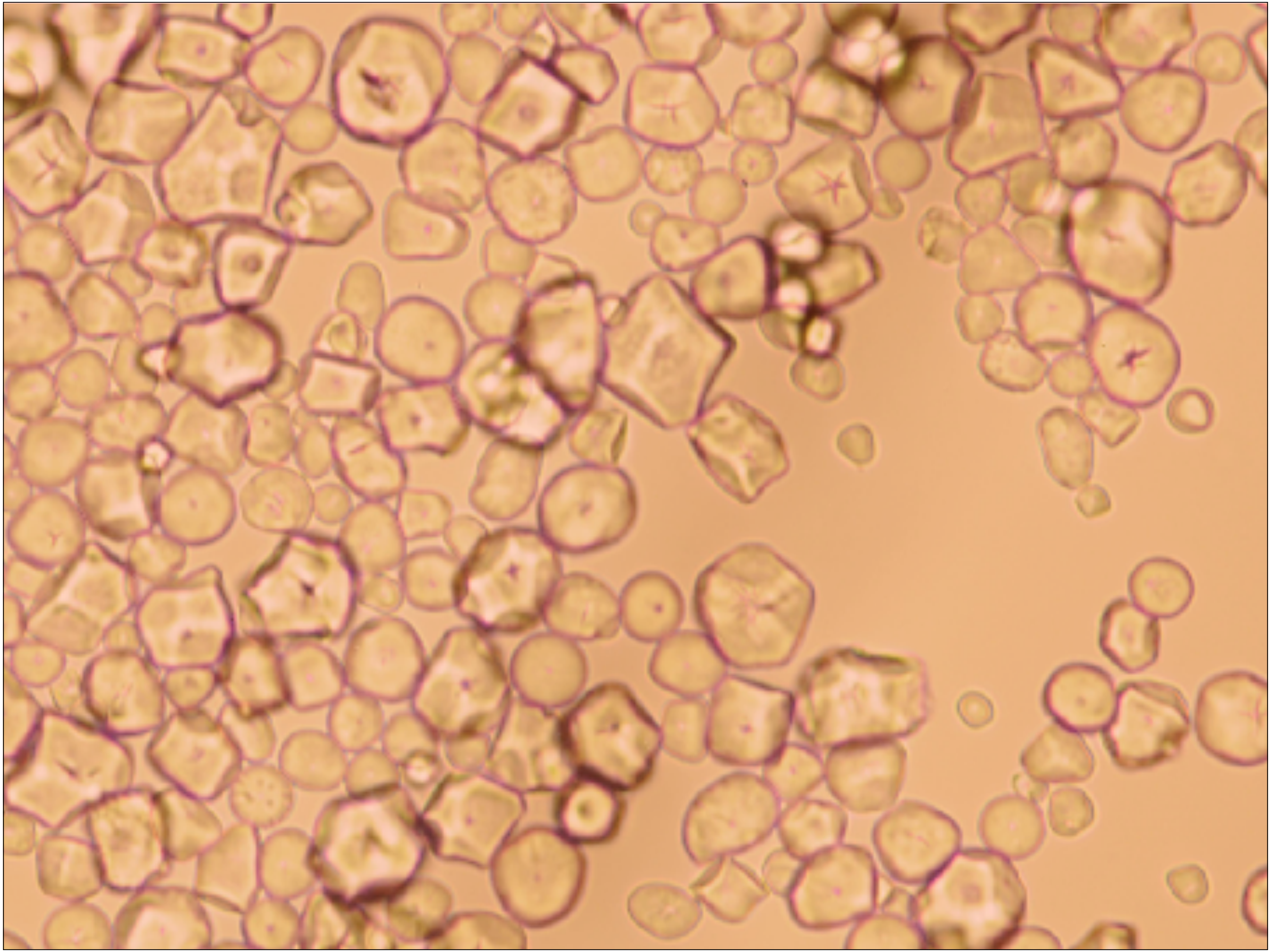
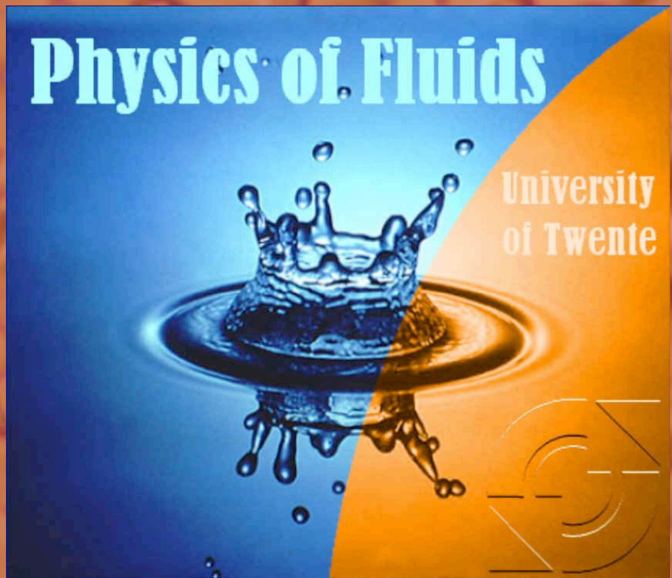


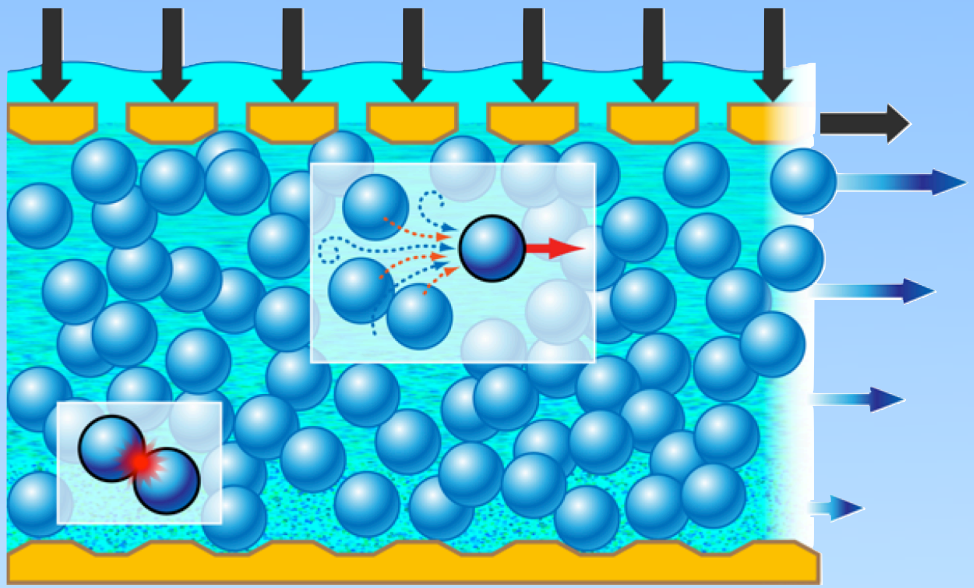
Cornstarch and other suspensions from a different perspective



Devaraj van der Meer
Stefan von Kann
Ceyda Sanli
Jacco Snoeijer
Detlef Lohse

Physics of Fluids – University of Twente – The Netherlands

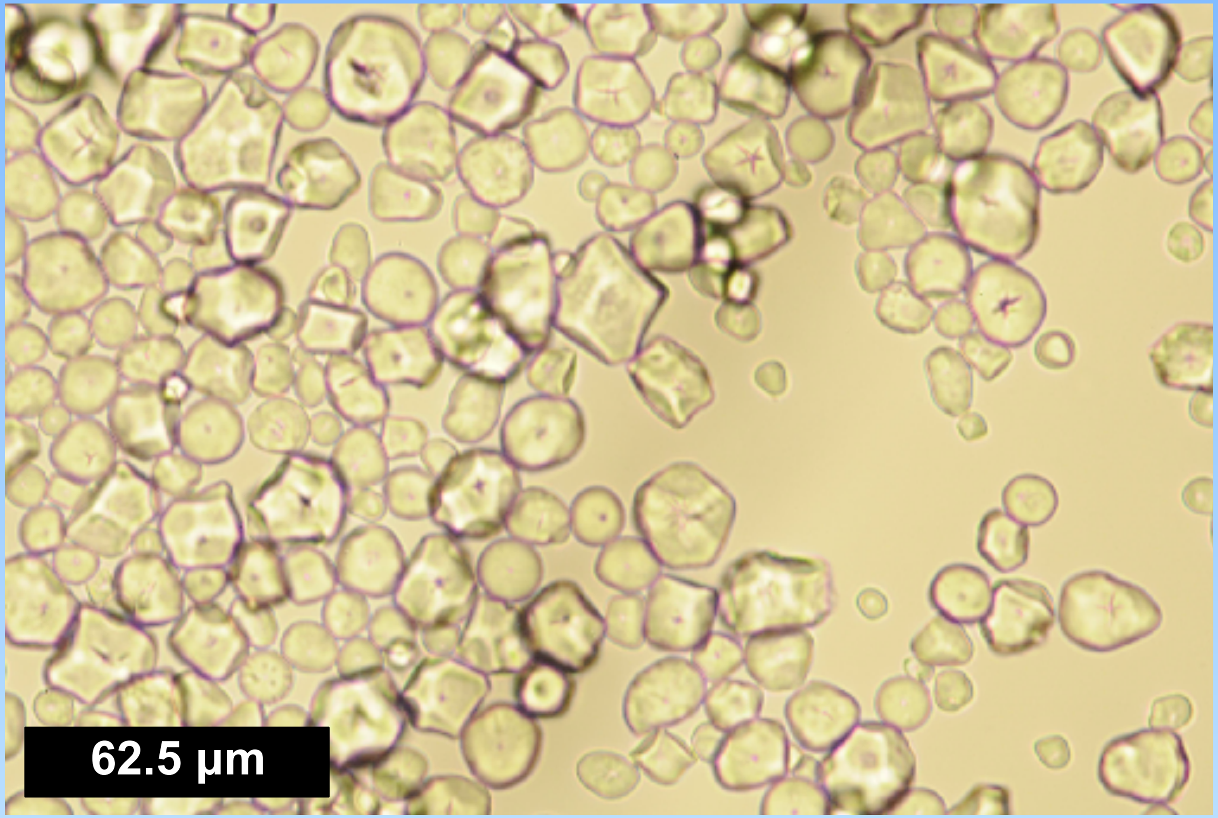
Suspensions:
A rheologist's view versus ?



What if we took the same materials for a completely different experiment?

typical rheological experiment:
well defined geometry, with
optimally controlled γ, σ_t, σ_n

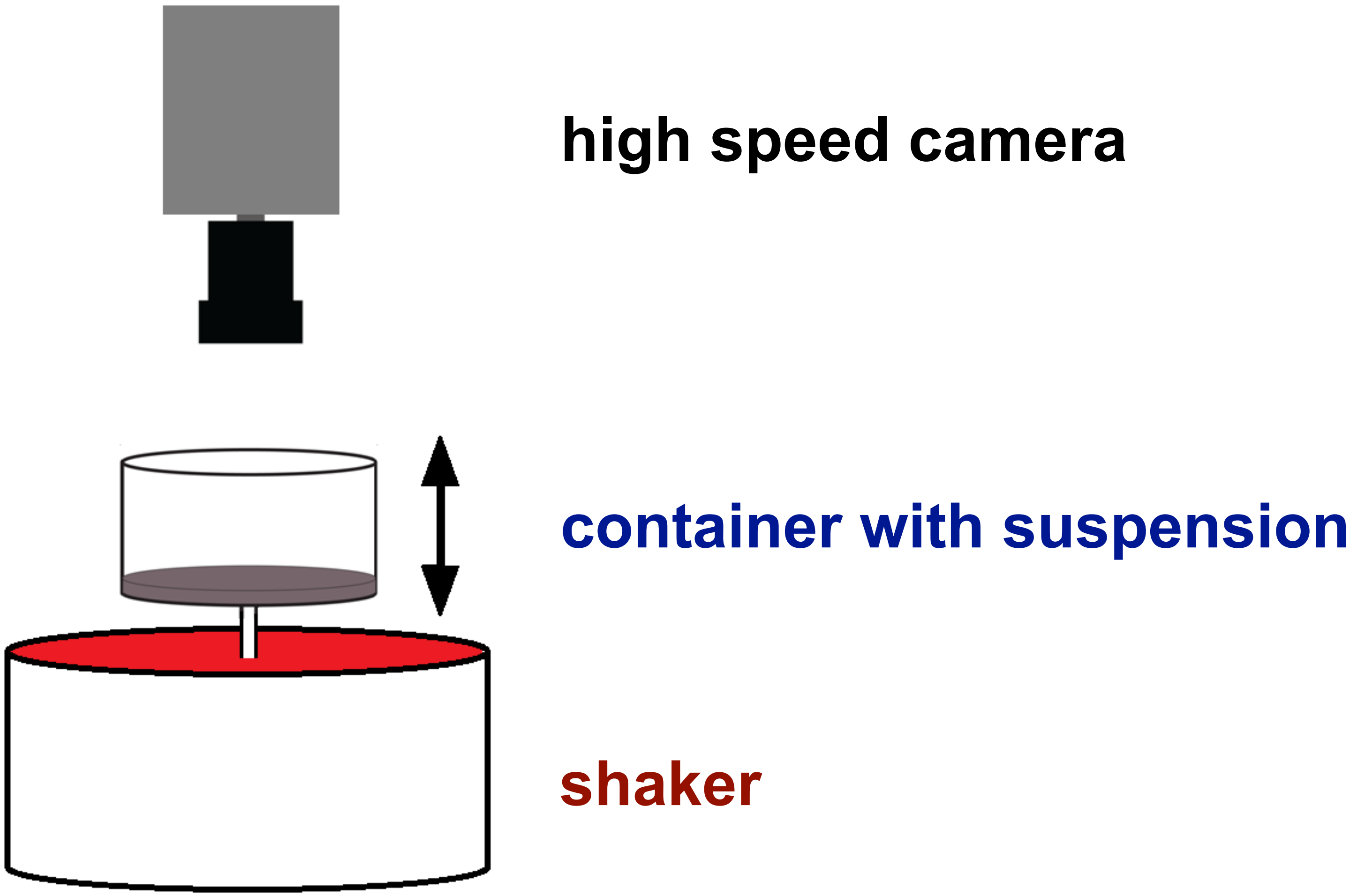
Cornstarch



diameter: 5-20 µm,
flat distribution of sizes (numbers)
Irregular shapes
ρ = 1.5 g/cm^3

"shear thickening suspension"

