Chiral transport in viscous flows: from micro-helices to bacteria

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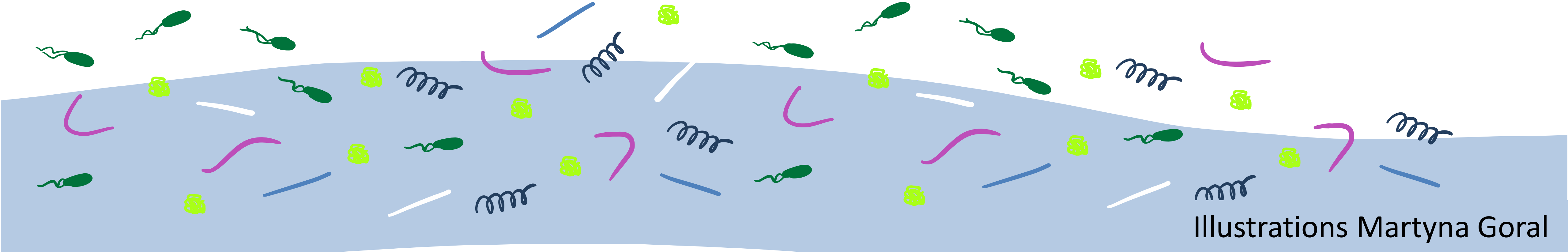
Institut Universitaire de France

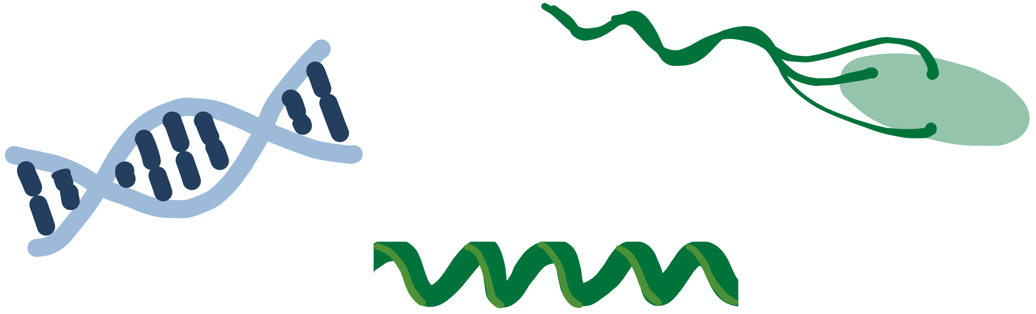
Chiral particles and Odd fluids
Eindhoven January 2026



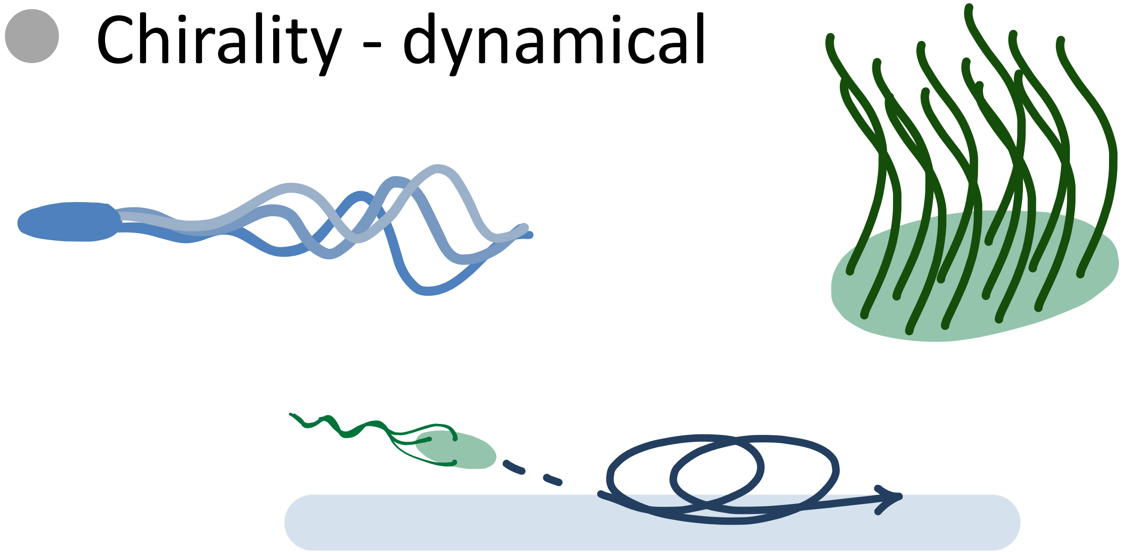
Illustrations Martyna Goral

Chirality occurs in many forms in nature....

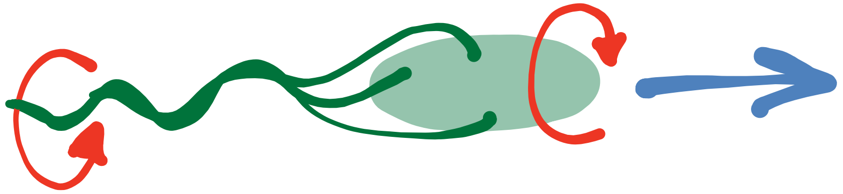
- Chirality - rigid

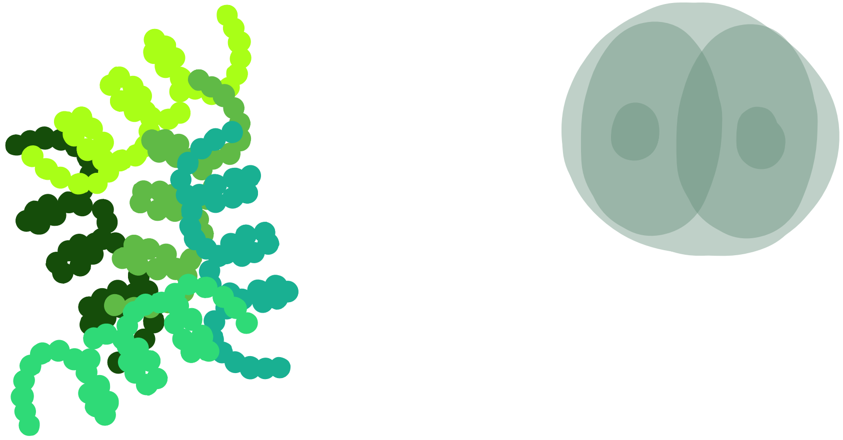


- Chirality - dynamical



- Biological function

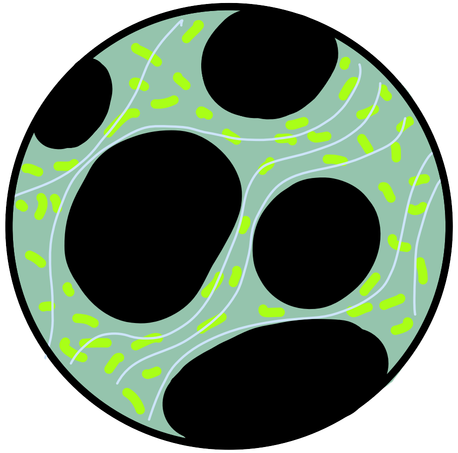


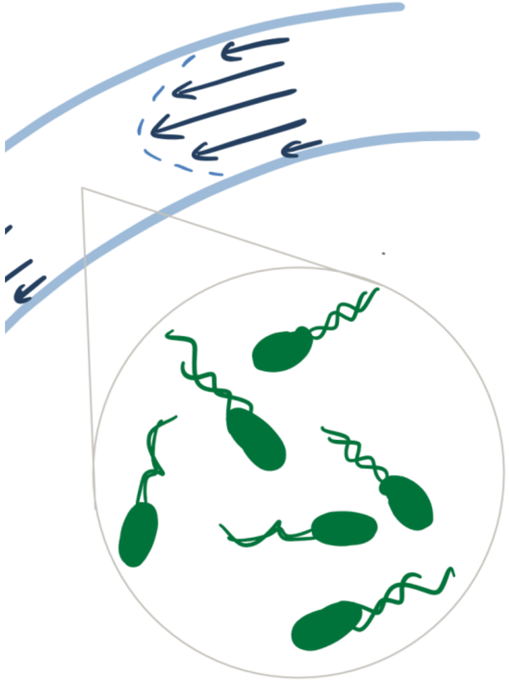


... and plays important role in symmetry breaking

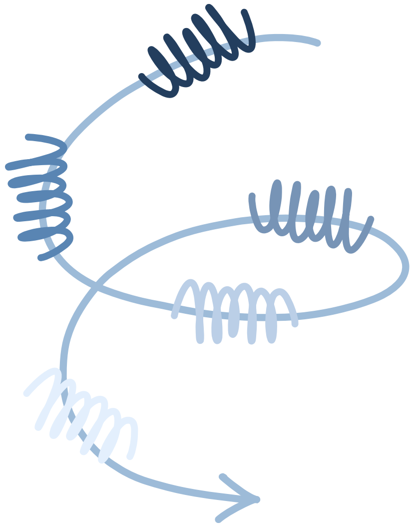
Chirality impacts particle transport....

- Nature

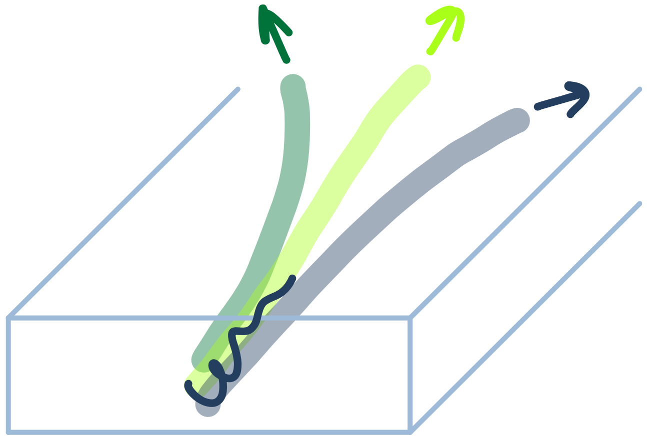




- Applications



Palusa *et al.*, PRF (2018)



Marcos, PRL, 2009

Bechert, AL, et al, EPL, 2019

... essential to understand their fluid structure interactions

To set the stage ….. describing flow properties

Incompressibility

$$\nabla.\boldsymbol{u} = 0$$

Momentum equation (Navier-Stokes equation)

$$\rho\ \frac{\partial \boldsymbol{u}}{\partial t} + \rho(\mathbf{u}.\nabla)\boldsymbol{u} = \boldsymbol{f} - \nabla p + \eta\nabla^2\boldsymbol{u}$$

For Re<<1 viscous forces dominate inertial forces

$$Re = \frac{\rho(\mathbf{u}.\nabla)\boldsymbol{u}}{\eta\nabla^2\boldsymbol{u}} = \frac{\rho U L}{\eta}$$

To set the stage .... Viscous flows

Incompressibility

$$\nabla.\boldsymbol{u} = 0$$

Momentum equation (Navier-Stokes equation)

$$\cancel{\rho\frac{\partial \boldsymbol{u}}{\partial t}} + \cancel{\rho(\mathbf{u}.\nabla)\boldsymbol{u}} = \boldsymbol{f} - \nabla p + \eta\nabla^2\boldsymbol{u}$$

To set the stage .... Viscous flows

Incompressibility

$$\nabla . \boldsymbol{u} = 0$$

Momentum equation (Stokes equation)

$$-\nabla p + \eta \nabla^2 \boldsymbol{u} = 0$$

Implies very specific flow properties

- Linearity
- Reversibility
- Instantaneity

To set the stage …. Fluid structure interactions

Incompressibility

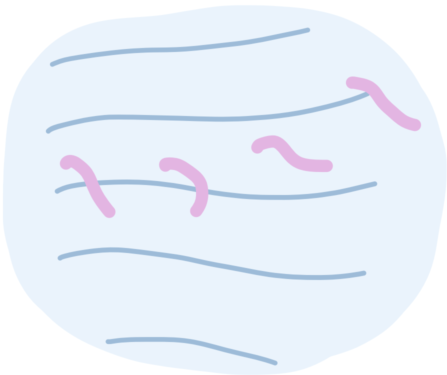
$$\nabla.\boldsymbol{u} = 0$$

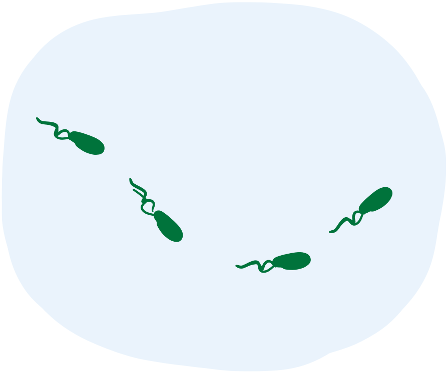
Momentum equation (Stokes equation)

$$-\nabla p + \eta \nabla^2 \boldsymbol{u} = 0$$

Implies very specific flow properties … and nature of fluid structure interactions

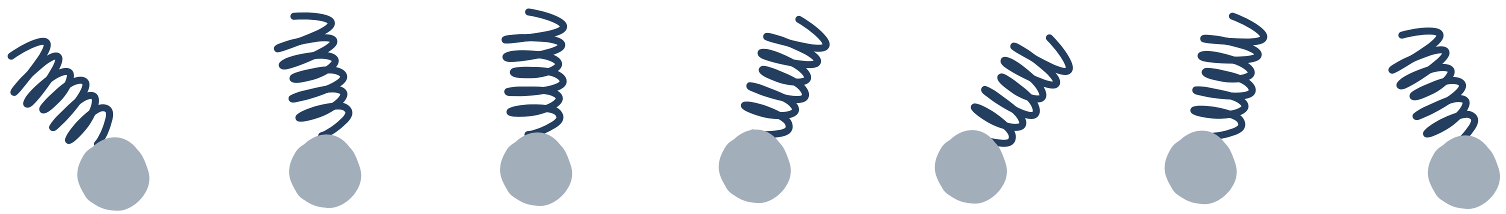
- Linearity
- Reversibility
- Instantaneity





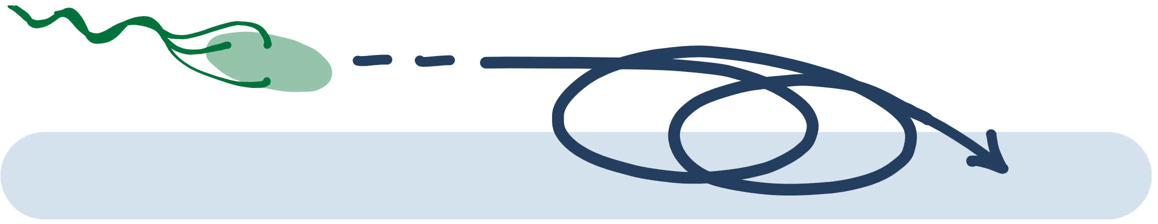
Study a number of well controlled model systems ....

- Active and passive chiral particles in shear flows



- Interlude: flexible helix fabrication

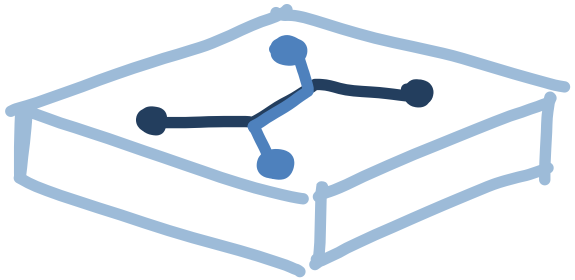
- Chirality in swimming trajectories and their role on bacteria transport



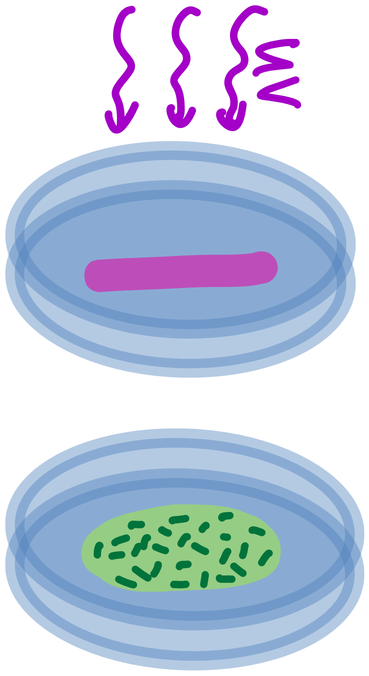
.... to better understand the role of chirality on transport properties

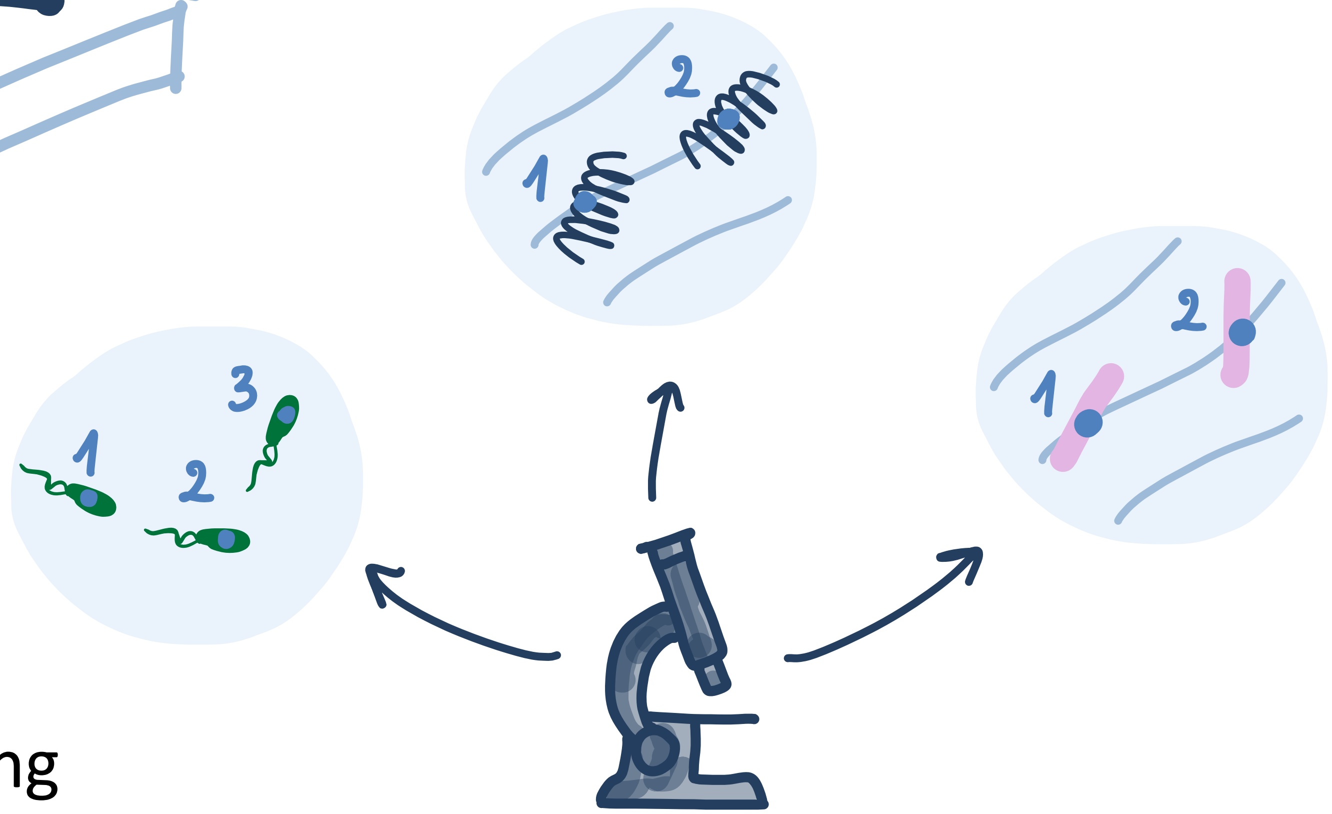
Investigation requires well controlled model systems…

- Flow and geometries : Microfluidics



- Particles : Microfabrication and biological objects

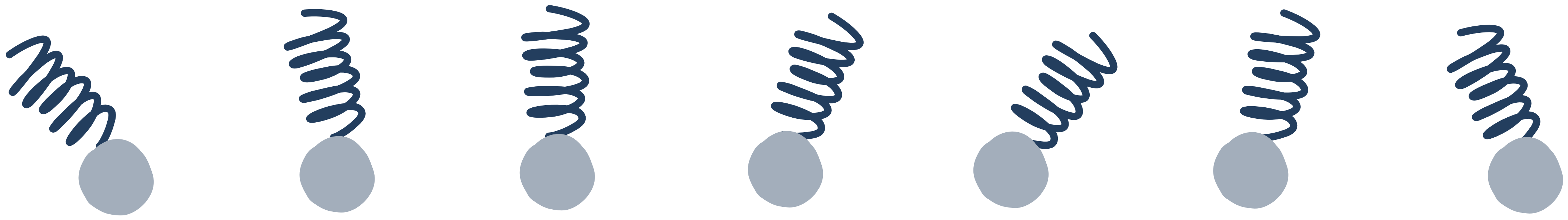




- Particle tracking

…microfluidic systems lead perfect control on flow and particle properties

Active and passive chiral particles in shear flows

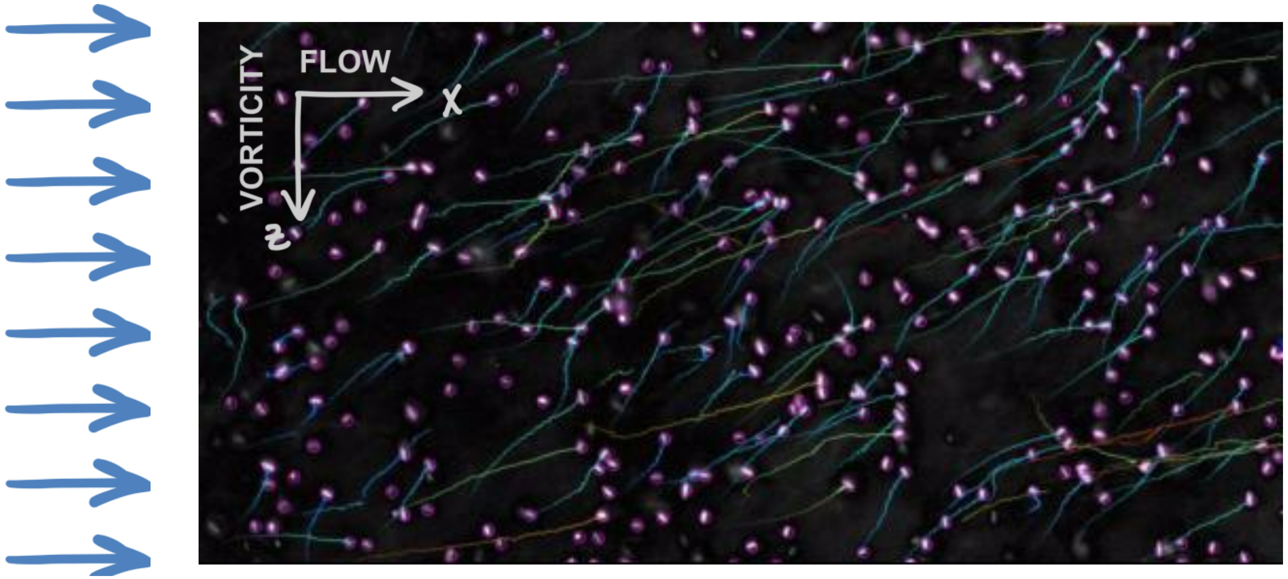


Francesca Tesser, Guangyin Jing (now Northwest University, Xi'an, China), Justine Laurent, Eric Clement, Olivia du Roure (PMMH-ESPCI, Paris, France)
Arnold Mathijssen (UPenn, USA), Daiki Matsunaga (Osaka, Japan) and Andreas Zöttl (Uni Wien, Austria)

Chiral particles and Odd fluids - Eindhoven January 2026

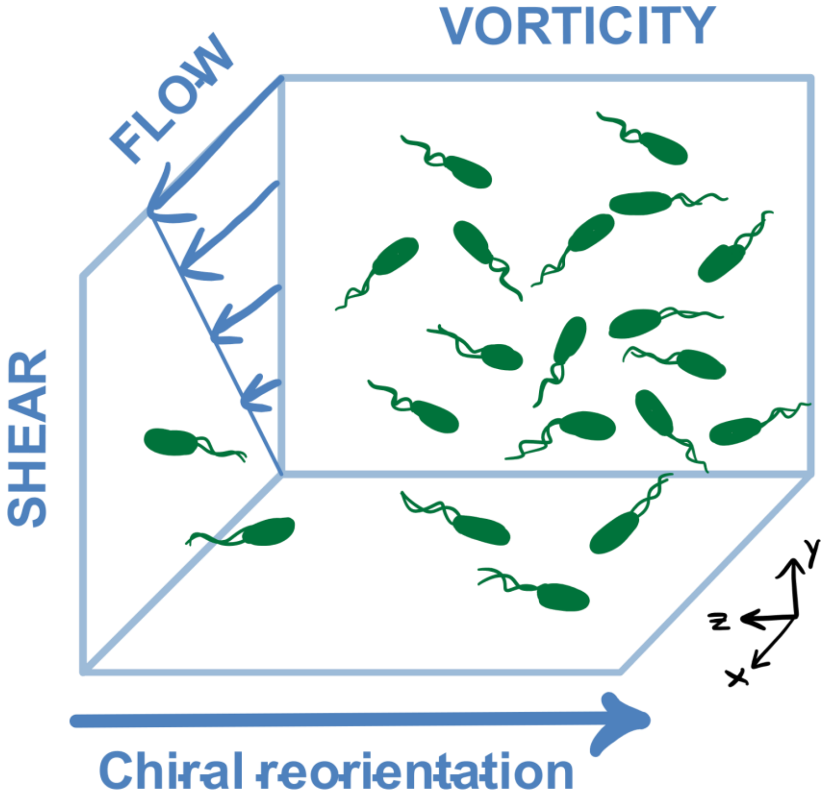
Surprising transport properties of chiral particles: bacterial rheotaxis

- Experimental observation of flagellated bacteria in shear flows



Jing, Zöttl, AL et al, Science Advances 2020

- Drift into the vorticity direction

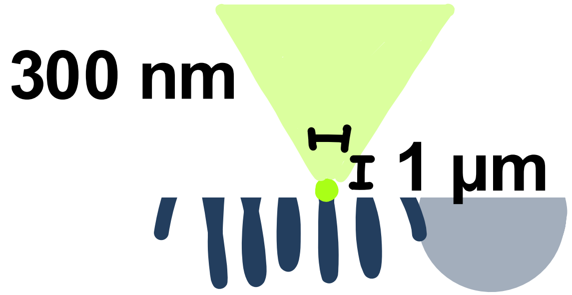


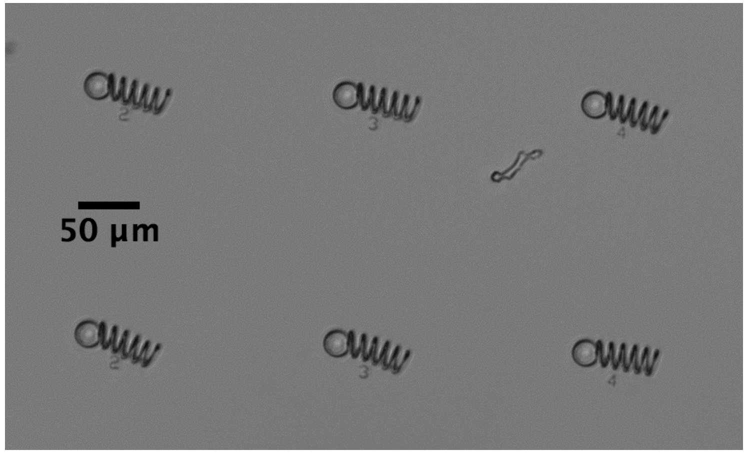
Marcos et al, PNAS, 2012

Have been attributed to bacteria shape

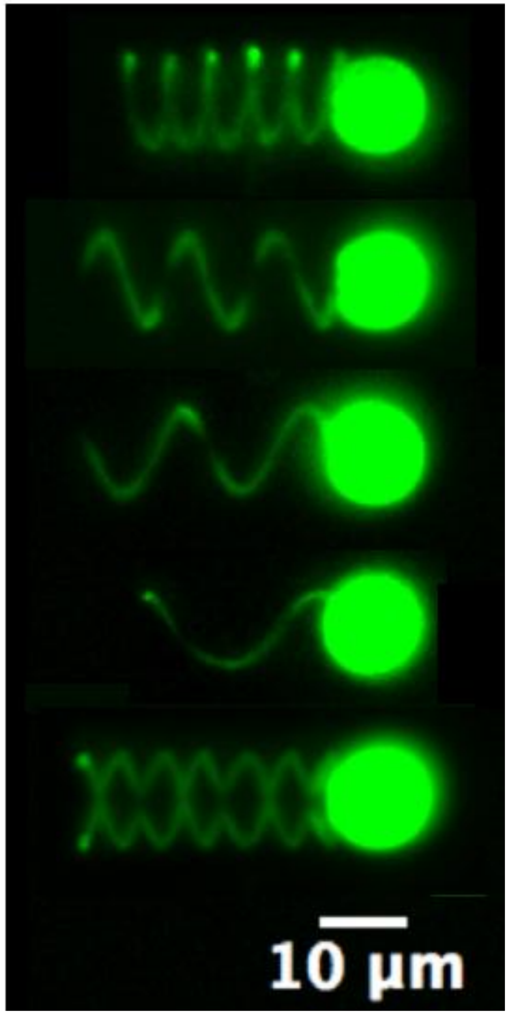
Can we build a non biological model system with full control on particle shape?

