

Constraints on heavy asymmetric and symmetric dark matter from the Glashow resonance

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The decay of asymmetric dark matter (ADM) can lead to distinct neutrino signatures characterized by an asymmetry between neutrinos and antineutrinos. In the high-energy regime, the Glashow resonant interaction $\bar{\nu}_e + e^- \rightarrow W^-$ yields an increase in sensitivity to the neutrino flux, and stands out as the only way of discerning the antineutrino component in the diffuse high-energy astrophysical neutrino flux. This offers a unique opportunity in the search for dark matter with masses above the PeV scale. We examine the neutrino signal stemming from ADM decay and set the first stringent constraints on ADM lifetime τ_X . For ADM with mass $m_X \gtrsim 10$ PeV, we exclude $\tau_X \lesssim 10^{29}$ s using the data from the recent IceCube search for Glashow resonance events. Our projections further show that sensitivities at the forthcoming IceCube-Gen2 could approach 10^{30} s, depending on the decay channel. The current constraints on symmetric dark matter decay to neutrinos are also improved by up to a factor of 3 thanks to the Glashow resonance.

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Introduction. High-energy astrophysical neutrinos in the TeV–PeV range have been detected in large Cherenkov telescopes, most notably IceCube [1]. Detection is primarily through deep inelastic scattering (DIS) with nucleons, producing event morphologies that are recognized as showers (or cascades), tracks, or double cascades in or near the detector. Although the morphologies allow some reconstruction of the flavor of high-energy neutrinos, the identification of the neutrino charge conjugation-parity (CP) eigenstates in these interactions remains impossible. The only way to pin down the antineutrino component from the total neutrino flux at high energies is the so-called Glashow resonance (GR) [2], i.e., the resonant scattering of $\bar{\nu}_e$ on electrons in the detector $\bar{\nu}_e + e^- \rightarrow W^-$, which dramatically enhances the cross section for neutrino energies near $E_{\text{GR}} = 6.3$ PeV.

Such an event was first reported by IceCube as a partially contained cascade with a reconstructed energy

of 6.05 ± 0.72 PeV [3]. The detection of GR events with neutrino telescopes such as IceCube can grant a deeper understanding of astrophysical processes [4–18], and opens the door to new physics searches, e.g., neutrino decay and Lorentz invariance violation [19–22]. In a variety of models, dark matter (DM) interacts primarily with neutrinos, enabling the decay or annihilation of DM into neutrinos [23–32]. In such scenarios, the direct detection of DM becomes challenging, although indirect searches for neutrino-DM elastic scattering benefit from an enhanced cross section at high energies [33]. Searches for neutrino signals from DM annihilation [34] or decay [35] have also led to strong constraints on these models. Decay to neutrinos is particularly well-constrained at very high energies thanks to the growing neutrino-nucleus cross section and the presence of gamma rays from electroweak corrections.

As the GR breaks the degeneracy between neutrinos and antineutrinos, it is a sensitive probe of asymmetric dark matter (ADM), an alternative to the widely studied weakly interacting massive particles (WIMPs). Asymmetric models were proposed to connect the relic abundance of DM to the baryon asymmetry in the Universe [36], but are not generically tied to baryogenesis. If the dark sector's asymmetry is linked to the standard model (SM) sector, then decay could give rise to an asymmetry between SM decay products [37–43], including neutrinos [44,45].

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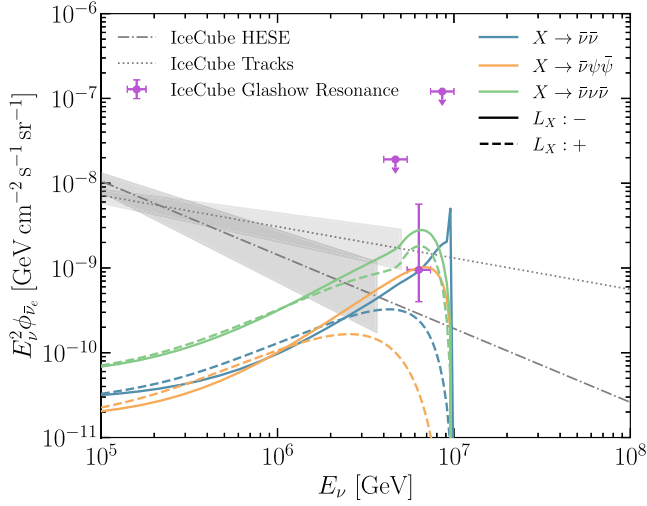


