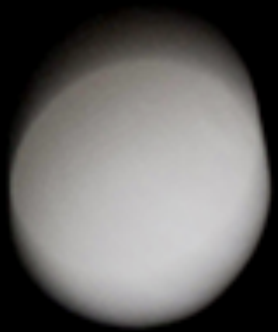
BLENDING LIQUID AND GRAINS

ACCRETION DYNAMICS ON WET GRANULAR MATERIALS

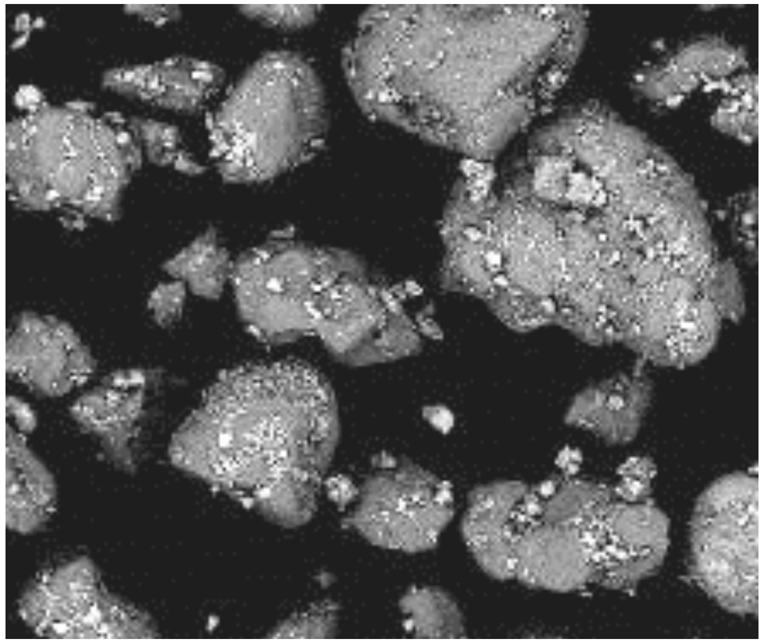


Alban SAURET
Guillaume SAINGIER, Pierre JOP

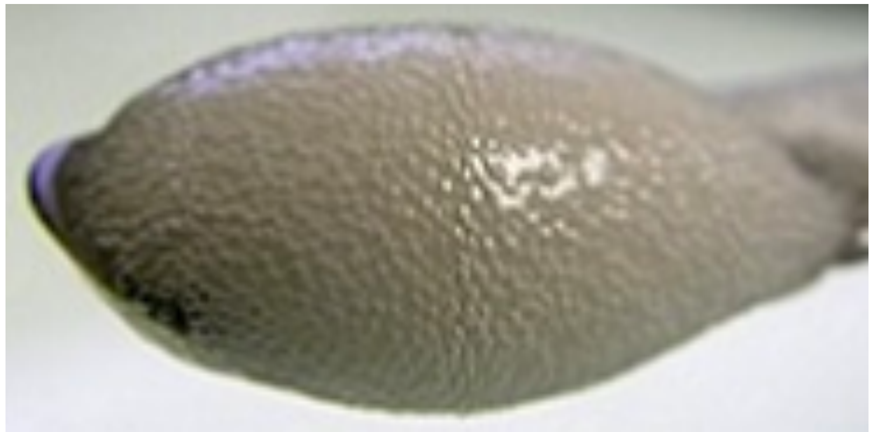
SVI, CNRS/Saint-Gobain

INDUSTRIAL PROCESSES : GRAINS AND SUSPENSIONS

Building materials: cement, concrete, mortars, plasters

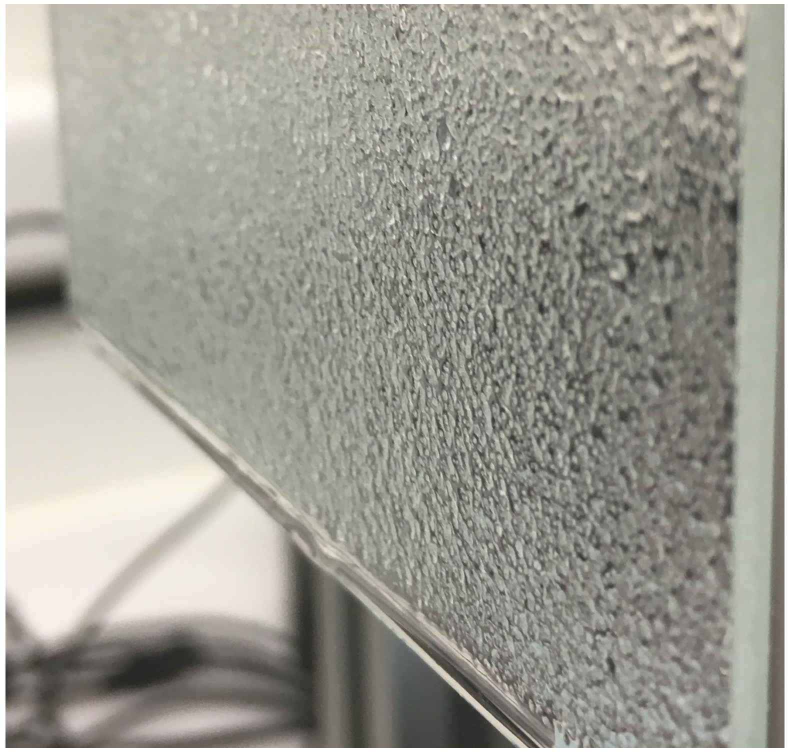


Suspensions of bubbles in yield stress fluids

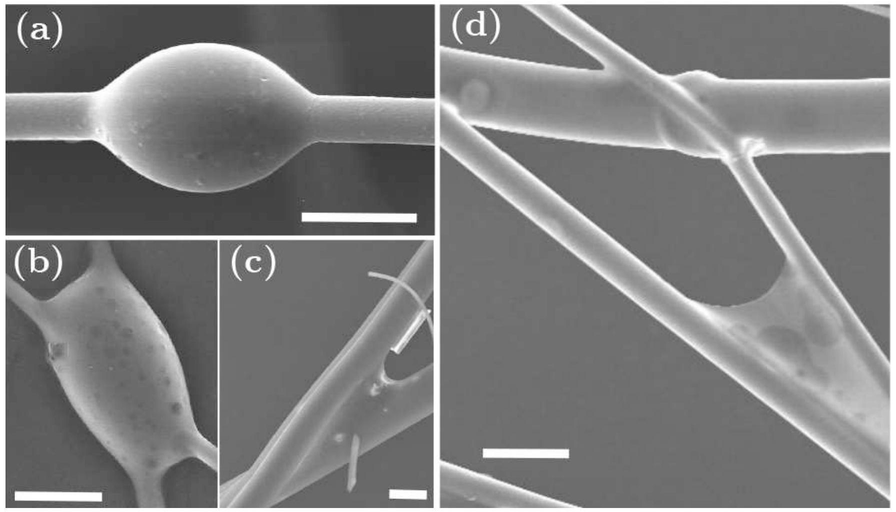


e.g. L. Ducloué, O. Pitois, J. Goyon, X. Chateau, & G. Ovarlez, J. non-Newton. Fluid Mech. (2015).

Glass and substrates



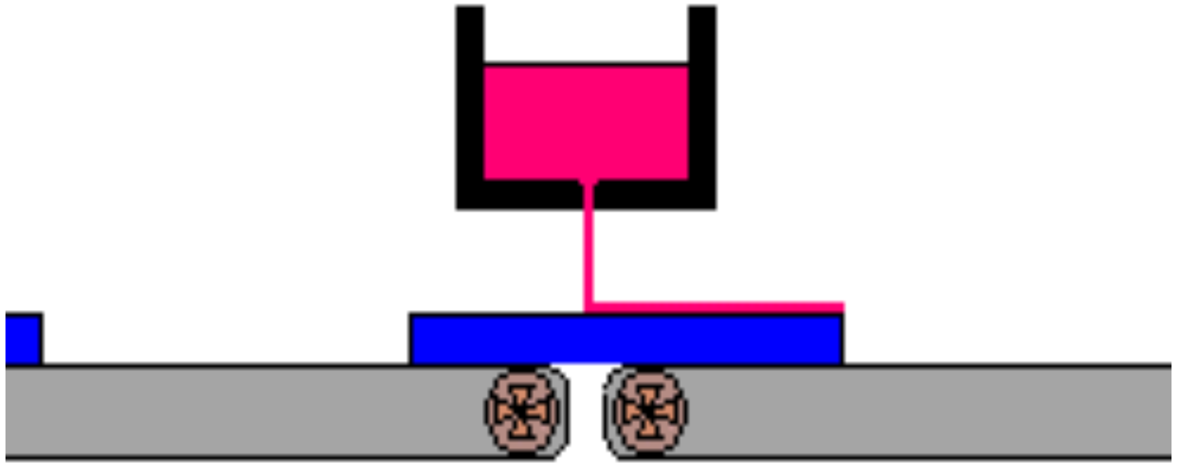
Glass wool: fibers

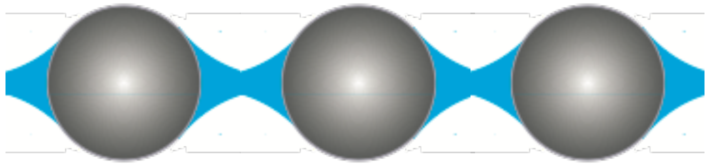


A. Sauret, F. Boulogne, E. Dressaire & H.A. Stone, EPJE (2015)

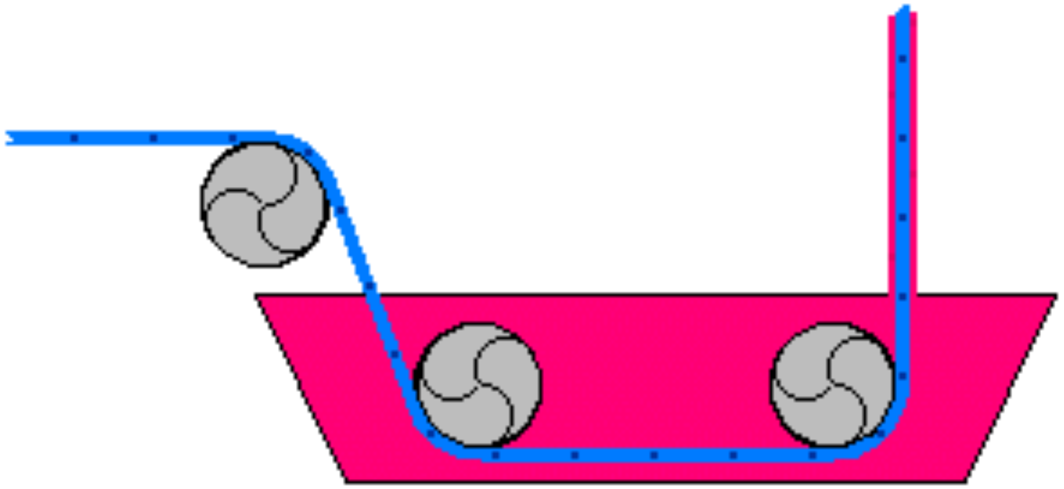
INDUSTRIAL PROCESSES : WET COATING

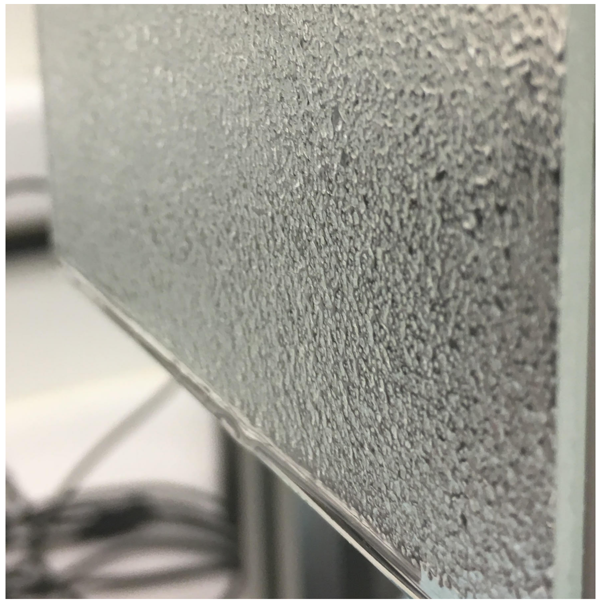
Liquid curtain



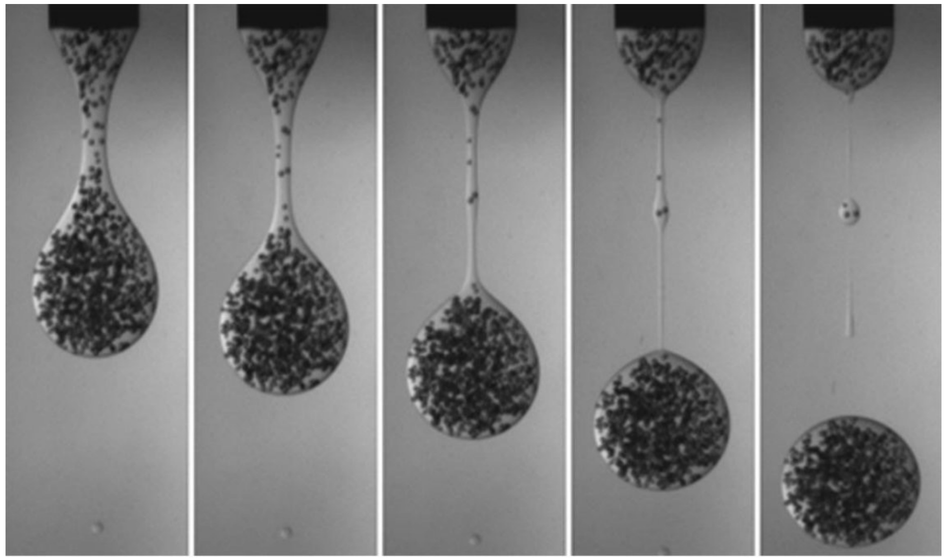


Dip-coating

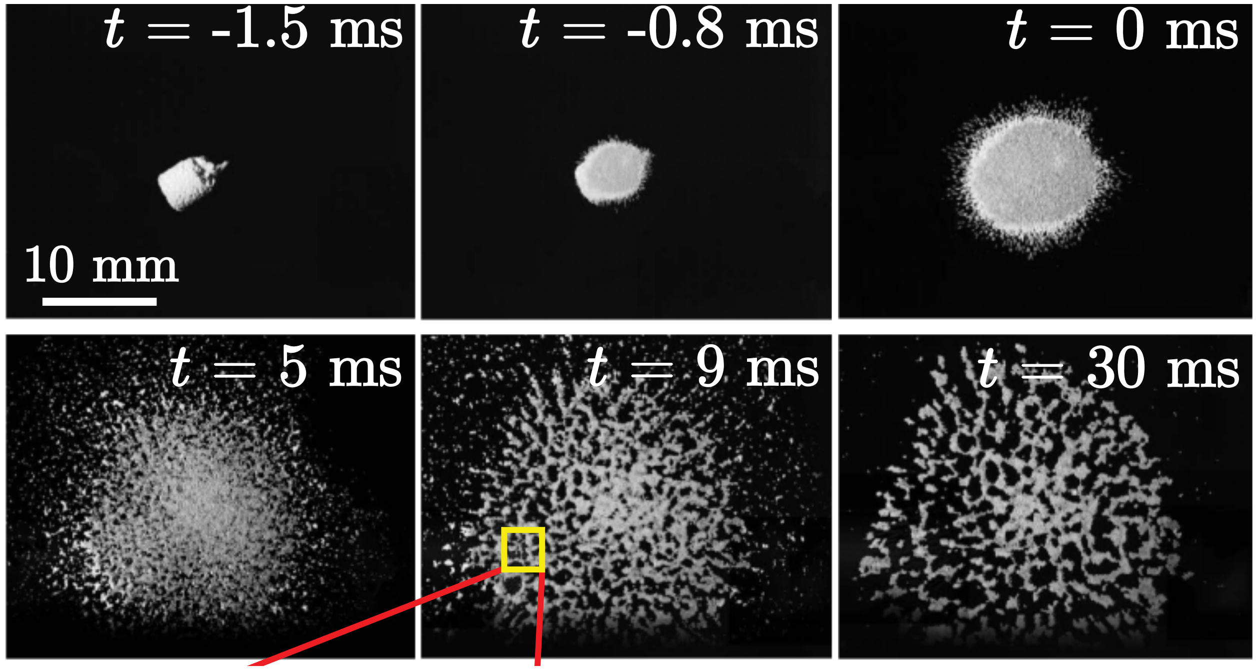




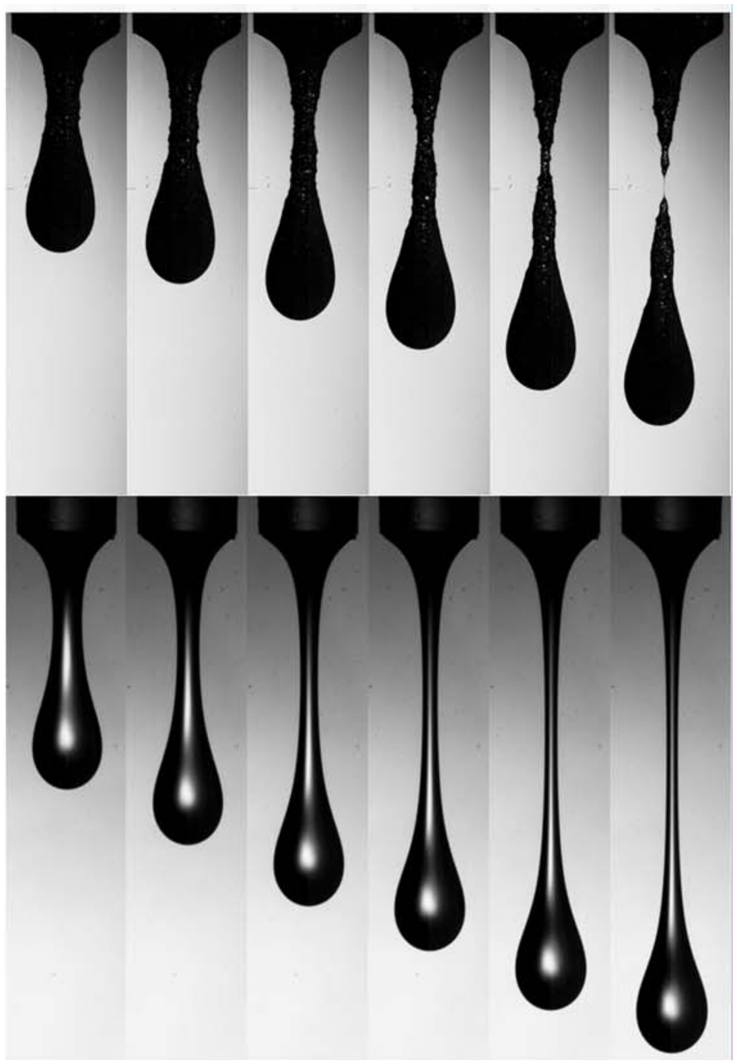
INTERFACIAL EFFECTS IN SUSPENSIONS



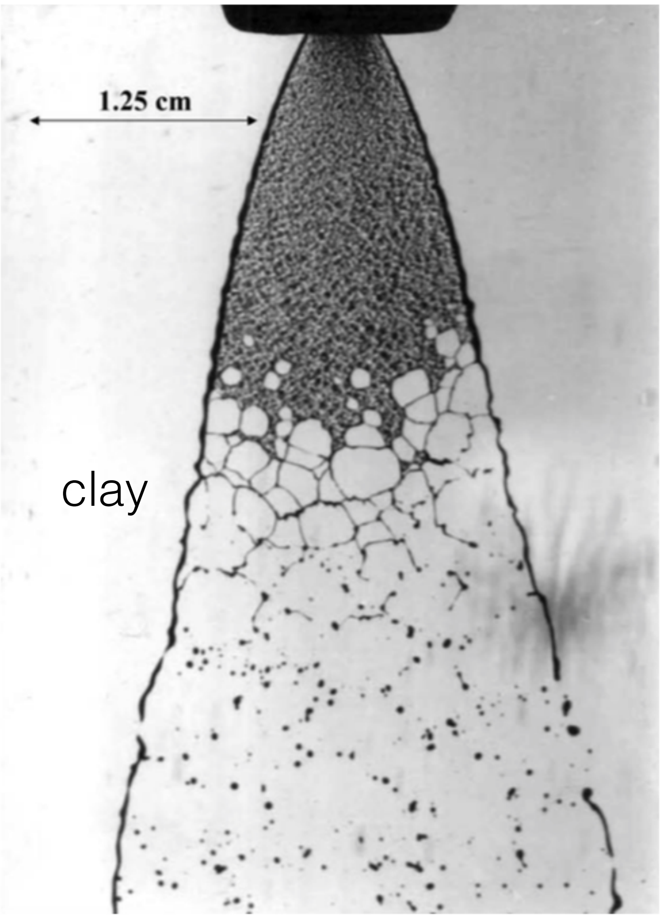
Furbank & Morris, Phys. Fluids (2004)



Lubbers *et al.*, Phys. Rev. Lett. (2014)



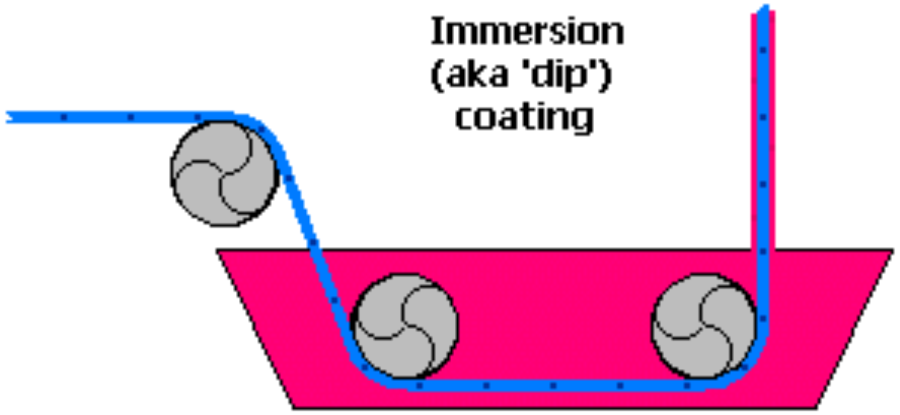
Bonnoit *et al.*, Phys. Fluids (2012)



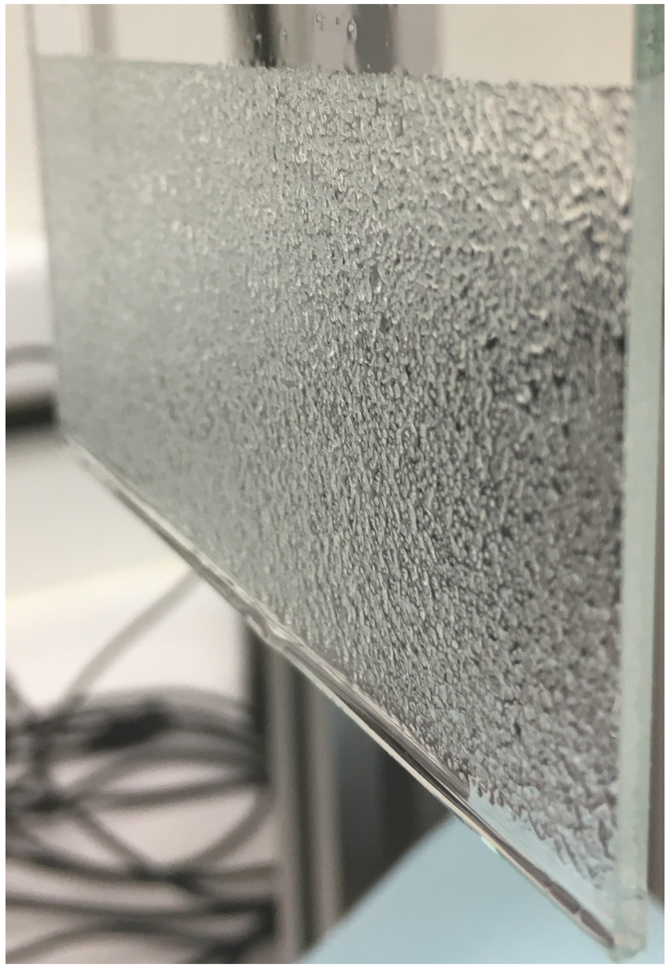
Addo-Yobo et al.,
AIChE (2010)

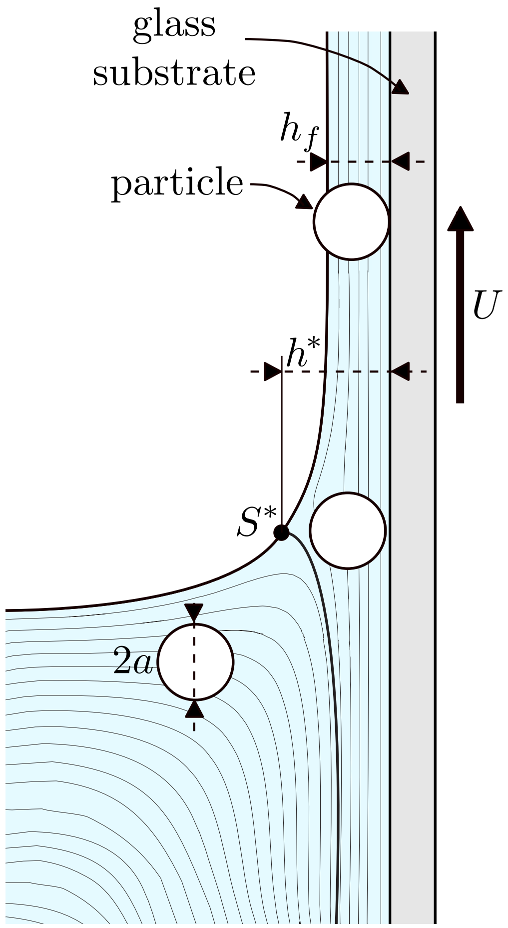
Buchanan *et al.*,
Langmuir (2007)

DIP COATING

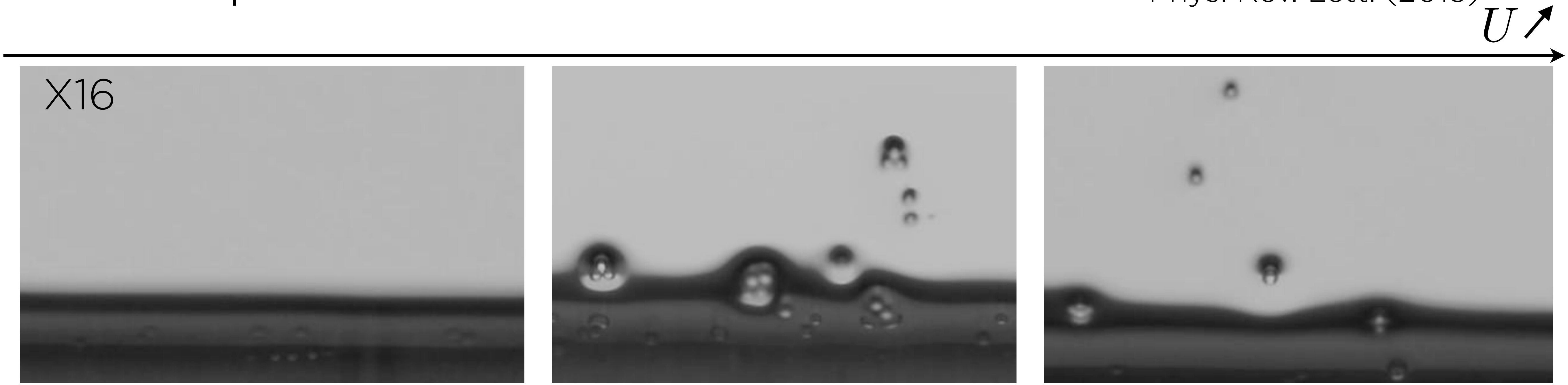


Presence of particles during coating processes ?





