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Search for dark matter signals toward the irregular dwarf galaxy WLM with H.E.S.S.

Céline Armand[a], Emmanuel Moulin[b], Vincent Poireau[c], Lucia Rinchiuso[b], for the H.E.S.S. collaboration

a Department of Astronomy, University of Geneva, Chemin Pegasi 51, CH-1290 Versoix, Switzerland

b IRFU, CEA, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France

c Laboratoire d'Annecy de Physique des Particules, Univ. Grenoble Alpes, France

E-mail: `celine.armand@unige.ch`, `emmanuel.moulin@cea.fr`, `vincent.poireau@lapp.in2p3.fr`, `lucia.rinchiuso@cea.fr`

Abstract. Cosmological and astrophysical probes suggest that dark matter (DM) makes up for 85% of the total matter of the Universe. The determination of its nature, however, remains one of the greatest challenges of fundamental Physics. In the DM indirect detection framework, Weakly Interacting Massive Particles (WIMPs) particles would produce signals by self-annihilating and creating SM products such as γ rays, which might be detected by ground-based telescopes. Dwarf irregular galaxies represent promising targets for the search for DM as they are assumed to be dark matter dominated. These dwarf irregular galaxies are rotationally supported with relatively simple and well measured kinematics which lead to small uncertainties on their dark matter distribution profiles. In 2018, the H.E.S.S. telescopes observed the irregular dwarf galaxy Wolf-Lundmark-Melotte (WLM) for 18 hours. These observations are the very first ones made by an imaging air Cherenkov telescope toward this kind of objects. We search for a DM signal looking for excess of γ rays towards WLM dwarf galaxy. We perform the first analysis of this source in stereoscopy using the data taken by the five H.E.S.S. telescopes. In this proceeding, we present the new results on the observations of WLM interpreted in terms of velocity-weighted cross-section for DM self-annihilation $\langle\sigma v\rangle$ as a function of DM particle m_χ mass for the eight annihilation channels W^+W^-, Z^+Z^-, $b\bar{b}$, $t\bar{t}$, e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$, and $\gamma\gamma$.

1. Introduction

Cosmological and astrophysical observations suggest that Dark Matter (DM) accounts for 85% of the total matter of the Universe. However, its nature remains one of the most challenging and fundamental open questions of particle physics. Many models have been developed to attempt unraveling the nature of DM such as Weakly Interacting Massive Particles (WIMPs), the most favored particle candidates. In the WIMP hypothesis, DM particles may be present in large quantites in dense regions such as the Galactic center or dwarf galaxies and would send some indirect signals by pair-annihilating and creating Standard Model particles, which might be detected. Among these particles used as probes for indirect dark matter searches are γ-rays. High-energy γ rays present the advantage of not being deflected by the Galactic magnetic field, and so their emitting source can be well localized in the sky. Our study focuses on Wolf-Lundmark-Melotte (WLM), one of the most promising dwarf irregular galaxies for a DM search, since it offers one of the largest J factors among this type of object [1]. In 2018, the H.E.S.S. (High Energy Stereoscopic System) telescope array observed WLM for about 18 hours, which makes H.E.S.S. the first imaging air Cherenkov telescopes to present an analysis on this class of potential γ-ray source. This new search complements the studies carried out for DM from dwarf spheroidal galaxies [2, 3, 4] and from the Galactic center [5, 6]. Full details of this work are available in the following paper [7].

2. Properties of WLM

WLM is a dwarf irregular galaxy located at 985 ± 33 kpc from the Milky Way at RA = $00^{\rm h}01^{\rm m}58^{\rm s}$ and Dec = $-15°27'39''$ (J2000) [8], corresponding to $l = 75.86°$ and $b = -73.62°$ in Galactic coordinates. WLM hosts a star-forming region at its center [9, 10] whose low star formation rate of about $10^{-3}\,M_{\odot}{\rm yr}^{-1}$ suggests that WLM is in quiescent phase at the present time. The expected γ-ray flux associated with this star-forming region is $\sim 10^{-15}\,{\rm TeV cm^{-2}s^{-1}}$ [1], hence it is negligible compared to the expected signal from the thermal relic DM at TeV scale. This dwarf is believed to have developed away from the influence of other systems [11] since its nearest neighbor within the Local Group, the Cetus dwarf spheroidal galaxy, is located at about 175 kpc [12]. WLM presents a halo of 50 kpc extension and shows a smooth HI distribution with a well-measured photometry and stellar kinematics [13, 8]. In addition, WLM is rotationally supported with no significant non-circular motions in the gas [13]. A smooth and well-constrained rotation curve can then be derived from measurements of the gas motion out to ~ 3 kpc [14]. The measurements of its dynamical, stellar, and gas masses imply that WLM is DM dominated since only 1.2% of the dynamical mass is accounted for by baryonic matter.

