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Implications of catalyzed BBN in the CMSSM with gravitino dark matter

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ABSTRACT

We investigate gravitino dark matter scenarios in which the primordial ^{6}Li production is catalyzed by bound-state formation of long-lived negatively charged particles X^- with ^{4}He. In the constrained minimal supersymmetric Standard Model (CMSSM) with the stau $\tilde{\tau}_1^-$ as the X^-, the observationally inferred bound on the primordial ^{6}Li abundance allows us to derive a rigid lower limit on the gaugino mass parameter for a standard cosmological history. This limit can have severe implications for supersymmetry searches at the Large Hadron Collider and for the reheating temperature after inflation.

1. Introduction

Big Bang Nucleosynthesis (BBN) is a powerful tool to test physics beyond the Standard Model. Recently, it has been realized that the presence of heavy long-lived negatively charged particles X^- can have a substantial impact on the primordial light element abundances via bound-state formation [1–9]. In particular, when X^- and ^{4}He form Coulomb bound states, (^{4}HeX^-), too much ^{6}Li can be produced via the catalyzed BBN (CBBN) reaction [1]

$$\left(^4\mathrm{He}X^-\right) + \mathrm{D} \to {}^6\mathrm{Li} + X^-. \tag{1}$$

The formation of (^{4}HeX^-) and hence the CBBN production of ^{6}Li becomes efficient at temperatures $T \sim 10$ keV, i.e., at cosmic times $t > 10^3$ s at which standard BBN (SBBN) processes are already frozen out. The observationally inferred bound on the primordial ^{6}Li abundance then restricts severely the X^- abundance at such times.

A long-lived X^- may be realized if the gravitino is the lightest supersymmetric particle (LSP). In particular, it is reasonable to consider gravitino LSP scenarios within the constrained minimal supersymmetric Standard Model (CMSSM) [4,10–13] in which the gaugino masses, the scalar masses, and the trilinear scalar couplings are parameterized by their respective universal values $m_{1/2}$, m_0, and A_0 at the scale of grand unification $M_{\rm GUT} \simeq 2\times 10^{16}$ GeV. Within this framework, the lighter stau $\tilde{\tau}_1$ is the lightest Standard Model superpartner in a large region of the parameter space and thus a well-motivated candidate for the next-to-lightest supersymmetric particle (NLSP). Since its couplings to the gravitino LSP are suppressed by the (reduced) Planck scale, $M_{\rm P} = 2.4\times 10^{18}$ GeV, the stau will typically be long-lived for conserved R-parity[1] and thus $\tilde{\tau}_1^-$ can play the role of X^-.

In scenarios with conserved R-parity, the gravitino LSP is stable and a promising dark matter candidate. Gravitinos can be produced efficiently in thermal scattering of particles in the primordial plasma. If the Universe, after inflation, enters the radiation dominated epoch with a high reheating temperature $T_{\rm R}$, the resulting gravitino density $\Omega_{\tilde{G}}^{\rm TP}$ will contribute substantially to the dark matter density $\Omega_{\rm dm}$ [15–17].

In this work we calculate the amount of ^{6}Li produced in (1) by following the treatment of Ref. [18]. In particular, we employ a recent state-of-the-art result for the CBBN reaction cross reaction [5]. The obtained upper limit on the X^- abundance from possible ^{6}Li overproduction vanishes for sufficiently short τ_{X^-}. This allows us to extract a lower limit on the universal gaugino mass parameter $m_{1/2}$ within minimal supergravity scenarios where the gravitino is the LSP and the X^- is the $\tilde{\tau}_1^-$ NLSP.[2] This limit leads directly to an upper bound on $T_{\rm R}$ since $\Omega_{\tilde{G}}^{\rm TP}$ cannot exceed the observed dark matter density. The bounds on $m_{1/2}$ and $T_{\rm R}$ derived below depend on the gravitino mass but are independent of the CMSSM parameters.

