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Non-thermal Higgsino dark matter, heavy gravitino and 125 GeV Higgs boson in modulus/anomaly-mediated supersymmetric models

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If the lightest supersymmetric particle (LSP) is Higgsino-like, the thermal relic density is lower than the observed dark matter content for a LSP mass in the sub-TeV region. We outline constraints arising from the Fermi Gamma-ray Telescope data and LSP production from gravitino decay that must be satisfied by a successful nonthermal Higgsino scenario. We show that in a generic class of models where anomaly- and modulus-mediated contributions to supersymmetry breaking are of comparable size, Higgsino arises as the only viable sub-TeV dark matter candidate if gravitinos are heavy enough to decay before the onset of big bang nucleosynthesis. The correct relic density can be obtained via modulus decay in these models. As an explicit example, we consider a modulus sector in effective field theory ($D = 4$, $N = 1$ supergravitiy arising from type IIB Kachru-Kallosh-Linde-Trivedi compactification). Within this class of mirage mediation models, heaviness of the gravitino forces a sub-TeV Higgsino LSP and gives a Higgs mass around 125 GeV. In this example, the constraints from direct detection experiments are also satisfied.

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I. INTRODUCTION

Supersymmetry not only stabilizes the Higgs mass against quantum corrections, it also provides a candidate for dark matter. In R-parity conserving models, the lightest supersymmetric particle (LSP) is stable, hence, a dark matter candidate. The lightest neutralino, which is a mixture of Bino, Wino and Higgsinos, is the most suitable dark matter candidate with the prospect for detection in various direct and indirect searches.

In this work we point out that a comprehensive solution to the cosmological gravitino problem motivates the dark matter to be Higgsino-like. Gravitinos heavier than $\mathcal{O}(40)$ TeV have a lifetime shorter than 0.1 s and decay before the onset of big bang nucleosynthesis (BBN). This results in a considerable relaxation as the gravitino abundance will not be subject to tight BBN bounds [1].

In effective supergravity, the masses of the Bino and Wino are sensitive to the mass of the gravitino $m_{3/2}$ [2], and in particular, for $m_{3/2} > 40$ TeV, one typically has Bino and Wino masses above TeV in type IIB modulus mediation models. On the other hand, the Higgsino mass depends on the μ parameter, which can be reduced by anomaly-mediated contribution to supersymmetry breaking. As a result, if we demand that the dark matter particle has a mass in the sub-TeV region, the Higgsino becomes a more natural candidate.

If the lightest neutralino is predominantly Higgsino, with mass in the sub-TeV region, the annihilation rate is typically larger than the nominal value $\langle \sigma_{\rm ann} v \rangle = 3 \times 10^{-26}\ {\rm cm}^3\,{\rm s}^{-1}$, thus resulting in an insufficient thermal relic abundance [3]. A natural way to obtain the correct dark matter relic density is to consider nonthermal sources of Higgsino production.

We consider scenarios where Higgsino dark matter is nonthermally produced by a late decaying modulus [4]. We find that for the annihilation rate to be compatible with bounds from the Fermi Gamma-ray Telescope [5], the modulus decay should reheat the universe to a temperature $T_{\rm d} \sim \mathcal{O}({\rm GeV})$. An additional requirement is that the branching ratio for modulus decay to the gravitino is $\lesssim \mathcal{O}(10^{-5})$, so that the decay of gravitinos thus produced does not lead to dark matter overproduction.

As an example of the modulus sector, we consider the standard scenario of Kachru-Kallosh-Linde-Trivedi (KKLT) compactification [6], with the Kahler modulus reheating the universe around 1 GeV. Within this framework, for appropriate values of the relative contributions of anomaly- and modulus-mediated contributions, Higgsino emerges as the dark matter candidate. The annihilation rate is consistent with the Fermi bounds, and the correct relic density is obtained by nonthermal production. The Higgs mass $m_h \sim 125$ GeV [7] is also satisfied in this scenario, and we find that it actually requires the gravitino mass to be in the cosmologically safe region. Moreover, the spin-independent scattering cross section is consistent with the latest bounds from direct detection experiments [9].

Within this specific example, however, decay of the gravitinos that are directly produced from modulus decay overproduces dark matter. This is a direct consequence of the couplings between the modulus and the helicity $\pm 1/2$ components of the gravitino, which are in turn set by the underlying Kähler geometry of the effective $D = 4$, $N = 1$ supergravity theory. We summarize a set of geometric conditions in the modulus sector that are sufficient to ensure consistent nonthermal Higgsino dark matter as outlined above.

