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Distribution of Dark Matter in the globular cluster M15

Bachelor thesis

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Abstract

This work of thesis is devoted to the study of Dark Matter (DM) distribution in the globular cluster M15 and will be a basis for a next study of searching for DM signals with the MAGIC (Major Atmospheric Gamma-ray Imaging Cherenkov) telescopes with M15 as a target. Cherenkov telescopes as MAGIC operate in the VHE γ-ray range, meaning they can detect γ-rays at energies higher than 100GeV. The search of DM with such telescopes is performed as an indirect measurement: what can be observed are γ-rays coming from the annihilation or decay of DM particles. The strength of the signal provided by annihilating (or decaying) DM is represented by the astrophysical J-factor. The J-factor depends on the target distance and its DM distribution. This work is divided in two main parts: first I studied the globular cluster M15 and define its DM profile using existing spectroscopic measurements of the relative velocities of stars in the cluster. After collecting the necessary measurements of the radial velocities of stars in M15 from recent literature, I run a Jeans analysis using the program CLUMPY (`https://clumpy.gitlab.io/CLUMPY/`), a code for the study of γ-ray signal from DM structures. After this step, I performed a statistical analysis and calculate the astrophysical J-factor. In this way, I obtained a complete and updated description of the J-factor in M15 which can be used to search for DM annihilation or decay in M15 with MAGIC data.

Keywords: Dark Matter, globular clusters, M15, IACTs, VHE gamma-rays, MAGIC telescopes

Introduction

1 Dark Matter

In the standard model of particles, gravity is the weakest of the four interaction forces and it is characterised by an infinite range of action. On a microscopic scale, it is irrelevant, but on a cosmological scale, gravity is the dominant force. It drives planets, stars and even galaxies in motion. It is responsible for keeping the planets in orbit around the Sun. It attracts different parts of the Sun's material together, which makes nuclear reactions possible. Gravity acts at the distance, and a good way to describe it would be with a field. Every massive object creates its own gravitational field in all points in space. Force that acts on a second body in some point in space is response to the first body's field at that point [1]. Gravitational fields from objects interact which makes object to attract. Even if it can be described by the simple algebra equation 1 by sir Isaac Newton in 1660s, we still do not have full understanding of it.

$$F = \frac{Gm_1m_2}{r^2} \tag{1}$$

The Newton formulation was sufficiently explanatory until it failed to explain Mercury's orbit in 1859 [2]. Scientists concluded that Mercury is moving in an ellipse around the Sun, and that ellipse precesses around the Sun. But when scientists calculated how fast it precesses and measured it, these two numbers did not match. Such a contradiction was solved with the introduction of Einstein general relativity. Einstein deduced that we can envision gravity's action at a distance as a warp on fabric of space-time. General relativity describes gravitational effects on a large scale with perfect precision, but quantized gravity does not exist yet. Although scientist weren't able to detect gravitational radiation, it has already been named graviton, and by gravitational field nature, it should be a spin-2 particle.

In 1933. Swiss physicist Fritz Zwicky observed abnormally large speeds of galaxy velocities in Coma Cluster of galaxies. There should be a lot of mass for that large speed, which he could not observe, so he deduced that there is some matter that we are not able to see. This was the beginning of Dark Matter (DM) concept. The longest-standing and maybe the most important problem in modern physics. DM accounts for 84.4% of the total matter density in the Universe [3].

1.1 Observational evidence

We could observe the effects of DM on regular matter, but we do not observe it directly. Following, the evidences for the existence of DM are reported:

1.1.1 Galactic evidence

In galaxies, there are from 100 million to trillions of stars. Stars do not collide with each other due to gravity, because they are rotating or moving in random motions which prevents that from happening. These speeds can be computed by measuring their mass and seeing how far away they are from each other. In the same way, it is possible to calculate the speeds for each star by mass distribution in a galaxy.

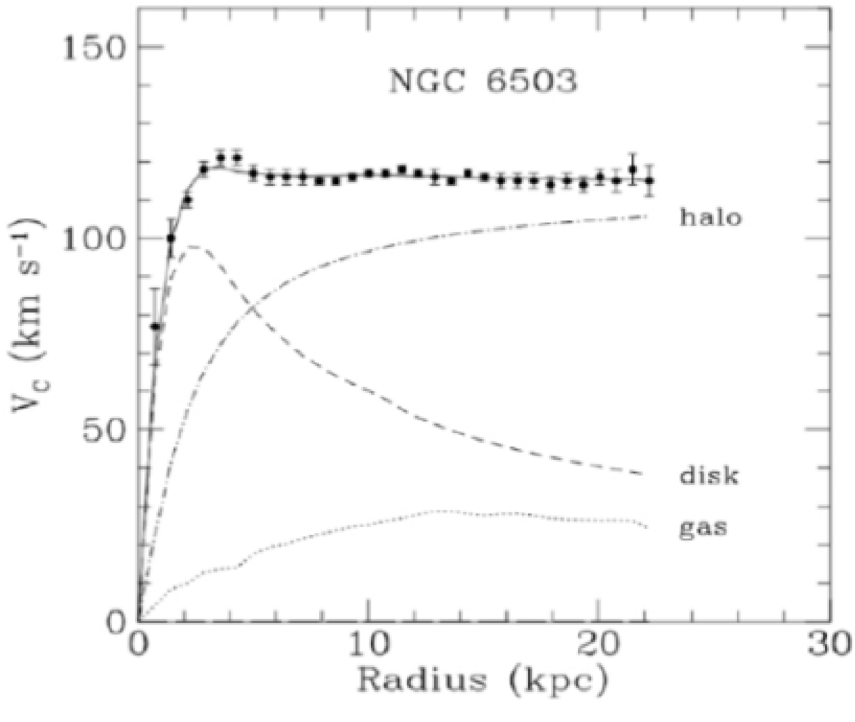

Figure 1: Rotational speeds of stars orbiting around a galaxy as a function of the distance to the center of the galaxy

The matter scientists can observe is insufficient to explain such large velocities of stars at large radii. At large radii, galaxy halo is the dominant source of matter, and it extends much further than luminous matter.

