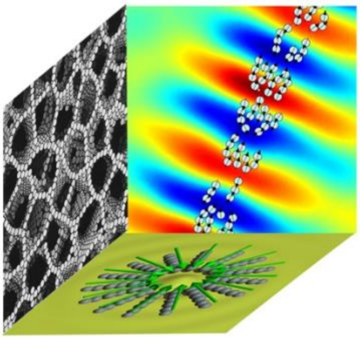
Emerging colloidal dynamics away from equilibrium.
Chiral active systems.



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The Condensed matter Journal

1. Description

Soft matter systems in Nature, at length-scales spanning the nano- and the microscale, exhibit self-assembly far from the thermal equilibrium. Modern self-assembly techniques aiming to produce complex structural order or functional diversity often rely on non-equilibrium conditions in the system. Light, electric, or magnetic fields are often used to induce complex out-of-equilibrium ordering. Such dissipative colloidal materials use energy to generate and maintain structural complexity. Nontrivial collective dynamics and emerging large-scale structures are often observed in experiments and numerical simulations [1-24].

Chirality is an intrinsic fundamental property of many natural and artificial systems. Understanding the role of chirality in dynamics of interacting many-body systems is a major challenge. There has been a surge of interest in collective phenomena that arise when chirality comes into play in both biological [2-4] or artificial [5-9] systems. Microsystems driven out-of-equilibrium by external torques [10-18] are ideal model systems to investigate these phenomena since they avoid the inherent complexity of biological active matter [19]. Spinning particles dispersed in a fluid represent a special class of artificial active systems that inject vorticity at the microscopic level [20-23]. Dense collections of interacting spinning particles represent a chiral fluid [24], which breaks parity and time-reversal symmetries, and displays a novel viscosity feature called the odd viscosity [25, 26]. The odd viscosity has been identified in interacting chiral spinners [24], and it led to remarkable effects such as production of flow perpendicular to the pressure [26], topological waves [27], or the emergence of edge currents [24]. Magnetic rollers dynamically assemble into a vortex under harmonic confinement, that spontaneously selects a sense of rotation and is capable of chirality switching [28, 29]. Multiple motile vortices unbound from any confinement have been revealed in ensembles of magnetic rollers powered by a uniaxial field [30]. Oscillating chiral flows were generated when a roller liquid was coupled to certain obstacles [31]. There has been an increasing effort to investigate collective phenomena in systems with chiral active units [8, 32-38]. Synchronized self-assembled magnetic spinners at the liquid interface revealed structural transitions from liquid to nearly crystalline states and demonstrated reconfigurability coupled to a self-healing behavior [39]. Activity-induced synchronization leading to a mutual flocking, and chiral self-sorting has been observed in modeled ensembles of self-propelled circle swimmers [40]. Shape anisotropic particles powered by the Quincke phenomenon led to the realization of chiral rollers (similar to circle swimmers) with spontaneously selected handedness of their motion and activity-dependent curvature of trajectories [42]. Multiple unconfined vortices with either polar or nematic ordering of particles have been revealed [42].

Developing an understanding of complex dynamics in chiral systems driven out-of-equilibrium by external fields represents a significant theoretical and computational challenge. Some of the features may be understood using phenomenological continuum descriptions [43,44,45] Nevertheless, the microscopic mechanisms leading to the dynamic self-assembly and their relations to the emergent behavior in chiral fluids often remain unclear. *Computer simulations are practically the only method to theoretically investigate such questions*; however, modeling the nonequilibrium self-assembly presents a huge computational challenge due to the complex many-body interactions and collective dynamics on different time scales. One of the main challenges is to properly account for the particle-fluid coupling. On a coarse-grained level, the fluid flow around colloids is modeled by molecular dynamics methods like Lattice-Boltzmann [41] and Multi Particle Collision Dynamics [46, 47]. An alternative approach is to describe the colloidal dynamics by molecular dynamics simulations or an amplitude equation (Ginzburg-Landau type equation) coupled to the Navier-Stokes equations describing large-scale time-averaged hydrodynamic flows induced by the colloids [30, 48].

Key References

[1] Guo-Jun Liao, S.H.L. Klapp, "Emergent vortices and phase separation in systems of chiral active particles with dipolar interactions", Soft Matter, Advance Article (2021)

[2] V. Soni, E. S. Bililign, S. Magkiriadou, S. Sacanna, D. Bartolo, M. J. Shelley, and W. T. M. Irvine, "The odd free surface flows of a colloidal chiral fluid" Nat. Phys. ***15****, 1188 (2019)*

[3] A. Souslov, K. Dasbiswas, M. Fruchart, S. Vaikuntanathan, and Vincenzo Vitelli, "Topological Waves in Fluids with Odd Viscosity" Phys. Rev. Lett. ***122****, 128001 (2019)*

[4] G. Kokot, A. Snezhko, "Manipulation of emergent vortices in swarms of magnetic rollers." Nat. Commun. ***9****, 2344 (2018)*

[5] A. Kaiser, A. Snezhko, I. S. Aranson, "Flocking ferromagnetic colloids." Sci. Adv. ***3****, e1601469 (2017)*

[6] K Han, G Kokot, O Tovkach, A Glatz, IS Aranson, A Snezhko, "Emergence of self-organized multivortex states in flocks of active rollers." Proc. Nat. Acad. Sci. U. S. A. ***117*** *(18), 9706 (2020)*

[7] B. Zhang, B. Hilton, C. Short, A. Souslov, A. Snezhko, "Oscillatory chiral flows in confined active fluids with obstacles." Phys. Rev. Res. ***2****, 043225 (2020)*

[8] S. Farhadi, S. Machaca, J. Aird, B. O. Torres Maldonado, S. Davis, P. E. Arratia, D. J. Durian, Dynamics and thermodynamics of air-driven active spinners. Soft Matter ***14****, 5588 (2018)*

[9] C. Scholz, M. Engel, T. Pöschel, Rotating robots move collectively and self-organize. Nat. Commun. ***9****, 931 (2018)*

[10] A. M. Brooks, M. Tasinkevych, S. Sabrina, D. Velegol, A. Sen, K. J. M. Bishop, Shape-directed rotation of homogeneous micromotors via catalytic self-electrophoresis. Nat. Commun. ***10****, 495 (2019)*