We note that apart from the purely cosmological motivations shown in this study, the Higgsino also emerges as the LSP within the framework of natural supersymmetry as discussed in Refs. [3,10,11].

The paper is organized as follows. In Sec. II, we relate the cosmological gravitino problem with the preference for Higgsino dark matter. In Sec. III, we outline the conditions that must be satisfied by any successful scenario of nonthermal Higgsino dark matter. In Sec. IV, we work out an explicit example of a nonthermal scenario. In Sec. V, we outline the general constraints on an effective modulus sector in order to avoid overproduction of gravitinos. We conclude the paper in Sec. VI.

II. COSMOLOGICAL GRAVITINO PROBLEM AND HIGGSINO DARK MATTER

In this section, we discuss the cosmological gravitino problem and argue that requiring dark matter in the sub-TeV range makes Higgsino a natural candidate due to an interplay between modulus and anomaly mediation contributions.

A. Cosmological gravitino constraint

The decay width of a particle ϕ, which may be a modulus or the gravitino, with couplings of gravitational strength to the visible sector fields is

$$\Gamma_\phi = \frac{c}{2\pi}\frac{m_\phi^3}{M_{\rm P}^2}, \tag{1}$$

where c depends on the couplings of the decaying field. For moduli fields, we typically have $c \sim 0.1$–1. For gravitinos, c can be computed explicitly since supersymmetry fixes the couplings of the gravitino to the visible sector. One has a maximal value of $c \sim 1.5$ in this case [12].

The decay occurs when $H \simeq \Gamma_\phi$, with H being the Hubble expansion rate of the universe. Modulus decay reheats the universe to the following temperature

$$T_{\rm d} \simeq (5~{\rm MeV}) c^{1/2}\left(\frac{10.75}{g_*}\right)^{1/4}\left(\frac{m_\phi}{100~{\rm TeV}}\right)^{3/2}, \tag{2}$$

where g_* is the total number of relativistic degrees of freedom at $T_{\rm d}$ ($g_* = 10.75$ for $T_{\rm d} \gtrsim \mathcal{O}({\rm MeV})$).

Gravitinos that have a lifetime shorter than 0.1 s decay before the onset of BBN and avoid any conflict with its successful predictions. Such a lifetime corresponds to $T_{\rm d} \gtrsim 3$ MeV, which requires that $m_{3/2} \gtrsim \mathcal{O}(40)$ TeV from Eq. (2).

B. Higgsino lightest supersymmetric particle

To obtain a TeV scale spectrum in the observable sector for such heavy gravitinos, one needs to consider models where there is a hierarchy between the gravitino and the other superpartner masses. We consider modulus mediation, where supersymmetry is broken by a gravitationally coupled modulus in the hidden sector. An example of a broad class of models that provide the required hierarchy is in compactifications of Type IIB string theory, with the following ingredients: (a) a Kähler modulus T_a stabilized by nonperturbative effects, (b) complex structure moduli stabilized by fluxes, and (c) visible sector on $D7$ branes [13]. In such cases, the gaugino masses obey

$$M_{\tilde g} \approx \frac{m_{3/2}}{\ln(M_{\rm P}/m_{3/2})}. \tag{3}$$

When anomaly-mediated contributions are subdominant, the Bino is the LSP. However, for $m_{3/2} > 40$ TeV, the Bino mass is typically above $\mathcal{O}(1)$ TeV as seen from Eq. (3). We will demonstrate this in our explicit example later.

For the Higgsinos, there is an additional freedom. Starting with equal modulus-mediated contributions, anomaly mediation lowers the mass of the gluino, while increasing the mass of the bino and wino. In this case, one has

$$M_3 : M_2 : M_1 \sim (1-0.3\alpha)g_3^2 : (1+0.1\alpha)g_2^2 : (1+0.66\alpha)g_1^2, \tag{4}$$

where M_0 is the modulus-mediated contribution at the grand unified theory scale, $\alpha \equiv m_{3/2}/M_0 \ln(M_{\rm P}/m_{3/2})$ denotes the relative strength of anomaly- and modulus-mediated contributions, and $g_{1,2,3}$ are the gauge-coupling constants [14,15]. The limit $\alpha \to 0$ corresponds to vanishing anomaly-mediated contributions and binolike LSP.

