Program

Nonlinear Dynamics and Emergence Across Scales: Active, Chaotic, and Complex Systems

866. WE-Heraeus-Seminar

14 – 18 September 2026

at the Station Biologique de Roscoff, France

WILHELM UND ELSE HERAEUS-STIFTUNG

Introduction

The Wilhelm und Else Heraeus-Stiftung is a private foundation that supports research and education in science with an emphasis on physics. It is recognized as Germany's most important private institution funding physics. Some of the activities of the foundation are carried out in close cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft). For detailed information see https://www.we-heraeus-stiftung.de

Aims and scope of the 866. WE-Heraeus-Seminar:

Nonlinear processes underlie the emergence of most nontrivial physical phenomena across a wide range of topics, such as active matter, biological physics, turbulence and ecology. These systems, characteristically out of equilibrium, show a plethora of interesting and exotic behaviors and typically defy attempts to describe them by simple mean field or linearization techniques, which often miss crucial aspects of their dynamics. Popular examples include turbulent atmospheric flows, networks of spiking neurons, and biological swarms, which all exhibit large, non-Gaussian fluctuations that enhance the influence of nonlinear processes. Often, similar or analogous concepts from nonlinear dynamics prove fruitful when applied to different problems or fields. Understanding and controlling these systems constitutes a fundamental challenge to be met by integrating different tools of nonlinear dynamics, including nonperturbative methods, dimensional reduction, advanced numerical techniques and machine learning approaches.

This WE-Heraeus Seminar will bring together leading experts in nonlinear dynamics working on a broad range of different subjects in order to identify and discuss common challenges in the development and application of nonlinear methods to the study of emergent behaviors. Mixing leading figures in the nonlinear dynamics and complex systems communities with promising young scientists, we aim to forge new collaborations as much as strengthen and rekindle existing ones. This seminar will also be the occasion to celebrate the 65th birthday of Hugues Chaté, a leading figure in this community, whose seminal results, wide-ranging collaborations, and connecting role have contributed to shaping the current field landscape.

Scientific Organizers:

Prof. Dr. Theo Geisel	MPI für Dynamik und Selbstorganisation, Göttingen, Deutschland email: geisel@ds.mpg.de
Prof. Dr. Francesco Ginelli	Università degli Studi dell'Insubria, Como, Italia email: francesco.ginelli@uninsubria.it
Prof. Dr. Benoît Mahault	Université de Montpellier, France email: benoit.mahault@umontpellier.fr

Introduction

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Registration:

Monday, September 14, 2026 from 3 pm

Program

Program

Monday, 14 September 2026

15:00 – 15:50	Registration & welcome coffee	
15:50 – 16:00	Words from the organizers	
16:00 – 16:35	Igor Aronson	**Partial Fluidization Theory of Collective Cell Migration**
16:35 – 17:10	Isabella Guido	**Active Microtubule Networks in Evaporation Droplets**
17.10 – 17:35	Guiseppe Fava	**Density-protected States in Active Matter under Virtual Confinement**
17:35 – 18:00	**Poster spotlight**	
18:30 – 19:30	**Poster session**	
19:30	*DINNER*	

Program

Tuesday, 15 September 2026

09:00 – 09:35	Julien Tailleur	**Flocking with Hugues: Collective Motion With(out) a Leader**
09:35 – 10:10	Alexandre Solon	**Robustness and Fragility of Polar Active Fluids**
10:10 – 10:45	Thibault Bertrand	**Flocking Against the Odds**
10:45 – 11:20	*COFFEE BREAK*	
11:20 – 11:55	Sriram Ramaswamy	**Nonreciprocal Planar Lattice Models**
11:55 – 12:30	Andrea Cavagna	**Spin-waves without Spin-waves: A Case for Soliton Propagation in Starling Flocks**
13:00 – 14:30	*LUNCH*	
15:00 – 15:35	Carolina Brito	**Statistical Signatures of Microorganism Motility Under Environmental Stress**
15:35 – 16:00	Rajesh Singh	**Flocking Transition in Phoretically Interacting Active Particles: Role of Disorder**
16:00 – 16:35	*COFFEE BREAK*	
16:35 – 17:10	Masaki Sano	**Classifying Tissue Properties via Collective Dynamics around Topological Defects**
17:10 – 17:45	Karsten Kruse	**Defects States in Renewing Active Matter**
17:45 – 18:00	Stefan Jorda	**About the Wilhelm and Else Heraeus Foundation**
18:30 – 19:30	**Poster Session**	
19:30	*DINNER*	

Program

Wednesday, 16 September 2026

09:00 – 09:35	Leihan Tang	**From Domain Walls to "Entropy-ons": Building the State Space of a 2D Spin Glass**
09:35 – 10:10	Antonio Politi	**Metastability and Condensation Phenomena in Statistical Systems with Two Conservation Laws**
10:10 – 10:35	Roos De Boer	**Ghost State of Light**
10:35 – 11:10	*COFFEE BREAK*	
11:10 – 11:45	Anaël Lemaître	**TBA**
11:45 – 12:20	Hugues Chaté	**TBA**
13:00 – 14:00	*LUNCH*	
14:30	**Excursion: ferry departure to Ile de Batz**	
17:00	**Excursion: ferry departure to Roscoff**	
19:00	**WE-Heraeus Conference Banquet**	

Program

Thursday, 17 September 2026

09:00 – 09:35	Arkady Pikovsky	**Scaling Properties of Kuramoto Chaos**
09:35 – 10:10	Léonie Canet	**Scaling Regimes of the Kuramoto-Sivashinsky Equation**
10:10 – 10:45	Peter Grassberger	**Simulations of Parity-conserving Directed Percolation**
10:45 – 11:20	*COFFEE BREAK*	
11:20 – 11:55	Silvia De Monte	**Fluctuations and Patterns in Complex Ecological Communities**
11:55 – 12:30	Fred Wolf	**Learning the Laws of Collapse**
13:00 – 14:30	LUNCH	
15:00 – 15:35	Xiaqing Shi	**Kuramoto-Vicsek Model for Active Matter**
15:35 – 16:00	Ananyo Maitra	**Active Translation Symmetry-broken States in Disordered Environments**
16:00 – 16:35	*COFFEE BREAK*	
16:35 – 17:10	Ramin Golestanian	**Quantifying Dissipation in Active Matter**
17:10 – 17:45	Leonardo Brunnet	**Activity-Controlled Segregation Time Scales in Self-Propelled Particle Ensembles**
17:45 – 18:20	Serena Dalena	**Building Physics Together: A Decade of *Physical Review Letters* and What's Next**
18:20 – 19:00	**Open discussion**	
19:30	*DINNER*	

Program

Friday, 18 September 2026

09:00 – 09:35	Viola Priesemann	**Learning and Information Spread in Neural Networks**
09:35 – 10:10	Holger Kantz	**Understanding the Superiority of Multi-model Ensemble Forecasts through Reservoir Computing**
10:10 – 10:35	TBA	
10:35 – 11:10	*COFFEE BREAK*	
11:10 – 11:45	Yuhai Tu	**Dynamics of Learning: Lessons from Living Systems to Artificial Neural Networks**
11:45 – 12:20	Eric Bertin	**Theory of Collective Learning in Populations of Adaptive Agents**
13:00 – 14:30	LUNCH	
15:00 – 15:35	Jacques Prost	**Living Layered Systems**
15:35 – 16:10	Kazumasa Takeuchi	**Experimental Approaches to Statistical Physics in Large Chaotic Systems**
16:10	**Concluding words from the organizers and coffee**	

