21-cm observations and warm dark matter models

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Observations of the redshifted 21-cm signal (in absorption or emission) allow us to peek into the epoch of the “Dark Ages” and the onset of reionization. These data can provide a novel way to learn about the nature of dark matter, in particular about the formation of small-size dark matter halos. However, the connection between the formation of structures and the 21-cm signal requires knowledge of a stellar to total mass relation, an escape fraction of UV photons, and other parameters that describe star formation and radiation at early times. This baryonic physics depends on the properties of dark matter and in particular, in warm-dark-matter (WDM) models, star formation may follow a completely different scenario, as compared to the cold-dark-matter case. We use the recent measurements by EDGES [J. D. Bowman, A. E. E. Rogers, R. A. Monsalve, T. J. Mozdzen, and N. Mahesh, An absorption profile centred at 78 megahertz in the sky-averaged spectrum, Nature (London) 555, 67 (2018).] to demonstrate that when taking the above considerations into account, the robust WDM bounds are in fact weaker than those given by the Lyman-α forest method and other structure formation bounds. In particular, we show that a resonantly produced 7-keV sterile neutrino dark matter model is consistent with these data. However, a holistic approach to modeling of the WDM universe holds great potential and may, in the future, make 21-cm data our main tool to learn about DM clustering properties.

The hyperfine splitting of the lowest energy level of the neutral hydrogen atom leads to a cosmic 21-cm signal thanks to the abundance of primordial hydrogen. The 21-cm signal from the post-reionization Universe has been studied by a number of experiments (e.g., LOFAR [1, 2], GMRT [3], PAPER [4] (see however [5]), MWA [6]), but the only tentative detection of the 21-cm signal in absorption against the CMB background at $z \sim 16 - 19$ has recently been claimed by the EDGES experiment [7]. It is clear that the forthcoming experiments, such as the staged HERA [10] or future SKA [11, 12] will offer detailed information about the distribution of the 21-cm signal, thus allowing for the full 3D tomography of the signal, offering an unprecedented reach into the early Universe. This makes the study of the 21-cm signal a promising tool to learn not only about cosmological parameters (see, e.g., [13] [15]) but also about different properties of dark matter, including its decays and annihilations [16–21], dark matter-baryon interactions [22–27], and the formation of gravitationally bound structures [28–33].

In this work we focus on the global (sky-averaged) 21-cm absorption signal that appears when the spin temperature (logarithm of the ratio of population of two levels of the hydrogen’s $1S$ state) becomes smaller than the CMB temperature (for a review see, e.g., [29, 32, 34]). The standard explanation for this difference of temperatures is the presence of a bath of Ly-α photons which induce transitions between $1S_1$ and $1S_0$ levels: Ly-α pumping. Therefore, a detection of the global 21-cm absorption signal at some redshift $z_0$ implies that sources of radiation have already been active at that epoch.

With our current knowledge of baryonic physics, we can robustly state that such radiation sources can only form inside dark matter overdensities. Hence, to predict the 21-cm signal one has to follow several steps:

a) Start from the description of bound gravitational structures at a given redshift $z$.

b) Continue with the description of how baryons collapse into these structures (which depends both on the size of the structures, on redshift and on cosmology).

c) Assuming a particular type of radiation sources (as they cannot be modeled from first principles), estimate the number of produced photons and model them (usually through a combination of semianalytical and numerical methods) how radiation escapes from the bound structures and heats the ambient medium;

d) Given the resulting function of radiation density $d\rho_{\text{rad}}/dz$ one can then use available codes (such as ARES [35] or 21CMFAST [36]) to predict the 21-cm signal.

Uncertainties as well as differences in predictions, between DM models are introduced at every step in this process.

