3.55 keV line in minimal decaying dark matter scenarios

This content has been downloaded from IOPscience. Please scroll down to see the full text.

JCAP07(2015)023

(<http://iopscience.iop.org/1475-7516/2015/07/023>)

View [the table of contents for this issue](#), or go to the [journal homepage](#) for more

Download details:

IP Address: 134.76.162.165

This content was downloaded on 07/09/2015 at 13:58

Please note that [terms and conditions apply](#).

3.55 keV line in minimal decaying dark matter scenarios

Giorgio Arcadi,^a Laura Covi^b and Federico Dradi^b

^aLaboratoire de Physique Théorique, Université Paris-Sud,
F-91405 Orsay, France

^bInstitute for Theoretical Physics, Georg-August University Göttingen,
Friedrich-Hund-Platz 1, Göttingen, D-37077 Germany

E-mail: giorgio.arcadi@th.u-psud.fr, Laura.Covi@theorie.physik.uni-goettingen.de,
Federico.Dradi@theorie.physik.uni-goettingen.de

Received January 13, 2015

Revised May 27, 2015

Accepted June 23, 2015

Published July 20, 2015

Abstract. We investigate the possibility of reproducing the recently reported 3.55 keV line in some simple decaying dark matter scenarios. In all cases a keV scale decaying DM is coupled with a scalar field charged under SM gauge interactions and thus capable of pair production at the LHC. We will investigate how the demand of a DM lifetime compatible with the observed signal, combined with the requirement of the correct DM relic density through the freeze-in mechanism, impacts the prospects of observation at the LHC of the decays of the scalar field.

Keywords: dark matter theory, X-ray telescopes, particle physics - cosmology connection, cosmology of theories beyond the SM

ArXiv ePrint: [1412.6351](https://arxiv.org/abs/1412.6351)

Contents

1	Introduction	1
2	Minimal scenario	2
3	Dark matter and dark radiation scenario	8
4	DM as sterile neutrino	11
5	Conclusions	13

1 Introduction

The identification of the Dark Matter component of the Universe is one of the most important puzzles in modern astrophysics and particle physics. Although conventional paradigms rely on stable particle states, there are no a-priori arguments against decaying dark matter candidates, provided that their lifetimes largely exceed the age of the Universe. In order to satisfy this requirement, the couplings of the DM with ordinary matter are too suppressed to allow Direct Detection of DM in experiments like e.g. XENON [1, 2], LUX [3]. On the contrary there are rather promising prospects on Indirect Detection, in cosmic rays, of the DM decays occurring at present times. Already strong limits on the DM lifetime have been set on a broad variety of decay products by observations like those performed by Fermi [4–6], AMS [7] and XMM/CHANDRA [8].

γ /X-rays are among the most promising signatures of DM Indirect Detection. Indeed DM decays (and annihilations) can give rise to sharp peaks (“lines”) which can be hardly accounted for by astrophysical sources. A spectral feature of this kind has been recently identified in the combined spectrum of a large set of X-ray galaxy clusters [9] as well as in the combined observation of the Perseus Cluster and the M31 galaxy [10]. This signal can be accounted for by a rather broad variety of models of decaying DM [11–43] as well as annihilating DM [44, 45] although an astrophysical/instrumental origin is still feasible [46, 47] as the line has not been seen in stacked spheroidal galaxies or galaxy groups [48, 49].

A very simple and rather predictive decaying Dark Matter scenario has been proposed and studied in [50, 51]. Here a SM singlet Majorana fermion is the Dark Matter candidate and it is coupled with a scalar field charged under (at least some of) the gauge interactions of the Standard Model and Standard Model fields. In its simplest realization this model can be described by only four parameters: the masses of the DM and of the scalar field and two Yukawa-type couplings λ and λ' for the scalar field. The correct DM relic density is ensured by a combination of the freeze-in and SuperWIMP mechanisms which are effective at the low values of the couplings λ and λ' compatible with constraints from Indirect Detection. An hypothetical detection of the DM decays can in such a simple setting be related to LHC signals associated to the LHC production of the charged scalar field with the latter being long-lived or even detector-stable, thus producing peculiar signatures in the form of displaced decays and/or disappearing tracks.

This kind of relation has been established in [50, 51] for rather massive, at least at the GeV scale, DM candidates, for which three body tree-level decay processes of the DM

into SM fermions are kinematically allowed. In this work we want to investigate whether a similar interplay between collider and DM indirect detection can be established for DM masses at the keV scale, for which only two-body, one-loop induced, decays into a neutrino and a photon are possible, thus reproducing in the model the X-ray line signal. We will as well discuss two extensions/modifications of the scenario, allowing for further couplings and fields. In the first case we will consider the case in which the DM decays into a photon and a new SM singlet, rather than the neutrino. This new state is required to be extremely light, $O(\text{eV})$, and can then contribute to the number of light species N_{eff} which are probed by CMB experiments. We will finally consider the case in which the DM plays the role of a sterile neutrino. Although in this case the line signal is accounted for by the mixing with SM neutrinos, the presence of the scalar field is still relevant since it provides an additional DM generation mechanism and lightens some of the cosmological tensions characteristic of this kind of scenarios.

The paper is organized as follows. In the next section we will briefly review the minimal decaying DM model and investigate the impact on the parameter space of the combined requirement of the agreement with the X-ray signal and of the correct DM relic density. In section 3 and 4, we will then discuss the two simple extensions and finally state our conclusions.

2 Minimal scenario

A very simple and economic scenario of decaying dark matter has been discussed in [50] (see also [52–54]). A Majorana DM particle ψ , singlet with respect to the SM gauge group, features a renormalizable Yukawa type interaction with a scalar field Σ_f , with not trivial SM charges, and a SM fermion, being a lepton or a quark according to the assignment of the quantum numbers of Σ_f :

$$L_{\text{eff}} = \lambda \bar{\psi} f \Sigma_f^\dagger + h.c. . \quad (2.1)$$

In absence of symmetries protecting the DM stability, interactions of the same type are also allowed between Σ_f and two SM fermions (see [51] for a complete list of all the allowed operators), such that the DM can decay into three SM fermions. These kind of processes are already severely constrained by antiproton searches [54, 55] and, more recently, by the measurements by AMS of the positron flux and positron fraction [56]. A photon line can be produced by a DM decay process into a photon and a neutrino, induced at one loop by diagrams like the one reported in figure 1. This kind of process has a sizable branching ratio only when tree-level decays into SM fermions are kinematically forbidden. The energy of the photon emitted per DM decay is simply given, by kinematics, by $E_\gamma = \frac{m_\psi}{2}$. This fixes the DM mass to about 7 keV if one wants to explain the recently observed X-ray line.

This kind of decay occurs only if the following couplings between the scalar field and SM fermions are present:

$$\begin{aligned} L_{\text{eff}} &= \lambda' \bar{d}_R \ell_L \Sigma_q + h.c. & \Sigma_q &= (3, 2, 1/3) \\ L_{\text{eff}} &= \lambda' \bar{\ell}_R^c q_L \Sigma_d^\dagger + h.c. & \Sigma_d &= (3, 1, -2/3) \\ L_{\text{eff}} &= \lambda' \bar{\ell}_R^c \ell_L \Sigma_e^\dagger + h.c. & \Sigma_e &= (1, 1, -2) \\ L_{\text{eff}} &= \lambda' \bar{e}_R \ell_L \Sigma_\ell + h.c. & \Sigma_\ell &= (1, 2, -1) . \end{aligned} \quad (2.2)$$

Besides the ones shown in (2.2) other operators coupling the scalar field with two SM fermions can be in general present but have no impact in the analysis performed in this work, as long

Figure 1. DM 2-body decay into γ and ν with the loop induced by Σ_d .

as they are of the same order of magnitude as or smaller than λ' . We remark however that all these operators violate baryon or lepton number and very severe constraints from proton decay may arise if both these two quantum numbers are violated. We will thus implicitly assume throughout all this work that there is no contemporary presence of operators which violate B and L numbers. We also assume, in analogous fashion as [50, 51], that possible renormalizable couplings of the scalar field with the SM Higgs, not forbidden by gauge interactions, like e.g. $\lambda_{hh\Sigma} |H|^2 |\Sigma_f|^2$, $\lambda_{hh\Sigma} (H\Sigma_{q\ell})^\dagger (H\Sigma_{q\ell})$ are set to zero. This kind of couplings does not affect the relevant processes in this work, since they do not open new decay channels for the scalar field or Dark Matter, but might influence the mass of the scalar field. We will come back to this point in the next sections. In the case of Σ_ℓ -type field only, also a coupling $\lambda_{h\Sigma} H\Sigma_\ell$ (with $\lambda_{h\Sigma}$ being a dimensionful coupling) could arise, which could generate a mixing between the scalar field and the Higgs field and also a non-vanishing v.e.v. for Σ_ℓ . We disregard this possibility in order to keep a single purely Standard-Model-like Higgs field. Note that for what regards DM phenomenology a non-vanishing Σ_ℓ^0 v.e.v. mixes DM with the neutrinos in a very similar way as discussed in section 4.

