DESY 10-162

Supersymmetric leptogenesis and light hidden sectors

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arXiv:1009.5865v1 [hep-ph] 29 Sep 2010

Abstract. Thermal leptogenesis and supergravity are attractive scenarios for physics beyond the standard model. However, it is well known that the super-weak interaction of the gravitino often leads to problems with primordial nucleosynthesis in the standard scenario of matter parity conserving MSSM + three right-handed neutrinos. We will present and compare two related solutions to these problems: 1) The conflict between BBN and leptogenesis can be avoided in presence of a hidden sector with light supersymmetric particles which open new decay channels for the dangerous long-lived particles. 2) If there is a condensate in the hidden sector, such additional decay channels can be alternatively opened by dynamical breaking of matter parity in the hidden sector.

1. Introduction

Thermal leptogenesis [1] via the out-of-equilibrium decay of heavy right-handed neutrinos is one of the most promising models for the generation of the baryon asymmetry in the universe. However, it is known that this mechanism requires a high reheating temperature above 10^9 GeV. In supersymmetric extensions of the standard model, such temperatures can lead to the so-called gravitino problem, which can be circumvented when the gravitino itself is the LSP and hence dark matter. Indeed, it is well known that, given a high reheating temperature $T_R \sim \mathcal{O}(10^9$–$10^{10}\,\mathrm{GeV})$ and gravitino masses around $m_{3/2} \sim \mathcal{O}(10\text{–}100\,\mathrm{GeV})$, the thermal relic density of gravitinos reproduces the correct dark matter abundance.

However, the above scenario is not free of problems: The next-to-lightest supersymmetric particle (NLSP), which is often the stau, typically decays into the gravitino with lifetimes that are of the order of minutes or days. This is generically in conflict with the successful predictions of standard primordial nucleosynthesis (BBN), since the NLSP decay can destroy some of the primordial elements or lead to catalytic over-production of ^{6}Li and ^{9}Be [2, 3].

Different solutions to the above problem were proposed. In this note we shortly review two possible solutions that are related to extensions of the MSSM with light hidden sectors: 1) We will assume the existence of a hidden sector fermion, X, lighter than the lightest observable supersymmetric particle (LOSP). Then new decay channels are possible for the LOSP, for instance, when the LOSP is the lightest stau or the lightest neutralino, $\widetilde{\tau}_1 \to \tau X$ and $\chi_1^0 \to (Z^0, \gamma, h^0, f\bar{f})X$. If these decays are fast enough, the density of LOSPs at the time of nucleosynthesis can be significantly reduced and thus the successful predictions of the standard BBN scenario will not be jeopardized (for details see Ref. [4]). 2) It is well known in the literature that in cases where matter parity (or R-parity) is weakly violated, the NLSP can decay into standard model particles before the onset of BBN [5], while being compatible with

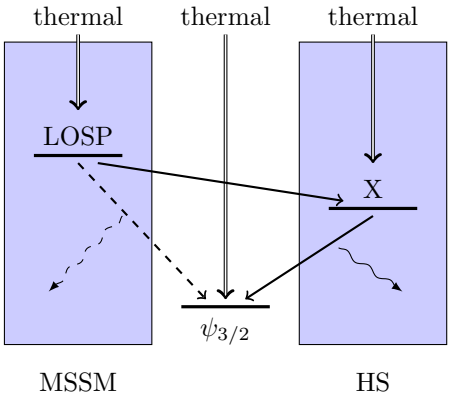

Figure 1. The LOSP, the gravitino and the hidden fermion can be produced thermally or non-thermally through the decays of heavier particles. If the reheating temperature is high, $T_R \gtrsim 10^9\,\mathrm{GeV}$, the LOSP decay into the gravitino occurs during or after the time of primordial nucleosynthesis, altering the predictions of the standard BBN scenario, yielding abundances in conflict with observations. However, if the LOSP coupling to the hidden fermion is large enough, this decay can occur before the onset of the nucleosynthesis reactions, thus avoiding altogether any possible effect of the LOSP on nucleosynthesis. See Ref. [4].

all cosmological constraints. We will present a model which can give rise to the required small matter-parity violation (for details see Ref. [6]) and discuss cosmological constraints.

