Reconciling thermal leptogenesis with the gravitino problem in SUSY models with mixed axion/axino dark matter

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Abstract: Successful implementation of thermal leptogenesis requires re-heat temperatures $T_R \gtrsim 2 \times 10^9$ GeV, in apparent conflict with SUSY models with TeV-scale gravitinos, which require much lower $T_R$ in order to avoid Big Bang Nucleosynthesis (BBN) constraints. We show that mixed axion/axino dark matter can reconcile thermal leptogenesis with the gravitino problem in models with $m_{\tilde{G}} \gtrsim 30$ TeV, a rather high Peccei-Quinn breaking scale and an initial misalignment angle $\theta_i < 1$. We calculate axion and axino dark matter production from four sources, and impose BBN constraints on long-lived gravitinos and neutralinos. Moreover, we discuss several SUSY models which naturally have gravitino masses of the order of tens of TeV. We find a reconciliation difficult in Yukawa-unified SUSY and in AMSB with a wino-like lightest neutralino. However, $T_R \sim 10^{10} - 10^{12}$ GeV can easily be achieved in effective SUSY and in models based on mixed moduli-anomaly mediation. Consequences of this scenario include: 1. an LHC SUSY discovery should be consistent with SUSY models with a large gravitino mass, 2. an apparent neutralino relic abundance $\Omega_{\tilde{Z}_1} h^2 \lesssim 1$, 3. no WIMP direct or indirect detection signals should be found, and 4. the axion mass should be less than $\sim 10^{-6}$ eV, somewhat below the conventional range which is explored by microwave cavity axion detection experiments.

Keywords: Supersymmetry Phenomenology, Supersymmetric Standard Model, Dark Matter
1. Introduction

Recent measurements of neutrino oscillations \cite{1} are elegantly interpreted in terms of seesaw neutrino masses \cite{2}, wherein heavy right-handed neutrino (RHN) states $N_i$ ($i = 1–3$ for three generations) are introduced, and the light neutrino masses are given approximately by $m_{\nu_i} \simeq m_{D_i}^2 / M_{N_i}$, where $m_{D_i} \sim f_{\nu_i} v$ with $f_{\nu_i}$ the neutrino Yukawa coupling and $v$ the Higgs field vacuum expectation value. A value of $M_{N_i} \sim 10^{15}$ GeV yields $m_{\nu_\tau} \sim 0.03$ eV in the GUT-inspired case where $f_{\nu_\tau} = f_t$ at $M_{\text{GUT}}$.

One of the appealing consequences of such heavy RHN states is that the baryon number of the universe can be explained in terms of thermal leptogenesis \cite{3}. In thermal leptogenesis, the right-hand neutrinos are present in thermal equilibrium at high temperatures in the early universe, and decay asymmetrically to leptons versus anti-leptons. The lepton asymmetry is converted to a baryon asymmetry via $B$- and $L$-violating but $B - L$ conserving sphaleron interactions. In a scheme with hierarchical right-hand neutrino masses, a re-heat temperature

$$T_R \gtrsim 2 \times 10^9 \text{ GeV} \quad \text{(thermal leptogenesis)}$$

is required to reproduce the observed baryon asymmetry of the universe \cite{4}.

The existence of a heavy mass scale like $M_N$ or $M_{\text{GUT}}$ brings about the infamous hierarchy problem of the Standard Model (SM). The gauge hierarchy problem is elegantly resolved by introducing supersymmetry (SUSY) into the theory. SUSY is a novel spacetime symmetry which relates bosons and fermions, see e.g. \cite{5}. In realistic models, SUSY is broken “softly” at the weak scale—implying that all SM particles must have superpartners with masses in the range up to $O(1)$ TeV that ought to be accessible to colliders such as the CERN LHC. SUSY not only stabilizes the hierarchy between weak scale and other high scales such as $M_{\text{GUT}}$; indeed with weak-scale SUSY the gauge couplings, when evolved upwards from $Q = M_Z$ under renormalization group evolution (RGE), are found to unify at $Q \approx 2 \times 10^{16}$ GeV, which is nicely consistent with the idea of a grand unified theory. Sensible implementations of supersymmetry invoke SUSY as a local symmetry (supergravity or SUGRA), which requires in addition the existence of a graviton/gravitino supermultiplet. In SUGRA models, supergravity is broken via the superHiggs mechanism, leading to a massive gravitino $\tilde{G}$. The soft SUSY breaking mass terms are expected to be closely related to the gravitino mass $m_{\tilde{G}}$, and so $m_{\tilde{G}}$ is also expected to be of the order of the weak scale.

One of the impediments to successful SUGRA model building is known as the gravitino problem \cite{6}. Gravitinos can be produced thermally in the early universe, even though their Planck-suppressed couplings preclude them from participating in thermal equilibrium. The gravitino decay rate is also suppressed by the Planck scale, leading to very long gravitino lifetimes of order $1 - 10^5$ sec. There are actually two parts to the gravitino problem. Part 1 is that for $m_{\tilde{G}} \sim 1$ TeV, the late time gravitino decays can inject hadronic or electromagnetic energy into the cosmic plasma at a time scale during or after Big Bang Nucleosynthesis (BBN), leading to destruction of the successful agreement between theory and observation for the light element abundances. For re-heat temperatures $T_R \lesssim 10^5$ GeV,
thermal gravitino production is suppressed enough to evade BBN limits \[7\]. However, these low of temperatures are in conflict with those needed for thermal leptogenesis.

If \(5 \text{ TeV} \lesssim m_{\tilde{G}} \lesssim 30 \text{ TeV}\), then the gravitino lifetime drops below 1 sec, and the BBN constraints are much more mild, allowing \(T_R \lesssim 10^9 \text{ GeV}\). This range of \(T_R\) is consistent with non-thermal leptogenesis \[8\], wherein other sources of \(N_i\), such as inflaton decay, contribute to \(N_i\) production. For heavier yet gravitinos with \(m_{\tilde{G}} \gtrsim 30 \text{ TeV}\), the value of \(T_R\) can reach as high as \(7 \times 10^9 \text{ GeV}\). In this case—part 2 of the gravitino problem—the upper bound on \(T_R\) comes from overproduction of neutralino dark matter due to their combined thermal production and production via gravitino decay. Models such as AMSB, with multi-TeV gravitino masses and very low thermal neutralino abundances, thus naturally reconcile thermal leptogenesis with the gravitino problem, but only for the narrow range \(2 \times 10^9 \text{ GeV} \lesssim T_R \lesssim 7 \times 10^9 \text{ GeV}\) \[9\].

One way out is to invoke a gravitino as LSP, with a stau or neutralino as the next-to-LSP (NLSP) which decays via a small \(R\)-parity violating interaction \[10\] (in the \(R\)-parity conserving case, it is very difficult to reconcile gravitino DM with thermal leptogenesis \[10, 11\]). The gravitino, which may also decay via \(R\)-parity violating interactions, has a lifetime of order the age of the universe; it can still function as dark matter, but its occasional decays in the galactic halo could be the source of Pamela, ATIC and Fermi cosmic ray anomalies \[12\].

Another way out involves mixed axion/axino DM, and this is the topic of this paper. Indeed, the strong \(CP\) problem remains as one of the central puzzles of QCD which evades explanation within the context of the Standard Model. The crux of the problem is that an additional \(CP\) violating term in the QCD Lagrangian of the form \(\bar{\theta} g_s^2 / 32 \pi^2 G_\mu^\nu A_\mu A^\nu \) ought to be present as a result of the \(t'\)Hooft resolution of the \(U(1)_A\) problem via instantons and the \(\theta\) vacuum of QCD \[13\]. The experimental limits on the neutron electric dipole moment however constrain \(|\bar{\theta}| < 10^{-10}\) \[14\]. Why this term should be so small is the essence of the strong \(CP\) problem.

