The Gravitino-Stau Scenario after Catalyzed BBN

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Abstract

We consider the impact of Catalyzed Big Bang Nucleosynthesis on theories with a gravitino LSP and a charged slepton NLSP. In models where the gravitino to gaugino mass ratio is bounded from below, such as gaugino-mediated SUSY breaking, we derive a lower bound on the gaugino mass parameter $m_{1/2}$. As a concrete example, we determine the parameter space of gaugino mediation that is compatible with all cosmological constraints.

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1 Introduction

The observed primordial abundances of light elements produced in Big Bang Nucleosynthesis (BBN) allow to place stringent constraints on supergravity theories with conserved R parity. Due to the extremely weak coupling of the gravitino, there is likely a long-lived particle whose decays happen during or after BBN and induce nuclear reactions that change the element abundances [1–3]. If this particle is the gravitino itself, which is the case in the standard scenario with a neutralino LSP, either it has to be very heavy or the reheating temperature has to be rather low [4]. An attractive alternative is to make the gravitino the LSP. Then BBN is endangered by late decays of the next-to-lightest superparticle (NLSP). This yields significant constraints for gravitino masses in the GeV range, which are expected in gravity and gaugino mediation, for example. A neutralino NLSP is excluded [5, 6]. Scenarios with a sneutrino NLSP are essentially unconstrained but very hard to test experimentally [7, 8]. Therefore, a charged slepton is a particularly interesting NLSP candidate, the more so as this might allow for an indirect observation of the gravitino at colliders [9] and neutrino telescopes [10]. The slepton NLSP abundance and lifetime can satisfy the limits obtained from BBN by considering NLSP decays alone [5, 6, 11–18]. However, it was recently discovered that there is another process involving long-lived charged particles, which was called Catalyzed BBN (CBBN). Charged NLSPs form bound states with light nuclei, which leads to a drastic change of some reaction rates resulting in an overproduction of $^{6}$Li [19]. A number of works [17, 19–26] have studied this effect, typically finding upper bounds of a few thousand seconds on the NLSP lifetime, unless its relic abundance is a lot smaller than what is generically expected with supersymmetry and the standard cosmology.

In order to obtain such a short lifetime, a relatively heavy superpartner mass spectrum with a large hierarchy between NLSP and gravitino mass is required. In constrained scenarios for SUSY breaking like the CMSSM, this leads to a lower bound on the gaugino mass parameter $m_{1/2}$, which depends on the gravitino mass as long as the latter is a free parameter [26] (see also [17, 18]). Thus, the bound can in principle be avoided by lowering $m_{3/2}$ sufficiently. In the following, we study the impact of CBBN constraints on the slepton NLSP region of SUSY-breaking scenarios where the ratio of gravitino and gaugino mass is bounded from below and where the gaugino masses unify at the GUT scale. In this case, there is an absolute lower bound on $m_{1/2}$. As a specific example, we consider gaugino mediation [27, 28]. The situation should be similar in concrete models for gravity mediation that establish a relation between $m_{3/2}$ and other mass parameters such as $m_{1/2}$ or the universal scalar mass $m_{0}$. We determine the parameter space of gaugino mediation for moderate values of $\tan \beta$ that leads to a charged slepton NLSP and is allowed by all cosmological constraints, i.e. the bound on the NLSP lifetime, the bound on the energy release in decays, and the observed dark matter density.

We will start by reviewing the parameter space of gaugino mediation in the next section. Afterwards, we will consider consequences of the bound from CBBN on the NLSP lifetime, first in a more general setup and then applied to gaugino mediation. Adding the other cosmological constraints, we will numerically determine the parameter space that remains allowed and briefly discuss phenomenological consequences.
2 Gaugino Mediation and its Parameter Space