First experiment

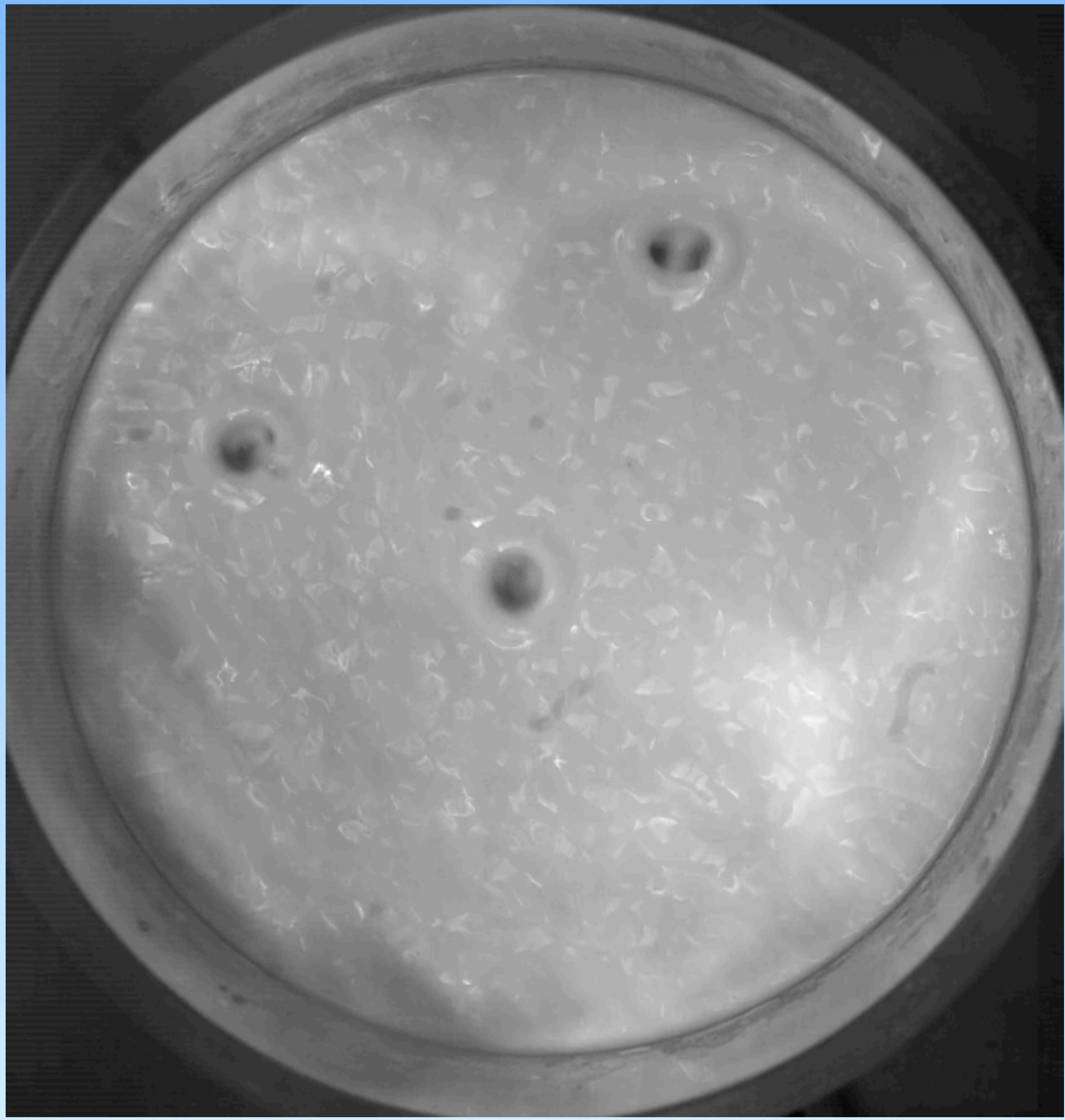


Shaken cornstarch 1

jumping liquid

40 Hz
30 g

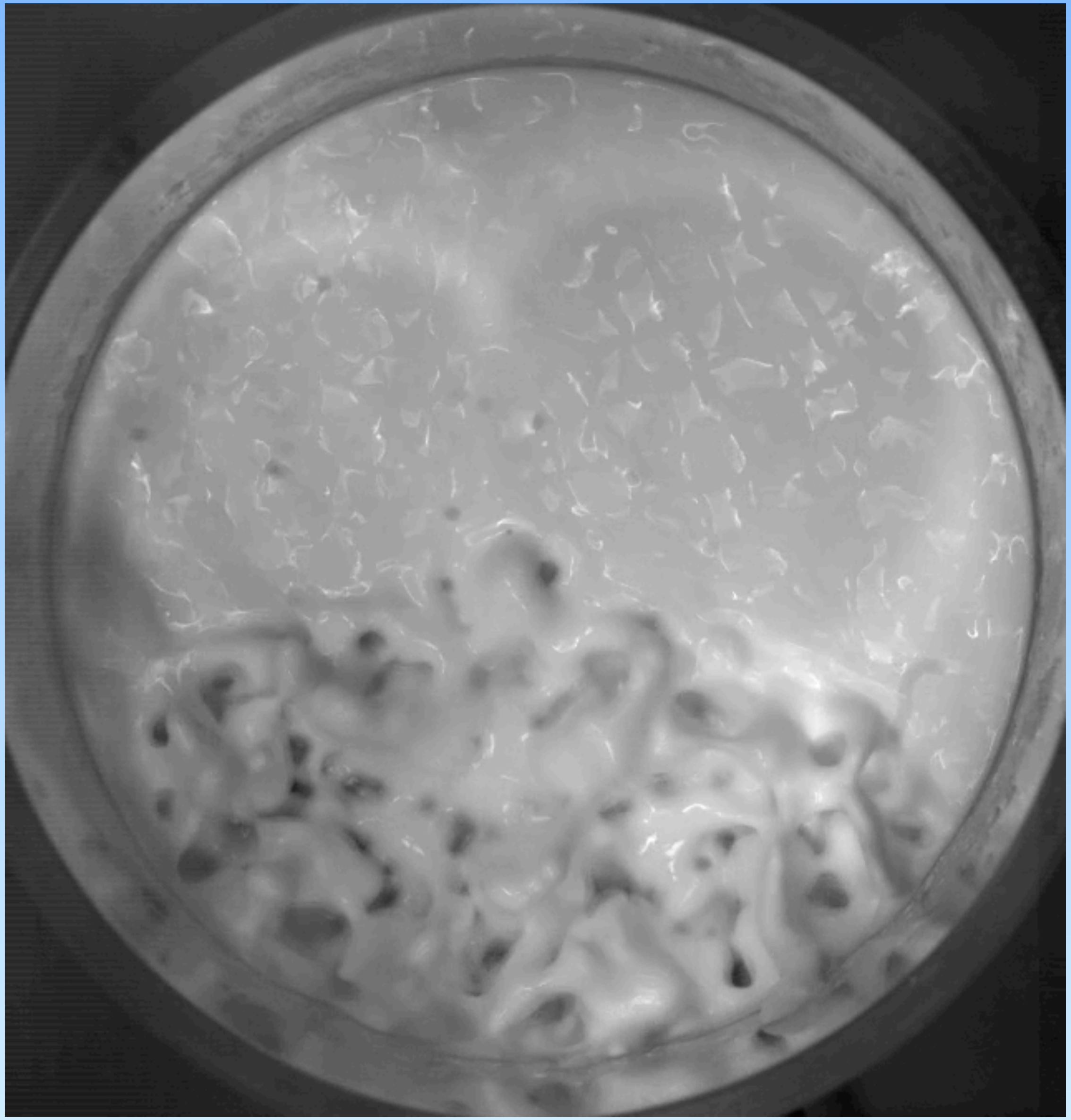
Shaken cornstarch 2



stable holes

80 Hz
20 *g*

Shaken cornstarch 3

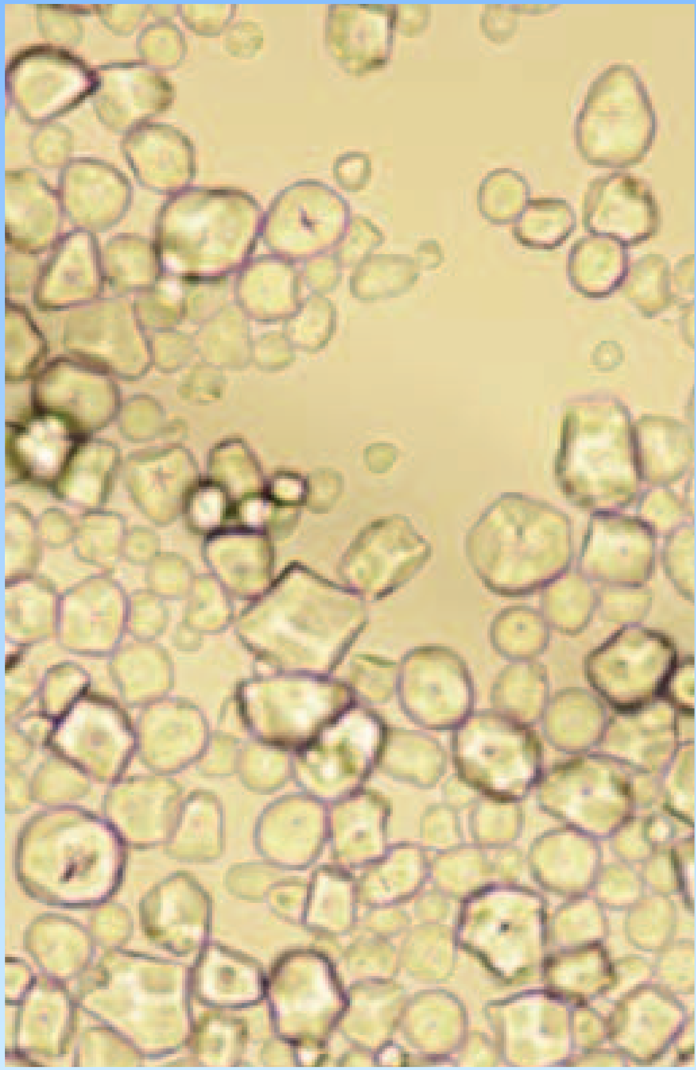


fingers

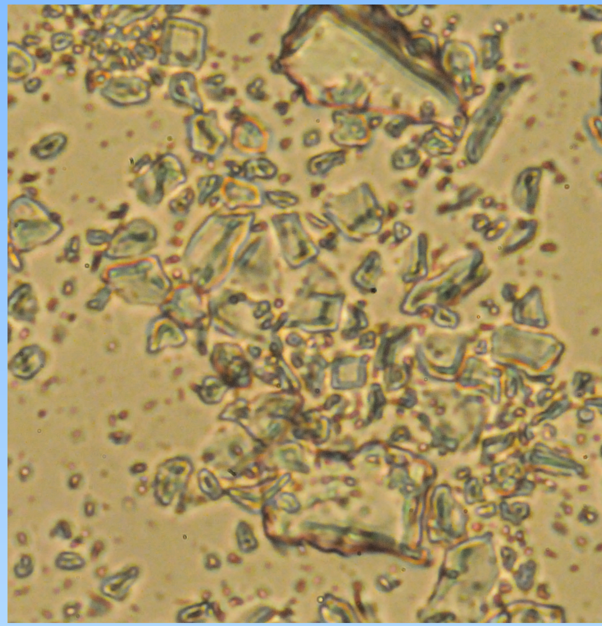
80 Hz
30 g

Other suspensions

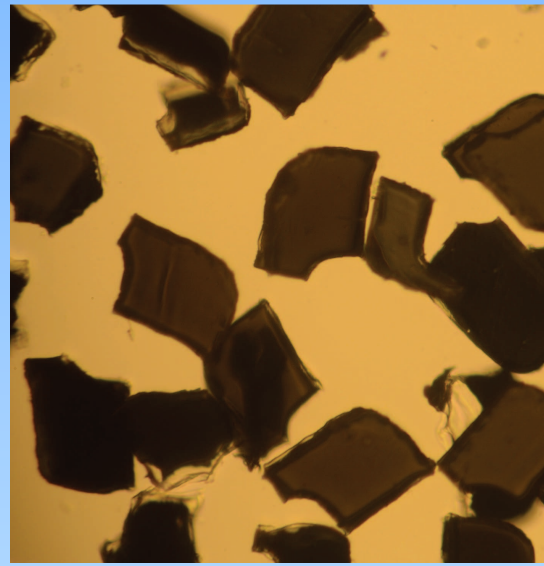
cornstarch



quartz flour

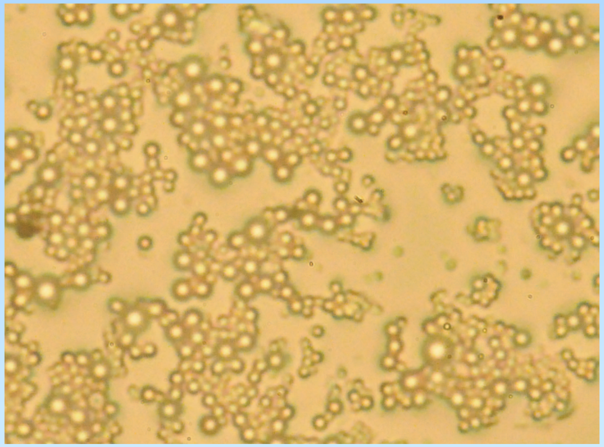


glitter platelets

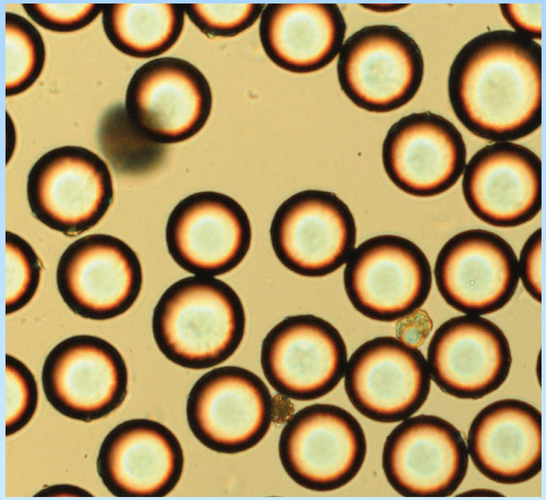


cornstarch

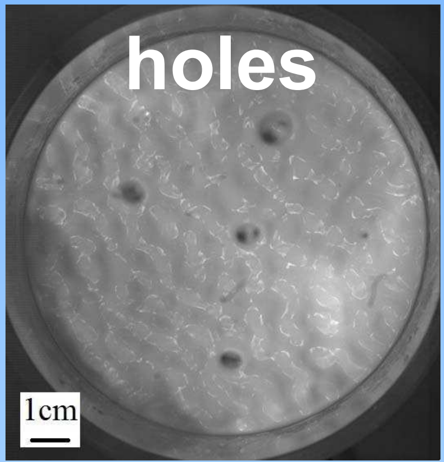
polydisperse silica

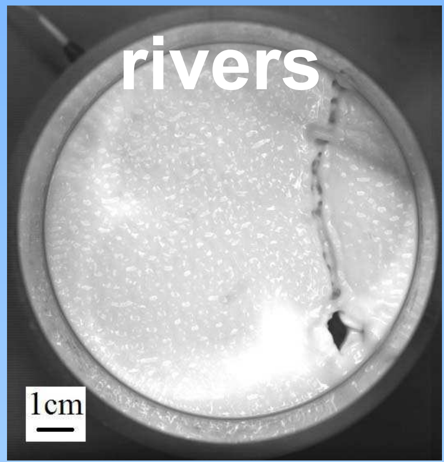


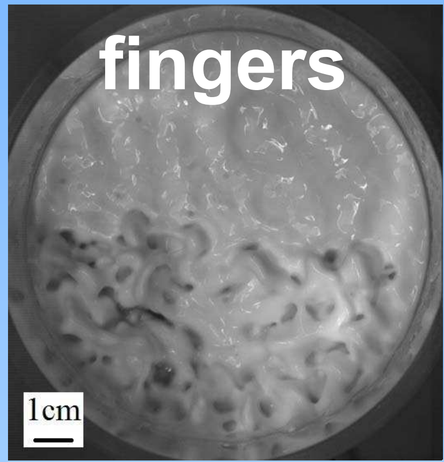
monodisp. silica

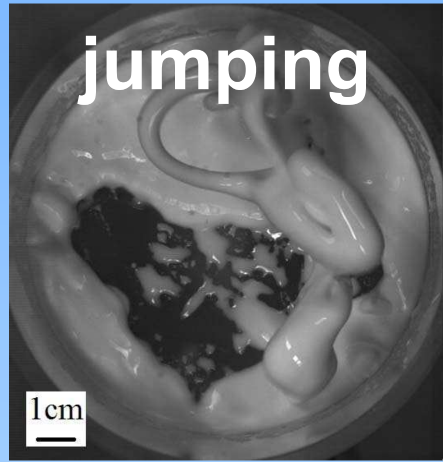


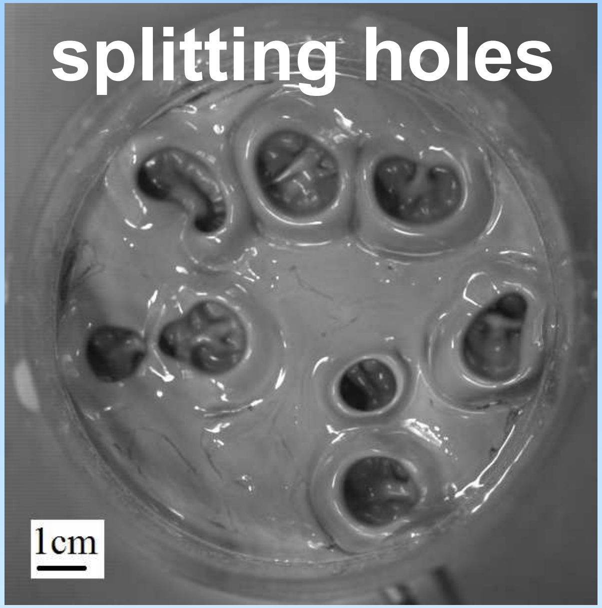
Shaken suspensions

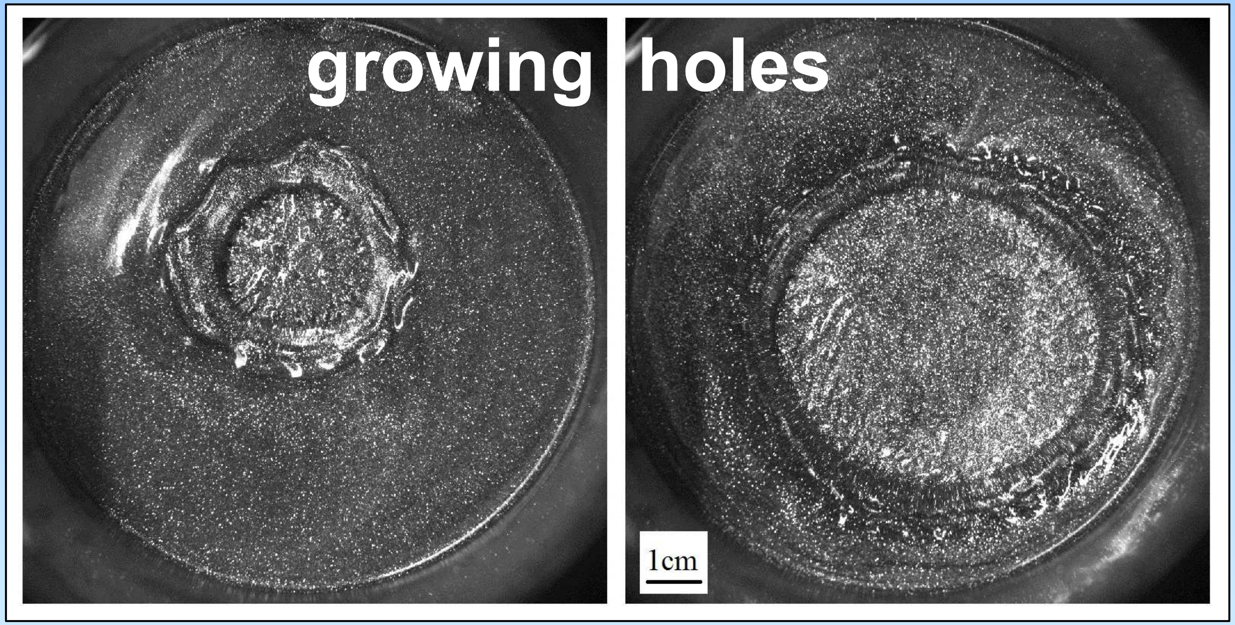






