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Viable Supersymmetry and Leptogenesis with Anomaly Mediation

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The seesaw mechanism that explains the small neutrino masses comes naturally with supersymmetric (SUSY) grand unification and leptogenesis. However, the framework suffers from the SUSY flavor and CP problems, and has a severe cosmological gravitino problem. We propose anomaly mediation as a simple solution to all these problems, which is viable once supplemented by the D-terms for $U(1)_Y$ and $U(1)_{B-L}$. Even though the right-handed neutrino mass explicitly breaks $U(1)_{B-L}$ and hence reintroduces the flavor problem, we show that it lacks the logarithmic enhancement and poses no threat to the framework. The thermal leptogenesis is then made easily consistent with the gravitino constraint.

The past several years have seen revolutionary progress in neutrino physics. The atmospheric neutrinos showed the first convincing evidence for neutrino oscillation in the SuperKamiokande experiment [1]. The long-standing solar neutrino problem since 1960s was shown to be due to the neutrino flavor conversion by the SNO experiment [2], and all possibilities other than neutrino oscillation have been excluded by the KamLAND experiment [3]. All these experiments suggest finite but extremely small neutrino mass in the sub-electronvolt range, more than a million times smaller than the smallest particle mass known before, namely the electron mass.

The standard framework to understand the newly discovered neutrino masses and mixings is the seesaw mechanism [4], which comes naturally with the supersymmetric (SUSY) grand-unified theories (GUT). Here, SUSY plays a dual role: it stabilizes the hierarchy and makes the gauge coupling constants unify. Furthermore, the seesaw mechanism predicts new heavy particles, right-handed neutrinos, whose decay can potentially produce the baryon asymmetry of the universe [5]. This possibility is called leptogenesis, which requires $T_{RH} > 4 \times 10^9$ GeV to generate the observed baryon asymmetry [6] [49]. The combination of seesaw, SUSY GUT, and leptogenesis is further supplemented by the possibility of SUSY dark matter, which predicts the cosmic abundance of the dark matter particle in the right ballpark.

There are, however, severe problems with this attractive framework. SUSY tends to induce unacceptably large flavor-changing and CP-violating effects; SUSY flavor and CP problems [8]. Generic SUSY parameters imply a lower limit on the masses in excess of 100 TeV, making supersymmetry not a viable mechanism to stabilize the electroweak scale $m_Z = 91$ GeV. It is customary to make an *ad hoc* assumption of the universal scalar mass at the GUT- or Planck-scale to avoid the flavor problem. However, the rates of Lepton Flavor Violation (LFV) processes are typically predicted to be too high in SUSY-GUT models based on the seesaw mechanism and flavor symmetries even with the universal scalar mass [9]. At the same time, SUSY predicts the existence of the gravitino, the superpartner of the graviton. Once it is produced in early universe, it decays only by the gravitational interaction and hence slowly, upsetting the success of BBN [10]. The gravitino yield is larger for higher reheating temperatures. A detailed analysis including the hadronic decay of gravitino shows a very tight upper limit $T_{RH} \ll 10^6$ GeV [11] for $m_{3/2} = 0.1$–1 TeV as commonly assumed in the literature. Therefore the leptogenesis appears incompatible with the gravitino problem.

There had been suggestions to achieve leptogenesis at a relatively low temperature (for a compilation of proposals, see [12]). In particular, coherent oscillation of right-handed scalar neutrino [13] had been considered a natural possibility, and it may even be the inflaton [14]. However, this proposal requires the reheating temperature to be above 10^6 GeV [15] which is still in conflict with the gravitino problem. More recent suggestions include the gravitino LSP [16], but even this case is getting tightly constrained.

In this Letter, we revisit these problems and propose a simple solution: anomaly-mediated supersymmetry breaking [17, 18]. It predicts a heavy gravitino that decays before BBN and makes leptogenesis viable. It solves the flavor and CP problems automatically if supplemented by the UV-insensitive D-terms [19]. Even though the strict version of the UV-insensitive anomaly mediation requires $B - L$ conservation, it was pointed out that the seesaw mechanism can be used with minimal flavor-changing effects [19]. However, the details of reintroduced flavor-changing effects had not been worked out. We present consequences of the seesaw mechanism on LFV. We find that the LFV effects lack logarithmic enhancements unlike in conventional supergravity-based scenarios and hence are easily compatible with current limits. Therefore this framework preserves all virtues of anomaly mediation to solve the SUSY flavor and CP problems and makes the thermal leptogenesis viable. On the other hand, the small LFV may lead to a signature observable in the near future.