[11] B. C. van Zuiden, J. Paulose, W. T. M. Irvine, D. Bartolo, V. Vitelli, Spatiotemporal order and emergent edge currents in active spinner materials. Proc. Natl. Acad. Sci. U.S.A. ***113****, 12919 (2016)*

[12] N. H. P. Nguyen, D. Klotsa, M. Engel, S. C. Glotzer, Emergent collective phenomena in a mixture of hard shapes through active rotation. Phys. Rev. Lett. ***112****, 075701 (2014)*

[13] T. Markovich and T. C. Lubensky, "Odd viscosity in active matter: Microscopic origin and 3D effects" arXiv:2006.05662 (2020)

[14] K. Yeo, E. Lushi, P. M. Vlahovska, Collective dynamics in a binary mixture of hydrodynamically coupled microrotors. Phys. Rev. Lett. ***114****, 188301 (2015)*

[15] K. Han, G. Kokot, S. Das, R. G. Winkler, G. Gompper, A. Snezhko, "Reconfigurable structure and tunable transport in synchronized active spinner materials." Science advances ***6*** *(12), eaaz8535 (2020)*

[16] D. Levis, I. Pagonabarraga, B. Liebchen, Activity induced synchronization: Mutual flocking, chiral self-sorting. Phys. Rev. research ***1****, 023026 (2019)*

[17] S. Chen, G.D. Doolen, "Lattice Boltzmann method for fluid flows", Annu. Rev. Fluid Mech. ***30****, 329 (1998)*

[18] B. Zhang, A. Sokolov, A.Snezhko, Reconfigurable emergent patterns in active chiral fluids. Nature Comm. ***11****,1 (2020)*

[19] Brenner, H. and Nadim, A. The Lorentz reciprocal theorem for micropolar fluids. Journal of EngineeringMathematics, ***169*** *(1996)*

[20] Avron, J. E., Seiler, R. Zograf, P. G. Viscosity of Quantum Hall Fluids.Physical Review Letters, ***697*** *(1995)*

[21] P. Wiegmann, P. and Abanov, A. G. Anomalous Hydrodynamics of Two-Dimensional Vortex Fluids. Physical Review Letters ***113****, 034501 (2014)*

[22] A. Malevanets and R. Kapral, "Solute molecular dynamics in a mesoscale solvent", J. Chem. Phys. ***112****, 7260 (2000)*

[23] G Gompper, T Ihle, DM Kroll, RG Winkler, "Multi-particle collision dynamics: A particle-based mesoscale simulation approach to the hydrodynamics of complex fluids", Advances in polymer science ***221****, 1 (2009)*

[24] M. Belkin, A. Glatz, A. Snezhko, I. Aranson, "Model for dynamic self-assembled surface structures", Phys. Rev. E ***82*** *(R), 015301 (2010)*

[25] P. Tierno, R. Muruganathan, and T. M. Fischer, "Viscoelasticity of Dynamically Self-Assembled Paramagnetic Colloidal Clusters", Phys. Rev. Lett. ***98****, 028301 (2007)*

[26] Riedel, K. Kruse, and J. Howard, "A Self-Organized Vortex Array of Hydrodynamically Entrained Sperm Cells", Science ***309****, 300 (2005)*

[27] Y. Sumino, K. H. Nagai, Y. Shitaka, D. Tanaka, K. Yoshikawa, H. Chaté, K. Oiwa "Large-scale vortex lattice emerging from collectively moving microtubules", Nature ***483*** *(7390), 448*

[28] A. P. Petrov, X.-L. Wu, and A. Libchaber, "Fast-Moving Bacteria Self-Organize into Active Two-Dimensional Crystals of Rotating Cells" Phys. Rev. Lett. ***114****, 158102 (2015)*

[29] Bartosz A. Grzybowski, Howard A. Stone and George M. Whitesides, "Dynamic self-assembly of magnetized, millimetre-sized objects rotating at a liquid–air interface", Nature ***405****, 1033 (2000)*

[30] C. Scholz, A. Ldov, T. Pöschel, M. Engel, H. Löwen "Surfactants and rotelles in active chiral fluids" Science Advances ***7*** *(16), eabf8998 (2021)*

[31] G. Kokot, S. Das, R. Winkler, G. Gompper, I. Aranson, and A. Snezhko, "Active turbulence in a gas of self-assembled spinners" Proc. Nat. Acad. Sci. U.S.A. ***114****, 12870 (2017)*

[32] B. C. van Zuiden, J. Paulose, W. T. M. Irvine, D. Bartolo, and V. Vitelli, "Spatiotemporal order and emergent edge currents in active spinner materials" Proc. Natl Acad. Sci. USA ***113****, 12919 (2016)*

[33] C. Scholz, M. Engel, and T. Pöschel, "Rotating robots move collectively and self-organize" Nature Comm. ***9****, 931 (2018)*

[34] J. Dobnikar, A. Snezhko, A. Yethiraj, "Emergent colloidal dynamics in electromagnetic fields", Soft Matter ***9****, 3693 (2013)*

[35] F. Ma, S. Wang, D. T. Wu and N. Wu, "Electric-field–induced assembly and propulsion of chiral colloidal clusters" Proc. Natl. Acad. Sci. U. S. A. ***112****, 6307 (2015)*

[36] Z. Shen, A. Würger and J. S. Lintuvuori "Hydrodynamic self-assembly of active colloids: Chiral spinners and dynamic crystals" Soft Matter, ***15****, 1508 (2019)*

[37] B. A. Grzybowski and G. M. Whitesides, "Dynamic Aggregation of Chiral Spinners" Science ***296****, 718 (2002)*

[38] J. Yan, M. Bloom, S. Chul Bae, E. Luijten "Linking synchronization to self-assembly using magnetic Janus colloids", Nature, ***491****, 7425 (2012)*

[39] J. E. Martin, A. Snezhko, "Driving self-assembly and emergent dynamics in colloidal suspensions by time-dependent magnetic fields", Rep. Prog. Phys. ***76****, 126601 (2013)*

[40] R. Di Leonardo, A. Buzas, L. Kelemen, G. Vizsnyiczai, L. Oroszi, and P. Ormos, "Hydrodynamic Synchronization of Light Driven Microrotors" Phys. Rev. Lett. ***109****, 034104 (2012)*

[41] N. Narinder, C. Bechinger and J. R. Gomez-Solano "Memory-Induced Transition from a Persistent Random Walk to Circular Motion for Achiral Microswimmers", Phys. Rev. Lett. ***121****, 078003 (2018)*