The decay rate of the DM into a neutrino and a photon is given by [52]:

$$\Gamma(\psi \rightarrow \gamma\nu) = \frac{e^2 m_\psi^3}{2048\pi^5} \left(\sum_i \frac{m_i}{m_{\Sigma_f}^2} \lambda'_i \lambda_i f_1 \left(\frac{m_i^2}{m_{\Sigma_f}^2} \right) \right)^2, \quad \text{where } f_1(x) = \frac{1}{1-x} \left[1 + \frac{1}{1-x} \ln x \right] \quad (2.3)$$

and the sum runs over the fermions flowing inside the loop. We notice that the decay rate depends on the mass of the SM fermion in the loop since a chirality flip in the internal fermion line is required. Unless particular hierarchies in the couplings λ and λ' with respect to the fermion flavors are assumed, the DM decay rate is mostly sensitive to the couplings of Σ_f with third generation fermions. From now on, unless differently stated, we will assume the couplings λ and λ' flavor universal and keep only the contribution of the third generation.

It is straightforward to see that the maximal value of the rate is achieved in the case of a bottom quark running in the loop, since, due to the SM neutrino quantum numbers, it is impossible to construct a loop with an intermediate top quark. Taking $m_b = 4 \text{ GeV}$, the

lifetime of the DM in this case can be estimated as:

$$\tau(\psi \rightarrow \gamma\nu) \simeq 5.6 \times 10^6 \text{ s} \left(\frac{m_\psi}{7 \text{ keV}} \right)^{-3} \left(\frac{m_{\Sigma_f}}{1 \text{ TeV}} \right)^4 (\lambda\lambda')^{-2}. \quad (2.4)$$

By requiring a value of the lifetime of the order 10^{28} s , as expected for the detected photon line, we obtain the condition:

$$\lambda\lambda' \simeq 2.4 \times 10^{-11} \left(\frac{m_\psi}{7 \text{ keV}} \right)^{-3/2} \left(\frac{m_{\Sigma_f}}{1 \text{ TeV}} \right)^2 \left(\frac{\tau(\psi \rightarrow \gamma\nu)}{10^{28} \text{ s}} \right)^{-1/2}. \quad (2.5)$$

As evident the prediction for the value of the product $\lambda\lambda'$ is much higher than the one considered in [50, 51]. This is consequence of the strong sensitivity of the DM lifetime on the DM mass. We can determine the single values of the two couplings λ and λ' by combining eq. (2.5) with the requirement of the correct relic DM relic density. Indeed the latter is determined by a combination of freeze-in [57] and SuperWIMP [58, 59] mechanisms, both relying on the decay of the scalar field into DM, as:

$$\begin{aligned} \Omega_{\text{DM}} h^2 &= \Omega_{\text{DM}}^{\text{FI}} h^2 + \Omega_{\text{DM}}^{\text{SW}} h^2 \\ &\simeq 1.09 \times 10^{27} \frac{g_{\Sigma_f}}{g_*^{3/2}} \frac{m_\psi}{m_{\Sigma_f}} \frac{\Gamma(\Sigma_f \rightarrow f\psi)}{m_{\Sigma_f}} + \frac{m_\psi}{m_{\Sigma_f}} Br(\Sigma_f \rightarrow f\psi) \Omega_{\Sigma_f} h^2, \end{aligned} \quad (2.6)$$

where g_* is the number of relativistic degrees of freedom in the Early Universe at the time of DM production while g_{Σ_f} and Ω_{Σ_f} represent, respectively, the internal degrees of freedom and the abundance at freeze-out of Σ_f . The abundance of the scalar field is fixed by interactions mediated by its gauge couplings and is not influenced by the couplings λ and λ' . As shown in [50], the contribution of the SuperWIMP mechanism is negligible when $m_\psi \ll m_{\Sigma_f}$. It is then possible to directly relate the value of the DM relic density to the coupling λ as:

$$\lambda \simeq 0.8 \times 10^{-8} \left(\frac{m_\psi}{7 \text{ keV}} \right)^{-1/2} \left(\frac{m_{\Sigma_f}}{1 \text{ TeV}} \right)^{1/2} \left(\frac{g_*}{100} \right)^{3/4} \left(\frac{\Omega h^2}{0.11} \right)^{1/2}. \quad (2.7)$$

We remind, since this will turn out to be relevant for the results presented below, that the freeze-in mechanism requires that the DM is out of equilibrium in the Early Universe. This translates into a general upper bound on the coupling λ , responsible for the interactions of the DM, mediated by the scalar field, with the SM particles. As a rule of thumb we can translate this requirement through the condition $\Gamma(\Sigma_f \rightarrow DM)/H < 1$, evaluated at $T = m_{\Sigma_f}$, where H is the Hubble expansion parameter. Assuming, as customarily, radiation domination during the whole phase of DM generation, we can express this condition as:

$$\lambda < \left(\frac{8\pi}{g_{\Sigma_f}} \sqrt{g_*(T = m_{\Sigma_f})} \frac{m_{\Sigma_f}}{M_{\text{pl}}} \right)^{1/2} \approx 0.6 \times 10^{-7} \left(\frac{m_{\Sigma_f}}{1 \text{ TeV}} \right)^{1/2} \quad (2.8)$$

where $M_{\text{pl}} = 1.22 \times 10^{19} \text{ GeV}$ is the Planck mass while g_{Σ_f} represents the number of internal degrees of freedom of the scalar field and for definiteness has been set to $g_{\Sigma_f} = 6$.

For values of λ sensitively above (2.8) the DM would get into thermal equilibrium in the Early Universe and decouple at temperature of the order of m_{Σ_f} , thus while still relativistic. However a relativistic relic with mass of the order of keV would overclose the Universe (the correct relic density is achieved for masses of the order of 100 eV).

Figure 2. Summary plot for the minimal decaying dark matter scenario. The blue solid and dashed lines correspond to the required values of λ' in order to match the experimentally favored DM lifetime for the values of λ given by, respectively, eq. (2.7) (correct DM relic density) and (2.8) (out-of-equilibrium condition). The violet region corresponds to a long-lived scalar field, decaying through displaced vertices or even outside the LHC detector. The gray and yellow regions are excluded by present LHC searches while in light gray we give the expected exclusion in case less than five prompt decays will be detected in the next LHC run after collecting 100 fb^{-1} (see text for details). For reference, we show as well with a brown line the case $\lambda' = \lambda$ and with a green band the case $\lambda' = \tilde{\lambda}$, both relevant in the scenario, described in section 4, where the X-ray line is generated by the coupling of the DM with the SM Higgs and the lepton doublet, given as $\tilde{\lambda} H l$.

Substituting eq. (2.7) into eq. (2.5) we can determine the value of the coupling λ' as:

$$\lambda' \simeq 3 \times 10^{-3} \left(\frac{m_\psi}{7 \text{ keV}} \right)^{-1} \left(\frac{m_{\Sigma_f}}{1 \text{ TeV}} \right)^{3/2} \left(\frac{\tau(\psi \rightarrow \gamma \nu)}{10^{28} \text{ s}} \right)^{-1/2}. \quad (2.9)$$

We note that there is a much stronger hierarchy between the couplings λ and λ' with respect to the one found in [50, 51]. Indeed, in order to compensate the suppression of the decay rate due to the DM mass of the order of keV, we can only increase the coupling λ' since the coupling λ , instead, fixed by the freeze-in mechanism as in eq. (2.7), is a rather slowly varying function of the DM mass and is still very suppressed.

