Constraints on cross-section and lifetime of dark matter with HAWC Observations of dwarf Irregular galaxies

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It has been shown that the dynamics of dwarf Irregular (dIrr) galaxies are dominated by dark matter. It is also observed that these galaxies have low star formation rates and metallicities, and no gamma-ray emission at ultra very high energies is expected. Because of their distance, dark matter content and vast number, dIrr galaxies are good targets to perform indirect dark matter searches by ground-based and wide field of view gamma-ray experiments, like HAWC. We analyzed data at the position of 31 dIrr galaxies within the HAWC field-of-view and no significant excess was found. Here, we present the individual and combined limits on the annihilation cross-section and decay lifetime of weakly interacting massive particles with mass between 1 and 100 TeV.

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1. Introduction

While some indirect dark matter searches are focused on observing a small number of targets, wide field of view experiments can perform these searches on multiple populations at the same time. In particular, a combined analysis leads to stronger constraints on physical parameters of dark matter candidates. At the TeV scale, one population of interest is dwarf irregular (dIrr) galaxies. Several studies showed that these galaxies are dominated by dark matter. It is then plausible to expect a positive signature of gamma-rays from annihilation or decay of dark matter. Unlike dwarf spheroidal (dSph) galaxies, dIrr galaxies have gas and star-formation regions which can contribute to the gamma-ray flux. Because of the environmental characteristics in dIrr galaxies, it is expected that the gamma rays produced have energies in the GeV range [2, 3]. Above 1 TeV this gamma-ray flux is negligible, and we treat dIrr galaxies as background-free targets. The present approach allows us to apply the analysis used for dSph galaxies to dIrr ones.

In this work, we used a sample of 31 dIrr galaxies within the HAWC field-of-view, see Table 1. We selected these galaxies from [1]. As a result of analysis using kinematic data, dIrr galaxies have dark matter haloes described by a Burkert profile. We computed the astrophysical factors, both for annihilation and decay, using the Clumpy package [4]. After that, we obtained the gamma-ray flux using the photon spectra for channels $b\bar{b}$ and $\tau^+\tau^-$. The Pythia software [5] is used to compute the photon spectra, as in previous HAWC analysis [6].

2. Data and Analysis

We analyzed HAWC data from 1017 transits. We divided the analysis into two classes: individual and combined analysis. For the individual analysis, a maximum Likelihood method is used for each individual dIrr galaxy to obtain the best fit parameters of the model including annihilation or decay of dark matter particles (signal model). The Likelihood is calculated using:

$$L_{\text{Signal}} = \prod_i \ln\left(\frac{1}{N_i!}(B_i + Si)^{N_i} \times e^{B_i + S_i}\right) \tag{2.1}$$

where S_i is the number of expected events produced by annihilation or decay of dark matter particles, B_i is the number of background counts observed, and N_i is the total number of events observed in a bin.

We also computed the Likelihood of the Signal model with respect to the Null hypothesis ($L_{\text{Null}} = L_{\text{Signal}}(S_i = 0)$). We do not observe any significant excess at the position of all dIrr galaxies. Therefore we calculated the exclusion limits at 95% C.L.

In the combined analysis, we used the joint-likelihood approach to compute the value of the parameter common to all signal models, either annihilation cross-section or decay lifetime. As in Individual analysis, we compute the significance of the joint model with respect to the null hypothesis. We did not observe any significant excess and the significance was converted into an exclusion limit.

We used the Liff package to compute the significance and exclusion limits. Liff is part of the HAWC internal software. For more details about the HAWC Observatory and the analysis see [6, 7].

Name	R.A. (deg)	DEC. (deg)	$\log_{10}(\frac{J}{\text{TeV}^2\text{cm}^5})$	$\log_{10}(\frac{D}{\text{TeVcm}^2})$
(1)	(2)	(3)	(4)	(5)
And IV	10.62	40.57	9.764	13.463
DDO 101	177.91	31.51	10.356	14.312
DDO 125	186.92	43.493	10.467	14.165
DDO 133	188.22	31.54	11.501	15.274
DDO 154	193.52	27.15	11.800	15.397
DDO 168	198.61	45.91	11.365	15.271
DDO 43	112.07	40.77	10.109	13.853
DDO 52	127.11	41.85	10.452	14.401
Haro 29	186.56	48.49	9.974	13.764
Haro 36	191.73	51.61	10.642	13.581
IC 10	5.10	59.29	11.857	15.619
IC 1613	16.19	2.13	11.632	15.325
NGC 3741	174.02	45.28	9.814	13.417
NGC 6822	296.23	-14.80	12.173	15.943
UGC 11583	307.56	60.44	10.676	14.605
UGC 1281	27.38	32.59	10.854	14.739
UGC 1501	30.31	28.84	10.937	14.843
UGC 2455	194.92	25.23	10.392	14.250
UGC 5272	147.59	31.48	10.721	14.731
UGC 5427	151.17	29.36	10.133	14.007
UGC 5918	162.40	65.53	10.512	14.420
UGC 7047	181.01	52.58	10.630	14.444
UGC 7232	183.43	36.63	10.845	14.581
UGC 7559	186.77	37.14	11.105	14.938
UGC 7603	187.18	22.82	11.368	15.251
UGC 7861	190.46	41.27	10.804	14.715
UGC 7866	190.56	38.50	10.672	14.462
UGC 7916	191.10	34.38	11.012	14.898
UGC 8508	202.68	54.91	10.362	14.071
UGC 8837	208.68	53.90	10.856	14.802
WLM	0.49	-15.46	12.062	15.777