3. DM induced γ-ray flux

WIMPs are expected to annihilate into Standard Model particles whose interactions via hadronization or decay would produce observable γ rays. Assuming WIMPs are Majorana particles, the expected differential γ-ray flux (in ${\rm m^{-2}s^{-1}GeV^{-1}}$) in a solid angle $\Delta\Omega$ produced by DM annihilation reads:

$$\frac{d\Phi_\gamma}{dE_\gamma}(\Delta\Omega) = \frac{1}{2}\frac{\langle\sigma v\rangle}{4\pi m_\chi^2}\sum_f B_f \frac{dN_\gamma^f}{dE_\gamma} \times \int_{\Delta\Omega}\int_s \rho_{\rm DM}^2(r(s,d,\theta))\, ds\, d\Omega, \tag{1}$$

where m_χ is the DM particle mass, $\langle\sigma v\rangle$ is the annihilation cross-section averaged over the velocity distribution, and dN_γ^f/dE_γ is the differential spectrum of each annihilation channel f with their branching ratio B_f. The last term after the product sign, is so-called astrophysical J factor describing the amount of dark matter annihilations within a given source and hence the strength of the emitted signal.

4. DM distribution

The DM distribution in WLM can be well modeled by the *CoreNFW* profile, an intermediate DM distribution between a "cuspy" and a core profile. This recent model takes into account the *baryonic feedback* mechanism responsible for the decrease of the central density. A review on this topic is available in Ref. [15]. We use the CoreNFW fitting function of the DM density profile, introduced by [13, 8], which is given by the following:

$$\rho_{\rm coreNFW}(r) = f^n(r)\rho_{\rm NFW}(r) + \frac{nf^{n-1}(r)(1-f^2(r))}{4\pi r^2 r_c}M_{\rm NFW}(<r), \tag{2}$$

where $\rho_{\rm NFW}(r)$ and $M_{\rm NFW}(<r)$ are the NFW density profile and cumulative mass [16], and f^n is responsible for generating a shallower density profile at radii $r < r_c$, with r_c the core radius. More details on these expressions can be found in [13, 8].

5. J factor

In this work, we use the results of the MCMC analysis of [17] corresponding to the parameters of the DM density profile of WLM in Eq. 2. For each of their 75,000 MCMC parameter sets, we compute the J factor of WLM and obtain a histogram. We perform a fit of the distributions with an asymmetric function, whose mean and left/right standard deviations provide the nominal value and uncertainties of the J factor. We perform this computation of the J factor for each angular radius as shown in Fig. 1. We provide the value of the J factor, $\log_{10}(J_{\theta_{\rm vir}}/{\rm GeV^2cm^{-5}sr}) = 16.91^{+0.10}_{-0.09}$, for the whole galaxy defined by its virial radius $R_{\rm vir}$.

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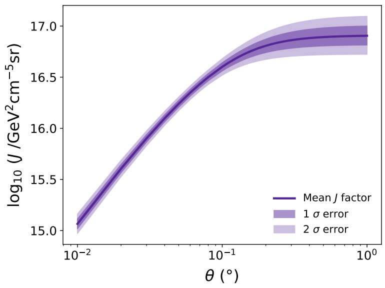

Figure 1. J factor as a function of the angular radius θ. The solid line corresponds to the mean values of J while the dark and light purple bands represent the 1 and 2 σ uncertainty bands.