FIG. 1. Expected $\bar{\nu}_e$ spectra of with the three decay modes, i.e., $X \rightarrow \bar{\nu}\bar{\nu}(\nu\nu)$ (blue), $X \rightarrow \bar{\nu}(\nu) + \psi\bar{\psi}$ (orange), and $X \rightarrow \bar{\nu}(\nu) + \nu\bar{\nu}$ (green) for $m_X = 20$ PeV when the lifetime $\tau_X = 10^{29}$ s. A solid line corresponds to the mode with a negative lepton number and the dashed line corresponds to a positive lepton number. The IceCube GR observation [3] is shown as purple points. Gray lines are IceCube diffuse astrophysical neutrino measurements of high-energy starting events (dash-dotted) [46] and through-going muon tracks (dotted) [47] assuming equal contribution of each flavor. For IceCube diffuse astrophysical neutrino measurements shown here, we assume $\bar{\nu}_e$ constitutes 1/6 of the total flux.

Figure 1 shows predictions from a few such scenarios overlaid on observational data. These scenarios will be described later in this text.

In this work, we will exploit the enhanced cross section in the Glashow region to (1) improve on existing constraints on the decay of *symmetric* dark matter to $\bar{\nu}\nu$, and (2) derive new constraints on *asymmetric* dark matter decay to a number of neutrinophilic channels, setting stringent constraints on the ADM lifetime at $\tau_X \lesssim 10^{29}$ s for ADM mass $m_X \gtrsim 10$ PeV. Neutrinos produced from electroweak radiation preserve information about the asymmetry, and allow us to cover a mass range between 10^7 GeV and 10^{10} GeV. We will present constraints from currently available IceCube data, and projected sensitivities from the upcoming IceCube-Gen2.

Heavy Asymmetric Dark Matter Decay. Although some of the first ADM models predicted new particles in the 5–15 GeV mass range [36], models exist spanning a vast range of scales, and heavy ADM in particular has been widely explored [37–39, 43, 48–51]. Such constructions can be naturally realized in various scenarios, e.g., if the SM and the dark sector were never in thermal equilibrium and they both originate from the decay of a heavy mother particle with nonzero primordial baryon/lepton number asymmetry [48–50], or the thermally produced ADM goes through self-annihilating process producing lighter dark

TABLE I. Operators of the lowest dimensions and the corresponding neutrino-dominant decay modes of dark matter X . L is the Standard Model lepton doublet, and ψ is a dark fermion or SM particle.

	B1	B2	B3	B4
Benchmark	(scalar X)	(scalar X)	(fermion X)	(fermion X)
$\mathcal{O}_{X \rightarrow \nu}$	$\frac{1}{\Lambda} X \psi L \Phi$	$\frac{1}{\Lambda^2} X (L \Phi)^2$	$\frac{1}{\Lambda^2} X L \psi^2$	$\frac{1}{\Lambda^2} X L L \nu^c$
Decay	$X \rightarrow \bar{\nu} \psi / \nu \bar{\psi}$	$X \rightarrow \bar{\nu} \bar{\nu} / \nu \nu$	$X \rightarrow \bar{\nu} \psi \bar{\psi} / \nu \psi \bar{\psi}$	$X \rightarrow \bar{\nu} \bar{\nu} / \nu \nu$

particles and depleting its abundance to the level observed today [43, 51]. The mass of ADM is effectively unconstrained in these scenarios, so we treat m_X as a free parameter.

