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Searching for TeV DM evidence from Dwarf Irregular Galaxies with the HAWC Observatory

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The dynamics of dwarf irregular (dIrr) galaxies are observed to be dominated by dark matter (DM). Recently, the DM density distribution has been studied for 31 dIrrs. Their extended DM halo (Burket type profile) makes these objects good candidates for DM searches. Located in Puebla (Mexico), the High Altitude Water Cherenkov (HAWC) Observatory is an optimal instrument to perform such DM searches, because of its large sky coverage (8.4 sr per day). We analyzed a set of two years of HAWC data and we found no significant DM signal from dIrr galaxies. We present the upper limits for DM annihilation cross-section with dIrr galaxies.

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1. Introduction

It has been shown that local ($d < 11$Mpc) Dwarf Irregular (dIrr) Galaxies are Dark Matter (DM) dominated systems [1]. Using available data for rotation curves, the DM distribution is constrained to be described by an spherical DM halo with a Burkert density profile which extends up to radius greater than 15 times the optical radius r_{opt}[1]. These Galaxies can be treated as systems with null gamma-ray emission because dIrr galaxies have a very low star-formation rate ($\sim 0.003 M_{\odot} yr^{-1}$) [2], [3], low metalicity and are composed of stars with masses between 1 and 3 $M_{\odot}$. Although it has been proposed that Stellar Formation Regions can present gamma-ray emission with energies of several hundreds of GeV up to several TeV, the necessary conditions for this processes require that the young stars must be super-massive ($M > 8M_{\odot}$) and/or have very strong stellar winds that can produce collective strong chock bubbles where charged particles can efficiently accelerated up to relativistic velocities [4]. These conditions are not fulfilled by dIrr Galaxies, so any detected gamma-ray emission from these sources could be an indication of the annihilation of DM particles in the halo. In this sense, dIrr galaxies can be analyzed in a similar way to dSph galaxies and are another way to look for DM. In this work, we show for the first time the upper limits for annihilation cross-section of WIMPs with masses between 1 TeV and 100 TeV for 31 dIrr Galaxies within the HAWC field-of-view. The data set comprises about 2 years of data.

2. The HAWC Observatory

Located in Sierra Negra, Mexico at an altitude of 4100 meters, the High Altitude Water Cherenkov (HAWC) Observatory is an extended array of 300 Water Cherenkov Detectors (WCD) to detect air showers produced by VHE gamma-rays. Every WCD is 7.3m in diameter and 4.5m deep, filled with 200,000L of purified water and is instrumented with 4 Photo-Multiplier Tubes (PMT) to collect the Cherenkov light produced by charged particles passing through the WCDs. The HAWC Observatory has an instantaneous field of view of ~2 sr and a duty cycle $> 95\%$, and is sensitive to gamma-rays with energies in the range from 1 TeV to 100 TeV. Therefore it is able to investigate the emission from several kind of sources [5, 6], such as AGNs [7], GRBs [8, 9], PWNs [10], and, in particular, the expected production of photons from annihilating or decaying DM [11, 12].

3. DM photon flux

To compute the expected gamma-ray flux from DM annihilation, the information about the structural properties of the DM halo and the production mechanisms of photons are needed. The differential gamma-ray flux produced from a source is:

$$\frac{d\Phi_{(\gamma)}}{dE} = \underbrace{\frac{\langle \sigma v \rangle}{8\pi m_{\chi}^2} \frac{dN_{(\gamma)}}{dE}}_{\text{Particle Physics Factor}} \underbrace{\int_{\Delta\Omega} \int_{l.o.s.} dl d\Omega \, \rho\,(r(l))^2}_{\text{Astrphysical Factor J}} \tag{3.1}$$

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[1] The optical radius is the radius where the baryonic or luminous matter is contained

