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Hořava Gravity in the Effective Field Theory formalism: From cosmology to observational constraints

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ABSTRACT

We consider Hořava gravity within the framework of the effective field theory (EFT) of dark energy and modified gravity. We work out a complete mapping of the theory into the EFT language for an action including all the operators which are relevant for linear perturbations with up to sixth order spatial derivatives. We then employ an updated version of the EFTCAMB/EFTCosmoMC package to study the cosmology of the low-energy limit of Hořava gravity and place constraints on its parameters using several cosmological data sets. In particular we use cosmic microwave background (CMB) temperature–temperature and lensing power spectra by *Planck* 2013, WMAP low-ℓ polarization spectra, WiggleZ galaxy power spectrum, local Hubble measurements, Supernovae data from SNLS, SDSS and HST and the baryon acoustic oscillations measurements from BOSS, SDSS and 6dFGS. We get improved upper bounds, with respect to those from Big Bang Nucleosynthesis, on the deviation of the cosmological gravitational constant from the local Newtonian one. At the level of the background phenomenology, we find a relevant rescaling of the Hubble rate at all epoch, which has a strong impact on the cosmological observables; at the level of perturbations, we discuss in details all the relevant effects on the observables and find that in general the quasi-static approximation is not safe to describe the evolution of perturbations. Overall we find that the effects of the modifications induced by the low-energy Hořava gravity action are quite dramatic and current data place tight bounds on the theory parameters.

1. Introduction

In their quest to find a quantum theory of gravity that could describe physical phenomena at the Planck scale ($\sim 10^{19}$ GeV/c^2), relativists have recently started to explore Lorentz violating theories (LV) (see [1] and references therein). Indeed, even though Lorentz invariance (LI) is considered a cornerstone of our knowledge of reality, the challenge presented by physics at Planck energy is forcing us to question also our firmest assumptions. In the cosmological context, LV theories represent interesting candidates for cosmic acceleration, since in their low-energy limit they generally predict a dynamical scalar degree of freedom (DoF) which could provide a source for the late time acceleration, in alternative to the cosmological constant. While the standard model of cosmology, based on the laws of General Relativity (GR), is to date a very good fit to available data, some outstanding theoretical problems related to the cosmological constant have indeed led people to explore alternative theories. To this extent, a wide range of models have been proposed, which either introduce a dynamical dark energy (DE) or modify the laws of gravity on large scales (MG) in order to achieve self accelerating solutions in the presence of negligible matter. All these alternatives generally result in the emergence of new scalar dynamical DoF (see [2–4] for a comprehensive review), as it is the case with LV theories.

Interestingly, LV theories typically break LI at all scales, and are therefore constrainable with many different measurements and data sets over a vast range of energies. Constraints and measurements on the parameters of a general realistic effective field theory for Lorentz violation [5], usually referred to as the Standard Model Extension [6,7], support LI with an exquisite

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accuracy. Furthermore, LI has been tested to high accuracy on solar system scales, and stringent bounds have been placed on the Post Newtonian parameters (PPN), in particular on those corresponding to the preferred frame effects, since such effects are typical of LV theories [8]. Phenomena on astrophysical scales, and in particular tests of gravity in the strong regime, such as those of binary pulsars [9,10], provide further bounds on LV [8]. On the contrary, the exploration of cosmological bounds on LV theories is still in its infancy [11–15].

In the present work, we focus on the class of LV theories known as Hořava gravity [16,17] which modifies the gravitational action by adding higher order spatial derivatives without adding higher order time derivatives, thus modifying the graviton propagator and achieving a power-counting renormalizability. This is possible if one considers that space and time scale differently. Such a prescription is implemented through a breaking of full diffeomorphism invariance, which leads to LV at all scales. The resulting theory propagates a new dynamical scalar DoF, i.e. the spin-0 graviton. As a candidate for quantum gravity, Hořava theory is expected to be renormalizable and also unitary. Nevertheless, at the moment there is no evidence for renormalizability beyond the power-counting arguments.

Hořava gravity shows a rich phenomenology on cosmological scales, e.g. the higher curvature terms in the action lead to a matter bouncing cosmology [18,19]; it also shows different mechanisms by which it is possible to explain the nearly scale invariant spectrum of cosmological perturbations without introducing an inflationary phase [20–24], finally, cosmological perturbations at late time have been investigated in Refs. [11,25–30].

