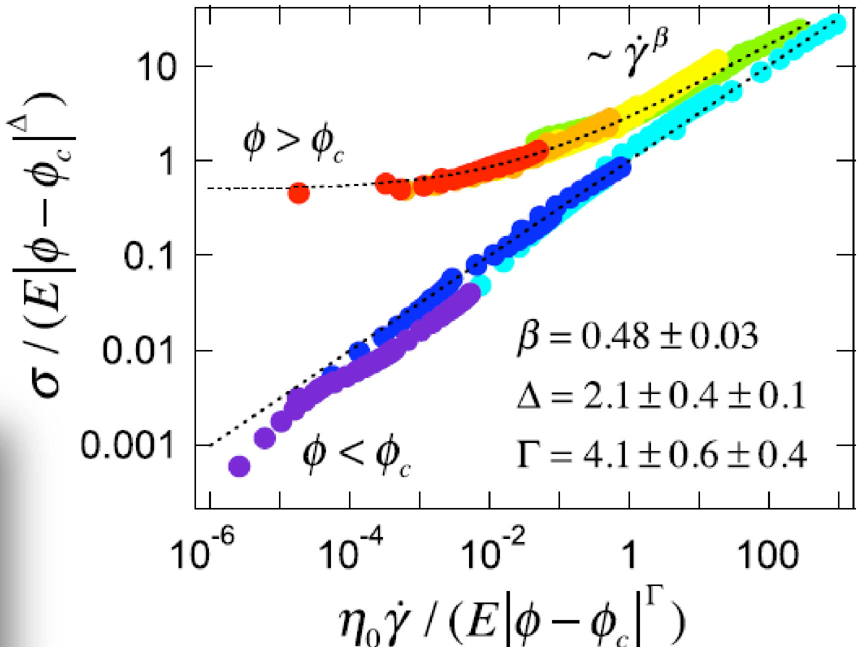




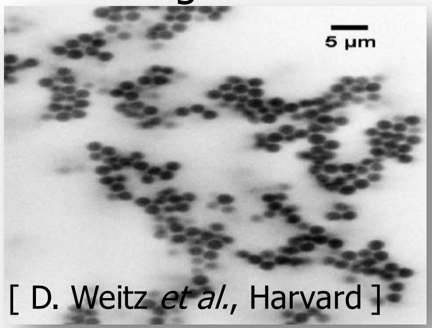
Close packed colloids



Dense emulsions



Colloidal gels

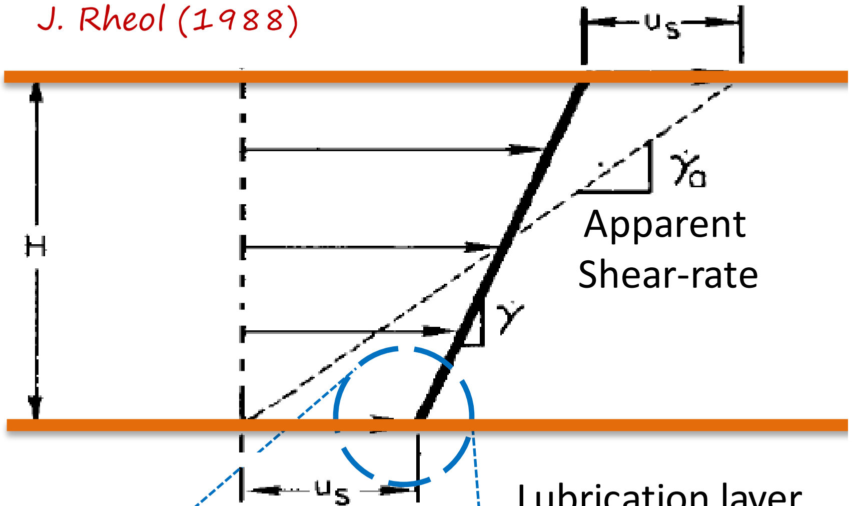


Clays

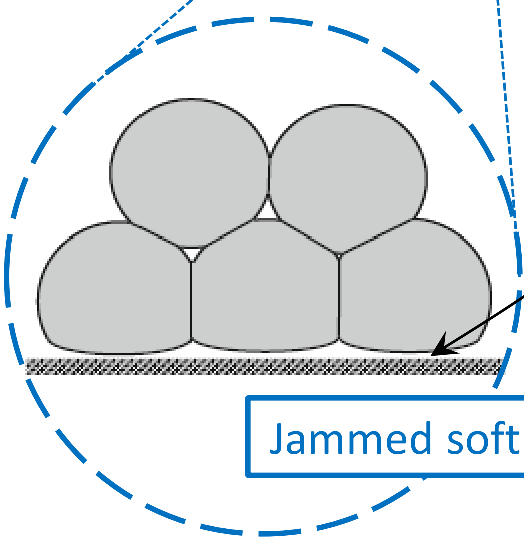
Nordstrom et al., Phys. Rev. Lett. (2010)
Bonnecaze & Cloitre, Adv. Polym. Sci. (2010)
Bonn, Denn, Berthier, Divoux, Manneville, Rev. Mod. Phys. (2017)

What is wall slip?

Yoshimura & Prud'homme
J. Rheol (1988)



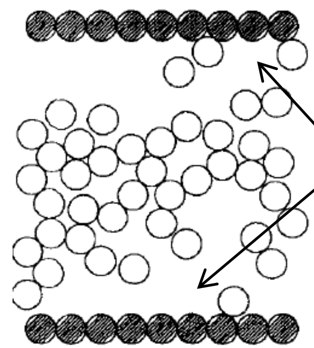
Lubrication layer



Jammed soft particles

Meeker et al., J. Rheol (2004)
Seth et al., Nature Materials (2011)

Dilute suspensions/gels (hard/soft particles)

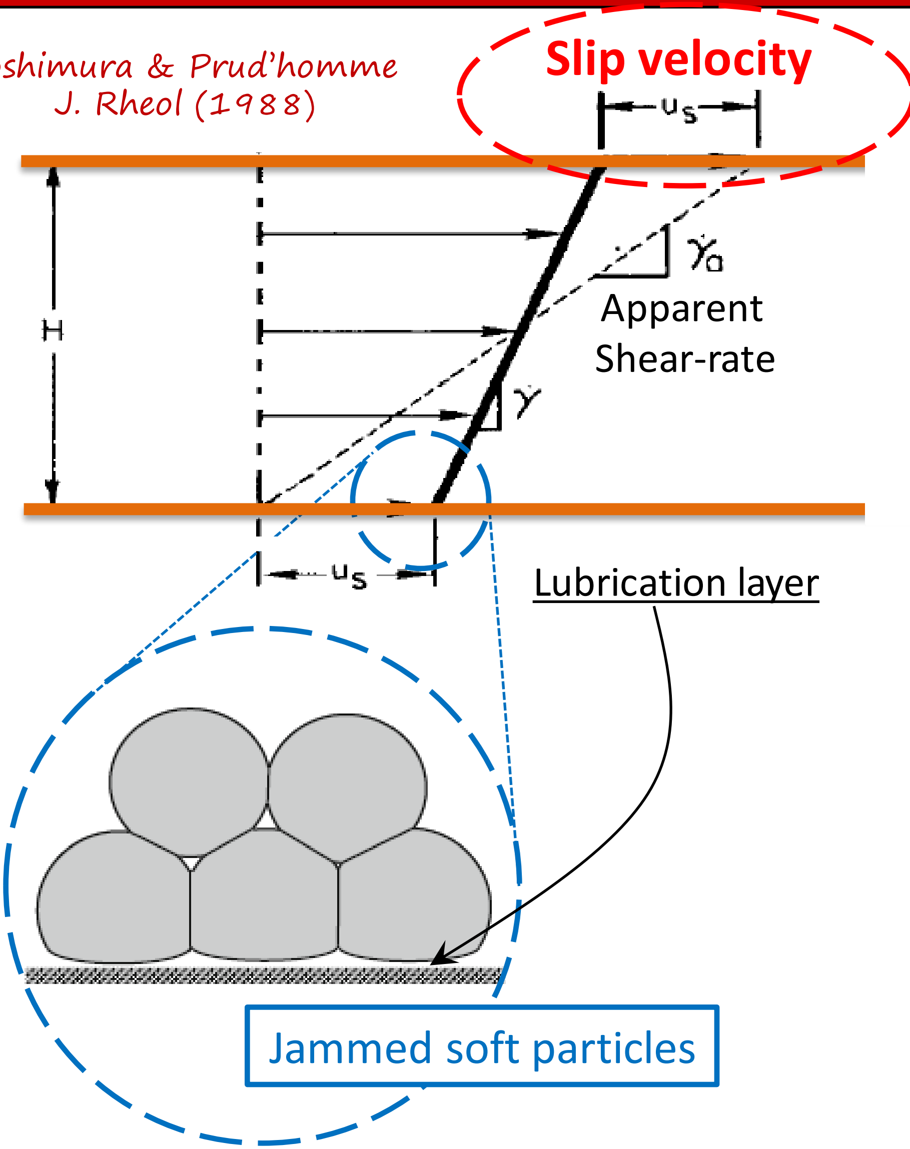


Hartman Kok *et al.*, J. Colloid Interface Sci. (2004)
+ "Discussion: Migration" by E. Guazzelli – Jan. 29th

Study	System	Particle radius R	Slip layer thickness δ
Aral and Kalyon (1994)	Glass spheres in polymer binder ($\phi = 0.63$)	$\sim$ 50 μm	1.6 μm
Buscall *et al.* (1993)	Stabilized latex particles in organic solvent+nonadsorbing polymer	160 nm	2 μm $\rightarrow$ 3 nm ($\phi \sim 0.2 \rightarrow 0.55$)
Princen (1985)	Concentrated silicone oil in water emulsions	$\approx$ 9 μm	$\approx$ 20 nm
and Grant	Silica particles+grafted poly(butyl methacrylate) in a poor solvent	$\approx$ 70 nm	$<$ 1 nm
Salmon *et al.* (2003)	Monodisperse silicone oil in water/glycerol emulsion ($\phi = 0.75$)	$\approx$ 1 μm	10 nm $\rightarrow$ 90 nm
This work	Microgel pastes	220 nm	$\approx$ 2–10 nm

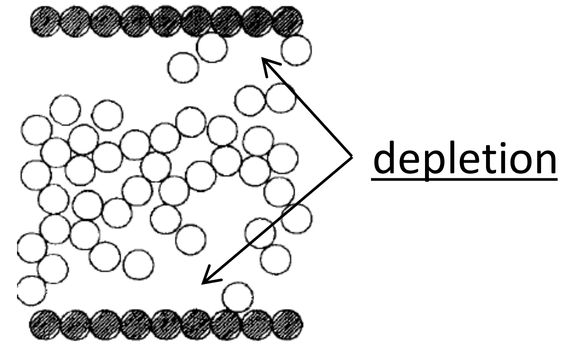
What is wall slip?