The value of λ' given by (2.9), as function of the mass m_{Σ_f} of the scalar field (taken to be of Σ_d -type as clarified below), has been reported in figure 2. For this value of λ' one obtains a decay length for the scalar field of:

$$l_{\Sigma_f} \simeq 5.6 \times 10^{-11} \text{ cm} \left(\frac{m_\psi}{7 \text{ keV}} \right)^2 \left(\frac{m_{\Sigma_f}}{1 \text{ TeV}} \right)^{-4} \left(\frac{\tau(\psi \rightarrow \gamma \nu)}{10^{28} \text{ s}} \right). \quad (2.10)$$

which implies a scalar field promptly decaying only into SM particles. We remark that, due to the dependence of eq. (2.3) on the internal fermion mass, the value of λ' reported

in (2.9) is the minimal achievable. The conclusion above hence is valid for all the realizations given in (2.2). For this reason we will focus from now on, for definiteness, on the case of Σ_d -type field.

Figure 2 also shows, as dashed blue line, the value of λ' that would be obtained by combining eq. (2.5) with the condition (2.8) of not equilibrium for the DM. As evident, this value is always more than two orders of magnitude higher than the one needed for observable displaced decays (violet region). As consequence, a cosmologically viable scenario compatible with the generation of the observed 3.55 keV line from the decay of DM necessarily implies a strong hierarchy between the couplings λ and λ' , and therefore prompt decays of the scalar field into only SM states. On the other hand we remark that this requirement relies on the assumption of a standard cosmological evolution and can be relaxed in non-standard cosmological scenarios where, for example, entropy injection occurs during the phase of DM generation [60, 61]. The brown line in figure 2 shows instead the scenario with comparable values of the couplings λ and λ' , thus giving, for $m_{\Sigma_d} \gtrsim 750(1300)$ at $\sqrt{s} = 7(14)$ TeV, a long-lived (on detector scales) scalar field, with both types of decay channels, namely DM+SM and only SM, potentially observable at the LHC. Note that such case corresponds to a DM lifetime of the order of $O(10^{38})$ s which is incompatible with the observed X-ray line and far beyond the sensitivity of next future ID experiments.

Contrary to the scenarios discussed in [50, 51], for the case of keV DM, cosmological viability enforces the prediction of a promptly decaying scalar field with at least two possible decay channels into a third generation quark and a neutrino or a charged lepton, arising through the same coupling constant λ' . Conventional constraints from LHC searches then apply. In the case, under consideration, of a color charged scalar field the relevant bounds come from searches of leptoquarks. The most severe limits have been, at the moment, set by CMS excluding for the scenario under consideration masses of the scalar field below approximately 840 GeV [62]. This limit is relaxed down to 740 GeV [63] if coupling with only third generation fermions is assumed. We have determined, according to these limits, the excluded region in the plane (m_{Σ_f}, λ') (the coupling λ has been set by requiring the correct DM relic density as in eq. (2.7)), focussing for simplicity on the case of coupling between the scalar and only third generation fermions, by simulating through the package Madgraph [64, 65] the pair production of the scalar field Σ_d and subsequently determining the spatial distribution of the decay events and considering the detector efficiency, as function of m_{Σ_d} , reported in [63]. In order to apply LHC searches of prompt decays we have imposed the detection of at least 5 events, corresponding to the expected signal for a leptoquark with mass of 750 GeV, before the pixel region of the detector (see [51, 66] for details). The excluded region determined through this procedure corresponds to the dark gray region in figure 2 and, as can be noticed, is in good agreement with the experimental exclusion as regards the mass of Σ_d . It extends down to values of $\lambda' \approx 10^{-(7 \div 8)}$ (the coupling λ has been kept fixed according to eq. 2.7). At lower values of λ' leptoquark searches are complemented by searches for metastable particles [67, 68], shown in yellow in figure 2. An analogous analysis can be done for the case of only electroweakly interacting scalar field. The most suitable searches for this scenario are the ones of supersymmetric particles decaying into leptons and missing energy. From these one can infer a lower limit on the mass of the scalar as $m_{\Sigma_{\ell,e}} > 160 - 200$ GeV [69–72].

We have in addition determined the expected sensitivity for next LHC run at 14 TeV of centre of mass energy and for a luminosity of 100 fb^{-1} . We have thus generated pair production events of Σ_d , assuming the same experimental efficiency as in the 8 TeV searches

and requiring again at least 5 detected events. The region of sensitivity of future searches is reported as a light gray region in figure (2). Note that those searches for prompt decays can probe arbitrary low values of λ' , since even for negligibly small λ' , there is a substantial decay rate set by the coupling λ , given by (2.7). Although for this value of the coupling, the naive expectation, i.e $l_{\Sigma_f} = c\tau_{\Sigma_f}$, of the decay length corresponds to displaced vertices, as shown in figure 2 by the brown line, it is near to the boundary with prompt decays and once the proper statistical distribution of the decay events is taken into account, a residual number of prompt decays, within the reach of experimental searches, is nonetheless present. This does not occur for larger DM masses, as studied in [50, 51], since there the value of λ is several orders of magnitude below that considered here and guarantees the absence of observable prompt decays. The LHC searches in the next run will then probe masses of Σ_d up to approximately 1400 GeV (a higher mass reach can be achieved by considering a high luminosity upgrade of LHC with $O(1000) \text{ fb}^{-1}$ of luminosity), covering a wider parameter region compared to that where the X-ray line can be explained by DM decay.

As evident in the discussion, also for a keV DM the combined requirement of an ID DM signal and the correct relic density establishes rather definite prospects for an eventual LHC detection of the scalar field. We might then ask whether an hypothetical LHC detection, combined with the X-ray signal, allows an unambiguous determination of the relevant parameters and a clear discrimination with respect to other particle physics models. The clearest LHC signature would be the contemporary detection of the two different kinds of decay channel of the scalar field, through the couplings λ and λ' . Unfortunately this result is not achievable since, as we can see from eq. (2.7) and (2.9), the decay channel into DM has a too suppressed branching ratio to be observable. A possibility of inferring the parameters of the model would nonetheless occur if the LHC detection of the decay into two SM fermions would allow the reconstruction of the mass of the scalar field and the measurement of its lifetime. Indeed these two information, combined with the ID of the X-ray line, which provides the DM mass and the value of $\lambda\lambda'$, as function of m_{Σ_f} , would allow the individual determination of the parameter λ , which could be used to test the FIMP paradigm. This task is however very challenging since the coupling (2.9) corresponds to a decay width of the order of few MeVs, which is much below the resolution, $O(\text{GeV})$, of the LHC detector. It has been shown anyway e.g. in [73] that it is in principle possible to probe decay widths below these energy resolutions. Although most probably values of the order of (2.9) are accessible only to precision machines like linear colliders [74, 75], LHC measurements can potentially set upper bounds down to approximately one order of magnitude above the expected value. In addition one could adopt a similar procedure to the one used for determining the exclusion region from leptoquark searches looking for the presence of residual displaced vertices in the case of mostly promptly decaying states. Non observation of these events would also allow to set a lower bound on λ' which, combined with the previous upper bound, could determine a window of allowed values of λ to be compared with the value needed for FIMP production testing its viability. On the contrary the observation of displaced vertices could be translated into a strong upper bound on λ' which might possibly rule out our cosmological framework.

We remark that the picture depicted above is strictly valid only in the case if the scalar field is a SU(2) singlet. In the doublet case we are implicitly assuming that the two components are exactly degenerate in mass. If this is not the case additional signals originated by the production and decay of the heavier components might results detectable. In particular we would have decays into the lighter component and a W boson (either on- or off-shell). These processes are determined by gauge interactions and cannot be directly

Figure 3. Diagrams contributing at one-loop to the DM 2-body decay into γ and χ induced by scalar-mixing.

related to DM phenomenology. This issue is particularly relevant in the case of Σ_ℓ -type fields since the dominant production process is, in general, $pp \rightarrow \Sigma_\ell^0 \Sigma_\ell^\pm$, where Σ_ℓ^0 and $\Sigma_\ell^\pm$ are, respectively, the charged and the neutral component of the doublet.

