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Indirect search for dark matter in dwarf spheroidal galaxies with Cherenkov Telescope Array

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Indirect search for dark matter in dwarf spheroidal galaxies with Cherenkov Telescope Array

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To the Brazilian citizens, who supported the public University where I developed this work.

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"We can't stay in the dark about it forever. Just because it's dark doesn't mean it doesn't matter" Jorge Cham & Daniel Whiteson (We Have no idea)

ABSTRACT

NAKASHIMA, D. K. Indirect search for dark matter in dwarf spheroidal galaxies with Cherenkov Telescope Array. 2018. 77p. Dissertation (Master in Science) - Instituto de Física de São Carlos, Universidade de São Paulo, São Carlos, 2018.

Dark matter (DM), whose nature and interaction mechanisms are still an open issue, constitutes about 25 % of the Universe energy density. Weakly Interacting Massive Particles (WIMPs) are considered as strong candidates for particle DM and their search is conveniently carried out through the detection of gamma rays. The newly discovered ultra-faint dwarf spheroidal galaxies (dSphs), located in the vicinity of the Galaxy, exhibit high values of the mass to luminosity ratio, and are therefore considered as strongly dominated by DM. These objects are within reach of the Cherenkov Telescope Array (CTA), which is the future project for gamma-ray astronomy, with an better sensitivity (one order of magnitude) with respect to the current generation experiments. The main goal of the present work is the study of the sensitivity of CTA to WIMPs DM particles, by simulating the observation of the ultra-faint dwarf spherical galaxies Triangulum II, Reticulum II and Carina III, as well as of the classical dwarf galaxy Sculptor, for different annihilation channels, between 70 GeV and 100 TeV. The sensitivity curve in the WIMPs parameter space (velocity-averaged annihilation cross section $\langle \sigma v \rangle$ and DM mass m_{DM}) was computed. We found that, within the sample of dwarf galaxies tested, Triangulum II is the most promising source, able to reach the thermal freeze-out values in the annihilation channel $\tau^+\tau^-$ for only 50 hours of observation. Our result, the first estimation of the sensitivity for DM searches in ultra-faint dwarfs with CTA, is consistent with results from current generation experiments, showing better performance over an extended energy range. The limited sample of available stars in the targets induces uncertainties on the DM content. Future measurements, leading to a better understanding of the sources dynamic equilibrium, can improve this situation. Even so, the combination of the high DM content in the ultra-faint dwarf galaxies, together with the excellent expected performance of the future CTA, provides a promising result for indirect DM searches.

Keywords: Dark matter indirect searches. Cherenkov Telescope Array. Dwarf spheroidal galaxies. Triangulum II galaxy.

RESUMO

NAKASHIMA, D. K. Detecção indireta de matéria escura em galáxias esferoidais anãs com o Cherenkov Telescope Array. 2018. 77p. Dissertação (Mestrado em Ciências) - Instituto de Física de São Carlos, Universidade de São Paulo, São Carlos, 2018.

A matéria escura, cuja natureza e mecanismos de interação ainda estão em aberto, compõe 25% da densidade de energia do Universo. Weakly Interacting Massive Particles (WIMPs) apresentam-se como forte candidatas e sua busca é convenientemente conduzida através de raios gama. As recém descobertas galáxias esferoidais anãs ultra-fracas, situadas nos arredores da Galáxia, apresentam altos valores da razão entre massa e luminosidade, sendo portanto consideradas objetos fortemente dominados por matéria escura. Esses objetos estão ao alcance do Cherenkov Telescope Array (CTA), que é o futuro projeto da astronomia gama, com sensibilidade de uma order de grandeza melhor do que os experimentos atuais. O presente trabalho teve como objetivo estudar o potencial de detecção indireta de WIMPs através de raios gama com o futuro observatório CTA, observando as galáxias esferoidais anãs ultra-fracas Triangulum II, Retículum II e Carina III e a galáxia anã clássica Sculptor, para diferentes canais de aniquilação, entre 70 GeV e 100 TeV. A curva de sensibilidade no espaço de parâmetros livres de WIMPs (massa da partícula m_{DM} e médida da seção de choque de aniquilação ponderada pela velocidade $\langle \sigma v \rangle$ foi calculada. Nós encontramos que dentro da amostra de galáxias anãs testadas, Triangulum II é a fonte mais promissora, capaz de testar os valores térmicos no canal de aniquilação $\tau^+\tau^-$ considerando apenas 50 horas de observação pelo CTA. Nosso resultado, a primeira estimativa da sensibilidade para busca de matéria escura em galáxias esferoidais anãs ultra-fracas com CTA, é consistente com resultados de experimentos da geração atual, e mostra um melhor desempenho em uma faixa de energia estendida. Os resultados são afetados pelas incertezas devido à pequena amostra de estrelas dos alvos escolhidos, que se reflete no conhecimento do conteúdo de matéria escura. Novas medidas podem ajudar a esclarecer essa situação. Ainda assim, a combinação de galáxias anãs ultra-fracas, aliada às melhorias do futuro CTA, apresenta-se como um passo muito promissor para buscas indiretas de matéria escura.

Palavras-chave: Detecção indireta de matéria escura. Cherenkov Telescope Array. Galáxias esferoidal anã. Galáxia Triangulo II.

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1 INTRODUCTION

The Universe composition has been discussed for a long time and it still remains far from being fully understood. With the advance of technology and the development of different types of sophisticated experiments, it is current known that 25% of the Universe total energy density is composed by a peculiar type of matter, which does not emit nor absorb light, called "Dark Matter" (DM). (1)

The first evidence of the non-luminous matter arose in the 30's (2) and gained importance during the 70's thanks to the studies of rotation curves of galaxies. (3) Such measurements showed that a non-luminous mass contributes significantly to the gravitational potential, increasing the orbital velocity of stars located far from the galaxy center. Additional evidence appeared later, allowing to reveal some DM characteristics, such as the fact that it does not interact electromagnetically, while it is approximately 5 times more abundant than the luminous matter and it does interacts through gravitation. (4)

Since these characteristics do not correspond to any know astrophysical phenomenon that science have already experienced, the search for answers beyond the known is necessary. Many hypotheses arose from the most diverse fields as attempt to solve the DM puzzle. Weakly Interacting Massive Particles (WIMPs) constitute a popular DM candidate, (5) since the WIMPs parameter space covers the values that gives the right DM abundance calculated by Cosmic Microwave Background. In the WIMP scenario, the DM particles can self-annihilate into Standard Model particles. Many of them, being unstable, will pass through different processes resulting in stable particles, such as electrons, positrons, neutrinos and gamma rays. The search for DM via the study of gamma rays produced in astrophysical sources is a very promising strategy, mainly because by studying these particles we can point back to the sources. (6)

The gamma-ray signal from DM annihilation is boosted in environments rich in DM. Moreover, a much cleaner detection could be obtained in case of very low astrophysical background. The dwarf spheroidal galaxies (dSphs) of the Milky Way are very well suited in this frame, given their high mass to luminosity ratio and low gamma-ray flux from other astrophysical processes, proving very promising target for the DM searches. (7) In particular, the recently discovered ultra faint dwarf galaxies appear to be the most DM dominated environment known, providing a promising channel to solve the DM mystery.

The future Cherenkov Telescope Array (CTA) observatory, the next generation of Imaging Atmospheric Cherenkov Technique (IACT) experiment, expected to start its operations in 2020, will provide an unprecedented sensitivity in the TeV energy range. (8) The CTA observatory will be composed by approximately 100 telescopes, divided in three sizes (small, medium and large) and located in both hemispheres. Thus, with the unprecedented improvement in sensitivity even the faint gamma-ray signal from DM annihilation will have the chance to be detected.

Combining the CTA characteristics with the high content of DM in the ultra-faint dSphs and the low astrophysical background expected from them, the WIMP scenario can be probed. Within this frame, this work aims to understand the potential of DM detection for each source by computing its sensitivity curve, which presents the WIMP parameter values that CTA will be able to detect. The rest of this work is structured as follows: chapter 2 is devoted to a general description of DM, presenting evidence, hypotheses about its nature and detection methods. The chapter 3 describes the indirect search for DM through gamma rays and the importance of the dSphs as astrophysical targets, in particular discussing the ultra-faint dSphs, the focus of this work. A description of the CTA observatory is given in chapter 4, together with the prospectives for DM searches and the description of the analysis pipeline used. The results, namely the sensitivity curves for several dwarf galaxies, are presented in chapter 5. In particular, our method was initially established studying the Sculptor galaxy and was later extended to Triangulum II, Reticulum II and Carina III. Lastly, the conclusions are presented in chapter 6.

2 DARK MATTER

Understanding the Universe has always been a fascinating and open question for scientists: cosmology indicates that 25% of the universe energy density is made of an unkown type of matter which does not emit nor absorb light, and is at most weakly interacting. This type of matter has been called DM. Because of its peculiar characteristics, DM is extremely hard to be detected: the search for DM has been a lively field of research since several decades, at the boundary between cosmology, particle physics and astrophysics.

This chapter provides an overview of the DM evidence, models and search strategies: section 2.1 provides a short description of the DM evidence, while section 2.2 briefly outlines some of the most popular DM models. The different search strategies will be described in section 2.3.

2.1 Evidence

Dark matter plays a very important role in the understanding of the Universe and its existence has been inferred from several observations, both astrophysical and cosmological. To identify the DM problem, the estimation of the total mass is compared to the estimated baryonic matter of the system. Interestingly, a mismatch between this two quantities is found in different scales, providing evidence for the existence of a new type of matter. In the following we will provide a short overview of some of the most relevant observations, while a very interesting review of the DM history can be found in (4).

2.1.1 Galaxy scale

A remarkable evidence of DM on galactic scales is the rotation curve of galaxies, namely the graph of the orbital velocity of stars and gas in the galaxy, as a function of the distance from the center r. The first application of this method, that points out the existence of non luminous matter, arose in the 1970s. (3) The kinematics of tracers (depending on the galaxy, tracers could be gas clouds, masers or even peculiar population of stars), located at a distance r from the center of the galaxy, is given by the gravitational field of the mass within the sphere of radius r, (9-10) thus:

$$F_{cent} = \frac{m_{tracer}v^2}{R} = \frac{m_{tracer}M(< r)G}{r^2}.$$
(2.1)

From the equation above, it is expected that the orbital velocity of stars far from the center, located at distance r, in which inside the sphere delimited by r is enclosed the majority of the galaxy mass, the relation $v \propto r^{-1/2}$ is expected. However, it is not observed in the data. (11) It is noticed that some galaxies present a flat rotation curve even for large r. To explain this behavior, we have to invoke either the limitation of Newtonian gravity at galaxy scales, either the existence of a non-luminous massive halo surrounding some galaxies. The figure 1 presents the measured rotation curve for the galaxy NGC 6503 and the expected rotation curve due to stellar components (dashed line), due to gas component (dotted line), due a non-visible matter halo (dash-dot line) and the a rotation curve due to the sum of these three components (solid line), that is in good agreement with the data. A discrepancy between the observed data and the expected result from the baryonic matter contribution is observed. (12)



Figure 1 – The rotation curve for galaxy NGC 6503 with dashed curve representing the contribution due to visible components, dotted curve due to gas, dash-dot curve for a non-luminous mass halo and the solid line representing the rotation curve due to the contribution of the sum of these three components.

