LEVERAGING MULTI-MESSENGER ASTROPHYSICS FOR DARK MATTER SEARCHES

By

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ABSTRACT

I did Dark Matter with HAWC and IceCube. I also used Graph Neural Networks

ACKNOWLEDGMENTS

I love my friends. Thanks to everyone that helped me figure this out. Amazing thanks to the people at LANL who supported me. Eames, etc Dinner Parties Jenny and her child Kaydince Kirsten, Pat, Andrea Family. You're so far but so critical to my formation. Unconditional love. Roommate

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Proof I know how to include

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MSU Michigan State University

LANL Los Alamos National Laboratory

DM Dark Matter

SM Standard Model

HAWC High Altitude Water Cherenkov Observatory

CHAPTER 1

INTRODUCTION

Is the text not rendering right? Ah ok it knows im basically drafting the doc still

CHAPTER 2

DARK MATTER IN THE COSMOS

2.1 Introduction

The dark matter problem can be summarized in part by the following thought experiment.

Let us say you are the teacher for an elementary school classroom. You take them on a field trip to your local science museum and among the exhibits is one for mass and weight. The exhibit has a gigantic scale, and you come up with a fun problem for your class.

You ask your class, "What is the total weight of the classroom? Give your best estimation to me in 30 minutes, and then we'll check your guess on the scale. If your guess is within 10% of the right answer, we will stop for ice cream on the way back."

The students are ecstatic to hear this, and they get to work. The solution is some variation of the following strategy. The students should give each other their weight or best guess if they do not know. Then, all they must do is add each student's weight and get a grand total for the class. The measurement on the giant scale should show the true weight of the class. When comparing the measured weight to your estimation, multiply the measurement by 1.0 ±0.1 to get the ±10% tolerances for your estimation.

Two of your students, Sandra and Mario, return to you with a solution.

They say, "We weren't sure of everyone's weight. We used 65 lbs. for the people we didn't know and added everyone who does know. There are 30 of us, and we got 2,000 lbs.! That's a ton!"

You estimated 1,900 lbs. assuming the average weight of a student in your class was 60 lbs. So, you are pleased with Sandra's and Mario's answer. You instruct your students to all gather on the giant scale and read off the weight together. To all your surprise, the scale reads *10,000 lbs.*! 10,000 is significantly more than a 10% error from 2,000. In fact, it is approximately 5 times more massive than either your or your students' estimates. You think to yourself and conclude there must be something wrong with the scale. You ask an employee to check the scale and verify it is well calibrated. They confirm that the scale is in working order. You weigh a couple of students individually to assess that the scale is well calibrated. Sandra weighs 59 lbs., and Mario weighs

62 lbs., typical weights for their age. You then weigh each student individually and see that their weights individually do not deviate greatly from 60 lbs. So, where does all the extra weight come from?

This thought experiment serves as an analogy to the Dark Matter problem. The important substitution to make however is to replace the students with stars and the classroom with a galaxy, say the Milky Way. Individually the mass of stars is well measured and defined with the Sun as our nearest test case. However, when we set out to measure the mass of a collection of stars as large as galaxies, our well-motivated estimation is wildly incorrect. There simply is no way to account for this discrepancy except without some unseen, or dark, contribution to mass and matter in galaxies. I set out in my thesis to narrow the possibilities of what this Dark Matter could be.

This chapter is organized like the following. . . TODO: Text should look like ... Chapter x has blah blah blah.

2.2 Dark Matter Basics

Presently, a more compelling theory of cosmology that includes Dark Matter (DM) in order to explain a variety of observations is Λ **C**old **D**ark **M**atter, or Λ**CDM**. I present the evidence supporting Λ**CDM** in Section 2.3 yet discuss the conclusions of the Λ**CDM** model here. According to Λ**CDM** fit to observations on the Cosmic Microwave Background (CMB), DM is 26.8% of the universe's current energy budget. Baryonic matter, stuff like atoms, gas, and stars, contributes to 4.9% of the universe's current energy budget [1, 2, 3].

DM is dark; it does not interact readily with light at any wavelength. DM also does not interact noticeably with the other standard model forces (Strong and Weak) at a rate that is readily observed [3]. DM is cold, which is to say that the average velocity of DM is below relativistic speeds [1]. 'Hot' DM would not likely manifest the dense structures we observe like galaxies, and instead would produce much more diffuse galaxies than what is observed [3, 1]. DM is old; it played a critical role in the formation of the universe and the structures within it [1, 2].

Observations of DM have so far been only gravitational. The parameter space available to what DM could be therefore is extremely broad. The broad DM parameter space is iteratively tested in

DM searches by supposing a hypothesis that has not yet been ruled out and performing observations to test them. When the observations yield a null result, the parameter space is constrained further. I present some approaches for DM searches in Section 2.4.

2.3 Evidence for Dark Matter

Dark Matter (DM) has been a looming problem in physics for almost 100 years. Anomalies have been observed by astrophysicists in galactic dynamics as early as 1933 when Fritz Zwicky noticed unusually large velocity dispersion in the Coma cluster. Zwicky's measurement was the first recorded to use the Virial theorem to measure the mass fraction of visible and invisible matter in celestial bodies [4]. From Zwicky in [5], "*If this would be confirmed, we would get the surprising result that dark matter is present in much greater amount than luminous matter.*" Zwicky's and others' observation did not instigate a crisis in astrophysics because the measurements did not entirely conflict with their understanding of galaxies [4]. In 1978, Rubin, Ford, and Norbert measured rotation curves for ten spiral galaxies [6]. Rubin et al.'s 1978 publication presented a major challenge to the conventional understanding of galaxies that could no longer be dismissed by measurement uncertainties. Evidence has been mounting ever since for this exotic form of matter. The following subsections provide three compelling pieces of evidence in support of the existence of DM.

2.3.1 First Clues: Stellar Velocities

Zwicky, and later Rubin, measured the stellar velocities of various galaxies to estimate their virial mass. The Virial Theorem upon which these observations are interpreted is written as

$$2T + V = 0. \tag{2.1}$$

Where T is the kinetic energy and V is the potential energy in a self-gravitating system. The classical Newton's law of gravity from stars and gas was use for gravitational potential modeled in the observed galaxies:

$$V = -\frac{1}{2}\sum_{i}\sum_{j\neq 1}\frac{m_i m_j}{r_{ij}}. \tag{2.2}$$

Zwicky et al. measured just the velocities of stars apparent in optical wavelengths [5]. Rubin et al. added by measuring the velocity of the hydrogen gas via the 21 cm emission line of Hydrogen [6]. The velocities of the stars and gas are used to infer the total mass of galaxies and galaxy clusters via Equation (2.1). An inferred mass is obtained from the luminosity of the selected sources. The two inferences are compared to each other as a luminosity to mass ratio which typically yielded [1]

$$\frac{M}{L} \sim 400 \frac{M_\odot}{L_\odot} \tag{2.3}$$

$M_\odot$ and $L_\odot$ referring to stellar mass and stellar luminosity, respectively. These ratios clearly indicate a discrepancy in apparent light and mass from stars and gas and their velocities.

Rubin et al. [6] demonstrated that the discrepancy was unlikely to be an underestimation of the mass of the stars and gas. The inferred "dark" mass was up to 5 times more than the luminous mass. This dark mass also needed to extend well beyond the extent of the luminous matter.

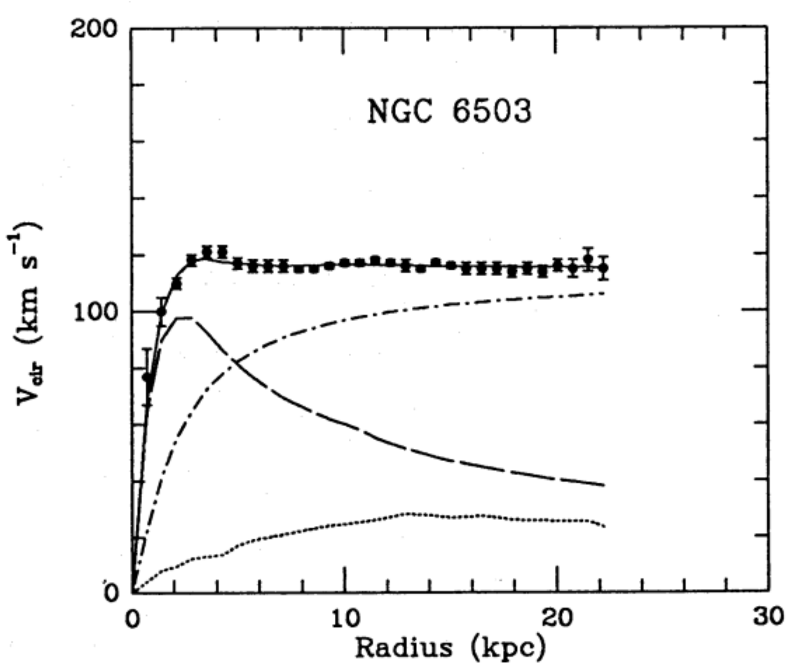

Figure 2.1 Rotation curve fit to NGC 6503 from [7]. Dashed line is the contribution from visible matter. Dotted curves are from gas. Dash-dot curves are from dark matter (DM). Solid line is the composite contribution from all matter and DM sources. Data are indicated with bold dots with error bars. Data agree strongly with a matter + DM composite prediction.

Figure 2.1 features one of many rotation curves plotted from the stellar velocities within galaxies.

The measured rotation curves mostly feature a flattening of velocities at higher radius which is not expected if the gravity was only coming from gas and luminous matter. The extension of the flat velocity region also indicates that the DM is distributed far from the center of the galaxy. Modern velocity measurements include significantly larger objects, galactic clusters, and smaller objects, dwarf galaxies. Yet, measurements along this regime are leveraging the Virial theorem with Newtonian potential energies. We know Newtonian gravity is not a comprehensive description of gravity. New observational techniques have been developed since 1978, and those are discussed in the following sections.

2.3.2 Evidence for Dark Matter: Gravitational Lensing

Modern evidence for dark matter comes from new avenues beyond stellar velocities. Gravitational lensing from DM is a new channel from general relativity. General relativity predicts aberrations in light caused by massive objects. In recent decades we have been able to measure the lensing effects from compact objects and DM halos. Figure 2.2 shows how different massive objects change the final image of a faraway galaxy resulting from gravitational lensing. Gravitational lensing developed our understanding of dark matter in two important ways.

Gravitational lensing provides additional compelling evidence for DM. The observation of two merging galactic clusters in 2006, shown in Figure 2.3, provided a compelling argument for DM outside the Standard Model. These clusters merged recently in astrophysical time scales. Galaxies and star cluster have mostly passed by each other as the likelihood of their collision is low. Therefore, these massive objects will mostly track the highest mass, dark and/or baryonic, density. Yet, the intergalactic gas is responsible for the majority of the baryonic mass in the systems [4]. These gas bodies will not phase through and will heat up as they collide together. The hot gas is located via x-ray emission from the cluster. Two observations of the clusters were performed independently of each other.

The first was the lensing of light around the galaxies due to their gravitational influences. When celestial bodies are large enough, the gravity they exert bends space and time itself. The warped space-time lenses light and will deflect in an analogous way to how glass lenses will bend

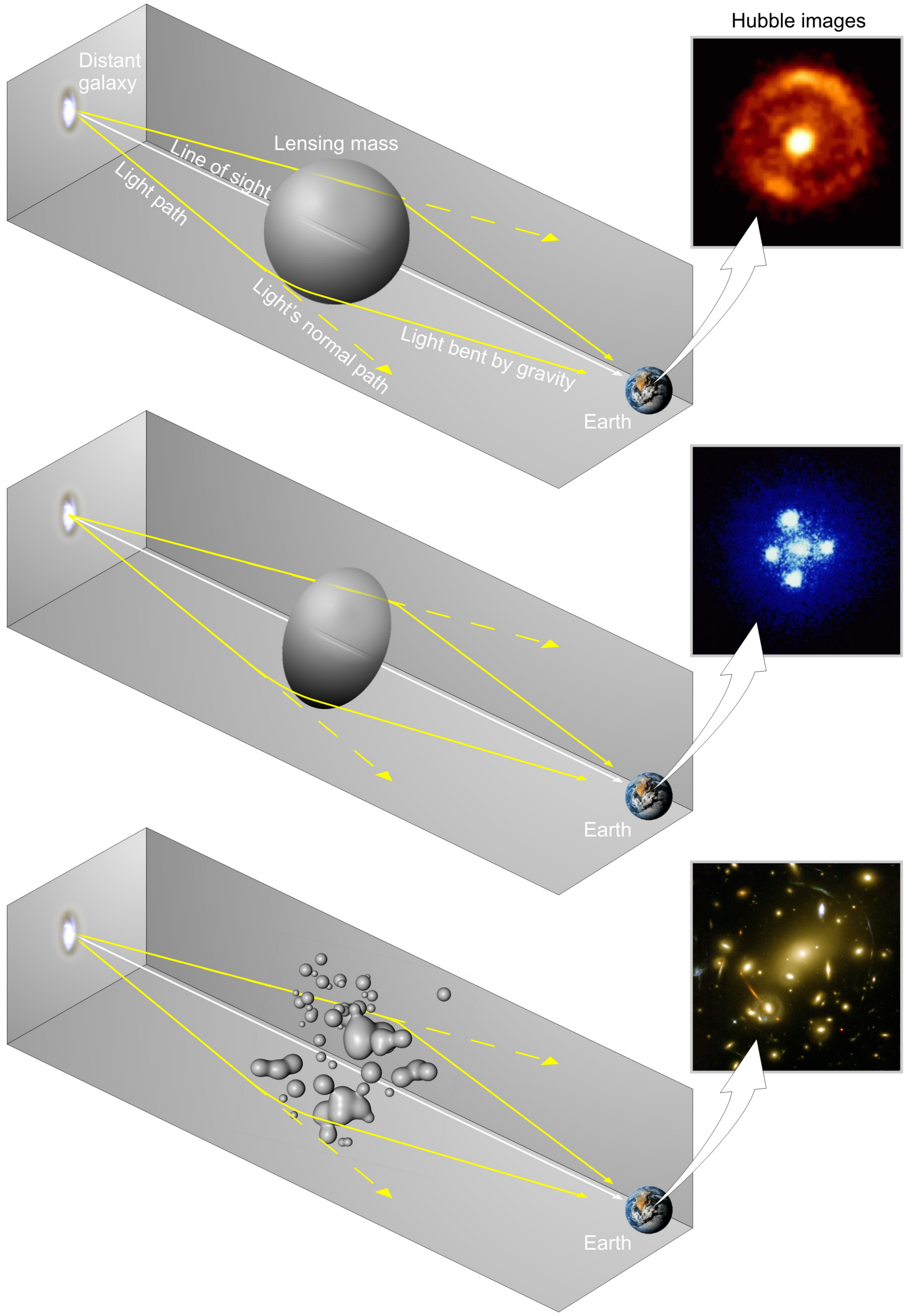

Figure 2.2 Light from distant galaxy is bent in unique ways depending on the distribution of mass between the galaxy and Earth. Yellow dashed lines indicate where the light would have gone if the matter were not present [8].

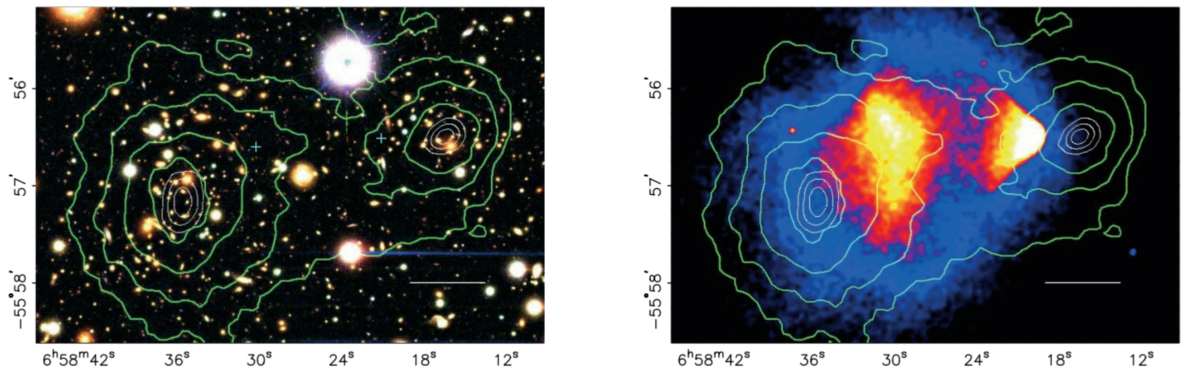

Figure 2.3 (left) Optical image of galactic cluster 1E0657-558. (right) X-ray image of the cluster with redder meaning hotter and higher baryon density. (both) Green contours are reconstruction of gravity contours from weak lensing. White rings are the best fit mass maxima at 68.3%, 95.5%, and 99.7% confidence. The matter maxima of the clusters are clearly separated from x-ray maxima. [9]

light, see Figure 2.2. With a sufficient understanding of light sources behind a massive object, we can reconstruct the contours of the gravitational lenses. The gradient of the contours shown in Figure 2.3 then indicates how dense the matter is and where it is.

The x-ray emission can then be observed from the clusters. Since these galaxies are mostly gas and are merging, then the gas should be getting hotter. If they are merging, the x-ray emissions should be the strongest where the gas is mostly moving through each other. Hence, X-ray emission maps out where the gas is in the merging galaxy cluster.

The lensing and x-ray observations were done on the Bullet cluster featured on Figure 2.3. The x-ray emissions do not align with the gravitational contours from lensing. The incongruence in mass density and baryon density suggests that there is a lot of matter somewhere that does not interact with light. Moreover, this dark matter cannot be baryonic [9]. The Bullet Cluster measurement did not really tell us what DM is exactly, but it did give the clue that DM also does not interact with itself very strongly. If DM did interact strongly with itself, then it would have been more aligned with the x-ray emission [9]. There have been follow-up studies of galaxy clusters with similar results. The Bullet Cluster and others like it provide a persuasive case against something possibly amiss in our gravitational theories.