End of the seminar

Posters

Poster List

Elia Bronzo	Collective Behavior of Self-propelled Rods: Continuum Theories Derived from Vicsek Models with Nematic Alignment and Repulsive Interactions
Debasish Das	Weakly Nonlinear Interactions and Full Numerical Simulations of a Pair of Quincke Rotors
Alireza Hassanzadeh	A Stochastic Dynamical Model to Explain Robustness of Gene Expression
Martin James	Advective Stabilization of Active Vortex Crystals
Amit Jangid	Volatile but Persistent Co-existence of Self-compatibility and Self-incompatibility in Plants
Yuxin Jia	Finite Wavelength Reshapes Nonlinear Polarization in Confined Bacterial Suspensions
Harshit Joshi	Periodically Modulated Poiseuille Flow as a Route to Chaos for Microswimmers
Sander Kammeraat	Understanding the Oscillations and Mode Spectra of Active Self-aligning Disordered Solids
Navdeep Rana	Topological Defects in Non-reciprocal Mixtures
Yihong Shi	Mixing Induced by Microswimmers as Probed by Mutual Information
Filipe Thewes	Thermodynamic Control of Active Ddroplets: Transitions in Loop Protocols

Poster List

Alain Bertrand Togueu Motcheyo	Wave Propagation in Nonlinear Topological Transmission Line
Dzmitry Vaido	Characterizing Nonlinear Dynamics of Sound Detection in the Auditory System via Entrainment Analysis

Abstracts of Lectures

(in alphabetical order)

Automated Detection of Scaling Regimes for Quantifying Climate Memory

Fatemeh Aghaei
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With the increasing rate of global warming, understanding and modeling climate-system dynamics has become crucial for both characterizing and predicting the evolution of the climate system. Long-range correlations (LRCs) are a prominent feature of non-Markovian near-surface temperature records and are generally interpreted as signatures of memory within the climate system. Therefore, quantifying the range and strength of these correlations is essential for constructing accurate data-driven stochastic models of climate dynamics, including generalized Langevin equations that explicitly account for memory effects. Even when the objective is to formulate a Markovian model, charac-terizing LRCs remains essential. Identifying and accounting for the long-range correlated component can help isolate the short-memory dynamics and thereby improve the estimation of the drift and diffusion terms in a data-driven Langevin equation.

Since the physical origins of long-range correlations remain poorly under-stood, it remains unclear how global warming may reshape the correlation structure of the climate system across space and time, and whether systematic changes in these correlations could serve as early indicators of an approaching qualitatively different climate state.

A key challenge in quantifying LRCs is the reliable estimation of scaling exponents from non-monotonic and strongly non-stationary climate records. Standard approaches, such as detrended fluctuation analysis (DFA), are sen-sitive to the choice of scaling range, which is often ambiguous in climate data. To address this issue, we develop an automated procedure for identifying the ap-propriate scaling regime in DFA. We further validate the selected scaling regime using Bayesian statistical analysis and maximum-likelihood estimation, provid-ing a consistent framework for estimating the Hurst exponent and its associated uncertainty.

Applying this framework to gridded temperature reanalysis data, we obtain a spatially and temporally resolved characterization of long-range correlations and their evolution. Our results reveal substantial spatial heterogeneity in scal-ing behavior: some regions exhibit robust temporal changes in their correlation structure, whereas others show weaker or less interpretable variations. This framework provides a systematic approach for quantifying climate-system mem-ory and investigating whether changes in long-range correlations are associated with the evolving dynamics of a warming climate.

Partial Fluidization Theory of Collective Cell Migration

Lev S. Tsimring[1] and Igor S Aranson[2]

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[2] *Departments of Biomedical Engineering, Chemistry, and Mathematics, Pennsylvania State University, USA*

Collective cell and tissue migration is essential for numerous biological processes, including morphogenesis, wound healing, and cancer metastasis. Migrating cell monolayers often exhibit complex viscoelastic behavior, with the coexistence of solid- and liquid-like states that remain insufficiently understood within existing theoretical frameworks. In this talk, I introduce a partial fluidization approach to describe collective cell migration [1], inspired by a model originally developed for flowing granular matter [2]. We treat the cell monolayer as a single, spatially and temporally heterogeneous phase that bridges two limiting states: a viscous liquid and a soft solid with an elastic response to shear. The continuous transition between these states is governed by a fluidization order parameter that depends on the normalized shear stress. The order parameter equals one in the solid phase, zero in the liquid phase, and varies continuously in partially fluidized regions. The model successfully reproduces key experimental observations, including solid-like plug flow in microfluidic channels, spatial coexistence of mobile and immobile domains in cell monolayers, and solid-body-like rotational motion in circular confinement. This framework provides insight into the physical mechanisms underlying collective cell migration. It can be further extended to more realistic scenarios, such as confluent monolayers on curved, compliant, or degradable substrates, as well as three-dimensional proliferating tissues with chemical signaling.

References

[1] I.S. Aranson and L.S. Tsimring, “Partial Fluidization Theory of Collective Cell Migration”, Communications Physics (2026)

[2] I.S. Aranson and L.S. Tsimring, “Patterns and collective behavior in granular media: Theoretical concepts”, Rev. Mod. Phys., **78**, 641-692 (2006)

Theory of collective learning in populations of adaptive agents

G. Jung[1,2], J. Asnacios[3], M. Ozawa[1], O. Dauchot[3], E. Bertin[1]

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Adaptive agents have the ability to control their motion and adapt their dynamical rules to achieve prescribed collective goals. Such agents may for example represent simple microrobots [1], and may be modeled as active particles with information storage and exchange capacities. The exchanged information between agents comprises values of tunable parameters governing agents dynamics, referred to as the individual policy, together with an internal memory encoding previously visited states. We develop a kinetic theory formalism to describe the collective and decentralized learning process occuring in such a population of adaptive agents [2]. The formalism allows us to derive explicit macroscopic equations for the policy dynamics. For spatially homogeneous systems, a central outcome of our theory is the emergence of an effective reward function that determines the evolution of the policy distribution and encapsulates the microscopic details of the agents physical and memory dynamics [3]. We apply the theory to several microscopic models where policies correspond either to physical parameters of the dynamics (e.g., speed or diffusion coefficient), or to parameters characterizing the response to external fields. The theory captures key aspects of collective learning, including the influence of population diversity and reward fluctuations on learning performance.

References

[1] M.Y. Ben Zion, J. Fersula, N. Bredeche, O. Dauchot, Science Robotics **8**, eabo6140 (2023).
[2] G. Jung, M. Ozawa, E. Bertin, Phys. Rev. Lett. **134**, 248302 (2025).
[3] G. Jung, J. Asnacios, M. Ozawa, O. Dauchot, E. Bertin, preprint arXiv:2607.02171 (2026).

