PROCEEDINGS OF SCIENCE

Dark Matter Decay to Neutrinos

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Dark matter (DM) particles are predicted to decay into Standard Model particles which would produce signals of neutrinos, gamma-rays, and other secondary particles. Neutrinos provide an avenue to probe astrophysical sources of DM particles. We review the decay of dark matter into neutrinos over a range of dark matter masses from MeV to ZeV. We examine the expected contributions to the neutrino flux at current and upcoming neutrino and gamma-ray experiments, such as Hyper-Kamiokande, DUNE, CTA, TAMBO, and IceCube-Gen2. We consider galactic and extragalactic signals of decay processes into neutrino pairs, yielding constraints on the dark matter decay lifetime that ranges from $\tau \sim 1.2 \times 10^{21}$ s at 10 MeV to 1.5×10^{29} s at 1 PeV.

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1. Introduction

The existence of weakly-interacting dark matter (DM) has been implied by observations of gravitational effects on the matter distribution on large scales and the clustering of galaxies, among other examples. Exploring the possibility of Dark Matter and Standard Model (SM) interactions can lead to the discovery of the nature of the DM particle. Here we consider the neutrino sector as the principal portal through which the DM interacts with the SM. This is the objective in "scotogenic" models, in which neutrino mass generation occurs through interactions with the dark sector.

Neutrinos are light, neutral, and notoriously difficult to detect. If DM is unstable enough to decay into heavy states such as muons, quarks, or weak bosons, a neutrino signal will be produced. The indirect detection of DM-neutrino at low energies is ruled by the small neutrino cross section and at high energies by the momentum transfer. We then choose to focus on the most invisible channel: direct decay of DM into neutrino-antineutrino pairs, whose energy will be equal to half of the DM rest mass.

2. Dark Matter Decays to Neutrinos

The expected flux from decaying DM at Earth per neutrino flavor with mass m_χ and lifetime τ_χ is

$$\frac{d\Phi_{\nu+\bar{\nu}}}{dE_\nu} = \frac{1}{4\pi}\frac{1}{\tau_\chi m_\chi}\frac{1}{3}\frac{dN_\nu}{dE_\nu}D(\Omega). \tag{1}$$

Below the electroweak scale, the neutrino spectrum per decay is $dN_\nu/dE_\nu = 2\delta(1-2E/m_\chi)m_\chi/2E^2$; at higher masses a low-energy tail emerges as discussed in [3]. In the Eq. 1, $D(\Omega)$ is the D-factor, an integral of the DM distribution $\rho(x)$ along the solid angle ($\Delta\Omega$) and line of sight (l.o.s):

$$D \equiv \int d\Omega \int_{\text{l.o.s.}} \rho_\chi(x)dx. \tag{2}$$

The D-factors for each experiment are computed by integrating their exposure over 24 hours.

We assume the Galactic DM density distribution is modeled by an Navarro–Frenk–White (NFW) [2] profile with a slope parameter $\gamma = 1.2$ and scale radius $r_s = 20$ kpc. We set the local DM density to $\rho_0 = 0.4$ GeV cm^{-3} and take the distance to the galactic centre to be $R_0 = 8.127$ kpc. We have assumed equal production of each neutrino flavor, which implies equal neutrino flavors detected on Earth. Due to neutrino oscillation, this approximation remains valid regardless of the initial flavor composition. From Eq. 1, we produce limits on the DM decay lifetime, using results from multiple experiments and their analyses of existing data or forecasted sensitivities.

The full list of neutrino experiments, including the neutrino energy range and flavor sensitivity covered by each experiment, is given in Ref. [1]. The neutrino energy range spans from 10 MeV at Borexino to $> 10^{11}$ GeV at IceCube and AUGER. For a detailed description of each experiment and its sensitivity, see Ref. [4]. Our forecasts assume five years of exposure for each of the following experiments: JUNO, DUNE, Hyper-Kamiokande (HK), RNO-G, IceCube-Gen2, KM3NeT, P-ONE, TAMBO, and GRAND. Constraints of experiments or other groups that are not explicitly calculated in this work are rescaled to match the D-factors as described aboved. This enables an equitable comparison between different experimental constraints.

2.1 Gamma rays from electroweak corrections

Above the TeV scale, electroweak loop corrections can lead to the production of photons. These result in two distinct gamma-ray fluxes: a high-energy flux of prompt photons emitted during decay and a lower-energy (GeV–TeV) signal due to photon scattering with the Cosmic Microwave Background (CMB) and extragalactic background light (EBL). The prompt gamma-ray spectra can be obtained via the `HDMSpectra` [3] package, which calculates the effects of particle showers, hadronization, and light particle decays beyond the electroweak scale.