Source: BEGEMAN (12)

DM is also present in our galaxy, the Milky Way. (13) From a recent analysis, figure 2 shows as a function of the distance, a comparison between the measured rotation curve (red dots), and the expectations from baryonic matter models (gray band). The black curve indicates the fiducial model. Once again, the discrepancy between the measured and the expected curves above 6 kpc represents an evidence for the DM presence in the

Galaxy.



Figure 2 – Milky Way rotation curve.

Source: IOCCO (13)

2.1.2 Galaxy cluster scale

At the scale of Galaxy Clusters, a discrepancy between the total mass estimated by the gravitational potential and the baryonic mass estimated by different methods is present as well.

In the past, the existence of a non-luminous matter appeared by comparing the luminous mass and the total mass using the Virial theorem, which relates the average of kinetic energy to the average of potential energy of a bound system of a non-relativistic particles. This method provided the first indication of DM existence in 1933 to estimate the mass of the Coma Cluster. (2) In this analysis, two methods were used to estimate the mass of the cluster: using the luminous matter and using the velocity of the galaxies of the cluster. The Virial theorem was used to derive the potential energy from the kinetic energy, estimated using the galaxies velocity measurements. From this calculation it was found that the luminous matter, measured by spectroscopy, is not enough to generate the gravitational force that holds the cluster together. The result found was mass-to-light ratio of approximately $400 \text{ M}_{\odot}/\text{L}_{\odot}^*$, two orders of magnitude higher than the expected value due to the contribution of luminous matter only. Despite this method presents equivalent results to the present methods, it carries larger uncertainties.

Today, a cluster total mass is determined from gravitational lensing, allowing to map spatially the gravitational potential of the system. The baryonic mass contribution in

^{* 400} solar masses per solar luminosity

a cluster is mainly due to the presence of hot gas (temperature of order of 10^7 to 10^8 K), which can be weighted by X-ray measurements. (9,14)

2.1.3 Cosmological scales

Cosmology provides important insights about the DM existence and its contribution to the energy density of the Universe, by means of the study of the Cosmic Microwave Background (CMB) radiation. (15) The CMB is an ubiquitous radiation, which follows the black body spectrum corresponding to a temperature of 2.7 K, (16) picturing the infant Universe. (17) Because of the coupling of matter and radiation during the early Universe, the temperature anisotropies in the CMB map, indicate anisotropies in the matter density. Therefore, based on temperature measurements, information about matter is derived. (18) Despite the almost homogeneous temperature distribution, tiny anisotropies at the 10^{-5} K level are present, as it is shown in figure 3.



Figure 3 – CMB temperature map by Planck, in galactic coordinates.

Source: THE PLANCK COLLABORATION (16)

From the power spectrum of the temperature anisotropies, informations about cosmological parameters can be obtained, such as the contribution of baryonic matter and DM to the Universe energy density. This analysis indicates that the baryonic matter composes 5% of the Universe energy density, being 5 times less than the total matter contribution, 25% of the Universe energy density. (1) Such difference indicates the necessity of a type of non-baryonic matter even on cosmological scales.

2.2 Hypothesis for the dark matter contribution

As showed above, the discrepancy between the estimated baryonic matter and the total matter in different scales is undeniable. Over the past years, several hypothesis to solve it arose and in the following, a brief description of some of them will be given.

An hypothesis for the missing mass considered in the past is the MAssive Compact Halo Objects (MACHOs). The MACHOS are astrophysical objects which do emit little or no radiation, with mass in the range of 10^{-7} until some hundreds of solar masses, such as brown dwarf, neutron stars and black holes, and they should be measured by microlensing effects. (19-20) However, since the CMB gives a intrinsic beautiful probe that DM cannot be baryonic, this hypothesis was ruled out as the only explanation for DM.

Assuming the DM is made of a cold gas, it not expected to shine in X-rays, but its effect could be observed in a merger of clusters, for instance. The Bullet Cluster, a collision between two galaxy clusters, presented in figure 4 was measured by combination of X-rays and gravitational lensing methods, exhibits the spatial map of two clusters: the green line shows the reconstruction of gravitational potential and the white area the measurement of the hot gas. (21) The observed spatial separation between the center of the gravitational potential and the gas of the cluster indicates a collisionless characteristic of DM in form of cold gas, otherwise they should be approximately at the same spatial position of the hot gas of the cluster. This result provides a threshold for the DM self-interaction, the ratio of the cross-section and the DM particle mass σ/m_{DM} . (22)



Figure 4 – The Bullet Cluster, the collision between two galaxy cluster, measured by X-rays and gravitational lensing. Through gravitational lensing a gravitational map obtained and presented in the green line. Through the X-ray measurement, the distribution of the gas of each cluster is revealed and presented in the colors (being the white the region with higher concentration of gas).

Source: CLOWE (21)

Several observations on different scales can convincingly explained by the existence of a new and yet unknown type of particles. In this frame, several hypotheses were proposed. Some examples are: (i) Neutrinos, from the Standard Model (SM) of particle physics; (ii) the Lighest Kaluza-Klein Particle (LKP), derived from extra dimension theory; (iii) the axions, from the Quantum Chromo Dynamics; (iv) neutralinos, from the Super Symmetry of the Standard Model (SUSY); (v) Weakly Interacting Massive Particles (WIMPs). (4) Since this work is focused on the search for a gamma ray signal from WIMPs as DM candidates, in the next section we will discuss this hypothesis in more detail.

2.2.1 WIMP as dark matter particle candidate

Weakly Interacting Massive Particles (WIMPs) have been a very popular DM particle candidate over last decades. They were produced with the thermal mechanism in the early Universe. Being in both collisional and chemical equilibrium to SM particles (to which they are coupled through weak scale process), until they "freeze-out". (10)

The thermal freeze-out is reached when the WIMPs annihilation rate equals the universe expansion rate H(t):

$$n < \sigma v > \approx H(t_{freeze-out}).$$
 (2.2)

In this scenario, the bigger is the cross section, the later the freeze-out will occur, resulting in a lower abundance. Thus a link between the WIMP abundance and the annihilation cross-section is stated. A sketch of this process is presented in figure 5: the vertical axis indicates the WIMPs abundance and the horizontal axis shows WIMP mass divided by the universe temperature, such ratio being proportional to the time. The full black line is the co-moving WIMP equilibrium abundance in case of the coupling with SM particles, the dashed lines presents the WIMP abundance today for three different scenarios assuming different DM cross-section and the encounter of the black and dashed line represents the freeze-out time. (18)

In order to measure the relic abundance inferred by the CMB, one recovers the value of $\langle \sigma v \rangle = 3 \times 10^{-26}$ cm³/s for a DM particle averaged velocity cross section and DM particle mass of order of some hundred GeV, $m_{DM} \approx 100$ GeV. This combination of mass and cross-section values obtained are known as thermal values and they have the order of magnitude of the weak scales. Such coincidence, named as "WIMP miracle", constitutes the main motivation for the WIMPs popularity as DM candidates. (18)

2.3 Detection techniques

Different physical phenomena can be exploited to search for DM: annihilation (or decay) of DM particles into SM particles, the scattering between DM and SM particles and the production of DM particles through SM particle collisions. This allows different experimental strategies, schematically described in figure 6.



Figure 5 – WIMP density represented by Y, full black line in case of density in thermal equilibrium and the dashed line in case of freeze-out, showing the different abundance for different values of cross-section. All this as a function of x = mass/temperature.

Source: KOLB (18)

The work described in this is dissertation was carried out in the frame of the indirect searches for WIMP DM particles, and for this reason the next subsection is devoted to a short description of this detection strategy.

2.3.1 Dark matter indirect detection

The indirect detection follows the idea to search for DM annihilating into SM particles. Because the new created particles from DM annihilation are usually unstable, the indirect method searches for stable particles resulted from subsequent process of the created instable particles. Therefore, the indirect search can be carried out by observing photons, charged cosmic rays and neutrinos. Each of them, with their own inherent characteristics provides unique advantages and also challenges, which are presented in Table 1, together with their specific experiments. This subsection is based on the review of indirect searches for particle DM available in (24).

Gamma-rays for DM indirect searches is convenient mainly because the mass scale of WIMPs implies gamma-ray emission detectable by the experiments. Additionally, because the photons have no charge, they can travel through the Universe without being deflected by magnetic field, thus their source direction can be inferred. Besides, the shape of the



Figure 6 – Sketch of the complementary DM search methods. The symbol χ represents the DM particles while *P* represents the SM particles. The left down to top arrow indicates the collider search method, in which is expected DM creation from SM particles. The top arrow from left to right represents the direct detection, in which scattering is expected between DM and SM particles. Lastly, the left arrow from top to bottom represents the indirect searches, in which is expected the DM annihilation (or decay) into SM particles.

Source: UNDAGOITIA (23)

expected gamma-ray spectrum carries basic information on DM particle properties, such as the mass and annihilation cross-section, and its coupling to the SM. The detection of the gamma rays can be performed directly by space-borne experiment, such as Fermi-LAT, or indirectly (because the Earth atmosphere is opaque to gamma rays) by ground based Imaging Atmospheric Cherenkov Telescopes (H.E.S.S., MAGIC, VERITAS and the future CTA) and water Cherenkov experiments, as HAWC.

Neutrinos also have no electric charge, meaning that they can indicate the source direction. The detection basic idea is to measure the Cherenkov light as result of the interaction of neutrinos with water (ANTARES/KM3NET, BAIKAL-GVD, Super-Kamiokande and Hyper-Kamiokande) or ice (Ice-Cube/DeepCore/PINGU). The neutrino experiments use large detection volumes (water, ice) in order to increase the detection probability, given by the low interaction cross-section of neutrinos, typical weak interactions.

The DM indirect searches through cosmic rays are performed by measuring the tiny antimatter component of cosmic rays, mainly made of positrons and antiprotons. Antimatter particles, as gamma rays, can be final product of the DM annihilation and they have low flux compared with matter particles, like electrons and protons. The search for dark matter with charged cosmic rays can be mainly performed by searching for spectral features in the particle fluxes. The search for light antinuclei, like antideuterons and

Table 1 – DM indirect searches strategies, pointing the particle in which is detected, the experiment (the names highlighted in blue represent the panned experiments), and its inherent advantages and challenges.

