X-ray lines from *R*-parity violating decays of keV sparticles

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If R parity is only mildly violated, then the lightest supersymmetric particle (LSP) can be stable over cosmologically time scales and still account for the dark matter relic density. We examine the possibility of generating detectable x-ray lines from R-parity violating decays of keV-scale LSP dark matter to neutrino-photon pairs. Specifically, we consider scenarios in which the LSP is a light gravitino, bino, or hidden sector photino. Potential signals are discussed in the context of recent claims of an unidentified 3.5 keV x-ray line in studies of stacked galaxy clusters. We comment on the difficulties in obtaining the observed relic density for keV-scale bino or hidden photino dark matter and some possible resolutions.

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I. INTRODUCTION

Despite negative searches at the LHC thus far, TeV-scale supersymmetry (SUSY) remains the leading resolution to the hierarchy problem, particularly in light of the discovery of a Higgs boson not much above the Z mass. While experimental searches and theoretical considerations suggest that most of the SUSY spectrum should be above the weak scale, it is quite conceivable that certain neutral states could be substantially lighter. Such light sparticles could have interesting cosmological and astrophysical implications. Here we shall focus on the prospect of keV-scale SUSY states which can decay in such a manner as to produce observable x-ray signals. We are inspired to think about decays of light particles by the tentative 3.5 keV line observed in the combined spectra of multiple galaxy clusters as studied by the XMM-Newton x-ray observatory [1,2]. Thus we shall typically phrase our discussion in terms of this benchmark point and examine models of dark matter (DM) which might accommodate this phenomenon. This signal can be interpreted in terms of DM which decays to a photon and an (effectively) massless degree of freedom with a mass and lifetime around

$$\begin{aligned} m_{\mathrm{DM}} &\simeq 7\ \mathrm{keV}, \\ \tau_{\mathrm{DM}} &\simeq 2\times 10^{27}\text{–}2\times 10^{28}\ \mathrm{s}. \end{aligned} \tag{1}$$

Some potential models have been proposed which might account for this observational anomaly [1,3–16], the possibility of decaying sterile neutrinos or axions receiving particular attention. Given the wide expectation that SUSY should play a leading role in physics beyond the Standard Model, it is interesting to explore possible SUSY explanations for this signal.

As is well known, the canonical SUSY extension of the Standard Model, the MSSM, requires the imposition of an (*ad hoc*) discrete Z_2 symmetry: R parity

$$(-1)^{3(B-L)+2s}. \tag{2}$$

Under this discrete symmetry the Standard Model (superpartner) states transform as even (odd) representations. This is necessary purely for phenomenological purposes since there are dimension four and five operators of the form

$$\mu' \boldsymbol{L H_u}, \qquad \lambda \boldsymbol{L L \bar{E}}, \qquad \lambda' \boldsymbol{L Q \bar{D}}, \qquad \lambda'' \boldsymbol{\overline{UDD}}, \tag{3}$$

which, unless the couplings are small, are problematic as they lead to fast proton decay in conflict with experimental searches [17,18]. If R parity is an exact symmetry, then the lightest supersymmetric particle (LSP) is stable. Intriguingly a stable LSP can play the role of DM and the occurrence of a well motivated DM candidate is arguably one of the great triumphs of SUSY extensions of the Standard Model; see e.g. [19].

An interesting variation is the scenario in which R parity is mildly violated [20–23] such that the LSP is effectively stable on cosmologically time scales and can still account for the DM. However, a small fraction of these states will decay presently and for an appropriate lifetime can potentially generate detectable signals. Good candidates for the LSP in the MSSM are the fermion superpartners to the known boson fields, such as the neutralino or gravitino. Assuming mild R-parity violation (RPV), a fermion LSP lighter than the electron will dominantly decay to a photon-neutrino pair, unless the spectrum is supplemented with additional light fermion states. For an LSP decaying to a photon and an effectively massless state to produce x-ray signals, the parent state must be around the keV scale. More specifically, to match the recent anomaly at 3.5 keV [1] the parent state should be roughly 7 keV. Since we suppose that the LSP constitutes the DM, this will be "warm" DM. It

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should be noted that sub-keV thermally produced "hot" DM leads to the erasure of density perturbations at scales shorter than its free streaming length and is in conflict with observations of small-scale structure; see e.g. [24].