Colosqui et al., Phys. Rev. Lett. (2013)

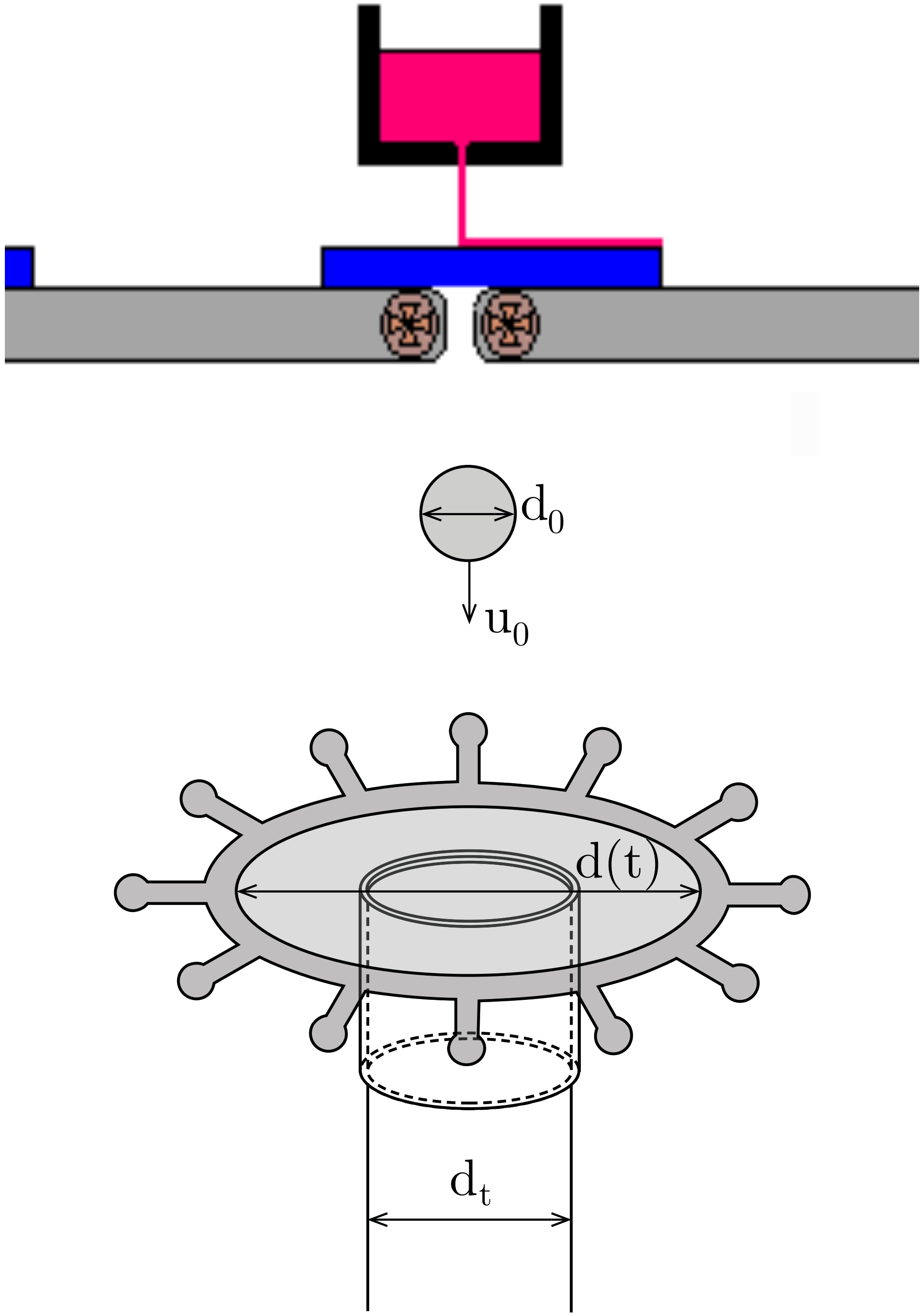


$U = 7.3\,\mu\text{m/s}$
$h = 14\,\mu\text{m}$

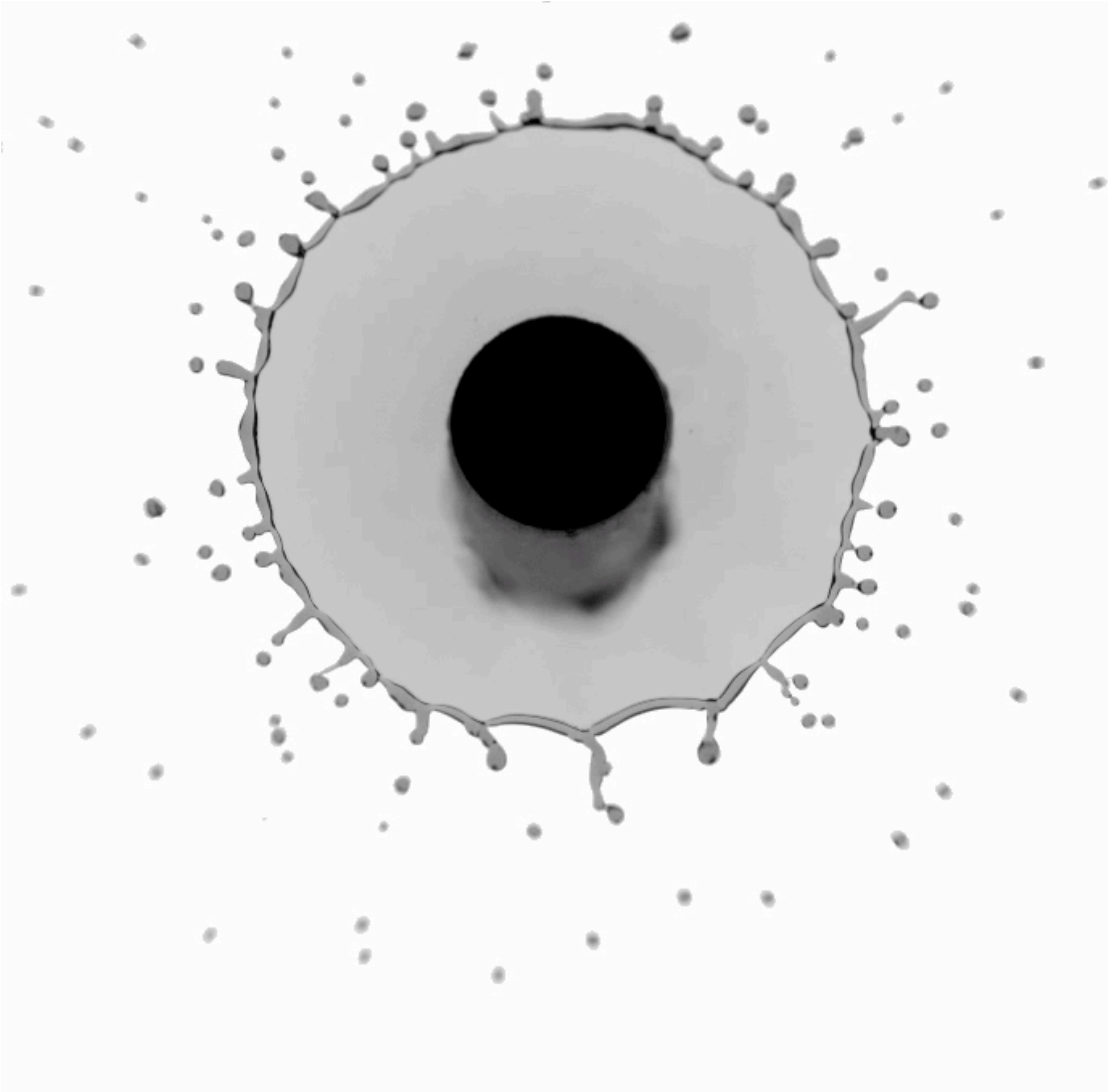
$U = 17\,\mu\text{m/s}$
$h = 24\,\mu\text{m}$

$U = 36\,\mu\text{m/s}$
$h = 40\,\mu\text{m}$

LIQUID CURTAIN

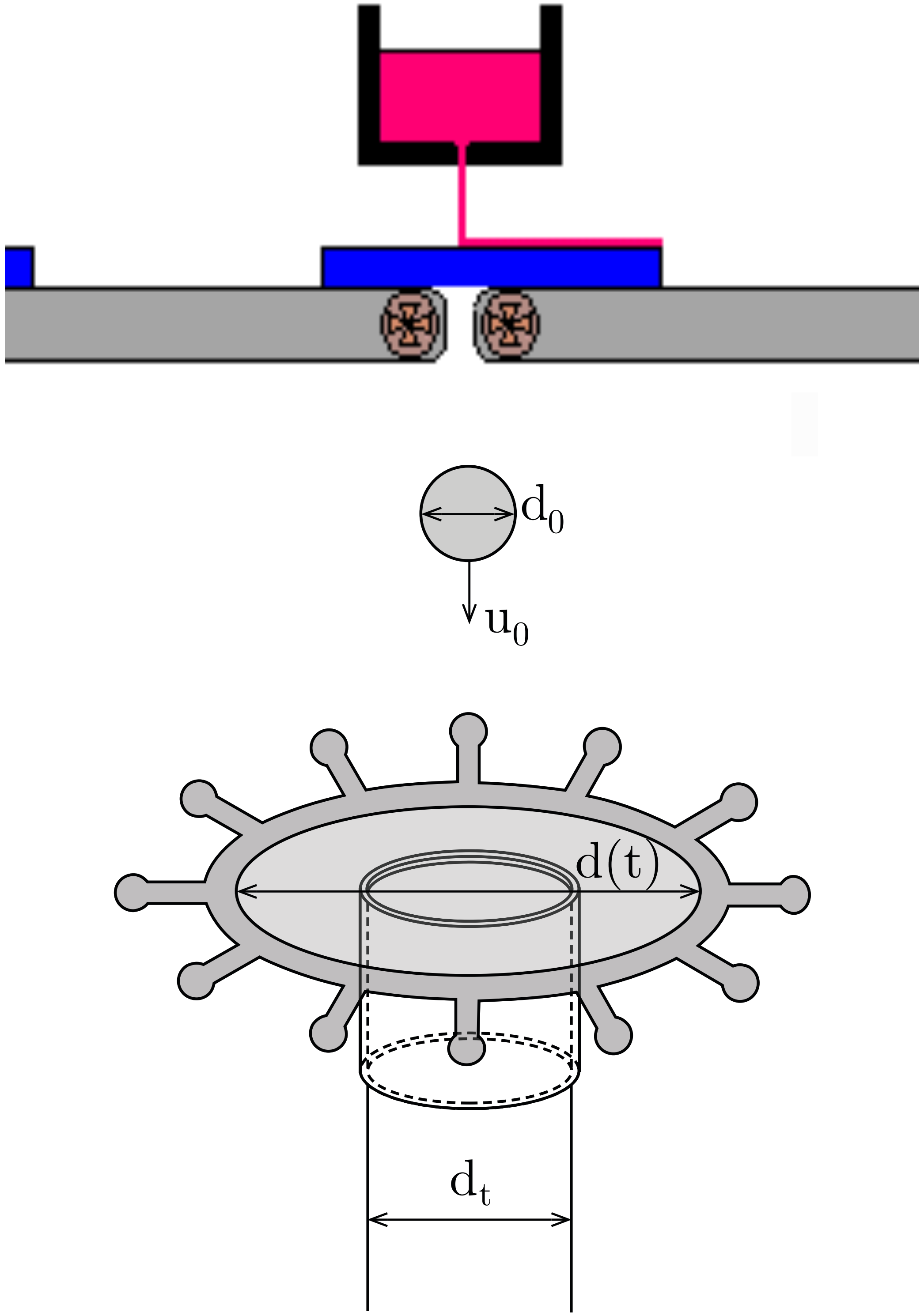


Bossa & Villermaux, JFM (2011)
Vernay et al., PRL (2015)

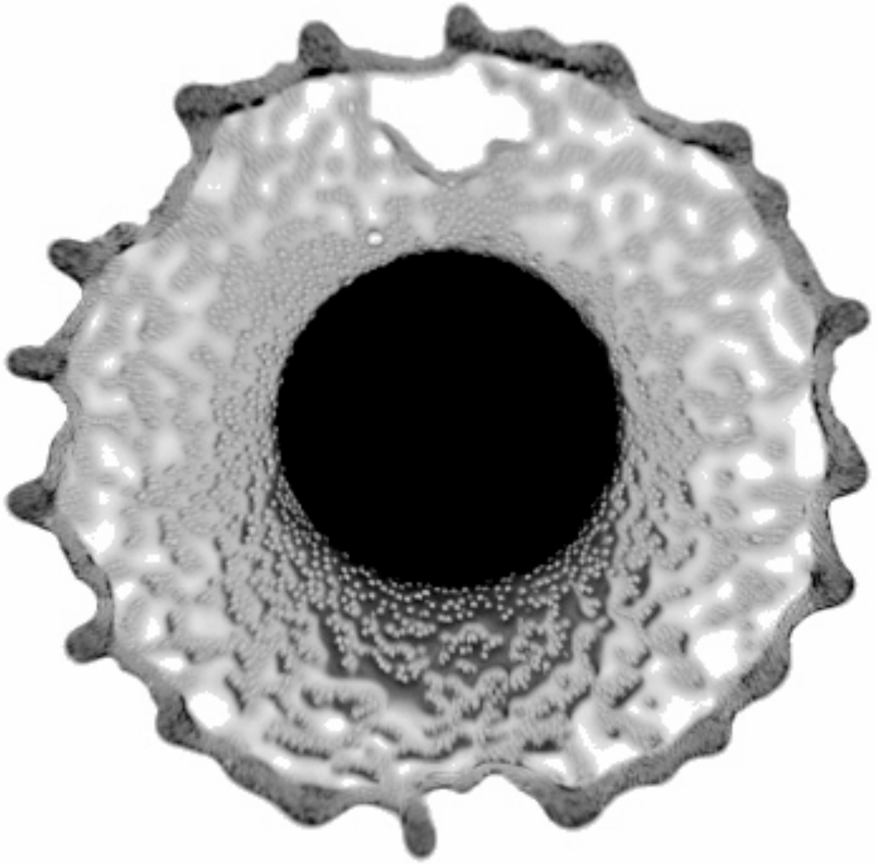


duration: 15 ms

LIQUID CURTAIN

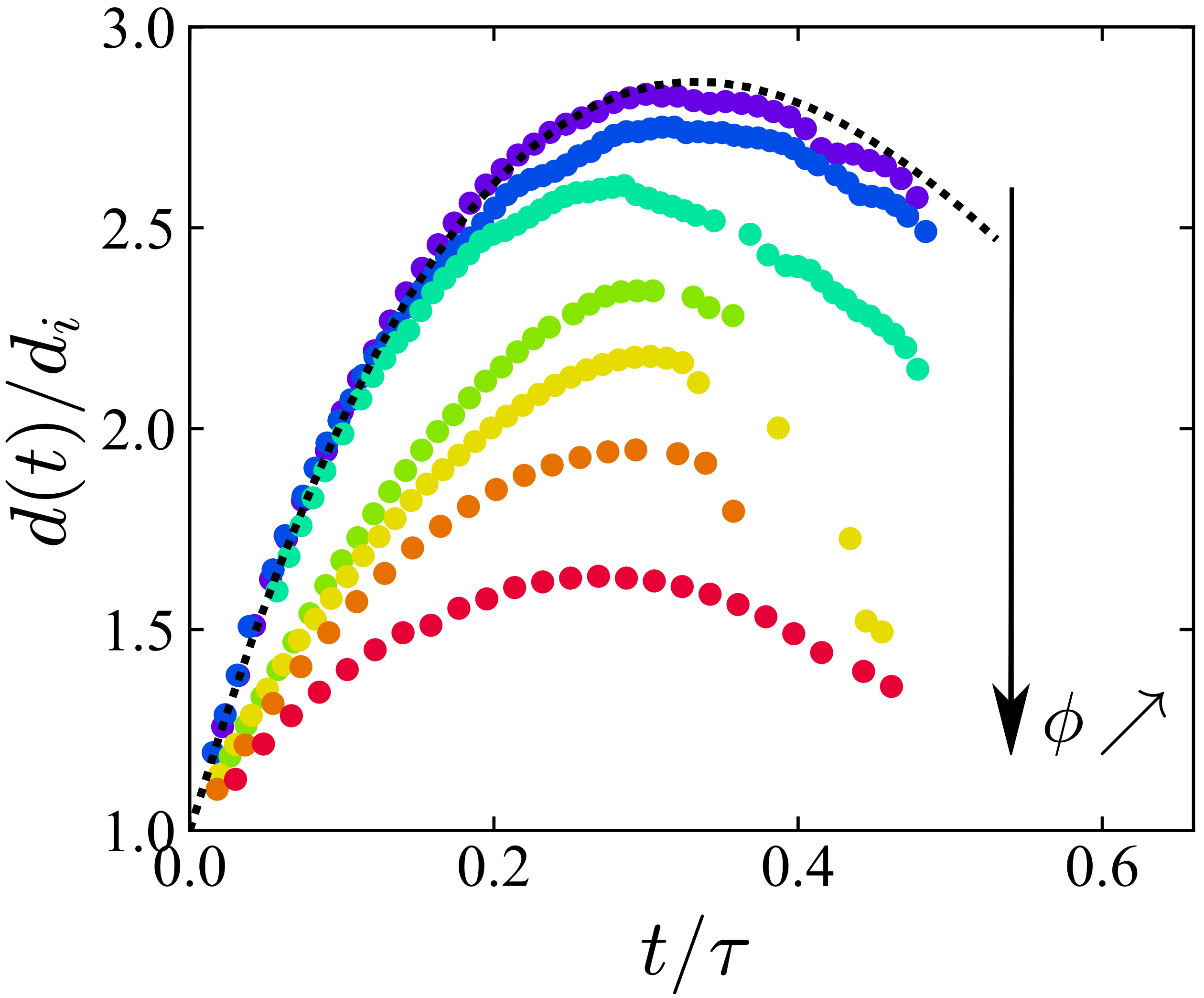


Bossa & Villermaux, JFM (2011)
Vernay et al., PRL (2015)



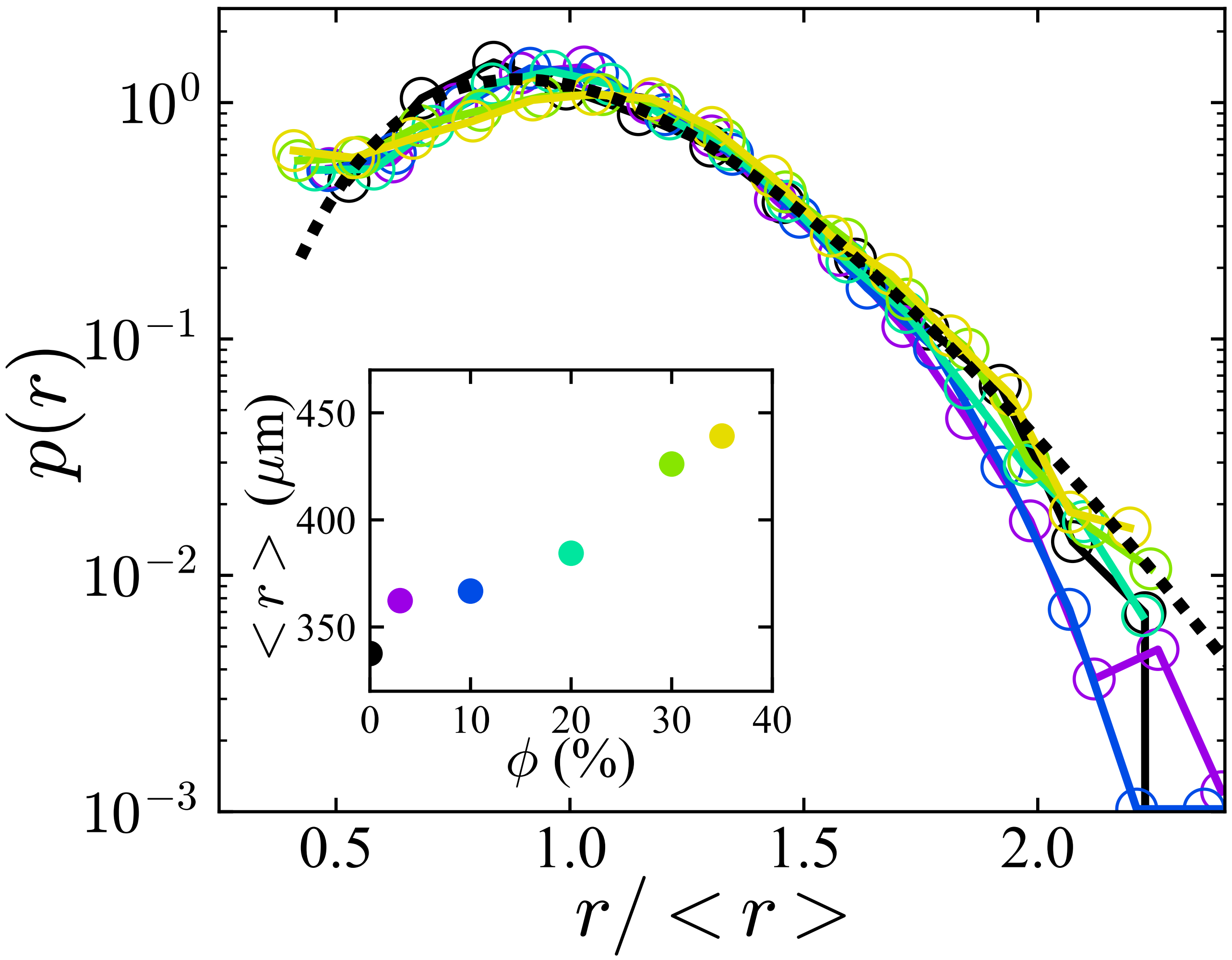
duration: 15 ms

PARTICLE-LADEN LIQUID SHEET



Expansion : captured using the viscosity of the suspension

S. Arora, C. Ligoure, & L. Ramos,
Phys. Rev. Fluids (2016)



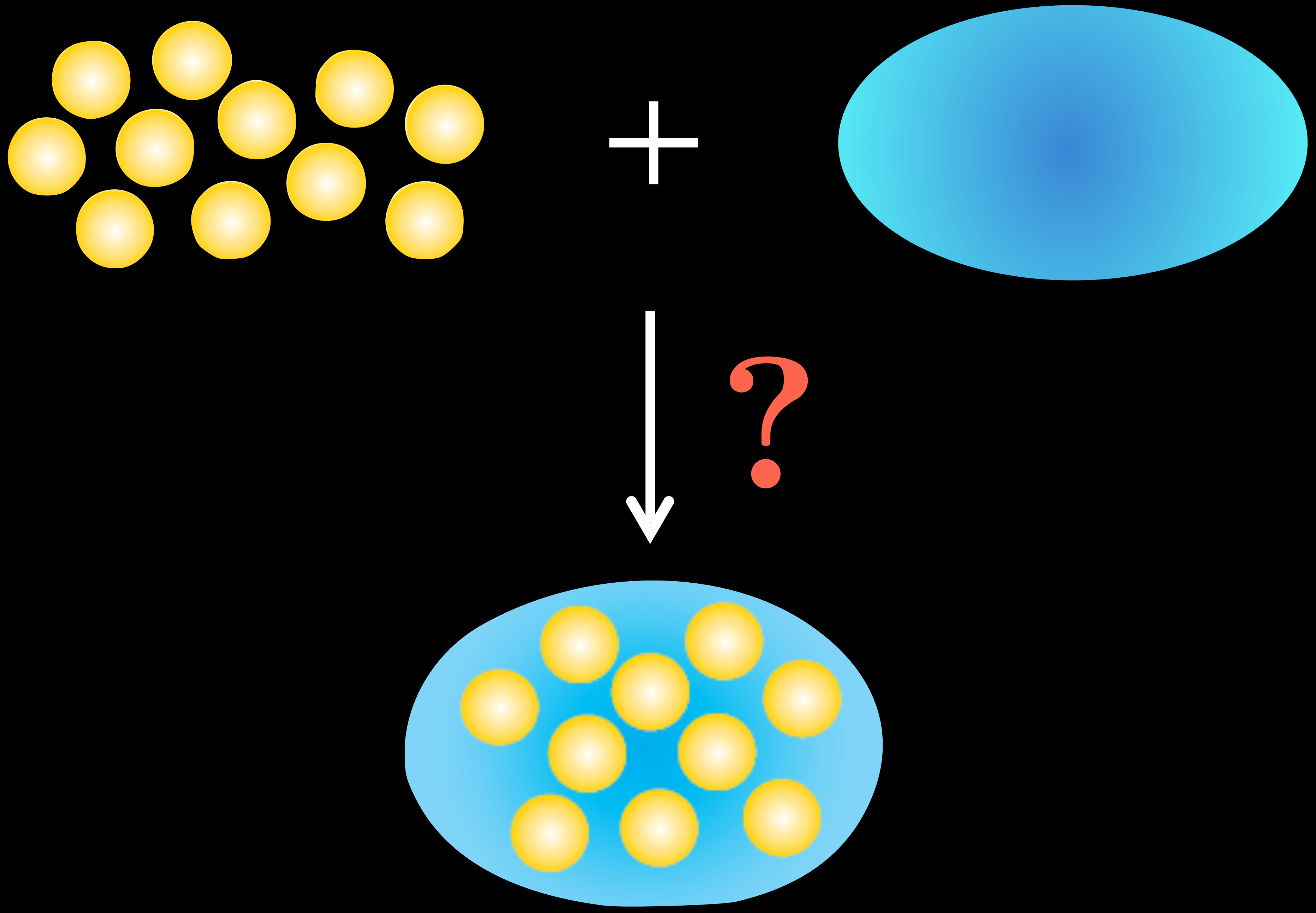
Atomization modified by the formation of clusters

$$\Gamma(n, x = d/\langle d\rangle) = \frac{n^n}{\Gamma(n)}\, x^{n-1}\, \mathrm{e}^{-nx}$$

B. Keshavarz, E. C. Houze, J. R. Moore, M. R. Koerner & G. H. McKinley, Phys. Rev. Lett (2016).

Role of the interfacial effects in suspension flows: Particles modify thin film dynamics through viscous and local effects

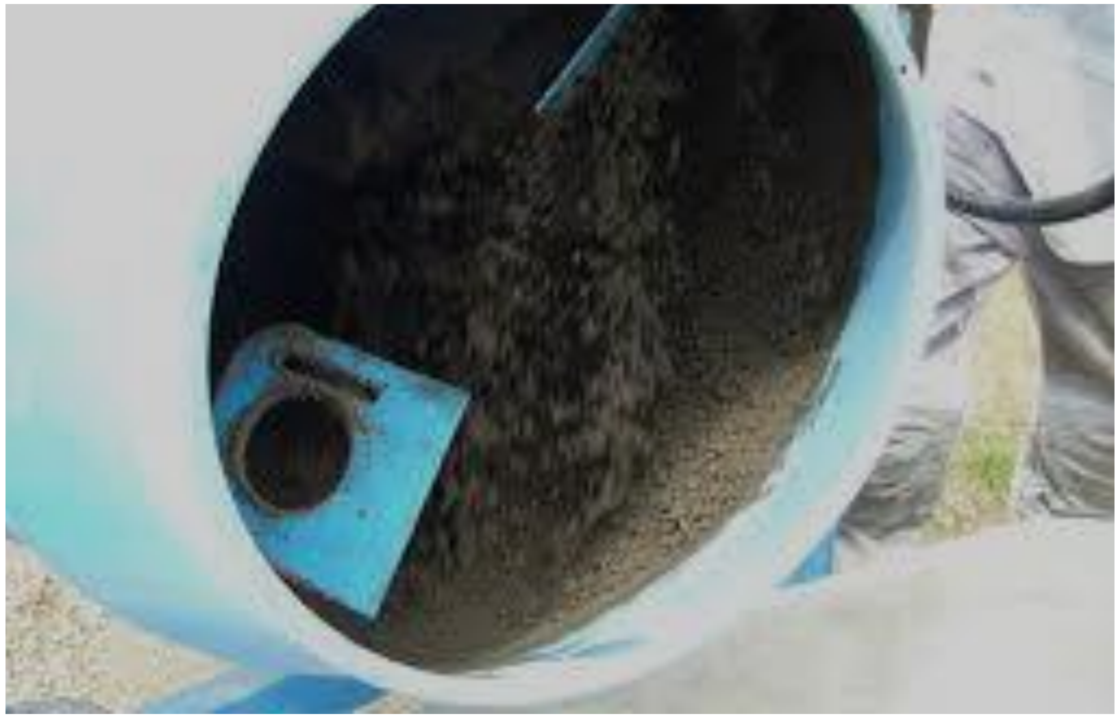
BLENDING LIQUID AND GRAINS

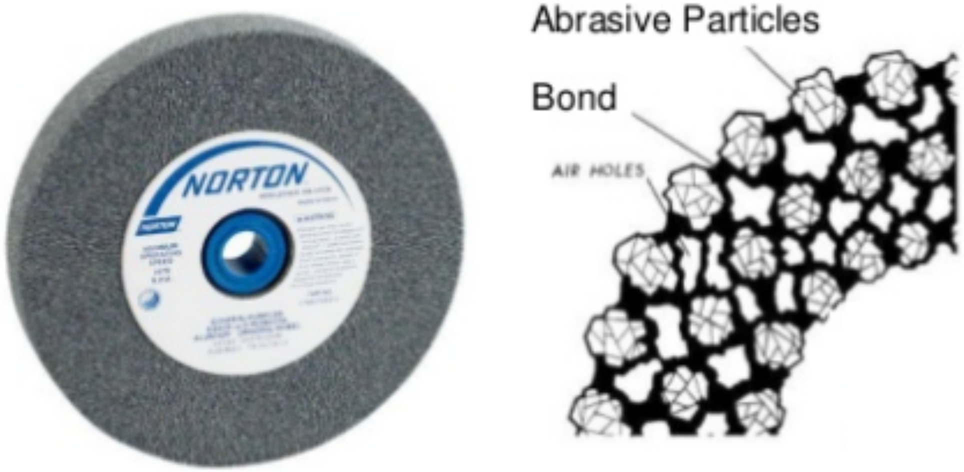


How to prepare a dense suspension or a wet granular media ?

BLENDING LIQUID AND GRAINS


Hydration of plaster


Preparation of mortar



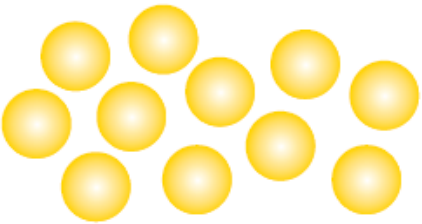
Preparation of adhesive wheels

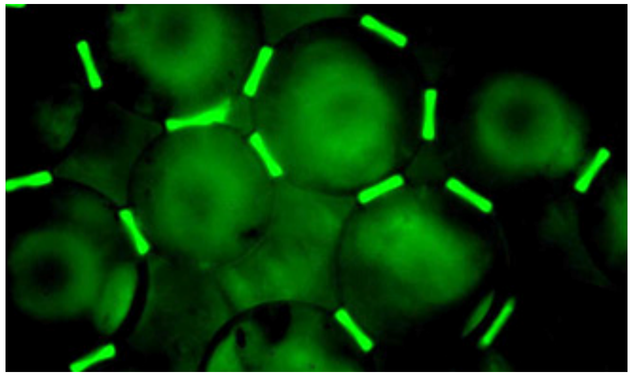

Wet granulation in powder

How to efficiently blend liquid and grains ?

