Conformal invariance and microscopic sensitivity in cosmic inflation

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Motivation

1.1 On being a string cosmologist

Our universe had a beginning —or at least, so it seems. With the technological advances of previous decades and the incredible achievements in the theoretical understanding of nature's workings, we are tantalizingly close to answering existential questions that are as old as mankind itself. *"Where do we come from?"*, *"What are we made of?"* These questions, that have always been of a philosophical nature, are now almost in reach of observational verification. Science is painting us a picture of our universe, which we can understand from as early as 10^{-10} seconds after the supposed beginning, the *big bang*. Since its beginning the universe has been expanding, which led to a cooling down of the initial hot, dense state. This allowed atoms to combine to molecules and stars to be born, finally leading to the universe we observe today. Our current knowledge of the cosmic evolution of our universe is an astonishing feat, but there is always the quest to learn more. Driven by curiosity, we are trying to push our knowledge to within the first 10^{-10} seconds. This tour de force requires a perfect orchestrated collaboration between observational achievements and theoretical advances.

To understand observations, we need a theoretical foundation. For observations from the early universe, we need to acquire knowledge about nature's working from the smallest to the largest energy scales or equivalently on all distance scales. In the early beginning of the universe, the typical energy of particles was beyond imagination, as the whole universe was tightly packed into a hot, energetic plasma. Such energies probe microscopic particle interactions that happen at the tiniest of scales. Without an accurate understanding of the processes happening at the highest energies, it is impossible to correctly interpret any observation from the primordial epoch and to truly understand how our universe came to be.

Vice versa, to verify theoretical predictions, we need an observational foundation. This is a rather obvious statement. The backbone of physics is its solid foundation in the form of verifiable and falsifiable claims, following from a consistent, coherent and ideally complete theoretical framework. However, given the progression of our theoretical understanding into ever more energetic realms of physics, achieving the required regime observationally is easier said than done. For example, the physics of particle interactions is uniformly described in one all-coordinating theory, called the *standard model*. It correctly describes processes of typical energies up to about 10^3 GeV and is currently under scrutiny precisely around this threshold energy at CERN's state-of-the-art Large Hadron Collider. However, the standard model misses one vital piece in its description of nature, as it does not contain the gravitational theory of general relativity. A unified theory of both gravity and particle physics would be an enormous achievement of our fundamental understanding of nature. However, since it is not expected that a unified theory of both gravity and particle physics interactions will appear below 10^{19} GeV —the scale where quantum effects are comparable to classical gravity—, testing such a theory will not happen in the foreseeable future with current terrestrial technology. Our only hope is to observationally explore the realm where such high energies occur naturally: astrophysics and cosmology. Without a way of probing processes at such high energies, we risk to bring any theoretical advance in this direction to a stop.

The lack of observations has not stopped us from formulating a candidate theory of quantum gravity, *string theory*. In this theory, fundamental interactions happen between strings rather than point particles. It is possibly a unifying theory for general relativity and the standard model, although its very nature, i.e. characteristic energy scales of 10^{19} GeV, currently prevents the theory from making testable predictions. Nevertheless a consistent combined theory of quantum mechanics and gravity must exist and at the moment string theory is the only real candidate.

This is where cosmology may help, especially since we now have good reasons to believe that the earliest evolution of the universe is described by a period of accelerated expansion, called *inflation*. Inflation is capable of solving many of the issues of a standard expanding universe. However, inflation, which is a generic phase of accelerated expansion, turns out to be surprisingly sensitive to its microscopic description, which is largely unknown. With a fundamental theory of everything without observational means to test it and with an observationally satisfying mechanism in need of a microscopic description, *string inflation* seems to provide a unique opportunity to address two problems at once. A string theory description of inflation would provide a means to probe microscopic physics by cosmological observations, while simultaneously providing a means to microscopically gain insight in the structure of the dawn of time.