Although the cluster anomaly at 3.5 keV might be regarded as tentative at this stage, it provides motivation for us to explore interesting, nonstandard, scenarios of SUSY. We begin in Sec. II by investigating if a keV gravitino can give rise to decay signals and show that generically this is not the case. In Sec. III, we explore the prospect of generating x-ray lines from decaying bino DM and argue that this is quite possible. However, as we discuss, obtaining the correct relic density for bino DM requires significant model building. In Sec. IV, we examine the motivation for light hidden sector photinos and argue that such a state could be the LSP. We show that a 7 keV hidden photino LSP can have a suitable abundance to match the observed DM relic density and give rise to the 3.5 keV cluster line via R-parity violating decays.

II. DECAYING GRAVITINO LSP

The archetypal example of a motivated light superpartner which can, in principle, decay on cosmological time scales is the gravitino. The gravitino is an integral aspect of supersymmetric extensions of the Standard Model. The mass of this state, which is tied to the scale of F-term SUSY breaking, is an unknown parameter and could vary over a large range. Once SUSY is broken, the effects of this breaking will generically be mediated via Planck-suppressed operators. However, if the superpartners of the Standard Model states feel additional sources of SUSY breaking, then the gravitino can be significantly lighter than the rest of the superpartner spectrum. The typical scale of the SUSY soft masses due to gauge mediation is

$$\tilde{m} \sim \frac{F}{M}, \tag{4}$$

where M is the mass scale of the SUSY breaking mediators and F is a SUSY breaking F term, whereas the gravitino mass is set by gravity mediation

$$m_{3/2} = \frac{F}{\sqrt{3}M_{\rm Pl}}. \tag{5}$$

This permits for large separations in the mass scales $m_{3/2} \ll m_{\tilde{f}}$ provided $M \ll M_{\rm Pl}$. While the gravitino is a well motivated candidate, we find that its lifetime is typically too long to reproduce the anomaly of interest.

A gravitino with mass $m_{3/2} < m_e$ in the MSSM will decay via $\tilde{G} \to \nu\gamma$ in the presence of R-parity violation. The details of the LSP decay depend on how the dominant source R parity is introduced and decays due to the presence of either the bilinear or trilinear RPV operator of Eq. (3) with sizable couplings are of particular interest; see e.g. [25–30].

Parameterizing the details of the RPV process which results in the gravitino decay in terms of a suppression factor $\mathcal{F}$, the lifetime can be generally expressed as follows [25,26]:

$$\tau_{\tilde{G}} = \left(\frac{\mathcal{F}}{16\pi}\frac{m_{3/2}^3}{M_{\rm Pl}^2}\right)^{-1} \simeq 6\times 10^{29}\ {\rm s}\left(\frac{1}{\mathcal{F}}\right)\left(\frac{7\ {\rm keV}}{m_{3/2}}\right)^3. \tag{6}$$

Typically $\mathcal{F} \ll 1$; for instance, in the case of R-parity violation due the bilinear operator $\boldsymbol{LH_u}$, the gravitino can decay to $\nu\gamma$ via a neutrino-bino mixing term and this factor is parametrically $\mathcal{F} \sim (m_\nu/m_{\tilde{B}}) \ll 1$. However, even in the extreme limit $\mathcal{F} \simeq 1$ the lifetime is still too long to account for the claimed 3.5 keV line of [1].[1] It is interesting to note that for $m_{3/2} \lesssim$ few keV the gravitino is essentially stable for all phenomenological purposes.

III. DECAYING LIGHT BINO LSP

Given that the gravitino scenario is seemingly unviable, we shall consider alternative LSP candidates which could generate this signal through decay processes. Specifically, we shall focus on models in which the LSP is a light bino or hidden sector photino.

It is traditional to constrain the values of the soft masses with GUT boundary conditions, which fix the ratios of the SUSY breaking gaugino Majorana masses

$$M_1 = \frac{5}{3}\tan^2\theta_W M_2 \simeq \frac{1}{2}M_2. \tag{7}$$

This typically implies that the binos and winos should receive comparable masses, and experimental bounds under this assumption limit the mass of the lightest neutralino to be in excess of around 50 GeV [18]. If the condition Eq. (7) is not imposed, then there is a great deal more freedom in the relative masses of the electroweakino states. In particular, it is possible to tune the soft masses μ, M_1 and M_2 such that the neutralino mass matrix develops a vanishing eigenvalue and thus the lightest neutralino can potentially be ultralight or even massless [33–36]. For the MSSM a vanishing eigenvalue for the neutralino mass matrix occurs for

$$M_1 = \frac{M_2 M_Z^2 \sin(2\beta)\sin^2\theta_W}{\mu M_2 - m_Z^2 \sin(2\beta)\cos^2\theta_W}. \tag{8}$$

[1] It was subsequently suggested [31] that gravitinos decaying radiatively via a trilinear RPV coupling could account for the signal. However, this result is based on an erroneous expression for the decay rate in [32]. For the correct form see e.g. [30], which conforms with our general conclusion.