The scenario of gaugino-mediated SUSY breaking [27, 28] postulates the existence of $D - 4$ extra spatial dimensions, which are compactified with radii $\sim 1/M_C$. At different positions in the compact dimensions, four-dimensional branes are located. The gauge superfields and the Higgs fields live in the bulk. The superfield responsible for SUSY breaking is localised on one of the branes, while the remaining MSSM fields are localised on different branes. As a consequence, only the bulk fields obtain SUSY-breaking soft masses at the compactification scale $M_C$. Assuming gauge coupling unification and $M_C \sim M_{\text{GUT}}$, one thus obtains the boundary conditions

$$
g_1 = g_2 = g_3 = g \simeq 1/\sqrt{2},$$ (1a)
$$M_1 = M_2 = M_3 = m_{1/2},$$ (1b)
$$m_{3/2} \neq 0,$$ (1c)
$$\mu, B\mu, m_{h_1}^2 \neq 0 \ (i = 1, 2),$$ (1d)
$$m_{\phi_L}^2 = m_{\phi_R}^2 = A_{\phi} = 0 \quad \text{for all squarks and sleptons } \tilde{\phi},$$ (1e)

where the GUT charge normalisation is used for $g_1$ and where $h_1$ is the Higgs which couples to the down-type quarks, whereas $h_2$ is the up-type Higgs. We have neglected small corrections from gaugino loops and brane-localised terms breaking the unified gauge symmetry. Eqs. (1) are valid at the compactification scale. The renormalisation group running to low energies generates non-zero squark and slepton masses as well as $A$ terms, so that a realistic mass spectrum can be obtained.

Taking the boundary conditions (1) at the GUT scale, the resulting allowed parameter space leads to several different candidates for the (N)LSP [29,30]. Besides the lightest neutralino, the lightest MSSM superparticle can be a stau, a selectron or a sneutrino. As the latter particles are not viable dark matter candidates, they can only be the NLSP, with the gravitino as the LSP, as long as R parity is conserved. We will be interested in charged NLSPs only. The corresponding parameter space region, usually denoted as charged slepton or $\tilde{\ell}$ region in the following, lies around the origin in the plane of the soft Higgs masses $m_{h_1}^2$ and $m_{h_2}^2$. Below its lower end (for too small $m_{h_1}^2$), there are no physical points. On the other sides, the region is bounded by the neutralino LSP domain. The charged sleptons are predominantly composed of the superpartners of the right-handed leptons here. The squark and slepton mass spectrum depends on the soft Higgs masses only via the combination $m_{h_1}^2 - m_{h_2}^2$ to a good approximation. The effect of a change of $m_{1/2}$ is mainly a rescaling of the mass spectrum and of the charged slepton region. For moderate values of $m_{h_2}^2$, the lightest neutralino is bino-like. For large positive $m_{h_2}^2$, the $\mu$ parameter becomes small, so that there is a sizable higgsino admixture in the lightest neutralino. A selectron is the NLSP in the lower part of the $\tilde{\ell}$ region, where at least one soft Higgs mass is negative. For larger values of $\tan \beta$, there is also a parameter space region where a predominantly “left-handed” charged slepton is the NLSP, but we will not study this option in detail here.

The $\tilde{\ell}$ region includes areas with negative $m_{h_1}^2$ or $m_{h_2}^2$. In parts of these areas, the scalar potential may have charge and colour breaking minima, and the GUT stability
constraint $\mu^2(M_{\text{GUT}}) + m_{h_{1,2}}^2(M_{\text{GUT}}) > 0$ that is invoked to avoid electroweak symmetry breaking at high energies may be violated [30–32]. To be conservative, we do not impose such constraints (see e.g. [33–36] for discussions of their applicability). They would mainly affect the selectron NLSP region.

The gravitino cannot be arbitrarily light. Using naïve dimensional analysis [37], one can estimate $m_3/2 \gtrsim 0.1 m_{1/2}$ for $D = 6, M_C \sim 2 \cdot 10^{16}$ GeV and a cutoff for the extra-dimensional theory at the $D$-dimensional Planck scale [38]. As NDA yields only a rough estimate of the lower limit, it does not appear unreasonable to violate it by say up to an order of magnitude. The bound can also be relaxed by increasing the number of compact dimensions or by lowering the cutoff of the $D$-dimensional theory. On the other hand, $D = 5$ or $M_C < M_{\text{GUT}}$ yields a larger gravitino mass. For example, changing only $D$ to 5 yields $m_{3/2} \gtrsim 0.2 m_{1/2}$. The case $M_C > M_{\text{GUT}}$ is less interesting in our context, since then the running above the unification scale tends to make the stau heavier than the lightest neutralino [40,41].

