

1 LEVERAGING MULTI-MESSENGER ASTROPHYSICS FOR DARK MATTER SEARCHES

By

Daniel Nicholas Salazar-Gallegos

A DISSERTATION

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

Physics—Doctor of Philosophy
Computational Mathematics in Science and Engineering—Dual Major

Today

ABSTRACT

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

⁴ Copyright by

⁵ DANIEL NICHOLAS SALAZAR-GALLEGOS

⁶ Today

ACKNOWLEDGMENTS

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

TABLE OF CONTENTS

12	LIST OF TABLES	vii
13	LIST OF FIGURES	viii
14	LIST OF ABBREVIATIONS	xiv
15	CHAPTER 1 INTRODUCTION	1
16	CHAPTER 2 DARK MATTER IN THE COSMOS	2
17	2.1 Introduction	2
18	2.2 Dark Matter Basics	3
19	2.3 Evidence for Dark Matter	4
20	2.4 Searching for Dark Matter: Particle DM	11
21	2.5 Sources for Indirect Dark Matter Searches	16
22	2.6 Multi-Messenger Dark Matter	18
23	CHAPTER 3 MULTIMESSENGER ASTROPHYSICS: DETECTING HIGH EN-	
24	ERGY NEUTRAL MESSENGERS	21
25	3.1 Introduction	21
26	3.2 Charged Particles in a Medium	21
27	3.3 Photons (γ)	22
28	3.4 Neutrinos (ν)	22
29	3.5 Opportunities to Combine for Dark Matter	22
30	CHAPTER 4 HIGH ALTITUDE WATER CHERENKOV (HAWC) OBSERVATORY .	24
31	4.1 The Detector	24
32	4.2 Events Reconstruction and Data Acquisition	24
33	4.3 Remote Monitoring	24
34	CHAPTER 5 ICECUBE NEUTRINO OBSERVATORY	25
35	5.1 The Detector	25
36	5.2 Events Reconstruction and Data Acquisition	25
37	5.3 Northern Test Site	25
38	CHAPTER 6 GLORY DUCK: MULTI-WAVELENGTH SEARCH FOR DARK MATT-	
39	TER ANNIHILATION TOWARDS DWARF SPHEROIDAL GALAX-	
40	IES	26
41	6.1 Introduction	26
42	6.2 Dataset and Background	28
43	6.3 Analysis	29
44	6.4 Likelihood Methods	34
45	6.5 HAWC Results	40
46	6.6 Glory Duck Combined Results	43
47	6.7 HAWC Systematics	48

48	6.8 <i>J</i> -factor distributions	49
49	6.9 Discussion and Conclusions	55
50	CHAPTER 7 MULTITHREADING HAWC ANALYSES FOR DARK MATTER	
51	SEARCHES	59
52	7.1 Introduction	59
53	7.2 Dataset and Background	59
54	7.3 Analysis	60
55	7.4 Likelihood Methods	65
56	7.5 Computational Methods: Multithreading	65
57	CHAPTER 8 HEAVY DARK MATTER ANNIHILATION SEARCH WITH ICE-	
58	CUBE'S NORTH SKY TRACK DATA	70
59	CHAPTER 9 NU DUCK	71
60	APPENDIX A MULTI-EXPERIMENT SUPPLEMENTARY FIGURES	72
61	APPENDIX B MULTITHREADING SUPPLEMENTARY FIGURES	73
62	B.1 <code>mpu_analysis.py</code>	74
63	BIBLIOGRAPHY	83

LIST OF TABLES

<p>65 Table 6.1 Summary of the relevant properties of the dSphs used in the present work. 66 Column 1 lists the dSphs. Columns 2 and 3 present their heliocentric distance 67 and galactic coordinates, respectively. Columns 4 and 5 report the J-factors of 68 each source given from the \mathcal{GS} and \mathcal{B} independent studies and their estimated 69 $\pm 1\sigma$ uncertainties. The values $\log_{10} J$ (\mathcal{GS} set) [45] correspond to the mean 70 J-factor values for a source extension truncated at the outermost observed star. 71 The values $\log_{10} J$ (\mathcal{B} set) [47] are provided for a source extension at the tidal 72 radius of each dSph. Bolded sources are within HAWC's field of view and 73 provided to the Glory Duck analysis.</p> 34
<p>74 Table 6.2 Summary of dSph observations by each experiment used in this work. A 75 ‘-’ indicates the experiment did not observe the dSph for this study. For 76 Fermi-LAT, the exposure at 1 GeV is given. For HAWC, $\Delta\theta$ is the absolute 77 difference between the source declination and HAWC latitude. HAWC is more 78 sensitive to sources with smaller $\Delta\theta$. For IACTs, we show the zenith angle 79 range, the total exposure, the energy range, the angular radius θ of the signal or 80 ON region, the ratio of exposures between the background-control (OFF) and 81 signal (ON) regions (τ), and the significance of gamma-ray excess in standard 82 deviations, σ.</p> 35
<p>83 Table 7.1 Summary of the relevant properties of the dSphs used in the present work. 84 Column 1 lists the dSphs. Columns 2 and 3 present their heliocentric distance 85 and galactic coordinates, respectively. Column 4 reports the J-factors of each 86 source given from the \mathcal{LS} studies and estimated $\pm 1\sigma$ uncertainties. The 87 values $\log_{10} J$ (\mathcal{LS} set) [65] correspond to the mean J-factor values for a 88 source extension truncated at 0.5°.</p> 63
<p>89 Proof I know how to include</p>	

LIST OF FIGURES

<p>91 Figure 2.1 Rotation curve fit to NGC 6503 from [7]. Dashed line is the contribution 92 from visible matter. Dotted curves are from gas. Dash-dot curves are from 93 dark matter (DM). Solid line is the composite contribution from all matter 94 and DM sources. Data are indicated with bold dots with error bars. Data 95 agree strongly with a matter + DM composite prediction.</p> <p>96 Figure 2.2 Light from distant galaxy is bent in unique ways depending on the distribution 97 of mass between the galaxy and Earth. Yellow dashed lines indicate where 98 the light would have gone if the matter were not present [8].</p> <p>99 Figure 2.3 (left) Optical image of galactic cluster 1E0657-558. (right) X-ray image of the 100 cluster with redder meaning hotter and higher baryon density. (both) Green 101 contours are reconstruction of gravity contours from weak lensing. White 102 rings are the best fit mass maxima at 68.3%, 95.5%, and 99.7% confidence. 103 The matter maxima of the clusters are clearly separated from x-ray maxima. [9]</p> <p>104 Figure 2.4 Plank CMB sky. Sky map features small variations in temperature in primor- 105 dial light. These anisotropies are used to make inferences about the universe's 106 energy budget and developmental history. [10]</p> <p>107 Figure 2.5 Observed Cosmic Microwave Background power spectrum as a function of 108 multipole moment from Plank [10]. Blue line is best fit model from ΛCDM. 109 Red points and lines are data and error, respectively.</p> <p>110 Figure 2.6 Predicted power spectra of CMB for different $\Omega_m h^2$ values for fixed baryon 111 density from [11]. (left) Low $\Omega_m h^2$ increases the prominence of first and 112 second peaks. (middle) $\Omega_m h^2$ is most similar to the observed power spectrum. 113 The second and third peaks are similar in height. (right) $\Omega_m h^2$ is large which 114 suppresses the first peak and raises the prominence of the third peak.</p> <p>115 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/</p> <p>116</p> <p>117</p> <p>118 Figure 2.8 Simplified Feynman diagram demonstrating with different ways DM can 119 interact with SM particles. The 'X's refer to the DM particles whereas the 120 SM refer to fundamental particles in the SM. The large circle in the center 121 indicates the vertex of interaction and is purposely left vague. The colored 122 arrows refer to different directions of time as well as their respective labels. 123 The arrows indicate the initial and final state of the DM -SM interaction in time.</p>	<p>5</p> <p>7</p> <p>8</p> <p>9</p> <p>10</p> <p>10</p> <p>10</p> <p>12</p> <p>13</p>
--	---

124	Figure 2.9 A single jet event in ATLAS detector from 2017 [16]. Jet momentum was 125 observed to be 1.9 TeV. Missing transverse momentum was observed to be 126 1.9 TeV compared to the initial transverse momentum of the event was 0. 127 Implied MET is traced by a red dashed line in event display.	14
128	Figure 2.10 More detailed pseudo-Feynman diagram of particle cascade from dark matter 129 annihilation into 2 quarks. The quarks hadronize and down to stable particles 130 like γ or the anti-proton (p^-). Diagram pulled from ICRC 2021 presentation 131 on DM annihilation search [17].	15
132	Figure 2.11 Dark Matter (DM) decay spectrum for $b\bar{b}$ initial state and γ final state. Redder 133 spectra are for larger DM masses. Bluer spectra are light DM masses. x is a 134 unitless factor defined as the ratio of the mass of DM, m_χ , and the final state 135 particle energy E_γ . Figure from [19].	17
136	Figure 2.12 Different dark matter density profiles compared. Some models produce ex- 137 ceptionally large densities at small r [20].	18
138	Figure 2.13 The Milky Way Galaxy in photons (γ) and neutrinos (ν) [22]. The Galactic 139 center is at $l=0^\circ$ and is the brightest region in all panels. (top) An Optical 140 color image of the Milky Way galaxy seen from Earth. Clouds of gas and dust 141 obscure some light from stars. (2nd down) Integrated flux of γ -rays observed 142 by the Fermi-LAT telescope [23]. (middle) Expected neutrino emission 143 that corresponds with Fermi-LAT observations. (2nd up) Expected neutrino 144 emission profile after considering detector systematics of IceCube. (bottom) 145 Observed neutrino emission from region of the galactic plane. Substantial 146 neutrino emission was detected.	19
147	Figure 2.14 Dark Matter annihilation spectra for different final state particle and standard 148 model annihilation channels [24]. Photons (red), e^\pm (green), \bar{p} (blue), ν (black).	20
149	Figure 3.1 TODO: Show a nuclear reactor with cherenkov radiation[NEEDS A SOURCE][FACT 150 CHECK THIS]	22
151	Figure 3.2 TODO: absorption spectrum of liquid and solid water[NEEDS A SOURCE][FACT 152 CHECK THIS]	23

