Published by Institute of Physics Publishing for SISSA
Received: *April 23, 2005*
Accepted: *May 9, 2005*
Published: *June 22, 2005*

Natural soft leptogenesis

Yuval Grossman
Department of Physics, Technion-Israel Institute of Technology
Technion City, 32000 Haifa, Israel, and
Physics Department, Boston University
Boston, MA 02215, U.S.A, and
Jefferson Laboratory of Physics, Harvard University
Cambridge, MA 02138, U.S.A.
E-mail: yuvalg@physics.technion.ac.il

Ryuichiro Kitano
School of Natural Sciences, Institute for Advanced Study
Einstein Drive, Princeton, NJ 08540, U.S.A
E-mail: kitano@ias.edu

Hitoshi Murayama
Department of Physics, University of California
Berkeley, CA 94720, U.S.A., and
Theoretical Physics Group, Lawrence Berkeley National Laboratory
Berkeley, CA 94720, U.S.A.
E-mail: murayama@hitoshi.berkeley.edu

Abstract: Successful soft leptogenesis requires small B-terms for the right-handed sneutrinos and a large CP violating phase between the A- and B-terms. We show that this situation is realized naturally within the framework of gauge mediated supersymmetry breaking. The A-term is dominated by contribution from gauge mediation, while supergravity effects are more important for the B-term. The different origins naturally explain simultaneously the smallness of the B-term and the large CP violating phase. The most stringent bounds on the model come from the cosmological gravitino problem. We find a viable parameter region with very light gravitino $m_{3/2} \lesssim 16$ eV, providing a consistent framework for supersymmetry phenomenology, soft leptogenesis and cosmology.

Keywords: Supersymmetry Breaking, Cosmology of Theories beyond the SM, Baryogenesis.

Contents

JHEP06(2005)058

1. Introduction

Low-energy supersymmetry (SUSY) and leptogenesis [1] are both elegant ideas which account for theoretical and observational insufficiencies of the standard model. However, although each scenario is quite successful, their combination is not necessarily good; there is basically no new positive effect in SUSY leptogenesis that is absent in non-SUSY leptogenesis [2]. Moreover, SUSY does introduce new problems. In particular, the gravitino, the superpartner of the graviton, causes serious cosmological problems [3–6]. Big-bang nucleosynthesis puts a severe constraint on the reheating temperature of the universe to avoid too much production of gravitinos at high temperature. A recent calculation gives an upper bound $T_{\rm RH} \lesssim 10^6\,\mathrm{GeV}$ for typical gravitino mass $m_{3/2} \sim O(100\,\mathrm{GeV})$ [6]. Such a bound is generally inconsistent with the requirement of thermal leptogenesis $T_{RH} \gtrsim M_N \gtrsim 10^9\,\mathrm{GeV}$ [7].[1]

Recently, a new leptogenesis scenario, "soft leptogenesis," was proposed in which SUSY and SUSY breaking effects are positively utilized [11, 12]. The presence of the SUSY breaking terms enable the oscillation between right-handed sneutrinos and their anti-particles to induce significant CP violation in the sneutrino-decay processes. Interestingly, successful soft leptogenesis is achieved with relatively light right-handed (s)neutrinos. Therefore, soft leptogenesis opens up a new possibility of leptogenesis with low reheating temperature.

There are several conditions for soft leptogenesis to work. First, as mentioned above, the right-handed neutrino has to be light, $M_N \lesssim 10^8\,\mathrm{GeV}$, in order for the SUSY breaking effects to be important. For fixed neutrino masses, this implies small Dirac Yukawa coupling constants for neutrinos and thus the decay width of the right-handed sneutrino is quite narrow. In order for the oscillation effect to be large, the mass splitting between the two

[1]Several ways out had been pointed out in the literature, such as the right-handed sneutrino condensate [8], heavy gravitino mass in anomaly-mediated supersymmetry breaking [9], and resonant leptogenesis [10].

mass eigenstates of the right-handed sneutrinos cannot be too large or too small compared to their decay width. Since the mass splitting is controlled by the SUSY breaking B-parameter for the right-handed sneutrinos (see definitions below), the narrow width implies that we need a small value for the B-term. Finally, a large CP violating phase for the neutrino B-term is necessary. This might be problematic because the phase of the Higgs B-term is tightly constrained by low-energy experiments such as the electric dipole moment of the electron and the neutron [13].

