Influence of $\sim 7$ keV sterile neutrino dark matter on the process of reionization

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Abstract. Recent reports of a weak unidentified emission line at $\sim 3.5$ keV found in spectra of several matter-dominated objects may give a clue to resolve the long-standing problem of dark matter. One of the best physically motivated particle candidate able to produce such an extra line is sterile neutrino with the mass of $\sim 7$ keV. Previous works show that sterile neutrino dark matter with parameters consistent with the new line measurement modestly affects structure formation compared to conventional cold dark matter scenario. In this work, we concentrate for the first time on contribution of the sterile neutrino dark matter able to produce the observed line at $\sim 3.5$ keV, to the process of reionization. By incorporating dark matter power spectra for $\sim 7$ keV sterile neutrinos into extended semi-analytical ‘bubble’ model of reionization we obtain that such sterile neutrino dark matter would produce significantly sharper reionization compared to widely used cold dark matter models, impossible to ‘imitate’ within the cold dark matter scenario under any reasonable choice of our model parameters, and would have a clear tendency of lowering both the redshift of reionization and the electron scattering optical depth (although the difference is still below the existing model uncertainties). Further dedicated studies of reionization (such as 21 cm measurements or studies of kinetic Sunyaev-Zeldovich effect) will thus be essential for reconstruction of particle candidate responsible the $\sim 3.5$ keV line.

Keywords: reionization, dark matter theory, dark matter experiments

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1 Introduction

The nature of missing mass of the Universe — presumably in form of gravitating dark matter — is largely unknown. For example, Standard Model of particle physics does not provide a viable candidate for a dark matter particle. If the dark matter consists of elementary particles, they may have non-zero initial velocities affecting the structure formation due to their ‘free streaming’ from potential wells, see e.g. [1]. The most commonly used type of dark matter is cold dark matter (CDM) where free streaming effects are negligible. Although there are well-motivated particle physics candidates for CDM such as weakly interacting massive particles (WIMPs) [2–5] or axions [7–9], they by no means exhaust the complete list of dark matter particle candidates, see e.g. reviews [10–12].

For example, one of the best physically-motivated dark matter candidates is the right-handed (sterile) neutrino [13, 14], see also an extensive recent review [15]. It has been shown that the minimal extension of the Standard Model by three sterile neutrinos (dubbed νMSM) [16, 17] can be responsible for dark matter as well as for a number of another observed phenomena including neutrino oscillations and observed asymmetry between matter and antimatter in the Universe, see [18] for a review. Formation of dark matter sterile neutrinos in early Universe primarily depends on production mechanism because they have never reached thermal equilibrium, contrary to WIMPs or Standard Model (‘active’) neutrinos. In the νMSM, the lightest sterile neutrinos responsible for dark matter are produced by oscillations of ‘active’ neutrinos in primeval plasma with a substantial amount of lepton asymmetry generated by earlier decays of two heavier sterile neutrinos [19–22]. As a result, the properties of sterile neutrino dark matter in the νMSM are determined by three parameters — the mass of dark matter particle $M_s$, its mixing angle $\theta$ with Standard Model neutrinos and the value of lepton asymmetry during the particle production.

The parameters $M_s$ and $\theta$ can be reconstructed from the 2-body radiative decay line flux $F_\gamma$ at energy $E_\gamma$ expected from direction of dark matter haloes located at distance $D_L$ with dark matter mass inside the instrument’s field-of-view $m_{DM}^{\text{fov}}$, see e.g. [23]:

$$\sin^2(2\theta) = 7.8 \times 10^{-10} \left(\frac{F_\gamma}{10^{-6} \, \text{ph/cm}^2/\text{s}}\right) \left(\frac{D_L}{1 \, \text{kpc}}\right)^2 \left(\frac{10^6 \, \text{M}_\odot}{m_{DM}^{\text{fov}}}\right) \left(\frac{1 \, \text{keV}}{M_s}\right)^4,$$

