Neutrinos are the least detectable Standard Model particle. By making use of this fact, we consider dark matter annihilations and decays in the galactic halo and show how present and future neutrino detectors could be used to set general limits on the dark matter annihilation cross section and on the dark matter lifetime.

1 Introduction

With the next generation of neutrino experiments we will enter the era of precision measurements in neutrino physics. As a consequence, a lot of efforts are being dedicated to decide which are the best experimental set-ups. However and in addition to the detailed study of neutrino parameters, present and future neutrino detectors, thanks to their great capabilities, might also be used for other purposes. Among the possible synergies of these detectors, they could be used to test some of the properties of the dark matter (DM) of the Universe. For instance, it has been pointed out\(^1\) that by using the spectral information of neutrinos coming from annihilations of DM particles in the center of the Sun, some of the DM properties could be reconstructed. In this talk however, we consider neutrinos coming from DM annihilations or decays in our galactic halo and show how they can be used to test some other DM properties.

We will use the fact that among the Standard Model (SM) particles, neutrinos are the least detectable ones. Therefore, if we assume that the only SM products from the DM annihilations (decays) are neutrinos, a limit on their flux, conservatively and in a model-independent way, sets an upper (lower) bound on the DM annihilation cross section (lifetime). This is the most conservative assumption from the detection point of view, that is, the worst possible case. Any other channel (into at least one SM particle) would produce photons and hence would give rise to a much more stringent limit. Let us stress that this is not an assumption about a particular
and realistic case. On the other hand, for the reasons just stated, it is valid for any generic model, in which DM annihilates (decays) at least into one SM particle. Hence, the bounds so obtained are bounds on the total annihilation cross section (lifetime) of the DM particle and not only on its partial annihilation cross section (lifetime) due to the annihilation (decay) channel into neutrinos.

In this talk, and following and reviewing the approach ofRefs.\textsuperscript{2,3,4,5}, we consider this case and evaluate the potential neutrino flux from DM annihilation (decay) in the whole Milky Way, which we compare with the relevant backgrounds for detection. In such a way, we obtain general constrains on the DM annihilation cross section and on the DM lifetime, which are more stringent than previous ones\textsuperscript{6,7,8,9,10}.

2 Neutrino Fluxes from the Milky Way

Detailed structure formation simulations show that cold DM clusters hierarchically in halos which allows the formation of large scale structure in the Universe to 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

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

where $R_{\text{sc}} = 8.5$ kpc is the solar radius circle, $\rho_{\text{sc}}$ is the DM density at $R_{\text{sc}}$, $r_s$ is the scale radius, $\gamma$ is the inner cusp index, $\beta$ is the slope as $r \to \infty$ and $\alpha$ determines the exact shape of the profile in regions around $r_s$. Commonly used profiles\textsuperscript{11,12,13} (see also Ref.\textsuperscript{14}) tend to agree at large scales, although they differ considerably in the inner part of the galaxy.

The differential neutrino plus antineutrino flux per flavor from DM annihilation or decay in a cone of half-angle $\psi$ around the galactic center, covering a field of view $\Delta \Omega = 2\pi (1 - \cos \psi)$, is given by

$$\frac{d\Phi}{dE_{\nu}} = \frac{\Delta \Omega}{4\pi} \mathcal{P}_k(E_{\nu}, m_\chi) R_{\text{sc}} \rho_0^k \mathcal{J}_{\Delta \Omega, k},$$

where $m_\chi$ is the DM mass, $\rho_0 = 0.3$ GeV cm$^{-3}$ is a normalizing DM density, which is equal to the commonly quoted DM density at $R_{\text{sc}}$, and $\mathcal{J}_{\Delta \Omega, k}$ is the average in the field of view (around the galactic center) of the line of sight integration of the DM density (for decays, $k = 1$) or of its square (for annihilations, $k = 2$), which is given by

$$\mathcal{J}_{\Delta \Omega, k} = \frac{2\pi}{\Delta \Omega} \frac{1}{R_{\text{sc}} \rho_0^k} \int_{\cos \psi}^{1} \int_0^{l_{\text{max}}} \rho(r)^k \, dl \, d(cos \psi'),$$

where $r = \sqrt{R_{\text{sc}}^2 - 2l R_{\text{sc}} \cos \psi' + l^2}$ and $l_{\text{max}} = \sqrt{(R_{\text{halo}}^2 - \sin^2 \psi R_{\text{sc}}^2) + R_{\text{sc}} \cos \psi}$. The contribution at large scales is negligible and thus, this integral barely depends on the size of the halo for $R_{\text{halo}} \gtrsim$ few tens of kpc.

