Testing MeV dark matter with neutrino detectors

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MeV particles have been advocated as dark matter (DM) candidates in different contexts. This hypothesis can be tested indirectly by searching for the standard model (SM) products of DM self-annihilations. As the signal from DM self-annihilations depends on the square of the DM density, we might expect a sizable flux of annihilation products from our galaxy. Neutrinos are the least detectable particles in the SM and a null signal in this channel would allow to set the most conservative bound on the total annihilation cross section. Here, we show that neutrino detectors with good energy resolution and low energy thresholds can not only set bounds on the annihilation cross section but actually test the hypothesis of the possible existence of MeV DM, i.e. test the values of the cross section required to explain the observed DM density. At present, the data in the (positron) energy interval [18–82] MeV of the Super-Kamiokande experiment is already able to put a very stringent bound on the annihilation cross section for masses between ∼15–130 MeV. Future large experiments, like megaton water-Čerenkov or large scintillator detectors, will improve the present limits and, if MeV DM exists, would be able to detect it.

I. INTRODUCTION

The existence of dark matter (DM) in the Universe, established from cosmological and astrophysical observations, remains an unsolved puzzle. Despite the precision with which the DM abundance is known [1], we have still limited information on its properties and its nature. Various heavy candidates have been proposed, from neutralinos, sneutrinos, and gravitinos in supersymmetry, to stable scalars in little Higgs models, to Kaluza-Klein modes in extra-dimensions and superheavy candidates (for a review see, e.g. Ref. [2]). Light particles have also been studied as possible DM constituents: axions [3], sterile neutrinos with masses in the keV range [4], and light scalars with MeV–GeV masses [5–8].

Here, we focus on light particles as DM candidates: they can evade the Lee-Weinberg limit [9] and successfully explain the observed amount of DM in the Universe. They can be coupled to heavy fermions [5,6,8] or to new light gauge bosons [5]. For masses below 100 MeV, the only standard model (SM) channels of annihilation allowed are into electron-positron pairs, photons, and neutrino-antineutrino pairs. Interestingly, if MeV DM annihilates into SM particles other than neutrinos, it could make an important contribution to the reionization of the Universe, as well as significantly raise the gas temperature prior to the reionization epoch, leaving a potentially detectable imprint on the cosmological 21-cm signal [10] (see Refs. [11] for different results). However, the couplings to electrons are strongly constrained by observations of gamma rays. In particular, the DM self-annihilations into electron-positron pairs is one of the candidate explanations [6] for the 511 keV emission line detected by INTEGRAL/SPI from the bulge of our galaxy [12]. Nevertheless, the required cross section (times the relative

velocity) is, by about 4 orders of magnitude, smaller than the one necessary to explain the observed abundance of DM in the Universe, $\langle \sigma_A v \rangle \simeq 3 \times 10^{-26}$ cm^3/s. Only velocity-dependent cross sections would be able to accommodate both evidences, but provide a bad fit to the INTEGRAL/SPI data for masses below ∼100 MeV [13,14]. In addition, higher order processes would lead to gamma ray production via internal bremsstrahlung [15–17] and positron annihilations in flight with the electrons in the interstellar medium [17,18]. The COMPTEL and EGRET data constrain either the cross section to be smaller than what is required to explain the 511 keV line or the DM mass to be smaller than a few MeV. Similarly, the annihilation into photons can be constrained even stronger than the electron-positron channel by searches of diffuse gamma rays. Thus, the self-annihilation cross section into electron-positron pairs or photons, either was subdominant at DM freeze-out in the early Universe or, if velocity-dependent, at present it is much smaller than it was at DM freeze-out and cannot be tested today in a model independent way.

It is natural to assume that these light DM particles couple to neutrinos as well, unless special models are invoked. While the couplings with charged leptons and photons are severely bounded as discussed above (see also Refs. [19–22]), the interactions with neutrinos are very poorly constrained and can be even stronger than weak interactions. Even more, the self-annihilation into neutrinos, $\chi \chi \rightarrow \nu \nu$, is the only channel into SM particles, whose velocity-independent cross section can be as large as required to reproduce the observed DM abundance! Therefore, the analysis of constraints on the $\chi \chi \rightarrow \nu \nu$ cross section might constitute a direct test of DM freeze-out, for DM with masses in the MeV range.

Interestingly, it was recently noted [8] that, for MeV range DM, the value of the annihilation cross section necessary to reproduce the observed DM abundance may induce neutrino masses in the experimentally constrained range of values via one-loop contributions. In addition, MeV DM could also have implications for observations of small scale structure [23,24]. On the other hand, it has also been noticed that DM could couple to neutrinos strongly enough to produce observable effects that can be constrained by cosmic microwave background [25] and large-scale structure formation observations [23,25]. However, in this case, only if an asymmetry between DM particle and antiparticle is produced at some early epoch in the evolution of the Universe, the DM density could be the required one today.

These models of light DM can be tested indirectly by the detection of SM particles (electrons, photons and neutrinos) emitted in DM self-annihilations in galaxies, in particular, the Milky Way. Here, we will assume the branching ratio into neutrinos to be dominant in DM self-annihilations. Since neutrinos are the least detectable particles in the SM, a limit on their flux would conservatively set an upper bound on the total annihilation cross section. The same approach, but for higher masses, was followed in Refs. [26,27]. We evaluate the expected signal from DM annihilations in the entire Milky Way in large neutrino detectors with low energy threshold, such as the existing Super-Kamiokande (SK) and the proposed liquid scintillator detector LENA [28]. By using SK data we are able to set a very stringent upper bound on the total annihilation cross section in the mass interval $\sim$15–130 MeV. In addition, for velocity-independent cross sections and DM masses below $\sim$130 MeV, this analysis constrains the only SM channel which could have been relevant at DM freeze-out in the early Universe. Finally, we also study the possibilities to detect a positive signal from MeV DM in future detectors like the proposed LENA detector.

