Gravitino production in an inflationary Universe and implications for leptogenesis

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Abstract

Models of leptogenesis are constrained by the low reheat temperature at the end of reheating associated with the gravitino bound. However a detailed view of reheating, in which the maximum temperature during reheating, $T_{\rm max}$, can be orders of magnitude higher than the reheat temperature, allows for the production of heavy Majorana neutrinos needed for leptogenesis. But then one must also consider the possibility of enhanced gravitino production in such scenarios. In this article we consider gravitino production during reheating, its dependence on $T_{\rm max}$, and its relevance for leptogenesis. Earlier analytical studies of the gravitino abundance have only considered gravitino production in the post-reheating radiation dominated era. We find that the gravitino abundance generated during reheating is comparable to that generated after reheating. This lowers the upper bound on the reheat temperature by a factor of 4/3.

Key words: Inflationary cosmology, gravitino abundance, leptogenesis

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I. INTRODUCTION

Gravitinos in supersymmetric theories can have important cosmological consequences. Stable gravitinos can overclose the universe while unstable gravitinos can affect the expansion rate of the universe during eras prior to their decay. The decay products of unstable gravitinos can also overclose the universe or affect light element abundances generated during nucleosynthesis. These cosmological consequences are a function of the gravitino energy density, $\rho_{\tilde{G}} = m_{\tilde{G}} n_{\tilde{G}}$, where $m_{\tilde{G}}$ and $n_{\tilde{G}}$ are the mass and number density of gravitinos.

In a non-inflationary universe, $n_{\tilde{G}} \sim T^3$ and therefore cosmological constraints on the energy density of gravitinos provide bounds on $m_{\tilde{G}}$, and equivalently on the scale of supersymmetry breaking [1, 2]. In an inflationary universe, $n_{\tilde{G}}$ is also a function of the reheat temperature, and so for a fixed $m_{\tilde{G}}$, often taken to be $O(100\,\mathrm{GeV} - 1\,\mathrm{TeV})$, cosmological constraints on the energy density of gravitinos provide an upper bound on the reheat temperature [3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13].

In Refs. [3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13] the number density of gravitinos is obtained by considering gravitino production in the radiation dominated era following reheating. It is presumed that $n_{\tilde{G}} = 0$ at the beginning of the radiation dominated era. Gravitinos are then produced through thermal scattering and $n_{\tilde{G}}$ is found to be proportional to the reheat temperature, $T_{\rm reh}$, which is the temperature of the thermal plasma at the beginning of the radiation dominated era when the inflaton field has decayed completely and the energy density of the universe is dominated by the inflaton decay products. The cosmological constraints on $n_{\tilde{G}}$ then provide an upper bound on $T_{\rm reh}$ of $10^{6-9}\,\mathrm{GeV}$.

If, as in Refs. [3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13], one assumes instantaneous reheating after inflation or that $T_{\rm reh}$ is the maximum temperature during reheating, then the upper bound on $T_{\rm reh}$ makes it difficult to create sufficiently high number densities of GUT gauge and Higgs bosons whose decays could generate the baryon asymmetry of the universe. Similarly, the gravitino bound constrains leptogenesis models in which the lepton asymmetry is generated by the decay of heavy bosons or fermions [14]. However, as discussed in Refs. [15, 16], after the inflationary era the temperature does not rise instantaneously to $T_{\rm reh}$ but rises initially to a maximum temperature $T_{\rm max}$ and then falls to $T_{\rm reh}$. In Ref. [16] the authors then argue that $T_{\rm max}$ can be as high as $10^3 T_{\rm reh}$ and that sufficient numbers of the lightest heavy Majorana right-handed neutrino of mass $\sim 10 T_{\rm reh}$ can be produced during reheating to allow for successful leptogenesis. This issue has also been studied in Ref. [14, 17].

