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Nonthermal dark matter in string compactifications

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Nonthermal cosmological histories are capable of greatly increasing the available parameter space of different particle physics dark matter (DM) models and are well motivated by the ubiquity of late-decaying gravitationally coupled scalars in UV theories like string theory. A nonthermal DM model is presented in the context of LARGE Volume Scenarios in type IIB string theory. The model is capable of addressing both the moduli-induced gravitino problem as well as the problem of overproduction of axionic dark radiation and/or DM. We show that the right abundance of neutralino DM can be obtained in both thermal under and overproduction cases for DM masses between $\mathcal{O}$(GeV) and $\mathcal{O}$(TeV). In the latter case the contribution of the QCD axion to the relic density is totally negligible, while in the former case it can be comparable to that of the neutralino thus resulting in a multicomponent DM scenario.

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I. INTRODUCTION

The standard paradigm of thermal dark matter (DM) assumes DM in thermal equilibrium following an initial inflationary era. Subsequently, the DM particle drops out of thermal equilibrium and its abundance freezes out when annihilation becomes inefficient at a temperature of order $T_{\rm f} \simeq m_{\rm DM}/20$. Due to the lack of direct observations of the history of the Universe before big bang nucleosynthesis (BBN), it is important to go beyond the standard thermal paradigm. In fact, nonthermal DM is well motivated both from a bottom-up and a top-down point of view.

From a bottom-up approach, nonthermal DM scenarios vastly enlarge the parameter space available in particle physics models. The most obvious example is the minimal supersymmetric Standard Model (MSSM), where neutralino DM candidates typically give too much (bino DM) or too little (Higgsino/wino DM) relic density. In a nonthermal scenario [1], both cases with thermal under (wino/Higgsino) and overabundance (bino) can be accommodated. Nonthermal production of wino DM [2] provides an explicit example. Another important example is pure Higgsino DM [3], which is motivated by naturalness conditions [4].

Furthermore, light DM with mass $\sim\mathcal{O}(10)$ GeV, motivated by results from recent direct detection experiments [5–8], typically has an annihilation cross section that is smaller in the context of most models due to the exchange of $\mathcal{O}$(TeV) particles [9] which leads to overabundance of dark matter in the current epoch in the thermal scenarios. Also, for DM with mass $\lesssim 40$ GeV the annihilation cross section is constrained to be less than the thermally required value by the gamma ray flux from dwarf spheroidal galaxies and Galactic center [10,11].

From a top-down approach, the ubiquity of gravitationally coupled moduli in string theory makes the scenario of a late-decaying scalar quite generic. Late-time decay will typically erase any previously produced DM relic density as well as baryon asymmetry, necessitating nonthermal production. The modulus should decay before BBN and late enough to produce interesting effects on IR physics. Hence nonthermal physics requires $T_{\rm BBN} \lesssim T_{\rm rh} < T_{\rm f}$, where $T_{\rm rh}$ is the modulus reheat temperature and $T_{\rm BBN} \simeq 3$ MeV is the lower bound required by the success of BBN. This typically places upper and lower bounds on the mass of the modulus. However, given that the scale of soft masses also depends on the moduli masses, the requirement of TeV-scale supersymmetry (SUSY) to solve the hierarchy problem, generically forces the moduli to be light enough to decay at temperatures below $T_{\rm f}$. Thus, from the point of view of string theory, nonthermal DM scenarios seem to be more generic than standard thermal ones [12].

The purpose of this paper is to explore nonthermal DM in string compactifications, specifically sequestered models in the context of type IIB LARGE Volume Scenarios (LVS) [13]. Several problems associated with nonthermal scenarios are readily addressed in this context: the moduli-induced gravitino problem [14] and the overproduction of axionic dark radiation (DR) [15–17] and DM [18]. Moreover, it is possible to accommodate cases of both thermal DM over and underproduction. Both cases can be realized using neutralinos for masses between $\mathcal{O}$(GeV) and $\mathcal{O}$(TeV). In the underproduction case, if needed, the QCD axion can be utilized to satisfy the abundance.

The plan of the paper is as follows. In Sec. II we review sequestered LVS models where the main challenges of nonthermal scenarios are addressed. In Sec. III we work out the production of nonthermal DM in these models before ending with our conclusions.

