Modern Developments in Quantum Chaos

753. WE-Heraeus-Seminar

20 – 24 September 2021
hybrid at the Physikzentrum Bad Honnef, Germany

Dedicated to the memory of Fritz Haake and Petr Braun

WILHELM UND ELSE HERAEUS-STIFTUNG

Introduction

The Wilhelm und Else Heraeus-Stiftung is a private foundation that supports research and education in science with an emphasis on physics. It is recognized as Germany's most important private institution funding physics. Some of the activities of the foundation are carried out in close cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft). For detailed information see https://www.we-heraeus-stiftung.de

Aims and scope of the 753. WE-Heraeus-Seminar:

Quantum chaos is a central research topic of modern quantum physics. It lies at the heart of the description of complex quantum systems, as encountered in atomic and nuclear physics, quantum optics, the phase-coherent dynamics of electrons and photons in condensed-matter systems including topological materials, as well as complex many-body systems, ranging from atoms and nuclei over spin chains to such as stipulated for quantum models of black holes. Conceptually, it provides the framework for unifying descriptions of such settings, and ties these to deep questions such as ergodicity and universality..

In this workshop, we explore the rapid advancements in this field to emphasize the contributions of one of its main proponents, the late Prof. Fritz Haake, who shaped it from its very beginnings. The workshop will address problems and applications at the forefront of diverse current research directions such as quantum and atom optics, topological materials, and many-body physics. The audience combines some of his former collaborators and students, who now are main drivers of these directions, with a diverse set of younger researchers working in these fields.

Scientific Organizers:

Prof. Sven Gnutzmann	University of Nottingham, UK E-mail: sven.gnutzmann@nottingham.ac.uk
Prof. Thomas Guhr	University of Duisburg-Essen, Germany E-mail: thomas.guhr@uni-due.de
Prof. Henning Schomerus	Lancaster University, UK E-mail: h.schomerus@lancaster.ac.uk
Prof. Karol Życzkowski	Jagiellonian University, Kraków and Polish Academy of Sciences Warszawa, Poland E-Mail: karol.zyczkowski@uj.edu.pl

Introduction

Administrative Organization:

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Registration:

Elisabeth Nowotka (WE Heraeus Foundation)
at the Physikzentrum, reception office
Sunday (17:00 h – 21:00 h) and Monday
morning

Program (CET times)

Sunday, 19 September 2021

17:00 – 20:00	Registration	
18:00	*BUFFET SUPPER and get-together*	

Monday, 20 September 2021

07:30	*BREAKFAST*	
08:45 – 08:55	Karol Życzkowski (on site)	**Opening remarks**
09:00 – 09:30	Klaus Richter (on site)	**Along Fritz' and Petr's semiclassical paths: Classical orbit correlations and many-body quantum chaos**
09:35 – 10:05	Roland Ketzmerick (on site)	**Classical and quantum transport: New phenomena in higher dimensions**
10:10– 10:40	Kazimierz Rzążewski (online)	**Fluctuations of Bose-Einstein condensate**
10:40 – 11:10	COFFEE BREAK	
11:10 – 11:40	Carlo Beenakker (online)	**Simulation of chaotic Dirac fermions on a lattice**
11:45 – 12:15	Boris Gutkin (on site)	**Many body quantum chaos in coupled cat maps**
12:20 – 12:50	Thomas Dittrich (on site)	**Quantum measurement and quantum randomness with finite heat baths**
13:00	*LUNCH*	

Program (CET times)

Monday, 20 September 2021

15:00 – 16:00	**Networking and discussion (online) with** *COFFEE*	
16:00 – 16:30	Alexander Altland (on site)	**Holographic interpretation of SYK quantum chaos**
16:35 – 17:05	Mark Srednicki (online)	**Bounds on out-of-time-order correlators from the eigenstate thermalization hypothesis**
17:10 – 17:40	Stephen Shenker (online)	**Quantum gravity and quantum chaos**
18:00 – 19:30	*DINNER*	
19:30 – 21:00	**Poster session (on site)**	

Program (CET times)

Tuesday, 21 September 2021

08:00	*BREAKFAST*	
09:00 – 09:30	Marek Kuś (online)	**Kicked top revisited**
09:35 – 10:05	Eva-Maria Graefe (on site)	**A non-Hermitian PT-symmetric kicked top**
10:10 – 10:40	Daniel Braun (on site)	**Quantum-chaotic sensors**
10:40 – 11:10	*COFFEE BREAK*	
11:10 – 11:40	Hans-Jürgen Stöckmann (on site)	**A microwave realization of the chiral ensembles**
11:45 – 12:15	Martina Hentschel (on site)	**Quantum chaos from Möbius systems to mesoscopic optics**
12:20 – 12:50	Barbara Dietz (online)	**Spectral properties of relativistic quantum billiards with shapes of integrable billiards**
13:00	*LUNCH*	
15:00 – 16:00	**Networking and discussion (online) with** *COFFEE*	
16:00 – 16:30	Steven Tomsovic (online)	**Post-Ehrenfest many-body quantum interferences in ultracold atoms**
16:35 – 17:05	Hui Cao (online)	**Fighting laser chaos with wave chaos**
17:10 – 17:40	Carlos Viviescas (online)	**Initial and final value for the semiclassical evolution of the Wigner function**
18:00 – 19:30	*DINNER*	
19:30 – 21:00	**Poster flash talks followed by the poster session (online, including poster which are on site)**	

Program (CET times)

Wednesday, 22 September 2021

08:00	*BREAKFAST*	
09:00 – 09:30	Uzy Smilansky (online)	**Can one hear a real symmetric matrix?**
09:35 – 10:05	Martin Zirnbauer (on site)	**Color-flavor transformation revisited**
10:10 – 10:40	Tomaž Prosen (on site)	**Exactly solved models of many–body quantum chaos**
10:40 – 11:10	*COFFEE BREAK*	
11:10 – 11:40	Hans Weidenmüller (on site)	**Tests of the Porter-Thomas distribution for reduced partial neutron widths**
11:45 – 12:15	Yan V. Fyodorov (online)	**Statistics of S-matrix poles: from Haake et al 1992 paper to the present day**
12:20 – 12:50	Dmitry Savin (on site)	**Diffusive field cross-correlations in complex media**
12:55 – 13:10	Stefan Jorda (on site)	**About the WE-Heraeus-Foundation**
13:10	*LUNCH*	
15:00 – 16:00	**Networking and discussion (partially online) with** *COFFEE*	

Program (CET times)

Wednesday, 22 September 2021

Celebration in honour of Fritz Haake

(chair: Sven Gnutzmann and Henning Schomerus, both on site)

16:00 – 16:50	Maciej Lewenstein (on site)	**Fritz' legacy revisited**
	Sharing memories of Fritz Haake	
17:00 – 17:10	Michael Berry (online)	
17:10 – 17:20	Kazimierz Rzążewski (online)	
17:20 – 17:30	Christine Benard (online)	
17:30 – 17:40	Bruno Lix (on site)	
17:40 – 17:50	Jean-Pierre Ressayre (on site)	
17:50 – 18:00	Karol Życzkowski (on site)	
18:00 – 18:10	Julia Haake (on site)	
18:10 – 18:20	Voices from the floor	
18:30 – 18:45	Reception	
18:45	*HERAEUS DINNER* *(social event with cold & warm buffet with complimentary drinks)*	

Program (CET times)

Thursday, 23 September 2021

08:00	*BREAKFAST*	
09:00 – 09:30	Eugene Bogomolny (on site)	**Barrier billiard and random matrices**
09:35 – 10:05	Nina Snaith (on site)	**Averages of secular coefficients**
10:10 – 10:40	Pragya Shukla (online)	**Quantum metric statistics for random-matrix families**
10:40 – 11:10	*COFFEE BREAK*	
11:10 – 11:40	Stefan Heusler (online)	**Encounters with Fritz and Petr**
11:45– 12:15	Gregor Tanner (on site)	**Sound radiation from vibrating plates – a classical phase space approach**
12:20 – 12:50	Martin Sieber (on site)	**Propagating correlation functions by ray methods with diffractive contributions**
13:00	*LUNCH* followed directly by a walk through the nearby forest	
16:40 – 17:10	*COFFEE BREAK*	
17:10 – 17:40	A. Douglas Stone (online)	**Controlling transmission of light using mesoscopic correlations**
17:45 – 18:15	Sandra Prado online)	**Wavefunctions extreme intensities: from chaotic to regular quantum maps**
18:20 – 18:50	Predrag Cvitanović (online)	**Amazing! I did not understand a single word**
19:00 – 21:00	*DINNER*	