From dry Granular Materials to Suspensions

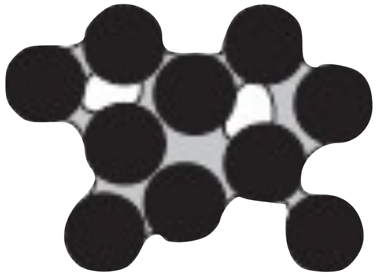
dry state



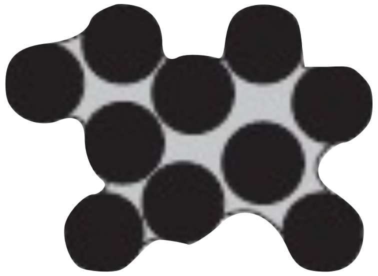


pendular

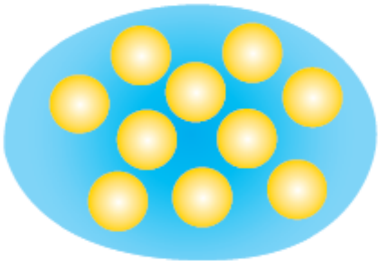
funicular



capillary



Suspension

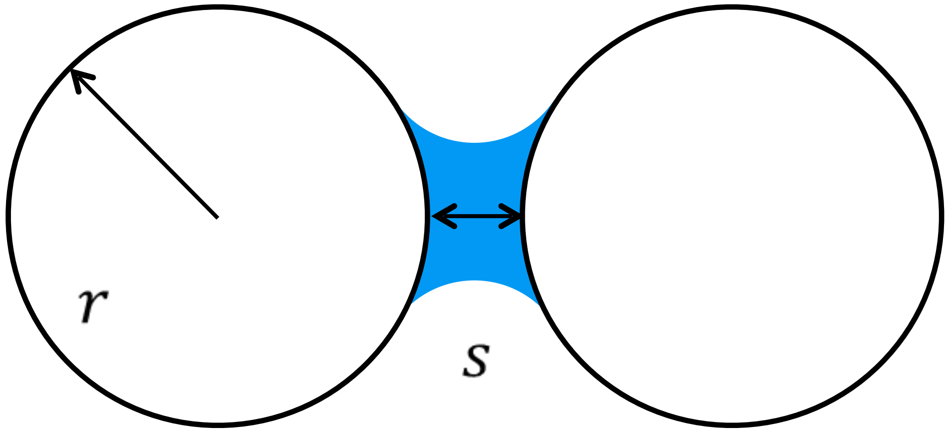


Saturation rate

Moller & Bonn, EPL (2007)

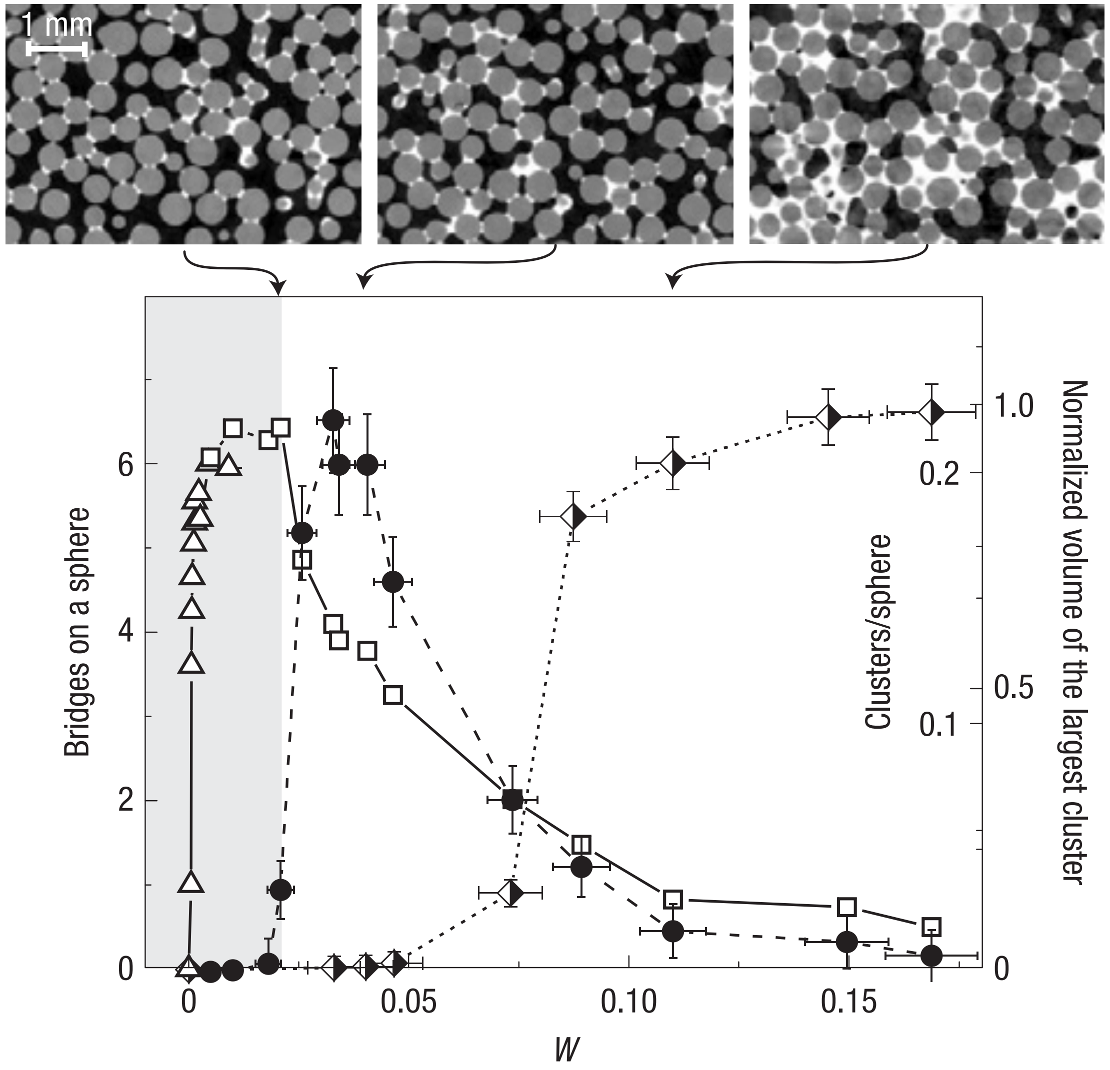
Herminghaus Adv. Phys. (2005)

Mitarai & Nori Adv. Phys. (2006)



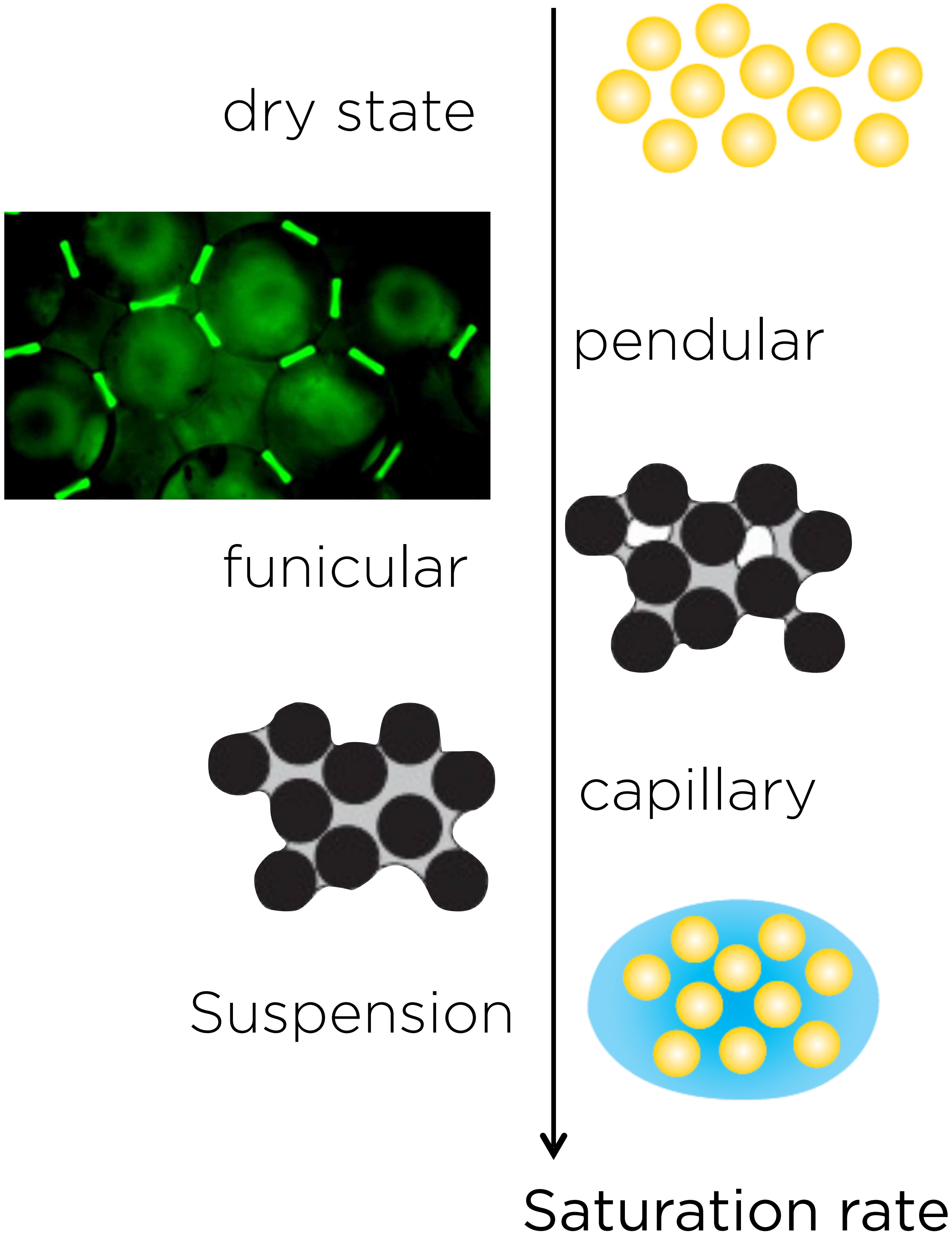
$$F_{cap} = 2\pi\gamma r\cos\theta_c$$

Willett et al., Langmuir (2000)



Scheel et al., Nat. Mater. (2008)

From dry Granular Materials to Suspensions



dry state

pendular

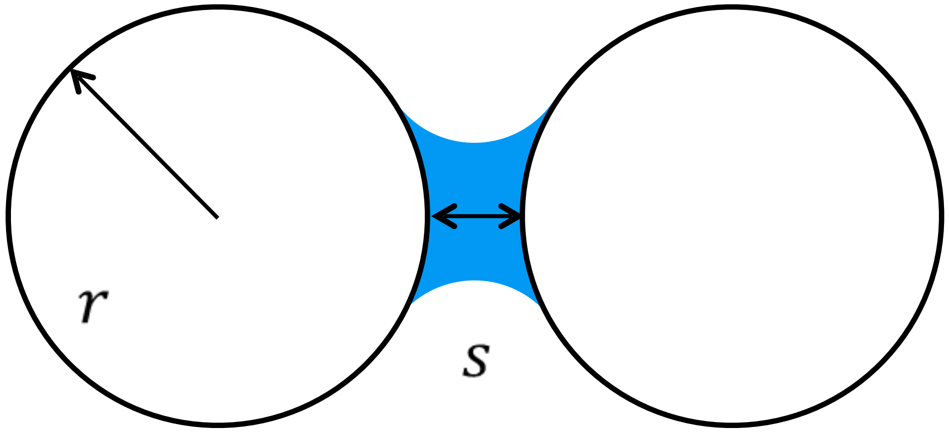
funicular

capillary

Suspension

Saturation rate

Moller & Bonn, EPL (2007)
Herminghaus Adv. Phys. (2005)
Mitarai & Nori Adv. Phys. (2006)

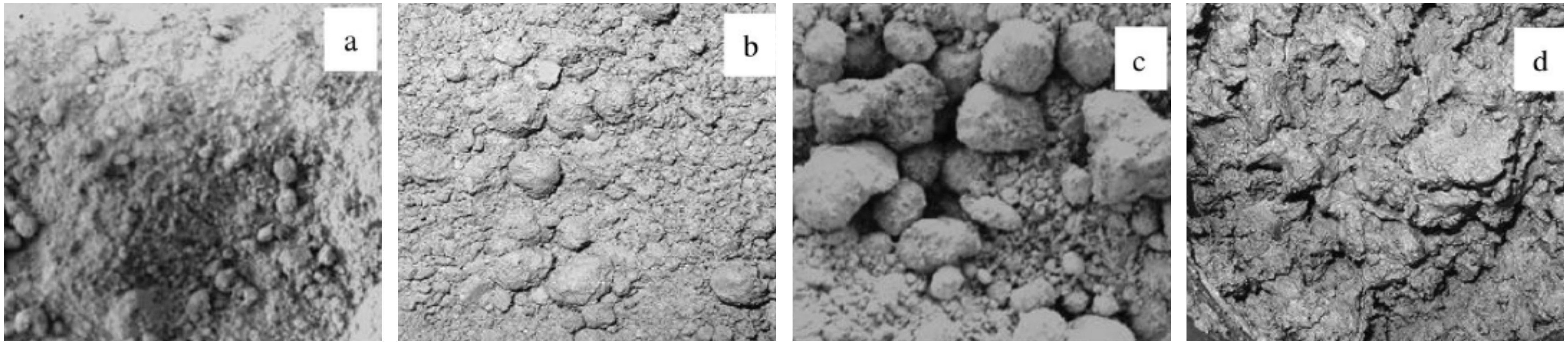


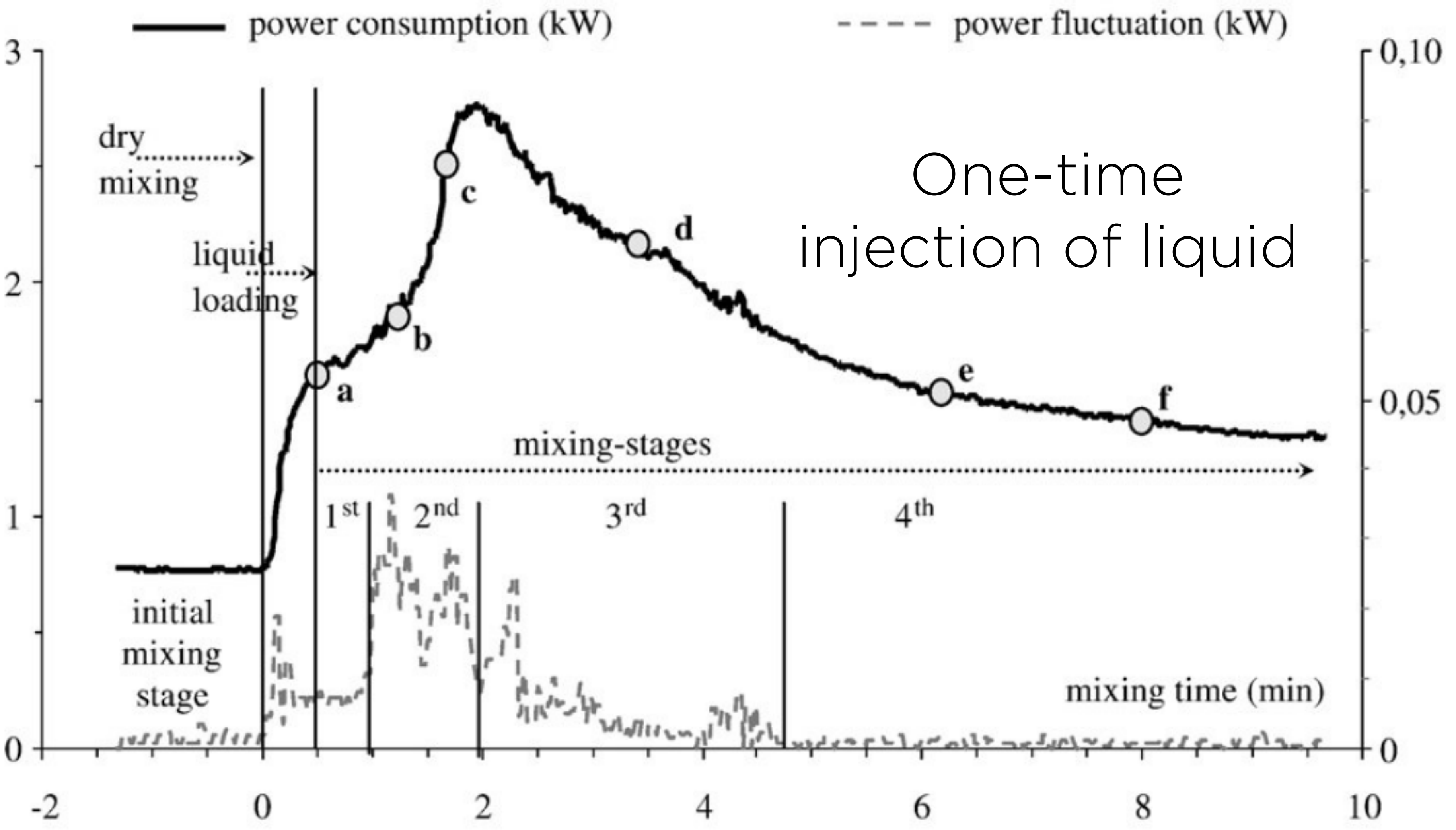
$$F_{cap} = 2\pi\gamma r\cos\theta_c$$

Willett et al., Langmuir (2000)

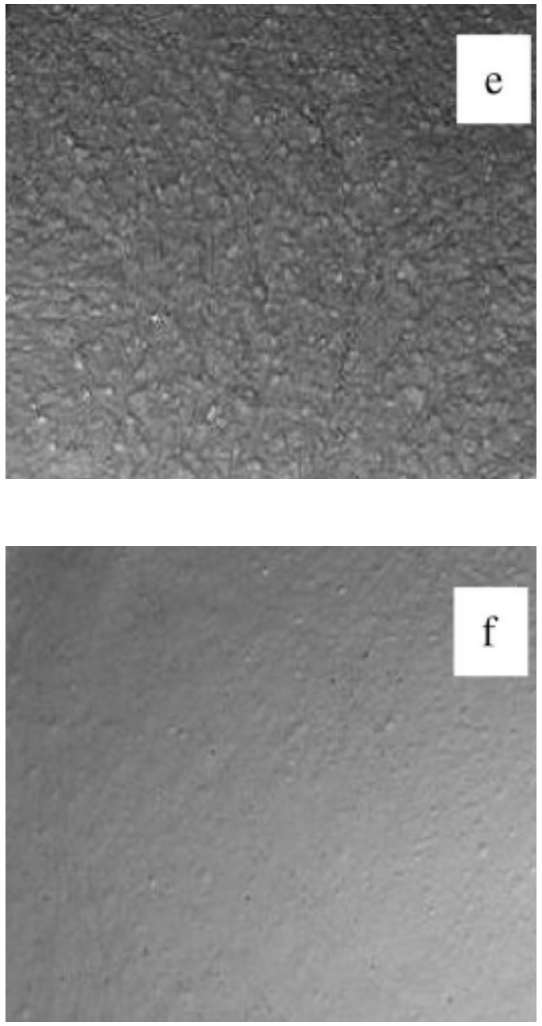
Pakpour et al., Sci. Rep. (2012)
Nowak et al., Nat. Phys. (2005)

FROM DRY GRANULAR MATERIALS TO SUSPENSIONS





One-time injection of liquid

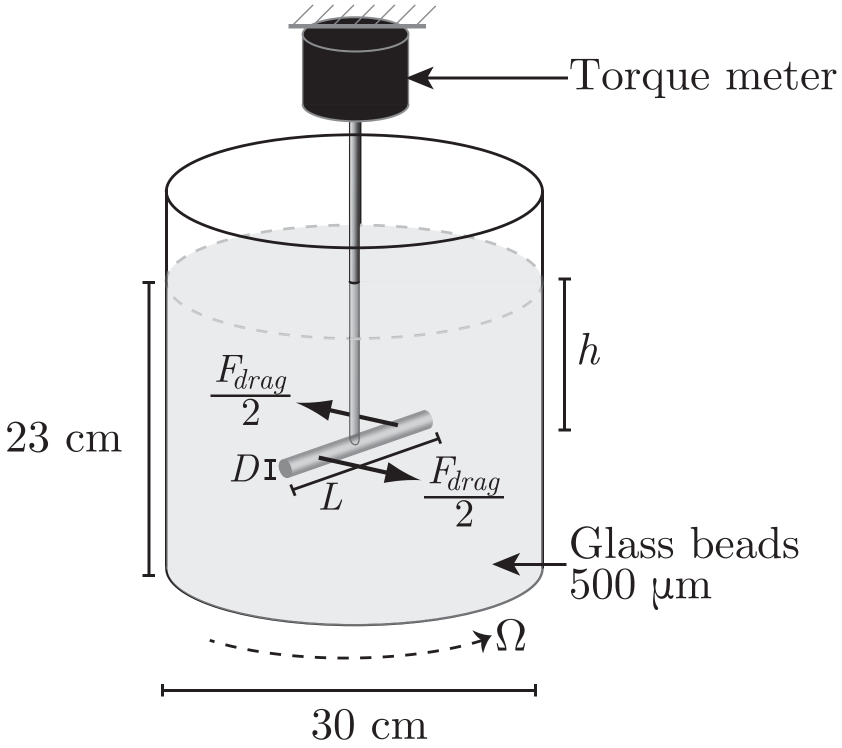


Cazacliu & Noquet, Cem. Concr. Res. (2009)

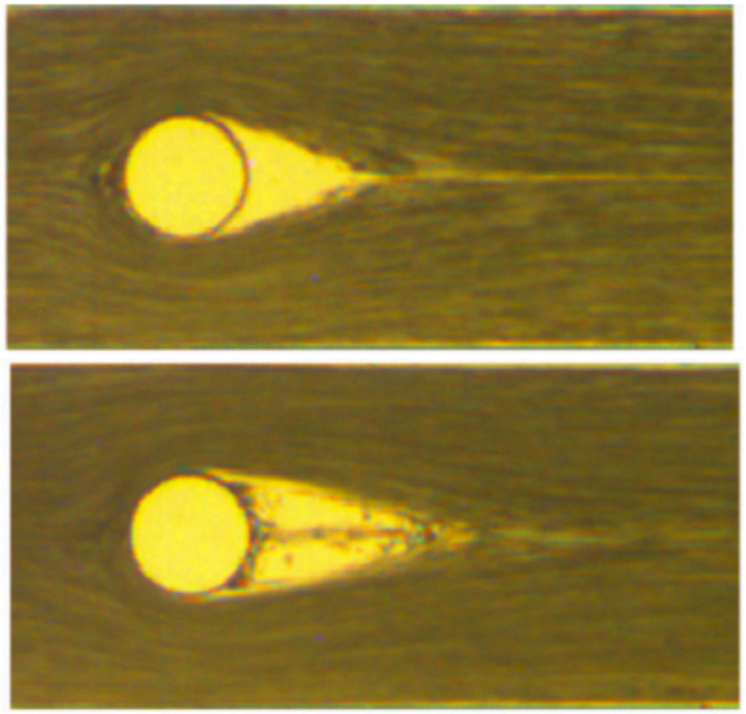
Betz *et al.*, *Int. J. Pharma*. (2003)

BLENDING LIQUID AND GRAINS

Fluid/suspension interactions

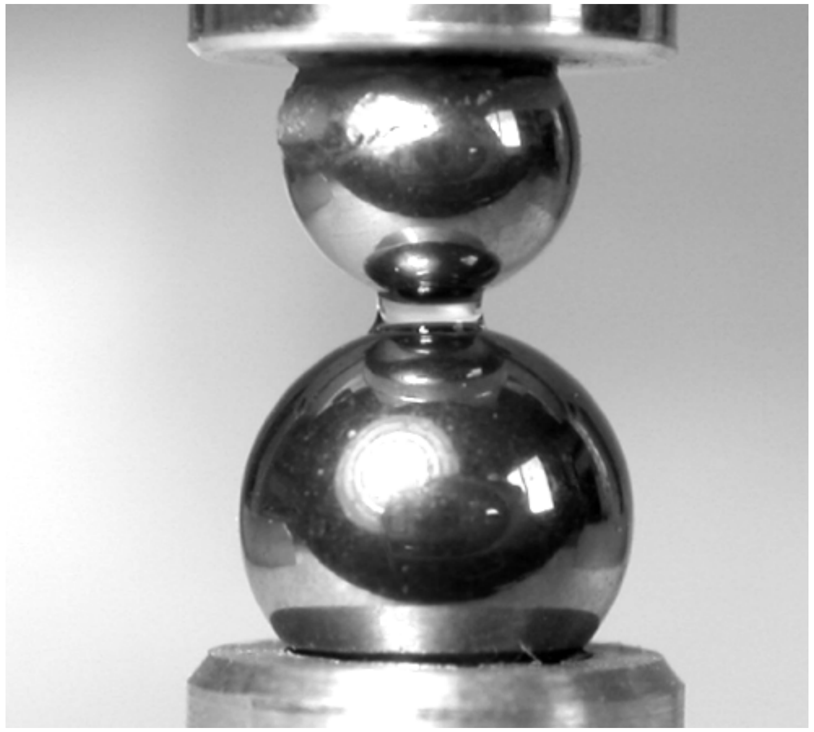


Guillart et al., PRL (2013)

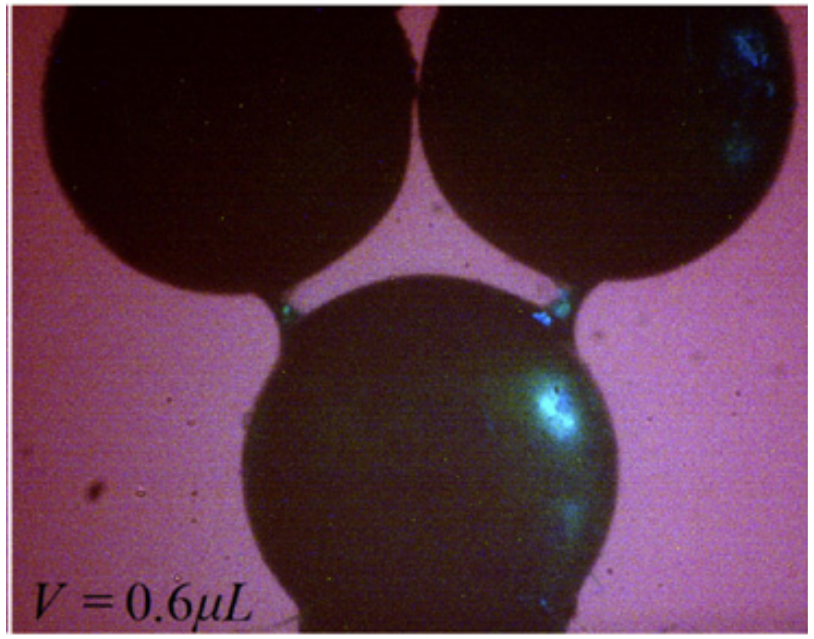


Haddadi et al., PRF (2016)

Capillary bridges

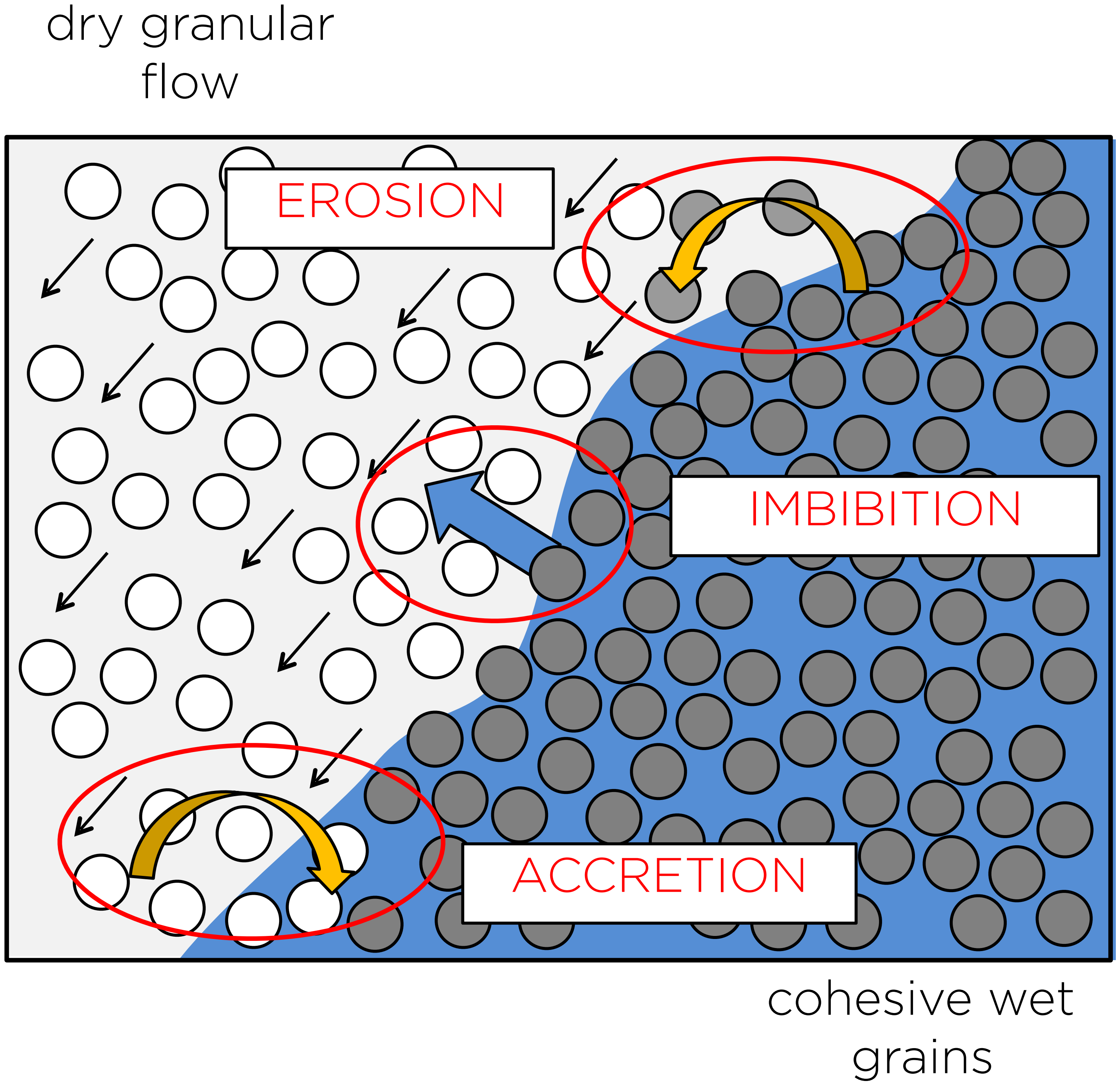


Soulie et al. EPJE (2006)

