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Constraints on MeV dark matter using neutrino detectors and their implication for the 21-cm results

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The recent results of the EDGES Collaboration indicate that during the era of reionization, the primordial gas was much colder than expected. The cooling of the gas could be explained by interactions between dark matter (DM) and particles in the primordial gas. Constraints from cosmology and particle experiments indicate that this DM should be light (~ 10 – 80 MeV), carry a small charge ($e \sim 10^{-6}$ – 10^{-4}), and only make up a small fraction of the total amount of DM. Several constraints on the DM parameter space have already been made. We explore the yet unconstrained region in the case that the millicharged DM makes up $\sim 2\%$ of the total dark matter, through the scenario in which this DM annihilates only into mu and tau neutrinos. We set upper limits on the annihilation cross section using the Super-Kamiokande data, and predict the limits that could be obtained through Hyper-Kamiokande, JUNO and DUNE. We find that data from Super-Kamiokande is not yet able to constrain this model, but future experiments might be. We furthermore explore DM annihilation into solely neutrinos in general, giving an update of the current limits, and predict the limits that could be placed with future experiments.

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I. INTRODUCTION

Early stars are expected to have imprinted their evidence in the cosmic microwave background (CMB). Their ultraviolet light hit the primordial hydrogen gas, resulting in emission at the 21 cm line. As a response to this, the absorption from CMB photons by the primordial gas caused a spectral signal in the CMB that we should be able to observe today. The recent 21-cm results of the EDGES Collaboration [1] show an absorption profile that is consistent with the expected effect induced by the early stars, although showing an amplitude twice as large as predicted. This result implies that the temperature of the primordial gas was much lower than expected, or that the temperature of the background radiation was higher than expected [2–4].

A possible explanation consistent with the observed results is the cooling of the gas due to interactions with dark matter (DM) [1,5–8], which is causing a lot of excitement in the field. The possibility of such a DM interaction was studied in Refs. [9–11], in which multiple constraints are

put on the nature of the responsible DM. Using data from a variety of experiments, it was found that most of the parameter space that is consistent with the 21-cm observations is ruled out [10] (see also Ref. [12]). The DM responsible for the cooling could only make up a small fraction of the total DM, ~ 0.3 – 2% , and their mass lies in the range of ~ 10 – 80 MeV. Furthermore, the DM should carry a small electric charge on the order of $e \sim 10^{-6}$ – 10^{-4} .

However, assuming that DM interacts with baryons mediated by only photons produces too much DM through the thermal freeze-out mechanism. In order to circumvent this issue, DM must have at least one more interaction channel with the standard model particles. The simplest possibility that has not been ruled out yet is that the DM interacts with lepton number $L_\mu - L_\tau$ via either a scalar or vector mediator [10]. This model is hard to constrain with lab experiments because DM does not interact with electrons, and especially for DM lighter than muons (as it is of main interest here), DM can annihilate only into muon and tau neutrinos.

We investigate this scenario, exploring the yet unconstrained parameter space in the energy range of ~ 10 – 100 MeV. Through flavor mixing, ν_e and $\bar{\nu}_e$ have been generated when the neutrinos reach the Earth, which makes it possible for detectors such as Super-Kamiokande (SK) [13] to detect them through charged-current interactions. These neutrinos will show a very specific spectral feature; e.g., in the simplest model investigated in Ref. [10],

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DM annihilation will produce a neutrino line at its mass ($\chi\chi \rightarrow \nu\bar{\nu}$). The energy range of ~ 10 – 100 MeV, where there are solar, reactor, and atmospheric neutrino backgrounds as well as cosmic-ray muons, has been studied well especially for detecting the diffuse supernova neutrino background [14–16].

We obtain upper limits on the annihilation cross section of this DM in the case that it makes up $\sim 2\%$ of the total DM, the model that could explain the EDGES result, using several years of SK data. We also predict the upper limits that could be obtained by the future experiments Hyper-Kamiokande (HK) [17], the Deep Underground Neutrino Experiment (DUNE) [18] and the Jiangmen Underground Neutrino Observatory (JUNO) [19]. A DM model like this, in which DM only annihilates into neutrinos, but makes up the entire amount of DM, has been studied before [20,21], obtaining upper limits on the cross section using the SK data. We also obtain updated upper limits for this scenario.

The paper is organized as follows. In Sec. II, we discuss millicharged DM and the DM scenario we investigate. In Sec. III, we determine the neutrino flux coming from the annihilation of this millicharged DM, while in Sec. IV, we explain the analysis we perform. In Secs. V and VI, we discuss our results and conclusions respectively.