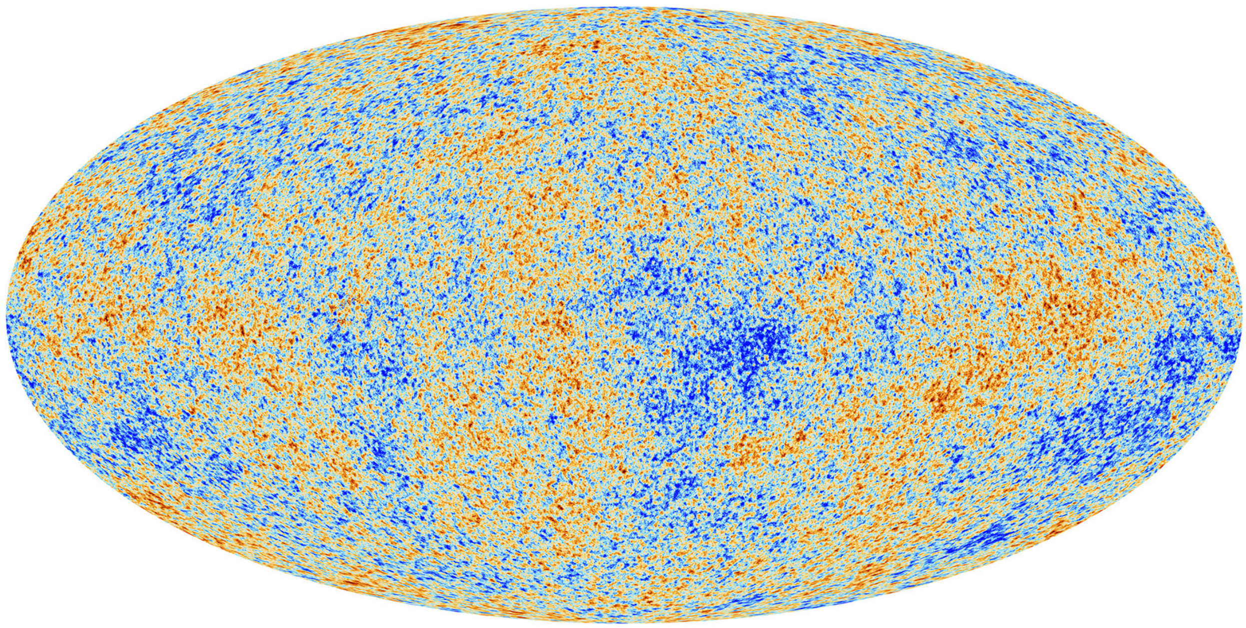

Figure 2.4 Plank CMB sky. Sky map features small variations in temperature in primordial light. These anisotropies are used to make inferences about the universe's energy budget and developmental history. [10]

2.3.3 Evidence for Dark Matter: Cosmic Microwave Background

The Cosmic Microwave Background (CMB) is the primordial light from the early universe when Hydrogen atoms formed from the free electron and proton soup in the early universe. The CMB is the earliest light we can observe; released when the universe was about 380,000 years old. Then we look at how the simulated universes look like compared to what we see. Figure 2.4 is the most recent CMB image from the Plank satellite after subtracting the average value and masking the galactic plane [10]. Redder regions indicate a slightly hotter region in the CMB, and blue indicates colder. The intensity variations are on the order of 1 in 1000 with respect to the average value.

The Cosmic Microwave Background shows that the universe had DM in it from an incredibly early stage. To measure the DM, Dark Energy, and matter fractions of the universe from the CMB, the image is analyzed into a power spectrum, which shows the amplitude of the fluctuations as a function of spherical multipole moments. **ΛCDM** provides the best fit to the power spectra of the CMB as shown in Figure 2.5. The CMB power spectrum is quite sensitive to the fraction of each energy contribution in the early universe. Low l modes are dominated by variations in gravitational potential. Intermediate l emerge from oscillations in photon-baryon fluid from

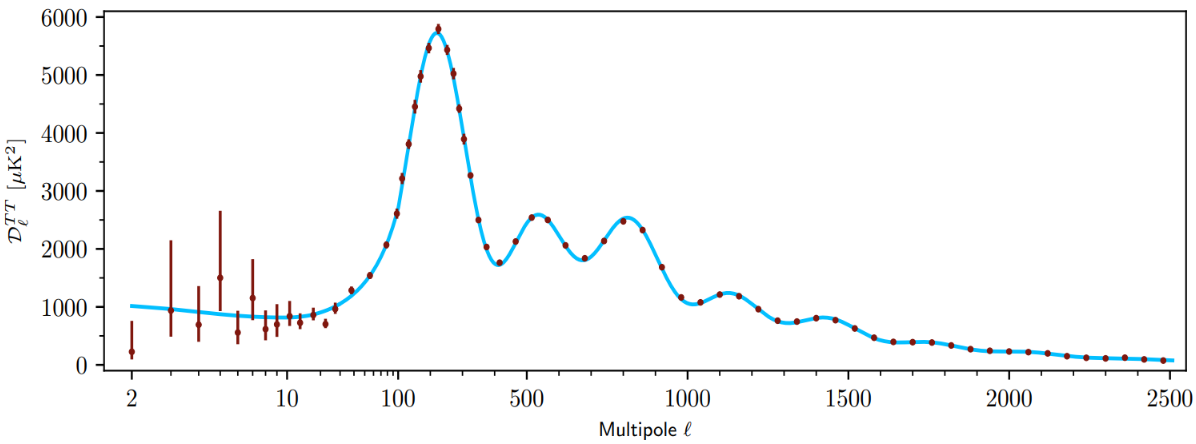

Figure 2.5 Observed Cosmic Microwave Background power spectrum as a function of multipole moment from Plank [10]. Blue line is best fit model from Λ**CDM**. Red points and lines are data and error, respectively.

competing baryon pressures and gravity. High l is a damped region from the diffusion of photons during electron-proton recombination. [1]

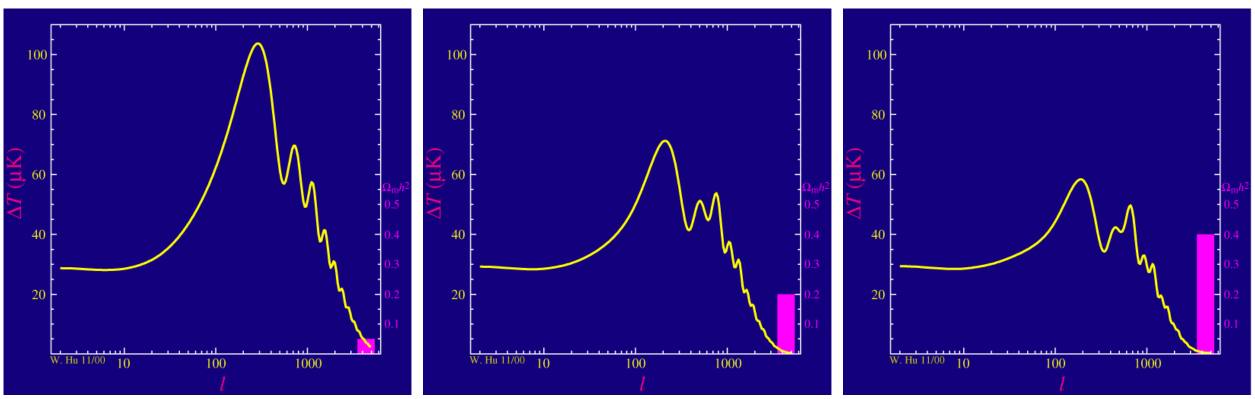

Figure 2.6 Predicted power spectra of CMB for different $\Omega_m h^2$ values for fixed baryon density from [11]. (left) Low $\Omega_m h^2$ increases the prominence of first and second peaks. (middle) $\Omega_m h^2$ is most similar to the observed power spectrum. The second and third peaks are similar in height. (right) $\Omega_m h^2$ is large which suppresses the first peak and raises the prominence of the third peak.

The harmonics would look quite different for a universe with less DM. Figure 2.6 demonstrates the effect $\Omega_m h^2$ has on the expected power spectrum for fixed baryon matter density. [11] Sweeping $\Omega_m h^2$ in this way clearly shows the effect dark matter has on the CMB power spectrum. The observations fit well with the Λ**CDM** model, and the derived fractions are as follows. The matter fraction: $\Omega_m = 0.3153$; and the baryon fraction: $\Omega_b = 0.04936$ [10]. Plank's observations also provide a measure of the Hubble constant, H_0. H_0 especially has seen a growing tension in the past decade that continues to deepened with observations from instruments like the James Webb Telescope [12, 13]. As Hubble tensions deepen, we may find that perhaps Λ**CDM**, despite its successes, is missing some critical physics.

Overall, the Newtonian motion of stars in galaxies, weak lensing from galactic clusters, and power spectra from primordial light form a compelling body of research in favor of dark matter. It takes another leap of theory and experimentation to make observations of DM that are non-gravitational in nature. In Section 2.3, the evidence for DM implies strongly that the DM is matter and not a lost parameter in the gravitational fields between massive objects. Finally, if we take one axiom: that this matter has quantum behavior, such as being described by some Bohr wavelength and abiding by some fermion or boson statistics; then we arrive at particle dark matter. One particle DM hypothesis is the Weakly Interacting Massive Particle (WIMP). This DM candidate theory is discussed further in the next section and is the focus of this thesis.

2.4 Searching for Dark Matter: Particle DM

Section 2.4 shows the Standard Model of particle physics and is currently the most accurate model for the dynamics of fundamental particles like electrons and photons. The current status of the SM does not have a viable DM candidate. When looking at the standard model, we can immediately exclude any charged particle because charged particles interact strongly with light. Specifically, this will rule out the following charged, fundamental particles: $e, \mu, \tau, W, u, d, s, c, t, b$ and their corresponding antiparticles. Recalling from Section 2.2 that DM must be long-lived and stable over the age of the universe which excludes all SM particles with decay half-lives at or shorter than the age of the universe. The lifetime constraint additionally eliminates the Z and H bosons. Finally, the candidate DM needs to be somewhat massive. Recall from Section 2.2 that DM is cold or not relativistic through the universe. This eliminates the remaining SM particles: $\nu_{e,\mu,\tau}, g, \gamma$ as DM candidates. Because there are no DM candidates within the SM, the DM problem strongly hints to physics beyond the SM (BSM).

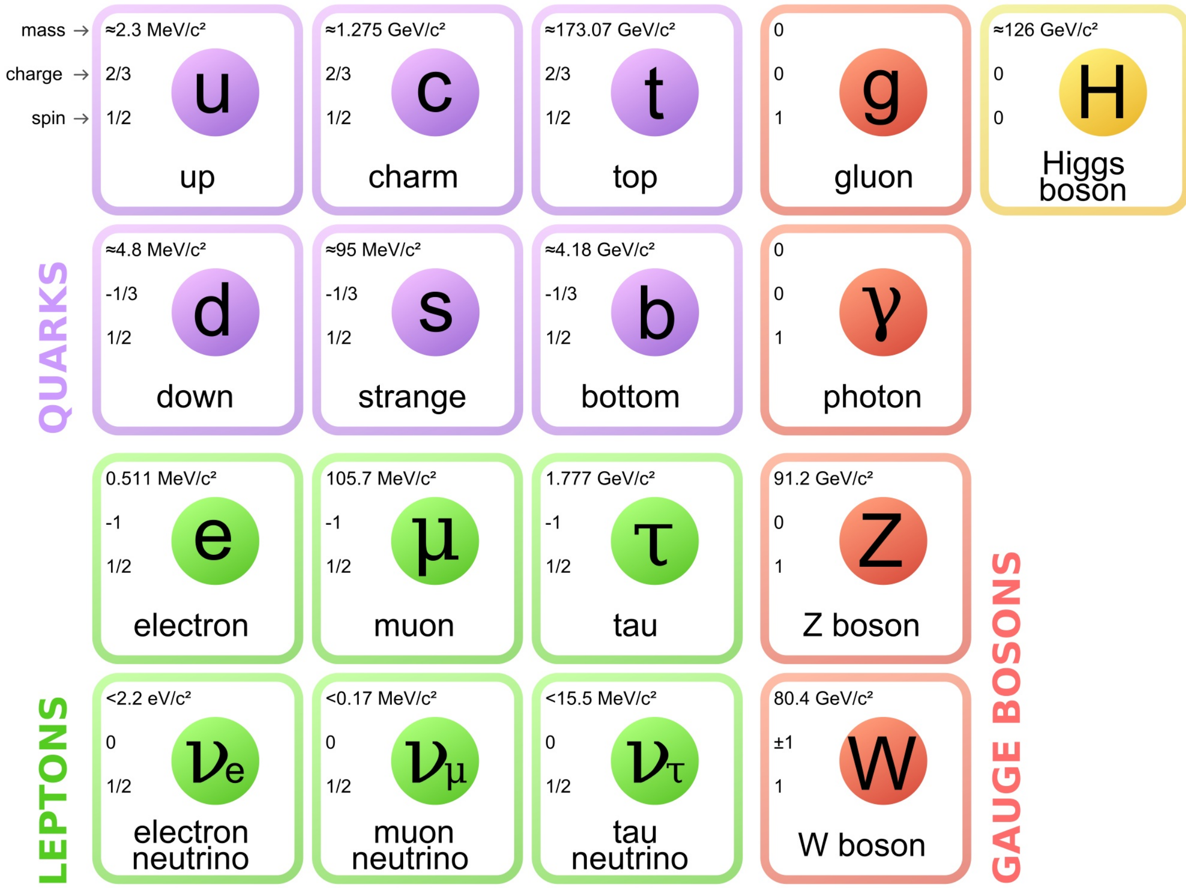

Figure 2.7 The Standard Model (SM) of particle physics. Figure taken from http://www.quantumdiaries.org/2014/03/14/the-standard-model-a-beautiful-but-flawed-theory/

2.4.1 Shake it, Break it, Make it

When considering DM that couples in some way with the SM, the interactions are roughly demonstrated by interaction demonstrated in Figure 2.8. The figure is a simplified Feynman diagram where the arrow of time represents the interaction modes of: **Shake it, Break it, Make it**.

Shake it refers to the direct detection of dark matter. Direct detection interactions start with a free DM particle and an SM particle. The DM and SM interact via elastic or inelastic collision and recoil away from each other. The DM remains in the dark sector and imparts some momentum onto the SM particle. The hope is that the momentum imparted onto the SM particle is sufficiently high enough to pick up with extremely sensitive instruments. Because we cannot create the DM in the lab, a direct detection experiment must wait until DM is incident on the detector. Most direct detection experiments are therefore placed in low-background environments with inert detection

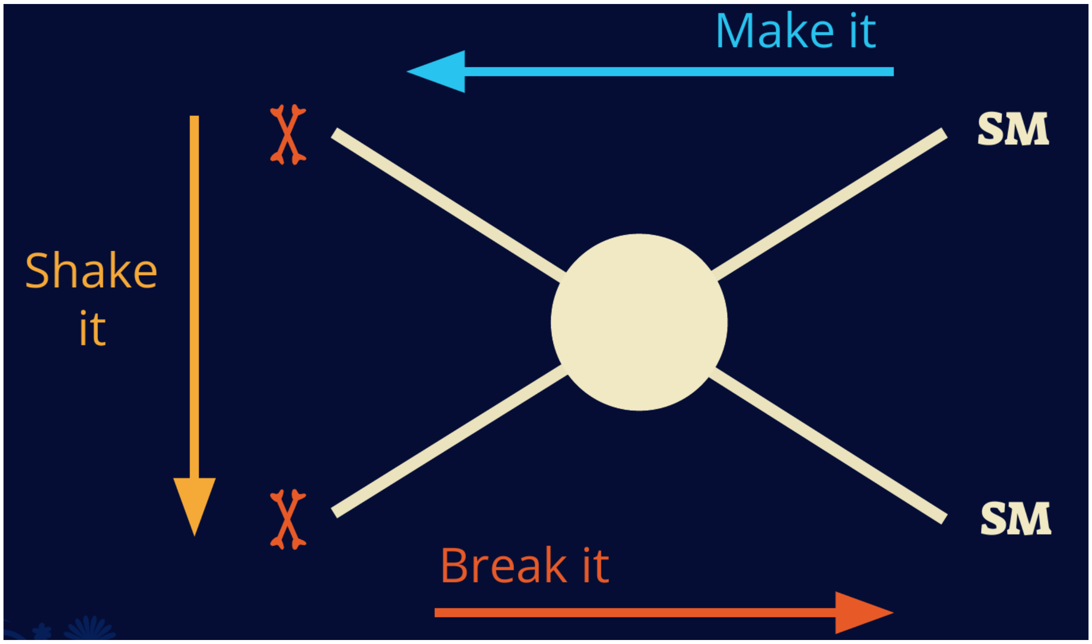

Figure 2.8 Simplified Feynman diagram demonstrating with different ways DM can interact with SM particles. The 'X's refer to the DM particles whereas the SM refer to fundamental particles in the SM. The large circle in the center indicates the vertex of interaction and is purposely left vague. The colored arrows refer to different directions of time as well as their respective labels. The arrows indicate the initial and final state of the DM -SM interaction in time.

media like the noble gas Xenon. [14]

Make it refers to the production of DM from SM initial states. The experiment starts with particles in the SM. These SM particles are accelerated to incredibly high energies and then collide with each other. In the confluence of energy, DM hopefully emerges as a byproduct of the SM annihilation. Often it is the collider experiments that are energetic enough to hypothetically produce DM. These experiments include the world-wide collaborations ATLAS and CMS at CERN where proton collide together at extreme energies. The DM searches, however, are complex. DM likely does not interact with the detectors and lives long enough to escape the detection apparatus of CERN's colliders. This means any DM production experiment searches for an excess of events with missing momentum or energy in the events. An example event with missing transverse momentum is shown in Figure 2.9. The missing momentum with no particle tracks implies a neutral particle carried the energy out of the detector. However, there are other neutral particles in the SM, like neutrons or neutrinos, so any analysis has to account for SM signatures of missing momentum. [15]