3 Dark matter and dark radiation scenario

In this section we discuss an extension of the minimal decaying DM scenario in which the spectrum of BSM states is augmented with another SM singlet χ and the scalar spectrum is constituted by two fields, a SU(2) doublet and a singlet. The photon line is now produced by the decay $\psi \rightarrow \chi\gamma$ (see figure 3) and it is described by the following lagrangian:

$$\begin{aligned}
L_{\text{eff}} = & \left(\lambda_L \bar{\psi} q_L \Sigma_q^\dagger + \lambda_R \bar{\psi} t_R \Sigma_u^\dagger \right) + h.c. \\
& + \left(\lambda'_L \bar{\chi} q_L \Sigma_q^\dagger + \lambda'_R \bar{\chi} t_R \Sigma_u^\dagger + h.c. \right) \\
& + \mu H \Sigma_\sigma \Sigma_\sigma^\dagger + h.c. .
\end{aligned} \tag{3.1}$$

We have assigned to the two scalar fields the quantum numbers of a left-handed and right-handed up-quark in order to enhance the loop function through the top mass and possibly achieve the desired value of the DM lifetime for suppressed couplings, such that the scalar fields are long-lived at the LHC. Given the strong sensitivity of the DM lifetime on the SM fermion masses, we have assumed for simplicity that the two SM singlets χ and ψ are coupled only with third generation quarks. The couplings of the scalar field with only SM fermions, which we have omitted for simplicity, are not relevant for the DM decay and then can be set to be of comparable value to the couplings governing the decay of the scalar field into DM.

In this case after electroweak symmetry breaking the fields Σ_q, Σ_u mix and the physical fields are instead $\Sigma_{1,2}$, the eigenstates of the mass matrix:

$$\mathcal{M} = \begin{pmatrix} m_{\Sigma_u}^2 & \mu v \\ \mu v & m_{\Sigma_s}^2 \end{pmatrix}, \quad (3.2)$$

where v is the v.e.v. of the Higgs field. $\mathcal{M}$ has eigenvalues

$$m_{\Sigma_{1,2}}^2 = \frac{1}{2} \left(m_{\Sigma_q}^2 + m_{\Sigma_u}^2 \mp \sqrt{\left(m_{\Sigma_q}^2 - m_{\Sigma_u}^2 \right)^2 + 4v^2\mu^2} \right) \quad (3.3)$$

and is diagonalized through the generic matrix:

$$\eta = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \quad (3.4)$$

where the mixing angle is given by

$$\tan 2\theta = \frac{2\mu v}{m_{\Sigma_q}^2 - m_{\Sigma_u}^2}. \quad (3.5)$$

In the expressions above m_{Σ_q} and m_{Σ_u} represent the mass terms of the SU(2) doublet and singlets. These are assumed to be originated by conventional mass terms of the form $m_{\Sigma_{q,u}}^2 \Sigma_{q,u}^\dagger \Sigma_{q,u}$. As already mentioned, additional mass terms can be originated by terms, allowed by gauge symmetries, of the type $\lambda_{hh\Sigma\Sigma} |H|^2 |\Sigma_{q,u}|^2$ and/or $\lambda_{hh\Sigma\Sigma} (H\Sigma_q)^\dagger (H\Sigma_q)$ whose contributions are $O(100\text{GeV})$ for couplings of order one and we expect them to be subleading compared to that proportional to the dimensionful quantity μ since they do not mix the two states and just change $m_{\Sigma_{u,d}}$. A theoretical investigation of the scalar sector of the theory is beyond the scope of this work; our results will be thus expressed in terms of the mass eigenstates m_{Σ_1} and m_{Σ_2} , assumed to be free parameters, and we will regard (3.2) and (3.4) as a generic parametrization.

The DM decay rate is then given by:

$$\begin{aligned} \Gamma(\psi \rightarrow \chi\gamma) = & \frac{\alpha m_\psi^3}{32\pi^4} \left(1 - \frac{m_\chi^2}{m_\psi^2} \right)^3 \\ & \left[m_t \sin \theta \cos \theta \left(\lambda_L \lambda'_R - \lambda_R \lambda'_L \right) \left(\frac{1}{m_{\Sigma_1}^2} f_1 \left(\frac{m_t^2}{m_{\Sigma_1}^2} \right) - \frac{1}{m_{\Sigma_2}^2} f_1 \left(\frac{m_t^2}{m_{\Sigma_2}^2} \right) \right) \right. \\ & \left. - \frac{1}{4} (m_\psi - m_\chi) \left(\lambda_L \lambda'_L - \lambda_R \lambda'_R \right) \left(\frac{\sin^2 \theta}{m_{\Sigma_1}^2} f_2 \left(\frac{m_t^2}{m_{\Sigma_1}^2} \right) + \frac{\cos^2 \theta}{m_{\Sigma_2}^2} f_2 \left(\frac{m_t^2}{m_{\Sigma_2}^2} \right) \right) \right]^2, \end{aligned}$$

where $f_2(x) = \frac{1}{(1-x)^2} \left[1 + x + \frac{2x}{1-x} \ln x \right]$. (3.6)

The term inside the square bracket in the DM decay rate is maximized for $\theta = \frac{\pi}{4}$, i.e. $m_{\Sigma_q}^2 - m_{\Sigma_u}^2 = 0$, and $\lambda_L = \lambda, \lambda_R = 0, \lambda'_L = 0, \lambda'_R = \lambda'$ (or vice versa). For substantial mass splitting, the DM lifetime is mostly determined by the contribution from the lightest eigenstate in that case.

Neglecting the mass of χ (the reason will be clarified in the following) it can be expressed as:

$$\tau(\psi \rightarrow \chi\gamma) \simeq 1.4 \times 10^4 \text{ s} \left(\frac{m_\psi}{7 \text{ keV}} \right)^{-3} \left(\frac{m_{\Sigma_1}}{1 \text{ TeV}} \right)^4 (\lambda\lambda')^{-2}. \quad (3.7)$$

The DM production is as well dominated by Σ_1 and λ is again determined by eq. (2.7). The expected value of λ' from the combined requirement of reproducing the photon-line and the correct DM relic density is:

$$\lambda' \simeq 1.5 \times 10^{-4} \left(\frac{m_\psi}{7 \text{ keV}} \right)^{-1} \left(\frac{m_{\Sigma_1}}{1 \text{ TeV}} \right)^{3/2}. \quad (3.8)$$

Figure 4. The same as figure 2 but for the DM+Dark Radiation scenario. We give here as red solid and dashed lines the values of the coupling λ' corresponding to the right DM lifetime and FIMP production and to the out-of-equilibrium condition respectively. The other lines are as in figure 2. Notice that the limits and the future sensitivity for prompt decays refer here to searches for supersymmetric top partners decaying into top quarks and missing energy.

This value, although sensitively lower than the one obtained in the previous case, is still large enough to make the scalar field decay promptly at the LHC. Note that if instead the mass eigenstates are nearly degenerate, a partial cancellation between the two contribution takes place and therefore larger couplings are required to match the same lifetime. Being substantially free parameters, the couplings of the scalar field with only SM fermions can be of comparable order as (3.8) in order to allow for the observation of a double LHC signal. Dealing with prompt decays one has anyway to cope already with strong limits from LHC searches. The most stringent ones come from searches of top squarks. Current limits allow $177 \lesssim m_{\Sigma_1} \lesssim 200 \text{ GeV}$ or $m_{\Sigma_1} > 750 \text{ GeV}$ [76–78]. This value can be actually relaxed in presence of a branching ratio of decay into missing energy lower than 1.

We have compared, analogously to what done in the previous section, in figure 4 the prospects of LHC detection with the information from DM phenomenology. The scenario depicted is analogous to the minimal scenario of the previous section with the (standard) cosmology strongly preferring prompt decays. Despite the different experimental signature (top plus missing energy) the prospects of hypothetical LHC detection are as well very similar to the previous scenario. On the other hand, within the assumption of no extra symmetries with respect to the SM, a coupling between the scalar field and only SM fermions is allowed and can be of the same order as λ' , providing then two types of decays and signatures (low and high amount of missing energy) for the scalar field. As already mentioned in the previous section, this discussion is strictly valid under the assumption that LHC phenomenology is dominated by a single heavy charged state. In case also the heavier mass eigenstate Σ_2 is

efficiently produced we would have additional signals like the one studied in [79] which could not be directly correlated with DM signals. We remind, on the other hand, that the two scalar fields Σ_q and Σ_u are mostly produced at the LHC through gluon fusion and their production cross-section is strongly sensitive to the mass of the pair produced state. Our scenario requires a sizable value of μv , in order not to suppress the mixing angle, implying a sizable mass splitting between the two mass eigenstates Σ_1 and Σ_2 . The assumption that the dominant LHC signals are mostly related to Σ_1 appears thus reasonable.

