Physics Letters B 743 (2015) 484–491

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Inhomogeneities from quantum collapse scheme without inflation

Gabriel R. Bengochea [a,*], Pedro Cañate [b], Daniel Sudarsky [b]

[a] Instituto de Astronomía y Física del Espacio (IAFE), UBA-CONICET, CC 67, Suc. 28, 1428 Buenos Aires, Argentina
[b] Instituto de Ciencias Nucleares, UNAM, México D.F. 04510, México

ARTICLE INFO

Article history:
Received 13 October 2014
Received in revised form 23 January 2015
Accepted 6 March 2015
Available online 10 March 2015
Editor: S. Dodelson

Keywords:
Cosmology
Inflation
Non-inflationary models
Quantum collapse schemes

ABSTRACT

In this work, we consider the problem of the emergence of seeds of cosmic structure in the framework of the non-inflationary model proposed by Hollands and Wald. In particular, we consider a modification to that proposal designed to account for breaking the symmetries of the initial quantum state, leading to the generation of the primordial inhomogeneities. This new ingredient is described in terms of a spontaneous reduction of the wave function. We investigate under which conditions one can recover an essentially scale free spectrum of primordial inhomogeneities, and which are the dominant deviations that arise in the model as a consequence of the introduction of the collapse of the quantum state into that scenario.

1. Introduction

Inflation is presently considered as an integral part of our understanding of cosmological evolution. Inflationary models are generally credited with explaining the large scale homogeneity, isotropy and flatness of our universe as well as accounting for the origin of the seeds of cosmic structure. All structures in our universe emerge from a featureless stage described by a background Friedmann–Robertson–Walker (FRW) cosmology with a nearly exponential expansion driven by the potential of a single scalar field, and from its quantum fluctuations characterized by a simple vacuum state.

In inflationary models, the modes relevant to cosmological perturbations are assumed to be born in their ground state at a time when their proper wavelengths are much shorter than the Hubble radius. That is, the state of the quantum field characterizing the seeds of structure is determined by the instantaneous vacuum state corresponding to the static universe that would be obtained by freezing the cosmological evolution in very early epochs (a precise description of such quantum state construction for arbitrary space times can be seen for instance in [1]). The resulting state in the case of a later exponential expansion (which is close to what is given in simple inflationary models) is known as the Bunch–Davies vacuum.

In the Heisenberg picture, the state of the field at later times is, of course, unchanged and the evolution of the field operators is encoded in the evolution of the modes. From such a setting, one obtains a fluctuation spectrum for these modes which corresponds to a scale free spectrum, and thus fits very well with the Harrison–Zel'dovich prediction [2]. Furthermore, that primordial spectrum, upon incorporation of plasma physics effects, taking place before decoupling, leads to a prediction for the Cosmic Microwave Background (CMB) that fits the data extremely well [3,4].

In a recent work [5], Hollands and Wald proposed an alternative model involving a simple fluid, which, under some more or less natural hypothesis, would be equally capable to reproduce the scale free spectrum and thus, in principle, account for the seeds of cosmic structure. Therefore, it may not be necessary to assume that an era of inflation actually occurred and to postulate the existence of a new fundamental scalar such as the inflaton field. The natural hypothesis referred to above concerns the 'birth time' and the initial state of the relevant modes, and will be discussed in more detail below.

In that work, Hollands and Wald also argue that the resolution of the flatness and horizon problems provided by inflation are not truly satisfactory, and that only a much deeper understanding of the conditions determining the initial state could shed light on that matter. We do not wish to engage in this part of the discussion here.

---

* Corresponding author.
E-mail addresses: gabriel@iafe.uba.ar (G.R. Bengochea), pedro.canate@nucleares.unam.mx (P. Cañate), sudarsky@nucleares.unam.mx (D. Sudarsky).

http://dx.doi.org/10.1016/j.physletb.2015.03.016

The model put forward in [5], starts with the assumption that semiclassical physics applies to phenomena on spatial scales larger than some fundamental length l_0, which, presumably, is of order of the Planck length (l_p) or the grand unification scale. Following this point of view, the authors argue, it would be natural to treat the modes as effectively being born at a time when their proper wavelength is equal to the fundamental scale l_0. Consequently, all the modes would be continuously created over all time. Assuming that the modes are created in their instantaneous ground state (a state that is thus isotropic and homogeneous), the authors obtained a prediction for a scale free spectrum with appropriate amplitude.

The starting point of the analysis corresponds to a universe that is well described by a flat FRW metric, and where there is a large background stress-energy that is linearly perturbed by quantum fluctuations. According to the model, the matter in the early universe can be described, on spatial scales greater than l_0, by a fluid with equation of state $p = w\rho$, where w is a constant. The analysis then continues along a line close to that followed in the standard analysis of inflationary models, by quantizing the perturbations of the coupled Einstein-fluid system, according to Section 10.2 of [6].

