Collective Motion:
From Active Colloids to Driven Bacteria.

Cécile Cottin-Bizonne

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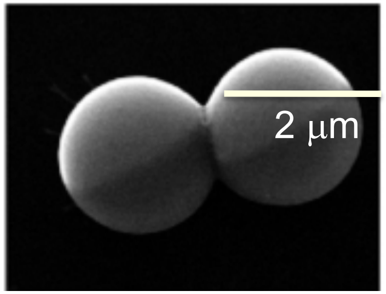

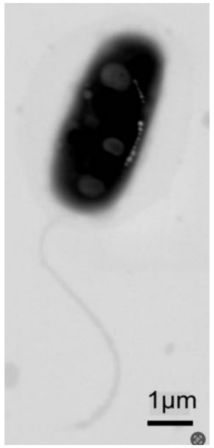

anr agence nationale de la recherche
PHYMOT Physics of Microbial Motility
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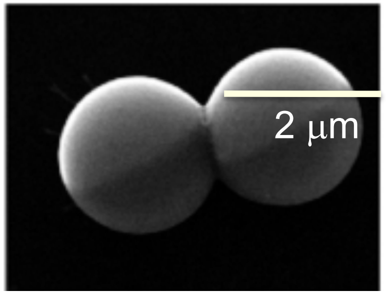
Active Colloids, Active Interfaces



Adam Wysocki

Heiko Rieger

Adérito Fins-Carreira

Mathieu Leocmach

Christophe Ybert

UNIVERSITÄT DES SAARLANDES

INM Leibniz-Institut für Neue Materialien

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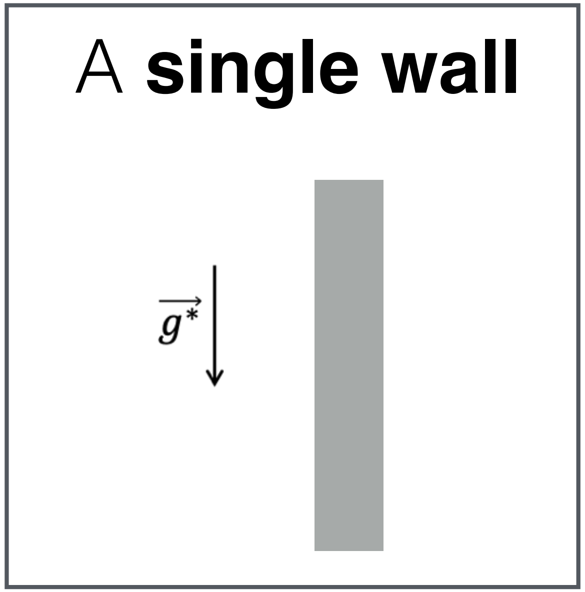
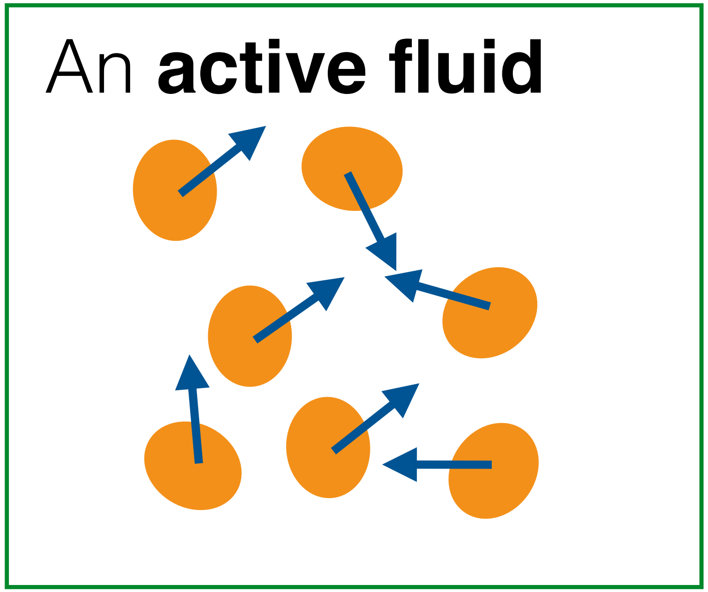
Active colloids, active interfaces

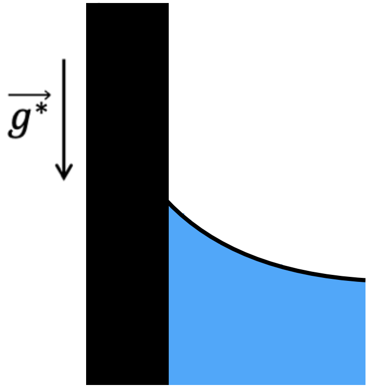
- Active interfaces





Wetting a wall: Motivations

- **Fluid** at a wall



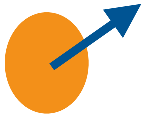
- **Passive** systems

Attractive interactions of the **molecules**
- with the wall
- between each other

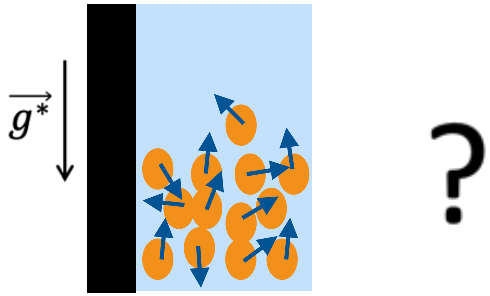
→

- Wetting layer
- Capillary rise
- Meniscus

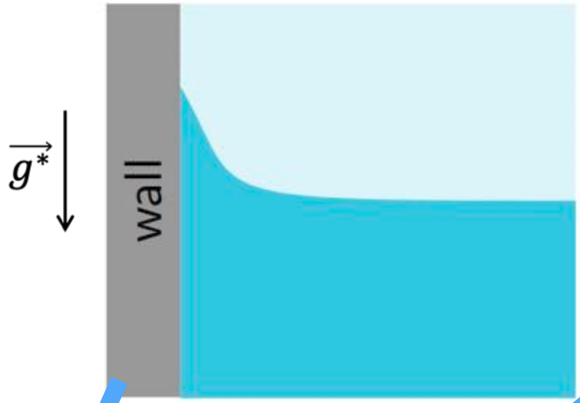
- **Active fluid** at a wall



Out of equilibrium system. Behavior at the wall?



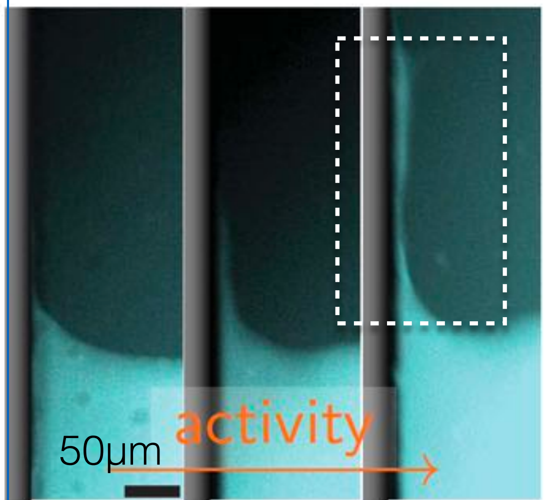
Active « wetting »



Phase separation
+ activity

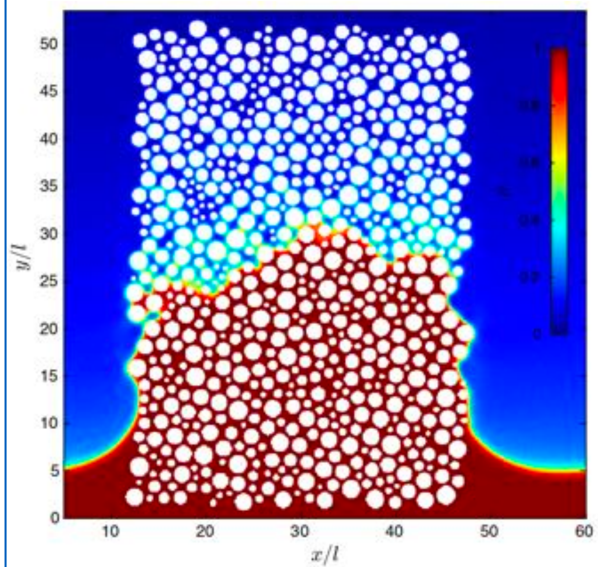
Phase separation
Induced by activity

Microtubule+ Polymer (PEG) +
kinesin-Streptavidin motor + ATP



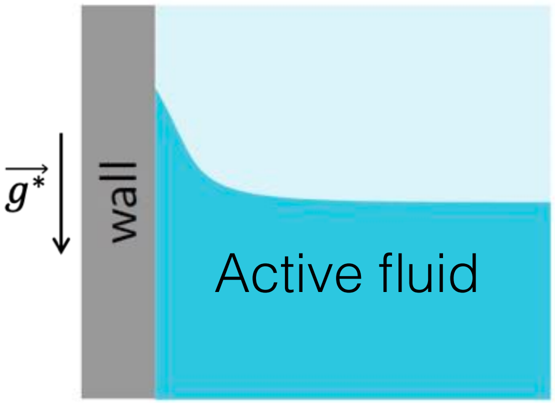
Formation of a 20µm thick boundary **climbing 100 μms above capillary rise**

