Cosmological scenario of the stop as the next lightest supersymmetric particle with the gravitino as the lightest supersymmetric particle, and the cosmic lithium problem

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(Received 7 December 2008; published 13 February 2009)

The discrepancy on ^{7}Li and ^{6}Li abundances between the observational data and the standard big-bang nucleosynthesis theory prediction has been a nagging problem in astrophysics and cosmology, given the highly attractive and successful big-bang paradigm. One possible solution of this lithium problem is through hadronic decays of a massive metastable particle which alter the primordial element abundances. We explore this possibility using a gravitino dark matter framework in which the next lightest supersymmetric particle is typically long-lived. We found that the stop as the next lightest supersymmetric particle may provide an attractive solution to the lithium problem.

DOI: 10.1103/PhysRevD.79.043514 PACS numbers: 26.35.+c, 11.30.Pb, 98.80.−k

I. INTRODUCTION

The identity of dark matter is one of the most important questions that we currently have in astrophysics and cosmology. There are many theoretical candidates for dark matter particles proposed by many beyond the standard model hypotheses in particle physics, and the gravitino is one of them within the supergravity framework [1–3]. Because of the smallness of the coupling between the gravitino and matter in supergravity models, $\sim 1/M_{\rm Pl}$, the next lightest supersymmetric particle (NLSP) is typically long-lived. This has a direct implication on the light element abundances if the NLSP decayed around or after the time of the big-bang nucleosynthesis (BBN). Thus BBN provides a stringent constraint on gravitino dark matter scenarios [4–15]. However, on the other hand, it seems that the standard BBN theory cannot explain all of the primordial light element abundances from observations, namely, the lithium problem described below. This leads to an interesting possibility that some nonstandard processes were involved in the BBN. In this paper, we study a feasible solution of the lithium problem by gravitino dark matter with the stop as the NLSP scenario.

There are many possibilities for the NLSP with the gravitino as the LSP, and each has its own phenomenological signatures. The ones that have been studied are the neutralino as the NLSP [4–8,10,11,14], the stau as the NLSP [4,6–8,10,11,13,14], the stop as the NLSP [12], and the sneutrino as the NLSP [5,6,9,11,14,15]. We do not discuss the details of those phenomenologies here but concentrate only on the BBN effects by looking at the NLSP decays, lifetime, and density before the decay. We found that the stop as the NLSP is the most interesting scenario in the sense that it may provide a solution to the lithium problem. Therefore we focus on the stop particle in this paper.

It has been recognized that the theoretical prediction of ^{7}Li abundance in the standard BBN does not agree with the observational results when we adopt the baryon-to-photon ratio of the WMAP 5-year study, $\eta = (6.225 \pm 0.170) \times 10^{-10}$ [16]. Using this ratio, the theoretical value for ^{7}Li is much larger than the observational one even if we adopt a relatively high value of the observational abundance $\log_{10}(^7{\rm Li/H})_{\rm obs} = -9.36 \pm 0.06$ [17].[1] Quite recently, Ref. [19] reported that the discrepancy gets worse if we adopt an updated theoretical calculation for the reaction rate of ^{4}He(^{3}He, γ)^{7}Be. As for ^{6}Li abundance, on the other hand, recent observation shows that the theoretical value is much smaller than that of the observation: $(^6{\rm Li}/^7{\rm Li})_{\rm obs} = 0.046 \pm 0.022$ [20]. We collectively call these discrepancies of ^{6}Li and ^{7}Li the "lithium problem."

If there is a metastable massive particle which decays, producing energetic standard model particles, around or after the BBN era, the light element abundances might be altered through electromagnetic and hadronic shower effects. In the hadronic-decay scenario, we might be able to solve the lithium problem because the hadron emission could possibly reduce ^{7}Li [21] and produce ^{6}Li simultaneously [22,23] as will be discussed later. To solve the lithium problem, the NLSP abundance times its net visible energy which fragments into hadrons $E_{\rm had}$ should be in the range of $E_{\rm had} n_{\rm NLSP}/s \simeq 10^{-14}$–$10^{-13}$ GeV with their lifetime 10^3–10^4 s [21–23]. It is attractive that the stop abundance is naturally tuned to solve the lithium problem when we consider a further (second) annihilation which must

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[1]On the other hand, in Ref. [18] a relatively low value of ^{7}Li abundance was reported: $\log_{10}(^7{\rm Li/H})_{\rm obs} = -9.90 \pm 0.06$. Obviously, it would be more difficult and problematic to fit this value.

occur just after the QCD phase transition as was pointed out by Ref. [24].[2]

The outline of this paper is as follows. In Sec. II, we discuss supersymmetric models with the stop as the NLSP, assuming the gravitino as the LSP. In Sec. III, we calculate the stop abundance before it eventually decays to the gravitino. In Sec. IV, we briefly review the big-bang nucleosynthesis theory and then present our analysis with the stop as the NLSP. Finally, we conclude in Sec. V.