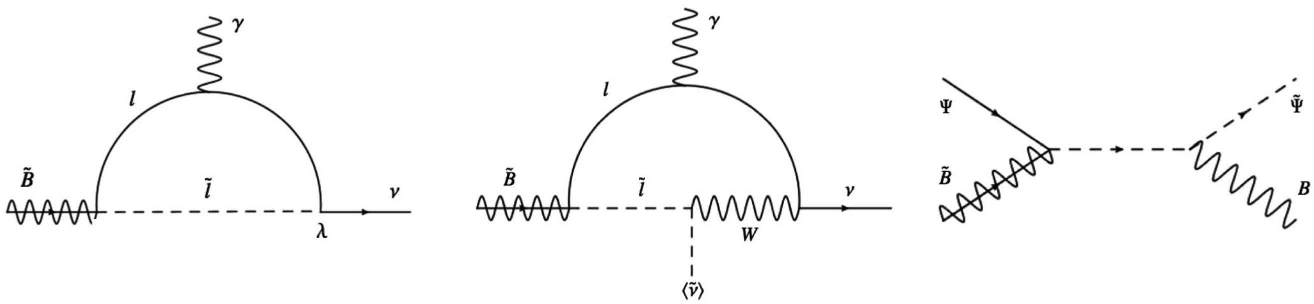

FIG. 1. Bino LSP decay involving the trilinear *R*-parity violating operator $\lambda \boldsymbol{LLE}$ (left) and due to a sneutrino VEV (center). The bino assimilation mechanism of [44] (right).

Notably, if this light neutralino is essentially pure bino, as is typical, it circumvents the current direct search bounds over much of parameter space [35].

A light bino LSP can be realized in an alternative manner, which does not require tuning of the MSSM electroweak soft masses. Gaugino Majorana masses can be forbidden at leading order by an R symmetry broken only by $M_{\rm Pl}$-scale operators, in which case the gauginos will typically be very light. However, if the MSSM spectrum is supplemented with additional chiral superfields transforming as an SU(2) triplet $\boldsymbol{T}$ and an SU(3) octet $\boldsymbol{O}$, then the winos and gluinos can acquire masses via Dirac terms of the form [37]

$$\int \mathrm{d}^2\theta \frac{\boldsymbol{W}'_\alpha}{M}[\lambda_G \mathrm{Tr}(\boldsymbol{O}\boldsymbol{G}^\alpha) + \lambda_W \mathrm{Tr}(\boldsymbol{T}\boldsymbol{W}^\alpha)], \tag{9}$$

where $\boldsymbol{W}'$ is a spurion field which develops a D term. Thus, the winos and gluino receive masses of order $m_{2,3} = \lambda_{W,G} D'/M$ and for appropriate sizes of the D-term breaking and mediation scale these can be phenomenologically viable (i.e. TeV scale). In the absence of a gauge singlet chiral superfield field (which are often deemed undesirable, as they can result in tadpole problems; see e.g. [38]) the bino will only receive a mass contribution from anomaly mediation [39,40]

$$m_{\tilde{B}} \sim \frac{g^2 b_1}{16\pi^2} m_{3/2} \sim 7\ \mathrm{keV}\left(\frac{m_{3/2}}{1\ \mathrm{MeV}}\right). \tag{10}$$

In this manner a natural hierarchy emerges between the bino and the other sparticles, as in [36], due only to the spectrum and symmetry structure. It should be noted that an MeV gravitino is cosmologically stable and, hence, also gives a contribution to the DM relic density of order [41]

$$\Omega_{3/2}h^2 \sim 0.01\left(\frac{1\ \mathrm{MeV}}{m_{3/2}}\right)\left(\frac{T_{\rm RH}}{1\ \mathrm{TeV}}\right)\left(\frac{\tilde{m}}{1\ \mathrm{TeV}}\right)^2. \tag{11}$$

If the DM relic density has significant contributions from both bino and gravitino components, then the lifetime of the decaying bino LSP must be scaled linearly, in terms of its fractional contribution to the relic density, in order to match the observed flux. For simplicity we shall focus on scenarios in which the bino accounts for essentially all of the DM relic density. This case arises, for instance, if the reheat temperature is low $T_{\rm RH} \ll 1$ TeV, such that only a small abundance of gravitinos is thermally produced.

