

# Rheology of granular media : role of friction and adhesion

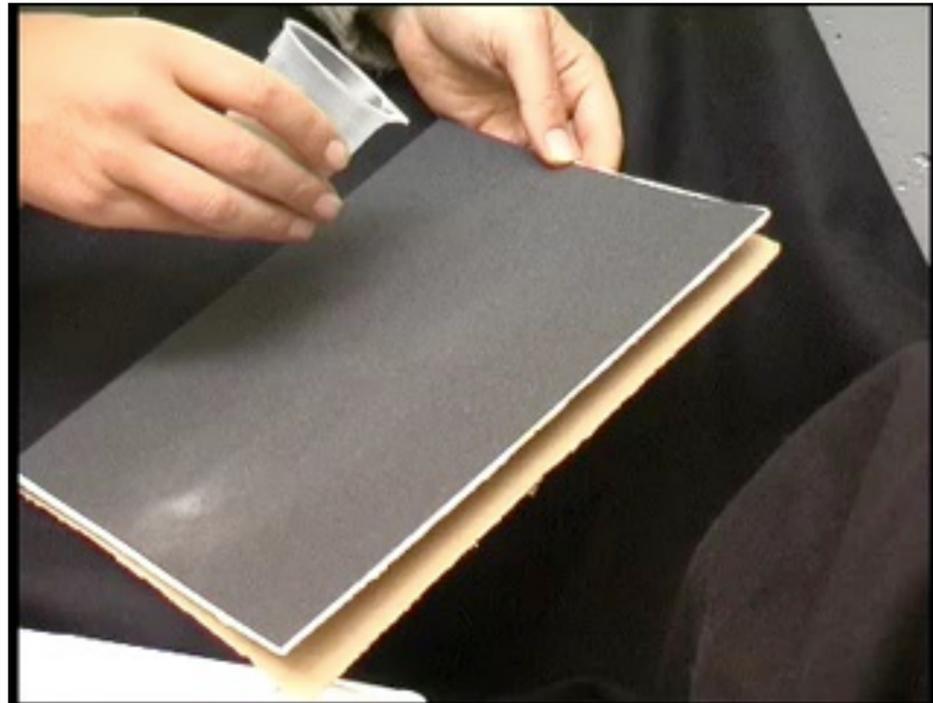
Olivier Pouliquen

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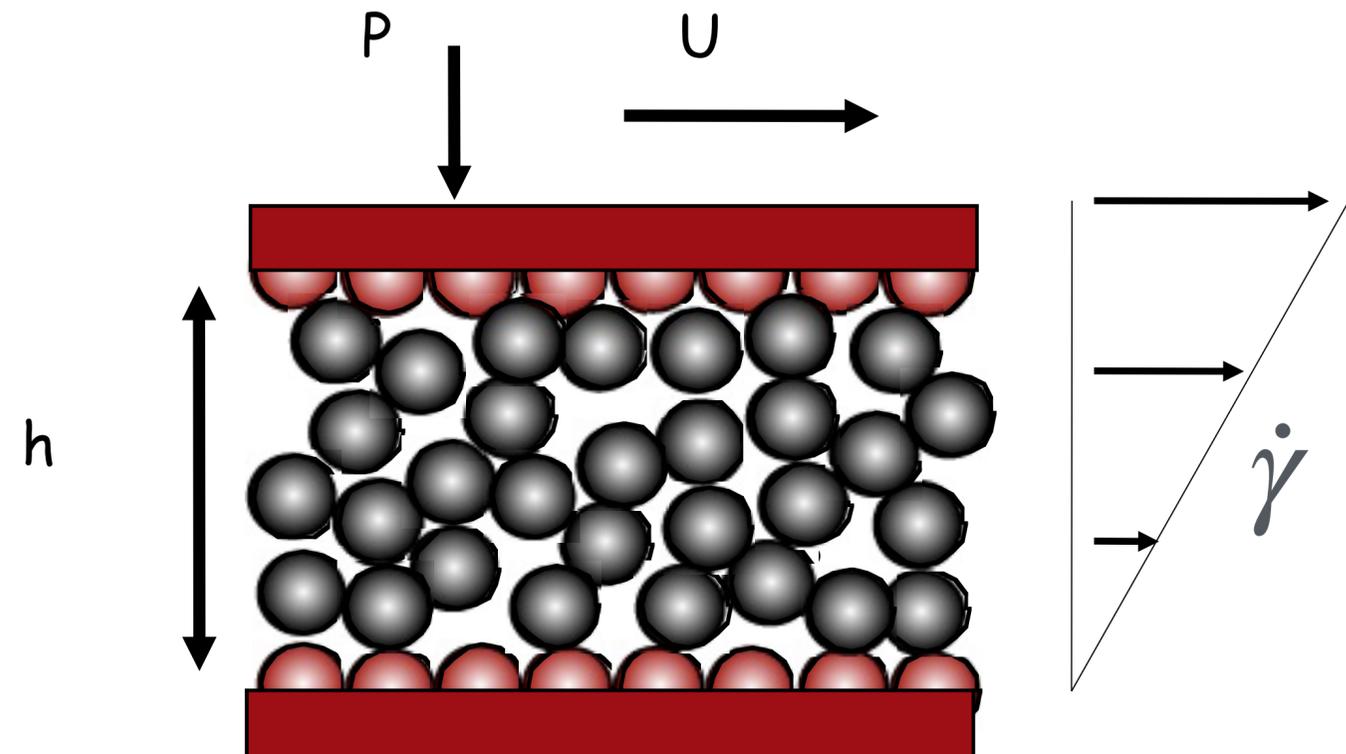


# Rheology of granular media:

a continuum description  
of granular flows?



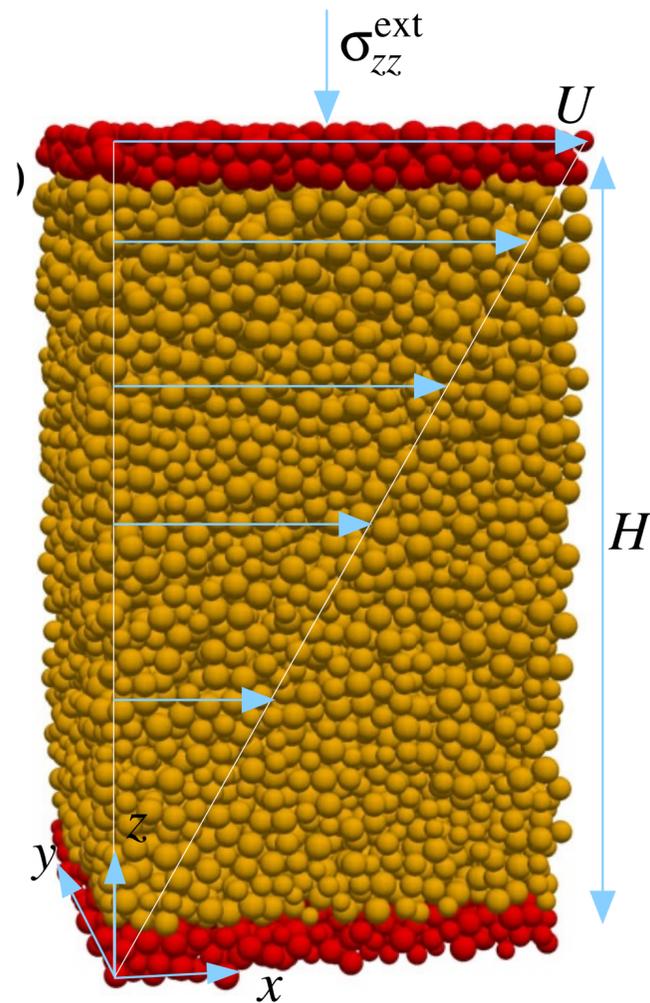
Plane shear under controlled pressure  $P$



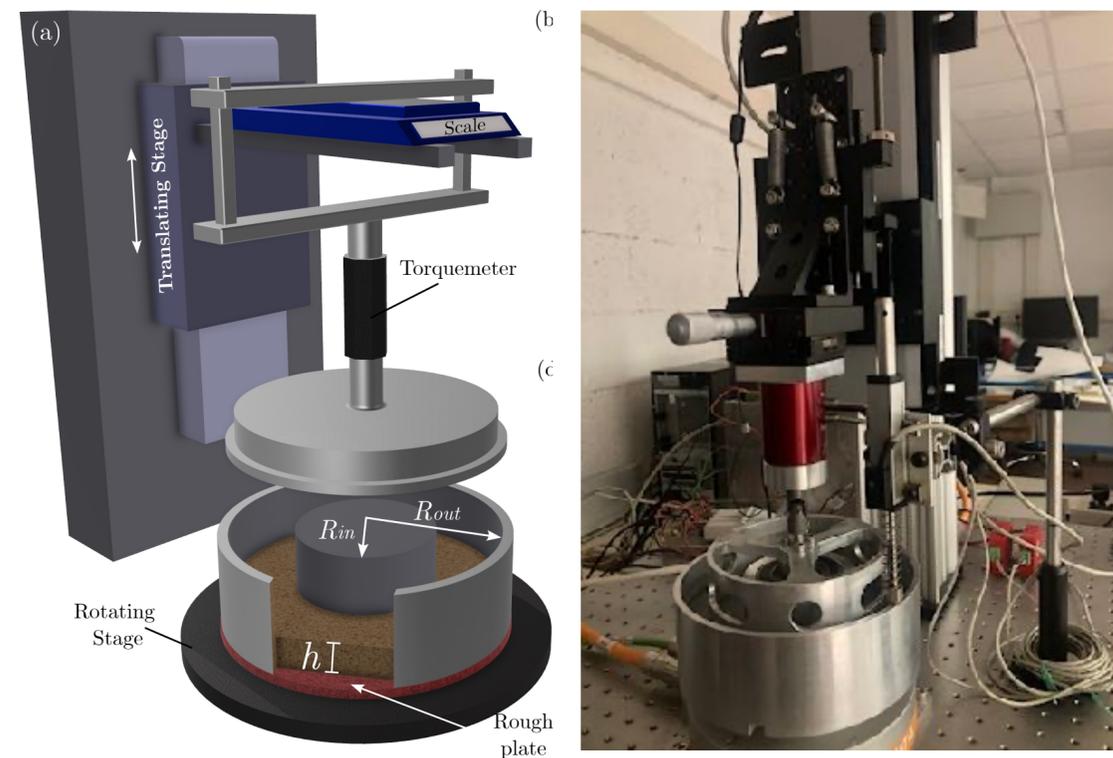
How the shear stress  $\tau$   
the volume fraction  $\phi$   
vary with  $P$  and  $\dot{\gamma}$  ....  
role of the grain properties ?

# tools to explore the granular rheology:

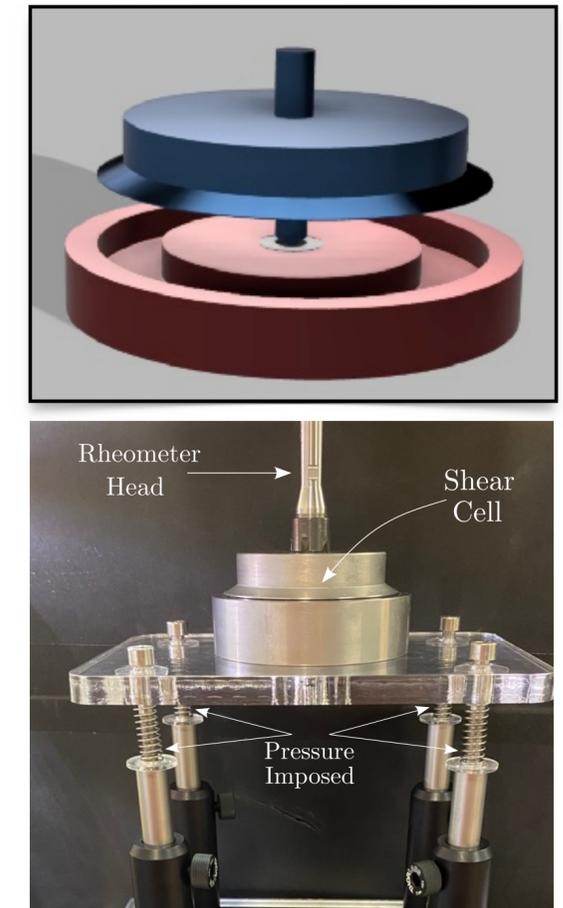
## DEM simulations



## Shear cell (adapted for steady shear!)



Big cell  
(for  $d > 800 \mu\text{m}$ )



small cell  
(for  $d > 150 \mu\text{m}$ )