II. MODELS WITH THE STOP AS THE NLSP

The lightest stop particle $\tilde{t}_1$ can be light by a (little) seesaw mechanism between left and right stop $\tilde{t}_L$ and $\tilde{t}_R$, respectively. Recall the stop mass matrix

$$\mathcal{M}^2_{\tilde{t}} = \begin{pmatrix} M^2_{LL} & M^2_{LR} \\ M^{2\dagger}_{LR} & M^2_{RR} \end{pmatrix}, \tag{1}$$

where

$$M^2_{LL} = M^2_{\tilde{t}_L} + m_t^2 + \tfrac{1}{6}(4m_W^2 - m_Z^2)\cos 2\beta, \tag{2}$$

$$M^2_{RR} = M^2_{\tilde{t}_R} + m_t^2 + \tfrac{2}{3}m_Z^2\cos 2\beta \sin^2\theta_W, \tag{3}$$

$$M^2_{LR} = -m_t(A_t + \mu\cot\beta). \tag{4}$$

The off-diagonal terms are multiplied by the top-quark mass m_t which is quite large. If A_t is also large, it is possible to have $\tilde{t}_1$ lighter than all of the other minimal supersymmetric standard model (MSSM) sparticles and therefore becomes the NLSP (with the gravitino as the LSP).

As we mentioned, in this gravitino as the LSP scenario, the stop as the NLSP has a long lifetime. In colliders, any metastable stop produced would quickly hadronize either into some sbaryons or mesinos. The superhadrons then decay to the lightest sbaryon $\tilde{t}ud$, which is charged, or the lightest mesino $\tilde{t}\,\bar{u}$, which is neutral [30].[3] They would then escape the calorimeter, and the charged ones could be detected by the muon detector. This hadronization complicates the determination of the detection rates of the stop. Nevertheless, there has been analysis by CDF at Tevatron, which set the lower bound of a (meta)stable stop mass at ~250 GeV [31].[4]

Realization of the stop as the NLSP scenario in some specific MSSM models was studied in [12]. However, it was found that in the constrained MSSM it is not possible to have the stop as the NLSP due to the Higgs mass and the stop mass lower bound constraints. In the nonuniversal Higgs masses model [34,35], we can still have a narrow allowed region with the stop as the NLSP. Nonetheless, the stop as the NLSP is still possible if we forgo the universality assumption for sfermion and gaugino masses. For example, in Ref. [36] it was shown that the stop would be relatively light if the gluino mass at the grand unified theory scale is lower than the b-ino and W-ino mass. In that paper, the author still assumed the neutralino to be lighter than the stop. However, it would be easy to check that we can combine this nonuniversality with a moderate value of trilinear coupling A_t to get the stop to be the lightest. Our approach here is not to look at a specific model of supersymmetry. We will just assume that the stop is the NLSP and treat the stop mass as a free parameter.

We then calculate the stop lifetime as a function of stop and gravitino masses. When the mass gap between the stop and the gravitino is larger than m_t, the dominant decay channel is the 2-body decay $\tilde{t} \to \tilde{G} + t$. The stop lifetime can then be determined as

$$\begin{aligned}\tau_{\tilde{t}} \simeq\, & 48\pi M_P^2 m^2_{\tilde{G}} m^3_{\tilde{t}}[m^2_{\tilde{t}} - m^2_{\tilde{G}} - m_t^2 \\ & + 4\sin\theta_{\tilde{t}}\cos\theta_{\tilde{t}} m_t m_{\tilde{G}}]^{-1}[(m^2_{\tilde{t}} + m^2_{\tilde{G}} - m_t)^2 \\ & - 4m^2_{\tilde{t}} m^2_{\tilde{G}}]^{-1}[(m^2_{\tilde{t}} + m_t^2 - m^2_{\tilde{G}})^2 - 4m^2_{\tilde{t}} m_t^2]^{-1/2},\end{aligned} \tag{5}$$