Notice also that the state χ is cosmologically stable if it is very light and might exist in sizable numbers contributing to the overall DM abundance. Indeed, contrary to the case of ψ , the value of the coupling λ' is high enough to create, at early stages of the history of the Universe, a thermal population of χ particles through decays/inverse decays of the scalar fields and $2 \rightarrow 2$ scattering processes with top quarks. χ particles then undergo a relativistic freeze-out at temperatures between 100 GeV and 1 TeV. In order to avoid bounds from overclosure of the Universe and structure formation we impose a very small mass for this new state, $m_\chi \lesssim O(\text{eV})$. Such light state would then remain relativistic for a long time and contribute to the number of effective neutrinos N_{eff} . The deviation from the SM prediction $N_{\text{eff}} = 3.046$ induced by the χ particles can be expressed as [80, 81]:

$$\Delta N_{\text{eff}} = \frac{23.73}{(g_*^s(T_d))^{4/3}}, \quad (3.9)$$

where T_d represents the decoupling temperature from the primordial thermal bath of the χ particles. Thanks to the rather high decoupling temperature, we have $g_*^s(T_d) \sim 100$ due to Standard Model states and therefore $\Delta N_{\text{eff}} \sim 0.05$, which is compatible with the current constraints [82]. Such a small contribution to the number of relativistic species is unfortunately at the boundary of detection even for an ideal CMB experiment including polarization [83].

We also remark the direct correlation of the X-ray signal with the presence of one of the SM singlets in our scenario in thermal equilibrium. Indeed, in order to ensure the desired lifetime of the DM we need $\lambda\lambda' \sim 10^{-12}$. Comparing this value with eq. (2.8) we notice that the two couplings cannot contemporarily satisfy the out-of-equilibrium condition.

4 DM as sterile neutrino

Another very simple way to reproduce the 3.55 keV line is to allow for a coupling with the Higgs boson and a SM neutrinos of the form $\tilde{\lambda}\bar{\psi}H\ell$, where for simplicity we have suppressed generation indices, thus identifying DM with a sterile right-handed neutrino. In this case the radiative decay of DM is achieved, irrespectively of couplings and mass of the scalar field, through loops involving charged leptons and the W boson, as shown in figure 5.

The decay rate of the DM is given by [84]:

$$\Gamma(\psi \rightarrow \nu\gamma) = \frac{9\alpha G_F^2 m_\psi^5}{256 4\pi^4} \sin^2 2\Theta, \quad (4.1)$$

where $\Theta = \frac{\tilde{\lambda}v}{m_\psi}$. The required value of the DM lifetime is obtained for $\sin^2 2\Theta = 2 - 20 \times 10^{-11}$ which corresponds to $\tilde{\lambda} \simeq 10^{-13}$.

Although the scalar field is not responsible for the radiative decay of the DM, its presence is anyway relevant for the DM production. As already shown for instance in [71, 85–88],

Figure 5. Diagrams contributing at one-loop to the DM 2-body decay into γ and ν induced by W .

the decay of an extra field provides a simple and economical mechanism for the production of sterile neutrinos with a low value of mixing angle with active neutrinos compatible with DM Indirect Detection. Indeed, the conventional, non-resonant, production through oscillations from active neutrinos, known as the Dodelson-Widrow mechanism [89], can provide no more than 1% of the DM relic density for the values of the parameters accounting for the present X -ray signal, and its resonant enhancement [90] requires the presence of a very large lepton asymmetry at low temperatures, which it is not trivial to achieve in realistic scenarios [91]. The LHC phenomenology depends on the size of eventual couplings between the scalar field Σ_f with only SM fields. These kinds of couplings are completely uncorrelated to DM phenomenology and are constrained only by the assumption that they do not contribute substantially to the DM decay nor allow for fast proton decay. The most interesting case is therefore when their value is suppressed and, as could be argued for example by a common generation mechanisms, is comparable with the one of the other couplings either $\tilde{\lambda}$ or λ fixed as in eq. (2.7). In such a case we would expect an LHC-metastable Σ field, whose prospects of detection have extensively discussed in [51]. Such a scenario is shown in figure 2 and 4 as the brown line and the green band respectively.

Before stating our conclusions we will mention possible additional constraints coming from structure formation (these are actually customarily discussed in sterile neutrino scenarios but most of the arguments can be straightforwardly extended to generic particle physics frameworks, including the one discussed in this work). Indeed DM with mass at the keV scale is conventionally considered as warm dark matter. The viability of warm DM candidates, as opposed to cold dark matter, is currently tested through rather different strategies, typically leading to lower limits on the DM mass. Interestingly the degree of “warmness” of the DM depends on its momentum distribution function which in turn is determined by its production mechanism. It is then possible, potentially, to exploit the bounds from structure formation to constrain the particular freeze-in production mechanism, and exclude scenarios that produce too warm DM.

Although several studies have determined the DM momentum distribution function for particles produced through freeze-in [85, 92] and, more in general, from the decay of a scalar field with different cosmological histories [93, 94], no quantitative analysis of structure formation for this kind of scenarios have been performed yet. As shown e.g. in [85, 92], for the same DM mass, DM produced by freeze-in has a lower average momentum with respect

to a thermal relic (by a factor $\simeq 0.77$) or a sterile neutrino arising from the DW mechanism (by approximately 0.27). A lower average momentum can be interpreted as a “colder” DM momentum distribution; as consequence it is customarily stated that DM produced from decay is more weakly constrained by structure formation bounds. Since recent bounds on the mass of WDM for thermal relics are around 3 keV [95], a FIMP Dark Matter candidate of mass around 7 keV is still perfectly viable.¹ Nevertheless a definitive word on the viability and especially on the detectability of a 7 keV FIMP DM compared to an analogous thermal relic requires dedicated numerical simulations.

5 Conclusions

We have here considered the possibility of reproducing the 3.55 keV X-ray line signal in few simple decaying DM scenarios. In the minimal realization, namely the extension of the SM with a DM Majorana fermion and a single scalar field at the TeV scale, it is possible to produce the right abundance of DM and obtain the correct DM lifetime for reasonable values of the couplings λ and λ' . The model then predicts prompt decays of the colored Σ_f scalar at LHC though the larger coupling λ' in only Standard Model states. Even if the second decay channel of Σ_f is too suppressed to be observable at LHC, the scenario can be tested and even excluded, if no prompt decays are observed, up to masses of the colored scalar field of about 1400 GeV. Moreover in case of a detection, the parameters of the model can be restricted by a combination of the Indirect Detection and LHC measurements and the assumption of freeze-in production for DM can be in principle tested.

We tried to see if it is possible to lower the λ' coupling and enhance the possibility to measure both decay channels at the LHC. Unfortunately this turned out to be not so simple to achieve. Enlarging the Dark Matter and Σ_f sector to have a top particle in the loop does allow for a wider range of possible λ' couplings, but does not modify strongly the hierarchy between λ' and λ . In this extended model DM decays into a photon and an extremely light SM singlet, which can affect the number of cosmological relativistic degrees of freedom N_{eff} and in an optimistic case perhaps be detected in the CMB. In this case the couplings between the Σ_f fields and purely SM fields are not fixed by the DM lifetime and the phenomenology strongly depends on their values. Indeed, if they are comparable to the coupling of the scalar with the new singlet fermion χ , the scalar Σ could decay promptly at the LHC in the two channels. Then it may be possible to contemporarily observe prompt decays into top quark and missing energy as well as decays into only SM states and determine again most of the parameters of the model. On the other hand, if the couplings of the Σ_f fields with only SM fields are of the order of the freeze-in coupling λ , the scenario will be difficult to disentangle at the LHC, since the singlet fermion χ could appear as a possible DM candidate.

