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Cosmological perturbations in an effective and genuinely phantom dark energy Universe

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ABSTRACT

We carry out an analysis of the cosmological perturbations in general relativity for three different models which are good candidates to describe the current acceleration of the Universe. These three set-ups are described classically by perfect fluids with a phantom nature and represent deviations from the most widely accepted ΛCDM model. In addition, each of the models under study induce different future singularities or abrupt events known as (i) Big Rip, (ii) Little Rip and (iii) Little Sibling of the Big Rip. Only the first one is regarded as a true singularity since it occurs at a finite cosmic time. For this reason, we refer to the others as abrupt events. With the aim to find possible footprints of this scenario in the Universe matter distribution, we not only obtain the evolution of the cosmological scalar perturbations but also calculate the matter power spectrum for each model. We have carried the perturbations in the absence of any anisotropic stress and within a phenomenological approach for the speed of sound. We constrain observationally these models using several measurements of the growth rate function, more precisely $f\sigma_8$, and compare our results with the observational ones.

1. Introduction

Cosmology has made a long way on the last years with the impressive amount of observations and theoretical advancements. Yet, it still faces many challenging questions like the fundamental cause of the recent acceleration of the Universe, which was found with SNeIa observations almost twenty years ago [1,2], and afterwards confirmed by several types of cosmological and astrophysical observations (see for example [3] for a recent account on this issue). The simplest approach which is in agreement with the current observations is to assume a cosmological constant that started recently to dominate the late-time energy density budget of the Universe [4]. But then the issues *of why is it so tiny?* and *why this cosmological constant has begun to be important only right now?* have to be addressed as well (see for example: [5–8]). Another, equally important, issue is what happens if the cosmological constant is not quite constant? This has led to a great interest in exploring other possible scenarios to explain the late-time acceleration of the cosmos by invoking either an additional matter component in the Universe, which we name dark energy (DE) [9–11], or by modifying appropriately the laws of gravity (for a recent account on this issue see, for example, [12,13] and the extensive list of references provided therein).

We will focus on the third question: *what happens if the cosmological constant is not quite constant?* More precisely, we will address this question on the framework of the cosmological perturbations and for some DE models whose equations of state; i.e., the ratio between its pressure and its energy density, deviate slightly from the one corresponding to a cosmological constant. Before proceeding let us remind the following well known fact: if the equation of state (EoS) of DE deviates from -1, the Universe fate might be quite different from the one corresponding to an empty de Sitter Universe. In particular, if the equation of state of dark energy is smaller than -1, i.e., DE is apparently (at least from an effective point of view) not fulfilling the null energy condition, several future singularities or abrupt events might correspond to the cosmic doomsday of the Universe. Amazingly, some of these models are in accordance with current data [14].

On the other hand, theory of cosmological perturbations is a cornerstone of nowadays cosmology. It provides us with a theoretical framework which allows us to determine, for example, the CMB predicted from an early inflationary era or compute the matter power spectrum and the growth rate of matter in order to make a comparison with the observational results. In addition, it

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allows us to compute the evolution and possible clustering of DE perturbations and investigate their effect on the growth of dark matter (DM). Even though no perturbations of DE have so far been detected, and are in fact absent in the ΛCDM model, the existence of a great number of experiments aiming to probe the physics of the late-Universe, like the Dark Energy Survey [15] and the Euclid mission [16], suggests that a thorough study and characterisation of such effects can be proven to be important to understand the nature of this mysterious fluid that drives the acceleration of the Universe. With this mindset, on this work we analyse the perturbative effects of phantom DE models[1] and look for observational fingerprints that could be used as a mean to favour or disregard such models.

There are three genuinely phantom DE fates; i.e., which happens if and only if a phantom DE component is present:

- Big Rip (BR) singularity: It happens at a finite cosmic time with an infinite scale factor where the Hubble parameter and its cosmic time derivative diverge [20–27].
- Little Rip (LR): This case corresponds to an abrupt event, i.e., it is not strictly speaking a future space–time singularity, as it takes place at an infinite cosmic time [28]. The radius of the Universe, the Hubble parameter and its cosmic time derivative all diverge at an infinite cosmic time [28–35].
- Little Sibling of the Big Rip (LSBR): This behaviour again corresponds to an abrupt event rather than a future space–time singularity. At this event, the Hubble rate and the scale factor blow up but the cosmic derivative of the Hubble rate does not [36,37]. Consequently, this abrupt event takes place at an infinite cosmic time where the scalar curvature diverges.

These three cases share in common the fact that in the (far) future all the structures in the Universe would be ripped apart in a finite cosmic time [33,36]. The classical singular asymptotic behaviour of these dark energy models has led to a quantum cosmological analysis of these setups [38–42]. In these works, it was concluded that once the Universe enters in a genuinely quantum phase; i.e., where coherence and entanglement effects are important, the Universe would evade a doomsday *à la rip*. This applies even to the smoother version of these singular behaviours corresponding to a LSBR [41] (see also [43–47]).

