** The Physics of Self-Organising Active Matter
8-10 July 2024, University of Edinburgh, Scotland**

**Abstracts**

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# Invited Speakers

**Self-Organization of Photoactive Microbial Matter**Oliver Bäumchen (University of Bayreuth, Germany)

Microbes have conquered almost all ecosystems of our planet by successfully adapting to their environment. Life on Earth has evolved under the exposure of sunlight and many species are equipped with a photosynthesis machinery enabling them to transform light into chemical energy. Their microhabitats include liquid-infused soil, porous rocks and microdroplets, featuring complex geometric architectures that support strong spatial and temporal fluctuations of light exposure. Thus, developing functionalities to rapidly respond to light variations has been pivotal for natural selection.

In this presentation, I will show how experimental methods from soft matter and biological physics, in conjunction with theoretical concepts from statistical physics, enable us to decipher fundamental physical principles of light-responsive microorganisms. In this presentation, I will bridge the gap between individual and collective microbial motility and shed light on the mechanisms underlying the geometry- and light-controlled emergence of coherent flows and self-organization in active microbial suspensions.

**A multitude of interfacial tensions in active phase separation**Michael Cates (University of Cambridge, UK)

A minimal model of diffusive phase separation of a scalar order parameter (Model B) can be extended to the active case by adding lowest-order terms that break time-reversal symmetry.  I will present recent (and not so recent) results on interfacial phenomena in this model, which is known as Active Model B+. Unlike in equilibrium where a single tension controls mutiple aspects of the physics, for the active model we can identify at least three distinct interfacial tensions. The first two [1] represent the interfacial tension of (i) a liquid droplet surrounded by vapour and (ii) a vapour bubble surrounded by liquid. In each case, the same tension controls both nucleation and growth. Notably, when the correct tension is chosen, classical nucleation theory (CNT) survives despite the absence of detailed balance [2]. The third tension, which is the average of the first two, controls capillary waves at a flat interface [3] and is implicated in the interfacial roughening transition (which is altered by activity) [4]. Either the droplet or the bubble tension -- but not both at once -- becomes negative at large enough activity, causing reversal of the Ostwald ripening process and the failure of CNT. At higher activities still, the capillary tension also turns negative leading to interfacial instability and formation of an active foam phase.

References:
[1] E Tjhung, C Nardini, ME Cates, PRX 8, 031080 (2018)
[2] ME Cates, C Nardini PRL 130, 098203 (2023)
[3] G Fausti, E Tjhung, ME Cates, C Nardini, PRL 127, 068001 (2020)
[4] M Besse, G Fausti, ME Cates, B Delamotte, C Nardin PRL 130, 187102 (2023)

**Migration of living droplets: a novel paradigm for chemotaxis of multicellular communities**
Giulia Celora (University College London, UK)

Collective cell migration is ubiquitous amongst multicellular communities and contributes to many phenomena, e.g., morphogenesis and cancer metastasis. Nonetheless, it is still poorly understood how cells coordinate to control the emergent collective motion of cell groups (or swarms). Recent experimental data suggests that physical interactions between cells within the swarms can result in emergent fluid-like properties. In this work, we propose a continuum, coarse-grained, active fluid model to study how physical interactions affect the complex spatiotemporal dynamics of cell swarms' collective chemotaxis in response to self-generated chemical gradients. Our results reveal that the interplay between physical interactions, cell proliferation and chemotaxis can lead to a new mode of pattern formation via self-organised shedding: as the swarms move collectively, they can periodically shed groups of cells at the rear. As such, our work offers a new perspective to the study of chemotaxis of multicellular communities revealing the role of physical interactions in mediating their collective dynamics.

**Odd turbulent flow in a chiral active fluid**Yongxiang Gao (Institute for Advanced Study, Shenzhen University, China)

Active fluids display collective phenomena such as active turbulence or odd viscosity, which refer to spontaneous complex and transverse flow. The simultaneous emergence of these seemingly separate phenomena is here reported in experiment for a chiral active fluid composed of a carpet of standing and spinning colloidal rods, and in simulations for synchronously rotating hard discs in a hydrodynamic explicit solvent. Experiments and simulations reveal that multi-scale eddies emerge, a hallmark of active turbulence, with a power-law decay of the kinetic-energy spectrum, a feature of self-similar dynamics. Moreover, the particles are dragged to the centre of the vortices, a telltale sign of odd viscosity. The weak compressibility of the system enables an explicit measurement of the odd viscosity in bulk via the relation between local vorticity and excess density. Our findings are relevant for the understanding of biological systems and for the design of microrobots with collective self-organized behavior.

**Chemotaxis, self-steering, and collective migration – how cells generate gradients together to obtain information about their surroundings**
Robert Insall (University College London, UK)

Normal biology requires cells that can migrate accurately to where they belong.  This needs accurate steering mechanisms. Chemotaxis, the process of directing cells using gradients of diffusible molecules, guides cell migration during development, in a healthy adult body, and in various diseases. Most studies on chemotaxis focus on how cells interpret gradients that have been created by some other process. However, our interest lies in self-generated gradients, where cells create their own gradients while moving, thereby generating their own steering cues.

