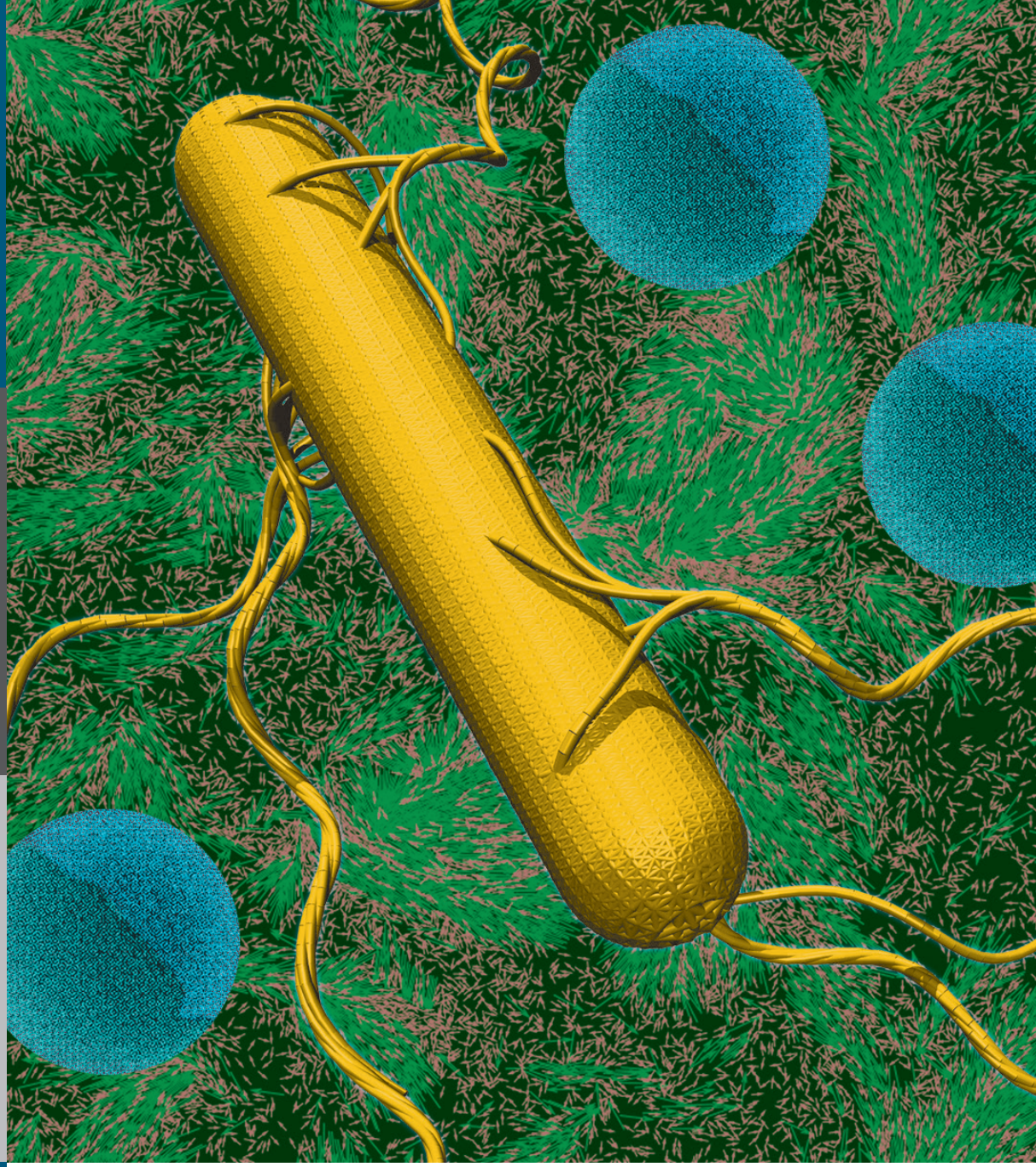

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International Conference: Microswimmers –

From Single Particle Motion to Collective Behaviour

4 – 7 October 2016 in Bonn, Germany

Book of Abstracts

MICRO-SWIMMERS

JÜLICH
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International Conference: Microswimmers

From Single Particle Motion to Collective Behaviour

4 - 7 October 2016

Forschungszentrum caesar Bonn, Germany

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Book of Abstracts

Front page picture
Bacteria propelled by bundles of rotating helical filamens, Janus colloids which catalyse a chemical reaction on a hemi-spherical cap (foreground) and motility-induced phase separation and segregation in mixtures of self-propelled rods (background)

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"Microswimmers –From Single Particle Motion to Collective Behaviour"

International Conference: Microswimmers

From Single Particle Motion to Collective Behaviour

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Scope

The motility of cells and microorganisms is a cornerstone of the existence of life and an outstanding achievement of evolution. Self-propulsion, sophisticated navigation strategies, and self-organized, spontaneous collective motion of swarms are prerequisites that facilitate, inter alia, bacteria to search for food, algae to orient toward light, and sperm cells to find and fertilize the ovum. The imitation of these evolutionary achievements by artificial microswimmers has an enormous potential impact on the life, environmental, and material sciences, but requires a deeper understanding of the various aspects of swimming at the microscale.

Interest in the field is increasing, and progress in understanding and designing microswimmers is rapidly advancing. Therefore the DFG Priority Programme 1726 “Microswimmers” is organizing this international conference with the aim of bringing together scientists from the various disciplines involved in microswimmer research and disseminating recent research highlights.

Topics

- Cells and Microorganisms
- Artificial Swimmers
- Nano- and Microbots
- Swimming Mechanisms
- Collective Behavior
- Synchronization
- Swimming in Confinement and External Fields
- Related Systems (Tissue Growth, Motility Assays, …)

Local Organizers

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International Conference: Microswimmers

From Single Particle Motion to Collective Behaviour

4 - 7 October 2016
Forschungszentrum caesar in Bonn, Germany

About the “Microswimmers”-DFG Priority Programme SPP 1726

The purpose of this DFG Priority Programme is to advance knowledge in the emerging field of active matter through collaborative support and networking over several locations. The SPP 1726 “Microswimmers – From Single Particle Motion to Collective Behaviour” facilitates connections between physicists, chemists, biologists, and material scientists throughout German academic research laboratories.

This combined expertise in experiment, theory, and simulation is used to investigate the behavior of microscopic swimmers. Overall, the three major objectives of the programme are

- understanding biological swimmers,
- designing and understanding artificial microswimmers,
- understanding cooperative behavior and “swarming”of ensembles of microswimmers.

Contents

Program

Microswimmers – From Single Particle Motion to Collective Behaviour

Tuesday, October 4

8.00-9:00 h *Registration*

Session 01

09:00 **W. Poon** (University of Edinburgh, United Kingdom)
Painting with bacteria

09:30 **V. Kantsler** (University of Warwick, United Kingdom)
Swimming navigation in-micro

10:00 **O. D. Lavrentovich** (Kent State University, USA)
Effects of director field on dynamics of bacteria in liquid crystals

10:20 **A. DeSimone** (SISSA, Trieste, Italy)
Metaboly in Euglenids: A Model and its experimental validation

10:40 **B. Eckhardt** (Philipps-Universität Marburg, Germany)
Exploiting a buckling instability to escape from traps

11:00 *Coffee*

Session 02

11:20 **E. Lauga** (University of Cambridge, United Kingdom)
Symmetry-breaking in flexible active filaments

11:50 **R. Adhikari** (The Institute of Mathematical Sciences, Chennai, India)
Tractions laws for active colloids and their application to crystallization

12:20 **D. R. Brumley** (ETH Zürich, Switzerland)
Long-range interactions disrupt synchronized states in chains of fluid-coupled oscillators

12:40 **B. M. Friedrich** (MPI für Physik komplexer Systeme, Dresden, Germany)
A force-velocity relationship of flagellar oscillations

13:00 **T. Palberg** (JGU Mainz, Germany)
Ion-exchange-based electroosmotic pumps utilized for microswimming

13:20 *Lunch*

Tuesday, October 4

Session 03

14:30 **I. Giardina** (Sapienza University of Rome, Italy)
Information propagation and collective changes of states in biological groups

15:00 **R. Di Leonardo** (CNR Sapienza University of Rome, Italy)
Holographic imaging reveals the mechanism of wall entrapment in swimming bacteria

15:30 **S. Sanchez** (Institute for Bioengineering Catalonia, Barcelona, Spain)
Enzyme-powered biocompatible mesoporous silica micro/nano-bots

15:50 **V. Magdanz** (Leibniz-Institut für Festkörper- und Werkstoffforschung, Dresden, Germany)
Tubular hybrid microswimmers for the controlled guidance and delivery of spermatozoa

16:10 **M. Pella** (TU Dortmund, Germany)
Synthesis and investigation of different types of alginate-based artificial microswimmers

16:30 *Coffee*

Session 04

16:50 **A. Würger** (Université de Bordeaux, France)
Charge-driven self-propulsion of hot Janus particles

17:20 **H. Chaté** (CEA - Saclay, France)
Weak synchronization and large-scale collective oscillations in dense bacterial suspensions

17:50 **K. Kroy** (Universität Leipzig, Germany)
Exact symmetries in the velocity fluctuations of a hot Brownian swimmer

18:10 **S. Santer** (Universität Potsdam, Germany)
Light driven diffusioosmosis: Manipulation of particle assembly

Wednesday, October 5

Session 05

09:00 **R. Kapral** (University of Toronto, Canada)
Collective dynamics of chemically-powered motors

09:30 **R. Golestanian** (Oxford University, United Kingdom)
Collective chemotaxis in active matter

10:00 **R. van Roij** (Utrecht University, The Netherlands)
From one force-free swimmer to an active dispersion: Mechanism, shape, and (osmotic?) pressure

10:20 **M. N. Popescu** (MPI für Intelligente Systeme, Stuttgart, Germany)
Chemically active particles near responsive interfaces

10:40 **J. de Graaf** (University of Edinburgh, United Kingdom)
Lattice-Boltzmann methods for autophoretic swimmers

11:00 *Coffee*

Session 06

11:20 **P. Peyla** (Université Grenoble Alpes, France)
Spreading of an active cloud of microswimmers

11:50 **L. G. Wilson** (University of York, United Kingdom)
3D holographic imaging of microswimmers

12:20 **K. Ishimoto** (Kyoto University, Japan)
Multiple mechanical functions of sperm hyperactivation

12:40 **L. Alvarez** (caesar, Bonn, Germany)
Sperm: The search machine

13:00 **J. Elgeti** (Forschungszentrum Jülich, Germany)
Sperm cells swimming in confinement

13:20 *Lunch*

Session 07

14:30 **J. F. Brady** (California Institute of Technology, Pasadena, USA)
The Force on a body in active matter

15:00 **P. Tierno** (Universitat de Barcelona, Spain)
Colloidal microworms and microcarpets propelling via a cooperative hydrodynamic conveyor-belt

15:30 **E. Climent** (Université Toulouse, France)
Vertical migration of motile phytoplankton chains through turbulence

15:50 **T. Voigtmann** (Deutsches Zentrum für Luft- und Raumfahrt, Köln, Germany)
Active Brownian-particle glasses: A mode-coupling theory

16:10 **M. Ripoll** (Forschungszentrum Jülich, Germany)
Hydrodynamic self-assembly of thermophoretic swimmers

16:30-18:30 **Poster Session I**

Thursday, October 6

Session 08

09:00 **I. S. Aronson** (Argonne National Laboratory, USA)
Expulsion of bacteria by a vortical flow

09:30 **D. Ahmed** (ETH Zürich, Switzerland)
Artificial swimmers in acoustic and magnetic fields

10:00 **P. Fischer** (Universität Stuttgart, Germany)
Artificial microswimmers

10:20 **C. Maaß** (MPI für Dynamik und Selbstorganisation, Göttingen, Germany)
Droplet swimmers in complex geometries: Autochemotaxis and trapping at pillars

10:40 **R. Seemann** (Universität des Saarlandes, Saarbrücken, Germany)
Evolutive self-propelling Janus droplets utilized for programmable DNA cargo delivery

11:00 *Coffee*

Session 09

11:20 **M. C. Marchetti** (Syracuse University, USA)
Jamming of cell monolayers

11:50 **Y. Kafri** (Technion, Haifa, Israel)
Pressure in active systems

12:20 **J. Blaschke** (Technische Universität Berlin, Germany)
Hydrodynamics of microswimmers: Phase Separation and influence of gravity

12:40 **P. Virnau** (JGU Mainz, Germany)
Phase behavior of active colloidal particles

13:00 **K. Günther** (TU Dresden, Germany)
Construction and characterization of artificial thermophoretic micro-& nanoswimmers

13:20 *Lunch*

Session 10

14:30 **D. B. Weibel** (University of Wisconsin, USA)
Bacterial cell mechanics and motility

15:00 **C. W. Wolgemuth** (University of Arizona, Tucson, USA)
Unexpected parallelisms: From swimming bacteria to wound healing and cancer metastasis

15:30 **K. Drescher** (MPI für terrestrische Mikrobiologie, Marburg, Germany)
Nematic ordering transitions in bacterial biofilms

15:50 **R. G. Winkler** (Forschungszentrum Jülich, Germany)
Bacterial swarmer cells in confinement

16:10 **M. Engstler** (Universität Würzburg, Germany)
Trypanosome microswimmers in the tsetse fly

16:30-18:30 **Poster Session II**

19:30 *Conference Dinner*

Friday, October 7

Session 11

09:00 **A. R. Bausch** (TU München, Germany)
Cytoskeletal pattern formation

09:30 **D. Saintillan** (UCSD, San Diego, USA)
Collective motion in confinement

10:00 **J. Kierfeld** (TU Dortmund, Germany)
Shapes of sedimenting soft elastic capsules in a viscous fluid

10:20 **A. Mourran** (DWI - Leibniz-Institut, Aachen, Germany)
Swimming of morphoelastic ribbon helix

10:40 **S. Klumpp** (Universität Göttingen, Germany)
Magnetism and motility of magnetotactic bacteria

11:00 *Coffee*

Session 12

11:20 **I. Pagonabarraga** (Universitat de Barcelona, Spain)
Collective behavior and pattern formation in actuated magnetic and Janus colloidal suspensions

11:50 **M. Bär** (PTB, Braunschweig, Germany)
Modelling pattern formation and waves in suspensions of bacterial microswimmers

12:20 **A. M. Menzel** (HHU Düsseldorf, Germany)
Statistical description and dynamical density functional theory of semidilute microswimmer suspensions

12:40 **C. Bechinger** (Universität Stuttgart, Germany)
Light controlled active Brownian motion

13:00 **V. Mikulich** (TU Bergakademie Freiberg, Germany)
Effect of cilia orientation on transport of micro-particles

13:20-14:30 *Lunch*

Talks

Tuesday, October 4

Talks Tuesday, October 4

S01-01 **Poon, W. C. K.** ; Arlt, J.; Martinez, V. A.; Dawson, A.; Pilizota, T.
Painting with bacteria

S01-02 **Kantsler, V.**
Swimming navigation in-micro

S01-03 **Lavrentovich, O. D.** ; Zhou, S.; Peng, C.; Turiv, T.; Guo, Y.; Sokolov, A.; Aronson, I. S.; Wei, Q.
Effects of director field on dynamics of bacteria in liquid crystals

S01-04 **DeSimone, A.** ; Arroyo, M.; Beran, A.; Noselli, G.
Metaboly in Euglenids: a Model and its Experimental Validation

S01-05 **Eckhardt, B.** ; Kühn, M.; Thormann, K.; Schmidt, F. K.
Exploiting a buckling instability to escape from traps

S02-06 **Lauga, E.**
Symmetry-breaking in flexible active filaments

S02-07 **Adhikari, R.**
Tractions laws for active colloids and their application to crystallization

S02-08 **Brumley, D. R.** ; Bruot, N.; Kotar, J.; Goldstein, R. E.; Cicuta, P.; Polin, M.
Long-range interactions disrupt synchronized states in chains of fluid-coupled oscillators

S02-09 **Friedrich, B. M.** ; Klindt, G. S.; Ruloff, Ch.; Wagner, Ch.
A force-velocity relationship of flagellar oscillations

S02-10 **Palberg, T.**
Ion-exchange-based electroosmotic pumps utilized for microswimming

S03-11 **Giardina, I.**
Information propagation and collective changes of states in biological groups

S03-12 **Di Leonardo, R.** ; Bianchi, S.; Saglimbeni, F.
Holographic imaging reveals the mechanism of wall entrapment in swimming bacteria

S03-13 **Sanchez, S.** ; Xing, M.; Hortelao, A.
Enzyme-powered Biocompatible Mesoporous Silica Micro/Nano-Bots

S03-14 **Magdanz, V.** ; Medina-Sánchez, M.; Schmidt, O. G.
Tubular hybrid microswimmers for the controlled guidance and delivery of spermatozoa

S03-15 **Pella, M.** ; Froin, A.; Rehage, H.
Synthesis and investigation of different types of alginate-based artificial microswimmers

S04-16 **Würger, A.**
Charge-driven self-propulsion of hot Janus particles

S04-17 **Chaté, H.** ; Chen, C.; Liu, S.; Shi, X.; Wu, Y.
Weak synchronization and large-scale collective oscillations in dense bacterial suspensions

S04-18 **Kroy, K.** ; Falasco, G.; Pfaller, R.; Bregulla, A. P.; Cichos, F.
Exact symmetries in the velocity fluctuations of a hot Brownian swimmer

S04-19 **Santer, S.** ; Feldmann, D.; Maduar, S.; Vinogradova, O. I.
Light driven diffusioosmosis: manipulation of particle assembly

Painting with bacteria

J. Arlt[1], V. A. Martinez[1], A. Dawson[1], T. Pilizota[2] and W. C. K. Poon[1]

[1] School of Physics and Astronomy, The University of Edinburgh, United Kingdom
[2] School of Biological Sciences, The University of Edinburgh, United Kingdom
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We construct strains of *Escherichia coli* that need to be illuminated by light before they can generate the proton motive force necessary for self propulsion. (A preliminary description is given in [1].) We show how to 'paint pictures' using such bacteria and externally-imposed spatially-structured light fields, Figure 1, and discuss the physical principles that control various features of the resulting patterns. Thus, for example, the sharpness of the features that can be so generated depends on how quickly bacteria stop swimming when the light intensity decreases to zero. We also use these bacteria to verify a fundamental prediction from the statistical mechanics of active particles, namely, that the product of the local density of swimmers and their local swimming speed $\rho(\mathbf{r})v(\mathbf{r})$ = constant [2].

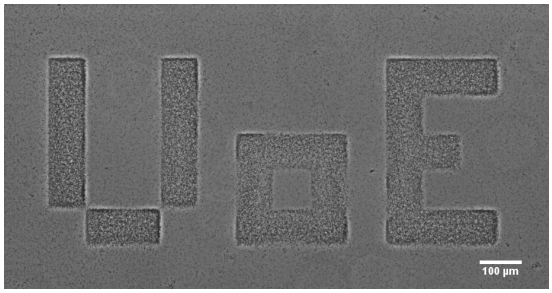

Figure 1 *A suspension of E. coli cells that need light to swim (initial optical density = 7.7) is uniformly illuminated with green light except inside a pattern of letters 'UoE' (standing for University of Edinburgh), where the illumination is blocked. Once a swimmer enters a dark region, it stops swimming quickly. Swimmers therefore accumulate inside the pattern of letters. This is the result after 16 minutes.*

References:

[1] J. Schwarz-Linek et al., *Colloids Surf. B* **137** (2016) 2-16.
[2] J. Tailleur and M. E. Cates *EPL* **86 (2009)** 60002.

Swimming navigation in-micro

Vasily Kantsler[1]

[1]*Department of Physics, University of Warwick, Coventry, United Kingdom*
E-mail: V.Kantsler@warwick.ac.uk

Interactions of microorganisms with solid boundaries and external flows play an important role in biological processes, such as egg fertilization, biofilm formation, and soil colonization, where microswimmers move within the flow and a structured environment. Despite recent efforts to understand their origin, it is not clear whether these interactions can be understood as being fundamentally of hydrodynamic origin, relying on the swimmer's direct contact with the obstacle or depending on biological mechano-sensing. Using microfluidic devices, one can investigate systematically the behavior swimming cells over a wide range of relevant parameters influencing their motion, including variable surface topography, external flows and viscosities. Here I will discuss recent studies on flagellated swimmers, such as sperm cells and chlamydomonas, the interaction mechanisms with the surfaces and shear flow, and resulting directed transport of the cells.

Effects of director field on dynamics of bacteria in liquid crystals

S. Zhou[1], C. Peng[1], T. Turiv[1], Y. Guo[1], A. Sokolov[2], I. Aranson[2], Q. Wei[1], and O.D. Lavrentovich[1]

[1]*Liquid Crystal Institute, Kent State University, Kent, OH 44242 USA*
[2]*Materials Science Division, Argonne National Laboratory, Argonne, IL 60439 USA*
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Orientationally ordered liquid crystal environment is known to align the swimming direction of rod-like bacteria such as *B. subtilis* parallel to the local director [1,2]. We present experimental studies of *B. subtilis* in the nematic cells with the director field that is either (i) perpendicular to the direction of swimming or (ii) contains topological defect. Perpendicular alignment (i) forces a bacterium to adopt one of the two dynamic states: (a) spinning around the longitudinal axis but not moving in the plane of the cell; (b) swimming perpendicularly to the director with hairpin-like reversals of the direction. The tumbling behavior of the bacteria adopts two modes not seen in isotropic media, namely, (1) a direct 180 degree reversal of swimming direction and (2) a random change of swimming direction through a transient spinning state. Pre-imposed topological defects (ii) allow one to control the trajectory of bacterial motion, in particular, to rectify polarity of circular orbiting and to trigger pumping. The work is supported by NSF DMR-1507637 and DMS-1434185.

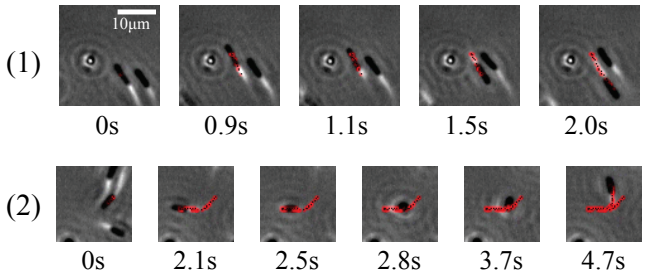

Fig. 1: *Two types of bacterial tumbling in a nematic cell with perpendicular alignment.*

References

[1] S. Zhou et al, PNAS **111**, 1265 (2014)
[2] P.C. Mushenheim et al, Soft Matter **11**, 6821 (2015)

Metaboly in Euglenids: a Model and its Experimental Validation

G. Noselli[1], M. Arroyo[2], A. Beran[3] and A. DeSimone[1]

[1]*SISSA–International School for Advanced Studies, Trieste, Italy*
[2]*UPC–Universitat Politècnica de Catalunya, Barcelona, Spain*
[3]*OGS–Istituto Nazionale di Oceanografia e di Geofisica Sperimentale, Trieste, Italy*
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Euglenids are unicellular aquatic organisms capable of moving either by beating a flagellum or by executing dramatic shape changes. These are accomplished thanks to a complex structure underlying the plasma membrane, made of interlocking proteinaceous strips, microtubules, and motor proteins.

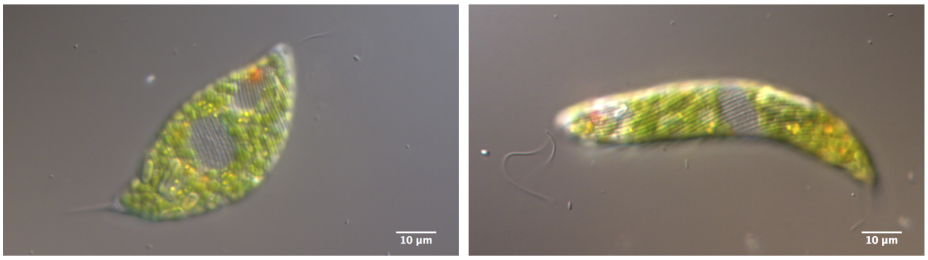

Fig. 1: *Two light micrographs of the protist Euglena Ehrenbergii, showing that shape changes are correlated with changes of orientation of the pellicle strips.*

We study the mechanisms by which the sliding of pellicle strips leads to shape control and locomotion, by means of both theory (through the mechanics of active surfaces and its coupling to computational fluid dynamics for the surrounding fluid) and experiments. Moreover, we implement them into a new concept of surfaces with programmable shape, obtained by assembling 3d-printed strips in a construct mimicking the biological template. We show that the subtle balance between constraints and flexibility leads to a wide variety of shapes that can be obtained with relatively simple controls. This suggests that euglenids exploit the passive resistance of body parts to reduce the complexity of controlling their shape.

G.N., A.B., and A.D.S. gratefully acknowledge financial support from the ERC Advanced Grant 340685-MicroMotility.

References

[1] Arroyo M., Heltai L., Milan D., DeSimone A.: Reverse engineering the euglenoid movement. PNAS **109**, 17874-17879, 2012.

[2] Arroyo M., DeSimone A.: Shape control of active surfaces inspired by the movement of euglenids. J. Mech. Phys. Solids **62**, 99-112, 2014.

[3] Noselli G., Arroyo M., Beran A., DeSimone A.: In preparation.

Exploiting a buckling instability to escape from traps

Marco Kühn[1], Kai Thormann[1], Felix K Schmidt[2] & Bruno Eckhardt[2]

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[2]*Fachbereich Physik, Philipps-Universität Marburg, 35032 Marburg, Germany*
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Shewanella putrefaciens is a polarly flagellated bacterium that lives in marine sediments. By switching the orientation of its flagellar motor, it can move forward and backwards. With high resolution microscopy their fluorescently labelled flagellae can be imaged, and the forward and backward motion as well as the helical modulation of the flagellum can be observed. When bacteria get stuck between argarose and glassplate, they try different motion patterns for escape. One of them involves a buckling instability that causes the flagellum to pull in and to warp around the cell body. The bacteria then escape through a corckscrew type motion of the entire cell body. Numerical simulations of a point-particle model for the flagellum reproduce the buckling instability, its onset near the cell body, and the final state with the flagellum wrapped around the cell. Observations and simulations show that the cell can return to the normal state of the flagellum by reversing the sense of orientation, thereby unwrapping the flagellum.

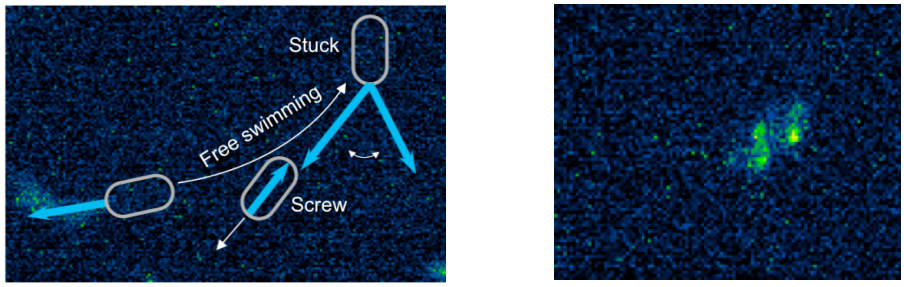

Fig. 1: *Sketch of the observed motion (left) and image of the flagellum wrapped around the cell body (right). The blue arrows indicate the flagellum, the white arrows the motion of the bacterium or the flagellum. It enters from the left, swims until it gets stuck at the upper right. Then the buckling instability sets in, the flagellum winds around the body (as shown on the right), and the bacterium escapes in a screw like motion towards the lower half of the frame.*

Symmetry-breaking in flexible active filaments

E. Lauga

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In this talk we present examples where flexible active filaments — as models for bacterial flagellar filaments or the active flagella of eukaryotes — undergo symmetry breaking in the form of conformational instabilities. We will show a few different situations where either rotation, flexibility, geometry or confinement conspire to break symmetries leading to the creation net flows and net locomotion.

Tractions laws for active colloids and their application to crystallization

R. Adhikari

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The velocity boundary condition in active colloids contains, in addition to the usual rigid body motion, a "slip", which is a macroscopic manifestation of microscopic active processes on the colloid surface. From linearity of slow viscous flow, the traction, that is the force per unit area on the colloid surface, must be a linear functional of the velocity boundary condition. We express this linear functional in a discrete basis of irreducible Cartesian tensors and provide a systematic way of calculating the basis coefficients given only the Green's function of the Stokes equation. A complete statistical mechanical theory of active suspensions can be constructed from the resulting "traction laws". We apply the theory to the crystallization of active colloids near a wall, reproducing and rationalizing the results of several recent experiments.

Long-range interactions disrupt synchronized states in chains of fluid-coupled oscillators

D. R. Brumley[1,2], **N. Bruot**[3,4], **J. Kotar**[4], **R. E. Goldstein**[5], **P. Cicuta**[4] **and M. Polin**[6]

[1]*Massachusetts Institute of Technology, Cambridge, USA;* [2]*ETH Zürich, Zürich, Switzerland;* [3]*Université Claude Bernard Lyon 1, France;* [4]*Cavendish Laboratory, University of Cambridge, UK;* [5]*DAMTP, University of Cambridge, UK;* [6]*University of Warwick, Coventry, UK*
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Eukaryotic cilia and flagella are biological chemo-mechanical oscillators capable of generating a variety of large scale coordinated motions commonly referred to as metachronal waves [1]. Despite recent progress in our understanding of the basic mechanism responsible for phase-locking of isolated pairs of cilia and flagella [2], it has become clear that pair synchronization is not a sufficient requirement for coordination of a group. Here we explore experimentally and with simulations the behaviour of a group of hydrodynamically coupled oscillators rotating above a no-slip plane, intended as a minimal model for a ciliated surface. As the oscillators' distance from the wall increases, their global synchronization state undergoes a transition from a travelling wave to either a steady chevron-like pattern or a profile punctuated by periodic phase defects. This is a consequence of long-range interactions whose amplitude is modulated by the distance from the wall. The transition is not sharp, but encompasses a range of distances from the wall within which the system displays mixed behaviour reminiscent of chimera states.

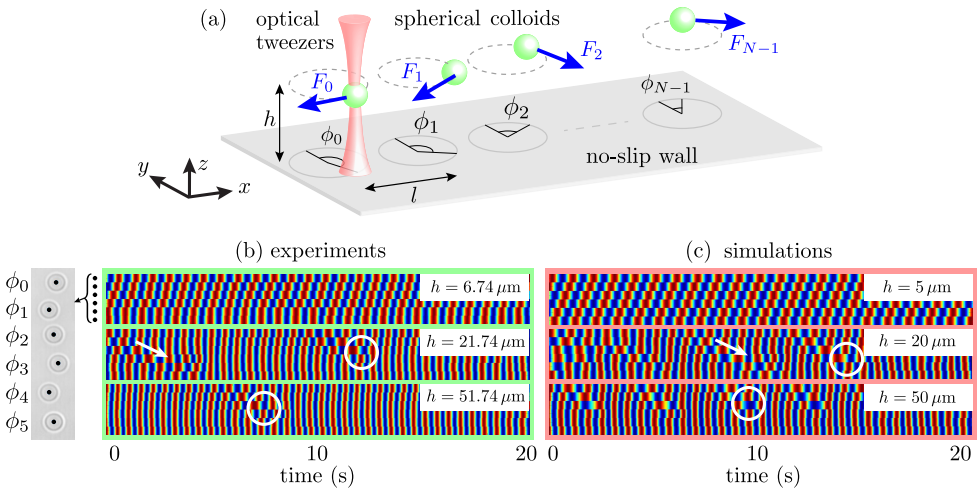

Fig. 1: *(a) Spherical colloidal particles are held at a fixed distance h above a no-slip boundary, and driven in circular trajectories by time-sharing optical tweezers. (b) Kymographs showing the phase $\sin\phi_i$ along the linear array of colloidal oscillators driven by OTs. (c) Deterministic numerical simulations of spherical colloids above a no-slip wall, interacting hydrodynamically through the Blake tensor.*

References

[1] D. R. Brumley, M. Polin, T. J. Pedley, and R. E. Goldstein, *Journal of The Royal Society Interface* **12(108)**, 1–12, (2015)

[2] D. R. Brumley, K. Y. Wan, M. Polin, and R. E. Goldstein, *eLife* **3**, e02750, (2014)

A force-velocity relationship of flagellar oscillations

Benjamin M Friedrich[1,2], Gary S Klindt[2], Christian Ruloff[3], Christian Wagner[3]

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Motile cilia and flagella bend periodically due to the collective dynamics of molecular motors inside. These flagellar oscillations propel cellular swimmers and pumps fluids inside organisms. Any change in hydrodynamic friction force is expected to feedback on the motor dynamics and change speed and shape of the flagellar beat. Here, we quantify the complex load-response of the beating flagellum, by exposing flagellated *Chlamydomonas reihnhardtii* cells to controlled microfluidic flows. A simple theory of flagellar limit cycle oscillations, calibrated by measurements in the absence of flow, reproduces this load-response quantitatively. The resultant force-velocity relationship of the flagellar beat provides an estimate for the chemo-mechanical efficiency of the flagellar beat and has direct consequences for flagellar function, *e.g.* the synchronization of multiple flagella.

Ion-exchange-based electroosmotic pumps utilized for microswimming

Thomas Palberg

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We investigated modular phoretic micro-swimmers that are assembled from non-active particles but show self-organized motion once assembled. We observe a wide range of different fascinating phenomena ranging from different swimming styles for small and large complexes, over schooling to chemotaxis. Since many experimental parameters are involved in these phenomena, like colloid particle density, size and charge, reservoir particle size and density, substrate charge and background electrolyte concentration, we have focused on a subset of these parameters that can be determined in situ. These are the relative sizes and numbers of the two main complex components, colloidal particles and reservoir particles. Here we have developed techniques to image the local gradients in pH, to determine colloid electrophoretic and substrate electro-osmotic mobilities and to follow the structural and dynamical evolution of the complexes by video microscopic methods. Qualitatively, the observations can be explained in a simple analytical model. They are further supported by simulations on the electro-osmotic flow and the assembly shapes. Now, further attention can be given to optimizing swimming performance.

Information propagation and collective changes of state in biological groups

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Collective changes in biological groups requires all individuals in the group to go through a behavioral change of state. Sometimes these changes are triggered by external perturbations, as in evasive maneuvers of animal groups under predatory attacks. Often, however, they occur spontaneously and are only due to internal behavioral fluctuations. In all cases, the efficiency of information transport is a key factor to prevent cohesion loss and preserve collective robustness. In this talk, I will present an experimental and theoretical study of collective movements in animal groups. Starting from experimental data on collective turns in starling flocks, I will discuss what is the mechanism that triggers a collective change (a turn) and grants efficient and fast information propagation through the system [1, 2]. Finally, I will discuss the role of heterogeneities, network unbalance, and boundary effects in initiating a collective change of state [3, 4].

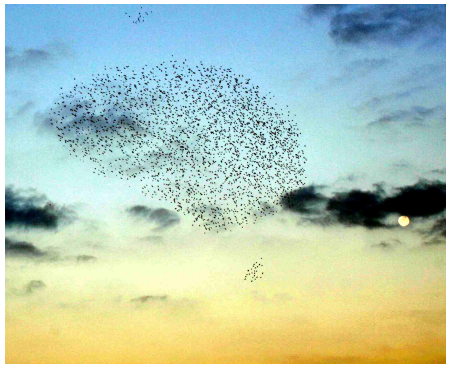

Fig. 1: *A flock of starlings in the sky of Rome.*

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Holographic imaging reveals the mechanism of wall entrapment in swimming bacteria

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Self propelled particles, both biological and synthetic, can be stably trapped by walls and develop high concentration peaks over bounding surfaces. In swimming bacteria, like *E. coli*, the physical mechanism behind wall entrapment is an intricate, and still disentangled mixture of hydrodynamic and steric interactions with a strongly anisotropic character. The building of a clear physical picture of this phenomenon demands direct and full 3D experimental observations of individual wall entrapment events. Here we demonstrate that, by using a combination of 3-axis holographic microscopy [1] and optical tweezers, it is possible to obtain volumetric reconstructions of individual *E. coli* cells that are sequentially released at a controlled distance and angle from a flat solid wall [2]. We find that hydrodynamic couplings can slow down the cell before collision but reorientation only occurs while the cell is in constant contact with the wall. Contrary to what predicted by numerical simulations of model *E. coli* cells, we find that in the trapped state all bacteria swim with the average body axis pointing into the surface. The amplitude of this swimming angle is correlated to the amplitude of wobbling, thus indicating that entrapment is dominated by near field couplings between the cell body and the wall. Our approach opens the way to three dimensional quantitative studies of a broad range of fast dynamical processes in motile bacteria and eukaryotic cells.

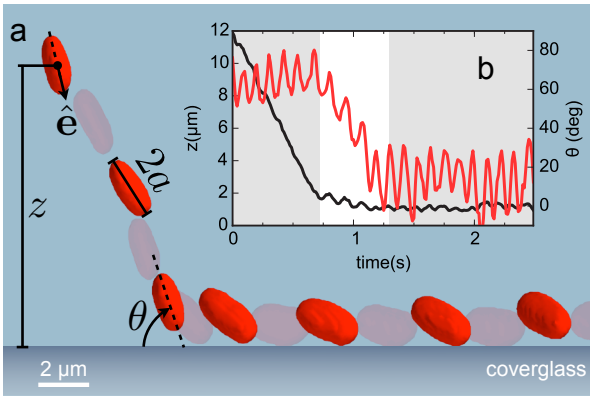

Fig. 1: (**a**) *Sequence of volumetric reconstructions of a swimming cell during a wall entrapment event.* (**b**) *For the same cell, wall distance is plotted as a black line while red line plots the angle of the cell body axis. In both curves, three stages can be identified: approach to the wall, reorientation and surface swimming.*

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Enzyme-powered Biocompatible Mesoporous Silica Micro/Nano-Bots

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Micro/nano-motors (MNM) capable of automatous motion and cargo delivery can lead to a new solution for target drug delivery.[1] However, such active delivery systems should be biocompatible in terms of fabrication materials, as well as fuel providing the energy to power their self-propulsion. Mesoporous silica has been widely explored for drug/gene delivery in biomedical field both *in vitro* and *in vivo*, in virtue of unique mesoporous structure, tunable nano structure, and its biocompatibility. Meanwhile, enzymes triggered bio-catalytic reactions have been regarded as most promising alternative to replace traditional propulsion strategy based on Pt/H_2O_2,[2] because of versatile enzyme/fuel combinations, e.g. catalase/H_2O_2, non-toxic glucose oxidase (GO_x)/glucose and urease/urea.[3]

Hereby, by integration between mesoporous silica and enzyme triggered bio-catalytic reactions, we successfully fabricated biocompatible MNM capable of self-propulsion by consuming non-toxic fuel.[3,4] We also achieved reversible velocity control on the motors by manipulating the enzymatic activity with inhibitors/re-activation molecules.[4] Magnetic guidance was utilized to control the motors' movement direction, *e.g.* towards target locations. The nano-pores of the mesoporous silica with internal pore diameter about 2-3 nm can be utilized for small drug molecules loading and delivery in large quantity. Sustained release of drug molecules from these mesoporous MNM indicates great potential of using them for active target drug delivery in future biomedical applications.

