Dark matter model favoured by reionization data: 7 keV sterile neutrino vs cold dark matter

A. Rudakovskyi, 1,2,3 ⋆ and D. Iakubovskyi 4,1
1 Bogolyubov Institute of Theoretical Physics, Metrologichna Str. 14-b, 03143, Kyiv, Ukraine
2 Taras Shevchenko National University of Kyiv, Physics Department, Glushkova ave. 2, Kyiv, Ukraine
3 Main Astronomical Observatory, Akademika Zabolotnoho str. 27, 03143, Kyiv, Ukraine
4 Discovery Center, Niels Bohr Institute, Blegdamsvej 17, Copenhagen, Denmark

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ABSTRACT

One of possible explanations of a faint narrow emission line at 3.5 keV reported in our Galaxy, Andromeda galaxy and a number of galaxy clusters is the dark matter made of 7 keV sterile neutrinos. Another signature of such sterile neutrino dark matter could be fewer ionizing sources in the early Universe (compared to the standard ‘cold dark matter’ (CDM) scenario), which should affect the reionization of the Universe. By using a semi-analytical model of reionization, we compare the model predictions for CDM and two different models of 7 keV sterile neutrino dark matter (consistent with the 3.5 keV line interpretation as decaying dark matter line) with available observations of epoch of reionization (including the final measurements of electron scattering optical depth made by Planck observatory). We found that both CDM and 7 keV sterile neutrino dark matter well describe the data. The overall fit quality for sterile neutrino dark matter is slightly (with $\Delta \chi^2 \approx 2 - 3$) better than for CDM, although it is not possible to make a robust distinction between these models on the basis of the given observations.

Key words: cosmology: dark ages, reionization, first stars – cosmology: dark matter – methods: statistical

1 INTRODUCTION

To this end, the constituents of dark matter — the largest gravitating substance in the Universe — have not been identified. A possible clue on the dark matter origin is the faint narrow emission line-like feature at 3.5 keV reported in our Galaxy, M31 and galaxy clusters. At the moment, there is an ongoing debate about the line status, but according to recent reviews (Adhikari et al. 2017; Abazajian 2017; Boyarsky et al. 2018), it can be interpreted as a signal from decaying dark matter, e.g., in the form of right-handed (‘sterile’) neutrinos with 7 keV mass and the mixing angle with Standard Model neutrinos $\sin^2 2\theta = (2 - 20) \times 10^{-11}$.

For such parameters, sterile neutrino dark matter would originate in the early Universe from resonant oscillations of usual left-handed (‘active’) neutrinos (Shi & Fuller 1999; Abazajian et al. 2001a; Liang & Shaposhnikov 2008; Abazajian 2014; Venumadhav et al. 2016). As a result, sterile neutrino dark matter, unlike cold dark matter (CDM), would be initially ultra-relativistic with non-thermal distribution function, smearing out density perturbations at small spatial scales. Such smearing, indeed, can be a result of warm dark matter with a few keV mass (see e.g. Dolgov & Hansen 2002; Abazajian et al. 2001b) or of a mixture of cold and warm dark matter (Boyarsky et al. 2009a; Macciò et al. 2013). It can be traced by a number of observations related to structure formation at different redshifts, such as Lyman-alpha forest power spectrum (Narayanan et al. 2000; Hansen et al. 2002; Viel et al. 2005, 2006, 2008, 2013; Abazajian 2006; Seljak et al. 2006; Boyarsky et al. 2009a, b; Garzilli et al. 2015; Iršič et al. 2017; Yeche et al. 2017; Baur et al. 2017), reionization of the Universe (Barkana et al. 2001; Yoshida et al. 2003; Somerville et al. 2003; Jedamzik et al. 2006; Yue & Chen 2012; Schultz et al. 2014; Dayal et al. 2017b; Rudakovskyi & Iakubovskyi 2016; Bose et al. 2016; Cen 2017; Lopez-Honorez et al. 2017), subhalo counts in the Local Group (Macciò & Fontanot 2010; Polisensky & Ricotti 2011; Lovell et al. 2014; Kennedy et al. 2014; Horiiuchi et al. 2014; Lovell et al. 2016, 2017a, b; Cherry & Horiiuchi 2017), luminosity functions at low (Menci et al. 2016, 2017a) and high (Song & Lee 2009; Schultz et al. 2014; Corasaniti et al. 2017; Menci et al. 2017b) redshifts, substructure counts...
in gravitational lensing systems (Zentner & Bullock 2003; Miranda & Macciò 2007; Inoue et al. 2015; Birrer et al. 2017), galaxy velocity function (Klypin et al. 2015; Schneider et al. 2017), stellar mass – halo mass relation of isolated field dwarf galaxies (Read et al. 2017), stellar mass functions at redshifts $z \lesssim 3.5$ together with the Tully–Fisher relation (Kang et al. 2013), star-formation history of the Local Group dSphs (Chau et al. 2017), and number density of direct collapse black hole hosts (Dayal et al. 2017a).