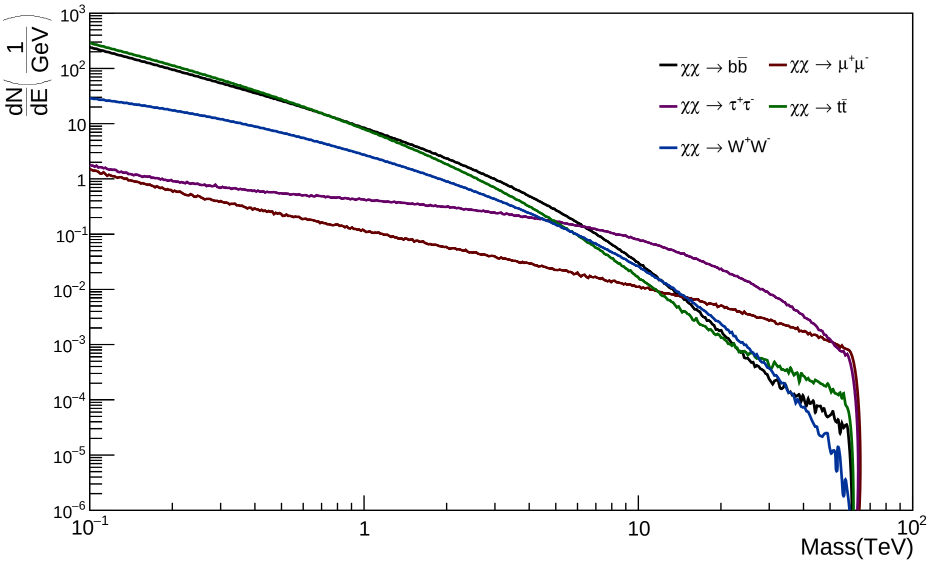

Figure 1: Spectrum of Photons computed for annihilation of WIMPs with mass of 60 TeV to five channels, assuming that the branching ratio for every channel is 100%.

where $\mathrm{d}N_{(\gamma)}/\mathrm{d}E$ is the differential spectrum of photons produced for an annihilation channel, m_χ is the mass of the WIMP, $\langle \sigma v \rangle$ is the thermal averaged annihilation cross-section, and $\rho\,(r(l))$ is the DM density profile. The second term in equation 3.1 is the Astrophyical Factor J, or J factor. The J factor is defined as the integral of the DM density (ρ) squared along the line of sight ($l.o.s.$) distance l and over the solid angle around the line of sight. For all the calculations, we assumed that the dIrr Galaxies are small and there is not appreciable contribution of sub-structures to J factors. The J factors are calculated over all the spatial extension of the sources and are listed in Table 1.

3.1 Photon Spectra

The production of photons from annihilation of DM particles is due to the decay or hadronization processes of the unstable products. The spectrum is continuous and has an energy cut-off at the mass of the DM particle. For this work, we considered WIMP masses in the range from 1 TeV to 100 TeV and annihilation to five channels: b and t quarks, μ and τ leptons, and the W boson. The spectrum of photons is calculated with PYTHIA 8 [13]. In Figure 1 the spectrum of photons for a WIMP with mass $m_\chi = 60$ TeV is shown.

3.2 The DM profile in dIrr Galaxies

With the proof that Large and Small Magellanic Clouds are rotating systems [14, 15], measurements of the rotation curve of other dIrr Galaxies were performed. It was observed that the rotation curve for these galaxies flatten after about 2 disk scale lengths and no cases of declining curves were found, indicating that dIrr Galaxies have no bulge. Early results indicated that they are objects dominated by DM at all radii and properties of their DM halos seem to be similar to those from galaxy halos [16].

