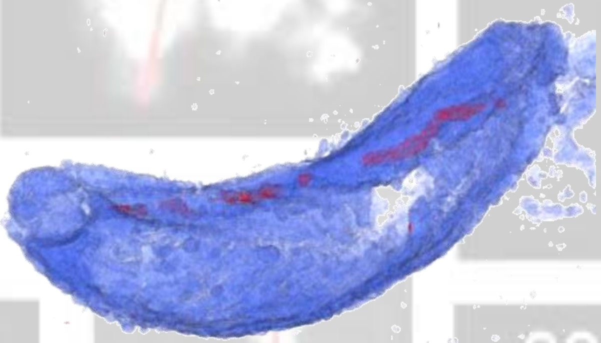
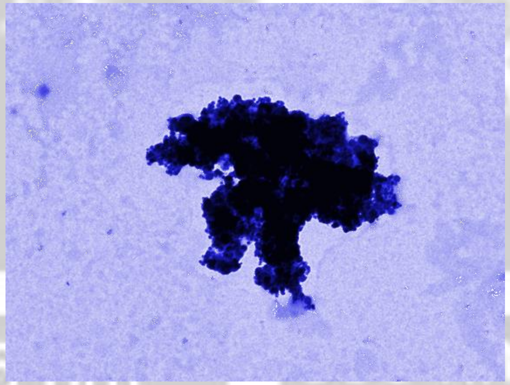
DE LA RECHERCHE À L'INDUSTRIE

Magnetic microswimmers

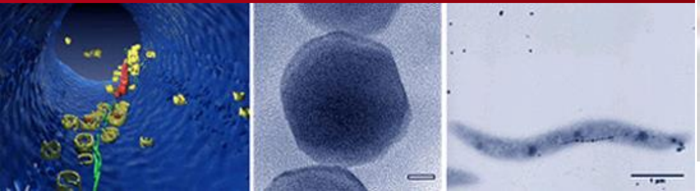




Damien Faivre

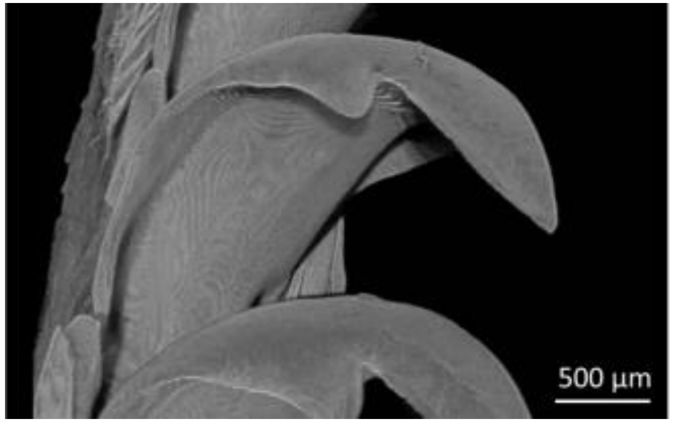
School on “Mobility, self-organization and swimming strategies”

Université Côte d’azur, October 20, 2021

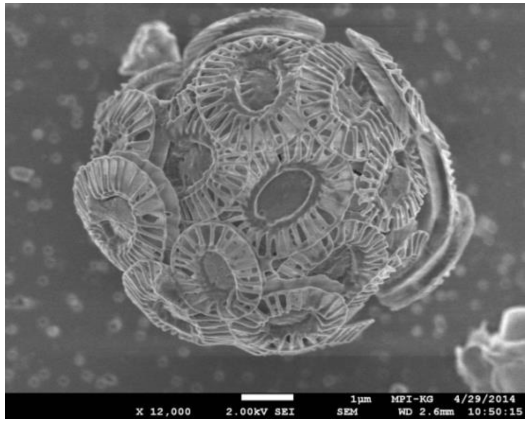


THE FAIVRE GROUP

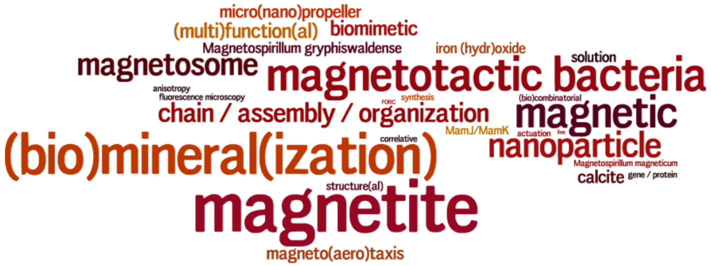
Biomineralization

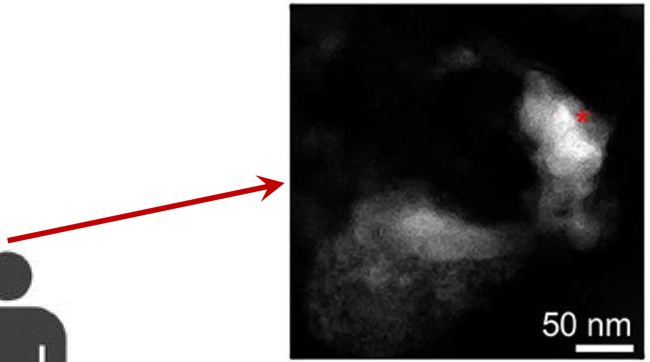


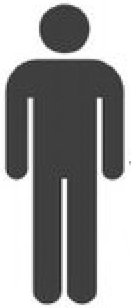
Limpets Ukmar Godec et al., Adv. Mater., 2017



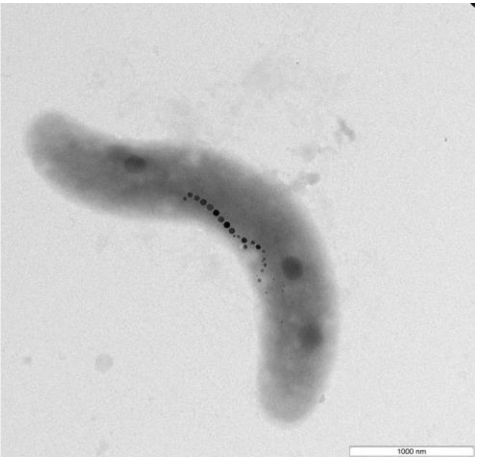
Coccolithophore algae Gal et al., Science, 2016







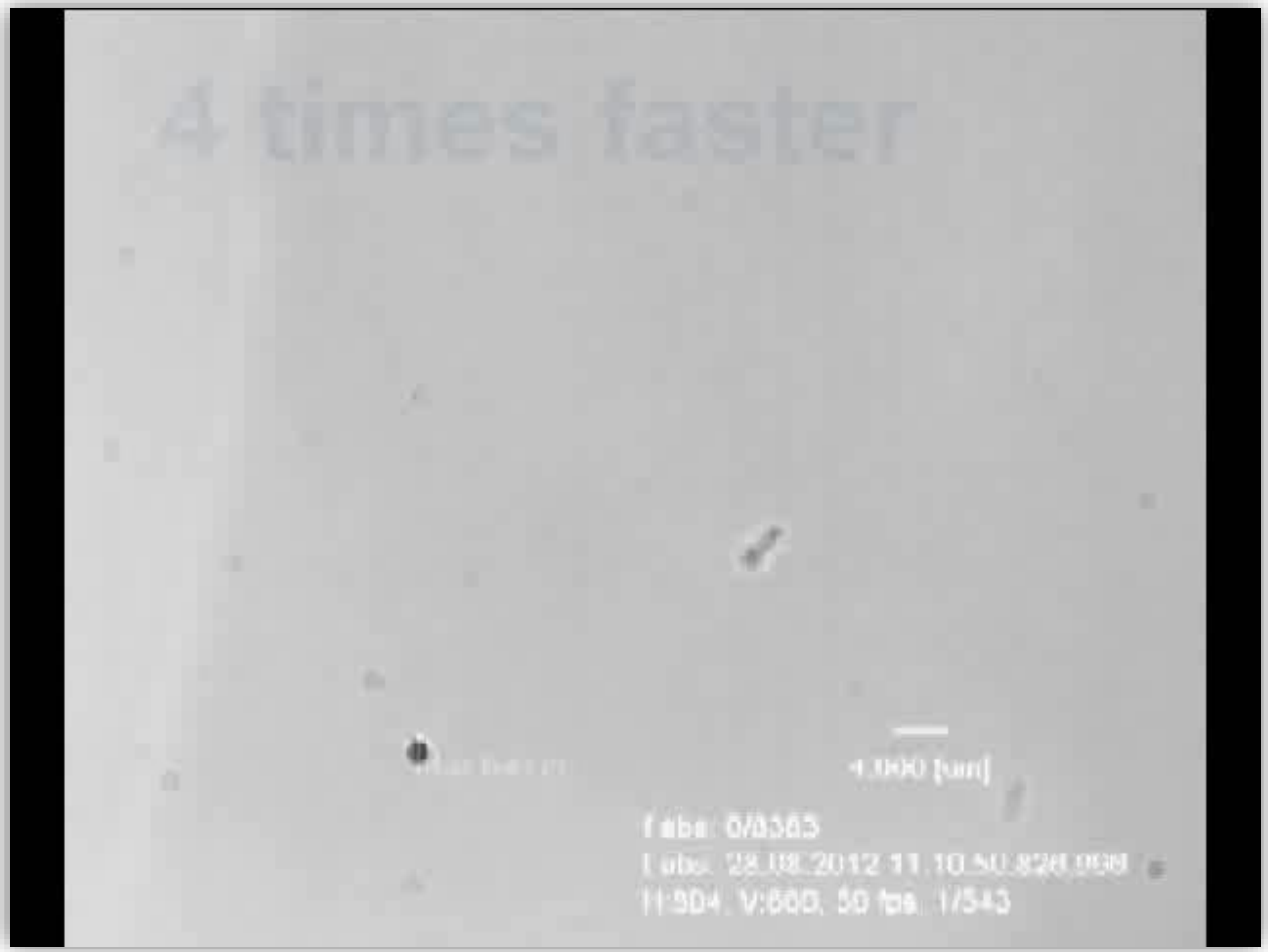
Humans Murros et al., Frontiers Medicine, 2019



Magnetotactic bacteria Pohl et al., Nano Lett., 2019

THE FAIVRE GROUP

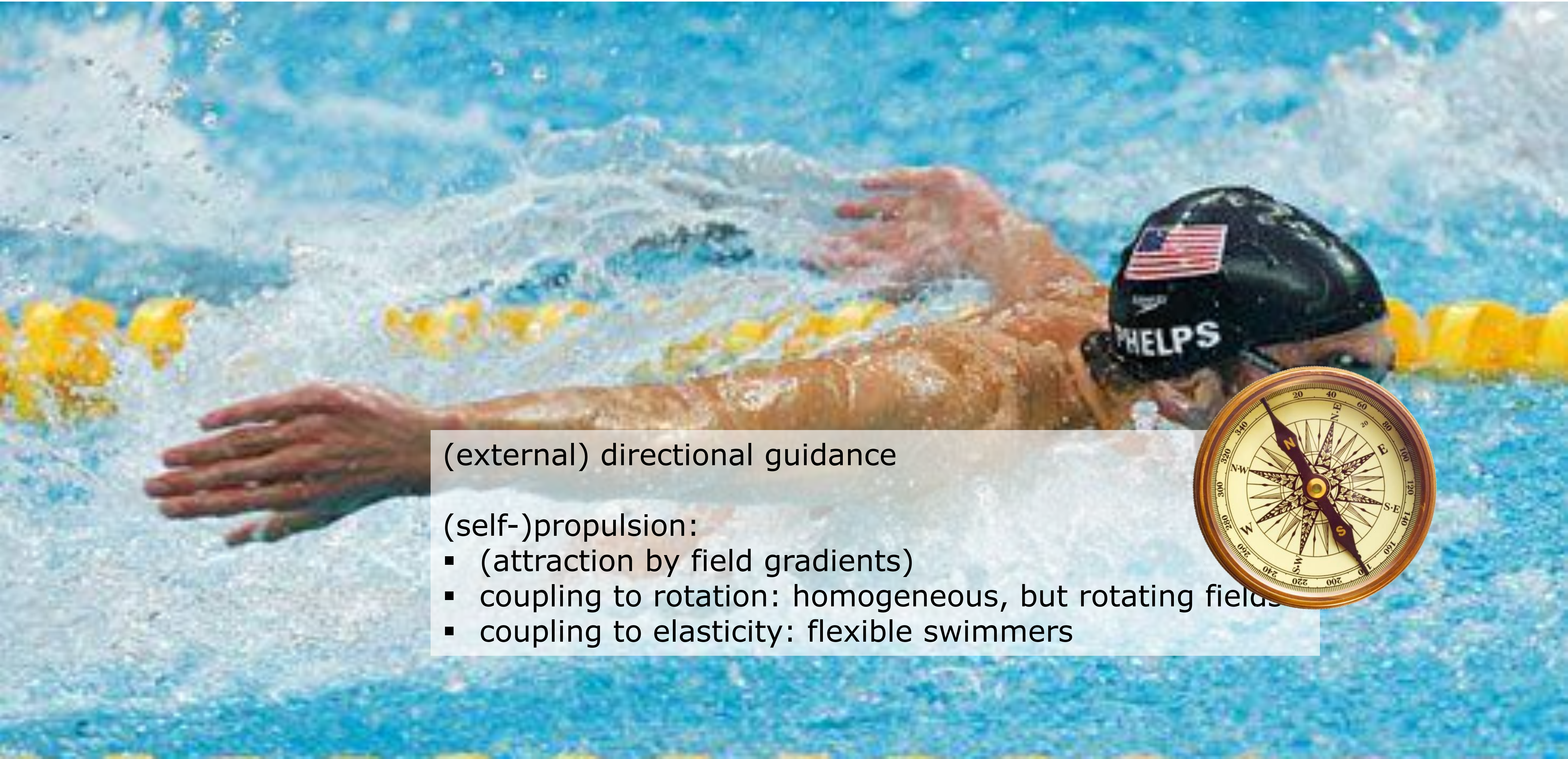
Microswimmers



Vach et al., Nano Lett., 2013
Lefèvre et al., Biophys. J,, 2014
Bennet et al., PLoS One, 2014
Vach et al., Nano Lett., 2015
Vach et al., Sci. Rep., 2015
Klumpp et al., Physica Scripta, 2015
Vach et al., J. Phys. D. Appl. Phys., 2016
Klummp and Faivre, Eur. Phys. J. Spe. Topics, 2016
Vach et al., J. Phys. D. Appl. Phys., 2017
Stanton et al., ACS Nano, 2017
Codutti et al., Frontiers Robot. A. I., 2018
Bente et al., Small, 2018
Bachmann et al., Phys. Rev. Appl., 2019
Codutti et al., PLoS Comp. Biol., 2019
Klumpp et al., Phys. Rep., 2019
Bente et al., eLife, 2020
Bachmann et al., Adv. Intell. Syst., 2020
Mohammadinejad et al., Eur. Phys. J. E, 2021
Bachmann et al., Appl. Phys. Lett., 2021
Bente et al., ACS Appl. Nano Mater., 2021
Codutti et al., BioRxiv, 2021
Blue: synthetic systems, green: bacteria, black: reviews

SWIMMING WITH MAGNETS

Requirements



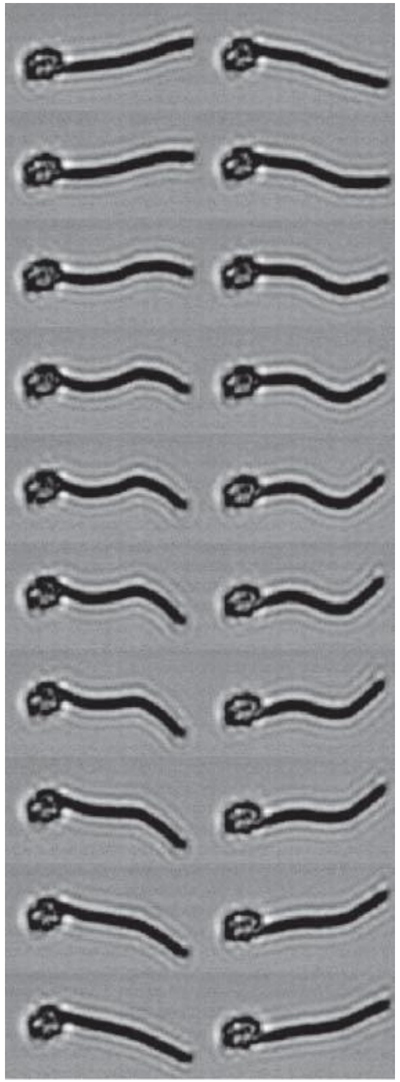
(external) directional guidance

(self-)propulsion:

- (attraction by field gradients)
- coupling to rotation: homogeneous, but rotating fields
- coupling to elasticity: flexible swimmers

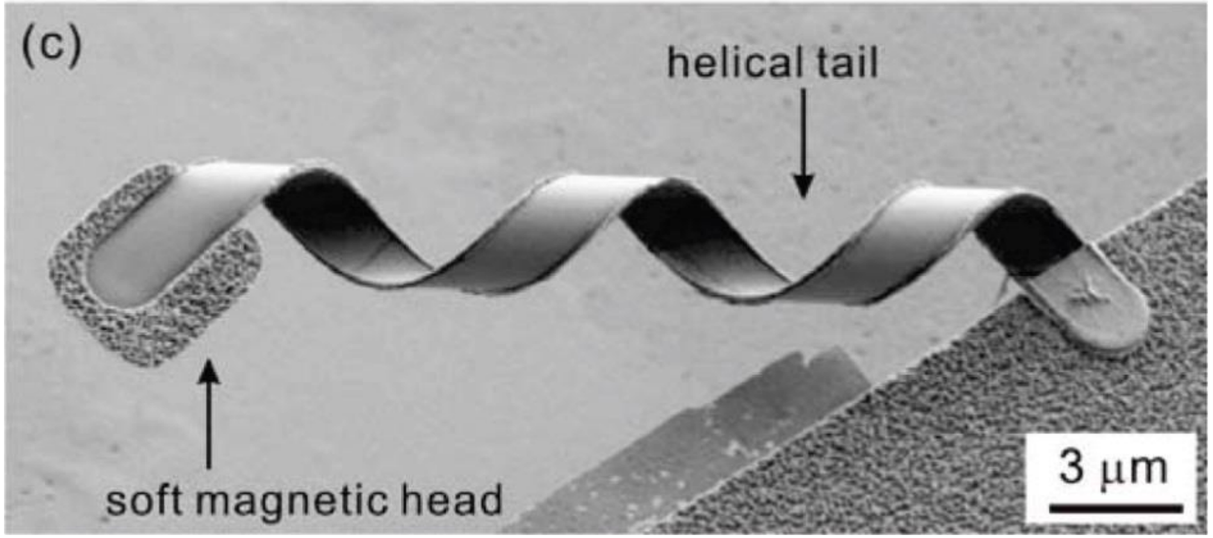
MAGNETIC MICROSWIMMERS

Some examples



- A flexible magnetic filament is actuated by an external magnetic field.

Dreyfus et al., Nature, 2005



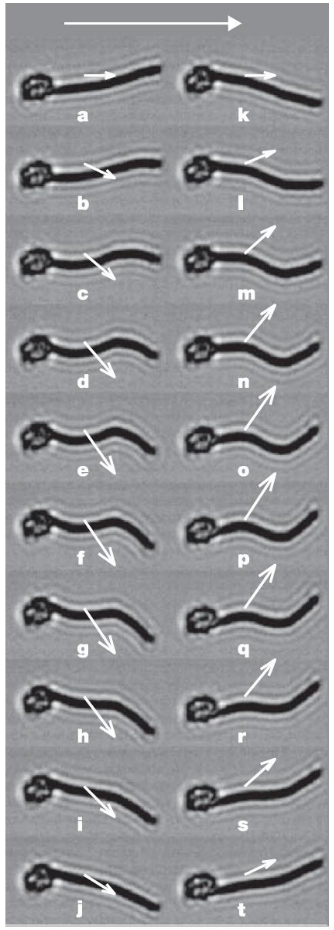
- A rigid “artificial bacterial flagella” can also be actuated by an external magnetic field.

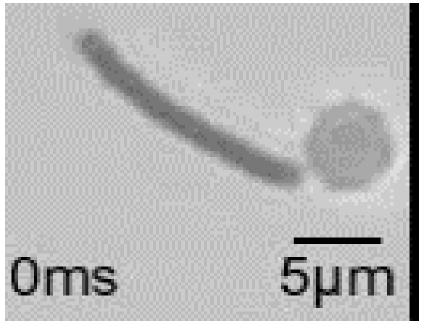
Zhang et al., NanoLetters, 2009

MAGNETIC MICROSWIMMERS

The original papers

Swimmer

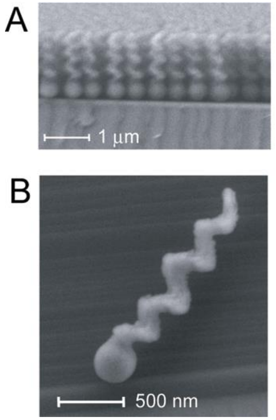


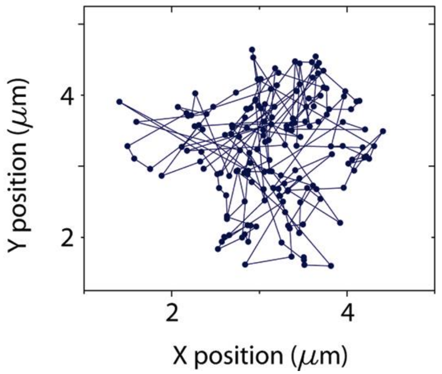


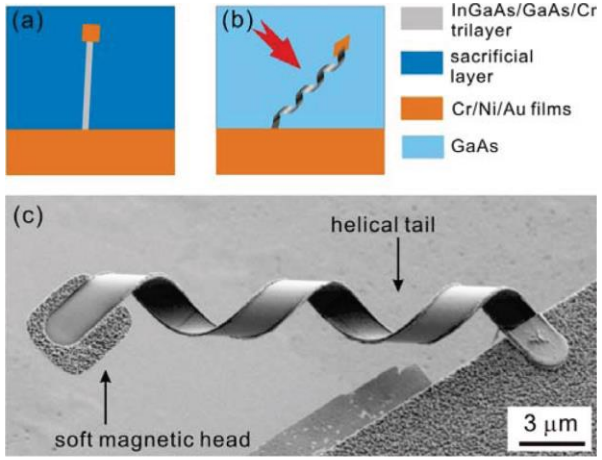
Beating pattern of the motion of a magnetic flexible filament attached to a red blood cell

Dreyfus et al., Nature, 2005

Propellers





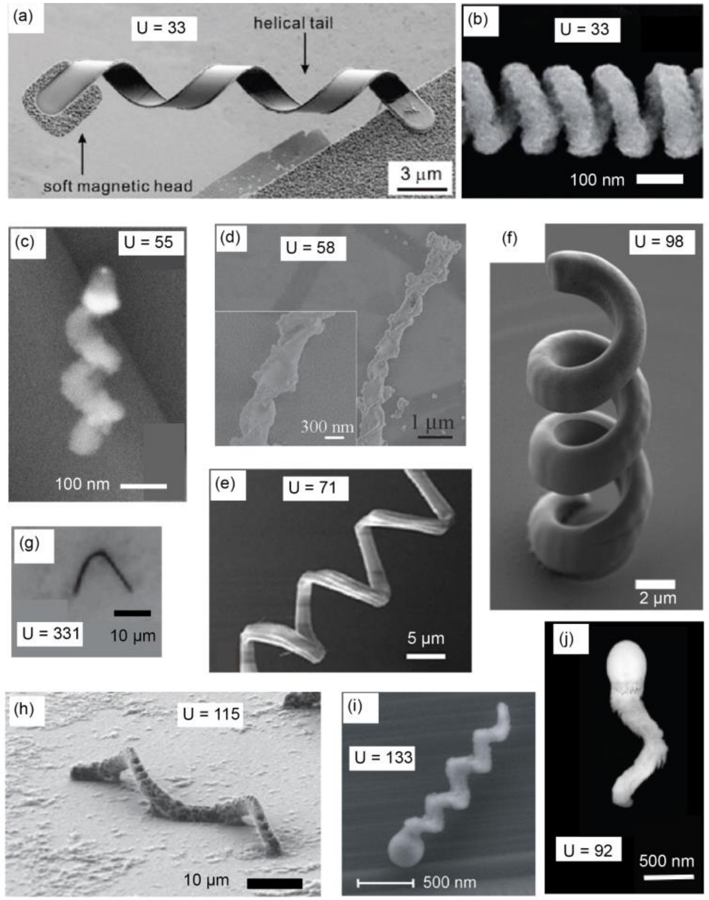


Ghosh and Fischer., Nano Letters, 2009

Zhang et al., Nano Letters, 2009

MICROPROPELLERS

Only helices



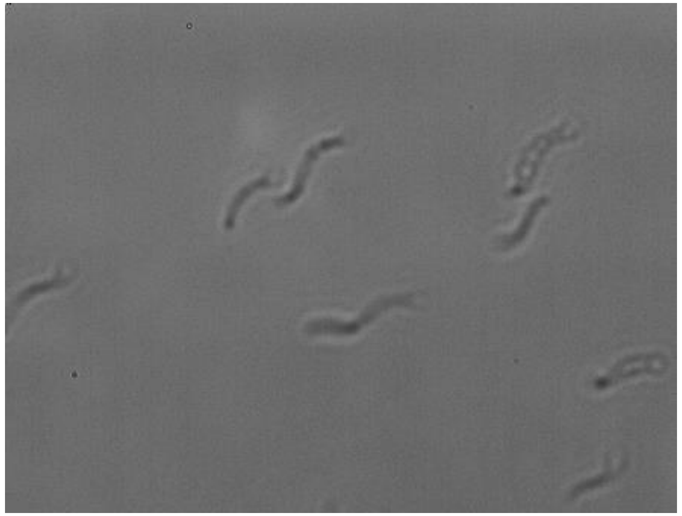
- Helices studied due to resemblance to flagella

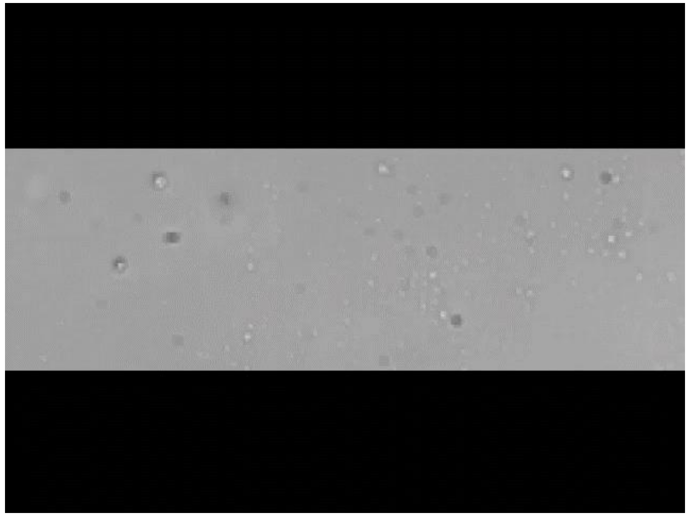
- Production with costly procedures e.g. glancing angle deposition

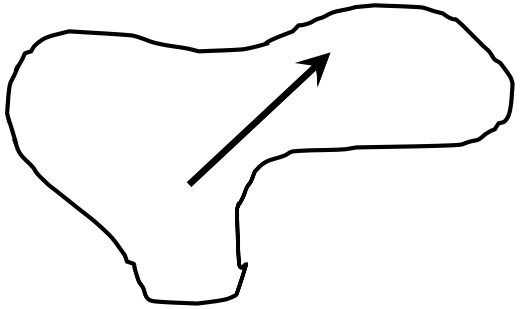
MICROPROPELLERS

Paradigm change

- Is an helix really the best suited morphology?
- In the bio-inspiration, is it rather the flagellar system or the cellular morphology to follow?

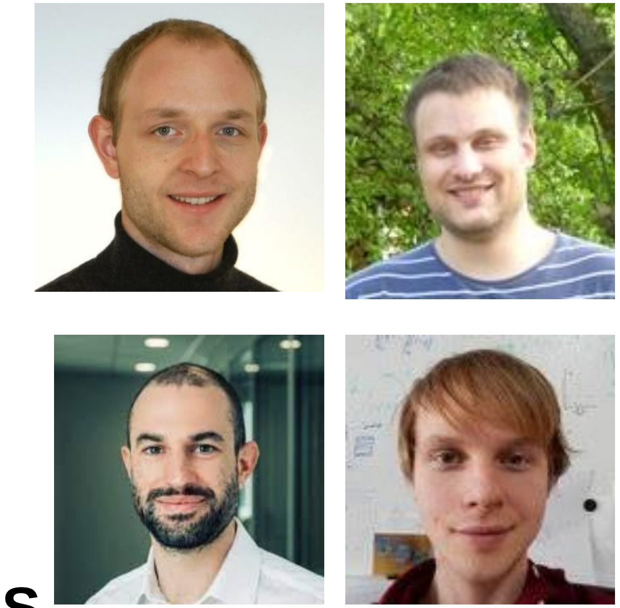






- Requirements:
  - A non symmetric structure
  - A magnetic dipole

Synthetic Microswimmers

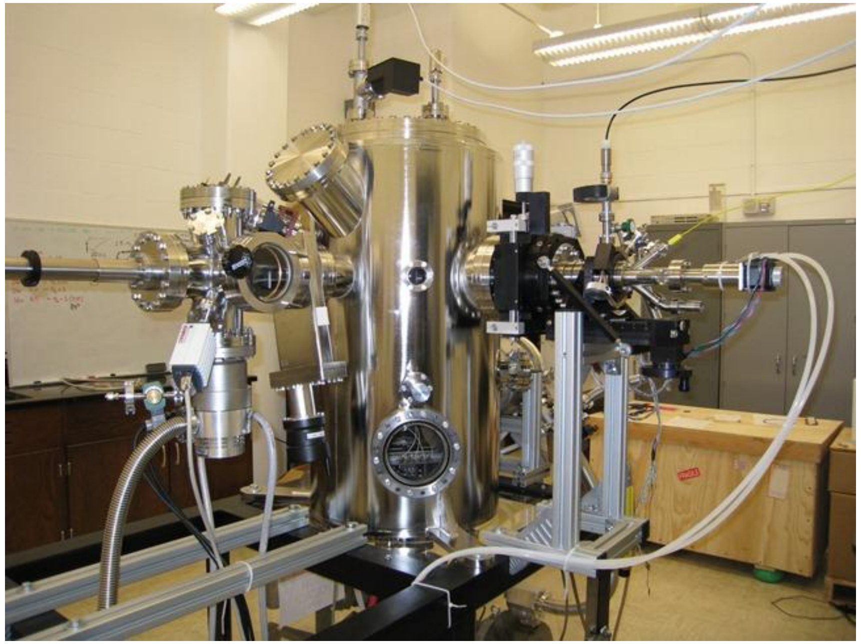


OUR SPECIALTY: RANDOMLY-SHAPED DEVICES

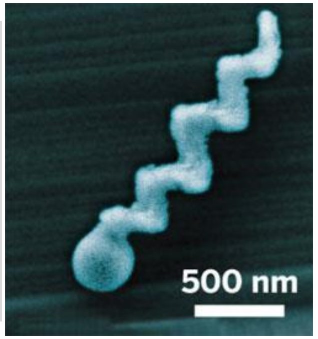
SYNTHETIC APPROACH

Hydrothermal carbonization

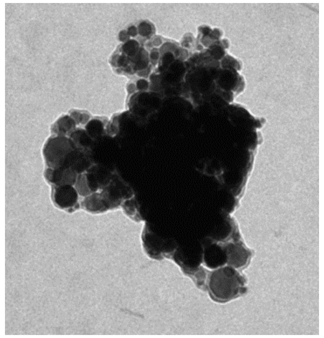
Literature: “glancing angle deposition”



- Complex
- Costly
- Small quantity
- All similar



Our approach

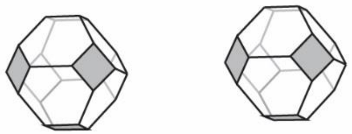


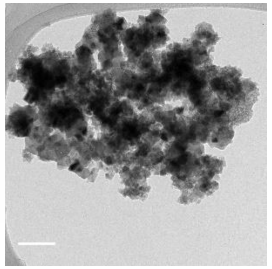
- Simple
- Cheap
- High quantity
- All different

PROPELLER SYNTHESIS

Synthetic set up

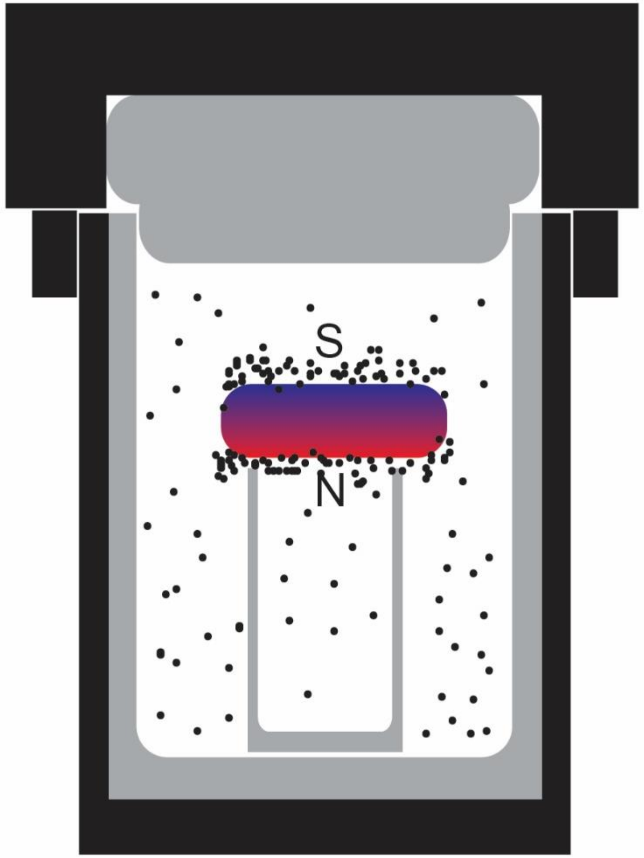
Start with colloidally stable magnetic nanoparticles in the stable single domain size range (20-200 nm)



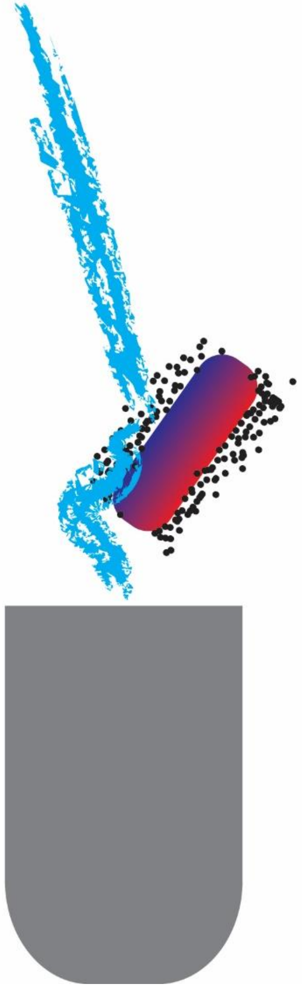


Mix with glucose in steel autoclave containing a strong permanent magnet (NdFeB).

Heat to 180 °C for 24 h



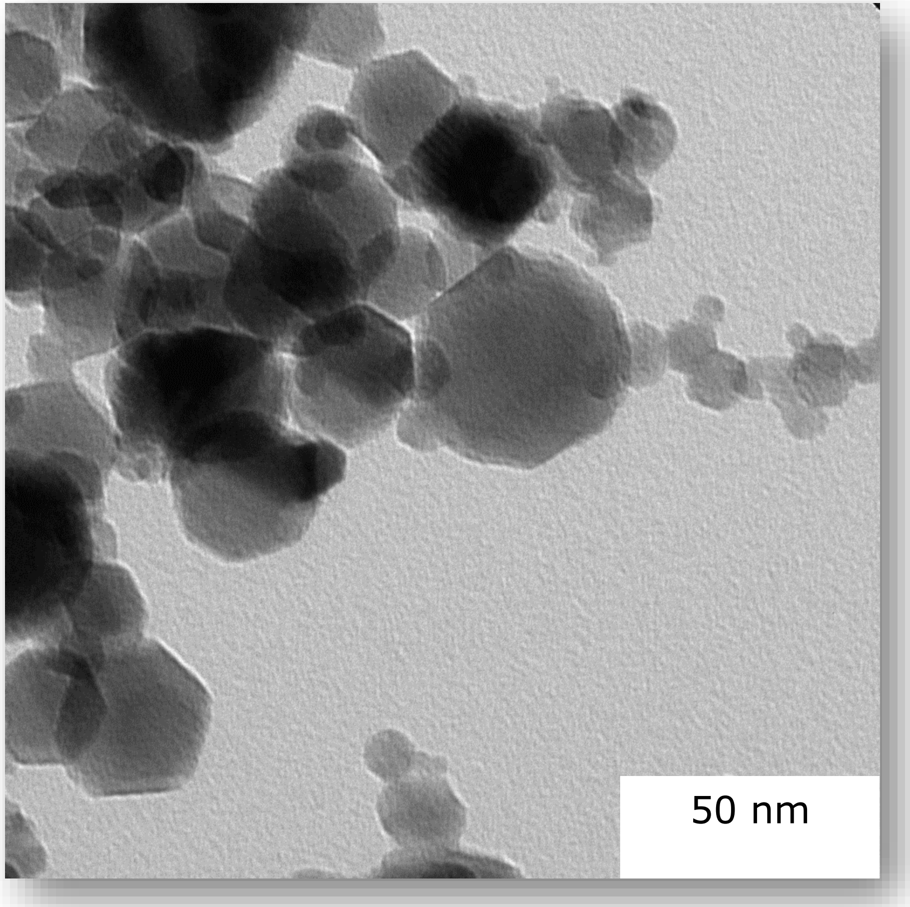
Wash structures off of magnet with dest. water.

