Low-energy supersymmetry breaking without the gravitino problem

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Low-energy Supersymmetry Breaking Without the Gravitino Problem

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In models of low-energy gauge mediation, the observed Higgs mass is in tension with the cosmological limit on the gravitino mass $m_{3/2} \lesssim 16$ eV. We present an alternative mediation mechanism of supersymmetry breaking via a $U(1)$ D-term with an E_6-inspired particle content, which we call *vector mediation*. The gravitino mass can be in the eV range. The sfermion masses are at the 10 TeV scale, while gauginos around a TeV. This mechanism also greatly ameliorates the μ-problem.

a. Introduction. Supersymmetry (SUSY) is the prime candidate for solving the naturalness problem of the Standard Model Higgs sector (see, *e.g.*, [1]). Models of low-energy SUSY breaking are particularly attractive because the light gravitino $\tilde{G}$ can also be produced at colliders with the striking signature of additional photons in the decay of the bino $\tilde{B} \to \tilde{G}\gamma$ [2]. The most extensively studied mechanism for this is gauge mediation [3–5].

However, cosmological limits on the gravitino are in strong tension with low-energy gauge mediation. In the Minimal Supesymmetric Standard Model (MSSM), the observed Higgs mass of 125 GeV [6, 7] requires large A-terms, stop masses in the 10 TeV range or non-decoupling D terms [8, 9]. In gauge mediation, generating large A-terms through renormalization group evolution [10] or large stop masses requires the SUSY breaking scale to be above 1000 TeV, and hence the gravitino mass $m_{3/2}$ to be above a keV [11]. Such a gravitino would overclose the Universe unless the reheating temperature after the inflation is kept unnaturally low [12, 13], leaving little room for any conceivable baryogenesis scenario. When $m_{3/2} \lesssim 1$ keV, the gravitino does not overclose the Universe, but would be a warm dark matter component, ruled out by the Lyman-α forest data unless $m_{3/2} \lesssim 16$ eV [14]. The tension may be eased if the Higgs sector is extended to the NMSSM or Dirac–NMSSM [15], if the messenger sector couples to the Higgs [16], or is strongly coupled [17–20]. However, these models are somewhat more complicated.

In this Letter, we present an alternative simple mediation mechanism of SUSY breaking, where the sfermion masses are generated at tree-level from a $U(1)$ D-term. $m_{3/2}$ can be brought down to the eV scale, solving the cosmological problem. In addition, the gluino is most likely within the reach of the HL-LHC.

b. Vector Mediation We first present the basic idea of what we call the *vector mediation* of SUSY breaking[21].

We assume that the SUSY breaking sector produces both an F-term and a D-term of a $U(1)$ vector multiplet under which the Standard Model matter fields are charged. In order for all of the sfermions in the Standard Model to acquire positive soft mass-squared, all quark and lepton multiplets must have $U(1)$ charges of the same sign (positive). Anomaly cancellation requires additional superfields with negative $U(1)$ charges, which acquire negative soft mass-squared from the D-term. They must come in Standard Model vector-like representations so that the vector-like masses can overcome the negative soft mass-squared. It is economical if the vector-like supermultiplets also act as messengers that generate gaugino masses at the one-loop level. Because of the tree-level generation of scalar masses, the scalar masses as well as the scale of SUSY breaking are both in the 10–100 TeV range, solving the cosmological gravitino problem.

The tree-level mediation of SUSY breaking via a $U(1)$ D-term was also considered in Refs. [22, 23]. Their interest was in a high-scale mediation mechanism which has a much more weakly coupled goldstino and thus have very different cosmology and collider signatures [24].

c. An Explicit Model The simplest particle content that satisfies the requirements explained above is one inspired by E_6 unification. By embedding $SO(10) \times U(1)_\psi$ into E_6, the fundamental representation **27** decomposes as

$$\mathbf{27} = \Psi(\mathbf{16}, +1) \oplus \Phi(\mathbf{10}, -2) \oplus S(\mathbf{1}, +4). \qquad (1)$$

We identify Ψ as the quark and lepton supermultiplets, while Φ plays the role of messengers as well as the Higgs. S is responsible for the SUSY breaking.

d. SUSY Breaking We introduce a vector-like mutiplet $X(-4)$ and $Y(+4)$ charged under $U(1)_\psi$. We also introduce a neutral field $Z(0)$ and write the superpotential

$$W = MSX + \lambda Z(XY - v^2). \qquad (2)$$

It is essential that the model here is *chiral* under $U(1)_\psi$, since charge conjugation invariance would prevent the generation of a D-term. Note that the above superpotential is generic and $U(1)_R$ invariant, which guarantees that it breaks SUSY [25] [26].