1.2 This thesis

In this thesis we present multiple, complementary approaches to the understanding of string inflation. As explained, the sensitivity of inflation to the microscopic details of the theory from which it originates, provides a great opportunity to probe this microscopics observationally. However, it also means that describing a consistent microscopic theory in which inflation can be embedded, is very hard. In this thesis we will study to what extent this sensitivity might hinder theoretical model building and what are possible approaches to circumvent these issues.

A fundamental ingredient in the approaches we present is *conformal invariance*, or (local) scale invariance. A theory that is scale invariant describes a system which looks the same on all length scales. This might be a surprising starting point to describe our universe, which certainly does not seem to be scale invariant, but in the mathematical description of inflation, conformal invariance plays an exceptionally important role. In this thesis we consider two (different) ways in which conformal invariance might prove crucial in our understanding of the primordial inflationary epoch.

A review of relevant aspects of conformal field theory is presented in chapter 3, explaining its relevance to string theory. There, we also present the three different guises in which string theory will be employed throughout the different chapters. Its *worldsheet* description; the low energy effective *supergravity* description derived from it; as well as the *holographic* conformal field theory description of an accelerating universe that arises from string theoretical considerations, are all addressed. These form the background material to chapters 5, 4 and 6 respectively, where we will explore the consequences for string inflation within each of the different approaches.

In chapter 4 we consider supergravity descriptions of inflation. Supergravity appears as the low energy limit of (super)string theory. Since string theory itself is not a fully understood theory and it is generally very hard to use it for explicit calculations, supergravity has become an interesting framework to reconcile inflation within stringlike physics [1, 2]. Due to the sensitive nature of inflation, it has proven to be very difficult to find models that are stable under quantum corrections. We study the sensitivity of inflation to possible additional physics such as the standard model, in a general supergravity set-up.

In chapter 5 we consider a new approach to string inflation, based on the (defining) worldsheet description of string theory. The worldsheet theory is described by a conformal field theory. In general, both the inflationary dynamics of a four-dimensional spacetime as well as other internal/matter sectors are encoded in the total worldsheet conformal field theory. We probe the interaction between the two sectors by enforcing a nearly marginal perturbation of the internal sector theory. Assuming worldsheet conformal invariance to be maintained for the total theory throughout the inflationary evolution, the deformation of the internal sector induces a response in the form of a deformation of the inflationary sector, which can be understood as a time evolution in the four-dimensional spacetime. Insisting on a slow-roll inflationary phase, this imposes constraints on the allowed deformations of the internal sector. In this way, observations from the inflationary era might be used to constrain the underlying string theory.

The final approach to obtain a fundamental understanding of the inflationary epoch is presented in chapter 6, in which we study the two- and three-point correlation functions of density perturbations generated during inflation. Since inflation is described by a quasi-de Sitter evolution, these correlation functions are expected to be constrained by the (broken) conformal isometry group of de Sitter spacetime at asymptotically late times. The approach is truly orthogonal to all other approaches, as it uses the symmetries of de Sitter space in a way that, tantalizingly, borrows heavily from a revolutionary insight from string theory: holographic duality. The origin of this holographic duality is rooted in string theory and it is one of the theory's most surprising predictions, maximizing the power that underlies the string theory surface. A true understanding of the duality and the microscopic origin behind it would provide an incredible improvement in the understanding of the origin of our universe. The investigations in chapter 6 of the symmetry constraints on the two- and three-point functions provide a first step in the investigation to what extent this duality might apply to the inflationary era.

Given the emphasis earlier in this motivation on the necessity of an amalgamation of observations and theory, this work admittedly contains only theoretical studies of a possible stringy origin of inflation. However, in all cases there is a clear observational component behind the initial motivation of the study, which permeates each approach. Therefore, to put our results into the required cosmological context, we present an introduction to inflationary cosmology in chapter 2. With this background, we hope to have made clear how this work can provide new and interesting insights in the development of a string theoretical description that underlies the inflationary, primordial stages of our universe.