153	Figure 6.1	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 dark 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 $m_\chi = 5$ TeV DM annihilating to bottom quarks (red), tau leptons (blue), and W bosons (green). Faded gray lines outline percentage flux of the Crab nebula. Figure is an augmented version of [25]	27
166	Figure 6.2	Effect of Electroweak (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 [44].	31
171	Figure 6.3	$\frac{dJ}{d\Omega}$ maps for Segue1 (top) and Coma Berenices (bottom). Origin is centered on the specific dwarf spheroidal galaxies (dSph). X and Y axes are the angular separation from the center of the dwarf. Plots of the remaining 11 dSph HAWC studied are linked in Fig. A.1.	33
175	Figure 6.4	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>i.e.</i> the resulting combined likelihood (thin black line). According to the test statistics of Equation (6.6), 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 how the uncertainties on the J factor effects 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.	38
190	Figure 6.5	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. [53] The solid line represents the observed combined limit. Dashed lines represent limits from individual dSphs.	41

194	Figure 6.6 HAWC TS values for best fit $\langle\sigma v\rangle$ versus m_χ for seven SM annihilation channels with J factors from \mathcal{GS} . The solid black line shows the combined best fit TS values. The colored, dashed lines are the TS values for each of the 13 sources HAWC studied.	42
198	Figure 6.7 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} [53]. 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.	43
203	Figure 6.8 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. [53] (\mathcal{GS} set in Table 6.1). 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 [54].	44
212	Figure 6.9 Same as Fig. 6.8, using the set of J factors from Ref. [47, 55] (\mathcal{B} set in Table 6.1).	45
213	Figure 6.10 Comparisons of the combined limits at 95% confidence level for each of the eight annihilation channels when using the J factors from Ref. [53] (\mathcal{GS} set in Table 6.1), plain lines, and the J factor from Ref. [47, 55] (\mathcal{B} set in Table 6.1), dashed lines. The cross-section given by the thermal relic is also indicated [54].	47
217	Figure 6.11 Comparisons of the combined limits at 95% confidence level for a point source analysis and extended source using [53] \mathcal{GS} J-factor distributions and PPPC [44] 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.	49
224	Figure 6.12 Same as Fig. 6.11 on Coma Berenices. This dSph also contributes significantly to the limit. The limits are identical in this case.	50
226	Figure 6.13 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.	51

232	Figure 6.14 Differential map of dJ/Ω from model built in Section 6.8.1 and profiles 233 provided directly from authors. (Top) Differential from Segue1. (bottom) 234 Differential from Coma Berenices. Note that their scales are not the same. 235 Segue1 shows the deepest discrepancies which is congruent with its large 236 uncertainties. Both models show anuli where unique models become apparent.	52
237	Figure 6.15 HAWC limits for Coma Berenices (top) and Segue1 (bottom) for two different 238 map sets. Blue lines are limits calculated on maps with poor model repre- 239 sentation. Orange lines are limits calculated on spatial profiles provided by 240 the authors of [45]. Black line is the ratio of the poor spatial model limits to 241 the corrected spatial models. The left y-axis measures $\langle\sigma v\rangle$ for the blue and 242 orange lines. The right y-axis measures the ratio and is unitless.	53
243	Figure 6.16 Comparisons between the J -factors versus the angular radius for the com- 244 putation of J factors from Ref. [53] (\mathcal{GS} set in Table 6.1) in blue and for 245 the computation from Ref. [47, 55] (\mathcal{B} set in Tab. 6.1) in orange. The solid 246 lines represent the central value of the J -factors while the shaded regions 247 correspond to the 1σ standard deviation.	56
248	Figure 6.17 Comparisons between the J -factors versus the angular radius for the com- 249 putation of J factors from Ref. [53] (\mathcal{GS} set in Tab. 6.1) in blue and for the 250 computation from Ref. [47, 55] (\mathcal{B} set in Tab. 6.1) in orange. The solid 251 lines represent the central value of the J -factors while the shaded regions 252 correspond to the 1σ standard deviation.	57
253	Figure 7.1 Difference between spectral hypotheses from PPPC [44] and HDM [64]. 254 Shown is the expected DM annihilation spectrum for $\chi\chi \rightarrow W^-W^+$. Solid 255 lines are spectral models with EW corrections from the PPPC. Dash-dot lines 256 are spectral models from HDM. Red lines are models for $M_\chi = 1$ TeV. Blue 257 lines represent models for $M_\chi = 100$ TeV.	62
258	Figure 7.2 Photon spectra for $\chi\chi \rightarrow \gamma\gamma$ (left) and $\chi\chi \rightarrow ZZ$ (right) after gaussian 259 convolution of line features. Both spectra have δ -features at photon energies 260 equal to the DM mass. Bluer lines are annihilation spectra with lower DM 261 mass. Redder lines are spectra from larger DM mass. All Spectral models are 262 sourced from the Heavy Dark Matter models [64]. Axes are drawn roughly 263 according to the energy sensitivity of HAWC.	63
264	Figure 7.3 $\frac{dJ}{d\Omega}$ maps for Coma Berenices, Draco, Segue1, and Sextans. Columns are 265 divided for the $\pm 1\sigma$ uncertainties in $dJ/d\Omega$ around the mean value from \mathcal{LS} 266 [65]. Origin is centered on the specific dwarf spheroidal galaxies (dSph). θ 267 and ϕ axes are the angular separation from the center of the dwarf	64

268	Figure 7.4	Infographic on how jobs and DM computation was organized in Section 6.3. Jobs were built for each permutation of CHANS and SOURCES shown by the left block in the figure. Each job, which took on the order 2 hrs to compute, had the following work flow: 1. Import HAWC analysis software, 2 min to run. 2. Load HAWC count maps, 5 min to run. 3. Load HAWC energy and spatial resolutions, 4 min. 5. Load DM spatial source templates and spectral models, less than 1 s. 6. Perform likelihood fit on data and model, about 8 min per DM mass. 7. Write results to file, less than 1s.	66
276	Figure 7.5	Graphic of Gustafson parallel coding pattern. f_s is the fraction of a program, in time, spent on serial computation. f_p is the fraction of computing time that is parallelizable. T_p is the total time for a parallel program to run. T_1 is the total time for a parallel program to run if only 1 processor is allocated. P_N is the N -th processor where it's row is the computation the processor performs. The Gustafson pattern is most similar to what is implemented for this analysis. Figure is pulled from [67].	67
283	Figure 7.6	Task chart for one multi-threaded job developed for this project. Green blocks indicate a shared resource across the threads AND computation performed serially. Red blocks indicate functional parallel processing within each thread. 3 threads are represented here, yet many more can be employed during the full analysis. Jobs are defined by the SOURCE as these require unique maps to be loaded into the likelihood estimator. The m_χ , CHAN, and $\langle\sigma v\rangle$ variables are entered into the thread pool and allocated as evenly as possible across the threads.	69
291	Figure A.1	Sister figure to Figure 6.3. Sources in the first row from left to right: Boötes I, Canes Venatici I, II. In second row: Draco, Hercules, Leo I. In the first row: Leo II, Leo IV, Sextans. In the final row: Ursa Major I, Ursa Major II.	72
294	Figure B.1	Sister figure to Figure 7.2 for remaining SM primary annihilation channels studied for this thesis. These did not require any post generation smoothing and so are directly pulled from [64] with a binning scheme most helpful for a HAWC analysis.	73

LIST OF ABBREVIATIONS

- 299 **MSU** Michigan State University
300 **LANL** Los Alamos National Laboratory
301 **DM** Dark Matter
302 **SM** Standard Model
303 **HAWC** High Altitude Water Cherenkov Observatory
304 **dSph** Dwarf Spheroidal Galaxy

305

CHAPTER 1

INTRODUCTION

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

CHAPTER 2

307

DARK MATTER IN THE COSMOS

308 **2.1 Introduction**

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

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

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

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

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

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

325 You estimated 1,900 lbs. assuming the average weight of a student in your class was 60 lbs.
326 So, you are pleased with Sandra's and Mario's answer. You instruct your students to all gather on
327 the giant scale and read off the weight together. To all your surprise, the scale reads *10,000 lbs.*!
328 10,000 is significantly more than a 10% error from 2,000. In fact, it is approximately 5 times more
329 massive than either your or your students' estimates. You think to yourself and conclude there
330 must be something wrong with the scale. You ask an employee to check the scale and verify it is
331 well calibrated. They confirm that the scale is in working order. You weigh a couple of students
332 individually to assess that the scale is well calibrated. Sandra weighs 59 lbs., and Mario weighs

333 62 lbs., typical weights for their age. You then weigh each student individually and see that their
334 weights individually do not deviate greatly from 60 lbs. So, where does all the extra weight come
335 from?

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

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

345 **2.2 Dark Matter Basics**

346 Presently, a more compelling theory of cosmology that includes Dark Matter (DM) in order
347 to explain a variety of observations is Λ Cold Dark Matter, or Λ CDM. I present the evidence
348 supporting Λ CDM in Section 2.3 yet discuss the conclusions of the Λ CDM model here. According
349 to Λ CDM fit to observations on the Cosmic Microwave Background (CMB), DM is 26.8% of the
350 universe's current energy budget. Baryonic matter, stuff like atoms, gas, and stars, contributes to
351 4.9% of the universe's current energy budget [1, 2, 3].

