

Dark Matter Search in Dwarf Irregular Galaxies with Ten Years of Data from the IceCube Neutrino Observatory Postprint

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Abstract

As rotationally supported systems, dwarf irregular galaxies (dIrrs) have more reliable J-factor measurements than dwarf spheroidal galaxies and have become important targets for dark matter detection in recent years. This work utilizes ten years of IceCube muon track data and employs an unbinned maximum likelihood ratio method to search for neutrino signals exceeding the background from the directions of seven dwarf irregular galaxies, aiming to detect neutrinos produced by heavy dark matter annihilation. No significant signal was detected. Based on these null results, we derive upper limits on the velocity-averaged annihilation cross-section for dark matter masses ranging from 1 TeV to 10 PeV. Although our constraints are weaker than the most stringent limits reported in the literature for this mass range, our results constitute an important complement to existing studies given the more reliable J-factor measurements of dwarf irregular galaxies.

Full Text

Preamble

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Abstract

Dwarf irregular galaxies (dIrrs), as rotationally supported systems, have more reliable J-factor measurements than dwarf spheroidal galaxies and have received attention as targets for dark matter detection in recent years. In this paper, we use 10 yr of IceCube muon-track data and an unbinned maximum-likelihood-ratio method to search for neutrino signals beyond the background from the directions of seven dIrrs, aiming to detect neutrinos produced by heavy annihilating dark matter. We do not detect any significant signal. Based on such null results, we calculate the upper limits on the velocity-averaged annihilation cross section for 1 TeV–10 PeV dark matter. Our limits, although weaker than the strictest constraints in the literature in this mass range, are also a good complement to the existing results considering the more reliable J-factor measurements of dIrrs.

Key words: (cosmology:) dark matter – cosmology: theory – galaxies: dwarf

1. Introduction

Astrophysical and cosmological evidence has suggested the existence of particles beyond the Standard Model—dark matter (DM)—which accounts for about 84% of the matter component in the universe (Planck Collaboration et al. 2016, 2020; Bertone & Hooper 2018; Arbey & Mahmoudi 2021). Although its nature remains unknown, many models such as primordial black holes (PBH) (Carr & Kuhnel 2021), weakly interacting massive particles (WIMPs) (Bertone et al. 2005; Roszkowski et al. 2018), axion/axion-like particles (ALPs) (Saikawa 2017), and sterile neutrinos (Kopp 2021) have been proposed as dark matter candidates. In recent years, most dark matter searches have focused on the sub-eV mass range (e.g., ALPs) or the GeV–TeV scale (e.g., WIMPs) and have not found any significant signal (Acharyya et al. 2023). This situation prompts us to consider models across a wider mass range, one example being ultra-heavy dark matter (UHDM).

UHDM has a mass above 10 TeV, which means it is too massive to be produced in current colliders. There are already many viable candidates for UHDM (Chung et al. 1998; Berlin et al. 2016a, 2016b; Kolb & Long 2017; Carney et al. 2022), and in this paper we focus on annihilating UHDM, which has received less attention previously. In the scenario of thermal production of dark matter, the annihilation cross section of DM to Standard Model particles scales as $\langle\sigma v\rangle \propto M^{-2}$ (Tak et al. 2022). As the mass increases, the cross section generally decreases. If it becomes too small, the DM will not be sufficiently depleted before freeze-out, leading to an inconsistency with the observed cosmological DM density. This unitarity consideration limits the DM mass to be below ~ 100 TeV (Griest & Kamionkowski 1990; Bramante & Unwin 2017). Although this unitar-

ity boundary has long hindered interest in searching for annihilating UHDM, several mechanisms have been proposed that can violate this boundary (Kim & Kuflik 2019; Carney et al. 2022). For instance, if DM exists in a composite state rather than as a point-like particle, thermal DM with PeV-scale masses could be possible (Harigaya et al. 2016; Tak et al. 2022). In such a scenario, the unitarity bound can be violated because the DM annihilation cross section no longer scales as M^{-2} . Instead, it is now related to the geometric size of the composite DM.