A keV-scale bino LSP can decay at loop level in the presence of one of the R-parity violating trilinear operators of Eq. (3). Specifically, we consider the case involving the leptonic operator $\lambda \boldsymbol{LLE}$, leading to the diagram illustrated in Fig. 1, left panel. The lifetime of the bino decaying $\tilde{B} \to \nu\gamma$ is given by [21,35]

$$\tau_{\tilde{B}} \simeq 5 \times 10^{27}\ \mathrm{s}\left(\frac{10^{-8}}{\lambda}\right)^2 \left(\frac{m_{\tilde{f}}}{2\ \mathrm{TeV}}\right)^4 \left(\frac{7\ \mathrm{keV}}{m_{\tilde{B}}}\right)^3. \tag{12}$$

Note that experimental limits bound the coupling to be $\lambda \lesssim 0.05$, assuming that this is the sole source of R-parity violation [22,23]. In the presence of multiple operators these limits can become substantially stronger [42]. Thus provided that R parity is only violated slightly then a 7 keV bino can be cosmologically stable and present a decay rate suitable to explain the 3.5 keV cluster line. Settings in which certain R-parity violating operators occur with small coefficients have been suggested in the literature, e.g. [27–29,43].

The above trilinear RPV operator will typically induce a sneutrino vacuum expectation value (VEV) $\langle\tilde{\nu}\rangle \neq 0$ which can provide an alternative decay process, as in Fig. 1, center panel. In Eq. (12) we have assumed that this VEV is small such that the RPV operator $\boldsymbol{LLE}$ sets the bino lifetime. Further, sneutrino VEVs can arise in alternative manners, for instance via the RPV bilinear $\mu' \boldsymbol{L}\boldsymbol{H}_{\boldsymbol{u}}$. The magnitude of the VEV is model dependent and linked to the associated RPV coupling constant which can (and is often required to) be small; see e.g. [23]. For the case of the bilinear operator $\mu' \boldsymbol{L}\boldsymbol{H}_{\boldsymbol{u}}$ a sneutrino VEV is generated of order [20]

$$\begin{aligned} \langle\tilde{\nu}\rangle &\simeq \left(\frac{\mu'}{m_{3/2}}\right)^2 v\cos\beta \\ &\simeq 10\ \mathrm{eV} \times \left(\frac{\mu'}{10\ \mathrm{eV}}\right)^2 \left(\frac{1\ \mathrm{MeV}}{m_{3/2}}\right)^2 \left(\frac{\cos\beta}{0.5}\right). \end{aligned} \tag{13}$$

Accordingly, the lifetime of a bino decaying via the diagram of Fig. 1, center panel, is given by [21]

$$\tau'_{\tilde{B}} \simeq 10^{28}\ \mathrm{s}\left(\frac{m_{\tilde{l}}}{1\ \mathrm{TeV}}\right)^4\left(\frac{10\ \mathrm{eV}}{\langle\tilde{\nu}\rangle}\right)^2\left(\frac{10\ \mathrm{keV}}{m_{\tilde{B}}}\right)^3. \qquad (14)$$

Thus a lifetime appropriate to match the aforementioned cluster anomaly can be found for reasonable values of the slepton masses and sneutrino VEV, with some parameter freedom. Note that the sneutrino VEV generates a mass contribution for the neutrino (assuming Majorana gauginos) of order [20] (see also [45])

$$\begin{aligned}\Delta m_\nu &\simeq g^2\langle\tilde{\nu}\rangle^2/m_{\tilde{B}}\\ &\simeq 10^{-3}\ \mathrm{eV}\left(\frac{\langle\tilde{\nu}\rangle}{10\ \mathrm{eV}}\right)^2\left(\frac{10\ \mathrm{keV}}{m_{\tilde{B}}}\right).\end{aligned} \qquad (15)$$

Observational limits on the neutrino masses ($m_\nu \lesssim 1$ eV) constrain the size of the sneutrino VEV.

