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Inflationary gravitational waves in collapse scheme models

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ABSTRACT

The inflationary paradigm is an important cornerstone of the concordance cosmological model. However, standard inflation cannot fully address the transition from an early homogeneous and isotropic stage, to another one lacking such symmetries corresponding to our present universe. In previous works, a self-induced collapse of the wave function has been suggested as the missing ingredient of inflation. Most of the analysis regarding the collapse hypothesis has been solely focused on the characteristics of the spectrum associated to scalar perturbations, and within a semiclassical gravity framework. In this Letter, working in terms of a joint metric-matter quantization for inflation, we calculate, for the first time, the tensor power spectrum and the tensor-to-scalar ratio corresponding to the amplitude of primordial gravitational waves resulting from considering a generic self-induced collapse.

1. Introduction

The vast majority of the cosmological community considers the inflationary paradigm on a stronger footing than ever given the agreement between its predictions and the latest observations (e.g. WMAP9 [1], Planck [2]). In particular, last year a claim by BICEP2 Collaboration regarding the detection of primordial tensor modes [3], in spite of the subsequent controversy of their results [4–6], has made some cosmologists think that this important prediction from the traditional inflation model will be confirmed in the foreseeable future, which in turn will reassert the standing of the model.

According to the traditional inflationary paradigm, the early universe undergoes an accelerated expansion (lasting at least some 70 e-folds or so), resulting in an essentially flat, homogeneous and isotropic space–time with an extreme dilution of all unwanted relics. Note that the dynamics of the space–time is governed by Einstein equations which are symmetry preserving, i.e. the symmetry being the homogeneity and isotropy (H&I). Another important aspect is that when considering the quantum features of the scalar field (the inflaton) driving the expansion. This field, is assumed to be in the vacuum state as a result of the same exponential expansion, and one finds also that it contains "fluctuations" with the appropriate nearly-scale-invariant spectrum. These vacuum fluctuations are considered responsible for all the structures we observe in the actual universe, and in particular, the observed cosmic microwave background (CMB) anisotropies.

One cannot deny the favorable matching between the model predictions and observations; nevertheless, from the conceptual point of view something is missing. Even if the inflaton contains quantum uncertainties (or vacuum fluctuations), according to the Quantum Theory, the physical state of the system is encoded in the quantum state. The vacuum state of the quantum fields is H&I, i.e. it is an eigen-state of the operators generating spatial translations and rotations (see Appendix A of Ref. [7] for a proof). The fact that a system contains quantum uncertainties does not necessarily implies that it contains actual inhomogeneities and anisotropies, since the quantum state, which characterize the physical state of the system, can still be perfectly H&I. Additionally, the dynamics of the quantum state is governed by Schrödinger equation, which does not break translational and rotational invariance. Consequently, the initial quantum state cannot be evolved into a final state lacking such symmetries. Thus, there is an important issue, namely: what is the precise mechanism by which the primordial perturbations are born given that the equations governing the dynamics are symmetry preserving? In other words, it is not clear how from an initial condition that is H&I (both in the background

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space–time and in the quantum state that characterizes the quantum fields), and based on a dynamics that supposedly preserves those symmetries, one ends up with a non-homogeneous and non-isotropic state associated to the late observed universe.

The above described situation is sometimes related to the issue of the quantum-to-classical transition of the primordial quantum fluctuations. And, although decoherence provides a partial understanding of the issue [8,9], it does not fully address the problem; mainly because decoherence does not solve the quantum measurement problem, which appears in an exacerbated manner in the case of the inflationary universe. We invite the interested reader to consult, for instance, Refs. [10,11] where a more detailed analysis has been made regarding the issues with decoherence and other approaches to the problem at hand.

In order to account for the aforementioned problem, Sudarsky et al. [10] proposed a self-induced collapse of the wave function, i.e. a spontaneous change from the original quantum state associated to the inflaton field into a new quantum state lacking the symmetries of the initial state. Also, their approach relies on the semiclassical gravity framework, in which matter is described by a Quantum Field Theory and the space–time is always treated in a classical manner. The self-induced collapse is considered as being the responsible of generating the primordial perturbations. In particular, by relying on Einstein semiclassical equations, the expectation value in the post-collapse state of the quantum matter fields is related to the metric of the space–time which is always classical. The result of the evolution of the metric perturbations, born after the collapse, is related to the actual anisotropies and inhomogeneities observed in the CMB radiation. Thus, in this proposal, after the collapse, the universe is described by a space–time and a quantum state that are no longer H&I.

