

Leptogenesis, Z bosons, and the reheating temperature of the Universe

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Leptogenesis, Z' bosons, and the reheating temperature of the Universe

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ABSTRACT: We study the impact for leptogenesis of new U(1) gauge bosons coupled to the heavy Majorana neutrinos. They can significantly enhance the efficiency of thermal scenarios in the weak washout regime as long as the Z' masses are not much larger than the reheating temperature ($M_{Z'} < 10T_{\text{rh}}$), with the highest efficiencies obtained for Z' bosons considerably heavier than the heavy neutrinos ($M_{Z'} \gtrsim 100M_1$). We show how the allowed region of the parameter space is modified in the presence of a Z' and we also obtain the minimum reheating temperature that is required for these models to be successful.

KEYWORDS: Cosmology of Theories beyond the SM, Neutrino Physics, CP violation, Discrete and Finite Symmetries

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1 Introduction

Leptogenesis is one of the most attractive known theories to explain the origin of the matter-antimatter asymmetry of the universe [1]. This is because it's based on a simple extension of the standard model (SM) which can also explain naturally why the neutrino masses are so tiny. In leptogenesis scenarios there are two well different regimes according to the strength of the Yukawa interactions, which is parametrized by the effective mass \tilde{m}_1 .¹ The strong washout regime ($\tilde{m}_1 \gg 10^{-3}$ eV) is characterized by small departures from equilibrium and a significant erasure of the asymmetries generated by the heavy neutrino decays. On the other hand, in the weak washout regime ($\tilde{m}_1 \ll 10^{-3}$ eV) the neutrinos decay far out from equilibrium and the erasure of the asymmetry produced in the decay epoch is negligible. Although the observed values of the differences of the squared masses of the light neutrinos may suggest a high value for the effective mass, the weak washout regime is well consistent with observations. In fact, the only bound on \tilde{m}_1 coming from the light neutrino masses is $\tilde{m}_1 \geq m_1 \geq 0$. Nevertheless, the generation of a lepton asymmetry in this regime faces some problems. If the SM is minimally extended adding only the heavy Majorana neutrinos and one considers thermal leptogenesis, so that the heavy neutrinos are produced by inverse decays and scatterings in the thermal bath, the production of an asymmetry is limited by the small rate of production of the lightest heavy neutrino. In the traditional computation in which one includes scattering processes in the production of N_1 but only considers the CP violation related to the decays, inverse decays and s -channel off-shell scatterings, the final baryon asymmetry turns out to be approximately proportional to \tilde{m}_1 , being hence strongly suppressed for very small \tilde{m}_1 . On the other hand, the CP violating asymmetry per decay, ϵ , can become larger for increasing heavy neutrino masses [2] and therefore

¹We will focus on hierarchical scenarios, for which the N_1 mass M_1 is much smaller than the masses of the other two heavy neutrinos $N_{2,3}$, i.e. $M_1 \ll M_{2,3}$ and we also assume that the lepton asymmetry generated during $N_{2,3}$ decays is not relevant. The effective mass \tilde{m}_1 is just the N_1 decay width normalized to $M_1^2/8\pi v^2$.

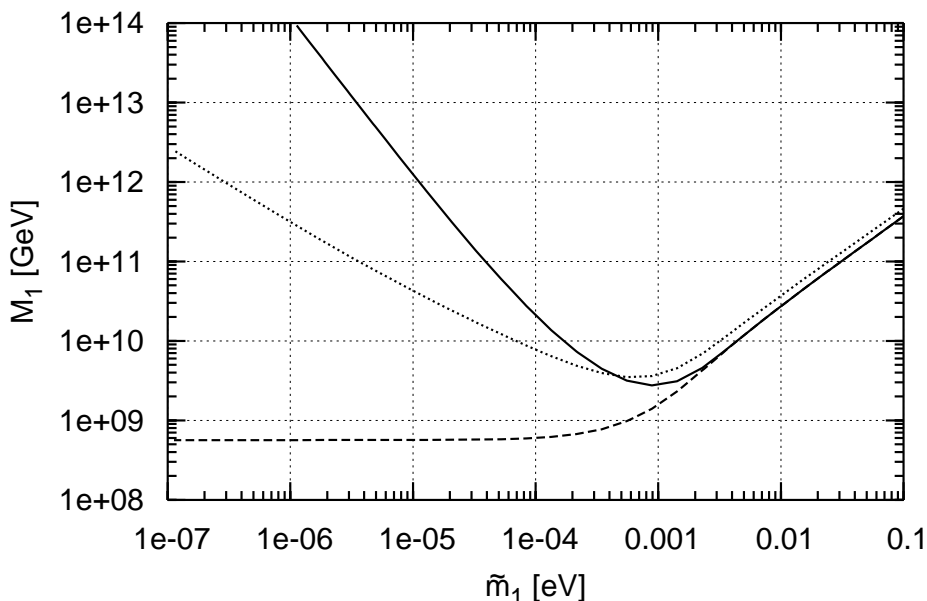


Figure 1. Allowed regions in the $\tilde{m}_1 - M_1$ plane assuming a null initial N_1 density, not including the CP violation in scatterings (region above the dotted line) and including it (region above the solid line). The allowed region for the case of an equilibrium initial density is also represented (region above the dashed line). The lines are the values leading to $Y_B = 8.7 \times 10^{-11}$ adopting the CP asymmetries saturating the Davidson-Ibarra bound [2].