II. THEORY

A. Millicharged DM

There are some requirements for the properties of DM that need to hold in order for it to be responsible for the extensive cooling of the primordial hydrogen gas [10]. Due to the equipartition theorem, the DM particles should be relatively light. Furthermore, models in which the cross section for dark matter scatterings with gas is independent of the velocity can already be ruled out by constraints from observations of the CMB.

To fulfil these requirements, the mediator of the dark matter–baryon interactions should be lighter than the temperature of the gas at $z \sim 17$. New light mediators in the mass range required to explain the EDGES result are ruled out [22,23], and their contribution to the radiation part of the energy density would exceed the current constraints [24]. When the DM carries a small electric charge, it could couple to the photon. Reference [9] found that, in order to cool the gas sufficiently, the following condition for the electric charge should be fulfilled:

$$\epsilon \approx 1.7 \times 10^{-4} \left(\frac{m_\chi}{300 \text{ MeV}} \right) \left(\frac{10^{-2}}{f_\chi} \right)^{3/4}, \quad (1)$$

where $\epsilon \equiv e_\chi/e$ is the electric charge of the millicharged DM particle, m_χ is its mass and f_χ is its mass fraction of the total DM. The existence of millicharged DM is already constrained by multiple experiments and astrophysical data, leaving only a small open window in its possible

parameter space, with a mass m_χ of ~ 10 – 80 MeV, and a total DM fraction of $f_\chi \sim 0.003$ – 0.02 [10].

However, the annihilation of millicharged DM particles through the exchange of a photon is not sufficient to yield the desired energy density for the particle, $f_{\text{DM}}\Omega_{\text{CDM}}$. Therefore, some additional annihilation needs to take place through a new mediator. Here we specifically study the case of a vector mediator V , while the results for the scalar mediator are essentially the same. Reference [10] found that annihilation through the new vector mediator V into standard model fermions is excluded if it couples to all flavors. This leads to the consideration of annihilation into mainly neutrinos. When the new vector V is related to the gauge group $U(1)_{L_\mu-L_\tau}$, only coupling to muons, taus, muon neutrinos and tau neutrinos is possible. Since V does not couple to electrons, there are currently few constraints from experiments. The annihilation cross section to any neutrino flavor for such a model is given by

$$\langle\sigma v\rangle = \frac{g_\nu^2 g_\chi^2 m_\chi^2 \kappa}{2\pi(4m_\chi^2 - m_\nu^2)^2}, \quad (2)$$

where g_ν and g_χ are the gauge coupling constants of the neutrino and DM particle, respectively, and $\kappa = 1$ ($v^2/6$) for fermion (scalar) DM. We put constraints on this model by evaluating the SK data, and make predictions for some future experiments.

Besides this, we also consider DM annihilation into neutrinos in a broader sense. If dark matter only annihilates into neutrinos, this would be harder to detect than the cases where gamma rays are produced. The limits on the annihilation cross section in this case will therefore be the most conservative ones, and therefore interesting to investigate. We update the limits obtained in Ref. [20], calculating the limits in both the case that DM annihilates to all three neutrino flavors, and the case where it only annihilates into muon and tau neutrinos as discussed above.

III. NEUTRINO FLUX FROM DARK MATTER ANNIHILATION

The final flavor ratio at Earth for pure ν_μ and ν_τ channels is 1:2:2. When Galactic DM annihilates into ν_μ and ν_τ , the expected monochromatic flux of electron (anti)neutrinos at Earth will therefore be given by

$$\frac{d\phi}{dE_\nu} = \frac{\langle\sigma v\rangle}{2} \mathcal{J}_{\text{avg}} \frac{R_{\text{sc}} \rho_0^2 f_\chi^2}{m_\chi^2} \frac{1}{5} \delta(E_\nu - m_\chi), \quad (3)$$

in the case of Majorana DM, where σ is the annihilation cross section, m_χ is the mass of the DM particle, E_ν is the neutrino energy, \mathcal{J}_{avg} is the angular-averaged “ J -factor” of the Milky Way, for which we use the canonical value $\mathcal{J}_{\text{avg}} = 5$ [25], $R_{\text{sc}} = 8.5$ kpc is the scale radius of the Milky Way, and $\rho_0 = 0.3$ GeV cm $^{-3}$ is the DM density at

