Breaching the horizons: Universal spreading laws confirmed

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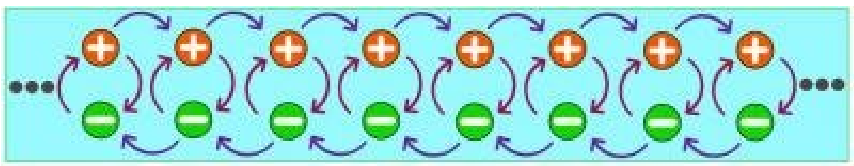


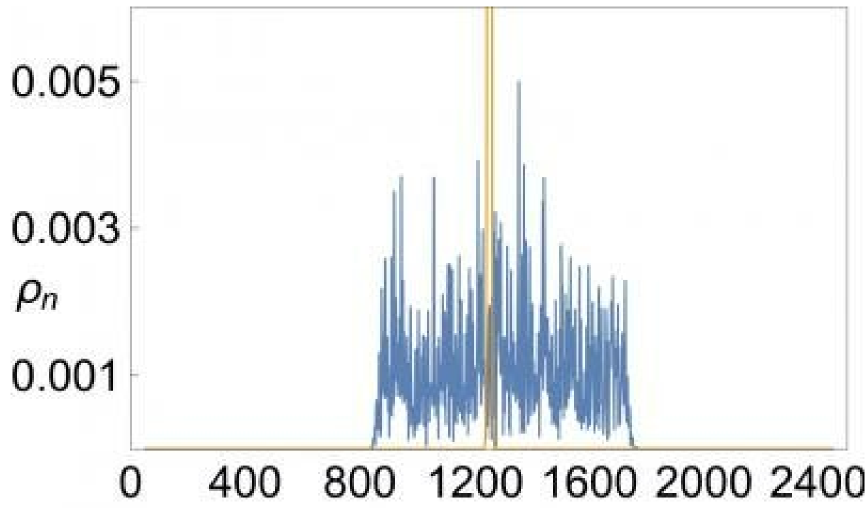
The vertical arrows indicate the quantum coin action within each two level system, while the horizontal ones show the action of the transfer operator. Credit: IBS

The universal laws governing the dynamics of interacting quantum particles are yet to be fully revealed to the scientific community. A team of researchers at the Center for Theoretical Physics of Complex Systems (PCS), within the Institute for Basic Science (IBS in Daejeon, South Korea) have proposed to use an innovative toolbox that enables them to obtain simulation data of equivalent to 60 years' experimental time. By extending the computational horizons from one day to unprecedented time scales, the IBS researchers were able to confirm that a cloud of quantum particles continues to spread even when particle to particle interactions, originally deemed to be the activator of the spreading, exert almost no strength. Their findings were published online on 30 January 2019 at *Physical Review Letters*.

The work deals with two of the most fundamental phenomena of condensed matter: interaction and disorder. Think about ultra-cold atomic gases. One atom from the gas is a quantum particle, and thus a quantum wave as well, which has both amplitude and phase. When such quantum particles, i.e. waves fail to propagate in a disordered medium, they get trapped and come to a complete halt. This destructive interference of propagating waves is Anderson localization.

Microscopic particles, described by quantum mechanics, interact when approaching each other. The presence of interaction, at least initially, destroys localization in a cloud of quantum particles, and allows the cloud to escape and smear out, though very slowly and subdiffusively. When atoms interact (collide) they exchange not only energy and momentum, but change their phases as well. The interaction destroys regular wave patterns, leading to the loss of the phase information. As time goes on the cloud spreads and thins out.

Hot debates over the past decade were devoted to the question of whether the process will stop because the effective strength of interaction becomes too low, or not. Experiments with Bose-Einstein condensates of ultracold Potassium atoms have been conducted for up to 10 seconds as researchers try hard to keep the atomic gas stable. Numerical computations were performed for an equivalent of one day. Remarkably theoretical computational physics was already in a unique situation to be way superior to experiments!



Wave packet density profiles of a zero (orange, respecting Anderson localization) and non-zero (blue, disrespecting Anderson localization) nonlinearity. The simulation times reach 2*10^12. Credit: IBS

The team of IBS researchers, led by Sergej Flach, decided to give the cloud dynamics a novel hard numerical test and to extend the computational horizons from one day to 60 years in experimental time equivalent. The main challenge is the slow pace of the process: one has to simulate the dynamics of the cloud for a long time to see any significant changes. The new goal was to extend the previous records drastically, by a factor of at least ten thousand, and to simultaneously develop a new approach to fast simulations of computationally hard physical models.

The research team observed subdiffusive clouds spreading up to the record timescales investigated. The key to the success was the usage of so-called Discrete Time Quantum Walks—theoretical and experimental platforms for quantum computations. Their unique feature is that time doesn't flow continuously, but increments abruptly, becoming one of the main speedup factors. Several additional technical tools were used to realize the new record times: massive supercomputing powers of IBS, program optimization, and the use of clusters of graphical processing units (GPU).

The results of the team pose complicated new questions on the understanding of the interplay of interaction and disorder. IBS-PCS researchers continue to work on different aspects of the problem, using tools including Discrete Time Quantum Walks. "We are currently employing the same technique to crack several other long-standing problems that require novel computational approaches and powers", says Ihor Vakulchyk—Ph.D. student of the research team. The proposed toolbox opens seemingly limitless possibilities for the novel field of Quantum Modeling and optimization of computer models in physics.

More information: Ihor Vakulchyk et al, Wave Packet Spreading with Disordered Nonlinear Discrete-Time Quantum Walks, *Physical Review Letters* (2019). DOI: 10.1103/PhysRevLett.122.040501

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