Yoshimura & Prud'homme
J. Rheol (1988)



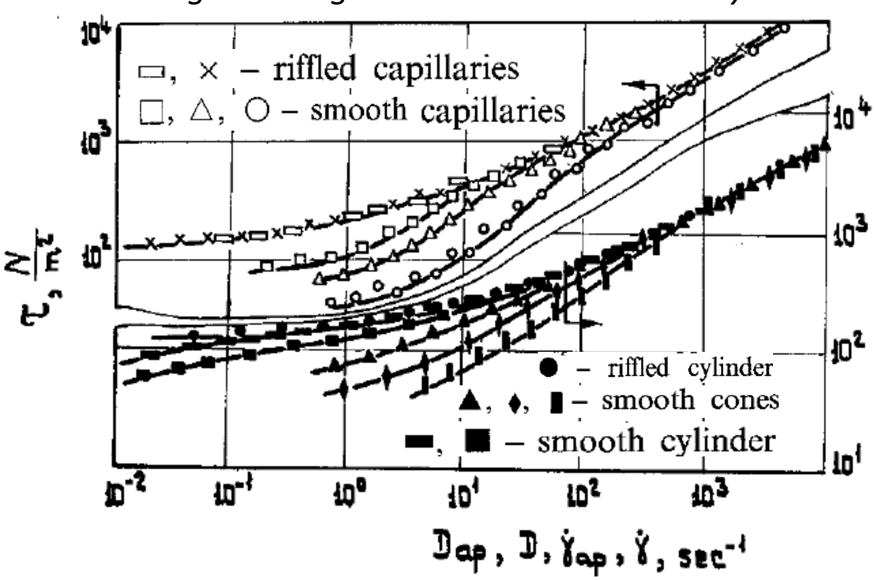
Meeker et al., J. Rheol (2004)
Seth et al., Nature Materials (2011)

Dilute suspensions/gels (hard/soft particles)



Hartman Kok *et al.*, J. Colloid Interface Sci. (2004)
+ "Discussion: Migration" by E. Guazzelli – Jan. 29th

High-melting ceresine in a low viscosity oil

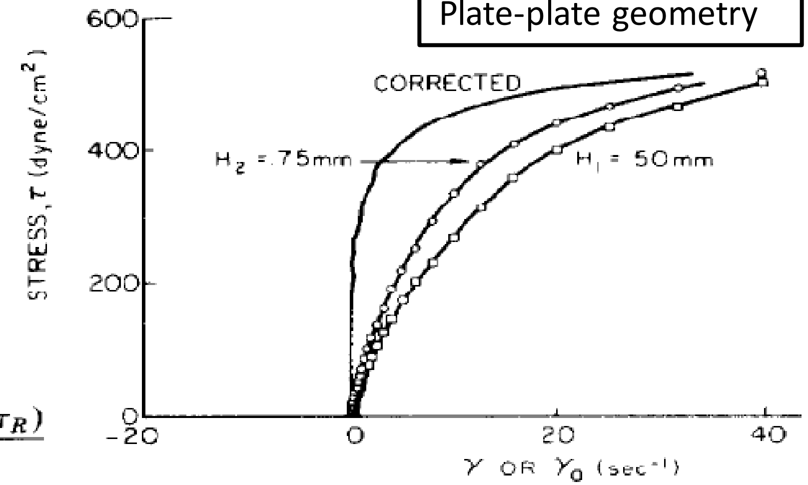


Vinogradov et al., Rheol. Acta (1975) & (1978)

How to measure slip velocities? [Indirect method]

✓**Measure the flow curve with smooth surfaces for different gap size**

Dense emulsion Ø=0.9
Plate-plate geometry



Hypothesis:
1. slip velocities are function of stress only
2. sliding layers are function of stress only
3. slip velocities are the same function at the rotor & stator

☹ Not always verified for low density suspensions!

See: *Salmon et al., EPJE (2003)*

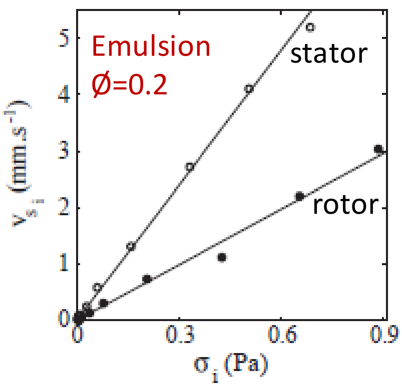
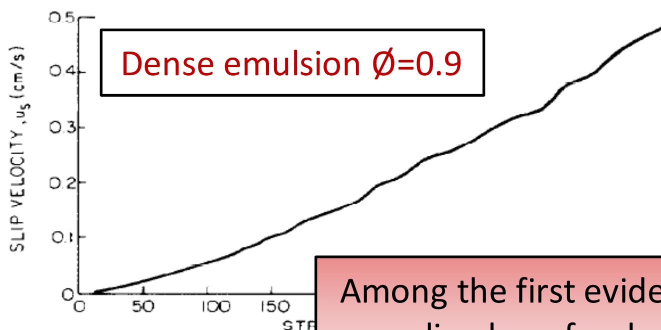


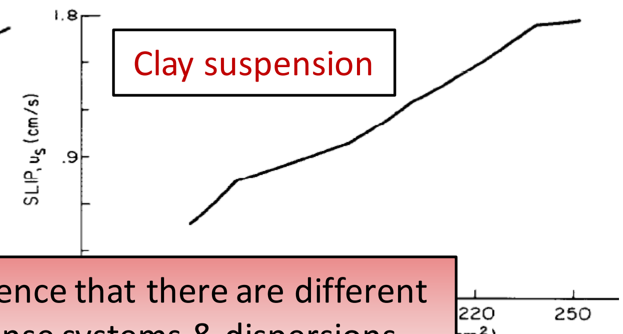
Plate-plate geometry:

$$u_s(\tau_R) = \frac{\dot{\gamma}_{aR1}(\tau_R) - \dot{\gamma}_{aR2}(\tau_R)}{2\left(\frac{1}{H_1} - \frac{1}{H_2}\right)}$$

Dense emulsion Ø=0.9



Clay suspension



Among the first evidence that there are different scaling laws for dense systems & dispersions

Mooney J. Rheol. **2**, *210 (1931)*
Yoshimura & Prud'homme J. Rheol. **32**, *53 (1988)*
Kiljanski, Rheol. Acta **28**, *64 (1989)*

Method later applied by:

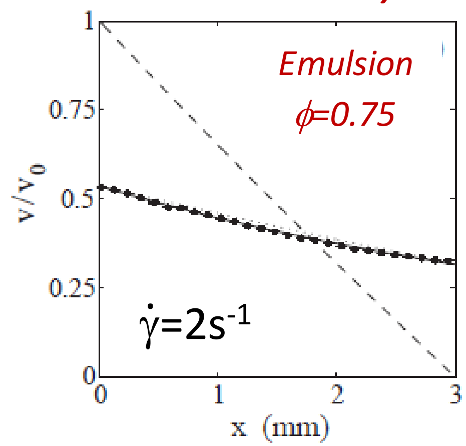
Yilmazer & Kalyon, J. Rheol. **33** *1197 (1989)*
Wein & Tovchigrechko, J. Rheol. **36**, *812 (1992)*
Hartman Kok et al., JCIS **280**, *511 (2004)*
Meeker et al., J. Rheol. **48**, *1295 (2004)*
etc. *Helal et al. Phys. Rev. Applied 6, 064004 (2016).*

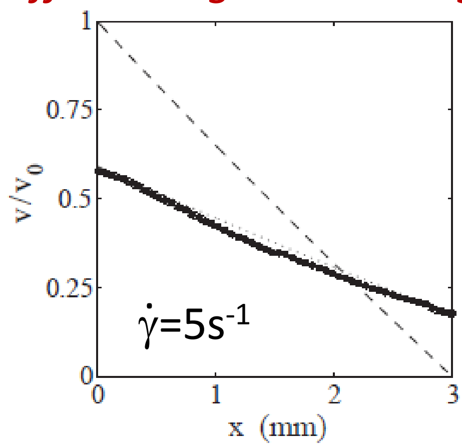
How to measure slip velocities? [Direct methods]

**Note that NMR Velocimetry has been barely used to measure V_s*

✓Rheology coupled to a velocimetry technique

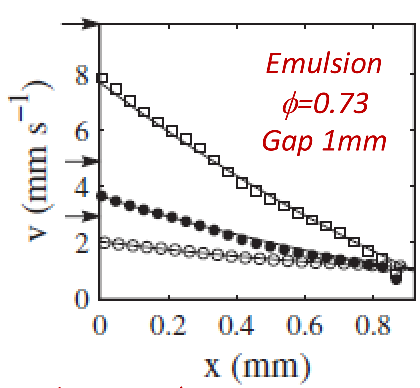
Homo & Hetero-dyne Diffusion Light scattering



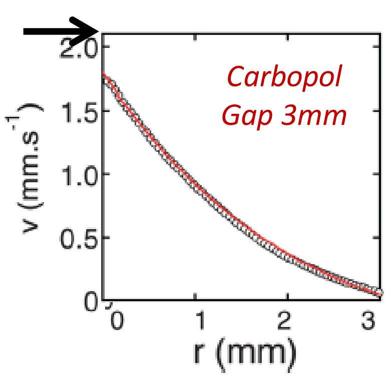


Salmon et al., Eur. Phys. J. E **10**, 209 (2003)

Ultrasonic Velocimetry

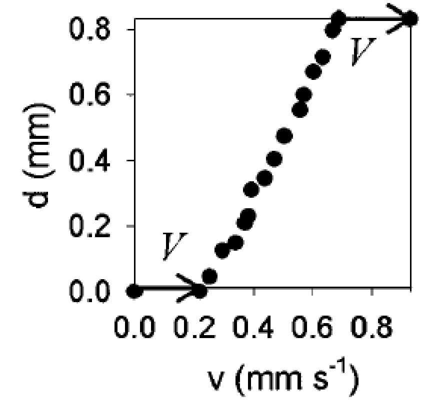


Bécu et al., PRL (2006)

