Probing the Reheating Temperature at Colliders and with Primordial Nucleosynthesis

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Considering gravitino dark matter scenarios with a long-lived charged slepton, we show that collider measurements of the slepton mass and its lifetime can probe not only the gravitino mass but also the post-inflationary reheating temperature $T_R$. In a model independent way, we derive upper limits on $T_R$ and discuss them in light of the constraints from the primordial catalysis of $^6$Li through bound-state effects. In the collider-friendly region of slepton masses below 1 TeV, the obtained conservative estimate of the maximum reheating temperature is about $T_R = 3 \times 10^9$ GeV for the limiting case of a small gluino–slepton mass splitting and about $T_R = 10^8$ GeV for the case that is typical for universal soft supersymmetry breaking parameters at the scale of grand unification.

We find that a determination of the gluino–slepton mass ratio at the Large Hadron Collider will test the possibility of $T_R > 10^9$ GeV and thereby the viability of thermal leptogenesis with hierarchical heavy right-handed Majorana neutrinos.

PACS numbers: 98.80.Cq, 95.35.+d, 12.60.Jv, 95.30.Cq

INTRODUCTION

Big bang nucleosynthesis (BBN) is a powerful tool to test physics beyond the Standard Model; cf. [1,2,3,4,5,6,7] and references therein. Indeed, in supersymmetric (SUSY) theories, severe constraints appear owing to the existence of the gravitino $\tilde{G}$ which is the gauge field of local SUSY transformations and whose mass is governed by the SUSY breaking scale. As the spin-3/2 superpartner of the graviton, the gravitino is an extremely weakly interacting particle with couplings suppressed by inverse powers of the (reduced) Planck scale $M_P = 2.4 \times 10^{18}$ GeV [8]. Accordingly, once produced in thermal scattering of particles in the hot primordial plasma [8,11,12,13,14,15,17], unstable gravitinos with a mass $m_{\tilde{G}} \lesssim 5$ TeV have long lifetimes, $\tau_{\tilde{G}} \gtrsim 100$ s, and decay during or after BBN. Since the decay products affect the abundances of the primordial light elements, successful BBN predictions imply a bound on the reheating temperature after inflation $T_R$ which governs the abundances of gravitinos before their decay [8,11,12,13,14,15,16,17]: $T_R \lesssim 10^8$ GeV for $m_{\tilde{G}} \lesssim 5$ TeV [8,11].

We consider SUSY extensions of the Standard Model in which the gravitino $\tilde{G}$ is the lightest supersymmetric particle (LSP) and a charged slepton $\tilde{l}_i$—such as the lighter stau $\tilde{\tau}_1$—the next-to-lightest supersymmetric particle (NLSP). Assuming R-parity conservation, the gravitino LSP is stable and a promising candidate for dark matter; cf. [10,12,13,14,16,17,18,19,20,21,22,23] and references therein. Because of the extremely weak interactions of the gravitino, the NLSP typically has a long lifetime before it decays into the gravitino. If these decays occur during or after BBN, the Standard Model particles emitted in addition to the gravitino can affect the abundances of the primordial light elements. For the charged slepton NLSP case, the BBN constraints associated with hadronic/electromagnetic energy injection have been estimated [19,21,22]. Taking into account additional constraints from large-scale-structure formation, apparently viable gravitino dark matter scenarios had been identified (see, e.g., benchmark scenarios $A_{1,2}$-$C_{1,2}$ in Ref. [24]) which are attractive for two reasons: (i) $T_R > 10^9$ GeV is possible so that thermal leptogenesis with hierarchical right-handed neutrinos [24] remains a viable explanation of the baryon asymmetry [12,14,21,22,36] and (ii) the gravitino mass can be close to the NLSP mass $m_{\tilde{l}_i}$, i.e., $0.1 m_{\tilde{l}_i} \lesssim m_{\tilde{G}} < m_{\tilde{l}_i}$, so that a kinematical $m_{\tilde{G}}$ determination appears viable [27,38,39]. With a kinematically determined $m_{\tilde{G}}$, one would be able to measure the Planck scale $M_P$ at colliders [37,38,39] and to test the viability of thermal leptogenesis in the laboratory [14]. Indeed, an agreement of the $M_P$ value determined in collider experiments with the one inferred from Newton’s constant $G_N = 6.709 \times 10^{-9}$ GeV$^{-1}$ would provide evidence for the existence of supergravity (SUGRA) in nature [37].

Already in the early paper [41] it had been realized that long-lived negatively charged massive particles $X^-$ (such as long-lived $\tilde{l}_i^-$’s) can form primordial bound states, which can affect the abundances of the primordial light elements. It was however only recently [42] when it was realized that bound-state formation of $X^-$ with $4^4$He can lead to a substantial overproduction of primordial $^6$Li via

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1 Note that flavor effects [24,25,26,27] do not change the lower bound $T_R > 10^9$ GeV required by successful thermal leptogenesis with hierarchical right-handed Majorana neutrinos [24]. However, in the case of (nearly) mass-degenerate heavy right-handed Majorana neutrinos, resonant leptogenesis can explain the baryon asymmetry at smaller values of $T_R$ [21,22,34,35]. Another example for a framework in which the limit $T_R > 10^9$ GeV is relaxed is non-thermal leptogenesis; see, e.g., [35] and references therein.
the catalyzed BBN (CBBN) reaction

\[(^{4}\text{He}X^-)+D\rightarrow ^6\text{Li}+X^- .\]

