Alice Pelosse – Doctorante en physique au laboratoire Matière et Systèmes Complexes

ECOULEMENTS CAPILLAIRES DE SUSPENSIONS GRANULAIRES

23 août 2023 – Ecole des Gustins, Lac d'Aiguebelette

Université Paris Cité

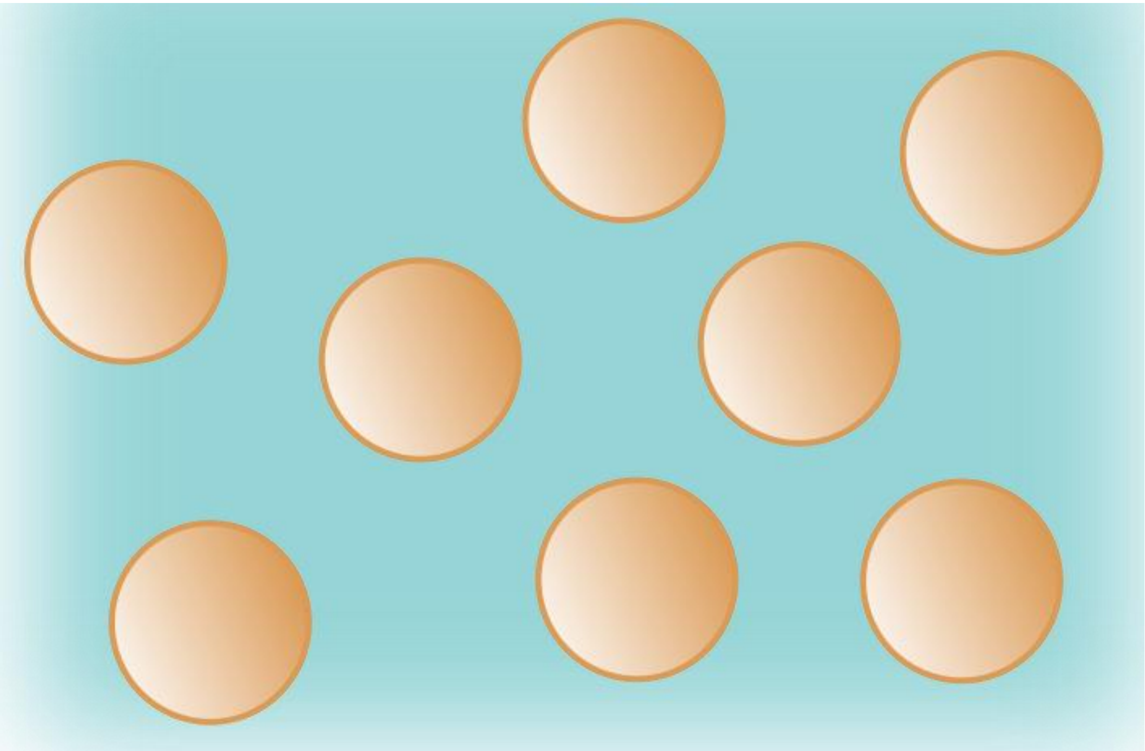
cnrs

MSC

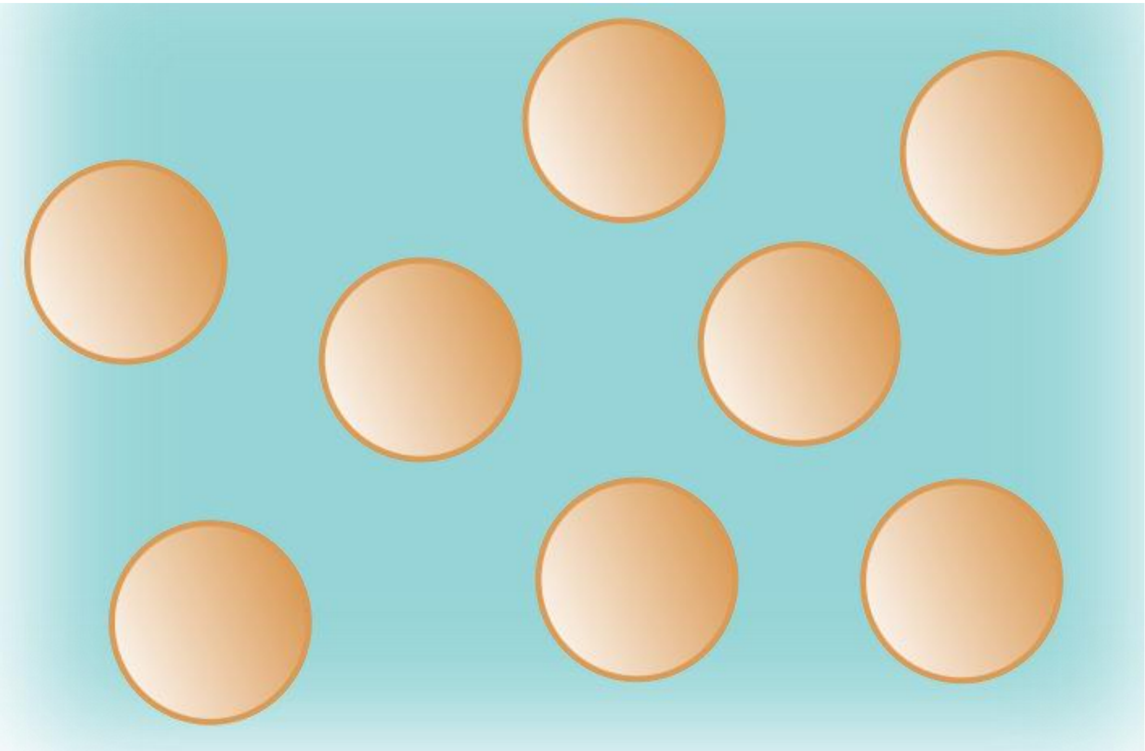
Ecoulements capillaires

Ecoulements capillaires

Suspensions granulaires



Suspensions granulaires



Plan

- Matière molle
- Notions de viscosité et rhéologie
- Viscosité de suspensions granulaires

****

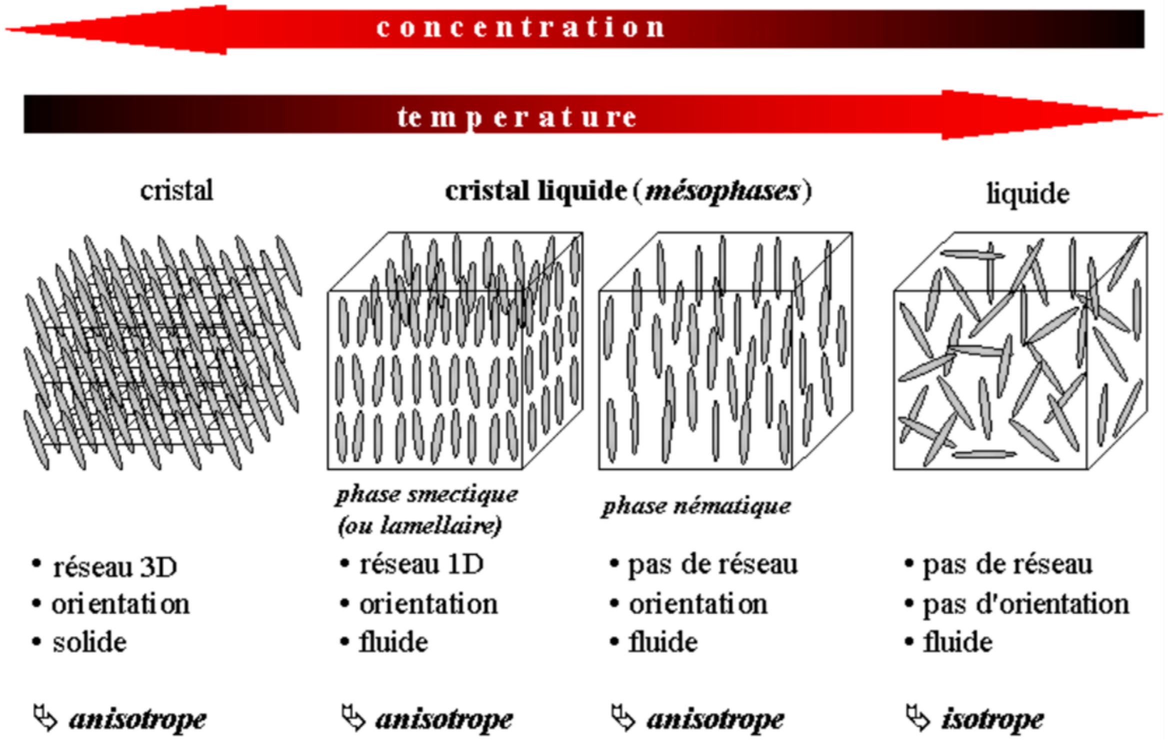
- Etalement de gouttes de suspensions granulaires
- Quelques pré-résultats sur l'instabilité de Rayleigh-Taylor avec des suspensions granulaires

FLUIDES COMPLEXES ET MATIÈRE MOLLE

Pierre-Gilles de Gennes (1932 – 2007)

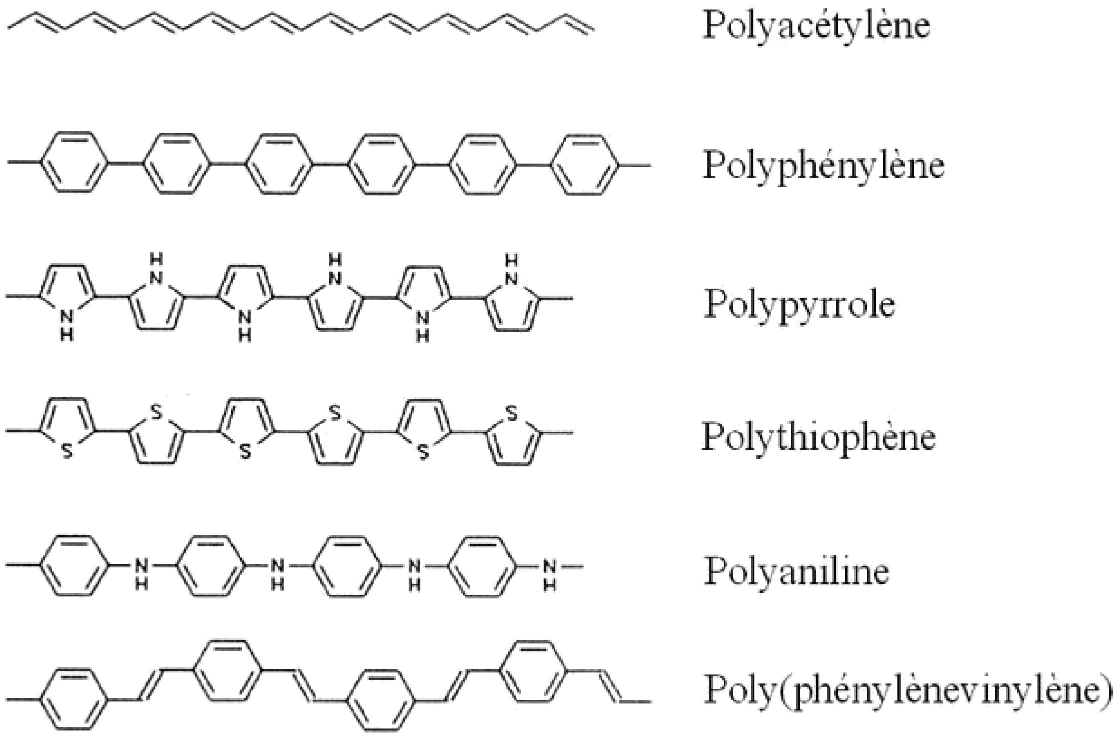
Cristaux liquides & polymères

Cristaux liquides



Arnaud Dessombz

Polymères



Akkouch Adil

Cristaux liquides & polymères

Cristaux liquides

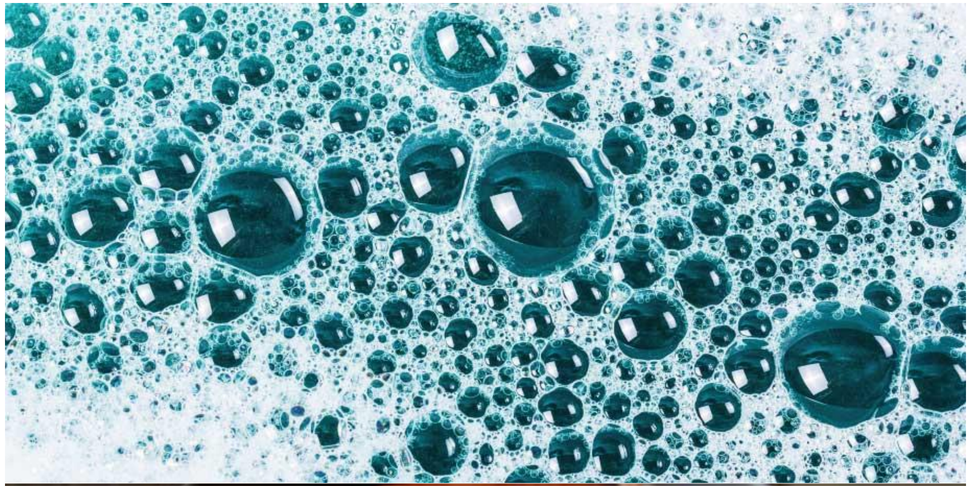
Polymères

Mélanges biphasiques

Gaz dans un liquide

Liquide dans liquide

Mélanges biphasiques



Fourmis

nature materials

Published: 26 October 2015

Mechanics of fire ant aggregations

Michael Tennenbaum, Zhongyang Liu, David Hu ✉ & Alberto Fernandez-Nieves

Nature Materials **15**, 54–59 (2016) | Cite this article

Université Paris Cité

> u-paris.fr > **Les chats sont-ils liquides ?**

FR

Les chats sont-ils liquides ?

Marc-Antoine Fardin est chercheur en rhéologie à l'Institut Jacques Monod (Université Paris Diderot/CNRS). Il a reçu le prix Ig Nobel de

Chercheur en rhéologie à l'Institut Jacques Monod, Marc-Antoine Fardin a réalisé ses études à l'université Paris Diderot, à l'université Columbia à New York et au MIT à Boston. Il a également travaillé pour la National University of Singapore et pour l'Ecole Normale Supérieure de Lyon. Il fait aujourd'hui partie de l'équipe d'adhésion cellulaire et mécanique, et a reçu le prix Ig Nobel de physique, le 14 septembre 2017, pour son étude **"les chats sont ils liquides ou**

Connexion

Felix catus rheology

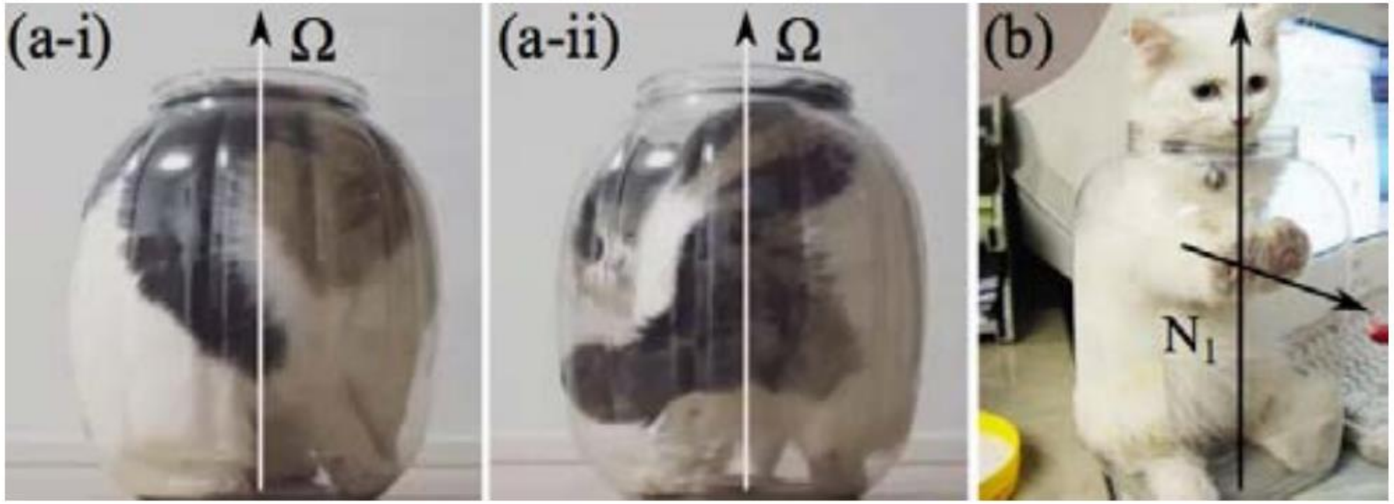
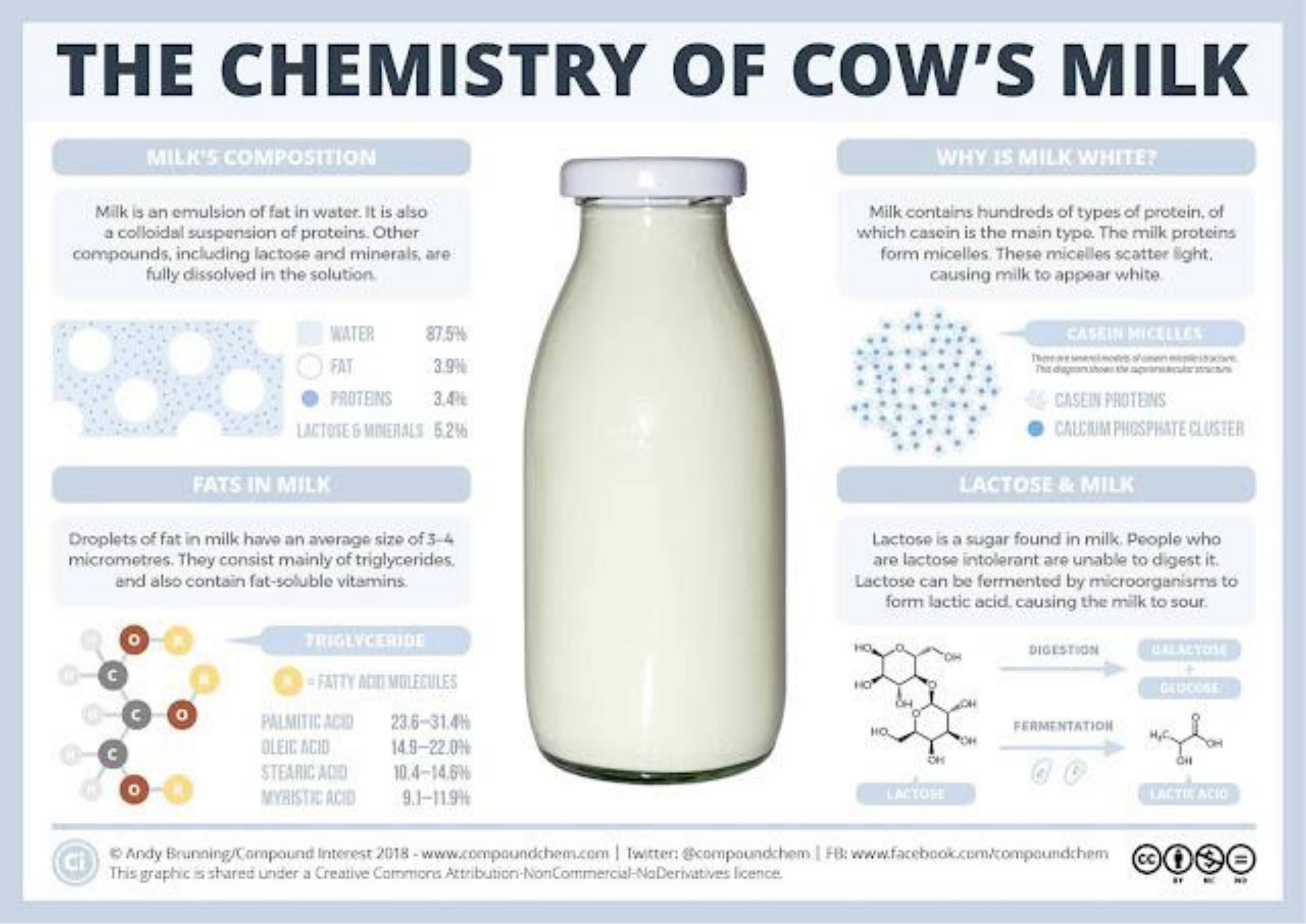
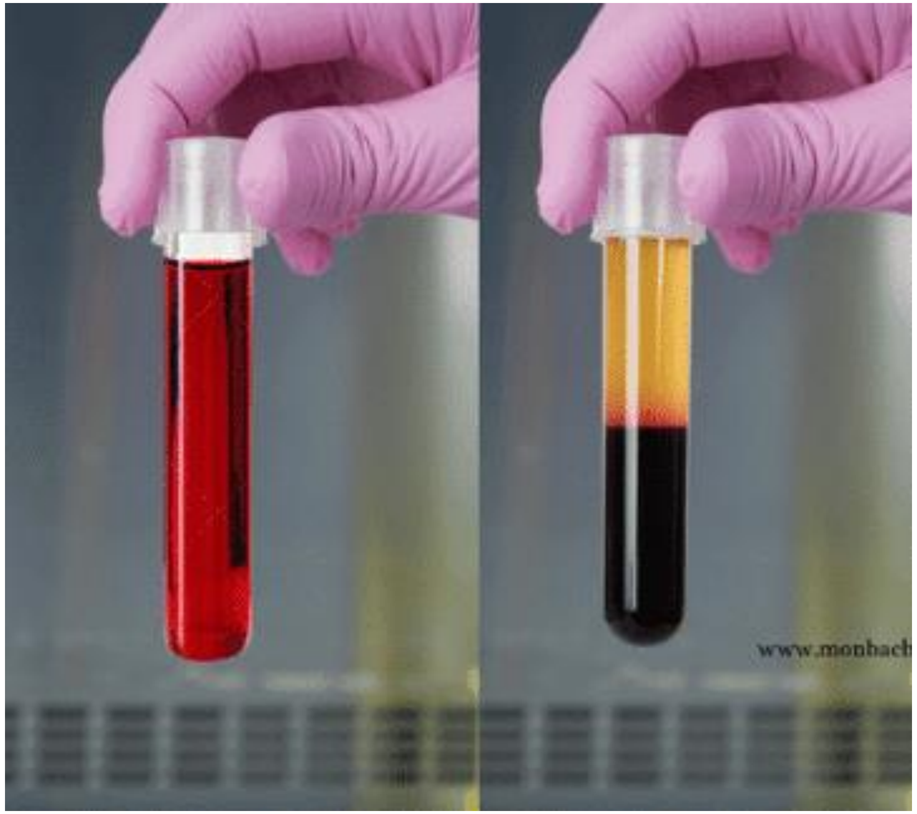