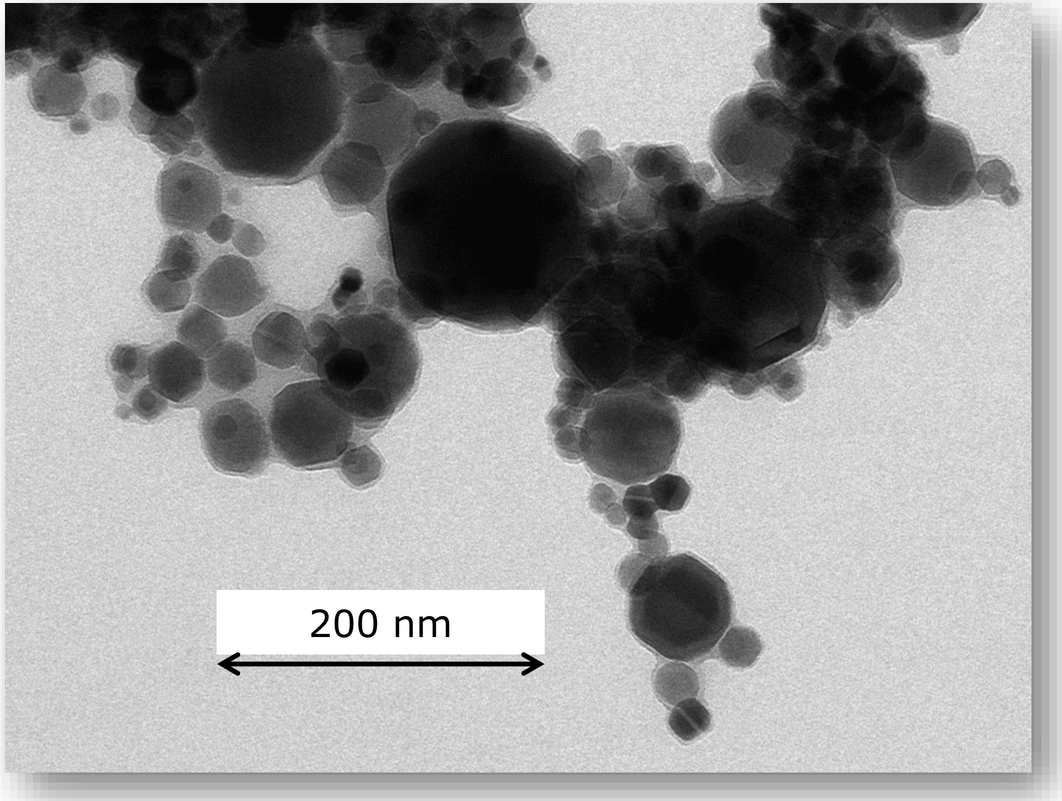


PROPELLER SYNTHESIS

Outcome of the synthesis

before HTC

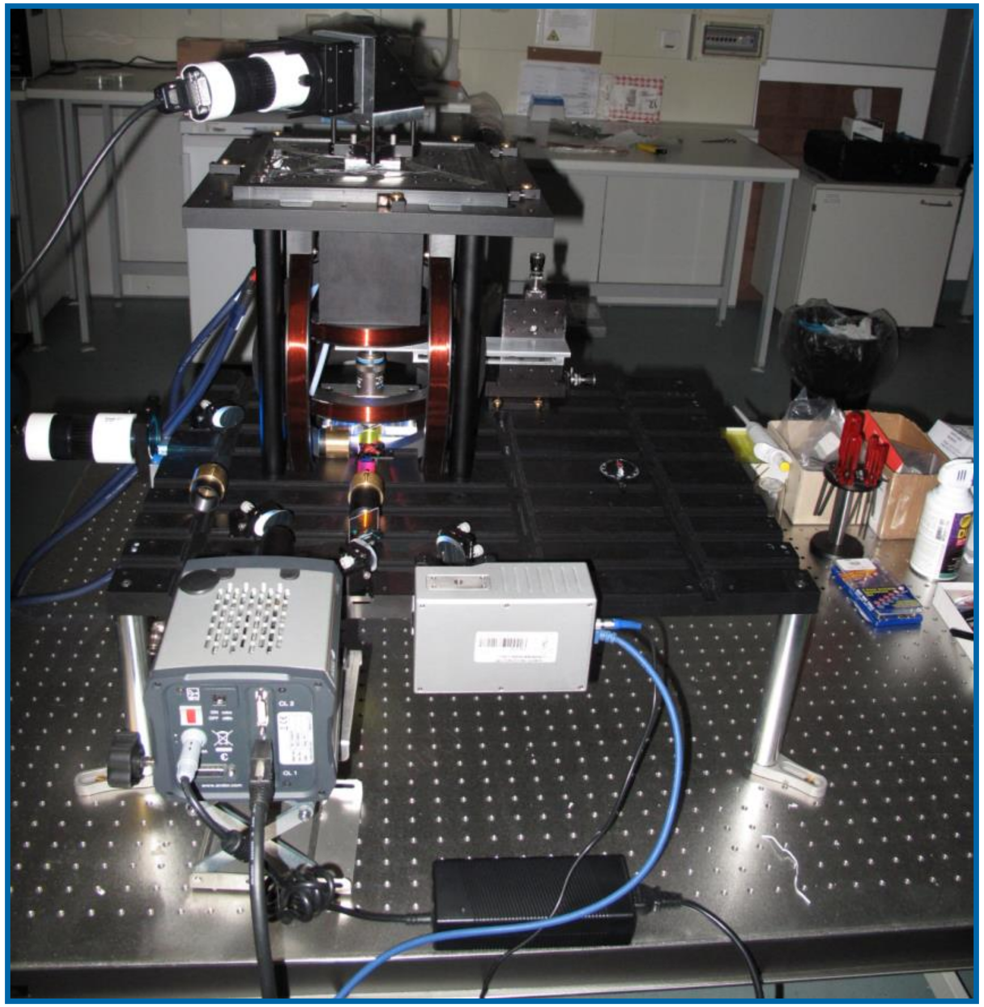




after HTC

OPEN-FRAME MICROSCOPE

The machine also to control microswimmers

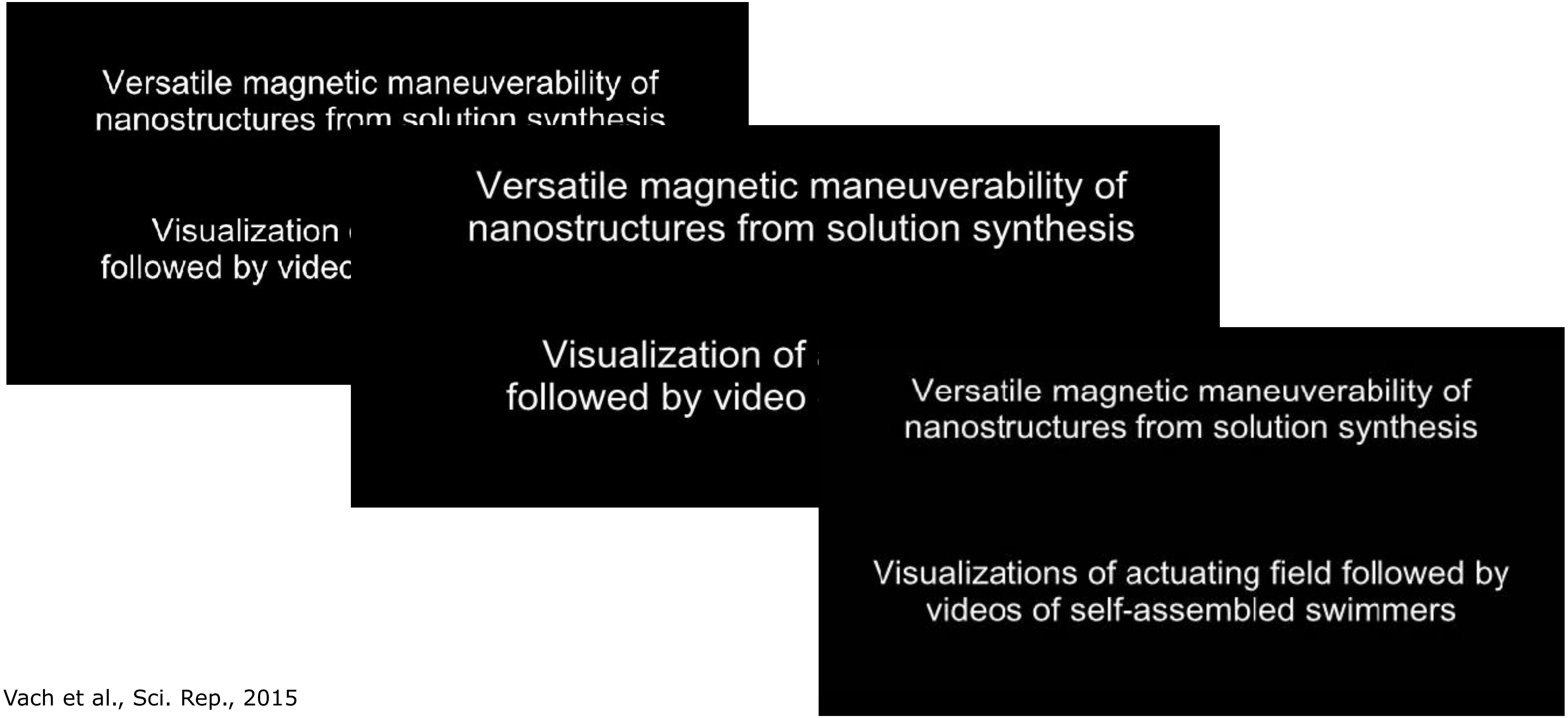


Bennet et al., PLoS One, 2014

- Magnetic set-up:
  - 3-dimensional control
  - From cancellation of Earth’s magnetic field to 5 mT
  - Homogeneity / possibility to generate gradient
  - DC and AC (0,2 Hz to 100 Hz)
- Optical set-up:
  - Fluorescence camera with large dynamic range
  - High-speed camera with up to 100 000 fps
  - Cooled LED 400, 470, 585 and 630 nm

MOVING UNDER WATER

One same material, several actuation schemes



Versatile magnetic maneuverability of
nanostructures from solution synthesis

Visualization
followed by video

Versatile magnetic maneuverability of
nanostructures from solution synthesis

Visualization of
followed by video

Versatile magnetic maneuverability of
nanostructures from solution synthesis

Visualizations of actuating field followed by
videos of self-assembled swimmers

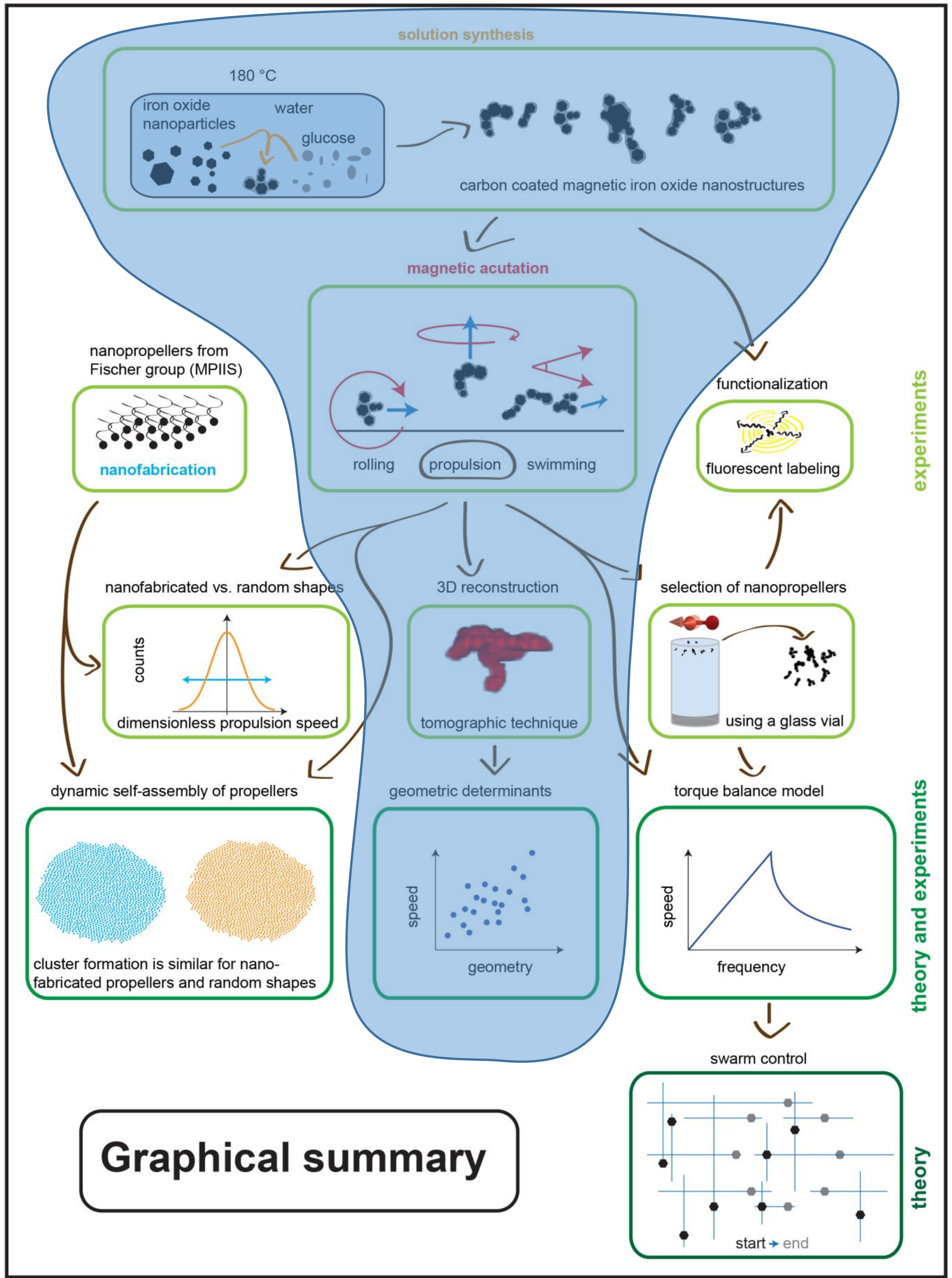
Vach et al., Sci. Rep., 2015

Synthetic Magnetic Microswimmers

MICROPROPELLERS

Original idea of / with Peter:

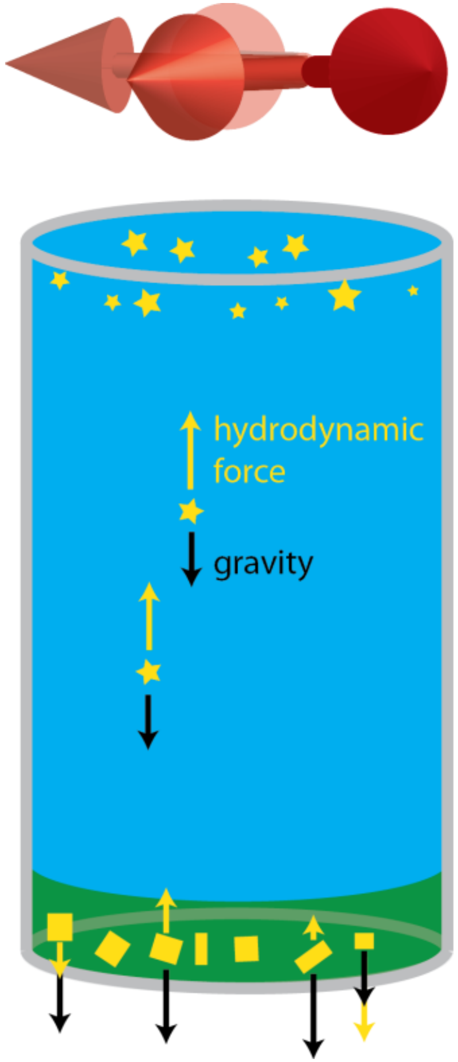
1. Show that basically anything can swim
2. Determine the morphological parameters responsible for the swimming
3. Study cluster formation



Graphical summary (conclusion) of Peter Vach’s doctoral thesis

FOCUS ON PROPELLERS

Actuation with rotating fields



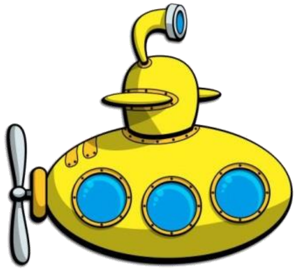
A rotating magnetic field actuates the magnetic structures

Fast propellers collect at the top of the vial

Nanostructures suspended in water (green) are deposited at the bottom of the vial, which is filled with 20 vol% EtOH in water (blue).

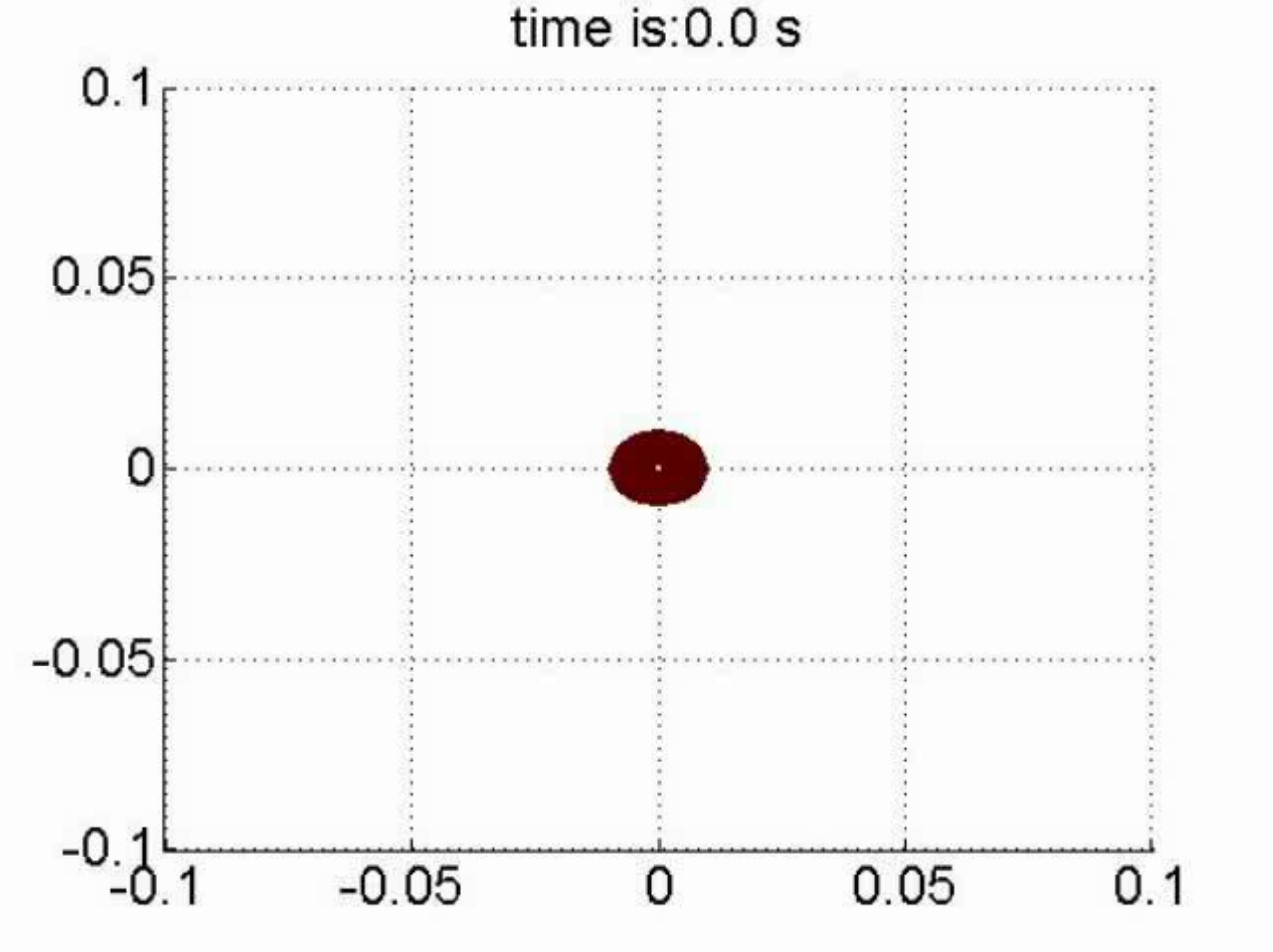
Propellers that move too slow or in the wrong direction collect at the bottom of the vial

The basic idea



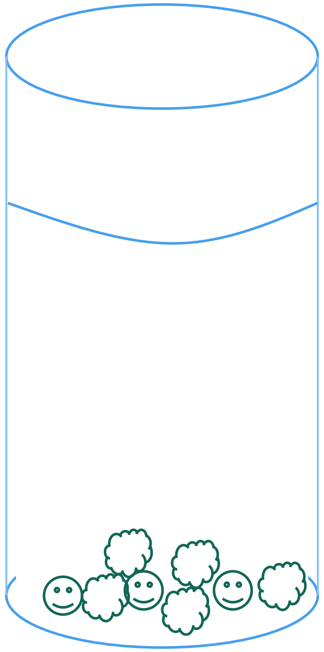
PROPELLER SELECTION

Time irreversible magnetic fields



Without magnetic field:
No particles at top

40 Hz turning field for about 10 h

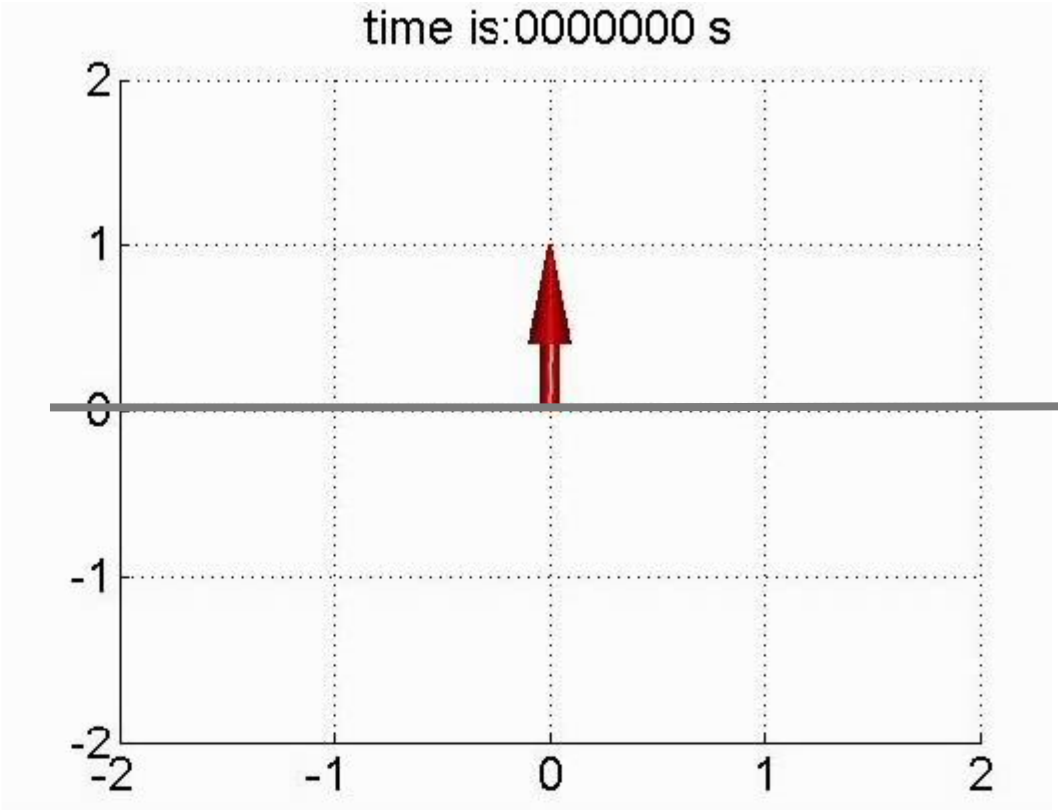


Vach et al., Nano Letters, 2013

FOCUS ON PROPELLERS

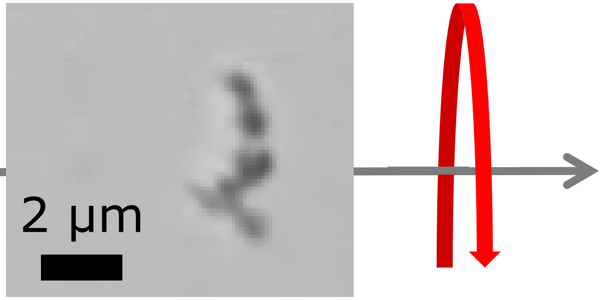
Actuation with rotating fields

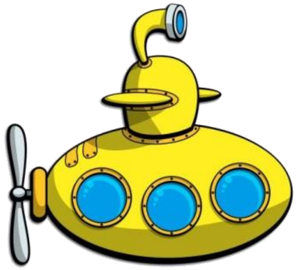
Frequency 10 Hz



$$\cancel{\boldsymbol{F} = \nabla(\boldsymbol{M} \cdot \boldsymbol{B})}$$

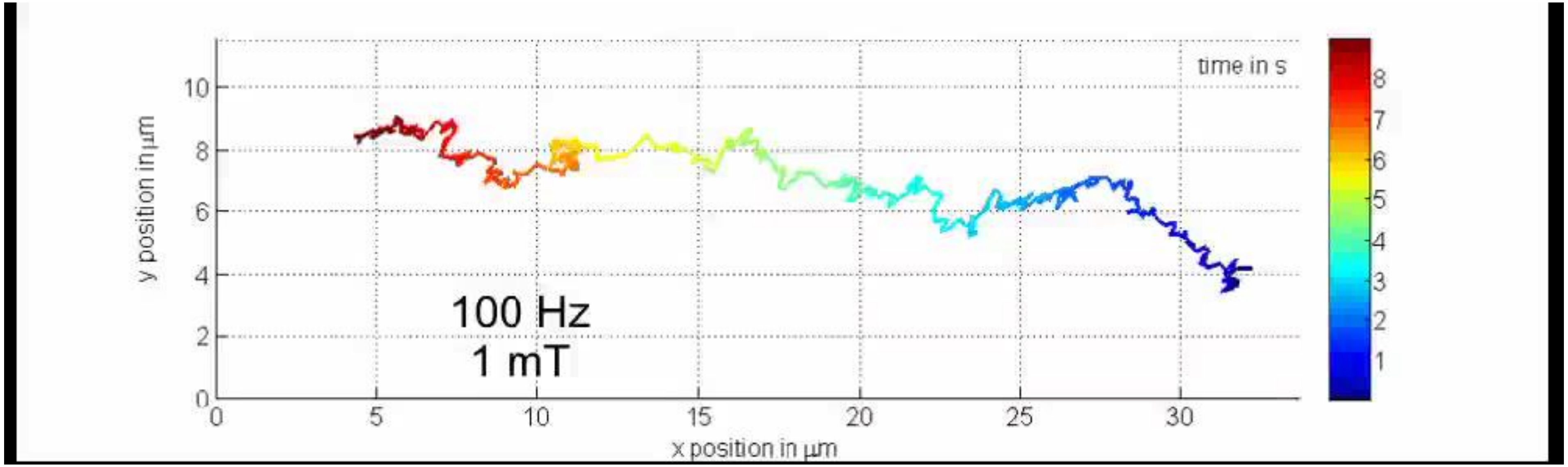
$$\boxed{\boldsymbol{\tau} = \boldsymbol{M} \times \boldsymbol{B}}$$

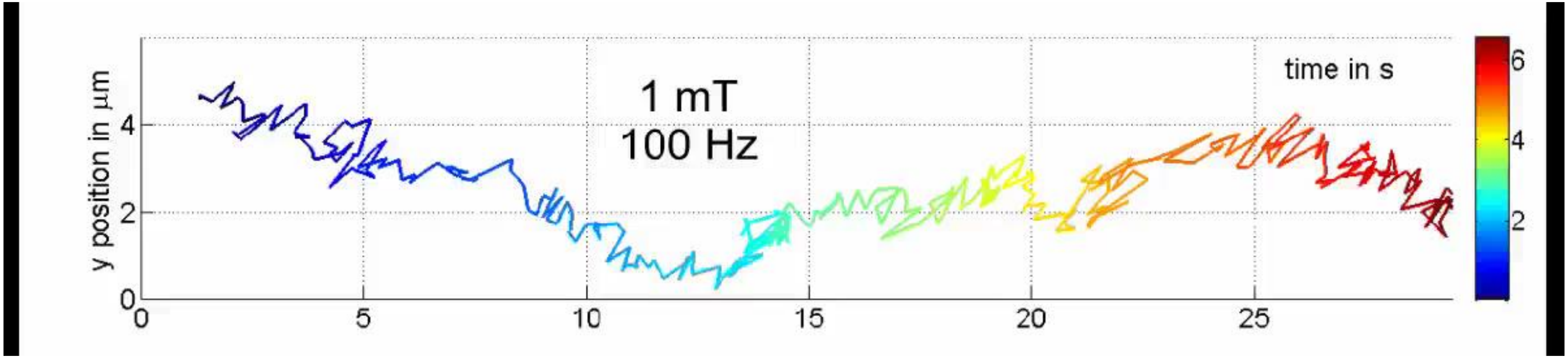




FOCUS ON PROPELLERS

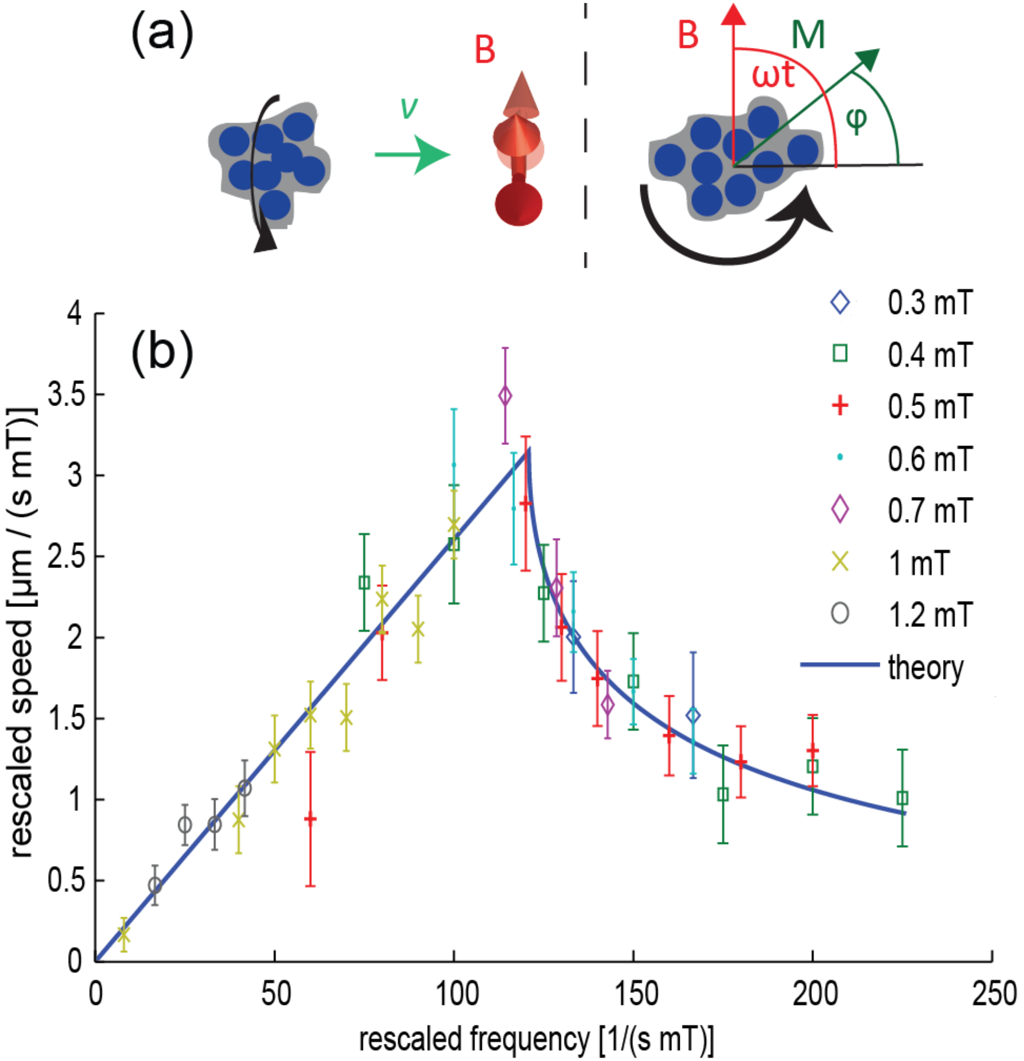
Actuation with rotating fields





UNDERSTANDING THE MOVEMENT OF PROPELLERS

Combinatorial approach towards the right size



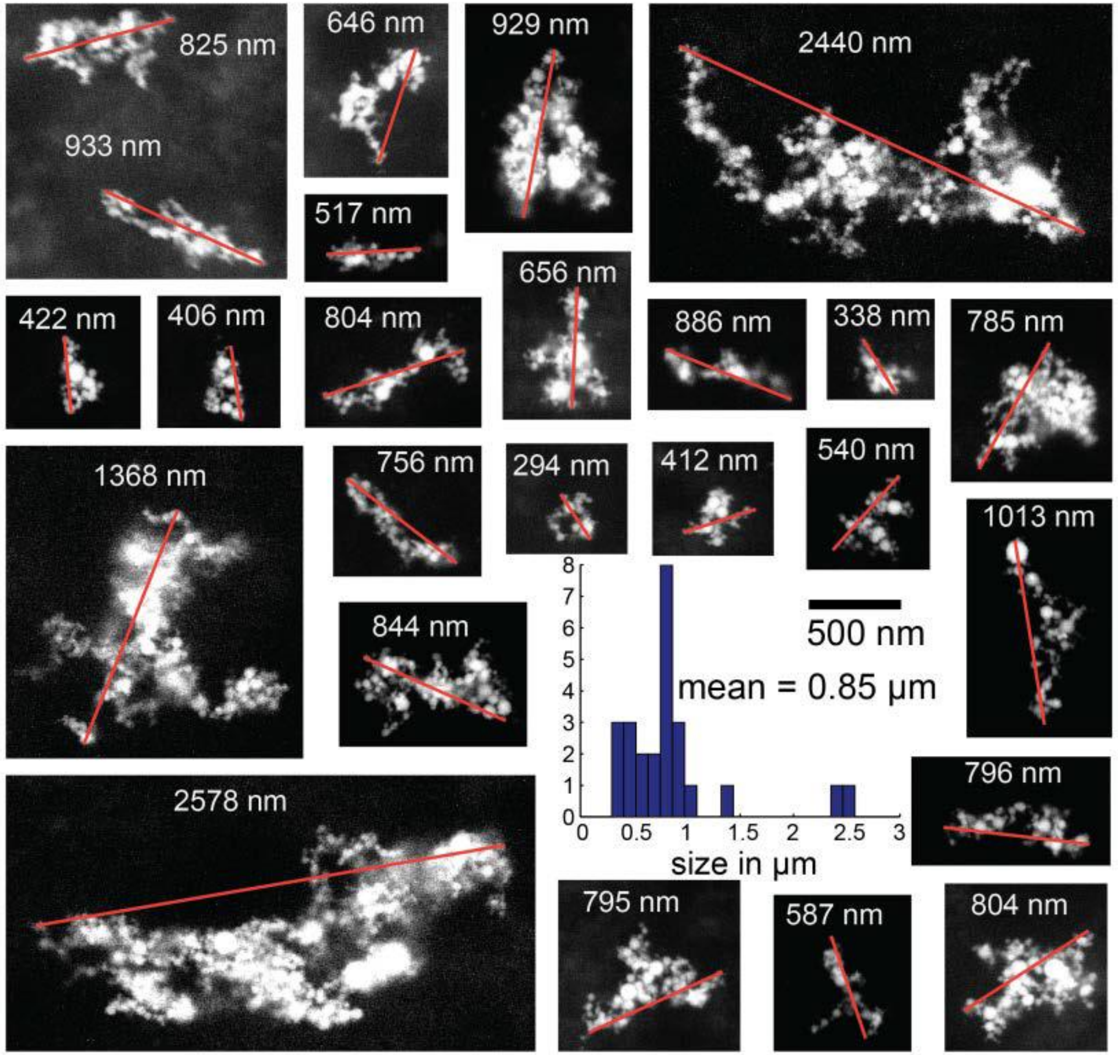
$$v(W)=\begin{cases} c_v W & W \pounds W_c \\ c_v\left(W-\sqrt{W^2-W_c^2}\right) & W>W_c \end{cases}$$

- The actuating magnetic field can be followed up to a certain limit.

Vach et al., Nano Letters, 2013

RANDOM-SHAPED MICROPROPELLERS

An alternative model system

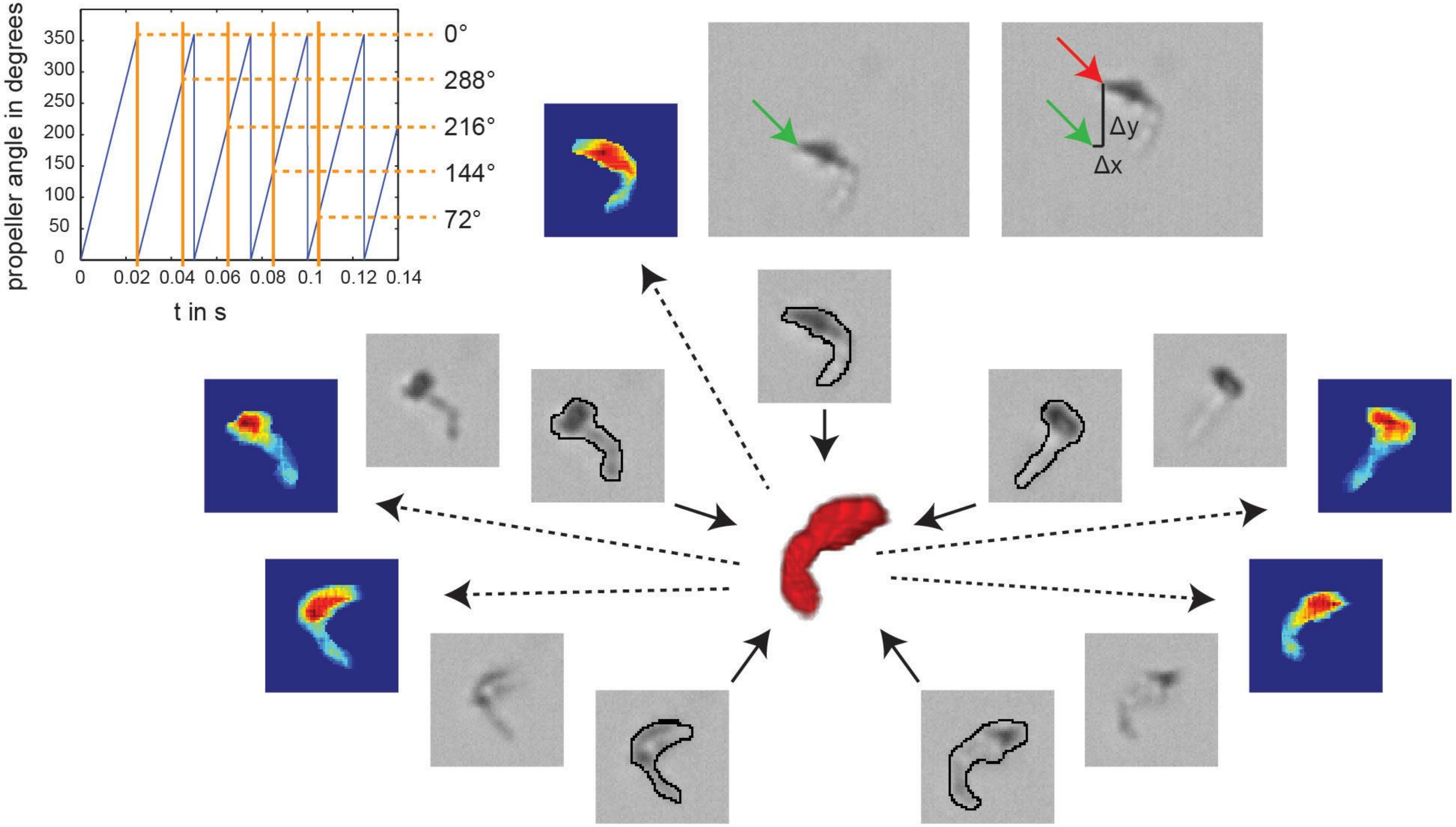


- Aggregated magnetite nanoparticles of random sizes and morphologies as versatile tool

Vach et al., Nano Letters, 2013

GEOMETRIC DETERMINANTS OF PROPULSION SPEED

Reconstructing the shape of micropropellers

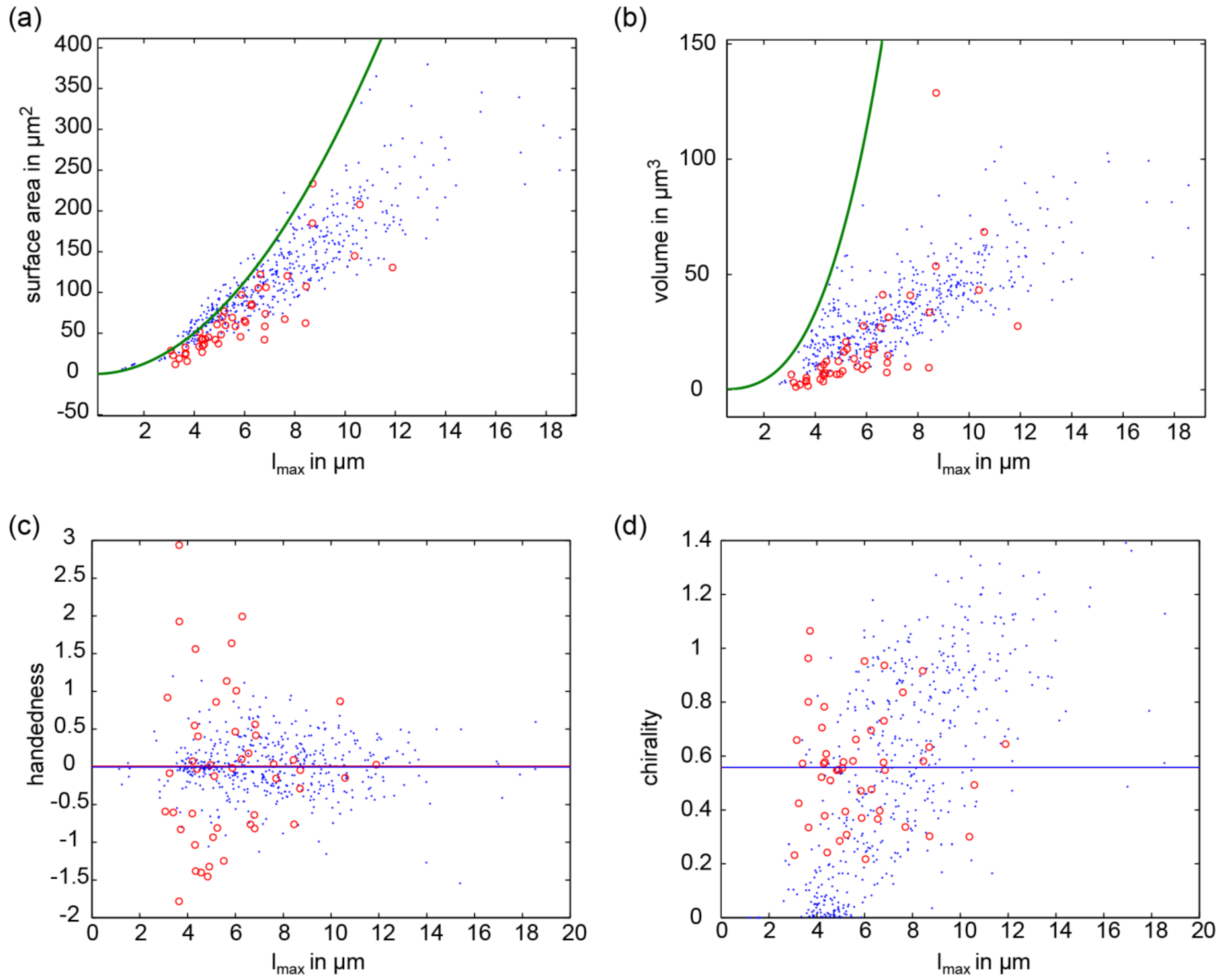


- Schematic explanation of the reconstruction method.

Vach et al., Nano Letters, 2015

GEOMETRIC DETERMINANTS OF PROPULSION SPEED

The synthesized micropropellers are of random shape

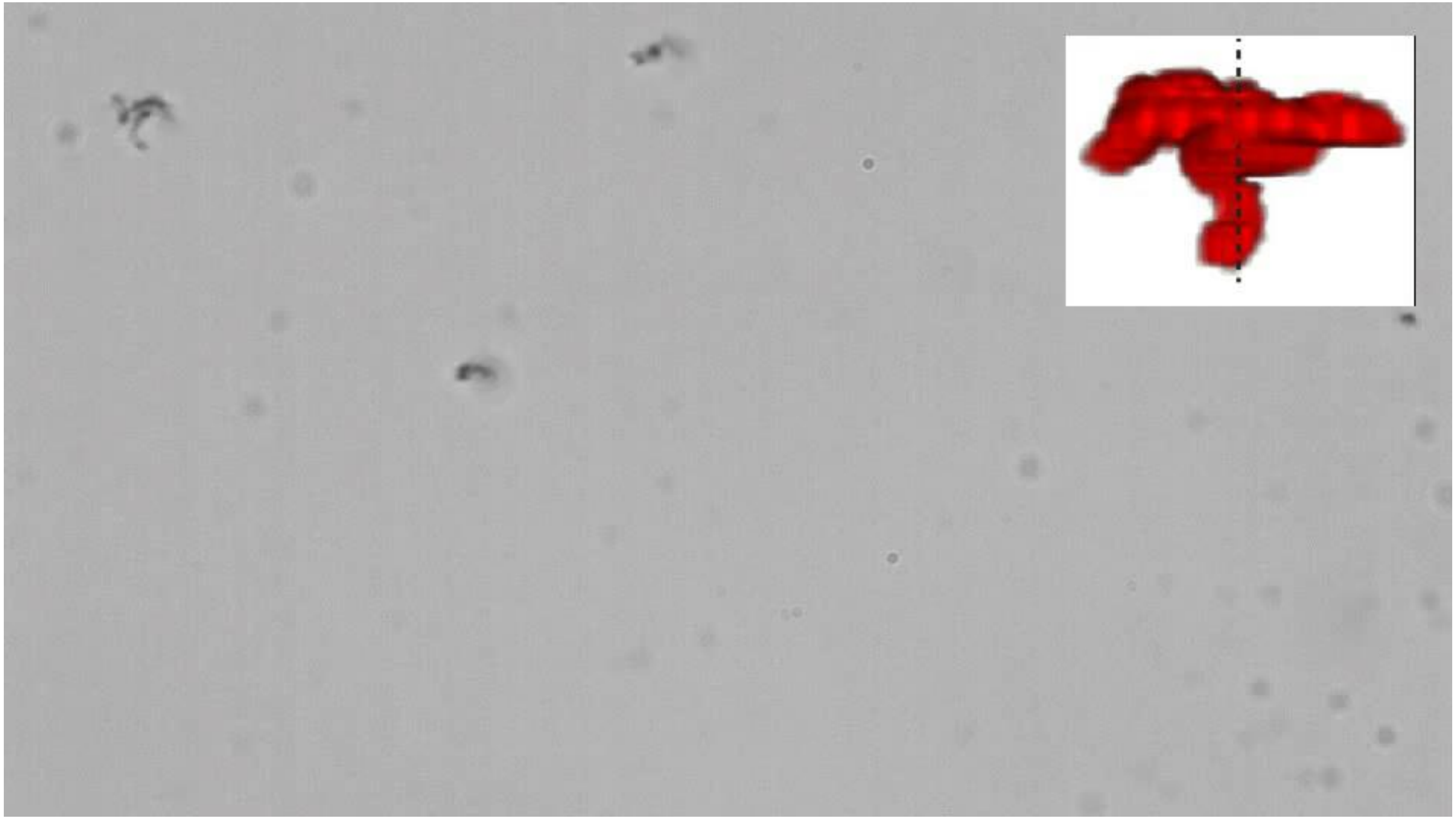


- Comparison of reconstructed shapes (red circles) with randomly generated shapes (blue dots). Exemplary geometric parameters are plotted against the maximum voxel to voxel distance *l*max in order to visualize their distributions.

