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Inflaton Decay in Supergravity and Gravitino Problem

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Abstract. We have recently shown that, if the inflaton has a nonzero vacuum expectation value, it generically couples to any matter fields that appear in the superpotential at the tree level, and to any gauge sectors through anomalies in the supergravity. Through these processes, the inflaton decays into the supersymmetry breaking sector, producing many gravitinos. The inflaton also directly decays into a pair of the gravitinos. Taking account of these processes, we derive constraints on both inflation models and supersymmetry breaking scenarios for avoiding overproduction of the gravitinos.

Keywords: inflation, reheating, gravitino, supergravity
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INTRODUCTION

Recently there has been much progress concerning the decays of scalar fields such as moduli [1, 2, 3] and inflaton [4, 5, 6, 7, 8, 9] in a framework of the local supersymmetry (SUSY), i.e., the supergravity (SUGRA). The supersymmetric extension is one of the most promising candidates for the theory beyond SM. If SUSY exists at the TeV scale, the inflaton dynamics is quite likely described in SUGRA. In addition, since the existence of a flat direction is mediocre in SUSY models, one can find extremely flat potentials appropriate for the slow-roll inflation. Throughout this article we consider inflation models in SUGRA. We have investigated the reheating of the universe in this framework, and found that the gravitinos are generically produced from the inflaton decay in most inflation models. In particular, Ref. [4] has first pointed out that the inflaton can directly decay into a pair of the gravitinos. Moreover, incorporating the gravitational effects, Refs. [6, 8] have shown that the inflaton generically decays into the SUSY breaking sector, which produces the gravitinos (in)directly. The gravitino production rates due to these processes depend on the inflaton parameters as well as the detailed structure of the SUSY breaking sector. Such gravitino production clearly goes beyond the simplification of the reheating that has been adopted so far, and interestingly enough, it provides severe constraints on inflation models as well as the SUSY breaking scenarios. These constraints, together with the future collider experiments and observations on CMB, should become an important guide to understand the high energy physics and the early universe. The purpose of the article is to provide both a rough sketch of the gravitino production and the constraints on the representative inflation models. The interested reader may refer to the original references and/or Ref. [9] for further details.

GRAVITINO PRODUCTION

Let us first briefly review the recent development on the gravitino production from the inflaton decay. There are three gravitino production processes; (a) the gravitino pair production [4, 5, 1, 2, 3]; (b) spontaneous decay at tree level [6]; (c) anomaly-induced decay at one-loop level [8]. For the processes listed above, the gravitino production rate can be expressed as

$$\Gamma_{3/2} = \frac{x}{32\pi}\left(\frac{\langle\phi\rangle}{M_P}\right)^2 \frac{m_\phi^3}{M_P^2}, \tag{1}$$

where m_ϕ is the inflaton mass, $\langle\phi\rangle$ a vacuum expectation value (VEV) of the inflaton, and $M_P = 2.4\times 10^{18}$GeV the reduced Planck mass. Here it should be noted that $\langle\phi\rangle$ is evaluated at the potential minimum after inflation. The precise value of the numerical coefficient x depends on the production processes, possible non-renormalizable couplings in the Kähler potential, and the detailed structure of the supersymmetry (SUSY) breaking sector [9]. To be concrete, let us assume the minimal Kähler potential and the dynamical SUSY breaking (DSB) [10] with a dynamical scale Λ. In the DSB scenario, the SUSY breaking field z can acquire a large mass m_z, which is assumed to be roughly equal to the dynamical scale $\Lambda \sim \sqrt{m_{3/2}M_P}$ in the following. Such a simplification does not essentially change our arguments. For a low-inflation model with $m_\phi < \Lambda$, the process (a) becomes effective, and $x = 1$. On the other hand, for the inflaton mass larger than Λ, the processes (b) and (c) become effective instead. The inflaton decays into the hidden quarks in the SUSY breaking sector via Yukawa couplings (process (b)), or into the hidden gauge sector via anomalies (process (c)). Since the hidden quarks and gauge bosons (and gauginos) are energetic when they are produced, they are expected to form jets and produce hidden hadrons through the strong gauge interactions. The gravitinos are likely generated by the decays of the hidden hadrons as well as in the cascade decay processes in jets. We denote the averaged number of the gravitinos produced per each jet as $N_{3/2}$. Then x is given by [9] [1]

$$x \;=\; \frac{N_{3/2}}{8\pi^2}\left(\frac{1}{2}N_y|Y_h^2| + N_g\alpha_h^2(T_g^{(h)} - T_r^{(h)})^2\right), \tag{2}$$

where Y_h and α_h are the Yukawa coupling and a fine structure constant of the hidden gauge group, respectively, N_y denotes a number of the final states for the process (b), N_g is a number of the generators of the gauge group, and $T_g^{(h)}$ and $T_r^{(h)}$ are the Dynkin indices of the adjoint representation and the matter fields in the representation r. Although x depends on the structure of the SUSY breaking sector, its typical magnitude is $O(10^{-3}-10^{-2})$ for $m_\phi > \Lambda$ [2]. To be explicit we take $x = 1/(8\pi^2)$ in the following analysis.

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[1] If the Kähler potential takes a form of the sequestered type, the spontaneous decay through Yukawa couplings is suppressed [8, 9].

[2] Roughly, we expect $N_{3/2} = O(1-10^2)$, $N_g = O(1)$, $\alpha_h = O(0.1)$, and $T_g^{(h)} - T_r^{(h)} = O(1)$, while Y_h strongly depends on the SUSY breaking models. Note also that the gravitino can be produced through the Yukawa interaction in the messenger sector, if the inflaton mass is larger than the messenger scale.