While the above scenario considers the possible production of heavy neutrinos during reheating it does not consider the possible enhancement in the gravitino production as well. If the gravitino abundance generated post-reheating is proportional to the maximum temperature during that era, namely $T_{\rm reh}$, one should ask whether the gravitino abundance generated during reheating is proportional to the maximum temperature, $T_{\rm max}$, of the reheating era. If this abundance is larger than the abundance generated in the post-reheating era it could affect the viability of the leptogenesis scenario of Ref. [16]. Therefore in this article we explicitly calculate the gravitino abundance generated during the reheating era. We then compare it to the standard calculation of the gravitino abundance generated after reheating in the radiation dominated era, and discuss its relevance for leptogenesis models.

As argued above, one might expect that the gravitino abundance generated during reheating will be a function of $T_{\rm max}$. Interestingly, what we find is that by manipulating the relations between $T_{\rm max}$, $T_{\rm reh}$, the inflaton decay rate and the scale of inflation the dependence on $T_{\rm max}$ cancels out and the gravitino abundance is proportional to $T_{\rm reh}$ only. Furthermore, while one would not expect the gravitino abundance generated in the reheating and the post-reheating eras to be similar that is indeed what we find. The resulting contraint on the reheat temperature and on leptogenesis models is then only slightly stronger than before.

Our results are valid for a reheating scenario that does not include preheating. Gravitino production during preheating has been considered in Ref. [18, 19, 20, 21, 22, 23, 24].

II. PRODUCTION OF GRAVITINOS

During inflation the Universe cools down by several orders of magnitude. Subsequently the inflaton decays while performing coherent oscillations about the minimum of its potential. Very soon after the inflaton enters the oscillating phase the temperature of the universe rises to a maximum value [15]

$$T_{\rm max} \simeq 0.8 g_*^{-1/4} M_{\rm I}^{1/2} \left(\Gamma_\phi M_{\rm Pl}\right)^{1/4} \,, \tag{1}$$

where $M_{\rm I} = V_{\rm I}^{1/4}$, $V_{\rm I}$ being the vacuum energy density during the inflationary epoch (taken to be constant). g_* is the number of relativistic degrees of freedom and Γ_ϕ is the decay rate of the inflaton field. Subsequently, the temperature of the thermal bath falls approximately as $R^{-3/8}$ [15], where R is the scale factor of expansion of the Universe. This particular dependence on R goes on until the universe becomes radiation dominated when the inflaton field decays completely at $t_{\rm reh} = \Gamma_\phi^{-1}$. The temperature of the universe at $t_{\rm reh}$ is given by [15]

$$T_{\rm reh} \simeq 0.55 g_{*{\rm reh}}^{-1/4} \left(M_{\rm Pl}\Gamma_\phi\right)^{1/2} . \tag{2}$$

In the following we examine the production of gravitinos during reheating between $T_{\rm max}$ and $T_{\rm reh}$, and during the subsequent radiation dominated era, and discuss its consequences.

Gravitinos are produced by the scattering of the inflaton decay products; see, for example, Tables 1 in Refs. [7, 12] for a list of processes. The number density of gravitinos generated is then given by the solution of the Boltzmann equation

$$\frac{dn_{\tilde{G}}}{dt} + 3Hn_{\tilde{G}} = \langle \Sigma_{\rm tot}|v|\rangle n^2 \,, \tag{3}$$

where $n = (\zeta(3)/\pi^2)T^3$ ($\zeta(3) = 1.20206..$ is the Riemann zeta function of 3), $\Sigma_{\rm tot}$ is the total scattering cross section for gravitino production, v is the relative velocity of the incoming particles, and $\langle ... \rangle$ refers to thermal averaging. We have ignored the gravitino decay term above as the gravitino lifetime is $10^{7-8}(100\,{\rm GeV}/m_{\tilde{G}})$s [7] and is not relevant during the gravitino production era for gravitinos of mass 10^{2-3} GeV. We may re-express this equation as

$$\dot{T}\frac{dn_{\tilde{G}}}{dT} + 3Hn_{\tilde{G}} = \langle \Sigma_{\rm tot}|v|\rangle n^2 \,, \tag{4}$$

