WIMP Dark Matter from Gravitino Decays and Leptogenesis

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Abstract

The spontaneous breaking of B-L symmetry naturally accounts for the small observed neutrino masses via the seesaw mechanism. We have recently shown that the cosmological realization of B-L breaking in a supersymmetric theory can successfully generate the initial conditions of the hot early universe, i.e. entropy, baryon asymmetry and dark matter, if the gravitino is the lightest superparticle (LSP). This implies relations between neutrino and superparticle masses. Here we extend our analysis to the case of very heavy gravitinos which are motivated by hints for the Higgs boson at the LHC. We find that the nonthermal production of 'pure' wino or higgsino LSPs, i.e. weakly interacting massive particles (WIMPs), in heavy gravitino decays can account for the observed amount of dark matter while simultaneously fulfilling the constraints imposed by primordial nucleosynthesis and leptogenesis within a range of LSP, gravitino and neutrino masses. For instance, a mass of the lightest neutrino of 0.05 eV would require a higgsino mass below 900 GeV and a gravitino mass of at least 10 TeV.

Introduction

We have recently proposed that the spontaneous breaking of B-L, the difference of baryon and lepton number, sets the initial conditions of the hot early universe [1,2]. In a supersymmetric extension of the Standard Model, with B-L breaking at the grand unification (GUT) scale, an initial phase of unbroken B-L yields hybrid inflation, ending in tachyonic preheating during which B-L is spontaneously broken. If the gravitino is the lightest superparticle (LSP), entropy, baryon asymmetry and gravitino dark matter can be produced in the subsequent reheating process. Successful baryogenesis via leptogenesis and the generation of the observed relic dark matter density require relations between neutrino masses and superparticle masses, in particular a lower bound of 10 GeV on the gravitino mass [2].

In this Letter we want to point out that the spontaneous breaking of B-L can also ignite the thermal phase of the universe if the gravitino is the heaviest superparticle. This possibility is realized in anomaly mediation [3, 4] and has recently been reconsidered in the case of wino [5], higgsino [6] and bino [7] LSP, motivated by hints of the LHC experiments ATLAS and CMS that the Higgs boson may have a mass of about 125 GeV [8,9]. It is known that a gravitino heavier than about 10 TeV can be consistent with primordial nucleosynthesis and leptogenesis [10–12]. In the following we shall discuss the restrictions on the mass of a weakly interacting massive particle (WIMP) as LSP, which are imposed by the consistency of hybrid inflation, leptogenesis, big bang nucleosynthesis (BBN) and the dark matter density.

Spontaneous B-L breaking as the origin of the hot early universe

Our starting point is the supersymmetric standard model with right-handed neutrinos and spontaneous B-L breaking, described by the superpotential

$$W = \frac{\sqrt{\lambda}}{2} \Phi \left(v_{B-L}^2 - 2S_1 S_2 \right) + \frac{1}{\sqrt{2}} h_i^n n_i^c n_i^c S_1 + h_{ij}^{\nu} \mathbf{5}_i^* n_j^c H_u + W_{\text{MSSM}} \,. \tag{1}$$

Here S_1 and S_2 are the chiral superfields containing the Higgs superfield S which breaks B-L at the scale v_{B-L} , Φ contains the inflaton, i.e. the scalar field driving inflation, and n_i^c denote the superfields containing the charge conjugates of the right-handed neutrinos; h and λ are coupling constants, and W_{MSSM} is the superpotential of the minimal supersymmetric standard model with quarks, leptons and Higgs fields. The requirement of consistency with hybrid inflation fixes the scale of B-L breaking to

a value close to the GUT scale, $v_{B-L} = 5 \times 10^{15}$ GeV, cf. Ref. [2]. The superfields are arranged in SU(5) multiplets, i.e. $\mathbf{5}_i^* = (d_i^c, l_i)$, i = 1, 2, 3, and we assume that the colour triplet partners of the electroweak Higgs doublets H_u and H_d have been projected out. The vacuum expectation values $v_u = \langle H_u \rangle$ and $v_d = \langle H_d \rangle$ break the electroweak symmetry. In the following we will assume large $\tan \beta = v_u/v_d$, implying $v_d \ll v_u \simeq v_{EW} = \sqrt{v_u^2 + v_d^2}$.