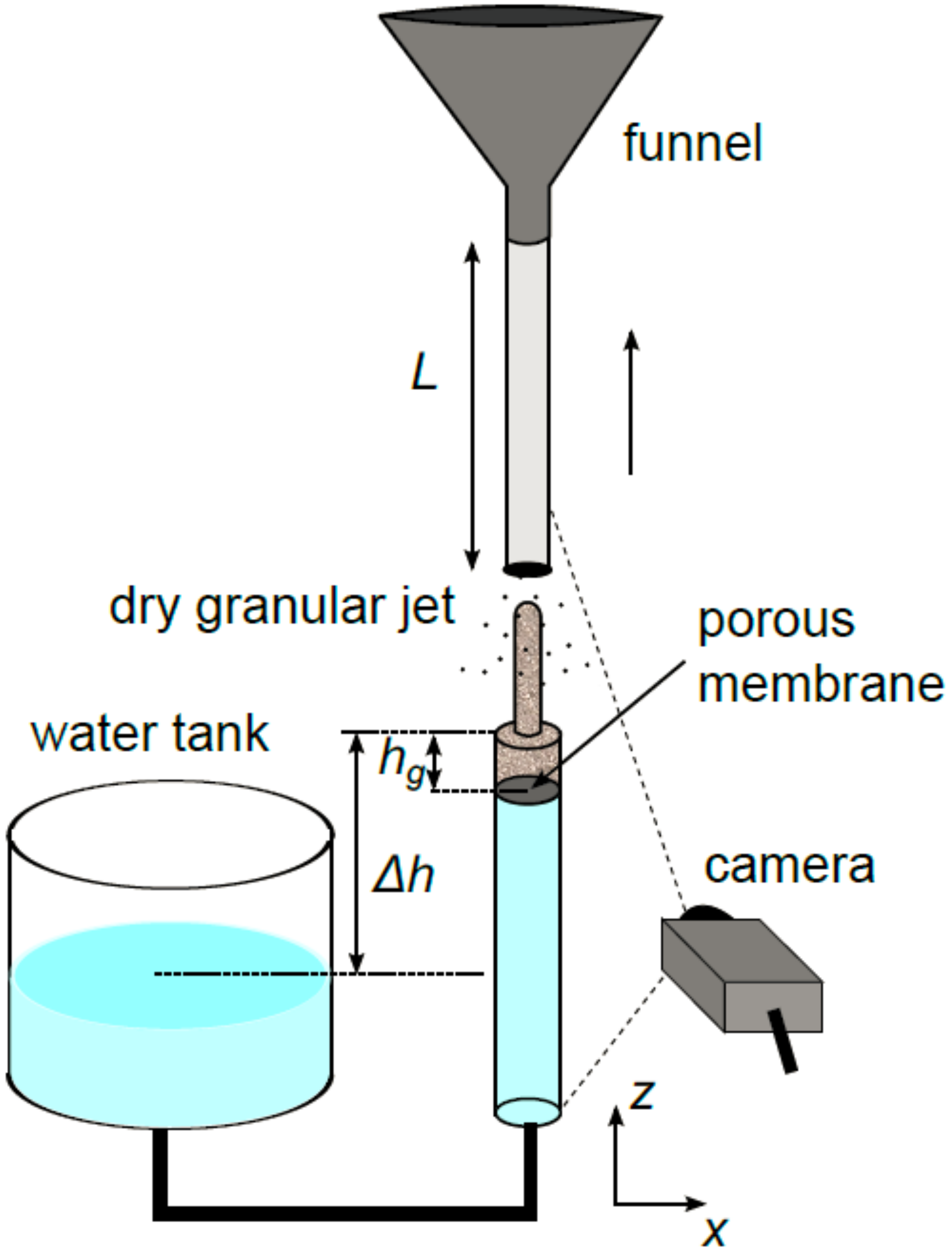


Wang et al. Powder Tech. (2017)

INTERACTION BETWEEN A GRANULAR FLOW AND A LIQUID



GRANULAR TOWER

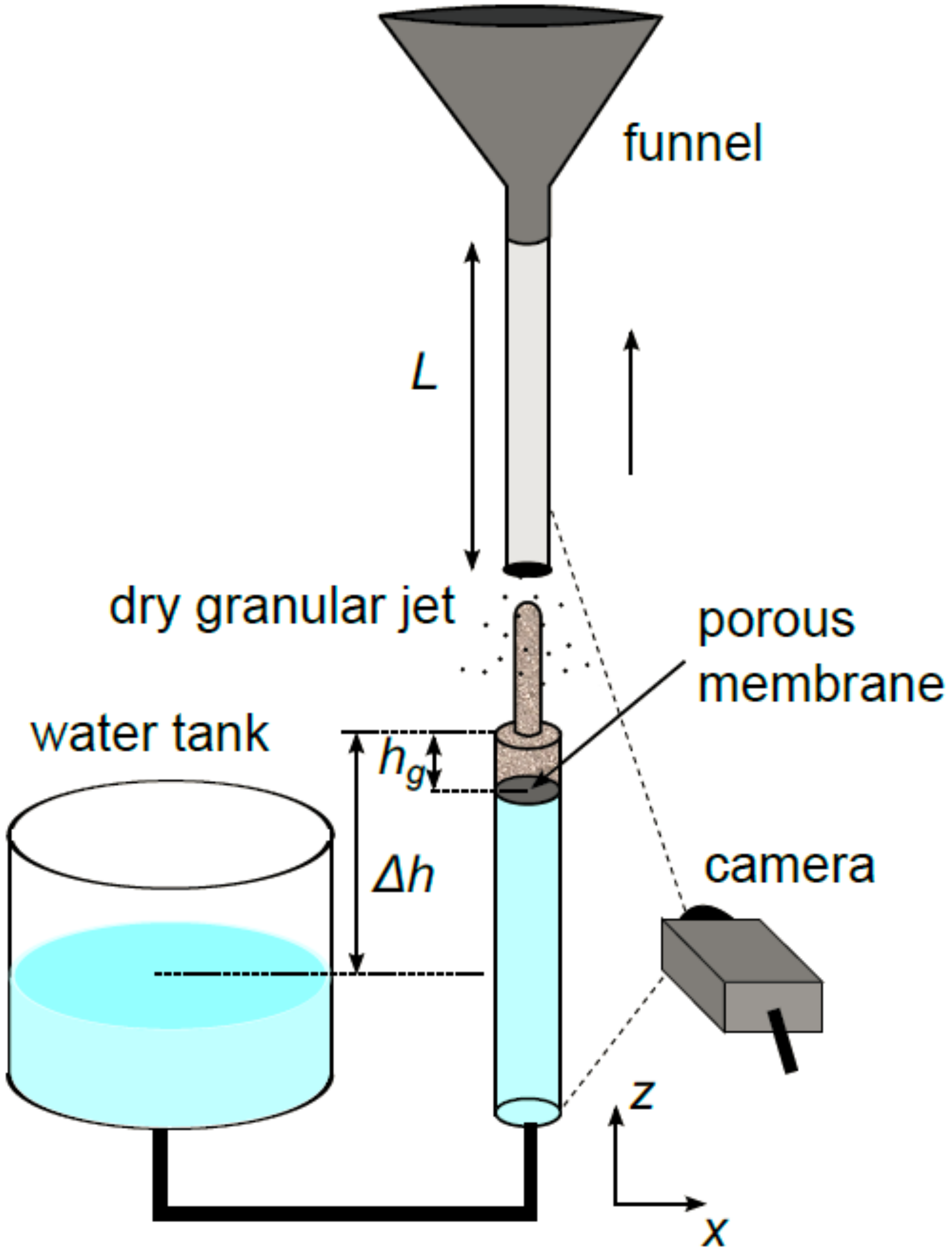


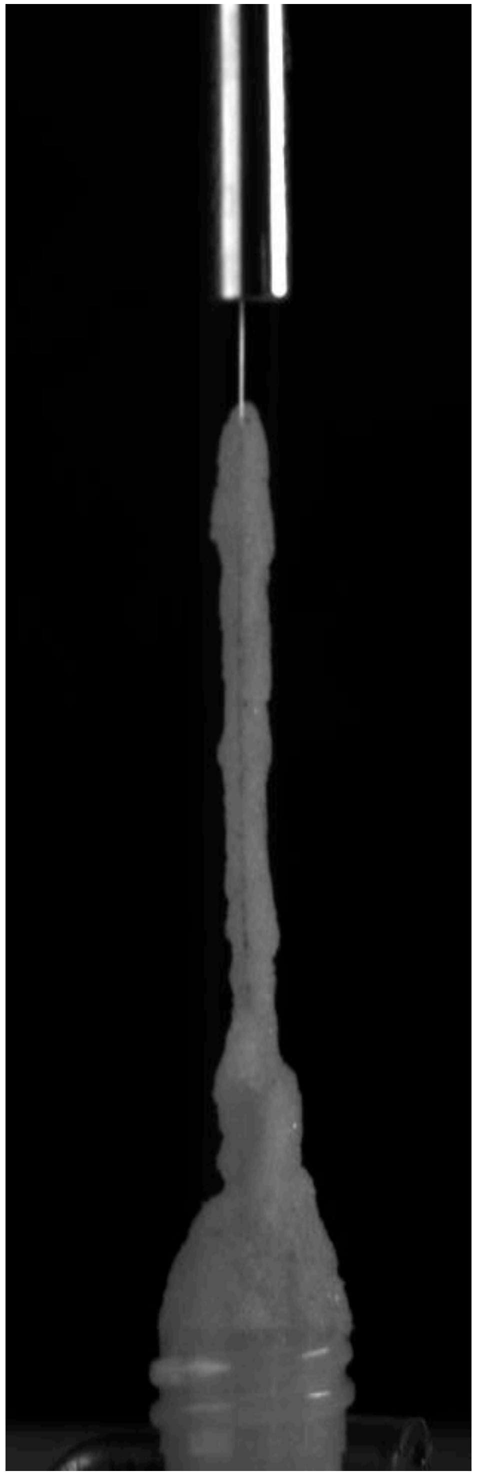
Pacheco-Vázquez *et al.*,
PRE (2012)

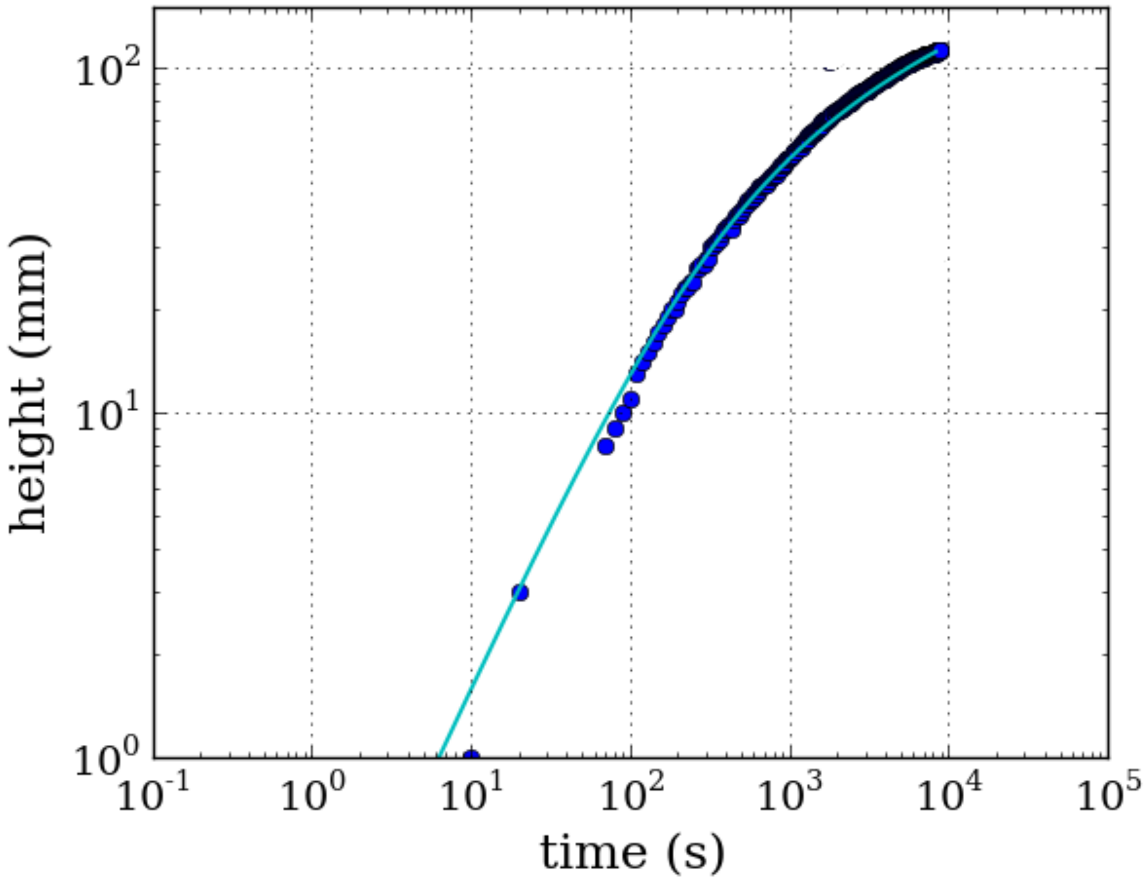
Inox tubing (2-100 cm)
Glass beads 100-315 µm

Reservoir of wet
granular material

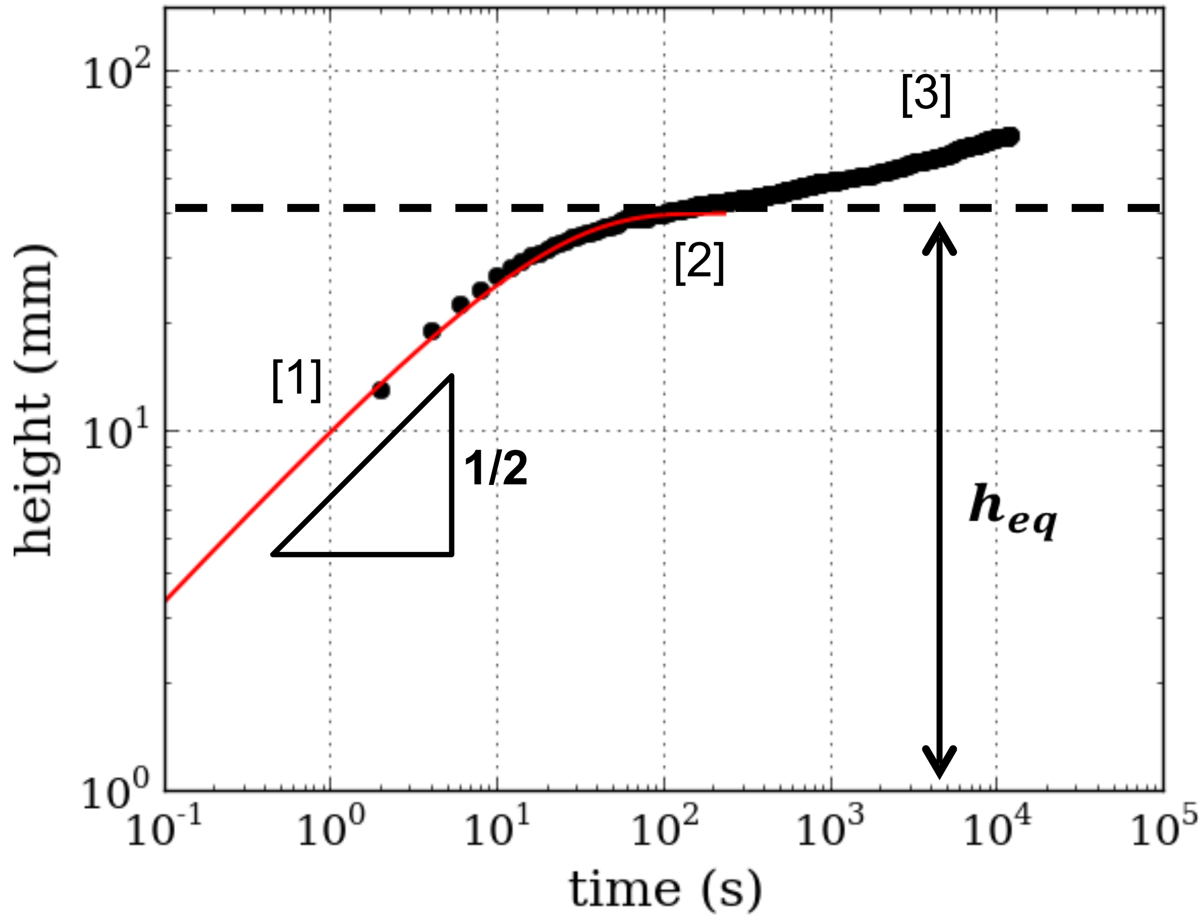
GRANULAR TOWER







CAPILLARY IMBIBITION VS VERTICAL ACCRETION



$$\boldsymbol{u} = -\frac{k}{\eta}\left(\nabla p - \rho\,\boldsymbol{g}\right)$$

viscous dissipation

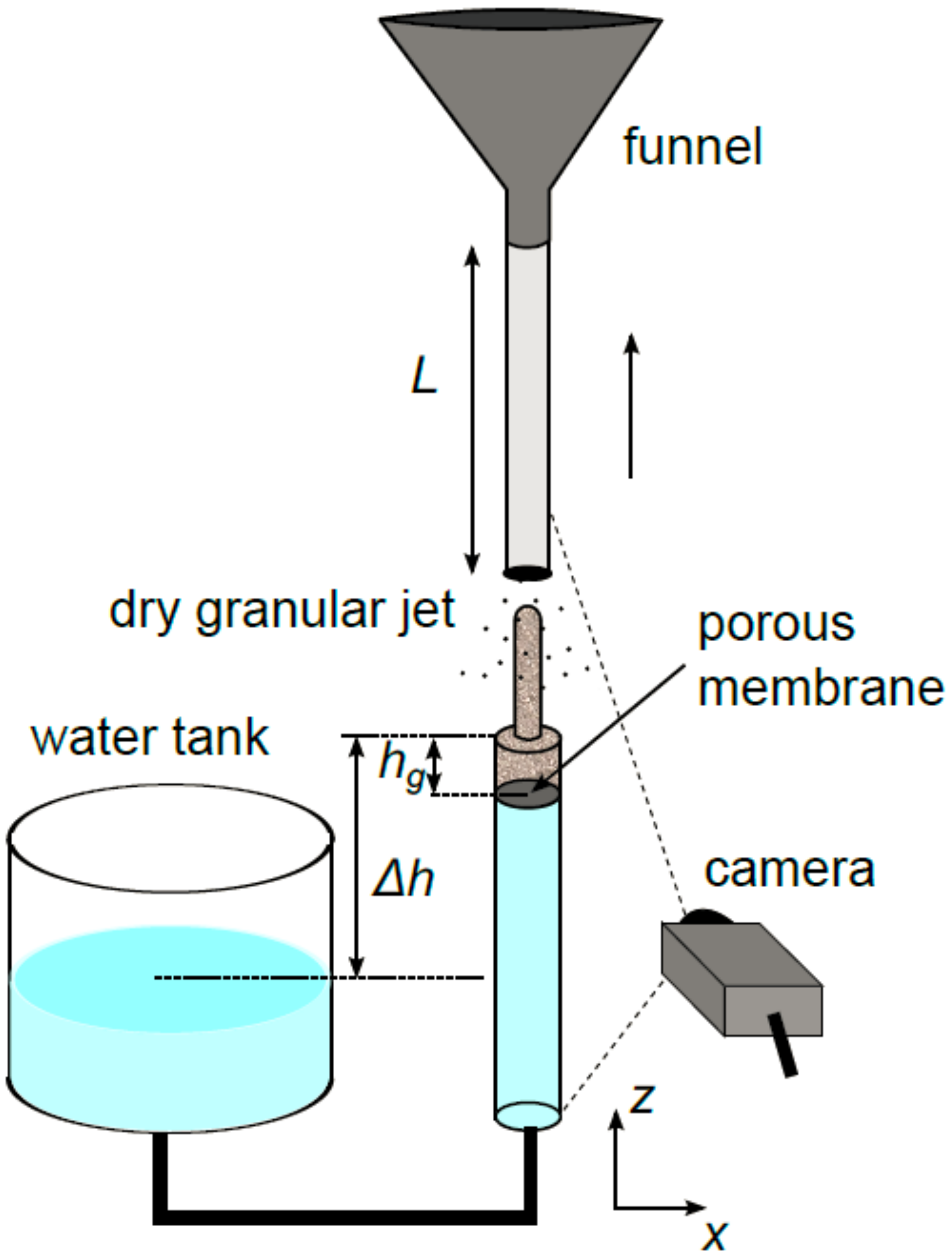
Driving force

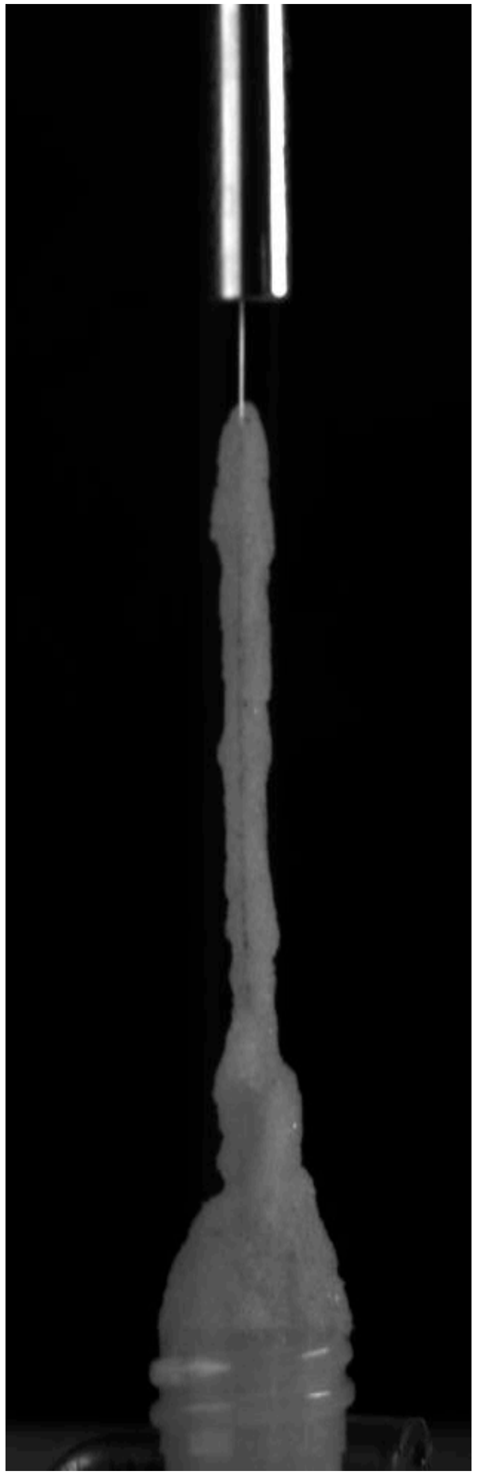
Pore size: $p_C = \dfrac{4\gamma\ \cos\theta_c}{d_p}$

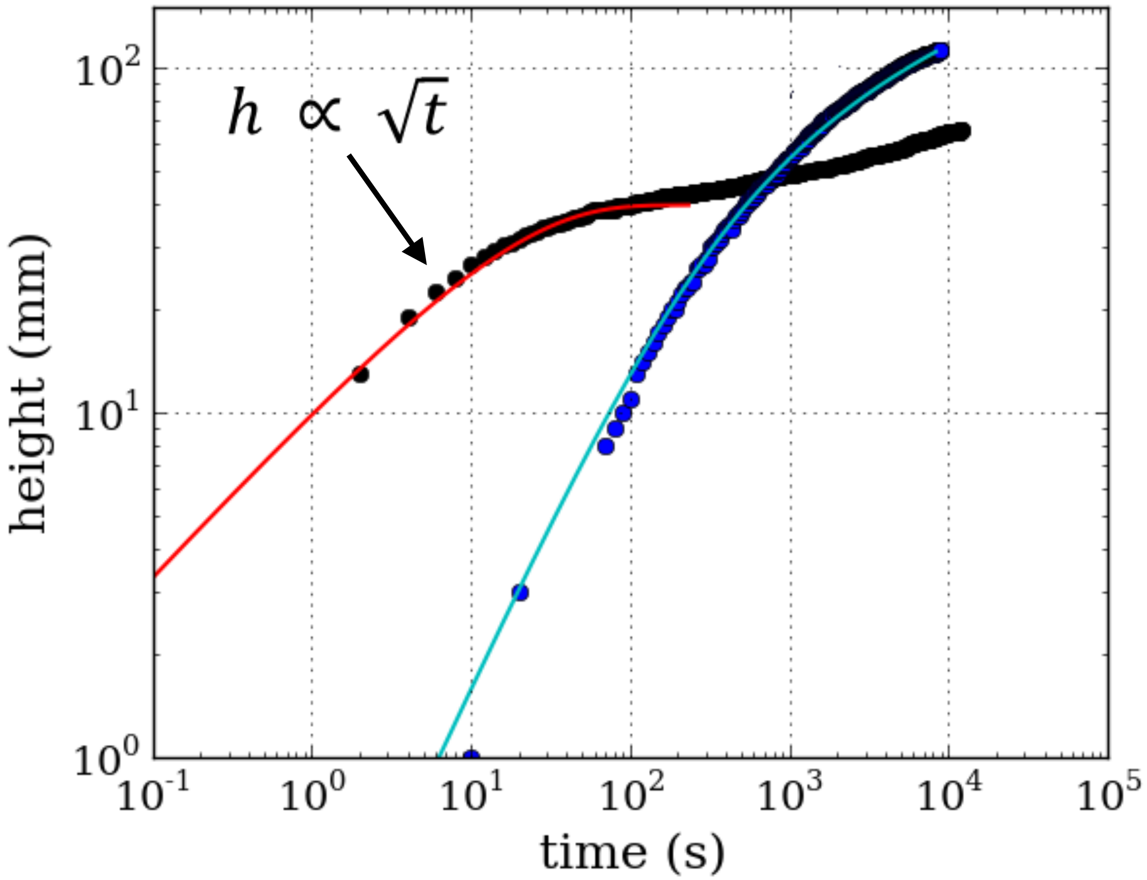
Lucas-Washburn law: $h^2(t) \sim \dfrac{R\gamma\cos\theta}{\eta}t$