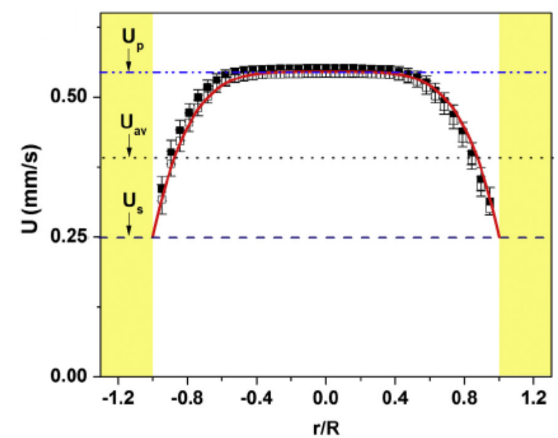


Divoux et al., Soft Matter (2012)

Particle Image Velocimetry



Meeker et al., PRL (2004)

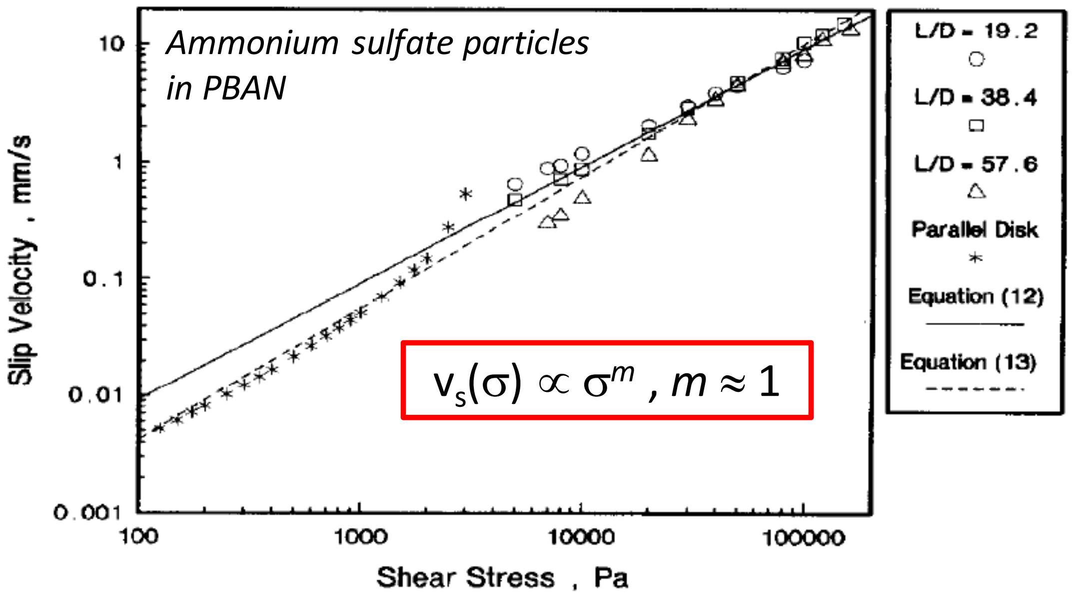


Poumaere et al., JNNFM (2014)

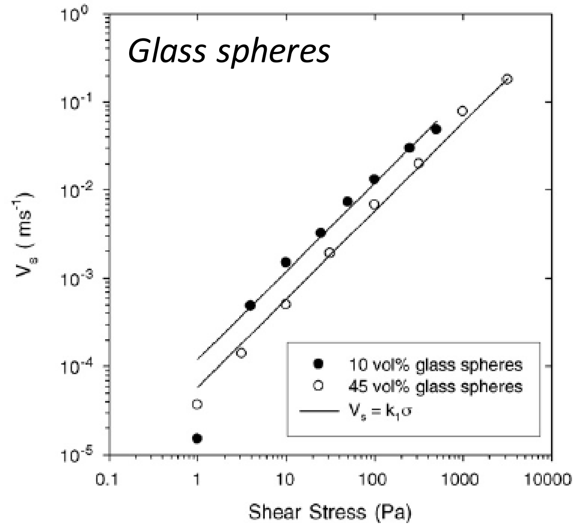
S. Manneville, Rheol. Acta **47**, 301 (2008)

Wall slip in suspensions of particles below jamming

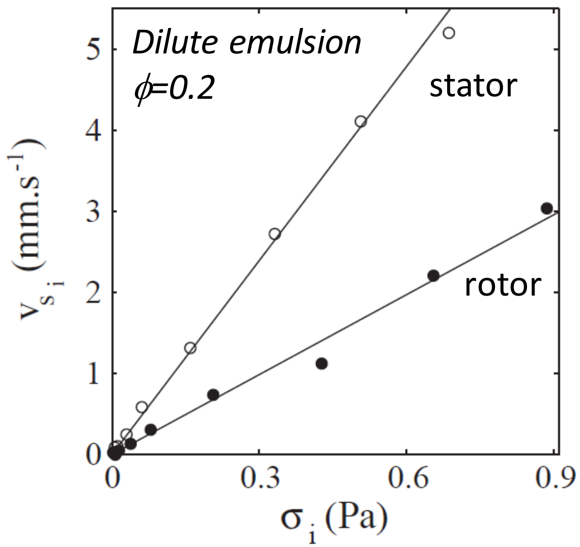
✓ **Scaling of the slip velocity with the shear stress σ ?**



Yilmazer & Kalyon, J. Rheol. (1989)
Aral & Kalyon, J. Rheol. (1994)
Kalyon, J. Rheol. (2005)



Davies & Stokes, JNNFM (2008)



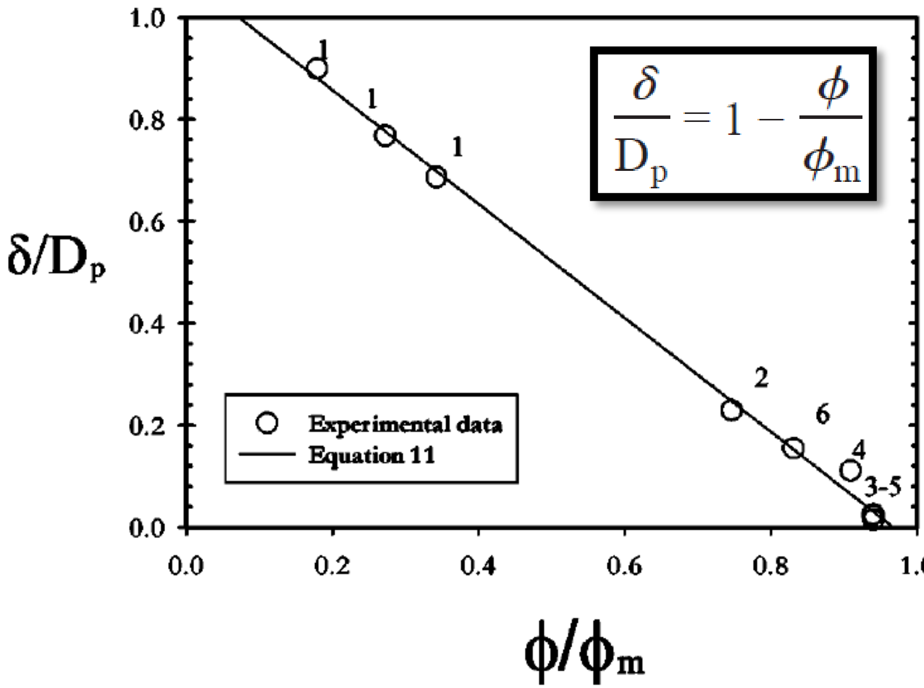
Salmon et al., Eur. Phys. J. E (2003)

✓ **Below jamming, $v_s(\sigma) \propto \sigma$**

✓ The scaling holds true for : - hard & soft particles
- different geometries

Wall slip in suspensions of particles below jamming

✓**Evolution of the slip layer thickness with ϕ and Pe**



The slip layer thickness decreases ~linearly for increasing packing fractions.

Kalyon, J. Rheol **49**, 621 (2005)
Ballesta et al., J. Rheol. **56**, 1005 (2012)

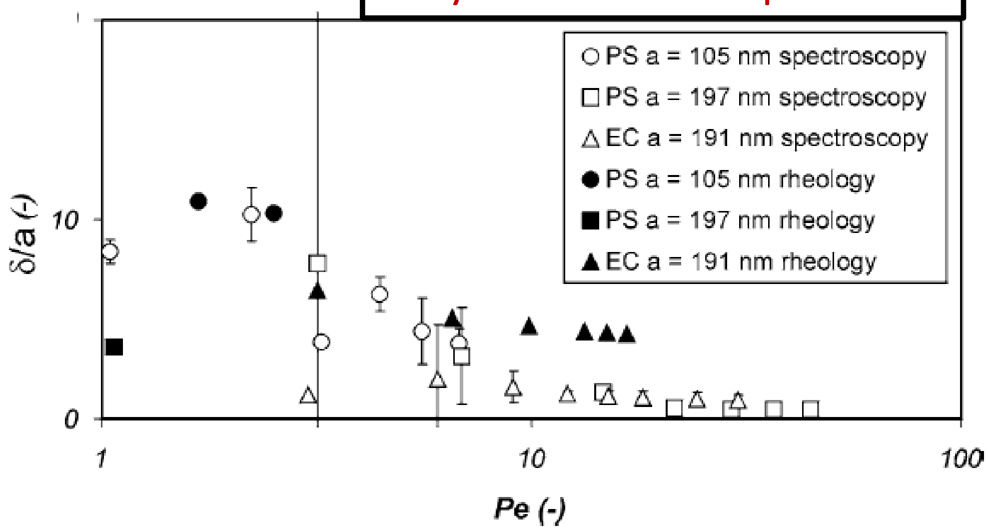
Remains true in presence of "weak" attractive interaction (depletion)

Buscall et al., J. Rheol **37**, 621 (1993)

The slip layer thickness decreases with the applied shear-rate

Hartman Kok et al., J. Rheol **46**, 481 (2002)
Hartman Kok et al., JCIS **280**, 511 (2004)

