MeV-GeV $\gamma$-ray telescopes probing gravitino LSP with coexisting axino NLSP as dark matter in the $\mu\nu$SSM

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Abstract

In $R$-parity violating supersymmetry, the gravitino as the lightest supersymmetric particle (LSP) is a good candidate for dark matter, with the interesting characteristic to be detectable through $\gamma$-ray telescopes. We extend this analysis considering an axino next-to-LSP (NLSP) as a coexisting dark matter particle contributing with a detectable signal in the $\gamma$-ray spectrum. The analysis is carried out in the framework of the $\mu\nu$SSM, which solves the $\mu$ problem reproducing simultaneously neutrino data only with the addition of right-handed neutrinos. We find that important regions of the parameter space can be tested by future MeV-GeV $\gamma$-ray telescopes through the line signal coming from the decay of the axino NLSP into photon-neutrino. In a special region, a double-line signal from axino NLSP and gravitino LSP is possible with both contributions detectable.

Keywords: Supersymmetry, Dark Matter, Gamma Rays.

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1 Introduction

Gravitino ($\psi_{3/2}$) LSP or axino ($\tilde{a}$) LSP are interesting candidates for dark matter (DM) in the framework of supersymmetry (SUSY). In addition, in SUSY models where there is $R$-parity violation (RPV) these particles decay with a lifetime longer than the age of the Universe, producing a line signal potentially detectable in $\gamma$-ray telescopes. This was analyzed for the gravitino LSP in Refs. [1–11] in the context of bilinear/trilinear RPV models [12], and in Refs. [13–16] in the 'μ from ν' supersymmetric standard model ($\mu\nu$SSM) [17]. Similar analyses for axino LSP in bilinear/trilinear RPV models were carried out in Refs. [18–27].

In a recent work [28], we analyzed a multicomponent DM scenario with axino LSP and gravitino NLSP. This is a decaying dark matter (DDM) scenario, where the gravitino in addition to the RPV decay channel into photon-neutrino, also undergoes an $R$-parity conserving (RPC) decay into axion-axino. The analysis was carried out in the framework of the $\mu\nu$SSM, where couplings involving right-handed neutrinos are introduced solving the $\mu$-problem and reproducing simultaneously the neutrino data [17,29,32]. A brief discussion and bibliography about the interesting phenomenology associated to the $\mu\nu$SSM, can be found in Ref. [28], where it was shown that significant regions of the parameter space of the model can be probed through a line signal coming from the axino decay. A double-line signal as smoking gun through the further contribution of the gravitino decay is also possible in a subset of those regions.

Here we want to extend our previous work, analyzing the opposite DDM scenario where the gravitino is the LSP and the axino the NLSP. Their masses, although model dependent can be of the same order in several realistic scenarios [33–37] such as in supergravity, and therefore if the axino (gravitino) is the LSP the gravitino (axino) becomes naturally the NLSP. As a consequence, the NLSP decays into the LSP plus an axion. In this not yet explored RPV scenario with gravitino LSP and axino NLSP, we will study its cosmological properties as well as the associated $\gamma$-ray constraints on spectral lines coming from current detectors such as Fermi-LAT, and prospects for future $\gamma$-ray space missions such as e-ASTROGAM [38] and AMEGO [39].
The paper is organized as follows. In Section 2, first we briefly review the simple scenario with gravitino as LSP. In second place, we discuss the multicomponent DDM scenario with the axino as the NLSP. We will show the axino NLSP decay rates into photon plus neutrino and into gravitino LSP plus axion, and its contribution to the relic density. Then, we will compute the $\gamma$-ray flux produced in this scenario. Armed with these results, in Section 3 we will show exclusion limits and prospects for detection under the assumption of decaying gravitino LSP plus axino NLSP. This scenario is fully explored along with its parameter space allowed by cosmological observations such as dark radiation constraints. Finally, we will present the $\gamma$-ray measurements by current detectors employed to probe RPV SUSY parameter space region, focusing on the $\mu\nu$SSM, and we will discuss the prospect for detection in the case of the proposed e-ASTROGAM instrument. The conclusions are left for Section 4.

2 Gravitino LSP and axino NLSP as dark matter

In the framework of supergravity, both gravitino and axino have in the Lagrangian an interaction term with photon and photino. In the presence of RPV, photino and left-handed neutrinos are mixed in the neutral fermion mass matrix, and therefore the gravitino LSP, as well as the axino NLSP, are able to decay into photon and neutrino through this interaction term. This has significant implications because the signals are sharp $\gamma$-ray lines with energies $m_{3/2}/2$ and $m_\tilde{a}/2$, that could be detected in $\gamma$-ray satellite experiments such as Fermi-LAT, or future MeV-GeV telescopes as the proposed e-ASTROGAM. In addition, the axino NLSP can decay into gravitino LSP and axion. We will study in what follows the implications of this scenario for DM and its detectability, reviewing first the gravitino LSP decay.