In this paper, we study the difference between the 7 keV sterile neutrino dark matter (that can be responsible for the origin of 3.5 keV emission line) models and the standard cold dark matter model on the reionization of the Universe. Some of previous works (Rudakovskyi & Iakubovskyi 2016; Lopez-Honorez et al. 2017) showed that the observational data on reionization may be described better in sterile neutrino dark matter or thermal-relic warm dark matter models compared to the CDM model. The goal of the present paper is to quantify this difference using available observations. This paper is organized as follows: Sec. 2 contains a description of our method and the observations (including the final measurements of electron scattering optical depth made by Planck); the obtained results are summarized in Sec. 3 and discussed in Sec. 4. Finally, our conclusions are summarized in Sec. 5.

2 METHOD

To calculate the ionized volume-filling fraction $Q_{\text{II}}(z)$ and the CMB electron scattering optical depth $\tau_{\text{es}}$, we used the extension of the ‘bubble model’ (Furlanetto et al. 2004; Yue & Chen (2012) of reionization, see Rudakovskyi & Iakubovskyi (2016) for more detailed description. We assume that the main source of ionizing photons are stars formed in galaxy-size dark matter halos, while smaller halos (starting from the Jeans mass) work as ‘recombination sinks’ of ionizing radiation due to their higher hydrogen density. At each redshift, we calculate the fraction of halos that contain ionization or recombination sources by using extended Press-Schechter formalism (Press & Schechter 1974; Bond et al. 1991; Bower 1991; Lacey & Cole 1993). By solving numerically the main equation of the ‘bubble model’ which relates the mass of ionized gas, the mass of recombined hydrogen and the mass of baryons collapsed into galaxies, we calculated the threshold $\delta_\text{crit}$ for initial mass overdensities as a function of redshift $z$ and the variance $\sigma^2$ of power density spectrum. Then, approximating threshold as a linear function of $\sigma^2$, $\delta_\text{crit}(z,\sigma^2) = \delta_0 + B_1\sigma^2$, we obtain an analytic expression for the halo mass function, finally used to calculate the ionizing volume filling fraction $Q_{\text{II}}(z)$.

The model contains several input parameters:

- linear dark matter power spectrum $P(k)$, e.g. for CDM or sterile neutrino dark matter;
- minimum ‘virial temperature’ $T_{\text{vir}}$ of dark matter halos that host stars responsible for reionization, see Haiman et al. (2000); Barkana & Loeb (2001) and references therein;
- ionizing efficiency $\xi$, which is the number of ionizing photons released by stars in galaxies per baryon collapsed into DM halos;
- recombination efficiency $\zeta$, which is the average number of recombinations per atom in collapsed minihaloes (Haiman et al. 2001; Iliev et al. 2005) during the whole epoch of reionization.