Jurin’s height: $h_{max} = \dfrac{2\,\gamma\ \cos\theta}{\rho\,g\,R}$

GRANULAR TOWER

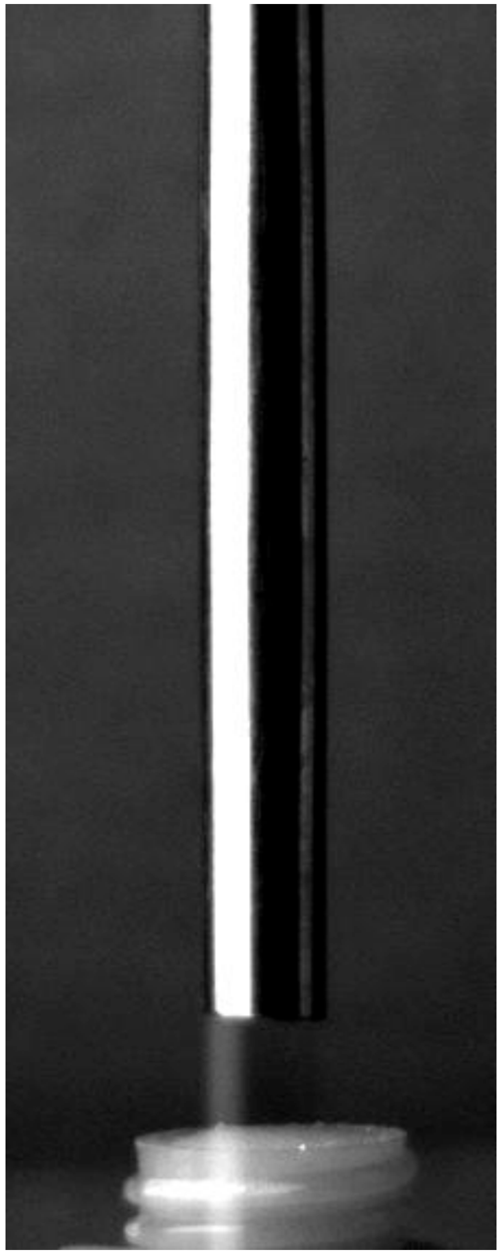


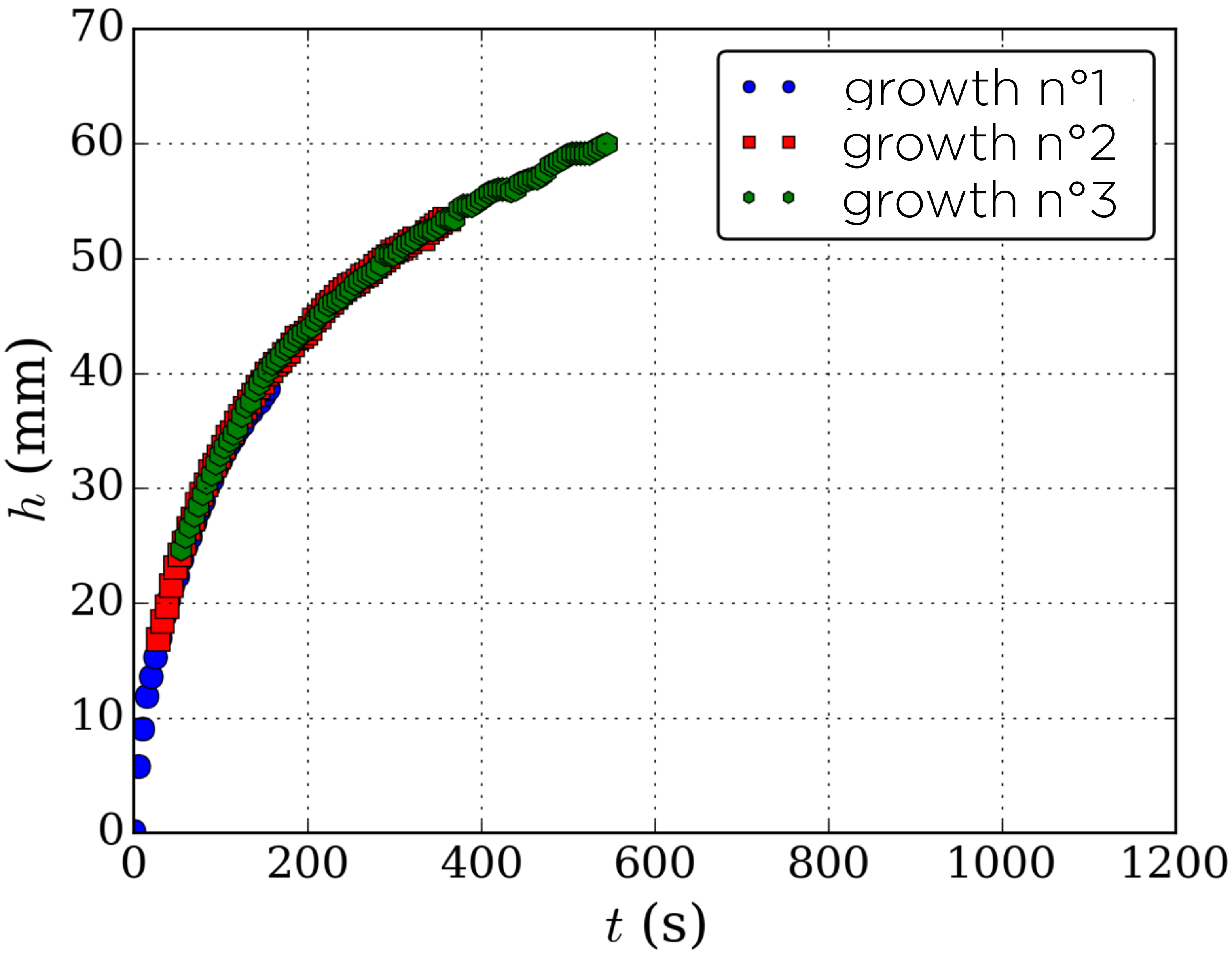




Growth dynamics cannot be fitted by the Lucas-Washburn law

GRANULAR TOWER



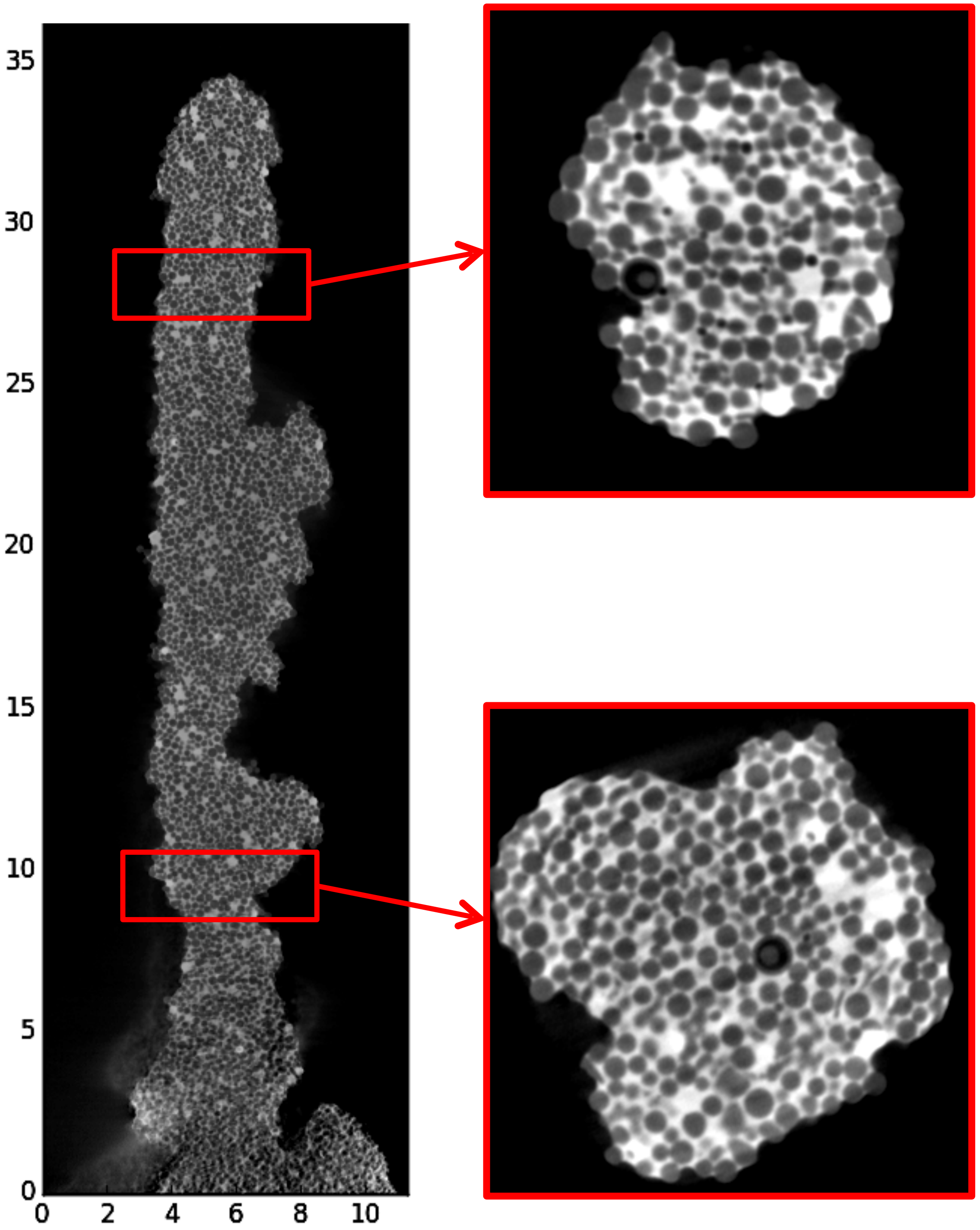


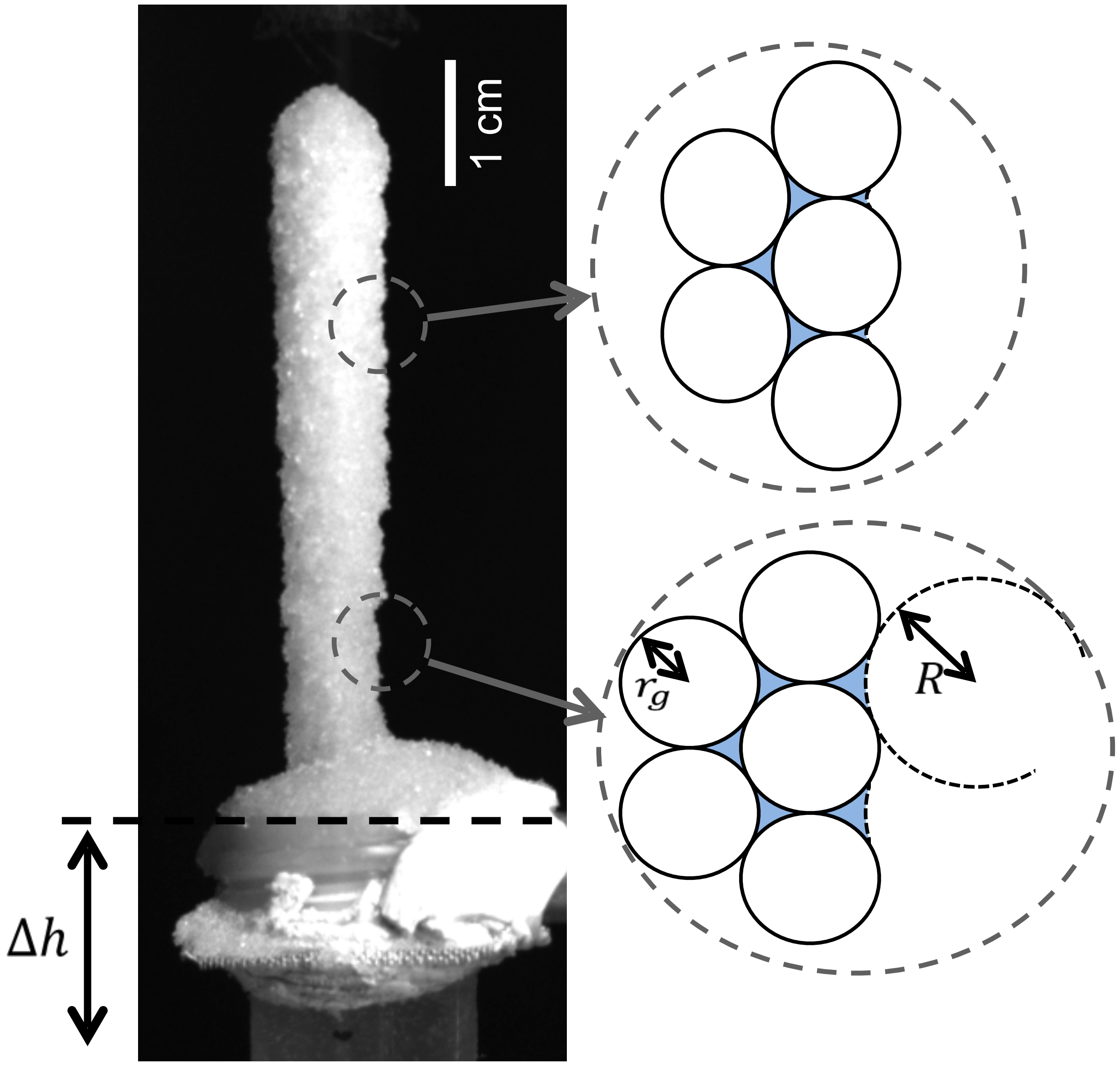
The growth of the wet aggregate only depends on the particle/liquid/air interface where the grains are impacting

Local effects

LIQUID DISTRIBUTION

X-Ray tomography: visualization of liquid phase (water+iode), air and beads

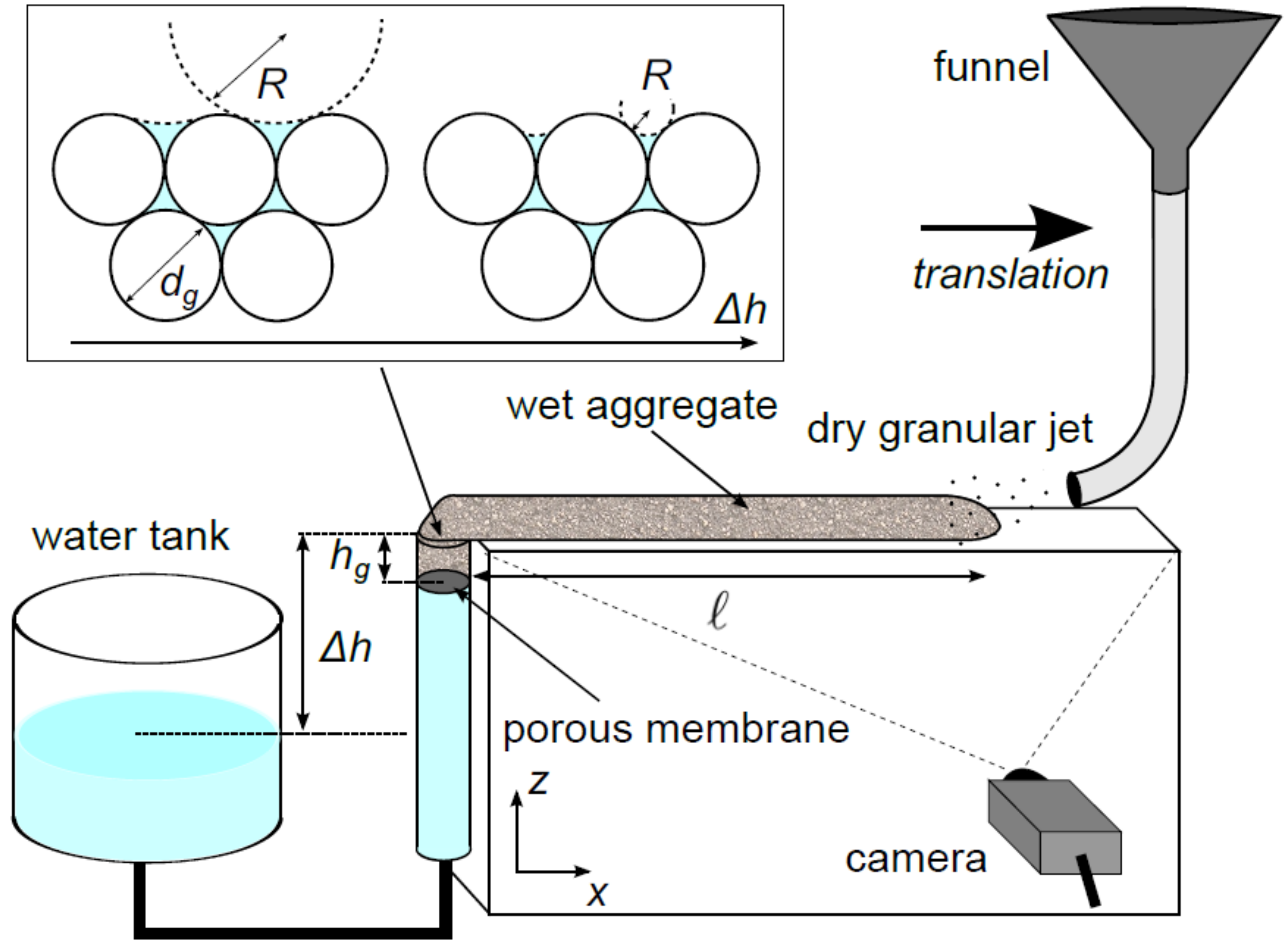


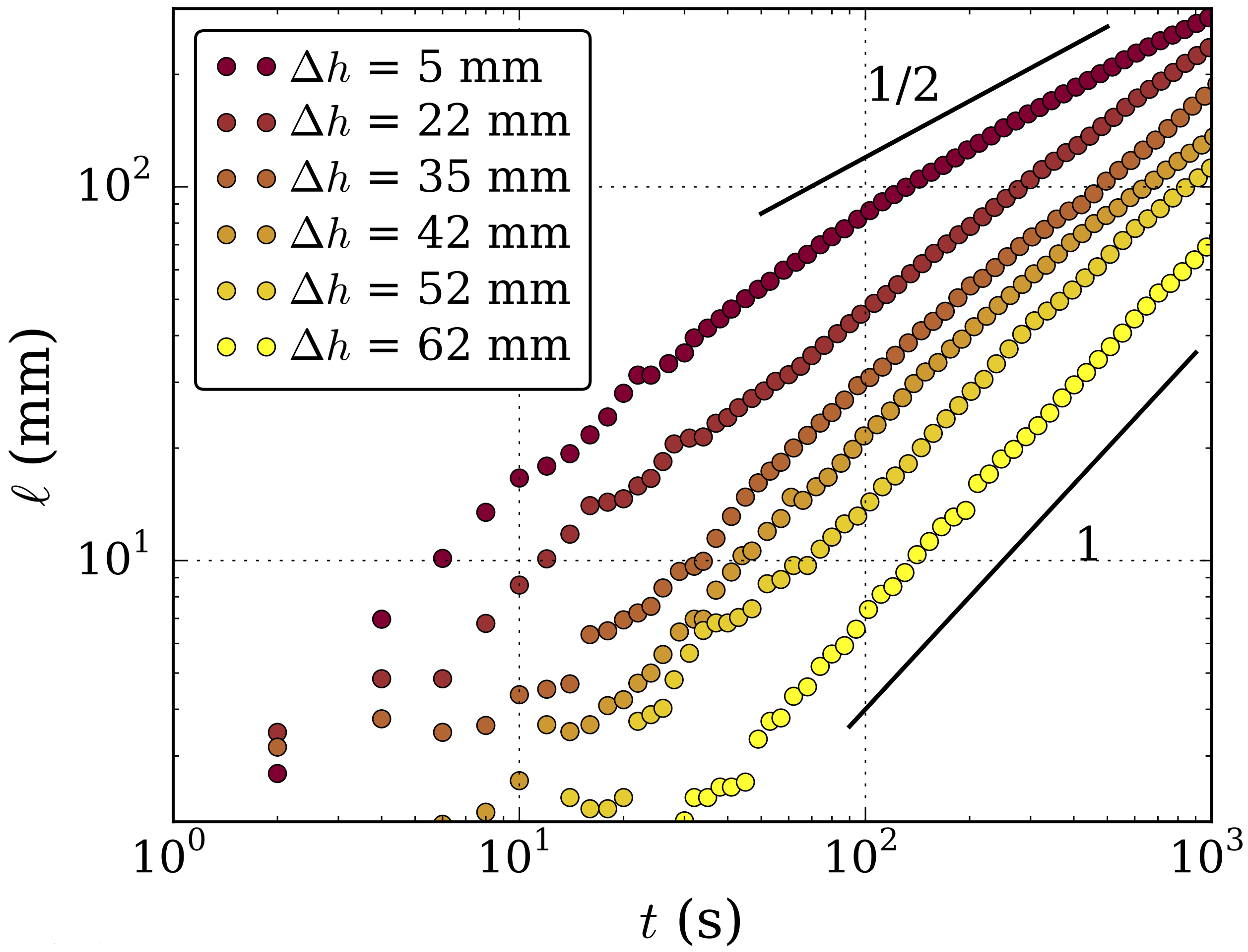


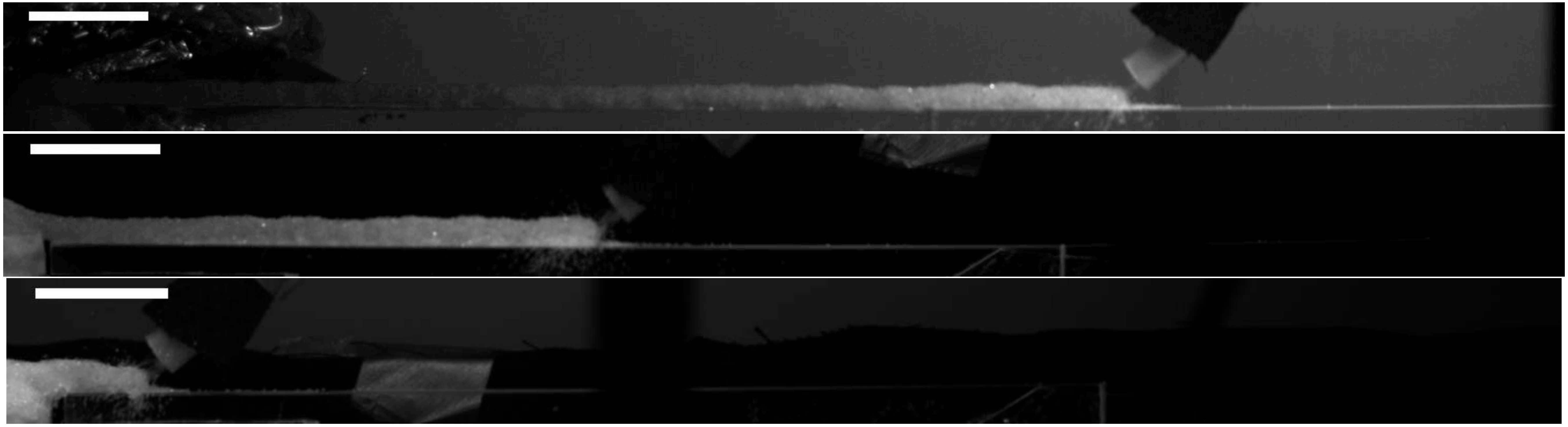
$$p_0 - \rho g z = p_0 - \frac{2\gamma\cos\theta}{R}$$