Program (CET times)

Friday, 24 September 2021

08:00	*BREAKFAST*	
09:00 – 09:30	Jan Mostowski (online)	**In search of the classical limit**
09:35 – 10:05	Sonja Barkhofen (on site)	**Increasing levels of quantumness in quantum walks**
10:10 – 10:40	Kouichi Hagino (online)	**Transition-state dynamics in complex quantum systems**
10:40 – 11:10	*COFFEE BREAK*	
11:10 – 11:40	Alessandro Romito (online)	**Entanglement transition from stroboscopic to continuous measurements**
11:45– 12:15	Lukas Pausch (on site)	**Chaos in the Bose-Hubbard model versus Gaussian orthogonal and embedded random matrix ensembles**
12:20 – 12:50	Sebastian Müller (on site)	**Semiclassics and higher-order correlation functions for chaotic systems**
12:55 – 13:00	Thomas Guhr (on site)	**Concluding remarks**
13:00	*LUNCH*	

End of the seminar and departure

NO DINNER for participants leaving on Saturday morning

Posters

Posters

Christian Chen	**Fock-space geometry and strong correlations in many-body localized systems**
Felix Fritzsch	**Eigenstate thermalization in dual-unitary quantum circuits: Spectral functions and decay of correlations**
Tabea Herrmann	**Entanglement in coupled kicked tops with chaotic dynamics**
Tara Kalsi	**Entanglement dynamics in different universality classes**
Maximilian Kieler	**Enhanced state transfer by complex instability in coupled kicked tops**
Pavel Kos	**Thermalisation dynamics and spectral statistics of extended systems with thermalising boundaries**
Julius Kullig	**Brewster-notched microcavities: Billiards without reflections**
Damian Kwiatkowski	**A programmable spin-based quantum simulator in diamond for quantum chaos and diffusion**
Ángel L. Corps	**Chaos in a broken-parity Dicke model**
Domenico Lippolis	**Scarring in open chaotic systems: The local density of states**
Manuel Muñoz-Arias Pablo Poggi	**Quantum chaos and complex dynamics in driven collective spin systems: from the kicked top to the kicked p-spin models**
Jethin Pulikkottil Jacob	**Entanglement production by interaction quenches of quantum chaotic subsystems**
Martin Richter	**Transfer operator methods for modelling high-frequency wave fields**

Posters

Lucas Sá	**The Sachdev-Ye-Kitaev Lindbladian and dissipative quantum chaos**
Sk Sazim	**The aging Harmonic oscillators and beyond**
Jan Robert Schmidt	**Drift-induced delocalization transition in resonance channels**
Jonas Stoeber	**Quantum signatures of partial barriers in 4D symplectic maps**
Marcin Szyniszewski	**Measurement-induced criticality in Clifford circuits and relation to percolation**

Abstracts of Talks

(in alphabetical order)

Holographic interpretation of SYK quantum chaos

Alexander Altland

Universität zu Köln, Institut für Theoretische Physik, Germany

Since its introduction in 2015, the SYK model has been intensively researched, and at this point is the perhaps best understood model system of many body quantum chaos. However, when Kitaev first proposed the model, his motivation was to define the boundary theory of a two-to-one dimensional holographic correspondence. In this talk, we will address the question what the lessons learned about the SYK system teach us about the nature of candidate bulk theories. Looking at the problem through the lens of quantum chaos, we will argue that perturbative studies inspired by periodic orbit analysis go a long way, but not all of it, in identifying the gravitational bulk. The solution of the problem might lie in a symmetry breaking principle — realized in all universality classes of quantum chaos, but not so far in the proposed bulk duals. We will suggest that this symmetry breaking must be present in bulk duals of chaotic boundary theories, and that the search for it might turn into a creative resource.

Increasing levels of quantumness in quantum walks

S. Barkhofen[1*], T. Nitsche[1], S. De[1], E. Meyer-Scott[1], J. Tiedau[1], J. Sperling[1], B. Brecht[1], I. Dhand[3], M. Plenio[3], A. Gábris[2], I. Jex[2], C. Silberhorn[1]

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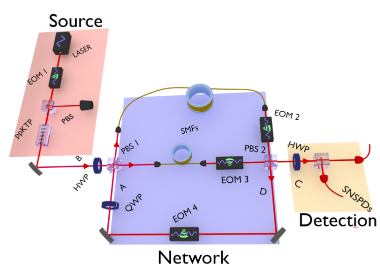
[2]*Department of Physics, Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Břehová 7, 11519 Prague, Czech Republic*

[3]*Institut für Theoretische Physik and Center for Integrated Quantum Science and Technology (IQST), University of Ulm, 89069 Ulm, Germany*

[*]*Sonja.Barkhofen@uni-paderborn.de*

Quantum walks constitute the quantum analogue of classical random walks and describe the dynamics of quantum particles in a discretized environment. Usually "quantum" in this context refers to the superposition principle describing a walker taking all possible paths simultaneously. Consequently, one observes interference and the final probability distribution looks very much different from the classically expected binomial shape. Various experimental implementations, e.g. based on time-multiplexing techniques, are successfully applied to demonstrate quantum walks with disorder [1] and topological effects [2]. However in many of these experiments, coherent light represents the walker. Such input states constitute the basis for classical optics and thus it is often questioned how quantum such implementations are.



Setup scheme of a time-multiplexed quantum walk with an external quantum source

By initializing the walk with two single photons, we are able to study many-particle interference with genuine quantum states in the quantum walk network [3] which can be viewed as a generalization of the Hong-Ou-Mandel interference. As an outlook, we present a new time-multiplexing setup which was originally used to generate Fock states [4]. Here, the source of the quantum states is placed within the network and realizes a truly quantum gain during the evolution of the walker.

References

1. A. Geraldi et al. "Transient subdiffusion via disordered quantum walks." Physical Review Research **3**, 023052, (2021).
2. D. Bagrets et al. "Probing the topological Anderson transition with quantum walks." Physical Review Research **3**, 023183 (2021).
3. T. Nitsche et al. "Local versus global two-photon interference in quantum networks," Physical Review Letters **125**, 213604 (2020).
4. M. Engelkemeier et al. "Climbing the Fock ladder: Advancing multiphoton state generation." arXiv preprint arXiv:2105.03720 (2021).

Simulation of chaotic Dirac fermions on a lattice

Carlo Beenakker

Leiden University, Lorentz Institute, Leiden, The Netherlands

The spatial discretization of the single-cone Dirac Hamiltonian on the surface of a topological insulator or superconductor needs a special "staggered" grid, to avoid the appearance of a spurious second cone in the Brillouin zone. We adapt the Stacey discretization from lattice gauge theory to produce a generalized eigenvalue problem, with Hermitian tight-binding operators, a locally conserved particle current, and preserved chiral and symplectic symmetries. This permits the study of the spectral statistics of chaotic Dirac fermions in each of the four symmetry classes A, AII, AIII, and D.

Barrier billiard and random matrices

Eugene Bogomolny

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The barrier billiard is the simplest example of pseudo-integrable models with interesting and intricate classical and quantum properties. Using the Wiener-Hopf method it is demonstrated that quantum mechanics of a rectangular billiard with a barrier in the centre can be reduced to the investigation of a certain unitary matrix. Under heuristic assumptions this matrix is substituted by a special low-complexity random unitary matrix of independent interest. The main results of the talk are (i) spectral statistics of such billiards is insensitive to the barrier height and (ii) it is well described by the semi-Poisson distributions.

References

[1] E.Bogomolny, arXiv:2107.03364 (2021).

Quantum-Chaotic Sensors

Lukas J. Fiderer[1,2], Jonas Schuff [1,3], and Daniel Braun[1]

[1] *Institut für Theoretische Physik, Universität Tübingen, Germany*
[2] *Institut für Theoretische Physik, Universität Innsbruck, Austria*
[3] *University Oxford, UK*

Quantum metrology has concentrated almost exclusively on using integrable systems as sensors, such as precessing spins or harmonic oscillators prepared in non-classical states. Here we show that large benefits can be drawn from rendering integrable quantum sensors chaotic, both in terms of achievable sensitivity as well as robustness to noise, while avoiding the challenge of preparing and protecting large-scale entanglement. In the presence of dissipation, a stationary non-equilibrium state can be reached for large times that contains substantial amount of quantum Fisher information about the parameter to be measured, while without chaotic driving the system has long decayed to its ground state. Classically, such a state corresponds to a strange attractor with a filigrane, fractal structure.