In Sec. II, we compute the neutrino flux from DM self-annihilations and briefly discuss halo profile uncertainties, and in Sec. III we review the commonly used techniques to detect MeV neutrinos and the main sources of background at these energies. The continuum background plays an important role in the sensitivity of present and future experiments and we discuss it in detail. In Sec. IV, we obtain a conservative bound on the total annihilation cross section from the present SK data, while we devote Sec. V to the study of the sensitivity of future experiments and their ability to test the hypothesis of light DM. Finally, we draw our conclusions in Sec. VI.

II. NEUTRINO FLUXES FROM DARK MATTER SELF-ANNIHILATIONS

Stable particles with masses in the MeV range constitute a cold DM candidate. Detailed structure formation simulations show that cold DM clusters hierarchically in halos and the formation of large scale structure in the Universe can be successfully reproduced. In the case of spherically symmetric matter density with isotropic velocity dispersion, the simulated DM profile in the galaxies can be parametrized via

$$\rho(r) = \rho_{\rm sc}\left(\frac{R_{\rm sc}}{r}\right)^{\gamma}\left[\frac{1 + (R_{\rm sc}/r_{\rm s})^{\alpha}}{1 + (r/r_{\rm s})^{\alpha}}\right]^{(\beta-\gamma)/\alpha}, \qquad (1)$$

where $R_{\rm sc} = 8.5$ kpc is the solar radius circle, $\rho_{\rm sc}$ is the DM density at $R_{\rm sc}$, $r_{\rm s}$ is the scale radius, γ is the inner cusp index, β is the slope as $r \rightarrow \infty$ and α determines the exact shape of the profile in regions around $r_{\rm s}$. Commonly used profiles [29–31] (see also Ref. [32]) can differ considerably in the inner part of the galaxy. However, this has only a relatively mild effect on the neutrino flux if a large field of view is considered [27].

Assuming DM annihilates into neutrino-antineutrino pairs, we can compute the neutrino flux coming from these annihilations in the halo (see, e.g. Ref. [33]). As we will see below, for energies below $\sim$100 MeV, information on the direction of the incoming neutrino is very poor if the detection is via interactions with nucleons. As this is the case presented here, we will be interested in considering the flux coming from all directions, so we shall take the flux averaged over the entire galaxy. This also helps in maximizing the observed neutrino flux while minimizing the impact of the choice of DM profile [27].

The angular-averaged intensity over the whole Milky Way, i.e. the average number flux, is given by the angular-averaged line of sight integration of the square of the DM density,

$$\mathcal{J}_{\rm avg} = \frac{1}{2R_{\rm sc}\rho_0^2}\int_{-1}^{1}\int_{0}^{l_{\rm max}}\rho^2(r)dld(\cos\psi), \qquad (2)$$

where $r = \sqrt{R_{\rm sc}^2 - 2lR_{\rm sc}\cos\psi + l^2}$, $\rho_0 = 0.3$ GeV cm^{-3} is a normalizing DM density, which we have chosen to be equal to the commonly quoted DM density at $R_{\rm sc}$, and the upper limit of integration is $l_{\rm max} = \sqrt{(R_{\rm halo}^2 - \sin^2\psi R_{\rm sc}^2)} + R_{\rm sc}\cos\psi$, and depends on the size of the halo $R_{\rm halo}$. As the contribution at large scales is negligible, different choices of $R_{\rm halo}$ do not affect $\mathcal{J}_{\rm avg}$ in a significant way, as long as it is a factor of a few larger than the scale radius, $r_{\rm s}$.

The differential neutrino and antineutrino flux per flavor from DM annihilations is then given by

$$\frac{d\phi}{dE_{\nu}} = \frac{\langle\sigma_{\rm A}v\rangle}{2}\mathcal{J}_{\rm avg}\frac{R_{\rm sc}\rho_0^2}{m_{\chi}^2}\frac{1}{3}\delta(E_{\nu} - m_{\chi}), \qquad (3)$$

where m_{χ} is the mass of the DM particle and $\langle\sigma_{\rm A}v\rangle$ is the averaged self-annihilation cross section (times the relative velocity of the annihilating particles). The factor $1/2$ accounts for DM being its own antiparticle, and the factor of $1/3$ comes from the assumption that the branching ratio of annihilation is the same in the three neutrino flavors. In

case of annihilation predominantly in one flavor, averaged oscillations between the production point and the detector would generate the other flavors with comparable intensity. In particular, given the present oscillation parameters [34], for pure ν_μ and ν_τ channels, the final flavor ratios would be $\nu_e:\nu_\mu:\nu_\tau \simeq 1:2:2$, whereas for a pure ν_e flux we would have $\nu_e:\nu_\mu:\nu_\tau \simeq 3:1:1$. Hence, thanks to neutrino oscillations, there is a guaranteed flux of neutrinos in all flavors. However, for simplicity herein we will consider equal annihilation into all flavors.