One potential difficultly is that, as the bino annihilation rate is low, if it is produced thermally, then it is typically overproduced and consequently it is challenging to realize the observed relic density via freeze-out. Furthermore, it is unlikely that the relic density can be reduced via tuning the reheat temperature [46] to below the mass of the bino $T_{\mathrm{RH}} \lesssim$ keV, as observations indicate that the temperature of the Universe was in excess of a few MeV. This is supported by the successful predictions of the primordial abundances of nuclei in theories of big bang nucleosynthesis; see e.g. [47]. One manner to potentially achieve the correct density of bino DM is the *assimilation* mechanism of D'Eramo, Fei and Thaler [44]. In this scenario the MSSM is supplemented with new exotic states Ψ which carry a particle asymmetry such that their number density remains considerable at temperatures below their mass. These exotic states coannihilate efficiently with the bino LSP via $\tilde{B}\Psi \to \tilde{\Psi}B$ (assimilation; see Fig. 1, right panel) and $\tilde{B}\,\tilde{\bar{\Psi}} \to \Psi B$ (destruction), where B is the hypercharge gauge boson. Subsequently, late decays of $\tilde{\Psi}$ to the bino LSP, which may violate the global quantum number carried by the Ψ, are responsible for setting the bino abundance. Clearly the Ψ must be sufficiently long lived such that they do not decay before the bino abundance is suitably depleted. Since the production of binos from the thermal bath is only suppressed once the bath cools to below the bino mass, the Ψ must survive to below $T \lesssim m_{\tilde{B}}/25$. For a 7 keV bino this corresponds to a temperature around 300 eV. If these states decay after recombination ($T \lesssim 1$ eV), then this can lead to cosmic microwave background signals which are strongly constrained; see e.g. [48]. Further, there are stringent bounds on hadronic decays of the Ψ or $\tilde{\Psi}$ from measurements of big bang nucleosynthesis observables [47]. For nonhadronic decays of the Ψ and $\tilde{\Psi}$ prior to recombination, constraints on energy injection can be satisfied, in particular for the case $\tilde{\Psi} \to \nu\tilde{B}$. Thus viable models can be constructed with bino abundances appropriate to account for the DM relic density. Also there could be a potentially observable deviation in the number of additional relativistic species N_{eff} due to the binos remaining in thermal equilibrium later than neutrino decoupling; see e.g. [49].

Under the assumption that the $\tilde{\Psi}$ is the next-lightest supersymmetric particle and each $\tilde{\Psi}$ decay produces a single bino LSP, an estimate for the required particle asymmetry $\eta_{\tilde{\Psi}} \equiv n_{\tilde{\Psi}} - n_{\tilde{\bar{\Psi}}}$ in order to generate the DM relic density can be found from the relation between the $\tilde{\Psi}$ asymmetry and the bino mass

$$\frac{\Omega_{\mathrm{DM}}}{\Omega_{\mathrm{B}}} \simeq \frac{m_{\tilde{B}}\eta_{\tilde{\Psi}}}{m_p\eta_B}, \qquad (16)$$

where $m_p \simeq 1$ GeV is the proton mass and $\eta_B \simeq 6\times10^{-10}$ is the baryon asymmetry. The ratio of relic densities is determined to be $\Omega_{\mathrm{DM}}/\Omega_{\mathrm{B}} \simeq 5$; hence for $m_{\tilde{B}} \simeq 7$ keV this implies

$$\eta_{\tilde{\Psi}} \simeq 10^6 \times \eta_B \simeq 6\times10^{-4}. \qquad (17)$$

Thus this scenario requires a significantly larger asymmetry than that associated to baryon number. This is a mild departure to the original model of [44] in which it was envisaged that baryon asymmetry would be generated via the late decays of the Ψ and $\tilde{\Psi}$ states, which is a requirement we do not retain here. This setting provides one method for obtaining the correct relic abundance of bino DM and it is conceivable that alternative mechanisms might be constructed.

IV. DECAYING HIDDEN PHOTINO LSP

Given the moderate model building necessary to obtain the observed relic density for keV bino DM, we turn to the possibility that the LSP is not a standard MSSM state, but rather the superpartner of some U(1) vector boson sequestered from the visible sector. Indeed, the existence of (many) light hidden sector Abelian vector bosons, and their associated superpartners, is motivated by string theory [50,51]. In type IIB string theory each three-cycle Σ_i^3, labeled by i, can be associated to a 4D vector field in terms of the Ramond-Ramond form C_4:

$$A_\mu^i = \int_{\Sigma_i^3} C_4. \qquad (18)$$

These vector bosons inherit a gauge symmetry from the 10D gauge symmetry of C_4. Typically in realistic string compactifications there are $\mathcal{O}(10)$ three-cycles, and as many associated gauge bosons. While a large number of these gauge symmetries are likely broken in the UV, by fluxes or otherwise, some may remain unbroken in the low energy theory [50]. There can also be further hidden U(1) gauge symmetries arising from branes separated from the

Standard Model brane stack on the compactification manifold. If these branes have only vectorlike matter content with high-scale masses (which is a common scenario), then the low energy theory contains an unbroken U(1) with no light charged states [51].