Flocking against the odds

E. Lardet[1] and T. Bertrand[1]

[1] *Imperial College London, London, UK*

Active matter systems, from bird flocks to bacterial swarms, consume energy to move and generate macroscopic order from purely microscopic interactions. While minimal models of identical, self-propelled particles effectively explain this emergent "flocking" behavior, natural systems are inherently heterogeneous. In this talk, we will test the robustness of collective order when these idealized models are perturbed away from this minimal simplified model. We introduce three key variations: multiple interacting species [1,2], quenched random interaction couplings [3], and temporally correlated noise. Using large-scale particle simulations alongside kinetic and hydrodynamic theories, we demonstrate that global order is often far more resilient, and occasionally more fragile, than expected. Built-in frustration drives system-wide self-organization that preserves, and can actively promote, collective order, yielding novel states. We conclude that minor particle-level changes have profound macroscopic consequences.

References

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[2] E. Lardet, L. Chen and T. Bertrand, arXiv:2512.19393 (2026)
[3] E. Lardet, R. Voituriez, S. Grigolon and T. Bertrand, arXiv:2409.10768 (2024)

Statistical Signatures of Microorganism Motility Under Environmental Stress

Luiza Treichel Mossi[1], Nicole Mazzitelli Narvaz[1], Leonardo Gregory Brunnet[1], Alexandre Arenzon[2], and Carolina Brito[1]

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2) Centro de Ecologia, Instituto de Biociências, Universidade Federal do Rio Grande do Sul, CEP 91501-970, Porto Alegre, Rio Grande do Sul, Brazil

The locomotion of microorganisms provides a natural platform for investigating active matter and the emergence of collective statistical behaviors under environmental perturbations. We experimentally studied the swimming dynamics of two organisms with distinct propulsion mechanisms and hydrodynamic regimes, *Paramecium caudatum* and *Artemia salina*, under control and stress conditions. Individual trajectories were reconstructed from video microscopy and characterized using a set of statistical observables. Environmental stress induced species-dependent changes in motility. To rationalize experimental observations, we developed minimal stochastic models whose parameters were extracted directly from the experimental data. Despite the distinct swimming mechanisms of the two organisms, the models accurately reproduced emergent spatial observables, including tortuosity and radius of gyration. Current experiments with *A. salina* navigating labyrinthine environments are being used to further test the ability of these coarse-grained models to predict exploration dynamics.

Activity-Controlled Segregation Time Scales in Self-Propelled Particle Ensembles

Leonardo G. Brunnet

IF-UFRGS, Porto Alegre, Brazil

Cell segregation is a fundamental process in development, tissue regeneration, and morphogenesis, with historical roots tracing back to Abraham Trembley's 1744 observations of Hydra regeneration. This work investigates the mechanisms driving cell segregation, comparing three principal hypotheses: Differential Adhesion (Steinberg, 1962), Surface Contraction (Harris, 1976), and Different Velocities (Jones, 1989). We compare computational models ranging from lattice-based Potts simulations and finite element methods to active particle and active ring models. The active ring model incorporates non-reciprocal contractile forces between particles from different rings, allowing simulation of differential adhesion, differential contraction, and different velocities—either separately or in combination.

Our findings demonstrate that all three hypotheses successfully produce cell sorting, but alignment interactions significantly accelerate the process. Activity, characterized by the Péclet number, acts analogously to temperature or membrane fluctuations, governing the phase behavior of the system. Under confinement, differential adhesion simulations yield segregation exponents of 1/4, consistent with mean cluster model predictions. The active ring model reveals both checkerboard and segregated states, mirroring results from Potts and finite element simulations, while exhibiting a distinct 1/3 segregation exponent attributable to a ballistic aggregation process. The active ring model provides a unified framework for studying multiple segregation mechanisms simultaneously, capturing complex behaviors including interface roughening and phase separation.

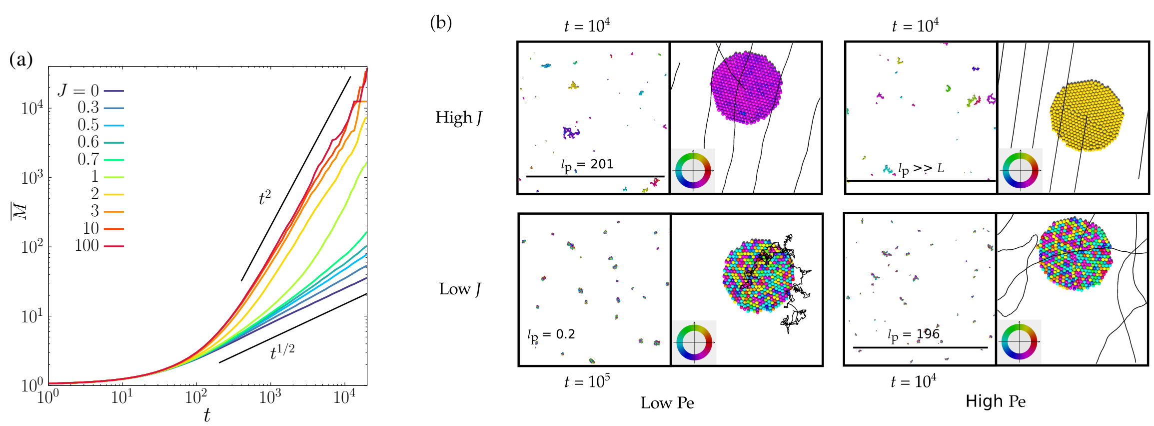

Figure 1: Adhesive active matter exhibits rich aggregation kinetics. (a) Evolution of the average cluster mass $\overline{M}(t)$ for different values of alignment J. Stronger alignment accelerates aggregation and increases exponents. Here, Pe = 1. (b) Snapshots of aggregation and cluster dynamics in different regimes for low alignment ($J = 0$), high alignment ($J = 100$), low individual-particle persistence (Pe = 1) and high individual-particle persistence (Pe = 10^3). Scale bars show cluster persistence length (the lower left case bar is too small to be visible). Colors indicate particle polarity (see color wheel). L is the simulation box length.

Keywords: Active matter, cell segregation, differential adhesion, active ring model, time scales, collective dynamics.

Scaling regimes of the Kuramoto-Sivashinsky equation

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[2]Instituto de Fisica, Facultad de Ingenieria, Universidad de la Republica, J.H.y Reissig 565, 11000 Montevideo, Uruguay

In this talk, I will revisit the renormalisation group (RG) approach to the one-dimensional stochastic Kuramoto-Sivashinsky (KS) equation and show that perturbative Wilsonian RG with a sharp cutoff is not well-defined for the KS model, even though it has been used in previous approaches. The problem can be solved using the functional RG, which allows one to establish that the KS RG flow leads to the Kardar-Parisi-Zhang (KPZ) fixed point at large scales. Furthermore, I will show that the two-point correlation function exhibits in fact three universal scaling regimes that I will characterise: the KPZ regime (with dynamical exponent z=3/2), the Edwards-Wilkinson regime (with z=2) and the recently discovered inviscid regime (with z=1). The latter develops over an extended range of large wave-numbers and is intrinsic to the KS dynamics since it arises from the vanishing of the effective viscosity when evolving from its microscopic negative KS value, to its macroscopic effective positive KPZ value.