$$\boxed{R = \frac{2\gamma\cos\theta}{\rho g z}}$$

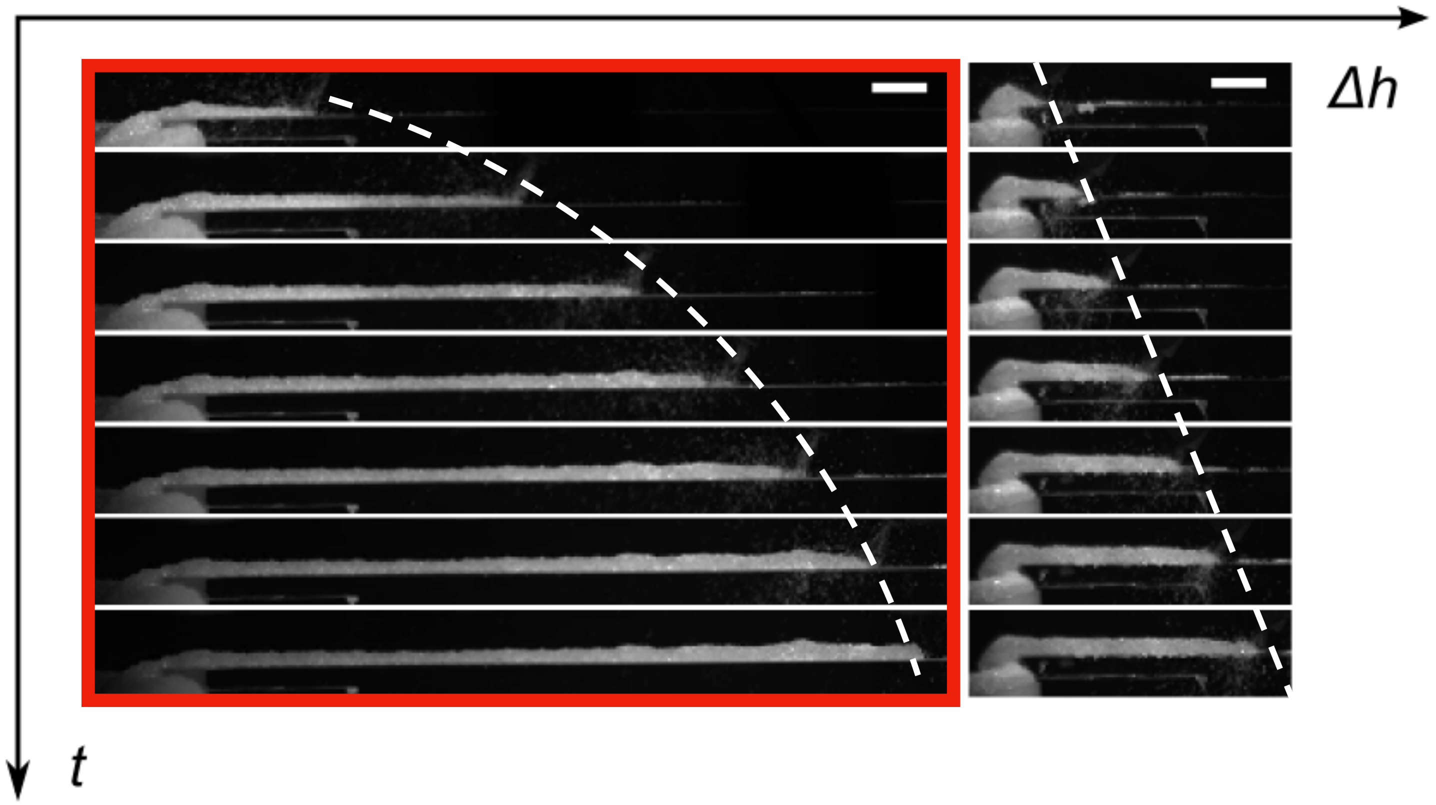
ACCRETION DYNAMICS

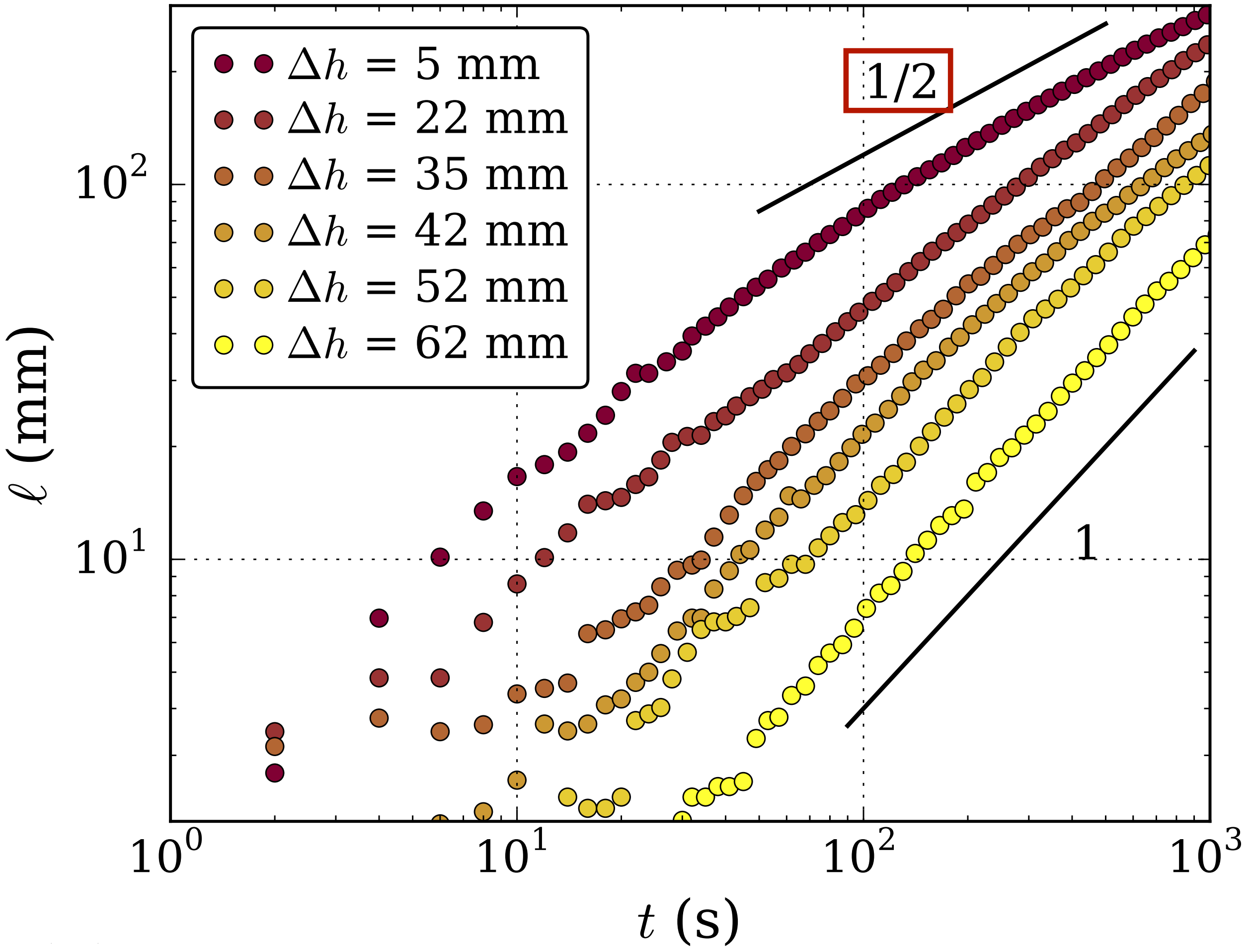


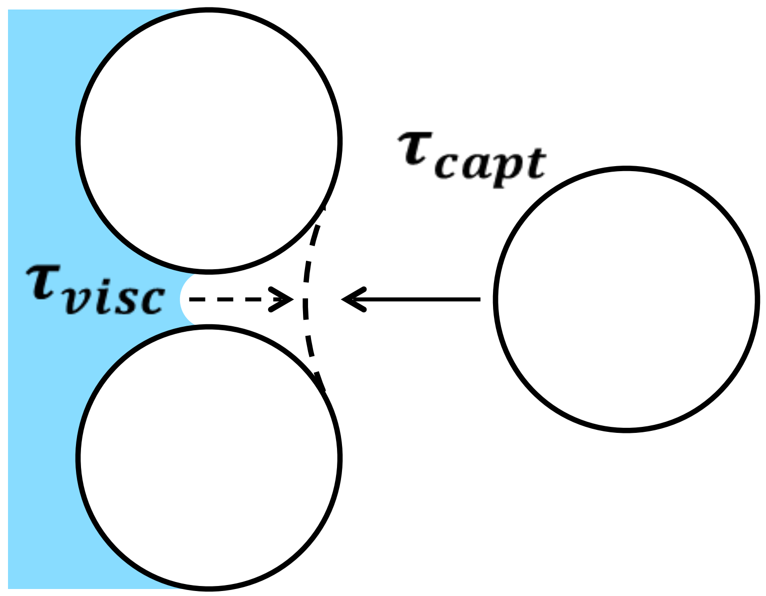




ACCRETION DYNAMICS





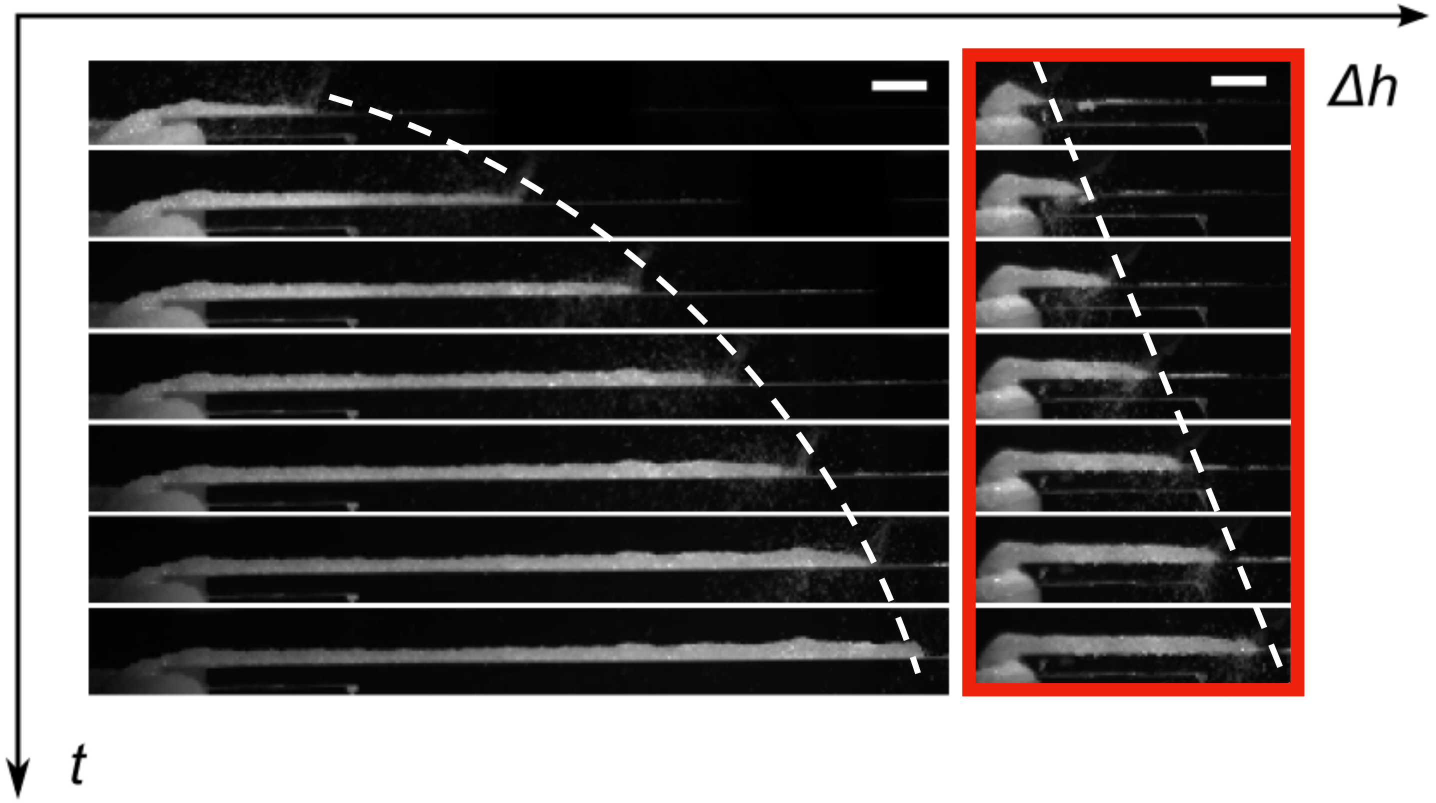


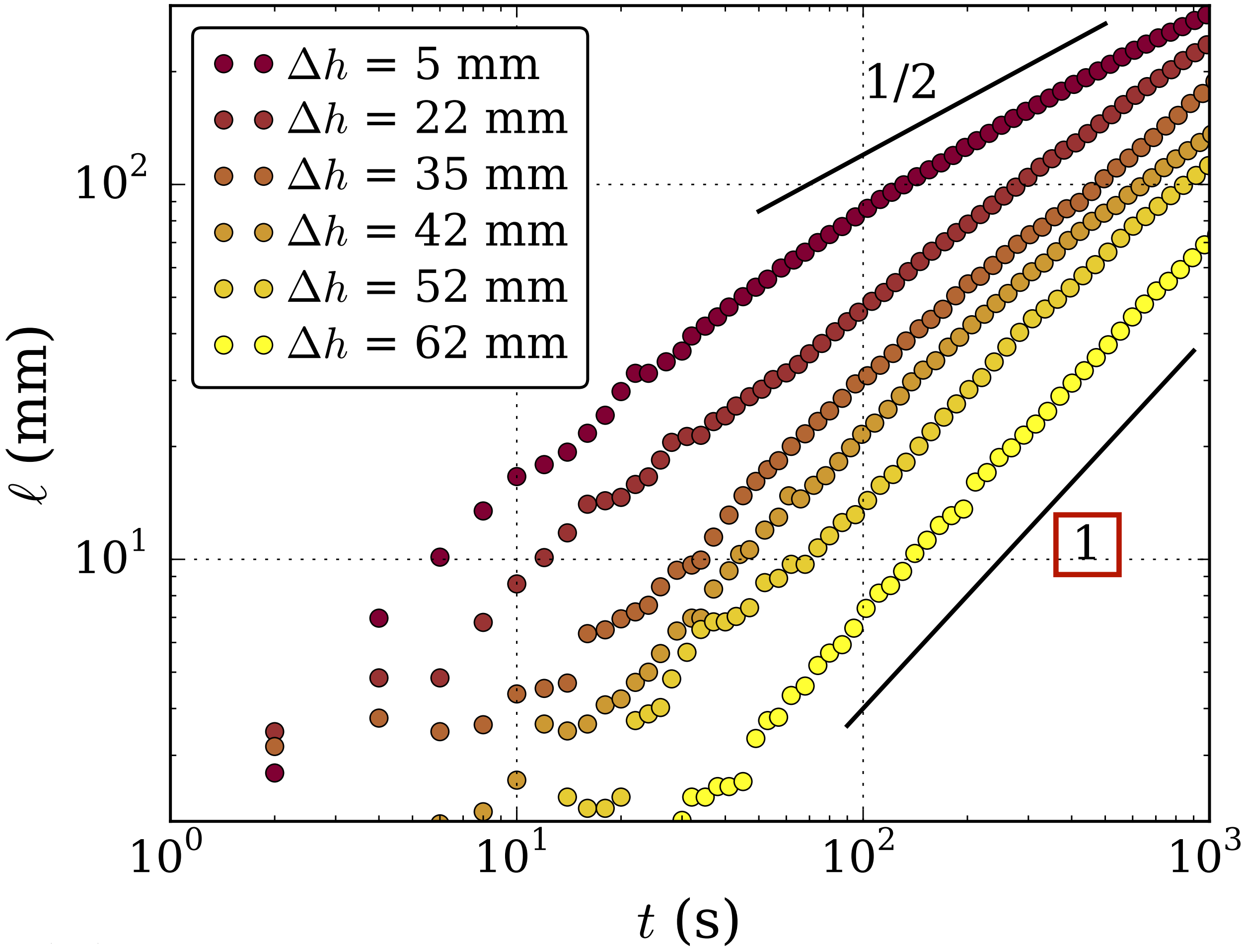
Viscous regime: $\tau_{visc} \gg \tau_{capt}$

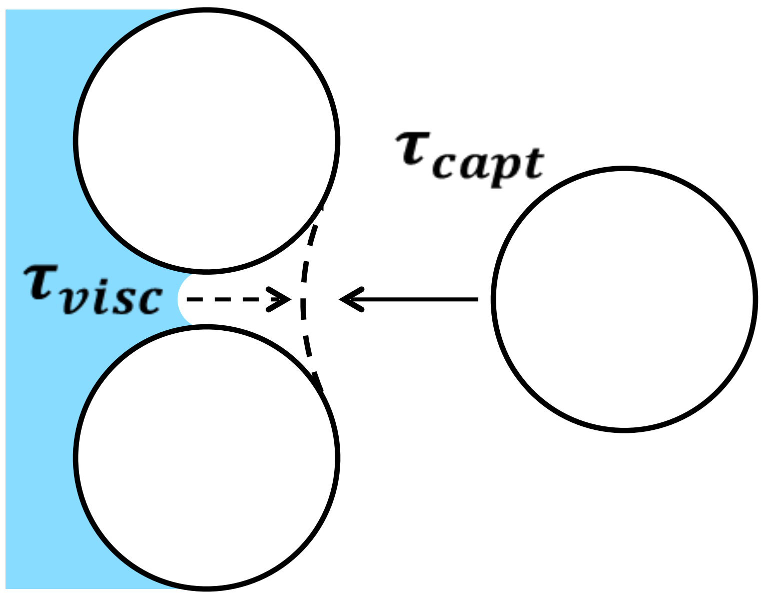
Aggregate growth is limited by the fluid flow in the granular packing

$$\boxed{l^v(t) = \sqrt{\frac{2\,k\,\Delta p}{\eta}\,t}}$$

ACCRETION DYNAMICS







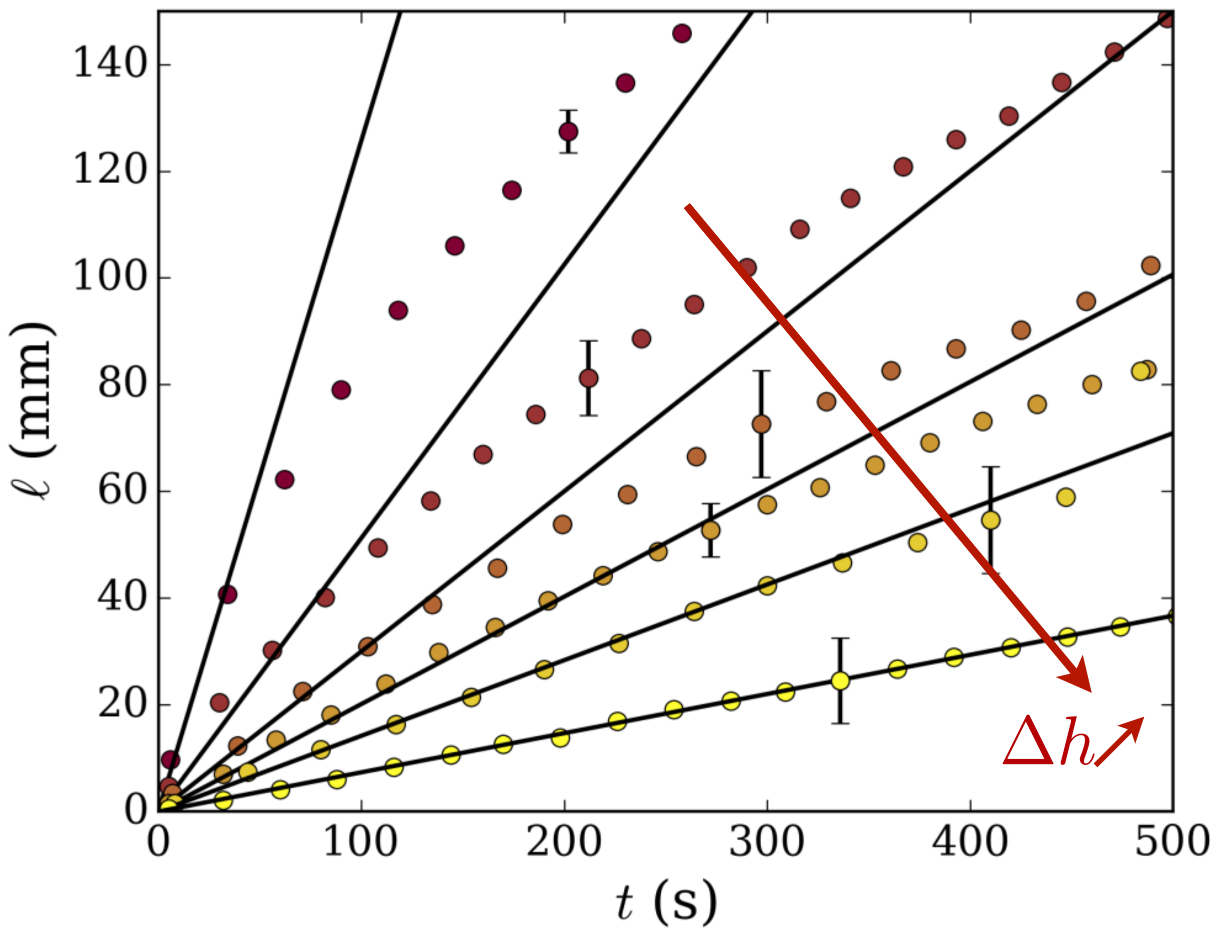
Capture regime: $\tau_{visc} \ll \tau_{capt}$

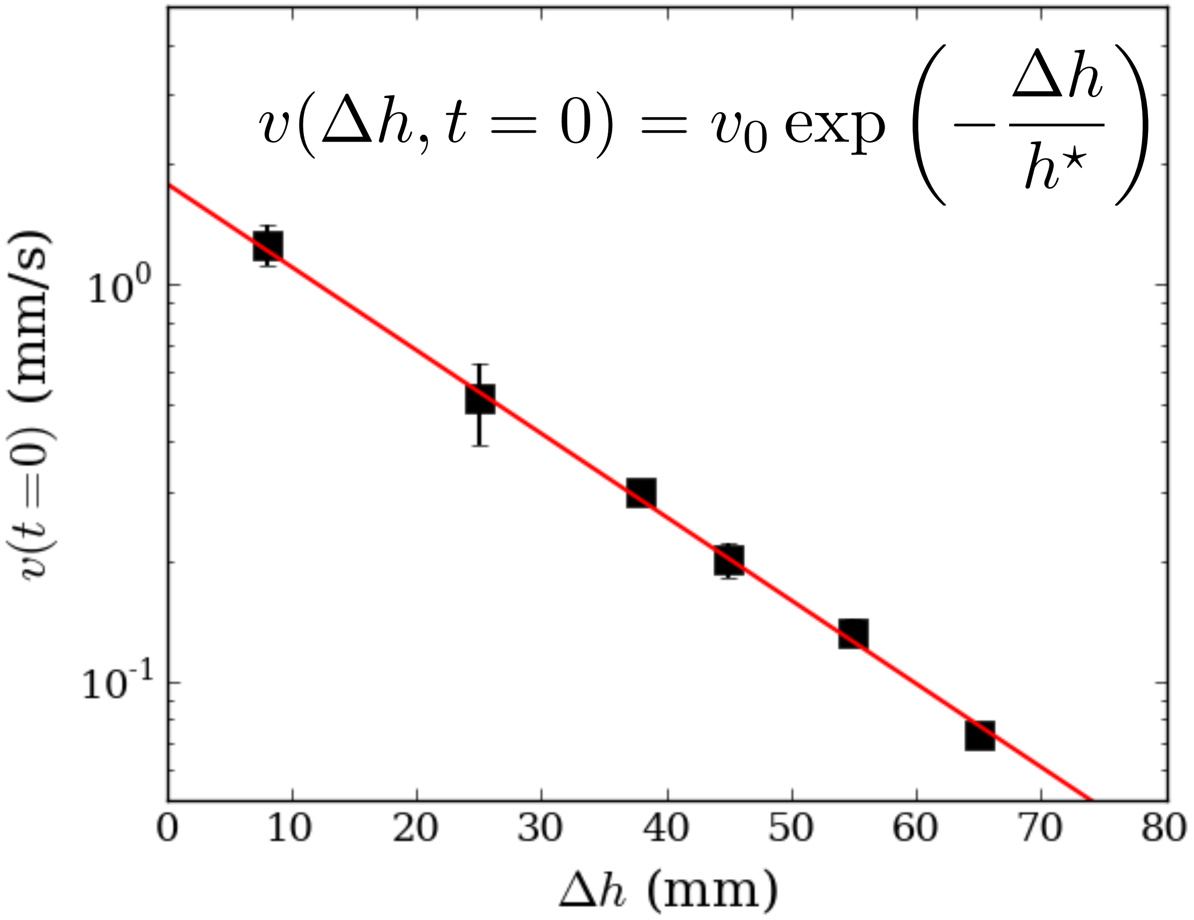
Growth limited by the fraction of dry grains trapped by the wet aggregate

$$\boxed{\ell^c(t) = \frac{Q_g}{\rho_s \phi S}\,\mathcal{P}_{capt}\, t}$$

INITIAL VELOCITY

Evolution of $\mathcal{P}_{capt}$ with Δh : transition between the 2 regimes



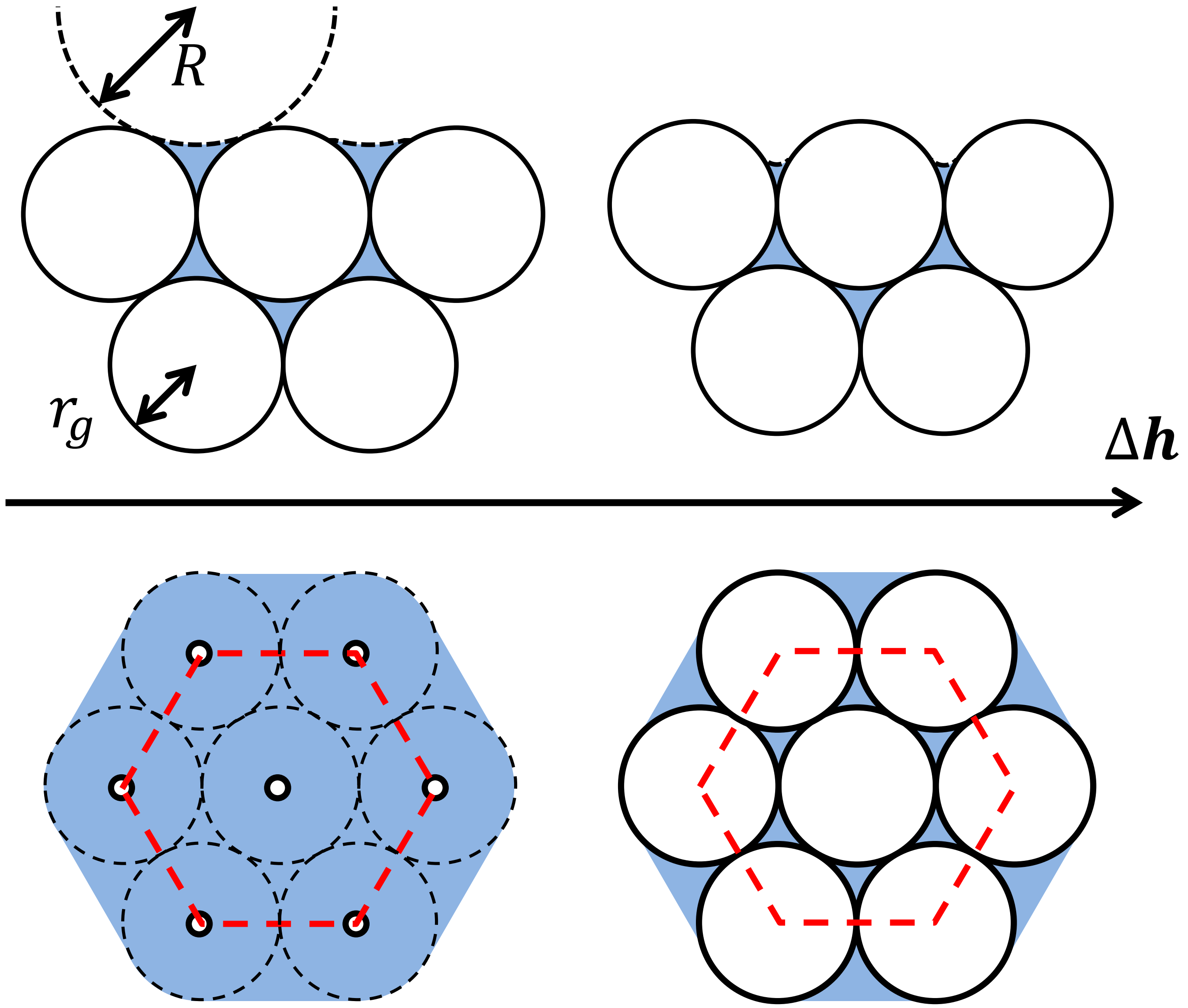


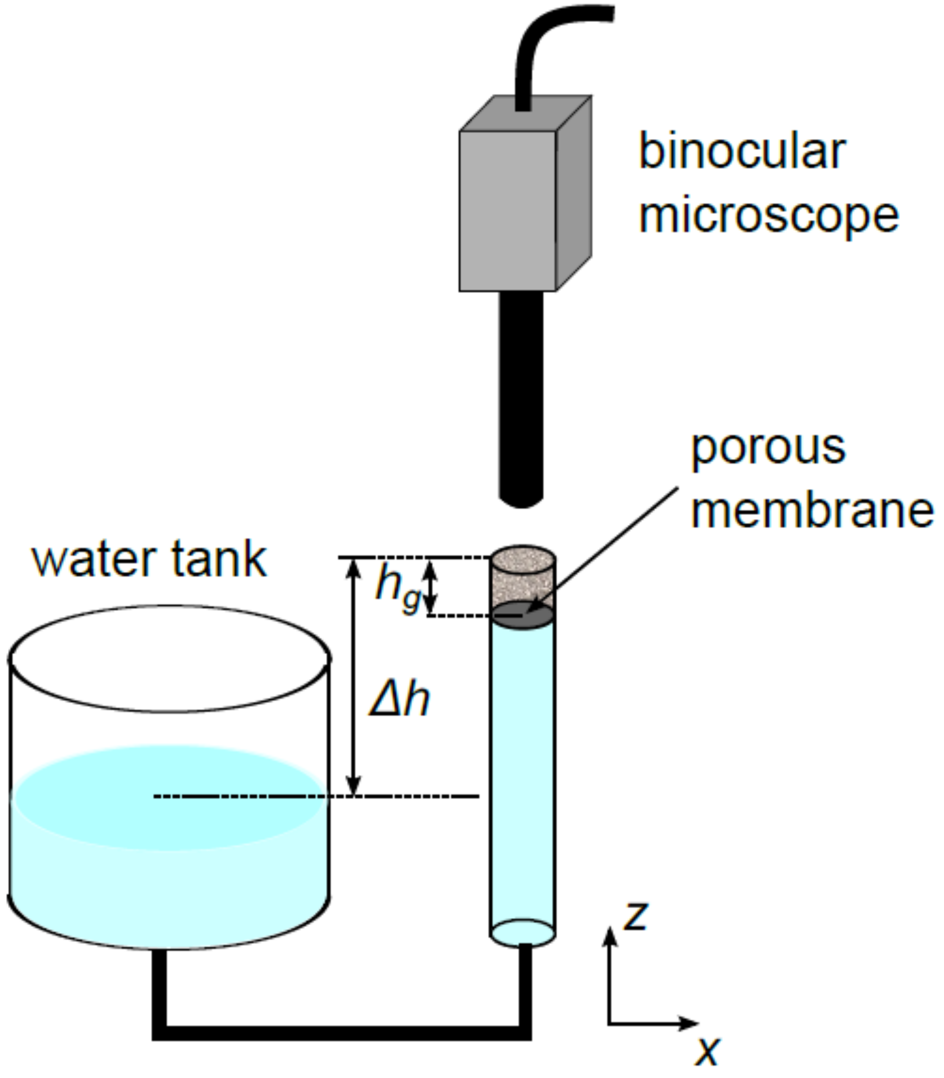
Initial growth velocity: $v(\Delta h, t=0) = v_0 \exp\left(-\frac{\Delta h}{h^\star}\right) = \frac{Q_g}{\rho_s \phi S}\mathcal{P}_{capt}(\Delta h)$

Capture probability: $\mathcal{P}_{capt}(\Delta h) = \mathcal{P}_0 \exp\left(-\frac{\Delta h}{h^\star}\right)$

CAPTURE MECHANISM

Accretion efficiency assumed to be captured by the liquid availability at the interfaces





CAPTURE MECHANISM

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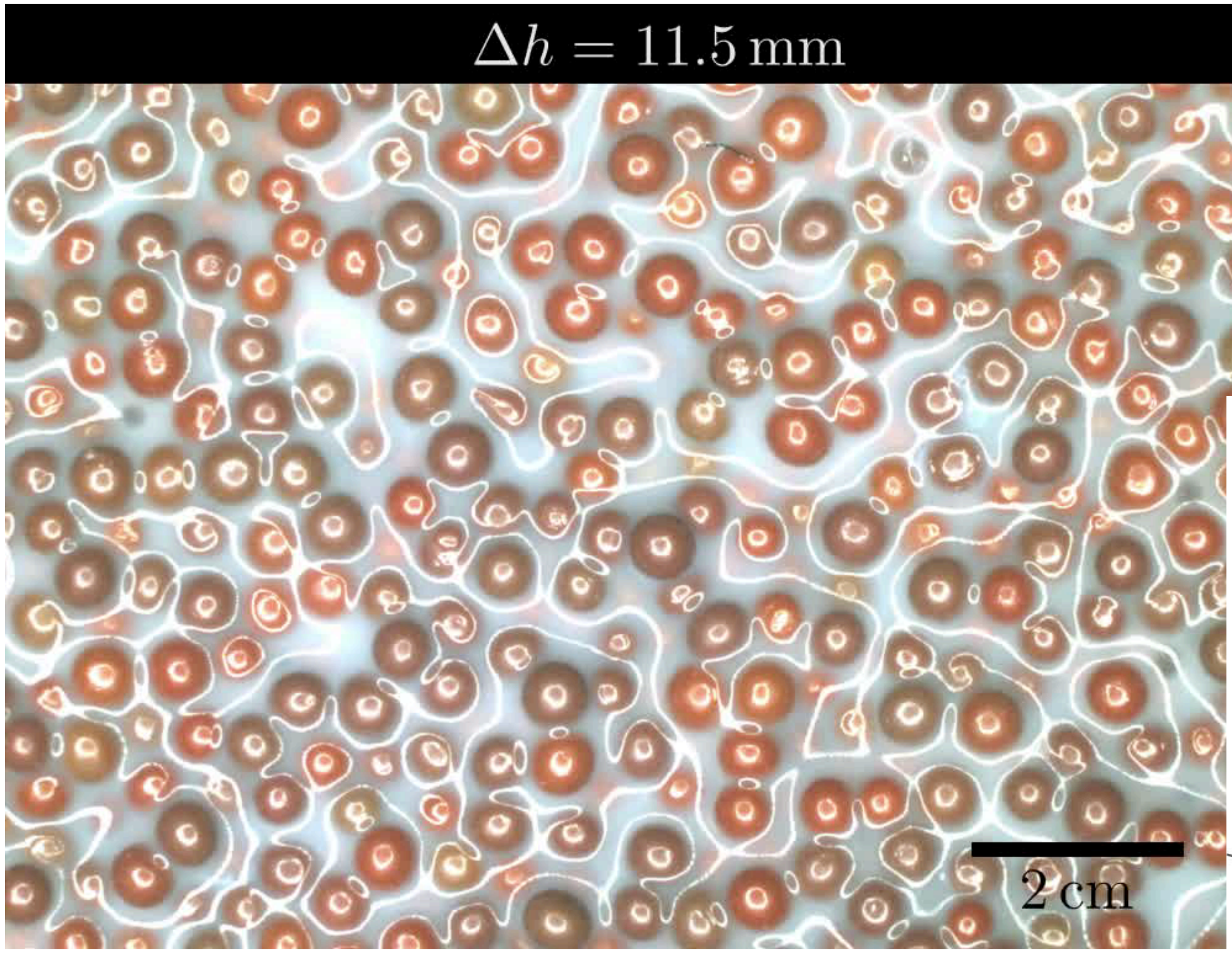
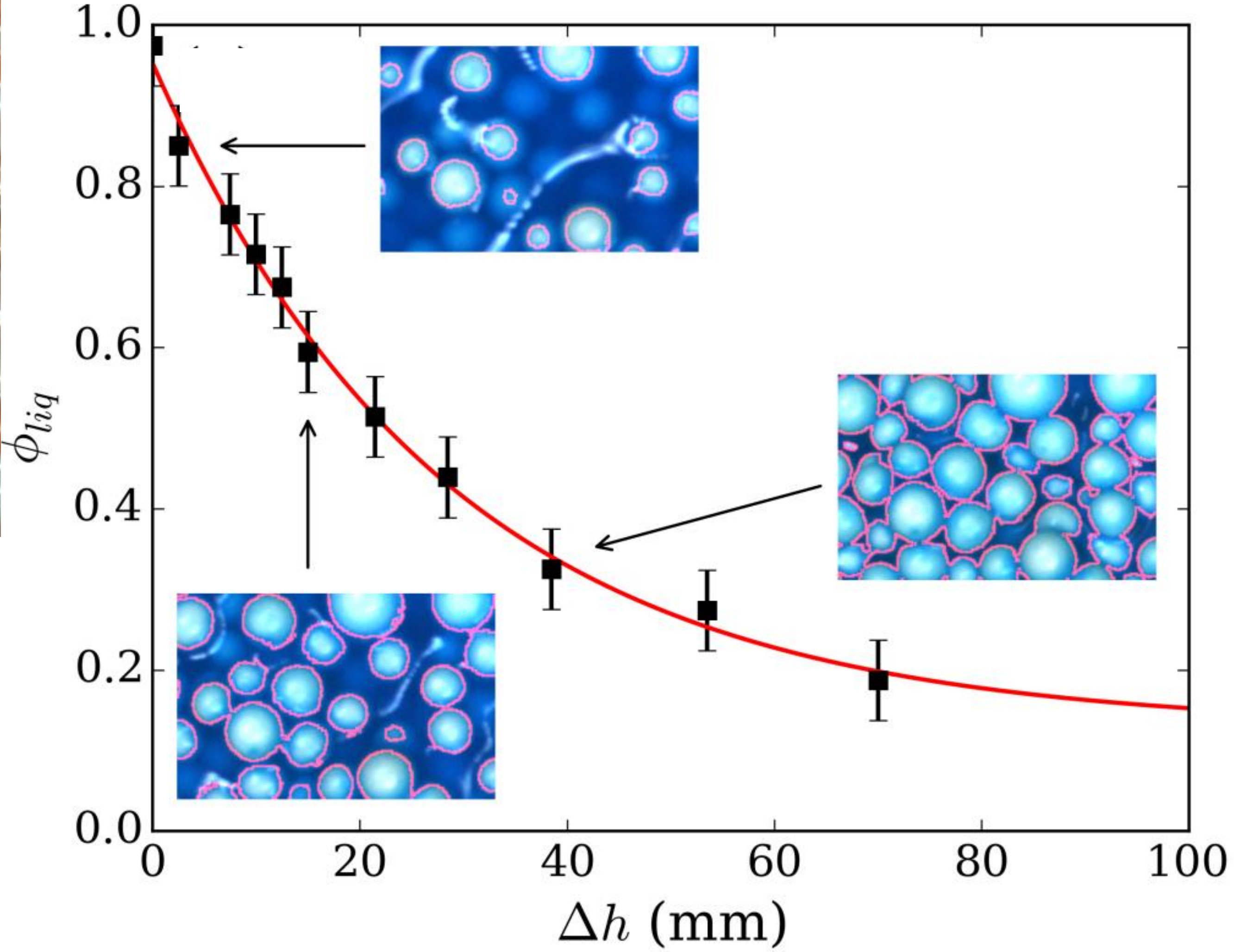
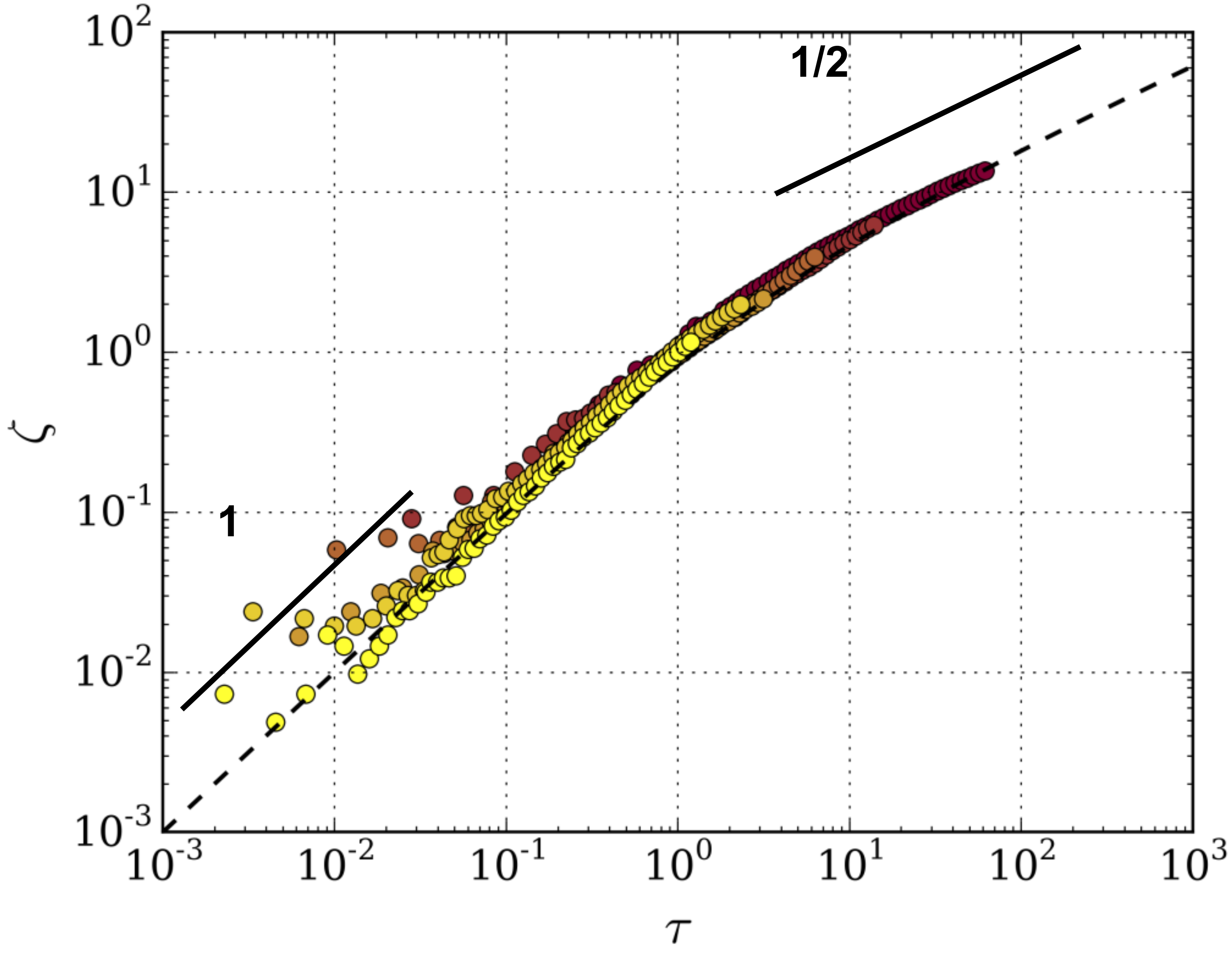




$$\phi_{liq}(\Delta h) = \phi_0 + (1-\phi_0)\exp\left(-\frac{\Delta h}{h^*}\right)$$

$$\mathcal{P}_{capt} \propto (\phi_{liq}-\phi_0) \propto \exp\left(-\frac{\Delta h}{h^*}\right)$$

