DY 43: Nonlinear Dynamics, Synchronizsation and Chaos

Time: Thursday 9:30–13:15 Location: ZEU 118

DY 43.1 Thu 9:30 ZEU 118

Optical injection in quantum dot micropillar lasers — •Xavier Porte[1], Elisabeth Schlottmann[1], Steffen Holzinger[1], Benjamin Lingnau[2], Kathy Lüdge[2], Christian Schneider[3], Martin Kamp[3], Sven Höfling[3], Janik Wolters[1,4], and Stephan Reitzenstein[1] — [1]Institut für Feskörperphysik, Technische Universität Berlin, Germany — [2]Institut für Theoretische Physik, Technische Universität Berlin, Germany — [3]Technische Physik, Julius-Maximilians-Universität Würzburg, Germany — [4]Present address: Department of Physics, University of Basel, Switzerland

Semiconductor lasers are well known to exhibit highly nonlinear behavior when subject to external optical injection and coupling. Particularly interesting nowadays is the case of microlasers, where such nonlinearities can be studied at the edge of cavity quantum electrodynamics (cQED). In the present work, we explore the phenomenon of optical injection applied to quantum dot micropillar lasers. These lasers are based on high-quality micropillar cavities containing a single layer of quantum dots as active medium. In contrast to the classical scenario of optical injection, high-β microlasers can oscillate simultaneously in a state which is synchronized to the external signal and at its solitary natural frequency, a phenomenon that we refer as partial injection locking (Schlottmann, E. et al, Phys. Rev. Applied 6, 044023 (2016)). We extensively investigate the influence of optical injection on the output power, polarization behavior, photon statistics and coherence times of the lasing modes. Our results enable the external control and tailoring of the emission of microlasers in the cQED regime.

DY 43.2 Thu 9:45 ZEU 118

Aging in deterministic classical oscillators — •Darka Labavić and Hildegard Meyer-Ortmanns — Physics and Earth Sciences, Jacobs University Bremen, Bremen, Germany

We study Kuramoto oscillators on small hexagonal lattices with repulsive coupling. Repulsive coupling in combination with the lattice topology makes bonds between individual oscillators frustrated, which induces multistability. In [1] we observe noise-driven migration of oscillatory phases in a rough potential landscape. Upon this migration, a multitude of different escape times from one metastable state to the next is generated. Based on these observations, it does not come as a surprise that the set of oscillators shows physical aging [2]. Here we introduce disorder into the system through a random distribution of natural frequencies, rather than additive or multiplicative Gaussian noise as in [2], so that the system is fully deterministic. Disorder in natural frequencies generates long time scales, observed in transients, and long periods of the order parameter. A typical trajectory of the system consists of a connected set of former (un)stable limit cycles. When our system is quenched from the regime of a unique fixed point towards the regime of multistable solutions, the autocorrelation function depends on the waiting time after the quench, so that time translation invariance is broken. So disorder in the natural frequencies leads to different exploration of the rich attracktor space as compared to noise. [1] F. Ionita, D. Labavić, M. Zaks, and H. Meyer-Ortmanns, Eur. Phys. J. B **86** (12), 511 (2013). [2] F. Ionita and H. Meyer-Ortmanns Phys. Rev. Lett. **112**, 094101 (2014).

DY 43.3 Thu 10:00 ZEU 118

Spontaneous symmetry-breaking in the Bose-Hubbard model — •Christopher D. B. Bentley[1], Alan Celestino[1], Ramy El-Ganainy[1,2], and Alexander Eisfeld[1] — [1]Max Planck Institute for the Physics of Complex Systems, Nöthnitzer Strasse 38, D-01187 Dresden, Germany — [2]Department of Physics and Henes Center for Quantum Phenomena, Michigan Technological University, Houghton, MI 49931, USA

Spontaneous symmetry-breaking has recently been experimentally observed with low photon numbers in a pair of cavities [1], which can be described by the Bose-Hubbard model. This phenomenon is well understood in the classical regime, and different approaches including quantum trajectories have been used to explore the equivalent quantum regime [2,3]. Here we extend the quantum trajectory approach, and present our results on the stability of spontaneous symmetry-breaking trajectories with symmetric Hamiltonian and control.

