Model-Independent Bound on the Dark Matter Lifetime

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Abstract

If dark matter (DM) is unstable, in order to be present today, its lifetime needs to be longer than the age of the Universe, \( t_U \sim 4 \times 10^{17} \) s. It is usually assumed that if DM decays it would do it with some strength through a radiative mode. In this case, very constraining limits can be obtained from observations of the diffuse gamma ray background. However, although reasonable, this is a model-dependent assumption. Here our only assumption is that DM decays into, at least, one Standard Model (SM) particle. Among these, neutrinos are the least detectable ones. Hence, if we assume that the only SM decay daughters are neutrinos, a limit on their flux from DM decays in the Milky Way sets a conservative, but stringent and model-independent bound on its lifetime.

PACS: 95.35.+d, 14.60.St, 95.55.Vj

1 Introduction

It is more than seventy years since an unknown missing mass was first postulated in order to understand the motion of galaxies in clusters [1]. Since then, a lot more evidences at different scales have been found in favor of the existence of this non-luminous matter, from the measurements of the rotation curves of galaxies to the observation of the cosmic microwave background (CMB) (for reviews see eg. Refs. [2]). Thus the question now is not if the dark matter (DM) exists, but what is its nature. Many non-baryonic candidates have been proposed, from the lightest particle in supersymmetric models, to the lightest Kaluza-Klein excitation in models of extra-dimensions, to sterile neutrinos, light scalar particles, axions, particles from little Higgs models, etc. (see eg. Refs. [2] for a comprehensive list).

It might well happen that DM consists of different species, with different interactions with Standard Model (SM) particles and among themselves. It might also happen that DM was not in thermal equilibrium in the early Universe, i.e. it is not a thermal relic. Nevertheless, in order for it to be present today, there is a requirement: it needs to be stable, or at least to have a lifetime longer than the age of the Universe, \( t_U \sim 4 \times 10^{17} \) s. The possibility of unstable DM is not new and models with decaying DM have been considered since long ago for different aims in astrophysics and cosmology [3]. Bounds on its radiative lifetime have been usually obtained from measurements of the diffuse gamma ray background [4]. However, although very stringent, they do not necessarily represent
constraints on the actual DM lifetime, but only set limits on its decay mode into pho-
tons. On the other hand, by evaluating how the expansion rate of the Universe is affected,
bounds on the DM lifetime can be set using CMB data \[6\]. In this more general case, it
is shown that already the first year of WMAP observations \[5\] constrains DM lifetime to
be longer than \(\tau_{\text{CMB}} = 1.6 \times 10^{18} \text{s} \) at 2\(\sigma\) confidence level (CL), with the only assumption
that the decay is into relativistic particles \[6\]. This bound is rather robust but difficult to
improve by further observations, for the DM decay affects CMB only at large scales, for
which errors are limited by cosmic variance \[6\]. Nevertheless, a recent study \[7\], which also
takes into account type Ia supernovae (SN) data, improves this limit by about an order of
magnitude, \(\tau_{\text{CMB+SN}} = 2.2 \times 10^{19} \text{s} \) at 2\(\sigma\) CL.

In this letter we obtain a lower bound on the DM lifetime, which is much more restrictive
(several orders of magnitude) than that set by CMB and SN observations and model-
independent, unlike that obtained from observations of the diffuse gamma ray background.

Among the stable SM particles, neutrinos are the least detectable ones. Therefore, if we
assume that the only SM products from the DM decay are neutrinos, a limit on their flux,
conservatively and in a model-independent way, sets a lower bound on the DM lifetime.
This is the most conservative assumption from the detection point of view, that is, the
worst possible case. Any other decay 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 with unstable DM, which decays at
least into one SM particle. Hence, the bound so obtained is a bound on the lifetime of the
DM particle and not only on its partial lifetime due to the decay channel into neutrinos.
Thus, following a similar approach to that of Refs. \[8, 9, 10\], we consider this case and
evaluate the potential neutrino flux from DM decay in the whole Milky Way, which we
compare with the relevant backgrounds for detection: mainly the well known and measured
atmospheric neutrino flux, which spans over about seven decades in energy.

2 Neutrino Fluxes from DM Decay in the Milky Way

In what follows we only study DM decays in the Milky Way and do not consider the diffuse
signal from cosmic decays. In general, the latter is likely to be smaller than, or at most of
the same order of, the former.