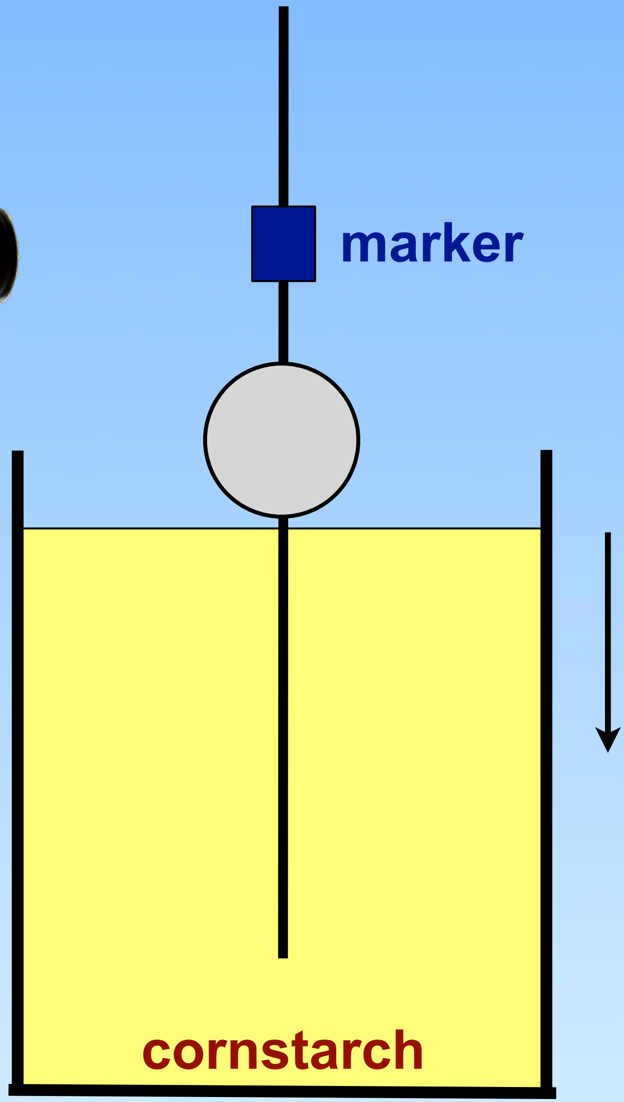






Second experiment

high-speed
camera

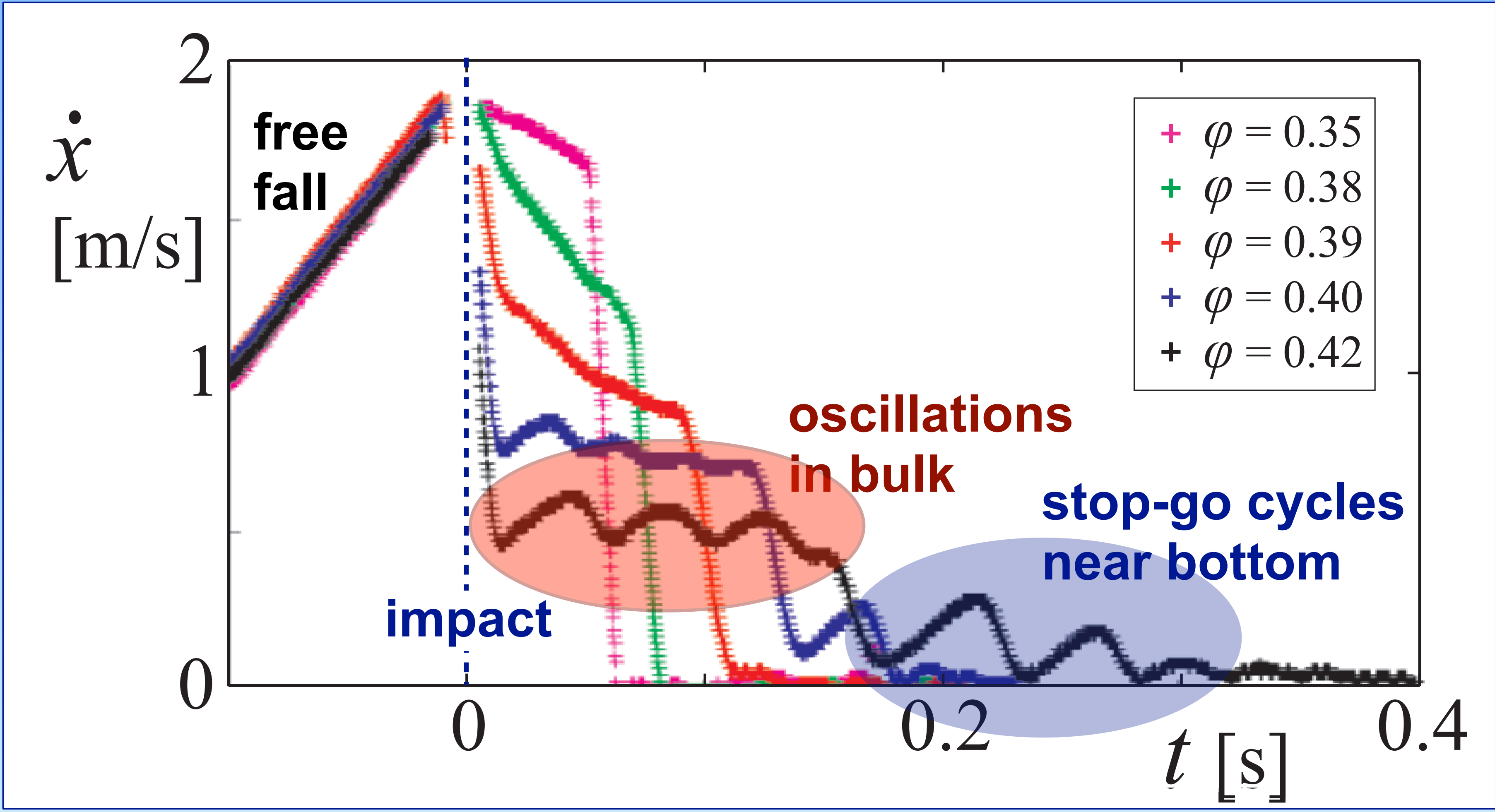


$x(t)$ (depth sphere
inside suspension)

Control parameters:

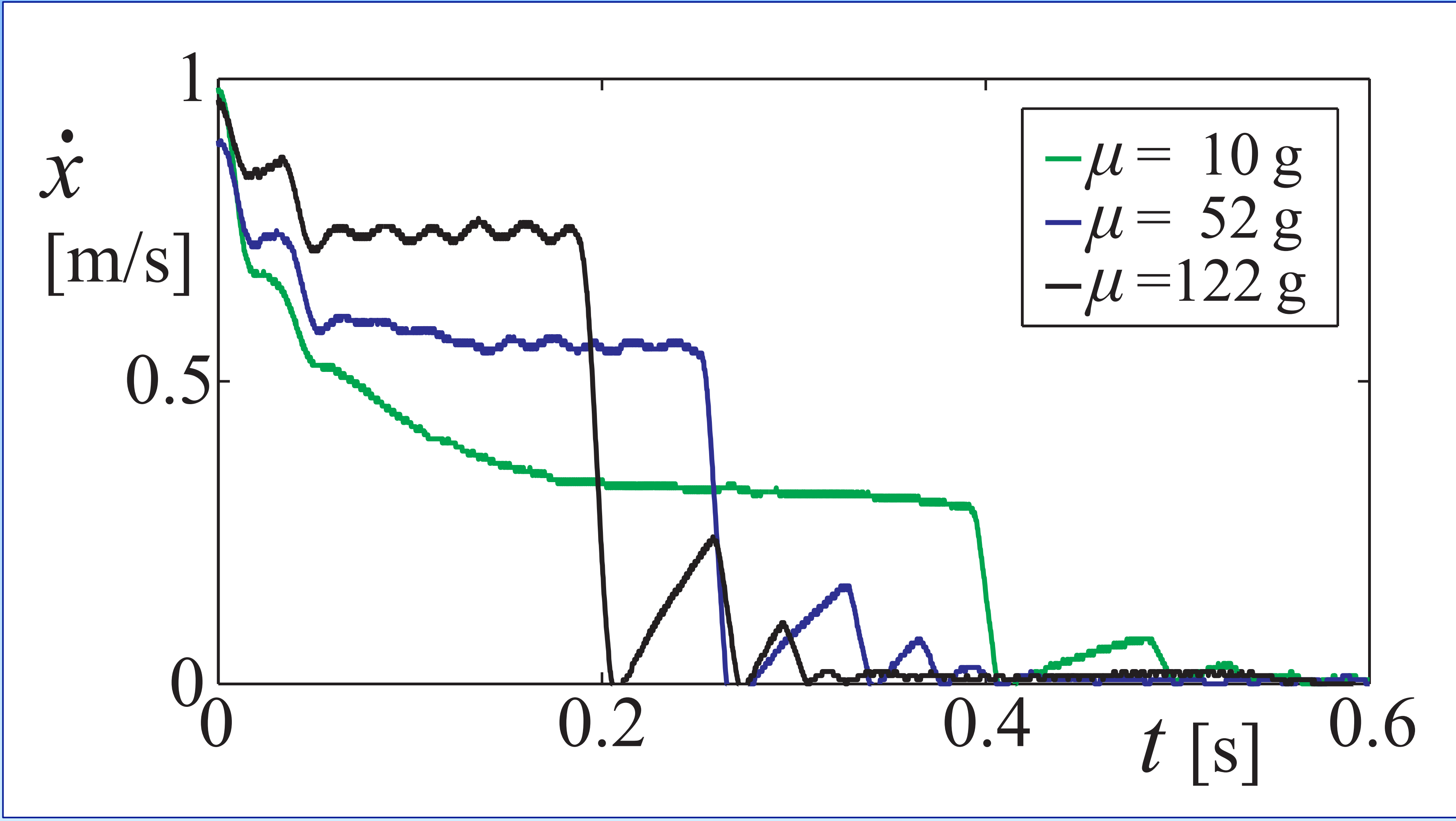
- packing fraction φ
- object mass

Increasing packing fraction φ



Increasing sphere mass μ

φ = 0.44



Equation of motion

$$\boxed{m\ddot{x} = \mu g + D}$$

Added mass corrected mass:

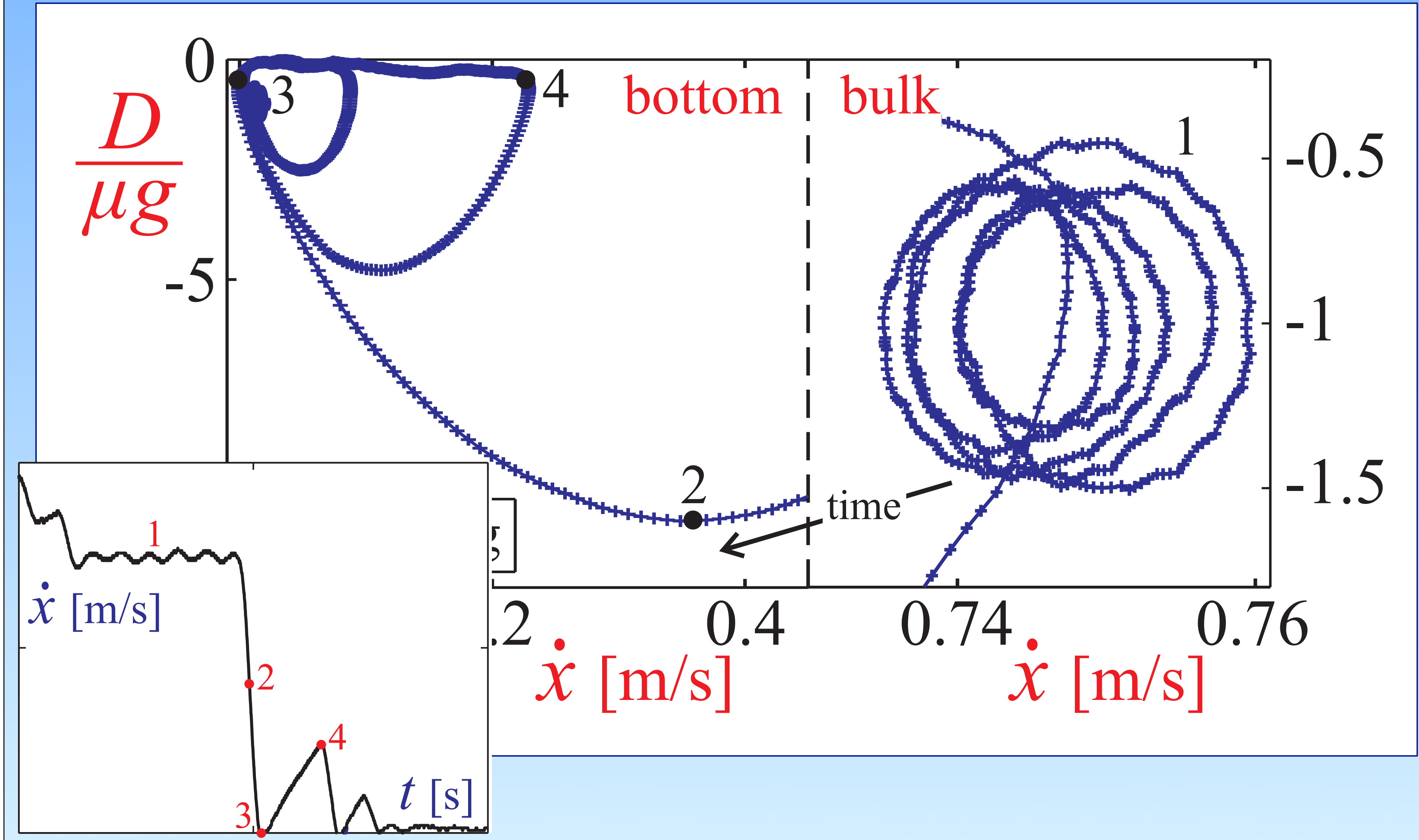
$$m = m_{sphere} + m_{added} = m_{sphere} + \frac{1}{12}\pi d^3 \rho_{susp}$$

Buoyancy corrected mass:

$$\mu = m_{sphere} - m_{buoy} = m_{sphere} - \frac{1}{6}\pi d^3 \rho_{susp}$$

use this equation to calculate drag D vs velocity $\dot{x}$

Drag D vs velocity $\dot{x}$



Bulk oscillations

What type of model could describe the bulk oscillations?