thermal scenarios in the weak washout limit ($\tilde{m}_1 \ll 10^{-3}$ eV) require large values of M_1 to be successful. This is represented by the dotted curve in figure 1 which delimits the region of the $\tilde{m}_1 - M_1$ space allowed by observations ($n_B/s = (8.82 \pm 0.23) \times 10^{-11}$ [3]).² But the situation is actually worse than usually stated because there’s a cancellation between the asymmetry generated at early times during the production of N_1 and the asymmetry of opposite sign generated during the decays. This cancellation shows up only with the proper inclusion of the CP asymmetries in scatterings [5, 6] and a final symmetric universe can be avoided only thanks to the action of the early washouts which erase some of the “wrong sign” asymmetry produced in the first stages. The weaker the early washouts are, the less asymmetry survives this cancellation, and taking this into account the final baryon asymmetry is actually proportional to approximately \tilde{m}_1^2 and not just to \tilde{m}_1 . The resulting lower bound on M_1 is represented by the solid curve of figure 1, which in the weak washout regime is clearly stricter than the traditionally quoted bound.

The high Majorana neutrino masses required to produce the observed asymmetry in the weak washout regime may be in conflict with the relatively low reheating temperature of many cosmological models and this is also a potential problem in supersymmetric scenarios affected by the possible overproduction of gravitinos.

²We take $m_1 = 0$, so that the bound [2, 4] on the CP asymmetry in N_1 decays takes its largest possible value for a given M_1 : $|\epsilon| \leq \frac{3}{16\pi} \frac{M_1}{v^2} m_3$, with $m_3 \simeq \sqrt{\Delta m_{32}^2} \simeq 0.05$ eV.

The situation just described is quite different if the abundance of the heavy neutrinos at the beginning of the leptogenesis era is, for some reason, equal to that of equilibrium. In this case the final $B-L$ asymmetry in the weak washout regime is $Y_{B-L} \approx -\epsilon Y_N^{\text{eq}}(T \gg M_1)$ (where $Y_i \equiv n_i/s$ and $N \equiv N_1$), i.e. the efficiency³ is approximately equal to unity and the allowed region in the $\tilde{m}_1 - M_1$ plane is greatly enlarged (dashed line in figure 1). One of the ways to reach an equilibrium density before the onset of leptogenesis is to have new interactions. In particular, the case for gauge interactions was considered in [7, 8]. Here we are going to extend and study in more detail the scenarios with Z' bosons. In section 2 we define the model we are going to concentrate on, we then describe in section 3 the different effects induced by the presence of the Z' and in section 4 we study situations in which the reheating temperature after inflation is less than the mass of N_1 and determine the minimum reheating temperature compatible with successful leptogenesis. The conclusions are presented in section 5.

2 The model and Boltzmann equations

In order to give numerical results we are going to work with a specific model, but the features that will be described are expected to be valid for different models that include a new neutral gauge boson. We will use the model described in [7] and here we give a brief summary of it, emphasizing the most relevant points for our work.

The gauge symmetry of the SM is extended to the group $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{Y'}$, which can arise as a step in the chain of spontaneous symmetry breakings from an unification gauge group like $SO(10)$ to the SM one. The covariant derivative is

$$D_\mu = \partial_\mu - ig\vec{W}_\mu \cdot \vec{T} - ig'B_\mu Y - ig'\sqrt{\frac{2}{3}}C_\mu Y' ,$$

where \vec{W}_μ, B_μ and C_μ are the $SU(2)_L, U(1)_Y$ and $U(1)_{Y'}$ gauge fields respectively. Note that both abelian groups have the same gauge coupling constant (g') as a consequence of their (assumed) common origin in the larger group $SO(10)$. It can also be shown that the $U(1)_Y$ and $U(1)_{Y'}$ charges of a particle are related by $Y' = Y - \frac{5}{4}(B-L)$, which gives the coupling between the different fermions of the model and the $U(1)_{Y'}$ gauge field in terms of the (known) weak hypercharges.

The scalar sector of the model consists of the SM Higgs and the field χ responsible for the spontaneous symmetry breaking (SSB) of $U(1)_{Y'}$ at a scale $v' = \langle 0|\chi|0 \rangle \gg v$ (with $v = 174 \text{ GeV}$ the vacuum expectation value of the SM Higgs). Due to the SSB of $U(1)_{Y'}$ the right handed neutrinos acquire a Majorana mass given by $M = yv'$, with y the matrix of Yukawa couplings between the right handed neutrinos and the χ field. The $U(1)_{Y'}$ gauge field also becomes massive: $M_{Z'} = \frac{5}{\sqrt{3}}g'v'$, where Z' is the massive $U(1)_{Y'}$ gauge boson. We will assume that $M_{Z'}$ is larger than M_1 , which is natural given that gauge couplings are usually larger than the Yukawa ones. As explained in [7], the Higgs boson associated to the SSB of $U(1)_{Y'}$ can be neglected when studying processes that occur at temperatures below $M_{Z'}$, in particular during the N_1 leptogenesis era.

