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## Instantons and cosmologies in string theory

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# Conclusions

This thesis has covered two separate topics: instantons and cosmologies in scalar-gravity truncations of supergravity and scalar-gravity theories in general. These were shown to be related in the final chapter.

The first chapter laid out the foundations of bosonic string theory and superstring theory. We learned that in a quantum theory of relativistic strings, mass and spin are actually the quantum numbers of a particle as opposed to Casimir operators (i.e. fixed properties). However, the main message of that chapter was the field theory limit of string theory. If we assume that strings couple weakly to each other, i.e. that the string coupling given by the constant value of the dilaton is small, then we can define a two-dimensional CFT on the world-sheet of the string. Fields such as the spacetime (target space) metric are viewed as field-dependent couplings of the  $\sigma$ -model, however, they can be shown to be operator insertions of coherent states of the string spectrum, such as the spin-2 particle called the graviton. Imposing that the classical conformal invariance of the CFT also hold at the quantum level requires setting the  $\beta$ -functions for the field-dependent couplings to zero. These constraints are perturbative in  $\alpha'$ , and, in the low energy approximation, we keep only the zeroth-order terms. This leaves us with constraints that look like the equations of motion of spacetime fields (such as the Einstein equation for the spacetime metric). By encoding these spacetime equations of motion into actions we get the supergravity actions, which are the ones that were used in this thesis.

In chapter 2 the basics of instantons were explained. We started with the example of the non-relativistic quantum mechanical particle in the double-well and periodic potentials. We learned that instantons are extrema of the Euclidean action that allow us to compute tunneling amplitudes. These tunneling effects taught us that the naïve degenerate perturbative vacua of the theory are actually not stationary states, since the particle can tunnel out of them. This allowed us to define the true vacuum of the theory, which is roughly a linear combination of the naïve vacua. The true vacuum samples all of the degenerate minima of a potential, thereby spontaneously restoring the symmetry of the theory. We then moved on to the application of instantons in quantum field theory, by treating the example of the Yang-Mills instanton. The latter showed us how the principles of instantons and true vacua generalize to quantum field theories. We saw that a path integral that takes instanton effects into account, i.e. a path integral that gives the *true-vacuum-to-true-vacuum* amplitude, effectively gets a topological  $\theta$ -term in its action. At the end of the chapter, I gave a brief explanation of how instantons in  $D$  Euclidean dimensions can sometimes correspond to solitons in  $D + 1$  spacetime dimensions.

In chapter 3 we put this knowledge to use in a scalar-gravity theory. First, a quick explanation

of the issues of the Euclidean path integral for gravity was given. Then, we defined a theory of gravity with two scalars, which can be embedded in type IIB supergravity for certain values of the dilaton coupling. We found the solutions of this theory and were able to classify them in terms of their  $SL(2, \mathbb{R})$  ‘conjugacy classes’. There turned out to be three  $SL(2, \mathbb{R})$ -unrelated families of solutions. The instanton-soliton correspondence that was explained in general in chapter 2 was put to use, as we realized that the three families of D-instantons can be viewed as spacelike sections of superextremal, extremal, and subextremal electrically charged black holes. We studied the singularity structure of these solutions and evaluated their actions. After a comment on the tunneling interpretation of these solutions, we discussed the possibility that they might lead to non-perturbative  $R^8$  corrections to the type IIB effective action.

Finally, I commented on some work in progress. Putting D-instantons in an AdS background can lead to interesting applications in AdS/CFT. The correspondence between the extremal D-instanton in type IIB supergravity and the self-dual instanton of  $\mathcal{N} = 4, d = 4$  super-Yang-Mills has been known for a while. We hope to understand the field theory dual of the non-extremal D-instantons, which may be pointing us toward non-self-dual super-Yang-Mills instantons.

The next part of this thesis was concerned with another kind of scalar-gravity solution that depends on one parameter: FLRW cosmologies. Chapter 4 introduced the basics of the standard cosmology and modern cosmology. Inflation and present day acceleration are experimentally undeniable events in our universe. If string theory is the theory of everything, it must be able to derive a realistic scenario for them. At the end of the chapter, I summarized a few of the many string theory based approaches toward modern cosmology, focusing on models that reduce to theories of four-dimensional gravity with scalar fields.

In chapter 5 we studied the gravity-scalar system with a single exponential potential. First, we showed that, by a proper field redefinition, the system effectively has only one scalar in the exponent of the potential. Then, the equations of motion were rewritten in the language of autonomous systems. We saw that, in this terminology, the familiar FLRW power-law and de Sitter solutions can be thought of as critical points, and the more interesting solutions are the ones that interpolate between those two regimes. This showed us how to recognize solutions that have periods of transient acceleration, which is phenomenologically interesting for models of both inflation and present day acceleration.

In chapter 6, we dropped all simplifications by studying the *most* general multi-exponential potential for an arbitrary number of scalars. A general formula for finding critical points was derived, which unveiled de Sitter critical points that had never been discovered. The general formula was then applied to some specific cases coming from reductions of pure gravity over three-dimensional group manifolds. At the end of the chapter, comments on possible extensions of this work were made. These possibilities are including a barotropic fluid in the system to mimic matter, and including spatial curvature. One possible application of such an extension is the cosmic coincidence problem, which might be solved by scaling solutions.

Chapter 7 was the concluding chapter that tied D-instantons and cosmologies together. Their mathematical similarity, due to the fact that both are solutions to scalar-gravity models that depend on only one coordinate, was translated into two concrete correspondences. First, we saw that some D-instantons are related to S(-1)-branes via Wick rotation. In the second part of the chapter we developed a formalism that put both types of solutions on equal footing. By interpreting the scalar fields as coordinates of a two-dimensional target space, and subsequently

performing coordinate transformations on this target space, we realized that instanton solutions can be thought of as the trajectories of particles on a  $dS_2$  space. The three families of instantons correspond to massive, massless and tachyonic particles. The cosmologies on the other hand are interpreted as trajectories of a particle on a Euclidean  $\mathbb{H}_2$  space.

The Ansätze for the spacetime metrics of both the instantons and the cosmologies are such that both metrics have only one degree of freedom. By interpreting this degree of freedom as an *extra* target space coordinate, we were able to combine both systems into the action of one particle in a three-dimensional Minkowski spacetime. In this formalism, an instanton and a cosmology are patched together, and are viewed as two portions of the trajectory of a single particle. This suggested a possible scenario to resolve cosmological singularities. For instance, in this target space language, the Big Bang is preceded by an instanton phase, which is itself preceded by a Big Crunch.

Understanding the deeper links between instantons and cosmologies may lead to interesting and unexpected results. For instance, by using AdS/CFT to further knowledge about the correspondence between gravity and gauge instantons, one might establish new cosmology/gauge correspondences in the context of dS/CFT.