# rigid, non adhesive grains : the $\mu(I)$ rheology



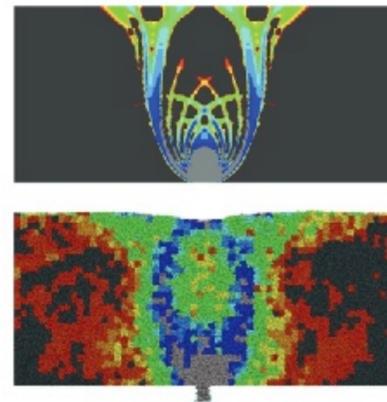
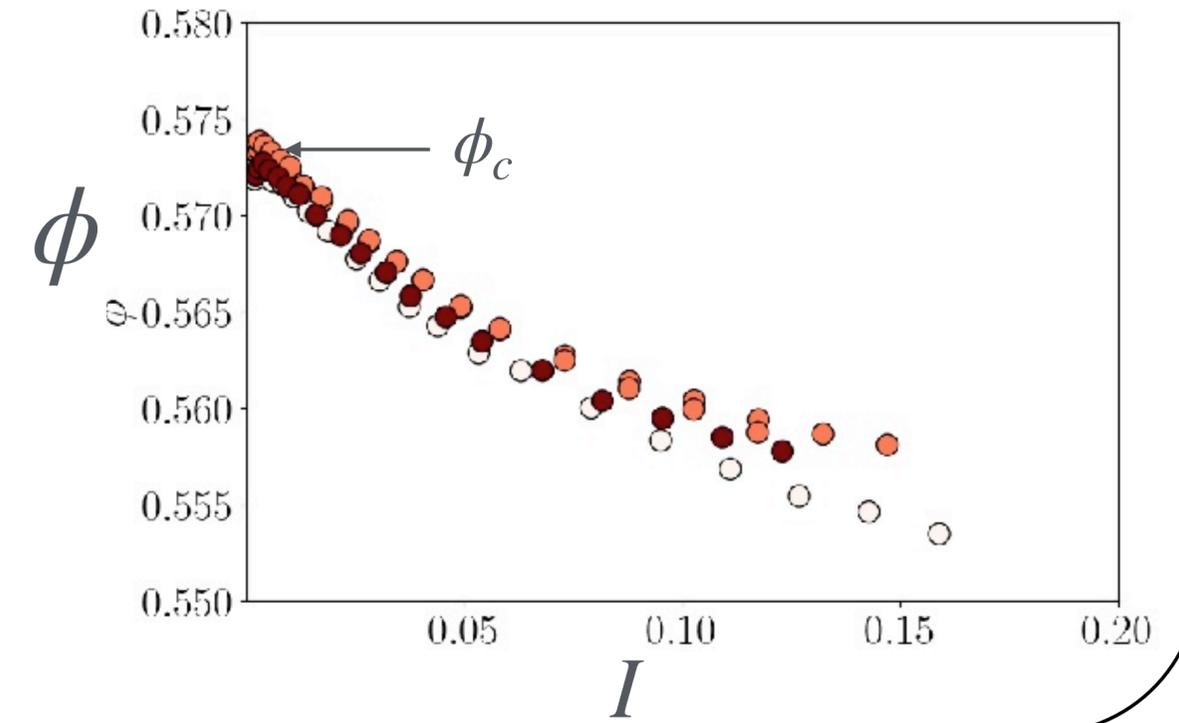
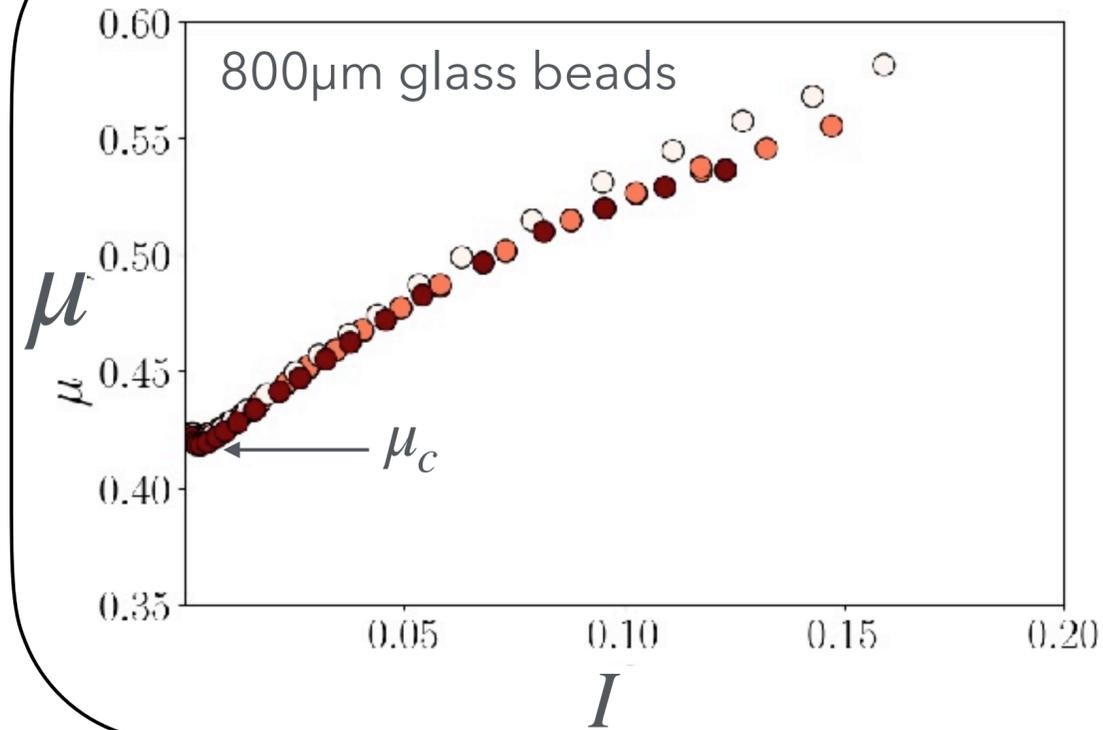
a single  
dimensionless number

$$I = \frac{\dot{\gamma}d}{\sqrt{P/\rho_s}}$$

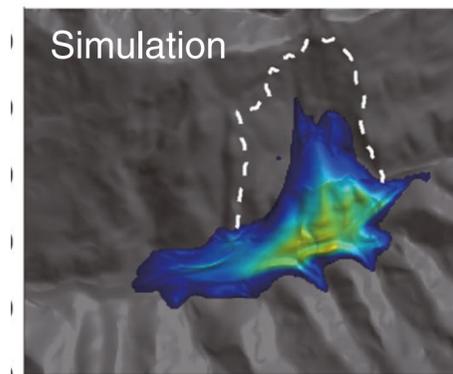
$$\tau = \mu(I)P$$

$$\phi = \phi(I)$$

inertial regime

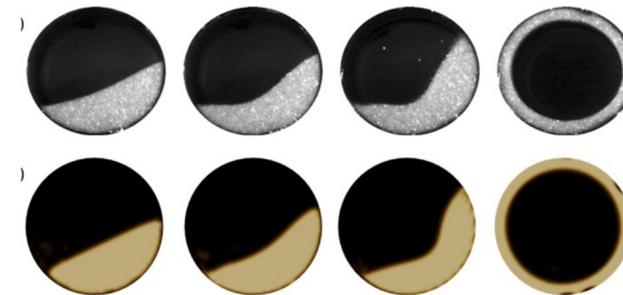


Kamrin 2015

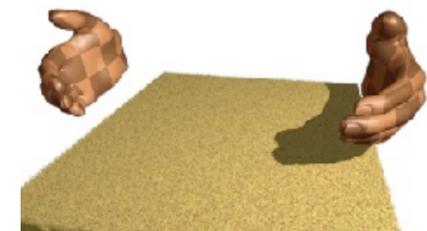


Yamada et al 2017,

applications:  
silos, avalanches, drums, ..



Arseni et al 2020



Davier et al 2016,

# rigid, non adhesive grains : the $\mu(I)$ rheology

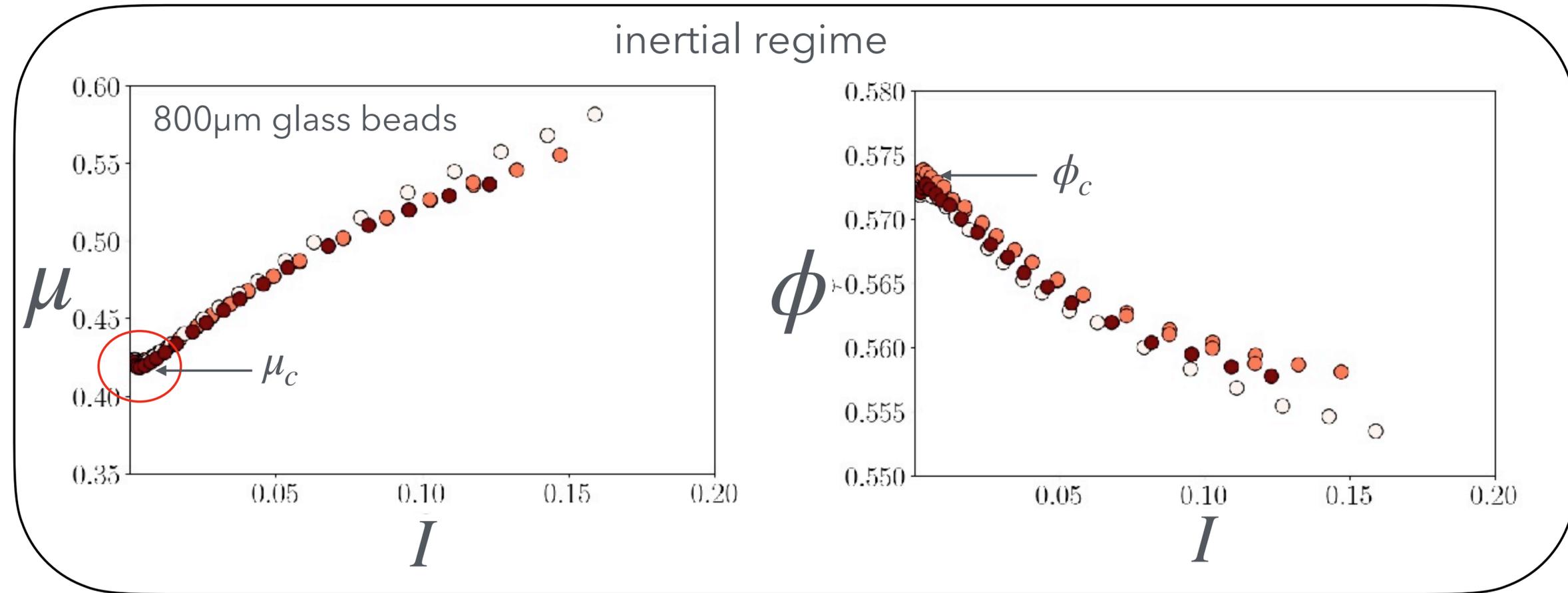


a single  
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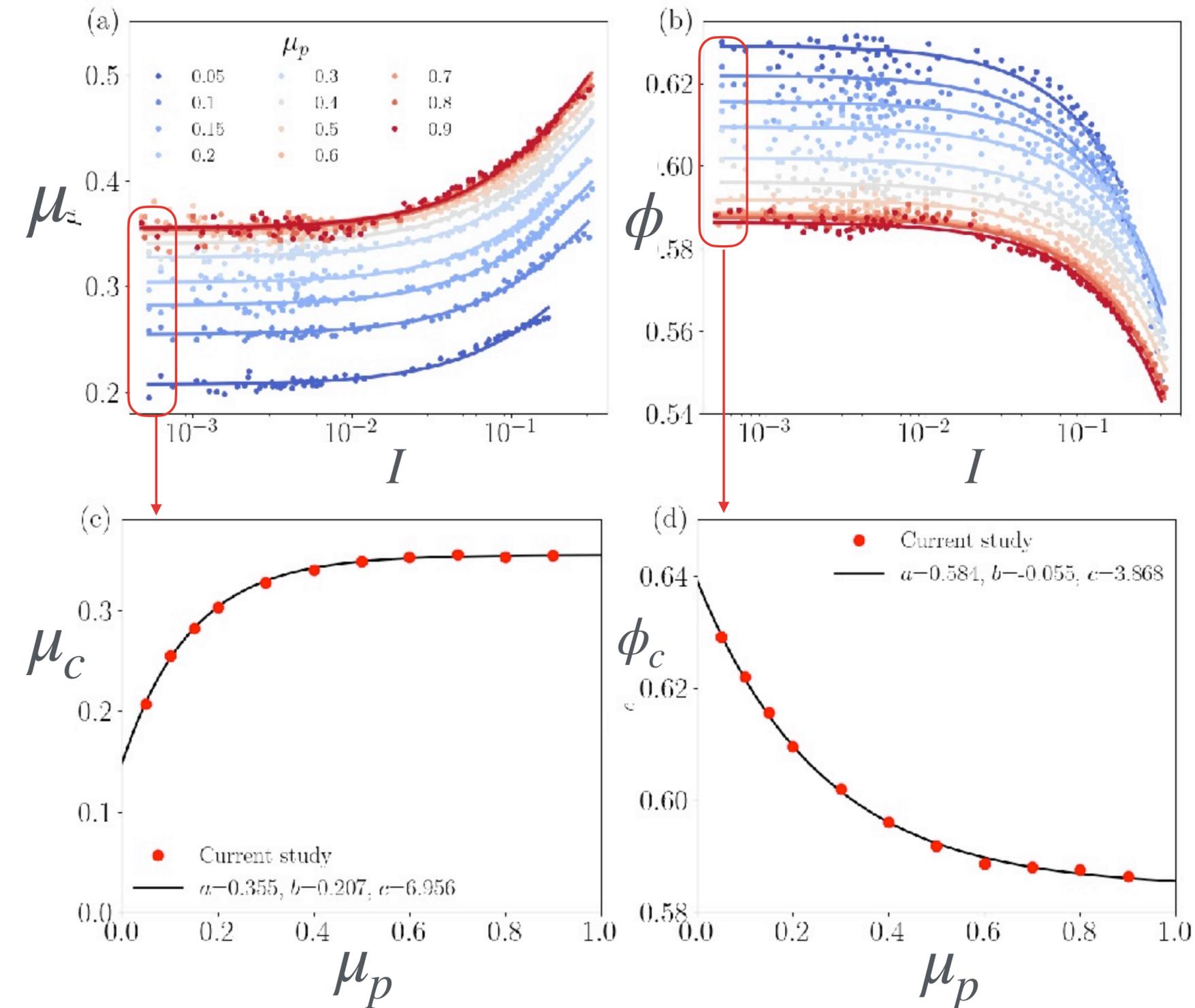
$$\phi = \phi(I)$$



influence of particles properties ?

