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Heavy concerns about the light axino explanation of the 3.5 keV X-ray line

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ABSTRACT

An unidentified 3.5 keV line from X-ray observations of galaxy clusters has been reported recently. Although still under scrutiny, decaying dark matter could be responsible for this signal. We investigate whether an axino with a mass of 7 keV could explain the line, keeping the discussion as model independent as possible. We point out several obstacles, which were overlooked in the literature, and which make the axino an unlikely candidate. The only viable scenario predicts a light metastable neutralino, with a mass between 0.1 and 10 GeV and a lifetime between 10^{-3} and 10^4 s.

1. Introduction

There has been interest recently in an unidentified 3.5 keV line in X-ray observations of galaxy clusters [1,2]. Despite its physical origin being subject to debate [3–8], there is still some room to speculate that decaying dark matter is responsible for this signal. The first obvious dark matter (DM) candidate in this context is a 7 keV sterile neutrino [1], but many other alternatives have been proposed. Some authors have pointed out that a decaying axino could explain the line [9–12]. In this paper we examine carefully the conditions under which a 7 keV axino would produce the observed X-ray line. Due to the large number of parameters at disposal in supersymmetric models, it is hard to exclude with certainty the axino scenario. However we show that various constraints leave almost no room available in the parameter space of these models. Therefore we deem the axino an unlikely candidate to explain the line. The authors of Ref. [13] also mentioned the axino as an unnatural explanation of the X-ray line. In this work we elaborate on the physical arguments that lead to such a conclusion.

There are a few reasons why it is appealing to consider a model with a light axino. First, introducing the axion multiplet (axion, axino, saxion) in models of supersymmetry (SUSY) solves the strong CP problem [14]. Second, the axion and the axino can both be DM candidates. Third, if the axino has a mass in the keV range, it is warm DM and it could help reconcile some small-scale structure issues [15–17] of cold DM. In the context of R-parity violating (RPV) SUSY [18], a light axino is unstable. Its lifetime is still longer than the age of the universe, but it can decay into a neutrino and a photon. It is this channel that would produce the 3.5 keV line. RPV models also have the virtue of explaining the null-results for SUSY searches at the LHC without introducing a little hierarchy problem: the limits on the masses of the sparticles become much weaker [19–23]. The axino could also produce an X-ray photon in R-parity conserving SUSY. This is possible if the lightest neutralino is very light or even massless. The axino can then decay into the neutralino plus a photon [12]. We comment also on this possibility, below.

This letter is organized as follows. In Section 2, we review how the axino abundance depends on the reheating temperature, in Section 3 we discuss various constraints that the 3.5 keV line puts on models with a decaying axino. We conclude in Section 4.

2. Axino relic density

Any supersymmetric model with an axino contains also an axion. The latter, as an invisible axion, is always a good DM candidate, while the former is suitable only if it is sufficiently long lived. We are here interested in a scenario where the axino constitutes almost the entire DM budget of the universe. This is typically realized for low values of the axion decay constant ($f_a \sim 10^{10}$ GeV), in which case the axion DM component is suppressed and can be neglected. See *e.g.* Ref. [24] for a review on axion DM.

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The axino as a DM candidate has been widely explored in the literature [25–32]. There are two axion/axino scenarios of interest: the Dine–Fischler–Srednicki–Zhitnitsky (DFSZ) model [33,34], and the Kim–Shifman–Vainshtein–Zakharov (KSVZ) model [35,36]. As far as the axino is concerned, the important difference between the two lies in the mass, M_Φ, of the heaviest Peccei–Quinn (PQ) charged and gauge-charged matter supermultiplet in the model [31]. In the DFSZ case M_Φ is the Higgsino mass, of order $\lesssim$ TeV, while in the KSVZ case it is the mass of the heavy vectorlike quarks, typically of order $f_a \gtrsim 10^9$ GeV. This difference leads to two different relic axino abundances as well as to a different dependence on the reheating temperature, $T_{\rm RH}$. For DFSZ models we have [29]

$$\Omega_{\tilde a}^{\rm DFSZ} h^2 \simeq 0.78 \left(\frac{m_{\tilde a}}{7\ \rm keV}\right)\left(\frac{10^{10}\ \rm GeV}{f_a}\right)^2 , \tag{1}$$