In this paper, we will analyse the cosmological perturbations of DE models that induce a BR, LR or LSBR. While the background analysis of the phantom DE scenario has been widely analysed, this has not been the case of its cosmological perturbations [48–52]. In [49,51,52] a kinematical approach was assumed, i.e., a dependence of the scale factor as a function of the cosmic time was considered for FLRW Universes with future singularities at a finite cosmic time. Within this setup and using approximated equations for the growth of the perturbations at late-time, the authors obtained the DM and DE perturbations [51]. Furthermore, in [49,52], DE perturbations are disregarded and only the growth rate of matter perturbations is calculated. In this work, we will rather assume a dynamical model, i.e., we assume a given EoS for DE. This is the approach employed in Ref. [50], where the future behaviour of the linear scalar perturbations is presented for a type of model that, depending on the value of the parameters, can lead to a BR or a Big freeze singularity [53]. In our analysis, we use the full theory of linear perturbation to study how the perturbations of DM and DE, as well as, the gravitational potential evolve for a range of different scales. Our numerical integrations start from well inside the radiation era and continue till the far future. In fact, in order to see the behaviour of the phantom DE models, we extend our numerical calculations till the Universe is roughly e^{12} times larger than at present, i.e., roughly $z \sim -1$. In the perturbative analysis carried out we (i) disregard any anisotropic stress tensor, (ii) consider the DE perturbations to be non-adiabatic and (iii) describe this non-adiabaticity within a phenomenological approach for the speed of sound. On the other hand, we disregard the contribution of neutrinos as a first approach where we do not use a more advanced Boltzmann code such as CAMB [54] or CLASS [55].

The paper is organised as follows: In Section 2, we briefly review DE models that induce a BR, LR or LSBR; i.e., we review perfect the fluids that can describe DE from a phenomenological point of view and leading to the above mentioned singularity or abrupt events. In Section 3, we present the framework for studying the scalar linear perturbations. The evolution equations obtained employ no approximations and are therefore valid for all relevant modes and redshifts, as long as the linear theory is itself valid. We present our numerical results in Section 4, where we show the evolution of different perturbed quantities related to DM and DE. We present as well the matter power spectrum for the different models. We equally constrain these models using several measurements of the growth rate function, more precisely $f\sigma_8$. Finally, in Section 5, we present our conclusions.

2. Background models

In this section, we briefly review the different models that, at the background level, lead to distinct future cosmological abrupt events: (i) Big Rip (BR), (ii) Little Rip (LR) and (iii) Little Sibling of the Big rip (LSBR). For each of these models, we begin by presenting an EoS for DE that can originate such genuinely phantom abrupt events in the future, while ensuring that the background evolution follows closely that of ΛCDM until the present time. These models should be interpreted as an effective description of a more fundamental field, therefore, even though at the background level they might be defined by a barotropic fluid, the same should not be assumed at the perturbative level. In fact, as we will discuss below, in order to avoid non-physical instabilities we will explicitly break the adiabaticity of the DE perturbations. Bearing in mind, from now on, the approach that we will follow, we next describe the effective background models that we will contemplate.

Let us consider a homogeneous and isotropic Universe described by the Friedmann–Lemaître–Robertson–Walker (FLRW) metric:

$$ds^2 = -dt^2 + a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2 d\theta^2 + r^2 \sin^2\theta d\varphi^2\right], \tag{2.1}$$

where $a(t)$ is the scale factor and $k = -1, 0, 1$ for open, flat and closed spatial geometry, respectively. We will focus on the spatially flat case ($k = 0$), for which the Friedmann and Raychaudhuri equations read

$$H^2 = \frac{8\pi G}{3}\rho, \tag{2.2}$$

$$\dot{H} = -4\pi G(\rho + p). \tag{2.3}$$

Here, H is the Hubble parameter, a dot represents a derivative with respect to the cosmic time, t, G is the cosmological constant and ρ and p are the total energy density and pressure of all the matter content of the Universe. In this work, we will consider the Universe to be filled by radiation, dust (cold dark matter and baryons), and DE. As such, we can decompose ρ and p as

$$\rho = \rho_r + \rho_m + \rho_d \qquad \text{and} \qquad p = p_r + p_m + p_d, \tag{2.4}$$

where ρ_r, ρ_m, and ρ_d correspond to the energy density of radiation, matter (cold dark matter and baryons) and DE. Similarly, p_r, p_m, and

[1] There are some promising phantom dark energy models [17,18] which are free from ghosts and gradient instabilities (see also Ref. [19]).