We focused on three dark matter models: cold dark matter (CDM) and two models of sterile neutrino dark matter able to explain the observed properties of the 3.5 keV line — the model L12 (sterile neutrino generated with lepton asymmetry $Q_\nu = 12$, that corresponds to sterile neutrino mixing angle $\sin^22\theta_{12} = 1.6 \times 10^{-11}$, see Fig. 1 of Lovell et al. (2016)) and the model s228899 (sterile neutrino with mixing angle $\sin^22\theta_{12} = 2.8899 \times 10^{-11}$, see Horiiuchi et al. (2016)). Our choice of sterile neutrino dark matter parameters is in agreement with the recent structure formation and X-ray constraints (Baur et al. 2017; Boyarsky et al. 2018).

The value of $T_{\text{vir}}$ is related to the minimal mass $M_{\text{vir}}$ of dark matter halos which host stars (Barkana & Loeb 2001):

$$M_{\text{vir}} = 1.0 \times 10^8 \left(\frac{1+z}{10}\right)^{-3/2} \frac{\left(\frac{\mu}{0.6}\right)^{-3/2} \left(\frac{T_{\text{vir}}}{1.98 \times 10^4 \text{K}}\right)^{1/2} \left(\frac{\Omega_m}{\Omega_m^\text{vir}}\right)^{-1/2}}{\Omega_m^\text{vir} 18\pi^2} \text{M}_\odot/\text{h}_1, \tag{1}$$

where $z$ is the halo redshift, $\mu = 0.60$ is the mean molecular weight, $\Omega_m^\text{vir} = 1 - \Omega_A/([\Omega_m(1+z)^3 + \Omega_A]$ and $\Delta_c = 18\pi^2 + 82(\Omega_m^\text{vir} - 1) - 39(\Omega_m^\text{vir} - 1)^2$ (Bryan & Norman 1998). According to Sec. 3.3 of Barkana & Loeb (2001), hydrogen cooling becomes efficient for $T_{\text{vir}} \gtrsim 6 \times 10^4 \text{K}$. In this paper, we fixed $T_{\text{vir}} = 10^4 \text{K}$ similarly to Barkana & Loeb (2001); Furlanetto et al. (2004); Yue & Chen (2012); Rudakovskyi & Iakubovskyi (2016). Finally, we assume the ionizing efficiency and the recombination efficiency to vary within the very wide ranges $\zeta = 5-100$ (which is in agreement with Greig & Mesinger (2017)\footnote{Note that our definition of $\zeta$ is similar to Rudakovskyi & Iakubovskyi (2016) and doesn’t include average number of recombinations in the Universe, unlike, e.g., Furlanetto et al. (2004); Lopez-Honorez et al. (2017).} and $\xi = 0-9$ (according to Iliev et al. (2005)\footnote{Our definition of $\xi$ is related to definition by Iliev et al. (2005) as $\xi = \xi_{\text{low}} - 1$.}).

For an up-to-date summary of observational constraints on reionization history, see, e.g., Mitra et al. (2015); Bouwens et al. (2015); Robertson et al. (2015); Greig & Mesinger (2017); Konno et al. (2018). However, many of the measurements reported in these papers were obtained by assuming some particular model of reionization. Since our goal is to compare reionization in different dark matter models — cold dark matter (CDM) and 7 keV sterile neutrino dark matter potentially responsible for the narrow line at 3.5 keV, — it is important to use measurements that are fully or almost fully model-independent, and to quantify the maximal level of uncertainty for the second case. Therefore, we constructed the following extension of the ‘Gold Sample’ of Greig & Mesinger (2017) (all error bars are quoted at 1$\sigma$ level) further used in our modeling:

- the final value of the electron scattering optical depth $\tau_{\text{es}} = 0.054 \pm 0.007$ obtained from the combination of the Planck temperature correlations (TT) and E-mode polarization (EE) correlations at low multipoles $l = 4-20$, see Planck Collaboration et al. (2018). According
to Mesinger et al. (2013), this value is only approximately model-independent in case of ‘patchy’ reionization: since regions with higher electron density become reionized earlier, the all-sky averaged value of $\tau_{\text{es}}$ can increase by $\lesssim 4\%$, or by $\lesssim 0.2\sigma$, so we assume the value of $\tau_{\text{es}}$ to be the same for sterile neutrino models and CDM.