³The efficiency η is defined by $Y_{B-L}^f = -\epsilon\eta Y_N^{\text{eq}}(T \gg M_1)$, where Y_{B-L}^f is the final $B-L$ asymmetry.

The most relevant processes for the thermalisation of the heavy neutrinos are those mediated by Z' which produce or destroy the heavy Majorana neutrinos, i.e. $f\bar{f}, h\bar{h} \leftrightarrow N_j N_j$ (where f is a SM fermion and h is the SM Higgs). We have calculated the reduced cross section obtaining:⁴

$$\hat{\sigma}_{Z'}(s) = \frac{4225\pi}{216} \frac{\alpha^2}{\cos^4 \theta_w} \sqrt{x(x-4a_j)} \frac{x-a_j}{(x-a_{Z'})^2 + a_{Z'}c}, \quad (2.1)$$

where all quantities with dimension of energy are normalized to the mass of the lightest heavy Majorana neutrino: $x \equiv s/M_1^2, a_j \equiv (M_j/M_1)^2, a_{Z'} \equiv (M_{Z'}/M_1)^2$ and $c \equiv (\Gamma_{Z'}/M_1)^2$, with $\Gamma_{Z'}$ the decay width of Z' which is given by [7] $\Gamma_{Z'} = \frac{\alpha}{\cos^2 \theta_w} M_{Z'} \left[\frac{169}{144} + \frac{25}{18} \sum_i \left(\frac{a_{Z'} - 4a_i}{4a_{Z'}} \right)^{3/2} \theta(a_{Z'} - 4a_i) \right]$. The cross section given is summed over all the degrees of freedom of the particles involved (the initial particles considered are the SM Higgs and fermions).

The processes $f\bar{f}, h\bar{h} \leftrightarrow N_j N_j$ don't violate lepton number, so they only enter in the Boltzmann equation for the evolution of Y_N , which becomes:⁵

$$\frac{dY_N}{dz} = -\frac{1}{sHz} \left\{ \left[\frac{Y_N}{Y_N^{\text{eq}}} - 1 \right] (\gamma_D + 2\gamma_{Ss} + 4\gamma_{St}) + \left[\left(\frac{Y_N}{Y_N^{\text{eq}}} \right)^2 - 1 \right] \gamma_{Z'} \right\}, \quad (2.2)$$

with $z \equiv M_1/T$. The quantities $\gamma_D, \gamma_{Ss}(\gamma_{St})$ and $\gamma_{Z'}$ are the reaction densities for decays, scatterings involving the top quark which are mediated by the Higgs in the s (t) channel and annihilation of N_1 pairs respectively. Note that, since $\gamma_{Z'}$ doesn't depend on the Yukawa couplings of the heavy Majorana neutrinos, the corresponding term in the Boltzmann equation has a different dependence on the parameters of the model than the other three terms: while these last are proportional to \tilde{m}_1 , the Z' term is inversely proportional to M_1 , so that for fixed values of $M_{Z'}$ and \tilde{m}_1 the Z' effects diminish for increasing values of M_1 .

We end up this section with some comments about the conditions under which the Boltzmann equations will be solved. Since we want to concentrate on the effects of the Z' bosons we will consider a simple flavor structure [9, 10], assuming that the τ is the only relevant lepton flavor. Anyway, flavor effects have a limited impact in the weak washout regime which is the most relevant one for this work. It's also necessary to specify the fast processes that, while not entering directly in the Boltzmann equations for Y_N or Y_{B-L} , have influence on the generation of the matter-antimatter asymmetry by redistributing the generated asymmetry among the different particles of the thermal bath [11, 12]. The set of spectator processes that are active depends mainly on the value of M_1 since this determines the typical temperatures of the leptogenesis epoch and to a smaller extent on \tilde{m}_1 because it establishes the duration of this epoch. Nevertheless, we will always include the same set of spectator processes, namely that corresponding to the temperature range $10^{11} \text{ GeV} \lesssim T \lesssim 10^{12} \text{ GeV}$ [12], independently of the value of M_1 and \tilde{m}_1 , since these processes modify the final baryon asymmetry by only some tens of percent, which is not important for our study of the Z' effects. Finally, we will also ignore finite temperature corrections to the particle masses and couplings [13].

⁴The expression given in eq. (2.1) differs from that obtained in [7] and also with that in [8].

⁵The processes involving the SM gauge bosons won't be included in this work.