[42] C. Lozano, J. Ruben Gomez-Solano and C. Bechinger "Active particles sense micromechanical properties of glasses" Nat. Materials, ***18****, 1118 (2019)*

[43] M. C. Marchetti, J. F. Joanny, S. Ramaswamy, T. B. Liverpool, J. Prost, M. Rao, and R. Aditi Simha "Hydrodynamics of soft active matter" Reviews of Modern Physics ***85*** *(3), 1143*

[44] I. Llopis and I. Pagonabarraga, "Dynamic regimes of hydrodynamically coupled self-propelling particles Europhys. Lett. ***75****, 999 (2006)*

[45] M. Leoni and T. B. Liverpool, "Dynamics and interactions of active rotors" Europhys. Lett. ***92****, 64004 (2010)*

[46] N. H. P. Nguyen, D. Klotsa, M. Engel, and S. C. Glotzer, "Emergent Collective Phenomena in a Mixture of Hard Shapes through Active Rotation" Phys. Rev. Lett. ***112****, 075701 (2014)*

[47] Z. Shen and J. S. Lintuvuori, "Hydrodynamic clustering and emergent phase separation of spherical spinners" Phys. Rev. Research ***2****, 013358 (2020)*

[48] D. Banerjee, A. Souslov, A. G. Abanov, and V. Vitelli, "Odd viscosity in chiral active fluids" Nature Comm. ***8****, 1573 (2017)*

2. Program

Day 1 - Wednesday March 1st 2023

- 08:45 to 08:50 - Registration
- 08:50 to 09:00 - Welcome and Introduction

Session 1. Chair: Pietro Tierno

- 09:00 to 09:30 - **Benno Liebchen**
  Memory-induced chirality in self-freezing active droplets
- 09:30 to 10:00 - **Helena Massana-Cid**
  Magnetic colloidal crystals activated by light-driven bacteria
- 10:00 to 10:30 - Coffee break

Session 2. Chair: Hugues Chaté

- 10:30 to 11:00 - **Andreas Menzel**
  Chiral active objects moving in discrete steps towards a remote target
- 11:30 to 12:00 - **Thomas Fischer**
  Topological manipulation of magnetic colloids on chiral magnetic patterns
- 12:00 to 14:00 - Lunch

Session 2. Chair: Thomas M. Fischer

- 14:00 to 14:30 - **Anton Souslov**
  Active solids
- 14:30 to 15:00 - **Pietro Tierno**
  Pattern formation in shaking achiral rotors
- 15:00 to 15:30 - **Tali Khain**
  Drifting and twirling in a 3D chiral fluid
- 15:40 to 16:40 - Poster session & aperitif
- 16:40 to 18:00 - Discussion
- 19:00 to 22:30 - Dinner (not organized by CECAM)

Day 2 - Thursday March 2nd 2023

Session 3. Chair: Sabine Klapp

- 09:00 to 09:30 - **Gerhard Gompper**
  Emergent active turbulence in dense bacterial and colloidal suspensions
- 09:30 to 10:00 - **Demian Levis**
  Dynamics and "thermodynamics" of dense assemblies of spinning particles
- 10:00 to 10:30 - Coffee break

Session 4. Chair: Gerhard Gompper

- 10:30 to 11:00 - **Alexey Snezhko**
  Emergent dynamics and control of chiral states in flocks of active colloids
- 11:00 to 11:30 - **Ignacio Pagonabarraga**
  Collective chirality and emergent patterns in active matter
- 11:30 to 12:00 - **Hugues Chaté**
  Robust edge flows in swarming bacteria colonies
- 12:00 to 14:00 - Lunch

Session 5. Chair: Ignacio Pagonabarraga

- 14:00 to 14:30 - **Ran Ni**
  Non-equilibrium hyperuniform fluids
- 14:30 to 15:00 - **Denis Bartolo**
  Active hydraulics
- 15:00 to 15:30 - Coffee break
- 15:30 to 16:00 - **Arthur Straube**
  Depinning transition of self-propelled particles
- 16:00 to 16:30 - **Petia Vlahovska**
  Active suspensions: Collective dynamics of quincke-powered colloids
- 16:30 to 18:30 - Poster session & aperitif
- 18:30 to 19:00 - Discussion by the poster/ Networking
- 19:00 to 23:00 - Social dinner

Day 3 - Friday March 3rd 2023

Session 6. Chair: Alexey Snezhko

- 10:00 to 10:30 - **Sabine Klapp**
  Chiral patterns in active systems: Vortex lattices and rotating swarms
- 10:30 to 11:00 - **Modesto T Lopez-Lopez**
  Soft magnetic actuators programmed at the preparation step by particle chaining
- 11:00 to 11:30 - Coffee break
- 11:30 to 12:00 - **Andrejs Cebers**
  Chirality determined motion of magnetotactic bacteria swarms

Closing session

- 12:00 to 12:50 - Discussions
- 12:50 to 13:00 - Closing Word

3. Abstracts

Active hydraulics

Denis Bartolo

École Normale Supérieure Lyon, France

Hydraulics consists in controlling fluid flows in networks of pipes and channels.
After eight millennia of fundamental and applied research, we know that the geometry of the channel-network, and the location of the actuators needed to power fluid motion fully determine the flows viscous liquids. However, over the past decade, we have learned how to engineer active fluids actuated from within. Countless experiments and theories have demonstrated their spontaneous laminar flows in isolated channels. But, the emergent flows of active matter filling interconnected channel networks remains virtually uncharted and poorly understood. I will try to lay out the primary laws of active hydraulics, and show how active flows in channel networks realize dynamical spin ices.

Active solids

Anton Souslov

University of Bath, United Kingdom

Active solids consume energy to allow for actuation and shape change not possible in equilibrium. In this talk, I will focus on the elasticity of systems as wide-ranging as living matter, far-from-equilibrium hydrogels, and mechanical structures composed of active robotic components. First, I will introduce our recent work on hydrogel spheres being lowered onto a hot plate [1]. As the bottom vaporizes, the resulting flow couples tightly to elastic deformations within the sphere, giving either spontaneous bouncing or steady-state floating as manifestation of the so-called elastic Leidenfrost effect. I will present theory and simulations of the floating case, which demonstrate a remarkable phenomenon: the heavier the solid, the higher it floats. Finally, I will discuss the general competition between active boundary stresses and an elastic bulk, giving rise to shape change via so-called active elastocapillarity [2]. These results provide theoretical underpinning for recent experiments and point to the design of novel soft machines.