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This model breaks SUSY with a positive D-term, which induces tree-level positive mass-squared to the matter fields Ψ. Motivated by models of dynamical SUSY breaking, *à la* Izawa–Yanagida–Intriligator–Thomas (IYIT) [27, 28], we take the values $\lambda = 4\pi$, $e = 0.1$ and $M = 2v$ as an example. One can view this theory as the IR of an IYIT type model where the additional matter has been removed by vector-like mass terms. We will use the notation $X_0 = \langle X \rangle$, etc. The minimum is at $X_0 = 0.58v$, $Y_0 = 1.71v$, $S_0 = 0$ and $Z_0 = 0$. The non-zero SUSY breaking parameters are $F_S = MX_0 = 1.16v^2$, $F_Z = \lambda(X_0Y_0 - v^2) = -0.1v^2$, and $D = 4e(-|X_0|^2 + |Y_0|^2) = 1.02v^2 > 0$. All particles here are massive except for the goldstino, which is a linear combination of the S fermion and the $U(1)_\psi$ gaugino. Hence there is no cosmological Polonyi problem [29, 30].

Note that the size of the D-term is completely fixed by the size of the F-term as

$$D = \frac{2}{M_V^2} F_S^* (4e) F_S, \quad M_V^2 = 2(4e)^2(|X_0|^2 + |Y_0|^2). \quad (3)$$

Here, M_V is the mass of the $U(1)_\psi$ gauge boson. This equation is a simple consequence of the equation of motion for the massive vector multiplet.

In our E_6 inspired model, there are two additional $S_{1,2}$ fields which do not play a role in SUSY breaking. To give $S_{1,2}$ a mass, we introduce two new neutral fields $N_{1,2}$ and introduce the couplings $W = \kappa N_{1,2} S_{1,2} X$. Once X obtains its vacuum expectation value, this superpotential combined with the D-term gives a mass to $S_{1,2}$ and $N_{1,2}$. If stable, $S_{1,2}$ and $N_{1,2}$ would overclose the universe. We allow for the additional interaction $W = S_{1,2}\Phi\Phi$, so that they can decay.

e. Tunneling to the true vacuum In order to generate gaugino masses at one-loop, we need the superpotential

$$W_\Phi = -\frac{g}{2} Y\Phi\Phi - \frac{k}{2} S\Phi\Phi. \quad (4)$$

Because this superpotential does not respect the $U(1)_R$ symmetry, a supersymmetric vacuum appears. It is located at

$$X_0 = \frac{v^2}{Y_0} = \frac{k\Phi_0^2}{2M}, \quad Z_0 = \frac{gM}{k\lambda}, \quad S_0 = -\frac{2gMv^2}{k^2\Phi_0^2}, \quad (5)$$

where the value of Φ_0 is determined by minimizing the D-term. Because there is both a SUSY-preserving and a SUSY-breaking vacuum, one must consider tunneling between the two vacua. From the form of the supersymmetric vacuum, it is clear that if k is small, the distance between the two vacua will be large. In the limit that $k \to 0$, the SUSY vacuum disappears and the metastable vacuum becomes stable.

The life-time of the metastable vacuum can be calculated using semiclassical techniques [31]. The tunneling rate per unit volume is $\Gamma \propto e^{-B}$ where $B = S_E(\overline{\phi}(r)) - S_E(\phi_0)$. ϕ_0 is the field configuration of the metastable vacuum, S_E is the Euclidean action and $\overline{\phi}(r)$ is the bounce profile. The Euclidean action is

$$S_E(\phi(r)) = 2\pi^2 \int_0^\infty dr r^3 \left[\sum_i \frac{1}{2} \left(\frac{d\phi_i}{dr} \right)^2 + V(\phi(r)) \right], \quad (6)$$

where the sum goes over all five fields, $\phi_i = (X, Y, Z, \Phi, S)$. $\overline{\phi}(r)$ is the solution to

$$\frac{d^2\phi_i}{dr^2} + \frac{3}{r}\frac{d\phi_i}{dr} = \frac{dV}{d\phi_i}, \quad (7)$$

subject to the boundary conditions

$$\frac{d\overline{\phi}_i}{dr}(r=0) = 0, \qquad \overline{\phi}_i(r \to \infty) = \phi_0. \quad (8)$$

We need $B \gtrsim 450$ for the metastable minimum to live longer than the age of the universe.