Let us set up notations to discuss seesaw mechanism with SUSY GUT. The relevant part of the superpotential is

$$W = h_{i\alpha} L_i N_\alpha H_u + \frac{1}{2} M_\alpha N_\alpha N_\alpha. \tag{1}$$

We use the basis where the right-handed neutrino masses M_α are diagonal and real positive. The light neutrino mass is then obtained by integrating out N_α, $(m_\nu)_{ij} = \sum_\alpha h_{i\alpha} h_{j\alpha} \langle H_u \rangle^2 / M_\alpha$. Therefore the light neutrino masses are suppressed relative to the other quark and lepton masses

by the inverse power of M_α. In order to obtain the heaviest mass $m_3 \gtrsim \sqrt{\Delta m_{\text{atm}}^2} \simeq 0.05$ eV, we find $M_3 \lesssim 6 \times 10^{14}$ GeV, which can be induced from the grand-unification scale $M_{GUT} \simeq 2 \times 10^{16}$ GeV.

How do we solve the SUSY flavor and CP problems, while make the leptogenesis consistent with the gravitino problem? There is a promising mechanism to make the whole framework consistent. Anomaly mediation of SUSY breaking [17, 18] induces the SUSY breaking effects from the superconformal anomaly, and hence they are determined solely by physics at the energy scale of interest. When applied to the SUSY standard model, it automatically solves the serious flavor and CP problems. Because the anomaly is a quantum effect and hence loop-suppressed, the typical SUSY masses are smaller than the gravitino mass by $(4\pi)^2$, implying that the gravitino is heavy, $m_{3/2} \simeq 100$ TeV. Such a large mass allows the gravitino to decay before BBN, and hence the gravitino is harmless. The only constraint is that stable Lightest Supersymmetric Particle (LSP) from the gravitino decay does not provide too much dard matter of the universe. It requires [20]

$$T_{RH} \leq 2.1 \times 10^{10} \text{ GeV} \left(\frac{m_{LSP}}{100 \text{ GeV}} \right)^{-1}. \qquad (2)$$

This constraint can be satisfied together with the requirement for the thermal leptogenesis $T_{RH} > 4 \times 10^9$ GeV. The upper bound on the LSP mass, $m_{\text{LSP}} \lesssim 500$ GeV, is derived from the consistency between those two requirements, by assuming there is no significant annihilation after the gravitino decays.

Despite these attractive features, anomaly mediation has not been used widely in the literature because of several initial problems. The slepton mass-squared comes out negative, breaking the electromagnetism spontaneously. Many fixes proposed in the literature [21, 22, 23, 24, 25, 26, 27, 28, 29] unfortunately spoils the UV insensitivity and hence reintroduces the flavor and CP problems, unless R-parity is violated [30]. On the other hand, the addition of D-terms for $U(1)_Y$ and $U(1)_{B-L}$ can make the slepton mass-squared positive [31], and furthermore the UV insensitivity is preserved [19]. The viable electroweak symmetry breaking was demonstrated only recently [32] which goes extremely well with the low-energy limit of the Minimal Fat Higgs Model [33]. Even though the original setting relied on extra dimensions [17], it can now be constructed in a purely four-dimensional setting [34] together with the required D-terms [35]. Therefore, anomaly mediation can be finally regarded as a consistent and viable framework of supersymmetry breaking.

The $U(1)_{B-L}$ gauge invariance is broken at some high scale, and its only remnant is its D-term $V_{B-L} = \theta^2 \bar\theta^2 D_{B-L}$ and an accidental global non-anomalous $U(1)_{B-L}$ symmetry to ensure the UV insensitivity. The Kähler potential $\int d^4\theta \phi_i^* e^{q_i V_{B-L}} \phi_i$ for a matter field of $B - L$ charge q_i gives a contribution to its mass-squared $(m_i^2)_D = -q_i D_{B-L}$ (there is also Fayet–Illiopoulos term for $U(1)_Y$ that is not relevant in this paper). On the other hand, the seesaw mechanism breaks $B - L$ explicitly by the Majorana mass of right-handed neu-

trinos, and reintroduces the flavor violation in a highly controlled fashion. This effect had not been worked out quantitatively in the original work [19], and we study it in detail in this Letter.