In this paper, we perform a thorough analysis of the cosmology in Hořava gravity by mapping the theory into the framework of Effective Field Theory (EFT) of cosmic acceleration developed in Refs. [31–37], on the line of the EFT of inflation and quintessence [38–40]. The basic idea of this framework is to construct an effective action with all the operators which are of relevance to study linear cosmological perturbations around a Friedmann–Lemaître–Robertson–Walker (FLRW) background and are invariant under time-dependent spatial diffeomorphisms. Indeed an expanding FLRW background breaks time-dependent diffeomorphism, allowing all these operators to enter the action and, furthermore, to be multiplied by a free function of time [38,35]. The resulting action encompasses most models of single scalar field DE and MG which have a well defined Jordan frame. In Refs. [41–44], the EFT framework has been implemented in the public Einstein–Boltzmann solver CAMB [45,46], and the associated Monte Carlo Markov Chain code CosmoMC [47]. The resulting patches, dubbed EFTCAMB/EFTCosmoMC, are now publicly available at http://wwwhome.lorentz.leidenuniv.nl/~hu/codes/ and represent a powerful package which allows to explore cosmological constraints both in a model independent and model specific way [41]. The original action considered in Ref. [32], and implemented in the public version of EFTCAMB, contains all Horndeski and some of the extensions like GLPV [37,48,49], but does not have all the operators necessary to study Hořava gravity. The inclusion of Hořava gravity in the context of EFT of DE/MG has been recently considered and investigated in Refs. [48,50]. In this paper, we consider the most general action for Hořava gravity with all the operators with up to sixth order spatial derivatives, which is the minimal prescription to achieve power counting renormalizability. We focus on the part of this action that contributes to linear order in perturbations [51]. For this action we work out a complete mapping to the EFT framework deriving also the generalization of the original EFT action used in Refs. [41,37]. When we compare the predictions of the theory to the observations, we consider only the low-energy operators of Hořava gravity, since those are the relevant ones to describe the large scale cosmology associated to the observables that we employ. We work out the contribution of these operators to the equations of motion for linear scalar and tensor perturbations, implementing them in an updated version of EFTCAMB that will be publicly released in the near future.

The structure of the paper is the following. In Section 2, we set up the theoretical background of the paper. In particular, in Section 2.1, we introduce Hořava gravity and its main features, while in Section 2.2, we summarize the EFT framework and its implementation in EFTCAMB/EFTCosmoMC. In Section 2.3 we work out the mapping of Hořava gravity in the EFT language focusing on the low-energy part of the action and leaving the mapping of the high-energy part of the action to Appendix A. Finally, in Section 2.4, we discuss the requirements that EFTCAMB enforces on the scalar and tensor DoFs to prevent instabilities in the theory. In Section 3, we study the cosmology of Hořava gravity, discussing in detail how the model is implemented in EFTCAMB and what are the general effects of the modifications on the background and the perturbations. Finally, in Section 4 we explore observational constraints from several combinations of cosmological data sets. To this extent we consider two cases: the low-energy Hořava gravity action which is characterized by three constant parameters; a subcase of the latter, that evades PPN constraints and is characterized by two parameters. We draw our conclusions in Section 5, discussing the main results.

2. Theory

In this section we set up the theoretical basis for our analysis. In Section 2.1, we introduce the main aspects of Hořava gravity, which is the theory we want to investigate and constrain by using the EFT approach. In Section 2.2, we review the EFT framework, discussing its implementation in EFTCAMB, which is the Einstein–Boltzmann solver we use to perform a thorough investigation of the cosmology of the theory. In Section 2.3, we work out the mapping of the low-energy Hořava gravity action in terms of the EFT functions. The mapping of the high-energy part of the action is discussed in Appendix A. Finally, in Section 2.4 we present the full set of equations evolved by EFTCAMB and the conditions that we impose on the tensor and scalar DoFs to ensure that the theory we are considering is viable.

2.1. Hořava gravity

Hořava gravity has been recently proposed as a candidate for an ultraviolet completion of GR [16,17]. The basic idea is to modify the graviton propagator by adding to the action higher-order spatial derivatives without adding higher-order time derivatives, in order to avoid the presence of Ostrogradski instabilities [52]. The theory is constructed in such a way to be compatible with a different scaling of space and time, i.e.

$$[dt] = [k]^{-z}\,, \qquad [dx] = [k]^{-1}\,, \tag{1}$$

where z is a positive integer and k is the momentum. In order to accommodate such a different scaling between space and time, the action of Hořava gravity cannot still be invariant under the full set of diffeomorphisms as in GR, but it can be invariant under the more restricted foliation-preserving diffeomorphisms

$$t \to \tilde{t}\,(t)\,, \quad x^i \to \tilde{x}^i\left(t, x^i\right). \tag{2}$$

Therefore, within this approach, space and time are naturally treated on different footing leading to Lorentz violations at all scales. The emergence of LV is reflected in modified dispersion relations for the propagating DoFs. From a practical point of view, the different behaviour of space and time is achieved by picking a preferred foliation of space–time, geometrically described within the Arnowitt–Deser–Misner (ADM) formalism.