The value of the Higgsino mass parameter μ depends on the low-scale value of $m_{H_u}^2$, which is mainly driven by the gluino mass [16]. Increasing α lowers the gluino mass, which in turn lowers the low-scale value of $m_{H_u}^2$ due to the top Yukawa coupling. On the other hand, the bino and the wino become heavier.

Thus, if we demand the dark matter candidate mass to be less than $\mathcal{O}(1)$ TeV, Higgsino LSP is preferred by the cosmological gravitino problem, provided that the anomaly-mediated contribution to the soft masses competes with the modulus-mediated contribution.

The mass hierarchy between the scalar masses and the gravitino mass is more model dependent and depends on the curvature properties of the underlying Kähler manifold. Stop masses of $\mathcal{O}(1)$ TeV, preferred by a 125 GeV Higgs mass in the minimal supersymmetric standard model, are obtained in models with heavy gravitinos where the suppression is similar to Eq. (3).

III. SCENARIOS OF NONTHERMAL HIGGSINOS PRODUCTION

In this section, we consider nonthermal production of Higgsino dark matter. Standard relic density calculations predict thermal underproduction of Higgsinos for masses less than about a TeV [3]. Thus, one is motivated to study nonthermal scenarios where enhancement of the relic density occurs naturally. Nonthermal production is inevitable if the modulus ϕ that participates in supersymmetry breaking, or any other modulus, reheats the universe at a scale below the dark matter freeze-out temperature $T_{\rm f} \sim m_\chi/25$.

The dark matter relic density from modulus decay is given by

$$\frac{n_\chi}{s} \approx 5\times 10^{-10}\left(\frac{1\ \mathrm{GeV}}{m_\chi}\right)\frac{3\times 10^{-26}\ \mathrm{cm}^3\,\mathrm{s}^{-1}}{\langle\sigma_{\rm ann}v\rangle_{\rm f}}\left(\frac{T_{\rm f}}{T_{\rm d}}\right), \tag{5}$$

where $\langle\sigma_{\rm ann}v\rangle_{\rm f}$ is the annihilation rate at the time of freeze-out.

The Higssino DM mainly annihilates into heavy Higgs bosons, W bosons and t quarks via S-wave annihilation if m_χ has necessary phase space for these particles to be produced. The S-wave nature of the annihilation implies that the annihilation rate at the freeze-out time is essentially the same as that at the present time. The latter is constrained by the gamma-ray flux from dwarf spheriodal galaxies [5]:

$$\begin{aligned}\langle\sigma_{\rm ann}v\rangle_f &\lesssim 10^{-25}\ \mathrm{cm}^3\,\mathrm{s}^{-1} \qquad m_\chi = 100\ \mathrm{GeV},\\ \langle\sigma_{\rm ann}v\rangle_f &\lesssim 3\times 10^{-24}\ \mathrm{cm}^3\,\mathrm{s}^{-1} \qquad m_\chi = 1\ \mathrm{TeV}.\end{aligned} \tag{6}$$

According to the analysis in Ref. [17], the constraint on the annihilation cross-section from the gamma-ray flux from the galactic center region is similar for the above neutralino masses to a core of 1 kpc in the $b\bar{b}$ final states. The constraint on the annihilation cross-section becomes about $4\times 10^{-26}\ \mathrm{cm}^3\,\mathrm{s}^{-1}$ for $m_{\tilde{\chi}} = 100$ GeV for the Navarro-Frenk-White profile without any core.

We note that an explanation of the PAMELA anomaly requires a much larger cross-section [18]. However, the explanation of this anomaly can be due to the pulsars [19]. We also note that the bounds on the cross-section from dark matter annihilation to neutrinos at the galactic center, obtained by IceCube, are weaker by a few orders of magnitude [20].

In order to obtain the correct DM abundance, see Eq. (5), one therefore needs to have

$$T_{\rm d} \gtrsim 0.4\text{–}1.6\ \mathrm{GeV} \qquad m_\chi = 100\ \mathrm{GeV}\text{–}1\ \mathrm{TeV}. \tag{7}$$

For $T_{\rm d} \sim \mathcal{O}(\mathrm{GeV})$, the corresponding modulus mass is found from Eq. (2) to be

$$m_\phi \sim \mathcal{O}(1000)\ \mathrm{TeV}, \tag{8}$$

with the exact value depending on the decay modes of the modulus.