In $SU(N)$ supersymmetric models with n_f pairs of fundamental and antifundamental chiral supermultiplets, $\langle \Sigma_{\rm tot}|v|\rangle$ is given by [25]

$$\begin{aligned} \langle \Sigma_{\rm tot}|v|\rangle \equiv \frac{\alpha}{M^2} &= \frac{1}{M^2}\left[1 + \left(\frac{m_{\tilde{g}}^2}{3m_{\tilde{G}}^2}\right)\right]\frac{3g_N^2(N^2-1)\pi}{32\zeta(3)} \\ &\times \left[\{\ln(T^2/m_{g,{\rm th}}^2) + 0.3224\}(N+n_f) + 0.5781 n_f\right], \end{aligned} \tag{5}$$

where $m_{\tilde{g}}$ is the gaugino mass and $m_{g,{\rm th}}$ is the thermal mass of the gauge boson which is given as

$$m_{g,{\rm th}}^2 = \frac{1}{6}g_N^2(N+n_f)T^2 \,. \tag{6}$$

In the above equations $g_N\,(N = 1,2,3)$ are the gauge coupling constants corresponding to $U(1)_Y$, $SU(2)_L$ and $SU(3)_C$ respectively and $M = M_{\rm Pl}/\sqrt{8\pi} \simeq 2.4 \times 10^{18}$ GeV is the reduced Planck mass. (For $U(1)$ gauge interactions, $N^2 - 1 \to 1$ and $N + n_f \to n_f$, where

n_f is the sum of the square of the hypercharges of chiral multiplets [29].) Using the one loop β-function of MSSM, the solution of the renormalization group equation for the gauge coupling constants is given by

$$g_N(T) \simeq \left[g_N^{-2}(M_Z) - \frac{b_N}{8\pi^2} \ln(T/M_Z) \right]^{-1/2} , \tag{7}$$

with $b_1 = 11$, $b_2 = 1$, $b_3 = -3$. It is presumed here that inflaton decays perturbatively and the products thermalise quickly as discussed in Appendix A of Ref. [16]. Also see Refs. [26, 27] for an alternate description of reheating and the gravitino bound.

A. Gravitino production during reheating

If the potential for the oscillating inflaton field is dominated by the mass term, then the energy density of the inflaton field scales as $1/R^3$ during reheating. (We ignore change in the inflaton energy density due to decays.) Einstein's equation then implies

$$\left(\frac{\dot{R}}{R} \right)^2 = \frac{8\pi G}{3} \rho_{\rm max} \left(\frac{R_{\rm max}}{R} \right)^3 , \tag{8}$$

where $\rho_{\rm max}$ and $R_{\rm max}$ are the inflaton energy density and scale factor at $T_{\rm max}$. Solving the above equation for R we get

$$R = R_{\rm max} \left[\frac{3}{2} H_{\rm max}(t - t_{\rm max}) + 1 \right]^{2/3} , \tag{9}$$

where

$$H_{\rm max} \simeq \sqrt{\frac{8\pi}{3}} \frac{M_I^2}{M_{\rm Pl}} . \tag{10}$$

(For $t \gg t_{\rm max}$, $R \sim t^{2/3}$.)