Vach et al., Nano Letters, 2015

GEOMETRIC DETERMINANTS OF PROPULSION SPEED

The mushroom

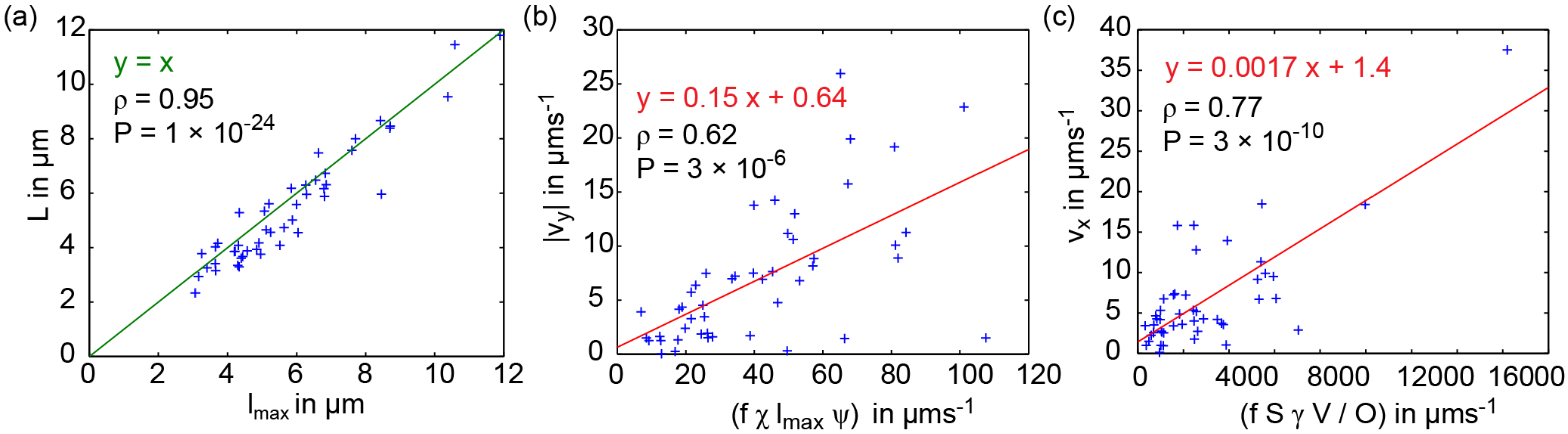


Exemplary movement with reconstructed shape

et al., Nano Letters, 2015

GEOMETRIC DETERMINANTS OF PROPULSION SPEED

No obvious correlation observed



Swimmer dimension vs. voxel size

Propulsion vs. best parameter fit

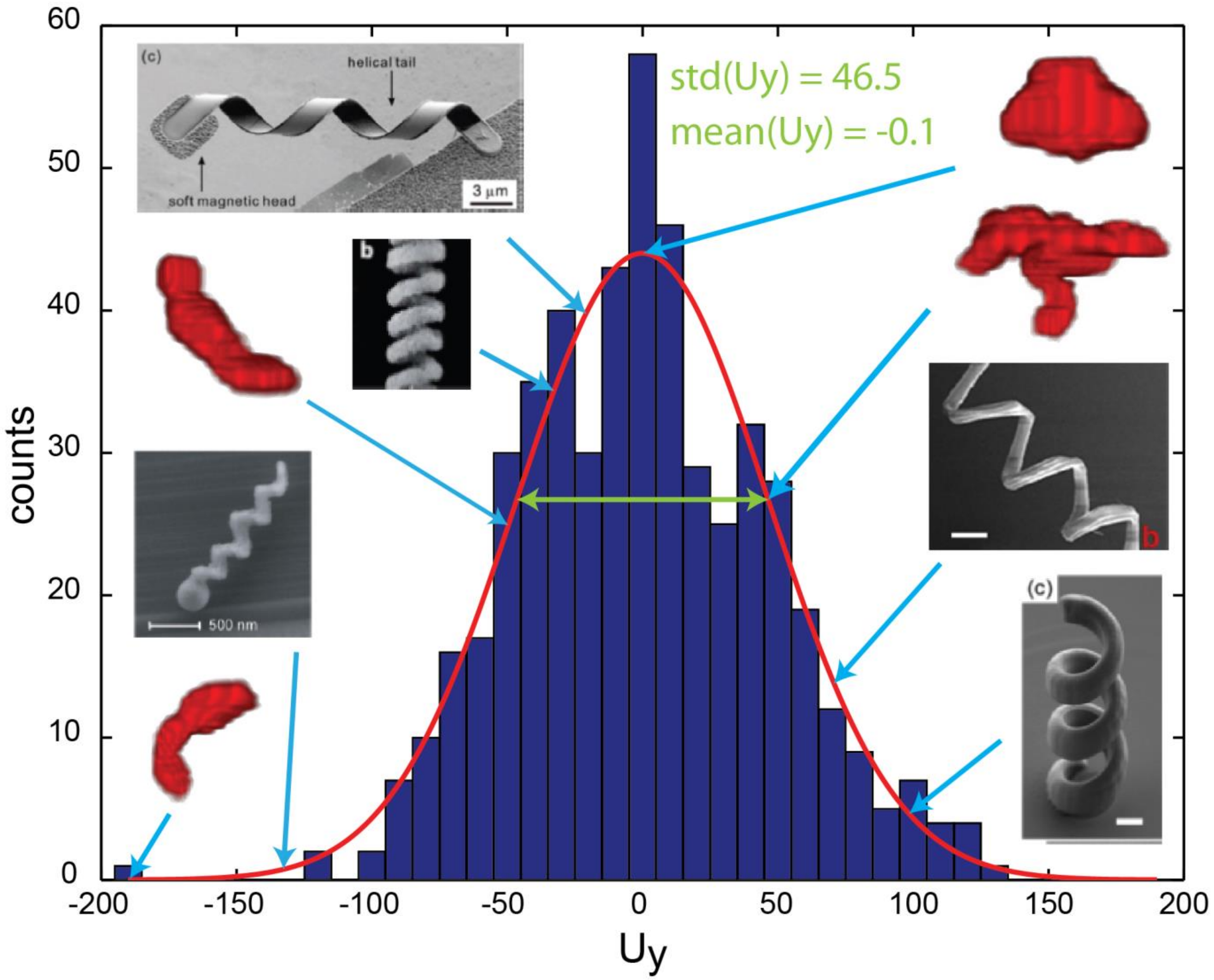
Rolling vs. best parameter fit

- The geometric reconstruction agrees well with the original dimensions.
- There is no apparent geometric determinant responsible for the propulsion.

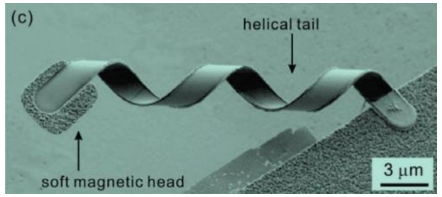
Vach et al., Nano Letters, 2015

PROPELLING EFFICIENCY

On the advantage of being an helix (or not)?



Comparison:



Zhang et al. 2009

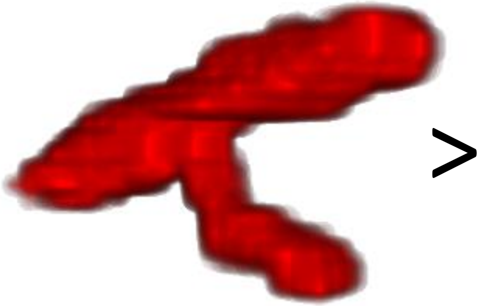
|U| = 33

49 % of observed random shapes have higher |U|

Vach et al., Nano Letters, 2015

PROPELLING EFFICIENCY

On the advantage of being an helix (or not)?



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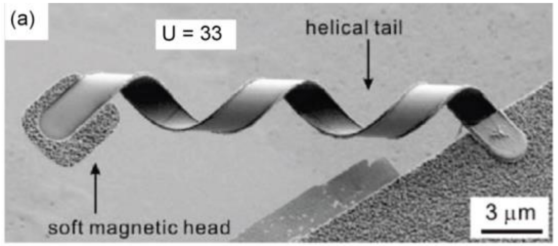

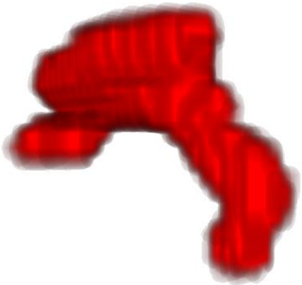

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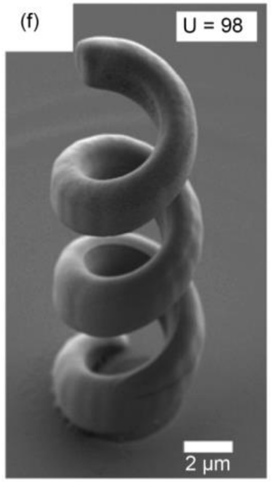

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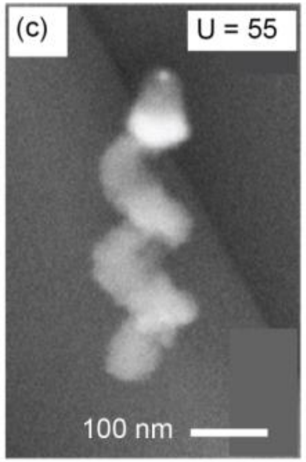

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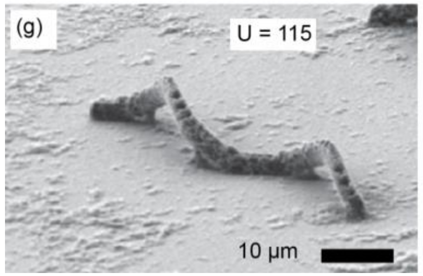
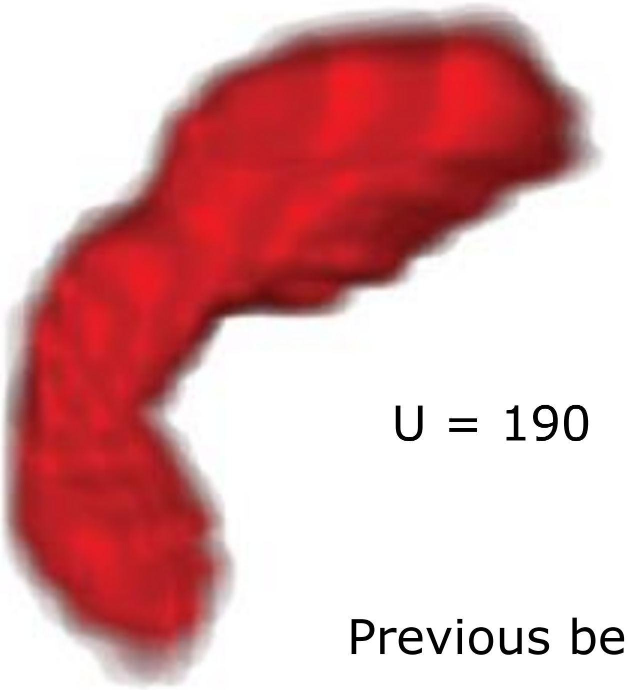


Vach et al., Nano Letters, 2015

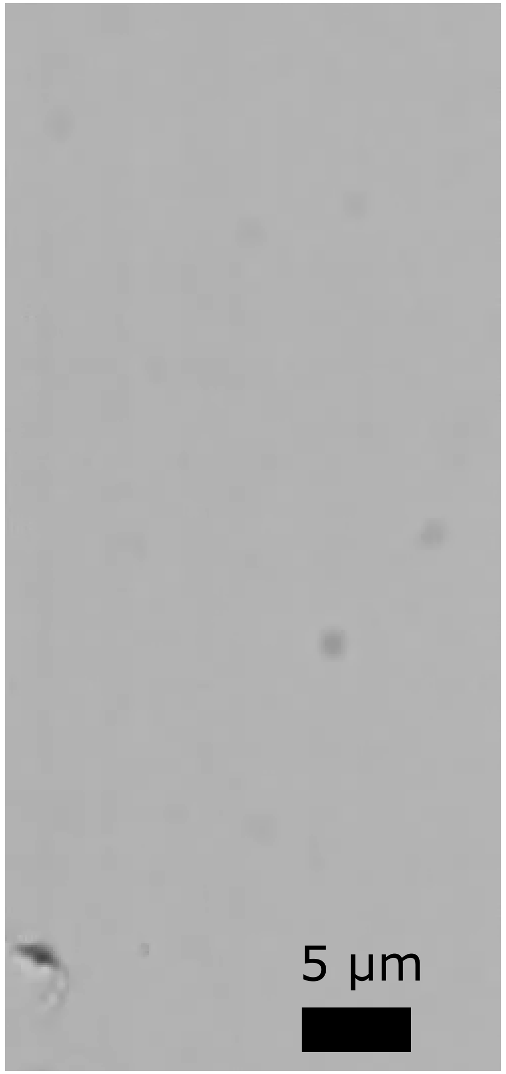
THE FASTEST ONE

Morphology and swimming speed



U = 190

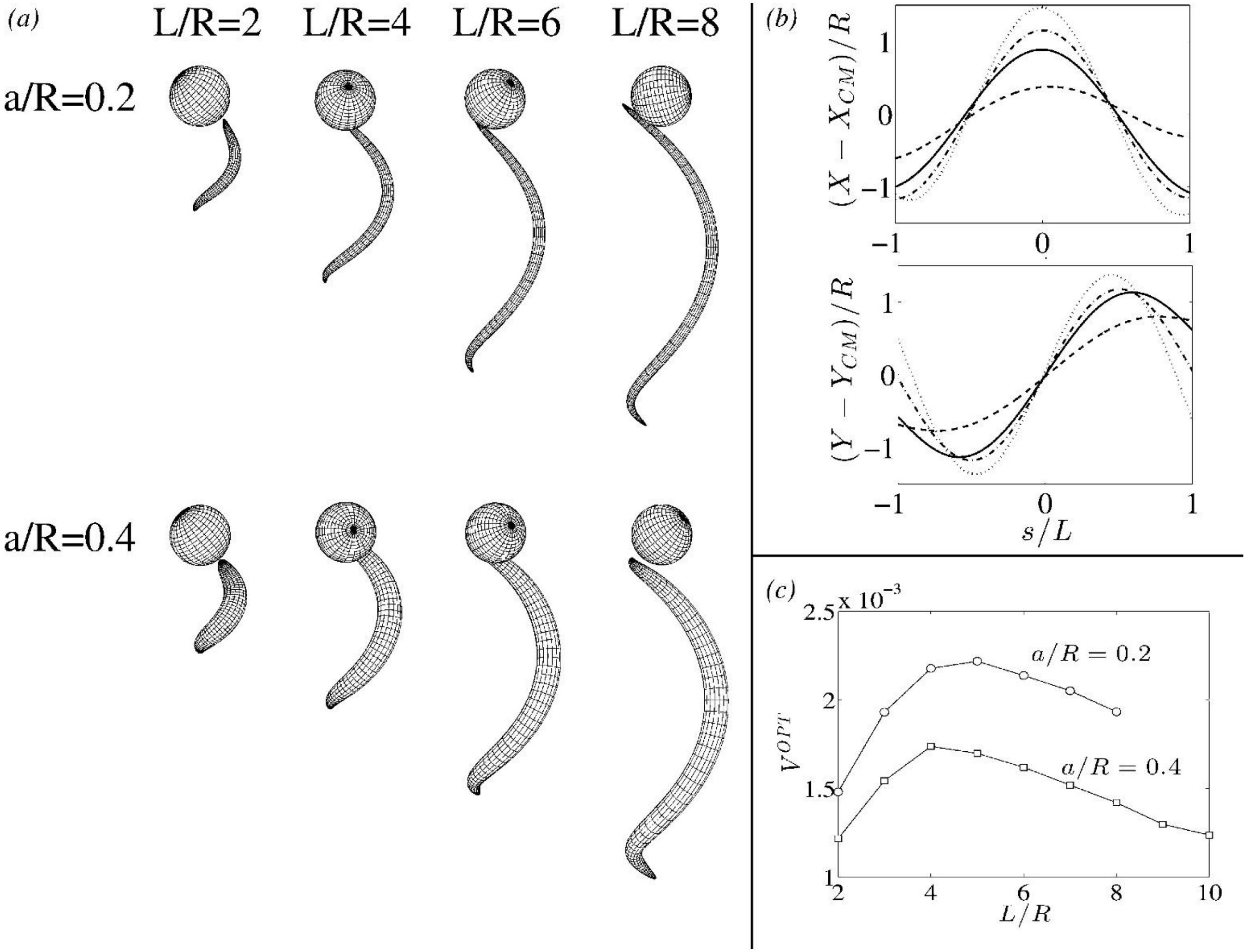
Previous best: U = 133



THE FASTEST ONE

Morphology and swimming speed

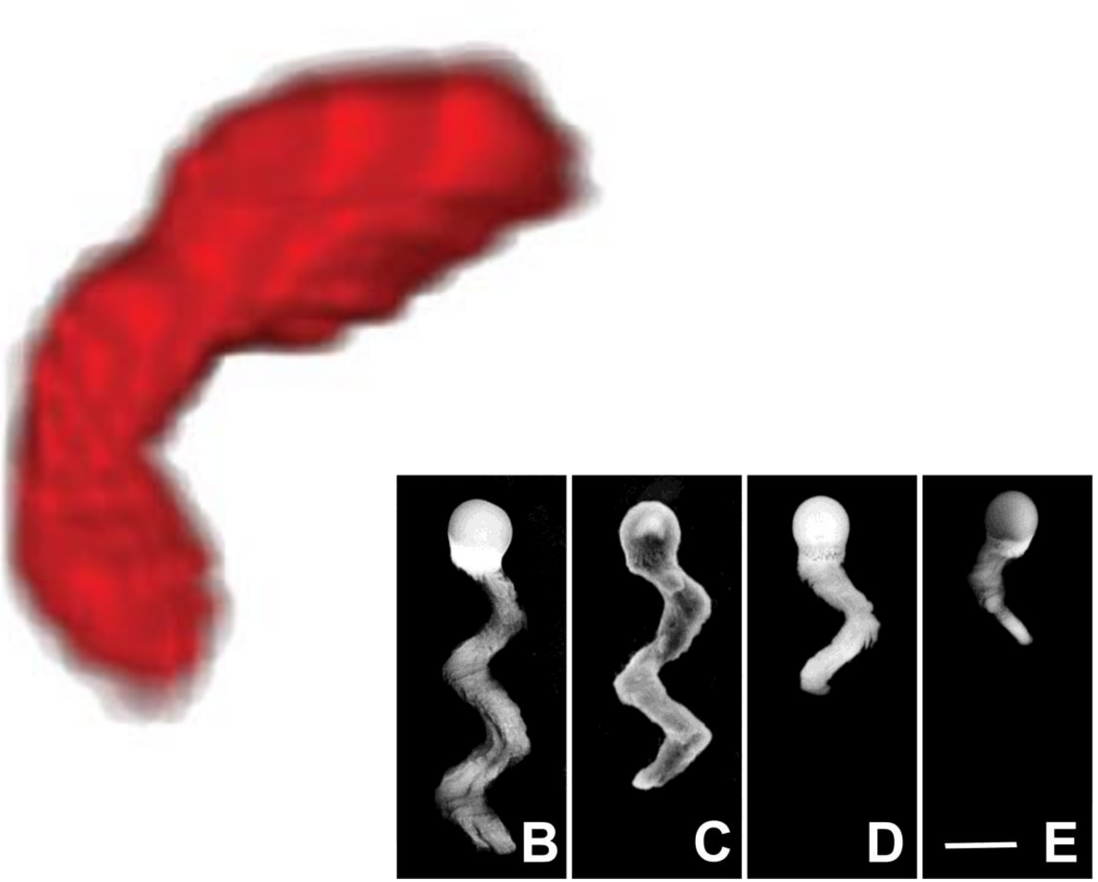
Vach et al., Nano Letters, 2015

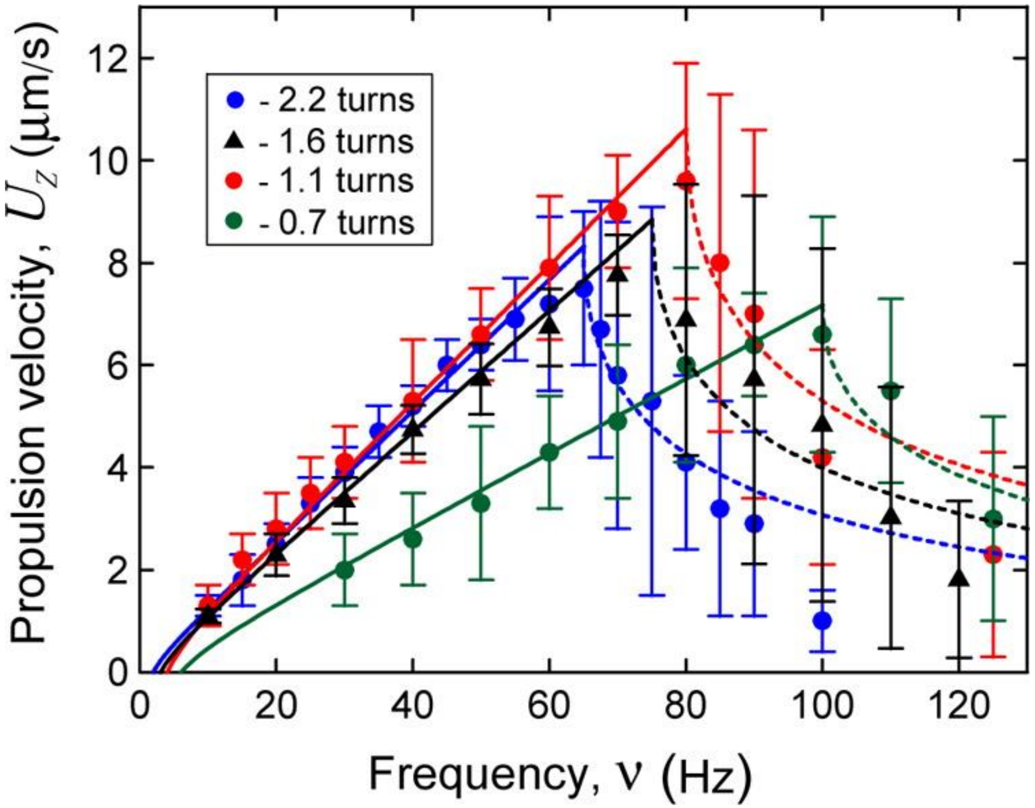


Keaveny et al., Nano Letters, 2013

THE FASTEST ONE

Morphology and swimming speed



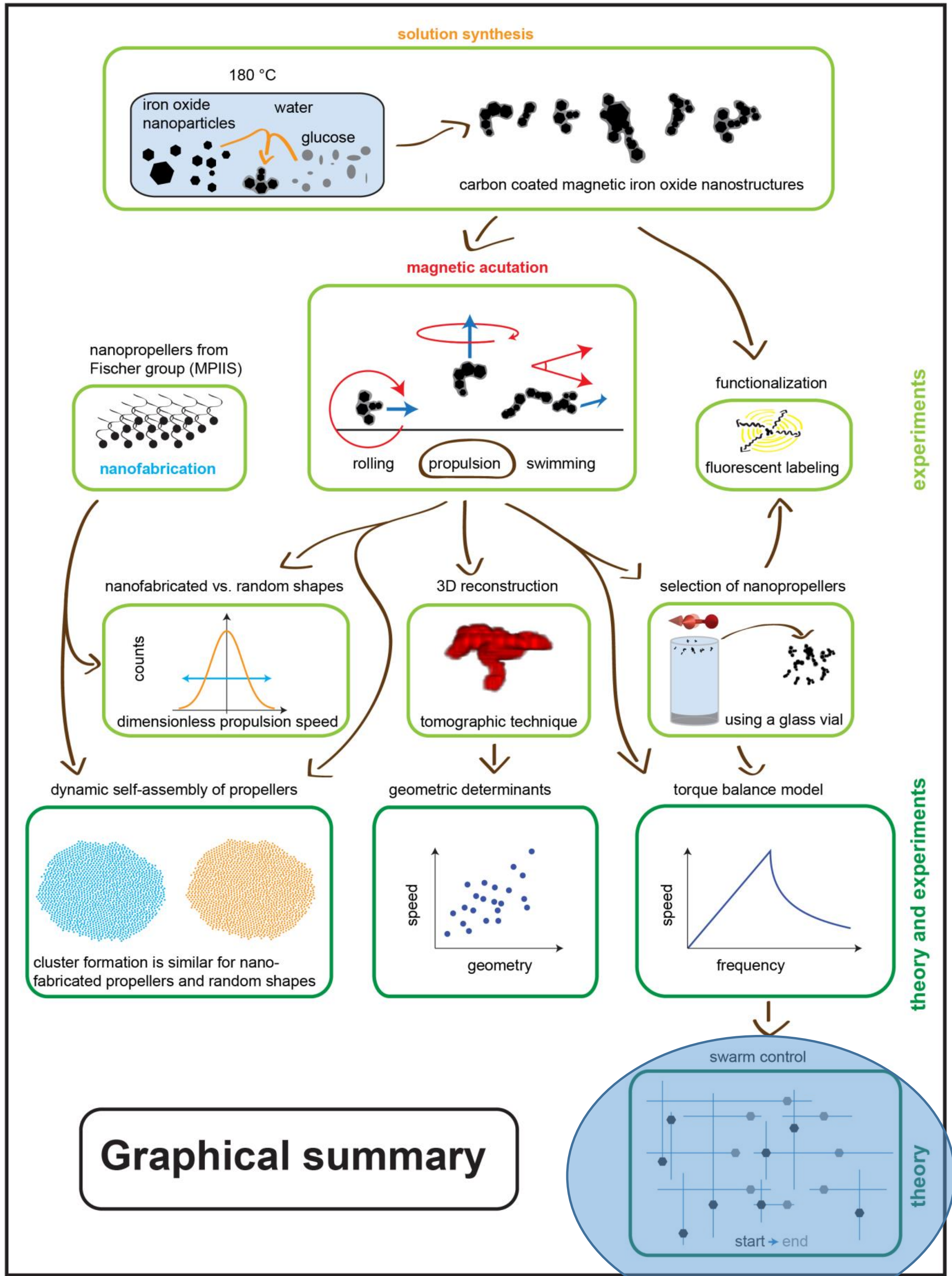


Vach et al., Nano Letters, 2015

Walker et al., Nano Letters, 2015

Original idea of / with Peter:

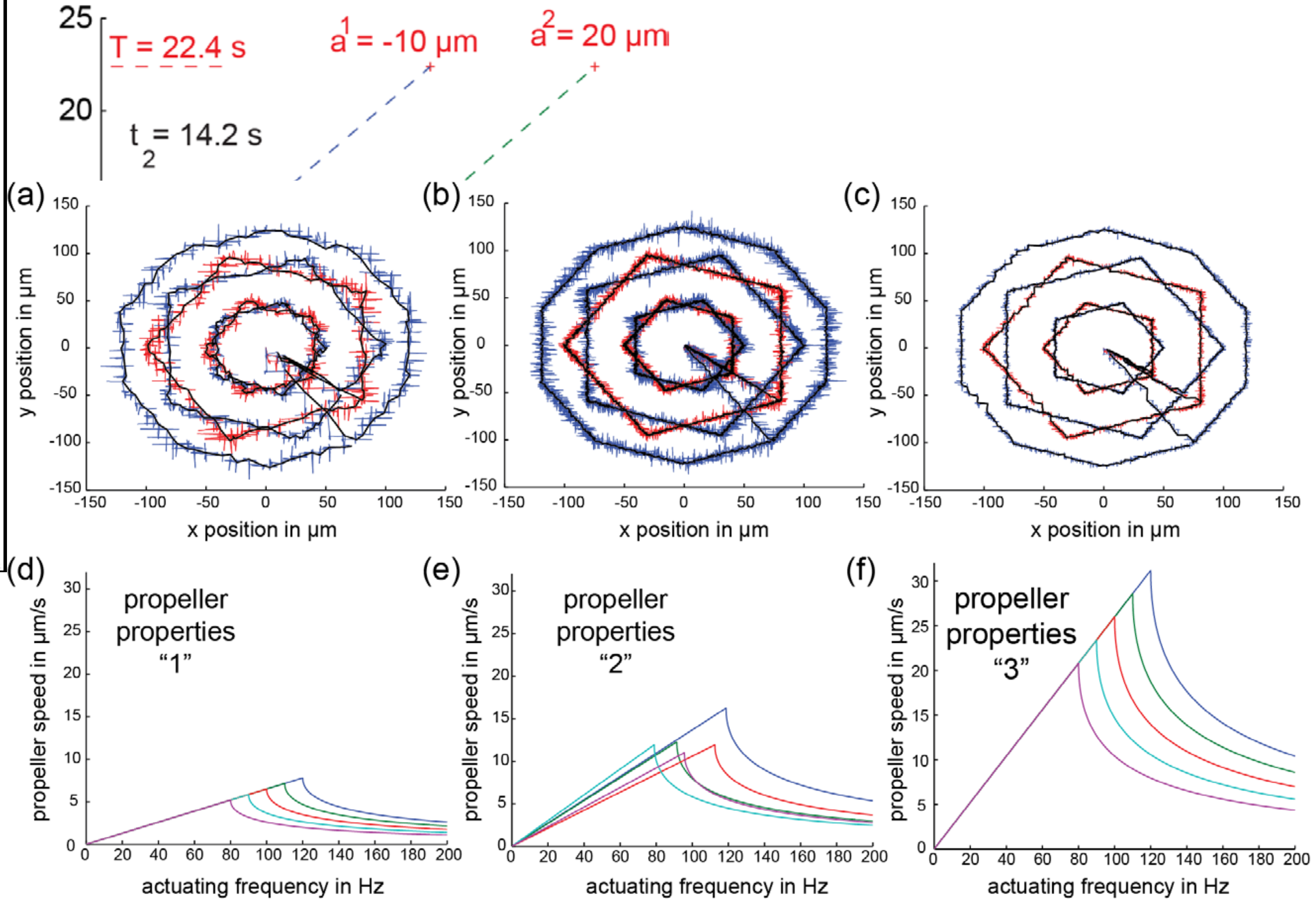
1. Show that basically anything can swim
2. Determine the morphological parameters responsible for the swimming
3. Study cluster formation



Graphical summary (conclusion) of Peter Vach's doctoral thesis

RANDOM SHAPE TO ACHIEVE MORE?

Steering along independent trajectories



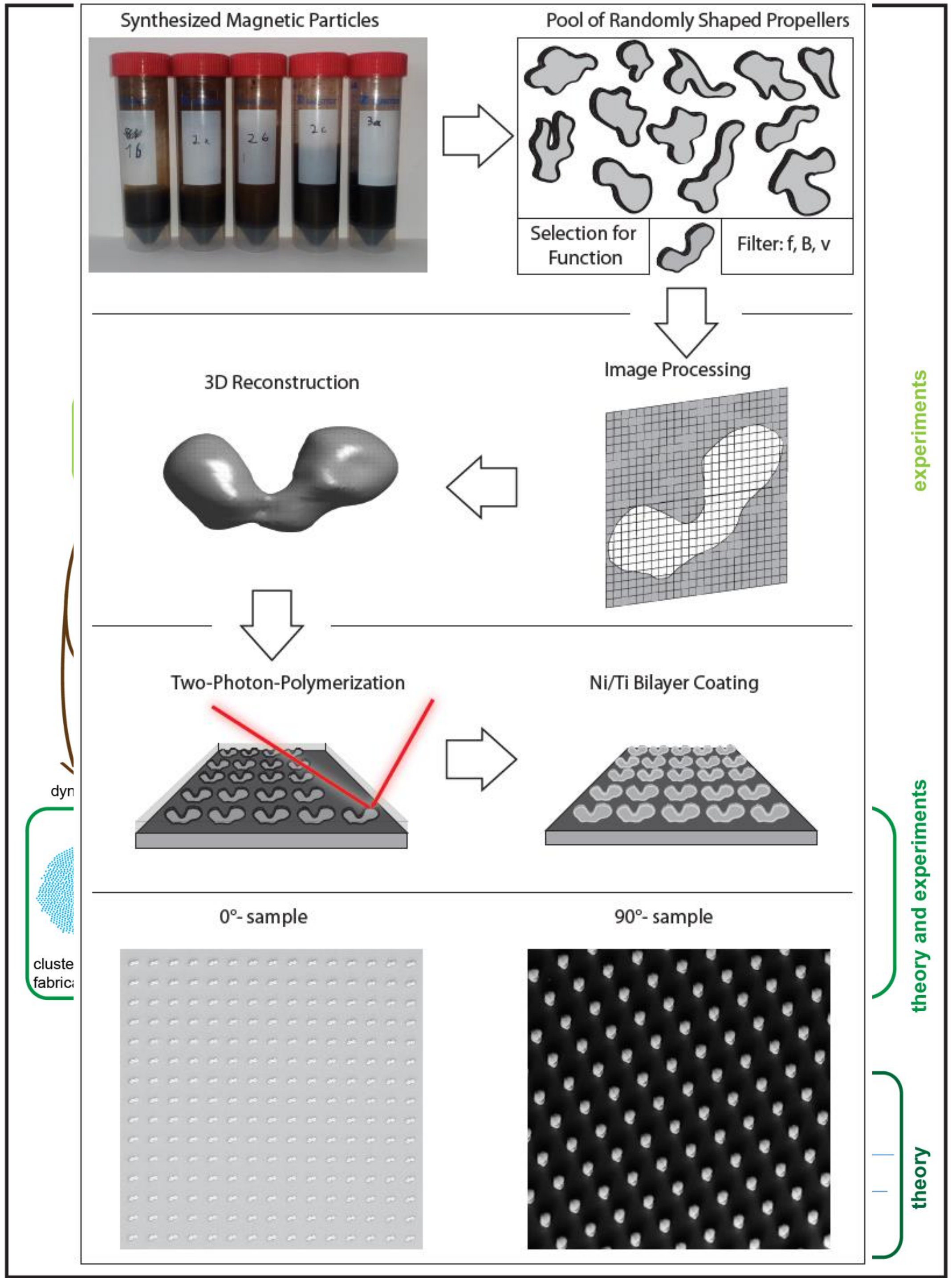
Vach et al., J. Phys. D.: Appl. Phys., 2016

Synthetic Magnetic Microswimmers

SELECTION FOR FUNCTION: FIRSD

Original idea of / with Peter:

1. Show that basically anything can swim
2. Determine the **morphological** parameters responsible for the swimming
3. Study cluster formation

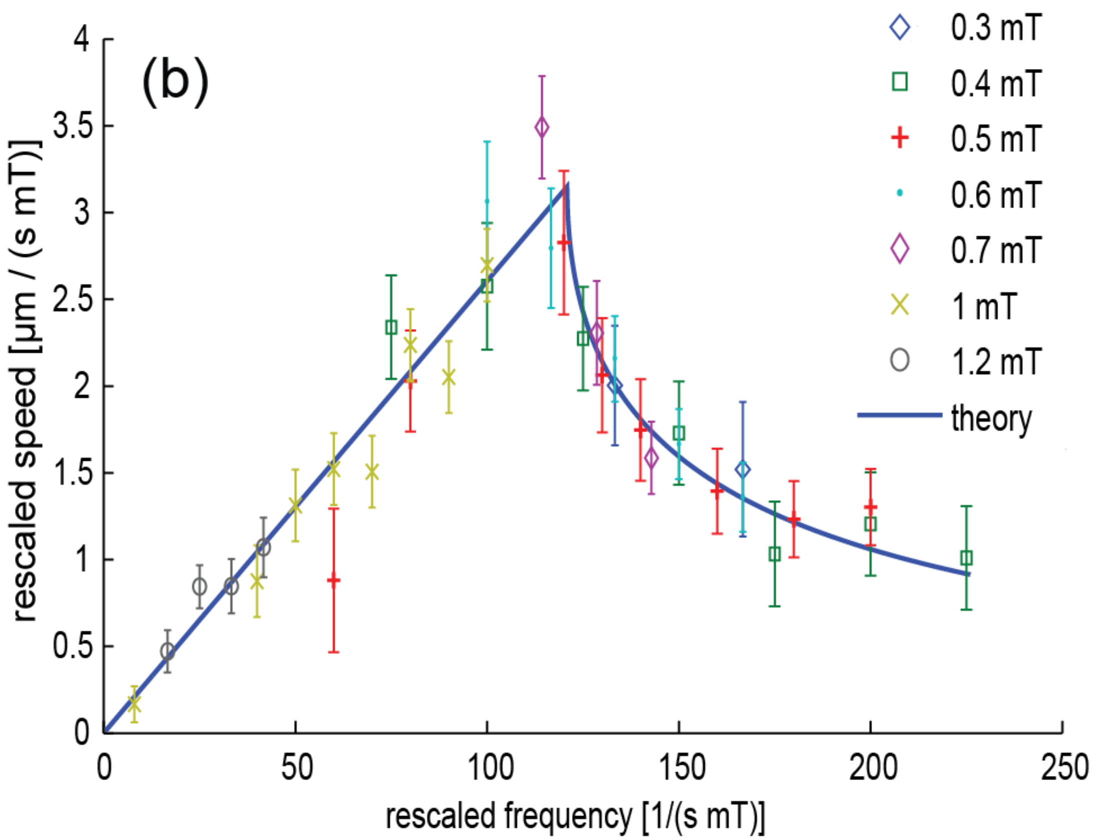


Original idea of Felix:

1. Determine the **general** parameters responsible for the swimming,
2. Determine if the propellers and their swimming properties can be reproduced by 3D printing

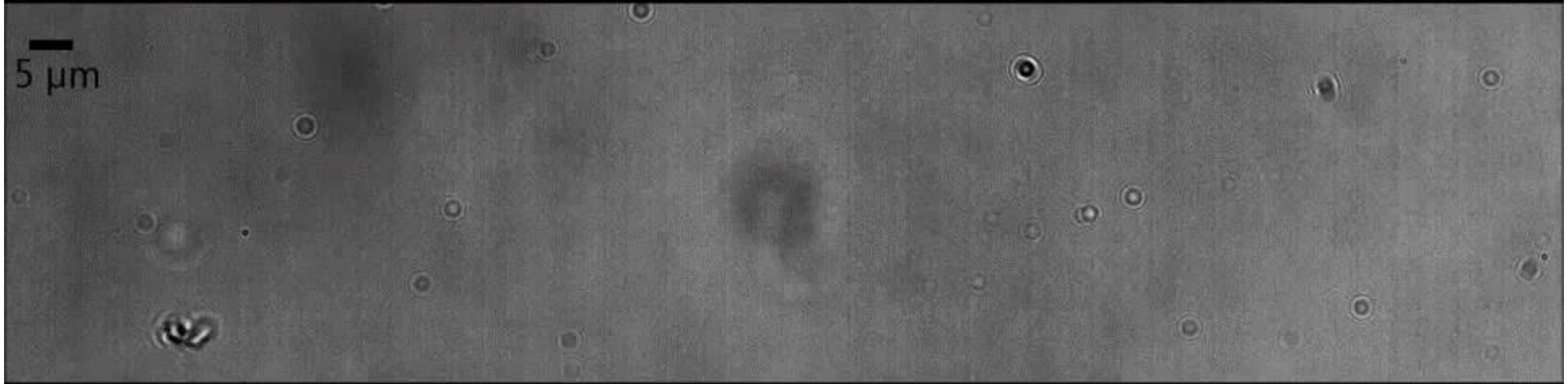
ADVANTAGES AND LIMITS OF THE SIMPLE DYNAMICS

A linear velocity-frequency function



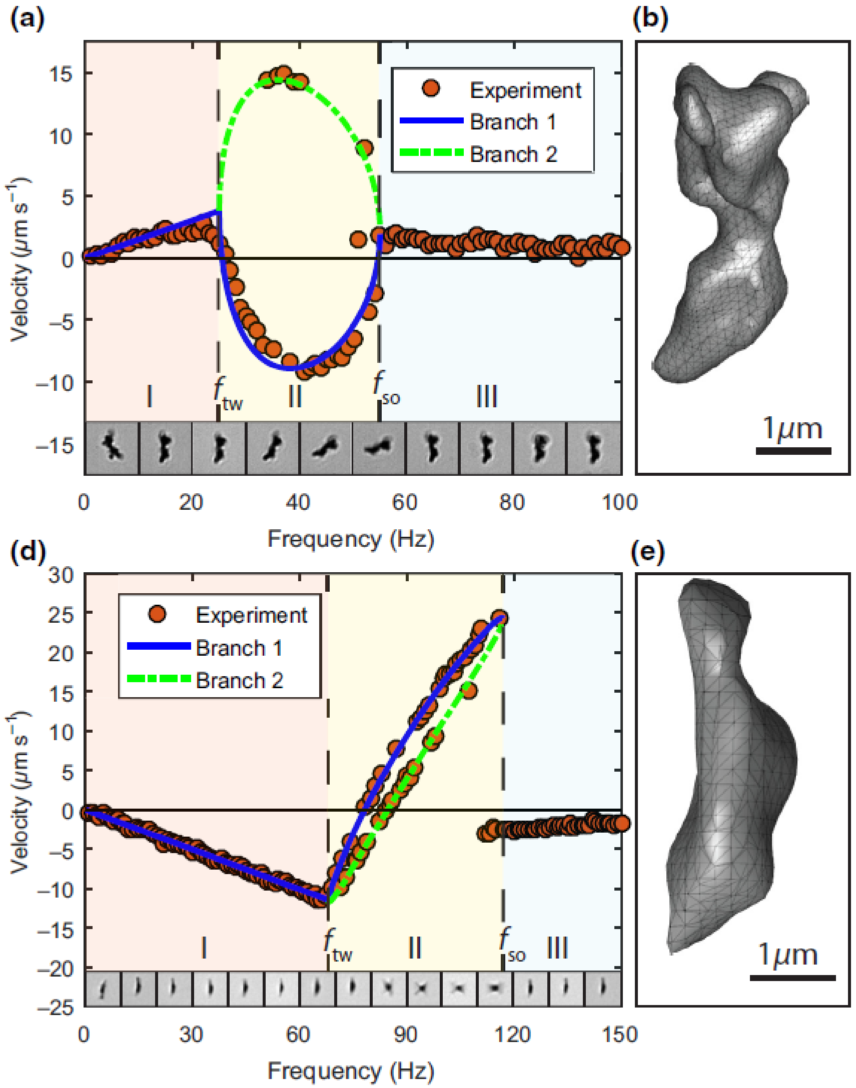
- The actuation strategy revolves around a simple linear relationship between the actuating field frequency and the propeller velocity.
- The simplicity of the linear relationship limits the possibilities and flexibilities of swarm control.