3 Constraints from Catalyzed BBN

3.1 Estimate of the Minimal Gaugino Mass

No cosmological constraints have been taken into account so far. As mentioned, CBBN places very stringent bounds on scenarios with long-lived charged particles [19]. We assume the standard cosmological scenario where the NLSP abundance equals its thermal relic abundance, determined at the time when the particle decouples from thermal equilibrium. In particular, we assume it to be in thermal equilibrium at early times and no significant entropy production after decoupling that would dilute the abundance. Then, the abundance in supersymmetric theories generically exceeds the bound from CBBN by orders of magnitude, if the NLSP lifetime is larger than $10^3–10^4$ s. Consequently, the only possibility is to decrease the lifetime to values where the NLSP decays before the catalysis can be completed. As the corresponding upper limit on the lifetime is still somewhat uncertain [17,19,22–26], we use a conservative value of

$$\tau_\ell \lesssim \tau_\ell^{\max} = 5 \cdot 10^3 \text{ s}.$$ (2)

The decay rate of a charged slepton NLSP is dominated by the two-body decay into lepton and gravitino,

$$\Gamma_\ell = \frac{m_\ell^5}{48\pi m_{3/2}^2 M_P^2} \left(1 - \frac{m_{3/2}^2}{m_\ell^2}\right)^4,$$ (3)

where $m_\ell$ is the slepton mass, $M_P = 2.44 \cdot 10^{18}$ GeV is the reduced Planck mass, and where the lepton mass has been neglected. In order to minimise the lifetime, we have to

\footnote{Note that the bound was derived for compact dimensions of equal size, which may be disfavoured for larger $D$ [39].}
1. maximise the NLSP mass, i.e. it should be just below the mass of the next-heavier particle, the lightest neutralino, and to

2. minimise the gravitino mass.

In theories with gaugino mass unification and with a lower bound on the ratio \(m_{3/2}/m_{1/2}\), both criteria involve only one mass scale, the gaugino mass parameter. Consequently, the upper limit on the NLSP lifetime can be translated into a lower limit on \(m_{1/2}\). This is a difference compared to the Constrained MSSM, where \(m_{3/2}\) is a free parameter, so that only the first criterion can be applied [26].

If the lightest neutralino is a pure bino, we can use the approximation

\[
m_{\chi} \approx M_{1}(M_{Z}) \approx m_{1/2} \frac{\alpha_1(M_{Z})}{\alpha_1(M_{\text{GUT}})} \approx 0.42 m_{1/2} ,
\]

where we have used \(\alpha_1^{-1}(M_{Z}) \approx 59\) and \(\alpha_1^{-1}(M_{\text{GUT}}) \approx 25\). The approximation for the low-energy value of \(M_{1}\) works very well, since the running of the gaugino masses is independent of the other soft parameters at the one-loop level.

We parametrise the minimal gravitino mass as

\[
m_{3/2}^{\text{min}} = c m_{1/2} .
\]

For example, the mentioned bound from naïve dimensional analysis in gaugino mediation corresponds to \(c = 0.1\). If we allow this bound to be violated by up to an order of magnitude, we obtain the minimal value \(c = 0.01\).

Using Eqs. (3–5) with \(m_{\tilde{\ell}} = m_{\chi}\) and \(m_{3/2} = m_{3/2}^{\text{min}}\), we find

\[
\tau_{\tilde{\ell}} \approx 48 \pi c^2 M_{P}^2 \left(1 - \frac{c^2}{0.42^2}\right)^{-4}
\]

or, imposing the CBBN bound,

\[
m_{1/2} \gtrsim 21 \text{ TeV} \cdot c^{2/3} \left(\frac{\tau_{\tilde{\ell}}^{\text{max}}}{5 \cdot 10^{3} \text{ s}}\right)^{-\frac{2}{3}} \left(1 + 7.6 c^2\right) ,
\]