2. Decay into hidden sector particles

We consider a scenario where the MSSM particle content is extended with a light standard model (SM) singlet superfield (chiral or vector). We will further assume that the fermionic component, the *hidden fermion* X, of this superfield couples to the LOSP and its standard model counterpart via a tiny Yukawa coupling, and we concentrate on the case where the LOSP is a stau. The interaction Lagrangian between the hidden fermion and the lightest stau, $\widetilde{\tau}_1$, is given by the renormalizable term $-\mathcal{L} = \lambda_{\widetilde{\tau}_1} \bar{X}\,\tau\,\widetilde{\tau}_1 + \text{h.c.}$ We will assume below that the gravitino is the LSP and the hidden fermion X the NLSP (see Ref. [4] for other scenarios). The stau can then decay either via $\widetilde{\tau}_1 \to \psi_{3/2}\,\tau$ or via $\widetilde{\tau}_1 \to X\,\tau$ with decay rates given by $\Gamma_{\widetilde{\tau}_1 \to \psi_{3/2}\tau} \sim m_{\widetilde{\tau}_1}^5\, m_{3/2}^{-2} m_P^{-2}$ and $\Gamma_{\widetilde{\tau}_1 \to X\tau} \sim |\lambda_{\widetilde{\tau}_1}|^2 m_{\widetilde{\tau}_1}$, respectively. If the coupling $\lambda_{\widetilde{\tau}_1}$ is large enough, the stau will decay before BBN, thus preventing the catalytic production of ^{6}Li. The mechanism is sketched in Fig. 1.

2.1. Cosmologically stable hidden fermions

If the hidden fermion is stable, gravitinos as well as hidden fermions contribute to dark matter, each of them having a thermal component and a non-thermal component:

$$\Omega_{\mathrm{dm}} = \Omega_{3/2}^{\mathrm{th}} + \Omega_{3/2}^{\widetilde{\tau}_1} + \Omega_X^{\mathrm{th}} + \Omega_X^{\widetilde{\tau}_1}\,. \tag{1}$$

Here, $\Omega_{3/2}^{\widetilde{\tau}_1} = (m_{3/2}/m_{\widetilde{\tau}_1})\mathrm{BR}(\widetilde{\tau}_1 \to \psi_{3/2}\tau)\,\Omega_{\widetilde{\tau}_1}^{\mathrm{th}}$ and $\Omega_X^{\widetilde{\tau}_1} = (m_X/m_{\widetilde{\tau}_1})\mathrm{BR}(\widetilde{\tau}_1 \to X\tau)\,\Omega_{\widetilde{\tau}_1}^{\mathrm{th}}$, are the non-thermal contributions to the gravitino and hidden fermion relic density, respectively, where $\Omega_{\widetilde{\tau}_1}^{\mathrm{th}}$ and $\Omega_{3/2}^{\mathrm{th}}$ are the stau and the gravitino thermal abundance. If the hidden fermion couples to the observable sector through a renormalizable coupling, the thermal production proceeds dominantly via the decay of thermally produced staus. The corresponding hidden fermion relic abundance is given by $\Omega_X^{\mathrm{th}} h^2 \sim 10^{23} |\lambda_{\widetilde{\tau}_1}|^2 (m_X/m_{\widetilde{\tau}_1})(1 - m_X^2/m_{\widetilde{\tau}_1}^2)^2$.

In order to sufficiently reduce the number density of staus at the time of BBN it is necessary that $\mathrm{BR}(\widetilde{\tau}_1 \to \tau X) \simeq 1$, and therefore, $\Omega_{3/2}^{\widetilde{\tau}_1} \simeq 0$. Requiring that the total dark matter density does not exceed the measured value by WMAP implies then $\Omega_{3/2}^{\mathrm{th}} + \Omega_X^{\mathrm{th}} + \frac{m_X}{m_{\widetilde{\tau}_1}} \Omega_{\widetilde{\tau}_1}^{\mathrm{th}} \lesssim 0.11 h^{-2}$. In the regime where the production of X is sizeable, this gives a strong upper bound of the order of 10^{-12} on the coupling $\lambda_{\widetilde{\tau}_1}$.