With an \(X^-\) abundance that is typical for an electrically charged massive thermal relic \[18\], this reaction becomes so efficient that an \(X^-\) lifetime of \(\tau_{X^-}\) \(\gtrsim 5 \times 10^3\) s is excluded by observationally inferred values of the primordial \(^6\text{Li}\) abundance \[12\]. In the considered gravitino LSP scenarios, this bound applies directly to the lifetime of the \(\tilde{\tau}_1\) NLSP \[15\, 13\, 23\, 43\, 44\, 45\, 46\, 47\, 48\]: \(\tau_{\tilde{\tau}_1} \lesssim 5 \times 10^3\) s.\(^2\) This implies \(m_{\tilde{G}} \lesssim 0.1 m_{\tilde{\tau}_1}\) in the collider-friendly mass range of \(m_{\tilde{\tau}_1} < 1\) TeV. Accordingly, the region \(0.1 m_{\tilde{\tau}_1} \lesssim m_{\tilde{G}} < m_{\tilde{\tau}_1}\), in which the kinematical \(m_{\tilde{G}}\) determination appears feasible, seems to be excluded by BBN constraints \[44\]. Moreover, within the framework of the constrained minimal supersymmetric Standard Model (CMSSM), we have found that the \(^6\text{Li}\) constraint implies the upper limit \(T_{\tilde{\tau}_1} \lesssim 10^7\) GeV in gravitino dark matter scenarios with unbroken R-parity and typical thermal \(\tilde{\tau}_1\) NLSP relic abundances \[15\, 43\, 48\]. For a standard cosmological history, this finding clearly disfavors successful thermal leptogenesis within the CMSSM in the case of hierarchical heavy right-handed Majorana neutrinos. For a gravitino LSP mass range that is natural for gravity-mediated SUSY breaking, the \(^6\text{Li}\) constraint can even point to a CMSSM mass spectrum which will be difficult to probe at the Large Hadron Collider (LHC) \[13\, 43\, 47\, 48\].

This letter provides a model independent study of gravitino LSP scenarios with a charged slepton NLSP that has a \(^6\text{Li}\)-friendly lifetime of \(\tau_{\tilde{\tau}_1} \lesssim 10^4\) s and a collider-friendly mass of \(m_{\tilde{\tau}_1} \lesssim 1\) TeV. In contrast to \[15\, 47\, 48\, 53\], the investigation presented in this work is not restricted to a constrained framework such as the CMSSM or to the gravitino mass range suggested by gravity-mediated SUSY breaking. Thereby, generic results are obtained with a range of validity that includes models with gauge-mediated SUSY breaking and/or non-standard mass spectra.

The remainder of this letter is organized as follows. In the next section we review that \(m_{\tilde{G}}\) could be determined by measuring \(m_{\tilde{\tau}_1}\) and \(\tau_{\tilde{\tau}_1}\) at colliders. We give also an upper limit on \(m_{\tilde{G}}\) that depends on \(m_{\tilde{\tau}_1}\) and \(\tau_{\tilde{\tau}_1}\). This limit allows us to derive a lower limit for the gravitino density \(\Omega_{\tilde{G}}\). Since \(\Omega_{\tilde{G}}\) cannot exceed the dark matter density \(\Omega_{\text{DM}}\), this leads to conservative \(T_R\) limits which can be probed in measurements of \(\tau_{\tilde{\tau}_1}\) and \(\tau_{\tilde{\tau}_1}\) (and the gluino mass \(m_{\tilde{\chi}}\)). We use the derived expressions to translate the \(\tau_{\tilde{\tau}_1}\) constraint from CBBN of \(^6\text{Li}\) into robust upper limits on \(T_R\) that depend on the mass ratio \(m_{\tilde{G}}/m_{\tilde{\tau}_1}\). Finally, we show that the requirement \(T_R > 10^9\) GeV needed for successful standard thermal leptogenesis provides an upper limit on this ratio and thereby a testable prediction for LHC phenomenology.

PROBING \(m_{\tilde{G}}\) AT COLLIDERS

In the considered SUSY scenarios with the gravitino LSP being stable due to R-parity conservation,\(^3\) the charged slepton NLSP has a lifetime \(\tau_{\tilde{\tau}_1}\) that is governed by the decay \(\tilde{\tau}_1 \rightarrow \tilde{G} \tau\) and thus given by the SUSY prediction for the associated partial width

\[
\tau_{\tilde{\tau}_1} \simeq \frac{48\pi m_{\tilde{G}}^2 M_{\tilde{G}}^2}{m_{\tilde{\tau}_1}^2} \left(1 - \frac{m_{\tilde{G}}}{m_{\tilde{\tau}_1}} \right)^{-4} \gtrsim \frac{48\pi m_{\tilde{G}}^2 M_{\tilde{G}}^2}{m_{\tilde{\tau}_1}^2},
\]

where the rightmost term underestimates \(\tau_{\tilde{\tau}_1}\) by at most 5% (30%) for \(m_{\tilde{G}} < 0.1 m_{\tilde{\tau}_1}\) \((m_{\tilde{G}} < 0.25 m_{\tilde{\tau}_1})\)\(^4\). Accordingly, using \(M_P = 2.4 \times 10^{18}\) GeV as inferred from Newton’s constant, the gravitino mass \(m_{\tilde{G}}\) can be determined by measuring both \(m_{\tilde{\tau}_1}\) and \(\tau_{\tilde{\tau}_1}\) at future colliders \[51\]. Moreover, from the rightmost expression in (2), one can extract an upper limit for the gravitino mass

\[
m_{\tilde{G}} \lesssim 0.41\text{ GeV} \left(\frac{\tau_{\tilde{\tau}_1}}{10^4\text{ s}}\right)^{1/2} \left(\frac{m_{\tilde{\tau}_1}}{100\text{ GeV}}\right)^{3/2} \lesssim m_{\tilde{G}}^{\text{max}},
\]

which turns into an equality for \(m_{\tilde{G}} \ll m_{\tilde{\tau}_1}\).

In Fig. 1 contours of \(m_{\tilde{G}}^{\text{max}}\) (solid lines) are shown in the plane spanned by \(\tau_{\tilde{\tau}_1}\) and \(m_{\tilde{\tau}_1}\). Only \(m_{\tilde{\tau}_1} \geq 100\text{ GeV}\) is considered since long-lived charged sleptons should have otherwise been observed already at the Large Electron–Positron Collider (LEP) \[10\].

