Confluence of constraints in gauge mediation: The 125 GeV Higgs boson and “Goldilocks” cosmology

Jonathan L. Feng, Ze’ev Surujon, and Hai-Bo Yu

Phys. Rev. D **86**, 035003 — Published 3 August 2012

DOI: 10.1103/PhysRevD.86.035003

UCI-TR-2012-06

Confluence of Constraints in Gauge Mediation: The 125 GeV Higgs Boson and Goldilocks Cosmology

Jonathan L. Feng,[1] Ze'ev Surujon,[1] and Hai-Bo Yu[2]

[1]*Department of Physics and Astronomy,*
University of California, Irvine, CA 92697, USA

[2]*Michigan Center for Theoretical Physics, Department of Physics,*
University of Michigan, Ann Arbor, MI 48109, USA

Abstract

Recent indications of a 125 GeV Higgs boson are challenging for gauge-mediated supersymmetry breaking (GMSB), since radiative contributions to the Higgs boson mass are not enhanced by significant stop mixing. This challenge should not be considered in isolation, however, as GMSB also generically suffers from two other problems: unsuppressed electric dipole moments and the absence of an attractive dark matter candidate. We show that all of these problems may be simultaneously solved by considering heavy superpartners, without extra fields or modified cosmology. Multi-TeV sfermions suppress the EDMs and raise the Higgs mass, and the dark matter problem is solved by Goldilocks cosmology, in which TeV neutralinos decay to GeV gravitinos that are simultaneously light enough to solve the flavor problem and heavy enough to be all of dark matter. The implications for collider searches and direct and indirect dark matter detection are sobering, but EDMs are expected near their current bounds, and the resulting non-thermal gravitino dark matter is necessarily warm, with testable cosmological implications.

PACS numbers: 12.60.Jv, 14.80.Da, 95.35.+d

I. INTRODUCTION

Recent results from the Large Hadron Collider (LHC) show intriguing hints of what might be interpreted as a Higgs boson. After having analyzed more than 4 fb^{-1} of integrated luminosity at 7 TeV, the ATLAS and CMS Collaborations report excesses of diphoton events with invariant mass around 125 GeV and local significances near 3σ [1, 2]. Further support for this interpretation comes from exclusion ranges. The combined ATLAS and CMS data constrain the mass of a standard model (SM) Higgs boson to be within three possible ranges, namely, $117.5 - 118.5$ GeV, $122.5 - 127.5$ GeV, and above 543 GeV. These results have profound implications for physics beyond the SM. In this study, we consider the implications of these results for supersymmetry and, in particular, supersymmetric models with gauge-mediated supersymmetry breaking (GMSB) [3–8].

In supersymmetric theories, the Higgs boson's mass is generically low, since its quartic coupling is determined by the electroweak gauge couplings. Radiative corrections may lift the Higgs boson's mass, but in the minimal supersymmetric SM (MSSM), a Higgs boson mass near 125 GeV requires either large trilinear scalar couplings, leading to large left-right stop mixing, or very large stop masses. Without additional structure, naturalness would seem to disfavor heavy stops, since they imply significant fine tuning. At the same time, heavy superpartners, at least in the first and second generations, generically relax other longstanding problems in supersymmetry, namely, those of unwanted flavor and CP violation. In fact, with generic flavor structures and phases, bounds on flavor and CP violation require superpartner masses to be much higher than even the masses preferred by the Higgs mass. A realistic and compelling supersymmetric model, then, should not only accommodate a 125 GeV Higgs boson, but also address these supersymmetric flavor and CP problems.

In GMSB models, the superpartner masses are generated by flavor-blind gauge interactions, thereby solving the supersymmetric flavor problem elegantly. Such models are therefore highly motivated in ways that generic supersymmetric theories, and particularly those with gravity-mediated supersymmetry breaking, are not. The recent Higgs boson results present an interesting challenge for GMSB, however. In GMSB, trilinear soft couplings typically vanish at the messenger scale. Although they are regenerated through renormalization group (RG) evolution at the weak scale, their value is too small to play a significant role in lifting the Higgs mass, requiring multi-TeV stops. The recent Higgs results have therefore motivated many new GMSB studies, which typically propose non-minimal field content to resolve this tension [9–17].

The Higgs mass constraints should not be considered in isolation, however, as GMSB has other significant and longstanding challenges. First, although GMSB elegantly suppresses flavor violation, it does not generically suppress the CP-violating electric dipole moments (EDMs) of the electron and neutron. These EDM constraints are stringent: for $\mathcal{O}(0.1)$ CP-violating phases, and using the underlying GMSB relations to relate first and third generation superpartner masses, current bounds on EDMs require the stop mass to be larger than $\sim 3 - 10$ TeV, depending on $\tan\beta$. Second, typical GMSB models have no viable dark matter candidates, as all SM superpartners decay to gravitinos, and thermally-produced gravitinos [18] are inconsistent with standard big bang cosmology.

In this work, we note that all of these problems are simultaneously solved by having heavy superpartners. In fact, taking minimal GMSB as a simple example, the constraints all point to the same region of parameter space. As indicated above and detailed below, the Higgs boson mass and EDMs point to the same range of multi-TeV superpartner masses. Remarkably, in this region of parameter space, the dark matter problem is also solved by Goldilocks cosmology [19], a superWIMP scenario, in which TeV-scale neutralinos freeze out with very large densities, but then decay to GeV gravitinos that are simultaneously light enough to solve the flavor problem and heavy enough to be all of dark matter. This scenario is subject to many additional astrophysical constraints [20–23]: the resulting gravitino dark matter should have the correct relic density and be sufficiently cold, and electromagnetic and hadronic energy produced in the decays should not destroy the successes of big bang nucleosynthesis (BBN). As we will see, even more remarkably, all of these constraints are also satisfied in the same region in GMSB parameter space preferred by the Higgs and EDM constraints, without the need to modify standard big bang cosmology.

In Sec. II, we discuss the implications of recent Higgs data for supersymmetry and minimal GMSB in particular. The generic CP problem of GMSB and the implications of bounds on EDMs are discussed in Sec. III. In Sec. IV we consider dark matter in GMSB, and discuss constraints from relic density, small scale structure, and BBN. As we will see, although the scenario we propose passes all constraints, for several observables, the favored region of parameter space is not far from current bounds. There are therefore several avenues where future sensitivities will be able to test these ideas, and we discuss these and conclude in Sec. V.

II. THE HIGGS BOSON MASS AND MINIMAL GMSB

As mentioned in the introduction, in the MSSM the Higgs boson is generically light, since the quartic coupling in the scalar potential arises from D-terms and is therefore determined by the electroweak gauge couplings. Indeed, the tree level value,

$$m_h^2(\text{tree}) = M_Z^2 \cos^2 2\beta \ , \tag{1}$$

cannot exceed the Z boson mass. This feature is retained even when supersymmetry is softly broken, since quartic couplings are dimensionless. Radiative corrections, however, may quite generally lift the value of m_h^2 by as much as 100%. The 1-loop correction to Eq. (1) is given by

$$\Delta m_h^2(\text{1-loop}) = \frac{3m_t^4}{2\pi^2 v^2}\left[\log\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right] \ , \tag{2}$$

where $v \simeq 246$ GeV, $M_S \equiv \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$, and $X_t \equiv A_t - \mu \cot\beta$ characterizes the stop left-right mixing. In addition, there are higher-loop contributions that are known to be sizable. Throughout the paper we use `SOFTSUSY 3.2.4` [24] to calculate the superpartner spectrum and Higgs boson mass, including 2-loop corrections and renormalization group (RG) evolution.