Before proceeding, let us comment on the present status of BBN constraints on gravitino dark matter scenarios with a long-lived charged slepton NLSP. In a recent ambitious study [9] it is argued that bound-state formation of X^- with protons at $T \sim 1$ keV might well reprocess large fractions of the previously synthesized ^{6}Li. This seems to relax the bound on the X^- abundance for $\tau_{X^-} > 10^6$ s. However, at present, the uncertainties in the relevant nuclear reaction rates in [9] make it difficult to decide whether a

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1 For the case of broken R-parity, see, e.g. [14].
2 In this work we assume a standard cosmological history with a reheating temperature $T_{\rm R}$ that exceeds the freeze-out temperature $T_{\rm f}$ of the $\tilde{\tau}_1$ NLSP.

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new cosmologically allowed region will open up. In this work we assume that this is not the case, in particular, since the ^{3}He/D constraint on electromagnetic energy release [19] becomes severe in this region and excludes stau lifetimes $\tau_{\tilde{\tau}_1} \gtrsim 10^6$ s [4,7,9,11]. Then only the constraint from hadronic energy release on D [11,20–23] can be slightly more severe than the one from catalyzed ^{6}Li production [4,7,13,24]. We neglect the D constraint in this work since it can only tighten the bounds on $m_{1/2}$ and $T_{\rm R}$ as can be seen, e.g., in Figs. 4(b)–(d) and 5 of Ref. [13]. For deriving conservative bounds on $m_{1/2}$ and $T_{\rm R}$, it is thus sufficient to consider the CBBN reaction (1) exclusively.

2. Catalyzed ^{6}Li production

The following set of Boltzmann equations [18] describe the time evolution of bound-state (BS) formation of X^- with ^{4}He and the associated evolution of the primordial light elements involved:

$$\frac{dY_{\rm BS}}{dt} = \langle\sigma_{\rm r} v\rangle s Y_\delta - \Gamma_{X^-} Y_{\rm BS} - \langle\sigma_{\rm C} v\rangle s Y_{\rm BS} Y_{\rm D}, \tag{2a}$$

$$\frac{dY_{X^-}}{dt} = -\langle\sigma_{\rm r} v\rangle s Y_\delta - \Gamma_{X^-} Y_{X^-} + \langle\sigma_{\rm C} v\rangle s Y_{\rm BS} Y_{\rm D}, \tag{2b}$$

$$\frac{dY_{^4{\rm He}}}{dt} = -\langle\sigma_{\rm r} v\rangle s Y_\delta + \Gamma_{X^-} Y_{\rm BS}, \tag{2c}$$

$$\frac{dY_{^6{\rm Li}}}{dt} = \langle\sigma_{\rm C} v\rangle s Y_{\rm BS} Y_{\rm D}, \tag{2d}$$

$$\frac{dY_{\rm D}}{dt} = -\langle\sigma_{\rm C} v\rangle s Y_{\rm BS} Y_{\rm D}. \tag{2e}$$

Here we scale out the expansion of the Universe by defining the yield $Y_i = n_i/s$ where n_i is the number density of species i and $s = 2\pi^2 g_{*S} T^3/45$ is the entropy density. In particular, $Y_{\rm BS}$, Y_{X^-}, $Y_{^4{\rm He}}$, $Y_{^6{\rm Li}}$, and $Y_{\rm D}$ denote the yields of the (^{4}HeX^-) bound state, free X^-, free ^{4}He, ^{6}Li produced in CBBN, and D, respectively. The quantity $Y_\delta \equiv (Y_{X^-} Y_{^4{\rm He}} - Y_{\rm BS} \tilde{Y}_\gamma)$ parameterizes the competition between recombination and photo-dissociation of bound states. For the latter, one defines $\tilde{Y}_\gamma = \tilde{n}_\gamma/s$ with [2]

$$\tilde{n}_\gamma \equiv n_\gamma(E > E_{\rm b}) = \frac{n_\gamma \pi^2}{2\zeta(3)} \left(\frac{m_\alpha}{2\pi T}\right)^{3/2} e^{-E_{\rm b}/T}, \tag{3}$$

where $E_{\rm b} = 337.33$ keV [5] is the (^{4}HeX^-) binding energy and $n_\gamma = 2\zeta(3)T^3/\pi^2$. Furthermore, $\Gamma_{X^-} = \tau_{X^-}^{-1}$ denotes the total decay width of X^-.

