Nonlinear Dynamics, Chaos, and Theoretical Brain Research

Complex systems typically exhibit nonlinearities in their equations of motion; the field of nonlinear dynamics offers the mathematical basis for their investigation, e.g., for one of the most complex systems we know, the network of interacting nerve cells in our brains. Here, one of our goals is to understand their collective dynamics, which forms the essence of brain function. As ground-breaking experimental progress, e.g. based on multiphoton imaging, now promises the observation of large brain networks at work in cognitive tasks, it is a challenging and promising endeavor for theoreticians to model this nonlinear many-body system in order to unravel brain function. More generally, our research led by Theo Geisel, Ragnar Fleischmann, and Viola Priesemann focuses on modelling a broad range of nonlinear dynamical systems in physics and biology, from theoretical brain research to chaotic transport in nanostructures and wave propagation in complex media.

Quantum dynamics and wave propagation in complex media

The interplay of nonlinear dynamics and wave propagation is a rich area of complex phenomena. Reaching back to the very beginnings of nonlinear science and computational physics in the celebrated Fermi-Pasta-Ulam computer experiment on the statistical physics of heat transport, this area of physics became prominent in the field of quantum chaos. Its implications are now subject of research in many fundamental and applied sciences, from atom-optics to oceanography.

The phenomena we address in our own research reach from the chaotic motion of ballistic electrons in graphene, to the dynamics of Bose-Einstein condensates in optical lattices and to the occurrence of extreme events in wave propagation through complex media.
Complex media due to their internal structure can often be described as random fields with spatial correlations. When waves are weakly scattered by such a medium, the weak but

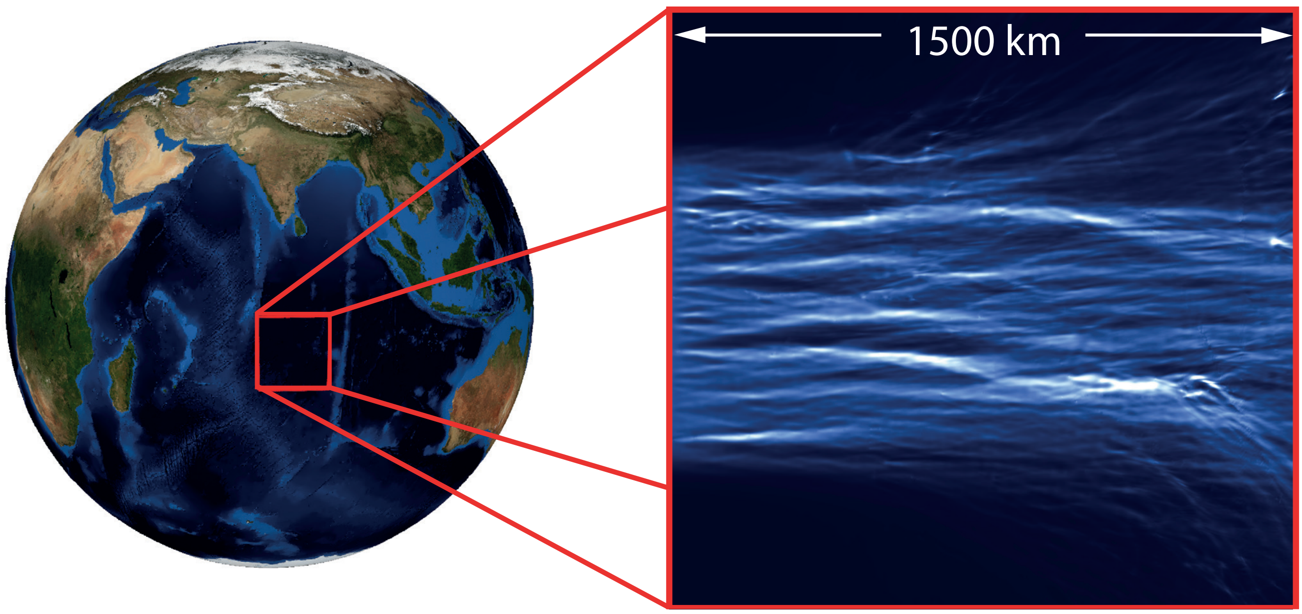

Fig. 1: The simulation of a tsunami wave in a region of the Indian Ocean where the ocean depth variations have a standard deviation of only less than 7% reveals the strong impact of branching on tsunami propagation [1].