In particular, in gravity mediated SUSY breaking scenarios, small B-term is difficult to realize since there is always a contribution of the order of the gravitino mass under the condition that the cosmological constant is canceled. We need a certain level of fine-tuning to realize $B \ll m_{3/2}$. For small Yukawa coupling, however, such smallness is stable under renormalization group equation (RGE) evolution. A model based on the assumption $B = 0$ at tree level has been considered in ref. [14]. Also, new ways of soft leptogenesis without small B-terms which require very light right-handed neutrinos, $M_N \lesssim 10^5\,\text{GeV}$, have been discussed in ref. [15].

In this paper we propose a natural framework that incorporates the above conditions and satisfies all the phenomenological and cosmological constraints such as CP violation in low-energy physics and the gravitino problem. The framework is quite simple; it is nothing but the gauge mediated SUSY breaking scenario [16, 17] without any additional structure. In gauge mediation, the neutrino B-term is generated by RGE running through the Yukawa interaction because the right-handed neutrinos are gauge singlet. In that case, the contribution from gravity mediation, which is of $O(m_{3/2})$, dominates the B-term which generally carries an $\mathrm{O}(1)$ CP violating phase. Since in gauge-mediation models the gravitino mass is smaller than the SUSY breaking scale, this is an ideal situation for soft leptogenesis.

This situation is perfectly consistent with bounds from low-energy phenomenology. Gravity-mediation effects are completely negligible to all other soft SUSY breaking terms, which are dominated by gauge mediation for low enough SUSY breaking scales, i.e., small gravitino mass parameters. Therefore our assumption of the large CP violation from gravity mediation does not pose new problems such as large flavor changing neutral currents (FCNCs) or CP violation. In particular, for the most dangerous term for CP violation, the Higgs B-term, the gauge-mediation contribution via RGE through the $\mathrm{SU}(2)_L$ gauge interaction is much larger than the gravity-mediation effect.

We find a viable parameter region, $10^3\,\text{GeV} \lesssim M_N \lesssim 10^6\,\text{GeV}$ with $m_{3/2} \lesssim 16$ eV, where soft leptogenesis can explain the baryon asymmetry of the universe without the gravitino problem. In gauge mediation, the gravitino is the lightest SUSY particle and thus stable (we assume R-parity conservation). The cosmological constraint comes from overproduction of the gravitinos at high temperature [18, 3] and also the suppression of the matter power spectrum at small scales [19]. However, these gravitino problems disappear for $m_{3/2} \lesssim 16$ eV since, simply, the gravitino energy density is small enough.

There is an interesting consistency of the scenario here. Gauge-mediation models with such a light gravitino have been constructed in refs. [20 – 23]. In particular, the models in ref. [20]–[22] are based on theories with a warped extra dimension. Inspired by the

AdS/CFT correspondence, these theories are claimed to be equivalent to four dimensional models with strong gauge dynamics. In the extra-dimensional or the conformal-field-theory setup, we are unable to discuss the conventional leptogenesis because the cosmology would be quite different from the four-dimensional or the weakly-coupled theory above temperatures of order 10 to 100 TeV. Since in our scenario the right-handed neutrinos can be lighter than that, our model provides a consistent framework for baryogenesis for such models. Explicit models with strongly coupled gauge theory are proposed in ref. [23]. These models have a weakly coupled description in high energy, and therefore both conventional and soft leptogenesis are operative in different parameter regions.

2. Soft leptogenesis

We start by briefly reviewing the mechanism of soft leptogenesis [11, 12, 15]. For simplicity, we consider a one-generation toy model which consists of the following superpotential

$$W = \frac{1}{2} M_N NN + YLNH \,. \tag{2.1}$$

Here N, L and H stand for, respectively, the gauge-singlet right-handed neutrino, lepton doublet and up-type Higgs doublet chiral superfields, and M_N and Y are the right-handed neutrino mass and the Yukawa coupling constant, respectively. Without SUSY breaking terms, the mass and the width of the right-handed neutrino and sneutrino are the same. Their mass is M_N and their width is given by

$$\Gamma = \frac{Y^2 M_N}{4\pi} = \frac{m M_N^2}{4\pi v^2} \,, \qquad m \equiv \frac{Y^2 v^2}{M_N} \,, \tag{2.2}$$

where $v \sim 174\,\mathrm{GeV}$ is the vacuum expectation value of the Higgs field. We defined the neutrino-mass parameter m which controls the efficiency of the out-of-equilibrium decay and is naturally of the order of the neutrino mass. Note that although it is identical to the neutrino mass in this one-generation model, this is, in principle, an independent parameter in a realistic three-generation model. The soft SUSY breaking terms relevant for soft leptogenesis are

$$\mathcal{L}_{\mathrm{soft}} = \frac{BM_N}{2} \widetilde{N}\widetilde{N} + AY\widetilde{L}\widetilde{N}H + \mathrm{h.c.} \tag{2.3}$$