II. SEQUESTERED LVS MODELS

The cosmological moduli problem (CMP) [19] and the overproduction of axionic DM [18] are two ubiquitous problems of any string compactification. However, a heavy modulus decaying in the window $T_{\rm BBN} \lesssim T_{\rm rh} < T_{\rm f}$ would dilute any previous relic and also have other beneficial effects. In particular, axionic DM is diluted if $T_{\rm rh} < \Lambda_{\rm QCD} \simeq 200$ MeV, so avoiding any overproduction [20]. The maximum dilution is obtained for $T_{\rm rh}$ very close to $T_{\rm BBN}$ allowing a decay constant of order $f_a \simeq 10^{14}$ GeV without fine-tuning the initial misalignment angle. Standard thermal DM is also diluted if $T_{\rm rh} < T_{\rm f} \simeq \mathcal{O}(10)$ GeV. DM would then be produced nonthermally by the moduli decay. The moduli decay can solve the problem of axionic DM overproduction, can give rise to nonthermal DM, and can also be responsible for baryogenesis [21].

There are also two general problems:

(i) *Gravitino problem* [14]: If $m_{3/2} < m_\phi$ the gravitino is produced by the decay of the light modulus ϕ. If $m_{3/2} \lesssim 10$ TeV, the gravitino decays after BBN, otherwise if $m_{3/2} \gtrsim 10$ TeV, the gravitino could annihilate into DM causing its overproduction.

(ii) *Dark radiation overproduction* [15–17]: The moduli are gauge singlets and so they do not prefer to decay into visible sector fields. Thus, if light hidden sector degrees of freedom like axionlike particles exist, the branching ratio into them could not be negligible, so giving a number of effective relativistic species which is above the tight bounds from cosmological observations, $\Delta N_{\rm eff} \simeq 0.5$ [22].

A very promising moduli stabilization mechanism in type IIB string theory is the LARGE Volume Scenario [13]. In this framework, all the moduli are fixed by background fluxes, D-terms from anomalous $U(1)$'s, and the interplay of nonperturbative and α' effects. The simplest realization involves an internal volume of the form (for explicit constructions see [23]):

$$\mathcal{V} = \tau_{\rm big}^{3/2} - \tau_{\rm np}^{3/2} - \tau_{\rm inf}^{3/2} - \tau_{\rm vs}^{3/2}, \tag{1}$$

where the τ's are Kähler moduli parametrizing the size of internal 4-cycles. The visible sector [a chiral MSSM- or grand unified theory (GUT)-like theory] is built via space-time filling D3-branes sitting at the singularity obtained by shrinking $\tau_{\rm vs}$ to zero size by D-terms [24]. On the other hand, the cycle $\tau_{\rm np}$ supports nonperturbative effects which fix it in terms of the string coupling: $\langle\tau_{\rm np}\rangle \simeq g_s^{-1}$. For $g_s \simeq 0.1$ in the perturbative regime, $\tau_{\rm np}$ is of order 10 in string units. The "big" cycle $\tau_{\rm big}$ is instead stabilized by α' plus nonperturbative effects at $\langle\mathcal{V}\rangle \simeq \langle\tau_{\rm big}\rangle^{3/2} \simeq W_0 e^{2\pi/(Ng_s)}$ where W_0 is the flux-generated superpotential and N is the rank of the condensing gauge group. This minimum breaks SUSY spontaneously. Minkowski vacua can be obtained by either D-terms [25] or nonperturbative effects at singularities [26]. The modulus $\tau_{\rm inf}$ behaves similarly to $\tau_{\rm np}$, and by displacing it from its minimum, it can drive 60 e-folds of inflation, generating a red spectrum and the right amount of density perturbations for $\mathcal{V} \simeq 10^7$ [27].