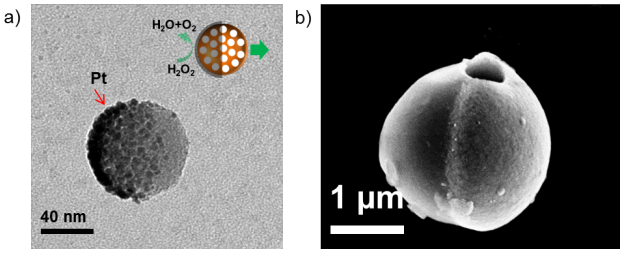

Fig. 1: ***a)*** *Janus Mesoporous Silica Nano-motors [1] and b) Hollow Janus Microcapsule Motors[4].*

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Tubular hybrid microswimmers for the controlled guidance and delivery of spermatozoa

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The search for autonomously moving, highly functional microdevices is one of the goals of the current micro-and nanotechnological studies. Especially in the area of biomedical applications, biocompatible solutions which offer high precision, remote control and noninvasive procedures are in demand. In this talk, a novel type of hybrid microswimmer is presented which arose from the combination of living spermatozoa and artificial microstructures. [1] These microswimmers are fabricated by microtubes which have been rolled up from thin nanomembranes and are able to capture spermatozoa in their hollow inside. The microbiorobot presented here uses the powerful motion of the sperm flagella as a propulsion source for the magnetic microtube. It will be demonstrated how the microswimmer performs its motion and how several factors such as temperature, radius of the microtube and the penetration of the cell inside the microtube have influence on its performance. Directional control mechanisms are offered by external magnetic fields and are presented to be useful for the on-chip separation of the microbiorobots from a mixture of cells and microtubes.[1] Furthermore, it will be demonstrated how the performance of such micromotor is increased by improved geometry of the microtube and additional functionalities.[2] A remote release mechanism for the sperm cells is demonstrated by the incorporation of thermoresponsive material into the microtubes, which makes them fold and unfold upon small temperature changes.[3]
The sperm-driven microswimmer displays great promise for a wide range of biomedical applications, in specific the development of assisted reproduction technologies which involves targeted single sperm cell delivery.

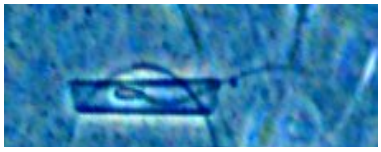

Fig. 1: *Bovine spermatozoon captured inside a 50 µm rolled up microtube.*

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Synthesis and investigation of different types of alginate-based artificial microswimmers

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Life involves motion, and motility plays a decisive role for the survival of different organisms like for instance bacteria. Microcapsules have already found a broad spectrum of different technical applications, and these particles can also be used as artificial cells.[1,2] Self-propelling capsules can simulate biological processes and contribute to their understanding.[3] A special advantage of these particles is the integration of different types of propulsion mechanisms and the fact, that they can easily transport and release stored ingredients as for instance drugs or herbicides.

In a series of different experiments, we investigated oscillating chemical reactions as driving forces. Oscillating systems are widespread in nature. For many biochemical systems the oscillation is even the condition for basic living processes as, for instance, the cell respiration.[4,5] As a simple driving system, we used the well-known Belousov-Zhabotinsky-reaction.[6] After inserting cerium cross-linked alginate capsules into this reacting liquid, we observed the production of tiny carbon dioxide bubbles at the surface of the gel beads. These bubbles lowered the density of these particles and stimulated creaming motions. At the water surface, the bubbles were released into the air and the particles sank toward the bottom of the glass beaker. Due to the production of new bubbles, the capsules moved after a short time again towards the water surface. This repeated motion of sedimentation and creaming occurred many times with a period of about 15 minutes.

In additional experiments, we investigated a swimming mechanism which was based on the development of surface tension gradients. Polyethylene glycol (PEG), which was stored in the core of alginate capsules, could be released through small membrane pores. Similar phenomena were observed for other ingredients. Due to the spreading of these liquids on the water surface, the alginate capsules showed rapid, circular motions. This special propulsion mechanism is used in nature by *Microvelia,* a genus of aquatic bugs.[7] The capsule movements were investigated by optical tracking analysis of positions and speeds. Further measurements of surface tensions and refractive index increments showed a large influence of the pore-size and the crosslinking density of the alginate microcapsules.

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Charge-driven self-propulsion of hot Janus particles

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Very recently, specific-ion effects were observed for self-proprelling laser-heated Janus particles in an optical trap [1], confirming previous studies of colloidal motion in an electrolyte solution [2,3]. We discuss several effects of a temperature gradient on the electric-double layer: thermo-osmosis [4], ion migration along the particle surface [5], and the thermo-electric polarization of the metal cap [6].

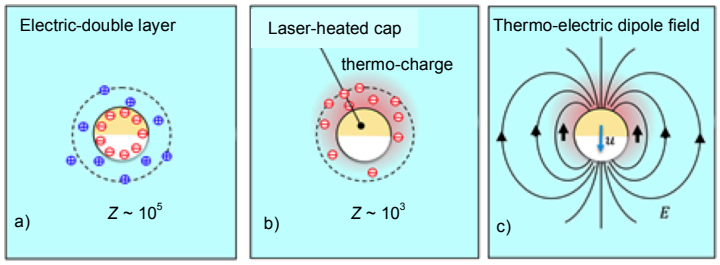

Fig. 1: *Self-thermo-electrophoresis of a charged Janus particle.*

We find that self-thermo-electrophoresis generated by the particle's non-uniform temperature, contributes significantly to its velocity. As illustrated in Fig. 1, this mechanism relies on the non-screened thermocharge (b) and the dipolar component of the corresponding Seebeck field (c). This salt-specific thermoelectric effect results in a velocity change which agrees with the observed motion in 10 mM solutions of NaCl, LiCl, and NaOH [1].

We conclude with a brief discussion of self-propulsion in a non-uniform laser beam. The intensity gradient exerts a torque on the Janus particle and aligns its axis as illustrated in Fig. 2 [7]. Since both self-propulsion and orientational order are linear in the laser intensity, we expect a quadratic variation of the particle's effective drift velocity.

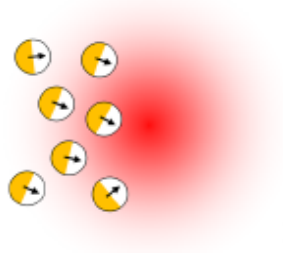

Fig. 2: *Polarization in an intensity gradient*

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Weak synchronization and large-scale collective oscillations in dense bacterial suspensions

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Collective oscillatory behavior is ubiquitous in nature and it plays a vital role in many biological processes, including embryogenesis, organ development, and pace-making in neuron networks or in cardiac tissues. Elucidating the mechanisms that give rise to collective oscillations is essential to the understanding of biological self-organization. In this talk, I report the discovery of striking very large-scale collective oscillations in a quasi- two-dimensional dense suspension of swimming E coli bacteria. This system was studied before but the phenomenon we observed was overlooked due to its elusive nature: individual trajectories and movies do not show the weak synchronization of cell trajectories. But passive particles floating on the surface or mesoscale averaging of the cell's velocities reveal regular oscillatory behavior organized over centimeter scales. I will then present a self-propelled particle model which demonstrates that this spectacular phenomenon can arise without long-range interactions. These findings expand our knowledge of biological self-organization as well as reveal a new type of long-range order in active matter systems.

Exact symmetries in the velocity fluctuations of a hot Brownian swimmer

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Symmetries constrain dynamics. We test this fundamental physical principle, experimentally and by molecular dynamics simulations, for a hot Janus swimmer operating far from thermal equilibrium. Our results establish scalar and vectorial steady-state fluctuation theorems and a thermodynamic uncertainty relation that link the fluctuating particle current to its entropy production at an effective temperature. A Markovian minimal model elucidates the underlying non-equilbrium physics.

Light driven diffusioosmosis: manipulation of particle assembly

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Recently, we have discovered a peculiar phenomenon related to colloids adsorbed at a liquid-solid interface, and immersed into aqueous solution of photosensitive surfactant (Figure 1b). Upon illumination with UV light, the colloids are driven out of the irradiated area (Figure 1c). Without the presence of the surfactant (Figure 1a), the particle assembly does not change, ruling out heating effects or gradients in the intensity of the electromagnetic field as a source of driving. The presence of the surfactant leads to two simultaneous effects. The first involves the local modification of surfaces even without illumination. The most important and novel aspect to be discussed in the talk is, however, that the same *trans-cis* photo-isomerization is also the basis for initiation of local hydrodynamic flows and corresponding forces on the colloids. We will provide a theoretical account of how the local liquid flows emerge. It will turn out that the phenomenon is best understood as light-driven diffusioosmosis. In this way, the surfactant becomes a *photo-soap* in a new sense: not only particle-surface interaction is reduced, but also control over the "rinsing" of contaminants (particles) can be gained.

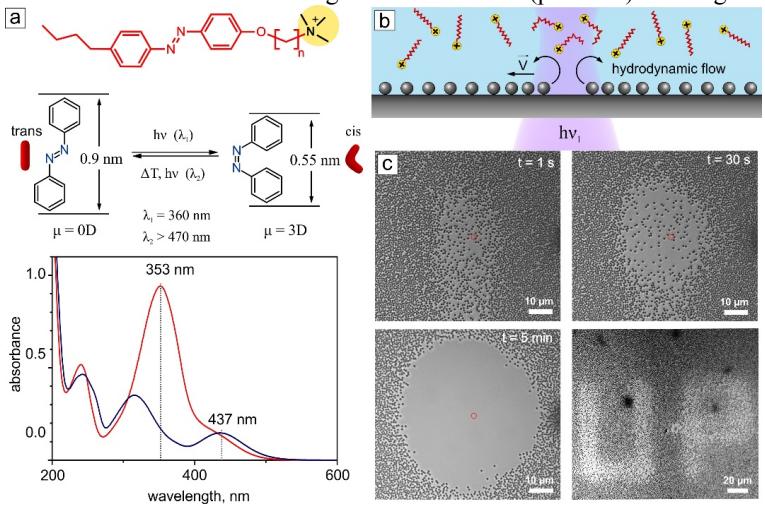

Figure 1. *(a) Chemical structure of an azobenzene containing cationic surfactant. Shown below is a scheme of the photo-isomerization of the azobenzene group, together with UV absorption spectra of the molecule in its trans state (red) and cis conformation (blue) (b) Scheme of the setup, consisting of a micro-channel filled with surfactant-water solution and adsorbed particles. Subsequently, irradiation with UV light is initiated, and a local removal of particles is achieved. (c) Three snapshots (after irradiation time t = 1 second, t = 30 seconds, and t = 5 minutes) documenting successive stages of the "cleansing". UP (University of Potsdam) logo written within the particles (diameter 2 μm) assembly.*

Wednesday, October 5

Talks Wednesday, October 5

S05-01 **Kapral, R.** ; Colberg, P.; Huang, M.-J.; Schofield, J. M.
Collective Dynamics of Chemically-Powered Motors

S05-02 **Golestanian, R.**
Collective Chemotaxis in Active Matter

S05-03 **van Roij, R.** ; Samin, S.; Bet, B.; Boosten, G.; Rodenburg, A. J.; Dijkstra, M.
From one force-free swimmer to an active dispersion: mechanism, shape, and (osmotic?) pressure

S05-04 **Popescu, M. N.** ; Uspal, W. E.; Malgaretti, P.; Dominguez, A.; Dietrich, S.
Chemically Active Particles near Responsive Interfaces

S05-05 **de Graaf, J.** ; Kuron, M.; Rempfer, G.; Brown, A.; Menke, H.; Holm, C.
Lattice-Boltzmann Methods for Autophoretic Swimmers

S06-06 **Peyla, P.** ; Martin, M.; Ortlieb, L.; Grebber, J.; Zimmermann, W.; Wagner, Ch.; Rafai, S.
Spreading of an active cloud of microswimmers

S06-07 **Wilson, L. G.** ; Thornton, K. L.; Farthing, N. E.; Bees, M. A.
3D holographic imaging of microswimmers

S06-08 **Ishimoto, K.** ; Gaffney, E. A.
Multiple mechanical functions of sperm hyperactivation

S06-09 **Alvarez, L.**
Sperm: the search machine

S06-10 **Elgeti, J.** ; Rode, S.; Gompper, G.
Sperm cells swimming in confinement

S07-11 **Brady, J. F.** ; Yan, W.
The Force on a Body in Active Matter

S07-12 **Tierno, P.** ; Martinez-Pedrero, F.; Ortiz-Ambriz, A.; Pagonabarraga, I.
Colloidal Microworms and Microcarpets Propelling via a Cooperative Hydrodynamic Conveyor-Belt

S07-13 **Climent, E.** ; Lovecchio, S.; Durham, W. M.; Stocker, R.
Vertical migration of motile phytoplankton chains through turbulence

S07-14 **Voigtmann, Th.** ; Liluashvili, A.
Active Brownian-Particle Glasses: A Mode-Coupling Theory

S07-15 **Ripoll, M.** ; Wagner, M.
Hydrodynamic self-assembly of thermophoretic swimmers

Collective Dynamics of Chemically-Powered Motors

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The nature of the collective dynamics of small, chemically-powered, self-diffusiophoretic motors depends on the interplay among several factors: direct intermolecular interactions among motors and motor geometry, interactions arising from many-body concentration fields and near- and far-field hydrodynamic flows, as well as thermal fluctuations. Most often theoretical descriptions are based on the continuum hydrodynamic and reaction-diffusion equations or Brownian dynamics methods that incorporate fluctuations, and in their implementations some, but never all, of the above effects are taken into account. The talk will focus on coarse-grain microscopic descriptions of the dynamics that account for fluctuations and all of the interactions mentioned above, and the results of simulations on systems comprising many diffusiophoretic motors in a solvent will be presented.

Three types of motor will be discussed: sphere-dimer motors comprising linked catalytic and noncatalytic spheres, Janus motors, and oligomeric motors comprising three linked spheres. The results of large-scale simulations of the collective dynamics of thousands of sphere-dimer motors will presented.[1] Next, the collective behavior of Janus motors, where the motors interact with their environment only through hard collisions, will be described.[2] Finally, results on the collective dynamics of chemically-powered oligomeric diffusiophoretic motors attached to a filament will also be discussed.[3]

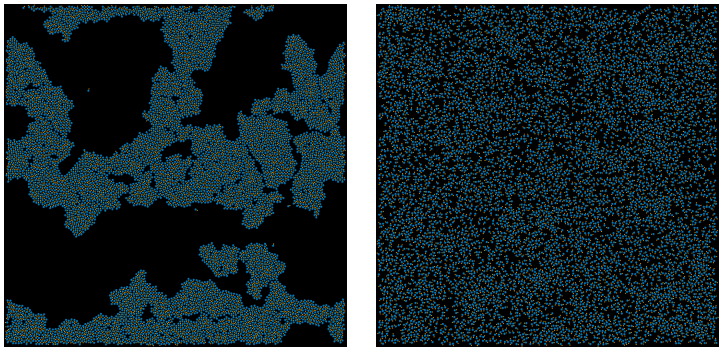

Fig. 1: *Instantaneous configurations of sphere-dimer motors showing their collective behavior when they propagate forward, in the direction of the catalytic sphere (left panel) and backward, in the direction of the noncatlaytic sphere (right panel).[1]*

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Collective Chemotaxis in Active Matter

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In my talk, I will discuss the non-equilibrium dynamics of particles, which have two types of activity: (1) chemical activitiy in the form of releasing or consuming chemicals, and (2) motility that is affected or caused by the chemical activity. These activities will mediate long-range interactions and lead to non-equilibrium fluxes, which join together to lead to interesting collective effects. I examine theoretically the consequences of this interaction, using several examples from synthetic and living systems, including: collective chemotaxis in a solution of catalytically active colloids that could lead to cluster formation, aster condensation, and spontaneous oscillations [1], swarming - in the form of a comet - of light-induced thermally active colloids with negative Soret coefficient due to a shadowing interaction [2], spontaneous formation of small static [3] and dynamic [4] clusters or "molecules" that can exhibit functionality that depends on geometry, and collective behaviour of a colony of cells that divide and interact chemotactically [5].

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From one force-free swimmer to an active dispersion: mechanism, shape, and (osmotic?) pressure

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In this contribution we will first present our microscopic analysis [1] of the swimming *mechanism* of a single illuminated Janus sphere in a near-critical binary mixture as studied experimentally in Bechinger's group. By solving simultaneously for the (coupled) steady-state profiles of the temperature, composition, pressure, and flow field in the rest frame of the particle, we can attribute the motion to body forces at the edge of a micron-sized droplet that nucleates at the hot side of the particle. Next we combine a general formulation of microswimmmer equations of motion with a numerical bead-shell model to calculate the hydrodynamic interactions with the fluid, from which the swimming speed, power and Lighthill efficiency follow for arbitrary-shaped bodies and swimming strokes. We apply this scheme to a variety of three-body swimmers and biologically inspired swimmers that propel using a rotating helical flagellum [2]. In the final part we will discuss the consequence of the force- and torque-free condition (that each of the self-propelled particles must obey by Newton's laws) on collective properties of an active dispersion, with a focus on the existence of a well-defined thermodynamic limit and the *(osmotic?) pressure* [3].

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Chemically Active Particles near Responsive Interfaces

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Micron-sized particles moving through solution by using self-generated chemical gradients serve as model systems for studying active matter. The self-generated hydrodynamic and chemical fields, which induce particle motion, probe and are modified by the environment, including its boundaries [1, 2]. If the boundaries are *responsive* interfaces, in the sense that the chemical released by the particle can induce hydrodynamics stresses at the interface, the active particle triggers surface-driven flows that extend in the solution and couple back to the particle [3, 4]. We discuss here two illustrative examples of such systems.

When a chemically active particle is close to a liquid-fluid interface, the inhomogeneous distribution of reactant and product molecules at the interface can induce local variations of the surface tension. This leads to the onset of so-called Marangoni flows, which drive the particle close to (or far away from) the interface [Fig. 1 (left)]. This effective interaction is long ranged and may provide means to control particle accumulation at fluid-fluid interfaces [3].

The second example considered is that of a chemically active particle in the vicinity of a hard planar wall with which the chemical produced by the particle interacts. In this case osmotic flows, driven by the phoretic slip induced at the wall, arise. If the wall is chemically patterned, these osmotic flows can "guide" the active colloid with respect to the pattern-defined direction. Under certain conditions, the interplay between self-diffusiophoresis and induced osmotic flows leads to the emergence of spatially-localized-particle steady-states [4] such as trapping at a chemical step or directional motion along a chemical stripe [Fig. 1 (right)]. .

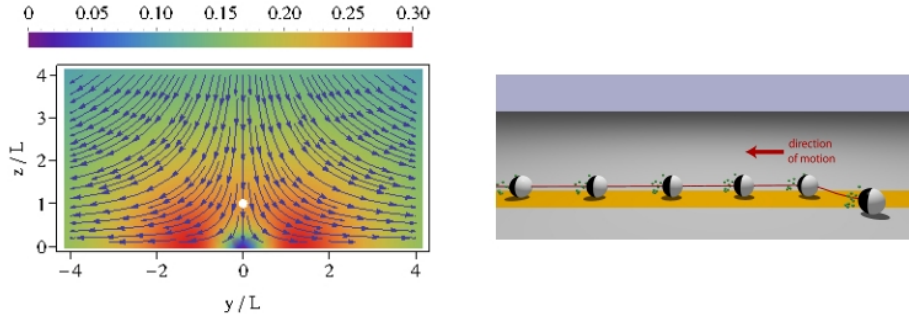

Fig. 1: *(Left) Activity-induced Marangoni flow driving the active particle (white disk) towards the liquid-fluid interface ($z = 0$). (Right) Cartoon depiction of "trapping and guiding" by a chemical stripe.*

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Lattice-Boltzmann Methods for Autophoretic Swimmers

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Man-made catalytically driven self-propelled colloids (swimmers) have gained immense popularity over the past decade. They are envisioned to have biomedical applications and their cooperative behavior mimics that of living organisms. To understand the collective dynamics of artificial swimmers many simulation studies focus on near-field (aligning) interactions. Only a few take into account the long-ranged hydrodynamic and phoretic effects, which can strongly modify swimmer interactions and have been shown to be important to understand experimentally realized systems. In this presentation we introduce two lattice-Boltzmann based algorithms that are capable of simulating self-electrophoretic particles and fully resolve hydrodynamic flow, solute fields, and the electrostatic potential.

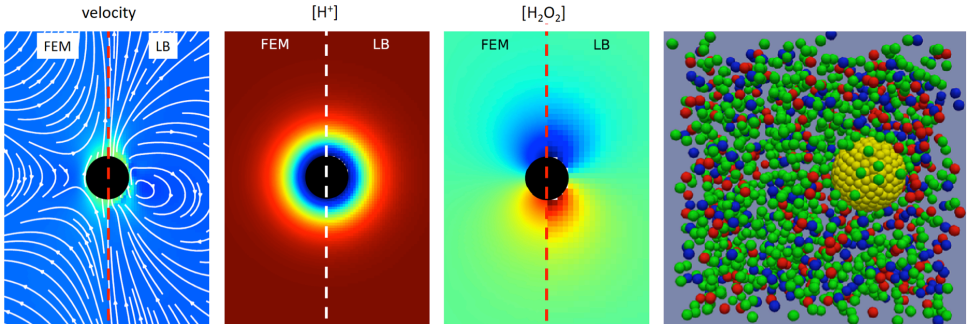

Fig. 1: *The left three panels show a comparison between our theory [2] and our continuum-based lattice-Boltzmann implementation. From left to right, the fluid velocity, the proton concentration, and the bulk-reaction-induced anisotropy in the hydrogen peroxide concentration. The fourth panel shows the explicit particle swimmer: ions are in blue and red; the reactant is green and the swimmer yellow.*

The first is a continuum model implemented in the *waLBerla* framework [1], which allows us to investigate the interactions between many swimmers. Here, we chose to implement the experimentally realistic model that accounts for ionic association-dissociation reactions in the bulk [2]. The second is an explicit particle model implemented within *ESPResSo* [3]. This model permits the study of nanoscale swimmers and allows us to probe the validity of our continuum approximation on such length scales. We go into the details of obtaining a working self-electrophoretic algorithm and show how these algorithms lead to new insights into swimmer-swimmer interactions as well as swimming on small length scales.

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Spreading of an Active Cloud of Microswimmers

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In nature, living organisms that move and interact with their group of congeners are ubiquitous. Crowd of people, herd motions, bird flocks and fish schools are the most cited and fascinating examples where elements remain grouped during their migration. On the contrary, micro-organisms suspended in a fluid like spermatozoa, micro-algae or bacteria, if locally concentrated, usually spread and invade the surrounding medium. If cells are initially sufficiently diluted, they simply follow a diffusive motion if each cell perform a run and tumbling like-motion. But starting with a concentrated colony, the law of spreading is unknown because of the presence of hydrodynamic interactions between the cells. Here, we show that a cloud of suspended interacting microalgae "*Chlamydomonas Reinhardtii*" - initially grouped in a lighted area - spreads with time t following a sub-diffusive power law $t^{2/3}$. We confirm this behaviour with numerical simulations. We also give a simple scaling law which allows us to plot a universal curve of the mean square displacement of the cloud of algae as a function of time. This result constitutes the first study on the spreading of an active cloud of micro-swimmers. We anticipate our result to be a starting point for dispersion in complex media in environmental, industrial and agricultural microbiology.

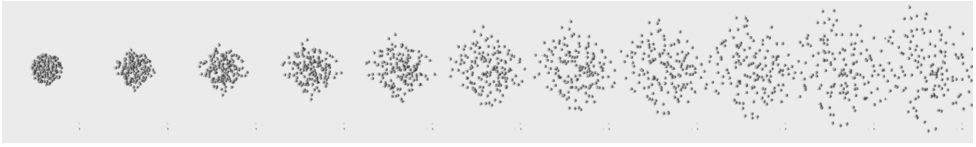

Fig. 1: ***Spreading of a cloud of microswimmers – Numerical simulation***.

3D holographic imaging of microswimmers

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Microswimmers usually move in three dimensions, but camera sensors are two-dimensional. This can restrict the scope of experiments using standard techniques. In the past, video microscopy data has been analysed by the most intuitive approach, simply viewing video images as we do everyday objects. Teaching a computer to track objects of a certain shape or size then yields information about their dynamics. This approach is the same used in the macroscopic domain, where 'machine vision' approaches to object recognition and tracking have been very successful. The work in our lab takes a different approach by using aspects of classical optics and signal processing to design new image processing algorithms, to 'mine' more information out of digital images. This has two advantages: (i) We can extract three dimensional imaging data from two-dimensional images; (ii) by moving away from traditional 'machine-vision' ideas, we can redesign imaging systems that are cheaper and more lightweight.

I will present several examples from recent work in holographic imaging of microswimmers that use image-processing algorithms to obtain three-dimensional data on microorganism swimming trajectory and shape. In particular, the ability to follow hundreds or thousands of individual swimming bacteria in volumes of up to a cubic millimetre allows us to address questions on the statistics and variability of cell swimming trajectories. The figures below show examples of the swimming trajectories of bacterial cells – E. coli in this case – rendered to scale.

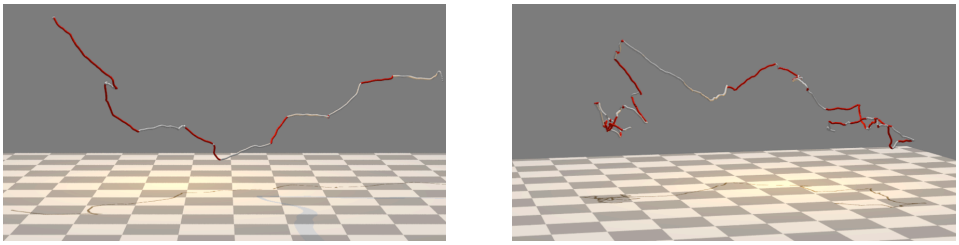

Fig. 1: *Experimental data from free-swimming E. coli cells, coloured to indicate different 'run' phases of their swimming behaviour. The run events are separated by a change in direction, a static interruption in swimming motion (a 'stop') or both of these things. The duration of each swimming trajectory ranges from around 10-30 seconds, and the squares on the ground of each image represent a distance of 50 μm.*

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Multiple mechanical functions of sperm hyperactivation

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During the great race of sperm, for successful fertilisation the cell needs to be properly functioning, facing the various environmental barriers. In the process of sperm capacitation, in the female oviduct, mammalian sperm cells change their waveforms to more vigorous, asymmetric beating, known as hyperactivation [1]. We have developed a fully three dimensional hydrodynamic simulation of swimming sperm which is adhesive to a wall boundary, based on the boundary element method [2, 3]. Then we first comprehensively demonstrated multiple mechanical functions of hyperactivation that have been experimentally suggested [4]: improvement of sperm detachment from oviductal epithelium and enhancement of sperm exertion to the zona surface. Further, with a progressive motion of hyperactivated sperm in very viscous medium, it has been indicated that the mechanical enhancement of sperm ability of zona penetration by the cumulus cell matrix around the oocyte, which can account experimental observations that aberrant zona-binding sperm can fertile only in the presence of the matrix.

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Sperm: the search machine

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Sperm must find an egg for fertilization. To achieve this goal, sperm gather chemoattractant molecules released by the egg to compute a local chemical field map; at the summit of this chemical field, the egg is to be found. Sperm move along periodic swimming paths. The periodic swimming is translated into oscillations of chemoattractant concentration in their surroundings, and thus, sperm are periodically stimulated. A signalling pathway translates the periodic stimulation into perfectly-timed behavioural changes that set sperm cells course up the chemical gradient toward the egg. In the past, we have studied sperm chemotaxis in two and three dimensions in well-defined chemical gradients to characterize the relationship between stimulus input, signalling, and steering output. I will present an updated account of our findings.

Sperm cells swimming in confinement

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Sperm cells in their natural environment often encounter moderate to strong confinement. Mamalian sperm have to navigate in the reproductive track, and epxeriments are performed in the finite observation chamber under the microscope. Recent experiments have even used very thin microchannels to further investigate the properties of sperm swimming in under strong confinement [1].
We use mesoscopic hydrodynamic modelling to study sperm in confinement [2]. We find that hydrodynamic interactions attract sperm to planar walls, and align their beating plane parrallel to the wall. In rectangular channels with sharp corners, the sperm display characteristic angles of scattering around the edge. It turns out that the beating plane alignement is a key factor in determining the resulting scattering angle.
On a slightly different note, we observed sperm tethered to surfaces with high frequency microscopy [3]. With the combination of precise experimental data, quantitative computational modelling, and analytic calculations we show that sperm can steer by using a second harmonic in the beat frequency. This second harmonic breaks the time-mirror symmetry, that otherwise enforces straight trajectories. We show analytically how a second harmonic creates a torque for low-amplitude beating. We demonstrate by simulations how the second harmonic can be used by swimming sperm to stear.
These examples show that confinement is a powerful tool to determine dynamical behavior of sperm cells, and microswimmers in general.

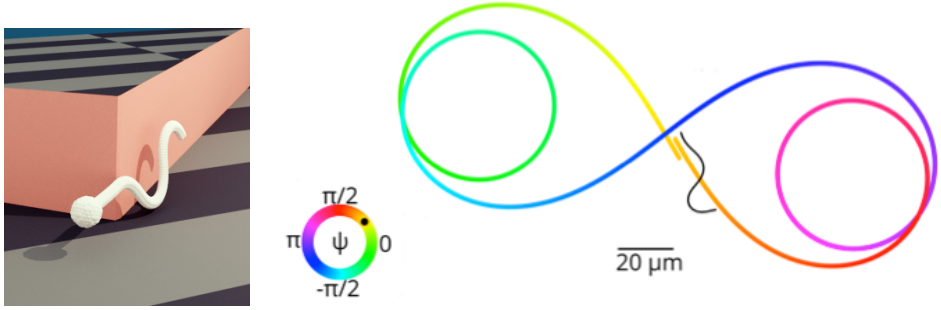

Fig. 1: *(left) Visualization of a sperm cell close to a corner. (right) Sperm steering along an eight figure by variation of the phase of the second harmonic.*

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The Force on a Body in Active Matter

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The statistical mechanics and microhydrodynamics of active matter systems have seen a dramatic increase in interest in the past several years. Much attention has focused on the fascinating nonequilibrium behaviors of active matter not observed in equilibrium thermodynamic systems, such as spontaneous collective motion and swarming. Even minimal kinetic models of active Brownian particles exhibit self-assembly that resembles a gas-liquid phase separation. Self-propulsion allows active systems to generate internal stresses that enable them to control and direct their own behavior and that of their surroundings. Recent work involving the unique 'swim pressure' exerted by active systems offers a perspective on the basic underlying physical mechanism responsible for self-assembly and pattern formation in active matter [1-3].

In this work we take a more microscopic view and present a general theory for determining the force (and torque) exerted on a body (or boundary) in active matter [4]. The theory extends the description of passive Brownian colloids to self-propelled active particles and applies for all ratios of the thermal energy k_BT to the swimmer's activity $k_sT_s = \zeta U_0^2\tau_R/6$, where ζ is the Stokes drag coefficient, U_0 is the swim speed and τ_R is the reorientation time of the active particles. The theory, which is valid on all length and time scales, has a natural microscopic length scale over which concentration and orientation distributions are confined near boundaries, but the microscopic length does not appear in the force. The swim pressure emerges naturally and dominates the behavior when the body size is large compared to the swimmer's run length $\ell = U_0\tau_R$. The theory is used to predict the motion of bodies of all sizes immersed in active matter.

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Colloidal Microworms Propelling via a Cooperative Hydrodynamic Conveyor-Belt

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We study propulsion arising from microscopic colloidal rotors [1] dynamically assembled and driven in a viscous fluid upon application of an elliptically polarized rotating magnetic field. Close to a confining plate, the motion of this self- assembled microscopic "worm" results from the cooperative flow generated by the spinning particles such as a hydrodynamic "conveyor-belt" effect. Chains of rotors propels faster than individual ones, until reaching a saturation speed at distances where flow additivity vanishes. By combining experiments with theoretical arguments, we elucidate the underlying mechanism of motion and fully characterize the propulsion speed in terms of the external field parameters [2]. Next, we demonstrate how to assemble these worms into highly maneuverable two-dimensional colloidal carpets which can be steered via remote control in any direction of the plane. These colloidal micropropellers are readily used to entrap, transport, and release biological cargos on command via the hydrodynamic conveyor-belt effect. An efficient control of the cargo transportation combined with remarkable "healing" ability to surpass obstacles demonstrate a great potential towards development of multifunctional smart devices at the microscale [3].

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Vertical migration of motile phytoplankton chains through turbulence

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Daily, phytoplankton needs to migrate vertically from and towards the ocean surface to find nutrients such as dissolved oxygen. To travel through the water column they need to fight against gravity (by swimming) and fluid turbulence which can make their journey longer.

It is often observed that cells migrate across the water column as chains. The first benefit to form chains is that micro-organisms sum up their thrust while reducing their drag. Therefore, upwards swimming is faster for chains in a quiescent fluid with steady vertical orientation. However, as chain length increases their tendency to periodically tumble in turbulent structures increases which reduces orientation stability and limits their capacity to swim upwards.

The purpose of our study is to elaborate on this apparent contradiction. We carried out direct numerical simulations and physical analysis of the coupled system of homogeneous isotropic turbulence and chain trajectories through Lagrangian tracking. Formation of chains is indeed favorable for vertical migration through the upper layer of the ocean.

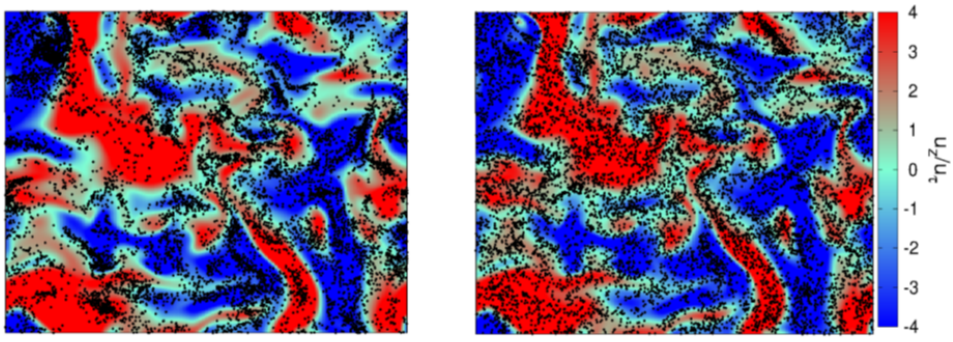

Figure: Horizontal snapshot of a 3D turbulent flow, at Re_λ =55 showing cell clustering (black dots) in upwelling (red area) and downwelling regions (blue area). On the left spherical cells, on the right the elongated cells . Color code shows the magnitude of fluid velocity.

Active Brownian-Particle Glasses: A Mode-Coupling Theory

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We consider a dense system of active Brownian hard spheres, arguably one of the simplest model systems to study collective behavior of microswimmers. The particles posses a randomly changing internal sense of orientation and undergo Brownian dynamics modified by an "active" driving velocity along that orientation. Using the integration-through transients framework, we have extended the mode coupling theory of the glass transition to include this active driving force, keeping both translational and orientational degrees of freedom. We discuss how the glass-transition dynamics depends on the two dimensionless forces that characterize the system - the translational and rotational Péclet number. In agreement with simulation and a simplified theory that treats the swimmers' orientations as a fast variable, we find that the glass transition is shifted to higher densities by increasing the activity (translational Péclet number). We study the effect of "persistence" in the orientation as mimicked by slow rotational dynamics; in this regime of large rotational Péclet number, the simplifying approach of mapping the dynamics to that of a system with an effective but FDT-breaking diffusivity fails. The theory is then used to study anomalous diffusion of an active Brownian particle in a crowded environment of passive hard spheres.

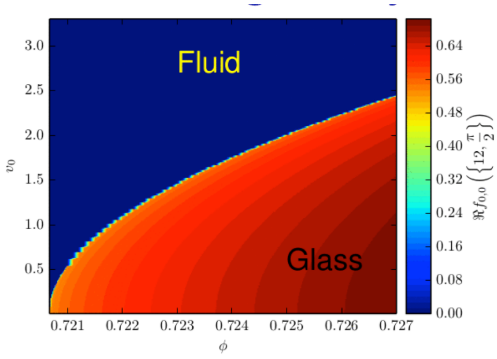

Fig. 1: *Glass-transition diagram of active Brownian particles as a function of two-dimensional packing fraction and self-propulsion velocity.*

Hydrodynamic self-assembly of thermophoretic swimmers

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Thermophoresis refers to the directed motion of colloidal particles in the presence of a temperature gradient, which can occur towards cold (thermophobic colloids) or warm areas (thermophilic colloids) [1]. Thermophoretic self-propelled motion can be induced in the cases of Janus or dimers colloidal particles with asymmetric heating capacity [2,3]. The thermophoretic properties of the non-heated part produce then a propulsion against or towards the heated part. Equally sized thermophobic microdimers have shown to hydrodynamically behave like pullers, thermophobic microdimers like pushers, and half-coated janus particles like neutral swimmers [4]. Hydrodynamic simulations of microdimers clearly indicate that these hydrodynamic behaviors can be modified and even reversed for microswimmers of unequal beads. Thermophobic microdimers with small heated beads show for example an important lateral attraction as expected for pusher type of swimmers [5]. The collective behavior of these microdimers exibit then a very interesting behavior. The interplay of the hydrodynamic attraction in the direction perpendicular to the propelling direction, and the thermophoretic repulsion in the propulsion direction, give rise to the self-assembly of the microdimers in planar moving structures with a well-defined orientation and hexagonal order [6].

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Thursday, October 6

Talks Thursday, October 6

S08-01 **Aronson, I. S.** ; Sokolov, A.
Expulsion of bacteria by a vortical flow

S08-02 **Ahmed, D.**
Artificial swimmers in acoustic and magnetic fields

S08-03 **Fischer, P.** ; Alarcón-Correa, M.; Choudhury, U.; Günther, J.-P.; Holst-Jahn, A.; Mark, A. G.; Palagi, S.; Sachs, J.; Singh, D. P.; Qiu, T.; Walker, D.
Artificial Microswimmers

S08-04 **Maaß, C. C** ; Jin, C.; Krüger, C.
Droplet swimmers in complex geometries: Autochemotaxis and trapping at pillars

S08-05 **Seemann, R.** ; Li, M.; Brinkmann, M.; Pagonabarraga, I.; Fleury, J.-B.
Evolutive Self-Propelling Janus Droplets utilized for Programmable DNA Cargo Delivery

S09-06 **Marchetti, M. C.**
Jamming of cell monolayers

S09-07 **Kafri, Y.**
Pressure in active systems

S09-08 **Blaschke, J.** ; Kuhr, J.-T.; Rühle, F.; Zöttl, A.; Maurer, M.; Menon, K.; Stark, H.
Hydrodynamics of microswimmers: Phase separation and influence of gravity

S09-09 **Virnau, P.** ; Siebert, J. T.; Trefz, B.; Speck, T.
Phase behavior of active colloidal particles

S09-10 **Günther, K.** ; Herms, A.; Bregulla, A. P.; Sperling, E.; Cichos, F.; Mertig, M.
Construction and Characterization of Artificial Thermophoretic Micro-& Nanoswimmers

S10-11 **Weibel, D. B.** ; Auer, G. K.; Rajendram, M.; Lee, T.; Yao, Q.; Jensen, G.; Huang, K. C.
Bacterial cell mechanics and motility

S10-12 **Wolgemuth, C. W.**
Unexpected parallelisms: From swimming bacteria to wound healing and cancer metastasis

S10-13 **Drescher, K.**
Nematic Ordering Transitions in Bacterial Biofilms

S10-14 **Winkler, R. G.** ; Eisenstecken, T.
Bacterial Swarmer Cells in Confinement

S10-15 **Engstler, M.** ; Schuster, S.; Krüger, T.
Trypanosome microswimmers in the tsetse fly

Expulsion of bacteria by a vortical flow

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Interactions of microswimmers with their fluid environment are exceptionally complex. Macroscopic shear flow alters swimming trajectories of bacteria in a highly nontrivial way and results in dramatic reduction of viscosity and heterogeneous bacterial distributions. We study experimentally and theoretically rapid expulsion of motile bacteria by a vortical flow created by a rotating microparticle. We observe a formation of a macroscopic depletion area in a high-shear region, in the vicinity of a microparticle, Figure 1. The rapid migration of bacteria from the shear-rich area is caused by a vortical structure of the flow rather than intrinsic random fluctuations of bacteria orientations, in stark contrast to planar shear flow. Our mathematical model reveals that expulsion is a combined effect of motility and alignment by a vortical flow. Our findings offer a novel approach for manipulation of motile microorganisms and shed new light on bacteria-flow interactions [1].