which does not depend on $T_{\rm RH}$, as long as $T_{\rm RH}$ is larger than[1] roughly 1 TeV [32]. The relic density drops very quickly for lower values of $T_{\rm RH}$ (see *e.g.* Fig. 3 in Ref. [29]). From eq. (1) we see that for a 7 keV DFSZ axino with $f_a < 10^{10}$ GeV the reheating temperature has to be below 1 TeV in order to avoid overabundance. Recall, observationally $\Omega_{\rm DM} h^2 = 0.1199 \pm 0.0027$ [37].

For the KSVZ case [29]:

$$\Omega_{\tilde a}^{\rm KSVZ} h^2 = 6.9 \times 10^{-3} \left(\frac{m_{\tilde a}}{7\ \rm keV}\right)\left(\frac{10^{10}\ \rm GeV}{f_a}\right)^2 \times \left(\frac{T_{\rm RH}}{10^3\ \rm GeV}\right) , \tag{2}$$

which is valid for 1 TeV $< T_{\rm RH} < M_\Phi \sim f_a$. Also in this case the abundance drops very quickly for reheating temperatures below about 1 TeV.

2.1. Including a light gravitino

Without tuning and/or cancellations, the axino is expected to be heavier than the gravitino [38,39]. This puts further constraints on our scenario. First, the axino can decay into a gravitino and an axion with a lifetime [38]

$$\tau_{\tilde a \to \tilde G + a} \simeq 6 \cdot 10^{28}\ \ {\rm s} \left(\frac{m_{3/2}}{\rm keV}\right)^2 \left(\frac{7\ \rm keV}{m_{\tilde a}}\right)^5 . \tag{3}$$

Here $m_{3/2}$ denotes the gravitino mass. If the 7 keV axino is to explain the X-ray line we must require its lifetime to be roughly greater than the age of the universe, $\tau_{\tilde a \to \tilde G + a} > 10^{18}$ s, otherwise it would have decayed away. This implies $m_{3/2} > 10^{-5}$ keV. A gravitino lighter than roughly 100 eV is a hot dark matter candidate. Its relic abundance [40],

$$\Omega_{\tilde G}^{\rm HDM} h^2 \sim 0.1\, \frac{m_{3/2}}{100\ \rm eV} , \quad \text{for } m_{3/2} < 100\ \rm eV , \tag{4}$$

is constrained to be less than 3% of the total DM abundance [41], which implies $m_{3/2} \lesssim 1$ eV.

In the range 1 keV $< m_{3/2} < 7$ keV, the gravitino is a warm dark matter candidate and its abundance depends on $T_{\rm RH}$ [42]:

$$\Omega_{\tilde G} h^2 = 0.27 \left(\frac{T_{\rm RH}}{100\ \rm GeV}\right)\left(\frac{\rm keV}{m_{3/2}}\right) , \text{ for } m_{3/2} > 1\ \rm keV . \tag{5}$$

In this case we require a reheating temperature below 1–10 GeV so that the gravitino contribution to the DM density is much smaller than that of the axino. However for such low values of $T_{\rm RH}$ the axino relic density, even with $f_a \sim 10^9$ GeV, is highly suppressed, $\Omega_{\tilde a} h^2 \ll 0.12$. Therefore, we exclude this case.

Thus if the axino constitutes most of the DM and produces the 3.5 keV X-ray line, the gravitino mass is restricted to the small window

$$10^{-2}\ {\rm eV} < m_{3/2} < 1\ {\rm eV} . \tag{6}$$

As both the axino and the gravitino are in the keV range and below, one might worry about their contribution to the relativistic degrees of freedom at Big Bang Nucleosynthesis (BBN). This turns out not to be a problem in most cases. When the universe reheats to 10–100 GeV, both the axino and the gravitino are out of thermal equilibrium [29]. The subsequent annihilations of SM particles heat up the photon bath so that the photon temperature at BBN is higher than the respective temperatures of the axino and the gravitino. As a consequence their contribution to $N_{\rm eff}$ is well within the bound. If there is also a very light or massless neutralino in the spectrum one has to worry about the constraint from $N_{\rm eff}$, as we discuss later.