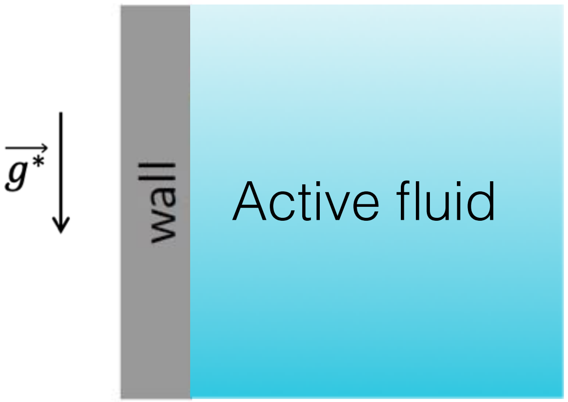
R. Adkins et al, Science, 377, 2022



Wysocki et al. PRL 2020

Active fluid and a wall



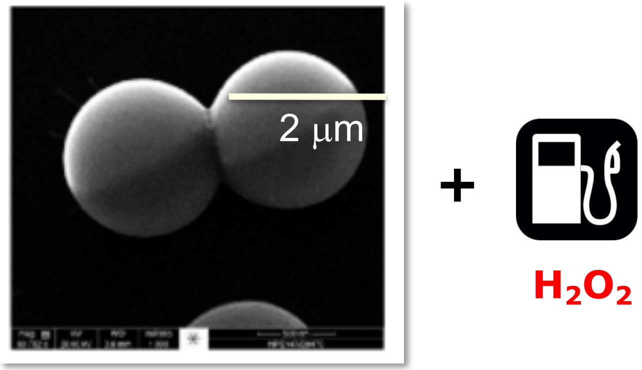


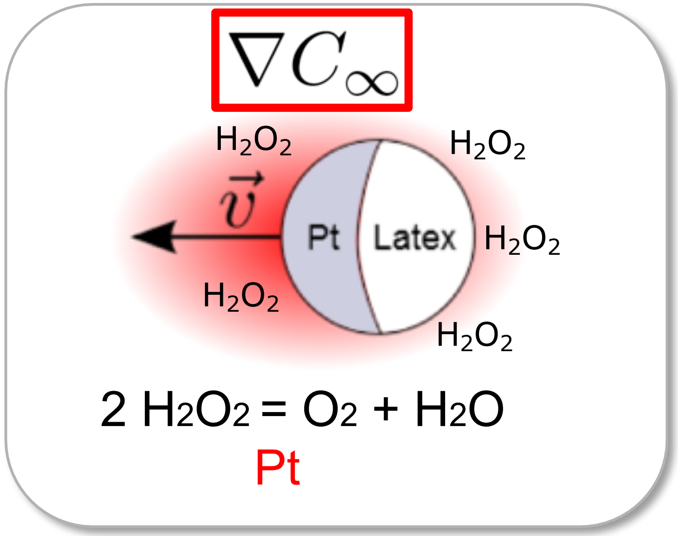
No phase separation

?

Active units: Janus Self Propelled Colloids

Phoretic motion inside a self-generated gradient





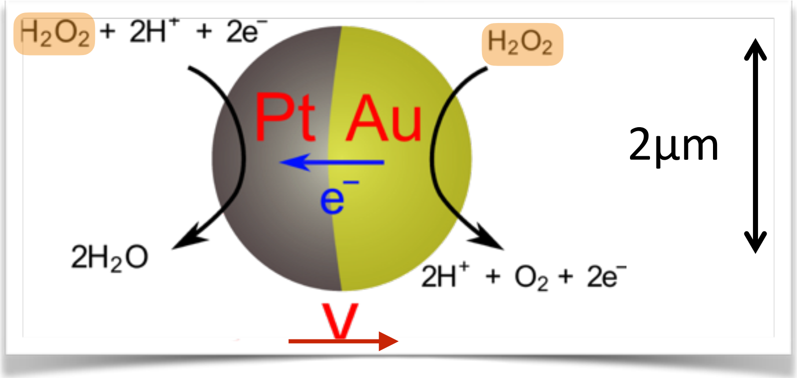
'Model' abiotic system…
yet not fully understood

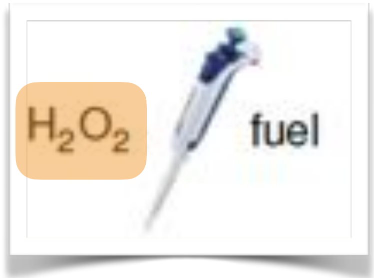
Paxton et al JACS 126, 13424, 2004
Golestanian et al PRL, 2005
Howse et al, PRL, 99, 048102, 2007
Mino et al PRL 106, 048102, 2011
A. Brown, et al Soft Matter, 10, 4016, 2014
…

Ebbens et al, EPL, 2014
Brown et al, Soft Matter, 2017
Ibrahim et al, JFM, 2017
Aubret et al, Curr. Op. Col. & Interf. Science, 2017…

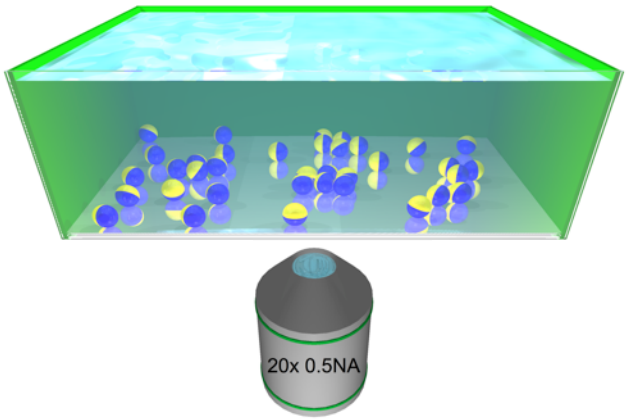
Our Active Colloids

Self-Induced Electro/Diffusiophoretic Propulsion





Propulsion control H_2O_2



$$\rho \simeq 10\,\mathrm{g/cm^3}$$

Sedimented particles:

