DY 15: Focus Session: Large Deviations and Rare Events II

The modeling and understanding of large deviations and rare events is of crucial importance in a wide range of real-world applications, including climate science, actuarial statistics (insurance statistics), natural disaster management, or the description of financial markets. At the same time, such effects are fundamental for the understanding of many systems in condensed-matter physics. In first-order phase transitions, for instance, the coexisting phases are connected by transition states involving droplet excitations whose probability is suppressed by dozens or hundreds of orders of magnitude as compared to the pure-phase peaks. Likewise, for many disordered systems the behavior of typical cases is incompatible with that of the average sample as the problem is described by very broad, heavy-tailed distributions, where averages are dominated by rare events. For many models, like the Kadar-Parisi-Zhang equation or random-graph properties, there has been considerable analytical progress in the last decade. Likewise, new or improved numerical techniques have been proposed that now allow for the treatment of previously inaccessible problems or regimes. This focus session is devoted to an update on the state of the art in this rapidly evolving area.

Organized by Alexander K. Hartmann (Oldenburg) and Martin Weigel (Chemnitz)

Time: Monday 15:00–18:30 Location: ZEU/0114

Invited Talk DY 15.1 Mon 15:00 ZEU/0114

Monte Carlo Simulation Methods for Rare-Event Sampling — •Wolfhard Janke — Institut für Theoretische Physik, Universität Leipzig, IPF 231101, 04081 Leipzig, Germany

Large fluctuations and rare events play an important role in many physical systems, with nucleation phenomena, first-order phase transitions and frustrated (disordered) systems being only the most prominent examples. To cope with such processes in Monte Carlo computer simulations, several generalized-ensemble approaches such as parallel and simulated tempering and "flat-histogram" methods have been devised and further improved over the years. After a brief overview of the basic ideas of multicanonical (MuCa), Wang-Landau (WL), and Stochastic Appxoximation Monte Carlo (SAMC) schemes, the talk will focus on more recently proposed "non-flat" variants that put even more emphasis on strongly suppressed rare events, and alternative formulations based on the (real) microcanonical ensemble. As illustrations, performance tests and results will be shown for spin glasses, first-order phase transitions in the q-state Potts and Blume-Capel model, Lennard-Jones particle and polymer clusters, and the density of states of O(n) spin models on triangular and hypercubic lattices spanning many hundreds orders of magnitude.

DY 15.2 Mon 15:30 ZEU/0114

Sampling rare events with neural networks — Moritz Riedel[1], Johannes Zierenberg[2], and •Martin Weigel[1] — [1]Institut für Physik, Technische Universität Chemnitz, 09107 Chemnitz, Germany — [2]Max Planck Institute for Dynamics and Self-Organization, 37077 Göttingen, Germany

Neural networks can be trained to generate samples from the Boltzmann distribution of many-particle systems. If suitable architectures such as normalizing flows or variational autoregressive networks are chosen, exact generation weights are known, and hence present biases can be corrected for. Still, such networks typically struggle to learn and reproduce configurations from the full range of configuration space, since effects such as mode collapse occur. For the simulation of rare events and suppressed states accessible in generalized frameworks such as the multicanonical ensemble such broad exploration is crucial. Here, we show how a combination of variational autoregressive network and autoencoder allows for a systematic exploration of configuration space in spin models, during which the network is able to learn the density of states. We demonstrate the efficacy of the approach in the Potts system in the strong first-order regime, and we also propose hybrid algorithms combining the neural network approach with traditional Monte Carlo techniques.

DY 15.3 Mon 15:45 ZEU/0114

Large deviation simulation of the coupling time of an Ising ferromagnet — •Mathis Groenhagen[1], Peter Werner[2], and Alexander K. Hartmann[1] — [1]Institut für Physik, Carl von Ossietzky Universität Oldenburg — [2]Laboratoire de Météorologie Dynamique - ENS, Paris

Coupling from the past, introduced by Propp and Wilson [1], is a Markov-chain Monte Carlo (MCMC) method capable of generating perfectly independent samples from a finite set of states, following exactly a given distribution. The performance of this algorithm for a given model can be characterized by it's *coupling time* τ_c, which measures the time to perfect statistical independence and depends on the used random numbers.

