DY 36: Focus: Chaos and Correlation in Quantum Matter (joint session DY/TT)

The irreversibility of dynamics of complex systems ("emergent arrow of time") has been a point of controversy lasting over a century. At its heart lies the seeming contradiction between the intrinsic reversibility of the microscopic laws of nature and the manifestly time-irreversible behavior of macroscopic phenomena. Chaos plays a crucial role in resolving this paradox. The past decade has seen a great revival of interest in this question concerning the foundations of quantum statistical mechanics and how chaos arises in quantum manybody systems. It has been driven by theoretical findings involving the long sought demonstration that many-body localization (MBL) exists as well as the derivation of exact bounds on chaos. On the experimental side, significant advances have been made in the study of cold atomic gases which provide examples of closed macroscopic quantum systems for which the foundational questions of quantum statistical mechanics are especially relevant. The focus session will summarize recent advances in this very active field of studies.

Coordinators: Frank Pollmann, David Luitz

Time: Wednesday 9:30–12:15 Location: EB 107

Invited Talk DY 36.1 Wed 9:30 EB 107

Computing quantum thermalization dynamics: from quantum chaos to emergent hydrodynamics — •Ehud Altman — Department of Physics, University of California, Berkeley, CA 94720

Computing the dynamics of strongly interacting quantum systems presents a fundamental challenge due to the growth of entanglement entropy in time. In the first part of the talk I will describe a new approach that overcomes this obstruction and captures chaotic dynamics and emergent hydrodynamic transport of quantum systems. Our scheme utilizes the time dependent variational principle with matrix product states to truncate "non-useful" entanglement, while retaining crucial information on local observables. In the second part of the talk I will offer a new viewpoint on the relation between quantum and classical chaos in many body systems, using a classical version of the Sachdev-Ye-Kitaev model as an example. Chaos in this model can be understood as arising from diverging geodesics on a SO(N) manifold equipped with a random metric with locally negative curvature. The quantum bound on chaos arises from a *chaotic mobility edge* in the classical Lyapunov spectrum, separating the lower part of the spectrum for which a classical chaos picture applies from the higher part of the spectrum for which quantum interference effects are strong enough to kill classical chaos. This edge corresponds to a curvature scale of the order of the de Broglie wavelength.

DY 36.2 Wed 10:00 EB 107

Hydrodynamics of operator spreading from random circuits — •Tibor Rakovszky[1], Curt von Keyserlingk[2], Shivaji Sondhi[3], and Frank Pollmann[1] — [1]Department of Physics, T42, Technische Universität München, James-Franck-Straße 1, D-85748 Garching, Germany — [2]University of Birmingham, School of Physics & Astronomy, B15 2TT, UK — [3]Department of Physics, Princeton University, Princeton, New Jersey 08544, USA

In this talk we use random local unitary circuits to gain insight into the scrambling of quantum information in many-body systems. For a circuit with no conserved quantities we show that the average spreading of operators obeys an exact "hydrodynamic" description, in terms of a biased diffusion equation, and discuss the consequences for out-of-time ordered correlators (OTOCs) and entanglement growth. We conjecture that a similar effective description should hold in more generic ergodic systems, a claim supported by numerical results. Furthermore, we consider random circuits with a U(1) symmetry and discuss the interplay between the hydrodynamics of the conserved charge and that of operator spreading, leading to the appearance of long-time power law tails in out-of-time-ordered correlators. We also discuss the behavior of OTOCs at different chemical potentials, an analogous quantity to the finite temperature OTOCs discussed in the literature, and find that their initial spreading is slowed down when the chemical potential is large.

DY 36.3 Wed 10:15 EB 107

Out-Of-Time-Ordered Correlators in Chaotic and Critical Many-Body Systems: Path Interference and Scrambling Times — •Josef Rammensee, Benjamin Geiger, Juan Diego Urbina, and Klaus Richter — Institut für Theoretische Physik, Universität Regensburg, Germany

Out-of-time-ordered correlators $\langle[\hat{V},\hat{W}(t)]^\dagger[\hat{V},\hat{W}(t)]\rangle$ have been identified to be highly suitable tools to identify the onset of chaos in many-body quantum systems[1]. Contrary to already known indicators, the unusual time ordering of the operators is able to directly capture the local hyperbolic nature of the classical counterpart. One expects an exponential increase at short times with a rate related to classical Lyapunov exponents. Numerical studies in chaotic systems[2] indicate a saturation after the time scale for the classical-to-quantum-crossover, known as Ehrenfest or scrambling time. Our numerical studies show, that many-body criticality mimics this behaviour of chaotic systems, however with an exponent given by the local instability rate. We provide insight into the physical origin of the exponential growth and the saturation by using semiclassical methods based on the Van-Vleck-propagator for single- and many-body systems[3]. We show that the notion of interfering classical trajectories is well suited to provide a quantitative picture and we explicitly discuss the emergence of the Lyapunov exponent, resp. instability rates and the relevant time scales.