TRANSITION BETWEEN REGIMES



Viscous regime:

$$l^v(t) = \sqrt{\frac{2\,k\,\Delta p}{\eta}\,t}$$

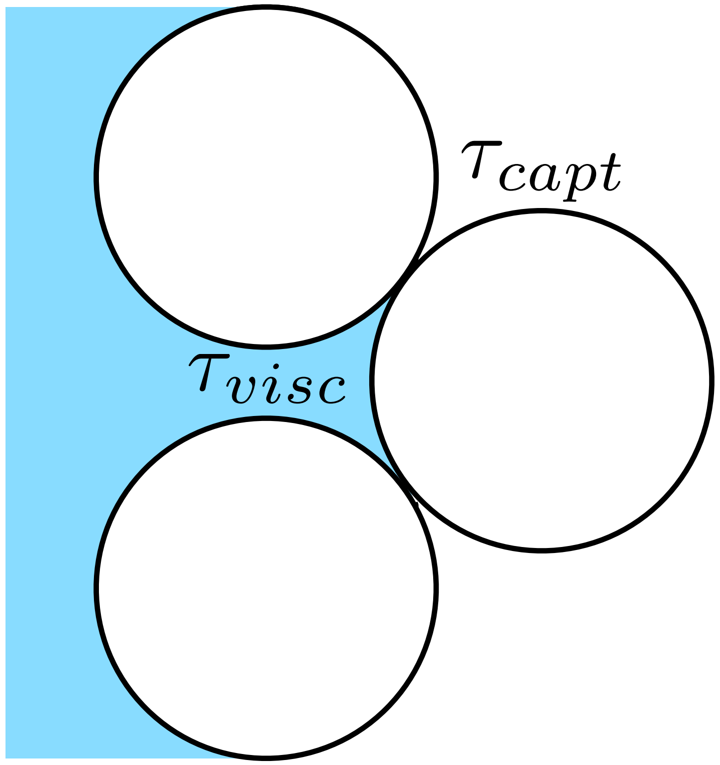
Capture regime:

$$\ell^c(t) = \frac{Q_g}{\rho_s \phi S}\,\mathcal{P}_{capt}\,t$$

Transition: $u^v = u^c$

$$\begin{cases} t_c = \dfrac{k}{2\eta}\left(\dfrac{\rho_g \phi S}{\mathcal{P}_{capt} Q_g}\right)^2 \Delta p \\ \ell_c = \dfrac{k}{2\eta}\,\dfrac{\rho_g \phi S}{\mathcal{P}_{capt} Q_g}\Delta p \end{cases} \longrightarrow \begin{cases} \tau = t/t_c \\ \xi = \ell/\ell_c \end{cases}$$

ACCRETION DYNAMICS



Time to increase ℓ of one grain diameter d_g

$$\delta\tau = \tau_{visc} + \tau_{capt}$$

$$u_{visc} = \frac{k}{\eta}\,\frac{\Delta p}{\ell} = \frac{d_g}{\tau_{visc}} \qquad u_{capt} = \frac{d_g\,\rho\,\phi\,S}{Q_g\,\mathcal{P}_{capt}} = \frac{d_g}{\tau_{capt}}$$

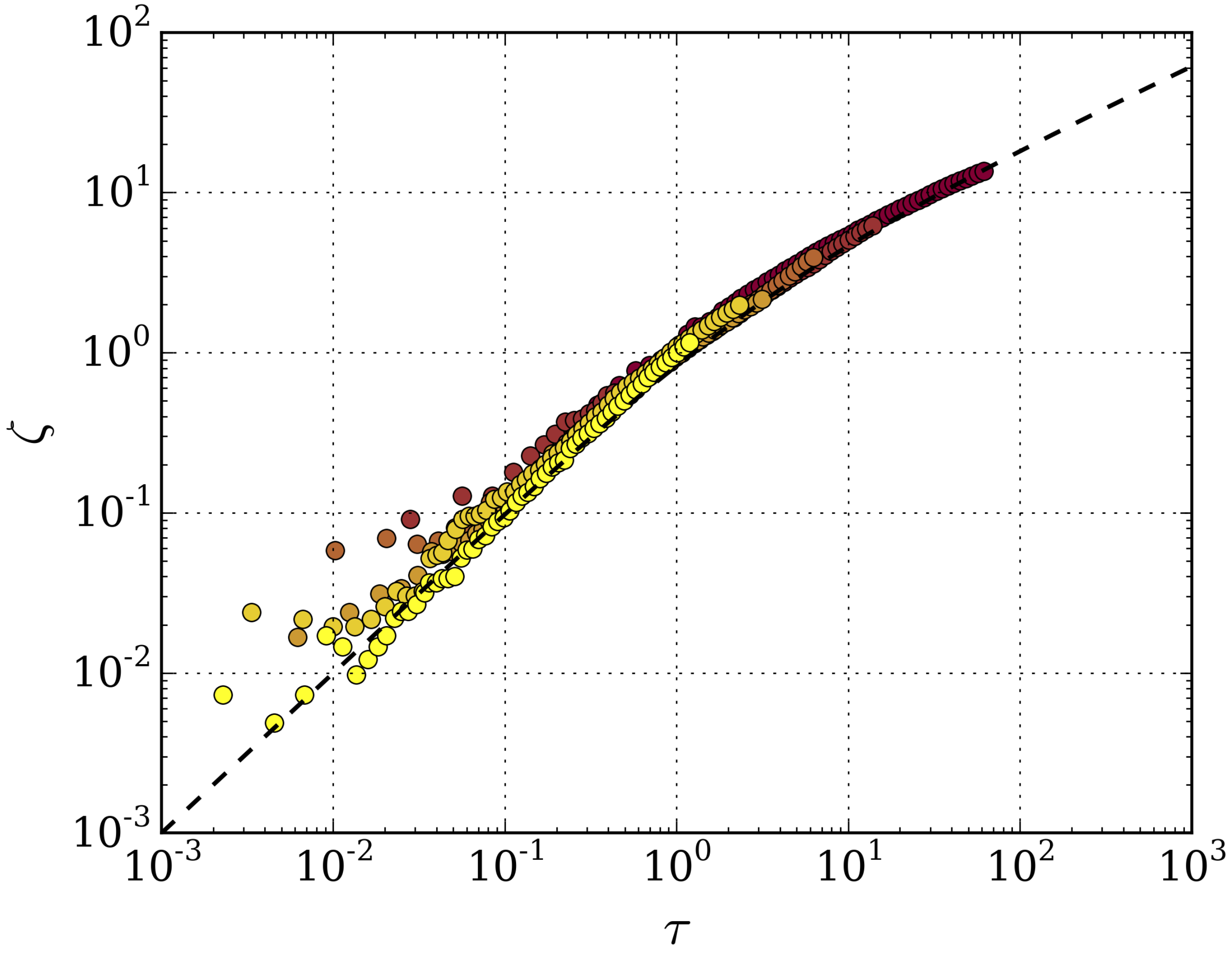
$$\frac{\mathrm{d}\ell}{\mathrm{d}t} = \frac{d_g}{\delta\tau}$$

$$\tau = t/t_c$$

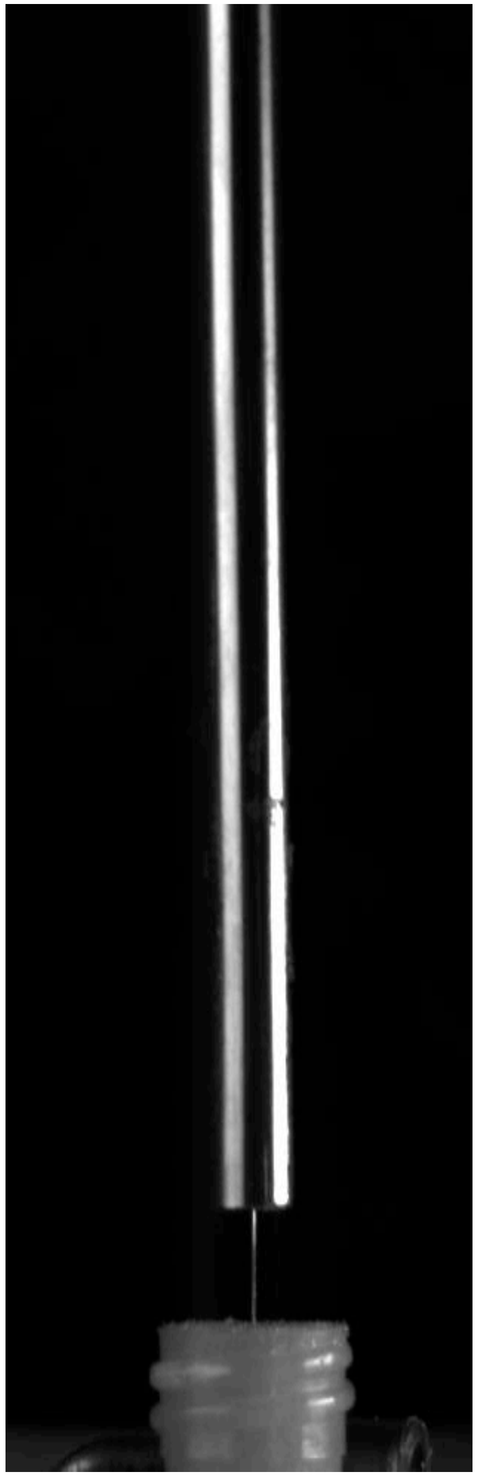
$$\xi = \ell/\ell_c$$

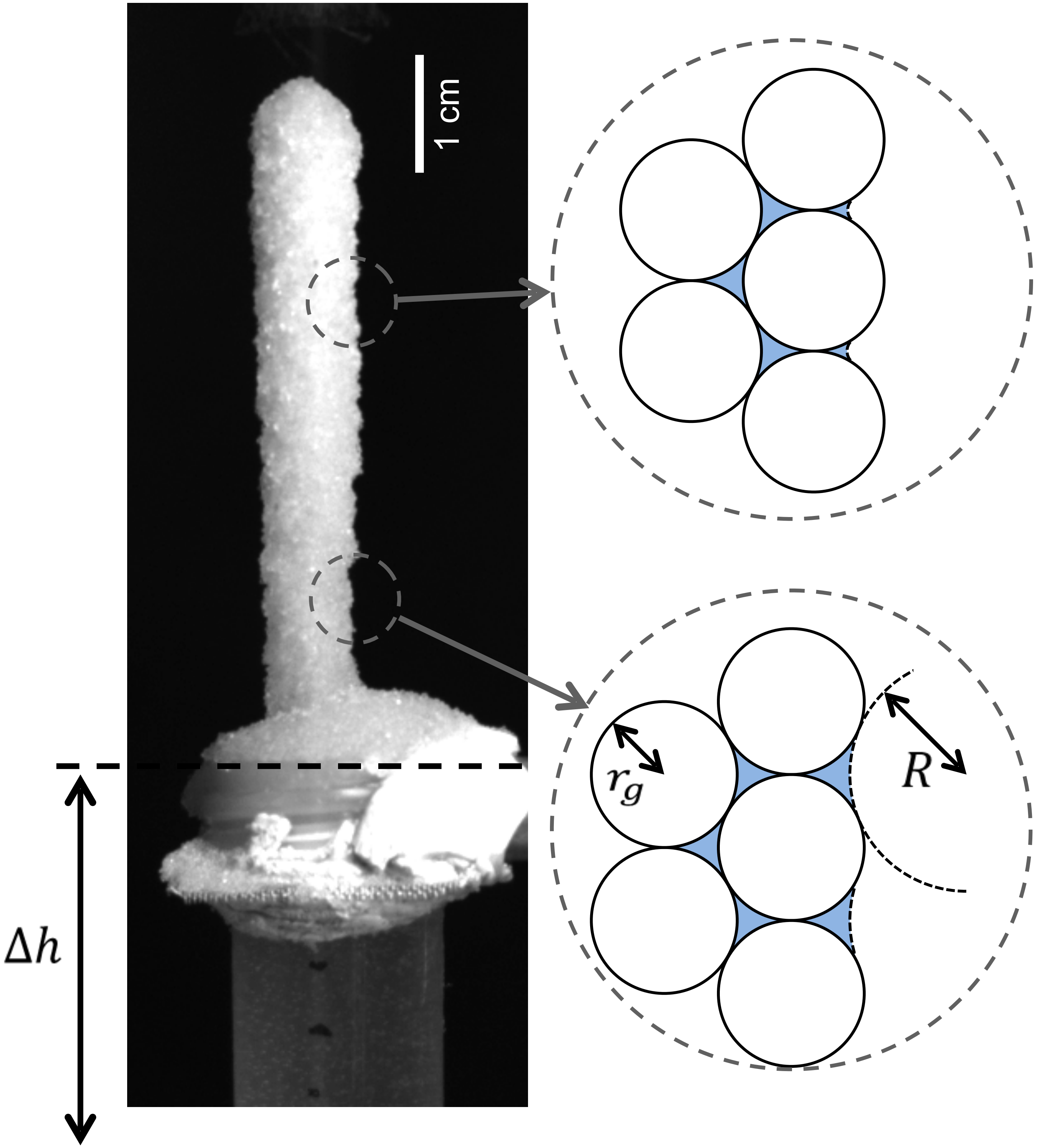
$$\frac{\mathrm{d}\zeta}{\mathrm{d}\tau} = \frac{1}{1+\zeta/2}$$

$$\boxed{\zeta(\tau) = 2(\sqrt{1+\tau} - 1)}$$



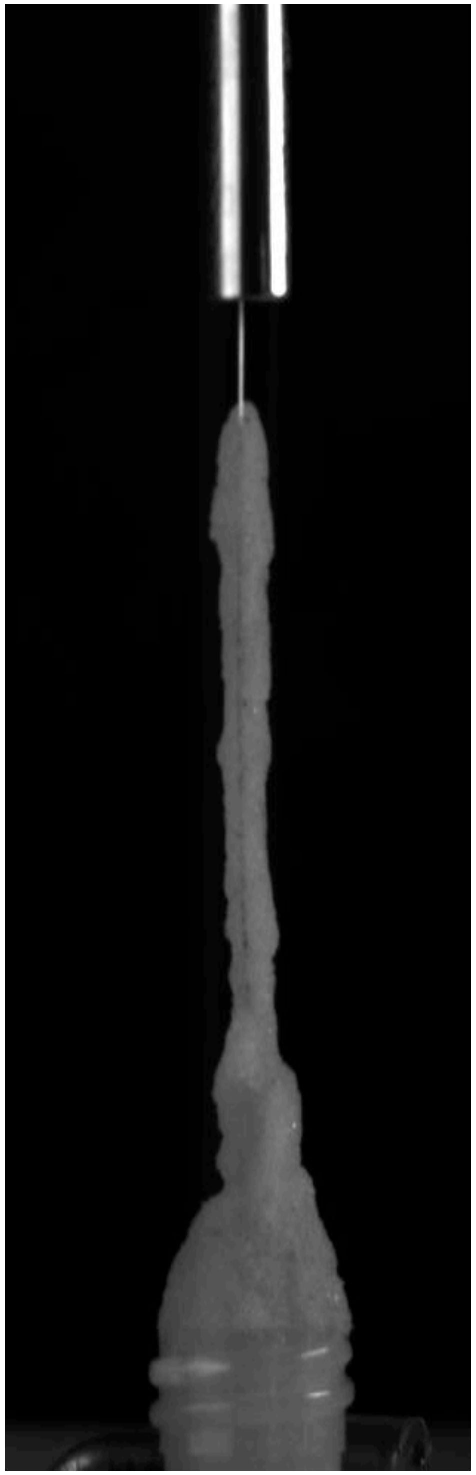
VERTICAL GROWTH: GRANULAR TOWERS





$$\mathcal{P}_{capt}(\Delta h) = \mathcal{P}_0 \exp\left(-\frac{\Delta h}{h^\star}\right)$$

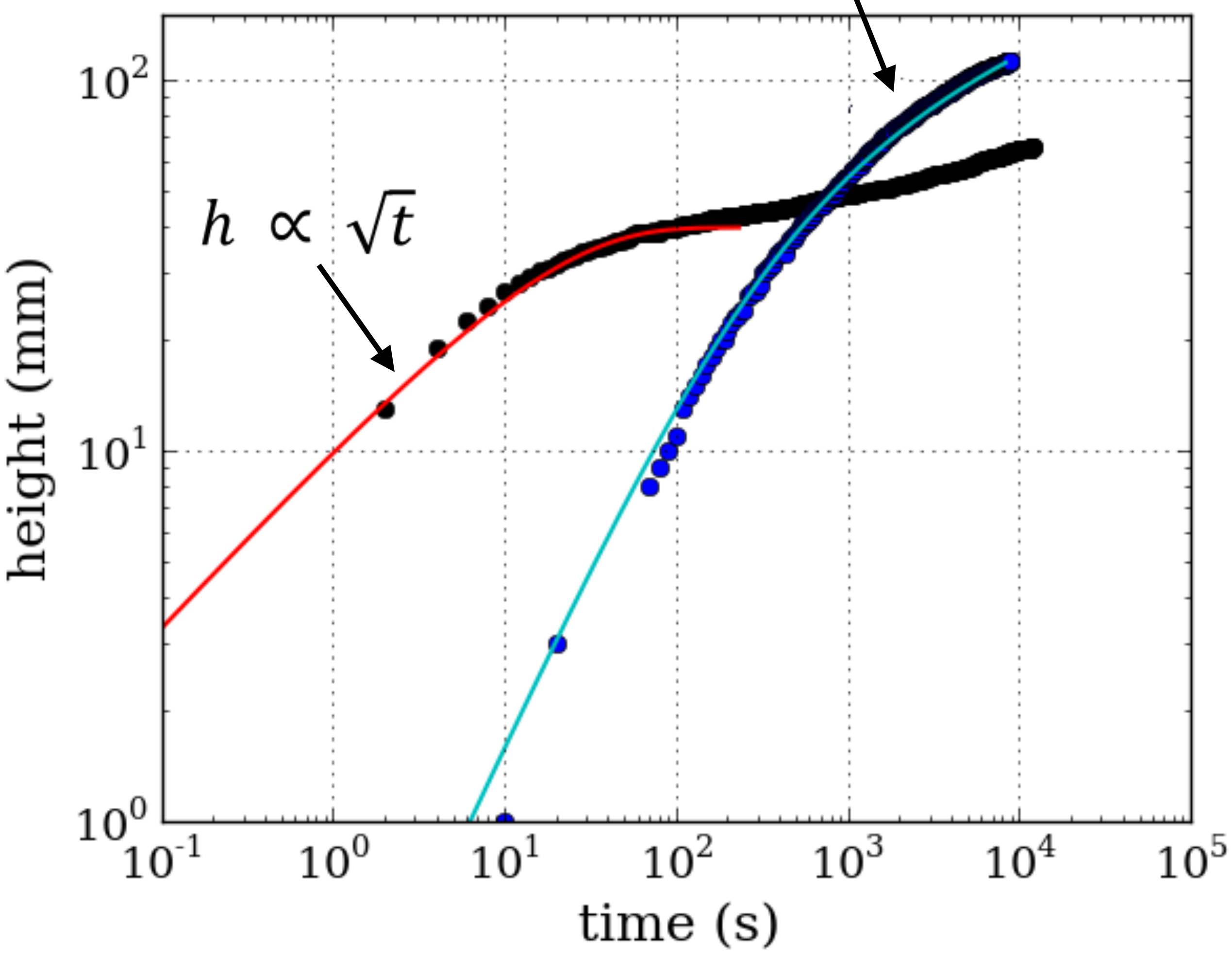
VERTICAL GROWTH: GRANULAR TOWERS



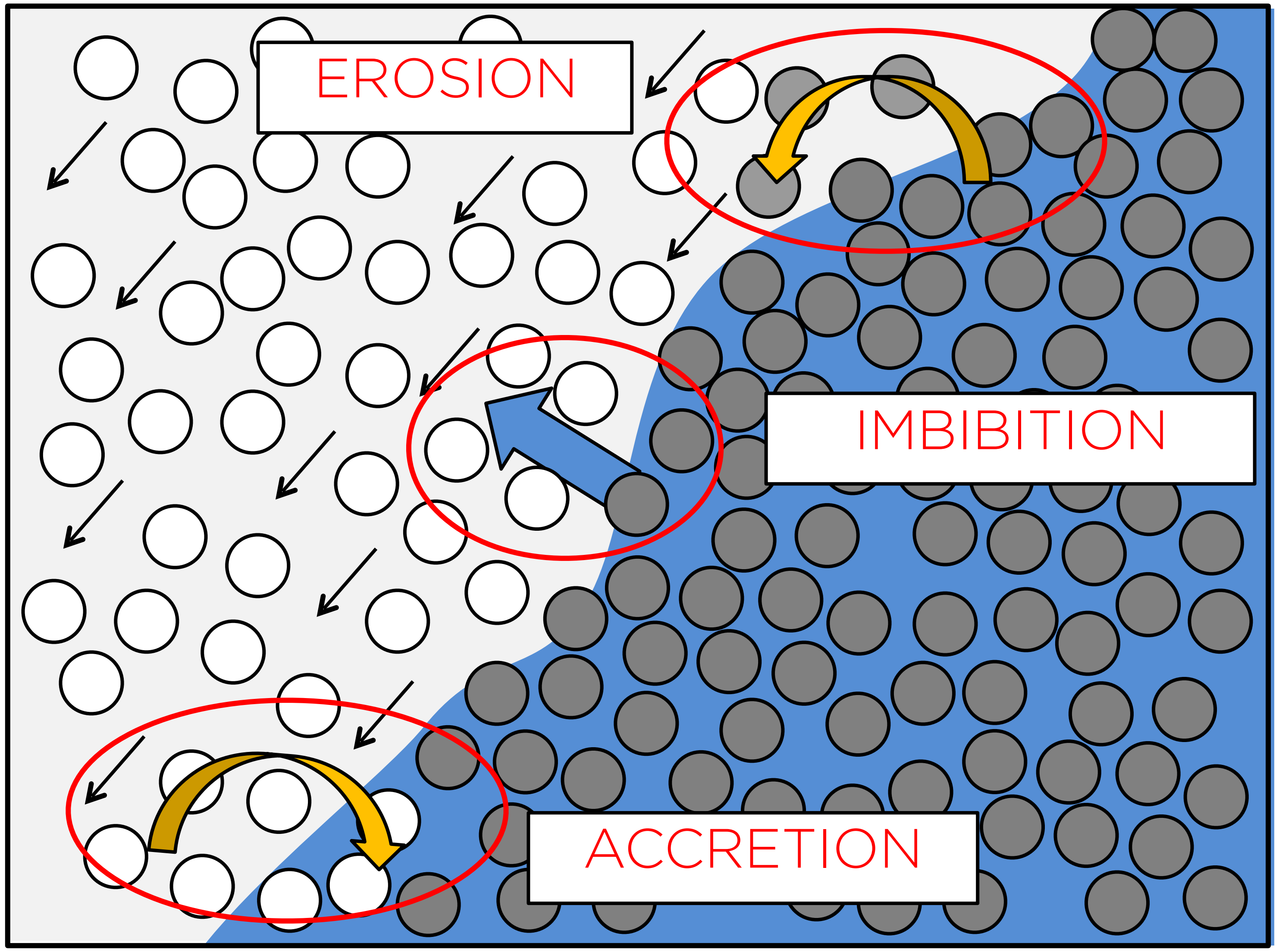
Capture probability related to the saturation rate

$$\mathcal{P}_{capt}(\Delta h) = \mathcal{P}_0 \exp\left(-\frac{\Delta h}{h^\star}\right) \longrightarrow v(h) = v_0 \exp\left(-\frac{h}{h^*}\right)$$