After demonstrating the principles at the hand of the “kicked top”, we apply the method to spin-precession magnetometry and show that the sensitivity of state-of-the-art magnetometers can be further enhanced by subjecting the spin-precession to non-linear kicks that renders the dynamics chaotic [1,2]. Going beyond periodic kicks, we demonstrate that further improvements can be achieved by optimizing the individual kicking strengths with reinforcement learning [3].

References

[1] Lukas J. Fiderer and Daniel Braun, Nature Communications **9**, 1351 (2018).
[2] Lukas J. Fiderer and Daniel Braun, Conf. Proceedings „Optical, Opto-Atomic, and Entanglement-Enhanced Precision Metrology”, **10934**, 10934S (2019); arXiv:1903.02393 [quant-ph]
[3] Jonas Schuff, Lukas J. Fiderer, and Daniel Braun, NJP **22**, 035001 (2020).

Fighting Laser Chaos with Wave Chaos

H. Cao

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In broad-area edge-emitting semiconductor lasers, the nonlinear interactions of multiple spatial modes with the active medium can result in filamentation and spatio-temporal chaos. These instabilities degrade the laser performance and are extremely challenging to control. We demonstrate a powerful approach to suppress spatio-temporal instabilities using wave-chaotic optical cavities. The interference of many propagating waves with random phases in such cavities disrupts the formation of self-organized structures like filaments, resulting in stable lasing dynamics. Our method provides a general and robust scheme to prevent the formation and growth of nonlinear instabilities for a large variety of high-power lasers.

References

[1] S. Bittner, S. Guazzotti, Y. Zeng, X, Hu, H. Yilmaz, K. Kim, S. S. Oh, Q. J. Wang, O. Hess, H. Cao, Science, **361**, 1225 (2018).

Time reversal: back to "Amazing! I did not understand a single word"

H. Liang and P. Cvitanović

Physics, Georgia Tech, Atlanta GA, USA

What is a `chaotic', or `turbulent' field theory? We call the simplest of all chaotic field theories the `spatiotemporal cat'. It is a discretization of the Klein-Gordon equation, with an unstable rotor at every lattice site, a rotor that gives, rather than pushes back. Such theories are formulated in terms of Hill determinants and zeta functions.

A zeta function relates the totality of admissible states to the orbits generated by all symmetries of a given theory. We do not yet know how to write down a spatiotemporal zeta function for any number of spacetime dimensions. We used instead the 1D version, a temporal 1D lattice for systems with time-reversal symmetry to explain how such zeta functions are constructed.

References

[1] ChaosBook.org/overheads/spatiotemporal

Spectral properties of relativistic quantum billiards with shapes of integrable billiards

Pei Yu[1], Weihua Zhang[1], Barbara Dietz[1] and Liang Huang[1]

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The central question is to what extent the Berry-Tabor conjecture, stating that the spectral properties of typical nonrelativistic quantum systems with an integrable classical counterpart agree with those of Poissonian random numbers, applies to relativistic neutrino billiards (NBs) [1,2] that consist of a spin-1/2 particle governed by the Dirac equation and confined to a bounded planar domain. In distinction to nonrelativistic quantum billiards (QBs), NBs do not have a well-defined classical limit. However, comparison of their length spectra revealed that NBs exhibit peaks at the lengths of periodic orbits of the billiard associated with the QB with an even number of reflections at the boundary, implying that there must be a connection between them. Yet, the spectral properties of neutrino billiards with shapes generating an integrable classical dynamics do not necessarily exhibit Poissonian statistics. We evaluate Husimi functions and length apectra and compare them to their semiclassical approximation which was recently derived for massive NBs [3,4] for an understanding of these findings in terms of the classical dynamics.

Supported financially by the National Natural Science Foundation of China through Grants No. 11775100, No. 11961131009, and No. 12047501.

References

[1] M. V. Berry and R. J. Mondragon, Proc. R. Soc. London A 412, 53 (1987).
[2] Yu Pei, B. Dietz, and L. Huang, New J. Phys. **21**, 073039 (2019).
[3] B. Dietz, Acta Physica Polonica A **136**, 770 (2019).
[4] B. Dietz and Z.-Y. Li, Phys. Rev. E 102, 042214 (2020).

Quantum measurement and quantum randomness with finite heat baths

T. Dittrich[1], S. Peña[1], O. Rodríguez[1], C. Viviescas[1],

F. Großmann[2], W. Strunz[2]

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[2]*Technische Universität Dresden, Dresden, Germany*

Quantum chaos and quantum measurement share a constitutive feature: They capture information at the smallest scales and lift it to macroscopic observability. However, in closed quantum systems with finite-dimensional Hilbert space, fundamental bounds of their information content do not allow a positive entropy production for an indefinite time. Only in open systems where fresh entropy can infiltrate from the environment, quantum dynamics (partially) recovers chaotic entropy production.

Also in quantum measurements, a macroscopic apparatus observes a quantum system. Generally, their results have a probabilistic character; they involve a component of randomness. The analogy with quantum chaos suggests that random outcomes of quantum measurements could, in a similar manner, reveal the entropy generated through the coupling to a macroscopic environment. Interaction with an environment is needed anyway to explain a crucial step in quantum measurement, the decoherence manifest in the collapse of the wavepacket. However, the subsequent step from a set of probabilities to a specific individual measurement outcome, the "second collapse" according to the traditional view of quantum measurement, still evades a proper microscopic modeling and remains shrouded in concepts such as "quantum randomness". Could it be understood as the impact of the macroscopic apparatus on the measured system? If this hypothesis is corretc, it would reveal quantum randomness as amplified quantum noise.

To explore it in a specific emblematic case, spin measurement, we combine the model of quantum measurement proposed by Zurek and others with a unitary approach to decoherence with heat baths comprising only a finite number N of modes, recently developed for quantum chemistry and quantum optics. We expect that for growing N, the dynamics of the measured spin will exhibit a scenario of increasingly long episodes of significant spin polarization, alternating with abrupt spin flips, determined by the initial conditions of the spin *and* of the apparatus. Preliminary analytical and numerical results confirm our expectation.

Complementing the quantum model, we study a classical system often considered as appropriate classical analogue of two-state systems: a bistable quartic double-well potential, coupled to a heat bath to model dissipation. A particle, launched from the unstable equilibrium on top of the barrier, will fall into one of the wells and relax there. Which well, depends on the random impact of the ambient degrees of freedom. We present simulations corroborating this scenario.

Statistics of S-matrix poles: from Haake et al 1992 paper to the present day

Yan V Fyodorov

Kings' College London

I am going to give an account of efforts to understand statistics of complex poles of scattering matrix in systems with chaos and disorder in the framework of Random Matrix Theory, demonstrating the modern legacy of the paper [1].

References

[1] F. Haake, F. Izrailev, N. Lehmann, D. Saher, and H.-J. Sommers, Zeitsch. Physik B, vol.88, 359-370 (1992)

A Non-Hermitian PT-symmetric kicked top

E. M. Graefe[1]

[1] *Imperial College London, United Kingdom*

While traditional quantum mechanics focusses on systems conserving energy and probability, described by Hermitian Hamiltonians, in recent years there has been ever growing interest in the use of non-Hermitian Hamiltonians. These can effectively describe loss and gain in a quantum system. In particular, systems with a certain balance of loss and gain, so-called PT-symmetric systems, have attracted considerable attention. It is an interesting and mostly open question how PT-symmetry interacts with chaos. An obvious choice for the investigation of this interplay is the kicked top, as one of the prime examples in the field of quantum chaos.

Here, a PT-symmetric version of the kicked top is introduced and analysed, with a particular focus on the identification of phase-space structures in the quantum system as well as spectral fingerprints of PT-symmetry and chaos.

References

[1] S. Mudute-Ndumbe, E. M. Graefe, New J. Phys. **22**, 103011 (2020)

Many Body Quantum Chaos in Coupled Cat Maps

Boris Gutkin

Holon Institute of Technology

For decades, Arnold's cat map served as a cornerstone model of classical and quantum chaos. I will discuss a natural extension of the model to many-body setting - a chain of cat maps linearly coupled by a nearest neighbour interaction. Despite of fully chaotic dynamics, the model is amenable to analytical treatment due to the duality between its spatial and temporal dynamics. The focus of the talk will be on correlations between local operators which as we show can be calculated explicitly in sufficiently long chains.

Transition-state dynamics of complex quantum systems

K. Hagino[1] and **G.F. Bertsch[2]**

[1]Department of Physics, Kyoto University, Kyoto 606-8502, Japan
[2] Department of Physics and Institute for Nuclear Theory, Box 351560, University of Washington, Seattle, Washington 98915, USA

In this contribution, we will propose a model for studying the reaction dynamics in complex quantum systems in which the complete mixing of states is hindered by an internal barrier. Such systems are often treated by the transition-state theory, also known in chemistry as RRKM theory, but the validity of the theory is questionable when there is no identifiable coordinate associated with the barrier.