352 DM is dark; it does not interact readily with light at any wavelength. DM also does not interact
353 noticeably with the other standard model forces (Strong and Weak) at a rate that is readily observed
354 [3]. DM is cold, which is to say that the average velocity of DM is below relativistic speeds [1].
355 'Hot' DM would not likely manifest the dense structures we observe like galaxies, and instead
356 would produce much more diffuse galaxies than what is observed [3, 1]. DM is old; it played a
357 critical role in the formation of the universe and the structures within it [1, 2].

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

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

363 **2.3 Evidence for Dark Matter**

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

377 **2.3.1 First Clues: Stellar Velocities**

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

$$2T + V = 0. \quad (2.1)$$

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

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

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

$$\frac{M}{L} \sim 400 \frac{M_{\odot}}{L_{\odot}} \quad (2.3)$$

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

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

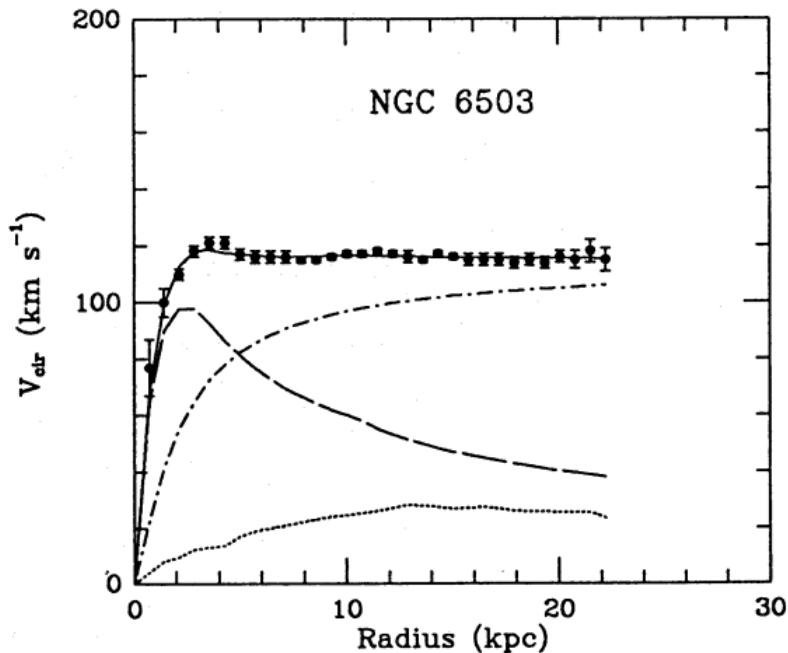


Figure 2.1 Rotation curve fit to NGC 6503 from [7]. Dashed line is the contribution from visible matter. Dotted curves are from gas. Dash-dot curves are from dark matter (DM). Solid line is the composite contribution from all matter and DM sources. Data are indicated with bold dots with error bars. Data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

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

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

402 **2.3.2 Evidence for Dark Matter: Gravitational Lensing**

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

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

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

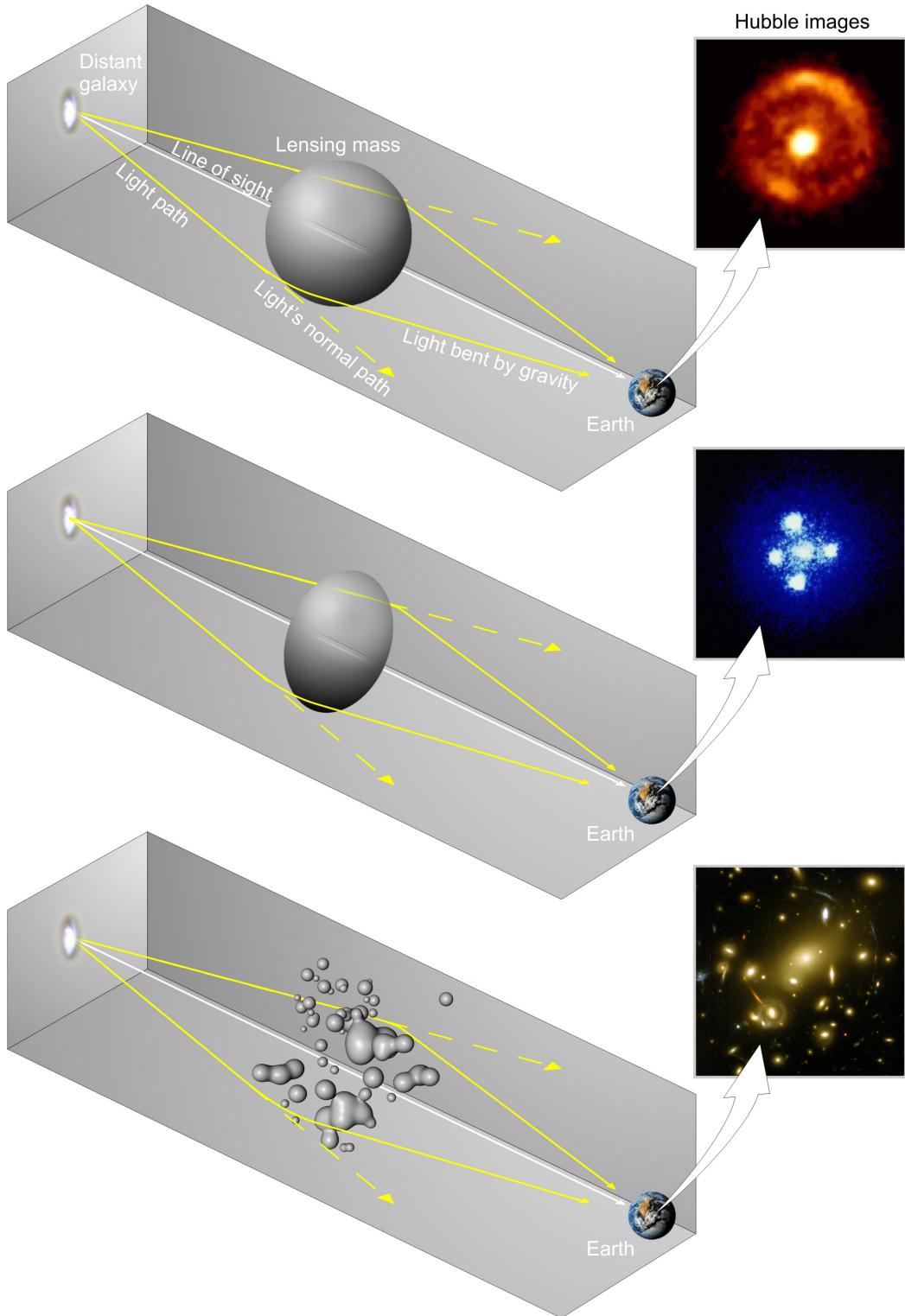


Figure 2.2 Light from distant galaxy is bent in unique ways depending on the distribution of mass between the galaxy and Earth. Yellow dashed lines indicate where the light would have gone if the matter were not present [8].

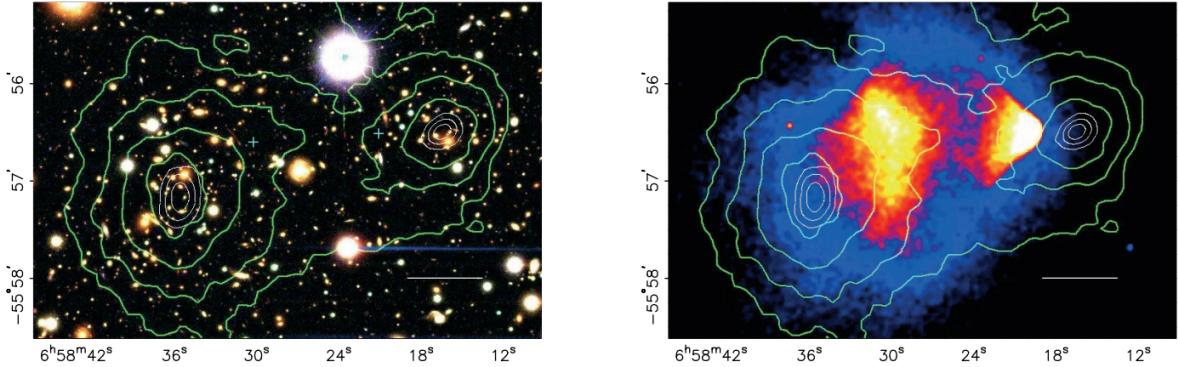


Figure 2.3 (left) Optical image of galactic cluster 1E0657-558. (right) X-ray image of the cluster with redder meaning hotter and higher baryon density. (both) Green contours are reconstruction of gravity contours from weak lensing. White rings are the best fit mass maxima at 68.3%, 95.5%, and 99.7%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