$$\longrightarrow h(t) = h^* \ln\left(1 + \frac{V_0}{h^*} t\right)$$



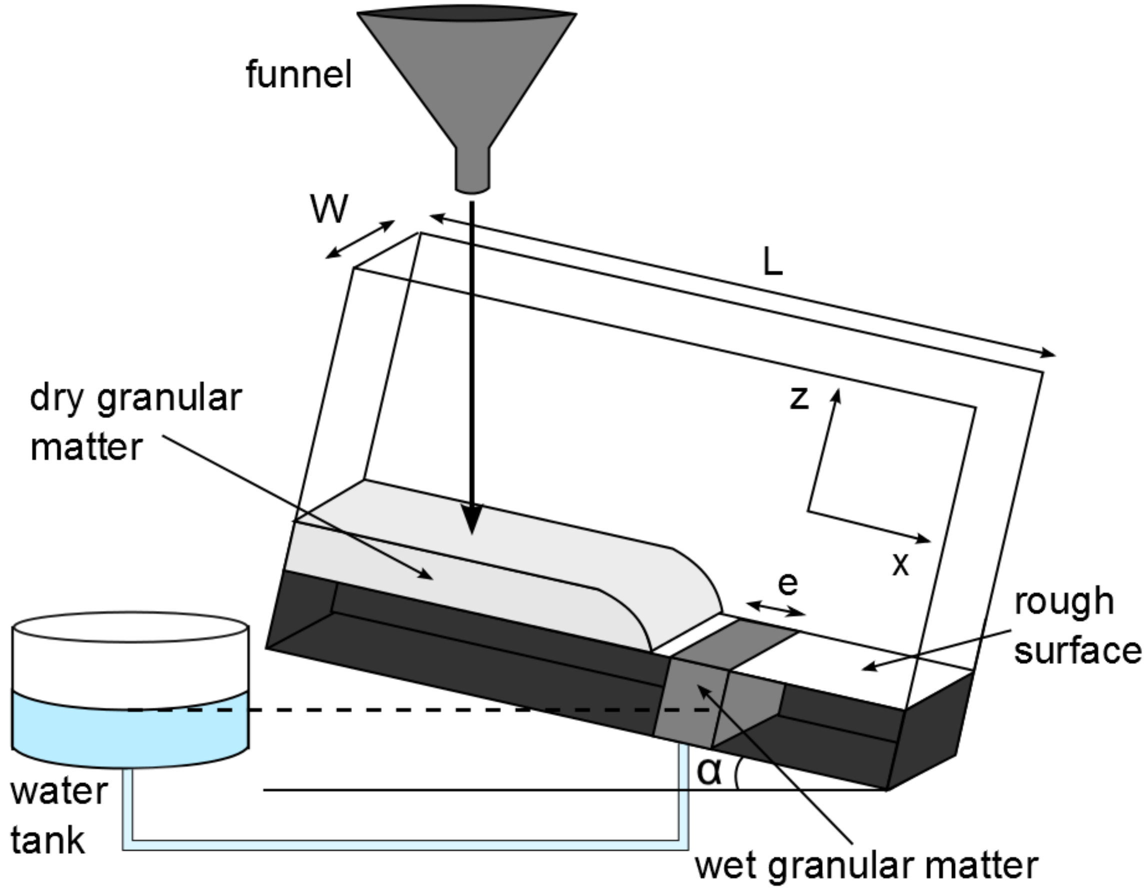
INTERACTION BETWEEN A GRANULAR FLOW AND A LIQUID

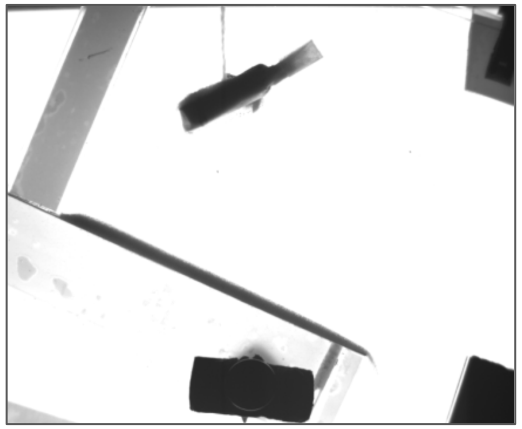


dry granular
flow

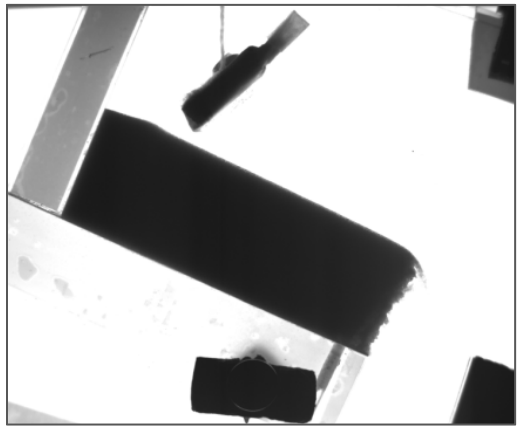
cohesive wet
grains

DENSE FLOW

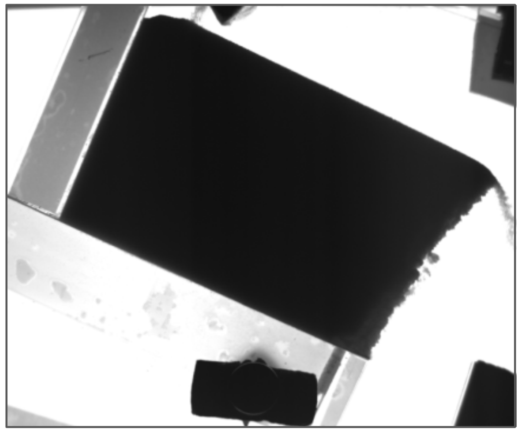




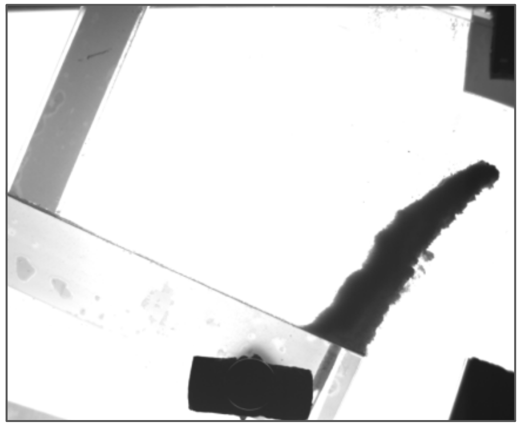
t = 0 min



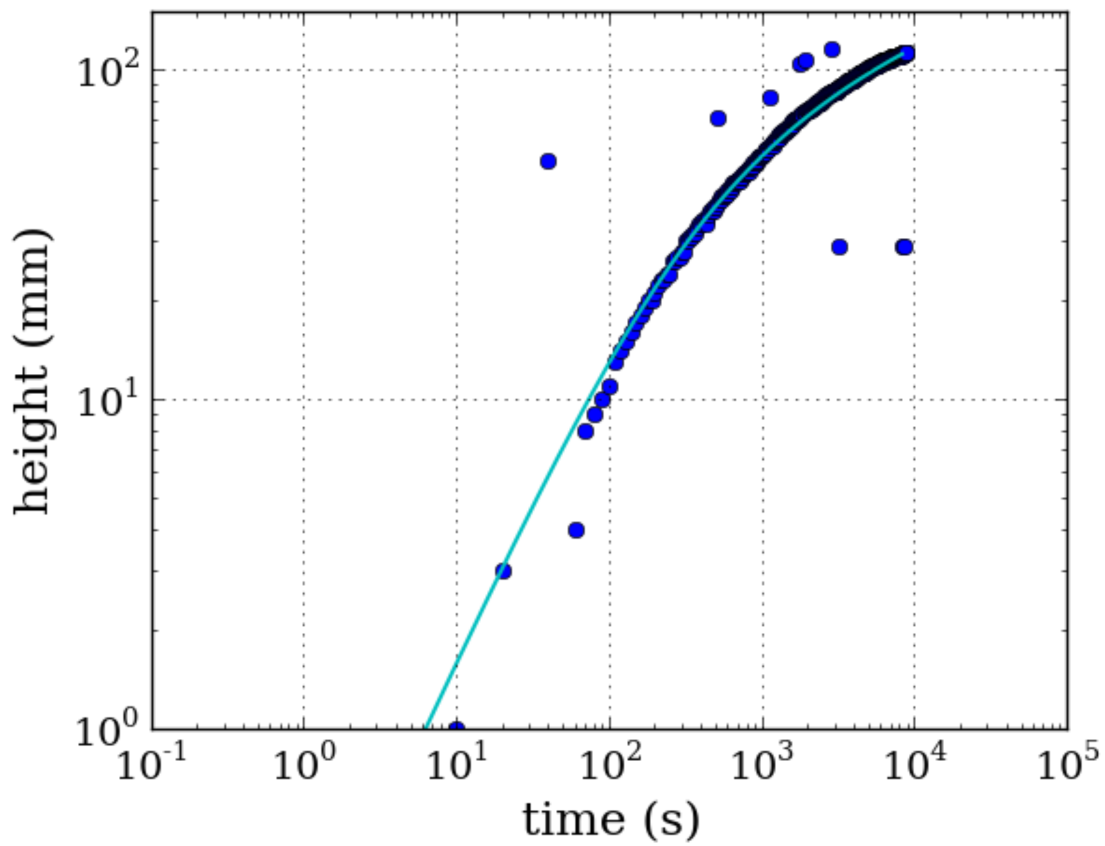
t = 15 min



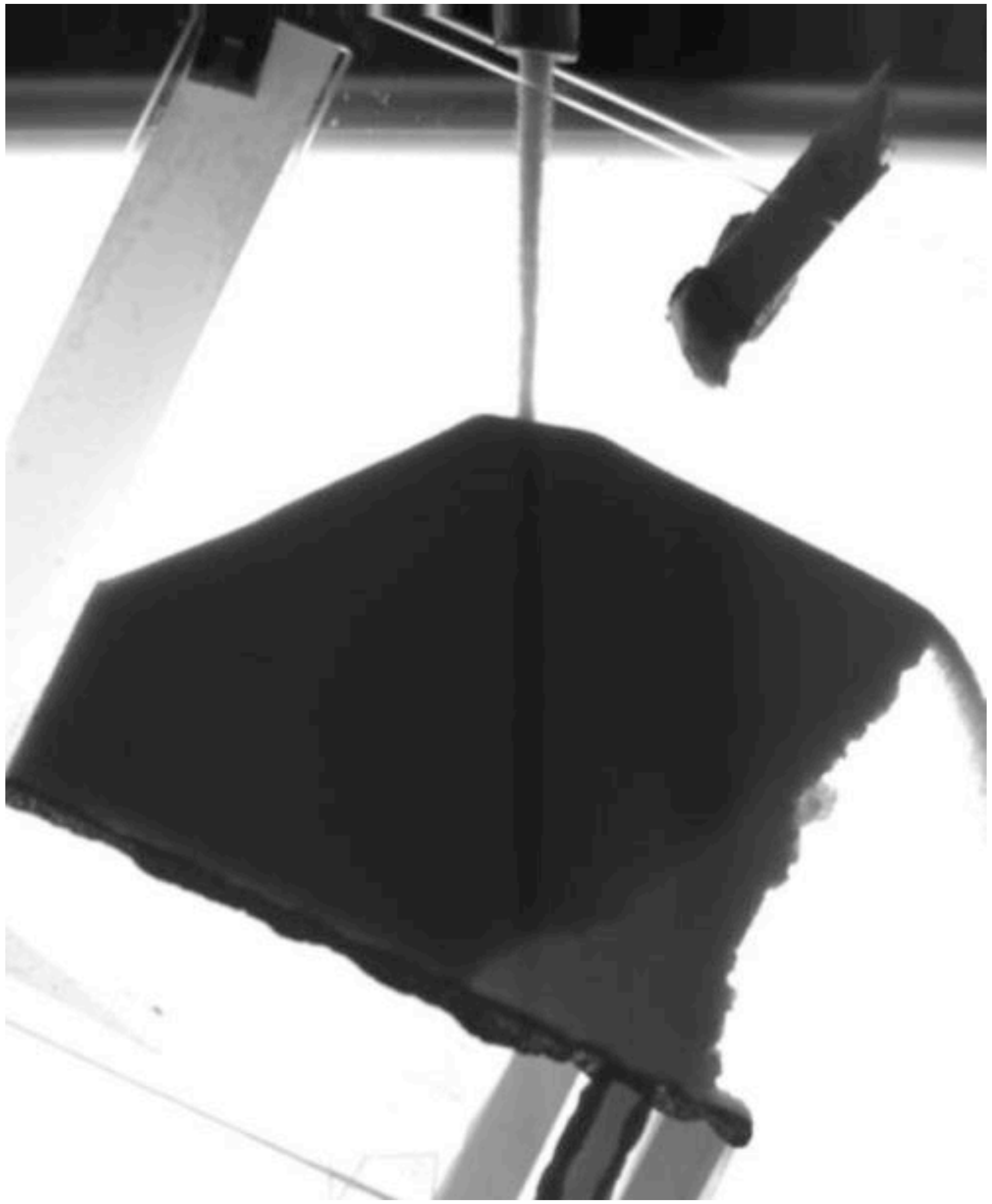
t = 2 h

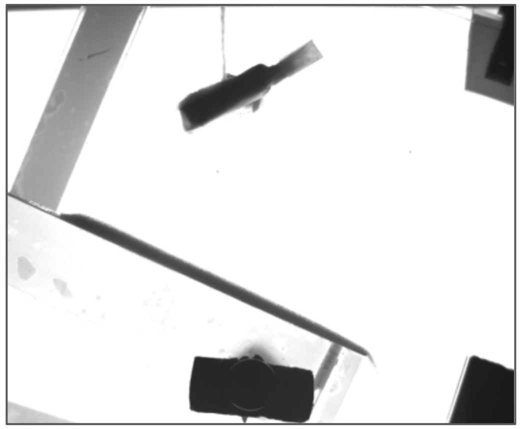


DENSE FLOW

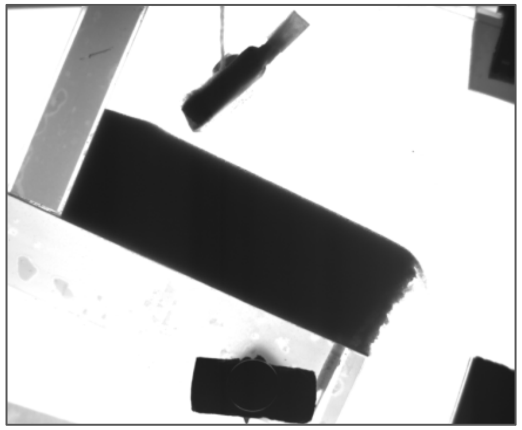


$$h(t) = h^* \ln\left(1 + \frac{V_0}{h^*} t\right)$$

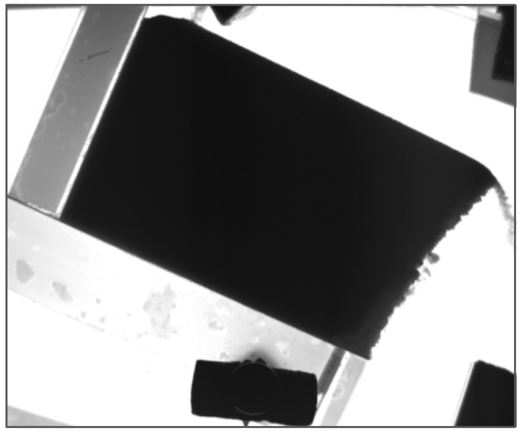




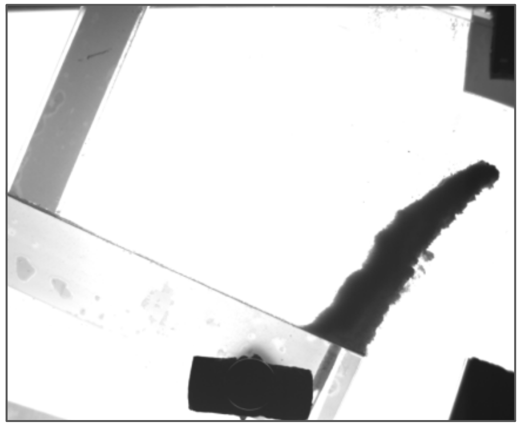
t = 0 min



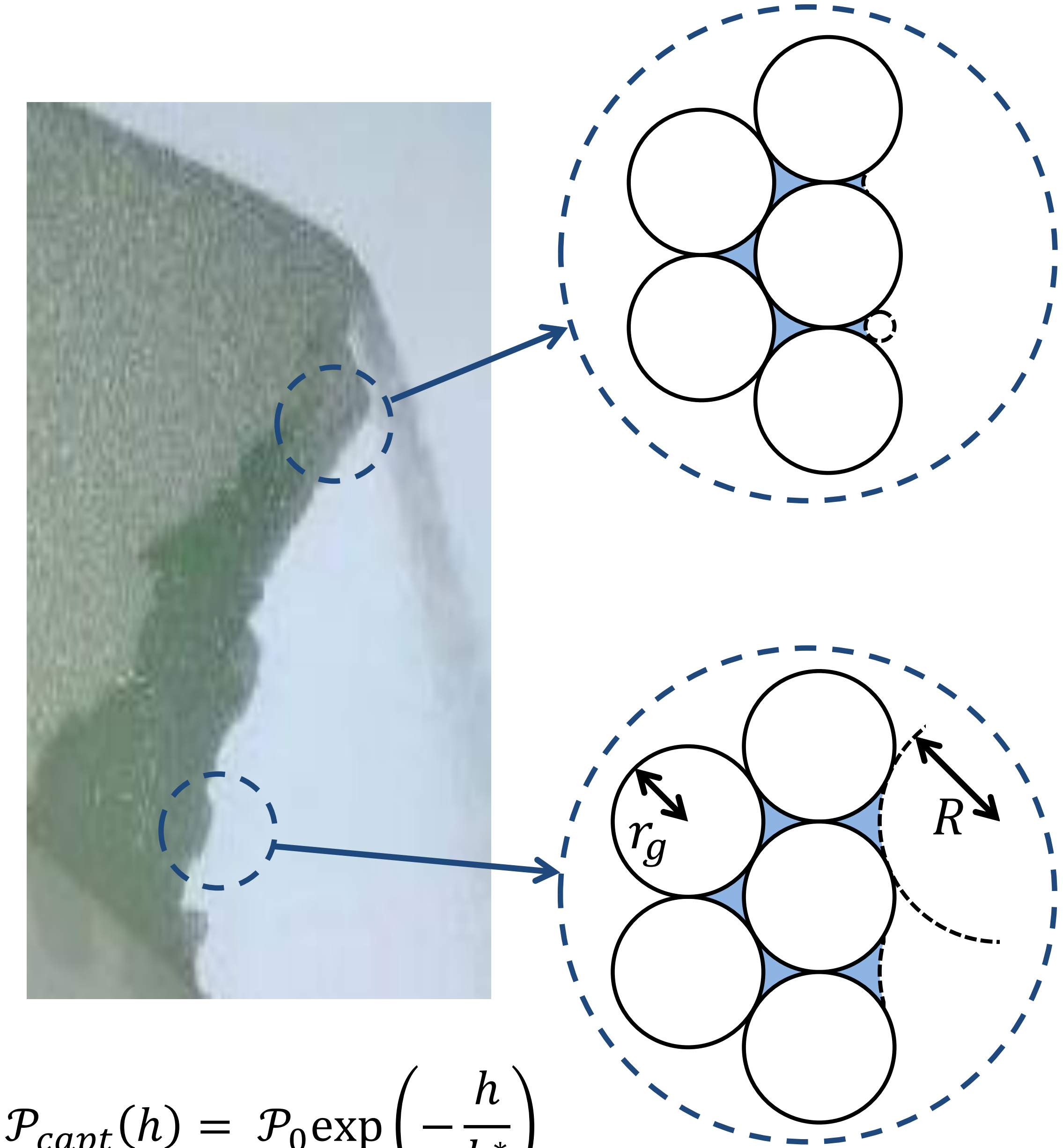
t = 15 min



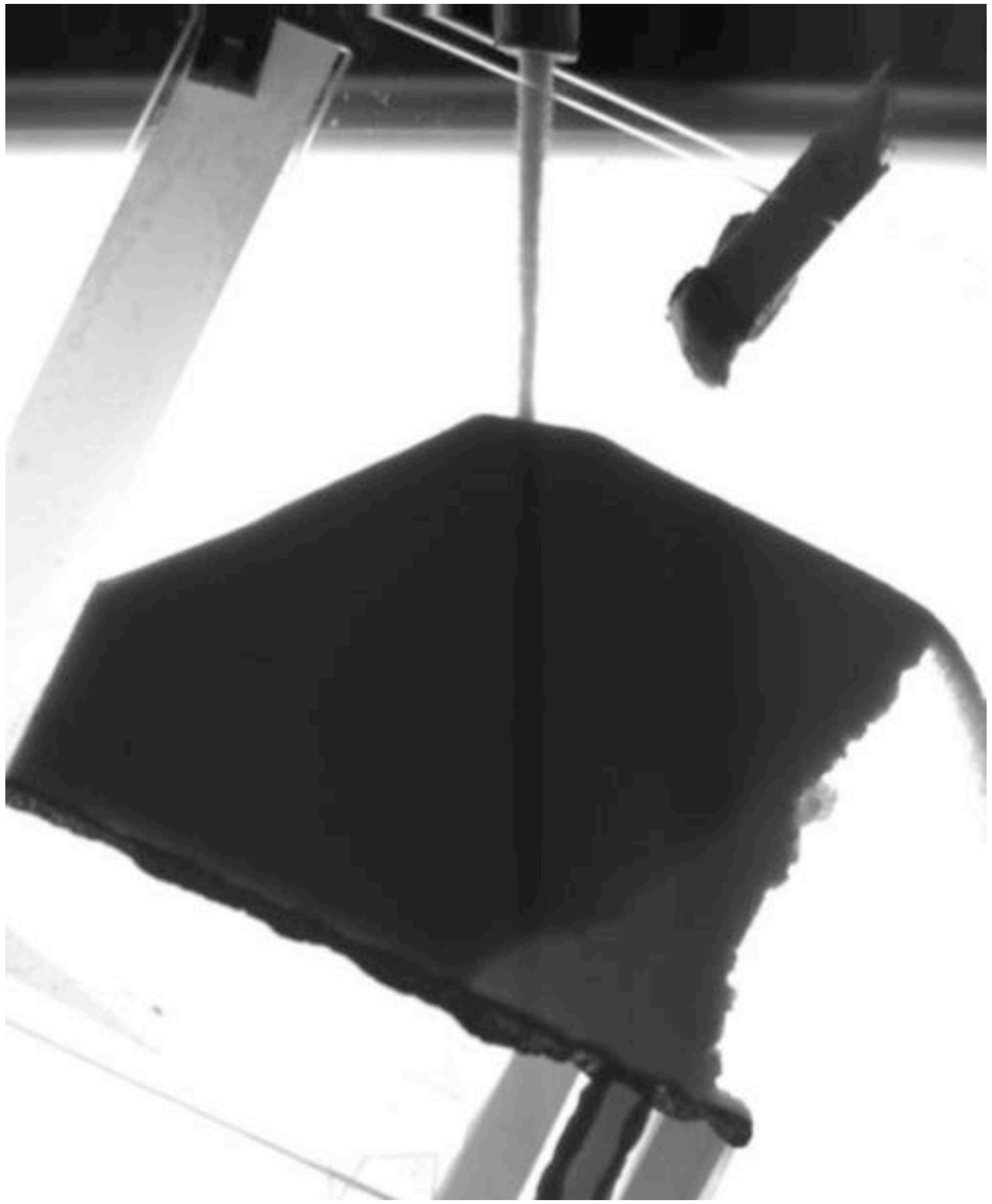
t = 2 h

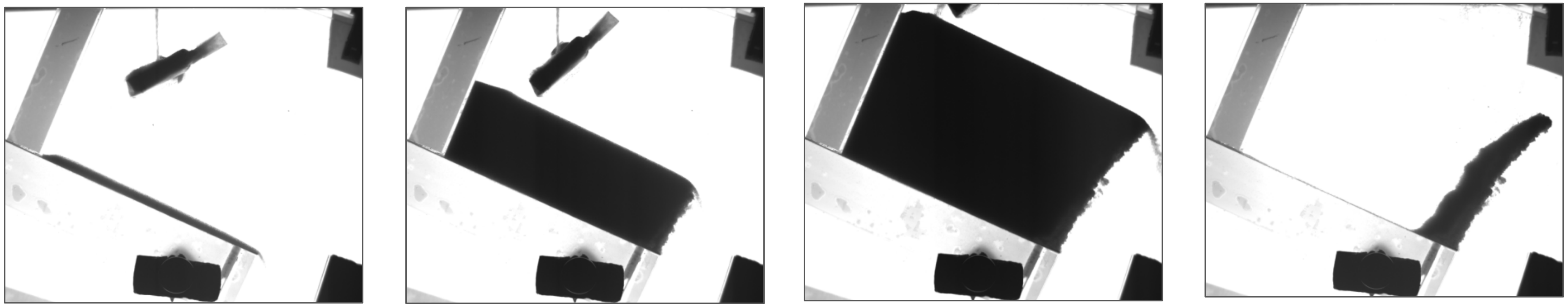


DENSE FLOW



$$\mathcal{P}_{capt}(h) = \mathcal{P}_0 \exp\left(-\frac{h}{h^*}\right)$$





t = 0 min

t = 15 min

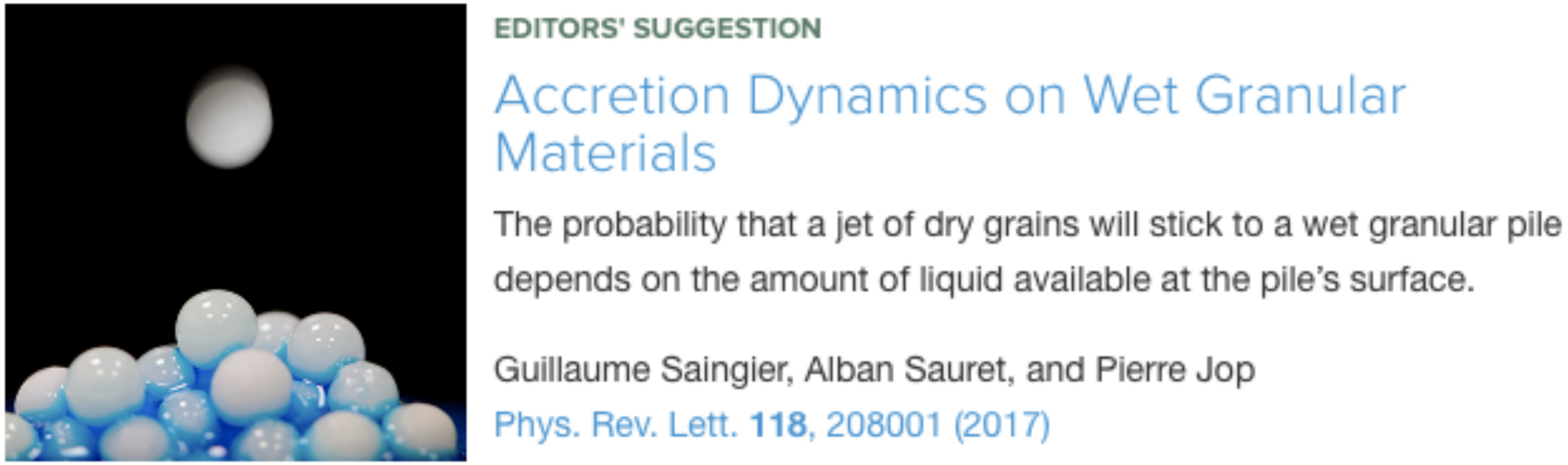
t = 2 h

SUMMARY

- Accretion: local phenomenon associated to the curvature of the meniscus
- Two regimes :

viscous: limited by the fluid flow in the porous media

capture: limited by trapping efficiency



EDITORS' SUGGESTION

Accretion Dynamics on Wet Granular Materials

The probability that a jet of dry grains will stick to a wet granular pile depends on the amount of liquid available at the pile's surface.

Guillaume Saingier, Alban Sauret, and Pierre Jop

Phys. Rev. Lett. **118**, 208001 (2017)

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LETTERS

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SUMMARY

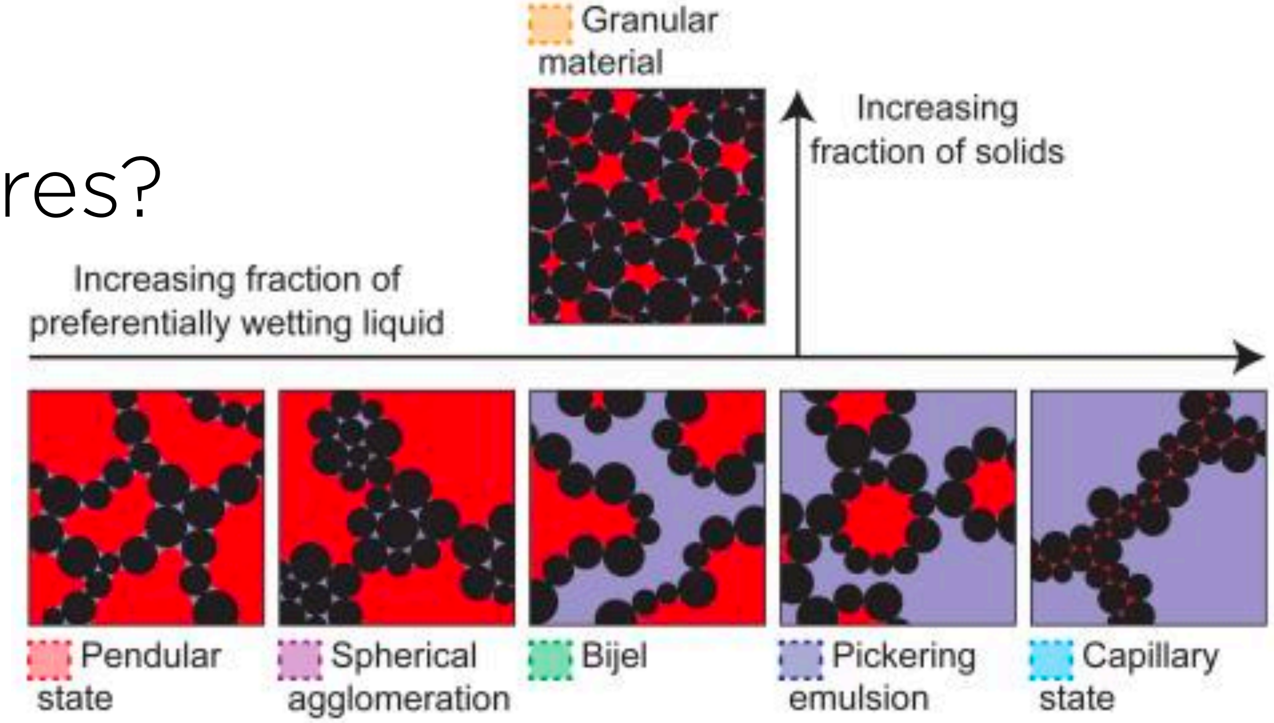
- Accretion: local phenomenon associated to the curvature of the meniscus
- Two regimes :

viscous: limited by the fluid flow in the porous media
capture: limited by trapping efficiency

Many open questions : three-phase systems

- How does the morphology of the grains/liquid mixture couple with its rheology ?
- How does the reorganization of the capillary bridges affect the rheology ?

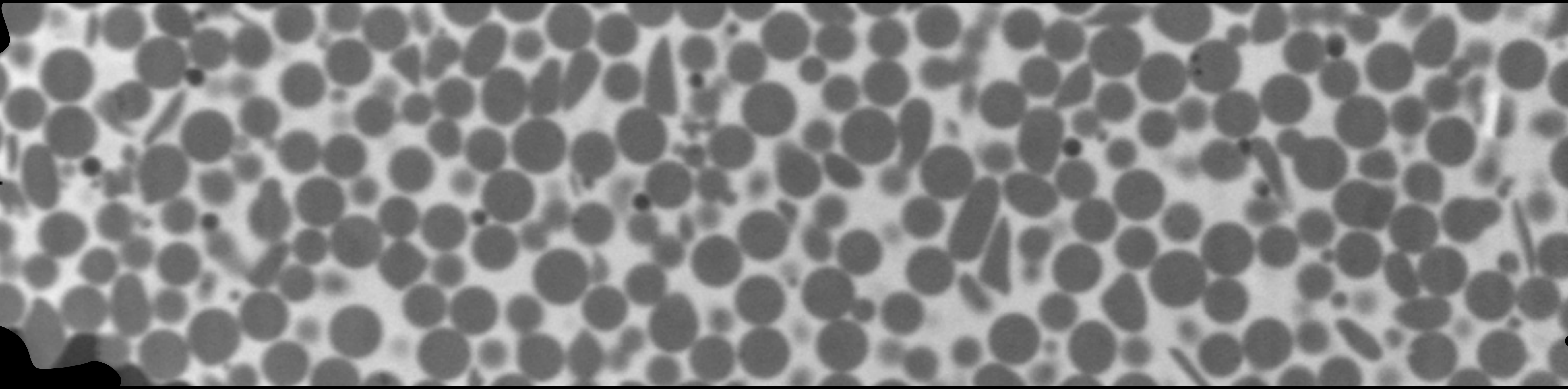
- Liquid/Liquid/Particles mixtures?



Koos & Willenbacher, Science (2011)
Koos, Curr. Opin. Colloid Interface Sci. (2014)

BLENDING LIQUID AND GRAINS

ACCRETION DYNAMICS ON WET GRANULAR MATERIALS



G. Saingier, P. Jop

P. Raux, A. Troger; M. Gomez, B. Colnet, M. Bazant, H. A. Stone, E. Dressaire

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