For Eq. (4) we require $\dot{T}$ and H as functions of the temperature T. During reheating the energy density of the relativistic particles is given by $\rho_r \propto R^{-3/2}$ [15]. Since $\rho_r \sim T^4$, we get

$$T = T_{\rm max} \left(\frac{R_{\rm max}}{R} \right)^{3/8} . \tag{11}$$

Using Eq. (9) the $T - t$ relation is then obtained as

$$T = T_{\rm max} \frac{1}{\left[\frac{3}{2} H_{\rm max}(t - t_{\rm max}) + 1 \right]^{\frac{1}{4}}} . \tag{12}$$

This implies that

$$\dot{T} = -\frac{3}{8} T H_{\rm max} \frac{1}{\left[\frac{3}{2} H_{\rm max}(t - t_{\rm max}) + 1\right]}$$
$$= -\frac{3}{8} T H_{\rm max} \left(\frac{T}{T_{\rm max}}\right)^4 . \tag{13}$$

The Hubble expansion parameter in terms of T is then given by

$$H = \frac{\dot{R}}{R} = -\frac{8}{3}\frac{\dot{T}}{T} = H_{\rm max} \left(\frac{T}{T_{\rm max}}\right)^4 . \tag{14}$$

Using Eqs. (13) and (14), Eq. (4) can be rewritten as

$$\frac{dn_{\tilde{G}}}{dT} - \frac{8}{T} n_{\tilde{G}} = -CT\,, \tag{15}$$

where

$$C = \frac{8}{3} \frac{T_{\rm max}^4}{H_{\rm max}} \frac{\alpha}{M^2} \left(\frac{\zeta(3)}{\pi^2}\right)^2 . \tag{16}$$

Solving for $n_{\tilde{G}}$ in the regime $T_{\rm max}$ to $T_{\rm reh}$ we get

$$n_{\tilde{G}}(T_{\rm reh}) = \frac{C}{6} T_{\rm reh}^8 \left(\frac{1}{T_{\rm reh}^6} - \frac{1}{T_{\rm max}^6}\right) \tag{17}$$
$$= \frac{C}{6} T_{\rm reh}^2 \quad \text{for } \mathrm{T}_{\rm max} \gg \mathrm{T}_{\rm reh}\,. \tag{18}$$

α has been taken to be constant although there is a log dependence due to the running gauge couplings in the one loop β function of MSSM.

B. Gravitino production in the radiation dominated era

After the inflaton field decays completely at $t_{\rm reh}$ the universe enters the radiation dominated era. Unlike the reheating era during which the entropy continuously increases, in the radiation dominated era the total entropy remain constant (except for epochs of out-of-equilibrium decays). Therefore it is useful to express the abundance of any species i as $Y_i = n_i/s$, where n_i is the number density of the species i in a physical volume and s is the entropy density given by

$$s = \frac{2\pi^2}{45} g_* T^3 . \tag{19}$$

$g_* = 228.75$ in the MSSM. With this definition, Eq. (4) reads as

$$\dot{T}\frac{dY_{\tilde{G}}}{dT} = \langle \Sigma_{\rm tot} |v| \rangle Y n\,. \tag{20}$$

For the radiation dominated era,

$$T = T_{\rm reh} \frac{1}{[2H_{\rm reh}(t - t_{\rm reh}) + 1]^{\frac{1}{2}}}\,, \tag{21}$$

where

$$H_{\rm reh} = \sqrt{\frac{8\pi^3 g_{*\rm reh}}{90}} \frac{T_{\rm reh}^2}{M_{\rm Pl}}\,. \tag{22}$$

This implies that $\dot{T}$ is

$$\dot{T} = -\frac{H_{\rm reh}}{T_{\rm reh}^2} T^3 = -\left(\frac{g_{*\rm reh}\pi^2}{90}\right)^{\frac{1}{2}} \frac{T^3}{M}\,. \tag{23}$$

Then

$$\frac{dY_{\tilde{G}}}{dT} = -\left(\frac{90}{g_{*\rm reh}\pi^2}\right)^{1/2} \left(\frac{1}{(2\pi^2/45)g_*}\right) \left(\frac{\alpha}{M}\right) \left(\frac{\zeta(3)}{\pi^2}\right)^2\,. \tag{24}$$