Self-generated gradients lead to information-rich scenarios that are often counterintuitive and require detailed mathematical modeling to be understood. Despite their complexity, these gradients yield exceptionally satisfying results, such as enabling cells to detect distant environmental features and solve complex mazes. We observe these gradients in a variety of cell types, with this talk focussing on immune cells like dendritic cells and macrophages.

Interestingly, some self-generated gradients repel cells rather than attracting them. Explaining this phenomenon is challenging and has led us to explore interactions between multiple chemoattractants detected by the same receptors. These interactions allow cells to use simple rules to create complex and unexpected migration patterns, similar to those observed in embryonic development.

**Emergence of odd elasticity in micromachines**
Shigeyuki Komura (Wenzhou Institute, University of Chinese Academy of Sciences, China)

The concept of odd elasticity is useful to characterize non-reciprocality in active systems such as micromachines and microswimmers. As an example, we first introduce a model for a thermally driven microswimmer in which three spheres are connected by two springs with odd elasticity. Using Onsager’s variational principle, we derive dynamical equations for a nonequilibrium active system with odd elasticity. We further investigate the emergence of odd elasticity in an elastic microswimmer model by using a reinforcement learning method.

**Self-Organising Hot Microswimmers**Klaus Kroy (Leipzig University, Germany)

Hot microswimmers are asymmetrically heated colloids that swim due to self-thermophoresis. They exhibit non-reciprocal and sometimes retarded mutual interactions that can give rise to a rich collective phenomenology. Spontaneous self-organised stationary and dynamical patterns may both arise from spontaneous symmetry breaking on the single-particle level and from proper many-body phase transitions. Examples comprise emergent polarisation-density patterns in stationary activity landscapes that can generate ratcheting currents, and chiral dynamical mesostructures, featuring jamming, yielding, and persistent “tidal quaking”. The local nonequilibrium seems to have a certain propensity to get cloaked upon coarse-graining to the field theoretic level, but will generally reveal itself through entropy producing and time-reversal-symmetry breaking fluctuations near transitions to collective dynamical phases.

**Active Transport in Complex Environments**Christina Kurzthaler (Max Planck Institute for the Physics of Complex Systems, Germany)

Unraveling the motion of microorganisms in complex media is important for our understanding of their survival strategies in microbial habitats. Their interactions with the environment can lead to a range of unusual physical phenomena. In this talk, I will first discuss the hydrodynamic interactions of a microswimmer with a nearby deformable membrane. Relying on a far-field description of the flow fields and using the Lorentz reciprocal theorem, we compute leading-order corrections of the agent’s swimming velocities. Our results reveal regimes of surface-scattering, near-surface circular motion, and trapping of pushers near a bending-dominated membrane, in contrast to their motion near planar walls. In the second part, I will discuss the impact of pressure-driven flow on the transport of microswimmers through a disordered, porous channel. We find  that the interplay of shear and swimming leads to trapping of active agents in dead-end-pores, which strongly affects the first-passage time distributions.

**Oscillating edge current in polar active ﬂuid**

Hiroki Matsukiyo (Kyushu University, Japan)

Dense bacterial suspensions exhibit a turbulence-like behavior called bacterial turbulence [1] whose velocity ﬁeld can be described well by the Toner-Tu-Swift-Hohenberg (TTSH) equation [1]. In recent years, the behavior of bacterial turbulence under geometrical conﬁnements is attracting interests [e.g. 2, 3], because understanding it is not only an exciting challenge from a purely scientiﬁc point of view, but also expected to lead to development of microﬂuidic devices controlling autonomous material transport. The numerical simulations based on the TTSH equation under the existence of boundaries have been performed in several previous works [e.g. 4, 5, 6]. However, the previous simulation studies employed a nonslip boundary condition and did not realize the uni-directional edge ﬂow called edge current which has been reported in several experimental systems [e.g. 2, 3]. In this study [7], we propose a numerical method to solve the TTSH equation under a slip boundary condition. As a result of our simulation, we successfully realized the edge current (Figure 1) and discovered temporal oscillation of the direction of the edge current (Figure 2). We revealed that the oscillation can be attributed to the advection term in the TTSH equation. Furthermore, we investigated the relations between the frequency of the oscillation and simulation parameters, e.g. the drag coeﬃcient and the advection strength, and found that the frequency becomes large for large drag coeﬃcient or large advection strength.

1.5

|***v***|/*v0*≥2

16

14

12 1.5

10

*y*/*Λ*0

8 1

6

4

0.5

2

1

0.5

〈*v*tan〉/*v0*

0

-0.5

-1

-1.5

0 50 100 150 200 250 300 350 400

*t/(Λ0/v0)*

0

0

0 2 4 6 8 10 12 14 16

*x*/*Λ*0

Figure 1: A typical snapshot of the velocity ﬁeld.

Figure 2: A typical example of the time evolu- tion of the edge current direction. *⟨v*tan*⟩ >* 0 and

*⟨v*tan*⟩ <* 0 correspond to the counterclockwise and

clockwise edge current, respectively. The vertical red line indicates the time at which the snapshot (Figure 1) was obtained.

**Acknowledgement**We thank Prof. Yusuke T. Maeda and Dr. Kazusa Beppu for fruitful discussions. A substantial part of thecomputation in this work has been done using the facilities of the Super-computer Center, the institute forSolid State Physics, the University of Tokyo. This work was supported by the JSPS Core-to-Core Program,“Advanced core-to-core network for the physics of self-organizing active matter (Grant No.JPJSCCA20230002)”.