The model consists of two Gaussian Orthogonal Ensembles (GOE) of internal levels coupled to each other and to the wave functions in the entrance and decay channels. We find that the transition-state formula can be derived from the model under some easily justifiable approximations. In particular, the assumption in transition-state theory that the reaction rates are insensitive to the decay widths of the internal states on the far side of the barrier is fulfilled for broad range of Hamiltonian parameters [1].

We will also discuss Porter-Thomas fluctuations in complex quantum systems. An important prediction of the random matrix theory is that the decay rates of the GOE eigenstates fluctuate according to the distribution for one degree of freedom, derived by Brink and by Porter and Thomas. However, we find that the coupling to the decay channels can change the effective number of degrees of freedom from ν=1 to ν=2 depending on the control parameter $\rho\Gamma$ [2], where ρ is the level density in the first reservoir and Γ is their decay width. The v = 2 distribution is a well-known property of the Gaussian Unitary ensemble (GUE); our model demonstrates that the GUE fluctuations can be present under much milder conditions.

References

[1] “Transition-state dynamics in complex quantum systems”, G.F. Bertsch and K. Hagino, arXiv:2105.12073 [quant-ph].

[2] “Porter-Thomas fluctuations in complex quantum systems”, K. Hagino and G.F. Bertsch, arXiv: 2106.15251 [quant-ph].

Quantum chaos from Möbius systems to mesoscopic optics

M. Hentschel[1]

[1]*Institute of Physics, Technische Universität Chemnitz, Germany*

The investigation of the propagation of light in mesoscopic, often micrometer-scale systems is a rich subject providing insights ranging from quantum chaos in open systems to new schemes for micro lasing devices. The concepts of quantum chaos and of quantum-classical, here wave-ray, correspondence, prove to be useful tools in many contexts. The application potential of optical micro cavities motivates to consider coupling between micro cavities as well as realistic, three-dimensional devices. We illustrate the consequences of chaotic light dynamics in deformed micro disk cavities and discuss its impact on the far-field emission characteristics of individual optical micro resonators with and without internal sources as well as for arrays of coupled micro cavities [1]. For comparison, we also address electronic billiards with sources in single and bilayer graphene systems and confirm particle-wave correspondence to hold semi-quantitatively.

The propagation of electromagnetic waves in three-dimensional optical micro cavities requires to pay attention to the light's polarization evolution as a new degree of freedom. In systems like dielectric Möbius-strips [2] or cone-shaped microtube cavities [3], the polarization state of resonant whispering gallery-type modes may differ strongly from the reference case of homogeneous cylinders. Whereas we find that the polarization of the electromagnetic field follows the wall orientation in thin Möbius strips, thereby reflecting the accumulated geometric phase, we observe that the electromagnetic field ignores the Möbius topology when the strip thickness is increased. In cylindrical three-dimensional optical systems, we observe spin-orbit interaction even for cylindrically symmetric cavities.

Symmetries and their specific breaking remain vital elements in the versatile toolbox of mesoscopics in different contexts, for example parity-time (PT) symmetry in ladder lattices [4]. Circular lattices show a crossing of energy levels with increasing on-site energy in the Hermitian case. Möbius-twisting the lattice induces a non-orientability that acts effectively as perturbation and yields avoided level crossing. Remarkably, in the related non-Hermitian (gain/loss) case, the avoided level crossing gives way to a PT-broken state with locked real energy parts and conjugate values of the imaginary parts in between two exceptional points.

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Encounters with Fritz

S. Heusler[1]

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Fritz Haake was a great teacher and researcher. While the results of his research remain visible in his papers and in the seminal textbook *Quantum Signature of Chaos*, the way how ideas evolved and discussions in his group finally culminated to key results such as a semiclassical description of level repulsion in classically chaotic quantum systems, cannot be deduced just from textbooks and papers.

In the first part of my talk, I will review some of these discussions, illuminating Fritz character and inspiring way to lead joung people into science.

In the second part of my talk, I will show some examples of my recent work on models for entanglement entropy and decoherence, which are also influenced by Fritz contributions in this field. In particular, I will present short-time corrections for the well-known Page equation describing the mean entanglement entropy of a quantum system in contact with a heat bath.

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Classical and quantum transport: New phenomena in higher dimensions

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Chaotic trajectories in Hamiltonian systems with two degrees of freedom cannot enter regular islands in phase space. In contrast, in higher-dimensional systems chaotic trajectories can come close to any phase-space point via the so-called Arnold web. But what is the quantum mechanical situation?

Obviously, a quantum wave packet cannot enter phase-space regions smaller than the size of a Planck's cell. Additionally, dynamical localization in regions with slow diffusion, like in the Arnold web, will prohibit quantum transport. Therefore quantum wave packets will mainly explore the intricate surface of predominantly regular phase-space regions. In this talk two phenomena in such a surface region will be presented classically and quantum mechanically:

- The Arnold web is spanned by so-called resonance channels which widen, as they enter the chaotic sea. We show that this geometry induces (i) classically a drift and (ii) quantum mechanically destroys dynamical localization, if the drift is strong enough. We propose a universal scaling of this delocalization transition.

- Classical transport between neighboring resonance channels is restricted by partial barriers and we generalize the concept of the most restrictive cantorus barrier to higher dimensions. Its classical flux limits quantum transport, but the usual scaling parameter, flux divided by Planck’s cell, has to be modified due to the presence of dynamical localization.

These transport phenomena are demonstrated for 4D symplectic maps, but should occur in any generic higher-dimensional Hamiltonian system.

Kicked top in coherent states

R. Przybycień and M. Kuś

Center for Theoretical Physics, PAS, Warsaw, Poland

We use spin coherent states to compare classical and quantum evolution of a simple paradigmatic, discrete-time quantum dynamical system exhibiting chaotic behavior in the classical limit, namely the celebrated kicked top. The spin coherent states are employed to define a phase-space quasidistribution for quantum states (*P*-representation). It can be, in principle, used for a direct comparison of the quantum and classical dynamics, where on the classical level one deals with the classical distribution function on the classical phase space. We present a different way by comparing evolution of appropriately defined moments of classical and quantum distributions, in particular the one-step propagators of the moments.

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Fritz’s legacy recisited: Building links between Germany and Pland

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In my lecture during the Wednesday memory session, I will focus on enormous role played by Fritz Haake for the buildup of the German-Polish collaborations and link in the field of physics, science and more…

On the classical limit of entangled states

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We consider a system of two particles, each with large angular momentum j, in the singlet state. The probabilities of finding projections of the angular momenta on selected axes are determined using numerical methods and approximations developed by Fritz Haake. Inspired by methods of quantum chaos we study generalized Bell inequalities involve these probabilities and we study them using statistical methods. We show that most of Bell's inequalities cannot be violated, or are violated only marginally, in the limit $j \rightarrow \infty$. The precision required to confirm a violation appears to be difficult to achieve. In practice, the quantum system, in spite of being entangled, becomes indistinguishable from its classical counterpart.

Semiclassics and higher-order correlation functions for chaotic systems

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We present a semiclassical approach to evaluate spectral correlation functions of quantum systems whose classical dynamics is chaotic. These function describe the statistics of the energy levels, and we consider correlation functions of arbitrary order. The basic ingredients are sets of periodic orbits that have nearly the same action and therefore provide constructive interference. We calculate explicitly the first correlation functions, to leading orders in their energy arguments, for both systems with and without time reversal invariance. The results agree with corresponding predictions from random matrix theory, thereby giving solid support to the conjecture of universality. For the non-oscillatory contributions to correlation functions of systems without time-reversal invariance we show analytically that the off-diagonal contributions to these correlation functions cancel and the conjectured universality holds.

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Chaos in the Bose-Hubbard Model versus Gaussian orthogonal and embedded random matrix ensembles

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We benchmark spectral and eigenvector statistics of the Bose-Hubbard Hamiltonian against those of the Gaussian orthogonal and the bosonic two-body embedded random matrix ensemble. The latter, in contrast to the Gaussian ensemble, mirrors the few-body nature of interactions and is therefore expected to better approximate actual quantum many-particle systems. Within the energy and parameter range where chaos fully unfolds in the Bose-Hubbard model, the associated eigenstates' fractal dimensions exhibit expectation values and variances well described by both random matrix ensembles. On top, the bosonic embedded ensemble reproduces the energy dependence of the chaotic domain. Notwithstanding the universal behaviour of all three models on the level of the fractal dimensions' lowest-order statistical moments, we observe a systematically enhanced distinguishability of the fractal dimensions' full probability distributions with increasing Hilbert space dimension. This provides a statistically robust hallmark of distinctive features of models of complex quantum systems.

