

3.55 KeV line in minimal decaying Dark Matter

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We present a simple model aimed at correlating the recently reported X-ray line with searches of new physics at LHC. The Standard Model is extended with a Majorana fermion DM, with mass set to 7 KeV, and a scalar field charged under the SM gauge group and capable of being pair produced at the LHC. The combined requirements of a DM lifetime in agreement with the line detection and the correct relic density, through the freeze-in mechanism, determine the typical decaying length and main decay channels at collider of the scalar field. It results promptly decaying into two SM fermions. This kind of channel is already probed by LHC searches. The decay channel into DM, responsible for the generation of its relic density, has instead a too low branching ratio to be observable.

1 Introduction

Although conventional paradigms rely on stable dark matter (DM) candidates, whose stability is enforced by a symmetry of the underlying particle sector, decaying dark matter candidates, with lifetimes largely exceeding the age of the Universe, are not a priori forbidden. This kind of scenarios feature interesting prospects of Indirect Detection (ID), in cosmic rays, of DM decay processes occurring at present times. Among the possible signals, the most spectacular are probably narrow lines originating from decays of the DM into photons. A signal of this kind has been recently identified in the combined spectrum of a large set of galaxy clusters[?] as well as the combined observation of the Perseus Cluster and the M31 Galaxy[?]. This line has an energy of approximately 3.55 KeV and can be interpreted as the decay into photons of a DM particle with mass $m_{\text{DM}} = 2E_\gamma \simeq 7 \text{ KeV}$ (see anyway[?]). We remark anyway that this DM interpretation is still controversial[?] and most probably new data are needed to confirm (or disprove) it.

In this document we will discuss the interesting possibility of correlating this hypothetical Indirect Detection with searches of New Physics at LHC.

In order to investigate this possible interplay we will consider the very simple extension of the Standard Model (SM), presented in^{?,?}. A SM singlet Majorana DM candidate is coupled with a scalar field, charged under the SM gauge group, and with the SM fermions. In the case of very light DM, namely below $\sim 1 \text{ GeV}$, the only kinematically allowed DM decay is a two body processes, induced at one loop, with the scalar field and SM fermions running inside it, into a photon and a neutrino, thus reproducing the X-ray line for a DM mass of approximately 7

KeV. In addition, the scalar field sets the DM relic density through the freeze-in mechanism. Combining the requirements of reproducing the detected line and the correct DM relic density it is possible to infer the relevant couplings of the model. These determine the typical decay length of the scalar field, possibly pair produced at the LHC, and its dominant decay channels, thus determining the most suitable search strategies and the prospects of detection.

The document is organized as follows. In section 2 we will briefly describe the minimal decaying Dark Matter model. Section 3 is devoted to a brief review of the freeze-in mechanism. In section 4 we will then 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 and infer the possible relevant LHC phenomenology of our scenario. We will then state our conclusions in section 5.

2 The model

As mentioned above we will consider a simple extension of the SM with two extra fields: a Majorana fermion ψ , the DM candidate, singlet with respect to the SM gauge group, and a scalar field Σ_f , with non trivial quantum numbers with respect to at least some components of the SM gauge symmetry group. This new state can couple to a SM fermion through a Yukawa type interaction of the form:

$$L_{\Sigma\psi f} = \lambda \bar{\psi} f \Sigma_f^\dagger + h.c. \quad (1)$$

where f is a quark or a lepton according the assignment of the quantum numbers of Σ_f . In absence of additional symmetries a similar interaction between the scalar field and only SM fermions:

$$L_{\Sigma f f} = \lambda' \bar{f} f \Sigma_f^\dagger + h.c. \quad (2)$$

is also allowed by gauge symmetry. In its simplest realization, our scenario can be described by just four free parameters: the two couplings λ and λ' and the masses m_ψ and m_{Σ_f} of the two new states. The interactions above induce a tree-level three-body decay of the DM into SM fermions mediated by the scalar field. A photon line can be produced by the two body decay of DM into a photon and a neutrino, originating at the loop level as shown in fig. (??). This last decay channel can be dominant only if the three-level one is kinematically forbidden. This requirement is easily fulfilled by imposing, by kinematics, $E_\gamma = \frac{m_\psi}{2}$, thus setting $m_\psi \simeq 7 \text{ KeV}$. From now on, unless differently stated, we will assume the DM mass fixed to this value, thus leaving three free parameters.