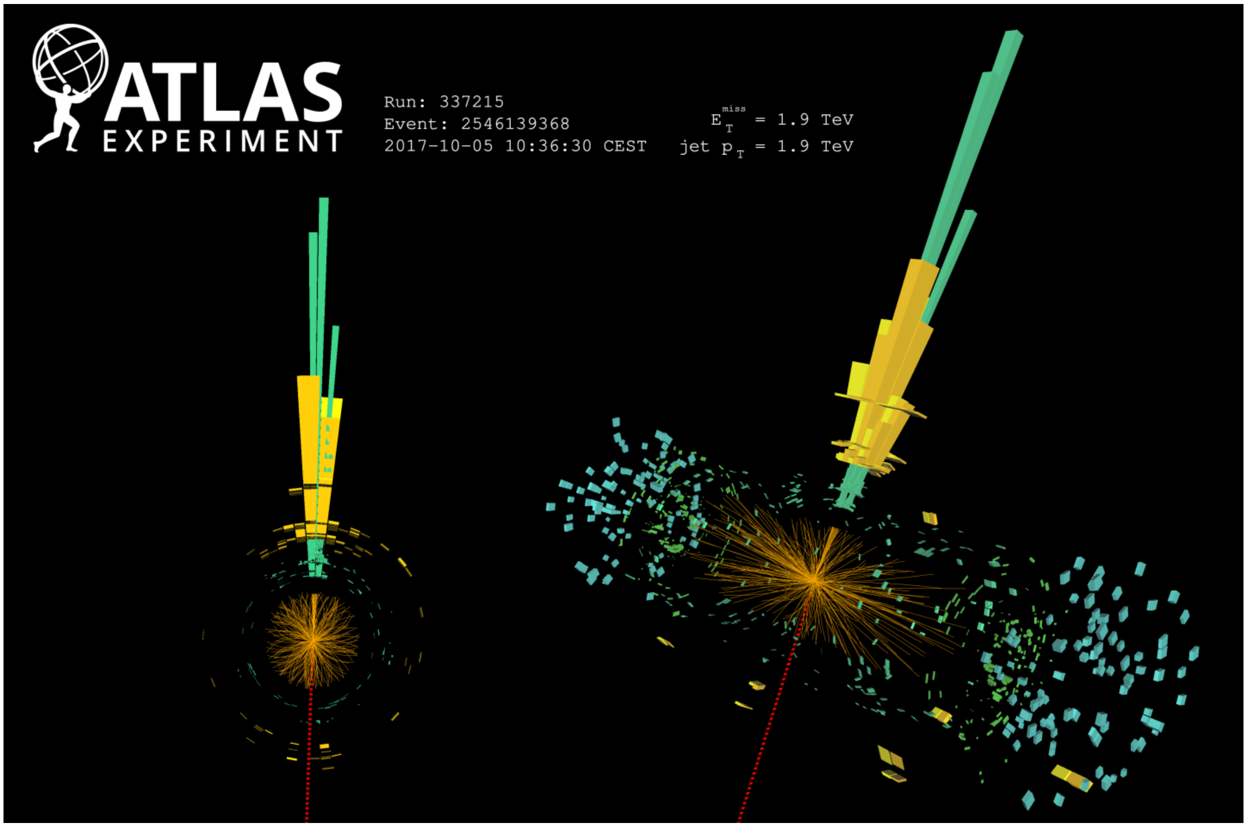

Figure 2.9 A single jet event in ATLAS detector from 2017 [16]. Jet momentum was observed to be 1.9 TeV. Missing transverse momentum was observed to be 1.9 TeV compared to the initial transverse momentum of the event was 0. Implied MET is traced by a red dashed line in event display.

2.4.2 Break it: Standard Model Signatures of Dark Matter through Indirect Searches

Break it refers to the creation of SM particles from the dark sector, and it is the primary focus of this thesis. The interaction begins with DM or in the dark sector. The hypothesis is that this DM will either annihilate with itself or decay and produce an SM byproduct. This method is often referred to as the Indirect Detection of DM because we have no lab to directly control or manipulate the DM. Therefore, most indirect DM searches are performed using observations of known DM densities among the astrophysical sources. The strength is that we have the whole of the universe and its 13.6-billion-year lifespan to use as a detector and particle accelerator. Additionally, locations of dark matter are well cataloged since it was astrophysical observations that presented the problem of DM in the first place.

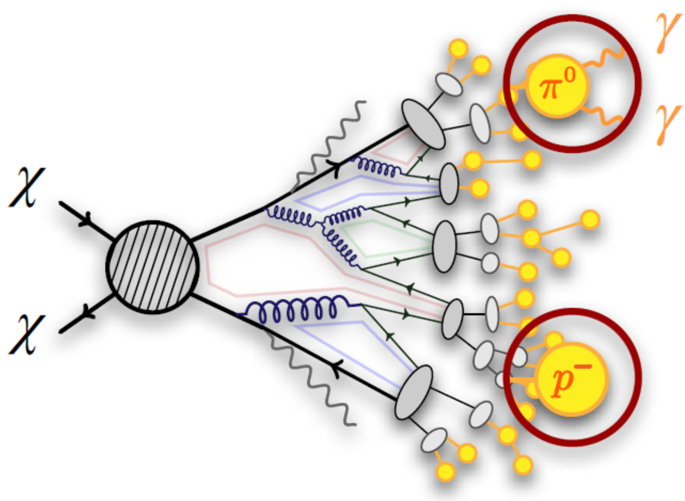

Figure 2.10 More detailed pseudo-Feynman diagram of particle cascade from dark matter annihilation into 2 quarks. The quarks hadronize and down to stable particles like γ or the anti-proton (p^{-}). Diagram pulled from ICRC 2021 presentation on DM annihilation search [17].

However, anything can happen in the universe. There are many difficult to deconvolve backgrounds when searching for DM. One prominent example is the galactic center. We know the galactic center has a large DM content because of stellar kinematics in our Milky Way and DM halo simulations. Yet, any signal from the galactic center is challenging to parse apart from the extreme environment of our supermassive black hole, unresolved sources, and diffuse emission from the interstellar medium [18]. Despite the challenges, any DM model that yields evidence in the other two observation methods, **Shake it or Make it** must be corroborated with indirect observations of the known DM sources. Without corroborating evidence, DM observation in the lab is hard-pressed to demonstrate that it is the model contributing to the DM seen at the universal scale.

In the case of WIMP DM, signals are described in terms of primary SM particles produced from DM decay or annihilation. The SM initial state particles are then simulated down to stable final states such as the γ, ν, p, or e which can traverse galactic lengths to reach Earth.

Figure 2.10 shows the quagmire of SM particles that emerges from SM initial states that are not stable [17]. There are many SM particles with varying energies that can be produced in such an interaction. For any arbitrary DM source and stable SM particle, the SM flux from DM annihilating to a neutral particle in the SM, ϕ, from a region in the sky is described by the following.

$$\frac{d\Phi_\phi}{dE_\phi} = \frac{\langle\sigma v\rangle}{8\pi m_\chi^2}\frac{dN_\phi}{dE_\phi} \times \int_{\text{source}} d\Omega \int_{l.o.s} \rho_\chi^2 dl(r,\theta') \tag{2.4}$$

n Equation (7.1), $\langle\sigma v\rangle$is the velocity-weighted annihilation cross-section of DM to the SM. m_χ refers to the mass of DM, noted with Greek letter χ. $\frac{dN_\phi}{dE_\phi}$ is the N particle flux weighted by the particle energy. An example is provided in Figure 2.11 for the γ final state. The integrated terms are performed over the solid angle, $d\Omega$, and line of sight, l.o.s. ρ is the density of DM for a location (r,θ') in the sky. The terms left of the '×' are often referred to as the particle physics component. The terms on the right are referred to as the astrophysical component. For decaying DM, the equation changes to...

$$\frac{d\Phi_\phi}{dE_\phi} = \frac{1}{4\pi\tau m_\chi}\frac{dN_\phi}{dE_\phi} \times \int_{\text{source}} d\Omega \int_{l.o.s} \rho_\chi dl(r,\theta') \tag{2.5}$$

In Equation (2.5), τ is the decay lifetime of the DM. Just as in Equation (7.1), the left and right terms are the particle physics and the astrophysical components respectively. The integrated astrophysical component of Equation (7.1) is often called the J-Factor. Whereas the integrated astrophysical component of Equation (2.5) is often called the D-Factor.

Exact DM DM → SM SM branching ratios are not known, so it is usually assumed to go 100% into an SM particle/anti-particle. Additionally, when a DM annihilation or decay produces one of the neutral, long-lived SM particles (ν or γ), the particle is traced back to a DM source. For DM above GeV energies, there are very few SM processes that can produce particles with such a high energy. Seeing such a signal would almost certainly be an indication of the presence of dark matter. Fortunately, the universe provides us with the largest volume and lifetime ever for a particle physics experiment.

2.5 Sources for Indirect Dark Matter Searches

The first detection of DM relied on optical observations. Since then, we have developed new techniques to find DM dense regions. As described in Section 2.3.1, many DM dense regions were through observing galactic rotation curves. Our Milky Way galaxy is among DM dense regions

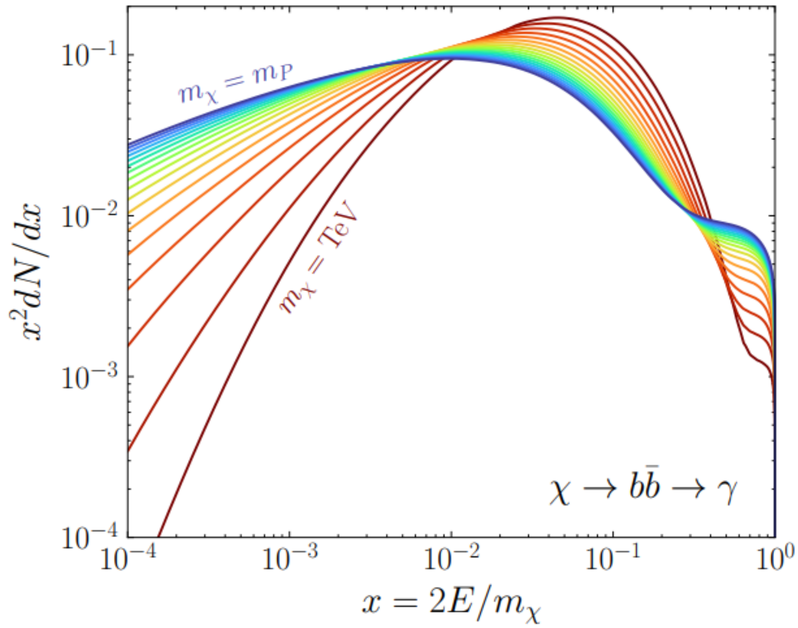

Figure 2.11 Dark Matter (DM) decay spectrum for $b\bar{b}$ initial state and γ final state. Redder spectra are for larger DM masses. Bluer spectra are light DM masses. x is a unitless factor defined as the ratio of the mass of DM, m_χ, and the final state particle energy E_γ. Figure from [19].

discovered, and it is the largest nearby DM dense region to look at. Additionally, the DM halo surrounding the Milky Way is clumpy [18]. There are regions in the DM halo of the Milky Way that have more DM than others that have captured gas over time. These sub-halos were dense enough collapse gas and form stars. These apparent sub galaxies are known as dwarf spheroidal galaxies and are the main sources studied in this thesis. Each source type comes with different trade-offs. Galactic Center studies will be very sensitive to the assumed distribution of DM. The central DM density can vary substantially as demonstrated in Figure 2.12. At distances close to the center of the galaxy, or small r, the differences in DM densities can be 3-4 orders of magnitude. Searches toward the galactic center will therefore be quite sensitive to the assumed DM distribution.

Searches toward Dwarf Spheroidal Galaxies (dSph's) suffer from uncertainties in the DM density less than the galactic center studies. This is mostly from their diminutive size being smaller than the angular resolution of most γ-ray observatories [18]. The DM content dSph's are typically determined with the Virial theorem, Equation (2.1), and are usually majority DM [18] in mass. DSph's tend to be ideal sources to look at for DM searches. Their environments are quiet with little

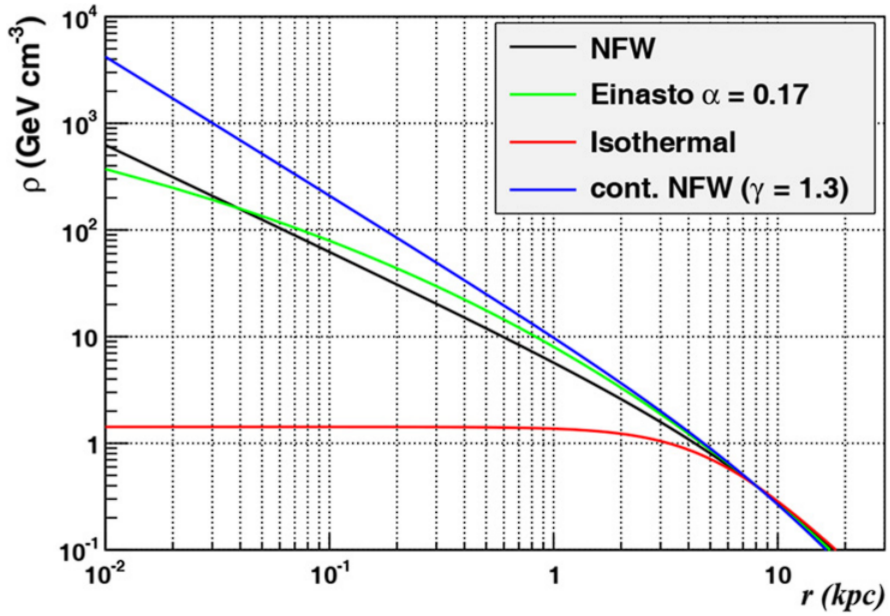

Figure 2.12 Different dark matter density profiles compared. Some models produce exceptionally large densities at small r [20].

astrophysical background. Unlike the galactic center, the most active components of dSph's are the stars within them versus a violent accretion disc around a black hole. All this together means that dSph's are among the best sources to look at for indirect DM searches. dSph's are the targets of focus for this thesis.

2.6 Multi-Messenger Dark Matter

Astrophysics entered a new phase in the past few decades that leverages our increasing sensitivity to SM channels and general relativity (GR). Up until the 21st century, astrophysical observations were performed with photons (γ) only. Astrophysics with this 'messenger' is fairly mature now. Novel observations of the universe have since only adjusted the sensitivity of the wavelength of light that is observed except at MeV energies. Gems like the CMB [10], and more have ultimately been observations of different wavelengths of light. Multi-messenger astrophysics proposes using other SM particles such the $p^{+/-}$, or ν or gravitation waves predicted by general relativity.

The experiment LIGO had a revolutionary discovery in 2016 with the first detection of a binary black hole merger [21]. This opened the collective imagination to observing the universe through gravitational waves. There has also been a surge of interest in the neutrino (ν) sector. IceCube demonstrated that we are sensitive to neutrinos in regions that correlate with significant photon emission like the galactic plane [22]. Neutrinos, like gravitational waves and light, travel mostly unimpeded from their source to our observatories. This makes pointing to the originating source of these messengers much easier than it is for cosmic rays which are deflected from their source by magnetic fields.

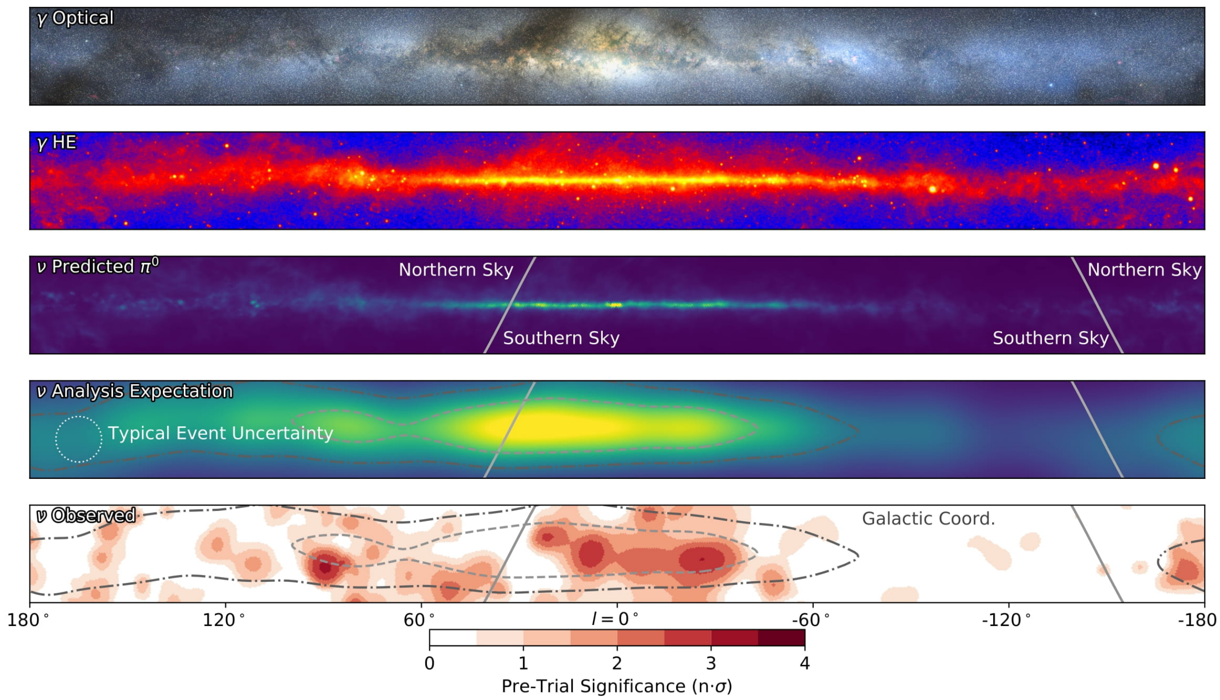

Figure 2.13 The Milky Way Galaxy in photons (γ) and neutrinos (ν) [22]. The Galactic center is at l=0°and is the brightest region in all panels. (top) An Optical color image of the Milky Way galaxy seen from Earth. Clouds of gas and dust obscure some light from stars. (2nd down) Integrated flux of γ-rays observed by the Fermi-LAT telescope [23]. (middle) Expected neutrino emission that corresponds with Fermi-LAT observations. (2nd up) Expected neutrino emission profile after considering detector systematics of IceCube. (bottom) Observed neutrino emission from region of the galactic plane. Substantial neutrino emission was detected.