Another nonthermal source of Higgsinos production is gravitino decay. Since gravitino decay occurs at a temperature $\ll \mathcal{O}(\mathrm{GeV})$, and the dark matter annihilation rate must satisfy the Fermi bounds (6), annihilation is very inefficient at this time. As a result, the density of Higgsinos produced from gravitino decay is, therefore, the same as that of the gravitinos. Therefore, we must have

$$\frac{n_{3/2}}{s} \lesssim 5\times 10^{-10}\left(\frac{1\ \mathrm{GeV}}{m_\chi}\right). \tag{9}$$

Gravitinos are produced via thermal and nonthermal processes in the early universe. Modulus decay dilutes gravitinos that were produced in the prior epochs (e.g., during inflationary reheating) by a huge factor. Thermal gravitino production after modulus decay is highly suppressed due to the low decay temperature $T_{\rm d} \sim \mathcal{O}(\mathrm{GeV})$.

However, gravitinos can also be produced directly from modulus decay $\phi \to \tilde{G}\tilde{G}$. The density of gravitinos thus produced is given by $(n_{3/2}/s) = \mathrm{Br}_{3/2}(3T_{\rm d}/4m_\phi)$, where $\mathrm{Br}_{3/2}$ is the branching ratio for $\phi \to \tilde{G}\tilde{G}$ process. From Eq. (2), we then find

$$\frac{n_{3/2}}{s} \sim 5\times 10^{-8}\left(\frac{m_\phi}{100\ \mathrm{TeV}}\right)^{1/2}\mathrm{Br}_{3/2}. \tag{10}$$

For the typical value of m_ϕ given in (8) and 100 GeV $\le m_\chi \le 1$ TeV, Eqs. (9) and (10) yield the following absolute upper bound:

$$\mathrm{Br}_{3/2} \lesssim 10^{-5}. \tag{11}$$

Any successful scenario for nonthermal Higgsino production from modulus decay must satisfy this limit.

IV. NONTHERMAL HIGGSINO DARK MATTER: AN EXAMPLE

As an explicit example, we take the case of mirage mediation in the context of KKLT compactification [6]. Working in $D = 4$, $N = 1$ effective supergravity, the superpotential of the modulus sector consists of a flux term that fixes complex structure moduli and a nonperturbative piece that fixes the Kähler modulus. The Kähler potential is given by $K = -3\ln(T+\bar{T}) + (T+\bar{T})^{-n_m}\Phi\Phi^\dagger$, where Φ denotes matter fields and n_m are the modular weights. The input parameters fixing the grand unified theory scale masses are $m_{3/2}$, α, n_m, and $\tan\beta$.

For our case study, we choose $n_m = 1/2$ for all matter fields and $\tan\beta = 50$. The general conclusions hold for other values of n_m and $\tan\beta$.

The scalar spectrum has the suppression given in Eq. (3) with respect to the gravitino mass. It is instructive to note that when the stops are themselves hierarchically related to the gravitino, as in this case, $m_h \sim 125$ GeV is compatible with heavy gravitinos that decay before the onset of BBN. Since the one-loop correction to the Higgs mass depends logarithmically on $m_{3/2}$, a little heavier Higgs is preferred by the cosmologically safe region. We plot the dependence of the Higgs mass on the gravitino mass in Fig. 1.

For given $n_m = 1/2$ and $\tan\beta = 50$, scanning over $0.1 < \alpha < 1.6$, and $m_{3/2} > 40$ TeV, one finds that for

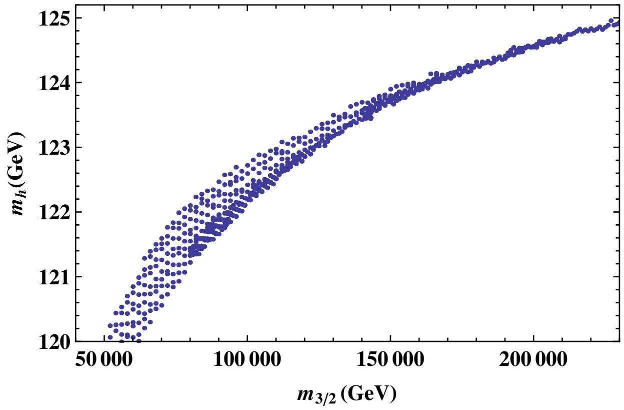

FIG. 1 (color online). Higgs mass versus gravitino mass. We choose $n_m = 1/2$ and $\tan\beta = 50$, and scan over α and $m_{3/2}$. Heavy gravitinos decaying before the onset of BBN are typically compatible with a Higgs mass above 120 GeV. A similar behavior is obtained for other values of $\tan\beta$ and n_m.