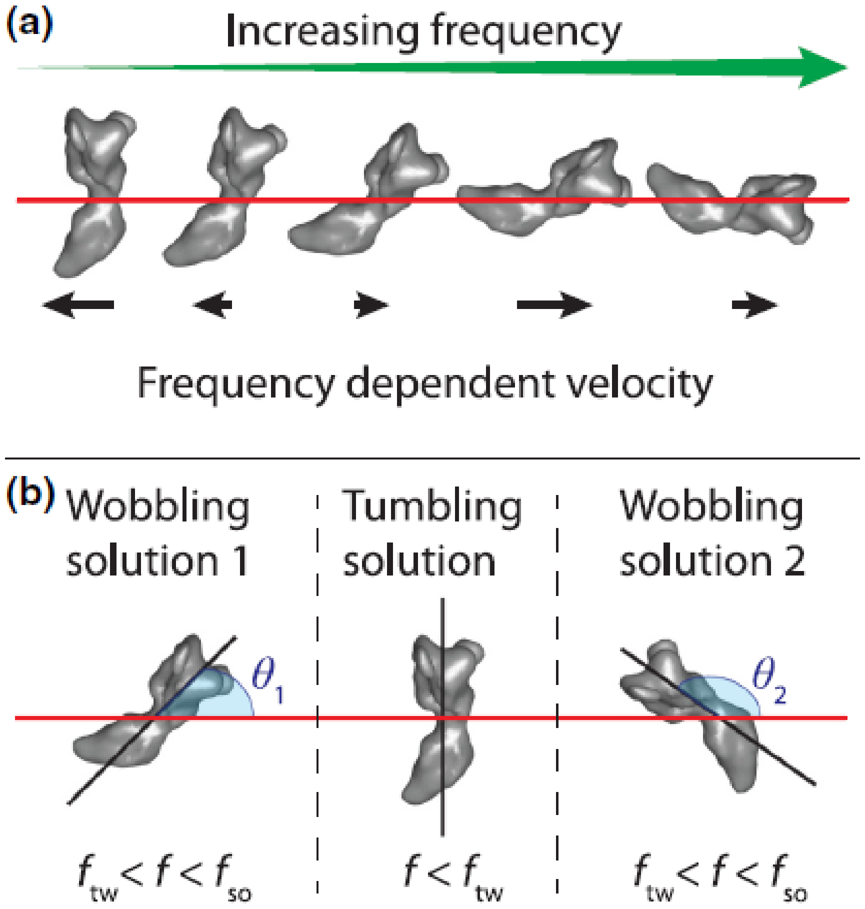
→ Can the complexity of shape be translated into enhanced control?


5 µm

A DYNAMICS RICHER THAN EXPECTED

A non linear velocity-frequency function

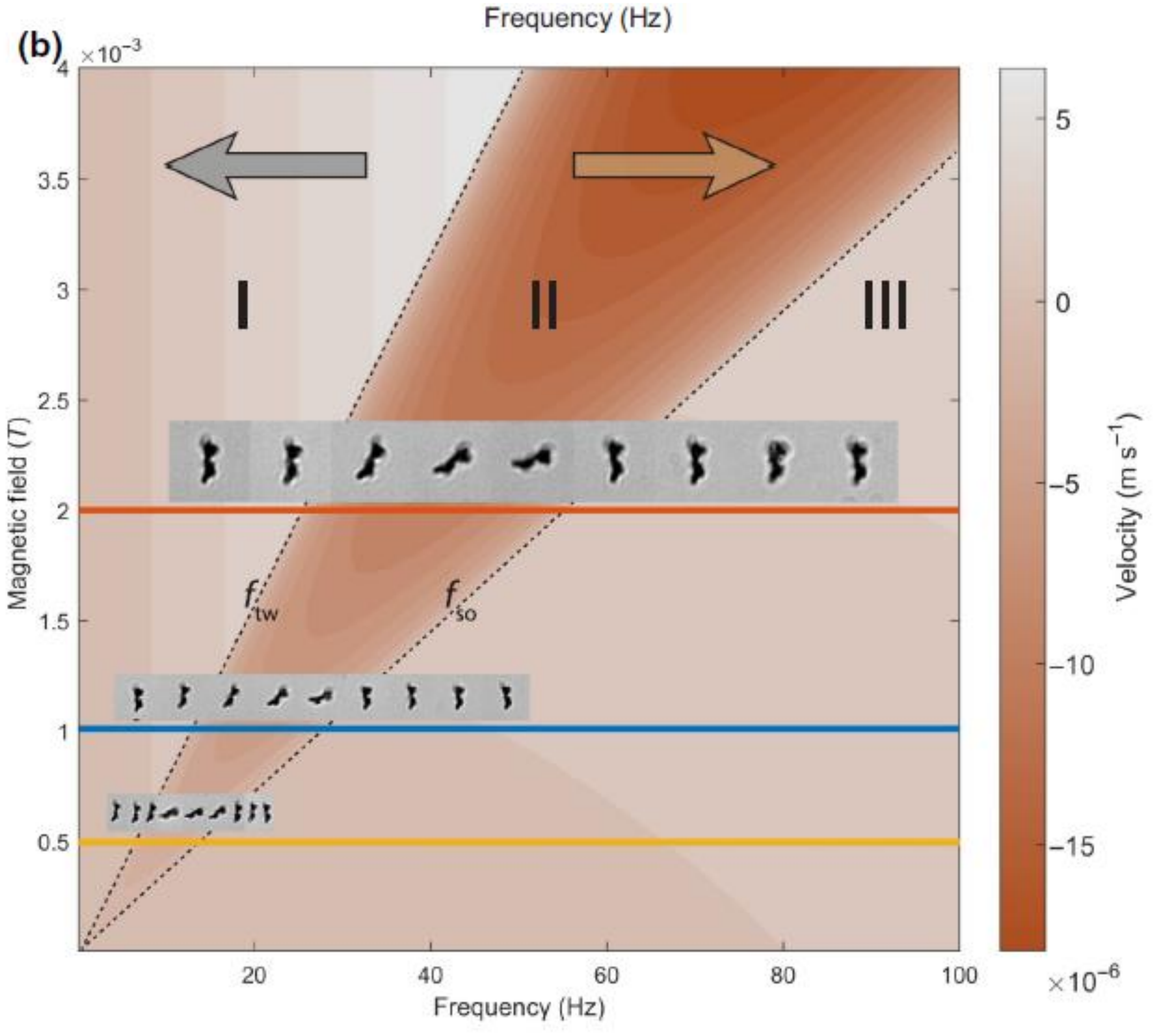




Bachmann et al., Phys. Rev. Appl., 2019

A DYNAMICS RICHER THAN EXPECTED

Frequency-induced reversal of swimming direction

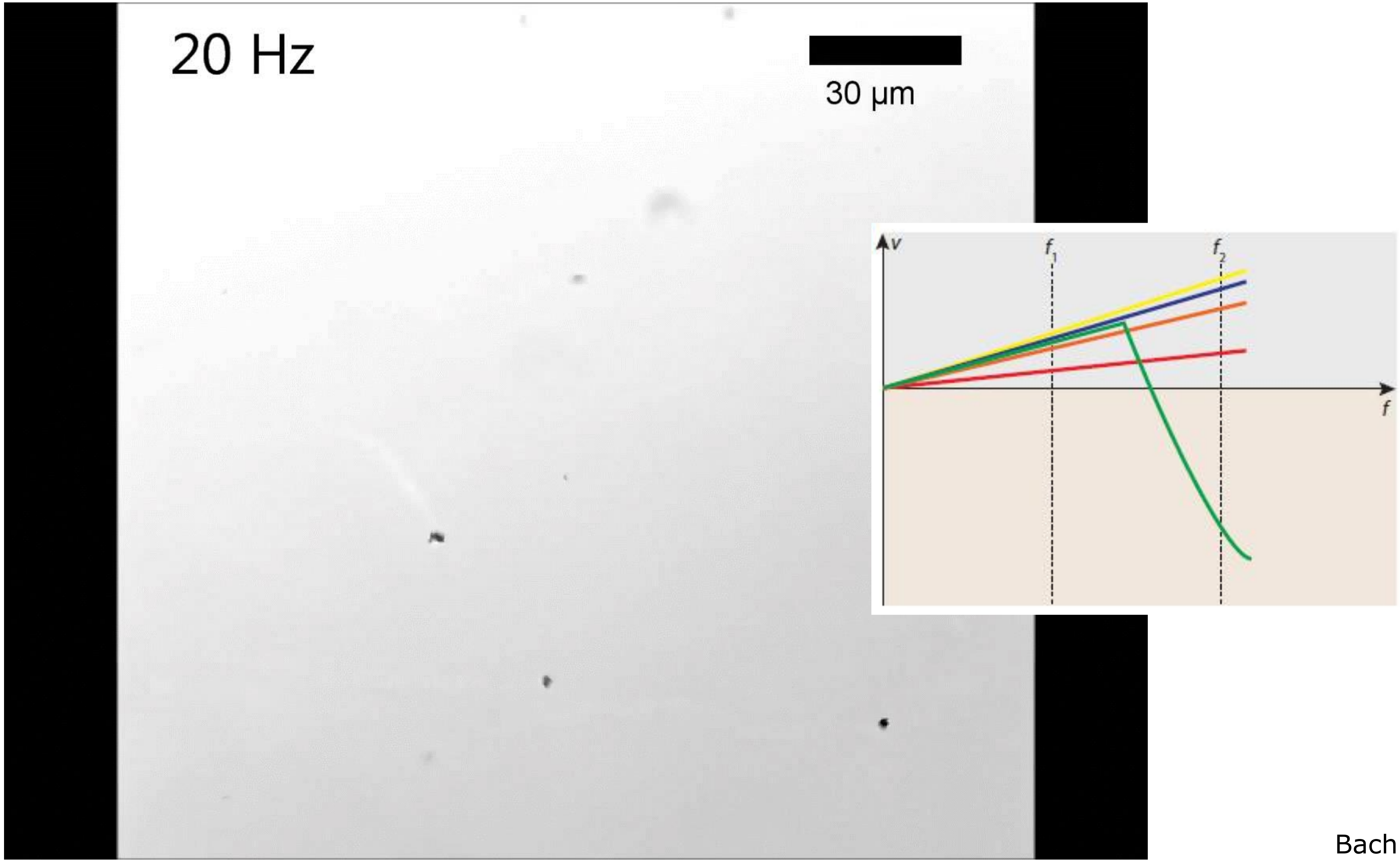


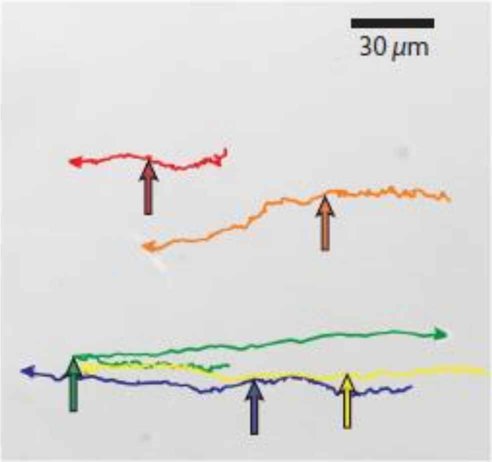
- I: linear regime
- II: wobbling regime
- III: after step out

Bachmann et al., Phys. Rev. Appl., 2019

FIRSD

A sorting mechanism





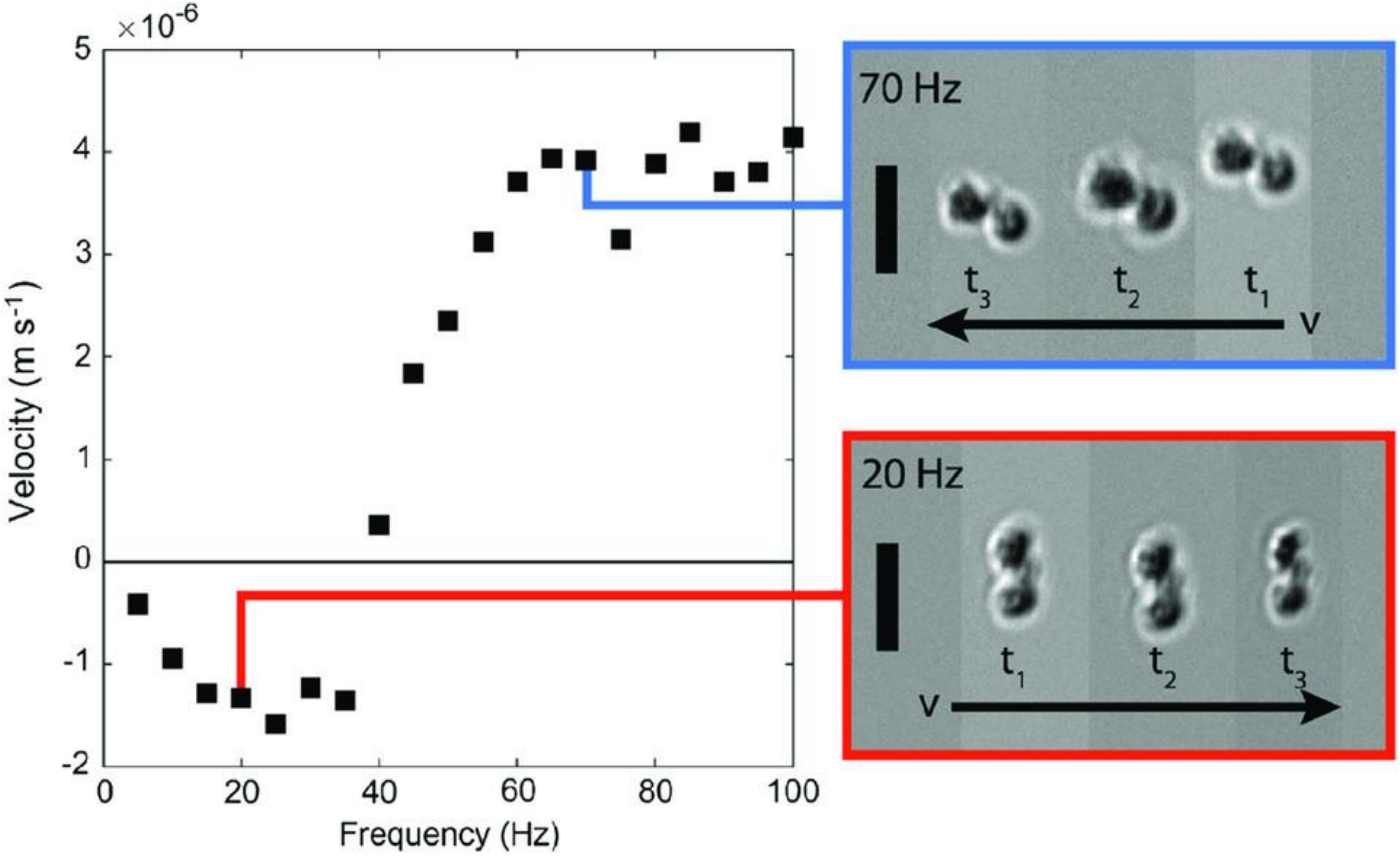
Bachmann et al., Phys. Rev. Appl., 2019

Synthetic Magnetic Microswimmers

CAN WE REPRODUCE THE FIRSD BEHAVIOR?

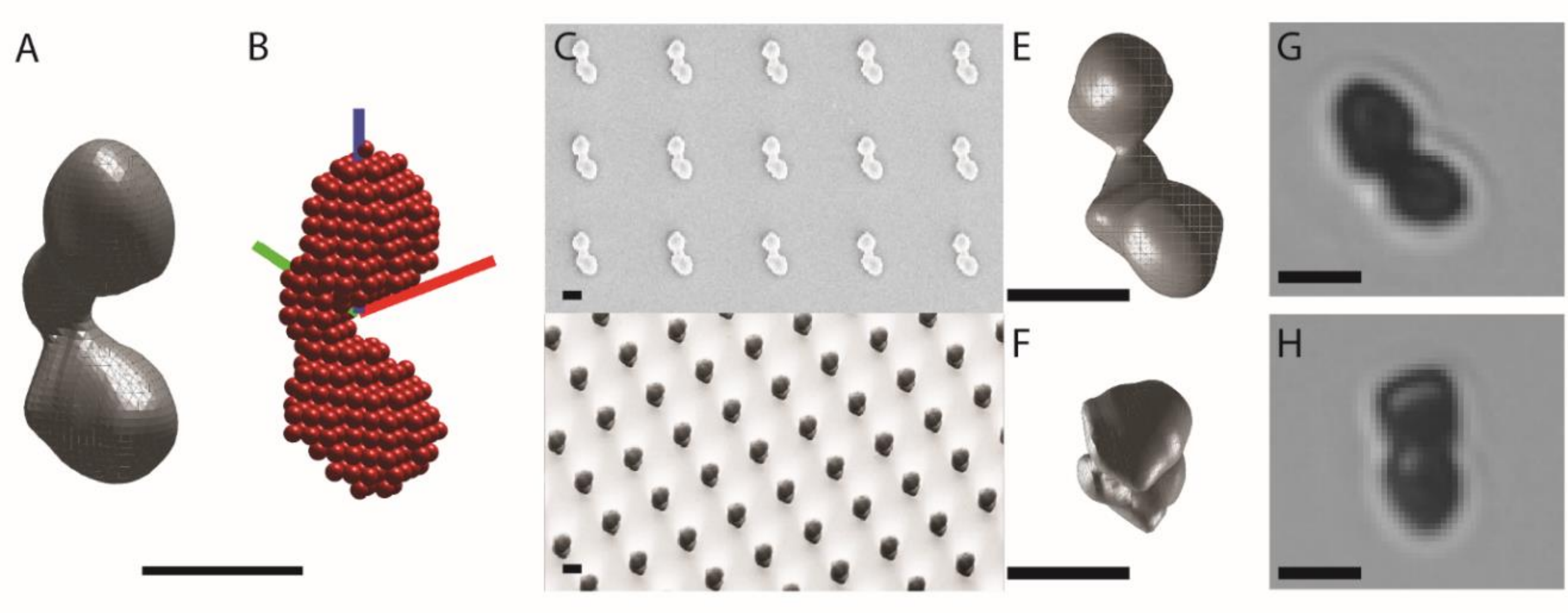
NON LINEAR SWIMMERS

The original behavior



NON LINEAR SWIMMERS

Leaving random by 3D printing

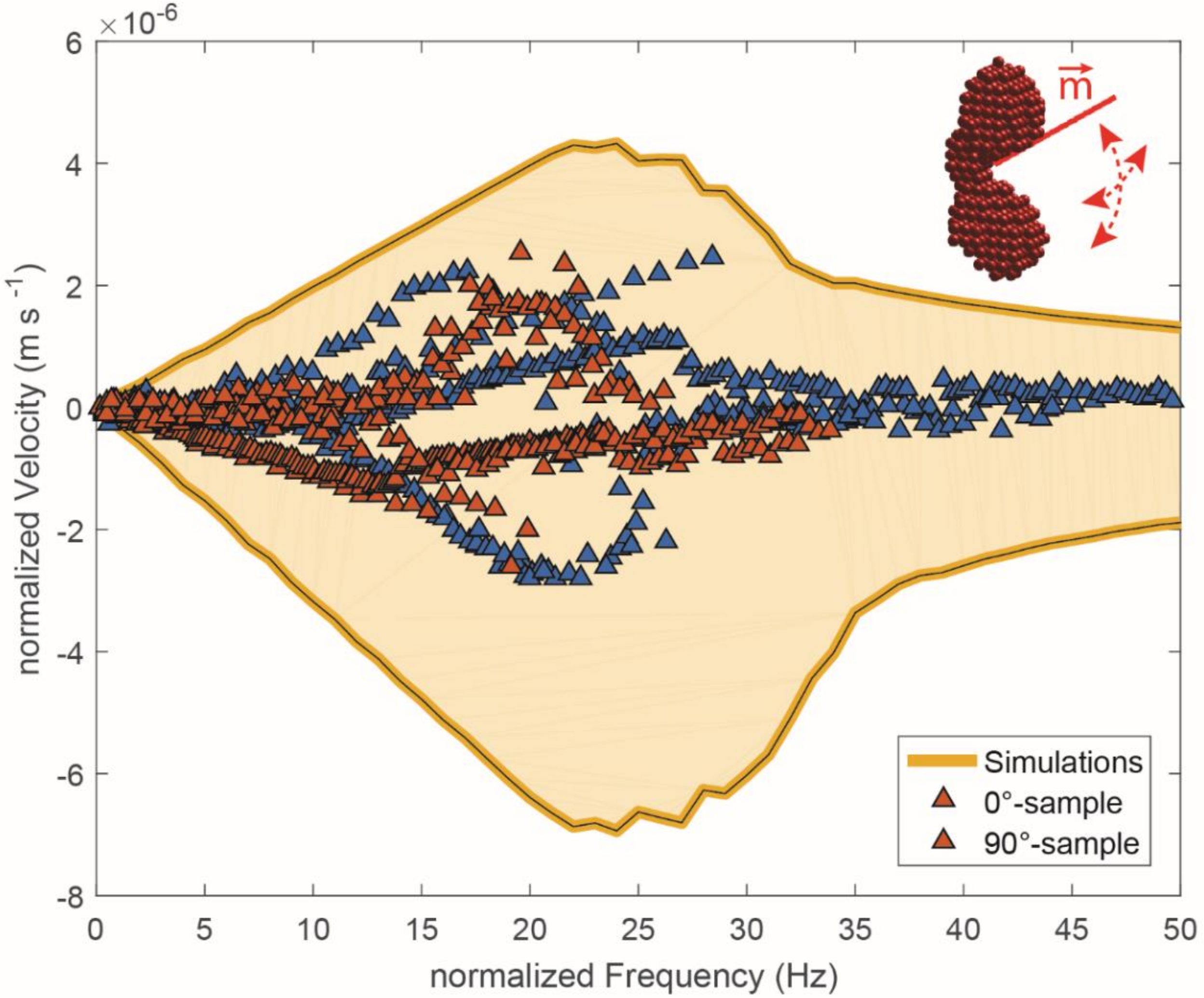


- The morphology of a FIRST swimmer can be reproduced by 3D printing

Bachmann et al., Adv. Intel. Syst., 2020

3D PRINTED MICROSWIMMERS

An unexpected dynamics due to varying magnetic properties



- The identically shaped swimmers do not only display the FIRSD swimming property
- The 3D printed device also exhibit a variety of swimming behaviors
- The differences arise from variation in the magnetic moment orientations.

→ This underlines not only the role of shape in microswimmer behavior but also the importance of determining magnetic properties of future micropropellers

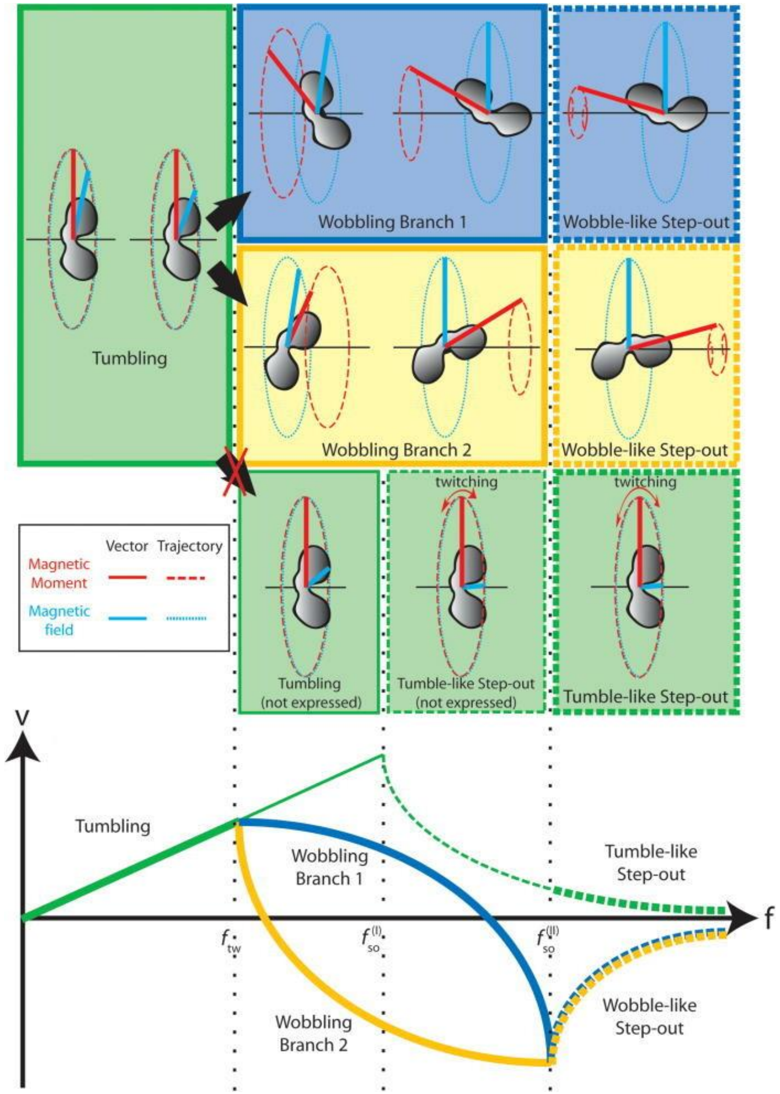
Bachmann et al., Adv. Intel. Syst., 2020

Synthetic Magnetic Microswimmers

CAN WE INFLUENCE A BEHAVIOR?

THE RICH LANDSCAPE OF PROPELLER’S BEHAVIOR

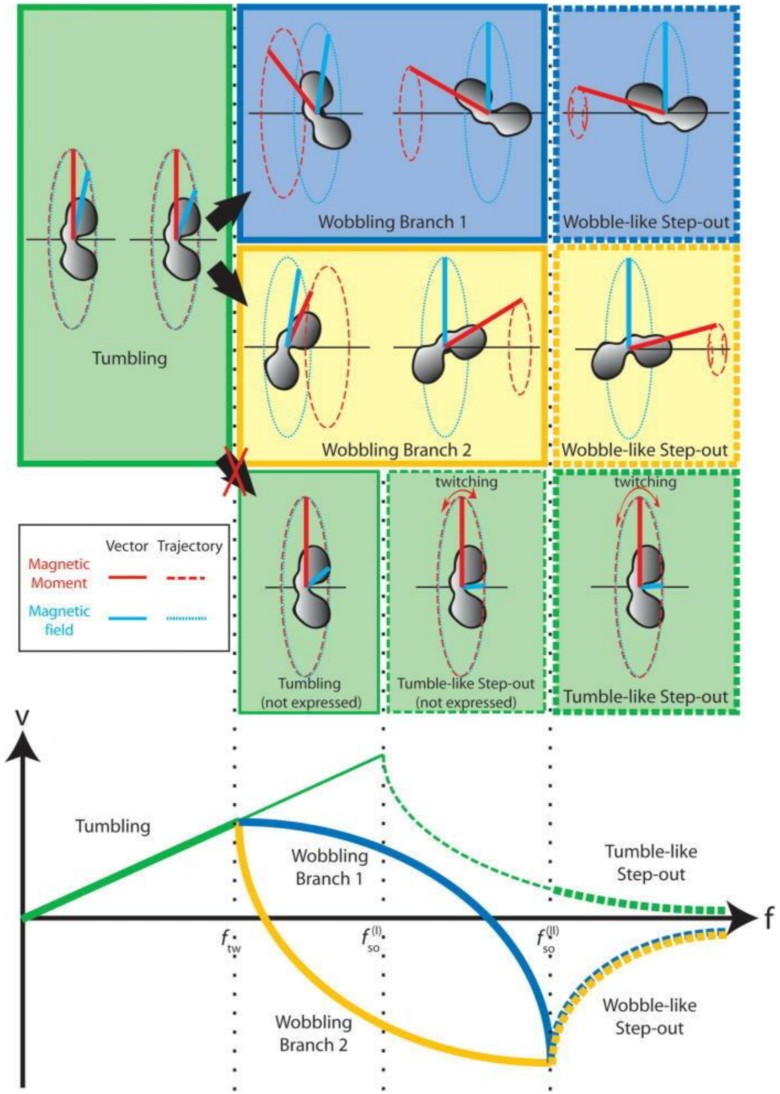
The original behavior



- At low frequencies, a tumbling motion occurs (green “Tumbling” box), where the magnetic moment (red line) follows the externally applied field (light blue line) on a circular rotation. Increasing frequency only increases the angle between these two vectors. The result is a linear slope in the velocity–frequency graph (green bold line).
- At the transition frequency f_{tw}, two wobbling branches occur, where the propeller changes its rotation axis to decrease its rotational friction, and thus, the magnetic moment moves out of the magnetic field plane. There are two possible scenarios for this to happen (blue and yellow “Wobbling branch” boxes). This process is energetically favorable compared to further following a tumbling motion with an increased angle between the magnetic moment and the magnetic field [bottom green “Tumbling (not expressed)” box

THE RICH LANDSCAPE OF PROPELLER’S BEHAVIOR

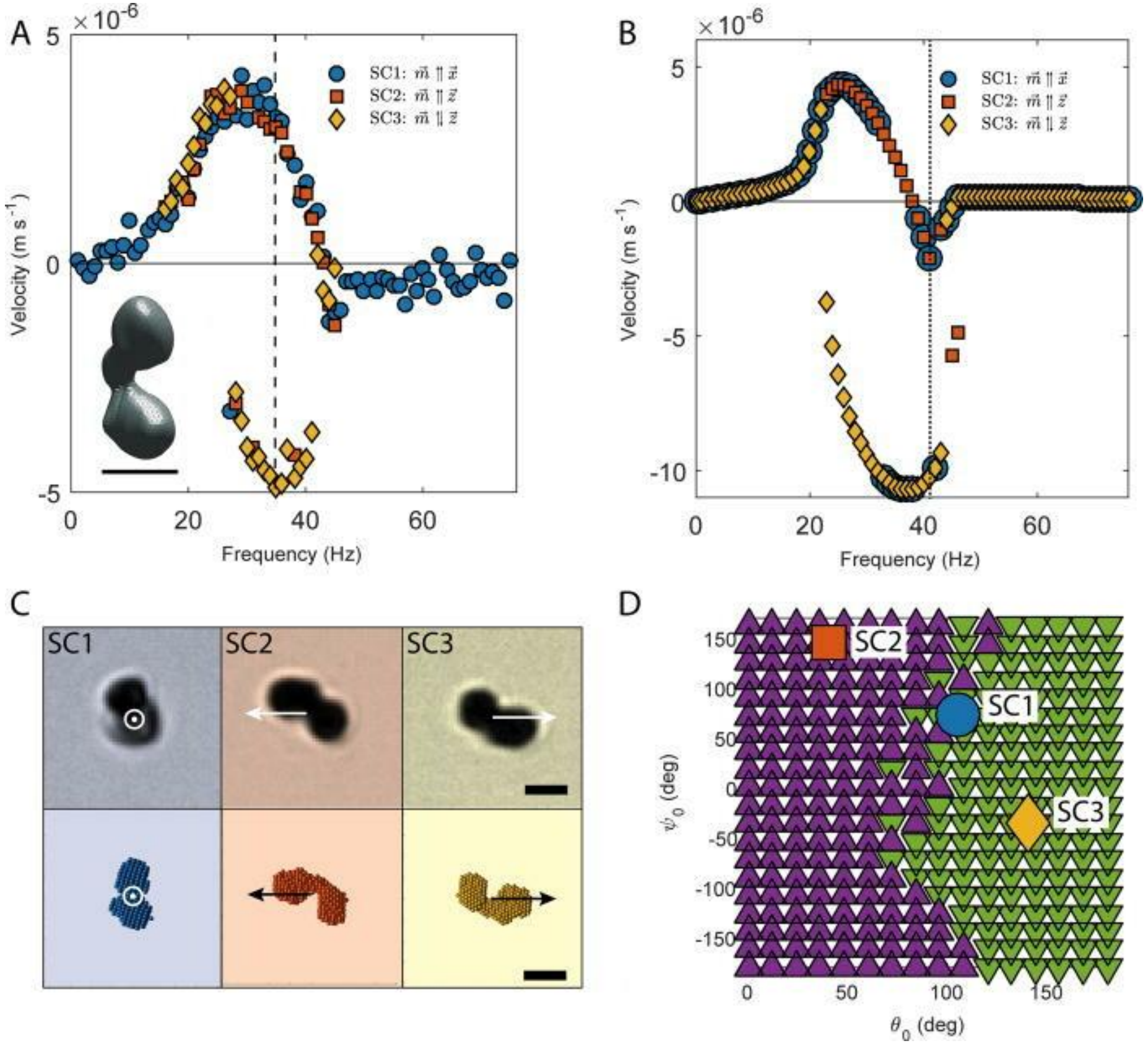
The original behavior



- At a certain frequency $f^{(I)}_{so}$, this not expressed tumbling behavior would result in a twitching step-out motion since the propeller can no longer follow the magnetic field through tumbling and the velocity would decrease, even for increasing field frequency [bottom green “Tumble-like step-out (not expressed)” box].
- At a secondary step-out frequency $f^{(II)}_{so}$, it is not possible to maintain the hydrodynamic/magnetic torque balance, even for the wobbling solutions. As a result, a wobble-like step-out behavior occurs. As we show, the propeller rotates then on a trajectory with three-dimensional compensation loops (yellow and blue dashed boxes and lines). Additionally, we found that the tumble-like step-out behavior can also be expressed after f(II)so (green dashed bold line).

INFLUENCING THE BRANCHING BEHAVIOR

Different starting conditions

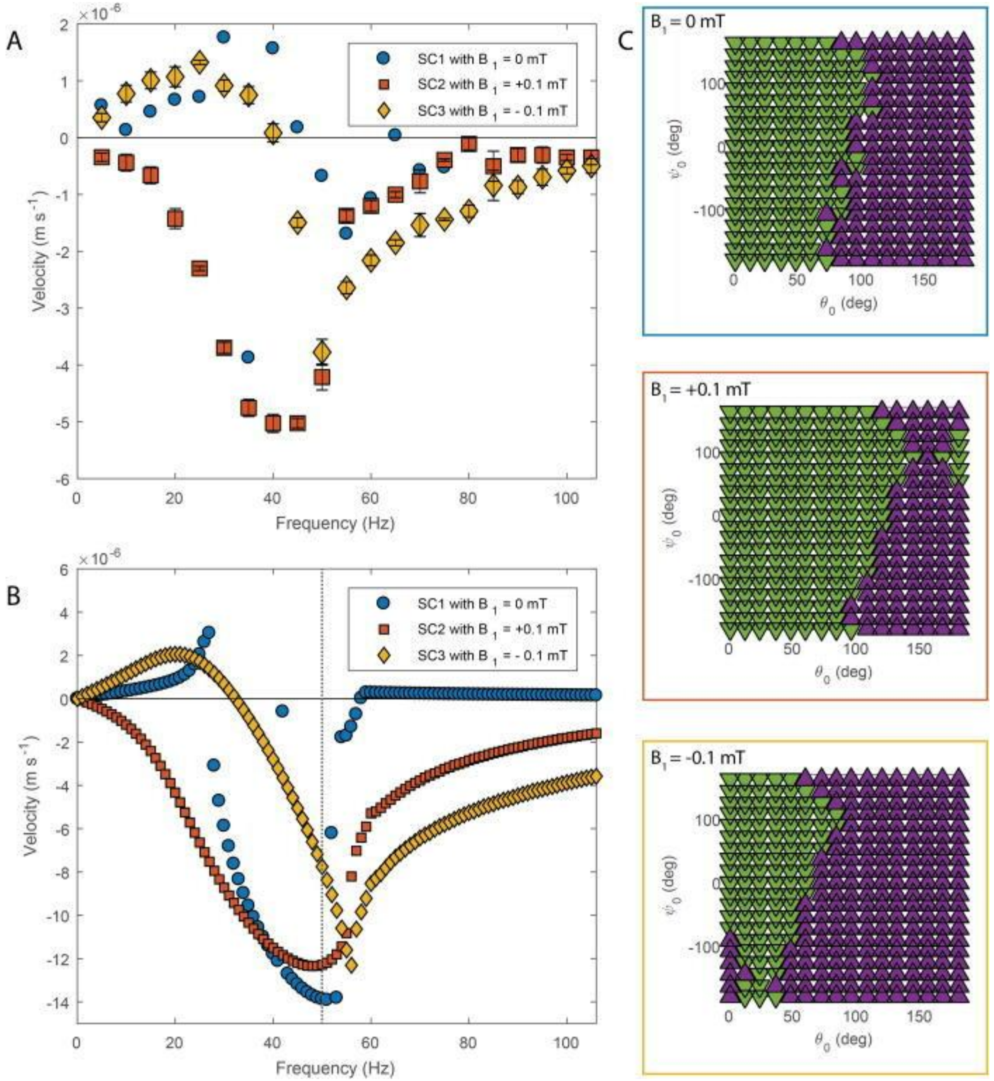


- A experimental and B simulated data showing different branching behavior for the different starting conditions (seen in C).
- D: Dependency of branching on the starting values θ_0 and ψ_0 at $f = 41$ Hz (dotted line in b): purple upward-pointing triangles represent the continuous upper branch (higher velocity) and green downward-pointing triangles the secondary lower branch (lower velocity)

Bachmann et al., Appl. Phys. Lett., 2021

INFLUENCING THE BRANCHING BEHAVIOR

Adding a component to the field



- A experimental and B simulated data using an additional constant field of $B_1 = +0.1$ mT and $B_1 = -0.1$ mT (red squares and yellow diamonds, respectively, standard error of the mean with n = 3). As a reference, the same propeller was measured without a constant field component (blue circles, $B_1 = 0$ mT)
- C is the phase diagram of branch assignment over the starting condition (”upper branch”: purple upward-pointing triangles; “lower branch”: green downward-pointing triangles; at f = 50 Hz, dotted line in B)

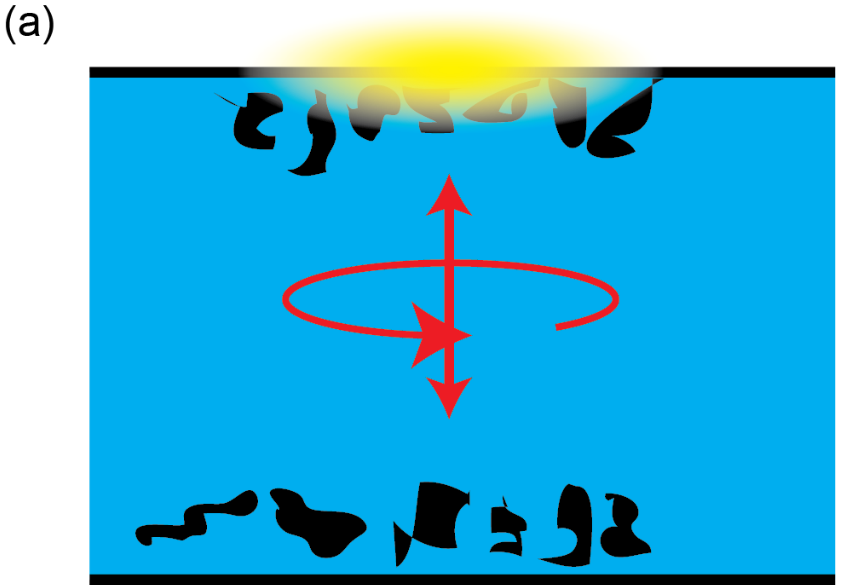
Bachmann et al., Appl. Phys. Lett., 2021