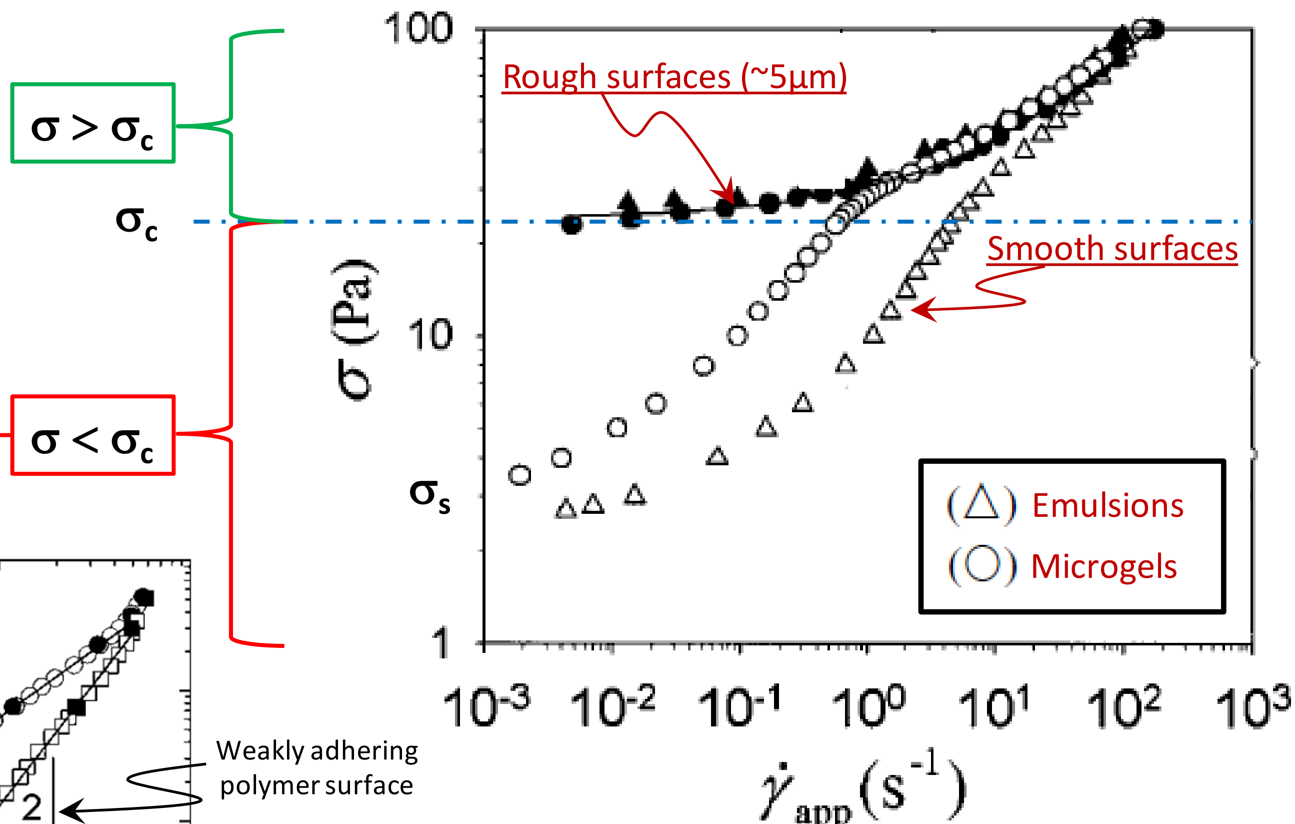
Ethylcellulose & PS particles

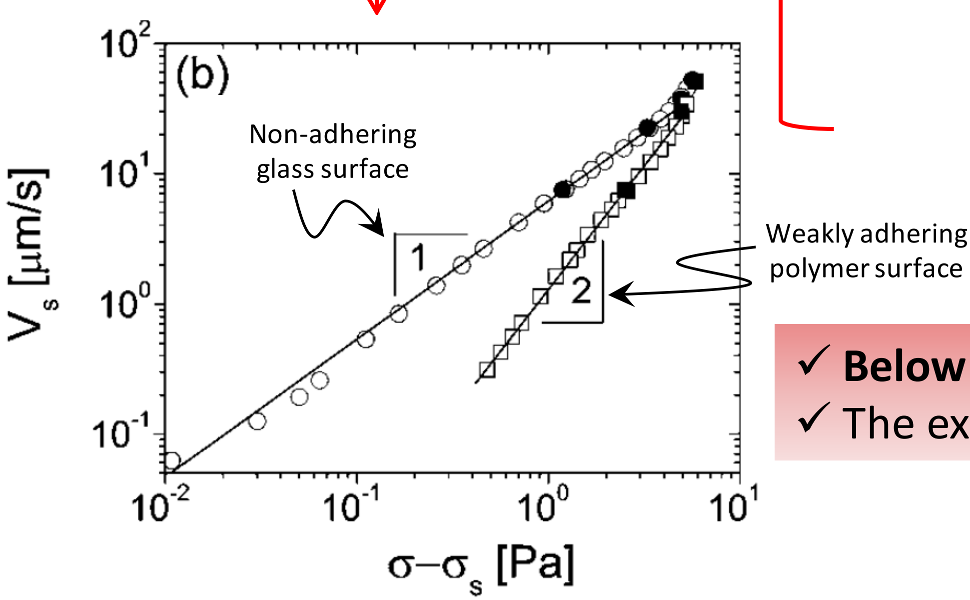


Wall slip in jammed suspensions of soft particles

✓ **Scaling of the slip velocity with the shear stress σ for $\sigma < \sigma_c$?**

What is the scaling of the slip velocity above the yield stress ?





✓ **Below the yield stress, $v_s(\sigma) \propto (\sigma - \sigma_s)^p$**

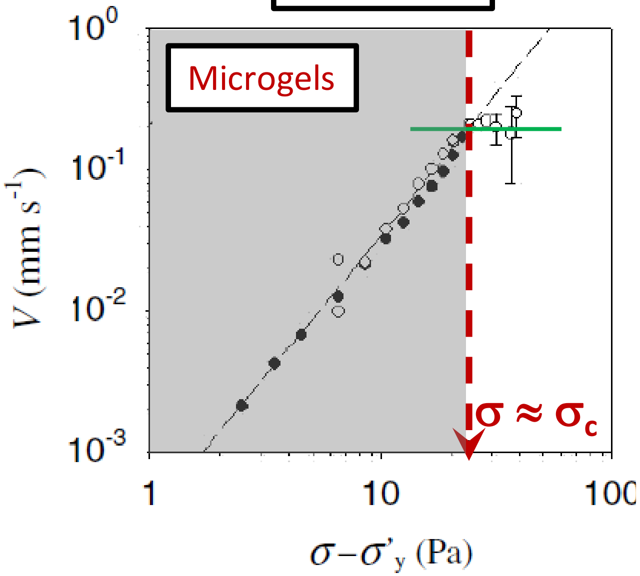
✓ The exponent depends on the boundary conditions

Meeker et al., Phys. Rev. Lett. (2004)
Seth et al., J. Rheol. ***52****, 1241 (2008)*
Seth et al., Soft Matter (2012)

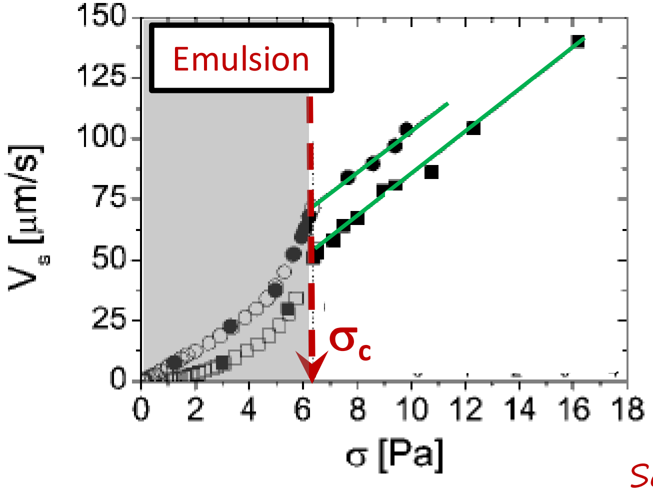
Wall slip in jammed suspensions of soft particles

✓ **Scaling of the slip velocity with the shear stress σ for σ > σ_c?**

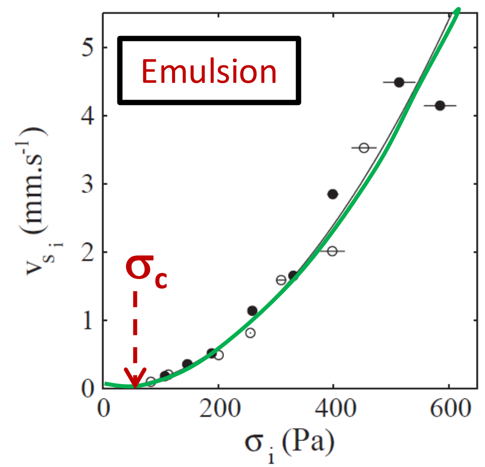
v_s = cste ≠ **$v_s \propto \sigma$** ≠ **$v_s \propto \sigma^2$**



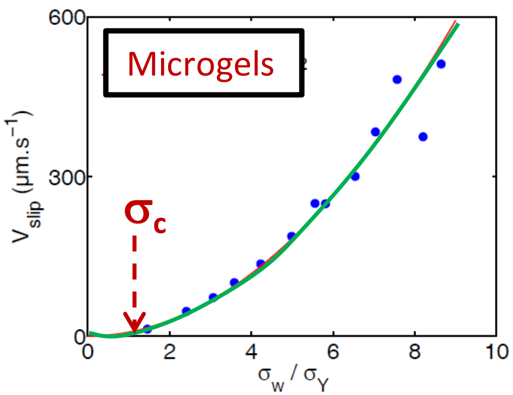
Meeker et al., Phys. Rev. Lett. (2004)



Seth et al., Soft Matter (2012)



Salmon et al., Eur. Phys. J. E (2003)

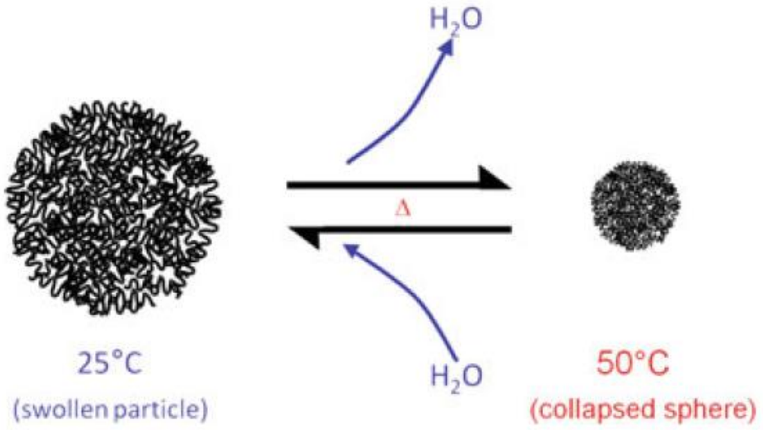


Geraud et al., Eur. Phys. J. E (2013)