This model has one physical CP violating phase

$$\phi = \arg(AB^*) \,. \tag{2.4}$$

The soft SUSY breaking terms introduce mixing between the sneutrino $\widetilde{N}$ and the anti-sneutrino $\widetilde{N}^\dagger$ in a similar fashion to the $B^0 - \bar{B}^0$ and $K^0 - \bar{K}^0$ systems. The mass and width difference of the two sneutrino mass eigenstates are given by

$$\Delta m = |B| \,, \qquad \Delta\Gamma = \frac{2|A|\Gamma}{M_N} \,. \tag{2.5}$$

A non-vanishing CP violating phase ϕ induces CP violation in the system. The CP violation in the mixing generates the lepton-number asymmetry in the final states of the $\widetilde{N}$ decay. This lepton asymmetry is converted into the baryon asymmetry through the sphaleron process. The baryon to entropy ratio is given by [12]:

$$\frac{n_B}{s} = -10^{-3}\eta \left[\frac{4\Gamma|B|}{4|B|^2+\Gamma^2}\right] \frac{|A|}{M_N} \sin\phi\,. \tag{2.6}$$

The efficiency parameter η slightly depends on the mechanism that produces the right-handed sneutrinos. Assuming thermal production, the value of η is suppressed for small and large m because of the insufficient $\widetilde{N}$ production and strong washout effect, respectively. The maximum value is $O(0.1)$ for $m \sim 10^{-(3-4)}$ eV [12]. From eq. (2.6) we learn that the right-handed neutrino mass, M_N, cannot be too large compared to the SUSY breaking scale because of the $|A|/M_N$ factor. Also, the B-parameter should not be much larger or smaller than the sneutrino width since otherwise the baryon asymmetry would be suppressed by $\Gamma/|B|$ or $|B|/\Gamma$, respectively. By fixing m, A, and the phase ϕ such that eq. (2.6) takes its maximal value, the above requirement gives a non-trivial constraint on the parameters [11, 12]:

$$Y \lesssim 10^{-4}, \qquad A \sim 10^2\,\mathrm{GeV}\,, \qquad M_N \lesssim 10^8\,\mathrm{GeV}, \qquad B \lesssim 1\,\mathrm{GeV} \qquad \phi \sim 1\,. \tag{2.7}$$

Smaller values of M_N, corresponding to smaller B, are preferred to avoid the gravitino constraint. For example, if we are to avoid the gravitino problem by lowering M_N to 10^6 GeV, $B \lesssim 1$ MeV is necessary. The value of B is somewhat problematic as its naively expected value is the weak scale, say, $B \sim 10^{2-3}$ GeV. It is our purpose to find a framework that can generate such a small B without affecting the other parameters.

3. Naturally small B-term

Next we show that gauge-mediation provides a natural framework for soft leptogenesis. The basic idea we are proposing is as follows. Consider gauge mediated SUSY breaking. This mechanism generates all the SUSY breaking parameters via the standard model gauge interactions [16, 17]. Therefore, the A-term in eq. (2.3) is generated through the gauge interactions of L and H. The B-term, on the other hand, remains very small because it is gauge singlet and its Yukawa coupling is tiny.[2] The dominant contribution to the B-term, in this case, comes from the gravity-mediation effect, which generates a B-term of the order of the gravitino mass with a phase that is generally different from that of the A-term.

We first estimate the size of the A- and B-terms in this scenario. We consider a messenger scale, M_{msg}, such that $M_N < M_{\mathrm{msg}} \ll M_{\mathrm{Pl}}$. At the messenger scale the gaugino masses, M_i, and the scalar masses squared, $\widetilde{m}^2$, are generated at the one- and two-loop

[2]Note that the right-handed neutrinos do not have to be gauge neutral above the messenger scale to avoid a large B-term. In particular, SO(10) unification is compatible with our framework.