6. Observations and data analysis

In 2018, H.E.S.S. collected about 18 hours of good quality data towards WLM with a zenith angle in the range 9 - 51°. The reconstruction and classication of the events are performed following standard calibration and selection procedures [18]. We use a technique based on the comparison of the γ-ray shower image in the camera between real events and the prediction of a semi-analytical model [19]. We choose a region of interest, also referred to as the "ON region", to be a disk of radius 0.12° centered at the nominal position of the source. The pointing positions of the telescopes are shifted by ±0.5° or ±0.8° with respect to the nominal source position according to the *wobble* mode method [20]. We use an exclusion region of radius 0.4° around the ON region to prevent from any contamination of the background "OFF regions" by the tails of the expected DM γ-ray signal. The background is determined following the multiple-OFF method [20]. Table 1 summarizes the results of the analysis.

N_{ON}	N_{OFF}	α	N_{OFF}/α	Live time (hours)	γ-ray excess	σ
823	11959	14.483	825.7	18.2	-2.7	-0.1

Table 1. Results of the data analysis of WLM where N_{ON} and N_{OFF} are the number of events detected in the ON and OFF regions, α is the acceptance corrected exposure ratio, the live time correspond to the observation time, γ gives the γ-ray excess detected and σ corresponds to the significance of the excess.

We cross-checked the results presented in Tab. 1 with a different calibration and analysis chain [21] yielding compatible results. We do not observe any significant excess in the signal region of WLM nor in the field of view of WLM as shown in Fig. 2.

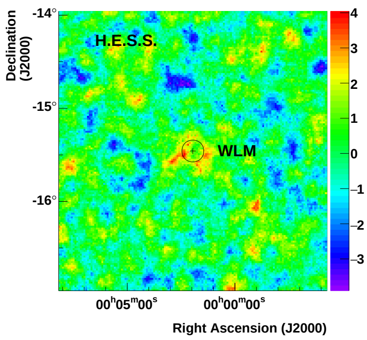

Figure 2. Map in equatorial coordinates showing the significance (color scale) of the γ-ray excess in number of standard deviations. The ON region is indicated by the black circle centered around the source position marked by a cross.

7. Statistical analysis

A log-likelihood ratio test is performed on the data in order to constrain a potential DM signal and set upper limits on the DM annihilation cross-section for a DM particle mass ranging from 150 GeV to 63 TeV. The total likelihood function contains two terms, a product of a Poisson likelihood $\mathcal{L}^{\mathcal{P}}{}_i$ on the events of all energy bins with a log-normal distribution $\mathcal{L}^J$ of the J factor. We perform a log-likelihood ratio statistical test to set upper limits at 95% C.L. on the annihilation cross-section $\langle\sigma v\rangle$, assuming a positive signal $\langle\sigma v\rangle > 0$, based on the method [22]:

$$\mathrm{TS} = \begin{cases} 0 & \text{for } \widehat{\langle\sigma v\rangle} > \langle\sigma v\rangle \\ -2\ln\dfrac{\mathcal{L}(\langle\sigma v\rangle, \hat{\hat{\boldsymbol{N}}}_{\mathrm{B}}(\langle\sigma v\rangle), \hat{\hat{J}}(\langle\sigma v\rangle))}{\mathcal{L}(\widehat{\langle\sigma v\rangle}, \hat{\boldsymbol{N}}_{\mathrm{B}}, \hat{J})} & \text{for } 0 \leq \widehat{\langle\sigma v\rangle} \leq \langle\sigma v\rangle \\ -2\ln\dfrac{\mathcal{L}(\langle\sigma v\rangle, \hat{\hat{\boldsymbol{N}}}_{\mathrm{B}}(\langle\sigma v\rangle), \hat{\hat{J}}(\langle\sigma v\rangle))}{\mathcal{L}(0, \hat{\hat{\boldsymbol{N}}}_{\mathrm{B}}(0), \hat{\hat{J}}(0))} & \text{for } \widehat{\langle\sigma v\rangle} < 0 \end{cases} \tag{3}$$

where $\hat{\hat{\boldsymbol{N}}}_{\mathrm{B}}(\langle\sigma v\rangle)$ is the vector of number of background events and $\hat{\hat{J}}(\langle\sigma v\rangle)$ the value of the J factor maximizing the likelihood function conditionally for a given annihilation cross-section $\langle\sigma v\rangle$. The quantity $\widehat{\langle\sigma v\rangle}$ is the value of the annihilation cross-section, $\hat{\boldsymbol{N}}_{\mathrm{B}}$ the vector of number of background events, and $\hat{J}$ the value of the J factor that maximize unconditionally the likelihood function. In the case of a one-sided test, the criterion value of the test statistic TS is 2.71 corresponding to a 95% C.L.