Shear thickening or other stress-strain rheology?

No. Leads to monotonic *D* vs $\dot{x}$-curve

Visco-elastic liquid models?

No. Leads to damped oscillations

Hysteretic drag model? [R.D. Deegan, *Phys. Rev. E* 81, 036319 (2010).]

Works reasonably well

Modeling bulk oscillations

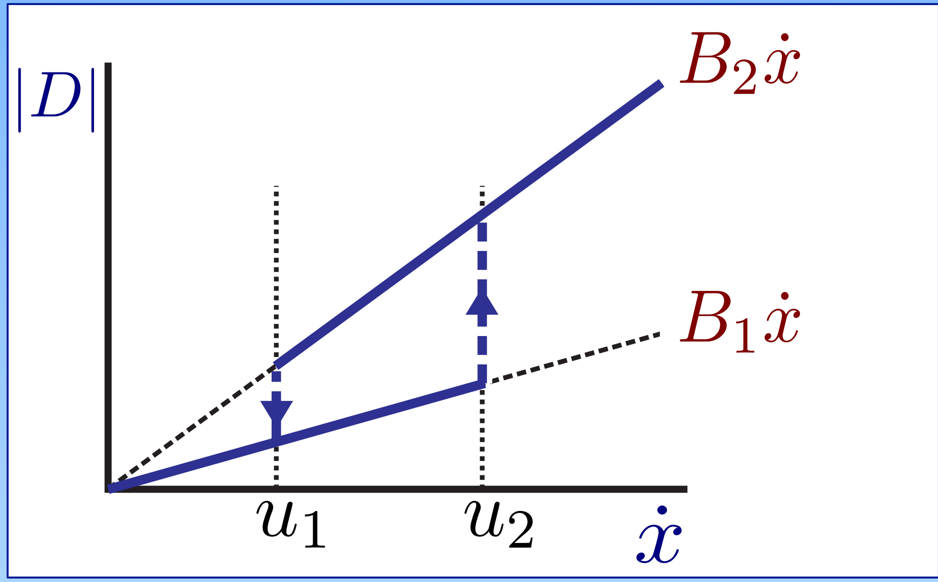
Hysteretic drag model

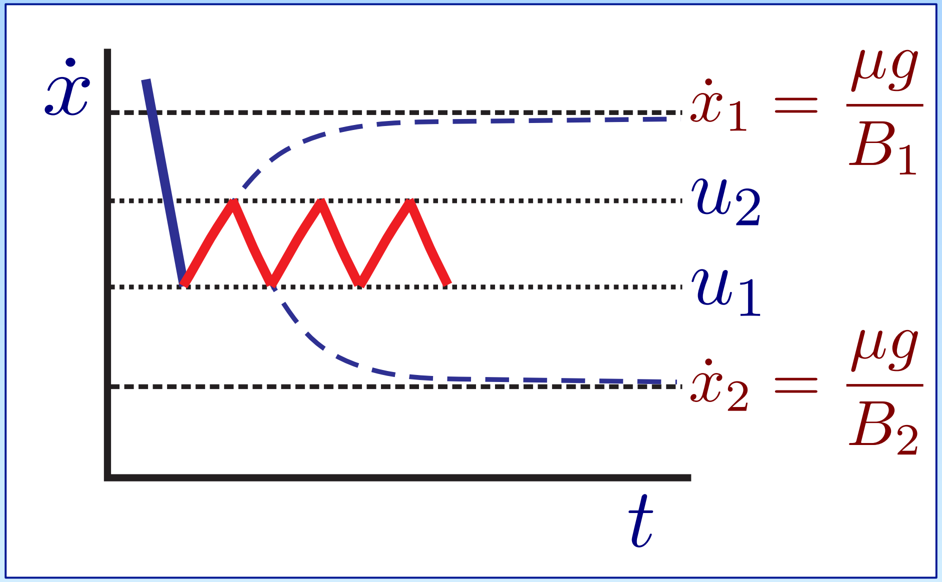
Inspired by:
R.D. Deegan,
***Phys. Rev. E* 81, 036319 (2010).**

$$m\ddot{x} = \mu g + D$$

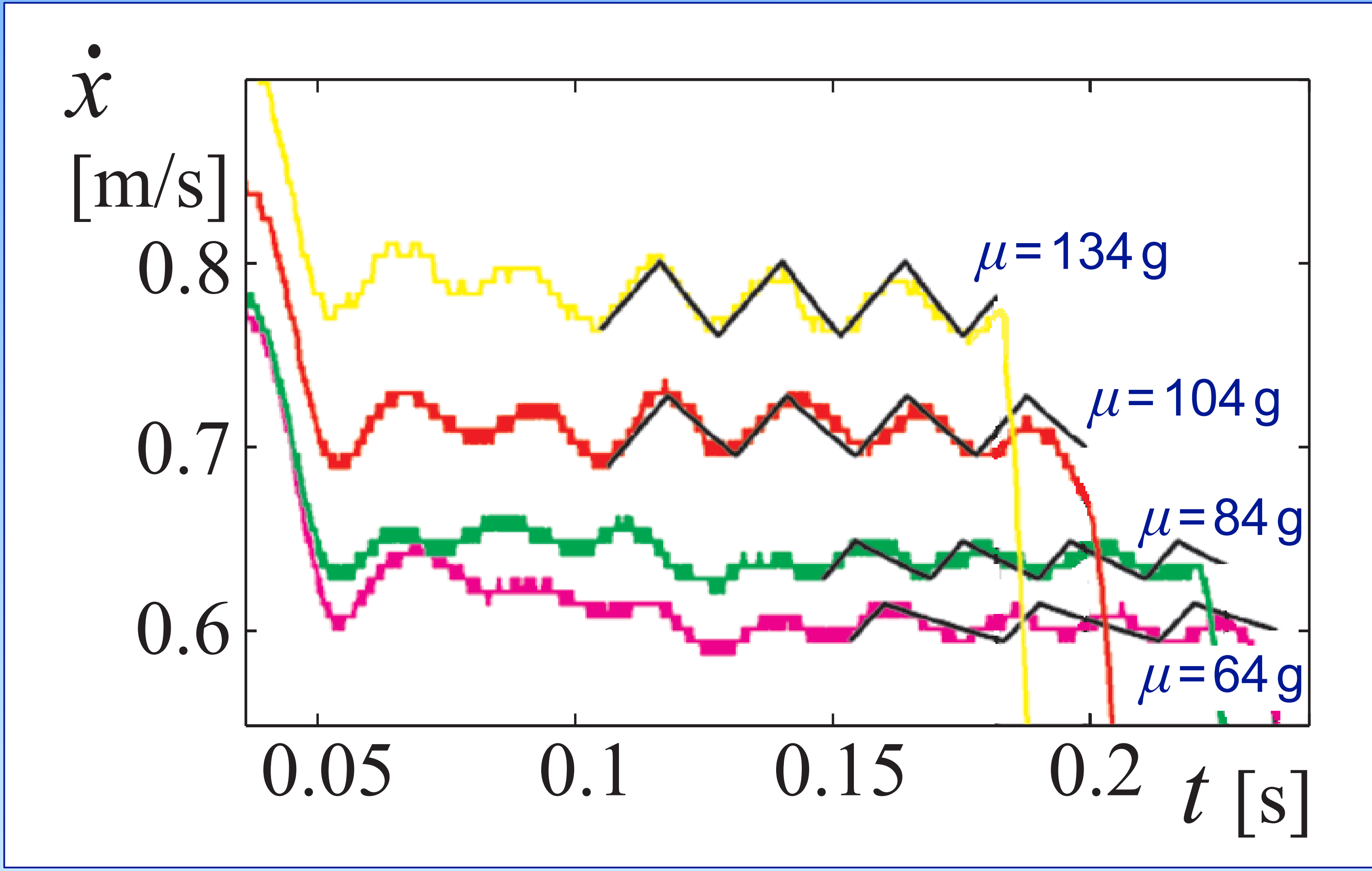
with:

$$D = \begin{cases} -B_1\dot{x} & \text{when } \dot{x} \text{ falls below } u_1 \\ -B_2\dot{x} & \text{when } \dot{x} \text{ rises above } u_2 \end{cases}$$