2.1 Gravitino LSP decay

Gravitino decay width into photon-neutrino through RPV couplings is given by [1,10]:

$$\Gamma(\psi_{3/2} \rightarrow \gamma\nu_i) \simeq \frac{m_{3/2}^3}{32\pi M_P^2} |U_{\tilde{\gamma}\nu}|^2,$$

(1)

where $\Gamma(\psi_{3/2} \rightarrow \gamma\nu_i)$ denotes a sum of the partial decay widths into $\nu_i$ and $\bar{\nu}_i$, $m_{3/2}$ is the gravitino mass, $M_P \approx 2.43 \times 10^{18}$ GeV is the reduced Planck mass, and the mixing parameter $|U_{\tilde{\gamma}\nu}|$ determines the photino content of the neutrino,

$$|U_{\tilde{\gamma}\nu}|^2 = \sum_{i=1}^3 |N_{i1} \cos \theta_W + N_{i2} \sin \theta_W|^2.$$  

(2)

Here $N_{i1}(N_{i2})$ is the bino (wino) component of the $i$-th neutrino, and $\theta_W$ is the weak mixing angle. As obtained in Refs. [13,16], performing scans in the low-energy parameters of the $\mu\nu$SSM in order to reproduce the observed neutrino masses and mixing angles, natural values of $|U_{\tilde{\gamma}\nu}|$ are in the range

$$10^{-8} \lesssim |U_{\tilde{\gamma}\nu}| \lesssim 10^{-6},$$

(3)
although relaxing some of the assumptions such as an approximate GUT relation for gaugino masses and/or TeV scales, the lower bound can be smaller:

\[ 10^{-10} \lesssim |U_{\tilde{7}_\nu}| \lesssim 10^{-6}. \] (4)

As we can see in Eq. (1), the gravitino decay is suppressed both, by the small RPV mixing parameter \(|U_{\tilde{\gamma}_\nu}|\), and by the scale of the gravitational interaction, making its lifetime much longer than the age of the Universe \(\tau_{3/2} \gg t_{\text{today}} \sim 10^{17} \text{ s}\), with

\[ \tau_{3/2} = \Gamma^{-1}(\psi_{3/2} \to \gamma \nu_i) \simeq 3.8 \times 10^{33} s \left( \frac{10^{-8}}{|U_{\tilde{7}_\nu}|} \right)^2 \left( \frac{0.1 \text{GeV}}{m_{3/2}} \right)^3. \] (5)

### 2.2 Axino NLSP decays

Axino partial decay width into photon-neutrino through RPV couplings satisfies [41]:

\[ \Gamma(\tilde{a} \to \gamma \nu_i) \approx \frac{m_{\tilde{a}}^3}{128 \pi^3 f_{\tilde{a}}^2} \alpha_{em}^2 C_{a\gamma\gamma}^2 |U_{\tilde{\gamma}_\nu}|^2, \] (6)

where \(\Gamma(\tilde{a} \to \gamma \nu_i)\) denotes a sum of the partial decay widths into \(\nu_i\) and \(\bar{\nu}_i\), \(m_{\tilde{a}}\) is the axino mass, \(C_{a\gamma\gamma}\) is a model dependent constant of order unity, \(\alpha_{em} = e^2/4\pi\), and \(f_{\tilde{a}}\) is the Peccei-Quinn (PQ) scale. This is the dominant decay for an axino LSP in the context of the \(\mu\nu\)SSM [28], and is suppressed both by the small RPV parameter \(|U_{\tilde{\gamma}_\nu}|\) and by the large PQ scale \(f_{\tilde{a}} \gtrsim 10^9 \text{ GeV}\) as obtained from the observation of SN1987A [33]. It is worth noticing here that in comparison with Eq. (1), \(\Gamma(\tilde{a} \to \gamma \nu_i) > \Gamma(\psi_{3/2} \to \gamma \nu_i)\) since \(f_{\tilde{a}} < M_P\), and \(m_{\tilde{a}} > m_{3/2}\) for the case we are interested in this work with axino NLSP and gravitino LSP. We can also compare Eq. (5) with

\[ \Gamma^{-1}(\tilde{a} \to \gamma \nu_i) \approx 3.8 \times 10^{25} s \left( \frac{f_{\tilde{a}}}{10^{13} \text{ GeV}} \right)^2 \left( \frac{10^{-8}}{|U_{\tilde{7}_\nu}|} \right)^2 \left( \frac{1 \text{ GeV}}{m_{\tilde{a}}} \right)^3, \] (7)

where to write this equation we have assumed \(C_{a\gamma\gamma} = 1\).

