WWU MÜNSTER

Center for Nonlinear Science

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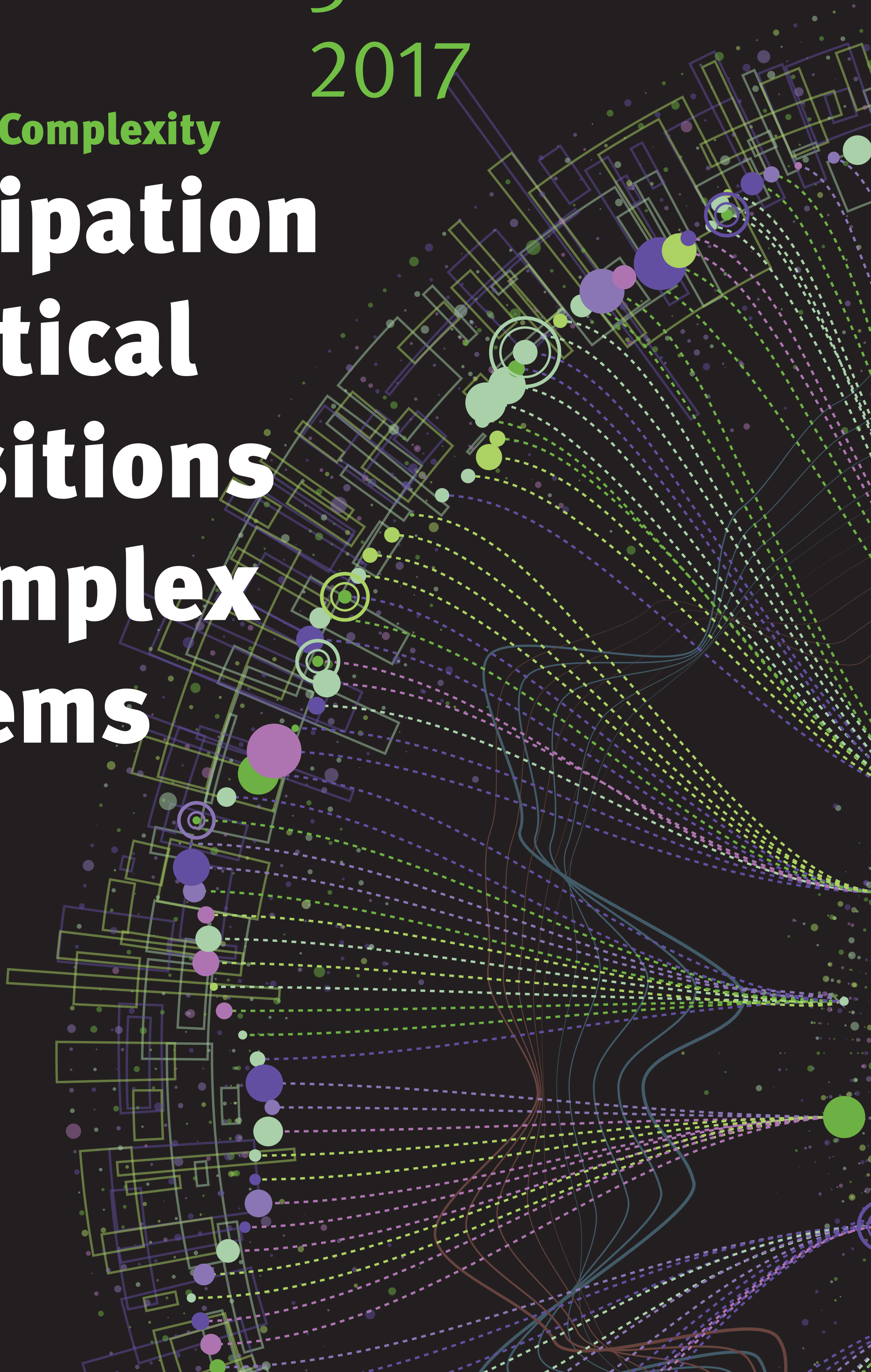
**Windows to Complexity**

# Anticipation of Critical Transitions in Complex Systems



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Contact:

J.-Prof. A. Telschow
Institut für Evolution u. Biodiversität
WWU Münster
Hüfferstr. 1
48149 Münster
Tel.: +49 251 83 21637
Fax: +49 251 83 24668
Arndt.Telschow@uni-muenster.de

Dr. O. Kamps
Center for Nonlinear Science
WWU Münster
Correnstraße 2
48149 Münster
Tel.: +49 251 83 33515
Fax: +49 251 83 33513
okamp@uni-muenster.de