(a) Bound DM structures. Historically, the first warm dark matter models were those of sufficiently massive Standard Model neutrinos (see, e.g., [37]). Such particles were in thermal equilibrium in the early Universe and froze out while still being relativistic. They remained relativistic for some period in the radiation dominated epoch and homogenized primordial density perturbations on scales below the free-streaming horizon, $\lambda_{\text{fs}}$ (for a proper definition see, e.g., [38, 39]). The number density of such WDM thermal relics is uniquely determined by the temperature of freeze-out or, equivalently, by their mass, $m_{\text{TH}}$. This mass of the thermal relic is the most typi-
The two models lead to an almost identical shape of the matter power spectrum and therefore their masses are related to one another in a nonlinear way; see [38, 41] for details. In this work we always indicate what definition of mass we are using.

2 An alternative parametrization is given by the mass of nonresonantly sterile neutrinos [30]. The two models lead to an almost identical shape of the matter power spectrum and therefore their masses are related to one another in a nonlinear way; see [38, 41] for details. In this work we always indicate what definition of mass we are using.

### FIG. 1. Halo mass functions of models of our interest at redshifts 17 (left) and 20 (right). The masses that correspond to \( T_{\text{vir}} = 10^3 \) K (molecular cooling) and \( T_{\text{vir}} = 10^4 \) K (atomic cooling) are marked as green dashed vertical lines. At both redshifts the molecular cooling threshold has little effect on the collapsed fraction (1) in WDM and sterile neutrino models, while for CDM the impact of molecular cooling is substantial, as Fig. 5 illustrates.
form stars.

The fraction \( f_{\text{coll}}(z) \) is derived from the halo mass function of a model as

\[
f_{\text{coll}}(z) = \frac{1}{\rho_m} \int_{M_{\text{min}}}^{\infty} \frac{dM}{d\ln M} \frac{dn}{d\ln M},
\]

with a cutoff for halos below mass \( M_{\text{min}} \) which are expected not to be able to form stars. This cutoff is set by the halo’s virial temperature \( T_{\text{vir}} \), the temperature which the gas reaches during the virialization of the halo [45]:

\[
M_{\text{min}} = 1.0 \times 10^8 \left( \frac{1+z}{10} \right)^{-3/2} \left( \frac{\mu}{0.6} \right)^{-3/2} \left( \frac{T_{\text{vir}}}{1.98 \times 10^5 \text{ K}} \right)^{3/2} \left( \frac{\Omega_m}{\Omega_m^*} \right) \left( \frac{\Delta_c}{18\pi^2} \right)^{-1/2} \frac{\text{M}_\odot}{h},
\]

where \( z \) is the halo redshift, \( \mu = 0.60 \) is the mean molecular weight, \( \Omega_m^* = 1 - \Omega_\Lambda / (\Omega_m^0 (1+z)^3 + \Omega_\Lambda) \) and \( \Delta_c = 18\pi^2 / 82(\Omega_m^0 - 1) - 39(\Omega_m^0 - 1)^2 \) [67]. Depending on which mechanism is responsible for cooling, this cutoff may vary: atomic cooling is associated with a cutoff \( T_{\text{vir}} \sim 10^8 \text{ K} \), while molecular cooling leads to a cutoff \( T_{\text{vir}} \sim 10^5 \text{ K} \), see, e.g., Fig. 12 of [45]. The consequences of this parameter are discussed later, and visualized in Fig. 1.

Galaxies or galaxy candidates have been observed for \( z \lesssim 10 \) [65], and we can only extrapolate the aforementioned ansatz for the redshifts of interest. The star-formation efficiency in halos can be estimated from the observed ultraviolet luminosity function (UV LF) (see, e.g., [60, 63]). The dependency \( f_s(M, z) \) on halo mass and redshift depends on the model of star formation, and possible values of \( f_s \) vary in a wide range. For example, in CDM halos \( f_s \) may reach 0.3 at \( z = 5 - 8 \) for \( 10^{11} - 10^{12} \text{ M}_\odot /h \) halos, increase with redshifts, and be close to unity during the Dark Ages [70]. In addition the observational estimates of star-formation efficiency depend on assumed cosmology and \( f_s \) in low-mass galaxies may be higher in WDM compared to CDM (see, e.g., [47, 64]).