The potential for collider measurements of \(m_{\tilde{\tau}_1}\) is promising since each heavier superpartner produced will cascade down to the \(\tilde{\tau}_1\) NLSP which will appear as a (quasi-) stable muon-like particle in the detector \[58\, 59\]. For slow \(\tilde{\tau}_1\)’s, the associated highly ionizing tracks and time–of–flight measurements can allow for a distinction from muons \[54\, 55\, 60\]. With measurements of the \(\tilde{\tau}_1\) velocity \(\beta_{\tilde{\tau}_1} = v_{\tilde{\tau}_1}/c\) and its momentum \(p_{\tilde{\tau}_1} = \frac{|p_{\tilde{\tau}_1}|}{\beta_{\tilde{\tau}_1}}\), \(m_{\tilde{\tau}_1}\) can be determined: \(m_{\tilde{\tau}_1} = p_{\tilde{\tau}_1} (1 - \beta_{\tilde{\tau}_1}^2)^{1/2}/\beta_{\tilde{\tau}_1}\) \[51\]. For the upcoming LHC experiments, studies of hypothetical scenarios with long-lived charged particles are actively pursued \[61\, 62\, 62\]. In Ref. \[61\], for example, it is shown that one should be able to measure the mass \(m_{\tilde{\tau}_1}\) of a (quasi-) stable slepton quite accurately at the LHC.

\(^2\) While numerous other bound-state effects can affect the abundances of \(^6\text{Li}\) and the other primordial light elements \[43\, 49\, 53\, 51\, 52\, 53\], the approximate \(\tau_{\tilde{\tau}_1}\) bound is found to be quite robust; cf. \[54\].

\(^3\) For the case of broken R-parity, see, e.g., \[56\].
The experimental determination of $\tau_{\tilde{l}_1}$ will be substantially more difficult than the $m_{\tilde{l}_1}$ measurement. If some of the sleptons decay already in the collider detectors, the statistical method proposed in [57] could allow one to measure $\tau_{\tilde{l}_1}$. Moreover, ways to stop and collect charged long-lived particles for an analysis of their decays have been proposed for the LHC and for the International Linear Collider (ILC) [37, 38, 39, 64, 65, 66, 67, 68, 69]. These challenging proposals could lead to a precise measurement of $\tau_{\tilde{l}_1}$.

In addition, these proposals could help to distinguish the case of the gravitino LSP from the one of the axino LSP [39, 70], which is—as the fermionic superpartner of the axion—another well-motivated dark matter candidate [23, 71]. Indeed, also the axino LSP can be produced thermally in the early Universe [72, 73] and can be associated with a $\tilde{l}_1$ NLSP with $O(\text{ms}) \lesssim \tau_{\tilde{l}_1} \lesssim O(\text{days})$ [70, 74]. In the axino LSP case, however, measurements of $\tau_{\tilde{l}_1}$ and $m_{\tilde{l}_1}$ will probe the Pececi–Quinn scale $f_\alpha$ [70] instead of $m_{\tilde{G}}$. Keeping in mind that the axino LSP could mimic the gravitino LSP at colliders (at first sight), we assume in the remainder of this work that it is the gravitino LSP scenario that is realized in nature.

**PROBING $T_R$ AT COLLIDERS**

Within a standard cosmological history, the gravitino LSP can be produced in decays of scalar fields such as the inflaton [75, 76, 77] in thermal scattering of particles in the primordial plasma [10, 12, 13, 14, 15, 17], and in NLSP decays [18, 21, 22, 36, 48, 84]. Focusing on the case $m_\tilde{G} \gg 100$ eV in which gravitinos are never in thermal equilibrium due to their extremely weak interactions, 4 the thermally produced gravitino density $\Omega_G^{TP}$ depends basically linearly on $T_R$—cf. [43] below—and thus can serve as a thermometer of the earliest moments of the radiation-dominated epoch [10, 12, 13, 14, 15, 17]. In particular, this allows for the derivation of upper limits on $T_R$ since the relic gravitino density is bounded from above by the observed dark matter density [10]:

$$\Omega_G^{TP} h^2 \lesssim \Omega_G^{h^2} \lesssim \Omega_{DM} h^2 \approx 0.1,$$

where $h \approx 0.7$ denotes the Hubble constant in units of 100 km Mpc$^{-1}$s$^{-1}$.

Aiming at a lower limit of $\Omega_G$, to arrive at a truly conservative upper limit on $T_R$, we do not take into account the model dependent contributions from decays of scalar fields such as the inflaton [75, 76, 77] or the ones from NLSP decays [18, 21, 78], which can be negligible anyhow, in particular, for $m_{\tilde{G}} \lesssim 1$ GeV. Indeed, we focus on the SUSY QCD contribution to the thermally produced gravitino density, as derived in the gauge-invariant calculation of [13, 14].

$$\Omega_G^{TP} h^2 \lesssim \Omega_G^{h^2} \lesssim \Omega_{DM} h^2 \approx 0.1,$$ (4)

with the strong coupling $g_s$ and the gluino mass $m_{\tilde{G}}$ to be evaluated at the scale given by $T_R$, i.e.,

$$g_s(T_R) = \left[ g_s^2(M_Z) + 3 \ln(T_R/M_Z)^2 / (8\pi^2) \right]^{-1/2}$$

and

$$m_{\tilde{G}}(T_R) = \left[ g_s^2(T_R) / g_s^2(M_Z) \right] m_{\tilde{G}}(M_Z),$$

where

$$g_s^2(M_Z) / (4\pi) = 0.1172$$

and $M_Z = 91.188$ GeV.

By discarding the electroweak contributions, $\Omega_G^{TP}$ is underestimated typically by 20%–50% depending on the size of the gaugino masses in the electroweak sector [13, 14, 15, 16]. Thus, these additional contributions would tighten the $T_R$ limits derived below only by a factor that is not smaller than about 2/3.

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4 In gauge-mediated SUSY breaking scenarios, light gravitinos can be viable thermal relics if their abundance is diluted by entropy production, which can result, for example, from decays of messenger fields [79, 80, 81, 82, 83].

5 For $T_R$ limits obtained by taking into account contributions to $\Omega_G$ from NLSP decays, see e.g. [14, 15, 16, 21, 22, 36, 84].
For high-temperatures, $10^6\text{GeV} \lesssim T_R \lesssim 10^{10}\text{GeV}$, where (5) derived in the weak coupling limit $g_s \ll 1$ is most reliable [13, 14], we do now derive a lower limit

$$\Omega_{G}^{\text{min}}h^2 \lesssim \Omega_{G}^{\text{TP}}h^2|_{\text{SU(3)}} \label{6}$$

by manipulating expression (5) as follows:

(i) We use the replacement

$$\ln \left[ \frac{1.271}{{g_s}(T_R)} \right] \rightarrow \ln \left[ \frac{1.271}{{g_s}(10^{10}\text{GeV})} \right] = 0.256 \, . \label{7}$$

Thereby, $\Omega_{G}^{\text{TP}}h^2|_{\text{SU(3)}}$ is underestimated at most at $T_R = 10^{10}\text{GeV}$ and there by a factor of about 5/8.