- 3D printing: two photon printer





J. Laurent, PMMH-ESPCI



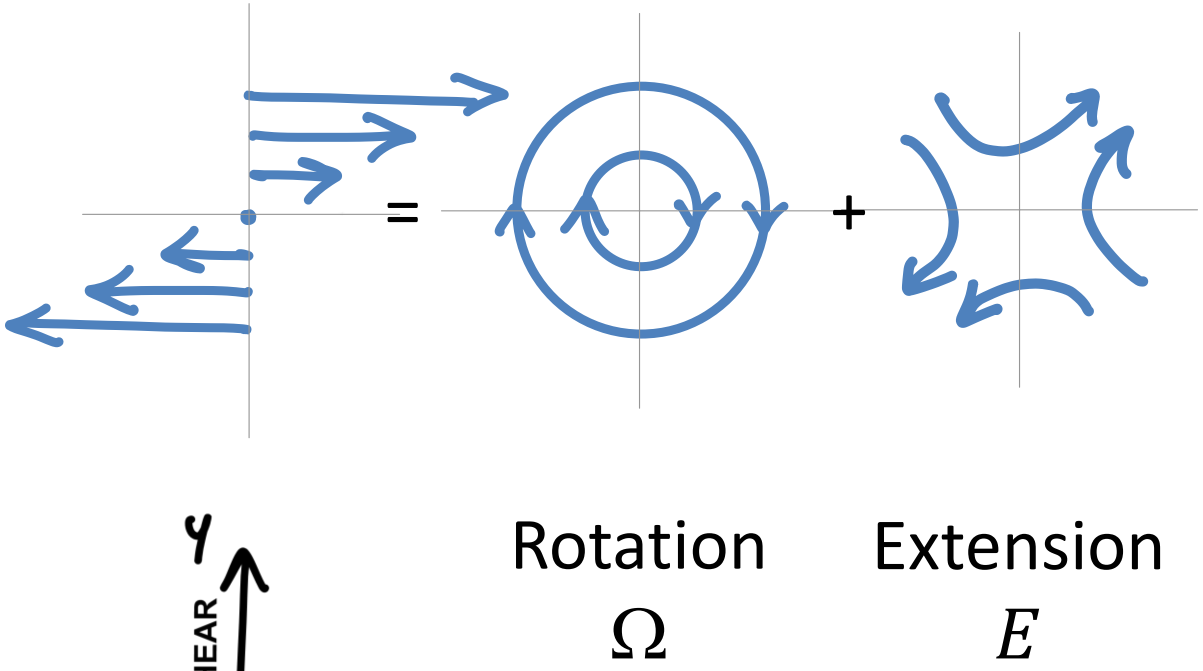
Zöttl, AL et al, PNAS, 2023

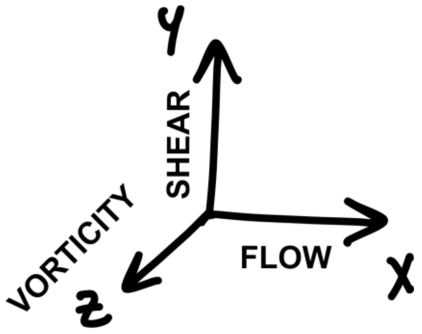
- Perfect control of shape (pitch, radius, length) and handedness
- Absence of biological and Brownian noise
- Nearly density matched
- … but printed one by one and quite delicate

Passive microprinted non – Brownian "bacteria"

Step back: what do we know on particle transport in viscous shear flows

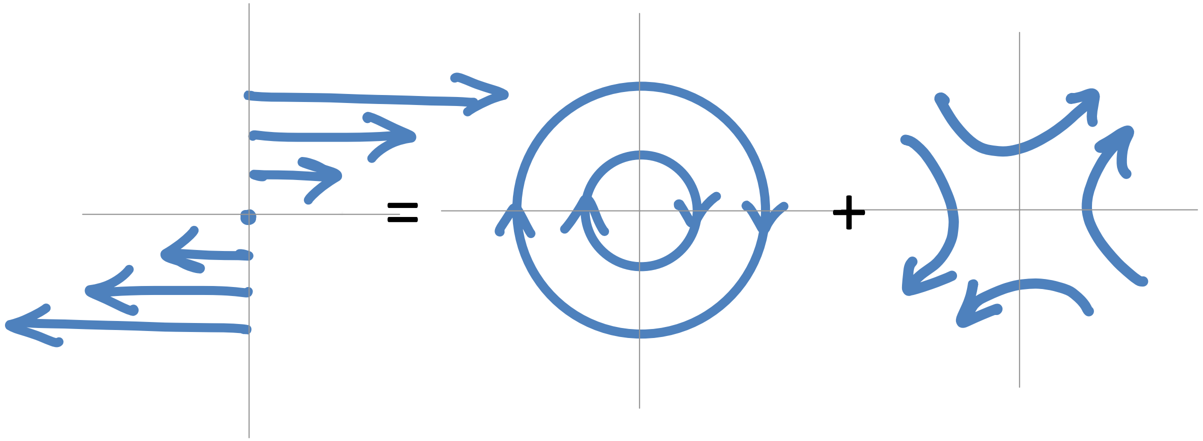
- Shear flow properties – velocity gradients





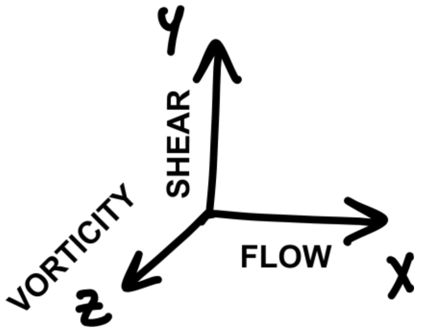
Particle transport in viscous shear flows - sphere

- Shear flow properties – velocity gradients

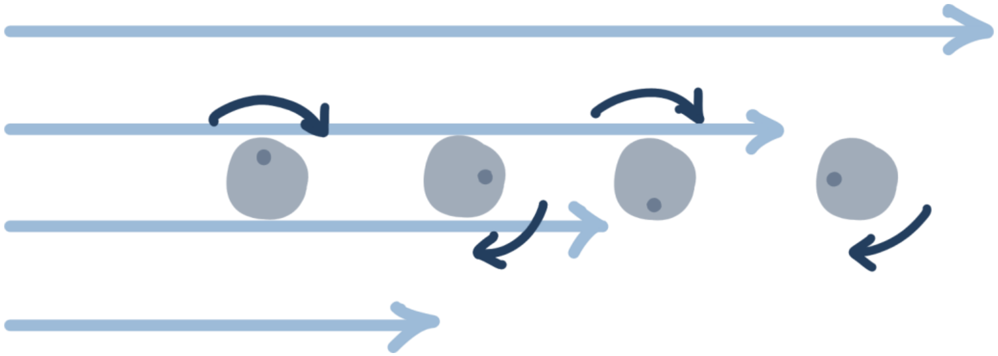


Rotation Ω

Extension E



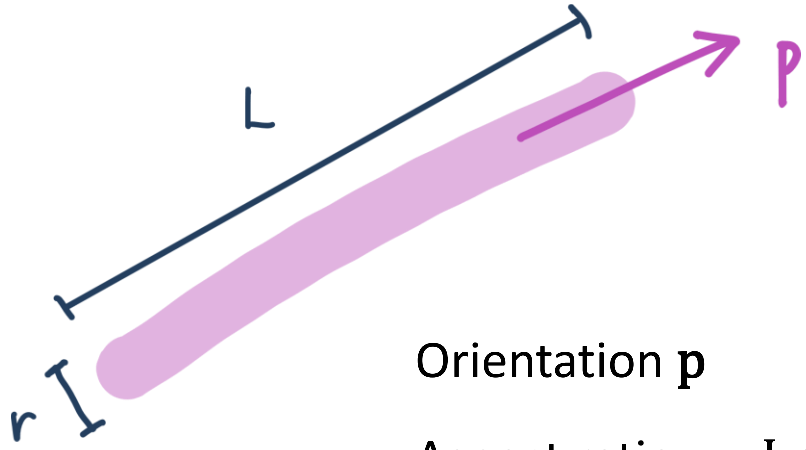
- Isotropic particle (sphere)



Transported along the streamlines while rotating with Ω

Particle transport in viscous shear flows - fiber

- Anisotropic particle – fiber



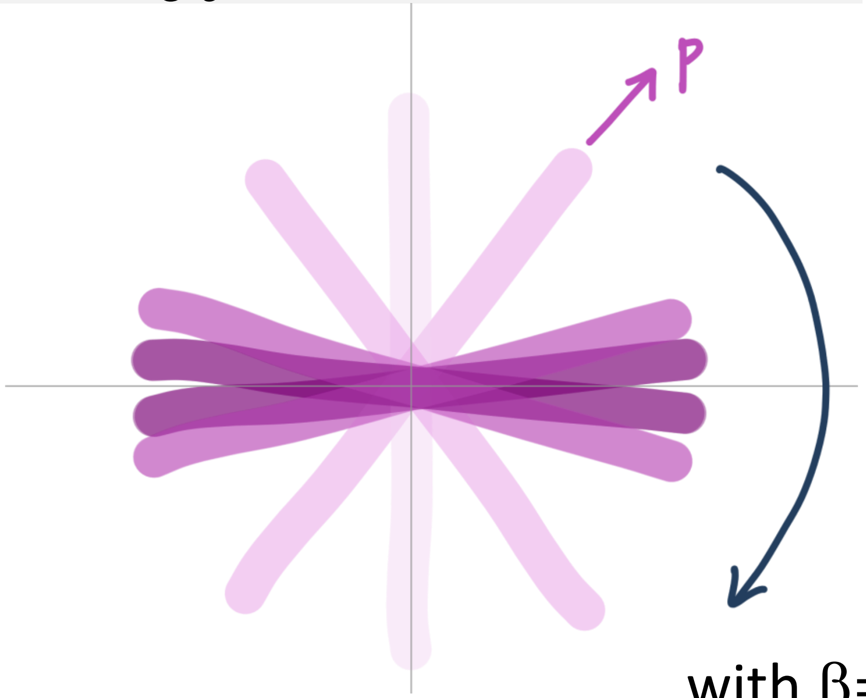
Orientation $\mathbf{p}$

Aspect ratio $\alpha = L/r$

Slender object with orientation

- Jeffery orbits

$$\frac{\partial \boldsymbol{p}}{\partial t} = (\Omega + \beta\, E)\boldsymbol{p}$$

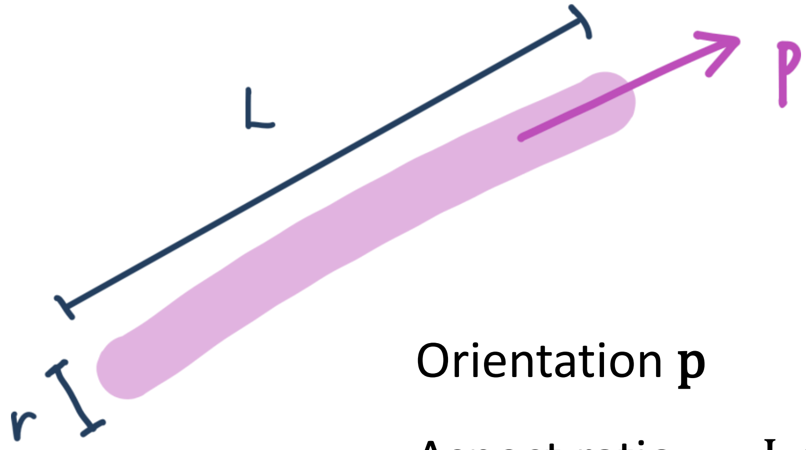


with $\beta = \frac{(\alpha^2 - 1)}{(\alpha^2 + 1)}$

Fiber tumbles spending most time aligned with the flow direction

Particle transport in viscous shear flows - fiber

- Anisotropic particle – fiber



Orientation **p**

Aspect ratio $\alpha = L/r$

Slender object with orientation

- Jeffery orbits

$$\frac{\partial \boldsymbol{p}}{\partial t} = (\Omega + \beta\, E)\boldsymbol{p}$$

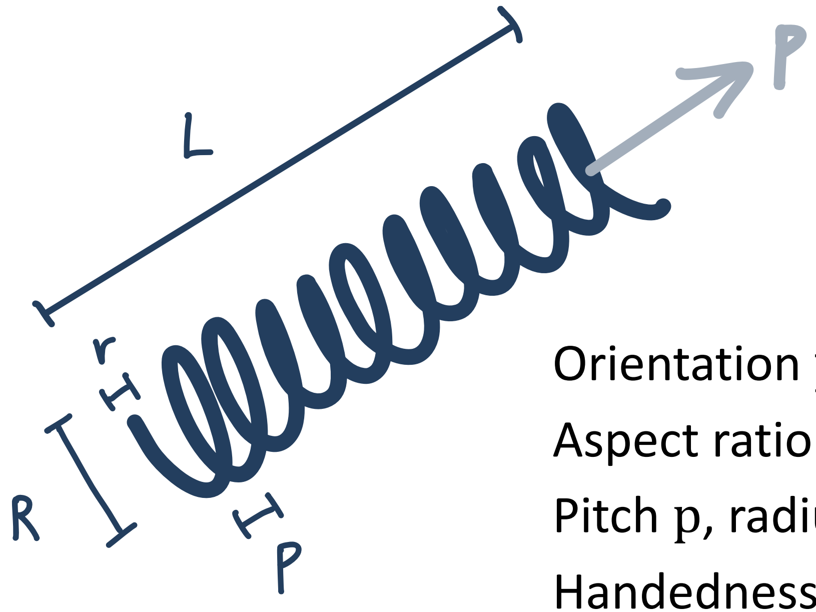
Periodic tumbling

Jeffery GB, Proc. R. Soc. Lond. 1922

Transported along the streamlines while tumbling

Particle transport in viscous shear flows - helices

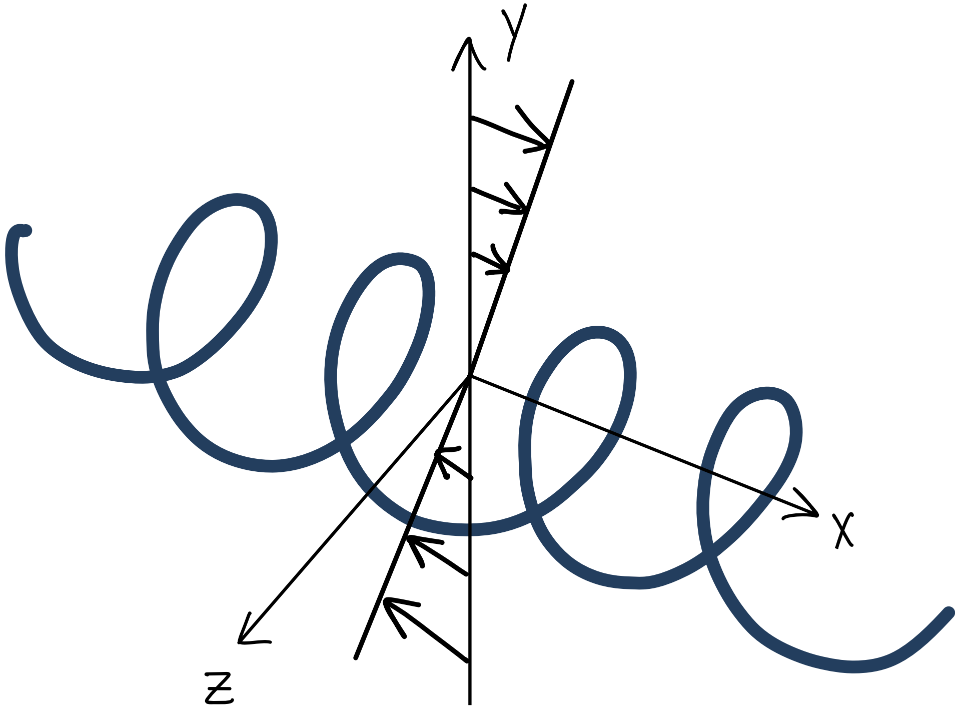
- Chiral particle – helix



Orientation **p**
Aspect ratio α~L/R
Pitch p, radius R
Handedness X

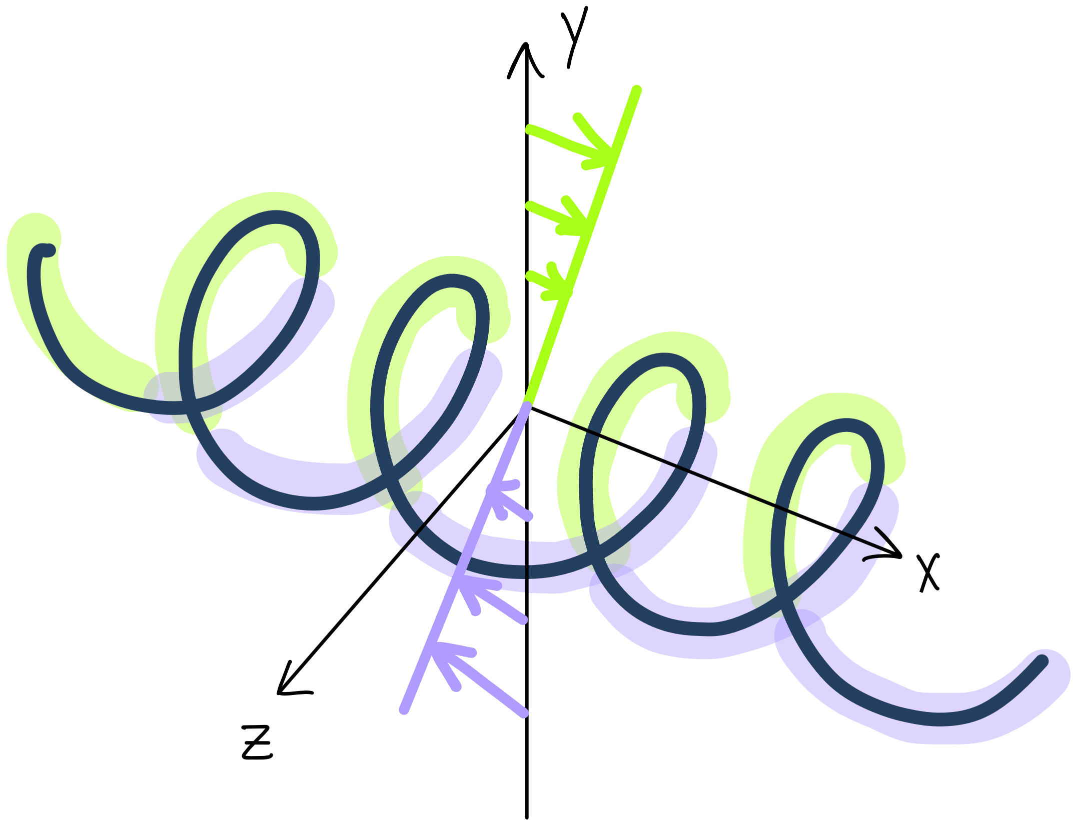
Effective slender object (α ~L/R),
local slender object (~ R/r)

- Jeffery orbits predominantly align helix with flow direction

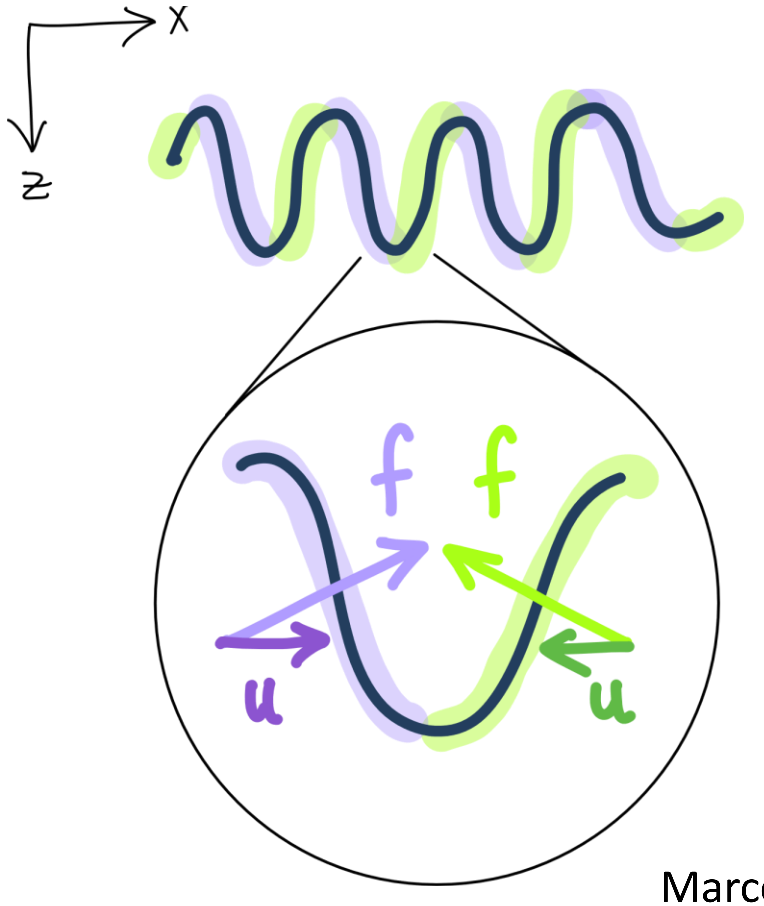


Particle transport in viscous shear flows - helices

- Different parts of the helix experience different flows



- Drift into vorticity direction (given by handedness)

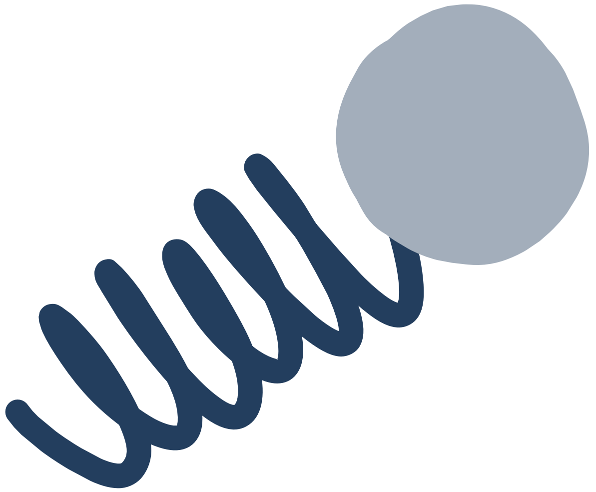


Marcos, PRL, 2009

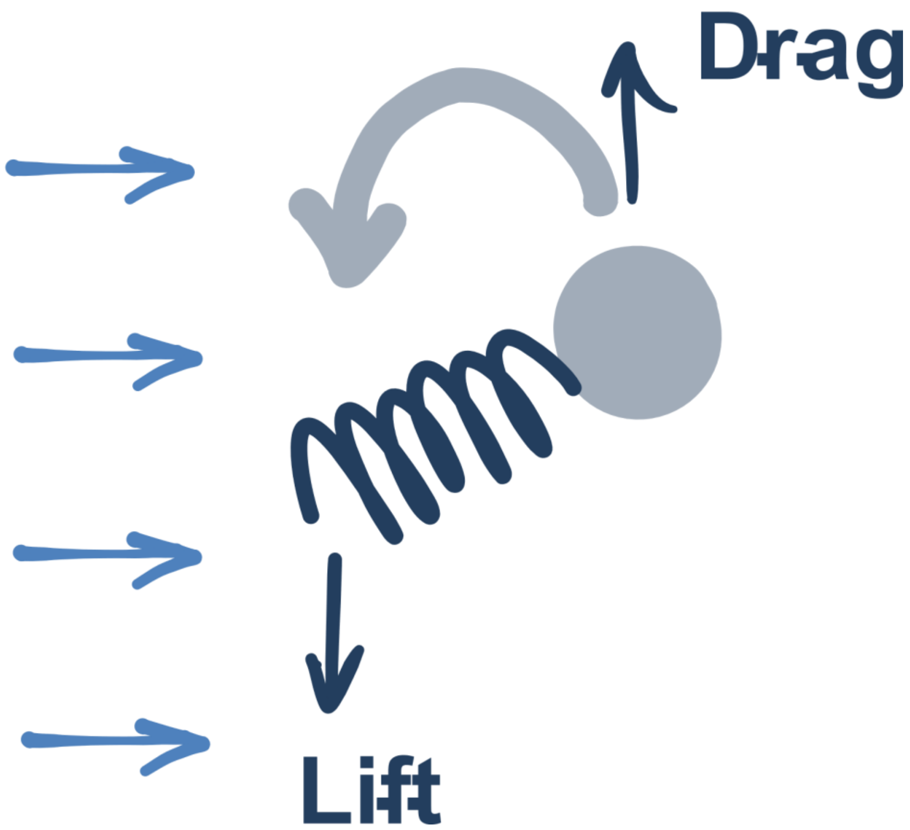
Helix drift can be explained from slender body theory

Particle transport in viscous shear flows - asymmetric chiral particle

- Asymmetric chiral particle



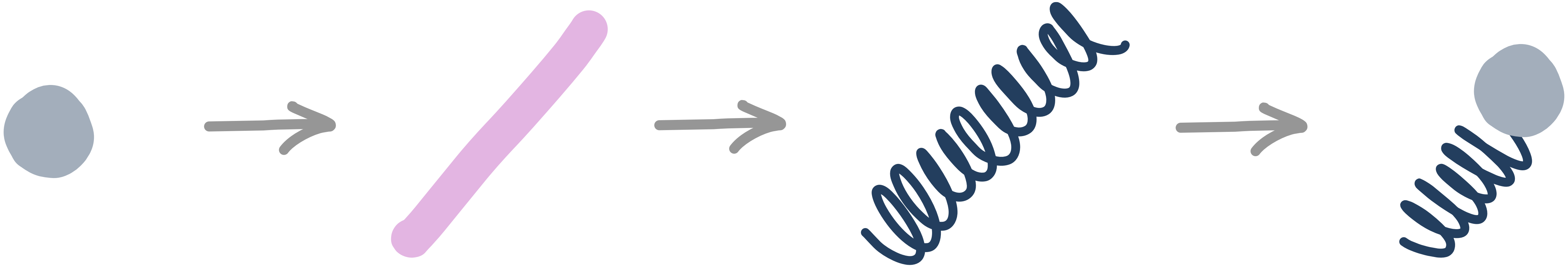
- Chirality induced rheotactic torque



Rheotactic torque reorients particles into the vorticity direction

Passive particle transport .....

- Isotropic
- Anisotropic
- Chiral
- Asymmetric chiral

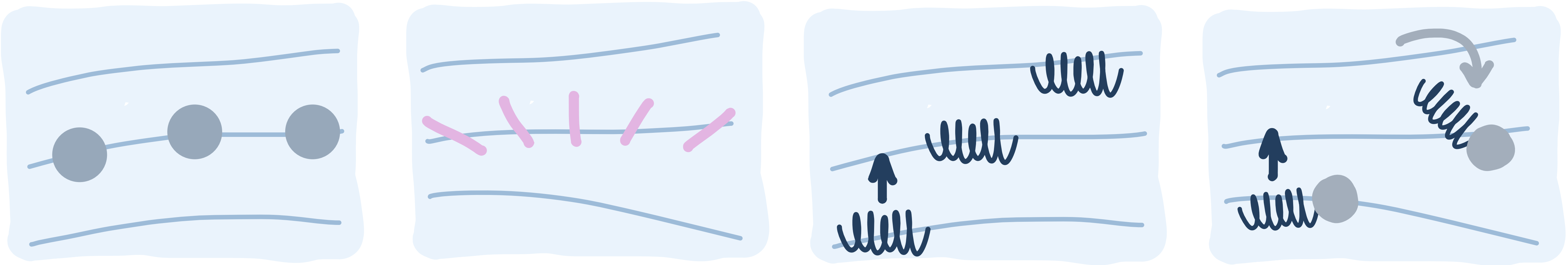


Follow streamlines

Tumble and follow streamlines

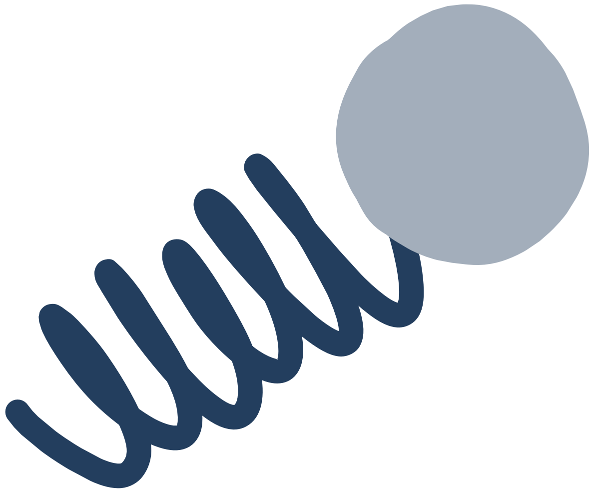
Drift along the vorticity direction

Orient into vorticity direction

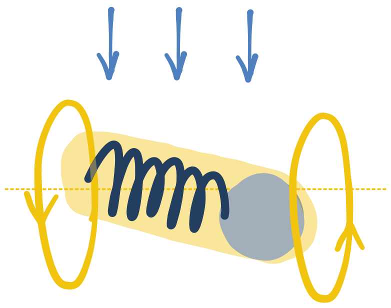


.....function of particle shape and symmetry

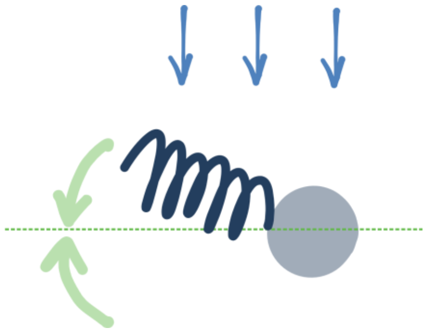
Transport of bacteria shaped particles: full dynamics