FIG. 3: (a) A cat spontaneously rotates in a cylindrical jar. (b) Normal forces and Weissenberg effect in a young sample of *Felis catus*. [Courtesy of (a) http://guremike.jp/, (b) http://buzzlamp.com/10-weird-places-cats-get-stuck-in/]

Suspensions

Suspensions





Suspensions

Suspensions

Suspensions colloidales = Mouvement brownien

Taille des particules < 1 µm

Interaction électrostatiques

Stables

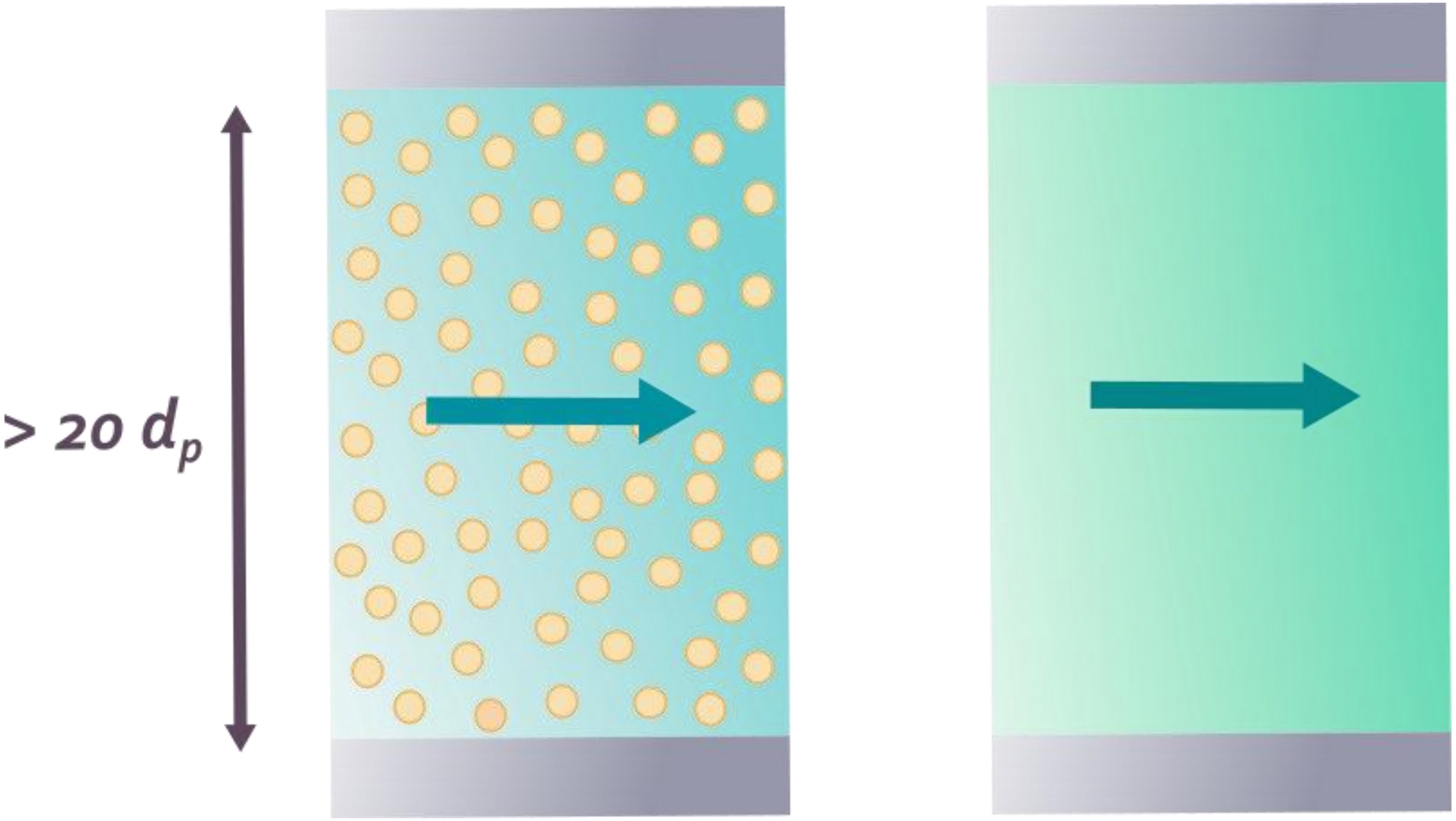
Suspensions granulaires = Pas de movement brownien

Taille des particules > 1 µm

Contacts et interactions hydro

Sédimentation / crémage

Modèle discret et continu



VISCOSITÉ

Viscosité

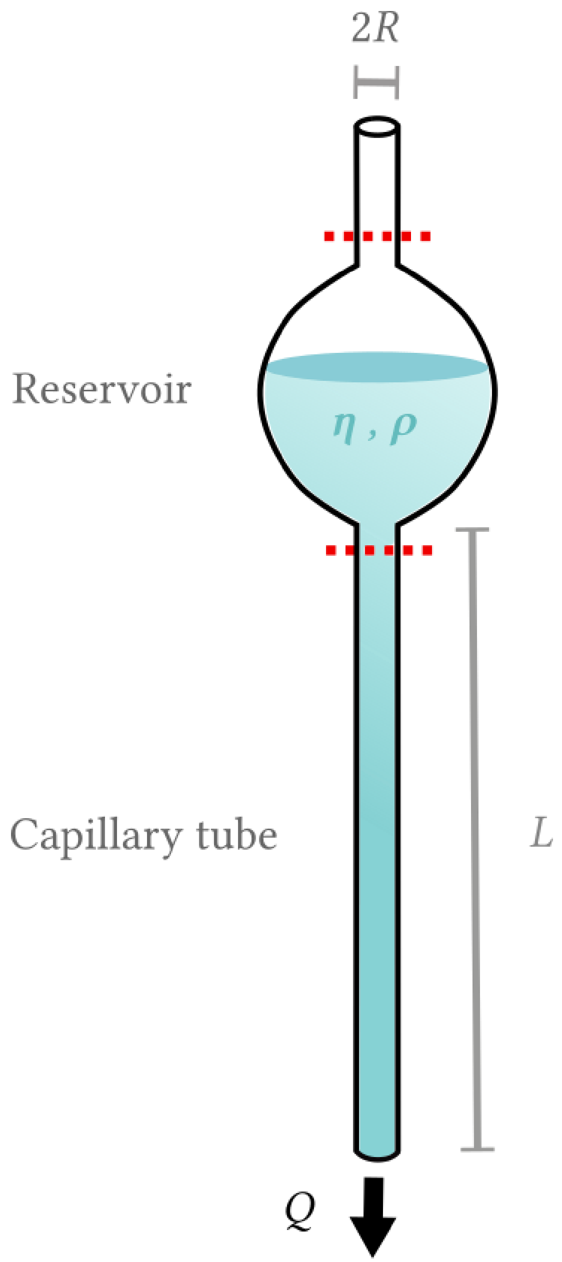
Viscosité

$$\eta = \frac{\text{contrainte}}{\text{taux de déformation}}$$

Air		Eau			Glycérol		Pa.s
10^{-5}	10^{-4}	10^{-3}	10^{-2}	10^{-1}	10^{0}	10^{1}	10^{2}



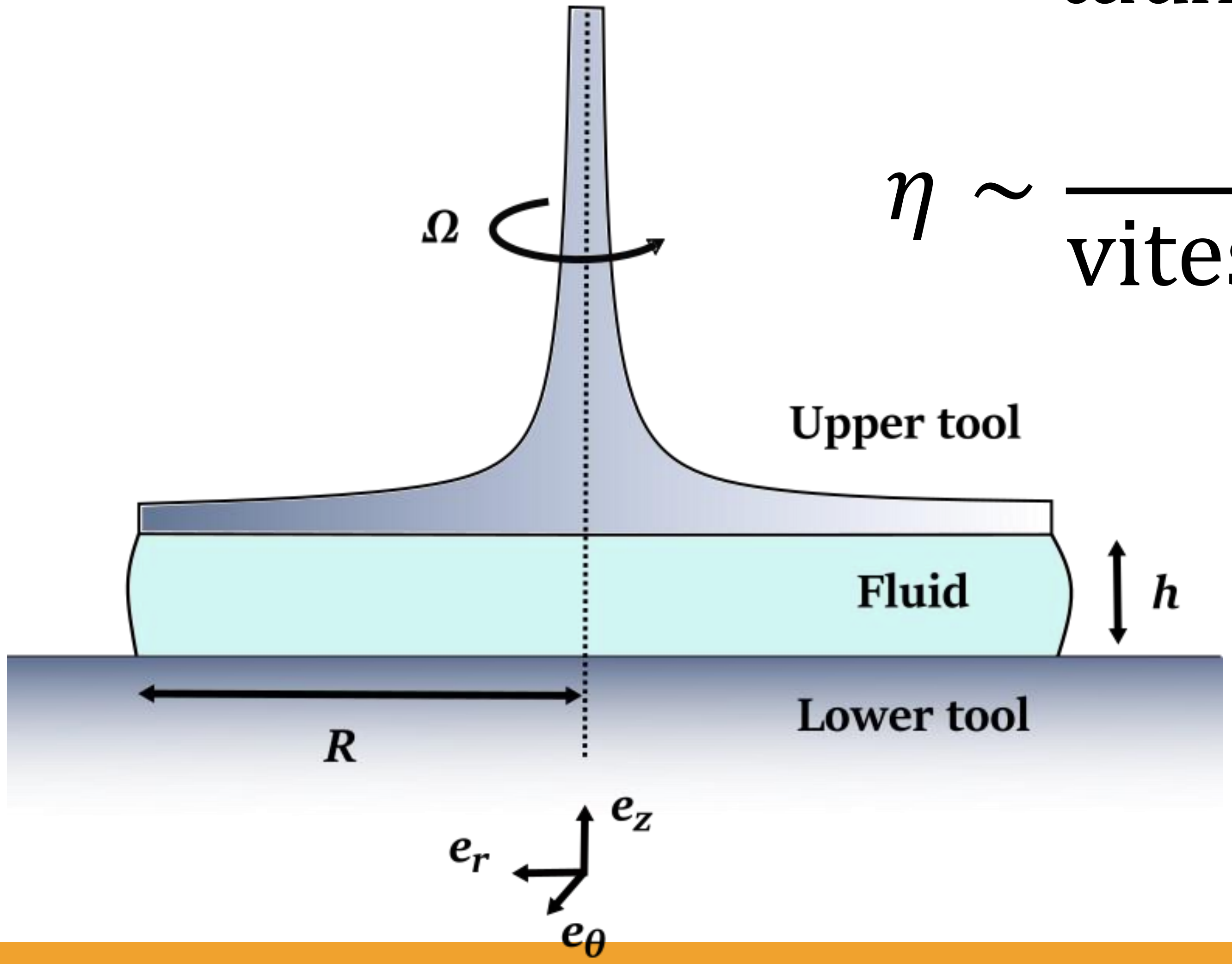

Viscosité



Rhéomètre

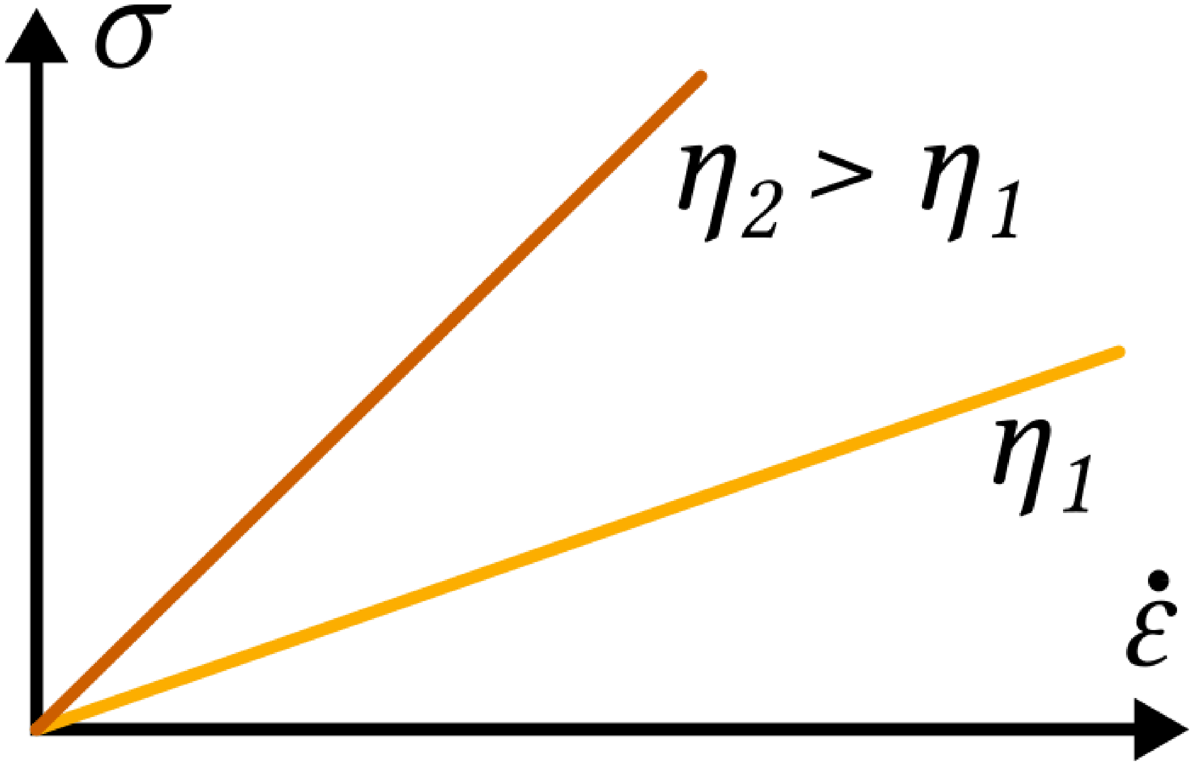
$$\eta = \frac{\text{contrainte } (\sigma)}{\text{taux de déformation } (\dot{\epsilon})}$$

$$\eta \sim \frac{\text{couple}}{\text{vitesse de rotation}}$$



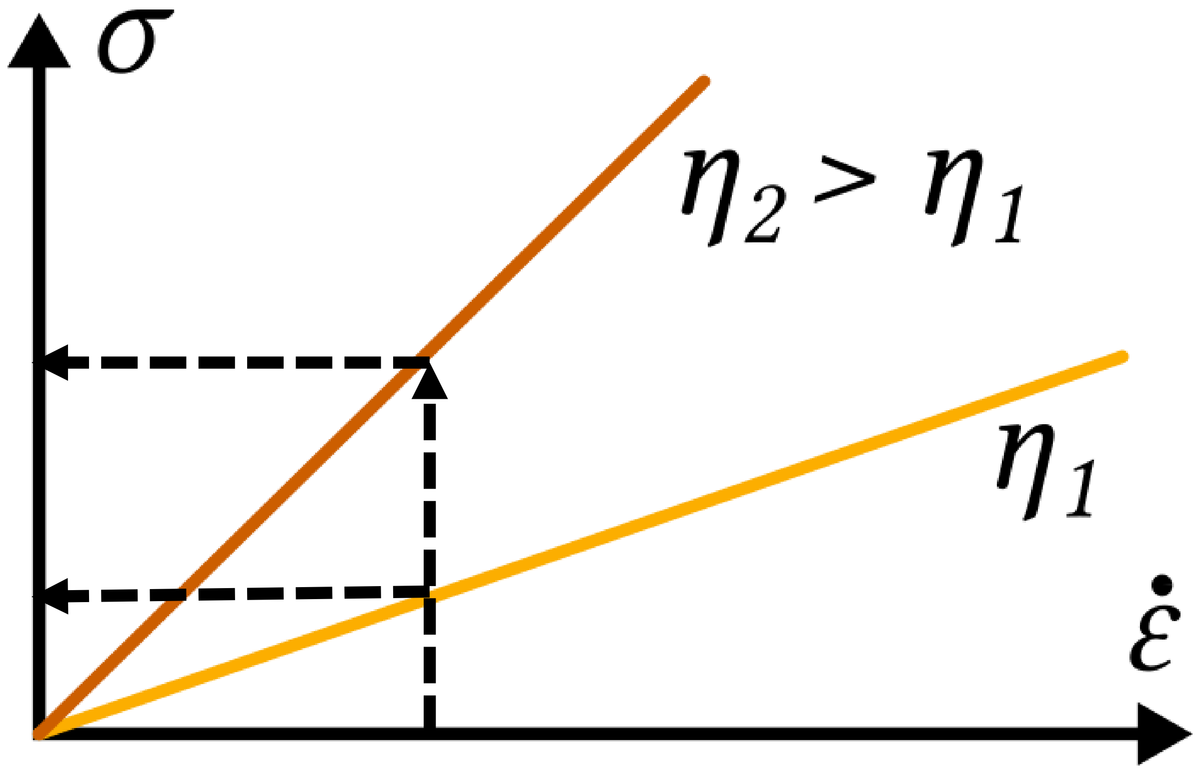
Viscosité

$$\eta = \frac{\text{contrainte } (\sigma)}{\text{taux de déformation } (\dot{\epsilon})}$$



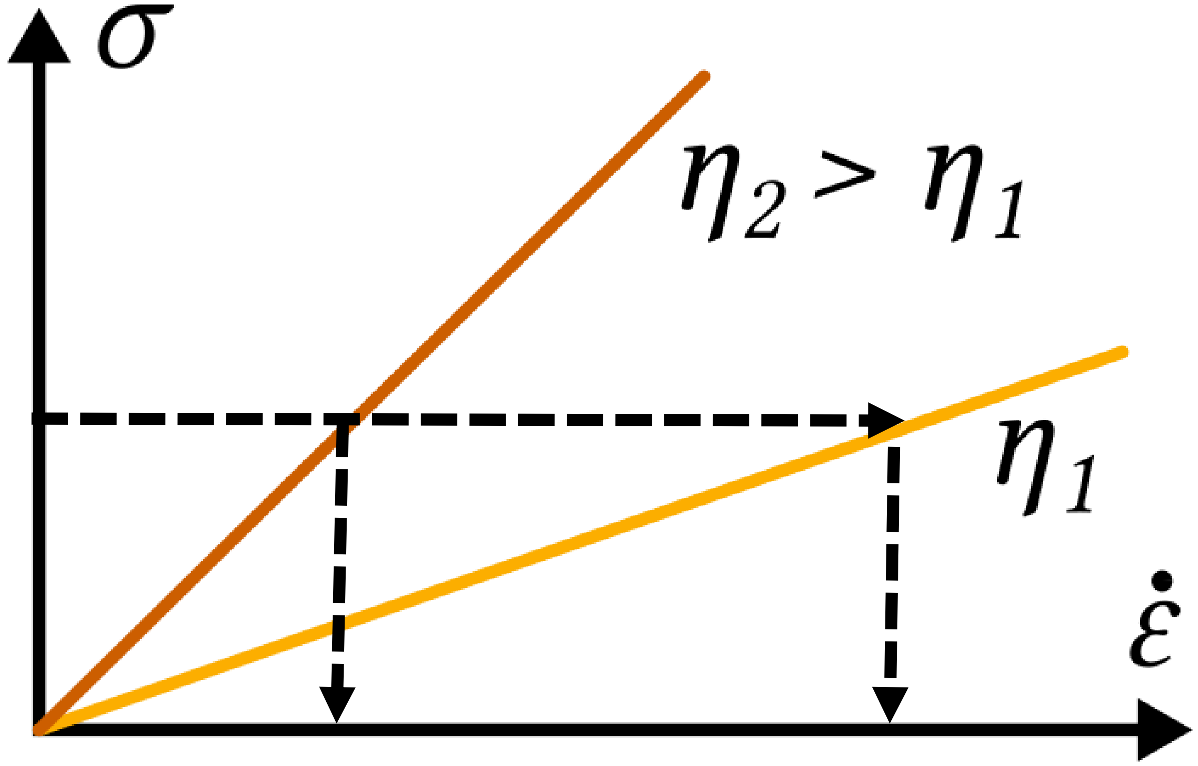
Viscosité

$$\eta = \frac{\text{contrainte } (\sigma)}{\text{taux de déformation } (\dot{\epsilon})}$$