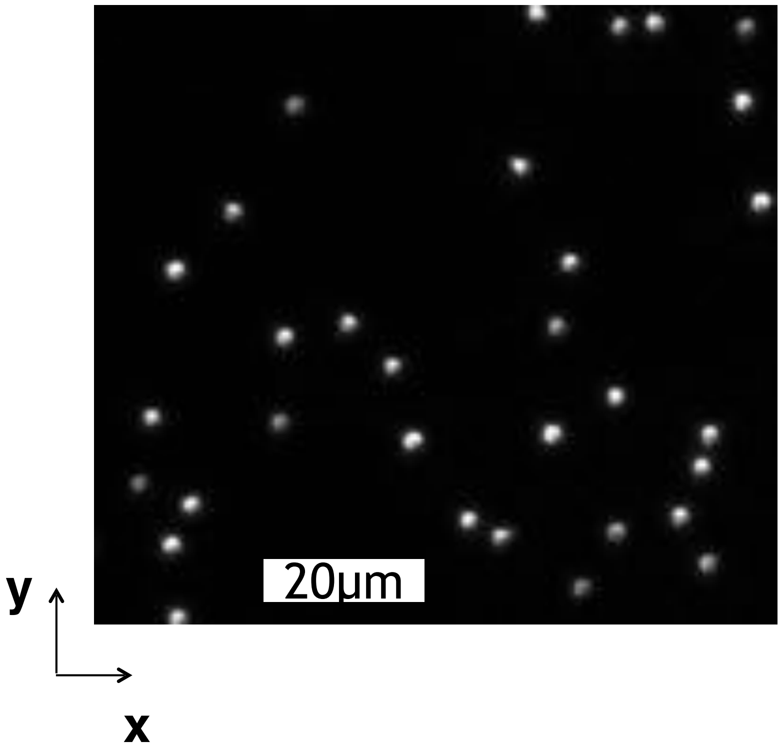
2D active system

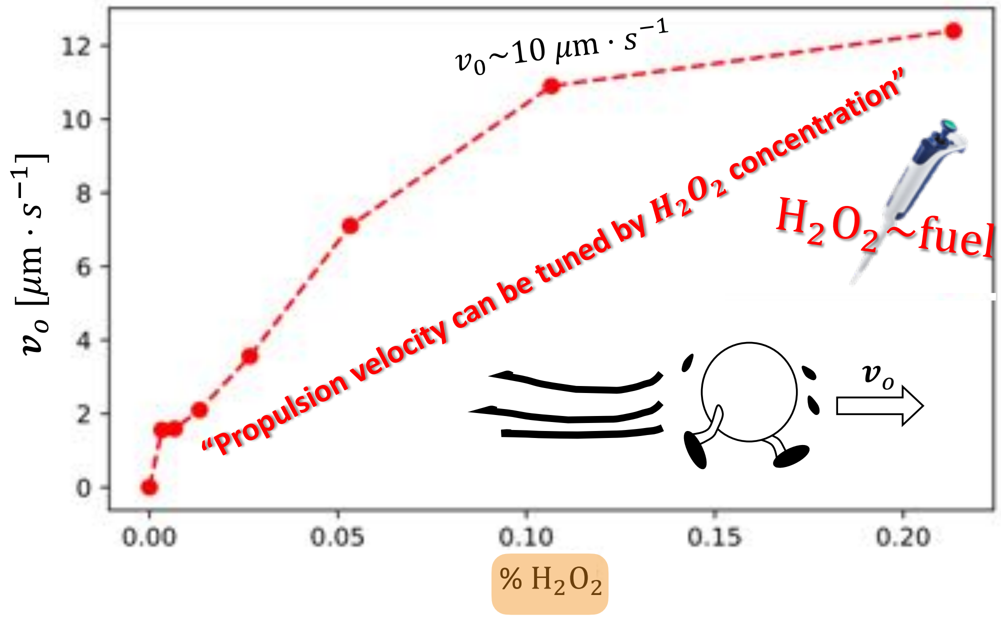
Single Particle Dynamics

Propulsion Velocity

$$v_o \sim 1 - 100\mu m.s^{-1}$$

$[H_2O_2]$





- Short time scale: $\Delta t \ll \tau_r$

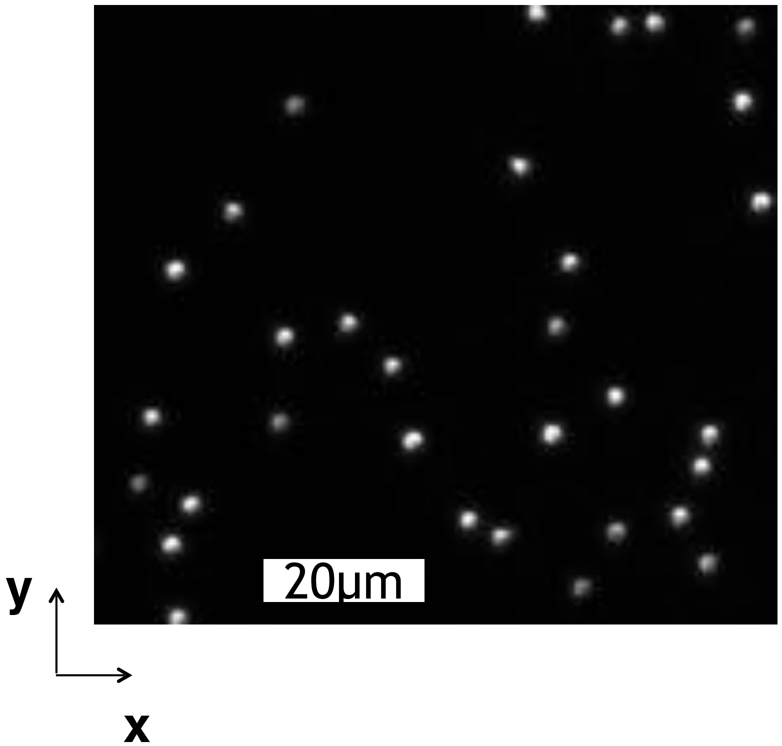
  $\longrightarrow$ Ballistic motion

Single Particle Dynamics

Propulsion Velocity
$v_o \sim 1 - 100\mu m.s^{-1}$
$[H_2O_2]$

\+

Rotational Diffusion
$\tau_r \sim 10s$
Reorientation time



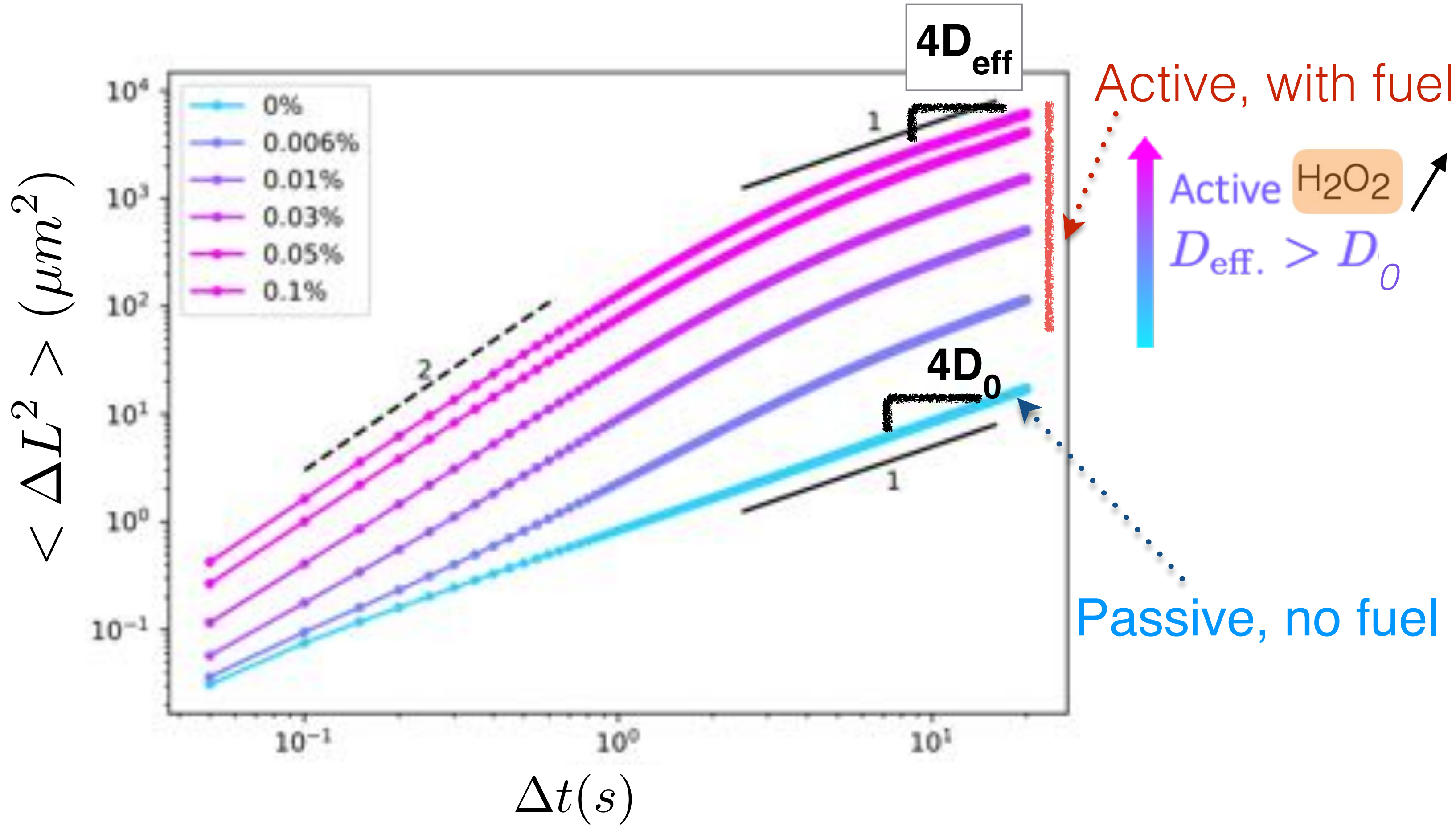
- Short time scale: $\Delta t \ll \tau_r$
  $\longrightarrow$ Ballistic motion

- Long time scale: $\Delta t \gg \tau_r$
  $\longrightarrow$ Diffusive motion D_{eff}

Self D.P. (V) + rotational Brownian motion τ_r = **Persistent Random Walk**

Single Particle Dynamics

Mean Square Displacement (MSD)