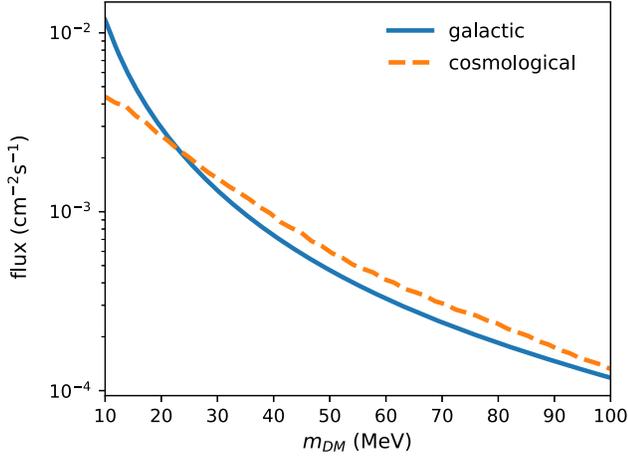


FIG. 1. The total integrated electron neutrino fluxes at Earth of both the cosmological and the Galactic contributions as a function of the DM mass, in the case of 2% Dirac DM annihilating into only muon and tau neutrinos.

the scale radius. To retrieve the electron (anti)neutrino flux for Dirac DM, Eq. (3) has to be divided by 2.

In the thermal freeze-out scenario, the annihilation cross section at freeze-out required to leave the correct relic abundance of MeV DM is given by

$$\langle\sigma v\rangle = \frac{5 \times 10^{-27} \text{ cm}^3 \text{ s}^{-1}}{\Omega_\chi h^2}, \quad (4)$$

for Majorana fermion DM, and is twice as large for Dirac fermion DM for masses below GeV [26]. Since $\Omega_\chi h^2 \approx 0.1 f_\chi$, the targeted annihilation cross section is $\langle\sigma v\rangle \approx 2.5 \times 10^{-24} (f_\chi/0.02)^{-1} \text{ cm}^3 \text{ s}^{-1}$ and $5 \times 10^{-24} (f_\chi/0.02)^{-1} \text{ cm}^3 \text{ s}^{-1}$ for Majorana and Dirac DM respectively.

Besides the Galactic neutrino flux, we also take into account the contribution to the flux coming from DM annihilations outside our galaxy. We adopt the calculation of Ref. [27] with the most recent model of substructure boost [28]. This cosmological neutrino flux is of the same order of magnitude as the Galactic contribution, but it is nonmonochromatic due to its redshift. In Fig. 1, the total integrated fluxes of both the cosmological and the Galactic contributions are shown as functions of the DM mass.

IV. THE ANALYSIS

We set upper limits on the DM annihilation cross section using the latest SK data [13], and predict the upper limits that could be obtained by the future experiments Hyper-Kamiokande [17], DUNE [18] and JUNO [19]. We use the SK data from the first three data periods [13], which contain 2853 days of data taking in total, in the energy range of 16–88 MeV, considering 18 bins with a width of 4 MeV. The expected number of events at the detector coming from DM annihilation is calculated through

$$N_{\text{events}} = \sigma_{\text{det}} \phi N_{\text{target}} \epsilon_{\text{det}} t, \quad (5)$$

where σ_{det} is the detection cross section, ϕ is the neutrino flux, N_{target} is the number of target particles in the detector, ϵ_{det} is the efficiency of the detector which we get from Ref. [13], and t is the exposure time. SK is a 22.5 kton water Cherenkov detector [13], detecting neutrinos through the measurement of Cherenkov radiation from relativistic electrons and positrons. The relevant detection channels in our energy range are inverse beta decay ($\bar{\nu}_e + p \rightarrow e^+ + n$), and the absorption of ν_e and $\bar{\nu}_e$ by oxygen in charged-current interactions ($\nu_e + {}^{16}\text{O} \rightarrow e^\pm + \text{X}$). The energies of electrons and positrons produced by these interactions are $E_e = E_\nu - 1.3 \text{ MeV}$ ($\bar{\nu}_e p$), $E_\nu - 15.4 \text{ MeV}$ ($\nu_e O$), and $E_\nu - 11.4 \text{ MeV}$ ($\bar{\nu}_e O$). The cross sections for these detection channels are taken from Refs. [29,30]. To correct for the energy resolution of the experiment, we smear the expected electron (positron) spectrum with a Gaussian function, using an energy resolution of width

$$\sigma = 0.40 \text{ MeV} \sqrt{E/\text{MeV}} + 0.03E, \quad (6)$$

that we take from Ref. [20]. We perform a χ^2 analysis of the expected number of events compared to the data, and calculate the upper limit at the 90% confidence level. We consider four different backgrounds coming from atmospheric neutrinos, which we also take from Ref. [13]. This background data is taken from the first running phase of SK, SK-I. We rescale it to the entire exposure time that we consider of 2853 days.