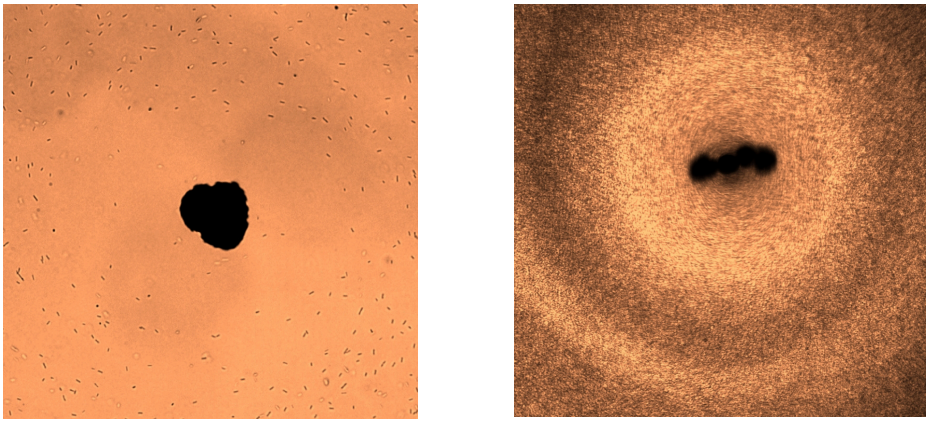

Fig. 1: ***Left:*** *Individual bacteria are expelled by a rotating microparticle.* ***Right****: Rotating chain of microparticles expels concentrated bacteria in its vicinity and creates a halo.*

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Artificial swimmers in acoustic and magnetic fields

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Recent studies have garnered considerable interest in the field of propulsion to maneuver micro and nano-sized objects. Acoustics provide an alternate and attractive method to derive propulsion. We will discuss multiple mechanisms to derive propulsion utilizing acoustic and magnetic fields. We describe a new mechanism of propulsion in which nano swimmers are propelled by small-amplitude oscillations of a flexible eukaryote-like tail in predominant travelling acoustic waves.

The artificial nanoswimmer, fabricated by multistep electrodeposition and layer-by-layer deposition, compromises a rigid bimetallic head and a flexible tail. The high contrast in densities of the materials between the bimetallic head and the polymeric tail serves to clamp the tail at one end, which results in a biased oscillation along the swimmer when acoustically excited at the natural frequency of the tail. This asymmetric oscillation breaks the mirror symmetry and results in a net locomotion. Moreover, we discuss a biomimetic rolling motion by introducing super paramagnetic particles in magnetic and acoustic fields, mimicking the behavior of a neutrophil rolling on a wall. Both acoustic and magnetic fields have matured in clinical settings and combining both fields can overcome the limitations encountered with single actuation techniques. We believe our method will have far-reaching implications, especially in targeted therapeutics.

Artificial Microswimmers

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In this talk an overview is given over a number of artificial microswimmers that we have recently studied [1-9]. We consider both swimmers that move by light-induced body shape changes [1], as well as magnetically propelled structures [2,3,4,8], magnetically driven swimmers [7], and chemically propelled swimmers [5,6,9]. We consider structures that are very small and may thus be considered sub-micron swimmers and nanopropellers [8,9] as well as swimmers that exploit non-Newtonian fluids for locomotion [3,7,8]. Several mimic natural biological swimmers [1,2,3,4,7,8] and move by body-shape changes [1,7]. Fig. 1 shows some of the microswimmers that we have developed. The challenge associated with swimming at the nano- and possibly molecular scale is discussed and we present our recent effort to realize active matter and collective swimmers.

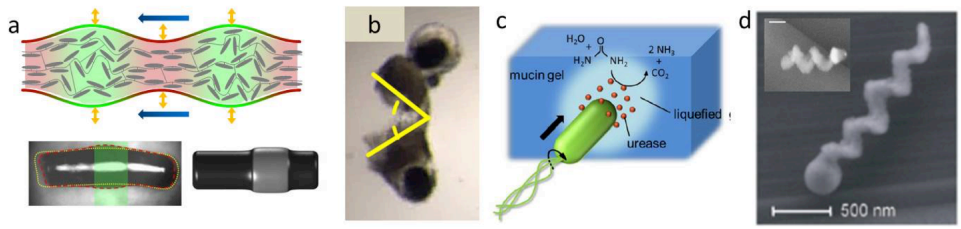

Fig. 1: *Images that illustrate some of the microswimmers we have built and experimentally analyzed.*

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Droplet swimmers in complex geometries: Autochemotaxis and trapping at pillars

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Many organisms communicate by trail mediated signalling or autochemotaxis: their motion is influenced by their own emission of a chemical attractant or repellent, diffusing slowly compared to typical agent velocities. This causes gradient forces acting both on themselves as well as on other individuals. Meanwhile, geometrical confinement also influences the behaviour of microswimmers, e.g., pusher-type swimmers attach to curved interfaces depending on the interplay of hydrodynamic interaction and trajectorial persistence. It is of high biological relevance to have a well-controlled, tunable artificial model system exhibiting these traits.
A promising candidate are self-propelling liquid crystal droplets in an aqueous surfactant solution. They gain propulsion energy by micellar solubilisation, with filled micelles acting as a chemical repellent. We are able to tune key parameters in the system, like swimmer size, velocity and persistence length.
We demonstrate autochemotactic effect in a number of model experiments:
While passing through symmetric bifurcating channels consecutively, the choice of the following droplet shows clear anti-correlation to the leading one, indicating negative auto-chemotaxis. In a second study, we use microfluidic pillar arrays of variable radii to provide a convex wall to attract the swimmer, bend its trajectory and to force it to revert to its own trail. We observe repulsion for highly curved surfaces, stable trapping at large pillars, and a narrow transition region, where negative autochemotaxis makes the swimmers detach after a single orbit.

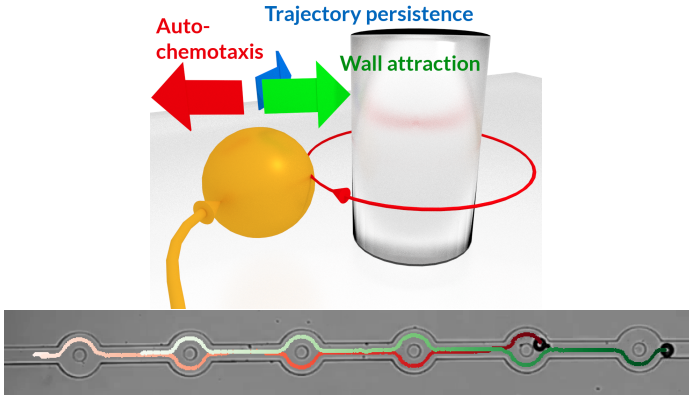

Fig. 1: *top: Illustration of the droplet swimmer's interaction with a micropillar, bottom: anticorrelated trajectories in bifurcationg channels*

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Evolutive Self-Propelling Janus Droplets utilized for Programmable DNA Cargo Delivery

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A novel class of time-evolutive self-propelled droplets are presented which is able to deliver cargo in a programmable manner. The self-propelling droplets are initially formed with a water/ethanol mixture, in a squalane/monoolein solution, and develop in up to three stages depending on ethanol concentration. In the first stage, the droplet propulsion originates from the spontaneous solubilization of ethanol in the oily phase; during this process the droplets absorb surfactant molecules. In combination with the continuous loss of ethanol the increasing surfactant concentration in the droplet finally leads to a phase separation of the water/ethanol mixture (stage 2) forming Janus droplet, i.e. a water rich droplet connected to an ethanol rich droplet. The drive in stage two results from the demixing of the ethanol and the water phase. In a third stage stable Janus droplets self-propel by a surface flow driven by the difference in chemical potential between surfactant molecules in the oily phase and the ethanol rich trailing droplet.

We characterize the different evolution stages during self-propulsion and the corresponding hydrodynamic properties of these microswimmers that evolve from a weak pusher, over a neutral swimmer, to a dimer of neutral swimmers, c.f. Fig. 1. Finally, we utilize this time-evolutive active system as smart carrier able to perform complex operations: During the phase separation, DNA is extracted in situ and transferred into the ethanol rich droplet. The ethanol rich droplet containing the DNA can be delivered at a target location. Interestingly, the droplet evolution stages and their corresponding self-propelling properties are only controlled by the initial chemical composition fairly independent on DNA concentration. Thus, several different cargo delivery processes could be realized in a programmable manner.

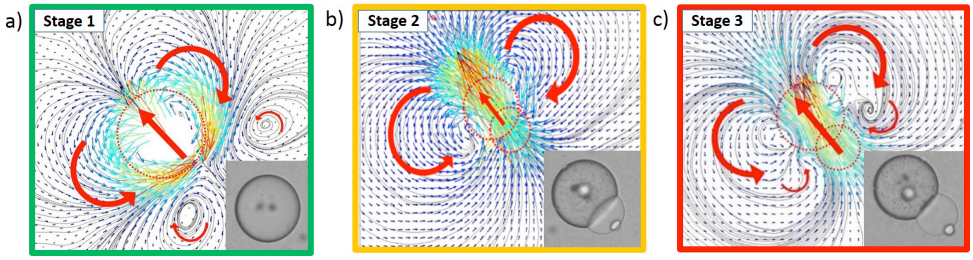

Fig. 1: *Flow fields around self-propelling droplets in their different stages determined by particle image velocimetry in the lab frame. Flow fields are similar to the rotational symmetric flow fields of a weak pusher in stage 1 (a), a neutral swimmer in stage 2 (b), and a chain of neutral swimmers in stage 3 (c).*

Jamming of cell monolayers

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Collective cell dynamics governs many biological processes, including wound healing, embryonic development and cancer metastasis. Recent experiments have revealed that cells in dense biological tissues exhibit many of the signatures of glassy materials, including caging, dynamical heterogeneities, and viscoelastic behavior. In this talk I will describe active matter models of the dynamics of confluent cell monolayers, where there are no gaps within cells. I will demonstrate that these systems exhibit a novel transition from a liquid-like to a solid-like glassy state that is independent of cell packing fraction and is controlled by the interplay of cell motility, cortical tension and cell-cell interactions, and describe comparison with experiments in epithelial cell monolayers..

Pressure in active systems

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Pressure is the mechanical force per unit area that a confined system exerts on its container. In thermal equilibrium, the pressure depends only on bulk properties (density, temperature, etc.) through an equation of state. The talk will show that in non-equilibrium active systems containing self-propelled particles, the pressure instead can depend on the precise interactions between the system's contents and its confining walls and on the shape of the walls. This implies that generic active systems have no equation of state. Implications of this result as well as forces on general objects embedded in an active fluid will be discussed.

Hydrodynamics of microswimmers: Phase Separation and influence of gravity

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Active motion of microorganisms and artificial microswimmers is relevant both to real world applications as well as for posing fundamental questions in non-equilibrium statistical physics. Microswimmers are often modelled as active Brownian particles, neglecting hydrodynamic interactions between them. However, real microswimmers, such as ciliated microorganisms, catalytic Janus particles, or active emulsion droplets, employ propulsion mechanisms reliant on hydrodynamics. Therefore, we use the squirmer as a model swimmer and the particle-based simulation method of multi-particle collision dynamics [1] to explore the influence of hydrodynamics on their phase behavior in a quasi-two-dimensional geometry and on their motion under gravity.

A striking feature of the collective behavior of spherical microswimmers is that for sufficiently strong self-propulsion they phase separate into dense clusters coexisting with a low-density disordered surrounding [2, 3]. Building on previous work [4], we examine the influence of hydrodynamic interactions on this motility-induced phase separation. For a range of mean densities and Péclet numbers, we observe how the system decomposes into a dilute and a cluster phase, which then coarsens over time. The most striking difference with the phase diagram of active Brownian particles [2, 3] is that a larger mean density results in a lower density of the coexisting dilute phase, which is a clear signature of hydrodynamics. Furthermore, we find that pushers or pullers suppress phase separation by increasing the critical Péclet number.

Inspired by experiments [5, 6] and theoretical work [7, 8], we also examine collective dynamics in the presence of gravity. We observe a rich phenomenology, depending not only on the relative strength of gravity but also on the long-range hydrodynamic interactions between swimmers and with the container's walls. For example, by carefully tuning sedimentation velocity close to self-propulsion speed, squirmers are able to float above the bottom wall due to the height-dependent friction coefficient. Furthermore, a system of dense squirmers exhibits layering followed by an exponential sedimentation profile in agreement with experiments [5].

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Phase behavior of active colloidal particles

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We determine the phase behaviour of two active colloidal systems: active Brownian particles (APBs) [1],[2] and a variant of the Asakura-Oosawa model driven by a Vicsek-like force [3],[4]. Both systems exhibit a phase transition, which resembles the liquid-gas transition in equilibrium. Apart from locating phase boundaries, we will also present ongoing simulation efforts, which aim at determining the critical point of the systems and corresponding critical exponents.

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Construction and Characterization of Artificial Thermophoretic Micro-& Nanoswimmers

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Very recently, self-propelling micro- and nanoswimmers have attracted scientific interest, because they allow studying active transport or assembly processes in fluids at the microscale [1]. One particularly important aspect of theses swimmers is steering their motion [2]. Here, we present DNA-based, artificial swimmers that are driven by self-thermophoresis, i.e. by an asymmetrical temperature gradient. The attached DNA element acts as steering unit.
For the microswimmer (Fig. 1a), a Janus particle, consisting of a polystyrene bead with a thin gold layer on one hemisphere and acting as the thermophoretic active element upon laser irradiation, is coupled to a several micrometre-long, double-stranded DNA molecule, serving as stabilizing element to reduce rotational diffusion. Its motion is investigated with regard to DNA length and additionally attached cargo particles [3].

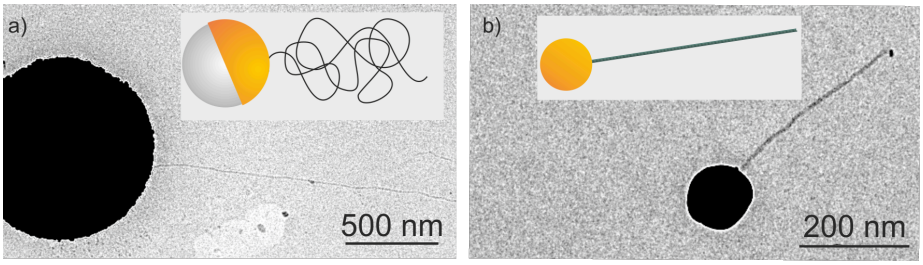

Fig. 1: *Schematic representations and electron micrographs of the investigated thermophoretic swimmers: a) microswimmer, consisting of a Janus particle and double-stranded DNA as control element, and b) nanoswimmer, composed of a 100 nm gold nanoparticle and a 6HB DNA origami structure, serving as thermophoretic driving and control element. Binding of DNA and particle is achieved by endspecific functional thiol- or thioct-modification of the DNA element.*

The constructed nanoswimmer (Fig. 1b) is composed of a 400-nm long, stiff DNA origami structure [4], a so called six-helix-bundle (6HB), attached to a gold nanoparticle with a size of about 100 nm. The latter acts as the temperature gradient source while the 6HB is considered as the propelling element. Different construction principles are discussed. The nanoswimmers are characterized in terms of their thermal stability, a crucial parameter for the usability as thermophoretic swimmers.

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Bacterial cell mechanics and motility

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Swarmer cells of the bacteria Proteus mirabilis and Vibrio parahaemolyticus become long (>10-100 μm), multinucleate, and flexible, which enables them to pack into multicellular structures and coordinate their surface motility in search for new resources. Using a microfluidic assay to measure single-cell mechanics, we identified large differences in swarmer cell stiffness (bending rigidity of P. mirabilis, 9.64 x 10^{-22} N m^2; V. parahaemolyticus, 9.75 x 10^{-23} N m^2) compared to vegetative cells (1.43 x 10^{-20} N m^2 and 3.22 x 10^{-22} N m^2, respectively). The reduction in bending rigidity (~3-15 fold) was not due to changes in peptidoglycan composition. Electron cryotomography and atomic force microscopy revealed that peptidoglycan thickness in P. mirabilis decreased from 1.5 nm (vegetative) to 1.0 nm (swarmer), which increased the susceptibility of swarmers to osmotic pressure and cell wall-modifying antibiotics (e.g., β-lactams). P. mirabilis and V. parahaemolyticus swarmer cells were 30-40% more likely to die after 3 h of treatment with a minimum inhibitory concentrations of the β-lactams cephalexin and penicillin G compared to vegetative cells. The adaptive cost of swarmer surface motility in these bacteria is offset by a fitness cost, as cells are more susceptible to physical and chemical changes in their environment. These observations may guide the design of new antibiotic regimens to treat infections of these (and other) motile bacterial pathogens.

Unexpected parallelisms: From swimming bacteria to wound healing and cancer metastasis

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Nearly 20 years ago, Neil Mendelson observed whirls and jets in dense colonies of *Bacillus subtilis* on top of agar [1]. This organized collective motion has since been shown to arise whenever swimming bacteria are at sufficient density (e.g., see [2,3]). Under appropriate conditions, hydrodynamic effects drive the alignment of nearby bacteria, but the dipole-distributed forces from the bacteria on the fluid destabilize the system and cause the formation of transient vortices and jets.

When your skin gets cut, one of the first processes is re-epithelialization. The top living layer of your skin, the epithelium, must heal itself, which is accomplished by the crawling of the epithelial cells over the wounded region. Experiments have shown that this process involves elaborate coordinated cell motions that include whirling vortices [4].

Are the similarities in these two disparate systems coincidence? Or is there fundamental similarities in the physics that drives these two systems?

Here I will discuss our attempts to construct mathematical models for these two systems that are grounded in the basic behaviour of the single cells that generate the motions. An intriguing connection is that both swimming bacteria and crawling epithelial cells exert dipole-distributed forces on their surroundings. In order to test these models, we have performed a number of experiments that produce unexpected results. For example, it has been shown that confined suspensions of *B. subtilis* form a single, stable, counter-rotating vortex [3]. However, we find that confined *E. coli* instead forms micro-spin cycles, a persistent periodically reversing vortex. What defines the marked difference between the collective dynamics of these two flagellated swimmers? And, in epithelial cells, perturbations that slow isolated cells are found to dramatically increase collective migration. I will show that our models naturally predict these behaviours and can quantitatively match our experimental data. Then, because many cancers arise from epithelial tissues, I will conclude by arguing for a biophysical examination of the transition to metastasis in cancer and discuss how our epithelial cell model may provide insights that are currently obscured by traditional genomic and proteomic methodologies.

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Nematic Ordering Transitions in Bacterial Biofilms

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Bacteria frequently occupy densely populated surface-bound communities, known as "biofilms", which are intrinsically resistant to antibiotic treatment. It is largely unknown how bacteria organize their collective behavior inside biofilms, and how biofilms behave in natural environments. In this presentation, I will introduce a new method that allows us to image all individual cells in *Vibrio cholerae* biofilms at different stages of development [1]. From these data, we extracted the precise 3D cellular arrangements, cell shapes, sizes, movement, and global morphological features during biofilm growth. We discovered several critical transitions of the internal and external biofilm architectures that separate the major phases of *V. cholerae* biofilm growth, including nematic ordering transitions to aster-like states. This presentation will illustrate the rich interplay of bacterial cooperative behaviors in biofilm communities and physics.

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Bacterial Swarmer Cells in Confinement

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Various motile bacteria are propelled by helical filaments, which protrude from their cell body and are driven by rotary motors located in the cell membrane [1]. Such bacteria exhibit different modes of locomotion, depending on the environment. Individual (planktonic) cells exhibit the so-called swimming motility, where the flagella of peritrichous bacteria self-organize into bundles. Another mode of motion is denoted as bacterial swarming, where bacteria migrate collectively over surfaces and are able to form stable aggregates, which can become highly motile. Some bacteria strains show distinctly different morphologies in the swarming mode compared to the planktonic cells as they are more elongated (2-50 times) by suppression of cell division and their number of flagella is significantly increased. This points toward the significance of flagella for swarming.

We adopt a mesoscale hydrodynamic simulation approach [2] and the *E. coli* model of Ref. [3] to study the properties of a swarmer cell confined in a thin film. Thereby, the cell is three times longer than a planktonic cell and is covered with 25 flagella. In general, we find a significant heterogeneity in the appearing structures and the dynamics [4]. Only for very narrow gaps confinement strongly affects the bundle arrangement and the dynamical properties of cells such as their rotation frequency and the migration velocity. The distribution of cells sensitively depends on the wall separation. In very narrow gaps, the bundle arrangement matters substantially and geometrical restrictions are essential. For intermediate wall separations, both walls are equally important and the cells migrate in the center between the walls, whereas for wide gaps cells stay preferentially close to one of the walls. Considering the migration patters, we find straight paths for narrow gaps, but also cell-rolling over a surface for wide gaps (Fig. 1).

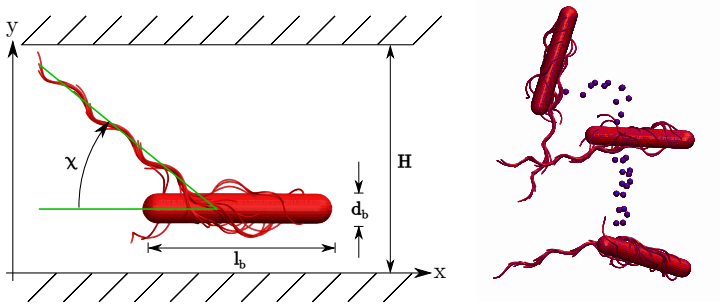

Fig. 1: *(Left) Illustration of a confined swarmer cells. (Right) Migration pattern of a cell "rolling" over a surface. The dots indicate subsequent positions in time of the center of mass of the cell.*

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Trypanosome microswimmers in the tsetse fly

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Trypanosomes are unicellular blood parasites, causing deadly human African sleeping sickness. They are transmitted between their mammalian hosts by the infamous tsetse fly. Trypanosome infections cannot be cured and vaccination is impossible, mainly due to the intriguing capacity of the swimming parasites to escape host immune destruction. While the actual infection of the mammal is reasonably well understood, the extended journey of the trypanosomes through the fly remains enigmatic. It takes several weeks for the parasites to complete their journey through different body parts. We found that the trypanosome itinerary is accompanied by successions of solitary and collective motion patterns, each marked by morphological adaptations of the parasite. We have tsetse flies with genetically engineered, differently fluorescent trypanosomes, allowing to unambiguously follow individual microswimmers within a population, in the living fly and with high spatio-temporal resolution. These analyses revealed that trypanosome populations can oscillate between apparently chaotic and highly ordered, collective motion behaviours. The time scales of switching between these motion patterns range from seconds to few minutes. At larger time scales, the different parasite morphotypes produce characteristic motility pattern, strictly dependent on the physical microenvironment. Using light sheet fluorescence microscopy, we succeeded in generating whole animal 3D-reconstuctions of tsetse flies - with single-cell resolution. This innovative imaging approach provided a blueprint for the compete tsetse digestive system. We will discuss how the geometry of the amazingly complex fly organs might account for the diverse microswimming behaviour of the flagellate trypanosomes. We conclude that trypanosome are versatile model microswimmers.

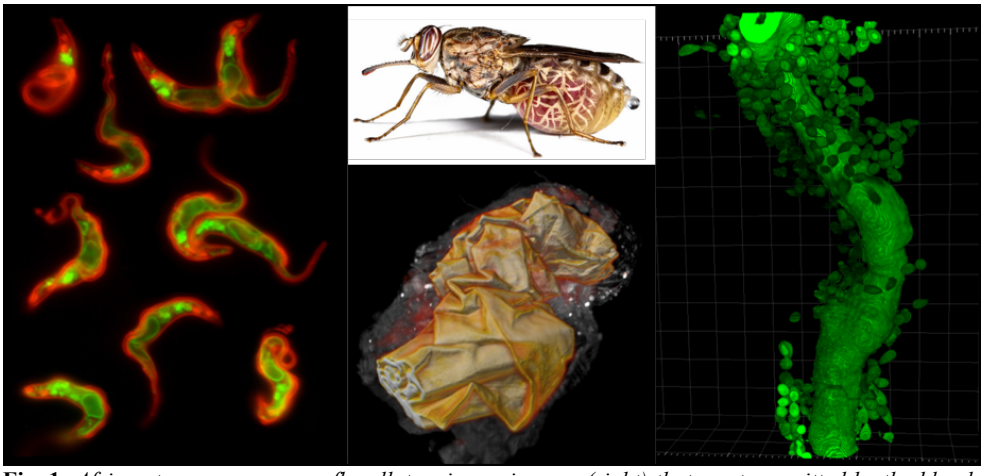

Fig. 1: *African trypanosomes are flagellate microswimmers (right) that are transmitted by the blood-sucking tseste fly (mid, upper picture). The physical architecture of the fly's digestive system (mid, lower picture, and left) supports distinct trypanosome motion patterns, from single cell swimming to collective behaviour.*

Friday, October 7

Talks Friday, October 7

S11-01 **Bausch, A. R.**
Cytoskeletal pattern formation

S11-02 **Saintillan, D.**
Collective motion in confinement

S11-03 **Kierfeld, J.** ; Boltz, H.-H.
Shapes of Sedimenting Soft Elastic Capsules in a Viscous Fluid

S11-04 **Mourran, A.** ; Zhang, H.; Moeller, M.
Swimming of morphoelastic ribbon helix

S11-05 **Klumpp, S.** ; Faivre, D.
Magnetism and Motility of Magnetotactic Bacteria

S12-06 **Pagonabarraga, I.**
Collective behavior and pattern formation in actuated magnetic and Janus colloidal suspensions

S12-07 **Bär, M.**
Modelling Pattern Formation and Waves in Suspensions of Bacterial Microswimmers

S12-08 **Menzel, A. M.** ; Hoell, C.; Löwen, H.
Statistical description and dynamical density functional theory of semidilute microswimmer suspensions

S12-09 **Bechinger, C.** ; Lozano, C.; Gomez-Solano, J. R.; Bäuerle, T.
Light controlled active Brownian motion

S12-10 **Mikulich, V.** ; Bruecker, Ch.; Rockenbach, A.; Schnakenberg, U.
Effect of cilia orientation on transport of micro-particles

Cytoskeletal pattern formation

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Living cells rely on the self organization mechanisms of cytoskeleton to adapt to their requirements. Especially in processes such as cell division, intracellular transport or cellular motility the controlled self assembly to well defined structures, which still allow a dynamic reorganization on different time scales are of outstanding importance. Thereby, the intricate interplay of cytoskeletal filaments, crosslinking proteins and molecular motors a central role. One important and promising strategy to identify the underlying governing principles is to quantify the physical process in model systems mimicking the functional units of living cells. Here I will present in vitro minimal model systems consisting of actin filaments, crosslinking molecules and myosin II exhibiting collective long range order and dynamics. I will discuss how a balance of local force exertion, alignment interactions, crosslinking and hydrodynamics affect the evolving dynamic structures. In a second part I will address how tension generation of an encapsulated active microtubule or acto-myosin network suffices for a remodelling and global shape transformation of cell-sized lipid vesicles.

Collective motion in confinement

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Recent experiments have shown that confinement can profoundly affect self-organization in semi-dilute active suspensions, leading to striking features such as the formation of steady and spontaneous vortices in circular domains and the emergence of unidirectional pumping motions in periodic racetrack geometries. Motivated by these findings, we analyze the two-dimensional dynamics in confined suspensions of active self-propelled swimmers using a mean-field kinetic theory where conservation equations for the particle configurations are coupled to the forced Navier-Stokes equations for the self-generated fluid flow. In circular domains, a systematic exploration of the parameter space casts light on three distinct states: equilibrium with no flow, stable vortex, and chaotic motion, and the transitions between these are explained and predicted quantitatively using a linearized theory. In periodic racetracks, similar transitions from equilibrium to net pumping to traveling waves to chaos are observed in agreement with experimental observations and are also explained theoretically. Our results underscore the subtle effects of geometry on the morphology and dynamics of emerging patterns in active suspensions and pave the way for the control of active collective motion in microfluidic devices.

Shapes of Sedimenting Soft Elastic Capsules in a Viscous Fluid

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Soft elastic capsules which are driven through a viscous fluid undergo shape deformation coupled to their motion. We introduce an iterative solution scheme which couples hydrodynamic boundary integral methods and elastic shape equations to find the stationary axisymmetric shape and the velocity of an elastic capsule moving in a viscous fluid at low Reynolds numbers. We use this approach to systematically study dynamical shape transitions of capsules with Hookean stretching and bending energies and spherical rest shape sedimenting under the influence of gravity or centrifugal forces. We find three types of possible axisymmetric stationary shapes for sedimenting capsules with fixed volume: a pseudospherical state, a pear-shaped state, and buckled shapes. Capsule shapes are controlled by two dimensionless parameters, the Föppl-von-Kármán number characterizing the elastic properties and a Bond number characterizing the driving force. For increasing gravitational force the spherical shape transforms into a pear shape. For very large bending rigidity (very small Föppl-von-Kármán number) this transition is discontinuous with shape hysteresis. The corresponding transition line terminates, however, in a critical point, such that the discontinuous transition is not present at typical Föppl-von-Kármán numbers of synthetic capsules. In an additional bifurcation, buckled shapes occur upon increasing the gravitational force. This type of instability should be observable for generic synthetic capsules. All shape bifurcations can be resolved in the force-velocity relation of sedimenting capsules, where up to three capsule shapes with different velocities can occur for the same driving force. All three types of possible axisymmetric stationary shapes are stable with respect to rotation during sedimentation. Additionally, we study capsules pushed or pulled by a point force, where we always find capsule shapes to transform smoothly without bifurcations.

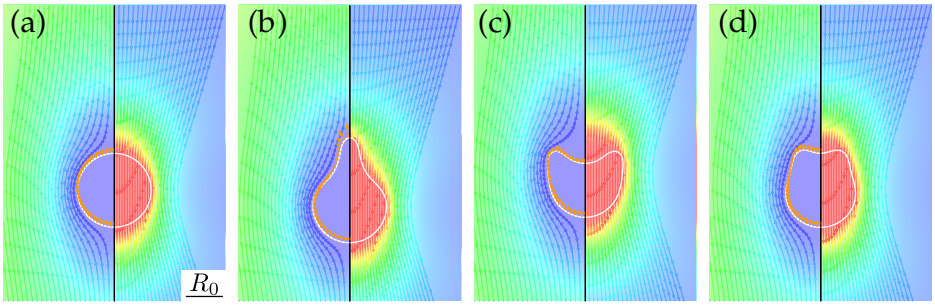

Fig. 1: *Fluid velocity field around the four stationary capsule shapes under volume control, (a) pseudospherical, (b) pear shape, (c) strongly buckled and (d) weakly buckled.*

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Swimming of morphoelastic ribbon helix

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Earth is home to a remarkable diversity of microswimmer species, and synthetic attempts have not reached the same level of sophistication. Artificial microswimmers that swim by a body shape deformation are notoriously difficult to realize. The challenge is twofold: (i) devising the shape of a microswimmer with sequences of geometrical configurations leading to translational motion; (ii) realizing an actuation mechanism generating the shape sequence and the requisite energy.

Morpho-elastic microgels are thin bodies which can swell and can change their intrinsic curvature and torsion. A swimmer may be devised from a hydrogel capable of actuation through swelling/shrinkage of the polymer network. So far, any volume change of hydrogel is a slow diffusion-controlled process with a strong dependence on size. We challenged this limitation and show that the swelling/shrinkage cycle of a micrometric hydrogel body can be photothermally modulated to sustain self-propulsion. We combined non-equilibrium inhomogeneous swelling/shrinkage and an anisometric microgel geometry to achieve large and fast bending deformations. Control of the deformation (dilation relative to the bending) ensures non-reciprocal actuation creating the thrust needed to propel the microgel body in water. A body shape deformation is triggered by photothermal heating of plasmonic nanoparticles embedded within a temperature-sensitive microgel. Absorption of high-intensity laser light by the nanoparticles allows rapid heating leading to fast dynamics. Hence, a temperature jump followed by a slow diffusion creates a destabilizing elastic instability of the hydrogel structure. Such a transient instability in combination with the anisometric geometry of the microgel enables a unique spatio-temporal control of the non-reciprocal actuation speed and amplitude

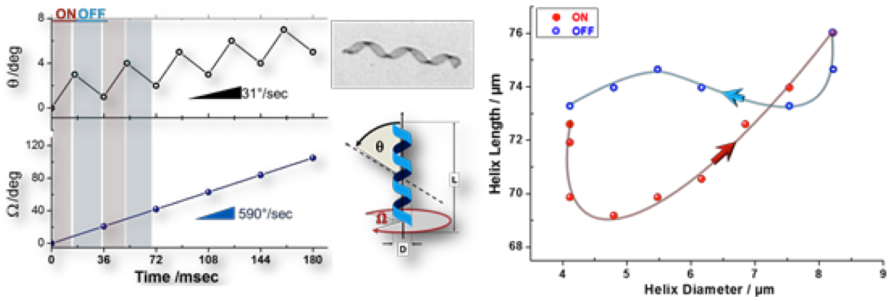

Fig. 1: *Photothermal actuation characteristics of a microgel ribbon that morphs into a cylindrical helix upon swelling. Through stroboscopic irradiation the helix undergoes complex rotational movement (a) with controlled speed and direction. Deformation in parameter space of the helix during irradiation (full symbol) and recovery (open symbol).*

Magnetism and Motility of Magnetotactic Bacteria

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Magnetotactic bacteria align along magnetic field lines with the help of magnetic organelles called magnetosomes. Magnetosomes contain magnetic nanoparticles and are aligned along a cytoskeletal structure to form a cellular 'compass needle'. We have conducted a joint theoretical and experimental study to understand how magnetic alignment helps the cells to swim in an oxygen concentration gradient towards the preferred micro-oxic zone, a behavior known as magneto-aerotaxis. In principle, the magnetic field can provide an axis and/or a direction for motility. A comparison of the magneto-aerotactic behavior of different strains of magnetotactic bacteria shows that some strains use the direction given by the magnetic field instead of sensing an oxygen concentration gradient and that such replacement can occur separately for low-oxygen and high-oxygen conditions [1].
To describe these magnetotactic behaviors theoretically, different approaches are used depending on the questions that are addressed: The interplay of the magnetic torque (which aligns the bacteria with respect to the magnetic field) with the forces arising from the flagellar rotation (which drives their propulsion) is studied with explicit hydrodynamic simulations, while coarse-grained active particle models are used to study the tactic behavior of individual cells and whole populations in oxygen gradients and magnetic fields. If time permits, some aspects of cell division in these bacteria may also be discussed [2].

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Collective behavior and pattern formation in actuated magnetic and Janus colloidal suspensions

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Actuated and autocatalytic colloids constitute systems that are intrinsically out of equilibrium. As a result of their dynamic interactions, they can show a rich variety of self assembly scenarios. The observed self assembled structures make these systems very sensitive to external forcing, hence making actuated and active matter a fertile ground to explore and develop mechanically tunable materials.

In this talk I will analyze the basic physical mechanisms that control the collective behavior of two kinds of colloidal particles that move in a liquid medium. On the one hand, confined magnetic colloids can rectify their motion when actuated with a rotating magnetic field, acting as a hydrodynamic conveyor belt. Self assembled chains of rotors propel faster than individual ones, until reaching a saturation speed at distances where induced-flow additivity vanishes. On the other hand, the development of Janus colloids has opened the possibility to create synthetic microrobots that can move due to the chemical reactions they catalyze on their heterogeneous surfaces. The motion of chemically powered colloids is intricate because the chemically active colloids perturb the spatial distribution of the chemical species and also the state of motion of the solvent. As a result, suspensions of chemically active colloids are characterized by long range, non-equilibrium interactions. These dynamic interactions have a strong impact in the collective behavior of these suspensions.
I will describe the analogies and specificities in the hydrodynamic coupling that characterize these two types of systems and the different structures they spontaneously form.

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A. Scagliarini, I. Pagonabarraga, submitted

Modelling Pattern Formation and Waves in Suspensions of Bacterial Microswimmers

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Active fluids are complex fluids wherein energy is injected by active internal units. In this talk I consider a prominent examples of an active biological fluid – dense suspension of swimming bacteria (e. g. *Bacillus subtilis*). For dense suspensions of bacterial swimmers, we propose a simple phenomenological model that predicts regular and turbulent vortex lattices [1] and reproduces recent experimental findings of mesoscale turbulence in two- and three-dimensional suspensions of *Bacillus subtilis* quantitatively [2], see Figs. 1a-b. Recently, we have been able to reproduce the observed behavior in a minimal microscopic model based on the competition between short-range and long-range antialignment of self-propelled particles (SPP) representing the bacterial swimmers [3], see Figs. 1c-d. Finally, coarse-grained continuum models are derived from stochastic equations of motions for individual active swimmers for the minimal SPP model as well as for a more realistic hydrodynamical model of swimmers in a fluid [4], enabling an understanding of the mechanism and properties of pattern formation in microswimmer suspensions and the relation of physical parameters characterizing the swimmers and the coefficient for macroscopic model equation.

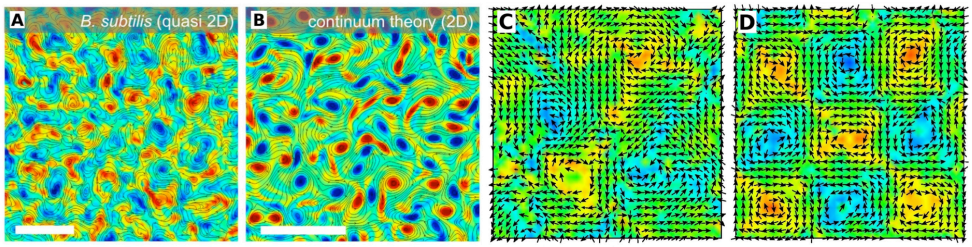

Fig. 1: *Comparison of vorticity patterns from experiments (A), continuum theory (B) and a discrete agent-based model (C,D).*

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Statistical description and dynamical density functional theory of semidilute microswimmer suspensions

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To characterize the collective behavior of microswimmer suspensions as a function of individual swimmer properties, statistical theories are mandatory [1]. Such descriptions should consistently contain the active drive of the swimmers, hydrodynamic and steric interactions between them, and interactions with confining external potentials.
Dynamical density functional theory provides a very successful approach to address all these ingredients. So far, it has been used to characterize sterically interacting and confined, yet "dry" crowds of self-propelled particles [2] on the one hand, and hydrodynamically interacting, yet passive colloidal particles [3] on the other hand. However, these different approaches have not been connected.
We have now inserted this missing link. A consistent dynamical density functional theory to characterize suspensions of microswimmers has been developed [4]. Its potential has been demonstrated by describing the behavior of spherically confined crowds, see Fig. 1 (a). Increasing the active drive, azimuthal instabilities in their concentration profiles lead to the formation of effective "hydrodynamic fluid pumps", as reported by particle-based simulations [5, 6]. Our dynamical density functional theory reproduces this behavior, see Fig. 1 (b).

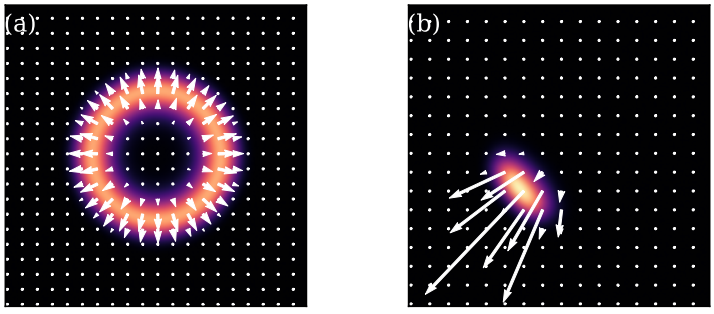

Fig. 1: *Two-dimensional numerical solution of our dynamical density functional theory under spherical confinement. (a) For low active drive, the microswimmers form a high-density ring when pushing against the confinement. (b) Symmetry is broken when increasing the active drive, which reproduces the "hydrodynamic fluid pump" described earlier in particle-based simulations [5, 6].*

As one next step, our plan is to apply the theory to suspensions of microswimmers exposed to external flow fields. For instance, we have recently found interesting dynamic behavior of individual microswimmers in rotationally symmetric swirl flows [7].