(ii) We use $g_s(10^{10}\text{GeV}) = 0.85$ in the numerator of (5) and to evolve $m_{\tilde{g}}(T_R)$ to the weak scale. Thereby, $\Omega_{G}^{\text{TP}}h^2|_{\text{SU(3)}}$ is underestimated at most at $T_R = 10^{10}\text{GeV}$ and there by a factor of about 2/5.

(iii) We use the constant $c > 1$ to parametrize $m_{\tilde{g}}(M_Z)$ in terms of the mass of the slepton NLSP:

$$m_{\tilde{g}}(M_Z) = c m_{\tilde{\ell}^i} \, . \label{8}$$

For concreteness, we use $m_{\tilde{g}}(M_Z)$ to represent the gluino mass at the weak scale. While the running mass $m_{\tilde{g}}$ decreases when evolved to higher energy scales, we assume implicitly $m_{\tilde{g}} > m_{\tilde{\ell}^i}$ (even in the limiting case $c \simeq 1$) at least up to energy scales accessible at the LHC and thereby up to temperatures well above the freeze-out temperature of the $\tilde{\ell}^i$ NLSP. For example, since $m_{\tilde{g}}$ decreases by about 20% when evolved from $M_Z$ to $10\text{TeV}$, $\Omega_{G}^{\text{TP}}h^2|_{\text{SU(3)}}$ can thereby be underestimated for $c \simeq 1$ by a factor of about $(4/5)^2$.

(iv) We drop the contributions from the spin 3/2 components of the gravitino which are given by the term in (5) that is independent of $m_{\tilde{g}}$. Focussing on $m_{\tilde{g}} \lesssim 0.1 m_{\tilde{\ell}^i}$, the relative importance of the spin 1/2 components is minimal for $m_{\tilde{g}} \simeq 0.1 m_{\tilde{\ell}^i}$, $c \simeq 1$, and $T_R = 10^{10}\text{GeV}$, where the associated second term in the first bracket of (5) becomes about 8 so that $\Omega_{G}^{\text{TP}}h^2|_{\text{SU(3)}}$ is underestimated without the spin 3/2 term by a factor that is not smaller than about 8/9.

Accordingly, we find a guaranteed gravitino density of

$$\Omega_{G}^{\text{min}}h^2 \simeq 0.174 \left( \frac{1\text{GeV}}{m_{\tilde{g}}} \right) \left( \frac{c m_{\tilde{\ell}^i}}{100\text{GeV}} \right)^2 \left( \frac{T_R}{10^{10}\text{GeV}} \right) \, . \label{9}$$

For $m_{\tilde{g}} \lesssim 0.1 m_{\tilde{\ell}^i}$, $10^6\text{GeV} (10^9\text{GeV}) \lesssim T_R \lesssim 10^{10}\text{GeV}$ and $c m_{\tilde{\ell}^i} > 200\text{GeV} (100\text{GeV})$, this expression is associated with $1.57 \lesssim \Omega_{G}^{\text{TP}}|_{\text{SU(3)}}/\Omega_{G}^{\text{min}} \lesssim 2.1 (1.9)$.

Accordingly, the limits derived below may be considered to be ‘too relaxed’ (or ‘too conservative’) by at least a factor of about 1.5. Indeed, $\Omega_{G}^{\text{TP}}|_{\text{SU(3)}}/\Omega_{G}^{\text{min}}$ increases by decreasing $T_R$ and/or $c m_{\tilde{\ell}^i}$ or by increasing $m_{\tilde{g}}$ so that the corresponding limits presented below will become even more conservative. For example, for $T_R = 10^6\text{GeV}$, $c m_{\tilde{\ell}^i} \simeq 100\text{GeV}$, and $m_{\tilde{g}} \lesssim 0.05 m_{\tilde{\ell}^i}$, $\Omega_{G}^{\text{TP}}|_{\text{SU(3)}}/\Omega_{G}^{\text{min}} \simeq 2.4$ is encountered so that the associated limits derived below may be considered as ‘too relaxed’ by at least a factor of about 2.4.

With $m_{\tilde{g}}^{\text{max}}$ from (4), expression (9) leads to a lower limit on $\Omega_{G}^{\text{TP}}$ in terms of $m_{\tilde{\ell}^i}$ and $\tau_{\tilde{\ell}^i}$:

$$\Omega_{G}^{\text{TP}}h^2 \gtrsim 0.422 c^2 \left( \frac{10^4\text{s}}{\tau_{\tilde{\ell}^i}} \right)^{1/2} \left( \frac{100\text{GeV}}{m_{\tilde{\ell}^i}} \right)^{1/2} \left( \frac{T_R}{10^{10}\text{GeV}} \right) \, . \label{10}$$

Comparing this lower limit with the dark matter constraint (11), we arrive at a conservative $T_R$ limit that can be determined at colliders by measuring the slepton mass $m_{\tilde{\ell}^i}$, its lifetime $\tau_{\tilde{\ell}^i}$, and $c$ (or the gluino mass $m_{\tilde{g}}$):

$$T_R \lesssim 2.37 \times 10^9\text{GeV} \left( \frac{\Omega_{G}^{\text{DM}}h^2}{0.1} \right)^{1/2} \left( \frac{\tau_{\tilde{\ell}^i}}{10^4\text{s}} \right)^{1/2} \left( \frac{m_{\tilde{\ell}^i}}{100\text{GeV}} \right)^{1/2} T_{R}^{\text{max}} \, . \label{11}$$

This is one of the main results of this letter. Note that this limit can be refined easily. Once an additional contribution $\Omega_{\phi}$ to $\Omega_{G}^{\text{TP}}$—such as an axion density or a non-thermally produced gravitino density $\Omega_{G}^{\text{NTG}}$—is taken for granted, the resulting tighter $T_R$ limits can be obtained from (11) after the replacement: $\Omega_{G}^{\text{TP}} \rightarrow \Omega_{G}^{\text{DM}} - \Omega_{\phi}$. In fact, based on the interplay between $\Omega_{G}^{\text{TP}}$ and the contribution from NLSP decays, $\Omega_{G}^{\text{NTG}}$-dependent upper limits on $T_R$ have been derived to be tested at colliders [54].