The future experiments that we consider show a lot of improvement in several ways. The invisible muon background originating from $\nu_\mu/\bar{\nu}_\mu$ charged-current events, which is the biggest background in SK below $\sim 40 \text{ MeV}$, might be significantly decreased in measurements of future water Cherenkov detectors by adding gadolinium [31]. In our analysis for Hyper-Kamiokande, we assume a reduction of this background by 80%. In the case of JUNO, this background is removed in total through the implementation of an extra system for cosmic muon detection and background reduction [32]. In the case of DUNE, this background is removed (e.g., see Ref. [33]). For our prediction, we consider an exposure time of 3000 days for each detector. We use the same background data as in SK, rescaling it to the right exposure time and the size of the specific experiment. In the case of Hyper-Kamiokande, a 520-kton upgrade of SK [17] with a fiducial volume of 374 kton, the same energy resolution is used [Eq. (6)].

DUNE is a 46.4-kton liquid argon detector [34]. The relevant detection channels are the detection of electron (anti)neutrinos through charged-current interactions ($\nu_e/\bar{\nu}_e + {}^{40}\text{Ar} \rightarrow e^-/e^+ + A' + nN$) [30], where nN are the emitted nuclei and A' is the remaining nucleus. JUNO is a 20-kton lab-based liquid scintillator [19]. The detection channels relevant for JUNO are again inverse beta decay

($\bar{\nu}_e + p \rightarrow e^+ + n$), and the capture of electron (anti) neutrinos on ^{12}C in charged-current interactions ($\bar{\nu}_e + ^{12}\text{C} \rightarrow ^{12}\text{B} + e^+/\nu_e + ^{12}\text{C} \rightarrow ^{12}\text{N} + e^-$) [30]. The energy resolutions for both JUNO and DUNE are significantly better than the water Cherenkov detectors. For DUNE, the energy resolution is given by [35]

$$\sigma = 0.025 \text{ MeV} \sqrt{E/\text{MeV}} + 0.060E. \quad (7)$$

For JUNO, the energy resolution we use is given by [36]

$$\sigma = 0.03 \text{ MeV} \sqrt{E/\text{MeV}}. \quad (8)$$

To predict the upper limit at the 90% confidence level, we use the PYTHON tool `swordfish` [37,38] that can, among other things, predict upper limits based on Poisson statistics, resulting in approximately the mean value of the results that one would get by performing a Monte Carlo simulation. Besides this, in the case of Hyper-Kamiokande, we explicitly perform a Monte Carlo simulation to obtain the full scope of possible values. We furthermore consider the reach of a hypothetical experiment with the size of Hyper-Kamiokande and the specifications of JUNO, which would result in a very strong experiment.

We obtain the upper limits for several cases. Besides the case of a millicharged Dirac DM particle responsible for 2% of the total DM, annihilating into only muon and tau neutrinos, we also consider the situation where 100% of DM only annihilates into neutrinos. In this situation we consider two subcases. In the first case, the DM has the same properties as in the 2% situation. In the second case, we consider Majorana DM, annihilating into all three neutrino flavors. Since in this case the expected flavor ratio at Earth is 1:1:1, the expected neutrino flux is given by

$$\frac{d\phi}{dE_\nu} = \frac{\langle\sigma v\rangle}{2} \mathcal{J}_{\text{avg}} \frac{R_{\text{sc}}\rho_0^2}{m_\chi^2} \frac{1}{3} \delta(E_\nu - m_\chi). \quad (9)$$

The latter case is similar to ordinary weakly interacting massive particle (WIMP) DM, except that the neutrino-only restriction makes it harder to detect. Therefore, the upper limits obtained in this situation will be the most conservative constraints for MeV WIMP DM annihilation.

