GRAVITINO DARK MATTER WITH CONSTRAINTS FROM HIGGS BOSON MASS AND SNEUTRINO DECAYS*

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We investigate gravitino dark matter produced thermally at high temperatures and in decays of a long-lived sneutrino in the framework of the Non-Universal Higgs Model (NUHM). We apply relevant collider and cosmological bounds. Generally, we find allowed values of the reheating temperature $T_{\rm R}$ below 10^9 GeV, *i.e.* somewhat smaller than the values needed for thermal leptogenesis, even with a conservative lower bound of 122 GeV on the Higgs boson mass. Requiring mass values closer to 126 GeV implies $T_{\rm R}$ below 10^7 GeV and the gravitino mass less than 10 GeV.

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Gravitino as the lightest supersymmetric particle is a well-motivated dark matter (DM) candidate. It is extremely weakly interacting and hence can escape detection in direct searches. Scenarios with gravitino DM can be, however, strongly constrained by the Big Bang Nucleosynthesis (BBN).

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Sneutrino is considered as a particularly good candidate for the lightest ordinary supersymmetric particle (LOSP) decaying into gravitino, since it allows higher reheating temperature $T_{\rm R}$ than neutralino (it has low yield at freezeout, hence gravitino thermal production is dominant) and is less constrained by BBN predictions than the stau.

The τ-sneutrino, $\tilde{\nu}_\tau$, is the lightest of the sneutrinos due to the τ-Yukawa coupling driving its mass slightly below the sneutrinos of the other two generations, and from now on, we will refer to it as simply the sneutrino.

As it is discussed in [1], sneutrino can be LOSP in two (mutually not exclusive) cases. The first one is described by the following condition

$$D^2 = m_{H_u}^2 - m_{H_d}^2 + \mathrm{tr}\left[\boldsymbol{m}_{Q,0}^2 - 2\boldsymbol{m}_{U,0}^2 + \boldsymbol{m}_{D,0}^2 - \boldsymbol{m}_{L,0}^2 + \boldsymbol{m}_{E,0}^2\right] < 0\,, \quad (1)$$

here $\boldsymbol{m}_{S,0}^2$ are the 3×3 sfermion mass matrices at the high scale, $m_{H_u}^2$ and $m_{H_d}^2$ are the soft supersymmetry breaking masses of the Higgs doublets at the high scale. This possibility is realized *e.g.* in the NUHM model. The second option is to relax the gaugino mass universality and is discussed in more details in [1].

At one loop, the lighter Higgs boson mass in the MSSM can be approximated as [2]

$$m_h^2 \approx m_Z^2 \cos 2\beta + \frac{3}{4\pi^2}\frac{m_t^4}{v^2}\left[\log\frac{m_S^2}{m_t^2} + \frac{X_t^2}{m_S^2}\left(1 - \frac{X_t^2}{12 m_S^2}\right)\right], \quad (2)$$

where $v = 174\,\mathrm{GeV}$, m_S^2 is the product of the stop masses and $X_t = A_t - \mu/\tan\beta$ with top trilinear coupling denoted by A_t. It is well known (see *e.g.* [3]) that consistency with the Higgs boson mass measurement at $\sim 126\,\mathrm{GeV}$ [4] points toward large values of $m_S > \mathcal{O}(1)\,\mathrm{TeV}$ and values of $X_t \sim A_t \sim \pm\sqrt{6}\,m_S$ maximizing the second term in the square bracket in (2).

The present abundance of gravitinos resulting from scatterings in thermal plasma [5] can be approximated by [6]

$$\Omega_{\tilde{G}}^{\rm TP} h^2 \approx \left(\frac{T_{\rm R}}{10^8\,\mathrm{GeV}}\right)\left(\frac{1\,\mathrm{GeV}}{m_{\tilde{G}}}\right)\sum_{r=1}^{3}\gamma_r\left(\frac{M_r}{900\,\mathrm{GeV}}\right)^2, \quad (3)$$

where $m_{\tilde{G}}$ is the gravitino mass, M_r denote gaugino mass parameters at low scale. The simple model of thermal leptogenesis requires the reheating temperature to be $T_{\rm R} > 2\times 10^9\,\mathrm{GeV}$ [7].

The lifetime of sneutrino LOSP can be approximated as

$$\tau_{\rm NLSP} = \left(5.9\times 10^4\,\mathrm{sec}\right)\left(\frac{m_{\tilde{G}}}{1\,\mathrm{GeV}}\right)^2\left(\frac{100\,\mathrm{GeV}}{m_{\rm NLSP}}\right)^5\left(1 - \frac{m_{\tilde{G}}^2}{m_{\rm NLSP}^2}\right)^{-4}, \quad (4)$$

which can easily be of the order of 10^5–10^7 sec. For such long lifetimes, it is then possible that hadro-dissociation processes induced by a subdominant decay process of sneutrino LOSP $\tilde{\nu} \to \nu \tilde{G} q \bar{q}$, where a quark–antiquark pair is produced, can alter the BBN predictions beyond the current observational uncertainties.