An extremely compelling solution proposed by Peccei and Quinn \[15\] is to hypothesize an additional global \(U(1)_{PQ}\) symmetry, which is broken at some high mass scale \(f_a\). A consequence of the broken PQ symmetry is the existence of a pseudo-Goldstone boson field: the axion \(a(x)\) \[16\]. The Lagrangian then also contains the terms

\[
\mathcal{L} \supset \frac{1}{2} \nabla_\mu a \nabla^\mu a + \frac{g^2}{32 \pi^2} \frac{a(x)}{f_a / N} G_\mu^\nu \tilde{G}_\mu^\nu ,
\]

where \(N\) is the model-dependent color anomaly factor, which is 1 for KSVZ \[17\] or 6 for DFSZ \[18\] models. Since \(a(x)\) is dynamical, the entire \(CP\)-violating term settles to its minimum at zero, thus resolving the strong \(CP\) problem. A consequence of this very elegant mechanism is that a physical axion field should exist, with axion excitations of mass \[19\]

\[
m_a \simeq 6 \text{ eV} \frac{10^6 \text{ GeV}}{f_a / N}.
\]

\[1\]Here \(G_\mu^\nu\) is the gluon field strength tensor and \(\tilde{G}_\mu^\nu\) its dual.
The axion field couples to gluon-gluon (obvious from Eq. (1.2)) and also to photon-photon and fermion-fermion. All the couplings are suppressed by the PQ scale $f_a$. The value of $f_a$ is constrained to lie above $\sim 10^9$ GeV by stellar cooling arguments [20], leading to a nearly invisible axion particle which may be searched for via microwave cavity experiments [21].

In addition, axions can be produced via various mechanisms in the early universe. Since their lifetime (they decay via $a \rightarrow \gamma \gamma$) turns out to be longer than the age of the universe, they can be a good candidate for the DM of the universe [22].

In the context of supersymmetry, the axion field is but one element of an axion supermultiplet which also contains an $R$-parity even spin-0 saxion field $s(x)$ and an $R$-parity odd spin-$\frac{1}{2}$ axino field $\tilde{a}$ [23]. The axino field $\tilde{a}$ may play a huge role in cosmology [24]: its mass may lie anywhere in the range of keV to TeV [23], and it may function as the LSP. As the LSP, in $R$-parity conserving models, it may constitute at least a portion of the DM of the universe [26, 27]. The saxion field may also play a role in cosmology, e.g. via dilution of relics by additional entropy production [28, 29], although we will not consider this here.

In [30], Asaka and Yanagida proposed to reconcile thermal leptogenesis with the gravitino problem by requiring an axino LSP with a gravitino NLSP. In this paper, we present a different reconciliation of thermal leptogenesis with the gravitino problem, nota bene for very heavy gravitinos. First, we require $m_{\tilde{G}} \gtrsim 30$ TeV so as to avoid part 1 of the gravitino problem. Next, we invoke the presence of mixed axion/axino dark matter into our scenario, which arises as a result of the PQ solution to the strong CP problem in the supersymmetric context [31]. We assume here that the lightest neutralino, $\tilde{Z}_1$, is the NLSP, so that each neutralino ultimately decays to an axino, and the neutralino relic mass abundance is then suppressed by a factor of $m_{\tilde{a}}/m_{\tilde{Z}_1}$, thus avoiding part 2 of the gravitino problem, the overproduction of neutralino dark matter.

In Sec. 3 of this paper, we evaluate the relic abundance of mixed axion/axino DM due to four sources. The first is ordinary production of axion cold DM via the vacuum misalignment mechanism. The second is thermal production (TP) of axinos: here, we restrict $T_R$ to values below the axino decoupling temperature ($T_{dcp}$), so axinos are never in thermal equilibrium. Nonetheless, axinos can still be produced thermally via bremsstrahlung and decays of particles which are in thermal equilibrium: the final result depends linearly on the re-heat temperature $T_R$ after inflation. The third is non-thermal production (NTP) of axinos via thermal neutralino production and decay. The fourth, also NTP of axinos comes from thermal production of gravitinos, followed by their cascade decays to the axino LSP state; this mechanism also depends linearly on $T_R$.

For low values of PQ breaking scale $f_a/N \sim 10^9 - 10^{11}$, the axino coupling to matter is large enough that thermal production of axinos tends to dominate the mixed axion/axino abundance. An upper bound on $T_R$ can be extracted by requiring the axino DM abundance lie below the WMAP-measured value [32]:

$$\Omega_{\text{DM}} h^2 = 0.1123 \pm 0.0035 \text{ at } 68\% \text{ CL.}$$

As $f_a/N$ increases, the portion of axino DM decreases, while the axion CDM increases. Simplistic estimates of the relic axion abundance assume an initial mis-alignment angle $\theta_i \simeq 1$, leading to an upper bound on PQ breaking scale $f_a/N \lesssim 5 \times 10^{11}$ GeV. By
adopting a smaller value of $\theta_i$, much larger values of $f_a/N$ in the $10^{13}$ to $10^{14}$ GeV range become allowed. This in turn suppresses the axino composition of DM, unless very high values of $T_R \gtrsim 10^{10}$ GeV are allowed. This is the crux of our reconciliation of thermal leptogenesis with the gravitino problem.

However, within this solution, another BBN bound emerges, since the lifetime of the lightest neutralino scales as $(f_a/N)^{-2}$. There exist additional strict limits on late decaying particles with electromagnetic and hadronic energy injection into the thermal plasma during BBN. Therefore, these limits provide an upper bound on $f_a/N$ for SUSY models including the PQ mechanism. In Sec. 3, we evaluate the neutralino lifetime and hadronic branching fraction, so that BBN constraints can be applied to $\tilde{Z}_1$ decay.

In Sec. 4, we present five scenarios which are consistent with gravitinos of mass $\gtrsim 30$ TeV. The first two cases come from gravity mediated SUSY breaking: the Yukawa-unified (YU) models and effective SUSY (ESUSY) models: both of these require GUT scale scalar masses in the $10 \sim 30$ TeV regime, and so should be consistent with gravitinos in this range. As we will see, the rather large abundance of bino-like neutralinos from YU models typically makes them inconsistent with $T_R$ values in excess of $2 \times 10^9$ GeV. ESUSY models can more easily accommodate a low production rate for neutralinos in the early universe, and do allow for $T_R > 10^{10}$ GeV. The third case, that of anomaly-mediated SUSY breaking (AMSB), requires gravitinos in the $30 \sim 100$ TeV range since soft SUSY breaking terms are loop suppressed. Most versions of AMSB include a nearly pure wino-like neutralino. Since only the bino component of $\tilde{Z}_1$ couples to the axino, the neutral wino-like $\tilde{Z}_1$ decay is suppressed, and just barely allows $T_R > 2 \times 10^9$ GeV, before BBN constraints kick in. The fourth and fifth benchmark points come from “mirage unification” (MU), or mixed moduli-anomaly mediation, which also allows $m_{\tilde{G}} \sim 30 \sim 100$ TeV. These models can easily include a bino-like $\tilde{Z}_1$ with a relatively low relic abundance, avoiding the worst of BBN constraints. In these models, values of $T_R \sim 10^9 \sim 10^{12}$ can easily be accommodated, thus reconciling thermal leptogenesis with the gravitino problem. In Sec. 5, we present a summary and conclusions.

2. Mixed axion/axino relic density

In this section, we list the four production mechanisms for mixed axion/axino dark matter which are considered here. It is possible that other more exotic mechanisms could also contribute, such as axino production from moduli or inflaton decay. We will not consider these additional mechanisms here.

2.1 Axions via vacuum misalignment

Here, we consider the scenario where the PQ symmetry breaks before the end of inflation, so that a nearly uniform value of the axion field $\theta_i \equiv a(x)/(f_a/N)$ is expected throughout the universe. The axion field equation of motion implies that the axion field stays relatively constant until temperatures approach the QCD scale $T_{QCD} \sim 1$ GeV. At this point, a temperature-dependent axion mass term turns on, and a potential is induced for the axion field. The axion field rolls towards its minimum and oscillates, filling the universe with
low energy (cold) axions. The expected axion relic density via this vacuum mis-alignment mechanism is given by \[33\]

\[
\Omega_{a}h^2 \simeq 0.23 f(\theta_i)\theta_i^2 \left( \frac{f_a/N}{10^{12}\,\text{GeV}} \right)^{7/6}
\]

(2.1)

where \(0 < \theta_i < \pi\) and \(f(\theta_i)\) is the so-called anharmonicity factor. Visinelli and Gondolo \[33\] parametrize the latter as

\[
f(\theta_i) = \left[ \ln \left( \frac{e}{1 - \theta_i^2/\pi^2} \right) \right]^{7/6}
\]

The uncertainty in \(\Omega_{a}h^2\) from vacuum mis-alignment is estimated as plus-or-minus a factor of three.