At this point, one has to clarify to which $T_R$ definition the limit (11) applies. The analytic expression (5) is derived by assuming a radiation-dominated epoch with an initial temperature of $T_i$ [13, 14]. In a numerical treatment, the epoch in which the coherent oscillations of the inflaton field dominate the energy density of the Universe can also be taken into account, where one usually defines $T_R$ in terms of the decay width $\Gamma_{\phi}$ of the inflaton field [4, 13]. In fact, the numerical result for $\Omega_{G}^{\text{TP}}$ has been found to agree with the corresponding analytic expression for $T_R$:

$$T_R \simeq \left[ \frac{90}{g_s(T_R)\pi^2} \right]^{1/4} \sqrt{\frac{\Gamma_{\phi} M_P}{1.8}} \, . \label{12}$$

which satisfies $\Gamma_{\phi} \simeq 1.8 H_{\text{rad}}(T_R)$ with the Hubble parameter $H_{\text{rad}}(T) = \sqrt{g_s(T)\pi^2/90 T^2/M_P}$ and an effective number of relativistic degrees of freedom of $g_s(T_R) = 228.75$. Thus, (12) provides the $T_R$ definition to which
the upper limit (11) applies. For an alternative \( T_R \) definition given by \( \Gamma_\phi = \xi H_{\text{rad}}(T_R^{[\ell]}), \)

\[
T_R^{[\ell]} \equiv \left( \frac{90}{g_6(T_R)^2} \right)^{1/4} \sqrt{\frac{\Gamma_\phi M_P}{\xi}},
\]

(13)

the upper limit (11) can be translated accordingly

\[
T_R^{\text{max}[\ell]} = \sqrt{\frac{1.8}{\xi}} T_R^{\text{max}}.
\]

(14)

In particular, the associated numerically obtained \( \Omega_{TP}^{\text{CMSSM}} \) can be reproduced with the analytical expression after substituting \( T_R \) with \( \sqrt{1/1.8} T_R^{[\ell]} \).

In Fig. 2 contours of the upper limit \( T_R^{\text{max}} \) given in (11) are shown for \( c = 1 \) (solid lines) and \( c = 7 \) (dashed lines) as obtained with \( \Omega_{DM} h^2 \leq 0.126. \)

The most conservative upper limit is represented by the limiting case \( c = 1 \) which holds even without insights into \( m_\tilde{g} \). Indeed, in this exceptional case, we assume implicitly a mass difference, \( \Delta m = m_\tilde{g} - m_\tilde{\chi}_1 > 0 \), such that \( 1\bar{\tilde{g}} \) coannihilation effects are negligible and such that long-lived gluinos do not appear (avoiding thereby possibly severe hadronic BBN constraints from late decaying \( \tilde{g} \)'s [36]).

With experimental insights into \( m_{\tilde{\chi}_1} \) and \( m_\tilde{g} \) (and thereby into \( c \)), the limit (11) can become considerably more severe than in the \( c = 1 \) case. In Fig. 2 this is illustrated for \( c = 7 \) which is a value that appears typically in constrained scenarios with universal soft SUSY breaking parameters at the scale of grand unification \( M_{\text{GUT}} \simeq 2 \times 10^{16} \text{GeV} \). For example, in the CMSSM in which the gaugino masses, the scalar masses, and the trilinear scalar couplings are assumed to take on the respective universal values \( m_{\tilde{g}}/2, m_0, \) and \( A_0 \) at \( M_{\text{GUT}} \), the \( \tilde{\chi}_1 \) NLSP region has been found to be associated with \( m_{\tilde{\chi}_1} \leq 0.21 m_{\tilde{g}}/2 \) and thus with \( c > 6 \) over the entire natural parameter range [17],

The \( T_R \) limits derived above are in spirit similar to the \( m_\tilde{g} \)-dependent \( T_R \) limits given in Refs. [10, 15, 17, 18, 21, 22, 54]. Also the sensitivity of these \( T_R \) limits on the gaugino masses has already been discussed and used to provide \( m_\tilde{g} \)-dependent upper limits on the gaugino masses for given values of \( T_R \) [12, 13, 14, 30]. In fact, once the gaugino masses and the gravitino mass \( m_\tilde{G} \) (inferred from \( m_{\tilde{\chi}_1} \) and \( \tau_{\tilde{\chi}_1} \)) are known, numerical results such as the ones shown in Fig. 2 of Ref. [15] will provide a \( T_R \) limit that is more restrictive than our analytic estimate (11). However, as long as insights into a SUSY model possibly realized in nature are missing, we find it important to provide a conservative and robust estimate of \( T_R^{\text{max}} \) that is insensitive to details in the SUSY spectrum (other than the assumption of the \( \tilde{G} \) LSP and a \( \tilde{\chi}_1 \) NLSP). In particular, the comparison of (11) with more model dependent limits—obtained, e.g., within the CMSSM [12, 17, 18]—demonstrates very clearly the impact of restrictive assumptions on the soft SUSY breaking sector. Moreover, the derivation of \( T_R^{\text{max}} \) contours as a function of \( m_{\tilde{\chi}_1} \) and \( \tau_{\tilde{\chi}_1} \) may turn out to become very useful since \( m_{\tilde{\chi}_1} \) and \( \tau_{\tilde{\chi}_1} \) are the quantities that might be directly accessible in collider experiments. Finally, as demonstrated below, the presentation of \( T_R^{\text{max}} \) in the plane spanned by \( \tau_{\tilde{\chi}_1} \) and \( m_{\tilde{\chi}_1} \) allows also for a convenient analysis of \( T_R^{\text{max}} \) in light of recent BBN constraints.