The Yukawa couplings are conveniently parametrized in terms of Froggatt-Nielsen flavour charges, cf. Ref. [2], which govern the hierarchy of quark and lepton masses and mixings. For simplicity, we restrict our analysis to the case of hierarchical heavy neutrino masses M_i and a heavy Higgs boson multiplet S, $m_S = M_3 = M_2 = M_1/\eta^2$, where $\eta \simeq 1/\sqrt{300}$ is the hierarchy parameter of the Froggatt-Nielsen flavour model.

The most important parameters for the reheating process are the masses and vacuum decay widths of S and N_1 , which can be expressed in terms of M_1 and the effective neutrino mass \tilde{m}_1 ,

$$\Gamma_{S}^{0} = \frac{1}{32\pi} \frac{M_{1}^{2}}{v_{B-L}^{2}} m_{S} \left(1 - 4\frac{M_{1}^{2}}{m_{S}^{2}} \right)^{1/2}, \quad \Gamma_{N_{1}}^{0} = \frac{1}{4\pi} \left(h^{\nu \dagger} h^{\nu} \right)_{11} M_{1} = \frac{1}{4\pi} \frac{\widetilde{m}_{1} M_{1}}{v_{EW}^{2}} M_{1} .$$
 (2)

Varying M_1 corresponds to varying one of the flavour charges. The uncertainty in \tilde{m}_1 is related to unknown $\mathcal{O}(1)$ coefficients in the Froggatt-Nielsen model; a typical value is $\tilde{m}_1 \sim 0.04$ eV [13]. It is well known that \tilde{m}_1 is bounded from below by the lightest neutrino mass m_1 [14]. Consequently, constraints on \tilde{m}_1 directly translate into constraints on the light neutrino mass spectrum.

The reheating process is dominated by decays of the B-L Higgs boson S into heavy neutrinos and the subsequent decay of these into Standard Model particles and their superpartners (cf. Fig. 1, upper panel). As the detailed analysis of Ref. [2] shows, the competition between these decays and the cosmic expansion leads to an intermediate plateau of approximately constant 'reheating temperature' $T_{\rm RH}(M_1, \tilde{m}_1)$ (cf. Fig. 1, lower panel), which is defined by $\Gamma_{N_1}^S(a_{\rm RH}) = H(a_{\rm RH})$ where H and $\Gamma_{N_1}^S$ are the Hubble parameter and the effective decay rate of the N_1 neutrinos produced in S decays, respectively. Note that this effective reheating temperature takes the dynamics of the reheating process into account. Hence, it depends on the decay rates of S and N_1 , and consequently on M_1 and \tilde{m}_1 , contrary to the mere decay temperature of the Higgs boson S, which would only depend on M_1 . Using $T_{\rm RH}(M_1, \tilde{m}_1)$ as a measure for the temperature scale, the standard formula for thermal gravitino production is a good approximation. Successful leptogenesis implies lower bounds on M_1 and $T_{\rm RH}(M_1, \tilde{m}_1)$,



Figure 1: Upper panel: Comoving number densities of Higgs bosons (S), thermally and nonthermally produced heavy neutrinos $(N_1^{\text{th}}, N_1^{\text{nt}})$, radiation (R), lepton asymmetry (B-L) and gravitinos (\tilde{G}) . Lower panel: Emergent plateau of approximately constant reheating temperature. Input parameters: Heavy neutrino mass $M_1 = 1 \times 10^{11}$ GeV, effective neutrino mass $\tilde{m}_1 = 4 \times 10^{-2}$ eV. The B-L scale is fixed by requiring consistency with hybrid inflation, $v_{B-L} = 5 \times 10^{15}$ GeV.

which can be obtained by solving the relevant set of Boltzmann equations. The results of the analysis in Ref. [2] are shown in Fig. 2.