### 2.2 Thermal production of axinos

If the reheat temperature \(T_R\) exceeds the axino decoupling temperature

\[
T_{dcp} = 10^{11}\,\text{GeV} \left( \frac{f_a/N}{10^{12}\,\text{GeV}} \right)^2 \left( \frac{0.1}{\alpha_s} \right)^3
\]

(2.2)

axinos will be in thermal equilibrium, with an abundance given by \(\Omega_{\tilde{a}}^{\text{TF}}h^2 \simeq \frac{m_{\tilde{a}}}{\text{keV}}\). To avoid overproducing axino dark matter, the RTW bound \[24\] then implies that \(m_{\tilde{a}} < 0.2\) keV. We will here consider only reheat temperatures below \(T_{dcp}\). In this case, the axinos are never in thermal equilibrium in the early universe. However, they can still be produced thermally via radiation off of particles that are in thermal equilibrium \[26, 34\]. Here, we adopt a recent calculation of the thermally produced axino abundance from Strumia \[35\]:

\[
\Omega_{\tilde{a}}^{\text{TP}}h^2 = 1.24 g_3^4 F(g_3) \frac{m_{\tilde{a}}}{\text{GeV}} \frac{T_R}{10^4\,\text{GeV}} \left( \frac{10^{11}}{f_a/N} \right)^2
\]

(2.3)

with \(F(g_3) \sim 20 g_3^2 \ln \frac{3}{g_3}\), and \(g_3\) is the strong coupling constant evaluated at \(Q = T_R\).

### 2.3 Axinos via neutralino decay

In supersymmetric scenarios with the neutralino as a quasi-stable NLSP, the \(\tilde{Z}_1\)S will be present in thermal equilibrium in the early universe, and will freeze out when the expansion rate exceeds their interaction rate, at a temperature roughly \(T_f \sim m_{\tilde{Z}_1}/20\). The present day abundance can be evaluated by integrating the Boltzmann equation. Several computer codes are available for this computation. Here we use the code IsaReD \[36\], a part of the Isajet/Isatools package \[37, 38\].

In our case, each neutralino will undergo decay to the stable axino LSP, via decays such as \(\tilde{Z}_1 \rightarrow \tilde{a}\gamma\). Thus, these non-thermally produced axinos will inherit the thermally produced neutralino number density, and we will simply have \[20\]

\[
\Omega_{\tilde{a}}h^2 = \frac{m_{\tilde{a}}}{m_{\tilde{Z}_1}} \Omega_{\tilde{Z}_1}^{\text{TP}}h^2.
\]

(2.4)

### 2.4 Axinos from gravitino cascade decay

Since here we are attempting to generate reheat temperatures \(T_R \gtrsim 10^9\,\text{GeV}\), we must also include in our calculations the thermal production of gravitinos in the early universe.
We here follow Pradler and Steffen, who have estimated the thermal gravitino production abundance as \[ \Omega_{\tilde G}^{TP} h^2 = \sum_{i=1}^{3} \omega_i g_i^2(T_R) \left( 1 + \frac{M_i^2(T_R)}{3m_{\tilde G}^2} \right) \ln \left( \frac{k_i}{g_i(T_R)} \right) \left( \frac{m_{\tilde G}}{100 \text{ GeV}} \right) \left( \frac{T_R}{10^{10} \text{ GeV}} \right), \] (2.5)

where \( \omega_i = (0.018, 0.044, 0.117) \), \( k_i = (1.266, 1.312, 1.271) \), \( g_i \) are the gauge couplings evaluated at \( Q = T_R \) and \( M_i \) are the gaugino masses also evaluated at \( Q = T_R \). For the temperatures we are interested in, this agrees with the calculation by Rychkov and Strumia\[39\] within a factor of about 2.

Since each gravitino cascade decays ultimately to an axino LSP, the abundance of axinos from gravitino production is given by

\[ \Omega_{\tilde a}^{TP} h^2 = \frac{m_{\tilde a}}{m_{\tilde G}} \Omega_{\tilde G}^{TP} h^2. \] (2.6)

For axino masses in the MeV range and gravitino masses in the 30 – 50 TeV range, the prefactor above is extremely small, and allows us to evade overproduction of dark matter via thermal gravitino production (part 2 of the gravitino problem). \(^2\) \(^3\)

### 2.5 Mixed axion/axino dark matter

In this paper, we will evaluate the mixed axion/axino relic density from the above four sources:

\[ \Omega_{a\tilde a} h^2 = \Omega_a h^2 + \Omega_{a\tilde G}^{TP} h^2 + \Omega_{a\tilde R} h^2 + \Omega_{a\tilde Z} h^2. \] (2.7)

Over much of parameter space, if \( m_{\tilde a} \) is taken to be of order the MeV scale, then the contributions from \( \tilde Z_1 \) and gravitino production are subdominant. In Fig. I, we illustrate in the upper frame the relative importance of the four individual contributions as a function of \( f_a/N \), for an mSUGRA scenario with \( m_{\tilde G} = 1 \text{ TeV}, m_{\tilde Z_1} = 122 \text{ GeV}, \Omega_{\tilde Z_1} h^2 = 9.6 \) (as in Ref. \[40\]). For the axion/axino sector we take \( \theta_i = 0.05 \) and \( m_{\tilde a} = 100 \text{ keV} \). The value of \( T_R \) is adjusted such that \( \Omega_{a\tilde a} h^2 = 0.1123 \). For low \( f_a/N \) values, the TP axino contribution is dominant. But as \( f_a/N \) increases, the axion component grows until at \( f_a/N \sim 4 \times 10^{13} \text{ GeV} \) it becomes dominant, and for even higher \( f_a/N \) it saturates the DM relic density.

The value of \( T_R \) which is needed is shown in the lower frame of Fig. I. We see that \( T_R \) grows quickly with increasing \( f_a/N \). This is because the thermal axino production decreases as the inverse square of \( f_a/N \), so larger values of \( T_R \) are needed to keep \( \Omega_{a\tilde a} h^2 = 0.1123 \). We see that \( T_R \) can reach \( \sim 10^{11} \text{ GeV} \) in the case of mainly axion CDM (similar to Ref. \[40\]). In

\(^2\)We have checked that for gravitinos in the mass range 5 TeV < \( m_{\tilde G} < 50 \text{ TeV} \), the temperature \( T_{\text{decay}} = \sqrt{\frac{\Gamma_{\tilde G} m_{\tilde G}}{\pi^2 g_*/90}} \) at which gravitinos decay ranges between 0.01-0.5 MeV, well after neutralino freeze-out. This means that the gravitino cascade decays indeed contribute to the ultimate axino relic density, rather than having the neutralinos from the cascade reprocessed in the thermal bath, as would occur for \( T_{\text{decay}} \gtrsim m_{\tilde Z_1}/20 \).

\(^3\)Along with gravitino cascade decays, the decay \( \tilde G \rightarrow a\tilde a \) can also occur, and give rise to a component of hot dark matter axions. Since this contribution to the axion density is \( \sim (m_a/m_{\tilde G})\Omega_{\tilde G} h^2 \) with \( m_a \sim \mu\text{eV} \), it will be a very tiny contribution to the total dark matter density, and so we are safe to neglect it here.
Figure 1: Upper frame: Contribution of axions and TP and NTP axinos to the DM density as a function of the PQ breaking scale $f_a/N$, for an mSUGRA point with $m_0 = 1000$ GeV, $m_{1/2} = 300$ GeV, $A_0 = 0$, $\tan \beta = 10$ and $\mu > 0$, and fixing $m_{\tilde{a}} = 100$ keV and $\theta_i = 0.05$; $T_R$ is adjusted such that $\Omega_{a\tilde{a}}h^2 = 0.1123$. Lower frame: the $T_R$ that is needed to achieve $\Omega_{a\tilde{a}}h^2 = 0.1123$ for $m_{\tilde{a}} = 0.1$ and 1 MeV, for the same mSUGRA point and $\theta_i$.