We first derive the expression of the threshold corrections from the right-handed neutrinos. The correction to the slepton mass matrices due to the $B - L$ breaking in right-handed Majorana masses can be worked out using the "analytic continuation into superspace" [36] used extensively in anomaly mediation [19, 21, 37]. M_α in Eq. (1) are the only $B - L$ violating parameters in the theory. Using the fictitious gauge invariance $N_\alpha \to e^{iq_\alpha \Lambda} N_\alpha$, $e^{V_{B-L}} \to e^{i\Lambda^*} e^{V_{B-L}} e^{-i\Lambda}$, and $M_\alpha \to M_\alpha e^{-i2q_\alpha \Lambda}$, it is clear that the only combination that can appear in the low-energy theory is $M_\alpha^* e^{-2q_\alpha V_{B-L}} M_\alpha$. It appears in the Kähler potential for the left-handed leptons L_i and H_u at the one-loop level

$$Z_{ij} = Z_{ij}^0 - \sum_\alpha \frac{h_{i\alpha} h_{j\alpha}^*}{(4\pi)^2} \log \frac{M_\alpha^* e^{-2q_\alpha V_{B-L}} M_\alpha}{\mu^2}, \qquad (3)$$

$q_\alpha = +1$ is the $B - L$ charge of the N_α superfield. μ is the renormalization scale. The wave-function renormalization factor Z_{ij}^0 is for the case of massless right-handed neutrinos and exact $U(1)_{B-L}$ invariance, and hence gives a fully UV insensitive supersymmetry breaking. The second term subtracts the contribution of the right-handed neutrinos between their mass thresholds M_α and the renormalization scale $\mu \ll M_\alpha$. Here, the vector superfield V_{B-L} contains the required D-term, and makes M_α dependence invariant under the (spurious) $U(1)_{B-L}$ symmetry. It induces the correction to the left-handed slepton mass-squared matrix,

$$\Delta m_{ij}^2 = -2 \sum_\alpha \frac{h_{i\alpha} h_{j\alpha}^*}{(4\pi)^2} D_{B-L}. \qquad (4)$$

Note that there is no flavor-violating correction to the right-handed sleptons. Corresponding formula in the minimal supergravity (mSUGRA) that assumes the universal scalar mass is [38]

$$\Delta m_{ij}^2 = -\sum_\alpha \frac{h_{i\alpha} h_{j\alpha}^*}{(4\pi)^2} (3m_0^2 + A_0^2) \log \frac{\Lambda_{UV}^2}{M_\alpha^2}, \qquad (5)$$

where m_0 is the universal scalar mass at the ultraviolet cutoff Λ_{UV} and A_0 the universal trilinear coupling.

There are several remarkable aspects in Eq. (4). First, there is no logarithmic enhancement. In contrast, the usual supergravity theories are UV sensitive and hence the contributions of the right-handed neutrinos are enhanced by $\log(\Lambda_{UV}/M_\alpha)$ as seen in Eq. (5). Therefore the size of possible LFV is under a much stronger control in the anomaly mediation. Related to the aspect, Eq. (4) is independent of physics above the right-handed mass scale since the contribution originates from the threshold effect of N_α as we see below in the explicit diagrammatic calculation. In the mSUGRA, in contrast, we need to know the theory above M_α, especially above M_{GUT}, to
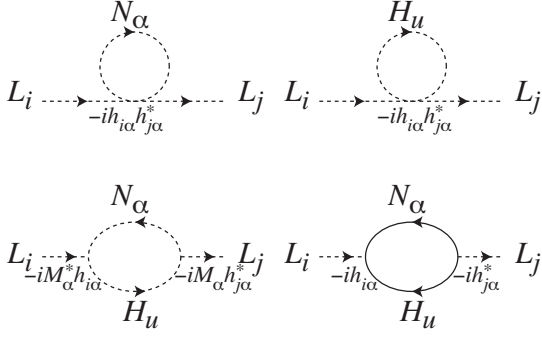
FIG. 1: The Feynman diagrams which contribute to the slepton soft masses.

calculate Δm_{ij}^2 by carrying out the integration of the renormalization group equations with initial conditions given at the Planck scale. Second, the corrections do not depend on the mass of the right-handed neutrinos M_α explicitly (but implicitly through $h_{i\alpha}$ once the light neutrino masses are held fixed). Once we observe LFV processes and measure the branching ratios, the simple structure of Δm_{ij}^2 in Eq. (4) enables us to extract easily the the Yukawa matrix $h_{i\alpha}$ which has important information on the origin of the large mixing among neutrinos, *i.e.*, whether the large mixing comes from the left-handed lepton sector, the right-handed neutrino sector, or both sectors. Third, because the corrections are suppressed by the one-loop factor relative to the leading anomaly-mediated contributions thanks to the absence of the logarithmic enhancement, the leading-order trajectory of the soft SUSY breaking parameters is still strictly that of the UV insensitive anomaly mediation. Finally, even if there is a flavor-violating interaction between quarks and leptons below M_α (*i.e.*, leptoquarks), the induced flavor-violation in quarks is at most of the order of Δm_{ij}^2 above, while the squarks are heavier than the typical size of D_{B-L} by a factor of g_s^4/g^4. Therefore it will not pose a serious threat.