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

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

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

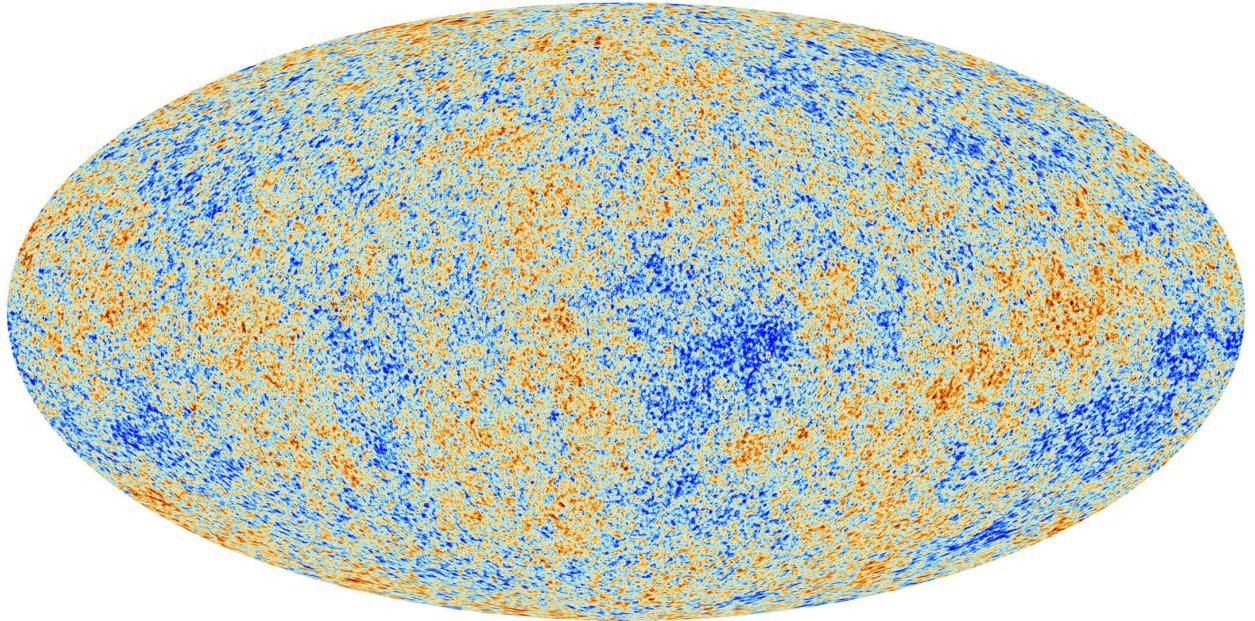


Figure 2.4 Plank CMB sky. Sky map features small variations in temperature in primordial light. These anisotropies are used to make inferences about the universe’s energy budget and developmental history. [10]

437 **2.3.3 Evidence for Dark Matter: Cosmic Microwave Background**

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

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

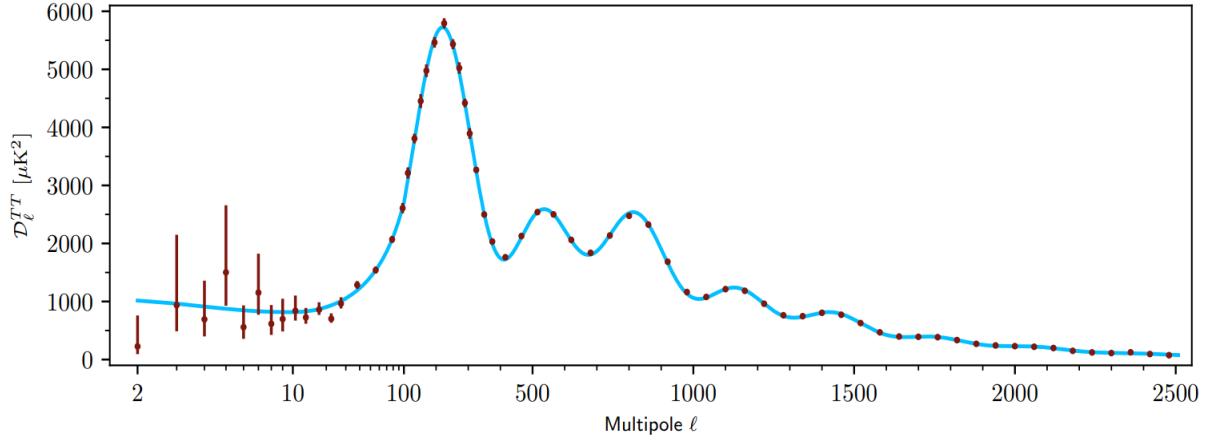


Figure 2.5 Observed Cosmic Microwave Background power spectrum as a function of multipole moment from Plank [10]. Blue line is best fit model from Λ CDM. Red points and lines are data and error, respectively.

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

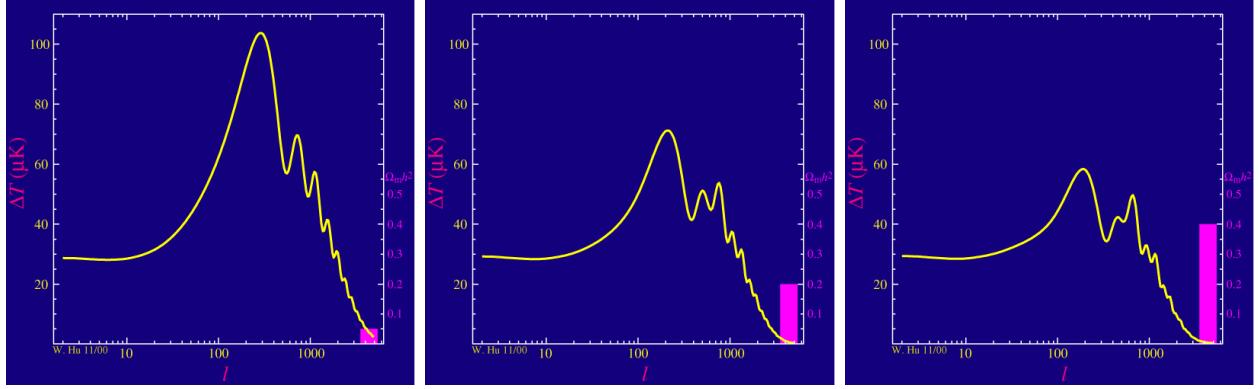


Figure 2.6 Predicted power spectra of CMB for different $\Omega_m h^2$ values for fixed baryon density from [11]. (left) Low $\Omega_m h^2$ increases the prominence of first and second peaks. (middle) $\Omega_m h^2$ is most similar to the observed power spectrum. The second and third peaks are similar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

454 The harmonics would look quite different for a universe with less DM. Figure 2.6 demonstrates
 455 the effect $\Omega_m h^2$ has on the expected power spectrum for fixed baryon matter density. [11] Sweeping
 456 $\Omega_m h^2$ in this way clearly shows the effect dark matter has on the CMB power spectrum. The
 457 observations fit well with the Λ CDM model, and the derived fractions are as follows. The matter
 458 fraction: $\Omega_m = 0.3153$; and the baryon fraction: $\Omega_b = 0.04936$ [10]. Plank's observations also
 459 provide a measure of the Hubble constant, H_0 . H_0 especially has seen a growing tension in the

460 past decade that continues to deepened with observations from instruments like the James Webb
461 Telescope [12, 13]. As Hubble tensions deepen, we may find that perhaps Λ **CDM**, despite its
462 successes, is missing some critical physics.

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

472 **2.4 Searching for Dark Matter: Particle DM**

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

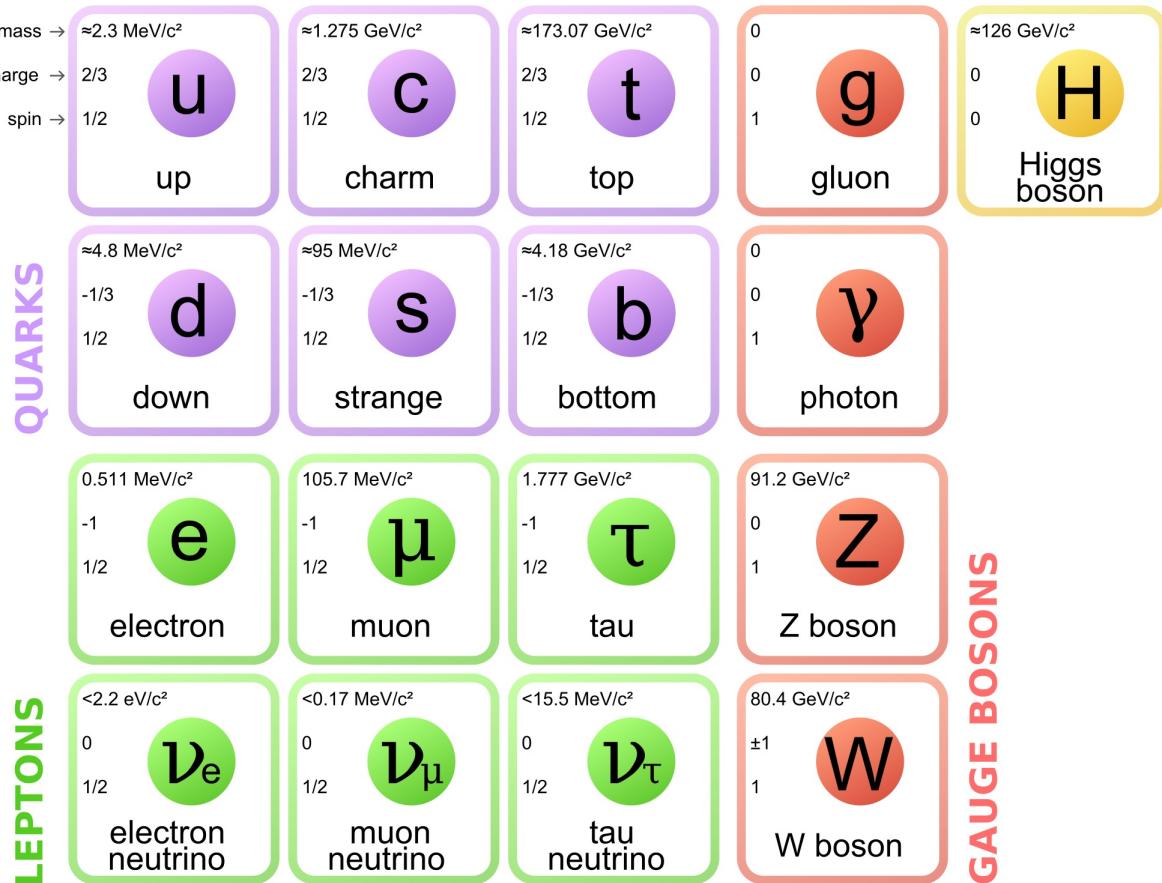


Figure 2.7 The Standard Model (SM) of particle physics. Figure taken from <http://www.quantumdiaries.org/2014/03/14/the-standard-model-a-beautiful-but-flawed-theory/>