Calculating the bounce properly requires solving a five-dimensional differential equation. To simplify the computation, we approximate the tunneling as confined to a one-dimensional sub-space proceeding in a straight line between the two minima. In this approach, solving for the bounce action is numerically very stable.

We expect this approximation to be valid when the potential has large first derivatives, *e.g.*, when the maximum separating the two minima is very large. Then the friction term, the $1/r$ term in Eq. (7), is important. In order for the bounce to travel between the two minimum, it first stays near the SUSY minima until large r where the friction term is irrelevant. The bounce then rolls to the SUSY breaking minimum. In this limit, because the bounce action is required to start very close to the SUSY minima and to end at the SUSY breaking minimum, we expect that this one-dimensional approximation is good. We have also checked that the maximum separating the two minima lies on the straight line between the two minima to within a few percent.

In Fig. 1, we plot contours of the bounce action on the (k, g) plane. The shaded region is where the messengers go tachyonic. Then there is no maximum between the two vacua and the bounce does not start near the SUSY vacua. Thus, we expect the approximation used to calculate the bounce action to be very poor. We have verified numerically that the one-dimensional approximations of the bounces in these regions of parameter space do not start near the SUSY vacua.

Aside from the vacuum transition rate, there is also the probability of thermally tunneling between the two vacua in the early universe. For $T \gtrsim v$, the SUSY vacuum disappears and there is only the SUSY-breaking vacuum. At a lower temperature, the SUSY-preserving vacuum appears. At the temperature T_c, the SUSY vacuum becomes the true minimum and tunneling between the two vacua can occur. We obtain the thermal bounce action, $B_{\rm th} = S_{\rm th}(\overline{\phi}(r)) - S_{\rm th}(\phi_0)$, by solving the three dimensional versions of Eqs. (7,8) .

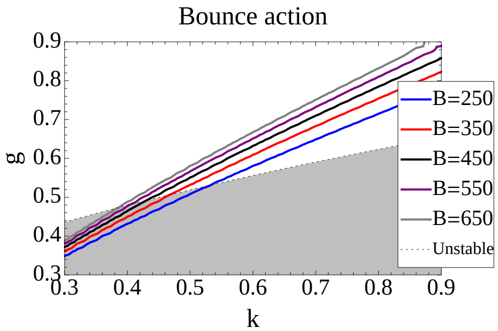

FIG. 1. Contours of the vacuum bounce action on the (k, g) plane. The solid blue, red, black, purple and gray lines are for $B = 250$, 350, 450, 550, and 650, respectively. For the universe to be stable, $B \gtrsim 450$. The dashed black line and the grey region show where the SUSY breaking minimum becomes tachyonic. We expect that the approximations used to calculate the bounce action fail in this region.

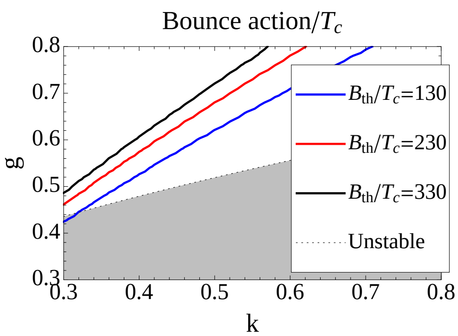

FIG. 2. Contours of $B_{\rm th}/T_c$ on the (k, g) plane. The solid blue, red, and black lines are for $B_{\rm th}/T_c = 130$, 230, and 330, respectively. For the universe to be stable, $B_{\rm th}/T_c \gtrsim 230$. The high temperature expansion is used to estimate T_c and hence the result is meant to be only qualitatively correct. See also the caption of Fig. 1.