[1] Thermodynamic lubrication in the elastic Leidenfrost effect. Jack Binysh, Indrajit Chakraborty, Mykyta V. Chubynsky, Vicente Luis Diaz Melian, Scott R. Waitukaitis, James E. Sprittles, Anton Souslov.arXiv:2207.02769

*[2] J. Binysh, T. Wilks, A. Souslov, Sci. Adv., **8**, (2022)*

Active suspensions: Collective dynamics of quincke-powered colloids

Petia Vlahovska

Northwestern University, United States

Self-propelled particles such as swimming bacteria or motile colloids spontaneously self-organize into large-scale dynamic structures that move around like fluid when viewed on a scale much larger than the individuals. A popular means to propel colloids is the Quincke rotation, e.g., by simply letting the particles roll on a surface [1]. In this talk, I will overview how Quincke rollers can be designed to perform Run-and-Tumble-like locomotion mimicking bacteria such as E. coli [2]. Populations of these Quincke random walkers self-organize and exhibit behaviors reminiscent of bacterial suspensions such as dynamic clustering and mesoscale turbulent-like flows, and new behaviors such as emergent multi-vortex states [3]. When enclosed in a drop, the Quincke rollers drive strong shape fluctuations and drop motility resembling amoeba crawling [4]. I will highlight a new regime where the Quincke rotors not roll but lift off the electrode. The hovering Quincke assemble into various structures like kebabs (unpublished).

*[1] A. Bricard, J. Caussin, N. Desreumaux, O. Dauchot, D. Bartolo, Nature, **503**, 95 (2013)*

*[2] H. Karani, G. Pradillo, P. Vlahovska, Phys. Rev. Lett., **123**, 208002 (2019)*

*[3] H. Ye, Y. Li, T. Zhang, Soft Matter, **17**, 3560 (2021)*

*[4] G. Kokot, H. Faizi, G. Pradillo, A. Snezhko, P. Vlahovska, Commun. Phys., **5**, 91 (2022)*

Chiral active objects moving in discrete steps towards a remote target

Andreas Menzel
Universität Magdeburg, Germany

Instead of self-propelling particles that move along straight lines when unperturbed, we consider chiral objects that follow persistently bent trajectories. Moreover, instead of particles that continuously evolve their positions in time, our objects proceed in discrete steps. A third ingredient makes the objects migrate towards a remote target or orient along an externally imposed direction [1].

Remarkably, this combination leads to pronounced nonlinear dynamics that is reflected by the shapes of the trajectories already for one single object [1]. We find regular polygon-shaped trajectories for vanishing tendencies of heading towards the target. They turn into cycloidal-like trajectories for slightly nonvanishing heading. Further increasing this trend, we observe straight, zigzag-like, double-zigzag-like, or higher-order-zigzag-like trajectories. From a nonlinear dynamics point of view, these emerge via bifurcations and period doubling. Finally, chaotic trajectories emerge that on shorter time scales can hardly be distinguished from those of stochastic motion.

Additionally, we address collective motion of such chiral self-propelled objects introducing basic Vicsek-type mutual alignment interactions [1]. Under these circumstances, a crowd of self-propelled objects in the chaotic regime can self-organize into a concentrated spot of high density that follows a chaotic trajectory. Adding stochastic fluctuations to the mutual alignment interactions reduces both orientational ordering and the spatial concentration. Similarly, polydispersity in the trend of external alignment counteracts orientational ordering.

Our results should be verifiable in experiments that focus on objects moving in discrete steps, for example, vibrated chiral hoppers [2]. The same is true for humans that persistently bend their steps towards one side. Moreover, the motion of bacteria along regular polygonal shapes has recently been achieved through light control [3] and could certainly be biased towards a certain direction exposing them, for instance, to gradients in nutrients.

*[1] A. Menzel, Phys. Rev. E, **106**, 064603 (2022)*
*[2] Y. Kubo, S. Inagaki, M. Ichikawa, K. Yoshikawa, Phys. Rev. E, **91**, 052905 (2015)*
*[3] A. Tsang, A. Lam, I. Riedel-Kruse, Nature. Phys., **14**, 1216 (2018)*

Chiral patterns in active systems: Vortex lattices and rotating swarms

Sabine Klapp
Technical University Berlin, Germany

I will give an overview of recent theoretical and numerical results from our group on pattern formation in active fluids with large-scale and/or intrinsic (particle-based) chirality. The first part is devoted to turbulent vortex structures emerging in bacterial active fluids. These can be organized into regular lattices by weak geometrical confinement such as obstacles. Using a continuum-theoretical approach, we show that the formation and destruction of these vortex patterns exhibit features of a continuous second-order equilibrium phase transition [1]. We also discuss transport properties accompanying the melting of vortex lattices [2]. The second part deals with systems of chiral active particles. Specifically, we consider a mixture of circle swimmers with steric interactions and non-reciprocal alignment couplings. The resulting systems display a rich collective behavior including synchronized rotating swarms, motility-induced phase separation and oscillatory behavior [3]. Based on microscopically derived hydrodynamic equations and a linear stability analysis we find that non-reciprocity can turn otherwise stationary instabilities into oscillatory ones, affect the relative orientation of flocks, and, crucially, change the general type of instability.

*[1] H. Reinken, S. Heidenreich, M. Bär, S. Klapp, Phys. Rev. Lett., **128**, 048004 (2022)*
*[2] H. Reinken, S. Klapp, M. Wilczek, Phys. Rev. Fluids, **7**, 084501 (2022)*
*[3] K. Kreienkamp, S. Klapp, New J. Phys., **24**, 123009 (2022)*

Chirality determined motion of magnetotactic bacteria swarms

Andrejs Cebers
University of Latvia, Latvia

When magnetotactic bacteria in thin cells are subjected to the action of a magnetic field perpendicular to its boundaries, they form swarms. In the case of pusher cells, it can be explained by the hydrodynamic flow arising due to their interaction with the solid walls. If a tangential magnetic field is applied to incline the axes of bacteria with respect to the normal of the wall, then, as observed in experiments, the swarm moves in a direction determined by the left-hand rule. In the model couple stress due to the torque dipoles of bacteria is taken into account. The swarm is considered as a droplet of definite height lying on the solid wall. In this case couple stress induces the velocity jump on its upper surface. The hydrodynamic equations for the droplet in the form of a stripe are solved in the 2D case in terms of functions of complex variable. The results obtained in the case of pusher bacteria are in good qualitative and quantitative agreement with the experimental results.

