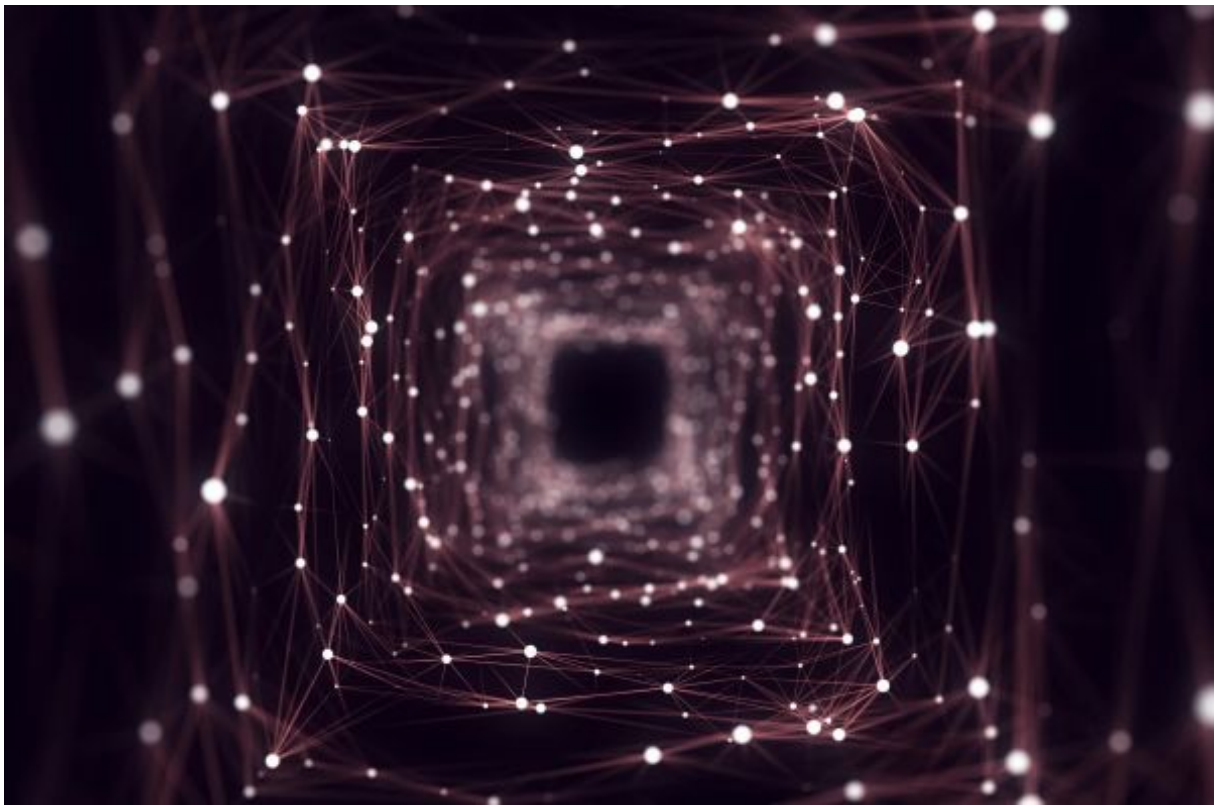


Many-body localization: current status and open questions

Researchers present an extensive review of many-body localization (MBL) -a phenomenon that prevents quantum many-body systems from reaching equilibrium- focusing on the main numerical results and the remaining open questions.

January 22, 2025

When many quantum particles evolve over time, they typically end up arriving to an equilibrium state through a process called thermalization. Something similar happens in many classical systems. For example, if you place an ice cube in a thermos with water, the ice melts and the final (equilibrium) state is just colder water than before.

In classical physics, complex systems eventually reach equilibrium (if you wait long enough, the ice always melts). However, certain quantum many-body systems defy this norm. For them, thermalization does not occur, and the system remains out of equilibrium. This behavior is due to many-body localization (MBL), a mechanism that retains the system's initial conditions over time.

However, a central question remains unanswered: why does MBL occur, and under what

conditions? Seeking to consolidate the knowledge accumulated over decades, ICFO researchers **Dr. Piotr Sierant** and **ICREA Prof. Maciej Lewenstein**, together with collaborators of Abdus Salam International Centre of Theoretical Physics, Jozef Stefan Institute, University Ljubljana and Uniwersytet Jagiellonski, have presented a comprehensive overview of the current understanding of the MBL phenomenon. The review, published in Reports on Progress in Physics, focuses on recent numerical results and highlights the critical open questions in the field.