In our numerical work, we used suspect [8] to solve the renormalization group equations and calculate mass spectra, micrOMEGAs [9] for the LOSP relic abundance and SuperIso [10] for flavour observables. For all the points of interest, low-energy observables lie within a conservative 95% C.L. ranges that take into account theoretical uncertainties: $2.8 \times 10^{-4} < \mathrm{BR}(b \to s\gamma) < 4 \times 10^{-4}$ [11], $0.7 \times 10^{-4} < \mathrm{BR}(B_u \to \tau \nu_\tau) < 2.7 \times 10^{-4}$ [12], $0.7 \times 10^{-9} < \mathrm{BR}(B_s \to \mu^+\mu^-) < 6.3 \times 10^{-9}$ [13], $12.9\,\mathrm{ps}^{-1} < \Delta M_{B_s} < 22.5\,\mathrm{ps}^{-1}$ [14]. We also checked that squark masses of the first and second generations are well above 1400 GeV, required by the LHC data [14].

The region of the NUHM parameter space where the sneutrino is the LOSP are given in the left panel of figure 1. For large enough values of $m_{1/2}$, it is bounded from above, by the bino LOSP region. Below the sneutrino LOSP region, we get unphysical points with tachyonic sleptons. We choose $A_0 = -3\,000\,\mathrm{GeV}$, so as to maximize mixing term in Eq. (2). A larger A_0 would increase the left–right stau mixing and lower the lighter stau mass below the sneutrino mass.

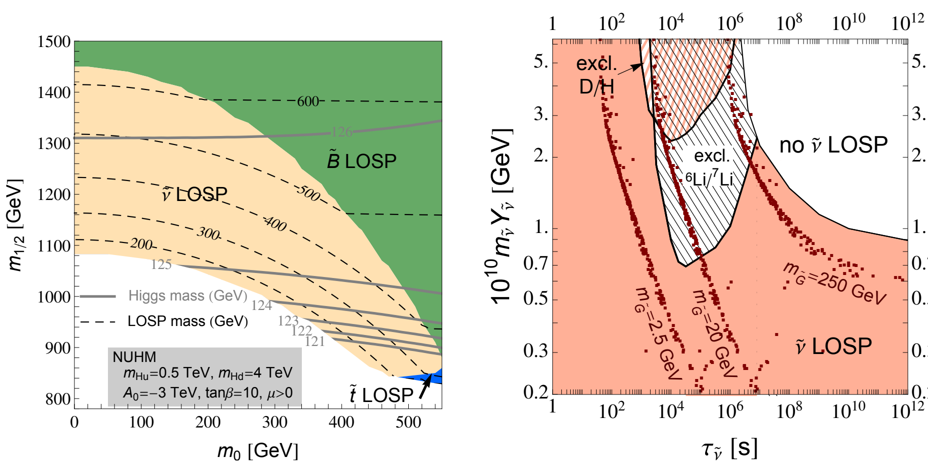

Fig. 1. Left panel: slice of the NUHM parameter space: m_0 *versus* $m_{1/2}$ with the other parameters fixed. Contours of constant LOSP (Higgs boson) masses are shown as dashed (solid) lines. Unphysical regions are marked in white. Right panel: BBN constraints shown in the $\tau_{\tilde{\nu}}$ *versus* $m_{\tilde{\nu}} Y_{\tilde{\nu}}$ plane for the sneutrino LOSP region. Dots (black) show the results of our scan with fixed $m_{\tilde{G}} = 2.5$, 20 and 250 GeV.

For the region with sneutrino LOSP shown in the left panel of figure 1, we calculate the abundances of light elements following the method outlined in [15] and apply the following observational limits relevant for the sneutrino LOSP scenario: $1.2 \times 10^{-5} < \mathrm{D/H} < 4 \times 10^{-5}$, ${}^{6}\mathrm{Li}/{}^{7}\mathrm{Li} < 0.1$ (stringent) or 0.66 (conservative). We note that for all points the result for D/H is altered with respect to the standard case, but most of these results are consistent with observational uncertainties. In the right panel of figure 1, we project all the analysed points onto the $\tau_{\tilde{\nu}}$ *versus* $m_{\tilde{\nu}} Y_{\tilde{\nu}}$ plane. We also show there the relevant BBN bounds. Bands of black/dark red dots correspond to the results of our scan with a three values of fixed gravitino mass of $m_{\tilde{G}} = 2.5, 20, 250$ GeV. Since $\Omega_{\tilde{\nu}} h^2$ is roughly proportional to $m_{\tilde{\nu}}^2$ and for $m_{\tilde{G}} \ll m_{\tilde{\nu}}$ the sneutrino lifetime scales as $\tau_{\tilde{\nu}} \propto m_{\tilde{G}}^2 m_{\tilde{\nu}}^{-5}$, one can note that, with increasing $m_{\tilde{G}}$, the constraints from D/H and ${}^{6}\mathrm{Li}/{}^{7}\mathrm{Li}$ first appear, next tighten up and then eventually become weaker. For all values of $m_{\tilde{G}}$, the bounds from ${}^{6}\mathrm{Li}/{}^{7}\mathrm{Li}$ are always more stringent than the D/H bounds.