One way to detect dark matter particles is to observe gamma-rays and neutrinos from DM annihilation or decay in astrophysical environments. Promising sites for observation of neutrinos from dark matter annihilation include galaxy clusters, the Galactic halo and center, as well as the cores of the Sun and Earth (Zornoza 2016). Among other targets, dwarf spheroidal galaxies (dSphs), one type of Milky Way satellite galaxies, are also considered promising because of their relatively close proximity and clean astrophysical background (Wood et al. 2015). However, the stellar kinematics of these pressure-supported galaxies are highly uncertain, which makes it difficult to determine their DM profiles accurately (Battaglia et al. 2013). Accurate determination of the DM profile is very important for estimating the astrophysical J-factor of DM indirect detection (Hayashi et al. 2016).

Dwarf irregular galaxies (dIrrs) are targets that have received less attention (Hernández Cadena et al. 2019; Abdallah et al. 2021; Gammaldi et al. 2021; Alfaro et al. 2023), yet they have some properties similar to dSphs, such as high DM abundance and low astrophysical background. Unlike dSphs, dIrrs are located further away and are rotationally supported star-forming dwarf galaxies (Oh et al. 2015; Gammaldi et al. 2021) (in contrast, dSphs are pressure-supported systems). Their DM profiles can be obtained from their rotation curves. Meanwhile, dIrrs are generally larger galaxies compared to dSphs and have larger dark matter halos (their halo masses are $M_{200} = 10^7 - 10^{10} M_{\odot}$), and may host more DM subhalos (Karukes & Salucci 2017). The standard Λ CDM cosmological model predicts that dark matter halos are filled with many self-bound substructures, which has been confirmed by N-body simulations (Frenk & White 2012; Planck Collaboration et al. 2016). The presence of subhalos is expected to significantly enhance the DM signal (Lacroix et al. 2022; Runburg et al. 2022). Therefore, the enhancement factor due to subhalos increases the detectability of dIrrs. These relevant properties make dIrrs interesting targets for DM searches.

Previous works by the IceCube collaboration, which have searched for dark matter signals from the Galactic center (Albert et al. 2020b; Iovine & IceCube Collaboration 2021), Galactic halo (Abbasi et al. 2023; Desai et al. 2023), Sun center (Argüelles et al. 2019; Abbasi et al. 2022), Earth center (Renzi 2019; Saveliev & Hyde 2022), and nearby galaxies and galaxy clusters (Aartsen et al. 2013a; Jeong et al. 2022), found no significant excess beyond background expectations. In our previous work, we used IceCube observations of dwarf

spheroidal galaxies to search for dark matter (Guo et al. 2023). In this paper, we further search for DM in dwarf irregular galaxies building upon that previous work. Different from the earlier analysis, we analyze dwarf irregular galaxies as extended sources and consider the enhancement of the annihilation signal due to their internal subhalos. We search for UHDM-induced neutrinos from dIrrs using 10 yr (2008 April to 2018 July) of IceCube muon track data (IceCube Collaboration et al. 2021) and an unbinned maximum-likelihood-ratio method (Braun et al. 2008). We select seven dIrrs; four sources (IC10, WLM, NGC 6822, IC1613) are the most promising objects for DM detection as proposed in previous works (Gammaldi et al. 2018, 2021), and the remaining three sources are selected from Alfaro et al. (2023). Note that the IceCube 10 yr muon track data have much higher sensitivity to the northern hemisphere sky. Nevertheless, we have also included two sources in the southern sky (WLM and NGC 6822) in the sample to demonstrate this sensitivity difference. The sample information is shown in Table 1 .

2. Signal Expectations

The expected differential neutrino flux for the annihilation of dark matter particles is calculated as follows:

$$\frac{d\Phi_\nu}{dE_\nu} = \frac{\langle\sigma v\rangle}{8\pi m_\chi^2} \frac{dN_\nu}{dE_\nu} \times J \times B,$$

where $\langle\sigma v\rangle$ is the velocity-averaged annihilation cross section, m_χ is the mass of the dark matter particle, dN_ν/dE_ν is the annihilation spectrum of DM particles, and B is the boost factor.

We assume dark matter annihilates into Standard Model particles with a 100% branching ratio and calculate the energy spectrum dN_ν/dE_ν . For this calculation, we use the neutrino spectrum package HDMSpectra (Bauer et al. 2021), a Python package providing spectra of various annihilation and decay channels of heavy dark matter. In this work, we consider DM masses ranging from 1 TeV to 10 PeV and six annihilation channels: $b\bar{b}$, $t\bar{t}$, $\tau^+\tau^-$, $\nu_\ell\bar{\nu}_\ell$, $\mu^+\mu^-$, and W^+W^- . Figure 1 [Figure 1: see original paper] shows the neutrino spectra for the annihilation of a 100 TeV DM particle through different channels.