The CBBN reaction cross section for the process (1) has recently been computed with an advanced method from nuclear physics [5]

$$\langle\sigma_{\rm C} v\rangle = 2.37 \times 10^8 (1 - 0.34 T_9) T_9^{-2/3} e^{-5.33 T_9^{-1/3}} \tag{4}$$

which is given in units of $N_{\rm A}^{-1}$ cm^3 s^{-1} mole^{-1} with T_9 denoting the temperature in units of 10^9 K. The recombination cross section of X^- with ^{4}He is estimated as [2]

$$\langle\sigma_{\rm r} v\rangle = \frac{2^9 \pi \alpha Z_\alpha^2 \sqrt{2\pi}}{3e^4} \frac{E_{\rm b}}{m_\alpha^2 \sqrt{m_\alpha T}} \tag{5}$$

with $m_\alpha = 3.73$ GeV [25] and $Z_\alpha = 2$.[3]

We solve (2) using as initial conditions the respective X^- yield prior to decay, $Y_{X^-}^{\rm dec}$, and the SBBN output values of the computer code PArthENoPE [26]: $Y_{\rm p} \equiv 4n_{^4{\rm He}}/n_{\rm b} = 0.248$, D/H $= 2.6 \times 10^{-5}$, ^{6}Li/H $= 1.14 \times 10^{-14}$, and $n_{\rm p}/n_{\rm b} = 0.75$; furthermore, $g_* = 3.36$ and $g_{*S} = 3.91$. While the variation of the D and ^{4}He abundances from their SBBN values are negligible, the catalyzed fusion of ^{6}Li is substantial as shown in Fig. 1 by the contour-lines of $^6{\rm Li/H} \equiv Y_{^6{\rm Li}} s/n_{\rm p}$ (solid lines). Contrasting with the observationally inferred upper limit on the primordial ^{6}Li abundance [27],

$$^6{\rm Li/H}|_{\rm obs} \lesssim 2 \times 10^{-11}, \tag{6}$$

one sees clearly that $^6{\rm Li/H}|_{\rm CBBN}$ can be far in excess.

The dashed lines in Fig. 1 show the solution of (2) where instead of (2a) the Saha type equation $Y_{\rm BS} = Y_{^4{\rm He}} Y_{X^-}/\tilde{Y}_\gamma$ is used as an approximation for the bound-state abundance. The obtained overestimation of the ^{6}Li abundance demonstrates the importance of the use of the Boltzmann equation (2a). However, focusing on $Y_{X^-}^{\rm dec} \gtrsim 10^{-14}$, we will read off the relevant constraint in the region $\tau_{X^-} < 10^4$ s in which the slope of the ^{6}Li contours is very steep. Therefore, the use of (2a) instead of the Saha type equation is an improvement on the conceptional side which has only a marginal effect on the bounds to be derived. By the same token, and from the comparison of our results with [4], we find that also the destruction of ^{6}Li due to X^- decays affects those bounds only marginally.

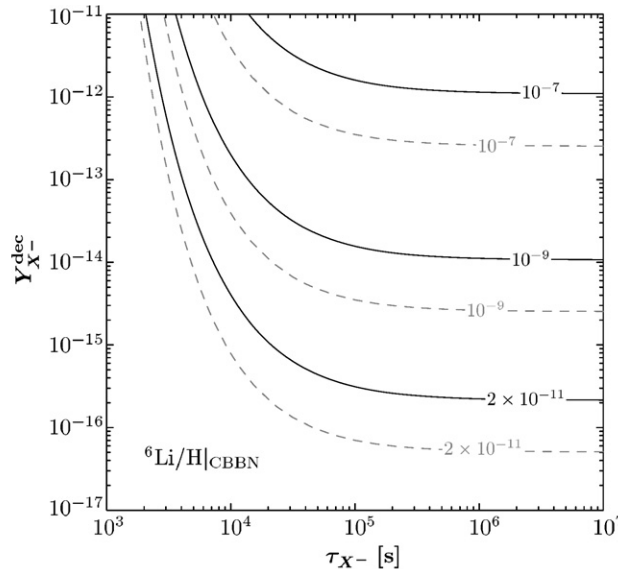

Fig. 1. Contour-lines of ^{6}Li/H produced in CBBN obtained by solving (2) (solid lines) and by using the Saha type approximation for $Y_{\rm BS}$ instead of computing (2a) (dashed lines).