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Wavefunctions Extreme Intensities:
from chaotic to regular quantum maps

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Inspired by the work done in [1,2], we have studied the extreme events of the eigenstates intensities of three parameter-dependent quantum maps: standard map, perturbed cat map, and kicked Harper map. In order to expand the extreme statistics in semiclassical systems, we have considered not only the very chaotic regime but also states from near-integrable and mixed regimes. Interesting results have been obtained from the computation of the kurtosis of the intensities distributions. It is expected from [3-5] that the high semiclassical intensities due to the scarring of eigenstates by classical periodic orbits that undergo generic bifurcations must be present. However, we will show that quantum phases also play a role.

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Exact results on dynamics of dual unitary circuits and their perturbations

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I will review the recent results on the proof of random matrix spectral form factor and explicit computation of correlation functions of local observables in the so-called dual-unitary brickwork circuits (including integrable, non-ergodic, ergodic, and chaotic cases) [1,2]. Further, I will show how these results can be extended to another quantum-circuit platform, specifically to unitary interactions round-a-face (IRF) [3]. I will argue that correlation functions of these models may be generally perturbatively stable with respect to breaking dual-unitarity, and describe a simple rigorous result within this framework [4].

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Along Fritz' and Petr's semiclassical paths: Classical orbit correlations and many-body quantum chaos

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Classical chaos and quantum dynamics get entangled in the semiclassical limit of small Planck constant. This regime is naturally reached in many-body systems where the thermodynamic limit of large particle numbers can be considered as semiclassical. The dynamics and spread of quantum information in such complex many-body systems is presently attracting a lot of attention across various fields, ranging from cold atom physics via condensed quantum matter to quantum gravity. There, echoes and OTOCs, so-called out-of-time-order correlators, are sensitive probes for chaos and the temporal growth of complexity.
In generalizing semiclassical tools developed, among others, in particular by Fritz Haake and Peter Braun for single-particle systems, we will address such echo phenomena using semiclassical many-body path integral techniques. We will discuss various aspects of OTOCs: their growth and quantum saturation [1], unscrambling information [2], a renormalized asymptotic expansion [3] and the bound on chaos [4].

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Entanglement scaling transition from stroboscopic to continuous measurements

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Quantum measurements can induce an entanglement transition between ergodic and localized dynamics with extensive and sub-extensive scaling of the entanglement entropy respectively. This transition is of great interest since it illuminates the intricate physics of thermalization and control in open interacting quantum systems. Whilst this transition is well established for stroboscopic measurements in random quantum circuits [1], a crucial link to physical settings is its extension to continuous observations where, for an integrable model, it has been shown that the transition changes its nature and becomes immediate [2].

Here we report results for a one-dimensional interacting quantum system subject to unitary dynamics which interpolates between continuous and stroboscopic projective measurements. We show that the entanglement transition at finite coupling persists if the continuously measured system is randomly nonintegrable, and it is smoothly connected to the transition in the stroboscopic models [3]. We further extend our results to systems in which the unitary dynamics is generated by noisy and disordered Hamiltonians [4]. Here the steady-state measurement induced transition provides a tool to diagnose the intricated features of the transient entanglement generation rate of the unitary dynamics. These results open the possibility to investigate the measurement induced entanglement transition in quantum architectures accessible via continuous measurements.

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Fluctuations of Bose-Einstein condensate

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Particle fluctuations of a number of condensed atoms is one of fundamental problems of quantum gases physics. In the last two years it is not only a theoretical, but also the experimental problem. I will review nearly a quarter of the century of our own efforts. I will explain our new method of the Fock states sampling in application to the condensate statistics.

Diffusive field cross-correlations in complex media

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Is it possible to retrieve information about the transmission amplitude and phase between two points from the cross-correlation of the field probed at two positions? The affirmative answer is provided by the so-called Green's function retrieval technique that is now widely used in seismology, acoustics, optics and electromagnetism. Such a technique relies on noninvasive measurements, but in many (e.g., electromagnetic) applications the probes (antennas) can be well matched to the complex environment. In this talk, we consider the case of efficient antennas embedded into a chaotic cavity with absorption, which is relevant for practical purposes. Using the scattering matrix approach, we provide a quantitative analysis of the cross-correlation function which is found to mainly depend on the impedance mismatch of the antennas and the losses within the cavity. The theoretical results are confirmed by experimental measurements carried out in 2D and 3D electromagnetic cavities, which are also briefly discussed.

[Based on a joint work with M. Davy, P. Besnier, P. del Hougne (Univ. Rennes, France), J. de Rosny (Inst. Langevin, France), E. Richalot, F. Sarrazin (Univ. Gustave Eiffel, France), F. Mortessagne, U. Kuhl, O. Legrand (Univ. Cote d'Azur, France).]

Quantum gravity and quantum chaos

S.H. Shenker[1]

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I will discuss some of the connections between quantum gravity and quantum chaos that have been uncovered in recent years. I will describe the kinds of questions of most importance from the gravitational point of view.

Quantum metric statistics for random-matrix families

Michael V. Berry[1] and Pragya Shukla[2]

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We analyse the statistical behavior of the quantum metric tensor G_{ij} for parameterised families of the quantum states of complex systems, in particular the trace $G = \mathrm{Tr} G_{ij}$, which can be well-modeled by the universality classes of random-matrix theory. We calculate the probability distribution of G, exactly for N=2, and approximately for N=3 and $N \to \infty$ and find it to be symmetry as well as size-dependent. Codimension arguments also establish the scalings of the distributions near the singularities at $G \to \infty$ and G=0, near which asymptotics gives the explicit analytic behaviour. Our numerical simulations support the theory.

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Propagating correlation functions by ray methods with diffractive contributions

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We consider correlation functions of wave fields in Poincaré surfaces of section. The semiclassical propagation of correlation functions between different surfaces of section is performed by summing over pairs of trajectories with appropriate boundary conditions. When averaged quantities are considered, interference effects between multiple paths are suppressed, and trajectory pairs can be replaced by single rays.

In this talk, we incorporate diffraction effects in this formalism. They are described by additional, diffractively scattered rays. It is important to account for interference between diffractive and non-diffractive rays in order to satisfy flux conservation. We consider cases that can be treated by the geometrical theory of diffraction (GTD), and we discuss modifications that are necessary when the uniform theory of diffraction (UTD) is required.

Reference

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Can One Hear a Matrix?

On the reconstruction of a real symmetric matrix from spectral data

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Abstract: The number of entries in a real and symmetric N dimensional matrix is Nx(N+1)/2. Thus, to reconstruct the full matrix the input spectral data should consist of at least this number of real numbers. The spectrum itself is certainly not sufficient, and it can be augmented by the spectra of the successive main minors of dimensions 1,..,N-1. This by itself is also not sufficient for unique reconstruction, and further sign information is required. Identifying the terms whose signs are necessary and how to compute them is the main impediment for the solution of the general inversion problem.

In this talk I shall first describe the solution of the general sign problem. However, in practice, the task is complicated since the necessary signs information is not directly accessible.

However, one can circumvent the sign problem by limiting the discussion to banded matrices, where the number of non-vanishing matrix elements is smaller than the amount of the available spectral information. Making use of this *redundancy*, one can simplify considerably the sign problem for *generic* matrices - by which we mean that the exceptional set of matrices is of zero measure.

This is the main result of our work which advocates *Redundancy for Genericity.*

Finally, it will be shown that one can optimize the ratio between redundancy and genericity (minimizing the input set and still keeping the exceptional set small) by using the freedom of choice of the spectral information input.

The construction will be illustrated by application for the set of penta-diagonal matrices.

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Averages of secular coefficients

Nina Snaith[1]

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In the 1990s Fritz Haake and collaborators investigated averages of secular coefficients in various matrix ensembles: that is, averages of the coefficients of the characteristic polynomial of random matrices. There are well-known connections between random matrix theory and the theory of the Riemann zeta function, but still I was surprised to see secular coefficients arise in very current number theoretical projects, leading me to decide that this talk will be a brief review of some interesting occurrences of and connections with secular coefficients from the work of Fritz to the present.