ADM typically carries $B - L$ (baryon minus lepton) numbers, and can transfer an asymmetry between the dark sector and SM via operators of the form $\mathcal{O}_{\text{ADM}} = \Lambda^{4-m-n} \mathcal{O}_X \mathcal{O}_{\text{SM}}$, where the dark sector $\mathcal{O}_X$ and SM $\mathcal{O}_{\text{SM}}$ operators have dimensions m and n respectively with Λ being the new physics scale [43, 44]. We intend to be model-independent and focus on a set of representative benchmark operators that lead to neutrino decay, as listed in Table I. We focus on dominant lowest-dimension operators that produce distinct GR signals depending on the $B - L$ charge of the DM. For all those scenarios, DM X carries a lepton number L_X . In Table I, L is the SM lepton doublet and Φ is a heavy scalar doublet which can be integrated out [44]. A scalar DM X can decay through the two-body process to a neutrino and a dark fermion ψ , i.e., $X \rightarrow \bar{\nu}(\nu) + \psi$ (B1) or two neutrinos $X \rightarrow \bar{\nu}\bar{\nu}(\nu\nu)$ (B2). The last two operators can arise from the operator $\bar{X} l \phi$ and $\frac{1}{\Lambda^{3n-3}} \phi \psi^n$ with the heavy scalar field ϕ integrated out [45, 52]. This leads to a multibody decay process for the fermionic DM $X \rightarrow \bar{\nu}(\nu) + 2n\psi$. At the lowest order $n = 1$, the decay produces a neutrino or antineutrino, depending on the lepton number carried by X (B3). The fermion ψ could be a new particle, or from the SM; if $\psi = \nu$ then X decays to three neutrinos (B4).

$\bar{\nu}_e$ Flux from ADM. Assuming ADM makes up all DM, we compute the expected high-energy $\bar{\nu}_e$ flux from ADM in the Galactic halo and beyond the Milky Way via decay channels discussed above.

The averaged contribution from the Galactic halo with a solid angle coverage Ω for DM with mass m_X and lifetime τ_X can be written as

$$\frac{d\Phi_{\bar{\nu}_e}^{\text{gal}}}{dE_\nu} = \frac{1}{4\pi m_X \tau_X} \sum_{\alpha}^3 \frac{dN_{\bar{\nu}_e}^{\text{ch}}}{dE_\nu} \frac{\mathcal{D}(\Omega)}{\Omega} P_{\bar{\nu}_e \rightarrow \bar{\nu}_e}, \quad (1)$$

where $\mathcal{D} = \int d\Omega \int_{\text{los}} \rho_X[r(s, l, b)] ds$ represents the column density of DM along the line of sight (los) over the solid angle $\Omega = 4\pi$. We adopt the generalized Navarro-Frenk-White (gNFW) profile for ρ_X with a slope

parameter 1.2, local DM density 0.4 GeV/cm^3 and a scale radius 20 kpc [53]. The galactocentric distance $r = \sqrt{s^2 + R_\odot^2 - 2sR_\odot \cos l \cos b}$, where l and b correspond to the Galactic latitude and longitude. Switching from the gNFW profile to a cored profile only introduces a $\lesssim 20\%$ difference in $\mathcal{D}$. We assume a universal production of neutrino flavor $\alpha \in \{e, \mu, \tau\}$, and $dN_{\bar{\nu}_\alpha}^{\text{ch}}/dE_\nu$ is the energy spectrum of neutrinos produced in the decay of a single DM particle via a specific decay channel to $\bar{\nu}_\alpha$. We also incorporate the neutrino oscillation probability after production, which leads to a $\sim 1/3$ contribution from each flavor to the total flux [54]. In practice, we adopt the best-fit oscillation parameters from NuFIT5.3 [55,56] to compute this probability.

The extragalactic DM contribution to the isotropic neutrino flux is

$$\frac{d\Phi_{\bar{\nu}_e}^{\text{ext gal}}}{dE_\nu} = \frac{\Omega_X \rho_c}{4\pi m_X \tau_X} \sum_\alpha \int_0^\infty \frac{dN_{\bar{\nu}_\alpha}^{\text{ch}}}{dE'_\nu} \frac{dz}{H(z)} P_{\bar{\nu}_\alpha \rightarrow \bar{\nu}_e}, \quad (2)$$

where $\Omega_X = 0.229$ is the DM density in the Universe, ρ_c is the Universe critical density and z is the redshift. $E'_\nu \equiv (1+z)E_\nu$ is the redshifted neutrino energy and $H(z) = H_0 \sqrt{(1+z)^3 \Omega_m + \Omega_\Lambda}$ is the Hubble expansion rate, for which we use $H_0 = 67.4 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.315$, and $\Omega_\Lambda = 0.685$ [57].

