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Eluding the BBN constraints on the stable gravitino

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Abstract

We investigate how late-time entropy production weakens the Big-Bang Nucleosynthesis (BBN) constraints on the gravitino as lightest superparticle with a charged slepton as next-to-lightest superparticle. We find that with a moderate amount of entropy production, the BBN constraints can be eluded for most of the parameter space relevant for the discovery of the gravitino. This is encouraging for experimental tests of supergravity at LHC and ILC.

Introduction

The gravitino $\widetilde{G}$ is a unique and inevitable prediction of supergravity (SUGRA) [1], and hence the discovery of the gravitino would provide unequivocal evidence for SUGRA. It has been pointed out that this test of SUGRA may be possible at LHC or ILC, if the gravitino is the lightest superparticle (LSP) and the long-lived next-to-lightest superparticle (NLSP) is a charged slepton [2].

From an experimental point of view, a relatively large gravitino mass $m_{\widetilde{G}}$ comparable to the slepton mass $m_{\tilde{\ell}}$, $m_{\widetilde{G}} \gtrsim \mathcal{O}(0.1)\, m_{\tilde{\ell}}$, is particularly interesting [2, 3]. This is because in such a gravitino mass region the kinematical reconstruction of the gravitino mass becomes possible, which leads to a determination of the "Planck scale", and even the gravitino spin might become measurable.

However, such a parameter region is strongly constrained by cosmology. In particular, the BBN constraints on a late decaying particle [4, 5] lead to an upper bound on the gravitino mass for a given slepton mass [6, 7], which makes the SUGRA test at collider experiments very challenging.

It is, however, easy to evade the BBN constraints if late-time entropy production occurs after the slepton decoupling (and before BBN). In this letter we explicitly show how much late-time entropy production weakens the BBN constraints on the NLSP decay into the gravitino. We find most of the relevant parameter space to survive for a moderate amount of entropy production. This is very encouraging with respect to experimental tests of SUGRA at LHC and ILC. It has also interesting implications for leptogenesis, which will be discussed elsewhere [8].

BBN constraint with late-time entropy production

For concreteness, we assume that the NLSP is the superpartner of the tau lepton, stau ($\widetilde{\tau}$). In the early universe, the stau NLSP is in thermal equilibrium until its decoupling at $T_d \sim m_{\widetilde{\tau}}/20$. If the stau particle decays during or after BBN, $T_{BBN} \sim 1$ MeV, it may spoil the successful BBN predictions [4, 5]. In the model with stau NLSP and gravitino LSP, this leads to severe constraints on the parameter space $(m_{\widetilde{\tau}}, m_{\widetilde{G}})$, in particular to upper bounds on the gravitino mass for a given stau mass [6, 7].

If there is no entropy production after the stau decoupling, the thermal relic abundance of the stau before its decay is given by [6]

$$Y_{\tilde{\tau}}^{\rm thermal} \equiv \frac{n_{\tilde{\tau}}}{s} = \kappa \times 10^{-13} \left(\frac{m_{\tilde{\tau}}}{100\ {\rm GeV}} \right), \tag{1}$$

where $n_{\tilde{\tau}}$ and s are the stau number density and the entropy density, respectively. Here, $\kappa = (0.7 - 1)$ is a numerical coefficient which depends on the model parameters (e.g., $\tan\beta$). In the following we take $\kappa = 0.7$ as a representative value. The decay rate of the stau NLSP is given by [2]

$$\begin{aligned} \Gamma_{\tilde{\tau}}(\tilde{\tau} \to \tilde{G}\tau) &= \frac{m_{\tilde{\tau}}^5}{48\pi m_{\tilde{G}}^2 M_{\rm P}^2} \left(1 - \frac{m_{\tilde{G}}^2 + m_\tau^2}{m_{\tilde{\tau}}^2} \right)^4 \left[1 - \frac{4 m_{\tilde{G}}^2 m_\tau^2}{(m_{\tilde{\tau}}^2 - m_{\tilde{G}}^2 - m_\tau^2)^2} \right]^{3/2}, \\ &\simeq (6 \times 10^6\ {\rm sec})^{-1} \left(\frac{m_{\tilde{\tau}}}{100\ {\rm GeV}} \right)^5 \left(\frac{10\ {\rm GeV}}{m_{\tilde{G}}} \right)^2 \left(1 - \frac{m_{\tilde{G}}^2}{m_{\tilde{\tau}}^2} \right)^4, \end{aligned} \tag{2}$$

where in the second equation we have neglected the mass of the tau–lepton, m_τ.

