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Cosmology of the spinor emergent universe and scale-invariant perturbations

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ABSTRACT

A nonsingular emergent universe cosmology can be realized by a nonconventional spinor field as first developed in [1]. We study the mechanisms of generating scale-invariant primordial power spectrum of curvature perturbation in the frame of spinor emergent universe cosmology. Particularly, we introduce a light scalar field of which the kinetic term couples to the bilinear of the spinor field. This kinetic coupling can give rise to an effective "Hubble radius" for primordial fluctuations which allows the scalar field to become squeezed at large length scales and to form a nearly scale-invariant power spectrum. We study the stability of the backreaction and constrain the forms of the coupling terms. Through a generalized curvaton mechanism, these almost scale-independent fluctuations are able to be transferred into curvature perturbation after the epoch of emergence and can thus explain cosmological observations.

1. Introduction

Inflation has become the most prevailing and successful model of describing physics of very early universe [2] (also see [3] for earlier work). It provides instructive clues of explaining conceptual issues of the hot Big Bang cosmology. In particular, inflationary cosmology has predicted a nearly scale-invariant power spectrum of primordial curvature perturbation which was confirmed by a series of Cosmic Microwave Background (CMB) observations [4]. However, it was pointed out in [5] that inflationary cosmology still suffers from the problem of the Big Bang singularity where conventional knowledge about mathematics and fundamental physics does not apply.

In past decades, alternative scenarios to inflationary cosmology have drawn a lot of the cosmologists' attention since some can be as successful as inflation in explaining the very early universe but they also avoid the initial Big Bang singularity (namely see [6] for a recent comprehensive review). These models can be divided into two categories. One is the bouncing cosmology in which the universe begins with the evolution of a contracting phase and then experiences a nonsingular bounce to connect to the regular thermal expansion [7–9]. Amongst many bounce models, the matter bounce [10,11] and the Ekpyrotic cosmology [12,13] are two representative scenarios as explanations for the origin of the CMB and the Large Scale Structure (LSS) of the universe.

In the literature there are various proposals to obtain nonsingular bounces, namely one can modify the gravitational theory as in non-local gravity [14], Horava–Lifshitz gravity [15,16] and in torsion gravity [17], or by introducing certain Null Energy Condition (NEC) violating fields such as nonconventional fermions [18], ghost condensate [19,20] or Galilean matter [21]. A bouncing phase can originate from the structure of quantum spacetime such as in loop quantum cosmology [22]. Particularly, in order to realize a nonsingular bounce within the frame of Einstein gravity, it was shown in [23] that the equation-of-state (EoS) of the universe has to effectively cross the cosmological constant boundary for a while at early times, which is the so-called Quintom scenario [24]. This type of bounce models was studied in detail in [25] and later was reviewed in [26]. The combination of matter bounce and Quintom scenario was achieved by virtue of a Lee–Wick scalar in [27]. This model nicely demonstrates that cosmological perturbations generated in contracting phase can evolve through the bouncing phase smoothly and eventually give rise to a scale-invariant power spectrum of observable interest. The perturbation theory of bouncing cosmology has recently been greatly developed in a series of works, including the investigation of primordial non-Gaussianities [28], the study of entropy fluctuations [29], and related reheating period [30]. The dynamics of cosmological perturbations within the pure Ekpyrotic cosmology were extensively studied in [31–33].

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A second interesting nonsingular paradigm of very early universe is the so-called emergent universe cosmology [34,35], in which our universe was emergent from a non-zero minimal length scale and experienced a sufficiently long period of quasi-Minkowski expansion to then begin the normal Big Bang expansion. Motivated by string theory, the scenario of emergent universe can be achieved in the string gas cosmology due to a Hagedorn phase of a thermal system composed of a number of fundamental strings [34]. Recently, the proposal of the Galilean model gives rise to the Galilean Genesis which also leads to the emergent universe scenario with an end of a big rip [36] (see [37] for a discussion relating how the scenario suffers from an issue of super-luminal propagation when a mater field is introduced). Phenomenologically, the study of the causal generation of primordial perturbation was developed in the setup of conformal cosmology [38], the pseudo-conformal cosmology [39,40], and later the cosmology of Galilean Genesis [41], respectively. Moreover, various deformed versions of the emergent universe cosmology were analyzed in the literature, such as the processes of slow contraction [12,42] and slow expansion [43], or connecting to inflationary cosmology [44] as well as the braneworld scenario [45].

The emergent universe scenario requires that the Hubble rate approaches zero during an infinitely long period in the past, this implies that the NEC violating field is needed at very early times. This profound property was for the first time pointed out explicitly in [1]. It was verified by considering a parameterized Quintom fluid and then explicitly realized by introducing a cosmic spinor field. Embedding a nonconventional spinor field consistently into a curved spacetime such as our universe, one can reconstruct the potential of the cosmic spinor field according to the expected background evolution. This remarkable feature was earlier applied in the study of dark energy models [46] and in inflationary cosmology [47]. The analysis of [1] shows that an enough long period of emergent universe can be achieved if the potential of the spinor field has another minimum in the ultraviolet (UV) regime. Along with an extremely slow-expanding process during the quasi-Minkowski epoch, the spinor field would exit the state of tachyonic condensate and recovers the regular form of a massive fermion. Then the universe gracefully exits to the normal thermal expansion. This model, however, does not explain the origin of the CMB and LSS as observed in experiments since the perturbations of the spinor field form a blue spectrum.