Let us note that while DM profiles tend to agree at large scales, uncertainties are still present for the inner region of the galaxy. As the neutrino flux from DM annihilations scales as ρ^2, this leads to an uncertainty in the overall normalization of the flux. To understand this effect quantitatively, we have studied the impact of the chosen halo profile by choosing three spherically symmetric profiles with isotropic velocity dispersion which, from more to less cuspy, are: Moore, Quinn, Governato, Stadel, and Lake (MQGSL) [29], Navarro, Frenk, and White (NFW) [30] and Kravstov, Klypin, Bullock, and Primack (KKBP) [31]. For each of the three profiles there is a range of values for the DM density at the solar circle, ρ_{sc}, which satisfy the present constraints from the allowed range for the local rotational velocity [35], the amount of flatness of the rotational curve of the Milky Way and the maximal amount of its nonhalo components [36]. We compile in Table I the values of the parameters in Eq. (1), the limiting values for ρ_{sc} [37], along with the corresponding limiting values of $\mathcal{J}_{avg}$ for each of the three profiles. Note also that, by choosing the same ρ_0 for all profiles, all the uncertainties in the neutrino flux from DM annihilations, coming from the lack of knowledge of the halo profile, lie in $\mathcal{J}_{avg}$.

Finally, let us mention that the diffuse signal from cosmic annihilations from all halos could in principle also be used to constrain the total DM annihilation cross section in the mass range considered here. However, the formation history of halos, although with a fairly universal dependence on the redshift, has a normalization which is quite uncertain and varies by several orders of magnitude for different halo profiles [38]. In addition to the uncertainties of the cosmic signal induced by those in the halo profiles, other important factors as the clustering of halos,

the halo mass function and the lower mass cutoff, are not completely well known and introduce further uncertainties in the cosmic signal. Therefore, the cosmic signal, being much more uncertain than that from the whole Milky Way, is less suitable to obtain reliable bounds on the total DM annihilation cross section. In addition, the cosmic signal is likely to be smaller than, or at most of the same order of, the galactic one [27]. Hence, and although the diffuse (redshifted) cosmic signal would allow to obtain bounds on the total DM annihilation cross section for higher masses than the galactic signal studied here, we will not consider it further.

III. MeV NEUTRINO DETECTION

The neutrinos produced in DM self-annihilations travel from their production point in the galaxy to the Earth where they can be revealed in present and future neutrino detectors. The number of neutrino events in a given detector is given by

$$\mathcal{N} \simeq \sigma_{det}(m_\chi)\phi N_{target}t\epsilon, \qquad (4)$$

where the detection cross section σ_{det} needs to be evaluated at $E_\nu = m_\chi$, the total flux of neutrinos (or antineutrinos) is given by ϕ, N_{target} indicates the number of target particles in the detector, t is the total time-exposure, and ϵ is the detector efficiency for this type of signal.

At the energies of interest, in the range of tens of MeV, the inverse beta-decay cross section ($\bar{\nu}_e p \rightarrow n e^+$) is by 2 orders of magnitude larger that the $\nu - e$ elastic scattering cross section. Neutrino interactions with free protons are also stronger than interactions with bound nucleons up to energies of about ~80 MeV. However, the latter interactions give non-negligible contributions and should be taken into account. Thus, in the following, we focus on $\bar{\nu}_e$ from DM annihilations and on neutrino interactions on both free and bound nucleons. However, for detectors with very low energy threshold like scintillator detectors, the inverse beta-decay reaction can be clearly tagged by the signal in coincidence of the positron annihilation followed by a delayed 2.2 MeV photon, which is emitted when the neutron is captured by a free proton. In water-Čerenkov detectors like SK, the threshold is above 2.2 MeV, so this

TABLE I. The parameters of Eq. (1) for the three halo profiles considered. Also shown the limiting values of ρ_{sc} in [GeV cm^{-3}] for the three profiles, as calculated in Ref. [37], which satisfy the present constraints from the allowed range for the local rotational velocity [35], the amount of flatness of the rotational curve of the Milky Way and the maximal amount of its nonhalo components [36]. Also shown the corresponding limiting values for $\mathcal{J}_{avg}$ which directly affect the total flux of the DM annihilation products. We will also use the canonical value of Ref. [27], $\mathcal{J}_{avg} = 5$. To avoid numerical divergences, when computing $\mathcal{J}_{avg}$, we consider a flat core in the innermost $0.1°$.

	α	β	γ	r_s [kpc]	$(\rho_{sc})_{min}$ [GeV/cm^3]	$(\rho_{sc})_{max}$ [GeV/cm^3]	$(\mathcal{J}_{avg})_{min}$	$(\mathcal{J}_{avg})_{max}$
MQGSL [29]	1.5	3	1.5	28	0.22	0.98	5.2	104
NFW [30]	1	3	1	20	0.20	1.11	1.3	41
KKBP [31]	2	3	0.4	10	0.32	1.37	1.9	8.5

reaction cannot be discriminated from neutrino interactions with nuclei. If the detector is doped with gadolinium trichloride ($GdCl_3$) [39], the neutron capture on Gd leads to 3–4 photons with a total energy of 8 MeV, and helps in this discrimination.

From Eq. (4), and assuming the annihilation cross section required to reproduce the observed amount of dark matter, $\langle \sigma_A v \rangle \simeq 3 \times 10^{-26}$ cm^3/s, we expect few events for an exposure of a Mton · yr. Therefore, we restrict our analysis to large neutrino detectors with low energy thresholds as SK and the proposed LENA scintillator detector [28]. Similar considerations would apply also for proposed liquid argon detectors as GLACIER [40].