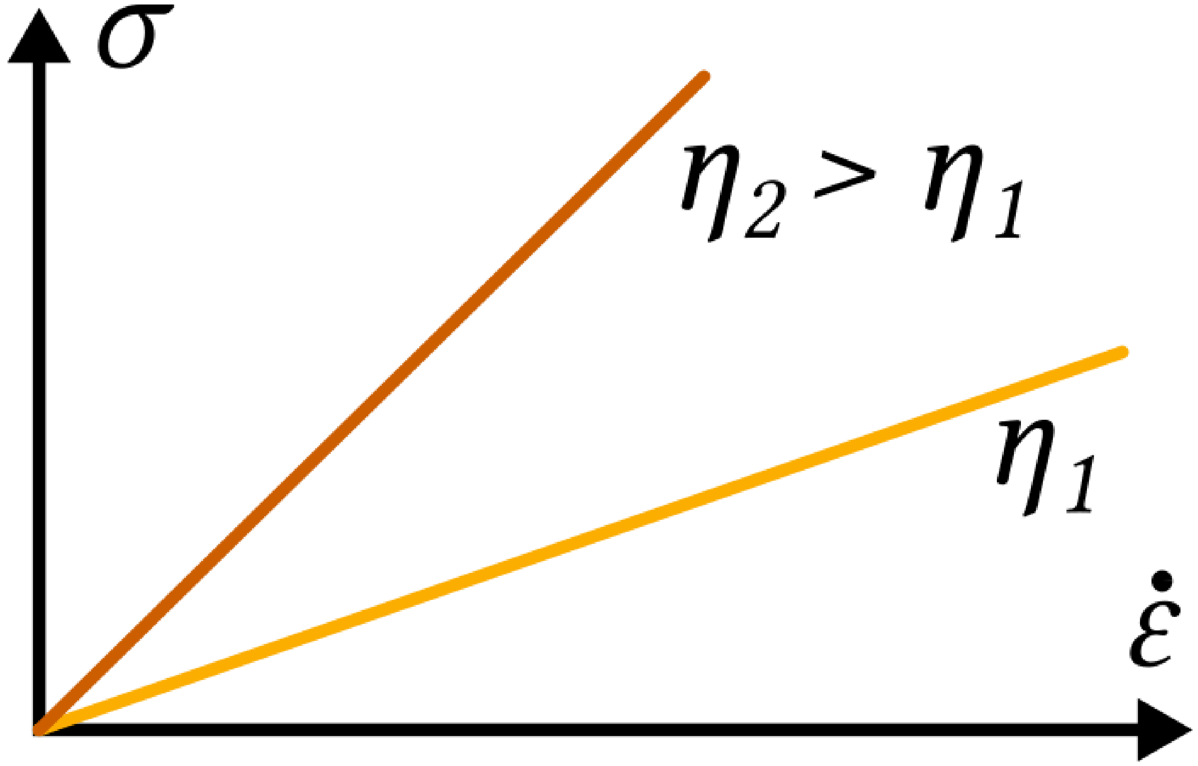
Viscosité

$$\eta = \frac{\text{contrainte } (\sigma)}{\text{taux de déformation } (\dot{\epsilon})}$$



Viscosité

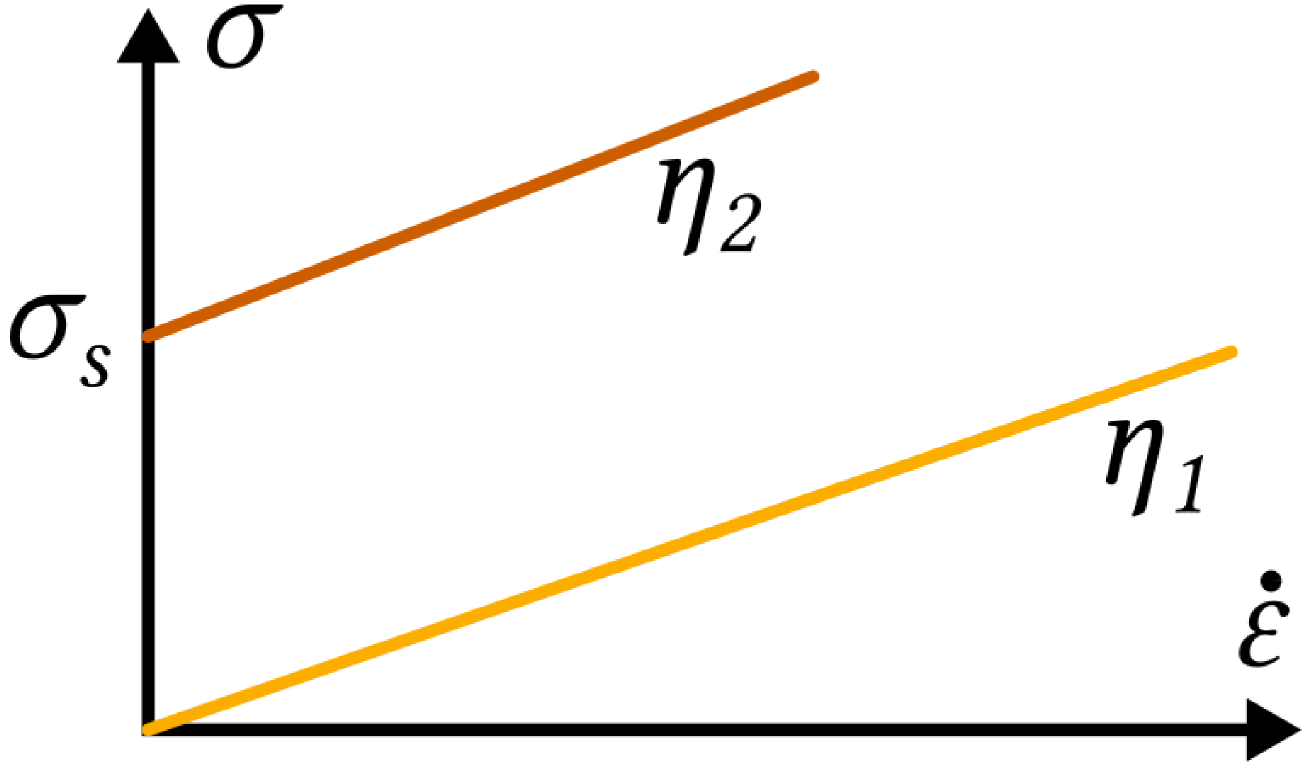
$$\eta = \frac{\text{contrainte }(\sigma)}{\text{taux de déformation }(\dot{\epsilon})}$$



Fluide newtonien :
Viscosité indépendante du taux de déformation

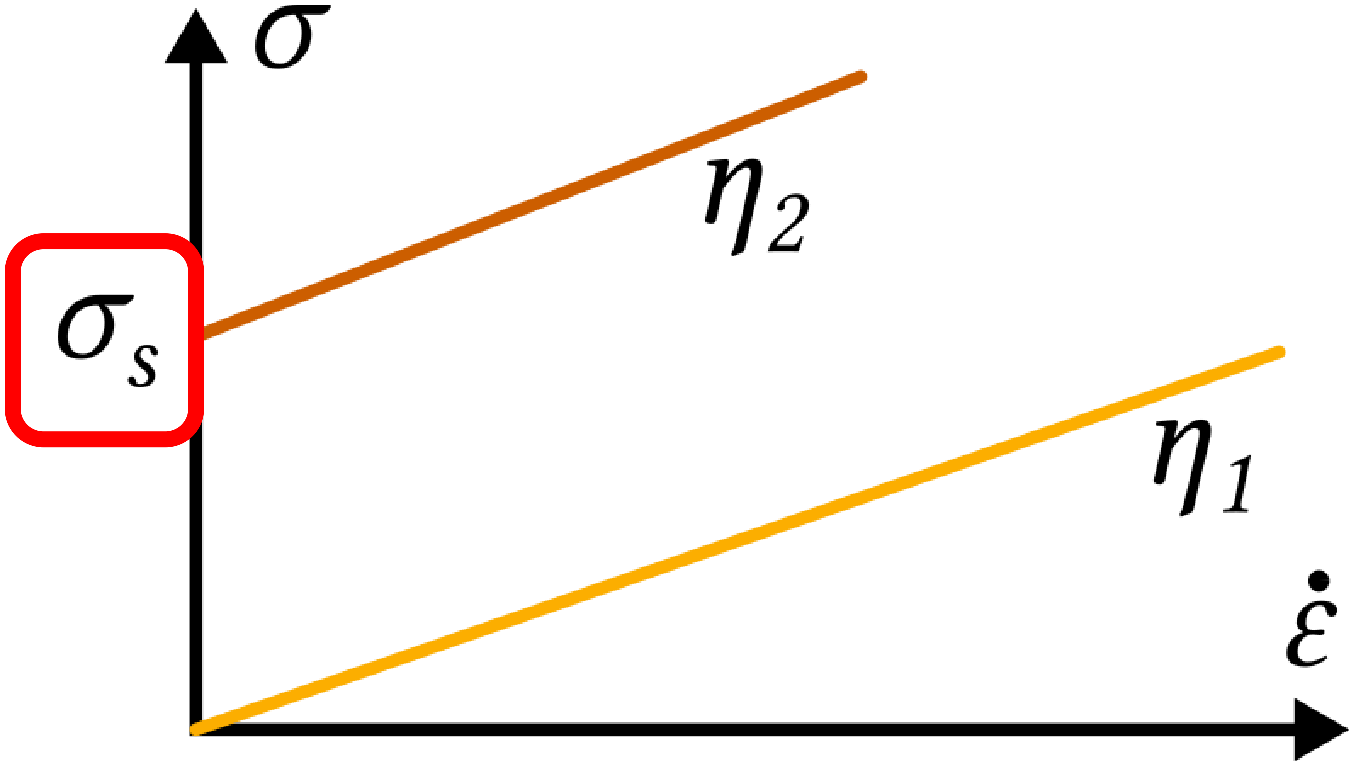
Viscosité

$$\eta = \frac{\text{contrainte } (\sigma)}{\text{taux de déformation } (\dot{\epsilon})}$$



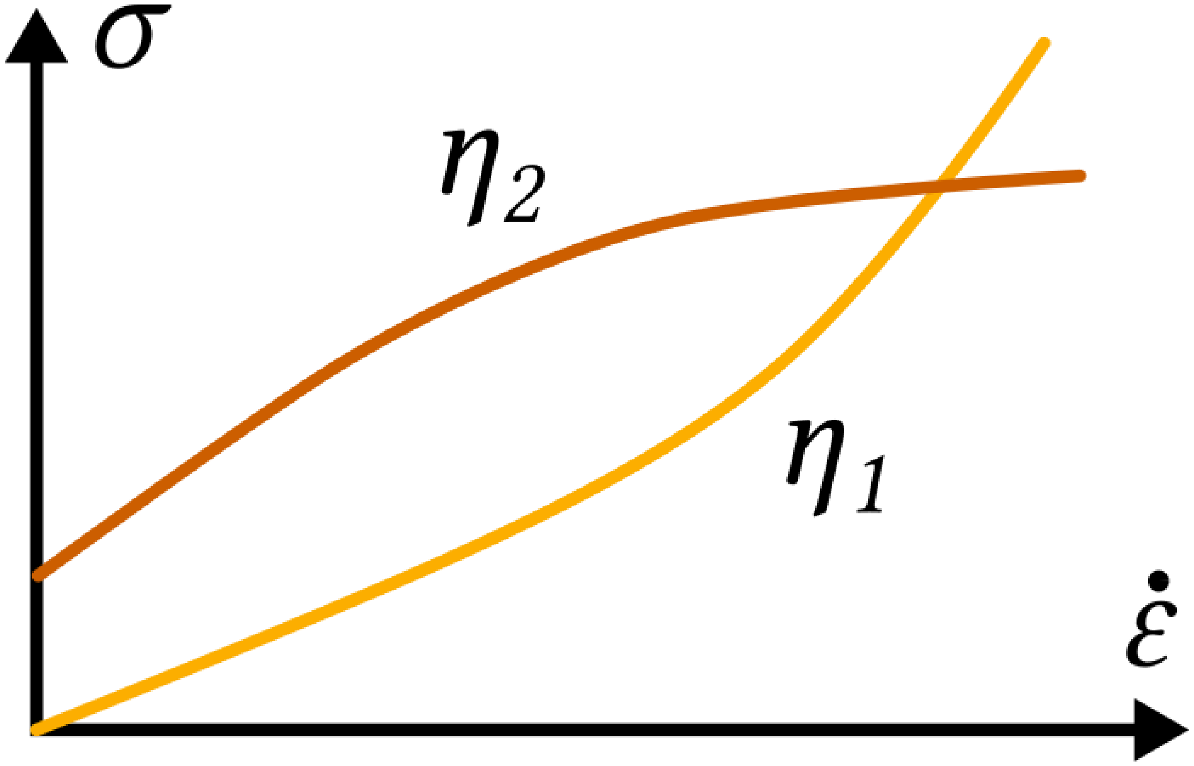

ReactionGIFS.me

Fluides à seuil



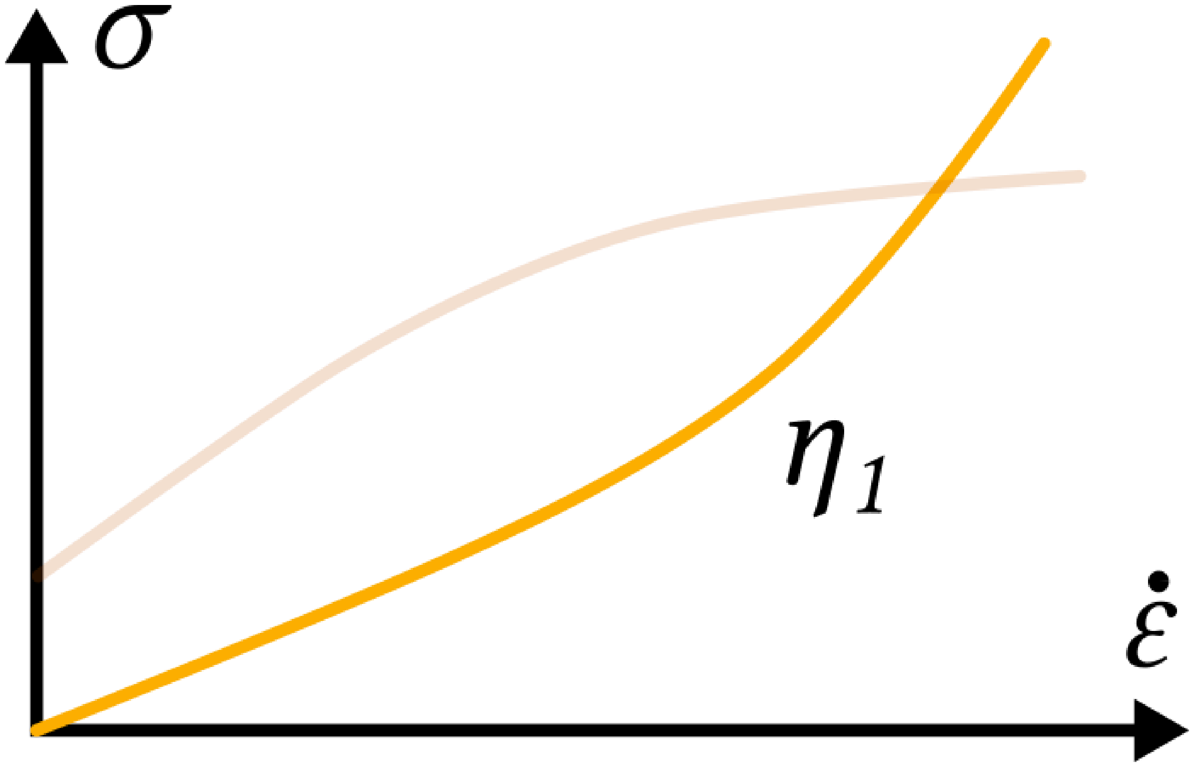
Viscosité

$$\eta = \frac{\text{contrainte}}{\text{taux de déformation}}$$



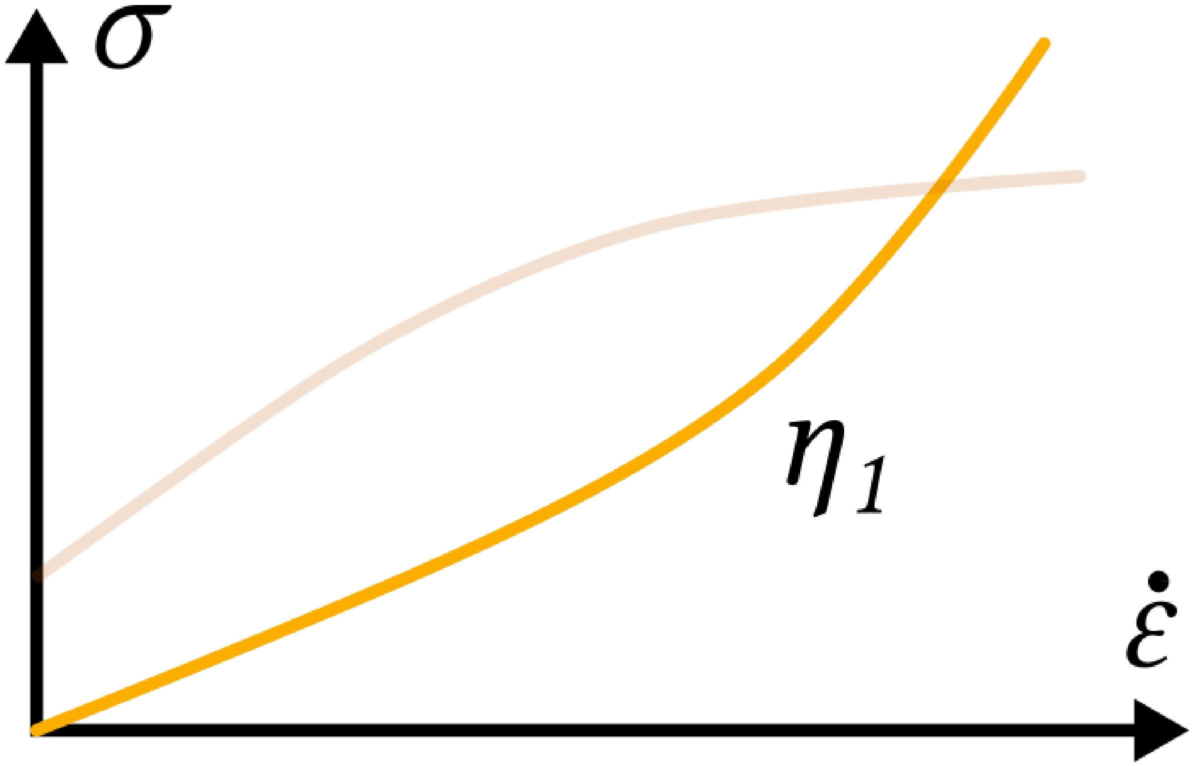
$$\eta = \frac{\mathrm{d}\,\sigma}{\mathrm{d}\,\dot{\epsilon}}$$

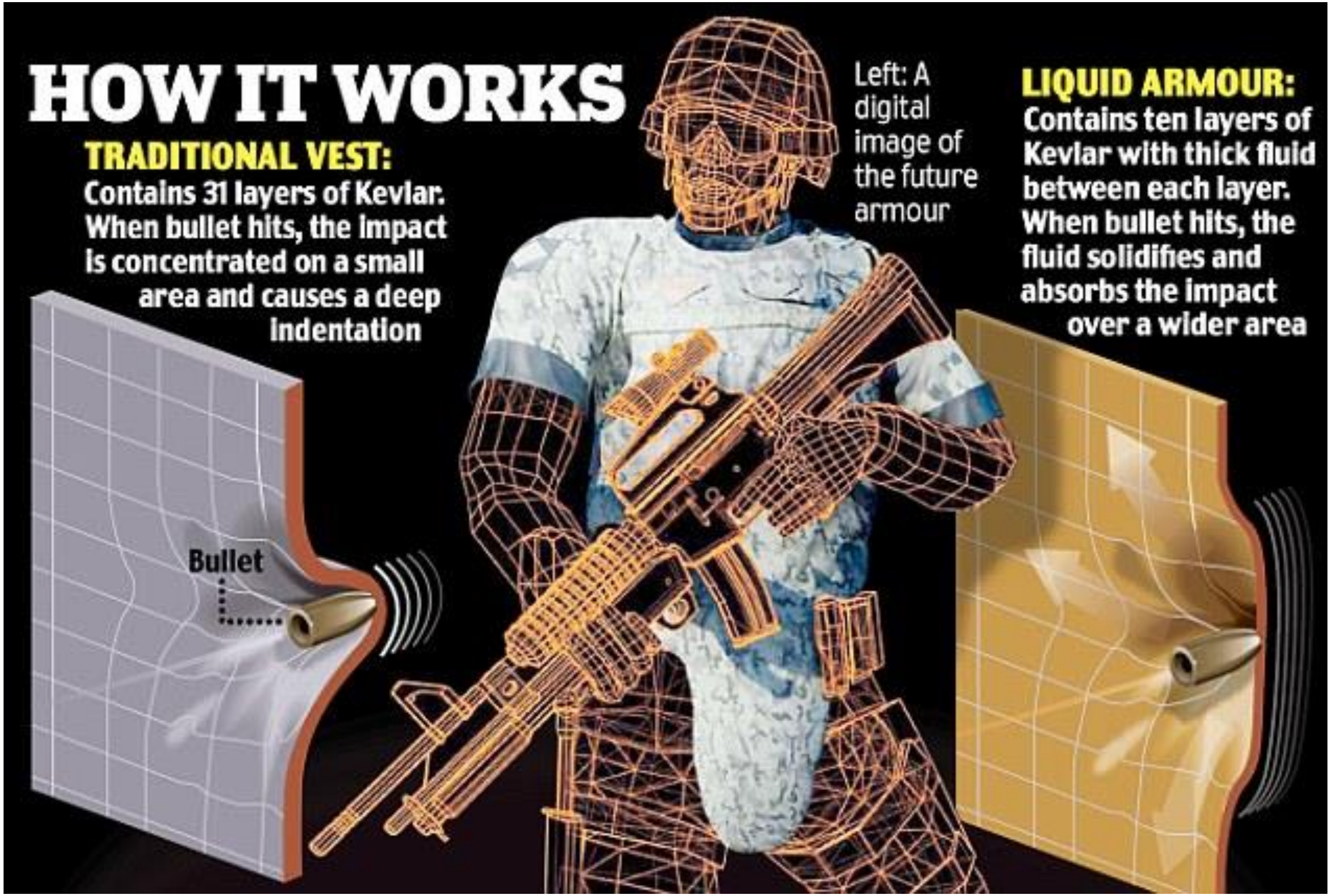
Fluides rhéo-épaississants



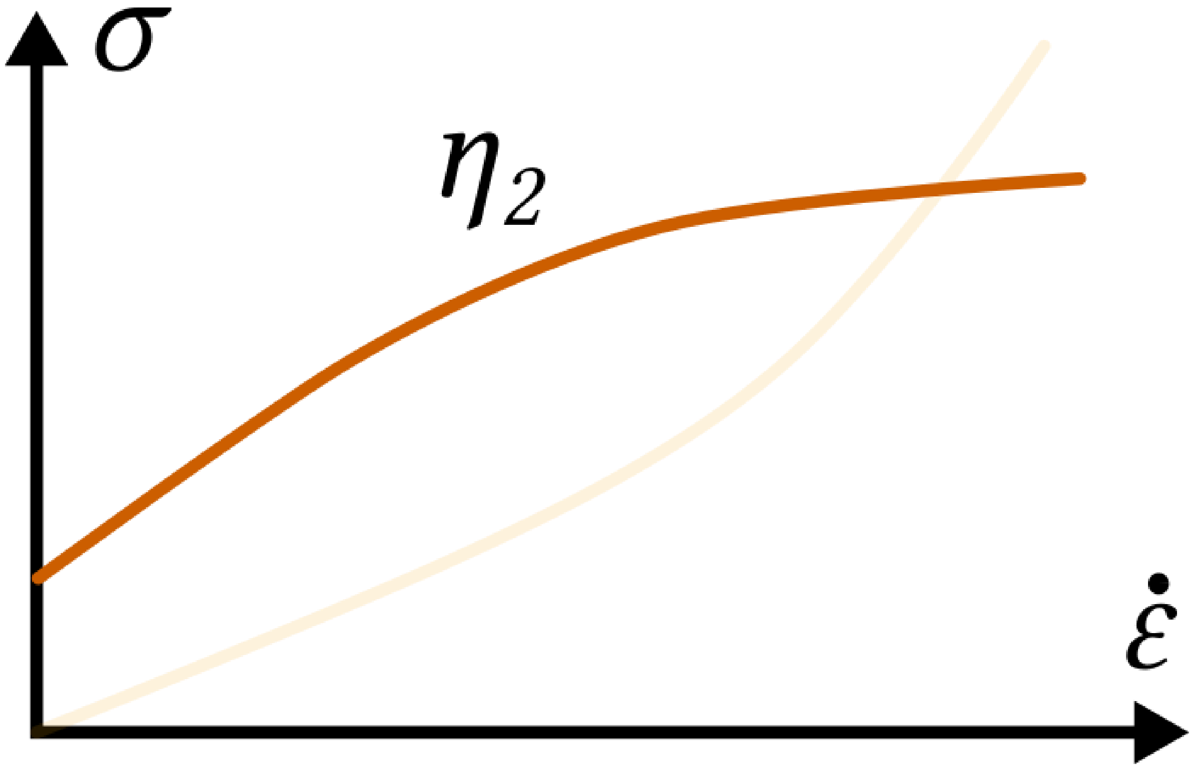
$$\eta = \frac{\mathrm{d}\,\sigma}{\mathrm{d}\,\dot{\epsilon}}$$

