# Outstanding Challenges in Nonlinear Dynamics

French-German WE-Heraeus-Seminar

20 - 25 March 2022

HYBRID

at the Ecole de Physique des Houches, 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 French-German WE-Heraeus-Seminar:

Nonlinear dynamics has reached considerable breadth and diversification in recent years. Physicists are applying it in fields as diverse as fluid dynamics, climate and weather forecast, neuroscience, socioeconomic systems, and many more. On the one hand we have witnessed amazing progress in many of these fields, as seen, e.g., in the intriguing level of detail with which cardiac dynamics is now studied and modeled. On the other hand, this diversification in applications is somewhat masking the fact that we are presently facing substantial but similar challenges in different fields. An outstanding example is the collective dynamics of and on networks, which plays a role in many disciplines and for which the many body techniques developed for interacting particles are usually of little help, cf. e.g. the spiking dynamics of interacting neurons. This workshop will bring together researchers on nonlinear dynamics working in diverse fields and will focus on common topical challenges that are showing up in various applications. The conference language will be English. The Wilhelm and Else Heraeus-Foundation bears the cost of full-board accommodation for all participants.

## Scientific Organizers:


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|---|---|
| Prof. Dr. Theo Geisel | Max Planck Institute for Dynamics and Self-Organization, Göttingen, Germany<br>E-mail: geisel@ds.mpg.de |
| Prof. Dr. Hugues Chaté | CNRS-CEA Saclay, Gif-sur-Yvette, France<br>E-mail: hugues.chate@cea.fr |

# Introduction

## Administrative Organization:

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## Venue:

Ecole de physique des Houches
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https://www.we-heraeus-stiftung.de/veranstaltungen/outstanding-challenges-in-nonlinear-dynamics/venue/

# Program

# Program *(CET)*

## Monday, 21 March 2022

| | | |
|---|---|---|
| 08:50 – 09:00 | Organizers | **Welcome** |
| 09:00 – 09:40 | Stefan Luther | **Spatio-Temporal Organization of Cardiac Fibrillation** |
| 09:40 – 10:20 | Arkady Pikovsky | **Active Oscillators and Active Particles: Synchronization vs Chaos** |
| 10:20 – 10:40 | *COFFEE BREAK* | |
| 10:40 – 11:20 | Jean-Christophe Loiseau | **Challenges in Nonlinear System Identification** |
| 11:20 – 12:00 | Fred Wolf | **Sparse Chaos and Localization in the Dynamics of Neuronal Circuits** |
| 12:30 | *LUNCH BREAK* | |
| 14:30 – 17:00 | **Discussion Groups** | |
| 17:00 – 18:00 | *TEA BREAK* | |
| 18:00 – 19:30 | **Poster Session** | |
| 19:30 | *APÉRITIF* | |
| 20:00 | *DINNER* | |
| 21:00 – 22:00 | ***Poster Session, continued*** | |

# Program *(CET)*

## Tuesday, 22 March 2022

| | | |
|---|---|---|
| 09:00 – 09:40 | Svetlana Gurevich (Online) | **Dynamics of Temporal and Spatio-Temporal Localized States in Time-Delayed Systems** |
| 09:40 – 10:20 | Markus Bär (Online) | **Modelling Dynamics and Control in Cardiac Systems and Active Fluids** |
| 10:20 – 10:40 | *COFFEE BREAK* | |
| 10:40 – 11:20 | Marc Timme (Online) | **Inferring Complex Systems Structure from Dynamics** |
| 11:20 – 12:00 | Jan Nagler (Online) | **Impact of Network Motifs on Response Dynamics** |
| 12:30 | *LUNCH BREAK* | |
| 14:30 – 17:00 | **Discussion Groups** | |
| 17:00 – 18:00 | *TEA BREAK* | |
| 18:00 – 18:40 | Alain Pumir | **Structure and Scaling of Extreme Events in Hydrodynamic Turbulence** |
| 18:40 – 19:20 | Ulrich Parlitz | **Challenges in Complex Cardiac Dynamics** |
| 20:00 | *DINNER* | |
| 21:00 – 21:40 | Oleh Omel'chenko (online) | **Collective States in a Ring Network of Theta Neurons** |

# Program *(CET)*

## Wednesday, 23 March 2022

| | | |
|---|---|---|
| 09:00 – 09:40 | Davide Faranda | **A Dynamical Systems Approach to the Study of Complex Systems** |
| 09:40 – 10:20 | Ulrike Feudel | **Tipping Phenomena and Resilience in Complex Systems** |
| 10:20 – 10:40 | *COFFEE BREAK* | |
| 10:40 – 11:20 | Holger Kantz (online) | **Power Law Error Growth Rates - a Dynamical Mechanism for a Strictly Finite Prediction Horizon in Weather Forecasts** |
| 11:20 – 12:00 | Antoine Venaille | **Chaos in the Stratosphere?** |
| 12:30 | *LUNCH BREAK* | |
| 14:30 – 17:00 | **Discussion Groups** | |
| 17:00 – 18:00 | *TEA BREAK* | |
| 18:00 – 18:40 | Demian Battaglia (online) | **Dynamics and Primitive Computations: Mapping the Algorithmic Effects of Brain Circuit Nonlinear Dynamics** |
| 18:40 – 19:00 | Thanos Manos | **Long-term Desynchronization by Coordinated Reset Stimulation in a Neural Network Model with Synaptic and Structural Plasticity** |
| 19:00 – 19:20 | Matthias Wolfrum | **Bumps, Chimera States, and Turing Patterns in Systems of Coupled Active Rotators** |
| 20:00 | *DINNER* | |
| 21:00 – 21:40 | Theo Geisel | **Psychophysics of Musical Rhythms and the Riddle of Swing** |

# Program *(CET)*

## Thursday, 24 March 2022

| | | |
|---|---|---|
| 09:00 – 09:40 | Vincent Hakim | **Metamorphosis of the Landau Transition in the Flow of a Resonantly-Driven Bistable Condensate** |
| 09:40 – 10:20 | Daniel Schertzer | **A Century of Cascade Processes from Turbulence and Intermittency to Climate: Successes, Limitations and Challenges** |
| 10:20 – 10:40 | *COFFEE BREAK* | |
| 10:40 – 11:20 | Alessandro Torcini (online) | **A Reduction Methodology for Fluctuation Driven Population Dynamics** |
| 11:20 – 12:00 | Simona Olmi (online) | **Exact Neural Mass Model for Synaptic-Based Working Memory** |
| 12:30 | *LUNCH BREAK* | |
| 14:30 – 17:00 | **Discussion Groups** | |
| 17:00 – 18:00 | *TEA BREAK* | |
| 18:00 – 18:40 | Francesco Ginelli | **Universal Mean Field Upper Bound for the Generalisation Gap of Deep Neural Networks** |
| 18:40 – 19:00 | Pau Clusella Coberó | **Complex Spatiotemporal Oscillations Emerging from Transverse Instabilities in Large-Scale Brain Networks** |
| 19:00 – 19:20 | Bastian Pietras | **Metastability in Mesoscopic Network Models of Spiking Neurons with Short-Term Plasticity** |
| 19:20 – 19:30 | Stefan Jorda | **About the Wilhelm and Else Heraeus Foundation** |
| 20:00 | *CONFERENCE DINNER + POSTER PRIZES* | |

# Program *(CET)*

## Friday, 25 March 2022

| | | |
|---|---|---|
| 09:00 – 09:40 | Jonas Ranft | **A Self-Consistent Analytical Theory for Rotator Networks Under Stochastic Forcing: Effects of Intrinsic Noise and Common Input** |
| 09:40 – 10:20 | Michael Rosenblum | **High-Order Phase Reduction Applied to Remote Synchronization** |
| 10:20 – 10:40 | *COFFEE BREAK* | |
| 10:40 – 11:20 | Georg Martius | **Finding Concise Formulas for Data Using Machine Learning** |
| 11:20 – 12:00 | Christophe Eloy | **Far-Field Hydrodynamic Interactions in a Model of Fish School** |
| 12:00 – 12:15 | Organizers | **Closing Remarks** |
| 12:30 | *LUNCH* | |

# Posters

# Poster Session, Monday, 21 March 2022

| | | |
|---|---|---|
| **1** | Fabián Álvarez Garrido | **Towards an Effective Description of Turbulent Superstructures in Simple Shear Flows** |
| **2** | Gabriel Brito Apolinário | **A Dynamical Model of the Turbulent Energy Cascade** |
| **3** | Konstantin Clauss | **Self-Adaptive Infectious Dynamics on Random Networks** |
| **4** | Jules Fillette | **Wave Focusing on the Surface of a Fluid** |
| **5** | Enzo Francisco | **Spatio-Temporal Measurements of Velocity Gradients by Diffusing-Wave Spectroscopy** |
| **6** | Alexander Gerdes | **Synchronization Patterns in Globally Coupled Stuart-Landau Oscillators** |
| **7** | Gabriel Hadjerci | **Scaling Properties of Heat Transport in Idealized Planetary Atmospheres and Oceans** |
| **8** | Sayedeh Hussaini | **Resonant Feedback Control of Cardiac Arrhythmia Using Optogenetics** |
| **9** | Johannes Kassel | **Inference of Fractional Nonlinear Models from Temperature Time Series and Application to Predictions** |
| **10** | Kim Kreienkamp | **Collective Behavior of Repulsive Chiral Active Particles with Non-Reciprocal Couplings** |
| **11** | Maxime Lucas | **Do Higher-Order Interactions Promote Synchronization?** |
| **12** | Erik Mau | **Optimizing Charge-Balanced Pulse Stimulation for Desynchronization** |