1.1.2 Extra-galactic evidence

Sometimes even Galaxies come together due to force of gravity to form Galaxy Clusters. With radii of few Mpc and total mass $M \sim (10^{14}-10^{15})M_{\odot}$, they are one of the biggest formations in the Universe. By measuring rotational velocities of galaxy members and then by knowing their masses, calculating their velocities, we again see that DM is present. In this case, it is filling space all the way between the Galaxies. Light is always travelling in a straight line through space. Einstein's general relativity explains how under the influence of matter, space-time curves.

So, when the light is travelling near massive object such as Galaxy Cluster, its path is altered in our frame of reference 2. In lights frame of reference, it is still travelling in a straight line. When that light comes to us we get distorted images from space. We call this effect of DM, strong gravitational lensing. Light is bend producing a ring effect, forming arcs, shown in image 3.

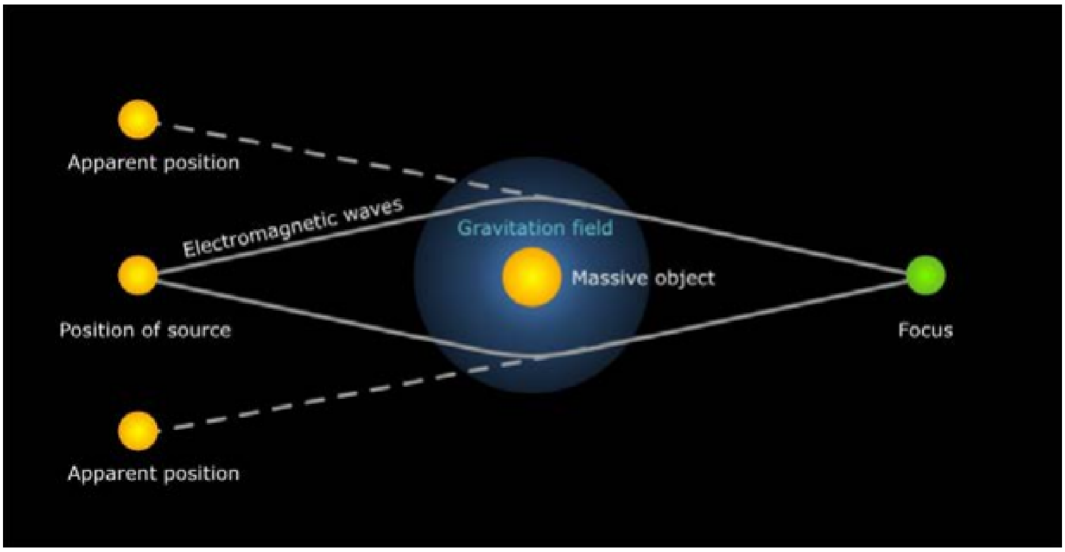

Figure 2: Diagram representing the gravitational lensing produced by a galaxy placed between the observer and a distant object.

Figure 3: The galaxy cluster SDSS as seen by the NASA Hubble Space Telescope. In this "happy face", the two eyes are very bright galaxies, and the smile lines are arcs caused by a strong gravitational lensing.

1.2 DM candidates

A valid candidate for DM must fulfill the following requirements. One of the required properties is for the particle to be neutral, because otherwise it would couple with charged SM particles, which would produce or absorb light, and we would see it. It must be stable on a cosmological scale and interact only gravitationally and possibly weakly, match the DM relic density, be consistent with experimental observations, and do not affect stellar evolution.

Neutrinos would be very good candidates, but the upper bound on neutrino masses is of the order of 1eV or less [4] making it difficult to fit in DM current models. There are some other theories that do not include particles. One of which would be MACHOs (Massive Compact Halo Objects) [5]. In that theory, excess of mass would come from Jupiter-like planets, brown dwarfs and similar hard to detect objects. The problem is that we can estimate the amount of these objects, and it is simply not enough. Calculations were performed in our own Galaxy and concluded that it almost certainly is not the case[6]. Another theory is MOND (Modified Newtonian Dynamics), considers the possibility that nothing is wrong with mass, but with gravity. Maybe gravity on such big scales acts differently than from gravity that we are used to. But that theory is also almost dismissed because we have a lot of evidence that Newtons and Einsteins GR explains gravity correctly. And it also creates more problems than it solves. [7].

Other candidates to be DM are WIMPs (Weakly interacting massive particles). WIMPs possess all the requirements listed above as DM candidates. So far they were never observed. The reason is that they interact only gravitationally and/ or via weak nuclear force. The WIMP miracle is that they produce correct relic density. At the beginning of the universe, matter and antimatter annihilated themselves. The same happened for DM and anti-DM. At that time WIMPs were in thermal equilibrium with primordial plasma. Then, the universe started to expand very rapidly which cooled it down. When its temperature dropped below WIMPs mass m_χ, they decoupled, their production stopped, and their number density started to fall exponentially as $e^{m_\chi T}$. The universe kept expanding which resulted in DM gas becoming so spread out that WIMPs couldn't find each other to annihilate. By that, their number and their density became constant. That constant is called thermal relic density. We know what that constant is 2, and it is surprising that it is the same as what we theorise for DM density to be. That is called the WIMP miracle [8].

$$\Omega_\chi h^2 \simeq \frac{10^{-27} cm^3 s^{-1}}{< \sigma v >} \quad (2)$$

Here Ω_χ is WIMPs density parameter, h is the scaled Hubble constant and $< \sigma v >$ is thermally averaged product of the annihilation cross section and velocity.