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Light controlled active Brownian Motion

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Despite their structural simplicity, active colloidal particles exhibit many properties of motile microorganisms including formation of clusters and biofilms, swarming or their response to external fields. Accordingly, active colloids provide an intriguing chance to understand the formation of dynamical structures in living systems but may also find use as micro robots which – similar to their biological counterparts – autonomously navigate through complex environments. In this talk, we will present recent advances in this field with a particular view on light-activated microswimmers, where the particle's motility is controlled by the amount of incident laser light. Using several examples, such as clustering, gravitactic behaviour and phototactic response of active colloids, we demonstrate a close relationship between artificial and biological microswimmers. Finally, we also investigate the motion of active colloids in viscoelastic fluids. Contrary to Newtonian liquids, we observe a drastic increase of the particle's rotational diffusion with increasing velocity. Such enhancement is attributed to the coupling between the particle's directed motion and the microstructural relaxation of the surrounding fluid.

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Effect of cilia orientation on transport of micro-particles

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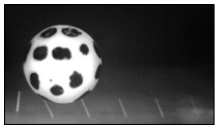
The transportation of particles along ciliated walls is of highly complex nature. In order to simplify the parameter space an artificial ciliated wall system is designed which allows us to study the transport of selected particles under defined beating conditions [1]. As reference, we selected spherical particles of slightly higher density than the carrier liquid water. In addition, their diameter is larger than the spacing between the flaps to ensure contact with the flap tips.

The method presented herein uses micro-structured surfaces with arrays of artificial cilia that are individually micro-pneumatically activated [2]. We studied the transport behaviour of the micro-particles when metachronal waves running along the ciliated wall are applied. Two different positions of the cilia in rest conditions were studied: the first with the cilia protruding into the liquid with a pre-tilt to the left and the second with a pre-tilt to the right. The results show that the pre-tilt and orientation of the flaps is an important parameter which decides about the transport direction.



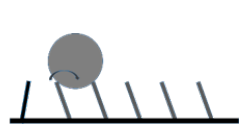


Fig. 1: *Symplectic transport along the ciliated wall.Pre-tilt is to the left. Wave direction is* ➡

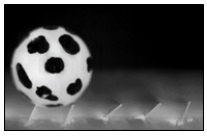


Fig. 2: *Antiplectic transport. Pre-tilt is to the right. Wave direction is* ⬅

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Poster

Poster

Pos-01 **Abaurrea Velasco, C.** ; Abkenar, M.; Marx, K.; Auth, T.; Gompper, G.
Collective behavior of swimmers with density-dependent motility

Pos-02 **Alaimo, F.** ; Voigt, A.; Praetorius, S.
A mesoscopic field theoretical approach for active systems

Pos-03 **Annepu, H.** ; Theers, M.; Gompper, G.; Winkler, R. G.
Dynamics of spheroidal squirmers in Poiseuille flow

Pos-04 **Auschra, S.** ; Falasco, G.; Pfaller, R.; Bregulla, A. P.; Chakraborty, D.; Cichos, F.; Kroy, K.
Hot Microswimmers: Theory, Experiments and Atomistic Simulations

Pos-05 **Baasanjav, D.** ; Samin, S.; Faez, S.
Single particle nano-capillary electrophoretic tracking: numerical considerations

Pos-06 **Babel, S.** ; Löwen, H.; Menzel, A. M.
Dynamics of a linear magnetic "microswimmer molecule"

Pos-07 **Bachmann, F.** ; Vach, P. J.; Faivre, D.; Klumpp, S.; Fratzl, P.
Morphology of Fast Magnetic Micro Propellers

Pos-08 **Bäuerle, T.** ; Haeufle, D.; Steiner, J.; Bremicker, L.; Schmitt, S.; Bechinger, C.
External control strategies for self-propelled particles: Optimizing navigational efficiency in the presence of limited resources

Pos-09 **Bäumchen, O.** ; Ostapenko, T.; Böddeker, Th.; Schwarzendahl, F.; Kreis, Ch.; Mazza, M. G.
Curvature-guided motility of microalgae in confinement

Pos-10 **Bayati, P.** ; Popescu, M. N.; Uspal, W. E.; Dietrich, S.; Najafi, A.
Interaction of chemically active particle with a planar wall: dependence on the model activity

Pos-11 **Bet, B.** ; Boosten, G.; Dijkstra, M.; van Roij, R.
Efficient shapes for microswimming: from three-body swimmers to helical flagella

Pos-12 **Blaschke, J.** ; Zöttl, A.; Maurer, M.; Menon, K.; Stark, H.
Hydrodynamically Tuned Phase Separation of Spherical Microswimmers

Pos-13 **Botin, D.** ; Niu, R.; Weber, J.; Wittenberg, Ch.; Palberg, T.
Quantitative approach to modular microswimmer

Pos-14 **Buchmann, A.** ; Cortez, R.; Fauci, L.
A Computational Model of Ciliary Beating

Pos-15 **Choudhury, U.** ; Singh, D. P.; Mark, A. G.; Fischer, P.
Collective behaviour of light driven active particles

Pos-16 **Cichos, F.** ; Bregulla, A. P.; Würger, A.; Günther, K.; Kick, A.; Mertig, M.
Thermo-Osmotic Flows in Thin Films

Pos-17 **Codina, J.** ; Pagonabarraga, I.
Emergent interactions in non-equilibrium suspensions

Pos-18 **Codutti, A.** ; Faivre, D.; Klumpp, S.
Swimming behavior of magnetotactic bacteria

Pos-19 **Colin, R.** ; Sourjik, V.
Fourier Image Analysis reveals the chemotactic behavior of populations of swimming bacteria at high density

Pos-20 **Dauparas, J.**
Flagellar flows around bacterial swarms

Pos-21 **Dietrich, K.** ; Renggli, D.; Buttinoni, I.; Isa, L.
Janus microswimmers at oil-water interfaces

Pos-22 **Djellouli, A.** ; Coupier, G.; Quilliet, C.; Marmottant, P.
Swimming through shell buckling

Pos-23 **Dominguez, A.**
Mean–field theory for the collective dynamics of active particles at a fluid interface

Pos-24 **Duman, Ö.** ; Elgeti, J.; Gompper, G.
Dynamics of Collective Cell Motility

Pos-25 **Eisenstecken, T.** ; Gompper, G.; Winkler, R. G.
Conformational properties of active semiflexible polymers

Pos-26 **Elgeti, J.** ; Isele-Holder, R.; Duman, Ö.; Gompper, G.;
Self-Propelled Semiflexible Fillaments

Pos-27 **El Hasadi, Y. M. F.** ; Crapper, M.; Larese, A.
Self-Propelled clusters

Pos-28 **Ender, H.** ; Kierfeld, J.
Bead-spring microswimmers in a MPCD fluid

Pos-29 **Eskandari, Z.** ; Popescu, M. N.; Tasinkevych, M.; Dietrich, S.
In-plane collisions between chemically active particles

Pos-30 **Faivre, D.** ; Vach, P. J.; Walker, D.; Fischer, P.; Fratzl, P.
Reversible dynamic assembly of magnetic colloidal clusters

Pos-31 **Feldmann, D.** ; Santer, S.; Maduar, S.; Vinogradova, O. I.
Photosoap: light-controlled particle assemblies through diffusio-osmotic flows

Pos-32 **Frangipane, G.** ; Vizsnyiczai, G.; Saglimbeni, F.; Maggi, C.; Bianchi, S.; Di Leonardo, R.
Light controlled motility in E. coli

Pos-33 **Froin, A.** ; Pella, M.; Rehage, H.
Characterization of asymmetric, viscoelastic micro-swimmers with a propulsion mechanism based on chemical reactions

Pos-34 **Geiseler, A.** ; Hänggi, P.; Marchesoni, F.; Mulhern, C.; Savel'ev, S.
Chemotaxis of Artificial Microswimmers in Active Density Waves

Pos-35 **Gomez-Solano, J. R.** ; Sahebdivani, M.; Blokhuis, A.; Bechinger, C.
Self-propelled Janus particles in viscoelastic fluids

Pos-36 **Heidari, M.** ; von Klitzing, R.
Thermophoresis of Janus Particles near a Polymer Brush Surface: Impact of the Cononsolvency Effect

Pos-37 **Hoell, C.** ; Menzel, A. M.; Löwen, H.
DDFT of microswimmers in a trap

Pos-38 **Hoore, M.** ; Fedosov, D. A.; Gompper, G.
Conformation-dependent polymer avidity, responsible for reversible critical shear-dependent platelet aggregation

Pos-39 **Ihle, T.** ; Kürsten, R.
Critical assessment of the von-Mises-distribution for self-propelled particles

Pos-40 **Kaiser, A.** ; Aronson, I. S.; Snezkho, A.
Flocking ferromagnetic particles

Pos-41 **Kandula, H. M.** ; Wang, W.; Granick, S.
Passive Particles Follow Active Particles

Pos-42 **Katuri, J.** ; Simmchen, J.; Uspal, W. E.; Popescu, M. N.; Tasinkevych, M.; Sanchez, S.
Designing surfaces to guide chemical microswimmers

Pos-43 **Kössel, F. R.** ; Jabbari-Farouji, S.
A kinetic theory for dynamics of self-propelled magnetic suspensions in a magnetic field

Pos-44 **Kree, R.** ; Zippelius, A.
Self-propulsion of droplets generated by active stresses

Pos-45 **Kreissl, P.** ; Niu, R.; Palberg, T.; Holm, C.; de Graaf, J.
Numerical Simulations of an Ion-Exchange Resin Based Microfluidic Pump

Pos-46 **Kromer, J. A.** ; Friedrich, B. M.
Cellular decision making during sperm chemotaxis

Pos-47 **Kühn, M.** ; Schmidt, F. K.; Eckhardt, B.; Thormann, K.
Novel Mechanism of Bacterial Motility

Pos-48 **Kuron, M.** ; Rempfer, G.; Holm, C.; de Graaf, J.
Probing the Dynamics of Self-Electrophoretic Swimmers using Lattice-Boltzmann

Pos-49 **Li, M.** ; Brinkmann, M.; Pagonabarraga, I.; Seemann, R.; Fleury, J.-B.
Collective Effects and Living-Clusters Formation with Pusher Self-Propelling Droplets

Pos-50 **Liebchen, B.** ; Marenduzzo, D.; Pagonabarraga, I.; Cates, M. E.
Pattern Formation and Clustering in Chemorepulsive Active Colloids

Pos-51 **Lisicki, M.** ; Lauga, E.;
Viscoelastic Synchronisation

Pos-52 **Lozano, C.** ; ten Hagen, B.; Löwen, H.; Bechinger, C.
Artificial Phototaxis: Rectified motion of self-propelled particles by spatial motility variations

Pos-53 **Martinez, V. A.** ; Arlt, J.; Dawson, A.; Pilizota, T.; Poon, W. C. K.
Spatial control of swimming bacteria using light

Pos-54 **Martinez, V. A.** ; Devailly, C.; Dawson, A.; Schwarz-Linek, J.; Arlt, J.; Poon, W. C. K.
Bacteria swimming in High Molecular-weight polymer: lambda-DNA

Pos-55 **Mazza, M. G.** ; Zwirnmann, H.; Schkolnik, G.; Schwarzendahl, F.; Ostapenko, T.; Böddeker, Th.; Kreis, Ch.; Bäumchen, O.
Active swimmers in confinement: taxis and wall-hugging effect

Pos-56 **Mertig, M.** ; Braun, M.; Bregulla, A. P.; Günther, K.; Cichos, F.
Single Molecule Manipulations by Dynamic Temperature Fields

Pos-57 **Mertig, M.** ; Günther, K.; Herms, A.; Bregulla, A. P.; Cichos, F.
Why to use DNA for constructing thermophoretic swimmers?

Pos-58 **Michelin, S.** ; Lauga, E.
Self-propulsion of autophoretic particles: shape matters

Pos-59 **Muiños Landin, S.** ; Park, C.; Bregulla, A. P.; Cichos, F.
Optimization of the active control of a microswimmer via Soft computing

Pos-60 **Najafi, J.** ; Altegoer, F.; John, T.; Bange, G.; Wagner, Ch.
Swimming Bacillus subtilis with different number of flagella

Pos-61 **Nardini, C.** ; Stenhammar, J.; Marenduzzo, D.; Morozov, A.
Collective effects: enhanced diffusivity of tracers and bacterial turbulence

Pos-62 **Nikola, N.** ; Solon, A.; Kafri, Y.; Kardar, M.; Tailleur, J.; Voituriez, R.
Active particles with soft and curved walls: Equation of state, ratchets, and instabilities

Pos-63 **Niu, R.** ; Palberg, T.
Modular Phoretic microswimming

Pos-64 **Oguzturk, H. E.** ; Rutkevicius, M.; Gradzielski, M.; Velev, O. D.
Preparation of Anisometric Supraparticles on Super Hydrophobic and/or Superamphiphobic Surfaces

Pos-65 **Ohmura, T.** ; Nishida, Y.; Ichikawa, M.
Periodic motions of self-propelled water-in-oil droplets driven by flow

Pos-66 **Oyama, N.** ; Molina, J. J.; Yamamoto, R.
Understanding hydrodynamic polar ordering in swimmer dispersion by binary collisions

Pos-67 **Palanisamy, D.** ; Luding, S.; den Otter, W. K.
Rigid-body aggregation of spheres and rods with hydrodynamics

Pos-68 **Palberg, T.** ; Niu, R.; Wittenberg, Ch.; Reinmüller, A.; Heuser, J.; Schmidt, F. K.
Bacteria swimming in a monolayer colloidal crystal: channelling, run and tumble characteristic and active annealing

Pos-69 **Pande, J.** ; Smith, A.-S.; Krüger, T.; Harting, J.
The many faces of the bead-spring model

Pos-70 **Parmar, J.** ; Vilela, D.; Pellicer, E.; Esqé-de los Ojas, D.; Sort, J.; Sanchez, S.;
Reusable and long-lasting active microcleaners for heterogeneous water remediation

Pos-71 **Plouraboué, F.** ; Creppy, A.; Praud, O.; Druart, X.; Kohnke, P. L.; Cazin, S.; Yu, H.; Degond, P.
Turbulent and vortex-induced behavior of confined concentrated semen

Pos-72 **Pushkin, D. O.** ; Bees, M. A.
Fluid flows created by microswimmers in thin fluid films

Pos-73 **Reichert, J.** ; Rieger, H.
Pressure and state functions of self-propelled particles with hydrodynamic interactions

Pos-74 **Reigh, S. Y.** ; Zhu, L.; Gallaire, F.; Lauga, E.
Squirming in a droplet

Pos-75 **Reisian-Nejad, M.** ; Fathian, M.; Najafi, A.
Levy swimmer in an asymmetric channel

Pos-76 **Ripoll, M.** ; Yang, M.
Thermophoretic microfluidics and microchanines

Pos-77 **Rode, S.** ; Elgeti, J.; Gompper, G.
Hydrodynamic and Steric Interactions of Sperm Cells in Structured Microchannels

Pos-78 **Rodenburg, A. J.** ; Dijkstra, M.; van Roij, R.
(Osmotic) presure of an active dispersion

Pos-79 **Rühle, F.** ; Kuhr, J.-T.; Blaschke, J.; Stark, H.
Squirmers under gravitation

Pos-80 **Schwarzendahl, F.** ; Herminghaus, S.; Mazza, M. G.
Run-reverse-flick strategy of interacting bacteria

Pos-81 **Shaebani, R.** ; Hafner, A.; Santen, L.; Rieger, H.
Run-and-tumble dynamics of cytoskeletal motor proteins

Pos-82 **Shats, M.** ; Xia, H.; Francois, N.; Punzmann, H.
Motion of microparticles and quasi-particles in surface waves

Pos-83 **Siebert, J. T.** ; Virnau, P.; Speck, T.
Phase behavior and pressure of active brownian particles

Pos-84 **Slomka, J** ; Dunkel, J.
Zero-viscosity modes in active fluids

Pos-85 **Smallenburg, F.** ; Löwen, H.
Swim Pressure on Walls with Curves and Corners

Pos-86 **Stanton, M. M.** ; Park, B.-W.; Miguel-López, A.; Sitti, M.; Sanchez, S.
Biohybrid Microtube Swimmers Powered by Captured Bacteria

Pos-87 **Sukhov, A.** ; Harting, J.; Xie, Q.
Computer simulations of magnetocapillary swimmers

Pos-88 **Tan, Z.** ; Yang, M.; Ripoll, M.
Anisotropic Thermophoresis of Colloidal Rods: Microscopic Geometry Matters

Pos-89 **Tanida, S.** ; Furuta, K.; Nishikawa, K.; Kojima, H.; Sano, M.
Pattern Formation of Microtubules Driven by Kinesins

Pos-90 **Tarama, M.** ; Ohta, T.
Back-and-forth motion of active deformable particles

Pos-91 **Theers, M.** ; Westphal, E.; Gompper, G.; Winkler, R. G.
Spheroidal Squirmers – Cooperativity and Clustering

Pos-92 **Uspal, W. E.** ; Katuri, J.; Simmchen, J.; Sanchez, S.
Cross-streamline migration of chemically active Janus particles in flow

Pos-93 **Vance, J. N.** ; Esguerra, J. P. H.
Diffusion of active Brownian swimmers confined in periodic serpentine channels

Pos-94 **Vilela, D.** ; Parmar, J.; Zeng, Y.; Zhao, Y.; Sanchez, S.
Graphene-Based Microbots for Toxic Heavy Metal Removal and Recovery from Water

Pos-95 **Voigtmann, Th.** ; Schilling, T.
Clearing out a maze: A random walk in search for food

Pos-96 **Wagner, M.** ; Ripoll, M.
Shape-Induced Hydrodynamic Effects in Thermophoretic Microswimmers

Pos-97 **Wu, Z.** ; Palagi, S.; Mark, A. G.; Melde, K.; Qiu, T.; Fischer, P.
Artificial microswimmers controlled by light

Pos-98 **Xu, H.** ; Medina-Sánchez, M.; Schwarz, L.; Magdanz, V.; Schmidt, O. G.
Spermbots for cargo transport and delivery

Pos-99 **Zeitz, M.** ; Stark, H.
Single active Brownian particles moving in a random environment

Collective behavior of swimmers with density-dependent motility

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Microswimmers span from bacteria to human-made nanorobots [1]. To simulate collective behavior, generic models allow to study a large number of particles and to still maintain particle properties, such as the aspect ratio. Because many biological swimmers are anisotropic, we use self-propelled rods in two dimensions that interact with a soft repulsive potential. A capped interaction potential allows rods to cross each other [**?**]. This makes our simulations suitable for studying quasi-2D experiments, such as microtubule motility assays or a thin layer of swimming bacteria.

The phase behavior of monodisperse rods with constant self-propulsion has been characterized systematically [**?**]. While for low densities cluster formation is observed, at high densities laning is found (Figure 1). However, many biological swimmers show density-dependent motility, such as E. coli. Density-dependent self-propulsion can be characterized by the ratio of the propulsion velocity of a single rod and a rod in a dense environment, and by an exponential dependence on the number of neighboring particles [3]. We study for the first time self-propelled rods with physical interactions and a density-dependent propulsion force. We show that by decreasing the self-propulsion of the rods with the local density of swimmers, polar alignment and phase segregation are favored (**Fig. 1**). Enhanced phase segregation helps bacterial colonies in biofilms become more compact, which increases their resistances against external chemical agents.

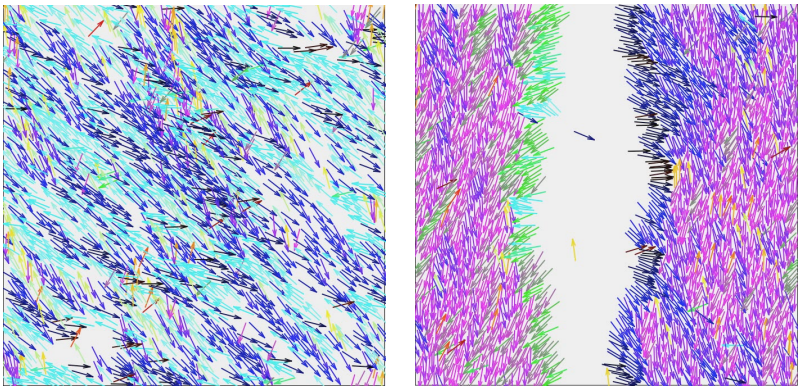

Fig. 1: *Snapshots of self-propelled rods with constant self propulsion (left) and density-dependent motility (right)*

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A mesoscopic field theoretical approach for active systems

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We introduce a mesocopic modeling approach for active systems. The continuum model allows to consider microscopic details as well as emerging macroscopic behavior and can be considered as a minimal continuum model to describe generic properties of active systems with isotropic agents. The model combines aspects from phase field crystal (PFC) models and Toner-Tu models and can be seen as an extension of the active crystal model [1] and reads

$$\begin{aligned} \partial_t \psi &= M_0 \Delta \tfrac{\delta \mathcal{F}_{\text{vpfc}}}{\delta \psi} - v_0 \nabla \cdot (\psi \mathbf{P}) \\ \partial_t \mathbf{P} &= \Delta \left(\alpha_2 \mathbf{P} + C_2 \mathbf{P}^3\right) - \left(\alpha_4 \mathbf{P} + C_4 \mathbf{P}^3\right) - v_0 \nabla \psi - \beta \mathbf{P} \mathbb{1}_{\psi \leq 0} \end{aligned} \tag{1}$$

with the one-particle density field ψ and the polar order parameter $\mathbf{P}$. The results are validated by reproducing results obtained with corresponding agent-based microscopic models [2]. We consider binary collisions, collective motion and vortex formation. For larger numbers of particles we analyze the coarsening process in active crystals and identify giant number fluctuation in the cluster formation process. Cluster formation is shown in Fig 1 for different particle densities ϕ. The results are published in [3].

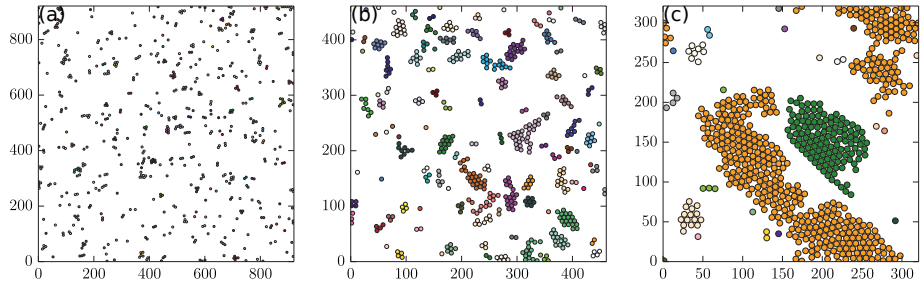

Fig. 1: *Snapshots of systems having different particle density ϕ. Particles with the same color belong to the same cluster. The particles are identified as maxima of the one-particle density field ψ. (a) For $\phi = 0.03$ no cluster is present. (b) ϕ is increased until 0.12 and some clusters appear. (c) We clearly observe two big clusters when $\phi = 0.25$, which move in different directions. The standard deviation ΔN in the mean number of particles N scales as N^α, with $\alpha \approx 0.8$ for $\phi = 0.25$.*

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Dynamics of spheroidal squirmers in Poiseuille flow

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Bacteria such as *E. coli* exhibit a remarkable rheological behavior. On the one hand, the viscosity exhibits a Newtonian plateau at low shear rates, which decreases with increasing concentration. On the other hand, the bacteria exhibit positive rheotaxis, i.e., they swim preferentially upstream next to surfaces. This points toward an intriguing interplay between the swimmer flow field with the surface [1]. An understanding of this behavior is important, for example, for biofilm formation and may also be helpful in applications with bacteria as viscosity modifiers. To analyze the properties of microswimmers in channel flows, we consider spheriodal squirmers [2] with a rotlet dipole embedded in a MPC fluid [3] and study their flow-induced structure and dynamics. Depending on where the thrust is generated, the squirmers are classified as pullers (thrust is generated in front of the organism), pushers (thrust is generated behind the organism), and ciliates (symmetric velocity field). The no-slip boundary condition at a surface combined with the swimmer characteristics (puller, pusher) leads to a preferential alignment parallel (pusher) or perpendicular (puller) to the wall. This applies to both, spherical as well as spheroidal squirmers as long as they are not to close to a surface and the hydrodynamics is determined by the far field. We want to shed light on the influence of near-field hydrodynamic interactions on the swimming behavior of spheroidal squirmers close to surfaces. Our simulations reveal a dependence of the swimming behavior under flow on the shape of the microswimmer. We find positive rheotaxis for spheroidal pushers in narrow channels, which disappears in the limit of zero rotlet dipole strength.

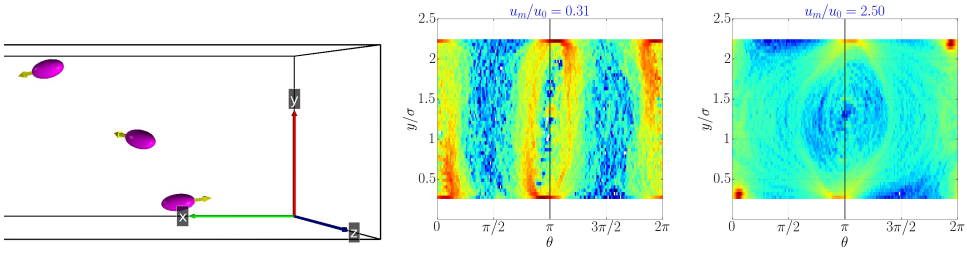

Fig. 1: *Spheroidal pushers displaying upstream motility (swimming in $x-$ direction) in a channel at low shear rates. Probability density function for the pushers' position y/σ within the channel and alignment angle θ along flow direction for low (left) and high (right) flow rates.*

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Hot Microswimmers: Theory, Experiments and Atomistic Simulations

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We study the autonomous motion of a hot Janus sphere using large scale atomistic molecular-dynamics simulations.
The observations can be rationalized by a Markov model that elucidates the underlying non-equilibrium physics of hot Brownian swimming and accurately predicts the velocity fluctuations governed by the entropy production at an effective temperature [1, 2].
Interactions are addressed by analyzing the polarization of a (passive) swimmer in an external temperature gradient.

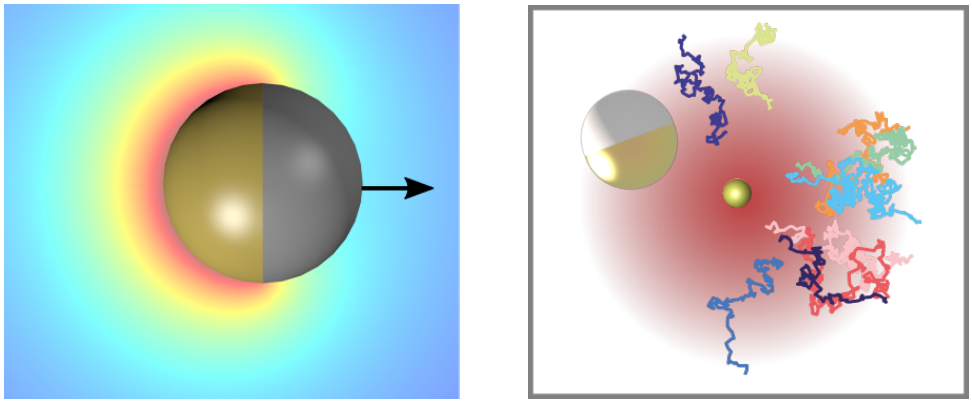

Fig. 1: *Left Panel: Heated two-faced Janus particle inducing an asymmetric temperature field in the surrounding fluid which leads to a self-propulsion. Right panel: Passive Janus sphere exposed to an external temperature gradient created by a single gold nanoparticle. Single Janus particle trajectories are shown.*

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Single particle nano-capillary electrophoretic tracking: numerical considerations

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We present numerical modelling of a new nanofluidic platform for measuring the mobility of charged nanoparticles inside a closed nanocapillary, also under external fields. This experimental method is recently developed by one of us [1] and enables tracking of mobility of a single particle and determining its charge fluctuations, akin to the famous Milikan's oil droplet experiment, for nanoparticles as small as 20 nm and at a measurement rate of several kHz.

To better understand the behaviour of the charged fluid under an external potential, we solve the Poisson-Nernst-Planck-Stokes equations in a system, shown in Fig. 1, that mimics the experiment. Using finite-elements analysis, we calculated the time dependence of the axial velocity of fluid and electric field inside the capillary for various salt concentrations and found a similar behaviour to that observed in the experiment. The bulk fluid velocity decays non-exponentially when the applied voltages at the electrodes is reversed in a step-like fashion. The axial electric field along the pore is also shown to be uniform both axially and radially thus further demonstrating the underlying electrokinetic dynamics inside the nanocapillary.

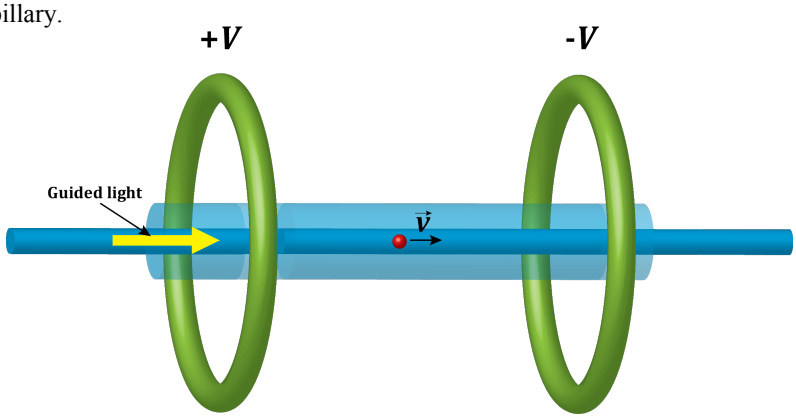

Fig. 1: *Schematic illustration of the computational domain. The deep blue region depicts a charged nanocapillary containing an aqueous solution. The capillary is embedded in a silica matrix (light blue region) and connected to two large electrolyte reservoirs. Two ring electrodes with opposite signs of voltages mimic the experimentally applied external field. The red sphere is a nanoparticle.*

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Dynamics of a linear magnetic "microswimmer molecule"

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A central issue driving the field of active matter is the question whether interacting self-propelled objects in a crowd manage to coordinate their motion, or whether their migration is disordered. These synchronization problems and directed motion of self-propelled objects [1], on the one hand, as well as colloidal compound objects ("colloidal molecules") [2], on the other hand, have already been subject to research. Here, we link these two fields by considering a compound object of colloidal microswimmers. Investigating its relaxation behavior we are particularly interested in the stability of the organized state.
For this purpose, we consider a model system of a three-bead compound of spherical microswimmers connected by springs. A straight configuration is stabilized via magnetic moments carried by the individual swimmers. In addition to that, hydrodynamic flows due to the bead movement [3] and due to the self-propulsion mechanism [4] of the microswimmers are taken into account. The stability of the linear aligned configuration of the molecule, see Fig. 1(a), with respect to small deviations in bead positions and orientations is investigated [5]. The relaxation behavior of the system is found to depend on the self-propulsion strength of the particles with a destabilization of the straight state in the form of a Hopf bifurcation scenario [6]. The center-of-mass motion for the unstable case is shown in Fig. 1(b). Moreover, the system shows hysteresis in the overall conformation as a function of the self-propulsion strength.

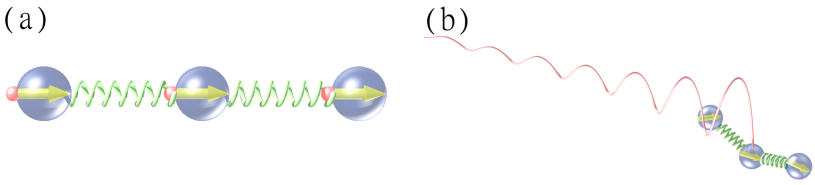

Fig. 1: *(a) Three-bead microswimmer molecule. The spherical microswimmers interact via magnetic and mechanical forces as well as hydrdynamic flows due to their movement and their self-propulsion mechanism. (b) Center-of-mass movement for the swimmer molecule. Crossing a certain threshold of self-propulsion strength, the straight trajectory destabilizes in a corkskrew-like way.*

As a next step, one could extend the system to a larger number of particles, more complicated particle geometries, or, as another possibility, include external flow fields.

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Morphology of Fast Magnetic Micro Propellers

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A well-established way to actuate and control micro robots is the utilization of rotating magnetic fields. Until recently the design of such micro propellers was mostly based on an example found in nature: rotating helical bacteria flagella. The rotational-translational coupling, and therefore the propulsion speed, depends on the geometry of the propeller, so that the search for the maximum speed is a search for the optimum propeller shape. Recent studies indicate that slender shapes with one helical turn in theory might be candidates for effective micro propellers. Vach [1, 2] showed that producing random shaped nanostructures might be a way to test different geometries for finding effective propellers. Hydrothermal Carbonization was used to create random shaped propellers of iron oxide nanoparticles. They were actuated in a rotating magnetic field and while a wide range of dimensionless speeds was found (Fig.1 a), the highest speed value was up to 190, setting a lower limit for the maximum speed for now (Fig.1 c). By using an optical tomographic technique, it is possible to get 3D reconstruction (Fig.1 b-e) and therefore to analyze the correlation between the geometric features and the propulsion speed of a propeller. In my work I will further investigate the morphologic characteristics of the very fast random shaped propellers using optical high speed microscopy, 3D reconstruction and microfluidic systems to filter propellers according to their properties. This knowledge might be used to formulate design guidelines for a targeted fabrication of micro propellers.

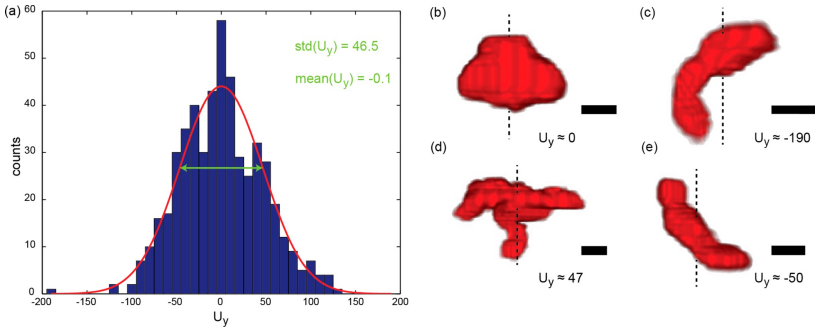

Fig. 1: *Dimensionless speed distribution and reconstructed shapes [2].*

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External control strategies for self-propelled particles: Optimizing navigational efficiency in the presence of limited resources

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We experimentally and numerically study the dependence of different navigation strategies regarding the effectivity of an active particle to reach a predefined target area. As the only control parameter, we vary the particle's propulsion velocity depending on its position and orientation relative to the target site. By introducing different figures of merit, e.g., the time to target or the total consumed propulsion energy, we are able to quantify and compare the efficiency of different strategies. Our results suggest that each strategy to navigate towards a target has its strengths and weaknesses, and none of them outperforms the other in all regards. Accordingly, the choice of an ideal navigation strategy will strongly depend on the specific conditions and the figure of merit which should be optimized.

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Curvature-guided motility of microalgae in confinement

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The characteristics of active fluids, such as suspensions of biological microswimmers, may not only originate from the mutual interactions between the constituents, but also from interactions with interfaces and confining walls. Such interactions have raised interest among researchers from several perspectives: The natural habitats of many living microorganisms are complex geometric environments, rather than bulk situations. In addition, the confinement and, in particular, the exposure to solid/liquid interfaces is expected to play an important role with regard to the adhesion of cell populations and, subsequently, the formation of biofilms. The influence of interfaces on the dynamics was recognized as an important factor, and there are differences in the way that pusher-type swimmers (e.g. *E. coli*) and puller-type swimmers (e.g. *C. reinhardtii*) behave close to interfaces. Using experiments and simulations, we report on the dynamics of single puller-type swimmers in 2D circular microfluidic compartments. We find that the radial probability distributions of trajectories display a characteristic wall hugging effect (see Figure), where swimmers remain trapped at the concave interface. This effect becomes strongly amplified upon decreasing the size of the circular compartment; in fact, its significance is found to scale as the curvature of the compartment walls. For trajectories in the vicinity of the concave wall, an alignment of the local swimming direction with the local wall tangent is observed. In contrast, the swimmers tend to scatter off convex interfaces with short interaction times. Based on geometric arguments involving the swimmer's persistence length and the size of the compartment, we explain this entrapment effect at concave interfaces.

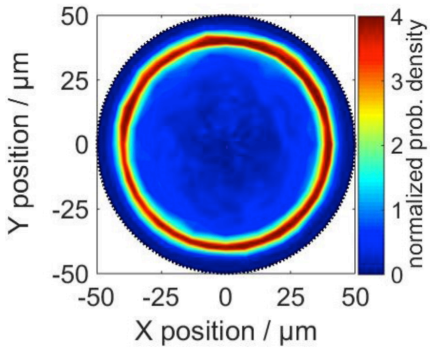

Fig. 1: *Probability density of the position of the microswimmer in circular microfluidic compartments.*

Interaction of chemically active particle with a planar wall: dependence on the model activity

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Chemically actives particles are able to move in a fluid by means of promoting surface chemical reactions within their environment. Usually these reactions take place asymmetrically on their surface, e.g., parts of the surface release some molecules (or ions), some parts consume them, and some parts are inert. Therefore, gradients in composition of the solution occur. Interaction of molecules (or ions) with surface of the particle leads to gradients in osmotic pressure along the surface and thus flow which is accounted via a phoretic slip velocity on the surface. This mechanism enables such active particles to propel in the fluid [1, 2].

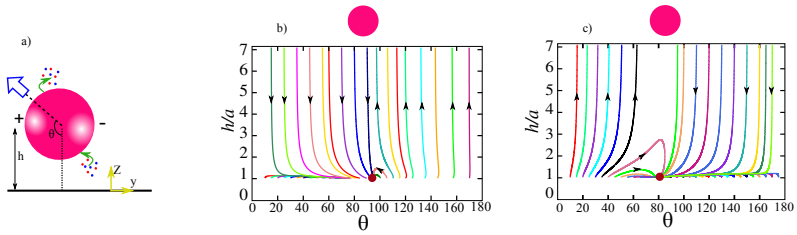

Fig. 1: *a) A chemically active particle near an inert planar wall. The particle is immersed in an electrolyte and releases ions (blue and red dots) at the pink side ("+") and absorbs them at the cyan side ("-"). b, c) Phase plots of active particle with b) half-coverage and ratio of phoretic mobilities $b_-/b_+ = -5$, and c) low-coverage and $b_-/b_+ = 1/5$. In both cases there is a sliding attractor (the red dot).*

Ref. [3] evidenced "sliding" and "hovering" wall-bound states for a kind of active particle interacting with a wall. Here, we generalize that study by investigating the effects due to chaning the activity function. We consider a charged spherical active particle immersed in an ionic solution emitting and absorbing ions asymmetrically through its surface (Fig. $1(a)$). The phoretic mobilities, i. e., the coefficient connecting the gradient of solute concentration to the phoretic slip, are also assumed to be distinct: $b_\pm$, respectively. We study the motion of such particle near an uncharged wall as a function of coverage (the fraction of the surface occupied by the emitting side) and of the ratio of phoretic mobilities b_-/b_+. Example phase plots for half- and low-coverages are illustrated in Fig. $1(b, c)$. These evidence the existence of sliding states fixed points, similar to the ones reported in [3]. Additionally, we have investigated the case in which there is also a direct interaction, manifesting as a repulsive force between the wall and the particle, which is short ranged. By varying the magnitude F of this force we have determined the depedence of the fixed points on F and identified sliding $\rightarrow$ hovering transitions.

