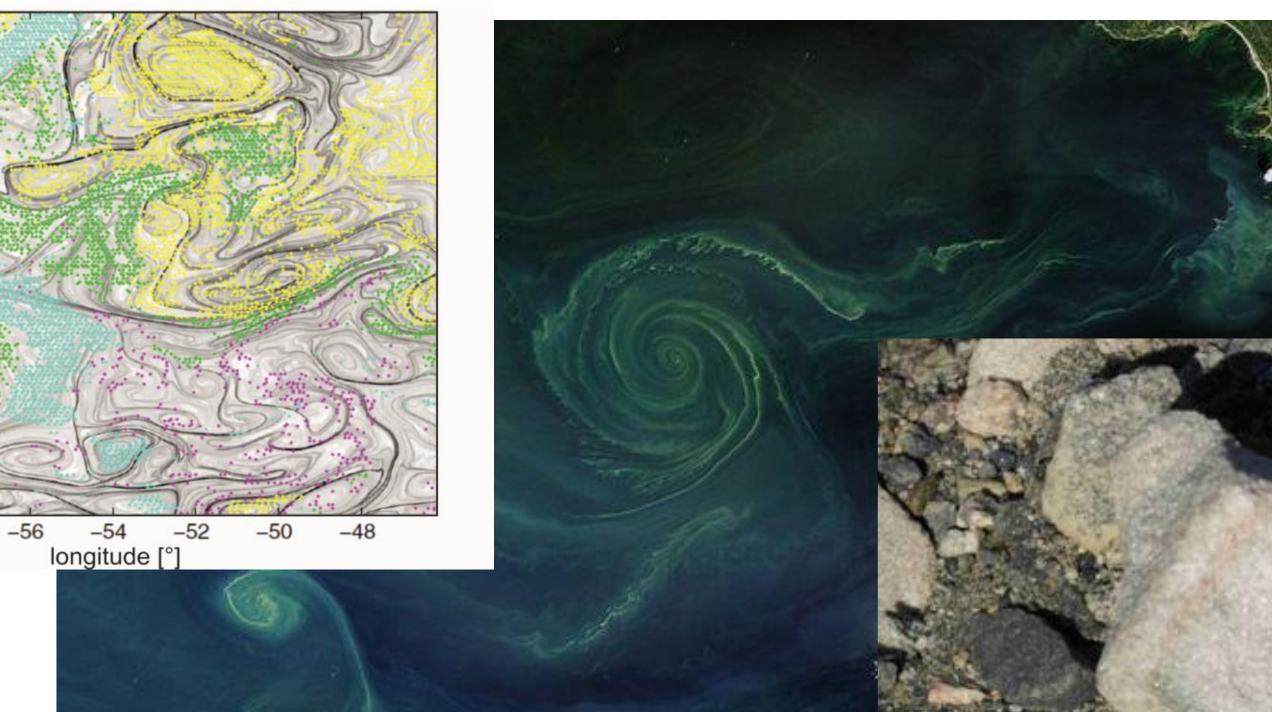
MAX-PLANCK-GESELLSCHAFT

Micro-Swimmers: Individual and Collective Behaviour

Department of Dynamics of Complex Fluids
Stephan Herminghaus, MPI-DS Göttingen

Photoactive Microorganisms in Nature

- microbes are the oldest and most abundant form of life on Earth
- photosynthetic microalgae are the primary producers of biomass on Earth



planktonic state

marine phytoplankton
algal blooms in Baltic Sea

biofilms on surfaces

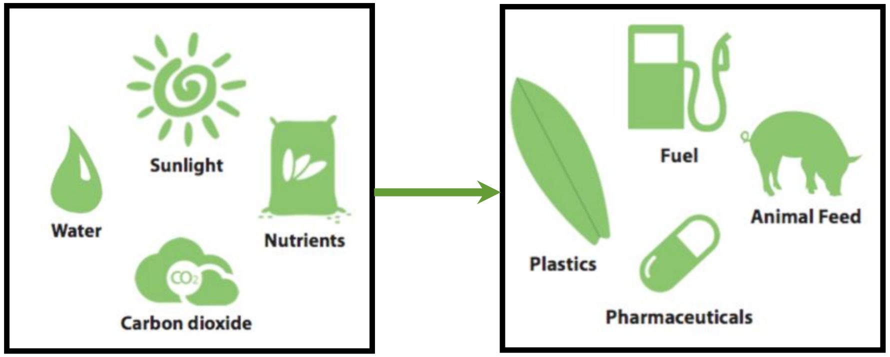
cyanobacteria communities
in Antarctica
interstitial space of porous media

conquered (and adapted to) all habitats and ecosystems

Photoactive Microorganisms in Biotechnology

photosynthetic (“green”) microalgae may produce hydrocarbons

photo-bioreactors for biofuel production: bio-diesel, bio-ethanol, bio-methanol, airplane fuel



biological hydrogen synthesis by green microalgae: towards a green fuel cell

• hydrogenase: biological hydrogen synthesis

biophotovoltaics: algae-powered solar cells

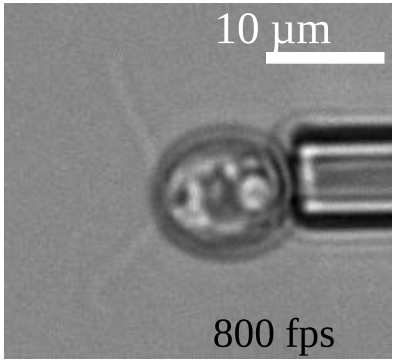
• convert light into electric current

synthesis of pharmaceutical agents

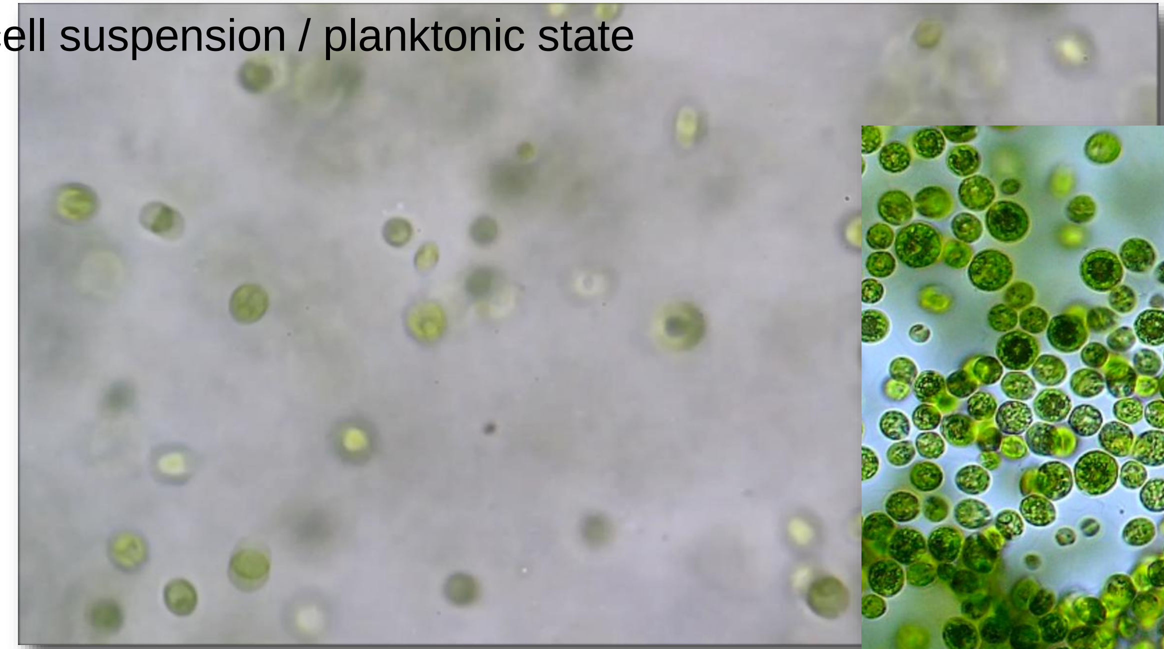
• synthesis of proteins for HIV drugs

The Model Organism Chlamydomonas reinhardtii

- unicellular, biflagellated green microalga
- approx. 10 microns diameter
- two flagella (beating frequency of 50-60 Hz)
- puller-type microswimmer (100 µm/s)
- chloroplast (perform photosynthesis)
- biological model system

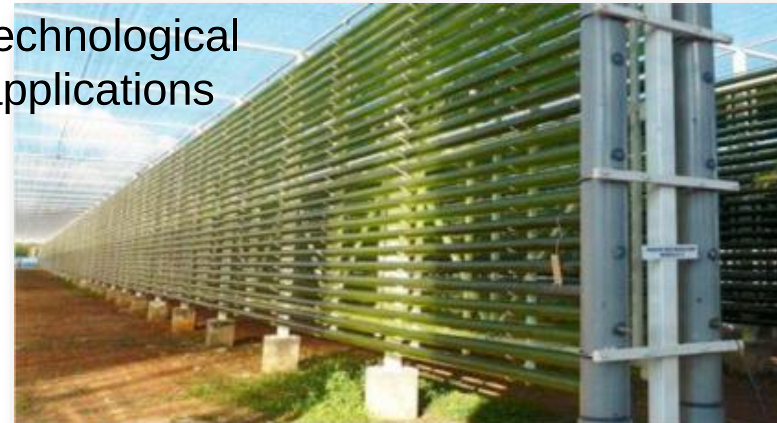


cell suspension / planktonic state

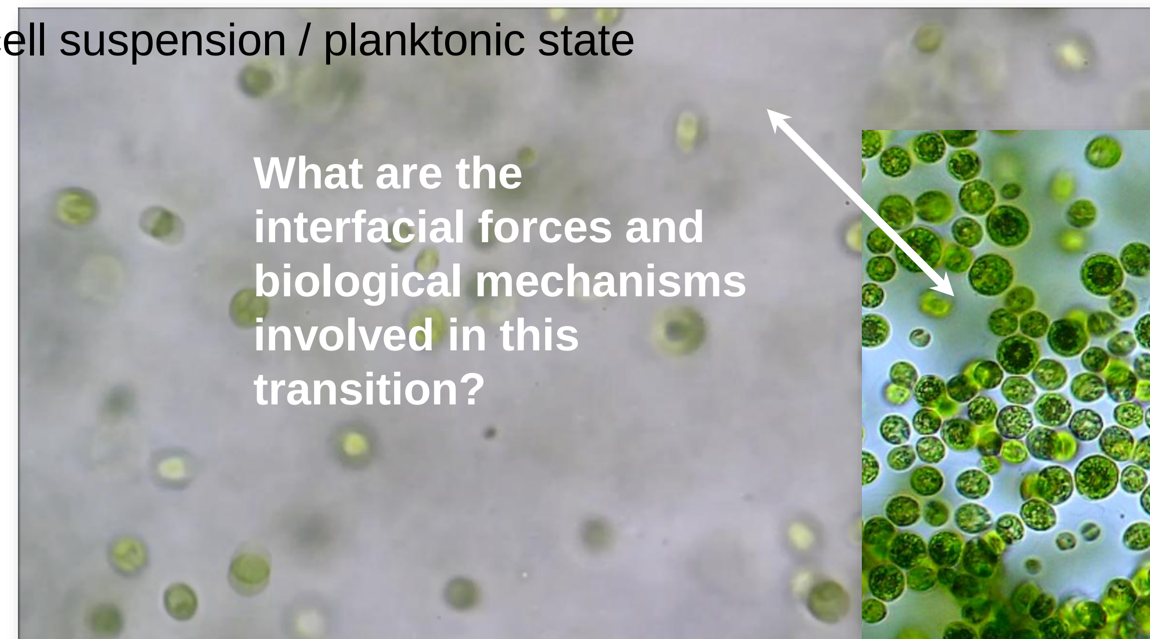


surface-adhered state

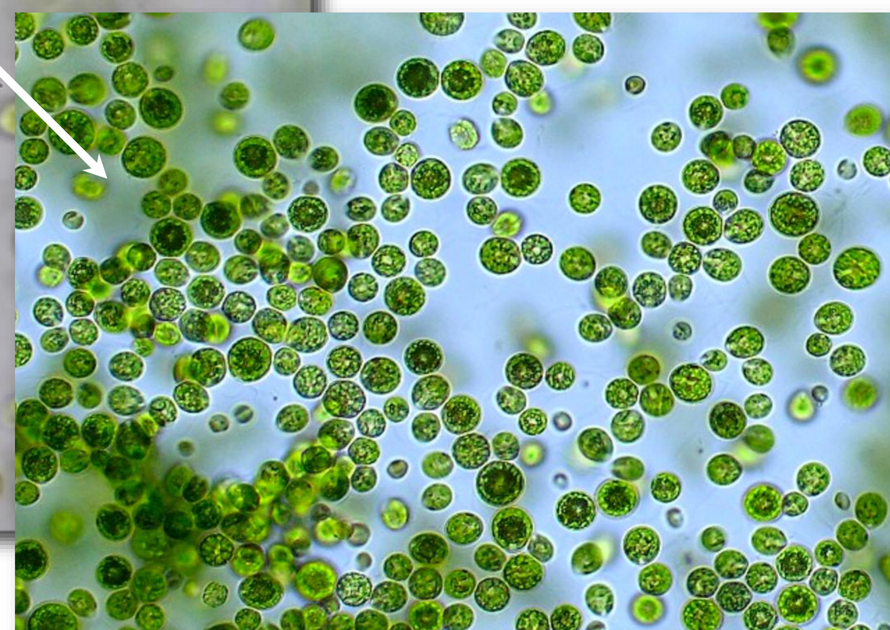
The Model Organism Chlamydomonas reinhardtii



cell suspension / planktonic state

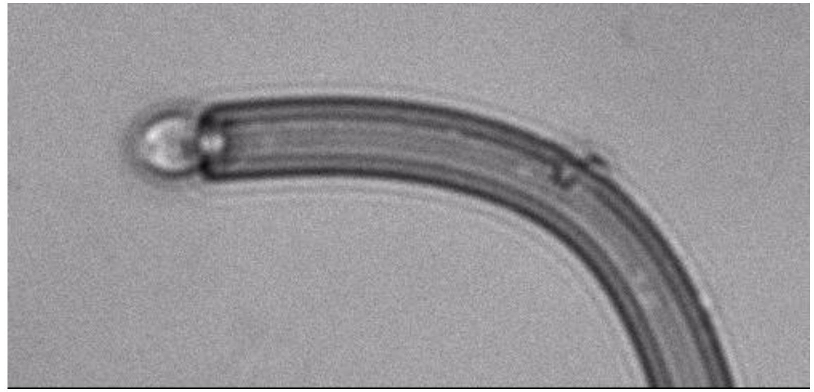


surface-adhered state

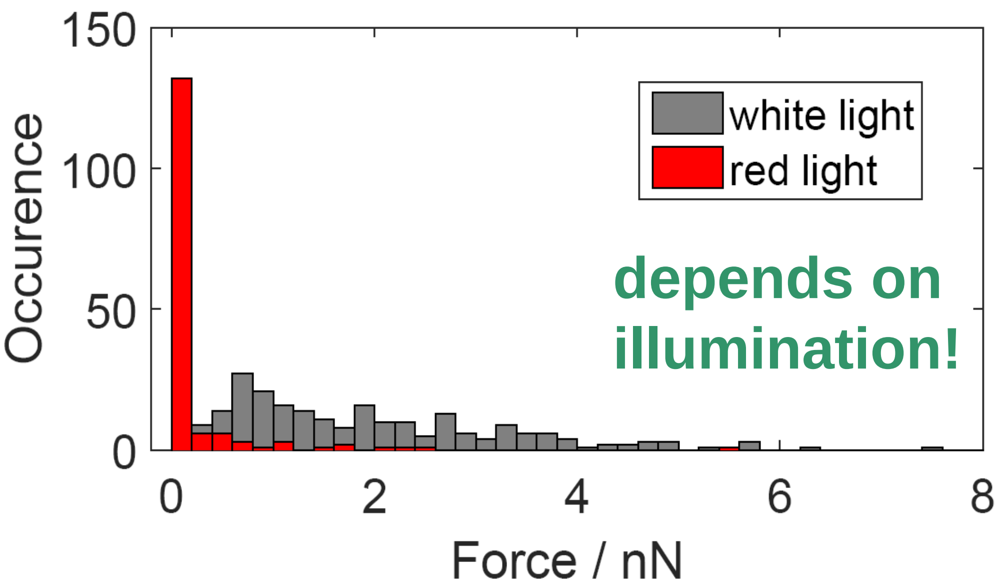


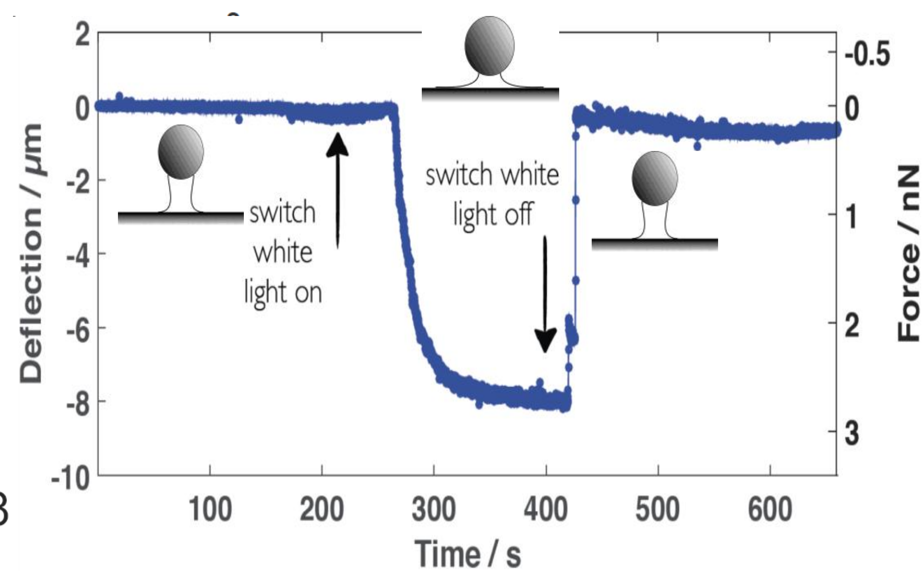
Life in complex geometry

Chlamydomonas reinhardtii on a pipette cantilever



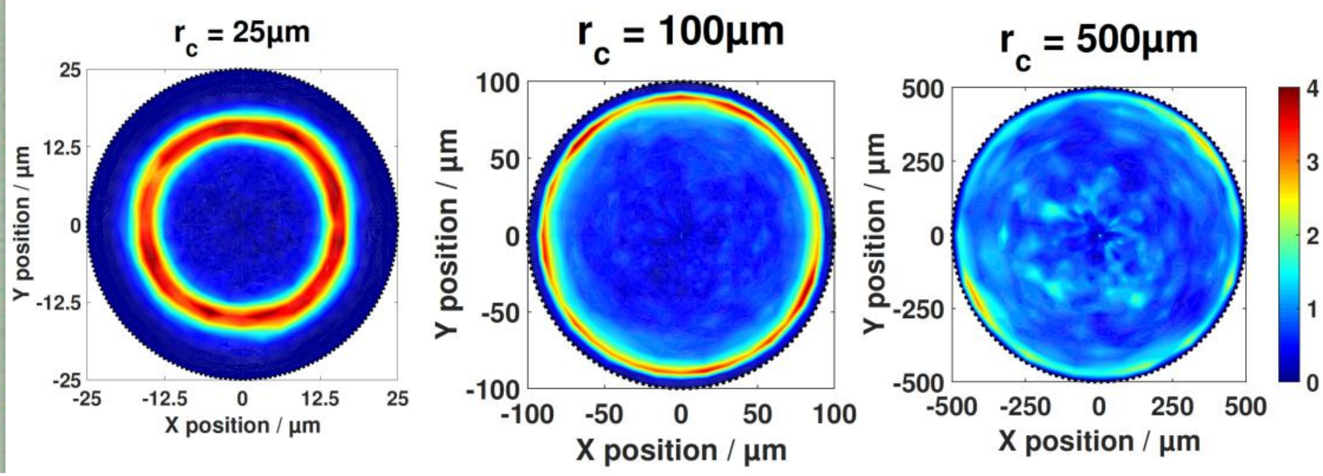
Non-Sticky Cells or Sticky Cells?