The algorithm is tested for one and two-dimensional Ising models without external field with the single-spin-update heat-bath algorithm. In order to access the distribution $p(\tau_c)$ over a wide range of the support down to densities as small as 10^{-200}, a large-deviation MCMC algorithm is used. With this, we have obtained $p(\tau_c)$ for different lattice dimensions D, edge lengths L and heat-bath temperatures T.

In particular, we observe a change of the shape of $p(\tau_c)$ at T_c for $D = 2$. For the paramagnetic case of $D = 2$ and $D = 1$, $p(\tau_c)$ follows a Gumbel distribution as predicted for the thermodynamic limit [2]. We have studied the dependency of the distribution parameters on T and L.

[1] J. Propp, D. Willson, Random Struct. Algoritms **9**, 223-252 (1996).
[2] A. Collevechio et al., J. Stat. Phys. **170**, 22-61 (2018).

DY 15.4 Mon 16:00 ZEU/0114

Large deviations in response functions of the two-dimensional bond-diluted Ising model — •Lambert Münster[1], Alexander K. Hartmann[2], and Martin Weigel[1] — [1]Institut für Physik, TU Chemnitz, 09107 Chemnitz, Germany — [2]Institut für Physik, Carl von Ossietzky Universität Oldenburg, 26129 Oldenburg, Germany

Studies in statistical physics are most commonly focused on the typical, average behavior of a system. However, there exist cases in which rare events can have a significant impact on physical properties. The Griffiths phase in systems with quenched disorder is one such example. In this case rare regions in the disorder degrees of freedom cause large tails in response functions of physical observables such as the magnetic susceptibility and the specific heat. In this study rare-region effects are investigated by analyzing the distributions of physical observables in the bond-diluted Ising model. In order to obtain these distributions over a wide range of their support, a special type of Markov chain Monte Carlo algorithm is utilized for sampling rare events [1].

[1] L. Münster, A. K. Hartmann and M. Weigel, Phys. Rev. E **110**, 054112 (2024).

DY 15.5 Mon 16:15 ZEU/0114

Universality of the order-parameter large-deviation function for the critical 2D Ising and Blume-Capel models — Nikolaos G. Fytas[1], Víctor Martín-Mayor[2], Attilio L. Stella[3], Gianluca Teza[4], Alexandros Vasilopoulos[1], and •David Yllanes[5] — [1]University of Essex — [2]Universidad Complutense de Madrid — [3]Università di Padova — [4]MPIPKS, Dresden — [5]Universidad de Zaragoza

We revisit the longstanding question of universality in the probability density function (pdf) of the order parameter at criticality, traditionally assumed to hold only for the central region of the distribution. Focusing on the dimensionless magnetization $u = m/\sqrt{\langle m^2 \rangle}$, whose moments are universally defined in the thermodynamic limit, we hypothesize that universality extends to the full pdf $p_L(u)$, including its exponentially suppressed large-deviation tails scaling as $u^{1+\delta}$. We test this conjecture with large-scale Tethered Monte Carlo simulations of the 2D Blume-Capel model at criticality for several values of the crystal field Δ, including the Ising limit ($\Delta = -\infty$) and approaching the tricritical point $\Delta_c \approx 1.97$. We simulate lattices up to $L = 4096$ with a tethered cluster algorithm, reaching the asymptotic regime for probability densities as small as 10^{-200}. Our results are strong numerical evidence for universality in the full $p_L(u)$ and settle the debated non-universality of the large-deviation function for m, where system-dependent amplitudes obscure scaling behavior. We consider the universality of the unusual combination of a finite-size amplitude with an amplitude for a scaling law related to the large-deviation function.