The energetic tau-lepton produced by the stau decay causes the electromagnetic (EM) cascade, which results in destructions or overproductions of light elements (D, ^{3}He, ^{4}He, etc.). However, the tau-lepton itself decays before interacting with background photons, and hence, some of the energy carried by the tau-lepton is lost to neutrinos. Thus, the electromagnetic energy released by the stau decay is given by

$$E_{EM} Y_{\tilde{\tau}} = \xi_{EM} \frac{m_{\tilde{\tau}}^2 - m_{\tilde{G}}^2}{2 m_{\tilde{\tau}}} Y_{\tilde{\tau}}, \tag{3}$$

where $\xi_{EM} \lesssim 1$ denotes the suppression factor due to the energy loss in the tau decay into neutrinos. In the following, we take $\xi_{EM} \simeq 0.5$ as a representative value [7]. On the other hand, the hadronic contribution relevant for BBN dominantly comes from the three- and four-body decay of the stau, and therefore the hadronic branching ratio of the stau NLSP is suppressed, $B_h \lesssim 10^{-3}$ [9]. Thus, the hadronic energy released by the stau decay is suppressed by a factor $\lesssim 10^{-3}$ compared to the EM energy.

Without late-time entropy production, the parameter region with a relatively large gravitino mass, $m_{\tilde{G}} \gtrsim \mathcal{O}(0.1)\, m_{\tilde{\tau}}$, which is wanted for tests of SUGRA, is severely constrained by the above BBN constraints. However, if an adequate entropy production occurs after the stau decoupling, the stau abundance is diluted by a factor Δ,

$$Y_{\tilde{\tau}} = \frac{1}{\Delta} Y_{\tilde{\tau}}^{\rm thermal}, \tag{4}$$

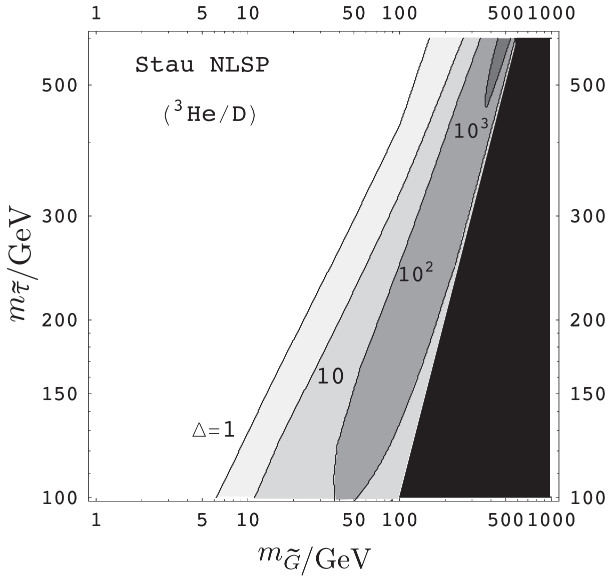

Figure 1: The BBN constraint (^{3}He/D bound) on the parameter space $(m_{\tilde{G}}, m_{\tilde{\tau}})$ with late-time entropy production. The regions excluded by the ^{3}He/D bound are shaded from light to dark gray for a dilution factor $\Delta = 1$, 10, 10^2, 10^3. In the black shaded region, the gravitino is not the LSP. Here we have neglected the effects of hadronic decay (see text).

and the BBN constraints can be easily eluded.[1]

To show this explicitly, we plot the BBN constraints in the $(m_{\tilde{G}}, m_{\tilde{\tau}})$ plane (Fig. 1). Here, we have used the constraint from the ^{3}He/D bound, and neglected other photo-dissociation and hadro-dissociation effects on the light elements. This is because, in the region $m_{\tilde{\tau}} Y_{\tilde{\tau}} \lesssim 10^{-11}$ GeV, the most stringent constraint comes from the ^{3}He overproduction for a late decaying particle with $B_h \lesssim 10^{-3}$ (see Fig. 41 and Fig. 42 in Ref. [4]). Thus, for our purposes, the ^{3}He/D bound is the most stringent BBN constraint for $m_{\tilde{\tau}} \lesssim 500$ GeV and $\Delta \gtrsim 10$.[2]

As Fig. 1 demonstrates, the ^{3}He/D bound severely constrains the parameter space

[1] If the entropy is provided by the late-time decay of a long-lived particle φ, the dilution factor Δ is given by $\Delta \simeq (T_d/T_\varphi)^3$ in terms of the decay temperature of φ, T_φ (assuming that the direct production of $\tilde{\tau}$ from φ is negligible). Thus, for instance, the dilution factor is $\Delta \sim 10^3$ for $T_\varphi \sim 1$ GeV and $m_{\tilde{\tau}} \simeq 200$ GeV.

[2] In Fig. 1, we have used the constraints in Fig. 41 of Ref. [4]. Our $\Delta = 1$ line in Fig. 1 almost reproduces the ^{3}He/D bound in Fig. 3 of Ref. [7].

for $\Delta = 1$, while the most of the interesting region is allowed for $\Delta = 10^3$. Therefore, the bulk of the relevant parameter space for the SUGRA test survives with a moderate amount of entropy production. Consequences of the present analysis for leptogenesis will be discussed in Ref. [8].

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