Table 1: Sample of dIrr galaxies. We show the 31 dIrr galaxies within the HAWC field-of-view used in this study. Columns: name of the galaxy (1), the right ascension (α) (2) and declination (δ) (3) of the galaxy, the astrophysical factor for annihilation (4) and decay (5), computed with CLUMPY [4].

3. Results and Discussion

We present the exclusion limits for the galaxies in our sample in Figures 1 (annihilation) and 2 (decay). In both figures, the solid-black line shows the combined limit using the 31 galaxies.

We can observe that galaxy DDO 154 gives the best limit because of its position in a declination band where HAWC has good sensitivity. Assuming a dark matter particle having mass of 10 TeV, $\langle \sigma_\chi v \rangle = 3.31 \times 10^{-22}$cm^{3}s^{-1} for annihilation to $\tau^+ \tau^-$ leptons, and $\tau_\chi = 6.16 \times 10^{+25}$s for decay to $\tau^+ \tau^-$ leptons. We can observe that the combined limit shows two behaviors: for energies < 10 TeV, the combined limit is the same or even worse than the DDO 154 limit; for energies > 10 TeV, the combined limit is better than DDO 154 limit. The combined limit is not better than the DDO 154 limit below 10 TeV because of the large dispersion in the values of the signal-to-background ratio of dIrr galaxies.
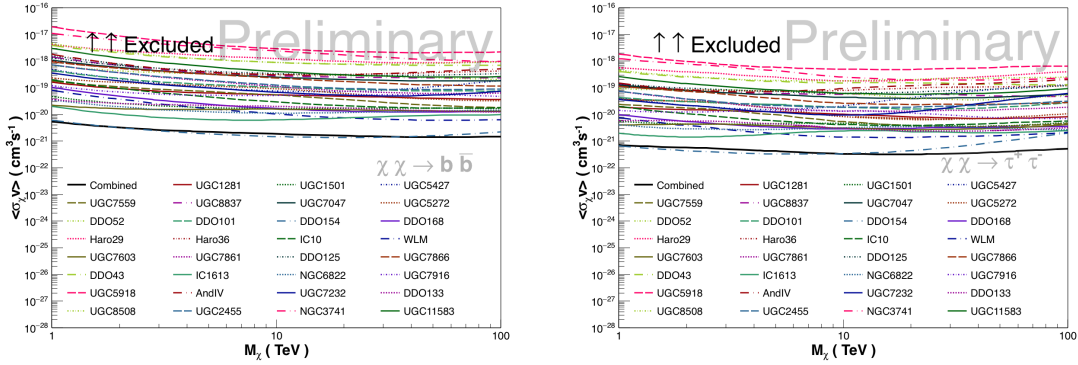
Figure 1: Exclusion limits for annihilation of dark matter particles. We show the individual limits for 31 dIrr galaxies and the combined limit (solid black line) for two different channels. Left: Annihilation to $b\bar{b}$ quarks. Right: Annihilation to $\tau^+ \tau^-$ leptons.
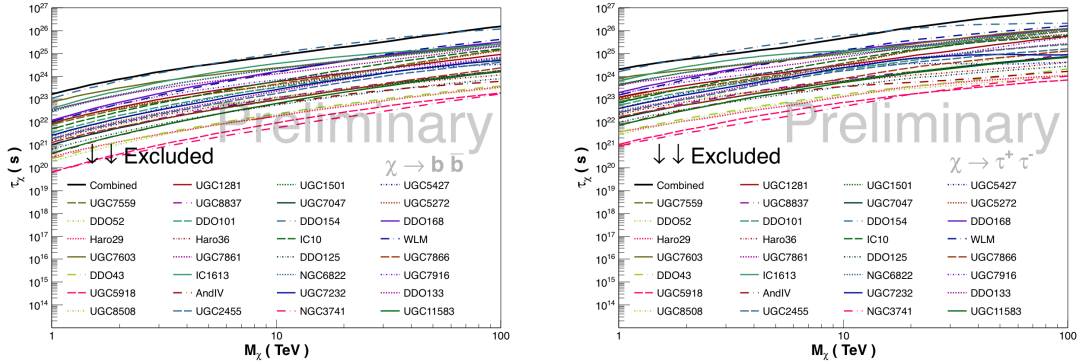

Figure 2: Exclusion limits for decay of dark matter particles. We show the individual limits for 31 dIrr galaxies and the combined limit (solid black line) for two different channels. Left: Decay to $b\bar{b}$ quarks. Right: Decay to $\tau^+ \tau^-$ leptons.