# Poster Session, Monday, 21 March 2022

| | | |
|---|---|---|
| **13** | Atul Tanaji Mohite | **Optimising Energetics of Field Theories: Pareto Front and Phase Transitions** |
| **14** | Thomas Phillips | **Synchronising Networks of Kuramoto Oscillators with Multiplicative Noise** |
| **15** | Kalel Luiz Rossi | **The Dynamics Behind Sample-to-Sample Fluctuations in Finite Networks of Phase Oscillators** |
| **16** | Michael te Vrugt | **Effects of Social Distancing and Isolation on Epidemic Spreading Modeled via Dynamical Density Functional Theory** |
| **17** | Caroline Wormell | **Linear Response in Large and Small Coupled Chaotic Ensembles** |
| **18** | Yiwei Zhang | **Pulsating Active Matter** |

# Abstracts of Lectures

(in alphabetical order)

# Modelling dynamics and control in cardiac systems and active fluids

**Markus Bär**

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Many relevant experimental systems and applications exhibit irregular dynamics such as spatiotemporal chaos or turbulence. In this talk, I will present two examples of such behavior where it is desirable to control such states by transforming their dynamics into homogeneous or periodic steady states or regular periodic patterns. The specific applications are (i) defibrillation of cardiac tissue by periodic pacing and (ii) turbulence in active suspensions. For the cardiac system, we used simulations as well as data analysis not only to identify suitable conditions e. g. pacing strength and periods [1, 2], but also to determine the mechanism of defibrillation in this specific modus. For active turbulence, a simple phenomenological deterministic continuum model was used for quantitative modelling of experimental control in bacterial suspensions. Detailed investigations showed how the turbulent collective dynamics could be transformed into more regular, periodic spatiotemporal patterns using a periodic array of obstacles. This is in line with recent experimental findings using confinement by an arrays of pillars [3]. A recent study addresses the competition between the controlling effect of confinement and a nonlinear advection term behind the emergence of turbulence in active fluids demonstrating that the breakdown of control is associated with an Ising-like phase transition [4].

## References

[1] P. Buran, M. Bär, S. Alonso and T. Niedermayer. Chaos **27**, 113110 (2017).

[2] P Buran, T Niedermayer, and M Bär. Preprint on https://www.biorxiv.org (2021).

[3] H. Reinken, D. Nishiguchi, S. Heidenreich, A. Sokolov, M. Bär, S. H. L. Klapp, and I. Aranson. Comm. Phys. **3**, 76 (2020).

[4] H. Reinken, S. Heidenreich, M. Bär, S. Klapp. Phys. Rev. Lett. **128**, 048004 (2022).

# When non-linear dynamics computes: algorithmic decomposition of neural circuit functions

**Nicole Voges[1,3], Andrea Brovelli[1,3], Demian Battaglia[2,3,4]**

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*[3] Aix-Marseille Université, Institute for Language, Communication and the Brain (ILCB), Marseille, France*

*[5] University of Strasbourg Institute for Advanced Studies (USIAS), Strasbourg, France.*

Cognitive functions must arise from the coordinated activity of neural populations distributed over large-scale brain networks. However, it is challenging to understand (and measure) how specific aspects of neural dynamics translate into operations of information processing, and, ultimately, cognitive function. An obstacle is that simple circuit mechanisms –such as self-sustained or propagating activity and nonlinear summation of inputs– do not directly give rise to high-level functions, even if they do, nevertheless, already implement simple transformations of the information carried by neural activity.

Here we show that distinct neural circuit functions, such as stimulus representation, working memory or selective attention stem from different combinations and types of low-level manipulations of information, or information processing primitives. To prove this hypothesis, we combine approaches from information theory with computational simulations of canonical neural circuits involving one or more interacting brain regions and emulating well-defined cognitive functions. More specifically we track the dynamics of information emergent from dynamic patterns of neural activity, using suitable quantitative metrics to detect where and when information is actively buffered ("active information storage"), transferred ("information transfer") or non-linearly merged ("information modification"), as different possible modes of low-level processing. We thus find that neuronal subsets maintaining representations in working memory or performing attention-related gain modulation are signaled by their boosted involvement in operations of, respectively, active information storage or information modification.

Thus, information dynamics metrics, beyond detecting *which* network units participate in cognitive processing, also promise to specify *how* they do it, i.e. through which type of primitive computation, a capability that could be exploited for the parsing of actual experimental recordings. This capacity to track how nonlinear dynamics pattern of the studied complex system translates into computation and ultimately, biological function is general and could be applied to analysis of time-series, beyond the considered simulated neural systems.

# Far-field hydrodynamic interactions in a model of fish school

**Audrey Filella[1], François Nadal[2], Clément Sire[3], Eva Kanso[4], and Christophe Eloy[1]**

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*[2] Department of Mechanical, Electrical and Manufacturing Engineering, Loughborough University, UK*
*[3] CNRS, Université Paul Sabatier, Laboratoire de Physique Théorique, Toulouse, France*
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Most models of fish schools are based on self-propelled particles supplemented by behavioural rules (avoidance, alignment, and attraction). Usually, these models ignore the presence of a fluid, whereas fish are known to sense the surrounding flow and exploit it. Here, we propose a model that couples behavioural rules [1] with far-field hydrodynamic interactions [2]. We show that (1) a new “collective turning” phase emerges; (2) on average, individuals swim faster thanks to the fluid; (3) the flow enhances behavioural noise. These results suggest that hydrodynamic effects are crucial to understanding the collective behaviour of fish.

## References

[1] D. S. Calovi, U. Lopez, S. Ngo, C. Sire, H. Chaté, and G. Theraulaz, New Journal of Physics, **16**, 015026 (2014)

[2] A. A. Tchieu, E. Kanso, and P. K. Newton, Proc. R. Soc. London Ser. A, **468**, 3006–3026 (2012)

# Extreme Events in Complex Systems: a common framework?

**Davide Faranda[1,2,3]**

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How to model complex systems? Complex is what we perceive as spatially, temporally and dynamically rich and esthetically beautiful. This richness is declined in the shapes of turbulent vortices, the rage of a storm, the exponentially fast diffusion of a virus or an economic crisis. In research activity, I have combined the point of view of statistical physics and dynamical systems theory to devise mathematical tools that act as magnifying glasses for complex systems. The first specific question I have tackled is to determine how many variables, equations or data we need to describe a specific event, whether this turns out or not to be extreme for the system we examine. One of the outcomes of this investigation is the possibility of studying some of the most complex systems we can figure out, namely an ensemble of turbulent vortices in a confined geometry with just three simple dynamical equations. These equations do not only describe the mean state of the system but they allow for short term predictability of its motion. Another counterintuitive result is that extreme events of the atmospheric circulation such as tropical or extratropical cyclones yield often a simpler structure than the mean behavior of the atmosphere: they act as *condensates* where all but few degrees of freedom of the dynamics are frozen. They correspond to specific bricks of the underlying and unknown mathematical geometry of those systems, namely the unstable fixed points of the dynamics. Equipped with these statistical tools, we can search the footprint of unstable fixed points in natural phenomena and discover their correspondence with extreme events encountered in the everyday life: so far – and I give an overview of these research - we have discovered that they appear either as extreme turbulent vortices in the atmosphere, or as storms, hurricanes, earthquakes or even as specific states of the brain. Finally, I also give an account of some imperfect but stimulating way to communicate the beauty and the richness of complex systems and their extremes to other human beings, in images, sounds and even with a video-game on climate extremes [1].

### References

[1] https://climarisq.ipsl.fr/

# Tipping phenomena and resilience in complex systems

**L. Halekotte[1], S. Schoenmakers[1], Anna Vanselow[1] and U. Feudel[1]**

[1] *ICBM, Carl von Ossietzky University, Oldenburg, Germany*

Many systems in nature are characterized by the coexistence of different stable states for a given set of environmental parameters and external forcing. Examples for such behavior can be found in different fields of science ranging from mechanical or chemical systems to ecosystem and climate dynamics. As a consequence of the coexistence of a multitude of stable states, the final state of the system depends strongly on the initial condition. Perturbations, applied to those natural systems can lead to a critical transition from one stable state to another. Such critical transitions are called tipping phenomena in climate science, regime shifts in ecology or phase transitions in physics. Such critical transitions can happen in various ways: (1) due to bifurcations, i.e. changes in the dynamics when external forcing or parameters are varied extremely slow (2) due to fluctuations which are always inevitable in natural systems, (3) due to rate-induced transitions [1], i.e. when external forcing changes on characteristic time scale comparable to the time scale of the considered dynamical system and (4) due to shocks or extreme events [2]. We discuss these critical transitions and their characteristics and illustrate them with examples from mechanical and natural systems. Moreover, we discuss the concept of resilience [3], which has been originally introduced by C.S. Holling in ecology, and reformulate it in terms of dynamical systems theory.