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Efficient shapes for microswimming: from three-body swimmers to helical flagella

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We combine a general formulation of microswimmmer equations of motion with a numerical bead-shell model to calculate the hydrodynamic interactions with the fluid, from which the swimming speed, power and efficiency are extracted. From this framework, a generalized Scallop Theorem emerges. The applicability to arbitrary shapes allows for the optimization of the efficiency with respect to the swimmer geometry. We apply this scheme to `three-body swimmers' of various shapes and find that the efficiency is characterized by the single body friction coefficient in the long-arm regime, while in the short-arm regime
the minimal approachable distance becomes the determining factor.
Next, we apply this scheme to a biologically inspired swimmer that propels itself using a rotating helical flagellum. Interestingly, we find two distinct optimal shapes, one of which is fundamentally different from the shapes observed in nature (e.g. bacteria).

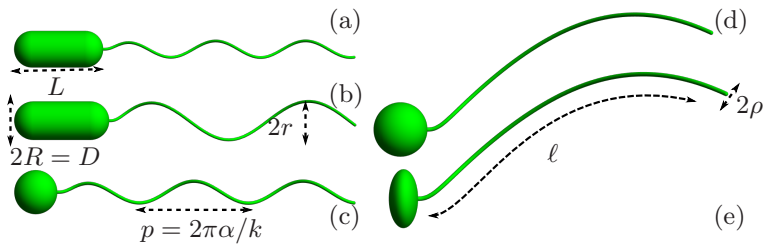

Fig. 1: *Swimmers with rotating helical flagella of various geometries are considered in this work.*

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Hydrodynamically Tuned Phase Separation of Spherical Microswimmers

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Active motion of microorganisms and artificial microswimmers is relevant both to real world applications, as well as for posing fundamental questions in non-equilibrium statistical physics. A striking feature of their collective behaviour is that for sufficiently strong self-propulsion dense clusters coexists with a low-density disordered surrounding. Due to the required computational effort, active particles are often modelled by neglecting the full hydrodynamic interactions. However, real microswimmers, such as ciliated microorganisms, catalytic Janus particles, or active emulsion droplets, employ propulsion mechanisms reliant on hydrodynamics. Thus nearby microswimmers can affect each other's velocity and orientation, which can potentially alter their collective behaviour.

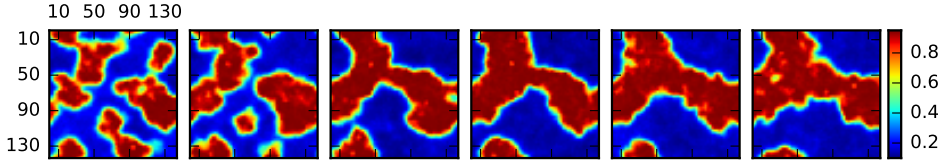

Fig. 1: *Temporal evolution of the local density function (high density regions represented in red, while low density regions are represented in blue). Each successive frame represents the system after 2 million further time steps (from left to right).*

We examine the influence of the full hydrodynamic interactions (by employing the MPCD [1] simulation technique) on the motility-induced phase separation of spherical microswimmers in quasi-2D confinement. For a range of total densities and Péclet number, the system decomposes into a dilute and a cluster phase, which then coarsens over time, *cf.* Figure 1. We follow up on previous work [2] by quantitatively resolving the phase-coexistence regime. This has allowed us to quantify the impact of hydrodynamic interactions on phase-separating microswimmer systems. The most striking difference with the phase diagram of active brownian particles [3-4], is that the total density effects the density of the constituent phases, viz. a higher overall density of the entire system results in a lower dilute-phase density. Furthermore, we explore the effect of pushers or pullers on the coexistence region. For instance, strong pushers or pullers suppress phase separation, by increasing the critical Péclet number.

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Quantitative approach to modular microswimmer

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Modular microswimmer is made of an electrolyte releasing reservoir particle (RP) settled to a charged surface. It may be realized in various ways, e.g. if RP is placed in a dispersion of colloidal spheres (non-active particles or NAPs) a moving complex consisting of the reservoir particles followed by the colloids is formed [1]. The motion mechanism is based on the formation of the electrolyte gradient around the RP. Within this gradient a local electric field is formed, which gives the rise to the electro-osmotic solvent flow along the charged substrate and electro-phoretic motion of NAPs.

To quantify the swimming behaviour of the complex we started with the characterization of the electrolyte gradient. The especially developed microphotography technique was applied to measure the gradients with high temporal and spatial resolution.

The electro-kinetic response of the substrate and NAPs to the field was studied with the integral Doppler velocimetry set up. It allows simultaneous detection and quantification of electro-osmotic and electro-phoretic phenomena [2, 3]. We've implemented a novel experimental cell with exchangeable walls to study influence of different substrate types on the solvent flow.

The length scale of the inner-complex interactions between RP and NAPs was studied with PIV. The range dependent velocity of the non-active particles reflects changes in the forces acting on the non-active particles.

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A Computational Model of Ciliary Beating

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Cilia, flexible hairlike appendages located on the surface of a cell, play an important role in many biological processes including the transport of mucus in the lungs and the locomotion of ciliated microswimmers. Cilia self-organize forming a metachronal wave that propels the surrounding fluid. To study this coordinated movement and motivated by the oscillator model in [4], we model each cilium as an elastic, actuated body whose beat pattern is driven by a geometric switch where the beat angle switches between two 'traps', driving the motion of the power and recovery strokes. The cilia are coupled to a viscous fluid using a numerical method based upon a centerline distribution of regularized Stokeslets [3]. We first characterize the beat cycle and flow produced by a single cilium and then investigate the synchronization states between two cilia [1, 7]. To examine mucociliary transport, we include a viscoelastic network above many cilia [6, 5, 2].

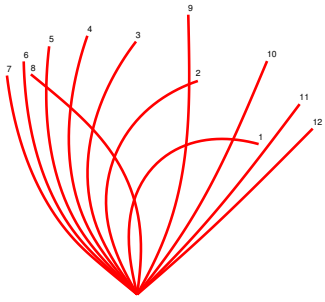

Fig. 1: *A beat cycle of a computational cilium.*

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Collective behaviour of light driven active particles

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Active colloids [1] exhibit unique non-equilibrium collective behaviours [2-3], that ranges from crystallization to microscale turbulence. Here, we have fabricated photo-catalytically active TiO_2 Janus particles that split hydrogen peroxide upon illumination by 365nm UV light. The asymmetric surface coating causes them to propel by self-diffusiophoresis and nucleate colloidal crystals of passive tracers around them. This effect can be reversibly

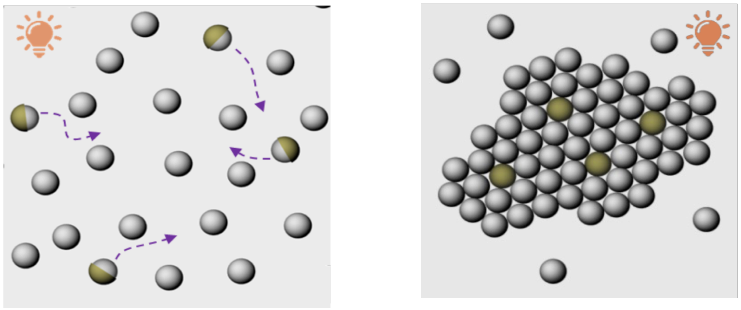

Fig. 1: *Light-controlled crystal formation in active-passive particles*

controlled by the intensity of light stimulus. We study how these light active particles form crystals and demonstrate a hydrodynamic application for such a colloidal system.

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Thermo-Osmotic Flows in Thin Films

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It is so far well known that concentration gradients or gradients in molecular composition generate an osmotic pressure on semi-permeable membranes. Such osmotic pressures are of fundamental relevance for life and have many applications reaching up to electrical power generation.
We show that in an equivalent way a non-uniform heat content along a solid liquid interface, as in our example generated by an optically heated gold nanoparticle, results in a thermo-osmotic flow [1]. We study this flow field in a thin water film between two glass cover slides with two different surface coatings by a single-particle tracking experiment.
The resulting flow fields do closely match the numerical and analytical flow fields, and even deliver quantitative values for the thermo-osmotic mobilities of the two surfaces. Our result state that any solid/liquid interface with a temperature gradient is subject to a thermally induced creep flow, which in a complex way depends on the interfacial interactions. This flow influences the dynamics of molecules and particles in particular in thin film geometries.

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Emergent interactions in non-equilibrium suspensions

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We present a simple framework to compute the interactions between inclusions in out of equilibrium solvents, i.e. suspensions of active particles or granular driven particles. The character of the interaction between inclusions is of key importance in such systems thus it determines the ability of the suspension to segregate intrusive particles.

We present a model of active, self-propelling ans self-aligning, particles. The ability of the particles to align and swim is ubiquitous in bacterial or autophoretic suspensions. By pinning a pair of inclusions we can directly measure the mean values of their effective interparticle force.

A systematic exploration of the pair force as a function of the competition between propulsion and alignment allows us to identify three different regimes. We report a change in the qualitative behaviour of the forces, compared to thermal equilibrium. Specifically, tuning the particle activity and aligning dimensionless numbers, we can go from a thermal depletion scenario [1] to a repulsive, as reported by [2] and identified by [3], to a new attractive regime.

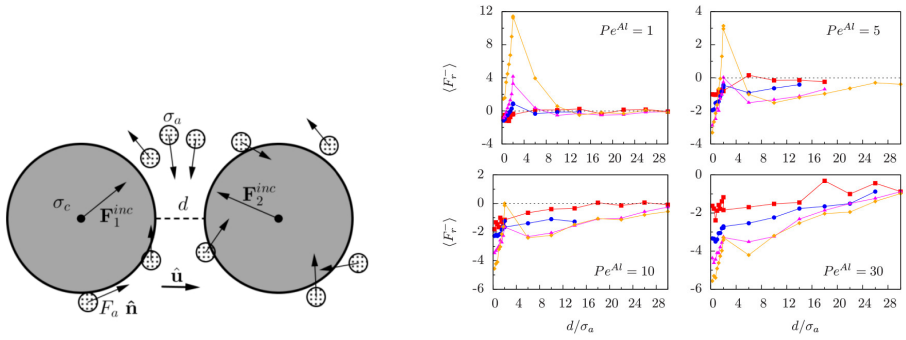

Fig. 1: *The left picture is a sketch of the system. On the right a plot of the mean radial force between inclusions as a function of the dimension less parameters that control activity Pe^{Ac} and alignment Pe^{Al}*

In addition to the fine tuning of the force we report an emergent long-range interaction. This feature is of special interest since the interactions in the model are characterized by a finite range, the diameters of the particles. Since the system is in a dilute regime, $\phi \approx 0.2$, the origin of the interaction may be attributed to the out of equilibrium nature of the system.

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Swimming behavior of magnetotactic bacteria

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Magnetotactic bacteria swimming behavior is determined by various parameters. First of all, these bacteria produce a chain of magnetosoms that acts like a compass, passively orienting the bacterium in the earth magnetic field. Thus the bacteria actively swim mostly in one dimension along the field lines, with probably run and reverse motion. Second, they perform aerotaxis to reach the oxic-anoxic transition zone, situated at the bottom of lakes and seas. Swimming along the field lines helps them to find the zone easily, since the oxygen gradient is antiparallel to the earth magnetic field lines in our hemisphere.
To better understand their swimming behavior we study it through a simulation. The chosen model is general, and can be applied to any swimming behavior. It consist in an active brownian particle model, in which there is a run state and a change of direction. Moreover in this model are included forces and torques due to interaction with external fields (for ex. the magnetic field), and also chemotaxis (for ex. aerotaxis). I will present the general model and show how it can be used to describe *E. Coli* run and tumble swimming behavior, and how it can be applied to magnetotactic bacteria.

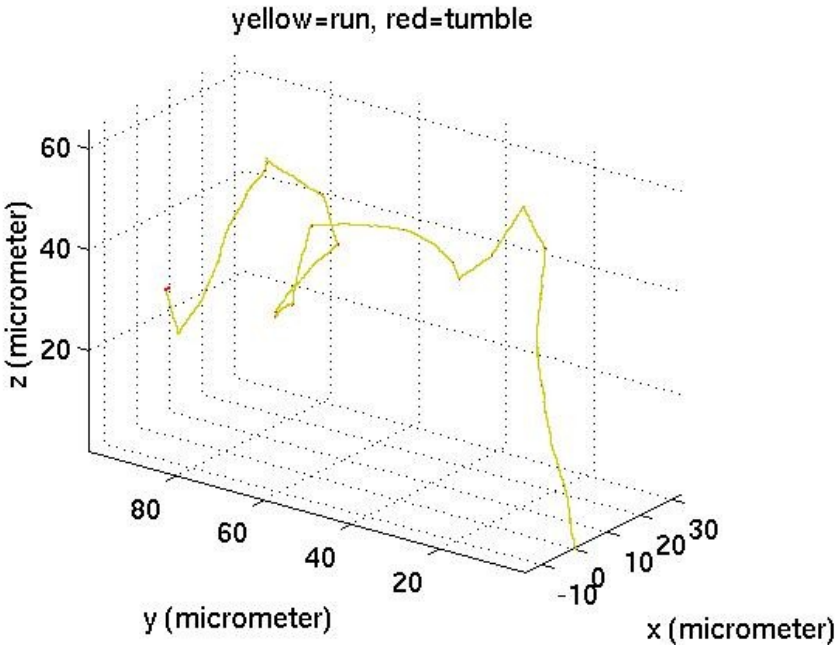

Fig. 1: *E. Coli run and tumble behavior from simulation.*

Fourier Image Analysis reveals the chemotactic behavior of populations of swimming bacteria at high density

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During infection or swarming, swimming bacteria have to be motile in a crowd of their peers, where physical interaction matters, while still having to perform essential functions like chemotaxis. Recent developments in Fourier image analysis have significantly improved the accuracy and processing time in measuring the dynamics of microorganisms. Using a new method (φDM) which allows the fast accurate measurement of collective drifts using video-microscopy, we investigated the effect of bacterial cell density on their chemotactic efficiency. The motion of thousands of planktonic flagellated bacteria subjected to steady gradients of attractants, created in millifluidic devices, is recorded using low-magnification video-microscopy. Subsequent Fourier method based computer analyses of the movies enables to measure the collective and local drift velocity of the population of cells, without individually tracking them [1].
We investigated the effect of increasing the cell density on the chemotactic drift of *E coli* suspensions. Interestingly the drift was found to decrease as the cell density increases, while the swimming speed keeps constant, down to almost zero at a density at which swirling patterns reminiscent of swarming behaviors arise. Using a particle image velocimetry analysis method, we found increasing correlations in the motion of the bacteria, correlating with the decrease in chemotactic drift. The physical interactions between cells which induce early reorientations and temper with the temporal comparisons necessary for performing chemotaxis are a likely explanation for this effect, which we investigate using computer simulations and modeling. This effect has important implications for our understanding of the role of chemotaxis in the various life styles of bacteria, especially during bacterial swarming.

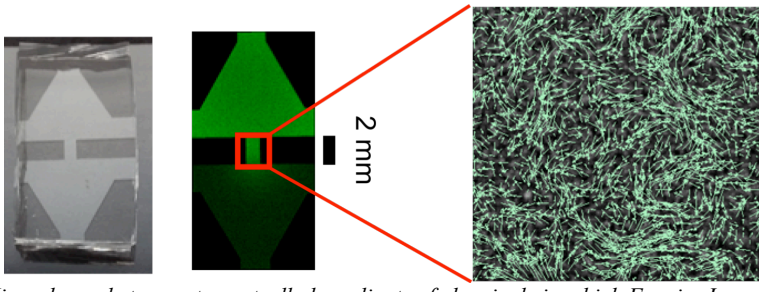

Fig. 1: *Microchannels to create controlled gradients of chemicals in which Fourier Image Analysis reveals the collective swimming behavior of thousands of bacteria.*

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Flagellar flows around bacterial swarms

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Flagellated bacteria on nutrient-rich substrates can differentiate into a swarming state and move in dense swarms across surfaces. A recent experiment measured the flow in the fluid around an *Escherichia coli* swarm (Wu, Hosu and Berg, 2011 Proc. Natl. Acad. Sci. USA **108** 4147). A systematic chiral flow was observed in the clockwise direction (when viewed from above) ahead of the swarm with flow speeds of about 10 μm/s, about 3 times greater than the radial velocity at the edge of the swarm. The working hypothesis is that this flow is due to the action of cells stalled at the edge of a colony which extend their flagellar filaments outwards, moving fluid over the virgin agar. In this work we quantitatively test his hypothesis. We first build an analytical model of the flow induced by a single flagellum in a thin film and then use the model, and its extension to multiple flagella, to compare with experimental measurements.

Janus microswimmers at oil-water interfaces

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Autonomous microswimmers hold a tremendous potential to overcome transport issues that play a key role in many biological, medical or mechanical applications reaching down to the nanoscale. We study the behavior of active Pt-coated particles swimming within the plane of a liquid-liquid interface. The colloids are propelled due to the catalytic decomposition of hydrogen peroxide dispersed in the water phase [1]. Whereas propulsion speeds are comparable to those measured in bulk, the particles exhibit an enhanced directionality due to the pinning of the three phase contact line [2]. To artificially increase the particle "tumbling rate" we create a two-dimensional environment that consists of loosely-packed colloidal lattices. The active particles orbit around individual "passive" colloids of the crystalline structure and hop between them stochastically. By controlling the lattice spacing and the particle speed we tune the effective diffusivity of the swimmers in the lattice. Finally, contact angle measurements reveal that the active motion is strongly affected by the immersion depth of the Janus colloids in the oil phase. Particles with a small contact angle (hydrophilic case) propel fast and see the crystal as a lattice of hard obstacles whereas particles with a large contact angle (hydrophobic case) behave as part of the lattice and deform it while undergoing active motion.

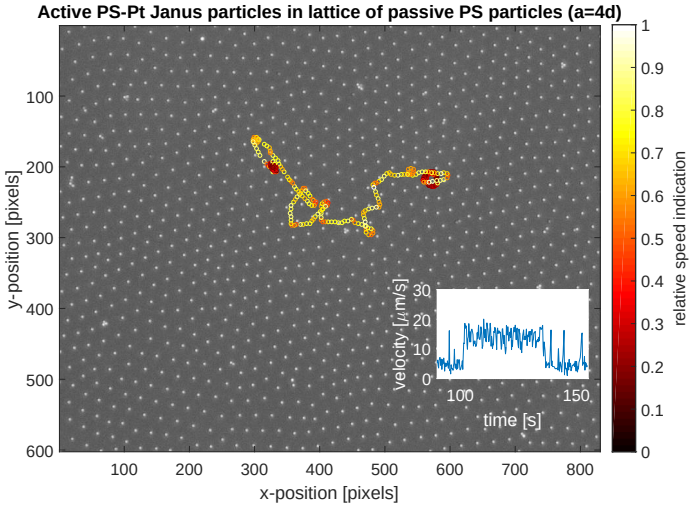

Fig. 1: *Pt-coated Janus particle (d=2.8 μm) that self-propels through a lattice of passive PS particles of the same size at an oil-water interface. Initially the active Janus particle is held by a cluster, which is also the final state in this picture. While interacting with the individual lattice points, the particle is slowed down and reorientation is enhanced compared to the case of freely moving actives.*

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Swimming through shell buckling

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For a few years, microswimmers have mobilized increasing attention and research forces. This is due to fundamental motivations to understand mobility at small scale, together with an interest towards applications such as drug delivery or the challenging build-up of miniaturized labs-on-a-chip or nanorobots. “Swimmers” is a wide terminology, which includes both motion of rigid bodies and motion through body deformation. Put aside a few exceptions [1], most of artificial microswimmers are in fact rigid bodies.

Our ultimate purpose is to realize fully artificial microswimmers, which would be robust and available in large quantities. The swimmer candidate we investigate is a simple thin polymer encapsulated bubble, propelled through the buckling of its shell and actuated by acoustic or ultrasonic pressures.

Previous works [2, 3] showed that shell deformation happens through the sudden appearance of a depression, with a size determined by the thickness of the shell and its radius. This symmetry breaking generates a first-order transition with hysteresis. Indeed, re-inflation allows to observe shapes non attainable during deflation. This hysteresis naturally fulfills the non-reversibility of the deformation, which is a pre-requisite for swimming at low Reynolds number.

To study individual swimmer dynamics, we used a simple macroscopic system using a thin rubber ball which is submitted to external pressure cycles. Through direct visualization, we can measure all external forces and deduce the energy released during the buckling and de-buckling of the ball and its displacement during a pressure cycle.

These results are correlated with the velocity field obtained by using the PIV technique.

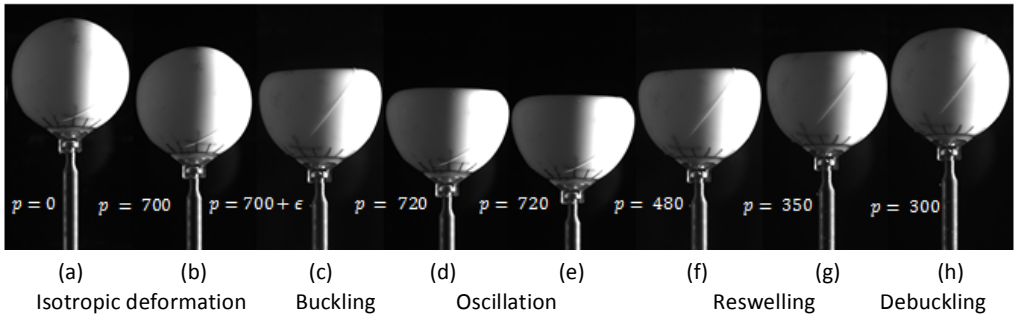

Fig. 1: *Evolution of the ball’s shape during a cycle of pressure (p in mbar).We can directly retrieve all forces from the displacement of the spring attached to the ball.*

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Mean–field theory for the collective dynamics of active particles at a fluid interface

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We study theoretically the dynamics of a monolayer of catalytically active particles trapped at a fluid interface. The chemical activity of the particles induces gradients in the concentration of some chemical that, in turn, cause an heterogeneous surface tension and, consequently, Marangoni flows. This provides a driving force for the monolayer dynamics in addition to those present in the analogous configuration for chemically passive particle. Of particular interest is the comparison of the advection by the Marangoni flow (a hydrodynamic effect driven by surface tension) with the motion induced by the capillary forces (due to surface tension), properly corrected to account for anomalous diffusion in monolayers (a purely hydrodynamic effect [1, 2]). Because the effective pair interaction associated to each of these effects decays with separation in the same fashion for colloidal monolayers, there arises a nontrivial competition which shows up in different dynamical regimes.
We combine the models developed separately for the dynamical evolution under capillary forces [3], under self–induced Marangoni flows [4], and for anomalous diffusion in monolayers [1]. All these models are of a mean–field type because of the long–ranged nature of the forces. The conclusions can be summarized in a diagram in the parameter space spanned by the capillary length λ_0 (setting the range of the capillary forces), the hydrodynamic length $L_{\rm hydro}$ (setting the crossover to anomalous diffusion [1]), and the time scales $T_{\rm jeans}$ (for the capillary instability [3]) and $T_{\rm surf}$ (for the advection by the Marangoni flow [4]). In particular, the chemically induced Marangoni flows can prevent the collapse of the monolayer under its own capillary attraction.
Finally, we provide numerical estimates for the values of the parameters in experimentally relevant configurations and discuss the predictions on the observability of the dynamical regimes.

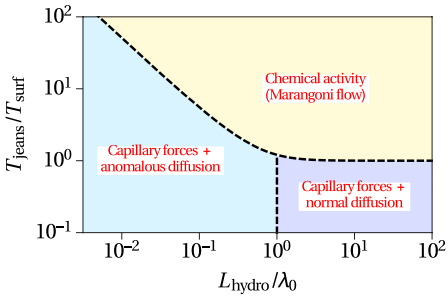

Fig. 1: *The diagram shows the dominant physical effects that drive the dynamics of the colloidal monolayer depending on the value of the relevant parameters.*

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Dynamics of Collective Cell Motility

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Collective cell migration plays a driving role in various phenomena spanning from pattern formation during embryonic development to wound healing and tumor invasion in cancer. Recent experiments have shown that, during the collective migration of cells, as cell density increases due to proliferation, migration slows down and yet the fastest cells move together in an increasingly cooperative manner, reminiscent of glassy dynamics [1, 2]. These glass-like dynamics, which has been observed in the behaviour of motile tissues at high densities, is accompanied with caging and dynamical heterogeneities [3]. In this work, we develop a model of deformable, motile cells to study confluent monolayers. We analyse the properties of cell monolayers to gain insight into the dynamics of collective cell behaviour. We observe a slowing down of dynamics, as a function of cell density, accompanied with increasingly cooperative motion at higher densities in accordance with the experimental results reported in the literature.

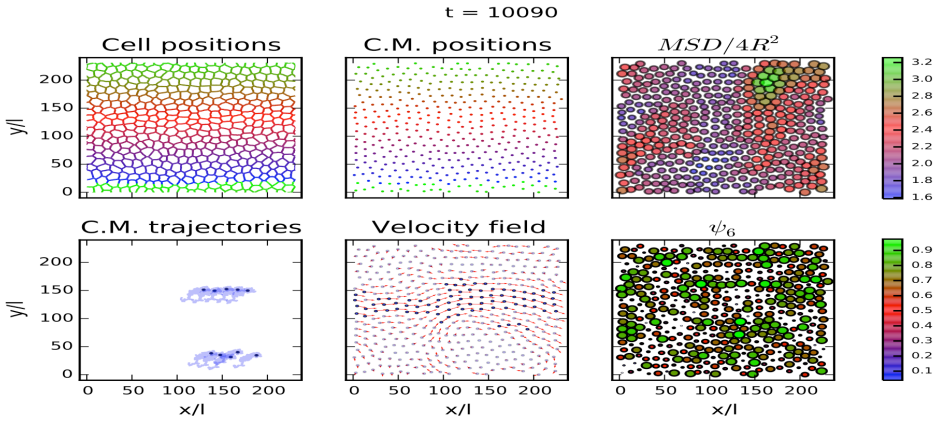

Fig.: *Behaviour of the cell monolayer at a packing fraction of 0.97.*

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Conformational properties of active semiflexible polymers

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Active motions of filamentous biopolymers are prevalent in living cells and are mainly driven by various types of molecular motors [1]. Such motors often move and transfer forces along biopolymers, which are well described as semiflexible polymers.
Here, we present analytical results for the conformational properities of flexible and semiflexible polymers exposed to active noise. For the description of the polymer, we adopt the continuous Gaussian semiflexible polymer model. Activity is incorporated by adding a self-propulsion velocity such that every point of the polymer is independently propelled in directions changing in a diffusive manner (cf. Fig. 1). Furthermore, the finite polymer extensibility is taken into account which turns out to be essentially for the polymer conformations [2]. Our calculations predict a strong dependence of the polymer internal relaxation times on the activity. The conformational properities of semiflexible polymers, determined via the relaxation times, exhibit a crossover from a bending elasticity dominated dynamics to the flexible polymer dynamics with increasing activity. This leads to a significant noise-induced polymer shrinkage over a large range of self-propulsion velocities (cf. Fig. 1) [3]. For large activities, the polymers swell and their mean square end-to-end distance approaches $L^2/2$, where L is the polymer contour length.

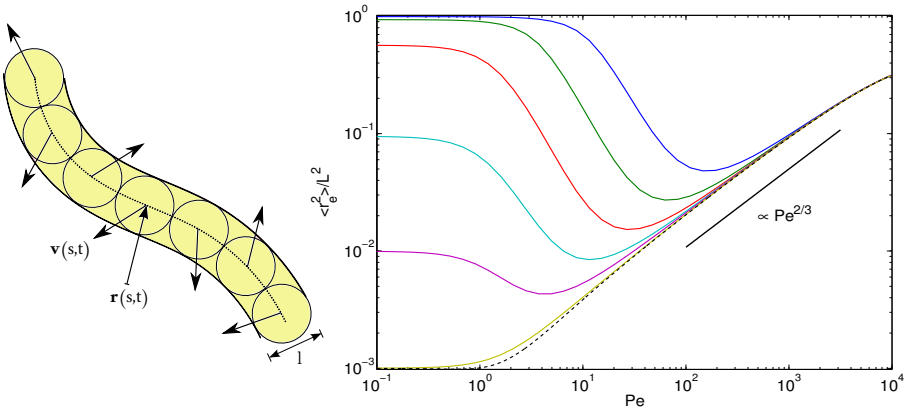

Fig. 1: *Active polymer model and the mean square end-to-end distances as function of the Péclet number Pe for the polymer stiffnesses $pL = 10^3$, 10^2, 10, 1, 10^{-1}, and 10^{-2} (bottom to top at $Pe = 10^{-1}$). Here, L is the polymer length and $l_p = 1/2p$ is the persistence length. The dashed line represents the flexible limit, $pL \to \infty$, with an asymptotic of $\langle r_e^2 \rangle \propto Pe^{2/3}$ for moderate Pe.*

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Self-Propelled Semiflexible Fillaments

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Filaments, like microtubules and actin, propelled by motor protein carpets in motility assays, are semiflexible or flexible, and can therefore change their shape due to active and thermal forces [1]. Also, chains of self-propelled Janus colloids are highly flexible. Therefore, we investigate the role of flexibility on the conformations on self-propelled filaments.
The model consists of a semiflexible worm-like chain that is propelled tangentially along its contour. Already at infinite dilution, the flexibility results in a rich phase behaviour where the filament can coil-up into a very compact structure [2]. Attached to a rigid load, the filament undergoes a buckling transition leading to rotating and beating states [3]. When many filaments interact, we observe clustering similar to self-propelled rods. However, again flexibility strongly effects the observed dynamics. Structure, dynamics and Interactions are different, not only quantitatively, but also qualitatively new phenomena are observed.

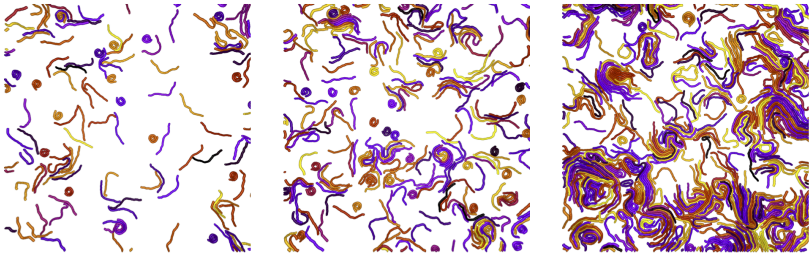

Fig. 1: *Ensembles of self-propelled filaments show show very distinct features. In particular coiling of individual filaments at low density, and swirl-like clusters at higher density.*

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Self-propelled clusters

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Self-propelled clusters are involved in many technological applications such as in material science biotechnology, and nanotechnology, understanding their interaction with the fluid that surrounds them is of a great importance. We present results of swimming velocity and energy dissipation obtained through Stokesian dynamics simulations of self-propelled clusters. The clusters are of diffusion limited aggregates (DLA), consisting of force- and torque-free spherical particles. The number of particles per cluster ranges from 100 to 400, and with two fractal dimensions of 2.1 and 2.4. The clusters are self-propelled by imposing an explicit gait torque applied in the y direction. The results of the computer code had been verified against the numerical and experimental results available in the literature. It is found that the swimming velocity of the cluster and the energy dissipation are strongly dependent on the number of particles in the cluster and its fractal dimension. The swimming velocity shows a non-linear variation with the number of particles as shown in Figure 2a, which indicates that at a certain conditions clusters with higher number of particles can swim faster than those with lower number of particles. However, the energy dissipation of the due to the swimming of the clusters is increased linearly as the number of the particles is increased.

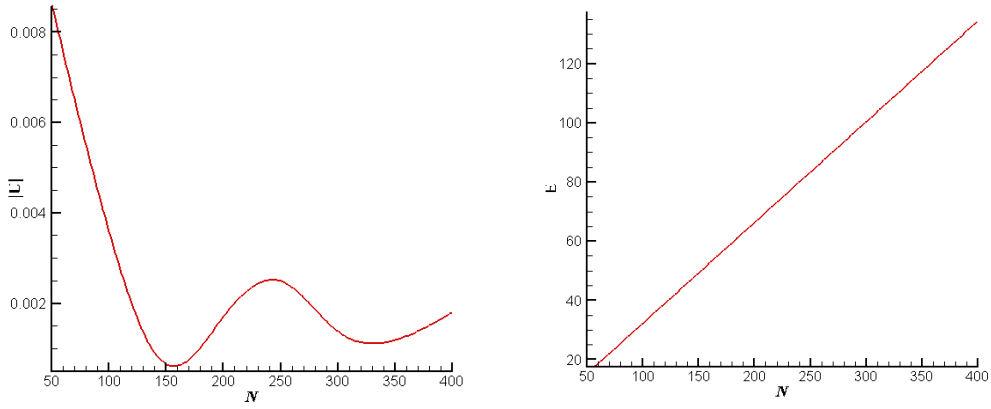

Fig 1 (a) *The variation of the swimming velocity with the number of the particles of the cluster for fractal dimension of 2.4* ***(b)*** *the variation of the energy dissipation for the same conditions as* ***(a)***.

Bead-spring microswimmers in a MPCD fluid

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Bead-spring structures undergoing cyclic shape changes in a viscous liquid can serve as model systems for artifical microswimmers. These cyclic shape changes can be induced by expansion and contraction of springs and serve as a swimming motion.
Using multi-particle collision dynamics, we simulate different swimmer shapes and show that cyclic changes of linker lengths can give rise to a net swimming motion. The model can be generalized by including more beads and represents a step towards the simulation of bigger capsule-like swimmers, which propel by cyclic swelling and shrinking.

In-plane collisions between chemically active particles

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Micron-sized particles with catalytically active coatings on part of their surfaces can move within a liquid solution by promoting chemical reactions in the solution. For example, the gradients of chemical species around the surface of the particle, can give rise to "phoretic" slip, due to their interaction with the surface of the particle, and leads to self-diffusiophoresis. When two such active particles approach each other, the distributions of solutes in the vicinity of the particles overlap, which modulates the phoretic slip distribution. Effective interactions arise due to this complex coupling between hydrodynamics and distribution of solute particles [1-3].
Here, we study in-plane collisions between two identical, chemically active, spherical particles. We present and discuss the outcome of such collisions as a function of the catalyst coverage and the relative orientation and separation between particles. For catalyst coverages above a certain threshold, we find that in the case of head-on collisions a stable steady state emerges, in which the self-propelled motion is balanced by the hydrodynamic repulsion. (See Fig. 1)

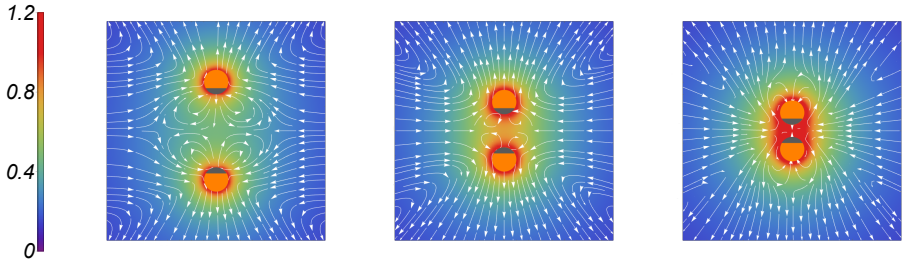

Fig. 1: *Two particles with most of their surface covered by catalyst (the orange caps) shown at various separations. From left to right: far from each other; in the stable steady state configuration; and very close to each other. The streamlines show the flow field and the color codes the density of solute.*

In this state, the particles are motionless, yet a steady state hydrodynamic flow is maintained. This stable configuration disappears if the phoretic slip at the surface of the particles is clamped to the one corresponding to a particle in bulk ("effective" squirmers), revealing that accounting for the coupling between the solute distribution and the hydrodynamics is essential [4].

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Reversible dynamic assembly of magnetic colloidal clusters

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Populations of motile organisms typically display dynamic assembling patterns and collective motions, universal behaviors that are not fully matched by active synthetic matter yet. Actuated colloidal particles have recently emerged as a model to understand the collective motion of living organisms. In such model systems the populations are, however, typically made up of identical particles, in contrary to biological swarms that consist of non-identical individuals.

One type of actuated colloids is magnetic micropropellers, for which the motion of individual micropropellers has been investigated extensively, but not their collective motion. By using magnetic micropropellers, we show that not only identical helical propellers but also propellers of varying dimensions and morphologies exhibit dynamic assembly patterns. The propellers reversibly assemble into rotating, circular clusters when moving towards an interface (Fig. 1). The cluster formation is thus a generic phenomenon that is not affected by "details" as variability within a group.

In addition, we show that the assemblies of random propellers can also exhibit translational motion (Fig. 1), with larger assemblies moving faster, just like sperm or birds do. This represents a step towards the mimicry of patterns typically associated with living systems. This finding is even more striking considering that the assemblies move with speeds surpassing the speed of the individual units they are composed of, similar to the positive feedback observed in the orientation bias found in several higher organisms.

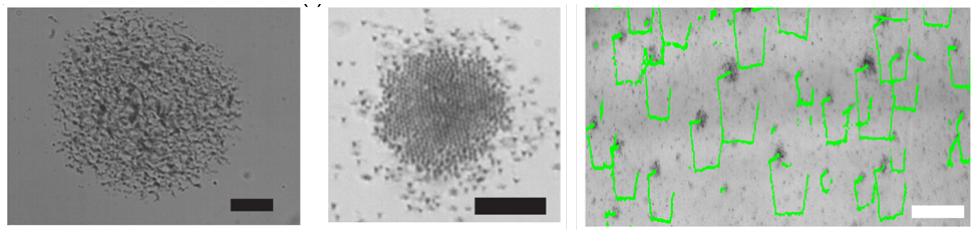

Fig. 1: *At the upper capillary surface, clusters are formed in the case of randomly shaped propellers (left), as well as in the case of identical nanofabricated propellers (center), scale bars are 10 µm. In the left panel, the cluster movement (in green) is shown in the final frame of a video. During the recording, the direction was changed 3 times by 90°. Several clusters have moved in parallel resulting in similar trajectories. Scale bar is 120 µm.*

Photosoap: light-controlled particle assemblies through diffusio-osmotic flows

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With this work, we show how to control particle assemblies through diffusio-osmotic flows induced by light using a *photosoap*. The *photosoap* is a cationic surfactant which incorporates an azobenzene group. Azobenzene molecules undergo reversible *trans-cis* photo-isomerization when illuminated with either UV or visible light leading to substantial changes in physico-chemical properties[1-3] such as a decrease of hydrophobicity, a change of free volume or an increase in the dipole moment. Solution of *photosoap* is mixed with silica particles and pipetted onto a substrate or into a micro channel where the photosoap adsorbs to the surface where an electrical double layer (EDL) is formed with a Debye length λ_D of ~10nm. The focused light induces a local *trans*-to-*cis* isomerization which creates a concentration gradient parallel and close to the solid-liquid interface. A diffusio-osmotic flow builds up in the EDL dragging objects on the surface away from the laser spot (schematic in Figure 1). Under green laser light the flow direction is reversed (in a cis-enriched solution). Particle velocities are on the order of micrometers per second depending on the concentration of the *photosoap*. With these flows we can clean areas, gather objects and structure particle assemblies on flat surfaces; and direct particles along patterned surface (see Figure 2).