After SUSY is broken and the effects of this breaking are mediated to the hidden sectors, the fermion partners to these hidden sector gauge bosons receive soft masses accordingly. Furthermore, it is natural for these hidden sector photinos to be significantly lighter than visible sector sparticles if they only feel SUSY breaking via gravitational effects. In this case the photinos will acquire masses near the gravitino mass $m_{3/2}$ of the form given in Eq. (5) or, alternatively, Eq. (10). In contrast, the visible sector superpartners, including the gauginos, can obtain their masses via some other mediation mechanism leading to TeV soft masses in the visible sector, for example via gauge mediation as given in Eq. (4).

Although the hidden sectors may not communicate directly with the visible sector, as is well known, U(1) vector bosons will generically mix [52]. For the case of two U(1)'s, this mixing appears in the gauge sector Lagrangian as follows [53]:

$$\mathcal{L}_{\text{gauge}} = \frac{1}{32}\int \mathrm{d}^2\theta (W_a W_a + W_b W_b - 2\chi W_a W_b), \tag{19}$$

where $W_{a,b}$ are chiral gauge field strength superfields for each U(1) symmetry, defined by $W = \bar{D}^2 D V$ in terms of V the vector superfield. In supergravity such kinetic mixing between U(1)'s generically arises due to Planck-suppressed operators and, from a stringy perspective, this occurs due to open strings stretching between the Standard Model brane stack and hidden sector D-branes [50,51]. Thus it is expected that the Abelian gauge symmetries, specifically U(1) hypercharge, will mix with any hidden sector U(1)'s.

The pure gauge part of the Lagrangian can be rewritten in canonical form by making the following field redefinition [53]:

$$V_a^\mu \to V_a'^\mu = V_a^\mu - \chi V_b^\mu, \tag{20}$$

such that $W_a \to W'_a = W_a - \chi W_b$, which diagonalizes the gauge sector Lagrangian contribution

$$\mathcal{L}_{\text{gauge}} = \frac{1}{32}\int \mathrm{d}^2\theta (W'_a W'_a + W_b W_b). \tag{21}$$

If there is no matter charged under the hidden sector U(1), the hidden sector photon is decoupled and its presence is only felt through a shift [54] in the hypercharge gauge coupling $\alpha_Y \to \alpha_Y/(1-\chi)$. The only physical impact is a perturbation in the precision of gauge coupling unification if χ is large, which we shall not dwell upon. While the hidden sector photon can be completely decoupled in the absence of light fields charged under the hidden sector U(1), the associated photino will still mix with the visible sector gauginos. This mixing between gaugino states is induced by kinetic mixing and off-diagonal terms in the gaugino mass matrix and appears in the Lagrangian in the form [50]

$$\mathcal{L} \supset iZ_{ab}\lambda_a^\dagger \partial \lambda_b + M_{ab}\lambda_a\lambda_b, \tag{22}$$

where Z_{ab} accounts for the kinetic mixing, M_{ab} is gaugino mass matrix from SUSY breaking and here the indices a, b run over the bino and the photino states. As previously, the kinetic term can be made canonical by a field redefinition $\lambda_a \to \lambda'_a = P_{ab}^{-1}\lambda_b$ such that

$$\mathcal{L} \supset i\lambda_a'^\dagger \partial \lambda'_a + M'_{ab}\lambda'_a\lambda'_b, \tag{23}$$

for $M'_{ab} = P_{ac}^\dagger M_{cd} P_{db}$. Provided that the original M_{ab} is not proportional to the gauge kinetic mixing matrix, there will be nonzero mixing between the bino and photino states. From this we expect the mixing between a hidden photino and the neutralino to be parametrically

$$\epsilon \sim 10^{-7} \times \left(\frac{\chi}{1}\right)\left(\frac{m_{\tilde{\gamma}'}}{10\ \text{keV}}\right)\left(\frac{100\ \text{GeV}}{m_{\tilde{\chi}}}\right). \tag{24}$$

The scenario in which the hidden photon can be decoupled is of particular interest as it allows for sizable mixing between the hidden photino and bino, while circumventing the constraints coming from the associated kinetic mixing between the visible and hidden sector vector bosons. For a recent analysis of the limits on mixing between gauge bosons see e.g. [55].