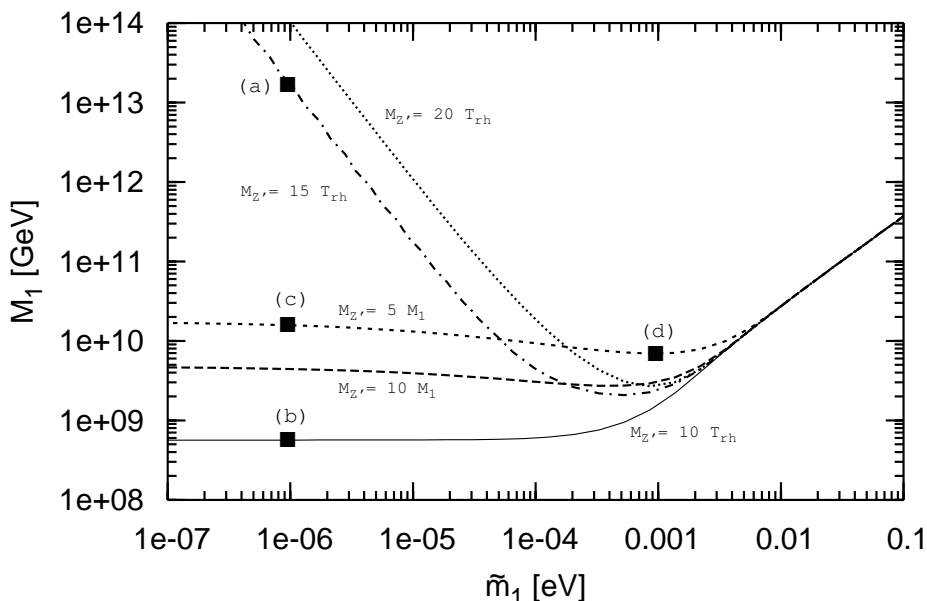


Figure 2. The regions allowed by observations in the $\tilde{m}_1 - M_1$ parameter space for different values of the Z' mass and $T_{\text{rh}} = 100M_1$. The regions allowed are those above the dotted line (for $M_{Z'} = 20T_{\text{rh}}$), the dash-dotted line (for $M_{Z'} = 15T_{\text{rh}}$), the solid line (for $M_{Z'} = 10T_{\text{rh}}$), the long dashed line (for $M_{Z'} = 10M_1$) and the short dashed line (for $M_{Z'} = 5M_1$). The points labeled (a) to (d) correspond to the panels of figure 3, where the evolution of the $B - L$ asymmetry is represented.

3 The effects of Z' in the weak washout regime

The coupling of N_1 with the Z' boson allows the production of the heavy neutrinos without generating a CP asymmetry (contrary to the case of production via the Yukawa couplings). This can help to solve the problems related with the production of the matter-antimatter asymmetry in the weak washout regime, since the cancellation mentioned in the introduction may no longer be enforced. But on the other hand, the neutrinos can also be destroyed by these interactions without generating an asymmetry, and this last effect can reduce the efficiency of the production of a cosmic asymmetry.

Two important energy scales in the study of leptogenesis are the reheating temperature T_{rh} , which determines the initial time at which the heavy neutrinos start to be produced in thermal scenarios, and the heavy neutrino mass M_1 which establishes the temperature at which the equilibrium distribution of the heavy neutrinos starts to become Boltzmann suppressed. The effects of the Z' boson depend on the value of its mass relative to these two scales. To study quantitatively these effects let's first fix $T_{\text{rh}} = 100M_1$, corresponding to a situation in which the thermal history of the universe starts well before the leptogenesis era (cases with T_{rh} close to M_1 will be dealt with in the following section). In figure 2 we depict the region in the $\tilde{m}_1 - M_1$ space that may lead to a sufficient generation of a baryon asymmetry for different values of $M_{Z'}$.