We have finally considered the case in which the DM has the additional coupling to the Higgs field and a SM neutrino, similarly to a sterile neutrino. The DM lifetime is determined only by the new mixing, but the coupling of DM with the SM-charged field Σ_f can help in obtaining the right DM abundance. In this last case, if also the couplings of Σ_f to SM fields are of similar size to λ , a detection of both Σ_f decays through displaced vertices could be possible at the LHC and allow to disentangle this scenario from a pure sterile neutrino.

¹But some tension has been found for FIMP produced DM in the keV range in a very recent study [94].

Acknowledgments

The authors thank Asmaa Abada, Torsten Bringmann and Ninetta Saviano for their useful comments and suggestions and Michele Frigerio for the update on the LHC bounds. G.A. thanks the Institute for Theoretical Physics of the Georg-August University Göttingen for the warm hospitality during part of the completion of this work.

G.A. acknowledges support from the ERC advanced grant Higgs@LHC. The authors acknowledge partial support from the European Union FP7 ITN-INVISIBLES (Marie Curie Actions, PITN-GA-2011-289442).

References

- [1] XENON100 collaboration, E. Aprile et al., *Dark Matter Results from 225 Live Days of XENON100 Data*, *Phys. Rev. Lett.* **109** (2012) 181301 [[arXiv:1207.5988](#)] [[INSPIRE](#)].
- [2] XENON100 collaboration, E. Aprile et al., *Limits on spin-dependent WIMP-nucleon cross sections from 225 live days of XENON100 data*, *Phys. Rev. Lett.* **111** (2013) 021301 [[arXiv:1301.6620](#)] [[INSPIRE](#)].
- [3] LUX collaboration, D.S. Akerib et al., *First results from the LUX dark matter experiment at the Sanford Underground Research Facility*, *Phys. Rev. Lett.* **112** (2014) 091303 [[arXiv:1310.8214](#)] [[INSPIRE](#)].
- [4] FERMI-LAT collaboration, G. Zaharijas, J. Conrad, A. Cuoco and Z. Yang, *Fermi-LAT measurement of the diffuse gamma-ray emission and constraints on the Galactic Dark Matter signal*, *Nucl. Phys. Proc. Suppl.* **239-240** (2013) 88 [[arXiv:1212.6755](#)] [[INSPIRE](#)].
- [5] FERMI-LAT collaboration, M. Ackermann et al., *Constraining Dark Matter Models from a Combined Analysis of Milky Way Satellites with the Fermi Large Area Telescope*, *Phys. Rev. Lett.* **107** (2011) 241302 [[arXiv:1108.3546](#)] [[INSPIRE](#)].
- [6] A. Morselli, *Fermi large area telescope results: The sky at high energies and the quest for dark matter signals*, *Acta Phys. Polon.* **B 43** (2012) 2187 [[INSPIRE](#)].
- [7] AMS collaboration, M. Aguilar et al., *First Result from the Alpha Magnetic Spectrometer on the International Space Station: Precision Measurement of the Positron Fraction in Primary Cosmic Rays of 0.5 – 350 GeV*, *Phys. Rev. Lett.* **110** (2013) 141102 [[INSPIRE](#)].
- [8] J.W. den Herder et al., *The Search for decaying Dark Matter*, [arXiv:0906.1788](#) [[INSPIRE](#)].
- [9] E. Bulbul, M. Markevitch, A. Foster, R.K. Smith, M. Loewenstein and S.W. Randall, *Detection of An Unidentified Emission Line in the Stacked X-ray spectrum of Galaxy Clusters*, *Astrophys. J.* **789** (2014) 13 [[arXiv:1402.2301](#)] [[INSPIRE](#)].
- [10] A. Boyarsky, O. Ruchayskiy, D. Iakubovskiy and J. Franse, *Unidentified Line in X-Ray Spectra of the Andromeda Galaxy and Perseus Galaxy Cluster*, *Phys. Rev. Lett.* **113** (2014) 251301 [[arXiv:1402.4119](#)] [[INSPIRE](#)].
- [11] K.N. Abazajian, *Resonantly Produced 7 keV Sterile Neutrino Dark Matter Models and the Properties of Milky Way Satellites*, *Phys. Rev. Lett.* **112** (2014) 161303 [[arXiv:1403.0954](#)] [[INSPIRE](#)].
- [12] S. Baek and H. Okada, *7 keV Dark Matter as X-ray Line Signal in Radiative Neutrino Model*, [arXiv:1403.1710](#) [[INSPIRE](#)].
- [13] S. Patra, N. Sahoo and N. Sahu, *Dipolar dark matter in light of the 3.5 keV x-ray line, neutrino mass and LUX data*, *Phys. Rev. D* **91** (2015) 115013 [[arXiv:1412.4253](#)] [[INSPIRE](#)].
- [14] T. Tsuyuki, *Neutrino masses, leptogenesis and sterile neutrino dark matter*, *Phys. Rev. D* **90** (2014) 013007 [[arXiv:1403.5053](#)] [[INSPIRE](#)].

- [15] S.K. Kang and A. Patra, *keV Sterile Neutrino Dark Matter and Low Scale Leptogenesis*, [arXiv:1412.4899](#) [INSPIRE].
- [16] H. Okada and T. Toma, *3.55 keV X-ray Line Signal from Excited Dark Matter in Radiative Neutrino Model*, *Phys. Lett. B* **737** (2014) 162 [[arXiv:1404.4795](#)] [INSPIRE].
- [17] J.M. Cline, Y. Farzan, Z. Liu, G.D. Moore and W. Xue, *3.5 keV X-rays as the “21 cm line” of dark atoms and a link to light sterile neutrinos*, *Phys. Rev. D* **89** (2014) 121302 [[arXiv:1404.3729](#)] [INSPIRE].
- [18] K.P. Modak, *3.5 keV X-ray Line Signal from Decay of Right-Handed Neutrino due to Transition Magnetic Moment*, *JHEP* **03** (2015) 064 [[arXiv:1404.3676](#)] [INSPIRE].
- [19] R. Allahverdi, B. Dutta and Y. Gao, *keV Photon Emission from Light Nonthermal Dark Matter*, *Phys. Rev. D* **89** (2014) 127305 [[arXiv:1403.5717](#)] [INSPIRE].
- [20] D.J. Robinson and Y. Tsai, *Dynamical framework for KeV Dirac neutrino warm dark matter*, *Phys. Rev. D* **90** (2014) 045030 [[arXiv:1404.7118](#)] [INSPIRE].
- [21] W. Rodejohann and H. Zhang, *Signatures of Extra Dimensional Sterile Neutrinos*, *Phys. Lett. B* **737** (2014) 81 [[arXiv:1407.2739](#)] [INSPIRE].
- [22] N. Haba, H. Ishida and R. Takahashi, *ν_R dark matter-philic Higgs for 3.5 keV X-ray signal*, *Phys. Lett. B* **743** (2015) 35 [[arXiv:1407.6827](#)] [INSPIRE].
- [23] T. Higaki, K.S. Jeong and F. Takahashi, *The 7 keV axion dark matter and the X-ray line signal*, *Phys. Lett. B* **733** (2014) 25 [[arXiv:1402.6965](#)] [INSPIRE].
- [24] D.P. Finkbeiner and N. Weiner, *An X-Ray Line from eXciting Dark Matter*, [arXiv:1402.6671](#) [INSPIRE].
- [25] J. Jaeckel, J. Redondo and A. Ringwald, *3.55 keV hint for decaying axionlike particle dark matter*, *Phys. Rev. D* **89** (2014) 103511 [[arXiv:1402.7335](#)] [INSPIRE].
- [26] H.M. Lee, *Magnetic dark matter for the X-ray line at 3.55 keV*, *Phys. Lett. B* **738** (2014) 118 [[arXiv:1404.5446](#)] [INSPIRE].
- [27] M. Cicoli, J.P. Conlon, M.C.D. Marsh and M. Rummel, *3.55 keV photon line and its morphology from a 3.55 keV axionlike particle line*, *Phys. Rev. D* **90** (2014) 023540 [[arXiv:1403.2370](#)] [INSPIRE].
- [28] S.P. Liew, *Axino dark matter in light of an anomalous X-ray line*, *JCAP* **05** (2014) 044 [[arXiv:1403.6621](#)] [INSPIRE].
- [29] J.-C. Park, S.C. Park and K. Kong, *X-ray line signal from 7 keV axino dark matter decay*, *Phys. Lett. B* **733** (2014) 217 [[arXiv:1403.1536](#)] [INSPIRE].
- [30] K.-Y. Choi and O. Seto, *X-ray line signal from decaying axino warm dark matter*, *Phys. Lett. B* **735** (2014) 92 [[arXiv:1403.1782](#)] [INSPIRE].
- [31] J.P. Conlon and A.J. Powell, *A 3.55 keV line from $DM \rightarrow a \rightarrow \gamma$: predictions for cool-core and non-cool-core clusters*, *JCAP* **01** (2015) 019 [[arXiv:1406.5518](#)] [INSPIRE].
- [32] N.E. Bomark and L. Roszkowski, *3.5 keV x-ray line from decaying gravitino dark matter*, *Phys. Rev. D* **90** (2014) 011701 [[arXiv:1403.6503](#)] [INSPIRE].
- [33] S.V. Demidov and D.S. Gorbunov, *SUSY in the sky or a keV signature of sub-GeV gravitino dark matter*, *Phys. Rev. D* **90** (2014) 035014 [[arXiv:1404.1339](#)] [INSPIRE].
- [34] K. Nakayama, F. Takahashi and T.T. Yanagida, *The 3.5 keV X-ray line signal from decaying moduli with low cutoff scale*, *Phys. Lett. B* **735** (2014) 338 [[arXiv:1403.1733](#)] [INSPIRE].
- [35] C.-W. Chiang and T. Yamada, *3.5 keV X-ray line from nearly-degenerate WIMP dark matter decays*, *JHEP* **09** (2014) 006 [[arXiv:1407.0460](#)] [INSPIRE].