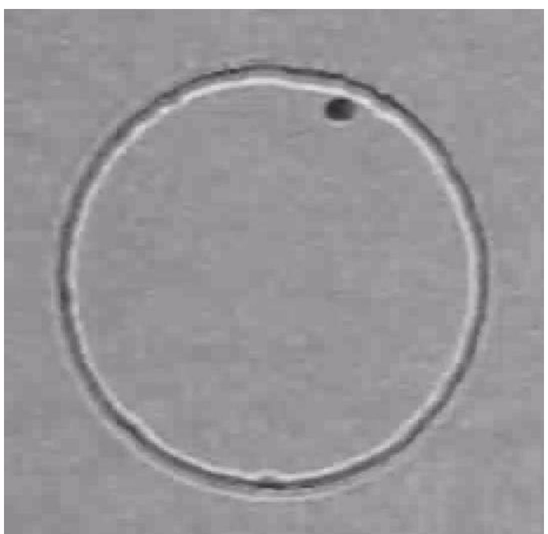




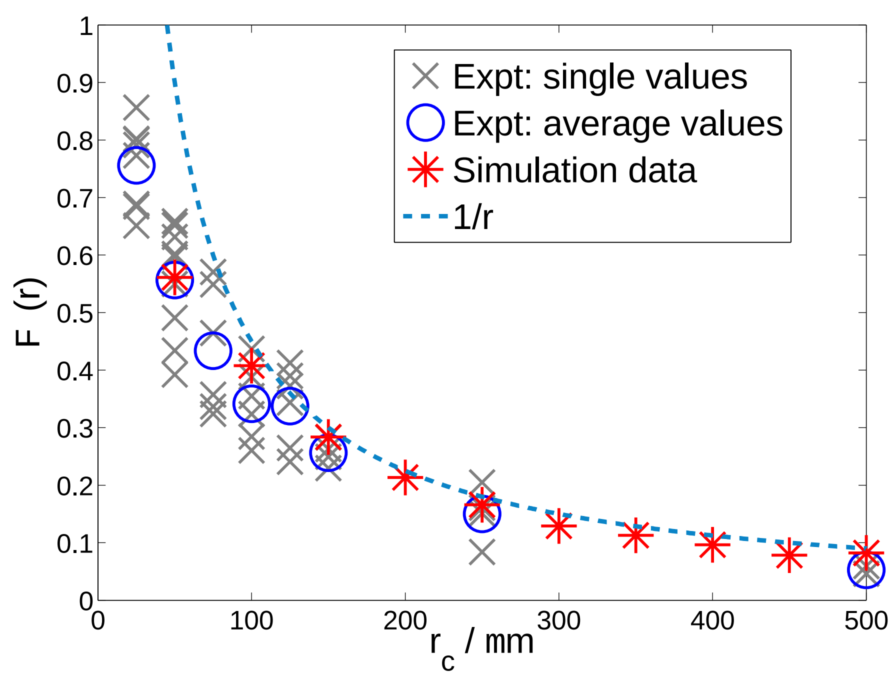
Life in complex geometry

Chlamydomonas reinhardtii





compartment diameter: 100 µm



$$\frac{d\vec{r}}{dt} = v_0\vec{e} + \gamma_w \vec{F}_w + \vec{\eta}\,, \qquad \langle \vec{\eta}(t)\vec{\eta}(t')\rangle = 2k_B T \gamma_w \mathbf{I}\delta(t-t')$$

$$\frac{d\vec{e}}{dt} = (\vec{T}_w/\tau_w + \vec{\xi}) \times \vec{e}\,, \qquad \langle \vec{\xi}(t)\vec{\xi}(t')\rangle = \frac{2k_B T}{\tau_p}\mathbf{I}\delta(t-t')$$

+ run & tumble motion

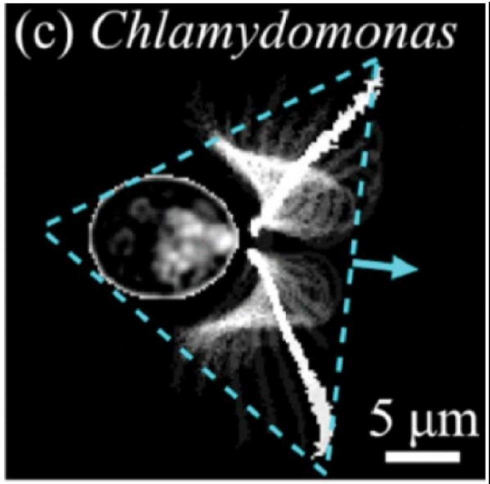
$$\vec{F}_w = \vec{F}_1 + \vec{F}_2$$ Steric wall interactions

$$\vec{T}_w = \vec{T}_1 + \vec{T}_2, \quad \vec{T}_i = (\vec{r}_i - \vec{r}) \times \vec{F}_i$$

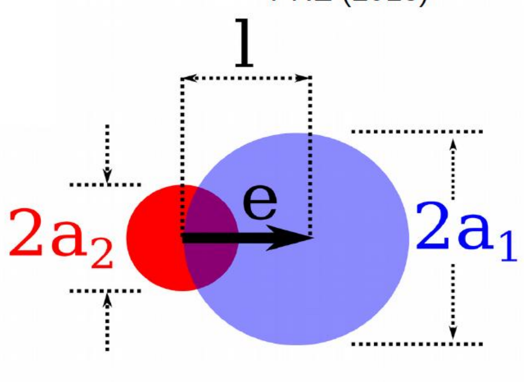
$$v_0 = 60\mu m/s$$

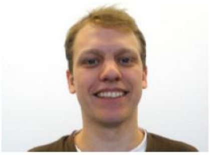
$$\frac{\tau_p}{k_B T} = 2s, \quad \frac{\tau_w}{k_B T} = 0.15s$$

- not connected through Fluctuation-Dissipation Theorem
- experimental value from [Kantsler *et al.* PNAS (2012)]



Wysocki, Elgeti, Gompper, PRE (2015)

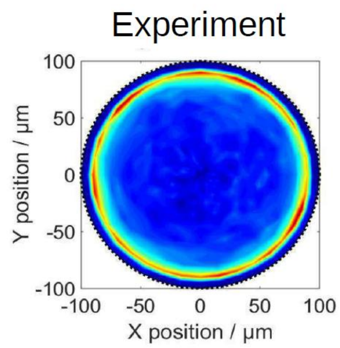


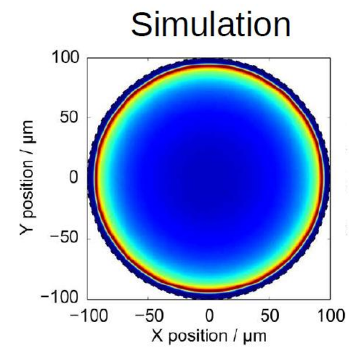


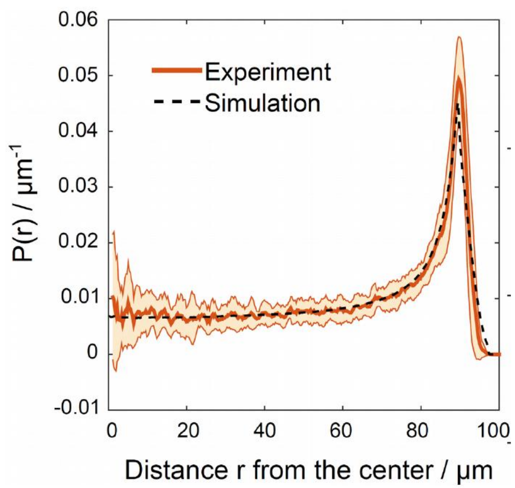
Fabian Schwarzendahl

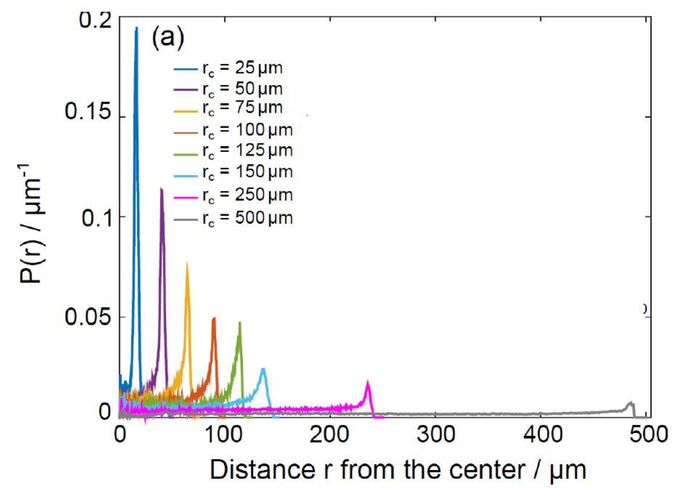
- Stroke-averaged model gives torque for reorientation

T. Ostapenko *et al.*, Phys. Rev. Lett. (2018)









- Experiments and simulations match (no fitting parameter)

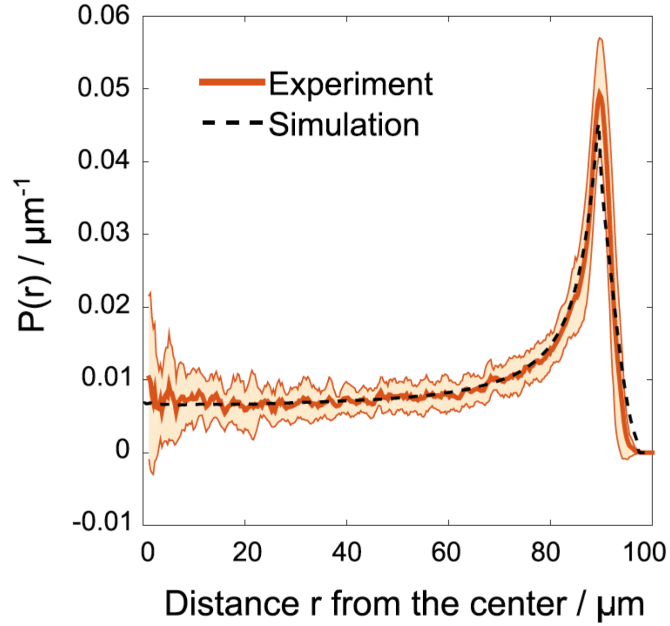
T. Ostapenko *et al.*, Phys. Rev. Lett. (2018)

Motility and Navigation of *Chlamydomonas* in Confinement

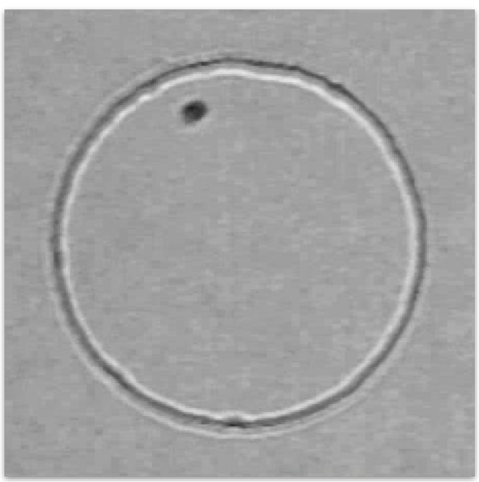
- *Brownian dynamics simulations*

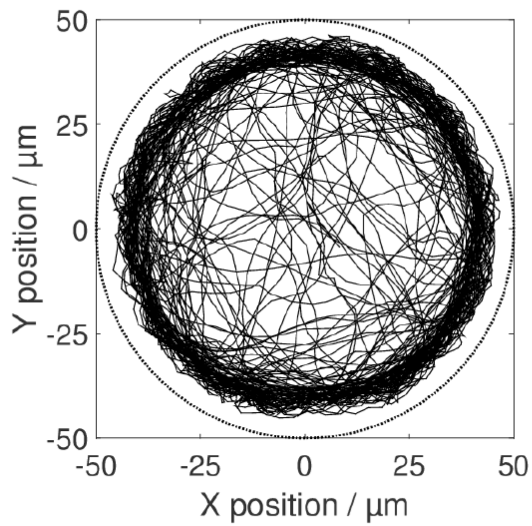
$$\frac{\mathrm{d}\vec{r}}{\mathrm{d}t} = v_0\vec{e} + \gamma_w\vec{F}_w + \vec{\eta}$$

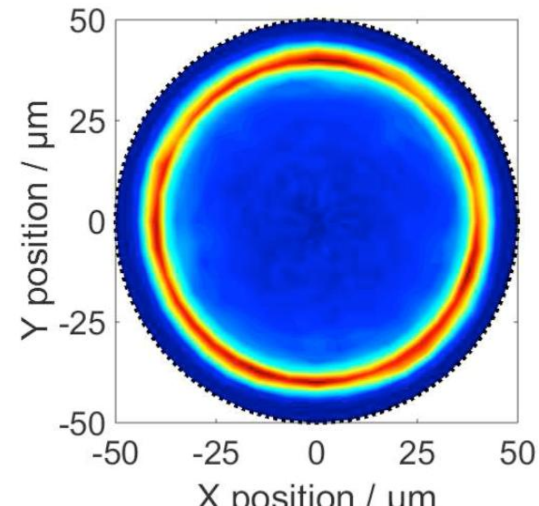
$$\frac{\mathrm{d}\vec{e}}{\mathrm{d}t} = (\vec{T}_w/\tau_w + \vec{\xi}) \times \vec{e}$$



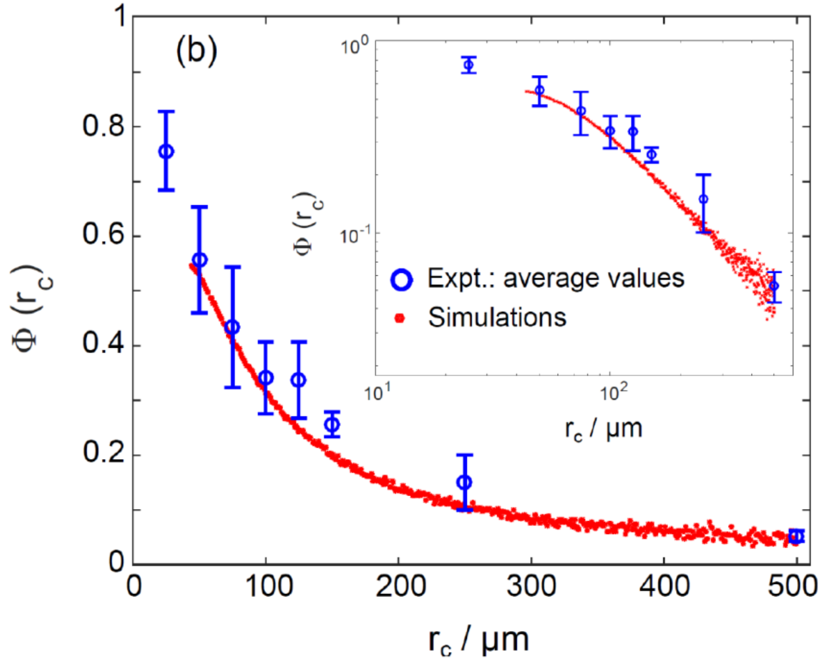
- Experiments in microfluidic model habit

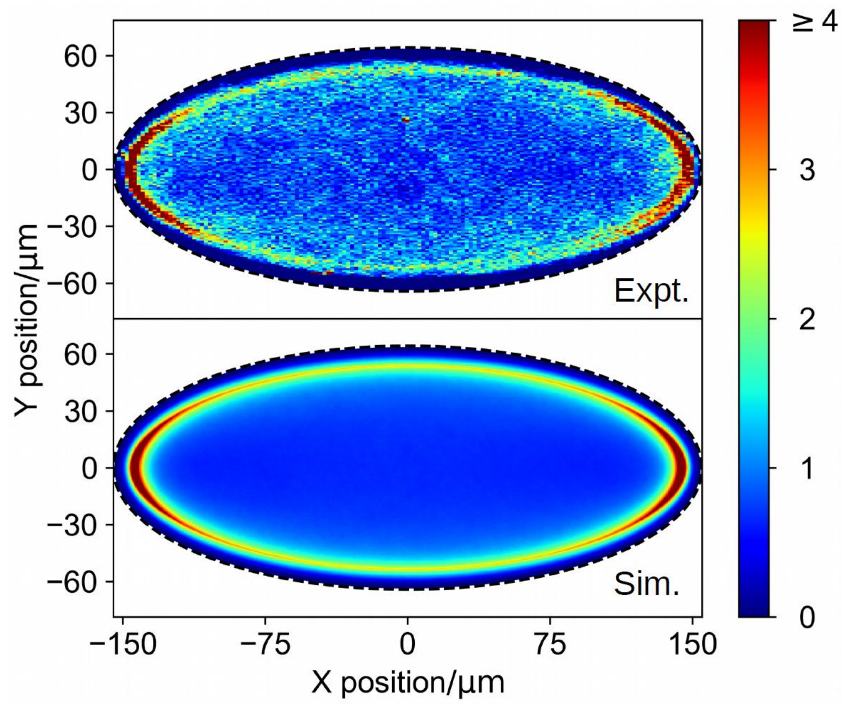


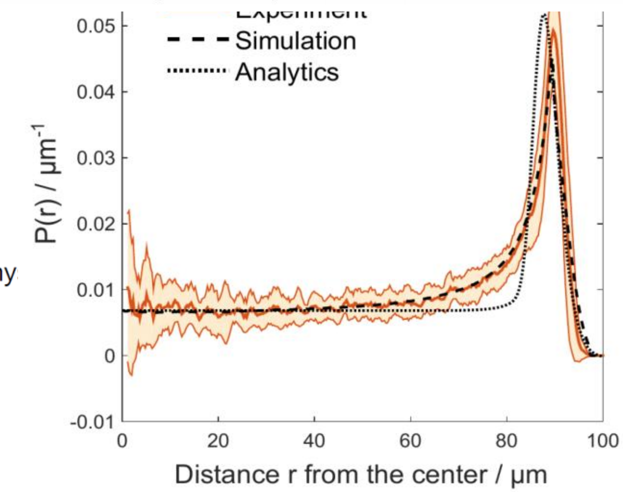




Ostapenko et al., *Phys. Rev. Lett.* (2018).