JHEP06(2005)058

levels, respectively, and thus M_i and $\widetilde{m}$ obtain $O(\alpha)$ contributions. At this order the A- and B-terms are both vanishing. Non-vanishing contributions at low energy are generated through renormalization-group evolutions. The RGEs are given by

$$(4\pi)^2 \frac{d}{d\log\mu}(AY) = 2(-g_Y^2 M_1 - 3g_2^2 M_2)Y\,, \tag{3.1}$$

$$(4\pi)^2 \frac{d}{d\log\mu}(BM_N) = 8M_N AY^2\,, \tag{3.2}$$

where g_Y and M_1 (g_2 and M_2) are the gauge coupling constant and the gaugino mass of the $\mathrm{U}(1)_Y$ ($\mathrm{SU}(2)_L$) group, respectively. By integrating the above RGEs, we obtain the A- and B-parameters at the scale $\mu = M_N$

$$A(M_N) = \frac{M_2}{g_2^2}\left[-\frac{5}{3}\beta_Y^{-1}(g_Y^2(M_N) - g_Y^2(M_{\rm msg})) - 3\beta_2^{-1}(g_2^2(M_N) - g_2^2(M_{\rm msg}))\right], \tag{3.3}$$

$$B_{\rm gauge}(M_N) \simeq \frac{8}{(4\pi)^2}A(M_N)Y^2\log\frac{M_N}{M_{\rm msg}}\,, \tag{3.4}$$

where the prefactor in eq. (3.3), M_2/g_2^2, is an RGE invariant quantity at one-loop level, and β_Y and β_2 are the beta-function coefficients. In the minimal SUSY standard model (MSSM), those are given by $\beta_Y = 11$ and $\beta_2 = 1$. Using the measured values at low energy, $g_i(M_Z)$, the gauge coupling constants at $\mu = M_N$ and $M_{\rm msg}$ are given by $g_i(M_Z)$:

$$\frac{1}{g_i^2(\mu)} = \frac{1}{g_i^2(M_Z)} - \frac{2\beta_i}{(4\pi)^2}\log\frac{\mu}{M_Z}\,, \tag{3.5}$$

where $i = Y, 2$.

The crucial point to note from eqs. (3.3), (3.4) and (3.5) is that the B-term is very small. An A-term of the order of $g_2^2 M_2/(4\pi)^2$ is obtained through one-loop diagrams with gauge interactions. The B-term, however, is further suppressed by a factor of Y^2 ($\lesssim 10^{-8}$). Although the smallness of the B-term is one of the requirements of soft leptogenesis, this small B-term does not help us to get a viable model. The main reason is that it is generated by loop diagrams through the A-term and thus ϕ, the physical CP violating phase, vanishes at one-loop level.

Therefore, we need another mechanism that generates the B-term with non-trivial CP violating phase. This mechanism is already there in the form of gravity mediation. As long as $M_{\rm msg} \ll M_{\rm Pl}$, gravity-mediation contributions to all other terms are negligibly small. Thus, it does not affect the good features of gauge mediation, for example, the absence of FCNCs. The gravity mediation is expected to generate

$$B_{\rm grav} \sim m_{3/2}\,, \tag{3.6}$$

with $m_{3/2}$ being the gravitino mass. Since there is no connection between the phases of A and $B_{\rm grav}$, it is likely to be of order one, as desired. The total B-term is the sum of the two contributions, $B = B_{\rm grav} + B_{\rm gauge}$. The phase ϕ is expected to be

$$\sin\phi \sim \left|\frac{B_{\rm grav}}{B}\right|. \tag{3.7}$$

JHEP06(2005)058

In order to get a large CP violating phase we need the gravity-mediation effect to dominate the B-term, $|B_{\rm grav}| \gtrsim |B_{\rm gauge}|$. This is the case as long as $m_{3/2} \gtrsim 10^{-3} m M_N/v$.

Now we can calculate the baryon asymmetry in this scenario. Once we fix m, $m_{3/2}$, M_2 and M_N, we can estimate the baryon asymmetry using eq. (2.6). The messenger scale $M_{\rm msg}$ is obtained through the following relations

$$m_{3/2} = \frac{F}{\sqrt{3} M_{\rm Pl}}\,, \qquad M_2 = \frac{g_2^2 N}{(4\pi)^2} \frac{F}{M_{\rm msg}}\,, \tag{3.8}$$

where F is the F-component of the hidden-sector field that breaks supersymmetry, and N is the Dynkin index of the messenger fields. In our calculation we took $N = 1$ which corresponds to a pair of $\mathbf{5}$ and $\bar{\mathbf{5}}$ representation of the SU(5) group. (Our results are not very sensitive to the choice of N because the baryon asymmetry depends on N only through logarithmic functions.) Then we can obtain the A-term by using eqs. (3.3) and (3.5), and the B-term as a sum of the contributions in eqs. (3.4) and (3.6). The natural value of the phase ϕ is given in eq. (3.7). The Yukawa coupling constant in eq. (3.4) is estimated by fixing m.

