# TT 11: Focus Session: Facets of Many-Body Quantum Chaos (organised by Markus Heyl and Klaus Richter) (joint session DY/TT)

This session covers the same topics as the TT-DY-MA symposium with the same name and five invited speakers on Tuesday, September 28th.

Time: Wednesday 10:00–13:00 Location: H6

TT 11.1 Wed 10:00 H6

**Probing many-body quantum chaos with quantum simulators using randomized measurements** — Lata K Joshi[1,2], •Andreas Elben[1,2,3], Amit Vikram[4,5], Benoit Vermersch[1,2,6], Victor Galitski[4], and Peter Zoller[1,2] — [1]Center for Quantum Physics, University of Innsbruck, Innsbruck A-6020, Austria — [2]Institute for Quantum Optics and Quantum Information of the Austrian Academy of Sciences, Innsbruck A-6020, Austria — [3]Institute for Quantum Information and Matter and Walter Burke Institute for Theoretical Physics, California Institute of Technology, Pasadena, CA 91125, USA — [4]Joint Quantum Institute, University of Maryland, College Park, MD 20742, USA — [5]Condensed Matter Theory Center, Department of Physics, University of Maryland, College Park, MD 20742, USA — [6]Univ. Grenoble Alpes, CNRS, LPMMC, 38000 Grenoble, France

Randomized measurements provide a novel toolbox to probe many-body quantum chaos in quantum simulators, utilizing observables such as out-of-time ordered correlators and spectral form factors (SFFs). Here, I will focus on a protocol to access the SFF, characterizing the energy eigenvalue statistics, in quantum spin models. In addition, I will introduce partial spectral form factors (pSFFs) which refer to subsystems of the many-body system and reveal unique insights into energy eigenstate statistics. I will show that our randomized measurement protocol allows to access both, SFF and pSFFs. It provides thus a unified testbed to probe many-body quantum chaotic behavior, thermalization and many-body localization in closed quantum systems.

TT 11.2 Wed 10:15 H6

**Exploring the bound on chaos due to quantum criticality** — •Mathias Steinhuber, Juan-Diego Urbina, and Klaus Richter — University of Regensburg, Regensburg, Germany

The 'bound on chaos' proposed by Maldacena, Shenker and Stanford [1] predicts a temperature-dependent upper bound on the initial exponential growth rate $\lambda_{\mathrm{OTOC}} \leq 2\pi T$ for out-of-time-order correlators (OTOCs) in quantum systems with chaotic classical limit. We explore the temperature dependence of the quantum Lyapunov exponent $\lambda_{\mathrm{OTOC}}$ in Bose-Hubbard systems near criticality of the ground state [2]. We find the conditions for a non-trivial temperature dependence satisfying the bound, indicating the requirement that the system shows signatures of classical instability at the ground state while reaching the semiclassical regime at the same time. This is guaranteed by many-body systems with a well defined mean-field limit close to a bifurcation [3].

[1] Maldacena J., Shenker S. H. & Stanford D. A bound on chaos. Journal of High Energy Physics 2016, 106 (2016).

[2] Hummel, Q., Geiger, B., Urbina, J. D. & Richter, K. Reversible Quantum Information Spreading in Many-Body Systems near Criticality. Phys. Rev. Let. 123, 160401 (2019).

[3] Eilbeck, J., Lomdahl, P. & Scott, A. The discrete self-trapping equation. Physica D: Nonlinear Phenomena 16, 318-338 (1985).

TT 11.3 Wed 10:30 H6

**Critically slow operator dynamics in constrained many-body systems** — •Johannes Feldmeier[1,2] and Michael Knap[1,2] — [1]Technical University of Munich — [2]Munich Center for Quantum Science and Technology (MCQST)

The far-from-equilibrium dynamics of generic interacting quantum systems is characterized by a handful of universal guiding principles, among them the ballistic spreading of initially local operators. Here, we show that in certain constrained many-body systems the structure of conservation laws can cause a drastic modification of this universal behavior. As an example, we study operator growth characterized by out-of-time-order correlations (OTOCs) in a dipole-conserving fracton chain. We identify a critical point with sub-ballistically moving OTOC front, that separates a ballistic from a dynamically frozen phase. This critical point is tied to an underlying localization transition and we use its associated scaling properties to derive an effective description of the moving operator front via a biased random walk with long waiting times. We support our arguments numerically using classically simulable automaton circuits.