$$D_{eff} = D_0 + \frac{1}{6} v_O^2 \tau_r$$

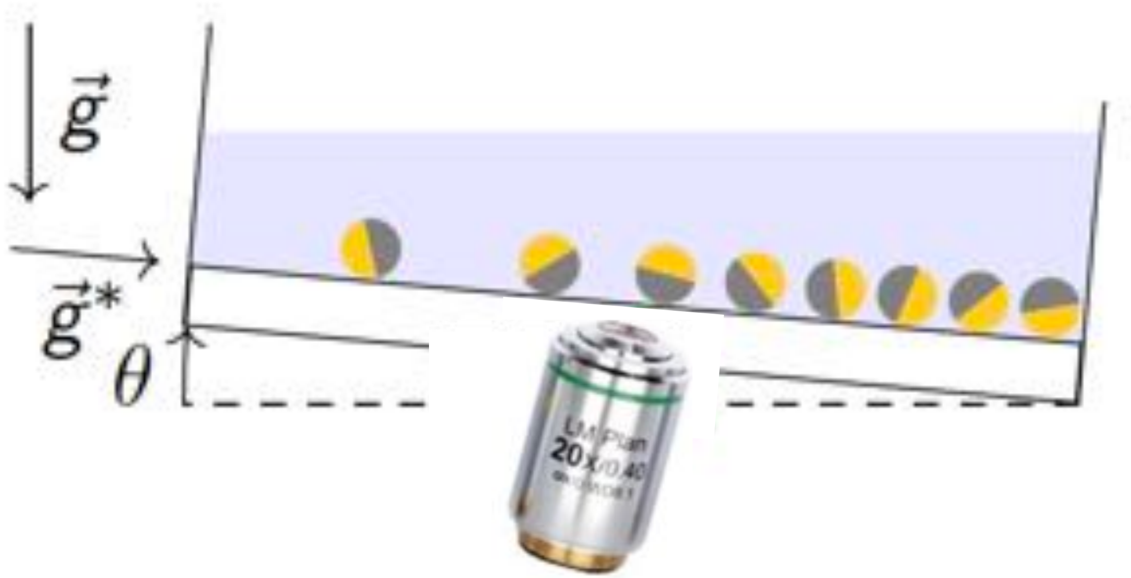
Generating denser assemblies

$\vec{g^*}$ ↓

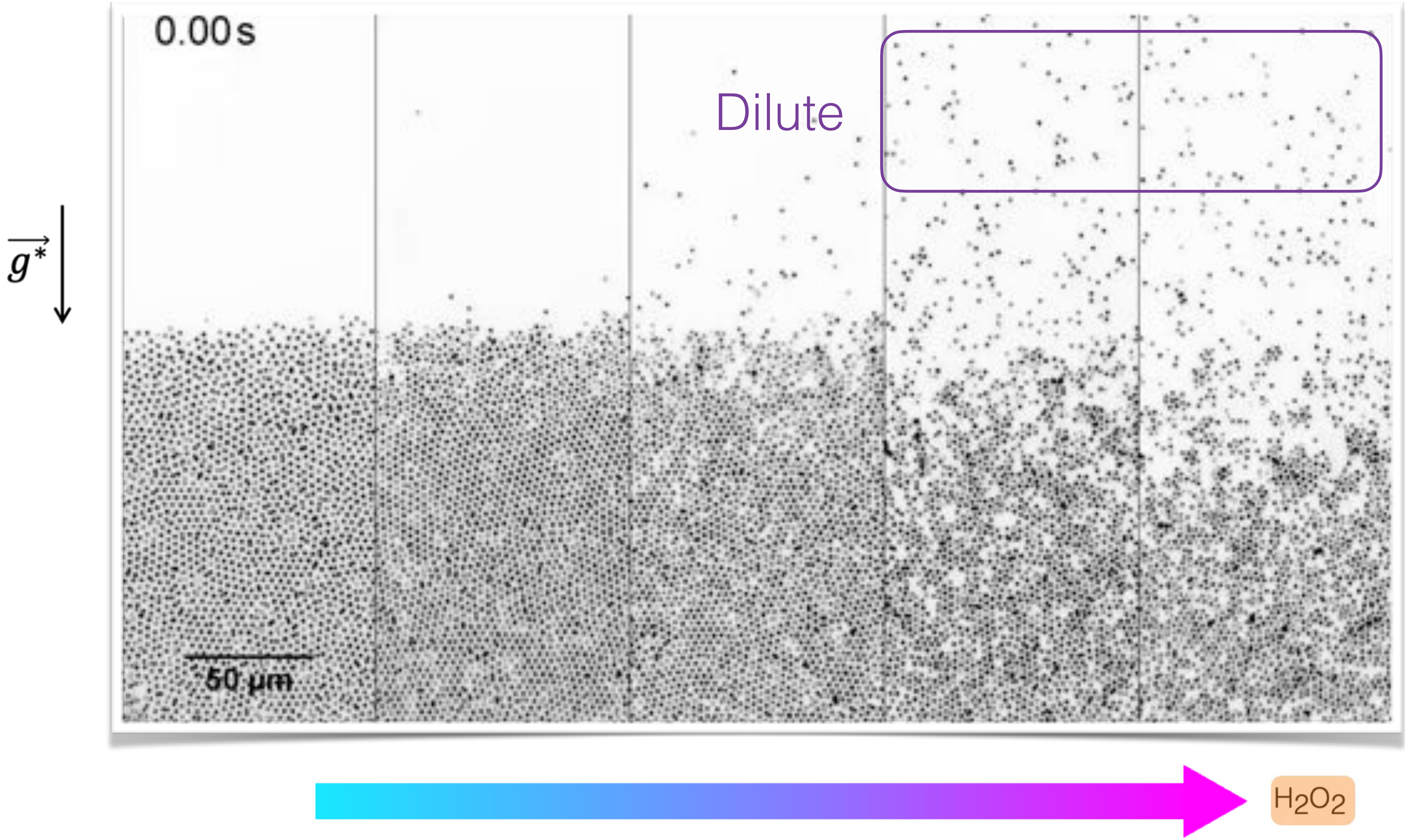
Active fluid

Tilting the microscope

$\theta \sim 0.1°$



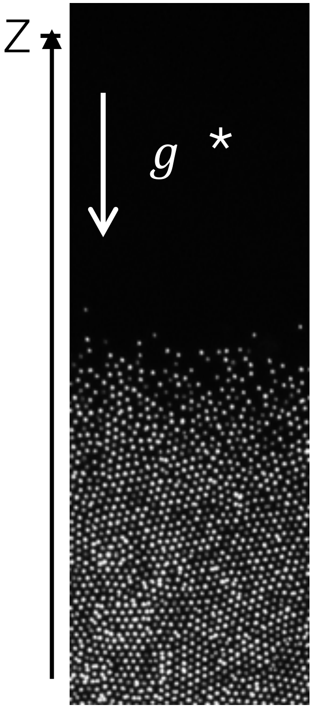
Sedimentation of Active Particles



Passive

Increasing Activity

Sedimentation profile



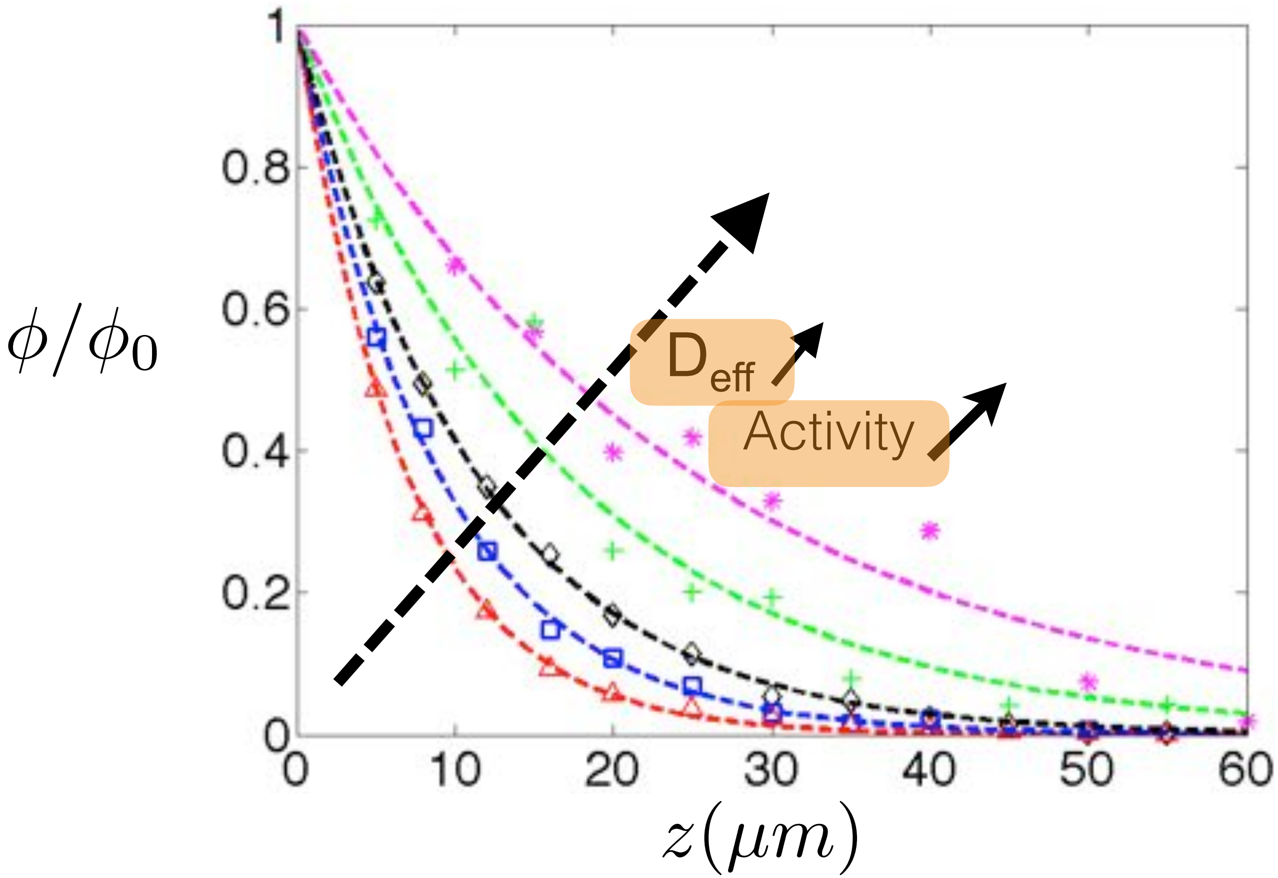
Passive case, a canonical experiment

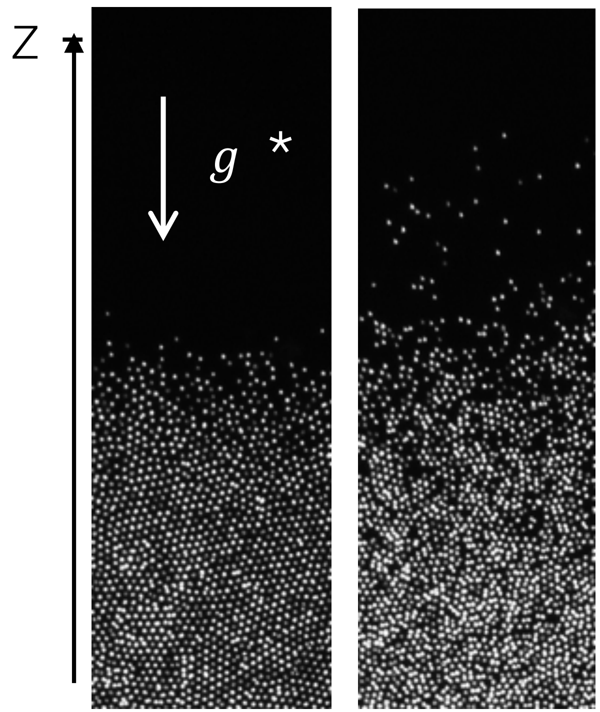
At equilibrium at T, Boltzmann distribution

$$\phi(z) = \phi_O exp\left(\frac{-mg^\star z}{k_B T}\right)$$

$$\phi = \phi_0 exp(-z/\lambda) \qquad \lambda = \frac{k_B T}{mg^\star}$$

Sedimentation profile Active case?





- Exponential decay

$$\phi = \phi_0 exp(-z/\lambda)$$

- λ increases with D_{eff}

?