(1.1)

$M_s = 2E_\gamma$. A possible line from decaying dark matter seen at $E_\gamma \simeq 3.55$ keV has been reported by [24–28], see also recent reviews [15, 29]. The observed line parameters are consistent with sterile neutrino parameters $M_s \simeq 7.1$ keV and $\sin^2(2\theta) \simeq (2 - 20) \times 10^{-11}$ with

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Note that the spectrum of ultra-light axion-like dark matter particles significantly differs from that for CDM, see [6] for a recent review.
the preferred region of $\sin^2(2\theta) \simeq (4.5 - 6) \times 10^{-11}$ [26, 28, 30]. The corresponding values of lepton asymmetry obtained under assumption that such sterile neutrino constitutes the bulk of dark matter in the Universe are then used to produce the power spectra of sterile neutrino dark matter [31–33] and to investigate their influence on various outputs of cosmological structure formation such as subhalo number counts [31, 34–36] and subhalo velocity function [34, 35, 37] in the Local Group, central mass density distributions in nearby haloes and subhaloes [34, 35, 37, 38], mass of Milky Way halo hosting observable number of satellite galaxies [33], high-$z$ galaxy counts [31] and 3D matter power spectra [36, 37], 1D matter power spectra probed by Ly-$\alpha$ observations [36], halo mass functions [38], concentration-mass scaling relation for dark matter haloes [38–41], maximal values of dark matter phase-space density in dwarf spheroidal galaxies [31], shapes and spins of dark matter haloes [38], mass assembly history and infall time of the Fornax dwarf spheroidal galaxy [42], anomalous flux ratios in strong lensed systems [43].

In this paper, we study the influence of sterile neutrino dark matter particles on the process of reionization, see e.g. extensive reviews [44–47]. Generally, in models with non-zero initial velocities of dark matter particles the structure formation should be delayed due to dark matter free streaming, see e.g. figure 3 of [48], causing a lack of HI ionizing photons, later end of reionization and smaller CMB electron scattering optical depth $\tau_{es}$. On the other hand, because the haloes with the smallest mass could significantly contribute to recombination process effectively reducing the number of ionizing photons, see e.g. [49–56], one may expect reionization to be completed at earlier times due to shortage of such smaller mass haloes in models with non-zero initial dark matter velocities. The effect has been first found in [57], see also [58–62] for study of reionization in dark matter models in form of thermal relics with the mass of keV range. In their figure 2, [57] showed that the reionization in thermal relic dark matter model with 10 keV mass finished earlier than in cold dark matter scenario, and that the process of reionization becomes sharper (in units of redshift) for warm dark matter compared to the CDM case. The results of these numerous studies, however, cannot be directly applied to study the process of reionization in realistic sterile neutrino dark matter models having non-thermal initial velocity distribution of dark matter particles [19, 20]. The goal of this paper is to extend the findings of [57] for the first time to the case of sterile neutrino dark matter able to reproduce the observed emission line at $\sim$3.5 keV, and to compare them with the up-to-date theoretical and observational uncertainties.

2 Methods

To describe the process of reionization, we extended the ‘bubble model’ formalism of [63] in a way close to [57] who analyzed reionization for dark matter models in form of thermal relics with masses 2 and 10 keV. We assume that the main source of ionizing photons are Pop II stars formed in galaxy-size haloes and consider mini-haloes only as additional ‘sinks’ of ionizing radiation.

In the original bubble model formalism [63], the mass of gas ionized by Pop II stars $m_{\text{ion}}$, the mass of recombed hydrogen $m_{\text{rec}}$ and the mass of baryons collapsed into galaxies $m_{\text{gal}}$ are related with the simple linear expression

$$\zeta m_{\text{gal}} = m_{\text{ion}} + m_{\text{rec}}, \quad (2.1)$$

where $\zeta$ is the number of ionizing photons per baryon released due to star formation during the process of halo collapse.
We consider the following parametrization for $\zeta$ similar to [57]:

$$\zeta = f_s \times N_{\gamma/b} \times f_{esc},$$  

(2.2)

where $f_s$, $N_{\gamma/b}$, $f_{esc}$ are the star formation efficiency, the number of ionizing photons emitted per baryon in stars, and the fraction of ionizing photons escaping from galaxies. Unlike e.g. [64, 65], we assume that these parameters remain constant with redshift.