Since in the framework of supergravity the axino has an interaction term with gravitino and axion, we have also to consider this RPC partial decay width [42]

\[ \Gamma(\tilde{a} \to \psi_{3/2} a) \approx \frac{m_{\tilde{a}}^5}{96\pi m_{3/2}^2 M_P^2} (1 - r_{3/2})^2 (1 - r_{3/2}^2)^3, \] (8)

where the axion mass has been neglected, and

\[ r_{3/2} \equiv \frac{m_{3/2}}{m_{\tilde{a}}}. \] (9)

Clearly, this decay width dominates over the one in Eq. (6), and therefore the axino lifetime can be approximated as

\[ \tau_{\tilde{a}} \approx \Gamma^{-1}(\tilde{a} \to \psi_{3/2} a) \approx 1.18 \times 10^{13} s \left( \frac{m_{3/2}}{0.1 \text{ GeV}} \right)^2 \left( \frac{1 \text{ GeV}}{m_{\tilde{a}}} \right)^5, \] (10)
where to write the second equality we have neglected the contribution of $r_{3/2}$ in Eq. (8) which is valid when $m_{3/2} \ll m_{\tilde{a}}$.

### 2.3 Relic density for multicomponent dark matter

Unlike the gravitino whose lifetime is much longer than the age of the Universe, the axino has a smaller lifetime as shown in the previous subsect., and thus one has to consider that its density changes in time with the result

$$\Omega_\tilde{a} h^2 = \Omega_{\tilde{a}}^{\text{TP}} h^2 e^{-(t_{\text{today}} - t_0)/\tau_\tilde{a}},$$

(11)

where $t_0$ is the time when the axinos are thermally produced, and $\Omega_{\tilde{a}}^{\text{TP}} h^2$ corresponds to the would-be axino NLSP relic density if it were stable and would not undergo through the decay process. This relic density depends heavily on the axion model considered. Here we will work in the framework of the KSVZ model \[43,44\], where the axino production is dominated by the scatterings of gluons and gluinos, thus its relic density from thermal production is \[45,46\]

$$\Omega_{\tilde{a}}^{\text{TP}} h^2 \simeq 0.3 \left( \frac{g_3(T_R)}{23} \right)^4 \left( \frac{m_{\tilde{a}}}{1 \text{ GeV}} \right) \left( \frac{T_R}{10^4 \text{ GeV}} \right) \left( \frac{10^{12} \text{ GeV}}{f_a} \right)^2,$$

(12)

where $T_R$ is the reheating temperature after inflation, $g_3$ is the running $SU(3)$ coupling, the rate function $F(g_3(T_R))$ describes the axino production rate with $F \simeq 24 - 21.5$ for $T_R \simeq 10^4 - 10^6$ GeV \[46\]. For our numerical computation we will use $F \simeq 23$. Other values will not change significantly the final results. Assuming the conservative limit $T_R \gtrsim 10^4$ GeV, an upper bound for $m_{\tilde{a}}$ is obtained for each value of $f_a$ from the measured value of the relic density by the Planck Collaboration \[47\] $\Omega_{\text{Planck}} h^2 \simeq 0.12$. For example, one obtains $m_{\tilde{a}} \lesssim 50, 0.5, 0.005$ GeV for $f_a = 10^{14}, 10^{12}, 10^{11}$ GeV, respectively.

To compute now gravitino relic density we need to consider thermal and non-thermal production mechanisms. The latter, in our multicomponent scenario, is related to the decay of the axino NLSP. Taking all the above into account, the density for gravitino LSP is given by:

$$\Omega_{3/2} h^2 = \Omega_{3/2}^{\text{TP}} h^2 + \Omega_{3/2}^{\text{NTP}} h^2,$$

(13)

where

$$\Omega_{3/2}^{\text{NTP}} h^2 = r_{3/2} \Omega_{\tilde{a}}^{\text{TP}} h^2 (1 - e^{-(t_{\text{today}} - t_0)/\tau_\tilde{a}}),$$

(14)

and \[48,49\] :

$$\Omega_{3/2}^{\text{TP}} h^2 \simeq 0.02 \left( \frac{T_R}{10^5 \text{ GeV}} \right) \left( \frac{1 \text{ GeV}}{m_{3/2}} \right) \left( \frac{M_3(T_R)}{3 \text{ TeV}} \right)^2 \left( \frac{\gamma/(T_R^6/M_P^2)}{0.4} \right).$$

(15)

Here $M_3(T_R)$ is the running gluino mass, and the last factor parametrizes the effective production rate ranging $\gamma/(T_R^6/M_P^2) \simeq 0.4 - 0.35$ for $T_R \simeq 10^4 - 10^6$ GeV \[49\]. For our numerical computation we will use $M_3(T_R) \simeq 3 \text{ TeV}$ and $\gamma/(T_R^6/M_P^2) \simeq 0.4$. Other
values will not modify significantly our results. Assuming as before $T_R \gtrsim 10^4$ GeV, a lower limit for the gravitino mass is obtained, $m_{3/2} \gtrsim 0.017$ GeV. Since the gravitino is the LSP, note that this limit is not compatible with the bound for the axino NLSP mass $m_{\tilde{a}} \lesssim 0.005$ GeV corresponding to $f_a = 10^{11}$ GeV, thus we will work with $f_a \geq 10^{12}$ GeV.