The SuSy (SuperSymmetry) provides other WIMP candidates for DM. It states that every SM particle has its own counter particle which has same set of quantum numbers 4. They are not discovered, but they are postulated to have much greater mass than their SM partners. In SuSy theory every fermion has its own supersymmetric force carries, boson, and vice versa, which relates fermions and bosons. SuSy also solves some SM problems, like: hierarchy problem, linked to the vast discrepancy between the aspects of the weak nuclear force and gravity [9], unification of the gauge coupling and also SUSY give DM candidate that is heavy, neutral and stable (Lightest Super-symmetric Particle). Among the particles SuSy produce, the ones that are electrically neutral and have weak interactions are good DM candidates. They would be gravitino and neutralino. Neutralino is better DM candidate. Neutralino is a mix of neutral fermion. So being Majorana fermion, it can self-annihilate into SM particles: fermions, photons, gauge and Higgs bosons.

SM particles/fiels		**SUSY partners**				
		Interaction eigenstates			Mass eigenstates	
quark	q	squark	$\tilde{q}_L, \tilde{q}_R$		squark	$\tilde{q}_1, \tilde{q}_2$
lepton	l	slepton	$\tilde{l}_L, \tilde{l}_R$		slepton	$\tilde{l}_1, \tilde{l}_2$
neutrino	ν	sneutrino	$\tilde{\nu}$		sneutrino	$\tilde{\nu}$
gluon	g	gluino	$\tilde{g}$		gluino	$\tilde{g}$
W-boson	$W^{\pm}$	wino	$\tilde{W}^{\pm}$	}	chargino	$\tilde{\chi}^{\pm}_{1,2}$
Higgs boson	$H^{\pm}$	higgsino	$\tilde{H}^{\pm}_{1,2}$			
B-field	B	bino	$\tilde{B}$	}	neutralino	$\tilde{\chi}^{0}_{1,2,3,4}$
Higs boson	$H^{0}_{1,2,3}$	higgsino	$\tilde{H}^{0}_{1,2}$			
W^3-field	W^3	wino	$\tilde{W}^{3}$			

Figure 4: SM particles and their superpartners in MSSM model

1.2.1 DM searches

There are three main techniques to detect DM: production of DM in particle accelerators, direct detection when DM scatterers from SM particles, and indirect detection of SM particles produced via DM annihilation or decay. Indirect detection is the one that is of our interest, since that method is being used to detect DM from data that I made in my work. We possibly could create WIMPs in large accelerators with big energies. Of course, we would not see WIMPs, but we could conclude their presence indirectly, after they collide. The way that this works is that after collision, momentum and energy must be conserved, and in some cases it is not. So, a possible solution is that DM is created and that's why sometimes do not see conservation. It is expected that Earth is passing through WIMPs flux with order of particles. As WIMP particles pass through Earth, they scatter from SM particles and we aim to measure nuclear recoil. Detector can detect that energy via ionization, heat aka photon production or scintillation.

Indirect detection- If DM particles are stable in cosmological scale, their lifetime is longer then the life of the Universe. They can annihilate/decay, only on really small rate so that DM density in not changed very much. When DM particle annihilate/decay, they produce SM particles that are possible to detect with the current instrumentation. In indirect searches we look stable SM particles that get created like photons, neutrinos, protons, electrons and their corresponding counter particle.

1.2.2 Dark Matter searches with γ rays

In this work of thesis, we study the DM distribution in the globular cluster M15 to be used for indirect searches of DM with VHE γ-rays.

γ-rays from WIMPs annihilation arriving at Earth from a given region of the sky ($d\Omega$) can be factorised as:

$$\frac{d\Phi(E,\Delta\Omega)}{dE} = \frac{d\overline{\Phi}^{PP}}{dE} \cdot J(\Delta\Omega) \tag{3}$$

Here, $d\overline{\Phi}^{PP}/dE$ is called the particle-physics factor, and depends on nature of DM. $J(\Delta\Omega)$ is called the astrophysical factor (JFactor), and depends on the target distance and its DM distribution.

DM density profile around different classes of DM dominated targets is universal by the N-body simulations, but it is only partially supported with experimental data. It can be calculated by Zhao-Hernquist equation:

$$\rho(r) = \frac{\rho_s}{(\frac{r}{r_s})^\gamma[1+(\frac{r}{r_s})^\alpha]^{(\beta-\gamma)/\alpha}}. \tag{4}$$

$\rho(r)$ is DM density in function of the distance r from the DM baricenter. ρ_s and r_s are the characteristic density and scale radius. $\alpha, \beta, and \gamma$ are free parameters. α controls the rate at which the density profile interpolates between its inner and outer values, β tunes logarithmic density gradient at large radii, while γ at small radii [10].

2 DM astrophysical targets

In the indirect search for DM there are multiple astrophysical targets. Such as dwarf spheroidal galaxies, or galaxy clusters (GCs), but for my work, we will focus on GCs. GCs are spherical collections of stars that orbit a galactic core as a satellite. GCs often do not have gas or dust. Stars are old, and GCs generally do not form new stars. They are common structures, with over 150–157 currently known in the Milky Way. They are home to some of the oldest stars in the galaxy, some being 10-13 billion years old. GCs in the Milky Way are really important for scientific research. They give us information about the evolution of stars, properties of binary stars, Galactic structure and dynamics, stellar dynamics, information about galaxy and cosmology formation, etc [11]. GCs are tightly bound via gravity, which gives them high stellar density toward the center and spherical shape. On the edge the have average of 0.4 star per cubic parsec, but at the core it has 100-1000 stars per cubic parsec, with distance of 1 ly between the stars [12].