3. The axino and the X-ray line

To explain the 3.5 keV X-ray line via the decay of a DM particle X, one needs a decay rate of $\Gamma_{X\to\gamma+\ldots} \sim (10^{28}\ \ {\rm s})^{-1} \sim 10^{-53}$ GeV [1], assuming that the decaying DM constitutes 100% to the relic abundance. If the decaying DM is a fraction $k < 1$ of the total DM, then the corresponding decay rate has to increase by $1/k$ to explain the signal.

There are two scenarios for a 7 keV axino to produce the 3.5 keV X-ray line, where R-parity is respectively conserved or violated. In either case the starting point is the following Lagrangian for the coupling of the axino to the SM gauge bosons and their gaugino supersymmetric partners:

$$\mathcal{L}_{a\lambda V} = \frac{\tilde a}{16\pi^2 f_a} \sigma_{\mu\nu} \Big(g_1^2 C_{aBB} \tilde B B^{\mu\nu} + g_2^2 C_{aWW} \tilde W^a W^{a\mu\nu} + g_3^2 \tilde G^\alpha G^{\alpha\mu\nu} \Big) . \tag{7}$$

Here $\tilde a$ is the axino mass eigenstate, while the gauginos and gauge fields are gauge eigenstates; g_i are the gauge couplings. These interactions are the supersymmetric version of those of the axion with gauge fields in the low energy (non-supersymmetric) Lagrangian [43]. The coefficients C are model dependent and are typically of order one [44].

3.1. R-parity conserving SUSY

In the R-parity conserved case, if the bino is lighter than the axino, the X-ray line could be produced by the decay $\tilde a \to \tilde B + \gamma$. This was pointed out in Ref. [12]. The axino partial decay rate with a massless bino is

$$\Gamma_{\tilde a \to \tilde B + \gamma} = \frac{1}{128\pi^3} \frac{m_{\tilde a}^3}{f_a^2} C_{aBB}^2 \left(\frac{g_1^2}{4\pi}\right)^2 \cos^2\theta_W \tag{8}$$

$$\sim 7 \times 10^{-52}\ {\rm GeV} \left(\frac{m_{\tilde a}}{7\ \rm keV}\right)^3 \left(\frac{10^{14}\ \rm GeV}{f_a}\right)^2 . \tag{9}$$

Note, a massless bino is consistent with all data provided the sfermions are heavy enough [45–47]. To match the rate needed for the X-ray line this scenario requires $f_a > 10^{14}$ GeV. This immediately excludes the DFSZ axino, whose relic abundance would be much too low.

[1] The exact value of $T_{\rm RH}$ depends on the SUSY spectrum, but it is expected to lie in the TeV range.

From eq. (2), a KSVZ axino with $T_{\rm RH} \sim 10^{12}$ GeV would seem viable. However this scenario is strongly disfavored by two arguments. First, the abundance of axions produced via the misalignment mechanism would be far too high [24] for $f_a \sim 10^{14}$ GeV, unless one tunes the initial misalignment angle to very small values. Second, a massless bino together with a light gravitino would contribute to the relativistic degrees of freedom [48], giving a value $\Delta N_{\rm eff} > 1$, in strong tension with BBN and with the data from the Cosmic Microwave Background (CMB) [49].

3.2. R-parity violating SUSY

In the context of R-parity violation, the terms $\epsilon_i L_i H_u$, $i = e, \mu, \tau$ in the superpotential introduce mixing among the neutrinos and the Higgsinos. The modified scalar potential also results in non-zero sneutrino vacuum expectation values (VEVs), which introduce mixing between the neutrinos and the bino and the neutral wino, respectively. In this case the RPC axino decay in Section 3.1 automatically includes the decay channel $\tilde{a} \to \nu_i + \gamma$. The new partial decay rate is simply modified by the appropriate mixing angles[2]