- Anisotropic – Jeffery orbits



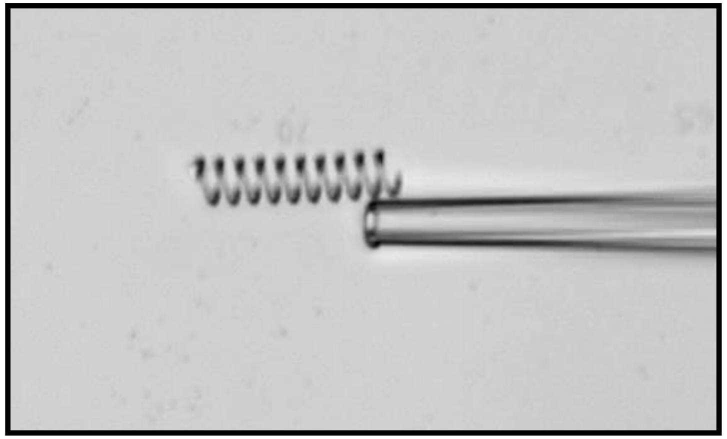
- Asymmetric chiral – rheotactic torque

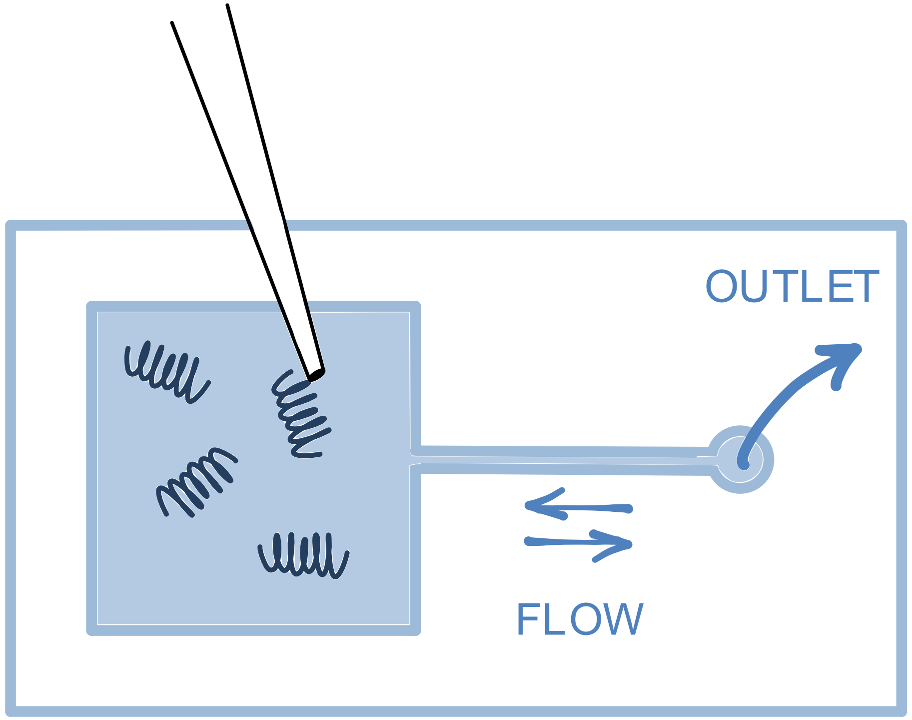


Investigate the interplay of the different effects under shear flow

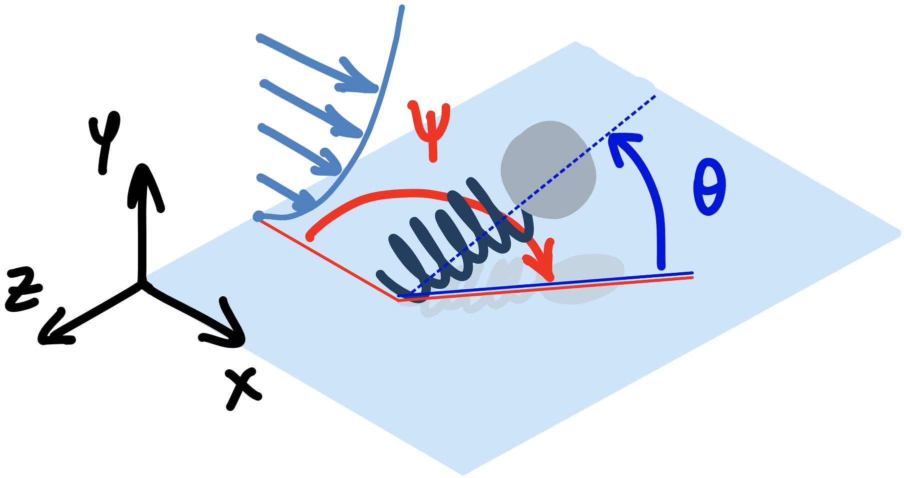
Microfluidic set-up

- Helix manipulation





- Flow geometry

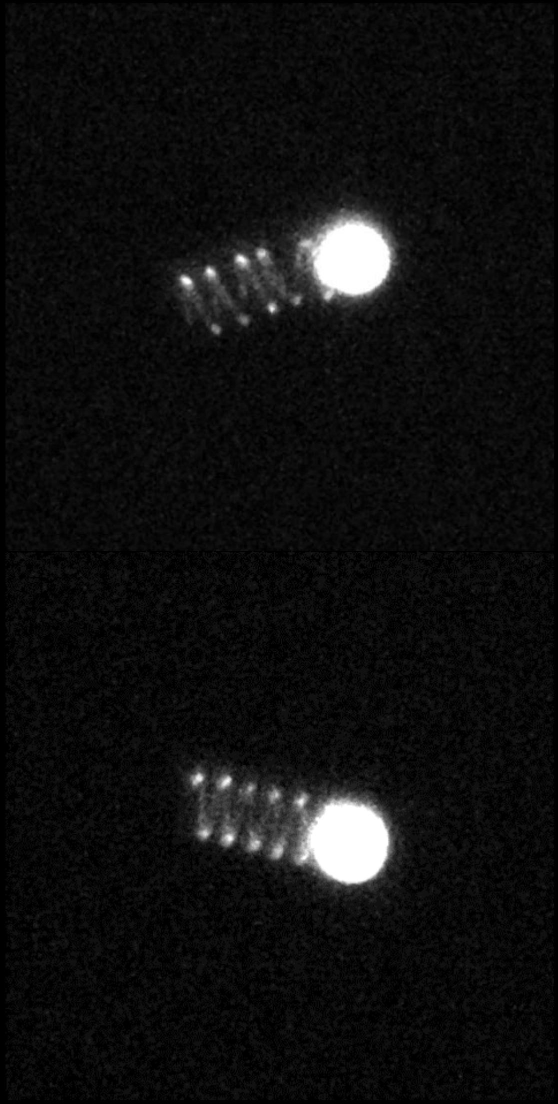


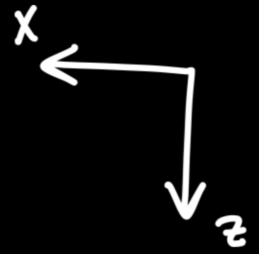
Particles transported close to bottom surface in shear flow

Experimental observations

Stage

Flow





Left handed

Right handed

10μm

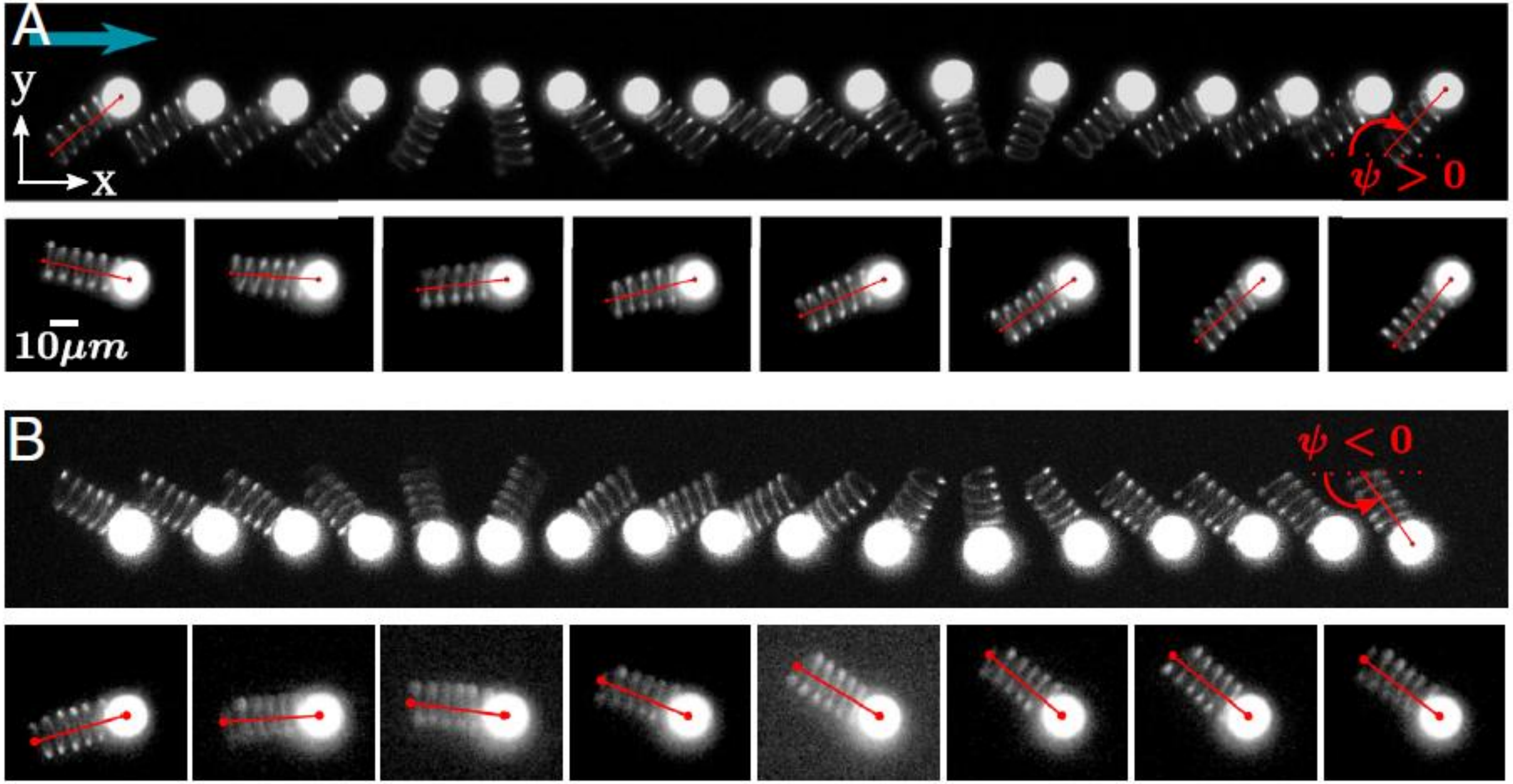
Zöttl, AL et al, PNAS, 2023

Fast oscillations and slow reorientation (function of handedness)

Experimental observations

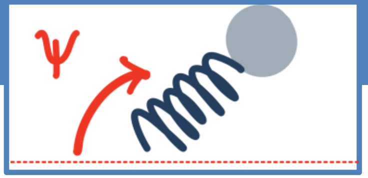
Left handed

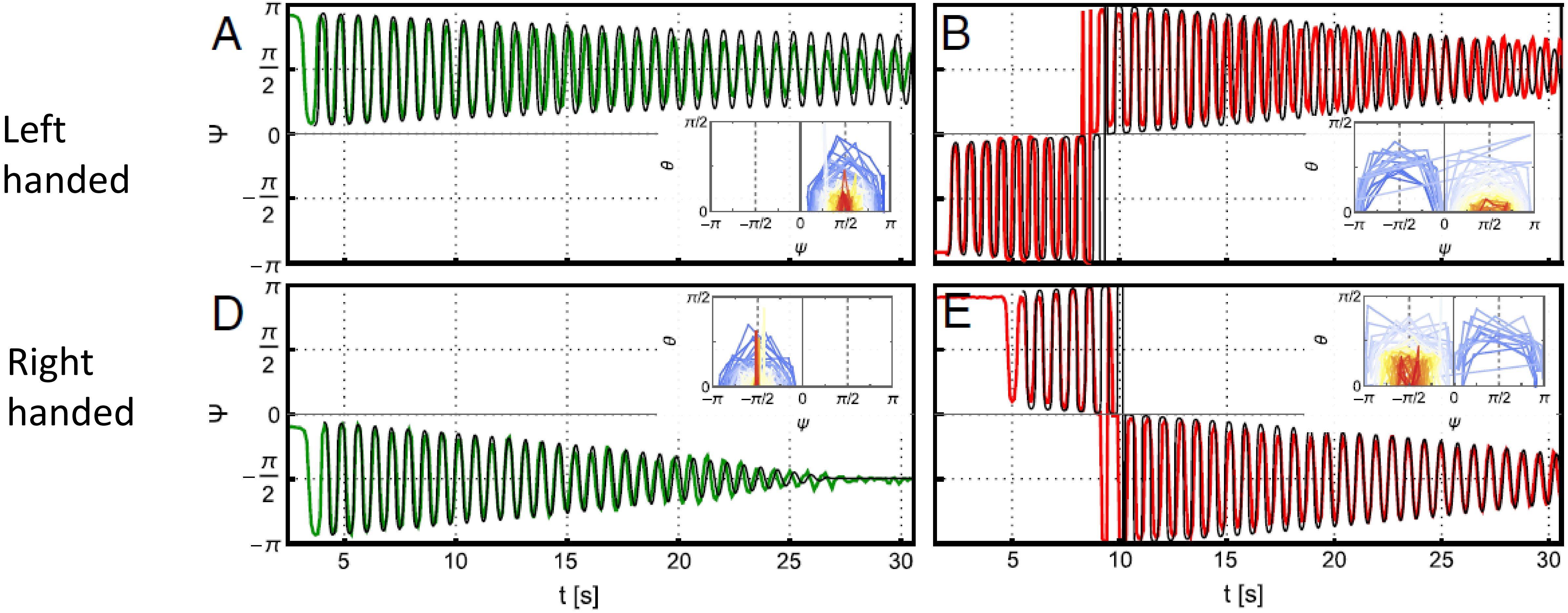
Right handed



Fast oscillations (3D) and slow reorientation (function of handedness)

Oscillation dynamics





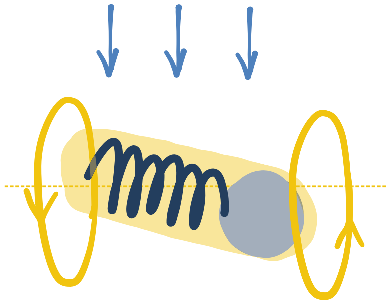
Left and right handed particles stabilize on opposite sides

Modeling: Jeffery orbits

- Jeffery orbits

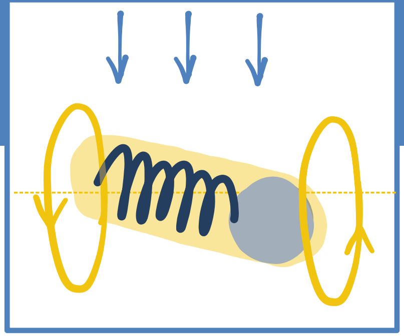
$$\dot{\psi} = \frac{\dot{\gamma}}{2}(1 + \beta)\sin\psi\tan\Theta$$

$$\dot{\Theta} = \frac{\dot{\gamma}}{2}(1 - \beta\cos 2\Theta)\cos\psi$$

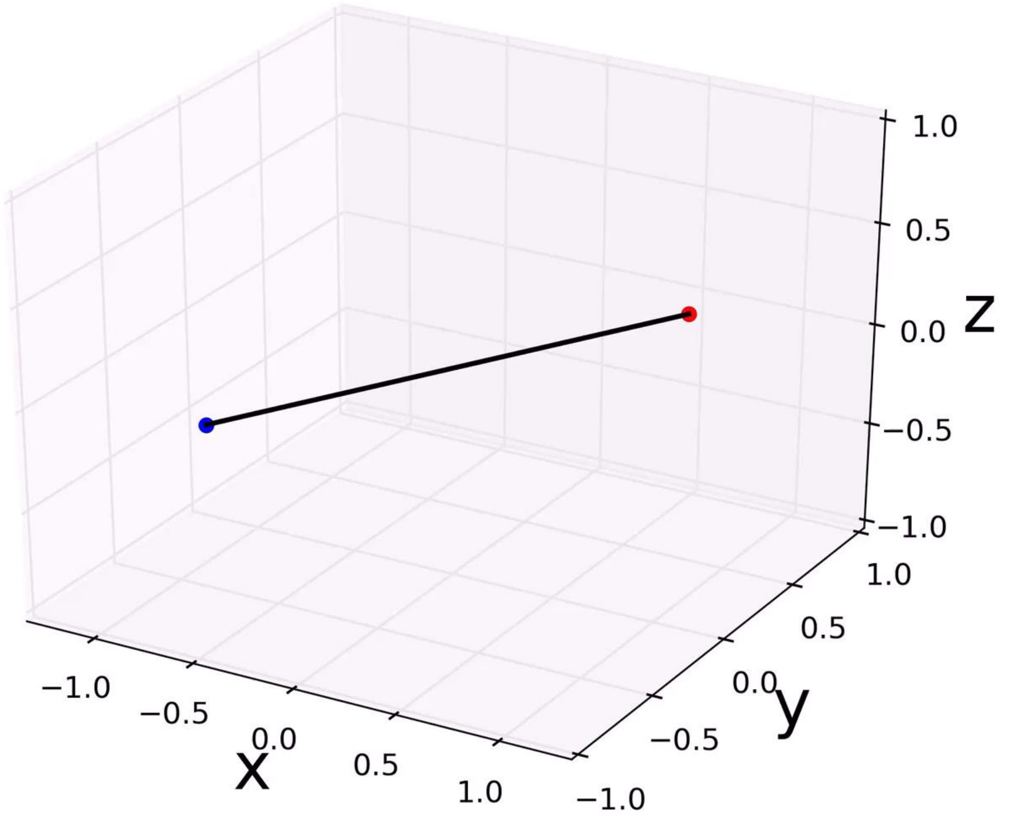


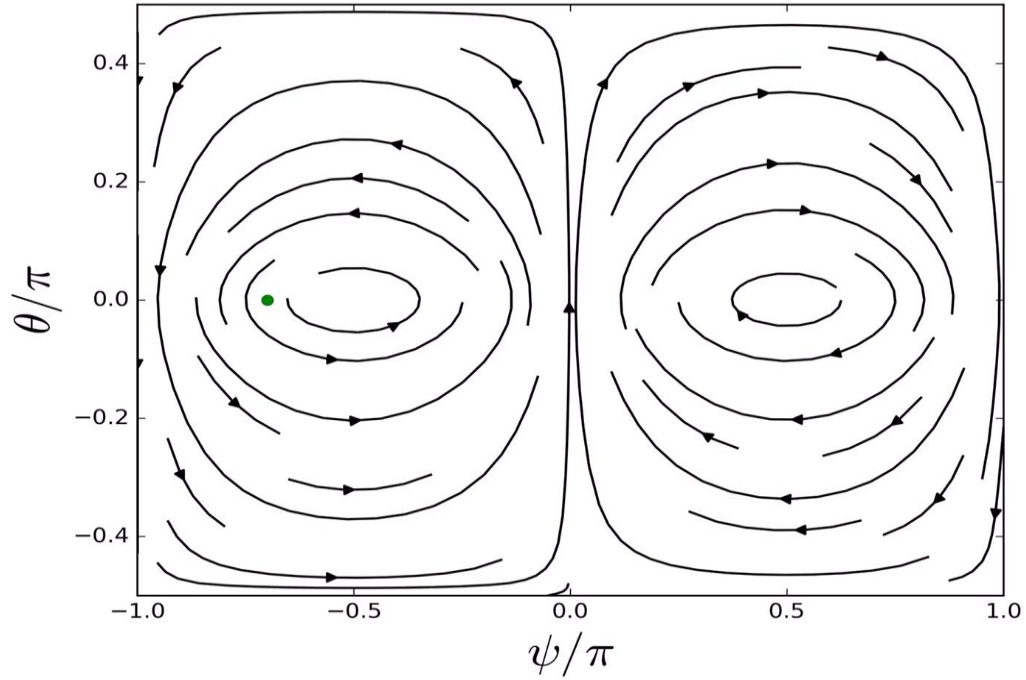
Jeffery GB, Proc. R. Soc. Lond. 1922

Modeling: Jeffery orbits



animation F. Tesser





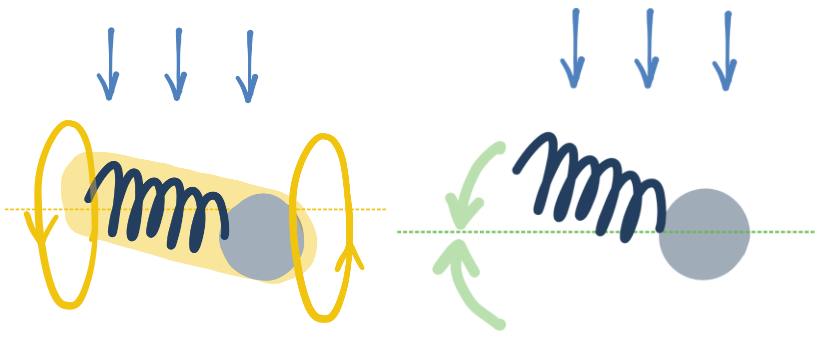
Can explain the fast oscillations but not the reorientation dynamics

Modeling – Jeffery orbits and rheotactic torque

- Jeffery orbits and rheotactic torque

$$\dot{\psi} = \frac{\dot{\gamma}}{2}(1 + \beta)\sin\psi\tan\Theta + \dot{\gamma}\,\nu\cos\psi\cos 2\Theta/\cos\Theta$$

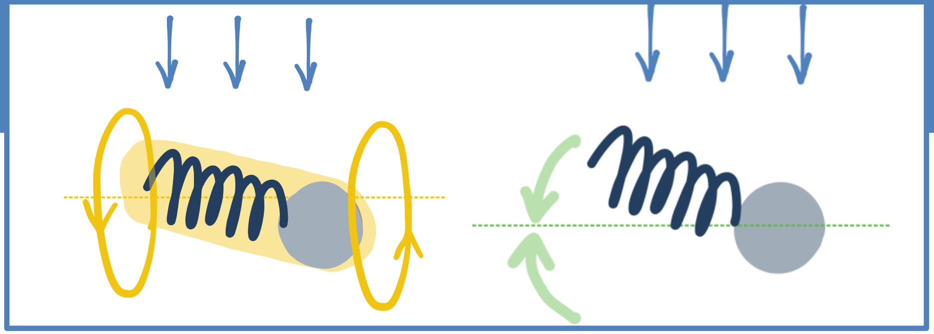
$$\dot{\Theta} = \frac{\dot{\gamma}}{2}(1 - \beta\cos 2\Theta)\cos\psi + \dot{\gamma}\,\nu\sin\psi\sin\Theta$$



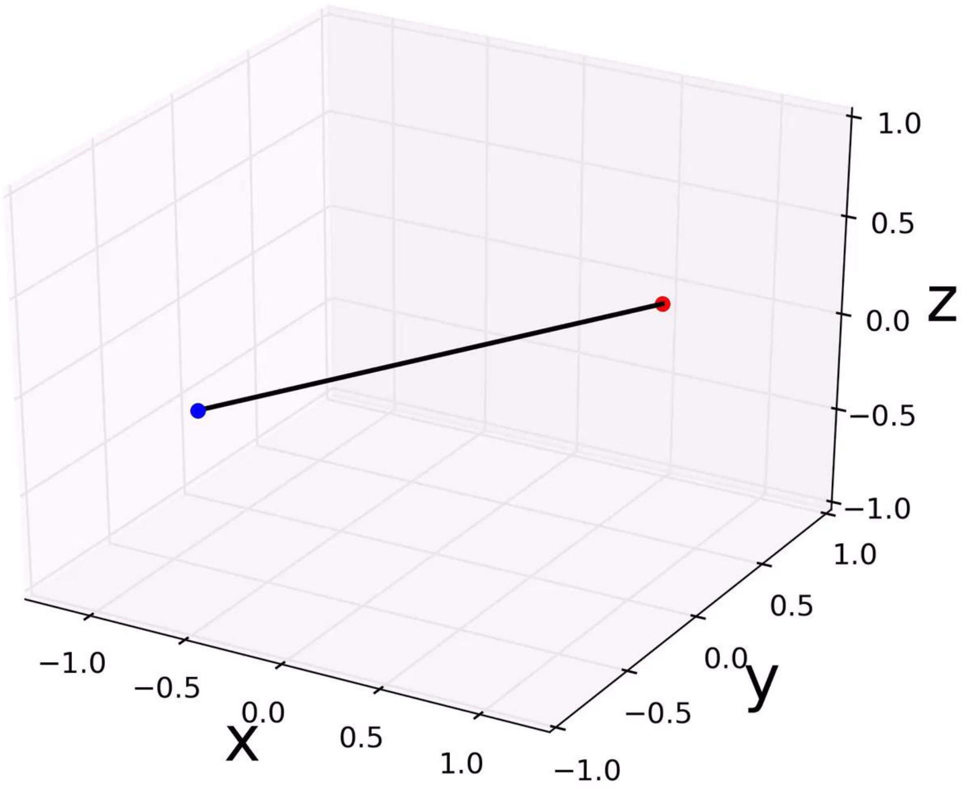
Jeffery GB, Proc. R. Soc. Lond. 1922

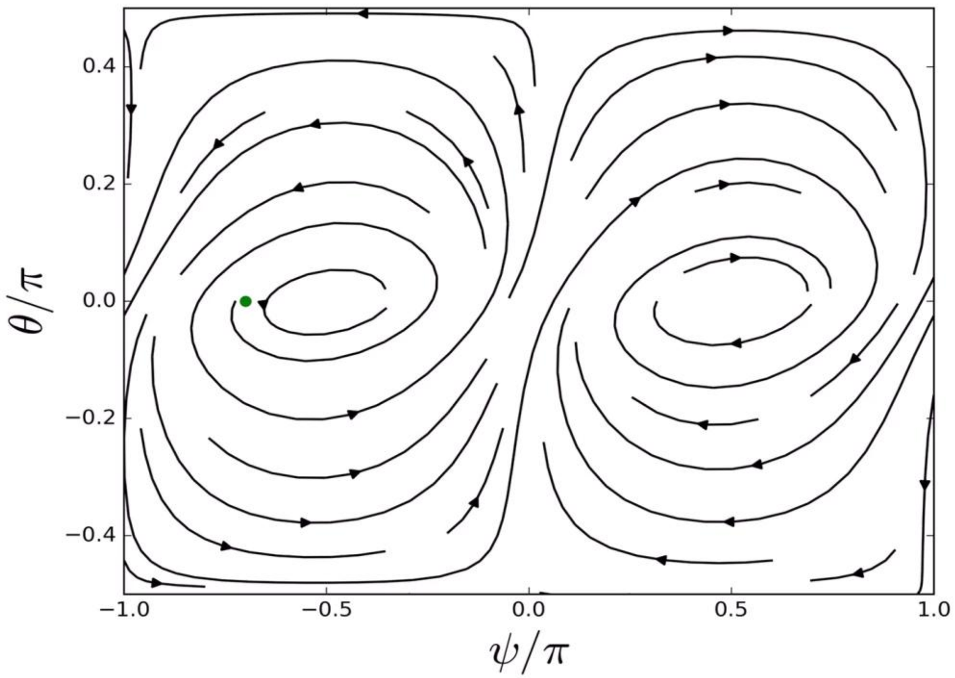
Mathijjsen, AL, et al, Nature Comm, 2019, Jing, AL et al, Science Advances, 2020

Modeling: Jeffery orbits + rheotactic torque



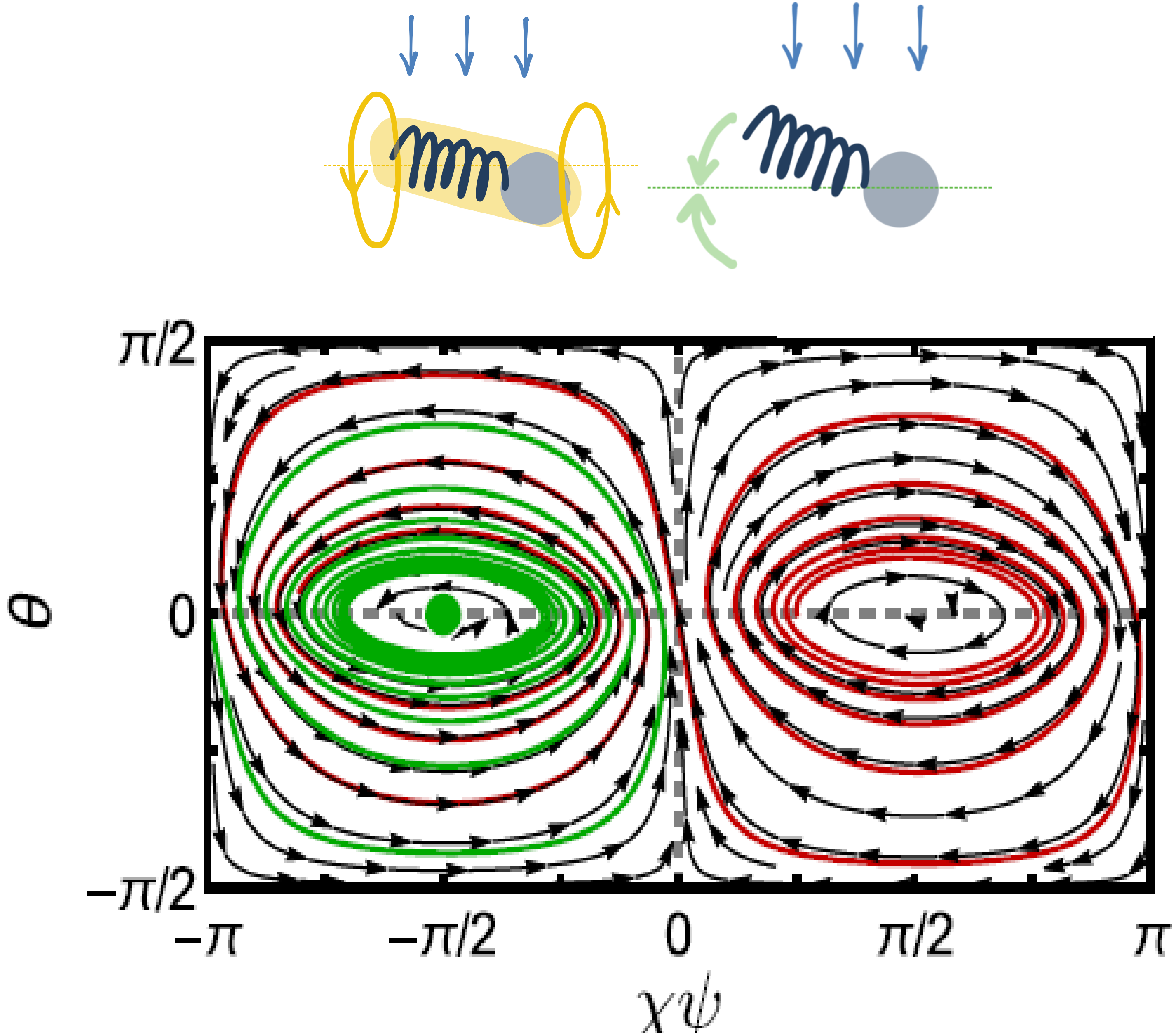
animation F. Tesser



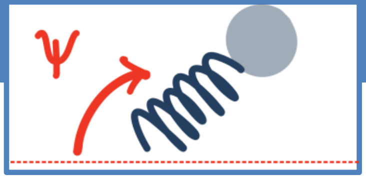


Reorientation induced by rheotactic torque.