There is a corresponding correction to the Higgs mass

$$\Delta m_{H_u}^2 = -2 \sum_{i,\alpha} \frac{h_{i\alpha} h_{i\alpha}^*}{(4\pi)^2} D_{B-L}. \qquad (6)$$

However, this is a loop-suppressed effect relative to the leading anomaly-mediated contribution, and does not lead to flavor-violating effects. It can be safely ignored for all practical purposes.

Because the absence of the logarithmic enhancement is a striking result, it is useful to examine it with the conventional Feynman diagrams shown in Fig. 1. We use regularization by dimensional reduction (DRED) in $D = 4 - 2\epsilon$ dimensions to perform loop integrals. Because the anomaly-mediated pieces due to the neutrino Yukawa couplings are canceled exactly by the threshold corrections [36, 37], we only consider D-term contributions to the scalar masses-squared, m_α^2 for N_α, $m_{H_u}^2$ for H_u, and m_i^2 for L_i (of course $m_{H_u}^2 \propto q_{H_u} = 0$, but we retain it for the clarity of presentation). The sum of all boson

	Point I	Point II
	$\tan\beta = 0.9$	$\tan\beta = 5$
	$m_{3/2} = 47$ TeV	$m_{3/2} = 142$ TeV
$BR(\mu \to e\gamma)$	$1.6 \times 10^{-8}|h_{1\alpha} h_{2\alpha}^*|^2$	$3.9 \times 10^{-7}|h_{1\alpha} h_{2\alpha}^*|^2$
$BR(\mu \to e; \text{Al})$	$5.4 \times 10^{-10}|h_{1\alpha} h_{2\alpha}^*|^2$	$8.9 \times 10^{-10}|h_{1\alpha} h_{2\alpha}^*|^2$
$BR(\tau \to \mu\gamma)$	$8.3 \times 10^{-10}|h_{2\alpha} h_{3\alpha}^*|^2$	$6.5 \times 10^{-8}|h_{2\alpha} h_{3\alpha}^*|^2$

TABLE I: The branching ratios of the LFV processes are shown in the two points of the parameter space chosen in [32]. The branching ratios scale as $m_{3/2}^{-4}$ and $\tan^2\beta$.

loops at $q^2 = 0$ gives

$$\frac{ih_{i\alpha} h_{j\alpha}^*}{(4\pi)^{2-\epsilon}} \left\{ -2m_\alpha^2 \right.$$
$$\left. + (2M_\alpha^2 + m_{H_u}^2 + m_\alpha^2) \left(\frac{1}{\epsilon} + 1 - \gamma - \log\frac{M_\alpha^2}{\mu^2} \right) \right\}, (7)$$

while the fermion loop gives the correction at $q^2 = 0$,

$$\frac{ih_{i\alpha} h_{j\alpha}^*}{(4\pi)^{2-\epsilon}} (-2M_\alpha^2) \left(\frac{1}{\epsilon} + 1 - \gamma - \log\frac{M_\alpha^2}{\mu^2} \right). \qquad (8)$$

Finally the leading q^2 dependence of the two-point function is

$$q^2 \frac{ih_{i\alpha} h_{j\alpha}^*}{(4\pi)^{2-\epsilon}} \left(\frac{1}{\epsilon} + 1 - \gamma - \log\frac{M_\alpha^2}{\mu^2} \right), \qquad (9)$$

which gives the wave function renormalization factor. Putting them together, the final correction to the slepton masses-squared is

$$-i\Delta m_{ij}^2 = \frac{ih_{i\alpha} h_{j\alpha}^*}{(4\pi)^{2-\epsilon}} \left\{ -2m_\alpha^2 \right.$$
$$\left. + (m_{H_u}^2 + m_\alpha^2 + m_i^2) \left(\frac{1}{\epsilon} + 1 - \gamma - \log\frac{M_\alpha^2}{\mu^2} \right) \right\}. (10)$$

Because the D-term contributions satisfy $m_{H_u}^2 + m_\alpha^2 + m_i^2 = -(q_{H_u} + q_\alpha + q_i)D_{B-L} = 0$ due to the $B - L$ conservation of the Yukawa coupling, the logarithmic piece automatically cancels, and the result agrees with the spurion method.