Although Eqs. (1) and (2) are modified significantly by higher-loop corrections, they reveal a few interesting features of the Higgs sector in the generic MSSM. First, increasing $\tan\beta$ increases the tree-level Higgs mass, an effect that saturates for $\tan\beta \sim 20$. It is also evident that the Higgs boson mass may be greatly increased either by large stop mixing ($X_t \sim M_S$) or by heavy stops ($M_S \gg m_t$). The large stop mixing scenario has been investigated in many papers recently. However, as we have reviewed in the introduction, there is ample motivation from considerations of flavor and CP violation to consider heavy superpartners.

As a particularly simple example, we consider minimal GMSB. In minimal GMSB, the low energy spectrum is completely determined by the five parameters

$$M_m, \ \Lambda \equiv \frac{F}{M_m}, \ \tan\beta \equiv \frac{\langle H_u^0 \rangle}{\langle H_d^0 \rangle}, \ N_5, \ \text{and} \ \text{sign}(\mu) \ , \tag{3}$$

where the first is the messenger mass, Λ (multiplied by a loop factor $\sim \alpha/4\pi$) parameterizes the superpartner mass scale, and the last two are discrete parameters that denote the equivalent number of $5+\bar{5}$ messengers and the sign of the Higgsino mass parameter. Regarding the Higgs potential, the soft scalar mass parameters $m^2_{H_u}$ and $m^2_{H_d}$ are completely determined by GMSB (and are essentially the same as the slepton doublet masses). The Higgsino mass parameter μ and the soft bilinear parameter B_μ are more problematic to generate. Here, we follow the traditional approach: we assume μ and B_μ are generated such that $v \simeq 246$ GeV, and we trade them for $\tan\beta$ and v. Assuming μ is real, the resulting free parameters are $\tan\beta$ and $\text{sign}(\mu)$.

Because the above parameters are flavor blind, the resulting low energy physics is minimally flavor violating, and therefore safe from flavor problems, as long as contributions from gravity-mediated supersymmetry breaking are small compared to the superpartner mass scale. The gravity-mediated contributions are of the order of the gravitino mass

$$m_{\tilde{G}} = \frac{F}{\sqrt{3}M_*} = \frac{M_m \Lambda}{\sqrt{3}M_*} , \tag{4}$$

where $M_* \simeq 2.4 \times 10^{18}$ GeV is the reduced Planck mass, and so the latter condition may be taken to be $m_{\tilde{G}} \ll (\alpha/4\pi)\Lambda$. From this it follows that the gravitino is the lightest supersymmetric particle (LSP). As for CP violation, the situation is less predictive, as we discuss in Sec. III.

One distinctive feature of minimal GMSB is that the A-terms vanish at the messenger scale. Although they acquire a renormalization contribution proportional to the gaugino mass at low energy scales, their values are typically small, which, in light of the recent Higgs signals, implies large stop masses.

To see the parameters required to generate a 125 GeV Higgs mass in minimal GMSB models, we present results for minimal GMSB in Fig. 1. For $\tan\beta = 10$, a Higgs mass in the range of $122.5 - 127.5$ GeV implies $\Lambda \sim 700 - 3000$ TeV and stop masses $M_S \sim 4.5 - 20$ TeV, with smaller and much larger values required for other values of $\tan\beta \gtrsim 5$. These results are for $N_5 = 1$ and $\mu > 0$. Choosing other values for N_5 and $\text{sign}(\mu)$ would lead to different values of Λ and would induce some changes in the details of the spectrum, but, of course, the same values of M_S would be required, and this would not change our conclusions qualitatively. The value of the top mass is taken to be $m_t = 173.2$ GeV, the most recent value from the Tevatron [25]. The ATLAS Collaboration has recently measured a central value of

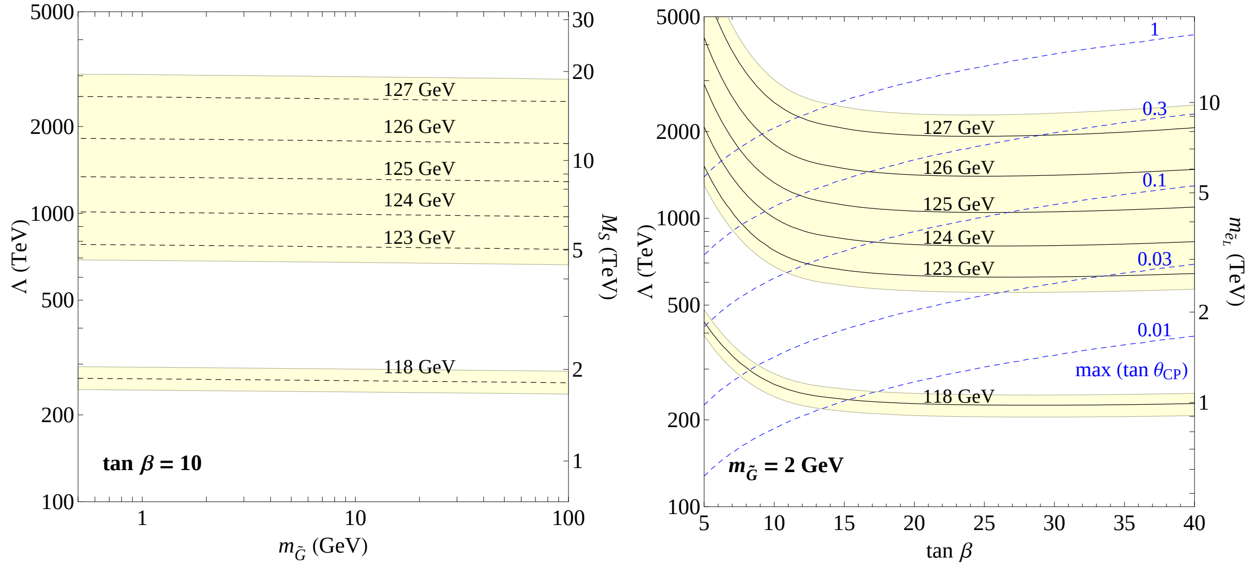

FIG. 1: *Left*: Contours of constant Higgs boson mass in minimal GMSB in the $(m_{\tilde{G}}, \Lambda)$ plane for $\tan\beta = 10$, $N_5 = 1$, and $\mu > 0$. The yellow shaded regions are the allowed ranges for the Higgs boson mass, given the recent exclusions from the LHC. The stop mass parameter M_S is largely determined by Λ and insensitive to $m_{\tilde{G}}$ in the range plotted, and it is given on the right-hand axis. *Right*: Dashed blue contours of constant maximal $\tan\theta_{\rm CP}$ allowed by the upper bound on the electron EDM in the $(\tan\beta, \Lambda)$ plane for $m_{\tilde{G}} = 2$ GeV, $N_5 = 1$, and $\mu > 0$. The preferred Higgs mass regions are as in the left panel. The left-handed selectron mass $m_{\tilde{e}_L}$ is largely determined by Λ and insensitive to $\tan\beta$, and it is given on the right-hand axis.