3. Neutralino lifetime and hadronic branching fraction

We have averted one problem with BBN by requiring the presence of a gravitino with $m_{\tilde{G}} \gtrsim 30$ TeV, so that it will decay largely before BBN starts. In the process, by asking for $T_R \gtrsim 2 \times 10^9$ GeV while avoiding overproduction of mixed axino/axion dark matter
(the latter requires large \( f_a/N \sim 10^{12} \) GeV and small \( \theta_i \)), we have pushed the \( \tilde{Z}_1 \) lifetime uncomfortably high, so that its hadronic decays in the early universe now have the potential to disrupt BBN.

Constraints from BBN on hadronic decays of long-lived neutral particles in the early universe have been calculated by several authors [41, 42, 43]. Here, we will adopt the results from the recent calculations by Jedamzik [43]. The BBN constraints arise due to injection of high energy hadronic particles into the thermal plasma during or after BBN. The constraints depend on three main factors:

- The abundance of the long-lived neutral particles. In Ref. [43], this is given by \( \Omega_X h^2 \) where \( X \) is the long-lived neutral particle which undergoes hadronic decays. In our case, where the long-lived particle is the lightest neutralino which decays to an axino LSP, this is just given by the usual thermal neutralino abundance \( \Omega_{\tilde{Z}_1} h^2 \), as calculated by IsaReD [36].

- The lifetime \( \tau_X \) of the long-lived neutral particle. Obviously, the longer-lived \( X \) is, the greater its potential to disrupt the successful BBN calculations.

- The hadronic branching fraction \( B_h \) of the long-lived neutral particle. If it is very small, then very little hadronic energy will be injected, and hence the constraints should be more mild.

The BBN constraints are shown in Fig. 9 (for \( m_X = 1 \) TeV) and Fig. 10 (for \( m_X = 100 \) GeV) of Ref. [43], as contours in the \( \tau_X \) vs. \( \Omega_X h^2 \) plane, with numerous contours for differing \( B_h \) values ranging from \( 10^{-5} \) to 1. For \( B_h \sim 0.1 \), for instance, and very large values of \( \Omega_X h^2 \sim 10 - 10^3 \), the lifetime \( \tau_X \) must be \( \lesssim 0.1 \) sec, or else the primordial abundance of \(^4\text{He} \) is disrupted. If \( \Omega_X h^2 \) drops below \( \sim 1 \), then much larger values of \( \tau_X \) up to \( \sim 100 \) sec are allowed. If one desires a long-lived hadronically decaying particle in the early universe with \( \tau_X \gtrsim 100 \) sec, then typically much lower values of \( \Omega_X h^2 \sim 10^{-6} - 10^{-4} \) are required. Such low neutralino relic densities are extremely hard to generate in SUSY models, even in the case of AMSB, or pure higgsino annihilation [44]. We have digitized the constraints of Ref. [43], implementing extrapolations for cases intermediate between values of parameters shown, so as to approximately apply the BBN constraints to our scenario with a long-lived neutralino decaying hadronically during BBN.

### 3.1 Neutralino lifetime

We have calculated the two-body decays of \( \tilde{Z}_1 \) to axinos, and find agreement with the results of Ref. [26]. In the notation of Ref. [3], we find

\[
\Gamma(\tilde{Z}_1 \to \tilde{a} \gamma) = \frac{\alpha^2 C^2_{\alpha Y} v_4^{(1)} \cos^2 \theta_W}{128 \pi^3} \frac{v_4^{(1)} \cos^2 \theta_W}{(f_a/N)^2} \frac{m_{\tilde{Z}_1}^3}{m_{\tilde{a}}^2} \left(1 - \frac{m_{\tilde{a}}^2}{m_{\tilde{Z}_1}^2}\right)^3 \tag{3.1}
\]

and

\[
\Gamma(\tilde{Z}_1 \to \tilde{a} Z) = \frac{\alpha^2 C^2_{\alpha Y} v_4^{(1)} \sin^2 \theta_W}{128 \pi^3} \frac{v_4^{(1)} \sin^2 \theta_W}{(f_a/N)^2} \frac{m_{\tilde{Z}_1}^3}{m_{\tilde{a}}^2} \left(1 - \frac{m_{\tilde{a}}^2}{m_{\tilde{Z}_1}^2}, \frac{m_{\tilde{a}}^2}{m_{\tilde{Z}_1}^2}\right)
\]
Figure 2: Lifetime (in seconds) of a bino-like $\tilde{Z}_1$ with a $\tilde{a}$ as LSP versus $m_{\tilde{Z}_1}$, for various choices of $(f_a/N)/v_4^{(1)}$ (in GeV units). We take $C_{aY} = 8/3$.

\[ \left(1 + \frac{m_{\tilde{a}}}{m_{\tilde{Z}_1}}\right)^2 - \frac{m_Z^2}{m_{\tilde{Z}_1}^2} \right] \left(1 - \frac{m_{\tilde{a}}}{m_{\tilde{Z}_1}}\right)^2 + \frac{m_Z^2}{2m_{\tilde{Z}_1}^2}, \]  

(3.2)

with $\alpha_Y = (e^2/4\pi)/\cos^2\theta_W$ the $U(1)_Y$ coupling; $C_{aY} = 8/3$ in the DFSZ model \[18\] and 0, 2/3 or 8/3 in the KSVZ model \[17\] depending on the heavy quark charge $e_Q = 0, -1/3$ or 2/3. Throughout our analysis we assume $C_{aY} = 8/3$. The above decays should be the only two-body decay modes allowed for the KSVZ model; for the DFSZ model, additional decays to higgs states may also be allowed. Since such decays depend on the type of DFSZ model, we do not consider them in our analysis.

Using the above formulae, in Fig. 2 we plot the lifetime $\tau(\tilde{Z}_1)$ in seconds versus $m_{\tilde{Z}_1}$ for various choices of $(f_a/N)/v_4^{(1)}$. The quantity $v_4^{(1)}$ denotes the bino-component of $\tilde{Z}_1$ in the notation of Ref. \[5\]. For models with a bino-like $\tilde{Z}_1$, $v_4^{(1)} \sim 1$. For models with a wino-like $\tilde{Z}_1$, as in AMSB, the lifetime will be enhanced by a large factor, since in these models $v_4^{(1)}$ is typically $10^{-2} - 10^{-3}$.

From Fig. 2, we see that for models with a bino-like neutralino and $\tau(\tilde{Z}_1) \lesssim 0.01$ sec, either very small $f_a/N \lesssim 10^{10}$ GeV are required, or if larger $f_a/N$ values are desired, then $m_{\tilde{Z}_1}$ must be very (perhaps uncomfortably) large. However, if $\tau(\tilde{Z}_1) < 10^2$ sec is needed, then values of $f_a/N$ as large as $10^{14}$ GeV are allowed, depending on $m_{\tilde{Z}_1}$.