2.1 M15 globular cluster

Messier 15 or, shorter, M15 is a GC located in the Milky Way in the constellation Pegasus 5. It has one of the highest central densities and it is one of the oldest of any GC in our galaxy. Imaging studies have not provided any evidence for a homogeneous core. Some believe that it has a small black hole in the middle. M15 is a proto-typical core-collapsed, metal-poor cluster [13]. Core collapse is a gravothermal instability that leads to very small and dense core surrounded by a power-law cusp [14]. It is one of the most massive and most luminous GC. M15 is rich with RR Lyrae stars, which helps a lot in calculating distance to it [15]. Our distance from M15 is 9.98 ± 0.47 kpc. Stars in M15 have absolute magnitude of $M_\nu(RR) = 0.51 \pm 0.11$. M15 is one of the oldest GC with age of 13.2 ± 1.5 Gyr. On the basis of N-body simulations, surface density profiles, and velocity profiles, it is estimated that M15 has a total mass of $(4.5 \pm 0.5)10^5 M_\odot$ [16].

Figure 5: Deep Broadband (RGB) image of M15 from the Mount Lemmon SkyCenter

2.2 CLUMPY

CLUMPY is the software I used for my research. It is a code for γ-ray and ν signals from DM structures [17]. CLUMPY provides many options to study different aspects of DM searches with γ-rays. With CLUMPY it is possible to look for J-factor or synthetic 2D γ-ray or ν skymaps from dark matter decay or annihilation, to calculate an instrumental sensitivity or to use in model/template analyses. It can also be used to explore the γ-ray or ν flux in the Galaxy, dSphs, or galaxy clusters for preferred particle physics model. It can also do Jeans analysis on kinematic data or compute halo mass functions for any cosmology, redshift, and overdensity definition Δ. In my work I used it to perform Jeans analysis to create DM profile from kinematic data (χ^2 analysis or MCMC analysis) and to calculate J-factor for annihilation and decay. More details on the CLUMPY software and the numerical codes that I used to obtain the results are described in section 4.

3 MAGIC

The results obtained in this work of thesis are thought to be used for DM searches using VHE γ-rays. Such photons possess energies above 100GeV and can be detected by Imaging Atmospheric Cherenkov telescopes (IACTS) such as MAGIC (Major Atmospheric Gamma-ray Imaging Cherenkov telescopes) 6. The search of DM with such telescopes is performed as an indirect measurement: what can be observed are γ-rays coming from the annihilation or decay of DM particles. MAGIC consists of two telescopes with the reflectors with diameter of 17 meters each, which makes them the most sensitive Cherenkov telescopes in the world, especially in the energy range below 200 gigaelectronvolts (GeV) [1]. The MAGIC telescopes have been in operation since 2003 and 2009 respectively. They are separated 85 meters and they are usually operated in coincidence, in the so-called stereoscopic mode. MAGIC's range of detection is energy range from 20GeV to 20TeV. It can detect γ-rays raging from 30 GeV to 100 teraelectronvolts (TeV). TeV γ-rays are easily absorbed by extragalactic background light, so MAGIC is aiming to measure sources of few tens of GeV, where the Universe becomes progressively transparent to γ-rays. At lower energies, it is possible to search for powerful sources residing at large redshifts. The telescopes measure Cherenkov light images of extended air showers from a target source direction. The software analysis allows, with very high efficiency, to select neutral γ-ray induced electromagnetic showers from the several orders of magnitudes more intense isotropic background due to the charged particle (mostly hadron) induced showers [2].

[1] https://www.mpp.mpg.de/forschung/magic-und-cta-gammastrahlenteleskope/magic

[2] https://magic.mpp.mpg.de/

MAGIC is located on the Canary Island of La Palma, 2200 meters above sea level. The sky of La Palma is particularly clear and free from light pollution, making the Observatory of the Roque de Los Muchachos one of the best location for astronomic observations.

Figure 6: The two MAGIC telescopes. Image credit: Daniel Lopez, IAC

4 Results

J-factor in M15 was outdated using old measurements [14]. By using new and precise measurements, new and updated J-factor have been acquired. First step was to download and install CLUMPY. CLUMPY is a software written in Python and available for Linux or MacOs operative systems. To work with CLUMPY I installed a recent version of Ubuntu, a Linux/Debian operative system. Step by step tutorial on how to download CLUMPY is on their website, so it was followed to install it. It was sequence of commands that had to be put in terminal. CLUMPY needs specific software to work with. In particular I had to install the Data analysis program ROOT [3], developed by CERN for particle physics experiments. For performing simulations with CLUMPY I installed also GreAT (Grenoble Analysis Toolkit) [18].