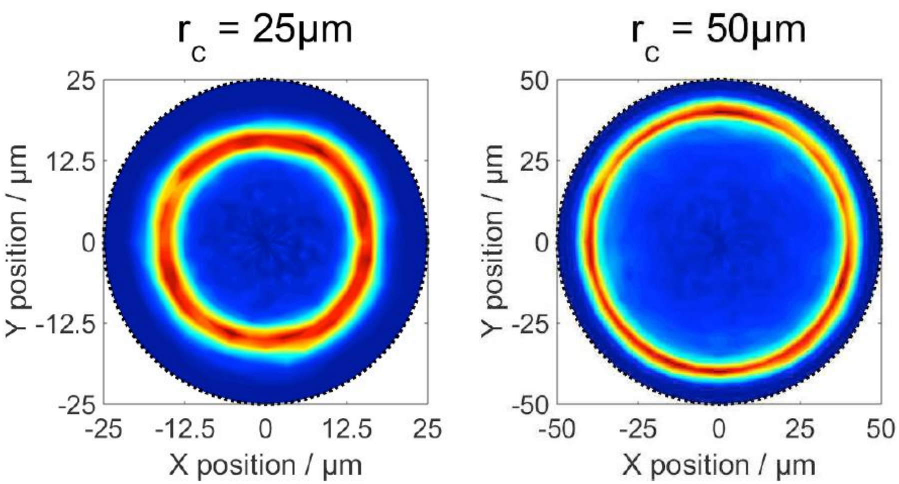


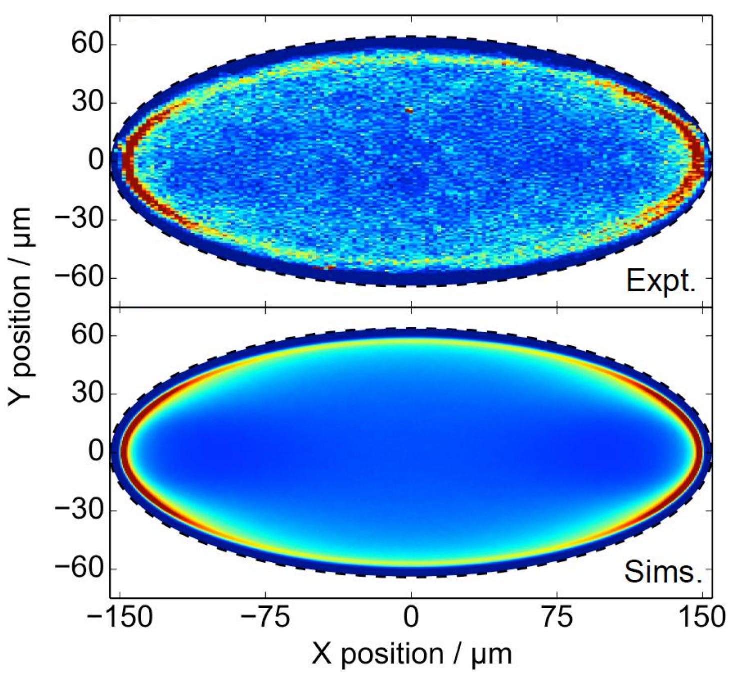
- *Chlamydomonas* ‘prefer’ large curvatures

T. Ostapenko *et al.*, Phy

Motility and Navigation of *Chlamydomonas* in Confinement

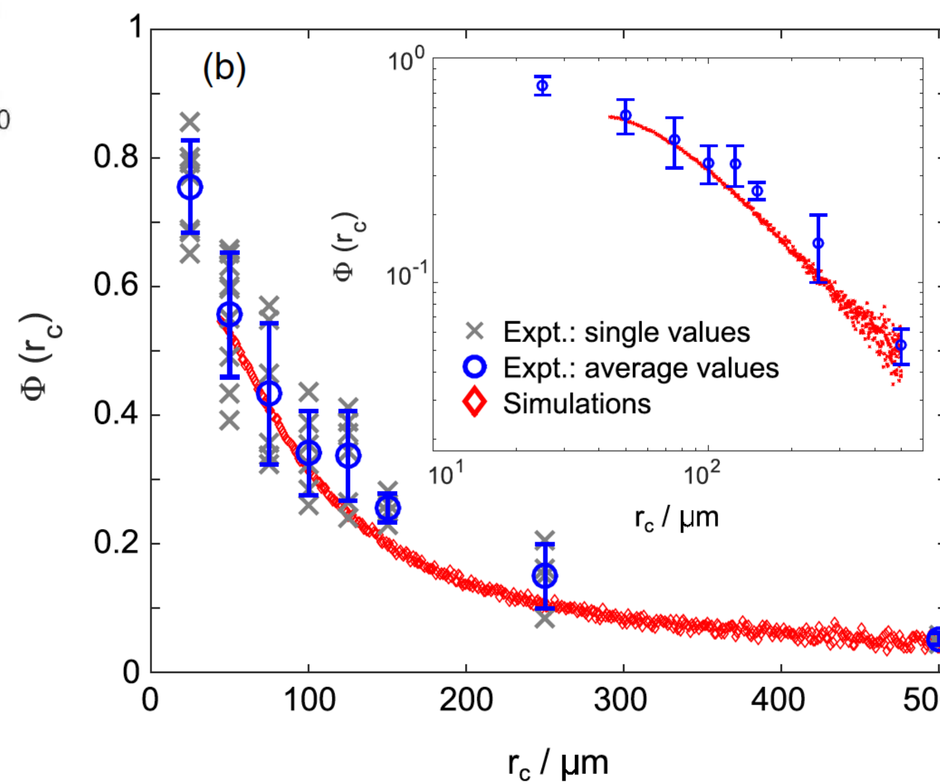
- *single-cell microfluidic experiments and Brownian dynamics simulations*





- near-wall swimming probability

$$\Phi(r_c) = 1 - \frac{r_c}{r_c - b}\int_0^{r_c - b} P(r)dr$$



Ostapenko et al., *Phys. Rev. Lett.* (2018).

d swimmers simulated by point particles

s governed by MPCD-AT+a algorithm, two

ng step:

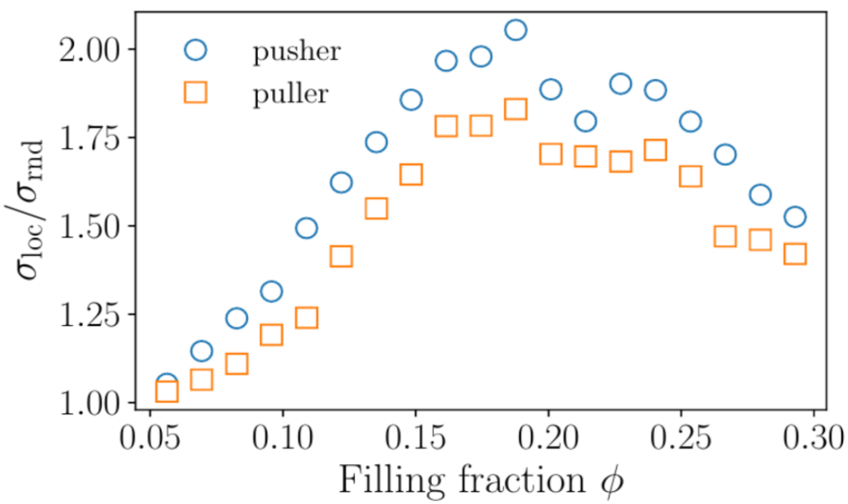
$$) = \boldsymbol{r}_i(t) + \boldsymbol{v}_i(t)\delta t$$

step:

$$\sum_{\in \mathsf{C}(i)} \boldsymbol{v}_j + \boldsymbol{v}_i^{\mathrm{ran}} - \frac{1}{N_{\mathsf{C}(i)}} \sum_{j \in \mathsf{C}(i)} \boldsymbol{v}_j^{\mathrm{ran}}$$

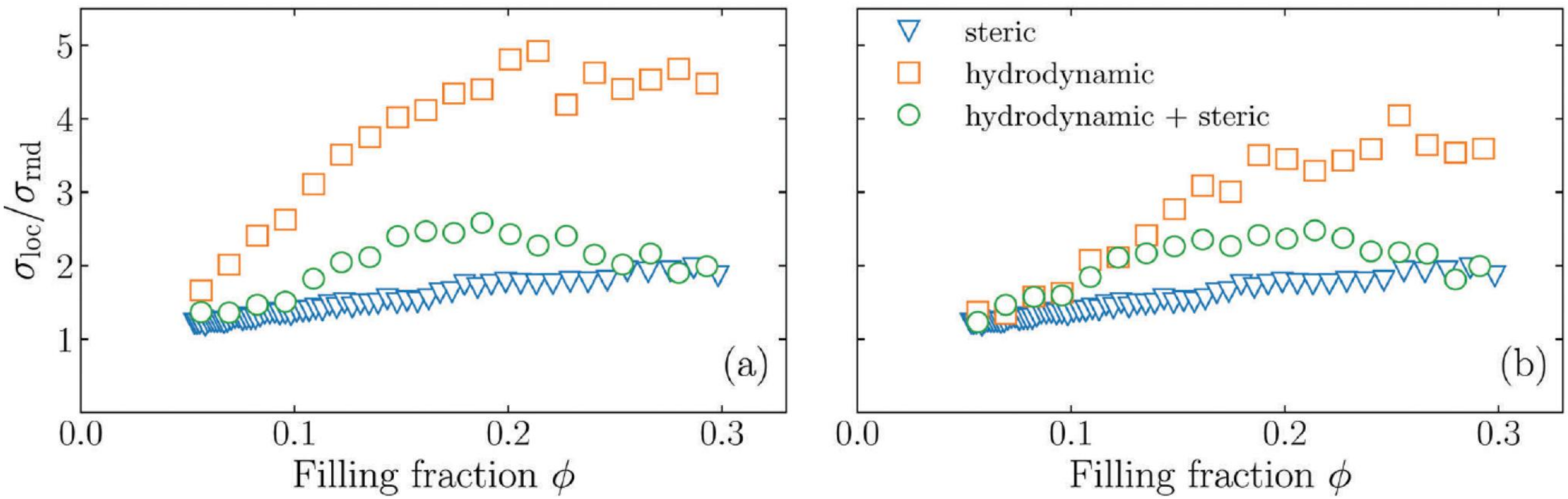
$$\boldsymbol{\Pi}^{-1} \sum_{j \in \mathsf{C}(i)} \left[\boldsymbol{r}_{j,c} \times (\boldsymbol{v}_i - \boldsymbol{v}_i^{\mathrm{ran}})\right] \Bigg\} \times \boldsymbol{r}_{i,c}$$

s Navier-Stokes behavior



- Both steric and hydrodynamic interactions contribute (steric interactions hinder the hydrodyn. instabilities

F. Schwarzendahl, MGM, Soft Matter (2018) pushers   pullers



Linear stability analysis:

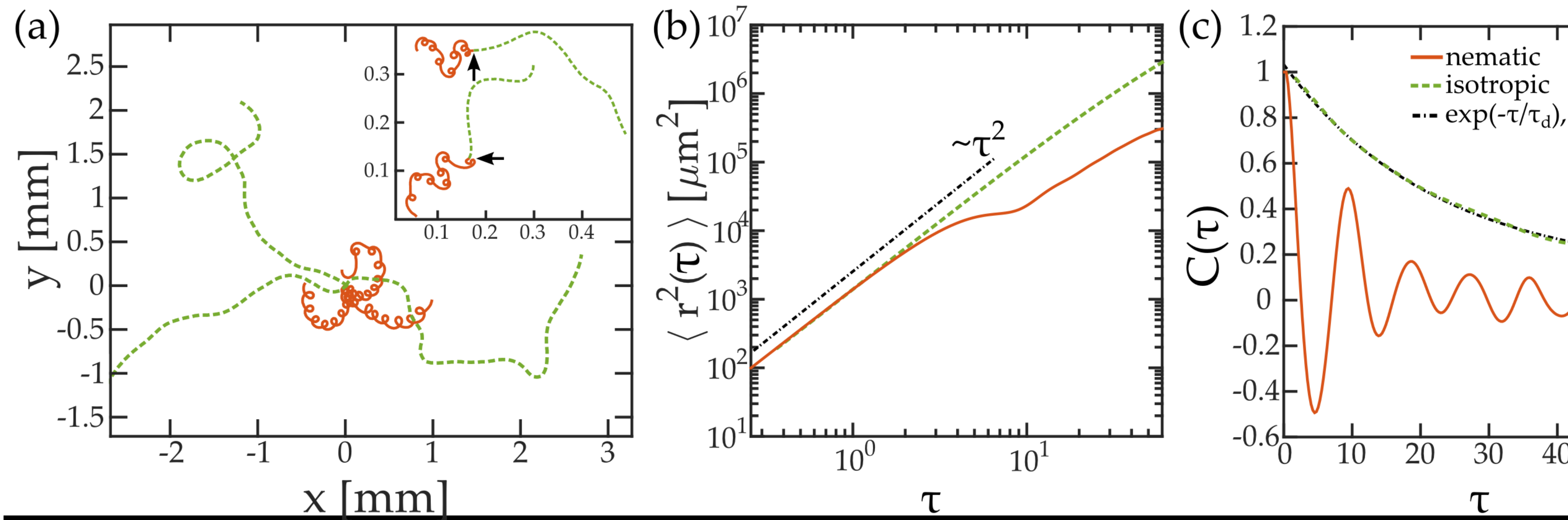
for pullers $f < 0$

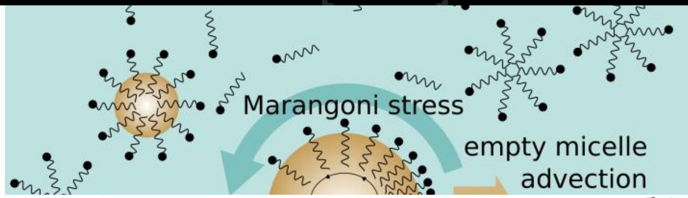
$$\partial_t \delta\tilde{c} = -\frac{k^2}{3D_R}\left[3DD_R + v_0^2 + c_0\left(-3v_0\zeta + \underset{\text{unstable}}{\boxed{\frac{\delta a l^2 v_0 f}{30\eta\bar{a}}}}\right) + \underset{\text{stable}}{\boxed{c_0^2 2\zeta\left(\zeta\right.}} \left. - \frac{\delta a l^2 f}{30\eta\bar{a}}\right)\right]\delta\tilde{c}$$

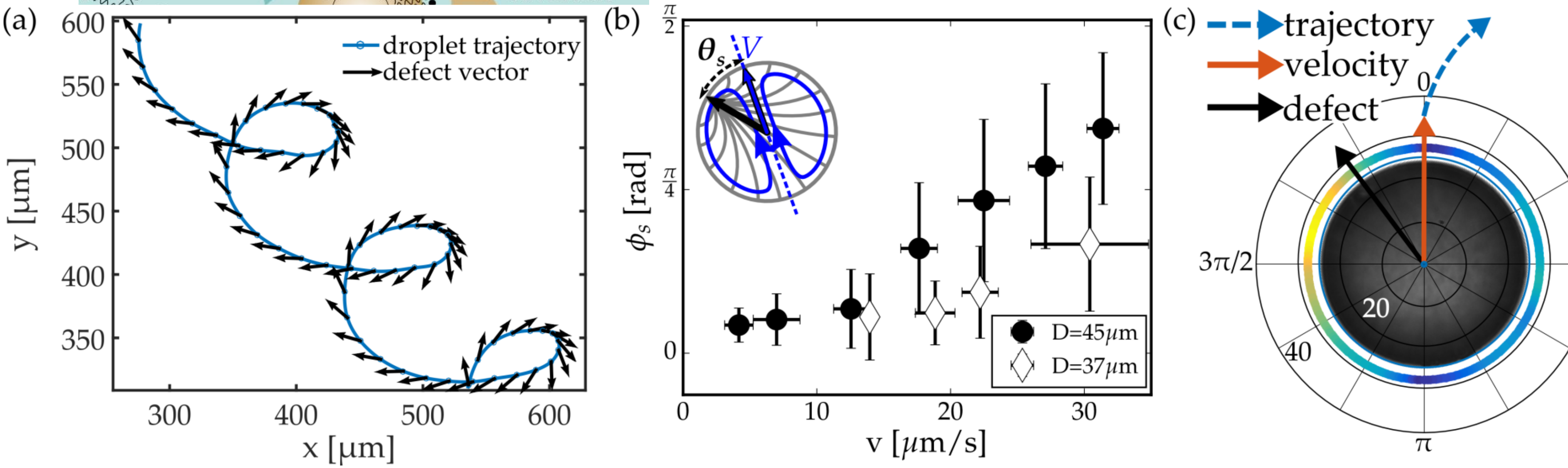
Linear stability analysis:

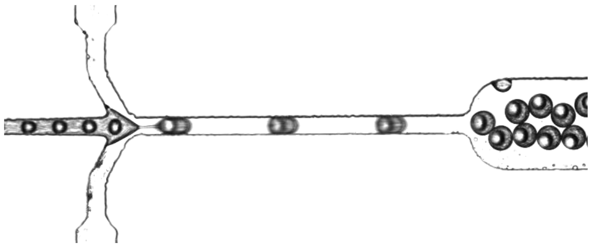
for pushers $f > 0$

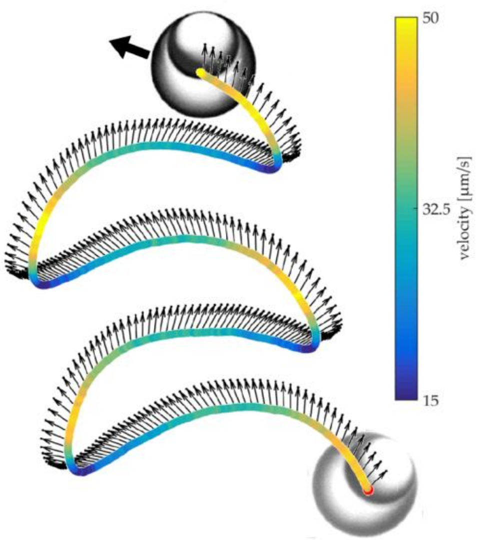
$$\partial_t \delta\tilde{\boldsymbol{Q}}_{\parallel\perp} = -\left[k^2\left(D + \frac{v_0^2}{5D_R}\right) + 4D_R - c_0\left(\frac{2\zeta v_0 k^2}{5D_R} \boxed{+\frac{3lf}{25}}\right) + \boxed{c_0^2\frac{k^2\zeta^2}{5D_R}}\right]\delta\tilde{\boldsymbol{Q}}_{\parallel\perp}$$

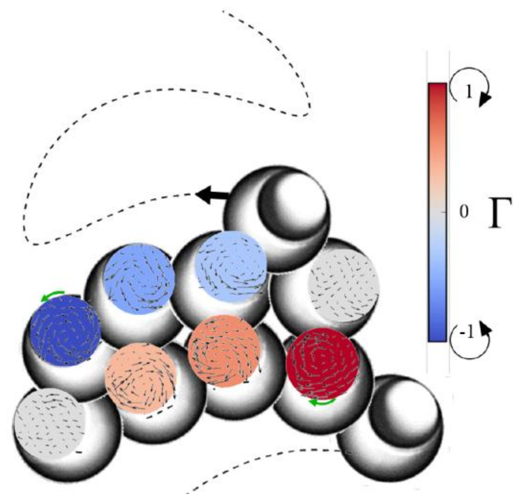

(a)
y [mm]
x [mm]
(b)
⟨ r²(τ) ⟩ [μm²]
~τ²
τ
(c)
nematic
isotropic
exp(-τ/τd),
C(τ)
τ

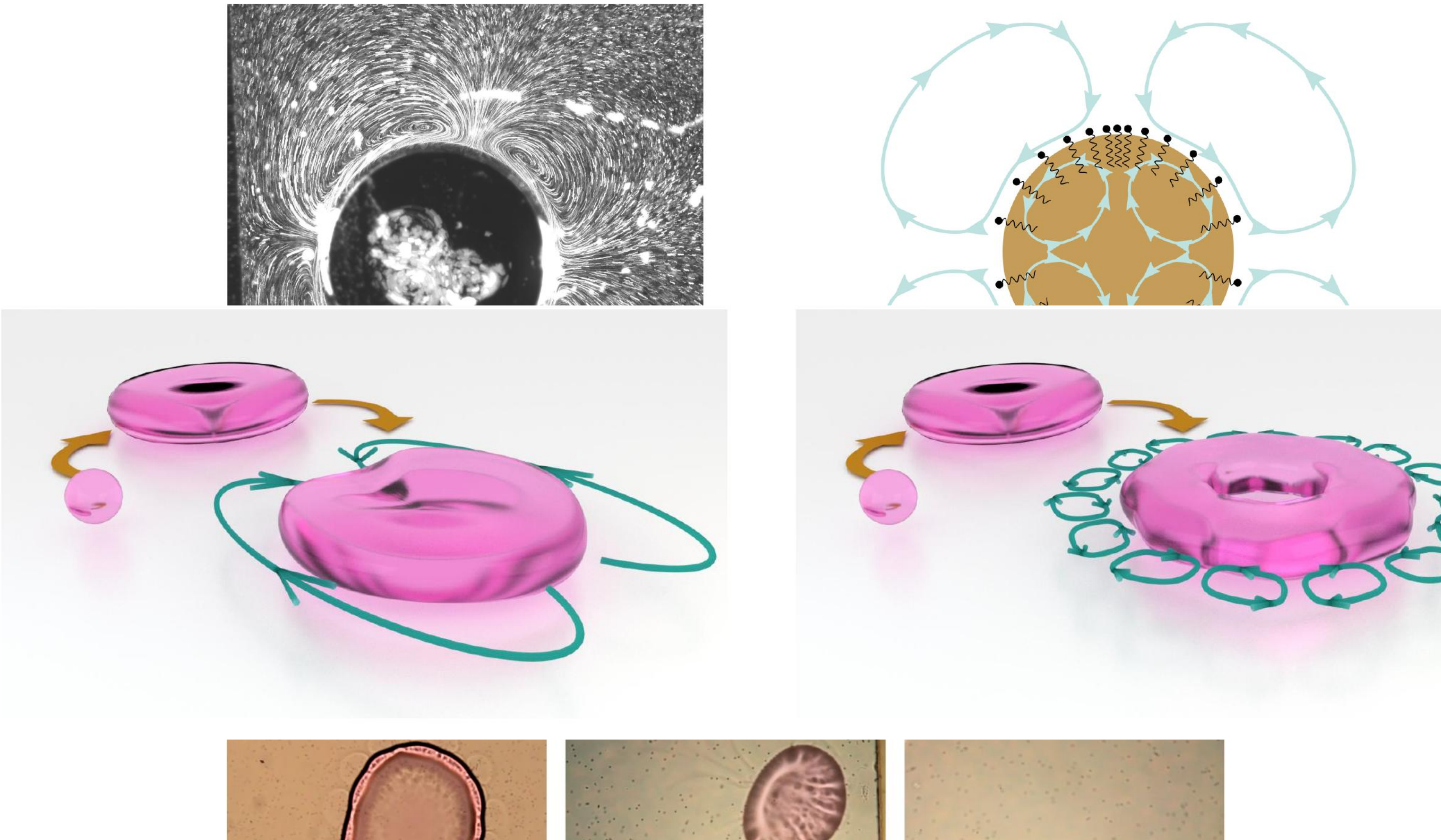

Marangoni stress
empty micelle
advection


(a)
droplet trajectory
defect vector
y [μm]
x [μm]
(b)
θs
V
ϕs [rad]
v [μm/s]
D=45μm
D=37μm
(c)
trajectory
velocity
defect
0
3π/2
π
20
40




50
32.5
velocity [μm/s]
15


1
0
Γ
-1

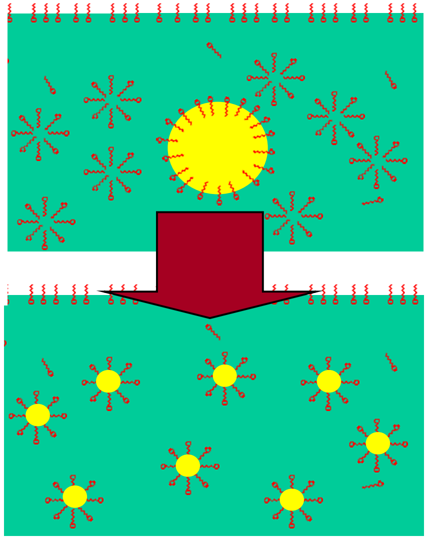


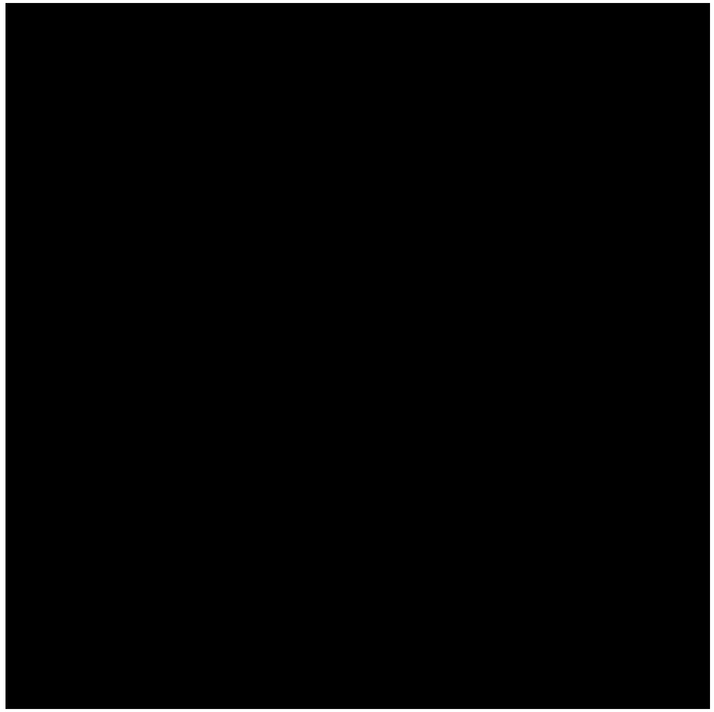
Swarms of model bugs: artificial microswimmers

MAX-PLANCK-GESELLSCHAFT

Oil-in-water

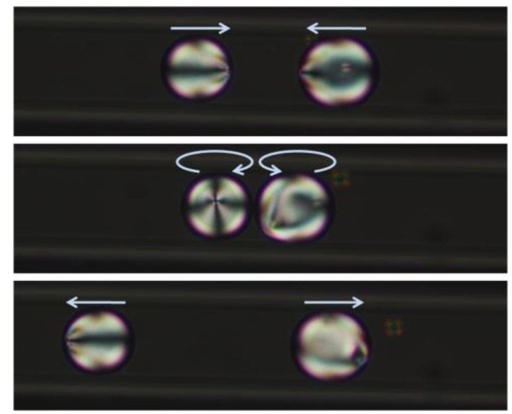
formation of a microemulsion:

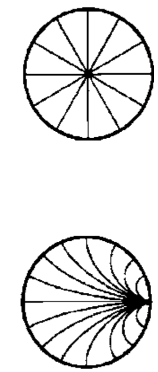




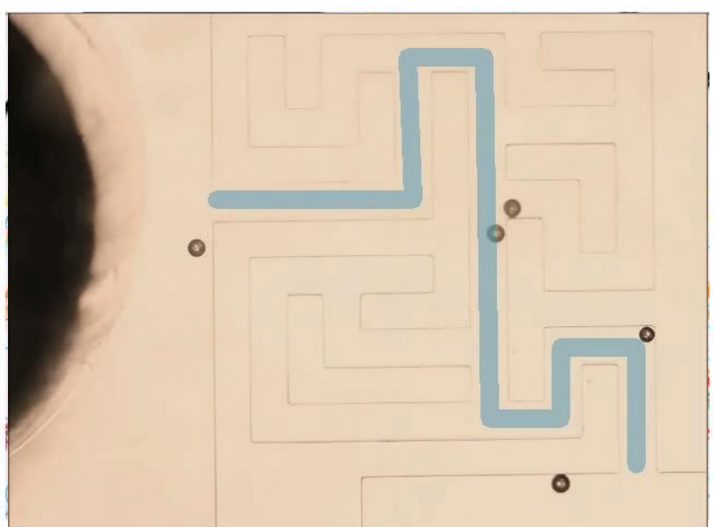
‚Oil' is a liquid crystal (5CB) water contains TTAB > cmc.

Drops just consist of fuel: run for many hours!





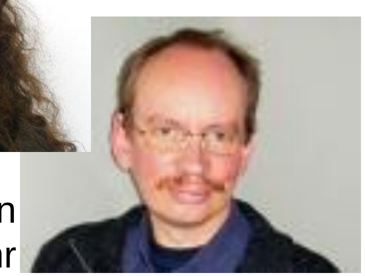
Chemotaxis
('seeking'
TTAB surfactant)



Chenyu
Jin

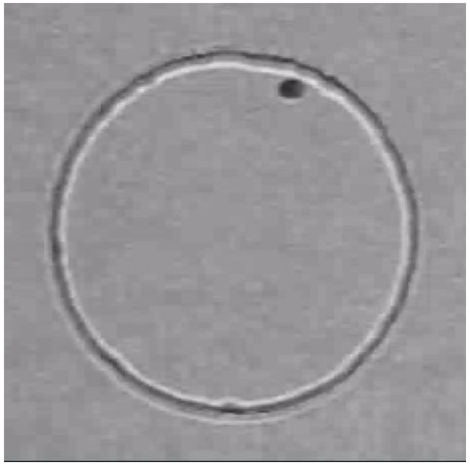
Corinna
Maass

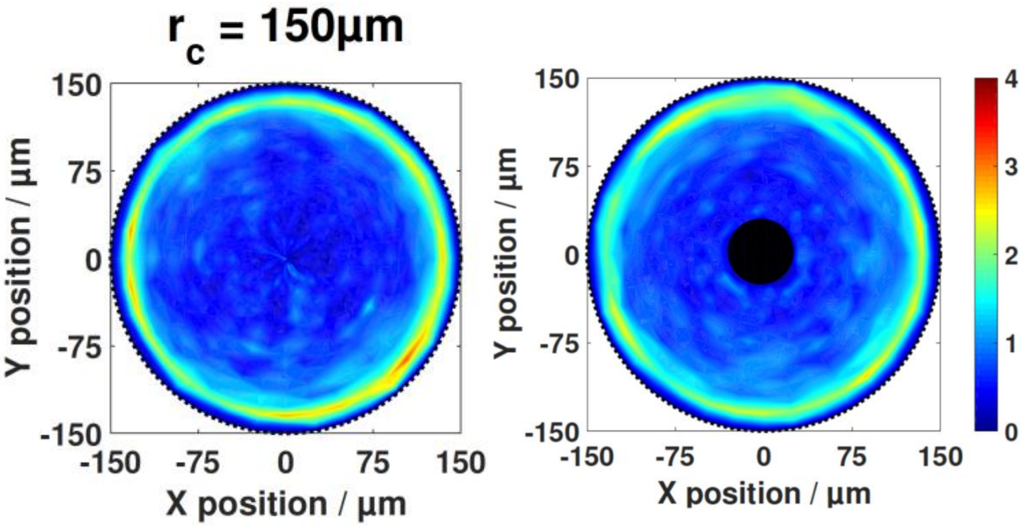
Christian
Bahr



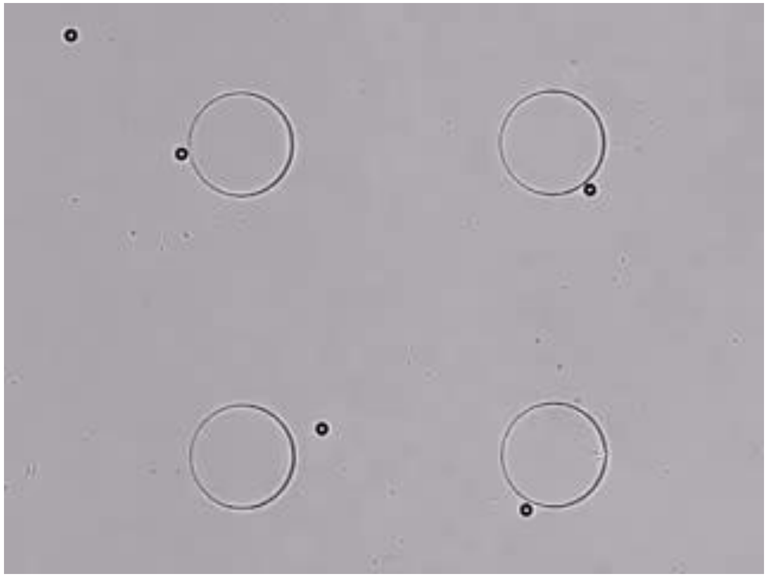
Artificial swimmers as a model

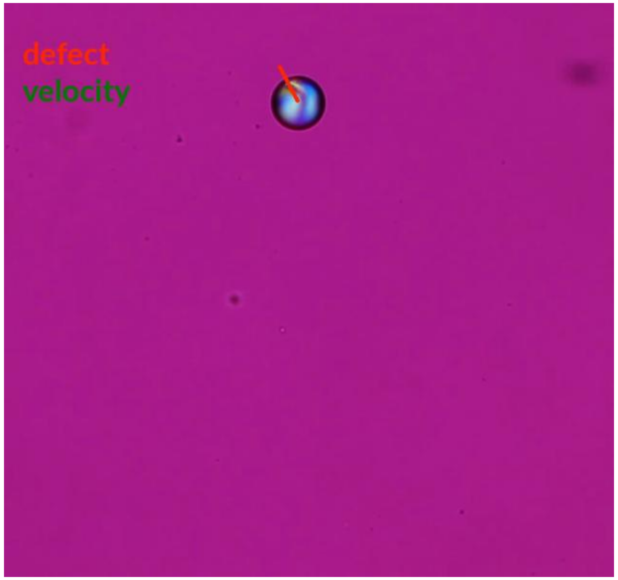
Chlamy:



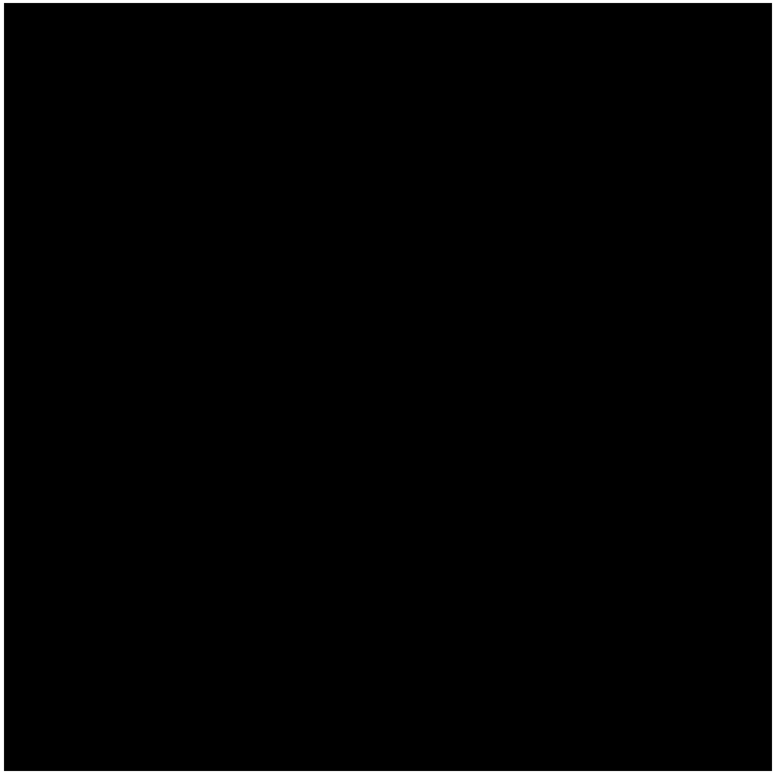


Droplets:

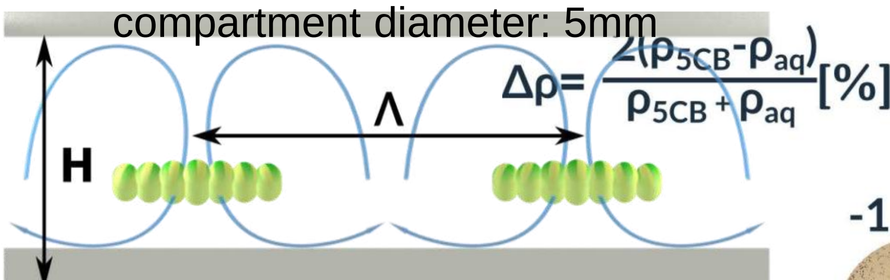


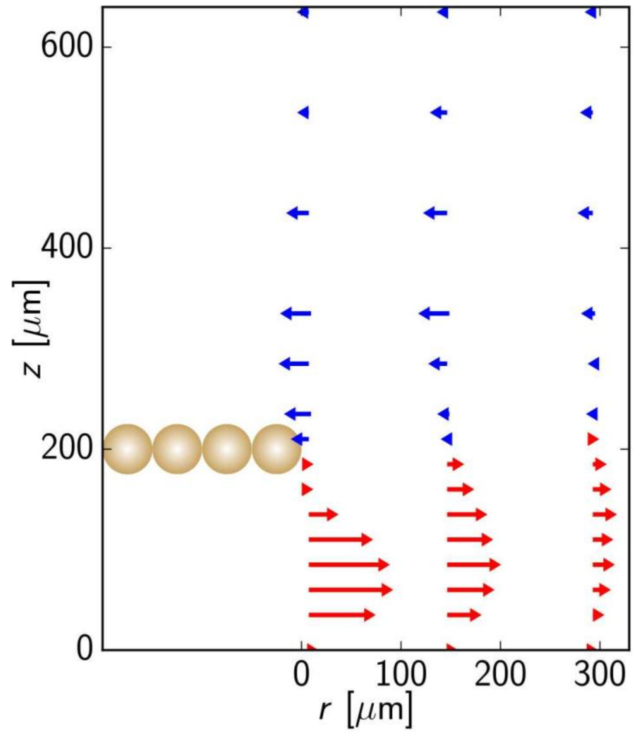


Artificial swimmers: collective behaviour

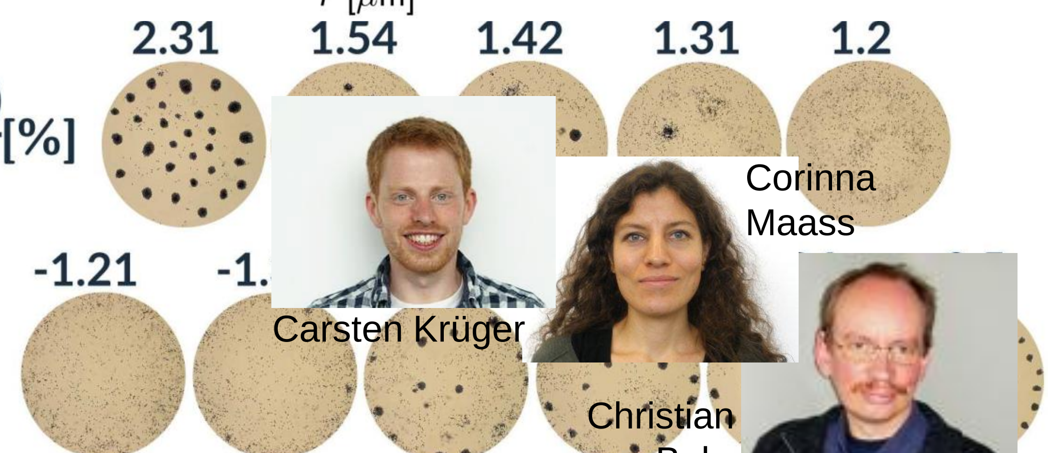


compartment diameter: 5mm





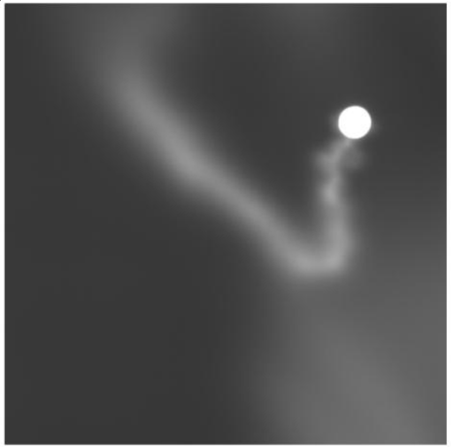
particle imaging velocimetry (PIV) shows the convective flow!

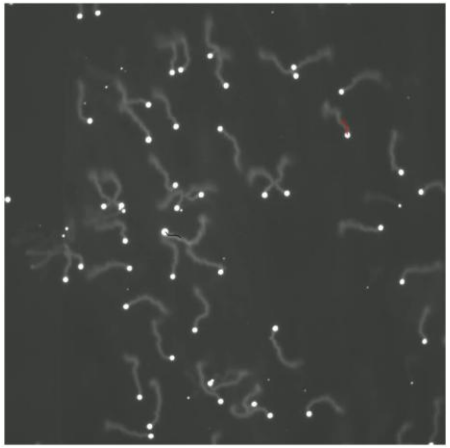


Carsten Krüger

Corinna Maass

Christian Bahr





Swarming studies in three dimensions

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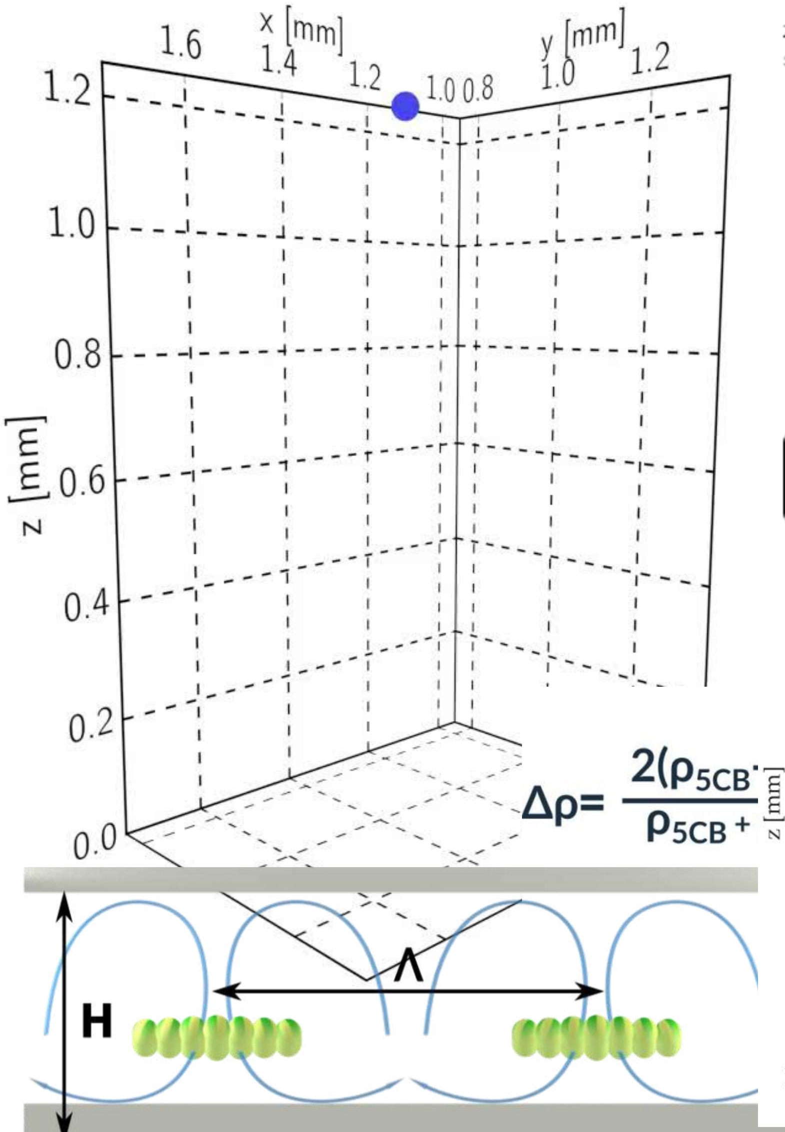
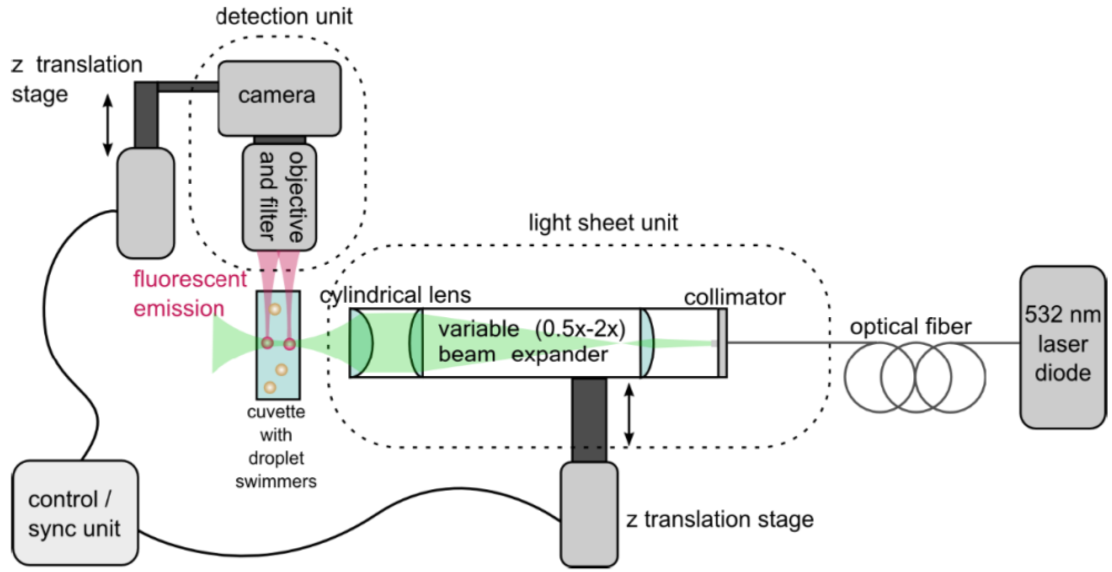
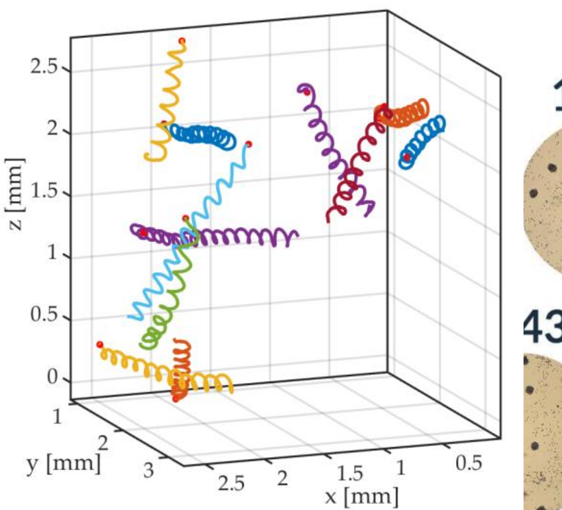
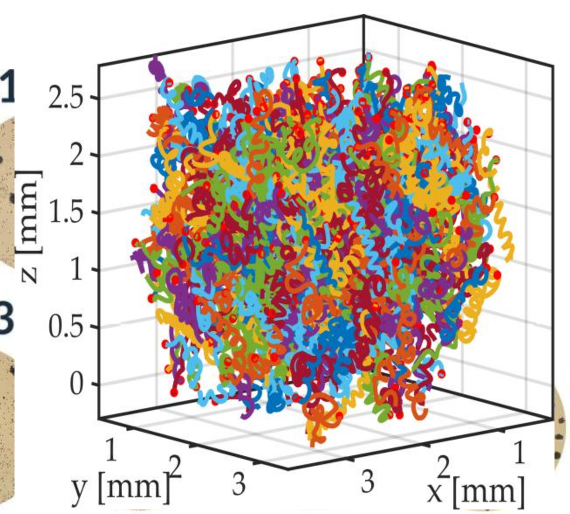
Plankton: swarming in turbulent flow









Causal entropic forces:
a minimal model of intelligence

PHYSICAL REVIEW LETTERS

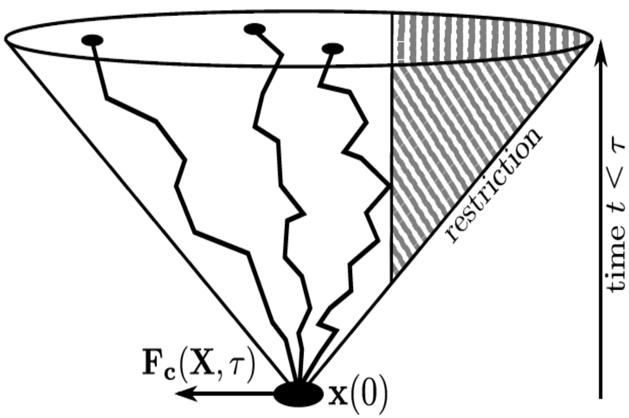
week ending
19 APRIL 2013

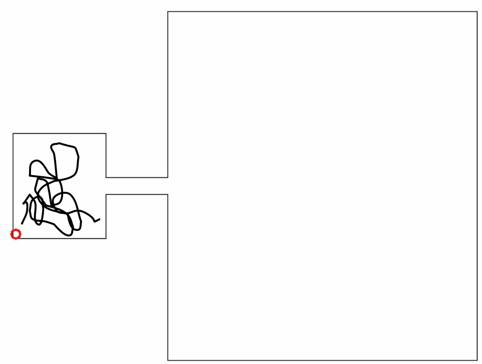
Causal Entropic Forces

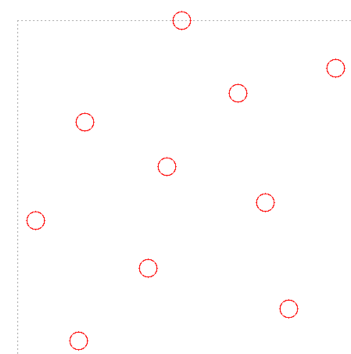
A. D. Wissner-Gross[1,2,*] and C. E. Freer[3,†]

Simple model of intelligence:
maximization of the **number of future options** to move

This represents a minimal **encoding of the external** (i.e., an ‚internal cognitive map‘) by just a single number