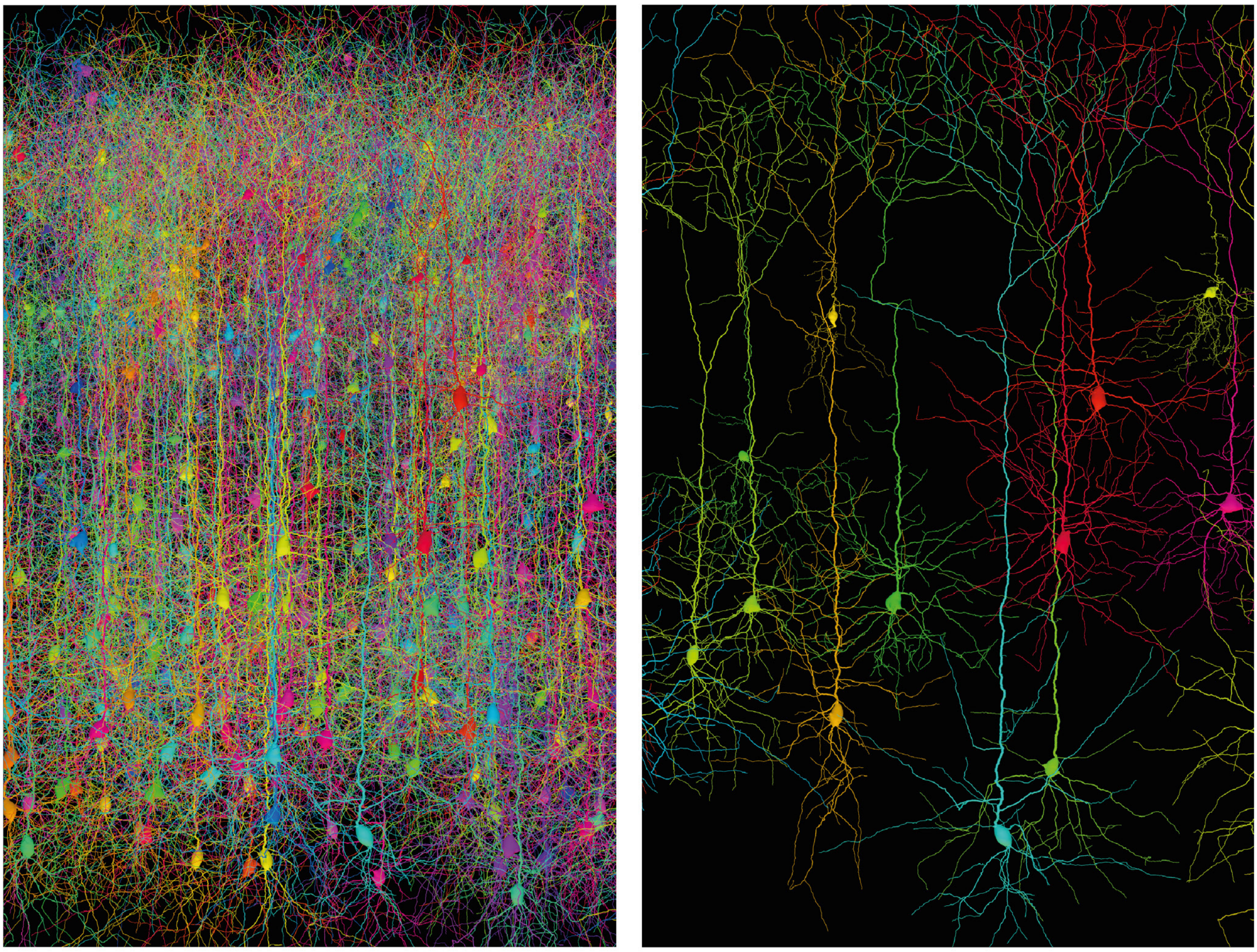

Fig. 2: The collective dynamics of the network of interacting nerve cells in our brains forms the basis of brain function and provides formidable challenges for innovative theoretical research. When recording activity from a brain area (left), we are constrained to sampling a fraction of the neurons (right). We are developing approaches for inferring the collective dynamics despite this subsampling constraint (figure generated using TREES toolbox by H. Cuntz).

correlated random forces conspire with nonlinear dynamics and diffraction to cause waves of extreme height or intensity in characteristic branch-like spatial structures [2]. This phenomenon can cause unexpected conductance features in semiconductors as well as giant "rogue waves" at sea. And even tiny fluctuations in the height-profile of the ocean floor can scatter tsunami waves and focus their energy by an order of magnitude (see Fig.1), with severe consequences for tsunami predictability. This line of our research is complemented by our studies on the intrinsic localization of nonlinear waves, e.g. of Bose-Einstein condensates in leaky optical lattices, which also leads to extreme events albeit by very different mechanisms.