Particle	Experiments	Advantages	Challenges
Gamma-ray	Fermi LAT, GAMMA-400,	point back to sources,	backgrounds,
photons	H.E.S.S.(-II), MAGIC,	spectral signatures	attenuation
	VERITAS, HAWC, CTA		
Neutrinos	IceCube/DeepCore/PINGU,	point back to sources,	background,
	ANTARES/KM3NET,	spectral signatures	low statistics
	BAIKAL-GVD,		
	Super-Kamiokande,		
	Hyper-Kamiokande		
Cosmic Rays	PAMELA, AMS-02, ATIC,	spectral signatures,	diffusion, do
	IACTs, Fermi LAT, Auger,	low backgrounds for	not point
	CTA, GAPS	antimatter searches	back to sources

Source: GASKINS (24)

antihelium, is also a promising target for dark matter studies, since the expected flux of these particles from conventional astrophysical processes is extremely faint compared to the flux of protons. The cosmic rays experiments can be either in space (PAMELA, AMS-02, ATIC, Fermi LAT and GAPS), either on the ground (IACTs, CTA and Auger).

Figure 7 shows a summary of recent constraints set in the WIMP parameter space from indirect searches, for the DM annihilation into $b \bar{b}$. Results from gamma rays, cosmic rays and high energy neutrinos are displayed. From this plot it can be seen that the gamma-rays experiments provide the most stringent constraints.



Figure 7 – The current important constraints on the annihilation cross-section versus WIMP mass, from gamma rays, cosmic rays and high energy neutrinos. The gray band represents the thermal value for comparison.

Source: CONRAD (7)

3 INDIRECT DETECTION: FROM DARK MATTER TO GAMMA RAYS

Gamma rays being neutral, they can travel through the Universe without being deviated by galactic and extra-galactic magnetic fields, indicating their origin, unlike charged particles. (5,25) The expected γ -ray flux $\left(\frac{d\Phi_{\gamma}}{dE}\right)$ from DM annihilation, that is the number of photons per area per time and per energy, encloses the DM particle mass m_{DM} , the velocity averaged cross-section $\langle \sigma v \rangle$, the annihilation channel f with its respective branching ratio B_f , the DM density distribution over the observed target ρ and the target distance from the observer d, as follows:

$$\frac{d\Phi_{\gamma}}{dE}(E) = \frac{1}{4\pi} \frac{\langle \sigma v \rangle}{2m_{DM}^2} \sum_f \frac{dN^f}{dE} B_f \times \int_{\Delta\Omega} \int_V \frac{\rho^2(r)}{d^2} dV' d\Omega'.$$
(3.1)

For convenience, the 3.1 can be separated in two parts: one, $\frac{d\Phi_{PP}}{dE}$, encoding the particle physics information:

$$\frac{d\Phi_{PP}}{dE} = \frac{1}{4\pi} \frac{\langle \sigma v \rangle}{2m_{DM}^2} \sum_f \frac{dN^f}{dE} B_f, \qquad (3.2)$$

and one encoding the astrophysical characteristics of the target, labeled as J:

$$J = \int_{\Delta\Omega} \int_{los} \frac{\rho^2(r)}{d^2} dV' d\Omega'.$$
(3.3)

Therefore, the gamma-ray flux from DM annihilation can be written as:

$$\frac{d\Phi_{\gamma}}{dE}(E) = \frac{d\Phi_{PP}}{dE} \times J. \tag{3.4}$$

This chapter is devoted to the indirect searches for WIMPs with gamma rays. In particular, the section 3.1 describes the particle physics term of equation 3.4, while the astrophysical term is described in section 3.2. The section 3.3 describes the most popular astrophysical targets for DM searches, while section 3.4 focuses on dwarf spheroidal galaxies as targets for DM searches.

3.1 The particle physics term

In the frame of the DM particle scenario, the information about the gamma rays from WIMP annihilation are included in the particle physics term, namely:

$$\frac{d\Phi_{PP}}{dE} = \frac{1}{4\pi} \frac{\langle \sigma v \rangle}{2m_{DM}^2} \sum_f \frac{dN^f}{dE} B_f.$$
(3.5)

The annihilation process encloses all the model characteristics: the velocity-averaged cross-section $\langle \sigma v \rangle$ and the DM particle mass m_{DM} , that are free parameters and in which particle physics channel (f) the DM particles are annihilated, weighted by the branching ratio B_f . (6)

The detection of a gamma-ray line would be considered as a compelling signature for the existence of dark matter, since it would be a clear signature of the direct annihilation of DM particles in two photons. However, due to the very low probability of this process to occur, it turns out to be more interesting to consider the DM annihilating into others channels, in which the newly created particles will pass through several subsequent processes resulting a continuum spectrum of gamma rays. Figure 8 presents the differential gamma-ray spectrum (per annihilation process), as a function of energy normalized to the DM mass of $m_{DM} = 10^3$ GeV, for several annihilation channels. The spectrum of photons for each annihilation channel is generated using the information available in (26). In order to generate the gamma-ray spectrum, two process are necessary to be considered: the decay of heavier particles and hadronization for quarks^{*}. (27)



Figure 8 – Differential photon spectra for DM mass of $m_{DM} = 10^3$ GeV. Each color represents different annihilation channels.

Source: By the author

From figure 8, it can be seen that the channels follow roughly the same shape, except for the $\tau^+\tau^-$. Such difference is due to the peculiar τ decay chain. The τ^- decay channels, together with the respective probabilities, are presented below (28):

^{*} The hadronization occurs due to the color confinement (which does not allow quarks to exist freely), consisting of the creation of hadrons by combining the quarks created from the DM annihilation and the spontaneously created quarks pair from the vacuum.
$$\begin{array}{ll} \tau^- \to \pi^- \pi^0 \nu_\tau & 25.5\% \\ \tau^- \to e^- \bar{\nu}_e \nu_\tau & 17.8\% \\ \tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau & 17.4\% \\ \tau^- \to \pi^- \nu_\tau & 10.8\%. \end{array}$$

The channel with higher probability contains π^0 , who will decay in one of the following channels:

$$\begin{array}{ccc} 2\gamma & 98.8\% \\ e^+e^-\gamma & 1.2\%. \end{array}$$

Thus, for the τ channel, the production of photons occurs promptly in the second step of the decay chain, while for other particles it takes some more steps. Consequently, the photons produced from the τ particle will be more energetic resulting into different shape on the differential spectrum of photons.

3.2 The astrophysical term

The astrophysical term, often referred to as *J*-factor, includes all the features of the astrophysical target relevant for the DM study: its density and distance from the Earth. To characterize this parameter it is necessary to assume a DM density distribution ρ , integrated over the volume defined by volume along the line of sight *los*, as defined according to equation below: (6,25,29)

$$J = \int_{\Delta\Omega} \int_{los} \frac{\rho^2(r)}{d^2} dV' d\Omega'.$$
(3.6)

3.2.1 Dark matter density distribution

In order to describe the DM density profile, several shapes arose, either guided by numerical simulations, either by observations. A discrepancy between the two classes of profiles is observed at small radii. In particular, some density profiles are called "cuspy", since they increase steeply at small radii, while the opposite behavior with a flattish density profile at small radii is usually called "cored".

All profiles depend on at least two free parameters: the density ρ_0 and radius scale r_s . One general equation for the density profile is described by Zhao (30), whose combination of three more free parameters α , β and γ can describe different DM profiles. The DM density profile derived by Navaro-Frenk-White (NFW) (31) is derived from N-body simulations and depends on 3 more parameters ($\alpha = 1, \beta = 3, \gamma = 1$). It is a cuspy profile, like the Einasto profile, (32-33) which depends on just one parameter α . Among the family of cored profile, one example is the Burkert profile (34), derived from the fit to the data from dSphs. The mentioned profiles are described by the equations below:

$$\rho_{ZHAO}(r) = \frac{\rho_0}{\left(\frac{r}{r_s}\right)^{\gamma} \left[1 + \left(\frac{r}{r_s}\right)^{\alpha}\right]^{(\beta - \gamma)/\alpha}},\tag{3.7}$$

$$\rho_{Ein}(r) = \rho_0 exp\left[-\frac{2}{\alpha}\left(\left(\frac{r}{r_s}\right)^{\alpha} - 1\right)\right],\tag{3.8}$$

$$\rho_{Bur}(r) = \rho_0 \frac{r_s^3}{(r+r_s)(r^2+r_s^2)}.$$
(3.9)

As an example, figure 9 shows the different density profile as a function of the radius for the Sculptor dwarf galaxy. By the plot is evidenced the flat behavior of the Burkert profile and the cuspy shape of NFW and Einasto profiles.



Figure 9 – Dark matter density profiles as a function of the radius for the Sculptor dwarf galaxy. The black curve presents the NFW profile, the red curve presents the Einasto profile and the blue curve presents the Burket profile.

Source: By the author

The free parameters of each model for each source are obtained from the fit to the observational data: the light surface brightness of the galaxy, the position in the sky and the velocity in the line of sight direction of the stars in it. There are different methods for obtaining the parameters of the DM density profile from observation of different astrophysical targets. Once one has the shape of the density profile, the J-factor can be calculated.



Figure 10 – Illustration of *J*-factor's integration parameters.

Source: Provided by Céline Armand

3.2.2 Calculating the *J*-factor

In order to turn the computation of the J-factor (equation 3.6) more manageable, the integration can be described by new variables:

$$J = \int_0^{2\pi} \int_0^{\alpha_c} \int_{s_{min}}^{s_{max}} \rho^2(s,\alpha) sin\alpha ds d\alpha d\phi.$$
(3.10)

The new frame is represented in figure 10, in which d is the distance from the astrophysical target, the line of sight is the represented by the parameter s and the parameters from the solid angle are ϕ and α , being the integration limits: α_c , s_{min} and s_{max} . Assuming the distance d, the parameter r can be defined by the cosine law as a function of the new variables as:

$$r^{2}(s,\alpha) = s^{2} + d^{2} - 2dscos\alpha.$$
(3.11)

By assuming the size of the DM halo as R, which is the maximum distance of r, the values of s_{min} and s_{max} can be obtained solving the following equation:

$$R^2 = s^2 + d^2 - 2sdcos\alpha. (3.12)$$

The limit values are:

$$s_{max} = d\cos\alpha + \sqrt{R^2 - d^2 \sin^2\alpha},\tag{3.13}$$

$$s_{min} = d\cos\alpha - \sqrt{R^2 - d^2 \sin^2\alpha}.$$
(3.14)

In order to validate the two equations above, we need to require:

$$\alpha \le \arcsin\left(\frac{R}{d}\right). \tag{3.15}$$

However, the parameters above depend on the size of the dark matter halo R, which is unknown. In order to solve this, different assumptions are used, for instance, the radius R being the distance of the farthest star of the system, relating it to an angle α_{max} . Or, in a more conservative scenario, the radius R can be related to the the angle $\alpha_{0.5}$, in which is valid the relation $J(\alpha_{0.5}) = 0.5J(\alpha_{max})$. (6,25)

3.3 Astrophysical sources

Due to the faint expected gamma ray signal from DM annihilation, identifying the sources which present the highest potential plays a crucial role in order to maximize the odds for DM detection. Within this context, two main features have significant weight on the source decision: the DM density and gamma-ray background from standard astrophysical processes. (35-36)

Figure 11 presents the gamma-ray sky map measured by Fermi-LAT experiment together with most promising targets for the DM indirect searches in gamma rays.