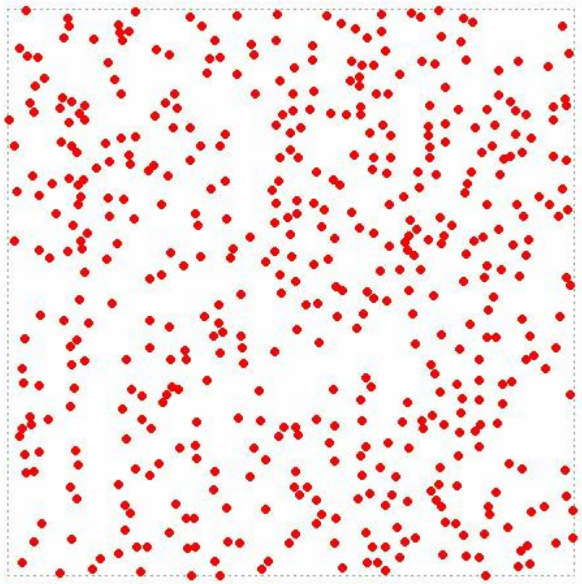


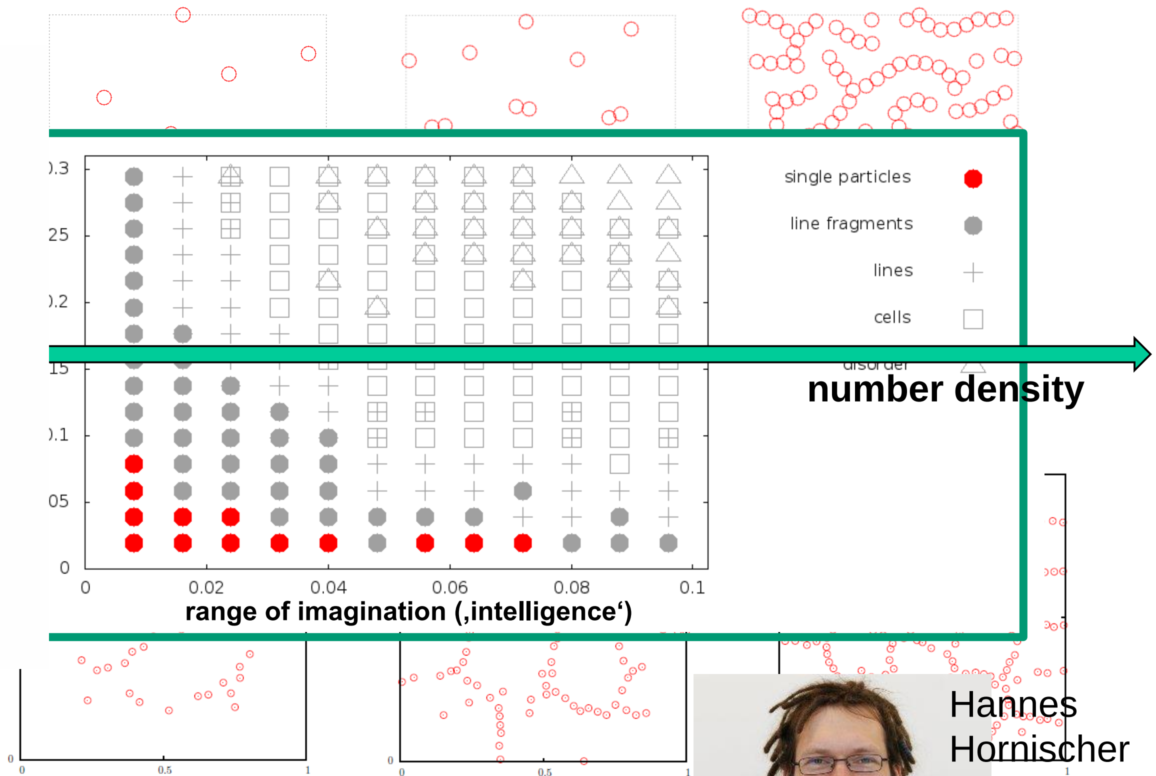


Marco
Mazza

Influence of 'intelligence' on swarming behaviour

MAX-PLANCK-GESELLSCHAFT



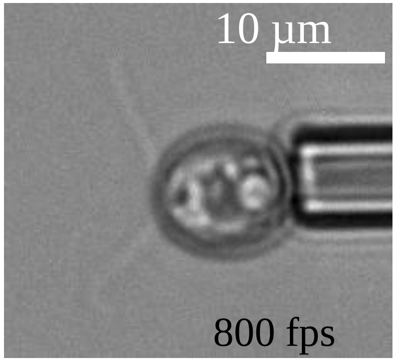


Hannes Hornischer

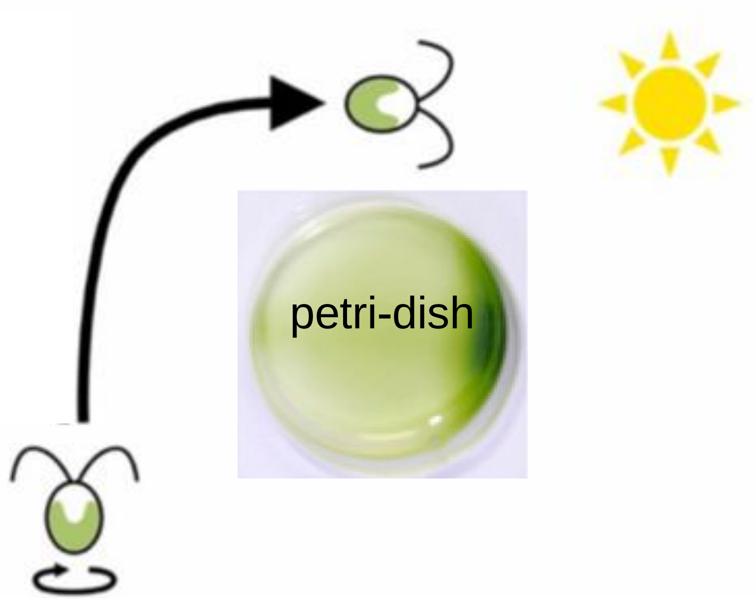
Marco Mazza

The Model Organism Chlamydomonas reinhardtii

- unicellular, biflagellated green microalga
- approx. 10 microns diameter
- two flagella (beating frequency of 50-60 Hz)
- puller-type microswimmer (100 µm/s)
- chloroplast (perform photosynthesis)
- biological model system

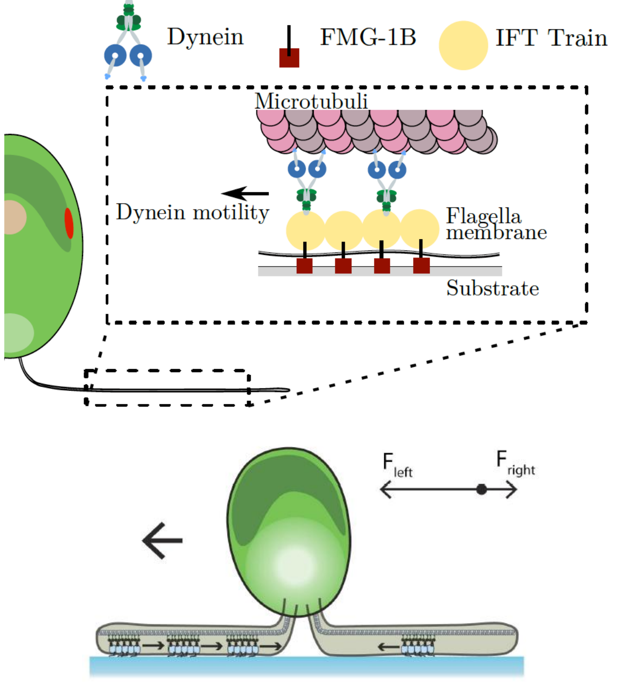


phototaxis



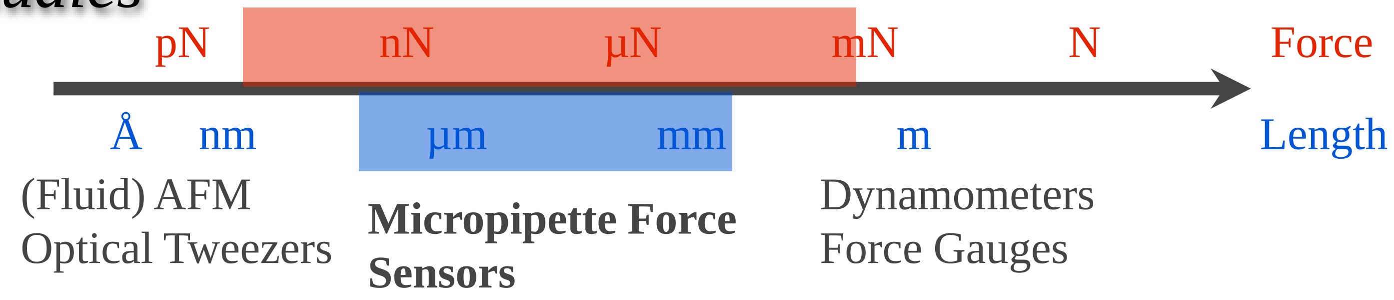
Ueki et al., PNAS 113 (2016).

gliding motility



Shih et al., eLife e00744 (2013).

Micropipette Force Spectroscopy for Biophysical Studies



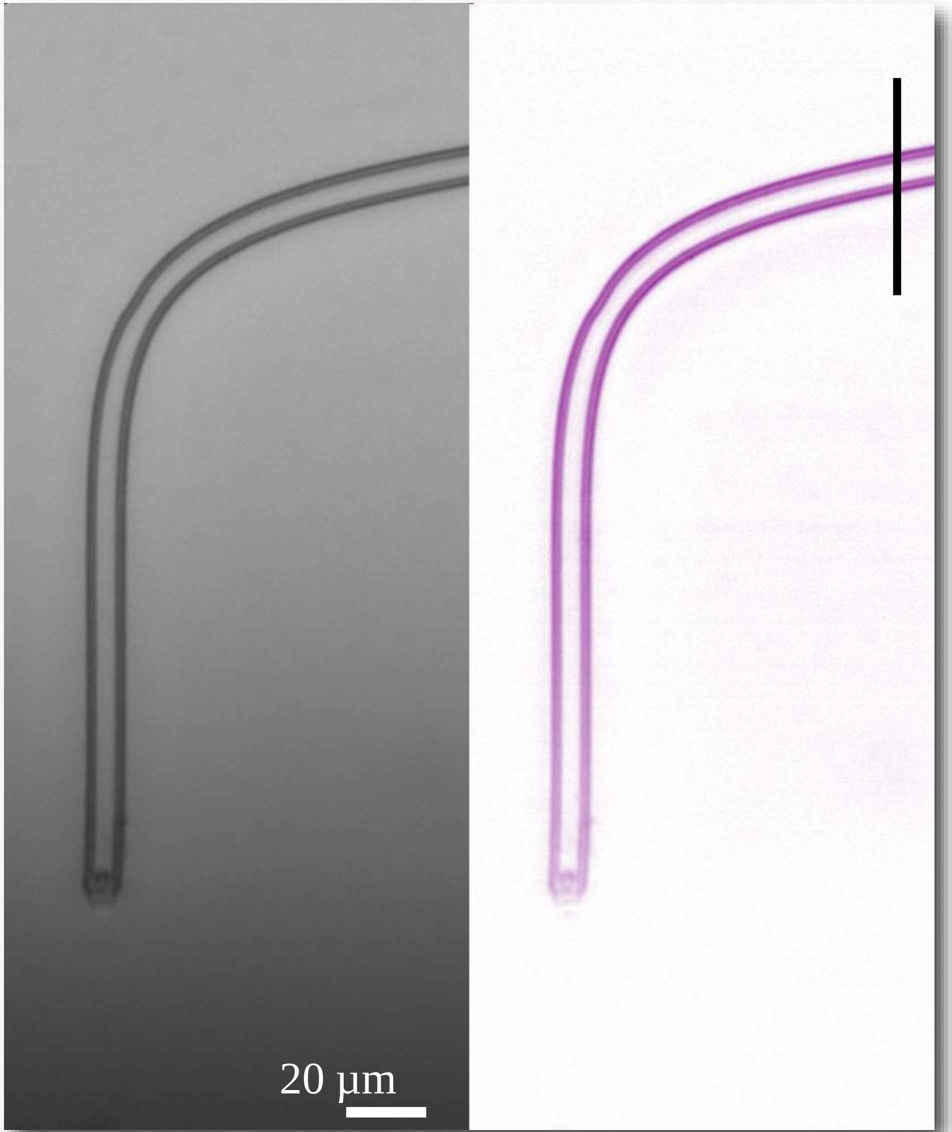
- visualization and force measurement through optical microscopy (e.g. fluorescence)
- *in vivo* measurements of living / motile cells and tissue
- time-resolved measurements
- forces in micro- and mesoscale living systems

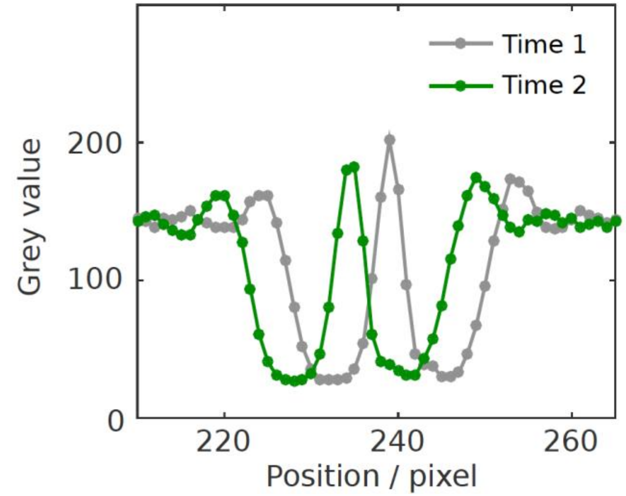
M. Backholm & O. Bäumchen, *Nature Protocols* (in review).

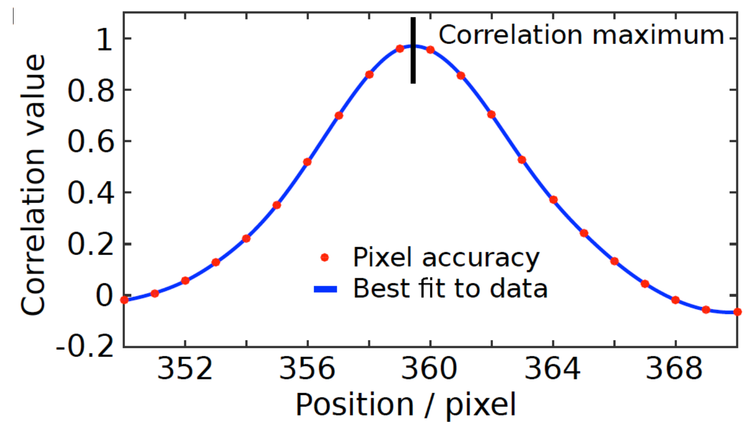
C. Kreis et al., *Nature Physics* (2018).

In vivo Micropipette Force Spectroscopy of Microalgae

• experiments are performed analogous to AFM force-distance experiments



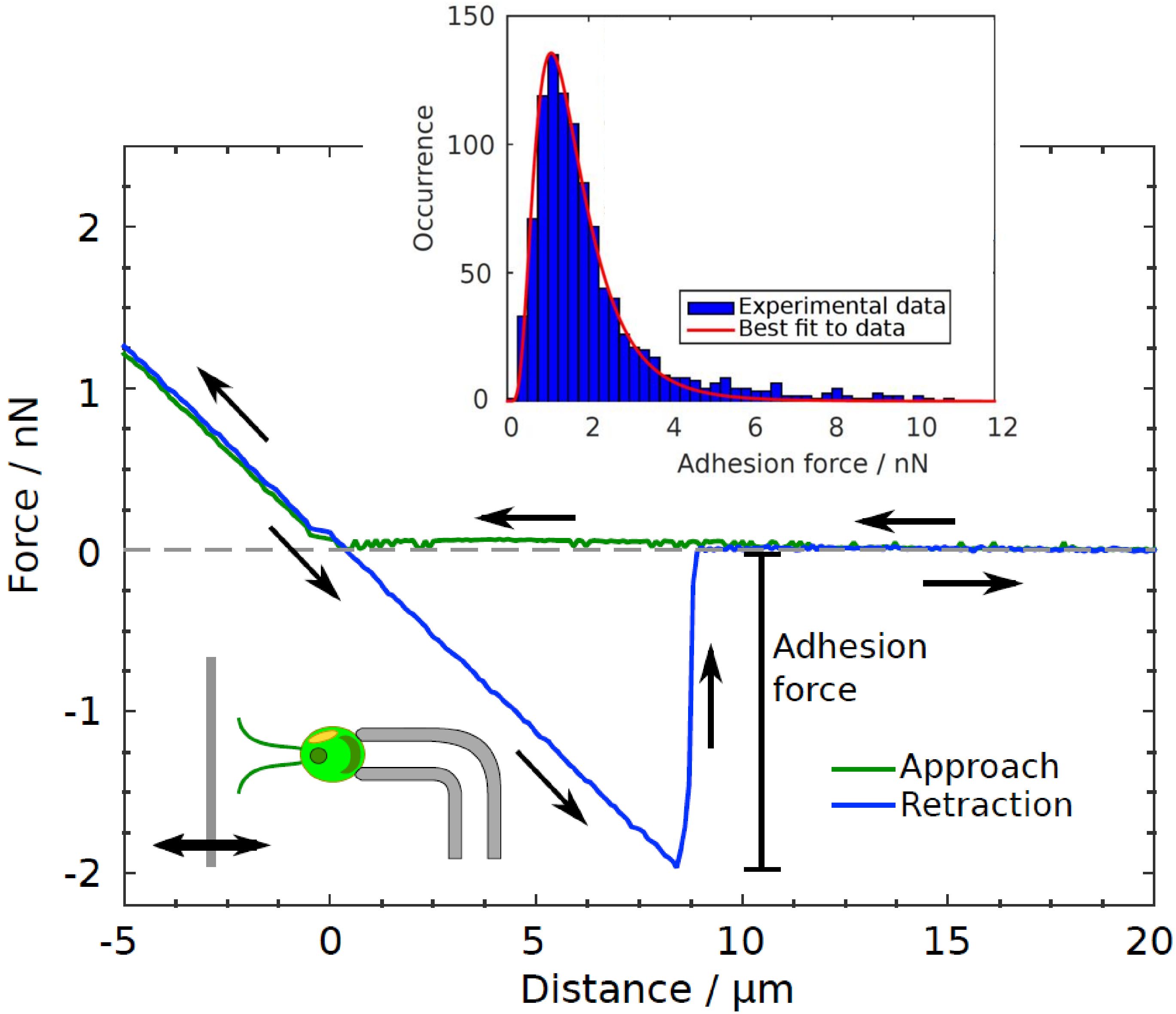




~10 pN force resolution !!