The scalar field Σ_f features also ordinary gauge interactions, strong and/or electroweak, which allow its efficient pair production at the LHC, in particular in the case of a color charged field. It can then decay through two possible kind of channels, DM and SM fermion or two SM fermions, with the corresponding rates proportional to, respectively, λ and λ' . As will shown below, it is possible to infer from DM phenomenology the values of these two couplings and then the prospects of probing the production of the scalar field at the LHC. Indeed the DM lifetime is sensitive to the product $\lambda\lambda'$ while the requirement of the correct relic density will allow an individual determination of the coupling λ , as function of the mass of the scalar field. Combining these two informations it is thus possible to infer the values of both the relevant couplings of the model. This allows to predict the typical collider decay length of the scalar field, thus determining whether it decays promptly, through displaced vertices or might even result detector stable, and its main decay channels. In such a way it is possible to determine the most suitable collider search strategy and the prospects for a future LHC detection.

3 Freeze-in mechanism

A very simple and economical mechanism for the DM production in our scenario is the so called freeze-in^{?,?,?}. The DM is produced by the decays of scalar field while this is still in thermal equilibrium with the primordial thermal bath, as guaranteed by its gauge interactions. On

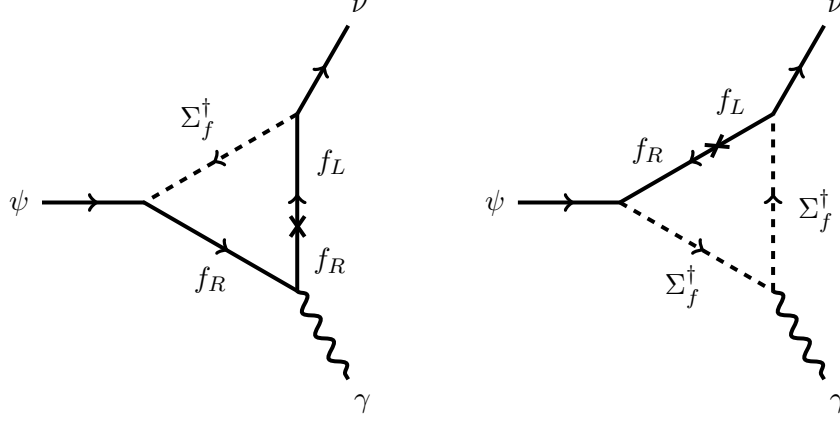


Figure 1: DM 2-body decay into γ and ν with the loop induced by Σ_d .

the contrary the DM should, instead, not be coupled to the thermal bath and have negligible abundance in the Early Universe. This condition can be fulfilled by imposing, as rule of thumb, that $\Gamma(\Gamma_f \rightarrow \psi + SM) < \mathcal{H}$, where $\mathcal{H} \approx 1.66 g_*(T) \frac{T^2}{M_{\text{Pl}}}$ is the Hubble expansion parameter, g_* represent the number of relativistic degrees of freedom at the temperature T , and the relation is computed at $T = m_{\Sigma_f}$. Taking $\Gamma(\Gamma_f \rightarrow \psi + SM) = \frac{\lambda^2 m_{\Sigma_f}}{8\pi}$ it is possible to obtain the upper limit $\lambda < O(10^{-7})$. If this limit is exceeded the DM would be in thermal equilibrium at early stages of the history of the Universe and decouple at temperatures of the order of the mass of the scalar field, while still relativistic, thus overclosing the Universe.

The relic density associated to the freeze-in mechanism is given by^a:

$$\Omega_{\text{DM}} h^2 \approx 1.09 \times 10^{27} \frac{g_{\Sigma_f}}{g_*^{3/2}} \frac{m_\psi}{m_{\Sigma_f}} \frac{\Gamma(\Sigma_f \rightarrow f\psi)}{m_{\Sigma_f}} \quad (3)$$

and is thus proportional to the decay rate of the scalar field into DM. Requiring the correct amount of DM abundance it is then possible to obtain, from eq. (??), a condition on the coupling λ . Combining this requirement with the one of reproducing the DM lifetime accounting for the X-ray line it is possible, as we will see in the next section, to determine the two relevant couplings λ and λ' as function of the DM mass (already set to a definite value) and the mass of the scalar field, which can be constrained through collider phenomenology.