LSP production from the thermal bath and in heavy gravitino decays

The WIMP dark matter abundance from thermal freeze-out strongly depends on the nature of the LSP. The mass spectrum of superparticles, motivated by anomaly mediation and the present hints for the Higgs boson mass from LHC, has a characteristic hierarchy [5–7],

$$m_{\rm LSP} \ll m_{\rm squark, slepton} \ll m_{\widetilde{G}} \,,$$
(3)

where $m_{\tilde{G}}$ denotes the gravitino (\tilde{G}) mass. Due to this hierarchy the LSP is typically a 'pure' gaugino or higgsino. It is well known that in this situation the thermal abundance of a bino LSP is generically too large, which is therefore disfavoured. Hence, the case of a light wino [5] or higgsino [6] is preferred.¹ A pure neutral wino or higgsino is almost mass degenerate with a chargino belonging to the same SU(2) multiplet. Hence, the current lower bound on chargino masses [16] also applies to the LSP. The thermal abundance of a pure wino (\tilde{w}) or higgsino (\tilde{h}) LSP becomes only significant for masses above 1 TeV where it is well approximated by [17]

$$\Omega^{\rm th}_{\widetilde{w},\widetilde{h}}h^2 = c_{\widetilde{w},\widetilde{h}} \left(\frac{m_{\widetilde{w},\widetilde{h}}}{1 \text{ TeV}}\right)^2 , \quad c_{\widetilde{w}} = 0.014 , \quad c_{\widetilde{h}} = 0.10 , \qquad (4)$$

for $wino^2$ and higgsino, respectively.

Let us now consider gravitino masses in the range from 10 TeV to 10^3 TeV, as suggested by anomaly mediation. The gravitino lifetime is given by

$$\tau_{\widetilde{G}} = \Gamma_{\widetilde{G}}^{-1} = \left(\frac{1}{32\pi} \left(n_v + \frac{n_m}{12}\right) \frac{m_{\widetilde{G}}^3}{M_{\rm P}^2}\right)^{-1} = 24 \left(\frac{10 \text{ TeV}}{m_{\widetilde{G}}}\right)^3 \text{sec} , \qquad (5)$$

where $M_{\rm P} = 2.4 \times 10^{18}$ GeV, and $n_v = 12$ and $n_m = 49$ are the number of vector and chiral matter multiplets, respectively. The lifetime (5) corresponds to the decay temperature

$$T_{\tilde{G}} = \left(\frac{90 \ \Gamma_{\tilde{G}}^2 \ M_{\rm P}^2}{\pi^2 g_*(T_{\tilde{G}})}\right)^{1/4} = 0.24 \left(\frac{10.75}{g_*(T_{\tilde{G}})}\right)^{1/4} \left(\frac{m_{\tilde{G}}}{10 \ {\rm TeV}}\right)^{3/2} {\rm MeV}\,,\tag{6}$$

¹Note that a 'pure' higgsino also occurs as next-to-lightest superparticle alongside multi-TeV coloured particles in hybrid gauge-gravity mediation, however with the gravitino as LSP [15].

²Compared to Ref. [17] we have reduced the abundance by 30% to account for the Sommerfeld enhancement effect [18, 19].



Figure 2: Lower bounds on the heavy neutrino mass M_1 and the reheating temperature $T_{\rm RH}$ as functions of the effective neutrino mass \tilde{m}_1 from successful leptogenesis.

with $g_*(T_{\tilde{G}}) = 43/4$ counting the effective number of relativistic degrees of freedom. For gravitino masses between 10 TeV to 10^3 TeV the decay temperature $T_{\tilde{G}}$ varies between 0.2 MeV and 200 MeV, i.e. roughly between the temperatures of nucleosynthesis and the QCD phase transition. In this temperature range the entropy increase due to gravitino decays and hence the corresponding dilution of the baryon asymmetry are negligible.