DY 15.6 Mon 16:30 ZEU/0114

Ising Model under Stochastic Resetting — •Shashank Kallappara[1], Parbati Saha[2], Varsha Banerjee[2], and Martin Weigel[1] — [1]Institut für Physik, TU Chemnitz, Germany — [2]Department of Physics, Indian Institute of Technology Delhi, India

Stochastic resetting refers to the interruption of a system's natural evolution by randomly returning it to a prescribed initial configuration. In this work, we investigate the effect of stochastic resetting on the Ising model and extend the results of Ref. [1] by examining how the resetting protocol modifies energetic properties of the system. In particular, we analyse the behaviour of the energy under different resetting rates and initial magnetisations. Furthermore, we study the impact of resetting in the case of conserved-order-parameter Ising model using Kawasaki dynamics, revealing qualitatively distinct behaviour compared to the nonconserved Glauber dynamics.

[1] Magoni, M., Majumdar, S. N. & Schehr, G. Ising model with stochastic resetting. Phys. Rev. Research 2, 033182 (2020).

15 min. break

DY 15.7 Mon 17:00 ZEU/0114

Classical nucleation theory for active non-conserved scalar field theories — •Michalis Chatzittofi[1], Noah Ziethen[1], Cesare Nardini[2], and Michael Cates[1] — [1]DAMTP, Centre for Mathematical Sciences, University of Cambridge, Cambridge CB3 0WA, United Kingdom — [2]Service de Physique de l' Etat Condense, CNRS UMR 3680, CEA-Saclay, 91191 Gif-sur-Yvette, France

Classical nucleation theory (CNT) has been successfully used in equilibrium conserved theories to explain the behaviour of growing droplets. However, in non-equilibrium field theories such description is more challenging since the dynamics cannot be derived from a free-energy. In this work, we show that it is possible to generalize CNT for the case of out-of-equilibrium non-conserved field theories. By projecting onto the slow manifold of the dynamics, we propose a systematic recipe for deriving an exact analytical expression for the dynamics of the growing nucleus and the corresponding quasipotential. Our findings allow for analytical progress in the context of large deviations and can compliment numerical/machine learning approaches for finding instanton trajectories.

DY 15.8 Mon 17:15 ZEU/0114

Precise large deviations in statistical field theories with weak noise — •Timo Schorlepp[1], Tobias Grafke[2], Rainer Grauer[3], Georg Stadler[1], and Shanyin Tong[4] — [1]NYU Courant, USA — [2]Warwick, UK — [3]Bochum, Germany — [4]UPenn, USA

Large deviation theory (LDT) provides a common theoretical framework to compute probabilities of rare events in stochastic systems out of equilibrium. The theory consists of a saddlepoint evaluation of the path integral describing the stochastic process under study, and has successfully been used in various systems such as growing interfaces, active matter, lattice gases and macroscopic fluctuation theory, fluid dynamics and turbulence, etc. I will describe recent progress in going beyond leading-order LDT asymptotics, developing tractable methods to evaluate 1-loop (Gaussian) corrections around nontrivial LDT minimizers for weak noise Langevin equations and field theories. This allows for quantitative rare event probability estimates, beyond the usual log-asymptotics. To compute the corresponding LDT prefactors, I will present two complementary approaches based on either matrix Riccati differential equations, or (possibly renormalized) Fredholm determinants. I will illustrate these methods in multiple analytical/numerical examples: extreme growth events in the 1d KPZ equation at short times [1], extreme concentrations of a randomly advected passive scalar [2], and extreme strain events in the stochastically forced incompressible 3d Navier-Stokes equations [3]. References: [1] Schorlepp, Grafke, Grauer, J Stat Phys, 2023; [2] Schorlepp, Grafke, arXiv:2502.20114, 2025; [3] Schorlepp, Tong, Grafke, Stadler, Stat. Comput., 2023.

DY 15.9 Mon 17:30 ZEU/0114

Probability graphons and large deviations for random weighted graphs — •Giulio Zucal — Max Planck Institute of Molecular Cell Biology and Genetics, Dresden, Germany — Max Planck Institute for Physics of Complex Systems, Dresden, Germany — Center for Systems Biology Dresden, Dresden, Germany

Graph limit theory studies the convergence of sequences of graphs as the number of vertices grows, providing an effective framework for representing large networks. In this talk, I will give a brief introduction to graph limits and report on recent extensions to weighted graphs and multiplex networks (probability graphons and P-variables). As an application of this theory I will present a large deviation principle (LDP) for random weighted graphs that generalizes the LDP for Erdős–Rényi random graphs by Chatterjee and Varadhan (2011), based on joint work with Pierfrancesco Dionigi.