[3] `https://root.cern/`

4.1 Relative velocities for M15 (Input for CLUMPY)

Radial velocities of member stars of M15 CG were necessary for creating input. Measurements of radial velocities are usually performed by experiments employing spectrographic techniques. The reason is because scientists can estimate mass of the stars and by that calculate what velocities should be. But by measuring actual velocities and how faster are they moving, from what it should be, the amount of DM, can be measured. And by knowing velocity and location, J-factor can be computed. New and precise data for star radial velocities was found in work from Christopher Usher and his colleagues [19]. In their work they obtained observations of stellar kinematics of the centre of the M15 with MUSE (The Multi Unit Spectroscopic Explorer) of the Very Large Telescope (VLT). MUSE was operating in Narrow Field Mode (NFM). They obtained spatial resolution of 0.1 arcsec and were able to precise measure radial velocities of 864 stars within 8 arcsec of the centre of the M15. The excellent quality of the measurements was obtained thanks to the GALACSI adaptive optics module which provides MUSE a 7.5 by 7.5 arcsec field of view with a spatial sampling of 0.025 arcsec in NFM. We received the radial velocities measurements presented in [19]. Input for CLUMPY needs data for each star comprised of RA (right ascension) and Dec (declination) coordinates. RA and Dec are coordinates on the sky that correspond to longitude and latitude on Earth. RA measures east and west on the celestial sphere and can be associated to longitude on the Earth. Dec measures north and south on the celestial sphere and can be associated to latitude on the Earth. It also needs to have velocity and error of velocity for each star. Last thing needed was distance of each star in kpc from the centroid of the cluster. The way it was calculated is in next formula: 7:

$$R = D \cdot \sqrt{(RA - RA_0)^2 + (Dec - Dec_0)^2} \tag{5}$$

where D is distance between the target and the observer, RA_0 and Dec_0 are centroid coordinates, and RA and Dec are the coordinates of each star. Also distance error was simply calculated same way, but instead of plugging distance from us to target, we plug distance error. Convertion between the different astronomical units were performed with the following phython code:

```
def decdeg2dms(dd):
    is_positive = dd >= 0
    dd = abs(dd)
    minutes,seconds = divmod(dd*3600,60)
    degrees,minutes = divmod(minutes,60)
    degrees = degrees if is_positive else -degrees
    return (degrees,minutes,seconds)
```

The coordinates used for the centroid of M15 were RA= 322,49304167 and DEC=12,167, taken from SIMBAD Astronomical Database [4]. For this work of thesis we used the measurements from 40 stars. The input file obtained is shown in 7. Next step was to input it in CLUMPY and run MCMC Jeans analysis 8.

```
TypeData
Vel
R[kpc]  dR[kpc]    V[km/s_or_km^2/s^2] dV[km/s_or_km^2/s^2] MembershipProba RA[deg] Dec[deg]
0.022700912887     0.00027173059103233      -102.746887546848    10.3214044536983    1.000000     322.494948409134     12.167816688787
0.02389173477      0.000285984763782488     -75.0835191284175    11.6996723355897    1.000000     322.494942309145     12.1680739887873
0.02389173477      0.000285984763782488     -89.1156939767639    6.92497743050218    1.000000     322.494942309145     12.1680739887873
0.020364495408     0.000243763605486946     -79.1091019226587    11.3639806195007    1.000000     322.494888809071     12.1672249887901
0.02017318374      0.000241473599225758     -101.839859308282    1.69788583933021    1.000000     322.494879609047     12.1668593887906
0.02017318374      0.000241473599225758     -102.210142029125    1.35344541449274    1.000000     322.494879609047     12.1668593887906
0.021729749119     0.000260105732321909     -61.6445957817496    1.42439349429851    1.000000     322.494871409092     12.1677709887909
0.021729749119     0.000260105732321909     -107.344337213508    2.19583894434587    1.000000     322.494871409092     12.1677709887909
0.024935065393     0.000298473461855668     -131.99533388915     2.62321572305317    1.000000     322.494831009105     12.168410488793
0.024221760412     0.000289935180368235     -114.359169630896    8.17840360754262    1.000000     322.494829109098     12.1683051887931
0.024485611892     0.000293093490296358     -108.574503922892    2.7614488620245     1.000000     322.494822509097     12.1683543887934
0.024485611892     0.000293093490296358     -114.300005827345    2.88716123407323    1.000000     322.494822509097     12.1683543887934
0.020120381742     0.000240841557769052     -125.321065097196    7.34209242748979    1.000000     322.494814209046     12.1674879887939
0.020129365734     0.000240949096416467     -104.549988469233    2.00475490031822    1.000000     322.494799309042     12.1675419887947
0.020129365734     0.000240949096416467     -108.390258587409    2.09002307438708    1.000000     322.494799309042     12.1675419887947
0.019050635143     0.000228036659696239     -110.487611055641    11.0797216215593    1.000000     322.494782209002     12.1669736887955
0.022351366291     0.000267546508054821     -112.168416982361    7.43117616394594    1.000000     322.494771409056     12.168085888796
0.022351366291     0.000267546508054821     -102.511762238605    3.7767716330035     1.000000     322.494771409056     12.168085888796
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0.019500130666     0.000233417134249561     -120.381510891266    9.95752467007076    1.000000     322.494765409019     12.1674511887964
0.019601749754     0.000234633517705452     -106.677527147501    5.35646011880833    1.000000     322.49476170902      12.1674994887966
0.023677121349     0.000283415834864075     -100.460205932286    1.5808612470822     1.000000     322.494741009054     12.1683389887976
0.023677121349     0.000283415834864075     -103.608765618012    7.77417084458703    1.000000     322.494741009054     12.1683389887976
0.020069358935     0.000240230813280825     -102.382116847238    14.6354768981022    1.000000     322.494731708939     12.1662881887981
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0.027231377559     0.000325960385614449     -123.2               5.4                 1.000000     322.494707009063     12.1688487887992
0.018103090807     0.000216694526287121     -99.1485269219893    8.76791039539157    1.000000     322.494690008948     12.1668613888003
0.018103090807     0.000216694526287121     -129.201570522647    10.9701611891165    1.000000     322.494690008948     12.1668613888003
0.01909310773      0.000228545057802879     -109.08707326631     9.343700435189      1.000000     322.494688708986     12.1675752888003
0.018018426237     0.000215681088910666     -120.782497333145    10.2898058024637    1.000000     322.494688008955     12.1670163888004
0.02108611595      0.000252401424479899     -117.814705925831    2.14331486028612    1.000000     322.494685409007     12.1680051888004
0.02108611595      0.000252401424479899     -124.204866128336    1.23504456698117    1.000000     322.494685409007     12.1680051888004
0.02108611595      0.000252401424479899     -128.7               2.4                 1.000000     322.494685409007     12.1680051888004
0.023278270811     0.000278641582259006     -102.94744794266     0.913340645980093   1.000000     322.494664109016     12.1683754888015
```

Figure 7: Finalised input file with the radial velocities of stars in M15.

