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Vacuum decay in an interacting multiverse

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ABSTRACT

We examine a new multiverse scenario in which the component universes interact. We focus our attention to the process of "true" vacuum nucleation in the false vacuum within one single element of the multiverse. It is shown that the interactions lead to a collective behavior that might lead, under specific conditions, to a pre-inflationary phase and ensued distinguishable imprints in the comic microwave background radiation.

1. Introduction

The idea that our universe is an element in a vast set of universes, the multiverse, has been argued to be an interesting way to address the cosmological constant problem in the context of string theory [1–3]. Of course, this scenario raises many questions. How is the vacuum of our world chosen? Through anthropic arguments [4]? Through quantum cosmology arguments [5]? Is the string landscape scenario compatible with predictability [6]? Do the universes of the multiverse interact [7] (see also Ref. [8])? Does the multiverse exhibit collective behavior [9]? The multiverse also arises in the context of the so-called Many World Interpretation of quantum mechanics [10] and in the eternal inflationary model [11].

Actually, it has been recently proposed that the multiverse of eternal inflation and the many-worlds interpretation of quantum mechanics can be identified, yielding a new view on the measure and measurement problems [12,13]. However, it has been argued that a non-linear evolution of observables in the quantum multiverse would be an obstacle for such a description as these non-linearities are expected from quite general arguments [14].

In this paper we shall study the process of vacuum decay in the context of an interacting multiverse [7,9]. The consideration of an interacting multiverse entails a new and richer structure for the whole set of universes. The aim of this paper is to analyze the influence of this enriched structure in the process of the vacuum decay of a single universe. First, we shall consider the Wheeler–De Witt equation for the wave function of the space–time. For many cases of interest the space–time is described by a homogeneous and isotropic geometry whose spatial section volumes scale as $a^3(t)$, where the scale factor $a(t)$ is a function of the cosmic time t of a given multiverse. In this case the wave function of the universe, ϕ, simplifies and it only depends on the values of the scale factor and the matter fields, i.e. $\phi = \phi(a, \vec{\varphi})$, with $\vec{\varphi} \equiv (\varphi_1(t), \varphi_2(t), \dots)$ being a set of scalar fields. These can thus be considered as a field that propagates in the space spanned by the variables $\{a, \vec{\varphi}\}$.

Following the usual prescriptions of quantum mechanics, a second quantization procedure can be applied to the field $\phi(a, \vec{\varphi})$, which can be described in terms of quantum oscillators with their corresponding creation and annihilation operators. These operators would represent, in an appropriate representation, the creation and annihilation of pieces of the space–time with a given geometry. This description allows for representing the fluctuations of the space–time in terms of baby universes [15], i.e. small particle-like portions of space–time that pop up and branch off from the parent space–time and propagate therein. Similarly, for a super-observer the field $\phi(a, \vec{\varphi})$ can be described in terms of particle-like pieces of space–time that we call universes.

The aim of this work is to examine if a supra-universal structure can influence the properties of a single causally isolated region of the space–time.

Whatever the definition of a universe is, it can be associate to some notion of causal closure, i.e. a region of the space–time man-

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ifold where all causally related events are self-contained. In other words, something that may cause or may be caused by any effect on any observed part of the universe should be included as being part of the universe. Thus, although it seems meaningless to consider *external* elements of the universe, we shall see that this is not the case.

The classical and local notion of causal closure does not exclude the possibility that non-local interactions among different regions of the space–time may determine some of the global properties of single universes. In fact, it has already been shown [9] that the interaction between two or more universes could determine the effective values of the cosmological constant of the universes. Despite that, light ray cones and local causal relations and properties within each single universe still obey the usual relations and remain causal. However, the value of a global property like its the cosmological constant can be affected by the interaction among the universes.

This cosmological picture is then completely different than the one single universe picture. Interactions and collective behavior might then occur among the universes of the multiverse. Actually, this collective behavior is fairly general and is at the very heart of quantum theory, which is a non-local theory and within which all the physical elements are fundamentally coupled to their environment and individual properties arise out of a result of some decoherence process. Thus, the true quantum state of the space–time must account for the states of all the universes, if they exist. The aim of this paper is to examine whether some of these collective processes may have an observable influence on the properties of our universe.

Irrespective of the consideration of a multiverse and its implications, it seems therefore interesting to analyze the influence, if any, that different distant regions of the space–time may have on the properties of the observable part of our local universe (see also Ref. [16]) with a two-fold aim: i) to analyze whether they might help to solve some of the open questions posed by the latest Planck data [17,18], and ii) to look for distinguishable imprints of other universes in, for instance, the properties of the cosmic microwave background (CMB) spectrum [19].