Before proceeding, we would like to stress that the relation of \( T_R^{\text{max}} \) to quantities \( m_{\tilde{\chi}_1}, \tau_{\tilde{\chi}_1}, \) and \( c \) (or \( m_\tilde{g} \)), which could be accessible at future collider experiments, relies crucially on assumptions on the cosmological history and the evolution of physical parameters. For example, for a non-standard thermal history with late-time entropy production, the thermally produced gravitino abundance can be diluted \( \Omega_{TP}^{\text{CMSSM}} \rightarrow \Omega_{TP}^{\text{CMSSM}}/\delta \) by a factor \( \delta > 1 \) so that \( T_R^{\text{max}} \rightarrow \delta T_R^{\text{max}} \).

Moreover, the limit (11) can be evaded if the strong coupling \( g_6 \) levels off in a non-standard way at high temperatures [50]. This emphasizes that (11) relies on the assumptions of a standard cosmological history and a strong gauge coupling that behaves
at high temperatures as described by the renormalization group equation in the minimal supersymmetric Standard Model (MSSM), i.e., as described by $g_s/T_R$ given below. While tests of these assumptions seem inaccessible to terrestrial accelerator experiments, futuristic space-based gravitational-wave detectors such as the Big Bang Observer (BBO) or the Deci-hertz Interferometer Gravitational Wave Observatory (DECIGO) could allow for tests of the thermal history after inflation and could even probe $T_R$ in a way that is complementary to the approach presented in this letter.

**PROBING $T_R$ WITH PRIMORDIAL NUCLEOSYNTHESIS**

Gravitino LSP scenarios with a long-lived charged slepton NLSP can affect BBN as described in the Introduction. Particularly severe is the catalytic effect of $(^4\text{He})^{-}$-bound states on the primordial abundance of $^6\text{Li}$. Indeed, the CBBN reaction (11) can become very efficient at temperatures $T \simeq 10$ keV depending on the $\tilde{\ell}_1$ abundance at that time. Observationally inferred upper limits on the primordial $^6\text{Li}/\text{H}$ abundance $^6\text{Li}/\text{H}|_p$ (cf. [90]) can thus be translated into $\tilde{\ell}_1$-dependent upper limits on the thermal relic abundance of the negatively charged $\tilde{\ell}_1$-NLSP $^6\text{Li}/\text{H}|_\text{CBBN}=0$ (16). For a given SUSY model, this abundance can be calculated, for example, with the computer program micrOMEGAs 2.1 [92]. By confronting the obtained abundance with the $\tilde{\ell}_1$-dependent upper limits (see, e.g., Fig. 1 in Ref. [47]), one can extract an upper limit on the $\tilde{\ell}_1$ limit that can then be used to determine $T_R^\text{max}$ directly from (11).

Let us perform this procedure explicitly for the following thermal relic $\tilde{\ell}_1$-NLSP abundance after decoupling and prior to decay [14, 60]:

$$Y_{\tilde{\ell}_1} \equiv \frac{n_{\tilde{\ell}_1}}{s} = 2 Y_{\tilde{\ell}_1} = 0.7 \times 10^{-13} \left( \frac{m_{\tilde{\ell}_1}}{100 \text{ GeV}} \right),$$

(15)

where $s$ denotes the entropy density and $n_{\tilde{\ell}_1}$ the total $\tilde{\ell}_1$ number density assuming an equal number density of positively and negatively charged $\tilde{\ell}_1$’s.

We confront (15) with the $Y_{\tilde{\ell}_1}$ limits that emerge from a calculation of the $^6\text{Li}$ abundance from CBBN, $^6\text{Li}/\text{H}|_{\text{CBBN}}$, which uses the state-of-the-art result of the catalyzed $^6\text{Li}$ production cross section [42] and the Boltzmann equation (instead of the Saha type approximation) to describe the time evolution of the $(^4\text{He})^{-}$-bound-state abundance [42, 91]. Contour lines of $^6\text{Li}/\text{H}|_{\text{CBBN}}$ obtained in this calculation are shown, e.g., in Fig. 1 of Ref. [47]. Working with an upper limit on the primordial $^6\text{Li}/\text{H}$ abundance $^6\text{Li}/\text{H}|_p \leq 2 \times 10^{-11}$, the corresponding contour given in that figure is the one that provides the upper limit for $Y_{\tilde{\ell}_1}$. As a second more conservative limit, we consider in this work also $^6\text{Li}/\text{H}|_p \leq 6 \times 10^{-11}$, which provides a more relaxed $Y_{\tilde{\ell}_1}$ limit.

In Figs. 1 and 2, the long-dash-dotted (red in the web version) lines show the constraints obtained by confronting (15) with the $Y_{\tilde{\ell}_1}$ limits for $^6\text{Li}/\text{H}|_p \leq 2 \times 10^{-11}$ (left line) and $6 \times 10^{-11}$ (right line). It is the region to the right of the respective line that is disfavored by $^6\text{Li}/\text{H}|_{\text{CBBN}}$ exceeding the limit inferred from observations. Only the constraint from the primordial D abundance on hadronic energy release [4, 6] in $\tilde{\ell}_1$ decays [20, 21, 22] can be more severe than the CBBN constraints [7, 15, 23, 43, 44, 46, 47, 91]. In Figs. 1 and 2 the associated disfavored region is the one above the short-dash-dotted (blue in the web version) line. For details on this constraint, see [12, 22] and references therein.

In Fig. 1 one sees explicitly that the BBN constraints disfavor the region $0.1 m_{\tilde{\ell}_1} \lesssim m_{\tilde{G}} < m_{\tilde{\ell}_1}$ as already emphasized in the Introduction. Moreover, the $^6\text{Li}$ constraint imposes for $m_{\tilde{\ell}_1} > 10$ GeV the lower limit $m_{\tilde{\ell}_1} > 400$ GeV which implies $m_{\tilde{G}}(M_Z) > 2.4$ TeV for $c > 6$. This is in agreement with what had previously been realized in the CMSSM (where $c > 6$ in the $\tilde{G}$ NLSP region [47]): For $m_{\tilde{G}}$ in the range that is natural for gravity-mediated SUSY breaking, the $^6\text{Li}$ constraint can point to a SUSY mass spectrum that will be difficult to probe at the LHC [13, 43, 44, 45]. On the other hand, Fig. 1 shows very clearly that the $^6\text{Li}$ constraint becomes negligible for $m_{\tilde{G}} < 1$ GeV, i.e., for the $m_{\tilde{G}}$ range that is natural for gauge-mediated SUSY breaking scenarios.