where we have assumed \(c\) to be small. For instance, \(c = 0.01\) yields \(m_{1/2} \gtrsim 970\) GeV for \(\tau_{\tilde{\ell}}^{\text{max}} = 5 \cdot 10^3\) s. By setting \(m_{\tilde{\ell}} = m_{\chi}\), we have implicitly assumed that this equality is satisfied in some part of the parameter space. This is the case for gravity mediation, NUHM models [42, 43] or gaugino mediation with moderate \(\tan \beta\) [29]. If for a given \(m_{1/2}\) the maximal slepton mass is smaller than the lightest neutralino mass, Eq. (7) still holds, but an even stronger limit on \(m_{1/2}\) exists. The same is true if the lightest neutralino is not a pure bino, since then \(m_{\chi}\) is smaller than \(M_{1}\).
3.2 Impact on Gaugino Mediation

3.2.1 Numerical Results

Let us now return to the specific setup of gaugino mediation and perform numerical studies of the impact of CBBN and other cosmological constraints on the allowed parameter space. In addition to the upper limit (2) on the NLSP lifetime, we have to take into account the non-thermal gravitino abundance resulting from NLSP decays:

\[
\Omega_{3/2}^{\text{non-th}} h^2 = \frac{m_{3/2}}{m_{\text{NLSP}}} \Omega_{\text{NLSP}}^{\text{th}} h^2 \, .
\]  

(8)

For large \( m_{1/2} \), it exceeds the observed cold dark matter density, resulting in an upper limit on \( m_{1/2} \). We use the 95\% C.L. bound given in [44],

\[
\Omega_{\text{DM}} h^2 < 0.136 \, .
\]  

(9)

Furthermore, there are the “usual” BBN constraints on the energy release from NLSP decays. With the short lifetime, the electromagnetic energy release is harmless, but the hadronic energy release becomes relevant with increasing stau mass. The calculation for the hadronic branching ratio of right-handed sleptons can be found in [15]. We use the hadronic constraints from Fig. 10 of [45]. These constraints assume that the whole rest energy of the decaying particle ends up in the hadronic shower, which is not the case here. Rather, the average invariant mass of the \( \tilde{q}q \) pair emitted in the hadronic decay \( \tilde{\ell} \to \ell \tilde{G}qq \) is close to the Z mass, almost independently of the slepton mass [15]. We therefore use the BBN bounds for a decaying particle of 100 GeV also for larger NLSP masses and rescale the bound on \( \Omega_{\text{NLSP}} \) by a factor \( m_{\tilde{\ell}}/100 \text{ GeV} \) [46].

Both for the constraints from BBN and for those from the observed cold dark matter density, the thermal relic density of the NLSP is essential. We use micrOMEGAs 1.3.7 [47, 48] to calculate it numerically. The superpartner spectrum is determined by SOFTSUSY 2.0.14 [49]. For the top quark pole mass, we use 170.9 GeV [50].

We restrict ourselves to the case \( \tan \beta = 10 \) and \( \mu > 0 \).

The parameter space in the \( m_{1/2}-m_{\tilde{\tau}_1}^2 \) plane resulting from the lifetime and cold dark matter constraint in addition to constraints from consistency (e.g. absence of tachyons) is shown in Fig. 11 for \( m_{\tilde{\tau}_2}^2 = 0 \) and different values of the gravitino mass. The green (dark-grey) area corresponds to a region with a stau NLSP, while the yellow (light-grey) area corresponds to a region with a selectron NLSP. The constraint from the observed cold dark matter density restricts the parameter space towards large values of \( m_{1/2} \), while the lifetime constraint restricts it towards small \( m_{1/2} \).

While for \( c = 0.01 \) and \( c = 0.02 \) only the constraints from overclosure and NLSP lifetime are relevant, the hadronic BBN constraints become important for \( c = 0.03 \) and \( c = 0.04 \). For \( c \gtrsim 0.05 \) there are no allowed regions left. The excluded region is indicated by the black line. In the selectron NLSP region, the smuon is only slightly heavier. Thus,