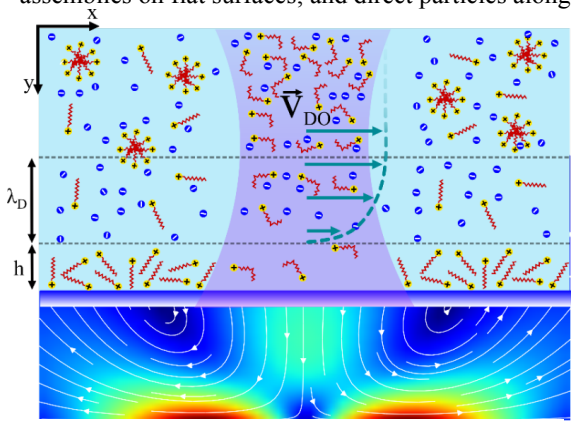

Figure 1: Schematic of light induced outward flow under local UV irradiation. The induced concentration gradient drives a diffusio-osmotic flow in the electric double layer. Below: calculated stream lines of the resulting flow.

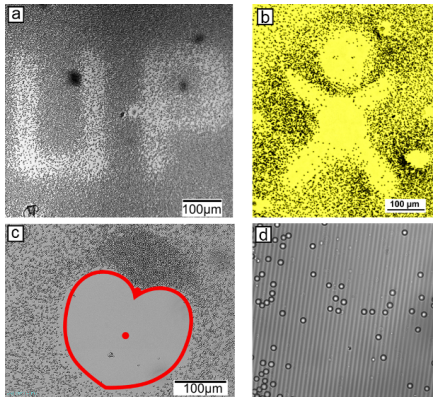

Figure 2: Silica particles in aqueous photosoap solution on a) - c) a flat surface with structured assemblies and d) guided particles on a patterned surface

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Light controlled motility in E. coli

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The bacterium E. coli is a self-propelled machine able to convert chemical energy into mechanical energy at the micron scale. Since the discovery of a genetically engineered E. coli [1] carrying a protein extracted from a γ-proteobacterium, a new source of energy can be used to power the flagellar motors of this type of micromachine: light. Moreover, illuminating with different levels of light it is possible to fine-tune the speed of these bacteria. Modern technologies allow to shape light and mold matter at the micron scale with a high degree of control. The combination of these tools paves the way to many previously unavailable experiments. I will show how this strain of E. coli can be used as motive force for specifically designed rotors and how we can arbitrarily manipulate the spatial distribution of these microswimmers.

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Characterization of asymmetric, viscoelastic micro-swimmers with a propulsion mechanism based on chemical reactions

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Analyzing the motion and self-organization processes of living cells, it is often difficult to differentiate between physical interactions and biological signaling[1]. Such distinctions can easily be performed using artificial particles as model systems. For this purpose microcapsules are especially suitable because they exhibit similar mechanical properties as biological cells. Special ingredients can be used as energy source for chemical reactions that finally lead to the propulsion of these artificial particles. If the energy source is stored in the core of the capsules, each swimmer has its own impellent, and all micro-swimmers move independently from each other. This simple approach exhibits great potential for modelling biological systems.
In a series of experiments we synthesized new agarose-based micro-swimmers, which were driven by the bubble propulsion mechanism. Such motions could be induced through the asymmetric incorporation of potassium permanganate crystals into the pores of the agarose matrix. The chemical reaction between potassium permanganate and the fuel hydrogen peroxide (see formula 1), which diffused from the surrounding water solution into the capsule, leaded to the production of tiny oxygen bubbles.

$$2MnO_4^- + 3\ H_2O_2 \rightarrow 3\ O_2 \uparrow + 2\ H_2O + 2\ MnO_2 + 2OH^-$$

Formula 1: Reaction between potassium permanganate and hydrogen peroxide

The bubble release on one side of the capsules induced the backstroke principle, which pushed the swimmer forward (see figure 1). The speed and swimming time correlated with the size of the swimmer. Due to the reduced density of the anisometric capsules, the swimming process always took place in the vicinity of the water surface. The micro-swimmers randomly changed their directions and their velocity varied gradually. The successive bubble production generated a step-wise locomotion. This special impellent mechanism is usually designed as “active Brownian motion”[2].

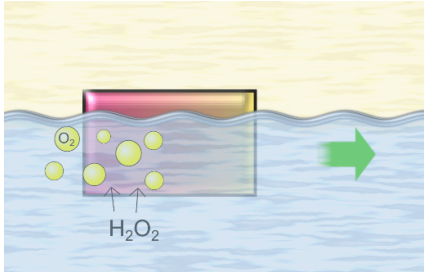

Figure 1: Schematic drawing of the swimming motion of an agarose capsule

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Chemotaxis of Artificial Microswimmers in Active Density Waves

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Taxis is the directed movement of microorganisms due to external stimuli, which allows them to effectively swim towards or away from the stimulus source. Such tactic responses play a crucial role in bacterial locomotion and cell migration, e.g. in finding food or fleeing from poison. Also regarding collective self-organization, tactic effects are assumed to be of major importance. In principle, organisms respond tactically by sensing an external stimulus gradient and adapting their pathways accordingly; however doing so they are also able to swim against the propagation direction of a traveling stimulus wave. This is remarkable, since a simple fore-rear asymmetry argument would suggest the opposite "chemotactic wave paradox"). Here, we study the paradox for artificial self-propelled particles, which lack any sensing mechanism and thus any adaptive capacity; the wave however locally influences the particles' self-propulsive velocity. We show, by means of analytical and numerical methods, that self-propelled particles can actually drift in either direction with respect to the stimulating wave, depending on its speed and waveform. Moreover, chiral swimmers, which move along spiraling trajectories, may drift preferably in a direction perpendicular to the wave propagation. Such a variety of tactic responses is explained with the modulation of the swimmers' diffusion inside the traveling wave pulses.

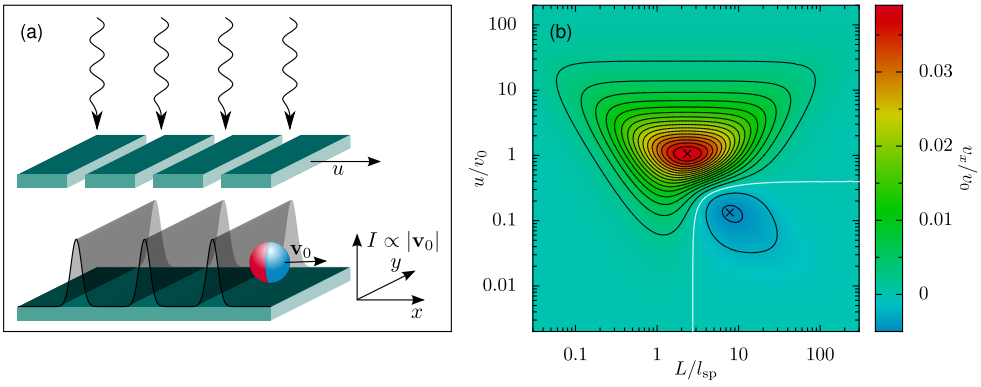

Fig. 1: (a) *Ideal experimental setup of a thermophoretic swimmer diffusing on a planar substrate irradiated by a laser beam. By pulling at constant speed a slit-screen sliding between the laser and the substrate, it is possible to modulate the laser intensity I. Since I is (approximately) proportional to the particle's self-propulsive velocity, this way a series of stimulating wave pulses hitting the particle can be created.* (b) *Longitudinal chemotactic drift v_x of a microswimmer in a sinusoidal train of stimulating wave pulses as a function of the pulse speed u and the wave periodicity L, where $v_0 = |\mathbf{v}_0|$ is the particle's self-propulsive velocity and $l_{\rm sp}$ its persistence length.*

Self-propelled Janus particles in viscoelastic fluids

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The motion of many natural microswimmers, such as bacteria and spermatozoa, commonly takes place in viscoelastic media. The understanding of their swimming mechanisms has triggered a lot of experimental and theoretical work in recent years as well as the development of artificial self-propelled particles. Despite their biological and application-related relevance, most experiments with autonomous synthetic microswimmers have been performed in Newtonian liquids [1], while only a few investigations have focused on the swimming of microorganisms in non-Newtonian fluids [2].

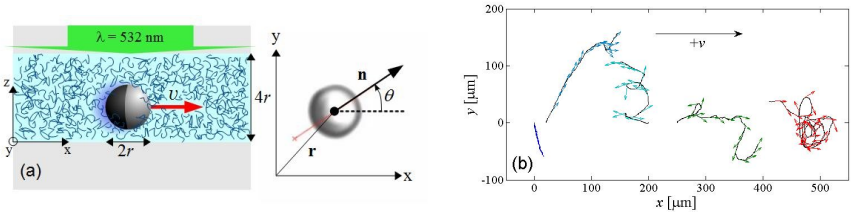

Fig. 1: *(a) Schematic illustration of the self-propulsion of Janus particles by light-induced demixing of the viscoelastic fluid and relevant coordinates for describing the 2D particle's motion. (b) Examples of trajectories of self-propelled particles at different velocities v, increasing from left to right.*

In this work, we experimentally investigate active motion of spherical Janus colloidal particles in a viscoelastic fluid. Self-propulsion is achieved by a local concentration gradient of a critical polymer mixture which is imposed by laser illumination. Even in the regime where the fluid's viscosity is independent of the deformation rate induced by the particle, we find a remarkable increase of up to 2 orders of magnitude of the rotational diffusion with increasing particle velocity, which can be phenomenologically described by an effective rotational diffusion coefficient dependent on the Weissenberg number [3]. Moreover, unlike self-propulsion of Janus particles in Newtonian liquids. we observe a highly anisotropic response in viscoelastic fluids to external biases, e.g. gravity and solid walls in confined geometries, depending on the particle orientation.

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Thermophoresis of Janus Particles near a Polymer Brush Surface: Impact of the Cononsolvency Effect

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Au-polystyrene Janus particles demonstrate a thermophoretic induced motion under laser illumination (λ=532 nm). The plasmons in the gold cap of the particle get excited and cause the particle to create a local temperature gradient. Such out-of-equilibrium condition at the surface of the particle leads to its self-propulsion.

In this study we explore the 2D self-propulsion of Janus particles between two glass substrates. The substrate is functionalized with PNIPAM brushes, and the particles are placed in a binary mixture of water/ethanol. PNIPAM/water/ethanol system exhibits the phenomenon of cononsolvency as the ratio of solvents varies. Upon cononsolvency, the conformation of brush chains changes from a swollen to a collapsed state. Hence, we investigate the thermophoresis motion of Janus particles near the substrate at two distinguished conditions.

DDFT of microswimmers in a trap

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Modelling the collective behaviour of a suspension of microswimmers calls for a statistical description starting from the microscopic level [1]. We provide such a description by developing a dynamical density functional theory (DDFT) for colloidal microswimmers. The theory includes comprehensive hydrodynamics of both the self-propulsion mechanism and the resulting hydrodynamic interactions between swimmers. To this end, a minimal model microswimmer is introduced and hydrodynamic terms up to and including the Rotne-Prager level are taken into account. Our work thus combines two branches of former studies, i.e. DDFTs of passive particles in the presence of hydrodynamic interactions [2], and DDFTs of active particles without hydrodynamic interactions [3].

As a first test, the resulting DDFT is applied to a quasi-2D setup, where swimmers in the bulk are confined to a plane in the surrounding liquid, and where an external radial trapping potential is additionally imposed [4]. Our numerical evaluation then characterizes the temporal evolution of such a system, which for broad parameter ranges leads to the formation of a steady state. For small hydrodynamic interactions, the formation of a high-density ring is observed [Fig. 1(a)], while, for larger hydrodynamic interactions, the formation of a "hydrodynamic pumping state" is reproduced [Fig. 1(b)]. Both states have previously been detected in particle-based computer simulations [5, 6]. Reproducing them by our DDFT underlines the significance of our approach.

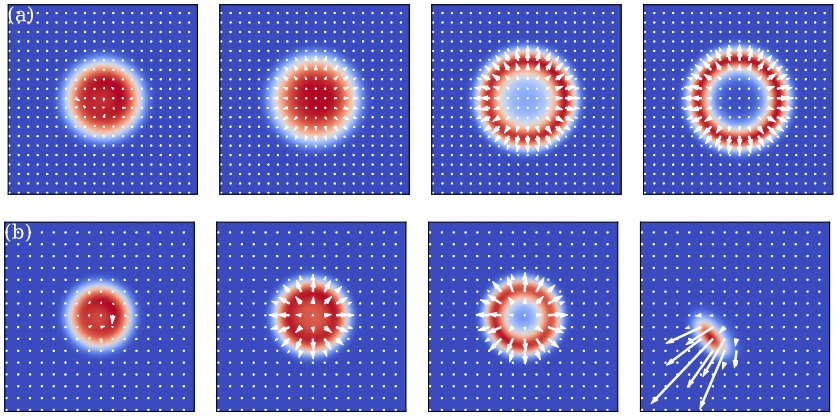

Fig. 1: *Numerical solution (time series from left to right) of our DDFT in a quasi-2D setup within a radial trapping potential. (a) For low active drive, the microswimmers form a high-density ring. They aggregate where active drive and trapping potential balance each other. (b) For an increased active drive, the former rotational symmetry is broken via hydrodynamic interactions. This reproduces the "hydrodynamic fluid pump" observed previously in particle-based simulations [5, 6].*

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Conformation-dependent polymer avidity, responsible for reversible critical shear-dependent platelet aggregation

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von Willebrand factor is a long soluble protein in the blood flow which binds to the subendothelial tissue of the injured site of the blood vessel and tethers platelets leading to blood clotting [2]. The conformation of VWF polymer is such that in the absence of shear stress, the polymer remains globular, thus hiding its adhesive sites (A1 domains) for binding platelet receptors or collagen. At sufficiently high shear rates, the VWF chain stretches, making the interaction of its adhesive A1-domain with platelet Glycoprotein Ibα or collagen possible [1]. Binding of platelets to the immobilized surface-adhered VWFs reduces their velocities to much lower values than those in blood flow [3] and leads to their firm adhesion to an injured wall.
According to recent studies, the adhesive interaction between VWF A1 domain and platelet receptor GPIbα has two bound states [4], which is modelled here by two-state catch-bonds. VWF and platelet adhesion is hypothesized to come from two distinct mechanisms, conformation-dependent avidity of the polymer and two-state affinity between VWF domains and platelet receptors [1]. Using meso-scale simulations, we show that the conformation-dependent avidity of VWF is crucial in the reversibly critical VWF-platelet adhesion in high shear rates. Therefore, beyond a certain shear rate, VWF polymers stretch and adhere to collagen and platelets. Interestingly when shear rate is reduced below this critical shear rate, the adhered VWFs lose their bonds and dissolve into the fluid. From our computational study, we conclude that the special characteristics of VWF polymers lead to the inhibition of thrombi growth and induction of hemostasis in case of an injury, simultaneously.

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Critical assessment of the von-Mises-distribution for self-propelled particles

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We consider a Vicsek model of self-propelled particles with bounded confidence, where each particle interacts only with neighbors that have a similar direction [1]. Depending on parameters the system exhibits a continuous or discontinuous transition from an isotropic state to a phase with a preferred direction. In a recent paper [2] the von-Mises distribution which is based on a maximum entropy principle was proposed as an ansatz for a mean-field theory of polar ordering. In the present system, the time evolution of the angular distribution can be solved in Fourier space. We compare the results of the Fourier analysis with the ones obtained by using the von-Mises distribution ansatz. In the latter case the qualitative behavior of the system is recovered correctly. However, quantitatively there are serious deviations. In particular, the position of the discontinuous transition significantly deviates from the correct value. We introduce an extended von-Mises distribution ansatz which leads to much better quantitative agreement.

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Flocking ferromagnetic particles

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Suspensions of microswimmers, show fascinating collective behaviours like clustering, flocking and turbulence [1]. Here, we demonstrate the discovery of ferromagnetic flocking colloids. The self-propulsion is an outcome of the spontaneous rotation of a ferromagnetic colloidal sphere in a vertical alternating (AC) magnetic field [2]. Depending on the frequency of this magnetic field, a sequence of transitions can be observed: from gas-like motion of individual particles to the onset of flocking and global rotation followed by a reentrant flocking and gas-like state for increasing frequency [3].

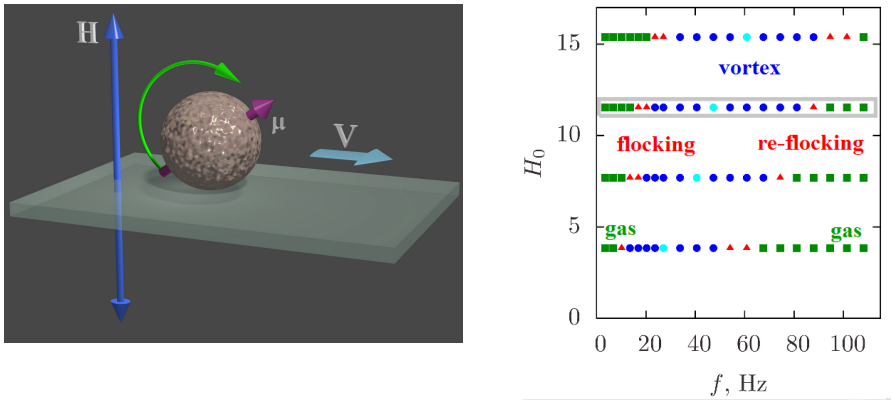

Fig. 1: (left) Schematics of the experiment. A non-smooth ferromagnetic particle is energized by an applied vertical AC magnetic field. (right) Diagram of the dynamic states spanned by the magnitude and frequency of the magnetic field.

We also emphasize a subtle role of rotational noise: While the low-frequency flocking appears to be noise-insensitive, the reentrant flocking happens to be noise-activated. Moreover, we uncover a new relation between collective motion and synchronisation.

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Passive Particles Follow Active Particles

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Active-passive particle mixture is one of the simplest model systems to study many non-equilibrium phenomena, including biological processes such as cell migration in tissues and bacterial biofilms [1, 2]. Here, we investigate mixtures of electric field driven active particles and dielectric passive ones of the same size. Intriguingly, we observe that, unlike most studies with mixtures [2, 3] where active and passive components segregate, here, they assemble together into a single entity- hexagonal lattice. By carefully controlling the frequency and strength of the applied electric field and the patch size of the active particle, we can precisely tune the interaction between two active particles as well as active-passive particle [4] so as to form an ordered structure. Importantly, contrary to equilibrium crystallization, we observe formation of crystallites rapidly and at low area fractions. Thus, our study provides a novel pathway to assemble colloids into ordered structures. Furthermore, insights gained from our studies could help develop strategies to assemble binary structures as well.

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Designing surfaces to guide chemical microswimmers

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An important challenge in designing systems with synthetic micro-swimmers is an ability to guide them. The methods employed so far have either involved using chemical gradients[1], which are challenging to control and lack spatial resolution, or sophisticated magnetic multilayer coatings which require external magnetic fields[2], thereby hindering the advantages of autonomous operation. Here, we show that the chemical and physical properties of a surface can be used to modify the swimming behavior of micro-swimmers, thus eliminating the need for external fields. We design a method to guide chemical micro-swimmers based on their phoretic and hydrodynamic interactions with sub-micron sized steps[3]. We use photo-lithography to fabricate patterns of different geometries and demonstrate guiding and docking of micro-swimmers (Fig 1). We show that this effect is dependent on the rate of chemical activity and explore the physical limits below which the mechanism no longer applies. Our findings have potential implications for developing autonomous devices at the micron-scale, such as self-assembled rotors[4].

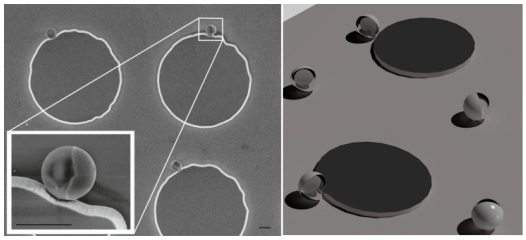

Fig 1:.*SEM and schematic representation of a self propelled Janus particles near a patterned surface. Sub-micron sized features of the surface can be used to control the propulsion behaviour of Janus particles.*

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A kinetic theory for dynamics of self-propelled magnetic suspensions in a magnetic field

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Inspired by novel dynamical patterns in magnetotactic bacteria, we present a minimal kinetic model for dilute suspensions of magnetic self-propelled particles. Our kinetic theory couples a Fokker-Planck equation of active particles in an external magnetic field to a Stokes-flow equation. Including the hydrodynamic stress contributions of self-propulsion [1] and magnetic torque [2] in the Stokes flow allows us to investigate, the interplay between internal and external drives on the dynamics and effective viscosity of active suspensions. Through the linear stability analysis and full numerical simulations of our model, we examine the role of the external magnetic field on stability of aligned suspensions and their complex flow patterns.

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Self-propulsion of droplets generated by active stresses

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Physical processes, which produce active flow and self-propulsion of microorganisms are controlled from the interior of the cell, in particular from the cytosceleton. On mesoscopic scales, the internal mechanical properties of cells are modelled as a continuum, with a distribution of stress tensors produced by molecular motors and (dis)-assembly of semi-flexible polymers. There are detailed hydrodynamical models of such active materials, which relate flow velocities, chemical potentials and polar order to stresses [1, 2]. But a complete mesoscopic mechanical model of self-propulsion should also connect these active stresses to the motion of the whole cell and the generated flow fields in the interior of the cell and in the ambient fluid. We find it worthwhile to study cases, which are analytically tractable and which may provide additional physical insight.

Therefore we calculate the internal and ambient flow fields and trajectories of active droplets, which are driven either by surface forces or by body forces with or without chirality. Forces, derived from active stresses and from external fields are treated, which can e.g. be generated by optical traps, myosin contractility, Marangoni surface stresses or by an active medium inside the droplet. The flow fields and the dissipated energy in the inside and outside fluid are calculated and the center of mass and rotation velocities are determined from the stresses and the viscosity contrast.

To demonstrate, how our framework provides a link betweeen hydrodynamic models of active media and models of self-propulsion, we consider several generic examples. First we treat active tractions in the droplet's interface, like Marangoni stresses, second we consider simple external potentials. Finally, we discuss stresses in active polar gels and polar fluids in the droplet's interior and relate the motion of the droplet and the fluid flows to configurations of the polar order parameter by using results from the hydrodynamics of active polar media [1, 2].

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Numerical Simulations of an Ion-Exchange Resin Based Microfluidic Pump

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We numerically and experimentally study the flow generated by an ion-exchange resin based microfluidic pump [1]. Our simulations demonstrate that the experimental observations can be explained by ion exchange taking place between the resin and the µM salt concentrations present in the system. The resin swaps impurity cations from solution with protons, which have a much higher electrophoretic mobility. This causes electro-osmotic fluid flow of $\mu\mathrm{m\,s^{-1}}$ towards the resin, which is experimentally characterized by tracer velocimetry. Our finite-element simulations of the flow and tracer behavior closely match the experiment, see Fig. 1.

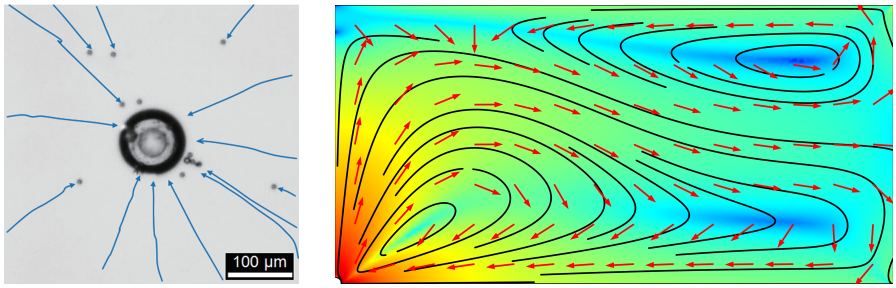

Fig. 1: *Left: the tracer trajectories observed in the experiment; top view. Right: numerical simulation of the fluid flow generated by a exchange-resin pump (located in the lower left corner); side view.*

The flow is appreciable over a very long range, close to a mm, and persists for more than $24\,\mathrm{h}$. Interestingly, we show that the geometry of the sample cell plays a crucial role in the decay of the flow, which can be changed from 1/distance to 1/distance^2 by simply changing the height. This can be understood by the ionic fluxes decaying quasi-2D, rather than 3D, for small cell heights. Our study demonstrates the importance of small ionic concentrations for microfluidic pumping and provides insights in the means by which pumping may be manipulated via the sample geometry, both of which should prove highly relevant to future developments in this field.

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Cellular decision making during sperm chemotaxis

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Sperm cells are guided to the egg by chemical cues in a process termed chemotaxis. While moving along helical paths, they can detect single molecules. This chemical input signal is translated by a cellular signaling system into modulations of the flagellar beat, which allows the cell to steer up-gradient.
Recent experiments [1] unveiled that sperm cells dynamically switch between two distinct modes of this helical chemotaxis: A "conservative" steering mode characterized by slow bending of the helical swimming path in the direction of the concentration gradient, and an "adventurous" mode, characterized by hard turns that bring the cell back on course fast. Using theory, we elucidate the competitive advantage this dynamic decision making conveys to sperm cells in their search for the egg. In a hypothetical case of noise-free cellular concentration measurements, the probability to find the egg would be maximal if cells employed the "adventurous" mode always. For realistic levels of sensing noise, however, we find that dynamic switching between the two steering modes provides a risk-balancing strategy that optimizes the chances to find the egg. Helical chemotaxis of sperm cells provides an ideal model system to study game-theoretic implications of decision making of biological cells in the presence of noise.

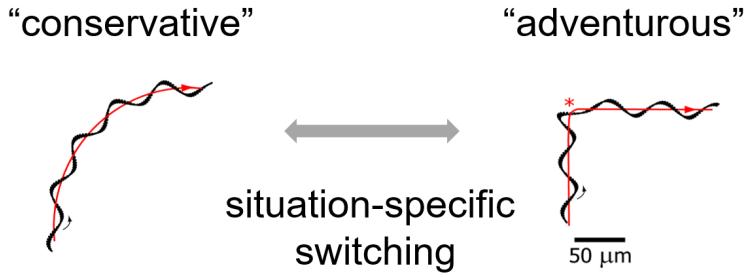

Fig. 1: *Sperm cells can switch between two distinct steering modes, characterized by either slow or fast course corrections of their helical swimming paths.*

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Novel mechanism of bacterial motility

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Many bacteria are motile by means of flagella, long proteinaceous fibres extending from the cell body. Numerous species possess a single filament at the cell's pole, which has a rather rigid corkscrew-like shape allowing forward and backward swimming in liquid or viscous environments. However, many natural bacterial habitats consist of structured environments, such as sediments, water-saturated soils, or tissues, where bacteria frequently encounter constricted channels where they might get stuck. Using *Shewanella putrefaciens* as a model organism we show that cells which are trapped or encounter environments with very high viscosity use a yet undescribed movement: the flagellar filament wraps around the cell body which allows realignments of the cell body and/or a screw-like motion. 'Screw' formation occurs upon an instability at the flagellar filament's base, predominantly at clockwise rotation which would drive the cells backward. Thus, an instability of the flagellar structure can be employed for a novel rescue or movement mechanism and is likely found in numerous environmental and pathogenic bacteria.

Probing the Dynamics of Self-Electrophoretic Swimmers using Lattice-Boltzmann

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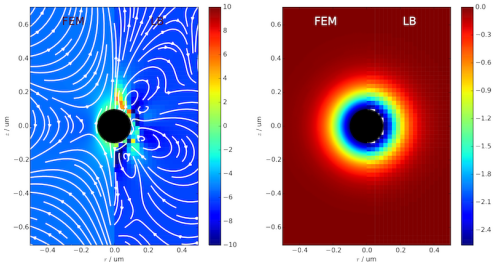
Many simulational studies are available of the rich transient and collective behavior in catalytically-driven colloids, i.e., microswimmers. However, virtually none consider both the hydrodynamic and phoretic fields and most do not take into account even one of them. We introduce a continuum model based on the lattice-Boltzman (LB) method that incorporates both effects and is capable of simulating the dynamic behavior of many swimmers. Our swimmers propel via experimentally relevant self-electrophoretic mechanisms with bulk reactions as outlined in Ref. [1]. In order to achieve this goal, we enhance the lattice electrokinetics method [2] in three ways:

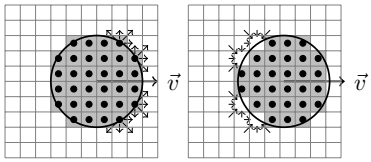
(i) We correct the diffusive flux expression to reduce spurious fluxes and modify the fluid force term to reduce spurious flow [3].

(ii) We implement moving boundaries for the phoretic fields by adopting a scheme similar to what Ref. [4] uses for pure LB, see Fig. 1b, with the addition of a partial-volume refinement.

(iii) We implement flux boundary conditions as a model for surface reactions. We demonstrate that our method works by comparing to theoretical predictions for a single swimmer, see Fig. 1a. The excellent agreement gives confidence in the applicability of the scheme to capture the dynamics of multiple swimmers.



(a) *Fluid flow and solute concentration for self-electrophoresis, comparing our lattice method against the FEM method of Ref. [1].*



(b) *Illustration of the moving boundary electrokinetics method.*

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Collective Effects and Living-Clusters Formation with Pusher Self-Propelling Droplets

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When a water/solvent mixture is dispensed as small droplets in an oil/surfactant solution, the droplets self-propel and develop in up to three stages depending on solvent concentration. In the first stage, the droplet propulsion originates from the spontaneous solubilization of solvent in the oily phase; during this process the droplets also absorb surfactant molecules which finally leads to a phase separation. The flow field around the self-propelling droplets in stage one is that of a weak pusher.

We studied the collection motion of self-propelled droplets in stage one where they behave as weak pusher. Droplets can form living clusters and we analyze the origin of the clusters formation. By changing the parameters like the height of reservoir, density of droplets, we investigate the conditions leading to the emergence of these living clusters.

Pattern Formation and Clustering in Chemorepulsive Active Colloids

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Chemotaxis is the directed motion of particles in response to a gradient in a chemical signal. It allows micro-organisms, like bacteria, to find food and to escape from toxins. Some micro-organisms can produce the species to which they respond themselves and use chemotaxis for signalling. This can, in the case of chemoattraction where particles migrate up chemical gradients, induce a clustering-instability of the uniform phase often proceeding to phase separation. This instability currently attracts renewed attention in artificial Janus colloids that swim by catalysing reactions in a chemical bath and show a similar signalling behaviour as micro-organisms.

In this talk, we will demonstrate that also the previously underappreciated case of purely chemorepulsive signalling (where particles migrate away from high chemical density) can destabilize the uniform phase generating a rich new route to clustering and pattern formation in active systems. The clustering instability may be caused either by anisotropic chemical production, or by a delayed response to changes in the chemical environment. In each case, chemorepulsion leads to clusters of a self-limiting area with grows linearly with self-propulsion speed. This agrees qualitatively with recent experimental observations of dynamic clustering in active Janus colloids and indicates that our findings might shed new light on (some of) these experiments (albeit not yet known to be chemorepulsive). Besides clustering we also find travelling wave patterns and continuously flowing and blinking cluster phases, suggesting that chemorepulsion might be useful as a design principle for structure formation with bacteria or chemorepulsive synthetic swimmers in nonequilibrium.

Viscoelastic Synchronisation

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Coordinated motion of biological filaments lies at the root of microbial propulsion and micro-scale fluid transport. In order to understand the route towards synchrony, recent years have brought significant advancement of the experimental techniques aiming to mimic biological systems in controlled laboratory conditions. A particular example of such systems involves colloidal oscillators [1]. These beads of micrometer size immersed in a solvent are subject to one-dimensional driving potentials which are coupled to the configuration of the system. In a class of "geometric switch" models, the force driving the oscillator switches when the particle reaches a certain limiting position. This is realised by the use of a time-shared optical laser trap which creates a potential energy landscape allowing to apply a constant force to an overdamped particle. In the presence of a second driving potential which is periodic in time (the "clock"), such beads have been experimentally shown to exhibit periodic trajectories. The system maintains synchronisation by adjusting the phase between the bead and the clock [2]. Such a single particle trapped by the switch and the clock forms the minimal system in which the properties of colloidal synchronisation may be investigated, as well as the role of destabilising noise.

In our work, we address the question of synchronisation of a single active colloidal bead moving in a viscoelastic fluid. Most biological fluids possess a polymeric microstructure, which causes them to respond to external forcing in a non-Newtonian way. In contrast to the Newtonian case, the dynamics is now determined by three time scales: the natural frequency of the driving force, and the two characteristic fluid retardation and relaxation times. These additional time scales may lead to a loss of synchrony of the system. Depending on the relation between the time scales of motion actuation and the response of the fluid, various dynamical regimes are found, which we quantify in terms of the dimensionless parameters characterising the motion.

By analysing the theoretical model, we determine trajectory of the particle for a given set of fluid and forcing characteristics which leads to the determination of the phase diagram for the synchronised and asynchronous states. Further on, we extend our analysis to include the effects of thermal noise and discuss the effect of noise on the phase diagram. The model will be directly verified by comparison to experiments in the group of Pietro Cicuta at the Cavendish Laboratory in Cambridge.

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Artificial Phototaxis: Rectified motion of self-propelled particles by spatial motility variations

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Phototaxis, i.e. the capability to move towards or away from light sources is an essential feature of many microorganisms like bacteria or motile cells. Unlike living systems, where this is achieved by a complex internal machinery, it is not obvious how such behaviour can be imposed on synthetic microswimmers. Using colloidal Janus spheres subjected to various light landscapes, we demonstrate artificial particle sensing and tactic behaviour, i.e. autonomous navigation in light gradients. This leads to a strongly rectified particle current which may find use for directed particle assembly and which is also confirmed by theory and simulations.

Spatial control of swimming bacteria using light

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Active matter is a burgeoning field of interdisciplinary endeavour. Suspensions of swimming bacteria, such as *Escherichia coli*, are widely used as model active colloids [1], but a real-time tuneable control of their swimming speed is lacking. Recently, *E. coli* has been genetically modified to swim only when illuminated with green light [2], potentially giving biological active colloids with a wide range of tuneable speed.

We studied several mutants of *E. coli* for which their swimming speed can be controlled by the intensity of incident green light and we specially engineered mutants, which adjust their speed rapidly in response to changes in intensity. By projecting intensity patterns of light onto a suspension of such bacteria we are then able to spatially control the activity of these suspensions over large length-scales (~ 1 cm) and create dynamic or static complex structure (see Figure).

It has been predicted theoretically that swimmer density is inversely proportional to swimming speed [3]. Whether this applies to swimming bacteria is investigated here. We developed Differential Dynamic Microscopy to spatially resolve the activity of such suspensions. This allows us to extract key parameters, e.g. swimming speed, relative change in local cell density and the fraction of non-motile cells over large length-scales. Providing suitable experimental conditions, we confirm the theoretical prediction.

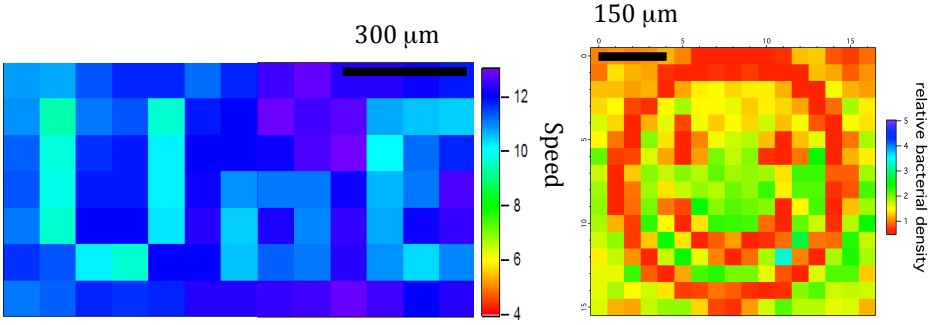

Figure: Examples of spatial control of bacterial swimming speed (Left) and density (right).

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Bacteria swimming in High Molecular-weight polymer: *lambda*-DNA

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Escherichia coli has become a model swimmer in the active matter field (e.g. [1]). Numerous studies focus on the swimming in water but bacteria as *E.coli* often live in viscoelastic media such as mucus in intestine tract. Mucus is a strong viscoelastic material with shear-thinning properties containing long polymer chains as proteins and DNA. It has been suggested recently [2] that in a solution of PolyVinylPirrolidone of molecular weight 360kDa, small and fast rotating flagella create a local high shear rate resulting in a polymer-free channel from its surrounding, while the slow rotating body of the bacterium observe the viscosity of the polymer solution. Thus, bacteria body and flagella observe two different environments. Here, we investigate the swimming of *E.coli* in solution containing larger polymer coils, i.e. lambda-DNA with a radius of gyration Rg~0.6mm of similar size than the body bacterium itself. By using Differential Dynamic Microscopy (DDM) and Dark Field Microscopy (DFM) analysis, we measure the swimming speed (V) and the body rotational speed (Ω), averaged over ~10^4 cells. Surprisingly, we found V and Ω are only weakly modified by increasing DNA concentration while the bulk viscosity increases by a factor of ~20 (see Fig.1), presumably due to shear-thinning. These phenomena are particular to active particles such as flagellated bacteria, as Brownian diffusion of non-swimming bacteria (D) is dependent on bulk viscosity.

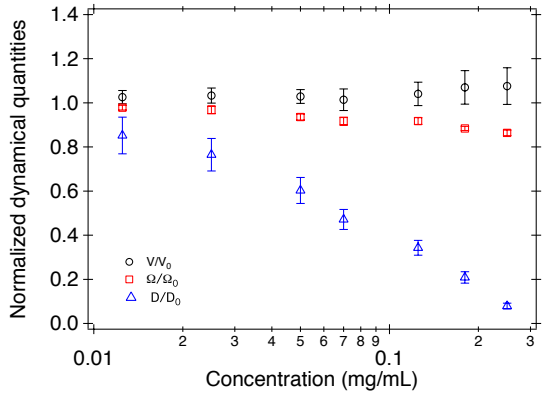

Fig. 1: *Swimming speed (V), rotational speed of body (Ω) and Brownian diffusion coefficient (D) of E.coli normalized by their respected value (0) in TE buffer, in function of λ-DNA concentration.*

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Active swimmers in confinement: taxis and wall-hugging effect

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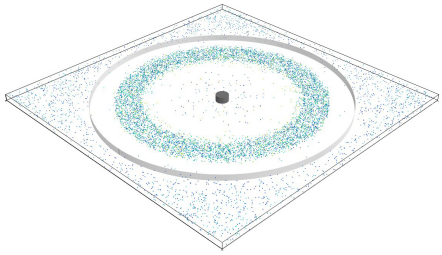
Active swimmers such as motile bacteria or algae have attracted remarkable interest recently because they constitute intrinsically out-of-equilibrium physical systems that pose fundamental challenges in modern statistical physics, and has the tantalizing potential to understand complex behaviors in biology and ecology. These microorganisms often live in complex environments where geometrical confinement and structures at the nano or microscale strongly influences their living conditions and collective behavior. The interplay of active motion and solid boundaries has in fact attracted considerable interest.
We report on computer simulations and theoretical calculations of two study systems:
(*i*) *Shewanella oneidensis*, a pusher-type swimmer, in the presence of an oxygen concentration perform an aerotactic motion along the gradient until they reach their optimal oxygen concentration. They often organize collectively by forming dense regions, called 'bands', that travel towards the oxygen source. We have developed a model of swimmers with stochastic interaction rules moving in proximity of an air bubble. We perform MD simulations that reproduce the aerotactic behavior of bacteria. If the oxygen concentration in the system sinks locally below a threshold value, the formation of a migrating aerotactic band toward the bubble can be observed. We reproduce quantitatively the experimental observations of the aerotactic band.
(*ii*) *Chlamydomonas reinhardtii*, a puller-type swimmer, confined within a quasi-2D circular chamber. We find a strong propensity of the swimmer to remain in proximity of the walls, the so-called wall-hugging effect. The dynamical behavior can be rationalized in terms of steric interactions with the walls. Comparison with the corresponding experiments shows a remarkable quantitative agreement.



Single Molecule Manipulations by Dynamic Temperature Fields

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Since the development of optical tweezers, a large variety of tools have been created to allow for a manipulation of single or multiple nano-objects in solution. This offers access to a new world of phenomena in physics, soft matter physics, biochemistry or biophysics. All of these techniques counteract the thermal fluctuations by a force, which is generated by an external electric field.