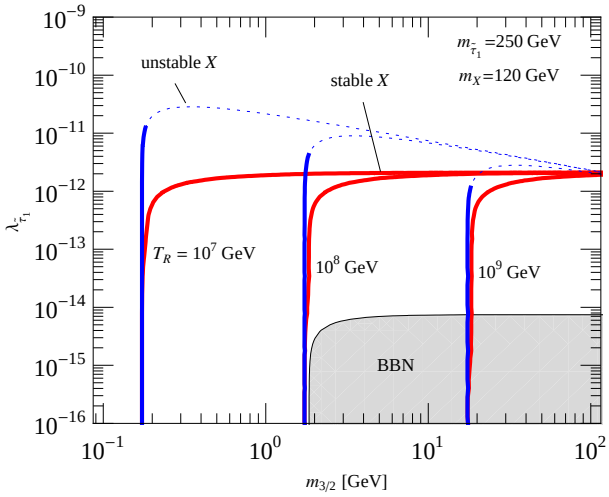

Figure 2. Summary of constraints. The masses of X and $\widetilde{\tau}_1$ are fixed as indicated. The *red* and *blue lines* show the values of $m_{3/2}$ and $\lambda_{\widetilde{\tau}_1}$ that yield the correct total relic abundance for different reheating temperatures $T_R = 10^7$–10^9 GeV, assuming that X is stable or unstable, respectively (the gluino mass has been set to $m_{\tilde{g}} = 800\,\mathrm{GeV}$). Furthermore, the *dashed* part of the blue lines is excluded by constraints on mixed warm/cold dark matter as discussed in the text, and the gray region is excluded by ^{6}Li overproduction during BBN. See Ref. [4].

The bounds are illustrated in Fig. 2 (red lines). The lines show, for different reheating temperatures and different masses of the hidden fermion, the value of the coupling $\lambda_{\widetilde{\tau}_1}$ as a function of the gravitino mass from the requirement that the *total* dark matter density is equal to the value inferred by the WMAP collaboration. For large enough couplings $\lambda_{\widetilde{\tau}_1}$, the BBN bounds (gray region) can be avoided.

2.2. Unstable hidden fermions

If kinematically allowed, the hidden fermion X decays into gravitinos and hidden sector particles (which are not dangerous for BBN) well before matter-radiation equality. In this case, dark matter consists of thermally produced gravitinos, as well as non-thermally produced gravitinos coming from the late decay of hidden fermions X and staus $\widetilde{\tau}_1$. The dark matter abundance is then given by

$$\Omega_{\mathrm{dm}} = \Omega_{3/2}^{\mathrm{th}} + \underbrace{\Omega_{3/2}^{\widetilde{\tau}_1} + \frac{m_{3/2}}{m_X}\left(\Omega_X^{\mathrm{th}} + \Omega_X^{\widetilde{\tau}_1}\right)}_{=\Omega_{\mathrm{WDM}}}, \tag{2}$$

where we assumed for simplicity that the hidden-sector particles produced in the decay of X are massless. The component coming from the late decay of X, as well as the small fraction of gravitinos produced directly in $\widetilde{\tau}_1$ decays, will typically act as warm dark matter (WDM), with free-streaming lengths $\lambda_{\mathrm{FS}} \gtrsim 5\,\mathrm{Mpc}$. Bounds on the fraction f of the dark matter density that is allowed to be warm with a free-streaming length above 0.5 Mpc were discussed in Ref. [7] in the context of sterile neutrinos. There, using Lyman-α data and WMAP5 results, 2σ-bounds around $f \lesssim 0.1$ were found for a warm component with free-streaming lengths around $\mathcal{O}(10\,\mathrm{Mpc})$, corresponding to $\mathcal{O}(1\,\mathrm{km/s})$ thermal velocities. Allowing a fraction f of dark matter to be warm, and provided that $\Omega_{3/2}^{\widetilde{\tau}_1} \simeq 0$, implies then the upper bound $(m_{3/2}/m_X)(\Omega_X^{\mathrm{th}} + \Omega_X^{\widetilde{\tau}_1}) \lesssim f\ 0.11\ h^{-2}$.

The allowed parameter space is shown in Fig. 2 (blue lines). The dashed part of the lines is excluded by constraints on mixed cold/warm dark matter. Compared to the scenario where the hidden fermion is stable, larger values of the coupling $\lambda_{\widetilde{\tau}_1}$ are allowed.