3. Lower limit on $m_{1/2}$

Applying the above results to gravitino dark matter scenarios with the lighter stau $\tilde{\tau}_1$ as the NLSP, we now derive the conservative lower limit on $m_{1/2}$. The stau NLSP with a mass of $m_{\tilde{\tau}_1}$ decouples from the primordial plasma with a typical yield of $Y_{\tilde{\tau}_1}^{\rm dec} \gtrsim 7 \times 10^{-14}(m_{\tilde{\tau}_1}/100\ {\rm GeV})$ [28]. With $Y_{X^-}^{\rm dec} = Y_{\tilde{\tau}_1}^{\rm dec}/2$, we find from Fig. 1 that the amount of ^{6}Li produced in CBBN can be in agreement with (6) only for stau lifetimes of

$$\tau_{\tilde{\tau}_1} = \tau_{X^-} \lesssim 5 \times 10^3 \ {\rm s}. \tag{7}$$

As can be seen from the supergravity prediction

$$\tau_{\tilde{\tau}_1} \simeq \Gamma^{-1}(\tilde{\tau}_1 \to \tilde{G}\tau) = \frac{48\pi m_{\tilde{G}}^2 M_{\rm P}^2}{m_{\tilde{\tau}_1}^5} \left(1 - \frac{m_{\tilde{G}}^2}{m_{\tilde{\tau}_1}^2}\right)^{-4}, \tag{8}$$

the requirement (7) implies a lower limit on the splitting between $m_{\tilde{\tau}_1}$ and $m_{\tilde{G}}$ provided $m_{\tilde{\tau}_1} \lesssim \mathcal{O}(1\ {\rm TeV})$. Because of this hierarchy, the factor $(1 - m_{\tilde{G}}^2/m_{\tilde{\tau}_1}^2)^{-4}$ can be neglected in the following.

[3] Eq. (5) assumes a radiative capture of X^- into the 1S bound state of a point-like α particle. We use, however, $E_{\rm b}$ obtained numerically in [5] rather than the Bohr-like formula $E_{\rm b}^0 \simeq Z_\alpha^2 \alpha^2 m_\alpha/2 = 397$ keV; $m_\alpha \ll m_{X^-}$.

Let us now turn to the CMSSM. In the region in which $\tilde{\tau}_1$ is the NLSP, we find

$$m^2_{\tilde{\tau}_1} \leqslant 0.21 m^2_{1/2} \tag{9}$$

by scanning over the following parameter range:

$m_{1/2} = 0.1\text{–}6$ TeV,

$\tan\beta = 2\text{–}60$,

$\operatorname{sgn}\mu = \pm 1$,

$-4m_0 < A_0 < 4m_0$

with m_0 as large as viable for a $\tilde{\tau}_1$ NLSP. Here $\tan\beta$ is the ratio of the two MSSM Higgs doublet vacuum expectation values and μ the higgsino mass parameter.[4]