The factor $\mathcal{P}_k$ embeds all the dependences on the particle physics model and it reads

$$\mathcal{P}_1 = \frac{1}{3} \frac{dN_1}{dE_{\nu}} \frac{1}{m_\chi \tau_\chi} \quad \text{for decays} \quad \text{and} \quad \mathcal{P}_2 = \frac{1}{3} \frac{dN_2}{dE_{\nu}} \frac{\langle \sigma_A v \rangle}{2 m_\chi^2} \quad \text{for annihilations},$$

where the neutrino plus antineutrino spectrum per flavor is given by

$$\frac{dN_1}{dE_{\nu}} = 2 \delta(E_{\nu} - \frac{m_\chi}{2}) \quad \text{for decays} \quad \text{and} \quad \frac{dN_2}{dE_{\nu}} = 2 \delta(E_{\nu} - m_\chi) \quad \text{for annihilations},$$

and the factor of 1/3 comes from the assumption that the annihilation or decay branching ratio is the same for the three neutrino flavors. Let us note that this is not a very restrictive
assumption, for even even when only one flavor is predominantly produced, there is a guaranteed flux of neutrinos in all flavors thanks to the averaged neutrino oscillations between the source and the detector. Hence, although different initial flavor ratios would give rise to different flavor ratios at detection, the small differences affect little our results and for simplicity herein we consider flavor democracy.

2.1 Annihilations versus Decays: DM Halo Uncertainties

As mentioned above, while DM profiles tend to agree at large scales, uncertainties are still present for the inner region of the galaxy. In the two cases considered (annihilations and decay), the overall normalization of the flux is affected by the value of $J_{AΩ,k}$. However, in the case of DM annihilations, it scales as $\rho^2$, whereas for DM decays, it scales as $\rho$. Our lack of knowledge of the halo profile is hence much more important for the neutrino flux from DM annihilations. For the three profiles considered here\textsuperscript{11,12,13}, astrophysical uncertainties can induce errors of up to a factor of 6 for the case of DM decays\textsuperscript{5}, but they can be as large as a factor of $\sim 100$ for DM annihilations\textsuperscript{3,4}. In addition, if the DM mass is not known, DM annihilation and DM decay in the halo might have the same signatures. However, due to the fact that the dependence on the DM halo density is different for each case, in case of a positive signal, directional information would be crucial to distinguish between these two possibilities.

For concreteness, in what follows we present results using the Navarro, Frenk and White (NFW) simulation\textsuperscript{12} as our canonical profile.

3 Neutrino Bounds

In order to obtain the constraints on the DM annihilation cross section and DM lifetime we assume that DM annihilates\textsuperscript{2,3,4} or decays\textsuperscript{5} only into neutrinos. If DM annihilates or decays into SM particles, neutrinos (and antineutrinos) are the least detectable ones. Any other possible annihilation or decay mode would produce gamma rays, which are much easier to detect, and would allow to set a much stronger (and model-dependent) bound. Thus, the most conservative approach\textsuperscript{2,3,4,5} is to assume that only neutrinos are produced in DM annihilations or decays. Even in this conservative case, it has been shown that stringent limits can be obtained by comparing the expected time-integrated annihilation signal of all galactic halos\textsuperscript{2} and the signal from annihilations\textsuperscript{3,4} or decays\textsuperscript{5} in the Milky Way Halo with the background at these energies.

3.1 The Atmospheric Neutrino Background

For $E_\nu \gtrsim 100$ MeV, the main source of background for a possible neutrino signal from DM annihilations or decays is the flux of atmospheric neutrinos, which is well known up to energies of $\sim 100$ TeV. Thus, in order to obtain a bound on the DM annihilation cross section and lifetime we need to compare these two fluxes, and in particular we consider the $\nu_\mu + \bar{\nu}_\mu$ spectra calculated with FLUKA\textsuperscript{15}.