**References**[1] Wensink et al.: PNAS 109(36), 14308-14313 (2012).[2] Wioland et al.: Nature physics 12(4), 341-345 (2016).[3] Beppu et al.: PNAS 118(39), e2107461118 (2021).[4] Puggioni et al.: Physical Review E 106(5), 055103 (2022).[5] Puggioni et al.: Physical Review E 107(5), 055107 (2023).[6] Shiratani et al.: arXiv preprint, arXiv:2304.0330.[7] Matsukiyo & Fukuda: Physical Review E, 109, 054604 (2024).

**Topologically Active Polymers**Davide Michieletto (University of Edinburgh, UK)

DNA is much more than the “molecule of life”, it arguably is nature’s smartest polymer. DNA is nowadays used to create complex 3D shapes at nanometer scale via DNA origami, hydrogels for organoids and tissue regeneration and even biocompatible batteries.

In this talk I will present yet another, and still poorly explored, avenue to use DNA to make next generation materials. I will present both simulations and experiments in which we investigate the material and rheological properties of entangled fluids and gels of DNA functionalised by a range of different proteins (Topoisomerase, Ligase, Restriction Enzymes, Recombinase and others) that alter DNA topology [1,2].

Due to the fact that some of these proteins consume ATP to perform their topological alterations on DNA, our systems of “topologically active polymers” can be thought of out-of-equilibrium living polymers, in which the topological operations and their timescales can be finely controlled independently of thermal fluctuations [3].

References
[1] He et al, PRX, 13, 021010 (2023)
[2] Fosado et al, PRL, 130, 058203 (2023)
[3] Michieletto et al, Nature Comm, 13, 4389 (2022)

**Non-equilibrium fluctuation and self-organized critical rheology of active cytoplasm**Daisuke Mizuno (Kyushu University, Japan)

Cytoplasm is a concentrated solution of biomacromolecules and colloids. Since intracellular organelles contain water molecules, the actual concentration should be even higher. This crowded environment is significantly different from dilute conditions typically used in in vitro biochemical assays. The cytoplasm is not a simple crowded environment. When protein solutions or cell extracts are concentrated to a physiological concentration (~ 0.3 g/mL) in vitro, they undergo glass transition, and then gelate gradually over time, completely losing fluidity. However, in living cells, even when the concentration is doubled, fluidity is maintained.

In living cells, the cytoplasm is vigorously stirred by the energy derived from metabolism. as evidenced by the presence of non-equilibrium fluctuations. We have measured the non-equilibrium fluctuations and fluidity of the cytoplasm, using optical-trapping based microrheology. Results showed that during processes such as cell competition (Warburg effect), intracellular droplet aging, ATP inhibition, and cell death, the non-equilibrium fluctuations change according to the metabolic state, and concurrently, the cytoplasm undergoes fluidization or solidification. The cytoplasmic rheology is coupled with the metabolic state, as expected for active glass that fluidizes under nonequilibrium fluctuations.

To investigate the rheology of active glasses, the dense suspensions of swimming bacteria, a typical model for active glassy suspensions, were developed in a chamber that exchange metabolites and metabolic byproducts with an external fresh medium. In this environment, the non-equilibrium activity of flagellar motors was sustained even at concentrations near precipitated pellets. Despite the high density of the active glass, the non-equilibrium fluctuations showed diffusive wave-number dependence, and maintained notable consistency between self and collective behaviors, a phenomenon not observed in dense inactive suspensions. The viscosity of active glass dramatically decreased compared to their inactive counterparts, where glassy features, such as non-Newtonian viscosity and dynamic heterogeneity, disappeared. This indicates that active glass is not discernible from simple fluids when observations are limited to fluctuations.

On the other hand, the complex shear modulus showed a power-law rheology with the same exponent as expected for critical jamming, suggesting the role of activity in steering the dense systems towards a critical contact state. To our surprise, our viscoelasticity of cytoplasm as well as various actively-driven colloids in literature seems to be consistent to this view, which we would like to summarize if time allows.

**Bayesian Machine Learning for Inverse Flow Problems in Soft Matter**John Molina (Kyoto University, Japan)

We present Machine-Learning approaches to solve two characteristic inverse flow problems encountered in Soft Matter: (1) reconstructing Stokes flows from partial and/or noisy data and (2) inferring the molecular weight distribution from rheological measurements (i.e., stress relaxation). For this, we rely on Gaussian Processes (GP), which provide a convenient framework for performing Bayesian inference on functions.

First, we develop a probabilistic Stokes flow solver (GPStokes) that exactly incorporates the Stokes and continuity equations into the inference machinery, allowing us to infer solutions to arbitrary (Stokes) flow problems from sparse data [1]. Second, we show how GP can be used to infer/learn the functional relationship between molecular weight distribution and stress relaxation curves for a linear polydisperse polymer melt. We will discuss the merits and limitations of our approach compared to alternative methods, as well as future extensions.

