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Cosmological perturbation and matter power spectrum in bimetric massive gravity

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ABSTRACT

We discuss the linear perturbation equations with the synchronous gauge in a minimal scenario of the bimetric massive gravity theory. We find that the matter density perturbation and matter power spectrum are suppressed. We also examine the ghost and stability problems and show that the allowed deviation of this gravitational theory from the cosmological constant is constrained to be smaller than $\mathcal{O}(10^{-2})$ by the large scale structure observational data.

1. Introduction

As the cosmological observations [1–5] have shown that our universe is undergoing an accelerated cosmic expansion, the Einstein equation in general relativity (GR) without the mystery cosmological constant term needs to be modified. Among these modified gravity theories, the DGP braneworld [6] and massive gravity theories can both explain the late-time acceleration without adding dark energy additionally.

Massive gravity with a massive spin-2 field was first constructed by Fierz and Pauli (FP) [7] in 1939. However, van Dam, Veltman and Zakharov (vDVZ) found that in the zero limit of the graviton mass, the modification of the Newtonian potential is not continuous [8–10], resulting in a large correction to the bending of light around the sun, which mismatches the current solar system observations. To

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resolve this problem, Vainshtein [11] proposed a mechanism of nonlinear interactions, which could recover GR in the zero graviton mass limit, which is applicable to many modified gravitational theory, such as the DGP braneworld and Galileon theories [12–19]. Nevertheless, the massive gravity also suffers from the Boulware Deser (BD) ghost instability at the same time [20].

Recently, de Rham, Gabadadze and Tolley (dRGT) [21,22] have successfully built the covariant theory of massive gravity by introducing a second reference metric in addition to the ordinary one, which can be fully BD ghost-free to both linear and non-linear orders [23]. Nevertheless, the homogeneous and isotropic cosmological solutions are not stable in such a non-linear theory [24–26]. To solve this problem, Hassan and Rosen have extended massive gravity with a non-dynamic second metric to bigravity with a dynamic one [27,28]. Besides being BD ghost-free [23] for massive gravitons, there exist some solutions in this bimetric theory with interacting massless and massive spin-2 fields. Furthermore, this model can be applicable to realize the late-time accelerated cosmic expansion without a cosmological constant [29,30]. As the theory contains six free coupling parameters, there are various possible cosmological solutions with different choices of these couplings. However, many bigravity models encounter with Higuchi ghosts [31,32] or gradient instabilities under cosmological perturbations [33–39]. There are several attempts to find viable cosmological solutions [40–48]. In Ref. [33], it is shown that the instabilities can be avoided by introducing a mirror dark matter sector minimally coupled to the second metric. In Ref. [42], the authors find that, in the case without the cosmological constant related parameter β_0, the stability condition requires that the Planck mass of the second metric is much less than that of the first one. In this study, we examine whether the absence of instabilities can occur in a minimal case with the parameter β_0 but without the mirror dark matter term. In particular, we use the general conditions given in Ref. [49] to avoid the Higuchi ghosts and gradient instabilities at the linear level. Some recent studies on bigravity can be seen in Refs. [50–65] and references therein.

As demonstrated in the literature,[1] the modified gravity theories without the ΛCDM approach are hard to fit the cosmic microwave background radiation (CMB) and large scale structure observational data. In order to check the viability of the bigravity model, it is helpful to explore the feature of the linear density perturbations as well as the matter power spectrum in a viable non-trivial minimal scenario, which has the ΛCDM limit associated with a modification term. This type of the study has been done in the DGP [67] and Galileon frameworks [68–70]. In this work, we plan to estimate the allowed window of the model parameter by comparing with our numerical calculations to the most recent observational data, and examine the stability with the constrained parameter. Our goal is to find out whether there are still some possible deviations between our viable minimal scenario of the bimetric massive gravity theory and the ΛCDM model.

This paper is organized as follows. In Section 2 we derive the effective equations of dark energy at the background level. In Section 3, we consider scalar perturbations in the synchronous gauge and obtain the perturbed equations. We numerically solve the linear perturbation equations in Section 4. We discuss the ghost and stability problems and show the matter power spectrum in Section 5. Finally, the conclusion is given in Section 6.

2. Background of bimetric massive gravity

In this section, we would first review some basic background of the bimetric massive gravity theory and then introduce our minimal scenario for the theory. We start with the action of the theory, given by [27],

$$\mathcal{S} = -\int d^4x \left(\frac{\sqrt{-g}}{16\pi G} R(g) + \frac{\sqrt{-f}}{16\pi G_f} R(f) \right) + m^2 \int d^4x \frac{\sqrt{-g}}{8\pi G} \sum_{n=0}^{4} \beta_n e_n \left(\mathbb{X}\right) + \mathcal{S}_M(g_{\mu\nu}, \Psi) \,, \quad (1)$$

where $R(g)$ and $R(f)$ are the Ricci scalars, corresponding to the ordinary and new metrics $g_{\mu\nu}$ and $f_{\mu\nu}$, respectively, G_f is the gravitational constants for the new metric, m is a mass parameter, $\mathcal{S}_M(g_{\mu\nu}, \Psi)$ is the action of the matter term with the matter field Ψ, β_n are the arbitrary constants, and e_n are

[1] See Ref. [66], for example.