The code for running MCMC Jeans analysis is:

```
$clumpy_jeansMCMC -r
$CLUMPY/data/data_sigmap.txt output/stat_example.root
output/stat_exampleAna.root 10000 8
$CLUMPY/data/params_jeans.txt 0.05
```

This analysis executes eight chains with 10000 trial points each, using a numeric accuracy of 5%. The output figure is 9.

We also obtained statistical file from which different quantities of interest can be obtained. Next step was to obtain J-factor from it. To do that we run a statistical analysis.

[4] http://simbad.u-strasbg.fr/simbad/sim-id?Ident=M15

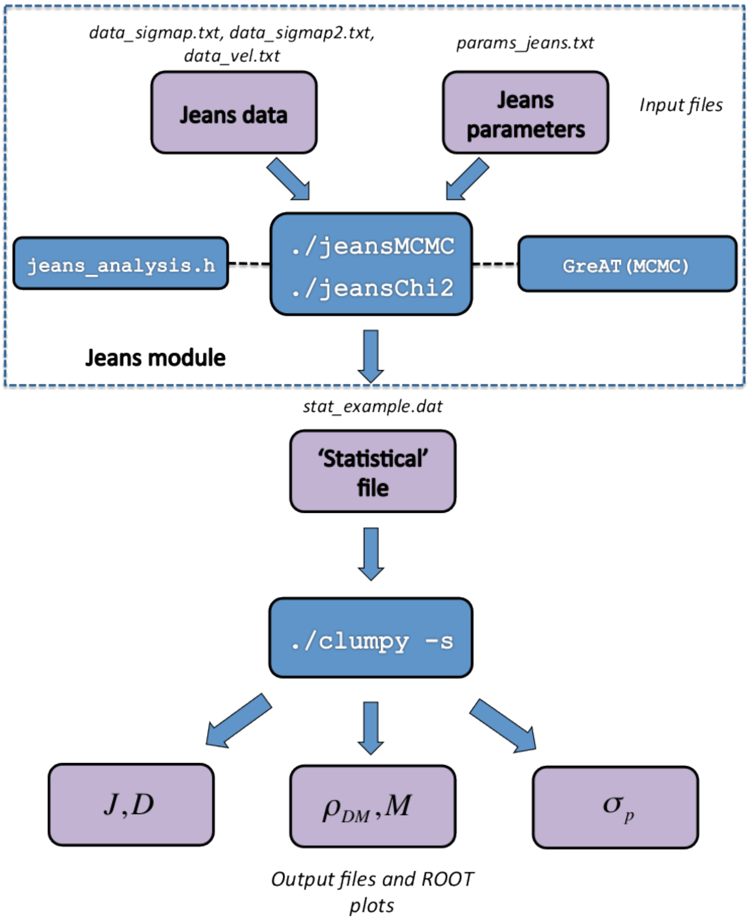

Figure 8: Diagram of Jeans analysis with CLUMPY. From a velocity data file and a parameter file describing the free parameters, a statistical Jeans analysis can be run. A statistical output file is created, from which estimators of different quantities of interest (i.e., J-factors) can be obtained.