Our fiducial value $\zeta = 15$ is chosen close to the most probable value of [66] which gives $\zeta \simeq 10 - 40$ based on $N_{\gamma/b} = 3200$. However, there is a large spread in the literature among astrophysical parameters coming to $\zeta$. For example, ref. [63] used $f_{esc} = 0.2$, $f_s = 0.05$, $N_{\gamma/b} = 3200$, which results in $\zeta = 32$. According to section 2.3 of [67], for Pop II low metallicity stars with a Salpeter IMF $N_{\gamma/b} = 3 \times 10^8$ [68], which gives $\zeta = 30 - 100$ for $f_{esc} f_s = 0.01$. Ref. [69] proposed the fiducial value $\zeta = 3200$. However, there is a large spread in the literature among astrophysical parameters coming to $\zeta$.

To collapse, a ‘bubble’ region is assumed to contain mass in stars enough to ionize all hydrogen atoms, so that the collapsed fraction $f_{coll}$ should not be smaller than the ratio of $m_{gal}/(m_{ion} + m_{rec})$:

$$\zeta f_{coll} \geq 1 + \xi f_{rec},$$  

(2.3)

where $f_{rec} = m_{rec}/(\xi m_{ion})$, $\xi$ is the average number of recombinations per atom in collapsed mini-haloes during the whole epoch of reionization.

We determine $f_{coll}$ and $f_{rec}$ as functions of halo mass $m$, redshift $z$ and mass overdensity $\delta_z$ by using the extended Press-Schechter formalism [78–81]:

$$f_{coll} = \mathcal{E}(m, \delta_z|m_{\min}, \delta_c/D(z)),$$

$$f_{rec} = \mathcal{E}(m, \delta_z|m_{1}, \delta_c/D(z)) - \mathcal{E}(m, \delta_z|m_{\min}, \delta_c/D(z)),$$

(2.4)

where

$$\mathcal{E}(m, \delta_z|m_i, \delta_c/D(z)) = \text{erfc} \left( \frac{\delta_c/D(z) - \delta_z}{\sqrt{2(\sigma^2(m_i) - \sigma^2(m))}} \right),$$  

(2.5)

$\delta_z \approx 1.676$ for a flat $\Lambda$CDM model, $D(z)$ is the perturbation growth function [84],

$$D(z) = D_1(z)/D_1(0), \quad D_1(z) = \frac{5\Omega_0}{2} g(z) \int_z^\infty dz' \frac{1 + z'}{g(z')}^3,$$

(2.6)

(see also [85] for an exact analytic expression for $D_1$), $\sigma^2(m)$ is expressed through power spectrum $P(k)$ using sharp $k$-space filter similar to [33, 36, 39, 87–89]:

$$\sigma^2(m) = \frac{1}{2\pi^2} \int_0^{k_s} k^2 P(k) dk, \quad k_s = a \left( \frac{4\pi\bar{\rho}}{3m} \right)^{1/3},$$

(2.7)

$a = 2.7$ [33], $\bar{\rho} = \Omega_0 \rho_{crit}$ is the present-day average mass density in the Universe.