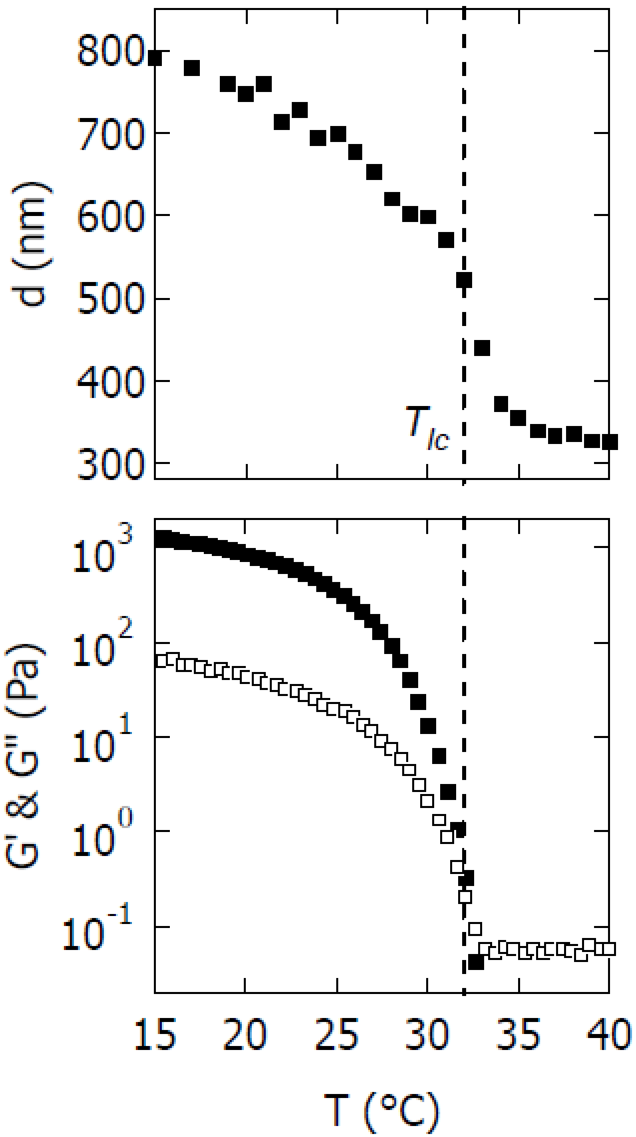
Why such apparent discrepancies in the scaling of the slip velocity in dense suspensions of soft particles above the yield stress ?

Temperature sensitive p-NIPAM microgels

poly(N-isopropylacrylamid) microgels



Pelton, Adv. Colloid. Interfac. (2000)
Senff & Richtering, Colloid Polym. Sci. (2000)
Menu et al., Soft Matter (2012)
…

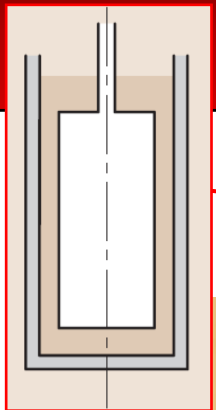


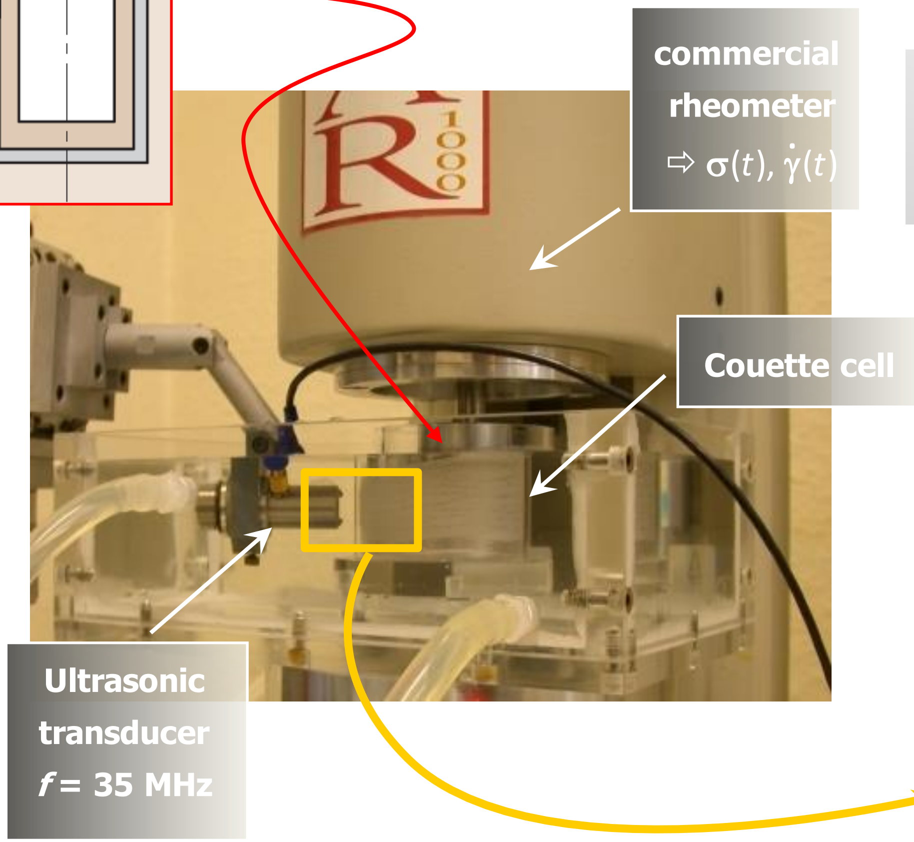
<u>The goal is to</u>:

(i) quantify the effect of the packing fraction on the scaling of the slip velocity…

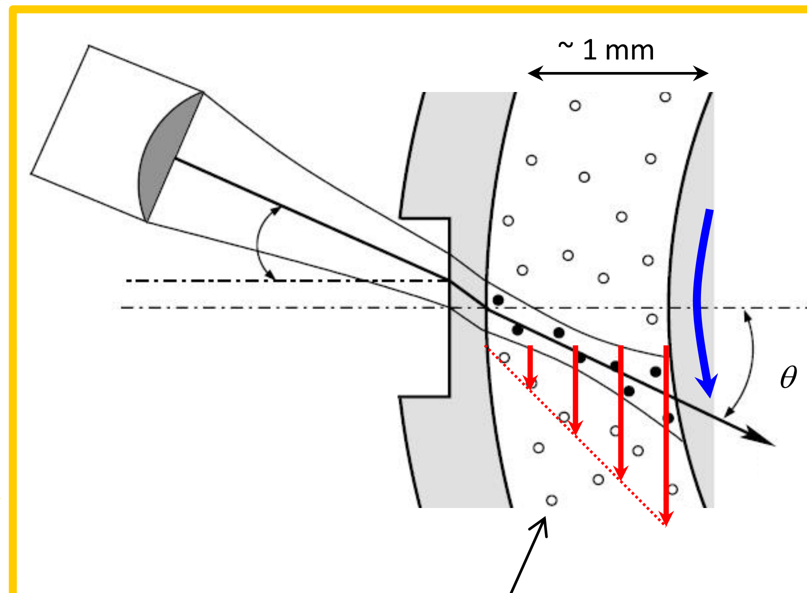
(ii) …from a jammed suspension of soft particles to a dispersion of hard particles

Rheology & time resolved velocimetry





- **Rheometer**: MCR 301 (Anton Paar)
- **Gap** e = 1 mm
- **Surface roughness** ≈ 15 nm (polished plexiglass)

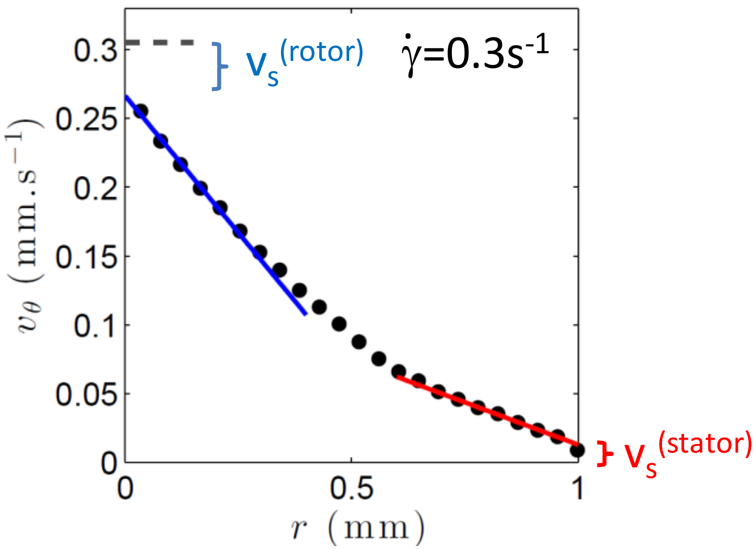


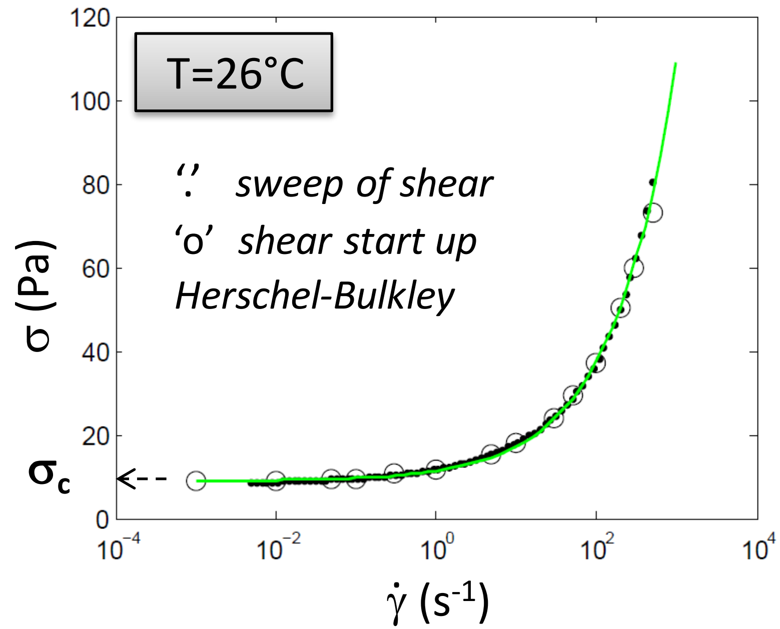
polystyrene microbeads
(Dynoseeds TS, 20 µm diameter, density 1.05)

- 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)

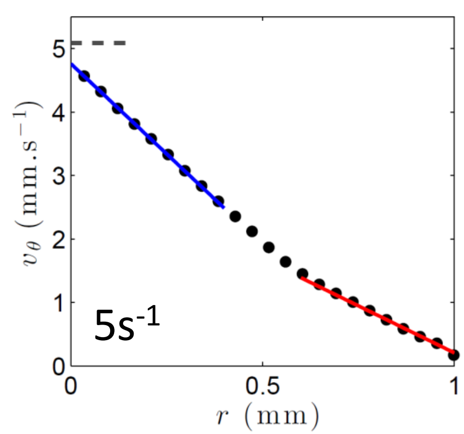
How to determine the scaling of the slip velocity ?