The IceCube collaboration recently published a groundbreaking result of the Milky Way in neutrinos. The recent result from IceCube, shown in Figure 2.13, proves that we can make observations under different messenger regimes. The top two panels show the appearance of the galactic plane to different wavelengths of light. Some sources are more apparent in some panels, while others are not. This new channel is powerful because neutrinos are readily able to penetrate through gas and dust in the Milky Way. This new image also refines our understanding of how high energy particles are produced. For example, the fit to IceCube data prefers neutrino production from the decay of π^0 [22].

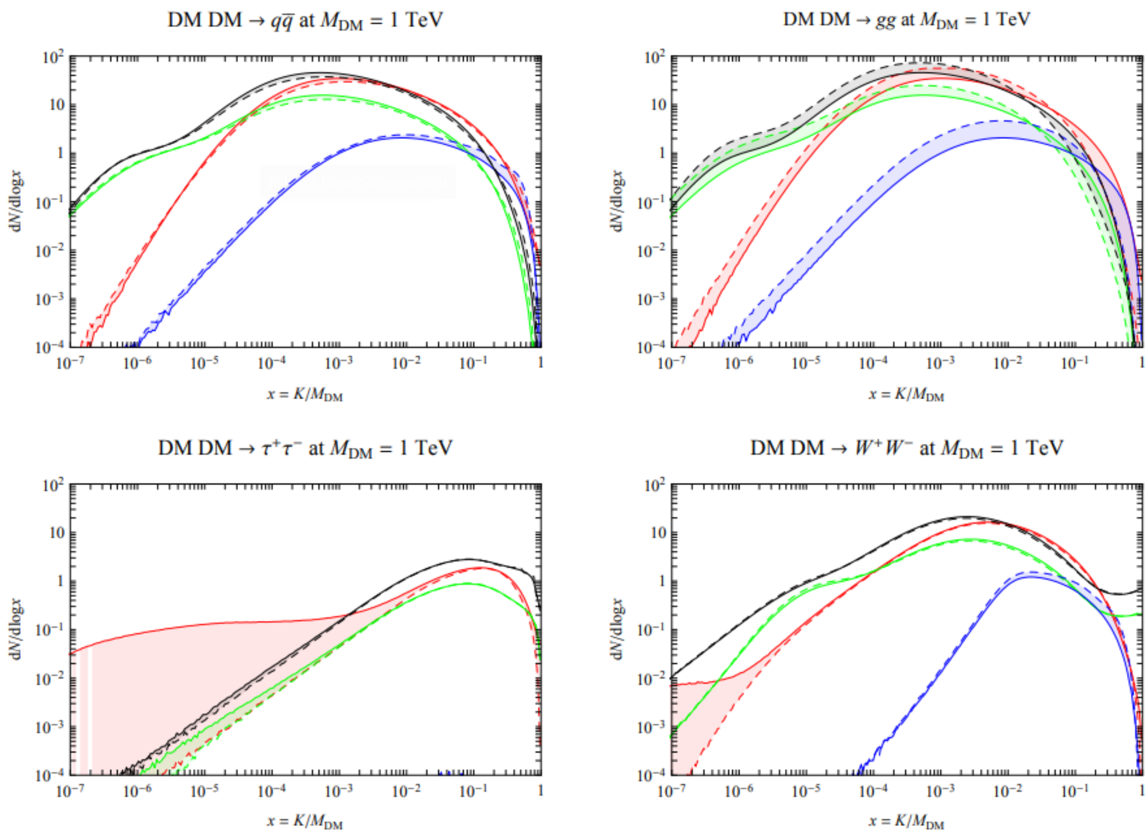

Figure 2.14 Dark Matter annihilation spectra for different final state particle and standard model annihilation channels [24]. Photons (red), $e^{\pm}$ (green), $\bar{p}$ (blue), ν (black).

Exposing our observations to more cosmic messengers greatly increases our sensitivity to rare processes. In the case of DM, Figure 2.14, there are many SM particles produced in DM annihilation. Among the final state fluxes are gammas and neutrinos. Charged particles are also produced however they would not likely make it to Earth since they will be deflected by magnetic fields between the source and Earth. This means observatories that can see the neutral messengers are especially good for DM searches and for combining data for a multi-messenger DM search.

CHAPTER 3

MULTIMESSENGER ASTROPHYSICS: DETECTING HIGH ENERGY NEUTRAL MESSENGERS

3.1 Introduction

Before the 20th century, all asttrophysics observations were optical in nature. We litterally only saw things with highly magnifiied optical observations. Then we discovered cosmic rays. cosmic rays are charged particles, typically naked protons or H+. This was seen by Victor Hess in 19??. Around the same time we discovered neutrinos from beta decay. Sometime around 1950 we started to build neutrino detectors which were mostly sensitive to neutrinos from the sun. Finally, it was theorized that compact objects like black holes and neutron stars would create waves in space-time when they experience mergers or collisions.

In the 21st century, we have developed new observation techniques and detectors that are no only sensitive to these four messengers - photons (TODO: photon), neutrinos (TODO: nu), Cosmic Rays (CR), and Gravitational Wave (WV) - we're collect high energy versions of these events. For the standad model particles, we're now sensitive to all messengers above the MeV eneryg range. Additionally, the GW's were sensitive to are in the stellar mass black hole region and above within our galactic neighborhood. This means were becoming sensitive to the fundamental physics occuring within the universe and we can rely on the universe as a TeV+ particle accelerator. We also have the abaility to correlate high energy events across messengers and gain new insights on the processes that occur in our universe.

This thesis focuses on very high energy (VHE) gamma rays and neutrinos. These can both be observed through the water cherenkov detection technique altho not exclusively. Methods on how to detect and observe these neutral messengers are discussed Section 3.3 and Section 3.4

3.2 Charged Particles in a Medium

For high enery gamma-rays and neutrinos, we can exploit the same effect that charged particles have with water. This effect is known as Cherenkov radiation. Cherenkov Radiation occurs when a charged particle, usually electrons (e) or muons (μ), traverse a medium, like water, faster than the speed of light in that medium. This is similar to sonic boom where an object moves through air faster than the speed of sound in air. Cherenkov radiation can therefor be thought of as an 'optic boom'. Many astro-particle physics experiments will use water as the medium as because water has a unique set of properties ideal for charged particle tracking.

Figure 3.1 TODO: Show a nuclear reactor with cherenkov radiation[NEEDS A SOURCE][FACT CHECK THIS]

The frequency of light emmited due to cherenkov radiation follows the equation:

$$INSERTCherenkovwavelengthcalcHERE. \tag{3.1}$$

The absorption spectra is shown in the following figure:

3.3 Photons (γ)

3.4 Neutrinos (ν)

3.5 Opportunities to Combine for Dark Matter

Figure 3.2 TODO: absorption spectrum of liquid and solid water[NEEDS A SOURCE][FACT CHECK THIS]

CHAPTER 4

HIGH ALTITUDE WATER CHERENKOV (HAWC) OBSERVATORY

4.1 The Detector

4.2 Events Reconstruction and Data Acquisition

4.2.1 G/H Discrimination

4.2.2 Angle

4.2.3 Energy

4.3 Remote Monitoring

4.3.1 ATHENA Database

4.3.2 HOMER

CHAPTER 5

ICECUBE NEUTRINO OBSERVATORY

5.1 The Detector

5.2 Events Reconstruction and Data Acquisition

5.2.1 Angle

5.2.2 Energy

5.3 Northern Test Site

5.3.1 PIgeon remote dark rate testing

5.3.2 Bulkhead Construction

CHAPTER 6

COMPUTATIONAL TECHNIQUES IN PARTICLE ASTROPHYSICS

6.1 Neural Networks for Gamma/Hadron Separation

6.2 Parallel Computing for Dark Matter Analyses

CHAPTER 7

GLORY DUCK: MULTI-WAVELENGTH SEARCH FOR DARK MATTTER ANNIHILATION TOWARDS DWARF SPHEROIDAL GALAXIES

7.1 Introduction

The field of astrophysics now has several instruments and observatories sensitive to high energy gamma-rays. The energy sensitivity for the modern gamma-ray program spans many orders of magnitude. Figure 7.1 demonstrates these similar sensitivities across energies for the five experiments: Fermi-LAT, HAWC, HESS, MAGIC, and VERITAS.

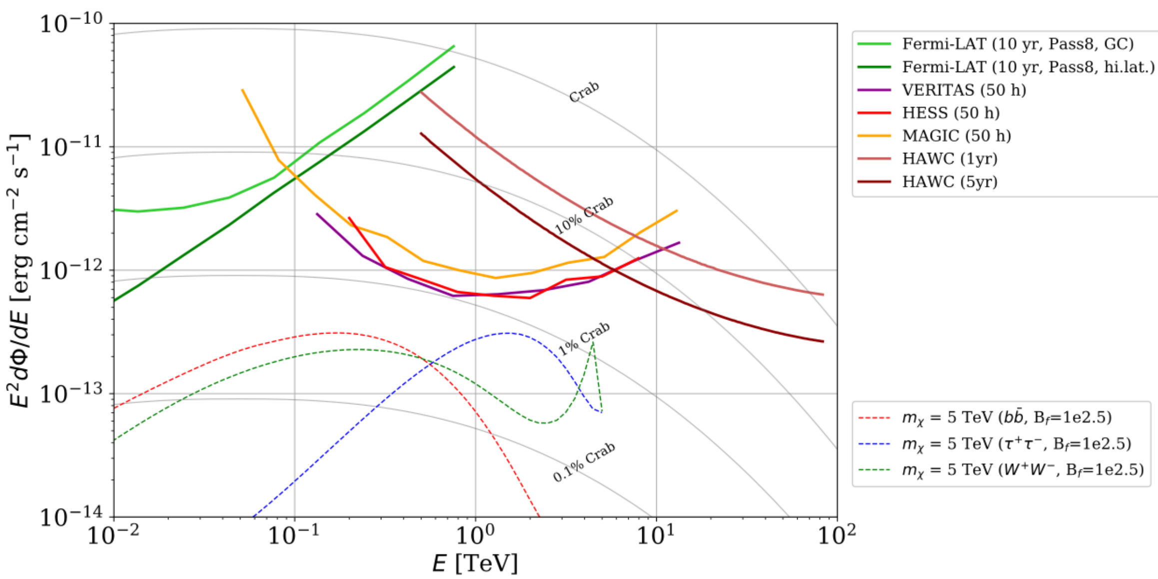

Figure 7.1 [NEEDS A SOURCE]Sensitivities of five gamma-ray experiments compared to percentages of the Crab nebula's emission and dark matter annihilation. Solid lines present estimated sensitivities to power law spectra [FACT CHECK THIS]for each experiment. Green lines are Fermi-LAT sensitivities where lighter green is the sensitivity to the galactic center and light green is its sensitivity to higher declinations. Orange, red, and purple solid lines represent the MAGIC, HESS, and VERITAS 50 hour sensitivities respectively. The maroon and brown lines are the HAWC 1 year and 5 year sensitivities. Across four decades of gamma-ray energy, these experiments have similar sensitivities on the order 10^{-12} erg cm^{-2}s^{-1}. The dotted lines are estimated dark matter fluxes assuming DM annhilating to bottom quarks (red), tau leptons (blue), and W bosons (green). Faded grey lines outline percentage flux of the Crab nebula.

Each of the five experiments featured in Figure 7.1 have independently searched for DM annihilation from dwarf galaxies and set limits. Intriguingly, their similarities overlap in regions where these observatories are less sensitive. This clearly motivates an analysis that combines data from these five. Each experiment has unique gammma-ray detection methods and their weaknesses and strengths can be leveraged with each other. The HAWC gamma-ray observatory is extensively introduced in chapter 4, so it is not introduced here. A brief description of the remaining experiments are in the following paragraphs.

The Large Area Telescope (LAT) is a pair conversion telescope mounted on the NASA Fermi satellite in orbit 550 km above the Earth [25]. LAT's field of view covers about 20% of the whole sky, and it sweeps the whole sky every 3 hours, approximately. LAT's gamma-ray energy sensitivity ranges from 20 MeV up to 1 TeV. Previous DM searches towards dwarf galaxies using Fermi-LAT are published in [26] and [27]

The High Energy Spectroscopic System (HESS), Major Atmospheric Gamma Imaging Cherenkov (MAGIC), and Very Energetic Radiation Imaging Telescope Array System (VERITAS) are arrays of Imaging Atmospheric Cherenkov Telescopes (IACT). These telescopes observe the Cherenkov light emmitted from gamma-ray showers in the Earth's atmosphere. The field for these telescopes is no larger than 5° with energy sensitivities ranging from 30 GeV up to 100 TeV. [28, 29, 30] IACTs are able to make precise observations in selected regions of the sky, however can only be operated in ideal dark conditions. HESS's observations of the dwarves Sculptor and Carina were between January 2008 and December 2009. HESS observations of Coma Berenices were from 2010 to 2013, and Fornax was observed in 2010 [31, 32, 33]. MAGIC provided deep observations of Segue1 between 2011 and 2013 [34]. MAGIC also provides data for three dwarves: Coma Berenices, Draco, and Ursa Major II where observations were made in: January - June 2019 [35], March - September 2018 [35], and 2014 - 2016 [36] respectively. VERITAS provided data for Boötes I, Draco, Segue 1, and Ursa Minor from 2009 to 2016 [37]

This chapter presents the Glory Duck analysis, the name given for the search for dark matter annihilation from dwarf galaxies by combining data from the five gamma-ray observatories: Fermi-LAT, HAWC, HESS, MAGIC, and VERITAS. Specifically, the methods in analysis and modeling are presented for the HAWC gamma-ray observatory. This work was published to ??? and presented at the International Cosmic Ray Conferance in 2019, 2021, and 2023 [38, 39, 40] and more.

7.2 Dataset and Background

This section enumerates the data and background methods used for HAWC's study of the dwarf spheroidal galaxies (dSph). Section 7.2.1 and Section 7.2.2 are most useful for fellow HAWC collaborators looking to replicate the Glory Duck analisys.

7.2.1 Itemized HAWC files

- Detector Resolution: `response_aerie_svn_27754_systematics_best_mc_test_nobroadpulse\_10pctlogchargesmearing_0.63qe_25kHzNoise_run5481_curvature0_index3.root`
- Data Map: `maps-20180119/liff/maptree_1024.root`
- Spectral Dictionary: `DM_CirrelliSpectrum_dict_gammas.npy`
- Analysis wiki: `https://private.hawc-observatory.org/wiki/index.php/Glory_Duck_Multi-Experiment_Dark_Matter_Search`

7.2.2 Software Tools and Development

This analysis was performed using HAL and 3ML, in Python version 2[41, 42]. I built software to implement the *Poor Particle Physicists' Cookbook* (PPPC) [43] DM spectral model and dSphs spatial model from [44] for HAWC analysis. A NumPy version of this dictionary was made for both Py2 and Py3. The code base for creating this dictionary is linked on my GitLab sandbox:

- Py2: Dictionary Generator (Deprecated)
- Py3: PPPC2Dict

The analysis was performed using the f_{hit} framework performed in the Crab paper[41]. The Python2 NumPy dictionary file for gamma-ray final states is `dmCirSpecDict.npy`. The corresponding Python3 file is `DM_CirrelliSpectrum_dict_gammas.npy`. These files can also be used for decay channels and the PPPC describes how. [43]. All other software used for data analysis, DM profile generation, and job submission to SLURM are also kept in my sandbox for the Glory Duck project.

7.2.3 Data Set and Background Description

The HAWC data maps used for this analysis contain 1017 days of data between runs 2104 (2014-11-26) and 7476 (2017-12-20). They were generated from pass 4.0 reconstruction. The analysis is performed using the f_{hit} energy binning scheme with bins (1-9) similar to what was done for the Crab and previous HAWC dSph analysis. [41, 45]. Bin 0 was excluded as it has substantial hadronic contamination and poor angular resolution.

This analysis was done on dwarf spheroidal (dSph) galaxies because of their large dark matter (DM) content relative to baryonic. We consider the following to estimate the background to this study.

- The dSphs are small in HAWC's field of view, so the analysis is not sensitive to large or small scale anisotropies.
- The dSphs used in this analysis are off the galactic plane.
- The dSphs are baryonically faint relative to their expected dark matter content and are not expected to contain gamma-ray sources.

Therefor we make no additional assumptions on the background from our sources and use HAWC's standard direct integration method for background estimation [41]. It is possible for gamma rays from DM annihilation to scatter in transit to HAWC via Inverse Compton Scattering (ICS). This was investigated and its impact on the flux is basically zero. Supporting information on this is in Section 7.6.1

7.3 Analysis

The expected differential photon flux from DM-DM annihilation to standard model particles over solid angle is described by the familiar equation.

$$\frac{d\Phi_\gamma}{dE_\gamma} = \frac{\langle\sigma v\rangle}{8\pi m_\chi^2}\frac{dN_\gamma}{dE_\gamma} \times \int_{\text{source}} d\Omega \int_{l.o.s} \rho_\chi^2 dl(r, \theta') \tag{7.1}$$

Where $\langle\sigma v\rangle$ is the velocity weighted annihilation cross-section. $\frac{dN}{dE}$ is the expected differential number of photons produced at each energy per annihilation. M_χ is the rest mass of the supposed DM particle. J is the astrophysical J-factor and is defined as

$$J = \int\int \rho_\chi^2(l,\Omega)\,dl\,d\Omega \tag{7.2}$$

ρ_χ is the DM density. How each component is generated and considered for HAWC's analysis is presented in the following sections.