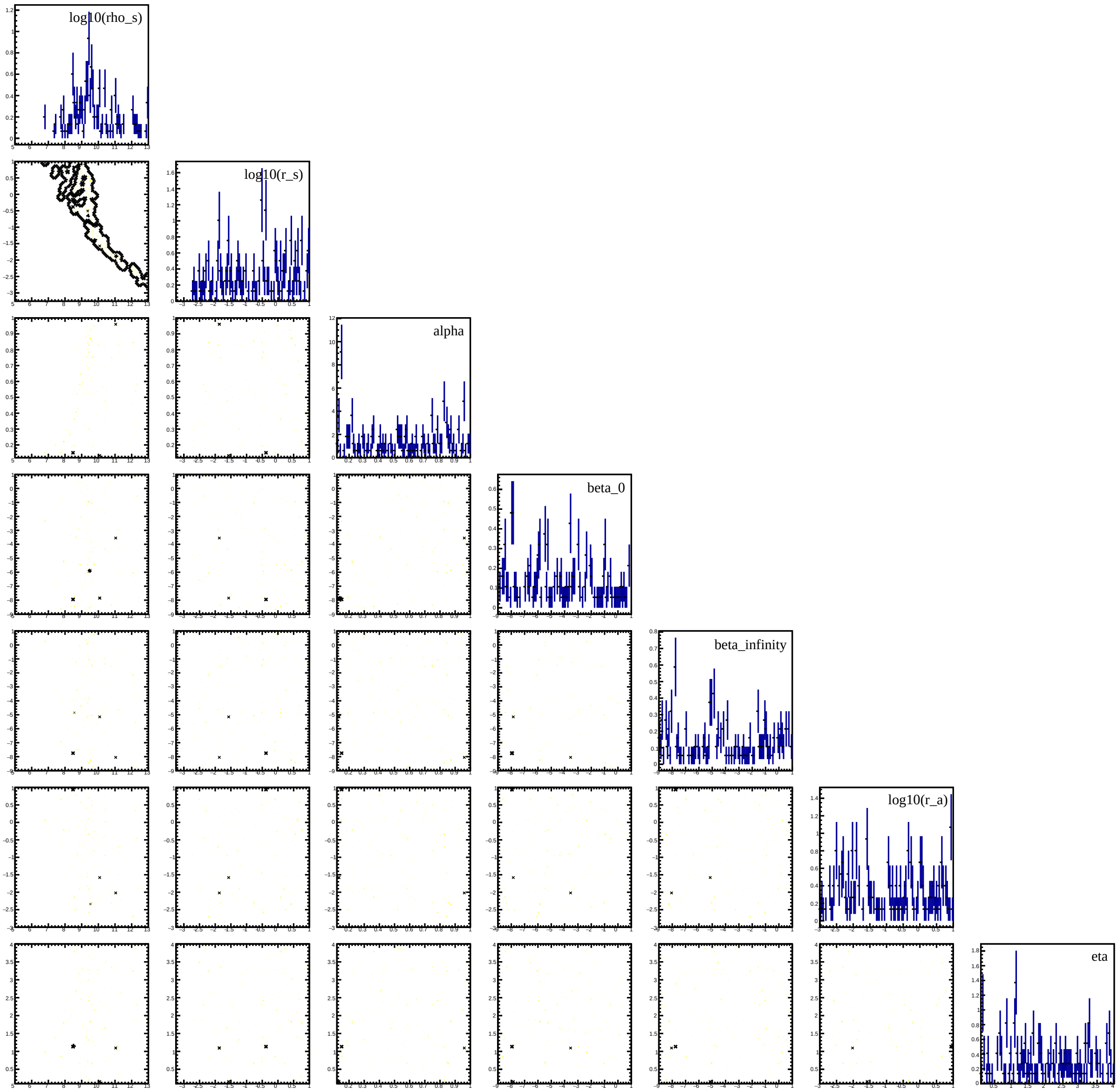

Figure 9: MCMC fit of M15. Triangle plot showing correlations and marginalised posterior distributions for the mass and DM profile parameters.

4.2 J-factor values

To obtain the J-factor, the program CLUMPY has been executed in statistic mode. Under this modality, CLUMPY runs on the file containing a list of parameters (obtained from a statistical analysis). The statistics mode deals with the results of a Jeans + MCMC analysis run on a set of kinematic data. It allows the reconstruction of parameter correlations and confidence intervals of any quantities.

x= #alpha_{int} [deg] , y= J(#alpha_{int}) [GeV^{2} cm^{-5}]

x	y_pdf_median	y_pdf_mean	y_mostlikely	y_chi2_best	CL_lo_PDF	CL_up_PDF	| 68.0% CL |	95.0% CL
1.0000e-02	5.41e+17	5.60e+17	4.92e+17	2.46e+18	1.20e+17	2.85e+18	2.01e+16	1.08e+19
1.3216e-02	8.71e+17	8.63e+17	7.32e+17	3.48e+18	2.03e+17	4.03e+18	3.33e+16	1.64e+19
1.7467e-02	1.36e+18	1.30e+18	1.08e+18	4.82e+18	3.32e+17	5.16e+18	5.24e+16	2.21e+19
2.3085e-02	2.10e+18	1.92e+18	5.74e+18	6.43e+18	5.07e+17	7.21e+18	8.11e+16	2.67e+19
3.0509e-02	2.94e+18	2.77e+18	1.85e+18	8.24e+18	7.54e+17	1.03e+19	1.22e+17	3.45e+19
4.0321e-02	4.47e+18	3.87e+18	2.18e+18	1.03e+19	1.14e+18	1.35e+19	1.88e+17	4.34e+19
5.3289e-02	6.05e+18	5.28e+18	2.26e+18	1.15e+19	1.66e+18	1.73e+19	2.79e+17	5.65e+19
7.0428e-02	7.77e+18	6.88e+18	7.72e+18	1.35e+19	2.23e+18	2.14e+19	3.71e+17	8.38e+19
9.3080e-02	9.80e+18	8.95e+18	3.23e+18	1.52e+19	2.86e+18	2.85e+19	4.38e+17	1.43e+20
1.2302e-01	1.17e+19	1.12e+19	3.29e+18	1.65e+19	3.25e+18	4.13e+19	5.10e+17	2.41e+20
1.6258e-01	1.35e+19	1.37e+19	3.37e+18	1.76e+19	3.39e+18	5.60e+19	6.19e+17	4.07e+20
2.1487e-01	1.49e+19	1.65e+19	3.30e+18	1.82e+19	3.61e+18	7.65e+19	6.37e+17	7.01e+20
2.8398e-01	1.61e+19	1.95e+19	1.64e+19	1.86e+19	3.68e+18	1.16e+20	6.42e+17	1.25e+21
3.7531e-01	1.67e+19	2.24e+19	3.38e+18	1.85e+19	3.74e+18	1.57e+20	6.78e+17	2.10e+21
4.9602e-01	1.72e+19	2.56e+19	1.61e+19	1.89e+19	3.87e+18	2.22e+20	7.24e+17	3.65e+21
6.5555e-01	1.74e+19	2.88e+19	3.46e+18	1.90e+19	3.87e+18	3.01e+20	8.01e+17	6.14e+21
8.6638e-01	1.79e+19	3.18e+19	3.40e+18	1.89e+19	4.09e+18	3.85e+20	8.25e+17	1.07e+22
1.1450e+00	1.77e+19	3.46e+19	1.67e+19	1.91e+19	4.16e+18	4.41e+20	7.94e+17	1.72e+22
1.5133e+00	1.82e+19	3.71e+19	3.26e+18	1.87e+19	4.15e+18	5.34e+20	7.82e+17	2.88e+22
2.0000e+00	1.85e+19	3.96e+19	3.46e+18	1.89e+19	4.17e+18	6.70e+20	7.94e+17	4.48e+22

Figure 10: Table of J-factor values

The J-factor represents the astrophysical contribution to the signal and is equal to:

$$J(\Delta\Omega) = \int_{\Delta\Omega} \int \rho^2(l,\Omega) dl/d\Omega \tag{6}$$

Here we have:

$$\Delta\Omega = 2\pi \cdot [1 - \cos\alpha_{int}] \tag{7}$$

where α_{int} is angle of integration[20].