References:
[1] J. J. Molina, K. Ogawa, T. Taniguchi, Mach. Learn.:Sci. Technol. 4, 045013 (2023)

**Reversals and oscillations as a prelude to bacterial turbulence**
Daiki Nishiguchi (University of Tokyo, Japan)

Chaotic collective motion, termed active turbulence, is often observed in concentrated suspensions of motile bacteria and other active matter systems. The very existence of the typical vortex size allows organizing bacterial motion into stable vortex arrays under geometrical confinements or in the presence of periodic obstacles [1,2] that are comparable to the vortex size. However, a fundamental question of how such regular vortices transit to chaotic motion in unconstrained systems remains ellusive.

Here, by combining large-scale experiments, computer modeling [3], and analytical theory, we have discovered a generic sequence of transitions occurring in bacterial suspensions confined in cylindrical wells of varying radii. As the confinement is weakened by increasing the well's radius, we observed that persistent vortex motion is destabilized and transit to periodic vortex reversals, four-vortex pulsations, and then well-developed active turbulence. The reversals were also captured as a periodic oscillation of vortices in our numerical simulations and analytical theory. Our findings indicate that the vortex reversal is a precursor of turbulence-like behavior in bacterial and related active systems.

[1] D. Nishiguchi et al. Nat. Commun. 9, 4486 (2018)
[2] H. Reinken, D. Nishiguchi, et al. Commun. Phys. 3, 76 (2020)
[3] S. Shiratani, K.A. Takeuchi and D. Nishiguchi, arXiv: 2304.03306 (2023)

**Chiral active particles with strategic reorientations**Kristian Stølevik Olsen (Heinrich-Heine-Universität Düsseldorf

A wide range of living organism perform hybrid patters of motion consisting of more than a single dynamical mode. Common on both micro- and macroscopic scales is intermittent reorientations, where a particle reorients either randomly or based on collected information. Here we consider a chiral active particle in two dimensions, that at a constant rate perform reorientations following a distribution of turning angles. While chiral motion and reorientations by themselves are modes of motility that decreases the late-time diffusion coefficient of the particle, we find that when chirality is combined with reorientations, diffusion can be enhanced. We study optimal strategies for reorientation, and derive a general expression for the optimal reorientation rate, valid for any distribution of turning angles. We show that for symmetric distributions of turning angles, the effective diffusion coefficient takes a universal value at optimality. Possible extensions to optimal strategies for maximising directed motion is discussed.

**Multifaceted dynamics due to nonreciprocity in active scalar mixtures**
Suropriya Saha (MPI Göttingen, Germany)

Non-reciprocal interactions between scalar fields that represent the concentrations of two active species are known to break the parity and time-reversal (PT) symmetries of the equilibrium state, as manifested in the emergence of travelling waves. In my talk I will discuss various aspects of the Non-reciprocal Cahn-Hilliard model. I will discuss the role of an active pressure in determining the dynamical steady state. I will explore the notion of nonlinear non-reciprocity and consider a model in which the non-reciprocal interactions can depend on the local values of the scalar fields. For generic cases where such couplings exist, we observe the emergence of spatiotemporal chaos in the steady-state associated with a local restoration of PT symmetry in fluctuating spatial domains, which leads to the coexistence of oscillating densities and phase-separated droplets that are spontaneously created and annihilated. Finally I will discuss the role of fluctuations in the ordered 'polar state' that arises in the system.

**Collective behavior of cohesive, aligning particles**
Jeanine Shea and Holger Stark (Technische Universität Berlin, Germany)

Collective behavior is all around us, from flocks of birds to schools of fish. These systems are immensely complex, which makes it pertinent to study their behavior through minimal models. We introduce a minimal model for cohesive and aligning self-propelled particles in which group cohesion is established through additive, non-reciprocal torques [1]. These torques cause constituents to effectively turn towards one another. We additionally incorporate an alignment torque, which competes with the cohesive torque in the same spatial range. By changing the strength and range of these torque interactions, we uncover a vast array of dynamics ranging from disperse states to worm-like formations. Several of the formations generated by this model exhibit collective dynamics which are reminiscent of those seen in nature, thereby providing insight into interactions amongst constituents of animal swarms. The model can additionally serve as inspiration for the future design of swarming microrobots.

[1] Knežević, M., Welker, T. and Stark, H. Collective motion of active particles exhibiting nonreciprocal orientational interactions. Sci Rep 12, 19437 (2022).

**Upstream rheotaxis of catalytic Janus spheres**Juliane Simmchen (University of Strathclyde

Fluid flow is ubiquitous in aqueous habitats. Many motile microorganisms respond to the presence of the water currents by either migrating up or down the flow and this behavior is termed as rheotaxis. Similar to their biological counterparts, artificial microswimmers have also been shown to respond to fluid flows **[1]**.

To deepen the understanding of how different microswimmers behave in an externally imposed flow, it is crucial to understand the influence played by their swimming patterns. Experimentally, pusher-type Pt@SiO2 Janus microswimmers have been shown to exhibit cross-stream migration in flow conditions. Whereas, theoretical studies have predicted an upstream response for puller-type microswimmers. In this work, we introduce Cu@SiO2 Janus spheres that swim towards their catalytic cap, quite differently from Pt@SiO2 which move towards SiO2. Using theoretical flow field calculations, we hypothesize that they behave as a puller-type system. Indeed, when placed in an externally imposed flow, these swimmers show a steady upstream response, which supports our hypothesis. Using a simple squirmer model for puller-type system, we reproduce all the experimental observations. To conclude, our study highlights the relevance of the flow field pattern around the microswimmers to comprehend the rheotactic behavior in motile systems **[2]**.