The decay of a heavy gravitino, $m_{\tilde{G}} \gg m_{\text{LSP}}$, produces approximately one LSP. This yields the nonthermal contribution to the dark matter abundance³,

$$\Omega_{\rm LSP}^{\tilde{G}}h^2 = \frac{m_{\rm LSP}}{m_{\tilde{G}}}\Omega_{\tilde{G}}h^2 \simeq 2.7 \times 10^{-2} \left(\frac{m_{\rm LSP}}{100 \text{ GeV}}\right) \left(\frac{T_{\rm RH}(M_1, \tilde{m}_1)}{10^{10} \text{ GeV}}\right) , \qquad (7)$$

where we have assumed that the gravitino density is produced from the thermal bath during reheating, cf. Fig. 1, upper panel. For LSP masses below 1 TeV, which are most interesting for the LHC as well as for direct searches, the total LSP abundance

$$\Omega_{\widetilde{w},\widetilde{h}}h^2 = \Omega_{\widetilde{w},\widetilde{h}}^{\widetilde{G}}h^2 + \Omega_{\widetilde{w},\widetilde{h}}^{\mathrm{th}}h^2 \tag{8}$$

³Note that the thermal gravitino production rate has a theoretical uncertainty of at least a factor of 2. The numerical prefactor used in Eq. (7) was obtained by solving the Boltzmann equations governing the reheating process for $T_{\rm RH} \in [10^8, 10^{11}]$ GeV, cf. Ref. [2]. For an analytical approximation, see Appendix D in Ref. [1].



Figure 3: Upper and lower bounds on the reheating temperature as functions of the gravitino mass. The horizontal dashed lines denote lower bounds imposed by successful leptogenesis for different values of the effective neutrino mass \tilde{m}_1 , cf. Fig. 2 and Ref. [2]. The curves labelled ⁴He and D denote upper bounds originating from the primordial helium-4 and deuterium abundances created during BBN, which are taken from [21] (case 2, which gives the most conservative bounds). The vertical dashed lines represent the absolute lower bounds on the gravitino mass for fixed effective neutrino mass \tilde{m}_1 and minimal reheating temperature. The shaded region marked $\Omega_{\text{LSP}} > \Omega_{\text{DM}}^{\text{obs}}$ is excluded as it corresponds to overproduction of dark matter, taking into account that the LSP mass is bounded from below, $m_{\text{LSP}} \ge 94$ GeV (see text).

is thus dominated by the contribution from gravitino decay.

The LSPs are produced relativistically. They form warm dark matter which can affect structure formation on small scales. A straightforward calculation yields the free-streaming length

$$\lambda_{FS} = \int_{\tau_{\tilde{G}}}^{t_0} dt \frac{v_{\rm LSP}}{a} \simeq \left(\frac{3}{4}\right)^{2/3} \frac{m_{\tilde{G}}}{2 \, m_{\rm LSP}} \left(\tau_{\tilde{G}} \, t_{eq}\right)^{1/2} \left(\frac{t_0}{t_{eq}}\right)^{2/3} \left(\ln \frac{16 \, t_{eq} \, m_{\rm LSP}^2}{\tau_{\tilde{G}} \, m_{\tilde{G}}^2} + 4\right) \,, \quad (9)$$

where t_{eq} and t_0 denote the time of radiation-matter-equality and the age of the universe, respectively. For the gravitino and LSP masses considered in this paper, one finds $\lambda_{FS} \lesssim 0.1$ Mpc, which is below the scales relevant for structure formation [20].