# LOCATION

The workshop takes place at the "Schloss" of the University of Münster

Schlossplatz 2
48149 Münster

# ANTICIPATION OF CRITICAL TRANSITIONS IN COMPLEX SYSTEMS

Complex systems are known to show at tipping points abrupt changes in their macroscopical behavior under smooth parameter variations. In recent years the identification and anticipation of tipping points of complex systems from measurement data received much attention in the scientific community. One approach relies on the general theory of complex systems and the result that close to tipping points systems that are formed by the nonlinear interaction of many subsystems show universal features. Although the constituting parts can be very different they all show phenomena like for example critical slowing down or critical fluctuations. This can be observed in a wide variety of systems from different scientific disciplines starting from Laser physics over pattern formation in chemical reactions, biological and medical systems and also in psychology. In the mathematical description of these phenomena the universality is reflected by the fact that close to such critical points the dynamics of very different systems can be described by the same basic types of equations. This universal behavior is the foundation of many of the current approaches to develop indicators for tipping points for ecological and social systems even in cases where modeling of the system of interest is difficult or up to now not possible. The intention of this workshop is to give an overview over recent developments in this field. The talks cover topics from such diverse fields as ecology, nero science and physics.

# PROGRAM

## THURSDAY 31.08.2017

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|---|---|---|
| 9.30 | Registration and Coffee | |
| 10.00 | Opening | |
| 10.15 | Anticipating critical transitions in ecosystems | **E. v. Nes** |
| 11.15 | Anticipating epileptic seizures | **K. Lehnertz** |
| 12.15 | Lunch | |
| 13.45 | Constructing risk profiles of critical transitions caused by boundary crises | **M. Adamson** |
| 14.30 | Edge States in the Climate System: Exploring Global Instabilities and Critical Transitions | **V. Lucarini** |
| 15.15 | Coffee | |
| 15.45 | Anticipating critical transitions in complex ecosystems: a nonlinear time series analysis approach | **A. Telschow** |
| 16.15 | Anticipating large scale power outtages - A case study | **O. Kamps** |

**E. v. Nes** Department of Environmental Sciences, Wageningen University

## Anticipating critical transitions in ecosystems

Some complex systems can have two alternative stable states. I will discuss when we can expect that complex systems have two attractors and give many examples, mostly from ecology. If a system is bistable, an important question is how resilient both states are. I will explain some indicators of resilience (also known as early warning signals) that are based on the phenomenon of critical slowing down (Scheffer et al. 2009, Nature). This phenomenon only occurs for systems that are close to equilibrium. However, in ecology many systems have a lot of noise. Such noisy systems may switch back and forth between alternative stable states. In such systems it is more interesting to know how often each of the states are visited, i.e. a kind of "relative resilience" of both states (Scheffer et al. 2015, Annual. Rev. Ecol. Evol. Syst.). I will discuss some ideas for such resilience measures that can measure the relative resilience and explain reconstructed stability landscapes for systems with a lot of data (potential analysis, Livina et al. 2010, Climate of the Past; Hirota et al. 2011 Science).

**K. Lehnertz** Department of Epileptology, University of Bonn

## Anticipating epileptic seizures

Although there are numerous studies exploring basic neuronal mechanisms that are likely to be associated with epileptic seizures, to date no definite information is available as to how or when or where or why a seizure occurs in humans. The sudden and apparently unpredictable nature of seizures is one of the most disabling aspects of the disease epilepsy that affects ~1% of the world population. Identifying seizure precursors from brain dynamics could drastically improve therapeutic possibilities and thus the quality of life of people with epilepsy. Over the last two decades, an improved characterization of the spatial-temporal dynamics of the epileptic process could be achieved with tools from nonlinear dynamics, statistical physics, synchronization and network theory. These tools appear to be capable of defining seizure precursors from electroencephalographic recordings. Studies on seizure prediction have advanced from preliminary descriptions of pre-seizure phenomena and proof of principle studies via controlled studies to the development of implantable seizure prediction and prevention systems.

**M. Adamson** Institute of Environmental Systems Research, University of Osnabrück

### Constructing risk profiles of critical transitions caused by boundary crises

Much research in recent years has been devoted towards the construction of generic methods for anticipating critical transitions from time series data so that steps could be taken to prevent them. While a lot of progress has been made in this direction, there are shortcomings in the currently existing toolbox. Present approaches based on time series almost exclusively focus on critical transitions of stable equilibria, such as saddle-node bifurcations, but in many critical transitions in nature, the state is fluctuating either periodically or chaotically before the transition. Therefore we still require methods for detecting all kinds of critical transition in which an attractor disappears after colliding with the basin of attraction of another attractor which can be either more, or less, favourable. Furthermore, the early warning signals given by contemporary methods can be difficult to interpret in real time: while it may be possible to see that autocorrelation and/or variance is rising, implying that a critical transition may be close, there is at present no reliable way to infer how likely a transition is from such signals, or to predict when it will occur. From the point of view of decision making in the prevention of critical transitions, such information is vital. In this talk, Iâll present a general method for anticipating critical transitions in which an attractor hits the basin of attraction of another and disappears. This can include saddle-node bifurcations of limit cycles, homoclinic/heteroclinic bifurcations of limit cycles and boundary crises of strange attractors. As well as signalling whether or not a critical transition is likely, the new method has the advantage that it also provides a risk profile of the transition: a prediction of the probability for the critical transition to occur at any given time in the future. Therefore the method could be used alongside the existing early warning signals for anticipating state changes from equilibrium, in order to provide more precise information as to how likely a transition is and when we should expect it to happen.