V. RESULTS

In the top panel of Fig. 2, the upper limits are plotted for the case of the 2% millicharged DM. The black dashed line is the cross section corresponding to the DM model that could explain the EDGES results. The SK limit is not strong enough to rule out the millicharged DM model. Based on 3000 running days, the predictions show that Hyper-Kamiokande, JUNO and DUNE cannot reach the desired limit as well. However, the actual data will probably

induce some fluctuations, possibly resulting in a stronger limit, as can be seen from the behavior of the Monte Carlo region of Hyper-Kamiokande, compared to its predicted line. The strongest limit comes from DUNE. Running the detector long enough might result in strong enough limits to constrain the millicharged DM model. A combined analysis of the data of these experiments could result in a stronger limit by up to a factor of 2. In the bottom panel of Fig. 2, we show the limits in terms of the coupling constants and the masses of the dark matter particle and the new mediator, $(g_\chi g_f)^2 (m_\chi m_V)^4$, specific to our DM model.

Figure 3 shows the SK limits both with and without taking the extragalactic DM annihilation flux into account. We note that the Galactic flux has a substantial contribution to the limit.

We note that the most recent CMB (re)analysis found that the fraction of millicharged DM might be constrained even more tightly, $f_\chi \lesssim 0.4\%$ [39] (and references therein). In the case of $f_\chi = 0.4\%$, our limits get weaker by a factor of $(2/0.4)^2 = 25$ [Eq. (3)]. However, the annihilation cross

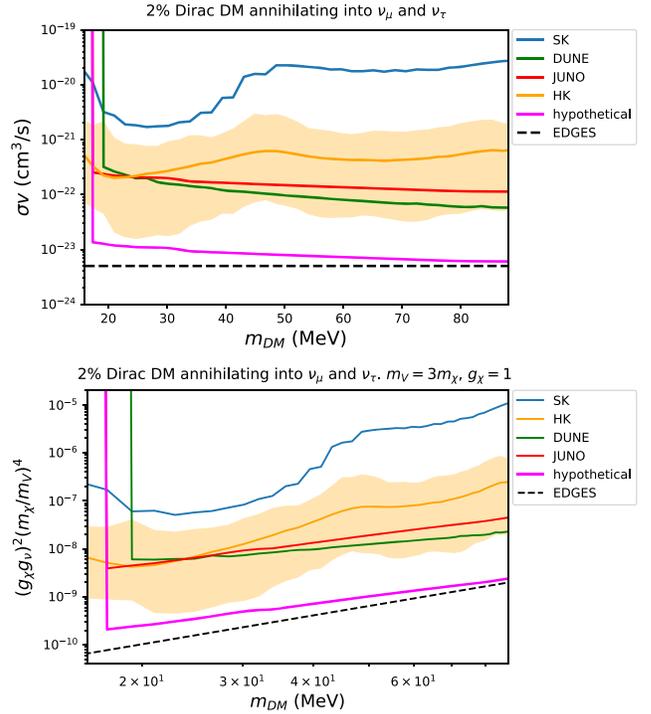


FIG. 2. Upper limits on the annihilation cross section $\langle\sigma v\rangle$ of millicharged Dirac DM into only muon and tau neutrinos, making up 2% of the total DM, as a function of the DM mass (upper panel). The lower panel shows the annihilation cross section in terms of the coupling constants, the DM mass, and the mass of the new mediator V . The black dashed line is the cross section induced by the EDGES results, in the case of Dirac DM. The blue line comes from the analysis of 2853 days of SK data. The other lines are predictions using `swordfish` [37,38]. The orange band shows the region between the minimum and maximum upper limit values predicted for Hyper-Kamiokande through a Monte Carlo simulation.

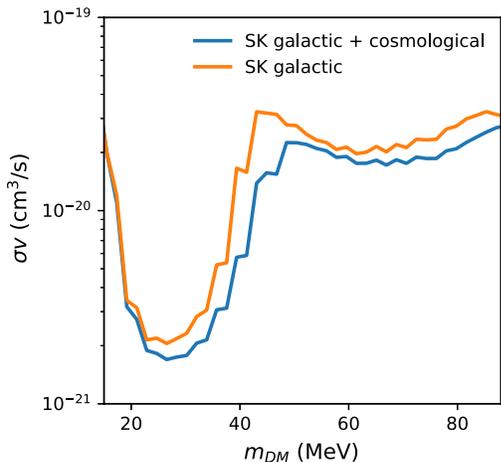


FIG. 3. Upper limits on the annihilation cross section of millicharged Dirac DM, making up 2% of the total DM, as a function of the DM mass, computed from the analysis of 2853 days of SK data. The orange line only contains the Galactic contribution to the neutrino flux coming from DM annihilations, while the blue line also includes the extragalactic contribution.