- interparticle friction coefficient ?
- adhesion between particles ?
- + stiffness, shape of the particles...

# Role of interparticle friction $\mu_p$ using DEM



-  $\mu(I)$  changes mainly at low  $\mu_p$

$\mu_c \searrow, \phi_c \nearrow$  when  $\mu_p \searrow$

- frictionless particles ( $\mu_p=0$ )

=> low, but non zero bulk friction

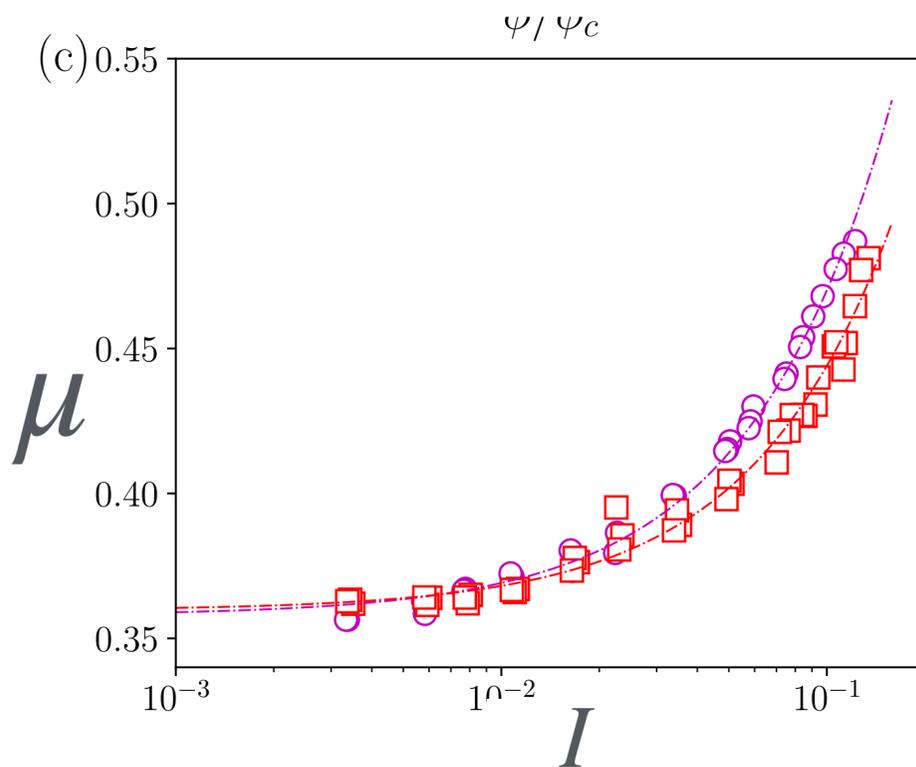
=> denser packing

in experiments ?

difficult to control  $\mu_p$

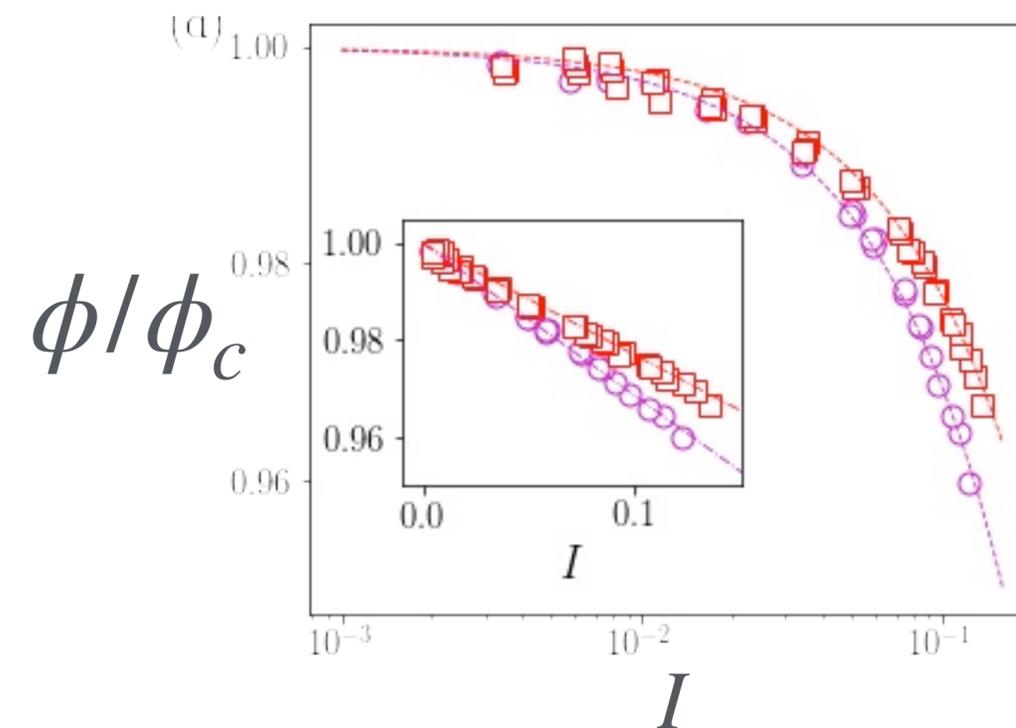
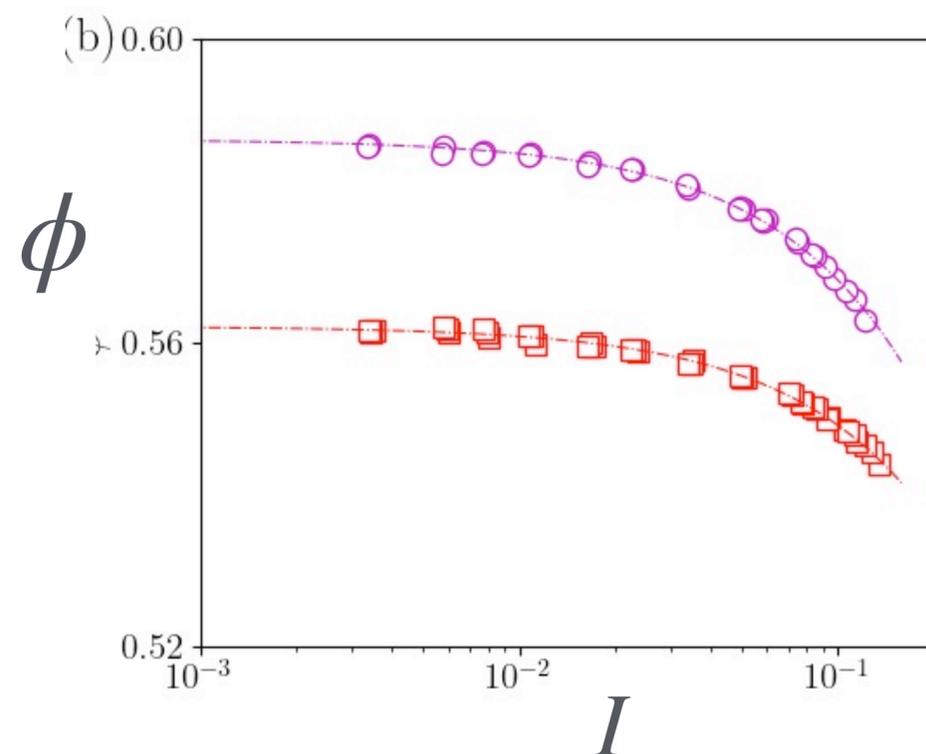
# increasing friction using roughness

$d = 540\mu\text{m}$   
 $\mu_p = 0.37$   
 $\mu_{rol} = 0.007$



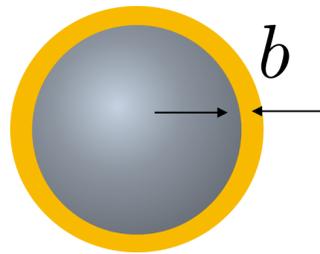
- $\mu(I)$  not affected
- $\phi(I)$  is shifted...  
but can be renormalised

$d = 580\mu\text{m}$   
 $\mu_p = 0.23$   
 $\mu_{rol} = 0.004$



# decreasing friction with a coating

silica particles coated  
with a pinch of polymers (PBS)

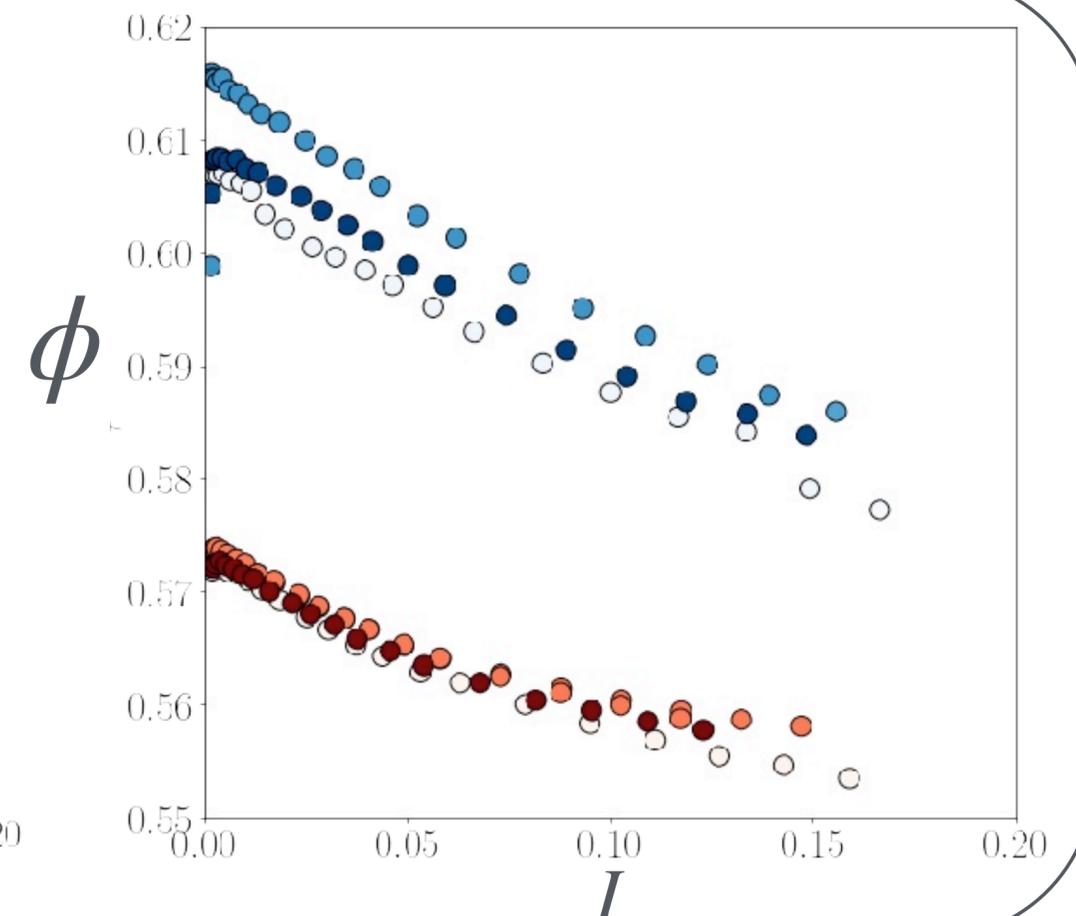
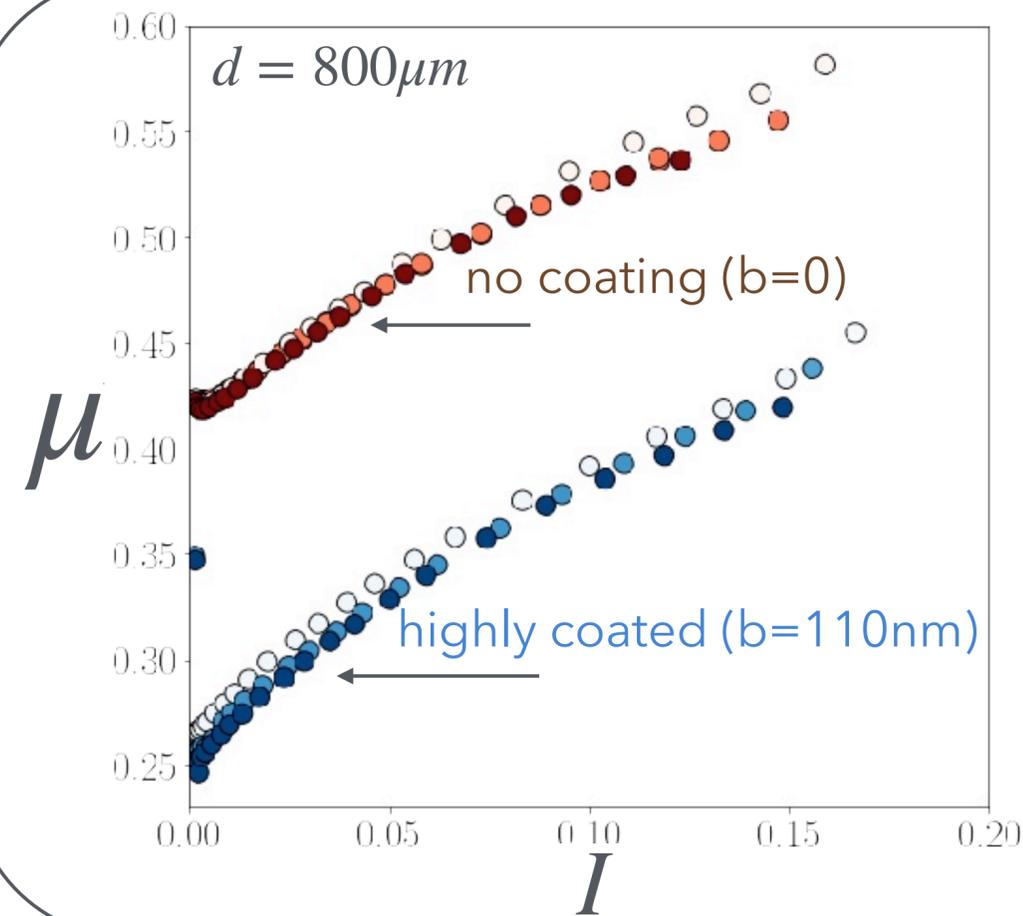


