Conformal invariance and microscopic sensitivity in cosmic inflation
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7

Conclusions

In this thesis we have collected the findings of three separate studies in inflationary string cosmology. The initial motivation for each of these studies is the important role inflation might play in our understanding of the microscopic structure of nature. This thesis helps to reveal important aspects of the theory, that we need to understand better before we can let inflation fulfill its intended role.

7.1 Microscopic sensitivity

One of the lessons of this thesis is that observations from the early universe might indeed be capable of unveiling hints of the universe at the tiniest scales, but that the sensitivity of inflation to microscopic physics requires a detailed and complete understanding of its underlying microscopic description before we can reap the benefits of the cosmological approach to quantum gravity. Both in the context of supergravity approaches to inflation as well as in the newly developed worldsheet approach, the sensitivity of inflation to the details of the full theory proves to be more restrictive than one would initially imagine.

In chapter 4 we have argued this by studying the η-problem in supergravity, which we have shown cannot be solved without knowledge of the hidden sectors that are gravitationally coupled to the inflaton. If the hidden sector breaks supersymmetry independently, its fields cannot be stabilized during the cosmological evolution of the inflaton. It is shown that both the subsequent dynamical mixing between sectors as well as the mass of the lightest field in the hidden sector are set by the scale of supersymmetry breaking in the hidden sector. The true cosmological η-parameter arises from a linear combination of the lightest mode of the hidden sector with the inflaton. Generically, either the true η deviates considerably from the naïve η implied by the inflaton sector alone, or one has to consider a multi-field model. Only if the lightest mass in the hidden sector is much larger than the inflaton mass and if the inflaton mass is much larger than the scale of hidden sector supersymmetry breaking, is the effect of the hidden sector on the slow-roll dynamics of the inflaton negligible.

Therefore, we argue that the η-problem is even more severe than what is usually understood from the literature. Typical models for inflation in supergravity do not include anything else but inflationary dynamics. The assumption that other physics, such as the standard model, does not contribute, imposes implicit constraints on this other physics that are in many cases unrealistic. One could therefore say that inflation does not only probe the microscopics of its own underlying theory, but also that of other fields that are initially assumed not even to partake in inflation.

For this reason we have turned our attention in chapter 5 to a description of inflation that explicitly includes all known and unknown physics. We have tried to make full use of the constraints imposed by slow-roll inflation on the string worldsheet, by using a general gravity-matter set-up in which the worldsheet consists of an abstract conformal field theory coupled to a 3+1-dimensional nonlinear σ model. The empirical slow-roll parameters are expressed in terms of the β functions of operators in the matter/internal conformal field theory and the β function of the dilaton. The result confirms that inflation is only sensitive to coarse properties of the matter sector, but that in string theory inflation is a non-perturbative (in g_s) phenomenon and one must go beyond tree-level string theory.

In principle the observed detailed sensitivity of the worldsheet approach to inflation, i.e. the necessity to go beyond tree-level, might be understood simply as the worldsheet variant of the well-known observation that inflation is sensitive to the details of the theory, like we have already seen in the supergravity situation. However, the worldsheet approach sharpens the statement, making exact what inflation is sensitive to. The results in chapters 4 and 5 complement each other, since their regimes of validity differ subtly but fundamentally, cf. figure 7.1. The supergravity approach is a low energy effective approach, i.e. valid for small values of α', which should essentially be enough to describe the classical phenomenon that is inflation. Although the motivation to study such supergravity theories comes from the low energy limit of g_s-perturbative expressions of the string worldsheet, one might hope that one can generalize this to also capture some higher order (in g_s) unknown physics, still within the low energy limit. In this language, our reasoning in the supergravity limit shows that certainly the low energy limit (in α') is insufficient for a full description of inflation. At that stage a possible resolution might be that either one needs to go to higher order in α' or that the assumption that a low energy limit might be sufficient to encode higher order g_s-effects is invalid. Initially one could hope that higher or-