7.3.1 $\frac{dN_\gamma}{dE_\gamma}$ Particle Physics Component

For this value, we import the PPPC with Electro-Weak (EW) corrections [43]. The spectrum is implemented as a model script in astromodels for 3ML. The PPPC model selected for this analysis included EW corrections. The EW corrections were previously not considered for HAWC and are significant for DM annihilating to EW coupled SM particles such as all leptons, and the γ, Z, and W bosons. [45]. Figure 7.2 demonstrates the significance of EW corrections for W boson annihilation. A class in atromodels created to include the EW correction from PPPC is aptly named `PPPCSpectra` within `DM_models.py`.

7.3.2 J Astrophysical Component

The J-factor profiles for each source is imported from Geringer-Sameth ($\mathcal{GS}$) [44]. Another DM distribution model from Bonnivard ($\mathcal{B}$) [46] was used for the complete study. However, to save computational time, limits from $\mathcal{GS}$ were scaled to $\mathcal{B}$ instead of each experiment performing a full study a second time. We create NSIDE 16384 maps of the J-factors for each dSph. These maps are integrated over every spatial bin and passed to the fitting software. Plots of these maps are provided for each source in the sandbox directory: `GD_mass_profiles`.

7.3.3 Source Selection and Annihilation Channels

We use many of the dSph presented in our previous dSph DM search [45]. HAWC's sources for Glory Duck include Boötes I, Coma Berenices, Canes Venatici I + II, Draco, Hercules, Leo I, II, + IV, Segue 1, Sextans, and Ursa Major I + II. A full description of all sources used in Glory Duck is found in Table 7.1. Triangulum II was excluded from the Glory Duck analysis because

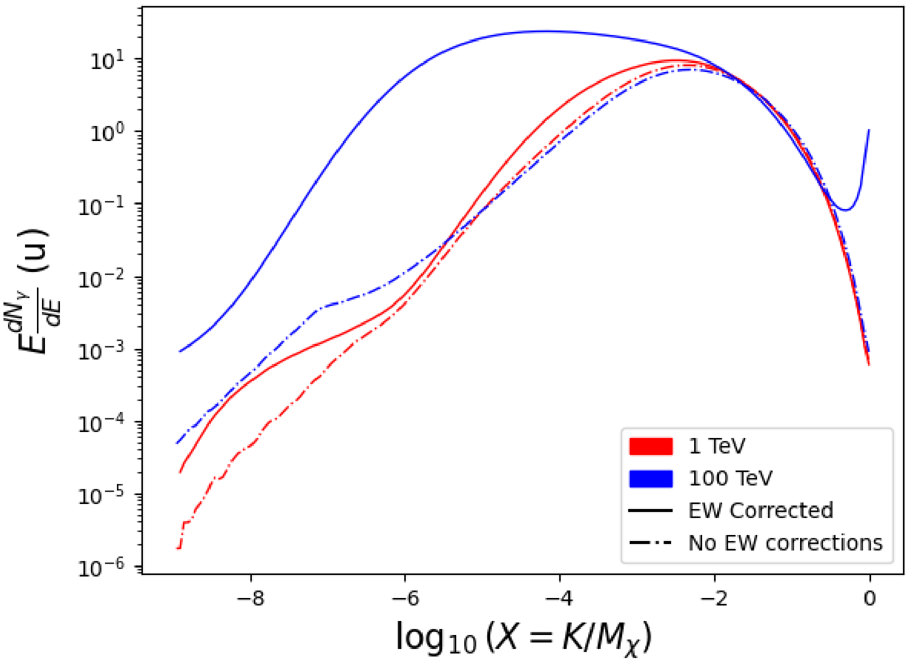

Figure 7.2 Effect of Electro-Weak (EW) corrections on expected DM annihilation spectrum for $\chi\chi \rightarrow W^-W^+$. Solid lines are spectral models that consider EW corrections. Dash-dot lines are spectral models without EW corrections. Red lines are models for $M_\chi = 1$ TeV. Blue lines represent models for $M_\chi = 100$ TeV. All models are sourced from the PPPC4DMID [43].

of large uncertainties in its J-factor. Ursa Minor was excluded from HAWC's contribution to the combination because the source extension model extended Ursa Minor beyond HAWC's field of view. Ursa Minor was not expected to contribute significantly to the combined limit, so work was not invested in a solution to include Ursa Minor.

The DM annihilation channels probed for the Glory Duck combination include $b\bar{b}$, $e\bar{e}$, $\mu\bar{\mu}$, $\tau\bar{\tau}$, $t\bar{t}$, W^+W^-, and ZZ. A summary of all sources, with a description of each experiments' sensitivity to the source, is provided in Table 7.2.

7.3.4 Likelihood Methods

We perform a standard HAWC binned maximum likelihood analysis using f_{hit} bins 1-9. This analysis was performed using HAL and 3ML, in Python2 [41, 42]. With these tools we compute the max from the likelihood profiles and perform a ratio test to calculate the significance of each source. This analysis is identical to the previous dSph analysis [45] except the sources are treated as extended. For the vast majority of our sources, this extension is no greater than 2 degrees. We

Table 7.1 Summary of the relevant properties of the dSphs used in the present work. Column 1 lists the dSphs. Columns 2 and 3 present their heliocentric distance and galactic coordinates, respectively. Columns 4 and 5 report the J-factors of each source given from the $\mathcal{GS}$ and $\mathcal{B}$ independent studies and their estimated $\pm 1\sigma$ uncertainties. The values $\log_{10} J$ ($\mathcal{GS}$ set) [44] correspond to the mean J-factor values for a source extension truncated at the outermost observed star. The values $\log_{10} J$ ($\mathcal{B}$ set) [46] are provided for a source extension at the tidal radius of each dSph. **Bolded sources are within HAWC's field of view and provided to the Glory Duck analysis.**

Name	Distance (kpc)	l, b (°)	$\log_{10} J$ ($\mathcal{GS}$ set) $\log_{10}(\mathrm{GeV^2 cm^{-5} sr})$	$\log_{10} J$ ($\mathcal{B}$ set) $\log_{10}(\mathrm{GeV^2 cm^{-5} sr})$
Boötes I	66	358.08, 69.62	$18.24^{+0.40}_{-0.37}$	$18.85^{+1.10}_{-0.61}$
Canes Venatici I	218	74.31, 79.82	$17.44^{+0.37}_{-0.28}$	$17.63^{+0.50}_{-0.20}$
Canes Venatici II	160	113.58, 82.70	$17.65^{+0.45}_{-0.43}$	$18.67^{+1.54}_{-0.97}$
Carina	105	260.11, −22.22	$17.92^{+0.19}_{-0.11}$	$18.02^{+0.36}_{-0.15}$
Coma Berenices	44	241.89, 83.61	$19.02^{+0.37}_{-0.41}$	$20.13^{+1.56}_{-1.08}$
Draco	76	86.37, 34.72	$19.05^{+0.22}_{-0.21}$	$19.42^{+0.92}_{-0.47}$
Fornax	147	237.10, −65.65	$17.84^{+0.11}_{-0.06}$	$17.85^{+0.11}_{-0.08}$
Hercules	132	28.73, 36.87	$16.86^{+0.74}_{-0.68}$	$17.70^{+1.08}_{-0.73}$
Leo I	254	225.99, 49.11	$17.84^{+0.20}_{-0.16}$	$17.93^{+0.65}_{-0.25}$
Leo II	233	220.17, 67.23	$17.97^{+0.20}_{-0.18}$	$18.11^{+0.71}_{-0.25}$
Leo IV	154	265.44, 56.51	$16.32^{+1.06}_{-1.70}$	$16.36^{+1.44}_{-1.65}$
Leo V	178	261.86, 58.54	$16.37^{+0.94}_{-0.87}$	$16.30^{+1.33}_{-1.16}$
Leo T	417	214.85, 43.66	$17.11^{+0.44}_{-0.39}$	$17.67^{+1.01}_{-0.56}$
Sculptor	86	287.53, −83.16	$18.57^{+0.07}_{-0.05}$	$18.63^{+0.14}_{-0.08}$
Segue I	23	220.48, 50.43	$19.36^{+0.32}_{-0.35}$	$17.52^{+2.54}_{-2.65}$
Segue II	35	149.43, −38.14	$16.21^{+1.06}_{-0.98}$	$19.50^{+1.82}_{-1.48}$
Sextans	86	243.50, 42.27	$17.92^{+0.35}_{-0.29}$	$18.04^{+0.50}_{-0.28}$
Ursa Major I	97	159.43, 54.41	$17.87^{+0.56}_{-0.33}$	$18.84^{+0.97}_{-0.43}$
Ursa Major II	32	152.46, 37.44	$19.42^{+0.44}_{-0.42}$	$20.60^{+1.46}_{-0.95}$
Ursa Minor	76	104.97, 44.80	$18.95^{+0.26}_{-0.18}$	$19.08^{+0.21}_{-0.13}$

Table 7.2 Summary of dSph observations by each experiment used in this work. A '-' indicates the experiment did not observe the dSph for this study. For Fermi-LAT, the exposure at 1 GeV is given. For HAWC, $|\Delta\theta|$ is the absolute difference between the source declination and HAWC latitude. HAWC is more sensitive to sources with smaller $|\Delta\theta|$. For IACTs, we show the zenith angle range, the total exposure, the energy range, the angular radius θ of the signal or ON region, the ratio of exposures between the background-control (OFF) and signal (ON) regions (τ), and the significance of gamma-ray excess in standard deviations, σ.

	Fermi-LAT	HAWC	H.E.S.S, MAGIC, VERITAS						
Source name	Exposure (10^{11} s m^2)	$\lvert\Delta\theta\rvert$ (°)	IACT	Zenith (°)	Exposure (h)	Energy range (GeV)	θ (°)	τ	S (σ)
Boötes I	2.6	4.5	VERITAS	15 – 30	14.0	100-41000	0.10	8.6	−1.0
Canes Venatici I	2.9	14.6	–	–	–	–	–	–	–
Canes Venatici II	2.9	15.3	–	–	–	–	–	–	–
Carina	3.1	–	H.E.S.S.	27 – 46	23.7	310 – 70000	0.10	18.0	−0.3
Coma Berenices	2.7	4.9	H.E.S.S.	47 – 49	11.4	550 – 70000	0.10	14.4	−0.4
			MAGIC	5 – 37	49.5	60 – 10000	0.17	1.0	–
Draco	3.8	38.1	MAGIC	29 – 45	52.1	70 – 10000	0.22	1.0	–
			VERITAS	25 – 40	49.8	120 – 70000	0.10	9.0	−1.0
Fornax	2.7	–	H.E.S.S.	11 – 25	6.8	230 – 70000	0.10	45.5	−1.5
Hercules	2.8	6.3	–	–	–	–	–	–	–
Leo I	2.5	6.7	–	–	–	–	–	–	–
Leo II	2.6	3.1	–	–	–	–	–	–	–
Leo IV	2.4	19.5	–	–	–	–	–	–	–
Leo V	2.4	–	–	–	–	–	–	–	–
Leo T	2.6	–	–	–	–	–	–	–	–
Sculptor	2.7	–	H.E.S.S.	10 – 46	11.8	200 – 70000	0.10	19.8	−2.2
Segue I	2.5	2.9	MAGIC	13 – 37	158.0	60 – 10000	0.12	1.0	−0.5
			VERITAS	15 – 35	92.0	80 – 50000	0.10	7.6	0.7
Segue II	2.7	–	–	–	–	–	–	–	–
Sextans	2.4	20.6	–	–	–	–	–	–	–
Ursa Major I	3.4	32.9	–	–	–	–	–	–	–
Ursa Major II	4.0	44.1	MAGIC	35 – 45	94.8	120 – 10000	0.30	1.0	−2.1
Ursa Minor	4.1	–	VERITAS	35 – 45	60.4	160 – 93000	0.10	8.4	−0.1

calculate the likelihood of each source and model, assuming events are Poisson distributed, with

$$\mathcal{L} = \prod_i \frac{(B_i + S_i)^{N_i} e^{-(B_i+S_i)}}{N_i!} \tag{7.3}$$

S_i is the sum of expected number of signal counts. B_i is the number of background counts observed. N_i is the total number of counts. The ith bin is iterated over spatial and f_{hit}. Then we combine the profiles across all five experiments. The profile likelihood ratio λ as a function of annihilation cross-section $\langle\sigma v\rangle$is computed by:

$$\lambda\left(\langle\sigma v\rangle \mid \mathcal{D}_{\mathrm{dSphs}}\right) = \frac{\mathcal{L}\left(\langle\sigma v\rangle; \hat{\hat{\boldsymbol{\nu}}} \mid \mathcal{D}_{\mathrm{dSphs}}\right)}{\mathcal{L}\left(\widehat{\langle\sigma v\rangle}; \hat{\boldsymbol{\nu}} \mid \mathcal{D}_{\mathrm{dSphs}}\right)} \tag{7.4}$$

for a considered annihilation channel and DM mass.

TODO: Section pasted from paper. Rephrase cause plagarism is a thing.As mentioned previously, each experiment computes the $\mathcal{L}_{lk}$ from Equation (7.4) differently. The remainder of this section highlights the differences in this calculation across the experiments. Four experiments, namely *Fermi*-LAT, H.E.S.S., HAWC and MAGIC, use a binned likelihood to compute the $\mathcal{L}_{lk}$. For these experiments, for each observation $\boldsymbol{\mathcal{D}_{lk}}$ of a given dSph l carried out using a given gamma-ray detector k, the binned likelihood function is:

$$\mathcal{L}_{lk}\left(\langle\sigma v\rangle; J_l, \boldsymbol{\nu_{lk}} \mid \boldsymbol{\mathcal{D}_{lk}}\right) = \prod_{i=1}^{N_{\mathrm{E'}}} \prod_{j=1}^{N_{\mathrm{P'}}} \left[\mathcal{P}(s_{lk,ij}(\langle\sigma v\rangle, J_l, \boldsymbol{\nu_{lk}}) + b_{lk,ij}(\boldsymbol{\nu_{lk}}) \mid N_{lk,ij})\right] \times \mathcal{L}_{lk,\boldsymbol{\nu}}\left(\boldsymbol{\nu_{lk}} \mid \boldsymbol{\mathcal{D}_{\nu_{lk}}}\right) \tag{7.5}$$

where $N_{\mathrm{E'}}$ and $N_{\mathrm{P'}}$ are the number of considered bins in reconstructed energy and arrival direction, respectively; $\mathcal{P}$ represents a Poisson PDF for the number of gamma-ray candidate events $N_{lk,ij}$ observed in the i-th bin in energy and j-th bin in arrival direction, when the expected number is the sum of the expected mean number of signal events s_{ij} (produced by DM annihilation) and of background events b_{ij}; $\mathcal{L}_{lk,\boldsymbol{\nu}}$ is the likelihood term for the extra $\boldsymbol{\nu_{lk}}$ nuisance parameters that vary from one instrument k to another. The expected counts for signal events s_{ij} for a given dSph l and detector k is given by:

$$s_{ij}(\langle\sigma v\rangle, J) = \int_{E'_{\min,i}}^{E'_{\max,i}} \mathrm{d}E' \int_{P'_{\min,j}}^{P'_{\max,j}} \mathrm{d}\Omega' \int_0^{\infty} \mathrm{d}E \int_{\Delta\Omega_{tot}} \mathrm{d}\Omega \int_0^{T_{\mathrm{obs}}} \mathrm{d}t \frac{\mathrm{d}^2\Phi(\langle\sigma v\rangle, J)}{\mathrm{d}E\mathrm{d}\Omega} \mathrm{IRF}\,(E', P' \mid E, P, t) \tag{7.6}$$

where E' and E are the reconstructed and true energies, P' and P the reconstructed and true arrival directions; $E'_{\min,i}$, $P'_{\min,j}$, $E'_{\max,i}$, and $P'_{\max,j}$ are their lower and upper limits of the i-th energy bin and the j-th arrival direction bin; T_{obs} is the (dead-time corrected) total observation time; t is the time along the observations; $\mathrm{d}^2\Phi/\mathrm{d}E\mathrm{d}\Omega$ is the DM flux in the source region (see Equation (7.1)); and $\mathrm{IRF}\,(E', P' \mid E, P, t)$ is the IRF, which can be factorized as the product of the effective collection area of the detector $A_{\mathrm{eff}}(E, P, t)$, the PDFs for the energy estimator $f_E(E' \mid E, t)$, and arrival direction $f_P(P' \mid E, P, t)$ estimators. Note that for Fermi-LAT, HAWC, MAGIC, and VERITAS the effect of the finite angular resolution is taken into account through the convolution of $d\Phi/dEd\Omega$ with f_P in Equation (7.6), whereas in the cases of H.E.S.S. f_P is approximated by a delta function. This approximation has been made in order to maintain compatibility of the result with what has been previously published. The difference introduced by this approximation is $< 5\%$ for all considered dSphs. TODO: End of paper section

From Equation (7.4), we can compute the test statistic (TS) with the ratio test:

$$\mathrm{TS} = -2\ln\left(\frac{\mathcal{L}}{\mathcal{L}^{\max}}\right). \tag{7.7}$$

$\mathcal{L}^{\max}$ here is equivalent to $\mathcal{L}(N_i, B_i, S_i = 0)$ or no signal counts.