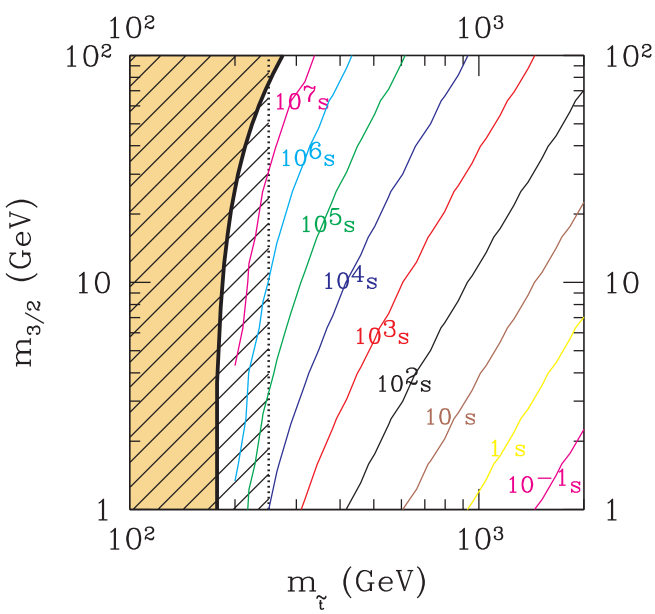

FIG. 1 (color online). Stop lifetime in the plane of stop mass $m_{\tilde{t}}$ and gravitino mass $m_{3/2} \equiv m_{\tilde{G}}$. The shadowed region on the left with respect to the dotted line is excluded by the experimental lower bound on the stop mass $m_{\tilde{t}} \gtrsim 250$ GeV. The left side of the thick line is not allowed by kinematic for 2-body decay $\tilde{t} \to t + \tilde{G}$.

[2]For another simultaneous solution to solve the lithium problem in astrophysics and cosmology, see also Refs. [25,26] and [27–29], respectively.

[3]For simplicity, we will ignore the label "1" to denote the lightest state for the rest of this paper.

[4]There are also studies for future detectabilities of a relatively long-lived stop in the Large Hadron Collider (LHC) [32] and the International Linear Collider [33]. However, these studies assume the neutralino as the LSP, and the analyses were based on the stop decay to a charm quark plus neutralino and therefore are not applicable to our case here.

where M_P is the reduced Planck mass ($M_P \equiv M_{pl}/\sqrt{8\pi} \simeq 2.4 \times 10^{18}$ GeV) and $\theta_{\tilde{t}}$ is the stop mixing angle. As shown in [12], the dependence on $\theta_{\tilde{t}}$ is small; hence, we can fix $\theta_{\tilde{t}}$ for our analysis ($= 1.3$ radian). Our numerical results are shown in Fig. 1, as contours in the $m_{\tilde{t}}$ vs $m_{\tilde{G}}$ plane. We do not need to calculate the 3-body decay rate since it is only important for a lifetime longer than $\sim 10^8$ s.

III. STOP ABUNDANCE

We can calculate the relic abundance of the thermally produced stop according to the standard method for calculating the freeze-out value [12]. Assuming that the coannihilation effect is negligible and that there is no resonance, we can simplify the calculation by considering only annihilation channels through gluon exchange. See [37] for a detailed discussion on this approximation. In this case, the relic density calculation depends only on the stop mass. We get a relic density of $\Omega_{\tilde{t}}h^2 = 10^{-4}$–$10^{-2}$ for $m_{\tilde{t}} = 10^2$–10^3 GeV, corresponding to $m_{\tilde{t}}Y_{\tilde{t}} = 10^{-13}$–$10^{-11}$ GeV. However, in addition to the standard annihilation process, there is a further annihilation that reduces the number density of the stop before it eventually decays [24].

After the QCD phase transition which occurs at a temperature $T = T_{\rm QCD} \approx 150$ MeV, all of the strong interacting particles are confined into hadrons. The strength of the strong interaction is then determined by the effective theory of hadron physics. According to the heavy-quark effective theory [38], the length scale for the interactions of heavy-quark hadrons is $R_{\rm had} \sim 1$–$10\ {\rm GeV}^{-1}$ [24], and we can parameterize the length scale as $R_{\rm had} \equiv f_\sigma/m_\pi$, with m_π the pion mass ($\simeq 140$ MeV) and f_σ a numerical parameter ranging from about 0.1 to 1.