\[ m_{\tilde{\tau}_1} = 1.777 \text{ GeV}. \]
Figure 1: Allowed regions for $m_{h_1}^2$ and $m_{1/2}$ with $m_{h_2}^2 = 0$, $\tan \beta = 10$ and different values of the gravitino mass $m_{3/2}$. The NLSP is the $\tilde{\tau}_1 \approx \tilde{\tau}_R$ in the green (dark-grey) region and the $\tilde{e}_R$ in the yellow (light-grey) region. The black lines indicate the BBN constraints from hadronic energy release. Note that the plots for $c = 0.03$ and $c = 0.04$ are scaled up in comparison to $c = 0.01$ and $c = 0.02$. 
it may directly decay into gravitinos and affect BBN. Consequently, the impact of the BBN constraints on this region may have been somewhat underestimated in the plots. For $c = 0.01$ we have allowed regions with large $m_{1/2}$ and therefore stau lifetimes around 10 s or less. Here the mesons from $\tau$ decays (where the $\tau$ stems from the dominant two-body decay $\tilde{\tau} \rightarrow \tau \tilde{G}$) become relevant, so that the hadronic stau branching ratio is $\mathcal{O}(1)$. However, one cannot apply the corresponding bound on $\Omega_{\text{NLSP}}$ directly here, because it is sensitive to the number of charged mesons emitted in an NLSP decay [46]. In most tau decay modes there is only one, while a $\bar{qq}$ pair of 1 TeV, which is assumed in Fig. 9 of [45], results in around 25 mesons [46]. Therefore, we relaxed the bound from this figure by a factor $25 m_\tau/1$ TeV. Applying the resulting limit puts no additional constraints on the parameter space of gaugino mediation. Also the cosmic microwave background does not yield constraints for $\tau_\text{e} < 10^5$ s [52].

Let us now turn to non-zero values of $m^2_{h_2}$. While increasing $m_{1/2}$, we also increase this soft mass in such a way that the ratio $m^2_{h_2}/m^2_{1/2}$ remains fixed. Otherwise, any value of $m^2_{h_2}$ allowed for smaller $m_{1/2}$ would become completely irrelevant at large $m_{1/2}$. As mentioned earlier, the slepton masses are determined mainly by $m^2_{h_1} - m^2_{h_2}$, and the lightest neutralino (bino) mass is almost independent of the soft Higgs masses if $m^2_{h_2}$ is not too large. Consequently, the effect of a non-zero but moderate value of $|m^2_{h_2}|/m^2_{1/2}$ is simply a vertical shift (to larger or smaller values of $m^2_{h_1}$) of the allowed parameter space region, and therefore we do not show any examples.

For rather large positive $m^2_{h_2}$, the lightest neutralino becomes lighter due to a significant higgsino admixture. For negative values, there is only little space between the unphysical region and the neutralino LSP domain. These effects are illustrated in Fig. 2. For $m^2_{h_2} = 0.75 m^2_{1/2}$, which is the maximal value allowed for all values of $m_{1/2}$ we consider, we always find a stau NLSP. The “trunk” in the upper right corner of the allowed region for this case is due to coannihilations with higgsinos, which reduce the stau abundance. For $m^2_{h_2} = -5 m^2_{1/2}$, close to the limit on the other side of the parameter space, we have a selectron NLSP. As in the case of $m^2_{h_2} = 0$, only the constraints from overclosure and lifetime are relevant for $c = 0.01$ and $c = 0.02$, while for $c = 0.03$ and $c = 0.04$ the hadronic BBN constraints become important. Again, for $c = 0.05$ there is no valid region left.

In summary, we conclude that catalyzed primordial nucleosynthesis as well as other cosmological constraints place an upper bound on the gravitino mass in the $\tilde{\ell}$ region of gaugino mediation, $m_{3/2} < 0.05 m_{1/2}$.

### 3.2.2 Consequences for the Superparticle Mass Spectrum

Tab. 1 shows an overview of the minimal values we find for $m_{1/2}$. We see that Eq. (7) works with an accuracy of a few percent. It can be further improved by evaluating $\alpha_1$ at the bino mass, i.e. close to a TeV for larger values of $m_{1/2}$. The results depend only weakly on $m^2_{h_2}$, varying by not more than 2% as long as $m^2_{h_2}$ does not lie very close to the border of the allowed parameter space. A moderate increase of $\tan\beta$ by a factor $\sim 2$ does not have a big effect either, since the decrease of the stau mass due to the larger
Figure 2: Allowed regions for $m_{h_1}^2$ and $m_{1/2}$ with $m_{h_2}^2 = 0.75 m_{1/2}^2$ (left) and $m_{h_2}^2 = -5 m_{1/2}^2$ (right) for different values of the parameter $c$. In the left panel we have a stau NLSP only, while in the right panel the NLSP is a selectron. The black lines indicate the allowed regions for different values of $c$.