We sum the galactic contribution in Eq. (1) and the extragalactic contribution in Eq. (2) to find the angular-averaged neutrino flux from ADM decay. As the DM mass considered in this work is well above the electroweak scale, final-state radiation will modify the neutrino spectrum, softening the primary neutrino spectrum, and producing an additional lower energy ν and $\bar{\nu}$ component from electroweak showers. With these corrections, the energy spectrum of $\bar{\nu}_\alpha$ is

$$\frac{dN_{\bar{\nu}_\alpha}^{\text{ch}}}{dE_\nu}(E_\nu) = \sum_i \int_{E_\nu/m_X}^1 \frac{1}{ym_X} \frac{df_i}{dy} D_i^{\bar{\nu}_\alpha}(x; ym_X) dy, \quad (3)$$

where the sum on i goes over each (anti)neutrino produced in the uncorrected decay, including a sum over flavors. f_i is the distribution function for decay product i , which we provide in the Supplemental Material [58]. We implement the fragmentation functions $D_i^j(x; ym_X)$ from HDMSpectrum [59] where y represents the fraction of energy taken away by particle i in the DM mass and $x \equiv E_j/(ym_X)$ is the energy fraction deposited to the final particle j from the initial particle energy. The subsequent evolution such as hadronization and showering handled by Pythia8.2 [60–62] is also included in the fragmentation functions.

The $\bar{\nu}_e$ spectra from the benchmark decay modes are shown in Fig. 1. The electroweak corrections tend to

broaden the Dirac delta spectrum in two-body decay, and generate a $\bar{\nu}_e$ flux even when antineutrinos are absent in the initial decay products. If X carries negative lepton number $L_X < 0$ which tends to decay more to anti-neutrinos, the flux is more peaked at high energies. On the contrary, if $L_X > 0$ the $\bar{\nu}_e$ spectrum is more suppressed at the highest energies and peaks at lower energies. At $E_{\bar{\nu}_e}/m_X \lesssim 10^{-2}$, the $\bar{\nu}_e$ spectral for $L_X > 0$ and $L_X < 0$ converge. This means that GR loses the ability to pin down the asymmetry and lepton number of X when $m_X \gtrsim \text{EeV}$.

Current IceCube Data. We set constraints on ADM with publicly available IceCube data [3]. The measured flux is under the assumption of $(\nu:\bar{\nu}) = (1:1)$ and a flavor ratio of $(\nu_e:\nu_\mu:\nu_\tau) = (1:1:1)$ at Earth. The segmented differential flux reported in Ref. [3] covers the energy range [4, 10] PeV assuming an E^{-2} power-law spectrum within each bin. We integrate the reported differential flux limits over each bin to obtain $\Phi_{\text{obs},i}$. The uncertainty can be similarly integrated to obtain $\sigma_{\Phi_{\text{obs},i}}^2$.

The measured $\bar{\nu}_e$ flux receives contributions mainly from two sources: the diffuse astrophysical neutrino flux and the flux from DM decay. We ignore the atmospheric neutrino flux which is negligible next to the astrophysical flux at PeV energies. The main background is therefore from the isotropic astrophysical neutrino flux which is typically modeled as a power-law $d\Phi_{\nu}^{\text{astro}}/dE_\nu = \phi_0 (E_\nu/100 \text{ TeV})^{-\gamma}$, where ϕ_0 is the flux normalization and γ is the spectral index. In this work, we fix the values to the best fits of the 7.5 yr high-energy starting events (HESE) analysis [46]. We assume that $\bar{\nu}_e$ makes up 1/6 of the total astrophysical flux at Earth, corresponding to the equal-flavor assumption used in the HESE analysis. This is consistent with a general scenario in which these neutrinos are produced from $\pi^\pm$ decays at the source and experience oscillation during the propagation. Since the statistics of PeV neutrinos are low, the spectral index plays an important role in the predicted event rate. We will discuss the effects of the spectral index and the $\bar{\nu}_e$ fraction when presenting the results.