## References

[1] A. Vanselow, S. Wieczorek, U. Feudel, J. Theor. Biol. **479**, 64-72 (2019)
[2] L. Halekotte, U. Feudel, Sci. Rep. **10**, 11783 (2020)
[3] S. Schoenmakers, U. Feudel, Chaos **31**, 053126 (2021)

**S. Ariosto[1,2], R. Pacelli[3], F. Ginelli[1,2], M. Gherardi[4,2], P. Rotondo[4,2]**

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Modern deep neural networks (DNNs) represent a notable challenge: according to the commonly accepted framework that describes their performance, these architectures should overfit due to the huge number of parameters to train, but in practice they typically do not [1]. Generalization capabilities are measured by the so-called generalisation gap, that is the difference between the network performance on the training set and on unseen data drawn from the same distribution.
In this work, we employ recent statistical physics results to derive a surprising simple and universal asymptotic mean field upper bound for the generalisation gap of deep neural networks for a regression problem.
In particular, in the thermodynamic limit of large training set size $P$ and last network layer size $N$ (with $N / P$ a small constant), the generalisation gap approaches zero faster than $2 N / P$. Numerical simulations validate our theory on a broad range of architectures, from toy fully-connected neural networks with few hidden layers to state-of-the-art deep convolutional neural networks.
Notably, the upper bound we establish drastically improves existing rigorous bounds, which grows with the total number of learnable parameters rather than with just the last network size. While our results are valid only asymptotically, this remarkable fact still lead us to conjecture that the last layer parameters may play a preferred role in establishing the generalisation capabilities of deep network beyond trivial overfitting expectations. We investigate this possibility via numerical simulations of deep networks with an increasing number of total learnable parameters.

## References

[1] M. Belkin, *Fit without fear: remarkable mathematical phenomena of deep learning through the prism of interpolation* Acta Numerica, **30**, 203 (2021)

[2] S. Ariosto *et al*, arXiv:2201.11022 (2022)

# Dynamics of temporal and spatio-temporal localized states in time-delayed systems

**Julien Javaloyes[1] and Svetlana V. Gurevich[1,2]**

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Time-delayed systems describe a large number of phenomena and exhibit a wealth of interesting dynamical regimes such as e.g., fronts, localized structures or chimera states. They naturally appear in situations where distant, pointwise, nonlinear nodes exchange information that propagates at a finite speed. In this talk, we review our recent theoretical results regarding the existence and the dynamics of temporal, spatial and spatio-temporal localized structures in the output of semiconductor mode-locked lasers. In particular, we discuss dispersive effects which are known to play a leading role in pattern formation. We show that they can appear naturally in delayed systems [1] and we exemplify our result by studying the influence of high order dispersion in a system composed of coupled optical microcavities [1,2].

## References

[1] C. Schelte, P. Camelin, M. Marconi, A. Garnache, G. Huyet, G. Beaudoin, I. Sagnes, M. Giudici, J. Javaloyes, and S. V. Gurevich, Third order dispersion in time-delayed systems, Phys. Rev. Lett., **123,** 043902, (2019).

[2] C. Schelte, D. Hessel, J. Javaloyes, and S. V. Gurevich, Phys. Rev. Applied, **13,** 054050, (2020).

**Metamorphosis of the Landau transition in the flow of a resonantly-driven bistable condensate.**

Vincent Hakim

Laboratoire de Physique de l'Ecole Normale Supérieure & CNRS, Paris, France.

It is well-known since the classical analysis of Landau that superfluid flows become time-dependent and dissipative above a critical velocity. This remarkable phenomenon has been experimentally observed and studied in liquid helium and more recently using Bose condensates in cold atomic vapors. In this latter case, the phenomenon can be precisely described using the Gross-Pitaevskii equation (GPE). Exciton-polariton fluids, so-called "quantum fluids of light", are currently attracting significant attention as semiconductor systems, with a high Bose condensation temperature. Their driven dissipative nature leads them to be described by a generalized GPE (GGPE), also known in nonlinear optics as the Lugiato-Lefever equation.  I will describe our study of the analog of the Landau transition in the framework of the GGPE with an added localized obstacle potential, when the driven-dissipative fluid is bistable, the case of most interest. I will report numerical simulations showing that the flow abruptly changes multiple times when the fluid velocity or the potential strength are increased, in contrast to the classical case. Moreover, instead of a transition to time dependence,  the transitions are observed to take place between stationary states and they involve the fluid bistability in an essential way. I will then explain how these phenomena can be analytically described in a suitable asymptotic limit.

Joint work with Amandine Aftalion and Simon Pigeon.

# Power law error growth rates - a dynamical mechanism for a strictly finite prediction horizon in weather forecasts

J. Brisch, B. Budanur, Holger Kantz

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We try to answer two questions related to weather forecasting when interpreting the atmospheric dynamics as a huge deterministic chaotic dynamical system, as actually the commonly used weather models are. We know that lack of precision in the knowledge of the initial condition will lead to an exponentially growing distance between the true solution of the system and our model solution, called sensitive dependence on initial conditions. If the true Lyapunov exponent of the atmosphere is of the order of 1/s (which is plausible from considering the instability of small scale motion), why then can one predict weather on the time scale of days? And how far could one push the weather predictions into the future, assuming perfect models and increasing accuracy of initial conditions? We present an answer to both questions by suggesting an error growth rate which depends on the error magnitude as an inverse power law, i.e, the smaller the error the faster it grows. Integration over time shows that then the error itself will grow like a positive but smaller than unity power of time (opposed to exponential error growth in conventional chaotic systems) and that improved accuracy of the initial condition will not extend the prediction horizon beyond a constant time interval which is determined by the tolerable forecast error. Inspired by the coupling of length and time scales of atmospheric phenomena, we introduce a class of hierarchically coupled low-dimensional chaotic systems which, due to proper scaling of length and time scales, exhibits exactly this power law error growth. We then re-analyse data of an error growth experiment performed 15 years ago by the Maryland-group with an operational weather forecast system (general circulation model) and show that on a log-log representation, their data support the idea of a power law divergence of the error growth rate at small scales. The fitted parameters then reveal an average maximal prediction horizon of about 15 days for weather forecasts.

# Challenges in nonlinear system identification

**Jean-Christophe Loiseau**[1]

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Over the past decade, identification of ordinary and partial differential equations from high-dimensional and/or noisy data has gained a renewed interest. As it often leads to generalization and interpretability, parsimony of the identified model has been an overarching goal in mathematical physics and biology. In this talk, a brief overview of recent progress in sparse and low-rank model identification techniques will be given. Three main challenges will be discussed, namely

- the importance of data representation (e.g. the reference frame, dimensionality reduction techniques, etc) [1, 2],
- how to incorporate prior physical knowledge or constraints (e.g. conservation laws, symmetries, etc) in the system identification procedure [3],
- how to include a stochastic component to account for unmodeled dynamics (e.g. high-frequency turbulence) [4].

Each aspect will be illustrated through a collection of examples primarily from (but not limited to) fluid dynamics. If time permits, Jupyter notebooks might be available from https://www.github.com/loiseaujc for the audience to play with.

## References

[1] A. Sansica et al. *AIAA Journal*, p. 1-17 (2022).
[2] K. Champion et al. *Proc. Natl. Acad. Sci. USA*, **116.45** (2019).
[3] J.-Ch. Loiseau & S. L. Brunton. *J. Fluid Mech.*, **838** (2018).
[4] J. L. Callaham et al. *Proc. R. Soc. A*, **477** (2021).

# Spatio-Temporal Organization of Cardiac Fibrillation

J. Schröder-Schetelig, T. Lilienkamp, A. Schlemmer, S. Hussaini, U. Parlitz, S. Luther

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Institute for the Dynamics if Complex Systems, University of Göttingen, Germany
University Medical Center Göttingen, University of Göttingen Germany
German Center for Cardiovascular Research (DZHK)

Cardiac fibrillation is an electro-mechanic dysfunction of the heart that is driven by complex three-dimensional electrical excitation waves, resulting in incoherent mechanical contraction, loss of pumping function, and risk of sudden cardiac death. The nonlinear dynamics of vortex-like rotating waves play an essential role in the spatial-temporal organization of fibrillation [1,2]. However, the visualization of these rotors, their interaction with each other and with the three-dimensional heterogeneous anatomical substrate remains a significant scientific challenge. In our talk, we will discuss the nonlinear dynamics of electrical and mechanical rotors during ventricular fibrillation [3-7]. We will also address the application of rotor mapping using high-resolution 4D ultrasound for novel diagnostic and therapeutic approaches including arrhythmia control [8-10].