4 DM lifetime and impact on collider searches

The decay process reported in fig. (??) occurs only for a limited set of operators, with respect to the ones allowed by gauge invariance, and only for some definite assignments of the quantum numbers of the field Σ_f :

$$\begin{aligned} L_{\text{eff}} &= \lambda' \bar{d}_R l_L \Sigma_q + h.c. & \Sigma_q &= (3, 2, 1/3) \\ L_{\text{eff}} &= \lambda' \bar{l}_R^c q_L \Sigma_d^\dagger + h.c. & \Sigma_d &= (3, 1, -2/3) \\ L_{\text{eff}} &= \lambda' \bar{l}_R^c l_L \Sigma_e^\dagger + h.c. & \Sigma_e &= (1, 2, -1) \\ L_{\text{eff}} &= \lambda' \bar{e}_R l_L \Sigma_l + h.c. & \Sigma_l &= (1, 1, -2) \end{aligned} \quad (4)$$

^aOn general grounds a contribution from out-of-equilibrium (i.e. after chemical freeze-out) decays of the scalar fields is expected as well. It is determined by the branching ratio of decay of the scalar field into DM and by its abundance at chemical freeze-out. The latter is however very low, because of the efficient gauge interactions, and thus its contribution to the DM relic density is negligible[?].

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

$$\Gamma(\psi \rightarrow \gamma\nu) = \frac{g_{\psi\gamma\nu}^2}{8\pi} m_\psi, \quad g_{\psi\gamma\nu} = -\frac{em_\psi}{16\pi^2} \sum_i \frac{m_i}{m_{\Sigma_f}^2} \lambda'_i \lambda_i f_1 \left(\frac{m_i^2}{m_{\Sigma_f}^2} \right)$$

$$f_1(x) = \frac{1}{1-x} \left[1 + \frac{1}{1-x} \ln x \right] \quad (5)$$

where the sum runs over the fermions flowing into 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. The DM decay rate is thus mostly sensitive to the couplings of the scalar field with third generation fermions. 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 not possible to construct a loop with an intermediate top quark. Taking $m_b = 4$ GeV, the lifetime of the DM in this case can be estimated as:

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

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

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

Combining (??) with the requirement of the correct relic density which, from eq. (??), gives:

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

we obtain the following prediction for the coupling λ' :

$$\lambda' \approx 3 \times 10^{-3} \left(\frac{m_\psi}{7 \text{ keV}} \right)^{-1} \left(\frac{m_{\Sigma_f}}{1 \text{ TeV}} \right)^{3/2} \left(\frac{\tau(\psi \rightarrow \gamma\nu)}{10^{28} \text{ s}} \right)^{-1/2}. \quad (9)$$

We notice that there is a strong hierarchy between the couplings λ' and λ . We thus expect that a pair produced scalar field at LHC would mostly decay into only SM fermions with typical decay length:

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

This very small decay length implies prompt decays of the scalar field at the LHC. We remark that, due to the dependence of eq. (??) on the internal fermion mass, the value of λ' reported in (??) is the minimal achievable. The conclusion above hence is valid for all the realizations given in (??). For this reason we will focus from now on, for definiteness, our analysis to the case of a Σ_d -type (i.e. quantum numbers of a right-handed d-quark) field.

This scenario can be probed at LHC by searches of Leptoquarks. Assuming that the scalar field is only coupled to third generation quarks (given the dependence on the quark masses of the DM decay rate this is the only coupling accessible to our analysis), LHC searches already exclude masses of the scalar field below 740 GeV[?].