Since the volume is exponentially large, it is easy to generate such large numbers for natural values of the underlying parameters. An important scale in the model is the mass of the soft terms $M_{\rm soft}$ generated by gravity mediation. Given that $\langle\tau_{\rm vs}\rangle = 0$, this modulus has a vanishing F-term as opposed to all the other moduli which develop nonzero F-terms. As a consequence, the visible sector is sequestered and the soft terms are significantly suppressed with respect to $m_{3/2}$. All the relevant energy scales in the model are set by value of $\mathcal{V}$ [24]:

(i) Reduced Planck scale: $M_{\rm P} = 2.4 \times 10^{18}$ GeV,

(ii) GUT scale: $M_{\rm GUT} \simeq M_{\rm P}/\mathcal{V}^{1/3}$,

(iii) String scale and $\tau_{\rm vs}$: $M_{\rm s} \simeq m_{\tau_{\rm vs}} \simeq M_{\rm P}/\mathcal{V}^{1/2}$,

(iv) Kaluza-Klein scale: $M_{\rm KK} \simeq M_{\rm P}/\mathcal{V}^{2/3}$,

(v) Inflaton and $\tau_{\rm np}$: $m_{\tau_{\rm inf}} \simeq m_{\tau_{\rm np}} \simeq m_{3/2} \ln \mathcal{V}$,

(vi) Gravitino mass: $m_{3/2} \simeq W_0 M_{\rm P}/\mathcal{V}$,

(vii) Big modulus: $m_{\tau_{\rm big}} \simeq m_{3/2}/\mathcal{V}^{1/2}$,

(viii) Soft terms: $M_{\rm soft} \simeq m_{3/2}/\mathcal{V}$.

Setting $W_0 \sim 0.1$ and $\mathcal{V} \simeq 10^7$, one obtains $M_{\rm GUT} \simeq 10^{16}$ GeV, $M_{\rm s} \simeq 10^{15}$ GeV, $M_{\rm KK} \simeq 5 \times 10^{13}$ GeV, $m_{\tau_{\rm inf}} \simeq m_{\tau_{\rm np}} \simeq 10^{11}$ GeV, $m_{3/2} \sim 10^{10}$ GeV, $m_{\tau_{\rm big}} \simeq 5 \times 10^6$ GeV and $M_{\rm soft} \simeq 1$ TeV. We note that the gauge coupling unification can be accommodated in this model despite $M_{\rm s} < M_{\rm GUT}$ as shown in Ref. [28].

This model produces supergravity (SUGRA) mass spectra that can be probed at the LHC. The minimal version of SUGRA (mSUGRA) is less preferred by the recent LHC constraints on squarks and gluinos, dark matter constraints, and constraints arising from BR($B_s \to \mu\mu$), Br($b \to s\gamma$) and muon anomalous magnetic moment results.

An interesting observation is that for $\mathcal{V} \simeq 10^7$, one can get both inflation and low-energy SUSY. Moreover, all the moduli are heavy, and so there is no CMP. The gravitino problem is also avoided since $m_{3/2} \gg m_{\tau_{\rm big}}$.

As far as the moduli couplings are concerned, the leading decay channels for $\tau_{\rm big}$ are to Higgses and closed string axions. Denoting as ϕ the canonically normalized modulus $\tau_{\rm big}$, the various decay rates of this modulus are (see [15] for details):

(i) *Decays to Higgs bosons*: The decays $\phi \to H_u H_d$ are induced by the Giudice-Masiero term in the Kähler potential, $K \supset Z\frac{H_u H_d}{2\tau_{\rm big}}$, where Z is an $\mathcal{O}(1)$ parameter. The corresponding decay rate is

$$\Gamma_{\phi\to H_u H_d} = \frac{2Z^2}{48\pi}\frac{m_\phi^3}{M_P^2}. \quad (2)$$

(ii) *Decays to bulk axions*: The axionic partner $a_{\rm big}$ of the big modulus is almost massless, and so $\tau_{\rm big}$ can decay into this particle with decay width: $\Gamma_{\phi\to a_{\rm big}a_{\rm big}} = \frac{1}{48\pi}\frac{m_\phi^3}{M_P^2}$.

(iii) *Decays to local closed string axions*: $\tau_{\rm big}$ can decay also to closed string axions $a_{\rm loc}$ localized at the singularity hosting the visible sector with decay rate: $\Gamma_{\phi\to a_{\rm loc}a_{\rm loc}} = \frac{9}{16}\frac{1}{48\pi}\frac{m_\phi^3}{M_P^2}$.