If DM has a lifetime longer than the age of the Universe, \(\tau_{\chi} > t_U\), the differential
neutrino (plus antineutrino) flux per flavor from DM decay in a cone of half-angle \(\psi\) around
the galactic center, covering a field of view \(\Delta \Omega = 2 \pi \left(1 - \cos \psi\right)\), is given by

\[
\frac{d\Phi}{dE_{\nu}} = \frac{\Delta \Omega}{4 \pi} J \Delta \Omega \frac{R_{\text{sc}} \rho_0}{m_{\chi} \tau_{\chi}} \frac{1}{3} \frac{dN}{dE_{\nu}},
\]

where \(m_{\chi}\) is the DM mass, \(R_{\text{sc}} = 8.5 \text{kpc}\) is the solar radius circle, \(\rho_0 = 0.3 \text{ GeV cm}^{-3}\)
is a normalizing DM density, which is equal to the commonly quoted DM density at \(R_{\text{sc}},\)
and $J_{\Delta \Omega}$ is the average in the field of view (around the galactic center) of the line of sight integration of the DM density, which is given by

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

where $r = \sqrt{R_{sc}^2 - 2lR_{sc} \cos \psi' + l^2}$, and the upper limit of integration is

$$l_{\max} = \sqrt{(R_{\text{halo}}^2 - \sin^2 \psi R_{sc}^2) + R_{sc} \cos \psi}.$$  \hspace{1cm} (3)

This integral barely depends on the size of the halo $R_{\text{halo}}$, as long as it is larger than few tens of kpc, for the contribution at large scales is negligible.

The neutrino (plus antineutrino) spectrum per flavor is given by $dN/dE_\nu$. If DM is the lightest particle of the new sector, which is introduced to render a more complete theory, then it can only decay into SM particles. Hence, the most conservative assumption is that it decays into neutrino-antineutrino pairs, $\chi \rightarrow \nu \bar{\nu}$. In this case $dN/dE_\nu = 2 \delta(E_\nu - m_\chi/2)$. However, if the lightest particle of the new sector ($\chi_L$) is stable, but the next-to-lightest particle ($\chi_{NL}$) is long-lived, the latter could also constitute part of the DM and decay into the former plus one or more SM particles, which we conservatively assume to be neutrinos. Commonly, in this class of models, these two new particles are almost degenerate in mass, and thus the total energy of the produced neutrinos is approximately equal to the difference of their masses ($\Delta M$). For two-body decays, $\chi_{NL} \rightarrow \chi_L + \nu$, $dN/dE_\nu = \delta(E_\nu - \Delta M)$, whereas for three-body decays, $\chi_{NL} \rightarrow \chi_L + \nu + \bar{\nu}$, the neutrino (and antineutrino) spectrum is continuous with a maximum energy equal to $\Delta M$. In what follows we shall consider for concreteness (and for comparison with the CMB bounds) the case of DM decay into neutrino-antineutrino pairs and obtain bounds on $\tau_\chi$ as a function of $m_\chi$. From this calculation, it is straightforward to obtain a bound on the combination $m_\chi \tau_\chi$ as a function of the neutrino energy, which for the second two-body decay case is equal to $\Delta M$. There are two main points to take into account. Whereas in the first case there is a produced neutrino-antineutrino pair, in the second there is only one final neutrino (or antineutrino). On the other hand, in the second case only half of the DM decays (the next-to-lightest particle of the new sector), for the lightest particle of the new sector is assumed to be stable, and it also contributes (usually at comparable level) to the DM. This implies an overall factor of 4. Finally, although a detailed analysis for three-body decays is model-dependent, in general this case would give bounds, for a given neutrino energy, of the same order of magnitude of those for the two-body decay case.

In Eq. (1), the factor of 1/3 comes from the assumption that the decay branching ratio is the same for the three neutrino flavors. Let us note that this is not a very restrictive assumption, for even in the case DM decays predominantly into one flavor, 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 equal decay into all flavors.
On the other hand, with our definition of $J_{\Delta \Omega}$, all the astrophysical uncertainties in the calculation of the neutrino flux from DM decays are encoded in $J_{\Delta \Omega}$. They come from our lack of knowledge of the exact DM density $\rho(r)$. As a matter of fact, the formation of large scale structure is successfully predicted by detailed N-body simulations which show that cold DM clusters hierarchically in halos. The simulated DM profile in a galaxy like the Milky Way, assuming a spherically symmetric matter density with isotropic velocity dispersion, can be parametrized as

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

where $\rho_{sc}$ is the DM density at $R_{sc}$, $r_s$ 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 around $r_s$.