3.2 Two- and three-body $\tilde{Z}_1$ decay to hadrons

Finally, to implement BBN constraints, we will need the hadronic branching fraction of $\tilde{Z}_1$ decay. If the decay $\tilde{Z}_1 \rightarrow \tilde{a}Z$ is open, then $B_h$ is just given by $B_h = \Gamma(\tilde{Z}_1 \rightarrow \tilde{a}Z)/\Gamma(\tilde{Z}_1) \times BF(Z \rightarrow hadrons)$. When the decay $\tilde{Z}_1 \rightarrow \tilde{a}Z$ is closed, we must instead calculate the three-body decay $\tilde{Z}_1 \rightarrow \tilde{a}q\bar{q}$. This decay is calculated in Ref. \[26\] via $\gamma$ and $Z^*$ exchange diagrams, but
neglecting interference terms. Here, we present the three-body width including interference:

\[
\frac{d\Gamma}{d\mu_k} = \frac{m_{\tilde{Z}_1}^3}{12\pi^2} \left[ G_\gamma^2 e^2 Q^2 \frac{(1 - \mu_k)^2(2 + \mu_k)}{\mu_k} + g_Z^2 G_Z^2 (g_V^2 + g_A^2) \frac{(1 - \mu_k)^2(2 + \mu_k)\mu_k}{m_{\tilde{Z}_1}^3} \right] + 2g_Z Qe g_V \Re(G_\gamma^* G_Z) \Re \left[ \frac{(1 - \mu_k)^2(2 + \mu_k)}{\mu_k - m_{\tilde{Z}_1}^2 + \frac{i\Gamma_Z m_{\tilde{Z}_1}}{m_{\tilde{Z}_1}} + \mu_k^2} \right],
\]

where the axino and quark masses have been neglected. In the above, \( G_Z = \frac{\alpha Y C a Y Y}{16\pi} \frac{v_1^{(1)}}{f_a/N} \sin \theta_W \), \( G_\gamma = \frac{\alpha V C a Y Y}{16\pi} \frac{v_1^{(1)}}{f_a/N} \cos \theta_W \), \( g_Z = \frac{e}{\sin \theta_W \cos \theta_W} \), \( g_V = T_3 - Q \sin^2 \theta_W \) and \( g_A = -T_3/2 \), where \( T_3 \) is the weak isospin of the quark \( q \). The above differential width is integrated over the range \( \mu_k : 4m_q^2/m_{\tilde{Z}_1}^2 \to 1 \). The quark mass acts as a regulator for the otherwise divergent photon-mediated contribution.

The hadronic branching fraction \( B_h \) of \( \tilde{Z}_1 \) is plotted in Fig. 3 versus \( m_{\tilde{Z}_1} \). The values of \( v_1^{(1)} \), \( C a Y Y \) and \( f_a/N \) cancel out in the branching fraction calculation, so the result is quite general. We see that for low values of \( m_{\tilde{Z}_1} \lesssim m_Z \), \( B_h \sim 0.02 \). Once \( m_{\tilde{Z}_1} \) exceeds \( m_Z \), the branching fraction for \( \tilde{Z}_1 \to \tilde{a}Z \) turns on and \( B_h \) increases asymptotically towards \( \sim 0.175 \). Armed with the values of \( \Omega_{\tilde{Z}_1} h^2 \), \( \tau(\tilde{Z}_1) \), \( B_h \) and the constraints of Ref. [43], we are now ready to explore allowed regions of PQMSSM parameter space which might reconcile thermal leptogenesis with the gravitino problem and at the same time satisfy the BBN constraints for late decaying neutralinos.

4. Allowed values of \( T_R \) in supersymmetric models

4.1 Five benchmark models

In this section, we discuss the sorts of models which might allow a reconciliation of thermal leptogenesis with the gravitino problem. Our starting point is to require models with a
rather heavy gravitino $m_\tilde{G} \gtrsim 30$ TeV, so as to avoid the gravitino BBN constraint. We also invoke mixed axion/axino dark matter with a light $a$ ($m_a \lesssim 1$ MeV) so as to avoid the gravitino-induced overclosure problem.

Models with multi-TeV scale gravitinos are rather limited. In ordinary gravity-mediation (SUGRA) models, the gravitino mass arises from the superHiggs mechanism in a hidden sector of the model. The gravitino mass then sets the scale for the soft SUSY breaking terms. This latter condition applies to the scalar sector in simple SUGRA models, while gaugino masses require in addition stipulation of the gauge kinetic function. We will assume here that gauginos are quite light; if instead gaugino masses are in the multi-TeV range, then RGE effects drive the third generation scalar soft masses into the multi-TeV range as well, thus engendering a conflict with naturalness.

Two types of SUGRA models have multi-TeV (1st and 2nd generation) scalar masses, while the 3rd generation is around the TeV scale, as motivated by the hierarchy problem. The first is Yukawa-unified SUSY (YU), in which scalar masses are preferred to be in the multi-TeV range at the GUT scale, while gauginos need to be quite light. In these models, the large, unified third generation Yukawa couplings drive the third generation soft terms down into the TeV range while first and second generation soft terms at $Q = M_{weak}$ remain in the multi-TeV regime \cite{15,16,17}. The SUSY particle mass spectrum for $\mu > 0$ is characterized as a radiatively driven inverted scalar mass hierarchy \cite{15}. When requiring consistency with B-physics constraints, the lightest neutralino is a nearly pure bino state, while scalars are quite heavy, thus suppressing the neutralino annihilation cross section. Generally, the neutralino relic density is large, of order $\Omega_{\tilde{Z}_1} h^2 \sim 10^{-10}$, far beyond the measured value. By invoking instead a light axino as LSP, the relic density of mixed axion/axino dark matter can be reconciled with observation \cite{10,19}. We present in Table 1 a Yukawa-unified benchmark model (model HSb from Ref. \cite{52}) with $m_{16} = 10$ TeV, which would be consistent with gravity mediation with a $\sim 30$ TeV gravitino mass. For this point, the lightest neutralino has mass $m_{\tilde{Z}_1} = 49$ GeV, and $\Omega_{\tilde{Z}_1} h^2 = 3195$.

The second type of gravity mediation model which would be consistent with $\sim 30$ TeV gravitinos is effective SUSY, or ESUSY \cite{53}. In Ref. \cite{54}, these models were explored with GUT scale soft SUSY breaking boundary conditions. Viable spectra with a weak scale inverted scalar mass hierarchy were found. For ESUSY models, first/second generation scalars could have mass $m_0 (1, 2)$ in the multi-TeV range at the GUT scale, while third generation scalar masses $m_0 (3)$ are in the few TeV range. Upon RG evolution, first/second generation scalars remain in the multi-TeV range, while third generation scalar masses are suppressed by two-loop RGE terms, and are sub-TeV at the weak scale. Benchmark point BM2 is an example of an ESUSY scenario.