[1] J. Maldacena *et al.*, JHEP 2016:106 (2016)
[2] E. B. Rozenbaum *et al.*, PRL **118**, 086801 (2017)
[3] T. Engl, J. Dujardin, A. Argüelles *et al.*, PRL **112**, 140403 (2014)

DY 36.4 Wed 10:30 EB 107

Out of time order correlators from the time dependent variational principle — •Kevin Hemery, Frank Pollmann, and David Luitz — Department of Physics, T42, Technische Universität Muenchen, James-Franck-Strasse 1, D-85748 Garching, Germany

Out of time order correlators (OTOCs), which measure the spreading of information in quantum systems, have drawn a lot of attention recently. However, the numerical calculation of OTOCs is extremely challenging, which renders the verification of theoretical predictions difficult. We tackle this problem within the Schroedinger picture in combination with a matrix-product state formulation of the time dependent variational principle (TDVP). First, we benchmark this technique by comparing the results with exact Krylov space time evolution results for small chains. Second, we calculate the OTOCs for system sizes which are unreachable by exact methods and analyze the hydrodynamic spreading of the light cone front.

DY 36.5 Wed 10:45 EB 107

Out-of-time-ordered correlation functions in the O(N) model — •Alexander Schuckert[1] and Michael Knap[1,2] — [1]Department of Physics, Technical University of Munich, 85748 Garching, Germany — [2]Institute for Advanced Study, Technical University of Munich, 85748 Garching, Germany

In classical systems, chaos can be characterized by the sensitivity of the particles' trajectories with respect to small deviations in the initial state. An exponential growth in time then marks chaotic behavior. Recently, it has been proposed that certain out-of-time-ordered correlation functions (OTOCs) may be a suitable extension to characterize chaos in quantum many-body systems. OTOCs also probe the scrambling of quantum information across the system and thereby provide a direct connection between an information theoretic measure and chaotic dynamics. We calculate the time evolution of OTOCs in an O(N) symmetric scalar field theory at high temperatures using non-perturbative expansion techniques. Apart from the Lyapunov exponent quantifying a potential exponential growth of chaos, we are also interested in the emergent time scales of information propagation, including light-cone and butterfly velocities.

15 min. break

Invited Talk DY 36.6 Wed 11:15 EB 107

Quantum Thermalization Dynamics: From Information Scrambling to Emergent Hydrodynamics — •Michael Knap — Department of Physics and Institute for Advanced Study, Technical University of Munich, 85748 Garching, Germany

Generic, clean quantum many-body systems approach a thermal equilibrium after a long time evolution. In order to reach a global equilibrium, conserved quantities have to be transported across the whole system which is a rather slow process governed by diffusion. By contrast, the scrambling of quantum information is ballistic and hence can be characterized by a "butterfly" velocity. One way of describing the propagation of quantum information is to study out-of-time ordered (OTO) correlation functions, which are unconventional correlation functions with time arguments that are not time ordered. Using matrix-product-state based numerical simulations, we compute such correlators at high temperatures in a one-dimensional Bose-Hubbard model and in generic spin-models, where well defined quasi-particles cease to exist [1]. Finally, we will discuss ways of experimentally characterizing these unconventional OTO correlation functions in synthetic quantum matter.

[1] A. Bohrdt, C. B. Mendl, M. Endres, M. Knap, New J. Phys. 19, 063001 (2017).

DY 36.7 Wed 11:45 EB 107

Entanglement Entropy in SYK — •Renato Miguel Alves Dantas[1], Daniele Trapin[1], Paul McClarty[1], Piotr Surówka[1], and Masudul Haque[1,2] — [1]Max Planck Institute for the Physics of Complex Systems, Nothnitzer Str. 38, 01187 Dresden — [2]Department of Theoretical Physics, Maynooth University, Co. Kildare, Ireland

Eigenstates of interacting systems far from the ground state are now recognized as important for understanding non-equilibrium phenomena. We present a study of the entanglement in eigenstates of zero-dimensional fermionic models with random interactions. We consider both chaotic and integrable versions of these Sachdev-Ye-Kitaev models, respectively having quartic and quadratic couplings.

DY 36.8 Wed 12:00 EB 107

What is the right theory of transverse Anderson localization of light? — •Walter Schirmacher[1,3,4], Behnam Abaie[2], Arash Mafi[2], Giancarlo Ruocco[3,4], and Marco Leonetti[3,4] — [1]Universität Mainz — [2]Univ. New Mexico, USA — [3]Istituto Italiano di Technologia, Roma, Italy — [4]Universit'a La Sapienza, Roma, Italy

Anderson localization of light is traditionally described in analogy to electrons in a random potential. Within this description, the random potential depends on the wavelength of the incident light. For transverse Anderson localization this leads to the prediction that the distribution of localization lengths – and hence its average – strongly depends on the wavelength. In an alternative description, in terms of a spatially fluctuating electric modulus, this is not the case. Here, we report on an experimentum crucis in order to investigate the validity of the two conflicting theories using optical samples exhibiting transverse Anderson localization. We do not find any dependence of the observed average localization radii on the light wavelength. We conclude that the modulus-type description is the correct one and not the potential-type one. We corroborate this by showing that in the derivation of the traditional, potential-type theory a term in the wave equation has been tacitly neglected. In our new modulus-type theory the wave equation is exact. We check the consistency of the new theory with our data using the nonlinear sigma model. We comment on the consequences for the general case of three-dimensional disorder.