Natural gravitino dark matter in $SO(10)$ gauge mediated supersymmetry breaking

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Abstract. It is shown that gravitinos with mass $m_{3/2} \sim 0.1 - 1$ MeV may provide suitable cold dark matter candidates in scenarios of gauge mediated supersymmetry breaking (GMSB) under $SO(10)$ grand unification coupled to supergravity, which accommodate a messenger sector of mass scale $M_X \sim 10^6$ GeV. This is due to the combined effects of renormalizable loop-suppressed operators and generic non-renormalizable ones governing the dilution of a pre-existing equilibrium gravitino abundance via messenger decay. The above range of gravitino and messenger masses can be accommodated in indirect GMSB scenarios. The gravitino abundance does not depend on the post-inflationary reheat temperature and it is shown that leptogenesis can generate successfully the baryon asymmetry.

1 Introduction

In particle physics models in which the dynamical breaking of supersymmetry is transmitted to the visible sector through renormalizable gauge interactions, the so-called GMSB models [1, 2, 3], the lightest supersymmetric particle is the gravitino. As such it can in principle make up the cold dark matter component of the Universe. Previous studies have demonstrated that the messenger sector that is responsible for the transmission of SUSY breaking in GMSB models, may play a key role in the determination of the relic abundance of gravitinos [4, 5, 6, 7]. In particular, the lightest messenger particle with mass $M_X \gtrsim 10^5$ GeV is assumed to be stable in GMSB models proposed so far. However messenger number must be violated in some way, otherwise this lightest messenger would overclose the Universe [8] (except for the particular case $M_X \sim 10^4$ GeV [9, 10]). On general grounds one expects this messenger to visible sector coupling to be suppressed in order to preserve the successful phenomenology of GMSB models, in particular with respect to the natural suppression of flavor changing neutral currents and correct electroweak breaking [12]. If the decay width of the lightest messenger is sufficiently suppressed, the decay may be a significant source of entropy which reduces the gravitino abundance.

Following this line of thought, we show in the present Letter that the gravitino can indeed provide a natural cold dark matter candidate in the “simplest” GMSB models under $SO(10)$ grand unification coupled to supergravity. More specifically, we find that for a gravitino mass $m_{3/2} \sim 1$ MeV and $M_X \sim$...
10^6 \text{ GeV}, generic non-renormalizable messenger-matter couplings allow to obtain the right relic abundance for dark matter independently of the post-inflationary reheat temperature. Leptogenesis can thus operate successfully at high temperatures and produce the observed baryon asymmetry. Such gravitino and messenger masses are predicted in indirect GMSB models such as proposed by Dine and collaborators [2].

In these models, dynamical breaking occurs at scale \( \Lambda_{\text{DSB}} \) in a secluded sector and results in \( M_X \sim \kappa \Lambda_{\text{DSB}} \), with \( \kappa < 1 \) denoting a combination of model dependent coupling constants, and \( m_{3/2} \sim \Lambda_{\text{DSB}}^2/m_{\text{Pl}} \). Hence for \( \Lambda_{\text{DSB}} \sim 10^6 - 10^7 \text{ GeV} \), one obtains \( M_X \lesssim 10^6 \text{ GeV} \) and \( m_{3/2} \sim \lesssim 100 \text{ keV} \). For the same values, one also finds a fermion-boson squared mass splittings in the messenger sector \( F_X \sim M_X^2 \) which results in correct sfermion, squark and gaugino masses \( m_{1/2} \sim m_0 \sim (\alpha/4\pi) F_X/M_X \sim 1 \text{ TeV} \) [2, 3, 13].

## 2 Gravitino abundance

We assume that the post-inflationary Universe reheats to high temperature \( T_{\text{RH}} \gtrsim 10^{10} \text{ GeV} \) as generically occurs in scenarios where the inflaton couples through renormalizable interactions to the visible sector. Then sparticles as well as messengers are initially brought to thermal equilibrium. Goldstinos, or equivalently helicity \( \pm 1/2 \) gravitinos, are also brought into thermal equilibrium as the temperature exceeds the threshold \( T_{\text{eq}} \sim 10^6 \text{ GeV} (m_{3/2}/100 \text{ keV})^2 (M_3/10^3 \text{ GeV})^{-2} (M_3 \text{ gluino mass}) \) at which production of goldstinos by sparticle scattering occurs faster than a Hubble time [5]. Note that gravitino production by messenger scatterings may further reduce this temperature [14]. Neglecting the abundance of helicity \( \pm 3/2 \) gravitinos, the number to entropy density ratio of gravitinos after reheating is thus well approximated by the thermal equilibrium value \( Y_{3/2}^{\text{eq}} \equiv n_{3/2}/s \approx 1.8 \cdot 10^{-3} (g_*/230)^{-1} \).