The flux is proportional to the J-factor (the integral over the square of the dark matter density),

$$J = \int_{\text{l.o.s.}} dl \int d\Omega \rho^2(l),$$

where l is the distance along the line of sight (l.o.s.), D is the distance to the source, and θ is the angular separation between the direction of the source center

and the line of sight. In our work, we adopt the J-factors reported in Alfaro et al. (2023).

The universal rotation curve model (Persic et al. 1996) can fit the dIrr rotation curve well (Gammaldi et al. 2018), and the DM distribution in these galaxies is well described by a Burkert profile (Burkert 1995):

$$\rho(r) = \frac{\rho_0 r_0^3}{(r + r_0)(r^2 + r_0^2)},$$

where ρ_0 is the normalization density and r_0 is the core radius.

The substructures within dIrrs can increase the expected DM flux. We parameterize this effect with the boost factor B in Equation (1). For the calculation of the boost factors we mainly refer to the formulas and results in Moliné et al. (2017). They considered the VL-II (Diemand et al. 2008) and ELVIS (Garrison-Kimmel et al. 2014, 2017) N-body cosmological simulations to study the properties of subhalos, obtaining the concentrations of the subhalos as a function of the distance R_{sub} to the main halo center. Together with the concentration-mass relation derived in Pieri et al. (2011) for the field halo, we can calculate the luminosity $\mathcal{L}_{\text{smooth}}$ of the smooth halo for a given halo mass M and the luminosity \mathcal{L}_{sub} of the subhalo for a given halo mass m at distance R_{sub} ($x_{\text{sub}} = R_{\text{sub}}/R_{\text{vir}}$ with R_{vir} the virial radius). Then the boost factor can be calculated with:

$$B(M) = \frac{\mathcal{L}_{\text{smooth}}(M) + \int dN/dm \mathcal{L}_{\text{sub}}(m, x_{\text{sub}})}{\mathcal{L}_{\text{smooth}}(M)}.$$

The normalization factor A is defined by $\int_{M_{\text{min}}}^M dm dN/dm = M$. The subhalo mass function reads $dN/dm = A(M/m)^\alpha$ with slope α . A equals 0.012 for a slope of the subhalo mass function of $\alpha = 2$ and 0.03 for $\alpha = 1.9$ (Sánchez-Conde & Prada 2014). It is important to note that there are large uncertainties in the calculation of the boost factor $B(M)$, which depends on the index α of the mass function, the assumed minimum subhalo mass M_{min} , the concentration-mass relation adopted for subhalos, and whether or not the tidal stripping effect is taken into account. In this work, we adopt the median value of the boost factors reported in Moliné et al. (2017): the mass function index is assumed to be 1.9, the minimum halo mass is $10^{-6} M_\odot$, and the tidal stripping effect is not considered. The boost factors are shown in Table 1.

3. IceCube Data Analysis

IceCube is a cubic-kilometer neutrino detector located at the South Pole. It consists of 5160 optical photosensors connected to the data acquisition system via cables (“strings”). Neutrinos interact with nuclei and electrons in the ice, producing charged particles that emit Cherenkov light, which is detected by

the photosensors (Aartsen et al. 2017b). The geometry and sensitivity of the photosensors lead to an effective low-energy threshold of about 100 GeV for neutrinos (Yoshida & IceCube Collaboration 2003).

In this work, we utilize the updated IceCube public data of muon tracks. This dataset consists of muon tracks observed by IceCube from April 2008 to July 2018, including a total of 1,134,450 muon-track events. We use all IC40 to IC86-VII data, with the number in the name corresponding to the number of installed detector strings. The data include direction and energy information of neutrino events, as well as instrument response functions (IRFs, including effective area, smearing matrix, etc.) for different periods over the ten years (IceCube Collaboration et al. 2021). We process the 19×2 double-counted tracks in the dataset found in Zhou & Beacom (2022), following the procedure in Chang et al. (2022). The analysis is performed using an unbinned maximum likelihood ratio method (Braun et al. 2008; Abbasi et al. 2011; Aartsen et al. 2013b, 2017a; Li et al. 2022; Pasumarti & Desai 2022). The likelihood function is defined as follows:

$$\mathcal{L} = \prod_k \prod_{i=1}^{N_k} \left[\frac{n_s^k}{N_k} S_i^k + \left(1 - \frac{n_s^k}{N_k} \right) B_i^k \right],$$

where S_i^k and B_i^k are the signal and background probability density functions (PDFs), respectively, N_k is the total number of events in sample k , and n_s^k is the number of signal events which depends on the model parameters. The superscript k refers to the k th IceCube data sample (IC40–IC86VII).