$m_t = 174.5$ GeV with a statistical error similar to that of the Tevatron combination, but with a larger systematic error [26].

III. ELECTRIC DIPOLE MOMENTS

In this section, we show that multi-TeV sfermion masses are also motivated by constraints from EDMs. Although flavor violation is highly suppressed in GMSB models, CP violation is not. In the absence of some additional mechanism to suppress CP violation [27, 28], the gaugino masses M_a, A-terms, and the μ and B_μ parameters can all have CP-violating phases. In minimal GMSB, where the gaugino masses have the same phase and A-terms vanish, the physical CP-violating phase can be parameterized as

$$\theta_{\rm CP} \equiv {\rm Arg}\left(\frac{\mu M_a}{B_\mu}\right) \ . \tag{5}$$

The EDMs of the electron and neutron are generated by penguin diagrams with gauginos, Higgsinos and sfemions in the loop. The dominant diagram involves Wino-Higgsino mixing and leads to the EDM contribution [29]

$$d_f = \frac{1}{2} e\, m_f\, g_2^2\, |M_2\, \mu|\, \tan\beta\, \sin\theta_{\rm CP}\, K_C\left(m^2_{\tilde{f}_L}, |\mu|^2, |M_2|^2\right) \ , \tag{6}$$

where K_C is a kinematic function defined in Ref. [30]. Note the factor of $\tan\beta$, which arises from the down-type mass insertion required by the chiral structure of the EDM operator.

The current upper bounds on electron and neutron EDMs are [31, 32]

$$d_e < 1.05 \times 10^{-27}\ e\ {\rm cm} \quad {\rm and} \quad d_n < 2.9 \times 10^{-26}\ e\ {\rm cm} \ . \tag{7}$$

Since the bound on d_e is stronger than that on d_n, and the theoretical value of d_n is suppressed by heavier squark masses in minimal GMSB, we will focus on the electron EDM. Instead of calculating the EDM diagram directly, we take advantage of the similarity between the EDM and magnetic dipole moment operators. We first use `micrOMEGAs 2.4.5` [33, 34], suitably modified to include GMSB, to extract the anomalous magnetic moment of the muon a_μ. The electron EDM is then given by

$$d_e = e\,\frac{m_e}{2m_\mu^2}\, a_\mu \tan\theta_{\rm CP} \ , \tag{8}$$

where $e \equiv \sqrt{4\pi\alpha}$, m_e is the electron's mass, and m_μ is the muon's mass. The maximal values of $\tan\theta_{\rm CP}$ allowed by the electron EDM bound are shown in Fig. 1 in the $(\tan\beta, \Lambda)$ plane. The dependence on $\tan\beta$ and Λ imply that regions with low $\tan\beta$ and large Λ (and more generally, large M_S) are preferred. It is interesting to note that the parameter space that gives rise to a 125 GeV Higgs boson mass coincides with the region preferred by EDM considerations, although these two constraints originate from completely different sources.

IV. DARK MATTER

The standard dark matter candidate in supersymmetry is the neutralino, which freezes out with the desired relic density naturally. This coincidence, the WIMP miracle, is not found in gauge mediation, because the LSP is the gravitino. The original thermally-produced keV gravitino dark matter possibility is also no longer consistent with the standard cosmological picture, as it is excluded by overclosure and small-scale structure constraints [35].

GMSB may, however, give rise a viable dark matter scenario if gravitino dark matter is produced non-thermally in neutralino decays [19].[1] In this scenario, the neutralino first freezes out with a large abundance, and then decays to the gravitino. The resulting gravitino inherits the neutralino's number density, but its energy density is given by $\Omega_{\tilde{G}}h^2 = (m_{\tilde{G}}/m_\chi)\Omega_\chi h^2$. Although $m_{\tilde{G}}$ must be much less than m_χ to preserve the flavor virtues of GMSB, this scenario realizes the WIMP miracle as much as is possible in a GMSB visible sector,[2] in the sense that the final dark matter density is brought to near its desired value by the thermal freezeout of a WIMP. In this section, we map out the allowed parameter space for gravitino dark matter and consider cosmological constraints.

In GMSB with $N_5 = 1$, the NLSP is a Bino-like neutralino throughout parameter space. Because neutralinos are Majorana particles, their annihilation to quarks and leptons is P-wave suppressed. For the Bino-like neutralino, its annihilation to gauge and Higgs bosons is also suppressed. Because of these effects, the neutralino density at freezeout may easily reach very large values. To see this, we use `MicrOMEGAs 2.4.5` to calculate the thermal relic density the neutralinos would have had had they been stable. This calculation includes all annihilation channels and effects from non-Bino contributions. In Fig. 2, we show the freezeout density of neutralinos $\Omega_\chi h^2$. As expected, the neutralino freezeout density is much larger than the observed dark matter density throughout the parameter space. For $\tan\beta = 10$ (30), the neutralino mass is close to 2 TeV (1.5 TeV) and its density is $\Omega_\chi h^2 \sim 100$ (50) in the region preferred by the Higgs mass constraints.

These freezeout densities are, however, not current relic densities, as neutralinos in GMSB are unstable and decay to gravitinos. In Fig. 3, we show values of the gravitino relic density $\Omega_{\tilde{G}}h^2$ along with the Higgs mass preferred regions and other constraints discussed below. The region with viable gravitino dark matter, where $\Omega_{\tilde{G}}h^2 = 0.112 \pm 0.006$, is a narrow band. The slope of the band can be understood by dimensional analysis. The freezeout

[1] For related work with GeV-scale dark matter produced in late decays of TeV-scale particles, see Refs. [36–39].

[2] If dark matter arises from hidden sectors in GMSB, a related "WIMPless miracle" may produce the desired amount of dark matter [40–42].