In Figures 3 and 4, we show a comparison between the HAWC dIrr and dSph exclusion limits. We present the exclusion limits for four classical dSph galaxies (dashed lines) and three ultrafaint dSph galaxies (solid lines). We also show the combined limits obtained for 15 dSph galaxies within the HAWC filed-of-view. For annihilation of dark matter (Figure 3), we observe that the combined limit for dIrr galaxies (solid black line) and the DDO 154 limit (solid red line) are comparable to
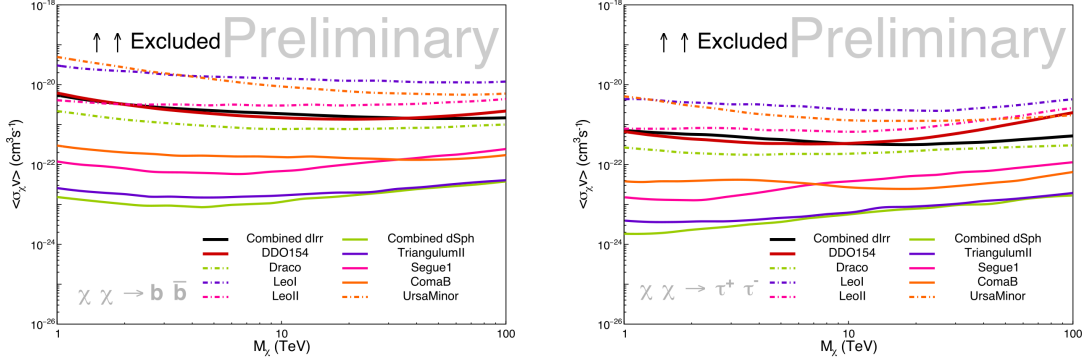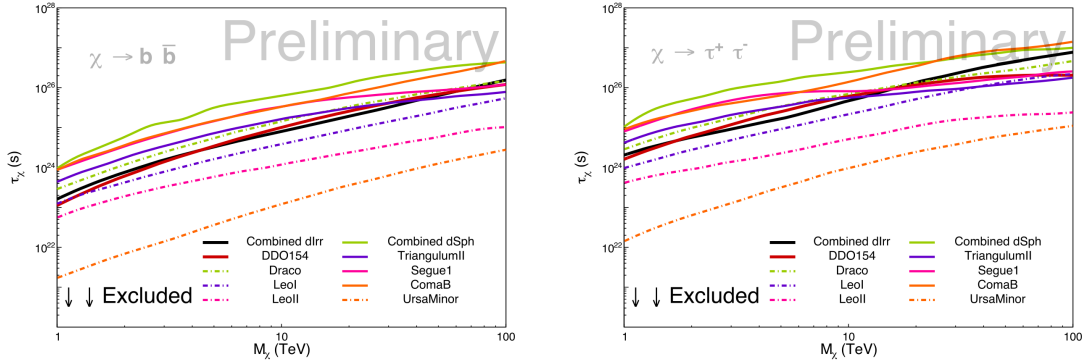
Figure 3: Exclusion limits for annihilation of dark matter particles. We show the individual limit for DDO 154 galaxy and the combined limit (solid black line) for two different channels. Left: Annihilation to b quarks. Right: Annihilation to τ leptons. We also show the limits for 7 dSph galaxies previously analyzed by HAWC.

the exclusion limits obtained for classical dSphs, but not to limits for ultra-faint galaxies which have large values of J-factor in comparison to dIrr galaxies. For decay (Figure 4), the exclusion limits for dIrrs are comparable to both populations, classical and ultrafaint galaxies. For decaying dark matter, it is possible to perform a combined analysis using a sample of dIrr and dSph galaxies to constrain the lifetime of dark matter candidates with masses at TeV scale.

Figure 4: Exclusion limits for decay of dark matter particles. We show the individual limit for DDO 154 galaxy and the combined limit (solid black line) for two different channels. Left: Annihilation to b quarks. Right: Annihilation to τ leptons. We also show the limits for 7 dSph galaxies previously analyzed by HAWC.

4. Conclusions

We show that dIrr galaxies comprise a suitable population to perform indirect dark matter searches. This analysis does not include detailed kinematics to compute J-factors and is therefore limited. The actual number of dIrr galaxies within the local volume is four times bigger than the sample of 30 we used here. Including more dIrr galaxies in the combined analysis will improve the

constraints on annihilation cross-section and decay lifetime of dark matter candidates. The combined analysis presented here is possible because of the characteristics of the HAWC Observatory, which can observe a large portion of the sky and test dark matter models in several populations simultaneously.

5. Acknowlegments

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