Obviously, if $\tau_{\tilde{a}} \ll t_{\text{today}}$, we get the usual relations \[50,52\]

\begin{align}
\Omega_{\tilde{a}} h^2 &\simeq 0, \\
\Omega_{3/2} h^2 &\simeq \Omega_{TP}^{3/2} h^2 + r_{3/2} \Omega_{TP}^{\tilde{a}} h^2. 
\end{align}

To continue we must address the axion production. The relevant contributions come from the misalignment mechanism and the axino NLSP decay. For the former production, the axion cold DM relic density can be accounted by

\[18\]

where $\theta_i$ is the initial misalignment angle. Since we are interested in studying scenarios with axino-gravitino as the only two components of the DM, we can set the axion primordial relic negligible choosing an appropriated value for $\theta_i$ if needed, i.e. when $f_a \gtrsim 10^{12}$ GeV. Nevertheless, it would be convenient to work with the upper bound $f_a \leq 10^{13}$ GeV to avoid too much tuning.

Taking all the above discussions into account, throughout this work we will adopt the following range for the PQ scale:

\[19\]

On the other hand, the axions produced by the axino NLSP decay will constitute ‘dark radiation’, i.e., ultrarelativistic and invisible species with respect to the cold DM measured by Planck. The amount of dark radiation is under stringent constraints \[53,57\], and as a consequence it gives a small contribution to the total DM density. A quantity that will be useful along this work is the fraction of axino NLSP that decays into dark radiation. For that we can define

\[20\]

with

\[21\]

as the axino NLSP fraction. The subscript $ddm$ denotes decaying dark matter, and DR stands for dark radiation. It is worth noticing the following:

- Planck obtains $\Omega_{\text{cdm}}^{\text{Planck}} h^2 \simeq 0.12$ today from measurements at recombination time using the standard $\Lambda$CDM model. We are working with decaying DM, so the cold DM density has a time dependence due to the fact that some of the axino NLSP energy density is ‘lost’ as dark radiation. Nevertheless, the latter quantity has to be small, as discussed above.
Decaying DM and its fraction to dark radiation, $f_{ddm}^{DR}$, refers to the contribution of the mentioned decay of axino NLSP into gravitino LSP plus axion, not to be confused with the decays of axino NLSP and gravitino LSP into photon plus neutrino.

Let us finally point out that due to the axion-photon mixing, the axions emitted from the axino decay can be converted into photons in the presence of a magnetic field, potentially producing a signal. However, the conclusion of Ref. [58] is that considering a QCD axion (as in our case), the conversion probability is too small to be observed.

2.4 $\gamma$-ray flux from gravitino and axino decays

The differential flux of $\gamma$-rays from DM decay in the Galactic halo is calculated by integrating its distribution around us along the line of sight:

$$\frac{d\Phi_{\gamma}^{\text{halo}}}{dE d\Omega} = \frac{1}{4 \pi \tau_{\text{DM}} m_{\text{DM}}} \frac{dN_{\gamma}^{\text{total}}}{dE} \int_{\Delta \Omega} \cos b \, db \, d\ell \int_{0}^{\infty} ds \, \rho_{\text{halo}}(r(s, b, \ell)) ,$$

where $\tau_{\text{DM}}$, $m_{\text{DM}}$ are the lifetime and mass of the DM particle respectively, $dN_{\gamma}^{\text{total}}/dE$ is the total number of photons produced in DM decay, $\Delta \Omega$ is the region of interest (ROI), i.e. the region of the sky we are studying, $b$ and $\ell$ denote the Galactic latitude and longitude, respectively, and $s$ the distance from the Solar System. The radius $r$ in the DM halo density profile of the Milky Way, $\rho_{\text{halo}}$, is expressed in terms of these Galactic coordinates.