Silica Microbeads  
+PDMS-OH,  
+Boric Acid ( $H_3BO_3$ )

Control parameter:  
coating thickness  $b$   
 $10nm < b < 1000nm$

(adhesion negligible for  $d \gtrsim 600\mu m$ )

Gans et al, PRE 2020



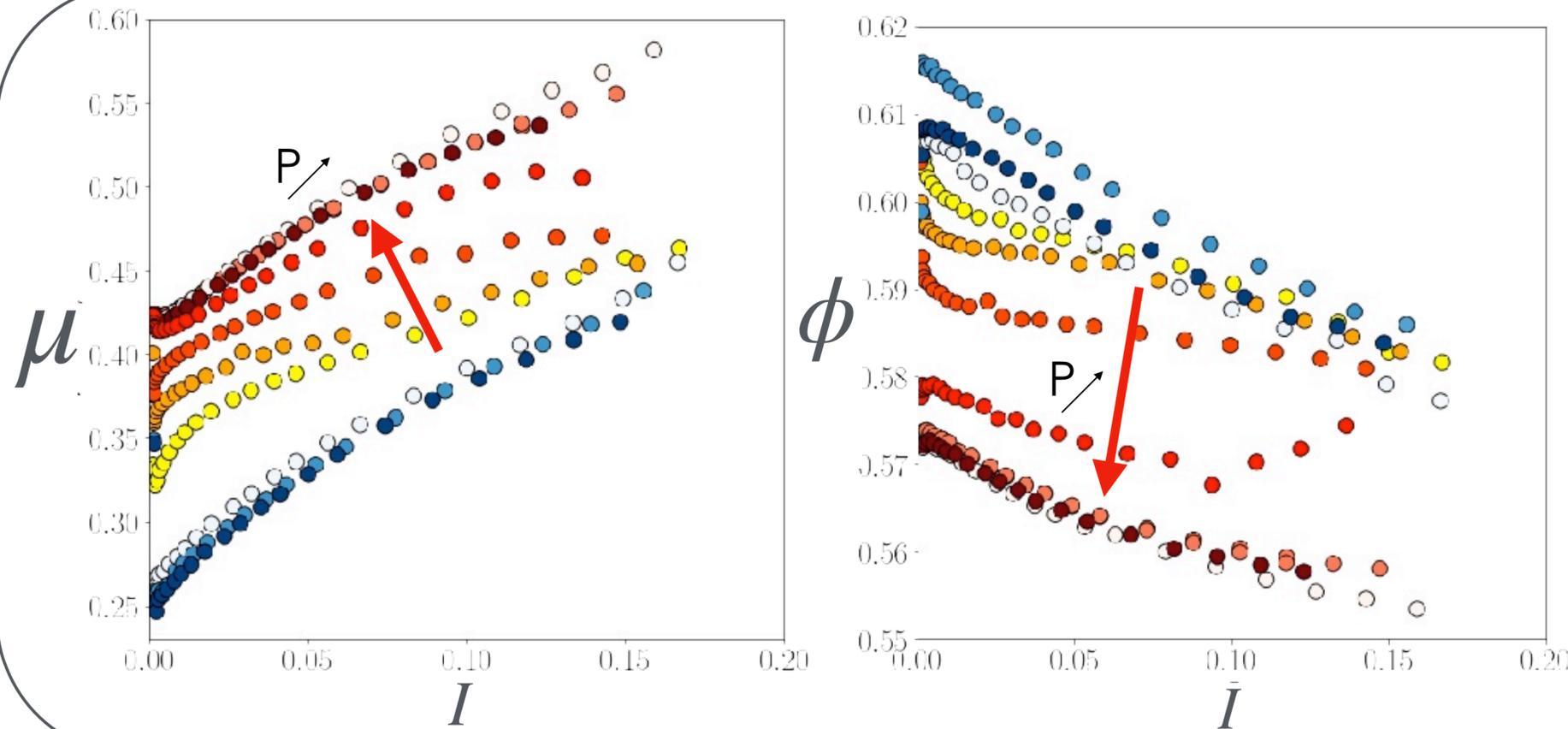
coated particles  
=  
a frictionless  
granular medium?

but not so simple:  
a complex lubrication transition

Rocha et al, 2026

# changing friction: with coating.

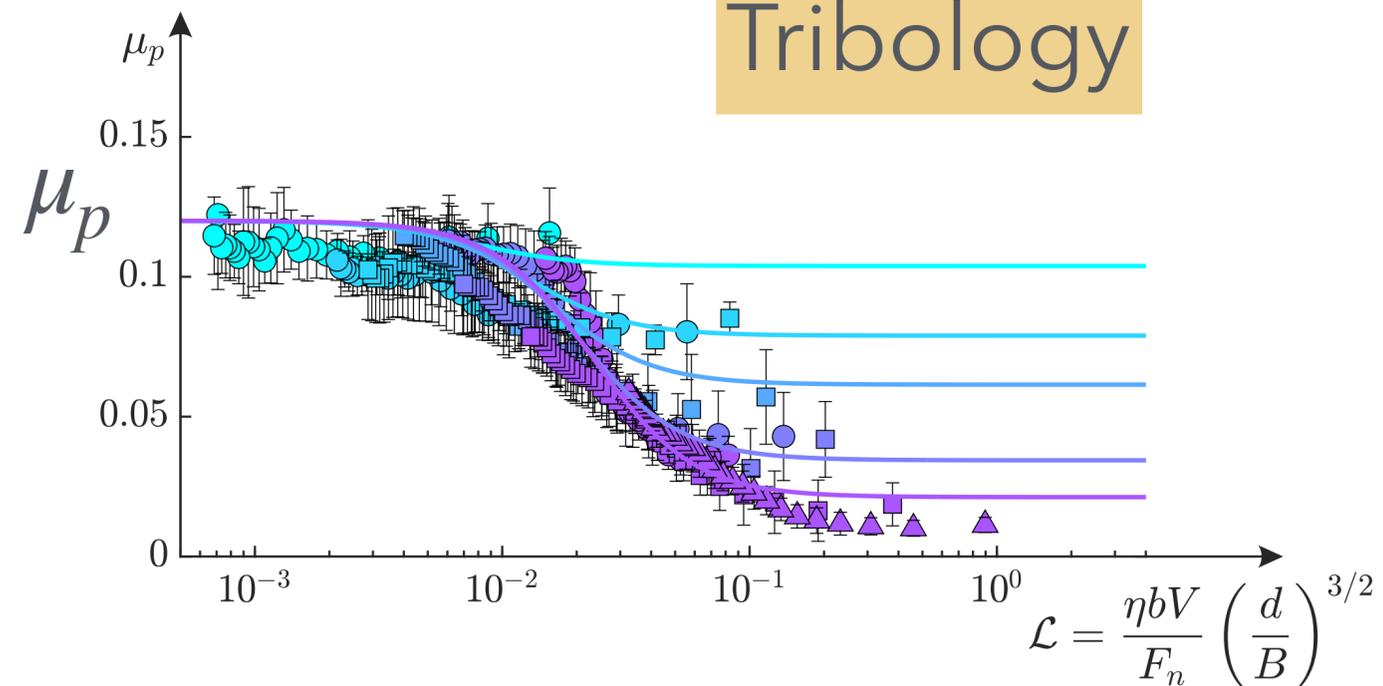
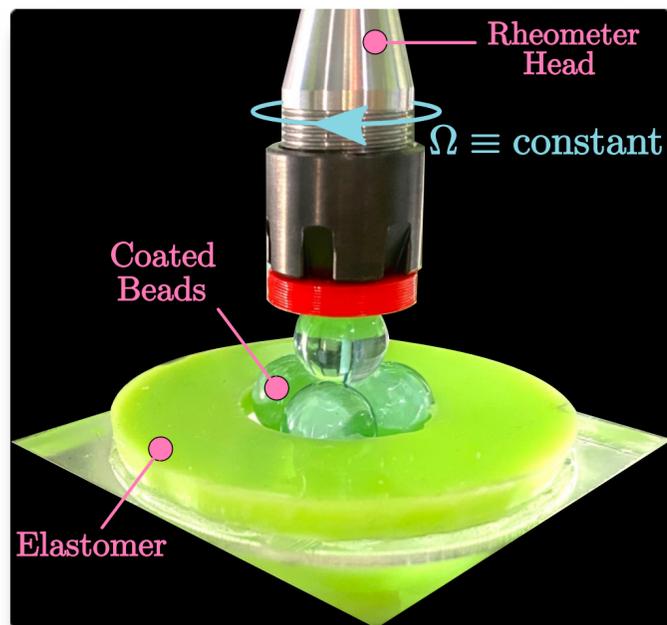
## Rheology



at intermediate coating ( $b=35\text{nm}$ ):  
a complex transition from frictionless  
to frictional curves which depends on

- pressure  $P$
- shear velocity
- coating thickness  $b$

## Tribology



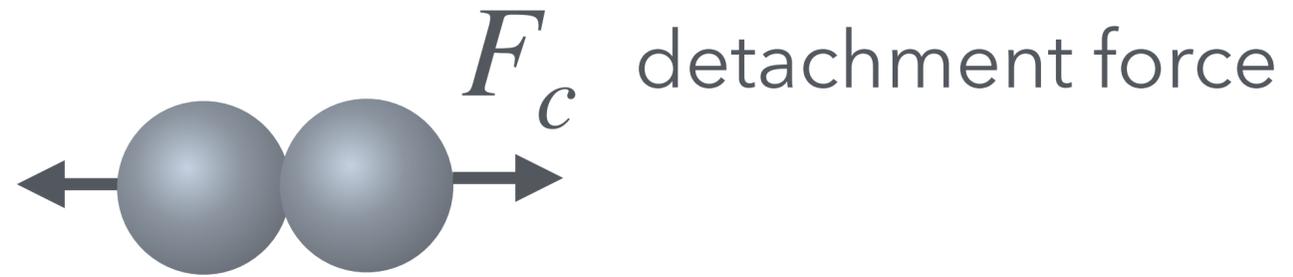
$\mu_p$  depends on :

- normal force  $F_n$
- sliding velocity  $V$
- coating thickness  $b$

« a kind of Stribeck effect »

Rocha et al, 2026

# Role of adhesion



What we may expect....