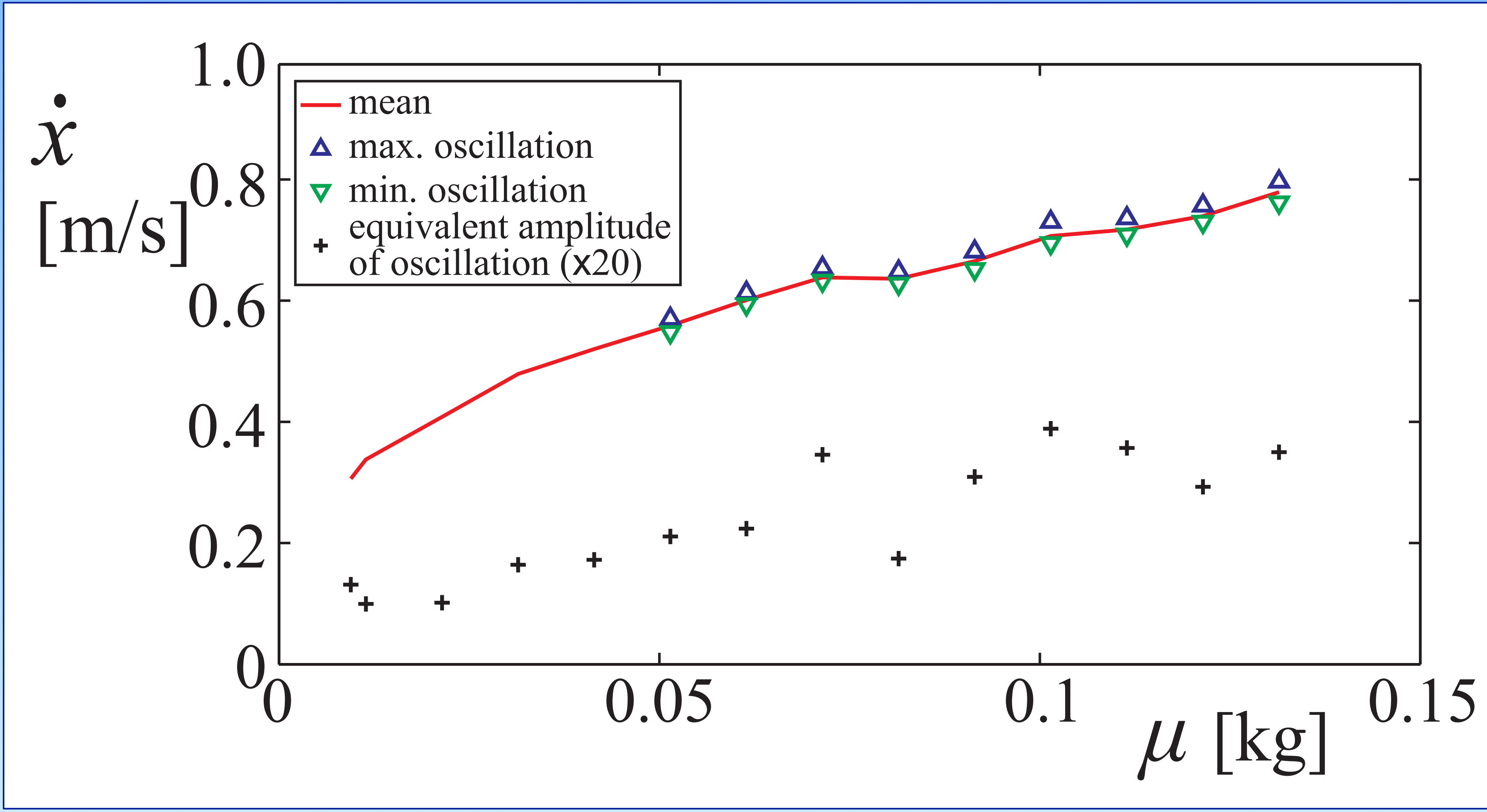


Results for fixed B_1, B_2

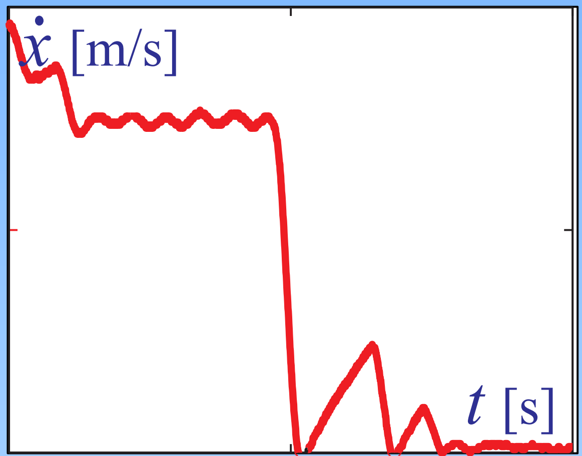


Drawback: u_1, u_2 need to be redefined for each μ

Velocities u_1, u_2 vs mass μ

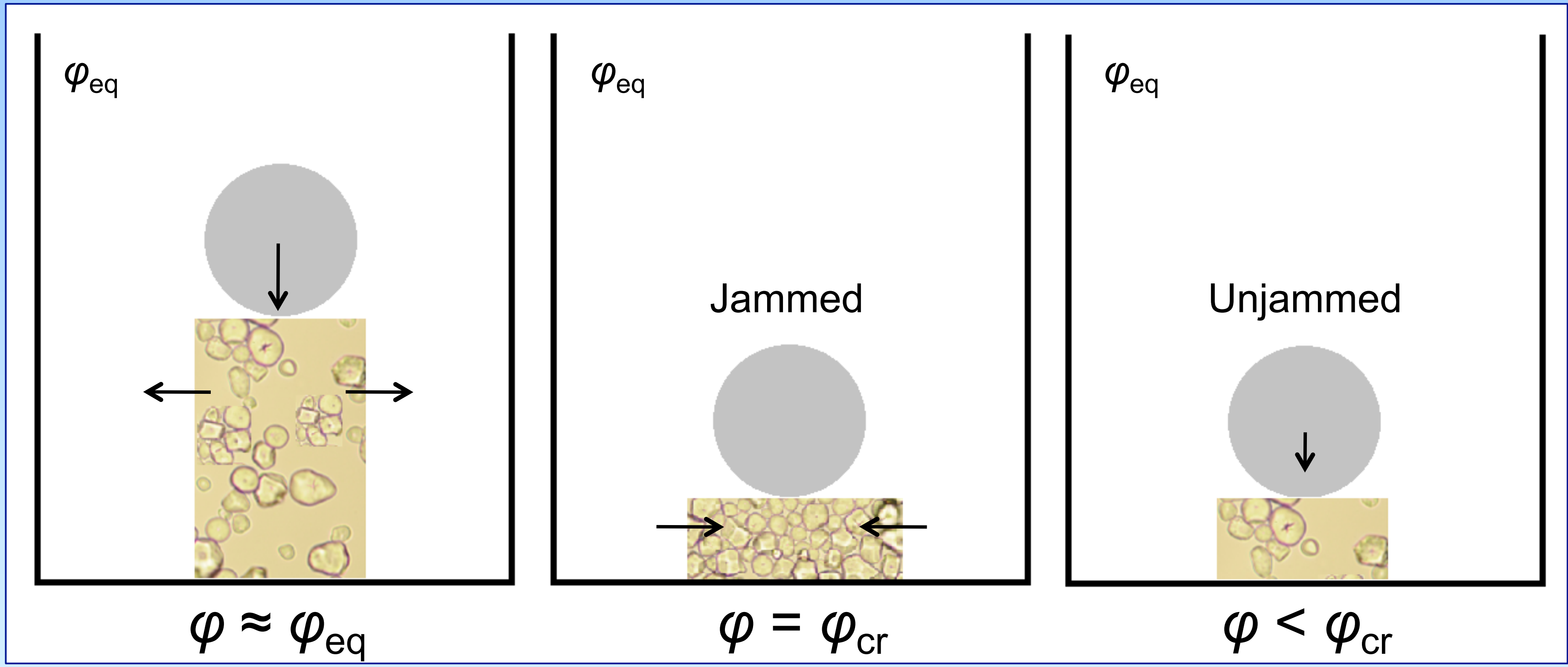


Stop-go cycles at the bottom



Fast deceleration points to jamming:

- $\dot{x} > 0$, liquid squeezed out
- φ increases
- jamming by compaction, $\varphi = \varphi_{cr}$, $\dot{x} = 0$
- particles rearrange on fluid time scale
- φ decreases, relaxation, $\dot{x} > 0$



A minimal model

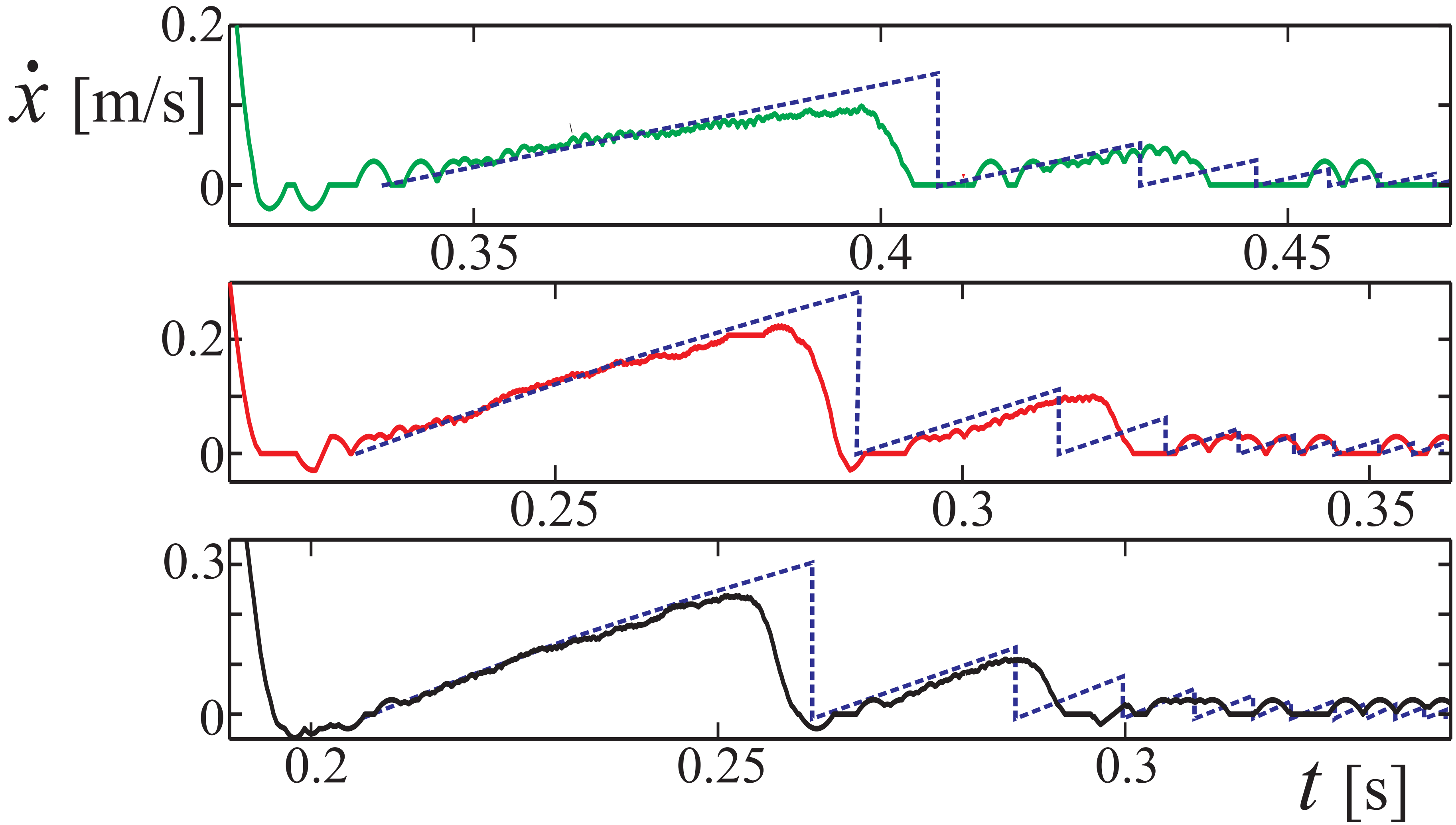
$$\begin{cases} m\ddot{x} = \mu g + D & \text{when } \phi < \phi_{cr} \\ \dot{x} = 0 & \text{when } \phi \geq \phi_{cr} \end{cases}$$

$$\dot{\phi} = -c\frac{\dot{x}}{x} - \kappa(\phi - \phi_{eq})$$

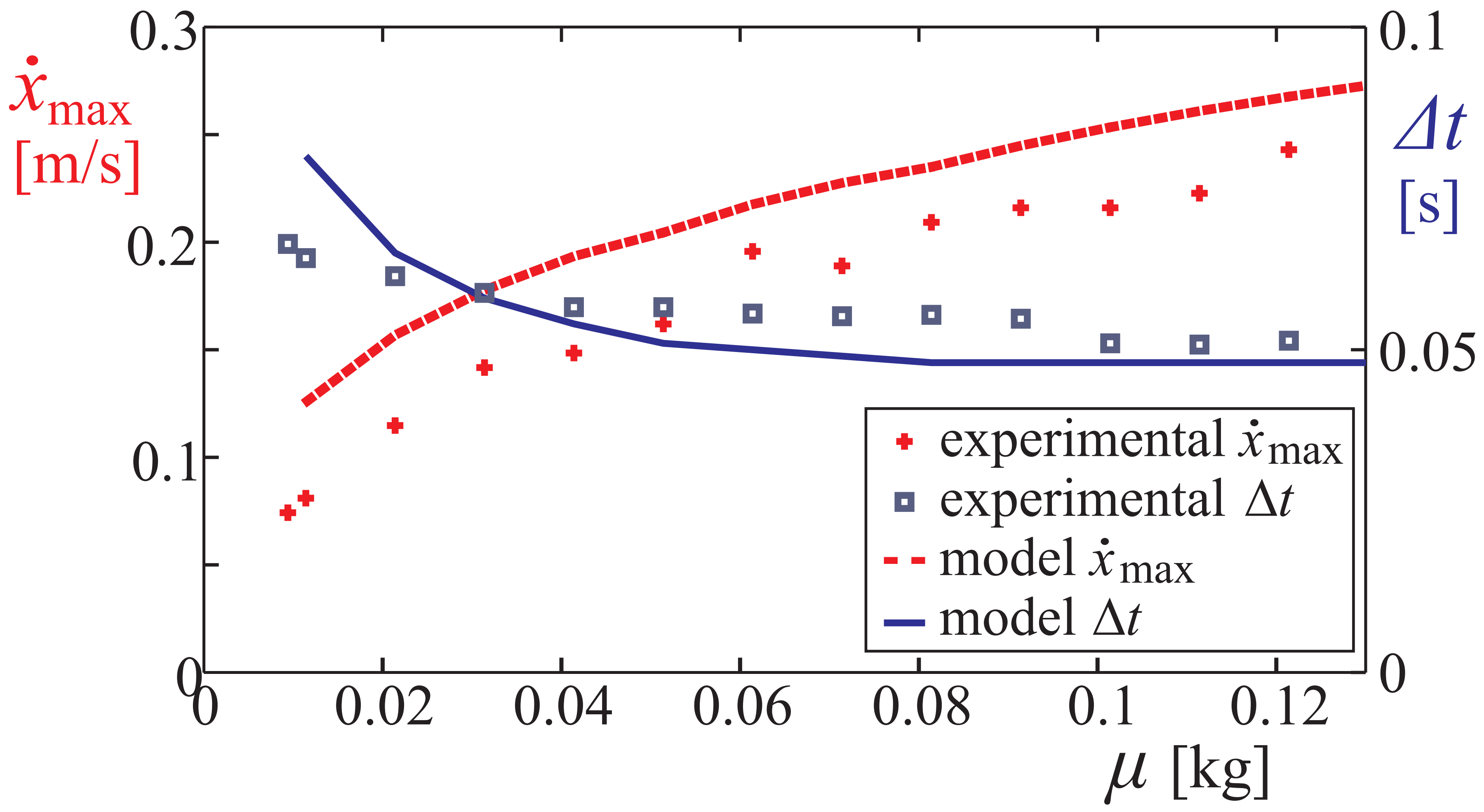
increases ϕ due to compression
($-\dot{x}/x$ = compression rate)

decreases ϕ due to relaxation

Comparing to experiment

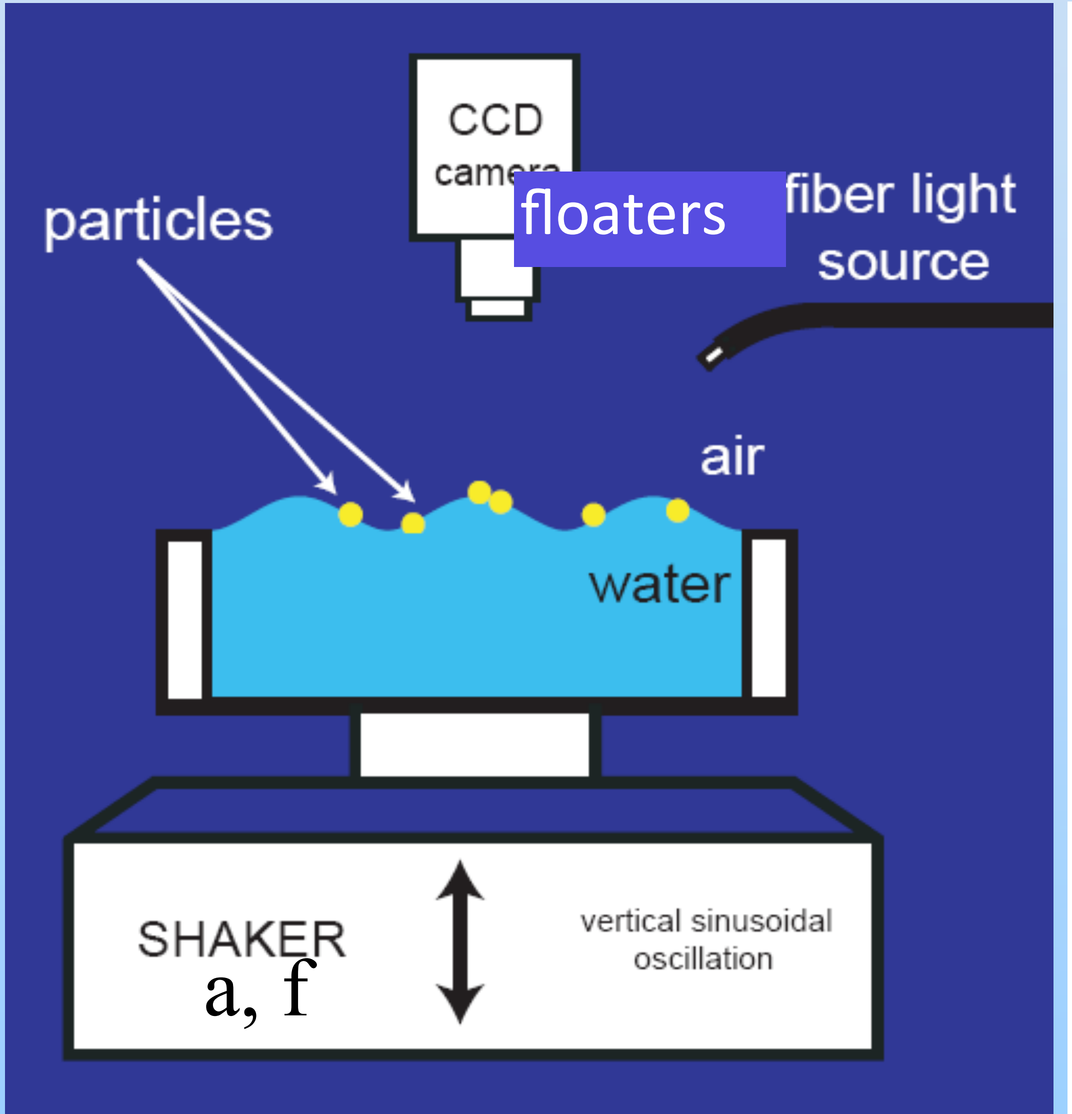


Comparing to experiment



Floating particles on Faraday waves

Floating particles on Faraday waves



Control Parameters:

- D = floater size
- θ = wetting angle
- a = amplitude
- f = frequency
- ϕ = concentration