7.4 HAWC Results

13 of the 20 dSphs considered for the Glory Duck analysis are within HAWC's field of view. These dSph are analyzed for DM content according to the likelihood method described in Section 7.3.4. The 13 likelihood profiles are then combined to create a combined limit on the dark matter cross-section. This combination is done for 7 of the 8 annihilation channels used in the Glory Duck analysis. Figure 7.4 shows the combined limit for all annihilation channels with HAWC only observations. We also perform 300 studies of Poisson trials on the background. These trials are used to produce HAWC Brazil bands are shared with the other collaborators for combined Brazil

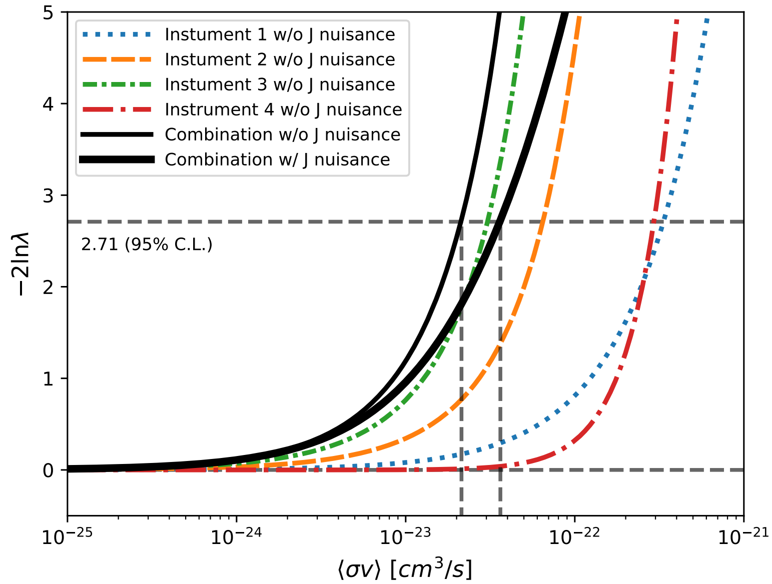

Figure 7.3 Illustration of the combination technique showing a comparison between $-2\ln\lambda$ provided by four instruments (colored lines) from the observation of the same dSph without any J nuisance and their sum, *i.e*. the resulting combined likelihood (thin black line). According to the test statistics of Equation (7.7), the intersection of the likelihood profiles with the line $-2\ln\lambda = 2.71$ indicates the 95% C.L. upper limit on $\langle\sigma v\rangle$. The combined likelihood (thin black line) shows a smaller value of upper limit on $\langle\sigma v\rangle$ than those derived by individual instruments. We also show the uncertainties on the J-factor affects the combined likelihood and degrade the upper limit on $\langle\sigma v\rangle$(thick black line). All likelihood profiles are normalized so that the global minimum $\widehat{\langle\sigma v\rangle}$ is 0. We note that each profile depends on the observational conditions in which a target object was observed. The sensitivity of a given instrument can be degraded and the upper limits less constraining if the observations are performed in non optimal conditions such as a high zenith angle or a short exposure time.

Bands. The results on fitting to HAWC's poisson trials of the DM hypothesis is shown in Figure 7.5 for seven of the DM annihilation channels.

No DM was found in HAWC observations. The limits are dominated by the dSph Segue1 and Coma Berenices. The remaining 11 dSphs do no contribute significantly to the limit. Even though the remaining dSphs have large J-factors, they are towards the edge of HAWC's field of view where this analysis is less sensitive.

7.5 Glory Duck Combined Results

The crux of this analysis is that HAWC's results are combined with 4 other gamma-ray observatories: Fermi-LAT, H.E.S.S., MAGIC, and VERITAS. The complete joint likelihood for the l-th

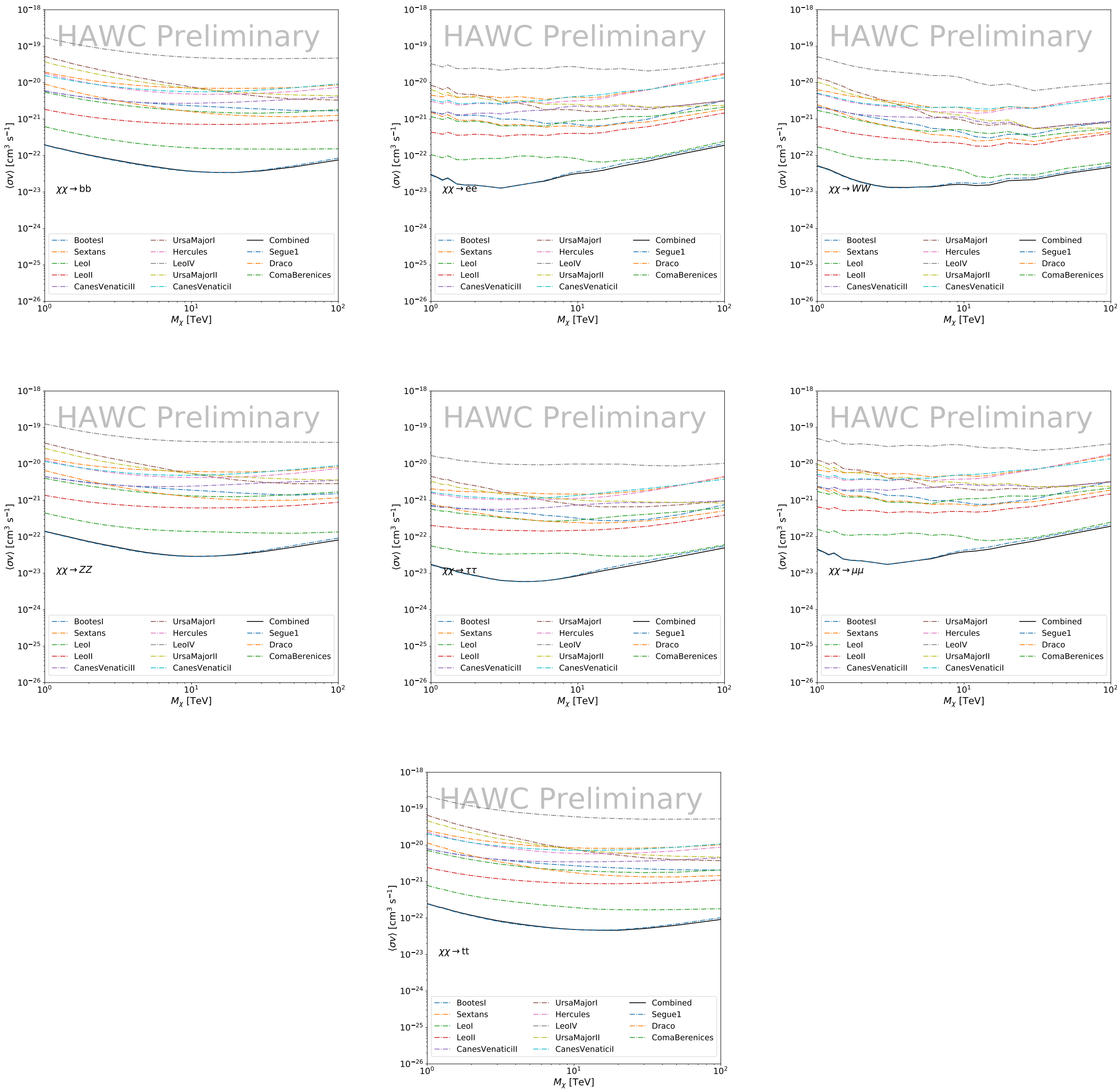

Figure 7.4 HAWC upper limits at 95% confidence level on $\langle\sigma v\rangle$versus DM mass for seven annihilation channels, using the set of J-factors from Ref. [47] The solid line represents the observed combined limit. Dashed lines represent limits from individual dSphs.

dSph is the product of likelihood functions of the 5 experiments.

TODO: place holder for results

No significant DM emission was observed by any of the five telescopes. We present upper limits on $\langle\sigma v\rangle$using the test statistics, Eq. (7.7).

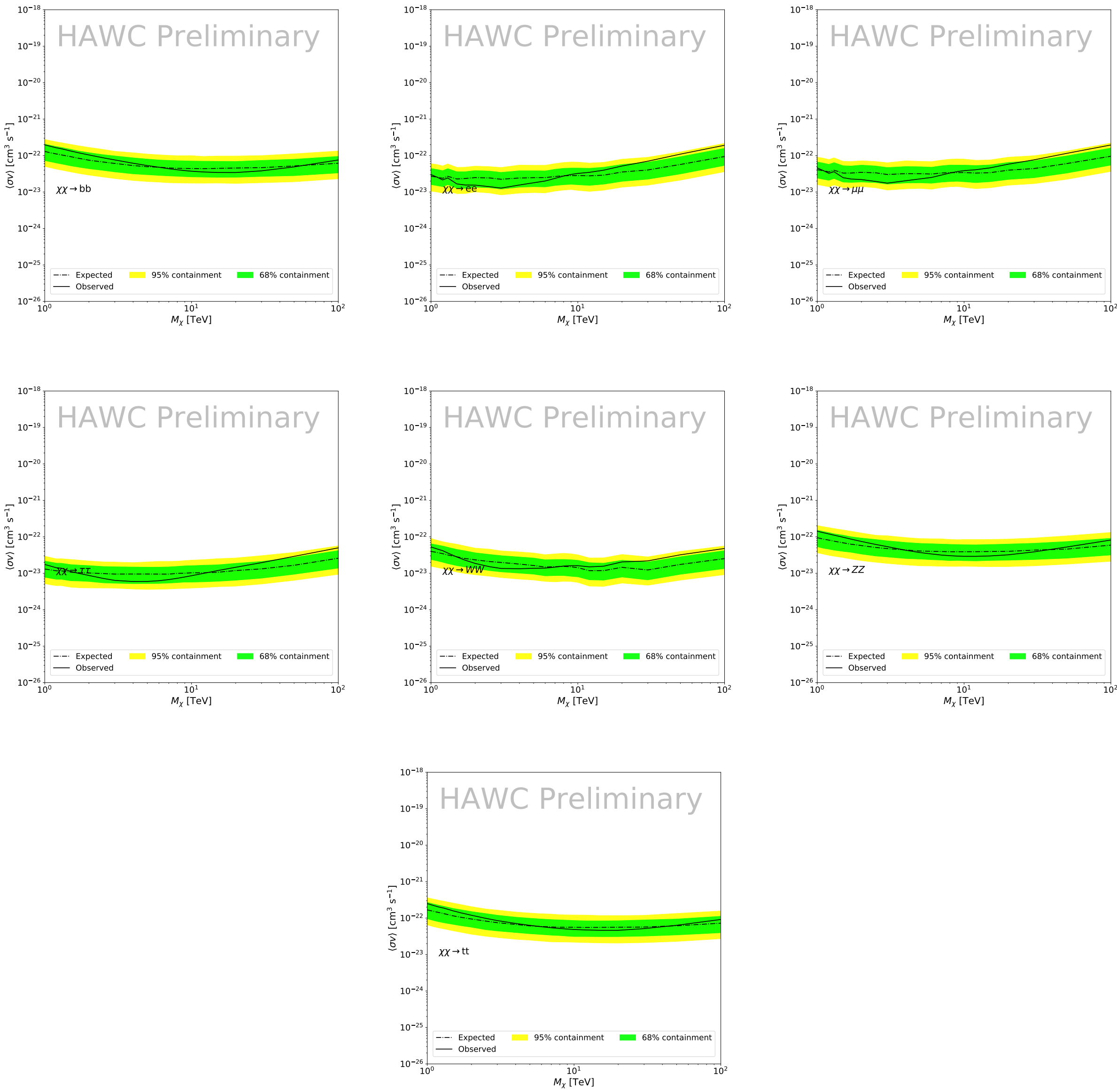

Figure 7.5 HAWC Brazil bands at 95% confidence level on $\langle\sigma v\rangle$versus DM mass for seven annihilation channels with J-factors from $\mathcal{GS}$ [47]. The solid line represents the combined limit from 13 dSphs. The dashed line is the expected limit. The green band is the 68% containment. The yellow band is the 95% containment.

$$\mathrm{TS} = -2\ln\lambda(\langle\sigma v\rangle), \tag{7.8}$$

No significant DM emission was observed by any of the five instruments. We present the upper limits on $\langle\sigma v\rangle$assuming seven independent DM self annihilation channels, namely W^+W^-, Z^+Z^-, $b\bar{b}$, $t\bar{t}$, e^+e^-, $\mu^+\mu^-$, and $\tau^+\tau^-$. The 68% and 95% containment bands are produced from 300

Poisson realizations of the null hypothesis corresponding to each of the combined datasets. These 300 realizations are combined identically to dSph observations. The containment bands and the median are extracted from the distribution of resulting limits on the null hypothesis. These 300 realizations are obtained either by fast simulations of the OFF observations, for H.E.S.S., MAGIC, VERITAS, and HAWC, or taken from real observations of empty fields of view in the case of Fermi-LAT [48, 49, 50].

The obtained limits are shown in Figure 7.6 for the $\mathcal{GS}$ set of J-factors [47] and in Figure 7.7 for the $\mathcal{B}$ set of J-factors [46, 51]. The combined limits are presented with their 68% and 95% containment bands, and are expected to be close to the median limit when no signal is present. We observe agreement with the null hypothesis for all channels, within 2σ standard deviations, between the observed limits and the expectations given by the median limits. Limits obtained from each detector are also indicated in the figures, where limits for all dSphs observed by the specific instrument have been combined.

Below ~300 GeV, the $Fermi$-LAT dominates the DM limits for all annihilation channels. From ~300 GeV to ~2 TeV, $Fermi$-LAT continues to dominate for the hadronic and bosonic DM channels, yet the IACTs (H.E.S.S., MAGIC, and VERITAS) and $Fermi$-LAT all contribute to the limit for leptonic DM channels. For DM masses between ~2 TeV to ~10 TeV, the IACTs dominate leptonic DM annihilation channels, whereas both the $Fermi$-LAT and the IACTs dominate bosonic and hadronic DM annihilation channels. From ~10 TeV to ~100 TeV, both the IACTs and HAWC contribute significantly to the leptonic DM limit. For hadronic and bosonic DM, the IACTs and $Fermi$-LAT both contribute strongly.

We notice that the limits computed using the $\mathcal{B}$ set of J-factor are always better compared to the ones calculated with the $\mathcal{GS}$ set. For the W^+W^-, Z^+Z^-, $b\bar{b}$, and $t\bar{t}$ channels, the ratio between the limits computed with the two sets of J-factor is varying between a factor of ~3 and ~5 depending on the energy, with the largest ratio around 10 TeV. For the channels e^+e^-, $\mu^+\mu^-$, and $\tau^+\tau^-$, the ratio lies between ~2 to ~6, being maximum around 1 TeV. Examining Figure 7.12 and Figure 7.13 in Section 7.7, these differences are explained by the fact that the $\mathcal{B}$ set provides higher J-factors for the majority of the studied dSphs, with the notable exception of Segue I. The variation on the ratio of the limits for the two sets is due to different dSph dominating the limits depending on the energy. This pushes the range of thermal cross-section which can be excluded to higher mass. This comparison demonstrates the magnitude of systematic uncertainties associated with the choice of the J-factor

This comparison demonstrates the magnitude of systematic uncertainties associated with the choice of the J-factor calculation. The $\mathcal{GS}$ and $\mathcal{B}$ sets present a difference in the limits for all channels of about This difference is explained, see Figure 7.12 and Figure 7.13 in Appendix, by the fact that the $\mathcal{B}$ set provides higher J factors for all dSph except for Segue I. This pushes the range of thermal cross-section which can be excluded to higher mass.

7.6 HAWC Systematics

7.6.1 Inverse Compton Scattering

The DM-DM annihilation channels produce many high energy electrons regardless of the primary annihilation channel. These high energy electrons can produce high energy gamma-rays through Inverse Compton Scattering (ICS). If this effect is strong, it would change the morphology of the source and increase the total expected gamma-ray counts from any source. The PPPC [43] provides tools in Mathematica for calculating the impact of ICS for an arbitrary location in the sky for a specified annihilation channel. We calculated the change in gamma-ray counts for DM annihilation to primary $e\bar{e}$ for RA and Dec corresponding to Segue1 and Coma Berenices. These dSphs were chosen because they are the strongest contributors to the limit. $e\bar{e}$ was selected because it would have the largest number of high energy electrons. The effect was found to be on the order of 10^{-7} on the gamma-ray spectrum. As a result, this systematic is not considered in our analysis.

7.6.2 Point Source Versus Extended Source Limits

The previous DM search toward dSph approximated the dSphs as point sources [45]. In this analysis, the dSphs are implemented as extended with J-factor distributions following those produced by [47]. The resolution of the cited map is much finer than HAWC's angular resolution.

