Precision holography and its applications to black holes
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SUMMARY

One of the most inspiring conjectures of the last fifteen years in search of a theory of quantum gravity is the conjecture of a holographic principle. In analogy to an optical hologram, which stores a three-dimensional picture on a two-dimensional photographic plate, this conjecture states that all gravitational phenomena in a \((d+1)\)-dimensional spacetime can be described by a \(d\)-dimensional quantum field theory without gravity. The best elaborated example of such a holographic duality is the so-called AdS/CFT correspondence.

This thesis discusses two different aspects of the AdS/CFT correspondence: On the one hand we apply the correspondence in order to examine a microscopic theory of black holes which was proposed about ten years ago and which contains promising features to solve long-standing black hole paradoxes, the fuzzball proposal. This application of a holographic duality is discussed in chapter 3 and 4. Before that, we provide an introduction to holography in chapter 1 and an introduction to the fuzzball proposal in chapter 2. On the other hand, the last part of the thesis, chapter 5 and 6, discusses a generalization of the AdS/CFT correspondence to cases in which the \(d\)-dimensional quantum field theory does not have conformal symmetry. We lay down the basics in chapter 5 and look at applications on the hydrodynamic limit of the quantum field theory in chapter 6.

THE INFORMATION LOSS PARADOXON AND THE FUZZBALL PROPOSAL

A black hole is an object whose mass density is so high that according to General Relativity not even light can escape its event horizon. An observer outside the event horizon has no possibility to explore what is happening inside the horizon and different black hole geometries are according to the no-hair theorem only distinguishable with respect to their overall mass, charge and angular momentum. As a consequence, all information about an object falling into a black hole is lost for the outside observer.

This by itself would not be a paradox, since it could be possible that the information is somehow contained near the singularity of the black hole, the area in the center in which the spacetime curvature is so high that General Relativity ceases to be valid and which then can only be described by a full theory of quantum gravity. At this point though Stephen Hawking's discovery
comes into play that, due to quantum field theory arguments, black holes emit radiation and, as a consequence, lose mass. The spectrum of this radiation is purely thermal, which means that it only depends on the mass, charge and angular momentum of the black hole and not of the detailed consistency of the previously infallen objects. Black holes radiate more the smaller they are, losing more and more mass, until they finally evaporate. But with the evaporation of the black hole also the singularity disappears and all information about infallen objects seems irretrievably lost. This loss of information is in sharp contradiction with quantum theory according to which all the information in the universe has to be conserved. Quantum theory namely says that given the exact knowledge of a later state it should always be possible to reconstruct an earlier state, including the earlier state of an object which has fallen into the black hole.

One possibility to overcome the information loss paradox is to conjecture that a full quantum gravity description of Hawking radiation would contain minuscule deviations from thermality which allow information about infallen objects to escape. But even if such a description could be successfully formulated, the information transfer from the singularity to the horizon would be necessarily non-local. Locality however is a principle physicists give up only unwillingly since it guarantees causality, i.e. the separation of cause and effect.

The fuzzball proposal, which has been formulated in the context of string theory, tries to resolve the information loss problem by assuming that the usual spacetime of a black hole is only an effective description of a sufficiently distant observer. According to the fuzzball proposal a microscopic description of a black hole does neither contain an event horizon nor a singularity. Hence, an object falling into the black hole can in principle escape (after a very long time) or its information can escape through non-thermal deviations of the Hawking radiation, without violating locality and causality.

In chapter 3 and 4 we discuss a simplified, supersymmetric toy model of a black hole in which all microscopic states are known. These microscopic states can also be described by means of a dual theory, which has been used fifteen years ago to count for the first time microscopically the entropy of a black hole. It turns out however that this dual theory is just the AdS/CFT dual of the usual gravitational description and we use the AdS/CFT correspondence to examine the precise map between the microscopic states in both descriptions.

**Nonconformal branes and their hydrodynamics**

Although it seems that the AdS/CFT correspondence can be applied to many spacetimes it could only be formulated explicitly for few spacetimes with enough precision to allow comparison between detailed calculations on the gravity side and on the quantum field theory side. Prime examples of precisely formulated correspondences are the spacetimes close to a large number of D3 branes or close to a bound state of D1 and D5 branes. (D$_p$ branes, with $p$ integer, are extended massive objects in String Theory with $p + 1$ spacetime dimensions.)

An important step towards a precise formulation of an AdS/CFT correspondence is a careful
handling of infinities which would arise in a naïve formulation. On the gravity side, there appear for example integrals over the whole spacetime which diverge due to the infinite volume of the latter. These infinities correspond to infinities in the quantum field theory which arise in the so-called renormalization and which require a careful redefinition of the theory. The according redefinition of the correspondence is therefore called holographic renormalization.

Holographic renormalization for the spacetimes of D3 branes and the D1/D5 system is already well-known. Both of these examples however correspond to quantum field theories which have a so-called conformal symmetry, at least at high energies. In chapter 5 we develop holographic renormalization for Dp branes with $p \neq 3$, which do not possess conformal symmetry and hence are called nonconformal.

An interesting application of the AdS/CFT correspondence are spacetimes whose dual quantum field theory describes a plasma. The plasma corresponding to the quantum field theory of (black) D3 branes for example has been proven useful as a toy model of the quark gluon plasma, which is examined by experimental physicists in accelerators like the Relativistic Heavy Ion Collider in New York and soon the Large Hadron Collider in Geneva. These plasmas can often be described by a fluid which obeys the laws of relativistic hydrodynamics. Using the AdS/CFT correspondence one can map the equations of motion of hydrodynamics to the gravitational fluctuation equations around the dual spacetime.

Even though the D3 brane plasma provides a reasonable model of the quark gluon plasma it differs from the latter in that the quantum field theory proper on which the quark gluon plasma is based, Quantum chromodynamics, is not conformal. For this reason it is interesting to study non-conformal plasmas using the AdS/CFT correspondence. In chapter 6 we therefore apply the results of chapter 5 to examine the hydrodynamics of nonconformal Dp branes.