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Bounds on out-of-time-order correlators from the eigenstate thermalization hypothesis

Mark Srednicki[1]

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The bound on the growth rate of the out-of-time-order four-point correlator in chaotic quantum many-body quantum systems, conjectured in [1], can be derived from the general structure of operator matrix elements that follows from the eigenstate thermalization hypothesis (ETH). This talk is based on joint work with C. Murthy [2].

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A microwave realization of the chiral ensembles

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Random matrix theory is a very versatile tool to describe the universal features of the spectra of quantum systems with a classically chaotic dynamics. Depending on symmetry with respect to time reversal and the presence or absence of a spin 1/2 there are three universal ensembles, the Gaussian orthogonal (GOE), Gaussian unitary (GUE), and Gaussian symplectic (GSE) one. With a further particle-antiparticle symmetry the chiral variants of these ensembles, the chiral orthogonal, unitary, and symplectic ensembles (the BDI, AIII, and CII in Cartan's notation) appear. A characteristic feature of the chiral ensemble is the existence of positive and negative energy eigenvalues coming in pairs as they appear, e.g., in the solution of the Dirac equation. This suggests an experimental realization of chiral symmetries in graphene-like systems, but it can be done easier. Our microwave realization is based on a linear chain of evanescently coupled dielectric cylindrical resonators allowing to study all three chiral ensembles experimentally. In all cases the predicted repulsion behavior between positive and negative eigenvalues for energies close to zero could be verified [1].

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Controlling Transmission of Light Using Mesoscopic Correlations

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Waves transmitted through chaotic or disordered media become correlated due to self-intersections of wave paths traversing the medium. This was first discovered in studies of mesoscopic electron transport [1] and leads to a bimodal distribution of transmission eigenvalues and the possibility of perfect transmission through disordered or chaotic media for an optimal input wavefront [2]. In the early 2000's Sieber, Richter and Haake showed how to derive these correlations and related effects from semi-classical theory applied to chaotic Hamiltonians, and to connect them quantitatively to Wigner-Dyson random matrix theory [3]. The predictions of the theory relating to enhanced transmission have never been accessible experimentally in quantum systems but in the past decade have been demonstrated for electromagnetic waves in disordered media. For a lossless disordered photonic crystal waveguide, order of magnitude enhanced transmission via wave front shaping has been observed [4]. At the same time the practically important question of the maximal transmission enhancement of a focused spot through a disordered *surface* was recognized as an unsolved theoretical and experimental problem. The theoretical question was addressed through the introduction of a new, "filtered" random-matrix (FRM) ensemble [5], which incorporated the effects of uncontrolled input channels and unobserved output channels. Detailed experiments, and further development of the FRM theory for application to experiment, led to strong confirmation of the FRM predictions and to the demonstration of a factor of three enhancement of the light transmission into a region much larger than the input wavelength, an effect which is only possible due to mesoscopic correlations [6]. A very brief summary of the history and a review of the modern developments will be presented in this talk.

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Sound radiation from vibrating plates – a classical phase space approach

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Paraphrasing Marc Kac's famous quote, I'd like to address the question 'Can you hear the structure of a classical phase space?' The background to this question is the following: vibrating structures give off sound - and controlling or even just modelling the radiated sound is of importance in many engineering applications. Both, calculating the vibrational waves on complex structures - think aeroplanes or cars - and estimating the acoustic radiation are non-trivial computational tasks for large structures. Solving the linear elasticity (wave) equations directly can lead to very large models scaling unfavourably with frequency. Especially at high frequencies - now think noise - it is in general much easier to compute the mean vibrational energy distribution using phase space calculations based on the underlying ray dynamics. As a result, one obtains a phase space density on the whole structure, however, without phase information. Such phase information is vital for sound radiation computations based on, for example, boundary integral equations such as the Rayleigh integral. Can we still obtain the sound being radiated from these structures? To some extend yes - by making use of the 'hidden' phase information retained in the 'momentum coordinate' which can be recovered by applying an inverse Wigner transformation. I will dwell on these ideas using some simple examples.

Post-Ehrenfest many-body quantum interferences in ultracold atoms

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Far out-of-equilibrium many-body quantum dynamics in isolated systems necessarily generate interferences beyond an Ehrenfest time scale, where quantum and classical expectation values diverge. Ultracold atomic gases provide a promising setting to explore these phenomena. Theoretically speaking, the heavily-relied-upon truncated Wigner approximation leaves out these interferences. We develop a semiclassical theory of coherent state propagation for many-body bosonic systems, which properly incorporates such missing quantum effects. For mesoscopically populated Bose-Hubbard systems, it is shown that this theory captures post-Ehrenfest quantum interference phenomena very accurately, and contains relevant phase information to perform many-body spectroscopy with high precision.

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Initial and final value for the semiclassical evolution of the Wigner function

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In recent years, numerical implementations suiting present computational architectures have fuelled a resurgence in the interest in phase space semiclassical approximations for the dynamics of quantum systems. In this work we present a careful treatment of the caustics emerging from the use of pairs of classical trajectories when the semiclassical propagator in the center-center representation, introduced by Dittrich et al [Phys. Rev. Lett. 96, 070403 (2006)], is used to generate the dynamics of the Wigner function. Following this, and in order to implement numerical applications, we introduce an initial and final value representations (IVR and FVR) of the semiclassical propagation, showing that they lead to better performance with less complexity than the IVR and FVR using different criteria.

Tests of the Porter-Thomas Distribution for Reduced Partial Neutron Widths

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Random-Matrix Theory is a key element in the statistical theory of nuclear reactions [1]. It predicts that reduced partial neutron widths follow the Porter-Thomas distribution. That distribution belongs with $k = 1$ to the family of χ^2-distributions characterized by the number k of degrees of freedom and by the width σ. Using a guessed value for σ and a maximum-likelihood analysis with respect to k of 411 (158) reduced neutron partial widths in ^{194}Pt (in ^{192}Pt, respectively) Koehler et al. [2] found that the Porter-Thomas distribution must be rejected with a statistical significance of at least 99.997 per cent. A somewhat smaller but still very high rejection rate was found by Koehler [3] in his analysis of the nuclear data ensemble.

Given N data points, Harney and the author [4] have used Bayesian inference to determine most likely values and confidence intervals for the parameters k and σ of a χ^2-distribution. We show that the values of σ guessed in Refs. [2, 3] lie far outside the Bayesian confidence interval determined for $N = 411$ ($N = 158$) data points in ^{194}Pt (in ^{192}Pt, respectively), casting serious doubt on the results and on the conclusions of Refs. [2, 3]. We show that a maximum-likelihood analysis cannot reliably be based upon a guessed value for σ but must encompass a search for both k and σ.

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Color-Flavor Transformation Revisited

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The “color-flavor transformation”, conceived as a kind of generalized Hubbard-Stratonovich transformation, is a variant of the Wegner-Efetov supersymmetry method for disordered electron systems. Tailored to quantum systems with disorder distributed according to the Haar measure of a compact Lie group of any classical type (A, B, C, or D), it has been applied to Dyson's Circular Ensembles, random-link network models, quantum chaotic graphs, disordered Floquet dynamics, and more. We review the method and, in particular, explore its limits of validity. We also sketch a new alternative method to treat models where the color-flavor transformation fails.

Abstracts of Posters

(in alphabetical order)

Fock-space geometry and strong correlations in many-body localized systems

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We adopt a geometric perspective on Fock space to provide two complementary insights into the eigenstates in many-body-localized fermionic systems. On the one hand, individual many-body-localized eigenstates are well approximated by a Slater determinant of single-particle orbitals. On the other hand, the orbitals of different eigenstates in a given system display a varying, and generally imperfect, degree of compatibility, as we quantify by a measure based on the projectors onto the corresponding single-particle subspaces. We study this incompatibility between states of fixed and differing particle number, as well as inside and outside the many-body-localized regime. We also calculate a benchmark for the expected maximum incompatibility via random matrix theory. This gives detailed insights into the emergence and strongly correlated nature of quasiparticle-like excitations in many-body localized systems, revealing intricate correlations between states of different particle number down to the level of individual realizations [1].