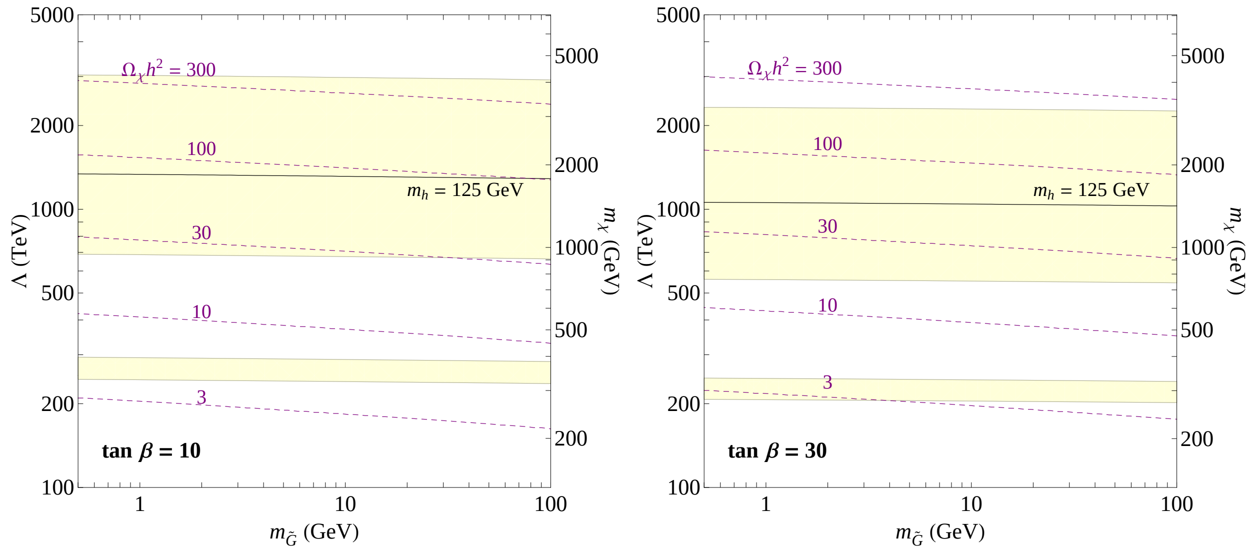

FIG. 2: Contours of constant neutralino relic density (dashed, purple) for $\tan\beta = 10$ (left) and 30 (right), $N_5 = 1$, and $\mu > 0$, computed with `MicrOMEGAs`. The preferred Higgs mass regions from Fig. 1 are also shown. The neutralino mass m_χ is largely determined by Λ and insensitive to $m_{\tilde{G}}$ in the range plotted, and it is given on the right-hand axis.

density of neutralinos is inversely proportional to the annihilation cross section, so $\Omega_\chi h^2 \propto \langle \sigma v \rangle^{-1} \sim \tilde{m}^2$, where $\tilde{m}$ is the superpartner mass scale. The gravitino relic density is $\Omega_{\tilde{G}} h^2 = (m_{\tilde{G}}/\tilde{m})\Omega_\chi h^2 \sim m_{\tilde{G}}\tilde{m}$. Roughly we have $\tilde{m} \propto \Lambda$, so $\Omega_{\tilde{G}} h^2 \sim m_{\tilde{G}}\Lambda$. The gravitino masses that yield the correct relic density are in the range $m_{\tilde{G}} \sim 1-10$ GeV. Such masses correspond to "high-scale GMSB," but are low enough to preserve the elegant flavor suppression that motivates GMSB.

In the above discussion, we have assumed that the relic gravitino dark matter is completely generated by neutralino decay after it freezes out. As is well known, if the reheating temperature is high, inelastic scattering processes can convert SM particles to gravitinos efficiently [43–46]. The gravitino relic density produced through these processes during reheating is approximately [46]

$$\Omega_{\tilde{G}} h^2 \approx 0.13 \left(\frac{T_R}{10^6 \text{ GeV}} \right) \left(\frac{1 \text{ GeV}}{m_{\tilde{G}}} \right) \left(\frac{m_{\tilde{g}}}{7 \text{ TeV}} \right)^2 , \tag{9}$$

where T_R is the reheating temperature, and $m_{\tilde{g}}$ is the running gluino mass. If the reheating temperature is significantly less than 10^6 GeV, the gravitino density produced by inelastic scattering in the thermal bath is negligible. Of course, we require also that T_R is large

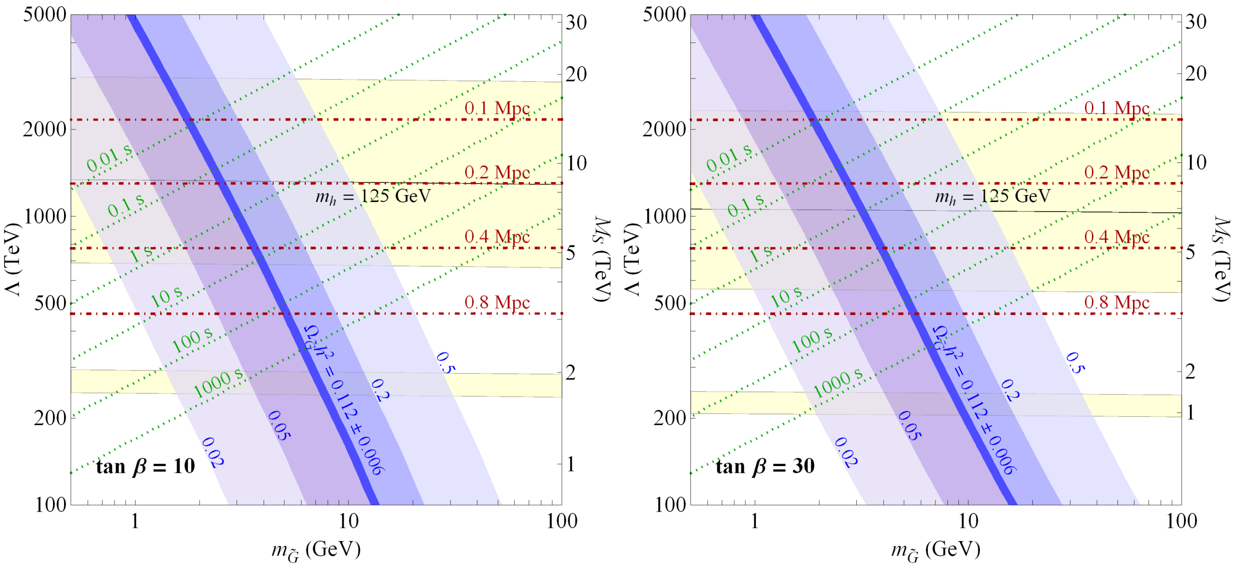

FIG. 3: Contours of constant gravitino relic density (blue, shaded), neutralino lifetime (dotted, green) and free-streaming length (dot-dashed, red) for $\tan\beta = 10$ (left) and 30 (right), $N_5 = 1$, and $\mu > 0$. The preferred Higgs mass regions from Fig. 1 are also shown. The stop mass parameter M_S is largely determined by Λ and insensitive to $m_{\tilde{G}}$ in the range plotted, and it is given on the right-hand axis.

enough that neutralinos are initially in thermal equilibrium. There is a large range of T_R, however, in which both conditions are satisfied, gravitino dark matter is dominantly from neutralino decays, and Goldilocks cosmology is realized, thereby keeping the virtues of the WIMP miracle.

Now we turn to the cosmological constraints on this dark matter scenario. Since the gravitino couples to the neutralino through its Goldstino component, its coupling is suppressed by $1/F$ and the neutralino may have a long lifetime. Neglecting the mass of the Z boson with respect to that of the neutralino, we estimate the neutralino's lifetime as

$$\tau_\chi \simeq \frac{48\pi m_{\tilde{G}}^2 M_*^2}{m_\chi^5} \simeq 0.02 \text{ sec} \left(\frac{m_{\tilde{G}}}{1 \text{ GeV}}\right)^2 \left(\frac{2 \text{ TeV}}{m_\chi}\right)^5 , \tag{10}$$

where we have included both the $\gamma\tilde{G}$ and $Z\tilde{G}$ decay channels.

Such late production of dark matter is constrained by various astrophysical and cosmological observations. Daughter particles from neutralino late decays deposit energy to the plasma in the early universe and lead to potentially observable effects. There are many constraints on late energy injections, such as entropy production, the cosmic microwave background, and BBN [20, 21]. For the model we consider here, the bound from BBN is the most stringent [19], and it requires the neutralino lifetime to be less than $\sim 0.1 - 1$ s. In Fig. 3, we show contours of constant neutralino lifetime in the $(m_{\tilde{G}}, \Lambda)$ plane for two values of $\tan\beta$. The BBN constraints exclude regions of parameter space with low Λ, but are consistent with the Higgs-preferred values of $\Lambda \gtrsim 500 - 2000$ TeV, depending on $m_{\tilde{G}}$.