Fluides rhéo-épaississants



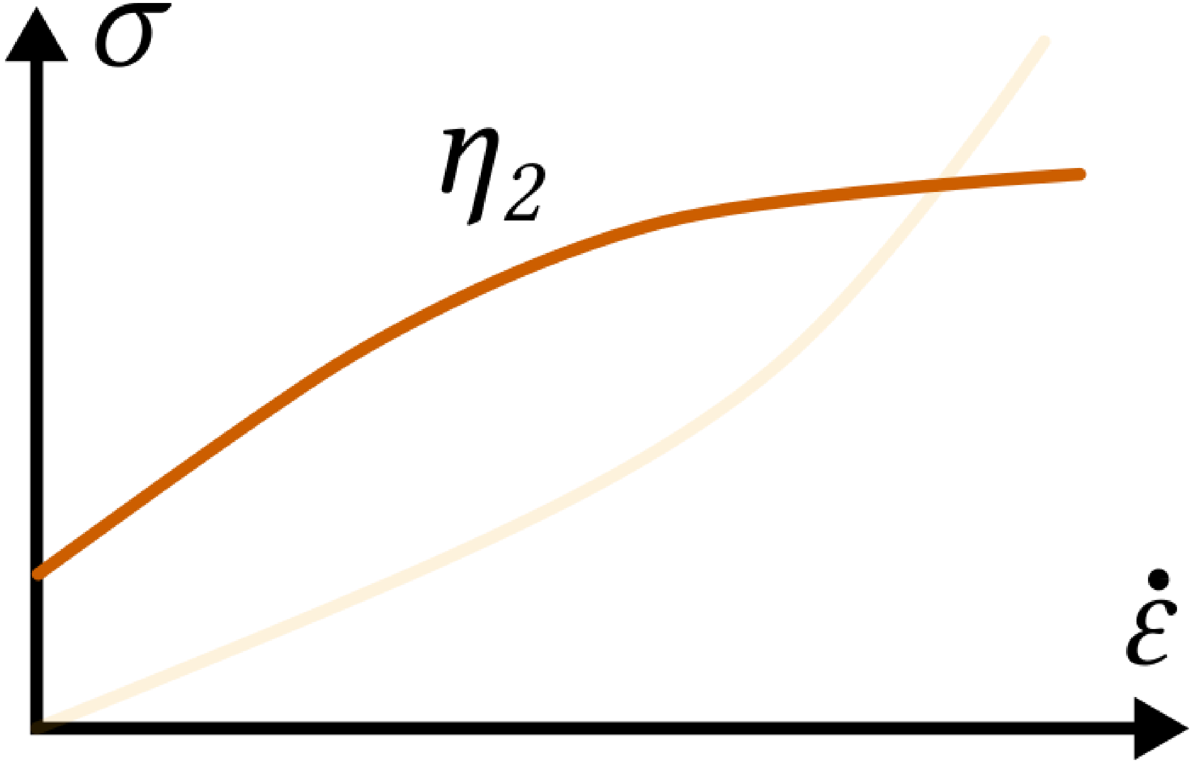

HOW IT WORKS
TRADITIONAL VEST:
Contains 31 layers of Kevlar. When bullet hits, the impact is concentrated on a small area and causes a deep indentation
Bullet
Left: A digital image of the future armour
LIQUID ARMOUR:
Contains ten layers of Kevlar with thick fluid between each layer. When bullet hits, the fluid solidifies and absorbs the impact over a wider area

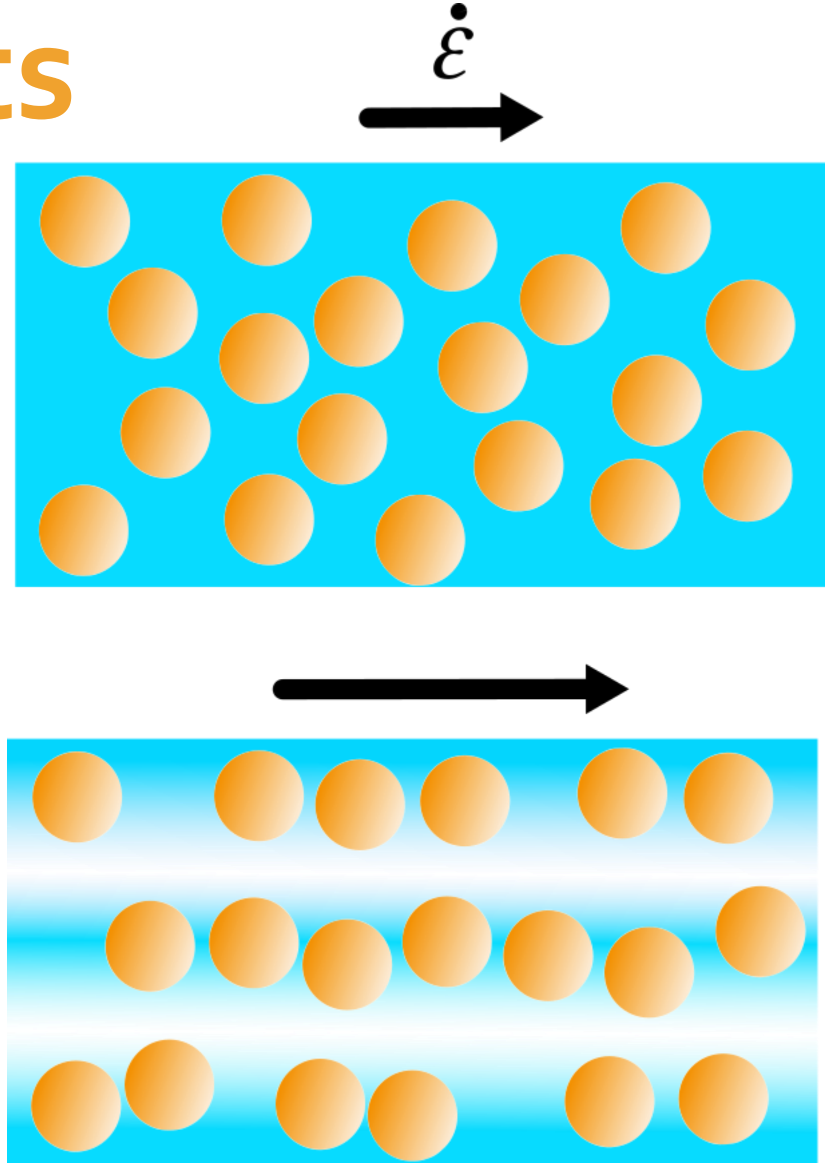
Fluides rhéo-fluidifiants



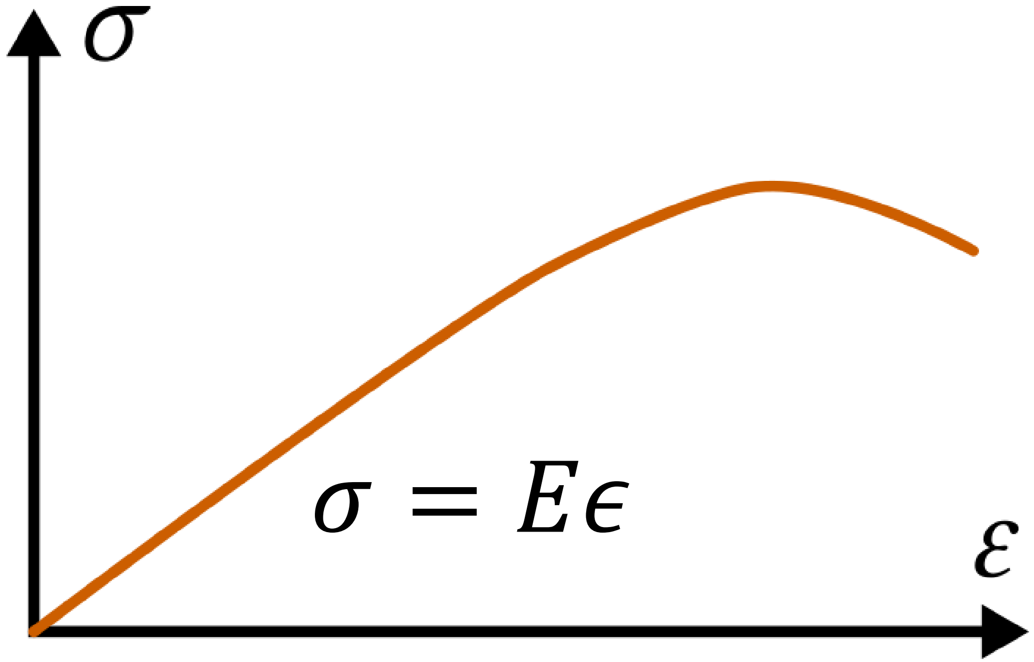
$$\eta = \frac{\mathrm{d}\,\sigma}{\mathrm{d}\,\dot{\epsilon}}$$

