Physics Letters B 718 (2013) 1181–1185

Contents lists available at SciVerse ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Primordial black holes from passive density fluctuations

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ARTICLE INFO

Article history:
Received 24 August 2012
Received in revised form 19 November 2012
Accepted 21 December 2012
Available online 28 December 2012
Editor: T. Yanagida

ABSTRACT

In this Letter, we show that if passive fluctuations are considered, primordial black holes (PBHs) can be easily produced in the framework of single-field, slow-roll inflation models. The formation of PBHs is due to the blue spectrum of passive fluctuations and an enhancement of the spectral range which exits horizon near the end of inflation. Therefore the PBHs are light with masses $\lesssim 10^{15}$ g depending on the number of e-folds when the scale of our observable universe leaves horizon. These PBHs are likely to have evaporated and cannot be a candidate for dark matter but they may still affect the early universe.

1. Introduction

Inflation [1] is becoming a standard model for the very early universe. The inflationary scenario, in which the present universe is only a small local patch of a causally connected region at early times which underwent an exponential expansion driven by the inflaton potential, is generally accepted for explaining the observed spatially flat and homogeneous universe. In addition, its quantum fluctuations during inflation give rise to primordial Gaussian matter density fluctuations with a nearly scale-invariant power spectrum, which is consistent with recent astrophysical and cosmological observations such as structure formation and cosmic microwave background anisotropies [2].

Although the simplest single-field, slow-roll inflation model works well, some basic questions have yet to be answered. What is the origin of the inflaton potential? Do classical matter density inhomogeneities that we observe today genuinely come from quantum fluctuations of the inflaton? Are the observed matter density fluctuations truly Gaussian? How robust are the predictions for a subdominant contribution of tensor modes to the metric fluctuations, a slightly broken scale invariance, and a negligible running spectral index of the power spectrum? Future cosmic microwave background measurements and mega-scale mappings of the large scale structure will definitely answer some of these questions or perhaps pose a challenge to the standard inflation scenario.

There has been a lot of studies on inflationary models that go beyond the simplest single-field, slow-roll inflation. A class of models has considered a new source for generating inflaton fluctuations (so-called passive density fluctuations) during inflation through a direct or gravitational coupling between the inflaton and other quantum fields. This leads to very interesting results such as the so-called warm inflation [3], the suppression of large-scale density fluctuations [4], possible constraints on the duration of inflationary expansion [5]. The bursts of particle production that result in infra-red cascading [6], the trapped inflation in which the inflaton rolls slowly down a steep potential by dumping its kinetic energy into light particles at the trapping points along the inflaton trajectory [7,8], and electromagnetic dissipation in natural inflation [9–12].

In all of these papers, essentially, the generation of passive density fluctuations is originated from quantum fluctuations in the back reaction of the couplings to the inflaton perturbation. The nature of passive fluctuations is usually non-Gaussian and non-scale-invariant. A particular feature is that the power spectrum of the passive fluctuations can be very blue [5,8–12]. These passive fluctuations cannot dominate the primordial density perturbation at large scales as confirmed by cosmological observations such as cosmic microwave background (CMB) anisotropies and the formation of large scale structures. However, depending on individual models, their significant contribution to the non-Gaussianity is still possible. This will be tested soon in the Planck CMB mission and in future large-scale-structure surveys. In this Letter, we point out that the passive fluctuations with a blue spectrum can dominate the primordial density perturbation in the very small scales, seeding the formation of primordial black holes (PBHs) in the radiation-domination era after inflation.

2. Passive density fluctuations during inflation

Let us consider a slow-rolling inflaton ϕ coupled to a certain quantum field χ. The Lagrangian that is relevant to ϕ is given by

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http://dx.doi.org/10.1016/j.physletb.2012.12.052

$$L = \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - V(\phi) + L_I(\phi, \chi), \tag{1}$$

where V is the inflaton potential, L_I is the interaction term, and the metric is

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

The equations of motion for the mean fields are then given by

$$H^2 \equiv \left(\frac{\dot a}{a}\right)^2 = \frac{8\pi}{3M_P^2}\left(\frac{1}{2}\dot\phi^2 + V + \rho_\chi\right), \tag{3}$$

$$\ddot\phi + 3H\dot\phi + V' = \frac{\partial L_I}{\partial \phi}, \tag{4}$$

where ρ_χ is the energy density of χ particles, the dot and the prime denote differentiating with respect to time and ϕ respectively, and $M_P = 2.4 \times 10^{18}$ GeV is the reduced Planck mass. In Eq. (4), the right-hand side of the equation is the back reaction of the interaction to the inflaton mean field. The back reaction arises due to copious production of χ quanta during inflation.