The signal and background PDFs for the i th event are functions of the reconstructed direction x_i and the reconstructed muon energy E_i . For time-integrated searches, the signal PDF S_i is given by:

$$S_i = S_i^{\text{spat}} \times S_i^{\text{ener}},$$

where S_i^{spat} is the spatial contribution that depends on the angular uncertainty of the event σ_i and the angular separation between the direction of the event x_i and the source x_s . We model the spatial term of the signal PDF as a two-dimensional Gaussian:

$$S_i^{\text{spat}} = \frac{1}{2\pi\sigma_i^2} \exp\left(-\frac{|x_i - x_s|^2}{2\sigma_i^2}\right),$$

where x_i is the direction of the i th event and x_s is the direction to the source. Given the larger size of the dIrrs (compared to dSphs), it is better to analyze them as extended sources to obtain more realistic limits. In Table 1, we present the extension corresponding to the virial radius and the 68% containment angle of these dIrrs. When searching for an extended source, the value of σ_i is replaced

with $\sqrt{\sigma_i^2 + \sigma_s^2}$ (Aartsen et al. 2014; Albert et al. 2020a), where σ_s quantifies the extension of the source. In this work, we adopt the angle containing 68% of the total emission as σ_s (Geringer-Sameth et al. 2015; Di Mauro et al. 2022). The signal PDF becomes:

$$S_i^{\text{spat}} = \frac{1}{2\pi(\sigma_i^2 + \sigma_s^2)} \exp\left(-\frac{|x_i - x_s|^2}{2(\sigma_i^2 + \sigma_s^2)}\right).$$

The energy term of the signal PDF, S_i^{ener} , is a function of the reconstructed muon energy proxy E_i . Assuming a power-law spectrum of spectral index γ and for a given declination δ_s of the source, the PDF is (Huang & Li 2022):

$$S_i^{\text{ener}} = \frac{dN_\nu/dE_\nu}{\int_{E_{\min}}^{E_{\max}} dE_\nu A_{\text{eff}}(E_\nu, \delta_s) (dN_\nu/dE_\nu)}.$$

For the search for DM signals, the dN_ν/dE_ν should be replaced by a DM spectrum (i.e., Equation (1)).

The background PDF B_i is obtained directly from the experimental data and is given by:

$$B_i = B_i^{\text{spat}} \times B_i^{\text{ener}},$$

where B_i^{spat} is the normalized event number per unit solid angle and varies with declination δ (Zhou et al. 2021):

$$B_i^{\text{spat}} = \frac{N_{\delta_i \pm 3^\circ}}{\Delta\Omega_{\delta_i \pm 3^\circ}},$$

where $N_{\delta_i \pm 3^\circ}$ is the number of events in the declination band of $\delta_i \pm 3^\circ$ and $\Delta\Omega_{\delta_i \pm 3^\circ}$ is its corresponding solid angle. The background PDF is R.A.-independent because the IceCube observatory is located at the South Pole.

The B_i^{ener} represents the energy term of the background PDF, where $N_{\delta_i \pm 3^\circ, \log_{10}(E_i) \pm 0.1}$ is the number of events within the declination range of $\delta_i \pm 3^\circ$ and the muon energy range of $\log_{10}(E_i) \pm 0.1$ for sample k .

We maximize the likelihood in Equation (5) to derive the best-fit model parameters. A likelihood ratio test statistic for the signal is defined as:

$$\text{TS} = 2 \log \left[\frac{\mathcal{L}(\hat{n}_s)}{\mathcal{L}(n_s = 0)} \right],$$

where n_s is the number of signal events and \hat{n}_s is the best-fit value of the parameter. For searching for DM signals, the number of signal neutrinos from DM annihilation in Equation (5) is related to the DM parameters through:

$$n_s = T_{\text{live}} \int_{E_{\text{min}}}^{E_{\text{max}}} dE_\nu A_{\text{eff}}(E_\nu, \delta_s) \times F_\nu(E_\nu),$$

where T_{live} is the detector uptime, A_{eff} is the effective area of the detector, $F_\nu(E_\nu)$ is the energy spectrum of dark matter annihilating into neutrinos given by Equation (1), and E_{min} and E_{max} are set to the minimum and maximum energies allowed by the effective area provided in the 10 yr IceCube data.