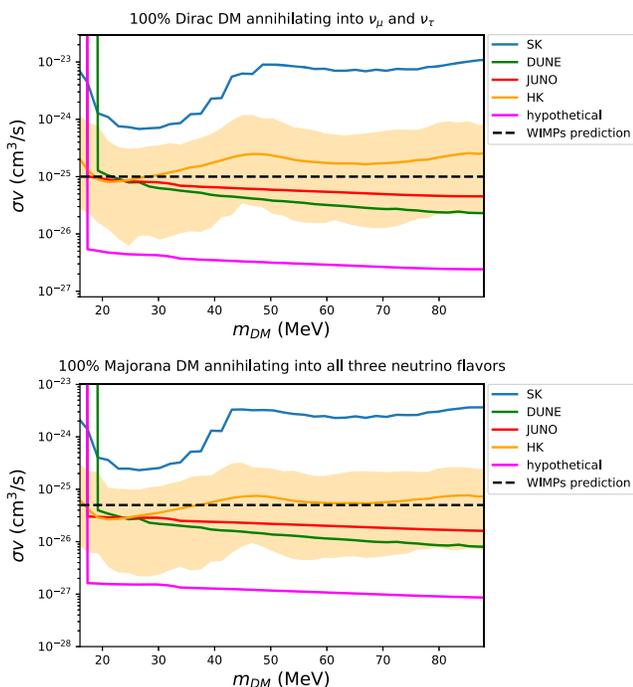


FIG. 4. Upper limits on the annihilation cross section of millicharged Majorana DM, making up 100% of DM, as a function of the DM mass. The upper panel shows the case of Dirac DM annihilating into only muon and tau neutrinos. The lower panel shows the case of Majorana DM annihilating into all three neutrino flavors with equal fraction. The black dashed line is the preferred cross section for WIMPs, in the case of Dirac (Majorana) DM in the upper (lower) panel. The blue line comes from the analysis of 2853 days of SK data. The other lines are predictions using *swordfish* [37,38]. The orange band shows the region between the minimum and maximum upper limit values for Hyper-Kamiokande predicted through a Monte Carlo simulation.

section required to explain the relic abundance becomes larger by a factor of $2/0.4 = 5$ [see Eq. (4) and subsequent sentences]. Hence our limits on the annihilation cross section relative to its canonical value will be weakened by a factor of 5.

Finally, besides exploring the millicharged DM model, we explore two more generic cases, where 100% of DM annihilates into neutrinos. First, we study the same Dirac DM annihilating into only muon and tau neutrinos, whose results are shown in the top panel of Fig. 4. The second case is Majorana DM annihilating into three neutrino flavors with equal fraction, shown in the bottom panel of Fig. 4. Since neutrinos are harder to detect than gamma rays, this results in a more conservative estimate, and hence the most general constraints on the DM annihilation [25]. While the current limit of SK could not yet constrain the WIMP prediction, in both of these cases, Hyper-Kamiokande, JUNO and DUNE will certainly be able to do so. We note that our updated limit is weaker than the limit found in Ref. [20] based on the previous data set of SK [40] by a factor of a few.

VI. CONCLUSIONS

The recent results of EDGES suggest that the primordial gas underwent extensive cooling from some additional DM species. Several constraints on the DM parameter space have already been made. We explored the yet unconstrained region in the case that millicharged DM makes up $\sim 2\%$ of the total dark matter, through the scenario in which this DM interacts with the standard model through the $\mu - \tau$ lepton number. This additional interaction is motivated by the thermal freeze-out scenario to explain the correct relic density, and also by the fact that it is largely unconstrained. If this DM has a mass of 10–100 MeV as suggested by the EDGES measurement, it annihilates only into mu and tau neutrinos.

By calculating the neutrino flux from the Galactic and extragalactic halos and comparing with existing data, we found that data from Super-Kamiokande are not yet able to constrain this model. We however found that future experiments might be able to detect neutrinos from this particular DM species. The hypothetical experiment that we studied with a size comparable to Hyper-Kamiokande and energy resolution comparable to JUNO or DUNE would be able to reach the desired limits. Although such an experiment is not scheduled to be built in the near future, there has been a Europe-wide initiative to study the possibility of an experiment with a size of the right order of magnitude [41]. We furthermore provided updated limits on the annihilation cross section for a more general WIMP DM model in the mass range 16–88 MeV, using (expected) data from the current and future neutrino experiments. We found that the current data of SK cannot yet put constraints on the WIMPs prediction, but the future experiments Hyper-Kamiokande, DUNE and JUNO will be capable of this.

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