Modeling: Jeffery orbits + rheotactic torque

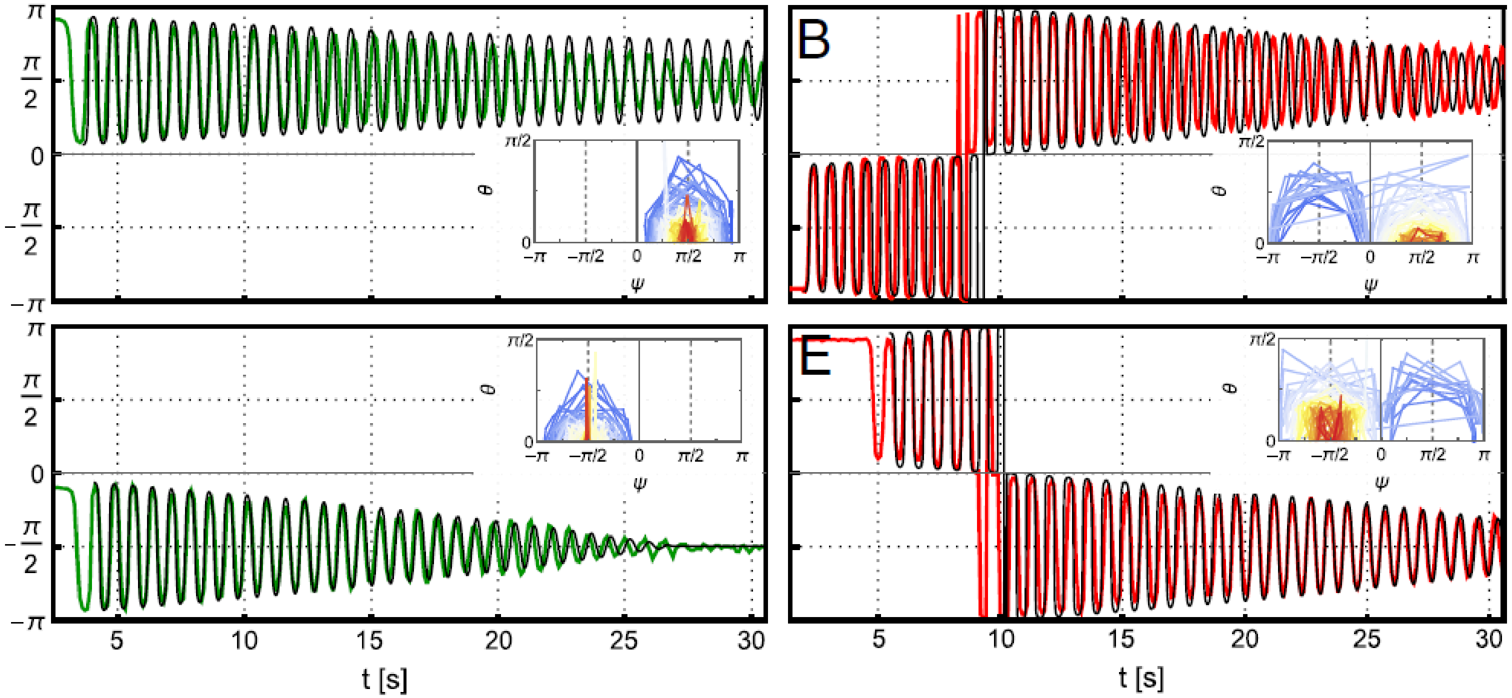


Oscillation dynamics: qualitative agreement with predictions



Left handed

Right handed



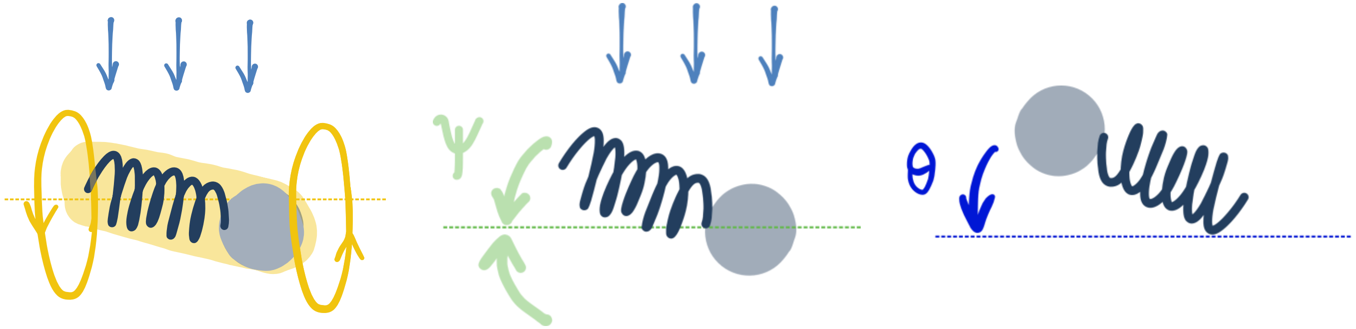
But: sometimes stabilization on the “wrong” side

Modeling – Jeffery orbits, rheotactic torque and bottom heaviness

- Jeffery orbits, rheotactic torque and bottom heaviness

$$\dot{\psi} = \frac{\dot{\gamma}}{2}(1+\beta)\sin\psi\tan\Theta + \dot{\gamma}\,\nu\cos\psi\cos2\Theta/\cos\Theta$$

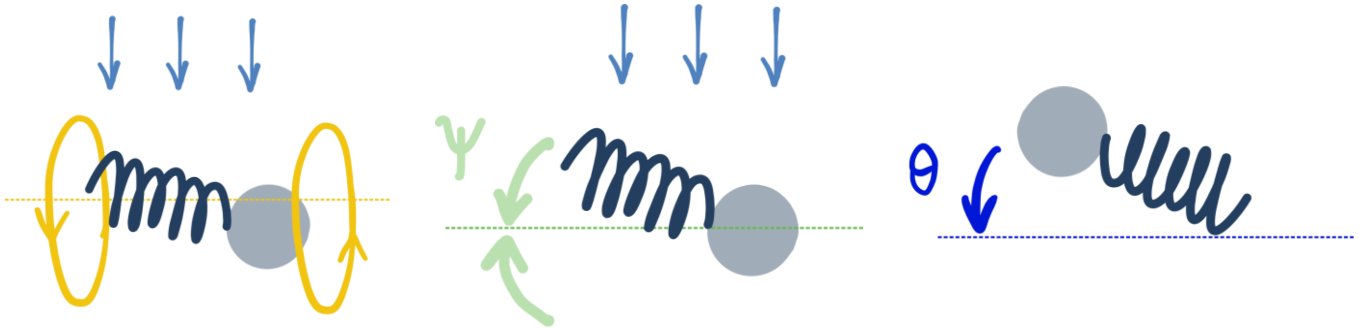
$$\dot{\Theta} = \frac{\dot{\gamma}}{2}(1-\beta\cos2\Theta)\cos\psi + \dot{\gamma}\,\nu\sin\psi\sin\Theta - \Omega_H\cos\Theta\,H(\Theta)$$

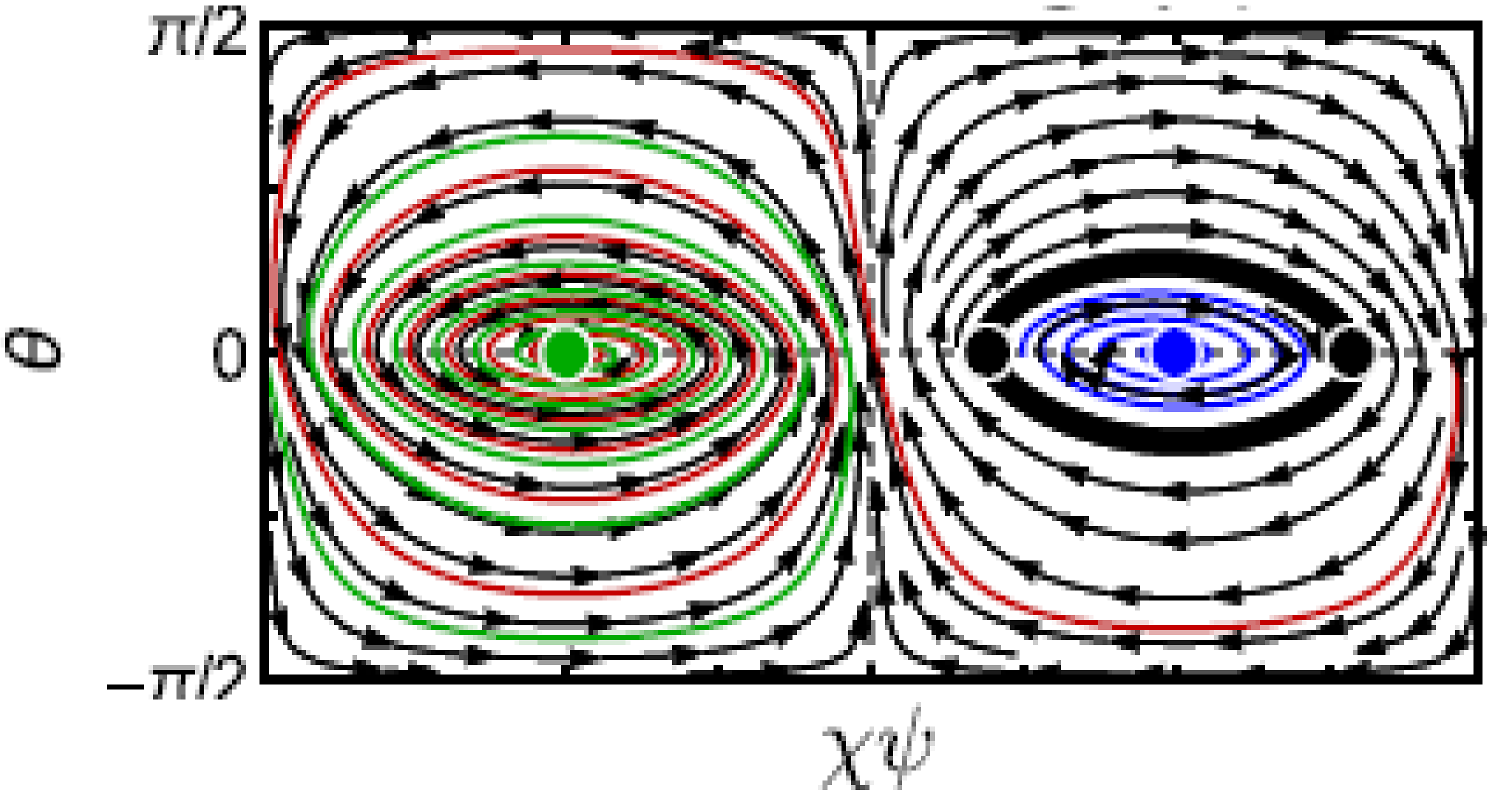


Jeffery GB, Proc. R. Soc. Lond. 1922

Mathijjsen, AL, et al, Nature Comm, 2019, Jing, AL et al, Science Advances, 2020, Zöttl, AL et al , PNAS, 2023

Jeffery + rheotactic torque + bottom heaviness

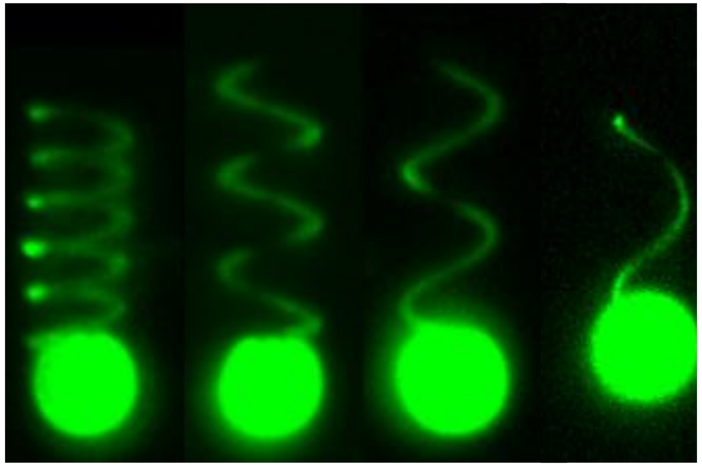


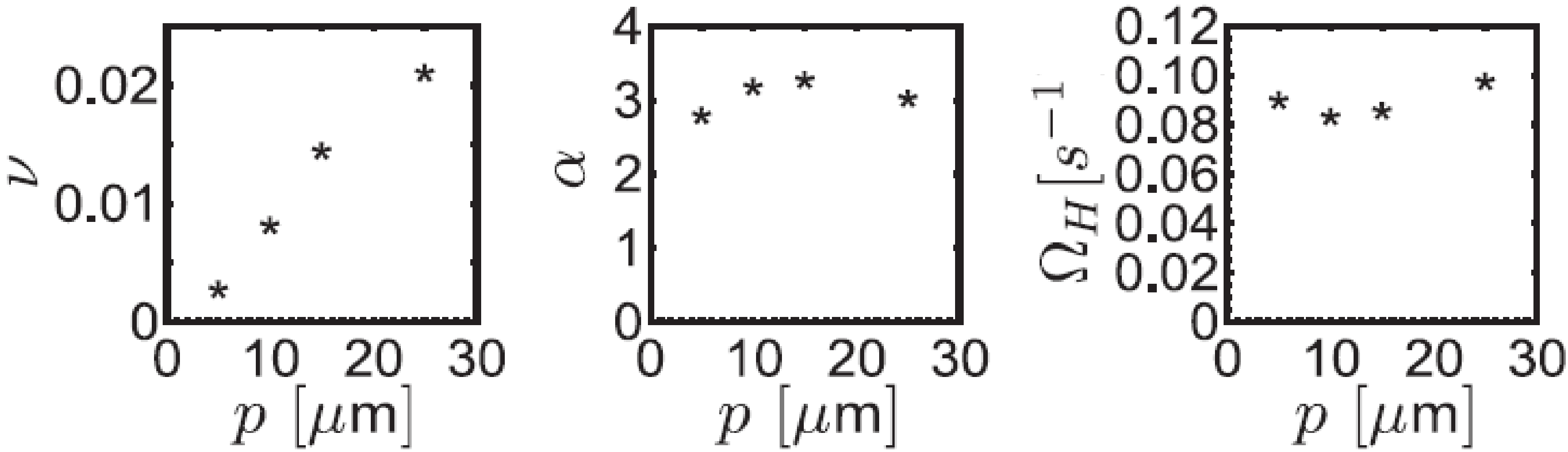


Quantitative comparison with experiments

Constants from BEM simulations

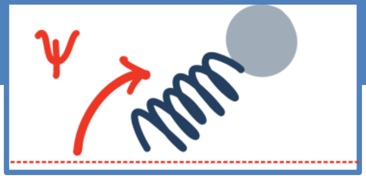
- Effective aspect ratio α –> β
- Rheotactic strength ν
- Bottom heaviness Ω_H





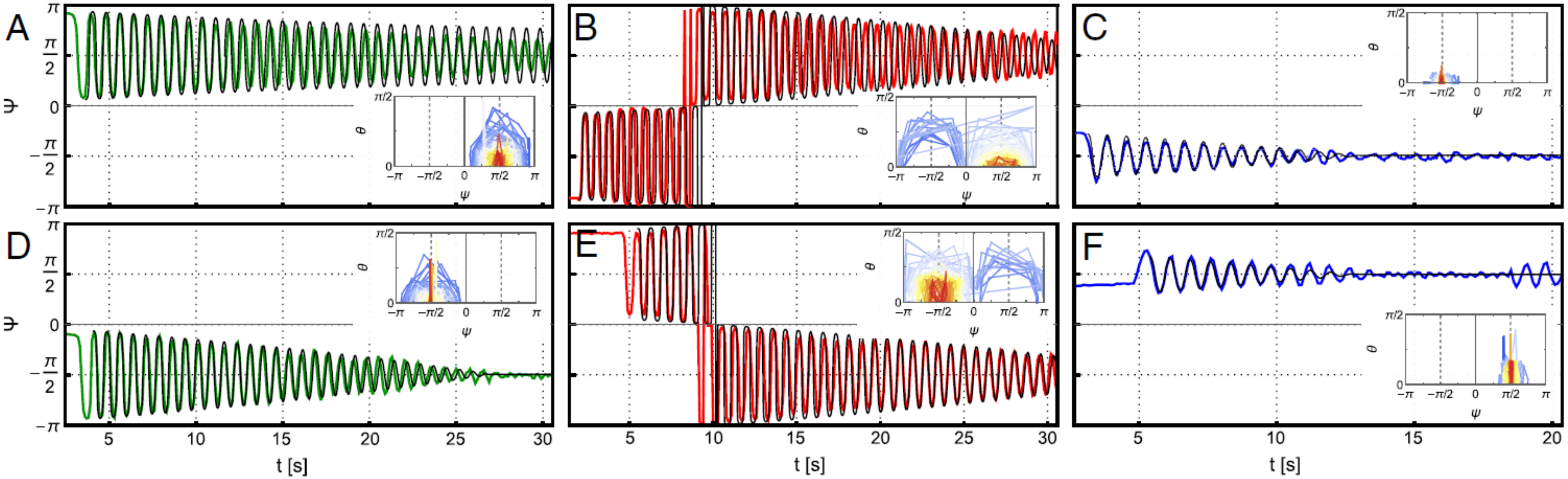
Adjust parameters to perfectly match experimental shapes

Comparison with experimental observations



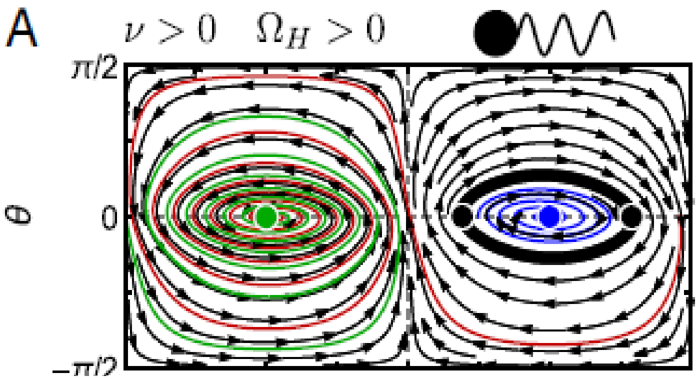
Left handed

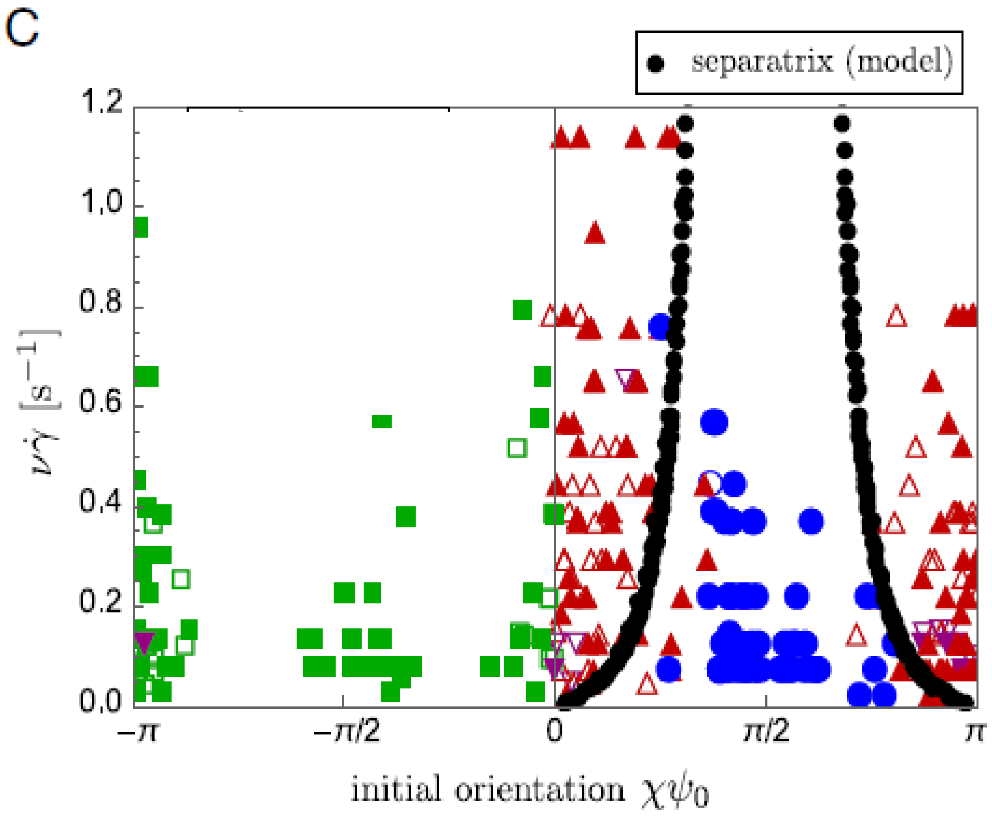
Right handed



Quantitative agreement without adjustable parameters

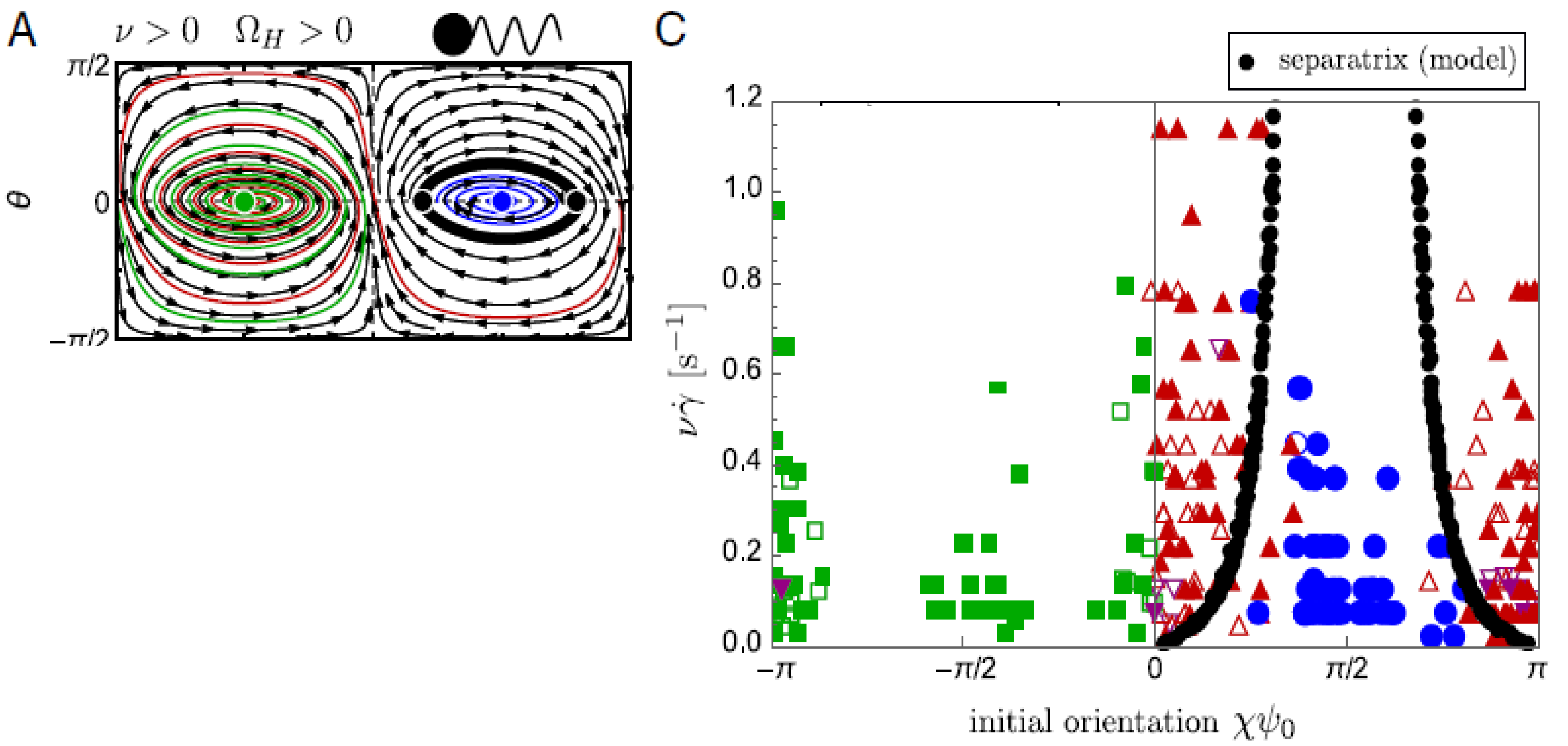
Phase diagram for asymmetric head heavy chiral particles



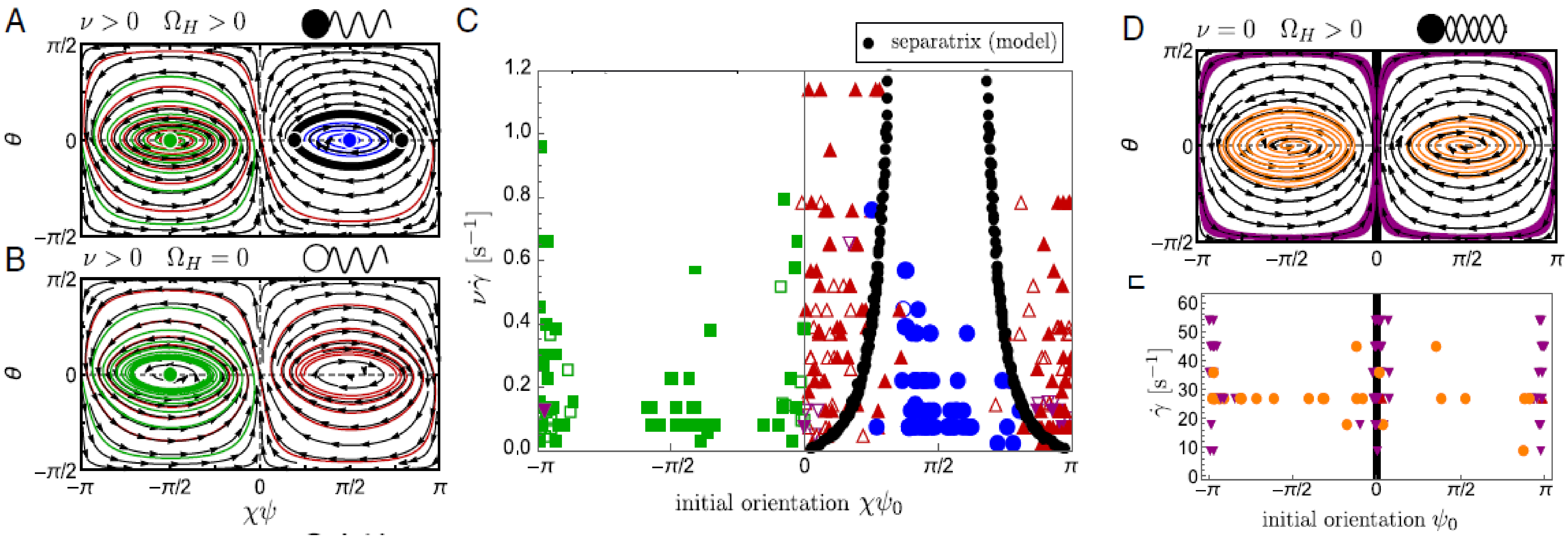


Asymmetric bistability

“Knock out” of specific properties



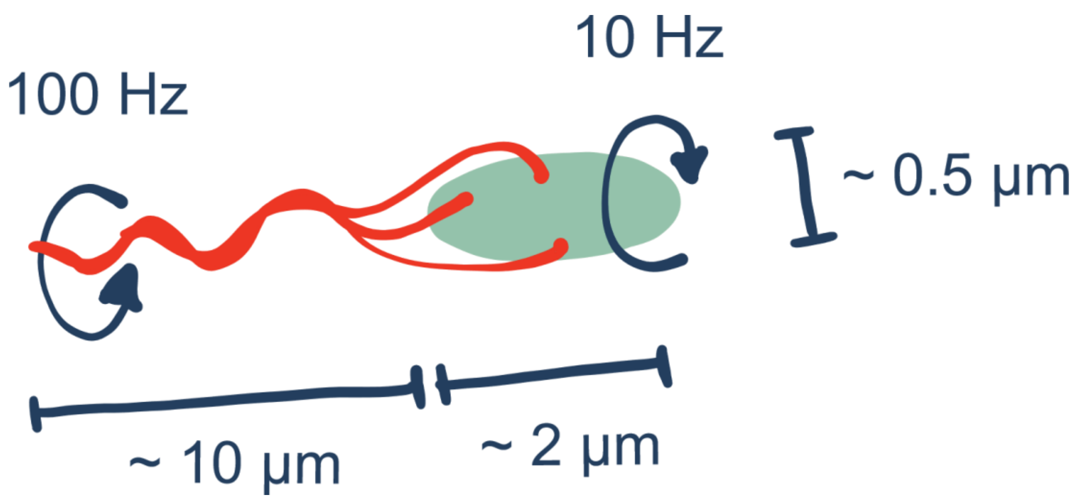
“Knock out” of specific properties



Full understanding of the reorientation dynamics of “passive bacteria”

What about active bacteria?