Name	α (°)	δ (°)	$\frac{M_{\mathrm{DM}}}{M_{\mathrm{Lum}}}$	R_{vir} (kpc)	ρ_0 $M_\odot/\mathrm{kpc}^3$	r_0 (kpc)	J $\mathrm{TeV}^2/\mathrm{cm}^5$	σ
UGC1281	27.3833	32.5925	66.80	82.1	4.04×10^7	2.93	9.2572×10^9	-1.1490
UGC1501	30.3167	28.8436	72.30	89.5	1.76×10^7	4.32	6.1530×10^9	-1.3726
UGC5427	151.1708	29.3664	48.21	54.1	46.7×10^7	0.76	1.0986×10^{10}	$+0.6616$
UGC7559	186.7708	37.1425	57.51	59.6	2.67×10^7	2.45	2.4702×10^9	-0.8200
UGC8837	208.6875	53.9047	75.33	92.7	1.09×10^7	5.40	1.9164×10^9	-1.2860
UGC7047	181.0083	52.5886	50.03	48.8	7.70×10^7	1.34	4.4390×10^9	-1.7911
UGC5272	147.5917	31.4875	72.65	94.9	2.30×10^7	4.14	4.1065×10^9	-1.0884
DDO52	127.1167	41.8567	76.17	102.3	2.63×10^7	4.24	2.8218×10^9	$+0.3556$
DDO101	177.9125	31.5194	67.15	86.8	5.52×10^7	2.71	1.2689×10^9	-1.0574
DDO154	193.520	27.1486	54.64	56.3	4.02×10^7	1.60	4.3494×10^9	$+0.2617$
DDO168	198.6167	45.9194	64.48	83.3	7.78×10^7	2.29	2.1513×10^{10}	-0.4791
Haro29	186.5667	48.4919	40.08	33.0	35.8×10^7	0.51	3.0811×10^9	$+0.7125$
Haro36	191.7333	51.6131	67.11	85.5	4.71×10^7	2.84	3.6515×10^9	-1.0719
IC10	5.100	59.2917	45.74	44.5	25.8×10^7	0.78	3.3740×10^{11}	-1.3696
WLM	0.4917	-15.4611	48.12	44.2	6.58×10^7	1.29	4.3553×10^{10}	-1.2415
UGC7603	187.1833	22.8225	71.84	95.6	3.86×10^7	3.42	4.7883×10^9	-0.4815
UGC7861	190.4667	41.2739	58.29	73.8	16.7×10^7	1.52	9.0994×10^9	-1.5236
DDO125	186.9208	43.4939	38.75	25.5	2.33×10^7	1.10	5.5139×10^8	$+0.1665$
UGC7866	190.5625	38.5019	46.22	39.6	5.12×10^7	1.27	1.4874×10^9	$+0.6805$
DDO43	112.0708	40.7703	48.76	47.2	6.92×10^7	1.35	2.0781×10^9	-0.8621
IC1613	16.1958	2.1333	41.92	30.1	1.75×10^7	1.46	5.8729×10^9	-0.6184
NGC6822	296.2375	-14.8031	49.17	46.6	7.09×10^7	1.32	1.1446×10^{11}	-0.5364
UGC7916	191.1042	34.3864	69.89	77.7	0.58×10^7	7.52	4.3566×10^8	-1.2203
UGC5918	162.4000	65.5306	67.98	79.6	1.73×10^7	3.88	1.7454×10^9	-0.3268
AndIV	10.6250	40.5758	45.90	40.8	9.07×10^7	0.99	1.0871×10^9	$+0.0012$
UGC7232	183.4333	36.6333	37.67	32.2	96.4×10^7	0.34	2.8365×10^{10}	$+1.2456$
DDO133	188.2208	31.5392	60.22	66.4	3.20×10^7	2.55	4.0290×10^9	$+0.9029$
UGC8508	202.6850	54.9100	37.09	27.4	22.6×10^7	0.50	5.2128×10^9	$+0.8416$
UGC2455	194.9267	25.2375	65.77	77.4	2.62×10^7	3.21	2.1165×10^9	-0.2209
NGC3741	174.0267	45.2853	33.53	21.4	65.7×10^7	0.26	3.8677×10^9	$+0.0136$
UGC11583	307.5637	60.4402	70.26	87.7	2.55×10^7	3.67	5.0994×10^9	-1.6305

Table 1: Astrophysical parameters and structural properties for the 31 dIrr Galaxies within the field-of-view of the HAWC Observatory. The source, right ascension (α), declination (δ), DM mass to luminous mass ratio, virial radius (R_{vir}), scale density ρ_0, scale radius r_0, the Astrophysical Factor J are listed above. The quantities related to the DM halo are taken from [1] and are computed assuming that density profile is described by a Burkert profile. The J factors are calculated over all the spatial extension of each source. All the significances σ (last column) are obtained for a WIMP with mass $m_\chi = 60 TeV$ and the $\chi\chi \to \tau^+\tau^-$ annihilation channel.