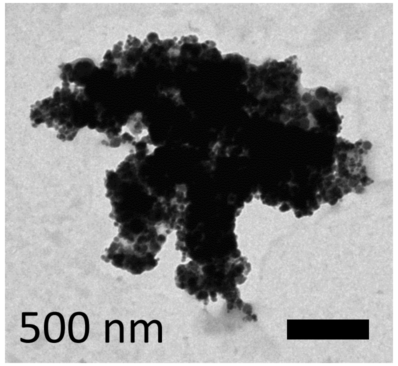
Swimming together

SYNTHETIC CLUSTERS

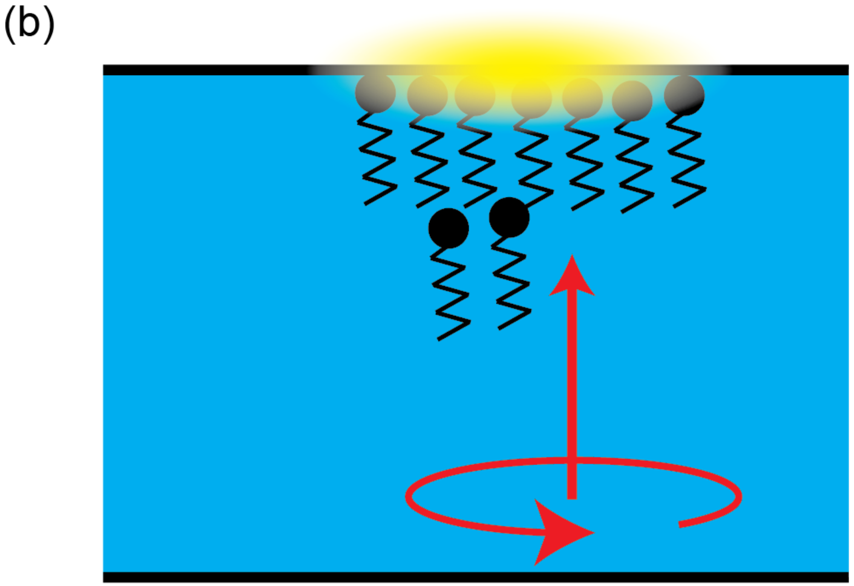
COLLECTIVE BEHAVIOR

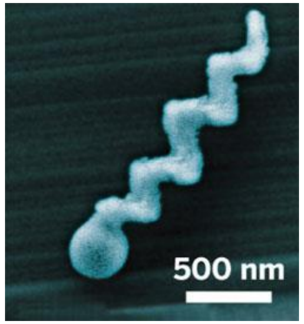
Random vs. helices





Vach et al., Nano Letters, 2013

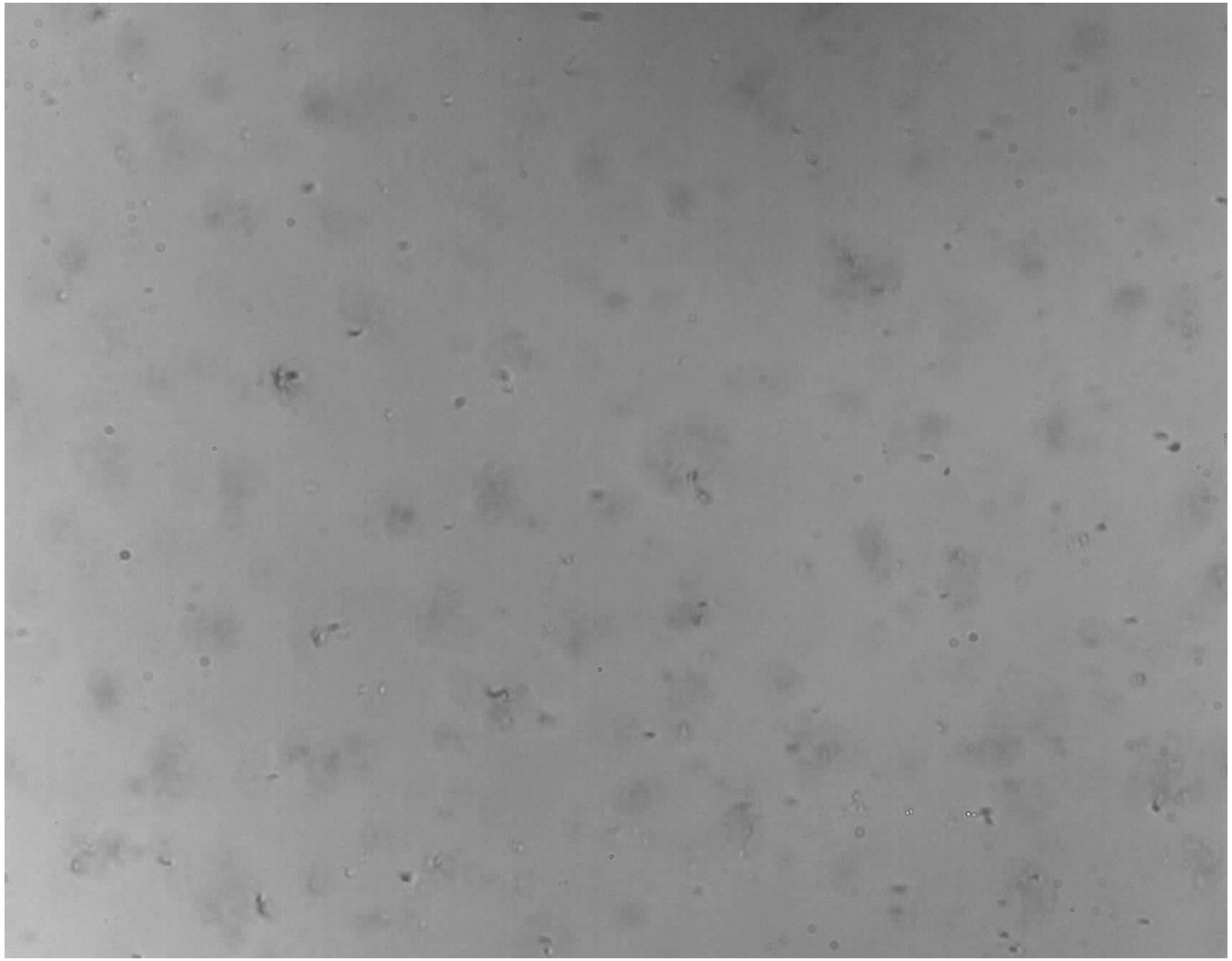




Ghosh & Fischer Nano Letters, 2009

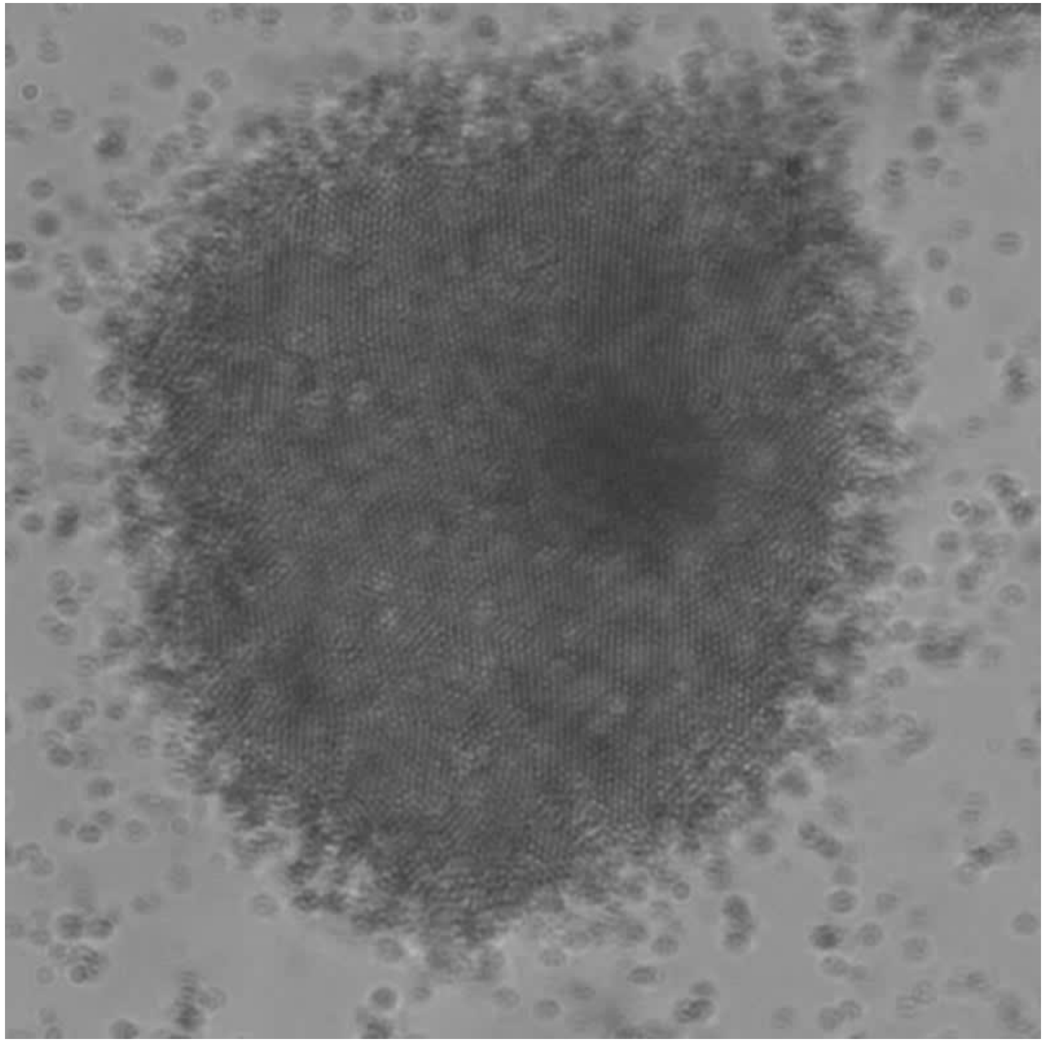
COLLECTIVE BEHAVIOR

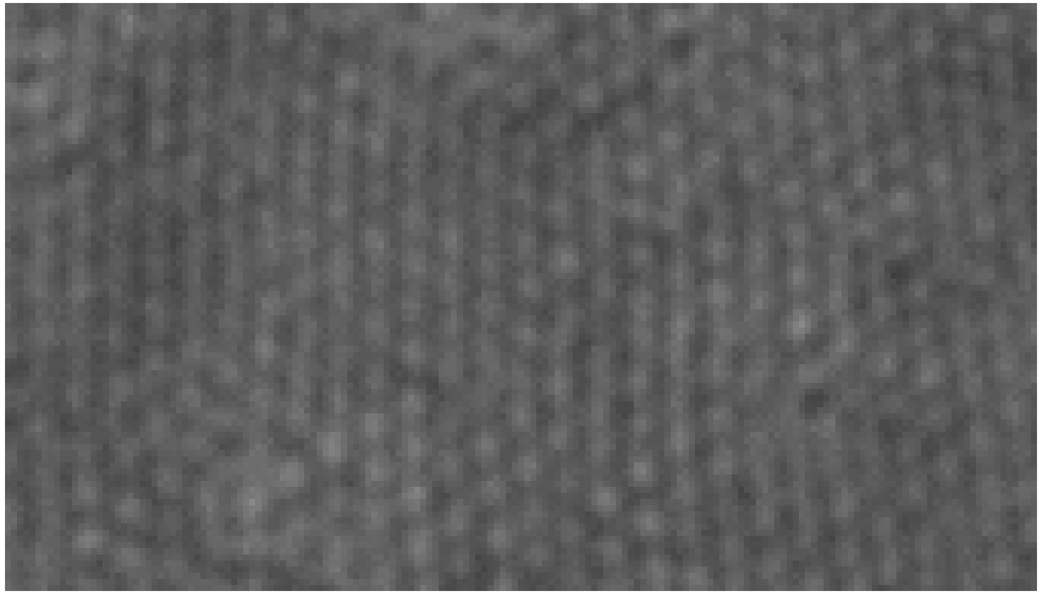
Random



COLLECTIVE BEHAVIOR

Helices



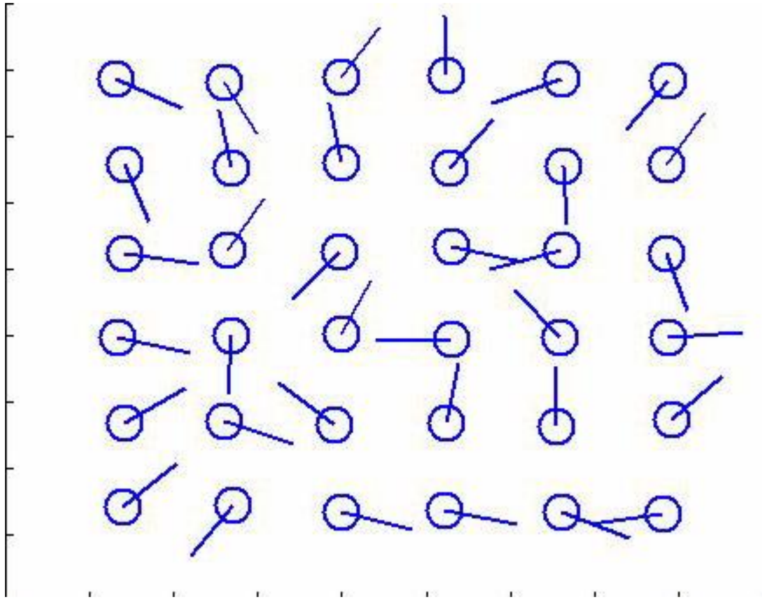


- Hexagonal patterns are formed

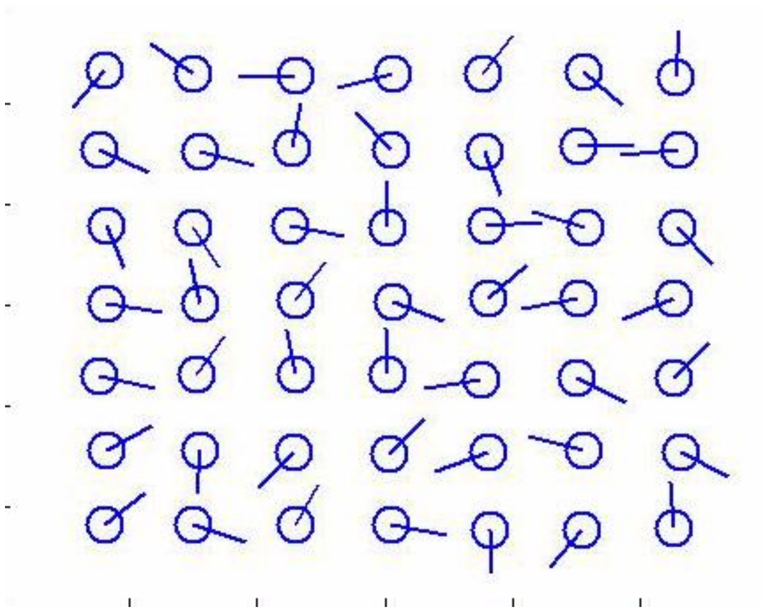
Vach et al., J. Phys. D.: Appl. Phys., 2017

COLLECTIVE BEHAVIOR

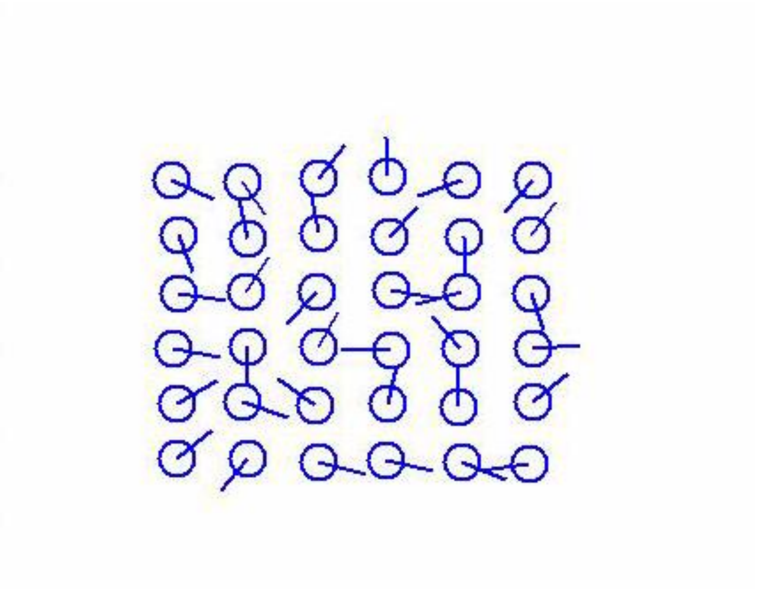
Simulation of cluster formation



low frequencies (3 Hz)



intermediate frequencies (40 Hz)

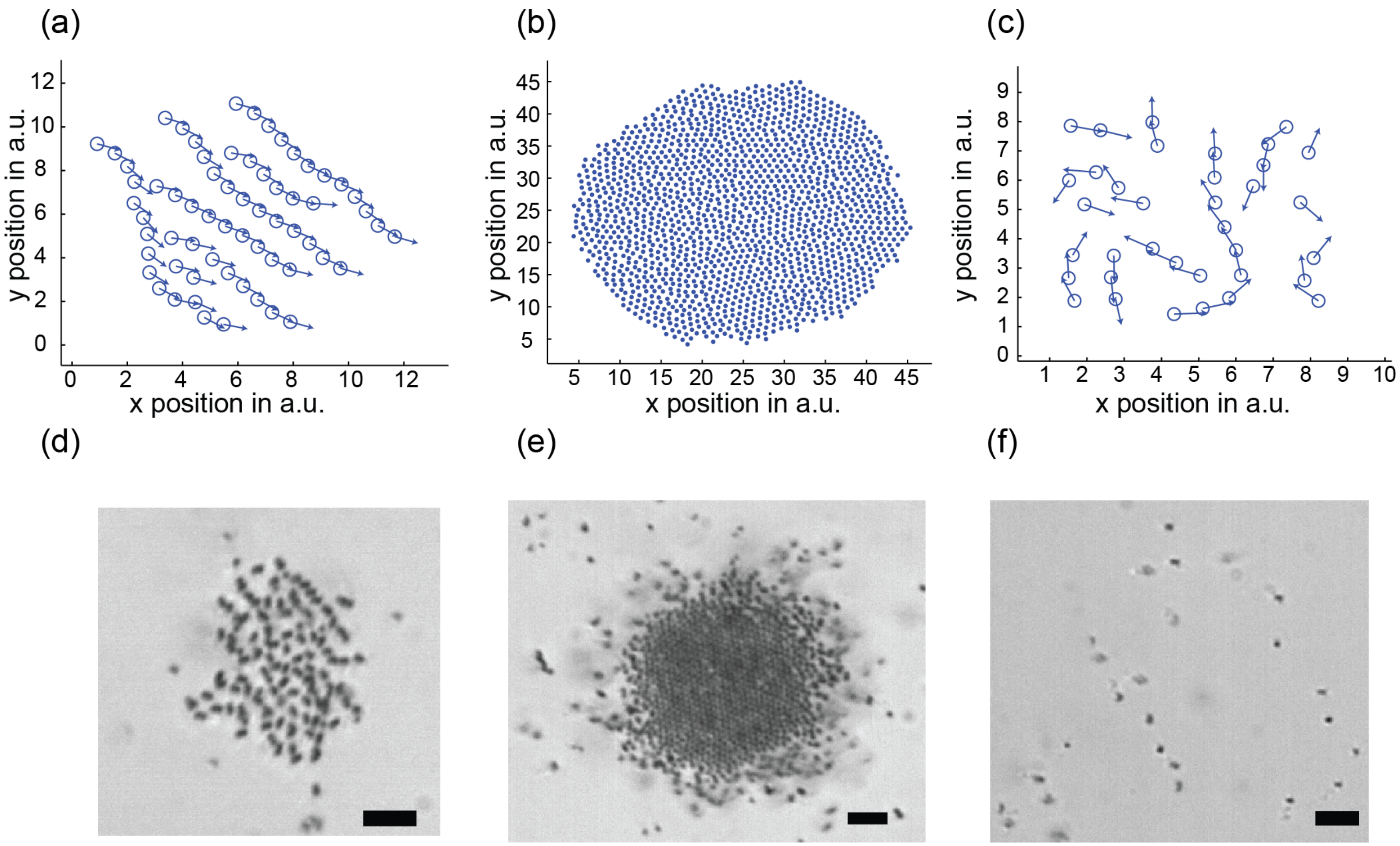


high frequencies (200 Hz)

Vach et al., J. Phys. D.: Appl. Phys., 2017

COLLECTIVE BEHAVIOR

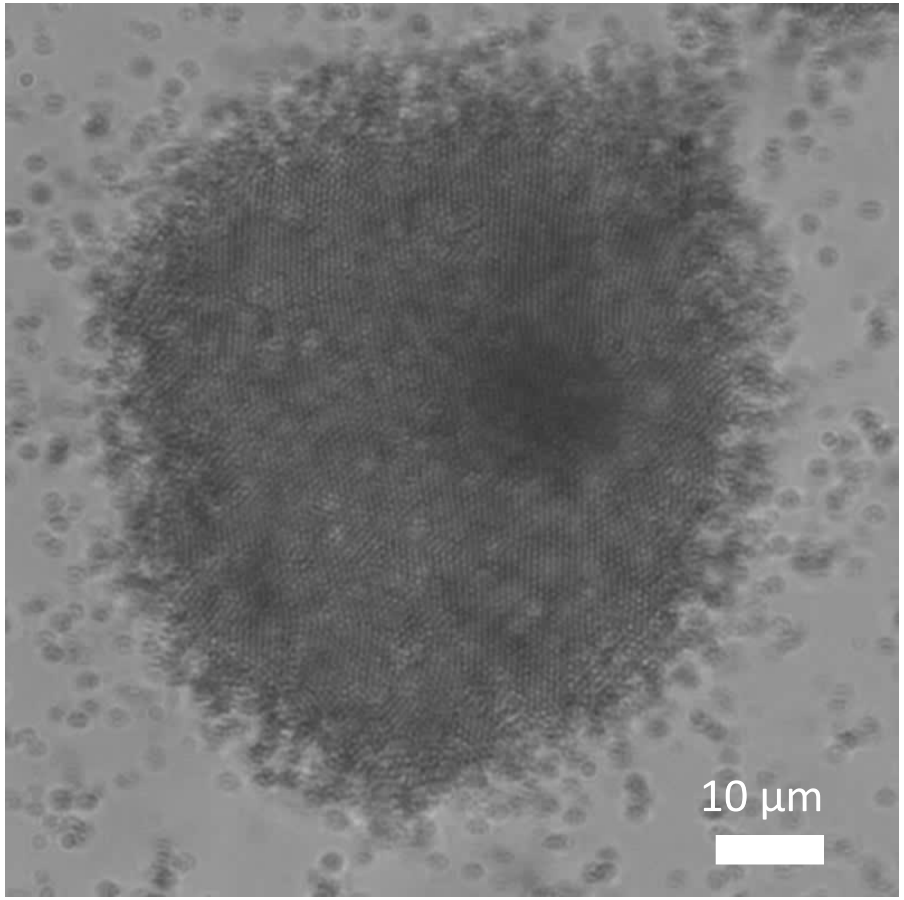
Simulation of cluster formation



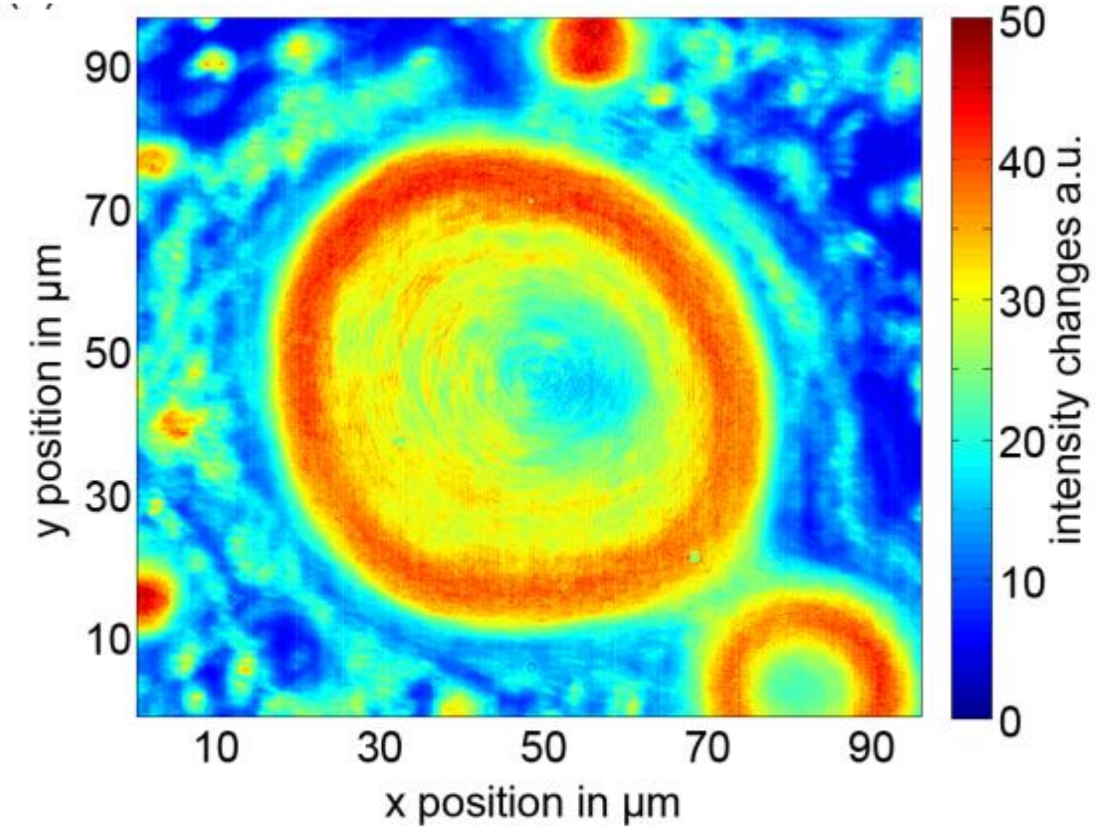
- Dipole model with short range repulsion can reproduce cluster formation

COLLECTIVE BEHAVIOR

Model of cluster formation



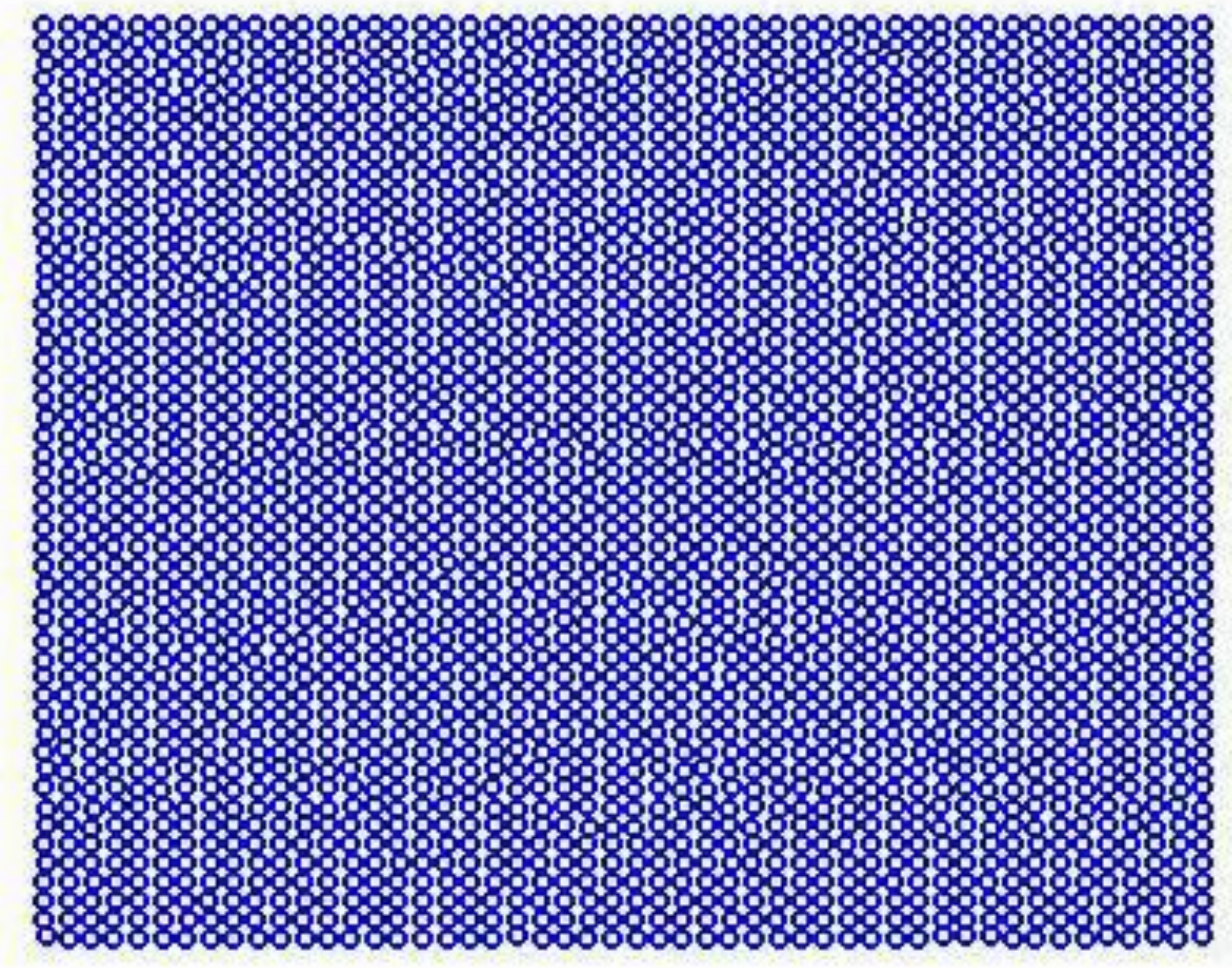
Visualization of speed distribution



- Dipole interactions alone cannot reproduce border region with increased angular velocities

COLLECTIVE BEHAVIOR

Effective hydrodynamic interactions

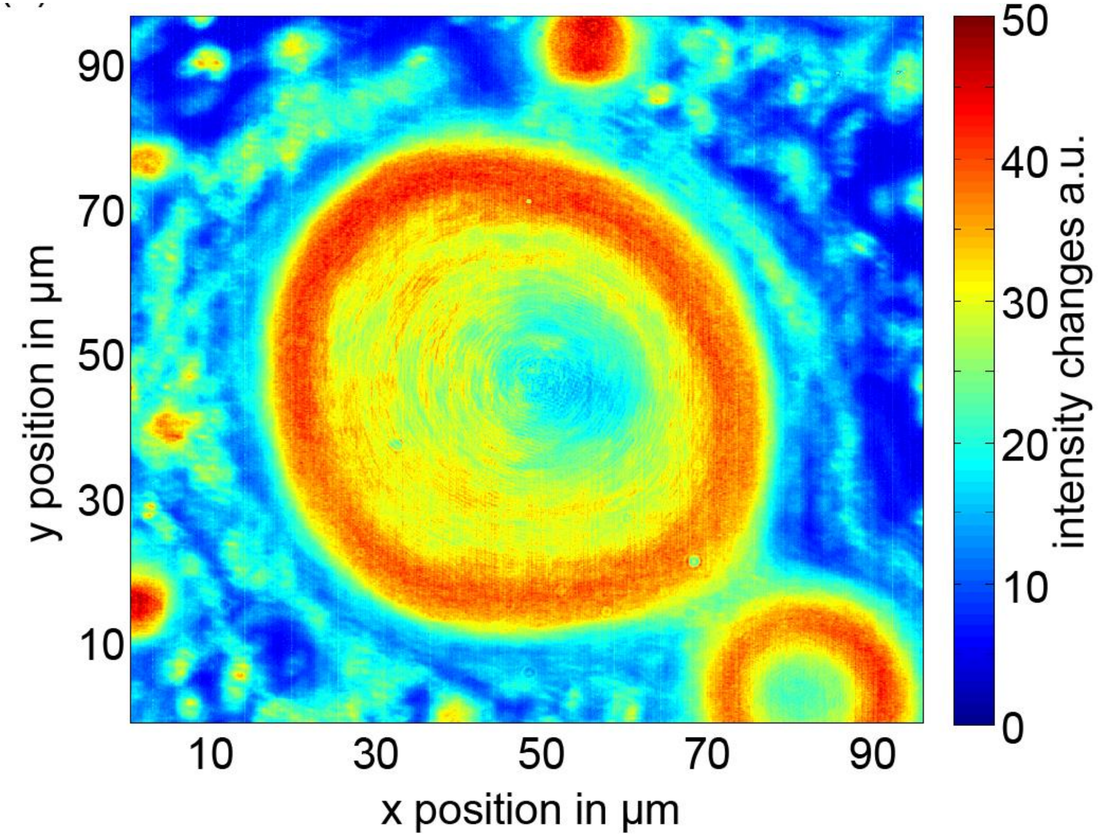


f_{sim}= 40 Hz,
playback speed
125%

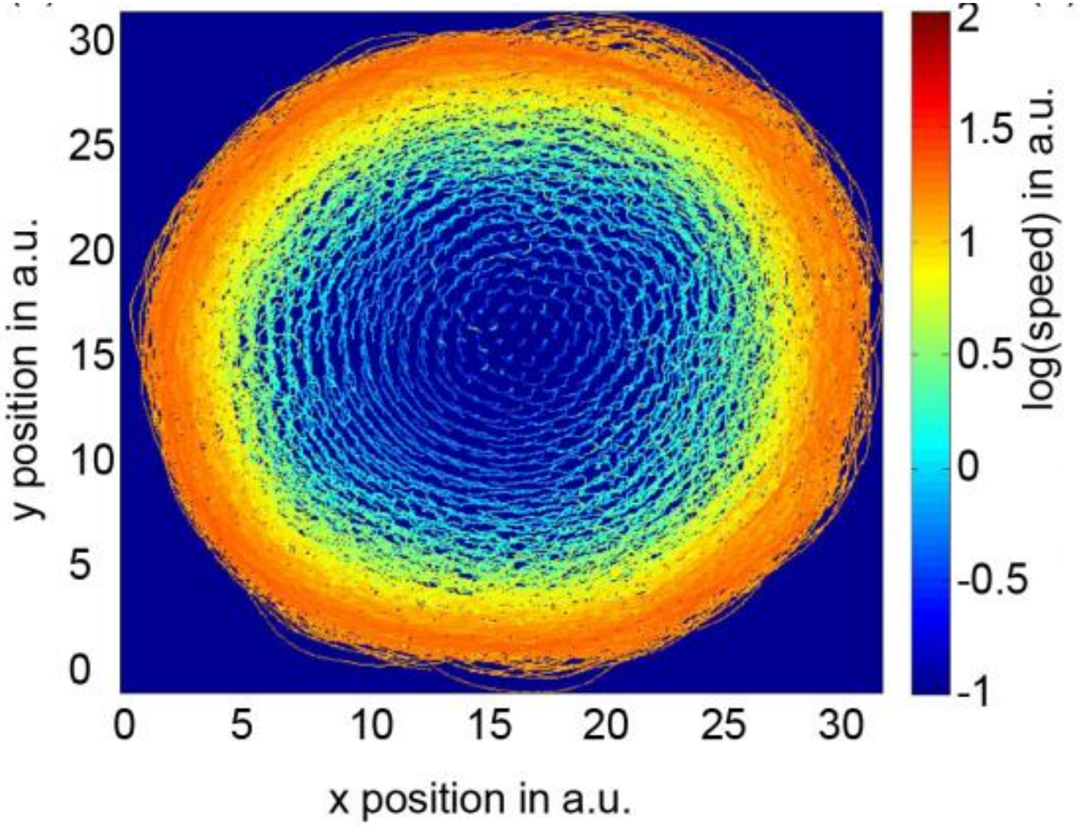
COLLECTIVE BEHAVIOR

Effective hydrodynamic interactions

Experiment



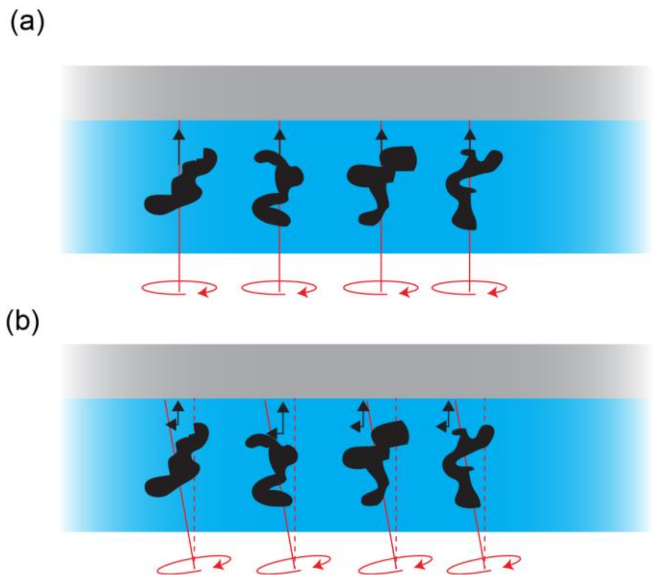
Simulation



- Including an effective hydrodynamic interaction reproduces the border region

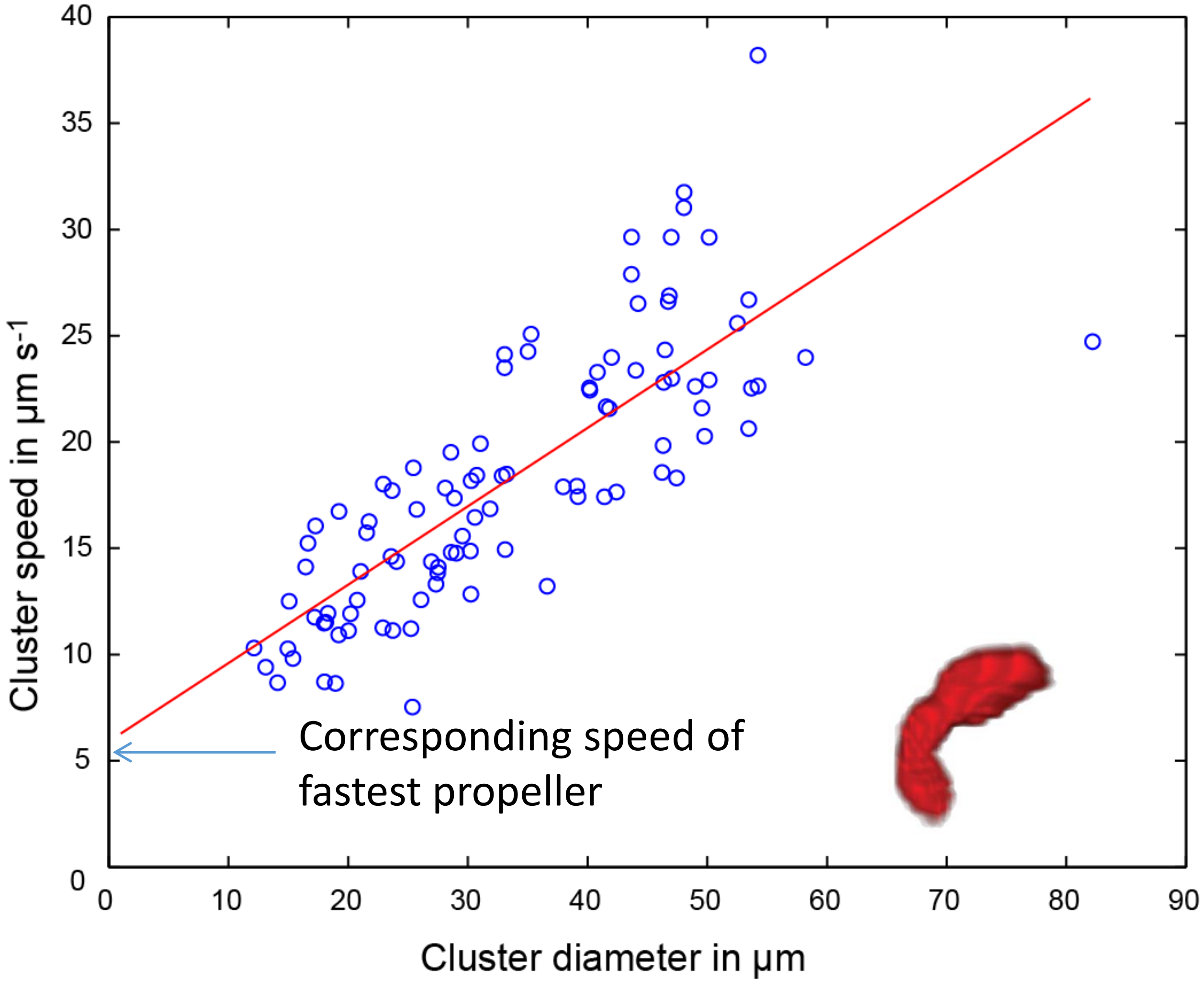
COLLECTIVE BEHAVIOR

Cluster actuation



COLLECTIVE BEHAVIOR

Larger clusters are faster



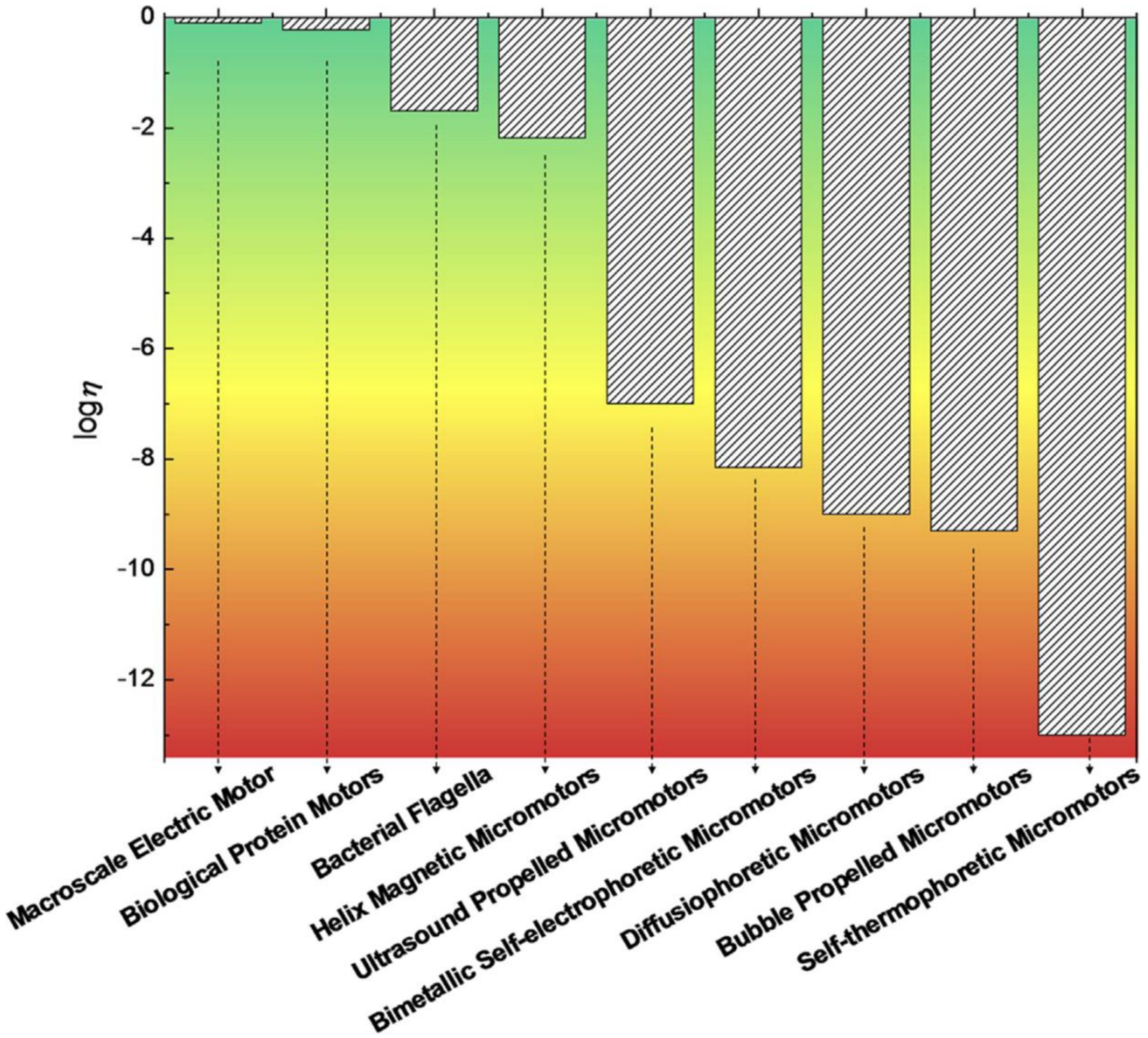
Corresponding speed of fastest propeller