The constraints to the $\gamma$-ray emission from DM decay are usually presented as lower limits to the particle lifetime, considering that the DM is composed by only one particle species. If gravitino and axino coexist, being one the LSP an the other the NLSP, respectively, both candidates can be sources of $\gamma$-ray radiation. As discussed recently in Ref. [28], in a multicomponent scenario it is useful to assume an effective lifetime to normalize the signal considering that a specific source is a fraction of $\Omega_{\text{Planck}}^{\text{cdm}}$. Assuming that the distribution of each species is homogeneous along the DM distribution, for the $i$-th DM component we can define

$$\tau_{\text{DM}_i, \text{eff}} = f_{\text{DM}_i}^{-1} \tau_{\text{DM}_i} , \quad \text{with} \quad f_{\text{DM}_i} = \frac{\Omega_{\text{DM}_i}}{\Omega_{\text{Planck}}^{\text{cdm}}} ,$$

where $f_{\text{DM}_i}$ is the $i$-th DM component fraction, $\tau_{\text{DM}_i}$ is the inverse of the decay width to photons, and the effective lifetime $\tau_{\text{DM}_i, \text{eff}}$ can be tested against the lower limit reported by the experimental collaborations.

However, we cannot apply straightforwardly the above formulas to our multicomponent DDM scenario made of gravitino LSP ($\text{DM}_1$) and axino NLSP ($\text{DM}_2$). The reason is that their fractions change in time due to axino decay into gravitino, so taking into account Eqs. (11) and (13), we must do the following replacements in Eq. (23) for axino and gravitino respectively:

$$f_{\text{DM}_2} \to f_\tilde{a} \, e^{-(t_{\text{today}}-t_0)/\tau_\tilde{a}} , \quad (24)$$
$$f_{\text{DM}_1} \to f_{3/2} + r_{3/2} f_\tilde{a} \left(1 - e^{-(t_{\text{today}}-t_0)/\tau_\tilde{a}}\right) , \quad (25)$$
with \( f_\tilde{a} \) given by Eq. (21) and

\[
\frac{f_{3/2}}{\Omega_{\text{Planck}}} = \frac{\Omega_{3/2}^{\text{TP}}}{\Omega_{\text{cdm}}}.
\]  (26)

As expected, if axino NLSP decay into gravitino LSP plus axion is not allowed, one gets the same result as in Eq. (23).

Finally, in a same fashion stated before, it is easier for the analysis to consider an effective lifetime in our multicomponent DDM scenario. Thus Eq. (23) becomes

\[
\tau_{\tilde{a}-\text{eff}} = (f_{\tilde{a}} e^{-(t_{\text{today}} - t_0)/\Gamma_{\tilde{a} \rightarrow \gamma \nu_i}})^{-1} \Gamma^{-1} (\tilde{a} \rightarrow \gamma \nu_i),
\]  (27)

\[
\tau_{3/2-\text{eff}} = \left[ f_{3/2} + r_{3/2} f_{\tilde{a}} \left(1 - e^{-(t_{\text{today}} - t_0)/\tau_{\tilde{a}}} \right) \right]^{-1} \Gamma^{-1} (\psi_{3/2} \rightarrow \gamma \nu_i).
\]  (28)

It is now straightforward to apply the analyses of these Subsections to study the current constraints on the parameter space of our scenario, as well as the prospects for its detection. For simplicity, in what follows we will use \( t_0 = 0 \) for the computation.

### 3 Results

#### 3.1 Constraints from cosmological observations

To analyze the regions of the parameter space that can satisfy the current experimental constraints on DDM models, similar as in Ref. [28] we show \( T_R \) versus \( m_\tilde{a} \) for a fixed \( r_{3/2} = 0.75 \) in Fig. 1. The left panel corresponds to the PQ scale \( f_a = 10^{12} \) GeV, whereas the right panel to \( f_a = 10^{13} \) GeV. We will also remark some differences with the results of Ref. [28], where the opposite situation, axino LSP and gravitino NLSP was analyzed.

The blue lines show points of the parameter space with \( \Omega_{3/2} h^2 + \Omega_{\tilde{a}} h^2 \) fulfilling Planck observations at recombination era. The regions above the blue lines are excluded by overproduction of cold DM. The region below them could be allowed if we assume a third DM contribution, but for simplicity we will focus on values of the parameters fulfilling the blue contours. On the other hand, the orange dashed lines correspond to different values of the axino NLSP fraction \( f_{\tilde{a}} \).

The magenta regions in both panels are excluded by cosmological observations for DDM models [53–57], taking in to account the stringent constraints on the fraction of axino NLSP relic density that decays to dark radiation, \( f_{\text{ddm}} \). Usually these constraints are presented as upper limits for this fraction, which are then translated into upper limits on \( f_{\tilde{a}} \), for a fixed \( r_{3/2} \) according to Eq. (20).

Note that unlike Ref. [28] for the axino LSP case, where we can show for a given \( r_\tilde{a} \) several blue lines, corresponding to different values of \( f_{\tilde{a}} \), with the corresponding DDM excluded region, here we cannot do the same for a given \( r_{3/2} \). The reason being that the axino thermal relic density depends on the PQ scale, and therefore the DDM constraints change when we change the axino relic density fraction \( f_{\tilde{a}} \).