Fluides rhéo-fluidifiants

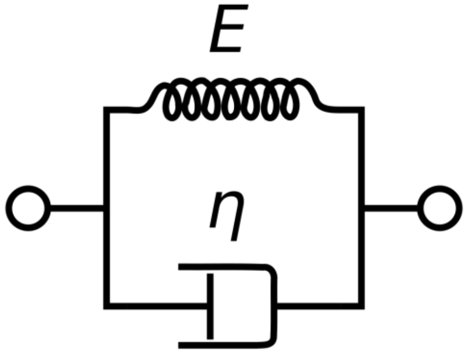




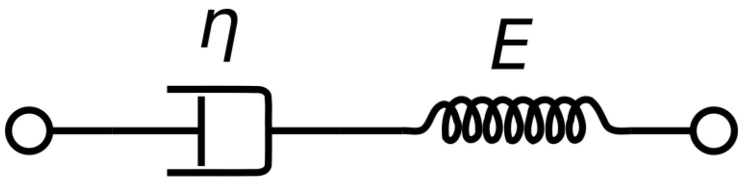
Elasticité et plasticité



Modèle de Kelvin-Voigt

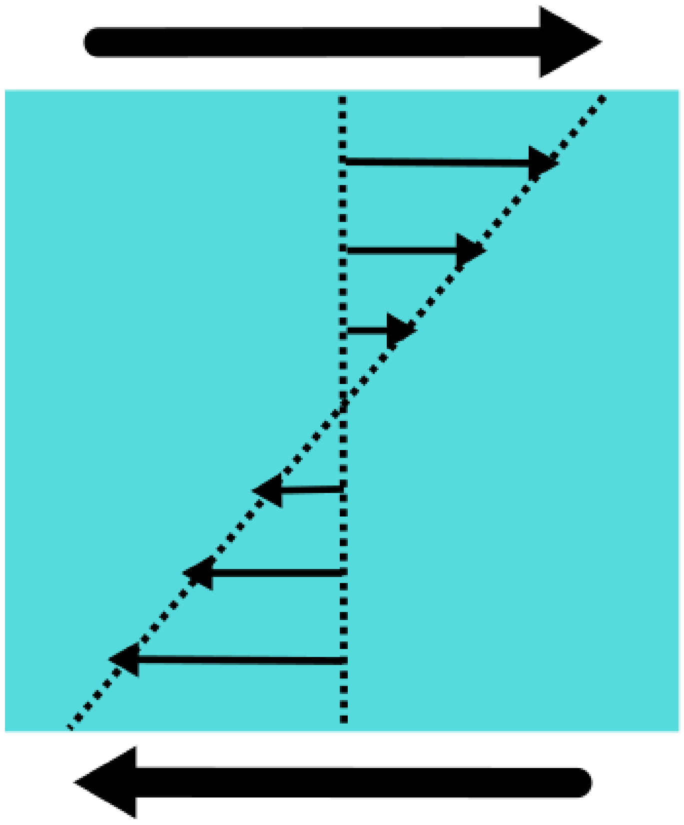


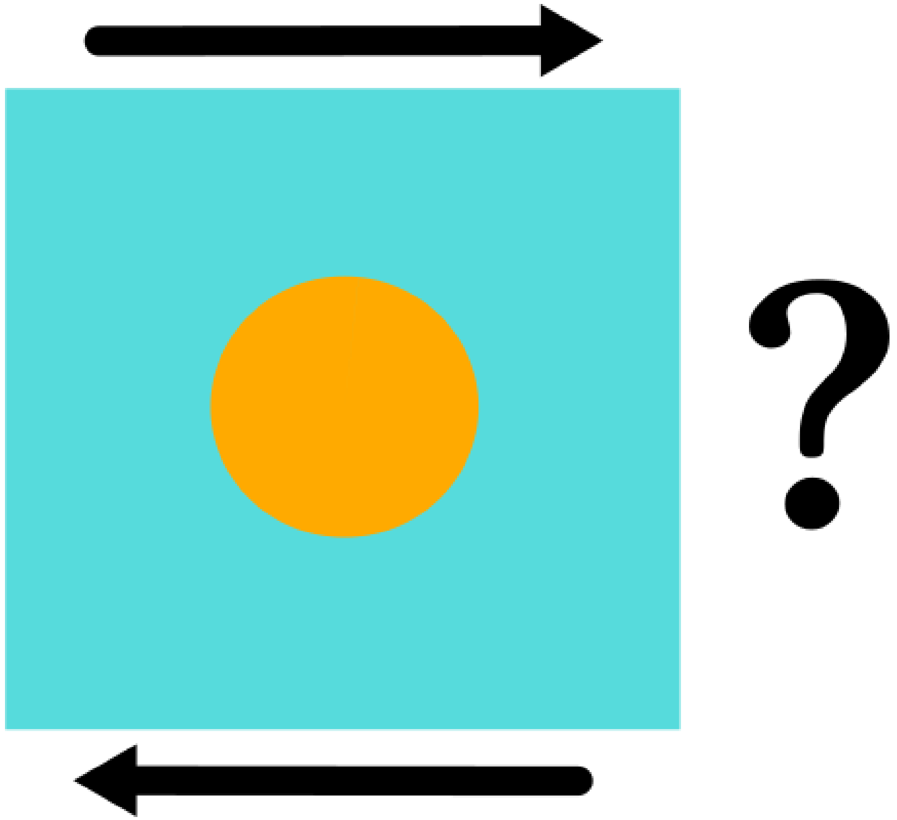
Modèle de Maxwell



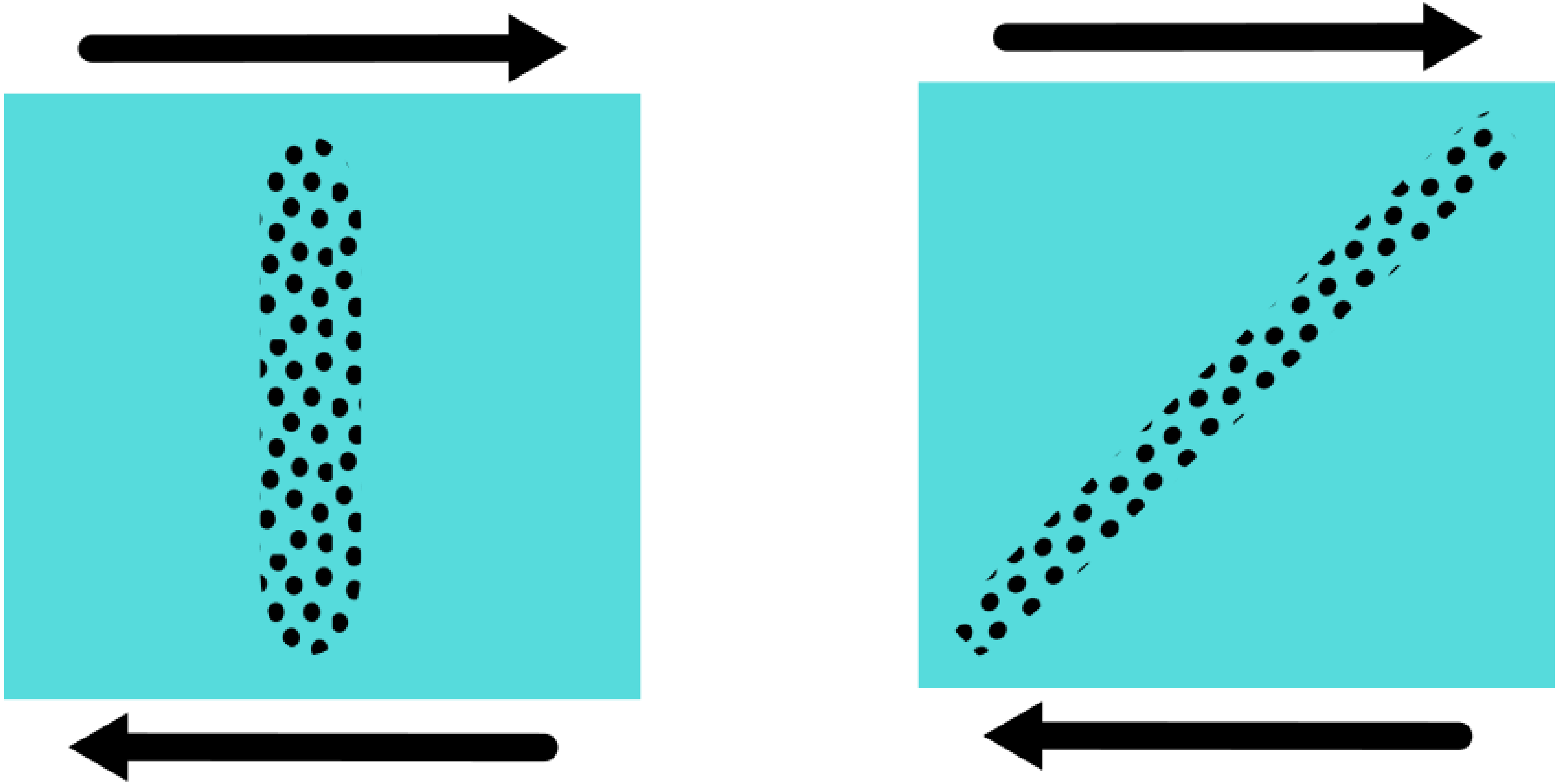
RHÉOLOGIES DES SUSPENSIONS GRANULAIRES

Une particule dans un cisaillement

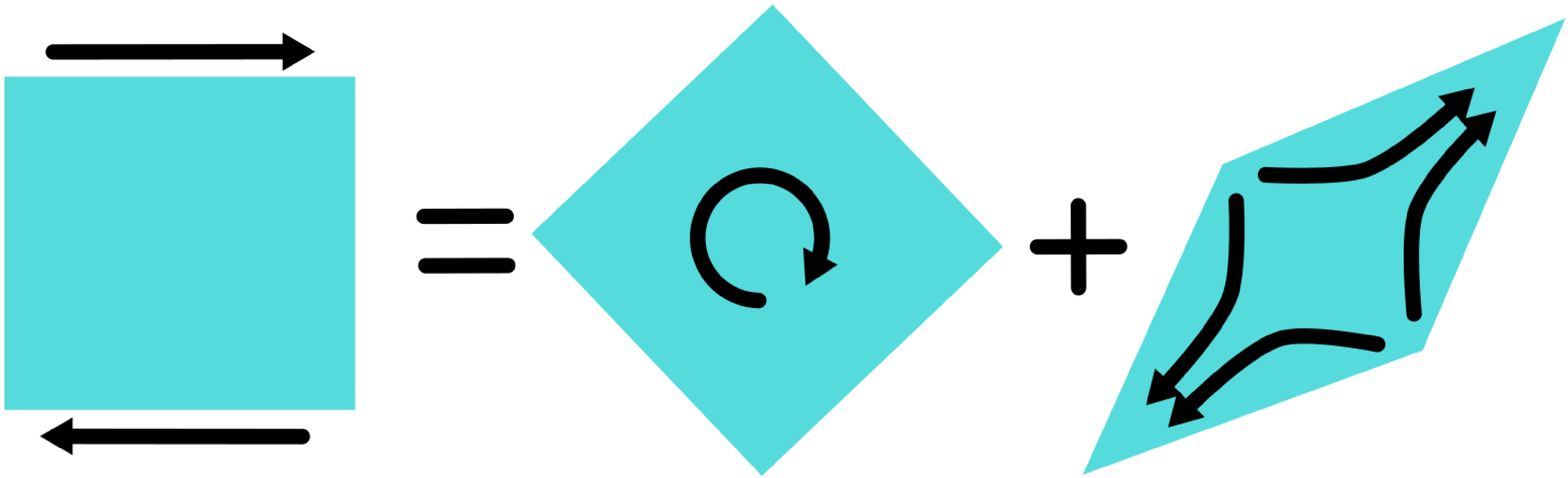




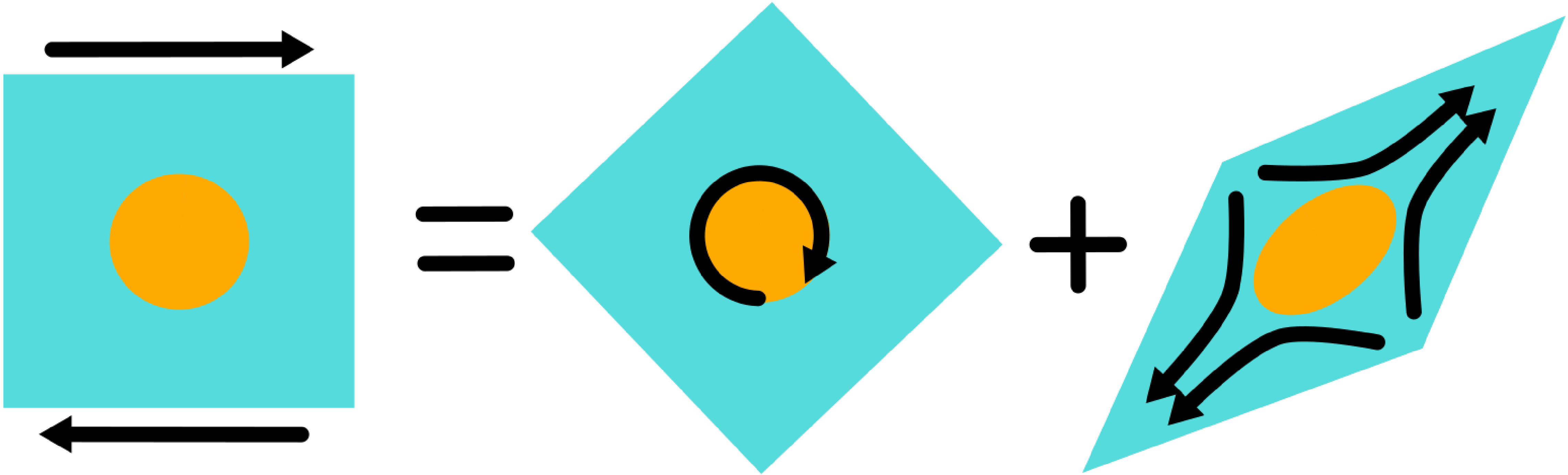
Une particule dans un cisaillement



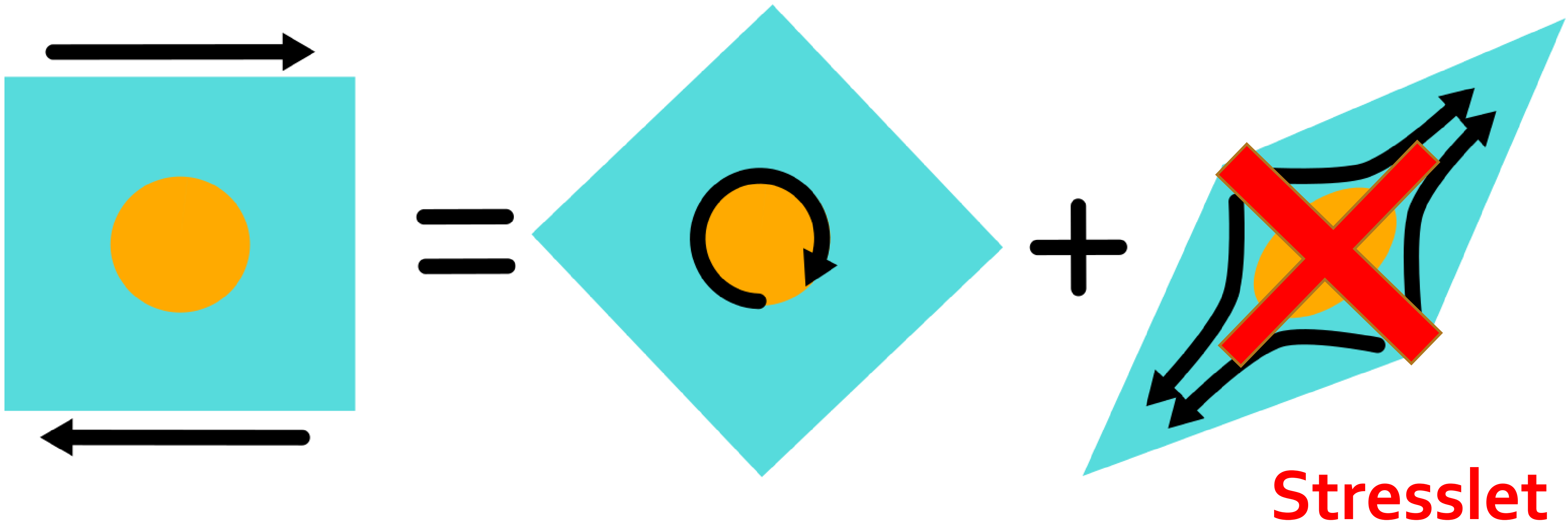
Une particule dans un cisaillement

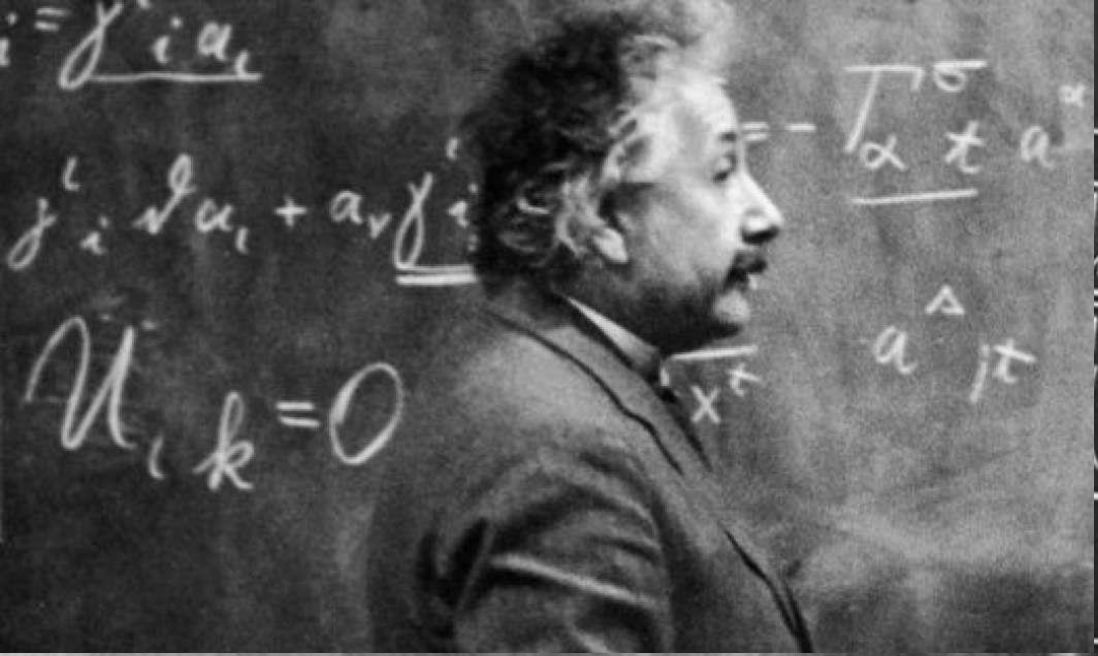


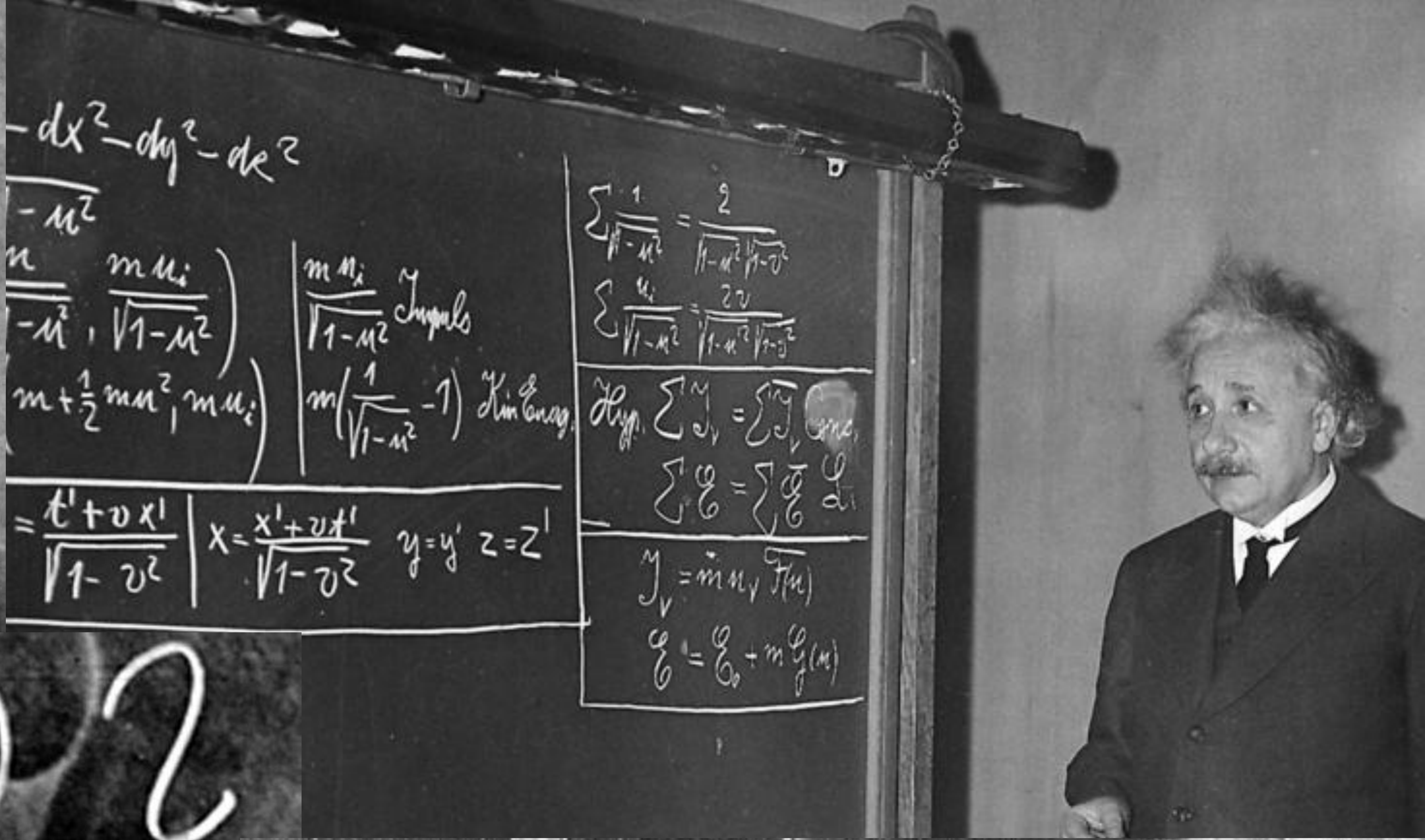
Une particule dans un cisaillement

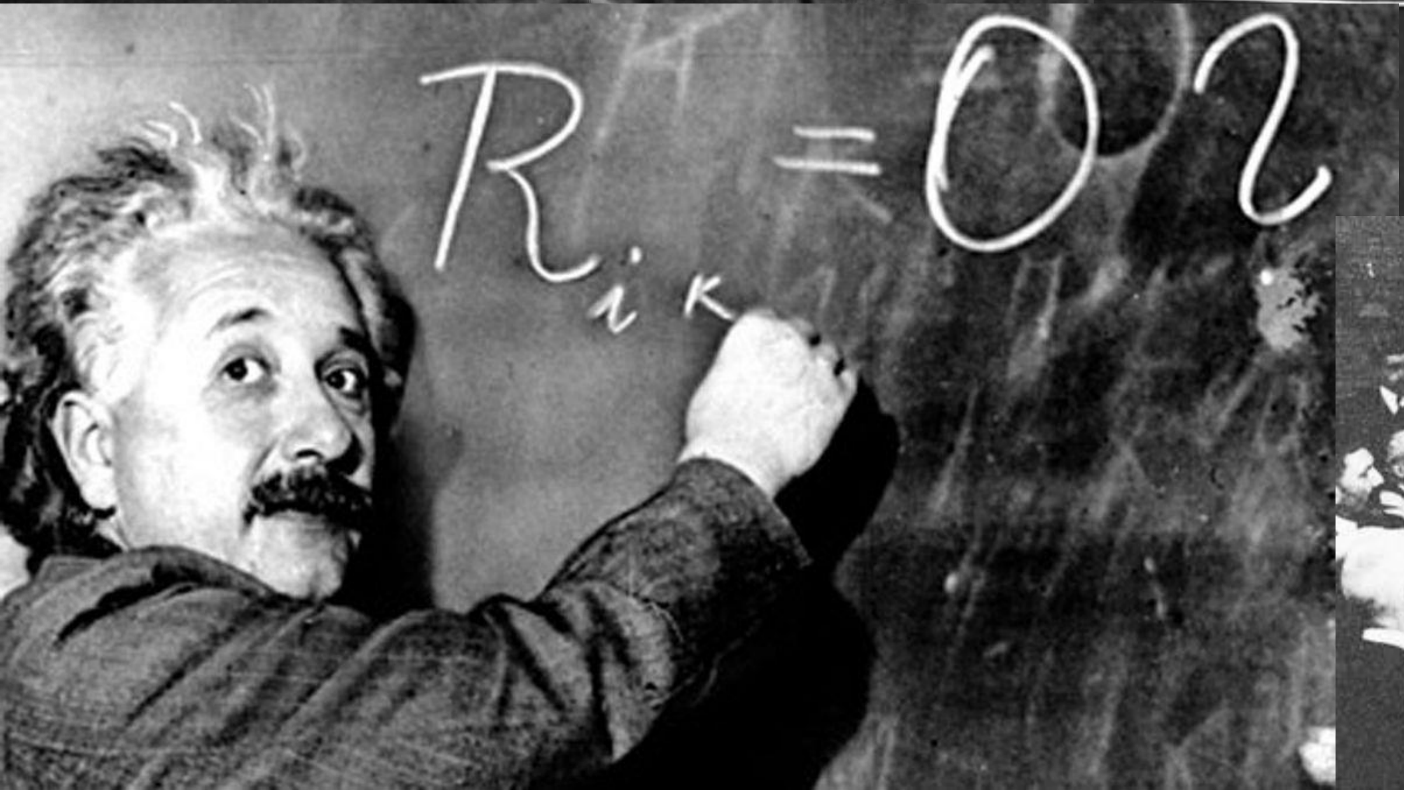


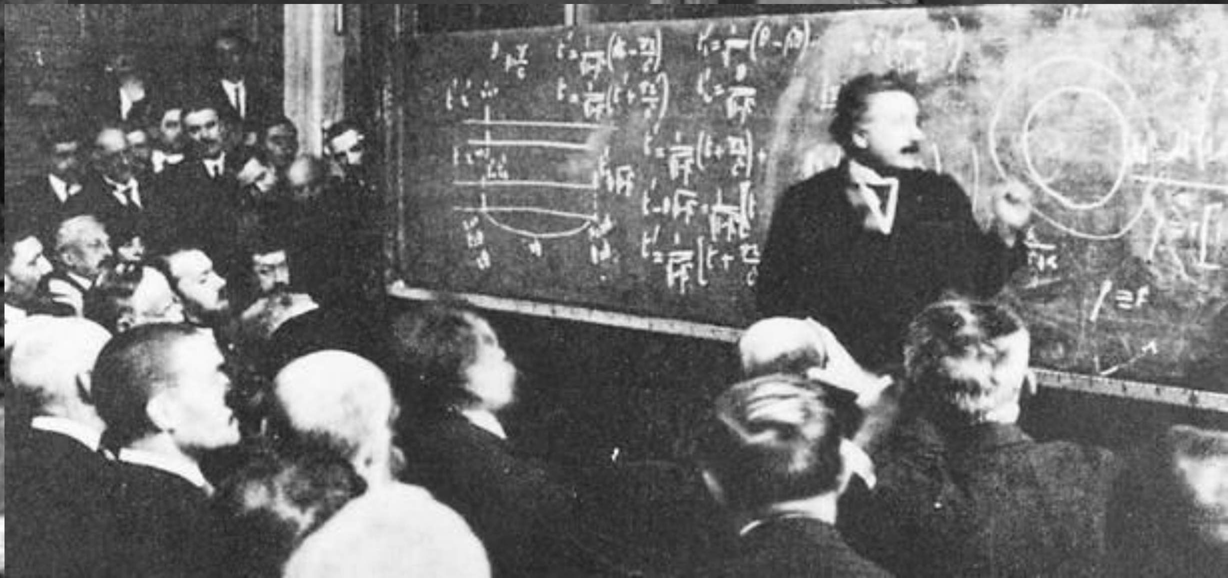
Une particule dans un cisaillement

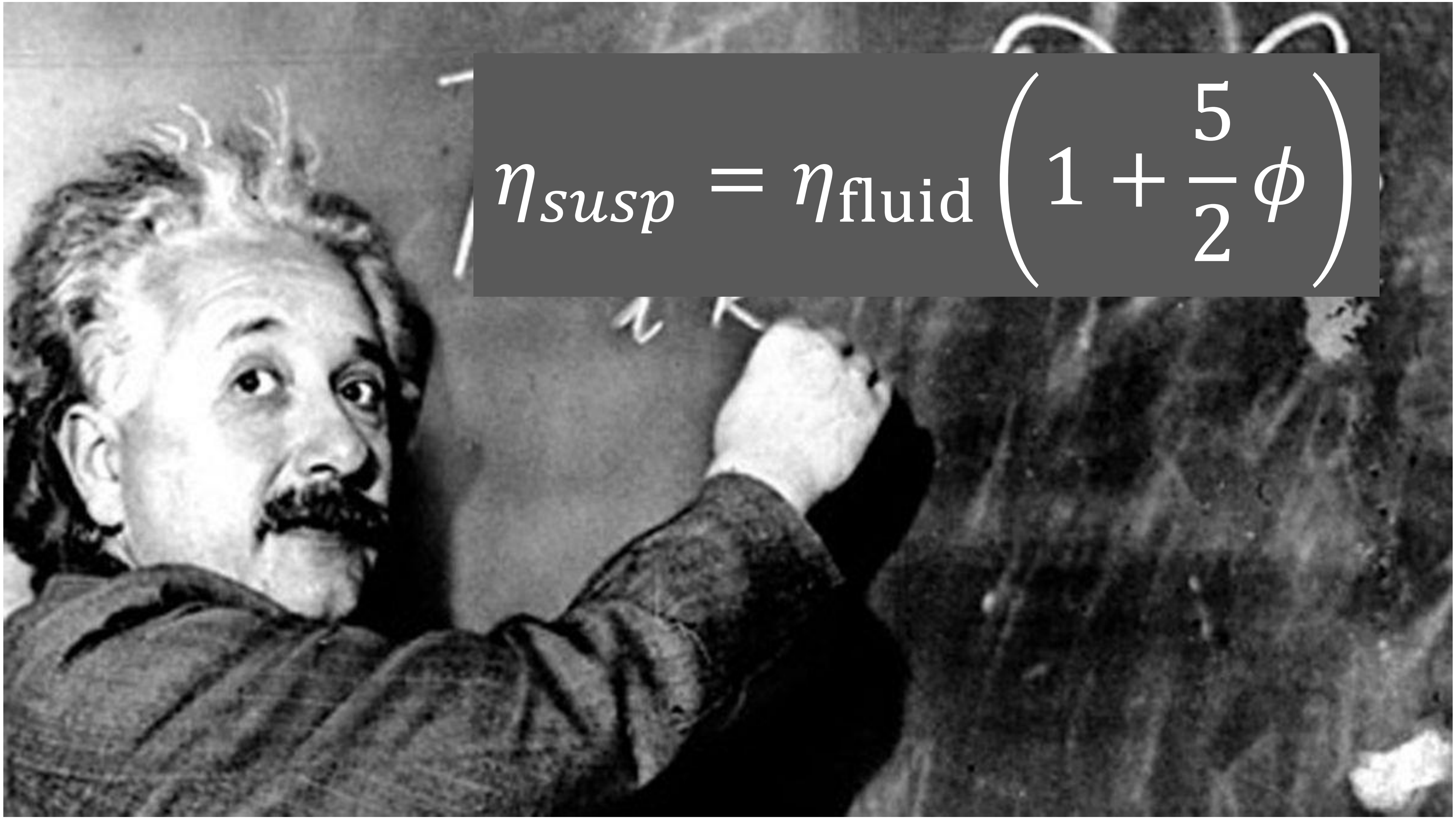



$U_{ik} = 0$


Impuls
Kin Energ.
$y = y'$ $z = z'$


$R_{ik} = 0?$





$$\eta_{susp} = \eta_{\text{fluid}}\left(1 + \frac{5}{2}\phi\right)$$

Une particule dans un cisaillement

Viscosité d'Einstein (1905)