In our numerical calculation, we took $M_2 = 200\,\text{GeV}$, $m = 10^{-3}$ eV, which corresponds to $\eta \sim 0.1$ (see ref. [12]), and two values for the B parameter, $B_{\rm grav} = m_{3/2}$ and $B_{\rm grav} = 10 m_{3/2}$. We found a large region in the parameter space that gives successful leptogenesis ($m_{3/2} \lesssim 1$ MeV and $M_N \lesssim 10^7$ GeV). We show in figure 1 the region in the $m_{3/2} - M_N$ plane where large enough baryon asymmetry is obtained. The shaded regions inside the solid lines are allowed corresponding to the values of B as indicated. The correct value of the baryon asymmetry is obtained on the lines when the phase is maximum, i.e., $\sin\phi \sim B_{\rm grav}/B$, while smaller values are needed inside the lines. In the left-upper region, the messenger scale is lower than the right-handed neutrino mass scale where gauge mediation does not generate the needed A-term. The region with $M_N \ll 1$ TeV is not allowed since in that case the sphaleron process is not active when the right-handed sneutrinos decay.

We checked the sensitivity of the allowed region to the input parameters. The allowed region is not very sensitive to M_2. On the other hand, it is rather sensitive to the variation of m mainly due to the fact that then η become smaller.

4. Constraints from gravitino cosmology

We consider the constraints on the model parameters from gravitino cosmology. In gauge-mediation models, the gravitino is the lightest SUSY particle and thus it is stable. Therefore the gravitinos generated at high temperature contribute to the matter density of the universe. In order for the gravitino energy density $\Omega_{3/2} h^2$ not to exceed the measured (non-baryonic) matter density of the universe, $\Omega_{\rm DM} h^2 = 0.11$, the reheating temperature is constrained to be [18, 3]:

$$T_{RH} \lesssim \begin{cases} 1\ \text{TeV} \left[\dfrac{m_{3/2}}{100\ \text{keV}}\right] \left[\dfrac{M_3}{1\ \text{TeV}}\right]^{-2} & \text{for } m_{3/2} \gtrsim 100\ \text{keV}\,, \\ 1\ \text{TeV} & \text{for } 100\ \text{keV} \gtrsim m_{3/2} \gtrsim 100\ \text{eV}\,, \\ \text{no bound} & \text{for } m_{3/2} \lesssim 100\ \text{eV}\,, \end{cases} \tag{4.1}$$

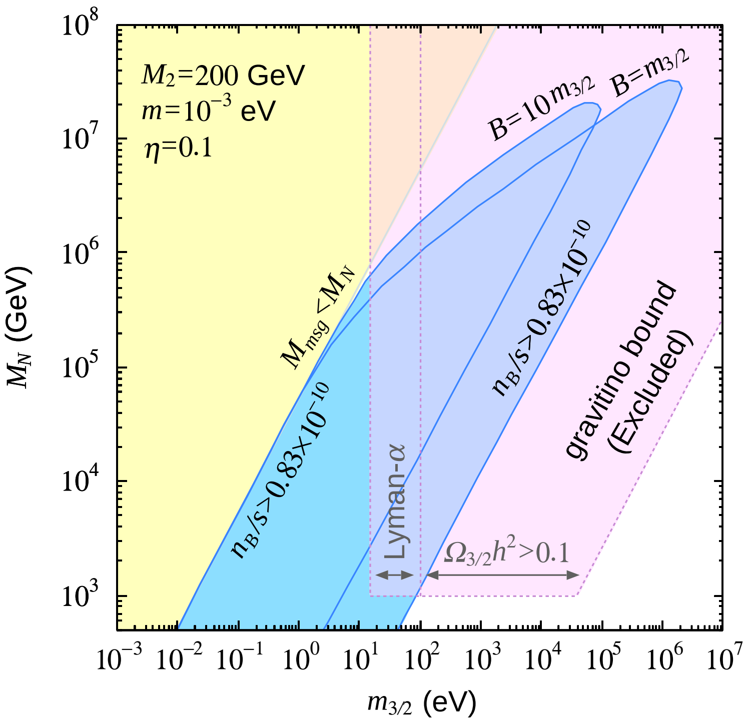

Figure 1: The region where we have successful baryogenesis is shown. We take $M_2 = 200$ GeV, $m = 10^{-3}$ eV, and $\eta = 0.1$. Contours of $n_B/s = 0.83 \times 10^{-10}$ are plotted for $B_{\rm grav} = m_{3/2}$ and $10m_{3/2}$ for the maximum CP phase. The baryon asymmetry is larger inside the lines, where the correct value can be obtained for smaller phases. The messenger scale is lower than M_N in the left-upper region. The regions inside the dashed lines are excluded by the too large gravitino energy density and the data from Lyman-α forest and WMAP.

