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Production of Sterile Neutrino dark matter and the 3.5 keV line

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ABSTRACT

The recent observation of an X-ray line at an energy of 3.5 keV mainly from galaxy clusters has initiated a discussion about whether we may have seen a possible dark matter signal. If confirmed, this signal could stem from a decaying sterile neutrino of a mass of 7.1 keV. Such a particle could make up all the dark matter, but it is not clear how it was produced in the early Universe. In this letter we show that it is possible to discriminate between different production mechanisms with *present-day* astronomical data. The most stringent constraint comes from the Lyman-α forest and seems to disfavor all but one of the main production mechanisms proposed in the literature, which is the production via decay of heavy scalar singlets. Pinning down the production mechanism will help to decide whether the X-ray signal indeed comprises an indirect detection of dark matter.

1. Introduction

A dream of particle physicists, cosmologists, and astrophysicists is to discover the true nature of dark matter (DM), which makes up more than 80% of the matter in the Universe [1]. The generic candidate is a Weakly Interacting Massive Particle (WIMP), i.e. a heavy particle which interacts as weakly as neutrinos. However, the many recent attempts to directly detect such a particle [2] or to produce it at colliders [3], as well as the hunts for its annihilation products [4], have so far not found a clear indication. In this situation, the detection of an X-ray line in several galaxy clusters and in the Andromeda galaxy [5,6] has attracted the attention of the community. This line, if stemming from DM decay, could be a smoking gun signal for a very different type of DM particle: an extremely weakly interacting ("sterile") neutrino with a mass smaller than that of a WIMP by about seven orders of magnitude. WIMPs are produced by *thermal freeze-out* [7] which means that they decouple from the primordial thermal plasma as soon as the Hubble expansion becomes larger than the interaction rate. Sterile neutrinos with keV-masses cannot be produced in this way because their interactions are too weak. However, even very feebly interacting particles can be gradually produced in the early Universe [8]. For sterile neutrinos this can be achieved by their tiny admixtures θ to active neutrinos, the so-called Dodelson–Widrow (DW) mechanism [9], but this is known to produce a too hot spectrum [10,11], i.e., too fast DM particles. However, active-sterile neutrino transitions could be resonantly enhanced if the background medium carries a net lepton number. This production proposed by Shi and Fuller [12] seems in a better shape when confronted with data [13], and it has been recently advocated to be able to produce DM in agreement with the line signal [14,15].

What is the status of the 3.5 keV line? Refs. [5,6] have independently reported evidence in samples by the XMM-Newton and Chandra satellites from nearby clusters and the Andromeda galaxy (stating $> 4\sigma$ significance for the stacked signal). These findings were criticised by Refs. [16,17], who state that Chandra should see a line signal from the center of the Milky way and that other chemical lines are able to explain the signal. However, these remarks were again criticised in Refs. [18–21], arguing that the centre of the Milky Way is too noisy for a clear signal. Ref. [19] questions the range of validity of the background model assumed in [17]. Finally, Ref. [22] has found no signal in stacked XMM-Newton data from dwarf galaxies, which they claim should provide a clean signal, although the constraint provided is not significantly more stringent than previous ones [23]. Obviously the situation is not clear at the moment and more data is required. On the other hand, the technical development of satellites proceeds slower than one would like, so that we cannot expect to see a very bright signal where none had been seen before. Ultimately, we should take

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the tentative 3.5 keV line as a motivation to scrutinize both the signal and its implications – the latter we will do here.

With the signal taken seriously, to find out whether DM decay causes it, non-standard production mechanisms must be tested. If the sterile neutrino was charged beyond the SM gauge group [see [24] for a review of several such settings], freeze-out may be revived if a significant amount of entropy is produced to dilute the abundance [25], but this is strongly constrained by Big Bang Nucleosynthesis [26]. However, there is another production mechanism which is in a better shape, using a scalar that decays into sterile neutrinos: $S \to \nu_s \nu_s$. This scalar could be the inflaton [27] or a general singlet S that is thermally produced in the early Universe by either freeze-out [28] or freeze-in [29]. Ultimately the production mechanism has an impact on the DM velocity profile and thus on structure formation.

In this letter we present a snapshot of an extensive study to be available soon [30]. We show that, contrary to common believe, sterile neutrino production by scalar decays seems to be in better agreement with data than Shi–Fuller production, in particular when looking at the Lyman-α (Ly-α) bound. Knowing which mechanisms fit the data will be of uttermost importance when aiming at identifying whether DM decay could be behind the X-ray signal.

2. Dark matter production from decays of scalar singlets

Just as the fermions in the SM obtain their masses by the so-called “Yukawa” couplings to the Higgs scalar field H, sterile neutrinos ν_s could couple to a singlet scalar field $\mathcal{S}$ like $\frac{y}{2}\mathcal{S}\overline{\nu_s^c}\nu_s + \text{h.c.}$ If $\mathcal{S}$ settles at its vacuum expectation value $v_S = \langle \mathcal{S} \rangle$, this leads to a sterile neutrino mass $m_s = y v_S$ similarly to the ordinary Higgs mechanism. However, the scalar field $\mathcal{S}$ is also allowed by all symmetries to couple to the SM Higgs field via a “portal” $H^\dagger H \mathcal{S}^2$. This coupling could produce sizeable amounts of S particles (i.e., the physical components of $\mathcal{S}$) which will decay with strength y into two sterile neutrinos. This mechanism can lead to efficient DM production.