- E-coli bacteria



Rotating bundle of rigid flagella lead to bacteria propulsion

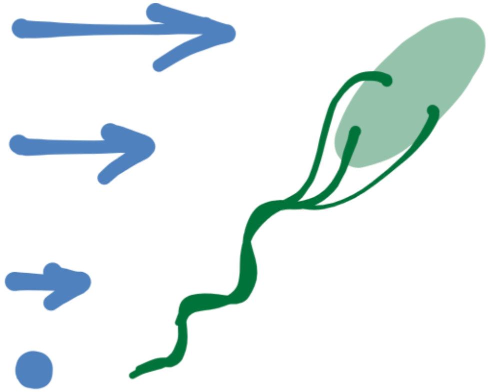
Typical swimming speed 20µm/s

- Very reproducible (pitch and radius)
- Very easy to produce large quantities

- Shape difficult to vary
- Biological and Brownian noise

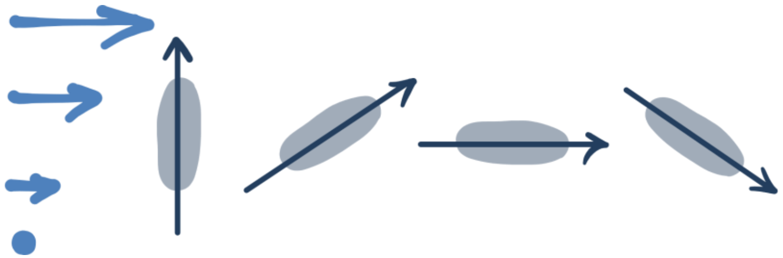
E-coli bacteria as a biological model system

E-coli bacteria in viscous flows



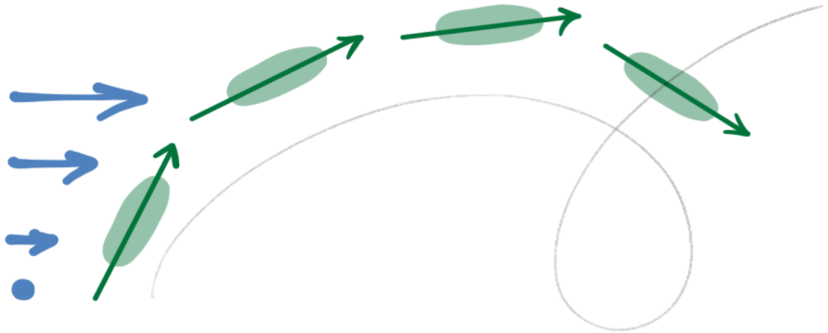
- Reorientation dynamics

  Given by fluid structure interactions in the presence of noise



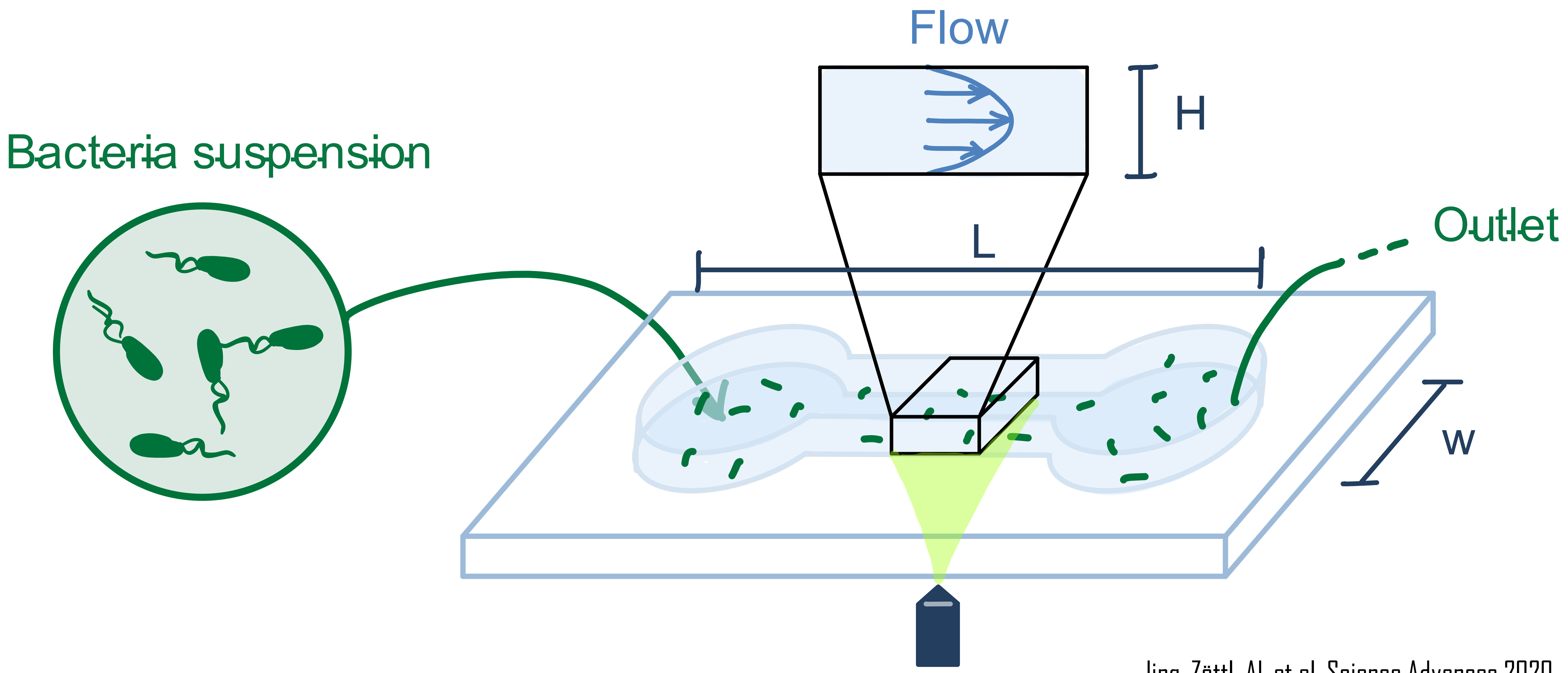
- Role of activity

  Orientation directly translates into swimming direction



Elongated chiral asymmetric shape, Brownian noise and activity

E-coli in Poiseuille flow



Jing, Zöttl, AL et al, Science Advances 2020

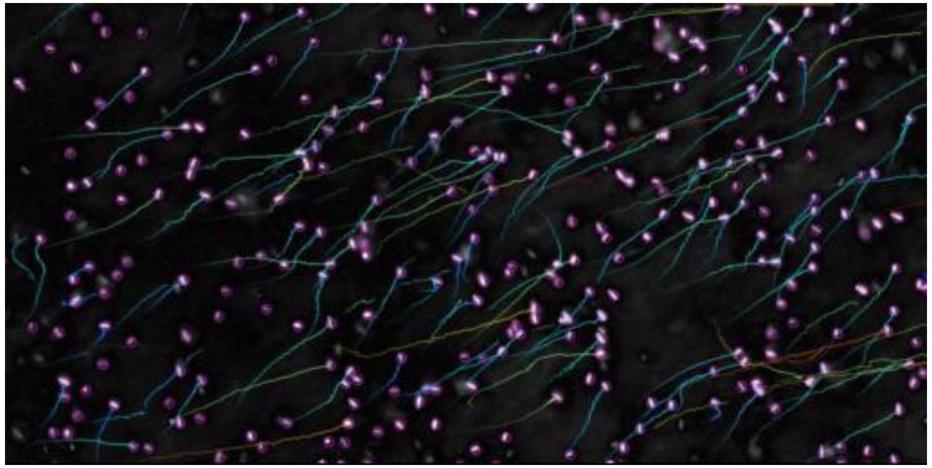
Investigate orientation and velocity distributions

Lateral drift

Flow

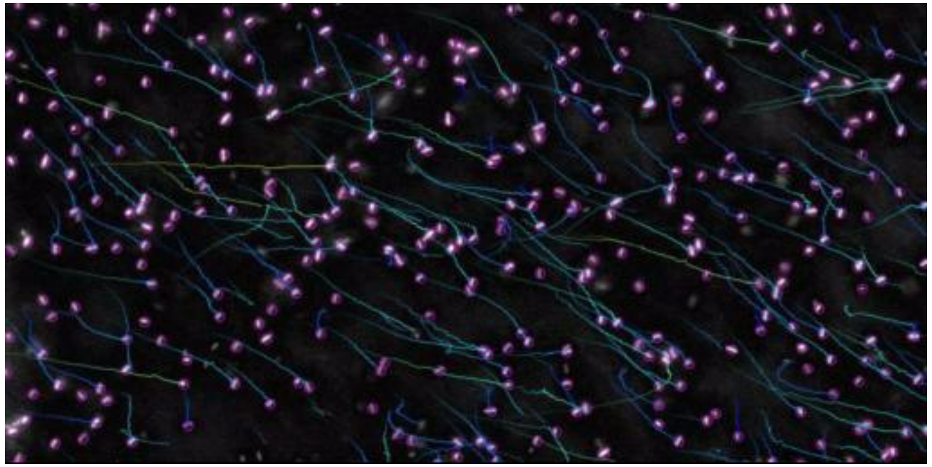
$$z = \frac{H}{7}$$

Close to bottom



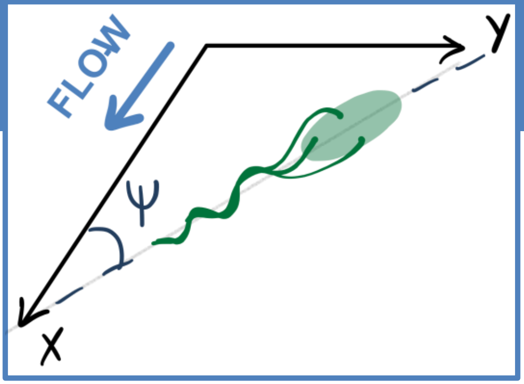
$$z = \frac{6H}{7}$$

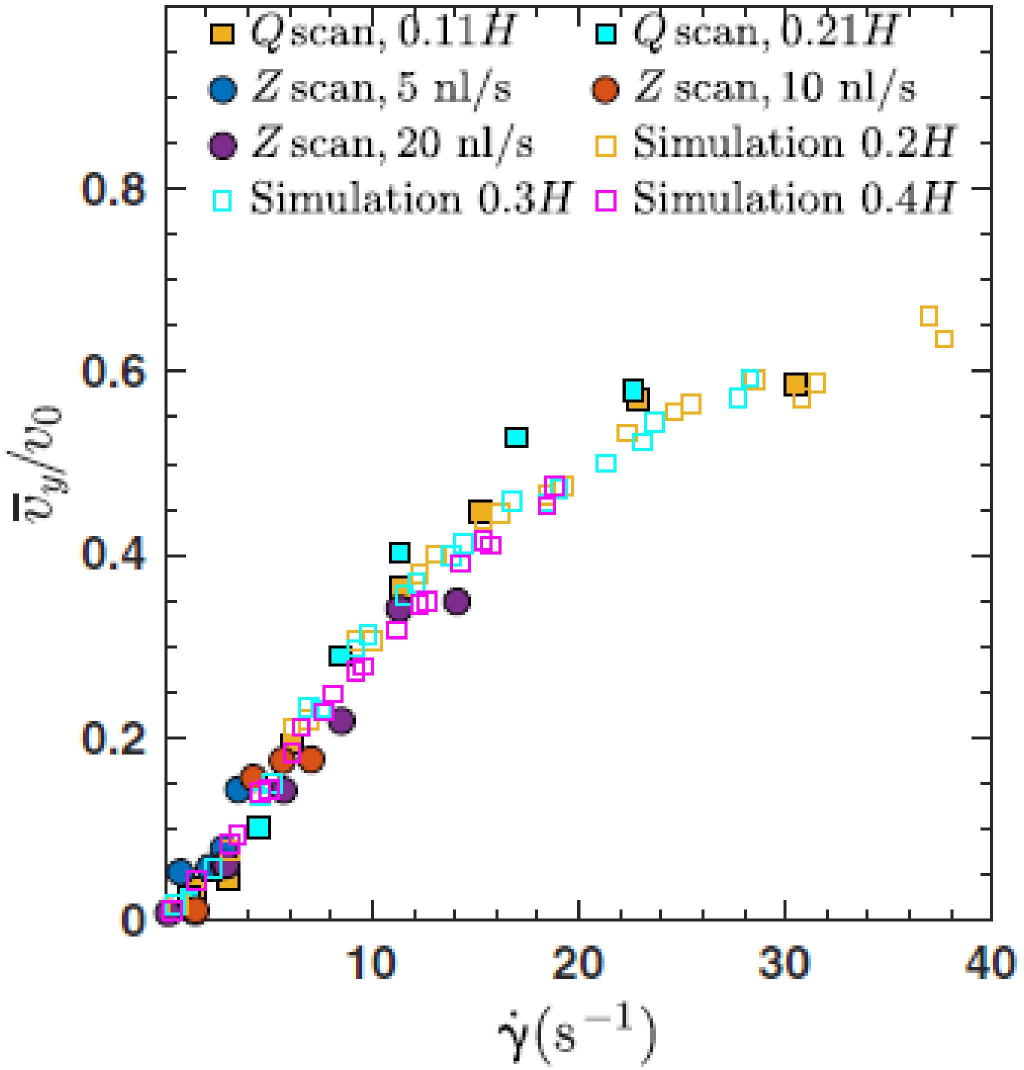
Close to top



Flow

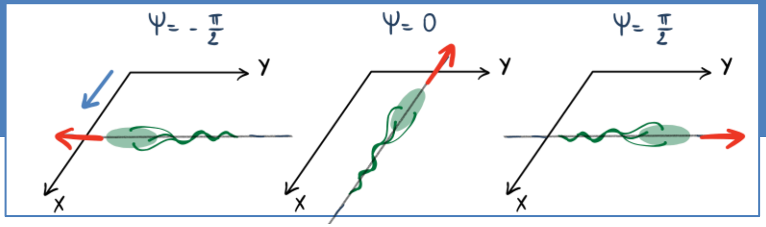
Drift velocities as a function of local shear rate



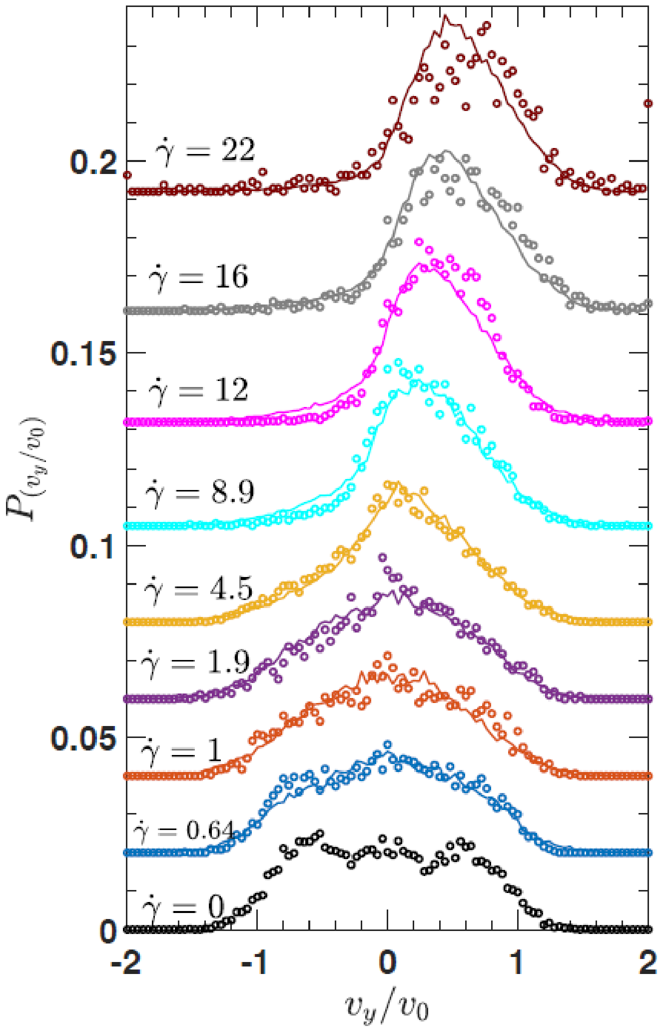


Origin of linear increase and saturation of drift velocity?

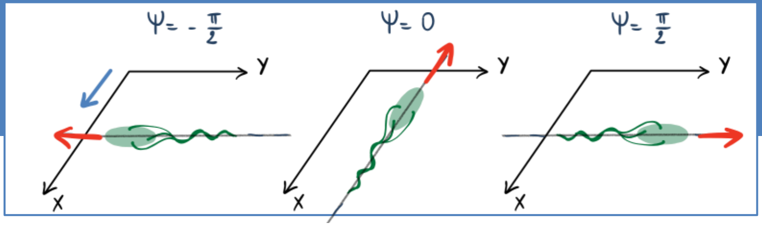
Velocity and orientation distributions



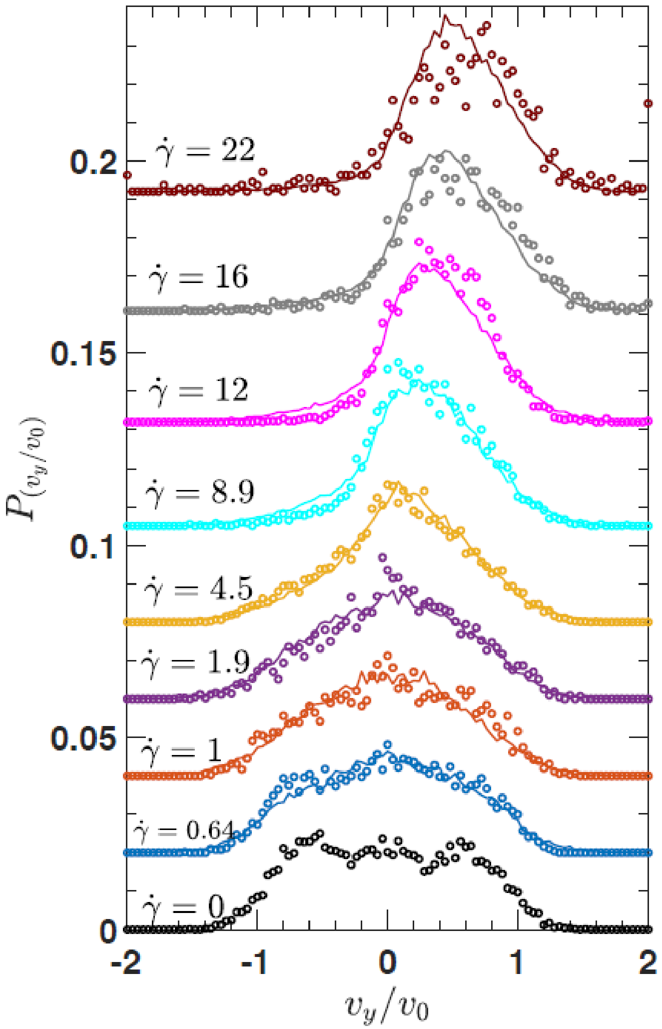
Velocity



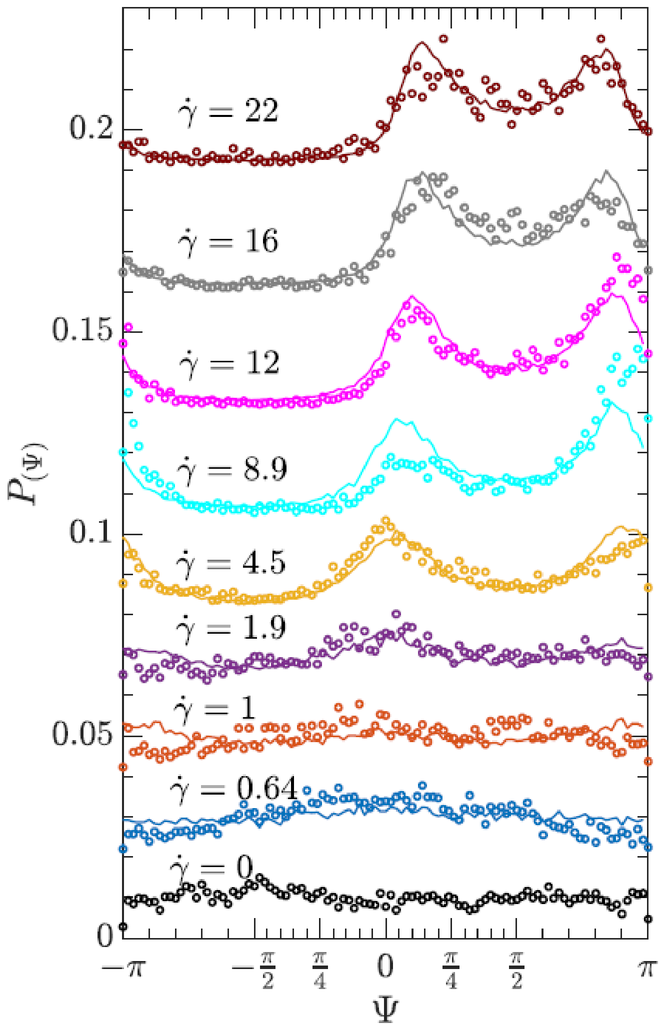
Velocity and orientation distributions



Velocity

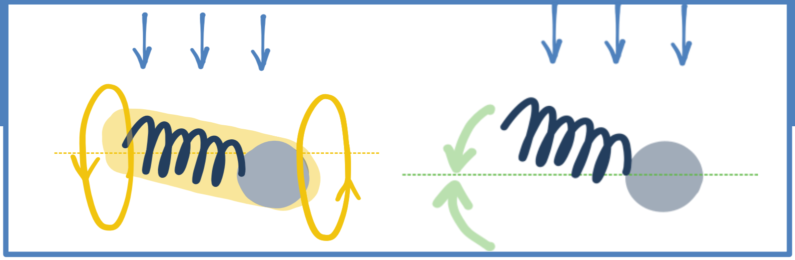


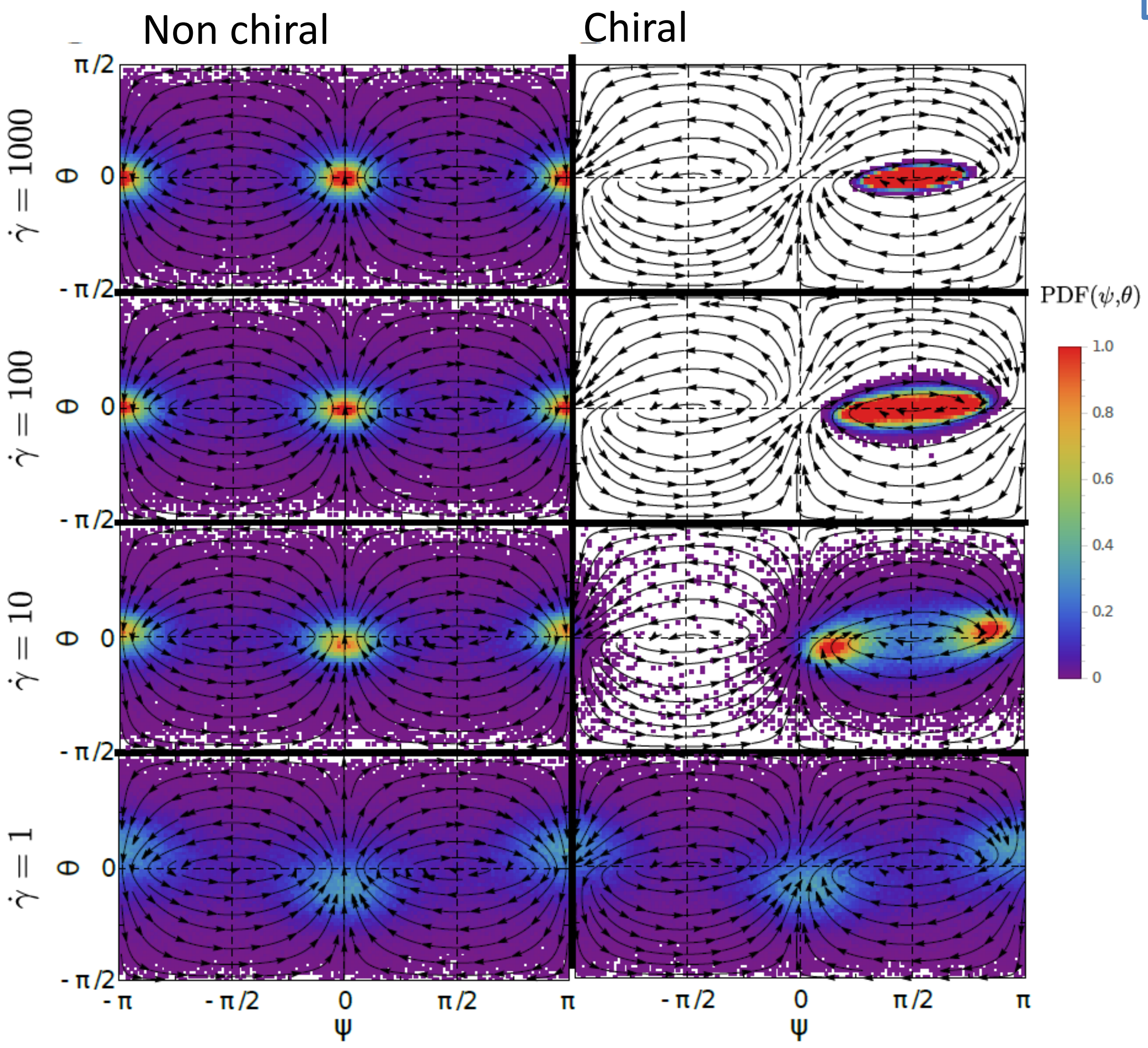
Orientation



Origin of velocity and orientation distributions?

Orientation distributions including rotational noise



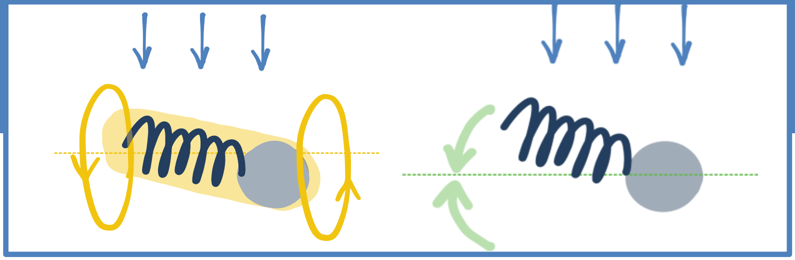


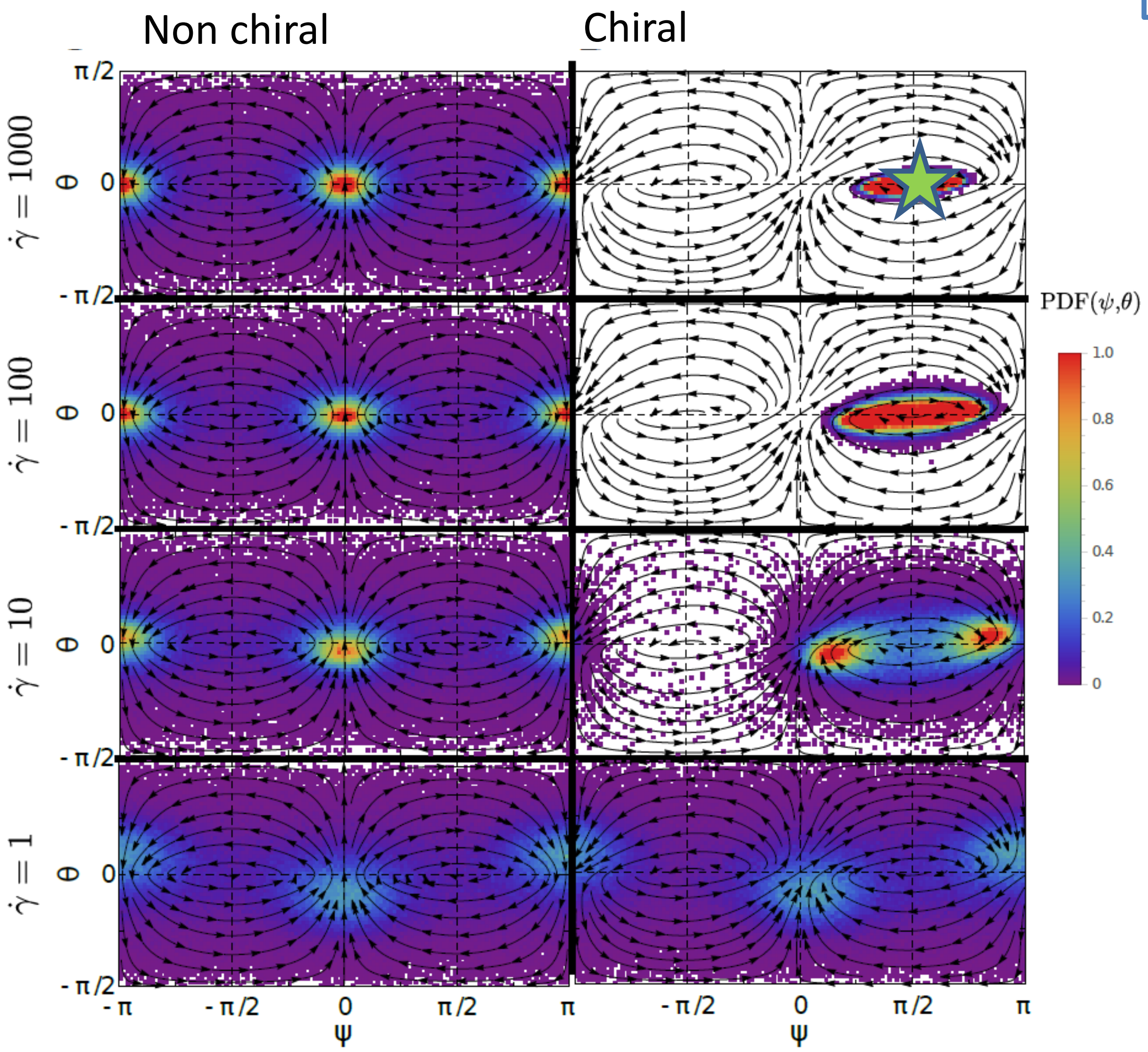
Adjust model parameters

- Effective aspect ratio
- Rheotactic strength
- Orientational noise

(Run & Tumble and rotational noise)