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Eigenstate Thermalization in Dual-Unitary Quantum Circuits: Spectral Functions and Decay of Correlations

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The eigenstate thermalization hypothesis (ETH) explains thermalization of typical observables by conjecturing statistical properties of their matrix elements, which in turn determine the relaxation of expectation values and of dynamical correlation functions towards their thermal equilibrium value. Here we present quantum circuit models in which scaling properties of dynamical correlations between typical operators can be accessed analytically in the limit of large system sizes.
In homogeneous dual-unitary circuits we obtain the initial dynamics and hence the initial exponential decay of autocorrelation functions of translationally invariant operators in terms of completely positive trace preserving maps build from the local gates of the circuit. From this we infer statistical properties of off-diagonal matrix elements: We compute the asymptotics of the spectral function, i.e., the second moment of their distribution analytically and study higher moments numerically, thereby confirming the behavior conjectured by ETH [1].
Additionally we study dynamical correlations between local operators in free quantum circuits perturbed by an impurity placed at the systems boundary. We map the correlation function onto a partition function on a two-dimensional lattice with a helix topology, which allows for an evaluation in terms of suitable transfer matrices. We study their spectral properties and show that in a particular scaling limit dynamical correlations are typically exponentially suppressed with system size both for dual-unitary and generic impurities as it is expected in thermalizing systems.

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Entanglement in coupled kicked tops with chaotic dynamics

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The entanglement of eigenstates in two coupled, classically chaotic kicked tops is studied in dependence of their interaction strength. In particular we consider not only the case of large equally sized subsystems but also a heat-bath situation, i.e. one subsystem is much smaller than the other. The transition from the noninteracting and unentangled system towards full random matrix behavior is governed by a universal scaling parameter. Using suitable random matrix transition ensembles we express this transition parameter as a function of the subsystem sizes and the coupling strength. The universality is confirmed for the level spacing statistics of the equal sized coupled kicked tops. In the heat-bath situation we find deviations in the level spacing statistics for the small coupling regime, which decrease with increasing coupling. The statistics of entanglement entropies of eigenstates is found to follow a universal scaling in both considered situations. We obtained a perturbative description, which can be extended to large couplings and provides very good agreement with numerical results. These results are published in Ref. [1].

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Entanglement dynamics in different universality classes

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The von Neumann bipartite entanglement entropy is critical in the characterization and statistical description of many-body quantum states. This entropy is extensively employed to quantify the entanglement in quantum systems, and its scaling properties with length can be used to characterize ergodic thermal-like or nonergodic localized phases. We utilize an established quantum-circuit model, specifically a one-dimensional quantum circuit evolving under alternating random unitary transformations and projective measurements performed with tunable probability. This simple model contributes versatility in the investigation of entanglement spreading in quantum circuits, namely the interplay between the competing ballistic entanglement growth induced by random unitary evolution, and entropy reduction by projective measurements. We extend the established model to consider entanglement dynamics in different universality classes, where the dynamics are generated by unitary operators from the CUE, COE, or CSE. The tunability of the measurement probability leads to intermediately-entangled quasistationary states, dependent on the different ensembles, whose dynamics may help to characterize entanglement evolution in generic many-body systems, for example, after a quantum quench - a focus of nonequilibrium quantum physics.

Enhanced state transfer by complex instability in coupled kicked tops

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By considering coupled kicked tops we provide a mechanism for a fast transfer between two specific states representing bits. This crucially relies on that fact that the semiclassical limit corresponds to a higher-dimensional system which allows for more types of stability of fixed points than the two-dimensional case. Tuning the parameters, the coupled kicked tops have fixed points with complex instability. Quantum mechanically this allows for a rapid transfer between coherent states located at these points, which is much faster than the coexisting dynamical tunneling.

Thermalisation Dynamics and Spectral Statistics of Extended Systems with Thermalising Boundaries

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We study thermalisation and spectral properties of extended systems connected, through their boundaries, to a thermalising Markovian bath. Specifically, we consider periodically driven systems modelled by brickwork quantum circuits where a finite section (block) is generated by generic local unitary gates while the complement is dual-unitary[2]. We show that the evolution of local observables and the spectral form factor are determined by the same quantum channel, which we use to characterise the system's dynamics and spectral properties. In particular, we identify a family of fine-tuned quantum circuits --- which we call strongly localising --- that fails to thermalise even in this controlled setting, and, accordingly, their spectral form factor does not follow the random matrix theory prediction. We provide a set of necessary conditions on the local quantum gates that lead to strong localisation, and in the case of qubits, we provide a complete classification of strongly localising circuits. We also study the opposite extreme case of circuits that are almost dual-unitary, i.e., where instead of being localised the information moves at the maximal speed allowed by the brick-work geometry. We show that, in these systems, local observables and spectral form factor approach respectively thermal values and random matrix theory prediction exponentially fast. We provide a perturbative characterisation of the dynamics and, in particular, of the time-scale for thermalisation.

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Brewster-notched microcavities: Billiards without reflections

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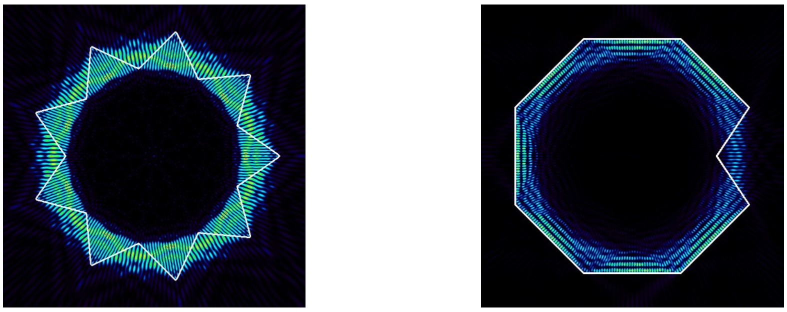
We report on a novel type of microcavities that confine light via the perfect transmittance at Brewster's angle, see Ref. [1]. As such our approach is contrary to traditional whispering-gallery cavities which are based on the billiard dynamics of light rays with total internal reflections. However, in a properly designed star-shaped cavity we rather utilize stable periodic orbits that sequentially leave and reenter the spikes of the cavity without loss of intensity. In addition to the ray simulations we show that long-lived optical modes arise that are supported by these orbits. We also demonstrate the unification of this concept with the traditional whispering-gallery cavity design, see Ref. [2].



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A programmable spin-based quantum simulator in diamond for quantum chaos and diffusion

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Nitrogen-vacancy (NV) centre spin qubit in diamond is surrounded by a naturally occurring bath of ^{13}C carbon nuclei of spin ½. Such bath is the main source of decoherence for the central qubit, but on the other hand, spins located in the close vicinity of the NV centre can leave characteristic traces in the coherence loss.

A recent paper from our group [1] shows that using state-of-the-art spectroscopy involving both dynamical decoupling on electron, as well as, radio-frequency pulses on nuclear spins, one can not only estimate couplings to the NV centre, but also internuclear interactions for 27 nuclear spins around the central qubit. Additionally we showed the possibility to create multi-qubit entangled states between the measured spins [2].

As a result, such a nuclear cluster can be used as a quantum simulator. A most recent result [3] shows that from this set, one can isolate a one dimensional 9-spin chain whilst controlling and reading out these spins individually or in groups. Finally, this system was successfully put into a many-body-localized discrete time crystal state.

I will try to show that our quantum simulator in diamond can be a nice platform for understanding the role of disorder in controllable quantum many-body systems, for example in the directions of controlled diffusion (see e.g. [4] for experiments a bath of electron spins around an ensemble of NV centres) and quantum chaos.

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Chaos in a broken-parity Dicke model

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We study the onset of chaos in a generalization of the paradigmatic Dicke model of quantum optics. This model admits a thermodynamic limit that coincides with a semiclassical analogue of two effective degrees of freedom. Classical chaos is analyzed by means of the Poincaré sections of the corresponding semiclassical analogue, which shows two asymmetric energy wells. The dynamics in each well depends on a conserved quantity associated to the semiclassical phase space of the system [1]. We show that classical chaos develops independently in each of these two wells at different energies. Within a certain energy width we find coexistence between fully chaotic and integrable dynamics. In the quantum version of the model, the signatures of quantum chaos are also shown to depend on the classical energy well, as exemplified by means of Peres lattices of relevant quantum observables. Chaos is also diagnosed through localization measures, such as the participation ratio.

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Scarring in open chaotic systems: The local density of states

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Chaotic Hamiltonians are known to follow the properties of Random Matrix Theory (RMT) ensembles in the apparent randomness of their spectra and wavefunction statistics. Deviations form RMT also do occur, however, due to system-specific properties. Scarring, for instance, is the enahancement or suppression of wavefunction intensity near classical periodic orbits, and it can be characterized by a local density of states (or local spectrum) exhibiting a peaked envelope, which has been described semiclassically. Here, dissipation in the form of leaking is included in the picture, the local density of states is introduced for the resulting non-Hermitian chaotic Hamiltonians, and estimated a priori in terms of the Green's function of the closed system and the open channels. With no deviations from RMT, ensemble averages can be taken and known results recovered. In the presence of scarring, one can construct a semiclassical Green's function for the closed system, hence obtain the predictions for the open system. Numerical demonstrations are perfomed on quantum cat maps, with both one- and miltiple-channel openings, showing how both RMT- and semiclassical predictions for the local spectrum are affected by dissipation.