\footnote{Throughout this paper we used the latest best-fit cosmological parameters of Planck satellite [82]: $\Omega_0 = 0.307$, $h = 0.678$, $\Omega_{\Lambda} = 0.693$, $\Omega_m = 0.0483$, $\Omega_s = 0.823$ and $n_s = 0.961$.}

\footnote{Here, $P(k)$ encodes the information about properties of dark matter particles, e.g. parameters $M_*, \sin^2(2\theta)$ and the value of lepton asymmetry, see [20, 31, 32, 86] for detailed calculations used in our paper.}
The minimal mass of collapsing haloes

\[ m_{\text{min}} = 3.59 \times 10^7 \ h^{-1} \ M_\odot \left( \frac{0.6}{\mu} \right)^{3/2} \left( \frac{10}{1+z} \right)^{3/2} \]  

(2.8)

is taken from an assumption [90] that the clouds will not fragment into new stars until their virial temperature is higher than \( T_{\text{vir}} > 10^4 \) K, so the haloes can be cooled by atomic hydrogen, according to e.g. figure 12 and eq. (26) of [44]. Here we use mean molecular weight \( \mu = 0.6 \) as the average of \( \mu = 0.59 \) for a fully ionized primordial gas and \( \mu = 0.61 \) for a gas with ionized hydrogen but only singly ionized helium, see section 3.3 of [91].

The minimal mass of mini-haloes responsible for recombinations (assumed to take place with the average number \( \xi \) per atom) is the Jeans mass,

\[ m_J = 3.96 \times 10^3 \ h^{-1} \ M_\odot \left( \frac{0.307}{\Omega_0} \right)^{1/2} \left( \frac{0.0222}{\Omega_b h^2} \right)^{3/5} \left( \frac{1+z}{10} \right)^{3/2} \]  

(2.9)

see eq. (41) of [44]. Our fiducial value of \( \xi = 5 \) and bounding values \( \xi = 1 \) and \( \xi = 9 \) were taken consistent with simulations of [51, 52], see also figure 1 of [92] as an illustration of apparent uncertainty.

By solving numerically eq. (2.1) using an approximation eq. (2.4) we obtained \( \delta(x, \sigma^2(m)) \). Consider then a linear barrier approximation \( \delta(x) \approx B(m) \equiv B_0 + B_1 \sigma^2(m) \) where \( B_0 \) and \( B_1 \) are calculated at the infinite masses (so that \( \sigma^2 = 0 \)). In this case, an analytic expression for the mass function is [93]:

\[ m \frac{dn}{dm} = \sqrt{\frac{2}{\pi m}} \left| \frac{d}{d \log m} \frac{B_0}{\sigma(m)} \exp \left[ - \frac{B^2(m)}{2\sigma^2(m)} \right] \right|. \]  

(2.10)

The volume filling fraction \( Q_\Pi(z) \) is then calculated:

\[ Q_\Pi(z) = \int \frac{m \ dn}{\rho \ dm} \ dm. \]  

(2.11)

Motivated by recent study of [94] we define the length of reionization \( \Delta z_{\text{rei}} \) as difference between the redshifts with volume fractions 0.9 and 0.1:

\[ \Delta z_{\text{rei}} = z(Q_\Pi = 0.1) - z(Q_\Pi = 0.9). \]  

(2.12)

We also assume that the reionization has been completed at \( z_{\text{rei}} = z(Q_\Pi = 0.99) \).

To calculate the CMB electron scattering optical depth \( \tau_{\text{es}}(z) \) at redshift \( z \), we used eq. (9) of [62]

\[ \tau_{\text{es}}(z) = c\bar{n}_H \sigma_T \int_0^z f_e(z') Q_\Pi(z') \left( \frac{1+z'}{H(z')} \right)^2 dz', \]  

(2.13)

where \( c \) is the speed of light, \( \bar{n}_H \) is the mean comoving number density of hydrogen atoms, \( \sigma_T \) is the Thomson cross section, \( f_e(z) \) is the number of free electrons per hydrogen atom calculated under assumption of [95], and \( H(z) \) is the Hubble parameter.

\textsuperscript{4}Note that our definition of \( \xi \) is different from that of [52]: \( \xi = \xi_{\text{ion}} - 1 \).
3 Results and conclusions

We analyze the process of reionization in several dark matter models, including cold dark matter and several sterile neutrino dark matter models depicted in figure 4 of [33] calculated using approach of [20, 86], as well as sterile neutrino dark models from figure 2 of [34] calculated using another approach [31, 32].