If messengers sit in a pair of \( \mathbf{16} + \overline{\mathbf{16}} \) spinor representations of \( SO(10) \), the lightest messenger is a linear combination of the \( \tilde{r}_R \)-like [i.e. \( SU(3) \times SU(2) \times U(1) \text{ singlet boson} \)] components of the \( \mathbf{16} \) and of the \( \overline{\mathbf{16}} \) conjugate, as was first noted in ref. [9]. Since the singlet nature of the lightest messenger is a key issue for our study, it is important to qualify its genericity. Indeed, the mass degeneracy in these representations is lifted by various contributions to the non-singlet states: tree-level electroweak \( D \)-term corrections, renormalization group running effects in \( M_X \) and \( F_X \), as well as genuine electroweak loop corrections. In the literature [9] [11] the focus was mainly on mass splitting in \( SU(2) \) doublets. Furthermore, the leading effects from the running of \( M_X \) and \( F_X \) can be milder in the GMSB models under consideration where these parameters are generated dynamically at scales much below \( M_{\text{GUT}} \). We have thus recomputed the loop corrections to the (squared) masses of the \( SU(3) \times SU(2) \times U(1) \) charged scalar messengers, both in the supersymmetric \( (F_X = 0) \) and susy breaking \( (F_X \neq 0) \) configurations, in a minimal subtraction scheme, and taking the renormalization scale \( \mu \sim M_X \) so as to resum the leading log effects. These corrections are found to be positive, both in the \( F_X = 0 \) limit and in most of the parameter space when \( F_X \neq 0 \), increasing the masses by \( \sim 10 - 20\% \). For instance, in the susy and \( M_X \gg m_Z \) limit, the correction to the \( (\tilde{\nu}_L, \tilde{L}) \)-like messenger masses is \( M_X \) while a somewhat larger correction obtains for the \( \tilde{H}_R \)-like and squark-like messengers. These corrections should be added to the renormalization group effects on \( M_X, F_X \) when running from the \( GUT \) scale down to the messenger scale. When applicable, the latter running largely dominates and increases further the masses of the \( SU(3) \times SU(2) \times U(1) \) charged messengers over that of the singlet by \( 20 - 60\% \). In the sequel we denote by \( X \) this lightest singlet messenger.

The relic abundance of this lightest messenger is determined as usual by annihilation freeze-out from thermal equilibrium (provided the decay width to the visible sector is sufficiently suppressed, as will be the case here). Since \( X \) is a singlet under the standard model gauge group, it can annihilate either \( i \) at the tree level into visible sector particles and only through the exchange of a GUT mass \( SO(10) \) gauge boson, \( ii \) at the tree-level into a pair of goldstinos, \( iii \) at the one-loop level where the heavy as well as the light particles of the visible (and spurion) renormalizable sector of the model contribute in the loops.

The contribution from \( i \) is highly suppressed by a factor \( (M_X/M_{\text{GUT}})^4 \) and can be safely neglected. Annihilation into goldstinos \( ii \) is induced by supergravitational interactions (see also [8]). It receives
contributions from various sectors including the purely gravitational \( s \)−channel exchange of gravitons, 4−leg contact interactions between \( X \) and the gravitino, \( t \)−channel exchange of the fermionic partner of \( X \), as well as \( s \)−channel exchange of the scalar partners of the fermions which make up the goldstino after supersymmetry breaking. The coupling of the latter scalars to the gravitinos is fixed by the super-Higgs mechanism, \([15][16]\), while their coupling to \( X \) has also a renormalizable non-hidden contribution through the coupling of the spurion to \( X \) in the GMSB superpotential. In contrast to the case of fermions or gauge bosons where the scale of unitarity violation is reduced from the Planck scale to much lower scales by the smallness of the gravitino mass \([15][16][17]\), the cross section for \( XX \to GG \) has a mild high energy behavior, barring non-minimal Kähler contributions which are Planck suppressed. Furthermore, we consider the configurations where the spurion is heavier than the lightest messenger scalar, which is indeed the case for parts of the parameter space.\(^1\) In the opposite case a quick annihilation of the lightest messenger to spurion pairs would occur through tree-level diagrams [accompanied by one-loop induced spurion decays mainly into gluons] leading typically to a too low \( X \) relic abundance. In the limit of very heavy spurion we find for the \( X \) particles annihilating at rest \( \langle \sigma v \rangle \sim (1/8\pi)F^2_X M_X^2/F^4 \), where \( F \equiv \sqrt{3m_3/m_{111}} \) is the goldstino decay constant.