The relic stop and antistop would also form hadrons, called superhadrons or shadrons, which then undergo further annihilation via bound states. The annihilation rate among these shadrons can be written as

$$\Gamma_{\rm ann} = \langle \sigma v \rangle n_{\tilde{t}}, \tag{6}$$

where σ is the annihilation cross section, v is the relative velocity, and the bracket means thermal average. Here we assume that all of the stop shadrons have decayed into the lightest one which is a neutral mesino $\tilde{T}^0 \equiv \tilde{t}\,\bar{u}$, and similarly $\tilde{T}^{0*} \equiv \tilde{t}^* u$ for the antistops. With this assumption, the number density of $\tilde{T}^0$ is equal to that of the stop $n_{\tilde{t}}$ [12]. We also assume that the number density of the stop is equal to that of the antistop. Here σ and v can be simply expressed by $\sigma \sim R_{\rm had}^2$ and $v \simeq \sqrt{3T/m_{\tilde{t}}}$, respectively.

The time scale of the annihilation is compared with the Hubble expansion rate:

$$\Gamma_{\rm ann} = 3H, \tag{7}$$

where $H = \sqrt{\rho}/(\sqrt{3}M_P)$, with M_P the reduced Planck mass and ρ the total energy density $\rho = \pi^2/30 g_* T^4$. We adopt effective degrees of freedom $g_* = 17.25$ (or 10.75), assuming that the QCD phase transition occurs at $T = T_{\rm QCD} \sim 150$ MeV (or ~ 100 MeV). We get the final abundance of the stop after the second annihilation to be

$$m_{\tilde{t}}Y_{\tilde{t}} = 0.87 \times 10^{-14}\ {\rm GeV}\left(\frac{f_\sigma}{0.1}\right)^{-2}\left(\frac{g_*}{17.25}\right)^{-1/2} \times \left(\frac{T_{\rm QCD}}{150\ {\rm MeV}}\right)^{-3/2}\left(\frac{m_{\tilde{t}}}{10^2\ {\rm GeV}}\right)^{3/2}, \tag{8}$$

where the yield variable of the stop is defined by $Y_{\tilde{t}} \equiv n_{\tilde{t}}/s$, with s the entropy density ($= \frac{4}{3}\rho/T$). From the temperature dependence in Eq. (8), it can be seen that $Y_{\tilde{t}}$ is lower for a higher temperature after the QCD phase transition, which means that the number density of the stop must immediately be frozen out just after their hadronization and annihilation at $T = T_{\rm QCD}$. We see that the stop abundance can naturally be cast into the attractive range of $10^{-14}\ {\rm GeV} \lesssim B_h m_{\tilde{t}} Y_{\tilde{t}} \lesssim 10^{-13}\ {\rm GeV}$[5] for a several hundred GeV stop mass with a reasonable hadronic branching ratio $B_h \sim \mathcal{O}(1)$. Note that the above final abundance is lower than the stop abundance after the standard freeze-out, which occurred at around $T \sim m_{\tilde{t}}/30$ [12]. Moreover, the decay of the thermally produced stop would have only a negligible contribution to the dark matter relic density $\Omega_{\rm DM}h^2 \simeq 0.1$ [16].

IV. BIG-BANG NUCLEOSYNTHESIS AND THE STOP AS THE NLSP

We consider the 2-body decay process of the stop into a gravitino and a top quark. The emitted top quark then immediately fragments into hadrons and produces lots of high-energy protons and neutrons. Those emitted particles may modify the abundances of light elements such as D, T, ^{3}He, ^{4}He, ^{6}Li, ^{7}Li, and ^{7}Be after/during the BBN epoch [39–42].

The high-energy hadrons scatter off the background protons and ^{4}He and induce a hadronic shower. These processes produce energetic neutrons D, T, and ^{3}He. These nonthermally produced neutrons and T (or ^{3}He) then scatter off the background protons and ^{4}He. It is followed by n-p (T-^{4}He) reactions, synthesizing D (^{6}Li). In addition, the nonthermally produced neutron also induces sequential reactions to reduce the ^{7}Be abundance through a set of processes ^{7}Be(n, p)^{7}Li(p, ^{4}He)^{4}He, reducing the primordial ^{7}Be abundance which means reducing the primordial ^{7}Li abundance as well through the electron capture at a later time. This mechanism in nonstandard

[5] To be more precise, it is $B_h(m_{\tilde{t}} - m_{\tilde{G}})Y_{\tilde{t}}$ that we need to look at. However, the stop mass is much larger than the gravitino mass in the interesting region.