$$\phi = \frac{V_{\text{particules}}}{V_{\text{total}}}$$

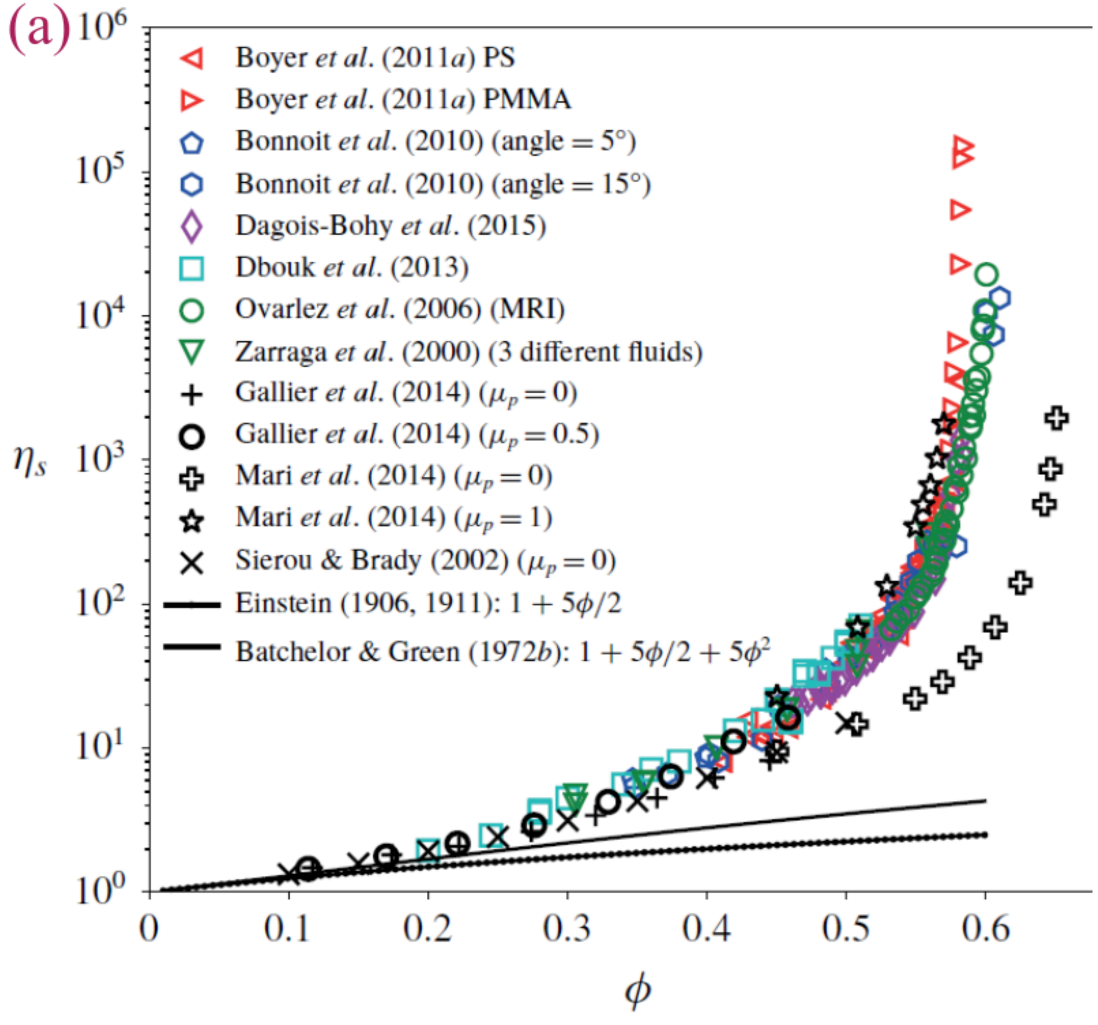
$$\eta_{susp} = \eta_{\text{fluid}}\left(1 + \frac{5}{2}\phi\right)$$

Une particule dans un cisaillement

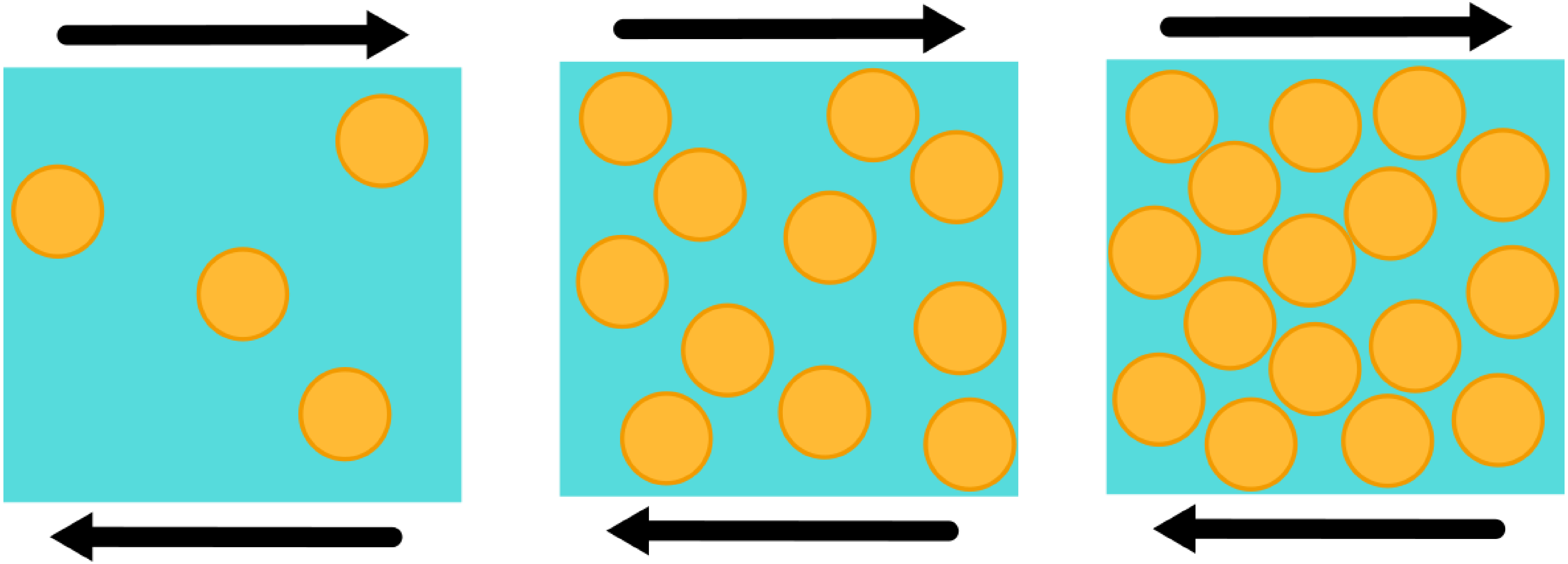
Viscosité d'Einstein (1905)

$$\phi = \frac{V_{\text{particules}}}{V_{\text{total}}}$$

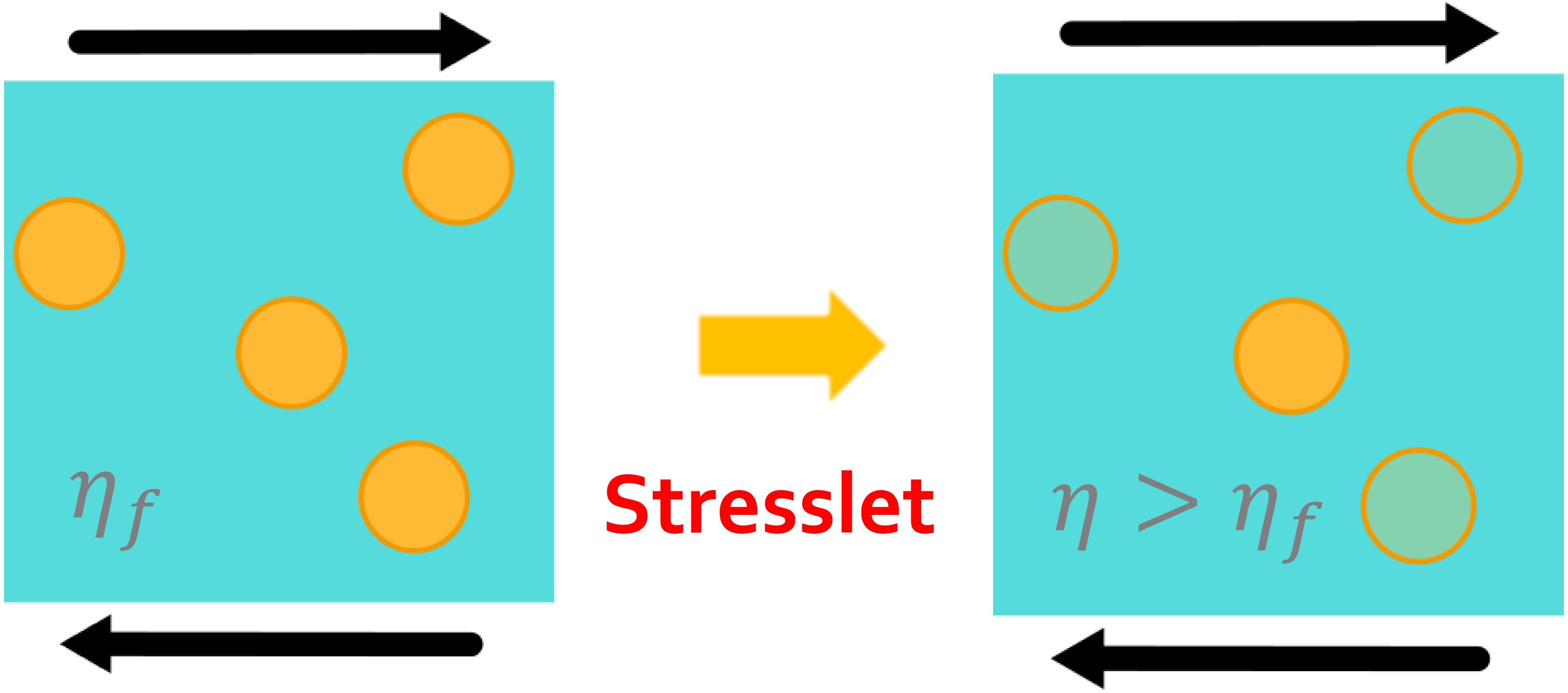
$$\eta_{\text{susp}} = \eta_{\text{fluid}}\left(1 + \frac{5}{2}\phi\right)$$



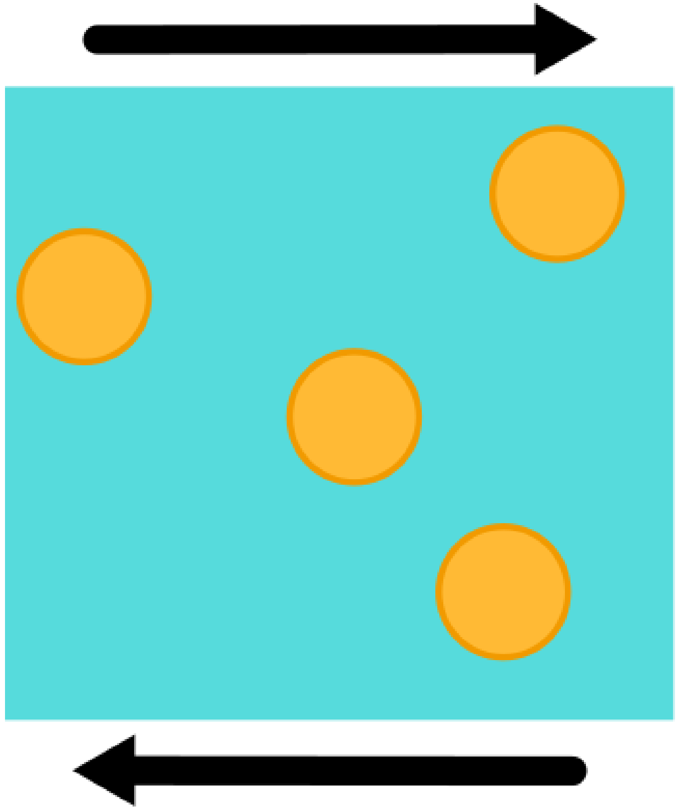
Plusieurs particules



Plusieurs particules

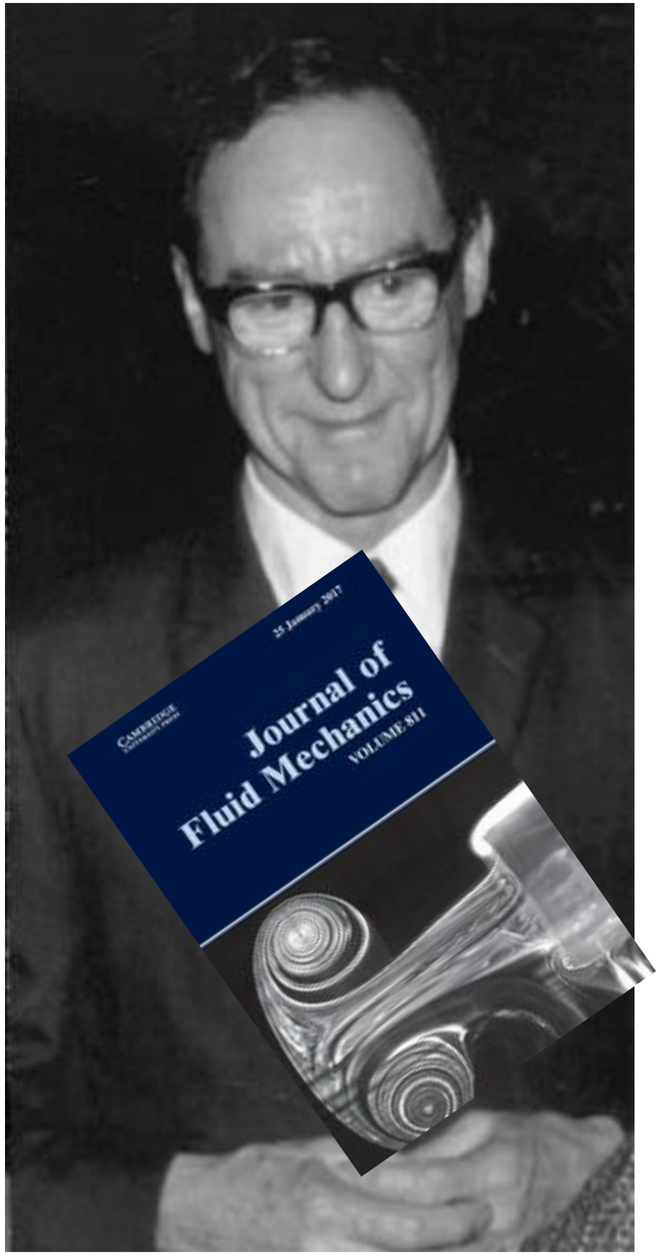


Plusieurs particules



Viscosité de Batchelor (1952)

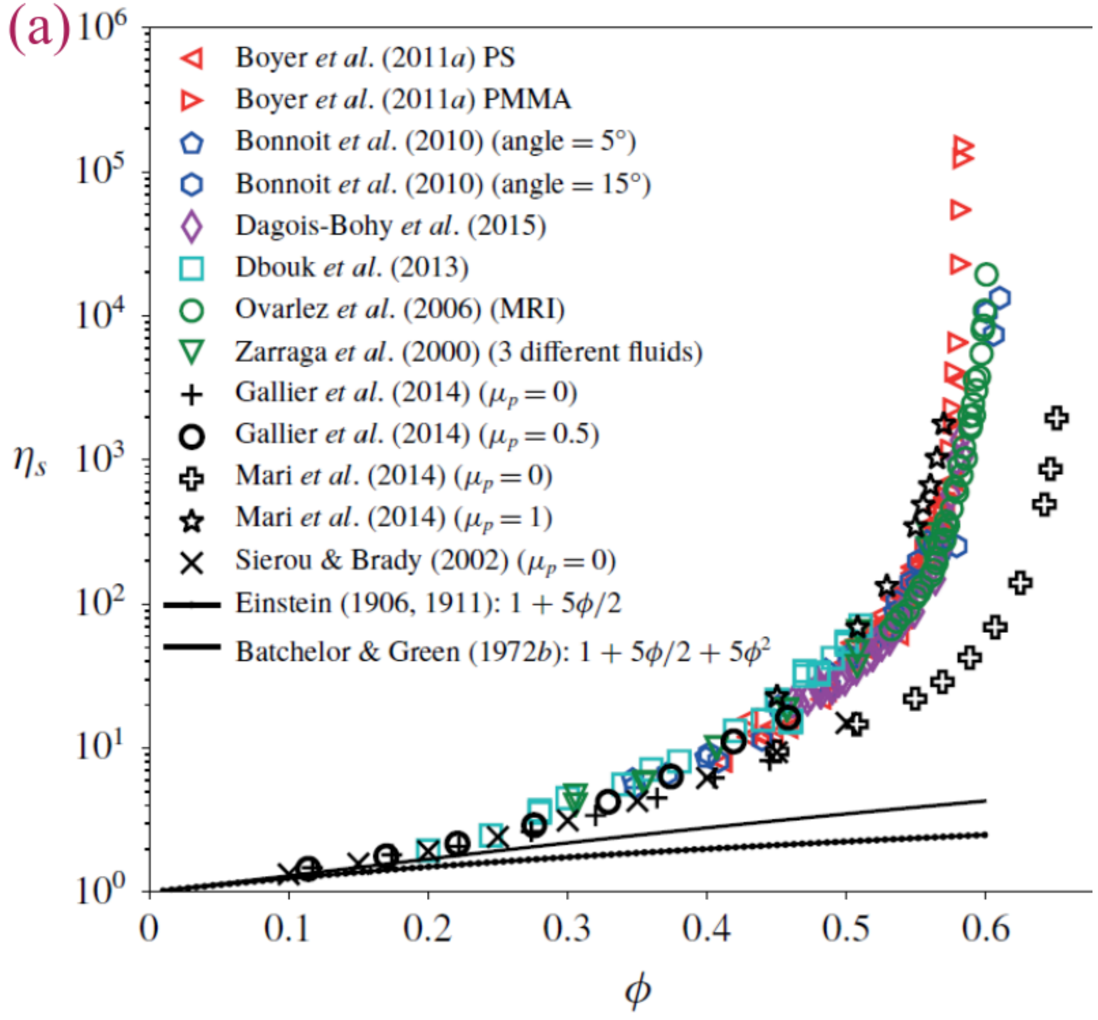
$$\eta_s = \frac{\eta_{\text{susp}}}{\eta_{\text{fluid}}} = \left(1 + \frac{5}{2}\phi + 5\phi^2\right)$$



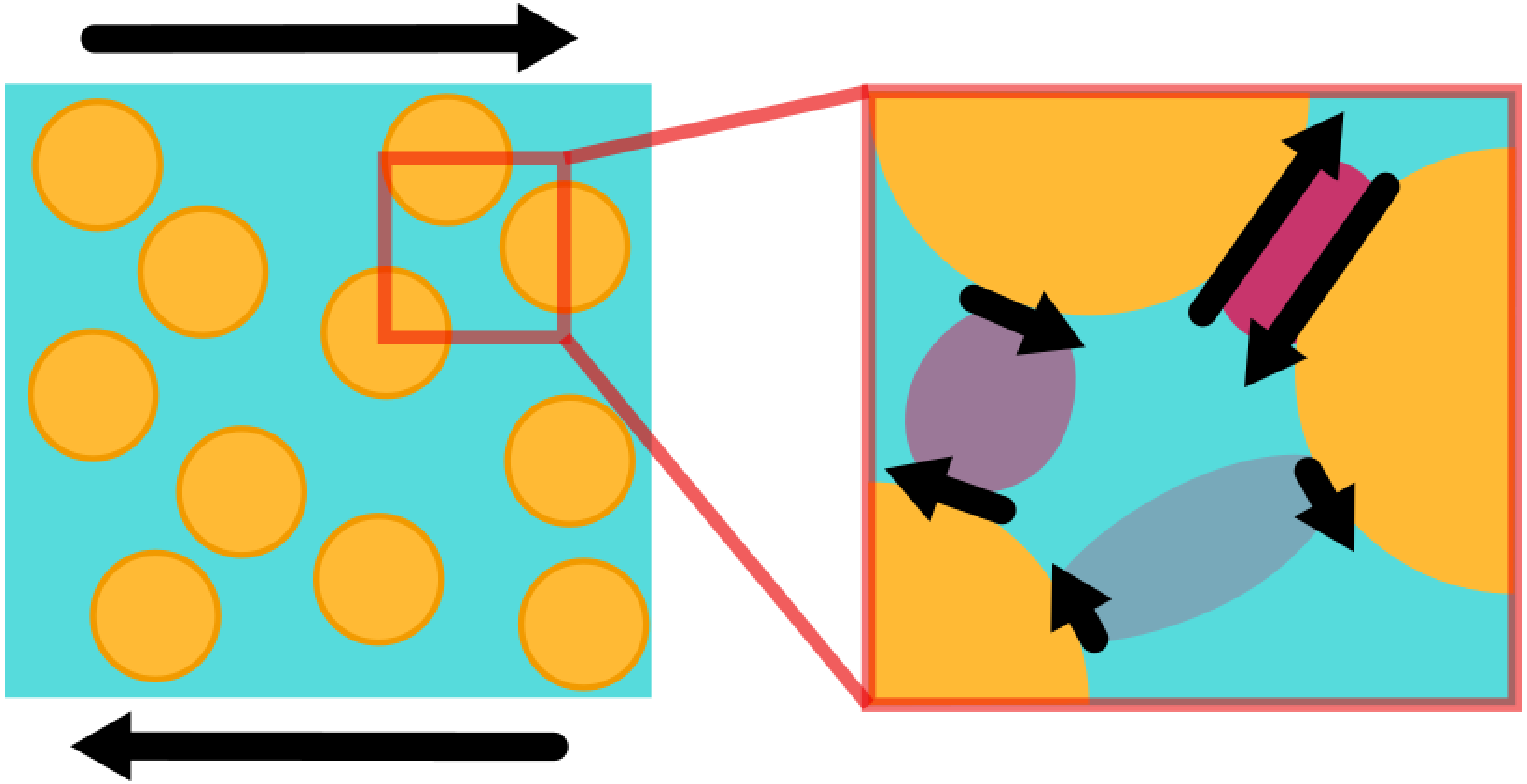
Plusieurs particules

Viscosité de Batchelor (1952)

$$\eta_s = \frac{\eta_{\text{susp}}}{\eta_{\text{fluid}}} = \left(1 + \frac{5}{2}\phi + 5\phi^2\right)$$