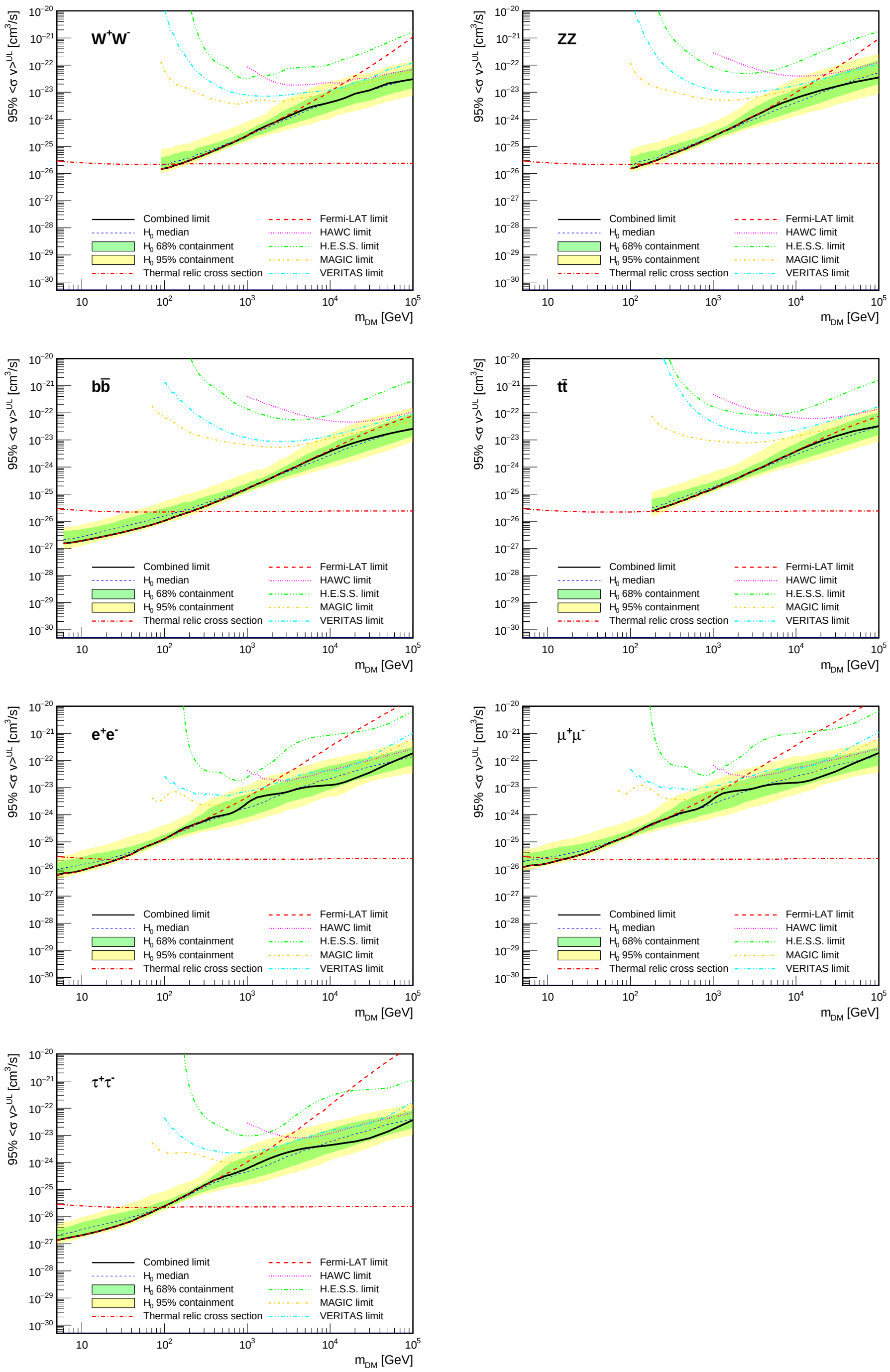

Figure 7.6 Upper limits at 95% confidence level on $\langle \sigma v \rangle$in function of the DM mass for eight annihilation channels, using the set of J factors from Ref. [47] ($\mathcal{GS}$ set in Table 7.1). The black solid line represents the observed combined limit, the black dashed line is the median of the null hypothesis corresponding to the expected limit, while the green and yellow bands show the 68% and 95% containment bands. Combined upper limits for each individual detector are also indicated as solid, colored lines. The value of the thermal relic cross-section in function of the DM mass is given as the red dotted-dashed line [52].

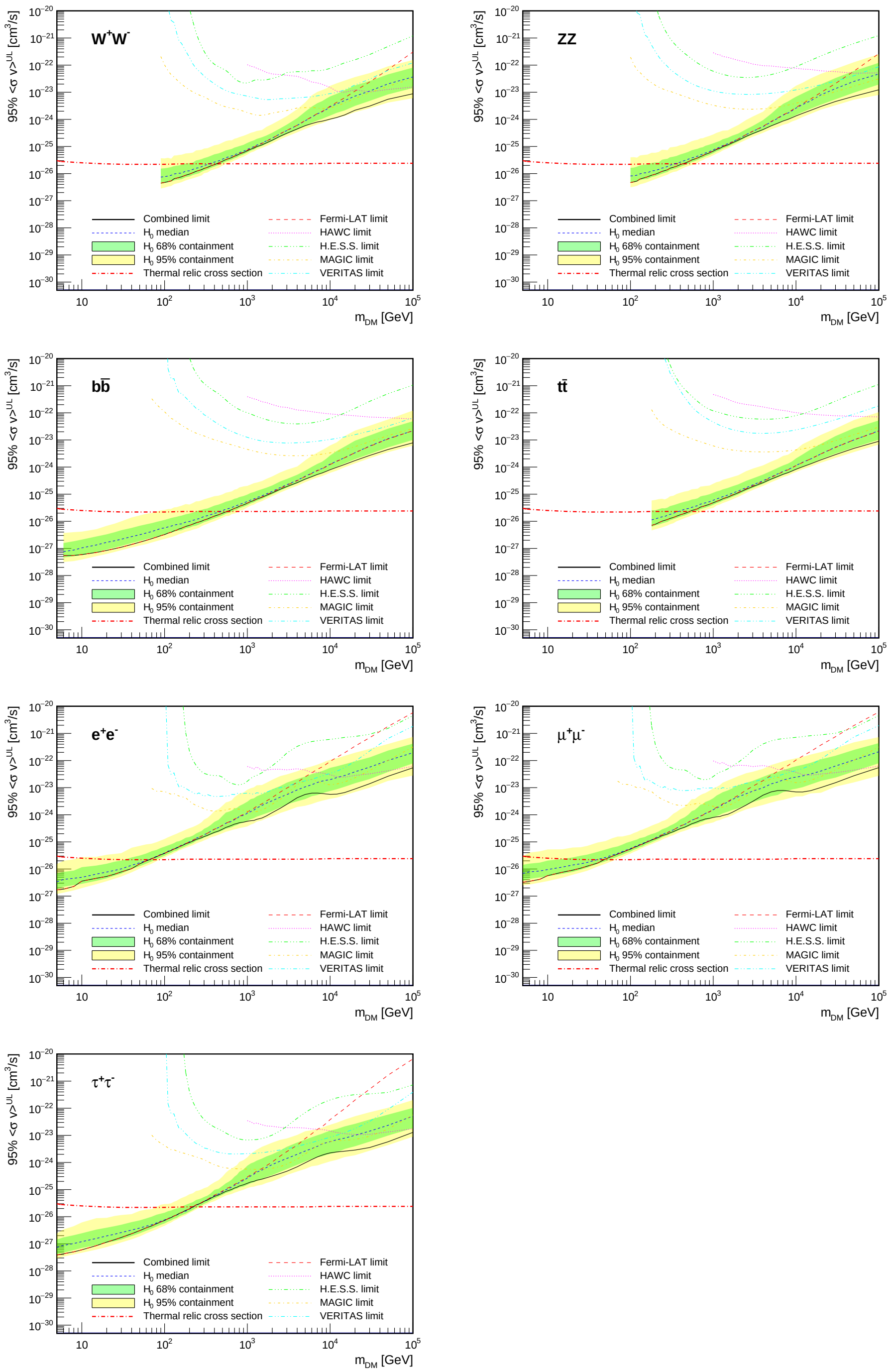

Figure 7.7 Same as Fig. 7.6, using the set of J factors from Ref. [46, 51] ($\mathcal{B}$ set in Table 7.1).

The vast majority of the J-factor distribution is represented on the central HAWC pixel of the dSph spatial map. However, the neighboring 8 pixels are not negligible and contribute to our limit.

Figure 7.9 shows a substantial improvement to the limit for Segue1. Fig. 7.10 however showed identical limits. These disparities are best explained by the relative difference in their J-Factors.

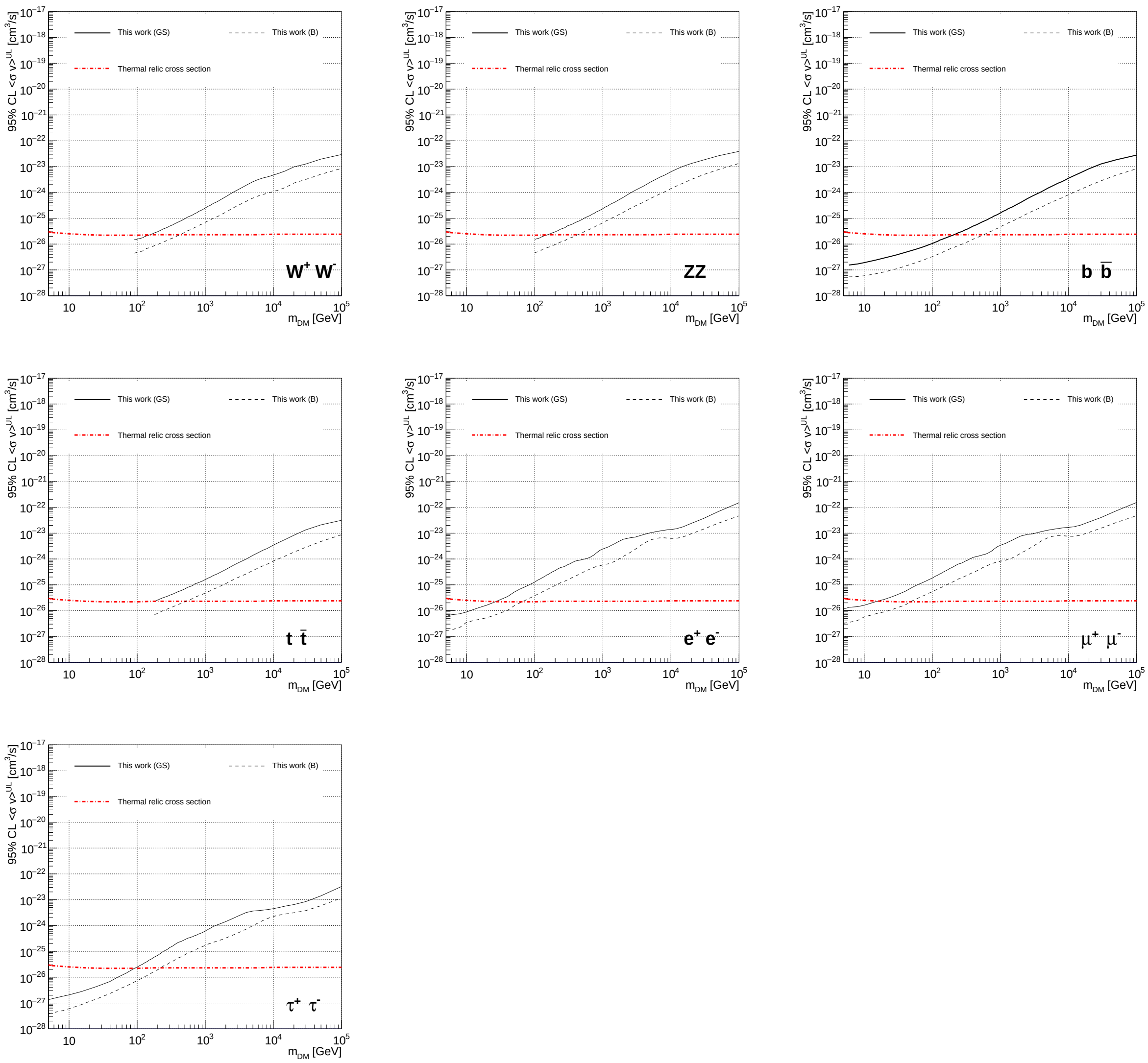

Figure 7.8 Comparisons of the combined limits at 95% confidence level for each of the eight annihilation channels when using the J factors from Ref. [47] ($\mathcal{GS}$ set in Table 7.1), plain lines, and the J factor from Ref. [46, 51] ($\mathcal{B}$ set in Table 7.1), dashed lines. The cross-section given by the thermal relic is also indicated [52].

Both dSphs pass almost overhead the HAWC detector, however Segue1 has the larger J-Factor between the two. Adjacent pixels to the central pixel will therefor contribute to the limits. This is the case for other dSph that are closer to overhead the HAWC detector.

Comparison plots for all sources and the combined limit can be found in the sandbox for the Glory Duck project.

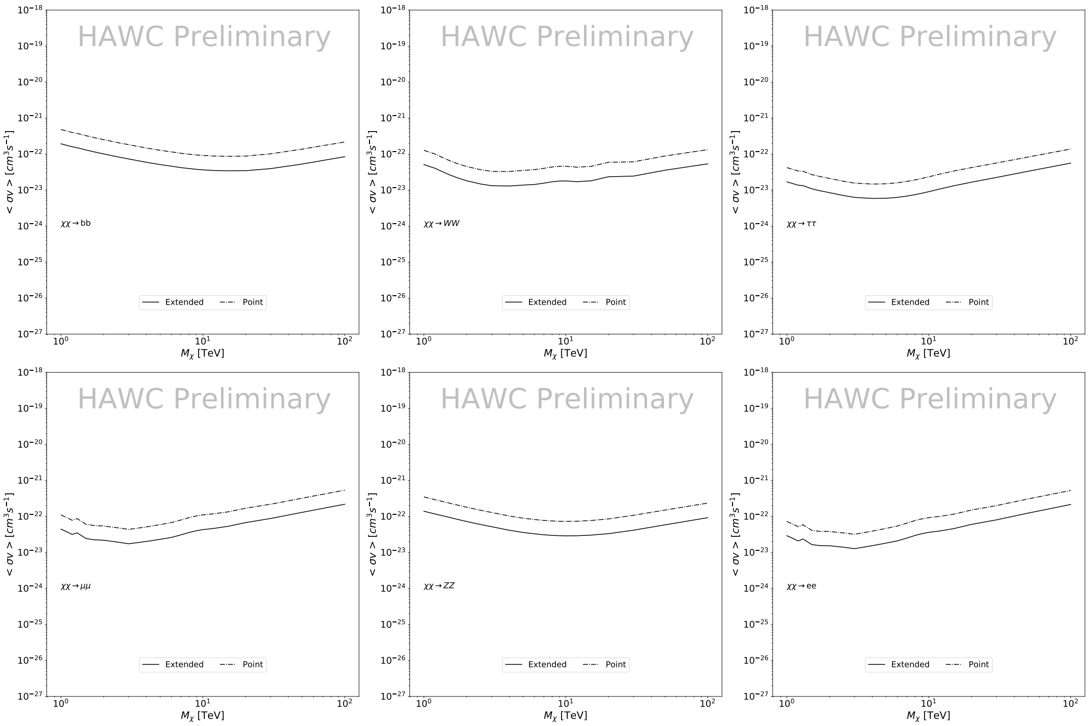

Figure 7.9 Comparisons of the combined limits at 95% confidence level for a point source analysis and extended source using [47] $\mathcal{GS}$ J-factor distributions and PPPC [43] annihilation spectra. Shown are the limits for Segue1 which will have the most significant impact on the combined limit. 6 of the 7 DM annihilation channels are shown. Solid lines are extended source studies. Dashed lines are point source studies. Overall, the extended source analysis improves the limit by a factor of 2.

7.6.3 Impact of Pointing Systematic

During the analysis it was discovered that reconstruction of gamma-rays. Slides describing this systematic can be found here. Shown on the presentation is dependence on the pointing systematic on declination. New spatial profiles were generated for every dSph and limits were computed for the adjusted declination.

Section 7.6.3 demonstrates the impact of this systematic for all DM annihilation channels studied by HAWC. The impact is a tiny improvement, yet mostly identical, to the combined limits.

7.7 J-factor distributions

We show in this appendix a comparison between the J-factors computed by Geringer-Sameth *et al.* [47] (the $\mathcal{GS}$ set) and the ones computed by Bonnivard *et al.* [46, 51] (the $\mathcal{B}$ set). The $\mathcal{GS}$ J-factors are computed through a Jeans analysis of the kinematic stellar data of the selected

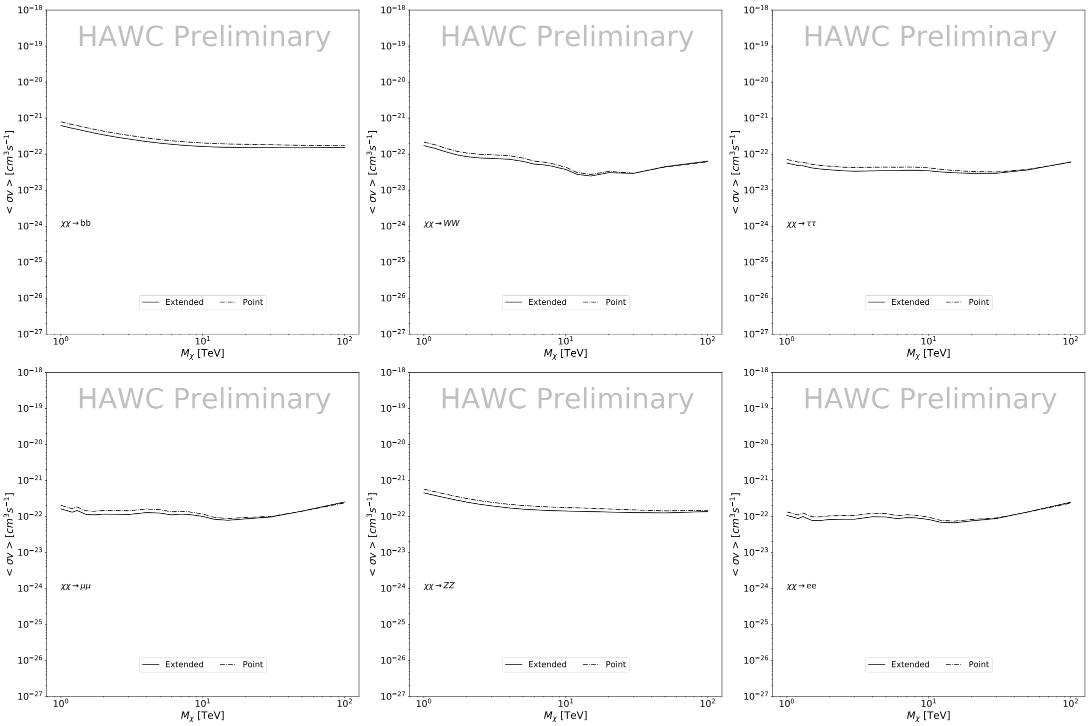

Figure 7.10 Same as Fig. 7.9 on Coma Berenices. This dSph also contributes significantly to the limit. The limits are identical in this case.

dSphs, assuming a dynamic equilibrium and a spherical symmetry for the dSphs. They adopted the generalized DM density distribution, known as Zhao-Hernquist, introduced by [53], carrying three additional index parameters to describe the inner and outer slopes, and the break of the density profile. Such a profile parametrization allows the reduction of the theoretical bias from the choice of a specific radial dependency on the kinematic data. In other words, the increase of free parameters with the use of the Zhao-Hernquist profile allows a better description of the mass density distribution of dark matter.