Another important difference is that here for higher LSP masses, the NLSP relic density increases. However, in the case discussed in Ref. [28], for higher LSP masses the NLSP relic density decreases. This modifies the shape of the DDM exclusion region, because the
Figure 1: Constraints on the reheating temperature versus axino NLSP mass for the multicomponent DDM scenario with gravitino LSP, and mass relation $r_{3/2} = 0.75$. Blue lines correspond to points with $\Omega_{3/2} h^2 + \Omega_{a} h^2$ equal to $\Omega_{\text{Planck}}^\text{cdm} h^2$ at recombination era in agreement with Planck observations, for two values of the PQ scale $f_a = 10^{12}$ GeV (left panel) and $10^{13}$ GeV (right panel). The regions above the blue lines are excluded by overproduction of cold DM. The magenta region is excluded by cosmological observations for DDM models [53–57], considering bounds on $f_{\text{ddm}}$. Orange dashed lines corresponds to the axino NLSP fractions $f_{{\tilde{a}}} = 0.5, 0.25, 0.1, 0.05$. The upper bounds $m_{\tilde{a}} \lesssim 0.5, 50$ GeV in left and right panels, respectively, are obtained from Eq. (12) assuming the conservative limit $T_R \gtrsim 10^4$ GeV.

NLSP decay is the source of the ultrarelativistic particles. The left panel of Fig. 1 depicts a long-lived axino (the axino decay into gravitino plus axion takes place after the present era), whereas the right panel an intermediate-lived axino (the decay takes place between recombination and the present era).

3.2 Constraints from $\gamma$-ray observations and prospects for detection

To analyze the effect on $\gamma$-ray searches of axino NLSP decaying into gravitino LSP, in Fig. 2 we show the effective lifetime versus the DM candidate mass for one example of the parameter region, $f_a = 10^{13}$ GeV and $r_{3/2} = 0.5$, where a double-line signal could be detected. The left (right) panel shows the limits on the parameter space considering the line produced by axino NLSP (gravitino LSP) decaying into $\gamma\nu$. Thus the two panels correspond to the same DDM scenario, and the constraints obtained from both of them have to be taken into account for each point of the parameter space.

The magenta regions are excluded by cosmological observations concerning dark radiation. The grey regions below the black solid lines are excluded by line searches by COMPTEL and Fermi-LAT [59]. The black dashed lines correspond to the projected e-ASTROGAM sensitivity [38], where we have considered the following DM profiles for
the observations of a ROI of $10^6 \times 10^6$ around the Galactic center: NFW, Moore, Einasto, Einasto B and Burkert. In particular, Einasto B (Burkert) is the most (least) stringent and corresponds to the figure to the upper (lower) dashed line.

Using the results from previous subsections, we also show in Fig. 2 with orange solid lines the values of the parameters predicted by the $\mu$SSM for several representative values of $|U_{5\mu}|$. In the left panel, which represents the limits considering the line produced only by axino NLSP decaying into $\gamma\nu$, we can see the effect of the reduction of the axino relic density due to its decay into gravitino LSP for $m_\tilde{a} \gtrsim 0.2$ GeV, as can be deduced from Eq. (27). The right panel considers the same parameter space, but analyzing the line produced by the gravitino LSP decaying into $\gamma\nu$. This case has a larger effective lifetime with respect to the case with only gravitino DM $\mu$SSM for $|U_{5\mu}|$, due to the non-thermal contribution discussed.