(iv) *Decays to gauge bosons*: Given that the holomorphic gauge kinetic function does not depend on $\tau_{\rm big}$ due to the localization of the visible sector at a singularity, this modulus couples to gauge bosons only due to radiative corrections, inducing a loop-suppressed decay width:

$$\Gamma_{\phi\to A^\mu A^\mu} = \lambda\left(\frac{\alpha_{\rm SM}}{4\pi}\right)^2\frac{m_\phi^3}{M_P^2}, \quad (3)$$

where $\lambda \sim \mathcal{O}(1)$ and $\alpha_{\rm SM}$ is the corresponding coupling constant.

There are also suppressed decays to other visible sector fields and to local open string axions. As pointed out in [15], the unsuppressed decays to bulk and local closed string axions can cause problems with DR overproduction. However, globally consistent brane constructions in explicit Calabi-Yau examples have revealed that both the light bulk axion $a_{\rm big}$ and all the local closed string axions $a_{\rm loc}$ tend to be eaten up by anomalous $U(1)$'s [23]. We shall therefore not consider it as a serious problem. On the other hand, the QCD axion can have different phenomenological features according to its origin as a closed or an open string mode [29]:

(i) *Closed string QCD axion*: If at least one local closed string axion is not eaten up by any anomalous $U(1)$, it can play the role of the QCD axion. Given that its decay constant is set by the string scale, $f_a \simeq M_s/\sqrt{4\pi} \simeq 10^{14}$ GeV, it needs to be diluted by the decay of $\tau_{\rm big}$ (otherwise one has to fine-tune the initial misalignment angle). Moreover, one has to make sure that it does not cause any problem with DR overproduction.

(ii) *Open string QCD axion*: If the QCD axion is the phase of a matter field, then the modulus decay rate to this particle is subleading, so leading to no DR production. Furthermore, in this case the axion decay constant gets reduced with respect to the string scale, $f_a \simeq M_s/\mathcal{V}^\alpha$ with $0 < \alpha < 1$. For $\alpha = 1/2$, one has $f_a \simeq 10^{11}$ GeV, perfectly within the QCD axion allowed window 10^9 GeV $\lesssim f_a \lesssim 10^{12}$ GeV.

III. NONTHERMAL DARK MATTER FROM LIGHTEST MODULUS DECAY

The lightest modulus $\tau_{\rm big}$ serves as the source of nonthermal DM. The modulus interacts gravitationally with other fields, leading to a decay width given by $\Gamma_\phi = \frac{c}{2\pi}\frac{m_\phi^3}{M_P^2}$, where c is a constant that depends on the decay modes of the modulus. The modulus decays when $H \sim \Gamma_\phi$ and reheats the Universe to a temperature: $T_{\rm rh} = c^{1/2}(\frac{10.75}{g_*})^{1/4}(\frac{m_\phi}{50\ {\rm TeV}})^{3/2}T_{\rm BBN}$, where $T_{\rm BBN} \simeq 3$ MeV and g_* is the number of relativistic degrees of freedom at $T_{\rm rh}$. The modulus decay dilutes the abundance of existing DM particles by at least a factor of order $(T_{\rm f}/T_{\rm rh})^3$, where $T_{\rm f}$ is freeze-out temperature of DM annihilation. This can be easily a factor of 10^6 or larger, hence requiring DM production from modulus decay in order to explain the DM content of the Universe. The abundance of DM particles produced in this way is

$$\frac{n_{\rm DM}}{s} = \min\left[\left(\frac{n_{\rm DM}}{s}\right)_{\rm obs}\frac{\langle\sigma_{\rm ann}v\rangle_{\rm f}^{\rm th}}{\langle\sigma_{\rm ann}v\rangle_{\rm f}}\left(\frac{T_{\rm f}}{T_{\rm rh}}\right), Y_\phi {\rm Br}_{\rm DM}\right], \quad (4)$$

where $\langle\sigma_{\rm ann}v\rangle_{\rm f}^{\rm th} \simeq 3\times 10^{-26}\ {\rm cm}^3\,{\rm s}^{-1}$ is the value needed in the thermal case to match the observed DM abundance:

$$\left(\frac{n_{\rm DM}}{s}\right)_{\rm obs} \simeq 5\times 10^{-10}\left(\frac{1\ {\rm GeV}}{m_{\rm DM}}\right), \quad (5)$$

whereas the yield of particle abundance from ϕ decay is $Y_\phi \equiv \frac{3T_{\rm rh}}{4m_\phi} = \frac{0.9}{\pi}\sqrt{\frac{cm_\phi}{M_P}}$. Here, ${\rm Br}_{\rm DM}$ denotes the branching ratio for ϕ decays into R-parity odd particles which subsequently decay to DM.