The contribution from iii) to the annihilation into standard model particles is fully controlled by the renormalizable sector, but can be comparable to the latter in the range of parameters we consider. Though a detailed description of these effects is beyond the scope of the present paper we point out here some qualitative features in the case of the leading annihilation into two gluons. In this case there is no tree-level annihilation of the type i) and all contributions proceed via one-loop diagrams. They originate either from the spurion/messenger sector or from the \( SO(10) \) gauge sector. In the latter case, only heavy particles will contribute to the loops since the lightest messenger is an MSSM singlet. The GUT scale contributions will thus decouple leading to negligible effects, unless the pattern of some qualitative features in the case of the leading annihilation into two gluons. In this case there is no

\[ \langle \sigma v \rangle = \frac{1}{8\pi}|F|^2 \frac{M_X^2}{F^4}, \]

\[ F \equiv \sqrt{3m_3/m_{111}}, \]

**```1**For instance, in the simplest model with an \( SU(6) \times U(1) \times U(1)_m \) gauge group in the dynamical breaking sector \([2]\), such configurations are achieved for \( \sqrt{3} \leq \kappa/\lambda \leq 2.2 \) and \( \lambda_1/\lambda \ll 1 \), where \( \lambda \), \( \kappa \) and \( \lambda_1 \) denote respectively the spurion self-coupling, its coupling to the messenger fields, and its coupling to the \( U(1)_m \) charged fields in the superpotential. Wider ranges are also found for larger values of \( \lambda_1/\lambda(< 1) \).

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The relic abundance of the lightest messenger can thus be written as:

\[ Y_X \simeq 8.4 \cdot 10^{-10} \left( \frac{M_X}{10^6 \text{ GeV}} \right) \left( \frac{4\pi}{\alpha_3} \right)^2 \lambda_{0.1}^{-4} x_f \]

with \( x_f = \log \left[ \frac{Q_f}{\sqrt{\log(Q_f)}} \right] \) and \( Q_f \simeq 1.5 \cdot 10^6 f (\alpha_3/4\pi)^2 \lambda_{0.1}^4 (M_X/10^6 \text{ GeV})^{-1} \). The parameter \( x_f \) denotes the ratio of the messenger mass to the temperature at which freeze-out of annihilations occurs. Hence

\[ Y_X \simeq 5.0 \cdot 10^{-5} f^{-1} \lambda_{0.1}^{-4} \left( \frac{M_X}{10^6 \text{ GeV}} \right) \left[ 1 + 0.26 \log(f) - 0.26 \log \left( \frac{M_X}{10^6 \text{ GeV}} \right) + 1.05 \log (\lambda_{0.1}) \right]. \]

When \( 10^{-2} \lesssim \lambda_{0.1}^{-4}(M_X/10^6 \text{ GeV})/f \lesssim 1 \), \( Y_X \simeq 5 \cdot 10^{-5}(M_X/10^6 \text{ GeV})^{0.8} f^{-0.8} \lambda_{0.1}^{-3.2} \) provides a good approximation. For other values of \( M_X \) and \( f \), one needs to keep the logarithmic correction.