- [36] B. Shuve and I. Yavin, *Dark matter progenitor: Light vector boson decay into sterile neutrinos*, *Phys. Rev. D* **89** (2014) 113004 [[arXiv:1403.2727](#)] [[INSPIRE](#)].
- [37] C. Kolda and J. Unwin, *X-ray lines from R-parity violating decays of keV sparticles*, *Phys. Rev. D* **90** (2014) 023535 [[arXiv:1403.5580](#)] [[INSPIRE](#)].
- [38] B. Dutta, I. Gogoladze, R. Khalid and Q. Shafi, *3.5 keV X-ray line and R-Parity Conserving Supersymmetry*, *JHEP* **11** (2014) 018 [[arXiv:1407.0863](#)] [[INSPIRE](#)].
- [39] F.S. Queiroz and K. Sinha, *The Poker Face of the Majoron Dark Matter Model: LUX to keV Line*, *Phys. Lett. B* **735** (2014) 69 [[arXiv:1404.1400](#)] [[INSPIRE](#)].
- [40] C.-Q. Geng, D. Huang and L.-H. Tsai, *X-ray Line from the Dark Transition Electric Dipole*, *JHEP* **08** (2014) 086 [[arXiv:1406.6481](#)] [[INSPIRE](#)].
- [41] J.M. Cline and A.R. Frey, *Nonabelian dark matter models for 3.5 keV X-rays*, *JCAP* **10** (2014) 013 [[arXiv:1408.0233](#)] [[INSPIRE](#)].
- [42] R. Krall, M. Reece and T. Roxlo, *Effective field theory and keV lines from dark matter*, *JCAP* **09** (2014) 007 [[arXiv:1403.1240](#)] [[INSPIRE](#)].
- [43] A. Falkowski, Y. Hochberg and J.T. Ruderman, *Displaced Vertices from X-ray Lines*, *JHEP* **11** (2014) 140 [[arXiv:1409.2872](#)] [[INSPIRE](#)].
- [44] S. Baek, P. Ko and W.-I. Park, *The 3.5 keV X-ray line signature from annihilating and decaying dark matter in Weinberg model*, [arXiv:1405.3730](#) [[INSPIRE](#)].
- [45] E. Dudas, L. Heurtier and Y. Mambrini, *Generating X-ray lines from annihilating dark matter*, *Phys. Rev. D* **90** (2014) 035002 [[arXiv:1404.1927](#)] [[INSPIRE](#)].
- [46] T.E. Jeltema and S. Profumo, *Discovery of a 3.5 keV line in the Galactic Center and a Critical Look at the Origin of the Line Across Astronomical Targets*, *Mon. Not. Roy. Astron. Soc.* **450** (2015) 2143 [[arXiv:1408.1699](#)] [[INSPIRE](#)].
- [47] E. Carlson, T. Jeltema and S. Profumo, *Where do the 3.5 keV photons come from? A morphological study of the Galactic Center and of Perseus*, *JCAP* **02** (2015) 009 [[arXiv:1411.1758](#)] [[INSPIRE](#)].
- [48] D. Malyshev, A. Neronov and D. Eckert, *Constraints on 3.55 keV line emission from stacked observations of dwarf spheroidal galaxies*, *Phys. Rev. D* **90** (2014) 103506 [[arXiv:1408.3531](#)] [[INSPIRE](#)].
- [49] M.E. Anderson, E. Churazov and J.N. Bregman, *Non-Detection of X-Ray Emission From Sterile Neutrinos in Stacked Galaxy Spectra*, [arXiv:1408.4115](#) [[INSPIRE](#)].
- [50] G. Arcadi and L. Covi, *Minimal Decaying Dark Matter and the LHC*, *JCAP* **08** (2013) 005 [[arXiv:1305.6587](#)] [[INSPIRE](#)].
- [51] G. Arcadi, L. Covi and F. Dradi, *LHC prospects for minimal decaying Dark Matter*, *JCAP* **10** (2014) 063 [[arXiv:1408.1005](#)] [[INSPIRE](#)].
- [52] M. Garny, A. Ibarra, D. Tran and C. Weniger, *Gamma-Ray Lines from Radiative Dark Matter Decay*, *JCAP* **01** (2011) 032 [[arXiv:1011.3786](#)] [[INSPIRE](#)].
- [53] M. Garny, A. Ibarra and S. Vogl, *Dark matter annihilations into two light fermions and one gauge boson: General analysis and antiproton constraints*, *JCAP* **04** (2012) 033 [[arXiv:1112.5155](#)] [[INSPIRE](#)].
- [54] M. Garny, A. Ibarra and D. Tran, *Constraints on Hadronically Decaying Dark Matter*, *JCAP* **08** (2012) 025 [[arXiv:1205.6783](#)] [[INSPIRE](#)].
- [55] N. Fornengo, L. Maccione and A. Vittino, *Constraints on particle dark matter from cosmic-ray antiprotons*, *JCAP* **04** (2014) 003 [[arXiv:1312.3579](#)] [[INSPIRE](#)].