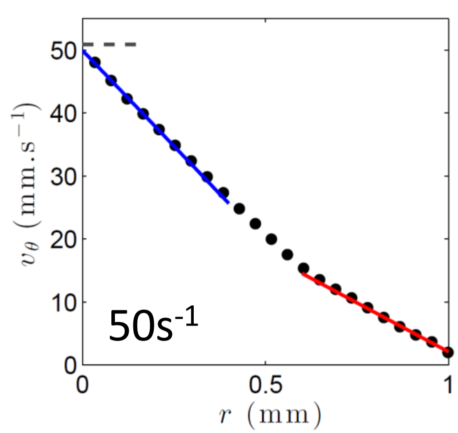




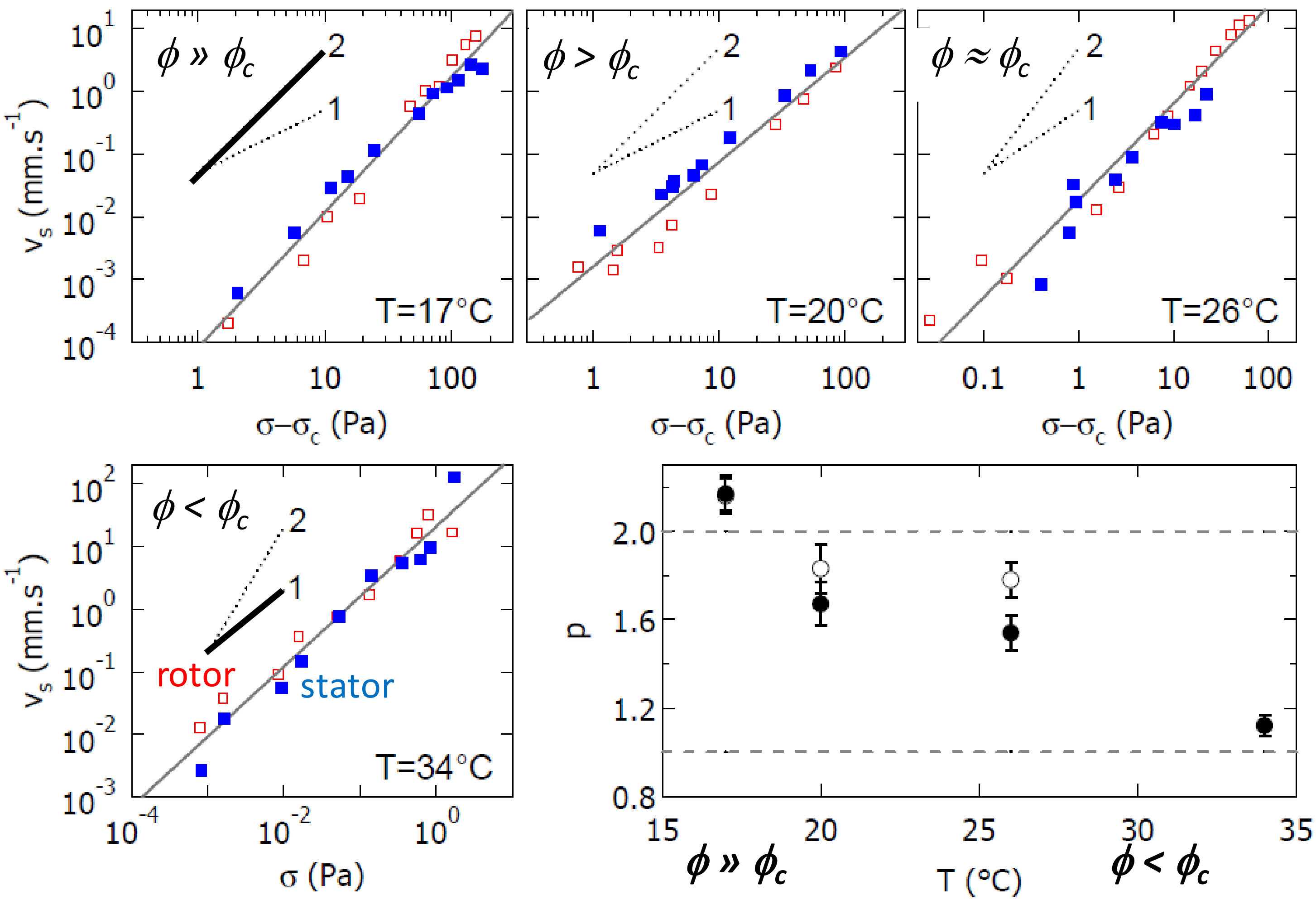
Extract the fluid velocity by extrapolating the velocity profile at the walls

(fit over ~100 µm @50µm from the wall)



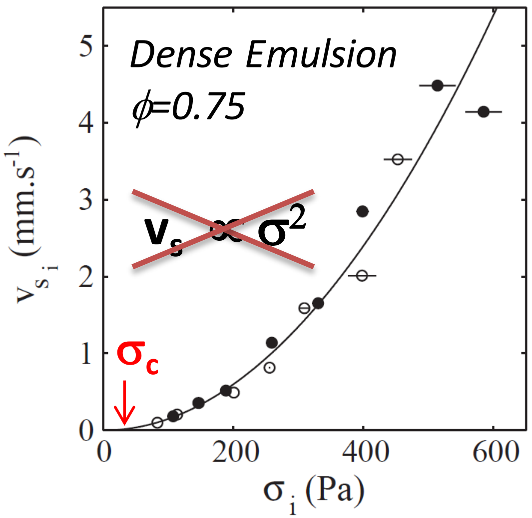


Scaling of the slip velocity at different temperatures

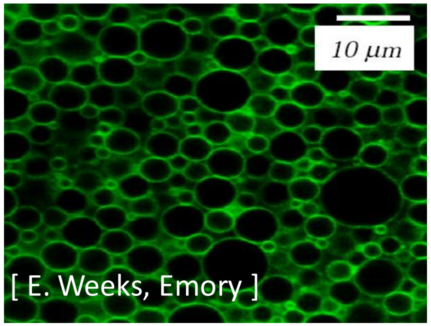


1) The slip velocity scales as a power law of the <u>**viscous stress**:</u> $v_s \propto (\sigma\text{-}\sigma_c)^p$
2) The exponent "p" depends on the packing fraction, including for $\phi > \phi_c$
3) p goes <u>continuously</u> from 1 to 2

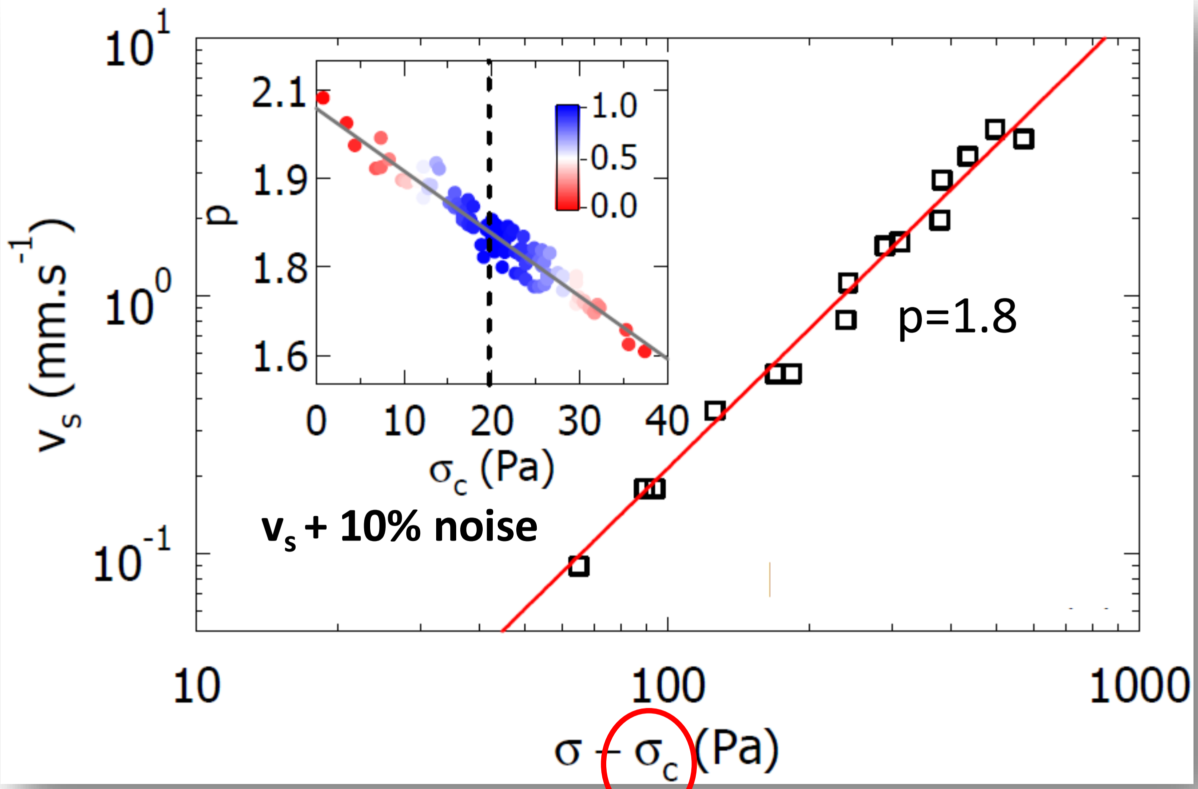
Revisit results from the literature – *example A*



Salmon et al., Eur. Phys. J. E (2003)



