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Inflation, quintessence, and the origin of mass

C. Wetterich

Institut für Theoretische Physik, Universität Heidelberg, Philosophenweg 16, D-69120 Heidelberg, Germany

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Abstract

In a unified picture both inflation and present dynamical dark energy arise from the same scalar field. The history of the Universe describes a crossover from a scale invariant "past fixed point" where all particles are massless, to a "future fixed point" for which spontaneous breaking of the exact scale symmetry generates the particle masses. The cosmological solution can be extrapolated to the infinite past in physical time – the universe has no beginning. This is seen most easily in a frame where particle masses and the Planck mass are field-dependent and increase with time. In this "freeze frame" the Universe shrinks and heats up during radiation and matter domination. In the equivalent, but singular Einstein frame cosmic history finds the familiar big bang description. The vicinity of the past fixed point corresponds to inflation. It ends at a first stage of the crossover. A simple model with no more free parameters than ΛCDM predicts for the primordial fluctuations a relation between the tensor amplitude r and the spectral index n, $r = 8.19(1 - n) - 0.137$. The crossover is completed by a second stage where the beyond-standard-model sector undergoes the transition to the future fixed point. The resulting increase of neutrino masses stops a cosmological scaling solution, relating the present dark energy density to the present neutrino mass. At present our simple model seems compatible with all observational tests. We discuss how the fixed points can be rooted within quantum gravity in a crossover between ultraviolet and infrared fixed points. Then quantum properties of gravity could be tested both by very early and late cosmology.

E-mail address: C.Wetterich@thphys.uni-heidelberg.de.

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1. Introduction

A scalar field plays a dominant role both in inflation in primordial cosmology and dynamical dark energy in the present epoch. The potential of this field constitutes primordial or late dark energy, driving an accelerated expansion in the big bang picture. Quintessential inflation [1,2] identifies the inflaton field for inflation with the scalar field of quintessence or cosmon which is responsible for present dynamical dark energy. In particular, cosmon inflation [3] formulates this unification in the context of variable gravity [4], where the strength of gravity depends on the value of the cosmon field.

Both inflation and quintessence can be closely related to approximate dilatation or scale symmetry. For inflation this symmetry is at the origin of the observed approximate scale invariance of the spectrum of primordial fluctuations. In present dynamical dark energy the cosmon plays the role of the pseudo Goldstone boson of spontaneously broken dilatation symmetry [5]. In case of exact dilatation symmetry it would be an exactly massless dilaton, while a tiny mass and potential are generated by a "scale symmetry violation" or "dilatation anomaly". Scale symmetry is intimately related to fixed points of "running" dimensionless couplings or mass ratios. At a fixed point any information about intrinsic mass or length scales is lost. Quantum scale symmetry is then realized even if the underlying quantum field theory is not scale invariant.

The presence of approximate scale symmetry both in the primordial and late cosmology suggests that the infinite past and infinite future of the universe correspond to fixed points. We propose here that the two fixed points have different properties. For the fixed point in the infinite past scale symmetry is not spontaneously broken. All masses vanish. In contrast, the fixed point that will be approached in the infinite future is characterized by spontaneous symmetry breaking of dilatation symmetry, resulting in a spectrum of massive particles and a massless dilaton.

The way how scale symmetry is realized and explicitly or spontaneously broken is directly related to the basic origin of mass. All particle masses are generated either by explicit or spontaneous breaking of scale symmetry. The explicit breaking by an intrinsic mass scale plays a crucial role in the crossover between the two fixed points. It is responsible for scale violation in the primordial fluctuation spectrum and for the end of inflation. Spontaneous breaking characterizes the "future fixed point" and our present universe. The presently observed particle masses are dominated by spontaneous scale symmetry breaking, while dark energy reflects the tiny explicit breaking. The basic mechanisms that generate the particle masses thus provide the physical "raison d'être" for inflation and late dark energy, such that these key cosmological ingredients appear less "ad hoc".

This work is motivated by a central assumption about the properties of quantum gravity that we call "crossover gravity". The running of dimensionless couplings or mass ratios as a function of some intrinsic mass scale μ is assumed to exhibit two fixed points for $\mu \to \infty$ and $\mu \to 0$, with a crossover between the fixed points for finite nonzero μ. Dimensionless functions can only depend on dimensionless quantities. If time and space gradients or momenta are proportional to μ (or can be neglected), the renormalized dimensionless functions can still depend on the ratio μ/χ, with χ the value of the scalar cosmon field which equals the variable Planck mass in our normalization. The ultraviolet (UV) field point is realized for $\mu \to \infty$ at fixed χ or $\chi \to 0$ at fixed μ. Indeed, with all particle masses proportional to χ this fixed point realizes unbroken scale symmetry. All excitations are massless. The infrared (IR) fixed point occurs for $\mu \to 0$ or $\chi \to \infty$. A nonvanishing value of χ spontaneously breaks scale symmetry. We will see that the cosmological solutions of our model realize an evolution where χ vanishes in the infinite past