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Novel vacuum conditions in inflationary collapse models

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ABSTRACT

Within the framework of inflationary models that incorporate a spontaneous reduction of the wave function for the emergence of the seeds of cosmic structure, we study the effects on the primordial scalar power spectrum by choosing a novel initial quantum state that characterizes the perturbations of the inflaton. Specifically, we investigate under which conditions one can recover an essentially scale free spectrum of primordial inhomogeneities when the standard Bunch–Davies vacuum is replaced by another one that minimizes the renormalized stress–energy tensor via a Hadamard procedure. We think that this new prescription for selecting the vacuum state is better suited for the self-induced collapse proposal than the traditional one in the semiclassical gravity picture. We show that the parametrization for the time of collapse, considered in previous works, is maintained. Also, we obtain an angular spectrum for the CMB temperature anisotropies consistent with the one that best fits the observational data. Therefore, we conclude that the collapse mechanism might be of a more fundamental character than previously suspected.

1. Introduction

Inflation is considered as a fundamental component of the standard ΛCDM cosmological model characterizing the initial stages of the universe [1–4]. Essentially, according to the inflationary paradigm, the early universe underwent an accelerated expansion induced by a scalar field named the inflaton. In addition, it is widely accepted that the quantum fluctuations of the inflaton gave birth to the primordial curvature perturbation, which in turn, generated the primeval density perturbations [5–9]. These primordial perturbations are thus responsible for the origin of all the observed structure in the universe. The predicted properties of such perturbations are consistent with recent observational data from the cosmic microwave background (CMB) [10–12]. In particular, the data are consistent with a nearly scale invariant spectrum associated to the perturbations, which also favors the simplest inflationary models [12,13].

According to the standard inflationary picture, the dynamical expansion of the early universe is governed by Einstein equations which are symmetry preserving; the symmetry being the homogeneity and isotropy. Another important aspect is that, when considering the quantum description of the fields, the vacuum state associated to the inflaton is also homogeneous and isotropic, i.e. it is an eigenstate of the operator generating spatial translations and rotations. Furthermore, the dynamical evolution of the vacuum satisfies the Schrödinger equation, which does not break translational and rotational invariance. As a consequence, we arrive at an important conundrum: it is not clear how from a perfect symmetric initial situation (both in the background spacetime and in the quantum state that characterizes the inflaton), and based on dynamics that preserves the symmetries (the homogeneity and isotropy), one ends up with a final state that is inhomogeneous and anisotropic describing the late observed universe. The aforementioned problem was originally introduced in [14] (and extensively discussed in [15,16]) together with a possible solution: the self-induced collapse hypothesis. The collapse proposal consists that at some point, during the inflationary epoch, a spontaneous change occurs, transforming the original quantum state of the inflaton (the vacuum) into a new quantum state lacking the symmetries of the initial state.

It is worthwhile to mention that the situation we are facing is connected with the so called quantum measurement problem. Sometimes in the literature, the problem is presented as the quantum-to-classical transition of the primordial quantum fluctua-

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tions, and then decoherence is introduced into the picture [17,18]. Although, decoherence can provide a partial understanding of the issue, it does not fully addresses the problem mainly because decoherence does not solve the quantum measurement problem. We will not dwell in all the conceptual aspects regarding the appeal of decoherence during inflation, neither the perceived advantages that the objective reduction models could offer when applied to the early universe. Instead, we referred the interested reader to Refs. [14,15] for a more in depth analysis.

The collapse hypothesis during inflation has been analyzed using two approaches: In the first, one characterizes the post-collapse state phenomenologically through the expectation values and quantum uncertainties of the field, and its conjugated momentum, evaluated at the time of collapse [14,19–21]. In the second approach, one employs a particular collapse mechanism called the continuous spontaneous localization model, where a modification of the Schrödinger equation is proposed, resulting in an objective dynamical reduction of the wave function [22–26]. In both approaches, one obtains a prediction for the scalar and tensor power spectra that, in principle, is different from the standard prediction [27,28]. The first approach has been tested using the most recent data provided by the Planck collaboration, and, under certain circumstances, provides the same Bayesian evidence of the minimal standard cosmological model ΛCDM [29]. Therefore, we will follow the first approach to characterize the self-induced collapse, but the framework exposed in the present work can be extended to the second approach.

Another important feature of the collapse proposal is the adoption of semiclassical gravity [30], which serves to relate the spacetime description in terms of the metric and the degrees of freedom of the inflaton. In the semiclassical picture, gravity is always classical while the matter fields are treated quantum mechanically. We assume such a framework to be a valid approximation during the inflationary era, which is well after the full quantum gravity regime has ended. This approach is different from the standards models of inflation in which metric and matter fields are quantized simultaneously. We should mention that there are many arguments suggesting that the spacetime geometry might emerge from deeper, non-geometrical and fundamentally quantum mechanical degrees of freedom [31–35]. Therefore, in this work, we will employ Einstein semiclassical equations $G_{ab} = 8\pi G \langle \hat{T}_{ab} \rangle$.