To evaluate the thermal tunneling rate $\Gamma \sim T^4 e^{-B_{\rm th}/T}$, we make the following approximations. We first assume that the thermal bounce $B_{\rm th}$ is a constant and determine it numerically using the zero temperature potential, again using the one-dimensional approximation. We find that in order for the universe to be stable, $B_{\rm th}/T_c \gtrsim 230$. The second approximation we use is the high temperature expansion to determine T_c. We make this approximation because it is numerically difficult to find when minima appear in a five dimensional space when the exact one loop integrals do not converge quickly. We find T_c tends to be smaller than v, where the high temperature expansion is not valid. Therefore, the result here should be viewed as only qualitatively correct.

We plot the contours of constant $B_{\rm th}/T_c$ on the (k, g) plane in Fig. 2. If the value of $B_{\rm th}/T_c$ were off by a factor of two, the limit on k changes by 20% for a fixed g. Again, the one-dimensional approximation is poor in the shaded region where messengers go tachyonic.

f. SUSY Spectrum All of the squarks and sleptons obtain the same mass-squared from the non-zero D-term,

$$m^2_{\tilde{\Psi}} = eD > 0. \tag{9}$$

and hence there is no flavor problem.

As mentioned earlier, gaugino masses are generated from one-loop diagrams involving Φ. The mass of the fermion component of Φ is $M_\Phi = gY_0$, while the boson components have the mass matrix (see Eq. (4)),

$$\mathcal{L} \supset -\frac{1}{2}(\tilde{\Phi}^*, \tilde{\Phi}) \begin{pmatrix} (gY_0)^2 - 2eD & kF_S \\ kF_S & (gY_0)^2 - 2eD \end{pmatrix} \begin{pmatrix} \tilde{\Phi} \\ \tilde{\Phi}^* \end{pmatrix}. \tag{10}$$

We choose $g = 0.5$ and $k = 0.35$, in addition to the parameters in the previous section. There are no tachyons and the metastable vacuum is stable on timescales of order the age of the universe.

At this point, we need to discuss the Higgs. In supersymmetric E_6 theories, we can regard the doublets in Φ as the Higgs superfields. We let the doublets in Φ have Yukawa couplings. To let the the triplets Φ_c decay without introducing proton decay, we introduce the interaction $W = ud\Phi_c$. The Higgses have the same mass matrix as in Eq. (10), and we fine-tune $\mu = g_H Y_0$ against $2eD$ to obtain a mass-squared at the 100 GeV scale. It represents a tuning at the level of 10^{-5}. $B\mu = k_H F_S$ can also be made at the 100 GeV scale by choosing $k_H \approx 10^{-4}$. Note that the bare μ-parameter is forbidden and is generated only with $U(1)_\psi$ breaking, ameliorating the μ-problem from the Planck scale to the 100 TeV scale.

We have three color triplets and two electroweak doublets acting as messengers to generate the gaugino masses. The 1-loop results for the gaugino masses can be found in Eq. (2.3) of Ref. [32]. The gaugino masses can be enhanced relative to the standard gauge mediation $3\frac{\alpha_s}{4\pi}\frac{kF_S}{M_\Phi}$ due to the D-term. For the above numerical example, the enhancement factor is 1.39. The on-shell gluino mass is further enhanced from M_3 by the QCD correction by $1 + \frac{4}{3}\frac{\alpha_s(M_3)}{\pi}$.

In these models, the scalars are heavy, the gauginos are light and the gravitino is the Lightest Supersymmetric Particle. For this type of mass spectrum, the current ATLAS bound on the gluino mass is 1.28 TeV [33] while the current CMS bound is around 1.15 TeV [34]. Because our gaugino masses are enhanced with respect to standard gauge mediation, it is not very difficult to obtain a heavy enough gaugino. For the choice of parameters mentioned earlier, we find $v \geq 87$ TeV from the gluino mass limit.