Collective chirality and emergent patterns in active matter

Ignacio Pagonabarraga
University of Barcelona, Spain

Suspensions intrinsically out of equilibrium disturb the liquid medium in which they are embedded as a result of nonequilibrium processes, such as chemical reactions, or inhomogeneous thermal heating. These are intrinsically out of equilibrium systems, which makes them very versatile, with a natural tendency to self-assemble. Due to their small size, these out of equilibrium dynamical states generates flows that induce long range hydrodynamic interactions. These interactions have profound effects in the collective behavior of suspensions of active particles. In particular, they can lead to emerging chirality.
I will analyze how hydrodynamic instabilities lead to novel, dynamically-stabilized, chiral mesostructures. I will discuss the impact that these mechanisms have in the emergence of patterns and different type of morphological structures in active suspensions. I will combine theoretical simple models and computer simulations to gain insight in the role of hydrodynamics in these out of equilibrium system.

Depinning transition of self-propelled particles

Arthur Straube[1], Felix Höfling[2]
[1]Zuse Institute Berlin, Germany
[2]Freie Universität Berlin, Germany

A depinning transition occurs when a system in an immobile, pinned state is driven out of equilibrium by an external force. At a critical value of the driving strength, the system depins and starts to slide. Being observed in various contexts, this phenomenon governs the onset of motion for, e.g., fronts, contact lines, magnetic skyrmions, and colloidal systems driven in disordered or ordered environments; for the latter, it is closely related to phenomena of dynamic mode locking and directional locking. In contrast to passive matter, self-propelled particles perform a directed motion also in the absence of any external driving; however, the direction is randomized by rotational diffusion. An intriguing and largely open question arises, whether and how such active motion affects the depinning transition. Based on the minimalistic framework of an active Brownian particle driven over a periodic landscape, we show that the activity not only shifts the critical point but also modifies the nature of the transition, with the exponent switching from 1/2 for passive to 3/2 for active particles. Furthermore, this active depinning transition can be accompanied by an effective diffusivity that grows without bounds; the passive counterpart is known as giant diffusion, which, however, remains bounded as a function of the driving force.

Drifting and twirling in a 3D chiral fluid

Tali Khain, Colin Scheibner, Michel Fruchart, Tom Witten, Vincenzo Vitelli
University of Chicago, United States

Chiral fluids - such as fluids under rotation or a magnetic field as well as synthetic and biological active fluids - flow in a different way than ordinary ones. Due to symmetries broken at the microscopic level, chiral fluids may have asymmetric stress and viscosity tensors, for example giving rise to a hydrostatic torque or non-dissipative (odd) viscosities. Here, we demonstrate the surprising motion of rigid bodies in such an odd fluid in the incompressible Stokes regime in three dimensions. By analyzing the symmetries of the mobility matrix, which encodes the response of a solid body to forces and torques, we reveal phenomena of chiral objects propelled under torques and achiral objects spinning under gravity. Moreover, through tuning the axis of odd viscosity, we explore the possibility of controlling the motion of such objects by changing the properties of the chiral fluid.

Dynamics and "thermodynamics" of dense assemblies of spinning particles

Demian Levis[1], Claudio Caporusso[2]
[1]University of Barcelona, Spain
[2]Universita di Bari Aldo Moro, Italy

Assemblies of 'persistent tops', particles spinning at a given rate, constitute a class of chiral soft matter systems which is receiving particular attention. A micronscale realization of such systems are monolayers of colloidal magnets driven by an external rotating field. I will discuss some general features that such chiral fluids exhibit, focusing on the emergence of patterns of different type and the role of the spinning frequency on the different phase transitions taking place in the system. I will present our recent results obtained from the theoretical analysis of minimalistic model systems of chiral active matter in light of recent experimental observations. I will show how to understand (and control!) the emergence of persistent chiral currents at the interface between different phases, the melting of a dense colloidal crystal and the formation of structures with a finite size. I will also critically assess the possibility of extending ideas from equilibrium thermodynamics to characterize the phase behavior (and dynamics) of these simple chiral soft materials.

Emergent active turbulence in dense bacterial and colloidal suspensions

Gerhard Gompper, Roland Winkler, Marisol Ripoll, Kai Qi, Joscha Mecke
Forschungszentrum Jülich, Germany

Active particles can be self-propelled internally are actuated externally [1,2]. In both cases, hydrodynamic and steric interactions can lead to a chaotic collective behavior in dense suspensions, which is generally denoted active turbulence, because it resembles hydrodynamic (high Reynolds number) turbulence in many ways -- despite the typically very low Reynolds number [3,4,5]. Such a behavior is predominantly observed in bacterial and colloidal suspensions.
Many physical mechanisms contribute to active turbulence: particle shape [3,6], chirality [3-5], active stress (for microswimmers) [4], and hydrodynamic interactions. We study numerically the emergence of active turbulence in both bacterial and colloidal systems by particle-based hydrodynamics simulations [3,4,5]. We characterize the turbulent behavior by a variety of observables, like cluster distribution, velocity distribution, spatial velocity correlation functions, and the kinetic-energy spectrum [3-6].

Here, internal and external propulsion is found to result in sometimes different dynamical properties. For example, the energy spectrum is predicted to have a peak at finite wave numbers only in the case of self-propulsion.