Because the S particles only decay efficiently once they are non-relativistic, they do not contribute to the DM momentum distribution. Only their abundance is important for the DM abundance, since every scalar singlet decays in exactly two sterile neutrinos.

The momentum distribution of a decay produced sterile neutrino with adjacent DW production is [31–33],

$$f(p) = \frac{\beta_{\rm SD}}{(p/T_{\rm SD})} \exp\left(-p^2/T_{\rm SD}^2\right) + \frac{\beta_{\rm DW}}{\exp(p/T_{\rm DW}) + 1}, \tag{1}$$

where $\alpha_{\rm DW} = T_{\rm DW}/T \sim 0.716$ and $\alpha_{\rm SD} = T_{\rm SD}/T \sim 0.35$ (T being the photon-temperature). A detailed derivation of Eq. (1) is given in Appendix A. The normalization factors $\beta_{\rm SD}$ and $\beta_{\rm DW}$ depend on the details of the production mechanism and are fixed by the required DM abundance. This can be determined with the help of the empirical formula from Ref. [34],

$$\Omega_{\rm DW} \sim 7.8 \cdot 10^{-5} \left[\frac{\sin^2(2\theta)}{10^{-10}}\right]^{1.23} \left[\frac{m_s}{\rm keV}\right]^2, \tag{2}$$

which gives an estimate for the fraction of DM produced non-resonantly via the active-sterile mixing θ.

It becomes clear from Eq. (2) that the exact form of the momentum distribution depends effectively on two parameters, namely the mass m_s of the sterile neutrino and the active-sterile mixing $\Theta \equiv \sin^2(2\theta)$. Both parameters can be unambiguously determined from the energy spectrum and the flux of the observed X-ray line and are reported to be $m_s = (7.14 \pm 0.07)$ keV and $\Theta = 6.8^{+2.2}_{-1.7} \cdot 10^{-11}$, respectively [5,35]. The resulting momentum distributions are plotted in Fig. 1. The black line corresponds to scalar decay production, cf. Eq. (1), while the thickness of the line illustrates mixing with different neutrino flavors. The surrounding red band designates the 3σ confidence level on the flux measurement. The distribution exhibits two maxima, one at very cold momenta coming from scalar production and a much smaller one at larger momenta associated with the subdominant active-sterile mixing. The blue dashed line in Fig. 1 shows the momentum distribution resulting from resonant production, calculated in [14]. It assumes a lepton number of $L = 4.6 \cdot 10^{-4}$ and has a characteristic spike at low momenta due to the resonance in the active-sterile mixing. The green dotted line in Fig. 1 illustrates the standard non-resonant production based on the DW mechanism [9] as sole source of DM. The X-ray line measurement trivially excludes this mechanism, since non-resonantly produced sterile neutrinos would require a considerably larger mixing angle to make up for all of the DM in the Universe (and they would be too hot). We nevertheless plot the non-resonant case as reference, however, with a mixing angle $\Theta = 4 \cdot 10^{-10}$ to obtain the correct DM abundance.

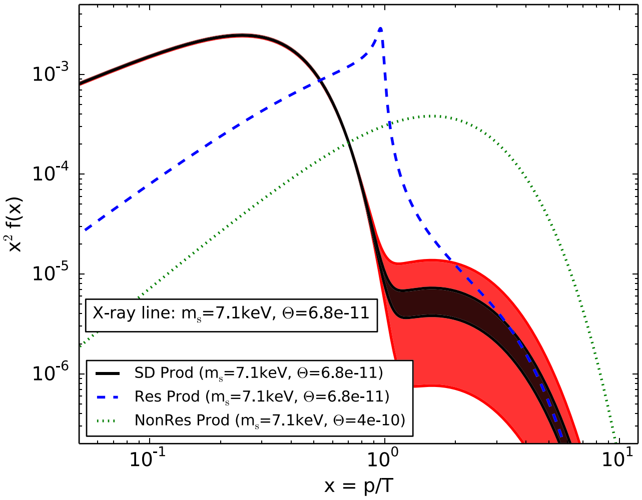

Fig. 1. Momentum distribution from scalar decay production (black), resonant production (blue dashed, [14]) and non-resonant production (green dotted). The black and the blue lines use parameters corresponding to the claimed signal [5]. The green dotted line assumes a larger mixing angle to allow for the right DM abundance. The red envelope around the black line corresponds to the 3σ C.L. from Ref. [5].

3. Cosmological perturbations

DM particles with a mass in the keV-range are usually categorized as warm DM (WDM) candidates because they generate an important amount of free streaming, which suppresses perturbations at dwarf galaxy scales. The free-streaming length ($\lambda_{\rm fs}$) does however not only depend on the particle mass but also on the average particle momentum, i.e. $\lambda_{\rm fs} \sim \langle q \rangle / m_s$. Since the average momentum of scalar-decay produced sterile neutrinos is comparatively small, the effect of free-streaming is expected to be reduced in comparison to production via active-sterile mixing. It is therefore important to properly calculate the free-streaming effect in order to see how strongly scalar decay sterile neutrinos suppress the collapse of dwarf galaxies and whether they act more like warm or cold DM (CDM) [36].

We use the numerical Boltzmann solver `CLASS` [37] to compute matter perturbations for the DM scenarios introduced above. The suppression of small structures with respect to pure CDM is shown in Fig. 2, where we plot the ratio of the transfer functions (i.e., the square-root of the linear power-spectrum $T/T_{\rm CDM} =$