Eventually, \( X \) will decay to visible sector particles, otherwise it would overclose the Universe. As mentioned earlier, we assume that \( X \) decay can occur through non-renormalizable operators. The main motivation for this is to preserve the phenomenological successes of GMSB models, notably with respect to flavor changing neutral currents and electroweak symmetry breaking. It is certainly possible to introduce renormalizable operators that violate messenger number and yet do not spoil the features of GMSB models, however such operators have to be suppressed by unnaturally small numerical prefactors [12], particularly for small messenger masses. Non-renormalizable higher dimension operators are expected to occur at the Planck scale, which respect the gauge symmetry of \( SO(10) \) as well as \( R \)-symmetry and possibly other global symmetries. Depending on the charge assignments [which should forbid dangerous couplings, e.g. between messengers and Higgses with GUT vev’s], some of these operators will violate messenger number by one unit. For these operators, the typical decay width of \( X \) is \( \Gamma_X \simeq (1/16\pi) f'M_X/m_{Pl}^2 \), with \( f' \) a numerical factor of order unity. Decay occurs when the Hubble rate \( H \simeq \Gamma_X \), or equivalently, at background temperature

\[ T^* \simeq 87 \text{ MeV} \left( \frac{M_X}{10^6 \text{ GeV}} \right)^{3/2} \left( \frac{g^*}{10.75} \right)^{-1/4}. \]

The decay width of the lightest messenger is so suppressed and its relic abundance is so large (due to its suppressed annihilation cross-section) that \( X \) actually comes to dominate the total energy density budget before decaying. This happens since \( X \) quanta become non-relativistic at temperatures \( \lesssim M_X \) and therefore their energy density redshifts less fast than that of radiation. This era of non-relativistic matter domination starts at background temperature \( T_{\text{dom}} \simeq (4/3) M_X Y_X \simeq 67 \text{ GeV} f^{-0.8} \lambda_{0.1}^{-3.2} (M_X/10^6 \text{ GeV})^{1.8} \), which indeed exceeds \( T^* \). The decay of this lightest messenger thus results in a significant amount of entropy generation, by reheating the Universe to temperature \( T^* \). The amount of entropy produced can be written in a rather simple way as [3]:

\[ \Delta S \simeq \frac{T_{\text{dom}}}{T^*} \simeq 7.6 \cdot 10^2 f^{-0.8} \lambda_{0.1}^{-3.2} f'^{-1/2} \left( \frac{M_X}{10^6 \text{ GeV}} \right)^{0.3}, \]

and all species are diluted with respect to the background entropy density by the factor \( \Delta S \).

In particular, the goldstino abundance after lightest messenger decay reads:

\[ Y_{3/2} \simeq \frac{1}{\Delta S} Y_{3/2}^{\text{eq}} \simeq 2.1 \cdot 10^{-6} f^{0.8} \lambda_{0.1}^{3.2} f'^{1/2} \left( \frac{M_X}{10^6 \text{ GeV}} \right)^{-0.3}. \]

This gives a present-day relic abundance:

\[ \Omega_{3/2} h^2 \simeq 0.067 f^{0.8} \lambda_{0.1}^{3.2} f'^{1/2} \left( \frac{M_X}{10^6 \text{ GeV}} \right)^{-0.3} \left( \frac{m_{3/2}}{0.1 \text{ MeV}} \right). \]
Hence one finds the correct relic abundance for dark matter for $m_{3/2} \sim 0.1 - 1 \text{ MeV}$, $M_X \sim 10^6 \text{ GeV}$ and $\lambda_{0,1}^3 f \sim f' \sim \mathcal{O}(1)$. If the one-loop annihilation cross-section prefactor $\lambda_{0,1}^3 f$ takes values significantly larger than unity, the region in which one finds suitable gravitino dark matter shifts down to smaller $m_{3/2}$, and remains at the same values of $M_X$. Indeed one must recall that the lower bound $M_X \gtrsim 10^5 \text{ GeV}$ is imposed by the phenomenology of GMSB models. Note also that as $M_X$ increases above $\sim 10^7 \text{ GeV}$, depending on $\lambda_{0,1}^3 f$ and $m_{3/2}$, annihilation into a pair of goldstinos may come to dominate the one-loop annihilation channel. Due to the strong dependence of the former on $M_X$, the relic abundance of $X$ quickly decreases in this case, as $M_X$ increases, hence entropy production becomes less effective and gravitinos tend to overclose the Universe. For $\lambda_{0,1}^3 f \sim 10^3$, the region in which one finds gravitino dark matter lies at $m_{3/2} \sim 1 \text{ keV}$ and $M_X \sim 10^6 \text{ GeV}$.