[1] P. Hamel et al. 2015, Nature Photonics 9, 311 [2] W. Casteels and C. Ciuti 2016, arXiv:1607.02578 [3] B. Cao, K. W. Mahmud and M. Hafezi 2016, arXiv:1608.07766

DY 43.4 Thu 10:15 ZEU 118

Sliding drops - from individual droplets to droplet ensembles — •Uwe Thiele, Sebastian Engelnkemper, Markus Wilczek, Walter Tewes, and Svetlana V. Gurevich — Institut für Theoretische Physik, Westfälische Wilhelms-Universität, Wilhelm-Klemm Str. 9, 48149 Münster

We study the dynamics of liquid drops on a solid inclined substrate [1] individually and in large ensembles employing a long-wave time evolution equation for partially wetting liquids. First, we discuss bifurcation diagrams that show how an individual sliding drop undergoes various transformations (e.g., a pearling instability) in dependence of driving force or volume. The resulting pearling states show a period-doubling route to chaos [2]. Second, we conduct large-scale numerical simulations and analyse the coarsening behaviour of drop ensembles. Ongoing merging and pearling results in a stationary distribution of drop sizes. We illustrate that aspects of this distribution may be deduced from the single-drop bifurcation diagrams. Finally, we construct a statistical model for the time evolution of the drop size distribution and show that it captures the main features of the full scale simulations.

[1] T. Podgorski, J.-M. Flesselles and L. Limat, Phys. Rev. Lett. 87, 036102 (2001). [2] S. Engelnkemper, M. Wilczek, S. V. Gurevich and U. Thiele, Phys. Rev. Fluids 1, 073901 (2016).

DY 43.5 Thu 10:30 ZEU 118

Wave control by cooperative excitation of cardiac tissue — •Pavel Buran[1], Sergio Alonso[2], Markus Bär[1], and Thomas Niedermayer[1] — [1]Physikalisch-Technische Bundesanstalt (PTB), Berlin — [2]Universitat Politècnica de Catalunya, Barcelona

Rotating excitation waves and electrical turbulence in cardiac tissue have been associated with arrhythmias like the life-threatening ventricular fibrillation. The application of an electrical shock (defibrillation) is an effective therapy, as it globally excites the tissue resulting in termination of all excitation waves, but also causes severe side effects. Recent experimental studies have shown that a sequence of electrical pulses is able to terminate fibrillation more gently than a single pulse. Only tissue at major conduction heterogeneities, such as large coronary arteries, may be activated by each of these very weak pulses. Therefore, global tissue activation and wave termination originates from few localized activation sites. In order to decipher the interplay of the individual pulses, we performed extensive simulations of cardiac tissue perforated by blood vessels and tested a variety of cellular models. For models exhibiting a dominant excitation period during fibrillation, the pulses appear to be highly cooperative if the period between these pulses matches the dominant period. These findings are elucidated by the analysis of the dynamical variables, such as the fraction of excited tissue and the number of phase defects, both during the state of electrical turbulence and during cooperative excitation. Moreover, we propose a simple stochastic model which integrates our results in an intuitive way.

DY 43.6 Thu 10:45 ZEU 118

Synchronization of mutually coupled quantum dot high-Q micropillar lasers — •Sören Kreinberg[1], Felix Krüger[1], Steffen Holzinger[1], Elisabeth Schlottmann[1], Martin Kamp[2], Christian Schneider[2], Sven Höfling[2,3], Xavier Porte[1], and Stephan Reitzenstein[1] — [1]Institut für Festkörperphysik, Technische Universität Berlin, Germany — [2]Technische Physik, Julius-Maximilians-Universität Würzburg, Germany — [3]School of Physics and Astronomy, University of St Andrews, Scotland

Mutual coupling and synchronization of semiconductor lasers is an exciting topic in the field of non-linear dynamics with potential applications to secure data communication. In this work, we aim at pushing the phenomenon of synchronization towards the quantum regime of cavity enhanced microlasers. We address this novel regime by experimental studies on mutually coupled quantum dot microcavity lasers with sub-μW emission power.

The structures under study are electrically driven GaAs/AlAs micropillar cavities containing a single layer of In-GaAs quantum dots (QD) as active medium. In contrast to conventional macroscopic lasers, these high-β microcavity lasers exhibit a strong influence of spontaneous emission on their dynamics. In the field of non-linear dynamics, this peculiarity leads to the effect of partial injection locking as was recently demonstrated [1]. We investigate the pump-dependent detuning range of phase locking, frequency pulling and partial locking, as well as the existence of mutually correlated chaotic intensity fluctuations. [1] E. Schlottmann et al., *Phys. Rev. Applied* 6, 044023 (2016)

DY 43.7 Thu 11:00 ZEU 118

The load-response of the flagellar beat and its implications for synchronization — •Gary Klindt[1], Christian Ruloff[2], Christian Wagner[2,3], and Benjamin Friedrich[4] — [1]MPI PKS, Dresden, Germany — [2]University of the Saarland, Saarbrücken, Germany — [3]University of Luxemburg, Luxemburg — [4]TU Dresden, Germany

Cilia and flagella exhibit regular bending waves that perform mechanical work on the surrounding fluid, to propel cellular swimmers and pump fluids inside organisms. Conversely, hydrodynamic forces feedback on flagellar oscillations, changing speed and shape of the flagellar beat. This flagellar load-response is a prerequisite for self-organized synchronization observed in collections of cilia and flagella.