Orientation distributions including rotational noise

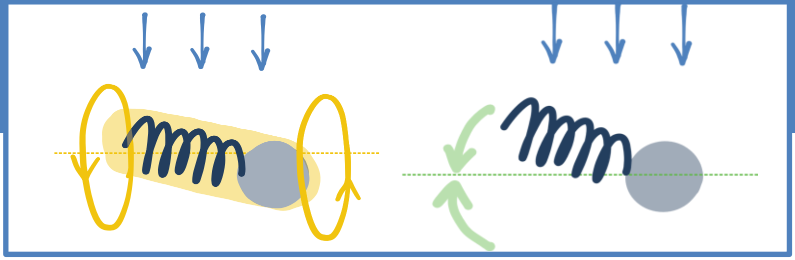


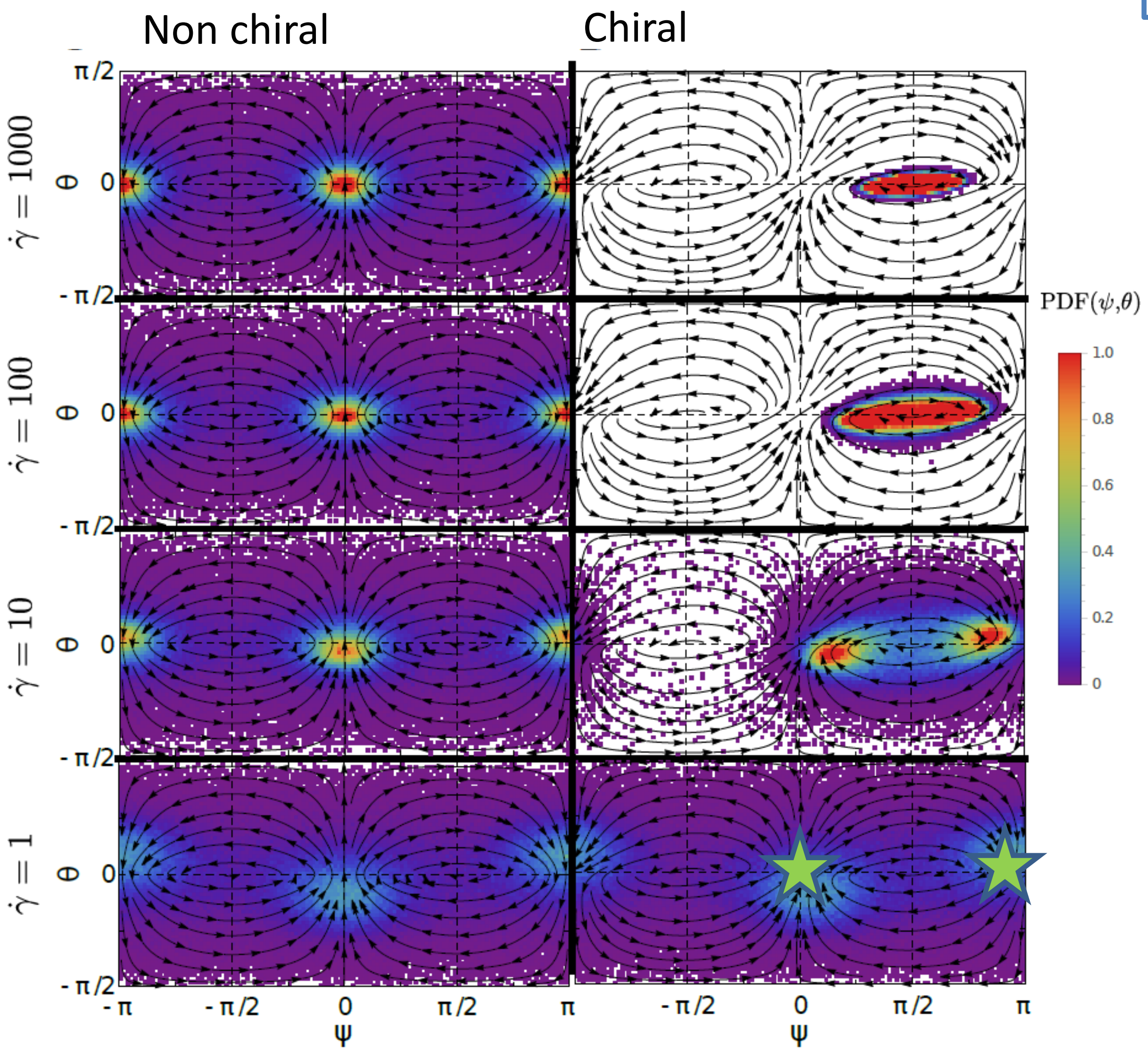


High shear rates

Linear analysis:
fixed point only
marginally stable

Orientation distributions including rotational noise



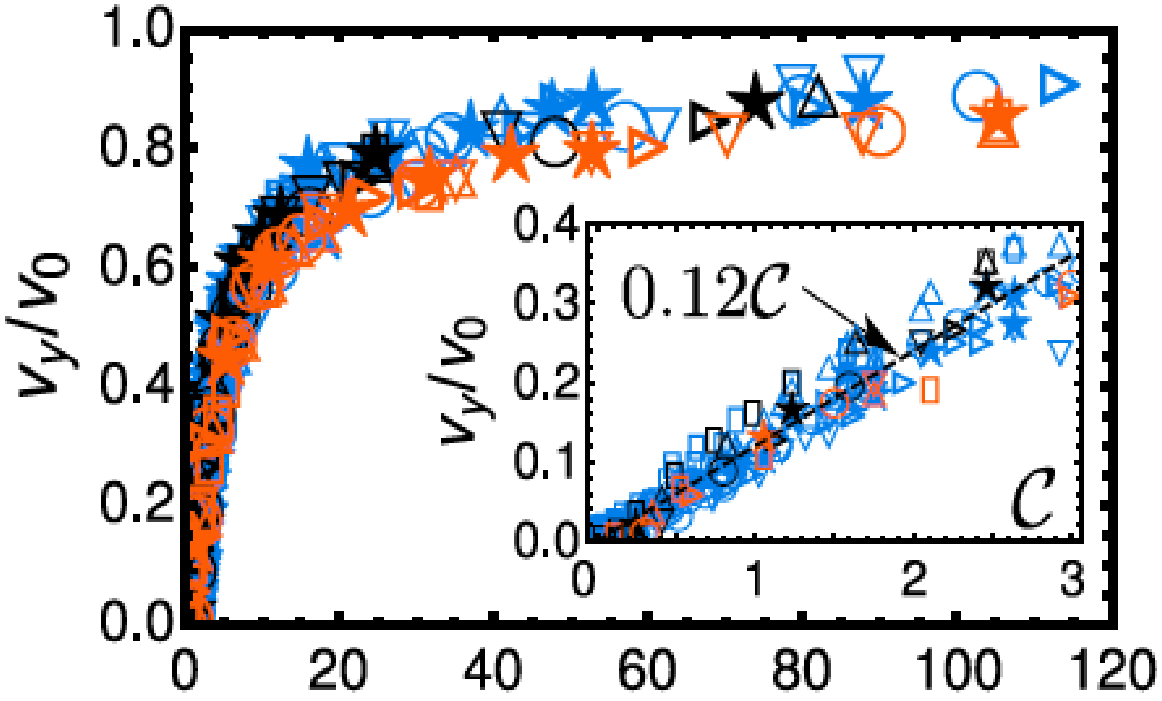


Low shear rates

Linear analysis:
reorientation rates
linear in shear rate
compete with
rotational noise

Master curve for rheotactic drift in bulk flow (Jeffery, rheotaxie and noise)

- ❑ **Small shear rate**: linear increase of rheotactic velocity with the chirality number C
- ❑ **High shear rates**: very slow increase of plateau value due to marginally stable fixed point



$$\mathcal{C} = \frac{\dot{\gamma}\nu}{D_r^{\mathrm{eff}}}$$

Jing, Zöttl, AL et al, Science Advances 2020

Full understanding of rheotactic drift from chirality and noise

Summary –active and passive chiral particle transport

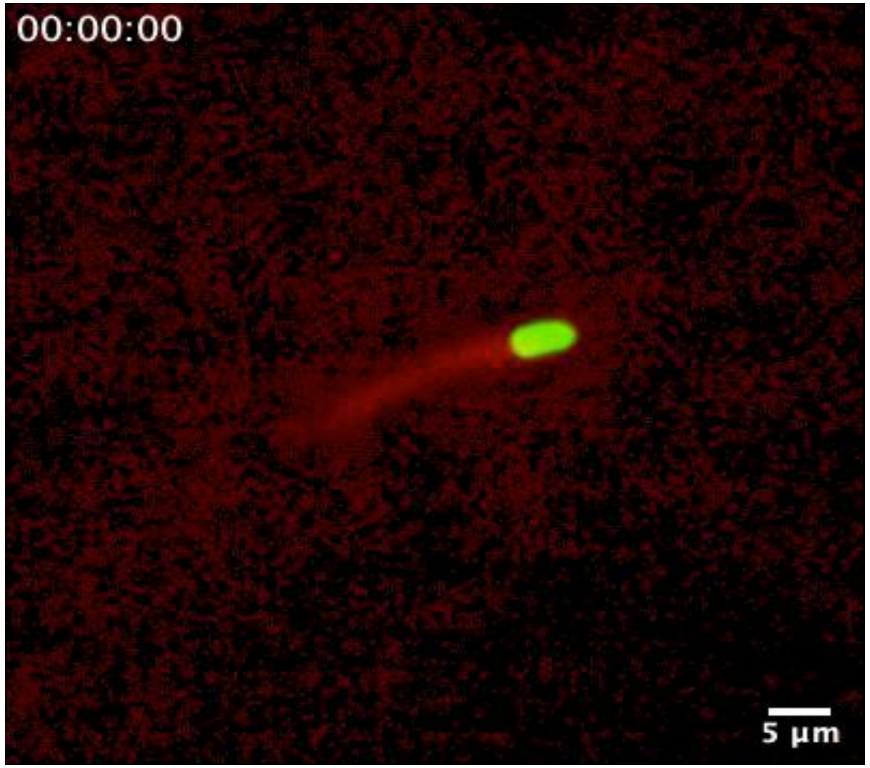
- Model systems allow to investigate different contributions separately
- Reorientation dynamics fully explained by particle shape
- Brownian noise has to be taken into account for flagellated bacteria
- Full description of rheotactic drift from orientation distributions

- Can help explaining flagellated micro-organism transport in more complex flows
- Basis for sorting of micro-organism and chiral objects
- Targeted delivery of microprinted particles

Fully governed by chiral particle shape

Summary –active and passive chiral particle transport

- Reorientation dynamics fully explained by particle shape
- Role of chirality and head heaviness taken into account separately
- Brownian noise has to be taken into account for flagellated bacteria
- Full description of rheotactic drift from orientation distributions



Hector Urra and Eric Clement, PMMH-ESPCI

What about flexibility?

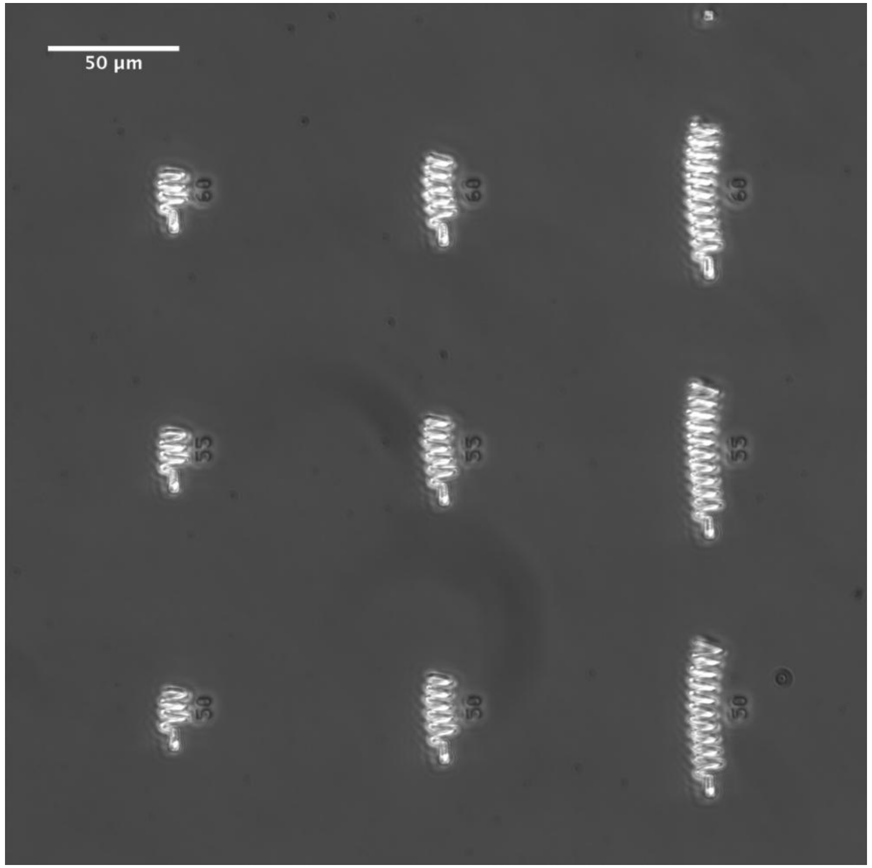
Flexible micro-helices

Lucas Prevost, Marine Daiëff, Olivia du Roure (PMMH-ESPCI, Paris, France)
Jonathan Pham, Dylan Barber, Al Crosby (UMAss, Amherst, USA)
Alexander Morozov (Edinburgh University, UK)

Chiral particles and Odd fluids - Eindhoven January 2026

Challenges of flexible fiber fabrication

3D printed microhelices



Flexibility increases with softness of material and decreasing rod thickness:

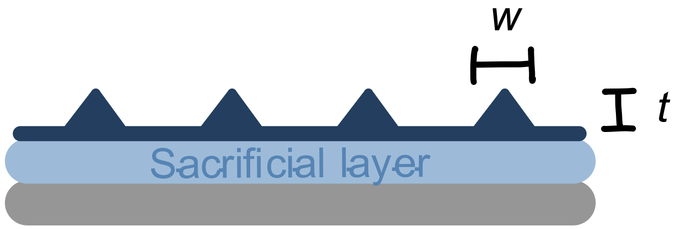
- Size resolution limits going to even thinner rods
- Increasingly difficult to handle for softer material

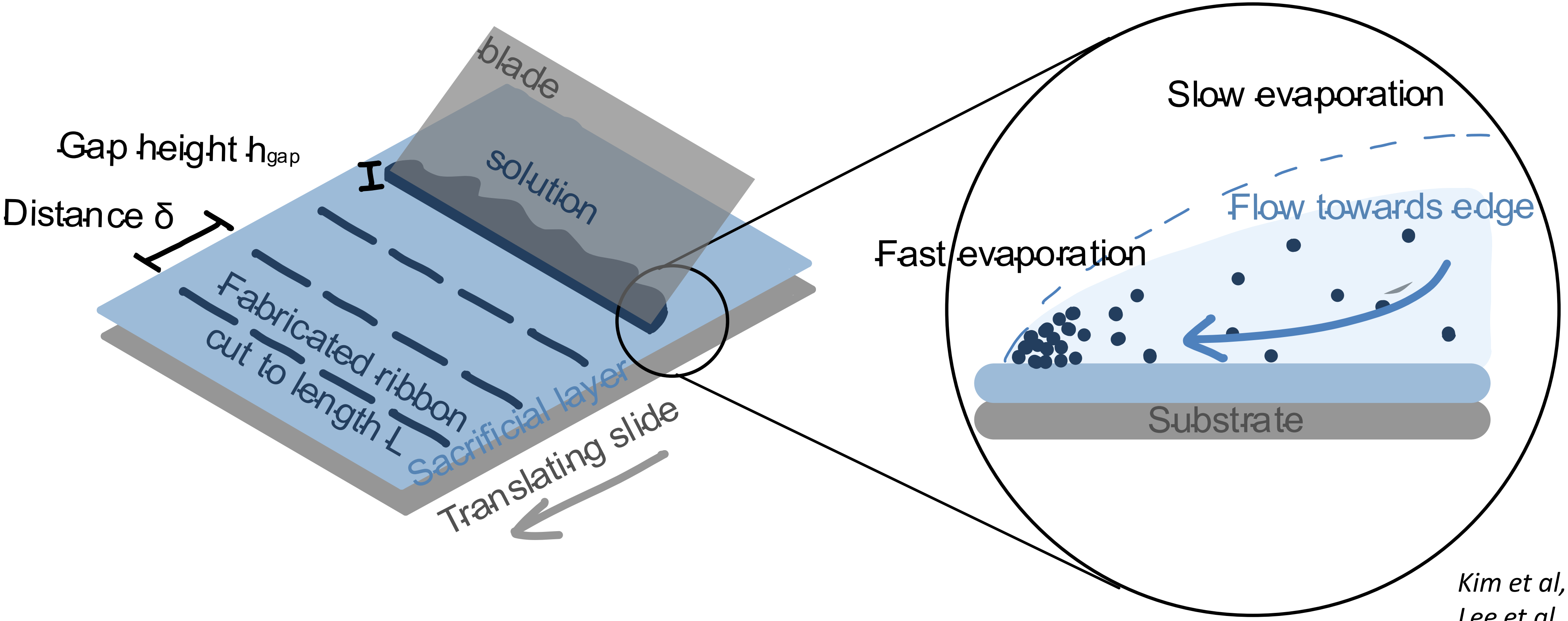
Time consuming to make 3D structures

Chose a 2D fabrication method that autoassembles into 3D structure

2D nano-ribbon fabrication

Stop flow method.... … using coffee ring effect



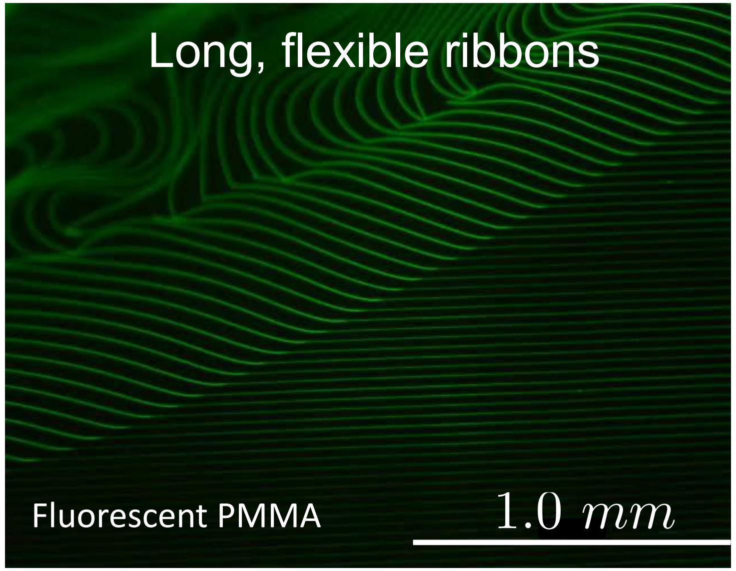


Kim et al, Adv. Mater., 2010
Lee et al, Adv. Mater., 2013

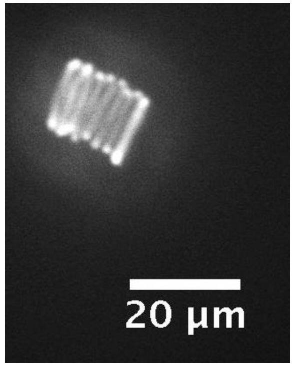
Millimetric length, microscopic width, nanoscopic thickness

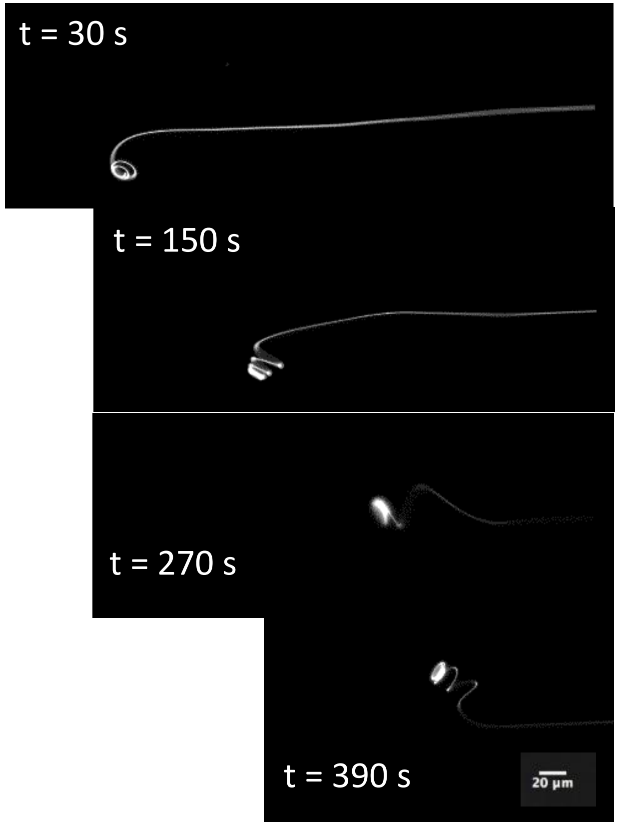
Nano-ribbons are very flexible

- At the water-air interface
- Immersed in water



Lee et al, Adv. Mater., 2013



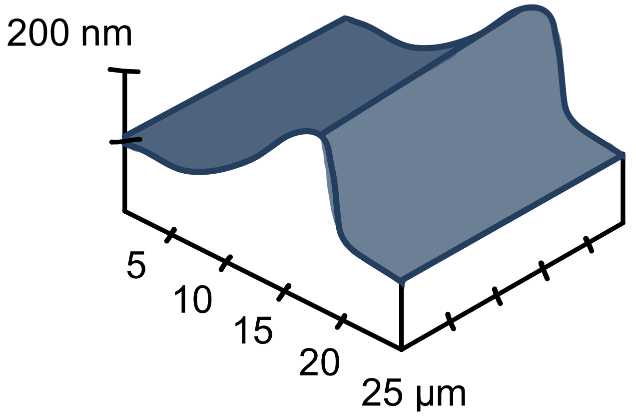


Pham et al, Adv. Mater., 2013

Ribbons from PMMA, glassy polymer
Bulk modulus ~GPa

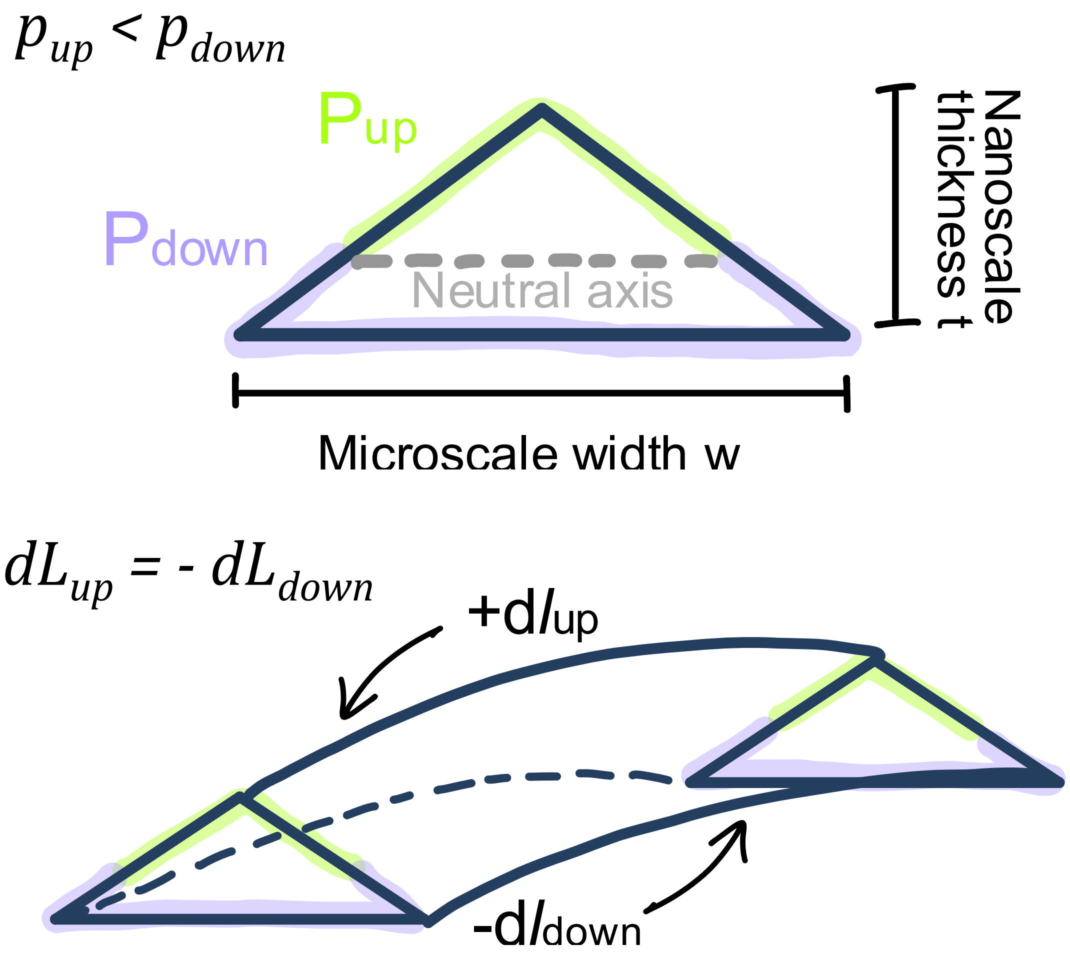
Coil into helical 3D structures when immersed in water!

Why do ribbons coil?



Why do ribbons coil?

- Net change of area during bending

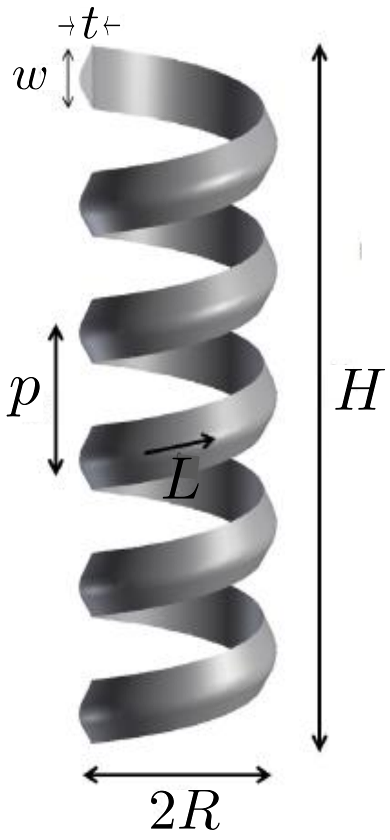


- Gain in surface energy balanced by elasticity

$$R \sim \frac{Et^2}{\gamma}$$

E : modulus

γ : surface tension



Elasticity and surface tension determine helix radius, pitch uncontrolled

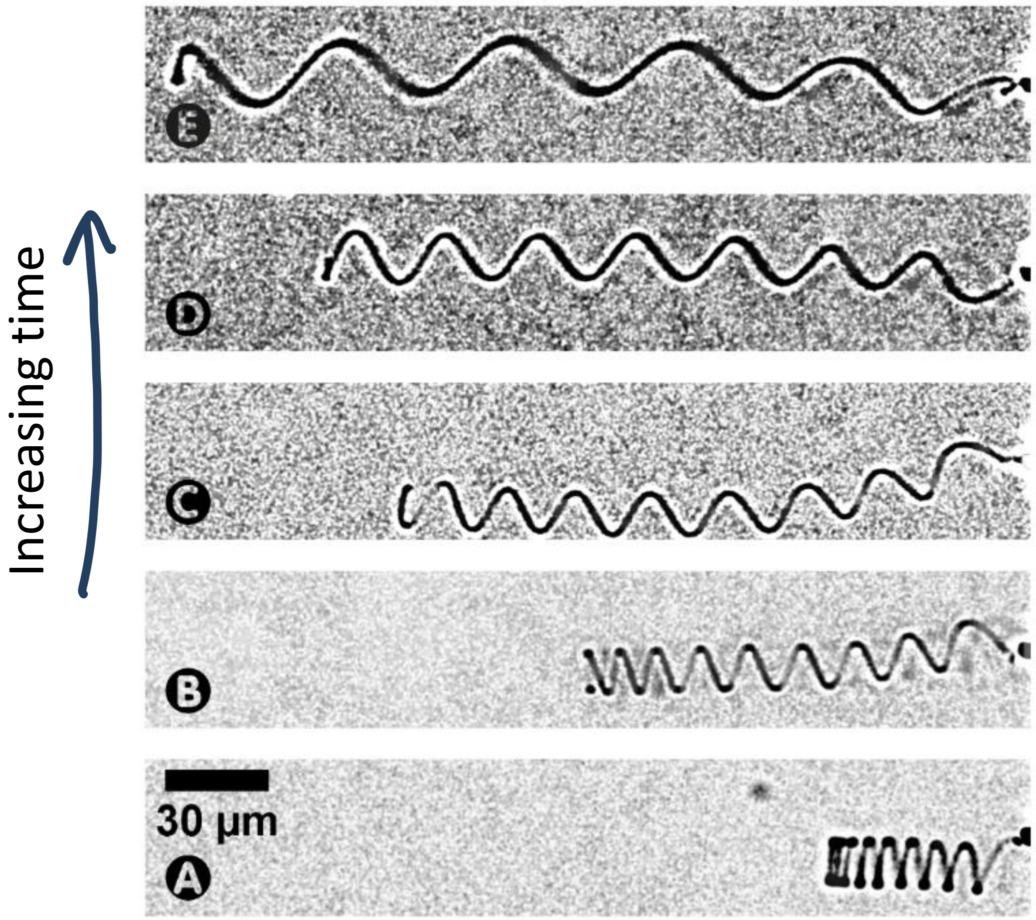
How to control helix pitch

- Stretching for a given amount and time

Prévost, AL et al, ACS Nano 2022

How to control helix pitch

- Induces permanent shape change



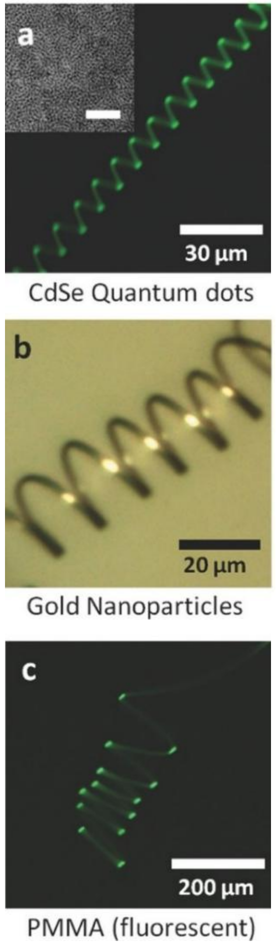
- Significant change to pitch angle with radius and length nearly constant
- Very low stresses applied, material creep of glassy polymer in highly confined nanometric ribbons

Prévost, AL et al, ACS Nano 2022

Full control of helix pitch can be obtained leveraging weak material creep

Simple 2D fabrication leads to fully controlled 3D structures

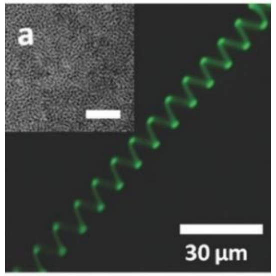
- Versatile method



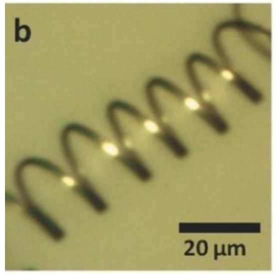
Pham AL et al, PRE, 2015
Prevost, AL et al, Extreme Mechanics Letters, 2023

Simple 2D fabrication leads to 3D structures

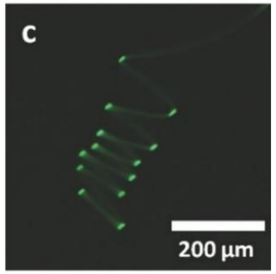
- Versatile method
- Extension under flow



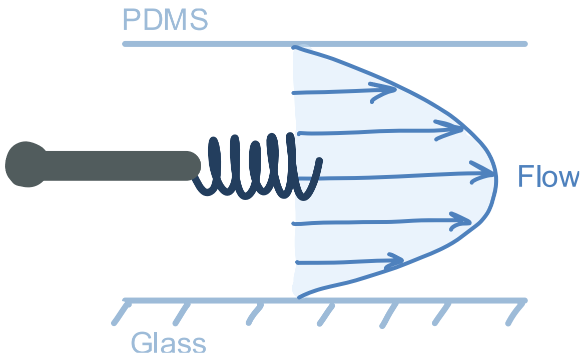
CdSe Quantum dots

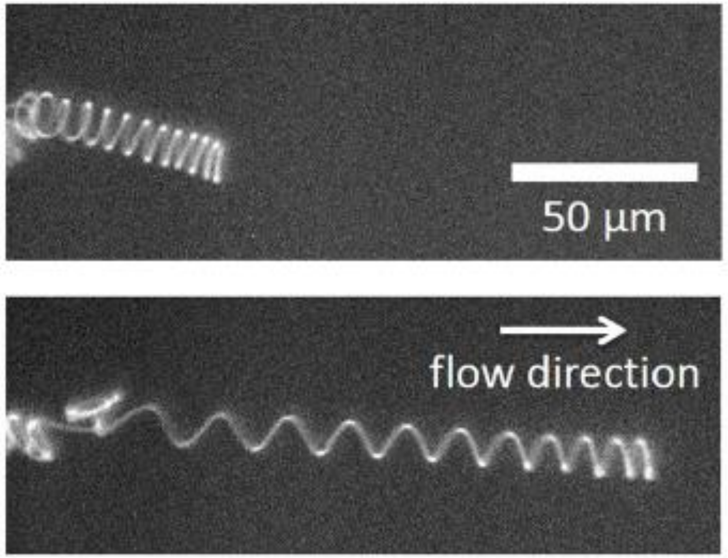


Gold Nanoparticles



PMMA (fluorescent)





Highly stretchable helices with strain stiffening specific to helical ribbons

Pham AL et al, PRE, 2015
Prevost, AL et al, Extreme Mechanics Letters, 2023

Highly flexible helices from various materials

Summary – very flexible micro-helices

- Simple and versatile method
- Full control of shape via ribbon geometry and stretching treatments
- High flexibility due to helix geometry
- Novel rheology of highly confined polymeric material

- Remain to be studied under flow

Remain to be fully exploited

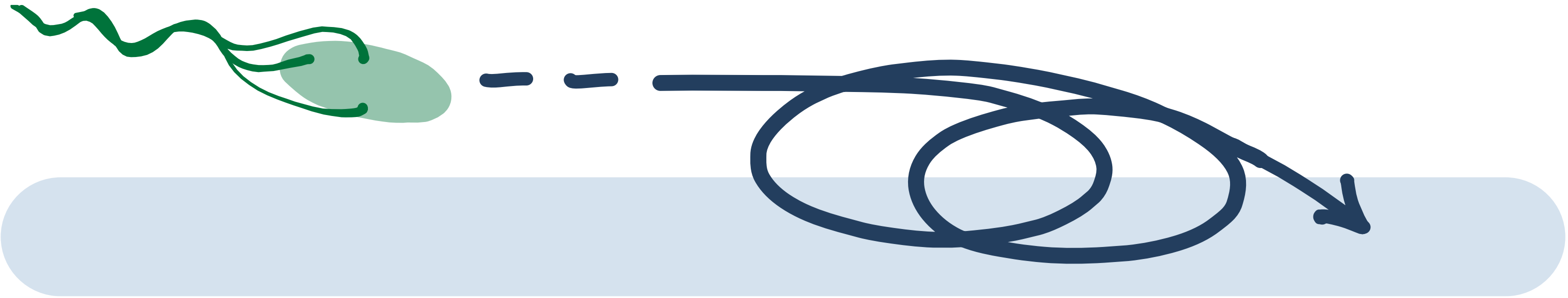
Summary – very flexible micro-helices

- Simple and versatile method
- Full control of shape via ribbon geometry and stretching treatments
- High flexibility due to helix geometry
- Novel rheology of highly confined polymeric material

- More complex shapes?