References

[1] J.M. Davidenko et al. *Nature* **355**, 349–351 (1992).
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[3] J. Christoph et al., *Nature* **555**, 667–672 (2018).
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# Finding concise formulas for data using machine learning

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Abstract:
In classical machine learning, regression is treated as a black box process of identifying a suitable function without attempting to gain insight into the mechanism connecting inputs and outputs. In the natural sciences, finding an interpretable function for a phenomenon is the prime goal as it allows to understand and generalize results. In particular, for non-linear systems, identifying the governing equations is highly non-trivial. I will present our work on a function learning network, called equation learner (EQL) [1], that can learn analytical expressions from data. In addition to interpolation it is also able to extrapolate to unseen domains. It is implemented as an end-to-end differentiable feed-forward network and allows for efficient gradient-based training. Due to sparsity regularization concise interpretable expressions can be obtained.
We developed the system initially for control robotic systems with high data efficiency, but we have now also applied and modified it for problems in statistical physics, namely to density functional theory [2].
I would love to discuss the potential applications in the field of non-linear dynamics at the workshop. In comparison to works like SINDy [3] our system can learn arbitrary functions and is not restricted to predefined basis functions.

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# Impact of network motifs on response dynamics

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Many collective phenomena such as epidemic spreading and cascading failures in socio-economic systems on networks are caused by perturbations of the dynamics. How perturbations propagate through networks, impact and disrupt their function may depend the network, the type and location of the perturbation as well as the spreading dynamics. Previous work has analyzed the effects that nodes along propagation paths induce, suggesting few transient propagation ``scaling'' regimes as a function of the nodes' degree, but irrespectively of higher-order motifs such as triangles. Yet, the majority of empirical networks consists of small loops and motifs in a great percentage, which permit the proper functioning of the system. Triangles, for instance, can enhance the stability against perturbations in power grids, and play a central role in the emergence and maintenance of social networks. Here, we show that triangles and higher-order motifs along the propagation path jointly determine the regimes. This allows us to identify the hidden universal propagation patterns for a range of prototypical complex systems and empirical networks. We show how network motifs determine the response times to perturbations as a function of the network structure and its dynamics. This affords a powerful framework of response dynamics to perturbations on networks.

# Exact neural mass model for synaptic-based working memory

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Working Memory (WM) is the ability to temporarily store and manipulate stimuli representations that are no longer available to the senses. A synaptic theory of Working Memory (WM) has been developed in the last decade as a possible alternative to the persistent spiking paradigm [1]. In this context, we have developed a neural mass model able to reproduce exactly the dynamics of heterogeneous spiking neural networks encompassing realistic cellular mechanisms for short-term synaptic plasticity. This population model reproduces the macroscopic dynamics of the network in terms of the firing rate and the mean membrane potential [2]. The latter quantity allows us to gain insight of the Local Field Potential and electroencephalographic signals measured during WM tasks to characterize the brain activity. More specifically synaptic facilitation and depression integrate each other to efficiently mimic WM operations via either synaptic reactivation or persistent activity. Memory access and loading are related to stimulus-locked transient oscillations followed by a steady-state activity in the $\beta$-$\gamma$ band, thus resembling what is observed in the cortex during vibrotactile stimuli in humans and object recognition in monkeys. Memory juggling and competition emerge already by loading only two items. However more items can be stored in WM by considering neural architectures composed of multiple excitatory populations and a common inhibitory pool. Memory capacity depends strongly on the presentation rate of the items and it maximizes for an optimal frequency range. In particular we provide an analytic expression for the maximal memory capacity. Furthermore, the mean membrane potential turns out to be a suitable proxy to measure the memory load, analogously to event driven potentials in experiments on humans. Finally we show that the $\gamma$ power increases with the number of loaded items, as reported in many experiments, while $\theta$ and $\beta$ power reveal non monotonic behaviours. In particular, $\beta$ and $\gamma$ rhythms are crucially sustained by the inhibitory activity, while the $\theta$ rhythm is controlled by excitatory synapses [3].

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# Collective states in a ring network of theta neurons

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The collective or emergent behavior of large networks of neurons is a topic of ongoing interest, with applications to the study of epilepsy, binocular rivalry, visual hallucinations, and working memory, among others. One type of network often considered is a ring, where neurons can be thought of as being arranged on a closed curve. This is natural if some property of a neuron is correlated with an angular variable such as heading in a head directional network, the direction in the plane to a visual stimulus which is to be remembered or the orientation of a neuron's receptive field. In this talk, we consider a ring network of theta neurons with nonlocal coupling (both symmetric and asymmetric) and describe a semi-analytical approach to study its collective dynamics. By considering a number of different parameter sets we describe a variety of possible collective states in this system and the typical bifurcation scenarios that mediate their appearance.

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## Challenges in complex cardiac dynamics

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The heart is an excitable medium consisting of a large number of electrically and mechanically coupled cardiomyocytes and exhibits a variety of nonlinear phenomena such as rotating waves and spatiotemporal chaos. Since some of these conditions (significantly) affect pump function, there is a high medical need for understanding, modeling, and controlling the nonlinear dynamics of the heart. In our talk, we will address the role of transient spatiotemporal chaos in the development of novel methods to terminate (lethal) arrhythmias and present approaches for using machine learning and nonlinear time series analysis to cope with complex cardiac dynamics and to support future diagnosis and therapy.

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Active Oscillators and Active Particles: Synchronization vs Chaos

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In this talk I focus on common dynamical properties of active (self-sustained) oscillators and active (self-propelled) particles. In both cases the limit of over-activity is especially simple, because it allows for a reduction of the numbers of relevant variables. I discuss several particular problems, where a nontrivial interplay between synchronization and chaos is observed: exact finite-dimensional reductions of a population of phase oscillators beyond the Ott-Antonsen ansatz [1]; synchronization transition for chiral active particles in absence of aligning forces [2], and an interplay of Hamiltonian chaos and synchronization for active particles in an inhomogeneous environment.

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# Structure and scaling of extreme events in hydrodynamic turbulence

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Fully turbulent flows are characterized by intermittent formation of very localized and intense velocity gradients. These gradients can be orders of magnitude larger than their typical value and lead to many unique properties of turbulence. These properties can be studied at large, but finite Reynolds numbers, using direct numerical simulations of turbulence. Based on our very well-resolved numerical results over a range of Taylor-scale Reynolds number from 140 to 1,300, we quantitatively relate the properties of the most intense vortices in the flow to the dependence of the strain, conditioned on vorticity. Namely, the strain conditioned on vorticity grows on average slower than vorticity, with a power law with an exponent $\gamma < 1$. The exponent g slowly increases as a function of the Reynolds number, possibly reaching $\gamma = 1$ when the Reynolds number goes to infinity. This leads to discrepancies with earlier predictions, which are expected to persist, even for the most turbulent flows on earth. The presentation will be based on refs.[1-3].

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# A self-consistent analytical theory for rotator networks under stochastic forcing: effects of intrinsic noise and common input

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Despite the incredible complexity of our brains' neural networks, theoretical descriptions of neural dynamics have led to profound insights into possible network states and dynamics. It remains challenging to develop theories that apply to spiking networks and thus allow one to characterize the dynamic properties of biologically more realistic networks. Here, we build on recent work by van Meegen & Lindner who have shown that "rotator networks," while considerably simpler than real spiking networks and therefore more amenable to mathematical analysis, still allow to capture dynamical properties of networks of spiking neurons [1]. This framework can be easily extended to the case where individual units receive uncorrelated stochastic input which can be interpreted as intrinsic noise. However, the assumptions of the theory do not apply anymore when the input received by the single rotators is strongly correlated among units. As we show, in this case the network fluctuations become significantly non-Gaussian, which calls for a reworking of the theory. Using a cumulant expansion, we develop a self-consistent analytical theory that accounts for the observed non-Gaussian statistics..

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# High-order phase reduction applied to remote synchronization

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We discuss the analytical and numerical approaches to phase reduction in networks of coupled oscillators in the higher orders of the coupling parameter. Particularly, for three coupled Stuart–Landau (SL) oscillators, where the phase can be introduced explicitly, an analytic perturbation procedure yields the explicit second-order approximation [1]. We exploit the analytical result from [1] to analyze the mechanism of the remote synchronization (RS). RS, briefly reported by Okuda and Kuramoto as early as 1991, implies that oscillators interacting not directly but via an additional unit (hub) adjust their frequencies and exhibit frequency locking while the hub remains asynchronous. Previous studies uncovered the role of amplitude dynamics and of nonisochronicity: RS appeared in a network of isochronous SL units but not in its first-order phase approximation, the Kuramoto network. Furthermore, RS emerged in networks of phase oscillators with the Kuramoto-Sakaguchi interaction, but not in the case of zero phase shift in the sine-coupling term; this result indicates the role of nonisochronicity. In this work, we analytically demonstrate the role of two factors promoting remote synchrony. These factors are the nonisochronicity of oscillators and the coupling terms appearing in the second-order phase approximation. We explain the contribution of both factors and quantitatively describe the transition to RS. We demonstrated that the RS transition is determined by the interplay of the nonisochronicity and the amplitude dynamics. The impact of the latter factor renders the standard first-order phase dynamics descripion of the RS phenomenon invalid. Our result emphasizes the importance of higher-order phase reduction and highlights the crucial role amplitude dynamics may have in governing the behavior of networks of nonlinear oscillators. We show a good correspondence between our theory and numerical results for small and moderate coupling strengths and argue that the effect of the amplitude dynamics neglected in the first-order phase approximation and revealed by the higher-order one holds for general limit-cycle oscillators.