DY 15.10 Mon 17:45 ZEU/0114

Extreme Value Analysis for Finite, Multivariate and Correlated Systems with Finance as an Example — •Benjamin Köhler, Anton J Heckens, and Thomas Guhr — Universität Duisburg-Essen, Germany

Extreme values and the tail behaviour of probability distributions are essential for quantifying and mitigating risk in complex environmental and socio-economic systems. In multivariate settings, accounting for correlations is crucial. Although extreme value analysis for truly infinite correlated systems remains an open challenge, we propose a practical framework for handling a large but finite number of time series.

We study the extremal behavior of high-frequency stock returns after rotating them into the eigenbasis of the correlation matrix. This separates information on the market as a whole and on sectoral behavior while allowing us to use univariate tools of extreme value analysis, even for high-frequency data where discretization effects normally complicate analysis.

Using a Peaks–over–threshold approach, we estimate the tail shape of the rotated returns while explicitly accounting for non-stationarity, a key feature in finance and many other complex systems. Our framework allows for tail risk estimation relative to larger trends and intraday seasonalities at both market and sectoral levels.

DY 15.11 Mon 18:00 ZEU/0114

On the Reconstruction and Predictability of Ocean Rogue Waves — Christian Behnken, Finn Köhne, Metthias Wächter, and •Joachim Peinke — Institute of Physics, University Oldenburg, Oldenburg

We present a data-driven algorithm which allows to reconstruct rogue wave events from surface elevation measurements of ocean gravity waves. In particular we extract from the data stochastic equations for joint multipoint statistics [1]. Our procedure is applied to measurements from the Sea of Japan and the German North Sea over several days. The estimated stochastic equations allow to generate large ensembles of realistic wave time series to investigate the predictability of rogue waves. Furthermore we use the large deviation algorithm "Trajectory-Adaptive Multilevel Sampling" [2] to predict up to now unkown extreme wave events. While the North Sea equations do not lead to Rogue Waves, we do find those for the Sea of Japan. Averaging over several similar rogue waves, we obtain well-known rogue wave patterns like the "three sisters", proposed by from nonlinear-wave equations. i.e. nonlinear Schrödinger equation [3].

[1] Hadjihoseini, A.; et al: EPL (Europhysics Letters) 120 (2017), Nr. 3, 30008

[2] Lestang, T.; et.al Journal of Statistical Mechanics: Theory and Experiment 2018 (2018), Nr. 4, S. 043213

[3] Akhmediev, N.; et al: Physics Letters A 373 (2009), Nr. 6, S. 675–678

DY 15.12 Mon 18:15 ZEU/0114

Forecasting Extreme Events in Atmospheric Turbulence — •Finn Köhne and Joachim Peinke — Institute of Physics and ForWind, University of Oldenburg, Küpkersweg 70, D-26129 Oldenburg, Germany

Extreme wind speed fluctuations on time scales of seconds to minutes generate potentially significant mechanical loads for example on wind turbines and may lead to strong fluctuations in the power output [1,2].

Reliable short-term forecasts of such turbulent events are therefore of high relevance for many applications.

In this contribution, we use a stochastic framework based on the Fokker-Planck-equation (FPE) to forecast wind speed fluctuations in the atmospheric turbulence. We estimate drift and diffusion from measurement data to derive FPEs that describe the probabilistic evolution of wind speed increments without requiring data normalization [3].

The resulting model is used to perform probabilistic forecasts for extreme wind speed fluctuations. The quality of the forecast is quantified using receiver operating characteristic curves. The results demonstrate that the Fokker-Planck-based approach provides reliable short-term predictions of extreme events in the atmospheric turbulence.

[1] Davenport, A. G.; Proc. Inst. Civ. Eng. 19 (1961), Nr. 4, S. 449-472.

[2] DeMarco, A.; Basu, S.; Wind Energy 21 (2018), Nr. 10, S. 892-905.

[3] Peinke, J.; Tabar, M. R. R.; Wächter, M.; Annu. Rev. Condens. Matter Phys. 10 (2019), S. 107-132.