Remain to be fully exploited

Chirality in swimming trajectories and their role on bacteria transport

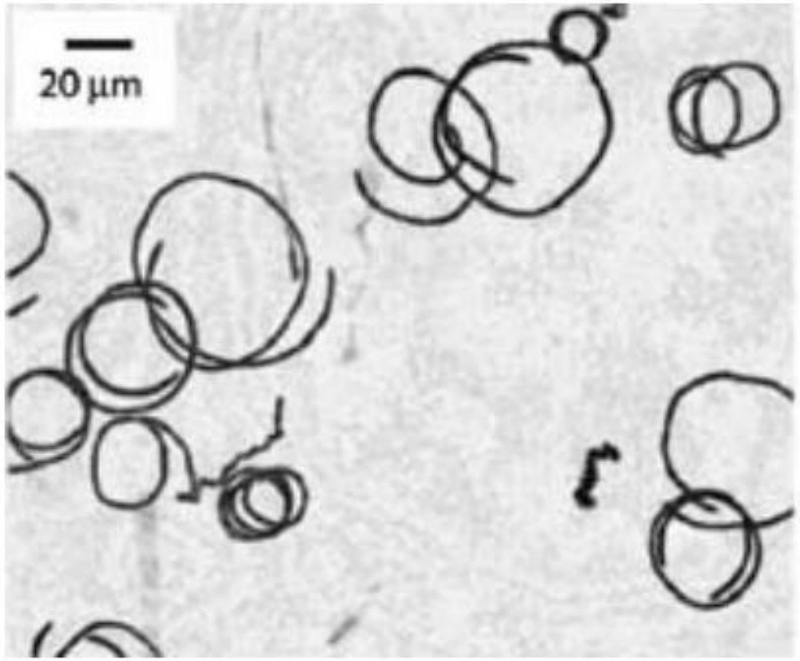


Peixin Zhang, Gaspard Junot (now Univ. Bordeaux), Nuris Figuerao-Morales (now Univ. Boulder) Eric Clement (PMMH-ESPCI, Paris, France)
Selma Köhler, Arnold Mathijssen (UPenn), Andreas Zöttl (Uni Wien, Austria)

Chiral particles and Odd fluids - Eindhoven January 2026

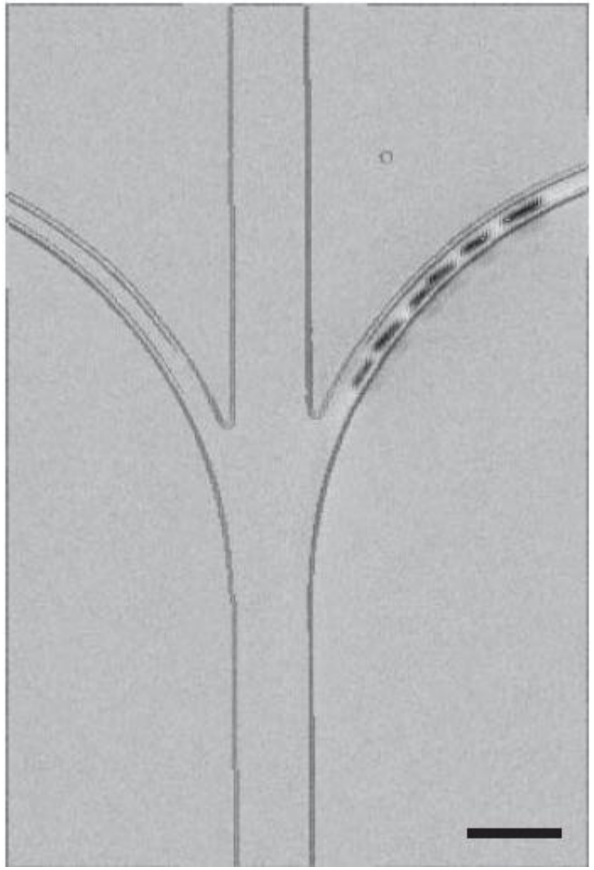
Bacteria swim in circles close to bounding walls….

- Hydrodynamic interactions with walls lead to swimming in circles at solid interfaces



Lauga, et al. Biophys. journal (2006)

- Observed to lead to swimming towards the “right” in confined geometries

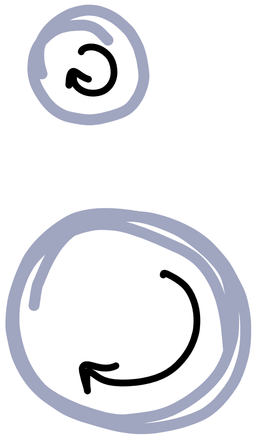


DiLuzio, et al.
Nature 2005

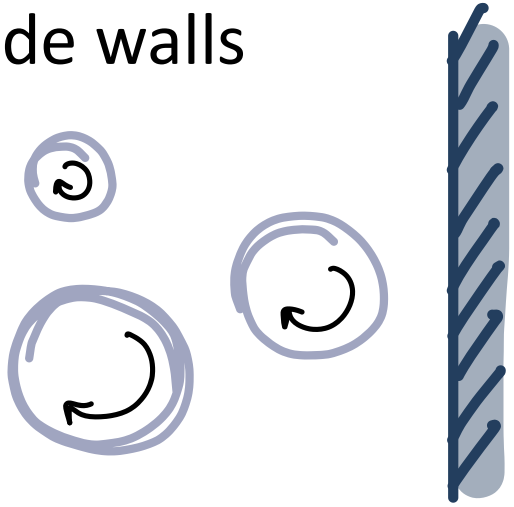
…. leading to surprising transport properties

How does chirality of circular trajectories ….

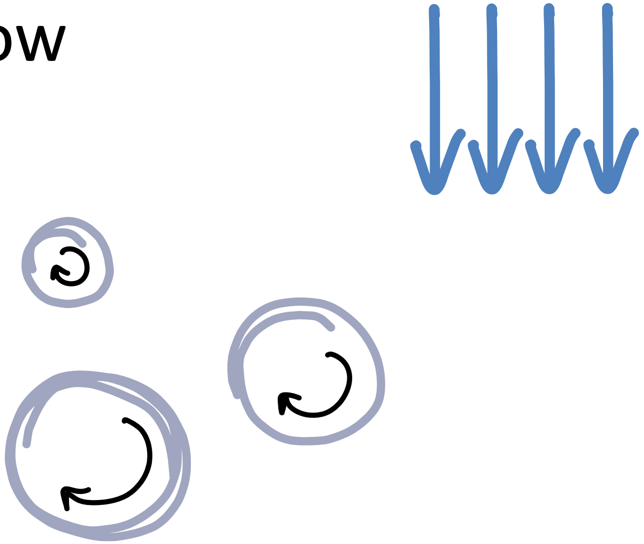
- Circular trajectories



- Side walls



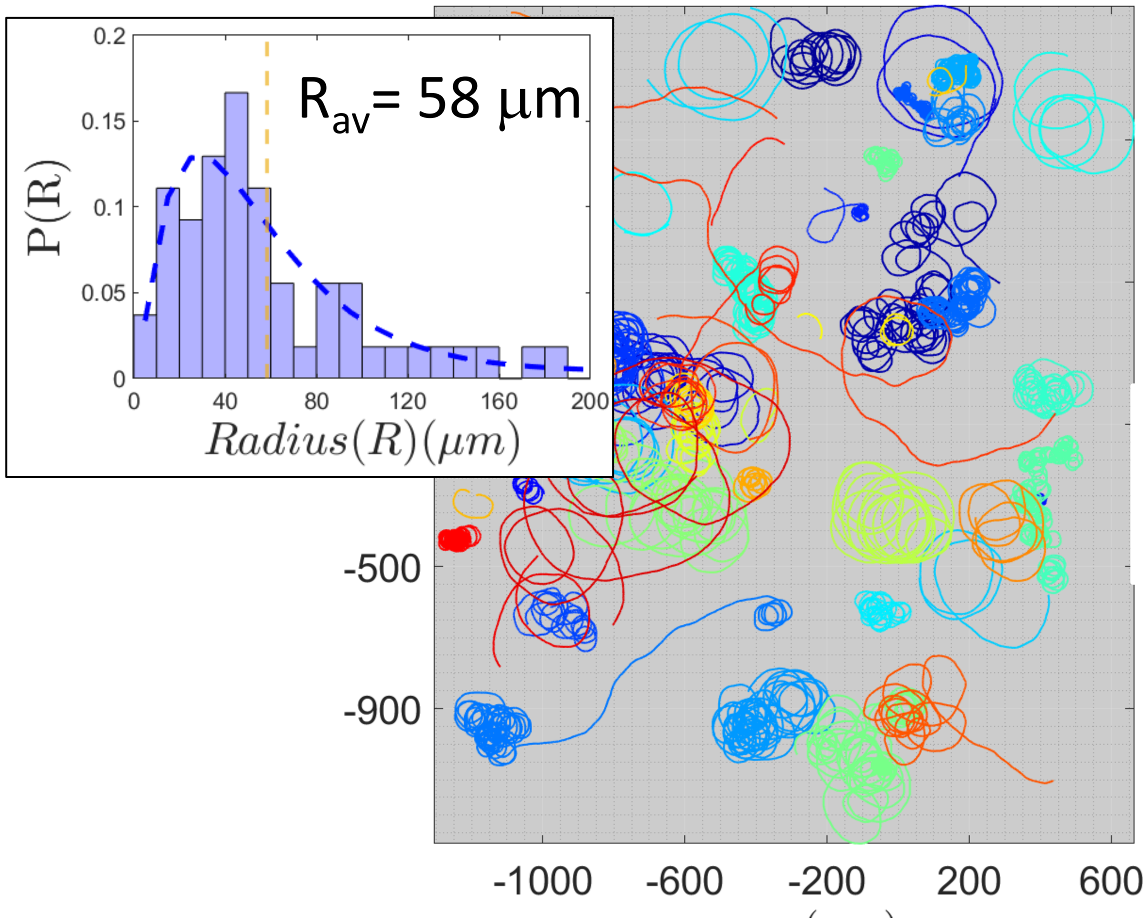
- Flow



…. break transport symmetry

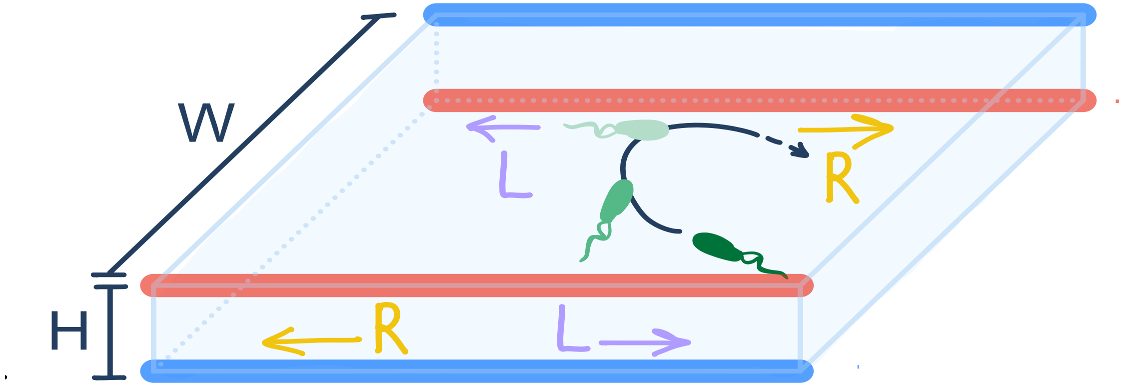
Chiral circular trajectories in the presence of walls

- CW circular trajectories of E-coli bacteria close to surfaces



- Experimental set-up

W=20-200μm
H=50μm

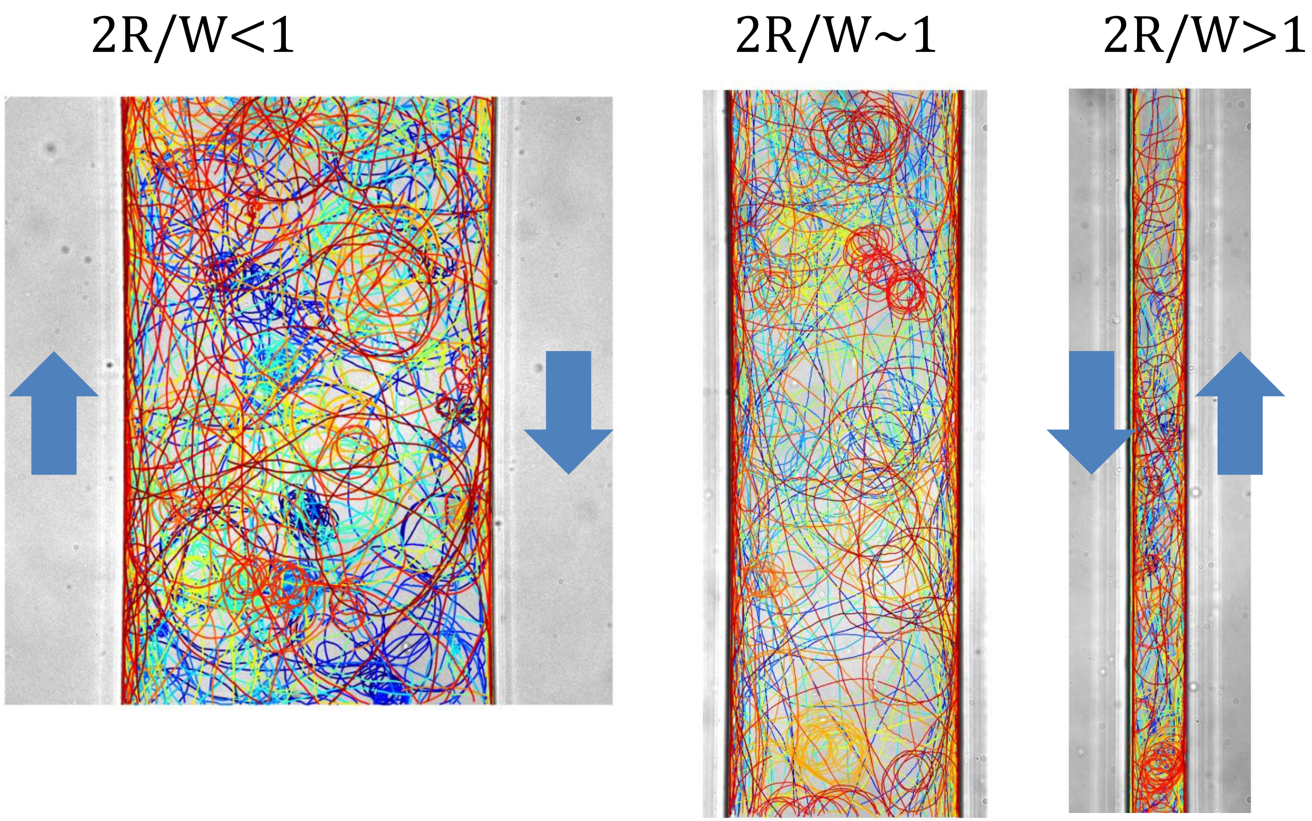


Lateral confinement given by 2R/W

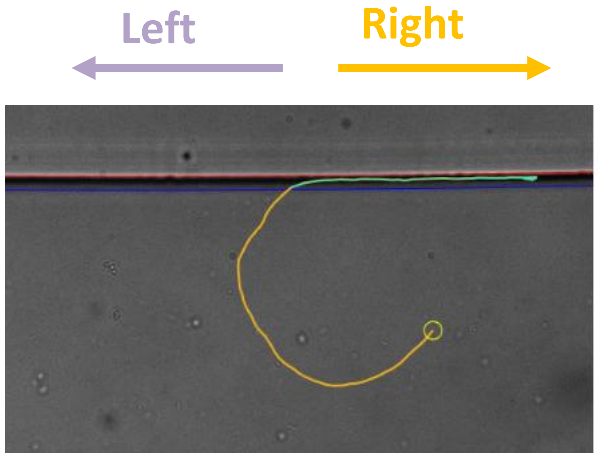
Investigate transport along the edges as a function of lateral confinement

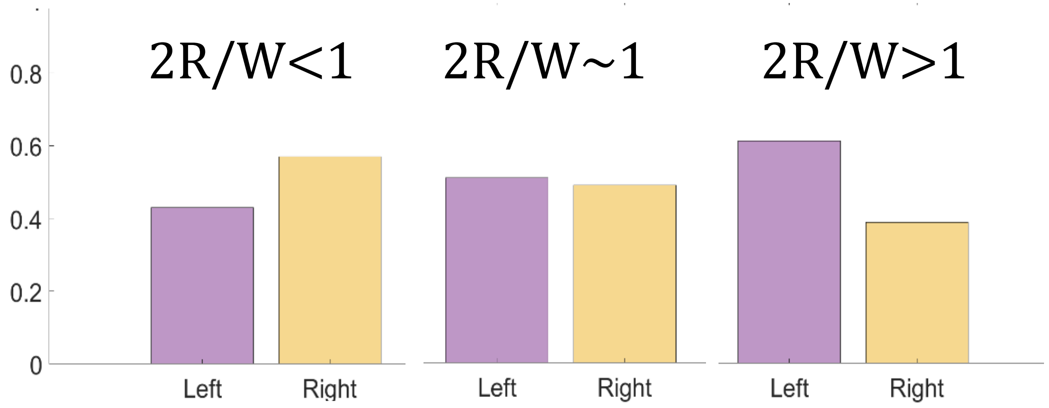
First experimental observations

- Varying confinement



- Look at arrival at the edges....

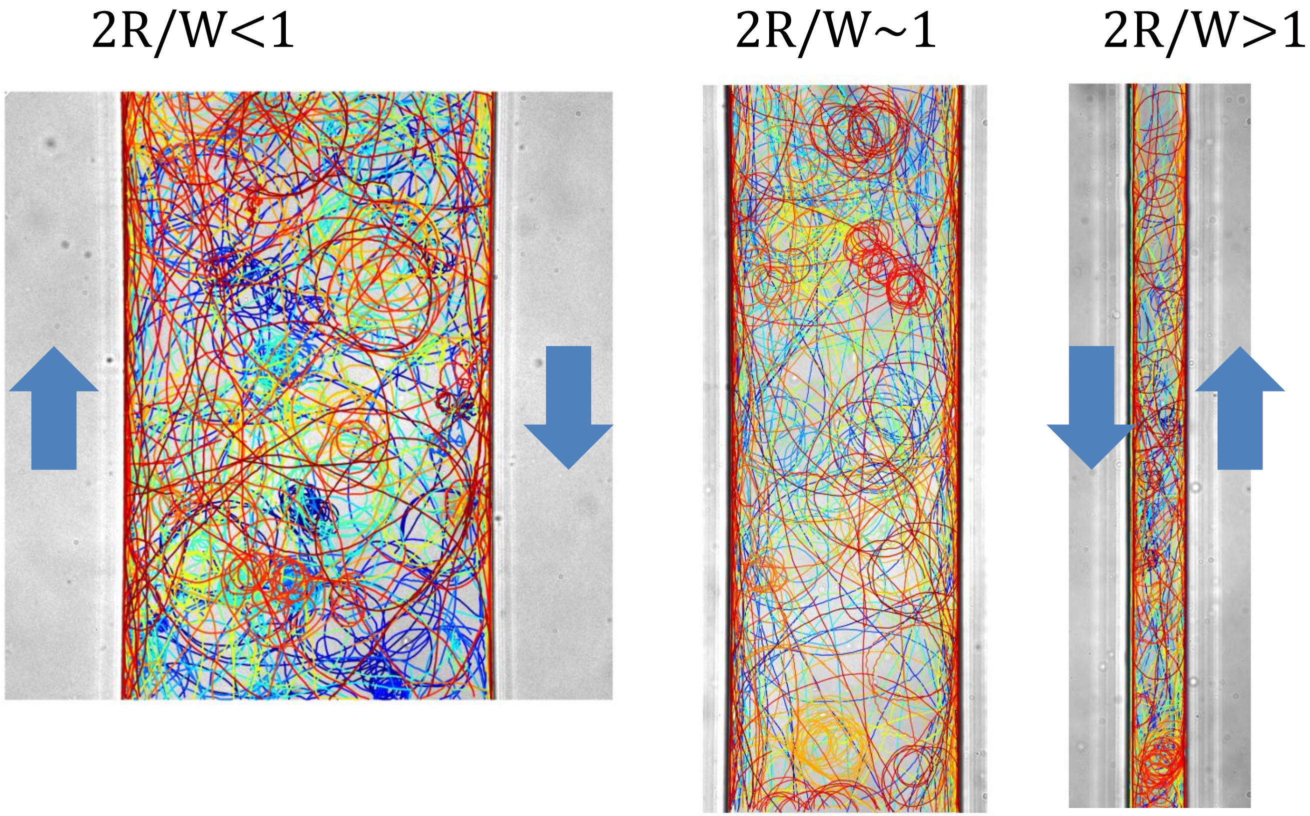




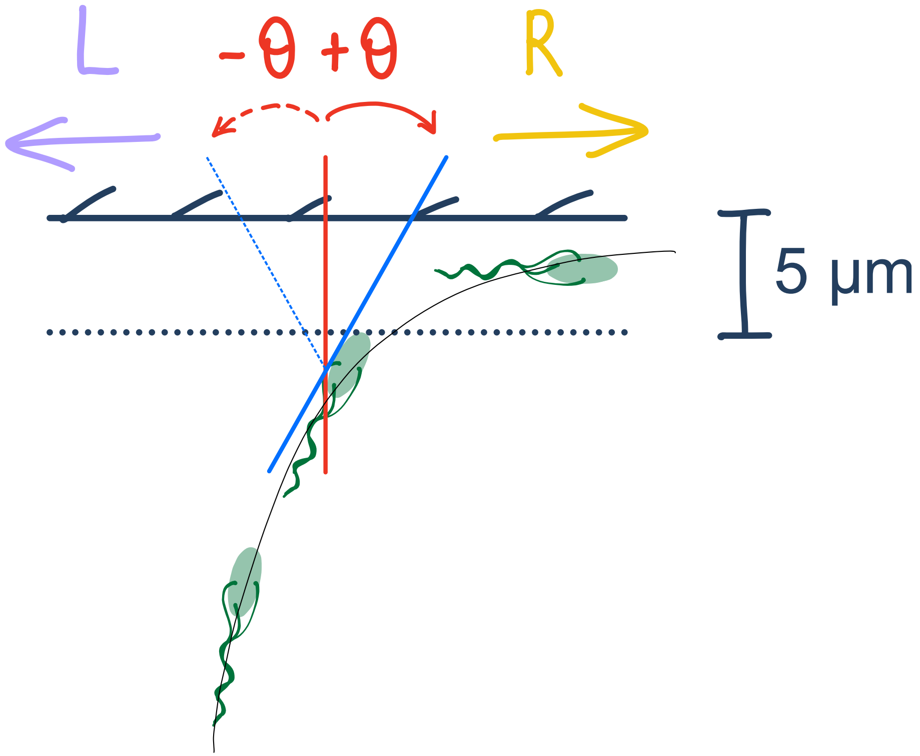
Bacteria flux close to the edges seems reversed for increasing confinement

First experimental observations

- Varying confinement



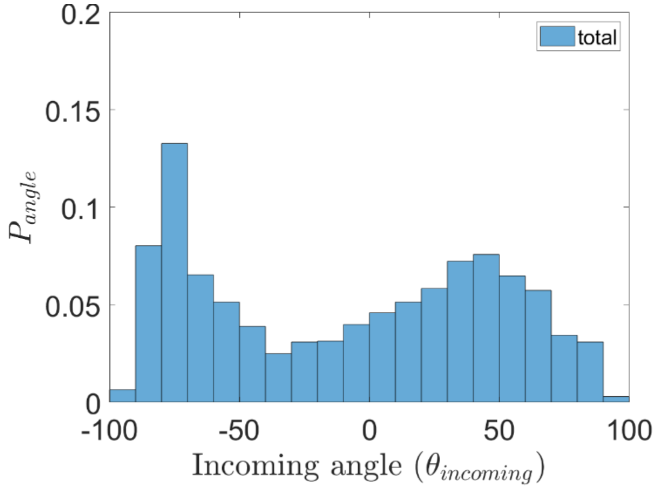
- Look at arrival at the edges….