4. Result

Assuming a power-law spectrum, the TS values of the putative neutrino signals from these dIrrs are listed in Table 1. We do not find any significant excess beyond the background expectation in the directions of the seven sources within our sample. Therefore, we derive flux upper limits at the 95% confidence level, assuming source energy spectra of E^{-2} , $E^{-2.5}$, and E^{-3} , respectively. The results are shown in Figure 2 [Figure 2: see original paper].

Next, we explore neutrino signals from dark matter annihilation. We use Equation (1) to perform searches for the DM mass range from 1 TeV to 10 PeV and different annihilation channels, and find no annihilation signal. We calculate the upper limits at the 95% confidence level in the $\langle\sigma v\rangle$ - m_χ parameter space for each dIrr. In Figure 3 [Figure 3: see original paper] we show the limits for the six annihilation channels ($b\bar{b}$, $t\bar{t}$, $\tau^+\tau^-$, $\nu_\ell\bar{\nu}_\ell$, $\mu^+\mu^-$, W^+W^-). The strongest constraints we obtain are for the $\chi\chi \rightarrow \mu^+\mu^-$ channel.

In Figure 3, for the two southern sky sources, it can be seen that they place overall much weaker limits on $\langle\sigma v\rangle$ than the dIrrs in the northern sky, especially at lower DM masses. However, at large DM masses ($\gtrsim 10^6$ GeV), they give stronger constraints. Such results are reasonable. In the southern hemisphere, since the event rate of atmospheric muons is orders of magnitude higher than that of neutrinos (Aartsen et al. 2017b), harsh cuts on reconstruction quality and minimum energy are applied to suppress this atmospheric muon background, and these cuts remove most southern hemisphere events with estimated energy below ~ 10 TeV (IceCube Collaboration et al. 2021) (so for NGC 6822 and WLM we only show limits for DM masses > 10 TeV in Figure 3). In contrast, in the northern hemisphere, we can filter out atmospheric muon contamination using the Earth. For neutrinos at the high-energy end ($> 10^6$ GeV), however, events from the northern sky may interact far from the detector while crossing the Earth, resulting in unobservable energy losses and thus becoming difficult to reconstruct. This leads to a significantly smaller effective area for the northern sky than the southern sky at $> 10^6$ GeV energies (see Figure 2 of IceCube Collaboration et al. 2021). Since the energy spectra of atmospheric muon and

neutrino fluxes are expected to be softer than astrophysical/DM neutrinos, their contribution to the background becomes less significant at these high energies. Therefore, for large-mass DM, the analysis of the two dIrrs (NGC 6822, WLM) gives stronger constraints on $\langle\sigma v\rangle$.

To improve sensitivity, we also jointly analyze the data from the five northern-sky sources simultaneously. In this case, the combined likelihood function is:

$$\mathcal{L}_{\text{joint}} = \prod_{j=1}^5 \mathcal{L}_j(n_s^j; \langle\sigma v\rangle, m_\chi, J_j, B_j),$$

where \mathcal{L}_j is the likelihood in Equation (5) for the j th source. The details of the combined analysis method can be found in Guo et al. (2023) and Zhu et al. (2023). The limits from the combined analysis are shown as black lines in Figure 3. The results of the combined analysis are about 2.5 times stronger than those from DDO154, which gives the strongest constraints among the seven dIrr galaxies.

Finally, in Figure 4 [Figure 4: see original paper] we compare the results of this analysis with limits obtained in other works (Aartsen et al. 2013a; Ackermann et al. 2015; Abdallah et al. 2021; Gammaldi et al. 2021; Miener et al. 2022; Acharyya et al. 2023; Alfaro et al. 2023). The combined limits are stronger than the results from HESS observations of the WLM dIrr (Abdallah et al. 2021) at DM masses above 10 TeV. Compared to other results from analyzing dSphs, our constraints are weaker, mainly because dwarf irregular galaxies are more distant and thus have smaller J-factors. The advantage of our results, however, is that the J-factors of dIrr galaxies can be more accurately determined compared to dSphs, making the constraints more robust, as dIrrs are rotationally supported galaxies. In contrast, as pressure-supported systems, dSphs have larger systematic uncertainties in J-factor determination (Battaglia et al. 2013).