To evaluate the limits on the DM lifetime we define a Gaussian likelihood,

$$-2 \ln \mathcal{L}(\tau_X, m_X) = \sum_i \frac{(\Phi_{\text{exp},i} - \Phi_{\text{obs},i})^2}{\sigma_{\Phi_{\text{obs},i}}^2}, \quad (4)$$

where we integrate the DM and astrophysical differential neutrino fluxes to obtain the expected flux $\Phi_{\text{exp},i}$ within each bin. For each of the two bins where there are only upper limits, we take the measured value as 0 with the 68% upper limit being the standard deviation and treat it as a half Gaussian distribution. The test statistic $\text{TS} = 2 \ln[\mathcal{L}(\hat{\tau}_X, m_X)/\mathcal{L}(\tau_X, m_X)]$, where $\hat{\tau}_X$ is the value that maximizes Eq. (4). Assuming Wilks's theorem holds,

we obtain the 90% limit on the lifetime for each individual mass by finding the value of τ_X for which $\text{TS} = 2.71$.

Future Projections. We can also study the detectability of ADM decay at the next-generation neutrino telescopes. There is a suite of facilities under construction or proposed for the detection of high-energy astrophysical neutrinos with substantially larger exposure and event statistics. Here we focus on IceCube-Gen2, which will extend the current IceCube detector to a volume of 8 km^3 [63]. We will discuss other next-generation experiments in the Supplemental Material [58].

We focus on the partially contained event selection [3], which is the selection used for the IceCube GR observation and enlarges the effective area by approximately a factor of 2 in the GR energy window compared to the contained event selection (HESE, [46]). We build our projection on the expectation that GR events can be identified on an event-wise basis. As discussed in Ref. [17], the dominant hadronic decay channel $W^- \rightarrow \text{hadrons}$ and the $W^- \rightarrow \mu^- + \bar{\nu}_\mu$ channel should be differentiable from DIS events from the energy deposition and morphology.

We therefore perform a binned likelihood ratio analysis based on the Poisson likelihood of Glashow-induced cascades and tracks in each of the three bins defined in Ref. [3]. To compute the sensitivity, the test statistic has $\text{TS} = 2 \ln[\mathcal{L}(\tau_X, m_X)/\mathcal{L}_{\text{null}}]$ in which $\mathcal{L}_{\text{null}}$ is the likelihood value of the null hypothesis where there is no contribution from the DM, i.e., τ_X is infinite.

Results. We first present updated constraints on symmetric DM decay, $X \rightarrow \nu\bar{\nu}$, in the top panel of Fig. 2. Thanks to the Glashow-enhanced cross section, our constraint on the dark matter lifetime surpasses the IceCube extremely high-energy astrophysical neutrino flux limit [64] in the $10\text{--}50 \text{ PeV}$ mass window, and is up to a factor of 3 stronger.

The constraints obtained with GR typically peak at $m_X \sim 2E_{\text{GR}}$ where the cross section is largest, this is different from the smoother limits from IceCube extremely high-energy (EHE) neutrino flux mainly determined by the shape of the EHE measurement [35,64].

The constraints on ADM lifetime obtained with the IceCube GR dataset are shown in the bottom two panels of Fig. 2 for the representative decay modes listed in Table I. For B1 (therefore also B2) and B3, when the DM mass is around the GR energy, the constraint for the antineutrino decay $L_X < 0$ is about two orders of magnitude stronger than $L_X > 0$. The difference shrinks as the ADM mass increases and eventually the two branches intersect at $m_X \sim 100 \text{ PeV}$. For $m_X \gtrsim \text{EeV}$ the difference between $L_X < 0$ and $L_X > 0$ decay diminishes, and constraints on ADM become indistinguishable from those on symmetric particles, consistent with the $\bar{\nu}_e$ spectrum in Fig. 1. On the other hand, the constraints on $L_X < 0$ and $L_X > 0$ decay branches in B4 are always very similar regardless of