For small left-right mixing, $\tilde{\tau}_1 \simeq \tilde{\tau}_R$, (9) can be understood qualitatively from the estimate for the mass of the right-handed stau $m_{\tilde{\tau}_R}$ near the electroweak scale [30]

$$m^2_{\tilde{\tau}_R} \simeq 0.15 m^2_{1/2} + m_0^2 - \sin^2\theta_W m_Z^2 \cos 2\beta \tag{10}$$

since $m_0^2 \ll m^2_{1/2}$ in a large part of the $\tilde{\tau}_1$ NLSP region. In fact, (9) tends to be saturated for larger m_0, i.e., in the stau–neutralino-coannihilation region where the mass of the lightest neutralino $m_{\tilde{\chi}^0_1} \simeq m_{\tilde{\tau}_1}$. This can be understood since the neutralino is bino-like in this region so that $m^2_{\tilde{\chi}^0_1} \simeq 0.18 m^2_{1/2}$.[5] In the remaining part of the stau NLSP region, smaller values of $m_{\tilde{\tau}_1}$ satisfying, e.g., $m^2_{\tilde{\tau}_1} = 0.15 m^2_{1/2}$ can easily be found.

To be on the conservative side, we set the stau NLSP mass $m_{\tilde{\tau}_1}$ to its maximum value at which (9) is saturated: $m^2_{\tilde{\tau}_1} = 0.21 m^2_{1/2}$. Then, constraint (7) together with (8) yields

$$m_{1/2} \geqslant 0.9\ \text{TeV} \left(\frac{m_{\tilde{G}}}{10\ \text{GeV}}\right)^{2/5} \tag{11}$$

which is shown in Fig. 2. The shaded region is disfavored by (6). Below the dashed line, $m_{\tilde{G}} \geqslant m_{\tilde{\tau}_1}$ is possible.

Since for a $\tilde{\tau}_1$ NLSP typically $m_0^2 \ll m^2_{1/2}$, it is the gaugino mass parameter $m_{1/2}$ which sets the scale for the low energy superparticle spectrum. Thus, depending on $m_{\tilde{G}}$, the bound (11) implies rather high values of the superparticle masses. This is particularly true for the masses of the squarks and the gluino since their renormalization group running from M_{GUT} to $Q \simeq \mathcal{O}(1\ \text{TeV})$ is dominated by $M_3(Q) \simeq m_{1/2}\alpha_s(Q)/\alpha_s(M_{\text{GUT}})$. Since these masses govern the size of the total cross section for the production of superparticles at the Large Hadron Collider (LHC), the cosmologically favored region for $m_{\tilde{G}} \gtrsim 10$ GeV is associated with a mass range that will be very difficult to probe at the LHC.

Let us stress at this point that the bounds (7) and (11) and their severe implications for phenomenology at the LHC are valid only for the assumed standard cosmological history with $T_R > T_f$ and the associated considered values of $Y^{\text{dec}}_{\tilde{\tau}_1} \gtrsim 7 \times 10^{-14}$. For example, non-standard entropy production after the thermal $\tilde{\tau}_1$ NLSP freeze out and before BBN might dilute the stau abundance prior to decay. Thereby, the $m_{1/2}$ limit can be relaxed [13]. Also for the case of inflation with a low reheating temperature, $T_R < T_f$, one can obtain a stau abundance prior to decay that respects the ^{6}Li constraint even for $\tau_{\tilde{\tau}_1} \gtrsim 5 \times 10^3$ s [18]. Thus, for a non-standard cosmological history, an observation of staus with $\tau_{\tilde{\tau}_1} \gtrsim 5 \times 10^3$ s and other CMSSM phenomenology at the LHC could still be viable even in gravitino LSP scenarios with $m_{\tilde{G}} \gtrsim 10$GeV.