- [56] A. Ibarra, A.S. Lamperstorfer and J. Silk, *Dark matter annihilations and decays after the AMS-02 positron measurements*, *Phys. Rev. D* **89** (2014) 063539 [[arXiv:1309.2570](#)] [[INSPIRE](#)].
- [57] L.J. Hall, K. Jedamzik, J. March-Russell and S.M. West, *Freeze-In Production of FIMP Dark Matter*, *JHEP* **03** (2010) 080 [[arXiv:0911.1120](#)] [[INSPIRE](#)].
- [58] J.L. Feng, A. Rajaraman and F. Takayama, *Superweakly interacting massive particles*, *Phys. Rev. Lett.* **91** (2003) 011302 [[hep-ph/0302215](#)] [[INSPIRE](#)].
- [59] J.L. Feng, A. Rajaraman and F. Takayama, *SuperWIMP dark matter signals from the early universe*, *Phys. Rev. D* **68** (2003) 063504 [[hep-ph/0306024](#)] [[INSPIRE](#)].
- [60] T. Asaka, M. Shaposhnikov and A. Kusenko, *Opening a new window for warm dark matter*, *Phys. Lett. B* **638** (2006) 401 [[hep-ph/0602150](#)] [[INSPIRE](#)].
- [61] M. Nemešsek, G. Senjanović and Y. Zhang, *Warm Dark Matter in Low Scale Left-Right Theory*, *JCAP* **07** (2012) 006 [[arXiv:1205.0844](#)] [[INSPIRE](#)].
- [62] CMS collaboration, *Search for Pair-production of First Generation Scalar Leptoquarks in pp Collisions at $\sqrt{s} = 8$ TeV*, *CMS-PAS-EXO-12-041* (2014).
- [63] CMS collaboration, *Search for pair production of third-generation scalar leptoquarks and top squarks in proton-proton collisions at $\sqrt{s} = 8$ TeV*, *Phys. Lett. B* **739** (2014) 229 [[arXiv:1408.0806](#)] [[INSPIRE](#)].
- [64] J. Alwall, M. Herquet, F. Maltoni, O. Mattelaer and T. Stelzer, *MadGraph 5 : Going Beyond*, *JHEP* **06** (2011) 128 [[arXiv:1106.0522](#)] [[INSPIRE](#)].
- [65] J. Alwall et al., *The automated computation of tree-level and next-to-leading order differential cross sections and their matching to parton shower simulations*, *JHEP* **07** (2014) 079 [[arXiv:1405.0301](#)] [[INSPIRE](#)].
- [66] L. Covi and F. Dradi, *Long-Lived stop at the LHC with or without R-parity*, *JCAP* **10** (2014) 039 [[arXiv:1403.4923](#)] [[INSPIRE](#)].
- [67] CMS collaboration, *Searches for long-lived charged particles in pp collisions at $\sqrt{s}=7$ and 8 TeV*, *JHEP* **07** (2013) 122 [[arXiv:1305.0491](#)] [[INSPIRE](#)].
- [68] ATLAS collaboration, *Search for long-lived stopped R-hadrons decaying out-of-time with pp collisions using the ATLAS detector*, *Phys. Rev. D* **88** (2013) 112003 [[arXiv:1310.6584](#)] [[INSPIRE](#)].
- [69] ATLAS collaboration, *Search for direct production of charginos, neutralinos and sleptons in final states with two leptons and missing transverse momentum in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector*, *JHEP* **05** (2014) 071 [[arXiv:1403.5294](#)] [[INSPIRE](#)].
- [70] CMS collaboration, *Searches for electroweak production of charginos, neutralinos and sleptons decaying to leptons and W, Z and Higgs bosons in pp collisions at 8 TeV*, *Eur. Phys. J. C* **74** (2014) 3036 [[arXiv:1405.7570](#)] [[INSPIRE](#)].
- [71] M. Frigerio and C.E. Yaguna, *Sterile Neutrino Dark Matter and Low Scale Leptogenesis from a Charged Scalar*, *Eur. Phys. J. C* **75** (2015) 31 [[arXiv:1409.0659](#)] [[INSPIRE](#)].
- [72] M. Frigerio, *private communication* (2015).
- [73] CMS collaboration, *Constraints on the Higgs boson width from off-shell production and decay to Z-boson pairs*, *Phys. Lett. B* **736** (2014) 64 [[arXiv:1405.3455](#)] [[INSPIRE](#)].
- [74] F. Richard, G. Arcadi and Y. Mambrini, *Searching for dark matter at colliders*, *Eur. Phys. J. C* **75** (2015) 171 [[arXiv:1411.0088](#)] [[INSPIRE](#)].
- [75] G. Moortgat-Picka et al., *Physics at the e^+e^- Linear Collider*, [arXiv:1504.01726](#) [[INSPIRE](#)].

- [76] ATLAS collaboration, *Search for direct third-generation squark pair production in final states with missing transverse momentum and two b-jets in $\sqrt{s} = 8$ TeV pp collisions with the ATLAS detector*, *JHEP* **10** (2013) 189 [[arXiv:1308.2631](#)] [[INSPIRE](#)].
- [77] ATLAS collaboration, *Search for direct pair production of the top squark in all-hadronic final states in proton-proton collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector*, *JHEP* **09** (2014) 015 [[arXiv:1406.1122](#)] [[INSPIRE](#)].
- [78] ATLAS collaboration, *Measurement of the $t\bar{t}$ production cross-section using $e\mu$ events with b-tagged jets in pp collisions at $\sqrt{s} = 7$ and 8 TeV with the ATLAS detector*, *Eur. Phys. J. C* **74** (2014) 3109 [[arXiv:1406.5375](#)] [[INSPIRE](#)].
- [79] ATLAS collaboration, *Search for direct top squark pair production in events with a Z boson, b-jets and missing transverse momentum in $\sqrt{s}=8$ TeV pp collisions with the ATLAS detector*, *Eur. Phys. J. C* **74** (2014) 2883 [[arXiv:1403.5222](#)] [[INSPIRE](#)].
- [80] M. Blennow, E. Fernandez-Martinez, O. Mena, J. Redondo and P. Serra, *Asymmetric Dark Matter and Dark Radiation*, *JCAP* **07** (2012) 022 [[arXiv:1203.5803](#)] [[INSPIRE](#)].
- [81] E. Di Valentino, A. Melchiorri and O. Mena, *Dark radiation sterile neutrino candidates after Planck data*, *JCAP* **11** (2013) 018 [[arXiv:1304.5981](#)] [[INSPIRE](#)].
- [82] PLANCK collaboration, P.A.R. Ade et al., *Planck 2013 results. XVI. Cosmological parameters*, *Astron. Astrophys.* **571** (2014) A16 [[arXiv:1303.5076](#)] [[INSPIRE](#)].
- [83] S. Galli et al., *CMB Polarization can constrain cosmology better than CMB temperature*, *Phys. Rev. D* **90** (2014) 063504 [[arXiv:1403.5271](#)] [[INSPIRE](#)].
- [84] A. Boyarsky, A. Neronov, O. Ruchayskiy and M. Shaposhnikov, *Constraints on sterile neutrino as a dark matter candidate from the diffuse x-ray background*, *Mon. Not. Roy. Astron. Soc.* **370** (2006) 213 [[astro-ph/0512509](#)] [[INSPIRE](#)].
- [85] K. Petraki and A. Kusenko, *Dark-matter sterile neutrinos in models with a gauge singlet in the Higgs sector*, *Phys. Rev. D* **77** (2008) 065014 [[arXiv:0711.4646](#)] [[INSPIRE](#)].
- [86] A. Merle, V. Niro and D. Schmidt, *New Production Mechanism for keV Sterile Neutrino Dark Matter by Decays of Frozen-In Scalars*, *JCAP* **03** (2014) 028 [[arXiv:1306.3996](#)] [[INSPIRE](#)].
- [87] E. Molinaro, C.E. Yaguna and O. Zapata, *FIMP realization of the scotogenic model*, *JCAP* **07** (2014) 015 [[arXiv:1405.1259](#)] [[INSPIRE](#)].
- [88] A. Abada, G. Arcadi and M. Lucente, *Dark Matter in the minimal Inverse Seesaw mechanism*, [arXiv:1406.6556](#) [[INSPIRE](#)].
- [89] S. Dodelson and L.M. Widrow, *Sterile-neutrinos as dark matter*, *Phys. Rev. Lett.* **72** (1994) 17 [[hep-ph/9303287](#)] [[INSPIRE](#)].
- [90] X.-D. Shi and G.M. Fuller, *A New dark matter candidate: Nonthermal sterile neutrinos*, *Phys. Rev. Lett.* **82** (1999) 2832 [[astro-ph/9810076](#)] [[INSPIRE](#)].
- [91] M. Shaposhnikov, *The nuMSM, leptonic asymmetries and properties of singlet fermions*, *JHEP* **08** (2008) 008 [[arXiv:0804.4542](#)] [[INSPIRE](#)].
- [92] D. Boyanovsky, *Clustering properties of a sterile neutrino dark matter candidate*, *Phys. Rev. D* **78** (2008) 103505 [[arXiv:0807.0646](#)] [[INSPIRE](#)].
- [93] A. Merle and A. Schneider, *Production of Sterile Neutrino Dark Matter and the 3.5 keV line*, [arXiv:1409.6311](#) [[INSPIRE](#)].
- [94] A. Merle and M. Totzauer, *keV Sterile Neutrino Dark Matter from Singlet Scalar Decays: Basic Concepts and Subtle Features*, [arXiv:1502.00101](#) [[INSPIRE](#)].
- [95] M. Viel, G.D. Becker, J.S. Bolton and M.G. Haehnelt, *Warm dark matter as a solution to the small scale crisis: New constraints from high redshift Lyman- α forest data*, *Phys. Rev. D* **88** (2013) 043502 [[arXiv:1306.2314](#)] [[INSPIRE](#)].