Here we report a novel single molecule trapping concept, which is not based on applying any external force, but on a manipulation of local temperature, which is the actual driving force behind the Brownian motion [1]. This generation and dynamic manipulation of local temperatures using very simple and easy to fabricate plasmonic nanostructures allows us to confine single biomolecules such as DNA in solution over minutes. Our results go beyond a simple object trapping demonstrating a vast amount of possibilities to shape effective trapping regions. Moreover, the newly developed scheme is able to hold a well-defined number of single molecules as presented for DNA. Thus, for the first time the trap itself can be arbitrarily shaped *in situ* to control multiple objects of the same or even of different type. The major advantages of the introduced technique as compared to others lie in the extremely simple fabrication procedure, the scalability to large arrays and the so far unachieved controlled trapping of multiple individual molecules. This will provide a set of new thermophoretic micro beakers as an analytical tool at the edge of analytical chemistry.

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Why to use DNA for constructing thermophoretic swimmers?

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In order to use self-propelling microswimmers as cargo transporters, methods are required that offer ways to control the directionality of motion. Artificial microswimmers that propel by self-phoretic effects do not only undergo translational but also rotational diffusion that randomizes directed motion on a certain time scale [1]. The latter has to be efficiently suppressed to accomplish directionality.

The rotational relaxation time, τ_R, of spherical thermophoretic microswimmers, as realised in laser-driven Janus particles [2, 3], is increased by attaching a long double-stranded DNA molecule to the Janus particle. A further stabilisation of motion has been achieved by coupling of passive cargo beads to thermophoretically driven Janus particles via DNA; the cargo beads follow in a well-defined distance. Due to the well-known force-extension behaviour of double-stranded DNA [4], the load involved in the transport of such cargo hybrids can be determined from the distance between the Janus and the cargo particle. Controlled conjugation of beads and DNA is achieved by making use of the enzymatic DNA toolbox that allows the incorporation of functional groups in a site-specific manner.

Apart from the demonstrated stabilization of directionality, DNA itself also exhibits thermophoretic behaviour [5] that supposedly influences the driving properties, i.e. affects the propelled motion of DNA-modified Janus particles and allows for the design of a novel kind of swimmers where DNA is explicitly both: the thermophoretic active and steering element. In this case, DNA nanotechnology allows also for the creation of complex, almost arbitrarily shaped DNA structures with tuneable micromechanical properties tailoring the swimmers morphology.

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Self-propulsion of autophoretic particles: shape matters

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Phoretic drift of colloids results from the interaction of the colloid's surface with thermodynamic gradients in its environment [1]: attractive/repulsive forces between the solid boundary and solute molecules lead to a slip flow outside a thin interaction layer surrounding the particle. Self-propulsion is achieved when the required gradients are generated by the particle itself, e.g. through chemical reaction at its surface. It requires an asymmetry in the solute distribution, which is classically obtained using chemical patterning [2] but can also be achieved using particle geometry [3]. When solute diffusion is slow, we also recently demonstrated that phoretic advection of the solute can lead to an instability-based propulsion mechanism for chemically-isotropic (or front-back symmetric) particles [4].

Geometry plays an essential role in the propulsion and interaction properties of chemically-patterned particles (e.g. Janus systems, with one active site and one passive site). We will show that the swimming velocity (and its sign!) can be critically influenced by the aspect ratio of the particle (whether a disk, sphere or rod). The influence of geometry on its far-field signature, which drives interactions among particles and suspension dynamics, will also be presented.

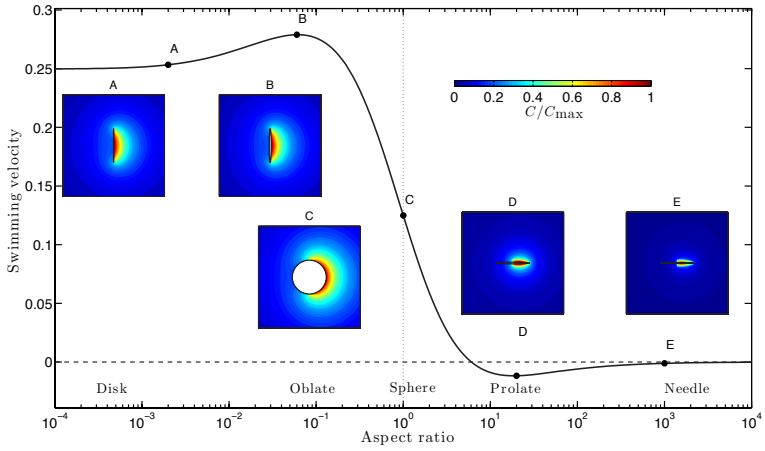

Fig. 1: *Swimming velocity of a Janus particle. The right half of the particle is chemically active while the left half is inert. Insets show the concentration distribution around the particles*

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Optimization of the active control of a microswimmer via Soft computing

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Self-thermophoretic microswimmers are swimmers, which are driven by temperature gradients that are induced by laser light absorption. They can be thus controlled by switching the laser intensity. Photon nudging as applied for Janus type swimmers is a particular control strategy using a feedback of the swimmers position and orientation to control their propulsion speed. Thus steering of individual and multiple swimmers to well defined target positions becomes possible. Nevertheless this method depends on a parameter called acceptance angle that defines how good is the current orientation of the particle in order to reach the target once we heat the swimmer. Here we present a method based on machine learning algorithms that analyses the relationship between state and action through a policy, with the objective of optimize the definition of this acceptance angle. This represents a first step into the possibility of an autonomous navigation of this kind of self-thermophoretic swimmer using soft computing techniques.

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Swimming Bacillus subtilis with different number of flagella

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Microorganisms generally use so called flexible appendages known as flagella to swim in aqueous media. We statistically investigate the swimming of multi-flagellated bacteria by characterizing the influence of flagellar number of genetically manipulated strains of Bacillus subtilis. We find that while numerous flagella are not significantly advantageous in terms of velocity and running time, it changes the active diffusive behavior of cells. In a homogeneous medium, the strain with more flagella has an increased average wobbling angle and turning angle after tumbling. The cells with less flagella tend to turn in smaller angles that causes larger translational diffusion coefficient. Consequently, the active rotational diffusion coefficient increases with increasing number of flagella. We use Langevin simulation based on experimental parameters which allows disentangling the effect of turning angle and rotational diffusion on translational diffusion [1-4].

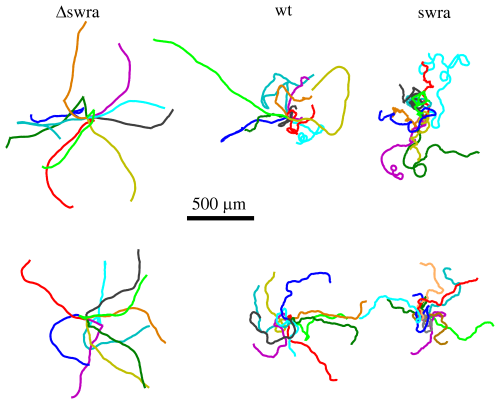

Fig. 1: *Upper row indicates the typical trajectories for different strains. Number of flagella increases from left to right. Below row shows the results of Langevin simulation using experimental parameters.*

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Collective effects: enhanced diffusivity of tracers and bacterial turbulence

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Tracers in a suspensions of micro-swimmers are known to show enhanced diffusion, i.e. much higher diffusion constant than the one expected from pure thermal motion. Such phenomena is currently explained in terms of a superposition of single-scattering events [1]. However, in dilute suspensions, far field hydrodynamics dominates. One then expects that collective effects, due to the simultaneous interaction among many swimmers, to be important.
Employing a mean-field kinetic theory approach [2, 3] valid in the low density regime, we fully treat collective effects and show their strong effect: a tracer in a suspension of pushers or pullers behave very differently, with diffusion constants varying more than one order of magnitude. As a by-product, we show this to be a precursor of the self-organisation in large scale structures that is observed at higher density (bacterial turbulence) [3].
We compare our analytical predictions to numerical simulations based on a Lattice-Boltzmann algorithm [4] which is capable of simulating hydrodynamic interactions between a large number of model swimmers ($N \geq 10^5$), modelled as extended force dipoles. These simulations go much beyond previous computational results that were constrained to much smaller systems ($N \sim 10^3$ particles). With these statistical data in hand, we finally present numerical results that shed light on the nature of the bacterial turbulent state.

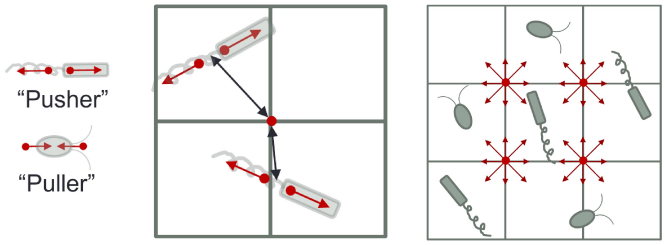

Fig. 1: *Schematic picture of the LB algorithm. The microswimmers are modelled as pairs of point forces acting on the fluid (left panel), which interact hydrodynamically by an interpolation of their forces to the LB lattice (centre and right panels)*

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Active particles with soft and curved walls: Equation of state, ratchets, and instabilities

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We study, from first principles, the pressure exerted by an active fluid of spherical particles on general boundaries in two dimensions. We show that, despite the non-uniform pressure along curved walls, an equation of state is recovered upon a proper spatial averaging. This holds even in the presence of pairwise interactions between particles or when asymmetric walls induce ratchet currents, which are accompanied by spontaneous shear stresses on the walls. For flexible obstacles, the pressure inhomogeneities lead to a modulational instability as well as to the spontaneous motion of short semi-flexible filaments. Finally, we relate the force exerted on objects immersed in active baths to the particle flux they generate around them.

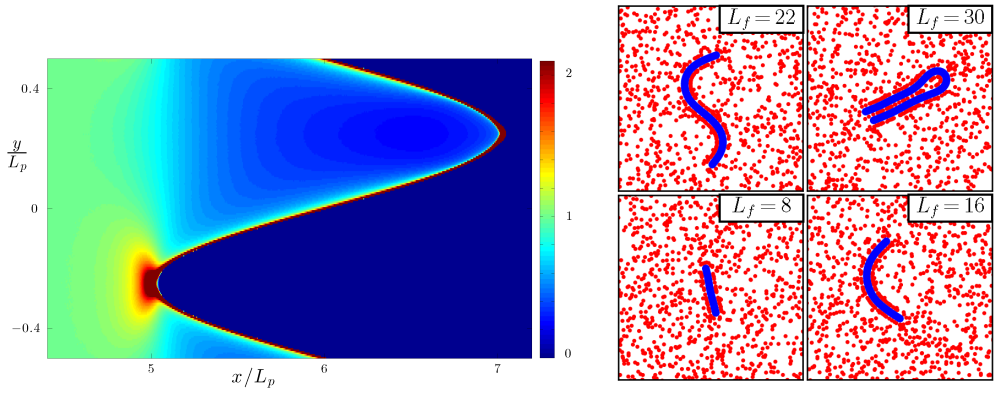

Fig. 1: *Left: A colorized density map of active Brownian particles near a sinusoidal hard wall surface. Right: Different dynamic regimes of a filament immersed in an active gas.*

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Modular Phoretic microswimming

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There currently is a strong interest in understanding and applying self-propulsion on the microscale. Typical biological and artificial micro-swimmers use non-reciprocal motion (e.g. flagellae) or phoretic propulsion (e.g. driven by chemical reactions) [1]. We here present a complementary approach to micro-swimming by combining several non-active parts to self-organize into a self-propelling complex. Our modular phoretic micro-swimmer consists of an ion exchange resin (IEX) particle (being the fuel reservoir) and a charged colloidal particle (CP, acting as gearing), both settled to a charged substrate and hydro-dynamically coupled by an electro-osmotic solvent flow along the substrate (acting as a motor), which is caused by the gradient generated by the IEX [2,3]. Using different optical techniques, we carefully characterize the swimming performance of this complex as a function of gradient strength, substrate charge, size and electro-kinetic mobility of the CP, size of the IEX and number of CP coupled to the IEX. We further report interesting structures and shapes of the swimming complex formed under specific conditions

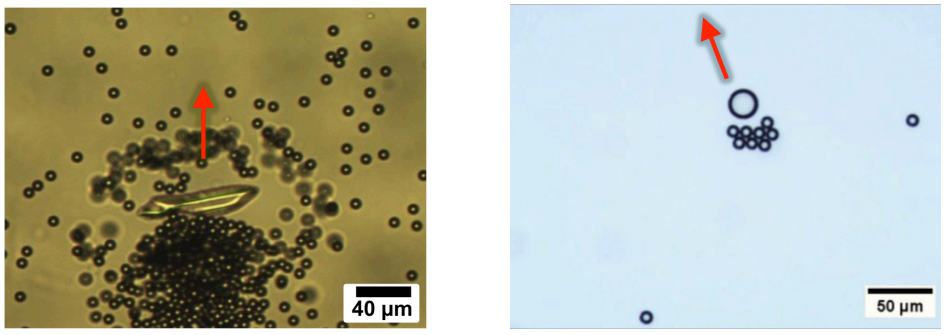

Fig. 1. ***Optical micrographs of linearly self-propelling complex of colloidal particles accumulated at a fragment of IEX (left) and a spherical IEX (right) with the arrows indicating the moving direction.***

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Preparation of Anisometric Supraparticles on Super Hydrophobic and/or Superamphiphobic Surfaces

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In this project, supraparticles are prepared on superhydrophobic surfaces that contain as structural main component fumed silica (FS) particles. By changing the ionic strength of the FS solutions, it is possible to control the anisometry of the particles in a systematic fashion. By obtaining anisometric particles, our motivation is to obtain sub-millimeter sized particles that have tunable movement condition for self-propulsion. Such self-propelling properties were imparted by adding Pt-covered magnetite (Fe_3O_4) nanoparticles to the FS solution. In this way, supraparticles are gaining both magnetic and catalytic properties which enables us to make the particles self-propelling with a suitable fuel.

Experiments were conducted both on flat and bent surfaces. By fixing a magnet with a fixed position, the Pt@Fe_3O_4 nanoparticles can be attracted selectively to one predetermined position on the anisometric supraparticle. These asymmetrical patchy particles are self-propelling when put into H_2O_2 solution due to the Pt-catalyzed decomposition. The buoyancy of these supraparticles then was in addition controlled by variation of the density, via addition of polystyrene lattices, and heat treatment. The trajectories of these boat-like supraparticles then were studied by means of videomicroscopy as a function the shape of the supraparticles, the position of the catalytically active patch, and the concentration of fuel. From these studies systematic correlations between these parameters and the observed trajectories could be deduced, where in particular the extent of anisometry of the supraparticles has a profound effect.

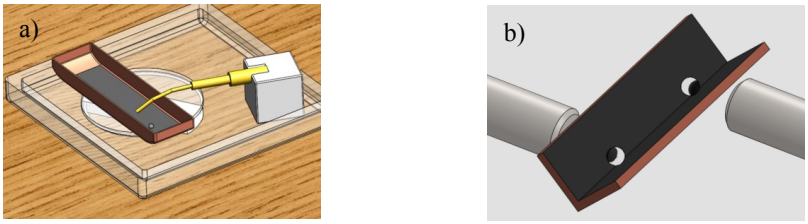

Figure 1: *Employed set-ups to obtain patchy particles; a) Flat surface, b) Bent surface.*

Periodic motions of self-propelled water-in-oil droplets driven by flow

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Multiple microparticles moving in fluid sometimes show spatial or temporal patterns, such as colloidal particles, droplets, red blood cell, and so on. The patterns can be caused by various factors, self-propulsion, alignment, hydrodynamic interaction, and concentration gradient. In order to identify the mechanism in complex phenomena, it is useful to study it in a simple system. For example, one-dimensionally ordered droplets flowing in a straight channel exhibit a regular motion [1]. When 140 μm and 20 μm water-in-oil droplets alternately aligned in the microfluidic channel, each smaller droplet oscillated between two neighbour larger droplets (Fig. 1). This oscillation of the small droplet can be explained only by hydrodynamic interactions with large droplets and wall of the channel. The droplets are driven by the outside flow, so that is passive matter.

In contrast to the moving droplets driven by external factors, active matter driven itself exhibits novel manners. Pure water droplets placed in oil with mono-olein 25 mM begin to swim spontaneously [2]. This phenomenon has been explained by reverse micelles in oil emitted from the water droplet. Concentration gradient of the reverse micelles generates Marangoni flow along the surface of the droplet when the droplet fluctuating, which can propel the droplet to one direction. In order to propel the droplet, Peclet number $\mathrm{Pe} = (AM'a/D^2)$ must be more than 4. The three parameters in Pe, A, M', D exhibit water-emitting rate, coefficient of Marangoni effect, diffusion number and depend on the property of solutions. The parameter which is able to be continuously changed is only a, which is the diameter of the droplet. We here investigate the size effect on the motion of droplets.

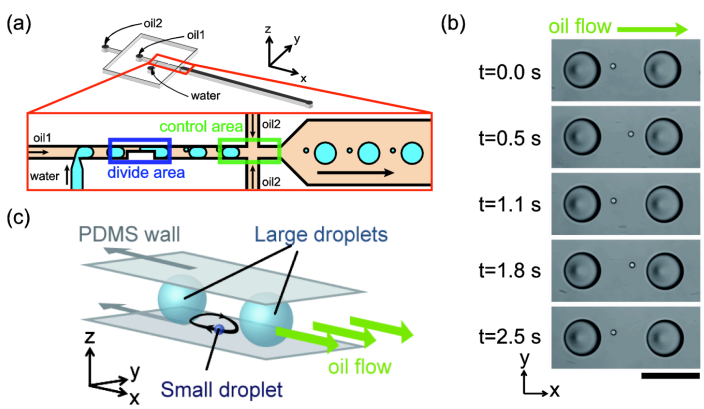

Fig. 1: (a) *Microchannel for the experiment.* **(b)** *Snapshots of a small droplet between two large droplets.* **(c)** *Schematic mechanism of the oscillation.*

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Understanding hydrodynamic polar ordering in swimmer dispersion by binary collisions

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We investigated the origin of polar order in systems of model microswimmers, so-called squirmers. With this squirmer model, we can consider different types of swimming by just tuning the swimming parameter, α. We conducted three dimensional direct numerical calculation of bulk squirmer dispersions with various parameter sets with full hydrodynamics. Then, we also studied the binary collision dynamics of squirmers and composed a simplified Vicsek-like model for bulk systems. Comparing the results from the regular and the simplified squirmers in bulk systems, we clarified that the polar order in squirmer dispersions is mostly explained by binary collisions (Fig.(1)). The discrepancy can be seen in the region where we observe swarming behavior in bulk (gray shaded region in figure, and reported in [1]).

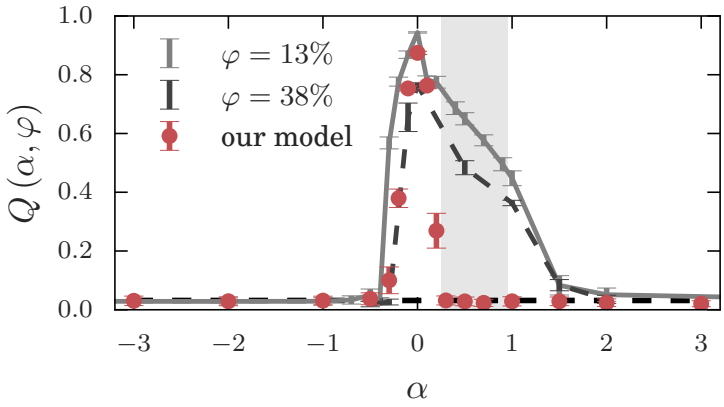

Fig. 1: *The α dependence of polar order parameter Q (defined as the magnitude of the average swimming direction). Lines are results obtained from simulations of the regular squirmer bulk systems for two different volume fractions φ, and the circles are the results of the simplified, Vicsek-like model. We see good agreement, except in the gray-shaded region where we observe swarming behavior in bulk.*

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Rigid-body aggregation of spheres and rods with hydrodynamics

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The aggregation of sticky colloidal particles in the diffusion limited regime has thusfar been simulated using isotropic cluster mobilities obtained from scaling laws. Our novel rotational Brownian dynamics scheme enables the use of cluster-specific anisotropic mobilities [1], obtained from rigid macromolecular bead models developed by de la Torre [2]. The simulation results in faster aggregation and more stringy clusters than previous simulations. The effect becomes more pronounced for rod shaped particles with increasing aspect ratio [3]. The cluster-size distributions collapse onto a master curve in the dilute regime, while the deviations observed for more concentrated systems are in agreement with experiments [4]. This method will be extended to sheared systems by including shear-disturbance tensors in the mobility calculation and the stresslets experienced by the aggregates will be calculated. Ultimately a simulation framework will be developed to estimate particle/aggregate shape-specific contribution to suspension properties like viscosity enhancement.

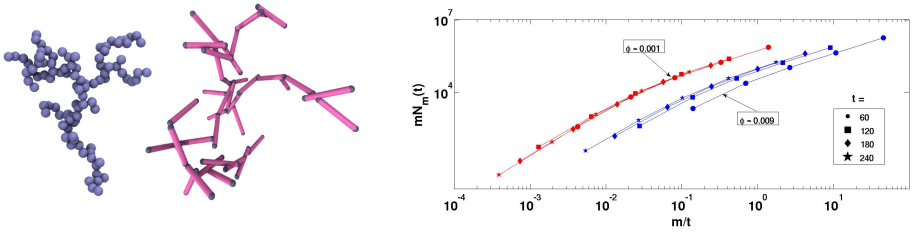

Fig. 1: *(a) snapshots of two clusters formed in simulation with spheres and rods as primary particles respectively. (b) Time-dependent cluster distribution for sphere aggregate systems at two volume fractions,* ϕ *.*

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Bacteria swimming in a monolayer colloidal crystal: channelling, run and tumble characteristic and active annealing

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Using experiments and simulations, we studied a mixture of active and passive colloidal particles. We prepared layered colloidal crystals from slit-confined charged spheres in low salt aqueous suspension. The colloidal solids are doped by small amounts of bacteria with a size comparable to that of the non-active colloids. In the experiments, the bacteria inside the loosely packed periodic confinement of the crystallite interior, develop an elegant and efficient channelling type of motion. In the less well ordered grain boundary regions they reveal a digging type of motion. Remarkably, for both types, the bacteria retain the run and tumble characteristic known from their unconstrained motion in bulk liquids. This kind of motion is also investigated in the simulations. There, the crystals binding energy is chosen somewhat larger and the driving force for bacterial motion has to exceed a threshold value. In both simulation and experiment, the bacteria modify their environment through their motion. With time, we observe a significant coarsening and an improvement of the orientational alignment of the crystals mainly through large scale collective rearrangements of the non-active colloids.

The many faces of the bead-spring model

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In this talk we present many fundamental results concerning microswimming, gained by successively adding greater levels of sophistication to the three-sphere microswimmer model of Najafi and Golestanian while preserving its analytical approachability. These results, often running counter to the prevailing wisdom in the field, are in all cases supplemented with matching lattice Boltzmann simulations using the waLBerla [1] and LB3D [2] systems.

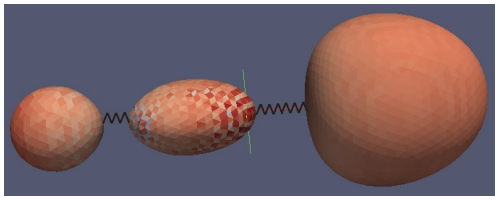

Fig. 1: *A bead-spring swimmer with flexible beads.*

We augment the original model with springs and explicit forces driving the swimmer, and calculate its velocity analytically through a perturbation method based on the instantaneous displacement of each bead from the equilibrium configuration [2]. In addition, we allow the beads in different studies to be non-spherical, flexible, and heavier than the surrounding fluid (Fig. 1). We first show that our swimmer naturally synchronizes the beating of its two arms to optimize its velocity [3]. Then, analyzing a family of ellipsoidal shapes, we uncover the existence of two regimes of microswimming, where the motion is dominated either by a reduction in the drag force opposing the beads or by the hydrodynamic interaction amongst them [3]. We then show that our model helps explain how, in direct contrast to the classical theories of microlocomotion, mechanical microswimmers swim quicker in fluids of increasing viscosity if the driving forces are weak enough [2]. We next increase the flexibilities of the beads in the swimmer. For the parameters in our simulations, our theory correctly predicts the velocity decreasing with bead flexibility, while for other parameters, it also suggests that the velocity may increase. We then investigate inertial microswimming by adding a mass acceleration term to the equations of motion, and find excellent agreement to the swimming velocity and effective radius found from simulations [4]. We next study the motion of our swimmers in channels using simulations with the LB3D system. Due to a complex coupling of bead flexibility and channel width, the swimmer may swim unimpeded, migrate to the surfaces, or not swim at all. Lastly we present our simulations results with many swimmers together. Utilizing the massive parallelization capability of waLBerla [5], we find different kinds of collective motion exhibited by pushers, pullers and neutral swimmers.

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Reusable and long-lasting active microcleaners for heterogeneous water remediation

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Micro-nano machines have shown potential to act as future tools for environmental remediation[1–4]. Fe/Pt micromotors can degrade organic pollutants via Fenton-like advanced oxidative processes[4]. We demonstrated that the micromotors, dubbed as microcleaners, can swim continuously for hours for long term cleaning applications, can be stored for weeks and can be reused for multiple times without sacrificing much of the activity[5].

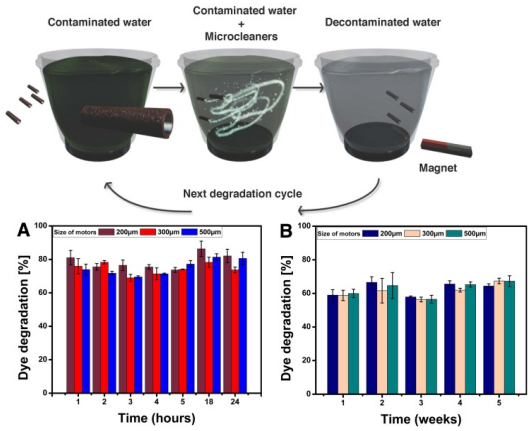

Fig. 1: *Reusability of microcleaners: (Left) Schematic diagram A) performance of different sizes of microcleaners in 5 consecutive degradations and after short-term storage B) performance of microcleaners after 1 to 5 weeks of storage.*

Iron removal is a major challenge for the cost effective Fenton reaction for water treatment. We found that microcleaners release a very low concentration of iron and act as the heterogeneous catalyst by in situ generated iron oxide species on the surface.

We also observed enhanced mechanical properties due the formation of iron oxides along with the tightening of the rolled-up layers. To thoroughly understand the system, we studied the effects of the size of microcleaners, hydrogen peroxide concentration and the addition of acid on the degradation of organic pollutants. The applicability was extended for phenol degradation to show the versatile remediation functionalities

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Turbulent and vortex-induced behavior of confined concentrated semen

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We experimentally study the collective dynamics of confined concentrated semen. (i) When the semen is confined between two glass plates, being distant within 100 to 400 μm, a "small-scale turbulent" behaviour is recovered, and studied. We report the first observation of universal enstrophy cascade in concentrated swarming sperm consistent with a body of evidence built from various independent measurements. We found a well-defined k^{-3} power-law decay of velocity field power-spectrum and relative dispersion of small beads consistent with theoretical predictions in two-dimensional turbulence. Concentrated living sperm displays long-range, correlated whirlpool structures of a size that provides an integral scale of turbulence. We propose a consistent explanation for this quasi two-dimensional turbulence based on self-structured laminated flow forced by steric interactions and alignment, and develop scaling arguments consistent with this interpretation. (ii) When the semen in confined into an annular shaped micro-fluidic chip, a spontaneous vortex state of the fluid is found at sufficiently large sperm concentration. The rotation occurs unpredictably clockwise or counterclockwise and is robust and stable. Furthermore, for highly active and concentrated semen, richer dynamics can occur such as self-sustained or damped rotation oscillations. Experimental results obtained with systematic dilution provide a clear evidence of a phase transition toward collective motion associated with local alignment of spermatozoa akin to the Vicsek model. A macroscopic theory based on previously derived Self-Organized Hydrodynamics (SOH) models is adapted to this context and provides predictions consistent with the observed stationary motion.

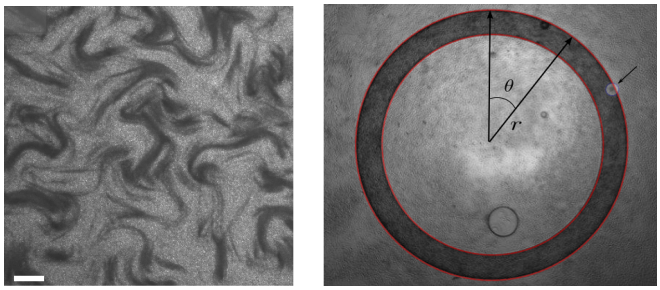

Fig. 1: *Left : Phase-contrast microscope image of the whirlpools structures formed by a pure (higly concentrated) fresh ram semen confined into a 100 μm depth chamber (scale bar 200 μm). Right : annular chamber into which the fresh semen exibits a vortex state transition at large concentration*

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Fluid flows created by microswimmers in thin films

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Many pathogenic microorganisms live in close association with surfaces, typically in thin films that either arise naturally or that they themselves create. In response to this constrained environment, the cells adjust their behaviour and morphology, invoking communication channels and inducing physical phenomena that allow for rapid colonization of biomedically relevant surfaces. Thus, it is very important to measure and theoretically understand the key mechanisms for the apparent advantage obtained from swimming in thin films.

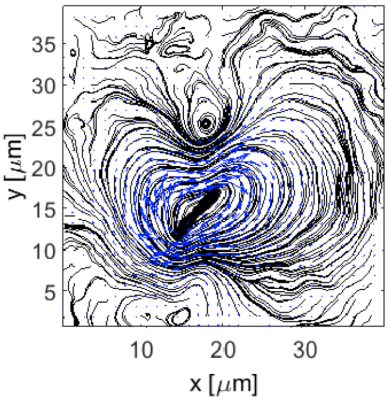

Fig. 1: *The flow field around a stuck cell of Bacillus subtilis (with permission* [2]*).*

We discuss experimental measurements of flows around a peritrichously flagellated bacterium constrained in a thin film, present a simplified mathematical theory and Green's functions for flows in a thin film with general slip boundary conditions, and establish connections between theoretical and experimental results [1]. Our theory extends and corrects previously obtained results [3] and explains the dependence of fluid flows generated by motile cells on their morphology.

Next, we apply our mathematical theory to discuss advection of small passive particles by microswimmers in thin films. We show that this process occurs qualitatively and quantitatively differently in films and in bulk [4]. Our results shed light on the mechanisms of biomixing enhancement in fluid films observed experimentally but remaining unexplained [5].

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Pressure of self-propelled particles with hydrodynamic interactions

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Self-propelled particles, such as E. Coli bacteria or self-diffusiophoretic swimmers are one of the easiest examples of active systems. These particles are able to convert free energy into systematic self-propulsion and are therefore permanently driven out of thermodynamic equilibrium. Nevertheless, an equilibrium quantity like pressure, the mean force acting on a confining wall, is still well-defined. Assuming Brownian dynamics, the pressure of self-propelled spherical particles does even fulfill an ideal gas-like state function, which is independent of the explicit wall-particle interaction [1]. More generally, the existence of a state function is conditioned by the absence of wall-induced torques and the specific type of interaction between the active particles. We are interested in how these results change when using a different model for describing the interaction with the solvent, such as the Multi-particle-collision dynamics technique [2], which includes hydrodynamic interactions between the particles. Even for spherical particles, hydrodynamic torques can arise and make an equation of state less likely to exist.

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Squirming in a droplet

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Active micro- and nano-particles have potential applications as transporters for restoration of damages in machinery and drug delivery to the target cell *in vivo* [1, 2]. They may be encapsulated by a droplet to achieve their tasks, for example, to contain the chemicals in a droplet. Microorganisms may be also surrounded by a form of droplets during their growth from eggs or invasion to host cells [3, 4, 5]. From this sense, we investigated locomotion of micro-swimmers in a droplet and the droplet dynamics in viscous fluid. A squirmer is taken for a general model of micro- and nano-swimmers and two different viscosity inside and outside the droplet is considered. Analytic solutions for the fluid flow fields are obtained by solving Stokes equations in incompressible fluid and compared with the numerical simulations using finite elements methods. Fluid flow fields inside and outside the droplet for pusher, puller and neutral swimmers are characterised and quantitatively compared between theory and simulations. The squirmer's swimming velocity and the droplet velocity are calculated and stability of the swimmer in a droplet is numerically analysed. Specially we found that swimmers may move together with the droplet with the same velocity, which is expected to inspire experimental observation and applications.

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Levy swimmer in an asymmetric channel

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In this article, we numerically study the dynamics of a Levy walker, moving in a two dimensional medium confined by the walls of an asymmetric channel. We show that, the Levy walker will achieve a net directed velocity in the direction preferred by the channel. Other statistical properties of the walker such as mean first passage time and the mean square displacement are also examined.

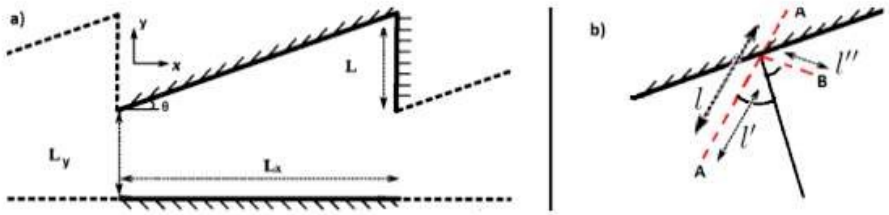

Fig. 1: a) Geometry of an Asymmetric channel. b) The prescription for the scattering from wall. Walker is supposed to have a walk from A to A' that falls out of the channel. The true position after scattering is shown by point B.

It has been shown recently that, in a suspension of diffusing bacteria, it is possible to rotate a small scale asymmetric gear immersed in the suspension [1]. The Levy walk characteristics are also observed for bacteria moving in turbelent flows and also for swarming bacterai [2].
To study net current of run and tumble swimmers in channel, we start with a random initial position inside the channel and study the trajectory for a long time. In conclusion, we show that the out of equilibrium distribution for the step size of a walker, can produce a net current for walker when it is moving in an asymmetric channel.

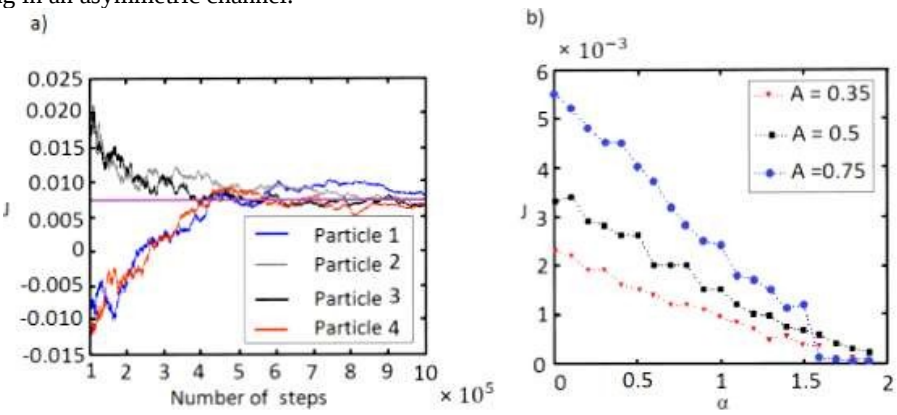

Fig. 2: a) Net current as a function of time steps is shown for some different realizations of the noise. As one can see the current asymptotically reachs a steady value. b) total current of particles in channel with different asymmetry paramete and different Levy indexes α. Current reduces with increasing Levy index and it decreas with asymmetry parameter. Currents tends to zero when Levy index reachs α = 2.

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Thermophoretic microfluidics and microchanines

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Microchannels with asymmetrically ratcheted walls are here shown to behave as effective and versatile microfluidic pumps if locally heated [1]. When the boundary walls have different temperatures, the confined liquid experiences a temperature gradient along the sawtooth edges, which can induce a thermoosmotic flow. Microchannels can be composed by one or two ratcheted walls which can be straight or cylindrical. Varying the channel geometry can not only change the overall fluid flux, but also vary the flow pattern from shear to capillary type, or even to extensional flow. This scheme does not require, multiphase fluids, nor any movable channel parts, although they are possible to be implemented. Similarly, asymmetric non-fixed microgears which are locally heated in a cooled surrounding solvent can be shown to rotate spontaneously and unidirectionally [2]. Interestingly, similar effects can be found by exploiting the diffusiophoretic effect which rely on concentration gradients [3,4]. A mesoscale molecular simulation approach is here employed to investigate the flows which are contrasted with an analytical approach [5,6]. The proposed principle is then very versatile to locally manipulate complex fluids, and a promising tool to recover waste heat, to facilitate cooling of microchips, or to manifacture portable lab-on-a-chip devices.

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Hydrodynamic and Steric Interactions of Sperm Cells in Structured Microchannels

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In confinement, the directed motion of a self-propelled microswimmer is strongly influenced by steric and hydrodynamic surface interactions. Mesoscale hydrodynamics simulations are a powerful tool to study various flagellated and ciliated microorganisms in this environment, ranging from a single flagellated sperm cell to multiciliated microswimmers.

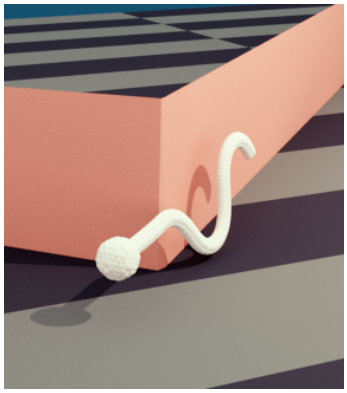

Fig. 1: Sperm cell swimming in a structured microchannel around a 90° corner.

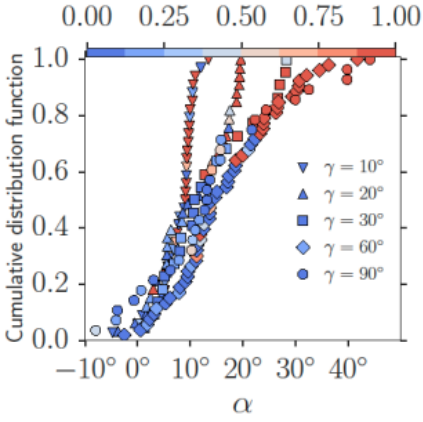

Fig. 2: Accumulated probability distribution of the sperm cell deflection angle α at the corner.

In particular, we have studied the motion of sperm in geometrically structured (zig-zag) microchannels, as shown in Figure 1. This is an interesting geometry for the manipulation and sorting of sperm cells. In general, sperm swim close to walls and surfaces. However, at sharp corners, sperm deflect from the wall with a deflection angle α. This deflection angle is found to depend both on the envelope of the sinusoidal beating shape of the sperm cell and on the orientation of its beating plane (Figure 2). We present a heuristic argument explaining this dependence by an interplay of steric and hydrodynamic surface interactions. Our results are in agreement with recent microfluidic experiments and might provide a better insight in the mechanisms of sperm navigation under strong confinement.

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(Osmotic) Pressure of an active dispersion

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This poster focusses on the concept of pressure of an active dispersion. Whereas for a passive dispersion the pressure exerted on the bounding wall is given by the equation of state of the system, for an active dispersion it has been shown to generally depend on the wall potential [1]. In this poster, we discuss the consequence of the force-free condition on the self-propelled particles (that have to obey Newton's laws) on the interpretation of the concept of pressure, focusing on the influence of the wall potential and the existence of an equation of state.

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Squirmers under gravitation

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A simple yet versatile model for many microswimmers is the spherical squirmer [1]. It propels by means of a tangential flow field it creates on its surface. We investigate different types of squirmers using the method of multi-particle collision dynamics (MPCD) [2], just as in previous simulations, where swimmers in flow [3] and under quasi-two-dimensional confinement [4] were considered.