Conversely, if $\lambda_{0,1}^3 f$ is significantly smaller than unity, more precisely $\lambda_{0,1}^3 f \lesssim 10^{-1}(M_X/10^6 \text{ GeV})$, freeze-out of lightest messenger annihilations can occur as early as in the relativistic regime, i.e. $x_f \lesssim 1.5$. In this case, the relic abundance $Y_X \sim 1.2 \times 10^{-3}$ does not depend anymore on the annihilation cross-section, and the relic gravitino abundance reads:

$$\Omega_{3/2} h^2 \simeq 0.028 f'^{1/2} \left( \frac{M_X}{10^6 \text{ GeV}} \right)^{1/2} \left( \frac{m_{3/2}}{1 \text{ MeV}} \right).$$

One may still find satisfactory solutions for gravitino dark matter, if $m_{3/2} \gtrsim 1 \text{ MeV}$, $M_X \gtrsim 10^6 \text{ GeV}$ and/or $f' \gtrsim 1$. Note that $m_{3/2} \lesssim 10 \text{ MeV}$ is imposed by big-bang nucleosynthesis constraints on high energy injection if the NLSP is a bino [8]; for a stau NLSP, the constraint is generally weaker, $m_{3/2} \lesssim 5 \text{ GeV}$ [10].

It is safe to ignore the production of goldstinos during this second stage of reheating since the corresponding temperature $T^*$ given by Eq. (4) is well below the sparticles masses. Goldstinos are also produced by the decay of the next-to-lightest supersymmetric particle (NLSP), which depending on the underlying mass spectrum, may be generally a bino or a stau. NLSPs result not only during a thermal freeze-out but possibly also during the messenger decays themselves. The former contribution to goldstinos is negligible due to the entropy release that follows NLSP freeze-out; the latter is also generally small when compared to the previously existing gravitino abundance. The decay width of the NLSP is $\Gamma_{\text{NLSP}} \simeq (1/48\pi)M_{\text{NLSP}}^2/(m_{3/2}^2 m_{\Phi i}^2)$, so that decay occurs at background temperature $T_{\text{NLSP}} \simeq 5 \text{ MeV} (M_{\text{NLSP}}/100 \text{ GeV})^{5/2} (m_{3/2}/1 \text{ MeV})^{-1}$. If one assumes that $X$ can produce NLSPs in its decay, the NLSPs produced have time to annihilate before decaying to goldstinos, depending on the comparison of $T_{\text{NLSP}}$ and $T^*$. To be conservative, one may assume that $N_{\text{NLSP}}$ NLSPs are produced per messenger decay, with [5]:

$$N_{\text{NLSP}} \approx \frac{M_X}{M_{\text{NLSP}}^2/T^*} \simeq 5 f'^{1/2} \left( \frac{M_X}{10^6 \text{ GeV}} \right)^{5/2} \left( \frac{M_{\text{NLSP}}}{100 \text{ GeV}} \right)^{-2}.$$  \hspace{1cm} (8)

If these can decay to goldstinos directly without annihilating, the amount of gravitinos produced is:

$$Y_{3/2}^{\text{NLSP}} \sim N_{\text{NLSP}} \frac{Y_X}{\Delta S} \sim 2 \cdot 10^{-7} f' \left( \frac{M_X}{10^6 \text{ GeV}} \right)^3 \left( \frac{M_{\text{NLSP}}}{100 \text{ GeV}} \right)^{-2},$$

which remains small compared to $Y_{3/2}$ calculated in Eq. (5) above provided $M_X \lesssim 10^6 \text{ GeV}$ and/or $M_{\text{NLSP}} \gtrsim 100 \text{ GeV}$. Moreover NLSP annihilations prior to NLSP decay, reduce this estimate [20] [5] to

$$Y_{3/2}^{\text{NLSP}} \simeq 1.8 \cdot 10^{-11} f'^{-1/2} \left( \frac{\langle \sigma_{\text{NLSP}} v \rangle}{10^{-7} \text{ GeV}^{-2}} \right)^{-1} \left( \frac{M_X}{10^6 \text{ GeV}} \right)^{-3/2} \left( \frac{g_{\ast}^2}{10.75} \right)^{1/4},$$