*[1] J. Elgeti, R. Winkler, G. Gompper, Rep. Prog. Phys., **78**, 056601 (2015)*

*[2] G. Gompper, R. Winkler, T. Speck, A. Solon, C. Nardini, F. Peruani, H. Löwen, R. Golestanian, U. Kaupp, L. Alvarez, T. Kiørboe, E. Lauga, W. Poon, A. DeSimone, S. Muiños-Landin, A. Fischer, N. Söker, F. Cichos, R. Kapral, P. Gaspard, M. Ripoll, F. Sagues, A. Doostmohammadi, J. Yeomans, I. Aranson, C. Bechinger, H. Stark, C. Hemelrijk, F. Nedelec, T. Sarkar, T. Aryaksama, M. Lacroix, G. Duclos, V. Yashunsky, P. Silberzan, M. Arroyo, S. Kale, J. Phys.: Condens. Matter, **32**, 193001 (2020)*

*[3] G. Kokot, S. Das, R. Winkler, G. Gompper, I. Aranson, A. Snezhko, Proc. Natl. Acad. Sci. U.S.A., **114**, 12870 (2017)*
*[4] K. Qi, E. Westphal, G. Gompper, R. Winkler, Commun. Phys., **5**, 49 (2022)*
[5] J. Mecke, Y. Gao, C. Ramírez-Medina, D. Aarts, G. Gompper, M. Ripoll, Simultaneous emergence of active turbulence and odd viscosity in a colloidal chiral active system (2022)
*[6] M. Theers, E. Westphal, K. Qi, R. Winkler, G. Gompper, Soft Matter, **14**, 8590 (2018)*

Emergent dynamics and control of chiral states in flocks of active colloids

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Active matter, both synthetic and biological, demonstrates complex spatiotemporal self-organization and the emergence of collective behavior. We use shape anisotropy of colloidal particles to introduce chiral rollers with activity-controlled curvatures of their trajectories and spontaneous handedness of their motion. By controlling the activity of the Quincke rollers through variations of the energizing electric field, we reveal emergent dynamic phases, ranging from a gas of spinners to aster-like vortices and rotating flocks, with either polar or nematic alignment of the particles. Control and reversibility of those novel dynamic states by the activity are demonstrated. The evidence of hyperuniformity realized in a chiral active fluid comprised of pear-shaped Quincke rollers of arbitrary handedness is revealed.
Temporal modulation of activity is an effective tool to induce complex collective response and non-trivial self-organization in active roller liquids ranging from vortices and dynamic lattices to spontaneous activity shockwaves. We reveal that a global vortex formed by spherical Quincke rollers exhibits polar state memory and that a subsequent formation of the collective states upon re-energizing the system is not random. By combining experiments and simulations we elucidate how a combination of hydrodynamic and electrostatic interactions leads to hidden asymmetries in the local particle positional order, reflecting the chiral state of the system. These asymmetries can be exploited to systematically command subsequent polar states of active colloidal fluids. We also show how shape anisotropy of the active unitary blocks could be effectively used to control the dynamic response of the system to activity modulations. The studies provide insights into the mechanism for the emergence of coherent collective motion on the macroscale from the coupling between microscale rotations, chirality, and translation of individual active units.

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*[1] B. Zhang, A. Sokolov, A. Snezhko, Nat. Commun., **11**, 4401 (2020)*
*[2] B. Zhang, A. Snezhko, A. Sokolov, Phys. Rev. Lett., **128**, 018004 (2022)*
*[3] B. Zhang, H. Yuan, A. Sokolov, M. de la Cruz, A. Snezhko, Nat. Phys., **18**, 154 (2021)*

Magnetic colloidal crystals activated by light-driven bacteria

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Active solids, or self-propelling units elastically coupled on a lattice, are recently of growing interest and have already shown phenomena such as collective oscillations and global rotation [1,2]. However, experimental studies have been limited due to the difficulty of realizing such large confined systems while also inducing and controlling activity. In this talk I will present recent results on the out-of-equilibrium dynamics of an active and magnetic colloidal crystal. This system consists of two-dimensionally confined repulsive paramagnetic particles immersed in a bath of light-driven bacteria. When adding an external magnetic field, the colloids assemble into an ordered bidimensional triangular lattice of non-close packed repulsive particles. The bacterial bath induces active motion into the crystal by pushing its particles. In a simplified picture, this can be described by an equilibrium state with a higher effective temperature. Nevertheless, this framework breaks down qualitatively because of the active fluctuation’s time correlations due to the persistent motion of bacteria [3]. We explore the emerging dynamics of this active solid for different values of activity, controlled by the applied light, and repulsion strength, determined by the external magnetic field. Our findings pave the way to unveil the properties of a novel out-of-equilibrium system, an active colloidal solid, which presents questions vastly interesting from a statistical mechanics point of view.

*[1] P. Baconnier, D. Shohat, C. López, C. Coulais, V. Démery, G. Düring, O. Dauchot, Nat. Phys., **18**, 1234 (2022)*

[2] H. Xu, Y. Huang, R. Zhang, Y. Wu, Nat. Phys., ***19****, 46 (2022)*
[3] C. Maggi, M. Paoluzzi, N. Pellicciotta, A. Lepore, L. Angelani, R. Di Leonardo, Phys. Rev. Lett., ***113****, 238303 (2014)*

Memory-induced chirality in self-freezing active droplets

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Which mechanisms do we know to create chirality in microswimmers? Is there a route to induce self-propulsion and chirality even in isotropic particles without any imposed symmetry breaking? To approach these questions, I will start with a brief overview on known mechanisms to create chirality in (micro)swimmers.

I will then introduce experiments and simulations of a new type of droplet swimmer that is based on a mixture of polyelectrolytes and slowly solidifies at the surface of a Petri dish containing weakly acidic water. During solification, the droplet emits polymers into the surrounding solvent, leading to self-generated concentration gradients that evoke Marangoni-flows and induce self-propulsion through spontaneous symmetry breaking. The emitted polymers diffuse slowly, leading to long-lived "trails" with which the swimmer interacts. As time evolves, these interactions and the associated memory effects become more and more important and at some point, they induce a transition from ballistic to chiral motion, showing that an isotropic droplet in an isotropic environment can acquire chiral self-propulsion.

Non-equilibrium hyperuniform fluids

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Disordered hyperuniform structures are an exotic state of matter having vanishing long-wavelength density fluctuations similar to perfect crystals but without long-range order, in which the direct correlation function is long ranged. This implies that to realize the disordered hyperuniform structures in equilibrium, one needs to use delicately designed effectively long-ranged interactions which are challenging for experimental realization. However, this requirement is not necessary in non-equilibrium systems. In this talk, I will present our recent work on non-equilibrium hyperuniform fluids originating from reciprocal active excitations, which suggests a new way for designing and fabricating dynamic hyperuniform materials [1].