The three commonly used DM density profiles we consider [12, 13, 11] (see also Ref. [14]) tend to agree at large scales, but uncertainties can be significant in their inner parts. However, for a large field of view, these uncertainties are much less relevant and do not affect significantly the calculation of the neutrino flux from DM decay. In addition, and unlike the case of DM annihilations, the neutrino flux depends on the line of sight integral of the DM density and not of its square, which reduces considerably the effect of the inner cusp uncertainty.

As we will see below, and following a similar approach as in Ref. [9], we are interested in signals corresponding to different components of the halo: the full-sky signal and the signal from a 30° half-angle cone around the galactic center. Whereas for the former, the value of the average of the line of sight integration of the DM density, $J_{180}$, for the three considered profiles, can vary at the very most from 1.3 to 8.1, for the latter, the value of $J_{30}$ might be anything from 3.9 to 24. These limiting cases are obtained from the range of values for $\rho_{sc}$ [15] which satisfy present constraints from the allowed range for the local rotational velocity [16], the amount of flatness of the rotational curve of the Milky Way and the maximal amount of its non-halo components [17]. For the usually quoted value of $\rho_{sc}$, for each of the profiles, $(\rho_{sc}, J_{180}, J_{30}) = (0.27 \text{ GeV/cm}^3, 1.9, 6.5)$ [11], $(0.30 \text{ GeV/cm}^3, 2.0, 6.1)$ [12] and $(0.37 \text{ GeV/cm}^3, 2.2, 5.5)$ [13]. Thus, uncertainties in the halo profile have fairly small effects on our final results. Here we consider the simulation by Navarro, Frenk and White (NFW) [12] as our canonical profile. From the limiting cases just discussed, this implies that in the worst scenarios we could be overestimating (underestimating) the neutrino flux by a factor of about 1.5 (3.9).

### 3 Neutrino Bounds on the DM lifetime

For $E_{\nu} \gtrsim 50$–60 MeV, the main source of background for a possible neutrino signal from DM decays is the flux of atmospheric neutrinos, which has been measured in a number of detectors up to energies of $\sim 100$ TeV [18]. Its spectrum is also well understood theoretically and different calculations using different interactions models agree within 20-30% [19, 20, 21].
Thus, in order to obtain a bound on the DM lifetime we need to compare these two fluxes, and in particular we consider the $\nu_\mu + \bar{\nu}_\mu$ spectra calculated with FLUKA [21].

Assuming two-body DM decays into neutrino-antineutrino pairs, we first obtain a general lower bound for $m_\chi \sim 100$ MeV–200 TeV, by comparing the $(\nu_\mu + \bar{\nu}_\mu)$ neutrino flux from DM decays in the halo with the corresponding atmospheric neutrino flux in an energy bin of width $\Delta \log_{10} E_\nu = 0.3$ around $E_\nu = m_\chi/2$. For each value of $m_\chi$, the limit on $\tau_\chi$ is obtained by setting its value so that the neutrino flux from DM decays in the Milky Way equals the atmospheric neutrino spectrum integrated in the chosen energy bin. The reason for choosing this energy bin is two-fold: on one side, the neutrino signal is sharply peaked around a neutrino energy equal to half of the DM mass and this choice is within the experimental limits of neutrino detectors, and on the other side, for the sake of comparison, we follow the approach of Ref. [9]. Nevertheless, following Ref. [10], a more detailed analysis is performed below for $m_\chi \sim 30$–200 MeV.

The most conservative bound is obtained by using the full-sky signal, and this is shown in Fig. 1 where the dark area represents the excluded region. 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. [9] and being conservative, we consider a field of view with a half-angle cone of $30^\circ \times \sqrt{10 \text{ GeV}/E_\nu}$ for neutrinos with energies above (below) 10 GeV. This limit is shown in Fig. 1 by the dashed line (light area), which improves upon the previous case by about a factor of three for $m_\chi > 10$ GeV.