Biological Microswimmers

OUR SPECIALTY: MAGNETOTACTIC BACTERIA

MICROSWIMMERS

Why choosing bacteria

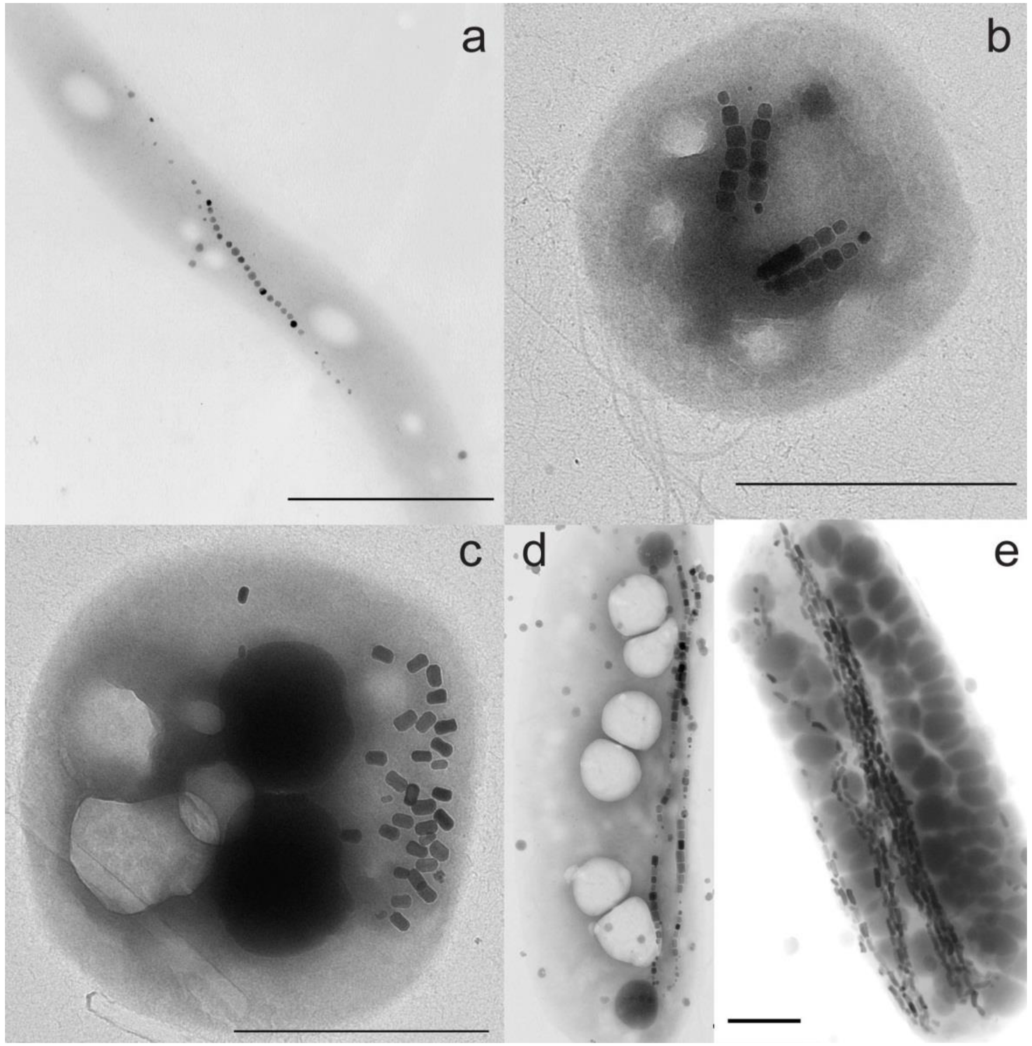


- The helix magnetic micromotors (micropropellers) are by far the most efficient synthetic microswimmers
- Bacterial flagella are at least 5 orders of magnitude more efficient than the most efficient synthetic micromotors

Wang et al., Nano Today, 2013

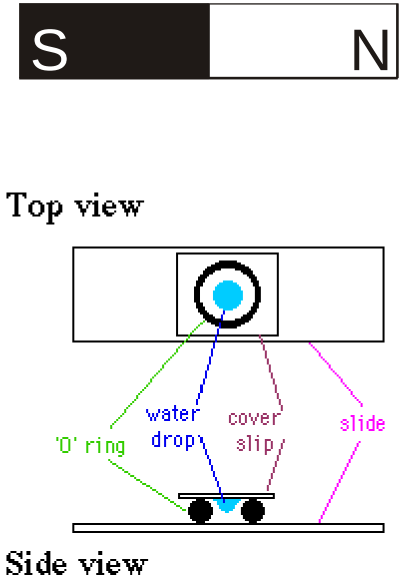
MAGNETOTACTIC BACTERIA

Diversity



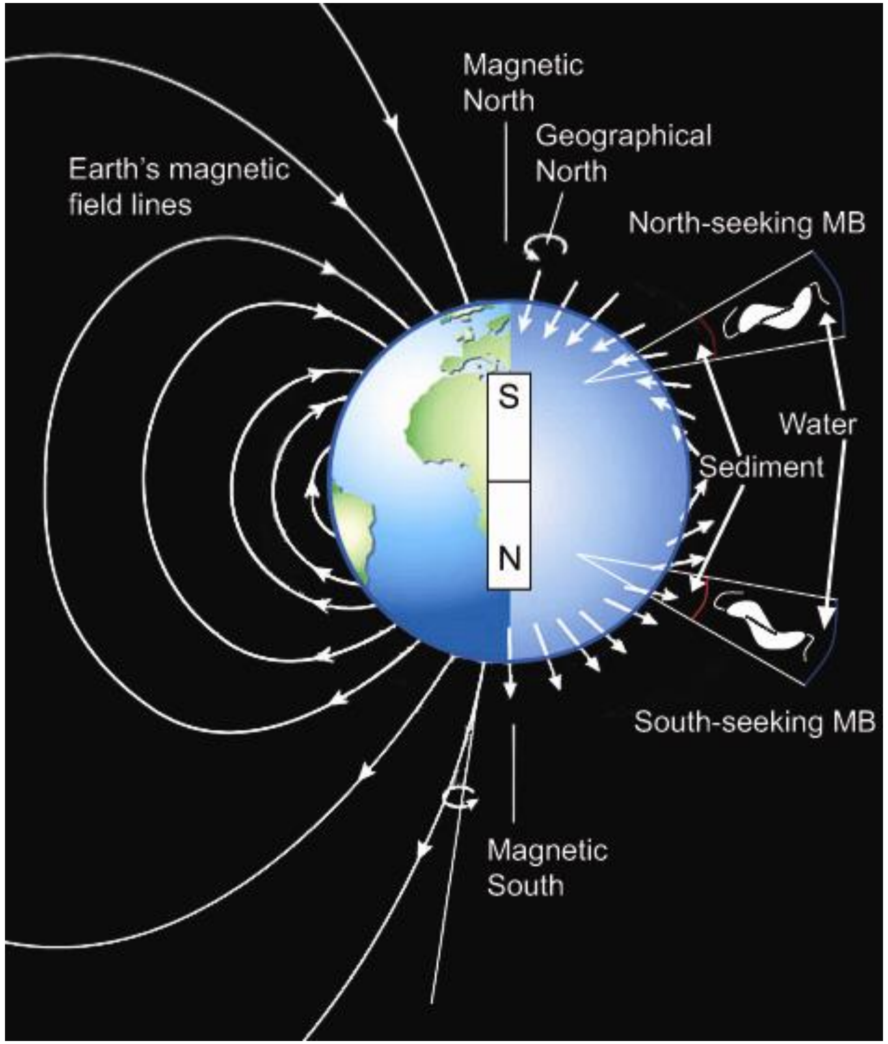
- Single-cell, prokaryotes
- Strain-specific bacterial shape
- Strain-specific magnetosome organization

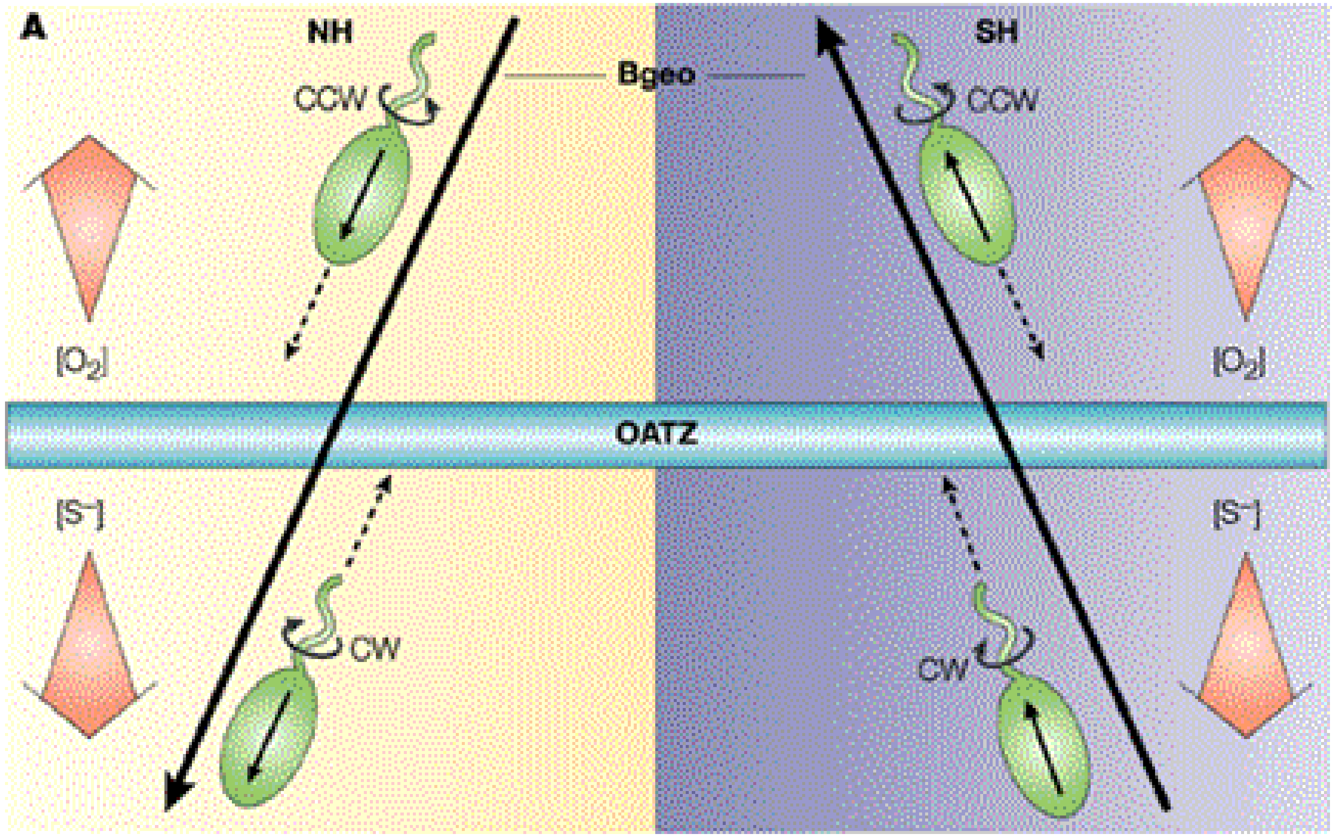
THE EXPERIMENT WE ALL HAVE DONE



MAGNETOAEROTAXIS

Finding the preferred place on Earth



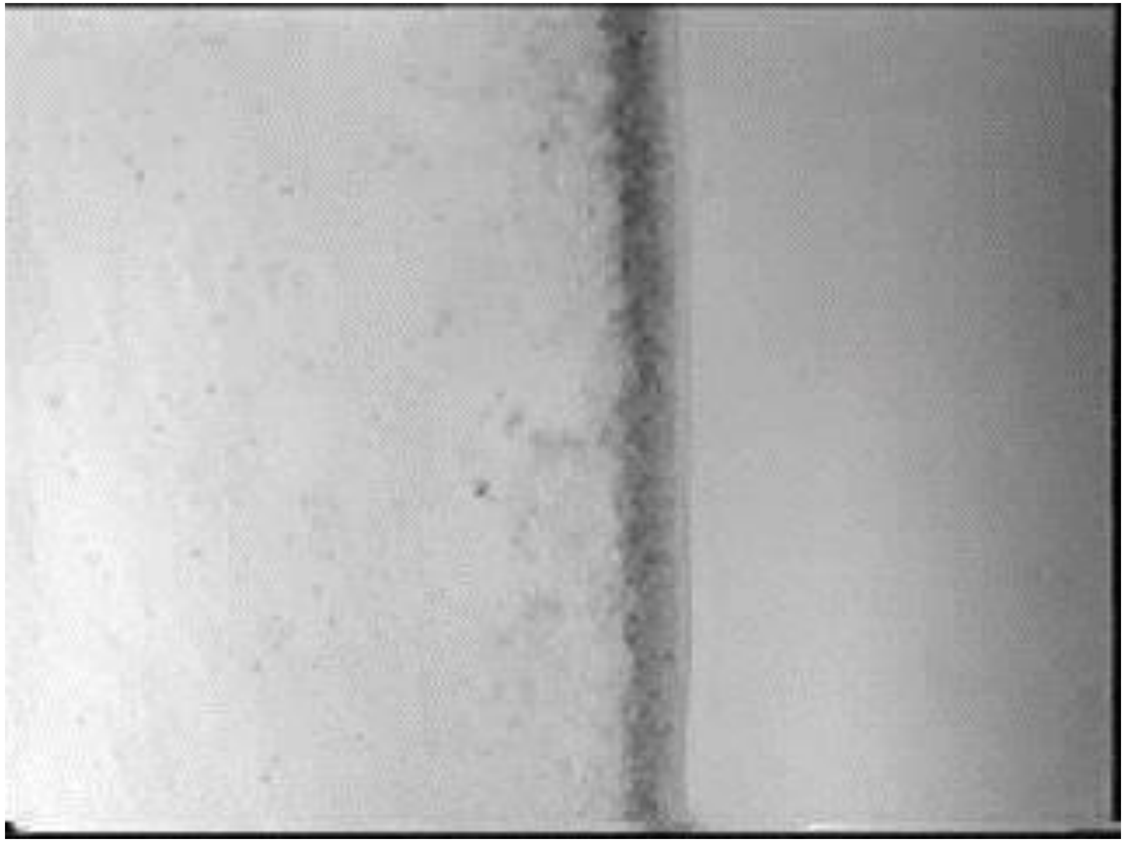


- MTB use magnets to find the OATZ, their best place on Earth

MAGNETOAEROTAXIS

2 original types

Axial magneto-aerotaxis



Polar magneto-aerotaxis

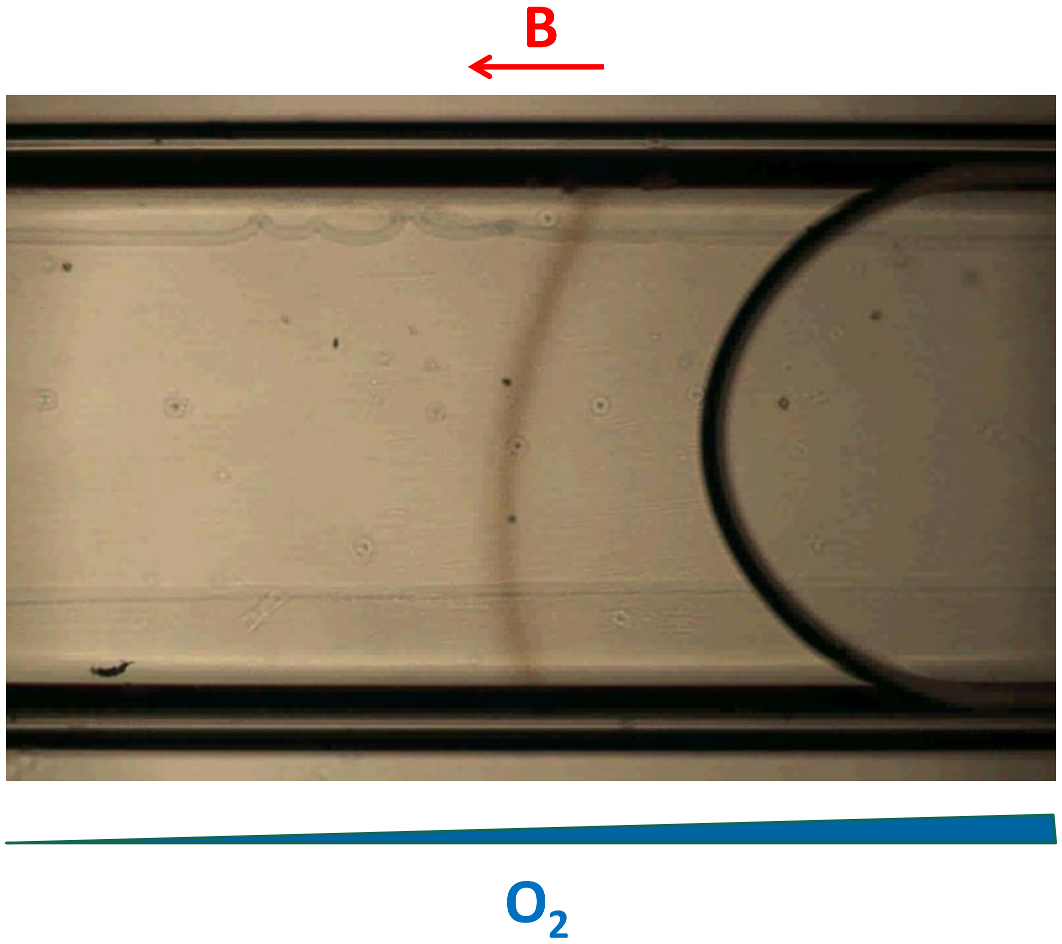
Frankel et al., Biophysical Journal, 1997

MAGNETO-AEROTAXIS

The experiment

Culture in oxygen gradient

Microcapillary

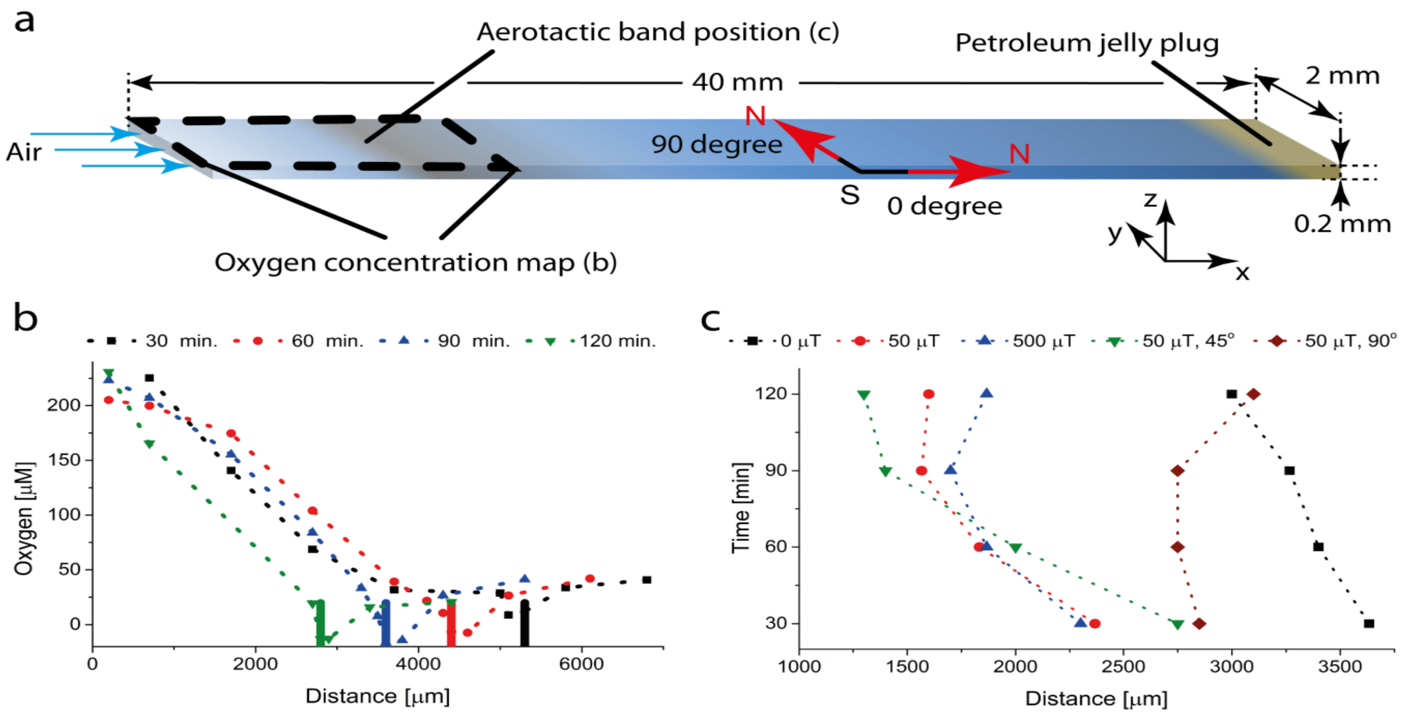


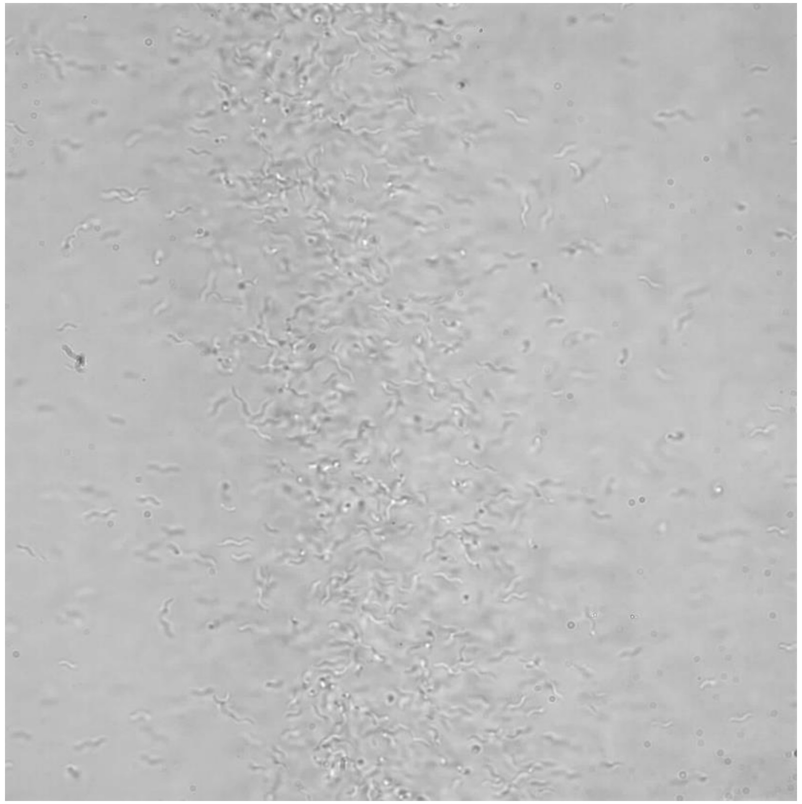
Magnetotactic bacteria

MAGNETOAEROTAXIS

MAGNETO-AEROTAXIS

Magnetism and oxygen gradients





- Magnetotactic bacteria form a band at 1.5 < $[O_2]$ < 3.6 µM.
- The magnetic field help the cells to find their preferred oxygen concentration more rapidly.

Bennet et al., PLoS One, 2014

MAGNETO-AEROTAXIS

A model

Density of (left) moving cells

Bacterial velocity

Reversal rate

$$\partial_t \rho_L = +v\partial_x \rho_L - k_{LR}\rho_L + k_{RL}\rho_R$$

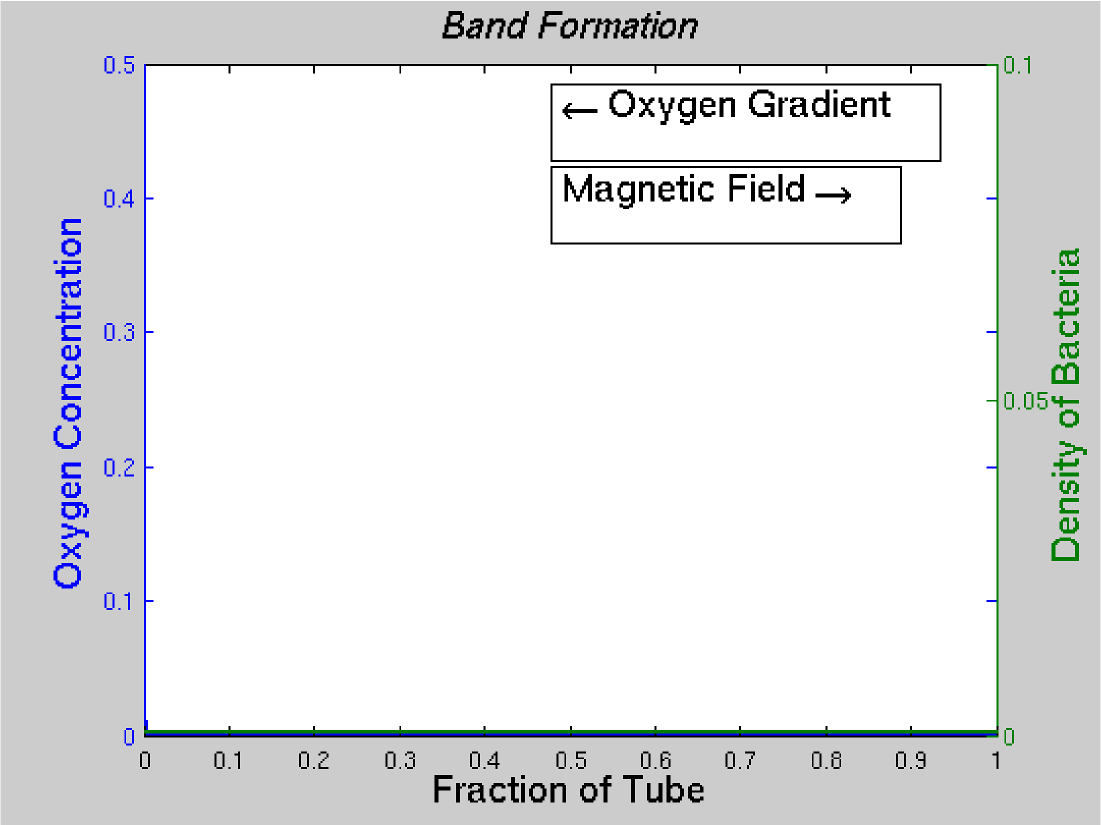
$$\partial_t \rho_R = -v\partial_x \rho_R + k_{LR}\rho_L - k_{RL}\rho_R$$

$$\partial_t c_{O_2} = D\partial_x^2 c_{O_2} - k(c)\left(\rho_L + \rho_R\right)$$

O_2 Bacterial consumption

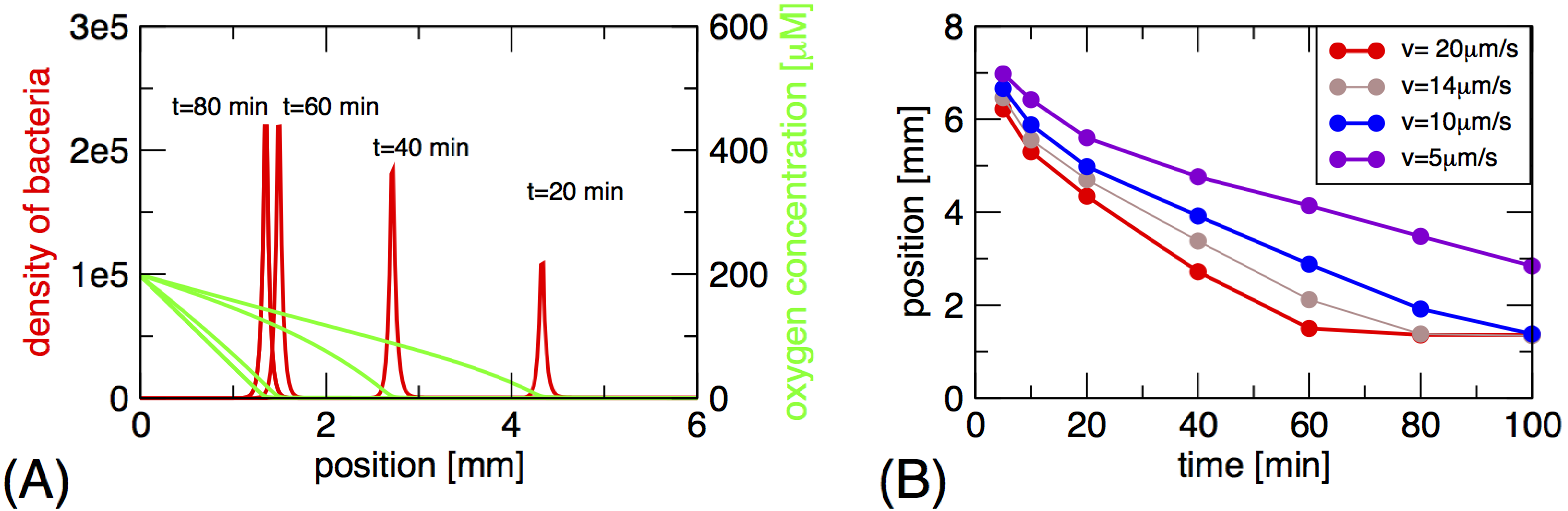
O_2 diffusion coefficient

O_2 concentration



MAGNETO-AEROTAXIS

A model



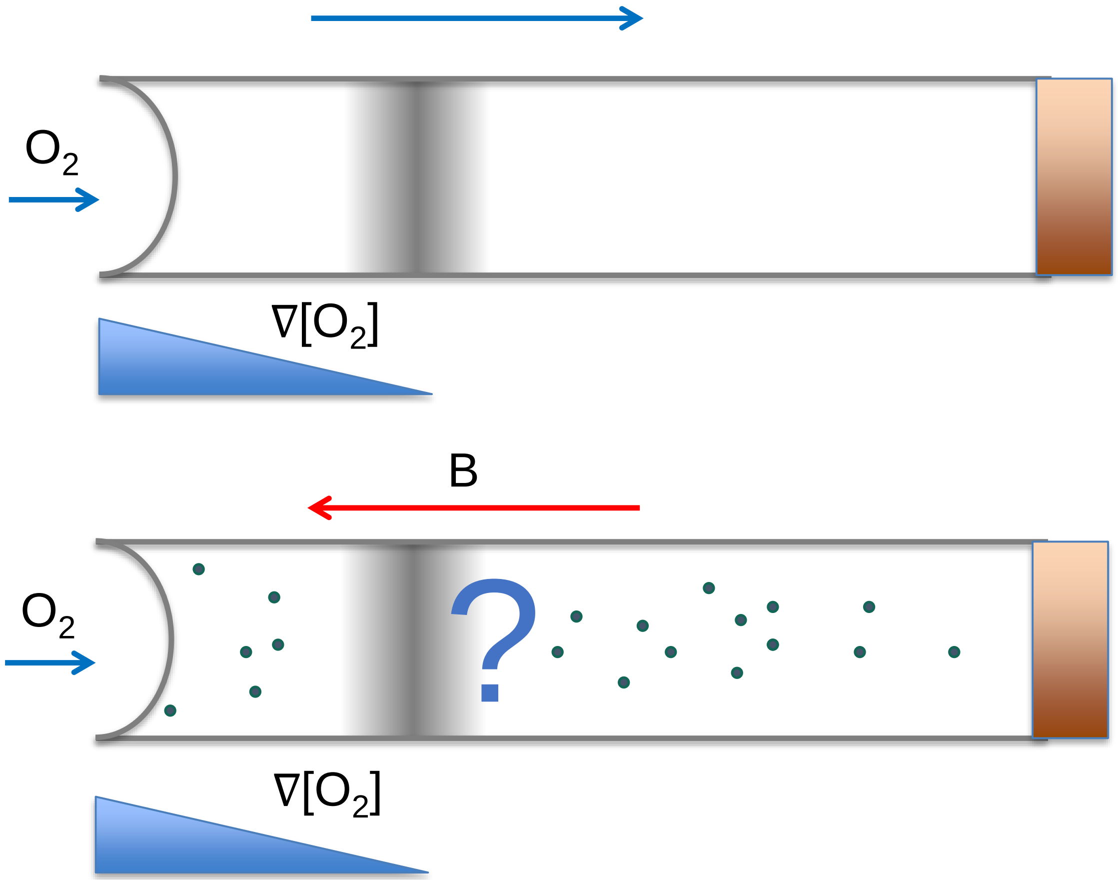
- The model shows a band formation only with a 2-sensors system (C_{min} and C_{max})
- The model confirms a reduced aerotactic capability in the absence of field or for a field at 90° with respect to the gradient direction

Bennet et al., PLoS One, 2014


Déviation
Déviation

DIFFERING MAGNETO-AEROTAXIS

Field reorientation



1. Band formation

2. Field inversion

Lefèvre et al., Biophysical Journal, 2014

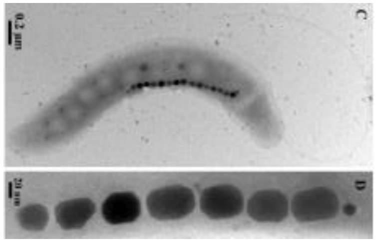
DIFFERING MAGNETO-AEROTAXIS

Species studied

1 polar flagellum

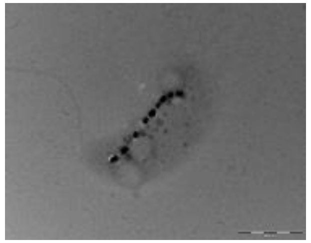
Strain LM-1:

Freshwater vibrio.



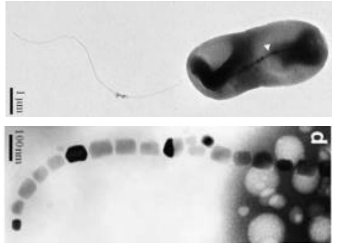
Strain PR-2:

marine vibrio.



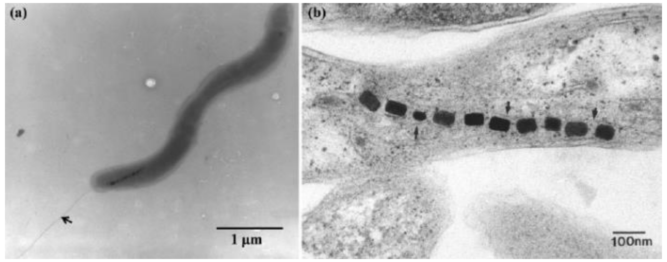
Strain SS-5:

hypersaline rod.



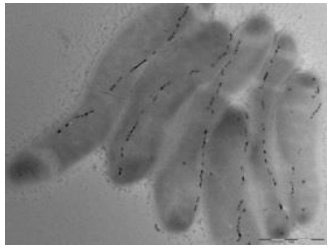
***Magnetovibrio blakemorei* MV-1**:

marine vibrio.



***Desilfovibrio magneticus* RS-1**:

freshwater vibrio.



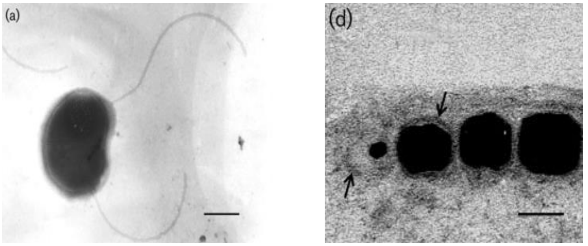
DIFFERING MAGNETO-AEROTAXIS

Species studied

2 polar flagella

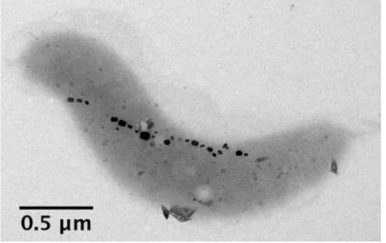
***Magnetospira thiophila* MMS-1**:

marine spirillum.



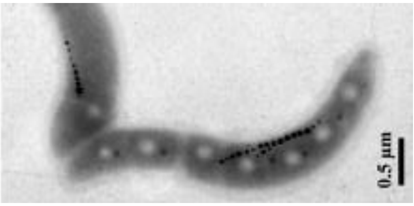
Strain PR-1:

marine spirillum.



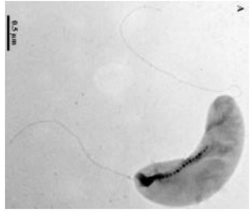
Magnetospirillum gryphiswaldense MSR-1:

freshwater spirillum.



Strain UT-4:

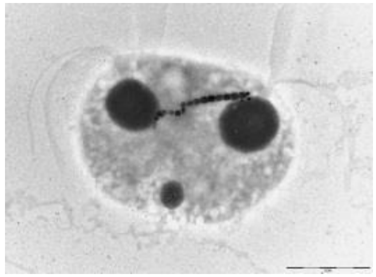
freshwater spirillum.



2 polar bundles

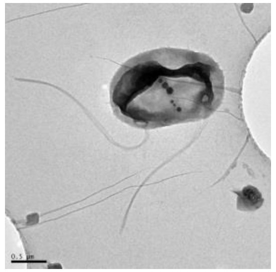
Strain PR-3:

Marine cocci .



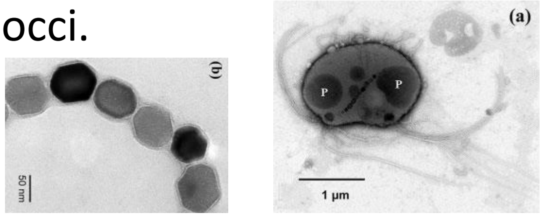
Strain SS-1:

Hypersaline cocci .



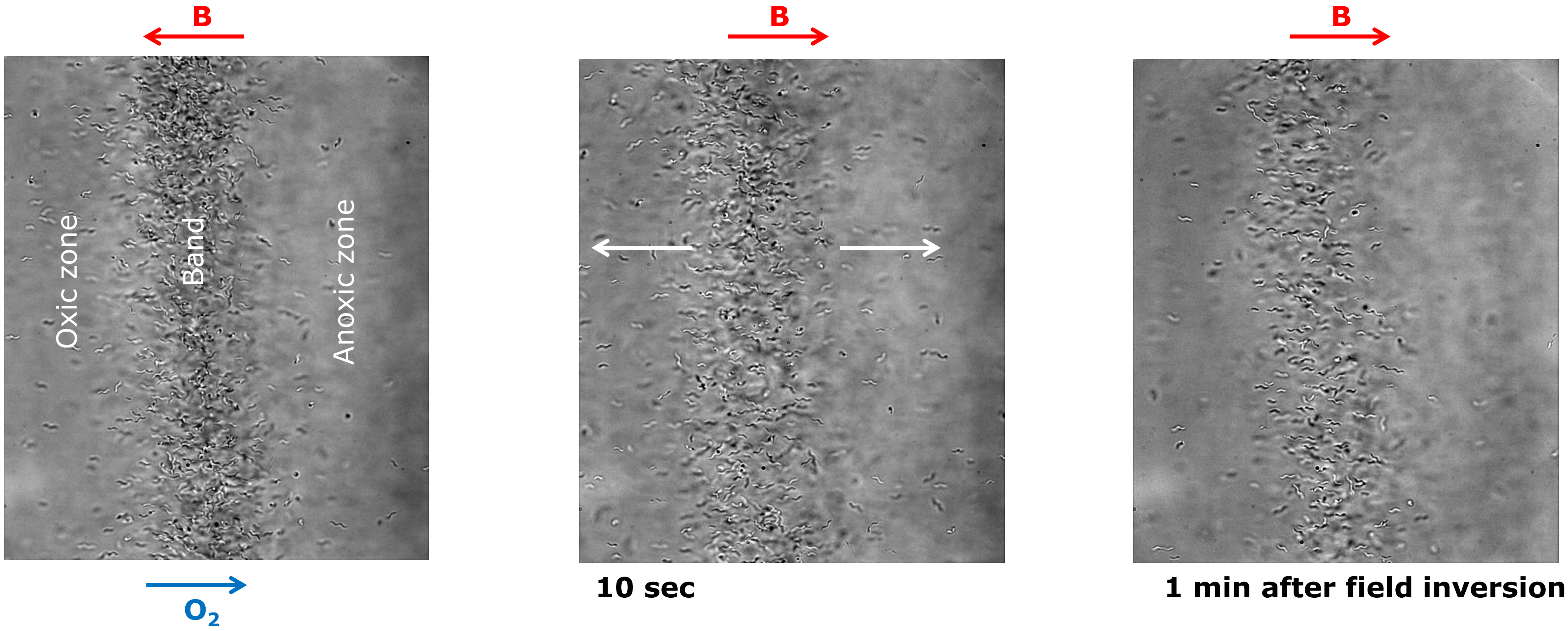
***Magnetococcus marinus* MC-1**:

marine cocci.