References

[1] L. Gosteva, D. Roy, N. Wschebor, L. Canet, arXiv:2605.23364
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Spin-waves without spin-waves: A case for soliton propagation in starling flocks

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Collective turns in starling flocks propagate linearly with negligible attenuation, indicating the existence of an underdamped sector in the dispersion relation. Beside granting linear propagation of the phase perturbations, the real part of the frequency should also yield a spin-wave form of the unperturbed correlation function. However, new high-resolution experiments on real flocks show that underdamped traveling waves coexist with an overdamped Lorentzian correlation. Theory and experiments are reconciled once we add to the dynamics a Fermi-Pasta-Ulam-Tsingou term.

References

arXiv:2505.19665 - PRL in press

Ghost State of Light

R.M. de Boer[1], **C. Toebes**[2], **J. Klärs**[2], **and S.R.K. Rodriguez**[1]

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We report the observation of a long-lived non-stationary state of light in a single-mode optical cavity. The observed state is a ghost of a saddle-node bifurcation which creates a bottleneck in phase space. While such ghosts are known to exist, accessing them is challenging because it requires a mechanism that steers the relaxation pathway away from the true attractor and into the bottleneck where the ghost emerges. Here we identify such a mechanism, namely a nonlinear response with memory. Our experimental system leverages this mechanism, enabling us to observe ghost states with lifetimes exceeding the cavity photon lifetime by more than ten orders of magnitude, even in the presence of strong fluctuations. The ghost manifests as a plateau in the relaxation dynamics of the cavity transmission, reminiscent of prethermalization. We show how the ghost lifetime depends on the memory time and the distance to the bifurcation, and we observe signatures of scaling in the distribution of ghost lifetimes at fixed driving conditions. Our work establishes minimal conditions for realizing parametrically long-lived non-stationary states.

Fluctuations and patterns in complex ecological communities

Silvia De Monte
CNRS, IBENS, Paris, France & MPI for Evolutionary Biology, Plön, Germany

Microbial communities harbour hundreds to thousands of genetically distinct populations, whose dynamics is shaped by ecological processes that are extremely challenging to quantify at the species level. Many empirical studies have therefore focused on statistical features, as underpinned by the distribution of species abundances or by their variation in time, revealing recurrent patterns.

A range of models have been successful in explaining at least part of such regularities, but the difference in their underlying hypotheses makes it difficult to draw conclusions on what ecological processes are important and where.

I will briefly talk of how models of randomly and strongly interacting species can produce, in a regime of intermittent chaotic oscillations, abundance distributions akin to the empirical observations.

In order to better understand what key features underpin such out-of-equilibrium patterns, I will then introduce a stylized model encompassing three features commonly assumed to structure population dynamics: fluctuating species fitness, self-limitation and dispersal.

Both models admit effective, low-dimensional approximate descriptions that allow us to identify macroscopic parameters controlling the shape of the abundance distribution. Such approach informs us on what ecological processes can, or cannot, be distinguished by community-level patterns.

References

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[2] E. Mallmin, A. Traulsen, S. De Monte (2025) Chaotic turnover of rare and abundant species in a strongly interacting model community. *PNAS* 121 (11), e2312822121

Density-protected states in active matter under virtual confinement

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[6]*Max Planck Institute for Dynamics and Self-Organization (MPI-DS), Göttingen, Germany*

We investigate photo-responsive structure formation in a minimal model of dry active nematics. Combining microscopic simulations with the analysis of the corresponding hydrodynamic theory, we show that the system generically self-assembles into a dense, nematically ordered ring at the boundary of compact illumination patterns. Remarkably, this boundary structure gives rise to a disordered core whose density is self-selected and independent of the global particle density.
Our analysis reveals that these protected states emerge from a generic interplay between local nematic alignment and curvature-driven active currents.
These results identify a robust route to boundary-induced structure formation in active matter and provide experimentally testable predictions.

Quantifying Dissipation in Active Matter

Ramin Golestanian[1,2]

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The intersection of stochastic thermodynamics and active matter is a very exciting and active field with great potential for opening new horizons for both disciplines. There are a number of important questions in the field: (1) How can we quantify dissipation? (2) How can we control active matter? (3) How can we build thermodynamically-consistent frameworks? (4) What is the role of momentum conservation? (5) Why should we care about dissipation? To answer these questions, we need to incorporate a minimal amount of the mechanistic aspects of active matter. In this talk, I will address these questions and present concrete examples in which one can obtain partial answers.

References

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Simulations of parity-conserving directed percolation

P. Grassberger

[1] *FZ Juelich, Germany*

Parity conserving directed percolation (pcDP; also called parity conserving branching annihilating random walks, pcBARW) is one of the most important models with an absorbing state transition. In contrast to ordinary DP, particle number is conserved modulo 2 in pcDP. Thus there are two distinct sectors in systems with a finite initial number of particles: Realizations with even and odd particle numbers show different scaling behaviors. An intriguing feature of pcDP is that some of its critical exponents seem to be very simple rational numbers. The most prominent is the one describing the average number of particles in the even sector, which is asymptotically constant. In contrast, the dynamical critical exponent (which is the same in both sectors) seems not close to any simple rational. Finally, the order parameter exponent (which is also the same in both sectors) is, according to previous simulations, rather close to 1, but incompatible with it. We present high statistics simulations which show that all exponents which were close to rationals are even closer, and the order parameter exponent is 1.000 (1).

Active microtubule network in evaporation droplets

Isabella Guido, University of Surrey, UK

Active networks of cytoskeletal filaments and motor proteins provide powerful *in vitro* models for studying intracellular processes and dynamic structures within the framework of active matter physics. These systems enable investigation of self-driven assemblies that operate far from thermodynamic equilibrium generating dynamic patterns on length scales far larger than those of their individual components. In our study we investigate the emergent behaviour of active microtubule–kinesin networks subjected to external mechanical forces acting at the air–liquid interface. To this end, we use a simple approach by confining active networks composed of microtubules, kinesin motors, and ATP within a sessile droplet. We observe that evaporation-driven flows generate shear stresses that couple with motor activity and this interplay produces non-trivial dynamics that lead to wetting followed by dewetting of the droplet. Interestingly, the temporal evolution of these dynamics strongly depends on motor crosslinking, ATP availability, and the ionic strength of the bulk solution.

We believe that our findings can contribute to understanding how intracellular ionic strength may regulate cytoskeletal mechanics and organization through electrostatic interactions between microtubules and motor proteins.

Understanding the superiority of multi-model ensemble forecasts through reservoir computing

Daniel Estevez-Moya[1], Francesco Martinuzzi[1], Edmilson Roque dos Santos[1], Erick Alejandro Madrigal Solis[1], Ernesto Estevez-Rams[2], Holger Kantz[1]

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Weather forecasting and climate projection frequently use multi-model ensembles (MMEs) to improve forecasts by averaging across models, since often there is no single best model for all forecasts tasks. However, this practice is often not well justified or validated. Using reservoir computing (RC) as a computationally efficient alternative to large-scale physical models, we assess the validity of the MME approach for chaotic time series prediction. By training multiple randomly constructed RCs on the same dataset, we create a multi-model ensemble in which each model has its own unique model error. These model errors lead to very different forecasting performances, with forecast error distributions that exhibit heavy tails. The arithmetic mean across forecasts from multiple models for the same target is usually closer to the ground truth than most individual forecasts, and further improvement is achieved by weighted arithmetic means where the weights are constructed based on each model's test-set performance. We show that iterated forecasts over many time steps deviate from the ground truth along the unstable manifold of the target point, in both directions, so that, if forecast errors were independent and had zero mean, the arithmetic mean forecast should approach the true target like $1/\sqrt{N_{ens}}$ where N_{ens} is the number of different models in the multi-model ensemble. We observe deviations from this behavior, which we attribute to the tails of the error distribution of random RCs.