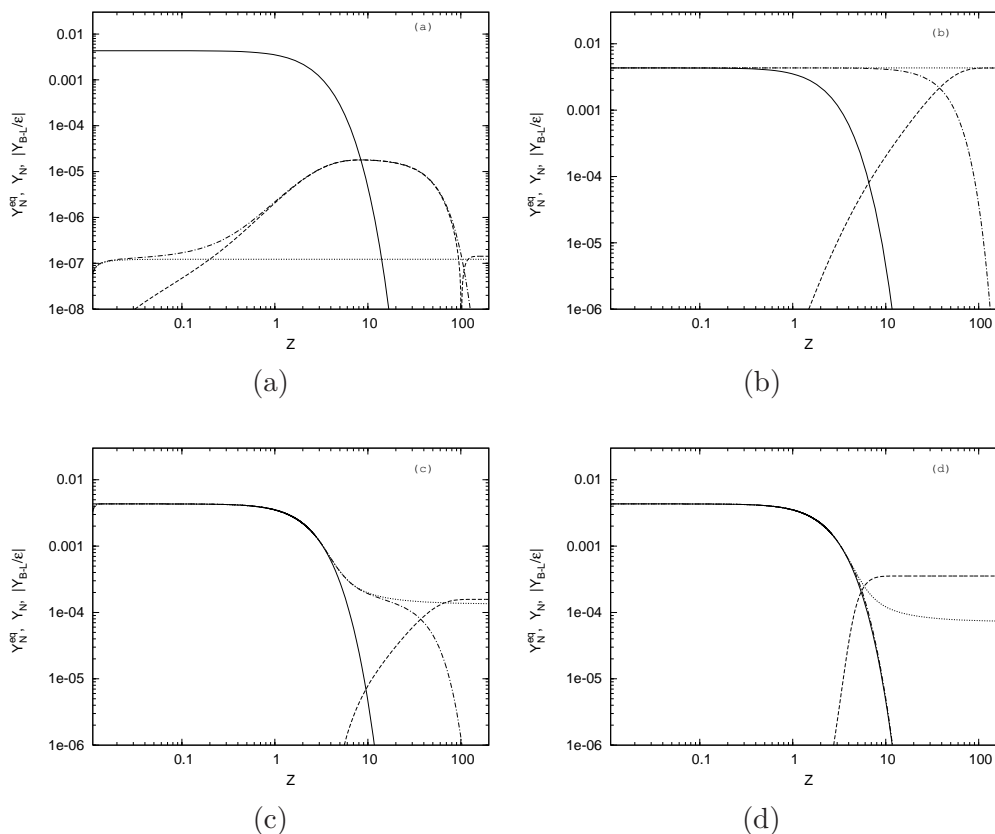


Figure 3. The evolution of Y_N^{eq} (solid line), Y_N (dash-dotted line) and $|Y_{B-L}/\epsilon|$ (dashed line) as a function of z for different values of $M_{Z'}$. For comparison, the evolution of the N_1 density assuming that the Yukawa interactions are null is also depicted (dotted curve). The values of $M_{Z'}$, M_1 and \tilde{m}_1 for each of the four panels (a), (b), (c) and (d) are those corresponding to the equally named points in figure 2.

Three different situations can be distinguished:

- (i) $M_{Z'} \gg 10T_{\text{rh}}$: The Z' boson is too heavy relative to the reheating temperature of the universe so that the rate of pair production of N_1 is very small after reheating (compared to the expansion rate of the universe) and the effects of the Z' are hence negligible (note that the curve in figure 2 corresponding to $M_{Z'} = 20T_{\text{rh}}$ is similar to the solid line in figure 1, which ignored the effects of new gauge bosons).
- (ii) $100M_1 \lesssim M_{Z'} \lesssim 10T_{\text{rh}}$: An equilibrium population of N_1 is produced due to the new gauge interactions and on the other hand these last depart from equilibrium before the N_1 become non-relativistic. This situation is optimal for the generation of a baryon asymmetry and the highest efficiencies are obtained, since the Z' effects allow to achieve an equilibrium density of N_1 before the decay epoch, and they do not lead to significant late suppression effects. This will be explained with more detail below.

As can be seen in figure 2 the change from regime (i) to (ii) takes place abruptly for $M_{Z'}$ in the range $(10 - 20)T_{\text{rh}}$. Although the reheating temperature in figure 2 was

fixed to $T_{\text{rh}} = 100M_1$, a similar change is also found for other values of T_{rh} . This abrupt change is due to the strong dependence of the cross section with $M_{Z'}$ when this mass is large: $\hat{\sigma}_{Z'} \propto M_{Z'}^{-4}$.

- (iii) $M_{Z'} \lesssim 100M_1$: As in the previous regime, the universe is filled with an equilibrium population of N_1 after reheating. However, in this regime the new gauge interactions are still in equilibrium when the heavy neutrinos become non-relativistic, so the N_1 have a significant probability of disappearing without producing an asymmetry via the Z' mediated annihilation into two fermions or Higgs bosons (which are CP symmetric processes). For Z' masses quite above M_1 ($M_{Z'} \gtrsim 3M_1$) it's clear that the lighter the Z' is, the later the gauge interactions fall out from equilibrium, then the more neutrinos disappear via CP symmetric channels and the less asymmetry is produced. However, for Z' masses close to M_1 the dependence of this “suppression effect” with $M_{Z'}$ is more complex due to two different reasons. On one hand, since the annihilations involve two heavy neutrinos the corresponding reaction density is suppressed by two Boltzmann factors, so these processes cannot remain in equilibrium for temperatures much lower than M_1 . This fact is independent of the Z' mass and therefore sets an upper limit to the suppression effect for a given Z' model.⁶ On the other hand, when $M_{Z'} \sim 2M_1$ the reaction density is enhanced at the beginning of the decay epoch, i.e. at $T \sim M_1$, because the Z' that mediates the annihilation can be produced resonantly. The conclusion is that the suppression effect induced by the $U(1)_{Y'}$ gauge interaction is maximum for $M_{Z'} \approx 2M_1$ (this will be apparent in figure 6). It must also be noted that when the Z' bosons are light, the effects of the Higgs field χ should also be taken into account to get quantitatively accurate results.

The previous results can be understood as the combination of two stages. In the first one the gauge interactions dominate over the Yukawa interactions basically until they depart from equilibrium at a temperature T_{fo} , leaving a relic density of N_1 which will be similar to that of a massless degree of freedom in equilibrium if $100M_1 \lesssim M_{Z'} \lesssim 10T_{\text{rh}}$ while it will be Boltzmann suppressed like the usual cold relics, with density $Y_N^{\text{relic}} \propto \exp(-M_1/T_{\text{fo}})$, if $M_{Z'} \lesssim 100M_1$. In the second stage, the neutrinos decay via their Yukawa interactions producing a final asymmetry $Y_{B-L}^f \approx -\epsilon Y_N^{\text{relic}}$. Therefore the efficiency $\eta \simeq 1$ for $100M_1 \lesssim M_{Z'} \lesssim 10T_{\text{rh}}$ (regime (ii)) whereas it is suppressed ($\eta < 1$) for $M_{Z'} \lesssim 100M_1$ (regime (iii)), with the suppression increasing for decreasing values of T_{fo} .