- Define T_{eff}

$$\lambda = \frac{kT_{eff}}{mg^\star}$$

Sedimentation profile Active case

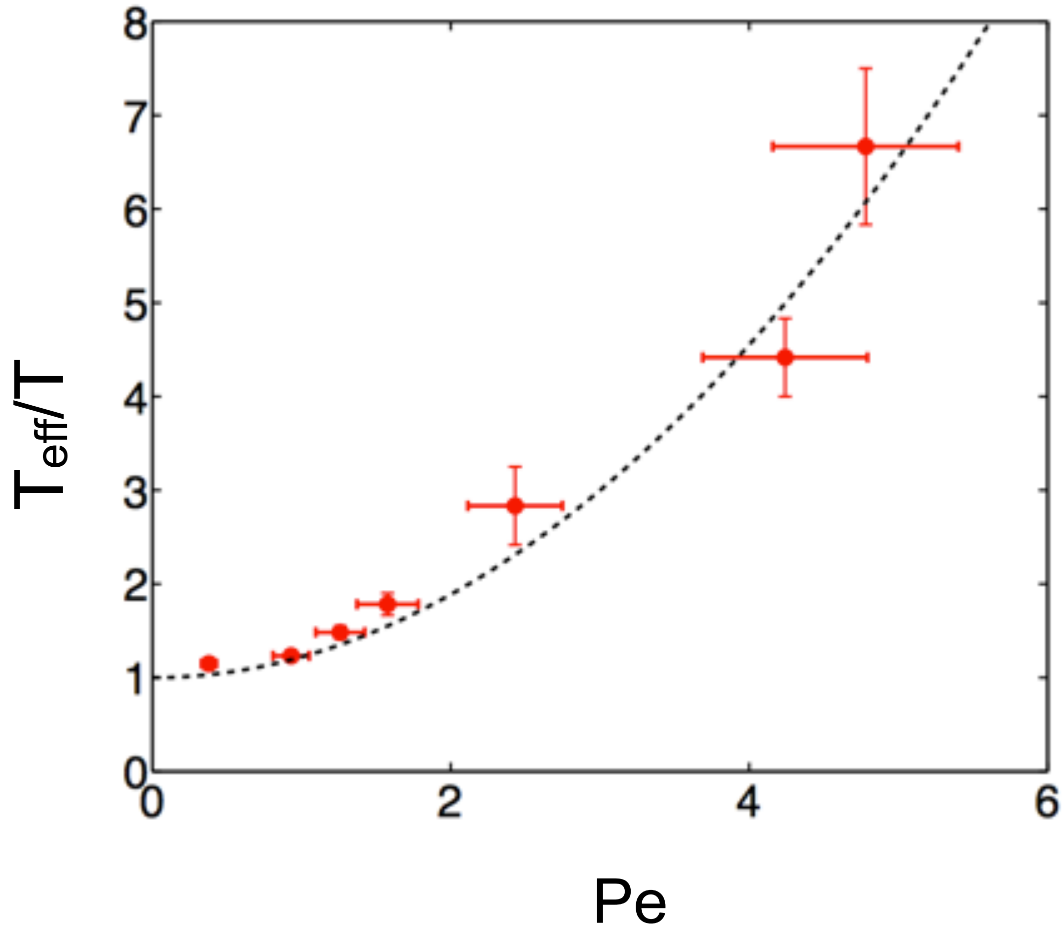
Dilute regime

Hot colloids with T_{eff} driven by Pe

$$\frac{T_{eff}}{T} \propto \frac{D_{eff}}{D_0}$$

$$D_{eff} = D_0 + \frac{1}{6} v_0^2 \tau_r$$

$$Pe = \frac{v_0 R}{D_0}$$



Dilute regime **activity** can be described by T*eff*

Tailleur et al, EPL 2009
Palacci et al, PRL 2010
Ginot et al, PRX 2015

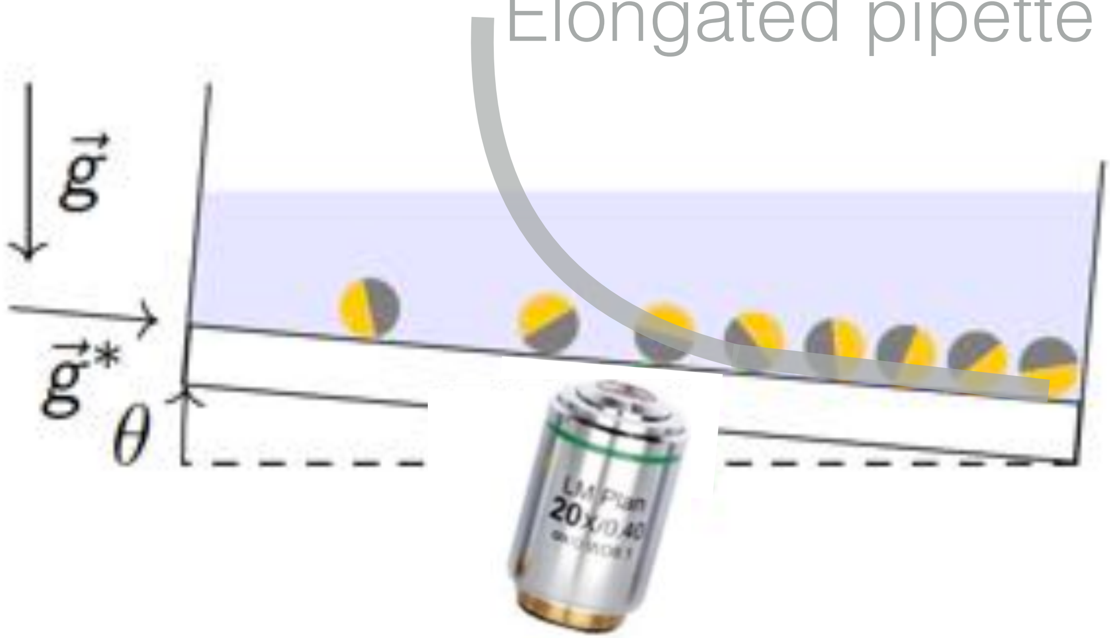
Active Colloids « wetting » a wall?

'Dipping' experiment

Under gravity

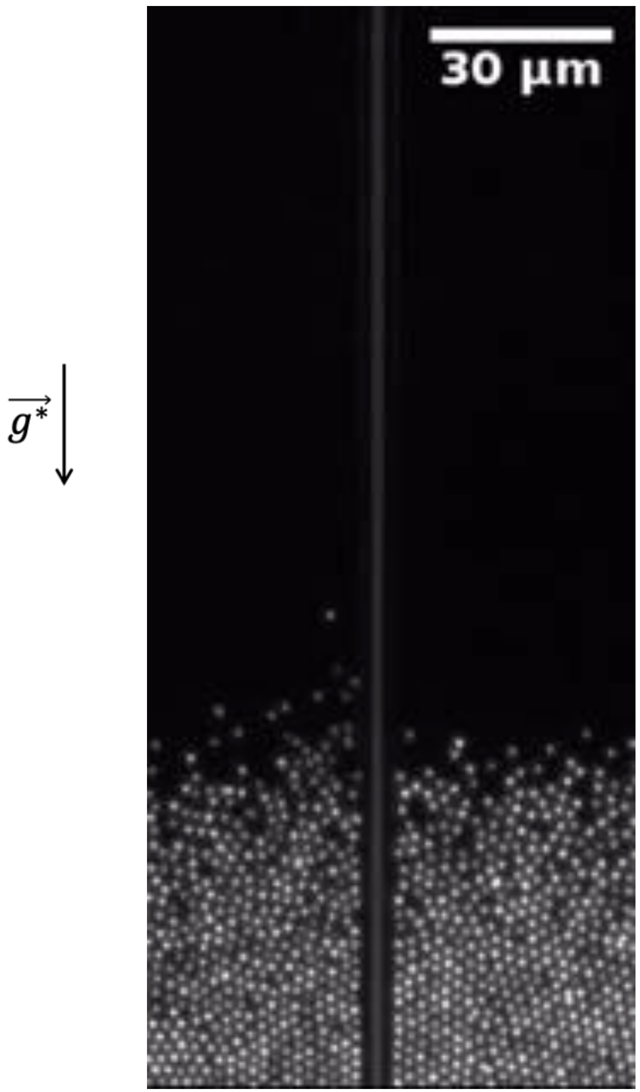
Elongated pipette

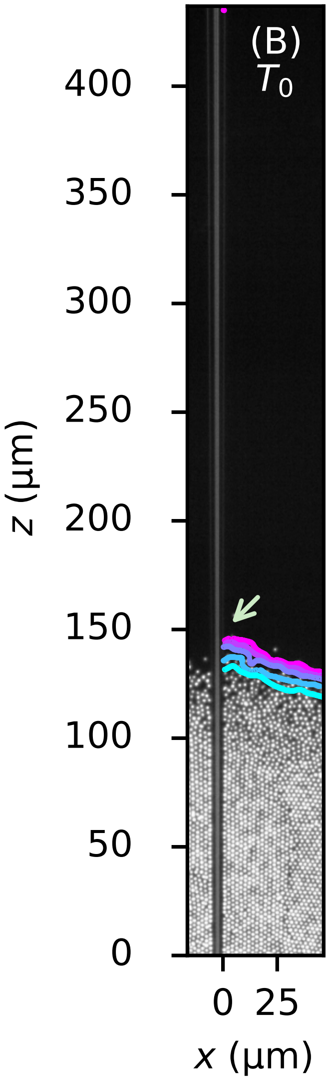
Borosilicate glass
Very flexible rod



Passive Colloids at the wall

Passive case speed x4





Isodensities

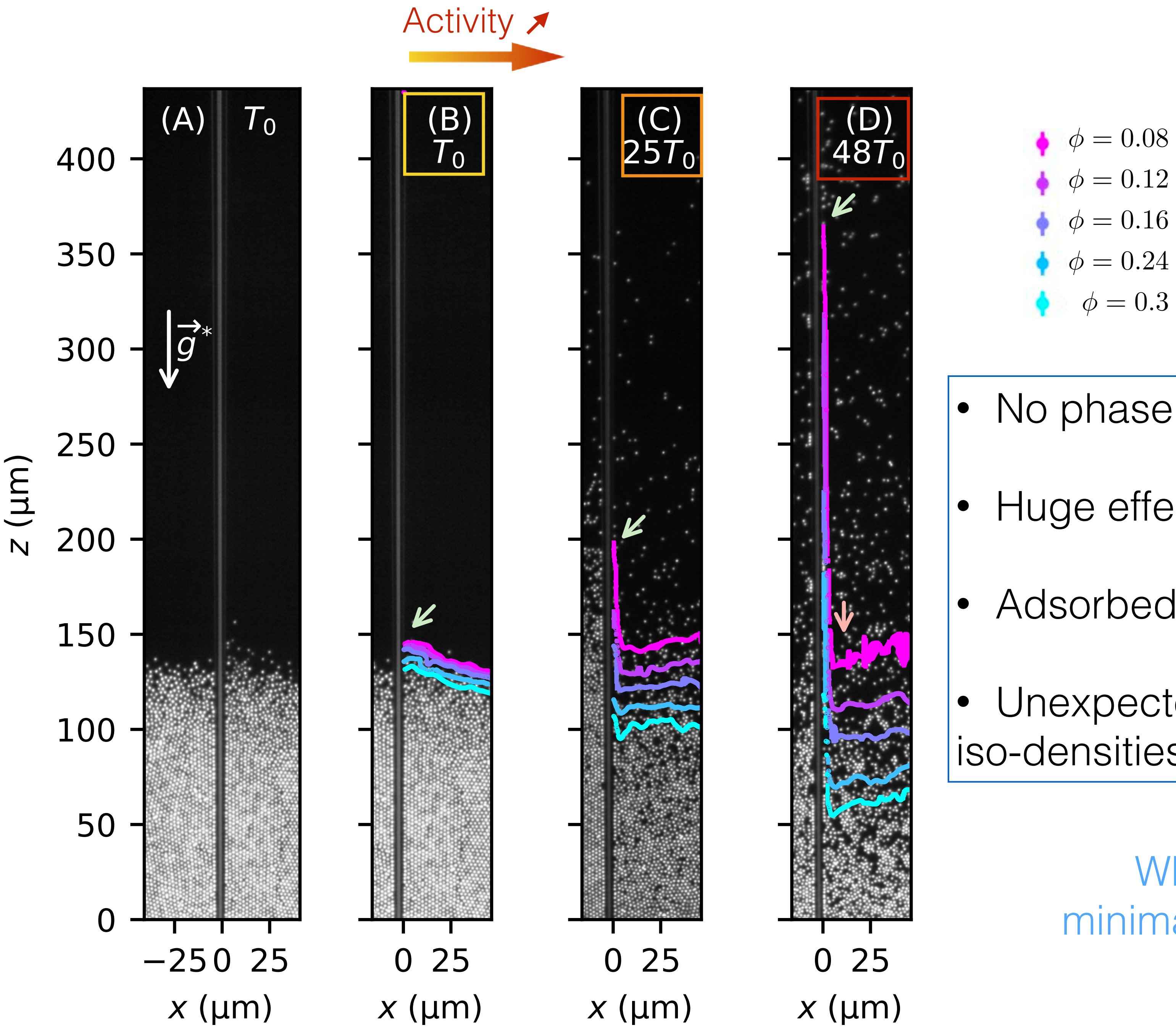
- $\phi = 0.08$
- $\phi = 0.12$
- $\phi = 0.16$
- $\phi = 0.24$
- $\phi = 0.3$