Assuming α to be independent of temperature and integrating the above equation from $T_{\rm reh}$ to $T_{\rm f}$, the final temperature, we get the number density of gravitinos at $T_{\rm f}$ to be

$$\begin{aligned} Y_{\tilde{G}}(T_{\rm f}) \;=\; & Y_{\tilde{G}}(T_{\rm reh}) + \left(\frac{90}{g_{*\rm reh}\pi^2}\right)^{1/2} \left(\frac{1}{(2\pi^2/45)g_{*\rm reh}}\right) \\ & \times \left(\frac{\alpha}{M}\right) \left(\frac{\zeta(3)}{\pi^2}\right)^2 (T_{\rm reh} - T_{\rm f})\,. \end{aligned} \tag{25}$$

Since most of the gravitinos are generated close to $T_{\rm reh}$ we have ignored the variation of g_* with temperature and used $g_{*\rm reh}$ in the final expression. Using Eqs. (18), (16) and (19) the first term on the right hand side of the above equation is given by

$$Y_{\tilde{G}}(T_{\rm reh}) = \frac{\alpha}{M^2} \left(\frac{\zeta(3)}{\pi^2}\right)^2 \left(\frac{1}{(2\pi^2/45)g_{*\rm reh}}\right) \frac{4}{9} \frac{T_{\rm max}^4}{H_{\rm max} T_{\rm reh}}\,. \tag{26}$$

This term is usually neglected while estimating the gravitino abundance [3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13]. However as we see below this is comparable with the second term in Eq. (25). Now using Eq. (26) in Eq. (25) we get the effective number density of gravitinos at $T_{\rm f}$ to be

$$\begin{aligned} Y_{\tilde{G}}(T_{\rm f}) \;=\; & \frac{\alpha}{M^2} \left(\frac{\zeta(3)}{\pi^2}\right)^2 \left(\frac{1}{(2\pi^2/45)g_{*\rm reh}}\right) \left[\frac{4}{9} \frac{T_{\rm max}^4}{H_{\rm max} T_{\rm reh}} \right. \\ & \left. + M \left(\frac{90}{g_{*\rm reh}\pi^2}\right)^{1/2} T_{\rm reh}\right]\,, \end{aligned} \tag{27}$$

where we have used $T_{\rm f} \ll T_{\rm reh}$. Relating $T_{\rm max}$ to $T_{\rm reh}$ from Eqs. (1) and (2) the number density of gravitinos in a comoving volume is then given as

$$Y_{\tilde{G}}(T_f) = \frac{\alpha T_{\rm reh}}{M} \left(\frac{\zeta(3)}{\pi^2}\right)^2 \left(\frac{1}{(2\pi^2/45)g_{*\rm reh}^{3/2}}\right) (1.0 + 3.0)\,, \tag{28}$$

where we have used $g_{*\rm reh}$ in the expressions for $T_{\rm max}$.

III. DISCUSSION AND COMMENTS

Generalizing Eq. (17) for any T during reheating one sees that $n_{\tilde{G}}$ does not vary monotonically during reheating. As shown in Fig. (1), $n_{\tilde{G}}$ rises dramatically from $T_{\rm max}$ to $T_1 = T_{\rm max}/4^{1/6}$ and then falls from T_1 to $T_{\rm reh}$. However $R^3 \sim T^{-8}$ and the number density per comoving volume, $\bar{n}_{\tilde{G}} = (1/R^3_{\rm max}) \int_{T_{\rm max}}^{T} dT\, d/dT(n_{\tilde{G}}R^3)$, is proportional to $(1/T^6 - 1/T^6_{\rm max})$ and so most gravitinos are produced close to $T \sim T_{\rm reh}$. ($s \sim T^3$ and, as shown in Fig. (2), $Y_{\tilde{G}}$ increases steadily in the reheating phase for $T_{\rm reh} < T < T_{\rm max}$.) For $T < T_{\rm reh}$, one can show from Eq. (25) that $dn_{\tilde{G}}/dT$ is always greater than 0, indicating that the gravitino number density is always decreasing during the radiation dominated era. (If $Y_{\tilde{G}}(T_{\rm reh})$ is set to 0, then $n_{\tilde{G}}$ first increases and then decreases.) $Y_{\tilde{G}}$ is always increasing but for $T \ll T_{\rm reh}$ it becomes approximately constant, as seen in Fig. (2).