In 10, the first column represents the angle of interaction α_{int}, while from second to fifth column, J-factor values in function of the α_{int} angle. Last two rows provide the accuracy, 68% and 95% respectively. The J-factor is plotted in the following graphs:

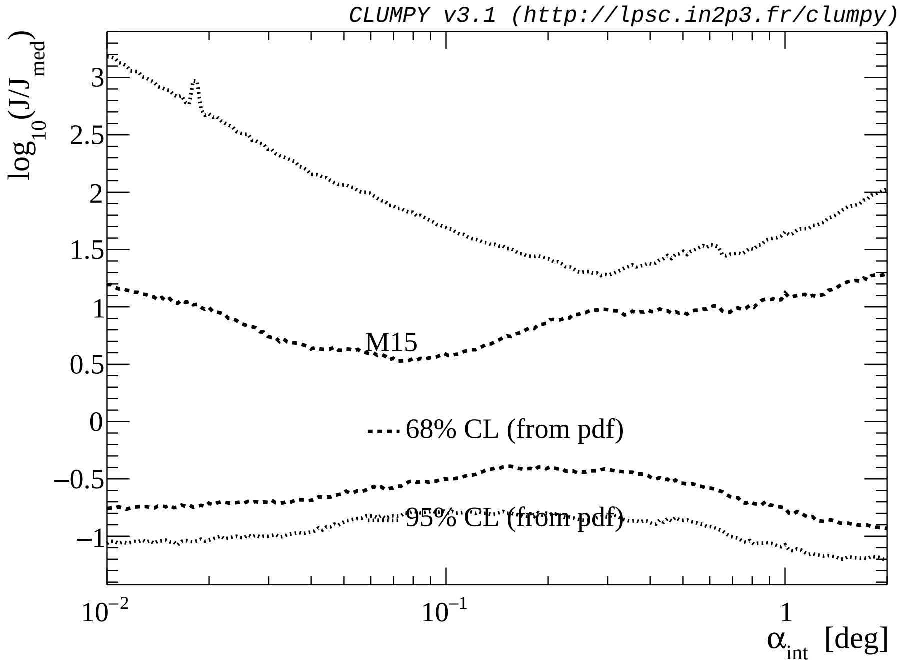

Figure 11: J-factor as a function of angle α_{int} graph.

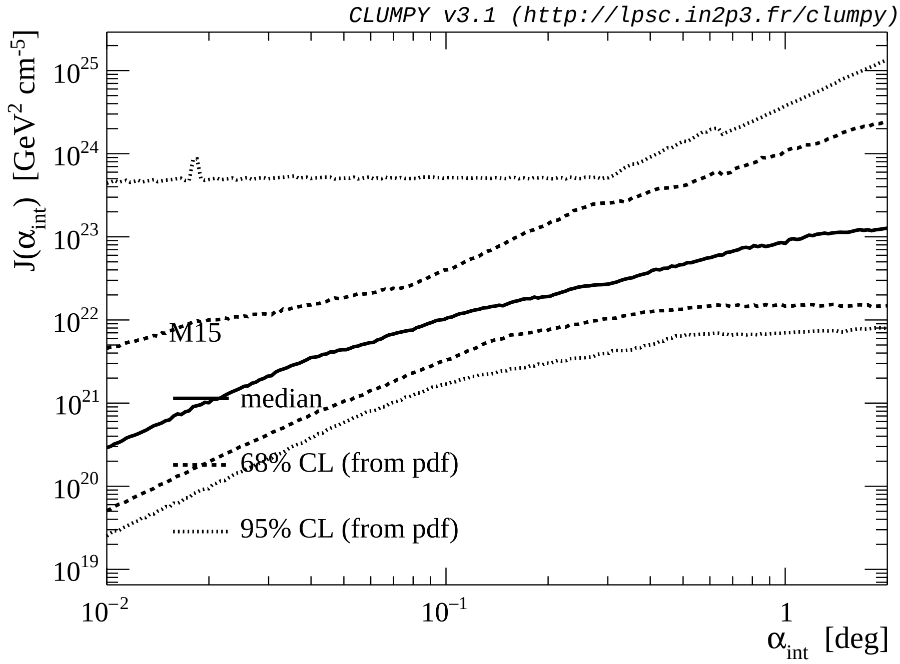

Figure 12: J-factor median values in function of the α_{int} angle.

5 Conclusions

GCs are very difficult objects to be studied for Dark Matter searches, due to the extreme density of baryonic matter. Nevertheless, with accurate measurements of radial velocities of the stars composing the cluster, it is possible to perform more precise searches of DM signal from annihilation or decay. In this work of thesis the content of DM in the globular cluster M15 has been investigated, using the most recent measurements of radial velocities of stars in M15 taken by the experiment MUSE. With the program CLUMPY, a Jeans MonteCarlo simulation was performed using such velocities, followed by a statistical analysis, in order to obtain the astrophysical J-factor for annihilation of DM in this target. The results obtained in this work of thesis will be used for further studies of DM searches in M15 with VHE γ-ray data.

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