In this contribution we turn towards systems where gravitational forces that act on the microswimmers are included. This setting allows us to both investigate generic features of such systems and mimic experimental setups, for example, active emulsion droplets [5], Janus colloids [6], and *Volvox* algae [7] under gravity. Previously, theoretical studies on active Brownian particles in external fields, including their sedimentation profiles, have been performed [8, 9]. However, systematic numerical and experimental studies of the collective dynamics under gravity are still rare, especially of the role of hydrodynamics.

Our studies account for effects due to buoyancy, confinement and geometry, and a variation of swimmer type (pusher/puller). We observe a rich phenomenology, depending on the relative strength of graviational forces vs. the swimmers' active propulsion, but also the density of squirmers in the simulation volume.

First, we study single squirmers. After a transient they "float" at a stable height above the bottom wall, only subject to fluctuations, which implies a balance of active speed and sedimentation speed. By changing the gravitational acceleration the point of balance is shifted. This is consistent with the height-dependent friction, and therefore sedimentation velocity, due to the presence of walls [10]. For weak gravitation the swimmer can travel all the way to the upper wall and the dynamics is mainly governed by activity and hydrodynamic interactions.

For small densities of squirmers hydrodynamic interactions (with both the confining walls and other squirmers) influence sedimation profiles, whereas for large densities volume exclusion resulting in layering also becomes important.

In future works we plan to include bottom-heaviness [9] of the squirmers.

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Run-reverse-flick strategy of interacting bacteria

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Bacteria have different swimming strategies for finding nutrition. *Escherichia coli* follow a run and tumble strategy whereas *Vibrio alginolyticus* have a run-reverse-flick pattern [1]. We simulate the latter using molecular dynamics. Furthermore, we study an analytical model based on a master equation. We present effective hydrodynamic equations for this model. Both approaches are validated by comparing to the results of Taktikos et. al. [2]. We also study the effect of particle interactions by varying the filling fraction as well as the ratio of mean forward-to-backward run time (biased run). We find that the diffusion-density coupling parameter has a minimum at a forward to backward runtime ratio of 0.7, which is close to the value 0.6 that was measured for *Vibrio alginolyticus* by Xie et. al. [1].

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Run-and-tumble dynamics of cytoskeletal motor proteins

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Cytoskeletal motor proteins are involved in major intracellular transport processes which are vital for maintaining appropriate cellular function. The motor exhibits distinct states of motility: active motion along filaments, and effectively stationary phase in which it detaches from the filaments and performs passive diffusion in the vicinity of the detachment point due to cytoplasmic crowding. The transition rates between motion and pause phases are asymmetric in general, and considerably affected by changes in environmental conditions which influences the efficiency of cargo delivery to specific targets. By considering the motion of molecular motor on a single filament as well as a dynamic filamentous network, we present an analytical model for the dynamics of self-propelled particles which undergo frequent pause phases. The interplay between motor processivity, structural properties of filamentous network, and transition rates between the two states of motility drastically changes the dynamics: multiple transitions between different types of anomalous diffusive dynamics occur and the crossover time to the asymptotic diffusive or ballistic motion varies by several orders of magnitude. We map out the phase diagrams in the space of transition rates, and address the role of initial conditions of motion on the resulting dynamics.

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Motion of microparticles and quasi-particles in surface waves

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Parametrically excited waves in vertically vibrated containers are referred to as the Faraday waves. Parametric wave excitation has become a standard laboratory tool for generating constantly driven surface ripples in the gravity-capillary range of frequencies. In 2012 it was suggested that ordered or disordered fields of the Faraday waves represent ensembles of oscillating solitons, or oscillons [1]. Such oscillons can be viewed as quasi-particles, which form regular patterns on the liquid surface when the dissipation is high. However when the dissipation on the surface is low (e.g. distilled water), the wave field becomes strongly disordered, or "turbulent", Fig. 1. It was found that at low dissipation and sufficiently high vertical acceleration, the motion of fluid particles on the water surface reproduces in detail the motion of fluid in two-dimensional turbulence. In particular, the Kolmogorov-Kraichnan spectrum $E_k \propto k^{-5/3}$ of flow kinetic energy characterizes the fluid motion in the horizontal plane. Several papers on the Lagrangian statistics of floating tracers revealed that fluid transport follows the classical Taylor single particle dispersion, e.g. [2]. It is possible to bridge the gap between the quasi-particle description of the Faraday waves and the statistical characteristics of the fluid motion on the surface if we consider the horizontal motion of oscillons from the Lagrangian perspective. We compare the motion of the actual fluid particles on the water surface with the motion of the oscillons, or quasi-particles, tracked as the motion of the local wave phase. New results presented here point to a strong connection between the random-walk type motion of fluid particles on the surface and that of the oscillons, or the local wave phases [3].

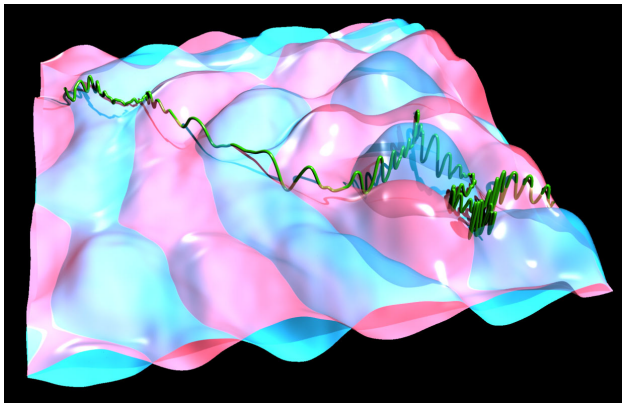

Fig. 1: *Perspective view of a three-dimensional particle trajectory (green) in the Faraday waves.*

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Phase behavior and pressure of active brownian particles

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We study the phase behavior of active colloidal particles by means of computer simulations of the well known, simplistic model system of active Brownian particles in two dimensions. This model exhibits a phase transition that closely resembles the liquid-gas phase transition in equilibrium. After determination of the binodal lines, we aim at finding the critical point of the system.
Apart from the phase diagram, we also studied the pressure in a phase separated state. By inclusion of the active swimming pressure proposed by Takatori et al. in 2014 [1], we found an intensive pressure that shows a negative excess stress in the interface region [2]. This fascinating property is a purely nonequilibrium effect.

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Zero-viscosity modes in active fluids

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Recent experiments report zero- and negative-viscosity states in a bacterial liquid, thought to arise from the cells' collective swimming. Biologically, chemically or physically driven 'superfluids' promise considerable technological potential, but the non-equilibrium conditions under which intrinsic activity and confinement geometry can create inviscid flows are not well understood. Here, we identify the generic mechanisms underlying friction-less dynamics in active liquids, building on a generalized Navier-Stokes model that captures the experimentally observed bulk vortex dynamics in microbial suspensions. We present exact analytical solutions that demonstrate the existence of zero-viscosity modes in active fluids and introduce a computational framework that allows the efficient treatment of previously intractable higher-order shear boundary conditions. Large-scale parameter scans characterize the low-viscosity phase, predict geometry-induced shear-stress resonances and specify conditions for negative-viscosity states amenable to energy-harvesting. Our approach builds on generic assumptions about the symmetries and long-wavelength structure of stress tensors, suggesting that an inviscid phase may be achievable in a broad class of non-equilibrium fluids by tuning confinement geometry and pattern scale selection.

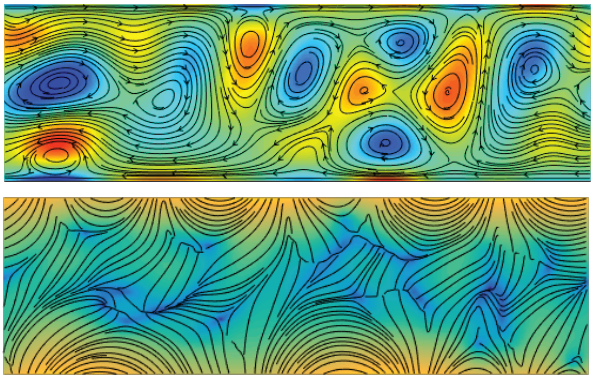

Fig. 1: *Vorticity (top) and stress (bottom) fields in a low-viscosity state.*

Swim pressure on walls with curves and corners

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We investigate the pressure exerted by a gas consisting of "active" particles, which move by their own power. Examples of such particles include living cells and bacteria, as well as artificial swimmers. Using computer simulations and numerical techniques, we study the pressure exerted on walls of different shapes in a simple model for active particles. Our results show that particles easily become trapped on the inside of corners and curved walls, leading to an increase of the pressure in these regions. As a result, objects with the right shape immersed in an "active gas" can be pushed in a specific direction by the active particles. Using our calculations, we provide a way to predict the direction and strength of the force on an obstacle of any shape [1]. Our results can be directly connected to experiments on movable obstacles immersed in suspensions of living bacteria.

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Biohybrid Microtube Swimmers Powered by Captured Bacteria

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Biohybrids are the integration of bioactuators with artificial materials; they exploit the motility and sensing capability of biological cells for micro cargo and drug delivery without reliance on toxic fuel sources[1,2]. For a new type of biohybrid, motile *Escherichia coli* (*E. coli*), were captured in electropolymerized microtubes modified internally with an adsorbed polymer coating. The positively charged, internal polymer coating acted as an attractant and lure for the negatively charged *E. coli*. Single bacteria became partially trapped within the tube and became a source of propulsion to push the microtube though solution generating a biohybrid with an average velocity of approximately 5.0 μm/s. This system could be further modified for magnetic guidance allowing the biohybrids to swim in user defined paths. The biohybrid is the first of its kind and offers exciting opportunities for future bacteria-interface systems and micro-biorobots.

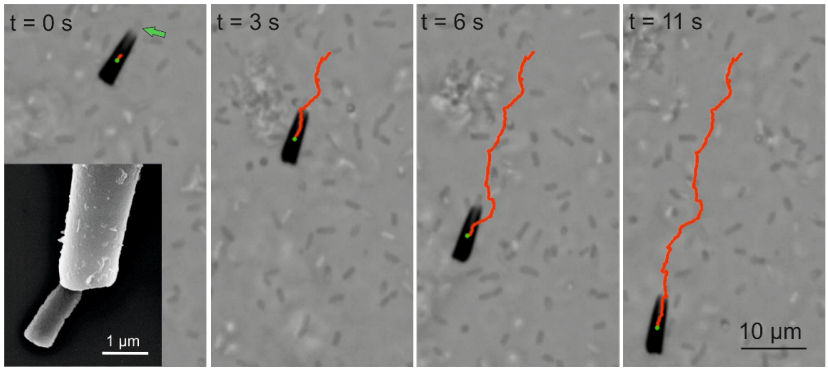

Fig. 1. *Example of E. coli swimming with microtube. Green arrow indicates single bacteria trapped inside tube.*

References

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Computer simulations of magnetocapillary swimmers

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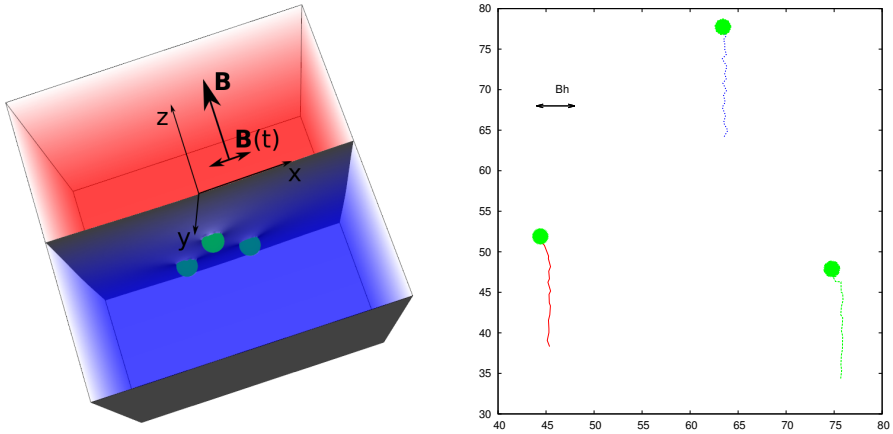
Self-assembled magnetocapillary microswimmers were experimentally demonstrated recently [1]. Here, we study the motion of a magnetocapillary swimmer by means of a hybrid lattice Boltzmann and discrete element method. Three magnetic particles are placed at a fluid-fluid interface, as shown in Fig. 1a. The particles deform the interface due to their weights, leading thus to a capillary attraction force. At the same time, the particles experience a repulsive magnetic dipole-dipole force along with an upwards applied static magnetic field. Through the competing of attractive capillary and repulsive magnetic forces, a stable assembly of the three magnetic particles is achieved. By applying an oscillating horizontal magnetic field, the triplet demonstrates a directed motion (Fig. 1b). We numerically investigate the effect of frequency and direction of the mangetic field on the motion of the swimmer and analyze the results theoretically. In addition, we demonstrate a possible application of magnetocapillary swimmers for cargo transportation [2].



(a) **(b)**

Figure 1: *a) Simulation snapshot of a* 3*-bead magnetocapillary swimmer, b) the bead trajectories of the swimmer.*

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Anisotropic Thermophoresis of Colloidal Rods: Microscopic Geometry Matters

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Colloidal migration in temperature gradient is referred to as thermophoresis. In contrast to particles with spherical shape, elongated colloids may have a thermophoretic response depends on colloid orientation, and more interestingly a non-vanishing thermophoretic force can be induced in a direction perpendicular to the temperature gradient [1]. By means of mesoscale hydrodynamic simulations, we investigate anisotropic thermophoresis of rod-like colloids.

The anisotropic thermophoretic effect can be characterized by two orthogonal thermal diffusion factors, which determine, by linear decomposition approach, the thermal diffusion factor in arbitrary orientation (Fig.1, *left*). In dilute limit, this linear combination relation explains that the temperature gradient induces no alignment in the rods, and shows that the thermophoretic force increases monotonously with the rod length. Rods are constructed by the so-called 'shish-kebab' model what allows us to vary the surface geometry. Remarkably, the degree of anisotropy can be changed, or even reversed by tuning rugosity (Fig.1, *right*). This can be understood since the local microscopic geometry induces different interfacial temperature gradients what results in diverse surface mobilities of colloid. Our study shows that the anisotropic thermophoresis may be controllable by interfacial tunability [2]. This anisotropic effect of thermophoresis has shown to be the basic mechanism that allows the construction of thermophoretic turbines, which move in the presence of an external temperature gradient [1]. Furthermore, this phenomena enables to fabricate micropumps which drive flow flux in a microchannel, when the temperature gradient is employed perpendicularly to the channel.

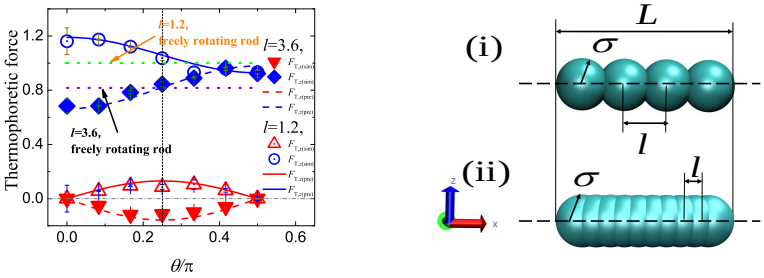

Fig. 1: *Left: Thermophoretic forces measurement of rods with different orientations. Right: Schematic representation of model of rods; rugosity can be differed by tunning number of beads and rod length.*

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Pattern Formation of Microtubules Driven by Kinesins

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It is known that a variety of microorganisms, from bacteria to an epithelial monolayer [1, 2], gather and exhibit characteristic dynamical patterns. In the context of non-equilibrium physics, these are regarded as an example of collective motions of active particles with local interactions. Recently, there has been an increasing interest in both theoretical [3] and experimental studies [1, 2, 4, 5] of collective motions. In particular, the particle-density dependence of dynamical patterns was reported in detail in some theoretical models as well as in experiments. However, it is still an open question how the dynamical patterns are affected by other factors, including the shape of the particles and the microscopic interaction among the particles.

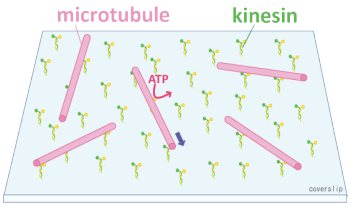

Fig. 1: *A schematic image of motility assay*

To this end, we constructed an *in vitro* system called 'motility assay' (Fig.1), which is composed of microtubules (cytoskeleton) and kinesins (motor proteins). Using surfactant to coat the surface of a cover slip, we succeeded to confine the motions of microtubules to the plane. Here, we report the contribution of the microscopic interaction to the macroscopic pattern formation. In this system, we found a novel pattern of active filaments (Fig.2, left), which we call 'dynamic cluster'. In this pattern, microtubules form dense 'cluster' regions like phase separation at first, and then the clusters swarm. This pattern has not been reported in the other combinations of motility assay [4, 5] and it is rather similar to cluster patterns observed in the collective motion of bacteria [3]. To investigate the mechanism of this pattern formation, we measured collision angles between two microtubules.

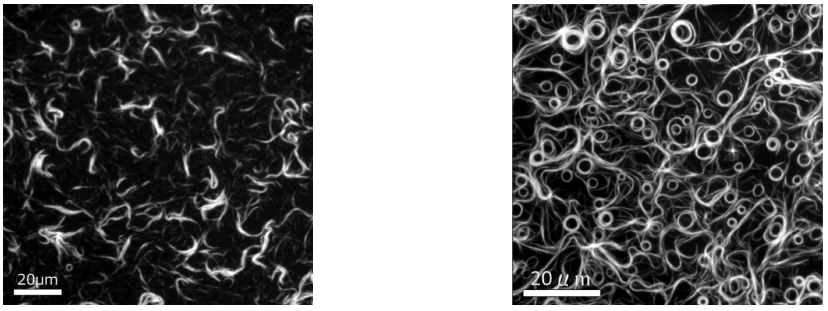

Fig. 2: *Dynamic clusters emerge in the system employing short microtubules (~3um, left) and many loops in the system employing longer microtubules (~8um, right)*

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Back-and-forth motion of active deformable particles

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Active particles exhibit not only a simple translational motion but also other dynamical motions including active spinning motion, spontaneous deformation, and self-replication, even without external cues. Recently the existence of reciprocating motion, i.e. a periodic back-and-forth motion in a straight line, in a homogeneous medium has been found in several different experimental systems such as active droplets floating on aqueous phase [1] and a vertically-vibrated water droplet on a viscus liquid [2].

Here we have carried out a systematic study on the reciprocating motion from a theoretical viewpoint [3]. In order to keep our analysis general, we used a model derived from symmetry considerations for the centre-of-mass velocity and second- and third-mode deformations. We have found two routs to the reciprocating motion. One is due to Hopf instability of a motionless elliptically deformed state. The other is a transition from a rectilinear motion with an oscillatory speed. In both cases, the second-mode deformation breaks the symmetry of the homogeneous space to determine a axis of motion and, together with the third-mode deformation, induces front-rear asymmetry.

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Spheroidal Squirmers – Cooperativity and Clustering

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We propose a hydrodynamic model for a spheroidal microswimmer [1] with two surface velocity modes which is analytically solvable and reduces to the spherical squirmer model of Lighthill and Blake [2] in the limit of equal major and minor semi-axes. Furthermore, we present an implementation of such a spheroidal squirmer in a multiparticle collision dynamics simulation [3]. We investigate the scattering of two spheroidal squirmers in a slit geometry and find a stable fixed point, where two pullers swim cooperatively at a small constant angle (cf. Fig. 1 (left)). Furthermore, we study the collective behavior of spheroidal squirmers in a quasi-2D geometry. Compared to results for spherical squirmers [4], we observe phase separation already at relatively small densities and Péclet numbers. We find that hydrodynamics enhances phase separation (as found in Ref. [4]) and that pullers phase separate at lower densities than neutral squirmers and pushers (in contrast to spherical squirmers, see Ref. [4]).

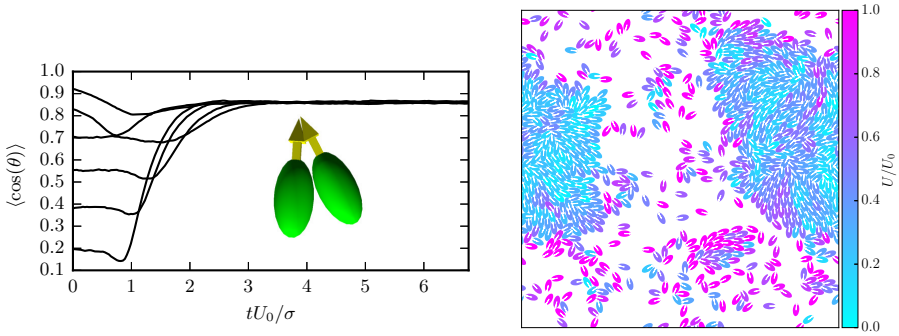

Fig. 1: *Left: Cooperative swimming of two spheroidal pullers in a narrow slit. Right: Phase separation of spheroidal squirmers in quasi-2D system.*

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Cross-streamline migration of chemically active Janus particles in flow

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For microswimmers, the interplay of swimming activity, confinement, and external flow can promote robust directional motion. For example, their direction of propulsion can align against the flow ("upstream rheotaxis") [1,2] or perpendicular to it ("cross-streamline migration") [3]. We report on an experimental and theoretical study of catalytic Janus particles in channel flow. When the particles are inactive, they simply rotate and are carried downstream along fluid streamlines. When the particles are active, they are attracted to certain orientations that are nearly perpendicular to the direction of the flow, and they swim across the channel (Fig. 1, left). We reproduce and rationalize these observations within a deterministic theoretical model of a Janus particle in shear flow near a planar wall (Fig. 1, center). When we add the effect of thermal noise, we obtain probability distributions for the swimmer orientation (Fig. 1, right) that show good agreement with the experimental observations. Our findings could be used to sort microswimmers by activity, as well as to understand how microswimmers would behave in applications involving fluid flow through tight spaces.

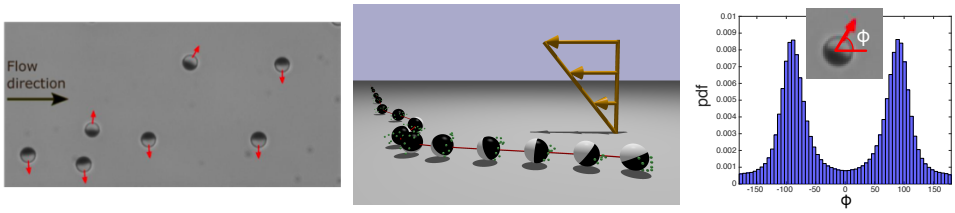

Fig. 1: *(left) Chemically active Janus particles in flow. The particles tend to align (red arrows) mainly in the vorticity direction (i.e., perpendicular to both the direction of flow and the normal of a nearby confining surface), but with a slight downstream orientation. The particles swim across flow streamlines as they move downstream. (center) Trajectory of an active particle in flow obtained from a deterministic theoretical model. The model reproduces the experimentally observed average alignment, including the slight downstream orientation. (right) Theoretical probability distribution for the orientation ϕ (see inset) of a Brownian active Janus particle in flow. The probability is peaked near $\phi = 90^\circ$ and $\phi = 270^\circ$.*

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Diffusion of active Brownian swimmers confined in periodic serpentine channels

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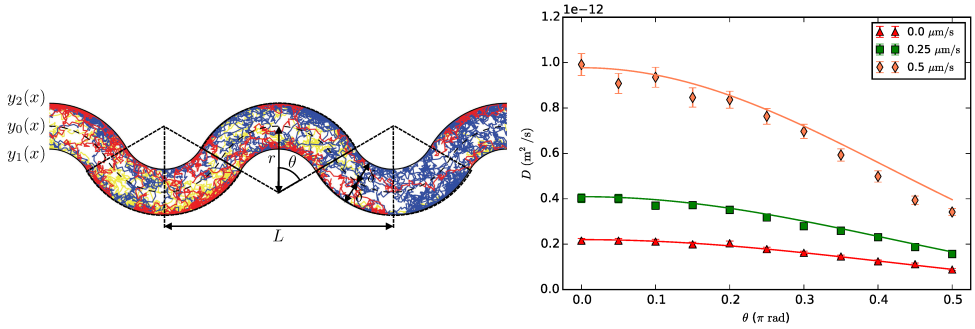
We study the diffusion of a self-propelling microswimmer that is subjected to thermal fluctuations and confined in a narrow two-dimensional periodic channel. In straight channels, the effective diffusion constant D_{eff} of a passive Brownian particle with translational and rotational diffusion coefficients D_T and D_R, respectively, is enhanced by the particle's active self-propulsion at some constant speed v_0 given by $D_{\text{eff}} = D_T + v_0^2/2D_R$ [1]. For channels with varying width and midline, a Fick-Jacobs equation approach is applied and a general expression for the spatially-dependent diffusion coefficient $D(x)$ is obtained after physically arguing that confinement reduces the diffusivity of passive and active particles in the same manner [2].



(a) (b)

Fig. 1: *(a) Schematic of a periodic serpentine channel. The walls $y_1(x)$ and $y_2(x)$, and midline $y_0(x)$ are formed by successive circular arcs of periodic length L characterized by an angle θ, midline radius r and channel width 2δ. (b) Effective diffusion coefficient of a self-propelled microswimmer at various self-propulsion speeds v_0 in serpentine channels of varying tortuosity parameter θ.*

This approach is applied to the periodic serpentine channel described in Figure 1a whose geometry is defined by variations in its midline. The effective diffusion coefficient is obtained by using the Lifson-Jackson formula which averages out the periodic expression for $D(x)$ [3]. The analytical diffusion constant was found to be dependent only on the tortuosity of the channel parametrized by the angle θ, and independent of the width 2δ and period length L. In Figure 1b, analytical results for the effective diffusion coefficients are compared with numerical results obtained from Brownian dynamics simulations [4]. Good agreement is observed for self-propelled particles with low swimming speeds and for channels with slowly varying width and midline.

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Graphene-Based Microbots for Toxic Heavy Metal Removal and Recovery from Water

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Heavy metal contamination in water is a serious risk to the life on earth[1]. Currently, new nanosystems and nanomaterials have been developed for the fast and efficient removal of pollutants and heavy metals from water[2-4].

Here, we report graphene oxide-based microbots (GOx-microbots) as active self-propelled systems for the capture, transfer, and removal of a heavy metal (i.e., lead) and its subsequent recovery for recycling purposes[5]. Microbots' structure consists of nanosized multilayers of graphene oxide[6], nickel, and platinum, providing different functionalities. The outer layer of graphene oxide captures lead on the surface, and the inner layer of platinum functions as the engine decomposing hydrogen peroxide fuel for self-propulsion, while the middle layer of nickel enables external magnetic control of the microbots. Mobile GOx-microbots remove lead 10 times more efficiently than nonmotile GOx-microbots, cleaning water from 1000 ppb down to below 50 ppb in 60 min. Furthermore, after chemical detachment of lead from the surface of GOx-microbots, the microbots can be reused.

Finally, we demonstrate the magnetic control of the GOx-microbots inside a microfluidic system as a proof-of-concept for automatic microbot-based system to remove and recover heavy metals[5].

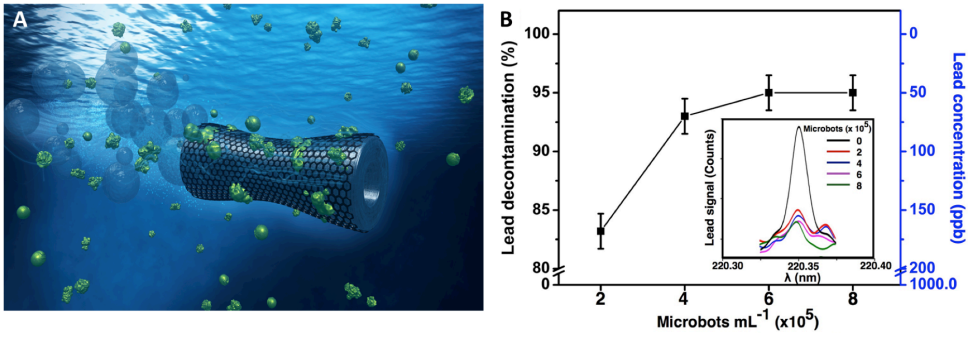

Fig. 1 *(A)GOx-microbot swimming in polluted water. (B) Decontamination of Pb(II) ions for different concentrations of GOx-microbots after 1 h in the presence of H_2O_2 (1.5% v/v) and of SDS.*

(0.1% w/v). (Inset: ICP-OES signal of lead concentration after 1 h of decontamination process for increasing amount of motors.)

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Clearing Out a Maze: A Random Walk in Search for Food

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We study chemotaxis in a porous medium using as a model a biased, "hungry" random walk on a percolating cluster of a randomly diluted two-dimensional lattice. The walker performs random nearest-neighbor jumps, biased to the places where it encounters a resource ("food") that it then consumes. The model thus resembles the 1980s arcade game Pac-Man controlled by a player making random decisions. Following a food bias in a stochastic process resembles the chemotactic motion of bacteria in porous media. The dynamics of microswimmers in crowded environments of obstacles is of obvious importance for the physics of biological systems, and also for applications such as groundwater decontamination or microbial enhanced oil recovery.

The unbiased random walk on the percolating cluster is one of the simplest models for transport in porous media. It shows anomalous dynamics: e.g., the mean-squared displacement grows like a nontrivial power law in time. We observe that the hungry walk on the percolating cluster exhibits power-law dynamics with a new exponent that is smaller than that controlling the unbiased motion. Changing the propensity of the walker towards food, power laws with a propensity-dependent exponent are found over more than five decades in time. We rationalize this finding by conjecturing that the hungry walker is drawn more strongly into the culs-de-sac of the percolating cluster, out of which the process has to return more slowly.

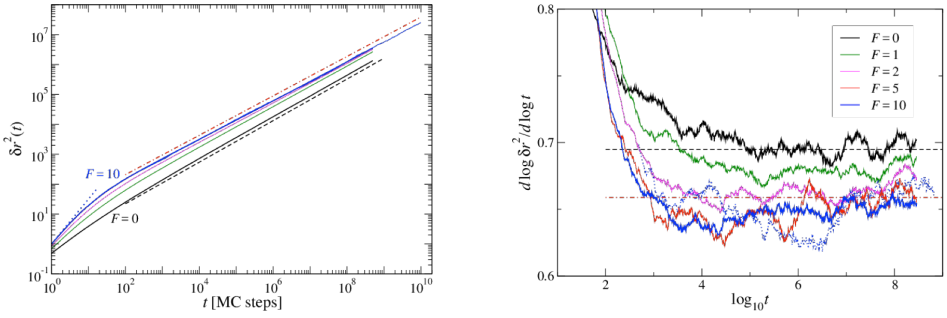

Fig. 1: *(left) Mean-squared displacements (MSD) of the "Pac-Man" process or different food propensities (increasing from bottom to top), as a function of time. (right) Effective exponent obtained from the logarithmic derivative of the MSD. Horizontal dashed lines indicate the exponents expected for the unbiased random walk on the percolating cluster (upper line), respectively for its all-cluster average (bottom line).*

Shape-Induced Hydrodynamic Effects in Thermophoretic Microswimmers

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Thermophoresis refers to the drift motion experienced by particles immersed in a fluid with an intrinsic gradient of temperature. In thermophoretic swimmers a local temperature gradient is generated due to the existence of a material that can quickly absorb heat from a heating source such as irradiating light. An asymmetric distribution of the heated material on the particle surface translates into a persistent particle motion [1]. The motion direction is determined by the thermophoretic character of the particle, whether thermophobic or thermophilic [2]. Experimentally, these particles have been synthesized as Janus spherical particles being half coated with gold [1]. Other shapes such as dimer swimmers have already been investigated resulting in a significantly different hydrodynamic behaviour [3, 4].
In this work, we first study the effect of the swimmer shape by means of computer simulations. We employ a well-established mesoscale simulation technique that couples multi-particle collision dynamics (MPC) as a coarse-grained description of the fluid with molecular dynamics for an adequate resolution of fluid-colloid interactions [5]. This methodology offers an efficient inclusion of hydrodynamics, thermal fluctuations, and the sustainability of temperature gradients. Moreover, the tunable fluid-solvent interactions allow us to explore various thermophoretic behaviors. We characterize the swimming behavior as a function of the swimmer shape, *e.g.* self-propelled dimers with asymmetric sizes, or rod-like swimmers with parallel and perpendicular propulsion.
Interaction between pairs of swimmers is investigated as well. Thermophoretic self-propelled particles interact with each other not only through direct pair interactions, but they will react as well to each other's temperature gradients and to their hydrodynamically induced flow fields. Whether and how pairs of swimmers form persistent geometric structures, or swim independently, will determine the collective behavior of large assemblies of these swimmers.

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Artificial microswimmers controlled by light

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Since light can be easily and widely manipulated, photoresponsive materials are particularly attractive as actuators in micro-scale applications, such as the development of microswimmers [1-2]. In particular, light allows for the independent control of multiple microswimmers at the same time. Here we describe an experimental setup adopted for the optical control of the microswimmers. We also present the fabrication and selective control of photoresponsive artificial microswimmers by structured light. Their performances as a function of the incident light field are analysed. In particular, we demonstrate the achievement of selective control of the microswimmers, and we investigate hydrodynamic interactions among optically-controlled microswimmers.

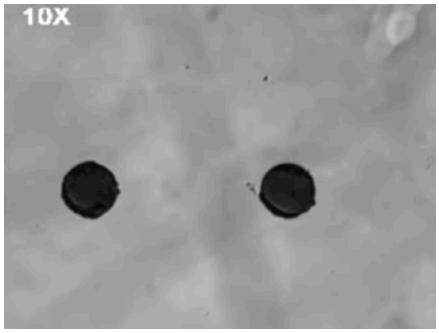

Fig. 1: *Two microswimmers independently controlled by light.*

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Spermbots for cargo transport and delivery

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Spermbots, are tiny motors with sizes in the micrometer range which are coupled to a sperm cell to help them carry cargo to a target. This cargo can be of different nature, either genetic information for the fertilization of an oocyte or a drug for treating cervical cancer.
In the first case, we aimed to help sperms carry out their natural function when sperms do not show progressive motion or are not physically strong enough to swim through the female reproductive tract to reach the fertilization site. These two sperm deficiencies are the main causes of male infertility, diagnosed in about 30 % of the cases. Up to now, these problems have been mainly addressed by artificial insemination and *in vitro* fertilization. With spermbots we aim to enhance the success rate of the artificial insemination, which takes place in *in vivo* conditions. For achieving this goal, two different microrobotic devices are presented: the first one is based on a rolled-up magnetic thermoresponsive tube that serves to capture a motile sperm, direct its motion toward the oocyte, and release it there [1]. The second one is a customized microhelix that is able to actively collect an immotile sperm, carry it to the oocyte, and release the sperm to let it fuse with the oocyte cell membrane. Those micromotors are suitable for these tasks due to potent, controllable and harmless 3D motion behavior that is directed by an external magnetic field controller. The potential of this novel approach toward assisted reproduction will be put into a perspective without forgetting some of the remained challenges that we still need to address to achieve successful fertilization by using artificially motorized/guided sperms [2].
For the second case of cargo delivery, the use of sperm as potential DNA- or protein-based drug carrier has been proposed. Here, sperms serve as propulsion source while a tetrapod-like microstructure is used for magnetic guidance as well as for releasing the sperm mechanically. When the arms of the microstructure hit Hela Cells, they bent, opening a way to release the sperm. Bovine serum albumin (BSA), as a model drug, has been loaded into the sperm cells and is locally distributed onto Hela cells after the sperm release. In the near future, not only the hybrid system could be used for drug delivery, but also, the mechanically triggered arms themselves could be applied on microscaled intelligent robotics.

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Single active Brownian particles moving in a random environment

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From the perspective of physics, biological microswimmers such as bacteria can be viewed as active particles. Since bacteria often inhabit porous or crowded environments, we examine the dynamics and transport of active particles in a complex environment. We focus on active Brownian particles (ABP), which provide a simple model for microswimmers. ABPs have an intrinsic speed and perform rotational as well as translational diffusion.

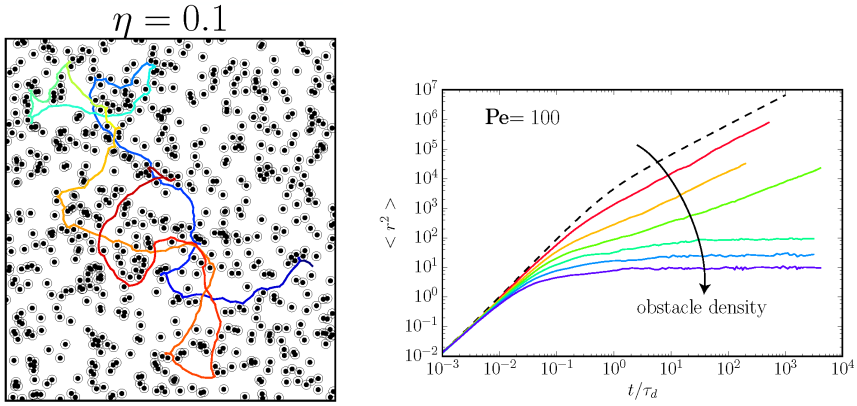

Fig. 1: *Left: Trajectory of a microswimmer at* Pe$= 100$ *in an disordered environment. The black circles represent the obstacles and the surrounding circles indicate the excluded volume. Right: Mean squared displacement for a microswimmer at* Pe$= 100$ *for different obstacle densities* η*. The dashed line shows the analytical solution in free space.*

We study the transport of ABPs moving in a two-dimensional environment of randomly placed and fixed obstacles of a given number density η. A typical obstacle configuration and a trajectory of an ABP at Pe$= 100$ is shown in the left figure. Beyond a critical density η_c no percolating cluster of free space exists and the mean squared displacement of the swimmers saturates at a characteristic trap size. Below this density the swimmer shows diffusive dynamics with an effective diffusion coefficient which is smaller then the diffusion coefficient in free space. At intermediate time scales and close to the percolation threshold the swimmers exhibit subdiffusive transport. These results are summarized in the right figure, which shows the mean squared displacements for different obstacle densities η.

We observe that passive particles or swimmers with a low Péclet number stay longer in the subdiffusive regime than swimmers with a high Péclet number. We also find that increasing the Péclet number influences the spatial distribution of swimmers in the environment. Active swimmers accumulate at the surface of obstacle clusters whereas passive particles or slow swimmers are typically found in the bulk. Moreover, the persistence length of a swimmer severely decreases in the presence of obstacles.

Index

Talks

Poster

	Tuesday Oct-04	Wednesday Oct-05	Thursday Oct-06	Friday Oct-07
08:00	Registration			
09:00	Poon	Kapral	Aronson	Bausch
09:30	Kantsler	Golestanian	Ahmed	Saintillan
10:00	Lavrentovich	van Roij	Fischer	Kierfeld
10:20	DeSimone	Popescu	Maaß	Mourran
10:40	Eckhardt	de Graaf	Seemann	Klumpp
11:00	Coffee	Coffee	Coffee	Coffee
11:20	Lauga	Peyla	Marchetti	Pagonabarraga
11:50	Adhikari	Wilson	Kafri	Bär
12:20	Brumley	Ishimoto	Blaschke	Menzel
12:40	Friedrich	Alvarez	Virnau	Bechinger
13:00	Palberg	Elgeti	Günther	Mikulich
13:20	Lunch	Lunch	Lunch	Lunch
14:30	Giardina	Brady	Weibel	
15:00	di Leonardo	Tierno	Wolgemuth	
15:30	Sanchez	Climent	Drescher	
15:50	Magdanz	Voigtmann	Winkler	
16:10	Pella	Ripoll	Engstler	
16:30	Coffee	Poster	Poster	
16:50	Würger			
17:20	Chate			
17:50	Kroy			
18:10	Santer			
			Dinner	

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