C. Kreis et al., *Nature Physics* (2018)

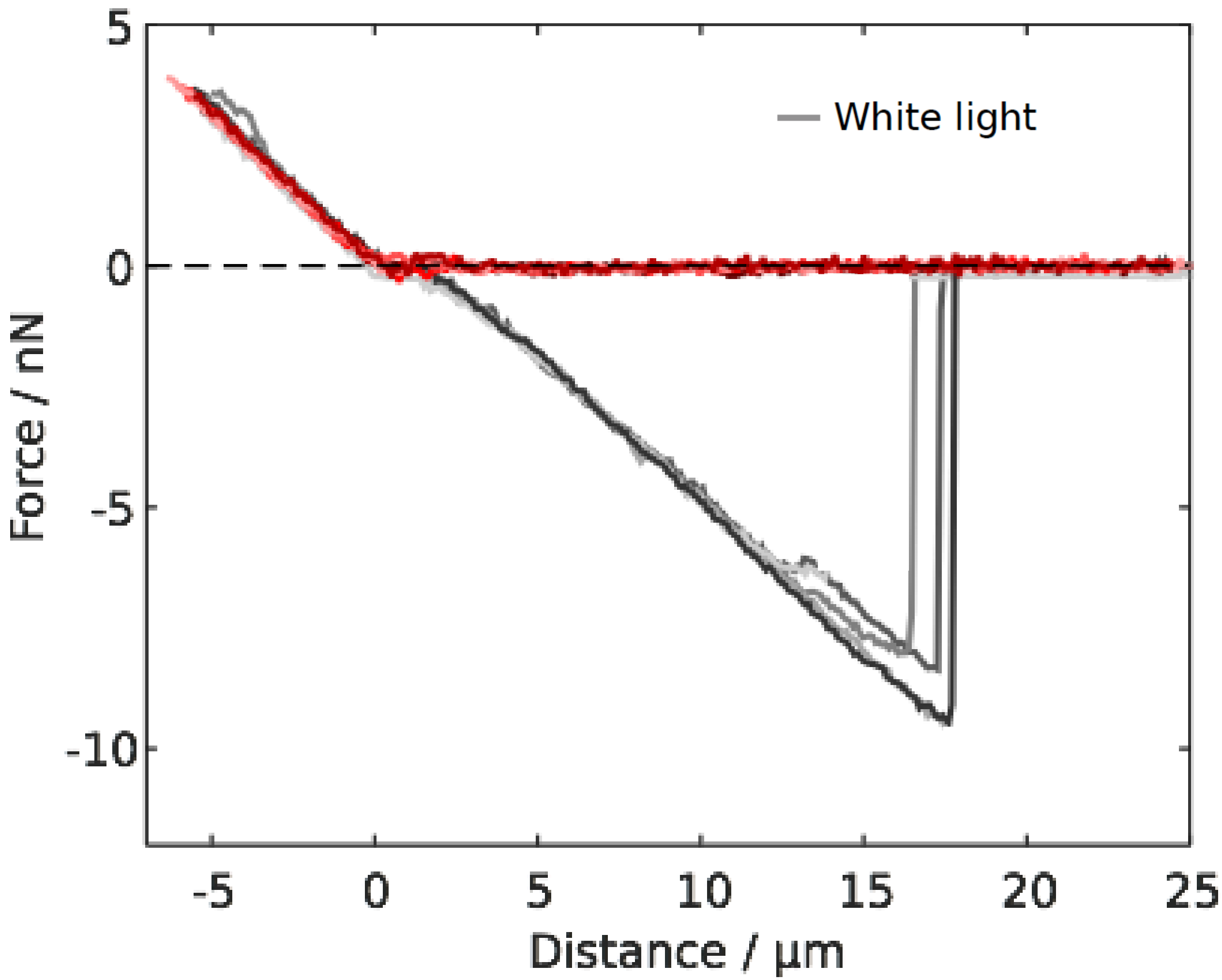
In vivo Micropipette Force Spectroscopy of Microalgae



C. Kreis et al., *Nature Physics* (2018)

In vivo Micropipette Force Spectroscopy of Microalgae

• flagella mediate the adhesion between the microalga and a solid surface

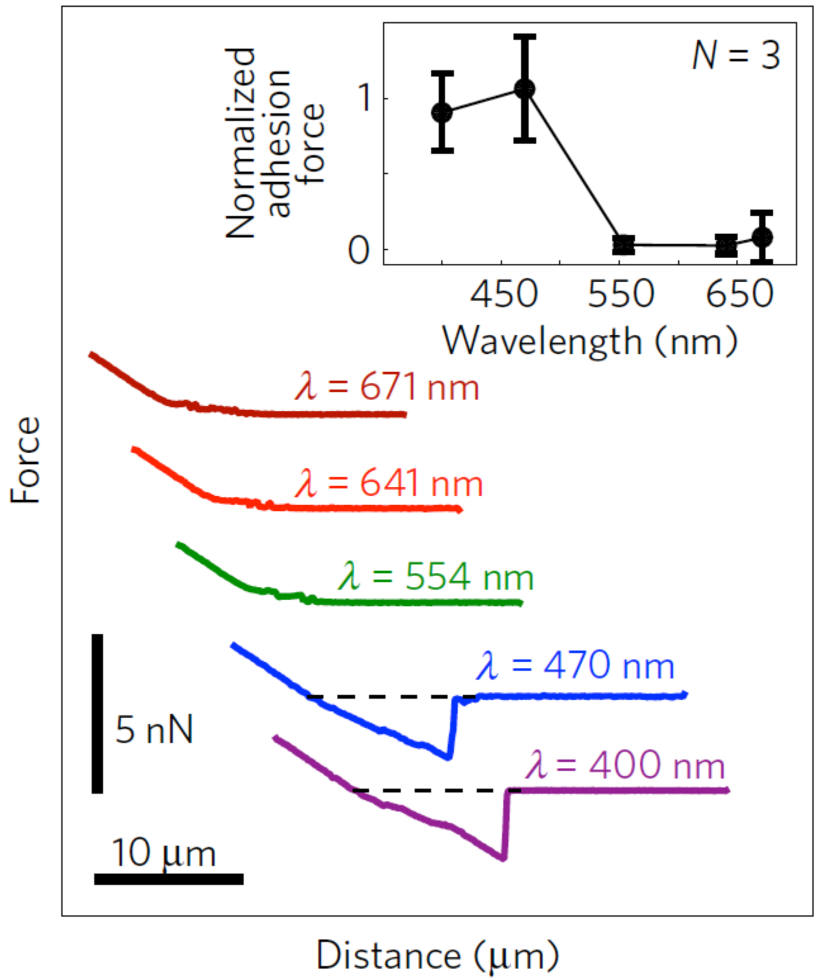


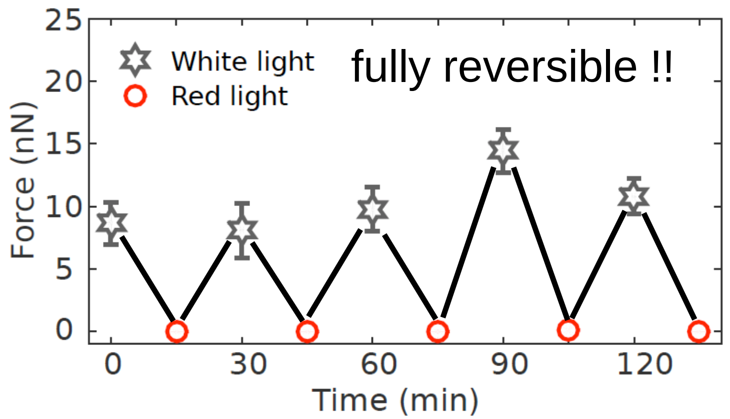
C. Kreis et al., *Nature Physics* (2018)

In vivo Micropipette Force Spectroscopy of Microalgae

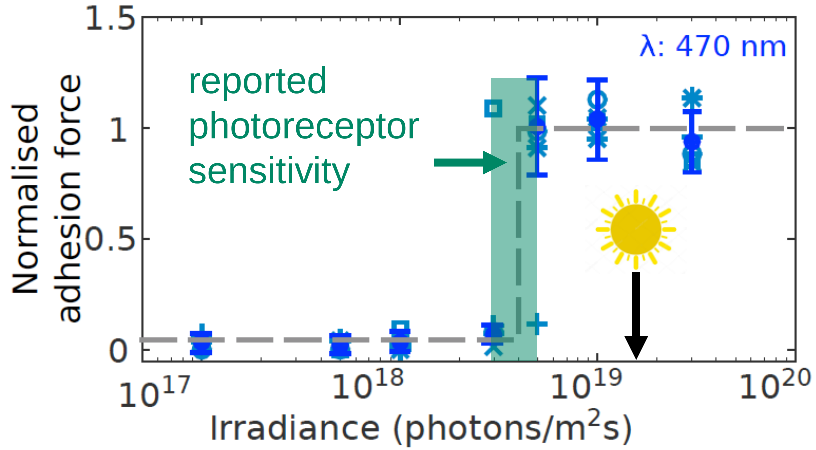
• flagella adhesion can be triggered by light

• blue-light photoreceptor triggers adhesion



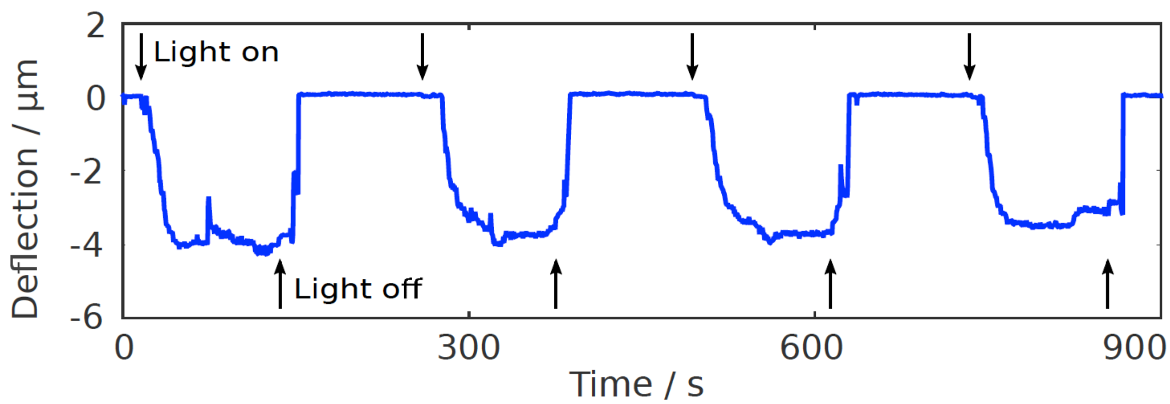


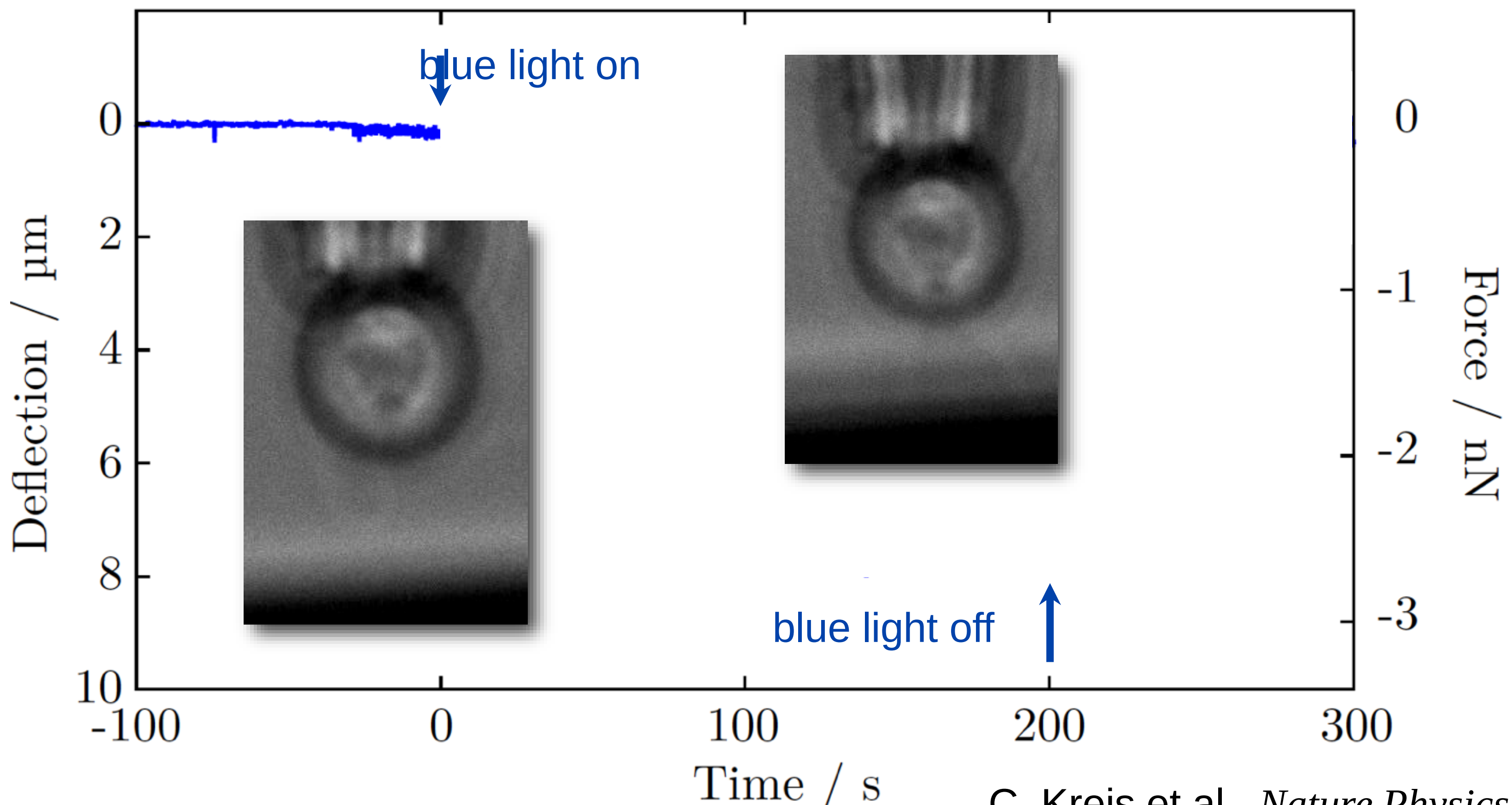
• sharp photon density threshold



C. Kreis et al., *Nature Physics* (2018)

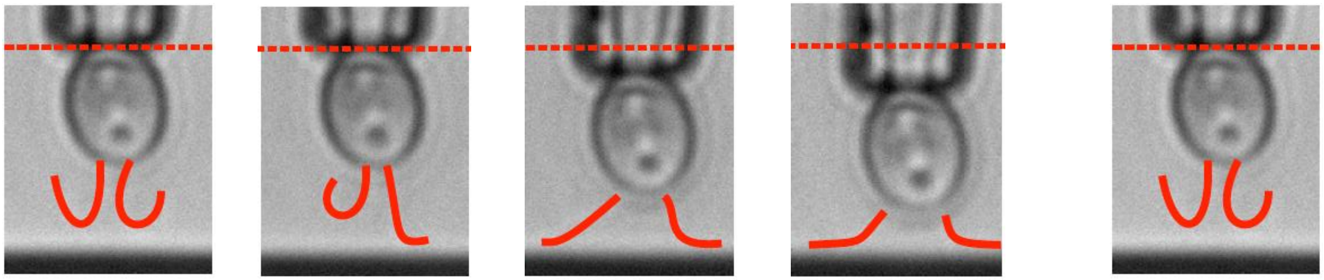
In vivo Auto-Adhesion Experiments

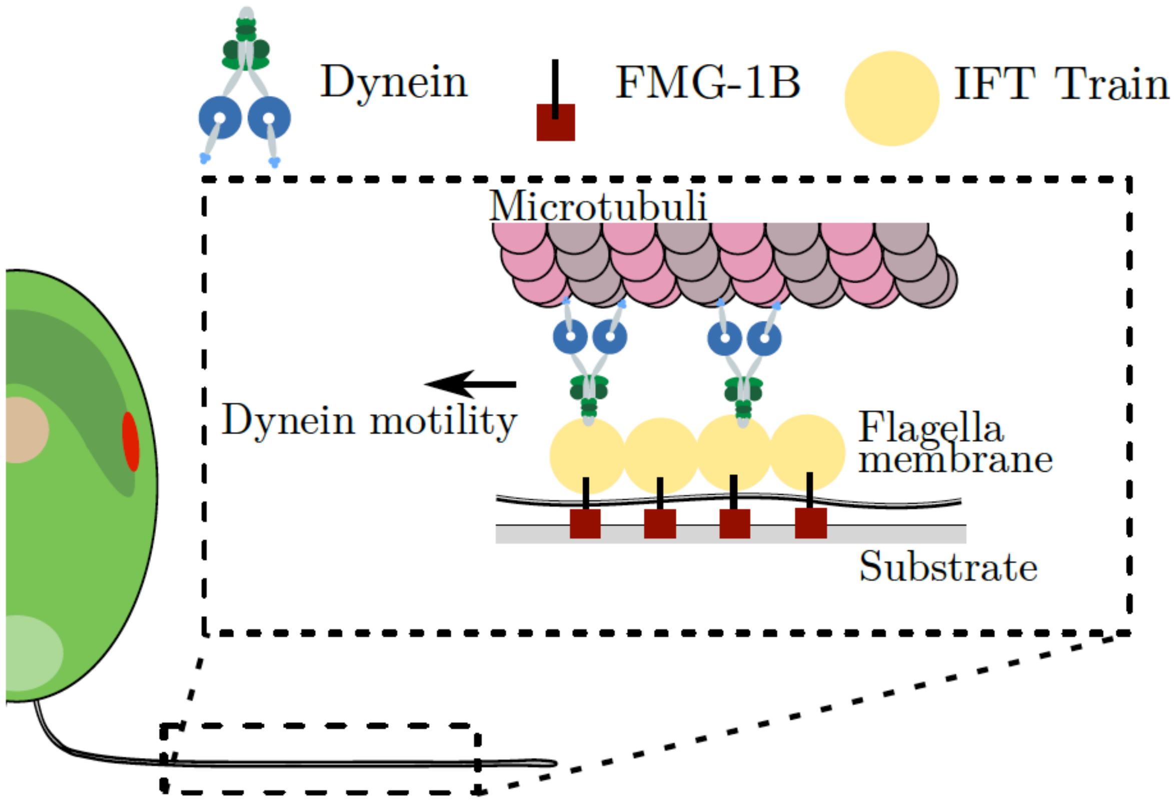




C. Kreis et al., *Nature Physics*

In vivo Auto-Adhesion Experiments

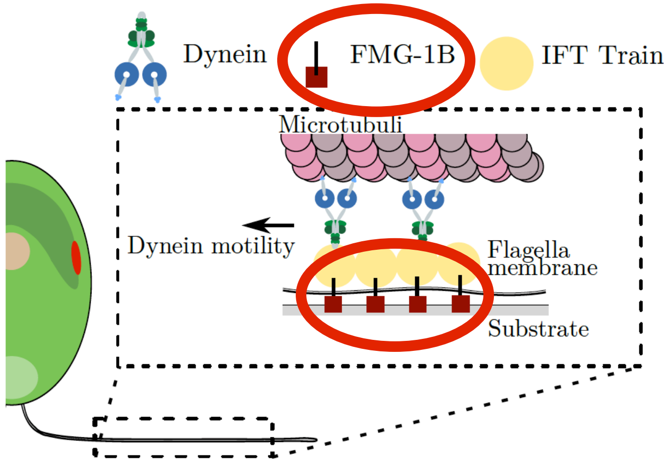


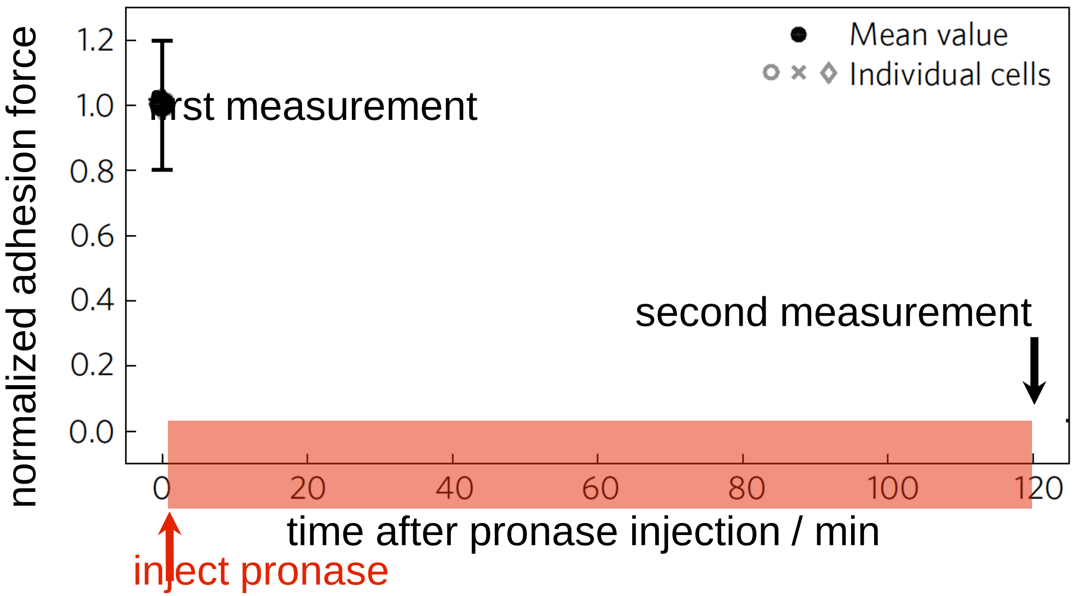


C. Kreis et al., *Nature Physics*

Molecular Mechanism of Light-Switchable Flagella Adhesion

- flagella membrane proteins (FMG-1B) are involved in the adhesion during gliding