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Defects states in renewing active matter

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Biological active matter like the cytoskeleton or tissues are characterized by their ability to transform chemical energy into mechanical stress. In addition, it often exhibits orientational order, which is essential for many cellular and morphogenetic processes. Experimental evidence suggests that defects in the orientational order field play an important role in organizing active stress. However, defects tend to annihilate unless the material is in a chaotic state or hydrodynamic interactions are suppressed. Using a hydrodynamic description of compressible active polar fluids, we show that turnover readily leads to a stabilization of defects [1]. Depending on the turnover rate, topological defects arrange in a multitude of different phases, including lattices, active foams and vortex glasses [1]. In nematopolar fluids stable topological strings can form [2]. Our work suggests that turnover plays a crucial role for organizing biological active matter.

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Active translation symmetry-broken states in disordered environments

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I will discuss the effect of activity on translation symmetry-broken motile states—polar smectics and solids—and demonstrate that motility stabilises order. The equal-time statistics of displacement fluctuations of motile smectics in d dimensions with quenched disorder are equivalent to time-displaced correlations of the height field in the d-1-dimensional KPZ equation. In particular, in two dimensions, this implies that motile smectics are as (dis)ordered in the presence of quenched disorder as passive smectics in the absence of disorder, in two dimensions. For one class of motile solids, I will show that the equal-time displacement correlations in the presence of quenched disorder are only as large as the equal-time displacement correlations of passive solids in the absence of quenched disorder, attesting to the annealising effect of motion. I will further comment on the effect of disorder on immotile but active smectics and time cholesterics and show that the spin-wave theory of the former is equivalent to a random field XY model and that of the latter to a KPZ equation with quenched noise. Beyond active systems, the results I will discuss are relevant for a large class of externally-driven systems including charge-density waves, vortex lattices in type II superconductors and exciton-polariton condensates.

Scaling properties of Kuramoto chaos

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The Kuramoto model of globally coupled phase oscillators demonstrates a nonequilibrium synchronization phase transition. While this transition is well understood in the thermodynamic limit of an infinite population, finite-size effects are less explored. While both disordered and ordered states in the thermodynamic limit are quasiperiodic, finite ensembles demonstrate chaos. We explore the properties of chaos (the largest Lyapunov exponent and correlations) as a function of the two main parameters: the size of the population and the coupling strength.

Metastability and condensation phenomena in statistical systems with two conservation laws

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Abstract

Statistical-mechanics of systems characterized by two conservation laws are reviewed, showing the existence of a parameter region where absolute negative temperatures emerge.

A typical example of this scenario is offered by the Discrete NonLinear Schroedinger (DNLS) equation, a model used both in optics (waveguides) and for the characterization of polymer dynamics.

One of the key features is the spontaneous emergence of highly energetic spots (so-called breathers), which exchange energy very slowly with the background; a phenomenon that can be also interpreted as an instance of energy condensation.

Close to the infinite-temperature line, the waiting time for the emergence of a breather out of an otherwise homogeneous environment can be determined by invoking the existence of a critical barrier separating decaying (below) from diverging (above) breathers.

Interestingly, many features of the DNLS equation are reproduced by a stochastic model, which allows performing some analytical calculations.

The main properties are illustrated both referring to equilibrium and non-equilibrium setups.

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Learning and Information Spread in Neural Networks

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Life hinges on information processing: to navigate the world, animals rely on their brains – and thus on the fine, collective interactions of millions or billions of neurons. Importantly, these networks can learn in a self-organized manner, i.e., the neurons update their connectivity and information transmission without any explicit teacher signal. We aim to understand the basic principles of this emergent information flow or "infogenesis" using the approaches from statistical physics and information theory. Understanding infogenesis is very interesting per se; in addition, it also serves as a starting point to understand the flow of (mis)information in social networks, pointing to surprising similarities. With studying these two distinct active networks side-by-side, our aim is to extract their specific self-organization principles.

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“Living layered systems”

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Structures exhibiting a periodicity only in one direction, can be observed in biological systems such as the acto-myosin network in lamellipodia, stress fiber patterns in epithelia, endoplasmic reticulum, myelin sheets, bones and glioblastoma tumors, but also in many out-of-equilibrium patterns. Such systems are often not mono-crystalline and display dislocations densities, dynamical behavior etc. This raises the question of the description of active smectics in the presence of dislocation densities in two and three dimensions. After discussing the existence or non-existence of a steady state depending on boundary conditions, I'll give a few examples of non-equilibrium behavior hopefully relevant to life and in particular to tumor growth.

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Nonreciprocal planar lattice models

Sriram Ramaswamy

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I will summarise findings from our recent studies on two-dimensional lattice models of rotors that align more strongly with neighbours that they point to. I will discuss our recent [1] work on polar systems, its origin in advection without motility [2], and a contrast with new results (with N Peteri, P Popli & A Maitra) on nematic and chiral systems.

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Classifying Tissue Properties via Collective Dynamics around Topological Defects

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Elongated cell tissues and monolayers frequently exhibit local orientational order, allowing them to be modeled as "living liquid crystals" characterized by topological defects. While these defects are well-known to play a pivotal role in morphogenesis, a systematic framework for classifying the distinct characteristics among different tissues remains elusive. In this work, we successfully engineered defects with +1/2 and -1/2 topological charges by implementing micropatterns on substrates. By further inducing various configurations of +1 and -1 defects, we precisely quantified collective cell dynamics around these regions. Based on these findings, we characterized the intrinsic properties of the tissues and proposed a novel classification scheme. Furthermore, it was suggested that topological defects are also involved in the formation of lumens in three-dimensional tissues, where cell polarity plays an important role.

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Kuramoto-Vicsek Model for Active matter

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Abstract： The Vicsek model is perhaps the most celebrated model in active matter, interpretable as an off-lattice XY model where spins self-propel at constant speed—a feature that drives the system out of equilibrium and permits true long-range polar order in 2D, as well as spontaneous segregation into dense, ordered structures traveling through a sparse gas[1].

There is a natural way to introduce chirality into this framework: endow each self-propelled particle with an intrinsic rotational frequency. The resulting equation governing particle polarity then becomes akin to that of the celebrated Kuramoto synchronization model, but with coupling that is local in physical space. This Kuramoto-Vicsek model provides an ideal playground for studying dry chiral aligning active matter.

In this talk, we present a synthetic overview of the remarkable properties of this model uncovered over recent years. We show that homogeneous ordered phases are unstable or metastable. Even zero-mean chirality disorder suffices to destabilize polar order[2]. For uniform chirality, the rotating ordered liquid is Floquet-stable –a regime that some would call a time-crystal with novel scaling properties. Yet it is ultimately metastable. In all cases, ordered phases give way to rotating polar packets and vortices that undergo coarsening, not into microphases, but into macroscopic condensates[3]. These condensates exhibit phase and/or frequency synchronization and are captured by a phenomenological kinetic theory based on angular Fourier mode expansions with scaling-based closure.