However, for dIrrs there exists another systematic uncertainty from the determination of the boost factor, as discussed in Section 2. For this reason, we also present the upper limits from the joint analysis when the boost factor is not taken into account, shown as dashed black lines in Figures 3 and 4.

From the individual constraints in Figure 3, we see that the strength of the constraints depends mostly on the values of the dIrr J-factors, so the uncertainty of our results comes primarily from J-factor uncertainty. The (statistical) uncertainty on the dIrr J-factors includes mainly the error on the DM profile parameters obtained in the fit to the rotation curve, which depends on the quality of kinematical measurements. This error is $\sim 15\%$ for ρ_0 and r_0 and leads to a $\sim 75\%$ uncertainty in the astrophysical J-factor (Gammaldi et al. 2018). In addition, there are systematic uncertainties in J-factor estimation; for example, the choice of model for the DM density profile causes a systematic uncertainty of ~ 0.2 dex (Gammaldi et al. 2021).

The J-factors used in this paper, derived in Gammaldi et al. (2018), assume a cored density distribution described by the Burkert profile (Burkert 1995). Such a profile is supported by high-resolution HI observations (Oh et al. 2011, 2015) and can fit the rotation curves better (Gammaldi et al. 2021). However, DM-only N-body cosmological simulations favor a cuspy Navarro–Frenk–White profile (Navarro et al. 1997).

The largest uncertainty in the predicted DM annihilation flux comes from the uncertain nature of the dark matter substructure (i.e., the uncertainty in the enhancement factor B). As can be seen from Figure 4, whether the boost factor is considered or not, there is a factor of ~ 5 difference in the results. In the case of considering the boost factor, different choices of parameters of the subhalo population (e.g., the slope of the subhalo mass function, the minimal subhalo mass) lead to distinct (boosted) J-factors, as discussed in Section 2 (see also Liang et al. 2017; Moliné et al. 2017; Gammaldi et al. 2021). Overall, for a dIrr of $10^{10} M_{\odot}$, the boost factor varies over a range of about 2.1–15.9 (Moliné et al. 2017), and thus the constraints (with B) on the DM parameters have the same level of uncertainty.

5. Conclusions

Pressure-supported dSphs are often considered among the most promising targets for indirect DM searches because of their close proximity and negligible astrophysical background. The problem, however, is that the DM content of dSphs and their astrophysical J-factors are usually subject to significant systematic errors due to their kinematic uncertainty. In contrast, dIrrs are rotationally supported dwarf galaxies that are also DM-dominated objects. Unlike dSphs, the kinematics of dIrr galaxies provide a good estimate of their DM halo density distribution and hence of J-factors. Although there is some star formation activity within dIrrs, it has been shown that the astrophysical background component is negligible (Gammaldi et al. 2018). They are therefore interesting novel targets for indirect detection of dark matter.

In this work, we search for signals from UHDM annihilation in seven dIrrs using 10 yr of IceCube neutrino data. In calculating the J-factors of the dIrrs, we use a Burkert profile to characterize their DM distribution and consider boost factors due to the existence of subhalos. Also, considering the angular extension of dIrr galaxies in the sky, we analyze them as extended sources.

We do not detect any significant signal of DM annihilation in the directions of these seven dIrrs. Based on these null results, we place constraints on dark matter model parameters, since emission from annihilation should be detected if the annihilation cross section is large enough. Consequently, we derive upper limits on the annihilation cross section at the 95% confidence level for DM masses between 1 TeV and 10 PeV. For the single-source analysis, the dIrr DDO154 gives the strictest exclusion limits. We also compute results from the joint analysis of the five dIrrs in the northern sky. The joint analysis gives stronger

constraints (by a factor of 2–3) on the annihilation cross section compared to the single-source analysis.

In contrast to other experimental results, our constraints are equivalent to those given by HAWC observations of dIrrs (Alfaro et al. 2023) and stronger than constraints from HESS observations of the WLM dIrr (Abdallah et al. 2021). We also find that the exclusion limits from dIrrs are weaker than but close to those from dSphs (especially for the latest VERITAS results (Acharyya et al. 2023) at PeV masses). Considering the smaller J-factor uncertainties of dIrrs, our results therefore provide a valuable complement to existing results.

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