If the detection technique allows to distinguish the inverse beta-decay reaction from neutrino interactions off nuclei (either with a scintillator detector or with a water-Čerenkov detector doped with $GdCl_3$), the expected signal has a very specific experimental signature being given by a peak (sharper the lower the DM mass is) in the neutrino spectrum and would be easily distinguished from the continuum background if a sufficient energy resolution is available. In general, the backgrounds for these events are due to geoneutrinos, solar and reactor neutrinos, to muon-induced spallation products, and to atmospheric and diffuse supernova neutrinos:

(i) *Geoneutrinos*, produced in the Earth interior, result from the radioactive decay chains of nuclear isotopes with lifetimes comparable to or longer than the Earth age, like ^{238}U, ^{232}Th, ^{40}K, ^{235}U and ^{87}Rb (see, e.g. Ref. [41]). Their spectrum extends up to 3.27 MeV with a total flux, $\sim 10^6 \bar{\nu}_e$ cm^{-2} s^{-1}, several orders of magnitude higher than that of neutrinos from DM self-annihilations being larger in regions with a thick continental crust.

(ii) *The solar neutrino flux*, similar in magnitude to that of geoneutrinos, drops rapidly at energies $\gtrsim$ 10 MeV, and in water-Čerenkov detectors it can be eliminated by applying an angular cut by exploiting the directionality of $\nu - e$ elastic scattering. On the other hand, the solar neutrino flux being a flux of neutrinos, in scintillator detectors it induces a different type of signal from inverse beta-decay and does not constitute a relevant background.

(iii) *The flux of reactor $\bar{\nu}_e$'s*, below 10 MeV, is by orders of magnitude higher than the expected neutrino flux from DM self-annihilations. In reactors, $\bar{\nu}_e$ are generated in the beta-decay of the fission products of ^{235}U, ^{238}U, ^{239}P and ^{241}P. The shape and the normalization flux can be estimated with good precision taking into account experimental data and theoretical calculations. The tail of the spectrum, up to $E_{\bar{\nu}_e} =$ 13 MeV, is less well known due to the presence of ^{94}Br with Q-value of 13.3 MeV, whose exact decay scheme is not know. However, its continuum spectrum could be easily distinguished from a peaked

neutrino signal from DM annihilation. Typically, one expects a flux of $\sim 10^6 \bar{\nu}_e$ cm^{-2} s^{-1} at sites as Kamioka (Japan) and Frejus (France), and an order of magnitude smaller at Pyhäsalmi (Finland), Homestake (US) and Henderson (US). The lowest reactor fluxes can be found at Hawaii (US), 1×10^4 cm^{-2} s^{-1}, and Wellington in New Zealand, 5×10^3 cm^{-2} s^{-1}, due to their distance from the northern hemisphere power plants [42]. Even in the latter locations, the neutrino flux from DM annihilations is by orders of magnitude smaller. Thus, we restrict the analysis to energies above 10 MeV.

(iv) *Muon-induced spallation products* constitute a very important background in water-Čerenkov detectors and a sufficient reduction sets the lower energy threshold of the detector. For SK, a threshold of 18 MeV has been set and a tight spallation cut used. An efficient background reduction can be obtained in this way [43]. In scintillator detectors, as LENA, the topology of the event allows to reduce this background sufficiently [42].

(v) *The flux of atmospheric ν_e and $\bar{\nu}_e$* should also be taken into account in the energy window under consideration. The normalization of the flux depends on the location of the detector [44–47], more specifically on the geomagnetic latitude, varying roughly by a factor of 2.5 between Hawaii (1.5° latitude N) and Pyhäsalmi (63.7° latitude N) [42]. The shape of the spectrum of atmospheric neutrinos, however, is not sensibly affected by the position of the underground laboratory. In detectors able to tag the neutron produced in the inverse beta-decay reaction, the flux of $\bar{\nu}_e$ constitutes the dominant background.

(vi) *Invisible muons from atmospheric ν_μ and $\bar{\nu}_\mu$* constitute the dominant background in water-Čerenkov detectors. If the kinetic energy of the produced muon is below 54 MeV, then the muon is below the threshold for emitting Čerenkov radiation. These muons, produced by atmospheric ν_μ and $\bar{\nu}_\mu$ with typical energies of about ~ 200 MeV, are slowed down rapidly and subsequently decay, giving rise to a signal which cannot be distinguished from that of an ν_e or $\bar{\nu}_e$, and hence pose an important source of background. On the other hand, in detectors for which it is also possible to tag the neutron from the inverse beta-decay, like scintillator detectors as LENA [28], these muons do not constitute a background. In water-Čerenkov detectors doped with $GdCl_3$ [39], this background can be reduced by a factor of ~ 5 by rejecting events with a preceding nuclear gamma or which are not followed by a neutron.

(vii) *The diffuse supernova neutrino background (DSNB)*, although not yet detected, might potentially represent a background for the signal coming from neu-

trinos from DM self-annihilations. This flux might be relevant in the interval of energies between ~ 10 MeV and ~ 30 MeV, dropping very rapidly with energy, and being completely negligible above 50 MeV–60 MeV.