On the other hand, it is evident that the collapse mechanism should be a physical process independent of external entities, since in the early universe there is not a clear notion of observers, measurement devices, environment, etc. It is worthwhile to comment that models involving an objective dynamical reduction of the wave function (in different contexts from cosmology) have been proposed in past years [12–17]. These models attempt to provide a solution to the so-called measurement problem of Quantum Mechanics by eliminating from the theory the need of an external agent responsible for localizing the wave function. It is also interesting that these models give predictions that can be tested experimentally and that are different from the standard Quantum Theory [18]. We will not deal with all the conceptual framework concerning the self-induced collapse and instead we will refer the interested reader to Refs. [7,10,11,19] for a more in depth analysis.

Previous works, e.g. [10,20,21], have analyzed the characteristics of the spectrum associated with the scalar perturbations resulting from considering the self-induced collapse hypothesis in different inflationary scenarios, e.g. multiple collapses [22], correlation between the modes caused by the collapse [23], collapse occurring during the radiation dominated era [24], and also in a non-inflationary model [25]. Moreover, in Ref. [26] two quantum collapse schemes were tested with recent data from the CMB, including the 7 year release of WMAP [27] and the matter power spectrum measured using LRGs by the Sloan Digital Sky Survey [28]. However, as we have mentioned, most previous mentioned works have been based on the semiclassical gravity approximation, which enables a quantum treatment of the matter fields, while a classical description of gravitation is maintained. In particular, the amplitude of primordial tensor modes provided by the collapse hypothesis, within the semiclassical gravity approximation, is exactly zero at first-order in perturbation theory [10,21]. At second-order, the model prediction for the amplitude is too low that is practically undetectable by any recent and future experiments [29].

On the other hand, last year an allegation concerning the detection of primordial B-modes polarization of the CMB by BICEP2 Collaboration [3] (notwithstanding the apparent tension with the results provided by Planck mission and a strong evidence of probable contamination by Galactic dust [30]), has made the revelation of primordial gravity waves a real possibility. In the plausible scenario of a confirmed detection of primordial B-mode polarization, the framework of semiclassical gravity applied to the inflationary universe faces several issues, nevertheless, one could still implement the self-induced collapse hypothesis. One possible option (and probably the simplest) is to apply the collapse proposal directly within the standard analysis, in terms of a quantum field jointly characterizing the inflaton and metric perturbations, the so-called Mukhanov–Sasaki variable. In Ref. [31] a first step, regarding the implications of considering the collapse of the wave function characterizing the state of the quantum field associated to the Mukhanov–Sasaki variable, was made. In particular, it was shown that the standard shape of the spectrum associated to the scalar perturbations becomes altered by introducing the collapse hypothesis. Furthermore, in Refs. [32,33] a particular objective collapse model, called Continuous Spontaneous Localization (CSL) collapse model [14–16], was implemented resulting in interesting modifications to the standard scalar power spectrum corresponding to the Mukhanov–Sasaki variable field.

In this work, we will make a step further and obtain the spectrum associated to the tensor modes within the framework of quantizing both the matter and metric perturbations. We will show that, as in the scalar case, the tensor power spectrum becomes modified by introducing the collapse hypothesis. Additionally, we will obtain the tensor-to-scalar ratio r and show that it is of the same order of magnitude as the one predicted by standard single-field slow-roll inflation. Nevertheless, an interesting result is that r is independent of the collapse parameters. Thus, the precise measurement of r sets the energy scale of inflation (the same as in the standard case), but cannot yield any significant information concerning the collapse. Moreover, we will not consider a specific collapse mechanism, but we will parameterize the collapse generically through the expectation values of the field and its conjugated momentum evaluated in the post-collapse state. It is worthwhile to mention that, in Ref. [34], the CSL collapse model was used to analyze the tensor modes in the same context as the present work, in relation to the quantum treatment of the fields. The authors conclude that accurate measurements of r and the tensor spectral index n_T can help to constraint such model parameters. However, their point of view regarding the physical implications of the collapse is different from ours. Specifically, in our picture if there is no quantum collapse the quantum state of the field is homogeneous and isotropic and there are no perturbations of the space–time, thus $r = 0$. On the other hand, within the model analyzed in [34], in the absence of a quantum collapse one recovers the standard inflationary predictions concerning the tensor and scalar power spectra. This is an important distinction with further implications regarding the observational quantities, as it will be shown in future work, but more importantly it constitutes a difference in the physical implication of the self-induced collapse.

The present Letter is organized as follows: in Section 2 we review some basics about previous results regarding the power spectrum of scalar perturbations, in the framework of collapse scheme models and working in terms of a joint metric-matter quantization for inflation; in Section 3 we show our results for the power spectrum of tensor modes and the tensor-to-scalar ratio; and finally, in Section 4 we summarize our conclusions.