In this Letter we study the possibility of generating a nearly scale-invariant primordial power spectrum in the model of spinor emergent universe. We propose a generalized curvaton mechanism by introducing a second curvaton field which kinetically couples to the spinor field. Although during the emergent universe phase the background spacetime is almost static, the kinetic coupling term can change the friction term of the curvaton. Depending on the detailed form of the kinetic coupling, the curvaton field could feel it is in a "de-Sitter"-like background or a "matter-contraction"-like one. In both situations, a nearly scale-invariant power spectrum of iso-curvature perturbations can be formed. Afterwards, these iso-curvature fluctuations must be converted into curvature perturbation. One way to achieve this is through the standard curvaton mechanism by assuming a process of adiabatic curvaton decay.

The Letter is organized as follows. In Section 2, we briefly review the model of spinor emergent universe. Then, in Section 3 we present two important issues existing in this model. To solve these issues, we introduce a curvaton scalar field kinetically coupled with the cosmic spinor field. Section 4 is devoted to the study of the primordial perturbations of this curvaton field. In particular, we perform a detailed analysis of the curvaton fluctuation and study the condition for producing a scale-invariant power spectrum. Then we reconstruct the form of the kinetic coupling as a function of the scalar bilinear of the spinor field with the stability issue being investigated. Numerical computation is performed in Section 5 to examine the validity of the semi-analytical calculation in the end of this section. In Section 6 we study the conversion of the iso-curvature fluctuations into curvature perturbations by virtue of a generalized curvaton mechanism. We conclude with a discussion in Section 7. Throughout the Letter we take the sign of the metric to be $(+,-,-,-)$ and define the reduced Planck mass by $M_p = 1/\sqrt{8\pi G}$.

2. The model of the spinor emergent universe

To start, we briefly review the emergent universe cosmology realized by a nonconventional spinor field minimally coupled with Einstein gravity [1]. The Dirac action in a curved spacetime background can be expressed as

$$\mathcal{L}_\psi = e\left[\frac{i}{2}\left(\bar\psi\Gamma^\mu D_\mu\psi - D_\mu\bar\psi\Gamma^\mu\psi\right) - U(\bar\psi\psi)\right], \tag{1}$$

where e is the determinant of the vierbein e^a_μ. The Gamma matrices Γ^μ are defined under the Dirac–Pauli representation through $\Gamma^\mu \equiv e^\mu_a\gamma^a$, which satisfy the algebra $\{\Gamma^\mu, \Gamma^\nu\} = 2g_{\mu\nu}$. Moreover, the covariant derivatives of the spinor field and its Dirac adjoint follow the relations below,

$$D_\mu\psi = \partial_\mu\psi + \Omega_\mu\psi, \qquad D_\mu\bar\psi = \partial_\mu\bar\psi - \bar\psi\Omega_\mu, \tag{2}$$

where the spin connection $\Omega_\mu \equiv \frac{1}{2}e^\nu_a\nabla_\mu e_{\nu b}\Sigma^{ab}$ is defined. Additionally, we have introduced the generators of the spinor representation of the Lorentz group $\Sigma^{ab} = \frac{1}{4}[\gamma^a, \gamma^b]$.

By varying the Lagrangian with respect to the vierbein, we can derive the energy stress tensor as follows,

$$T_{\mu\nu} = \frac{i}{2}[\bar\psi\Gamma_{(\mu}D_{\nu)}\psi - D_{(\mu}\bar\psi\Gamma_{\nu)}\psi] - \frac{g_{\mu\nu}}{e}\mathcal{L}_\psi. \tag{3}$$

Further, one can vary the Lagrangian with respect to the spinor field and the adjoint, respectively, and then derive the equations of motion, which are expressed as

$$i\Gamma^\mu D_\mu\psi - U_{,\bar\psi\psi}\psi = 0, \qquad iD_\mu\bar\psi\Gamma^\mu + U_{,\bar\psi\psi}\bar\psi = 0, \tag{4}$$

where we have defined $U_{,\bar\psi\psi} \equiv \partial U/\partial(\bar\psi\psi)$. Note that, we assume the potential of the spinor field is only a function of the scalar bilinear $\bar\psi\psi$ in the case of interest.

Now we consider a spatially flat FRW universe with the metric of

$$ds^2 = dt^2 - a^2(t)\,d\mathbf{x}^2, \tag{5}$$

and correspondingly, the vierbein are given by $e^\mu_0 = \delta^\mu_0$, $e^\mu_i = \frac{1}{a}\delta^\mu_i$. To assume the spinor field is only time-dependent, the equations of motion (4) simply yield [1]

$$\bar\psi\psi = \frac{\mathcal{N}}{a^3}, \tag{6}$$

within the FRW background with a positively defined constant $\mathcal{N}$. Moreover, the combination of the equations of motion (4) and the energy stress tensor (3) determines the energy density and the pressure of the spinor field as follows,

$$\rho_\psi = U, \qquad P_\psi = U_{,\bar\psi\psi}\bar\psi\psi - U, \tag{7}$$

as well as the corresponding EoS

$$w_\psi \equiv \frac{P_\psi}{\rho_\psi} = -1 + \frac{U_{,\bar\psi\psi}\bar\psi\psi}{U}. \tag{8}$$