Figure 4: Upper and lower bounds on the LSP mass in the higgsino and wino case, respectively, and lower bounds on the gravitino mass. These bounds are in one-to-one correspondence with the bounds on the reheating temperature and the gravitino mass in Fig. 3. The horizontal dashed lines denote the upper bounds on the LSP mass imposed by successful leptogenesis for different values of the effective neutrino mass \tilde{m}_1 . The curves labelled ⁴He and D denote lower bounds on the LSP as well as on the gravitino mass originating from the primordial helium-4 and deuterium abundances created during BBN. The vertical dashed lines represent the absolute lower bounds on the gravitino mass for fixed effective neutrino mass \tilde{m}_1 and maximal LSP mass. The dark shaded regions on the upper edge of the plots correspond to thermal overproduction of dark matter and are hence excluded. We do not consider LSP masses below 94 GeV due to the present lower bound on the chargino mass (see text).

Relations between LSP, gravitino and neutrino masses

The LSP has to be heavier than 94 GeV, the current lower bound on chargino masses [16]. From the requirement of LSP dark matter, i.e. $\Omega_{\text{LSP}}h^2 = \Omega_{\text{DM}}h^2 \simeq 0.11$ [16], one then obtains an upper bound on the reheating temperature, $T_{\text{RH}} < 4.2 \times 10^{10}$ GeV. For gravitino masses below 40 TeV, primordial nucleosynthesis provides a more stringent upper bound on the reheating temperature [21]. In Fig. 3 we compare upper and lower bounds on the reheating temperature from dark matter density, nucleosynthesis and leptogenesis, respectively, as functions of the gravitino mass. It is remarkable that for the entire mass range, 10 TeV $\leq m_{\tilde{G}} \leq 10^3$ TeV, nucleosynthesis, dark matter and leptogenesis can be consistent.

The dark matter constraint $\Omega_{\text{LSP}}h^2 = \Omega_{\text{DM}}h^2 \simeq 0.11$, with $\Omega_{\text{LSP}}h^2$ calculated according to Eqs. (4), (7) and Eq. (8), establishes a one-to-one connection between LSP masses and values of the reheating temperature. This relation maps the viable region in the $(m_{\tilde{G}}, T_{\text{RH}})$ -plane for a given effective neutrino mass \tilde{m}_1 into the corresponding



Figure 5: Upper bounds on wino (\tilde{w}) and higgsino (\tilde{h}) LSP masses imposed by successful leptogenesis as well as absolute lower bound on the gravitino mass according to BBN as functions of the effective neutrino mass \tilde{m}_1 . Note that in Fig. 4 these bounds are indicated by horizontal and vertical dashed lines, respectively, for different value for \tilde{m}_1 . Wino masses larger than 2.8 TeV and higgsino masses larger than 1.0 TeV result in thermal overproduction.

viable region in the $(m_{\tilde{G}}, m_{\text{LSP}})$ -plane. We present our results for higgsino and wino LSP in the two panels of Fig. 4, respectively. The upper bound on the LSP mass is a consequence of the lower bound on the reheating temperature from leptogenesis, which is why it depends on the effective neutrino mass \tilde{m}_1 . The lower bound on the LSP mass corresponds to the upper bound on the reheating temperature from BBN and hence depends on the gravitino mass $m_{\tilde{G}}$. This latter relation between m_{LSP} and $m_{\tilde{G}}$ can also be interpreted the other way around. As each LSP mass is associated with a certain reheating temperature, we find for each value of m_{LSP} a lower bound on the gravitino mass. For given \tilde{m}_1 we then obtain an absolute lower bound on the gravitino mass by raising the LSP mass to its maximal possible value.