The models of [33] are parametrized by the value of lepton asymmetry

$$L_6 \equiv 10^6 \frac{n_{\nu_e} - n_{\bar{\nu}_e}}{s},$$

(3.1)

where $n_{\nu_e}$ and $n_{\bar{\nu}_e}$ are the number densities of electron neutrinos and antineutrinos, $s$ is the total entropy density. For a sterile neutrino dark matter with the mass of 7 keV, the value of $L_6$ can be translated to sterile neutrino mixing angle (eq. (1.1)), according to figure 1 of [33]. For example, the region for $\sin^2(2\theta) \simeq (4.5 - 6) \times 10^{-11}$ preferred by the $\sim 3.5$ keV line measurements [26, 28, 30] corresponds to $L_6 \simeq 9 - 10$. As a result, we consider the model with $L_6 = 10$ as our fiducial model, in addition to the model s228899 of [34] which corresponds to $\sin^2(2\theta) = 2.8899 \times 10^{-11}$. The values of $L_6 \gtrsim 10$ would produce smaller mixing angles and therefore cannot explain the observed $\sim 3.5$ keV line but are not excluded by existing measurements, so we consider them for illustrative purposes, as well as the model s208 of [34] which corresponds to $\sin^2(2\theta) = 0.8 \times 10^{-11}$.

We summarize the obtained results in table 1 where we mark in bold our fiducial models that match the existing observational constraints ($z_{\text{reion}} \gtrsim 5.6$, $\tau_{\text{es}} = 0.046 - 0.103$), see also detailed discussion in [96, 97]:

- Lyman-\(\alpha\) forest transmission [98] requires $Q_{\text{II}} \simeq 0.96 - 0.99$ at $z = 6.2$;
- dark Lyman-\(\alpha\) pixels [99] suggests 1\(\sigma\) upper bounds: $Q_{\text{II}} > 0.89$ at $z = 5.9$, $Q_{\text{II}} > 0.91$ at $z = 5.5$;
- the presence of Gunn-Peterson damping wings in high-$z$ quasar spectra, see e.g. [100, 101] (see however [102]) suggests upper bound $Q_{\text{II}} \lesssim 0.97$ at $z \approx 6$;
- the absence of Gunn-Peterson damping wings in high-$z$ GRB spectra implies 2\(\sigma\) bound $Q_{\text{II}} \geq 0.89$ at $z = 5.913$ [103];
- the redshift decline of the Lyman-\(\alpha\) emitter luminosity function suggests $Q_{\text{II}} \sim 0.58 - 0.88$ at $z = 6.6$ and $Q_{\text{II}} \sim 0.46 - 0.88$ at $z = 7.0$ [104], and $Q_{\text{II}} \gtrsim 0.5 - 0.6$ (with the strongest model-dependent constraint $Q_{\text{II}} \gtrsim 0.8 \pm 0.2$) at $z = 6.6$ [105];
- electron scattering optical depth $\tau_{\text{es}}$ inferred from CMB measurements. Throughout this paper, we used the latest values $\tau_{\text{es}} = 0.058 \pm 0.012$ recently reported by Planck collaboration [106] for their combined analysis of Planck E-mode polarization correlations at low-$l$ (lollipop) and Planck temperature-temperature (TT) correlations. However, we should also be aware of the previous release of Planck data resulting in $\tau_{\text{es}} = 0.066 \pm 0.016$ [82], and of previous experiment WMAP which gives $\tau_{\text{es}} = 0.089 \pm 0.014$ [107].