We use the expected gamma-ray distribution to derive constraints using gamma-ray data sets in a similar way to how we set constraints with neutrinos. High-energy gamma rays traversing the intergalactic medium (IGM) are absorbed and scattered by photons from the CMB and EBL, which attenuate the signal. Hence, we include an additional absorption factor of $\exp(-\tau_{\gamma\gamma})$ in Eq.(1) to account for attenuation due to pair-production from scattering with CMB photons. We conservatively include the absorption factor as a constant by taking the average attenuation rate over a distance of 10 kpc, considering only CMB interactions. We will present limits of the following gamma-ray experiments: *Fermi*-LAT, HAWC, LHAASO, IceTop, KASCADE-Grande, CASA-MIA, EAS-MSU, and TA-SD, as well as a projected sensitivity for CTA. All integrated gamma-ray fluxes are compared to the expected total flux from DM decay to neutrinos with the photon emission spectrum from electroweak corrections. This comparison then yields our constraints on the DM decay lifetime.

At sufficiently large masses, gamma rays produced from decays outside our galaxy can scatter down to produce an extragalactic signal that is observable at lower energies in experiments such as *Fermi*-LAT. However, the absorption of gamma rays results in cascades that transform any reasonably high-energy source into a universal spectrum that peaks within the *Fermi* telescope's sensitivity range. Ref. [5] set constraints on the lifetime for DM decay to SM particles using *Fermi* observations of the isotropic gamma-ray background. We will use the limits presented there for DM decays to neutrino pairs, which extend up to $m_\chi = 10^7$ GeV.

3. Results

From the methods described above, we provide the constraints on the dark matter decay lifetime in Fig. 1. We label the results derived for this work with a heart (♡).

Constraints from neutrino telescopes are shown as solid lines with shaded regions. The intersection of experimental sensitivities yields continuous constraints on the dark matter lifetime that are much greater than the age of the Universe, ranging from $\tau > 10^{19}$ s at $m_\chi \sim 50$ MeV to $\tau > 10^{27}$ s for $m_\chi \sim 10^{11}$ GeV. Below $\sim 10^7$ GeV, the sensitivities follow closely the growth of the electroweak cross section with energy, with some scaling between experiments resolving the differences in effective volumes.

Projected sensitivities from future observatories are shown as dashed lines; these assume five years of data taking. JUNO, HyperK, DUNE, KM3NeT, P-ONE, and IceCube-Gen2 provide an improvement of one to two orders of magnitude over current bounds, mainly owing to much larger effective detector volumes. Projected improvements from future radio (GRAND, RNO-G) and modular Cherenkov arrays (TAMBO) are more modest, which we mainly attribute to restricted fields of view.