ϕ = Area $_{\text{floater}}$ / Area $_{\text{total}}$

low ϕ

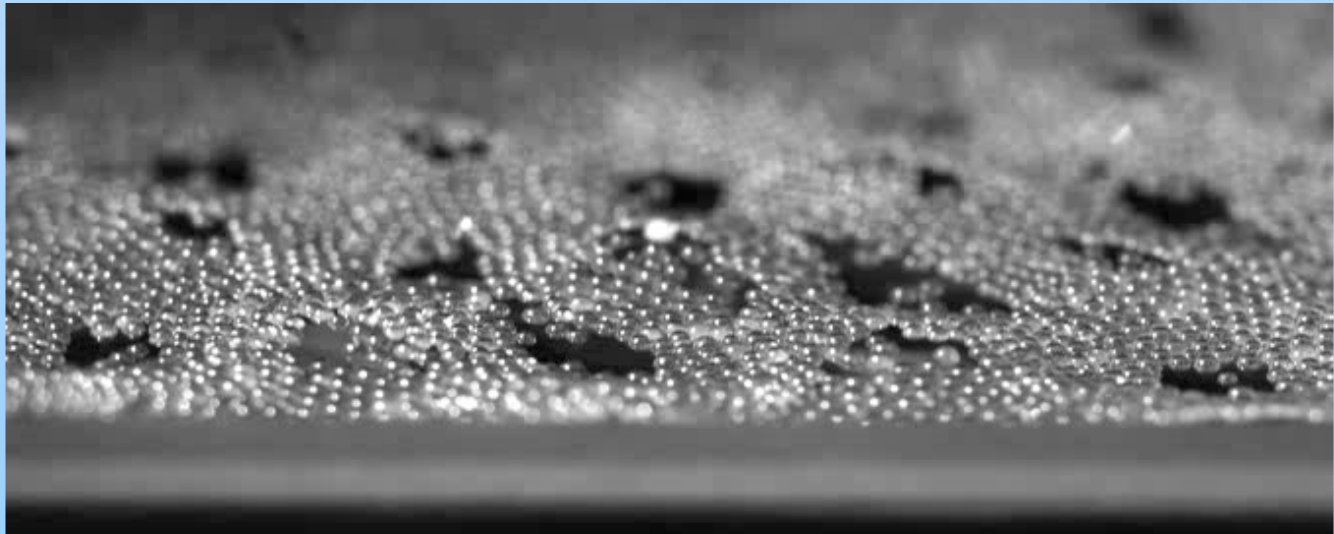
5 mm

antinode clusters

f = 19 Hz
a = 2 mm

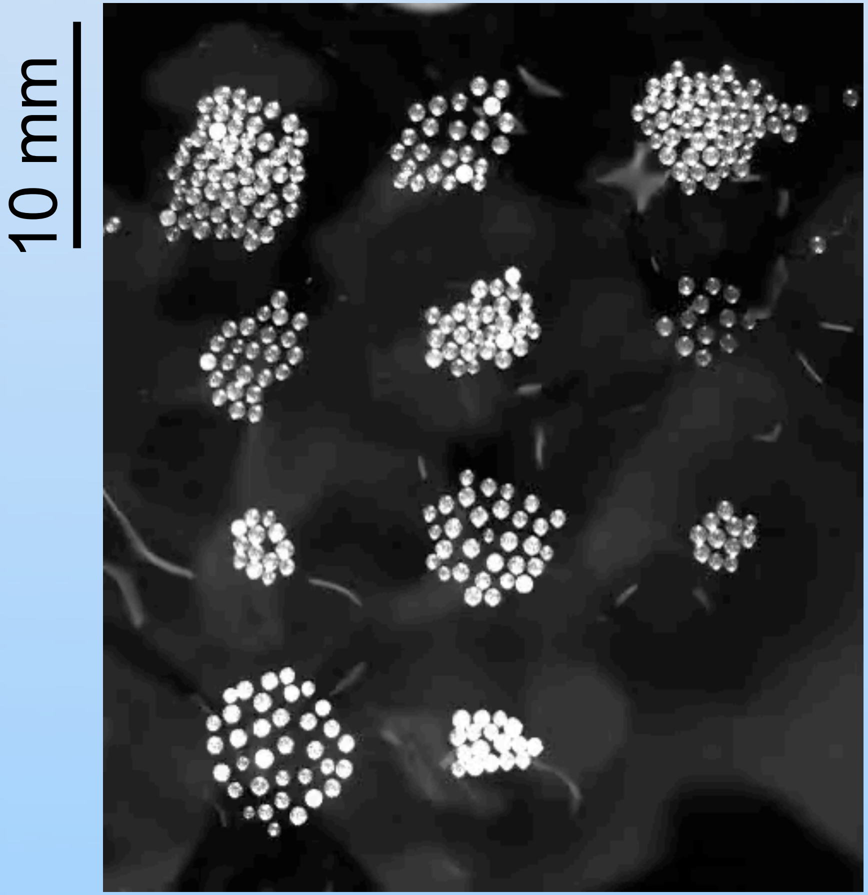
adding more floaters

high ϕ

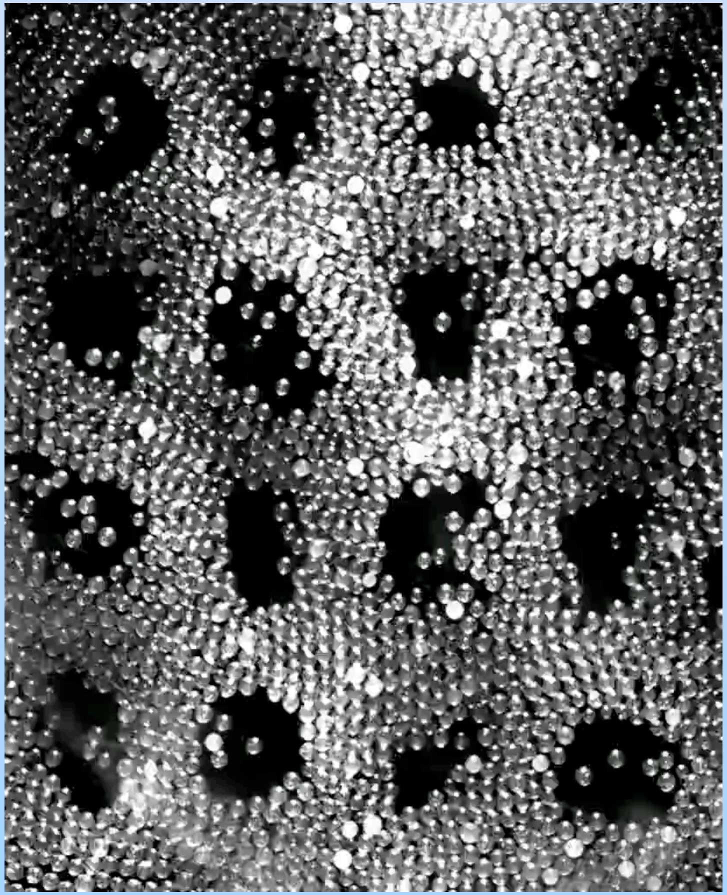


node clusters

f = 20 Hz
a = 2.2 mm



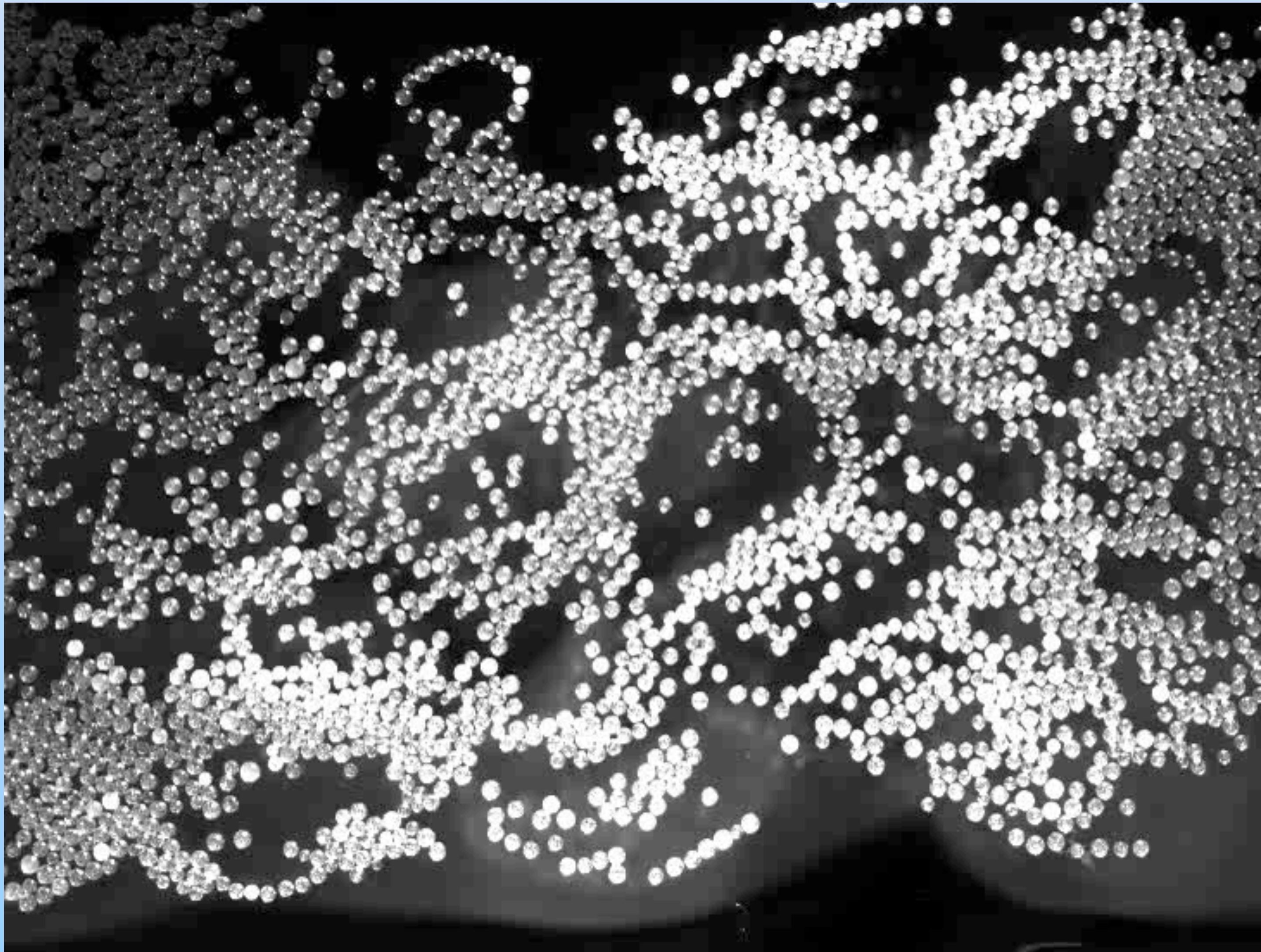
low ϕ: antinode clusters



high ϕ: node clusters

- What is the physical origin of the clustering?
- What happens at intermediate ϕ?

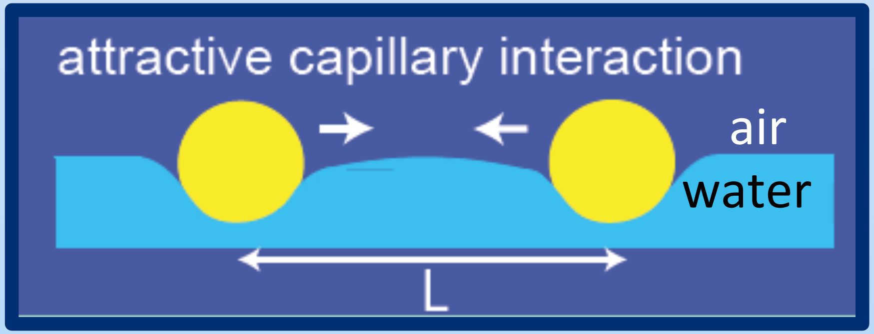
Structures at intermediate ϕ



Competition between forces

capillarity

(weak)

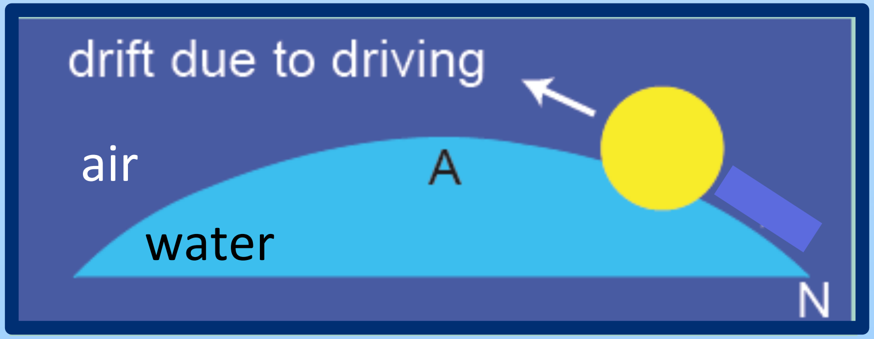


F ~ 1.2 nN at L~D (experiment)

+

drift force

(strong)



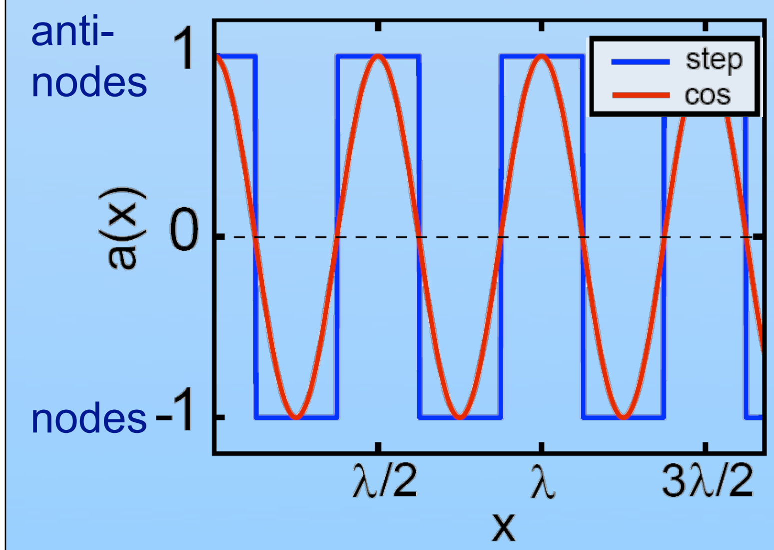
F ~ 2000 nN (theory* - one particle model)

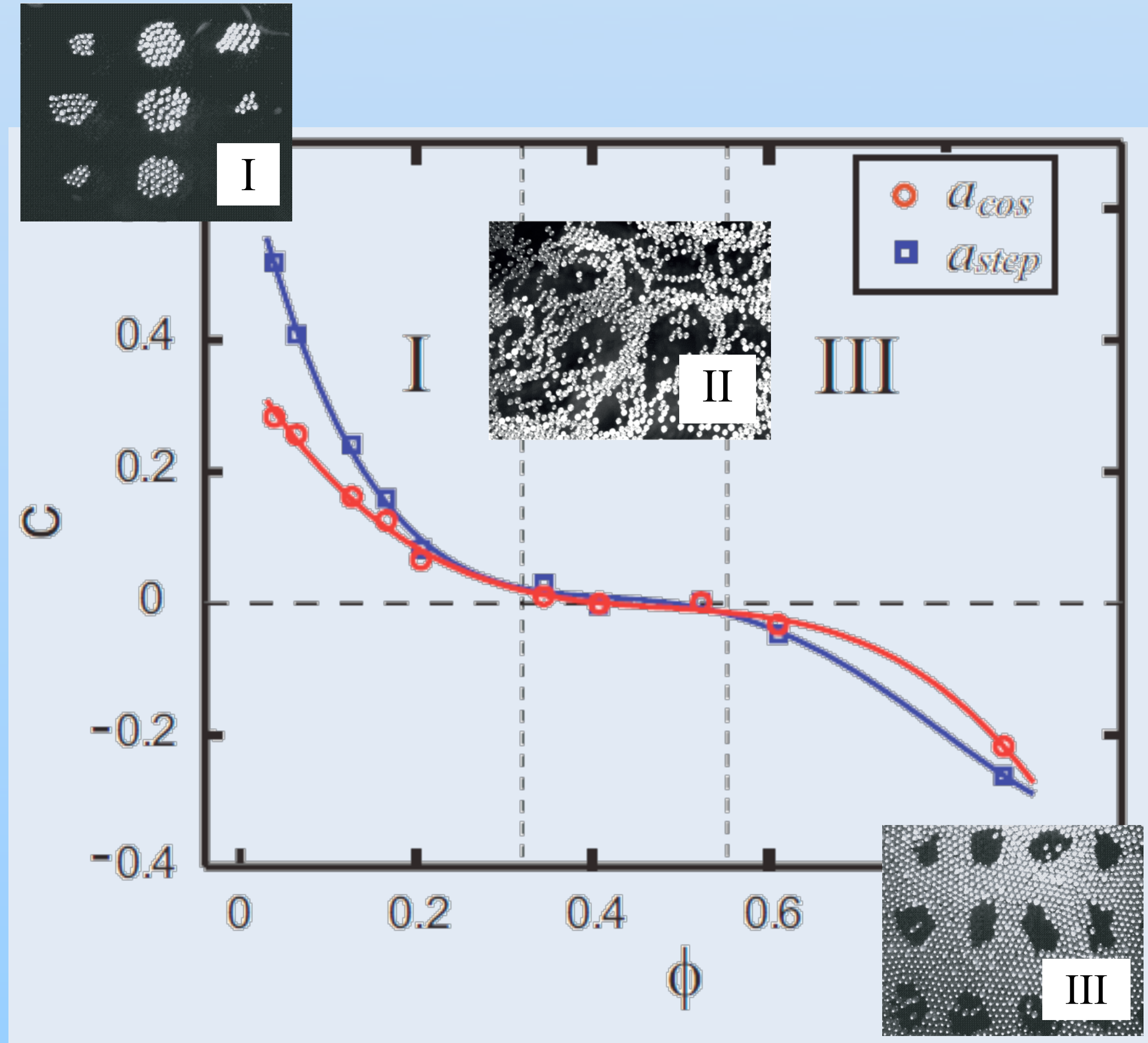
*** G. Falkovich *et al.* Nature 435, 1045 (2005).**