The article also gives a concise historical overview, describes the key features of MBL, discusses the recent experiments and their remaining challenges, and qualitatively characterizes the challenges associated with the interpretations of numerical data, which to this day remain inconclusive.

Researchers highlight that the primary obstacle in numerical experiments lies in the rapid increase in computational complexity as the number of particles and the desired simulation time grow. To accurately emulate a relevant MBL system, both parameters must be sufficiently large, which typically pushes the problem beyond the capabilities of even the most advanced supercomputers. This limitation underscores the potential of quantum computers, which, as the authors suggest, "might open an entirely new chapter in MBL studies."

Reference:

Piotr Sierant et al 2025 Rep. Prog. Phys. 88 026502

DOI 10.1088/1361-6633/ad9756

Acknowledgements:

P.S., L.V., J.Z. acknowledge the workshop "Dynamical Foundation of Many-Body Quantum Chaos" at Institute Pascal (Orsay, France) at which foundations for several Sections of this review were laid. P.S. and L.V. acknowledge the program "Stability of Quantum Matter in and out of Equilibrium at Various Scales" (code: ICTS/SQMVS2024/01) at International Centre for Theoretical Sciences (Bengaluru, India) at which many useful discussions about ergodicity breaking phenomena took place. P.S acknowledges the school "Quantum localization and Glassy physics" at Institut d'etudes scientifiques de Cargese (Corsica, France) at which many useful conversations about MBL occurred.

The work of A.S. is funded under the National Recovery and Resilience Plan (NRRP), Mission 4 Component 2 Investment 1.3 funded by the European Union NextGenerationEU. National Quantum Science and Technology Institute (NQSTI), PE00000023, Concession Decree No. 1564 of 11.10.2022 adopted by the Italian Ministry of Research, CUP J97G22000390007. L.V. acknowledges support by the Slovenian Research and Innovation Agency (ARIS), Research core funding numbers P1-0044, N1-0273, J1-50005, and N1-0369. The research of J.Z. was

funded by National Science Centre (Poland) under grant No. OPUS18 2019/35/B/ST2/00034 and the OPUS call within the WEAVE programme 2021/43/I/ST3/01142. Support by Poland's high-performance Infrastructure PLGrid (HPC Centers: ACK Cyfronet AGH) via providing computer facilities within computational Grant No. PLG/2023/016370 is acknowledged. The research has been also supported by a grant from the Priority Research Area (DigiWorld) under the Strategic Programme Excellence Initiative at Jagiellonian University (J.Z.). P.S. and M.L. acknowledge support from ERC AdG NOQIA; MCIN/AEI (PGC2018-0910.13039/501100011033, CEX2019-000910-S/10.13039/50110 0011033, Plan National FIDEUA PID2019-106901GB-I00, Plan National STAMEENA PID2022-139099NB-I00 project funded by MCIN/AEI/10.13039/501100011033 and by the i¿½European Uni n NextGenerationEU/PRTRi¿½ (PRTR-C17.I1), FPI); QUANTERA MAQS PCI2019-111828 2); QUANTERA DYNAMITE PCI2022-132919 (QuantERA II Programme co-funded by Euro ean Union's Horizon 2020 program under Grant Agreement No 101017733), Ministry of Econ mic Affairs and Digital Transformation of the Spanish Government through the QUANTUM NIA project call - Quantum Spain project, and by the European Union through the Recov ry, Transformation, and Resilience Plan - NextGenerationEU within the framework of the Dig tal Spain 2026 Agenda; Fundacio Cellex; Fundacio Mir-Puig; Generalitat de Catalunya (Euro ean Social Fund FEDER and CERCA program, AGAUR Grant No. 2021 SGR 01452, Quantu CAT U16-011424, co-funded by ERDF Operational Program of Catalonia 2014-2020); Barc lona Supercomputing Center MareNostrum (FI-2024-1-0043); EU Quantum Fla ship (PASQuanS2.1, 101113690); EU Horizon 2020 FET-OPEN OPTOlogic (Grant No 899794 ; EU Horizon Europe Program (Grant Agreement 101080086- NeQST), ICFO Int rnal i¿½QuantumGaudii¿½ project; European Union's Horizon 2020 program under he Marie Sk?odowska-Curie grant agreement No 847648; i¿½La Caixai¿½ Junior Leaders fellowships, i¿½La Caixai¿½ Foundation (ID 100010434): CF/BQ/PR23/11980043.