LSP mass below ~1 TeV, the LSP is always a Higgsino. We plot μ against the LSP mass in Fig. 2. This result is independent of the choice of $\tan\beta$. Since the gaugino mass does not depend upon n_m, this conclusion is also independent of n_m.

We also plot the spin-independent scattering cross-section $\sigma_{\tilde{\chi}_1^0-p}$ for various values of the gravitino mass in Fig. 3. Since larger gravitino mass is correlated to a larger heavy Higgs (H) mass in this model, $\sigma_{\tilde{\chi}_1^0-p}$ becomes smaller as $m_{3/2}$ increases. Again, this is compatible with the cosmologically safe region and $m_h \sim 125$ GeV. The current bound on the cross section is $\sim 2 \times 10^{-9}$ pb for a dark matter mass of 55 GeV [9] and relaxes as dark matter mass increases.

Table I depicts a few benchmark points of consistent nonthermal Higgsino dark matter in this model. In the table, we show the annihilation rates at present $\langle\sigma_{\rm ann}v\rangle_0$ and at the time of freeze-out $\langle\sigma_{\rm ann}v\rangle_f$. We see that for all of

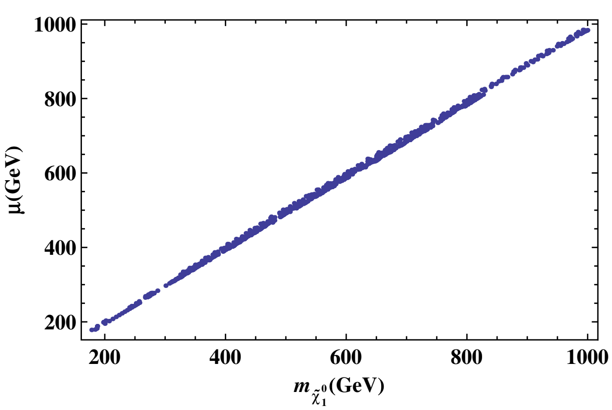

FIG. 2 (color online). μ versus LSP mass. For sub-TeV LSP, the dark matter is always a Higgsino.

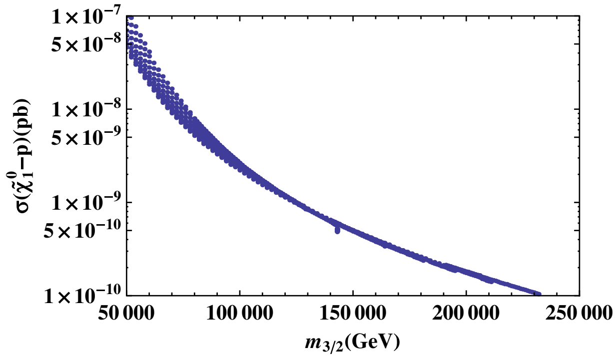

FIG. 3 (color online). Spin-independent scattering cross section versus gravitino mass. For values of $m_{3/2}$ that are compatible with 125 GeV Higgs, see Fig. 1, $\sigma_{\tilde{\chi}_0^1-p}$ satisfies the experimental data.

these points, $\langle\sigma_{\rm ann}v\rangle_0$ satisfies the Fermi bounds. Of the three points presented in Table I, the first two cases satisfy the constraint from the dwarf spheroidals and the flux arising from galactic center region with a core of 1 kpc. The third satisfies the constraints from dwarf spheroidals and flux from the galactic center with and without any core for Navarro-Frenk-White profile.

Dark matter annihilation at the freeze-out occurs mostly through the S-channel and a coannihilation component. The latter arises due to the fact that masses of the second lightest neutralino and chargino are close to LSP mass $m_{\tilde{\chi}_0^1}$. The dark matter content of the universe is obtained by multiplying the $\langle\sigma_{\rm ann}v\rangle_f$ by $T_{\rm f}/T_{\rm d}$. We have taken $c = 0.4$ to calculate $T_{\rm d}$, which is the leading-order value appearing in the decay width of the modulus in this particular example, in the limit of $\alpha = 1$ corresponding to zero dilaton-modulus mixing in the gauge kinetic function. But c can also be ~1 depending on relative contributions of the modulus and dilaton in the gauge kinetic function, and $T_{\rm d}$ can be $\mathcal{O}(1\text{–}2)$ of its central value. With this taken into account, it is seen that $T_{\rm f}/T_{\rm d}$ is in the right range to yield the correct dark matter content of the universe.