where M_3 is the gluino mass. Note that there is no constraint for $m_{3/2} \lesssim 100$ eV. This is because, for such light gravitinos, the goldstino component of the gravitino has large interaction rate with the MSSM particles, and therefore the gravitino can thermalize at high temperature. The number density in this case is just the equilibrium value and thus the energy density is approximately given by $\Omega_{3/2}h^2 \sim 0.1(m_{3/2}/100 \text{ eV})$ with taking into account the dilution effect by the decoupling of heavy particles.

In this light gravitino region, we have another constraint from the matter power spectrum obtained by the Lyman-α forest and the WMAP data [19]. Since the gravitinos are warm (the free-streaming scale is comparable to galaxy scales) once they are thermalized, they would smear out the density perturbation at small scales if the gravitino contributes significantly to the matter density even though it is subdominant. This requires small $m_{3/2}$ such that the gravitino energy density is less significant. The excluded region is [19]

$$16 \text{ eV} \lesssim m_{3/2} \lesssim 100 \text{ eV}\,. \tag{4.2}$$

Assuming that right-handed sneutrinos are thermally produced, the reheating temperature has to be higher than M_N. Therefore eq. (4.1) gives a non-trivial constraint on the parameters. On the other hand, the excluded region in eq. (4.2) applies as long as the gravitinos are once thermalized. The bounds from eqs. (4.1) and (4.2) are superimposed on the allowed region in figure 1. We see that we still have an allowed region for very light gravitinos $m_{3/2} \lesssim 16$ eV and 10^3 GeV $\lesssim M_N \lesssim 10^6$ GeV.

Once we specify a mechanism for non-thermal production of the right-handed sneutrinos, the condition of $T_{RH} > M_N$ is relaxed and therefore the region where $m_{3/2} \gtrsim 100$ keV revives. The region 16 eV $\lesssim m_{3/2} \lesssim 100$ keV is still excluded since the bound is applicable as long as the gravitinos are thermalized. Our scenario needs the sphaleron process to be active. That requires temperatures higher than about 300 GeV where some of the SUSY particles are in thermal equilibrium with reasonable SUSY-breaking scales. The gravitinos are thermalized in that circumstance, and therefore the region is excluded regardless of the mechanism of the right-handed sneutrino production. Examples of the non-thermal production are direct production from inflaton decay and non-thermal production from coherent oscillation of $\widetilde{N}$. Such possibilities are worth further studies.

5. Discussions and conclusions

We considered soft leptogenesis in gauge mediated SUSY breaking scenario. We found that the needed small B-term and large CP violating phase are naturally obtained through gravity-mediation effects. We found a region in the parameter space with light right-handed neutrino 10^3 GeV $\lesssim M_N \lesssim 10^6$ GeV and light gravitino $m_{3/2} \lesssim 16$ eV, where the model observe all experimental and cosmological constraints.

The large CP phase in the neutrino B-term would not imply large phases in other soft terms, which would conflict with the low energy data. The source of the phase, the supergravity effect, is important for the terms which only involve gauge-singlet fields. For all other terms the gauge-mediation contributions overwhelm the tiny gravity-mediation effect, realizing an ideal situation for soft leptogenesis and low energy phenomenology.

Gauge mediated SUSY breaking with $m_{3/2} \lesssim 16$ eV is a very interesting possibility among various SUSY breaking scenarios because it completely avoids the FCNC/CP and cosmological gravitino problems. If we confirm the spectrum pattern of gauge mediation at the LHC/ILC experiments, this soft-leptogenesis scenario becomes an outstanding possibility for baryogenesis among various mechanisms. The low SUSY breaking scale, corresponding to the light gravitino, requires some models with strong dynamics or (probably equivalently) extra dimensions. In the extra-dimensional models, where the high-temperature physics is unclear, our scenario provides a simple and natural mechanism of baryogenesis at low temperature.