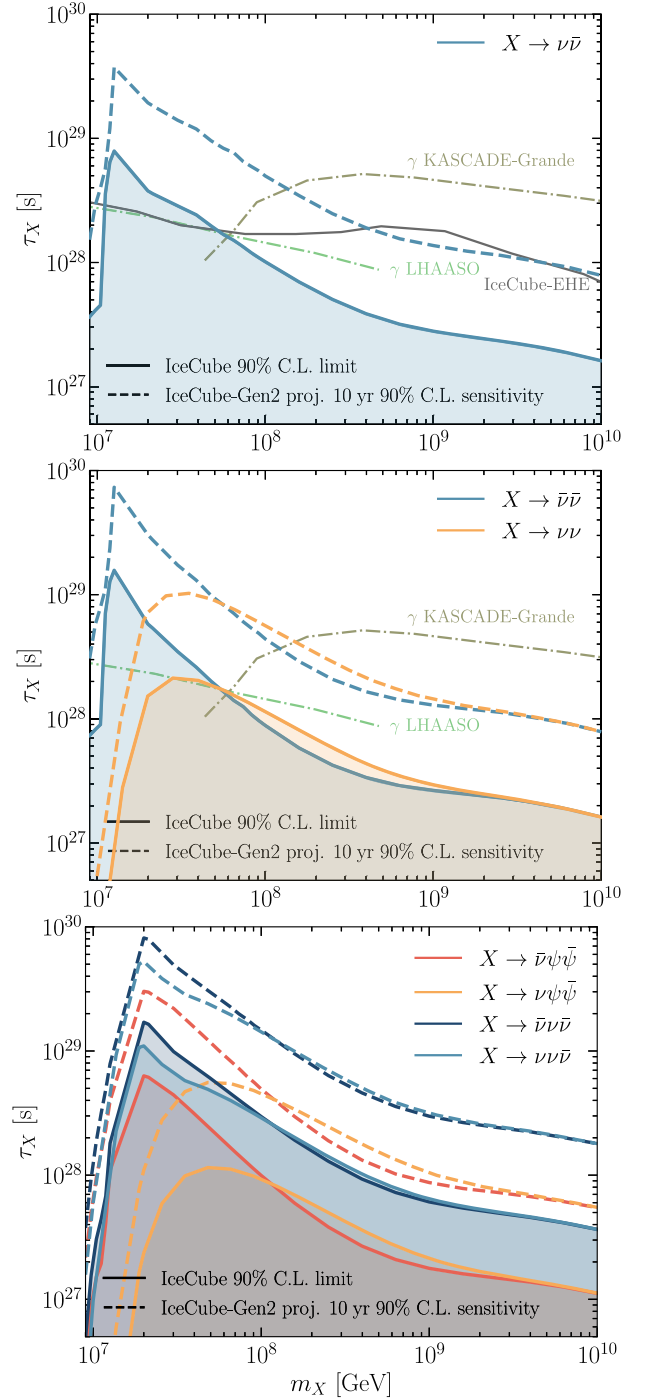


FIG. 2. *Top:* 90% C.L. constraints on the lifetime of X in $X \rightarrow \nu\bar{\nu}$ decay with the current IceCube observation of GR (shaded regions), and the projected sensitivities in the future with 10 yr exposure of IceCube-Gen2 (dashed). We also show the corresponding limits with neutrino and gamma-ray observations from Ref. [35] derived from the diffuse gamma flux limit by KASCADE-Grande [65] (light green) and the extremely-high-energy (EHE) astrophysical neutrino flux limit by IceCube [64] (gray), as well as the LHAASO limit [66] (dark green). *Middle and bottom:* 90% C.L. constraints on the lifetime of ADM for the three decay modes. The gamma-ray limits here may also apply to the scenario of $X \rightarrow \bar{\nu}\bar{\nu}(\nu\nu)$.

m_X , as the decay spectra are less distinguishable. Scenarios with even more symmetric final states should in turn make any CP asymmetry more difficult to identify. In all these scenarios, the data has a preference on DM decay for $m_X \gtrsim 10$ PeV, although the preference is very mild with $\sim 1.2\sigma$ significance. Including the IceCube HESE and EHE measurements may improve the limits at low and high masses away from the GR energy, though they are not sensitive to the sign of L_X , as detailed in the Supplemental Material [58].