$$\tau = \tau_c + \mu(I)P$$

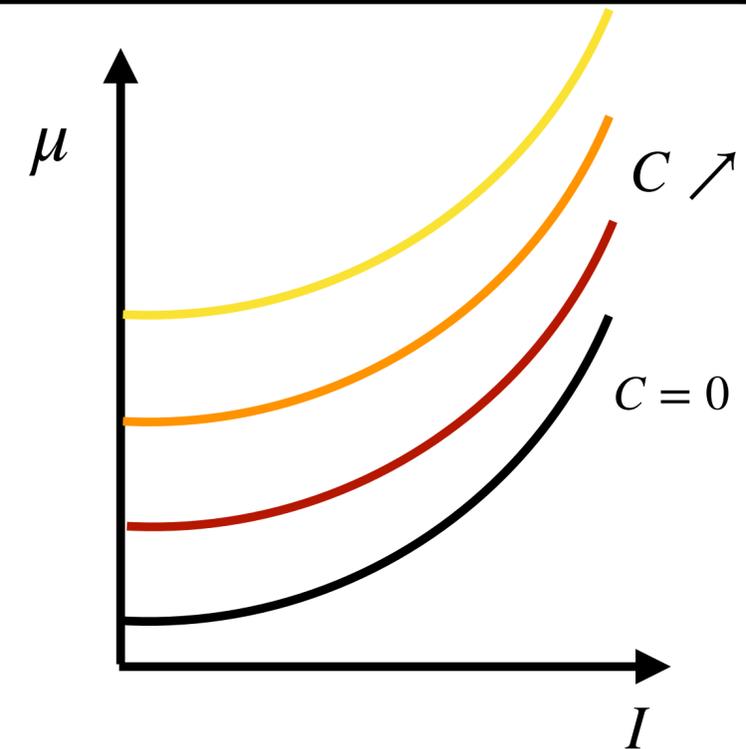
↑  
cohesive stress  $\propto F_c/d^2$

$$\frac{\tau}{P} = \frac{\tau_c}{P} + \mu(I)$$

$$\mu = C + \mu(I)$$

↑

cohesion number,  $C = \tau_c/P$ ,  
a new dimensionless number



a more general approach

$$\tau = \mu(I, C)P$$

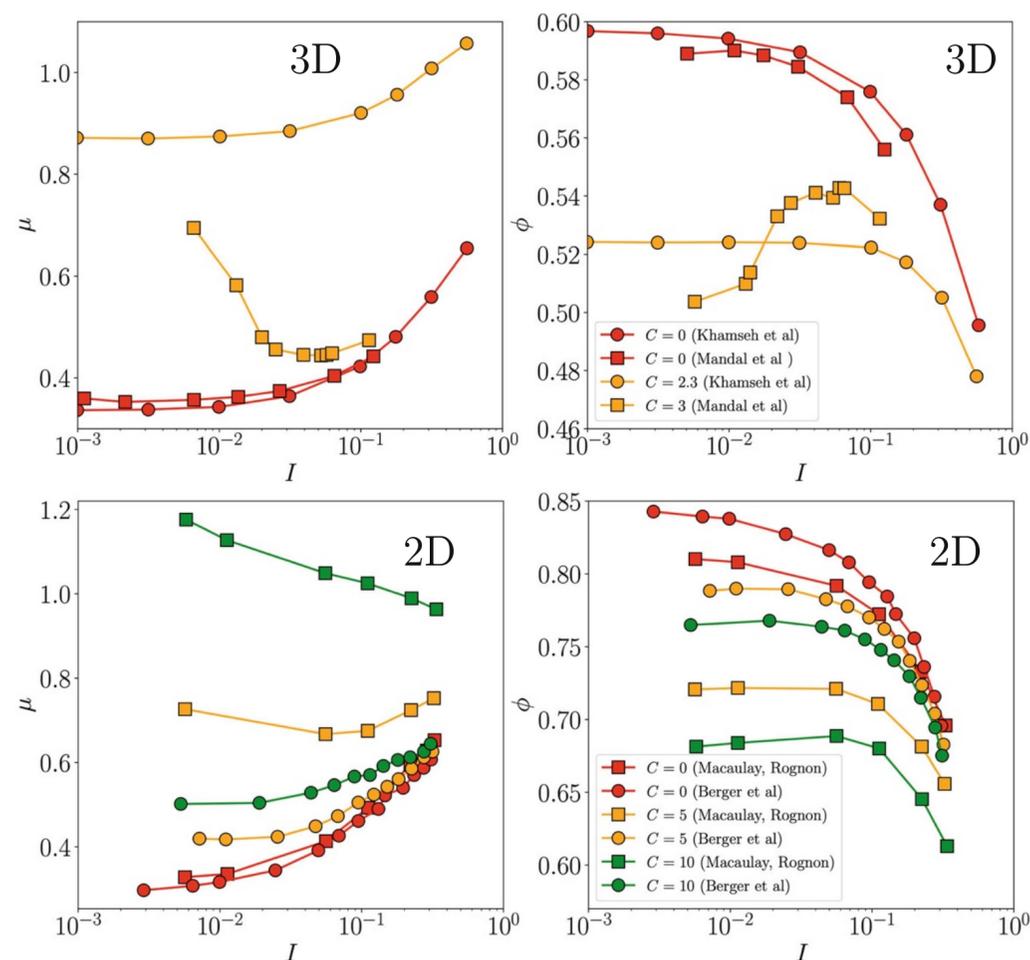
$$\phi = \phi(I, C)$$

Rognon et al JFM 2008,  
Berger et al EPL 2015,  
Kamshed PRE 2015,  
Roy et al NJP 2019,  
Vo et al Nature Com, 2020...

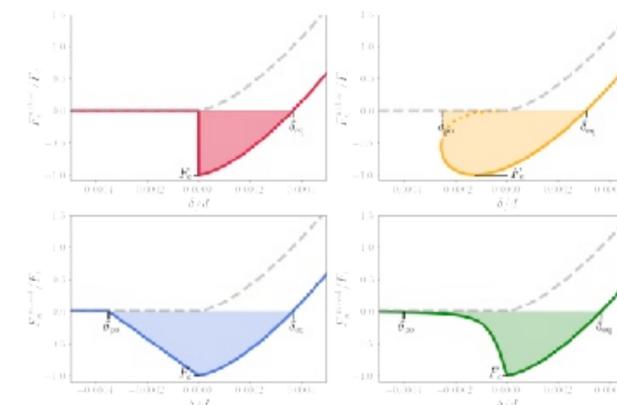
# Role of adhesion : DEM

We have a problem !! difficult to compare the different studies ...

C not enough to describe the data :  
same C => different rheological curves...)



-different adhesion models:  
DMT, JKR, capillary...



-role of the different parameters ?

Elasticity,  $E$

adhesion  $F_c$

dissipation (viscosity)  $\eta$

interaction length  $\delta$

5 dimensionless numbers!!

inertial number  $I = \dot{\gamma}l/\sqrt{P\rho}$

cohesion number  $C = F_c/Pd^2$

adhesive energy  $W = F_c\delta_{eq}/Pd^3$

quality factor  $Q = E^{2/3}R^{1/6}/\eta F_c^{1/6}$

relative detachment length  $\lambda = \delta/d$

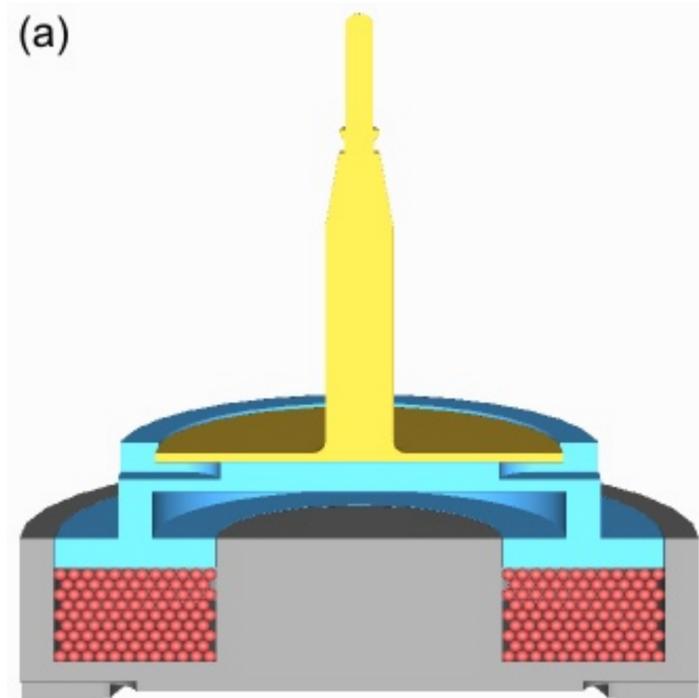
$$\mu(I, C, W, Q, \lambda)$$

$$\phi(I, C, W, Q, \lambda)$$

Roy et al, CPM 2016, Mandal et al, PRX 2020,....

# Role of adhesion : experiments

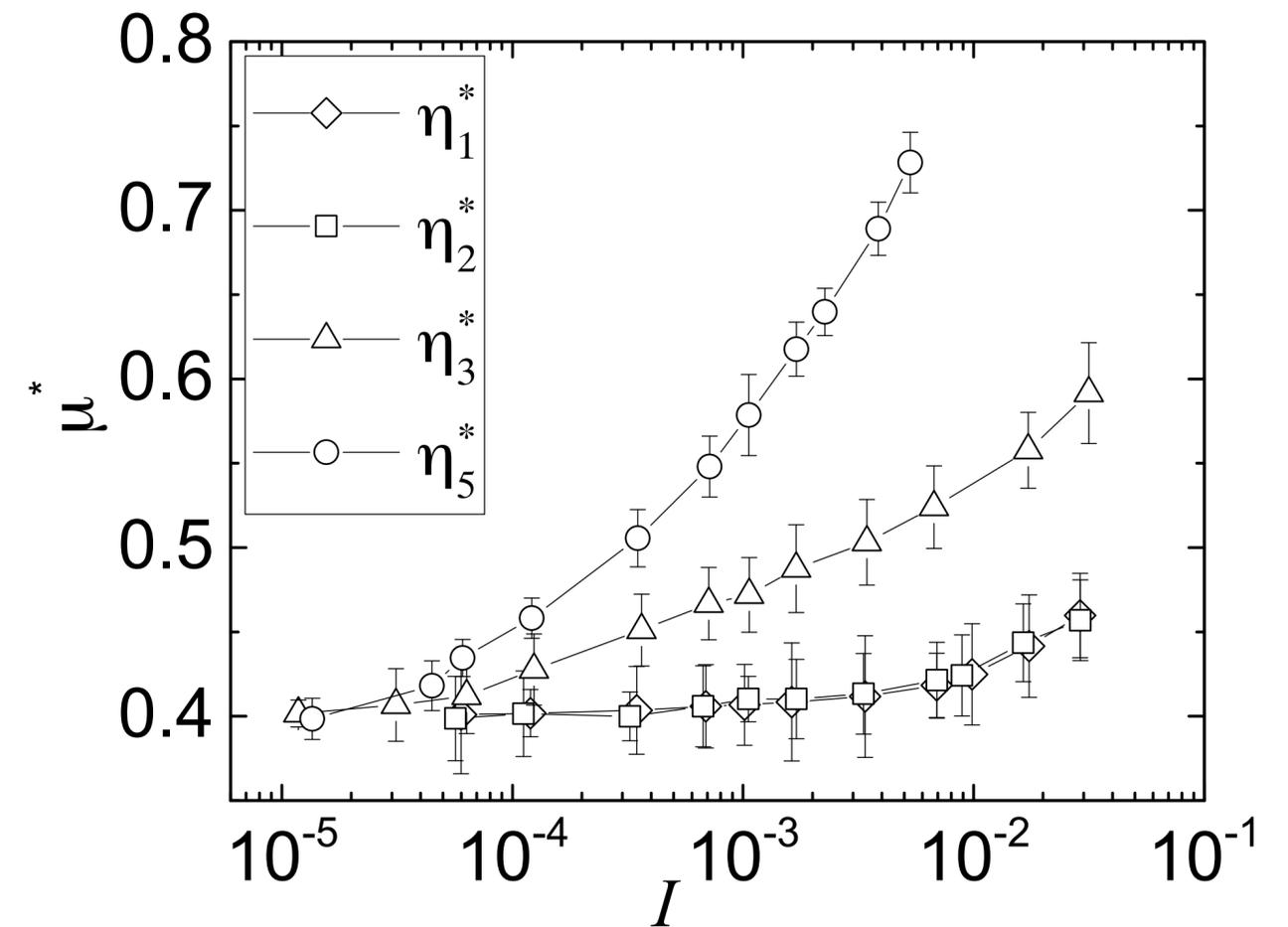
Amarsi et al, J. Rheo, 2024



- wet granular medium (capillary interaction)
- small adhesion  $C < 0.5$

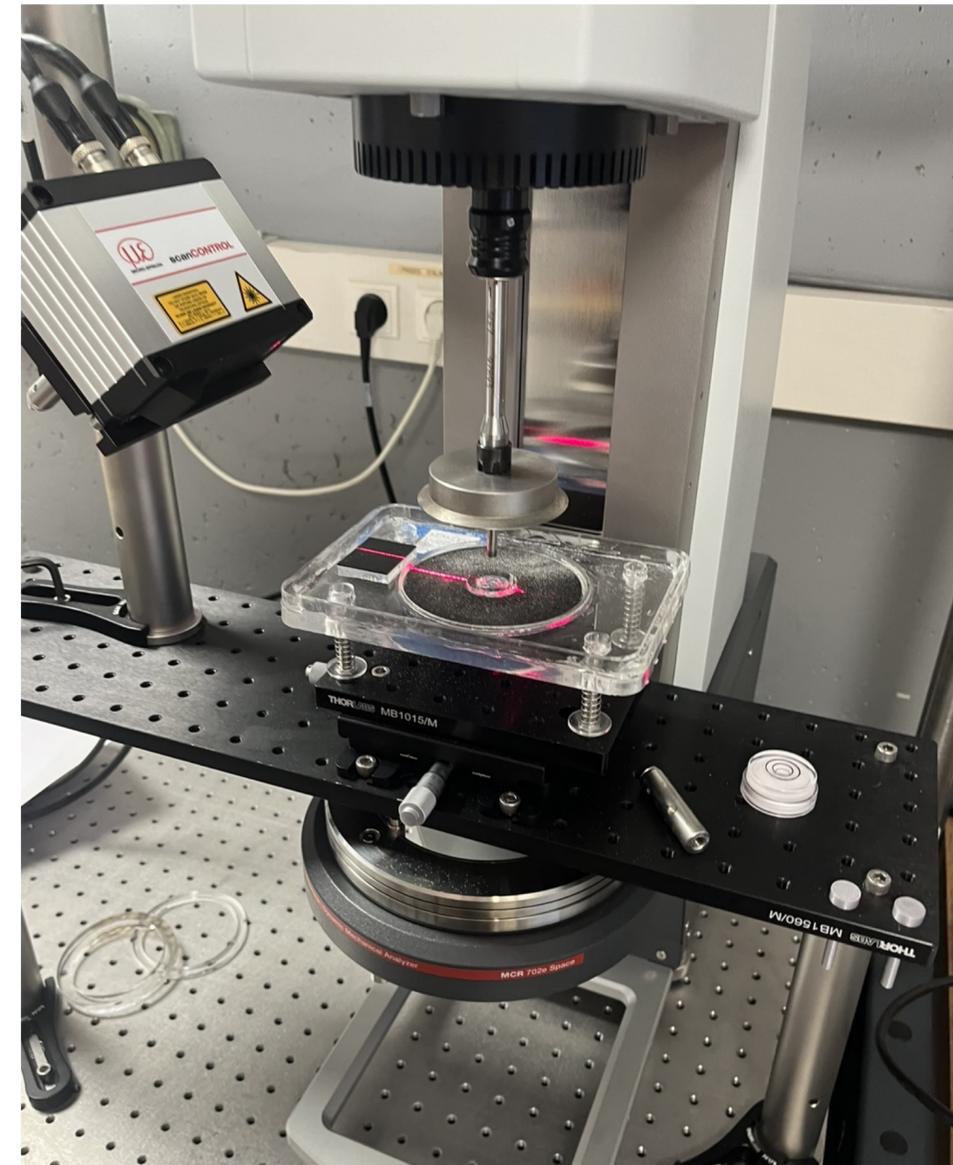
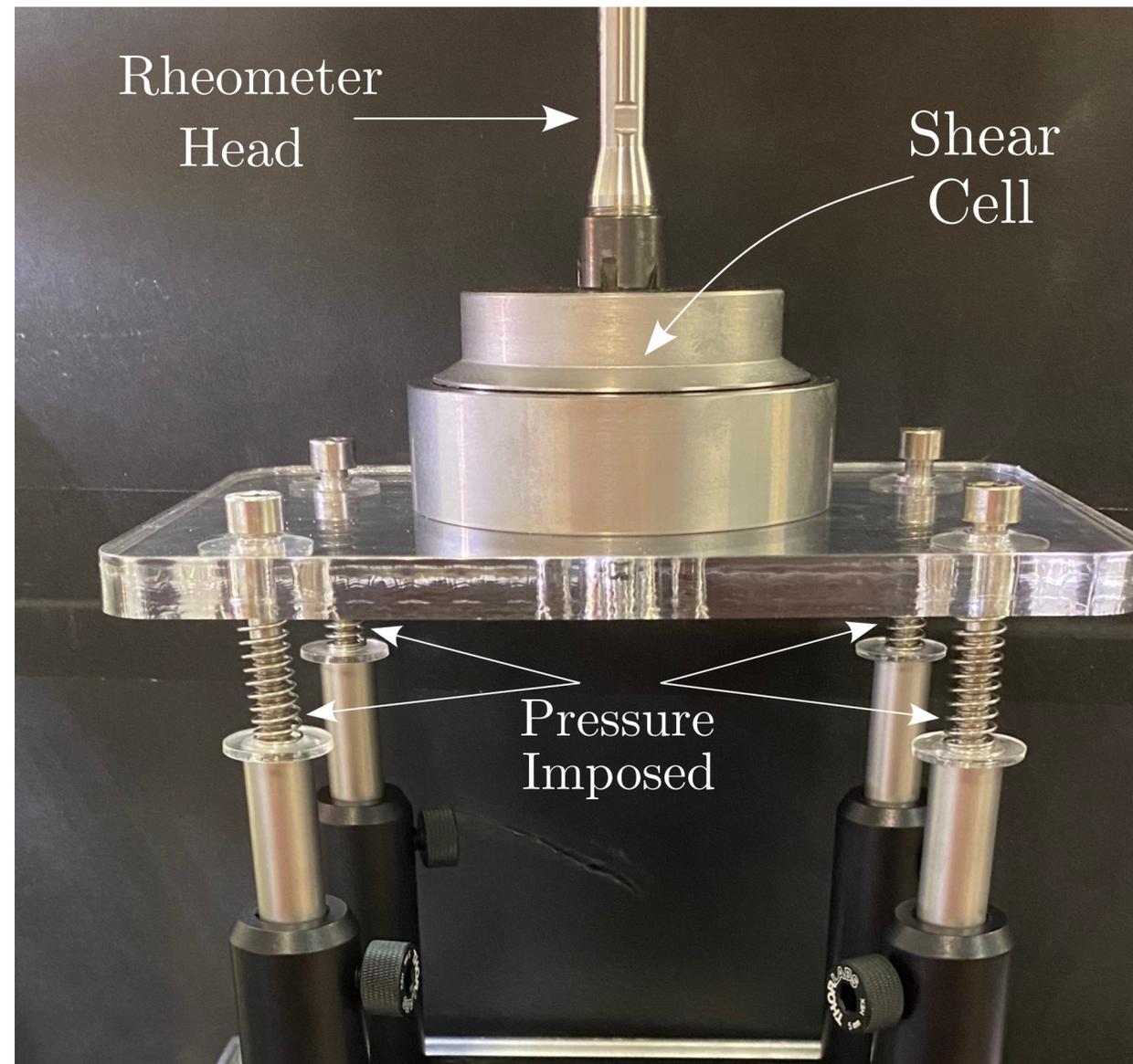
## results:

- quasi static controlled by  $C$ ,
- viscosity of the fluid changes the inertial regime...

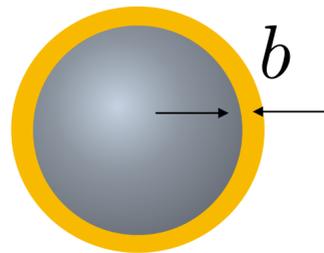


changing the viscosity

# Role of adhesion : experiments



Low pressure accessible ( $P \gtrsim 100Pa$ ), small grains  $d=200\mu m \Rightarrow$  up to  $C \approx 5$



$b = 15nm$   
 $F_c = 4.3\mu N$

$b = 34nm$   
 $F_c = 9.4\mu N$

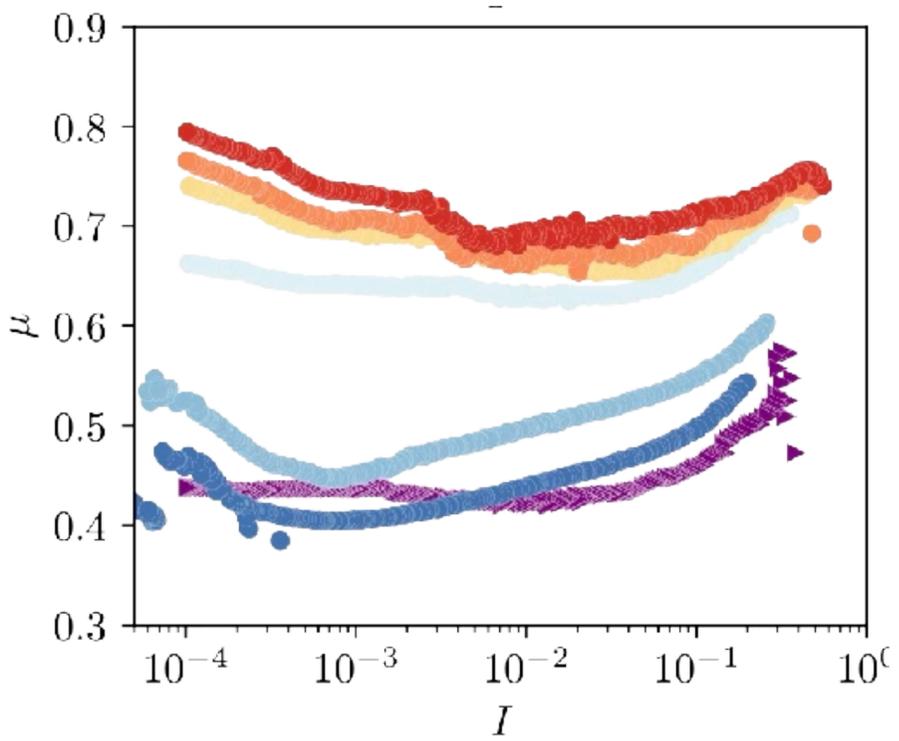
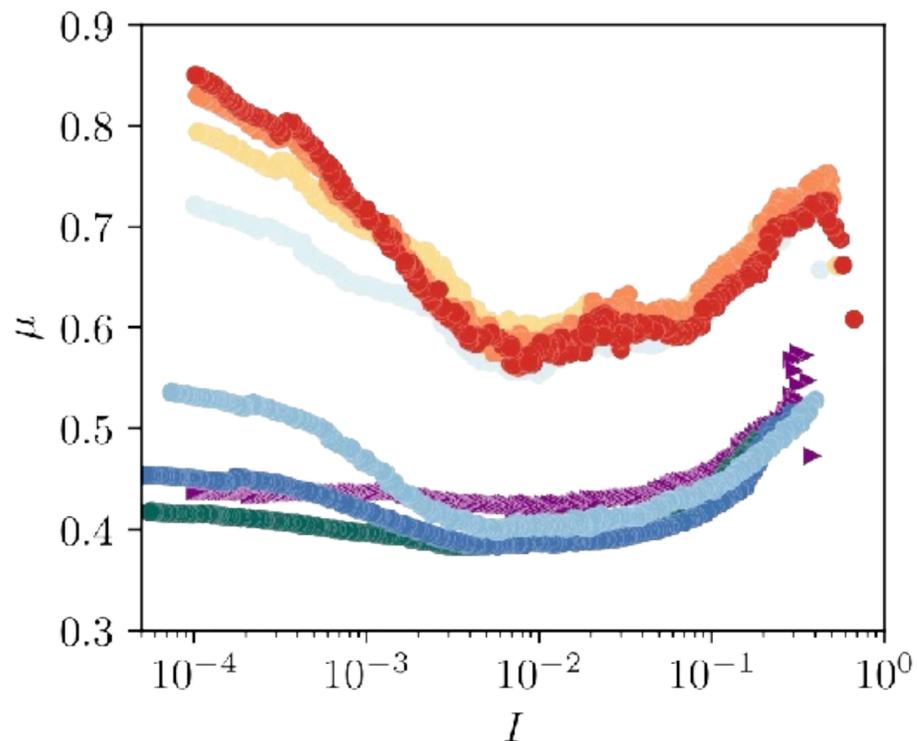
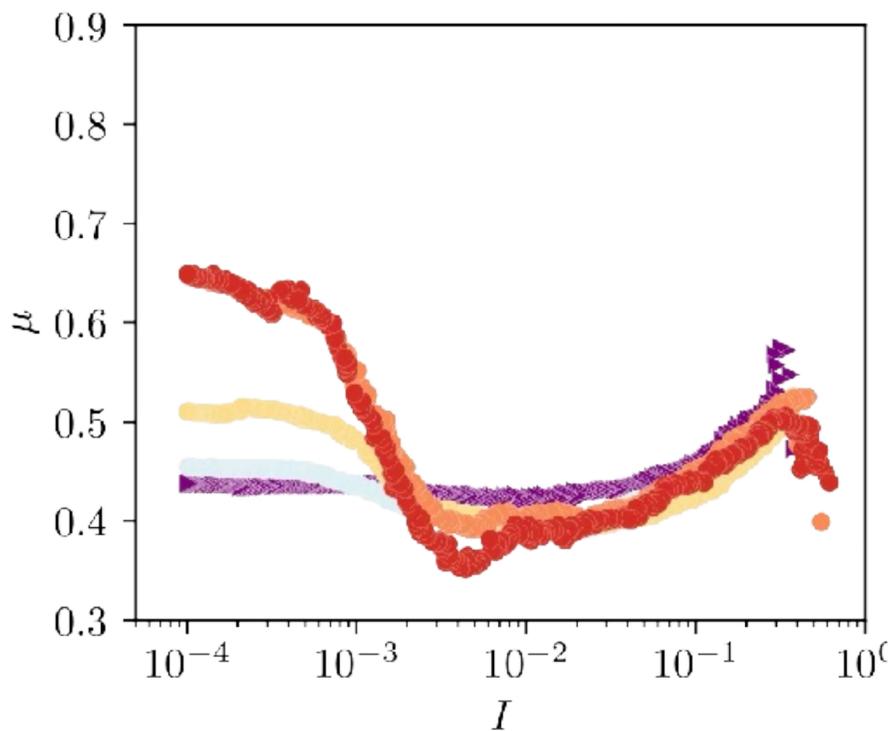
$b = 110nm$   
 $F_c = 14.2\mu N$