On the other hand, the selection of the pre-collapse state, i.e. the vacuum state, which is perfectly homogeneous and isotropic, is not generic. It is known that since we are dealing with a theory of a scalar field (the inflaton) in a curved spacetime, the choice of the vacuum state is not unique [30,36]. Traditionally, the Bunch–Davies (BD) vacuum is selected when considering the quantum theory of the inflaton. The criterion used for the BD vacuum is based on finding a state $|0\rangle$ such that it minimizes the expectation value $\langle 0|\hat{H}(\eta_i)|0\rangle$ at some initial time η_i, with $\hat{H}$ the Hamiltonian associated to the perturbations [37,38]; this prescription is also called Hamiltonian diagonalization. On the other hand, there are known unresolved issues with such procedure. One is that $\langle 0|\hat{H}(\eta_i)|0\rangle$ can be minimized only at an instant η_i; at some other time $\eta_1 > \eta_i$, the BD vacuum does not achieve the sought minimization of the expectation value. In other words, the zero "particle" state is only defined at the time η_i, and as inflation unfolds, the state $|0\rangle$ contains "particles" at other time η_1. Another related issue is that usual renormalization methods, which make $\langle 0|\hat{H}(\eta_i)|0\rangle$ finite, can only be defined at $\eta_i \to -\infty$, that is, at the very early stages of inflation. Some authors consider those arguments sufficient to find alternatives to the Hamiltonian diagonalization method [39–41]. Here it is also important to mention that different choices other than the BD vacuum state have been analyzed previously. For example in Refs. [42–44] it is presented an analysis regarding the observable effects of trans-Planckian physics in the CMB and its relation with a non-BD vacuum. In addition, a non-BD vacuum is usually associated with large non-Gaussianities in the CMB [45,46].

One of the possible alternatives is proposed in Ref. [41]. Those authors suggest that, instead of minimizing $\langle 0|\hat{H}|0\rangle$, one should focus on minimizing the renormalized $\langle \hat{T}_{00}(x)\rangle$. Specifically, the vacuum $|\tilde{0}\rangle$ (which is not the same as the BD vacuum), is such that it minimizes the 0–0 component of the renormalized expectation value of the energy–momentum tensor, which can be considered as a local energy density. Moreover, the vacuum $|\tilde{0}\rangle$ only minimizes the renormalized $\langle \tilde{0}|\hat{T}_{00}(x)|\tilde{0}\rangle$ at some particular time η_0. However, conceptually, it is easier to handle a notion of an instantaneous local energy density minimum than dealing with a notion of "particle" that changes with time. Also, the time η_0 does not need to be taken in the limit $\eta_0 \to -\infty$, although, if one chooses to set η_0 at such early times, then $|\tilde{0}\rangle$ coincides with the prescription of the BD vacuum, but not with its physical interpretation of a "particle-less" state.

All previous works regarding the self-induced collapse proposal, when applied to the inflationary scenario, have been based on selecting the BD vacuum, which is the usual choice in traditional models of inflation as well. Nonetheless, one of the key objects in the inflationary collapse proposal, based on the semiclassical gravity framework, is the expectation value $\langle \hat{T}_{ab}(x)\rangle$. In our approach, if the post-collapse state does not share the same symmetries as the initial-vacuum-state then $\langle \hat{T}_{ab}\rangle$, evaluated in the post-collapse state, will result in a geometry that is no longer homogeneous and isotropic, thus, providing the primordial perturbations for cosmic structure. Therefore, a criterion based on selecting a vacuum state that minimizes the renormalized expectation value of $\hat{T}_{00}$ seems better suited for our picture than one based on choosing a zero "particle" state at a particular time. Furthermore, after the collapse, clearly $\langle \hat{T}_{00}\rangle$ will no longer be the same as the one evaluated in the vacuum state. Hence, if one thinks the collapse as a dynamical process, changing continuously from $|\tilde{0}\rangle$ to the post-collapse state, then it is clear to picture the expectation value of $\hat{T}_{00}$ also changing continuously. In particular, the value $\langle \tilde{0}|\hat{T}_{00}|\tilde{0}\rangle$ will transform from a minimum, which produces a perfectly symmetric spacetime, into a different value generating the perturbations of the geometry.

From discussion above the motivation for the present work is established. That is, we are interested in analyzing the possible effects on the primordial power spectrum generated by choosing the novel prescription based on minimizing the renormalized $\langle \hat{T}_{00}\rangle$. In particular, we are interested in analyzing which aspects of the collapse proposal are modified when the initial conditions are also changed. As we will show, one of our findings indicate that the parametrization of the time of collapse, for each mode of the field, surprisingly remains the same. This led us to think that the physics behind the self-induced collapse of the wave function should be studied in more detail.

The article is organized as follows: in Sect. 2, we review some basics about inflation in the semiclassical gravity framework; in Sect. 3, we analyze the quantization of perturbations, the vacuum choice and present the emergence of curvature perturbation within the collapse hypothesis. Then, we show our prediction for the scalar power spectrum. In Sect. 4 we make a discussion of our results, and finally in Sect. 5 we summarize our conclusions.

Regarding conventions and notation, we will be using a $(-,+,+,+)$ signature for the spacetime metric, and we will use units where $c = 1 = \hbar$.

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