At high energies, electroweak corrections also give rise to photons that can be observed at gamma-ray telescopes; these spectra are of course insensitive to the $\nu:\bar{\nu}$ ratio. In the panels of Fig. 2 that depict two-body final states, we also show the derived gamma-ray constraints from LHAASO [66] and KASCADE-Grande [35,65]. These gamma-ray constraints are up to an order of magnitude stronger for masses above 100 PeV. However, this channel remains insensitive to the sign of the $B-L$ number and hence to any asymmetry in the dark sector.

The projected sensitivities with 10 yr IceCube-Gen2 exposure are also shown in Fig. 2 as dashed lines. They have similar mass dependence as the current constraints, achieving a factor of 5 improvement in sensitivity. We find that the lifetime sensitivity scales with the exposure by the relation $\tau_X \propto \mathcal{E}^{0.59}$ where $\mathcal{E}$ is the exposure. The combination of future neutrino telescopes will of course further improve the sensitivity.

The constraints on decaying dark matter have mild dependence on the neutrino spectral index γ and the $\bar{\nu}_e$ fraction $f_{\bar{\nu}_e}$ of the diffuse astrophysical flux. As displayed in Fig. 1, current measurements of the diffuse astrophysical flux report spectral indices vary from 2.37 (through-going muons) to 2.87 (HESE) [46,47]. Figure 2 assumes $\gamma = 2.87$. Using $\gamma = 2.37$ gives a fivefold increase in the astrophysical flux in the GR energy range, leaving less room for a DM signal and an improvement of ~ 2 in the limits. Future projections work in the opposite direction, as expected data would give a larger background, and thus a lower sensitivity if the astrophysical spectrum is harder.

In typical astrophysical production scenarios, the fraction of electron antineutrinos $f_{\bar{\nu}_e}$ can range from 0 to $\lesssim 20\%$ [14]. We find that varying $f_{\bar{\nu}_e}$ from $1/6$ to 0 leads to a factor ~ 1.2 decrease in the lifetime constraints and a factor ~ 5 improvement in the lifetime sensitivity.

Finally, we note that if X discussed here is only a fraction f_X of the cosmological DM, then these constraints simply scale to $\tau_X \rightarrow f_X \tau_X$ since the neutrino flux scales with the DM density.

The exact relation between lifetimes constrained here and other observables such as relic abundance depend on

which of the operators in Table I are present in the full theory, as well as on other details of the UV completion (see e.g., [43]). These may also lead to other observables, such as neutrino-dark matter elastic scattering at high [33,67,68] and low [69,70] energies. The interplay of these constraints with the ones we have presented in this work will be, once again, model-dependent.

Conclusions. In this work, we have exploited the large increase in neutrino-electron cross section at the Glashow resonance to place leading limits on dark matter decays to neutrino pairs, and have placed the first constraints on heavy ADM decaying to neutrinos. As GR provides unique opportunities for disentangling neutrinos and antineutrinos, current IceCube data sets the ADM lifetime to be longer than 10^{27} – 10^{29} s for $m_X \gtrsim 10$ PeV depending on the decay modes. Thanks to the GR, constraints place here are competitive with—and in some ranges, stronger than—those from gamma ray searches for decay to electromagnetically charged final states such as $b\bar{b}$, $\tau^+\tau^-$, or e^+e^- [66]. Even stronger sensitivities will be achieved in the near future with the upcoming generation of neutrino telescopes which provide considerably larger exposure than IceCube.

Distinct from charged cosmic rays, neutrinos directly point back to their sources, and unlike gamma rays, they travel without being attenuated and carry information about the initial CP state. A strong case for complementarity exists; because dark matter in this mass range would produce a flux of gamma rays and neutrinos, a simultaneous measurement of both of these signals would be the only way to pin down the existence and asymmetry of the dark sector, and map out its distribution in the local cosmos.

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