Finally, the resulting power spectrum is obtained (as is customary in this kind of analysis), by considering the two point function in the above described state of the quantum field. As noted, this result is such that for modes with wavelength greater than the Hubble radius, at the time of decoupling, one finds a scale free spectrum of density perturbations. The adequate value for the spectrum amplitude is obtained by adjusting the value for l_0, ($l_p/l_0 \sim 10^{-5}$). Furthermore, the authors argue that, within this approach, one can expect a larger ratio of tensor to scalar perturbations than that which are typical for the inflationary models. We plan to study this issue in a future work.

In the present manuscript, we focus on the following issue: it is a fact that in both, the inflationary picture as in the proposal by Hollands and Wald, one must face the difficulties posed when considering a quantum description for the early universe. A form that the problem takes in the present setting is that, according to the two proposals, a completely homogeneous and isotropic stage (evolving according to dynamical equations that cannot break such symmetries), must nevertheless lead, after some time, to a universe containing actual inhomogeneities and anisotropies, presumably characterized by the fluctuation spectrum. This issue has been considered at length in other works, including detailed discussions of the shortcomings of the most popular attempts to address the problem, and we will not repeat such extensive discussions here, except for a brief description intended only as an introduction for the reader who is not familiar with the problem. It is clear that such transition from a symmetric situation to one that is not, cannot be simply the result of quantum unitary evolution, since, as we noted, the dynamics does not break these initial symmetries of the system. As discussed in [7], and despite multiple claims to the contrary (e.g. [8]), there is no satisfactory solution to this problem within the standard physical paradigms. Recently, some books that presents the standard inflationary paradigm have referred to this subject acknowledging to a certain extent the unresolved difficulty (see e.g. [9–12]).

The proposal to handle this shortcoming was considered for the first time in [13]. There, the problem was addressed by introducing a new ingredient into the inflationary account of the origin of the seeds of cosmic structure: the self-induced collapse hypothesis. The basic idea is that an internally induced spontaneous collapse of the wave function of the inflaton field is the mechanism by which inhomogeneities and anisotropies arise at each particular scale. That proposal was inspired on early ones for the resolution of the measurement problem in quantum theory [14–21], which regarded the collapse of the wave function as an actual physical process taking place spontaneously. Also, on the ideas by R. Penrose and L. Diósi [24–29] who assumed that such process should be connected to quantum aspects of gravitation. There are other promising proposals based on Bohemian versions of quantum theory applied to the inflationary field [30], but they will not be considered further in this work.

The simplest way this kind of process can be described is, by assuming that at a certain stage in the cosmic evolution, there was a self-induced jump in the state describing a particular mode of the quantum field, in a manner that is similar to the quantum mechanical reduction of the wave function associated with a measurement. However, the reduction here is assumed to be spontaneous and no external measuring device or observer is called upon as triggering such collapse. A collapse scheme is a recipe to characterize and select the state into which each of the modes of the scalar field jumps at the corresponding time of collapse. The collapse itself is described in a purely phenomenological manner, without reference to any particular mechanism. As reported in, for instance, [13,31,32], the different collapse schemes generally give rise to different characteristic departures from the conventional Harrison–Zel'dovich flat primordial spectrum. There are, of course, more sophisticated theories describing the collapse dynamics, such as those in [14–23], however we will not consider those in the present study, which is meant a first exploration of such ideas in the context of the model proposed by Hollands and Wald.

The main objective of this article is to obtain the effects on the shape of the primordial spectrum, that arise from a particular collapse scheme, into the framework of the proposal of [5]. We will show that with a simple collapse scheme and for a certain range of values of the model parameters, one can effectively recover a scale free spectrum. We will also consider the dominant deviations from the flat spectrum that would arise in this model.

The paper is organized as follows. In Section 2, we develop the necessary formalism of the model, describe the collapse scheme implemented and show the results. Finally, in Section 3, we make our conclusions.

Throughout the work, we will use $c = 1 = \hbar$ and $l_p^2 = \frac{8\pi G}{3}$. Moreover, l_0 is a free parameter and its value is set at the end of our calculations.

2. The original model

2.1. The Einstein-fluid system

Following the original work [5], we start assuming that, on spatial scales grater than l_0, the early universe is dominated by a fluid with pressure p and energy density ρ, which are related by the equation of state $p = w\rho$ where $w \in (0, 1)$ is a constant. We will also assume that the background is well described by a flat FRW metric.

Fixing the gauge (longitudinal) and restricting consideration to the scalar modes, the perturbed metric in this case can be written as

$$ds^2 = a(\eta)^2[-(1+2\Phi)d\eta^2 + (1-2\Phi)\delta_{ij}dx^i dx^j], \quad (1)$$

where $\Phi = \Phi(\eta, x^i)$ characterizes all deviations from homogeneity and isotropy in the space–time.

The background is completely described by the value of w. In particular, the scale factor is $a(\eta) = B\eta^{\frac{2}{3w+1}}$, where B is fixed so that $a(\eta_{\text{today}}) = 1$, and the background fluid density is $\rho \propto a^{-3(w+1)}$.

The next step in the analysis of this model, consists in the quantization of the perturbations of the coupled Einstein-fluid system. We will adhere to the treatment of the problem in [5], which