2.3. Experimental signatures

In the above scenario the coupling constant of the LOSP to the hidden fermion X is typically smaller than 10^{-12}, therefore the LOSP decay length is much larger than the size of typical

collider detectors. If the LOSP is the lightest stau, it propagates through the detector leaving a heavily ionizing charged track. Furthermore, if the stau velocity is small enough, it could get trapped in the detector and decay eventually, producing a tau moving in a non-radial direction. This signature, albeit very spectacular, is not specific of this scenario but also arises in scenarios with stau NLSP and gravitino or axino LSP.

However, a hint towards our proposed scenario arises from the measurement of the coupling stau-tau-hidden fermion. More concretely, at colliders it will be possible a determination of the stau mass and the stau lifetime, from which the coupling $\lambda_{\tilde{\tau}}$ could be inferred. If the coupling lies in the range preferred by cosmology, this scenario would gain strength. Further more model dependent predictions can be found in Ref. [4].

3. Dynamical matter-parity violation

As mentioned above, a small violation of matter parity can help to reconcile leptogenesis with gravitino dark matter. If we consider the matter parity to be the $\mathbb{Z}_2$ subgroup of the anomaly-free $\mathrm{U}(1)_{B-L}$ gauge symmetry, a very natural explanation of the required smallness of the breaking is to relate it to the condensation scale Λ of an asymptotically free hidden sector gauge group factor. This scale can be much lower than the $\mathrm{U}(1)_{B-L}$ breaking scale M_S, and if the hidden sector is charged under $B-L$, the condensate induces bilinear matter-parity breaking of order Λ^2/M_S.

3.1. Model

We consider an extension of the supersymmetric standard model with gauge group

$$G = \mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \times \mathrm{U}(1)_{B-L} \times \mathrm{SU}(2)_{\mathrm{hid}} \ . \tag{3}$$

We assume that light neutrino masses are generated in the standard way by the see-saw mechanism after the breaking of $\mathrm{U}(1)_{B-L}$ at a high scale M_S. Large Majorana masses for the right-handed neutrinos N^c are generated by a singlet field S in our model,

$$W_{\text{see-saw}} = h_{ij}^{(n)} L_i N_j^c H_u + \frac{1}{2}\lambda_i^S S N_i^c N_i^c \ , \tag{4}$$

where we have taken the basis where the Majorana mass matrix for N^c is diagonal. We assume $\langle S\rangle = M_S$. Then, the N_i^c have Majorana masses, $M_i = \lambda_i^S \times M_S$ for $i = 1-3$, respectively, and we define $M_1 < M_2 < M_3$ (we will assume that $M_3 = M_S$ below). For successful thermal leptogenesis, we require $M_1 > 10^9$ GeV. Since $\mathrm{U}(1)_{B-L}$ is gauged initially, the corresponding Nambu–Goldstone (NG) mode will be absorbed by the gauge field, which then decouples from the low-energy effective theory. The field S necessarily has $B-L$ charge -2, hence a global discrete $\mathbb{Z}_2$ subgroup remains unbroken during this process, the 'matter parity'.

Furthermore, the hidden sector is assumed to contain two doublet quarks $\mathcal{Q}_1^\alpha$, $\mathcal{Q}_2^\alpha$ with $B-L$ charge $+1/2$, and two doublet quarks $\mathcal{Q}_3^\alpha$, $\mathcal{Q}_4^\alpha$ with charge $-1/2$.[1] Here and in the following $\alpha, \beta = 1, 2$ are $\mathrm{SU}(2)_{\mathrm{hid}}$ indices. The low-energy degrees of freedom are the antisymmetric combinations $V_{ij} = -V_{ji} = \Lambda^{-1}\mathcal{Q}_i^\alpha \mathcal{Q}_{j\alpha}$ with convention $\mathcal{Q}_{i\alpha} = \epsilon_{\alpha\beta}\mathcal{Q}_i^\beta$, where $\epsilon_{\alpha\beta}$ is totally antisymmetric and $\epsilon_{12} = 1$. Condensation gives rise to non-vanishing vacuum expectation values for the two charged effective mesons, $\langle V_{12}\rangle = \langle V_{34}\rangle = \Lambda$ (for details see [6]). Since V_{12} and V_{34} have $B-L$ charge $+1$ and -1, respectively, we conclude that matter parity is broken dynamically at the scale Λ in the hidden sector, and we will take $\Lambda \ll M_S$.