The first term on the right-hand side of Eq. (4) is the *annihilation scenario* since DM particles produced from the modulus decay undergo some annihilation. This can happen when $\langle\sigma_{\rm ann}v\rangle_{\rm f} = \langle\sigma_{\rm ann}v\rangle_{\rm f}^{\rm th}(T_{\rm f}/T_{\rm rh})$. Since $T_{\rm rh} < T_{\rm f}$, this scenario can yield the correct DM abundance only if $\langle\sigma_{\rm ann}v\rangle_{\rm f} > \langle\sigma_{\rm ann}v\rangle_{\rm f}^{\rm th}$ (as for Higgsino DM).

The second term on the right-hand side of Eq. (4) is the *branching scenario* where the residual annihilation of DM particles is inefficient and the final DM abundance is the same as that produced from the modulus decay. This happens if $\langle\sigma_{\rm ann}v\rangle_{\rm f} < \langle\sigma_{\rm ann}v\rangle_{\rm f}^{\rm th}(T_{\rm f}/T_{\rm rh})$. We note that this is always the case for $\langle\sigma_{\rm ann}v\rangle_{\rm f} < \langle\sigma_{\rm ann}v\rangle_{\rm f}^{\rm th}$ (like in the case of bino DM). It may also happen for $\langle\sigma_{\rm ann}v\rangle_{\rm f} > \langle\sigma_{\rm ann}v\rangle_{\rm f}^{\rm th}$ if $T_{\rm rh}/T_{\rm f}$ is too small.

The Fermi results, based on data from dwarf spheroidal galaxies and the Galactic center, have already placed tight constraints on the "annihilation scenario." The limits from dwarf galaxies [10] indicate that $T_{\rm f} \lesssim 30T_{\rm rh}$ for $m_{\rm DM} > 40$ GeV, which implies $T_{\rm rh} > 70$ MeV. For $m_{\rm DM} < 40$ GeV, the Fermi bounds require $\langle\sigma_{\rm ann}v\rangle_{\rm f} < \langle\sigma_{\rm ann}v\rangle_{\rm f}^{\rm th}$, if DM annihilates into $b\bar{b}$ with S-wave domination, implying that the annihilation scenario cannot work in this case.

The constraints become stronger when Galactic center data [11] are included.

As a result, the "branching scenario" is strongly preferred as the only option in the mass range $m_{\rm DM} < 40$ GeV. Since $5 \times 10^{-3} \lesssim {\rm Br}_{\rm DM} \lesssim 1$, with the lower bound set by three-body decay of ϕ into R-parity odd particles [21], we need $Y_\phi \lesssim 10^{-8}$ in order to obtain the correct DM abundance within this scenario. For $m_\phi \simeq 5 \times 10^6$ GeV, $Y_\phi \lesssim 10^{-8}$ requires $T_{\rm BBN} \lesssim T_{\rm rh} \lesssim 70$ MeV.

Based on the above arguments, we find that there are two interesting regimes for $T_{\rm rh}$:

(1) Annihilation scenario for $T_{\rm f}/30 \lesssim T_{\rm rh} < T_{\rm f}$;

(2) Branching scenario for $T_{\rm BBN} \lesssim T_{\rm rh} \lesssim 70$ MeV.

We shall now discuss these two cases in more detail.

A. Annihilation scenario for high $T_{\rm rh}$

In the regime $T_{\rm f}/30 \lesssim T_{\rm rh} < T_{\rm f}$ the annihilation scenario is at work. As we have seen in Sec. II, ϕ decays primarily to Higgses, giving $c = Z^2/12$. Inserting this value and the modulus mass $m_\phi \simeq 5 \times 10^6$ GeV that gives TeV-scale SUSY, we find a reheat temperature of order $T_{\rm rh} \simeq 0.8Z$ GeV.