Figure 1 illustrates evolution histories for $Q_{\text{II}}$ and $\tau_{\text{es}}$ for our fiducial models. Interestingly, in our sterile neutrino dark matter models L8-15-5 and L10-15-5 reionization completed at earlier times compared to the corresponding cold dark matter model CDM-15-5; despite
**Table 1.** The values of $z_{\text{rei}} = z(Q_{\text{II}=0.99})$, $\Delta z_{\text{rei}}$ (eq. (2.12)) and $\tau_{\text{es}}$ (eq. (2.13)) for reionization models considered in this paper. For models starting with L, the first number denotes the value of electron lepton asymmetry $L_6$ according to eq. 3.1; for models starting with s2, the first number denotes sterile neutrino mixing angle $\sin^2(2\theta)$ in units of $10^{-11}$ according to eq. 1.1. Our model parameters $\zeta$ and $\xi$ denote dimensionless ionization efficiency (the number of UV ionizing photons produced per baryon in haloes released in the process of halo collapse) and minihalo recombination efficiency (the number of recombinations per atom in collapsed mini-haloes), see section 2. The models CDM-5-5 and CDM-5-1 are excluded having reionization finished too late; on the other hand, the models CDM-45-5, CDM-15-1 and CDM-45-9 are in tension with Planck measurements of $\tau_{\text{es}}$ [82, 106] and have reionization too early contrary to upper bounds on $Q_{\text{II}}$ obtained by [100, 101]. In addition to CDM models, we show the behavior of sterile neutrino dark matter models L10-15-5 of [33] and s228899-15-5 of [34] as our fiducial models able to reproduce the observed emission line at $\sim$3.5 keV, see [26, 28, 30] for details. Other sterile neutrino dark matter models are presented for illustrative purposes. The obtained change in $z_{\text{rei}}$ (up to 0.4) and $\tau_{\text{es}}$ (up to 0.018) between these models and the cold dark matter model CDM-15-5 is below the existing uncertainties on reionization efficiency $\zeta$ and the possible QSO contribution [108] but is comparable with e.g. possible contribution of Pop III stars [109] and Lyman-limit systems [110]. More important is the systematic decrease in $\Delta z_{\text{rei}}$ (up to 2.6). In all models, matter power spectra were calculated by using the latest best-fit cosmological parameters obtained by Planck satellite, see [82].
Figure 1. Left: dependence of the HII volume filling fraction $Q_{II}$ on redshift $z$ for our fiducial dark matter models, see table 1. L10 indicates the value of electron lepton asymmetry $L_6 = 10$ for models of $[33]$ while s228899 indicates the values of $\sin^2(2\theta) = 2.8899\times 10^{-11}$ for models of $[34]$. Here one may see that in L10 model the reionization is to be completed at earlier times compared to CDM scenario; despite the decrease of halo number density in L10 model should delay the reionization, this is overcompensated by the sufficient decrease in recombinations, see the back dashed line for the same CDM model without recombinations. Right: the same for dependence of electron scattering optical depth $\tau_{es}$ on redshift $z$, plotted against the latest measurements by Planck satellite $[82, 106]$. Although the models CDM-15-5 and L10-15-5 depicted here become offset from 1σ range of $\tau_{es}$ obtained by $[106]$, table 1 shows that this difference can be adjusted with a slight change of ionization efficiency $\zeta$, much smaller than allowed by existing observations.

the decrease of halo number density in sterile neutrino dark matter models should delay the reionization compared to CDM scenario, this is overcompensated by the corresponding shortage of recombinations (see the model CDM-15-0 for details). We should stress, however, that the fact that in the models L8-15-5 and L10-15-5 reionization ends close to that in the model CDM-15-5 is a pure numerical coincidence between smaller halo suppression and the fiducial values of model parameters $\zeta$ and $\xi$. For example, smaller values of $\xi$ adopted in a subsequent paper $[111]$ leads to qualitatively different behaviour of $z_{rei}$: namely, in sterile neutrino dark matter models reionization ends later than in CDM. We discuss this in more details at the end of section 4.