Acknowledgments

We thank Esteban Roulet and Yossi Nir for comments. We also thank the Aspen Center for Physics where this work was initiated. RK thanks the hospitality of the High Energy Theory Group at Harvard University. This work was supported by funds from the Institute for Advanced Study. The work of HM was supported in part by the DOE under contract DE-AC03-76SF00098 and in part by NSF grant PHY-0098840.

References

[1] M. Fukugita and T. Yanagida, *Baryogenesis without grand unification*, *Phys. Lett.* **B 174** (1986) 45.

[2] See, for example, M. Plümacher, *Baryon asymmetry, neutrino mixing and supersymmetric* SO(10) *unification*, *Nucl. Phys.* **B 530** (1998) 207 [hep-ph/9704231].

[3] H. Pagels and J.R. Primack, *Supersymmetry, cosmology and new TeV physics*, *Phys. Rev. Lett.* **48** (1982) 223.

[4] S. Weinberg, *Cosmological constraints on the scale of supersymmetry breaking*, *Phys. Rev. Lett.* **48** (1982) 1303.

[5] M.Y. Khlopov and A.D. Linde, *Is it easy to save the gravitino?*, *Phys. Lett.* **B 138** (1984) 265.

[6] M. Kawasaki, K. Kohri and T. Moroi, *Hadronic decay of late-decaying particles and Big-bang nucleosynthesis*, astro-ph/0402490; *Big-bang nucleosynthesis and hadronic decay of long-lived massive particles*, *Phys. Rev.* **D 71** (2005) 083502 [astro-ph/0408426].

[7] For recent numerical calculation, see G.F. Giudice, A. Notari, M. Raidal, A. Riotto and A. Strumia, *Towards a complete theory of thermal leptogenesis in the SM and MSSM*, *Nucl. Phys.* **B 685** (2004) 89 [hep-ph/0310123];
W. Buchmüller, P. Di Bari and M. Plümacher, *Leptogenesis for pedestrians*, *Ann. Phys. (NY)* **315** (2005) 305 [hep-ph/0401240];

[8] H. Murayama and T. Yanagida, *Leptogenesis in supersymmetric standard model with right-handed neutrino*, *Phys. Lett.* **B 322** (1994) 349 [hep-ph/9310297];
K. Hamaguchi, H. Murayama and T. Yanagida, *Leptogenesis from sneutrino-dominated early universe*, *Phys. Rev.* **D 65** (2002) 043512 [hep-ph/0109030].

[9] M. Ibe, R. Kitano, H. Murayama and T. Yanagida, *Viable supersymmetry and leptogenesis with anomaly mediation*, *Phys. Rev.* **D 70** (2004) 075012 [hep-ph/0403198];
M. Ibe, R. Kitano and H. Murayama, *A viable supersymmetric model with UV insensitive anomaly mediation*, *Phys. Rev.* **D 71** (2005) 075003 [hep-ph/0412200].

[10] M. Flanz, E.A. Paschos and U. Sarkar, *Baryogenesis from a lepton asymmetric universe*, *Phys. Lett.* **B 345** (1995) 248 [hep-ph/9411366];
M. Flanz, E.A. Paschos, U. Sarkar and J. Weiss, *Baryogenesis through mixing of heavy Majorana neutrinos*, *Phys. Lett.* **B 389** (1996) 693 [hep-ph/9607310];
A. Pilaftsis, *Resonant CP-violation induced by particle mixing in transition amplitudes*, *Nucl. Phys.* **B 504** (1997) 61 [hep-ph/9702393]; *CP-violation and baryogenesis due to heavy Majorana neutrinos*, *Phys. Rev.* **D 56** (1997) 5431 [hep-ph/9707235];
A. Pilaftsis and T.E.J. Underwood, *Resonant leptogenesis*, *Nucl. Phys.* **B 692** (2004) 303 [hep-ph/0309342].

[11] Y. Grossman, T. Kashti, Y. Nir and E. Roulet, *Leptogenesis from supersymmetry breaking*, *Phys. Rev. Lett.* **91** (2003) 251801 [hep-ph/0307081].

[12] G. D'Ambrosio, G.F. Giudice and M. Raidal, *Soft leptogenesis*, *Phys. Lett.* **B 575** (2003) 75 [hep-ph/0308031].