proteins protected in
red light

relocalization of FMG-1B
in response to light

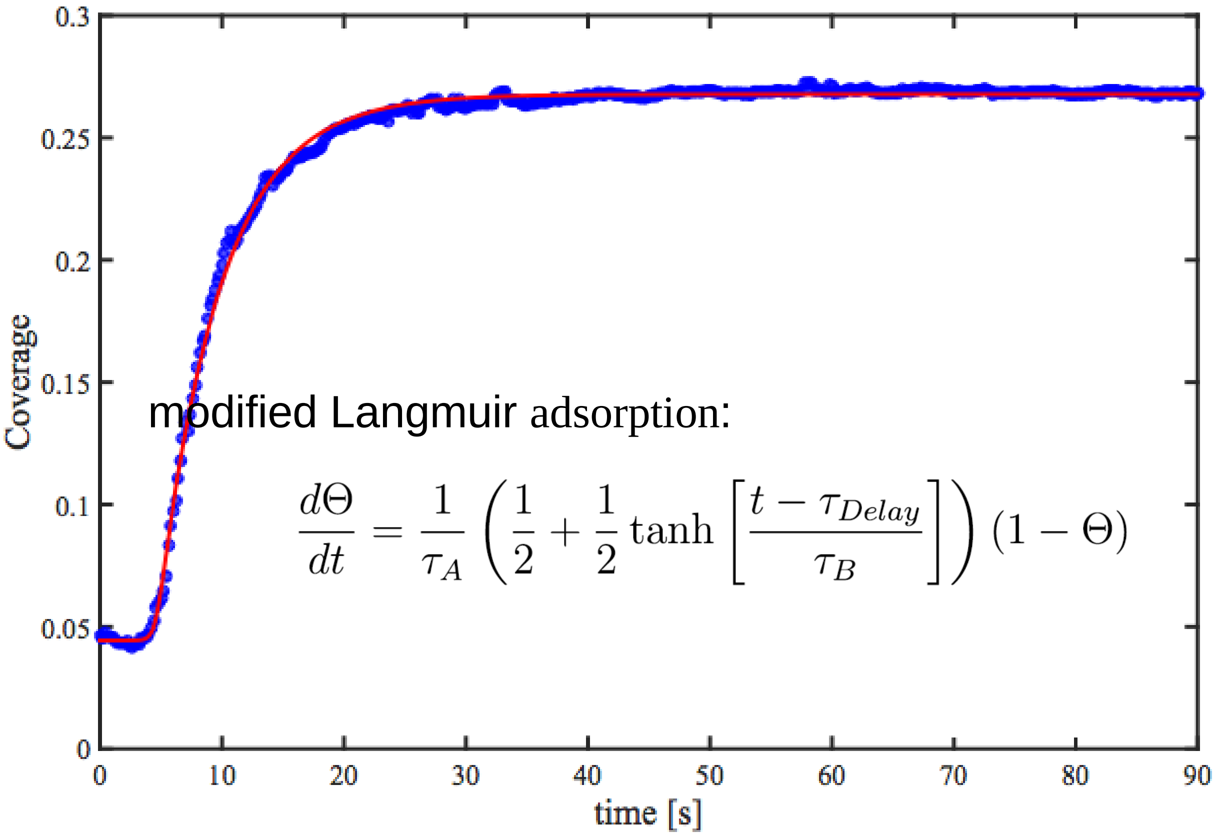
C. Kreis et al.,
Nature Physics (2018).

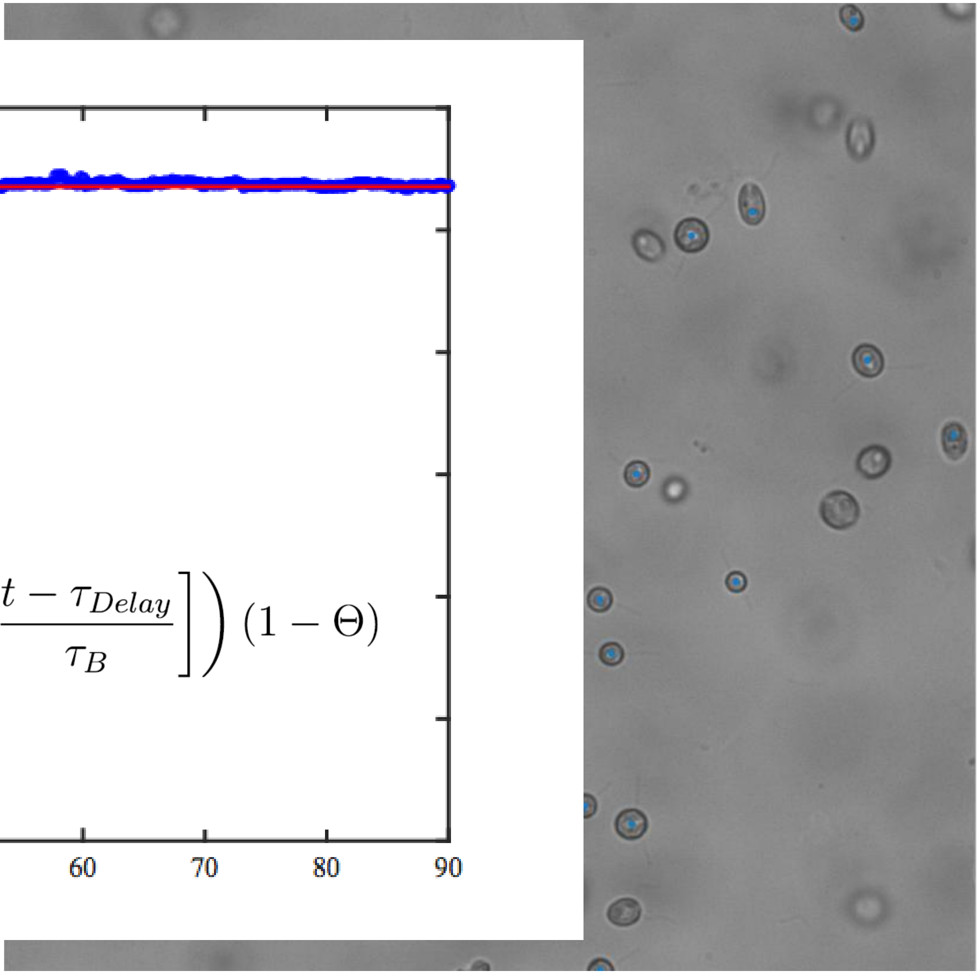
Light-Switchable Surface Association of Cell Populations

• red light / white light: light-switchable surface colonization (fully reversible)

• delay time of cell adhesiveness, its variability and the adsorption rate

• surface mobility (gliding)

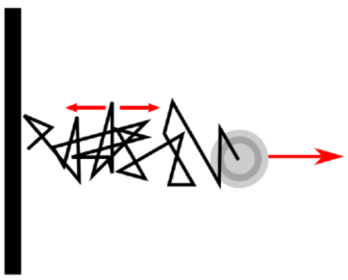


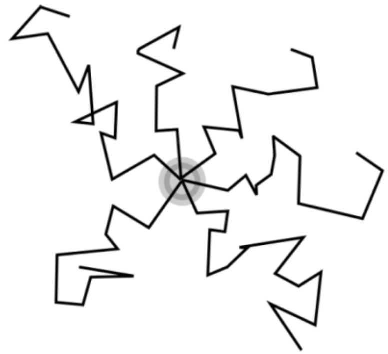


modified Langmuir adsorption:

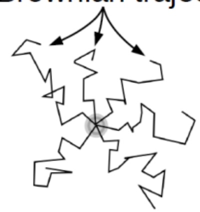
$$\frac{d\Theta}{dt} = \frac{1}{\tau_A}\left(\frac{1}{2} + \frac{1}{2}\tanh\left[\frac{t-\tau_{Delay}}{\tau_B}\right]\right)(1-\Theta)$$

A. Fragkopoulos et al., *in preparation* (2018)





Brownian trajectories $\mathcal{X}$

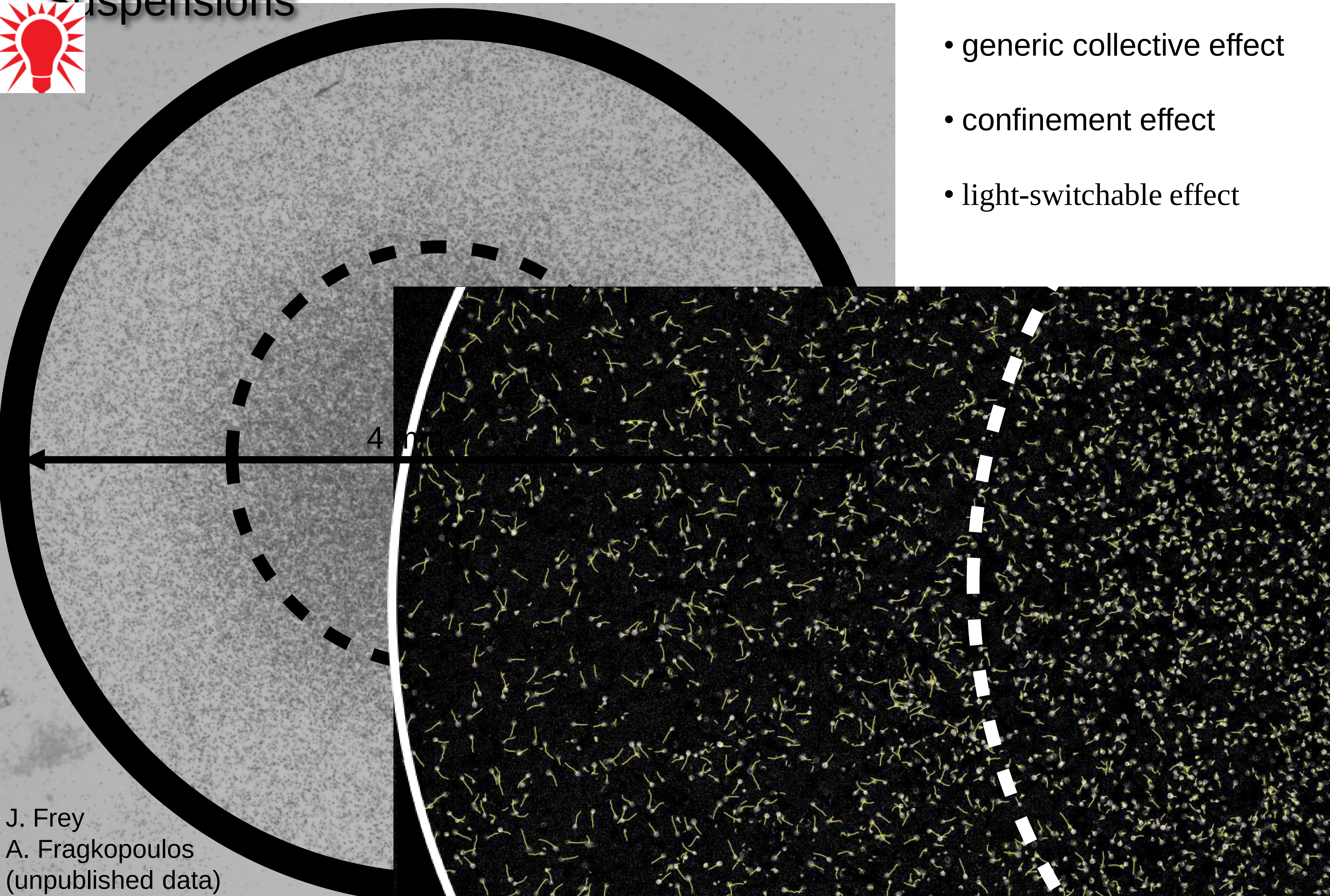


$$\vec{F}_C \sim \vec{\nabla} \int \mathrm{p}_{\mathcal{X}} \ln(\mathrm{p}_{\mathcal{X}})$$

$$\dot{\vec{v}} = -\gamma \vec{v} + \vec{F}_C + \vec{h}(\vec{x})$$

- we can study the dynamical effects of such CEF

Light-Switchable Collective Effects in *Chlamydomonas* Suspensions

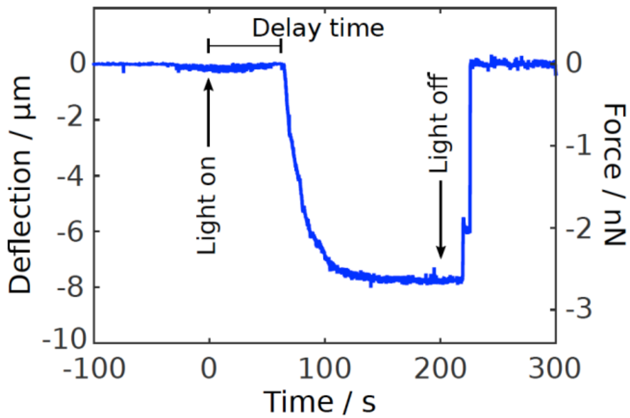


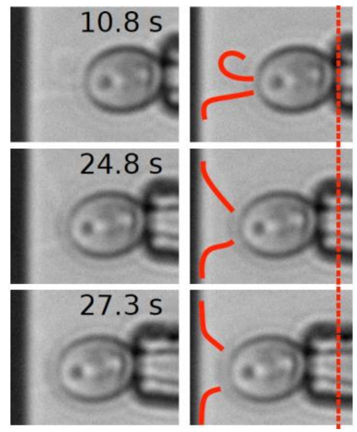
- generic collective effect
- confinement effect
- light-switchable effect

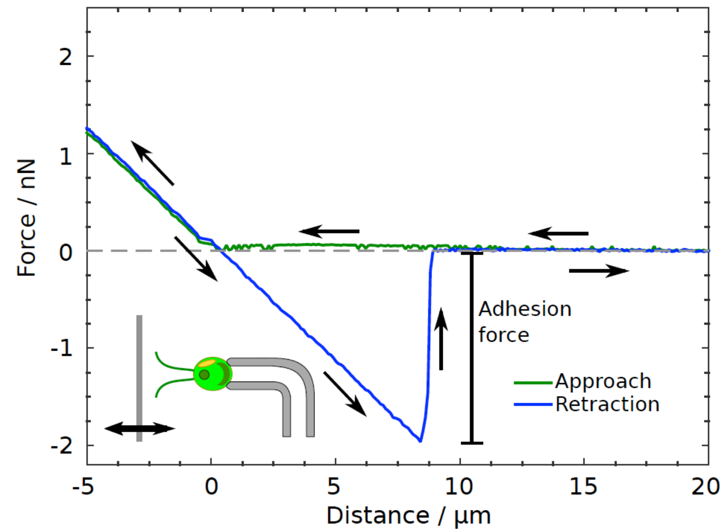
J. Frey
A. Fragkopoulos
(unpublished data)

Take Home Messages & Summary

- adhesion of Chlamydomonas is switchable by light
- evolutionary adaptation of photoactive microalgae to optimize the photosynthesis in their natural habitats

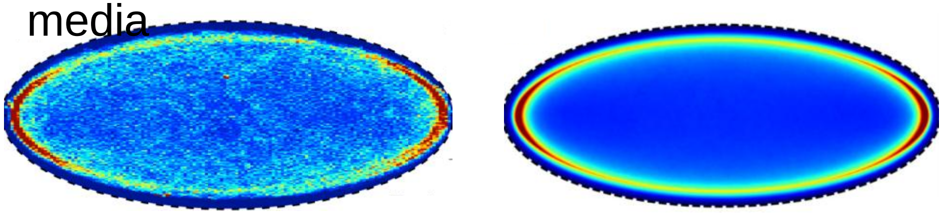






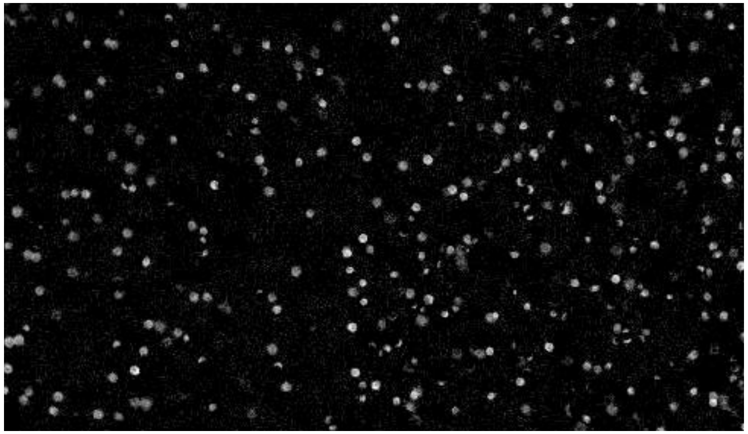
C. Kreis, M. Le Blay, C. Linne, M. Makowski, and O. Bäumchen,
Nature Physics 14, 45-49 (2018).

- wall curvature guides navigation in confinement
- colonization and biofilm formation in porous media



T. Ostapenko, F.J. Schwarzendahl, T. J. Böddeker, C.T. Kreis, J. Cammann, M.G. Mazza, and O. Bäumchen,
Physical Review Letters 120, 068002 (2018)

- Chlamydomonas suspensions: collective effects in confined geometries



- Fabian Schwarzendahl (MPIDS)
- Jan Camman (MPIDS)
- Tanya Ostapenko (MPIDS)
- Thomas Böddeker (MPIDS)
- Christian Kreis (MPIDS)
- Oliver Bäumchen (MPIDS)

- Stephan Herminghaus (MPIDS)

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