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Tracing primordial black holes in nonsingular bouncing cosmology

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ABSTRACT

We in this paper investigate the formation and evolution of primordial black holes (PBHs) in nonsingular bouncing cosmologies. We discuss the formation of PBH in the contracting phase and calculate the PBH abundance as a function of the sound speed and Hubble parameter. Afterwards, by taking into account the subsequent PBH evolution during the bouncing phase, we derive the density of PBHs and their Hawking radiation. Our analysis shows that nonsingular bounce models can be constrained from the backreaction of PBHs.

1. Introduction

The matter bounce scenario [1–3] is one type of nonsingular bounce cosmology [4–9], which is often viewed as an important alternative to the standard inflationary paradigm [10–13]. By suggesting that the universe was initially in a contracting phase dominated by dust-like fluid (with a vanishing equation-of-state parameter $w = 0$), then experienced a phase of nonsingular bounce, and afterwards entered a regular phase of thermal expansion. The matter bounce cosmology can solve the horizon problem as successfully as inflation and match with the observed hot big bang history smoothly. Based on primordial fluctuations generated during matter contracting and their evolution through the nonsingular bounce, one can obtain a scale invariant power spectrum of cosmological perturbations. Unlike inflation, the matter bounce scenario does not need a strong constrain on the flatness of the potential of the primordial scalar field that drives the evolution of the background spacetime [14,15]. Also, this scenario can avoid the initial singularity problem and the trans-Planckian problem, which exists in inflationary and hot big bang cosmologies [16,17].

The aforementioned scenario has been extensively studied in the literature, such as the quintom bounce [18,19], the Lee–Wick bounce [20], the Horava–Lifshitz gravity bounce [21–23], the $f(T)$ teleparallel bounce [24–26], the ghost condensate bounce [27], the Galileon bounce [28,29], the matter-ekpyrotic bounce [30–32], the fermionic bounce [33,34], etc. (see, e.g. Refs. [1,35] for recent reviews). In general, it was demonstrated that on length scales larger than the time scale of the bouncing phase, both the amplitude and the shape of the power spectrum of primordial curvature perturbations can remain unchanged through the bouncing point due to a no-go theorem [36,37]. A challenge that the matter bounce cosmology has to address is how to obtain a slightly red tilt on the nearly scale invariant primordial power spectrum. To address this issue, a generalized matter bounce scenario, which is dubbed as the Λ-Cold-Dark-Matter (ΛCDM) bounce, was proposed in [38] and predicted an observational signature of a positive running of the scalar spectral index [39,40].

As a candidate describing the very early universe, the matter bounce scenario is expected to be consistent with current cosmological observations and to be distinguishable from the experimental predictions of cosmic inflation as well as other paradigms [7,41]. Meanwhile, a possible probe of primordial black holes (PBHs) may offer a promising observational approach to distinguish various paradigms of the very early universe [42,43]. PBHs could form at very early times of the universe, where a large amplitude of density perturbations would have obtained. Correspondingly, the formation process and the abundance of PBHs strongly depend on those early universe models, in which fluctuations of matter fields are responsible for such large amplitudes of density perturbations [44].

In the literature, most of attentions were paid on the computation of PBH predictions from the inflationary paradigm (for instance see [45–49]), while so far, only a few works addressed the PBH formation in a bouncing scenario [50,51]. Furthermore, those studies of PBHs in a bouncing scenario have not yet been discussed in detail, for specific cosmological paradigms or been applied to

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falsify various early universe cosmologies, especially the matter bounce scenario. In the context of matter bounce cosmology, there are several differences on the computation of the PBH abundance comparing with that in an expanding universe. First, comparing with inflation where the primordial fluctuations become frozen at the moment of the Hubble exit, those primordial fluctuations on matter fields in bounce cosmology would continue to increase after the Hubble exit during the contracting phase until the universe arrive at the bouncing phase [9,20], and the contracting phase would yield a different initial condition for the PBH formation and evolution. Second, once these PBHs have formed, the contraction of spacetime could also compress and enlarge the primordial matter density, thus change the PBH horizon radius which then can lead to effects on their evolution.

In this paper, we perform a detailed survey on the PBH formation and evolution in the background of the matter bounce cosmology. In Section 2, we briefly introduce the matter bounce scenario and describe the formation of the power spectrum of primordial curvature perturbation in an almost model-independent framework. In Section 3, a physical picture of the PBH formation in the contracting background is presented. After a process of detailed calculations, the threshold for forming PBHs and the corresponding mass fraction are provided. In Section 4, we discuss the evolution of PBHs in the bouncing phase by taking into account the effects arisen from the contraction of the background and the Hawking radiation. In Section 5, we summarize our results and discuss on some outlook of the PBH physics within the nonsingular bouncing cosmology.