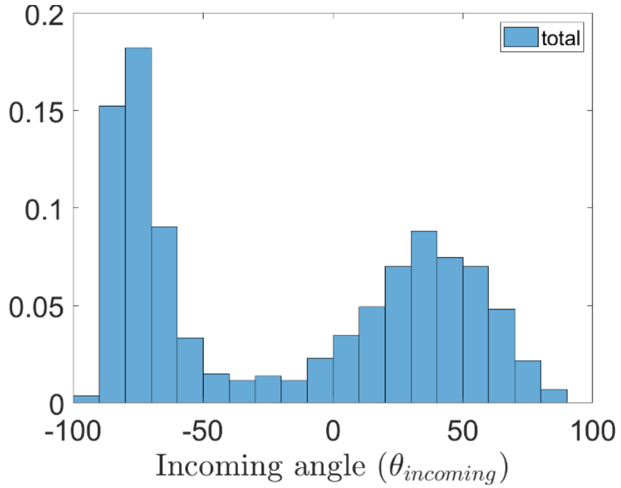
Bacteria flux close to the edges seems reversed for increasing confinement

Arrival at channel edges

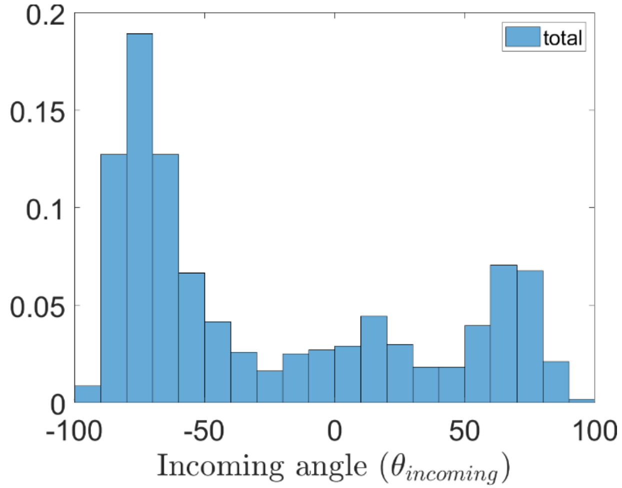
2R/W<1



2R/W~1

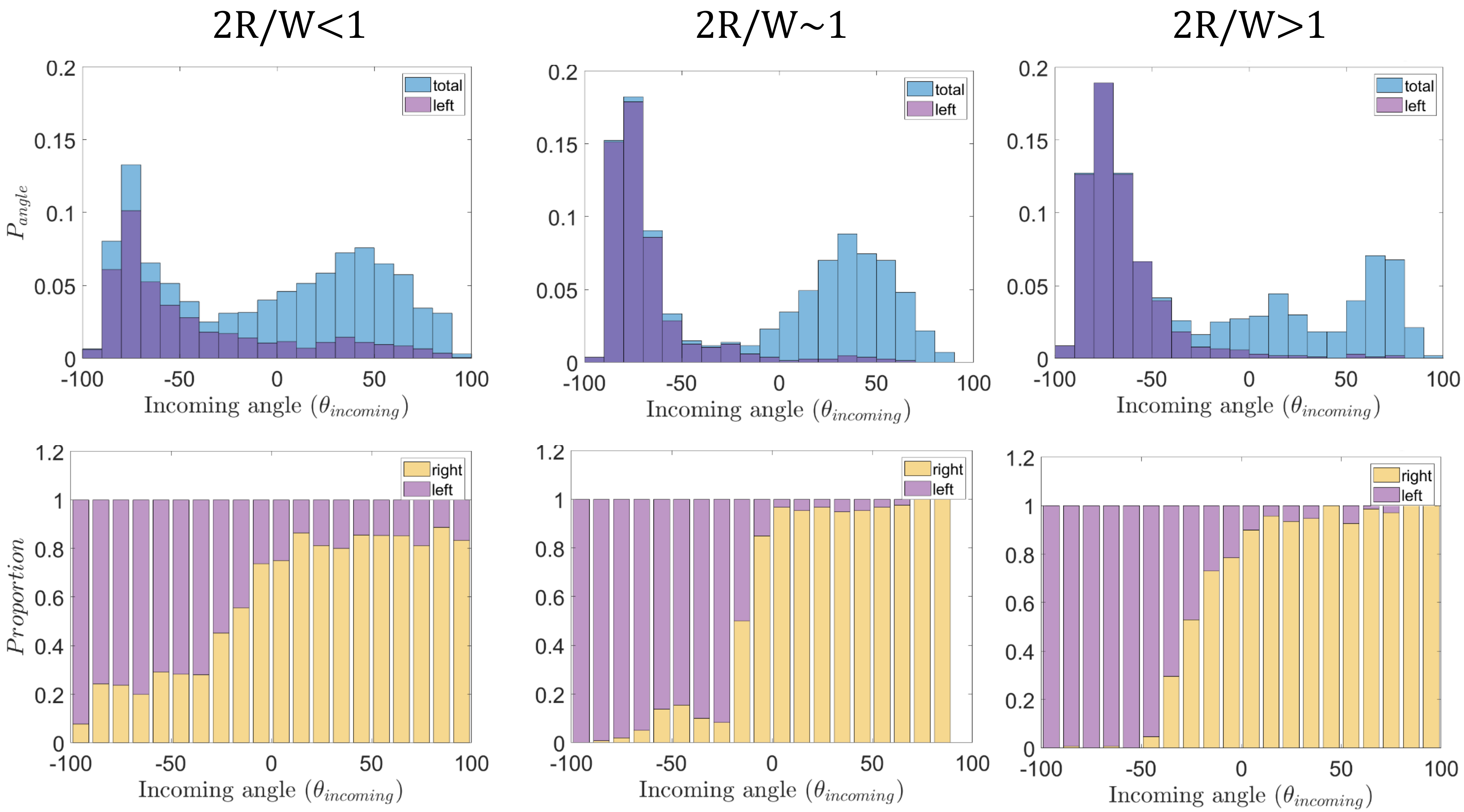


2R/W>1



Angle distributions vary as a function of channel confinement

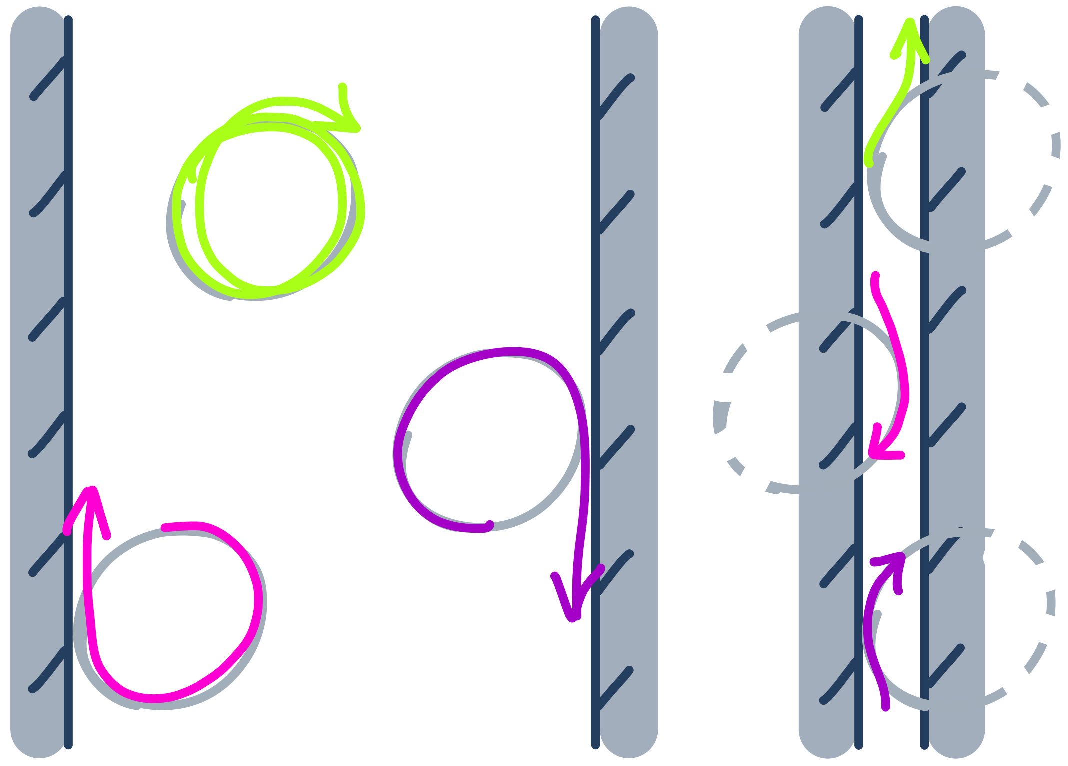
Arrival at channel edges



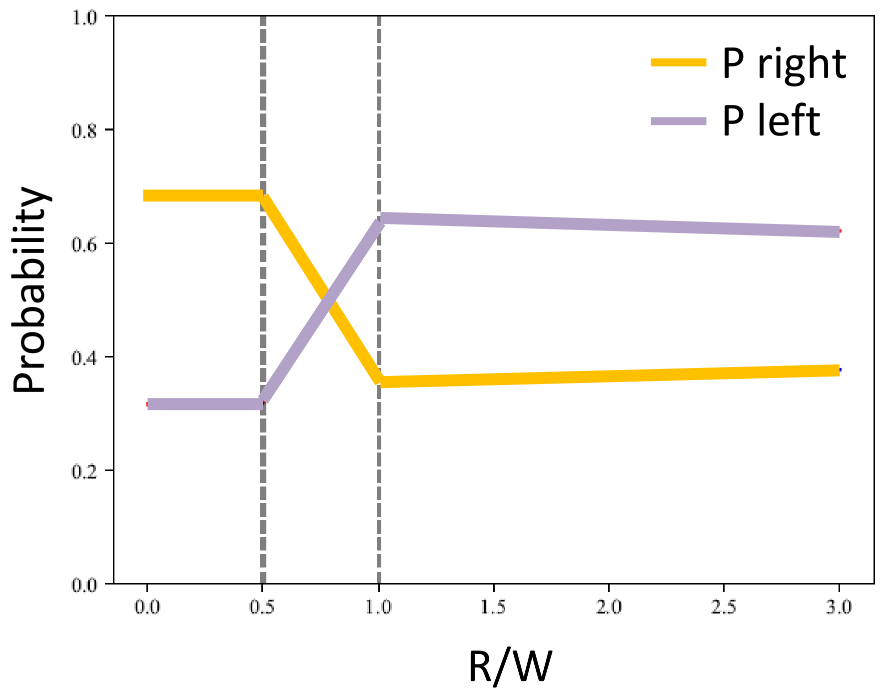
Swimming direction entirely given by angle distribution of bacteria arrival

What sets the angle distribution at the approach of the channel wall

- Angle distribution and confinement



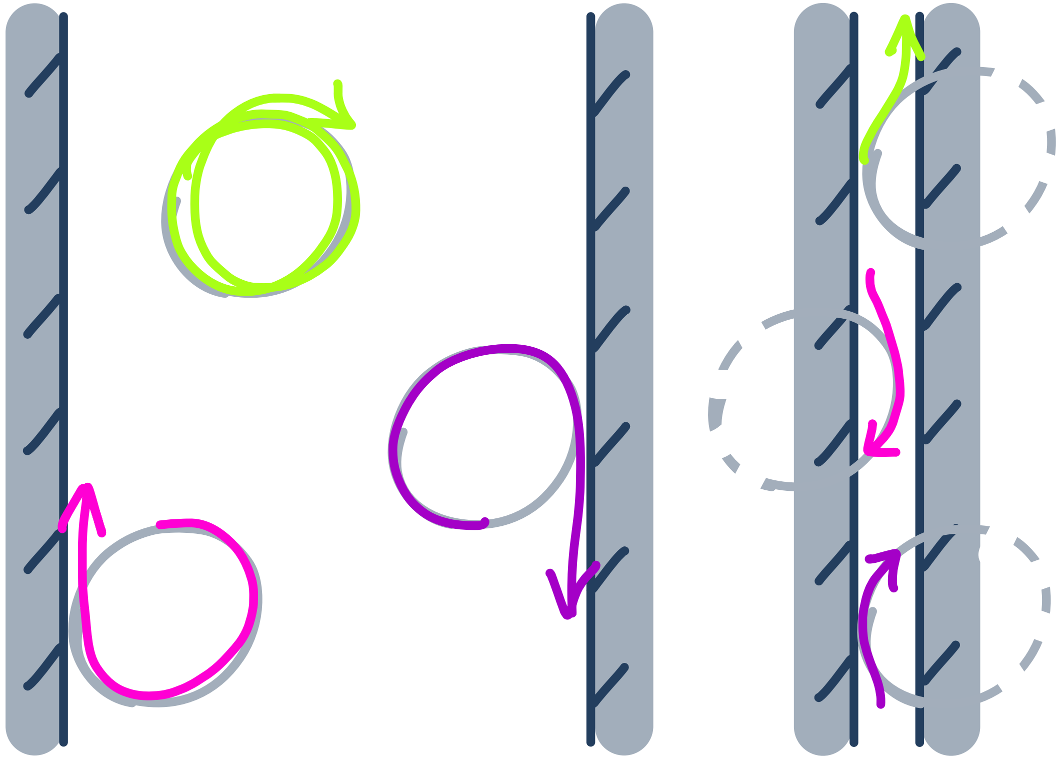
- Probability to “arrive” left or right for equally distributed position and orientation



Angle distribution given by geometry

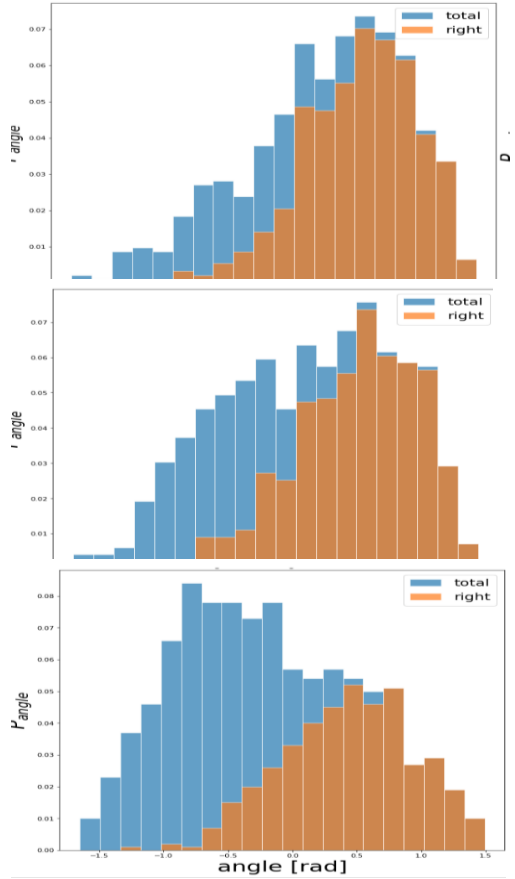
What sets the angle distribution at the approach of the channel wall

- Angle distribution and confinement



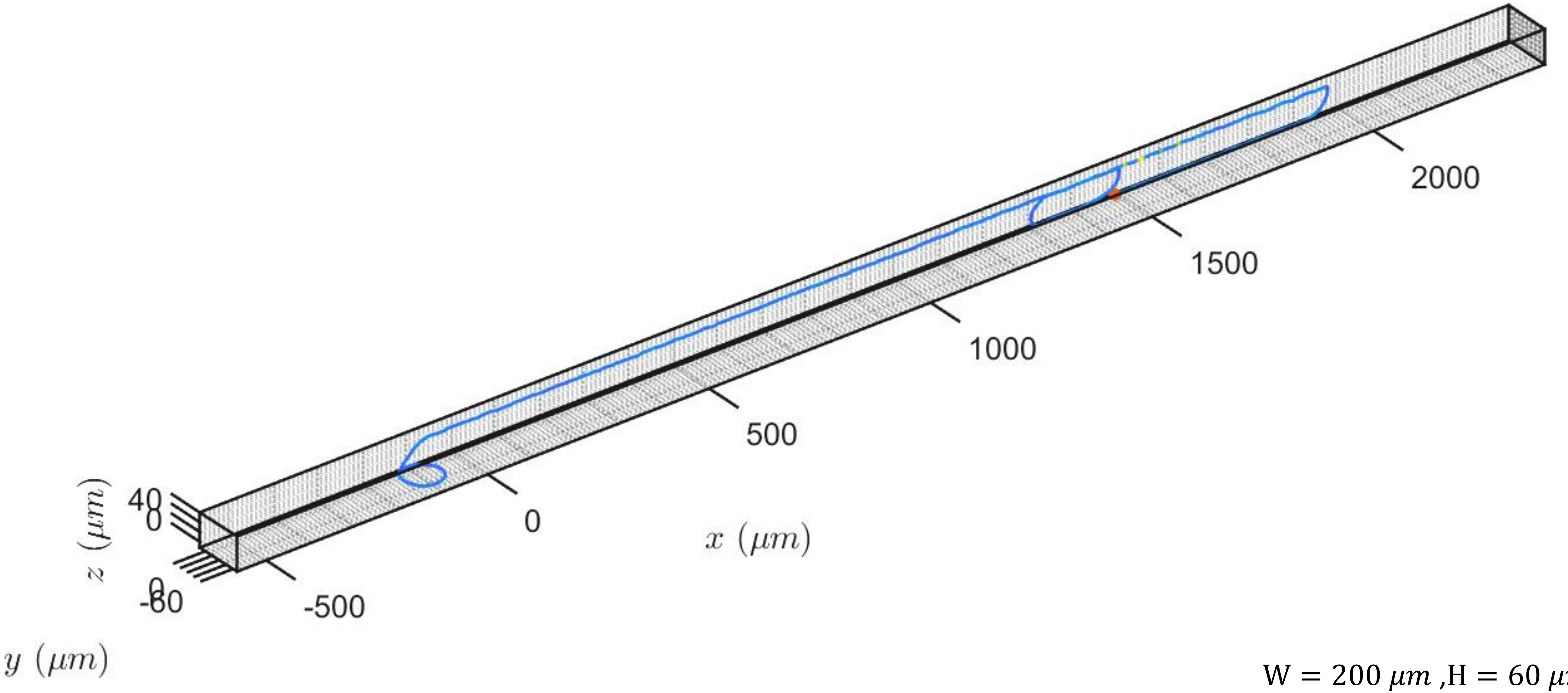
- From active Brownian particle simulations with noise

Increasing confinement



Flux inversion also observed in simulations

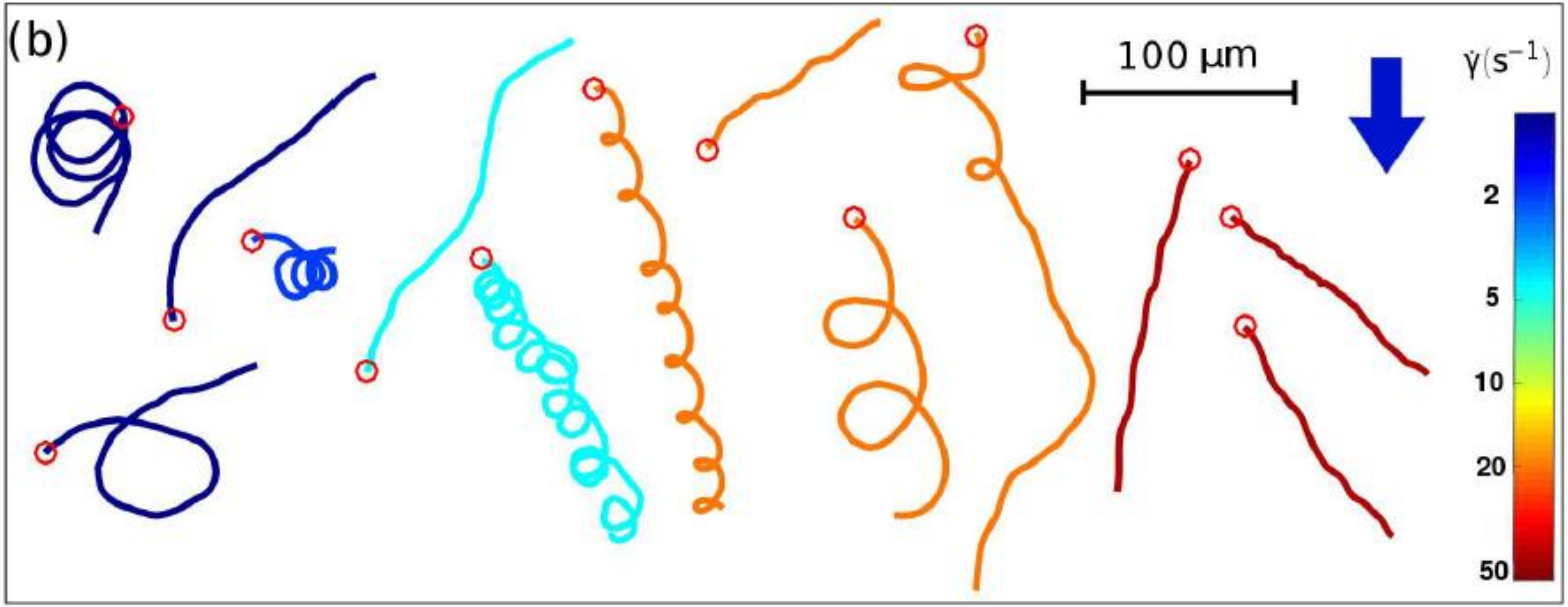
Understand full 3D transport....



$\mathrm{W} = 200\ \mu m$,$\mathrm{H} = 60\ \mu m$

Competing effects of different channel surfaces

Chiral circular trajectories in the presence of flow



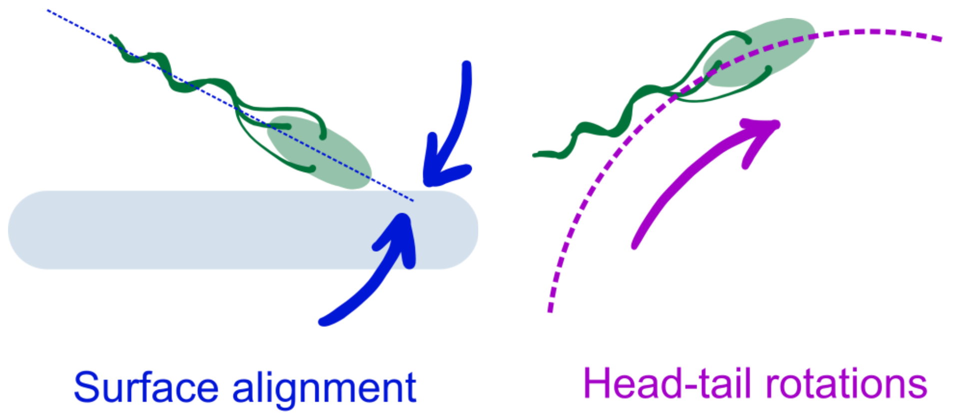
Kaya and Koser, Biophys. J. 2012
Lauga, J. Biophys, 2006

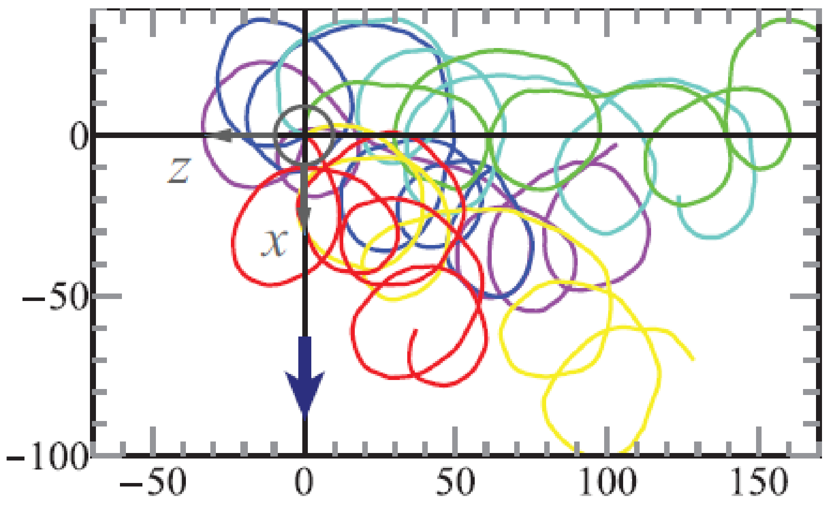
Mathijssen, AL et al, Nature Comm. 2019

Complex trajectories observed with increasing flow strength

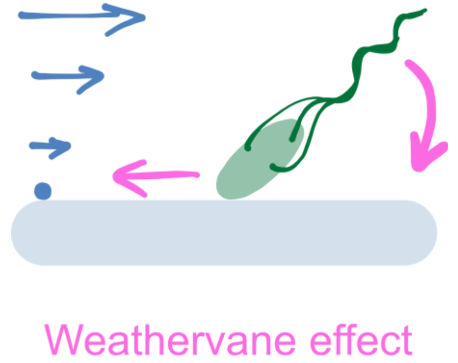
From simulations: weak flows

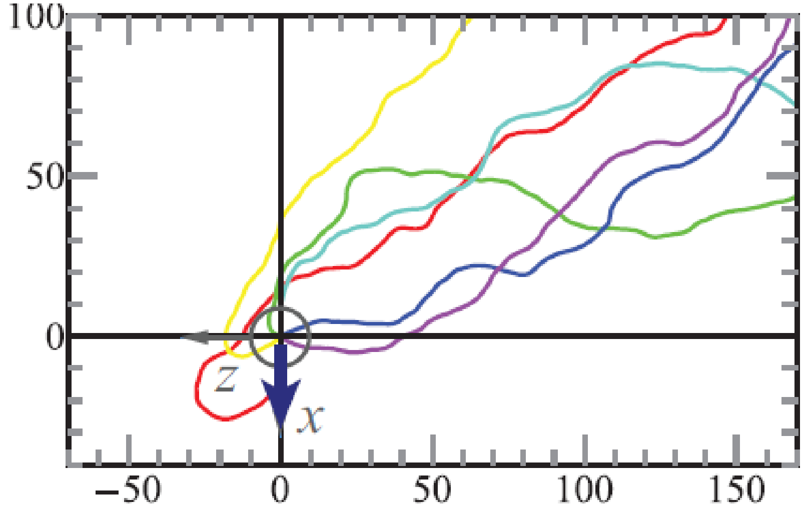
Wall interactions (no flow)





Flow and surface



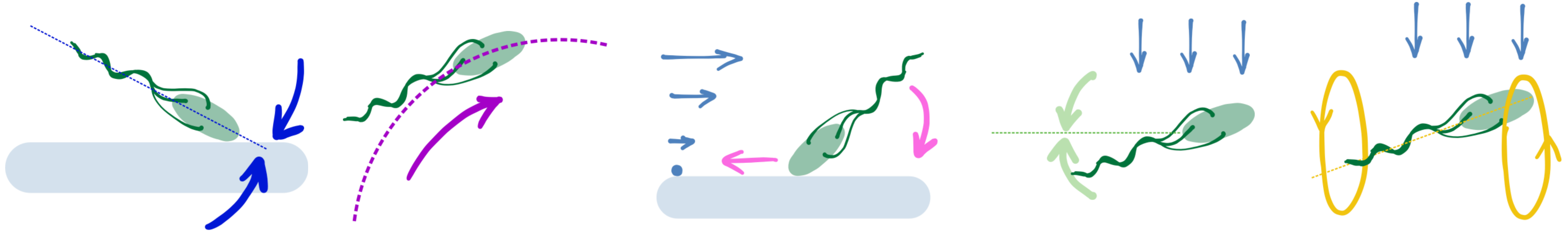


Mathijssen, AL et al, Nature Comm. 2019

Adler transition: CW trajectories bent right and then upstream

From simulations: strong flows

Wall interactions (no flow) ***Flow and surface*** ***Flow (bulk)***



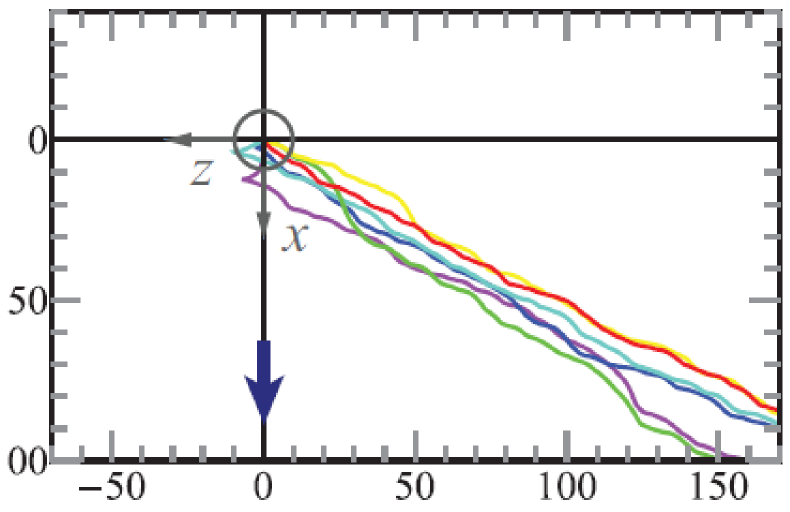
Surface alignment

Head-tail rotations

Weathervane effect

Flagellar chirality

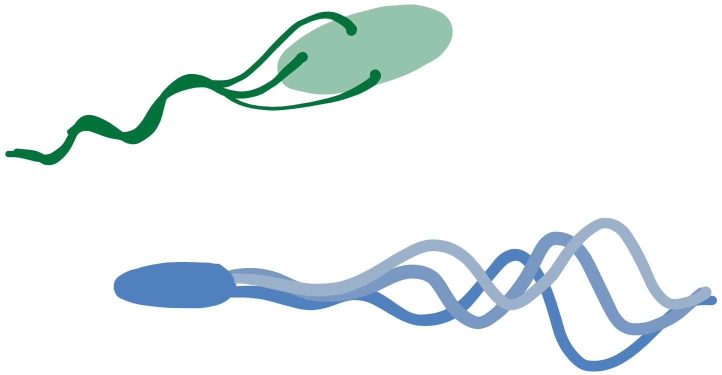
Jeffery orbits

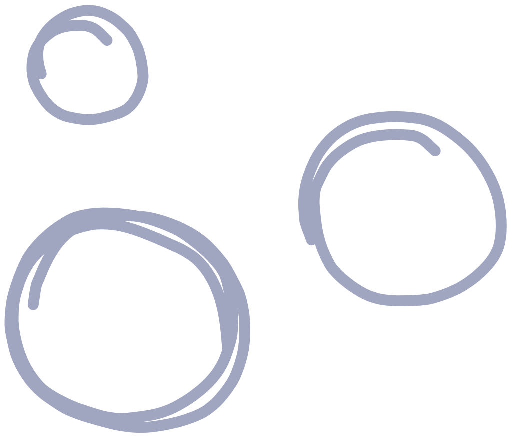


Rheotaxis induced by chiral particle shape becomes dominant

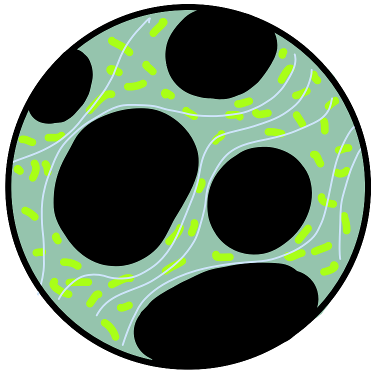
Transport properties of active and passive chiral particles

Chirality occurs in many ways … strongly influencing transport properties

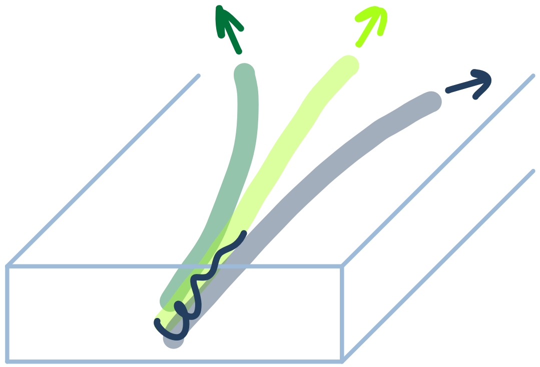




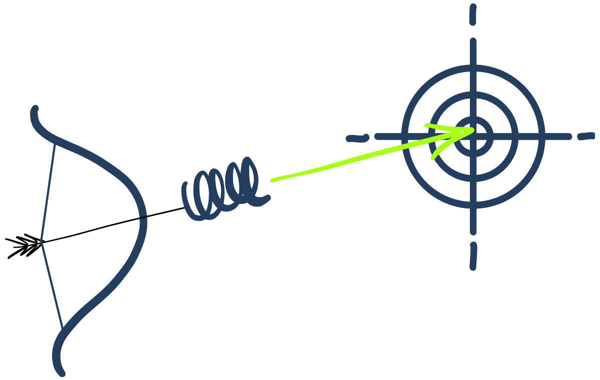
Understanding micro-organism transport



Separation



Particle design for targeted delivery



Martyna Goral
Illustrations

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