As can be seen from figure 3 this picture explains the results very well except when the Z' is not very heavy and \tilde{m}_1 approaches the equilibrium mass $m^* \simeq 10^{-3} \text{eV}$ (figure 3d), since in this case the Yukawa interactions begin to dominate over the gauge interactions before these last depart from equilibrium. This explains why the curve in figure 2 corresponding to $M_{Z'} = 5M_1$ passes through lower values of M_1 as \tilde{m}_1 approaches m^* : as \tilde{m}_1 increases the (CP asymmetric) N_1 decay channel becomes dominant over the (CP symmetric) pair annihilation channel at earlier times (i.e. when the N_1 abundance is greater),

⁶If there were also charged gauge bosons W_R^\pm associated to a right handed SU(2) symmetry, the suppression effect on leptogenesis would be highly enhanced because of the existence of scatterings involving a single heavy neutrino and new N_1 decay channels which are CP symmetric [14, 15].

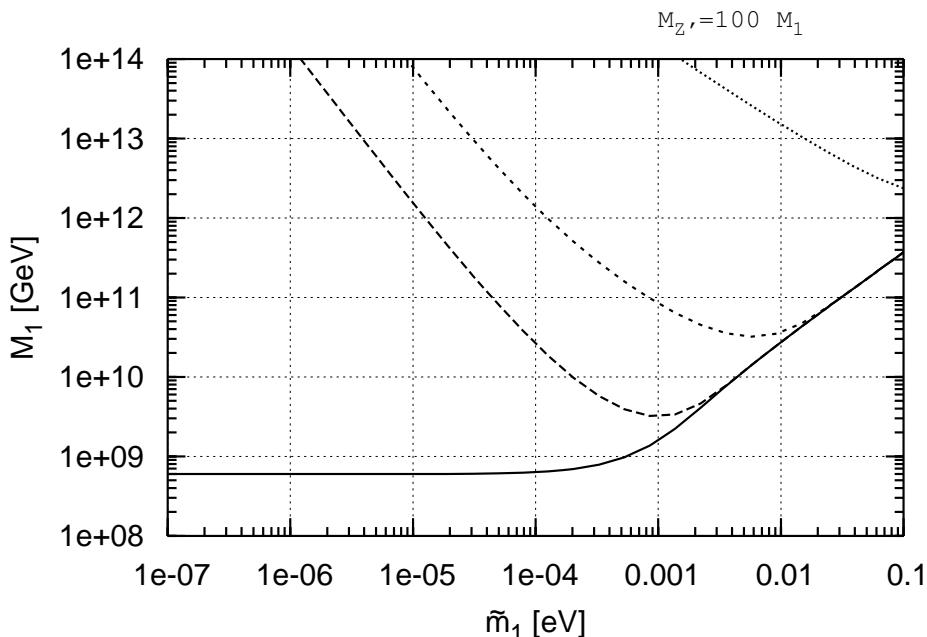


Figure 4. The allowed regions in the $\tilde{m}_1 - M_1$ plane for $M_{Z'} = 100M_1$ and different values of the reheating temperature: the regions above the solid, long dashed, short dashed and dotted curves correspond respectively to $T_{\text{rh}} = 10M_1, M_1, M_1/5$ and $0.1M_1$.

leading to higher efficiencies and therefore to successful leptogenesis for lower values of M_1 .⁷ Finally, note that in figure 3a, which corresponds to a case in which $M_{Z'} > 10T_{\text{rh}}$ but still the Z' effects are important, the final asymmetry is also given by $Y_{B-L}^f \approx -\epsilon Y_N^{\text{relic}}$ but here $Y_N^{\text{relic}} \ll Y_N^{\text{eq}}(T \gg M_1)$ since the cross section for pair production of N_1 mediated by the Z' bosons is too small after reheating to populate the universe with an equilibrium density of heavy neutrinos.

4 The reheating temperature

The existence of Z' bosons coupled to the heavy neutrinos also has an impact on the lowest reheating temperature compatible with successful leptogenesis. When Z' bosons are absent, it has been shown that the reheating temperature can be several times smaller than M_1 in the strong washout regime [16]. This is due to the fact that the Yukawa interactions, being strong in this regime, can produce a considerable amount of N_1 even if they begin to act when $T < M_1$. On the other hand, the minimum reheating temperature for a given value of \tilde{m}_1 in the weak washout regime is approximately equal to the lower bound on M_1 for that value of \tilde{m}_1 .

⁷Note however that the slope of that curve is actually quite mild (in the weak washout regime). This is due to the combination of the just mentioned effect with the fact that the Z' effects, in particular the suppression one, are inversely proportional to M_1 (see section 2).