IV. BOUNDS FROM SK DATA

In this section we extend previous works [26,27,48–50] by setting neutrino constraints on the dark matter total annihilation cross section for masses below ~ 130 MeV. In doing this we adopt a similar approach to that in Refs. [26,27], and assume that dark matter annihilates only into neutrinos. If dark matter annihilates into SM particles, neutrinos (and antineutrinos) are the least detectable particles. Any other possible decay mode would produce gamma rays, which are much easier to detect, and would allow to set a much stronger (and model-dependent) bound on the total annihilation cross section. Thus, the most conservative approach [26,27] is to assume that only neutrinos are produced in DM self-annihilations. Even in this conservative case, it has been shown that a stringent upper limit on the total DM annihilation cross section can be obtained for masses above ~ 100 MeV by comparing the expected time-integrated annihilation signal of all galactic halos (cosmic signal) [26] and the signal from annihilations in the Milky Way Halo [27] with the dominant background at these energies: the flux of atmospheric neutrinos.

In this paper, we consider the low mass region below ~ 130 MeV, for which the best present data comes from the SK detector [43]: a search for the DSNB was performed by looking for positrons in the energy range 18 MeV–82 MeV, produced by $\bar{\nu}_e$ interactions. The same data can be analyzed to search for neutrinos from DM self-annihilations. As explained above, in this energy range, the two dominant backgrounds in water-Čerenkov detectors are the atmospheric ν_e and $\bar{\nu}_e$ flux and, mainly, the Michel electrons (positrons) from the decays of low energy muons which are below detection threshold. Below 18 MeV, muon-induced spallation products are the most serious background, and it is indeed the ability to remove this background what determines the lower energy threshold for the DSNB search.

As mentioned above, below ~ 80 MeV, the dominant interaction of $\bar{\nu}_e$ is through the inverse beta-decay reaction, $\bar{\nu}_e + p \rightarrow e^+ + n$. However, the interactions of neutrinos with oxygen nuclei need also to be taken into account. We have included in our analysis both the interactions of antineutrinos with free protons and the interactions of neutrinos and antineutrinos with bound nucleons, by considering, in the latter case, a relativistic Fermi gas model [51] with a Fermi surface momentum of 225 MeV and a binding energy of 27 MeV.

At very low energies, the inverse beta-decay reaction relates the energy of the outgoing positron to that of the

incoming neutrino ($E_e \simeq E_\nu - 1.3$ MeV). However, at higher energies corrections of the order of $\mathcal{O}(E_\nu/M)$, where M is the nucleon mass, start to become important and the difference between the maximum and minimum positron energy is to first order given by $\Delta E_e \approx 2E_\nu^2/M$. Hence, although the DM self-annihilation gives rise to monochromatic neutrinos, the signal would have a significant energy spread for DM masses of tens of MeV. In addition, the finite energy resolution of the detector will also contribute to the spread of the signal. In order to take this into account, we consider the energy resolution of the SK I detector, which is determined by the photocathode coverage, as given by the LINAC calibration [52] up to 16.09 MeV and perform a simple fit, extrapolating to higher energies. The energy resolution that we consider is

$$\sigma = 0.40 \text{ MeV}\sqrt{E/\text{MeV}} + 0.03E. \quad (5)$$

The monochromatic neutrino flux is folded with a Gaussian energy resolution function of width σ, $R(E_e, E_{\text{vis}})$, with E_e and E_{vis} being the original and detected electron (or positron) energy, respectively. We have also taken into account the energy-dependent efficiency after all cuts, which is $\epsilon = 0.47$ for $E_{\text{vis}} < 34$ MeV and $\epsilon = 0.79$ for $E_{\text{vis}} > 34$ MeV [43].

The expected fraction of signal from DM self-annihilation into neutrino-antineutrino pairs in the visible (positron) energy interval $E_{\text{vis}} = [E_l, E_{l+1}]$ is given by

$$A_l = A_s \int \left[\frac{d\sigma_{\text{f}}^{\bar{\nu}}}{dE_e}(m_\chi, E_e) + \frac{1}{2}\left(\frac{d\sigma_{\text{b}}^{\nu}}{dE_e}(m_\chi, E_e) \right.\right.$$
$$\left.\left. + \frac{d\sigma_{\text{b}}^{\bar{\nu}}}{dE_e}(m_\chi, E_e)\right)\right] dE_e$$
$$\times \int_{E_l}^{E_{l+1}} \epsilon(E_{\text{vis}})R(E_e, E_{\text{vis}})dE_{\text{vis}}, \quad (6)$$

with $E_1 = 18$ MeV and $E_{l+1} - E_l = 4$ MeV. A_s is a normalization constant so that $\sum A_l = 1$. We indicate with σ_{f} and σ_{b} the neutrino cross sections off free nucleons and off nuclei (bound nucleons), respectively, and the factor of $1/2$ is due to water having twice as many free protons as oxygen nuclei.

In order to obtain the upper limit on the total DM annihilation cross section, we use the data reported by the SK collaboration [43] and perform an analogous analysis. We consider the 16 4-MeV bins in which the data were divided and define the following χ^2 function [43]

$$\chi^2 = \sum_{l=1}^{16} \frac{[(\alpha \cdot A_l) + (\beta \cdot B_l) + (\gamma \cdot C_l) - N_l]^2}{\sigma_{\text{stat}}^2 + \sigma_{\text{sys}}^2}, \quad (7)$$

where the sum l is over all energy bins, N_l is the number of events in the lth bin, and A_l, B_l and C_l are the fractions of the DM self-annihilation signal, Michel electron (positron) and atmospheric ν_e and $\bar{\nu}_e$ spectra that are in the lth bin, respectively. The fractions A_l are calculated as described above. The fractions B_l are calculated taking into consid-

eration that in water 18.4% of the μ^- produced below Čerenkov threshold ($p_\mu < 120$ MeV) get trapped and enter a K-shell orbit around the oxygen nucleus and thus, the electron spectrum from the decay is slightly distorted with respect to the well-known Michel spectrum [53]. In the calculation of the fractions B_l and C_l we have used the low energy atmospheric neutrino flux calculation with FLUKA [47]. Note that, in a two-neutrino approximation and for energies below ~ 300 MeV (where most of the background comes from), half of the ν_μ have oscillated to ν_τ, whereas ν_e remain unoscillated. Although this approximation is not appropriate, in principle, to calculate the low energy atmospheric neutrino background, however, for practical purposes, it introduces very small corrections [54]. Thus, in order to calculate B_l and C_l we use the two-neutrino approximation.