References:
[1] Cross-stream migration of active particles, J Katuri, WE Uspal, J Simmchen, A Miguel-Lopez, S Sanchez, Science Advances, eaao1755, 2018.
[2] Upstream rheotaxis of catalytic Janus spheres, P Sharan, Z Xiao, V Mancuso, W.E Uspal, J Simmchen, ACS Nano, 16, 4599-4608, 2022.

**Extending the vertex model for tissue dynamics to include effects of activity**
Rastko Sknepnek (University of Dundee)

Gastrulation is an essential, highly conserved process in the development of all vertebrate embryos, including humans. It involves large-scale cell and tissue movements. When not executed properly, it can lead to a wide range of congenital defects, or, in more extreme cases, cause abortion of development. Gastrulation requires the integration of critical cell behaviours such as cell differentiation, division, and movement through chemical and mechanical cell-cell signalling, to achieve the morphogenesis essential for proper functions. These interactions between signalling and cell behaviours create complex feedback loops between tissue, cell, and molecular length- and timescales that have evolved to enable robust formation of complex multi-cellular structures. In this talk, using the vertex model for cell-level description of epithelial tissues, we will discuss how various forms of active processes, such as mechano-chemical feedback, cell growth, division, ingression, etc. couple to cell mechanics and lead to patten formation and flows in model tissues. We will also make qualitative comparisons to the primitive steak formation (i.e. the gastrulation) in chick embryos.

**Image-based inference for epithelial mechanics**Kaoru Sugimura, Shuji Ishihara (University of Tokyo, Japan)

Measuring forces and mechanical properties of cells is essential to decipher the mechanical control of tissue development and repair. We have formulated Bayesian force inference and mechanical parameter inference, both utilizing image data of epithelial cells to infer physical quantities. In addition, we have employed Bayesian inversion stress microscopy for stress measurements on a monolayer of mammalian epithelial cells. These methods have been validated for accuracy and robustness through tests using synthetic and in vivo data. In this symposium, I will discuss how these methods have helped elucidate the mechanisms underlying cell rearrangement and cell competition.

1. Yan et al. Bayesian parameter inference for epithelial mechanics. bioRxiv, 2024
2. Gauquelin et al. Mechanical convergence in mixed populations of mammalian epithelial cells. EPJE, 2024
3. Ogita et al. Image-based parameter inference for epithelial mechanics. PLoS Comput Biol, 2022
4. Ishihara and Sugimura. Bayesian inference of force dynamics during morphogenesis.. J Theor Biol, 2012

**Coiling patterns of soft filaments**Marie Tani (Kyoto University, Japan)

Coiling structures are ubiquitously observed from nanometer to centimeter scales, and in natural and artificial materials. For examples, we coil soft rods such as threads, ropes, and cables around cylindrical objects to store or transport them without defects. DNAs and vines often wind around other objects by themselves. As coiling structures, we can find some distinct morphologies: tight coiling, helical twining and failed coil (no wrapping). When does a soft filament coil around another object and when does not? To address that, we conducted a model experiment where a soft filament hanged by cramping one end to a horizontally placed cylinder, coils around the slowly rotated cylinder. We observed the three coiling patterns (tight, helical, and no coiling) and the transition of them. These coiling morphologies and the transition were also observed by numerical simulations and a geometrically nonlinear Kirchhoff rod theory [1]. In other words, the local shape of the rod is explained by the interplay between bending elasticity, gravity, and the geometry of the system. In the presentation, we will share our results and introduce related recent works such as soft grippers in the field of soft robotics, to discuss the possibility of understanding similar behaviors of active filaments.

[1] M. Tani and H. Wada, *Phys. Rev. Lett.* 132, 058204 (2024).

**Crowd Dynamics as Active Matter: Unveiling the Pattern Formation in Elevator Traffic and Pedestrian Movements**
Sakurako Tanida (Tokyo, Japan) -

It is empirically known that multiple elevators in crowded buildings often arrive simultaneously, a phenomenon that necessitates a deeper understanding for effective operations optimization. To investigate this self-organizing mechanism, we conducted numerical simulations of passengers arriving at each floor according to a Poisson process and moving to the ground floor by elevators. To examine how synchronization of elevator motions occurs under noisy conditions, we replicated the phenomena using a simple mathematical model. We will discuss methodologies to address in-phase synchronization based on these findings.

**Nonreciprocal demixing - oscillatory states and Maxwell construction**
Uwe Thiele (University of Münster, Germany)

A nonreciprocal Cahn-Hilliard (NRCH) model couples densities with mass-conserving dynamics via a combination of reciprocal and nonreciprocal interactions [1]. First, we briefly discuss how a gradient dynamics stucture may be broken by different types of nonreciprocity. We then show that in some cases a transformation results in a "spurious gradient dynamics structure" that, in consequance, allows for a spurious Maxwell construction and spurious phase diagrams. At the example of the NRCH model (that features conserved-Turing and conserved-Hopf instabilities beside the usual Cahn-Hilliard instability) we show that resulting predictions for phase coexistence of nonequilibrium phases are confirmed by time simulations, e.g., for the coexistence of uniform and oscillatory phases.Finally, we sketch the NRCH model’s role in a hierarchy of AE [2].