Apart from observations, \( f_s \) can be predicted in CDM by use of detailed numerical simulations of the Universe during redshifts \( z \sim 6 - 15 \) [71, 77, 81]. However, there is a three-orders-of-magnitude scatter among the values of \( f_s \) in individual simulated galaxies. As Figs 15 and 16 of [78] demonstrate, a few galaxies with \( f_s \sim 0.3 \) produce an amount of starlight which is several times larger than that of the bulk of galaxies with \( f_s \sim 0.01 \). As a result, it is currently impossible to derive a robust constraint on \( \dot{\rho}_s(z \approx 17) \).

An escape fraction of ionizing photons in galaxies during the reionization and Dark Ages has not been determined directly and is still uncertain (see, e.g., Sec. 7.1 in [32]). However, varying the ionizing photon escape fraction in a wide range does not change the redshift of the \( 21 \)-cm absorption signal significantly. The escape fraction of photons in the band 10.2 – 13.6 eV is usually assumed to be close to unity (see Sec. 3.5 of [71] and references therein).

\( \text{(d) Predicting the 21-cm signal}\) The above-mentioned uncertainty on \( f_s \), translates into a strong systematic uncertainty on WDM parameters that can be probed with a 21-cm absorption signal. In order to demonstrate this, we computed the 21-cm absorption signal using the ARES code for three models: CDM, thermal relics with a mass \( m_{\text{TR}} = 6 \text{ keV} \) (claimed to be excluded in [43, 50]) and the resonantly produced sterile neutrino, with particle mass of \( 7 \text{ keV} \) and lepton asymmetry \( L_9 = 10^2 \). This sterile neutrino model is consistent with all astrophysical and cosmological bounds: x-ray bounds on decaying DM [39, 58, 62], suppression of the power spectrum as inferred from the Lyman-\( \alpha \) forest [33, 65], cosmic reionization [61, 96, 97], and Milky Way satellite and galaxy counts [50, 61].

The results are shown in Fig. 2. The results strongly depend on the range of assumed values of \( f_s \). From the discussion above we see that it should be at least from \( f_s \sim 0.01 \) to \( f_s \sim 0.3 \) (see, e.g., [78]). We see that for \( f_s = 0.09 \) in both 7-keV sterile neutrinos and thermal relics with \( m_{\text{TR}} = 6 \text{ keV} \), the minimum of \( \delta T_\text{res} \) happens around \( z = 17 \), in agreement with the EDGES results. On the contrary, taking \( f_s = 0.03 \) (as done in [43]) would make CDM consistent with the EDGES data, while the two WDM models would have an insufficient number of Lyman-\( \alpha \) photons at the redshifts of interest.

In Fig. 3, we plot the range of \( f_s \)'s that have the minimum of the absorption trough for \( 15.8 \leq z \leq 18.7 \). We see that starting from \( m_{\text{TR}} \lesssim 4 \text{ keV} \), \( f_s \) can be as large as 100% and that for masses of this order or above. Given several orders of magnitude uncertainties in \( f_s \) (as discussed above), the only robust bound can be obtained if one chooses \( f_s = 1 \); at most all baryons enter star formation.

In this case, for example, thermal WDM masses as light as \( m_{\text{TR}} \gtrsim 2 \text{ keV} \) cannot be excluded (see Fig. 4). This puts the sensitivity of the EDGES signal in line with a number of previous bounds on WDM parameters (see, e.g., the Lyman-\( \alpha \) constraints [63], taking into account proper marginalizations over possible thermal histories; bounds [98] from counting of high-z galaxies; bounds [29, 108] from strong gravitational lensing; bounds [101, 102] from the Milky Way satellite counts, etc.). As [103] demonstrates, future measurements of star-formation efficiency at high redshifts, as well as the \( 21 \)-cm power spectrum, are required to improve the sensitivity for WDM particles.

In this paper we have concentrated on the redshift position of minimum of \( \delta T_\text{res}(z) \) as an indicator of star-forming processes at high-redshifts. However, both the depth of the \( 21 \)-cm absorption trough and its width carry important information about the underlying physics.