$$\Gamma_{\tilde{a}\to\nu_i+\gamma} = \frac{1}{128\pi^3}\frac{m_{\tilde{a}}^3}{f_a^2}\left[r^2_{\nu_i\tilde{B}} C^2_{aBB}\left(\frac{g_1^2}{4\pi}\right)^2 \cos^2\theta_W + r^2_{\nu_i\tilde{W}} C^2_{aWW}\left(\frac{g_2^2}{4\pi}\right)^2 \sin^2\theta_W \right] \tag{10}$$

$$\sim 7\times 10^{-42}\ \text{GeV}\ (r^2_{\nu_i\tilde{B}} + 3r^2_{\nu_i\widetilde{W}}) \times \left(\frac{m_{\tilde{a}}}{7\ \text{keV}}\right)^3 \left(\frac{10^9\ \text{GeV}}{f_a}\right)^2 . \tag{11}$$

Here $r_{\nu_i\tilde{B}}$ ($r_{\nu_i\widetilde{W}}$) parametrizes the mixing of the neutrino mass eigenstate with the gaugino gauge eigenstate $\tilde{B}$ ($\widetilde{W}^0$). The lifetime of the axino to explain the X-ray line requires $r^2_{\nu_i\tilde{B}}$ ($r^2_{\nu_i\widetilde{W}}$) to be of order 10^{-12} for f_a fixed at its lowest possible value [51], 10^9 GeV.

One of the outstanding features of RPV models with lepton number violation, is that they automatically provide for massive neutrinos. Assuming that the neutrino masses solely arise from the RPV sector, we can estimate bounds on the mixings $r_{\nu_i(\tilde{B},\widetilde{W})}$ as follows. Neglecting loop contributions, the terms $\epsilon_i L_i H_u$ lead to one massive neutrino [52–54] and two non-vanishing lepton mixing angles, which we take to be θ_{13} and θ_{23} [52]. The neutrino mass is given in terms of the model parameters as

$$m_{\nu_3} = \frac{g_2^2 M_1 + g_1^2 M_2}{4 \det \mathcal{M}_{\chi_0}} |\vec{\Lambda}|^2 , \tag{12}$$

where [52]

$$\Lambda_i \equiv \mu\omega_i - v_d\epsilon_i , \quad i = e, \mu, \tau \tag{13}$$

are the alignment parameters and $\omega_i \equiv \langle\tilde{\nu}_i\rangle$ are the sneutrino VEVs. Furthermore $\det \mathcal{M}_{\chi_0}$ denotes the determinant of the 4×4 neutralino sub-mass-matrix of the MSSM

$$\det \mathcal{M}_{\chi_0} \equiv -\mu^2 M_1 M_2 + \frac{1}{2}\mu v_u v_d (g_2^2 M_1 + g_1^2 M_2) , \tag{14}$$

where $v_u \equiv \langle H_u\rangle$, $v_d \equiv \langle H_d\rangle$ are the Higgs VEVs. The parameters Λ_i are related to the two remaining neutrino mixing angles [52]:

$$\tan\theta_{13} = -\frac{\Lambda_e}{(\Lambda_\mu^2 + \Lambda_\tau^2)^{1/2}} , \qquad \tan\theta_{23} = \frac{\Lambda_\mu}{\Lambda_\tau} . \tag{15}$$

These angles are measured [55] to be $\theta_{13} \sim \pi/20$ and $\theta_{23} \sim \pi/4$, thus we have $\Lambda_\mu = \Lambda_\tau \equiv \Lambda$ and $\Lambda_e = 0.23\,\Lambda$. The cosmological bound on the sum of the neutrino masses [49], $\sum_i m_{\nu_i} < 0.23$ eV, in our case amounts to a bound on the single massive neutrino, and thus

$$\Lambda < (3.2\times 10^{-13}\ \text{TeV})^{1/2} \left(\frac{\det \mathcal{M}_{\chi_0}}{g_2^2 M_1 + g_1^2 M_2}\right)^{1/2} . \tag{16}$$