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Flocking Transition in Phoretically Interacting Active Particles: Role of Disorder

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Recent studies on the collective behavior of active colloids have demonstrated that global polar order can spontaneously emerge driven purely by long-ranged chemo-repulsive interactions. In this work, we investigate the robustness and control of this flocking transition in the presence of quenched spatial disorder. We model a system of chemically interacting active colloids where a variable fraction of particles is randomly pinned in space. These pinned particles act as "translationally inert" obstacles—unable to translate, but fully capable of rotating and phoretically interacting with the surrounding active bulk. By systematically varying the pinning fraction and interaction strengths, we quantify the global polarization and examine finite-size effects across the transition.
Key findings include: (a) Melting of Crystalline Order: In the crystallite flocking regime, introducing even a minimal fraction of pinned particles destroys spatial crystalline order. However, global polar order is preserved, transitioning the system into a polar liquid phase. (b) Role of Chemo-Repulsive Interactions: Higher obstacle densities suppress flocking, but global polar order can be sustained if long-ranged chemo-repulsion is increased accordingly. In contrast, without chemo-repulsive forces, polar order rapidly decays even at low pinning fractions.

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Robustness and fragility of polar active fluids

Alexandre Solon (CNRS, Sorbonne Université)

Understanding how self-propelling entities manage to move collectively, even in the simplest settings, remains a topical issue after more than thirty years of investigations. In this talk, I will first present an hydrodynamic theory for the homogeneous phase of collective motion that allows to derive the scaling exponents of the fluctuations in this phase, thus proving the fact, well established by numerical simulations, that it exhibits long-rang order in two dimensions and is thus more robust to fluctuations than its equilibrium counterparts. However, we will see that, compared to equilibrium systems, polar active fluids are more fragile to the nucleation of topological defects. In particular, in systems with discrete symmetry, the ordered phase is always metastable, while stability is recovered only at low temperature in systems with continuous symmetry.

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Flocking with Hugues: Collective Motion With(out) a Leader

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The past thirty years have taught us a lot on the transition to collective motion. In this talk I will review what my collaborations with Hugues have taught me and I will try to explain why I think that we will learn even more in the next thirty years.

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Experimental Approaches to Statistical Physics in Large Chaotic Systems

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In this talk I will cover the following three topics, which are apparently unrelated but all significantly influenced by Hugues: non-equilibrium scaling laws, instability analysis of large chaotic systems, and collective dynamics of bacteria.

The first part is about an old experimental finding of universal non-equilibrium scaling laws, namely those of the directed percolation class [1] and the Kardar-Parisi-Zhang class [2], in turbulent liquid crystal. An important remaining problem is why those scaling laws arose clearly in this experimental system. I will argue that being spatiotemporal chaos may have contributed. I will mention our ongoing work for inspecting this chaotic experimental system, by focusing on dynamics of topological defect lines [3].

The second part is about instability analysis of large chaotic systems. We showed how we can use Lyapunov vectors associated with Lyapunov exponents to capture collective dynamics [4] and effective dimension [5], specifically the inertial manifold dimension, of large chaotic systems.

The third part is about active matter, specifically turbulent collective dynamics of bacterial populations. We recently characterized the route to turbulence of this active matter system [6] through combination of large-scale experiments, simulations, and theory based on nonlinear dynamics. This motivated us to characterize bacterial turbulence through the lens of spatiotemporal chaos. If time allows, I will describe our ongoing attempt to evaluate chaotic aspects of bacterial turbulence, by employing a machine learning approach.

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WE-Heraeus-Seminar "Nonlinear Dynamics and Emergence Across Scales: Active, Chaotic, and Complex Systems", 14 – 18 September, 2026, Roscoff, France

From Domain Walls to "Entropy-ons": Building the State Space of a 2D Spin Glass

Lei-Han Tang

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Hugues Chaté and I have long shared an interest in how disorder and fluctuations generate unexpected collective behavior. Our approaches are complementary: I tend to search for a physical picture, while Hugues—shaped by his work on dynamical systems with many degrees of freedom—insists that such pictures earn their credibility through precise numerical computation. This combination informed our earlier work on directed polymers and heteropolymer localization, and it also captures the spirit of the work I will present here.

The subject is the two-dimensional ±J\pm J±J random-bond Ising model. We begin with Fisher–Huse domain walls, suitably adapted to describe the energetics of the ferromagnet-to-spin-glass transition. High-precision numerical results show that a system-spanning wall behaves as a directed polymer in a random medium, providing a simple physical explanation for the unusual, mixed-order character of the transition.

Domain walls, however, tell only part of the story. The organization of the many degenerate ground states is governed by zero-energy loops: localized objects that carry freedom—and therefore entropy—rather than energy. I will introduce these loops as **"entropy-ons,"** entropic analogues of quasiparticles. Their compatibility, exclusion, and locking fragment the state space into competing basins and may provide a real-space route toward its hierarchical organization.

The aim of the talk is to develop this picture step by step: from domain-wall energetics to entropy-ons and, finally, to the architecture of state space—with each conceptual step tested against quantitative numerical evidence.

Dynamics of Learning: Lessons from Living Systems to Artificial Neural Networks

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What is learning, and how does it emerge in both living systems and machines? In this talk, we first introduce a concise and general definition: learning is the process by which a system acquires information, encodes and stores it in its internal degrees of freedom (memory), and uses this memory to improve performance on specific tasks. This perspective naturally casts learning as a dynamical process evolving in time. Within this theoretical framework, we compare learning mechanisms across a broad spectrum of systems—from adaptive responses in single cells, to associative learning in biological neural networks, to algorithmic methods such as stochastic gradient descent in artificial neural networks.

Learning the laws of collapse

Target state directed dynamics in living systems and beyond

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Across the living world, from cell biology and morphogenesis to behaviour and cognition, system dynamics is often directed towards functionally important goals one might call target states. Structurally similar dynamics are active during systems breakdown as in ecosystem collapse or the collapse of financial assets that drive a system to a terminal state. Dynamics towards such target and terminal states is never in equilibrium, always nonstationary, and typically swiftly over, terminating once the goal is reached. Here we examine such dynamics from the viewpoint of robust biological design and data-driven inference. We present a reverse-time stochastic dynamics theory for ensembles of target state directed processes and uncover a universal space-time core of such ensembles. Examining this core structure, we demonstrate that ensembles undergo a phase transition from an opaque phase, in which their space-time core is uninformative about the underlying dynamics, to a transparent phase, in which the dynamics is directly encoded in its low-order moment functions. Confirming the fundamental nature of this inference phase transition, we show that even the most advanced methods for simulation-based inference break down near this phase transition. We use the reverse-time theory of target state directed processes to construct core-based methods for data-driven dynamical systems inference and demonstrate their power through examples ranging from the biophysics of cytokinesis, to the dynamics of bankruptcy, and to the dynamics of goal-directed animal behaviour. Reverse-time ensemble theory establishes a versatile toolset for understanding target state directed biological processes and reveals that the mere presence of target states in living systems induces a novel kind of phase transition in dynamical systems inference.