[1] Q. Lei, R. Ni, Proc. Natl. Acad. Sci. U.S.A., ***116****, 22983-22989 (2019)*

Pattern formation in shaking achiral rotors

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In this talk, I will describe recent results obtained in my group by using microscopic magnetic particles are driven back and forward in a viscoelastic fluid by an oscillating magnetic field. Due to the complex nature of the dispersing medium, these particles behave like shaker force dipoles, a type of squimers that shakes the fluid without self-propelling. Those active shaker-like particles trigger a novel instability which aggregates a population of microscopic particles into large scale dynamic bands with a zig-zag shape and composed of an alternation of vortices having opposed chirality. The vortices are connected by topological cusps that act both as sink and sources of sliding particles. By annihilating cusps, the bands coarsen, a process that is scale invariant with time. By combining experiments, finite element and particle-based simulations, we demonstrate that the observed spatiotemporal pattern is produced only by the hydrodynamic flow field generated by the shakers without considering magnetic or gravitational forces. Moreover, such flow field has a cunning resemblance to that of several microorganisms such as E. coli bacteria but without the polar component, which prevent them from self-propelling.

Robust edge flows in swarming bacteria colonies

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The building blocks of biological systems, such as cytoskeleton filaments and molecular motors, often exhibit chiral asymmetry. In principle, this should give rise to active processes that reflect this structural chirality. This has been documented in many contexts, but microorganism motion offers a mixed picture: chirality often arises at individual level, with algae cells and flagellated bacteria swimming in helical trajectories. At collective level, however, this inherent chirality seems to be often absent. This is in particular the case of studies of active turbulence in dense bacterial suspensions. We address this surprising situation by examining multi-scale dynamics in *Paenibacillus vortex* colonies growing on agar plates. We show that while active turbulence without manifest chirality takes place in the bulk, cells self-organize into a wide, clockwise (viewed from the air side) flow all along the typically tortuous centimeter-scale external boundary, while similar but counter-clockwise flows follow the internal boundaries formed by remaining islands not invaded by the colony. We trace the origin of these robust edge flows back to a weak chiral symmetry breaking mechanism at the individual level. We rationalize our findings with a model of noisy self-propelled particles immersed in a Stokes fluid that accounts faithfully for our observations. Our modeling and experimental efforts reveal that local nematic alignment and hydrodynamic interactions amplify the weak chiral bias in individual motion, promoting the formation of strong edge flows.

Soft magnetic actuators programmed at the preparation step by particle chaining

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Soft actuators are deformable materials that change their dimensions and/or shape in response to external stimuli. Among the different stimuli, remote magnetic fields represent one of the most attractive ways of actuation due to the ease of use, prompt response and safe penetration in biological environments. The combination of magnetic particles with a polymer network is the most common approach for the preparation of magnetic soft actuators. In this work, we demonstrate that the motion of magnetic hydrogel actuators under a homogeneous magnetic field can be programmed by a simple approach. In our approach, the hydrogel curing was performed inside a mold of the desired shape, aggregating the particles into columnar structures. The so-prepared actuators transitioned between two shapes when subjected to successive cycles of application and removal of magnetic field. In the case of planar actuators, this resulted in bending to different preprogrammed shapes under a magnetic field. What is more, by additionally subjecting the gelling samples to a torsion after the gel point was reached, actuators with chiral particle structures were fabricated, that responded by twisting under a magnetic field. The experimental results were accompanied by theoretical analysis to understand the physics behind the observed phenomena.

Topological manipulation of magnetic colloids on chiral magnetic patterns

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We apply time-periodic external magnetic field loops to paramagnetic colloids on a periodic pattern that is either chirally deformed or chirally modulated.

The chiral deformed pattens lead to a cloaked transport of colloids: There exist topological loops where the colloidal particles avoid to trespass cloaked regions by robustly traveling around the cloak but continue with a transport exactly the same as if the distorted region where nonexistent and if the particles would have trespassed an undeformed and periodic region. We construct the cloak by continuously squeezing new conformally mapped unit cells between those of the originally undeformed and periodic pattern. A cloaking/decloaking transition disrupts the topological transport of colloids as a function of the size and shape of the newly squeezed-in region.

The chirally modulated patterns allow the robust and controlled polymerization of single colloids to bipeds of a desired length:

The colloids are exposed to a fixed external control loop that causes multiple simultaneous responses.

Small bipeds and single colloidal particles interpret the external magnetic loop as an order to walk toward the polymerization site, where they assemble and polymerize, while large enough bipeds interpret the same loop as an order to walk away from the polymerization site. The topological transition occurs solely for the growing biped and nothing is changed in the environment nor in the magnetic control loop. We can conclude that the decision to walk away from the reaction site is made internally, not externally.

[1] M. Mirzaee-Kakhki, A. Ernst, D. de las Heras, M. Urbaniak, F. Stobiecki, J. Gördes, M. Reginka, A. Ehresmann, T. Fischer, Nat. Commun., ***11****, 4670 (2020)*

[2] J. Loehr, M. Loenne, A. Ernst, D. de las Heras, T. Fischer, Nat. Commun., ***7****, 11745 (2016)*

4. Posters

Chiral active particles with non-reciprocal couplings: Results from particle-based simulations

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Non-reciprocal interactions manifest their drastic impact on the collective dynamics of active matter systems by changing, for example, the general type of observed instabilities [1] and leading to time-dependent states [2,3]. In particular, the combination of non-reciprocity and chirality in terms of intrinsically rotating chiral active particles ("circle swimmers") reveals intriguing non-trivial time-dependent collective dynamics [1].

After having developed an understanding of the collective dynamics on the continuum level in previous work [1], we here present first results of particle-based simulations of chiral active particle systems with non-reciprocal alignment couplings. Indeed, quantitative predictions from continuum approaches are somewhat limited by the approximations made during the coarse-graining process. Thus, the first goal of our particle-based simulations is to explore the validity of the previously obtained continuum results regarding the overall state diagram. Second, we aim at investigating microscopic aspects of the various time-dependent states. Finally, we discuss possibilities to characterize the thermodynamic behavior of the non-reciprocal chiral system based on the stochastic trajectories obtained in particle-resolved simulations.

*[1] K. Kreienkamp, S. Klapp, New J. Phys., **24**, 123009 (2022)*
*[2] M. Fruchart, R. Hanai, P. Littlewood, V. Vitelli, Nature, **592**, 363 (2021)*
*[3] Z. You, A. Baskaran, M. Marchetti, Proc. Natl. Acad. Sci. U.S.A., **117**, 19767 (2020)*

Ising-like critical behavior of vortex lattices in an active fluid

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Turbulent vortex structures emerging in bacterial active fluids can be organized into regular vortex lattices by weak geometrical constraints such as obstacles [1]. Using a continuum-theoretical approach [2,3], we show how appropriate geometrical arrangements of these artificial obstacles enable the stabilization of vortex patterns with tunable properties. Beyond the stabilization of square and hexagonal lattices, we also provide a striking example of a chiral, antiferromagnetic lattice induced by arranging the obstacles in a Kagome-like array [4]. We further show that the formation and destruction of these vortex patterns in the square lattice case exhibit features of a continuous second-order equilibrium phase transition. The emerging vorticity field can be mapped onto a two-dimensional (2D) Ising model, where the resulting effective temperature is found to be proportional to the strength of the nonlinear advection in the continuum model [5].