Neural Dynamics and Information Processing

Studying the human brain, one is faced with a complex network of 80 billion neurons, each of them interacting with thousands of other neurons by means of action potentials, short electrical pulses. In our research at the Institute for Nonlinear Dynamics and the Max Planck Institute for Dynamics and Self-Organization we address three major questions: What is the collective dynamics of the interacting neural network? How does this network give rise to information processing and thus to our cognitive abilities? And how can we infer these properties from neural recordings, if we can assess the activity of only a fraction of all neurons?

We investigate these questions building on approaches from statistical physics and information theory. In collaboration with experimentalists from the Hôpital Salpetrière in Paris we recently showed that the human brain can exhibit collective dynamics close to a "critical state", as in a 2nd order phase transtition [3,5]. This state appears functionally particularly versatile for brain function, because in models it has been found to maximize information processing capacity. To precisely infer the properties of collective dynamics from neural recordings, we are deriving mathematical approaches that allow to infer the collective dynamics from only a small subset of all neurons (subsampling). This approach for the first time formalizes the inference of system dynamics from observations that are limited to a small fraction of units, and is thus relevant not only for brain research, but also for infering system properties from sparsely sampled networks in general.

Human Dynamics and Neural Mechanisms of Timing

Human dynamics is a new branch of statistical physics, which aims to understand statistical properties of human behavior as expressed e.g. in inter-event times and waiting time distributions. This is particularly important for the modeling and forecast of the spreading of epidemics, where re-

liable statistics of human traveling behavior is required. In a seminal study [6], we have used banknotes (dollar bills) as a proxy for human travel and determined e.g. an inverse power law for the traveling distances. More recently we have investigated the nature of temporal fluctuations in performed musical rhythms (Fig. 3). We found that these fluctuations exhibit long-range correlations, i.e., a small rhythmic fluctuation at some point in time still influences rhythmic fluctuations after tens of seconds [4]. Our findings have led to patents for the so-called humanizing of computer-generated musical sequences.

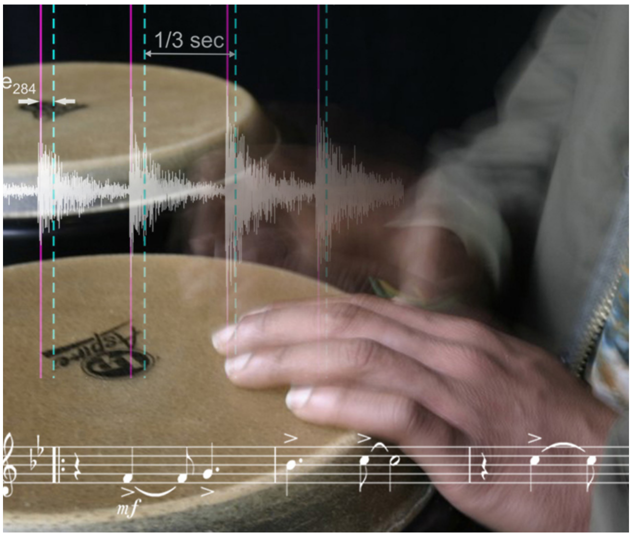

Fig. 3: We aim to characterize the nature of temporal fluctuations in musical performances and the neuronal mechanisms underlying musical timing.

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[2] J. J. Metzger, R. Fleischmann, and T. Geisel, "Statistics of Extreme Waves in Random Media," Phys. Rev. Lett. 112(20), 203903 (2014).

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Fig. 4: Some of the problems we address require extensive computing power. For that purpose our group operates dedicated high-performance computing platforms with approximately 10,000 CPU cores.

Theo Geisel

Theo Geisel studied physics and mathematics at the Universities of Frankfurt and Regensburg. Following postdoctoral research at the Max Planck Institute for Solid State Research and the Xerox Palo Alto Research Center he was Heisenberg Fellow of the DFG. In 1988 he was appointed Professor of Theoretical Physics at the University of Würzburg, in 1989 at the University of Frankfurt. Since 1996 he is Professor of Theoretical Physics at the University of Göttingen and Director at the Max Planck Institute for Dynamics and Self-Organization, where he founded the Bernstein Center for Computational Neuroscience in 2005. Theo Geisel is editorial board member of Physical Review X, Fellow of the American Physical Society, and recipient of the Gottfried Wilhelm Leibniz Prize (1994) and the Gentner-Kastler Prize (2009) of the Deutsche Physikalische Gesellschaft and the Société Française de Physique.