Using our result Eq. (4), we list in Table I the branching ratios of the $\mu \to e\gamma$ decay, the $\mu \to e$ conversion process in Al nuclei [39], and the $\tau \to \mu\gamma$ decay using representative parameter sets point I and II worked out in [32] [50]. For other parameter sets, the branching ratios can be estimated by the scaling of $m_{3/2}^{-4}$ and $\tan^2\beta$.

To get a sense on the size of LFV, we consider a simple neutrino mass model based on flavor $U(1)$ symmetry that is consistent with leptogenesis. It assigns the flavor $U(1)$ charges $L_1(1), L_2(0), L_3(0), N_1(2), N_2(1), N_3(0)$. The flavor $U(1)$ is assumed to be broken by an order parameter $\epsilon \simeq 0.1$. The

Yukawa matrix is

$$h_{i\alpha} \simeq h_t \begin{pmatrix} \epsilon^3 & \epsilon^2 & \epsilon \\ \epsilon^2 & \epsilon & 1 \\ \epsilon^2 & \epsilon & 1 \end{pmatrix}, \tag{11}$$

while the right-handed neutrino masses are $M_1 : M_2 : M_3 \simeq \epsilon^4 : \epsilon^2 : 1$. The top Yukawa coupling is approximately $h_t(M_3) \simeq 0.6$ for $\tan\beta \gtrsim 5$. The light neutrino masses from the seesaw mechanism are

$$m_\nu \propto \begin{pmatrix} \epsilon^2 & \epsilon & \epsilon \\ \epsilon & 1 & 1 \\ \epsilon & 1 & 1 \end{pmatrix}. \tag{12}$$

This type of model was considered in [40], and can successfully produce the observed baryon asymmetry from the decay of N_1. Note that the mass of N_1 is about 10^{10} GeV and is allowed by the gravitino constraint Eq. (2) from the overclosure by the LSP. We find $|h_{1\alpha} h_{2\alpha}^*| \simeq h_t^2(M_3)\epsilon \simeq 0.036$ in this model [9]. Thus the branching ratios are roughly estimated to be 10^{-11} (point I) and 10^{-10} (point II). By taking into account the $O(1)$ ambiguity in the model parameters, the predictions are comparable to the current experimental upper bound 1.2×10^{-11} [41]. In both points, observation of the $\mu \to e\gamma$ decay in the planned experiments [42, 43] is quite promising. Also, the values for $\tau \to \mu\gamma$ and $\mu \to e$ conversion are in the interesting range for on-going [44, 45], or future [43, 46] experiments, respectively.

The corresponding analyses have been done in the mSUGRA, and stringent bounds on the model parameters are obtained since the logarithmic factor in Eq. (5) gives $O(100)$ enhancement in $BR(\mu \to e\gamma)$. The situation is particularly severe in models with Yukawa unification and flavor symmetries [9]. With fixing $\tan\beta$ and the $SU(2)_L$ gaugino mass M_2 to be $\tan\beta = 3$ and $M_2 = 150$ GeV, the lower bound on the scalar electron mass is found to be more than 1 TeV for the same Yukawa couplings as above. The bound is more severe for larger values of $\tan\beta$. Too large LFV is a generic feature in the mSUGRA with the seesaw model when the right-handed neutrino scale is relatively high, unless we assume a specific texture of the Yukawa matrix [47] or a cancellation among the diagrams [48]. It is interesting to recall that the universal scaler mass is introduced by hand to avoid too large FCNC in the mSUGRA. However, the prescription is insufficient in the seesaw model. The situation is significantly improved in the anomaly mediation because of the absence of the logarithmic factor.

In conclusion, we have presented a framework where SUSY flavor and CP problems are automatically solved and the thermal leptogenesis is made consistent with the gravitino constraint. It relies on UV insensitive anomaly-mediated supersymmetry breaking supplemented by the D-terms for $U(1)_{B-L}$ and $U(1)_Y$. The right-handed neutrino mass explicitly breaks $U(1)_{B-L}$ and reintroduces the lepton flavor violation (LFV), but it lacks the logarithmic enhancement unlike in mSUGRA. Therefore the size of LFV is easily consistent with the current limits while it is already threatening in the mSUGRA for the same neutrino parameters. Also, calculation of the LFV processes is less ambiguous in the framework, since the corrections to the slepton masses are independent of physics above the mass scale of the right-handed neutrinos.

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[49] A high degree of degeneracy among right-handed neutrinos may resonantly enhance the baryon asymmetry and may allow for lighter right-handed neutrinos [7].

[50] Strictly speaking, the Fat Higgs model [33] requires an $O(1)$ mixing between the composite and elementary Higgs fields, and the Yukawa couplings $h_{i\alpha}$ need to be scaled by the mixing angle.