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Hydrodynamics and the quantum butterfly effect in black holes and large N quantum field theories

Scopelliti, V.

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Author: Scopelliti, V.

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Summary

One of the exciting things about research is that we never know in which topic and when the next important discovery will occur. We can only follow our curiosity and our instinct, maybe guided by the power of analogies. This thesis summarizes a few answers to the many questions we have been puzzled and fascinated by in the course of the last four years. Some of these questions arose by having in mind the technological development of the (hopefully) near future. The understanding of high-temperature superconductors and the mysterious behaviour of strongly coupled physics, together with the role of quantum information, might potentially have a big impact on our lives. Another motivation is purely theoretical.

We know that, if a system is chaotic, a small change of the initial condition can dramatically affect its time evolution (the *butterfly effect*). This sensitivity to the initial condition is a property of the early time and small scale of the system, *i.e.*, we need to zoom in to see it. On the other side, if we want to study the large scale properties and the collective behaviour at late times, *i.e.*, zooming out, we can likely apply a hydrodynamic description. The idea that two phenomena belonging to different time scales could be related is very charming, and can reveal the existence of a new symmetry. This is one of the theoretical motivations of this thesis: is it possible that chaos, which happens at a very early time, can affect hydrodynamic transport in a system? Even at the classical level, this question appears enigmatic. On the other side, for quantum systems, understanding many-body chaos is even more intriguing. Nevertheless, over the past few years some progress has been made on both topics, often by means of the AdS/CFT duality.

In this thesis we investigated these questions from two opposite directions, both from weakly coupled field theories, using a combination of field theory techniques, and from strongly-coupled field theories, using the AdS/CFT correspondence. Moreover, we studied a fermionic and bosonic quantum critical point, which are 'exotic' states of matter where quantum information plays an important role.

The main results of this thesis consist of the formulation of a Boltzmann-like equation for many-body chaos, the discovery of a new property of thermal correlation functions (*pole-skipping*), and the analysis of which is

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the correct and meaningful observable to measure experimentally in order to probe quantum chaos. The tool for this investigation is a particular correlation function, extensively analysed in this thesis, the out-of-time ordered correlation function (OTOC).

In chapter two, we write the kinetic equation for many-body chaos. This equation, with a Boltzmann-like structure, gives a precise microscopic understanding of what quantum chaos represents in diluted systems, namely a gross energy exchange. A qualitative picture of this kinetic equation is the following: imagine a network where each node has ingoing and outgoing connections. It can be the power network of a country where the nodes correspond to the sites where electricity is generated/used or a social network where the nodes are the users and the links are any orientable connections (tweet/retweet, like/dislike). In this framework, the traditional Boltzmann equation for transport counts the time evolution of the net *gain* of the node (respectively how much electricity is generated with respect to the amount used, or the number of tweets minus the number of retweets of a single account). The kinetic equation for quantum chaos, on the other side, counts the sum of the ingoing and outgoing contributions. This quantity is not constant in time, and for quantum systems typically grows exponentially, a signature of quantum chaos. The rate of exponential growth can be shown to be bounded [16]. Our kinetic theory interpretation of quantum chaos indicates that, for some classes of networks, this counting has a specific behaviour, exponential in time. This raises several questions of why, microscopically, this quantity is bounded and whether similar results can be extended to general networks, beyond quantum systems.

In chapter three we try to understand the generality of this kinetic theory for chaos. We check what happens for systems where quantum information and long range entanglement begin to play a role, as for example in the proximity of a quantum critical point. We show that, for two paradigmatic theories, the bosonic $O(N)$ vector model and the Gross-Neveu model, close to the quantum critical point (QCP), chaos is still described by our kinetic theory.

In chapter four we analyse strongly coupled systems by means of the holographic duality. We show that the chaotic properties of black holes can be probed with a highly out-of-equilibrium experiment that corresponds to diffusive behaviour near the horizon. For systems dual to black holes, chaos leaves imprints in the late-time correlation functions that determine hydrodynamic transport. This phenomenon is highly surprising and has been named *pole-skipping* [56].

In the last chapter we address an important question regarding the

out-of-time correlation (OTOC) function. Over the last years there has been much interest in experimental protocols to measure the OTOC. The discussion has relied on the statement, often found in literature, that the OTOC is insensitive to the way it is regularized. We challenge this statement and show that both in weak and strongly coupled theories the OTOC strongly depends on the regularization. We indicate which regularization corresponds to the physical one and we interpret this result both in terms of the kinetic theory derived in the previous chapters and the Loschmidt echo experiment.