485 2.4.1 Shake it, Break it, Make it

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

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

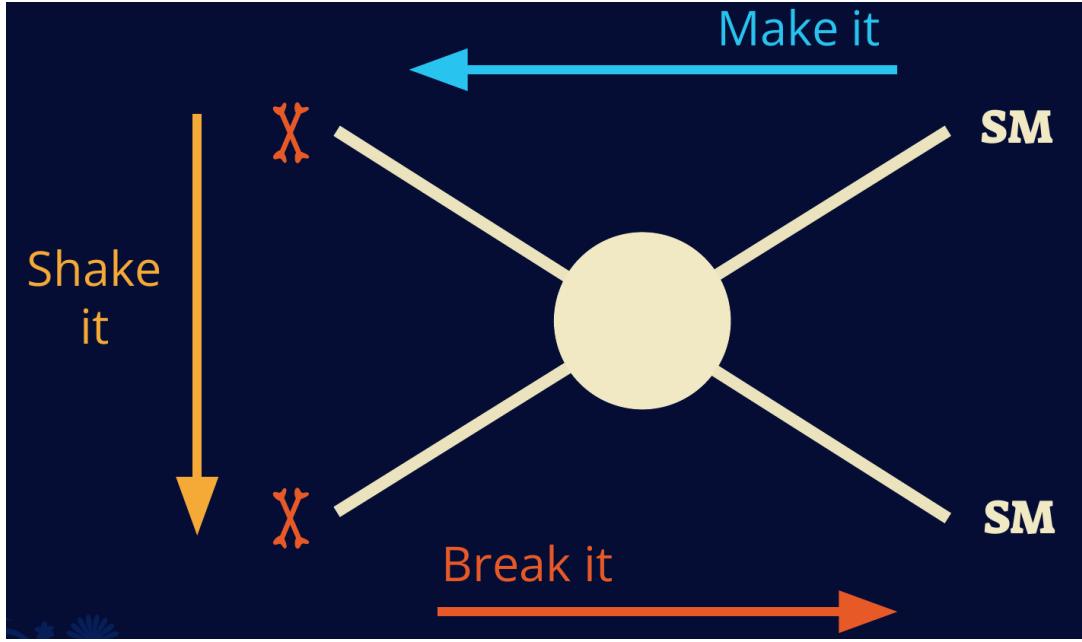


Figure 2.8 Simplified Feynman diagram demonstrating different ways DM can interact with SM particles. The 'X's refer to the DM particles whereas the SM refer to fundamental particles in the SM. The large circle in the center indicates the vertex of interaction and is purposely left vague. The colored 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.

496 media like the noble gas Xenon. [14]

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

509 momentum. [15]

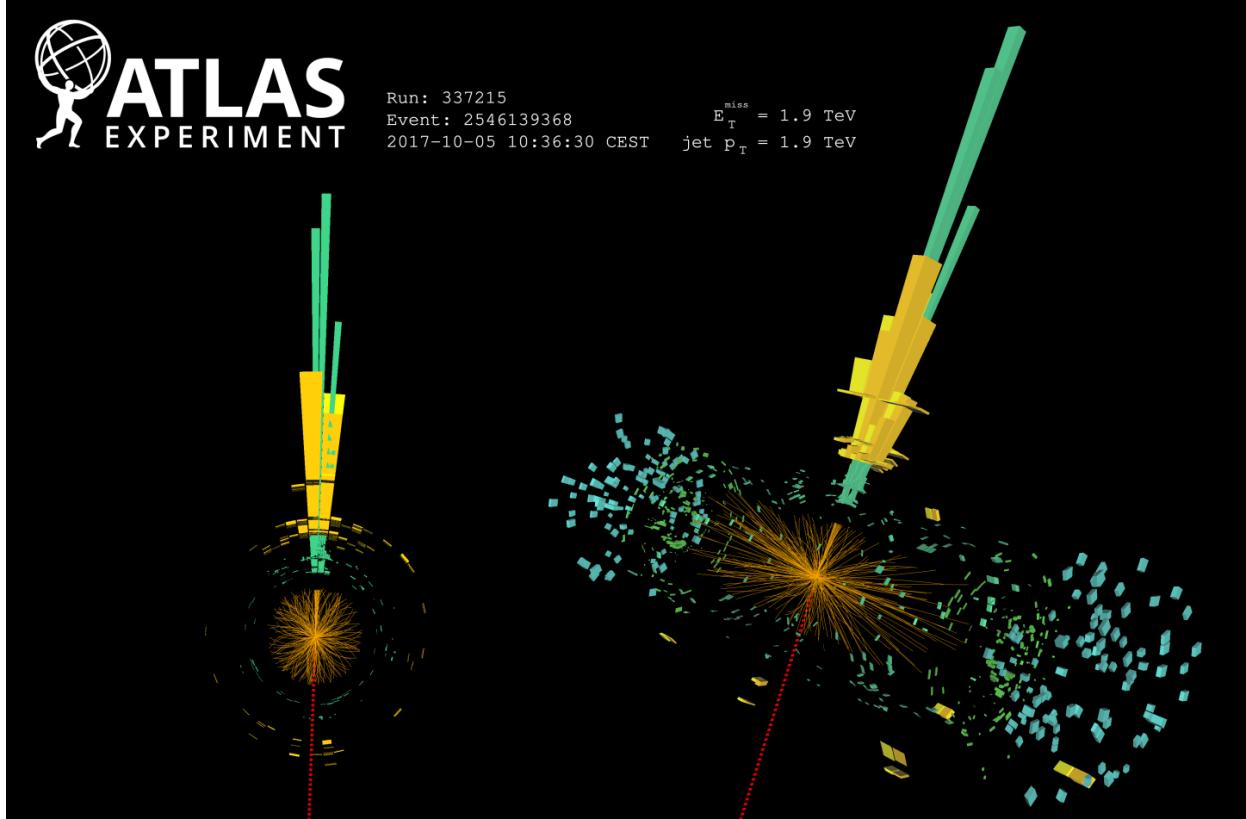


Figure 2.9 A single jet event in ATLAS detector from 2017 [16]. Jet momentum was observed to be 1.9 TeV. Missing transverse momentum was observed to be 1.9 TeV compared to the initial transverse momentum of the event was 0. Implied MET is traced by a red dashed line in event display.

510 2.4.2 Break it: Standard Model Signatures of Dark Matter through Indirect Searches

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

519 the problem of DM in the first place.

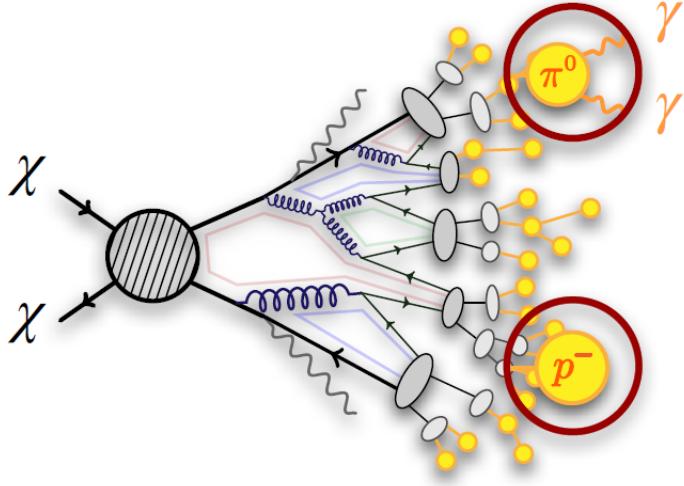


Figure 2.10 More detailed pseudo-Feynman diagram of particle cascade from dark matter annihilation into 2 quarks. The quarks hadronize and down to stable particles like γ or the anti-proton (p^-). Diagram pulled from ICRC 2021 presentation on DM annihilation search [17].

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

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

532 Figure 2.10 shows the quagmire of SM particles that emerges from SM initial states that are not
533 stable [17]. There are many SM particles with varying energies that can be produced in such an

534 interaction. For any arbitrary DM source and stable SM particle, the SM flux from DM annihilating
 535 to a neutral particle in the SM, ϕ , from a region in the sky is described by the following.

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

536 In Equation (6.1), $\langle\sigma v\rangle$ is the velocity-weighted annihilation cross-section of DM to the SM. m_χ
 537 refers to the mass of DM, noted with Greek letter χ . $\frac{dN_\phi}{dE_\phi}$ is the N particle flux weighted by the
 538 particle energy. An example is provided in Figure 2.11 for the γ final state. The integrated terms
 539 are performed over the solid angle, $d\Omega$, and line of sight, l.o.s. ρ is the density of DM for a
 540 location (r, θ') in the sky. The terms left of the '×' are often referred to as the particle physics
 541 component. The terms on the right are referred to as the astrophysical component. For decaying
 542 DM, the equation changes to...

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

543 In Equation (7.1), τ is the decay lifetime of the DM. Just as in Equation (6.1), the left and right
 544 terms are the particle physics and the astrophysical components respectively. The integrated
 545 astrophysical component of Equation (6.1) is often called the J-Factor. Whereas the integrated
 546 astrophysical component of Equation (7.1) is often called the D-Factor.