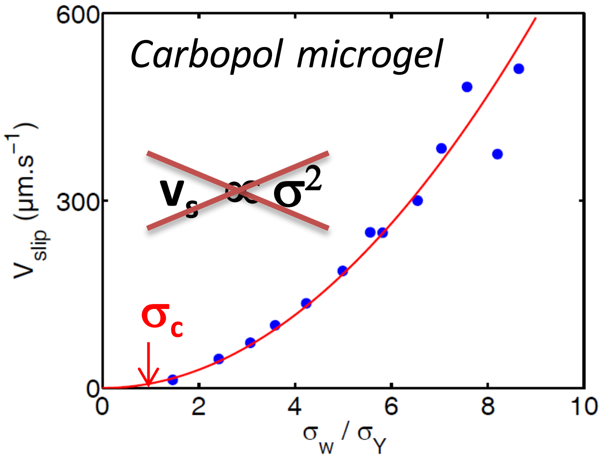
Taylor-Couette cell – 3mm gap (smooth BC)



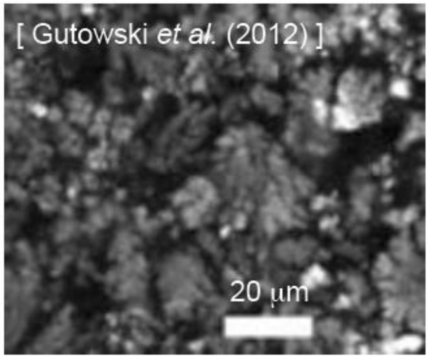
Yield stress that minimizes χ^2
$\sigma_c \approx 20$ Pa

- ✓ Minimization of χ^2 (+10% noise) rules out the quadratic scaling.
- ✓ The slip velocity scales as a power law of the <u>viscous stress:</u> $v_s \propto (\sigma-\sigma_c)^{1.8}$

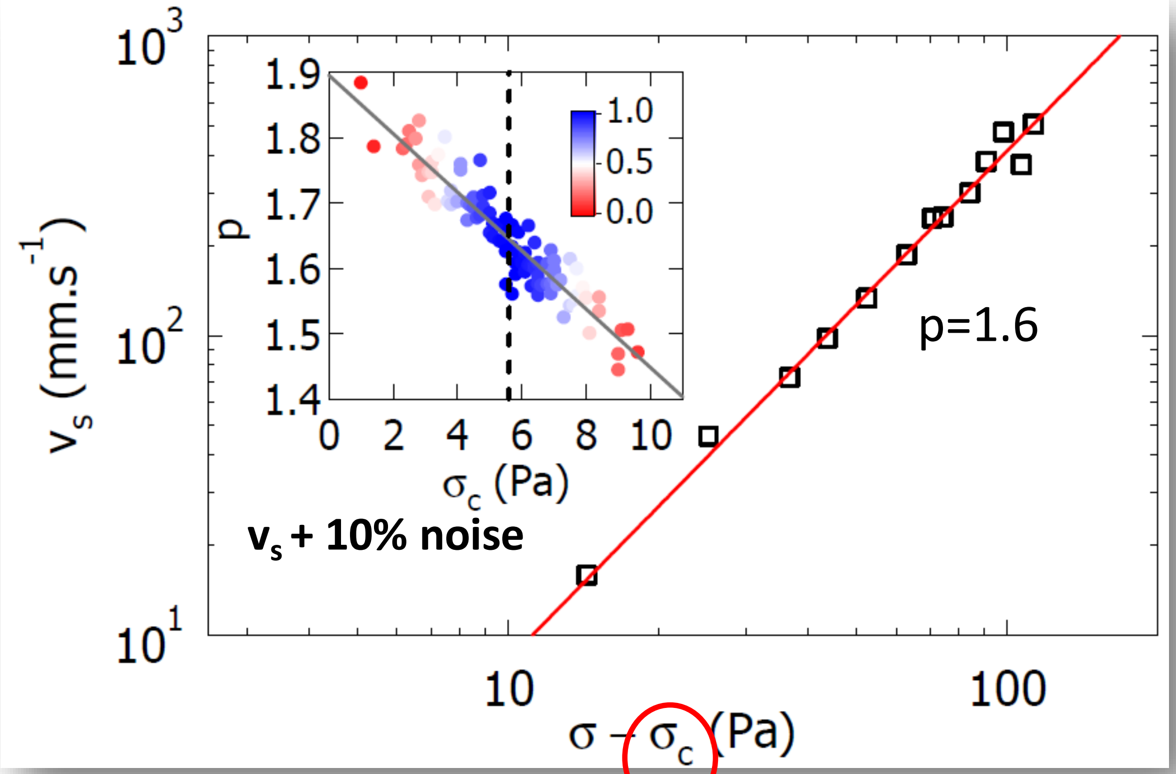
Revisit results from the literature – *example B*



Geraud et al., Eur. Phys. J. E (2013)



Microchannel – w ≈ 110µm (rough BC)



Yield stress that minimizes χ^2
$\sigma_c \approx 5.5$ Pa

- ✓ Minimization of χ^2 (+10% noise) rules out the quadratic scaling.
- ✓ The slip velocity scales as a power law of the <u>viscous stress:</u> $v_s \propto (\sigma-\sigma_c)^{1.6}$

First round of take home messages

Conclusions:

- **Be aware that wall slip may be present for $\sigma > \sigma_c$!**
- **The slip velocity v_s scales as a power law of a stress difference (σ-$\sigma_{s\ \mathrm{or}\ c}$):**

$$v_s(\sigma) \propto [\sigma-\sigma_c(\phi)]^{p(\phi,\ chemistry)}$$

and depends of ϕ

$v_s(\sigma) \propto [\sigma-0]^1$	$v_s(\sigma) \propto [\sigma-\sigma_c]^1$	$v_s(\sigma) \propto [\sigma-\sigma_c]^{1\rightarrow 2}$
$\phi < \phi_c$	$\phi \approx \phi_c$	$\phi > \phi_c$

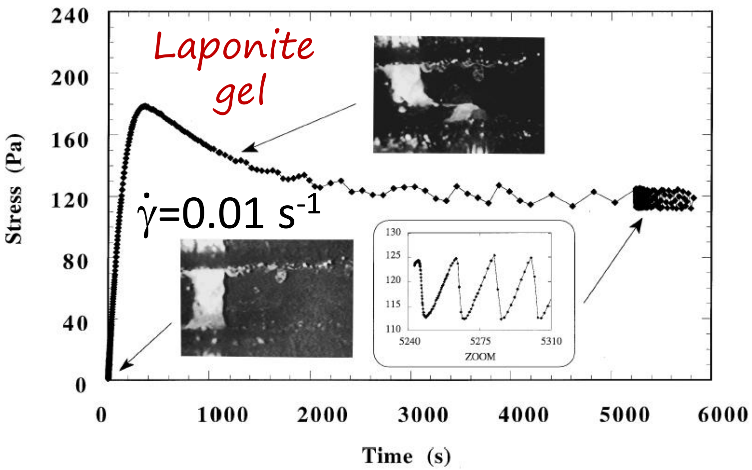
- **The power-law scaling introduced in** *Meeker et al. Phys. Rev. Lett. (2004)* **extends above the yield stress.**

Open questions:

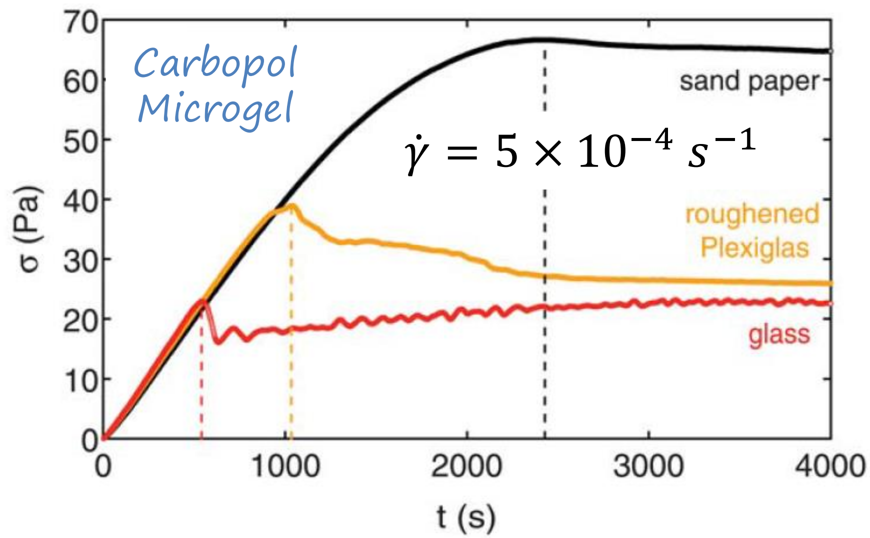
- **Effect of the geometry/particle-particle interactions?**
- **Modeling ? Need for spatially-resolved models!**
  - Recover the power-law scaling of the slip velocity
  - Test the influence of the adhesion to the wall, Brownian effects, etc.
  - Comparison Chemistry (adhesion) vs Mechanics (surface roughness)

T. Divoux, V. Lapeyre, V. Ravaine & S. Manneville, *Phys. Rev. E* **92**, 060301 Rapid Com (2015)

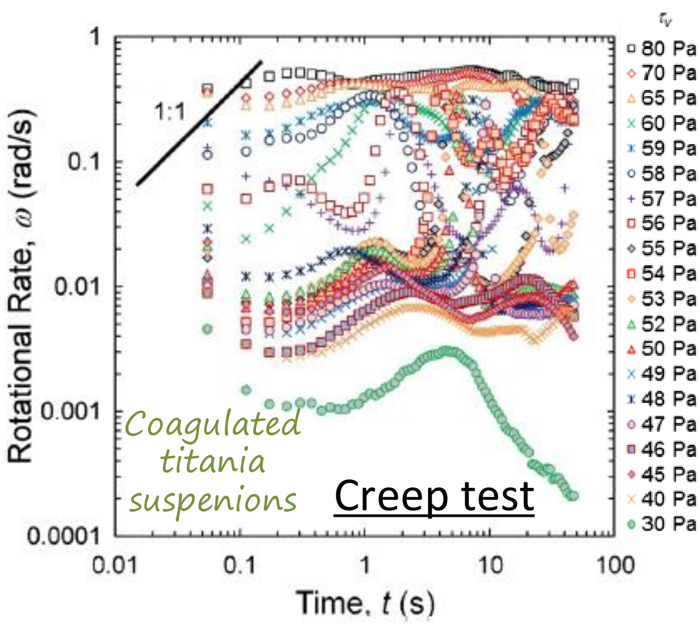
Wall slip & yielding (solid→liquid transition) – **stick-slip**



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



Divoux et al., Soft Matter 7, 9335 (2011)