*[1] D. Nishiguchi, I. Aranson, A. Snezhko, A. Sokolov, Nat. Commun., **9**, 4486 (2018)*
*[2] H. Reinken, S. Klapp, M. Bär, S. Heidenreich, Phys. Rev. E, **97**, 022613 (2018)*
*[3] H. Reinken, S. Klapp, M. Wilczek, Phys. Rev. Fluids, **7**, 084501 (2022)*
*[4] H. Reinken, D. Nishiguchi, S. Heidenreich, A. Sokolov, M. Bär, S. Klapp, I. Aranson, Commun. Phys., **3**, 76 (2020)*
*[5] H. Reinken, S. Heidenreich, M. Bär, S. Klapp, Phys. Rev. Lett., **128**, 048004 (2022)*

Nano-channels with helical geometry display stereospecific sensitivity and induce handedness to chiral superstructures

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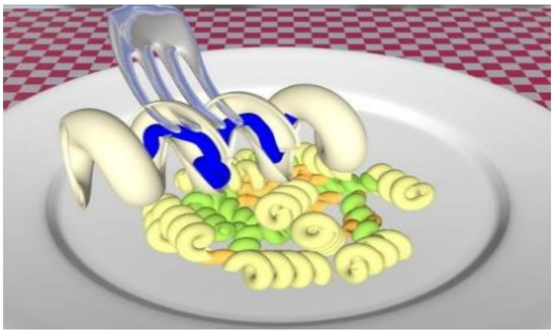

Polymer knots occur naturally on long molecules where they are created spontaneously or in the case of DNA by means of biological processes. In addition, well-defined knots can be produced artificially by single molecular manipulations, in biological experiments, synthetically or by compressing polymers in nano-devices called knot factories. Topological state of molecule greatly affects physical and biophysical properties of the molecules; hence, it is important to study them. Most of knots are chiral and from the group of knots up to 11 crossing containing 820 knot types only 20 are achiral.

By means of molecular dynamics simulations we study knotted polymers confined in chiral spaces achieved by helical geometry of channels. Such chiral spaces are experimentally realized by chiral membranes or are encountered in biological environments, such as packed plectonemic DNA. The simulations show, that the knots with the same handedness as the handedness of the channels, i.e., equichiral structures have considerably higher mobility than antichiral ones. We see also the distribution of the knots across the channel and consequently the free energy differs substantially. In consequent simulations we also show, that polymer chains compressed in channels with helical modulation have higher probability of getting knotted than in smooth channels, while the handedness of the channels induces handedness of the knots.

The molecular dynamics simulations of polymer knots in chiral spaces addresses a range of practical situation, e.g. knots can be sorted based on geometrical criteria, nano-devices employing slits and channels to detect topological state of molecule could be modified to detect also chirality of the knots, further nano-technological devices known as knot factories could be modulated to produce knots with a desired handedness, but also different mobility of knots could have biological consequences and potentially explain abundance of lefthanded knots observed in experiments.

Keywords: soft-matter, polymer, knot, chirality, chiral spaces, confinement, nanotechnology, DNA, molecular dynamics, coarse-grained model

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*[1] R. Rusková, D. Račko, Polymers, **14**, 4201 (2022)*
*[2] R. Rusková, D. Račko, Polymers, **13**, 3726 (2021)*

Interactions-Enhanced Self-Diffusion in Odd Systems

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It is generally believed that collisions of particles reduce the self-diffusion coefficient, closely related to autocorrelation functions, which are assumed to decay monotonically in the overdamped limit. We show that these beliefs are only limiting cases in odd-diffusive systems, which are characterized by diffusion tensors with antisymmetric off-diagonal elements. In these systems, particle interactions can reduce, not influence, and even enhance the self-diffusion. The underlying particle dynamics thereby can be analytically captured by the force autocorrelation function in the dilute limit. We show that this autocorrelation function can become negative and even exhibit temporal oscillations, despite the isotropic and overdamped nature of the system. Furthermore, the knowledge of the force autocorrelation function alone is not sufficient to determine the self-diffusion coefficient; the full autocorrelation tensor is required which also has an antisymmetric part. These unusual properties finally translate into the predicted enhanced dynamics of the tagged particle.

*[1] E. Kalz, H. Vuijk, I. Abdoli, J. Sommer, H. Löwen, A. Sharma, Phys. Rev. Lett., **129**, 090601 (2022)*

[2] E. Kalz, H. Vuijk, J. Sommer, R. Metzler and A. Sharma, arXiv preprint arXiv:2302.01263 (2023)

Transport properties of microswimmer suspensions exhibiting mesoscale turbulence

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Microwsimmer suspensions, a paradigmatic example of an active fluid, self-organize into complex spatio-temporal flow patterns, including regular vortex lattices and mesoscale turbulence, a highly dynamical state that exhibits a characteristic length scale in its spatial structure. This work investigates the transport properties of these suspensions by tracking the diffusive motion of passive tracers in the turbulent flow. We apply a continuum-theoretical approach for the effective microswimmer velocity field [1], where the dynamics is governed by the competition between relaxation to a regular vortex lattice and destabilization by nonlinear advection, which drives the transition to the fluctuating, turbulent state. Varying the strength of nonlinear advection, we observe two qualitatively different regimes [2]. Right above the transition to turbulence, the flow field evolves very slowly and the spatial vortex structure with its characteristic scale leads to dominant trapping effects. In contrast, for large advection strength, much faster dynamics leads to transport properties completely determined by the temporal correlations of the flow. In between, we observe a regime of optimal transport, where the diffusion coefficient reaches a maximum.

*[1] H. Reinken, S. Klapp, M. Bär, S. Heidenreich, Phys. Rev. E, **97**, 022613 (2018)*
*[2] H. Reinken, S. Klapp, M. Wilczek, Phys. Rev. Fluids, **7**, 084501 (2022)*

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