Figure 11 – Possible astrophysical targets for indirect DM searches with gamma rays.

Source: CONRAD (7)

The most promising targets include:

- The Galactic Center (GC) is a very popular target for DM searches due to its expected high density of DM and the short distance (≈ 8 kpc) from Earth. However, this region hosts many active gamma-ray sources, producing a huge foreground for the search for DM, making the detection of an unambiguous DM signal very challenging. Several claims of DM signals from the GC were made in the past decade, see for example (37).
- Dwarf Spheroidal galaxies (dSphs) have very high mass to luminosity ratio, thus they are dominated by DM. Besides, the lack of astrophysical background in this type of sources increases the chance of DM detection.

The dSphs are the targets for the work presented in this dissertation, therefore the next section is devoted to them.

3.4 Dwarf spheroidal galaxies as astrophysical targets

The dSphs are very promising targets for DM indirect searches, being small systems, composed by old star populations, with low luminosity and dust content. (35) They are known to have high mass-to-light ratio, of order of $\approx 10^2$ [†], implying that they are dynamically dominated by DM. Dwarf spheroidal galaxies are usually divided in two categories: classical dwarf galaxies such as Draco, Sculptor, and Fornax and ultra-faint such as Triangulum II or Reticulum II. Classical dwarf galaxies have significantly smaller uncertainties on the *J*-factor than the ultra-faint dSphs, but some of the recently discovered ultra-faint dSphs have big *J*-factors, very promising for indirect DM search. Ultra-faint dSphs being spheroidal in some cases is not yet unambiguously established, but this assumption is needed to investigate the presence of a dense dark matter halo.

Since the luminous mass in the dSphs is mainly composed of stars, without a sizable contribution from gas and other form of baryonic matter, all the characterization of the system is based on stars measurable components, such as: the line of sight velocity of each star and the light distribution of the entire sample. (36,38) The description of the dynamics of the galaxy, whose precision depends crucially of the stellar sample available, is essential for the system description. In particular the inference of the dynamics of the system is needed to obtain the parameters of the DM density profile for dSph, which can be obtained applying the Jeans equation. (38) The equation presents six degree of freedom: three spatial and three in the velocity. However, the measurements provides only 2 spatial component (the star latitude and longitude, translated into projected distance R) and one component in velocity (along the line of sight). In order to overcome this mismatch between the number of degrees of freedom and the number of measured components, it is assumed a free parameter β_a named anisotropy parameter, which is a function only of r,

[†] while it is usually ≈ 5

the distance from the center of the galaxy[‡]. The anisotropy parameter characterizes the shape of the orbit of a star around the galaxy[§], and it is defined as:

$$\beta_a(r) \equiv 1 - \frac{2v_\theta^2(r)}{\bar{v}_r^2(r)},\tag{3.16}$$

with $\bar{v_{\theta}^2}(r)$ and $\bar{v_r^2}(r)$ being the velocity dispersion in spherical coordinates θ and r respectively.

Photometry measurements provide the projected light profile $\Sigma(R)$ (also known as surface brightness), that is necessary because it relates to the star density distribution $\nu(r)$, which is required in the Jeans equation. The relation between these two parameters is given by:

$$\Sigma(R) = 2 \int_{R}^{\infty} \frac{\nu(r)rdr}{\sqrt{r^2 - R^2}}.$$
(3.17)

Assuming spherical coordinates for a system in dynamical equilibrium, the Jeans equation can be written relating the kinematics of the star and the gravitational potential from DM distribution:

$$\frac{1}{\nu(r)}\frac{d}{dr}(\nu(r)\bar{v_r^2}) + 2\frac{\beta}{r}\bar{v_r^2} = -\frac{GM(r)}{r^2} = -\frac{G}{r^2}4\pi\int_0^r \rho_{DM}(s)s^2ds.$$
 (3.18)

Although the strong feature of the Jeans equation is the relation between the DM density profile and the stars measurements, this equation has parameters regarding of 3D space, while the observed measurements provides information only in the 2D space, the projected plane. This issue is overcome by considering the following equation 3.19, which relates the line of sight velocity dispersion as a function of the projected radius $\sigma_p(R)$ with the anisotropy parameter β_a and the radial velocity dispersion $\bar{v}_r^2(r)$:

$$\sigma_p^2(R) = \frac{2}{\Sigma(R)} \int_R^\infty \left(1 - \beta_a(r) \frac{R^2}{r^2} \right) \frac{\nu(r) v_r^2(r)}{\sqrt{r^2 - R^2}} dr.$$
(3.19)

Combining equations 3.18 and 3.19, we can define the DM density parameters by fitting the free parameters: the β_a and the free parameters of the DM density profile. (38) An open software widely used for this analysis is CLUMPY (39), using the Markov Chain Monte Carlo method to optimize and encounter the value of the best fit. (29)

An example of J-factor and its parameter values calculated with this method is presented in Table 2 for the Sculptor galaxy. (40)

[‡] Note: the variable r is the radial component in spherical coordinates, while the variable R is the projected distance (in a 2D plane) from the center

[§] For instance, for a circular orbit $\beta_a \to -\infty$; for an open orbit, with only variation in r,

Distance	$86 \pm 6 \text{ kpc}$
NFW $\log_{10}\rho_s$	$-1.33 \ { m M}_{\odot} { m pc}^{-3}$
NFW $\log_{10} r_s$	3.02 pc
NFW α	1.68
NFW β	5.80
NFW γ	0.81
α_{max}	1.94°
$\alpha_{0.5}$	$0.15\pm0.05^\circ$
$\log_{10} J(\alpha_{max})$	$18.57^{+0.07}_{-0.05} \text{ GeV}^2/\text{cm}^5$
$\log_{10} J(\alpha_{0.5})$	$18.54^{+0.06}_{-0.05} \text{ GeV}^2/\text{cm}^5$

Table 2 – Parameters for the J-factor calculation and its value for the Sculptor dwarf galaxy.

Source: GERINGER-SAMETH (40)

Notably, since the J-factor is computed by integrating over the DM density profile, it is sensitive to the shape of DM density profile assumed: core or cuspy. A distant source may be identified as point-like (as it is the case for dSphs): in this case the uncertainties due to different DM profiles are negligible compared to the uncertainties related to the stars measurements. For nearby sources, observed as extended objects, the spatial resolution plays an important role. In this case, different assumptions for the DM density profile play an important role. (36)

The *J*-factor for dSphs is dependent on the quality and precision of star measurements. This dependence does not limit only its calculation, but also the robustness of the result: the smaller is the stars sample, the less reliable is the result. This issue is particularly relevant for the recently discovered ultra faint dwarf galaxies: systems with few known stars, with possibly higher DM content than the classical dSphs. As it will be discussed in more detail in section subsection 3.4.2, the DM content of the ultra-faint dSph is not yet well established, due to the limited knowledge of the baryonic matter. (35-36)

The galaxies used as a target in work will be described in the following.

3.4.1 Sculptor

Among the classical dSph of the Milky Way, one of the best known is Sculptor: (41) it was discovered in 1937 and it was the first source to be classified as dSph, with mass to light ratio of $158\pm33 \text{ M}_{\odot}/\text{L}_{\odot}$. (42) This source is visible from the Southern hemisphere, having equatorial coordinates $RA=15.03^{\circ}$ and $Dec=-33.71^{\circ}$. It is located at 86 ± 6 kpc from the Sun.

The Sculptor galaxy includes 1365 stars[¶] and for this abundant sample, its J-factor

 $[\]beta_a = 1.$

[¶] While the majority of dwarf galaxies contain about $10^1 \sim 10^2$ known stars

is known with low uncertainties, as presented in Table 2. (40) Consequently, due to this reliable results, Sculptor is often used as a benchmark for DM searches.

3.4.2 Triangulum II

The Triangulum II ultra faint dwarf galaxy was discovered in 2015. It is visible from the Northern hemisphere, with equatorial coordinates: $RA=33.32^{\circ}$ and $Dec=36.18^{\circ}$ and it lays 30 ± 2 kpc away from the Sun. Its detection was first conducted by the photometric measurements using the Panoramic Survey Telescope and Rapid Response System (PAN-STARRS 1). (43-44) In the same year, Triangulum II was confirmed as a galaxy by the spectroscopy measurements carried out by two independent groups, using the data collected with the KECK II telescope. (45)

The group lead by Martin (46) reported the observation of 13 stars, while the group lead by Kirby (47) reported initially the observation of 6 stars, while an reviewed analysis published in 2017 reported the observation of 14 stars (48). Data collected using two techniques, photometry and spectroscopy, point to a high ratio mass-luminosity: 3600^{+3500}_{-2100} M_{\odot}/L_{\odot} , a strong indication of presence of DM. (47, 49)

As of today, only 14 stars are known to belong to Triangulum II. With this small sample it is very challenging to firmly conclude characteristics of the galaxy, carrying large uncertainties on each parameter value, which can lead to different conclusions, even in the same group with the same data, as presented by Kirby group in 2015 (47) and 2017 (48). Given the limited information on the stellar content of this particular object, its dynamics is at present poorly understood. For this reason, it is necessary to make some assumptions in order to perform the Jeans analysis used to derive its J-factor.

Photometric measurements by the Martin and Kirby groups, as well as the CLUMPY software for the Jeans analysis, were used by Dr. F. G. Saturni, a collaborator within our working group, to obtain an updated estimation of the *J*-factor of Triangulum II. ^{||} The data used as input are the surface brightness from (35) for the measured photometric data in (41) and the stars data presented by Martin and Kirby. The Einasto DM density profile is assumed, due to the smaller number of free parameters for a cuspy shape. The sample of stars is presented in Table 3, where for each star ID(M) and ID(K) respectively indicate the star identification number for the Martin group and for the Kirby group, RA and Dec are the equatorial coordinates, R is the projected distance from the center of the galaxy, v_r indicates the star heliocentric velocity and δv_r indicates the star velocity uncertainties. For the overlapping stars presented by both groups, the weighted average is provided.

The J-factor obtained has the value of $\log_{10} J(\alpha_{op}) = 20.7 \text{ GeV}^2/\text{cm}^5$, calculated at the optimal angle defined as $\alpha_{op} \approx 2r_h/d = 0.13^\circ$ (r_h is the half light radius), where the

Value obtained in private communication.