- the lower bounds of the ionized volume-filling fraction (together with their lower 1σ errorbars) $Q_{\text{II}} \geq 0.96 - 0.05$, $Q_{\text{II}} \geq 0.94 - 0.05$ and $Q_{\text{II}} \geq 0.62 - 0.20$ obtained from the model-independent analysis of ‘dark pixel’ fraction in QSO spectra (McGreer et al. 2015) at redshifts $5.48-5.68$, $5.77-5.85$ and $5.97-6.17$, respectively.

- the value of $Q_{\text{II}}$ obtained from the analysis of Lyman-α damping wing in the spectra of the quasars ULASJ1120+0641 (Greig et al. 2017) and ULASJ1342+0928 (Greig et al. 2018). To convert the Lyman-α damping wing observations into $Q_{\text{II}},$ (Greig et al. 2017, 2018) used different models where the driving sources for reionization are faint galaxies (with halo masses $10^8-10^9M_\odot$) and bright galaxies (with halo masses $\sim 10^7M_\odot$). For these models, one obtained $Q_{\text{II}} = 0.60_{-0.21}^{+0.19}$ and $0.54_{-0.21}^{+0.21}$ at redshift $z = 7.1$, and $Q_{\text{II}} = 0.79_{-0.17}^{+0.19}$ and $0.72_{-0.30}^{+0.23}$ at redshift $z = 7.5$. The observed difference between these two models is about $0.3\sigma$, and the expected difference between the CDM and sterile neutrino models is even less (see Discussion in Rudakovskiy & Jakubovskiy 2016), so we constructed the average value $Q_{\text{II}} = 0.56 \pm 0.23$ for $z = 7.1$, and $Q_{\text{II}} = 0.75 \pm 0.23$ for $z = 7.5$ (by incorporating the error bars from both models) to be the same for CDM and sterile neutrino dark matter.

For each dark matter model of our interest (CDM, L12, s228899), we calculate the best-fit values of $\xi$ and $\xi$ by minimizing $\chi^2_{\text{tot}}$ — the value of $\chi^2$ statistics between the model predictions for $Q_{\text{II}}(z)$ and $\tau_{\text{es}}$ and observations. Because the ‘dark pixel’ priors indicate only the lower bounds on the fraction of ionized hydrogen, we assume no contribution to $\chi^2_{\text{tot}}$ if the theoretically predicted $Q_{\text{II}}(z)$ are larger than the mean values of ‘dark pixel’ data at the corresponding redshift. Throughout this paper, we assumed the following values of the cosmological parameters consistent with the final Planck results (Planck Collaboration et al. 2018): $\Omega_\Lambda = 0.685$, $\Omega_m = 0.315$, $\Omega_b = 0.049$, $n = 0.961$, $\sigma_8 = 0.811$ and $h = 0.674$ (we also repeated our calculations using the Planck-LXVI parameters Planck Collaboration (2016) and obtained that the our results do not change significantly).

3 RESULTS

We summarize the obtained results in Fig. 1, which shows evolution of ionized volume filling fraction $Q_{\text{II}}(z)$ and the value of electron scattering optical depth $\tau_{\text{es}}$. The filled light-green regions correspond to the range of reionization histories with $\Delta \chi^2_{\text{tot}} = \chi^2_{\text{tot}} - \chi^2_{\text{tot, min}} \leq 4.61$, 3 obtained for each of three dark matter models of our interest (CDM, L12 and s228899), together with the observational priors described in detail in Sec. 2.