The upper bound on the LSP mass as well as the absolute lower bound on the gravitino mass both depend on the effective neutrino mass \tilde{m}_1 . In Fig. 5 we now finally show the explicit dependence of these bounds on \tilde{m}_1 . The upper bound on the LSP mass imposed by successful leptogenesis increases when lowering \tilde{m}_1 , i.e. when extending the range of allowed reheating temperatures to lower values. For very small

 \tilde{m}_1 it approaches the upper bound on the LSP mass above which thermal freeze-out leads to an overabundance of LSPs. At large values of \tilde{m}_1 , the bound on the LSP mass from leptogenesis becomes stronger. Furthermore, we find that the absolute lower bound on the gravitino mass is rather insensitive to the effective neutrino mass for $\tilde{m}_1 \leq 10^{-1}$ eV, but rapidly increases as a function of \tilde{m}_1 for larger values of \tilde{m}_1 . This reflects the fact that small values of \tilde{m}_1 correspond to low reheating temperatures, for which the allowed range of gravitino masses, being determined by the BBB abundance of deuterium, hardly changes with when varying the temperature. It turn, when the allowed range of gravitino masses is determined by the BBN abundance of helium-4, which is the case for very large \tilde{m}_1 , the absolute lower bound on $m_{\tilde{G}}$ increases with \tilde{m}_1 .

Prospects for direct detection and collider experiments

For pure wino and higgsino LSPs, the exchange of the lightest Higgs boson yields at tree level for the spin-independent elastic scattering cross section [22],

$$\sigma_{\rm SI}^{\tilde{w}} \sim 2 \times 10^{-43} \,\,{\rm cm}^2 \left(\frac{125 \,\,{\rm GeV}}{m_{h^0}}\right)^4 \left(\frac{100 \,\,{\rm GeV}}{m_{\tilde{h}}}\right)^2 \left(\sin 2\beta + \frac{m_{\tilde{w}}}{m_{\tilde{h}}}\right)^2 \,\,, \qquad (10)$$

$$\sigma_{\rm SI}^{\tilde{h}} \sim 7 \times 10^{-44} \,\,{\rm cm}^2 \left(\frac{125 \,\,{\rm GeV}}{m_{h^0}}\right)^4 \left(\frac{100 \,\,{\rm GeV}}{m_{\tilde{w}}}\right)^2 \,,$$
(11)

where m_{h^0} is the mass of the lightest Higgs boson. For the hierarchical mass spectrum of Eq. (3) one has $r_{\tilde{w}} \equiv m_{\tilde{w}}/m_{\tilde{h}} \ll 1$ for wino LSP and $r_{\tilde{h}} \equiv m_{\tilde{h}}/m_{\tilde{w}} \ll 1$ for higgsino LSP, respectively. Hence, the spin-independent scattering cross sections are significantly below the present experimental sensitivity for LSP masses below 1 TeV.

For the considered hierarchy of superparticle masses, gluinos and squarks are heavy. Hence the characteristic missing energy signature of events with LSPs in the final state may be absent and the discovery of winos or higgsinos therefore very challenging [23]. In both cases the neutral LSP is almost mass degenerate with a chargino, which increases the discovery potential. One may hope for macroscopic charged tracks of the produced charginos. A generic prediction is also the occurrence of monojets caused by the Drell-Yan production of higgsino/wino pairs associated by initial state gluon radiation.

Conclusion

We have shown that spontaneous breaking of B-L symmetry can successfully generate the initial conditions for the hot early universe, i.e. entropy, baryon asymmetry and dark matter, for the hierarchical superparticle mass spectrum given in Eq. (3). Very heavy gravitinos, as motivated by hints for the Higgs boson at the LHC, are produced from the thermal bath during the reheating phase after inflation. They eventually decay at some time between the QCD phase transition and BBN into wino or higgsino LSPs, which then account for the observed dark matter abundance. By additionally imposing the requirement of successful leptogenesis, we obtain upper bounds on the LSP masses and a lower bound for the gravitino mass. We emphasize that the initial conditions of the radiation dominated phase of the early universe, in particular the reheating temperature, are not free parameters but are determined by parameters of a Lagrangian, which in principle can be measured by particle physics experiments and astrophysical observations.

Acknowledgements

The authors thank T. Bringmann and F. Brümmer for helpful discussions and comments. This work has been supported by the German Science Foundation (DFG) within the Collaborative Research Center 676 "Particles, Strings and the Early Universe".

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