In the large λ limit, Y and Z can be integrated out, and the mass spectrum of the singlets can be computed as follows. Among the singlets, S is a complex scalar and X has only its real part (the imaginary part is eaten by

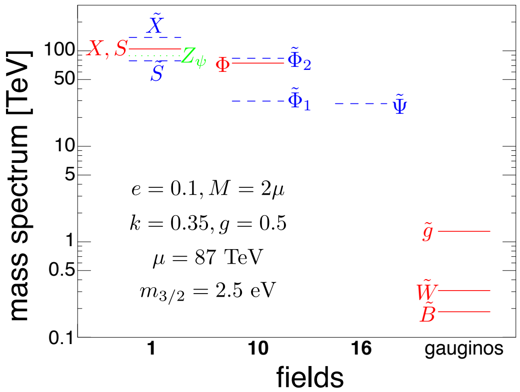

FIG. 3. An example mass spectrum in our model. The fields are presented according to the $SO(10)$ representations, **1**, **10**, and **16**, as well as the Standard Model gauginos. The gravitino is too light to be shown.

the $U(1)_\psi$ gauge boson), with masses

$$m_S^2 = M^2 \frac{X_0^2}{X_0^2 + Y_0^2} + 16e^2(-X_0^2 + Y_0^2), \qquad (11)$$

$$m_X^2 = M^2 \frac{X_0^2 + 16e^2(3X_0^2 + 5Y_0^2)}{X_0^2 + Y_0^2}. \qquad (12)$$

Fermions of X and S become a Dirac particle of mass

$$m_F^2 = M^2 \frac{X_0^2}{X_0^2 + Y_0^2} + 32e^2(X_0^2 + Y_0^2). \qquad (13)$$

The $U(1)_\psi$ gauge boson acquires a mass

$$m_V^2 = 32e^2(X_0^2 + Y_0^2). \qquad (14)$$

We have already presented the mass spectrum of the Φ and Ψ multiplets. We verified that $\mathrm{Str}M^2 = 0$ once spectrum integrated out at $O(\lambda^2(X_0^2 + Y_0^2))$ is included.

In order for the gluino to be heavier than a TeV, we typically have scalars at 20–100 TeV. If $e \sim O(1)$, this is a similar mass spectrum to mini-split [35], pure gravity mediation [36], and SUSY breaking mechanisms with accidental R-symmetries, *e.g.*, metastable Intriligator-Seiberg-Shih (ISS) SUSY breaking [37]. The main difference of vector mediation with previous models is the presence of a superlight gravitino. The mass spectrum is shown in Fig. 3. The radiative corrections from stops at the 10 TeV scale easily raise the lightest Higgs boson mass to the observed mass of 125 GeV. Note that the fine-tuning is smaller compared to other models with a split spectrum because the mass of three **16** is at ~ 30 TeV whereas the other scalar masses are at ~ 100 TeV. This is because the $U(1)_\psi$ charges differ by a factor of four and the D-term is always smaller than the F-term. These scalars may be discovered at a 100 TeV pp collider.

g. Implications The most important implication is that the gravitino mass is

$$m_{3/2}^2 = \frac{V}{3M_{Pl}^2} = \frac{1.9v^4}{3M_{Pl}^2} = (2.5 \text{ eV})^2 \qquad (15)$$

for the above parameters. Here, $M_{Pl} = 2.4 \times 10^{18}$ GeV. Such a low mass gravitino is not possible in the usual low-energy gauge mediation and is completely compatible with the cosmological limit of $m_{3/2} < 16$ eV. There is a clear upper limit on the gluino mass from the cosmology of about 5 TeV. The LHC would most likely discover the gluino, and a 100 TeV pp collider would completely close the window. The bino decays promptly $\tilde{B} \to \gamma\tilde{G}$, giving evidence of low-energy SUSY breaking. The ratio among gaugino masses is also unique, different from the standard gauge-mediation or unification scenarios.

The right-handed neutrino is charged under $U(1)_\psi$ and hence we cannot use the seesaw mechanism for neutrino masses. One can use a linear combination of $U(1)_\psi$ and $U(1)_\chi$ instead to make the right-handed neutrino neutral [38]. This is an interesting variation to be considered. In the simplest realization of these models presented in this Letter, the right-handed neutrinos are Dirac, are present at low energies, and can contribute to energy densities at BBN. Much of the number density in right handed neutrinos is diluted away by the entropy generated at the QCD phase transition, resulting in $\Delta N_\nu \simeq 0.19$. This may be verified in the future cosmological data.

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