The fitting parameters in the χ^2-function are α, β, and γ, which represent the total number of each type of event. For the systematic error we take $\sigma_{\text{sys}} = 6\%$ for all energy bins [43]. Our fit agrees very well with the SK analysis, and we obtain as best fit points, $\beta_{\text{BF}} = 181 \pm 23$ and $\gamma_{\text{BF}} = 80 \pm 17$, with $\chi^2 = 7.9$ for 13 degrees of freedom. Our best fit to α is $\alpha_{\text{BF}} = 0$, which means that there are no events from DM self-annihilation into neutrino-antineutrino pairs in the current SK data.

In absence of a DM signal, a 90% confidence level (C.L.) limit can be set on α for each value of the DM mass. The limit is obtained by increasing the value of α and evaluating the χ^2 function using β and γ as free parameters. The minimum χ^2 value obtained for each α (χ^2_α) corresponds to a relative probability given by

$$P(\alpha) = K \cdot e^{-\chi^2_\alpha}, \qquad (8)$$

with K a normalizing constant so that $\sum_{\alpha=0}^\infty P(\alpha) = 1$.

The 90% C.L. upper limit on the number of events coming from dark matter annihilation into neutrino-antineutrino pairs, that we also call α_{90}, is defined by

$$\sum_{\alpha=0}^{\alpha_{90}} P(\alpha) = 0.9. \qquad (9)$$

The limit on α can be translated into a limit on the annihilation cross section, which is given by

$$\langle \sigma_A v \rangle_{90} = \alpha_{90} \frac{6 m_\chi^2 \cdot A_s}{t \cdot N_{\text{target}} \cdot \mathcal{J}_{\text{avg}} R_{\text{sc}} \rho_0^2} \qquad (10)$$

where t = 1496 days and $N_{\text{target}} = 1.5 \times 10^{33}$ free protons in the fiducial volume (22.5 kton) of the SK detector.

This limit is depicted in Fig. 1. The solid line is obtained for the canonical value of Ref. [27], $\mathcal{J}_{\text{avg}} = 5$, while for the dashed line we use $\mathcal{J}_{\text{avg}} = 1.3$ (see Table I), which represents the lowest possible value of $\mathcal{J}_{\text{avg}}$ for the three profiles considered. This smallest value of $\mathcal{J}_{\text{avg}}$ corresponds to the NFW profile and to the minimum density allowed for this profile by observational constraints,
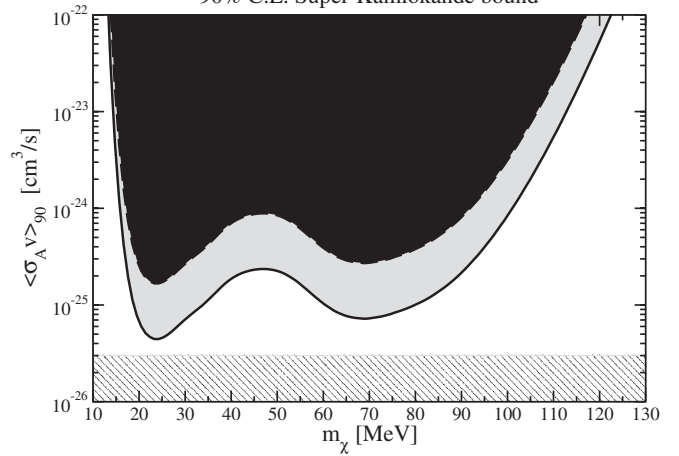

FIG. 1. 90% C.L. bound on the total DM self-annihilation cross section from the whole Milky Way, obtained from SK data. The dashed line (boundary for the black area) represents the most conservative bound by using the smallest value observationally allowed of $\mathcal{J}_{\text{avg}} = 1.3$, whereas for the solid line (boundary for the gray area), we have used the canonical value, $\mathcal{J}_{\text{avg}} = 5$, of Ref. [27]. The hatched area represents the natural scale of the annihilation cross section.

$(\rho_{\text{sc}})_{\text{min}} = 0.2$ GeV cm^{-3} [37]. Thus, the gray and black areas represent, respectively, the excluded regions for the case of the canonical value of Ref. [27] and for the case of the lowest value of $\mathcal{J}_{\text{avg}}$. Hence, the black region is the most reliable and conservative 90% C.L. upper limit on the total DM annihilation cross section we obtain. In Fig. 1, the hatched region represents the natural scale for the DM annihilation cross section. For masses below ~ 100 MeV, the bound is very stringent, being within an order of magnitude of the natural scale for the most conservative of the DM profiles, and within a factor of a few for the canonical value of Ref. [27]. Notice that more cuspy DM profiles than the NFW profile or large values for the density at the solar circle, ρ_{sc}, would set a bound on the total DM annihilation cross section below the natural scale, and hence, excluding in those cases a velocity-independent cross section. Also note that our bound extends beyond the interval $m_\chi = (19.3, 83.3)$ MeV, which would represent the naïve case where only the inverse beta-decay reaction (interaction of antineutrinos off free protons) is considered with the approximation $E_\nu = E_e + 1.3$ MeV, and without taking into account the finite energy resolution of the detector. Finally, note that the shape of the curves can be easily understood from the shape of the background [43].