Another important constraint on dark matter produced in late decays is from considerations of small scale structure [22, 23, 47–51]. Since the gravitino is much lighter than the neutralino in the preferred region, it is relativistic when it produced. Moreover, it is produced at late times, when the Hubble expansion rate has decreased and the redshift effect is not efficient in reducing the gravitino velocity significantly. Thus the late-produced gravitino may have a large free-streaming length and hence suppress structure on small scales. The free-streaming length $\lambda_{\rm FS} = \int_\tau^{t_{\rm EQ}} dt v(t)/a(t)$ is approximated by

$$\lambda_{\rm FS} \simeq 1.0 \text{ Mpc} \left[\frac{u_\tau^2 \tau}{10^6 \text{s}}\right]^{1/2} \left[1 - 0.07 \ln\left(\frac{u_\tau^2 \tau}{10^6 \text{ s}}\right)\right] \ , \tag{11}$$

where

$$u_\tau \equiv \frac{|\vec{p}_{\tilde{G}}|}{m_{\tilde{G}}} \approx \frac{m_\chi}{2 m_{\tilde{G}}} \tag{12}$$

is evaluated at the decay time τ. Note that the free-streaming length is independent of $m_{\tilde{G}}$. As evident from Eq. (11), $\lambda_{\rm FS}$ depends only on $u_\tau^2 \tau$, but since $u_\tau \propto 1/m_{\tilde{G}}$ and $\tau \propto m_{\tilde{G}}^2$, the dependence on the gravitino mass cancels. Current constraints require $\lambda_{\rm FS} \lesssim 0.5$ Mpc, but values near this bound may, in fact, be preferred by observations. Values for $\lambda_{\rm FS}$ are also shown in Fig. 3. Constraints on $\lambda_{\rm FS}$ again exclude low values of Λ, but are consistent with the values $\Lambda \gtrsim 1000$ TeV required to produce the desired Higgs boson mass.

All of the particle physics and cosmological constraints discussed so far are summarized in Figs. 4 and 5. In Fig. 4, we simplify the presentations of bounds in previous figures by selecting a contour for each observable that can be thought of as the boundary between the excluded and viable regions of parameter space. We require that the electron's EDM bound be satisfied for $\tan\theta_{\rm CP} = 0.1$, the correct relic density $\Omega_{\tilde{G}} h^2 = 0.112 \pm 0.006$, the neutralino lifetime to be $\tau < 1$ s to avoid ruining BBN successes, and the gravitino to be sufficiently cold, with $\lambda_{\rm FS} < 0.5$ Mpc. Finally, we also show the regions with the Higgs mass in the currently allowed range. Note that uncertainties from the experimental measurement, the theoretical calculation of m_h in supersymmetry, and parametric uncertainties from uncertainties in α_s and m_t are all at the few GeV level. Within the uncertainties that enter this and the other

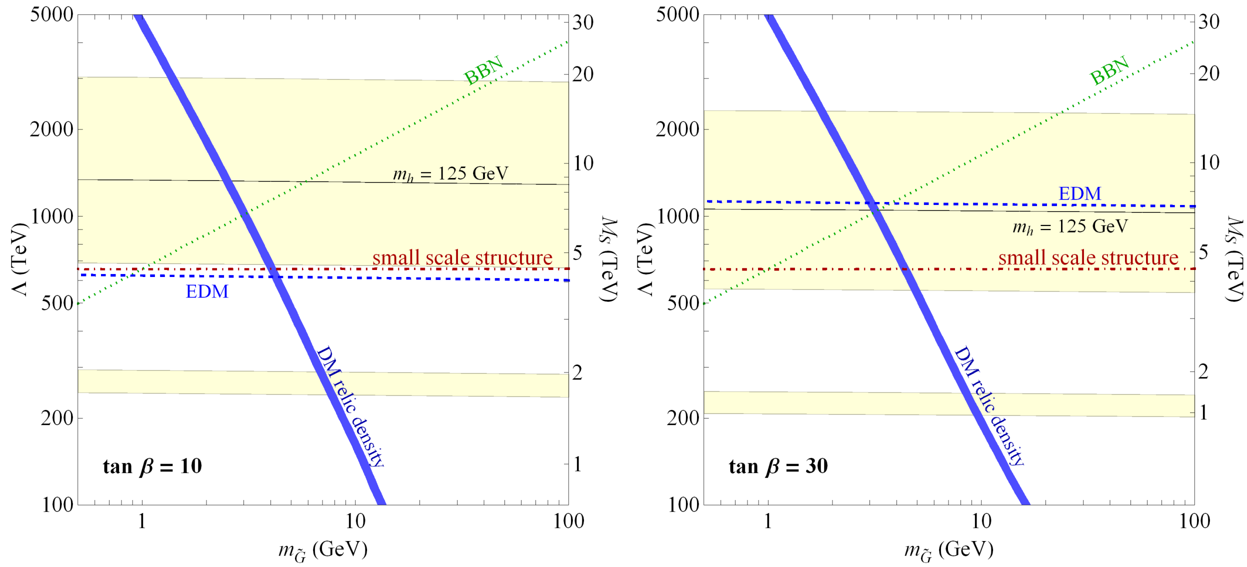

FIG. 4: Summary plot of all constraints on the minimal GMSB scenario in the $(m_{\tilde{G}}, \Lambda)$ plane for $\tan\beta = 10$ (left) and 30 (right), $N_5 = 1$, and $\mu > 0$. The Higgs mass is in the allowed range in the light yellow shaded regions, and $\Omega_{\tilde{G}} h^2 = 0.112 \pm 0.006$ in the dark blue shaded bands. The EDM constraint (for $\tan\theta_{\rm CP} = 0.1$) and BBN constraint ($\tau_\chi < 1$ s) exclude parameter space below the indicated contours, and small-scale structure ($\lambda_{\rm FS} \lesssim 0.5$ Mpc) favors parameter space above or near the indicated contour. The stop mass parameter M_S is largely determined by Λ and insensitive to $m_{\tilde{G}}$ in the range plotted, and it is given on the right-hand axis.

observables, however, it is a remarkable fact that all of the constraints may be satisfied in the region of minimal GMSB parameter space corresponding to a Higgs boson mass in the currently allowed range.

In Fig. 5, we present an alternative summary view of our results, in which we scan over a wide range of $\tan\beta = 5 - 40$. For a given point in the resulting $(\tan\beta, \Lambda)$ parameter space, $m_{\tilde{G}}$ is set by requiring the current gravity relic density. The required Λ for four representative values for $m_{\tilde{G}}$ are shown. All points in this parameter space therefore have the correct relic density, and constraints from the various observables are then shown, as in Fig. 4. Although some of the constraints, notably those from m_h and the electron EDM, have significant dependence on $\tan\beta$, we again see that, within the uncertainties associated with the various observables, all of the constraints may be simultaneously satisfied in regions of parameter space indicated by current hints for Higgs boson discovery.