[1] [ZH You, A Baskaran, MC Marchetti, PNAS 117, 19767 (2020); S Saha, J Agudo-Canalejo, R Golestanian, PRX 10, 041009 (2020); T Frohoff-Hülsmann, J Wrembel, U Thiele, PRE 103, 042602 (2021)](https://journals.aps.org/pre/abstract/10.1103/PhysRevE.103.042602)
[2] [T Frohoff-Hülsmann, U Thiele, PRL 131, 107201 (2023)](https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.131.107201)
[T Frohoff-Hülsmann, U. Thiele, and L. M. Pismen, Philos. Trans. R. Soc. A 381, 20220087 (2023](https://royalsocietypublishing.org/doi/10.1098/rsta.2022.0087))
[T Frohoff-Hülsmann and U Thiele, IMA J. Appl. Math. 86, 924–943 (2021)](https://academic.oup.com/imamat/article/86/5/924/6316625)

[D Greve, G Lovato, T Frohoff-Hülsmann, and U Thiele](https://arxiv.org/abs/2402.08634),

**Phenotypic Heterogeneity of Extracellular Matrix Production within Bacterial Proliferating Active Matter**Fumiaki Yokoyama(The University of Tokyo, Japan)

Even in an isogenic cell population, there is a phenomenon called phenotypic heterogeneity. This heterogeneity arises from random events and differences in the microenvironment where the cells reside, contributing to multicellular form development. While much research has been conducted on elucidating the stochastic distribution of cellular components happening on genetically identical cells of bacteria, our understanding of their microenvironment-driven heterogeneity is still in its infancy. In the present study, we are looking into the heterogeneity in extracellular matrix production focusing on microenvironment through the lens of proliferating active matter, mainly focusing on cell orientation and topological defects in an *Escherichia coli* population. Our results suggest that partly non-uniform cell orientation can cause cellular phenotypic heterogeneity through mechanical interactions. As this heterogeneous production of extracellular matrix was initiated after cellular protrusion to the Z-direction, it is speculated that the produced extracellular matrix may support the protruding cells and contribute to the formation of larger biofilm structures.

**Manipulating LLPS using patterned flow**Zhihong You (Xiamen University, China)

Liquid-liquid phase separation (LLPS) is the basis of many cutting-edge technologies in industry and research labs. In this talk, I will show how patterned flow can be used to control diverse aspects of LLPS, including the capture of droplets, directed material transport between two droplets, reverse Ostwald ripening, as well as the dynamics and structures of LLPS. These results demonstrate that mechanics can be used to control thermodynamic processes precisely and effectively.

**Field Theory of Active Brownian Particles with Dry Friction**
Ziluo Zhang (Wenzhou Institute, China)

We present a field theoretic approach to capture the motion of a particle with dry friction for one- and two-dimensional diffusive particles, and further expand the framework for two-dimensional active Brownian particles. Starting with the Fokker-Planck equation and introducing the Hermite polynomials as the corresponding eigen-functions, we obtain the actions and propagators. Using a perturbation expansion, we calculate the effective diffusion coefficient in the presence of both wet and dry frictions in a perturbative way via the Green-Kubo relation. We further compare the analytical result with the numerical simulation. Our result can be used to estimate the values of dry friction coefficient in experiments.

# **Oral Presentations** (selected from submitted abstracts)

**Active Spaghetti: Collective Organization in Cyanobacteria**
Jan Cammann (Loughborough University, UK)

Filamentous cyanobacteria can show fascinating examples of nonequilibrium self-organization, which, however, are not well understood from a physical perspective. We investigate the motility and collective organization of colonies of these simple multicellular lifeforms. As their area density increases, linear chains of cells gliding on a substrate show a transition from an isotropic distribution to bundles of filaments arranged in a reticulate pattern. Based on our experimental observations of individual behavior and pairwise interactions, we introduce a nonreciprocal model accounting for the filaments’ large aspect ratio, fluctuations in curvature, motility, and nematic interactions. This minimal model of active filaments recapitulates the observations, and rationalizes the appearance of a characteristic length scale in the system, based on the P´eclet number of the cyanobacteria filaments.

[Faluweki, M. K., Cammann, J., Mazza, M. G., & Goehring, L. (2023). Active spaghetti: collective organization in cyanobacteria. Physical Review Letters, 131(15), 158303]

**Dissipation-accuracy tradeoffs in autonomous control of smart active matter**
Luca Cocconi (Max Planck Institute for Dynamics and Self-Organization, Germany)

Recent advancements in stochastic thermodynamics have paved the way for a systematic exploration of the fundamental physical constraints underlying the functioning of biological as well as artificial micro-machines operating far from thermodynamic equilibrium. The framework of autonomous, taxis-based navigation in ``smart'' active matter offers a promising stepping stone in this direction by integrating concepts of control theory and motility. Here, we establish a stochastic thermodynamic description of self-propelled particles capable of autonomous steering in accordance with a predefined steering policy depending only on local measurements, dissecting the ensuing dissipation into distinct contributions related to self-propulsion and adaptation, respectively. Our analysis reveals the existence of fundamental dissipation-accuracy tradeoffs limiting the quality of a swimmer's adherence to a given steering policy.