Passive case, purely repulsive colloids

No phase separation

No wall adhesion

Active Colloids at a wall

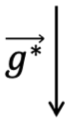


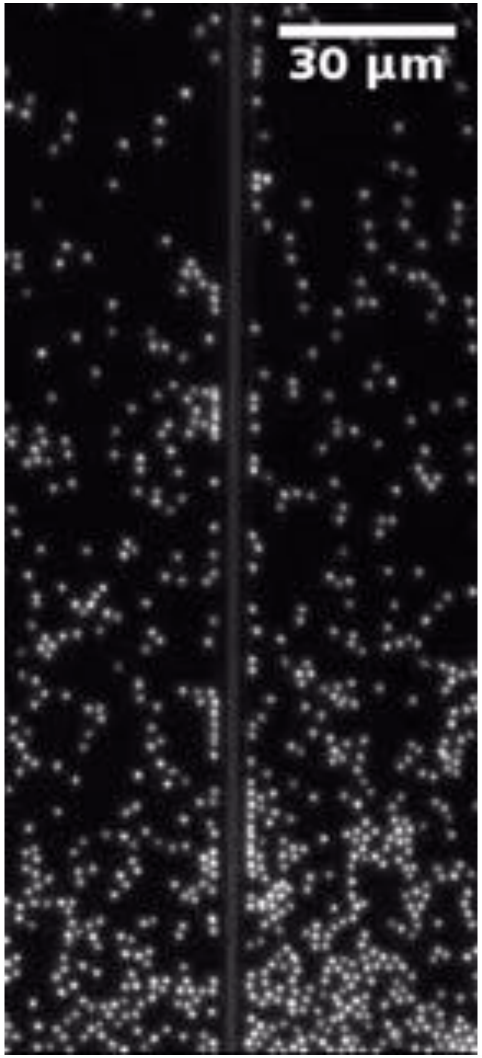
- No phase separation
- Huge effect at the wall
- Adsorbed layer
- Unexpected **upturn** of the iso-densities **close to the wall**

What are the minimal ingredients?

Trains at the wall

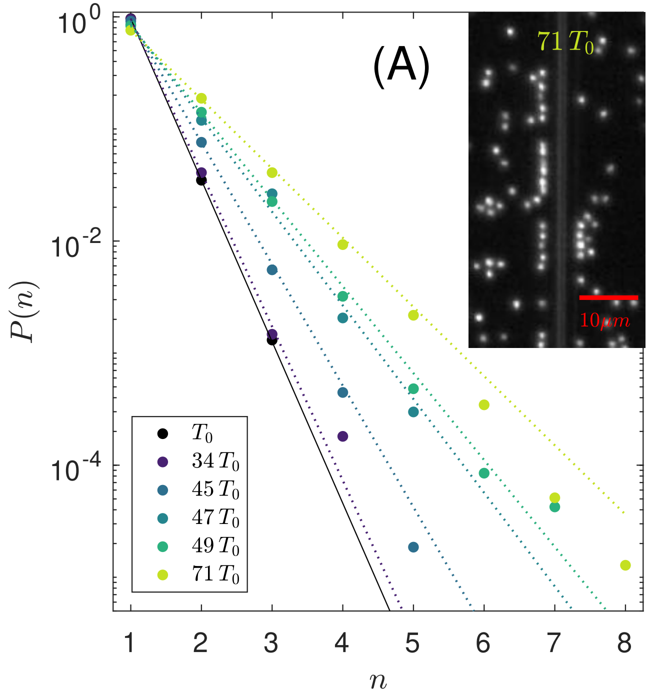
Active case speed x4





Very different from « classical » meniscus

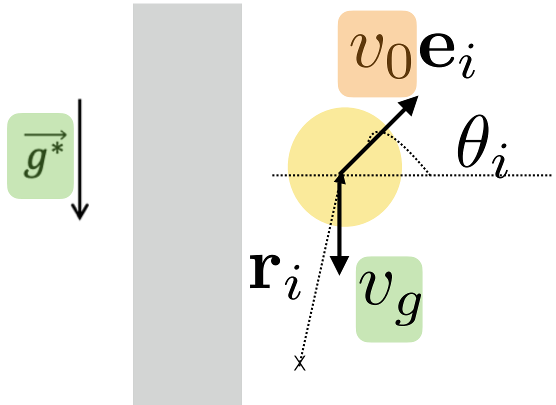
Train Statistics



- Probability distribution dominated by **monomers**
- **Random site-adsorption** model

Active Brownian Particle simulations @ Saarbrücken

- Sedimenting repulsive **A**ctive **B**rownian **P**article **+ a wall**



Overdamped Langevin equation

- Position $\mathbf{r}_i$:

$$\dot{\mathbf{r}}_i = v_0\mathbf{e}_i + \gamma_t^{-1}\mathbf{f}_i - v_g\mathbf{e}_z + \sqrt{2D_t}\,\boldsymbol{\eta}_i$$

- Orientation θ_i :

$$\dot{\theta}_i = \sqrt{2D_r}\,\xi_i + \gamma_r^{-1} t_i^{\mathrm{wall}}$$

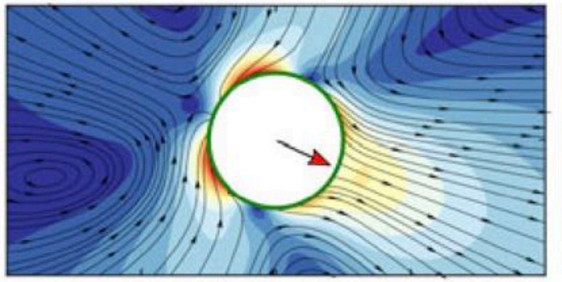
Particles: repulsive pair potential

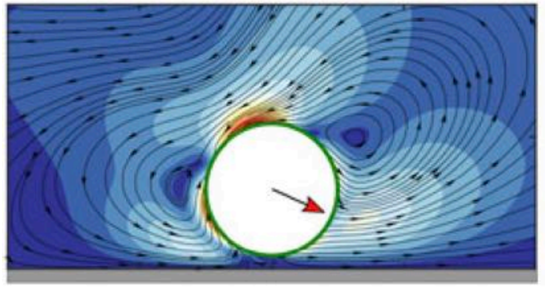
$$\gamma_t = k_B T_0 / D_t$$
$$\gamma_r = k_B T_0 / D_r,$$

- Pe < 17 : **No Phase separation** (no MIPS)
- **Wall-particle interactions?**

Active colloids interacting with wall (no external force)

- Hydrodynamic interaction of force dipole microswimmers with surfaces:





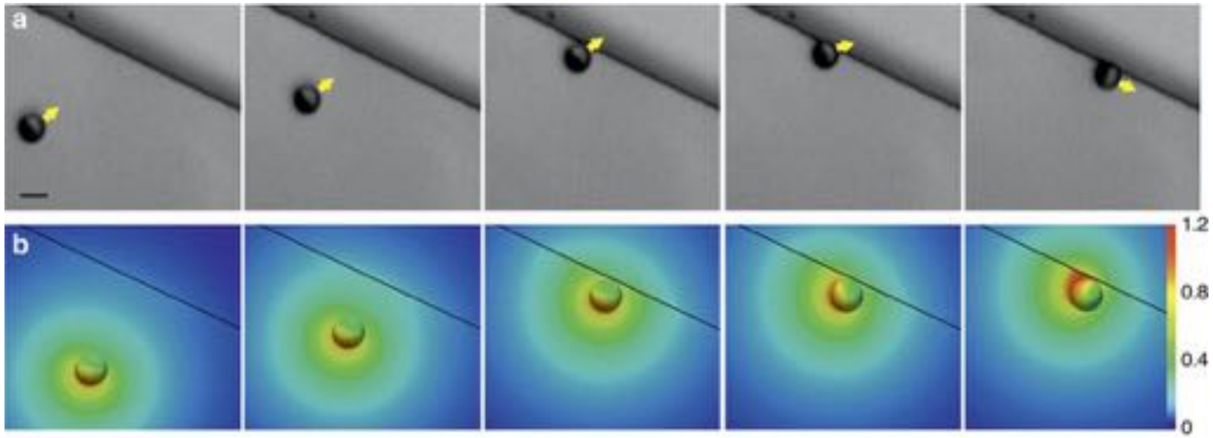
Bercke et al, PRL 2008
Poddar, JFM, 2020

- **Alignement** with the surface

Active colloids interacting with wall (no external force)

- **Phoretic interaction** with **surfaces**:

Self-generated gradient **modified by the wall**



J. Simmchen et al., Nature Communication, 2016

- **Adhesion** and **Alignement** with the surface

$\mathrm{Pe}_s = v_0/(RD_r)$

- Wall-particle interactions in the simulations:

  Adhesion: ϵ

  Nematic alignement: Γ

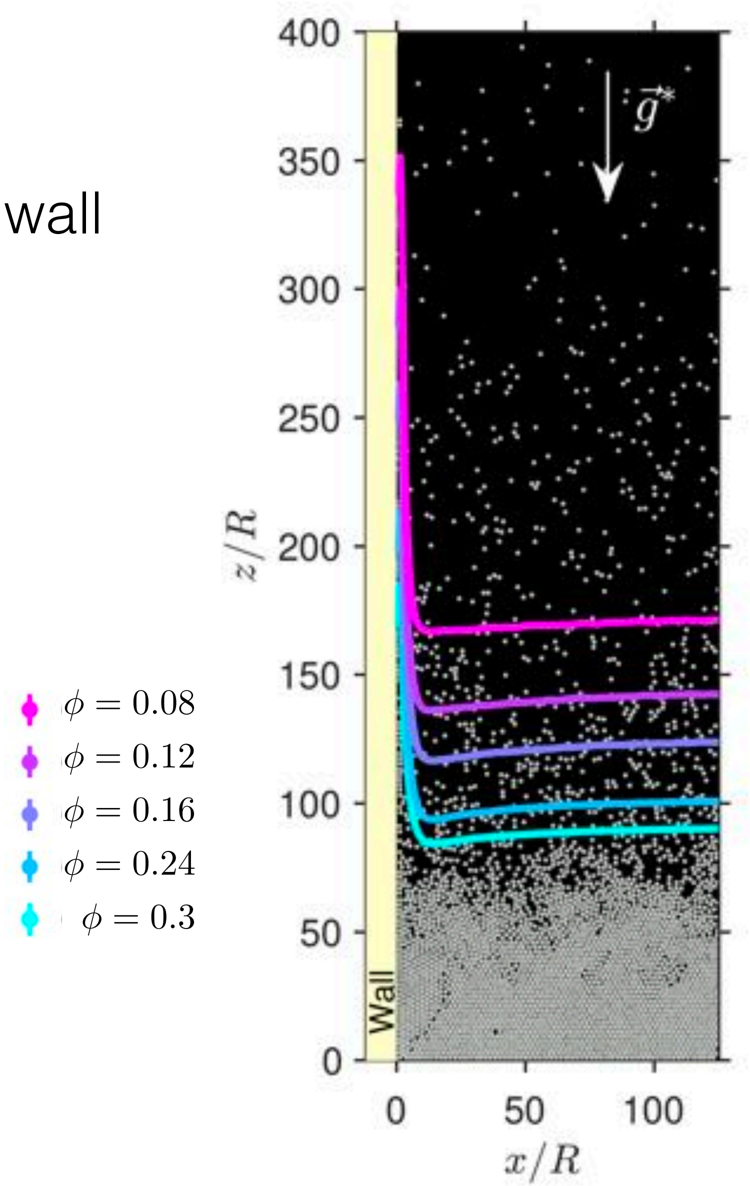
$\widetilde{\epsilon} \propto \mathrm{Pe}_s$