We obtained statistically acceptable fit for all three models (given 4 degrees of freedom), resulting in $\chi^2_{\text{tot, min}} = 5.79$ for CDM, $\chi^2_{\text{tot, min}} = 3.80$ for L12, and $\chi^2_{\text{tot, min}} = 2.98$ for s228899 model. Although 7 keV sterile neutrino dark matter models appear to be more statistically preferred than the CDM model, the difference of $\chi^2_{\text{tot, min}}$ is too small to make statistically robust preferences between these models.

4 DISCUSSION

In this paper, the Pop II stars in galaxies are assumed as the main source of ionizing photons. In reality, other sources (such as active galactic nuclei (AGN) or possible decays of dark matter particles) could produce ionizing photons during reionization epoch. However, the AGN contribution to reionization budget is usually thought to be sub-dominant, according to recent observational (see Kashikawa et al. (2015); Ricci et al. (2017); Onoue et al. (2017); Parsa et al. (2018)) and numerical studies (Oførbe et al. 2017; Qin et al. 2017; Hassan et al. 2018) (see, however, Giannone et al. (2015); Madau & Haardt (2015); Chardin et al. (2017); Bosch-Ramon (2018)). The contribution from the sterile neutrino DM decays is negligible since the expected lifetime of 7 keV sterile neutrino that may be responsible for the 3.5 keV emission line is at least at two orders of magnitude greater than the maximum lifetime of decaying dark matter particles that could re-ionize the universe near $z = 6$ (Liu et al. 2016; Oldengott et al. 2016; Slatyer & Wu 2017; Poulin et al. 2017).

The recombination rate is proportional to the squared density of ionized gas; thus it is substantially boosted in high-dense neutral regions. The presence of neutral inhomogeneities should significantly affect the reionization history (Haiman et al. 2001; Iliev et al. 2005; Ciardi et al. 2006; McQuinn et al. 2007; Finlator et al. 2012; Kaurow & Gnedin 2014; Sobacchi & Mesinger 2014; Park et al. 2016). In this paper, we assumed that the sinks of ionizing photons are the neutral minihaloes with masses in range from the Jeans mass up to the mass of the lightest galaxies and modelled them similarly to Rudakovskiy & Jakubovskiy (2016). For $\xi = 3-9$ we obtain that, on average, two to three photons per hydrogen atom are required to ionize the Universe in the CDM cosmology, which is in good agreement with Kaurow & Gnedin (2014); So et al. (2014); Sobacchi & Mesinger (2014). In the warm dark matter models based on thermal relics or sterile neutrino, the formation of minihaloes is suppressed; therefore, the average number of recombinations is reduced, see (Yue & Chen 2012; Rudakovskiy & Jakubovskiy 2016).

5 CONCLUSIONS

By using the extended ‘Gold sample’ (Greig et al. 2017) of the existing measurements during the epoch of reionization, we found that both CDM and the 7 keV sterile neutrino
models describe well the observational data on reionization. The obtained difference between the $\chi^2$ statistics for CDM and sterile neutrino dark matter is $\Delta \chi^2_{\text{tot}} < 2 - 3$ depending of the sterile neutrino model of our choice\textsuperscript{4}. Taking into account the effects of baryonic feedback into reionization model could make this difference even smaller, in accordance with Dayal et al. (2017a); Lopez-Honorez et al. (2017). Therefore, we conclude that existing observations of reionization do not allow to make any statistically significant distinction between the cold dark matter and 7 keV.

\textsuperscript{4}The difference of $\chi^2_{\text{tot}}$ values for L12 and s228899 sterile neutrino models is only 0.82, significantly smaller than the difference between CDM and each of sterile neutrino models (1.99 and 2.81 for L12 and s228899 models, respectively). Therefore, we expect that the fact that sterile neutrino models slightly better fit the available data on reionization to be independent of particular choice of sterile neutrino models.
sterile neutrino dark matter models. Also, our results qualitatively confirm the recent findings (Dayal et al. 2017a; Lopez-Honorez et al. 2017) for the warm dark matter model with thermal relics.

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