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Quantum chaos and complex dynamics in driven collective spin systems: from the kicked top to the kicked *p*-spin models

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The quantum Kicked top, introduced by Haake, Kuś and Scharf in a seminal paper in 1987, is a paradigmatic model of quantum chaos. Thanks to the dual nature of the model, describing both a quantized top undergoing rotations and twisting on a sphere, and a system of spin-½ particles with all-to-all pairwise interactions, the QKT has served as a connector between foundational aspects of quantum chaos and of quantum information. Here, we present a generalization of the QKT, the kicked p-spin models, which includes p-order twisting (or, equivalently, *p*-body interactions) thus recovering the QKT for $p = 2$ [1]. We fully characterize the classical nonlinear dynamics of these models, including the transition to global Hamiltonian chaos. The classical analysis allows us to build a classification for this family of models, distinguishing between $p = 2$ and $p > 2$, and between models with odd and even *p*'s. Many signatures of these classes carry over to the quantum domain leading to interesting and complex behavior. We illustrate several potential applications of these models in diverse fields, from the study of emergent phases in many-body quantum systems, as well as quantum simulation and quantum metrology.

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Entanglement production by interaction quenches of quantum chaotic subsystems

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The entanglement production in bipartite quantum systems is studied for initially unentangled product eigenstates of the subsystems, which are assumed to be quantum chaotic [1]. Based on a perturbative computation of the Schmidt eigenvalues of the reduced density matrix, explicit expressions for the time-dependence of entanglement entropies, including the von Neumann entropy, are given. An appropriate re-scaling of time and the entropies by their saturation values leads a universal curve, independent of the interaction. The extension to the non-perturbative regime is performed using a recursively embedded perturbation theory to produce the full transition and the saturation values. The analytical results are found to be in good agreement with numerical results for random matrix computations and a dynamical system given by a pair of coupled kicked rotors.

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Transfer operator methods for modelling high-frequency wave fields

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A big part of understanding of quantum chaotic systems comes from semi-classical correspondence. This link between quantum systems in their high-energy, short-wavelength asymptotics and classical ray dynamics can be taken over, mutatis mutandis, to describe other wave equations as well. Our main tool will be the classical Frobenius Perron Transfer operator.

We will focus on problems from vibrational acoustics and approach their solution using classical rays in complicated domains. The domains here are often given by large meshes from Finite Element Method (FEM) calculations. They are therefore built from very simple blocks, i.e. triangles or quadrilaterals. While the ray dynamics in such domains is very simple, the complexity arises from coupling millions of them with complicated scattering matrices [1,2].

More specifically, analyze the convergence properties of a ray-tracing approach to transfer operators. We compare our findings with recent proofs carried out for a circular domain and conclude with an outlook about its applicability for real-world problems [3].

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The Sachdev-Ye-Kitaev Lindbladian and dissipative quantum chaos

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The dynamics of complex interacting many-body open quantum systems, their timescales, and correlations, are a timely topic with major conceptual and experimental significance. A simplified Markovian description of dissipative systems, following Lindblad dynamics, is possible whenever characteristic memory times of the environment are much smaller than those of the system.
This simplified setup allowed considerable progress, both for integrable models, by exploiting recently found exact solutions, and chaotic ones, where tools of (non-Hermitian) random matrix theory have been successfully employed. However, physically motivated models have few-body interaction terms, rendering them very different from fully random Lindblad operators. To date, a generic yet sparse and solvable paradigmatic Lindbladian was still missing.
Here, we propose the Sachdev-Ye-Kitaev (SYK) Lindbladian as such a model. It describes N strongly-coupled Majorana fermions with random all-to-all interactions, with unitary evolution given by a quartic SYK Hamiltonian and the coupling to the environment described by M quadratic jump operators, rendering the full Lindbladian quartic in the Majorana operators. The full Lindbladian spectrum and the spectral gap (which rules the relaxation of the system to its steady-state) are studied numerically through exact diagonalization techniques. Furthermore, by performing disorder-averaging on the Keldysh (complex-time) contour, we derive an (exact) effective action for two collective fields (Green's function and self-energy) governing the late-time evolution (relaxation) of the system. In the large-N, large-M limit, we obtain saddle-point equations satisfied by the collective fields, determining the typical timescales of the dissipative evolution.

The aging Harmonic oscillators and beyond

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We study time dependent coupled quantum Harmonic oscillators near its unbinding phase. These time dependent Harmonic oscillators either have decaying spring constant/decaying coupling or both. Using entanglement entropy, we find that these systems show chaotic behavior near the dissociation point of a pair.

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Drift-induced Delocalization Transition in Resonance Channels

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In higher-dimensional Hamiltonian systems resonance channels play a prominent role. Transport is typically slow due to Arnold diffusion, leading quantum mechanically to dynamical localization. Resonance channels widen as they approach the chaotic sea. We show that this induces (i) classically a drift and (ii) quantum mechanically leads to delocalization if the drift is strong enough. We propose a scaling of the delocalization transition by a single transition parameter. These phenomena are confirmed in a 4D symplectic map with a large resonance channel.

Quantum signatures of partial barriers in 4D symplectic maps

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Partial transport barriers in the chaotic sea of Hamiltonian systems restrict classical chaotic transport, as they only allow for a small flux between phase-space regions. Quantum mechanically for 2D symplectic maps one has a universal quantum localizing transition. The scaling parameter is the ratio of flux to the Planck cell of size h, such that quantum transport is suppressed if h is much greater than the flux, while mimicking classical transport if h is much smaller.

In a higher-dimensional 4D map one naively expects that the relevant scaling parameter is the same, but now with a Planck cell of size h squared. We show that due to dynamical localization along resonance channels the localization length modifies the scaling parameter. This is demonstrated for coupled kicked rotors for a partial barrier that generalizes a cantorus to higher dimensions.

Measurement-induced criticality in Clifford circuits and relation to percolation

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Entanglement transitions in quantum dynamics present a novel class of phase transitions in non-equilibrium systems. When a many-body quantum system undergoes unitary evolution interspersed with monitored random measurements, the steady-state can exhibit a phase transition between volume- and area-law entanglement. There is a correspondence between measurement-induced transitions in non-unitary quantum circuits in d spatial dimensions and classical statistical mechanical models in d+1 dimensions. In certain limits, these models map to percolation, but there is analytical and numerical evidence to suggest that away from these limits the universality class should generically be distinct from percolation.

Intriguingly, despite these arguments, numerics on 1+1D qubit circuits give *bulk* exponents which are nonetheless close to those of 2D percolation, with some possible differences in surface behavior. In the first part of this work, we explore the critical properties of 2+1D Clifford circuits. In the bulk, we find many properties suggested by the percolation picture, including matching bulk exponents, and an inverse power-law for the critical entanglement growth, $S(t,L) \sim L(1-a/t)$, which saturates to an area-law. We then utilize a graph-state based algorithm to analyze in 1+1D and 2+1D the critical properties of entanglement clusters in the steady state. We show that in a model with a simple geometric map to percolation – the projective transverse field Ising model – these entanglement clusters are governed by percolation surface exponents. However, in the Clifford models we find large deviations in the cluster exponents from those of surface percolation, highlighting the breakdown of any possible geometric map to percolation. Given the evidence for deviations from the percolation universality class, our results raise the question of why nonetheless many bulk properties behave similarly to those of percolation.

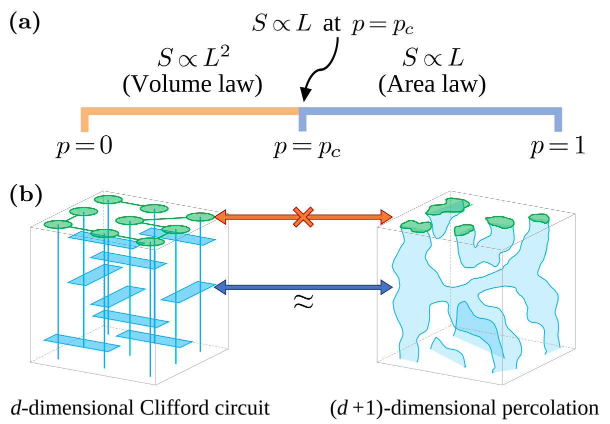

Figure 1. (a) Phase diagram of monitored Clifford circuit in 2+1D. (b) Schematic connection to percolation.

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