As anticipated, 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 $\sim 1$-100 GeV neutrino oscillations would give rise to a zenith-dependent background, roughly speaking a factor of two larger for downgoing neutrinos as compared to the upgoing flux, whereas we expect a nearly flat background for other energies for which oscillations do not take place. On the other hand, the signal from DM decays in the halo is expected to change by a factor of $\sim 7$ for a half-angle cone of $30^\circ$ around the galactic center as compared to the signal within the same field of view but coming from the opposite direction. Thus, making use of the directional information would certainly render more stringent bounds. Nevertheless, and although a detailed and detector-dependent analysis is beyond the scope of this letter, we show how such a more careful treatment of the energy resolution and backgrounds can substantially improve these limits. For this and also extending the bounds to lower DM masses, we consider the low energy window below $\sim 100$ MeV (i.e. for $m_\chi \lesssim 200$ MeV) and perform an analogous analysis to that in Ref. [10].

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, $\bar{\nu}_e+p \rightarrow e^++n$) in the energy interval 18 MeV–82 MeV [22]. As for these energies there is no direction information, we consider the $\bar{\nu}_e$ signal coming from the whole sky. In this search, the two main sources of background are the atmospheric $\nu_e$
Figure 1: Bounds on the DM lifetime 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 [22] (hatched area). Results are obtained for a NFW profile and assuming two-body decays into relativistic particles (see text). Also shown the bound obtained from CMB observations [6] and CMB plus SN data [7] (both at 2σ CL) and the line \( \tau_\chi = t_U \).

and \( \nu_e \) 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 \( \nu_e \) with bound nucleons, by considering, in the latter case, a relativistic Fermi gas model [23] 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 and perform a \( \chi^2 \) analysis so that we can extract the limit on the DM lifetime in an analogous way as it was done to obtain an upper bound on the annihilation cross section for the case of DM annihilation in Ref. [10], where
we refer the reader for all the details of this analysis. The 90% CL limit is shown in Fig. 1 by the hatched area and it clearly improves (and extends to lower masses) by up to an order of magnitude upon the general and very conservative bound obtained with the simple analysis described above.

Finally, let us note that in principle, if the DM mass is not known, DM annihilation and DM decay in the halo might have the same signatures. However, whereas the decay signal depends linearly on the DM halo density, the annihilation signal depends on its square. Hence, in case of a positive signal, directional information is crucial to distinguish between these two possibilities.

4 Conclusions

In this letter we have obtained a general bound on the DM lifetime, which is several orders of magnitude more stringent than previous limits. In order to do so, we have considered that the only SM products from DM decays are neutrinos, which are the least detectable particles of the SM. Thus, regardless of how likely this is, by making this assumption we can obtain a conservative but model-independent bound on the DM lifetime. To do so we have considered the flux of neutrinos coming from DM decays in the Milky Way for an energy interval from $\sim 50$ MeV to $\sim 100$ TeV and have compared it to the dominant background, the well known and measured atmospheric neutrino flux. For concreteness we only show results for two-body DM decays into relativistic SM particles, although it is straightforward to generalize this result to other two-body decays. On the other hand, the model-dependent case of three-body decays should render limits of the same order of magnitude. We have obtained a general bound by considering the signal from the whole Milky Way 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, following the analysis of Ref. [10], we have obtained the 90% CL lower bound on the DM lifetime for $m_\chi \sim 30$–200 MeV, which is an order of magnitude more stringent.

In summary, we have shown that neutrinos can be used to set very stringent and model-independent bounds on the DM lifetime, with the only assumption that if DM is unstable, it decays into at least one SM particle. As our main result, we have improved by several orders of magnitude upon previous limits.

Acknowledgments

The author thanks G. Battistoni for providing him with the atmospheric neutrino fluxes, J. Beacom and T. Montaruli for helpful comments and Y. Santoso for discussions. SPR is partially supported by the Spanish Grant FPA2005-01678 of the MCT.

\footnote{Note that there is an error in Eq.(8) of Ref. [10], which should read $P(\alpha) = K \cdot e^{-\chi^2/2}$. Nonetheless, this implies very small corrections to the results presented. I thank O. L. G. Peres for pointing this out.}
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