From Refs. [52,54] we can work out the mixings analytically, in terms of the supersymmetric parameters. For instance

$$r_{\nu_2\tilde{B}} = \frac{g_1 M_2 \Lambda_\mu \Lambda_\tau \mu}{\sqrt{\Lambda_\mu^2 + \Lambda_\tau^2}\cdot \det \mathcal{M}_{\chi_0}} \simeq \frac{g_1 M_2 \Lambda\mu}{\sqrt{2}\det \mathcal{M}_{\chi_0}} , \tag{17}$$

and similar expressions for the other mixings. Then the bound on Λ translates into

$$r^2_{\nu_1\tilde{B}} < (1.1\times 10^{-14}\ \text{TeV})\mathcal{M}^{-1} \tag{18}$$

$$r^2_{\nu_2\tilde{B}} < (4.6\times 10^{-13}\ \text{TeV})\mathcal{M}^{-1} \tag{19}$$

$$r^2_{\nu_3\tilde{B}} < (2.8\times 10^{-16}\ \text{TeV})\mathcal{M}^{-1} , \tag{20}$$

with

$$\mathcal{M}^{-1} \equiv \frac{g_1^2 M_2^2 \mu^2}{(g_2^2 M_1 + g_1^2 M_2)\det \mathcal{M}_{\chi_0}} , \tag{21}$$

and similar bounds for $r^2_{\nu_1\widetilde{W}}$. Given the null SUSY searches at the LHC so far, it is reasonable to expect the parameters M_1, M_2, μ to be of order TeV or larger, and $\det \mathcal{M}_{\chi_0} \sim \text{TeV}^4$, in absence of cancellations. In this case the bounds simplify to

$$r^2_{\nu_1\tilde{B}} < 2.3\times 10^{-15} , \tag{22}$$

$$r^2_{\nu_2\tilde{B}} < 9.2\times 10^{-14} , \tag{23}$$

$$r^2_{\nu_3\tilde{B}} < 5.6\times 10^{-17} . \tag{24}$$

These mixings are very small and thus the resulting axino decay rate too slow to explain the X-ray line.

Perhaps the assumption that all the SUSY parameters and masses are at least around a TeV is too strict. Suppose that the lightest neutralino, χ_1^0, has a mass of order GeV and the other neutralinos are at the TeV scale. Then $\det \mathcal{M}_{\chi_0} \sim 10^{-3}\ \text{TeV}^4$ and the bound on $r^2_{\nu_2\tilde{B}}$ becomes of order 10^{-10}, which is enough to fit the line. However this scenario faces another problem. A GeV neutralino has two decay channels: one into an axino and a photon with

$$\Gamma_{\chi_1^0\to\tilde{a}+\gamma} \simeq \frac{1}{128\pi^3}\frac{m_{\tilde{B}}^3}{f_a^2} C^2_{aBB}\left(\frac{g_1^2}{4\pi}\right)^2 \cos^2\theta_W ,$$

$$\tau_{\chi_1^0\to\tilde{a}+\gamma} \sim 60\ \text{s} \left(\frac{\text{GeV}}{m_{\chi_1^0}}\right)^3 \left(\frac{f_a}{10^9\ \text{GeV}}\right)^2 ; \tag{25}$$

the other into a neutrino plus leptons (or pions) via an off-shell Z boson, with [56]

$$\Gamma_{\chi_1^0\to\nu l^+ l^-} \simeq \frac{r^2_{\nu_i\tilde{B}}\alpha^2}{1024\pi^3}\frac{m^5_{\chi_1^0}}{M_Z^4} ,$$

$$\tau_{\chi_1^0\to\nu l^+ l^-} \sim 60\ \text{s} \left(\frac{10^{-10}}{r^2_{\nu_i\tilde{B}}}\right)\left(\frac{\text{GeV}}{m_{\chi_1^0}}\right)^5 . \tag{26}$$

[2] Note this decay would also occur with pure trilinear R-parity violation via the resulting sneutrino VEV's [50].