Experimental analysis: Characterizing the antinode – node cluster transition

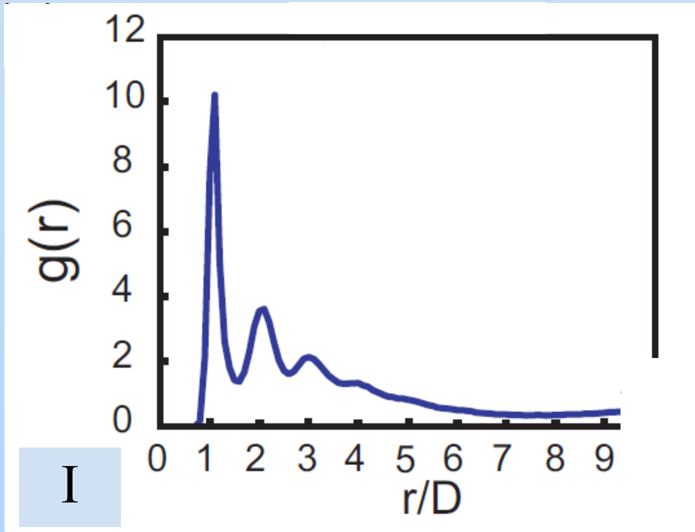
Global characterization: Correlation number *c*

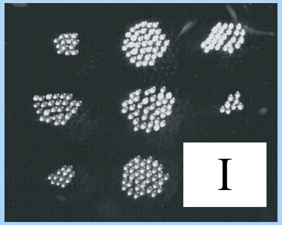
$$c = \frac{< \phi(\mathbf{r},t)a(\mathbf{r}) >_{\mathbf{r},t}}{< \phi(\mathbf{r},t) >_{\mathbf{r},t}}$$

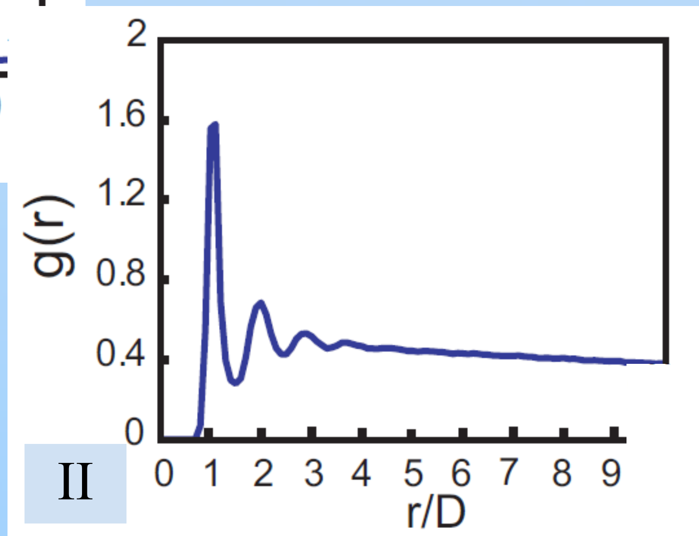


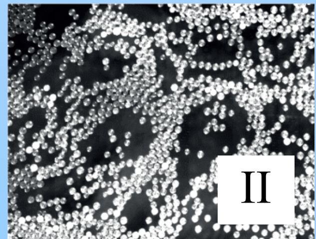


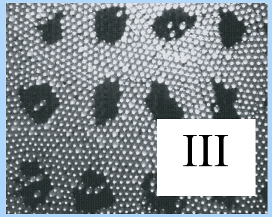
Local characterization:
Pair correlation function g(r)

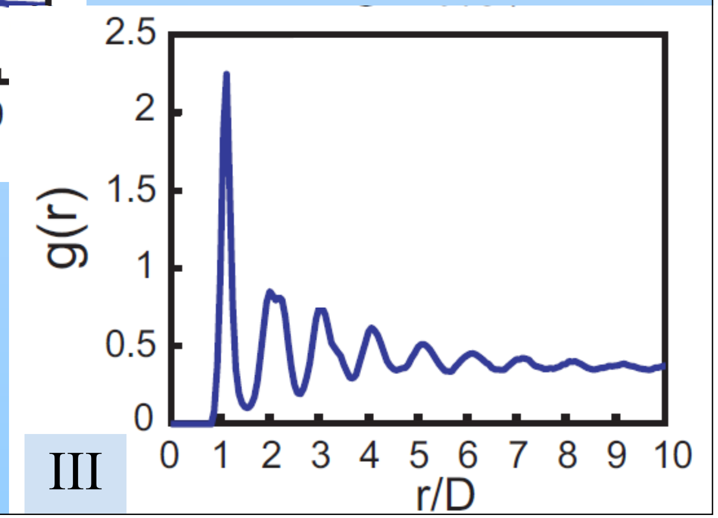






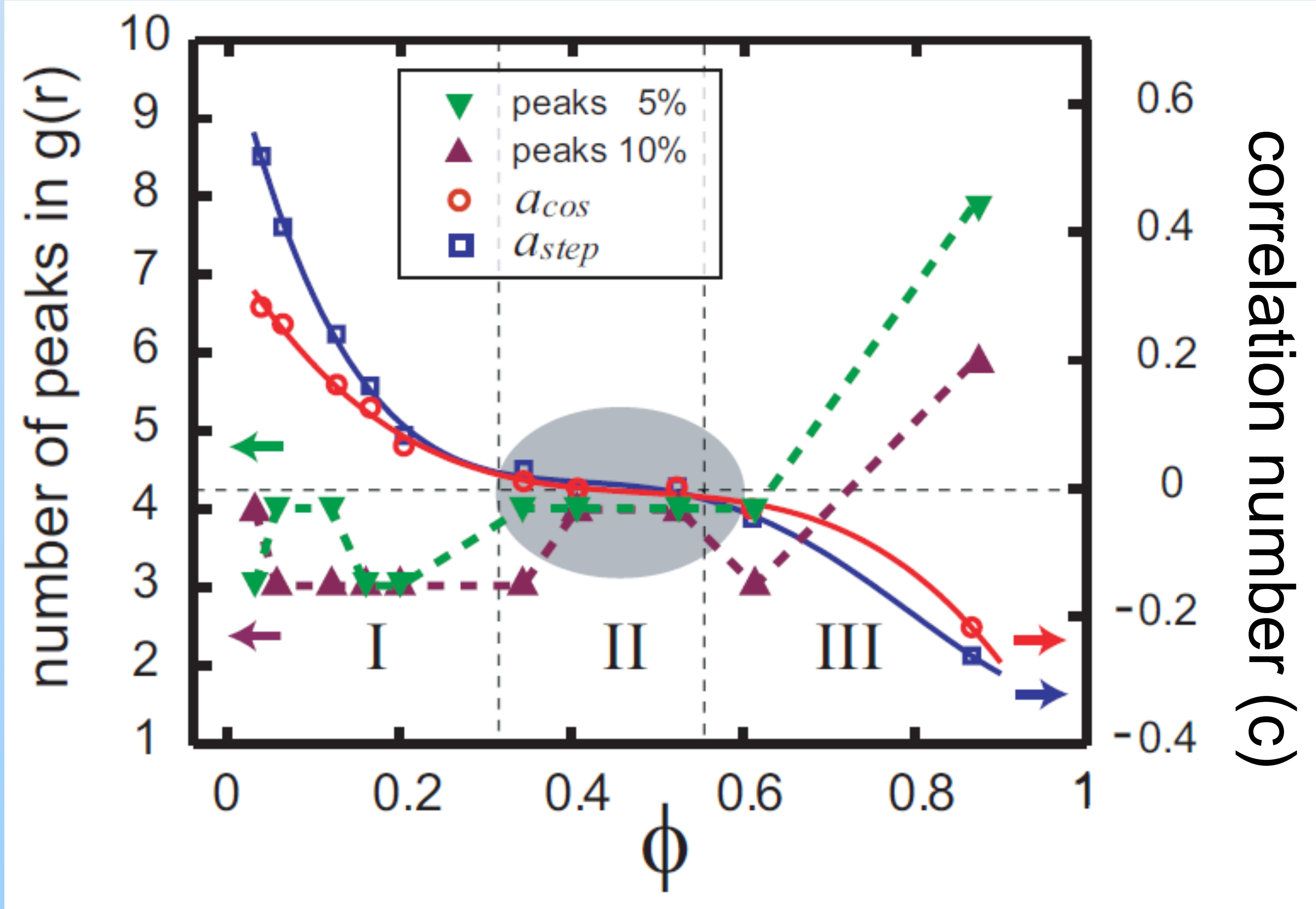






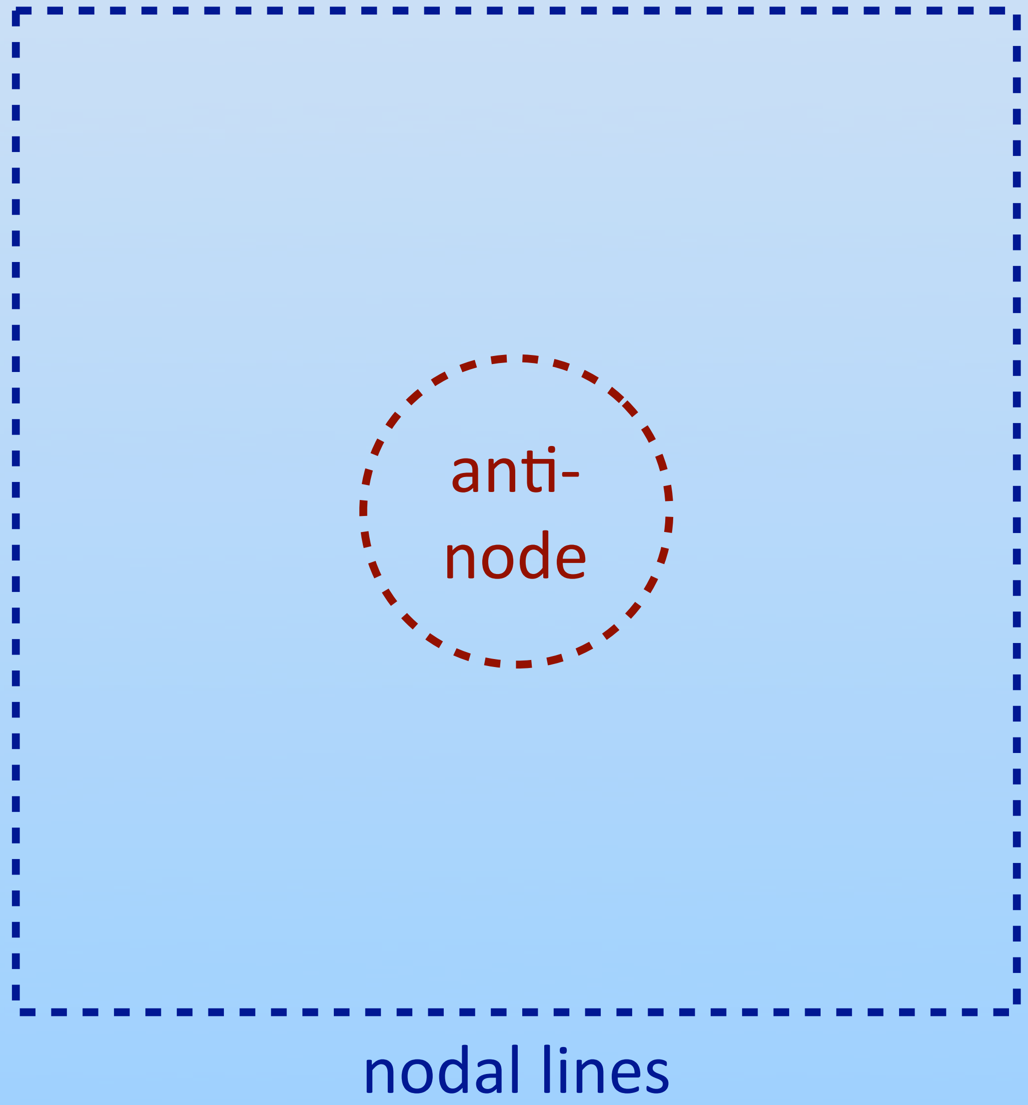
(D = floater diameter)

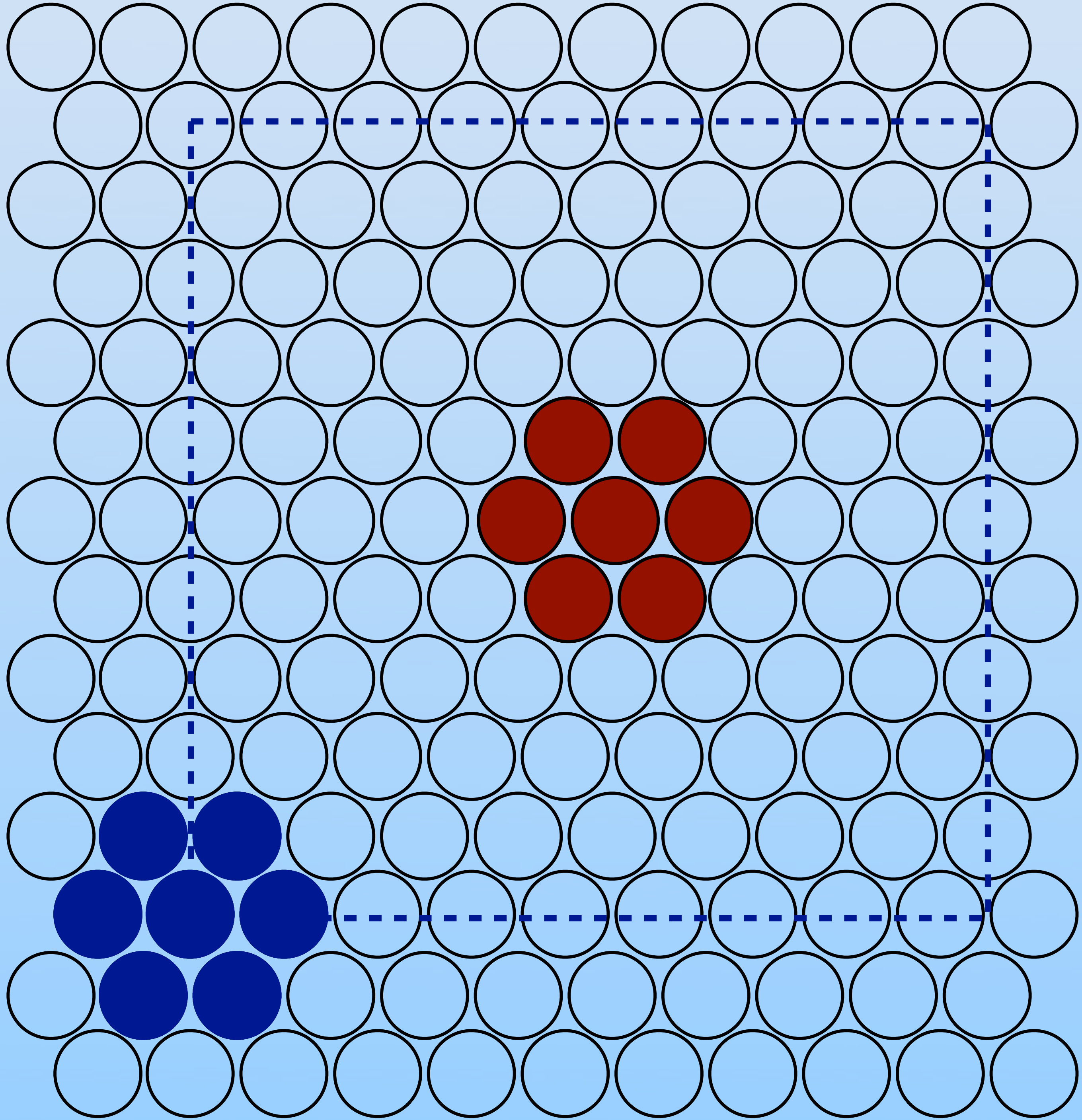
Global vs local characterization



What is the origin of the antinode-node cluster transition?