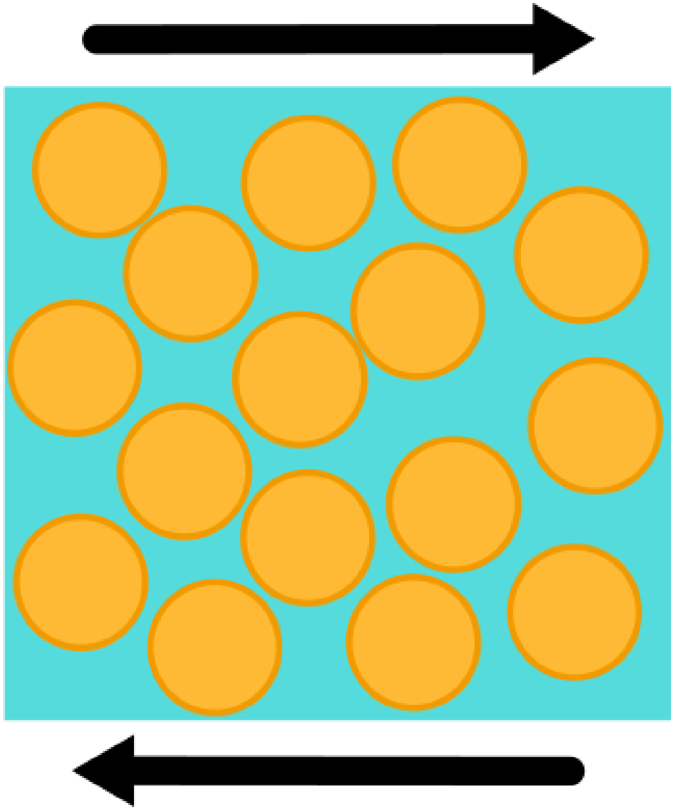


Plusieurs particules



→ Interactions hydrodynamiques

Plusieurs particules

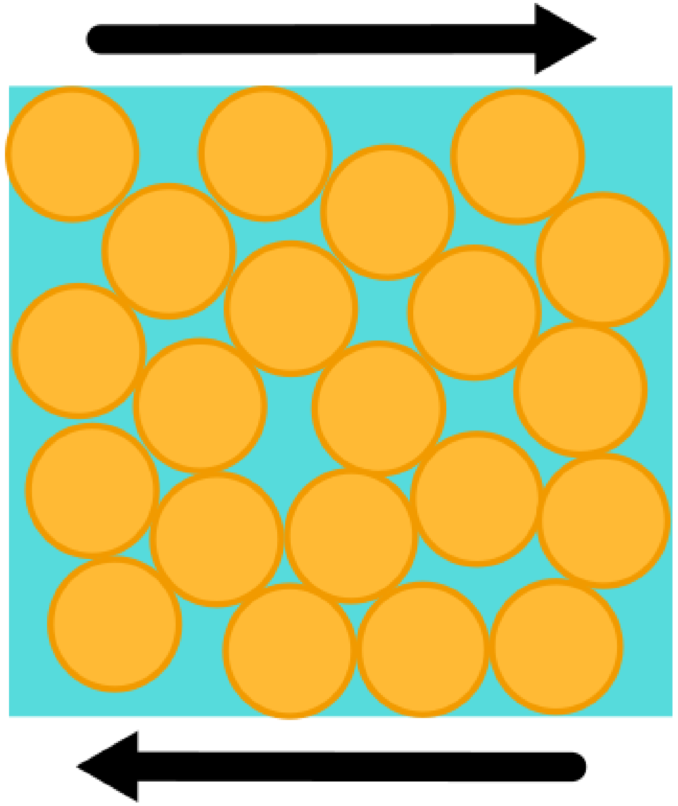


→ Contacts

Coefficient de friction microscopique

$$\mu_p$$

Jamming



Compacité maximum

$$\phi_c \simeq 55 - 60\ \%$$

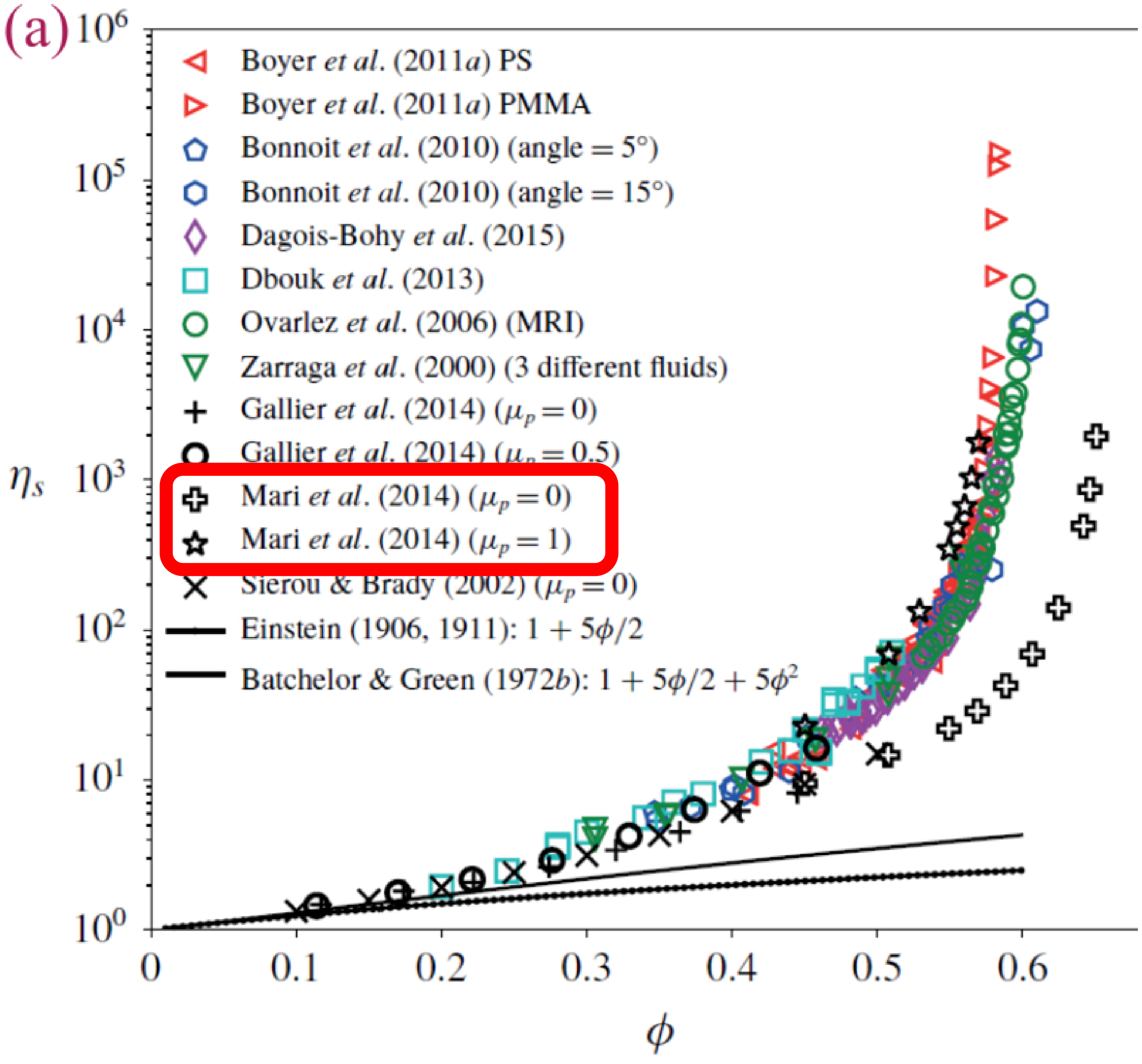
Déformation impossible

Viscosité des suspensions granulaires

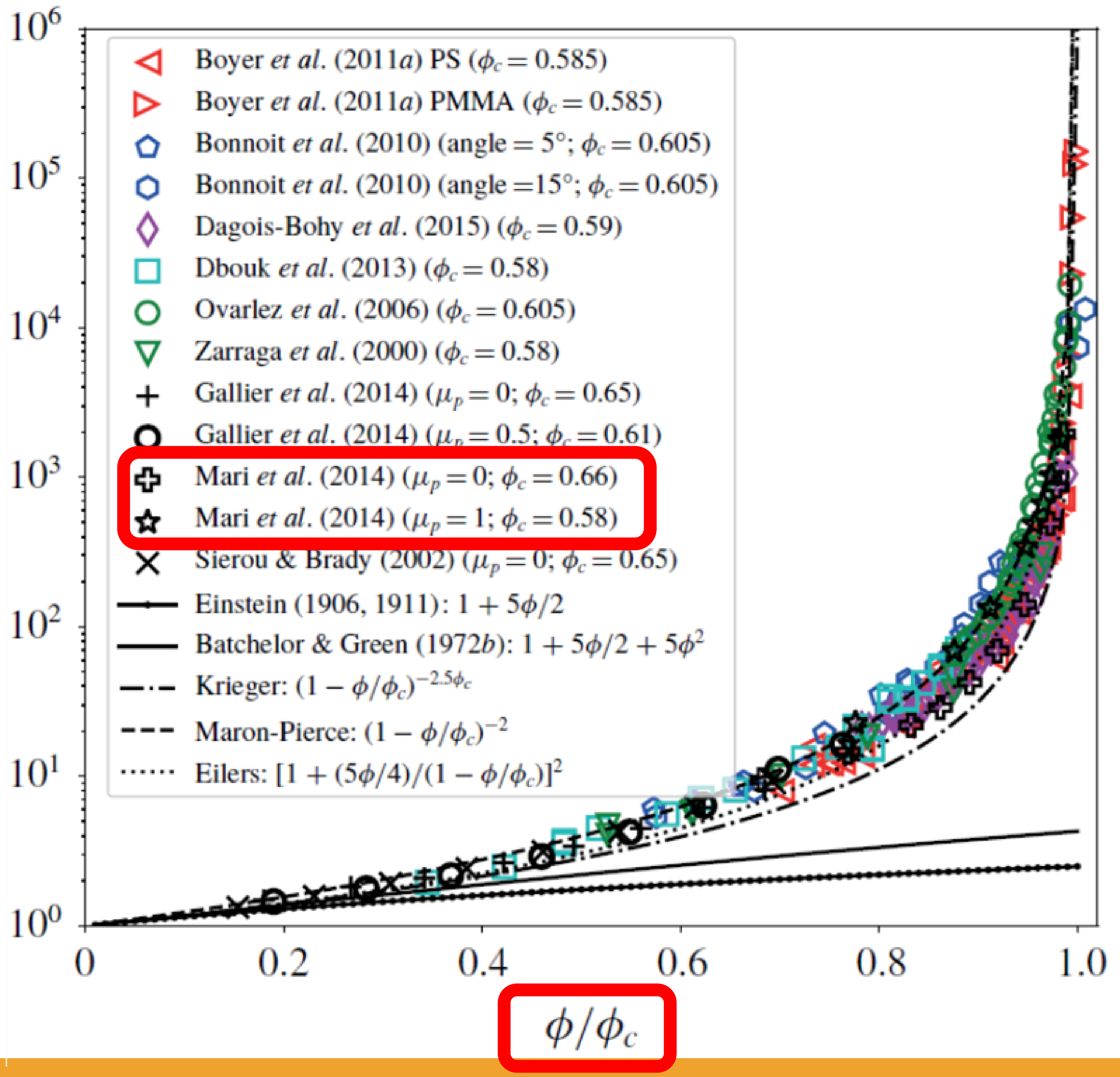
Regime	**Dilute**	**Semi-dilute**	**Dense**
ϕ **range**	0 - 10%	10% - 20%	20% - ϕ_c
Interpolation	Einstein et al. (1905) $\eta_s = 1 + \frac{5}{2}\phi$	Batchelor and Green (1972) and (Batchelor 1977) $\eta_s = 1 + \frac{5}{2}\phi + 6.2\phi^2$	Krieger and Dougherty (1959) $\eta_s = (1 - \phi/\phi_c)^{-[\eta]\phi_c}$ Eilers (1941) $\eta_s = \left(1 + \frac{[\eta]}{2}\frac{\phi}{1-\phi/\phi_c}\right)^2$ Mooney (1951) $\eta_s = \exp\left(\frac{[\eta]\phi}{1-\phi/\phi_c}\right)$

$$\lim_{\phi\to\phi_c} \eta_s = +\infty$$

Table 2.6: Relative viscosity of granular suspensions in different ϕ-regimes. We define $[\eta] = \lim_{\phi\to 0} \frac{\eta_s - 1}{\phi} = 2.5$ the intrinsic viscosity of the suspension.

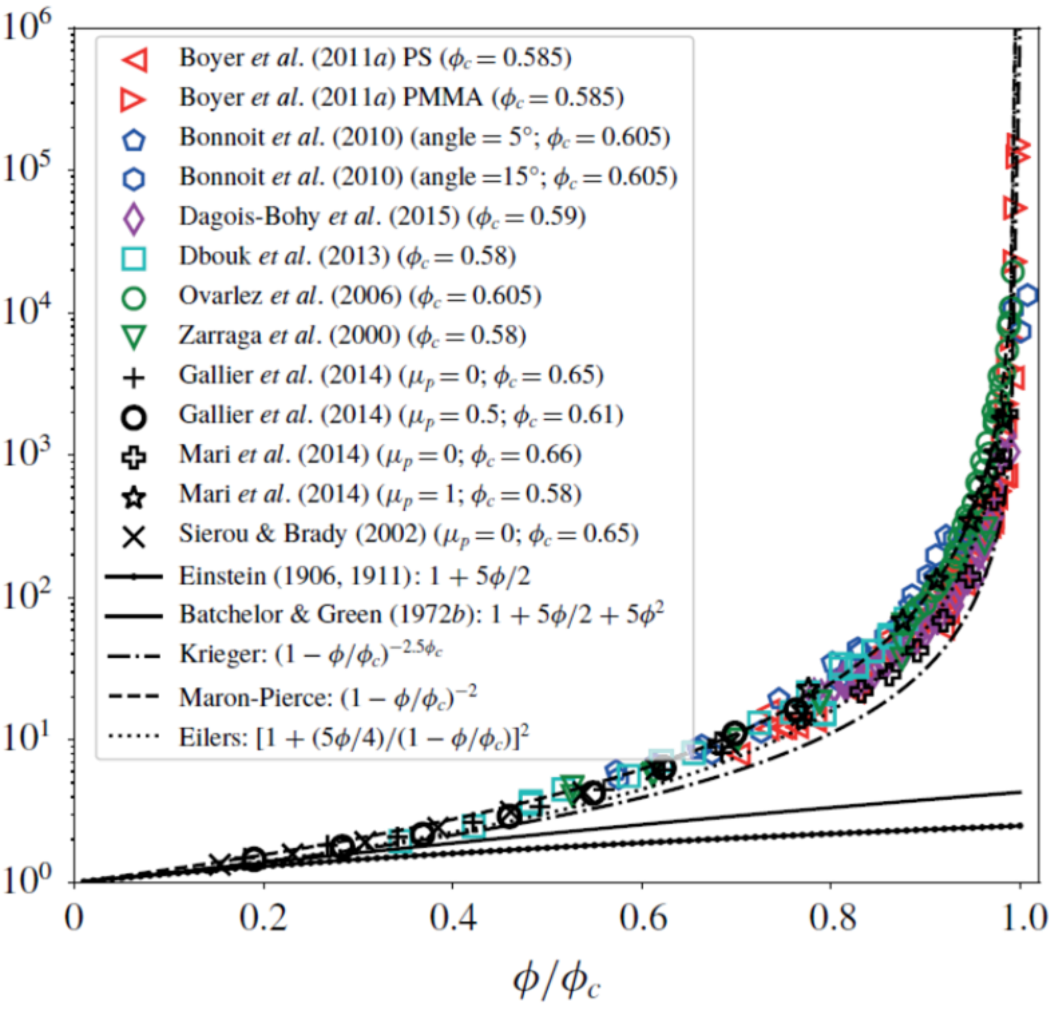


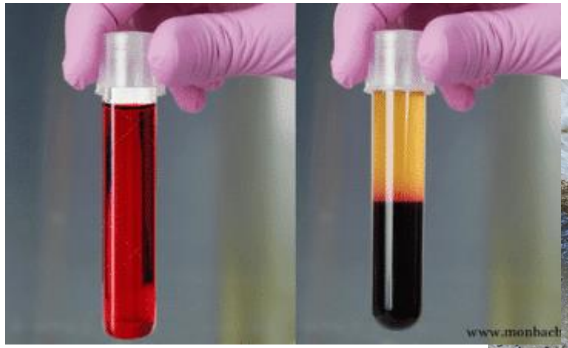
(a)
Boyer et al. (2011a) PS
Boyer et al. (2011a) PMMA
Bonnoit et al. (2010) (angle = 5°)
Bonnoit et al. (2010) (angle = 15°)
Dagois-Bohy et al. (2015)
Dbouk et al. (2013)
Ovarlez et al. (2006) (MRI)
Zarraga et al. (2000) (3 different fluids)
Gallier et al. (2014) ($\mu_p = 0$)
Gallier et al. (2014) ($\mu_p = 0.5$)
Mari et al. (2014) ($\mu_p = 0$)
Mari et al. (2014) ($\mu_p = 1$)
Sierou & Brady (2002) ($\mu_p = 0$)
Einstein (1906, 1911): $1 + 5\phi/2$
Batchelor & Green (1972b): $1 + 5\phi/2 + 5\phi^2$
η_s
10^0
10^1
10^2
10^3
10^4
10^5
10^6
0
0.1
0.2
0.3
0.4
0.5
0.6
ϕ

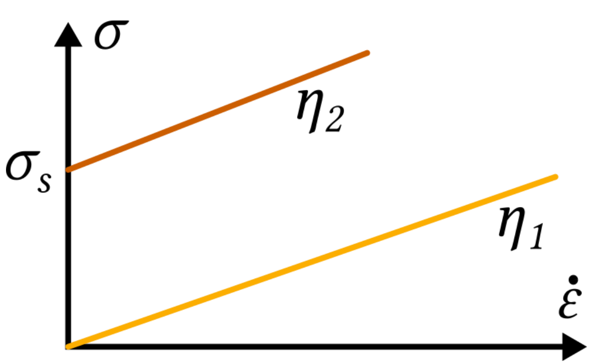


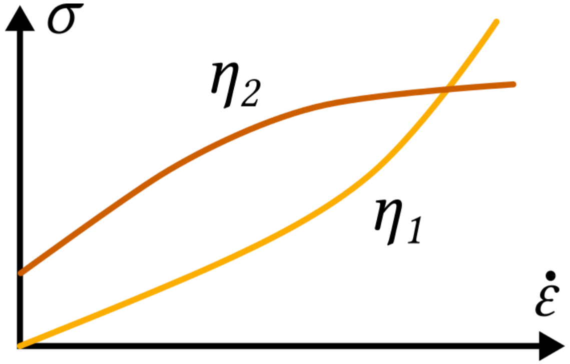
10^6
10^5
10^4
10^3
10^2
10^1
10^0
Boyer *et al.* (2011*a*) PS ($\phi_c = 0.585$)
Boyer *et al.* (2011*a*) PMMA ($\phi_c = 0.585$)
Bonnoit *et al.* (2010) (angle = 5°; $\phi_c = 0.605$)
Bonnoit *et al.* (2010) (angle = 15°; $\phi_c = 0.605$)
Dagois-Bohy *et al.* (2015) ($\phi_c = 0.59$)
Dbouk *et al.* (2013) ($\phi_c = 0.58$)
Ovarlez *et al.* (2006) ($\phi_c = 0.605$)
Zarraga *et al.* (2000) ($\phi_c = 0.58$)
Gallier *et al.* (2014) ($\mu_p = 0$; $\phi_c = 0.65$)
Gallier *et al.* (2014) ($\mu_p = 0.5$; $\phi_c = 0.61$)
Mari *et al.* (2014) ($\mu_p = 0$; $\phi_c = 0.66$)
Mari *et al.* (2014) ($\mu_p = 1$; $\phi_c = 0.58$)
Sierou & Brady (2002) ($\mu_p = 0$; $\phi_c = 0.65$)
Einstein (1906, 1911): $1 + 5\phi/2$
Batchelor & Green (1972*b*): $1 + 5\phi/2 + 5\phi^2$
Krieger: $(1 - \phi/\phi_c)^{-2.5\phi_c}$
Maron-Pierce: $(1 - \phi/\phi_c)^{-2}$
Eilers: $[1 + (5\phi/4)/(1 - \phi/\phi_c)]^2$
0
0.2
0.4
0.6
0.8
1.0
ϕ/ϕ_c