$\widetilde{\Gamma} \propto \mathrm{Pe}_s$

Active Brownian Particles

Adhesion and alignement at the wall

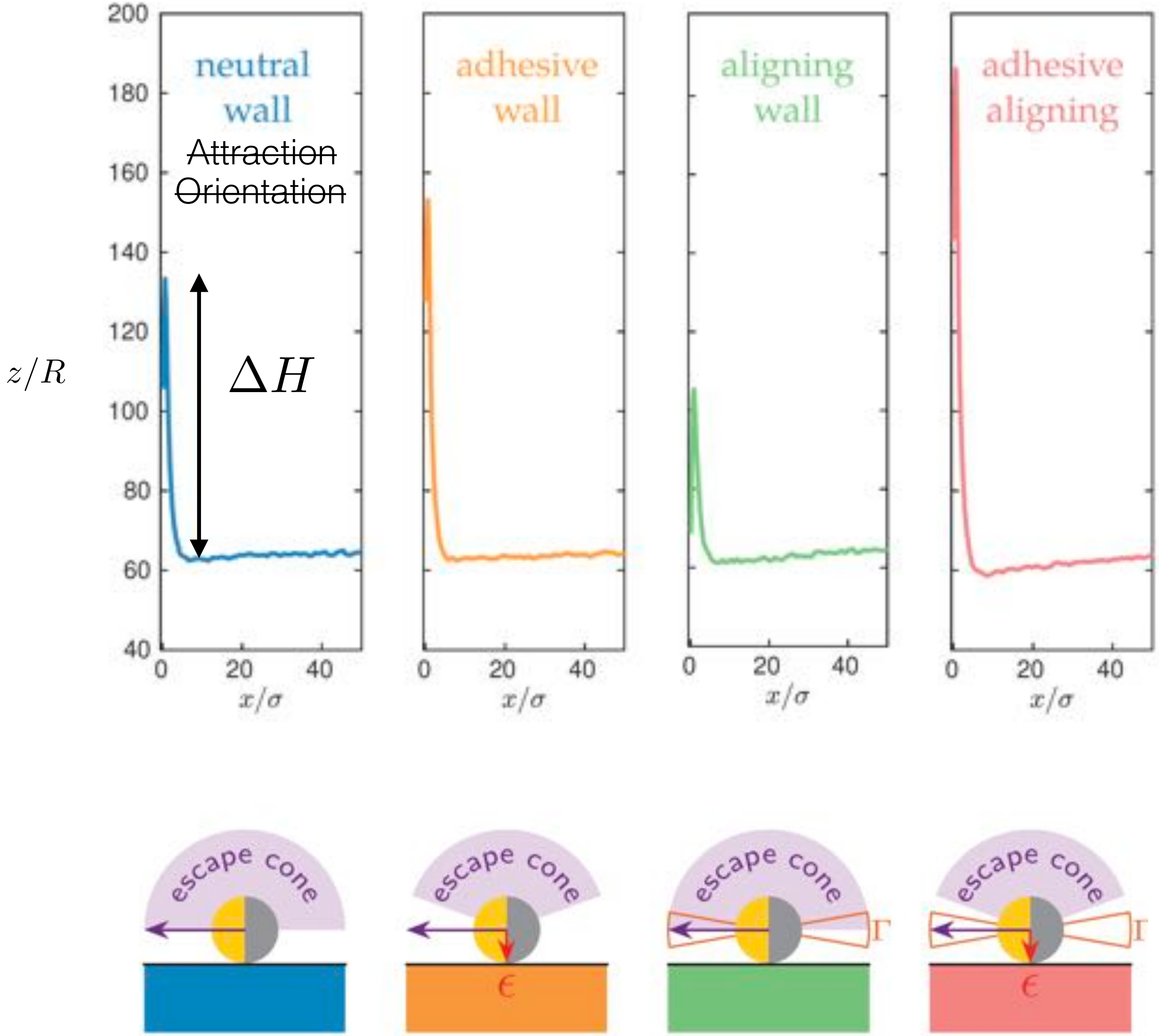
Recapitulates experiments



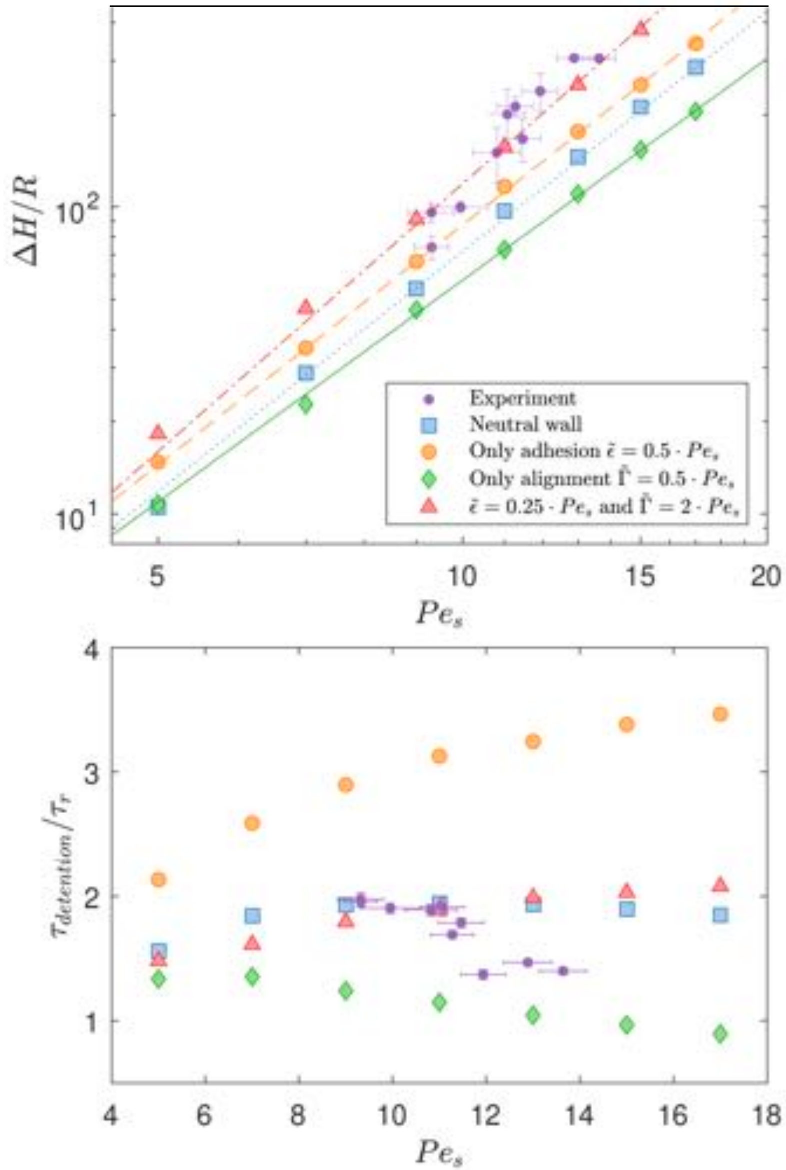
- We can define an Adhesion Height ΔH

Role of wall-particle interactions (simulations)

- For a given activity Pe_S



- As a function of Pe_S



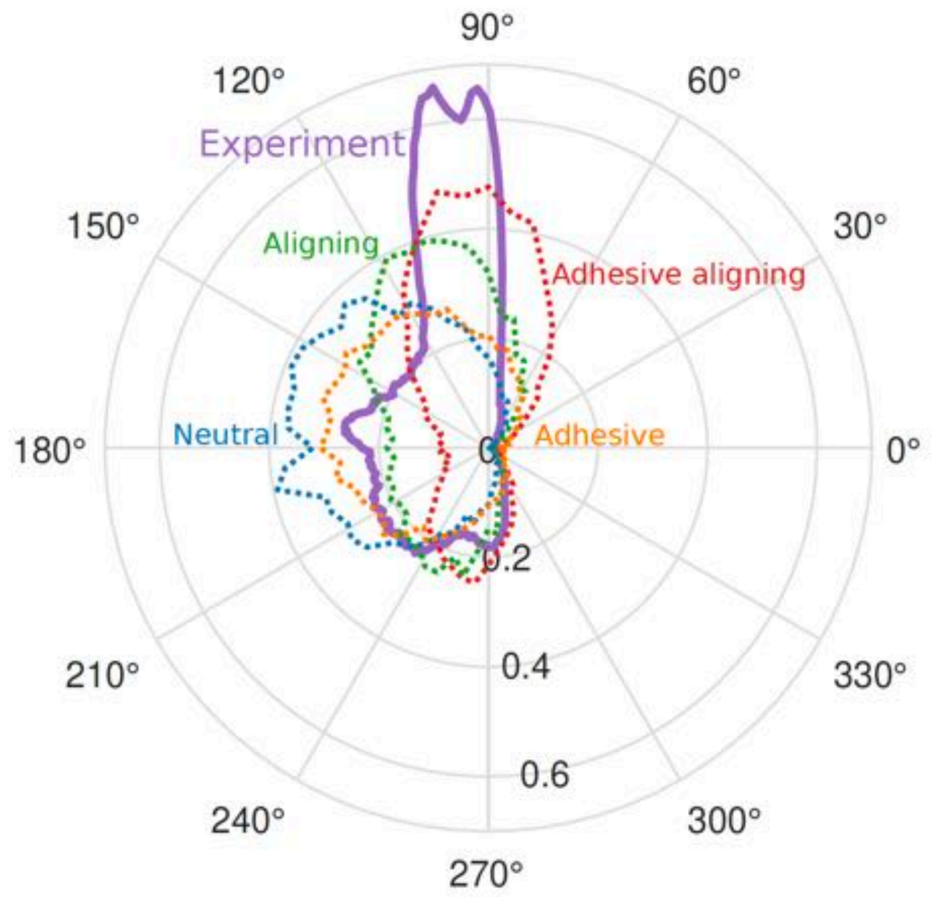
Generalized from *Schaar et al PRL 2015*