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# A century of cascades from turbulence intermittency to climate: successes, limitations and challenges

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The concept of cascade is usually traced back to the Richardson's famous quatrain [1] on the transfer of kinetic energy from large scales to smaller scales down to the dissipation scale. This concept has since inspired most theoretical developments on intermittency of turbulence and other nonlinear phenomena, particularly in geophysics [2] and climate [3]. Well-defined stochastic cascade processes, starting from Yaglom [4], helped to clarify many issues, such as: limitations of earlier multifractal formalisms based on deterministic dimensions [5,6], upscaling of small scale activity can generate first order multifractal phase transitions and statistical power-laws of extremes. Multifractal universality greatly reduces the number of relevant parameters, while a nontrivial analogy with classical statistical physics explains the relevance of Legendre transform to link the scaling function of statistical moments to codimension of the probability distribution.
However, these powerful results were obtained on scalar-valued observables and corresponding scalar scale symmetries, whereas the fundamental fields, such as a fluid velocity, are vector-valued with symmetry operators. The challenge is to extend scalar cascades to operator cascades acting on vector fields. We will discuss the generic example of Clifford algebra of Lévy stable generators, themselves generated by jumps distributed on cones of this algebra that define the domain of finite statistics [7,8]. We will highlight extensions to adjoint representations of Lie algebra.

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# Inferring complex systems structure from dynamics

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The dynamics of complex systems enables most of the functions our life depends on, from gene and protein regulation to neuronal networks and from public transportation to power grids [1-6]. However, it remains unclear to date how to extract many key features of a given multi-dimensional dynamical systems if only time series data from (some) variables are available. Here we report recent progress on the inference of structural features of complex from observed dynamics. First, we demonstrate how to identify the number N of dynamical variables making up a system – arguably its most fundamental property – from recorded time series of only a small subset of n<N variables [4]. We eludicate why N may be deducible even if time series from only one variable are available. Second, we present approaches to identify features of interaction topologies among the variables topological features from observed their time series data only, applicable to circadian clocks, metabolic circuits and other networks [1-3, 5-7]. If time permits, we discuss how to infer 3D images from recordings of one single pixel camera using fundamental properties of most physical objects such as connectedness and continuity [8].

This is work with Jose Casadiego, Mor Nitzan, Hauke Haehne, Malte Schröder, Georg Börner and others.

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# A reduction methodology for fluctuation driven population dynamics

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Lorentzian distributions (LDs) have been largely employed in statistical mechanics to obtain exact results for heterogeneous systems [1,2]. In particular, the Ott–Antonsen (OA) Ansatz [3] yielded closed mean-field (MF) equations for the dynamics of the synchronization order parameter for globally coupled phase oscillators on the basis of a wrapped LD of their phases. A very important recent achievement has been the application of the OA Ansatz to heterogeneous globally coupled networks of spiking neurons, namely of quadratic integrate-and-fire (QIF) neurons [4]. However, the OA Ansatz is unable to describe the presence of random fluctuations, which are naturally present in real systems. In brain circuits the neurons are sparsely connected and i*n vivo* the presence of noise is unavoidable. We have introduced a general reduction methodology for dealing with deviations from the LD on the real line, based on the characteristic function formulation and on its expansion based on *pseudo-cumulants*. This approach avoids the divergences related to the expansion in conventional moments or cumulants. The implementation and benefits of this reduction are demonstrated for populations of heterogenous QIF neurons in presence of extrinsic or endogenous noise sources, where the conditions for a LD of voltage [4] are violated as in [5,6]. In particular, we will derive low-dimensional MF models, generalizing the MF model in [2], for globally coupled networks with extrinsic noise and for sparse random networks with intrinsic current fluctuations. A peculiar focus will be devoted to the emergence of noise driven collective oscillations. The developed framework can be potentially fruitful for condensed matter problems and the study of collective phenomena [7].

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# Chaos in the stratosphere ?

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The quasibiennial oscillation (QBO) of equatorial winds on Earth is the clearest example of the spontaneous emergence of a periodic phenomenon in geophysical fluids. In recent years, observations have revealed intriguing disruptions of this regular behavior, and different regimes have been reported in a variety of systems. We will show that part of the variability in mean-flow reversals can be attributed to the intrinsic dynamics of wave-mean-flow interactions in stratified fluids.

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# Sparse chaos and localization in the dynamics of neuronal circuits

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Nerve impulses, the currency of information flows in the brain, are generated by an instability of the neuronal membrane potential dynamics. Neuronal circuits exhibit collective chaos that appears essential for learning, memory, sensory processing and motor control. What controls the nature and intensity of collective chaos in neuronal circuits, however, is not well understood. Here we use computational ergodic theory to demonstrate that basic features of nerve impulse generation profoundly affect collective chaos in neuronal circuits. Numerically exact calculations of Lyapunovspectra, Kolgomorov-Sinai-entropy, and upper and lower bounds on attractor dimension show that changes in nerve impulse generation in individual neurons only moderately modify rate of information encoding but qualitatively transform phase space structure, reducing the number of unstable manifolds, Kolgomorov-Sinai-entropy, and attractor dimension by orders of magnitude. Beyond a critical point, marked by a localization transition of the leading covariant Lyapunov vector, the networks exhibits sparse chaos: extended periods of near stable dynamics interrupted by short bursts of intense chaos. Analysis of large networks with more realistic structure indicate the generality of these findings. In cortical circuits biophysics appears tuned to this regime of episodic chaos. Our results demonstrate a tight link between fundamental features of single neuron biophysics and the collective dynamics of cortical circuits and suggest that the machinery of nerve impulse generation is tailored to enhance circuit controllability and information flow.

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# Abstracts of Posters

(in alphabetical order)

# Towards an effective description of turbulent superstructures in simple shear flows

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Turbulent flows driven by large-scale forces such as convection, shear, or rotation may display large-scale coherent flows, namely turbulent superstructures, which coexist with fully developed turbulence on the small scales. A complete description of these flows involves a large number of degrees of freedom, yet turbulent superstructures seem to evolve according to a comparably lower-dimensional set of equations. In addition, despite the ubiquity of turbulent superstructures, their interplay with the smaller scales is not yet fully understood. We study a simple shear-driven flow, precisely the three-dimensional Kolmogorov flow. The large scales in this flow feature the formation of large-scale vortex pairs. Moreover, the system exhibits permanent dynamics between states having a different number of vortex pairs. We explore to which extent the dynamics of turbulent superstructures can be understood based on flow features close to the onset of turbulence. Employing amplitude equations, we characterize the dynamics of the large scales close to the emergence of the vortex pairs. We show that the dynamics close to this onset resembles the one of a two-dimensional flow. We propose modifications to these amplitude equations to take into account the contribution of the small scales. These modified coupled amplitude equations can qualitatively reproduce the dynamics of the large-scale vortex pairs and shed light on the role of small-scale turbulence in the formation of turbulent superstructures.

# A Dynamical Model of the Turbulent Energy Cascade

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In three-dimensional Navier-Stokes turbulence, energy is injected at a large scale $L$ and is efficiently transported to small scales. In this process, the fluid reaches a state of finite variance and large spatial gradients, which can be approximately described by a rough velocity field of Holder exponent $H \approx 1/3$. Motivated by this phenomenon, in two recent works [1,2], we have studied a stochastic partial differential equation (SPDE) for a complex velocity field $u$ in one spatial dimension that is randomly stirred by a spatially smooth and uncorrelated in time forcing term. This dynamics includes linear operators responsible for a cascading transfer of energy from large to small scales [3,4] and to the development of fractional regularity of order $H$. Multifractal corrections are included drawing inspiration from a known probabilistic construction, the Gaussian multiplicative chaos, which motivates a quadratic nonlinear interaction in this model. Through numerical simulations, we observe the non-Gaussian and in particular skewed nature of these solutions, an important feature in the modeling of turbulent velocity fields.

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# Self-adapting infectious dynamics on random networks

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Self-adaptive dynamics occurs in many physical systems such as socio-economics, neuroscience, or biophysics. They usually inherit some optimization objective(s) such as maximizing individual or global payoffs. We formalize a self-adaptive modeling approach where adaptation takes place within a set of strategies based on the (recent) history of the state of the system. This leads to piecewise deterministic Markovian dynamics coupled to a time-delayed adaptive mechanism. We apply this framework to basic epidemic models (SIS, SIR) on random networks. We consider a coevolutionary dynamical network where node-states change through epidemics and network topology changes through creation, deletion and rewiring of edges. For a simple threshold base application of lockdown measures we observe regions with oscillatory behavior. For the SIS epidemics analytic expressions are derived from the pairwise closed model.