**V. Lucarini** Department of Mathematics and Statistics, University of Reading

## Edge States in the Climate System: Exploring Global Instabilities and Critical Transitions

Multistability is a ubiquitous feature in systems of geophysical relevance and provides key challenges for our ability to predict a system's response to perturbations. Near critical transitions small causes can lead to large effects and - for all practical purposes - irreversible changes in the properties of the system. The Earth climate is multistable: present astronomical and astrophysical conditions support two stable regimes, the warm climate we live in, and a snowball climate, characterized by global glaciation. We first provide an overview of methods and ideas relevant for studying the climate response to forcings and focus on the properties of critical transitions. Following an idea developed by Eckhardt and co. for the investigation of multistable turbulent flows, we study the global instability giving rise to the snowball/warm multistability in the climate system by identifying the climatic edge state, a saddle embedded in the boundary between the two basins of attraction of the stable climates. The edge state attracts initial conditions belonging to such a boundary and is the gate facilitating noise-induced transitions between competing attractors. We use a simplified yet Earth-like climate model constructed by coupling a primitive equations model of the atmosphere with a simple diffusive ocean. We refer to the climatic edge states as Melancholia states. We study their dynamics, their symmetry properties, and we follow a complex set of bifurcations. We find situations where the Melancholia state has chaotic dynamics. In these cases, the basin boundary between the two basins of attraction is a strange geometric set with a nearly zero codimension, and relate this feature to the time scale separation between instabilities occurring on weather and climatic time scales. We also discover a new stable climatic state characterized by non-trivial symmetry properties.

V. Lucarini and T. Bodai, Edge States in the Climate System: Exploring Global Instabilities and Critical Transitions, Nonlinearity 30 R32 (2017)

**A. Telschow** Institute for Evolution and Biodiversity, WWU Münster

## Anticipating critical transitions in complex ecosystems: a non-linear time series analysis approach

Complex dynamic systems such as ecosystems, the global climate of the earth, social and economic organizations, and the human brain may undergo critical transitions where a sudden shift from one state to another may occur. Although critical transitions are mathematically well characterized by dominante eigenvalues of local Jacobians, they are notoriously difficult to predict for (natural) systems with unknown dynamics. Here we present a new approach for predicting critical transitions in which the eigenvalues are estimated directly from (observation) time series data using non-linear time series analysis techniques. First, we applied the method to simulated time series data generated by stochastic dynamical models with fold, period doubling, and Hopf bifurcation. We show that the eigenvalues âcan be are accurately estimated even in the presence of noise, and that time point and bifurcation type of the transition is correctly predicted with a moving window approach. Second, we re-analyzed two empirical data sets with known fold bifurcation. Remarkably, we were able to accurately predict the time point and bifurcation type of a microcosm experiment. Reliable early warning signals for the transition were also derived for climate data (end of last greenhouse earth), although a quantitative prediction of the time point was not possible.

**O. Kamps** Center for Nonlinear Science, WWU Münster

## Anicipating large scale power outtages - A case study

The anticipation of critical transitions in complex systems is a field of active research in such diverse disciplines as ecology, climate research or engineering. In (Cotilla-Sanchez et.al, IEEE Transactions on Smart Grid,2012) large scale power outages are considered as critical transitions in the operation of power grids. It was shown for the large scale power outage on August 10 in 1996 in the USA that the event could be anticipated from critical fluctuations of the system frequency. In this talk we present results from the analysis of two different data sets of the system frequency from the same event that have been measured at two different positions in the grid. We show that critical fluctuations seem not to be a reliable indicator for a critical transition in the power grid. In contrast to that, analyzing the data from the viewpoint of Langevin equations by estimating the drift and diffusion coefficients shows to be more reliable to anticipate the outage.

NOTES

# NOTES

## THE CENTER FOR NONLINEAR SCIENCE

The study of nonlinear, complex systems is one of the most exciting and fastest growing branches in science nowadays. Understanding the mechanisms governing cooperative, emergent phenomena in complex systems is considered as one of the most important challenges in science, because it is a highly interdisciplinary field that has important applications in fields ranging from physics, mathematics, chemistry, engineering and computer science to life sciences, sociology and finances.

The Center for Nonlinear Science (CeNoS) was founded to foster research and education in the field of nonlinear science and to strengthen the dialogue between different scientific disciplines at the University of Münster. For further information visit:

**www.uni-muenster.de/cenos**