For the set of dIrr Galaxies we studied here, the structural properties of luminous and DM contributions are constrained using kinematical data taken from [1]. The DM density is constrained to be described by a Burkert Profile [17]. The Burkert profile is a density distribution that resembles an isothermal profile in the inner regions ($r < r_0$) and a distribution with slope -3 in the outer regions:

$$\rho(r) = \frac{r_0^3 \rho_0}{(r + r_0)(r^2 + r_0^2)} \tag{3.2}$$

where r_0 and ρ_0 are the scale radius and density. Unlike Navarro-Frenk-White (NFW) density profile, the Burkert profile is a cored profile. The coordinates and DM parameters (r_0, ρ_0 and R_{vir}) for the 31 dIrr Galaxies are listed in Table 1. The virial radius R_{vir} is computed assuming an overdensity parameter $\Delta = 100$. Additionally, we computed the DM mass to luminous mass ratio ($M_{\mathrm{DM}}/M_{\mathrm{Lum}}$, column 4 in Table 1) using the masses obtained for fit results in [1]. From these values, it is observed that the mean amount of DM in these galaxies is 56.43 times their luminous matter.

4. DM Upper Limits on annihilation Cross Section

We calculated the individual upper limits on annihilation cross-section for 31 dIrr Galaxies (see Table 1) within the field-of-view of the HAWC Observatory for 760 days of HAWC data. All the Galaxies were treated as point sources and with no non-DM gamma-ray backgrounds systems (see section 1). Through detailed simulation of the gamma-ray sensitivity and background for the HAWC Observatory, the significance of the gamma-ray flux for a range of DM masses, 1 TeV - 100 TeV, and five annihilation channels is computed. In Table 1 we report the significance obtained for the annihilation channel to τ leptons of a WIMP with mass $m_\chi = 60$ TeV. Because the HAWC Observatory has not seen statistical significant excess in these regions, the significance for every source is converted into exclusion curves of the annihilation cross-section of WIMPs for the 31 dIrr Galaxies. To get the exclusion curves, we used the Maximum Likelihood Method (for a detailed description of the method, please see [12]) that is implemented in the HAWC software utility LIFF [18]. The upper limits for the fifteen most sensitive dIrr Galaxies are shown in Figure 2.

5. Discussion

It can be observed from Figure 2, that the strongest limits from dIrr Galaxies come from the IC10 Galaxy because its large astrophysical factor J ($3.3740 \times 10^{11} \mathrm{TeV}^2 \mathrm{cm}^{-5}$). The limits from dIrr Galaxies are comparable to those obtained by HAWC for the Leo I, Leo IV, Hercules and Canes Venatici I Spheroidal Galaxies [12], and less restrictive than, for example, the limits from Triangulum II and Segue I, whose limits are 4 orders of magnitude more restrictive than the value for IC10, our best target in this sample. This is a consequence of: a) their large astrophysical factors (100-1000 times larger) and b) the suboptimal declination of IC10 (peaking at 40deg off zenith for HAWC). As it was mentioned in Section 3.1, J factors are calculated with a Burkert profile, because this profile reproduces the rotation curves for dIrr Galaxies [1]. However, it is possible that cusped profiles can properly fit the rotation curves by considering non-rotational motions in Galaxies [19].