**When swarm robotics loses control**
Olivier Dauchot (ESPCI Paris, France)

On one hand, active fluids are known for their rich collective dynamics, which emerge from dynamical phase transitions. It remains however challenging to control these phases and turn them into functional materials, following the valorization scheme of liquid crystalline phases into everyday life LCD. On the other hand, while swarm robotics has reached spectacular achievements, as exemplified by the live shows of drones displaying patterns in the night sky, these performances result from powerful central control and fast communication, rather than from smart distributed algorithms. As a matter of fact it remains challenging to program a simple swarm of more than a few tens of robots to autonomously form a swarm collectively moving in some direction. While active matter lacks control, swarm robotics suffocates under it. Tuning the right amount and form of control is therefore a promising route, yet not less challenging, In this talk, I will illustrate this tension with recents experiments conducted with a swarm of kilobots equipped with different exoskeletons, which radically determine their dynamical behavior. I will discuss how, already at the individual agent level, a small change in mechanical design, allows for radically different performance in a notoriously complex robotic task. The discussion will then be extended to the case of a task where the synergy between the two exoskeleton morphologies is the key success factor. Finally I will move to a collective phototactic task and stress how the morphology can be beneficial or detrimental to the realization of the task.

**Nonreciprocal response of microswimmers in fluids with odd viscosity**
Yuto Hosaka (Max Planck Institute for Dynamics and Self-Organization, Germany)

Chiral active fluids with broken time-reversal and parity symmetries are prevalent at various scales in nonequilibrium systems, ranging from electron fluids to biological and geophysical flows. Such fluids exhibit a peculiar transport coefficient called odd viscosity. This viscosity, which does not contribute to the fluid energy dissipation, leads to novel dynamics, such as nonreciprocal (transverse) transports, free-surface dynamics, or chiral edge currents characterized by topological protection, akin to quantum Hall systems. The lack of time-reversal symmetry leads to an asymmetric response and, thus, to an asymmetric mobility tensor. This suggests that the Lorentz reciprocal theorem, a powerful and versatile principle for solving swimming problems in low-Reynolds-number fluid dynamics, is violated in chiral active systems. Here we discuss the dynamics of microswimmers in “odd” flows at zero Reynolds number. First, we generalize the Lorentz reciprocal theorem to fluids of odd viscosity [Y. Hosaka, R. Golestanian, and A. Vilfan, Phys. Rev. Lett. 131, 178303 (2023).]. To demonstrate its applicability, we then use it to determine the swimming velocity of two categories of microswimmers in an odd Stokes flow (Fig. 1). Interestingly, a surface-driven microswimmer with a torque dipole (“twister”) can exhibit vertical motion due to the nonreciprocal response of the odd viscosity [Fig. 1(f)]. Our theoretical results will facilitate the solution of a number of swimming and flow problems in fluids with odd viscosity and should be applicable to various chiral active systems.

**Emergent morphologies of active surfaces**
Alexander Mietke (University of Oxford, UK)

Many force-generating structures in developing organisms, including the actomyosin cortex of cells and organ-lining epithelial tissues, are organised on effectively two-dimensional surfaces. A key challenge for the shape transformations such "active surfaces" are undergoing during morphogenesis is to organise locally generated active forces such that a desired global geometry robustly emerges. A popular theoretical framework that leads to the self-organisation of forces in an active material is mechano-chemical feedback, in which some “patterning agent”, e.g. a concentration or order parameter field, tunes local active stress and is itself changing due to the generated flows or deformations. While this feedback ultimately leads to self-organised shape changes of an active surface, surprisingly little is known about the potential impact of active stresses that directly depend on the local curvature and, in particular, what role curvature-driven active stresses could play in guiding the robust generation of a desired surface geometry. Importantly, such a scenario eliminates the need for a separate patterning agent. Instead, surface curvature itself becomes the patterning agent and stationary states of curvature patterns correspond to emergent stationary surface geometries. Investigating this idea using a novel numerical approach to solve the force-and moment-balance equations of deforming active surfaces, we show in this work that the fully self-organized formation of stationary tubular, ellipsoidal and biconcave surfaces, as well as global shape transformations akin to cell division, can be controlled by homogeneous active processes that respond only to the local curvature.

**A generic coupling between internal states and activity leads to activation fronts and criticality in active systems**
Fernando Peruani (CY Cergy Paris University, France)

We investigate active systems where particles switch on and off their self-propulsion. To understand the onset of collective motion, we prove that even when the only possible transition is off->on, an active 2-state system behaves as an effective 3-state system that exhibits a sharp phase transition in 1D, and critical behavior in 2D, with scale-invariant activity avalanches. The obtained results show how criticality can naturally emerge in active systems, providing insight into the way collectives distribute, process, and respond to local environmental cues.