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

554 2.5 Sources for Indirect Dark Matter Searches

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

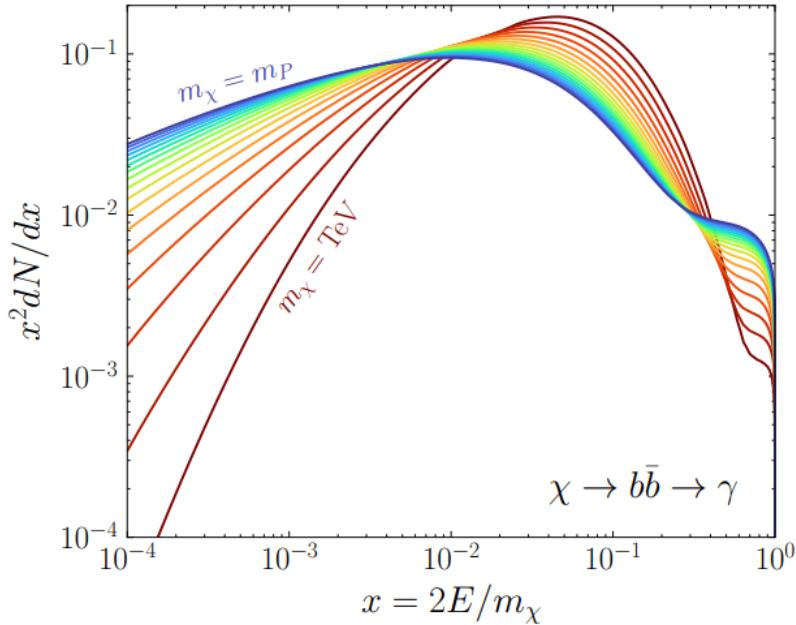


Figure 2.11 Dark Matter (DM) decay spectrum for $b\bar{b}$ initial state and γ final state. Redder spectra are for larger DM masses. Bluer spectra are light DM masses. x is a unitless factor defined as the ratio of the mass of DM, m_χ , and the final state particle energy E_γ . Figure from [19].

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 to 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

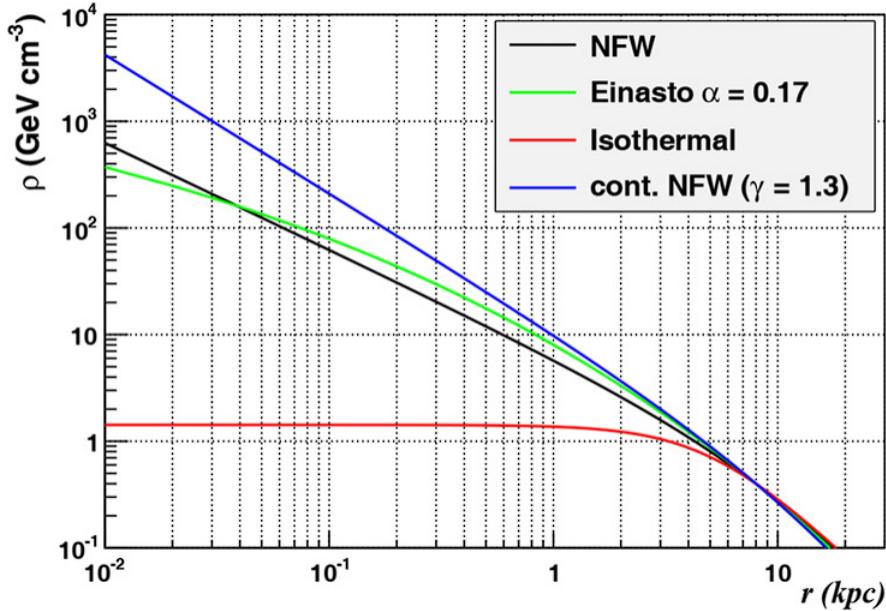


Figure 2.12 Different dark matter density profiles compared. Some models produce exceptionally large densities at small r [20].

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

576 2.6 Multi-Messenger Dark Matter

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

584 The experiment LIGO had a revolutionary discovery in 2016 with the first detection of a binary
 585 black hole merger [21]. This opened the collective imagination to observing the universe through
 586 gravitational waves. There has also been a surge of interest in the neutrino (ν) sector. IceCube

587 demonstrated that we are sensitive to neutrinos in regions that correlate with significant photon
 588 emission like the galactic plane [22]. Neutrinos, like gravitational waves and light, travel mostly
 589 unimpeded from their source to our observatories. This makes pointing to the originating source
 590 of these messengers much easier than it is for cosmic rays which are deflected from their source by
 591 magnetic fields.

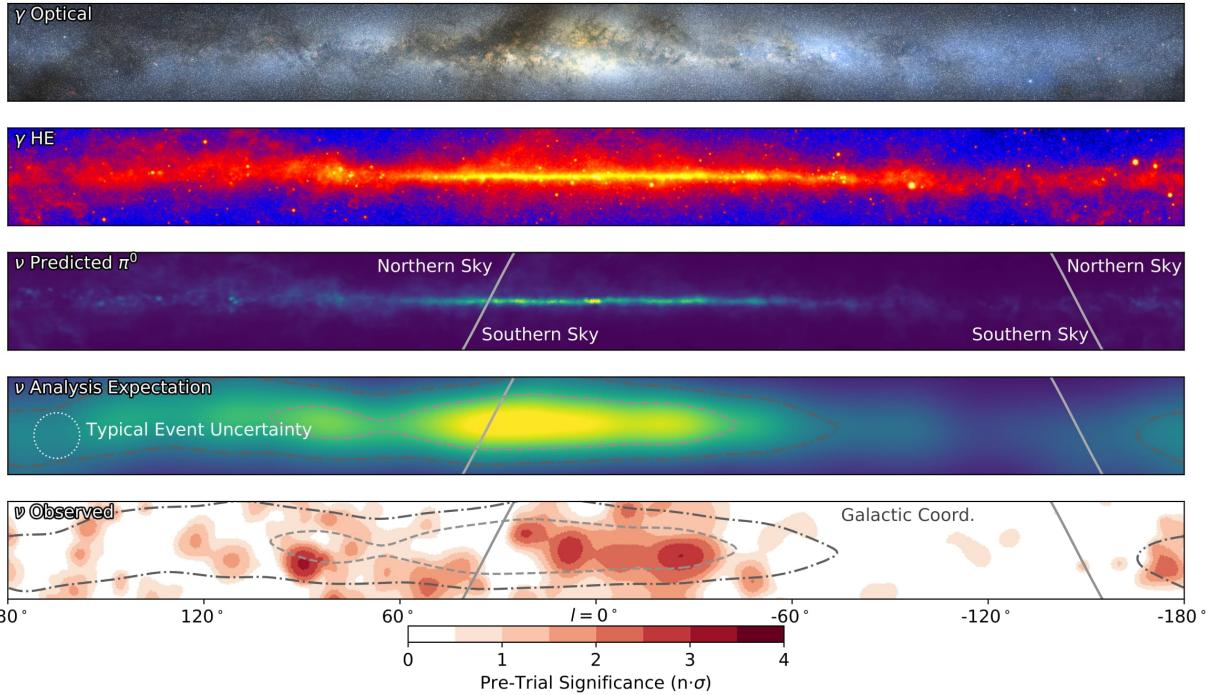


Figure 2.13 The Milky Way Galaxy in photons (γ) and neutrinos (ν) [22]. The Galactic center is at $l=0^\circ$ and is the brightest region in all panels. (top) An Optical color image of the Milky Way galaxy seen from Earth. Clouds of gas and dust obscure some light from stars. (2nd down) Integrated flux 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.

592 The IceCube collaboration recently published a groundbreaking result of the Milky Way in
 593 neutrinos. The recent result from IceCube, shown in Figure 2.13, proves that we can make
 594 observations under different messenger regimes. The top two panels show the appearance of the
 595 galactic plane to different wavelengths of light. Some sources are more apparent in some panels,
 596 while others are not. This new channel is powerful because neutrinos are readily able to penetrate
 597 through gas and dust in the Milky Way. This new image also refines our understanding of how high

598 energy particles are produced. For example, the fit to IceCube data prefers neutrino production
 599 from the decay of π^0 [22].

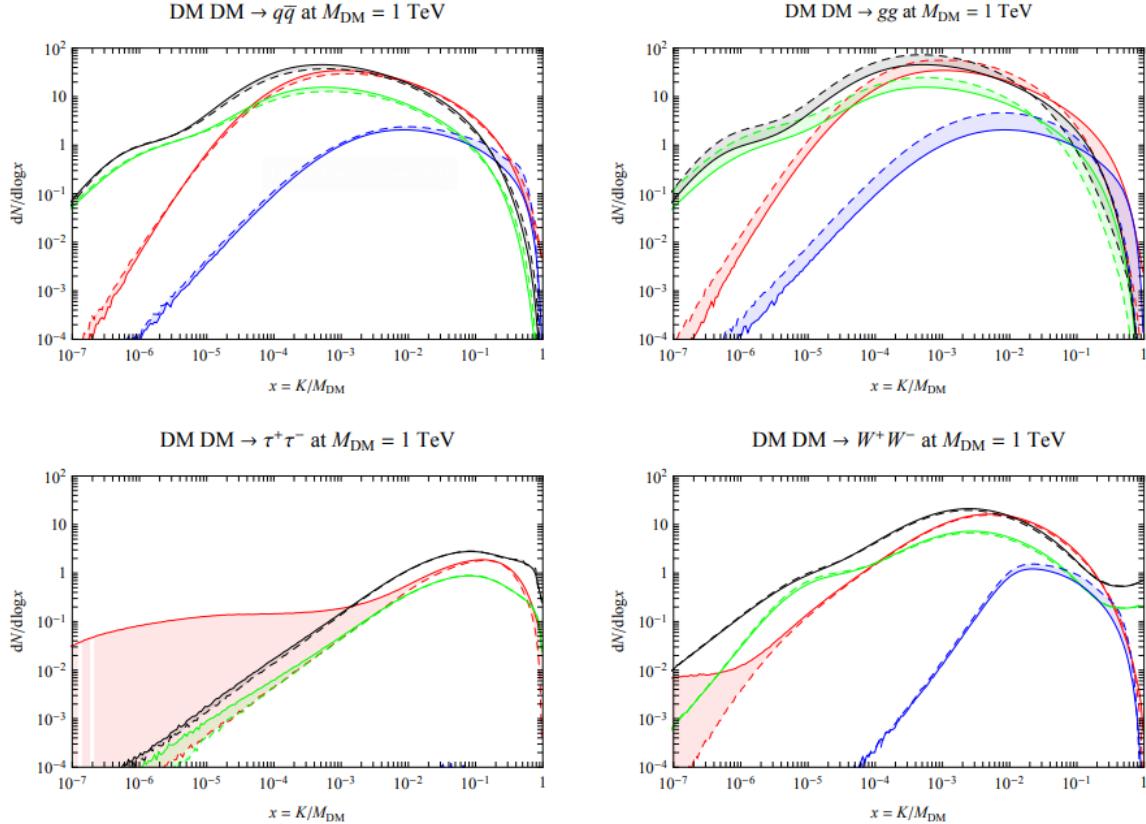


Figure 2.14 Dark Matter annihilation spectra for different final state particle and standard model annihilation channels [24]. Photons (red), e^\pm (green), \bar{p} (blue), ν (black).