In this energy range, we will follow the approach of Ref.\textsuperscript{3}. By assuming that the only resultant products of DM annihilation (decay) are neutrino-antineutrino pairs, we first obtain a general bound by comparing the $\nu_\mu + \bar{\nu}_\mu$ neutrino flux from DM annihilation (decays) in the halo with the corresponding atmospheric neutrino flux for $E_\nu \sim 100$ MeV–100 TeV in an energy bin of width $\Delta \log_{10} E_\nu = 0.3$ around $E_\nu = m_\chi \left( E_\nu = m_\chi / 2 \right)$. For each value of $m_\chi$, the limit on $\langle \sigma_A v \rangle \left( \tau_\chi \right)$ is obtained by setting its value so that the neutrino flux from DM annihilations (decays) in the Milky Way equals the atmospheric neutrino spectrum integrated in the chosen energy bin. The reason for choosing this energy bin is mainly that the neutrino signal is sharply peaked around a neutrino energy equal to the DM mass (half of the DM mass) and this choice is within the experimental limits of neutrino detectors.
Figure 1: Bounds on the total DM annihilation cross section (left panel) and DM lifetime (right panel) for a wide range of DM masses obtained using different approaches: full-sky signal (dark area), angular signal (light area) and 90% CL limit using SK data at low energies\(^{16}\) (hatched area). Results are obtained for a NFW profile. Other general bounds are also shown. Right panel: the unitarity bound\(^6\), the limit above which the cusps of the DM halos are too flat (KKT)\(^7\) and the natural scale for thermal relics. Left panel: bounds from Cosmic Microwave Background observations\(^3\) and Cosmic Microwave Background plus Supernovae data\(^10\) (both at 2\(\sigma\) confidence level) and the line \(\tau_\chi = t_U\), with \(t_U \simeq 4 \times 10^{17}\) s the age of the Universe. Adapted from Refs.\(^4,5\).

The most conservative bound is obtained by using the full-sky signal, and this is shown in both panels of Fig. 1 where the dark areas represent the excluded regions. However, a better limit can be obtained by using angular information. This is mainly limited by the kinematics of the interaction. In general, neutrino detectors are only able to detect the produced lepton and its relative direction with respect to the incoming neutrino depends on the neutrino energy as \(\Delta \theta \sim 30^\circ \times \sqrt{\text{GeV}/E_\nu}\). As in Ref.\(^3\) and being conservative, we consider a field of view with a half-angle cone of \(30^\circ\) (\(30^\circ \times \sqrt{10\ \text{GeV}/E_\nu}\)) for neutrinos with energies above (below) 10 GeV. This limit is shown in both panels of Fig. 1 by the dashed lines (light areas), which improves upon the previous case by a factor of a few for \(E_\nu > 5\) GeV.

### 3.2 MeV Dark Matter

As we have just described, it is expected that a more detailed analysis, making a more careful use of the directional as well as energy information for a given detector, will improve these results. Note for instance that for energies \(\sim 1\text{-}100\) GeV neutrino oscillations would give rise to a zenith-dependent background, whereas we expect a nearly flat background for other energies for which oscillations do not take place. We now show how a more careful treatment of the energy resolution and backgrounds can substantially improve these limits\(^4,5\).

Here we describe the analysis followed in Refs.\(^4,5\) to set neutrino constraints on the DM total annihilation cross section and DM lifetime in the energy range \(15\) MeV \(\lesssim E_\nu \lesssim 130\) MeV. In this energy range the best data comes from the search for the diffuse supernova background by the Super-Kamiokande (SK) detector which has looked at positrons (via the inverse beta-decay reaction, \(\nu_e + p \rightarrow e^+ + n\)) in the energy interval 18 MeV–82 MeV\(^{16}\). As for these energies there is no direction information, we consider the full-sky \(\overline{\nu}_e\) signal. In this search, the two main sources of background are the atmospheric \(\nu_e\) and \(\overline{\nu}_e\) flux and the Michel electrons and positrons from the decays of sub-threshold muons. Below 18 MeV, muon-induced spallation products are the dominant background, and below \(\sim 10\) MeV, the signal would be buried below the reactor antineutrino background.