If we proceed beyond gravity-mediation, then the class of models which necessarily supports multi-TeV gravitinos is anomaly-mediation (AMSB) \cite{55}. In these models, sparticle masses arise at the loop level via the superconformal anomaly. Sparticle masses are of order $m \sim \frac{g^2}{16\pi^2} m_{3/2}$, so that in order to support TeV scale sparticle masses, a gravitino mass of order $50 - 200$ TeV is needed. In AMSB models, the lightest neutralino is nearly a pure wino state with a relic density usually well below the measured $\Omega_{DM} h^2$, unless
|                  | BM1        | BM2        | BM3 (inoAMSB) | BM4        | BM5        |
|------------------|------------|------------|---------------|------------|------------|
| $m_{3/2}$ [TeV]  | 30         | 30         | 50            | 30         | 30         |
| $m_{16}$ or $m_0$| 10000      | 20575.6    | 0             | –          | –          |
| $m_{16(3)}$      | –          | 2922.94    | –             | –          | –          |
| $m_{1/2}$ or $M_2$| 43.94      | 1457.17    | 161.4         | –          | –          |
| $A_0$            | –19947.3   | 2177.84    | 0             | –          | –          |
| $m_{H_u}$        | 12918.9    | 3099.42    | –             | –          | –          |
| $m_{H_d}$        | 11121.0    | 2783.53    | –             | –          | –          |
| $\tan \beta$    | 50.398     | 6.8745     | 10            | 10         | 10         |
| $\alpha$         | –          | –          | –             | –1.6       | 6          |
| $n_m$, $n_H$     | –          | –          | –             | 0, 0       | $\frac{1}{2}$, 0 |
| $\mu$            | 3132.6     | 418.6      | 598.6         | 1136.8     | 992.6      |
| $m_{\tilde{G}}$  | 351.2      | 3507.1     | 1129.7        | 1354.1     | 1903.9     |
| $m_{\tilde{a}}$  | 9972.1     | 20739.8    | 993.9         | 1327.0     | 1770.1     |
| $m_{\tilde{t}}$  | 2756.5     | 652.8      | 861.6         | 804.3      | 1040.8     |
| $m_{\tilde{b}}$  | 3377.1     | 671.7      | 926.2         | 1123.7     | 1517.4     |
| $m_{\tilde{H}_L}$| 9940.7     | 20613.9    | 229.4         | 433.1      | 983.0      |
| $m_{\tilde{W}_1}$| 116.4      | 428.0      | 142.4         | 164.9      | 945.4      |
| $m_{\tilde{Z}_2}$| 113.8      | 425.3      | 443.5         | 164.6      | 943.7      |
| $m_{\tilde{Z}_1}$| 49.2       | 414.2      | 142.1         | 146.0      | 759.2      |
| $m_A$            | 1825.9     | 2832.5     | 632.8         | 1190.2     | 1584.1     |
| $m_h$            | 127.8      | 117.5      | 112.1         | 117.4      | 121.3      |
| $\Delta a_{\mu}$| $5.9 \times 10^{-12}$ | $2.4 \times 10^{-13}$ | $1.6 \times 10^{-9}$ | $-1.5 \times 10^{-10}$ | $1.3 \times 10^{-10}$ |
| $BF(b \to s\gamma)$ | $3.1 \times 10^{-4}$ | $2.9 \times 10^{-4}$ | $3.8 \times 10^{-4}$ | $3.5 \times 10^{-4}$ | $3.0 \times 10^{-4}$ |
| $BF(B_s \to \mu\mu)$ | $8.9 \times 10^{-9}$ | $3.8 \times 10^{-9}$ | $3.8 \times 10^{-9}$ | $3.8 \times 10^{-9}$ | $3.9 \times 10^{-9}$ |
| $v_4^{(1)}$      | 1          | 0.14       | 0.009         | 1          | $-0.99$    |
| $\Omega_{h^2}$   | 3195       | 0.04       | 0.0016        | 0.04       | 0.06       |
| $\sigma(\widetilde{Z}_{1p})$ [pb] | $3.3 \times 10^{-13}$ | $6.6 \times 10^{-9}$ | $4.4 \times 10^{-9}$ | $3.1 \times 10^{-11}$ | $1.4 \times 10^{-9}$ |

Table 1: Masses and parameters in GeV units for the five benchmark points. BM2–5 are computed with Isajet 7.81 using $m_t = 173.1$ GeV. BM1 uses Isajet 7.79 with $m_t = 172.6$ to be consistent with previous work.

$m_{\tilde{Z}_1} \gtrsim 1300$ GeV. For benchmark model BM3, we select a gaugino AMSB (inoAMSB) point with $m_{3/2} = 50$ TeV.\(^4\) It has been argued in Ref.\(^{56}\) that in string models the scalar soft masses and trilinear terms are actually suppressed, while gaugino masses assume the usual AMSB form. These models, with $m_0 = A_0 = 0$ at $M_{GUT}$, avoid the problem of tachyonic scalars which occurs in traditional AMSB models; the scalar masses are uplifted via RG running during their trajectories from $M_{GUT}$ to $M_{weak}$. While we do select the inoAMSB model as our benchmark point, very similar dark matter phenomenology occurs for mini-

\(^{4}\)We use different notations for the gravitino mass scale $m_{3/2}$ and the physical gravitino mass $m_{\tilde{G}}$, though $m_{\tilde{G}} \approx m_{3/2}$. 

---
mal AMSB (mAMSB) or hypercharged AMSB [57], since the defining characteristics are a wino-like lightest neutralino
[58].

The third class of models we examine also easily supports multi-TeV gravitinos. These are the mixed moduli-AMSB models [59], also known as mirage unification (MU). This class of models is inspired by the KKLT set-up of string models with flux compactifications and an uplifted scalar potential which can accommodate a positive cosmological constant [60]. While MU models require a multi-TeV gravitino mass, the lightest neutralino can easily remain bino-like, and can also have a very low relic abundance \( \Omega_{\tilde{Z}_1} h^2 \) at the 0.1 level or below. These models are stipulated by the parameters \( \alpha \), which governs how much gravity versus anomaly mediation occurs, along with \( m_{3/2} \) and \( \tan \beta \). One must also stipulate the matter and Higgs field modular weights \( n_m \) and \( n_H \), which take on values of 0, \( \frac{1}{2} \) or 1. The MU models are hard coded into the Isasugra spectrum generator.

Benchmark model BM4 takes \( \alpha = -1.6 \), \( m_{3/2} = 30 \) TeV, \( \tan \beta = 10 \) and \( n_m = n_H = 0 \). It has a bino-like lightest neutralino with \( m_{\tilde{Z}_1} = 146 \) GeV, but \( \Omega_{\tilde{Z}_1} h^2 = 0.04 \) due to binowo co-annihilation, or BWCA [61]. In BWCA, the gaugino masses \( M_1 \simeq -M_2 \) at the weak scale. Since the gaugino masses have opposite signs, there is no mixing between bino and wino states, although they can be close in mass and can thus co-annihilate. If instead \( M_1 \simeq +M_2 \) at the weak scale, then one obtains a \( \tilde{Z}_1 \) of mixed bino-wino content (which also occurs in MU models).

Benchmark model BM5 is also of the MU type, but with \( \alpha = 6 \), \( m_{3/2} = 30 \) TeV, \( \tan \beta = 10 \) and \( n_m = \frac{1}{2} \), \( n_H = 0 \). This model yields a bino-like \( \tilde{Z}_1 \) with mass \( m_{\tilde{Z}_1} = 759 \) GeV, but \( \Omega_{\tilde{Z}_1} h^2 = 0.06 \) due to neutralino annihilation through the pseudoscalar \( A \)-resonance [62].

In the following, we examine whether these scenarios are compatible with a \( T_R \) high enough to allow for thermal leptogenesis. To this aim we perform for each BM point a random scan over PQMSSM parameters in the range

\[
\begin{align*}
    m_{\tilde{a}} & \in [10^{-7}, 10^{-1}] \text{ GeV}, \\
    f_a/N & \in [10^{8}, 10^{14}] \text{ GeV}, \\
    \theta_i & \in [0, \pi].
\end{align*}
\]

and calculate the value of \( T_R \) which is needed to enforce \( \Omega_{a\tilde{a}} = 0.1123 \). As mentioned, a major constraint comes from the BBN bounds on the lifetime of the \( \tilde{Z}_1 \). A digitized version of these BBN bounds is shown in Fig. 4, in the \( \tau(\tilde{Z}_1) \) versus \( \Omega_{\tilde{Z}_1} h^2 \) plane. We also show the locus of benchmark points BM1–BM5 on the plot, along with the respective maximum allowed values of \( f_a/N \) which are consistent with the BBN bounds.

4.2 Gravity mediation: Yukawa unified SUSY

The YU model point BM1 has \( m_{\tilde{Z}_1} = 49 \) GeV, \( v_4^{(0)} = 1 \) and \( \Omega_{\tilde{Z}_1} = 3195 \). In addition we take \( m_{\tilde{G}} = 30 \) TeV. Since \( \Omega_{\tilde{Z}_1} h^2 \) is so large, the \( \tilde{Z}_1 \) lifetime is restricted to be \( \lesssim 0.03 \) sec by the BBN bounds from Ref. [43], see Fig. 4. The neutralino lifetime bound then translates into an upper bound on \( f_a/N \lesssim 3 \times 10^{10} \) GeV.
Figure 4: BBN bounds on late-decaying neutral particles with \( B_h = 0.1 \), digitized from Ref. \[43\], in the \( \tau(\tilde{Z}_1) \) versus \( \Omega_{\tilde{Z}_1} h^2 \) plane. We also show the locus of benchmark points BM1–BM5, along with their maximum allowed \( f_a/N \) values.