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Abstracts of Posters

(in alphabetical order)

Collective behavior of self-propelled rods: continuum theories derived from Vicsek models with nematic alignment and repulsive interactions

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Models of colliding self-propelled rods are abstractions of many real systems such as gliding bacteria and biofilaments displaced by molecular motors [1]. They have been studied mostly in two space dimensions and shown to display a wealth of different collective regimes with many parameters involved in the ensuing phase diagrams [2]. Continuum-level theories faithful to this phenomenology are largely lacking since coarse-graining models of explicit rods is notoriously difficult. Here we study collections of point particles nematically aligning their velocities [3], the geometry of the rods being accounted for effectively through repulsive interactions. These Vicsek-style models mimick more realistic rod models and are simple enough to be starting points for systematic coarse-graining. We study in particular a Vicsek model with nematic alignment and various forms of repulsion between particles—pairwise repulsive forces and repulsive torques —and derive, within the Boltzmann-Ginzburg-Landau approach [4], hydrodynamic equations that we show to have solutions qualitatively faithful to their particle-level origin.

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Weakly Nonlinear Interactions and Full Numerical Simulations of a Pair of Quincke Rotors

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Quincke rotation is a spontaneous electrohydrodynamic symmetry-breaking instability in which a dielectric particle begins to rotate when a uniform direct-current electric field exceeds a critical value [1]. More recently, placing Quincke rotors close to a solid surface was shown to convert rotation into translation, producing self-propelled "Quincke rollers" [2]; their interactions can generate collective states including macroscopic directed motion and vortices [2,3]. This direct conversion of a classical electrohydrodynamic instability into self-propulsion makes Quincke rotation a particularly clean model system for active matter. Geometric chirality provides a distinct route to convert Quincke rotation into self-propulsion even in an unbounded fluid [4]. These recent studies motivate understanding how the instability is modified fundamentally at the level of two interacting particles. Here we isolate this question by considering two identical spherical Quincke rotors in an infinite fluid, without walls or shape-induced propulsion. Near onset, the usual far-field interaction expansion becomes singular because the rotation amplitude vanishes. We develop a weakly nonlinear theory that resolves this singularity and yields coupled amplitude equations for the interacting rotors. The reduced dynamics predict symmetric and antisymmetric collective modes, orientation-dependent shifts of the Quincke threshold, nonlinear saturation, stability, and slow evolution of the relative rotation phase. A complementary regular far-field expansion describes the steady rotating states away from onset. The asymptotic predictions agree very well with simulations of the pairwise dynamical model [5] and full numerical simulations based on the boundary element method. The framework provides a systematic route from the single-particle Quincke instability to pairwise dynamics, and can be extended naturally to chiral Quincke swimmers in bulk [4] and to interacting rollers near walls [2,3].

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A stochastic dynamical model to explain robustness of Gene expression

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Gene expression is inherently stochastic, yet cells maintain functional protein levels despite molecular fluctuations. This robustness is believed to arise from the structure of gene regulatory networks, the network of interactions between transcription factors and genes. Understanding how network architecture shapes stochastic fluctuations and contributes to suppression of noise remains a fundamental challenge in complex biological systems.

We develop a stochastic framework describing the time evolution of gene activity. The model links the topology of a GRN to the statistics of gene expression in the stationary regime. Each gene is described by an effective expression variable, and by analyzing fluctuations around stable regulatory states(phenotypes) we derive the stationary covariance of gene expression for a given network. This provides a quantitative connection between network structure and noise propagation.

Using this model, we investigate how optimization under a fitness, defined as the growth rate of a population, influences the organization of GRNs. In reality, species undergo the process of natural selection which results in the increase of fitness. We employ optimization algorithms to identify network architectures that maximize fitness which is observed to be closely linked to fluctuations suppression. By comparing optimized and non-optimized networks across multiple structural tests, we identify features that consistently contribute to robustness to noise.

Beyond characterizing optimized networks, we explore whether the resulting high-dimensional stochastic dynamics admit effective low-dimensional descriptions. Such reductions provide insight into the dominant modes governing noise propagation and suggest general principles underlying robustness in complex regulatory systems.

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Advective stabilization of active vortex crystals

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Active fluids, composed of dense suspensions of active agents, can self-organize into well-ordered vortex lattices. This route to pattern formation exhibits several features that distinguish it from classical pattern-forming systems, including a long supertransient phase and nontrivial wavenumber selection. Similar behavior is also observed in other two-dimensional fluid systems. Here, we develop a theoretical framework to explain the mechanism underlying these observations. Starting from a phenomenological model of active fluids, we evaluate the energy transfer between wavenumber modes and show that advective coupling plays a key role in stabilizing these patterns. The stability of the vortex lattice is governed by the balance between advective and saturation nonlinearities. The resulting theoretical stability boundaries and amplitude predictions are in good agreement with numerical simulations. Building on these results, we derive a general reduced-order model that establishes the conditions under which two-dimensional vortex lattices can form in fluid systems.

Volatile but persistent co-existence of self-compatibility and self-incompatibility in plants

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Plants employ diverse mating strategies, including self- and cross-fertilization or their combination. Despite the ubiquity of mixed mating – the use of both self- and cross-fertilization within the same population – its evolutionary origins and dynamic stability remain elusive. Here, we study self-incompatibility, in which self-fertilization is disabled by molecular recognition and enabled when mutations disrupt this recognition. Using population-level stochastic simulations, we model the effects of two main parameters on the prevailing mating mode: promiscuity of molecular recognition and inbreeding depression, which penalizes self-compatibility. We reveal a phase diagram with three phases: complete self-incompatibility, complete self-compatibility, and a mixture combining both. The mixed phase exhibits newly-described vigorous, non-decaying fluctuations in the proportions of individuals occupying either mating mode. Pollen limitation extends the parameter range over which complete self-incompatibility is favored, contrary to the commonly held view. This study offers new insight into the evolutionary dynamics of plant reproductive systems.

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Finite Wavelength Reshapes Nonlinear Polarization in Confined Bacterial Suspensions

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Dense bacterial suspensions can display coherent, large-scale velocity oscillations even though individual cells move irregularly. The observed local velocity orbit is typically elliptical, but linear instability theory alone cannot determine whether nonlinear saturation selects circular, linear, or elliptical motion. Here we study this question within one conservative kinetic-hydrodynamic operator for a confined active suspension with a clean deformable interface. The model couples a Smoluchowski equation for swimmer position and orientation to active-stress-driven Stokes flow, with no slip at the lower boundary and moving-interface traction and flux conditions at the upper boundary.

At zero horizontal wavenumber, rotational symmetry gives two opposite circular helicities. A cubic normal-form calculation finds that cross-saturation exceeds self-saturation (chi = 1.24-1.37), so the stable homogeneous states are circular orbits. At finite wavenumber, the carrier wavevector distinguishes longitudinal and transverse modes. Interface compliance brings their linear thresholds close enough that cubic resonant coupling can lock their relative phase. This produces a sideband-stable elliptical orbit in a bounded region of wavelength and density. For a prescribed 5-mm carrier, a full kinetic-PDE simulation in a restricted Fourier sector reproduces the reduced-theory axis ratio and frequency to within 3.5 x 10^-4 and 3.7 x 10^-4 Hz, respectively.

The calculation therefore identifies a symmetry-controlled route from homogeneous circular motion to finite-wavelength elliptical polarization without changing the underlying physical operator. It also exposes a limitation: broadband simulations favor the shortest resolved longitudinal mode rather than the experimentally observed centimetre-scale wave. Thus, the present theory accounts for nonlinear polarization selection but indicates that additional physics is needed to select the experimental wavelength and period.