**Non-Reciprocal Interactions Reshape Topological Defect Annihilation**
Ylann Rouzaire (Universitat de Barcelona, Spain)

I will explore the impact of non-reciprocal ferromagnetic interactions among adjacent planar spins in two dimensions, influencing the behaviour of topological defects. By introducing non-reciprocity through an anisotropic kernel in the coupling strength of the two-dimensional XY model, we found that the shape (or phase) of defects, in addition to their topological charge, plays a crucial role in describing their dynamics. Non-reciprocal couplings induce twists in the spin field, selectively shaping defects and significantly altering the pair annihilation process. Defect annihilation is found to be either enhanced or hindered, depending on the specific defect shapes and the degree of non-reciprocity in the system.

This research sheds light on a novel aspect of defect dynamics influenced by non-reciprocal ferromagnetic interactions and draws a clearer connection between agent-based models with anisotropic perception and hydrodynamic approaches to non-reciprocal active matter.

Related article:
Non-Reciprocal Interactions Reshape Topological Defect Annihilation
Ylann Rouzaire, Demian Levis, Ignacio Pagonabarraga (2024)
<https://arxiv.org/pdf/2401.12637.pdf>

**Collective motion of colloids induced by the presence of binary size**
Yutaka Sumino (Tokyo University of Science, Japan)

Electrohydrodynamics (EHD) flow is induced by an electric field around an electrode. Particles dispersed in an aqueous phase sit close to an electrode surface, creating incoming EHD flow even under AC electric fields induced by the coupling of screening cloud with distorted electric field due to particles. The fact that the EHD flow depends on the size of particles can create non-reciprocal interaction between particles: effective force produced by EHD flow can be unbalanced when the particle sizes are different.

In this study, we created a system with binary-sized colloid particles dispersed in an aqueous phase under AC electric fields. Here, we found that the collection of particles created non-settling active dynamics. In order to account for the underlying mechanism, we introduced a simplified mathematical model adopting effective pair-wise attraction owing to EHD flow.

The model successfully reproduced experimental results in a semi-quantitative manner. Based on the model, we show that the pair can be self-propelled with a finite lifetime. In addition, we show that the non-settling collective behavior is caused by a spontaneous spray of self-propelled pair due to the asymmetric size of the excluded volume. We further introduced the effective continuous model incorporating the effect of spontaneous spray, which successfully reproduces non-settling collective behavior. The current study elucidates a novel field of active granular matter with non-reciprocal interaction.

# Poster Presentations

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| **Tal Agranov**University of Cambridge | Generating long time scales by tuning close to a bifurcation in actin condensates |
| **Yuv Agarwal**Doctoral Student at University of Geneva | Unraveling the Dynamics of Active Nematic Defects on Curved Surfaces |
| **Gabriel Amselem**Ecole Polytechnique | Controlled transport of passive beads by phototactic swimming micro-organisms |
| **Callum Britton**Imperial College London | Doi-Peliti Field Theory of Free Transiently Chiral Active Brownian Particles |
| **Sam Cameron**The Open University | Geometrically projected population dynamics in a one-dimensional system of particles. |
| **Xichen Chao**University of Bristol | Travelling strings of active dipolar colloids |
| **Dom Corbett**University of Geneva | Towards flocks of geometrically controlled swimmers embedded in active liquid crystals |
| **Alfons Córdoba**CY Cergy Paris Université | From condensates to flocking: First and Second Order Transition in a 1D discrete active system |
| **Hiroyuki Ebata**Kyushu University | Active softening and fluidization of crowded cytoplasm |
| **Haruki Hayano**The University of Tokyo | Distinct rheological behaviors between pusher and puller suspensions |
| **Richard Henshaw**ETH Zurich | Lagrangian stretching, structure and transport in active turbulence |
| **Alexander Houston**University of Glasgow | The Dynamics of Active Nematic Defect Loops |
| **Eloise Lardet**Imperial College London | Disorder-induced emergent behaviour in aligning self-propelled particle systems |
| **Ruma Maity**Technische Universität Wien | Hydrodynamics of a pair of Chiral Squirmers |
| **Charlie Maslen**University of Strathclyde | Directed- and Self-Assembly of Hydrogel Microrobots into Larger Structures with Robotic Functionality. |
| **Marco Mazza**Loughborough University | Self-Organization in Gliding Filamentous Cyanobacteria |
| **Joscha Mecke**Institute for Advanced Study, Shenzhen University, Shenzhen, China | Nonequilibrium signatures of tracer fluctuations in active filaments |
| **Bokusui Nakayama**Kyoto University | Self-viscophoresis of Janus Particles in a Thermal-responsive Polymer Solution |
| **Kristian Stølevik Olsen**Heinrich-Heine-Universität Düsseldorf | Optimal diffusion of chiral active particles with strategic reorientations |
| **Parisa Rahmani**CY Cergy-Paris University | How does information propagate within a flock? |
| **Mst Rubaya Rashid**Department of Physics, Kyoto University | Collective force generation of micro-sized active matters |
| **Henning Reinken**Otto von Guericke University Magdeburg | Pattern formation in non-Newtonian active suspensions |
| **Emir Sezik**Imperial College London | Renormalisation Group Analysis of Vision Cone Interactions |
| **Antonio Suma**Università degli Studi di Bari | Phase behaviour and dynamics of an active dumbbell systems |
| **Yuki Tao**Kyushu university faculty of science | Dependence of cytoplasmic viscoelasticity on intracellular non-thermal fluctuation |