Here, we combine theory and experiment to comprehensively characterize the load-response of the flagellar beat, including stalling of flagellar oscillations at high load [1]: Our description of the flagellar beat as a limit-cycle oscillations is calibrated by experimental data of flagellated Chlamydomonas cells exposed to controlled microfluidic flows.

Remarkably, in our simulations, two previously suggested mechanisms of flagellar synchronization, (i) flagellar waveform compliance, and (ii) elastic coupling between flagellar bases, each stabilize antiphase synchronization, yet their combination stabilizes in-phase synchrony as observed in experiments.

[1] G.S. Klindt, C. Ruloff, C. Wagner, B.M. Friedrich, Load-response of the flagellar beat, accepted at Phys. Rev. Lett.

15 min. break

DY 43.8 Thu 11:30 ZEU 118

Synchronizing cardiac activity during ventricular fibrillation — •Henrik tom Wörden — Max-Planck-Institut für Dynamik und Selbstorganisation, Göttingen, Deutschland

Ventricular fibrillation is a lethal condition of the heart which is still not well understood and medicine lacks a suitable treatment. The irregular and fast activation patterns during ventricular fibrillation make it hard to find efficient methods to control the dynamics of the myocardium. In contrast, e.g. monomorphic ventricular tachycardia can often be terminated by local stimulation with a train of uniform electric pulses. While such a local stimulation has a very limited region of influence in ventricular fibrillation, electric far field shocks allow the application of stimuli at many places of the ventricle at once. We demonstrate how the cardiac activity can be synchronized with such pulses and how it modifies the properties of the dynamics in the heterogeneous cardiac tissue.

DY 43.9 Thu 11:45 ZEU 118

Features and Control of Chaotic Transients in Excitable Media — •Thomas Lilienkamp, Stefan Luther, and Ulrich Parlitz — Max Planck Institute for Dynamics and Self-Organization, Goettingen, Germany

Cardiac tissue is a prominent example of an excitable medium. Cardiac dysfunctions of the heart like ventricular fibrillation can be associated with a (chaotic) spatio-temporal dynamics, which is mainly determined by spiral or scroll waves. Here we discuss which role chaotic transients play in this context, using numerical simulations of 2D and 3D systems. We investigate which properties of the system have an impact on the lifetime of the transients and how a chaotic transient can be terminated in an efficient way (control).

DY 43.10 Thu 12:00 ZEU 118

Impact of anisotropy on termination of pinned spiral waves using far field pulses — •Edda Boccia[1], Stefan Luther[1,2,3], and Ulrich Parlitz[1,3] — [1]Max Planck Institute for Dynamics and Self-Organization, Göttingen, Germany — [2]Department of Pharmacology, University Medical Center, Göttingen, Germany — [3]Institute for Nonlinear Dynamics, Georg-August-Universität Goettingen, Göttingen, Germany

Reentrant waves find a critical substrate in the multi-sized heterogeneities of myocardium. Spiral waves pinned to an heterogeneity can self-terminate or be unpinned (and terminated) by electric far field pulses exploiting heterogeneities as virtual electrodes. We implement a 2D bidomain formulation of the phase I of the Luo and Rudy model under acute ischemia. We investigate how anisotropy and size of the ischemic area may affect reentrant dynamics with and without exposing the tissue to far field pacing (FFP). Without FFP, we found that: 1. waves stability is affected more by changes in the intracellular space than by modifications in the extracellular space; 2. not only the size of the heterogeneity, but also the degree of intracellular anisotropy highly affects maintenance or self-termination of pinned spirals. How FFP contributes to unpinning or successful termination of pinned spirals in anisotropic media is much less clear compared to isotropic domains. In this contribution we focus on the impact of anisotropy and compare the success rate for several sequences of FFP pulses in both isotropic and anisotropic domains. Interestingly, anisotropic tissues result to be a more suitable substrate for successful termination of pinned spirals.

DY 43.11 Thu 12:15 ZEU 118

Finite Time Basin Stability and Basin Escape Rates — •Paul Schultz[1,2], Frank Hellmann[1], Kevin Webster[1], and Jürgen Kurths[1,2,3,4] — [1]Potsdam Institute for Climate Impact Research, P.O. Box 601203, 14412 Potsdam, Germany — [2]Department of Physics, Humboldt University of Berlin, Newtonstr. 15, 12489 Berlin, Germany — [3]Institute for Complex Systems and Mathematical Biology, University of Aberdeen, Aberdeen AB24 3UE, United Kingdom — [4]Department of Control Theory, Nizhny Novgorod State University, Gagarin Avenue 23, 606950 Nizhny Novgorod, Russia

We define the finite-time basin stability, which is the probability of a system returning closely enough to an equilibrium within a certain time while being subject to random shocks at specified time intervals.