Focusing on situations where bulk axions are removed from the spectrum, the QCD axion can either be a closed or an open string mode:

(1) The QCD axion is a local closed string mode $a_{\rm loc}$ with $f_a \sim 10^{14}$ GeV:
- (a) $\phi \to a_{\rm loc} a_{\rm loc}$ is a leading decay channel, and so we need to suppress the contribution to $\Delta N_{\rm eff} \simeq 1/Z^2$ [15]. In order to have $\Delta N_{\rm eff} \simeq 0.5$ we need $Z \simeq \sqrt{2}$, which gives $T_{\rm rh} \simeq 1$ GeV.
- (b) In order to have $T_{\rm rh} < T_{\rm f}$, one needs $m_{\rm DM} > 20 T_{\rm rh} \simeq 20$ GeV.
- (c) The reheat temperature is larger than the QCD scale, $T_{\rm rh} \simeq 1~{\rm GeV} > \Lambda_{\rm QCD}$, and so axion cold DM is not diluted. Hence one has either to tune the initial misalignment angle or to remove $a_{\rm loc}$ from the spectrum with the help of an anomalous $U(1)$ (the QCD axion has then to be an open string mode).
- (d) Tuning the misalignment angle suitably it is possible to make multicomponent DM (wino/Higgsino-like + closed string axions).[1]

(2) The QCD axion is an open string mode θ with $f_a \simeq 10^{11}$ GeV.
- (a) $\phi \to \theta\theta$ is a subleading decay channel, and so no DR is produced.
- (b) Due to the high value of $T_{\rm rh}$ the modulus decay does not result in any dilution of axion oscillations, but since f_a is intermediate, we do not need to tune the initial misalignment angle to avoid axionic DM overproduction.
- (c) Again DM is generically multicomponent (wino/Higgsino-like + open string axions). The open string axion contribution to the DM abundance reduces as f_a becomes smaller than 10^{12} GeV.

In summary, in the annihilation scenario the lightest neutralino (wino/Higgsino type) can satisfy the relic density.[2] If, however, the abundance is small, the QCD axion can be utilized to form a multicomponent DM scenario [31].

B. Branching scenario for low $T_{\rm rh}$

In order to have a low $T_{\rm rh}$ ($3~{\rm MeV} \lesssim T_{\rm rh} \lesssim 70$ MeV) the modulus decay width has to be very small. However, as we have seen in the previous section, if the QCD axion is a closed string mode, then we will need $Z \gtrsim \sqrt{2}$ in order to avoid the DR problem. This in turn sets $T_{\rm rh} \gtrsim 1$ GeV. In order to lower $T_{\rm rh}$ one could consider smaller values of m_ϕ which would however imply $M_{\rm soft} \ll 1TeV$. Hence the only way-out is to focus on cases where the closed string axions are absorbed by anomalous $U(1)$'s, and the QCD axion is realized as an open string mode θ. Due to its suppressed coupling to ϕ, θ does not cause any DR problem, allowing very low values of $T_{\rm rh} \ll \Lambda_{\rm QCD}$. Thus in this case the modulus decay will dilute the axion oscillations, leading to a negligible contribution of the QCD axion to DM.

There are two ways to lower the reheat temperature:

(1) If the Giudice-Masiero term is forbidden by some symmetries then $Z = 0$. For example, one can invoke appropriate $U(1)$ or discrete charges to prevent these terms (μ-term however can arise by breaking the symmetry). In this case the leading decay channel is to gauge bosons via a two-body final state with a loop-suppressed decay rate, giving $c = \lambda \frac{\alpha_{\rm SM}^2}{8\pi}$ [see Eq. (3)]. If $\lambda \simeq 1$, $\alpha_{\rm SM} \simeq 1/137$, and $m_\phi \simeq 5 \times 10^6$ GeV, the reheat temperature is $T_{\rm rh} \simeq 4$ MeV (slightly above BBN), giving $Y_\phi \simeq 6 \times 10^{-10}$. Two-body decays to gauginos and other MSSM particles are instead mass suppressed in this case. The suppression arises since the partial width for modulus decay to fermions or scalars is proportional to $M_{\rm soft}^2 m_\phi / M_{\rm P}^2$. However, gauginos are inevitably produced in three-body decays of the modulus (e.g., $\phi \to 1~{\rm gluon} + 2~{\rm gluinos}$) with ${\rm Br}_{\rm DM} \sim 5 \times 10^{-3}$. Then ${\rm Br}_{\rm DM} \simeq 5 \times 10^{-3}$ results in a DM abundance which matches the observed value for $m_{\rm DM} \simeq 165$ GeV. The DM mass is inversely proportional to $Y_\phi \propto \sqrt{\lambda m_\phi}$. Larger values of m_ϕ would require smaller values of $m_{\rm DM}$ but in this situation the soft terms would become larger than the TeV scale. On the other hand, smaller values of m_ϕ would imply larger values of $m_{\rm DM}$ but then

[1] Considering different astrophysical observations, the viability of nonthermal wino DM may be very constrained [30].

[2] See also [16] for similar models with wino/Higgsino DM from moduli decays.

$M_{\rm soft} \ll 1$ TeV. Hence we shall keep m_ϕ fixed at $m_\phi \lesssim 5 \times 10^6$ GeV and try to vary λ. The requirement $T_{\rm rh} \gtrsim 3$ MeV implies $\lambda \gtrsim 0.01$ and in turn $m_{\rm DM} \lesssim 900$ GeV.

(2) In the absence of symmetries forbidding the decay of ϕ to Higgses, it is still possible to have low $T_{\rm rh}$ for $Z \simeq 0.1$. In this case, for $m_\phi \simeq 5 \times 10^6$ GeV, we would have $T_{\rm rh} \simeq 80$ MeV, which implies $m_{\rm DM} \simeq 10$ GeV. Larger values of $m_{\rm DM}$ require smaller values of Z keeping m_ϕ fixed to get TeV-scale SUSY particles. Values of Z as small as $Z \simeq 0.01$ would give $m_{\rm DM} \simeq 100$ GeV. Note that in this case where ϕ decays mainly to Higgses, the production of R-parity odd particles in three-body decays requires the heavy and/or light Higgs decay to a gaugino/Higgsino pairs to be blocked kinematically.

In summary, in the branching scenario the lightest neutralino can be any mixture of bino, wino, and Higgsino and both thermal over- and underproduction cases can be accommodated. The abundance of the QCD axion is totally negligible due to dilution by modulus decay at $T_{\rm rh} \ll \Lambda_{\rm QCD}$.

IV. CONCLUSIONS

In this paper we showed how sequestered LVS models give rise naturally to nonthermal DM from the decay of the lightest modulus ϕ. Moreover, there is no moduli-induced gravitino problem since $m_{3/2} \simeq 10^{10}$ GeV $\gg m_\phi \simeq 5 \times 10^6$ GeV. Thanks to sequestering, the superpartner spectrum is still in the TeV range even with such a heavy gravitino. Depending on the way in which ϕ couples to the visible sector, there are two regimes for the reheat temperature $T_{\rm rh}$. The case of high $T_{\rm rh} \simeq 1$ GeV is realized when ϕ decays mainly to Higgses, and corresponds to the "annihilation scenario." Axionic DR overproduction is avoided either by the presence of anomalous $U(1)$'s which eat dangerous axions or by allowing suitable couplings in the Giudice-Masiero term. The resulting nonthermal DM has two components: wino/Higgisino-like neutralinos with masses $m_{\rm DM} > 40$ GeV and QCD axions (we note that indirect detection may limit the viability of nonthermal wino DM [30]). The reheat temperature can instead be lowered to $T_{\rm rh} \simeq 10$ MeV if ϕ decays mainly to gauge bosons (or if the decay to Higgses is suppressed). This is the case of the "branching scenario" where the QCD axion can only be an open string mode whose abundance is diluted by the decay of ϕ since $T_{\rm rh} \ll \Lambda_{\rm QCD}$. Both thermal over- and underabundance cases can be accommodated in this scenario and the DM mass can vary from $\mathcal{O}$(GeV) to $\mathcal{O}$(TeV).

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