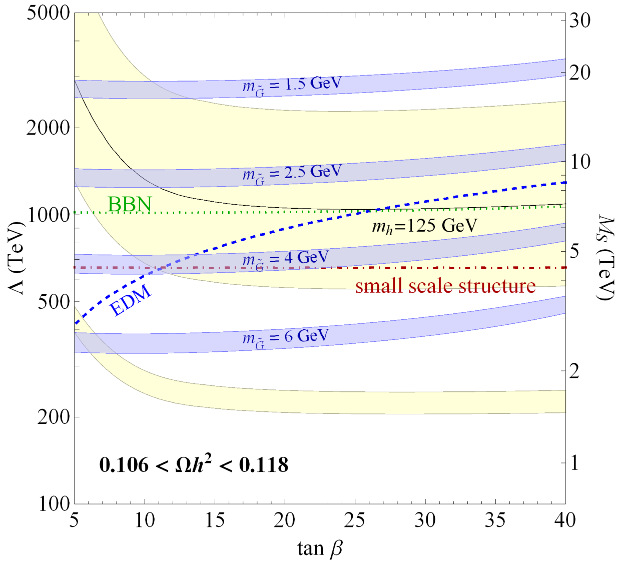

FIG. 5: Summary plot of all constraints on the minimal GMSB model in the $(\tan\beta, \Lambda)$ plane for $N_5 = 1$, $\mu > 0$. The blue-shaded bands correspond to regions where the correct gravitino relic density is achieved for the indicated gravitino mass. Constraints from EDMs, BBN, small scale structure, and the Higgs boson mass are as in Fig. 4. The stop mass parameter M_S is largely determined by Λ and insensitive to $\tan\beta$, and it is given on the right-hand axis.

V. SUMMARY AND DISCUSSION

Recent LHC results provide tantalizing hints that a SM-like Higgs boson exists at a mass around 125 GeV. These results have strong implications for supersymmetry, where they require stops with multi-TeV masses or significant left-right mixing. In this work, we have considered the framework of GMSB, in which flavor violation is elegantly suppressed. GMSB models typically have little left-right mixing, however, and so require multi-TeV stops to raise the Higgs boson mass. We have shown that such masses are highly motivated from other perspectives. In particular, they adequately suppress the EDMs, even for $\mathcal{O}(1)$ phases, and they allow for a solution to the dark matter problem in GMSB in the form of Goldilocks cosmology. In this scenario, TeV neutralinos freezeout with large densities, but then decay to GeV gravitinos, which have the correct relic density to be all of dark matter. This dark matter scenario brings with it its own set of additional constraints from the relic density, BBN, and small scale structure. Remarkably, we have shown that within the uncertainties that enter these constraints, all of them, from low energy particle physics, colliders,

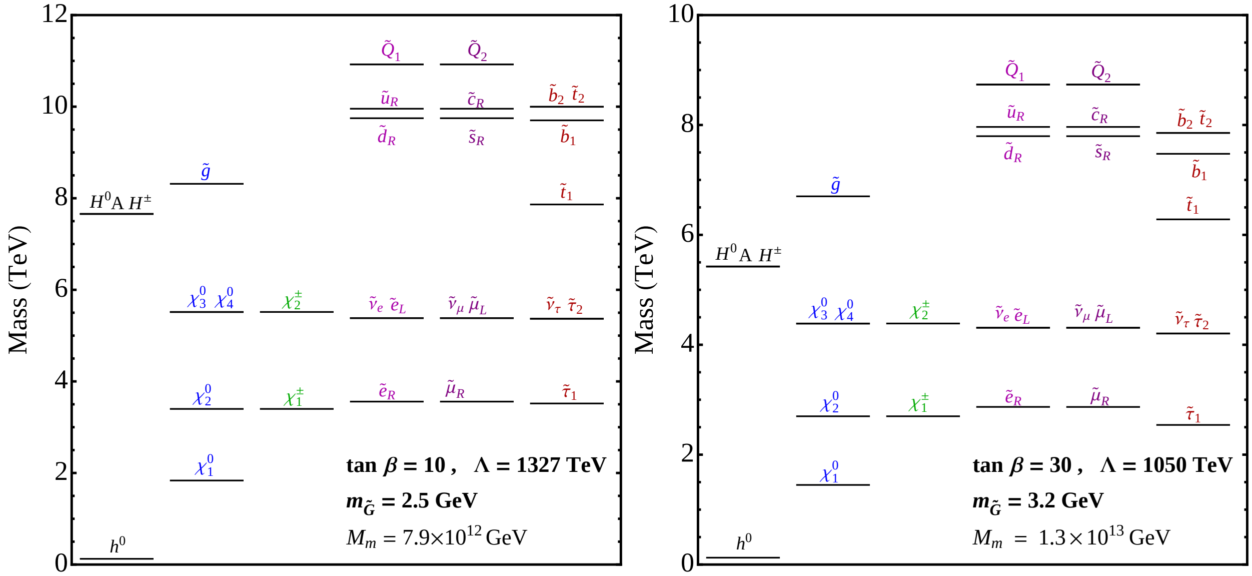

FIG. 6: Superpartner mass spectra for example models with $\tan\beta = 10$ (left) and 30 (right), Λ, $m_{\tilde{G}}$ and M_m as indicated, and $N_5 = 1$ and $\mu > 0$. For each case, the parameters Λ and M_m have been uniquely fixed by requiring that $m_h = 125$ GeV and $\Omega_{\tilde{G}} = 0.112$. For the $\tan\beta = 10$ example, $\tau_\chi = 0.18$ s, $\lambda_{\rm FS} = 0.19$ Mpc, and $\max(\tan\theta_{\rm CP}) = 0.43$. For the $\tan\beta = 30$ example, $\tau_\chi = 0.92$ s, $\lambda_{\rm FS} = 0.27$ Mpc, and $\max(\tan\theta_{\rm CP}) = 0.090$.

cosmology, and astrophysics, are satisfied in the region of minimal GMSB parameter space corresponding to a Higgs boson mass in the currently allowed range.

The model we have analyzed accommodates the 125 GeV Higgs boson without additional fields and without modifications to standard big bang cosmology. If the hints for a SM-like 125 GeV Higgs boson are born out, this will be among the simplest and most minimal of supersymmetric explanations. How can it be verified? The resulting spectrum has squark, gluino, and heavy Higgs masses around 5 TeV or above, and slepton, chargino, and neutralino masses around 1 to 4 TeV. Two example spectra are shown in Fig. 6. Such particles are unlikely to be seen at the 14 TeV LHC, and will be extremely challenging to discover even at future colliders.

The EDMs provide a more promising possibility. In the region of parameter space corresponding to a 125 GeV Higgs boson, the values of the electron and neutron EDMs are not far from their current bounds. There are many proposed experiments that will improve current bounds, in some cases by 2 or 3 orders of magnitude (see Section 7.2 of Ref. [52]). The prediction of the models studied here is that, assuming $\mathcal{O}(1)$ phases, non-zero values for the EDMs will be discovered with the next order-of-magnitude improvement.

Cosmological studies may also shed light on this scenario. As shown above, the parameter space corresponding to a 125 GeV Higgs implies free-streaming lengths in the range $\lambda_{\rm FS} \gtrsim 0.1$ Mpc. Such dark matter may explain current hints that the dark matter is not cold, but warm.