V. FUTURE PERSPECTIVES

Let us now consider the possibility to detect MeV DM annihilating into neutrino-antineutrino pairs with future neutrino detectors. We have seen in the previous section that the bounds already set by SK data are very close to the

natural scale for masses between 10 MeV and 100 MeV, and thus, the detection (or exclusion) of this type of signal might be possible in a matter of just a few more years. Moreover, the addition of GdCl$_3$ to SK would allow to reduce the backgrounds by a factor of about 5 [39], which would accelerate this search. In addition to this possibility, and also to the possible use of larger water-Čerenkov detectors (doped with GdCl$_3$ or not) [55], there are other type of large detectors which have been proposed in the context of measuring MeV neutrinos, for DSNB searches and for the study of solar neutrinos and geoneutrinos. We will consider here the proposed large-volume liquid scintillator detector LENA [28], which, as noted above, will provide a very good background discrimination.

The LENA detector is foreseen to have a fiducial volume of 50×10^3 m^3 of liquid scintillator and, at the moment, one of the preferred detector sites is a mine in Pyhäsalmi (Finland) (another option is underwater in the Mediterranean sea next to Pylos, Greece) [28]. As mentioned above, the inverse beta-decay reaction has a very clear signature in this type of detector, with the positron annihilation followed by a 2.2 MeV photon, released when the neutron is captured by a free proton in the scintillator ~ 180 μs after the interaction takes place. In this type of detector there is no background due to sub-Čerenkov muons. In addition, muon-induced spallation products can be efficiently removed, as well as the background of fast neutrons generated by muons passing the surrounding rock [42]. Hence, the only relevant backgrounds for the signal studied here come from reactor, atmospheric and diffuse supernova $\bar{\nu}_e$ interacting with free protons in the detector. The latter, albeit not yet measured, constitutes a potential background for the signal of MeV DM annihilation into neutrino-antineutrino pairs, but with a very different spectrum.

Below ~ 10 MeV the flux of $\bar{\nu}_e$ from nuclear reactors is the dominant one in LENA, and we use the reactor $\bar{\nu}_e$ spectrum calculated in Ref. [42]. In the energy interval between ~ 10 MeV and ~ 30 MeV, the DSNB is likely to dominate. The differential number flux of the DSNB is given by

$$\frac{dF_\nu}{dE_\nu}(E_\nu) = c \int_0^{z_{max}} R_{SN}(z) \frac{dN_\nu(E'_\nu)}{dE'_\nu}(1+z)\frac{dt}{dz} dz, \quad (11)$$

where we assume that the gravitational collapse begun at $z_{max} = 6$. The number spectrum of neutrinos emitted by one supernova is dN_ν/dE_ν, $E'_\nu = (1+z)E_\nu$ is the energy of neutrinos at redshift z with E_ν being the energy at the Earth, $R_{SN}(z)$ represents the supernova rate per comoving volume at redshift z and $dt/dz = (H_0(1+z) \times \sqrt{\Omega_M(1+z)^3 + \Omega_\Lambda})^{-1}$. We will adopt the standard ΛCDM cosmology ($\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$ and $H_0 = 70$ km s^{-1} Mpc^{-1}).

For the supernova rate per comoving volume we use the fit to ultraviolet and far-infrared data obtained by Ref. [56]

assuming a modified Salpeter initial mass function with a turnover below 1 $M_\odot$ [57], and the parametric form for the star formation rate of Ref. [58],

$$R_{SN}(z) = 0.00915 M_\odot^{-1} \frac{(0.0119 + 0.091z)}{1 + (z/3.3)^{5.3}}. \quad (12)$$

For the neutrino spectrum from each supernova, we consider the simulation by the Lawrence Livermore group [59] with the parametrization for each flavor given by [60]

$$\frac{dN_\nu}{dE_\nu} = \frac{(1+\beta_\nu)^{1+\beta_\nu} L_\nu}{\Gamma(1+\beta_\nu)\bar{E}_\nu^2}\left(\frac{E_\nu}{\bar{E}_\nu}\right)^{\beta_\nu} e^{-(1+\beta_\nu)E_\nu/\bar{E}_\nu}, \quad (13)$$

with $\bar{E}_{\bar{\nu}_e} = 15.4$ MeV, $\bar{E}_{\nu_x} = 21.6$ MeV, $\beta_{\bar{\nu}_e} = 3.8$, $\beta_{\nu_x} = 1.8$, $L_{\bar{\nu}_e} = 4.9 \times 10^{52}$ ergs, and $L_{\nu_x} = 5.0 \times 10^{52}$ ergs [61], and where ν_x represents nonelectron-flavor neutrinos and antineutrinos. Due to neutrino mixing, about 70% ($|U_{e1}|^2 \simeq 0.7$) of the emitted $\bar{\nu}_e$ survive and 30% ($1 - |U_{e1}|^2 \simeq 0.3$) of the emitted ν_x will appear as $\bar{\nu}_e$ at the Earth [61].