# Complex spatiotemporal oscillations emerging from transverse instabilities in large-scale brain networks

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Neural oscillations constitute a primary indicator of brain and cognitive function. Large-scale brain models aim to trace the principles underlying macroscopic neural activity from the intricate and multi-scale structure of the brain by combining neuroimaging data and neural mass modelling. Despite substantial progress in the field, many aspects about the mechanisms behind the onset of spatiotemporal neural dynamics are still unknown.

In this work we characterize a simple framework for the emergence of complex dynamics, including high-dimensional chaos and travelling waves, in a large-scale model of the human brain. The model consists of 90 brain regions connected through a complex network obtained from tractography data in which the activity of each brain area is governed by the dynamics of a Jansen-Rit model. In order to determine the dynamical landscape of the system, we consider a simplified formulation in which the total input received by each node is the same across brain areas. This allows for the existence of an homogeneous invariant manifold, i.e., a set of different stationary and oscillatory states in which all nodes behave identically. By means of the master stability function we provide a comprehensive bifurcation diagram of the system in which the synchronized oscillatory solution appears transversally unstable in a large region of the parameter space (figure 1a). Numerical simulations reveal that transverse instabilities give raise to complex spatiotemporal dynamics (figure 1b).

In order to illustrate the ubiquity of this route towards irregular oscillatory activity we also outline the onset of spatiotemporal chaotic gamma activity in a large-scale brain model with next-generation neural mass models. Overall, our work reveals that transverse instabilities are general mechanism for the onset of irregular spatiotemporal oscillations in large-scale brain networks.

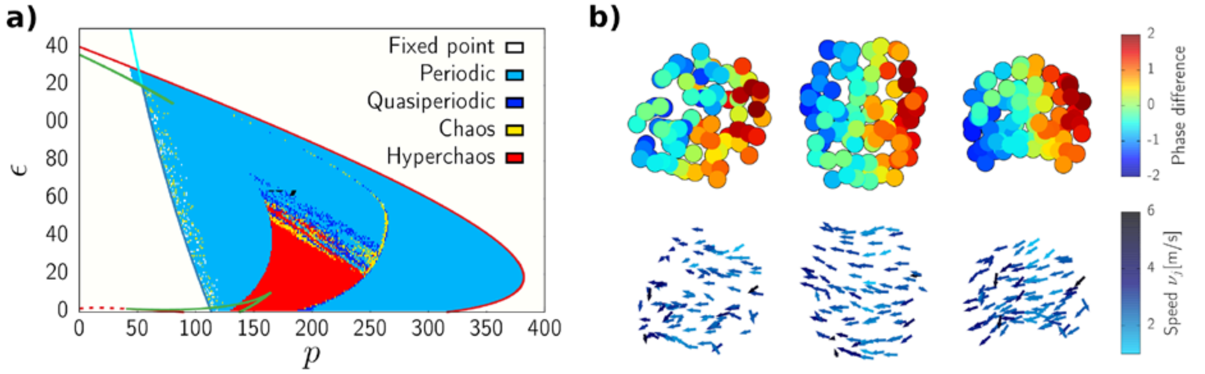


**Figure 1:** (a) Bifurcation diagram upon changing the external input and the coupling strength. (b) Phase dynamics and propagation velocities of a travelling wave.

# Focusing of circular waves on the surface of a fluid

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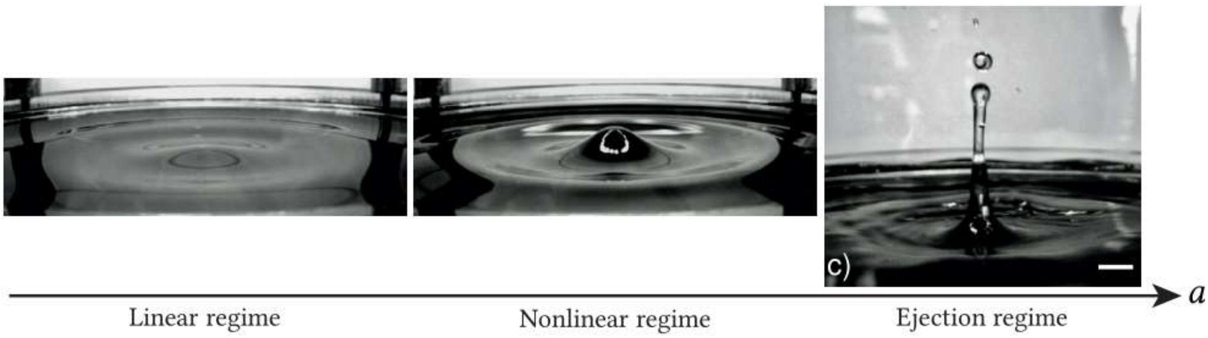
Hydrodynamics wave focusing has not been so much studied compared to wave focusing in optics and acoustics [1]. Here, we propose an original model experiment to study focusing of circular hydrodynamics waves generated by a vertically vibrating ring on a fluid surface. The solid ring is half immersed into the fluid and mechanically connected to a shaker. The vertical oscillation of the ring at given frequency $f$ and amplitude $a$ then generates converging circular waves on the surface of the fluid. We report on different regimes of axisymmetric standing waves.
Three typical regimes are observed as shown below. The phase diagram of these regimes is presented as a function of the control parameters, whereas experimental data are compared to linear and nonlinear theories [2, 3]. For weak forcing, and close to an eigen frequency of the circular basin, the wave pattern displays a resonant response well described by the linear theory. For stronger forcing a significant departure from the linear prediction occurs as nonlinearities break the up-and-down symmetry of the spatial profile of the wave pattern. This profile is found to be well-fitted by the third-order nonlinear theory. Finally, the maximum height of the wave reached at the basin center is proven to saturate which was not expected by both nonlinear theory [3] and numerical simulations [4].

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# Spatio-temporal measurements of velocity gradient by Diffusing-Wave Spectroscopy

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The velocity gradient is the key quantity of many hydrodynamic phenomena (boundary layers, dissipative structures, drags etc…). Here we report the first spatially and temporally resolved measurements of the velocity gradient in a Taylor-Couette flow both in the laminar and in the unstable regime (transition to turbulence). The measurements are performed using a dynamic light scattering technique called Diffusing-Wave Spectroscopy (DWS) [1,2], which takes advantage of the diffusive nature of the multiply scattered light in a turbid colloidal suspension. The time autocorrelation of the intensity $G^{(2)}(t) = \langle I(t_0)I(t_0+t)\rangle / \langle I(t_0)\rangle^2$ is measured and decays because of the dephasing of light in time at each scattering event [3,4]. This decay is due to the Brownian motion of particles and to the fluid motion. In addition to what Bicout and Maret have already done in a Taylor-Couette flow [5], we obtained a time-evolving map of the velocity gradient, which shows the Taylor-Couette instability, including Taylor vortices. The possibility of detecting mechanical defects with DWS is also presented, through a set-up where the inner cylinder presents a small defect. This work is the first step of the study of quasi-local velocity gradients and dissipation in some complex flows.

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# Synchronization patterns in globally coupled Stuart-Landau oscillators

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We study clusterized states in globally coupled Stuart-Landau oscillators, a paradigmatic model for patterning processes [5].
To investigate 2-Cluster states, we set up a reduced model using collective variables, in which the cluster size ratio [1] is an additional bifurcation parameter.
We analyse longitudinal instabilities leading to complex 2-Cluster behaviour in the reduced system.
By including test oscillators, we study instabilities transversal to the 2-Cluster manifold, i.e. changes of the cluster type.
Using numerical bifurcation analysis we find stability regions of cluster solutions of different types.
In these, solitary states serve as primary patterns for clustering processes and allow an analytical treatment. The identified instabilities can be seen as building blocks of pathways to complex behaviour such as chimeras [2] and extensive chaos [3] as well as splay states [4] occuring for varying parameters.
With the analytical and numerical approach presented here we identify different transition scenarios from synchrony to complex behaviour by reducing the coupling strength. We locate each of these scenarios in regions in the plane of shear parameters.

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# Scaling properties of heat transport in idealized planetary atmospheres and oceans

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The meridionally inhomogeneous heating of planetary atmospheres and oceans induces turbulent flows through the baroclinic instability mechanism. This phenomenon greatly enhances the heat transport between the equator and the poles and needs to be properly parameterized in global climate models. Using the canonical two-layer quasi-geostrophic model, we augment a recently proposed scaling theory to describe the strongly turbulent very-low-drag regime with arbitrary density stratification. The augmented theory is based on an asymptotic remapping of the equations, which leads to quantitative predictions with no additional fitting parameters.