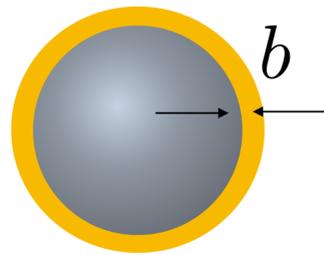
$F_c$



$C = 0 \nearrow 5$

$d = 200\mu m$   
no lubrication  
adhesion controlled by  $b$





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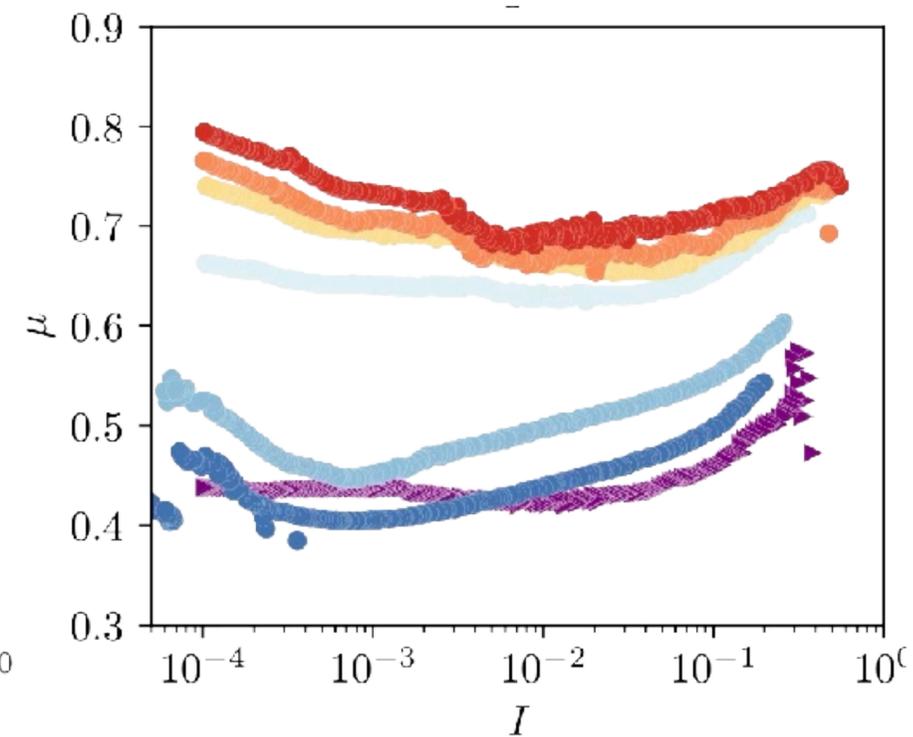
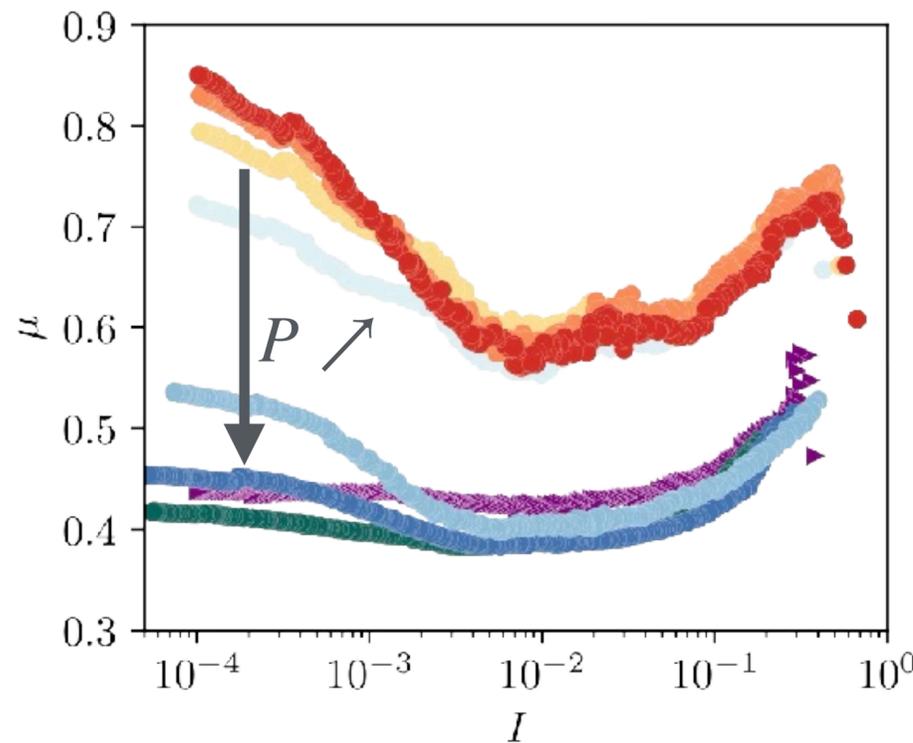
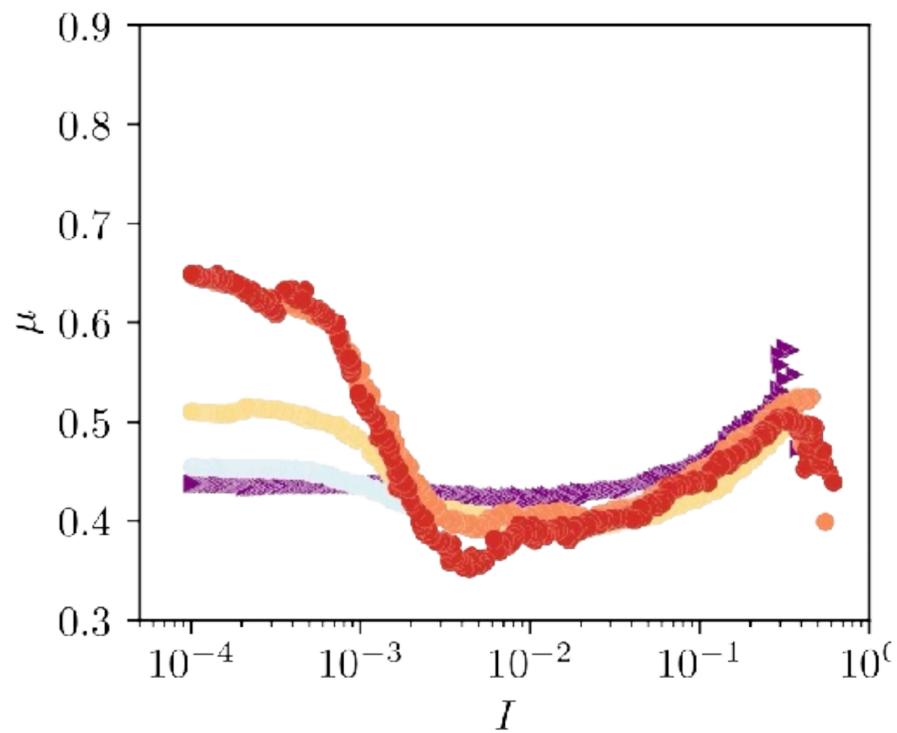
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$F_c$



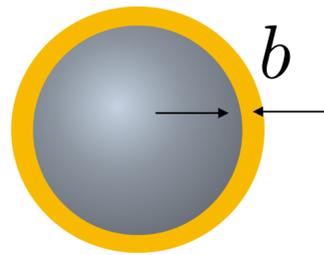
$C = 0 \nearrow 5$



$d = 200\mu m$   
 no lubrication  
 adhesion controlled by  $b$

- increasing  $P$  ( $C \rightarrow 0$ )  $\Rightarrow$  the dry rheology

- a shear weakening branch



$b = 15nm$   
 $F_c = 4.3\mu N$

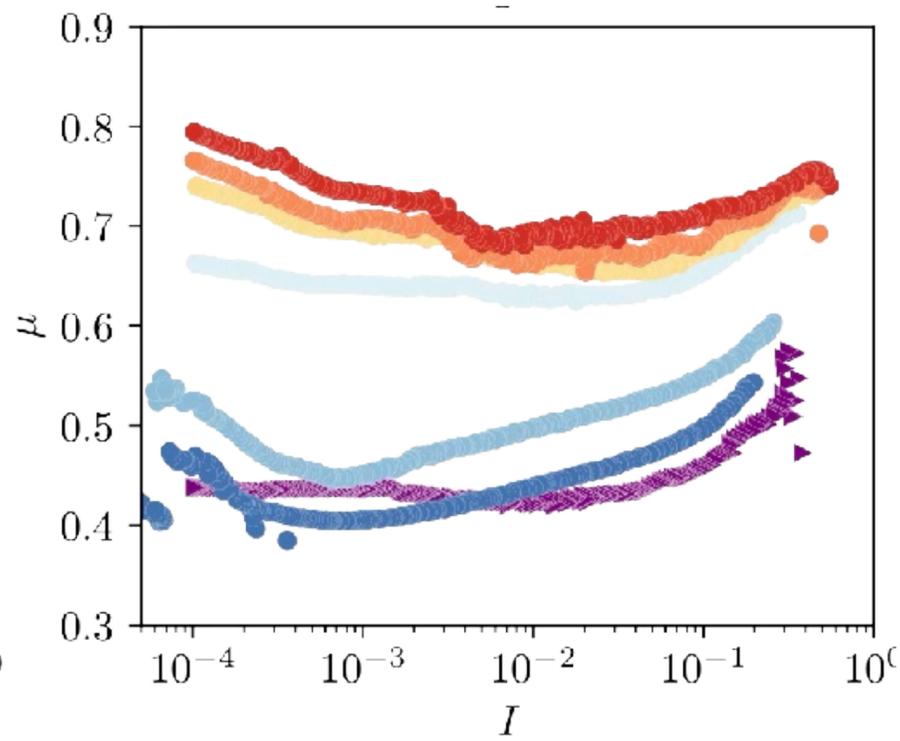
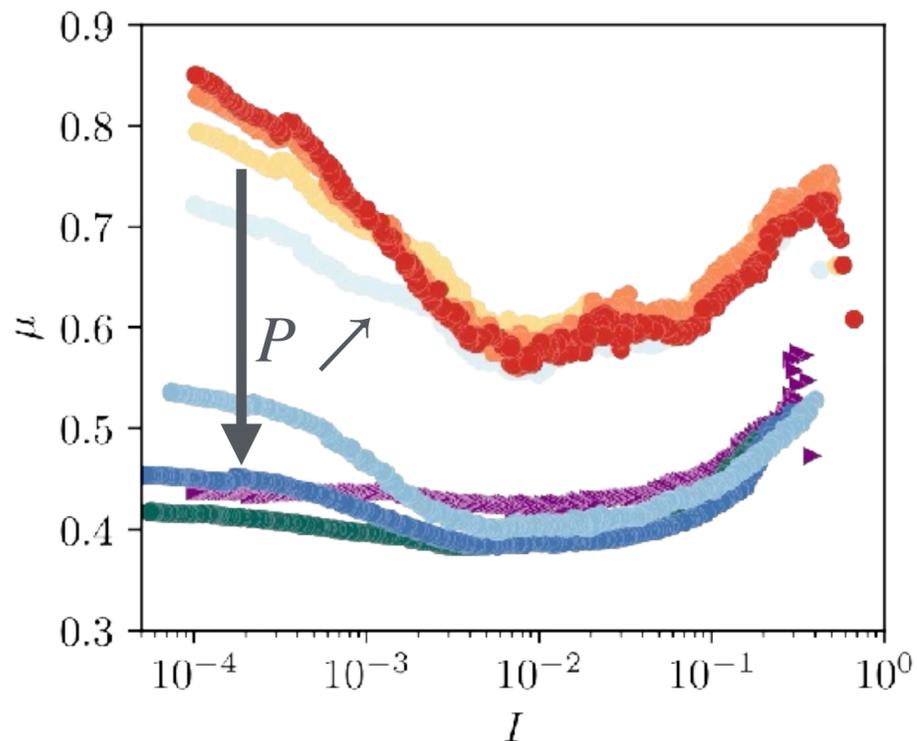
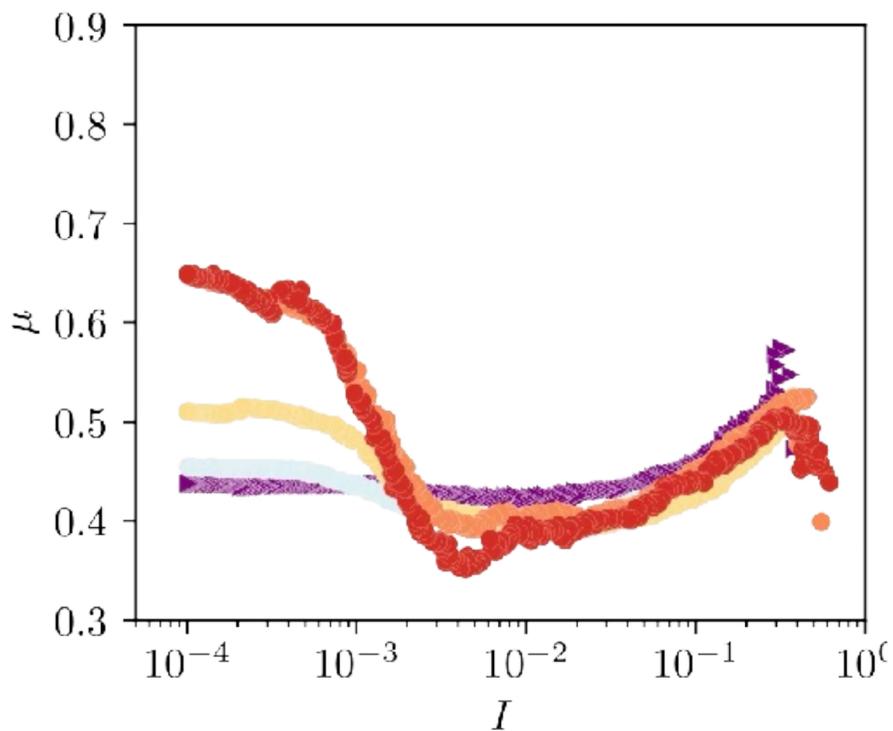
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$F_c$



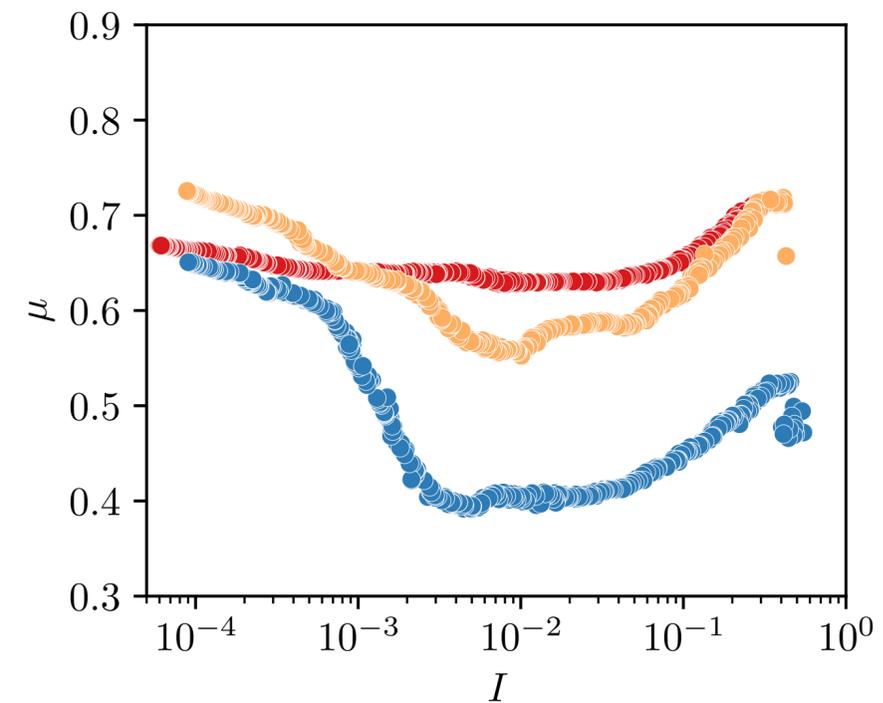
$C = 0 \nearrow 5$

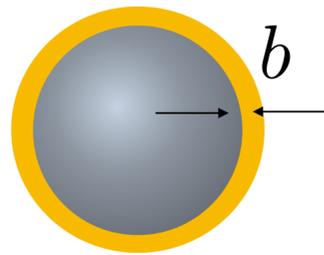


$d = 200\mu m$   
 no lubrication  
 adhesion controlled by  $b$

- increasing  $P$  ( $C \rightarrow 0$ )  $\Rightarrow$  the dry rheology
- a shear weakening branch
- $C$  does not control the inertial regime