[13] J.R. Ellis, S. Ferrara and D.V. Nanopoulos, *CP violation and supersymmetry*, *Phys. Lett.* **B 114** (1982) 231;

W. Buchmüller and D. Wyler, *CP violation and R Invariance in supersymmetric models of strong and electroweak interactions*, *Phys. Lett.* **B 121** (1983) 321;
F.del Aguila, M.B. Gavela, J.A. Grifols and A. Mendez, *Specifically supersymmetric contribution to electric dipole moments*, *Phys. Lett.* **B 126** (1983) 71, erratum *ibid.* **B129** (1983) 473;
J. Polchinski and M.B. Wise, *The electric dipole moment of the neutron in low-energy supergravity*, *Phys. Lett.* **B 125** (1983) 393;
E. Franco and M.L. Mangano, *CP and flavor nonconservation in softly broken supersymmetric theories*, *Phys. Lett.* **B 135** (1984) 445;
J.M. Gérard, W. Grimus, A. Masiero, D.V. Nanopoulos and A. Raychaudhuri, *Aspects of CP violation in supersymmetric theories*, *Nucl. Phys.* **B 253** (1985) 93;
S.T. Petcov, *CP violation effect in neutralino pair production in $e^+ - e^-$ annihilation and the electric dipole moment of the electron*, *Phys. Lett.* **B 178** (1986) 57.

[14] E.J. Chun, *Late leptogenesis from radiative soft terms*, *Phys. Rev.* **D 69** (2004) 117303 [hep-ph/0404029].

[15] Y. Grossman, T. Kashti, Y. Nir and E. Roulet, *New ways to soft leptogenesis*, *JHEP* **11** (2004) 080 [hep-ph/0407063].

[16] M. Dine, A.E. Nelson and Y. Shirman, *Low-energy dynamical supersymmetry breaking simplified*, *Phys. Rev.* **D 51** (1995) 1362 [hep-ph/9408384];
M. Dine, A.E. Nelson, Y. Nir and Y. Shirman, *New tools for low-energy dynamical supersymmetry breaking*, *Phys. Rev.* **D 53** (1996) 2658 [hep-ph/9507378].

[17] For a review see, for example, G.F. Giudice and R. Rattazzi, *Theories with gauge-mediated supersymmetry breaking*, *Phys. Rept.* **322** (1999) 419 [hep-ph/9801271].

[18] T. Moroi, H. Murayama and M. Yamaguchi, *Cosmological constraints on the light stable gravitino*, *Phys. Lett.* **B 303** (1993) 289;
A. de Gouvêa, T. Moroi and H. Murayama, *Cosmology of supersymmetric models with low-energy gauge mediation*, *Phys. Rev.* **D 56** (1997) 1281 [hep-ph/9701244].

[19] M. Viel, J. Lesgourgues, M.G. Haehnelt, S. Matarrese and A. Riotto, *Constraining warm dark matter candidates including sterile neutrinos and light gravitinos with WMAP and the Lyman-alpha forest*, *Phys. Rev.* **D 71** (2005) 063534 [astro-ph/0501562].

[20] T. Gherghetta and A. Pomarol, *Bulk fields and supersymmetry in a slice of AdS*, *Nucl. Phys.* **B 586** (2000) 141 [hep-ph/0003129];
T. Gherghetta and A. Pomarol, *A warped supersymmetric standard model*, *Nucl. Phys.* **B 602** (2001) 3 [hep-ph/0012378].

[21] W.D. Goldberger, Y. Nomura and D.R. Smith, *Warped supersymmetric grand unification*, *Phys. Rev.* **D 67** (2003) 075021 [hep-ph/0209158];
Y. Nomura, *Supersymmetric unification in warped space*, hep-ph/0410348.

[22] Z. Chacko, Y. Nomura and D. Tucker-Smith, *A minimally fine-tuned supersymmetric standard model*, hep-ph/0504095.

[23] K.I. Izawa, *Strongly coupled messenger gauge theory*, *Prog. Theor. Phys.* **98** (1997) 443 [hep-ph/9704382];
K.I. Izawa, Y. Nomura, K. Tobe and T. Yanagida, *Direct-transmission models of dynamical supersymmetry breaking*, *Phys. Rev.* **D 56** (1997) 2886 [hep-ph/9705228];

K.I. Izawa, Y. Nomura and T. Yanagida, *A gauge-mediation model of dynamical SUSY breaking with a wide range of the gravitino mass*, *Phys. Lett.* **B 452** (1999) 274 [hep-ph/9901345];
K.I. Izawa and T. Yanagida, *Strongly coupled gauge mediation*, hep-ph/0501254.