8. Constraints on $\langle\sigma v\rangle$ and discussion

As no significant excess has been found in the data towards WLM, upper limits on the DM annihilation cross-section $\langle\sigma v\rangle$ at 95% C.L. as a function of the DM mass are computed using the log-likelihood ratio method for each annihilation channel. In this proceeding, we only present the case of $b\bar{b}$ and $\tau^+\tau^-$. The other annihilation channels can be found in [7]. Each annihilation channel is treated individually which corresponds to a branching ratio of $B_f = 100\%$ in Eq. 1 and all spectra are simulated using Pythia [23] with final state radiative corrections taken into account. We use the value of the mean J factor with its uncertainty σ_J integrated up to $\theta = 0.12°$, $\log_{10}(J_{0.12°}/\mathrm{GeV^2cm^{-5}sr}) = 16.68 \pm 0.05$. We also include the uncertainties on J as a nuisance parameter in our analysis. Figure 3 shows the upper limits obtained for these two annihilation channels. The mean expected limits and 1-2σ containment bands are derived from a sample of 300 Poisson realizations of the background events in the ON and OFF regions. The mean expected limits correspond to the mean of the distribution of $\log_{10}\langle\sigma v\rangle$ on these Poisson realizations and the uncertainty bands are given by the standard deviation of this distribution. The observed upper limits on $\langle\sigma v\rangle$ at 95% C.L. reach 4×10^{-21} cm^3.s^{-1} in the quark annihilation channel at a DM mass of 1 TeV. The upper limits lower by an order of magnitude in the case of the leptonic annihilation channel where $\langle\sigma v\rangle$ reaches 4×10^{-22} cm^3.s^{-1} at 1 TeV.

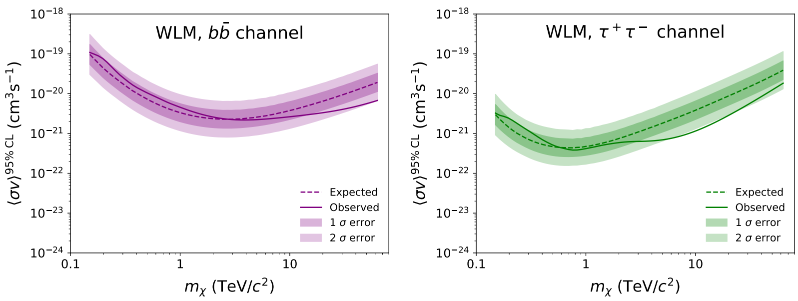

Figure 3. Upper limits on the annihilation cross-section $\langle\sigma v\rangle$ at 95% C.L. for WLM, in the $b\bar{b}$ and $\tau^+\tau^-$ annihilation channels. These upper limits include the uncertainties on the J factor. The solid lines are the observed limits, the dashed lines the mean expected limits and the dark (resp. light) bands are the 1 σ (resp. 2 σ) containment bands.

We compare our results to those of the HAWC experiment [10] that present preliminary results on 31 dwarf irregular galaxies including WLM. The authors use a Burkert profile to model the DM halo and compute the J factor up to the virial radius. In order to properly make the comparison, we compute the J factor with the *coreNFW* profile used here up to the virial radius, and rescale the HAWC limits accordingly. The H.E.S.S. results are more constraining on the whole DM mass range, by up to a factor of more than 200 depending on the annihilation channel. Dwarf irregular galaxies represent complementary targets to dwarf spheroidal galaxies and provide an alternative for dark matter indirect searches with the next generation of Cherenkov telescopes. More details on this work can be found in the associated publication of the H.E.S.S. collaboration [7]

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