The only unsuppressed and renormalizable interaction allowed by the gauge symmetries, connecting hidden and visible sector, is given by the term $W \supset -f_i \mathcal{Q}_3^\alpha \mathcal{Q}_{4\alpha} N_i^c$. Here, f_i with

[1] We also require in our model the existence of five neutral singlets $Z_{13}, Z_{14}, Z_{23}, Z_{24}$ and X, see Ref. [6].

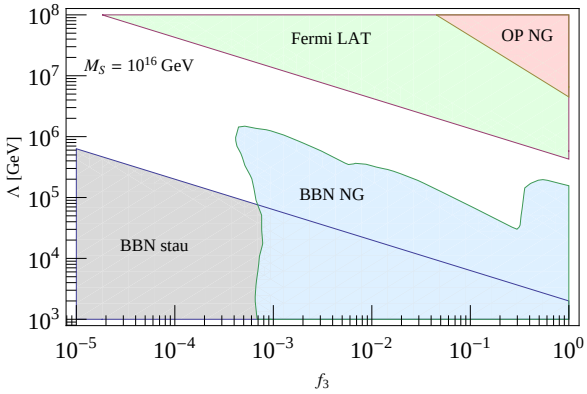

Figure 3. Summary of constraints on condensation scale Λ. We assumed $m_{3/2} = 120\,\mathrm{GeV}$, $h_{ij}^{(n)} \sim 10^{-1}$, $M_S = 10^{16}\,\mathrm{GeV}$, and $T_R = 10^{9.8}\,\mathrm{GeV}$. We show the bounds coming from BBN catalysis by late decaying staus (BBN stau, $m_{\tilde{\tau}} \simeq 150$–$200$ GeV), from the late decay of the fermionic partner of the pseudo NG boson of matter-parity breaking (BBN NG), and from the non-observation of gamma-ray lines from gravitino decay by Fermi LAT. In the red region the pseudo NG boson relic density exceeds the observational limit (OP NG). See Ref. [6].

$i = 1, 2, 3$ are free parameters, and we will assume a simple situation where $f_3 \leq 1$ and $f_1 = f_2 = 0$, to show the presence of a consistent parameter region in the model. After $\mathrm{SU}(2)_{\mathrm{hid}}$ condensation, this becomes a linear term for the right-handed neutrino multiplets, which together with the mass term in Eq. (4) implies a non-vanishing vacuum expectation value for the corresponding sneutrinos,

$$\langle N_i^c \rangle = \frac{f_i}{\lambda_i^S} \frac{\Lambda^2}{M_S} \,. \tag{5}$$

Hence, the matter-parity breaking is mostly bilinear in our model, originating from the Yukawa couplings in (4). Its scale is related to the condensation scale of the hidden sector gauge group.

Since the interactions between hidden and visible sector are suppressed by M_S, an approximate global $\mathrm{U}(1)_{B-L}$ symmetry in the hidden sector remains after S acquires a vev. This $\mathrm{U}(1)_{B-L}$ symmetry is broken by $\mathcal{Q}^\alpha \mathcal{Q}_\alpha$ condensation, producing a nearly massless pseudo NG multiplet in the hidden sector. After supersymmetry breaking, soft mass terms raise the masses of the modes in the pseudo NG multiplet. If we assume pure gravity mediation to the hidden sector, this yields a mass for the pseudo NG boson given by $m_a \sim f_3 \Lambda (m_{3/2}/M_3)^{1/2} \sim 100\,\mathrm{MeV} f_3 (m_{3/2}/100\,\mathrm{GeV})^{1/2} (\Lambda/10^6\ \mathrm{GeV}) (M_3/10^{16}\ \mathrm{GeV})^{-1/2}$, whereas the tree-level masses of the fermion partner ψ and the radial scalar pseudo NG component ρ are given by $m_\psi \approx m_{3/2}$ and $m_\rho \approx 4\ m_{3/2}$. Below we will always assume that $m_\psi > m_{3/2}$, since we are interested in gravitino dark matter.