TT 11.4 Wed 10:45 H6

**Universal equilibration dynamics of the Sachdev-Ye-Kitaev model** — •Soumik Bandyopadhyay, Philipp Uhrich, Alessio Paviglianiti, and Philipp Hauke — INO-CNR BEC Center and Department of Physics, University of Trento, Via Sommarive 14, I-38123 Trento, Italy

The Sachdev-Ye-Kitaev (SYK) model was introduced in the context of explaining the properties of "strange metals," and has been found to manifest the characteristics of a quantum theory which is holographically dual to extremal charged black holes with two-dimensional anti-de Sitter horizons. Being maximally chaotic, black holes are the best known scramblers of quantum information in nature. Same features are shared by the SYK model, which has triggered a massive interest in its chaotic dynamics. Yet, many questions about the dynamics of the SYK model remain open. In this presentation, we shall be discussing the equilibration process of a fermionic system under the SYK Hamiltonian evolution. Our study, based on a state-of-the-art exact diagonalization method, reveals that the system exhibits an universal equilibration process. By devising a master equation for disordered systems, we successfully explain some of the key features of this dynamics. We infer the universality from the spectral analysis of the corresponding Liouvillian. We expect our findings shed light on challenging questions for systems far from equilibrium, such as, thermalization of closed and disordered quantum many-body systems.

TT 11.5 Wed 11:00 H6

**Periodic orbit sums and their relation to JT gravity correlators** — •Fabian Haneder, Torsten Weber, Camilo Moreno, Juan Diego Urbina, and Klaus Richter — University of Regensburg, Germany

Jackiw-Teitelboim (JT) gravity is a two-dimensional dilaton gravity theory originally used to describe the near-horizon physics of charged, static black holes, but has recently garnered much attention due to its exact duality to a particular double-scaled Hermitian matrix model [1]. Applications are believed to be as a toy model for the black hole information paradox, the AdS/CFT correspondence, and holography and quantum gravity more generally.

The duality with a matrix model suggests the existence of a classical chaotic system which, after semiclassical (periodic orbit) quantisation [2], leads to the same spectral correlations. Finding such a system would solve the long-standing problem of identifying a single dual, rather than an ensemble of theories, as expected from orthodox AdS/CFT.

In this contribution, we will give a very brief overview of the JT/matrix model duality and show the structural similarity of JT correlators and stochastically projected periodic orbit sums, at the level of the one-point function, as well as propose a candidate dual system.

[1] P. Saad, S. Shenker, D. Stanford, arXiv:1903.11115

[2] See e.g. M. Gutzwiller, *Chaos in classical and quantum mechanics*, Springer 2019

TT 11.6 Wed 11:15 H6

**Entanglement entropy of fractal states** — Giuseppe De Tomasi[1] and •Ivan Khaymovich[2] — [1]T.C.M. Group, Cavendish Laboratory, JJ Thomson Avenue, Cambridge CB3 0HE, United Kingdom — [2]Max Planck Institute for the Physics of Complex Systems

In this talk we will discuss the relations between entanglement (and Renyi) entropies and fractal dimensions $D_q$ of many-body wavefunctions.

As a simple example we introduce a new class of *sparse* random pure states being fractal in the corresponding computational basis and show that their entropies reach the upper bound of Page value for fractal dimension larger than the subsystem size ($D_q > 0.5$ for equipartitioning) and grow linearly with $D_q$ otherwise.

Moreover this dependence poses the upper bound for entanglement and Renyi entropies for any multifractal states and uncovers the relation between multifractality and entanglement properties of many-body wavefunctions.

**15 min. break.**

TT 11.7 Wed 11:45 H6

**Chaos for Interacting Bosons and Random Two-Body Hamiltonians** — Lukas Pausch[1], Edoardo Carnio[1,2], Andreas Buchleitner[1,2], and •Alberto Rodríguez[3] — [1]Physikalisches Institut, Albert-Ludwigs-Universität-Freiburg, Hermann-Herder-Straße 3, D-79104, Freiburg, Germany — [2]EUCOR Centre for Quantum Science and Quantum Computing, Albert-Ludwigs-Universität Freiburg, Hermann-Herder-Straße 3, D-79104, Freiburg, Germany — [3]Departamento de Física Fundamental, Universidad de Salamanca, E-37008 Salamanca, Spain

We investigate the chaotic phase of the Bose-Hubbard model [1] in relation to the bosonic embedded random-matrix ensemble, which mirrors the dominant few-body nature of many-particle interactions, and hence the Fock space sparsity of quantum many-body systems. Within the chaotic regime, mean and fluctuations of the fractal dimensions of Bose-Hubbard eigenstates show clear fingerprints of ergodicity and are well described by the embedded ensemble, which is furthermore able to capture the energy dependence of the chaotic phase. Despite such agreement, the distributions of the fractal dimensions for these two models depart from each other and from the Gaussian orthogonal ensemble as Hilbert space grows.

[1] L. Pausch et al, Phys. Rev. Lett. **126**, 150601 (2021).