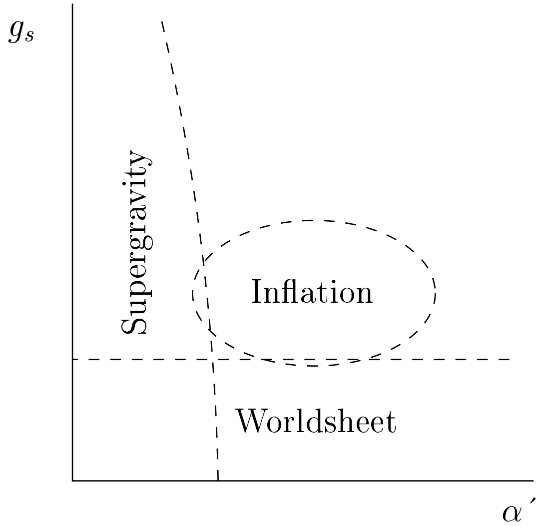

Figure 7.1: *The regimes of applicability for a worldsheet set-up and in a supergravity context. Supergravity is the small α'-regime of string theory and is (without a strong justification) also applied at higher values of g_s. The worldsheet approach of chapter 5 is valid for all α' but certainly not in the large g_s-regime. Inflationary models in supergravity are very sensitive to the physics of hidden sectors, indicating that inflation is strongly coupled in α'. In chapter 5 we have shown that no tree-level (in g_s) string inflationary models can be found. This means that inflation is located in the upper right part of the diagram.*

der effects in g_s are not really relevant, since inflation seems to be not a specifically strongly coupled string phenomenon. In a leap of faith, this would mean that by including all α' corrections to any unknown sector in the theory, inflation can be fully understood. Although the worldsheet approach is only a lowest order expansion in α' for the inflationary part of the theory, the unknown theory is explicitly incorporated to all orders in α'. Hence, while the former should be sufficient to describe the classical evolution of inflation, the latter exactly achieves the sought-for parameterization of the remaining unknown physics. In this language, chapter 5 shows that inflation is also sensitive to strong coupling effects in g_s. As such, the worldsheet approach rules out a whole class of theories that have previously been inaccessible in the approach of the supergravity low energy limit, while at the same time producing a qualitatively very similar conclusion: inflation is more sensitive to the details of the full theory than one would initially imagine. It is both strongly coupled with respect to the α'-as well as with respect to the g_s-corrections of the theory.

7.2 Conformal invariance

The approach taken in chapter 6 could provide a completely new perspective on inflationary cosmology. Guided by holographic principles, it possibly evades the problems from which the more conventional approaches of chapters 4 and 5 suffer. In chapter 6 we have investigated the constraints imposed by symmetry on the three-point correlation function of primordial density fluctuations in slow-roll inflation. It follows from the defining property of slow-roll inflation that primordial correlation functions inherit most of their structure from weakly broken de Sitter symmetries. Using holographic techniques borrowed from the AdS/CFT correspondence, the symmetry constraints on the bispectrum are mapped to a set of stress-tensor Ward identities in a weakly broken three-dimensional Euclidean conformal field theory. The most general solution to these Ward identities can be constructed using conformal perturbation theory. Translating back to the gravity side, our answer illustrates the full underlying symmetry structure of slow-roll non-Gaussianities.

Once again, the approach in chapter 6 is a testimony to the importance of the guiding hand of symmetries in physics. Another conclusion of this thesis is therefore the ubiquity of the applicability of conformal symmetry in our understanding of the universe. The appearance of conformal invariance in any description of quantum gravity is perhaps not very surprising, since it is a core ingredient of the renormalization procedure inherent to any quantum theory. On the other hand, the role conformal symmetry plays in each of the two approaches presented in chapters 5 and 6 is surprisingly different. In chapter 5, conformal invariance of the two-dimensional worldsheet theory is a strict consistency condition for the quantum string description. Formally we have shown that the coarse slow-roll description in terms of ϵ and η can be related to coarse properties of the hidden conformal field theory, like its β functions. Thus, inflation might in principle be described by a two-dimensional conformal field theory and this can be used to observationally constrain the theory. This conformal description happens at the level of the worldsheet, where the gravity and inflaton degrees of freedom appear as background fields. In chapter 6, conformal invariance is used at the level of the three-dimensional asymptotic future of the inflationary gravity theory itself. The conformal symmetry and its spontaneously broken rendition present themselves through constraints on the structure of curvature perturbations, which suggests an underlying holographic transcription of quantum gravity. For now, the relation between both conformal theories eludes any detailed understanding. Such a relation would be highly non-trivial and is perhaps unlikely —for one thing, the dimensions of the theories differ. Nonetheless, it is very interesting to see that conformal field theories play such an important role in inflation at several levels of the string theory description. It puts conformal invariance at the heart of inflationary cosmology, albeit in two variously different guises.

In conclusion, the different viewpoints on string inflation investigated in this thesis shed a brighter light on different aspects of the merits and problems of our current understanding of inflationary cosmology and its underlying microscopic structure. Although —or precisely because— each chapter investigates a different aspect of early universe cosmology, together they sketch a more detailed picture which may prove to be useful for further research. Our studies help crystalizing some of the fundamental problems and overarching guiding principles, which will help to pave the way in the understanding of the primordial universe and, with it, of the microscopic origin of nature.