We also show the value of $\sigma_{\tilde{\chi}_1^0-p}$ for these points, which are well allowed by the experimental data. The table also includes masses of the gluino and stops and the Higgs mass m_h for these points.

It is interesting to calculate the level of fine-tuning for the $m_h = 125$ GeV point in the table. A robust estimator of fine-tuning may be obtained from Refs. [21,22]. The UV parameters of our model are α and $m_{3/2}$, and the fine-tuning of the Higgs mass and μ with respect to them are as follows:

$$\Delta_{h,\alpha} = \frac{\partial \ln m_h}{\partial \ln\alpha} = 5.7 \quad \Delta_{h,m_{3/2}} = \frac{\partial \ln m_h}{\partial \ln m_{3/2}} = 2.1$$
$$\Delta_{\mu,\alpha} = \frac{\partial \ln\mu}{\partial \ln\alpha} = 6034 \quad \Delta_{\mu,m_{3/2}} = \frac{\partial \ln\mu}{\partial \ln m_{3/2}} = 16. \qquad (12)$$

TABLE I. Some benchmark points of nonthermal Higgsino dark matter for mirage mediation model in the context of KKLT compactification. The input parameters are α and $m_{3/2}$. The modular weights are fixed to be $n_m = 1/2$ and $\tan\beta = 50$. All masses are in GeV.

α	$m_{3/2}$	m_h	$m_{\tilde{\chi}_1^0}$	$m_{\tilde{\chi}_2^0}$	$m_{\tilde{g}}$	$m_{\tilde{t}_1}$	$m_{\tilde{t}_2}$	$\langle\sigma_{\rm ann}v\rangle_0$ (cm^3/s)	$\langle\sigma_{\rm ann}v\rangle_f$ (cm^3/s)	$T_{\rm f}/T_{\rm d}$	$\sigma_{\tilde{\chi}_1^0-p}$ (pb)
1.49	143×10^3	123.5	248.4	250.8	3828	2441	2781	1.49×10^{-25}	1.63×10^{-25}	~6	5×10^{-10}
1.46	200×10^3	124.5	258.9	260.6	5536	3564	3991	1.38×10^{-25}	1.52×10^{-25}	~3.4	1.4×10^{-10}
1.44	232×10^3	125	306	308	6505	4197	4677	1.01×10^{-25}	1.01×10^{-25}	~3.2	8.9×10^{-11}

V. GENERAL CONDITIONS FOR SUPPRESSING GRAVITINO PRODUCTION

In the KKLT model discussed above, the partial decay rate for $\phi \to \tilde{G}\tilde{G}$ is $\Gamma_{3/2} = m_\phi^3/288\pi M_{\rm P}^2$. Then, after using Eq. (1), we find that ${\rm Br}_{3/2} \sim \mathcal{O}(10^{-2})$. This implies that gravitino decay will overproduce Higgsinos by three orders of magnitude in this model, see Eq. (10). The main reason for obtaining such a large ${\rm Br}_{3/2}$ is that modulus decay to helicity $\pm 1/2$ gravitinos is not helicity suppressed in the KKLT model [23].

The problem can be overcome if the modulus ϕ does not dominate the energy density of the universe when it decays. In such a case, the right-hand side of Eqs. (10) and (11) will be multiplied by f_ϕ and f_ϕ^{-1}, respectively, where f_ϕ is the ratio of the energy density in ϕ to the total energy density of the universe at the time of decay. For $f_\phi < 10^{-3}$, the abundance of gravitinos will be suppressed to safe levels.

Alternatively, one can seek conditions for suppressing gravitino production from modulus decay (for example, see Ref. [23]). Here, we briefly outline general conditions for such a suppression and stress that the main ingredients of a successful scenario for nonthermal Higgsino production presented above should also hold in cases where the gravitino production is suppressed.