# Resonant Feedback Control of Cardiac Arrhythmia Using Optogenetics

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The nonlinear dynamic system of the heart is capable of sustaining abnormal electrical rhythm disorders known as arrhythmia, such as ventricular tachycardia (VT). Cardiac arrhythmia is the most common precursors of sudden cardiac death, which accounts for the largest proportion of morbidity in industrialized countries. Implantable cardioverter defibrillators (ICDs) deliver a sequence of local high-energy electrical pulses to the heart to control VT. However, these devices are often unable to terminate very high-frequency VT and also has significant side effects such as tissue damage and depression. Therefore, developing an effective arryhthmia control technique to overcome these adverse effects is of great importance.

Many theoretical and numerical studies show that resonant feedback pacing could provide an alternative to current clinical therapeutic approaches [1]. In this technique, a sequence of low-energy global pulses is delivered to the heart tissue at a frequency close to the frequency of the arrhythmia detected by a sensing electrode placed on the heart tissue. This results in drifting of the electrical spiral wave associated with the arrhythmia and its subsequent termination via collision with a non-excitable boundary. Although this technique has been investigated in many simulation studies, it has never been validated in experiments due to the absence of a suitable stimulation source.

Optogenetics has demonstrated its great potential to be used as an optical stimulation source to control arrhythmias in a genetically modified light-responsive heart tissue. In this work, we investigate the control of VTs in 5 optogenetic mouse hearts by applying a series of global optical pulses using the resonant feedback method at different light intensities (LIs) and a pulse length of 20 ms. We use optical mapping to visualize the arrhythmia dynamics during resonant feedback pacing. The dose-response curve shows termination rates of ≈ 50% and 100% at the lowest and highest LIs of 3.1 and 100 μW/mm$^2$, respectively. The fluorescence images suggest that resonant drift may be the underlying mechanism for termination of VTs at very low LIs, similar to our numerical findings in two-dimensional optogenetically modified mouse ventricular tissue in the arrhythmic state [2, 3, 4].

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# Inference of fractional nonlinear models from temperature time series and application to predictions

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We introduce a method to reconstruct macroscopic models of one-dimensional nonlinear stochastic processes with long-range correlations from sparsely sampled time series by combining fractional calculus and discrete-time Langevin equations. We reconstruct models for daily mean temperature data and use them to predict the first frost date at various weather stations. Our findings illustrate the potential of long-memory models for predictions in the subseasonal-to-seasonal range.

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# Collective behavior of repulsive chiral active particles with non-reciprocal couplings

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Mixtures of chiral active particles [1] as well as non-reciprocal systems [2] show intriguing collective behavior like pattern formation and traveling waves. The combination of both – non-reciprocal couplings in mixtures of chiral active particles – promises a rich variety of collective dynamics.

Here, we investigate how non-reciprocal couplings and naturally occurring repulsive interactions due to finite particle sizes affect the collective behavior in a mixture of two species of particles. We analyze the effects due to non-reciprocity and finite size individually as well as their interplay based on a field description of the system in terms of the particle concentration and director field, measuring the overall orientation of particles at a certain position.

We derive the field equations under the mean-field assumption by coarse-graining microscopic Langevin equations for individual chiral particles, which are modeled as self-propelling circle swimmers with soft repulsive forces, comprising the finite size effects. Particles of the two species rotate with different intrinsic frequencies and align with near-by particles. Focusing on non-reciprocity, we use a non-mutual alignment between the particles.

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# Do higher-order interactions promote synchronization?

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Higher-order interactions, i.e. between more than two units simultaneously, play an important role in complex systems. Recently, many research efforts have investigated the effect of these interactions on the dynamics of the interacting units for various dynamical processes. For synchronization, interestingly, several of those efforts have shown examples where higher-interactions promote synchronization, raising speculation that this might be general phenomenon. Here, we show that even for simple phase oscillators, the effect of higher-order interactions is highly nuanced and depends on the structure at hand. In particular, we found that random hypergraphs tend to improve synchronization whereas random simplicial complexes tend to have the opposite effect (Figure 1). We provide analytical explanations for this phenomenon, identifying degree-heterogeneity as the key structural factor when a fixed coupling budget is enforced. We also identify regimes where pairwise and nonpairwise interactions synergize to optimize synchronization.

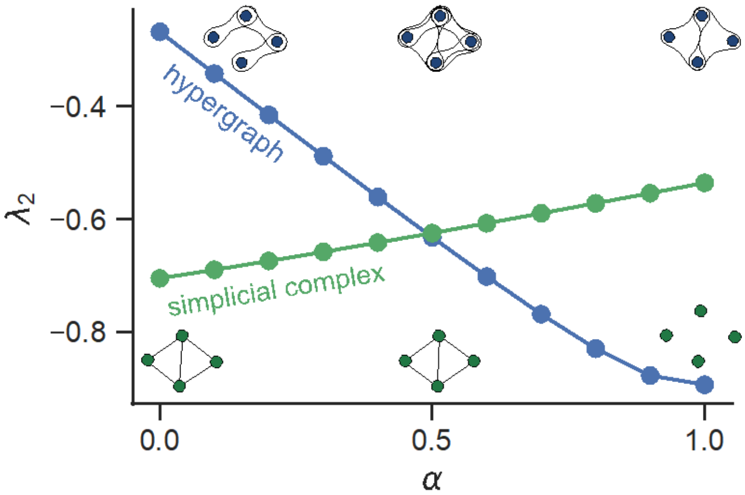


*Figure 1 : Synchronization is enhanced by higher-order inter- actions in hypergraphs but impeded in simplicial complexes.*

# Long-term desynchronization by coordinated reset stimulation in a neural network model with synaptic and structural plasticity

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Several brain disorders are characterized by abnormal neuronal synchronization. To specifically counteract abnormal neuronal synchrony and, hence, related symptoms, coordinated reset (CR) stimulation was computationally developed. In principle, successive epochs of synchronizing and desynchronizing stimulation may reversibly move neural networks with plastic synapses back and forth between stable regimes with synchronized and desynchronized firing. Computationally derived predictions have been verified in pre-clinical and clinical studies, paving the way for novel therapies. However, as yet, computational models were not able to reproduce the clinically observed increase of desynchronizing effects of regularly administered CR stimulation intermingled by long stimulation-free epochs. We show that this clinically important phenomenon can be computationally reproduced by taking into account structural plasticity (SP), a mechanism that deletes or generates synapses in order to homeostatically adapt the firing rates of neurons to a set point-like target firing rate in the course of days to months. If we assume that CR stimulation favorably reduces the target firing rate of SP, the desynchronizing effects of CR stimulation increase after long stimulation-free epochs, in accordance with clinically observed phenomena. Our study highlights the pivotal role of stimulation- and dosing-induced modulation of homeostatic set points in therapeutic processes.

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# Optimizing charge-balanced pulse stimulation for desynchronization

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Collective synchronization in a large population of self-sustained units appears both in natural and engineered systems. Sometimes this effect is in demand, while in some cases, it is undesirable, which calls for control techniques. In this paper, we focus on pulsatile control, with the goal to either increase or decrease the level of synchrony. We quantify this level by the entropy of the phase distribution. Motivated by possible applications in neuroscience, we consider pulses of a realistic shape. Exploiting the noisy Kuramoto–Winfree model, we search for the optimal pulse profile and the optimal stimulation phase. For this purpose, we derive an expression for the change of the phase distribution entropy due to the stimulus. We relate this change to the properties of individual units characterized by generally different natural frequencies and phase response curves and the population's state. We verify the general result by analyzing a two-frequency population model and demonstrating a good agreement of the theory and numerical simulations.

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# Optimising Energetics of Field Theories: Pareto Front and Phase Transitions

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Understanding finite time optimal processes is a frontier of non-equilibrium statistical physics. Phase transitions are ubiquitous in Physics with many applications . Field theories have been extremely successful in characterizing the universal properties of various phase transitions, and in delineating a few canonical models which capture the essential Physics at play in a large class of systems [1-3]. Interestingly, a generic framework for optimizing the energetic cost associated with the finite-time driving of such systems is still largely missing. What is the optimal process for a change of phase in finite time?

Here, building on recent advances in stochastic thermodynamics and optimal transport theory [4-7], we show how to analytically derive the optimal driving protocols that minimizes work for a finite driving time, which we apply to cases with either conserved or non-conserved scalar order parameter in the weak noise regime. We compute exact closed form analytical expressions for the optimal driving protocols and the optimum energy cost associated with it. Moreover, we formulate a numerical multi-optimization problem to simultaneously optimize the mean and variance of work, leading to revealing a first-order phase transition in the corresponding Pareto front, which features the coexistence of multiple optimal protocols. Overall, our results elucidate how to drive field theories to minimize the average and fluctuations of energy cost , with the potential to be deployed to a broad class of systems.