BEHAVIOR 1

MSR-1



10 sec

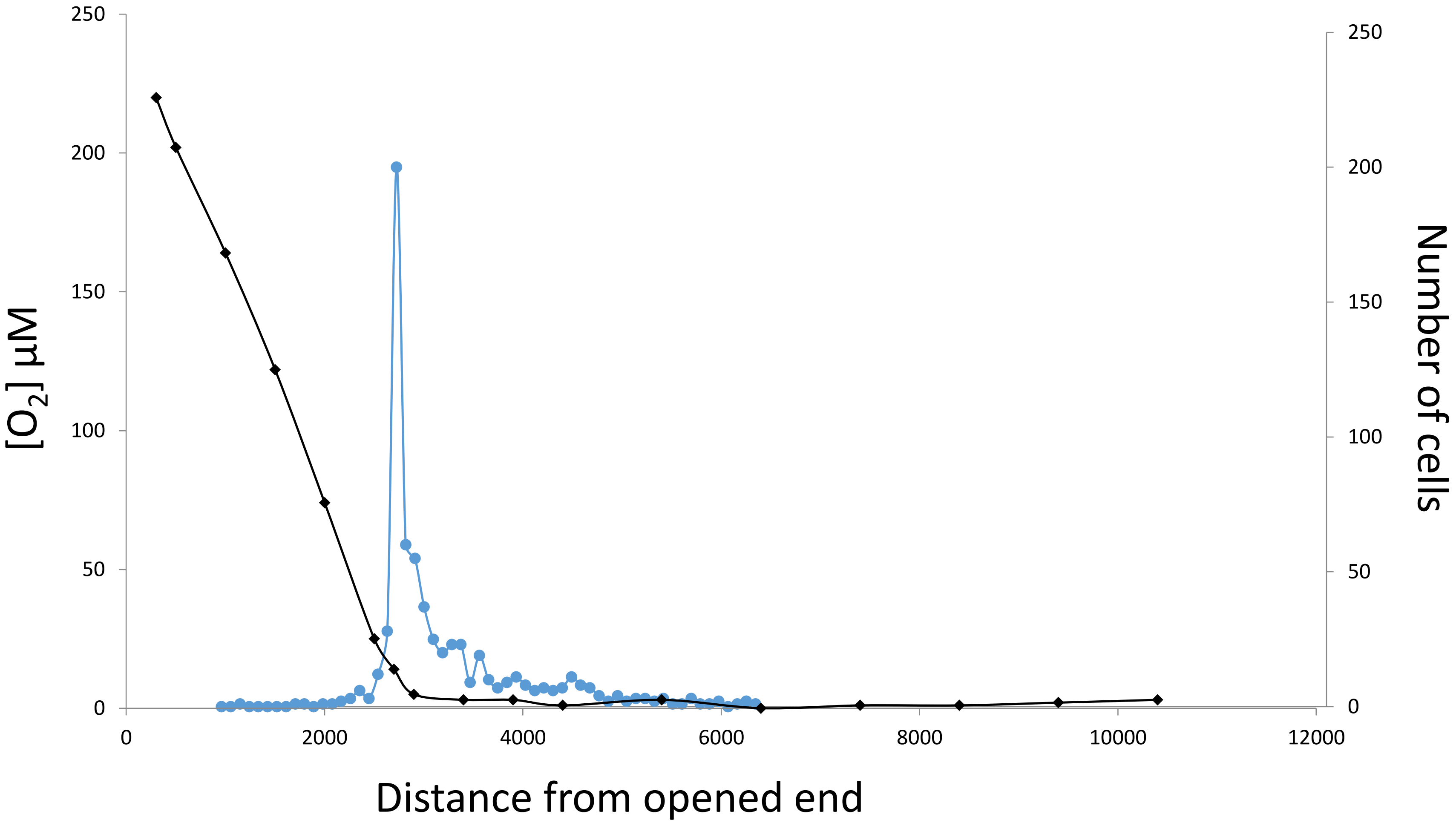
1 min after field inversion

3 different behaviors when **B reversed** :

- cells going toward the anoxic zone,
- cells going toward the oxic zone and,
- cells staying in the band.

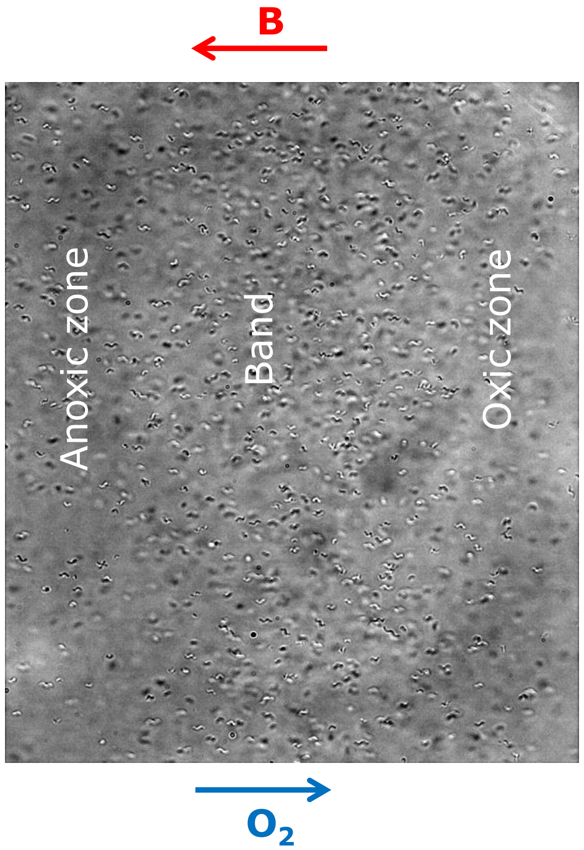
BEHAVIOR 1

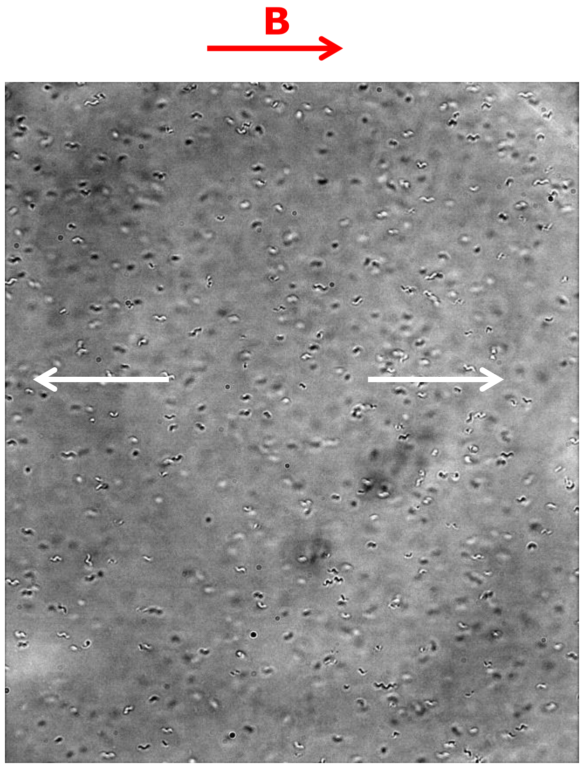
MSR-1



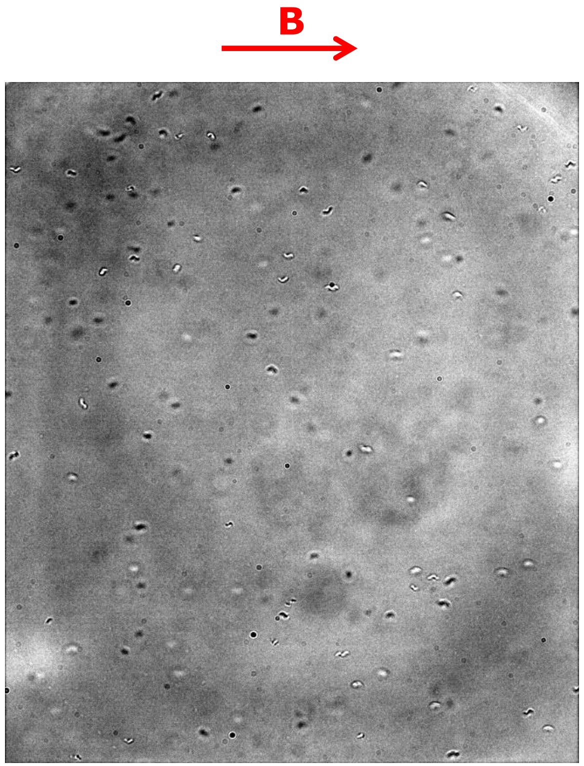
BEHAVIOR 2

LM-1





10 sec



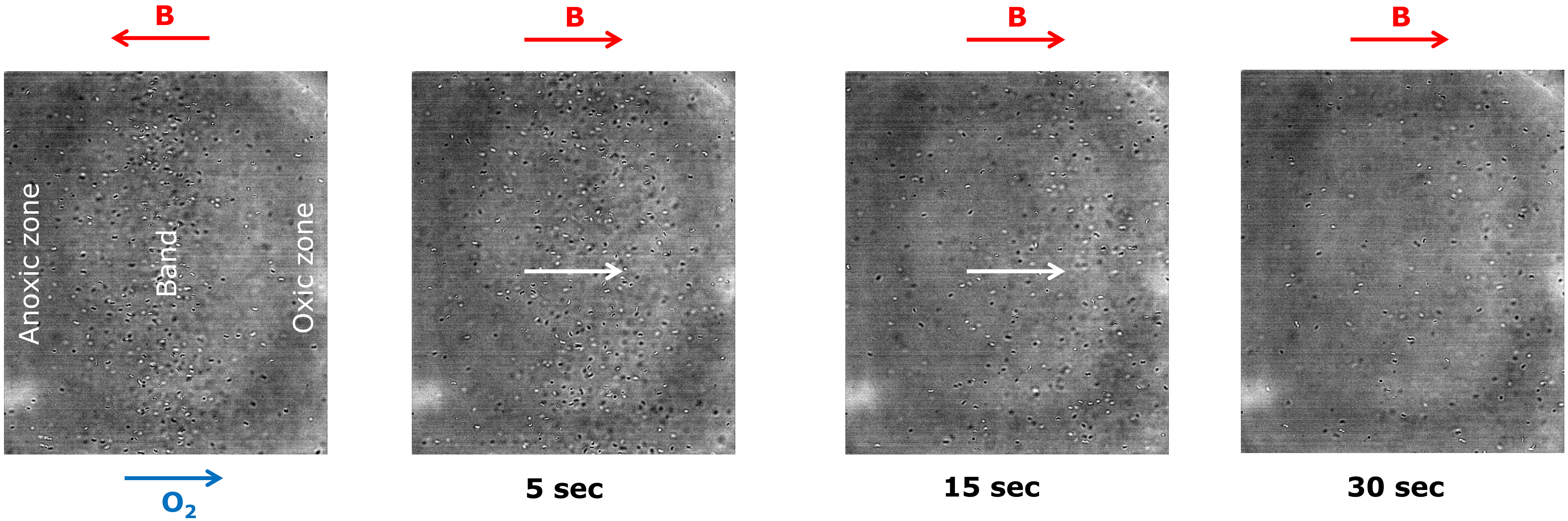
1 min after field inversion

2 different behaviors when **B reversed** :

- cells going toward the anoxic zone,
- cells going toward the oxic zone

BEHAVIOR 3

MV-1



5 sec

15 sec

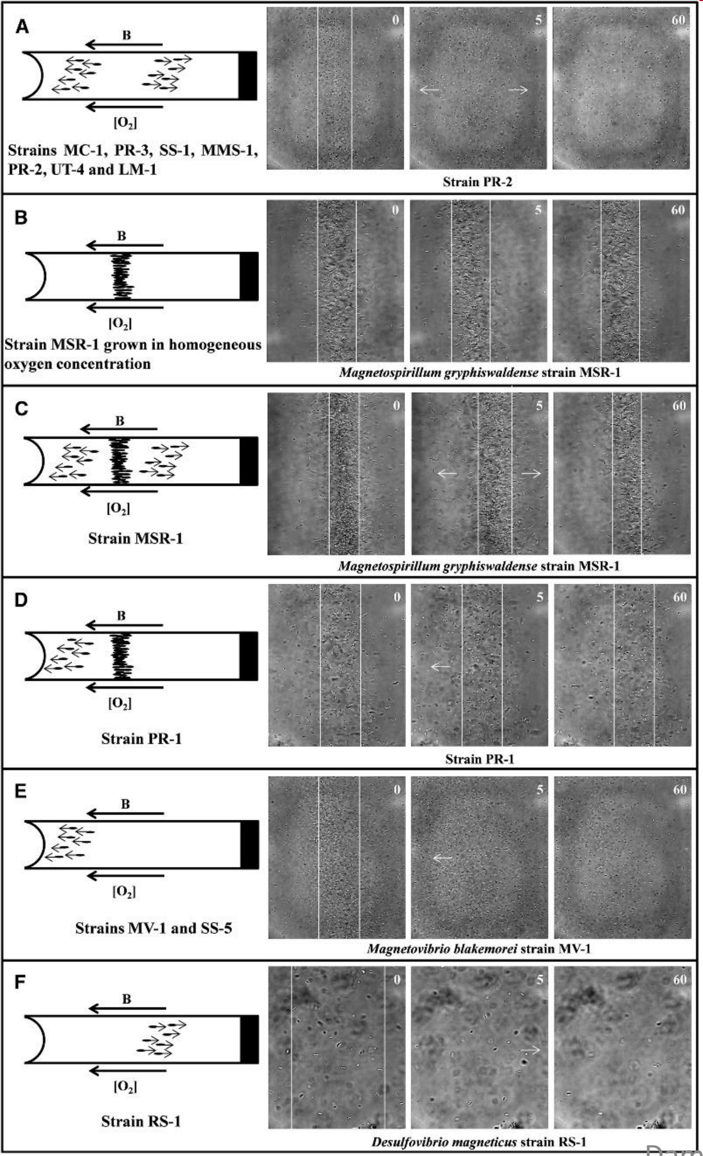
30 sec

After magnetic field inversion

Only 1 behavior when **B reversed** :

- cells going toward the oxic zone

SUMMARY OF BEHAVIORS



- 1 or 2 polar flagella, 2 flagellar bundles
- Cocci, vibrios, spirilla
- Marine and freshwater

- 2 polar flagella
- Spirilla
- Freshwater

- 2 polar flagella
- Spirilla
- Marine

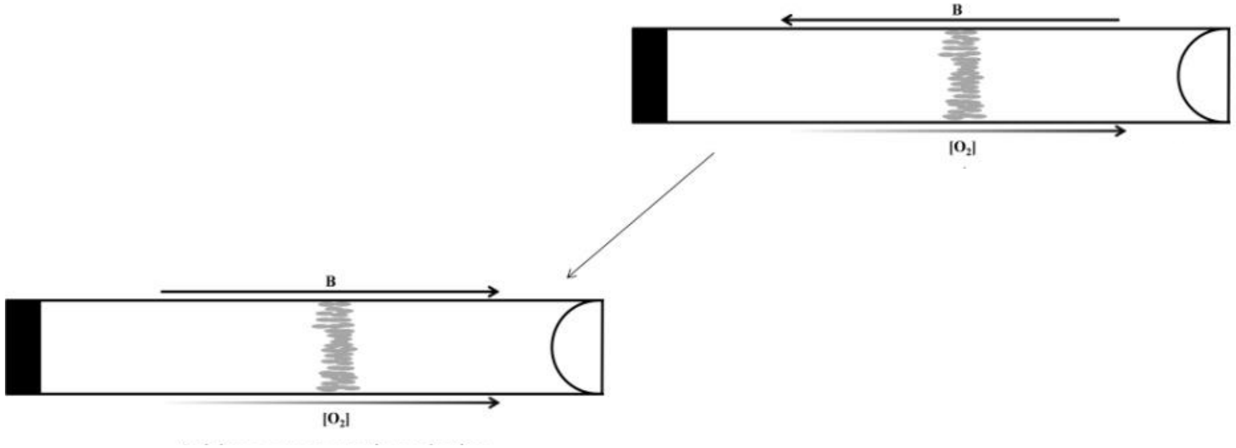
- 1 polar flagellum
- Vibrios, Rods
- Marine, hypersaline

- 1 polar flagellum
- Vibrios
- Freshwater

Lefèvre et al., Biophysical Journal, 2014

SUMMARY OF BEHAVIORS

Mechanistic background



axial

- true aerotaxis with gradient sensing
- ∇c_{O2} dominant over B
- B (only) provides axis

→ 1d aerotaxis

$$k_{LR,RL} = k_{LR,RL}(c_{O_2}, \vec{\nabla} c_{O_2})$$

dipolar

- no aerotaxis
- B provides direction and replaces gradient sensing

$$k_{LR,RL} = k_{LR,RL}(c_{O_2}, \vec{B})$$

unipolar

- Axial on one side
- Dipolar on the other side

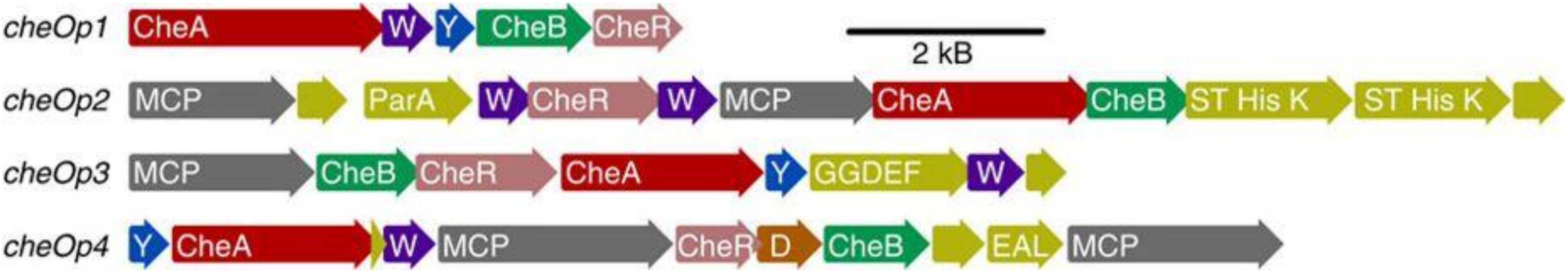
Magnetoaerotaxis

THE MOLECULAR BACKGROUND

MAGNETOAEROTAXIS

Some genes

Molecular organization of magnetoaerotactic genes in *M. gryphiswaldense*

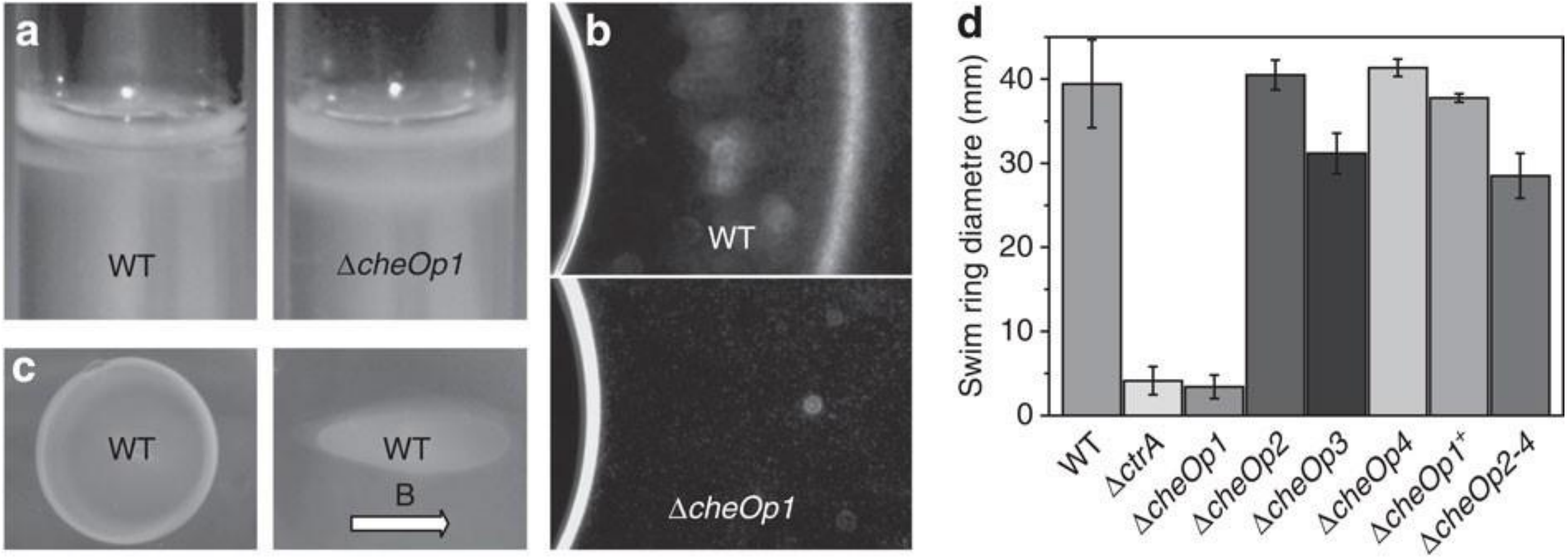


- 4 operons are identified
- *cheOp1* is the ~~only~~ major operon impacting magnetoaerotaxis

Popp et al., Nature Communications, 2014

MAGNETOAEROTAXIS

Aerotactic behavior of *M. gryphiswaldense*

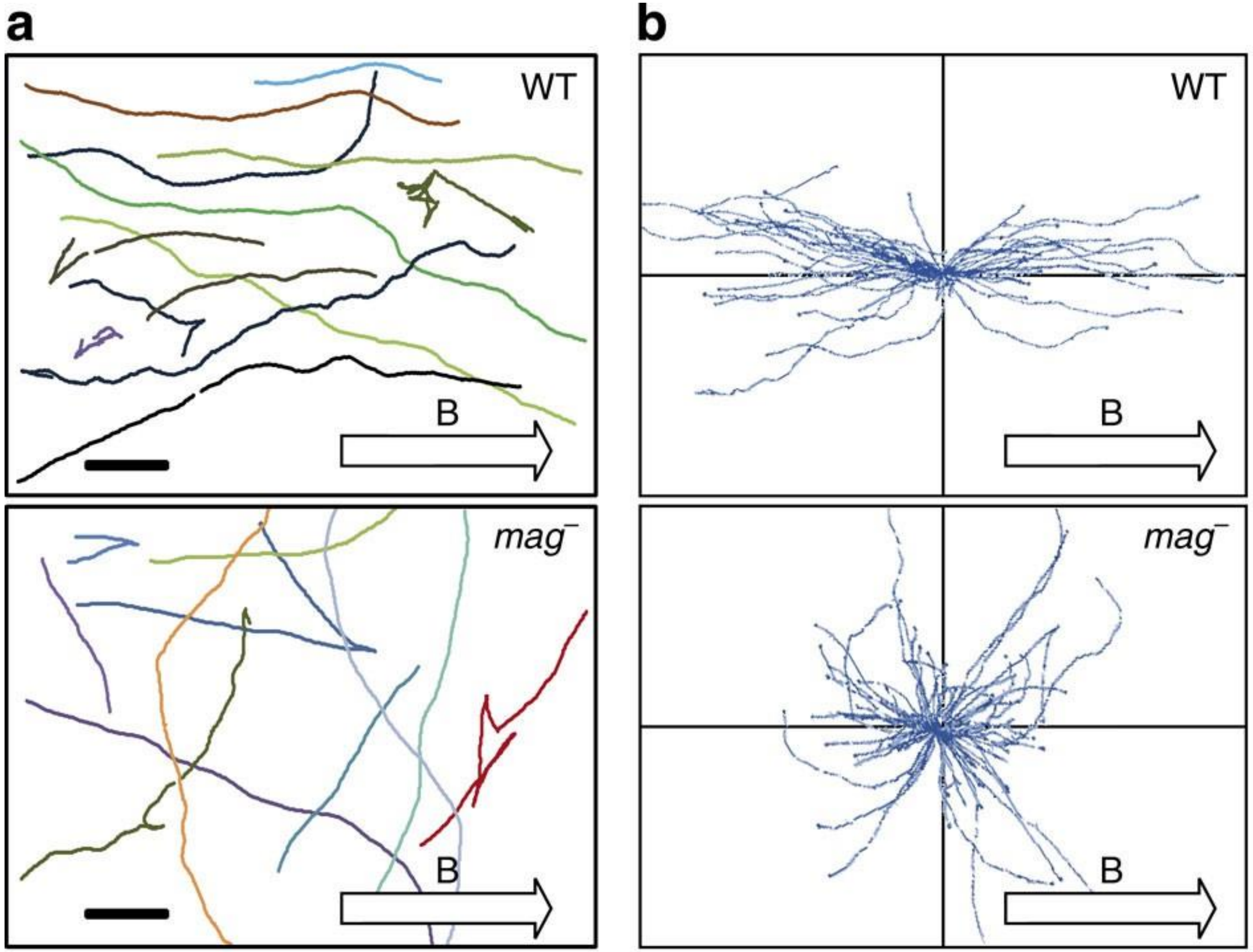


- *cheOp1* deletion mutant shows a defect in the aerotactic band formation

Popp et al., Nature Communications, 2014

MAGNETOAEROTAXIS

Aerotactic behavior of *M. gryphiswaldense*

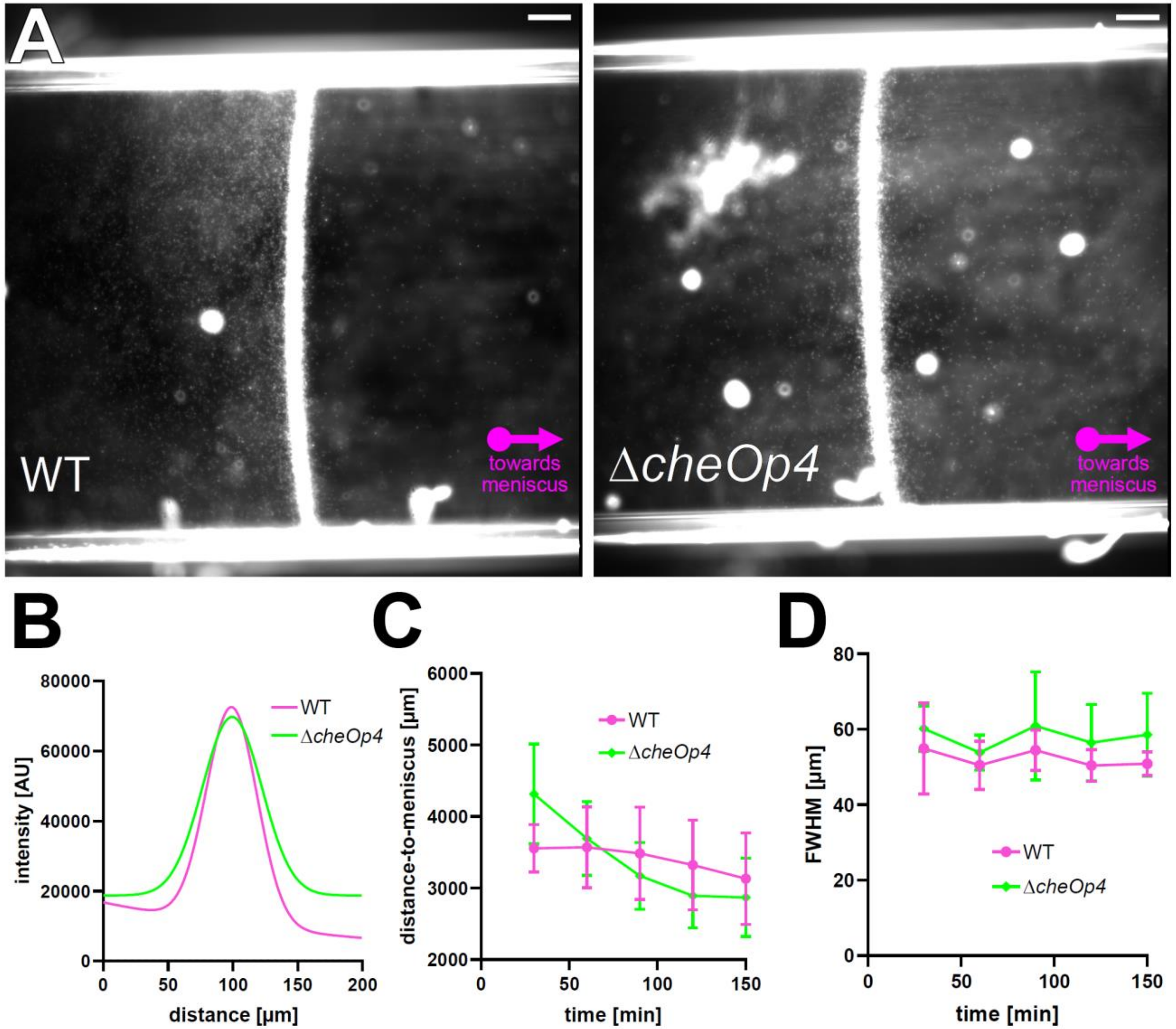


- *cheOp1* deletion mutant shows a defect in the response to a homogeneous magnetic field (0,26 mT, exposed to air under a cover slip)

Popp et al., Nature Communications, 2014

MAGNETOAEROTAXIS

Aerotactic behavior of *M. gryphiswaldense*

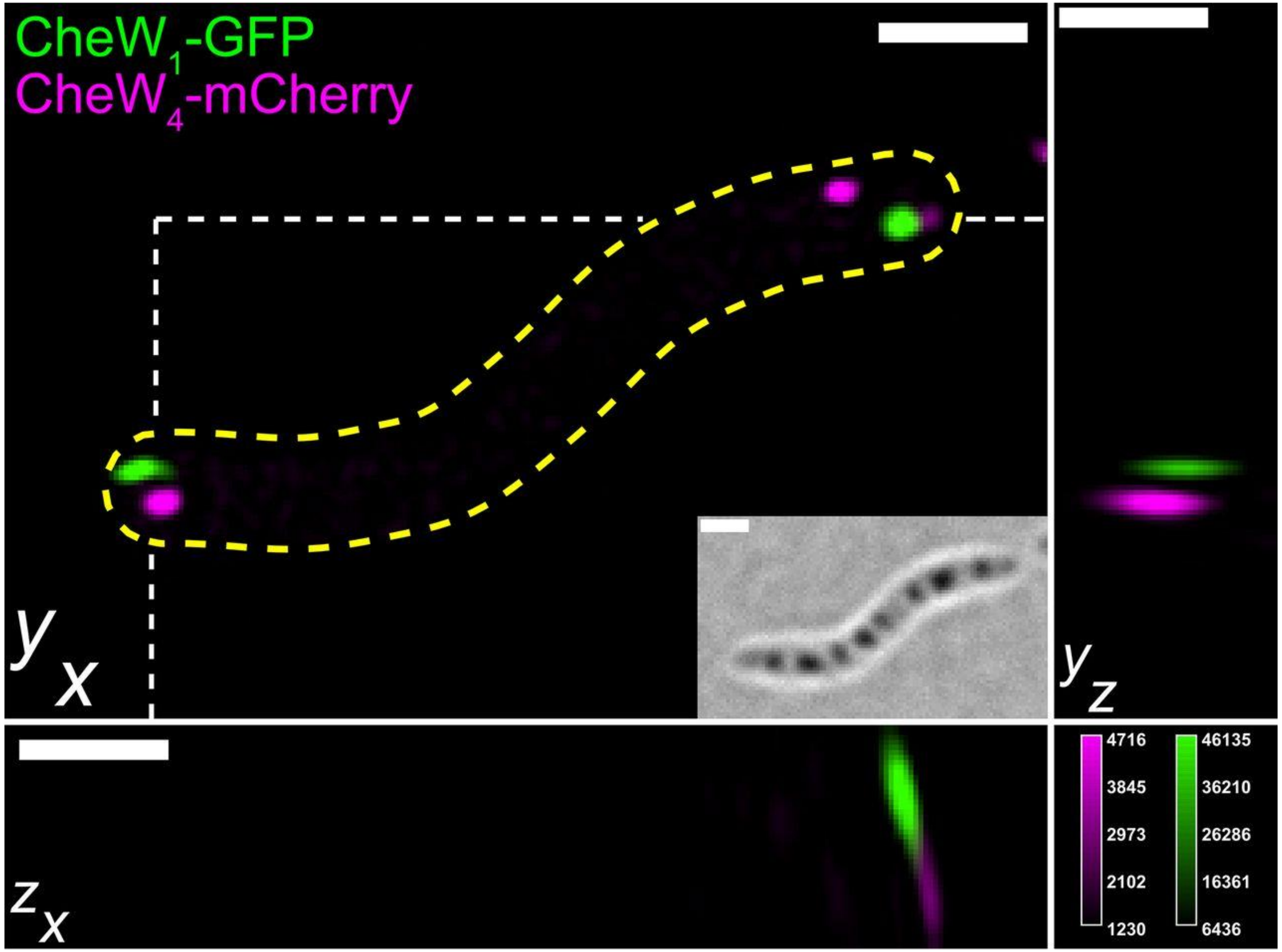


- *cheOp4* is not mandatory for aerotaxis but bears an unrecognized aerotaxis-related function, contributing to a sharper separation of the aerotactic band toward higher oxygen concentration

Pfeiffer et al., Applied and Environmental Microbiology, 2020

MAGNETOAEROTAXIS

Aerotactic behavior of *M. gryphiswaldense*



- CheW1 and CheW4 localize to spatially distinct arrays that are often located in close proximity (they do not interact)

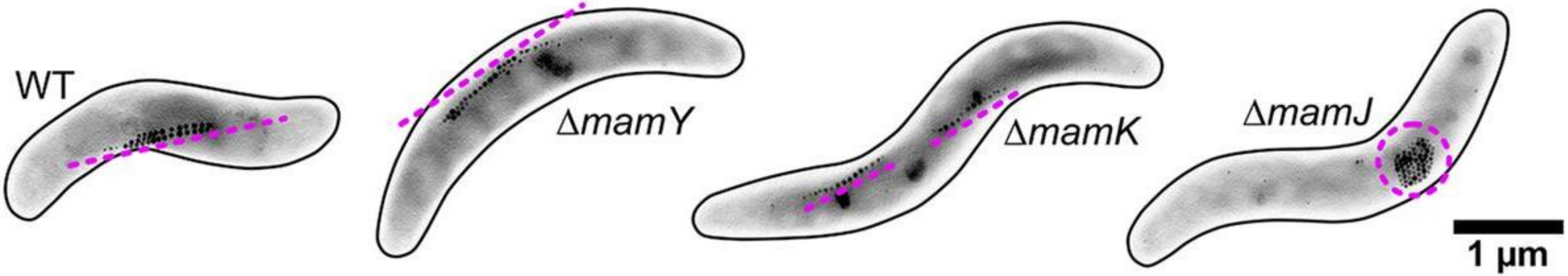
Pfeiffer et al., Applied and Environmental Microbiology, 2020

Structure / function

MAGNETOSOME ORGANIZATION / MAGNETOAEROTAXIS

MAGNETOSOME ORGANIZATION

M. gryphiswaldense mutant

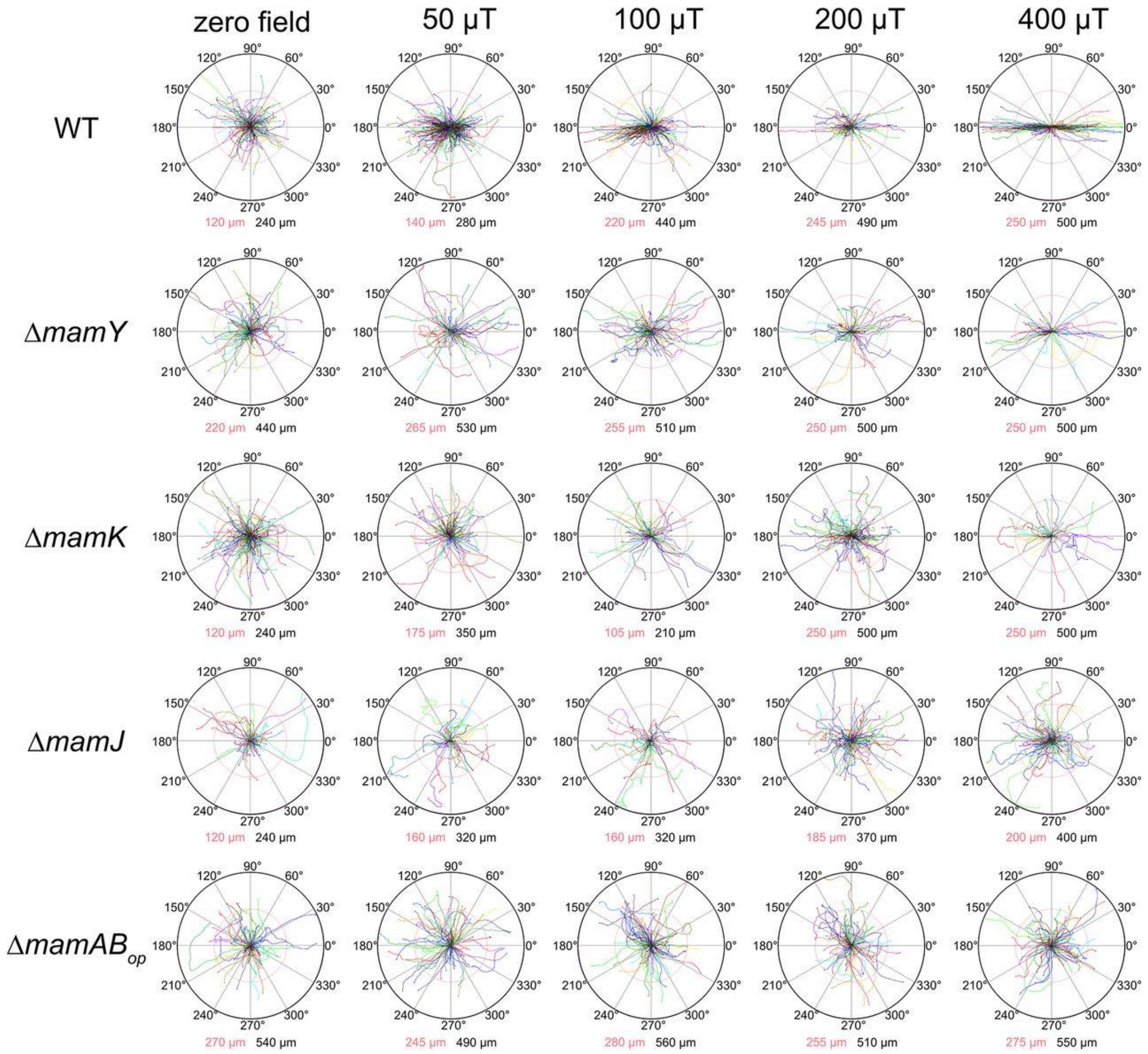


- Look at how different organization impact magnetoaerotaxis

Pfeiffer et al., Applied and Environmental Microbiology, 2020

RESPONSE TO MAGNETIC FIELDS

M. gryphiswaldense mutant



- Clustered magnetosomes behave like absent magnetosomes
- Altered chain resembles WT

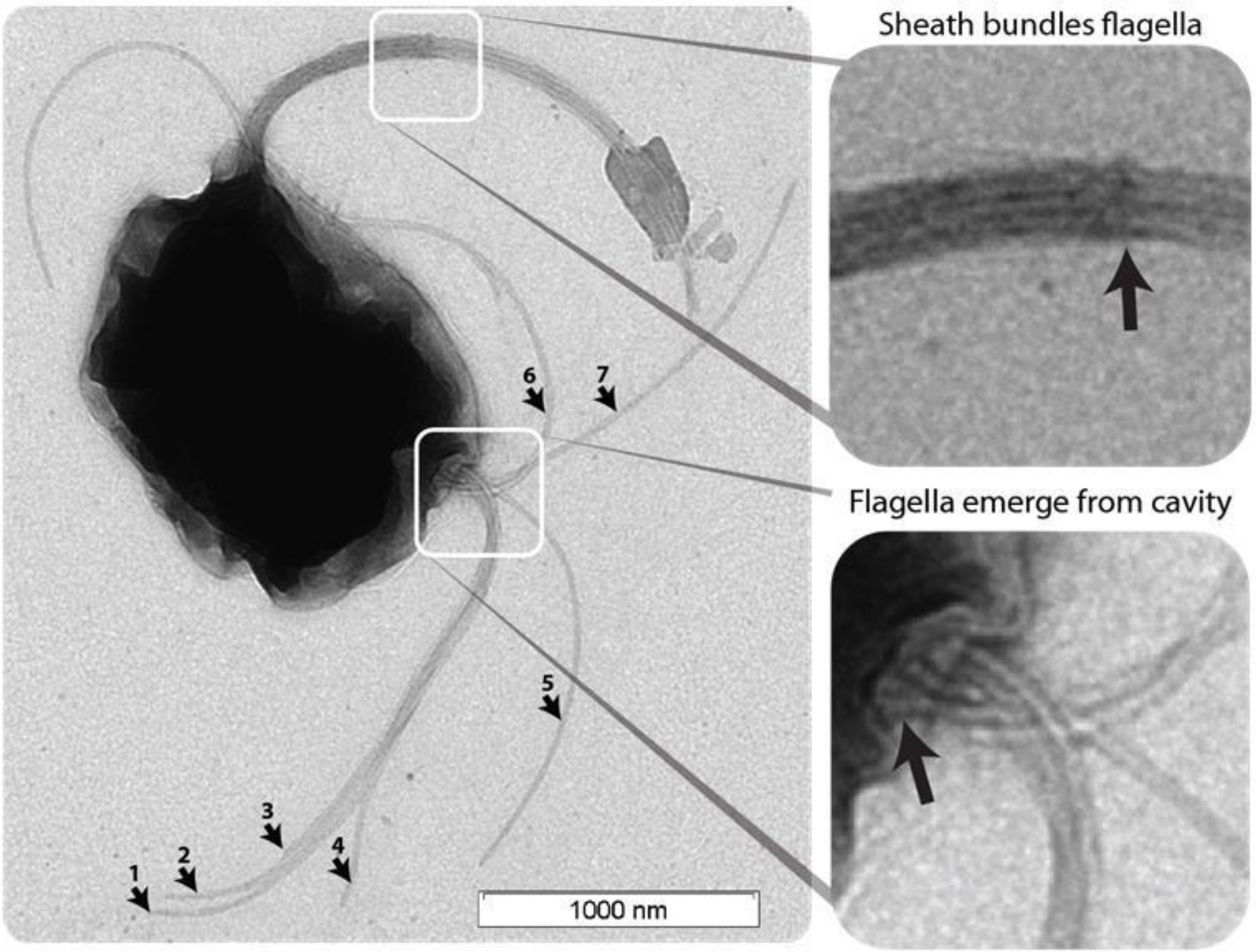
Pfeiffer et al., Applied and Environmental Microbiology, 2020