As we can see in the figure, significant regions below the dashed lines could be probed. This is specially true thanks to the line signal coming from axino NLSP for $0.03 \lesssim m_\tilde{a} \lesssim 0.5$ GeV and $10^{-8} \lesssim |U_{5\mu}| \lesssim 10^{-6}$ (see the left panel). Moreover, for this example there is also a narrow region in the right panel corresponding to a detectable line signal coming from gravitino LSP, for $0.15 \lesssim m_{3/2} \lesssim 0.25$ GeV and $|U_{5\nu}| \approx 10^{-6}$. Given the parameter used in the figure $r_{3/2} = 0.5$, this gravitino mass range corresponds to axino masses $0.3 \lesssim m_\tilde{a} \lesssim 0.5$ GeV, which are embedded in the range producing a line signal from axino, thus we expect a detectable double line as an overwhelming smoking gun of this parameter region.
Figure 3: Constraints on gravitino LSP mass versus axino NLSP mass, with the lower bound $m_{3/2} \gtrsim 0.017$ GeV obtained from Eq. (15) assuming the conservative limit $T_R \gtrsim 10^4$ GeV. The $\gamma$-ray signals from axino and gravitino decays are analyzed separately in left and right panels, respectively, assuming a NFW profile. The grey region corresponds to points excluded by line searches in the Galactic halo by COMPTEL and Fermi-LAT [59]. Blue and green regions correspond to points that could be probed by e-ASTROGAM for the representative ranges $10^{-10} \leq |U_{\tilde{\gamma} \nu}| < 10^{-8}$ and $10^{-8} \leq |U_{\tilde{\gamma} \nu}| \leq 10^{-6}$, respectively, in the $\mu$SSM. In the top left panel, the values in the border between regions are labeled, and for the rest of the panels the labeling is the same. If the same point can be probed in both panels, a double-line signal could be measured. The red region corresponds to points disfavored by e-ASTROGAM. In the left panels, the black solid lines show different values of $\tau_{\tilde{a}} \simeq \Gamma^{-1}(\tilde{a} \rightarrow \psi_{3/2} a)$ between $10^5$ and $10^{21}$ s. All the points shown satisfy $\Omega_{3/2} h^2 + \Omega_{\tilde{a}} h^2$ equal to $\Omega_{\text{Planck}} h^2$ at recombination era in agreement with Planck observations, as well as DDM constraints for $f_{d_{\text{ddm}}}^{\text{DR}}$.

To carry out now the complete analysis of the allowed parameter space, for $m_{3/2} \gtrsim 0.017$ GeV we have performed a scan over the ranges: $1.05 m_{3/2} \lesssim m_{\tilde{a}} \lesssim 50, 0.5$ GeV for $f_a = 10^{13}, 10^{12}$ GeV, respectively, taking into account that axino is always heavier than gravitino and the bounds on their masses discussed below Eqs. (12) and (15). The result is shown
in Fig. 3 where the $\gamma$-ray signals from axino and gravitino decays are analyzed separately in the left and right panels, respectively. Green and blue regions correspond to points that could be probed with the projected sensitivity of e-ASTROGAM assuming a NFW profile, for different values of the photino-neutrino mixing parameter $|U_{\tilde{\gamma}\nu}|$. In particular, the green points correspond to the most natural range of $|U_{\tilde{\gamma}\nu}|$ as discussed in Eq. (3). It is worth mentioning here that this range includes the typical parameter space that can reproduce the observed neutrino physics in bilinear RPV models, thus the constraints obtained also apply to those models.

As we can see in the figure, for values of $r_{3/2}$ close to 1, i.e. the upper border line, we recover the allowed parameter space obtained in the work [28] with axino LSP and gravitino NLSP if we consider now both gravitino LSP and axino NLSP effect. Even though the DDM constraints for $f_{\text{ddm}}^{\text{DR}}$ become relaxed since $\tau_{\tilde{a}}^{-1} \simeq \frac{1}{\Gamma(a \rightarrow \psi_{3/2} a)} \rightarrow 0$ when $r_{3/2} \rightarrow 1$ (see Eq. (8)), the remaining effect concerning the $\gamma$-ray flux dominates: the initial relic density fractions of the LSP and NSLP that do not change in time, as can be seen from Eqs. (24) and (25), cannot be ignored. For the allowed mass region, the initial axino NLSP relic density is relevant, and its decay to photon-neutrino can give rise to a signal and set constraints on the parameter space that otherwise would not exist considering only the contribution from gravitino LSP.

From Fig. 3 we can conclude that a significant region of the parameter space of our DDM scenario could be tested by next generation $\gamma$-ray telescopes. Similar to the case discussed in Ref. [28], where the axino (LSP) is the main source of the relevant photon signal, here also the axino (NLSP) plays the same role as shown in the left panels, instead of the gravitino LSP as one would expect naively. Note in this sense that, on the one hand, the black solid lines in the left panels show us that this photon signal lies in the region of the parameter space with $\tau_{\tilde{a}} \simeq \frac{1}{\Gamma(a \rightarrow \psi_{3/2} a)} > t_{\text{today}}$, and, on the other hand, the axino and gravitino decay widths to photon-neutrino which are relevant quantities for the amount of photon flux (see Eqs. (22), (27) and (28)) fulfills always $\Gamma(a \rightarrow \gamma \nu_i) > \Gamma(\psi_{3/2} \rightarrow \gamma \nu_i)$ as discussed in Sect. 2.2. In particular, this detectable region is inside the following mass ranges: $20 \text{ MeV} \lesssim m_{\tilde{a}} \lesssim 3 \text{ GeV}$ and $17 \text{ MeV} \lesssim m_{3/2} \lesssim 3 \text{ GeV}$. According to this discussion, we also expect a line signal coming from gravitino LSP to be measured in a smaller region. This is actually the green region of the top right panel corresponding $f_a = 10^{13} \text{ GeV}$. It is inside the ranges $300 \lesssim m_{\tilde{a}} \lesssim 500 \text{ MeV}$ and $150 \lesssim m_{3/2} \lesssim 250 \text{ MeV}$. Since this region is also probed with a line from axino NLSP, a double-line signal could be measured as an overwhelming smoking gun. Note that this is the same region already discussed in the example of Fig. 2.