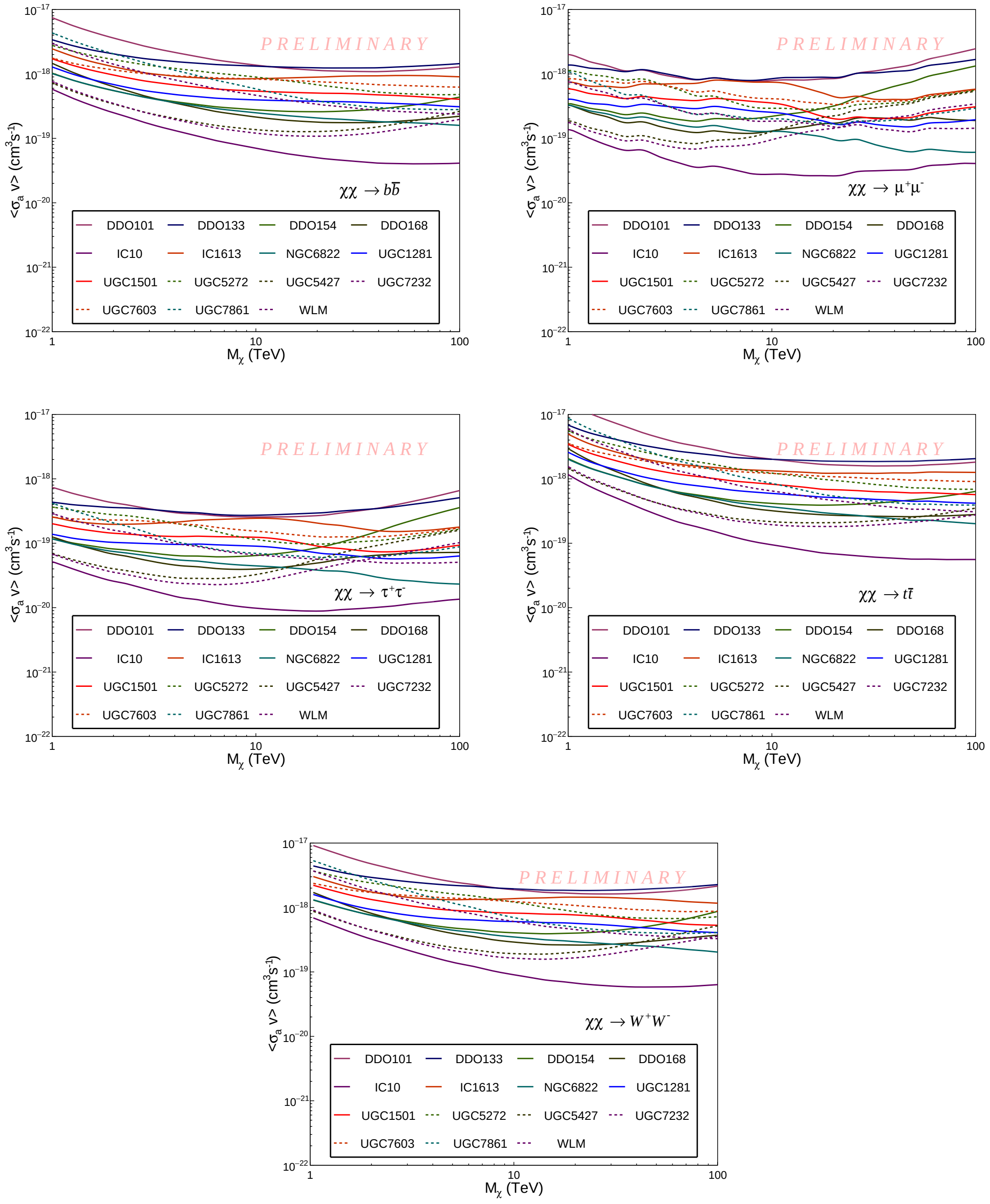

Figure 2: Individual upper limits for DM annihilation cross section for the fifteen best dIrr Galaxies in the field of view of the HAWC Observatory: DDO101, DDO133, DDO154, DDO168, IC10, IC1613, NGC6822, UGC1281, UGC1501, UGC5272, UGC5427, UGC7232, UGC7603, UGC7861, WLM. The region above the curves is excluded.

We are investigating the effect of considering cusped profiles, such as Einasto or Navarro-Frenk-White [20, 21], in the calculations of J factors. Future work includes the calculation of lower limits for decay-lifetime τ_χ of WIMPs for dIrr Galaxies. Because astrophysical factor D depends only in the amount of DM in the halo, and is less sensitive to profile shape, calculations for dIrr Galaxies, plus a combined analysis, can improve our limits for τ_χ. As an example, the astrophysical factor D for IC10 is 4.1631×10^{15}TeV cm^{-2}, comparable to the value for Triangulum II.

6. Summary

In this work we show the individual 95% CL limits on the annihilation cross-section for 31 dIrr Galaxies. The limits are calculated for a DM range of masses, 1 TeV – 100 TeV, and for several DM annihilation channels, $\{b, \mu, \tau, t, W\}$, resulting from data collected over 760 day period. These curves are the first experimental limits calculated for DM searches in dIrr Galaxies in VHE regime. Future work will include a source stacked analysis and an extended source analysis for dIrr Galaxies considered in these proceedings.

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