Figure 2 allows us to read off the $T_R^\text{max}$ value imposed by the $^6\text{Li}$ constraint in the collider-friendly region of $m_{\tilde{\ell}_1} \lesssim 1$ TeV. Our most conservative and thereby most robust limit is the one obtained in the limiting case $c=1$. There one finds the $T_R^\text{max} \approx 3 \times 10^6$ GeV contour in the region that is allowed by the BBN constraints. If the gluino turns out to be significantly heavier than the $\tilde{\ell}_1$ NLSP, the $T_R^\text{max}$ value will become considerably more severe. For example, for the case of $c=7$, shown by the

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8 We thank Josef Pradler for providing us with the $^6\text{Li}/\text{H}|_{\text{CBBN}}$ data from the CBBN treatment of Ref. [42].

9 Comparisons of [42] with [33, 34, 38, 39], in which also the possible destruction of $^6\text{Li}$ due to $\tilde{\ell}_1$ decays is considered, show that these effects affect the $^6\text{Li}$ constraint only marginally.

10 The additional primordial bound-state effects discussed in [43, 48, 49, 53, 54, 55, 56, 57] do not affect the conclusions of this letter; cf. [54].
dashed lines in Fig. 2 one finds that a reheating temperature above $T_R^{\text{max}} = 10^6\,\text{GeV}$ is disfavored by BBN constraints. Note that these limit are quite robust since they emerge from the conservative limit (11). In fact, one may consider these limits as overly conservative by at least a factor of about 1.5 as discussed below (9). Indeed, a more restrictive limit of $T_R \lesssim 10^7\,\text{GeV}$ is found within the CMSSM by using the full expressions for $\Omega_G^{\text{TP}}$ given in (14) which include also the electroweak contributions to thermal gravitino production (12, 47).

Let us comment on the model dependence of the BBN constraints. As described above, the BBN constraints shown in Figs. 1 and 2 are derived with the yield (15). This does introduce a model dependence into the $T_R^{\text{max}}$ values discussed in the preceding paragraph. However, one should stress two points: (i) The yield (15) is quite typical for an electrically charged massive thermal relic (18). (ii) The $\tau_{\tilde{t}_1}$ dependent upper limits on $Y_{\tilde{t}_1}$ are very steep in the relevant region as can be seen, e.g., in Fig. 1 of Ref. [47]. Indeed, this steepness is reflected by the relatively weak $m_{\tilde{t}_1}$ dependence of the $^6\text{Li}$ constraints that can be seen in Figs. 1 and 2. These two points support the indicated BBN constraints and the associated $T_R^{\text{max}}$ values are quite robust. Only for very generous upper limits on the primordial $^6\text{Li}$ abundance and/or exceptionally small $Y_{\tilde{t}_1}$ values can the CBBN bound be relaxed substantially. The latter could be achieved, for example, with non-standard entropy production after thermal freeze out of the $\tilde{t}_1$ NLSP and before BBN (15, 16, 62) which we do not consider since we assume a standard cosmological history throughout this letter.

**PROBING $T_R$ BY MEASURING THE GLUINO–SLEPTON MASS RATIO**

In this section we present a way that could allow us to probe with collider experiments the $T_R^{\text{max}}$ value imposed by the $^6\text{Li}$ constraint—or any other constraint that can be translated into a similar upper limit on $\tau_{\tilde{t}_1}$—and the dark matter constraint (4). As discussed above, the $^6\text{Li}$ constraint implies basically an upper limit on the $\tilde{t}_1$ NLSP lifetime

$$\tau_{\tilde{t}_1} \leq \tau_{\text{max}},$$

which is, e.g., $\tau_{\text{max}} \approx 5 \times 10^4\,\text{s}$ for the case of the yield (15) as can be seen explicitly in Fig. 2. With a given $\tau_{\text{max}}$ and (11) derived from the dark matter constraint (4), one arrives immediately at the following $m_{\tilde{G}}$-independent upper limit on the gluino–slepton mass ratio

$$c = \frac{m_{\tilde{g}}(M_Z)}{m_{\tilde{t}_1}}$$

at the weak scale:

$$c \leq \left( \frac{2.37 \times 10^9\,\text{GeV}}{T_R^{\text{max}}} \right)^{\frac{1}{2}} \left( \frac{\Omega_{\text{DM}} h^2}{0.1} \right)^{\frac{1}{2}} \times \left( \frac{\tau_{\text{max}}}{10^4\,\text{s}} \right) \left( \frac{m_{\tilde{t}_1}}{100\,\text{GeV}} \right)^{\frac{1}{2}} \equiv c_{\text{max}},$$

i.e., a reheating temperature of at most $T_R^{\text{max}}$ can viable with a given $m_{\tilde{t}_1}$ only for a mass ratio $c \leq c_{\text{max}}$. In other words, for a lifetime constraint $\tau_{\text{max}}$ inferred from cosmological considerations (such as CBBN) and/or collider experiments, a simultaneous measurement of $m_{\tilde{t}_1}$ and the mass ratio $c$ will provide a model-independent conservative limit $T_R^{\text{max}}$ for $\tilde{G}$ LSP scenarios with a $\tilde{t}_1$ NLSP.

In Fig. 3 the solid lines (dashed lines) show $c_{\text{max}}$ imposed by the lifetime constraint $\tau_{\tilde{t}_1} \leq 3 \times 10^3\,\text{s}$ (10^4\,\text{s}) and and the dark matter constraint $\Omega_G h^2 \leq \Omega_{\text{DM}} h^2 \leq 0.126$ as a function of $m_{\tilde{t}_1}$ for values of $T_R^{\text{max}}$ ranging from $10^6\,\text{GeV}$ up to $3 \times 10^9\,\text{GeV}$. The lifetime constraint $\tau_{\tilde{t}_1} \lesssim 5 \times 10^3\,\text{s}$ is slightly weaker (and thereby more conservative) than the $^6\text{Li}$ CBBN constraint obtained with the yield (15) for $m_{\tilde{t}_1} > 100\,\text{GeV}$ as can be seen in Fig. 2. Accordingly, the $T_R^{\text{max}}$ values for $c = 1$ and $c = 7$ discussed in the previous section are more restrictive than the corresponding $T_R^{\text{max}}$ values in Fig. 3. The even more conservative $c_{\text{max}}$ curves obtained for $\tau_{\tilde{t}_1} \lesssim 10^4\,\text{s}$ are presented to cover also the case of a more relaxed CBBN constraint which could result, for example, from $^6\text{Li}/H/_{\text{p}} \leq 2.7 \times 10^{-10}$ (62), i.e., an upper limit that is
about an order of magnitude more generous than \([16,10]\). This emphasizes the conservative character of the corresponding \(e^{\text{max}}\) curves shown in Fig. 3.