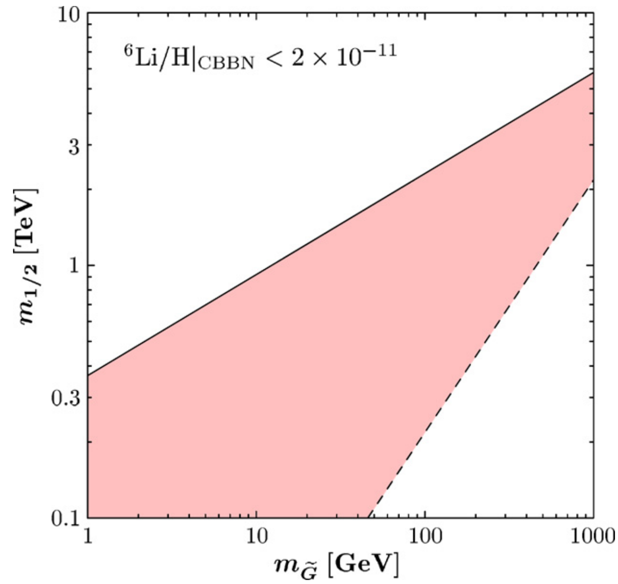

Fig. 2. The shaded region indicates cosmologically disfavored $m_{1/2}$ values. Below the dashed line, $m_{\tilde{G}} \geqslant m_{\tilde{\tau}_1}$ is possible.

4. Upper bound on T_R

The amount of gravitinos produced in thermal scattering is sensitive to the reheating temperature T_R and to the masses of the gauginos and hence to $m_{1/2}$ [16]. For a standard cosmological history, the associated gravitino density can be approximated by[6]

$$\Omega^{\text{TP}}_{\tilde{G}} h^2 \simeq 0.32 \left(\frac{10\ \text{GeV}}{m_{\tilde{G}}}\right) \left(\frac{m_{1/2}}{1\ \text{TeV}}\right)^2 \left(\frac{T_R}{10^8\ \text{GeV}}\right). \tag{12}$$

This follows from Eq. (3) of Ref. [16]. Here we use that the running gaugino masses M_i associated with the gauge groups $SU(3)_c$, $SU(2)_L$, and $U(1)_Y$ satisfy $M_3 : M_2 : M_1 \simeq 3 : 1.6 : 1$ at a representative scale of 10^8 GeV at which we also evaluate the respective gauge couplings. Furthermore, we only need to take into account the production of the spin-1/2 components of the gravitino since (11) implies $M_i^2/3m^2_{\tilde{G}} \gg 1$ for $m_{\tilde{G}} \gtrsim 1$ GeV.

For a given $m_{1/2}$, the reheating temperature T_R is limited from above because $\Omega^{\text{TP}}_{\tilde{G}}$ cannot exceed the dark matter density [25] $\Omega^{3\sigma}_{\text{dm}} h^2 = 0.105^{+0.021}_{-0.030}$ where h is the Hubble constant in units of $100\ \text{km}\,\text{Mpc}^{-1}\,\text{s}^{-1}$. Requiring

$$\Omega^{\text{TP}}_{\tilde{G}} h^2 \leqslant 0.126 \tag{13}$$

and using the derived lower bound (11) allows us to extract the conservative upper limit:

$$T_R \lesssim 4.9 \times 10^7\ \text{GeV} \left(\frac{m_{\tilde{G}}}{10\ \text{GeV}}\right)^{1/5}. \tag{14}$$

This constraint is a slowly varying function of $m_{\tilde{G}}$: $(m_{\tilde{G}}/10\ \text{GeV})^{1/5} = 0.6\text{–}2.5$ for $m_{\tilde{G}} = 1$ GeV–1 TeV. Therefore, (14) poses a strong bound on T_R for the natural gravitino LSP mass range in gravity-mediated supersymmetry breaking scenarios.

[4] We employ `SPheno 2.2.3` [29] to compute the low energy mass spectrum using $m_t = 172.5$ GeV for the top quark mass. In addition, we use the Standard Model parameters $m_b(m_b)^{\overline{\text{MS}}} = 4.2$ GeV, $\alpha_s^{\overline{\text{MS}}}(m_Z) = 0.1172$, $\alpha_{\text{em}}^{-1\overline{\text{MS}}}(m_Z) = 127.932$.

[5] This estimate is relatively independent of $\tan\beta$ and valid in the $m_{1/2}$ region in which also the LEP bound on the Higgs mass [25], $m_h > 114.4$ GeV, is respected.

[6] For a discussion on the definition of T_R, see Section 2 in Ref. [13].