Finally, as noted above, multi-TeV stops are typically considered unnatural. Naturalness is, of course, quite subjective and there are well-known mechanisms by which the sensitivity of the weak scale to variations in the fundamental parameters can be reduced (see, for example, Refs.[53–57]. We note, however, that, although the case of sub-TeV stops with significant left-right stop mixing might appear more natural, as shown in this study, even in flavor-conserving frameworks, the CP-violating EDMs typically require multi-TeV scalars. Models advanced to resolve the conflict between naturalness and the Higgs constraints with sub-TeV stops are incomplete unless they simultaneously also explain the suppression of low-energy flavor and CP violation and the origin of dark matter.

Acknowledgments

We thank Kevork Abazajian, James Bullock, Manoj Kaplinghat and David Sanford for useful discussions. JLF and ZS are supported in part by NSF grant PHY-0970173. HBY is supported in part by NSF grant PHY-1049896 and by NASA Astrophysics Theory grant NNX11AI17G.

Note added: As this work was being submitted, a paper [58] appeared that also discusses the implications of a 125 GeV Higgs boson for GMSB.

[1] **ATLAS** Collaboration, G. Aad *et al.*, "Combined search for the Standard Model Higgs boson using up to 4.9 fb-1 of pp collision data at sqrt(s) = 7 TeV with the ATLAS detector at the LHC," *Phys.Lett.* **B710** (2012) 49–66, `{\ttarXiv:1202.1408[hep-ex]}`.

[2] **CMS** Collaboration, S. Chatrchyan *et al.*, "Combined results of searches for the standard model Higgs boson in pp collisions at sqrt(s) = 7 TeV," `{\ttarXiv:1202.1488[hep-ex]}`.

[3] M. Dine, W. Fischler, and M. Srednicki, "Supersymmetric Technicolor," {\emNucl.Phys.}{\bfB189}(1981)575--593.

[4] S. Dimopoulos and S. Raby, "Supercolor," {\emNucl.Phys.}{\bfB192}(1981)353.

[5] C. R. Nappi and B. A. Ovrut, "Supersymmetric Extension of the SU(3) x SU(2) x U(1) Model," {\emPhys.Lett.}{\bfB113}(1982)175.

[6] L. Alvarez-Gaume, M. Claudson, and M. B. Wise, "Low-Energy Supersymmetry," {\emNucl.Phys.}{\bfB207}(1982)96.

[7] M. Dine, A. E. Nelson, and Y. Shirman, "Low-energy dynamical supersymmetry breaking simplified," {\emPhys.Rev.}{\bfD51}(1995)1362--1370, {\ttarXiv:hep-ph/9408384}.

[8] M. Dine, A. E. Nelson, Y. Nir, and Y. Shirman, "New tools for low-energy dynamical supersymmetry breaking," {\emPhys.Rev.}{\bfD53}(1996)2658--2669, {\ttarXiv:hep-ph/9507378}.

[9] P. Meade, N. Seiberg, and D. Shih, "General Gauge Mediation," {\emProg.Theor.Phys.Suppl.}{\bf177}(2009)143--158, {\ttarXiv:0801.3278[hep-ph]}.

[10] M. Buican, P. Meade, N. Seiberg, and D. Shih, "Exploring General Gauge Mediation," {\emJHEP}{\bf03}(2009)016, {\ttarXiv:0812.3668[hep-ph]}.

[11] J. L. Evans, M. Ibe, and T. T. Yanagida, "Relatively Heavy Higgs Boson in More Generic Gauge Mediation," {\emPhys.Lett.}{\bfB705}(2011)342--348, {\ttarXiv:1107.3006[hep-ph]}.

[12] P. Draper, P. Meade, M. Reece, and D. Shih, "Implications of a 125 GeV Higgs for the MSSM and Low-Scale SUSY Breaking," {\ttarXiv:1112.3068[hep-ph]}.

[13] J. L. Evans, M. Ibe, S. Shirai, and T. T. Yanagida, "A 125GeV Higgs Boson and Muon g-2 in More Generic Gauge Mediation," {\ttarXiv:1201.2611[hep-ph]}.

[14] Z. Kang, T. Li, T. Liu, C. Tong, and J. M. Yang, "A Heavy SM-like Higgs and a Light Stop from Yukawa-Deflected Gauge Mediation," {\ttarXiv:1203.2336[hep-ph]}.

[15] M. A. Ajaib, I. Gogoladze, F. Nasir, and Q. Shafi, "Revisiting mGMSB in light of a 125 GeV Higgs," {\ttarXiv:1204.2856[hep-ph]}.

[16] M. Ibe and R. Sato, "A 125 GeV Higgs Boson Mass and Gravitino Dark Matter in R-invariant Direct Gauge Mediation," {\ttarXiv:1204.3499[hep-ph]}.

[17] H. Shao, "Gauge mediation with heavy doublet superparticles,"

{\ttarXiv:1205.1285[hep-ph]}.

[18] H. Pagels and J. R. Primack, "Supersymmetry, Cosmology and New TeV Physics," {\emPhys.Rev.Lett.}{\bf48}(1982)223.

[19] J. L. Feng, B. T. Smith, and F. Takayama, "Goldilocks Supersymmetry: Simultaneous Solution to Dark Matter and Flavor Problems of Supersymmetry," {\emPhys.Rev.Lett.}{\bf100}(2008)021302, {\ttarXiv:0709.0297[hep-ph]}.

[20] J. L. Feng, A. Rajaraman, and F. Takayama, "Superweakly-interacting massive particles," {\emPhys.Rev.Lett.}{\bf91}(2003)011302, {\ttarXiv:hep-ph/0302215}.

[21] J. L. Feng, A. Rajaraman, and F. Takayama, "SuperWIMP Dark Matter Signals from the Early Universe," {\emPhys.Rev.}{\bfD68}(2003)063504, {\ttarXiv:hep-ph/0306024}.

[22] M. Kaplinghat, "Dark matter from early decays," {\emPhys.Rev.}{\bfD72}(2005)063510, {\ttarXiv:astro-ph/0507300}.

[23] J. A. R. Cembranos, J. L. Feng, A. Rajaraman, and F. Takayama, "SuperWIMP solutions to small scale structure problems," {\emPhys.Rev.Lett.}{\bf95}(2005)181301, {\ttarXiv:hep-ph/0507150}.

[24] B. C. Allanach, "SOFTSUSY: a program for calculating supersymmetric spectra," {\emComput.Phys.Commun.}{\bf143}(2002)305--331, {\ttarXiv:hep-ph/0104145}.

[25] **CDF, D0** Collaboration, O. Brandt, "Measurements of the top quark mass at the Tevatron," {\ttarXiv:1204.0919[hep-ex]}.

[26] **ATLAS** Collaboration, G. Aad *et al.*, "Measurement of the top quark mass with the template method in the top antitop $\rightarrow$ lepton + jets channel using ATLAS data," {\ttarXiv:1203.5755[hep-ex]}.

[27] M. Dine, Y. Nir, and Y. Shirman, "Variations on minimal gauge mediated supersymmetry breaking," {\emPhys.Rev.}{\bfD55}(1997)1501--1508, {\ttarXiv:hep-ph/9607397[hep-ph]}.