Taille des particules et taux de cisaillement

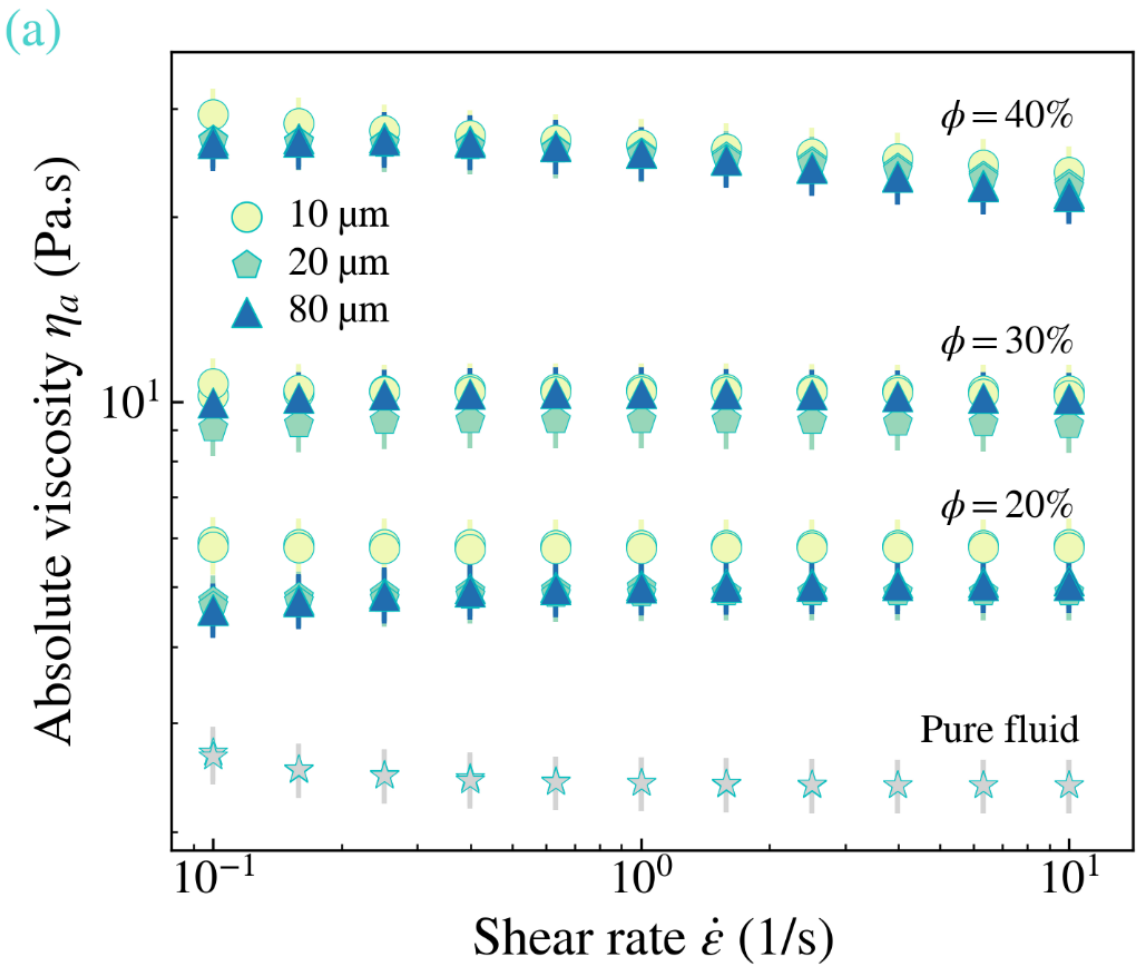


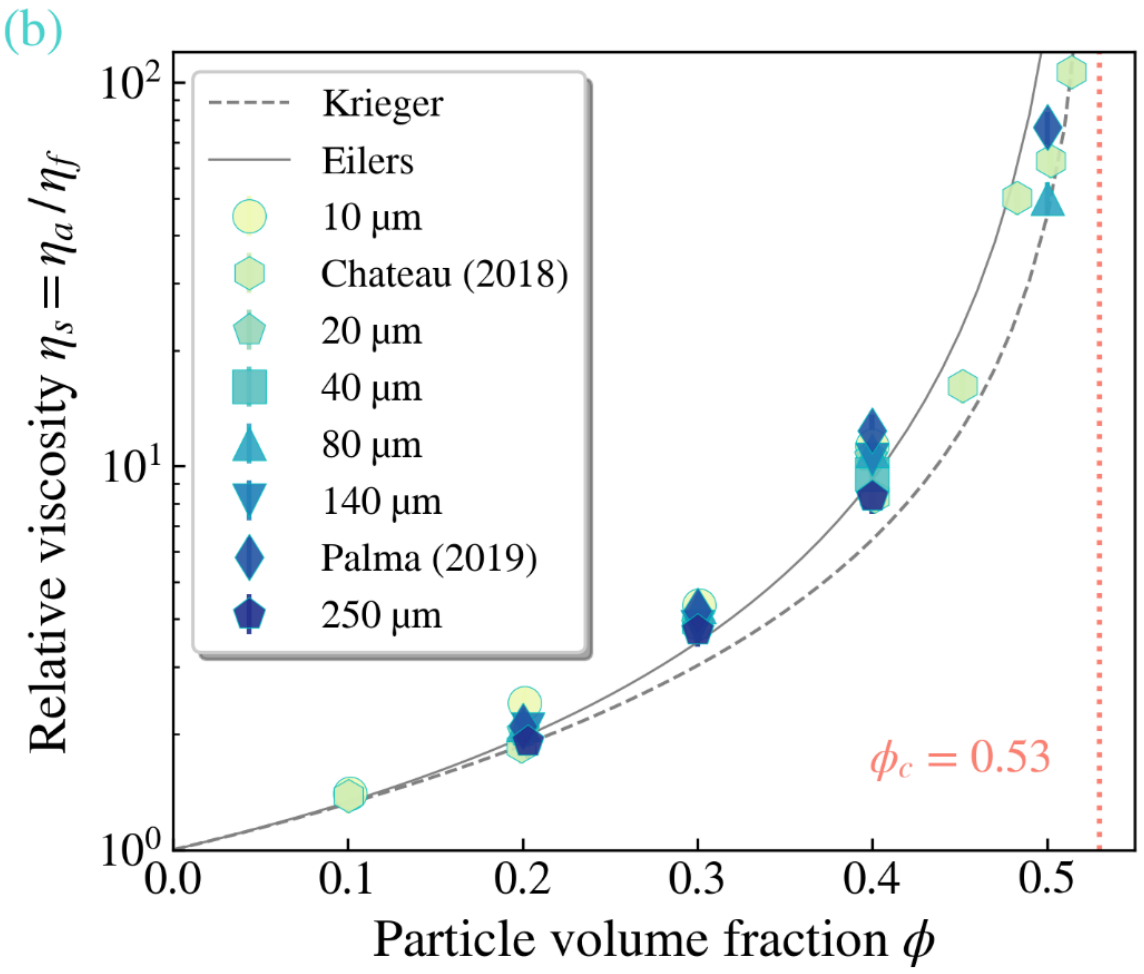






Taille des particules et taux de cisaillement





ECOULEMENTS CAPILLAIRES DE SUSPENSIONS GRANULAIRES

Ecoulements capillaires

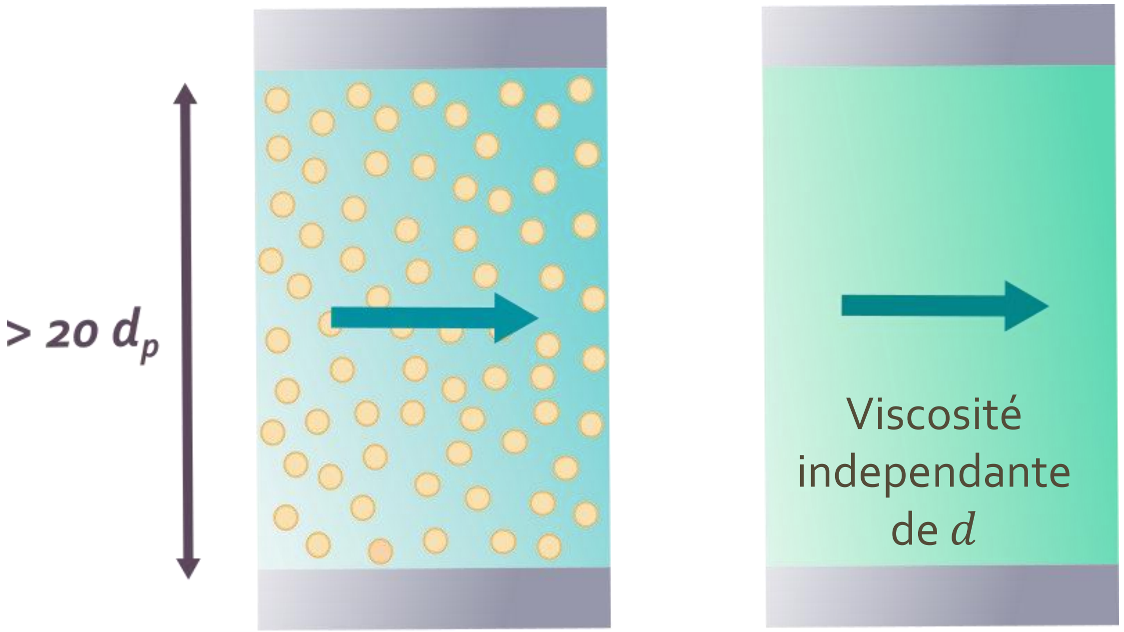
Tension de surface γ

- Interface libre
- "Petit" → Longueur capillaires

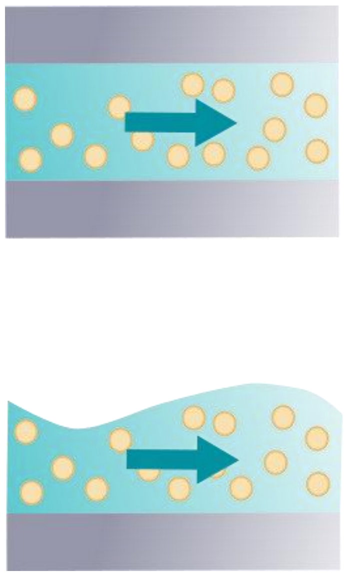
$$\ell_c = \sqrt{\frac{\gamma}{\rho g}} \sim 1\ \mathrm{mm}$$

Confinement de suspensions granulaires

Suspension de volume ~ milieu continu

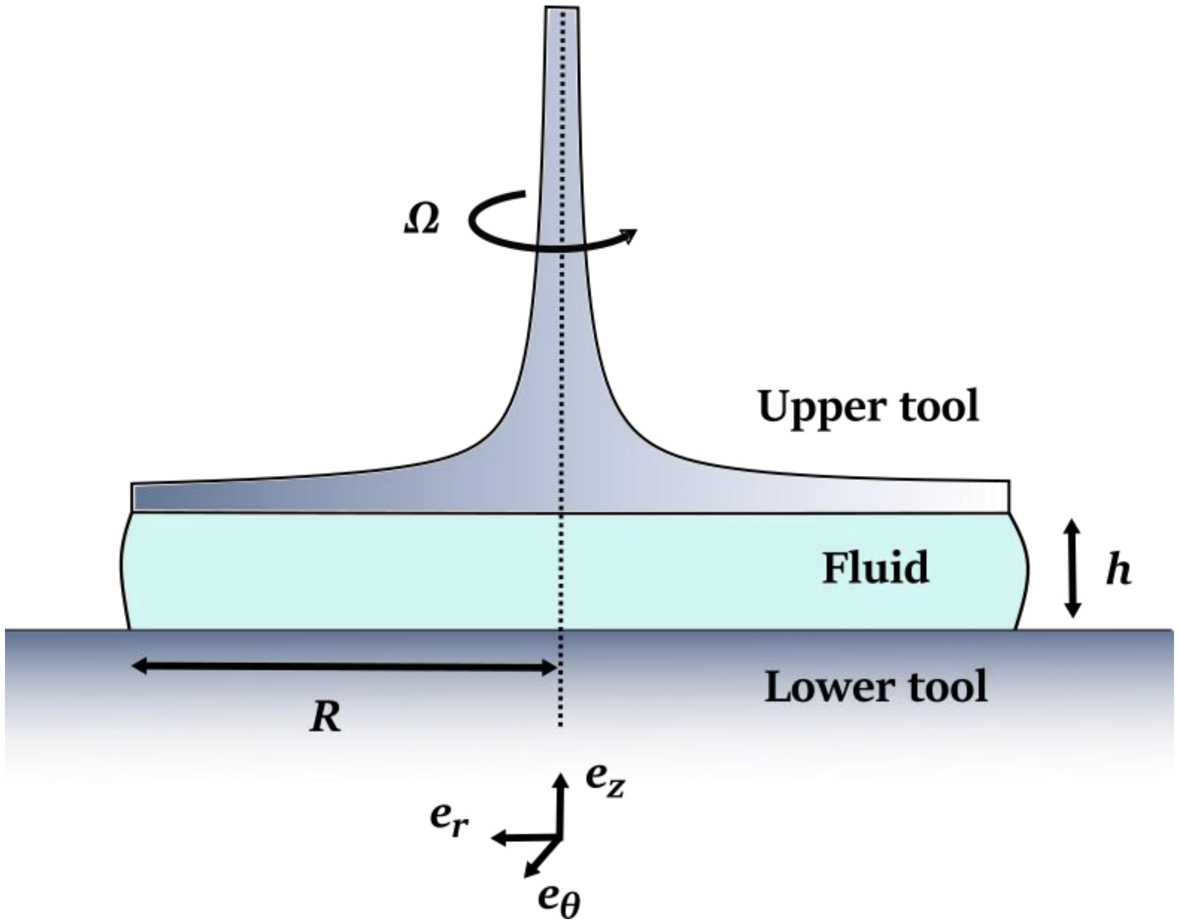


Confinement ~ Effets de taille finie des particules

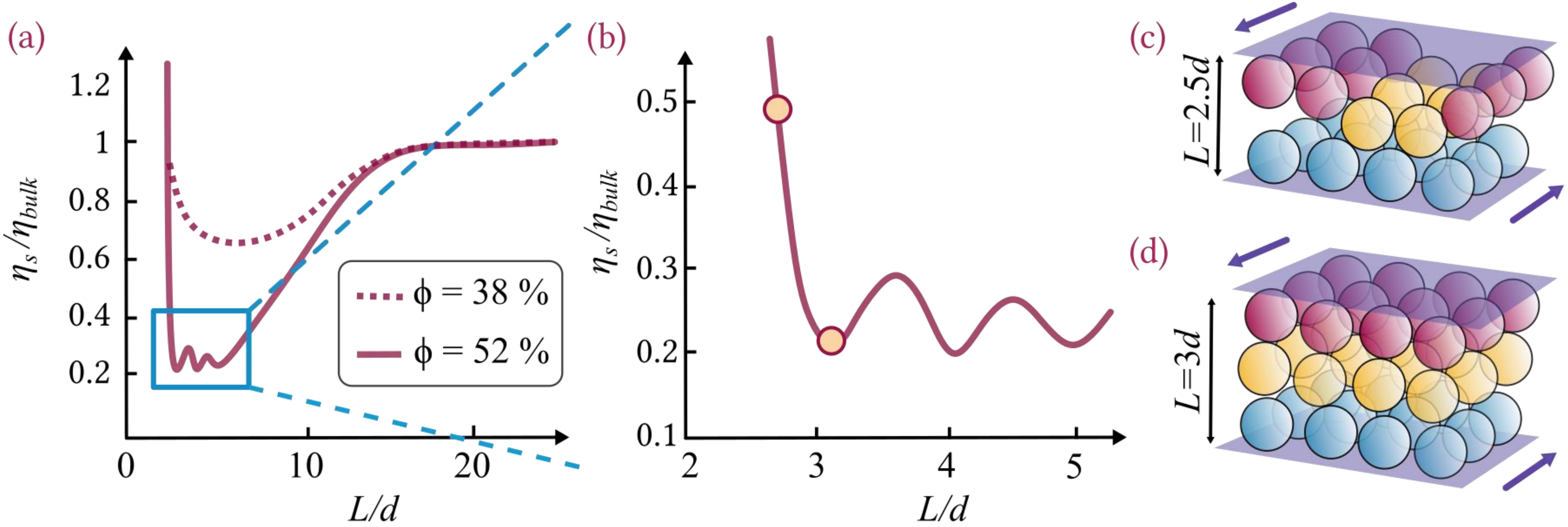


- Viscosity of confined suspensions?
- Interaction between particles and a free surface?
- Effect of the particles on surface instability?

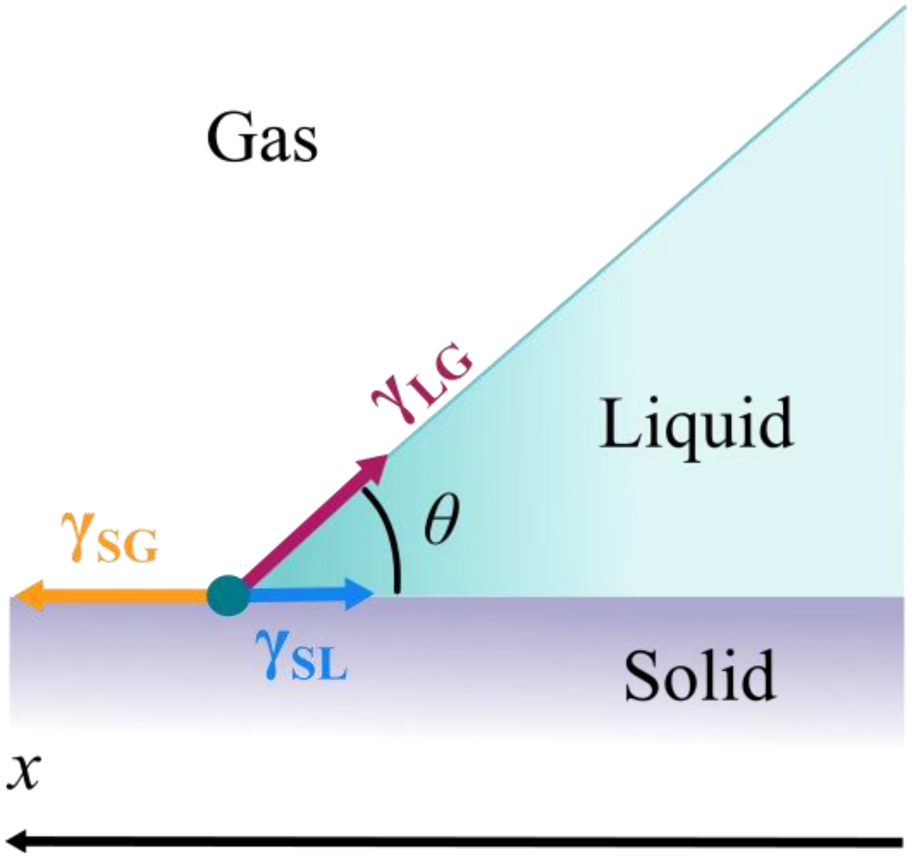
Mesure de viscosité confinée



Viscosité de suspension confinée

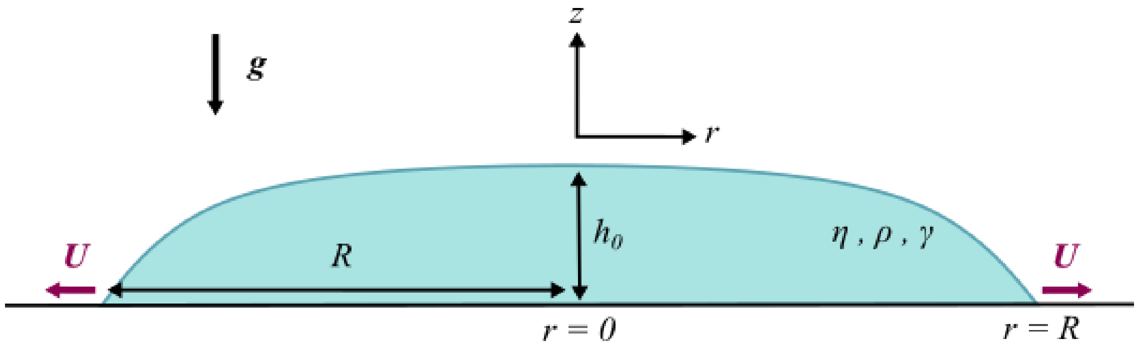


Mouillage d'un solide

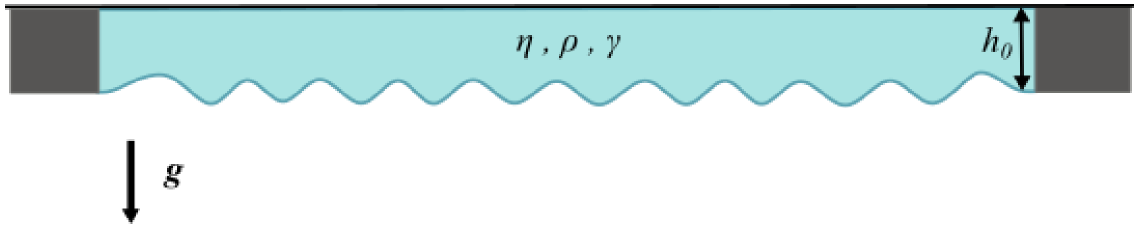


Projects

Drop spreading



Rayleigh-Taylor instability of thin films



Do particles affect drop spreading or the Rayleigh-Taylor instability?