In addition, a constant velocity anisotropy profile and a Plummer light profile [54] for the stellar distribution were assumed. The velocity anisotropy profile depends on the radial and tangential velocity dispersions. However, its determination remains challenging since only the line-of-sight velocity dispersion can be derived from velocity measurements. Therefore, the parametrization of the anisotropy profile is obtained from simulated halos (see [55] for more details). They provide the values of the J-factors of regions extending to various angular radius up to the outermost member star.

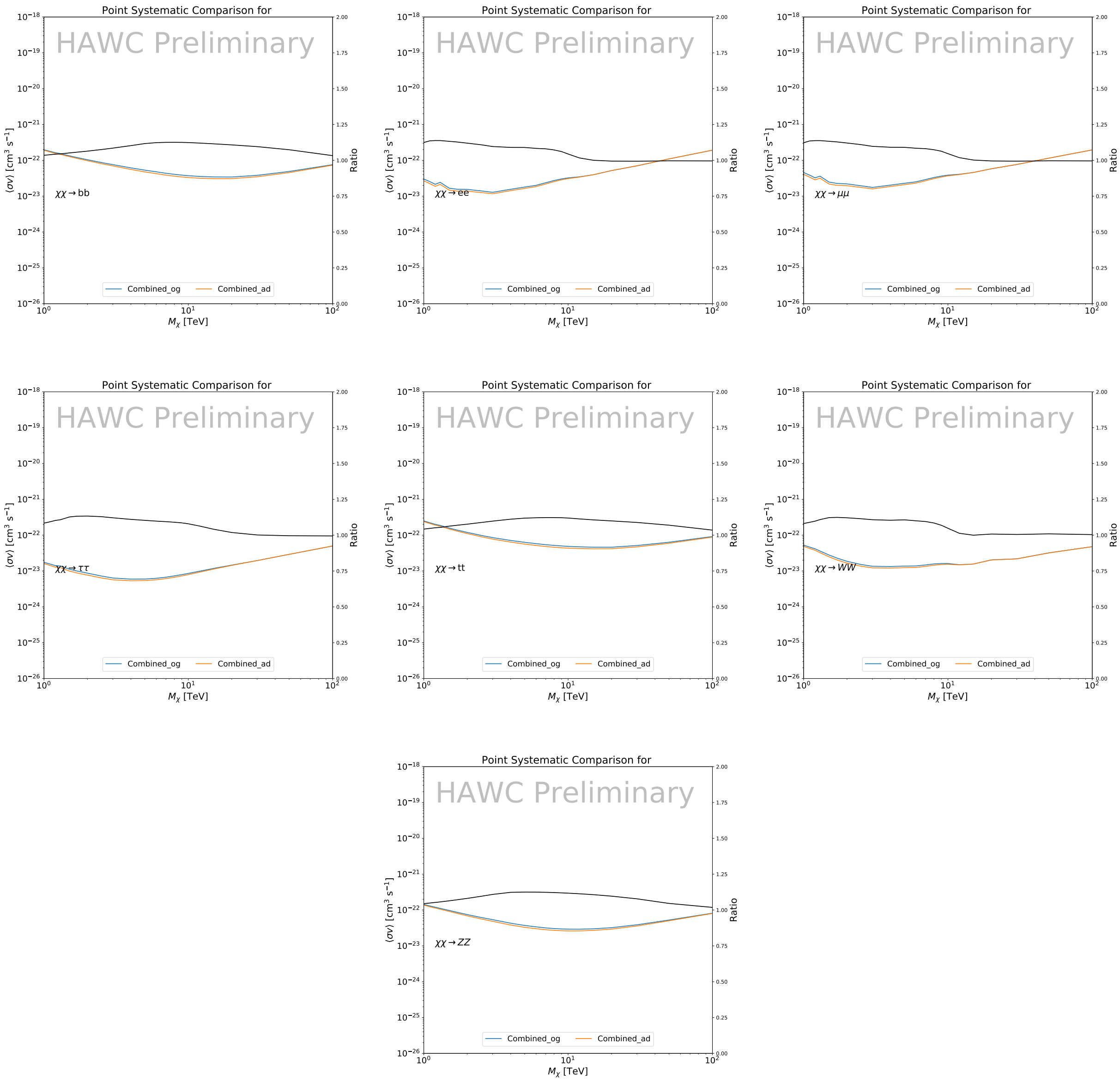

Figure 7.11 Comparison of combined limits when correcting for HAWC's pointing systematic. All DM annihilation channels are shown. The solid black line is the ratio between published limit to the declination corrected limit. The blue solid line or "Combined_og" represented the limits computed for Glory Duck. The solid orange line or "Combined_ad" represented the limits computed after correcting for the pointing systematic.

The $\mathcal{B}$ J-factors were computed through a Jeans analysis taking into account the systematic uncertainties induced by the DM profile parametrization, the radial velocity anisotropy profile, and the triaxiality of the halo of the dwarf galaxies. They performed a more complete study of the dSph kinematics and dynamics than $\mathcal{GS}$ for the determination of the J-factor. Conservative values of the

J-factors where obtained using an Einasto DM density profile [56], a realistic anisotropy profile known as the Baes & Van Hese profile [57] which takes into account that the inner regions can be significantly non-isotropic, and a Zhao-Hernquist light profile [53].

For both sets, J-factor values are provided for all dSphs as a function of the radius of the integration region [47, 46, 51]. Table 7.1 shows the heliocentric distance and Galactic coordinates of the twenty dSphs, together with the two sets of J-factor values integrated up to the outermost observed star for $\mathcal{GS}$ and the tidal radius for $\mathcal{B}$. Both J-factor sets were derived through a Jeans analysis based on the same kinematic data, except for Draco where the measurements of [58] have been adopted in the computation of the $\mathcal{B}$ value. The computations for producing the $\mathcal{GS}$ and $\mathcal{B}$ samples differ in the choice of the DM density, velocity anisotropy, and light profiles, for which the set $\mathcal{B}$ takes into account some sources of systematic uncertainties.

Figure 7.12 and Figure 7.13 show the comparisons for the J-factor versus the angular radius for each of the 20 dSphs used in this study. The uncertainties provided by the authors are also indicated in the figures. For the $\mathcal{GS}$ set, the computation stops at the angular radius corresponding to the outermost observed star, while for the $\mathcal{B}$ set, the computation stops at the angular radius corresponding to the tidal radius.

7.8 Discussion and Conclusions

In this multi-instrument analysis, we have used observations of 20 dSphs from the gamma-ray telescopes Fermi-LAT, H.E.S.S., MAGIC, VERITAS, and HAWC to perform a collective DM search annihilation signals. The data were combined across sources and detectors to significantly increase the sensitivity of the search. We have observed no significant deviation from the null, no DM, hypothesis, and so present our results in terms of upper limits on the annihilation cross section for seven potential DM annihilation channels.

Fermi-LAT brings the most stringent constraints for continuum channels below approximately 1 TeV. the remaining detectors dominate at higher energies. Overall, for multi-TeV DM mass, the combined DM constraints from all five telescopes are 2-3 times stronger than any individual telescope for multi-TeV DM.

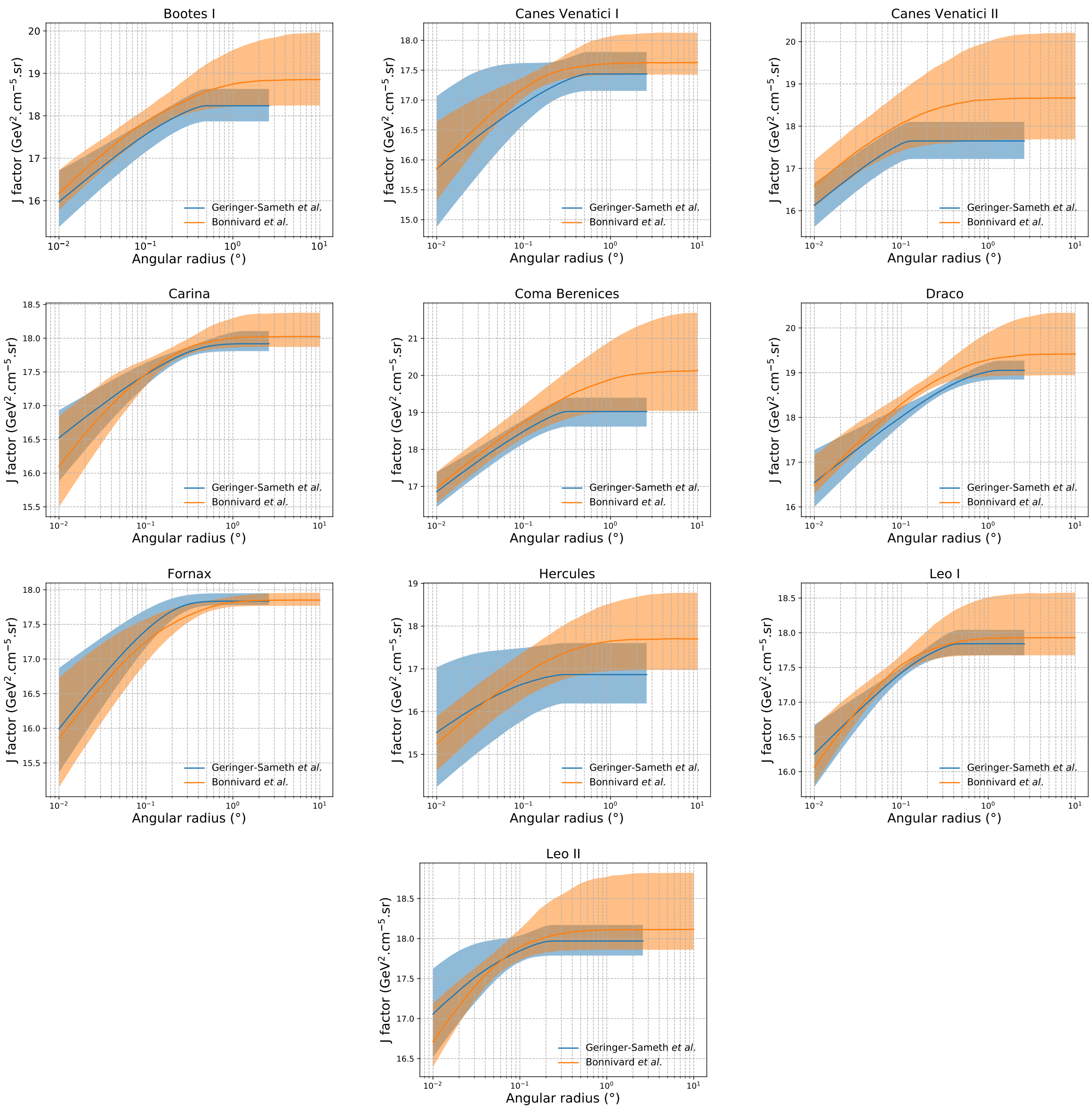

Figure 7.12 Comparisons between the J-factors versus the angular radius for the computation of J factors from Ref. [47] ($\mathcal{GS}$ set in Table 7.1) in blue and for the computation from Ref. [46, 51] ($\mathcal{B}$ set in Tab. 7.1) in orange. The solid lines represent the central value of the J-factors while the shaded regions correspond to the 1σ standard deviation.

Derived from observations of many dSphs, our results produce robust limits given the DM content of the dSphs is relatively well constrained. The obtained limits span the largest mass range of any WIMP DM search. Our combined analysis improves the sensitivity over previously published results from each detectors which produces the most stringent limits on DM annihilation from dSphs. These results are based on deep exposures of the most promising known dSphs with

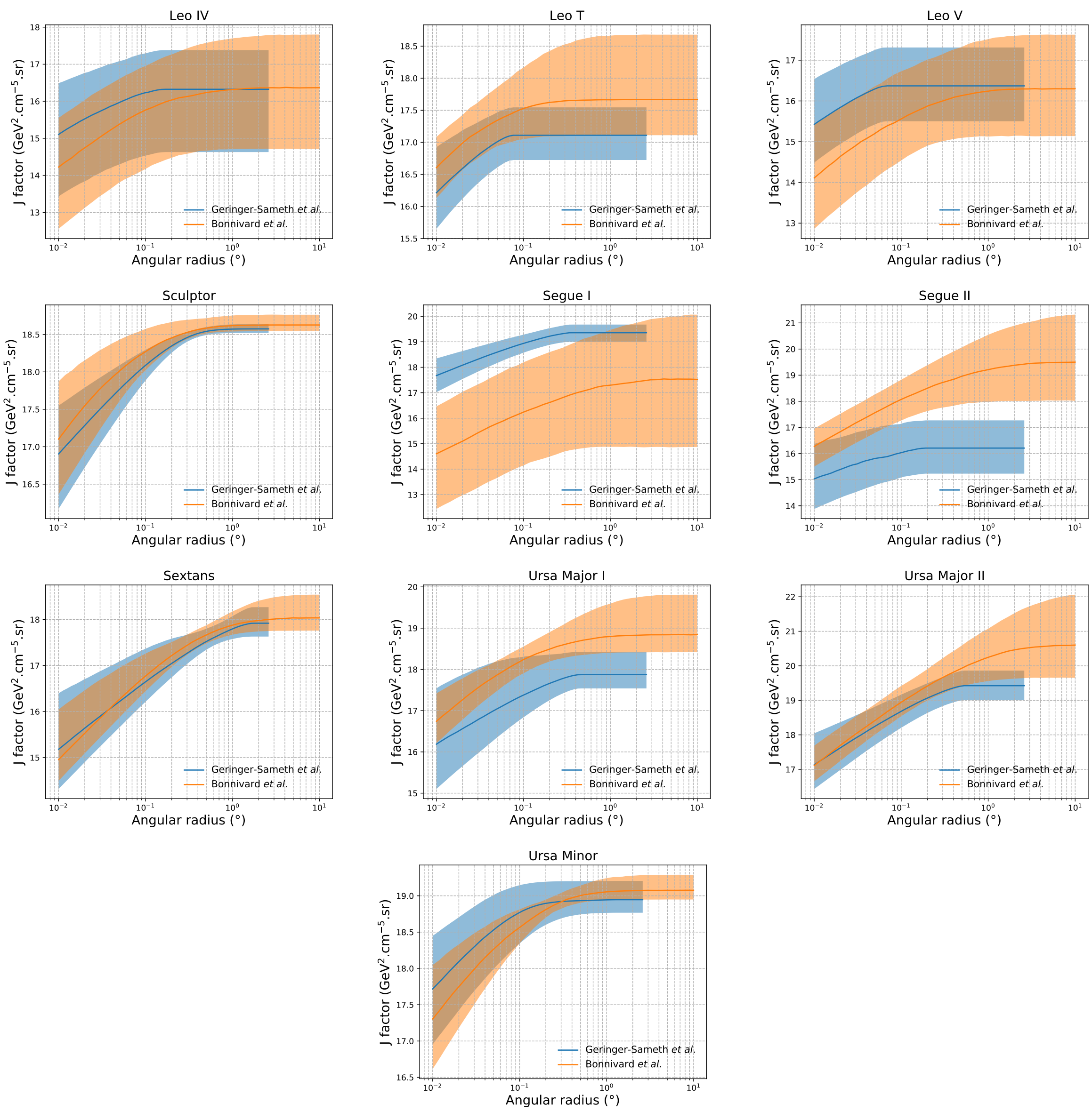

Figure 7.13 Comparisons between the J-factors versus the angular radius for the computation of J factors from Ref. [47] ($\mathcal{GS}$ set in Tab. 7.1) in blue and for the computation from Ref. [46, 51] ($\mathcal{B}$ set in Tab. 7.1) in orange. The solid lines represent the central value of the J-factors while the shaded regions correspond to the 1σ standard deviation.

the currently most sensitive gamma-ray instruments. Therefore, our results constitute a legacy of a generation of gamma-ray instruments on WIMP DM searches towards dSphs. Our results will remain the reference in the field until a new generation of more sensitive gamma-ray instruments begin operations, or until new dSphs with higher J-factors are discovered.

This analysis serves as a proof of concept for future multi-instrument and multi-messenger combination analyses. With this collaborative effort, we have managed to sample over four orders in magnitude in gamma-ray energies with distinct observational techniques. Determining the nature of DM continues to be an elusive and difficult problem. Larger datasets with diverse measurement techniques could be essential to tackling the DM problem. A future collaboration using similar techniques as the ones described in this paper could grow even beyond gamma rays. The models we used for this study include annihilation channels with neutrinos in the final state. Advanced studies could aim to merge our results with those from neutrino observatories with large data sets. Efforts are already underway to add data from the IceCube, ANTARES, and KM3NeT observatories to these gamma-ray results.

From this work, a selection of the best candidates for observations, according to the latest knowledge on stellar dynamics and modelling techniques for the derivation of the J-factors on the potential dSphs targets, is highly desirable at the time that new experiments are starting their dark matter programmes using dSphs. Given the systematic uncertainty inherent to the derivation of the J-factors, an informed observational strategy would be to select both objects with the highest J-factors that could lead to DM signal detection, and objects with robust J-factor predictions, i.e. with kinematic measurements on many bright stars, which would strengthen the DM interpretation reliability of the observation outcome.

This analysis combines data from multiple telescopes to produce strong constraints on astrophysical objects. From this perspective, these methods can be applied beyond just DM searches. Almost every astrophysical study can benefit from multi-telescope, multi-wavelength gamma-ray studies. We have enabled these telescopes to study the cosmos with greater precision and detail. Many astrophysical searches can benefit from multi-instrument gamma-ray studies, for which our analysis lays the foundation.

CHAPTER 8

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CHAPTER 9

MULTITHREADING HAWC ANALYSES FOR DARK MATTER SEARCHES

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