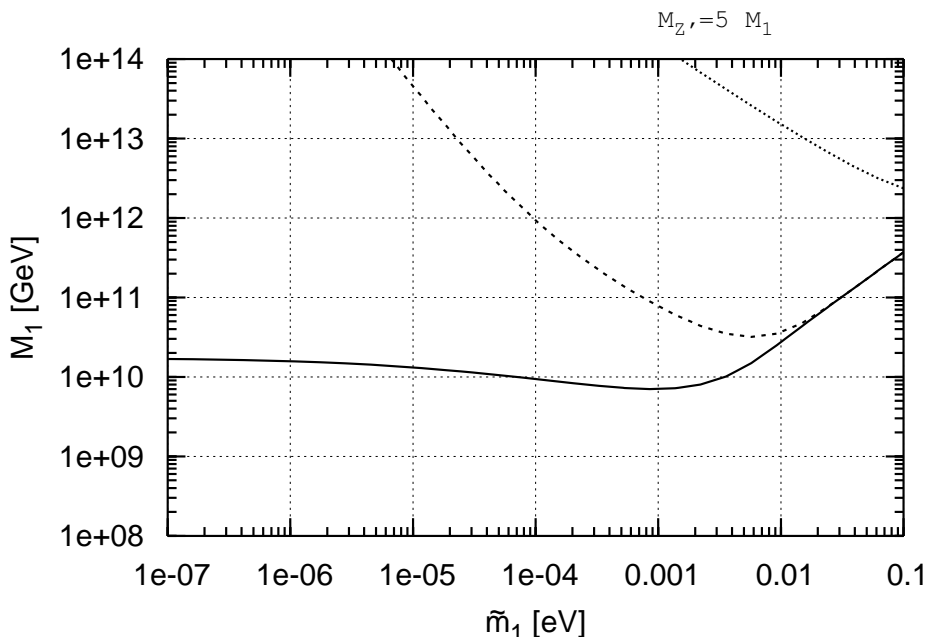


Figure 5. The allowed regions in the $\tilde{m}_1 - M_1$ plane for $M_{Z'} = 5M_1$ and different values of the reheating temperature: the regions above the solid, dashed and dotted curves correspond respectively to $T_{\text{rh}} = M_1/3, M_1/5$ and $0.1M_1$.

The situation changes when the heavy neutrinos can also be produced via gauge interactions. If the Z' bosons are very massive (cases labelled (i) and (ii) in the previous section), the gauge interactions are already out of equilibrium at $T \sim M_1$ and therefore the reheating temperature has to be greater than M_1 in order to enhance the efficiency of leptogenesis by means of the Z' induced production of N_1 (see figure 4 for the case $M_{Z'} = 100M_1$); but if they are light (case (iii)) successful leptogenesis is possible for reheating temperatures lower than M_1 also in the weak washout regime. This is shown in figure 5 for $M_{Z'} = 5M_1$, where the allowed regions of the $\tilde{m}_1 - M_1$ plane for different values of T_{rh} (relative to M_1) are plotted. The allowed region is the same for all values of T_{rh} satisfying $T_{\text{rh}} \gtrsim M_1/3$, so the reheating temperature in this case can be up to approximately three times smaller than M_1 for any value of \tilde{m}_1 . On the other hand, for $T_{\text{rh}} \lesssim M_1/5$ the allowed region is significantly reduced and doesn't depend on the presence of the Z' bosons (note that the curves corresponding to $T_{\text{rh}} = M_1/5$ are almost the same in figures 4 and 5).

In the two cases ($M_{Z'} = 5, 100M_1$) illustrated in figures 4 and 5 the lowest values allowed for T_{rh} are quite above 6×10^8 GeV, which is the lowest possible value of T_{rh} for hierarchical leptogenesis scenarios where the heavy neutrinos are thermally produced. That bound corresponds to the idealized situation in which the main interaction that produces the heavy neutrinos is very fast before decoupling abruptly at a certain value of z (say $z = z_{f_0}$). This is because when that kind of interaction is present an equilibrium

population of N_1 can be achieved for a reheating temperature as low as M_1/z_{fo} , while for $z > z_{fo}$ the (CP conserving) interaction effectively vanishes and hence all the neutrinos disappear via the CP violating Yukawa couplings. In this case the final asymmetry (in the weak washout regime) would be given by $Y_{B-L}^f \approx -\epsilon Y_N^{\text{relic}} = -\epsilon Y_N^{\text{eq}}(z = z_{fo})$ and taking into account that the maximum CP asymmetry is proportional to M_1 it's straightforward to find that the optimum values for z_{fo} are near unity.⁸ However, in a realistic model the interactions depart from equilibrium gradually, so the bound on T_{rh} is always above the ideal one. To check this we display in figure 6 for the whole range of masses $M_{Z'}/M_1 < 100$ (i.e. for case (iii)) the lower bounds on M_1 and T_{rh} in the weak washout regime (we have taken $\tilde{m}_1 = 10^{-6}$ eV but the results are almost the same for any value of $\tilde{m}_1 \ll 10^{-3}$ eV). Several things are apparent from the plot. First we see that the lowest possible value of T_{rh} in the Z' model we are studying is approximately equal to 1.2×10^9 GeV, i.e. a factor of two greater than the ideal bound. This value of T_{rh} is possible only for a special range of Z' masses around $M_{Z'} = 20M_1$, for which the corresponding $U(1)_{Y'}$ gauge interactions depart from equilibrium at $z \sim 1$ (note that in this range the bounds on M_1 and T_{rh} are very similar), while for $M_{Z'}$ approaching $100M_1$ the bound is 5 times greater than the ideal one. It's also clear that for low Z' masses the bound on T_{rh} can be several (up to 7) times smaller than the corresponding bound on M_1 , as discussed at the beginning of this section. On the other hand, the bound on M_1 shows the behavior already explained in the previous section: when $M_{Z'}$ is small⁹ the suppression of the efficiency must be compensated with large values of the CP asymmetry (and hence of M_1), while for $M_{Z'}$ approaching $100M_1$ the interactions mediated by Z' depart from equilibrium when the N_1 are still relativistic, so the bound on M_1 reaches it's lowest possible value (equal to 6×10^8 GeV). Note also that the lowest efficiencies occur when $M_{Z'} \approx 2M_1$.