Note that the constraint (14) relies on thermal gravitino production only. In addition, gravitinos are produced in stau NLSP decays with the respective density

$$\Omega_{\tilde{G}}^{\mathrm{NTP}} h^2 = m_{\tilde{G}} Y_{\tilde{\tau}_1}^{\mathrm{dec}} s(T_0) h^2 / \rho_{\mathrm{c}}, \quad (15)$$

where $\rho_{\mathrm{c}}/[s(T_0)h^2] = 3.6 \times 10^{-9}$ GeV [25]. While the precise value of $Y_{\tilde{\tau}_1}^{\mathrm{dec}}$ depends on the concrete choice of the CMSSM parameters, the upper limit (14) can only become more stringent by taking $\Omega_{\tilde{G}}^{\mathrm{NTP}}$ into account. For exemplary CMSSM scenarios, this can be seen from the $(m_{1/2}, m_0)$ planes shown in Figs. 4 and 5 of Ref. [13].[7] These figures illustrate that the severe limits (11) and (14) are conservative bounds.

5. Conclusion

We have considered the catalysis of ^{6}Li production in CMSSM scenarios with the gravitino LSP and the stau NLSP. Within a standard cosmological history, the calculated ^{6}Li abundance drops below the observational limit on primordial ^{6}Li for $\tau_{\tilde{\tau}_1} \lesssim 5 \times 10^3$ s. Taken at face value, we find that this constraint translates into a lower limit $m_{1/2} \geqslant 0.9$ TeV$(m_{\tilde{G}}/10\ \mathrm{GeV})^{2/5}$ in the entire natural region of the CMSSM parameter space. This implies a conservative upper bound $T_{\mathrm{R}} \lesssim 4.9 \times 10^7$ GeV$(m_{\tilde{G}}/10\ \mathrm{GeV})^{1/5}$. The bounds on $m_{1/2}$ and T_{R} not only confirm our previous findings [13] but are also independent of the particular values of the CMSSM parameters for the considered $\tilde{\tau}_1$ NLSP abundances.

Note added

After submission of this work, a substantially revised version (v3) of [9] together with [33] appeared on the arXiv. The results of these works affect our limits only mildly. Because of the huge effect of (1) on the ^{6}Li abundance, our relatively simple treatment of CBBN is sufficient for our purposes. This is also confirmed by a direct comparison of our data with Figs. 1 and 2 of the more elaborate CBBN treatment in [33] for $B_{\mathrm{h}} \lesssim 3 \times 10^{-3}$ ($m_{\tilde{\tau}_1} \leqslant 2.7$ TeV, i.e., $m_{1/2} \leqslant 6$ TeV) [23] at the relevant times of $t \simeq \mathrm{few} \times 10^3$ s. For a given $^6\mathrm{Li/H}|_{\mathrm{obs}}$ bound, the effect on the $\tau_{\tilde{\tau}_1}$ limit is less than a factor of 1.5. In addition, adopting $^6\mathrm{Li/H}|_{\mathrm{obs}} \lesssim 4 \times 10^{-11}$ (2.7×10^{-10}) as used in [33], the numbers in our Eqs. (7), (11), and (14) change respectively to 6×10^3 (10^4), 0.87 (0.78), and 5.3×10^7 (6.5×10^7). Furthermore, by taking into account the uncertainties in the relevant nuclear reaction rates, it is shown explicitly in Fig. 14 in v3 of [9] and in Fig. 5 in [33] that cosmologically allowed regions for $\tau_{\tilde{\tau}_1} \gtrsim 10^5$ s are indeed extremely unlikely ($< 1\%$) for $Y_{\tilde{\tau}_1}^{\mathrm{dec}} \gtrsim 7 \times 10^{-14}(m_{\tilde{\tau}_1}/100\ \mathrm{GeV})$ even with f_{em} as small as 3×10^{-2}. Only with a finely tuned $m_{\tilde{\tau}_1}$–$m_{\tilde{G}}$ degeneracy leading to $B_{\mathrm{h}} \to 0$ and $f_{\mathrm{em}} \to 0$ can any bound on energy release and, in particular, the one from ^{3}He/D be evaded.

[7] Gravitino production from inflaton decay can also be substantial; see, e.g., [31,32]. This can further tighten the bound (14).

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