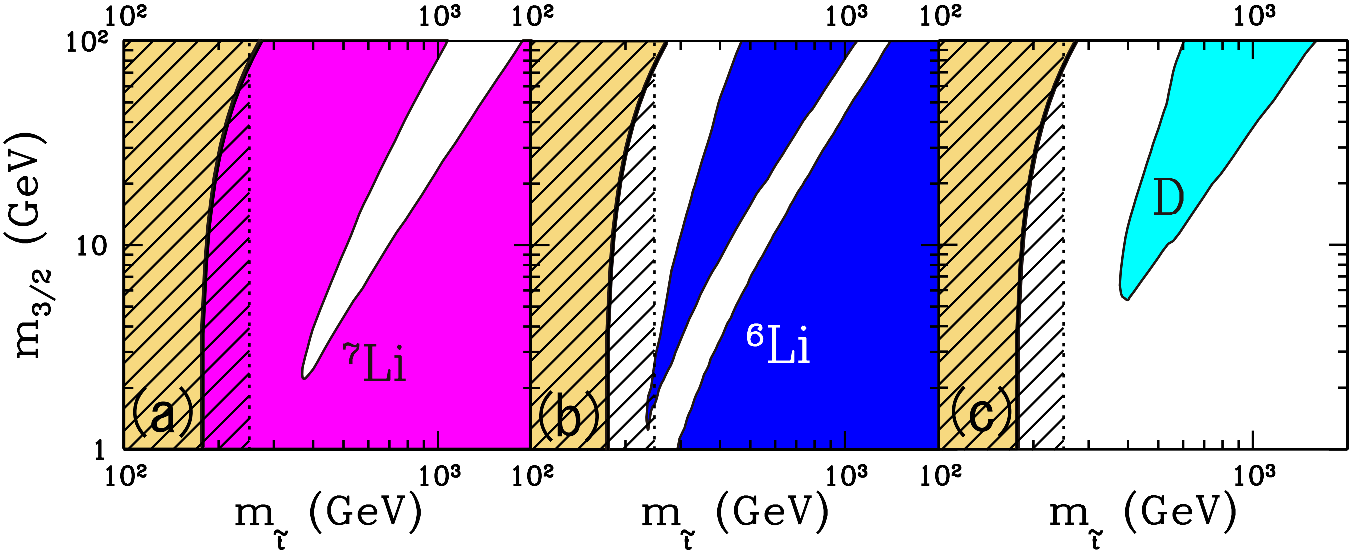

FIG. 2 (color online). Allowed regions in the plane of the stop mass and the gravitino mass in the case of $R_{\rm had} = 0.1/m_\pi$. Each white region is observationally allowed for (a) ^{7}Li, (b) ^{6}Li, and (c) D, respectively. The shadowed region which is left with respect to the dotted line is excluded by the experimental lower bound $m_{\tilde{t}} \gtrsim 250$ GeV. The left region with respect to the thick line is not allowed kinematically when we consider only the 2-body decay $\tilde{t} \to t + \tilde{G}$.

BBN scenarios has been studied in Refs. [21–23] in detail. Because we are interested in a relatively short lifetime of stop $\tau_{\tilde{t}} \lesssim 10^7$ s with its high branching ratio into hadrons ($B_h \sim 1$), the photodissociation processes induced by the emitted high-energy charged particles and photons are not important in this study [41,42].

We would have to check whether the abundances of the other light elements also agree with the observational data. In particular, it would be a crucial problem if copious deuteriums are produced in this scenario. For the observational deuterium abundance, we adopt (D/H)obs $= (2.82 \pm 0.26) \times 10^{-5}$ [43]. Because the stop abundance before its decay is very small as was discussed in the previous section, the stop decay does not significantly affect the ^{4}He mass fraction and the ^{3}He to D ratio.

In Fig. 2, we plot allowed regions in the plane of the stop mass and the gravitino mass, assuming $f_\sigma = 0.1$. Each white region is observationally allowed for (a) ^{7}Li, (b) ^{67}Li, and (c) D, respectively. The left region with respect to the thick line is not kinematically allowed for the 2-body decay mode, $\tilde{t} \to t + \tilde{G}$, and has a stop lifetime longer than $\sim 10^9$ s which we do not consider here. Note that, even if we include this region, our results would not be changed. Furthermore, there is an experimental constraint which excludes $m_{\tilde{t}} \lesssim 250$ GeV.