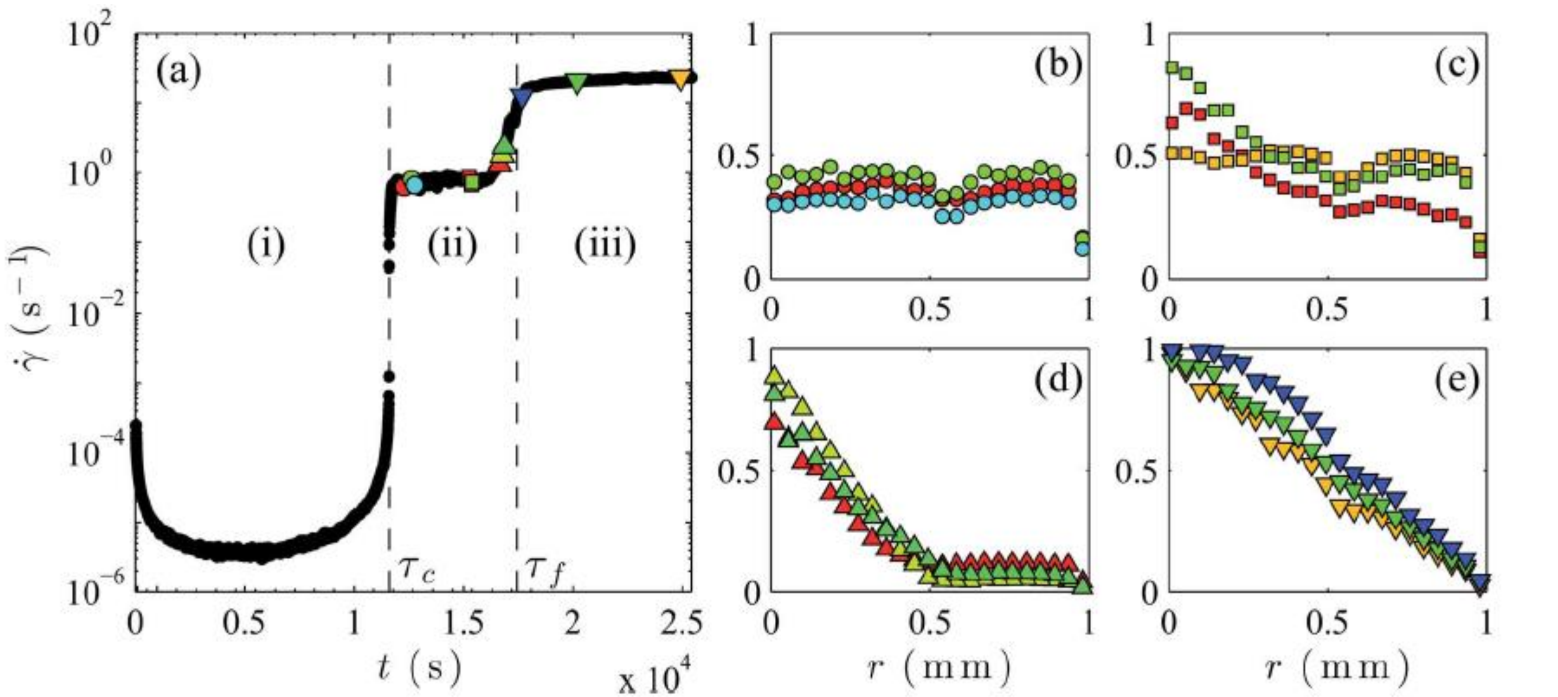
Stickland et al., Rheol. Acta **54**, 337 (2015)

For "low shear-rates", the competition between wall-slip and adhesion can lead to stick-slip

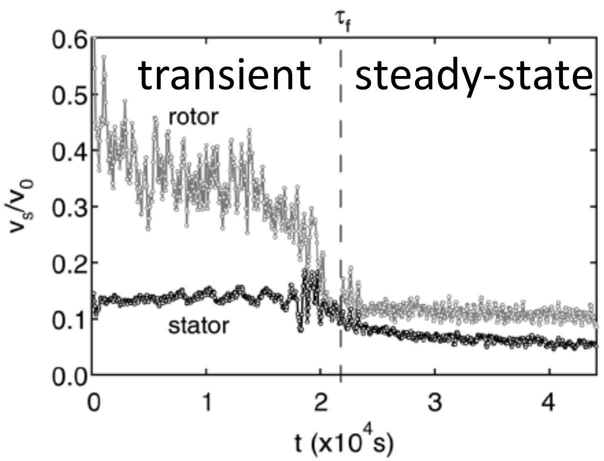
- *in general a strong influence of the gap size* ***(but not directly related to confinement)***
- *Stick-slip observed for both stress & rate controlled experiments* ***(conditions for stick-slip to occur?)***

Wall slip & yielding (solid→liquid transition) – **intrinsic slip**

Carbon-black gel (10% wt.)
Creep test - σ = 55 Pa
"**rough**" boundary conditions



Grenard, Divoux, Taberlet & Manneville, Soft Matter **10**, 1555 (2014)



Divoux et al., Phys. Rev. Lett. (2010)
& Soft Matter 8, 4151 (2012)

Wall-slip may take place during the fluidization of SGM even with rough/adhesive boundary conditions

Wall slip = intrinsic behavior

- *Wall-slip takes place at the wall & from the very early stage of the yielding process*

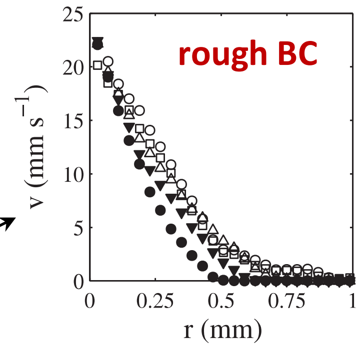
⇒ ***Wall slip as a limit case of shear-banding phenomena?***

Divoux et al., Annu. Rev. Fluid Mech. 48, 81 (2016)

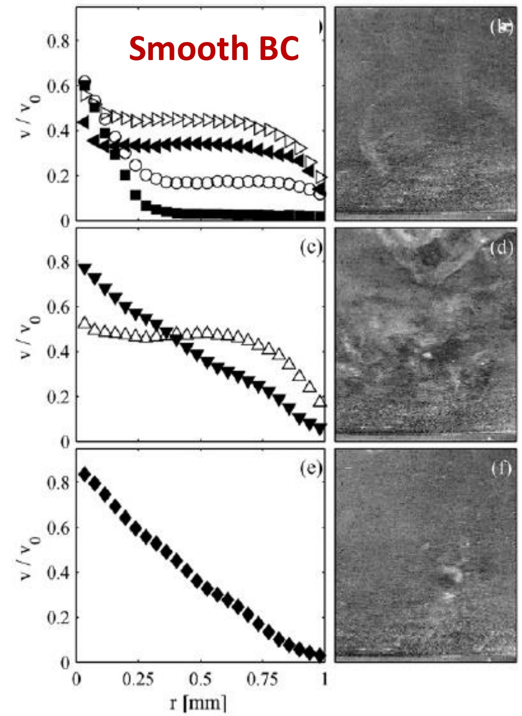
Wall slip & yielding (solid→liquid transition) – **driving the steady-state**

Laponite suspensions

steady shear-banding under rough BC



but steady homogeneous flow under smooth BC

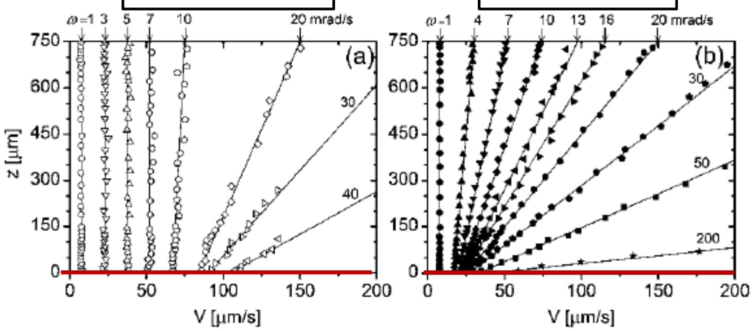


Gibaud et al. Phys. Rev. Lett. (2008) & Soft Matter (2009)

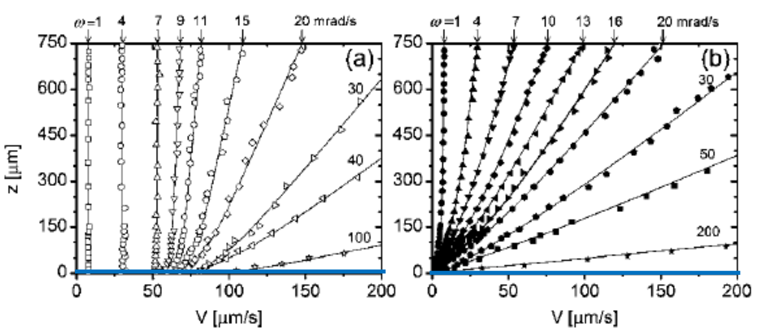
Emulsion

Microgel

Repulsive BC



Attractive BC



Seth et al. Soft Matter 8, 140 (2012)

Boundary conditions (& wall-slip) may impact the steady-state flow-curve!

- *Dramatic consequences in dilute systems!*
- *Steady-state velocity profiles in the vicinity of the wall well-described by non-local approach*

See also: *Nicolas & Barrat, PRL 110, 138304 (2013)*
Mansard et al. Soft Matter 10, 6984 (2014)

Final Take home messages

Wall slip & transient flows:

- Wall slip often leads to **stick-slip behavior** at "low enough" shear rates
- Wall slip goes had in hand with **solid→liquid transition** = **intrinsic behavior**, *i.e. may not be suppressed by modifying the boundary conditions*
- Fostering **wall slip may strongly affect the steady-state behavior**, when investigating the solid→liquid transition.

Letter to the Editor: Wall slip in dispersion rheometry

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Even though our appreciation of the importance and ubiquity of wall slip has grown substantially over the last decade or two, it is still common to find papers on disperse systems wherein scant details of the measurement methods are given and where no mention of the possibility of slip is made. It seems then that there is a need still to raise awareness and to promote the idea that the rheometry of disperse systems is not so straightfoward as it might seem. It takes experience, judgment, and skill to make meaningful measurements on disperse systems and it is suspected that the nature of the experimental challenge is under-estimated grossly by too many workers even now. Slip is not merely a rheometric complication; of course, it an intrinsic feature of the response of disperse systems and one deserving of more attention in its own right. [DOI: 10.1122/1.3495981]