<u>REPORT:</u> Advanced Study Group (ASG)

Open quantum systems far from equilibrium

(Convenor: Prof. Dr. Dr. h.c. mult. Peter Hänggi, 2019 - 2022)
(Core members: Prof. Dr. Sergey Denisov and Prof. Dr. Dario Poletti, 2019 - 2022)

The objective of this Advanced Study Group (ASG) has been aimed at exploring the realm of open many-body quantum systems which are taken far out of equilibrium. As objects of studies, these systems are located on the interface of several, currently very active, timely research fields such as the physics of open quantum systems, many-body quantum physics, the role of heat and work within quantum thermodynamics, and, last but not least, computational quantum physics.

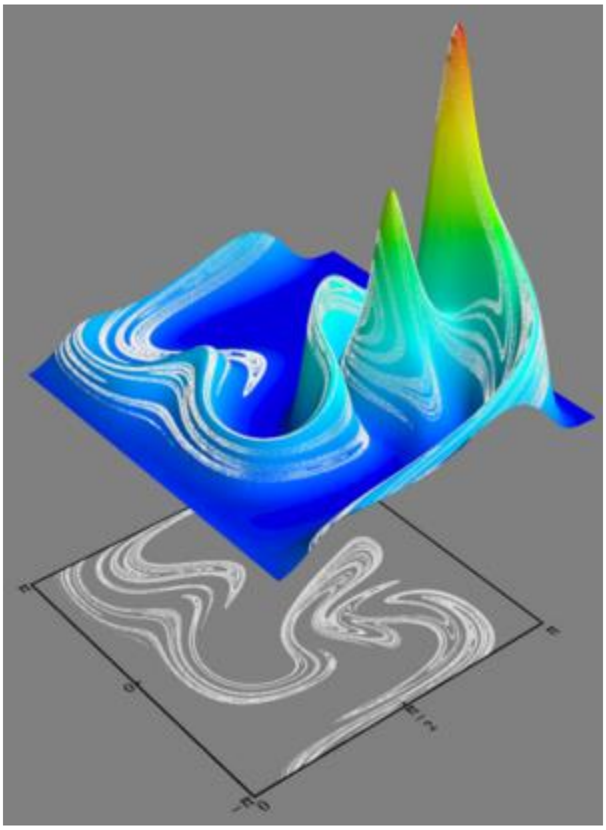
Time-periods and composition of the ASG:

The group work was organized in three consecutive stages: December 2019 - January 2020 (first stage), June-August 2021 (second stage), and December 15-Ferbruary 15 2022 (third and final stage). This ASG was been composed with the convenor *Peter Hänggi* (University of Augsburg, Germany), together with his two core members, *Sergey Denisov* (Oslo Metropolitan University, Norway) and *Dario Poletti* (Singapore University for Technology and Design).

Despite those repeatedly occurred severely obstructing impact, caused by the still ongoing COVID-19 pandemic, the group benefited from visits by other distinguished researchers and collaborators. Main visitors included Prof. Darius Chruscinski (Nicolas Copernicus University, Torun), Prof. Karol Zyczkowski and Dr. Wojciech Tarnowski (Jagellonian University, Cracow), Prof. Juzar Thingna (Center for Theoretical Physics of Complex Systems, Institute for Basic Science, South Korea), Prof. Mikhail Ivanchenko and Dr. Tetyana Laptyeva (Lobachevsky University of Nizhny Novgorod, Russia), and Dr. Alexander Schnell (TU Berlin). In addition, several MPIPKS members engaged into an active part in the group's work, among which we name Dr. David Luitz (leader of the group "Computational Quantum Many-body Physics") and Dr. Francesco Piazza (leader of the group "Strongly Correlated Light-Matter System").

Main Objectives of the ASG

In some further detail the ultimate goal of the ASG has been to explore the role of dissipation in complex (many-body) quantum systems such as the concept of quantum attractors; i.e., strongly non-equilibrium asymptotic states of open quantum dissipative systems, being subjected to (controllable) dissipation and alike the consequences for the dynamics when time-periodically perturbations are applied. A particular challenging theme of the ASG-group was to investigate manifestations of Dissipative Quantum Chaos, i.e., phenomena emerging for the dynamics of open quantum systems that operate far out of thermal equilibrium.