We can understand the exclusion/allowed regions in Fig. 2 by looking at the yield $B_h m_{\tilde{t}} Y_{\tilde{t}}$ and the lifetime $\tau_{\tilde{t}}$. The analysis results in terms of these two variables is shown in Fig. 1 of Ref. [23]. From Eq. (8) we found that the yield of the stop grows as $m_{\tilde{t}}^{3/2}$ as the stop mass increases. For a small stop mass the effect on ^{7}Li is too small, while for a large mass the effect is too large. It is just right in between. In addition, the effect also depends on the stop lifetime which can be seen from Fig. 1, while for ^{6}Li, as shown in Fig. 1 of [23], it prefers a small yield with a relatively large lifetime or a certain range of lifetimes almost independent of the yield. As for D, it is allowed if the yield is small or the lifetime is small.

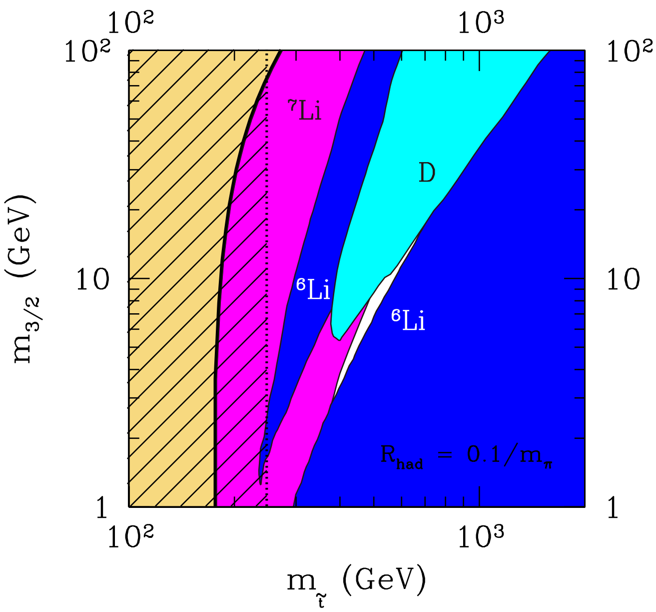

FIG. 3 (color online). Combined allowed region in the plane of the stop mass and the gravitino mass by using the constraints in Figs. 2(a)–2(c). The name of each element is written in the respective exclusion regions. There is an allowed region at around $m_{\tilde{t}} = 400$–600 GeV and $m_{3/2} = 2$–10 GeV.

By combining all three constraints shown in Figs. 2(a)–2(c), we get the favored region at around $m_{\tilde{t}} = 400$–600 GeV and $m_{3/2} = 2$–10 GeV which is clearly shown in Fig. 3.

V. CONCLUSIONS

We have studied the decays of the stop as the NLSP to the gravitino as the LSP and the effects on BBN. We found some range of stop and gravitino masses where all light element abundances agree with the observational data, including ^{7}Li and ^{6}Li, which are problematic in the standard BBN. This result depends, to some extent, on the assumptions made on the detailed history of the Universe, including the stop annihilation after hadronization and the precision of the BBN calculation and measurements. Nonetheless, we have shown here that a supersymmetric model with the gravitino as the LSP and the stop as the NLSP might solve the lithium problem naturally without any tuning. It is, therefore, very interesting to test this hypothesis further. The gravitino itself would be practically undetectable, aside from its gravitational effect, due to its very weak interaction. Direct detection of a dark matter particle can therefore exclude our model.[6] We can only hope that future collider experiments, such as the upcoming LHC, would be able to provide some evidence on the physics beyond the standard model and advance our understanding of the early Universe.

ACKNOWLEDGMENTS

The work of K. K. is partially supported by PPARC Grant No. PP/D000394/1, by EU Grants No. MRTN-CT-2004-503369 and No. MRTN-CT-2006-035863, and by the European Union through the Marie Curie Research and Training Network ''UniverseNet.'' Y. S. thanks Keith Olive for useful discussions.

[6]It might still be allowed if the gravitino is not the only dark matter, and the other dark matter particle is not a neutralino, i.e. decoupled from the gravitino.

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