For large gravitino masses, non-thermal gravitinos produced in sneutrino LOSP decays will have velocities much larger than those characteristic for thermal distribution. Such fast moving dark matter particles tend to erase the small scales of Large Scale Structures (LSS), especially when they constitute a sizable fraction of the dark matter density. Following [16], we account for these LSS constraints by requiring that the r.m.s. velocity of the non-thermally produced dark matter gravitinos does not exceed 1 km/s and that the non-thermal component makes less than 20% of the total dark matter abundance.

A summary of our results is presented in figure 2 which shows regions in the $(m_{\tilde{G}}, m_{\tilde{\nu}})$ plane excluded by our constraints. We see two distinct regions in the parameter space. For small $m_{\tilde{G}} < 10$ GeV, there are no constraints on $m_{\tilde{\nu}}$ but the allowed maximum reheating temperature is relatively low, $T_{\mathrm{R}}^{\mathrm{max}} \sim 10^7$ GeV. For larger $m_{\tilde{G}}$, the BBN and LSS bounds start constraining the sneutrino mass and the maximum allowed reheating temperature increases to $\sim 9 \times 10^8$ GeV. However, now the points for which T_{R} is maximal correspond to the Higgs boson masses much smaller than the LHC measurements. The requirement that the Higgs boson mass is at least 122 GeV, brings $T_{\mathrm{R}}^{\mathrm{max}}$ down to 7×10^8 GeV.

To summarize, in this paper, we have analysed scenario with gravitino dark matter and the τ-sneutrino as the lightest ordinary supersymmetric particle in a framework of the NUHM model, as a representative example of a unified model. We found that the constraints coming from BBN, LSS, Higgs boson mass measurements and bounds on reheating temperature required by simple model of thermal leptogenesis are inconsistent, albeit the maximum reheating temperature is only 2–3 times smaller than the value suggested by the leptogenesis bound. In particular, obtaining the value of the Higgs mass provides a new constraint that is difficult to satisfy at high $T_{\rm R} \sim 10^9$ GeV. Therefore, our results challenge the notion that models of gravitino dark matter with sneutrino LOSP are compatible with simple thermal leptogenesis.

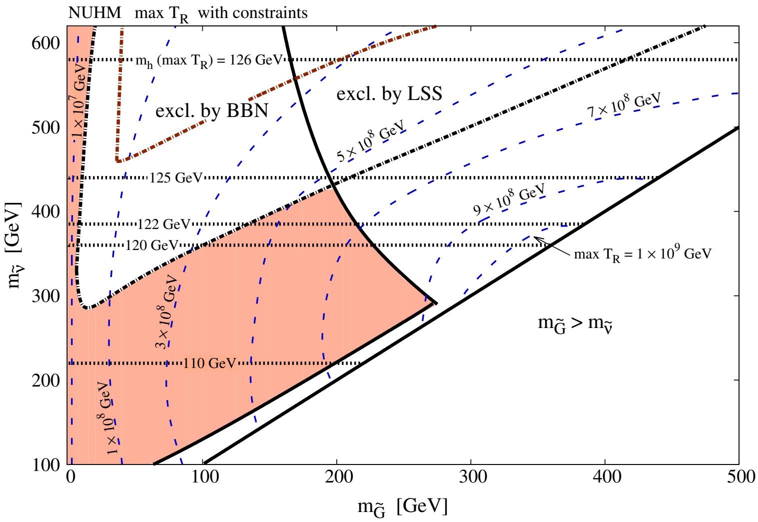

Fig. 2. A summary of the bounds in the NUHM in the $(m_{\tilde{G}}, m_{\tilde{\nu}})$ plane. The thick dash-dotted lines bound the region excluded by BBN, the solid line marks the boundary of the region excluded by LSS. Thinner dashed lines show the maximum reheating temperature, $T_{\rm R}^{\rm max}$, and thinner dotted lines show the Higgs boson mass corresponding to $T_{\rm R}^{\rm max}$. Lower (black) dash-dotted line corresponds to the stringent limit for ^{6}Li/^{7}Li, while the boundary of the excluded region with the more conservative constraint is represented by upper (red) dash-dotted line.

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