Figure 5: Scan over PQMSSM parameters for BM1 (YU model) plotted in the \( T_R \) vs. \( f_a/N \) plane. The blue points respect the \( \tilde{Z}_1 \rightarrow \tilde{a} + \text{hadrons} \) BBN bound, while the red points violate the BBN constraint. Points shown in light blue or light red have > 20% WDM or > 1% HDM, as discussed in the text.

The results of the scan over PQMSSM parameters, Eq. (4.1), are shown in Fig. 5 in the \( f_a/N \) vs. \( T_R \) plane. For \( T_R \) values above the diagonal line labelled \( T_R = T_{\text{dcp}} \), the axinos would have been in thermal equilibrium in the early universe; all points lie below, so the expression for \( \Omega_{\tilde{a}} h^2 \) in Eq. (2.7) is valid. In the figure, the [light and dark] blue dots denote points consistent with the neutralino BBN bound, while [light and dark] red dots denote points which violate BBN constraints. As shown in Fig. 1, the largest \( T_R \) values are mostly obtained for a light axino. Depending on its mass, the axino might constitute warm
(WDM) or hot (HDM) dark matter, which is severely constrained by the matter power spectrum and reionization [26, 63], see also [64, 65]. Since the bounds on the amount of HDM/WDM are model dependent [63], we do not impose such constraints on our results. However, as a guidance, we indicate by lighter colors the points which have:

- $m_{\tilde{a}} < 100$ keV and $\Omega_{\tilde{a}}/\Omega_{a} > 0.2$ or
- $m_{\tilde{a}} < 1$ keV and $\Omega_{\tilde{a}}/\Omega_{a} > 0.01$,

where $\Omega_{\tilde{a}} = \Omega_{\tilde{a}}^{TP} + \Omega_{\tilde{a}}^{\tilde{g}} + \Omega_{\tilde{a}}^{Z}$. Dark blue and dark red points thus have mostly CDM with at most 20% WDM and 1% HDM admixture.\(^5\)

As can be seen in Fig. 5, for values of $f_{a}/N$ consistent with BBN bounds, only $T_{R}$ values below $10^{8}$ GeV are allowed. Such low values of $T_{R}$ are insufficient to support thermal leptogenesis, but are sufficient to support non-thermal leptogenesis, which requires a more modest value of $T_{R} \gtrsim 10^{6}$ GeV [49, 50]. Note also that these points (with $T_{R} \sim 10^{6} - 10^{8}$ GeV) have a substantial fraction of WDM. In fact, as we will see later, for $Z_{1}$ masses of about 50 GeV, as typical for YU scenarios with $\mu > 0$, reconciling thermal leptogenesis with the gravitino problem requires a very low neutralino abundance, cf. Fig. 13. Such low abundances can indeed be achieved in a small region of the YU SUSY parameter space [47] or—perhaps more easily—using either generational non-universality, or gaugino mass non-universality [51].

### 4.3 Gravity mediation: Effective SUSY (ESUSY)

Another gravity-mediation model which requires multi-TeV scalars is effective SUSY. The ESUSY point BM2 has a mixed bino-higgsino NLSP with mass $m_{\tilde{Z}_{1}} = 414$ GeV. The $\tilde{Z}_{2}$ and $\tilde{W}_{1}$ are quite close in mass to the $\tilde{Z}_{1}$, followed by $\tilde{t}_{1}$ and $\tilde{b}_{1}$ which are just 60% heavier. This leads to $\Omega_{\tilde{Z}_{1}} h^{2} \sim 0.04$ due to simultaneous mixed bino-higgsino-wino enhanced annihilation, and also a contribution from stop and sbottom co-annihilation. The low $\Omega_{\tilde{Z}_{1}} h^{2}$ value allows $\tilde{Z}_{1}$ lifetimes up to $\sim 200$ sec, corresponding to $f_{a}/N$ values as high as $10^{13}$ GeV (see Fig. 4).

Such high $f_{a}/N$ values suppress the thermal production of axino dark matter, while low values of $\theta_{i}$ suppress the axion relic abundance. Scanning over PQMSSM parameters reveals that re-heat temperatures above $10^{12}$ GeV can be generated while avoiding overproduction of dark matter and maintaining consistency with BBN bounds. Thus, ESUSY models with a low abundance of neutralinos, mixed axion/axino dark matter with a high PQ scale and low $\theta_{i}$, apparently can reconcile thermal leptogenesis with the gravitino problem, although most of the solutions for BM2 have a potentially dangerous fraction of HDM/WDM.

We point out, however, that the BBN bounds will be less severe for similar scenarios with larger $\mu$ (i.e. less $\tilde{Z}_{1}$ higgsino admixture) but lighter $\tilde{t}_{1}$ or $\tilde{b}_{1}$, such that a low $\Omega_{\tilde{Z}_{1}} h^{2}$ arises from stop or sbottom co-annihilation; examples are discussed in [54].

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\(^5\)A rough estimate based on the neutrino mass limit [65] from cosmological data, $\sum m_{\nu} < 0.41$ to 0.44 eV, gives that up to 4–5% HDM contribution could be acceptable.
4.4 Anomaly mediation: gaugino AMSB

Next, we consider a gaugino AMSB model, point BM3. In this case, the relic abundance is much lower, $\Omega Z_1 h^2 = 0.016$, thus much longer $Z_1$ lifetimes of $\sim 800$ sec are allowed. Nevertheless, the $Z_1$ lifetime is suppressed in this case by the tiny value of $v_4^{(1)} \approx 0.01$, so that for BM3, $f_{a/N}$ values only as high as $2 \times 10^{11}$ GeV are allowed. The results are shown in Fig. 7 where we again show BBN-allowed and BBN-forbidden model points in the $f_{a/N}$ vs. $T_R$ plane. We see that just a few points barely exceed the rough requirement for thermal leptogenesis that $T_R > 2 \times 10^9$ GeV. If we increase $m_{\tilde{G}}$ beyond 50 TeV, then the value of $\Omega Z_1 h^2$ increases, requiring shorter $Z_1$ lifetimes, although the $Z_1$ lifetime also decreases as $\sim 1/m_{\tilde{Z}_1}^2$. We also note that the light blue points with $T_R > 2 \times 10^9$ GeV have axino masses of a few times $10^{-7}$ GeV. Overall, we conclude that AMSB models with a wino-like $Z_1$ can just barely reconcile thermal leptogenesis with the gravitino problem, however this would require a considerable fraction of axino HDM.

4.5 Mixed moduli/anomaly mediation with bino-wino co-annihilation

Let us now move to mirage unification models, and the BM4 point with bino-wino co-annihilation. In this case, the neutralino mass is 146 GeV and its relic density $\Omega Z_1 h^2 = 0.04$, so that $Z_1$ lifetimes of $\sim 200$ sec are allowed. Since the $Z_1$ is nearly pure bino, its decay is unsuppressed by $v_4^{(1)}$, and we find in Fig. 8 that $f_{a/N}$ values as high as $10^{13}$ GeV are allowed by BBN constraints. With such high $f_{a/N}$ values, the thermal production of axinos is suppressed, and $T_R$ values over $10^{12}$ GeV are allowed. Thus, these models are capable of reconciling thermal leptogenesis with the gravitino problem while avoiding BBN constraints.

In Fig. 9, we plot the scanned points for the BM4 point in the $\theta_i$ vs. $T_R$ plane. (In fact the analogous plot for BM2 looks almost the same.) We see that the BBN-allowed
blue points must have $\theta_i$ on the small side, certainly $< 1$ in order to avoid overproducing axions via vacuum mis-alignment, while maintaining $T_R \gtrsim 10^9$ GeV.