Table 1: Lower limits on $m_{1/2}$ in GeV. The numerical bound for $c = 0.04$ stems from the BBN constraint on energy release from NLSP decays, while the remaining bounds are due to the limit $m_\ell < m_\ell^{\text{max}}$ from CBBN. The values in the second line were obtained from the analytical estimate (7) for $\tau_\ell^{\text{max}} = 5 \cdot 10^3$ s. We set $m_{h_2}^2 = 0$ and $\tan \beta = 10$ in all cases.
| \(c\) | 0.01  | 0.02  | 0.03  |
|------|-------|-------|-------|
| \(m_{1/2}^{\text{min}}\) | 960   | 1480  | 1910  |
| \(m_{h_1}^2/\text{TeV}^2\) | 0.88  | 2.53  | 4.64  |
| \(\tilde{g}\) | 2096  | 3130  | 3972  |
| Other \(\tilde{q}\) | 1755 – 1902 | 2613 – 2827 | 3311 – 3578 |
| \(\tilde{t}_1\) | 1485  | 2217  | 2808  |
| \(\chi^\pm_2, \chi^0_3, \chi^0_4\) | 1107 – 1112 | 1605 – 1612 | 2002 – 2012 |
| \(\chi^0_1\) | 769   | 1198  | 1555  |
| \(\chi^0_2\) | 763   | 1188  | 1543  |
| \(\tilde{e}_L, \tilde{\mu}_L\) | 623   | 943   | 1205  |
| \(\tilde{\tau}_2\) | 620   | 937   | 1197  |
| \(\tilde{\nu}_e, \tilde{\nu}_\mu, \tilde{\nu}_\tau\) | 610 – 614 | 927 – 934 | 1187 – 1196 |
| \(\tilde{e}_R, \tilde{\mu}_R\) | 418   | 655   | 855   |
| \(\chi^0_1\) | 405   | 635   | 829   |
| \(\tilde{\tau}_1\) | 405   | 635   | 829   |
| \(\tilde{G}\) | 9.6   | 29.5  | 57.2  |

Table 2: Superparticle mass spectra corresponding to the minimal \(m_{1/2}\) allowed by the CBBN constraint [2] for \(\tan \beta = 10\) and \(m_{h_2}^2 = 0\). All masses are given in GeV unless stated otherwise. “Other \(\tilde{q}\)” refers to all squarks other than \(\tilde{t}_1\).

Yukawa coupling can be compensated by raising \(m_{h_1}^2\), and analogously for a decreased \(\tan \beta\). However, for \(\tan \beta \gtrsim 30\), a charged slepton is always lighter than the lightest neutralino for \(m_{h_2}^2 \sim 0\) [29, 30], so that larger values of \(m_{1/2}\) are required. To give an impression of the effect that a change of the lifetime constraint from CBBN can have, we also show some examples with different values of the maximal slepton lifetime in the table.

At the points in parameter space where \(m_{1/2}\) takes its minimal value for different values of \(c\), we obtain the mass spectra given in Tab. 2. Again, there is little variation for different values of \(m_{h_2}^2\), as long as they are not too close to the border of the allowed region. According to [53, 54], LHC will be able to find long-lived staus with masses up to around 700 GeV. Thus, for \(m_{3/2} \lesssim 0.02 m_{1/2}\), it should be possible to detect supersymmetry at least in a part of the allowed slepton NLSP region. Compared to similar points in the Constrained MSSM, the slepton spectrum is compressed (i.e. the difference between the masses of \(\tilde{\ell}_L\) and \(\tilde{\ell}_R\) is smaller) due to the non-zero \(m_{h_1}^2\).