This paper is organized as follows: In section 2, we discuss the Hamiltonian quantum cosmology model of an interacting multiverse. In section 3, we consider the bubble formation, that is, the nucleation of universes in a parent space–time and specifically address this nucleation in a setting where the universes are interacting. Finally, in section 4, we present a discussion of our results.

2. The interacting multiverse

Let us consider a simply connected piece of a homogeneous and isotropic space–time manifold endowed with a scalar field φ that represents the matter content. More general topologies can also be considered by splitting the whole manifold into simply connected pieces of space–time [20], each of which is quantum mechanically described by a wave function $\phi = \phi(a, \varphi)$ that is the solution of the Wheeler–De Witt equation [9]

$$\ddot{\phi} + \frac{1}{a}\dot{\phi} - \frac{1}{a^2}\phi'' + \omega^2(a, \varphi)\phi = 0, \tag{1}$$

where the scalar field has been rescaled according to Ref. [21], $\varphi \to \frac{2}{M_P}\sqrt{\frac{\pi}{3}}\varphi$, where M_P is the Planck mass. In Eq. (1) the dots represent derivatives with respect to the scale factor and the prime denotes derivative with respect to the scalar field. The function $\omega(a, \varphi)$ contains the potential terms of the Wheeler–De Witt equation. In the case of a closed space–time it is given by

$$\omega^2(a, \varphi) \equiv \sigma^2(H^2 a^4 - a^2), \tag{2}$$

where $\sigma \equiv \frac{3\pi M_P^2}{2}$ and $H \equiv H(\varphi)$ is the Hubble function. The frequency ω has units of mass or, equivalently, units of the inverse of time or length. We shall consider two contributions to the Hubble function, i.e., $H^2 = H_0^2 + H_1^2$. The first one is due to the existence of a cosmological constant, $H_0^2 = \frac{\Lambda_0}{3M_P^2}$, which is assumed to be very small. The second contribution is due to the potential of the scalar field, $H_1^2 = \frac{8\pi}{3M_P^2} V(\varphi)$.

Let us now develop a quantum field theory for the wave function ϕ in the curved minisuperspace spanned by (a, φ) with a minisuperspace metric given by

$$G_{MN} = \begin{pmatrix} -a & 0 \\ 0 & a^3 \end{pmatrix}, \tag{3}$$

where M, N stands for $\{a, \varphi\}$. The *line* element of the minisuperspace metric is therefore

$$d\mathfrak{s}^2 = -a da^2 + a^3 d\varphi^2. \tag{4}$$

The scale factor, a, formally plays the role of the time variable and the matter field the role of the spatial variable in the two dimensional Lorentzian minisuperspace metric (3) ($a(t)$ can actually be seen as a time reparametrization). We can now follow the usual procedure of a quantum field theory for the scalar field[1] $\phi(a, \varphi)$ by considering the following action

$$S = \int da d\varphi \; \mathcal{L}(\phi, \dot{\phi}, \phi'), \tag{5}$$

where the Lagrangian density is given, as usual, by

$$\mathcal{L} = \frac{1}{2}\sqrt{-G}\left\{G^{MN}\partial_M\phi\partial_N\phi - \mathcal{V}(\phi)\right\} \tag{6}$$

$$= \frac{1}{2}\left(-a\dot{\phi}^2 + \frac{1}{a}\phi'^2\right) + \frac{a\,\omega^2}{2}\phi^2, \tag{7}$$

where $G = \det(G_{MN})$. Then, the corresponding Euler–Lagrange equation [22]

$$\frac{1}{\sqrt{-G}}\partial_M\left(\sqrt{-G}G^{MN}\partial_N\right)\phi + \frac{1}{2}\frac{\delta\mathcal{V}}{\delta\phi} = 0, \tag{8}$$

turns out to be the Wheeler–De Witt equation, Eq. (1).

The Hamiltonian density that corresponds to the Lagrangian density, Eq. (6), is given by

$$\mathcal{H} = -\frac{1}{2}\left(\frac{1}{a}P_\phi^2 + \frac{1}{a}\phi'^2 + a\omega^2\phi^2\right), \tag{9}$$

where

$$P_\phi \equiv \frac{\delta\mathcal{L}}{\delta\dot{\phi}} = -a\dot{\phi}\,, \tag{10}$$

is the momentum conjugated to the field ϕ.

We can now pose an interaction scheme [7,9] among a set of N universes by considering a total Hamiltonian density given by [9]

$$\mathcal{H} = \sum_{n=1}^{N}\mathcal{H}_n^{(0)} + \mathcal{H}_n^{(i)}, \tag{11}$$

where $\mathcal{H}_n^{(0)}$ is the unperturbed Hamiltonian density of the n-universe, given by Eq. (9), and $\mathcal{H}_n^{(i)}$ is the Hamiltonian density of the interaction for the n-universe, that here we consider as the simple quadratic interaction between next neighbor universes,

[1] Spinorial and vector fields could also been considered.