Figure 10 shows the scan results for BM4 in the $m_{\tilde{a}}$ vs. $T_R$ plane. Here, we see that the points which are BBN-allowed, and also are consistent with reconciling thermal leptogenesis with the gravitino problem require $m_{\tilde{a}} \lesssim 100$ keV. For values of $m_{\tilde{a}}$ lower than 100 keV, the axinos may start becoming warm rather than cold dark matter, and for values lower than 1 keV they contribute to HDM. Thus, if CDM/WDM constraints are properly applied, we expect that a small region of parameter space will be consistent with thermal leptogenesis, as roughly indicated by the dark blue points in Figs. 8–10.
4.6 Mixed moduli/anomaly mediation with neutralino annihilation on the $A$-resonance

Next, we turn to benchmark point BM5, a MU model with a bino-like neutralino with $m_{\tilde{Z}_1} = 759$ GeV and $\Omega_{\tilde{Z}_1} h^2 = 0.06$ due to neutralino annihilation through the $A$-resonance ($m_A = 1584$ GeV, so that $2m_{\tilde{Z}_1} \sim m_A$). The low value of $\Omega_{\tilde{Z}_1} h^2$ again allows for $\tilde{Z}_1$ lifetimes as high as $\sim 200$ sec. But now, since $m_{\tilde{Z}_1}$ is so large, $f_a/N$ values up to $\sim 10^{14}$ GeV are allowed by Fig. 8. The scanned points are shown in Fig. 11. We see that all points pass the BBN constraints, allowing for $T_R$ values in excess of $10^{12}$ GeV. This model again easily reconciles thermal leptogenesis with the gravitino problem.
Figure 11: Scan over PQMSSM parameters for BM5 (MU with A-resonance annihilation) plotted in the $T_R$ vs. $f_a/N$ plane. Same color code as in Fig. 5.

Figure 12: Scan over PQMSSM parameters for BM5 MU model plotted in the $T_R$ vs. $m_a$ plane. Same color code as in Fig. 5.

As in the case of BM4, $\theta_i$ values must be $\lesssim 1$, and for very high $T_R > 10^{11}$ GeV, $\theta_i < 0.4$. We conclude that small values of $\theta_i$ are necessary to allow for thermal leptogenesis in SUSY models with mixed axion/axino dark matter. We also show in Fig. 12 the scan result for BM5 in the $m_a$ vs. $T_R$ plane. Here we see that consistency with thermal leptogenesis requires axino masses $m_a \lesssim 10$ MeV. Thermally produced axinos with mass $\gtrsim 0.1$ MeV should constitute cold dark matter, so these points would have a mix of cold axions plus cold thermally produced axinos.
5. Conclusions

In this paper, we examined $R$-parity conserving supersymmetric models with a goal of reconciling thermal leptogenesis with the gravitino problem, via the postulation of mixed axion/axino dark matter. The mixed dark matter arises naturally from the Peccei-Quinn solution to the strong $CP$ problem in supersymmetric models.

In order to reconcile thermal leptogenesis with cosmological constraints, such as the dark matter relic abundance and the BBN bounds on late decaying particles, we conclude that the following conditions are necessary:

- $T_R \gtrsim 2 \times 10^9$ GeV, to allow for efficient thermal production of right-handed neutrinos in the early universe;

- $m_{\tilde{G}} \gtrsim 30$ TeV, to avoid BBN constraints on gravitino production in the early universe. Models with such a heavy gravitino are also favored in SUGRA models in that they set the scale for the scalar soft mass terms; if the scalar masses are sufficiently high, then they can suppress unwanted FCNC and CP violating processes and also proton decay via a decoupling solution [67];

- An axino LSP in keV to MeV mass range; this condition allows us to avoid overproduction of dark matter from axino thermal production in the early universe as well as from $\tilde{Z}_1$ and $\tilde{G}$ decays, since the matter density is then suppressed by the ratio $m_{\tilde{a}}/m_{\tilde{Z}_1,\tilde{G}}$. We also require a neutralino NLSP, which is common in supersymmetric models with heavy scalar masses;

- $f_a/N \gtrsim 10^{12}$ GeV, to suppress thermal overproduction of axino dark matter. The high value of $f_a/N$ means the axion mass is likely to lie in the sub-micro-eV range;

- $\theta_i \lesssim 1$, to avoid overproduction of axions when $f_a/N > 10^{12}$ GeV;

- $\Omega_{\tilde{Z}_1} h^2 \lesssim 1$, $m_{\tilde{Z}_1} \gtrsim 100$ GeV and/or $v_4^{(1)} \sim 1$, to avoid BBN constraints on the late decaying neutralino.

For the SUGRA case, we examined Yukawa-unified and effective SUSY models, since these can easily accommodate a 30 TeV gravitino mass. These models typically have too low an annihilation cross section for the neutralino NLSP in the early universe, which leads to conflicts with BBN constraints on late decaying neutral particles: in this case, hadronic neutralino decay via $\tilde{Z}_1 \rightarrow Z^*/\gamma \rightarrow \tilde{a}qq$.

The ESUSY model can more easily allow for low neutralino abundances via stop, sbottom, stau or higgsino co-annihilation. In these models, requiring the sum of four production mechanisms for mixed axion/axino DM to equal the measured abundance can allow for $T_R \gtrsim 10^{10}$ GeV, thus reconciling thermal leptogenesis with the gravitino problem.

In AMSB models, one naturally has a gravitino mass in the 50–100 TeV range and small $\Omega_{\tilde{Z}_1} h^2$, but with a wino-like neutralino. The decay rate of the wino-like $\tilde{Z}_1$ is suppressed by the mixing factor $v_4^{(1)}$, leading to long-lived $\tilde{Z}_1$s, and likely conflicts with BBN.
We also examined models with mixed moduli-AMSB (mirage unification) soft terms. These models allow for 30–100 TeV gravitinos, but with a bino-like neutralino, so its lifetime is typically \( \lesssim 100 \) sec. We examined two cases: bino-wino co-annihilation and \( A \)-resonance annihilation. Both cases easily allow \( T_R \) to reach over \( 10^{12} \) GeV, thus easily reconciling thermal leptogenesis with the gravitino problem, while respecting BBN constraints on long-lived neutralinos.

These findings are summarized in a model-independent way in Fig. 13, which shows PQMSSM scan points with \( T_R \gtrsim 2 \times 10^9 \) GeV in the \( \Omega_{\tilde{Z}_1} h^2 \) vs. \( f_a/N \) plane for \( m_{\tilde{Z}_1} = 50 \) and 500 GeV.\(^6\) In both cases, \( v_4^{(1)} = 1 \); recall that the neutralino lifetime scales as \( [v_4^{(1)}/(f_a/N)]^2 \). It is interesting to note that the reconciliation of thermal leptogenesis and the gravitino problem, in the framework used for our analysis, spans a wide range of \( \Omega_{\tilde{Z}_1} h^2 \), from \( \Omega_{\tilde{Z}_1} h^2 \sim 1 \) down to very low values. In particular for a light neutralino NLSP, very low \( \Omega_{\tilde{Z}_1} h^2 \) is required. Models with neutralino DM, on the other hand, would have \( \Omega_{\tilde{Z}_1} h^2 \sim 0.1 \), while models with a light axino DM and non-thermal leptogenesis would prefer \( \Omega_{\tilde{Z}_1} h^2 \gtrsim 100 \). Therefore distinct regions of the (PQ)MSSM parameter space are prefered depending on which DM and baryogenesis solutions are chosen.

Experimental consequences of this scenario to reconcile thermal leptogenesis with the gravitino problem in supersymmetric models include 1. a discovery at LHC of any of the models discussed here (or others) which support a gravitino mass in excess of 30 TeV, 2. the inferred apparent relic abundance of neutralinos is typically \( \Omega_{\tilde{Z}_1} h^2 \lesssim 1 \), 3. null results from direct or indirect WIMP searches, and 4. a positive signal for the QCD axion at sub-\( \mu \)eV levels at ADMX \(^{[66]}\) or other axion detection experiments.

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\(^6\)Additional entropy production from saxion decay may soften the BBN bounds; this is left for future work.
Figure 13: Model-independent scatter plot of points with $T_R \gtrsim 2 \times 10^9$ GeV in the $\Omega_{\tilde{Z}_1} h^2$ vs. $f_a/N$ plane for $m_{\tilde{Z}_1} = 50$ GeV (upper frame) and $m_{\tilde{Z}_1} = 500$ GeV (lower frame). Same color code as in Fig. 5.

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