ID(M)	ID(K)	RA	Dec	$R \; [pc]$	$v_r \; [\rm km/s]$	$\delta v_r \; [\rm km/s]$
08		33.26	36.21	36.8	-387.1	7.7
09		33.36	36.23	32.7	-404.7	5.1
20	91	33.33	36.19	8.5	-382.1	2.1
21	116	33.32	36.17	5.0	-380.7	2.4
22		33.30	36.15	19.4	-387.0	3.8
23	76	33.36	36.16	10.7	-389.0	2.3
24		33.34	36.17	10.3	-383.1	4.9
25		33.32	36.12	30.3	-362.8	5.6
27		33.34	36.14	21.2	-401.4	6.6
29		33.38	36.20	31.4	-397.1	7.8
31		33.47	36.22	80.4	-375.8	3.1
40	106	33.32	36.18	1.9	-381.4	1.3
46	65	33.32	36.18	11.2	-373.8	1.4
	128	33.31	36.16	10.2	-384.9	3.2

Table 3 – Observed star list for Triangulum II galaxy.

Source: GENINA (49)

J-factor has the smallest error bars, as used in (35-36). Table 4 reports the Triangulum II J-factors obtained by independent groups. The first three results are very close, since the method used is equivalent, while the result published by the Fermi-LAT Collaboration, published in (50), is quite different but still compatible with the others. In particular, the Fermi-LAT J-factor result is obtained using a different method, where no definition of α is required.

Table 4 – J-factor for Triangulum II calculated by different methods and groups.

Group	$Log_{10}J \; [\text{GeV}^2/\text{cm}^5]$	α
F. Saturni	20.7 ± 0.6	α_{op}
A. Genina (49)	$20.77^{+0.60}_{-0.41}$	α_c
K. Hayashi (51)	$20.44^{+1.20}_{-1.17}$	α_c
Fermi-LAT (50)	19.1	

Source: By the author

The J-factor for Triangulum II is one of the highest among the dSph, approximately 100 times higher than the ones of the classical dSph. However, we strongly highlight the lack of information about the system dynamics, critical factor for the J-factor calculation. (35-36)

In our analysis, the value of *J*-factor calculated by Saturni will be used, since we consider it as the most updated one and it is the one from the CTA Consortium. The effect of a different choice will also be discussed.

3.4.3 Reticulum II

The photometric data of Dark Energy Survey (DES) in 2015, analyzed by (52), revealed 9 ultra faint objects in the vicinity of the Large Magellanic Cloud. Later in the same year, Reticulum II was confirmed as an ultra faint dwarf galaxy by spectroscopy measurements presented by three different groups (53–55), using different telescopes (Michigan/Magellan Fiber System (M2FS), VLT/GIRAFFE and Gemini South/GMOS).

Reticulum II has equatorial coordinates $RA = 53.92^{\circ}$ and $Dec = -54.05^{\circ}$, with heliocentric distance of 30 ± 2 kpc. Based on the spectroscopic data, its radial velocity indicates that the system is gravitationally independent from the Large Magellanic Cloud, despite being very close. Moreover, the mass to light ratio obtained from spectroscopy, of $\approx 500 \text{ M}_{\odot}/\text{L}_{\odot}$, indicates that Reticulum II is a promising target for DM searches.

The Reticulum II J-factor was calculated by (56), resulting in $\log_{10} J(\alpha_c) = 18.8 \pm 0.6$ GeV²/cm⁻⁵ within $\alpha_c = 0.1^{\circ}$ and independently confirmed by (57). The data used to calculate it were the photometric measurement presented in (52) and the star sample presented in (53), composed by 18 star members. Like for Triangulum II, the dynamics of Reticulum II is not yet fully understood confirmed, due to the limitations of the available stellar sample.

3.4.4 Carina III

Carina III (58) was discovered in the beginning of 2018, by photometric data from the Magellanic Satellites Survey (MagLiteS), together with Carina II, in the Large Magellanic Cloud neighborhood. Spectroscopy data using Magellan/IMACS, Anglo-Australian Telescope/AAOmega+2dF, and Very Large Telescope/GIRAFFE+FLAMES measured 14 stars members for Carina II and only 4 belonging to Carina III. From the data, Carina II was confirmed as an ultra faint dSph, however Carina III, due to small star sample, is still a non-confirmed dSph candidate.

Carina II and Carina III have RA= 114.11° and 114.63°, Dec= -58.00° and -57.90° , with heliocentric distance of 37.4 ± 0.4 kpc and 27.8 ± 0.6 kpc, respectively.

Once again, few stars members are known, driving to a fragile *J*-factor value, specially for Carina III. Current estimations of the *J*-factor for Carina II are $\log_{10} J(0.1^{\circ})=17.9^{+0.6}_{-0.5}$ GeV²/cm⁵ while for Carina III, $\log_{10} J(0.1^{\circ})=19.9^{+1.0}_{-0.9}$ GeV²/cm⁵. (59) Given its promising *J*-factor value together with the distance, in this work we will only focus on Carina III, under the assumption it is a ultra faint dSph.

4 THE CHERENKOV TELESCOPE ARRAY

Along the past years the scientific community acquired one more window to observe the universe: the gamma rays. The 10 m mirror array at the Whipple Observatory, located in Arizona, was the first example of an Imaging Atmospheric Cherenkov Telescope (IACT), that led to the first ever detection of TeV emission from the Crab Nebula in 1989. (60) Motivated by the success on the first demonstrations, the use of IACTs became a robust and high performance detection technique to explore the high energy universe.

This chapter is devoted to a general discussion about the ground based gamma-ray detection, to the current experiments and in particular to the future project Cherenkov Telescope Array (CTA). In section 4.1 we will discuss the ground based gamma-ray astronomy principle, while in section 4.2 and 4.3 we will describe the current experiments, together with the Cherenkov Telescope Array and its expected performance. In section 4.4 we will focus on the detector expected performance for dark matter searches, while in section 4.5 we will describe the CTA analysis pipeline, used to carry out the analysis presented in the next chapter.

4.1 Ground based gamma rays detection principle

Since the energetic gamma rays are absorbed by the Earth's atmosphere, they can either be observed directly using detectors operating in space or indirectly using ground based experiments that can detect the electromagnetic cascades generated by gamma rays. Gamma rays entering the Earth's atmosphere interact with the atmospheric molecules and will produce an extensive particle cascade made of electrons, positrons and photons, that is called electromagnetic air shower.

Two physical processes are essential to describe the development of extensive air showers initiated by photons in the atmosphere: pair production and bremsstrahlung. Photons undergo pair production in the vicinity of the nuclei of atmospheric molecules, when the energy is above the threshold energy (1.052 MeV). The bremsstrahlung effect occurs when an electron or positron, due to the Coulomb field of the atoms, is slowed down and deflected from the initial direction and as consequence radiation is emitted. This radiation is itself extremely energetic, with many of the photons undergoing further pair production that can again radiate energy and feed the cascade multiplication, that will go on until the particle energy reaches the value $E = E_c$, the critical energy, when ionization losses become dominant and no further radiation or pair production processes are possible. The critical energy in the atmosphere is around 100 MeV. (61)

The emission of coherent electromagnetic radiation, the Cherenkov light, is schemat-

ically described in figure 12. It takes place whenever a charged particles propagates with velocity higher than the speed of light in a medium. Cherenkov light is emitted along the surface of a cone, whose axis is coincident with the charged particle path. An important parameter to characterize the Cherenkov effect is the angle θ_C , defined as:

$$\cos\theta_C = \frac{1}{\beta n}.\tag{4.1}$$

where $\beta = v/c$ and n is the refraction index of the medium. (61)



Figure 12 – Schematic description of the Cherenkov emission.

Source: GRIEDER (61)

The IACTs work by imaging the very short flash of Cherenkov radiation generated by the extensive air shower initiated in the atmosphere at an altitude of 10–20 km. Figure 13 presents an overview of the detection principle. The total area on the ground illuminated by this flash, also called the "light pool", is of the order of 100 m².

The IACTs have an angular resolution of the order of 0.1 degrees together with background rejection power better than 99%. The drawback of IACTs is the low duty cycle, of the order of 10 %, together with the limited field of view, of the order of 5 degrees. (61) IACTs consist of a set of mirrors reflecting the Cherenkov light into a single focus, where a

camera is placed. The camera has two main components: (i) an array of photo-multipliers, which converts the light signal into electrical signal and transmit it to (ii) trigger systems to manage the data and convert it to data acquisition systems. Since the Cherenkov pulse has a short duration, approximately a few tens of nanoseconds, the trigger needs to operate with a frequency higher than the GHz. In order to measure the light pulse, one telescope is enough, however combining measurements of more telescopes a better angular resolution and background suppression can be achieved.



Figure 13 – Detection principle of IACTs. A gamma ray interacts with the Earth's atmosphere, creates a cascade of new particles, in which some of them will emit Cherenkov radiation forming a light pool that will be detected by the ground telescopes.

Source: THE CTA CONSORTIUM (8)

The image of the Cherenkov light flash on the camera has an elongated elliptic shape, whose parameters, also known as Hillas parameters, contain the necessary information to reconstruct the air shower. Figure 14 presents the Hillas parameters, being l and w the length and width of the shower respectively, D is the distance between the ellipse center and the position of the source pointed by the camera, the θ represents the angular distance of the reconstructed source and the real source on the camera and α is the angle between the ellipse's axis and the line linking the ellipse's center to the real source position. The particle identification, energy and arrival direction are obtained by comparing the Hillas parameters from the data with the same parameters given by the simulations. (62)



Figure 14 – Hillas parameters derived from the imaging of the Cherenkov pulse.

Source: VIANA (62)

Besides gamma rays, others types of particles can also reach the Earth and produce air showers. When the initial particle is a proton or nucleus, as the majority of the cosmic rays, the cascade of new particles is mainly hadronic. An important difference can be observed: in the hadronic showers we can find many particles, including muons, pions and kaons, while in electromagnetic showers we mainly have pairs e^{\pm} and photons. Such difference will lead to a different topology of the air showers, as presented in figure 15. The identification of the gamma ray signal and the rejection of cosmic ray background is mainly based on this characteristics.

4.2 Current atmospheric Cherenkov experiments

The present generation of IACTs is composed by the High Energy Stereoscopy System (H.E.S.S.), the Major Atmospheric Gamma-ray Imaging Cherenkov (MAGIC) and the Very Energetic Radiation Imaging Telescope Array System (VERITAS) experiments. A short description of each of them is given in the following.

The H.E.S.S. observatory (63) started its operations in 2002, is located in Namibia at 1800 meters above the sea level, and it is currently the only gamma-ray observatory located in the southern hemisphere. Given its location, H.E.S.S. can observe the Galactic center. The array was composed initially by 4 telescopes, with mirror area of 107 m², with focal length of 15 m. However, in its Phase II, the array was updated by the addition of a bigger telescope, with a mirror area of $\approx 600 \text{ m}^2$ and a focal length of 36 m. The H.E.S.S. energy range cover from 30 GeV to few TeV.