Although in Fig. 3 we used the projected e-ASTROGAM sensitivity assuming a NFW profile, we have checked that using a different DM profile such as Einasto B the detectable parameter space is not essentially modified.

Nonetheless, a source of significant uncertainty corresponds to the characteristics of the $\gamma$-ray telescopes. We have been conservative considering an already proposed telescope, but if the next generation instruments achieves an increase of sensitivity with respect to the proposed e-ASTROGAM (or a similar effect through the improvement of the background modeling), the impact on DM indirect detection can be very important. This is feasible considering the astonishing advances in techniques and technology of each successive proposal for this type of experiments in the recent years. In Fig. 4 we show for a NFW profile as in Fig. 3 the detectable parameter space for an enhanced sensitivity of an order of mag-
Figure 4: The same as in Fig. 3 but increasing e-ASTROGAM sensitivity an order of magnitude with respect to the current proposal.

We can see there the broadening of the green region where a $\gamma$-ray line can be probed, specially the region with a double-line signal as a smoking gun. For $f_a = 10^{13}$ GeV, this region is now inside the mass ranges $60 \lesssim m_{\tilde{a}} \lesssim 700$ MeV and $60 \lesssim m_{3/2} \lesssim 250$ MeV.

### 4 Conclusions

In this work, we have analyzed a mixture of gravitino and axino particles as DM, extending a previous work on the subject of multicomponent DM in RPV SUSY \[28\]. Now we have studied the scenario of gravitino LSP with axino NLSP. In this context of DDM, we have found that this combination of particles can reproduce the accumulated DM evidence, avoiding cosmological problems.

In the context of the $\mu\nu$SSM, we have analyzed the possibility of an axino NLSP having a RPC partial decay width into gravitino LSP plus axion, in addition to the RPV partial decay width into photon plus neutrino. The latter decay also occurs for the gravitino LSP, with a lifetime typically much longer than the age of the Universe due to the small values...
of neutrino Yukawas in the generalized electroweak-scale seesaw of the \( \mu\nu \)SSM. If axino and gravitino coexist, both DM particles can be sources of \( \gamma \)-ray radiation.

The corresponding relic density has been discussed, and assuming a conservative lower bound on the reheating temperature of \( T_R \gtrsim 10^4 \text{ GeV} \) an upper bound on the axino mass of \( m_\tilde{a} \lesssim 50 \text{ GeV} \) was obtained, as well as a lower bound on the gravitino mass of \( m_{3/2} \gtrsim 17 \text{ MeV} \). We have also found the regions of the parameter space excluded by cosmological observations, considering the stringent constraints on the fraction of axino NLSP relic density that decays to dark radiation (see Fig. [1]).

Then we have studied the \( \gamma \)-ray flux produced in this DDM scenario of the \( \mu\nu \)SSM, finding that a significant region of the parameter space could be tested by e-ASTROGAM searching in a ROI around the Galactic center. In particular, this region is inside the mass ranges \( 20 \text{ MeV} \lesssim m_\tilde{a} \lesssim 3 \text{ GeV} \) and \( 17 \text{ MeV} \lesssim m_{3/2} \lesssim 3 \text{ GeV} \). This is specially true thanks to the line signal coming from axino NLSP decay (see the left panels of Fig. [3]), which as expected is produced when \( \tau_\tilde{a} \simeq \Gamma^{-1} (\tilde{a} \rightarrow \psi_{3/2} a) > t_{\text{today}} \). On the other hand, a signal coming from gravitino LSP could be measured in a smaller region of the parameter space for \( f_\tilde{a} = 10^{13} \text{ GeV} \) inside the mass ranges \( 300 \lesssim m_\tilde{a} \lesssim 500 \text{ MeV} \) and \( 150 \lesssim m_{3/2} \lesssim 250 \text{ MeV} \) (see the top right panel of Fig. [3]). In this case a double-line signal from axino and gravitino decays could be measured as an overwhelming smoking gun.

We have finally considered the possibility that the sensitivity of the next generation telescopes increases an order of magnitude. Under this assumption, the detectable regions are enhanced (see Fig. [4]). Specially interesting is the double-line signal region inside now the following mass ranges: \( 60 \lesssim m_\tilde{a} \lesssim 700 \text{ MeV} \) and \( 60 \lesssim m_{3/2} \lesssim 250 \text{ MeV} \).

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