An example of a many body quantum system far from equilibrium we depict here the Quantum attractor (colored) versus its classical attractor (white dots); Figure adapted from M. Hartmann, D. Poletti, M. Ivanchenko, S. Denisov, and P. Hänggi, Asymptotic Floquet states of open quantum systems: the role of interaction, New J. Phys. ***19****, 083011 (2017).*

Particularly, a prime goal of the group was to investigate manifestations of Dissipative Quantum Chaos occurring for the dynamics of *many-body* open quantum systems when shifted far out of equilibrium. Knowingly, the existing well-developed theory of Quantum Chaos addresses exclusively Hamiltonian systems; i.e., for those being fully isolated from the influence of their environments. The corresponding theoretical predictions have been tested and validated, by use of either microwave billiards, ultra-cold atoms or stylized quantum electronic circuits, to name but a few. However, with the emergence of new types of real-life quantum systems, such as optomechanical systems, microwave superconductive circuits, and polaritonic devices, the Hamiltonian idealization lost much of its appeal. Particularly, the omnipresent impact of dissipation in these systems generates a full-fledged generator of time-evolution, no less complex and diverse than the unitary evolution generated by quantum Hamiltonians. Consequently, this situation calls for the challenge to delve the presumable rich and promising new physics this very type of complex quantum evolution may disclose.

Particularly, the ASG addressed the following challenges:

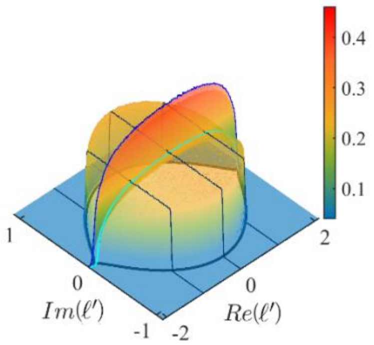
- What are the spectral signatures of Dissipative Quantum Chaos?
- Open (driven) Floquet systems: do there exist effective time-independent Lindbladians?
- Quantum thermodynamics: How to measure transport of mass and charge in open many-body systems far from equilibrium and above all how to quantify physical quantities such as quantum “work” and “heat” which formally are cannot be encoded in terms of quantum observables (but rather constitute quantum processes).

Results:

(i) Signatures of Dissipative Quantum Chaos.

Similar to conventional Quantum Chaos (QC), the notion of Dissipative Quantum Chaos (DQC) has been investigated by use those inherent spectral properties of the corresponding, non-unitary generators for the time evolution. Given this task, a strong need exists in establishing universalities, i.e., figuring out unique spectral features, being typical for those properly defined ensembles of generators.

The task in classifying the universal spectral properties has recently been accomplished by several independent groups. This in turn gave rise to a boost of research activities on the DQC topics. A paper on the notion of an ensemble of random Lindblad operators was published by the group’s members in October 2019 [S. Denisov, T. Laptyeva, W. Tarnowski, D. Chruściński, and K. Życzkowski, Phys. Rev. Lett. 123, 140403 (2019).]. Since then, a number of follow-up studies on spectral aspects of random Lindblad operators, containing different types of randomness, have been published. Quite recently, spectral properties of random Lindbladians, on which some additional constrains were imposed, were studied experimentally on the IBM Quantum Experience platform [O. E. Sommer, F. Piazza and D. J. Luitz, Phys. Rev. Research 3, 023190 (2021)].



In own work [1], we generalized the idea of random Lindbaldians further. We presented the concept of super-decoherece, i.e., a decoherence acting on the level of generators of dissipative quantum evolutions. We demonstrated that “superdecoherence” bridges, in a continuous way, Lindblad operators (generators of quantum open evolution) and their classical counterparts, Kolmogorov operators (generators of time-continuous Markovian evolution). We addressed random ensembles of generators, both quantum and classical, evaluated their spectral properties [*note the left-sided figure above, depicting the complex-valued spectral distribution of random Linbladians*], and demonstrated that the two ensembles are related by superdecoherence. We also defined a procedure of “coherefication” which allows crossing the bridge in the opposite directions, i.e. to obtain a Lindblad operator from a Kolmogorov one. Finally, we addressed the so-called

Complex Spacing Ratio measure, which is generalization of a measure used to quantify the degree of chaos in Hamiltonian systems.

In Ref. [2] we considered another quantifier of DQC. By unravelling the Lindblad equation describing an open quantum Kerr-nonlinear cavity, periodically modulated in time by coherent pumping of the intracavity photonic mode, into an ensemble of quantum trajectories and employing the recently proposed quantum Lyapunov exponents [I. I. Yusipov *et al.*, Chaos 29, 063130 (2019)], we identified “chaotic” and “regular” regimes . In particular, we showed that chaotic regimes manifest an intermediate asymptotic power-law in the distribution of photon waiting times. This distribution can be measured explicitly upon monitoring the photon emission with a single-photon detector.

(ii) Open Floquet systems

Here we moved along two directions: *Are there Floquet Lindbladians?* We investigated open quantum systems being subjected to a periodically varying perturbation in time. In other words, the corresponding Hamiltonian is a time-periodic Hermitian operator. The dynamics of such system at weak coupling is governed by a Lindblad equation, possessing a time-periodic generator. -- Would it be possible to construct *time-independen*t Lindblad generator (which we termed “Floquet Lindladian”) yielding at stroboscopic instants of times, T, 2T, 3T, ... , the same states of the system as in the case of original time-dependent generator? The answer is always a “yes” in the Hamiltonian limit; this is, however, no longer so when the system is open. In fact, as we demonstrated [3] with a simple driven qubit model, the Floquet Lindbladian does not exist in the most interesting case when the driving is neither diabatic nor adiabatic.

