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Christian Friedrich Steinwachs

Non-minimal Higgs Inflation and Frame Dependence in Cosmology

Doctoral Thesis accepted by
University of Cologne, Germany

Springer

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Publications Based on this Work

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2) Barvinsky, A.O., Kamenshchik, A.Yu., Kiefer, C., Starobinsky, A.A., Steinwachs, C.: *The Higgs Field as an Inflaton.* In *Proceedings of the 12th Marcel Grossmann Meeting On General Relativity* (ed. T. Damour, R.T. Jantzen, R. Ruffini), pp. 1244–1246 (2009)

3) Barvinsky, A.O., Kamenshchik, A.Yu., Kiefer, C., Steinwachs, C.F.: Tunneling cosmological state revisited: Origin of inflation with a nonminimally coupled Standard Model Higgs inflaton. Phys. Rev. D **81**, 043530 (2010)

4) Steinwachs, C.F., Kamenshchik, A.Yu.: One-loop divergences for gravity nonminimally coupled to a multiplet of scalar fields: Calculation in the Jordan frame. I. The main results. Phys. Rev. D **84**, 024026 (2011)

5) Barvinsky, A.O., Kamenshchik, A.Yu., Kiefer, C., Starobinsky, A.A., Steinwachs, C.: Higgs boson, renormalization group, and naturalness in cosmology. Eur. Phys. J. C**72**, 2219 (2012)

6) Steinwachs, C.F., Kamenshchik, A.Yu.: One-loop divergences for gravity nonminimally coupled to a multiplet of scalar fields: Calculation in the Jordan frame. II. Comparison with the Einstein frame results. (in preparation)

Supervisor's Foreword

The field of cosmology is undergoing an exciting phase of development. Observations have reached an amount of precision that can compete with the precision known from other fields of physics. The most recent manifestation of this state is the release of data from the PLANCK mission in March 2013. An important aspect of current cosmology is its deep connection with particle physics and quantum theory.

The present book gives an impressive testimony of this connection. It is based on the author's Ph.D. thesis, which he completed at the University of Cologne in 2012. Two of the main features of current cosmology have to do with an accelerated expansion of the Universe. As in particular the observations of type Ia supernovae indicate, our Universe is presently accelerating. The reason for this may be a positive cosmological constant or a so far unknown form of dark energy. The second type of acceleration is more speculative and has probably happened when the Universe was younger than 10^{-30} s. This phase is called inflation. Although there is strong support for inflation for both conceptual and empirical reasons, the exact mechanism leading to inflation has not yet been revealed. Most models make use of one or more scalar fields, whose dynamics is more or less introduced in an ad hoc way.

In this book, the idea is entertained that the scalar field responsible for inflation is the one scalar field that has so far been observed: the Higgs field of the Standard Model of the strong and electroweak interaction. The corresponding Higgs particle was detected at the LHC in Geneva in 2012 and possesses a mass of around 126 GeV. As has been clear for some time, *Higgs inflation* will only work if an additional coupling of the Higgs field to gravity is included—a strong non-minimal coupling of the field to the Ricci scalar. The consequences of this coupling are the main topic of this monograph.

In the first half of his book, Christian Steinwachs presents a detailed and pedagogical introduction to all the concepts that are needed to understand modern cosmology in general and Higgs inflation in particular. These include, on the one side, the Friedmann models, the inflationary scenario, and cosmological perturbation theory, and, on the other side, the Standard Model of particle physics, effective actions, and renormalization group equations. This part of the book is self-contained and can be read as an accessible introduction into the field itself, even if one is not interested in Higgs inflation.

In the second half, the mechanism of Higgs inflation is discussed at length, and its merits and shortcomings are critically evaluated. This part also addresses the more general question of the frame equivalence in cosmology, in particular that of the JORDAN and the EINSTEIN frame. It is shown that an equivalence is not present at the one-loop level of quantum field theory, and consequences are drawn from this result. I have so far not seen a clearer discussion of this point in the literature.

The monograph concludes with an important section on quantum cosmology. After a concise introduction into this field, it is shown that a certain boundary condition leads to a wave function that is peaked around a sufficiently high initial value of the inflaton field, which is necessary for inflation to occur in the first place.

The book is recognizable for its interdisciplinary character and should be of interest for cosmologists and particle physicists. I am sure it will find many readers.

University of Cologne, Cologne, June 2013 Prof. Dr. Claus Kiefer

Abstract

In this thesis, we investigate the cosmological model of non-minimal Higgs inflation. The basic idea is to unify the "low-energy" sector of the Standard Model with the high-energy phase of inflation during the early universe. Both sectors are described by different theories and rely on the existence of a fundamental scalar field. The scalar Higgs boson is an integral part of the Standard Model in order to maintain gauge invariance while explaining the origin of the masses of elementary particles. Likewise, in cosmology the scalar inflaton is necessary to describe inflation, the early phase of accelerated expansion of the universe. The basic assumption of the Higgs inflation scenario is that the two scalar particles are manifestations of one and the same particle, the *Higgs-inflaton*. Consistency with observational data of the cosmic microwave background radiation requires the assumption of a strong non-minimal coupling of the Higgs-inflaton to gravity. It turns out that quantum corrections of the heavy Standard Model particles mainly determine the cosmological parameters of the model and are crucial for the predictions. Moreover, we resort to the renormalization group flow in order to connect the energy scale of the electroweak vacuum with the inflationary energy scale, separated by many orders of magnitude. We derive a range of possible values for the mass of the Higgs-inflaton. These predictions can be tested by future experiments at the Large Hadron Collider (LHC) and by the satellite PLANCK.

We further investigate an application of the non-minimal Higgs inflation model in the context of quantum cosmology. Via the path integral approach, we calculate the cosmological probability distribution for the universe to tunnel "from nothing to existence". A sharp peak in this distribution—selecting a specific value of the inflaton field—can be interpreted as the initial condition for inflation. The predicted value can be tested by the detection of primordial gravitational waves.

In order to technically realize these models, we calculate the divergent part of the one-loop off-shell effective action of a *O(N)*-symmetric multiplet of scalar fields non-minimally coupled to gravity in a closed form. Due to the functional nature of the couplings, the result is very general and can be used as a reference for many different cosmological applications.

In cosmology it is convenient to transform between two specific field parametrizations, denoted *Jordan frame* and *Einstein frame*. There is an ongoing discussion whether these two frames are physically equivalent. Mathematically, both frames are equivalent at the classical level. We explicitly show that this does not hold anymore at the quantum level. Moreover, we identify this failure of equivalence to be part of a more general problem: the parametrization dependence of the conventional off-shell effective action. This reduces the cosmological debate between Jordan frame and Einstein frame to one problem: the non-covariance of the conventional formalism.

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