wave pattern





wave pattern

add particles:

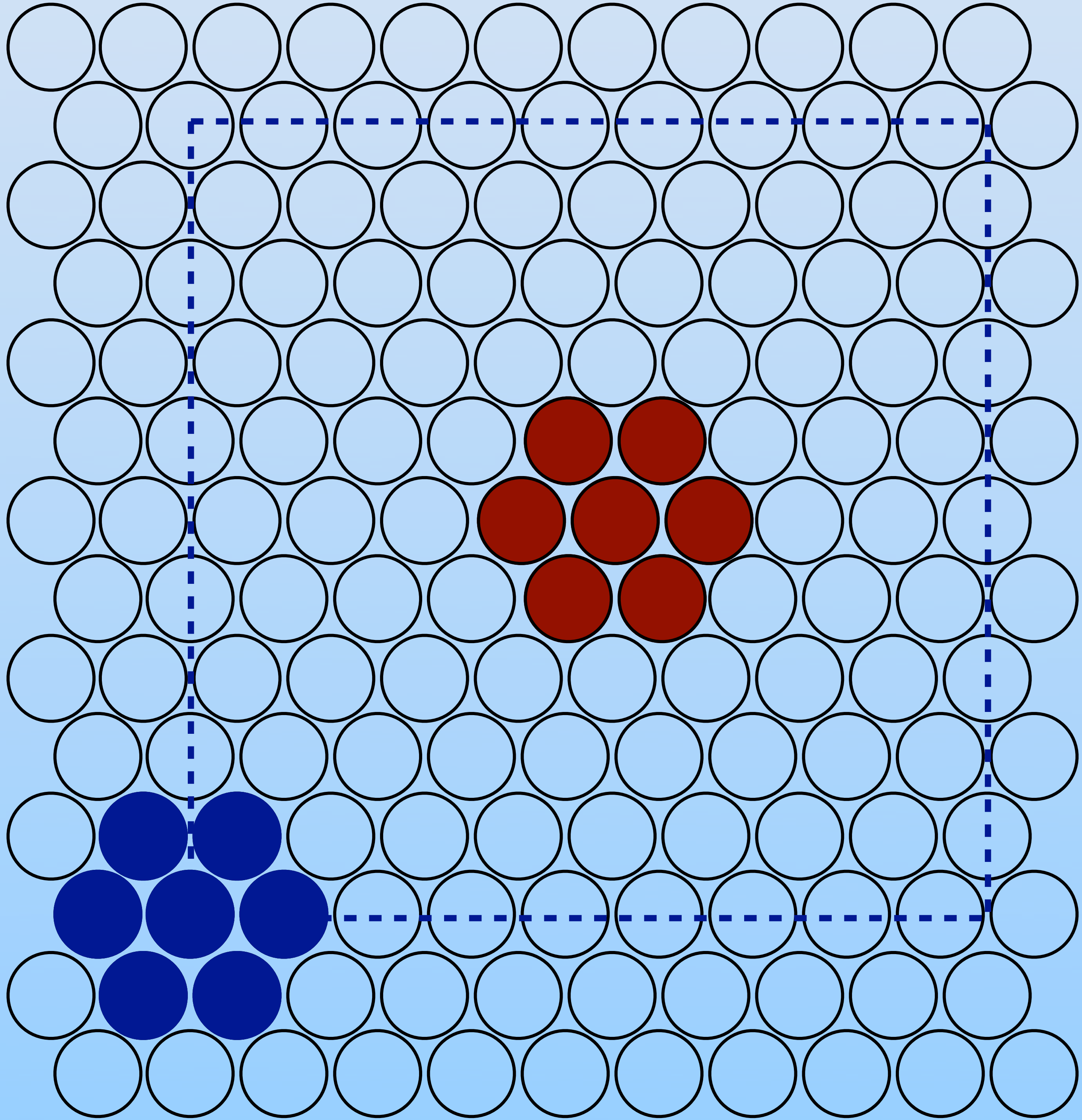
- at antinode
- at node

energy:

(capillary & drift)

$U_{\mathrm{cap,anti}} = U_{\mathrm{cap,node}}$

$U_{\mathrm{drift,anti}} < U_{\mathrm{drift,node}}$



wave pattern

add particles:

- at antinode
- at node

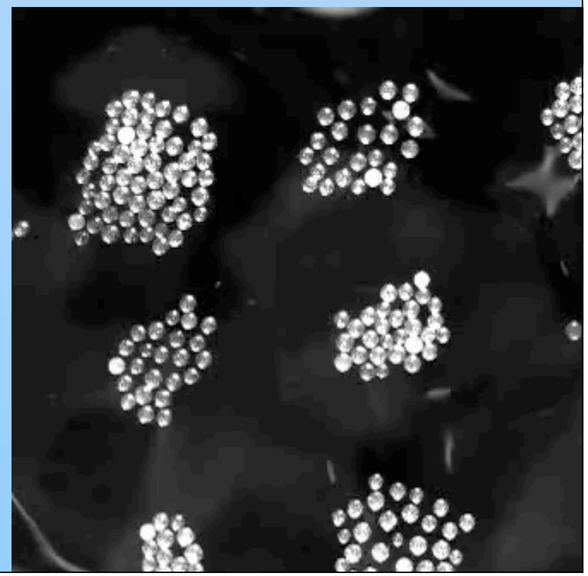
~~energy:~~

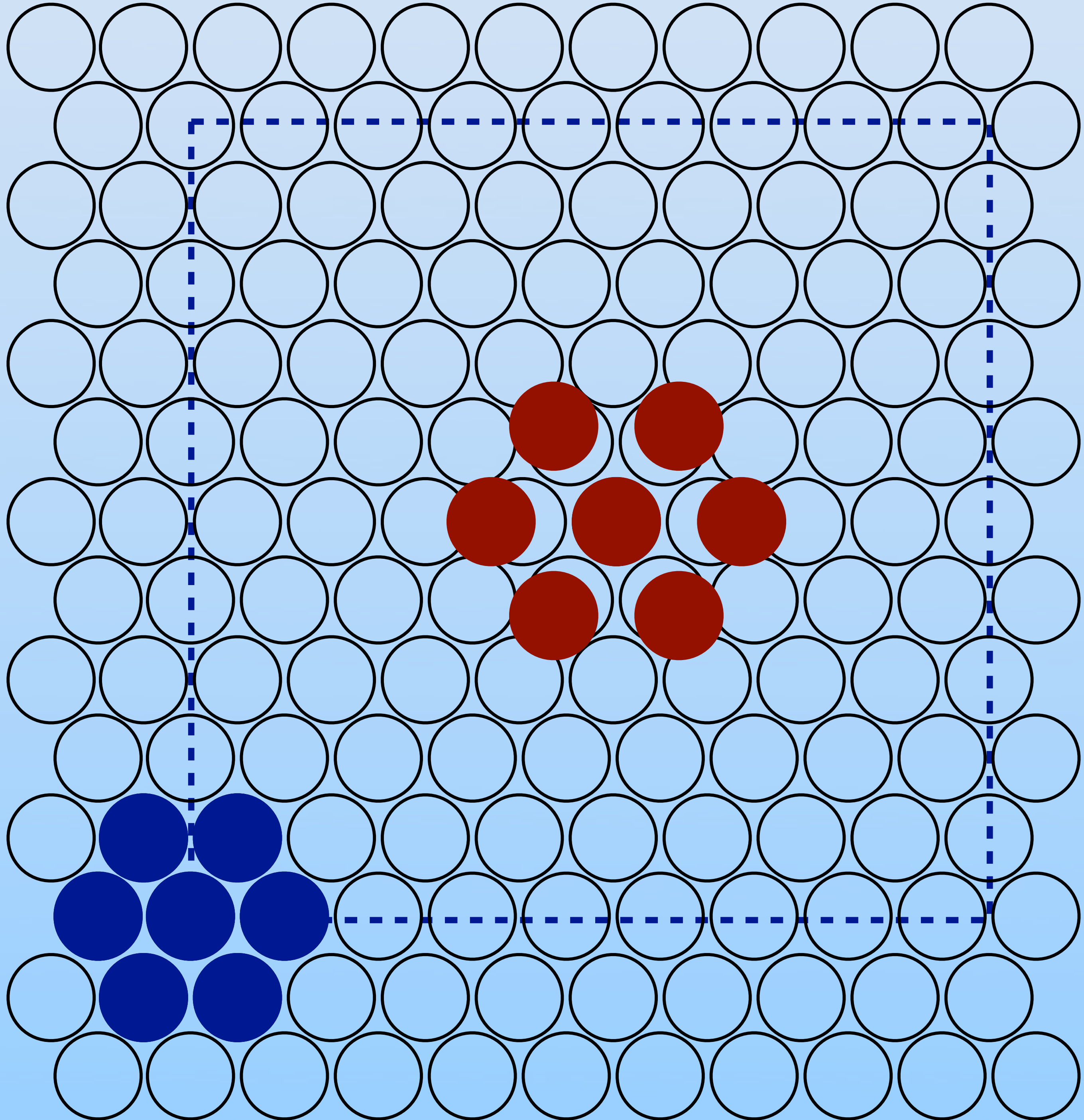
~~(capillary & drift)~~

$\cancel{U_{\mathrm{cap,anti}} = U_{\mathrm{cap,node}}}$

$\cancel{U_{\mathrm{drift,anti}} < U_{\mathrm{drift,node}}}$

add breathing:





wave pattern

add particles:

- at antinode
- at node

~~energy:~~

~~(capillary & drift)~~

$\cancel{U_{\mathrm{cap,anti}} = U_{\mathrm{cap,node}}}$

$\cancel{U_{\mathrm{drift,anti}} < U_{\mathrm{drift,node}}}$

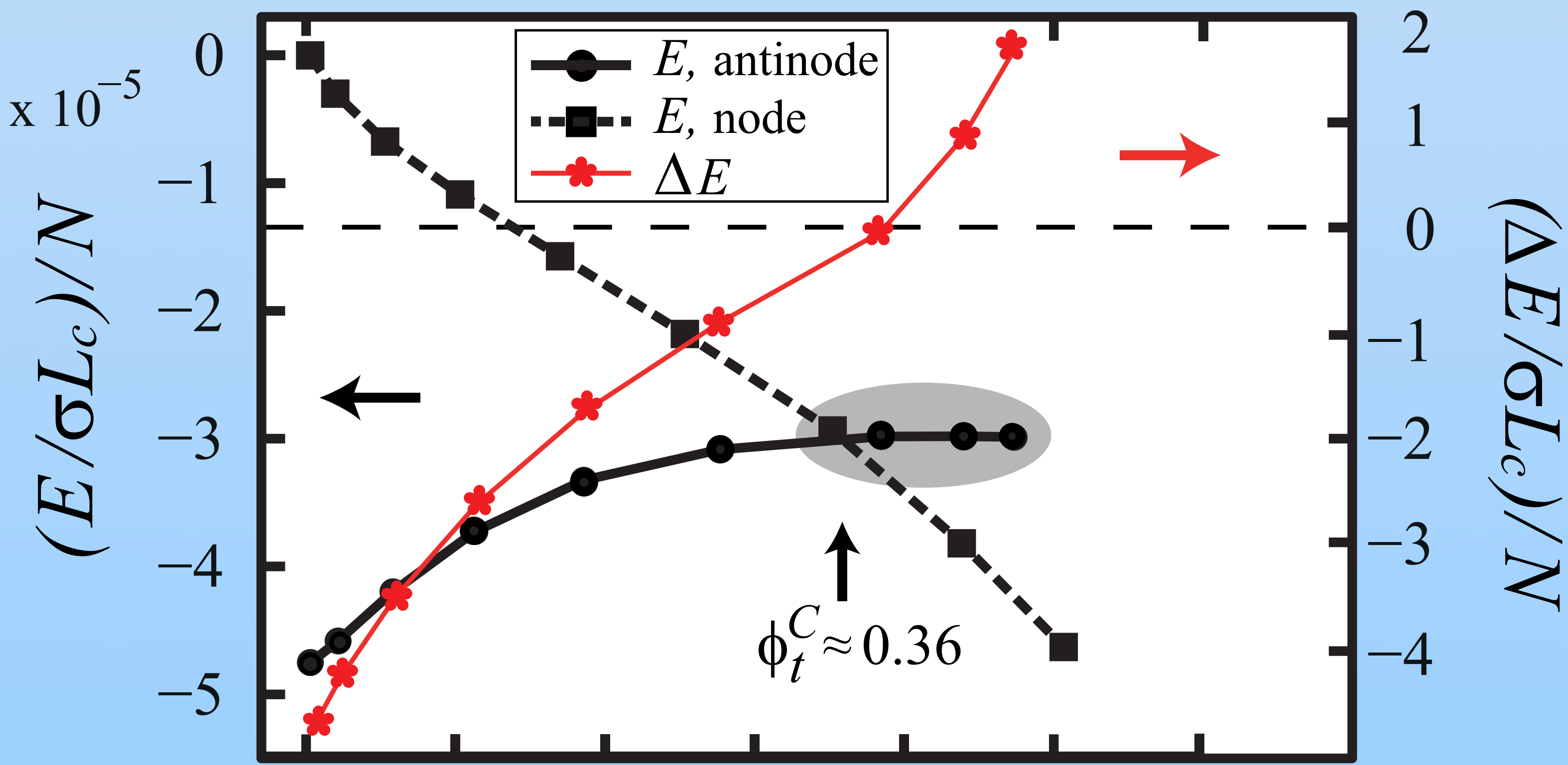
add breathing:

$U_{\mathrm{cap,anti}} > U_{\mathrm{cap,node}}$

$U_{\mathrm{drift,anti}} < U_{\mathrm{drift,node}}$

Competition between capillary and drift energy

- antinode: U_{drift} favorable, U_{cap} unfavorable
- node: U_{drift} unfavorable, U_{cap} favorable



Competition between capillary and drift energy

- antinode: U_{drift} favorable, U_{cap} unfavorable
- node: U_{drift} unfavorable, U_{cap} favorable