Figure 15 – Comparison between the topology of electromagnetic showers, left, and hadronic showers, right.

Source: VIANA (62)

The MAGIC observatory (64) is located $\approx 2,400$ m above the sea level in La Palma, Canary Islands. The observatory is composed by two large telescopes, with mirror area of ≈ 240 m², with low energy threshold of ≈ 50 GeV. Since it is located in the northern hemisphere, MAGIC targets are the extra-galactic sources, and due to the unique design of "lightweight" the telescopes have fast slewing system allowing to pursuit alerts of transient sources.

The VERITAS experiment (65) started its operations in 2007, and it is composed by four telescopes each of them covering 106 m² of the telescope mirror. Located in the United States (Arizona), the array is at 1268 meters above the sea leveal and covers the energy range from 50 GeV to 50 TeV.

These three telescopes compose the current generation of IACT and they suit as basis for the next generation of gamma-ray observatories.

4.3 The CTA Observatory

The CTA Observatory (8) will be operated by an international collaboration of more than one thousand scientists spread over 32 countries. (66) It is currently under construction and the first scientific data are expected to be taken in 2020. The main goals are: understand the origin of relativistic cosmic particles, probe extreme environment and explore the frontier of physics, such as understanding the nature of dark matter. The main characteristics of the future CTA observatory can be summarized as follows:

- Extended field of view: It will be the first ground-based observatory capable to observe the entire sky. To achieve this goal, the telescopes will be located in both hemispheres. The Northern site is located on the island of La Palma in the Canary Islands (Spain) and it will be mainly dedicated to extra-galactic objects, while the Southern site is located near Paranal (Chile), and it will focus on Galactic sources.
- Large energy coverage: It will explore wide energetic window (from 20 GeV to at least 300 TeV). For this purpose 3 different telescopes will be used: Large Size Telescopes (LST) with 23 meters diameter to explore lowest energies (above 100 GeV), Medium Size Telescopes (MST) with 12 meters diameter for the intermediate energy range and the Small Size Telescope (SST) with ≈ 4 meters diameter, for the highest energies (up to hundreds of TeV).
- Large detection area: The observatory will cover 4 km² in the South and 0.6 km² in the North. The proposed layout for both hemispheres is presented in figure 16.
- Improved sensitivity: Combining the previous improvements, CTA will have enhanced sensitivity with respect to current generation detectors. Figure 17 presents the CTA sensitivity curve for both hemispheres compared to the present gamma-ray observatories.
- Simultaneous observations: Due to the large number of telescopes composing the array, CTA will be able to point at different targets simultaneously.
- Open observatory: the scientific community will have the access to the data collected by the observatory. This is a unique feature for the ground based telescopes.



Figure 16 – Layout of the two CTA sites, in the Northern (left) and Southern hemisphere (right).

Source: THE CTA WEBSITE (66)



Figure 17 – Differential sensitivity for CTA North and South compared with present gamma-ray observatories.

Source: THE CTA WEBSITE (66)

4.4 Prospects for dark matter detection

As discussed in chapter 3, indirect searches for DM can be carried out with gamma-ray detectors. Given the expected powerful performance, in particular in terms of the extended energy range, CTA will reach unprecedented values of cross-section for self-annihilating DM for a wide range of DM masses, including those inaccessible to H.E.S.S..

The search for DM is one of the study themes of the CTA Consortium, and a research plan has been developed and published in the document that summarizes the Science with CTA (8), presented in Table 5.

The Galactic halo is the main CTA target in the context of DM searches, however, due to the large uncertainties regarding its background, the dwarf galaxies are also proposed as an additional primary target for observation. The observation strategy for dSph is not yet finalized, since the search proposal will be guided according to the results obtained in the initial years.

The sensitivity curve for the Galactic halo, Sculptor and the Large Magellanic Cloud (LMC) is presented in figure 18. The results from CTA are compared to present

Year	1	2	3	4	5	6	7	8	9	10
Galactic halo	$175 \mathrm{h}$	$175 \mathrm{h}$	$175 \mathrm{h}$							
Best dSph	100 h	100 h	100 h							
					in case	e of dete	ction a	t GC, la	rge σv	
Best $dSph$				150h	$150 \ h$	$150 \mathrm{h}$	150h	$150 \mathrm{h}$	$150 \ h$	150h
Galactic halo				100h	$100~{\rm h}$	$100~{\rm h}$	100h	$100~{\rm h}$	$100~{\rm h}$	100h
	in case of detection at GC, small σv									
Galactic halo				100h	$100 \ h$	$100~{\rm h}$	100h	$100 \ h$	$100~{\rm h}$	100h
					in c	case of n	o detec	tion at	GC	
Best Target				100h	100 h	100 h	100h	100 h	100 h	100h

Table 5 – Observation strategy for Dark Matter with CTA.

Source: THE CTA WEBSITE (66)

generation experiments (H.E.S.S. and Fermi). This figure also shows that the Galactic Center observed with CTA will be able to reach the thermal cross-section, with almost improvement of one order of magnitude with respect to H.E.S.S. experiment. However, it should be noticed that the large uncertainty on both the DM content and the astrophysical foreground for this source can change dramatically the detection prospects in the forthcoming years.



Figure 18 – Sensitivity curve for CTA Galactic halo, LMC and Sculptor compared to the H.E.S.S. Galactic halo and Fermi dSph sensitivities.

Source: THE CTA CONSORTIUM (8)

4.5 CTOOLs

In order to analyze the data collected by CTA and to provide a flexible analysis pipeline, the CTOOLs software package (67) was developed, with its first version release in end of 2015. Despite its creation was motivated to attend the CTA needs, the idea is to extend the software to be suitable for all IACT telescopes data. In order to minimize software maintenance cost and to open the use to a large variety of operating systems, the CTOOLs package is entirely dependent on the external GammaLib library. Both CTOOLs package and GammaLib library are open source codes available at (68).

All the events measured by IACT telescopes are characterized by three fundamental properties: trigger time t', instrument direction p' and measured energy E'. However, due to instrument limitations, the t', p' and E' are not the intrinsic characteristics of the photon originated in the source: the true time t, the true photon direction p and the true photon energy E. In order to correct these differences, the Instrument Response Function (IRF) is needed. The IRF, R(p', E', t'|p, E, t) is a set of air shower simulations used to convert the photon true informations to the measured information, in units of $cm^2sr^{-1}s^{-1}MeV^{-1}$ and can be written as follows:

$$R(p', E', t'|p, E, t) = A_{eff}(p, E, t) \times PSF(p'|p, E, t) \times E_{disp}(E'|p, E, t).$$
(4.2)

where the A_{eff} is the effective area of the observatory, the PSF is the instrument Point Spread Function, which relates the spatial deviation between the photon true direction and the measured direction and lastly, the E_{disp} is the instrument energy dispersion, taking into account the energy resolution of the instrument. For each particular analysis, different parameters of the IRF are required:

- the location of the used array (North or South);
- the software used to reconstruct the air shower;
- the observation angle of the telescope from the zenith;
- the location of the source;
- the number of telescopes used for observation;
- the type of telescope (SST, MST or LST);
- the observation time.

The IRF is available within the calibration database (caldb), whose last released calibration is named 'prod3b'. Thus, choosing a caldb and IRF, any CTOOLs function



can be used. A sketch of all the functions available in CTOOLs version 1.0 is presented in figure 19.

Figure 19 – CTOOLs functions.

Source: KNÖDLSEDER (67)

Within the DM context, the CTOOLs can be applied for the computation of the upper limit on the gamma-ray flux from DM annihilation. Such value indicates the boundary of the gamma-ray flux detectable by CTA. With this purpose, three CTOOLs functions are used: *ctobssim*, *ctbin* and *ctulimit*. The description of the functions as well as the details about the DM signal simulation are presented in the following.

4.5.1 Simulation of the detector response with *ctobssim*

The *ctobssim* function simulates a CTA observation according to the gamma-ray model provided. The inputs to produce the mock data are separated in two groups: the characteristics of the target (spatial coordinates and gamma-ray flux spectrum expected

from the source) and the characteristics of the observation (observation time, energy interval, calibration data base and IRF). Two gamma-ray flux models are considered as input for ctobssim: the signal and the background. In this work, the signal comes from DM and it is several orders of magnitude weaker than the background, and its strength depends on the particular value of the $\langle \sigma v \rangle$ chosen. The background is given by the cosmic rays misinterpreted as photons that remained after the data cuts treatment. It is enclosed within the IRF and obtained from several simulations.

The gamma-ray flux from DM annihilation, assuming it occurs into a single channel, is given by:

$$\frac{d\Phi}{dE} = \frac{\langle \sigma v \rangle}{8\pi m_{DM}^2} \frac{dN}{dE} \times J.$$
(4.3)

The output of *ctobssim* is a event list containing information of the detection time, sky coordinates and energy for each detected photon.

4.5.2 Binning the photon counts with *ctbin*

From the event list provided by *ctobssim* the tool *ctbin* creates a three dimensional counts cube in order to make the information more manageable. The counts cube is composed by 2 axis for space: the Right Ascension and Declination and 1 axis for the energy.

4.5.3 Estimation of the flux upper limit with *ctulimit*

The count cube obtained with *ctbin*, is used as input for the *ctulimit* function. The *ctulimit* provides as output a limit on the detectable gamma-ray flux for the adopted model, in this case for DM. In order to compute the flux upper limit, the background gamma-ray flux derived from the residual CR is compared with the gamma-ray flux from DM model (equation 4.3) where a free normalization parameter μ is added, namely:

$$\frac{d\Phi_{U.L.}}{dE} = \mu \frac{\langle \sigma v \rangle}{8\pi m_{DM}^2} \frac{dN}{dE} \times J.$$
(4.4)

Applying the fitting algorithm, based on the maximum likelihood ratio method (with 95% of confidence level), the best value for the μ parameter will be produced.

5 RESULTS AND DISCUSSION

In light of the main features of dSphs, namely the high mass to luminosity ratio (M_{\odot}/L_{\odot}) and the low astrophysical background, the expected gamma-ray flux from DM annihilation (obtained in equation 3.1) can be compared with the instrumental sensitivity curve. In the DM parameter space, $\langle \sigma v \rangle$ versus m_{DM} , such comparison can be translated into the sensitivity curve, to evaluate quantitatively the potential for DM detection in a source.

This chapter is structured as follows: the section 5.1 describes the DM model parameters, and section 5.2 presents a first estimation for the sensitivity curve, while a more detailed calculation obtained with CTOOLs is presented in section 5.3. Enclosed to the last section is presented the estimation of the sensitivity curve considering different parameter values (annihilation channels and J-factor) for the same source, Triangulum II, and the sensitivity curve for Reticulum II and Carina III.