The interplay between LHC searches and DM phenomenology is summarized in fig. (??) in the plane (m_{Σ_f}, λ') . The red line represents the value of λ' given by eq. (??). The blue line represents the value of λ' which is obtained by combining eq. (??) with the condition $\Gamma(\Sigma_d \rightarrow b\psi) = \mathcal{H}$, giving:

$$\lambda = 0.6 \times 10^{-7} \left(\frac{m_{\Sigma_f}}{1 \text{ TeV}} \right)^{1/2} \quad (11)$$

The light blue region below this last curve corresponds to a DM in thermal equilibrium in the Early Universe and, hence, largely overabundant if its mass is set to 7 KeV. The requirement of not overclosure of the Universe further enforces the prediction of a scalar field promptly decaying at the LHC^b. Interestingly this prediction would be valid even for similar line signals, with respect to the one considered, for a rather broad range of masses, given the rather weak dependence of eq. (??) on the DM mass. In order to have a scalar field decay length compatible with displaced decays (purple dashed line) one needs to require $\lambda\lambda' \lesssim 10^{-14}$, leading to unobservable DM decays in present and next future experiments. The gray region finally represents current exclusion from LHC searches of Leptoquarks.

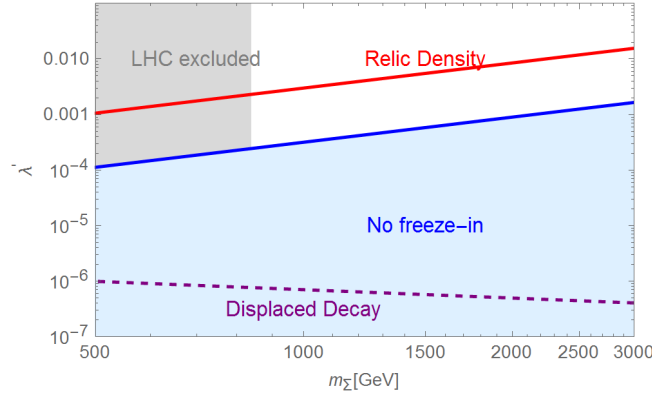


Figure 2: Summary plot in the (m_{Σ_f}, λ') plane. The red line corresponds to a DM lifetime compatible with the detection of the X-ray line and of the correct DM relic density through the freeze-in mechanism. The gray region is excluded by current LHC limits while in the blue region the DM is in thermal equilibrium in the early cosmological epochs and would overclose the Universe.

We just comment that the result obtained is sensitively different with respect to the case $m_\psi \gtrsim O(\text{GeV})$. In this case, by requiring an hypothetical signal from, for example, the tree-level decay $\psi \rightarrow \bar{b}b\nu$ (in this case one might observe a signal in antiprotons rather than a photon line), corresponding to a DM lifetime of $\tau \sim 10^{-(27 \div 28)}\text{s}$ (approximately corresponding to current experimental limits in this mass range), one would get $\lambda\lambda' \sim 10^{-20}$, leading to a long-lived scalar field, with respect to LHC detector scales, giving displaced vertices and/or disappearing tracks as possible signals[?].

As evident in the discussion, the requirement of a viable KeV DM reproducing the X-ray signal allows a rather clear prediction of the parameters of the model and definite prospects for LHC searches. On the other hand a reconstruction of these from an hypothetical LHC signal would be rather challenging. In particular it would be hard to discriminate our scenario from other models. Indeed the most peculiar signature, i.e. the presence of two different, namely DM+SM and only SM, decay modes of the scalar field, is not accessible to detection. In particular a direct test of the freeze-in paradigm is not possible because of the negligible branching fraction of the decay channel into DM. On the other hand, in case of LHC determination of the mass and lifetime of the scalar field, the combination with the Indirect DM signal would allow to infer the parameters of the model.

5 Conclusions

We have considered the possibility of reproducing the observation of X-ray signal through a minimal extension of the SM with a 7 KeV DM and a TeV scale DM. It has been possible to

^bNotice that this argument is strictly valid only assuming a standard cosmological history.

enforce a correlation between DM ID and searches at LHC of the scalar field. The requirement of viable DM is translated into the prediction of a scalar field promptly decaying into SM fermions which can be probed by current searches of leptoquarks in case the scalar field carries color charge. It is however not possible to test the freeze-in hypothesis since the decay channel into DM has a suppressed branching ratio.

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