Using the gravitino production rate given above, we can estimate the abundance of the gravitinos non-thermally produced by an inflaton decay:

$$
\begin{aligned}
Y_{3/2}^{(NT)} &= 2\frac{\Gamma_{3/2}}{\Gamma_\phi}\frac{3T_R}{4m_\phi}, \\
&\simeq 7\times 10^{-11}\,x\left(\frac{g_*}{200}\right)^{-\frac{1}{2}}\left(\frac{\langle\phi\rangle}{10^{15}\mathrm{GeV}}\right)^2\left(\frac{m_\phi}{10^{12}\mathrm{GeV}}\right)^2\left(\frac{T_R}{10^6\mathrm{GeV}}\right)^{-1}, \quad (3)
\end{aligned}
$$

where g_* counts the relativistic degrees of freedom, and $\Gamma_\phi \sim T_R^2/M_P$ denotes the total decay rate of the inflaton. It should be noted that the gravitino abundance is inversely proportional to the reheating temperature, which should be contrasted to the standard thermal production of the gravitinos.

CONSTRAINTS ON INFLATION MODELS

Now we would like to derive constraints on the inflation and SUSY breaking models, using the non-thermal production of the gravitinos discussed in the previous section. The abundance of the gravitinos are tightly constrained by e.g. BBN, depending on the properties of the gravitino. Using (3), therefore, we can constrain the inflaton parameters.

In Fig. 1, we show the constraints on the inflaton mass and VEV for $m_{3/2} = 1\,\mathrm{GeV}, 1\,\mathrm{TeV}$, and $100\,\mathrm{TeV}$, together with typical values of the inflation models. The region above each solid line is excluded. We find that in the case of $m_{3/2} = 1\,\mathrm{TeV}$ with the hadronic branching ratio $B_h = 1$, all the inflation models shown in the figure are excluded. For the gravitino mass lighter or heavier than the weak scale, the constraints become relaxed. Indeed, if the gravitino is stable, the non-thermally produced gravitino can account for the observed dark matter density [11]. The inflaton mass and its VEV depend on the inflation models. For larger m_ϕ and $\langle\phi\rangle$, the constraints become severer, because more gravitinos are produced by the inflaton decay (see (3)). On the other hand, if the inflaton is charged under some symmetries, its VEV becomes suppressed or even forbidden especially when the symmetry is exact at the vacuum. Then the bounds can be avoided for such inflation models. This is the case of the chaotic inflation model with a discrete symmetry (note that the chaotic inflation model shown in Fig. 1 is the one without such a symmetry). For the other possible solutions [7], see Ref. [9].

In Fig. 1, we have set T_R to be the highest value allowed by the cosmological constraints. As mentioned before, the abundance of the non-thermally produced gravitinos is inversely proportional to T_R, which is different from that of the thermally produced one. If T_R takes a smaller value, the constraints shown in the figure becomes severer. Thus, the bounds shown in Fig. 1 are the most conservative ones. Note that one may have to introduce couplings of the inflaton with the SM particles to realize the highest allowed reheating temperature.

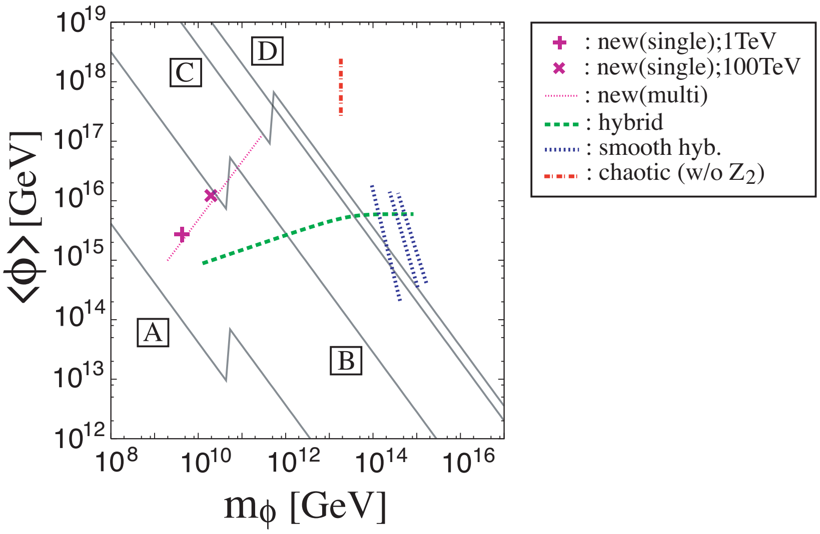

FIGURE 1. Constraints from the gravitino production by the inflaton decay, for $m_{3/2} = 1\,\text{TeV}$ with $B_h = 1$ (case A), $m_{3/2} = 1\,\text{TeV}$ with $B_h = 10^{-3}$ (case B), $m_{3/2} = 100\,\text{TeV}$ (case C), and $m_{3/2} = 1\,\text{GeV}$ (case D). The region above the solid (gray) line is excluded for each case. For $m_\phi \gtrsim \Lambda$, we have used the anomaly-induced inflaton decay into the hidden gauge/gauginos to estimate the gravitino abundance, while the gravitino pair production has been used for $m_\phi \lesssim \Lambda$. Since T_R is set to be the highest allowed value, the constraints shown in this figure are the most conservative ones.

CONCLUSION

We have shown that the gravitinos are generically produced by the inflaton decay, through several processes described above. Our discovery may provide us with a break-through toward the full understanding of the inflationary universe. In addition to the standard analyses on the density fluctuations, the inflation models in supergravity are subject to the constraints due to the (non)-thermally produced gravitinos. Whether a consistent thermal history after inflation is realized now becomes a new guideline to sort out the inflationary zoo, and hopefully it will pin down the true model, together with data in the future collider experiments.

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