5.1 Understanding the parameters of the model

The gamma-ray flux from DM annihilation is given by the following equation, as discussed in section 3.2.

$$\frac{d\Phi}{dE} = \frac{\langle \sigma v \rangle}{8\pi m_{DM}^2} \sum_f B_f \frac{dN_f}{dE} \times J.$$
(5.1)

A gamma-ray flux will be detectable if it lies above the instrument sensitivity. Figure 20 shows the sensitivity of the CTA Northern array as a function of energy, for 50 hours observations, compared with the expected gamma-ray flux from DM annihilation, using Triangulum II as a target. The gamma-ray flux is obtained from DM annihilation into $\tau^+\tau^-$, assuming the thermal value for the velocity-averaged cross-section $\langle \sigma v \rangle = 3 \times 10^{-26} cm^3/s$, and DM particle mass $m_{DM} = 1$ TeV.

Figure 21 shows the sensitivity of the CTA Northern array as a function of energy, compared to the gamma ray flux from DM annihilation obtained considering different parameters configurations. In particular, the top left panel shows the gamma ray flux obtained by changing the astrophysical target, including the classical dSph Sculptor, the top right shows the gamma ray flux obtained by changing the DM particle mass from 1 TeV to 0.1 TeV, the bottom left panel shows the result obtained by changing the annihilation channel from $\tau^+\tau^-$ to $b\bar{b}$ and the bottom right panel shows the gamma ray flux obtained by changing the velocity averaged cross-section from 3×10^{-26} to 10^{-31} cm³/s. Thus, it is noticed the different sets of DM parameter values can produce a detectable gamma-ray



Figure 20 – CTA sensitivity curve in the gamma-ray flux as a function of energy (for an observation time of 50 hours), compared to the gamma-ray flux produced due to the DM annihilation process in the $\tau^+\tau^-$ channel, for the DM particle mass of $m_{DM} = 10^3$ GeV and the thermal freeze-out cross-section.

Source: By the author

signal and the definition of such values is essential to build the sensitivity curve.

5.2 Understanding the principle of sensitivity curve

To provide a first estimation of the sensitivity curve, we compare directly the DM annihilation flux expected from a given source with the sensitivity curve of the instrument. We define as "detectable" a signal that provides at least 10 photon counts in the instrument, in a given time interval and in a given energy range. In order to count the detectable number of photons in a given energy range, it is considered the differential flux $d\Phi_{det}/dE$ (photon number per area per second per energy) that can be observed by the detector. Such a flux is described as:

$$\frac{d\Phi_{det}}{dE} = \frac{d\Phi_{src}}{dE} - \frac{d\Phi_{sen}}{dE}.$$
(5.2)

Where $d\Phi_{src}/dE$ is the flux expected from the source (Equation 5.1) and $d\Phi_{sen}/dE$ is the instrument sensitivity, the lowest flux measurable by the instrument. The total number of detected photons is given by:

$$N = \Delta t \int A_{eff}(E) \frac{d\Phi_{det}}{dE}(E) dE.$$
(5.3)



(c) Effect of different annihilation channels.



Figure 21 – CTA sensitivity for different observation hours as a function of energy, for the Northern array in comparison of gamma-ray flux produced by set of DM parameter labeled in each plot. The figure in the top left presents a comparison between the generated gamma-ray flux from different source; top right for different DM mass; down left considering different annihilation channel and down right for different DM cross-section.



Being Δt the time of observation and $A_{eff}(E)$ the effective area of the detector. The effective area presented in figure 22, extracted from (66).

Since $d\Phi_{src}/dE$ depends on m_{DM} and $\langle \sigma v \rangle$, as presented in equation 3.5, we seek for the set of parameter values which correspond to a detectable number of gamma-ray photons above the threshold. The outcome of this analysis is better illustrated by the detectability map shown in figure 23, where the velocity-averaged cross section $\langle \sigma v \rangle$ is shown as a function of the DM mass m_{DM} , for Sculptor (left) and Triangulum II (right). The green area indicates the allowed values in the parameter space, namely the sets of parameters values that can be detected above our threshold, while the red region falls



Figure 22 – Effective collection area for gamma-rays as a function of the photon energy.

Source: THE CTA WEBSITE (66)

below the CTA sensitivity. This plot is obtained considering 50 hours of observation, for the annihilation channel $\tau^+\tau^-$, for the Sculptor J-factor presented in Table 2 for $\alpha_{0.5}$ and Triangulum II J-factor value calculted by Saturni, presented in Table 4.



(a) Sculptor detectability map. The black dashed (b) Triangulum II detectability map. The black line presents the value of the thermal freezeout cross-section.

dashed line presents the value of the thermal freeze-out cross-section.

Figure 23 – Detectability map for (left) Sculptor and (right) for Triangulum II. The combination of mass and cross-section in green represents the set of DM parameters probed by CTA. Conversely, the red region represents the parameters which produces a gamma-ray flux too faint be detectable by the instruments. The dashed black line represents the thermal cross-section value.

Source: By the author

Therefore, the bigger is the green region, the wider is the accessible region in the parameter space. Notably, the Triangulum II detectability map shows that the allowed (green) region is bigger than the one of Sculptor, revealing its higher potential for DM searches. Moreover, the comparison of the boundary between the green and red regions shows that Triangulum II can probe values close to the ones which match with cosmological observations, illustrating even more the interesting potential of this source.

5.3 Detailed calculation of the sensitivity curve

For a detailed calculation of the sensitivity curve, it is considered the specific instrumental limitation for a given pointing direction, enclosed in the IRF and the method described in section 4.5, applying the CTOOLs. The upper limit (at 95% C.L.) on the gamma-ray flux from DM annihilation is obtained for the DM particle mass m_{DM} range between 70 and 10⁵ GeV, using the following CTOOLs functions: *ctobssim*, *ctbin* and *ctulimit*.

An upper limit on $\langle \sigma v \rangle$ is obtained, for each DM mass value, by inverting the equation 5.1 as follows:

$$\langle \sigma v \rangle_{U.L.} = \frac{8\pi m_{DM}^2}{J} \frac{d\Phi_{U.L.}/dE}{dN/dE}.$$
(5.4)

This procedure is repeated 20 times per each value of the simulated DM particle mass m_{DM} . Thus, the sensitivity curve shows the values of $\langle \sigma v \rangle_{U.L.}$ as a function of the DM mass m_{DM} . For simplicity, $\langle \sigma v \rangle_{U.L.}$ will be labeled as $\langle \sigma v \rangle$ in the following sensitivity curves.

5.3.1 Validating the method

In order to validate our method, we first estimate the sensitivity for Sculptor, a classical dSph widely studied in the literature and within the Dark Matter group of CTA. For this source, we compute the sensitivity curve for the DM annihilation into $\tau^+\tau^-$ for 500 hours. Figure 24 shows the sensitivity curve for Sculptor. The black line shows the result of this work, while the red line shows the official result of the CTA consortium. The good agreement between the two results indicates the robustness of the method. Confident about the method, we apply the same strategy to the study of ultra-faint dSphs. The details about the parameters used to obtain this result are presented in Table 6.

5.3.2 Estimation of observation time

The observation time of 500 hours, used to estimate the sensitivity for Sculptor (figure 24), is much higher than the actual observation time currently scheduled for the observation of dSphs with CTA. This value was only used for comparison, to validate our method. To perform a realistic assessment of the sensitivity to the search for DM with CTA for Triangulum II, we estimate the source visibility using an online tool provided by the HESS collaboration (69).

Annihilation channel	$\tau^+\tau^-$
J-factor	$3.5 \times 10^{18} \ { m GeV^2/cm^5}$
$<\sigma v>$	$10^{-31} \text{ cm}^3/\text{s}$
CTOOLs version	1.4.2
Observation time (hours)	500
Calibration database	cald3b
IRF	$South_z20_average_50h$
Number of simulations (per each mass)	20 times
Number of DM mass values	11

Table 6 – Parameters values used for the Sculptor sensitivity curve presented in figure 24.

Source: By the author



Figure 24 – Sensitivity curve for Sculptor in the DM parameter space. The vertical axis presents the velocity averaged cross-section and the horizontal axis shows the DM particle mass. It is obtained considering 500 hours of observation for the $\tau^+\tau^-$ annihilation channel. Our result is shown in the black curve and it is compared to the result obtained by G. Rodriguez, member of the CTA Collaboration.

Source: By the author

We compute the visibility of Triangulum II from the Canary Islands, where the CTA North will be located, for the year 2019, and the results are shown in figure 25. The white areas indicate the presence of the Sun in the sky, the gray regions correspond to civil, naval, and astronomical twilight, respectively and the yellow region indicates when the moon is above the horizon. Lastly, the times when the object is above given altitudes angle are indicated by the different degrees of the purple color. The visibility of Triangulum II in minutes per month, for different angles above the horizon, is presented in Table 7.



Figure 25 – Visibility of Triangulum II from the CTA North site, located in La Palma.

Source: THE H.E.S.S. COLLABORATION (69)

Considering the visibility of Triangulum II, combined with the scheduled observation time for dSphs by the CTA Collaboration, it is reasonable and conservative to consider for the analysis 50 hours of observation.

5.3.3 Sensitivity curve for Triangulum II for $\tau^+\tau^-$ annihilation channel

The sensitivity curve for Triangulum II was calculated. Figure 26 shows the results obtained considering the annihilation of DM particles into $\tau^+\tau^-$: the blue curve shows the sensitivity for Triangulum II, where the blue shaded region includes the uncertainties on the *J*-factor. For comparison, the green curve represents the sensitivity curve for Sculptor. The dashed black line is the value of the thermal cross-section, for reference. Table 10 shows all the parameters used in order to achieve this result.

The first conclusion is that the sensitivity curve of Triangulum II is about two orders of magnitude better the one of Sculptor, as it was already pointed out in (section 5.2), meaning that Triangulum II presents a more promising chance of DM detection than Sculptor. The allowed region of the parameter space that is found for Triangulum II is not only wider than that of Sculptor, but it includes the thermal values, presented as dashed line in figure 26. It is worth stressing that Triangulum II is probably the only dSph that can reach this value.

Month	above $0^{\circ}(\min)$	above 30° (min)	above $45^{\circ}(\min)$	above 70° (min)
1/2019:	7887	4872	3501	1263
2/2019:	4581	2031	897	0
3/2019:	3045	459	0	0
4/2019:	594	0	0	0
5/2019:	0	0	0	0
6/2019:	0	0	0	0
7/2019:	1545	522	261	0
8/2019:	6531	3825	2601	606
9/2019:	7728	5835	4692	2508
10/2019:	9171	8535	6918	2958
11/2019:	9339	7944	6537	2796
12/2019:	9162	6225	4914	2568
Overall total:	59583	40248	30321	12699

Table 7 – Visibility of Triangulum II in minutes per month, for different angles above the
horizon, for year of 2019.