We now address a concern as to whether one can distinguish production as occuring in the reheating era or in the radiation dominated era when production in both eras occurs close to $T_{\rm reh}$. In our analysis, for $T < T_{\rm max}$ during reheating the ratio of the radiation and inflaton energy densities increases as $\rho_{\rm rad}/\rho_{\rm inf} \sim R^{-3/2}/R^{-3} \sim R^{3/2} \sim T^{-4}$ while the gravitino abundance increases as $Y_{\tilde{G}} \sim T^{-1}$ (from Eq. (26)). Therefore much of the change in the gravitino abundance in the reheating era occurs when $\rho_{\rm rad} \ll \rho_{\rm inf}$. Similarly, Eq. (25) implies that in the radiation dominated era the gravitino abundance changes linearly with $T \sim t^{-1/2}$, while the inflaton energy density falls exponentially fast. Again much of the gravitino production at $T < T_{\rm reh}$ will occur when it is valid to treat the dynamics of the era as due to radiation only. Therefore we believe that our treatment of the problem is valid.

From Eq. (28) it is clear that the gravitino production during the reheating period is 1/3 of that during the radiation dominated era. A priori one would not have expected the gravitino production in both these eras to be similar. Furthermore, the gravitino abundance generated during reheating can be re-expressed as independent of $T_{\rm max}$, which is also unexpected. Interestingly, the contribution to $Y_{\tilde{G}}$ from the reheating era is linearly proportional to $T_{\rm reh}$, as it is for the radiation dominated era. It is then straightforward to revise the earlier upper bound on $T_{\rm reh}$ from the cosmological constraints on $n_{\tilde{G}}$. The bound of 10^{6-9} GeV will now be lowered by a factor of 4/3 and thus is not greatly affected. Since $T_{\rm max} \propto \sqrt{T}_{\rm reh}$, $T_{\rm max}$ is also not much affected. Therefore heavy particles of mass greater than $T_{\rm reh}$ can still be produced during reheating and leptogenesis scenarios are not significantly further

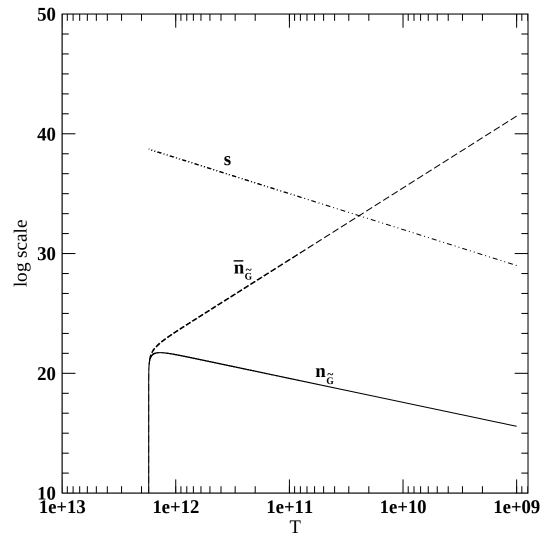

FIG. 1: The gravitino number density, $n_{\tilde{G}}$, the gravitino number density per comoving volume, $\bar{n}_{\tilde{G}}$, and the entropy density, s, are plotted as a function of the temperature T during reheating. $T_{\rm reh}$ and M_I are chosen to be $10^9\,\rm GeV$ and $10^{16}\,\rm GeV$ respectively, and so $T_{\rm max} \approx 2 \times 10^{12}\,\rm GeV$. $T_1 \approx T_{\rm max}$. α is treated as constant and evaluated at $T_{\rm reh}$, with $g_i(M_z)$ obtained from $\alpha_{EM}(M_Z) = 1/128$, $\sin^2\theta_W(M_Z) = 0.231$, $\alpha_s(M_Z) = 0.119$, and $M_Z = 91.2\,\rm GeV$ [28].

constrained than before.