Finally, by plugging Eqs. (12) and (13) into Eq. (11), we obtain the expected DSNB flux at the Earth. Note that the neutrino spectrum we have considered has a relatively large average energy for each flavor (still consistent with star formation history measurements [56]), which gives rise to a larger flux than in other simulations [60,62] at the energies where the DSNB spectrum may dominate over other backgrounds (~ 10–30 MeV). This is a conservative assumption for our purposes, for this flux represents a background for a potential signal from DM annihilation into neutrino-antineutrino pairs. Above ~ 30 MeV, it is the atmospheric $\bar{\nu}_e$ flux which gives the main contribution to the background in a detector like LENA. One should note that the atmospheric neutrino flux at Pyhäsalmi is a factor of 2 larger than at Kamioka. The rates are calculated considering a gaussian energy resolution function of width [42]

$$\sigma_{LENA} = 0.10 \text{ MeV}\sqrt{E/\text{MeV}}. \quad (14)$$

In Fig. 2, we show the expected signal in the LENA detector, if located in Pyhäsalmi (Finland), along with the expected backgrounds, after 10 years. We have considered a scintillator mixture in weight of 20% PXE (C$_{16}$H$_{18}$) and 80% Dodecane (C$_{12}$H$_{26}$) and a fiducial volume of 50×10^3 m^3, which amounts to 3.3×10^{33} free protons. We depict the case of two values for the DM mass, $m_\chi = 20$ MeV and $m_\chi = 60$ MeV, and we have considered here the canonical value for the halo profile of Ref. [27]. In the case of low values of the masses, e.g. $m_\chi = 20$ MeV, even with the small rate predicted, a rather easy discrimination between signal and background would be possible. For higher values of the masses, in the few tens of MeV, as clearly shown in Fig. 2, the energy of the initial neutrino cannot be uniquely reconstructed from the measured positron energy. Therefore, the signal for $m_\chi = 60$ MeV is not characterized by a delta-function in energy and has a
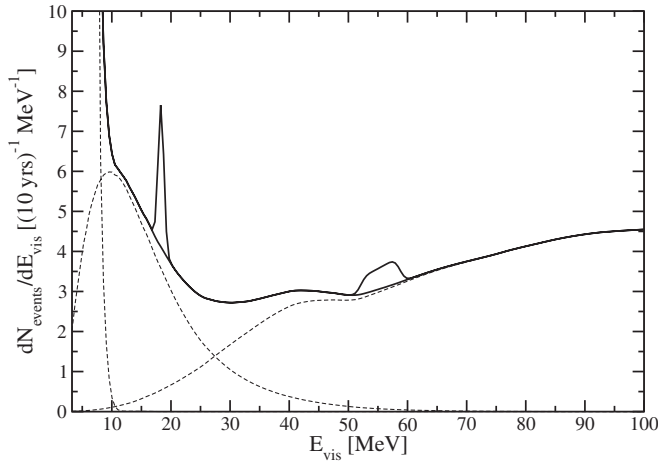
FIG. 2. Expected signal in the proposed LENA detector, located in Pyhäsalmi (Finland), after 10 years of running for two different values of the DM mass, $m_\chi = 20$ MeV, and $m_\chi = 60$ MeV. Dashed lines represent the individual contributions of each of the three different types of background events in this type of detector (reactor antineutrinos, DSNB, and atmospheric neutrinos), whereas the solid lines represent the backgrounds plus the expected signal from DM annihilation in the Milky Way. We have used the canonical value of Ref. [27], $\mathcal{J} = 5$, and $\langle \sigma_A v \rangle = 3 \times 10^{-26}$ cm^3 s^{-1}.

spread over an interval of ~ 10 MeV. In this case, the separation of the signal from the background will be more difficult, although still possible.

VI. CONCLUSIONS

In the present article we have considered the indirect bounds from the annihilation into neutrino-antineutrino pairs of DM particles with masses in the range of tens of MeV. These particles have been proposed as possible DM candidates and have been advocated in different contexts to explain the 511 keV emission line from the bulge as well as the observed values of neutrino masses. DM light particles would self-annihilate in the galaxy producing a sizable flux

of neutrinos of energy $E_\nu = m_\chi$. These neutrinos might be detected in present and future neutrino experiments. We have shown that the present data from the SK experiment in the 18 MeV–82 MeV energy region can constrain significantly the total DM annihilation cross section to be smaller than $\sigma_A \sim$ few $\times$ $(10^{-25}$–$10^{-26})$ cm^3/s, depending on the specific choice of the halo profile, for DM masses between ~ 15–100 MeV. We have also shown that future large neutrino detectors with sufficient energy resolution and good background discrimination could have the capability to observe a signal if these MeV particles exist and the annihilation cross section is the one required to reproduce the observed amount of DM. In particular, the LENA detector would have the capability to find a positive signal in a large part of the mass window under interest. A megaton-size water-Čerenkov detector, possibly doped with GdCl$_3$, and large liquid argon detectors with very good energy resolution at MeV energies, would have similar sensitivities. A null signal in future large neutrino experiments would either indicate that, if MeV DM exists, the annihilation cross section at freeze-out was velocity-dependent or exclude DM masses in the ~ 10–100 MeV. A positive signal would imply that DM is constituted by particles with masses in the tens of MeV range, would measure its mass and would determine, albeit halo profile uncertainties, the cross section which was relevant at DM freeze-out in the early Universe.

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