Although for \(E_\nu \lesssim 80\) MeV the dominant interaction is the inverse beta-decay reaction (with free protons), the interactions of neutrinos (and antineutrinos) with the oxygen nuclei contribute significantly and must be considered. For our analysis we have included both the interactions of
\( \nu_e \) with free protons and the interactions of \( \nu_e \) and \( \overline{\nu}_e \) with bound nucleons, by considering, in the latter case, a relativistic Fermi gas model\(^{17} \) with a Fermi surface momentum of 225 MeV and a binding energy of 27 MeV. We then compare the shape of the background spectrum to that of the signal by performing a \( \chi^2 \) analysis, analogous to that of the SK collaboration\(^{16} \). In this way, we can extract the limits on the DM annihilation cross section and DM lifetime\(^{4,5} \). Hence, we consider the sixteen 4-MeV bins in which the data were divided and define the following way, we can extract the limits on the DM annihilation cross section and DM lifetime.

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

where the sum \( l \) is over all energy bins, \( N_l \) is the number of events in the \( l \)th bin, and \( A_l \), \( B_l \) and \( C_l \) are the fractions of the DM annihilation or decay signal, Michel electron (positron) and atmospheric \( \nu_e \) and \( \overline{\nu}_e \) spectra that are in the \( l \)th bin, respectively. The fractions \( A_l \) are calculated taking into account the energy resolution of SK, interactions with free and bound protons and the correct differential cross sections\(^4 \). The fractions \( B_l \) and \( C_l \) are calculated taking into consideration that in water 18.4\% of the \( \mu^- \) produced below Čerenkov threshold \( (p_{\mu} < 120 \text{ MeV}) \) 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\(^{18} \). In the calculation of the fractions \( B_l \) and \( C_l \) we have used the low energy atmospheric neutrino flux calculation with FLUKA\(^{19} \). Note that, in a two-neutrino approximation and for energies below \( \sim 300 \text{ MeV} \) (where most of the background comes from), half of the \( \nu_{\mu} \) have oscillated to \( \nu_{\tau} \), whereas \( \nu_e \) 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\(^{20} \). Thus, in order to calculate \( B_l \) and \( C_l \) we use the two-neutrino approximation. The fitting parameters in the \( \chi^2 \)-function are \( \alpha \), \( \beta \) and \( \gamma \), which represent the total number of each type of event. For the systematic error we take \( \sigma_{\text{sys}} = 6\% \) for all energy bins\(^{16} \).

In absence of a DM signal, a 90\% confidence level (C.L.) limit can be set on \( \alpha \) for each value of the DM mass. The limiting \( \alpha_{90} \) is defined as

\[
\int_0^{\alpha_{90}} P(\alpha) \, d\alpha = 0.9,
\]

where \( P(\alpha) = K \cdot e^{-\chi^2_\alpha^2/2} \) is the relative probability and \( \chi^2_\alpha \) is the minimum \( \chi^2 \) for each \( \alpha \). The normalizing constant \( K \) is such that \( \int_0^\infty P(\alpha) \, d\alpha = 1 \). It is straightforward to translate the limit on \( \alpha \) into limits of the total DM annihilation cross section and DM lifetime and these 90\% CL bounds are shown in both panels of Fig. 1 by the hatched areas and they clearly improve (and extend to lower masses) by about an order of magnitude upon the general and very conservative bound obtained with the simple analysis described above for higher energies.

### 4 Conclusions

In this talk we have shown how neutrino detectors can also be used to test some of the DM properties and have obtained general bounds on the DM annihilation cross section and DM lifetime, which greatly improve over previous limits\(^{6,7,8,9,10} \). In order to do so, we have assumed that the only SM products from DM annihilations or decays are neutrinos, which are the least detectable particles of the SM. By making this assumption we have obtained conservative but model-independent bounds. In a simple way and for energies between \( \sim 100 \text{ MeV} \) and \( \sim 100 \text{ TeV} \), we have considered the potential signal from DM annihilations or decays in the Milky Way and

\(^{*}\text{Note that there is an error in Eq.(8) of Ref.}^4 \). Nevertheless, this implies very small corrections to the results presented. I thank O. L. G. Peres for pointing this out.
have compared it to the atmospheric neutrino background. The general bounds are obtained by considering this potential signal and imposing that it has to be at most equal to the background in a given energy interval. We have also shown how this crude, but already very stringent limit, can be substantially improved by more detailed analysis which make careful use of the angular and energy resolution of the detectors, as well as of backgrounds. In this way, we have obtained the 90% CL bounds on the DM annihilation cross section and DM lifetime for $m_\chi \lesssim 200$ MeV, which is about an order of magnitude more stringent.

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