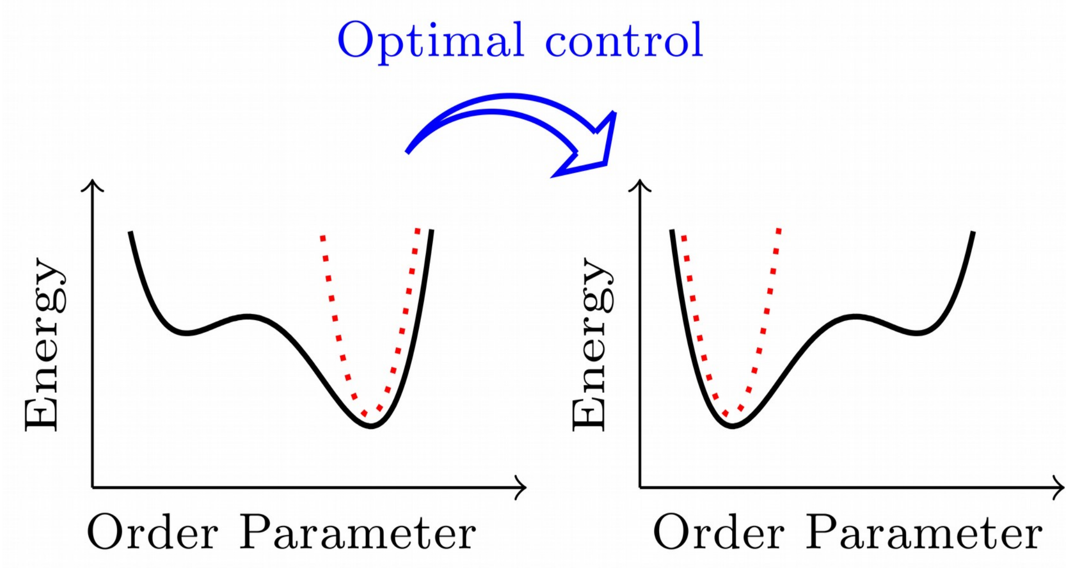


*Fig. 1: Free energy landscape is denoted by the solid black line. Changing control parameters exchanges the stability of the landscape minima, thus undergoing a change of phase. In small noise limit, the initial and final Gaussian probability distribution around the stable minima is denoted by dotted red line. We compute the optimal protocol and the energy cost for the finite-time driving of scaler field from the initial to the final phase.*

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# Synchronising networks of Kuramoto oscillators with multiplicative noise

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We study a two layer network of identical Kuramoto oscillators, where each layer is non-locally coupled, and as such can exist in both a partially synchronised state and a synchronised state. We demonstrate how transitions between these states can be induced, and that in certain circumstances a floating breathing chimera can come into being. Significantly we show that in such a system modulating the coupling between the two layers by noise can play a similar role to increasing the interlayer coupling strength, among other things counter-intuitively causing the two layers to synchronise with each other (which has thus far only been shown for discrete maps [1]). We then show how a different kind of disturbance caused by a slight mismatch in the coupling in both layers can play a similar synchronising role, suggesting how in such system disturbances generally improve synchronisation. We discuss how such a phenomena could be beneficial to cortical function and show how 1/f noise can play an especially efficient role in synchronising the system.

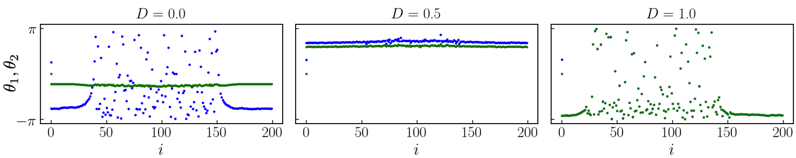


Figure 1: Phases $\theta_1$ and $\theta_2$ of two non-locally coupled layers of Kuramoto oscillators which are multiplexed. The interlayer coupling strength is weak and modulated by white noise $\xi(t)$ according to $\sigma_{12}(1 + D\xi(t))$.

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# Metastability in mesoscopic network models of spiking neurons with short-term plasticity

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The neuronal mechanisms of various cognitive functions have been linked to metastable dynamics of recurrent neural networks. Metastability, such as population spikes or spontaneous transitions between up- and down-states, may result from slow fatigue processes (e.g., short-term depression of presynaptic synapses), from noisy fluctuations, or from an interplay of both [1,2]. Previous modeling studies that consider either detailed spiking neuron networks, or heuristic firing rate models, have not provided satisfactory mechanistic insights how single neuron dynamics and finite-size fluctuations contribute to metastable population activity. In this talk, we will propose a mesoscopic description for networks of spiking neurons with short-term depression that is based on a rigorous reduction from microscopic neuron dynamics, cf. also [3]. With this novel mesoscopic model, we investigate typical examples of metastable network dynamics and, in addition, shed new light on hippocampal replay.

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# Dynamics behind sample-to-sample fluctuations in networks of phase oscillators

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It is known from Statistical Physics that finite systems have blurred and shifted transitions compared to systems in the thermodynamic limit, and that this leads to fluctuations between distinct samples (realizations) of a system [1, 2]. In particular for transitions to synchronization, which have been established as nonequilibrium phase transitions, this means the synchronization of a system varies between samples [1, 2]. In this work, we describe the dynamics behind these fluctuations, and the large and complex sensitivity induced by them. We study Kuramoto phase oscillators, a generic model of oscillators which serves as a paradigm for synchronization phenomena and is thus an appropriate model for several oscillating real-world systems like neural circuits and power grids. We couple them in topologies following the Watts-Strogatz algorithm, passing from a k-nearest-neighbor lattice, to small-world and to random by rewiring the connections. The generated networks have two synchronization transitions: one induced by increasing the coupling strength, another by the random rewiring of connections. We show that differences between realizations (obtained by either shuffling frequencies or even by changing the frequency of a single unit) peak during the transitions, with each transition exhibiting unique characteristics. The fluctuations can reach extremely high values, changing the whole network's dynamics, for instance from desynchronized to very synchronized, and they do so according to a complicated function of all the system's parameters. We also show that one of the mechanisms which enhances the fluctuations is a high degree of multistability. We have observed similar phenomenologies in distance-dependent networks, in networks of spiking neurons [3], and celullar automata. The commoness of this behavior, expected from Statistical Physics, and the large fluctuations it brings, can present a challenge for the control of such systems, as well as an opportunity to explore their flexibility.

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# Effects of social distancing and isolation modeled via dynamical density functional theory

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For preventing the spread of epidemics such as the coronavirus disease COVID-19, social distancing and the isolation of infected persons are crucial. However, existing reaction-diffusion equations for epidemic spreading are incapable of describing these effects. In this contribution, we present an extended model [1] for disease spread based on combining a susceptible-infected-recovered model with a dynamical density functional theory [2] where social distancing and isolation of infected persons are explicitly taken into account. We show that the model exhibits interesting transient phase separation associated with a reduction of the number of infections, and provides new insights into the control of pandemics. Since very similar mathematical models are used also in the study of chemical reactions, we expect the pattern formation effects to be of interest also beyond epidemiology. An extension of the model [3] allows for an investigation of adaptive containment strategies. Here, a variety of phases with different numbers of shutdowns and deaths are found, an effect that is of crucial importance for public health policy.

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# Bumps, chimera states, and Turing patterns in systems of coupled active rotators

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Self-organized coherence-incoherence patterns, called chimera states, have first been reported in systems of Kuramoto oscillators. For coupled excitable units similar patterns, where coherent units are at rest, are called bump states. Here, we study bumps in an array of active rotators coupled by non-local attraction and global repulsion. We demonstrate how they can emerge in a supercritical scenario from completely coherent Turing patterns: single incoherent units appear in a homoclinic bifurcation with a subsequent transition via quasiperiodic and chaotic behavior, eventually transforming into extensive chaos with many incoherent units. We present different types of transitions and explain the formation of coherence-incoherence patterns according to the classical paradigm of short-range activation and long-range inhibition.

## References

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# Linear response in large and small coupled chaotic ensembles

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The response of long-term averages of chaotic systems to small dynamical perturbations can often be predicted using linear response theory (LRT), but some very basic dissipative chaotic systems are known to have non-differentiable responses. Nonetheless, complex chaotic systems' macroscopic observables are widely assumed to have a linear response, but the mechanism for this is not well-understood.

We present a comprehensive picture for linear response at the macroscale in mean-field coupled deterministic dynamics, where the microscopic subsystems may or may not obey LRT. A stochastic reduction to mean-field dynamics yields conditions for linear response theory to hold both in large, finite-dimensional systems and in the thermodynamic limit, with LRT guaranteed in finite dimensions and a more complicated situation in the limit. LRT appears to hold even when the dimension is very small: we argue this can be connected to a conjecture of Ruelle.

# Pulsating Active Matter

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Active matter features the injection of energy at individual level keeping the system out of equilibrium, which leads to novel phenomenologies without any equilibrium equivalents. So far, most active matter models assign a velocity to each particle, whilst we herein consider a system of pulsating soft particles where the activity sustains particles' periodic deformation instead of spatial displacement. At sufficiently high density, we reveal the existence of wave propagation independent of any particle migration, and derive the corresponding phase diagram. We study the character of phase transitions, and investigate the underlying physical mechanisms, using both particle-based simulations and hydrodynamic analysis.