Much like the position, the width of the obtained profile also depends on the cosmology. When using \( T_{\text{vir}} = 10^3 \text{ K} \) (molecular cooling) and ignoring possible suppression due to the Lyman-Werner radiation"
FIG. 2. $\delta T_b$ as a function of redshift $z$ for three models of interest: CDM, thermal-relic WDM with mass $m_{TH} = 6$ keV, and resonantly produced sterile-neutrino DM with mass 7 keV and lepton asymmetry $L_6 = 10$. For all models the minimal virial temperature of halos is fixed at $T_{vir} = 10^4$ K, corresponding to atomic hydrogen cooling; see, e.g., Fig. 12 and Eq. (26) of [45]. The stellar formation efficiency $f_*$ is chosen to be 0.09. Due to higher star-formation efficiency as compared to e.g., [43, 66], the position of the 21-cm absorption trough becomes consistent with EDGES observations (indicated by the grey vertical lines) for all three models of our interest. The green horizontal line denotes half of the absorption depth; it is plotted in order to illustrate the full width at half maximum of the absorption troughs in the models of our interest.

FIG. 3. The range of values of $f_*$ for which the minimum of the absorption trough lies in the redshift range $15.8 \leq z \leq 18.7$, consistent with EDGES observations. For all models the minimal virial temperature of halos is fixed at $T_{vir} = 10^4$ K, corresponding to atomic hydrogen cooling background (see, e.g., [103]), we see that CDM predicts an absorption-trough width which is larger than the one observed by the EDGES experiment, Fig. 5. For the WDM and $\nu$MSM profiles the molecular cooling brings little to no effect due to the lack of substructures of the mass $\sim M_{\text{min}}$.

The depth of the observed trough is much greater than what any of the models discussed in this paper predict. To date, only additional nongravitational baryon-DM interactions can accommodate such a strong spin-temperature cooling, which is beyond the scope of this paper [22–24, 105].

To summarize, we discussed the large uncertainty in star formation at very high redshifts ($z \sim 17$), which are probed by recent EDGES observations of the global 21-cm signal. As a consequence, using only this signal it is impossible to robustly constrain the parameters of dark matter models, such as the mass of the warm dark matter particle. Conversely, various DM models need distinct star-formation scenarios to fit the signal. Detailed future studies of star formation at very high redshifts ($z \gtrsim 10$), together with detailed modeling of structure assembly and early star formation, will reduce the existing uncertainties. Ongoing and future studies of the 21-cm signal remain promising tools for inferring the key dark matter parameters.

Acknowledgements. We thank Tom Theuns for valuable comments on an earlier version of this paper and the authors of [45] for sharing with us results of their work before publication. The work of D.I. and O.R. was supported by the Carlsberg Foundation. The work of A.R. was partially supported by grant for Young Scientists Research Laboratories of the National Academy of Sciences of Ukraine. A.R. also acknowledges the grant from the Abdus Salam International Centre for Theoretical Physics, Trieste, Italy. This project has received funding from the European Research Council (ERC) under the European Union’s Horizon 2020 Research and Innovation Programme (GA 694896).

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FIG. 4. The same as in Figure 2 but for $f_*=1.0$. As we see, even the thermal WDM model with particle mass $m_{TH}=2$ keV is consistent with observations.

FIG. 5. Left panel: The same as in Fig. 2 but with minimal halo temperature $T_{\text{vir}}=10^3$ K, which corresponds to molecular hydrogen cooling; see, e.g., [109] and Fig. 12 of [45] for details. By comparing with Fig. 2 we see that the decrease of $T_{\text{vir}}$ from $10^4$ K to $10^3$ K essentially does not change absorption profiles for 6-keV WDM and L6 = 10 $\nu$MSM models. In contrast, in the CDM model, predictions change dramatically both in profile width and position of the minimum (here, the black solid curve denotes $T_{\text{vir}}=10^3$ K while black dashed curve denotes $T_{\text{vir}}=10^4$ K), owing to a significant number of small mass halos (cf. [48]).

Right panel: The same profiles as in the left panel but with values of $f_*$ adjusted to match the best-fit position of the EDGES absorption trough.
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