**TESTING THE VIABILITY OF THERMAL LEPTOGENESIS AT COLLIDERS**

Thermal leptogenesis provides an attractive explanation of the baryon asymmetry in the Universe \([24]\). Since successful thermal leptogenesis with hierarchical right-handed heavy Majorana neutrinos requires a reheating temperature of \(T_R > 10^9\) GeV \([23, 26, 27, 28]\), one will be able to test its viability at the LHC with the method described in the previous section.

From earlier studies of gravitino LSP scenarios \([12, 13, 14, 50]\), it is known that thermal leptogenesis can be associated with testable \((m_{\tilde{G}}\text{-dependent})\) upper limits on the masses of the gluino and the other gauginos. Nevertheless, the \(\tau_{\tilde{t}_1}\) constraint from CBBN of \(^6\)Li is not taken into account in any of these studies. In fact, as mentioned in the Introduction, this \(\tau_{\tilde{t}_1}\) constraint disfavors thermal leptogenesis in constrained scenarios with universal soft SUSY breaking parameters at \(M_{\text{GUT}}\) \([13, 48, 55]\). Interestingly, in this work, it is this upper limit on \(\tau_{\tilde{t}_1}\) that allows us to arrive in a model independent way at a testable prediction of thermal leptogenesis that does not depend on the gravitino mass \(m_{\tilde{G}}\).

As can be seen in Fig. 3 already the conservative limits imposed by \(\tau_{\tilde{t}_1} < 10^4\) s show that \(T_R^{\text{max}} = 10^9\) GeV is associated with a gluino-slepton mass ratio of \(c < 3\) in the collider-friendly region of \(m_{\tilde{l}_1} < 1\) TeV. Thus, this ratio favors a gluino mass that will be accessible at the LHC. In this way, \(c < 3\) can be understood as a testable prediction of thermal leptogenesis for phenomenology at the LHC. Indeed, the realistic, less conservative constraints \(\tau_{\tilde{t}_1} < 5 \times 10^3\) s and \(T_R \geq 3 \times 10^9\) GeV point even to the exceptional case with a gluino that is only slightly heavier than the slepton NLSP: \(c \lesssim 1.5\). If realized in nature, this will guarantee unique signatures at the LHC.

**CONCLUSION**

The observation of a (quasi-) stable heavy charged slepton \(\tilde{l}_1\) as the lightest Standard Model superpartner at future colliders could provide a first hint towards the gravitino LSP being the fundamental constituent of dark matter. Under the assumption that the gravitino is the LSP and a long-lived \(\tilde{l}_1\) the NLSP, we have shown that measurements of the slepton mass \(m_{\tilde{l}_1}\) and its lifetime \(\tau_{\tilde{l}_1}\) can provide the gravitino mass \(m_{\tilde{G}}\) and upper limits on the reheating temperature \(T_R\) after inflation, which can be tightened once the gluino mass \(m_{\tilde{g}}\) is measured.

The conceivable insights into \(m_{\tilde{G}}\) are a direct consequence of the SUGRA Lagrangian and of R-parity conservation. Thus, they will be valid for any cosmological scenario provided the \(\tilde{G}\) is the LSP and a \(\tilde{l}_1\) the NLSP. The possibility to probe \(T_R\) at colliders results from the \(T_R\) dependence of the thermally produced gravitino density and the fact that this density cannot exceed the dark matter density. Thereby, the given upper limits on \(T_R\) rely not only on the SUGRA Lagrangian and R-parity conservation but also on the assumptions of a standard cosmological history and on \((g\mu)\) couplings that evolve at high temperatures as expected from their standard MSSM renormalization group running. Nevertheless, under these assumptions, the presented \(T_R\) limits are very robust since they have been derived in a model independent way from a conservative lower limit on the (thermally produced) gravitino density.

Prior to collider measurements of \(m_{\tilde{t}_1}\), \(\tau_{\tilde{t}_1}\), and \(m_{\tilde{g}}\), primordial nucleosynthesis can be used to constrain \(m_{\tilde{G}}\) and \(T_R\). In particular, we have found that the constraint \(\tau_{\tilde{t}_1} < 5 \times 10^3\) s from CBBN of \(^6\)Li implies a truly conservative limit of \(T_R < 3 \times 10^9\) GeV in the collider-friendly region of \(m_{\tilde{l}_1} < 1\) TeV and in the limiting case of a small gluino–slepton mass splitting at the weak scale: \(c = m_{\tilde{l}_1}/m_{\tilde{g}} \approx 1\). Indeed, with \(c = 7\) as obtained in scenarios with universal soft SUSY breaking parameters at the scale of grand unification—our robust conservative upper limit is \(T_R < 10^8\) GeV and thus as severe as in scenarios with an unstable gravitino of mass \(m_{\tilde{G}} < 5\) TeV.

The \(\tau_{\tilde{t}_1}\) constraint from CBBN of \(^6\)Li has allowed us to derive upper limits on \(T_R\) that depend on \(m_{\tilde{l}_1}\) and \(c\) only. In particular, we find that the condition for successful thermal leptogenesis with hierarchical right-handed heavy Majorana neutrinos, \(T_R > 10^9\) GeV \((3 \times 10^9\) GeV\), implies an upper limit of \(c < 3\) \((1.5)\) for \(m_{\tilde{l}_1} < 1\) TeV. This is a prediction of thermal leptogenesis that will be testable at the upcoming LHC experiments.

I am grateful to Josef Pradler for valuable discussions and comments on the manuscript. This research was partially supported by the Cluster of Excellence ‘Origin and Structure of the Universe.’

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