Comparison with numerical analysis: The total gravitino density, including that generated during reheating, has been obtained numerically in Ref. [29]. Our analytical derivation agrees well with their fit to the gravitino abundance. For a reheat temperature of $10^9\,\rm GeV$, both Eq. (F12) of Ref. [29] and our Eq. (28) give $Y_{\tilde{G}} = 2 \times 10^{-13}$ indicating the robustness of our analysis. Furthermore, our analytical derivation allows one to appreciate various aspects of the gravitino abundance obtained in Ref. [29]. The fit to the gravitino abundance in Ref. [29] gives an abundance dependent on $T_{\rm reh}$, but not also on $T_{\rm max}$ as one might have expected. Our analysis above shows that the abundance generated during reheating does indeed depend on $T_{\rm max}$ (see Eq. (26)) but it also depends on the scale of inflation and $T_{\rm reh}$, and by manipulating the expressions relating these three quantities, as we have done, the dependence on $T_{\rm max}$ cancels out.

The dominant term in the fit of Ref. [29] for the total gravitino abundance has the same functional form as that obtained by earlier analytical calculations that did not include gravitino generation during reheating, namely, linear dependence on $T_{\rm reh}$. Our analysis indicates

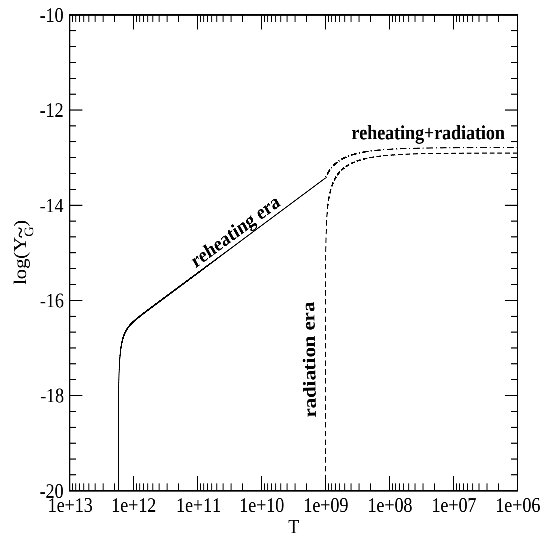

FIG. 2: $Y_{\tilde{G}} = n_{\tilde{G}}/s$ generated during the reheating era, the radiation dominated era, and the sum of contributions from both eras are shown as a function of the temperature T for the same parameters as in Fig. (1). Since $Y_{\tilde{G}}$ in both eras is largely generated close to $T_{\rm reh}$, α is evaluated at $T_{\rm reh}$. The final value of $Y_{\tilde{G}}$ is $\approx 2 \times 10^{-13}$.

that this is because gravitino generation during reheating also has a linear dependence on $T_{\rm reh}$, just as in the post-reheating era. We emphasise that it would be improper to naively conclude that the linear dependence is because the gravitino abundance generated during the radiation dominated era is dominant, since we have shown that the gravitino abundance generated in both eras differ only by a factor of 3.

IV. CONCLUSION

In conclusion, in this article we have calculated the gravitino abundance generated during reheating. We find that it is linearly proportional to the the reheat temperature $T_{\rm reh}$, as in the standard calculation of gravitinos produced in the radiation dominated era after reheating. Further, we find that it is about $1/3$ the number density of gravitinos generated in the radiation dominated era. Therefore this lowers the upper bound on $T_{\rm reh}$ from cosmological constraints on the gravitino number density by a factor of $4/3$. This does not significantly alter the viability of leptogenesis scenarios.

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