Source: H.E.S.S. COLLABORATION (69)

Table 8 – Parameters values used for the sensitivity curves presented in figure 26.

Annihilation channel	$ au^+ au^-$
<i>J</i> -factor	$5^{+15}_{-4} \times 10^{20} \text{ GeV}^2/\text{cm}^5$
$<\sigma v>$	$10^{-31} \text{ cm}^3/\text{s}$
CTOOLs version	1.4.2
Observation time (hours)	50
Calibration database	cald3b
IRF version	$North_z20_average_50h$
Number of simulations (per each mass value)	20 times
Number of DM mass values	11

Source: By the author

5.3.4 Sensitivity curve for Triangulum II for different annihilation channels

The sensitivity curve for the same target was also computed for other annihilation channels, namely: $b\bar{b}$ and W^+W^{-*} with results presented in figure 27. Different annihilation channels provide different gamma-ray flux shapes, due to the channel inherent features. All channels present very good discovery perspectives, however it is concluded the $\tau^+\tau^$ can cover a bigger region of the parameter space, including the thermal values.

^{*} For W^+W^- annihilation channel, the quantity of photons produced is negligible when considering DM mass of 70 GeV, therefore the plot presents results from DM particles mass starting from $m_{DM} = 100$ GeV.



Figure 26 – Triangulum II and Sculptor sensitivity curve for the $\tau^+\tau^-$ annihilation channel for 50 hours of observation.

Source: By the author

5.3.5 Sensitivity curve for Triangulum II for different *J*-factor values

In order to understand the influence of different J-factor values on the Triangulum II sensitivity curve, we performed the same analysis using the J-factor estimated by the Fermi-LAT team (50), whose value is $1.25 \times 10^{19} \text{ GeV}^2/\text{cm}^5$. The blue solid line in figure 28 presents the Triangulum II sensitivity curve obtained with our benchmark parameter values, shown in Table 8, and the shaded area indicates the effect of the J-factor uncertainties. The dot-dashed line shows the sensitivity curve assuming the J-factor from the Fermi-LAT team. The use of the latter, about one order of magnitude smaller than our benchmark value, provides a worse sensitivity.

We are aware of the fact that our result depends strongly on the *J*-factor value used to compute the flux upper limit. The *J*-factor is estimated based on the stellar kinematics data available for the source and, since for Triangulum II, as for many other ultra-faint dSphs, the sample is very limited the assumption on the dynamic equilibrium is not yet fully confirmed. By presenting the source with the highest potential for discovery, this work also aims at motivating more measurements in order to confirm its in dynamical equilibrium.



Figure 27 – Comparison of sensitivity curve for Triangulum II and Sculptor dwarf galaxies for different annihilation channels: left for $b\bar{b}$, right for W^+W^- .

Source: By the author



Figure 28 – Triangulum II sensitivity curve for different values of J-factor is presented, for the $\tau^+\tau^-$ annihilation channel and for 50 hours of observation.

Source: By the author

5.3.6 Sensitivity curve for different sources

Additionally, the method described in the previous sections was applied to obtain the sensitivity curve for Reticulum II and Carina III using the CTOOLs analysis pipeline, using the software version 1.4.2 and the Calibration database *cald3b* and the results are shown in figure 29. The sensitivity curves are obtained for different sources and for different annihilation channels. The green curve in shows the sensitivity curve for Sculptor, the yellow for Reticulum II, the purple for Carina III and the last is the blue curve for Triangulum II. The results for three annihilation channels are presented: $b\bar{b}$ (top left), W^+W^- (top right) and $\tau^+\tau^-$ (bottom). The equaorial coordinates of the sources as well as the value of the *J*-factor used in this analysis are shown in Table 9, while the parameters used for the simulations are indicated in Table 10.



Figure 29 – Comparison of sensitivity curve for Sculptor, Reticulum II, Carina III and Triangulum II for different annihilation channels: top left for $b\bar{b}$, top right for W^+W^- and centered down for $\tau^+\tau^-$.

Source: By the author

In conclusion, within the recently discovered ultra faint dSphs studied in this work, Triangulum II is the source which provides the best chance for DM detection. We compared our result with the current limits on DM searches obtained by several indirect DM search experiments, as it shown in figure 30. All the curves in this plot, adapted

Source Name	R.A.[deg]	Dec [deg]	$\log_{10} J \; [\mathrm{GeV}^2/\mathrm{cm}^5]$
Sculptor	15.3	-33.71	18.54
Triangulum-II	33.32	36.18	20.7
Reticulum-II	53.92	-54.05	18.8
Carina-III	114.63	-57.90	19.9

Table 9 – Name, equatorial coordinates and J-factor for the sources studied in this work.

Source: By the author

Table 10 – Parameters used for the analysis showed in figure 29.

Source Name	IRF version	Observation time [h]
Sculptor	$South_z20_average_50h$	50
Triangulum-II	$North_z20_average_50h$	50
Reticulum-II	$South_z20_average_50h$	50
Carina-III	$South_z20_average_50h$	50

Source: By the author

from subsection 2.3.1, are obtained for DM annihilation into $b\bar{b}$. However, it is worth stressing that our best result is obtained for the $\tau^+\tau^-$ channel. Figure 30 shows that our result, obtained simulating an observation time of 50 hours, is better than the H.E.S.S. sensitivity, obtained with a larger data set. Moreover, our result covers a broader energy range, between 70 GeV and 100 TeV.

Triangulum II appears to be a very promising target, providing a wide range of testable DM parameters values with CTA. Therefore, with the unprecedented sensibility of the CTA observatory, combined with the high potential of Triangulum II, the WIMP paradigm have a real chance to be tested.



Figure 30 – Most important constraints on DM model from the current experiments together with the Triangulum II sensitivity curve.

Source: Adapted from CONRAD (7)
6 CONCLUSIONS

The present research project was carried out in the frame of the indirect searches for DM with gamma rays, a well-suited method to detect WIMPs, with masses in the GeV to multi-TeV range and producing gamma rays of similar energies. If DM consists entirely of WIMPs produced thermally in the early universe, this implies that the velocity averaged annihilation cross section $\langle \sigma v \rangle$ is of the order of $10^{-26} cm^3 s^{-1}$. Indirect searches in gamma rays carried out by the Fermi-LAT have recently reached the sensitivity required to test this canonical annihilation cross section for low WIMP masses. However, the Fermi-LAT sensitivity is weaker for higher-mass WIMPs. In this context, very promising results have been obtained by the current generation IACTs, namely H.E.S.S., MAGIC and VERITAS. The upcoming CTA will improve significantly the current sensitivity to annihilation signals for DM masses above $\approx 100 \ GeV$, probing a parameter space that is complementary to that of the Fermi-LAT and extending the energy range and performance of current generation IACTs.

This study aimed at evaluating the sensitivity of the upcoming CTA to DM from the ultra-faint dSphs of the Milky Way. These objects are particularly promising targets for the indirect search for DM in gamma rays, and currently provide the best constraints on the properties of DM particles. Limits on annihilation cross-sections begin to probe regions favored by DM models, but they crucially depend on the information on the DM content of the sources. The dSphs are inferred to be highly dominated by DM, with large mass to light ratio of order of $\approx 10^3 \text{ M}_{\odot}/\text{L}_{\odot}$. Moreover, they present very low gamma-ray astrophysical background.

By comparing the CTA lowest detectable gamma-ray flux and the expected gammaray flux from DM annihilation for a given dSph, we obtained limits on the DM parameter space ($< \sigma v >$ and m_{DM}), producing a detectability map, which indicates the DM parameters values that could produce a signal detectable by the instrument. The boundary between the allowed and the forbidden regions of this detectability map provides a simplified estimation of the sensitivity curve between 70 GeV and 100 TeV.

A more refined result is obtained using one of the official analysis tools of the CTA consortium, called CTOOLs. By running a simulation of several observations considering only instrumental background and fitting the DM model, a limit to the detectable gamma-ray flux by CTA was obtained. The analysis was performed considering 11 DM mass values, between 70 and 10^5 GeV, and for each value of the DM mass the limit on the averaged velocity cross-section was calculated. In this way, the sensitivity curve in the parameter space $\langle \sigma v \rangle$ and m_{DM} was derived for 3 ultra-faint recently discovery dSphs, namely Triangulum II, Reticulum II and Carina III, assuming an observation time of 50h, for

the following annihilation channels: W^+W^- , $b\bar{b}$ and $\tau^+\tau^-$. The sensitivity curve for the classical dSph Sculptor was also computed for comparison. This work constitutes the first attempt to estimate the sensitivity of CTA to DM from these recently discovered, whose DM content is extremely promising, though not yet fully understood.

We found that, within the sources investigated, Triangulum II is the best target for DM searches, and the annihilation channel $\tau^+\tau^-$ is the most promising since it can probe the thermal values. This result is extremely attractive since Triangulum II is one of few current dSphs to reach this sensitivity value. This source is located at 37 kpc, and it was discovered in 2015 using the Pan-STARRS telescope. Its 14-member kinematic sample was obtained only two years ago, allowing to estimate its stellar kinematics and to infer its DM content. Jeans analyses conducted by several authors suggest an extremely strong *J*-factor for this object, greater than $10^{20} \text{ GeV}^2/\text{cm}^5$. For our work, we have used the value of $Log_{10}J = 20.7 \text{ GeV}^2/\text{cm}^5$ obtained by F. G. Saturni using a Jeans analysis, who is a collaborator of our working group within the CTA consortium. If this dSph is confirmed in dynamical equilibrium, it could be the most promising target for indirect DM searches.

Even though less optimistic than for Triangulum II, the results obtained for Reticulum II and Carina III also appear as very encouraging, since the sensitivity curve for these sources is still lower than that obtained for Sculptor. Highlighting the prominent potential of such sources, this work also aimed at motivating future observations and studies of the ultra-faint dSphs, in order to turn more robust the result.

To conclude, it is important to discuss the future perspectives of this work. The most important limitation of this analysis is the knowledge of the *J*-factor, due to the little information on the sources stellar kinematics. In order to understand this point we have repeated the analysis of Triangulum II using the *J*-factor provided by the Fermi-LAT. In this case, our result is about one order of magnitude lower, obtaining a more conservative result. It is worth mentioning that the *J*-factor used by the LAT team is obtained in a different way, not using a Jeans analysis, that is in this moment appears to be as the most accurate method to infer the *J*-factor, and for this reason we chose not to use it as our benchmark value.

The natural extension of this work is the application of described method to the CTA data, that will be available in 2020.

Lastly, the potential for Triangulum II combined with the high sensitivity of the future CTA, showed that this analysis constitutes an important step to solve the puzzle of the sources of DM.

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