For $m_{\chi_1^0} < 1$ GeV the dominant decay mode is into axino plus photon, while for $m_{\chi_1^0} > 1$ GeV it is into neutrino plus leptons. These decay rates are low enough that the neutralino freezes out before decaying. As a weakly interacting particle (WIMP), at freeze-out it has roughly the right DM relic abundance, $\Omega_{\chi_1^0} h^2 \sim 0.1$. If χ_1^0 is mostly bino, it will be slightly overabundant, while if it is mostly wino or Higgsino it will be underabundant [57]. In either case our subsequent conclusions do not change. When χ_1^0 decays it produces energetic photons, which are subject to constraints from BBN and CMB. The window 10 MeV $< m_{\chi_1^0} <$ 100 MeV, corresponding to 3×10^4 s $< \tau_{\chi_1^0} < 3 \times 10^7$ s, is excluded by bounds from photodestruction of D and photoproduction of $D + ^3He$ [58]. The window 300 keV $< m_{\chi_1^0} <$ 10 MeV, corresponding to 3×10^7 s $< \tau_{\chi_1^0} < 10^{12}$ s, is excluded by bounds from CMB spectrum distortions [58,59]. The window 7 keV $< m_{\chi_1^0} <$ 300 keV, with a lifetime $\tau_{\chi_1^0} > 10^{12}$ s, is excluded by CMB constraints on late decaying particles [60]. For $m_{\chi_1^0} < 7$ keV the neutralino is lighter than the axino and we are back to the situation of the R-parity conserving scenario, which is strongly disfavored as we discussed in the previous section.

The window 100 MeV $< m_{\chi_1^0} <$ 10 GeV, corresponding to 10^{-3} s $< \tau_{\chi_1^0} < 3 \times 10^4$ s, cannot be as easily excluded, so it is viable in principle. In this range most of the neutralinos decay around BBN time, which could be in some tension with the success of BBN itself. However a detailed study, beyond the scope of the current work, is needed to come to a definite conclusion. For $m_{\chi_1^0} > 10$ GeV one quickly hits the bound from neutrino masses.

We conclude that also the RPV scenario is strongly disfavored.

4. Summary

Motivated by recent claims of detection of an X-ray line at 3.5 keV we have investigated whether a decaying axino with a 7 keV mass could explain the signal. The R-parity conserving scenario is strongly disfavored mostly because it requires a very light bino, which together with a light gravitino would contribute to the relativistic degrees of freedom, $\Delta N_{\rm eff} > 1$, in contradiction with BBN and CMB bounds. RPV models require a mixing neutrino–bino or neutrino–wino which is typically too large and excluded by the cosmological bound on neutrino masses. To evade this bound one is forced to take the lightest neutralino with a mass around a GeV or below. Such a neutralino is long-lived and decays into energetic photons. If it is lighter than 100 MeV the scenario is excluded by BBN and CMB constraints. These arguments are generic, model independent, and make the 7 keV axino a very unlikely candidate for the observed 3.5 keV line.

If the lightest neutralino has a mass between 100 MeV and 10 GeV, the RPV scenario is still viable. The corresponding lifetime of the neutralino ranges from $\tau_{\chi_1^0} = \mathcal{O}(10^{-3}\text{ s})$, for $m_{\chi_1^0} = 10$ GeV, to $\tau_{\chi_1^0} = \mathcal{O}(10^4\text{ s})$, for $m_{\chi_1^0} = 100$ MeV. This is effectively stable for collider physics. Such a neutralino is very hard to observe in the laboratory, with no present bounds [46]. The low mass range is excluded by supernova cooling if the selectron is lighter than about 500 GeV [45]. The proposed SHiP facility at CERN is most likely not sensitive to these lifetimes, due to the restricted geometry [61]. A direct measurement at an e^+e^- linear collider is also unlikely [62]. This range of lifetimes is too short for possible astrophysical signatures. Therefore it is hard to verify whether this particular scenario is realized or excluded.

It might still be possible, at the expense of fine tuning, to find other corners of parameter space where the axino has the right abundance and decay rate to fit the line. One would have to do a numerical scan for a specific model, which is beyond the scope of this work. If such a corner were found, our arguments suggest that it would have a low axion decay constant, $f_a \sim 10^9$ GeV, at the edge of the astrophysical bound, and a low reheating temperature, below a TeV (for a KSVZ model) or even around a few tens of GeV (for a DFSZ model). This is troublesome for most of the proposed baryogenesis mechanisms.

5. Note added

As this work was being completed, Ref. [63] appeared, which casts further doubts on the DM interpretation of the 3.5 keV line.

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