5 Conclusions

The existence of neutral gauge bosons coupled to the heavy neutrinos notably affects the leptogenesis picture in the weak washout regime. The main new ingredient with respect to the simplest thermal leptogenesis scenarios is that they allow the production and destruction of the heavy neutrinos without generating a CP asymmetry. When the Z' bosons are not very heavy compared to the reheating temperature ($M_{Z'} \lesssim 10T_{\text{rh}}$) an equilibrium population of N_1 is always achieved before the neutrinos become non-relativistic (as long as $T_{\text{rh}} > M_1$). Moreover, if the new gauge bosons are not too light ($M_{Z'} \gtrsim 100M_1$) the corresponding gauge interactions depart from equilibrium before the heavy neutrinos become non-relativistic and in this case the efficiency reaches its maximum possible value. On the

⁸In fact, the optimum situation for obtaining low reheating temperatures happens when the interaction decouples abruptly at z values somewhat larger than unity, while for $z_{fo} < 0.5$ or $z_{fo} > 5$ the lower bound on T_{rh} is greater than the ideal bound by a factor of 2 or more, even for the idealized type of interactions just described.

⁹We have included Z' masses as low as M_1 in figure 6 with the purpose of testing different situations (i.e. interactions which produce N_1 and have different decouple behavior), but we remind that the correct calculation of the bounds for very low $M_{Z'}$ must take into account the effects of the χ field (it is to expect that it's inclusion will suppress even more the efficiency but won't change the picture qualitatively).

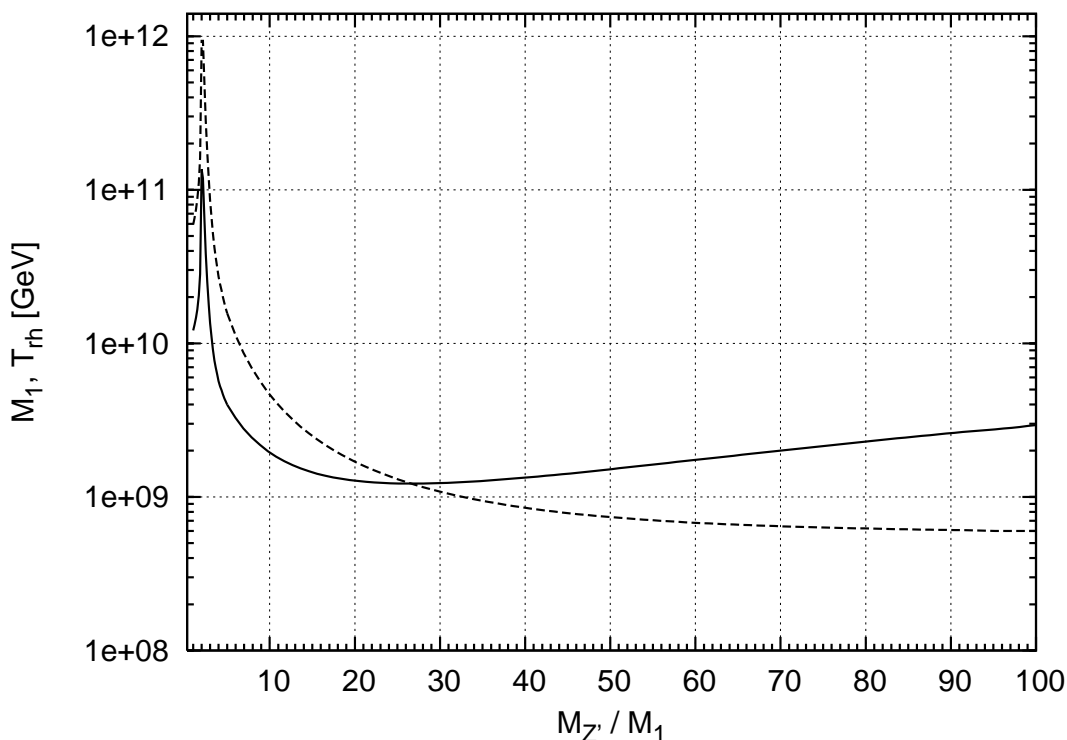


Figure 6. The lower bound on M_1 (dashed curved) and on T_{rh} (solid curve) as a function of $M_{Z'}/M_1$ for $\tilde{m}_1 = 10^{-6}$ eV.

other hand, for lighter Z' bosons ($M_{Z'} \lesssim 100M_1$) the gauge interactions remain in equilibrium until a temperature which is smaller than M_1 and hence the N_1 can partially disappear without producing a lepton asymmetry (via the interactions $N_1 N_1 \rightarrow \ell^+ \ell^-, h^+ h^-$). The suppression effect induced by these interactions is greatest for $M_{Z'} \approx 2M_1$.

We have also shown that the minimum reheating temperature required for successful leptogenesis in the scenario considered is always above $\sim 10^9$ GeV, even if in some regions of the parameter space it can be up to a factor seven smaller than the heavy neutrino mass. The presence of Z' bosons does not help then to solve the gravitino problem affecting some supersymmetric scenarios, but it certainly allows to extend the available parameter space of thermal leptogenesis scenarios.

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