3.2. Phenomenology

A number of astrophysical observations constrain the lifetime of the stau and the gravitino, which translates into bounds on the matter-parity breaking parameters. Firstly, the $\widetilde{\tau}_1$ has to decay before BBN, with a lifetime shorter than 2×10^3 s, to avoid catalytic overproduction of ^{6}Li. This implies a lower limit on the matter-parity breaking. Furthermore, the gravitino decay into gamma-ray lines is limited by observations of the Fermi LAT satellite to lifetimes $\Gamma^{-1}_{\psi_{3/2} \to \gamma\nu} \gtrsim 10^{29}$ s, yielding an upper limit if $m_{3/2} \sim 100\,\mathrm{GeV}$. The corresponding limits on the condensation scale Λ are summarized in Fig. 3 for a reference scenario.

Even when conservatively assuming that reheating only affects the MSSM sector, hidden sector particles are produced in the early universe by scattering of MSSM particles. The hidden sector contains 10 chiral multiplets with a mass at the condensation scale Λ, as well as one chiral multiplet that remains light and is the pseudo NG mode of the breaking of the accidental global

$B-L$ symmetry in the hidden sector. Depending on the details of the symmetries of the hidden sector, some of the heavy hidden sector states can be stable, which could lead to overclosure of the universe. However, depending on the details of the model, all these potentially stable heavy hidden sector states can either efficiently annihilate into the pseudo NG modes or decay into SM particles. Then, one only has to consider the effects of the NG modes (see Ref. [6] for details).

The most problematic hidden sector particle turns out to be the fermionic pseudo NG boson partner ψ, which mixes with the neutrinos ν_i and inherits their SM interactions. If $m_\psi > M_Z$, the fast two-body decays $\psi \to Z^0 \nu_i$ and $\psi \to W^\pm \ell^\mp$ are kinematically allowed, but BBN bounds are still relevant for small mixing angles and masses m_ψ. The bosonic pseudo NG boson partner ρ can perform two-body decays like $\rho \to \tilde{h}_u \nu$, if kinematically allowed, in which case the lifetime of ρ is much smaller than the lifetime of ψ, since its decay is not further suppressed by gauge couplings. The pseudo NG boson a is stable on cosmological time-scales.

In addition to the bounds mentioned above, one can find in Fig. 3 bounds from BBN that come from the late decay of the fermionic and bosonic pseudo NG boson partner. We also show the region where the relic density of the pseudo NG boson would exceed the observational limit. As apparent from Fig. 3, all constraints can be satisfied for condensation scales $\Lambda \sim 10^5$–10^8 GeV.

4. Conclusions

Cosmological scenarios where the observed matter-antimatter asymmetry is generated by the supersymmetric thermal leptogenesis mechanism generically fail to reproduce the observed abundances of primordial elements. We have discussed two possible solutions to this problem.

Firstly, we have shown that the existence of a light hidden sector fermion, which couples very weakly to the lightest observable supersymmetric particle (LOSP, *e.g.* the lightest stau), opens new decay channels for the LOSP. If the coupling is large enough, the LOSP will decay dominantly into hidden sector fermions before the epoch of primordial nucleosynthesis, avoiding all the nucleosynthesis constraints altogether. We have summarized the different constraints on this coupling and commented on the experimental signatures at particle colliders.

Secondly, we have discussed a possible mechanism that generates a small matter-parity violation in the visible sector. Due to the matter-parity breaking, the NLSP can then decay into standard model particles before conflicting with BBN. In our scenario, visible sector and part of the hidden sector are simultaneously charged under a gauged $\mathrm{U}(1)_{B-L}$. This $\mathrm{U}(1)_{B-L}$ is broken at a high scale M_S by right-handed neutrino masses to its matter-parity $\mathbb{Z}_2$ subgroup, and matter parity is then subsequently broken completely in the hidden sector by a $\mathrm{SU}(2)_{\mathrm{hid}}$ quark condensate at a scale Λ. This mechanism gives rise to bilinear matter-parity breaking in the visible sector of the order of Λ^2/M_S. We summarized the constraints coming from pseudo NG modes in the hidden sector and showed that the model can be phenomenologically viable for large enough $B-L$ breaking scales.

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