When the frequency of these perturbations becomes low enough for the system to equilibrate between two shocks, subsequent perturbations are independent and the measure yields the conventional basin stability (Menck et al. Nat. Phys. 9, 89-92. 2013).

Using an appropriately defined Lyapunov function, we show that finite-time basin stability reveals information about the maximum frequency of perturbations at which basin stability becomes the escape rate from the basin. As an example, we use Kuramoto oscillators with inertia.

DY 43.12 Thu 12:30 ZEU 118

Stabilization of three-dimensional scroll waves by heterogeneities — •Florian Spreckelsen[1], Daniel Hornung[1], Oliver Steinbock[2], Ulrich Parlitz[1,3,4], and Stefan Luther[1,3,4] — [1]Max Planck Institute for Dynamics and Self-Organization, Am Faßberg 17, 37077 Göttingen, Germany — [2]Department of Chemistry and Biochemistry, Florida State University, Tallahassee, FL 32306-4390, United States — [3]Institute for Nonlinear Dynamics, Georg-August-Universität Göttingen, Am Faßberg 17, 37077 Göttingen, Germany — [4]German Centre for Cardiovascular Research, partner site Göttingen, 37077 Göttingen, Germany

Scroll waves in a three-dimensional excitable medium with negative filament tension may break up and display spatiotemporal chaos. The presence of non-excitable heterogeneities can influence the evolution of the medium, in particular scroll waves may pin to such heterogeneities. We show [1] thin rodlike heterogeneities suppress otherwise developing spatiotemporal chaos and additionally clear out already existing chaotic excitation patterns.

[1] F. Spreckelsen, D. Hornung, O. Steinbock, U. Parlitz, and S. Luther. Phys. Rev. E 92 (2015): 42920. doi:10.1103/PhysRevE.92.042920.

DY 43.13 Thu 12:45 ZEU 118

Synchronisation Behaviour and the Emergence of Chaotic Dynamics in Systems of Viscoelastically Coupled Van der Pol Oscillators — •Sebastian Stein[1,2], Stefan Luther[1,2,3], and Ulrich Parlitz[1,2] — [1]Biomedical Physics Research Group, Max Planck Institute for Dynamics and Self-Organization, Am Faßberg 17, D-37077 Göttingen, Germany — [2]Institute for Nonlinear Dynamics, Georg-August-Universität Göttingen, Friedrich-Hund-Platz 1, D-37077 Göttingen, Germany — [3]Universitätsmedizin Göttingen, Georg-August-Universität Göttingen, Robert-Koch-Straße 40, D-37075 Göttingen, Germany

We investigate a system of viscoelastically coupled, modified Van der Pol oscillators to compare their synchronisation properties due to elastic and viscoelastic coupling. To study the impact of symmetry, the

Van der Pol oscillators are modified to exhibit either a symmetric or asymmetric restoring force. It will be shown that increasing viscosity of the coupling or symmetry breaking of the (harmonic) potential have a strong impact on the stability of synchronised periodic solutions and may lead to the emergence of chaotic behaviour.

DY 43.14 Thu 13:00 ZEU 118

Multi-node basin stability in complex networks of dynamical systems — Chiranjit Mitra[1], Anshul Choudhary[2,3], Sudeshna Sinha[2], Jürgen Kurths[1,4,5,6], and •Reik V. Donner[1] — [1]Potsdam Institute for Climate Impact Research, Germany — [2]IISER Mohali, India — [3]Carl von Ossietzky University of Oldenburg, Germany — [4]Humboldt University, Berlin, Germany — [5]University of Aberdeen, UK — [6]Nizhny Novgorod State University, Russia

In networks of interacting oscillators, the stability of the synchronized state in the presence of large perturbations is critical, with various real-world examples like ecosystems, power grids, the human brain, etc. The study of this problem calls for the development of appropriate quantifiers of stability of multiple stable states of such systems. Motivated by the concept of basin stability (BS) (Menck et al., Nature Physics 9, 89 (2013)), we propose here the general framework of multi-node basin stability for gauging global stability and robustness of networked dynamical systems in response to non-local perturbations simultaneously affecting multiple nodes of a system. The framework of multi-node BS provides an estimate of the critical number of nodes which when simultaneously perturbed significantly reduces the capacity of the system to return to the desired state. We demonstrate the potential of multi-node BS in assessing the stability of the synchronized state in a deterministic scale-free network of Rössler oscillators and a conceptual model of the power grid of the United Kingdom with second-order Kuramoto-type nodal dynamics.