Swimming magnetotactic bacteria

THE RECORD-BREAKING BUG

THE RECORD-BREAKING BUG

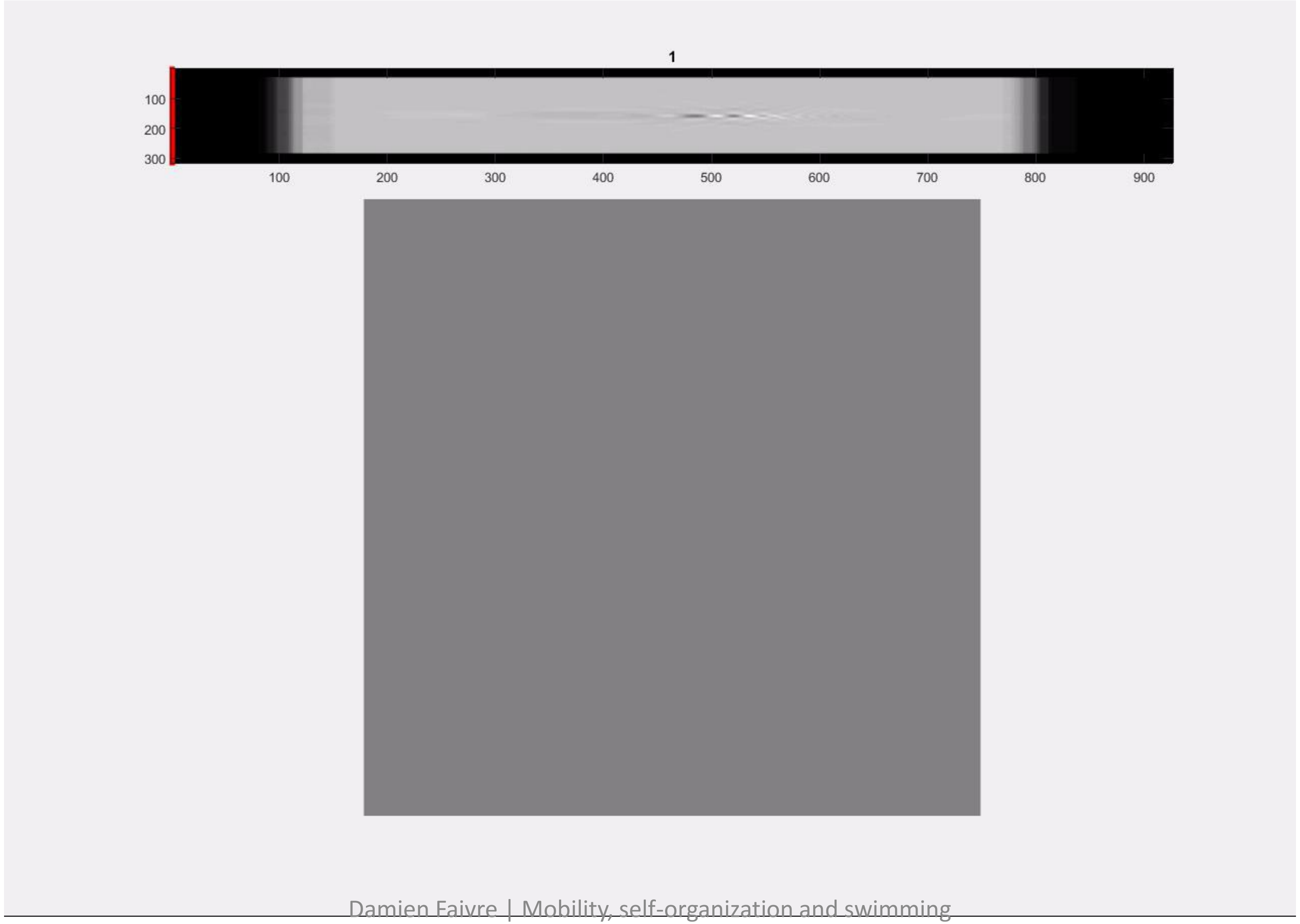
MC-1



Bente et al., eLife, 2020

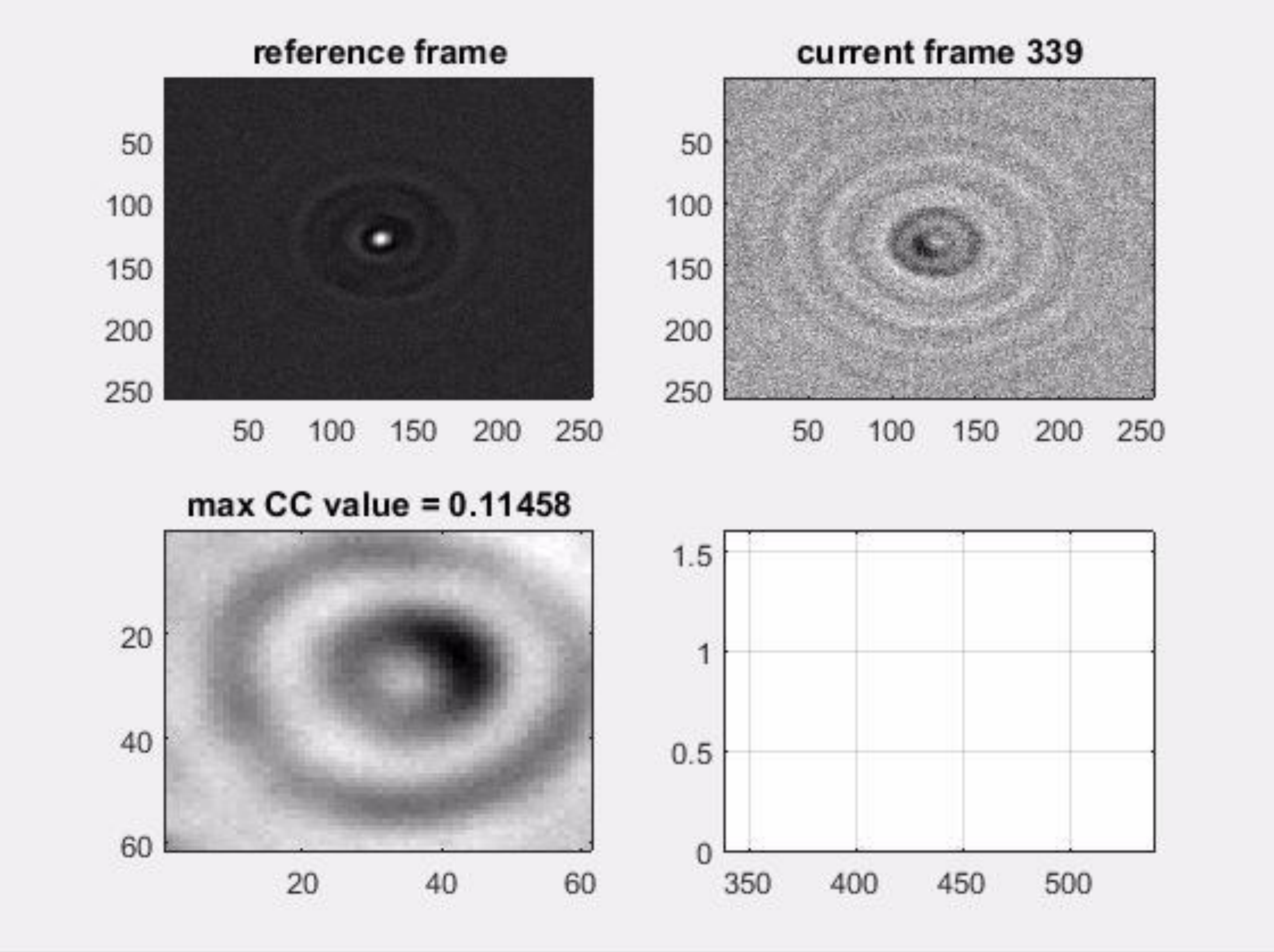
OPEN-FRAME MICROSCOPE

Introducing the third dimension



OPEN-FRAME MICROSCOPE

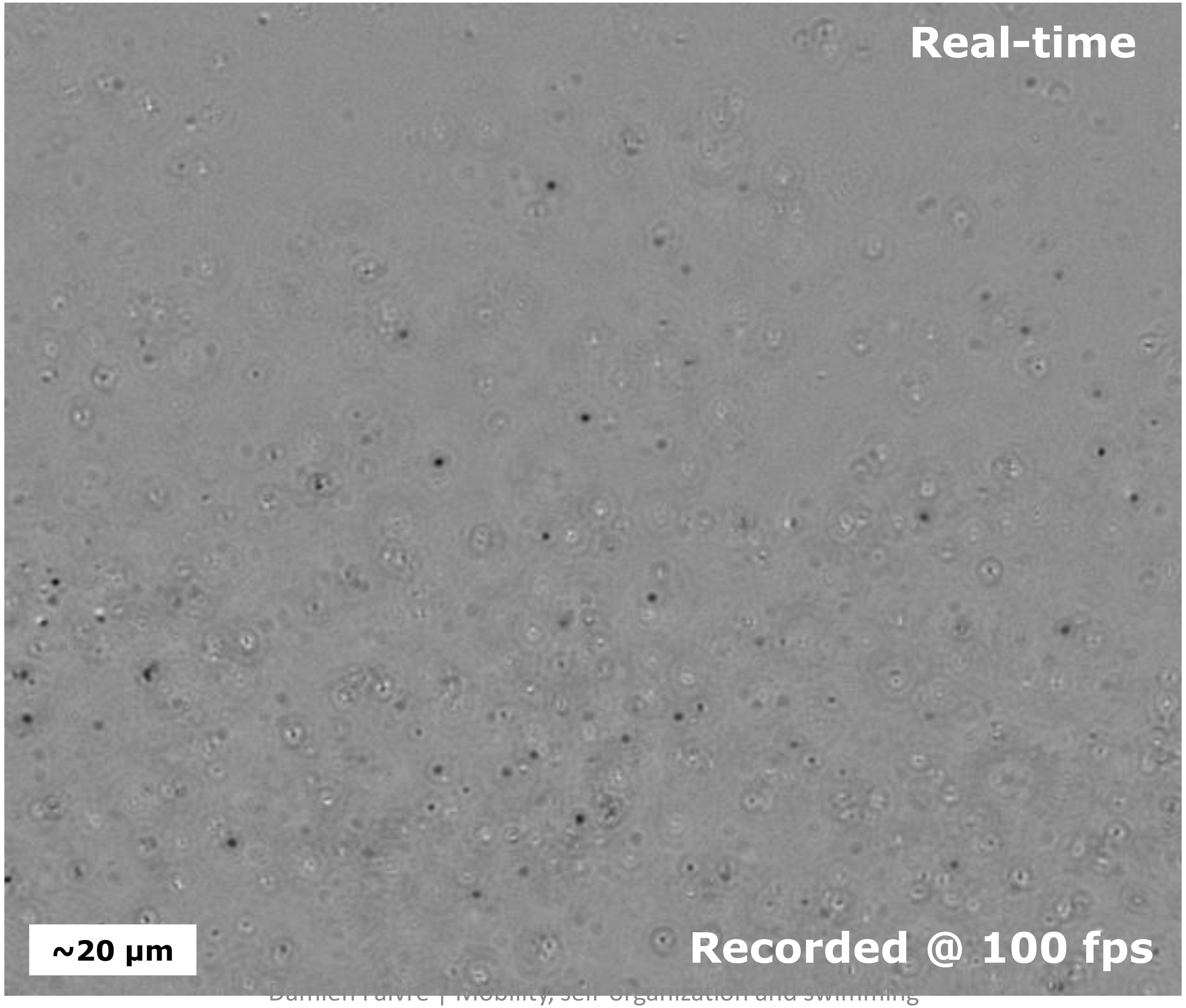
3D tracking



Following Taute et al., Nature Communications, 2014

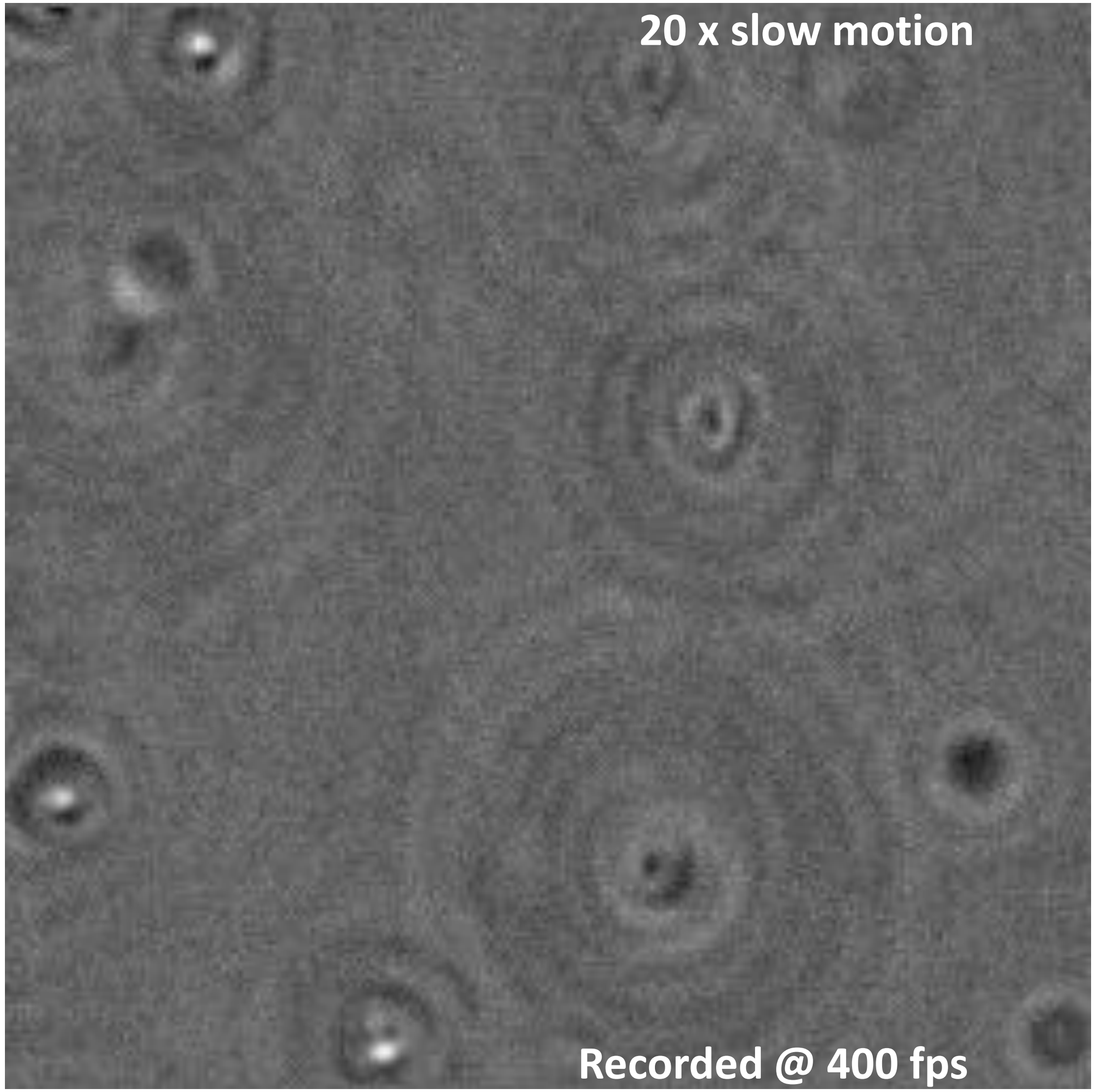
SWIMMING FAST

MC-1



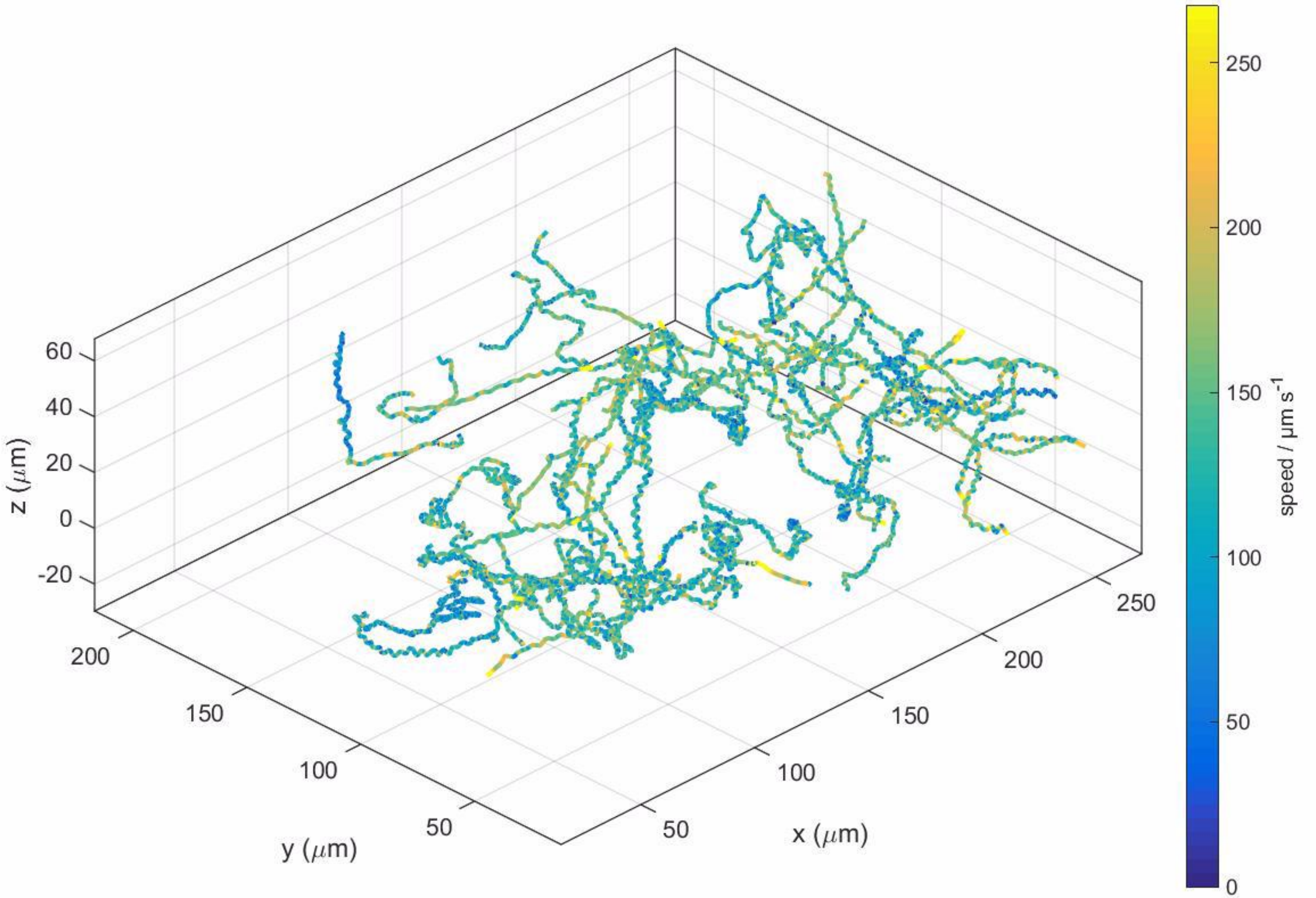
SWIMMING FAST

MC-1



SWIMMING FAST

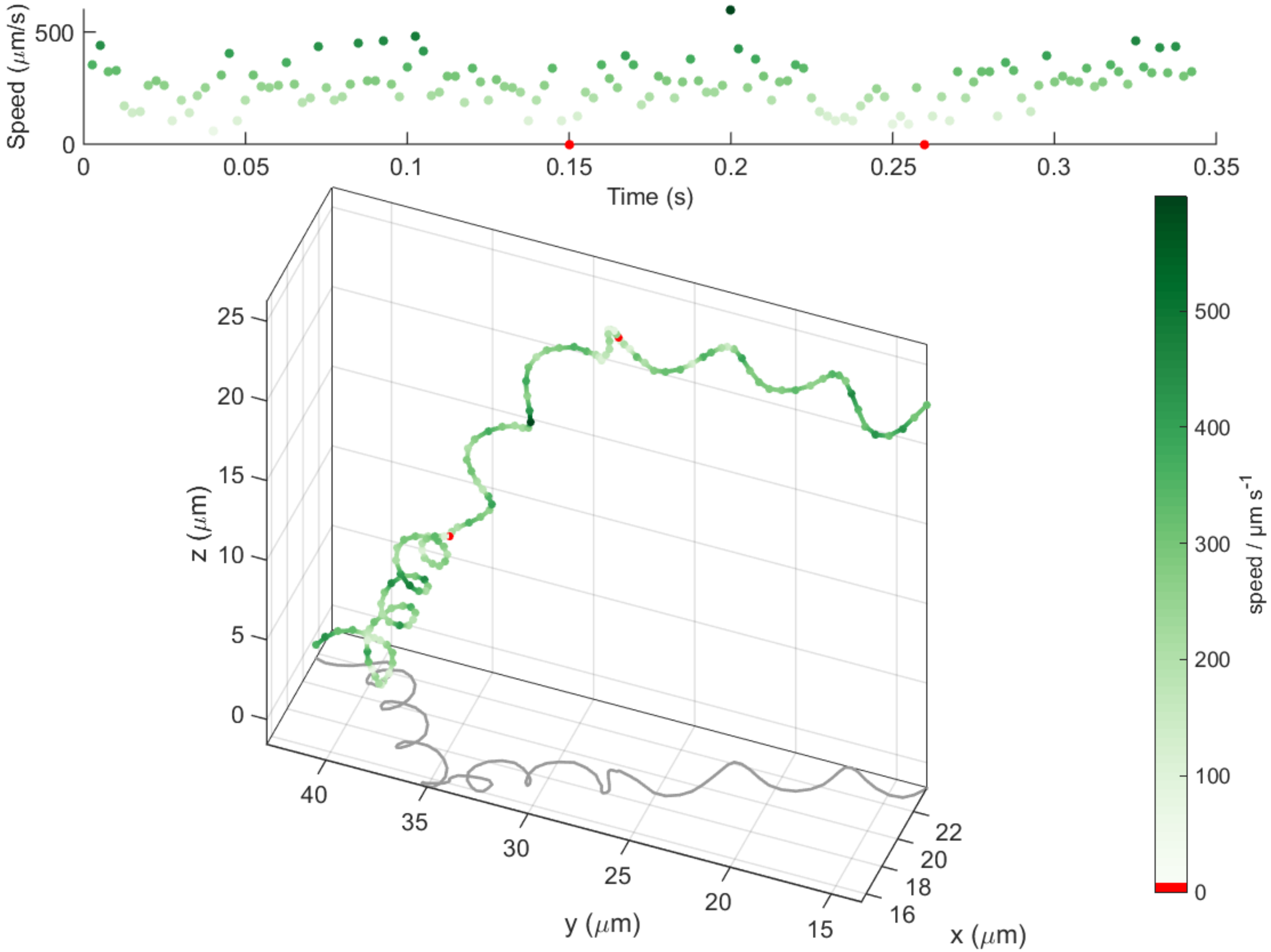
3D paths of MC-1 swimming



Bente et al., eLife, 2020

FAST REORIENTATION

Dark field @ 1640 fps

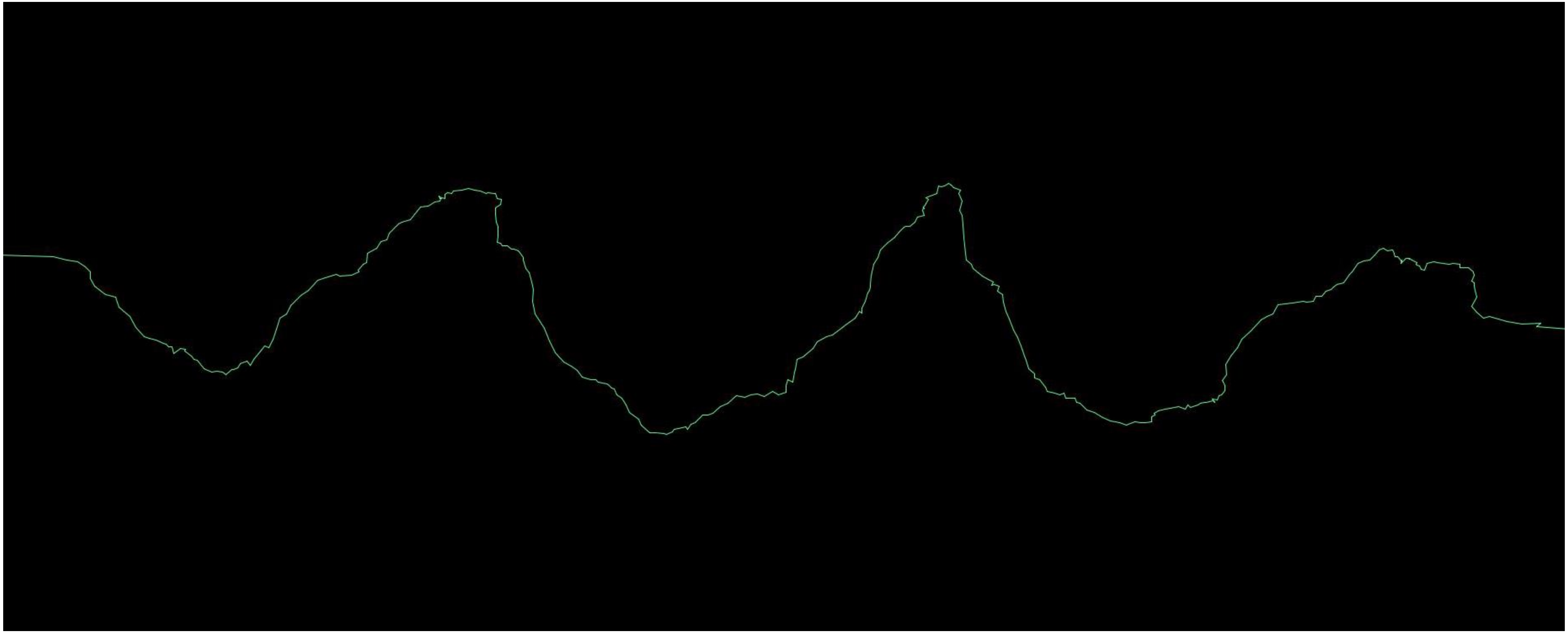


- Stop time of only 2.5 ms

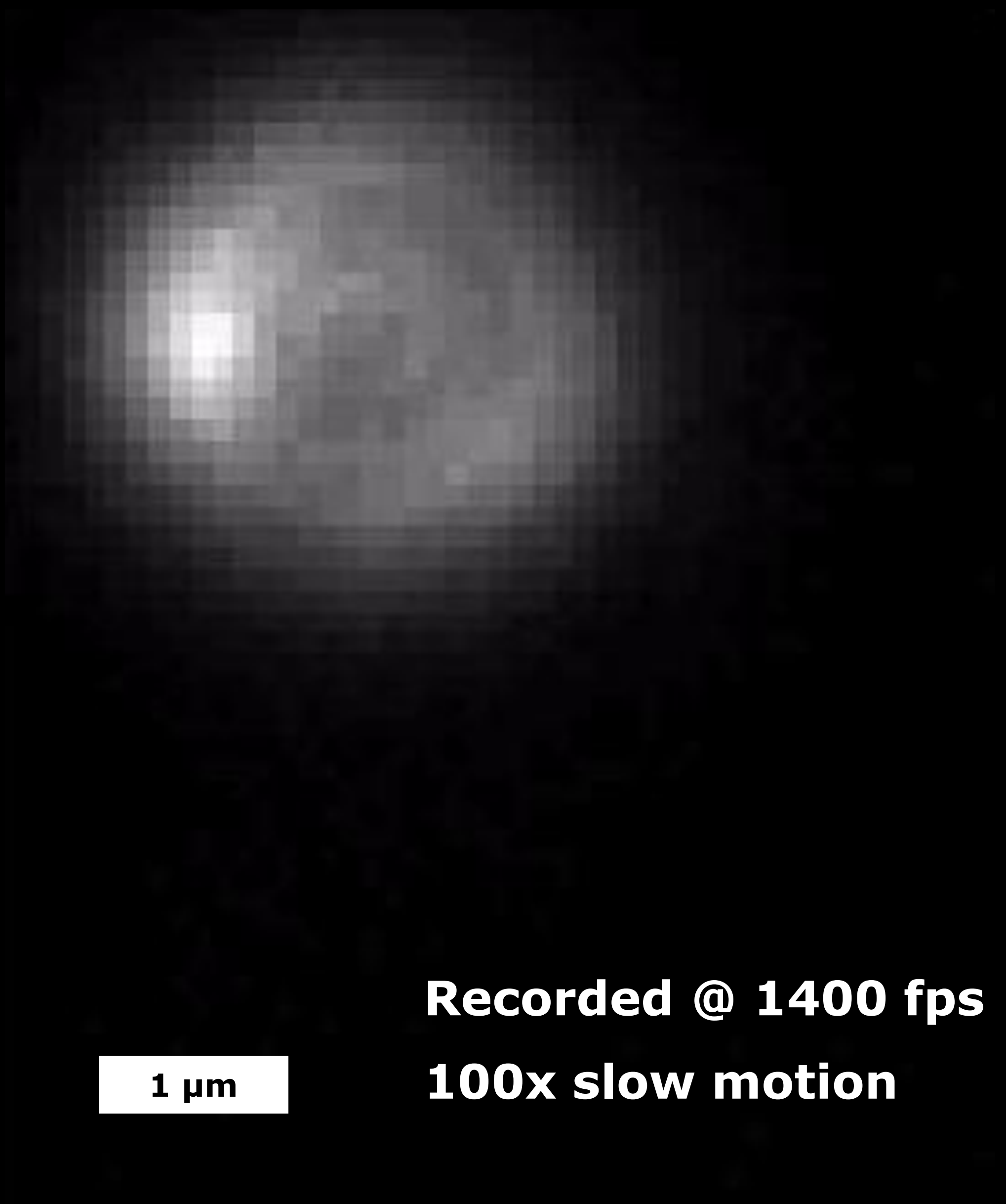
Bente et al., eLife, 2020

FAST BACTERIA

Looking at the effective path



…High Resolution, High Speed dark-field setup



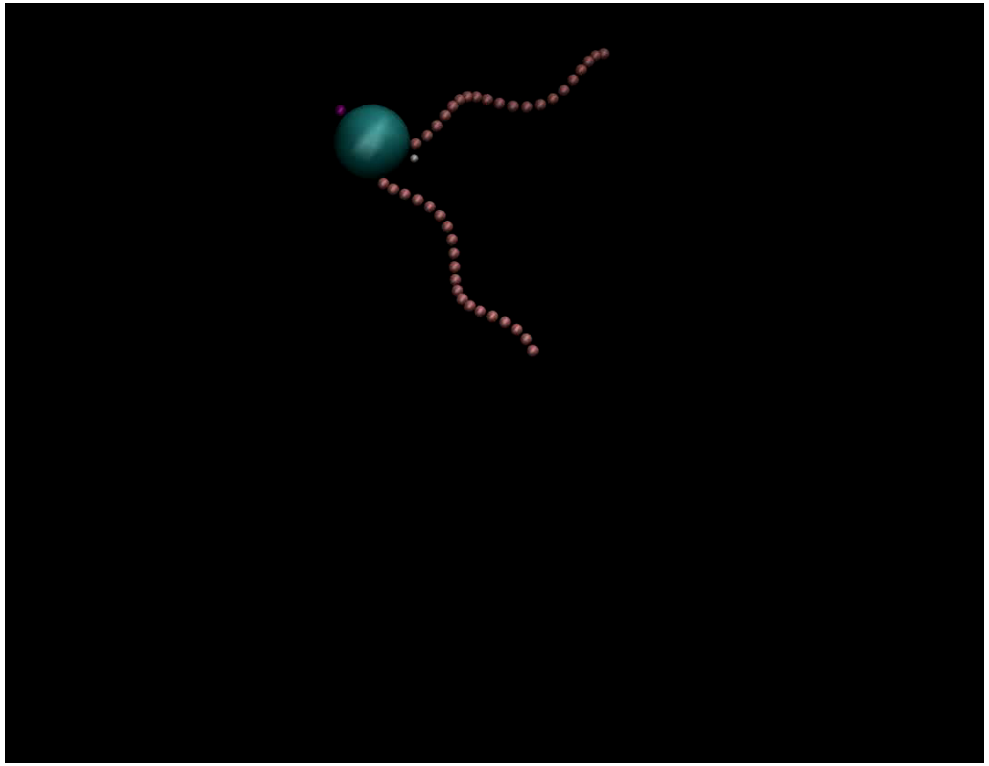
Recorded @ 1400 fps

100x slow motion

FAST BACTERIA

Simulation to explain

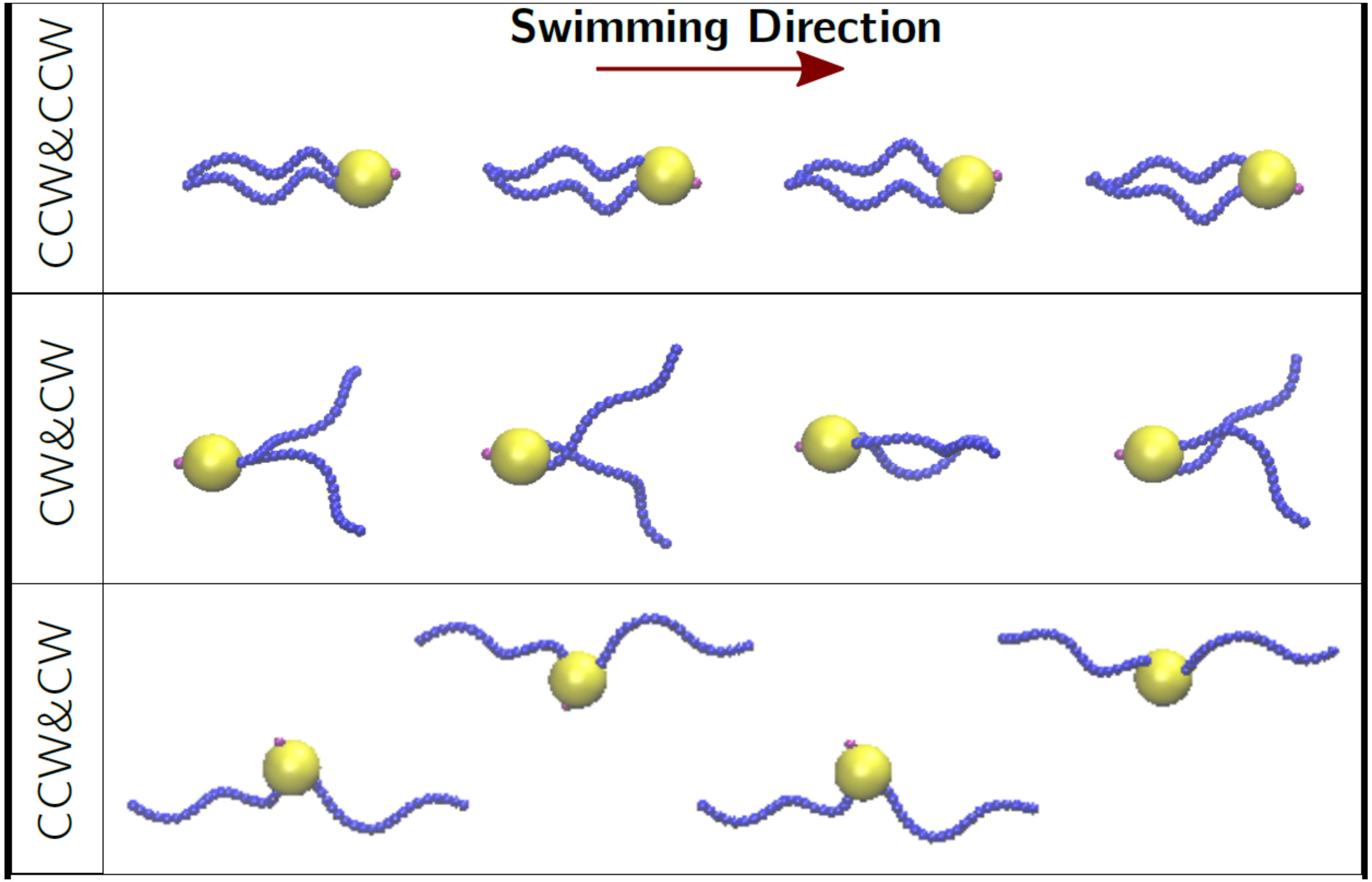
Simulations by group of S. Klumpp
Typical expected movement: both flagella rotate CCW
No large helices apparent



CCW and CW
Hooks revolve & large helices apparent

FAST BACTERIA

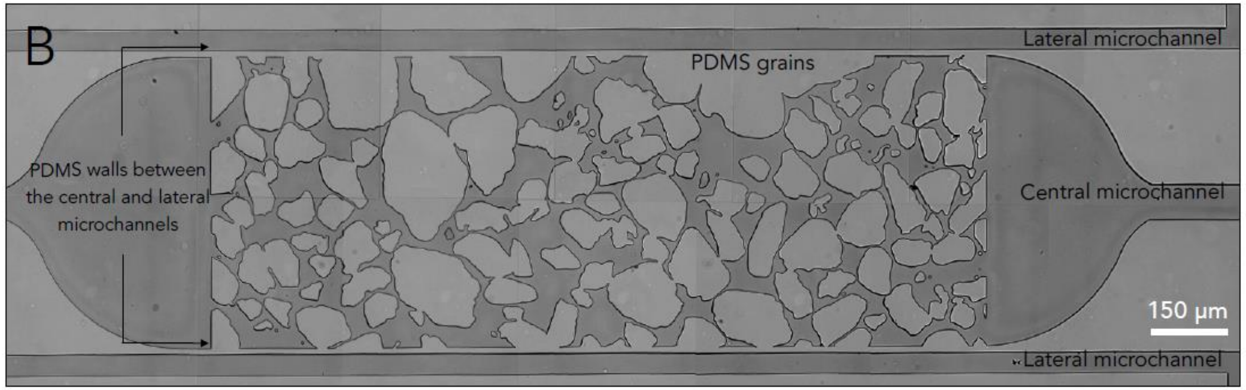
Summary scheme

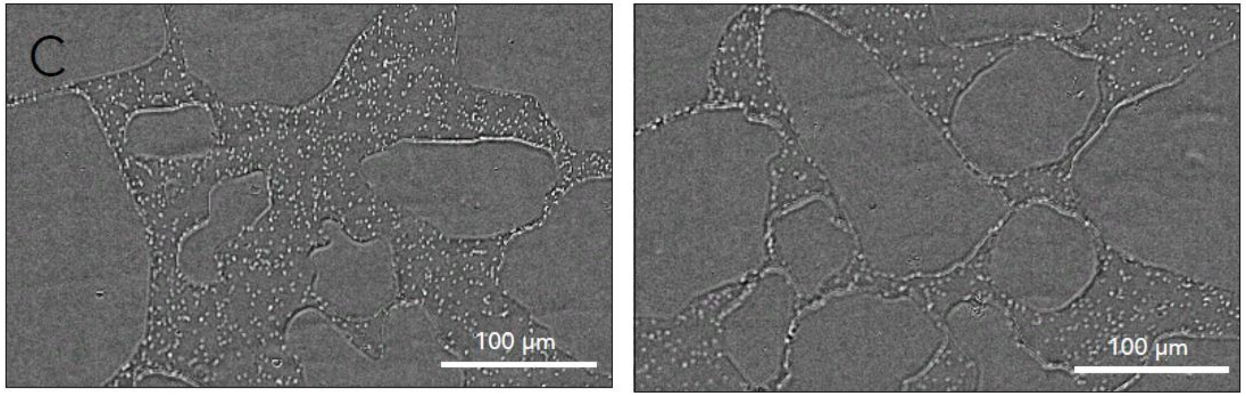


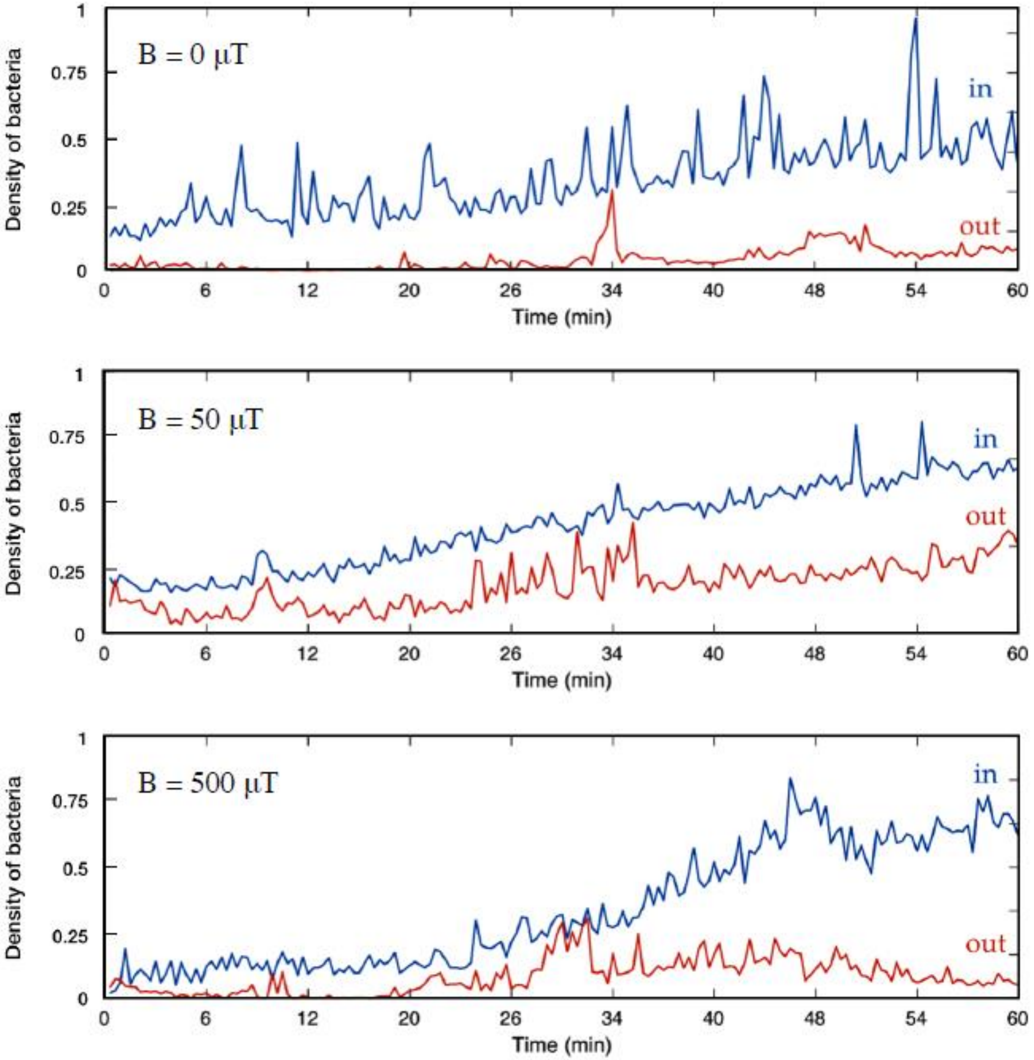
Bente et al., eLife, 2020

SEDIMENT BACTERIA

Summary scheme







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DFG

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erc

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Alexander von Humboldt
Stiftung/Foundation

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