[28] T. Moroi, "Electric dipole moments in gauge mediated models and a solution to the SUSY CP problem," {\emPhys.Lett.}{\bfB447}(1999)75--82, {\ttarXiv:hep-ph/9811257[hep-ph]}.

[29] J. L. Feng, K. T. Matchev, and Y. Shadmi, "Theoretical expectations for the muon's electric dipole moment," {\emNucl.Phys.}{\bfB613}(2001)366--381, {\ttarXiv:hep-ph/0107182[hep-ph]}.

[30] T. Moroi, “The Muon anomalous magnetic dipole moment in the minimal supersymmetric standard model,” {\emPhys.Rev.}{\bfD53}(1996)6565--6575, {\ttarXiv:hep-ph/9512396[hep-ph]}.

[31] J. Hudson, D. Kara, I. Smallman, B. Sauer, M. Tarbutt, *et al.*, “Improved measurement of the shape of the electron,” {\emNature}{\bf473}(2011)493--496.

[32] C. A. Baker *et al.*, “An improved experimental limit on the electric dipole moment of the neutron,” {\emPhys.Rev.Lett.}{\bf97}(2006)131801, {\ttarXiv:hep-ex/0602020}.

[33] G. Belanger, F. Boudjema, A. Pukhov, and A. Semenov, “MicrOMEGAs: A Program for calculating the relic density in the MSSM,” {\emComput.Phys.Commun.}{\bf149}(2002)103--120, {\ttarXiv:hep-ph/0112278[hep-ph]}.

[34] G. Belanger, F. Boudjema, A. Pukhov, and A. Semenov, “micrOMEGAs: Version 1.3,” {\emComput.Phys.Commun.}{\bf174}(2006)577--604, {\ttarXiv:hep-ph/0405253[hep-ph]}.

[35] J. L. Feng, M. Kamionkowski, and S. K. Lee, “Light Gravitinos at Colliders and Implications for Cosmology,” {\emPhys.Rev.}{\bfD82}(2010)015012, {\ttarXiv:1004.4213[hep-ph]}.

[36] R. Kitano and I. Low, “Dark matter from baryon asymmetry,” {\emPhys.Rev.}{\bfD71}(2005)023510, {\ttarXiv:hep-ph/0411133[hep-ph]}.

[37] R. Kitano and I. Low, “Grand unification, dark matter, baryon asymmetry, and the small scale structure of the universe,” {\ttarXiv:hep-ph/0503112[hep-ph]}.

[38] M. Ibe and R. Kitano, “Gauge mediation in supergravity and gravitino dark matter,” {\emPhys.Rev.}{\bfD75}(2007)055003, {\ttarXiv:hep-ph/0611111}.

[39] M. Ibe and R. Kitano, “Sweet Spot Supersymmetry,” {\emJHEP}{\bf0708}(2007)016, {\ttarXiv:0705.3686[hep-ph]}.

[40] J. L. Feng and J. Kumar, “The WIMPless Miracle: Dark-Matter Particles without Weak-Scale Masses or Weak Interactions,” {\emPhys.Rev.Lett.}{\bf101}(2008)231301, {\ttarXiv:0803.4196[hep-ph]}.

[41] J. L. Feng, H. Tu, and H.-B. Yu, “Thermal Relics in Hidden Sectors,” {\emJCAP}{\bf0810}(2008)043, {\ttarXiv:0808.2318[hep-ph]}.

[42] J. L. Feng, M. Kaplinghat, H. Tu, and H.-B. Yu, “Hidden Charged Dark Matter,”

{\emJCAP}{\bf0907}(2009)004, {\ttarXiv:0905.3039[hep-ph]}.

[43] S. Weinberg, "Cosmological Constraints on the Scale of Supersymmetry Breaking," {\emPhys.Rev.Lett.}{\bf48}(1982)1303.

[44] J. R. Ellis, J. E. Kim, and D. V. Nanopoulos, "Cosmological Gravitino Regeneration and Decay," {\emPhys.Lett.}{\bfB145}(1984)181.

[45] T. Moroi, H. Murayama, and M. Yamaguchi, "Cosmological constraints on the light stable gravitino," {\emPhys.Lett.}{\bfB303}(1993)289--294.

[46] M. Bolz, A. Brandenburg, and W. Buchmuller, "Thermal production of gravitinos," {\emNucl.Phys.}{\bfB606}(2001)518--544, {\ttarXiv:hep-ph/0012052[hep-ph]}.

[47] S. Borgani, A. Masiero, and M. Yamaguchi, "Light gravitinos as mixed dark matter," {\emPhys.Lett.}{\bfB386}(1996)189--197, {\ttarXiv:hep-ph/9605222}.

[48] W. B. Lin, D. H. Huang, X. Zhang, and R. H. Brandenberger, "Non-thermal production of WIMPs and the sub-galactic structure of the universe," {\emPhys.Rev.Lett.}{\bf86}(2001)954, {\ttarXiv:astro-ph/0009003}.

[49] J. Hisano, K. Kohri, and M. M. Nojiri, "Neutralino warm dark matter," {\emPhys.Lett.}{\bfB505}(2001)169--176, {\ttarXiv:hep-ph/0011216}.

[50] K. Jedamzik, M. Lemoine, and G. Moultaka, "Gravitino, axino, Kaluza-Klein graviton warm and mixed dark matter and reionisation," {\emJCAP}{\bf0607}(2006)010, {\ttarXiv:astro-ph/0508141[astro-ph]}.

[51] F. Borzumati, T. Bringmann, and P. Ullio, "Dark matter from late decays and the small-scale structure problems," {\emPhys.Rev.}{\bfD77}(2008)063514, {\ttarXiv:hep-ph/0701007[hep-ph]}.

[52] J. Hewett, H. Weerts, R. Brock, J. Butler, B. Casey, *et al.*, "Fundamental Physics at the Intensity Frontier," {\ttarXiv:1205.2671[hep-ex]}.

[53] J. L. Feng, K. T. Matchev, and T. Moroi, "Multi - TeV scalars are natural in minimal supergravity," {\emPhys.Rev.Lett.}{\bf84}(2000)2322--2325, {\ttarXiv:hep-ph/9908309[hep-ph]}.

[54] J. L. Feng, K. T. Matchev, and T. Moroi, "Focus points and naturalness in supersymmetry," {\emPhys.Rev.}{\bfD61}(2000)075005, {\ttarXiv:hep-ph/9909334[hep-ph]}.

[55] K. Agashe, "Can multi - TeV (top and other) squarks be natural in gauge mediation?," {\emPhys.Rev.}{\bfD61}(2000)115006, {\ttarXiv:hep-ph/9910497[hep-ph]}.

[56] R. Kitano and Y. Nomura, "A Solution to the supersymmetric fine-tuning problem within the MSSM," {\emPhys.Lett.}{\bfB631}(2005)58--67, {\ttarXiv:hep-ph/0509039[hep-ph]}.

[57] J. L. Feng and D. Sanford, "A Natural 125 GeV Higgs Boson in the MSSM from Focus Point Supersymmetry with A-Terms," {\ttarXiv:1205.2372[hep-ph]}.

[58] N. Okada, "SuperWIMP dark matter and 125 GeV Higgs boson in the minimal GMSB," {\ttarXiv:1205.5826[hep-ph]}.