The decay of a modulus to other fields depends on the interaction terms in the Lagrangian, and the requirement for suppressing decay to gravitinos will be reduced to a set of constraints in the effective theory. To have a more concrete demonstration of what kinds of constraints may emerge, we choose to work in effective supergravity, with a modulus coupling to the visible sector through the gauge kinetic function. This is the scenario in the class of Type IIB models discussed above.

In general, one can consider a scenario with multiple moduli ϕ_i, with the decaying modulus appearing in the gauge kinetic function. The normalized eigenstates ϕ_n are given by

$$(\phi)_i = \sum_j C_{ij}(\tau_n)_j, \qquad (13)$$

where the C_{ij} are eigenvectors of the matrix $K^{-1}\partial^2 V$. For simplicity, we will assume diagonal C_{ij} with entries C_i. The partial widths for modulus decay to gauge fields, gauginos, and helicity $\pm1/2$ gravitinos are

$$\Gamma_{\phi_i\to gg} = \frac{N_g}{128\pi}\frac{1}{\langle\tau\rangle^2}C_i^2\frac{m_{\phi_i}^3}{M_{\rm P}^2}$$
$$\Gamma_{\phi_i\to\tilde{g}\tilde{g}} = \sum_p \frac{N_g}{128\pi}C_p^2\langle\partial_p F^i\rangle^2\frac{m_{\phi_i}}{M_{\rm P}^2} \qquad (14)$$
$$\Gamma_{\phi_i\to\tilde{G}\tilde{G}} \sim \frac{1}{288\pi}(|G_{\phi_i}|^2 K^{-1}_{\phi_i\bar{\phi}_i})\frac{m_\phi^2}{m_{3/2}^2}\frac{m_{\phi_i}^3}{M_{\rm P}^2},$$

where $G = K + \log|W|^2$ is the Kähler function.

Under suitable choices of the Kähler potential, the required condition ${\rm Br}_{3/2} \sim 10^{-5}$ may be obtained. Similarly, the decay temperature of the modulus may be obtained in terms of the Kähler potential and superpotential. We refer to Ref. [24] for more details.

For a single modulus, the branching ratios to gauge bosons and gauginos are roughly equal, and the branching to the gravitino needs to be suppressed, leading to the condition

$$\frac{m_\phi}{m_{3/2}}|G_\phi|K_{\phi\bar{\phi}}^{-1/2} \sim 10^{-3}. \qquad (15)$$

For the KKLT example, the above quantity is $\mathcal{O}(1)$, which leads to overproduction of gravitinos. However, in a more general scenario, one can suppress this ratio to the required levels by a suitable choice of $K_{\phi\bar{\phi}}$ and vacuum expectation value of ϕ. This does not necessarily affect the existence of other conditions for successful nonthermal Higgsino production, such as comparable anomaly-mediated contributions or a modulus in the correct mass range. Moreover, the scalar masses depend on the holomorphic bisectional curvature of the plane (in tangent space) spanned by the scalars and the supersymmetry-breaking modulus, and this is not necessarily changed by a shift in the metric $K_{\phi\bar{\phi}}$. One can, therefore, expect to have a viable nonthermal scenario with the Higgs mass $m_h \sim 125$ GeV, while suppressing gravitino production from modulus decay. We leave the detailed exploration of these issues for future work.

VI. CONCLUSIONS

Considering dark matter in the sub-TeV range, thermal freeze-out underproduces Higgsino-like LSP. It is possible to enhance the relic density using nonthermal mechanisms of dark matter production. The enhancement, however, needs to obey the constraints from the gamma-ray flux from dwarf spheroidal galaxies and the galactic center region, as well as the dark matter content of the universe. Moreover, there should be no overproduction of dark matter at any later stage, for example by the decay of gravitinos.

In this paper, we demonstrated these ideas in a generic class of models where anomaly- and modulus-mediated contributions to supersymmetry breaking are comparable. Interestingly, we found that within this class of models, heavy gravitinos that are not subject to BBN bounds force the Higgsino as the only viable dark matter candidate in the sub-TeV range. We considered an explicit example of mirage mediation model in $D = 4$, $N = 1$ supergravitiy arising from type IIB KKLT compactification, where the modulus decay provides the nonthermal origin of Higgsino-like dark matter. The large gravitino mass is helpful to yield m_h around 125 GeV in this model and satisfy the constraints arising from the dark matter direct detection experiments. We also discussed the general conditions to avoid the overproduction of LSP from gravitino decay in such scenarios.

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