In what follows we shall restrict our attention to the simplest scenario with a single hidden sector photino, but in principle there could be many such states with similar or hierarchical masses. Also, we note in passing that the presence of photinos could potentially have an impact on collider phenomenology, as studied in [50,56]. Supposing that a hidden sector photino is the LSP (as it is a fermion), it is reasonable to suppose that the dominant decay channel for this state is to a neutrino-photon pair via mixing with the neutral gauginos of the MSSM. Hence, in analogy with the previous scenario involving a bino LSP, the lifetime of the hidden photino is

$$\tau_{\tilde{\gamma}'} \simeq 10^{27}\ \text{s}\left(\frac{10^{-7}}{\epsilon}\right)^2\left(\frac{10^{-2}}{\lambda}\right)^2 \times \left(\frac{m_{\tilde{f}}}{500\ \text{GeV}}\right)^4\left(\frac{7\ \text{keV}}{m_{\tilde{\gamma}'}}\right)^3. \tag{25}$$

As the decay rate is further suppressed by the mixing parameter ϵ, the coefficient λ of the R-parity violating operator can be substantially larger than in the bino case while ensuring that the LSP is cosmologically stable and with a lifetime suitable to account for the 3.5 keV x-ray line. Similarly, an expression can be obtained for the case that the dominant decay width arises from decays involving a sneutrino VEV, by dressing Eq. (14) with the factor ϵ^{-2} to account for the $\tilde{\gamma}'$-$\tilde{B}$ mixing. This yields a hidden photino LSP lifetime of order

$$\tau_{\tilde{\gamma}'} \simeq 10^{28}\ \mathrm{s}\left(\frac{10^{-7}}{\epsilon}\right)^2\left(\frac{m_{\tilde{l}}}{100\ \mathrm{GeV}}\right)^4 \times\left(\frac{1\ \mathrm{MeV}}{\langle\tilde{\nu}\rangle}\right)^2\left(\frac{10\ \mathrm{keV}}{m_{\tilde{\gamma}'}}\right)^3. \tag{26}$$

With weak-scale gauginos, the sneutrino VEVs of order $\langle\tilde{\nu}\rangle \sim 1$ MeV lead to sub-eV contributions to the neutrino masses; cf. Eq. (15).

As discussed previously, obtaining the correct relic density for bino DM is nontrivial. The hidden sector photino will also be typically overproduced for $\epsilon \gtrsim 10^{-6}$, in which case the photino relic density is given by [50]

$$\Omega_{\tilde{\gamma}'}h^2 \simeq 10^6 \times \left(\frac{m_{\tilde{\gamma}'}}{10\ \mathrm{keV}}\right)^3\left(\frac{\epsilon}{10^{-3}}\right)^2. \tag{27}$$

However, if the mixing is small $\epsilon \lesssim 10^{-6}$, the hidden sector will never be in thermal contact with the visible sector [50]. By inspection of Eq. (24), such small mixing is natural due to the hierarchy between the keV hidden photino, as required to produce x-ray signals, and weak-scale MSSM gauginos. If the inflaton decays preferentially (similar to [57]) to the MSSM states, with suppressed couplings to the hidden sector, then substantially fewer photinos will be produced than expected from thermal production. Neglecting the weak portal interaction the hidden sector is a noninteracting theory and thus the number density of the hidden photino is set primarily by the number produced by the inflaton decay. Thus the correct DM relic density can be obtained via tuning, somewhat similar to [58]. Settings in which reheating occurs preferentially have been studied in the context of certain string constructions [59,60].

A further abundance of photinos will always be generated via thermal freeze-in [57] due to energy "leaking" from the visible sector to the hidden sector. This can potentially lead to overproduction of the photino and for values of ϵ which give suitable lifetimes to produce observable signals, if the visible sector reheat temperature is greater than the mass scale of the MSSM superpartners $\tilde{m}$, then typically the photino will be overproduced. For the case $T_{\rm RH} > \tilde{m}$ the yield is parametrically

$$Y_{\tilde{\gamma}'} \sim \epsilon^2\left(\frac{M_{\rm Pl}}{\tilde{m}}\right), \tag{28}$$

and, in which case, the hidden sector photino is overproduced as the yield is related to the relic density as follows:

$$\Omega_{\tilde{\gamma}'}h^2 \sim 0.1 \times \left(\frac{Y_{\tilde{\gamma}'}}{10^{-5}}\right)\left(\frac{m_{\tilde{\gamma}'}}{10\ \mathrm{keV}}\right). \tag{29}$$