In addition, the fluctuations of ϕ satisfy

$$\delta\ddot\phi + 3H\delta\dot\phi - \frac{\nabla^2}{a^2}\delta\phi + V''\delta\phi = \delta\left(\frac{\partial L_I}{\partial\phi}\right). \tag{5}$$

The homogeneous solution of this fluctuation equation gives rise to the standard primordial density fluctuations. Here we call them as active fluctuations and denote their power spectrum by P_a. The right-hand side of Eq. (5), which comes from the fluctuations of the back reaction, acts as a source for generating additional fluctuations of ϕ. The particular solution of Eq. (5) with the source term is referred as passive fluctuations and the power spectrum is denoted by P_p. Hence, the total power spectrum is given by the contributions from both active fluctuations and passive fluctuations as

$$P = P_a + P_p = \left(\frac{H}{\dot\phi}\right)^2 \langle |\delta\phi_k|^2 \rangle, \tag{6}$$

where $\delta\phi_k$ is the Fourier mode of $\delta\phi$.

3. Primordial black holes

For single-field slow-roll inflation, the spectrum from active fluctuations is given by

$$P_a = \frac{1}{24\pi^2 M_P^4}\frac{V}{\epsilon}, \tag{7}$$

where the slow-roll parameter is

$$\epsilon \equiv \frac{M_P^2}{2}\left(\frac{V'}{V}\right). \tag{8}$$

In a given region with radius r, the criteria of black hole formation is given by

$$\frac{2G\delta M}{r} = \frac{2\delta M}{r M_P^2} > 1 \tag{9}$$

where G is Newton's constant and δM is the mass inside the region r.[1] The condition can be expressed by using the energy density $\delta M \sim \delta\rho r^3$ as

$$\delta\rho \gtrsim \frac{M_P^2}{r^2}. \tag{10}$$

The primordial density perturbation can be imagined as density fluctuation between different Hubble patches of the universe (so-called 'separate universes' [13]) with radius $r \sim 1/H$. Namely, in each patch of the universe, the energy density is regarded as homogeneous but each patch has different value of energy density. Therefore Eq. (10) becomes $\delta\rho \gtrsim M_P^2 H^2 \sim \rho$ where in the second equality Friedmann equation ($\rho \sim 3H^2 M_P^2$) is used and ρ should be regarded as the average of many patches. From this simple estimation, we can naively guess that if $P^{1/2} \sim (\delta\rho/\rho) \gtrsim \mathcal{O}(1)$, the whole patch of the separate universe will collapse into a black hole. The argument here is heuristic one. For those who concern about the gauge dependence of density fluctuation, our argument has assumed a spatially flat gauge in which we choose a slice with zero curvature perturbation and hence the relevant quantity is density fluctuation. More rigorous calculation for the condition of primordial black hole formation is given by Refs. [14,15] as

$$\frac{1}{3} < \delta \equiv \frac{\delta\rho}{\rho} < 1. \tag{11}$$

The upper bound is to avoid formation of a separate closed universe. If the spectrum is $P^{1/2} \sim \mathcal{O}(10^{-2})$, PBHs will be copiously produced [14]. This is certainly not the range of the matter power spectrum probed by CMB experiments. The range corresponds to the scale of quantum fluctuations that exits the horizon during inflation at a number of e-folds, $N = 60$, before inflation ends. It is because we have $P(N = 60) = (5 \times 10^{-5})^2$ from CMB observations. However, the spectrum can be large near the end of inflation,

$$P(N = 0) \sim 10^{-4} \sim 10^6 \times P(N = 60). \tag{12}$$

In this case black holes will form soon after inflation when the scale enters the horizon. These black holes are called primordial black holes (PBHs) (see Refs. [16,17] for review). The spectrum from active fluctuations is (almost) scale-invariant, therefore unless the running spectral index is large, PBHs cannot be formed [18,19]. We can see from Eqs. (7) and (8) that the slow-roll parameter ϵ has to decrease toward the end of inflation in order to enhance the (active) spectrum. However, inflation has to end so the usual tendency is an increasing ϵ. This is the reason why it is so difficult to have PBHs (for single-field slow-roll inflation with active fluctuations) [20–23]. However, we point out for the first time that it is very natural and easy to have PBHs formed even in the case of single-field slow-roll inflation if we consider passive fluctuations.

4. Inflation models and passive power spectra

In this section, we will discuss the passive fluctuations in different inflation models and explore the possibility of forming primordial black holes from the passive fluctuations.

4.1. Axion inflation

Let us consider the case that the inflaton ϕ is a pseudo Nambu–Goldstone boson with a typical potential after the shift symmetry is broken,

$$V(\phi) = \Lambda^4\left[1 - \cos(\phi/f)\right], \tag{13}$$

where Λ is a mass scale and f is the axion decay constant. And the coupling to a gauge field is

$$L_I = -\frac{\alpha}{4f}\phi F^{\mu\nu}\widetilde{F}_{\mu\nu}. \tag{14}$$

[1] Interestingly this relation can be found from Newtonian physics by requiring the escape velocity to be larger than the speed of light.