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

CHAPTER 3

606 MULTIMESSENGER ASTROPHYSICS: DETECTING HIGH ENERGY NEUTRAL 607 MESSENGERS

608 3.1 Introduction

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

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

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

628 3.2 Charged Particles in a Medium

629 For high enery gamma-rays and neutrinos, we can exploit the same effect that charged particles
630 have with water. This effect is known as Cherenkov radiation. Cherenkov Radiation occurs when a
631 charged particle, usually electrons (e) or muons (μ), traverse a medium, like water, faster than the

632 speed of light in that medium. This is similar to sonic boom where an object moves through air
633 faster than the speed of sound in air. Cherenkov radiation can therefore be thought of as an 'optic
634 boom'. Many astro-particle physics experiments will use water as the medium as because water
635 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]

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

$$INSERT\ Cherenkov\ wavelength\ calc\ HERE. \quad (3.1)$$

637 The absorption spectra is shown in the following figure:

638 **3.3 Photons (γ)**

639 **3.4 Neutrinos (ν)**

640 **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

641 **HIGH ALTITUDE WATER CHERENKOV (HAWC) OBSERVATORY**

642 **4.1 The Detector**

643 **4.2 Events Reconstruction and Data Acquisition**

644 **4.2.1 G/H Discrimination**

645 **4.2.2 Angle**

646 **4.2.3 Energy**

647 **4.3 Remote Monitoring**

648 **4.3.1 ATHENA Database**

649 **4.3.2 HOMER**

650

CHAPTER 5

ICECUBE NEUTRINO OBSERVATORY

651 **5.1 The Detector**

652 **5.2 Events Reconstruction and Data Acquisition**

653 **5.2.1 Angle**

654 **5.2.2 Energy**

655 **5.3 Northern Test Site**

656 **5.3.1 PIgeon remote dark rate testing**

657 **5.3.2 Bulkhead Construction**

CHAPTER 6

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

660 6.1 Introduction

661 The field of astrophysics now has several instruments and observatories sensitive to high
662 energy gamma-rays. The energy sensitivity for the modern gamma-ray program spans many orders
663 of magnitude. Figure 6.1 demonstrates these similar sensitivities across energies for the five
664 experiments: Fermi-LAT, HAWC, HESS, MAGIC, and VERITAS.

665 Each of the five experiments featured in Figure 6.1 have independently searched for DM
666 annihilation from dwarf spheroidal galaxies (dSph) and set limits. Intriguingly, there are regions of
667 substantial overlap in their energy sensitivities. This clearly motivates an analysis that combines data
668 from these five. Each experiment has unique gamma-ray detection methods and their weaknesses
669 and strengths can be leveraged with each other. The HAWC gamma-ray observatory is extensively
670 introduced in chapter 4, so it is not introduced here. A brief description of the remaining experiments
671 are in the following paragraphs.

672 The Large Area Telescope (LAT) is a pair conversion telescope mounted on the NASA Fermi
673 satellite in orbit \sim 550 km above the Earth [26]. LAT's field of view covers about 20% of the
674 whole sky, and it sweeps the whole sky approximately every 3 hours. LAT's gamma-ray energy
675 sensitivity ranges from 20 MeV up to 1 TeV. Previous DM searches towards dSphs using Fermi-LAT
676 are published in [27] and [28]

677 The High Energy Spectroscopic System (HESS), Major Atmospheric Gamma Imaging
678 Cherenkov (MAGIC), and Very Energetic Radiation Imaging Telescope Array System (VERI-
679 TAS) are arrays of Imaging Atmospheric Cherenkov Telescopes (IACT). These telescopes observe
680 the Cherenkov light emitted from gamma-ray showers in the Earth's atmosphere. The field of
681 view for these telescopes is no larger than 5° with energy sensitivities ranging from 30 GeV up
682 to 100 TeV [29, 30, 31]. IACTs are able to make precise observations in selected regions of the
683 sky, however can only be operated in ideal dark conditions. HESS's observations of the dwarves

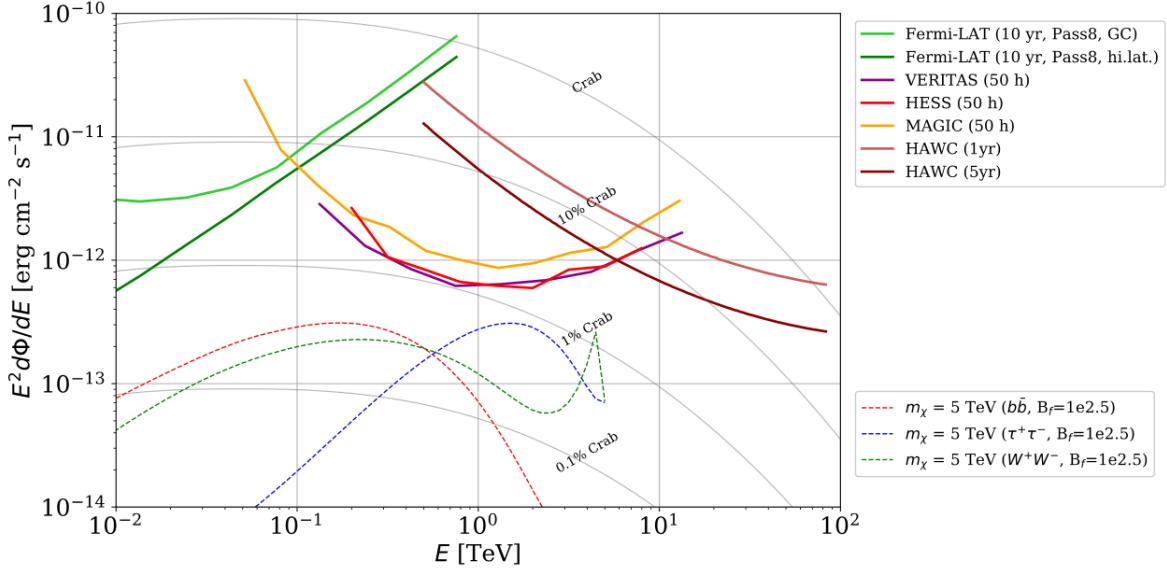


Figure 6.1 Sensitivities of five gamma-ray experiments compared to percentages of the Crab nebula’s emission and dark matter annihilation. Solid lines present estimated sensitivities to power law spectra [FACT CHECK THIS] for each experiment. Green lines are Fermi-LAT sensitivities where lighter green is the sensitivity to the galactic center and dark 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 $\text{cm}^{-2}\text{s}^{-1}$. The dotted lines are estimated dark matter fluxes assuming $m_\chi = 5$ TeV DM annihilating to bottom quarks (red), tau leptons (blue), and W bosons (green). Faded gray lines outline percentage flux of the Crab nebula. Figure is an augmented version of [25]

684 Sculptor and Carina were between January 2008 and December 2009. HESS’s observations of
 685 Coma Berenices were from 2010 to 2013, and Fornax was observed in 2010 [32, 33, 34]. MAGIC
 686 provided deep observations of Segue1 between 2011 and 2013 [35]. MAGIC also provides data
 687 for three dwarves: Coma Berenices, Draco, and Ursa Major II where observations were made
 688 in: January - June 2019 [36], March - September 2018 [36], and 2014 - 2016 [37] respectively.
 689 VERITAS provided data for Boötes I, Draco, Segue 1, and Ursa Minor from 2009 to 2016 [38].

690 This chapter presents the Glory Duck analysis, the name given for the search for dark matter
 691 annihilation from dSph by combining data from the five gamma-ray observatories: Fermi-LAT,
 692 HAWC, HESS, MAGIC, and VERITAS. Specifically, the methods in analysis and modeling are
 693 presented for the HAWC gamma-ray observatory. This work was published to the Journal of
 694 Cosmology and Astroparticle Physics and presented at the International Cosmic Ray Conference

695 in 2019, 2021, and 2023 [39, 40, 41] and others.

696 **6.2 Dataset and Background**

697 This section enumerates the data and background methods used for HAWC's study of dSphs.
698 Section 6.2.1 and Section 6.2.2 are most useful for fellow HAWC collaborators looking to replicate
699 the Glory Duck analysis.

700 **6.2.1 Itemized HAWC files**

- 701 • Detector Resolution: `response_aerie_svn_27754_systematics_best_mc_test_no`
702 `broadpulse_10pctlogchargesmearing_0.63qe_25kHzNoise_run5481_curvatu`
703 `re0_index3.root`
- 704 • Data Map: `maps-20180119/liff/maptree_1024.root`
- 705 • Spectral Dictionary: `DM_CirrelliSpectrum_dict_gammas.npy`
- 706 • Analysis wiki: https://private.hawc-observatory.org/wiki/index.php/Glory_Duck_Multi-Experiment_Dark_Matter_Search

708 **6.2.2 Software Tools and Development**

709 This analysis was performed using HAL and 3ML [42, 43] in Python version 2. I built software
710 to implement the *A Poor Particle Physicist Cookbook for Dark Matter Indirect Detection* (PPPC)
711 [44] DM spectral model and dSphs spatial model from [45] for HAWC analysis. A NumPy version
712 of this dictionary was made for both Py2 and Py3. The code base for creating this dictionary is
713 linked on my GitLab sandbox:

- 714 • Py2: [Dictionary Generator \(Deprecated\)](#)
- 715 • Py3: [PPPC2Dict](#)

716 The analysis was performed using the f_{hit} framework performed in the HAWC Crab paper
717 [42]. The Python2 NumPy dictionary file for gamma-ray final states is `dmCirSpecDict.npy`. The
718 corresponding Python3 file is `DM_CirrelliSpectrum_dict_gammas.npy`. These files can also

719 be used for decay channels and the PPPC describes how [44]. All other software used for data
720 analysis, DM profile generation, and job submission to SLURM are also kept in my sandbox for
721 [the Glory Duck](#) project.