provided $T_{\text{NLSP}} < T^*$, which is the case unless $f'$ is very small. Annihilations are quite effective for stau NLSPs with typical $\langle \sigma_{\text{NLSP}} v \rangle \sim 10^{-7} \text{ GeV}^{-2} (m_{\text{NLSP}}/100 \text{ GeV})^{-2}$.
The present scenario respects the various constraints from big-bang nucleosynthesis (BBN). For instance, the lightest messenger and the NLSP decay well before nucleosynthesis provided $M_X \gtrsim 10^5 \text{GeV}$ and $m_{3/2} \lesssim 10 \text{ MeV}$ so that their decay products can thermalize and constraints from high energy injection do not apply. On the other hand, for gravitino masses $\sim 0.1-1 \text{ GeV}$ decay occurs during BBN, and for the right NLSP abundance and hadronic branching ratio, interesting effects on the $^7\text{Li}$ and $^6\text{Li}$ abundances may occur \cite{21}. Nevertheless, such high $m_{3/2}$ are successfully accommodated in the present scenario only for $f' \ll 1$. The gravitinos produced in NLSP decay, although they remain highly relativistic at the time of big-bang nucleosynthesis, are in too small numbers to contribute significantly to the energy budget. One indeed evaluates the fractional contribution to the radiation energy density carried by those relativistic gravitinos at BBN to be $\sim Y^{\text{NLSP}}_{3/2} M_{\text{NLSP}}/T_{\text{NLSP}} \sim 2 \cdot 10^4 Y^{\text{NLSP}}_{3/2} (M_{\text{NLSP}}/100 \text{ GeV})^{-3/2} (m_{3/2}/1 \text{ MeV})$, hence it can be neglected. If $R$–parity does not hold, the NLSP can decay much earlier through other channels, and BBN constraints are actually replaced with constraints on the gravitino lifetime from the non-observation of cosmic diffuse backgrounds distortions. However, it has been shown that if $m_{3/2} \lesssim 10 \text{ MeV}$, these constraints are satisfied \cite{22}: the gravitino is then so long-lived that it can be considered as stable on our cosmological timescale. Hence the present scenario for gravitino dark matter remains valid even if $R$–parity is violated.

Finally, note that the bulk of gravitinos produced here behave as cold dark matter from the standpoint of large scale structure formation, even for gravitinos masses as small as $\sim \text{keV}$, due to the cooling of gravitinos during entropy release. One indeed calculates \cite{5} that the present-day gravitino velocity $v_0 \sim 0.0017 \text{ km/s} (m_{3/2}/1 \text{ keV})^{-1} f^{0.26} \lambda^{0.04}_1 f^{1/6} (M_X/10^6 \text{ GeV})^{-0.1}$ for the dominant component that results from thermal equilibrium (which excludes the non-thermal part from NLSP decay). The corresponding smoothing spatial scale for structure formation can be calculated as $R \sim 235 \text{ kpc} (v_0/0.05 \text{ km/s})^{0.86}$ \cite{23}, which confirms that these gravitinos are approximately cold. This situation is contrary to that encountered in scenarios in which more massive dark matter gravitinos $m_{3/2} \sim 10-100 \text{ GeV}$ are produced by non-thermal processes (in particular by the decay of the NLSP); in these models, indeed, the gravitino dark matter is warm in a large part of parameter space \cite{24}.

In conclusion, for a reasonable choice of parameters of the underlying GMSB model, one can obtain the right amount of gravitinos to explain the cold dark matter content of the Universe. The vast majority of these gravitinos have been produced in scatterings (or decays) at high temperatures and cooled and diluted by the lightest messenger out-of-equilibrium decay. A significant advantage of the present scenario is that the final abundance of gravitinos is independent of the post-inflationary reheating temperature $T_{\text{RH}}$. In particular, the stringent constraints on $T_{\text{RH}}$ for light gravitinos \cite{14} \cite{25} are irrelevant here. This implies notably that scenarios of leptogenesis from right-handed (s)neutrino decay can operate at high temperatures and produce the observed baryon asymmetry. This possibility has been discussed in some detail in a related context by Fujii & Yanagida \cite{5}. Here we omit the details for simplicity. The decay of each right-handed (s)neutrino yields a net lepton asymmetry:

$$|\epsilon_1| \simeq \frac{3}{8\pi} \frac{M_{R1} m_{\nu 3}}{(H_0^2)^{1/2}} \delta_{\text{eff}},$$

with $M_{R1}$ the lightest RH (s)neutrino mass, $m_{\nu 3} \sim 0.06 \text{ eV}$ the heaviest left-handed neutrino mass, $(H_0^2)$ a Higgs $\text{vev}$, and $\delta_{\text{eff}}$ an effective $CP$–violating phase. Assuming that the RH (s)neutrino is initially in thermal equilibrium (if $T_{\text{RH}} \gtrsim M_{R1}$), the net baryon asymmetry produced reads \cite{5}:

$$\frac{n_B}{s} \approx 3.6 \cdot 10^{-3} \frac{C}{\Delta S} |\epsilon_1| \alpha,$$  \hspace{1cm} (11)

where $C = -8/23$ in the minimal supersymmetric standard model denotes the effectiveness of $L$ to $B$ conversion, and $\alpha \sim 1$ characterizes the fraction of lepton asymmetry surviving after RH (s)neutrino decay. One finally obtains:
\[
\frac{n_B}{s} \approx 1.4 \cdot 10^{-10} f^{0.8} \alpha_{0.1}^{3.2} f^{1/2} \left( \frac{M_X}{10^6 \text{ GeV}} \right)^{-0.3} \left( \frac{M_R}{5 \cdot 10^{11} \text{ GeV}} \right),
\]

for \( \delta_{\text{eff}} \sim \alpha \sim 1 \), which matches the measured asymmetry \( \simeq 8 \cdot 10^{-11} \).

3 Conclusions

We have shown that a gravitino of mass \( m_{3/2} \sim 0.1 - 1 \text{ MeV} \) provides a natural cold dark matter candidate in \( SO(10) \) GMSB scenarios coupled to supergravity, with messenger mass scale \( M_X \sim 10^6 \text{ GeV} \) and non-renormalizable messenger-matter coupling. Although our conclusions are largely independent of the details of the underlying GMSB model, we find that our scheme can be accommodated in the so-called indirect “simplest” GMSB models à la Dine et al. [2], in which the dynamical supersymmetry breaking in a seceded sector is fed down radiatively to the messenger sector. For a reasonable choice of the various model parameters, e.g. the coupling constants, one obtains the correct dark matter abundance. Our results, and in particular the required combination of \( m_{3/2} \) and \( M_X \), depend on the numerical prefactor \( f \) of the one-loop annihilation cross-section of the lightest messenger, which is a \( SU(3) \times SU(2) \times U(1) \) singlet scalar, the spurion-messenger coupling constant \( \lambda \), as well as on \( f' \) the prefactor of the decay width of the lightest messenger via non-renormalizable messenger-matter interactions. Non-renormalizable interactions are preferred over their renormalizable counterparts in order to not violate existing limits on flavor-changing neutral currents. On the other hand, messengers have to decay to be cosmologically acceptable. When \( f \lambda^4 \) is sufficiently small, our results do not depend on the magnitude of the messenger annihilation cross section.

Our results do not depend on the mass spectrum in the visible sector. In effect the final relic gravitino abundance is simply the abundance of goldstinos at thermal equilibrium diluted by the entropy produced in the lightest messenger late decay. Goldstinos are initially brought in thermal equilibrium by scatterings and decays involving sparticles as well as messenger fields. This fact is at variance with other SUSY models in which the dark matter candidate is a neutralino LSP; in those models, one must find the right combination of the parameters that determine the visible sector mass spectrum, e.g. \( m_{1/2}, m_0, (A_0) \), \( \tan \beta \) and \( \text{sign}(\mu) \) to obtain the right dark matter abundance.

Gravitino dark matter in this mass range \( m_{3/2} \gtrsim \text{keV} \) cannot be observed in dark matter search experiments, either direct or indirect. However there exist interesting proposals to detect evidence for gravitinos/goldstinos [26] in next generation colliders. Such experiments should also confirm or dispute the GMSB phenomenology which leads to a highly predictive mass spectrum with distinctive features.

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