The existing uncertainty in halo ionization efficiency $\zeta$ has the largest impact on reionization parameters $z_{rei}$ (variations up to 7.6) and $\tau_{es}$ (variations up to 0.056), although these variations are well-correlated. The impact of this uncertainty is much above the expected influence of Pop III stars $[109]$ and of Lyman-limit systems $[110]$, and is comparable with the maximal estimated influence of high-$z$ quasars $[108]$. The influence on the length of reionization $\Delta z_{rei}$ is smaller (variations up to 5.4) and is also strongly correlated with the changes of $z_{rei}$ and $\tau_{es}$.

The influence of the uncertainty in minihalo recombination efficiency $\xi$ is the largest in CDM models inducing minor difference of $z_{rei}$ (variations up to 3.1) and $\tau_{es}$ (variations up to 0.031) with much smaller influence on $\Delta z_{rei}$ (variations up to 0.4). For sterile neutrino dark matter models, the influence is by a factor of $\gtrsim 20$ smaller due to strong suppression of mini-haloes and thus can be neglected.

Initial velocities of dark matter particles imposed by sterile neutrino dark matter models with parameters consistent with observation of the new line at $\sim 3.5$ keV (our fiducial models in table 1) introduce a modest influence on $z_{rei}$ (variations up to 0.4) and $\tau_{es}$ (variations up to
0.018), close to the expected influence of Pop III stars [109] and of Lyman-limit systems [110]. Due to much larger influence of $\zeta$ on $z_{\text{rei}}$ and $\tau_{\text{es}}$, it is not possible to prefer or rule out the selected dark matter model based on existing observational constrains on these parameters. The influence of sterile neutrino dark matter on $\Delta z_{\text{rei}}$, however, is much more profound (variations by 1.6-2.6). Moreover, it is impossible to 'imitate' the effect of sterile neutrino dark matter on the entire set of parameters $\{z_{\text{rei}}, \Delta z_{\text{rei}}, \tau_{\text{es}}\}$ with any reasonable value of $\zeta$ and $\xi$ for CDM models, as table 1 demonstrates.

## Discussion

Throughout this work we assume that the dominant sources of ionizing photons are Pop II stars forming at galaxies. Although such an assumption is often considered to be conventional, see e.g. [44], it by no means excludes possible significant contribution of other ionizing sources. For example, we do not take into account the ionizing UV emission from Pop III stars, because their contribution is very uncertain and is thought to be subdominant [112–114], see however [72, 115]. Recent detailed simulations of [109] show that UV radiation from Pop III stars advance reionization by $\Delta z \leq 1.3$ and increase $\tau_{\text{es}}$ by $\Delta \tau_{\text{es}} \leq 0.019$, comparable with other uncertainties. Similarly, we do not take into account Lyman-limit systems; ref. [110] found that they delay reionization by $\Delta z = 0.6 - 0.8$ with small (by $\sim 0.002$) decrease of $\tau_{\text{es}}$. Also, we do not take into account UV radiation from active galactic nuclei (AGN) because of their suppressed contribution at high redshifts shown in e.g. [66]; although [108] showed that it is even possible to reproduce reionization using AGN as only sources for reionization using new measurement of high-z AGN abundance [116], but this hypothesis is in apparent tension with recent observations of metal absorbers at $z \sim 6$ [117].

The presence of X-ray ionizing radiation may further complicate the description of reionization, because X-rays can easily escape UV bubbles due to their much larger mean free path compared to UV photons. Notably, they may originate in quantities required for reionization not only from conventional astrophysical sources such as X-ray binaries and accreting massive black holes, see e.g. [118], but also from decays of dark matter particles such as sterile neutrinos, see e.g. [119–124]. In addition, dark matter decays could broaden the CMB last scattering surface and could have an imprint on CMB anisotropies [125–127]. Another effect of X-rays (e.g. from decaying dark matter) catalyzing the formation of molecular hydrogen that may speed up gas cooling and star formation suggested by [128] later found negligible [129]. It is important to note, however, that the obtained upper limits on dark matter radiative decay lifetime are about two orders of magnitude weaker than the expected decay lifetime of sterile neutrino dark matter responsible for $\sim 3.5$ keV line, see e.g. figure 10 of [124]. This validates neglecting the effects of dark matter decays throughout this paper.