### 3.2.3 Constraints on the Reheating Temperature

At high temperatures, gravitinos are produced by thermal scatterings. The resulting energy density is approximately given by [55, 56]

\[
\Omega_{3/2}^{\text{th}} h^2 \approx 0.27 \left( \frac{T_R}{10^{10} \text{ GeV}} \right) \left( \frac{100 \text{ GeV}}{m_{3/2}} \right) \left( \frac{m_3}{1 \text{ TeV}} \right)^2,
\]

where \(m_3\) is the running gluino mass evaluated at low energy.
| $c$       | 0.01 | 0.02 | 0.03 | 0.04 |
|-----------|------|------|------|------|
| $m_{1/2}^\text{min}$/GeV | 960  | 1480 | 1910 | 4100 |
| $T_R^\text{max}$/GeV     | $6 \cdot 10^7$ | $8 \cdot 10^7$ | $9 \cdot 10^7$ | $6 \cdot 10^7$ |

Table 3: Upper limits on the reheating temperature $T_R$ in gaugino mediation with a stau NLSP.

We can obtain a constraint on the reheating temperature using $m_{3/2} = c \cdot m_{1/2}$, $m_\tilde{\tau} \sim \frac{\alpha_s(M_Z)}{\alpha_s(M_{\text{GUT}})} m_{1/2} \sim 2.9 m_{1/2}$ and $\Omega_{DM} h^2 < 0.136$,

$$T_R \lesssim 5.8 c \left(\frac{\text{TeV}}{m_{1/2}}\right) \times 10^9 \text{GeV}. \quad (11)$$

The corresponding maximal reheating temperatures for our values of $c$ and $m_{1/2}$ are given in Table 3. The results are similar to those obtained in the Constrained MSSM for gravitino masses of a similar order of magnitude [26]. Note that we have not taken into account the non-thermally produced gravitino density [8] here. These values imply [57] that generically thermal leptogenesis is not possible in gaugino mediation with charged sleptons as NLSPs [3], unless there is entropy production between the stau decoupling and primordial nucleosynthesis.

3.2.4 Left-Handed Stau NLSPs

For larger values of $\tan \beta$, there is a parameter space region where a predominantly “left-handed” stau is the NLSP. Since the decay rate is the same for left- and right-handed sleptas, the CBBN constraint resulting from the lifetime of the NLSP is similar. However, there will be a difference in the constraints from hadronic decays, since the hadronic branching ratio is considerably larger for left-handed sleptas. Unfortunately no detailed calculation for this branching ratio has been performed so far, but the result should be similar to the case of left-handed sneutrinos [7]. Despite the larger hadronic branching ratio a rough estimation indicates that there will be allowed regions also in the case of a left-handed slepton NLSP. We leave the detailed discussion of this region for future work.

4 Conclusions

We have discussed cosmological constraints on theories with a gravitino LSP and a charged slepton NLSP. In particular, the recently discovered effect of Catalyzed BBN places a stringent upper limit on the NLSP lifetime. From this, we have derived a lower limit on the unified gaugino mass parameter $m_{1/2}$ for scenarios with a lower bound $m_{3/2} > c m_{1/2}$ on the gravitino mass. We have numerically determined the part of the parameter space of gaugino mediation with a charged slepton NLSP that remains compatible with all constraints from BBN and the observed dark matter density. Allowed

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3 See, however, [58] for a special setup where thermal leptogenesis also works for low $T_R$. 

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regions exist for $c < 0.05$, which means that the gravitino mass bound from naïve dimensional analysis, corresponding to $c \sim 0.1$, has to be violated by a factor of at least 2 to 3. If we set a conservative lower limit of $c \gtrsim 0.01$, $m_{1/2}$ may be as small as 1 TeV, so that supersymmetry can still be within the discovery reach of the LHC.

Smaller superparticle masses can be viable, if one relaxes the assumptions on the cosmological scenario. For example, entropy production between NLSP freeze-out and the start of BBN can dilute the NLSP abundance sufficiently to satisfy all constraints even for long lifetimes [18, 22, 59, 60]. Alternatively, a reheating temperature significantly below the NLSP mass can result in a suppressed NLSP abundance, too [61].

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