2. Nonsingular bounce

Nonsingular bounce can be achieved in various theoretical models, namely, to modify the gravitational sector beyond Einstein, to utilize matter fields violating the Null Energy Condition (NEC), or in the background of non-flat geometries (see e.g. [52,53]). It is interesting to notice that, in general, on length scales larger than the time scale of the nonsingular bouncing phase, primordial cosmological perturbations remain almost unchanged throughout the bounce [36,37]. In this regard, one expects that the effective field theory approach should be efficient to describe the information of a nonsingular bounce model at background and perturbation level. Recently, it was found in [30] that a nonsingular bounce model can be achieved under the help of scalar field with a Horndeski-type, non-standard kinetic term and a negative exponential potential. Within this model construction, the matter contracting phase can be obtained directly by including the dust-like fluid or involving a second matter field [31]. Note that, in the present study we assume that the effective field approach of bouncing cosmology is valid through the whole evolution without modifications to General Relativity.

2.1. The model

It turns out that, under the description of the effective field theory approach, the background dynamics of the nonsingular bouncing cosmology can be roughly separated into three phases: the matter-dominated contraction, the non-singular bounce, and the thermal expansion. We consider a simple model starting with a matter contracting phase ($t < t_-$) from an initial time $t_{\rm initial} \to -\infty$, and then entering into a nonsingular bouncing phase at t_-, which lasts till t_+. After the bounce ends at t_+, the universe begins the hot big bang expansion, which is in accordance to the current observations.

The evolution of the matter bounce cosmology in each stage can be approximately described as follows.

(i) In the matter contracting phase, the scale factor of the universe shrinks as

$$a(t) = a_- \left(\frac{t - \tilde{t}_-}{t_- - \tilde{t}_-} \right)^{2/3} , \tag{2.1}$$

where a_- is the scale factor at time t_-, and $\tilde{t}_-$ is related to the Hubble parameter at t_- via the relation $t_- - \tilde{t}_- = \frac{2}{3H_-}$. The equation-of-state parameter during this phase is $w = 0$, which can be realized in many ways, such as by cold dust, by massive field or by the gravity sector involving non-minimal couplings. We parameterize these different mechanisms by introducing the sound speed c_s, which can affect the propagation of primordial perturbations in the gradient terms.

(ii) In the nonsingular bouncing phase, the scale factor of the universe can be approximately described as [30]

$$a(t) = a_{\rm B} e^{\frac{\Upsilon t^2}{2}} , \tag{2.2}$$

where the coefficient $a_{\rm B}$ is the scale factor exactly at the bouncing point, and from Eq. (2.2) one obtains $a_- = a_{\rm B} \exp[\Upsilon t_-^2/2]$. Υ is a model parameter describing the slope of Hubble parameter to time during the bouncing phase, as:

$$H(t) = \Upsilon t\, . \tag{2.3}$$

It can be seen that $t = 0$ corresponds to the bouncing point when the universe stops the contraction and starts the expansion. Thus, it can be found that $t_- = H_-/\Upsilon$, and the value of H vanishes at $t = 0$ which is at the bouncing point. Inserting Eqs. (2.2) and (2.3) into the Friedmann equation, one can see that the null energy condition $\rho + p > 0$ is violated around the bouncing point. It is the negative pressure that avoids the singularity and drives the universe to evolve from a contracting phase to an expanding phase.

(iii) In the era of radiation-dominated expansion, we have

$$a(t) = a_+ \left(\frac{t - \tilde{t}_+}{t_+ - \tilde{t}_+} \right)^{1/2} , \tag{2.4}$$

where $t_+ = H_+/\Upsilon$, $t_+ - \tilde{t}_+ = \frac{1}{2H_+}$ and $a_+ = a_{\rm B} e^{\frac{\Upsilon t_+^2}{2}}$. In present analysis we have adopted the assumption that the heating process happens instantly after the bounce (see [54,55] for relevant analyses).

From such parameterizations, the matter bounce cosmology can be approximately described by model parameters H_-, H_+, Υ, and also c_s if perturbations are taken into account. In Fig. 1 we depict the evolution of comoving Hubble length $|\mathcal{H}^{-1}| = |aH|^{-1}$, and one can read that one Fourier mode of cosmological perturbation in the matter bounce cosmology could exit the Hubble radius during the contracting phase, and then enter and re-exit the Hubble radius during the bouncing phase, and eventually re-enter the Hubble radius again in the classical Big Bang era. Note that the change of the Hubble radius in the vicinity of the bouncing point can be very large. In the literature, observational constraints upon the bounce cosmology can be derived from various cosmological experiments such as the cosmic microwave background [41] and primordial magnetic fields [56]. In this work we will provide the independent constraints on the model parameters from PBHs.

2.2. Curvature perturbation during matter contracting phase

During the matter contracting phase, equation of motion for the curvature perturbation can be expressed as

$$v_k'' + (c_s^2 k^2 - \frac{z''}{z}) v_k = 0\, , \tag{2.5}$$