$$C = \frac{F_c}{Pd^2} = 2$$





$b = 15nm$   
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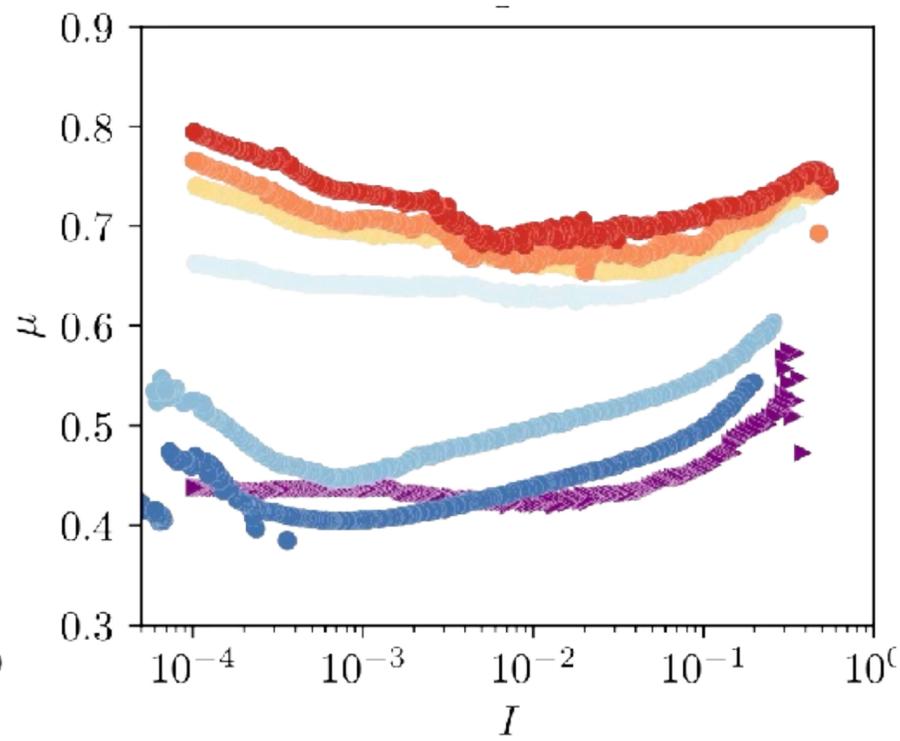
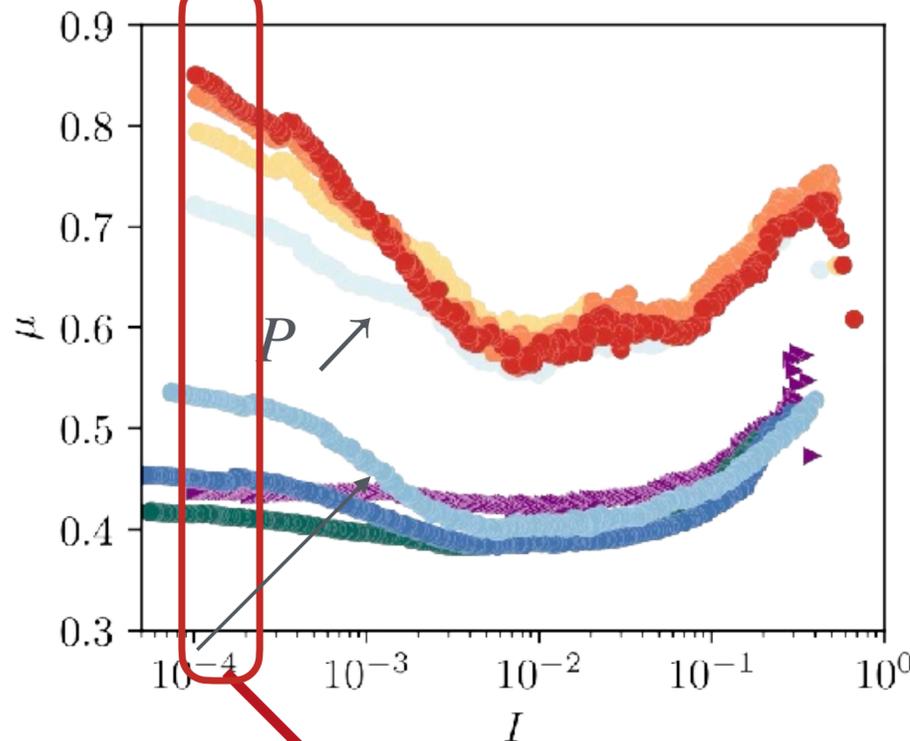
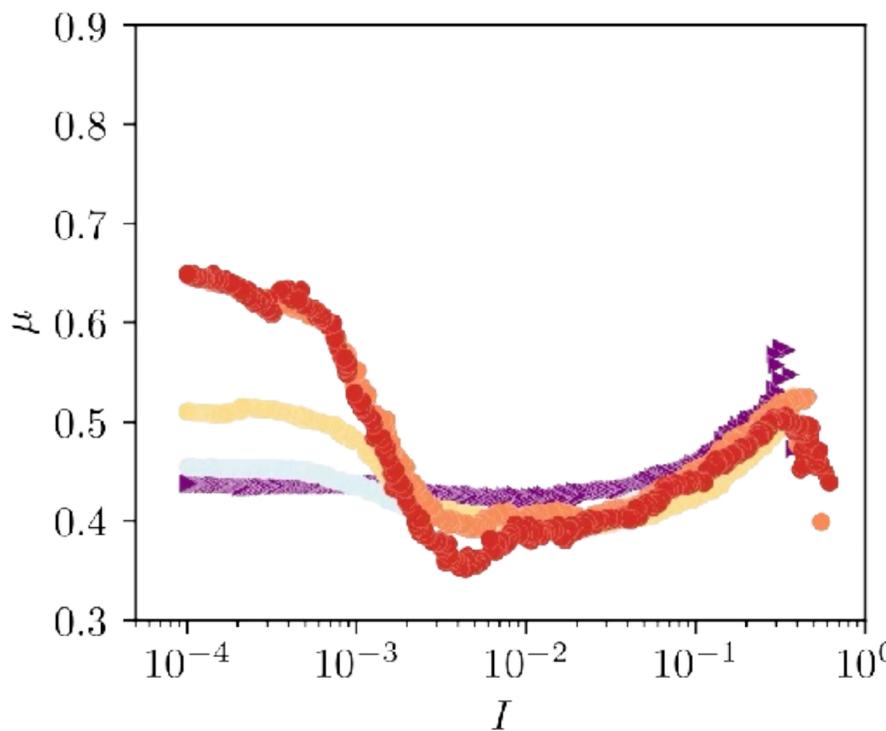
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$F_c$

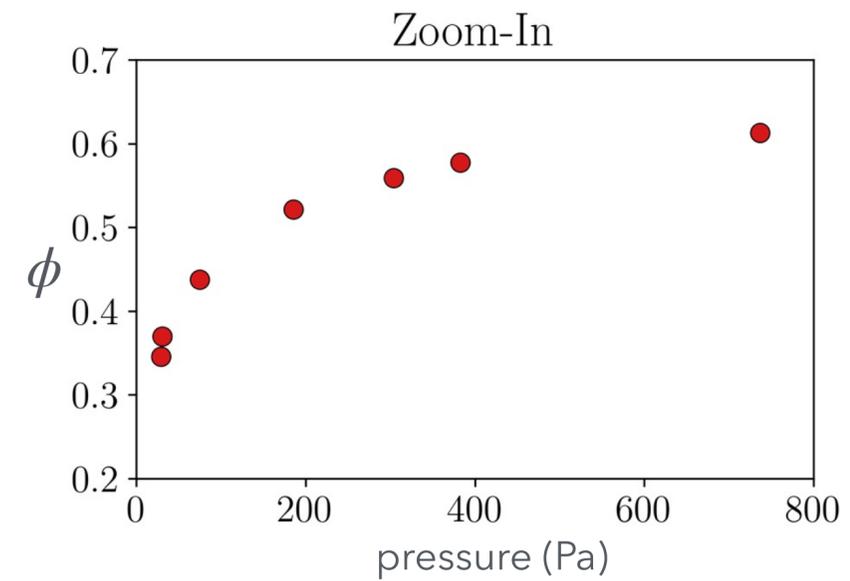
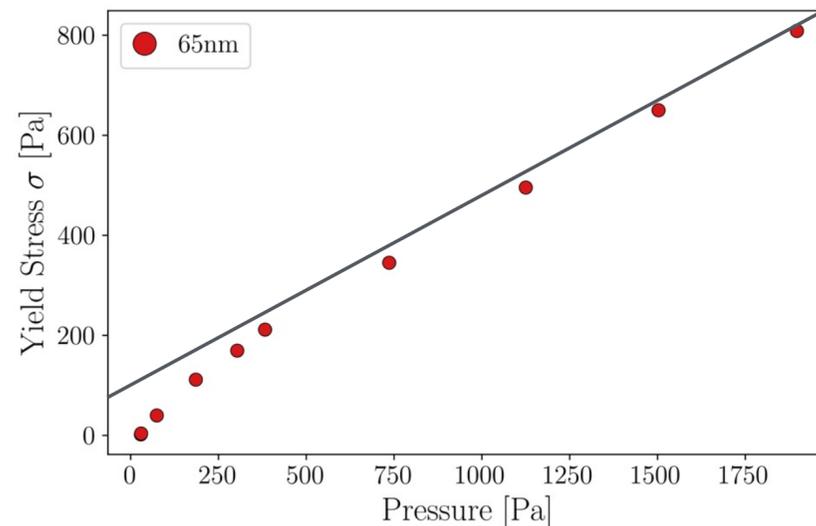


$C = 0 \nearrow 5$



$d=200\mu m$   
no lubrication  
adhesion controlled by  $b$

- increasing  $P$  ( $C \rightarrow 0$ )  $\Rightarrow$  the dry rheology
- a shear weakening branch
- $C$  does not control the inertial regime
- quasi-static  $\neq$  Mohr Coulomb



# Conclusions and open questions...

- a challenge: to play with interactions in granular media...

(we are far from what is done in suspensions... )

- role of friction : complex lubrication but understood

- role of adhesion : what control the flow regime (not just interparticle adhesion)?

- beyond rheology: other flow geometry to understand what is measured in powders rheometers... ?

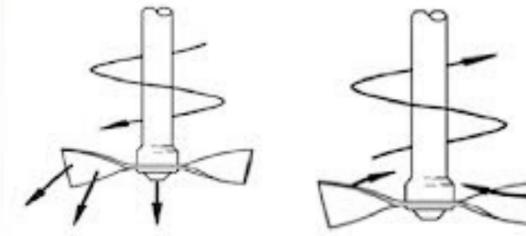
- fracture, tensile stress, localisation ....?

# Conclusions and open questions...

rotating drum



powder rheometer



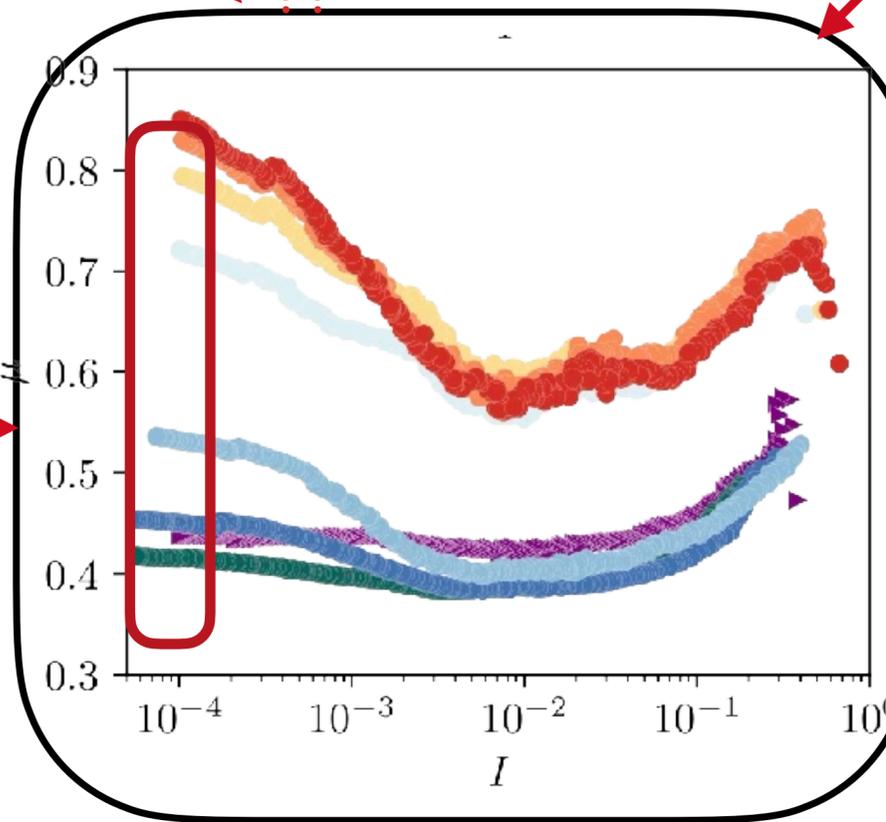
(a) Downwards testing

(b) Upwards testing

shear cell



hosokawa



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(we are far from what is done in suspensions... )
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Gans



Franco  
Tapia



Chico  
Rocha



Maxime  
Lajeunesse



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