Detention time ~~drives~~ adhesion height

Polarity measurement at wall

- No access to orientation of displacements
- Statistical **polarity measurement** by color camera

Polarity distribution in the adsorption layer, dilute regime

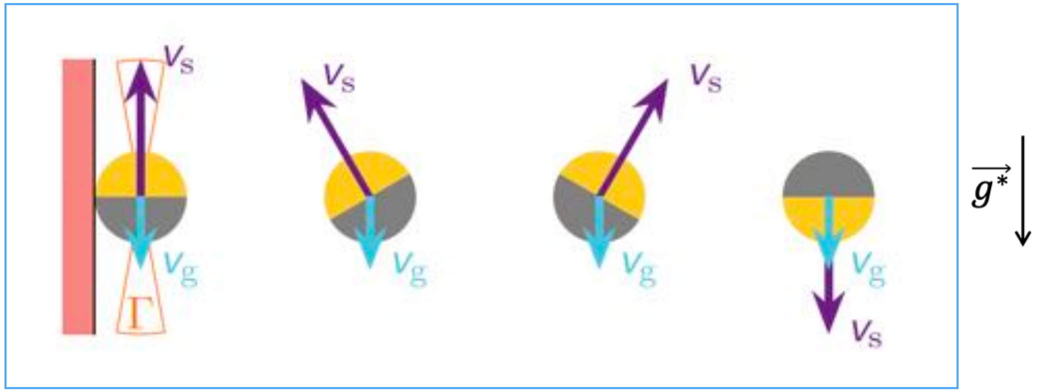


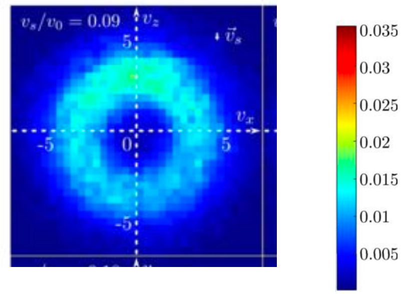
- Bipolar aligning wall but why **upward** polarity?

Why upward polarity at the wall (dilute)?

- Bulk without gravity: - zero net flux
  - no polarity

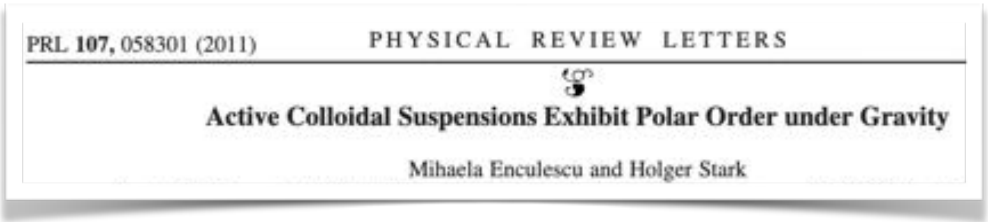
Probability distribution of measured velocity





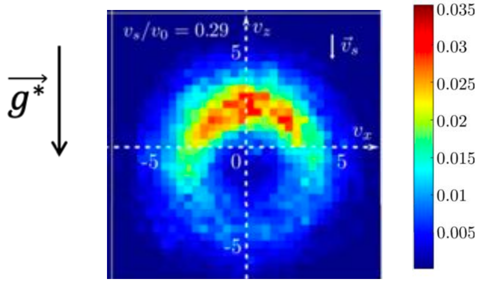
F. Ginot et al., NJP, 2018

- Bulk with gravity: - zero net flux
  - **Upward** polarity (dilute)


PRL 107, 058301 (2011) PHYSICAL REVIEW LETTERS

Active Colloidal Suspensions Exhibit Polar Order under Gravity

Mihaela Enculescu and Holger Stark



Mean swimming velocity oriented against Gravity

- Gravity at aligning wall:

- **enhances bulk polarity**
- this explains **increase** ΔH
- **breaks flux balance**

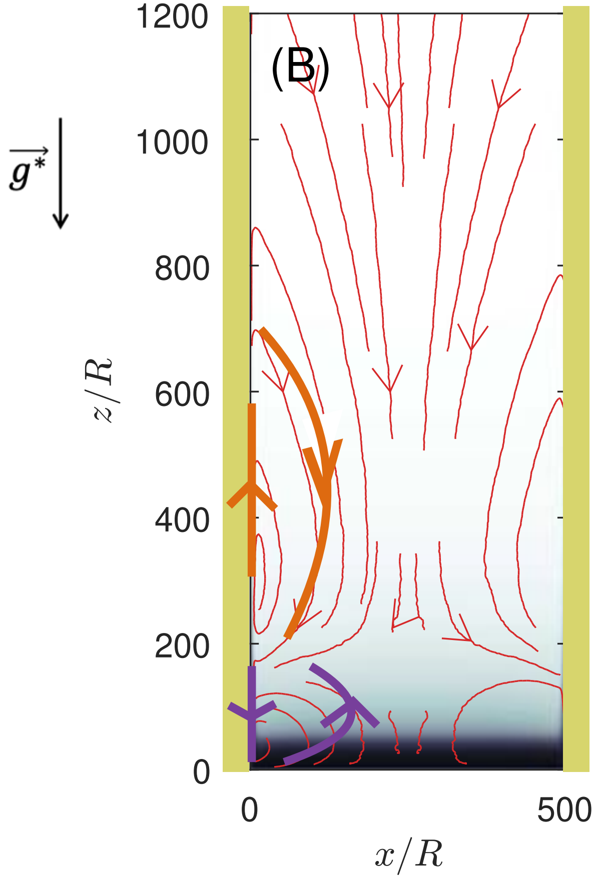
Fluxes, circulation

- **Under gravity, at an aligning Wall :**

Enhances the upward polarization in dilute regime
the downward polarization in the dense regime

Self-propelled particles → **Steady-state particle currents**

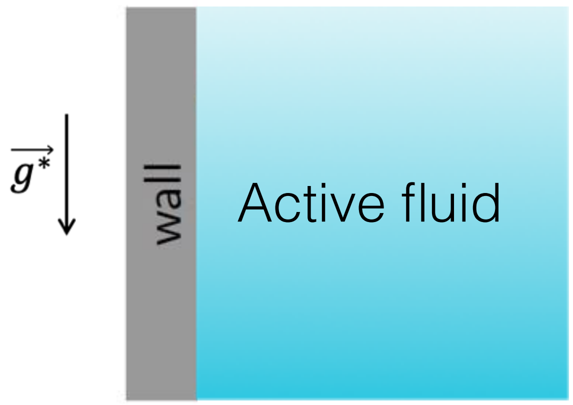
Forbidden in equilibrium systems

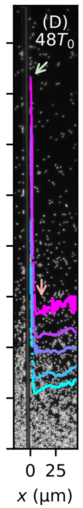


Simulation results, time averaged $\sim 10^6 \tau_r$

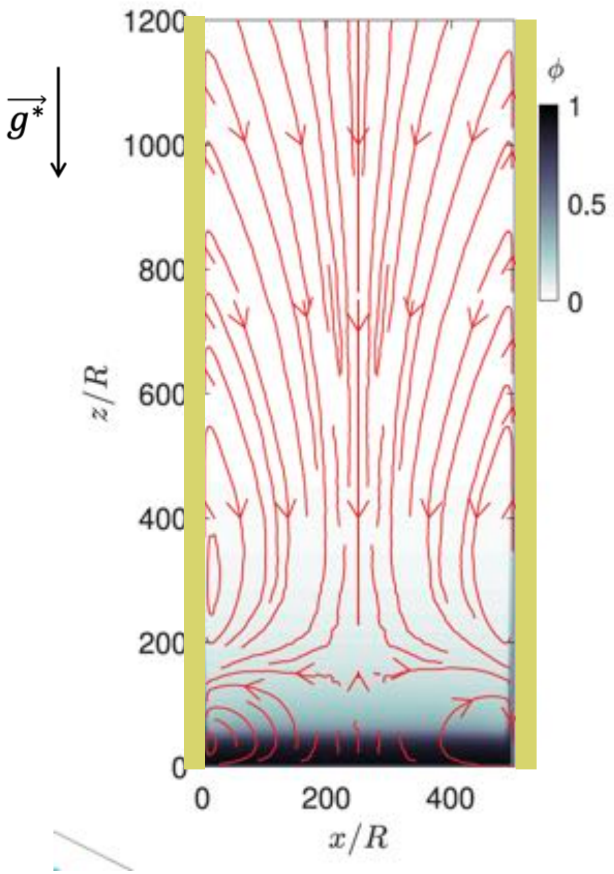
A. Fins Carreira et al Nature Comm. 2024

Take Home Message





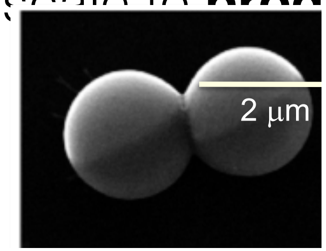
Broken Flux balance in an
Active Fluid @ wall

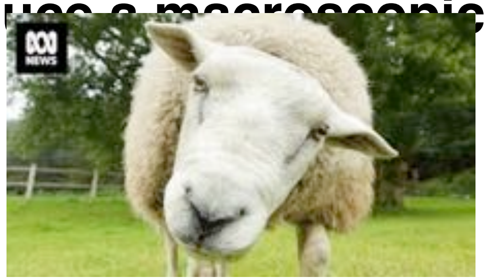


- Gravity+ **adhesive aligning wall** = pump up
- Adhesive aligning wall + $\vec{F}_{||}$ = **counter up**

Possible to extract work from Active fluid

A vertical wall **harvest energy** from the microscopic scale to **produce a macroscopic work**





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Valentin Poncet
François Détcheverry
Mathieu Leocmach
Christophe Ybert

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Thanks!

Adam Wysocki
Heiko Rieger

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PHYMOT Physics of Microbial Motility

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