To further probe the influence of sterile neutrino dark matter on reionization, one needs more detailed observations sensitive to $\Delta z_{\text{rei}}$, in addition to existing probes of $z_{\text{rei}}$ and $\tau_{\text{es}}$. Future measurements of 21-cm line fluctuations (see e.g. [130–133] and references therein) and more detailed study of kinetic Sunyaev-Zeldovich (kSZ) effect (see e.g. ref. [134–136] and references therein) are the straightforward candidates for such an analysis. For example, the value of $\Delta z_{\text{rei}}$ obtained in our preferred sterile neutrino dark matter models tends to be in better consistency with recent kSZ constraints [106, 137], compared with the standard $\Lambda$CDM scenario.

Our work is based on the extension of the initial formalism of [63]. Recently, several physically motivated semi-analytical models have been proposed, based on excursion set
peaks formalism [138], percolation theory [94, 139], the specially adapted GALFORM [140, 141] model of galaxy formation [33, 142, 143], and adjusting better consistency with up-to-date numerical simulations [144]. Because these extensions remain physically well-justified and computationally inexpensive compared to detailed simulations (see e.g. [38, 61, 145] for recent simulations with non-trivial dark matter power spectra), their usage is well-motivated in a future extension of this work.

For example, it is informative to compare our results with the recent findings of [111] who used the GALFORM semi-analytic model of galaxy formation to model reionization for CDM and several sterile neutrino dark matter models (including L8 and L700 models also analyzed in our table 1). First of all, we must emphasize that the authors of [111] have confirmed our major qualitative result — much sharper reionization in sterile neutrino dark matter models compared to ΛCDM. We also confirm the finding of [111] that the median halo mass responsible for reionization is much larger for sterile neutrino dark matter models than that for ΛCDM (expected due to decrease of substantial smaller-mass haloes in sterile neutrino dark matter models). For example, the median halo mass where the recombination is completed at \( z = 10 \) for the model CDM-15-5 is \( 0.8 \times 10^9 \) \( h^{-1} M_\odot \), while for the model L10-15-5 it is \( 5.5 \times 10^9 \) \( h^{-1} M_\odot \) and for the model s228899-15-5 it is \( 1.2 \times 10^{10} \) \( h^{-1} M_\odot \), in agreement with figure 5 of [111]. The fact that in our models L8-15-5 and L10-15-5 reionization finishes faster than in the CDM-15-5 model, contrary to findings of [111], see e.g. their footnote 2, is due to different description of recombination process. For example, the authors of [111] assume the number of recombinations per baryon to be the same for all halo masses, while in our approach it is the same only for minihaloes — where the effect of recombinations should be the most pronounced because of the largest baryon density — which experience the largest dearth due to non-zero initial velocities of sterile neutrino dark matter. Assuming instead that the number of recombinations per baryon is the same for all haloes (which is, in terms of our model, a simple redefinition of \( \zeta \) with taking \( \xi \) to 0), we are able to reproduce the result of [111] that in sterile neutrino dark matter models the reionization ends later than in ΛCDM. However, there is another notable difference between our findings and the results of [111]. Namely, in their models (involving either ΛCDM or sterile neutrino dark matter) the reionization evolves systematically faster (with \( \Delta z_{\text{rei}} \) smaller by a factor of \( \sim 2-3 \)) compared to our results, as well as the results of several other groups [57, 63, 66, 110, 118, 146] (see however [147, 148]). Successful resolution of this difference in \( \Delta z_{\text{rei}} \) (which appears to be sensitive to the very details of reionization astrophysics) will be essential to quantify how much the recently obtained kSZ constraints [106, 137] are better consistent with sterile neutrino dark matter than with conventional ΛCDM scenario.

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