With our consecutive work [4] we advanced further along this line and explicitly demonstrated that different high-frequency expansions, used in recent works as a tool to construct effective Floquet-Lindbladians are -- in fact -- ill-suited for this task. Correspondingly, the outcome of the study does not provide a firm basis in order to judge the existence of an effective stroboscopic generator. Nevertheless, we demonstrated that a proper Floquet Lindbladian can be derived from a high-frequency expansion when treating the problem within a suitably chosen rotating frame.

(iii) Spectral characteristics of Dissipative Quantum Chaos in Floquet-Markov systems.

Novel universal features emerged together with new concepts, such as the “Complex Spacing Ration”. These findings resulted upon investigating the Lindblad framework (as discussed above). However, stationary Lindblad generators do not provide a straightforward way to model the semi-classical chaotic regime; therefore, it is seemingly difficult to relate an open quantum dynamics to a dissipative classical dynamics exhibiting chaotic dynamics.

We next considered another type of generator of dissipative quantum evolution, the so-called Redfield generators, which emerge in the Floquet-Markov theory and in turn allow for a semi-classical transition [5]. We used a quantum version of the driven Duffing oscillator as a model to illustrate spectral properties of Redfield generators. Our two main findings here are the following: First, the notion of a random generator alike can be generalized to those being of Redfield-form. Second, Complex Spacing Ratios (CSR) of the generator exhibits Poisson statistics (typical to integrable Lindblad generators) in the chaotic regime, whereas for the regular regime it yields the horseshoe structure (typical to 'chaotic' Lindbladians). In other words, the behaviour becomes reversed when compared to the case of non-random Lindbladians. We attribute this to the fact that the chaotic behaviour of Floquet-Markov systems are encoded within coherent Floquet states of the corresponding Hamiltonians.

(iv) Transport in open many-body systems far from equilibrium.

Combinations of many-body effects, openness, and strong deviation from equilibrium can lead to transport regimes, which, however, are not accessible in the near-equilibrium limit. In Ref. [6], we explored spin transport in an open XXZ chain with strong interaction strength and we demonstrated that the transport features in this system are significantly suppressed, as the bias of the dissipative driving grows large enough. We also detected the regime of negative differential conductance caused by the formation of two oppositely polarized ferromagnetic domains at the edges of the chain. Thus, we demonstrated that this many-body effect, combined with a non-uniform magnetic field, allows for a high degree of control for the spin current.

Workshop "Openness as a resource"

An international workshop, entitled:
"Openness as a resource: Accessing new quantum states with dissipation" took place during the last term of the ASG at the MPI-PKS from January 31 – February 04, 2022. -- A full detailed report of this workshop is available on the web under the link:

https://www.pks.mpg.de/de/openq21/scientific-report

This workshop has been dated towards the end of the 3-rd term so as to crown the various activities addressed by the ASG. The workshop participants represented three different scientific communities: Researchers working on mathematical aspects of open quantum systems that make use of Lindblad generators, semi-groups, and quantum Monte-Carlo methods, their colleagues from the field of quantum thermodynamics. Additionally, theoreticians and experimentalists dealing with circuit-QED and solid-state based quantum systems have attended as well, including a very few topics that were somewhat off-topic although nevertheless quite inspiring.

References:

[1] W. Tarnowski, I. Yusipov, T. Laptyeva, S. Denisov, D. Chruściński, and K. Życzkowski *Random generators of Markovian evolution: A quantum-classical transition by superdecoherence*, Phys. Rev. E **104**, 034118 (2021).

[2] I. Yusipov, O. S. Vershinina, S. V. Denisov, and M. V. Ivanchenko, *Photon waiting-time distributions: A keyhole into dissipative quantum chaos*, Chaos **30**, 023107 (2020).
[3] A. Schnell, A. Eckardt, S. Denisov, *Is there a Floquet Lindbladian?* Phys. Rev. B **101**, 10030 (2020).
[4] A. Schnell, S. Denisov, A. Eckardt, *High-frequency expansions for time-periodic Lindblad generators* Phys. Rev. B **104**, 165414 (2021).
[5] J. Thingna. E. Kozinov, P. Hänggi, and S. Denisov, *Dissipative Quantum Chaos in Floquet systems*, in preparation.
[6] Kang Hao Lee , V. Balachandran, R. Tan , Chu Guo, and D. Poletti, *Giant spin current rectification due to the interplay of negative differential conductance and a non-uniform magnetic field*, Entropy **22**, 1311 (2020).