On the other hand, if $T_{\rm RH} < \tilde{m}$, then freeze-in only proceeds via higher dimension operators which connect the hidden sector photinos and the SM states, due to integrating out some heavy superpartners. This leads to a photino yield dependent on the reheat temperature of the visible sector

$$Y_{\tilde{\gamma}'} \sim 10^{-5}\left(\frac{\epsilon}{10^{-7}}\right)^2\left(\frac{T_{\rm RH}}{1\ \mathrm{GeV}}\right)\left(\frac{100\ \mathrm{GeV}}{\tilde{m}}\right)^2. \tag{30}$$

In this case, if the correct relic density is set by inflaton decay, the freeze-in abundance can be sufficiently small that it is not then overproduced. Furthermore, in the case that the inflaton does not couple to this sector, for appropriate parameter choices (such as those indicated) the observed DM relic density can be achieved directly through this UV freeze-in mechanism. Thus in order for this scenario to work it is crucial that the reheat temperature is below the superpartner mass scale.

Moreover, just as three-cycles in the internal space are associated to 4D vector bosons, pseudoscalar states—string axions—arise from integrals of C_4 over various four-cycles [61]. It is conceivable that one of these pseudoscalars could play the role of the QCD axion [62,63]. Assuming this is the case, the indirect indication of a light axion state (as suggested by the experimental requirement that the QCD θ parameter is near zero) motivates the possibility of a multitude of additional axion states and photinos, coined the *string axiverse* [61].

V. CONCLUDING REMARKS

We have discussed the prospect for generating keV x-ray signals in SUSY extensions of the Standard Model, with specific reference to the 3.5 keV line recently reported in analysis of the observations by the XMM-Newton X-ray Telescope [1,2]. Given that SUSY is the leading candidate for a framework of physics beyond the Standard Model, we believe that it is interesting to consider how such a signal might arise in this setting. We have highlighted the possibility of x-ray signals being generated by the decays of light LSP DM via R-parity violating operators and argued that such scenarios are viable and motivated, although in some cases require additional model building or some amount of fine-tuning. The gravitino is one of the best motivated light SUSY states, but generically we have argued that it cannot lead to signatures of this type. We have proposed rather that scenarios involving keV binos or hidden sector photinos could account for this signal.

Interestingly, both these models are sensitive to $T_{\rm RH}$ and typically to be successfully realized it is required that the maximum temperature after reheating is lower than a TeV.

We note in passing that while the axino is also a good candidate for a light LSP, similar to the gravitino, a keV axino is typically too long lived to account for the 3.5 keV line. Comparing with the model of e.g. [64], the axino lifetime is parametrically

$$\tau_{\tilde a} \sim 5\times 10^{29}\ \mathrm{s}\left(\frac{m_{\tilde a}}{7\ \mathrm{keV}}\right)^{-3}\left(\frac{f_a}{10^8\ \mathrm{GeV}}\right)^2 \times\left(\frac{m_{\tilde B}}{100\ \mathrm{GeV}}\right)^2\left(\frac{\langle\tilde\nu\rangle/v}{10^{-6}}\right)^2. \tag{31}$$

However, as noted in [13,14] for extreme parameter choices—with f_a, $m_{\tilde B}$ and $\langle\tilde\nu\rangle$ at the edge of experimental exclusion for most minimal models—axino interpretations of Eq. (1) can be constructed. Aside from these tensions with experimental constraints, this scenario may also be disfavored from a theoretical standpoint [65] as, in the absence of fine-tuning or sequestering, the axino mass is expected to be $m_{\tilde a}\gtrsim m_{3/2}$ [65]. Thus ensuring that the axino is the LSP requires some model building. Given these considerations we do not discuss this scenario in greater detail.

In closing, we highlight that there is a potential opportunity to distinguish between interpretations involving axions [5–8] and those invoking alternative light DM candidates (like the bino or hidden photino) using precision measurements of $\Delta N_{\rm eff} = 3\rho_{\rm hidden}/\rho_\nu$. As typically axions are dominantly produced nonrelativistically via the misalignment mechanism [62,63], their contribution to $N_{\rm eff}$ is negligible, in contrast to keV-scale thermally produced DM. It is projected that upcoming experiments [66] will be sensitive to percent-level changes in $N_{\rm eff}$ and thus should provide some insight regarding the nature of any light hidden sector states.

Further study of this 3.5 keV x-ray line is certainly warranted. A strong confirmation of this signal, particularly in conjunction with the observation of a factional increase in $N_{\rm eff}$, would be an exciting signal of physics beyond the Standard Model, possibly in the guise of supersymmetry.

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