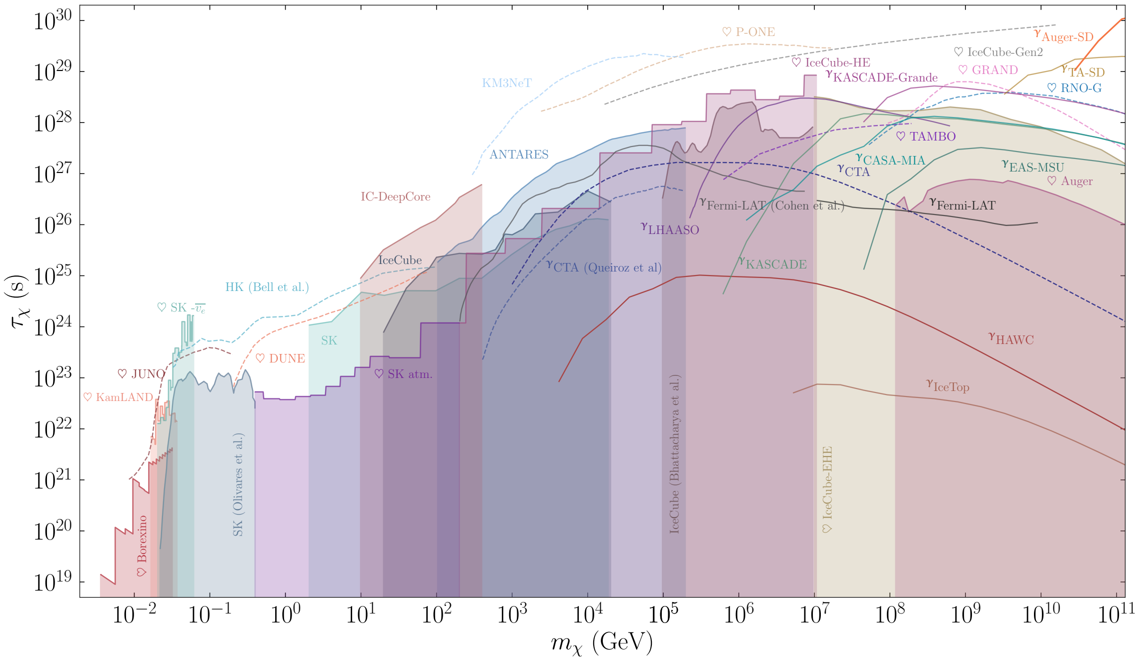

Figure 1: ***Constraints on the lifetime of dark matter decaying to neutrinos*** $\chi \to \bar{\nu}\nu$**.** Solid lines bordering shaded regions represent limits from existing neutrino telescope data, solid lines without shading correspond to limits from existing gamma-ray observatories, and dashed lines show the reach of future experiments. Labels with a heart symbol (♡) correspond to limits derived for this work.

Limits from gamma-ray observatories are marked with a γ superscript. These are also shown separately in Fig. 2. Four experiments dominate the constraints at three different energy ranges. At masses below $\sim 10^5$ GeV, the flux of extragalactic gamma-rays produced by interactions with the IGM is probed by *Fermi*-LAT, yielding the dominant source of gamma-ray constraints in this mass range. At masses between 10^6 and 10^7 GeV, recent measurements by LHASSO supersede prior experiments and improve constraints by nearly four orders of magnitude compared to HAWC. At masses above 10^8 GeV, KASCADE-Grande measurements establish the most competitive constraints on the DM decay lifetime limits until $m_\chi \gtrsim 10^{10}$ GeV, where the TA and Auger supersede all other experiments. Other experiments considered, such as HAWC or IceTop limits remain subdominant over the entire mass range probed here. Notably, we do not expect that the upcoming CTA experiment will yield a significant improvement over current constraints, due to its limited field of view.

4. Future Prospects & Conclusions

As seen in Fig. 1, existing neutrino telescopes are able to constrain the lifetime of dark matter decaying to neutrino pairs to values ranging from 10^3 to 10^{12} times the age of the Universe. Upcoming neutrino telescopes will make improvements of one to two orders of magnitude: DUNE and HyperKamiokande will fill in the gap around $m_\chi \sim$ GeV, while the strongest improvements will take place for the next generation of large-volume water and ice Cherenkov telescopes: KM3NeT, P-ONE, and IceCube-Gen2.

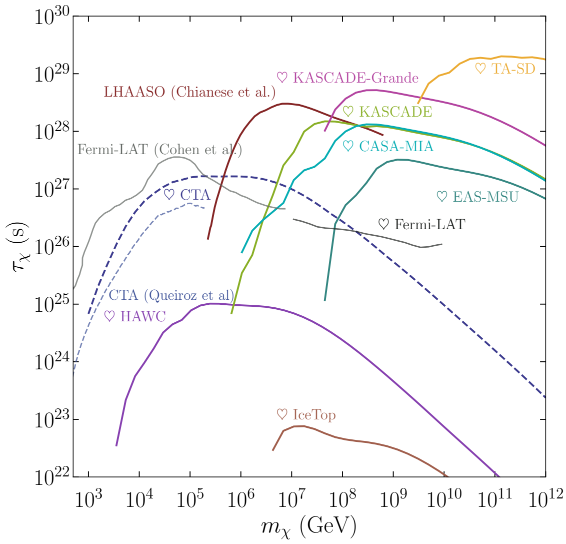

Figure 2: ***Gamma-ray constraints on dark matter decay lifetime $\chi \to \bar{\nu}\nu$ due to γ emission from electroweak processes.*** Solid lines correspond to existing constraints, while the dashed line is a projection for a future experiment. Hearts indicate the new constraints derived in this work. Gamma-ray emission below the electroweak scale is suppressed by powers of M_W [3].

Above the $\sim$ TeV range, electroweak emission of gamma-rays opens a new opportunity for discovery. However, these photons emerge at lower energies than their associated neutrinos, and so the gain in "detectability" at Earth, i.e. the ratio between Compton and electroweak cross-sections is a modest increase of four to six orders of magnitude. Combined with the peaked signal of a neutrino line and the wider field of view of neutrino telescopes, this means that constraints from neutrino telescopes remain stronger than those from gamma-ray observations across all energy ranges.

Even though the sensitivity of neutrino telescopes to such line signals is superior, the observation of an electromagnetic counterpart will be key in the event of a discovery. To conclude, in this proceeding we have provided a comprehensive, complete, consistent, compendium of constraints on dark matter decay to neutrinos.

References

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