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Periodically Modulated Poiseuille Flow as a Route to Chaos for Microswimmers

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The motion of a spherical microswimmer in Poiseuille flow is mathematically equivalent to the dynamics of a simple Hamiltonian pendulum [1]. Periodic driving, either through propulsion modulation [2] or imposed flow modulation, transforms the autonomous system into a periodically driven Hamiltonian system and generates chaotic trajectories through a separatrix-breaking mechanism analogous to that of a parametrically driven pendulum. We characterize the resulting chaotic dynamics induced by periodic flow modulation and examine its consequences for swimmer transport. Because the Hamiltonian dynamics is structurally unstable, we further investigate how leading-order hydrodynamic interactions with the channel walls modify the resulting chaotic dynamics of pusher and puller swimmers. Our results demonstrate that weak temporal modulation of the external flow provides a controlled route to chaotic dynamics for microswimmers, and show how confinement alters their chaotic behavior and transport.

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Understanding the oscillations and mode spectra of active self-aligning disordered solids

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Active disordered solids including dense human crowds and epithelial cells under confinement exhibit striking system-scale oscillatory spatiotemporal patterns. These have recently been linked to a local feedback mechanism, self-alignment, that aligns the direction of a particle's motility vector to the direction of the total force on it. Simulations and experiments of solids made of such agents show these spontaneous oscillation patterns. Theoretically, they have been linked to both a nonlinear bifurcation and to selection of the long-wavelength normal modes of these solids. To understand the mode selection and pattern formation in such systems, we derive a closed nonlinear equation for the displacement field of active self-aligning 2d solids subject to angular noise. Along the normal modes of the solid, the dynamics of the mode amplitudes correspond to nonlinearly damped and stochastically driven harmonic oscillators. To linear order, we show that the system transitions from Active Brownian type correlated motion to oscillatory motion that increasingly condenses onto the lowest modes of the solid. We compare the analytical predictions for the mode spectra with simulations of self-aligning self-propelled particles, finding very good agreement approaching the transition from the disordered side. Strong nonlinearities manifest deep in the oscillating phase and for crystal-ordered systems with small noise, consistent with the previously observed nonlinear mode selection under these conditions. At the continuum level, we predict travelling acto-elastic waves, together with the emergence of system-scale oscillations for confined systems and a flocking state in the absence of boundaries.

Topological defects in non-reciprocal mixtures

Navdeep Rana

I will present our recent findings on topological defects in non-reciprocal mixtures. The Non-Reciprocal Cahn Hilliard (NRCH) model — describing phase separation with non-reciprocal interaactions — admits topologically charged spirals and neutral target defects. These defects are the generators of radially outward going travelling waves and are the precursors of polar order created by travelling bands. Defects in the NRCH model exhibit nonreciprocity dependent topological selectivity — when nonreciprocity is small, spirals are selected, whereas targets are the dominant defects at higher nonreciprocity. Beyond a critical threshold of nonreciprocal interactions, we observe a disorder to order transition — from defect networks to travelling wave patterns.
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Mixing Induced by Microswimmers as Probed by Mutual Information

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Microswimmers generate complex flow fields that strongly influence transport and mixing in fluids, yet a quantitative characterization of mixing in active suspensions remains challenging. We investigate microswimmer-induced mixing using mutual information as a global, information-theoretic measure of mixing efficiency. For a two-dimensional squirmer model in a confined domain, we compute swimmer-generated flow fields and solve the advection-diffusion equation governing tracer transport.

We show that mixing is strongly affected by swimmer organization: aggregation suppresses mixing, whereas positional and orientational disorder enhance it. For a fixed energy dissipation rate, mixing efficiency depends non-monotonically on the squirmer parameter, reflecting a trade-off between swimmer propulsion and dipolar flow generation. When hydrodynamic interactions are included, pushers consistently outperform pullers. Extending our previously developed information-theoretic framework to active suspensions, we demonstrate that mutual information provides a robust quantitative measure of mixing in complex active flows.

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Thermodynamic control of active droplets: Transitions in loop protocols

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Equilibrium thermodynamics enforces that manipulating passive systems always costs less energy for slow protocols. In this quasistatic regime, the work produced by external perturbation equals the free-energy difference irrespective of protocol details [1]. Instead, active systems achieve minimal dissipation at finite protocol durations as a compromise between internal activity and external driving [2,3], and the work produced by slow protocols now depends on the specificities of paths in parameter space [4]. Here, we offer a systematic framework based on nonequilibrium response theory to examine optimal strategies that change the size and composition of droplets in active liquids. We reveal that controlling intercomponent interactions generically leads to transitions between a rich family of protocols. As the control procedure becomes slower, optimal protocols feature an increasing number of loops in parameter space that leverage the breakdown of Boltzmann statistics to reduce dissipation. Overall, our framework opens the door to predicting optimal protocols for various control problems in active liquids, and guides the search for transitions between distinct control strategies.

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Wave propagation in nonlinear topological transmission line

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We show that a coupled discrete nonlinear Schrödinger equation, mimicking Su-Schrieffer–Heeger (SSH)[1], models a topological electrical transmission line. The study of the dispersion relation reveals the presence of the topological band between the acoustic and optical bands in the Brillouin zone. The homoclinic tangles is obtained for the uniform line case by following the method in references [2-5] and shown in Figure 1. The numerical integration of the uniform line is extended to the no uniform lattice and reveals intriguing features of the model.

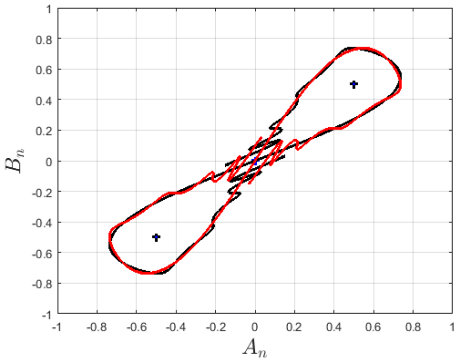

FIG1: Homoclinic connection for the uniform line

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Characterizing Nonlinear Dynamics of Sound Detection in the Auditory System via Entrainment Analysis

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The auditory system relies on fundamentally nonlinear active processes that enable sensitive and robust sound detection. A hallmark of this active amplification is the generation of spontaneous otoacoustic emissions (SOAEs), narrowband sounds that can be recorded in quiet environments from the ears of many animals, including geckos, guinea pigs, and humans. We have developed an analytical framework for characterizing the nonlinear dynamics underlying hearing by studying the interaction between SOAEs and external stimuli. A key advantage of this approach is its applicability to a broad range of in vivo measurements, including human recordings, because data acquisition leaves the ear completely intact. The main experimental challenge is that the recorded signal contains an inseparable superposition of the external stimulus, the system's response, and linear scattering from surrounding structures. Our framework overcomes this limitation by analyzing the entrainment of an SOAE peak to an external tone, allowing us to infer the underlying bifurcation structure of the active oscillator. We apply this framework to measurements from humans and Tokay geckos, identifying signatures of saddle-node on invariant circle (SNIC) and supercritical Hopf bifurcations. More broadly, this approach provides a general strategy for uncovering nonlinear dynamics in hearing and other active systems in which stimulus and response cannot be separated at the detector.