TT 11.8 Wed 12:00 H6

**Orthogonal quantum many-body scars** — •Hongzheng Zhao[1], Adam Smith Smith[2], Florian Mintert[1], and Johannes Knolle[1,3,4] — [1]Blackett Laboratory, Imperial College London, London, United Kingdom — [2]School of Physics and Astronomy, University of Nottingham, University Park, Nottingham, United Kingdom — [3]Department of Physics TQM, Technical University of Munich, Munich, Germany — [4]Munich Center for Quantum Science and Technology, Munich, Germany

Quantum many-body scars have been put forward as counterexamples to the Eigenstate Thermalization Hypothesis. These atypical states are observed in a range of correlated models as long-lived oscillations of local observables in quench experiments starting from selected initial states. The long-time memory is a manifestation of quantum non-ergodicity generally linked to a sub-extensive generation of entanglement entropy, the latter of which is widely used as a diagnostic for identifying quantum many-body scars numerically as low entanglement outliers. Here we show that, by adding kinetic constraints to a fractionalized orthogonal metal, we can construct a minimal model with orthogonal quantum many-body scars leading to persistent oscillations with infinite lifetime coexisting with rapid volume-law entanglement generation. Our example provides new insights into the link between quantum ergodicity and many-body entanglement while opening new avenues for exotic non-equilibrium dynamics in strongly correlated multi-component quantum systems. Reference: https://arxiv.org/abs/2102.07672

TT 11.9 Wed 12:15 H6

**Genuine many-body quantum scarring in a periodic Bose-Hubbard ring** — •Quirin Hummel and Peter Schlagheck — Université de Liège (Belgium)

Quantum scars have been known for decades to exist in quantum systems of low dimensionality (e.g. “quantum billiards”): While most eigenstates of a classically chaotic system are typically spread across the accessible phase space, individual states exist that are concentrated along unstable classical periodic orbits. On the other hand, recent studies in many-body quantum systems that admit no known meaningful classical limits have revealed eigenstates - now termed “quantum many-body scars” - that feature quantum mechanical properties reminiscent of scenarios of quantum scarring. An unambiguous classification as scars in the original sense, however, remains controversial, if not fundamentally impossible due to the lack of a classical limit. In order to bridge this gap, we investigate the phenomenon of quantum scarring in the prototypical Bose-Hubbard model, a many-body quantum system that combines both, a well-defined formally classical description and the typical high-dimensionality of many-body systems identified with the number of sites that constitute the one-body state space.

TT 11.10 Wed 12:30 H6

**Quantum scars of bosons with correlated hopping** — •Ana Hudomal[1,2], Ivana Vasić[2], Nicolas Regnault[3,4], and Zlatko Papić[1] — [1]School of Physics and Astronomy, University of Leeds, United Kingdom — [2]Institute of Physics Belgrade, University of Belgrade, Serbia — [3]Joseph Henry Laboratories and Department of Physics, Princeton University, USA — [4]Laboratoire de Physique de l'École Normale Supérieure, ENS, CNRS, Paris, France

Recent experiments have shown that preparing an array of Rydberg atoms in a certain initial state can lead to unusually slow thermalization and persistent density oscillations [1]. This type of non-ergodic behavior has been attributed to the existence of “quantum many-body scars”, i.e., atypical eigenstates that have high overlaps with a small subset of vectors in the Hilbert space. Periodic dynamics and many-body scars are believed to originate from a “hard” kinetic constraint: due to strong interactions, no two neighbouring Rydberg atoms are both allowed to be excited. Here we propose a realization of quantum many-body scars in a 1D bosonic lattice model with a “soft” constraint: there are no restrictions on the allowed boson states, but the amplitude of a hop depends on the occupancy of the hopping site. We find that this model exhibits similar phenomenology to the Rydberg atom chain, including weakly entangled eigenstates at high energy densities and the presence of a large number of exact zero energy states [2].

[1] H. Bernien et al., Nature **551**, 579 (2017).
[2] A. Hudomal et al., Commun. Phys. **3**, 99 (2020).

TT 11.11 Wed 12:45 H6

**Quantum local random networks and the statistical robustness of quantum scars** — •Federica Maria Surace[1,2], Marcello Dalmonte[1,2], and Alessandro Silva[1] — [1]International School for Advanced Studies (SISSA), via Bonomea 265, 34136 Trieste, Italy — [2]The Abdus Salam International Centre for Theoretical Physics (ICTP), Strada Costiera 11, 34151 Trieste, Italy

We investigate the emergence of quantum scars in a general ensemble of random Hamiltonians (of which the PXP is a particular realization), that we refer to as quantum local random networks. We find two types of scars, that we call stochastic and statistical. We identify specific signatures of the localized nature of these eigenstates by analyzing a combination of indicators of quantum ergodicity and properties related to the network structure of the model. Within this parallelism, we associate the emergence of statistical scars to the presence of motifs in the network, that reflects how these are associated to links with anomalously small connectivity (as measured, e.g., by their betweenness). Most remarkably, statistical scars appear at well-defined values of energy, predicted solely on the basis of network theory. We study the scaling of the number of statistical scars with system size: below a threshold connectivity, we find that the number of statistical scars increases with system size. This allows to define the concept of statistical stability of quantum scars.