722 6.2.3 Data Set and Background Description

723 The HAWC data maps used for this analysis contain 1017 days of data between runs 2104
724 (2014-11-26) and 7476 (2017-12-20). They were generated from pass 4.0 reconstruction. The
725 analysis is performed using the f_{hit} energy binning scheme with bins (1-9) similar to what was done
726 for the Crab and previous HAWC dSph analysis [42, 46]. Bin 0 was excluded as it has substantial
727 hadronic contamination and poor angular resolution.

728 This analysis was done on dSphs because of their large DM mass content relative to baryonic
729 mass. We consider the following to estimate the background to this study.

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

735 Therefor we make no additional assumptions on the background from our sources and use
736 HAWC’s standard direct integration method for background estimation [42]. It is possible for
737 gamma rays from DM annihilation to scatter in transit to HAWC via Inverse Compton Scattering
738 (ICS). This was investigated and its impact on the flux is basically zero. Supporting information
739 on this is in Section 6.7.1

740 6.3 Analysis

741 The expected differential photon flux from DM-DM annihilation to standard model particles,
742 $d\Phi_\gamma/dE_\gamma$, over solid angle, Ω is described by the familiar equation.

$$\frac{d\Phi_\gamma}{dE_\gamma} = \frac{\langle\sigma v\rangle}{8\pi m_\chi^2} \frac{dN_\gamma}{dE_\gamma} \times \int_{\text{source}} d\Omega \int_{l.o.s} \rho_\chi^2 dl(r, \theta') \quad (6.1)$$

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

$$J = \int d\Omega \int_{l.o.s} dl \rho_\chi^2(r, \theta') \quad (6.2)$$

746 l is the distance to the source from Earth. r is the radial distance from the center of the source. θ' is
 747 the half angle defining a cone containing the DM source. How each component is synthesized and
 748 considered for HAWC's analysis is presented in the following sections. Section 6.3.1 presents the
 749 particle physics model for DM annihilation. Section 6.3.2 presents the spatial distributions built
 750 for each dSph.

751 6.3.1 $\frac{dN_\gamma}{dE_\gamma}$ - Particle Physics Component

752 For these spectra, we import the PPPC with Electroweak (EW) corrections [44]. The spectrum
 753 is implemented as a model script in astromodels for 3ML. The EW corrections were previously not
 754 considered for HAWC and are significant for DM annihilating to EW coupled SM particles such
 755 as all leptons, and the γ , Z , and W bosons [46]. Figure 6.2 demonstrates the significance of EW
 756 corrections for W boson annihilation. Across EW SM channels, the gamma-ray spectra become
 757 harder than spectra without EW corrections. Tables from the PPPC were reformatted into Python
 758 NumPy dictionaries for collaboration-wide use. A class in astromodels was developed to include
 759 the EW correction from the PPPC and is aptly named `PPPCSpectra` within `DM_models.py`.

760 6.3.2 J - Astrophysical Component

761 The J-factor profiles for each source are imported from Geringer-Sameth (referred to with \mathcal{GS})
 762 [45]. These were pulled from the publication as $J(\theta)$, where θ is the angular separation from the
 763 center of the source. HAWC requires maps in terms of $\frac{dJ}{d\Omega}$, so the conversion from the maps was
 764 done in the following way...

765 First, convert the angular distances to solid angles

$$\Omega = 2 \cdot \pi(1 - \cos(\theta)) \quad (6.3)$$

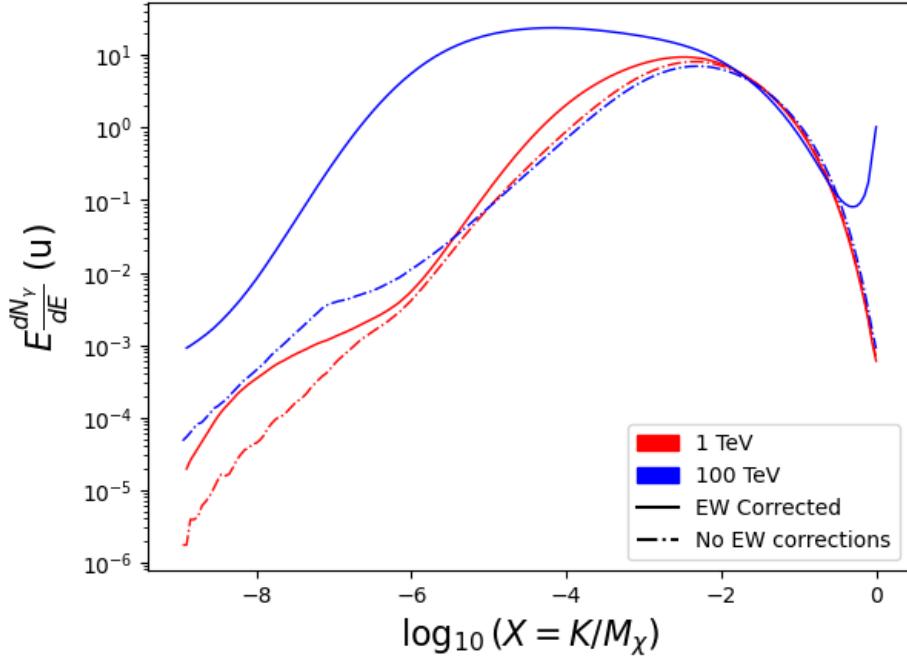


Figure 6.2 Effect of Electroweak (EW) corrections on expected DM annihilation spectrum for $\chi\chi \rightarrow W^-W^+$. Solid lines are spectral models that consider EW corrections. Dash-dot lines are spectral models without EW corrections. Red lines are models for $M_\chi = 1$ TeV. Blue lines represent models for $M_\chi = 100$ TeV. All models are sourced from the PPPC4DMID [44].

766 which reduces with a small angle approximation to $\pi\theta^2$. Next, the central difference for both the
 767 ΔJ and $\Delta\Omega$ value were calculated from the discretized $J(\theta)$ with the central difference stencil:

$$\Delta\phi_i = \phi_{i+1} - \phi_{i-1} \quad (6.4)$$

768 Where ϕ is either Ω or J . These were done separately in case the grid spacing in θ was not uniform.
 769 Finally, these lists are divided so that we are left with an approximation of the $dJ/d\Omega$ profile that
 770 is a function of θ . Admittedly, this is an approximation method for the map which introduces small
 771 errors compared to the true profile estimate. This was checked as a systematic against the author's
 772 profiling of the spatial distribution and is documented in Section 6.8.1.

773 With $\frac{dJ}{d\Omega}(\theta)$, a map is generated, first by filling in the north-east quadrant of the map. This
 774 quadrant is then reflected twice, vertically then horizontally, to fill the full map. Maps are then
 775 normalized by dividing the discrete 2D integral of the map. The 2D integral was a simple height

776 of bins, Newton's integral:

$$p^2 \cdot \sum_{i,j=0}^{N,M} \frac{dJ}{d\Omega}(\theta_{i,j}, \phi_{i,j}) \quad (6.5)$$

777 These maps are HEALpix maps with NSIDE 16384 and saved in the `.fits` format.

778 Another DM spatial distribution model from Bonnivard (\mathcal{B}) [47] was used for the Glory Duck
779 study. However, to save computational time, limits from \mathcal{GS} were scaled to \mathcal{B} instead of each
780 experiment performing a full study a second time. How these models compare is demonstrated
781 for each dSph in Figure 6.16 and Figure 6.17 Plots of these maps are provided for each source
782 in chapter A Examples of the two most impactful dSphs derived from \mathcal{GS} , Segue1 and Coma
783 Berenices are featured in Figure 6.3

784 **6.3.3 Source Selection and Annihilation Channels**

785 We use many of the dSphs presented in HAWC's previous dSph DM search [46]. HAWC's
786 sources for Glory Duck include Boötes I, Coma Berenices, Canes Venatici I + II, Draco, Hercules,
787 Leo I, II, + IV, Segue 1, Sextans, and Ursa Major I + II. A full description of all sources used
788 in Glory Duck is found in Table 6.1. Triangulum II was excluded from the Glory Duck analysis
789 because of large uncertainties in its J factor. Ursa Minor was excluded from HAWC's contribution
790 to the combination because the source extension model extended Ursa Minor beyond HAWC's field
791 of view. Ursa Minor was not expected to contribute significantly to the combined limit, so work
792 was not invested in a solution to include Ursa Minor.

793 This analysis improves on the previous HAWC dSph paper [46] in the following ways. Pre-
794 viously, the dSphs were treated and implemented as point sources. For this analysis, dSphs are
795 modeled and treated as extended source. The impact of this change with respect to the upper limit
796 is source dependent and is explored in Section 6.7.2. Previously, the particle physics model used for
797 gamma-ray spectra from DM annihilation did not have EW corrections where the PPPC includes
798 them. Finally, the gamma-ray ray dataset is much larger. The study performed here analyzes over
799 1000 days of data compared to 507.

800 The SM annihilation channels probed for the Glory Duck combination include $b\bar{b}$, $e\bar{e}$, $\mu\bar{\mu}$, $\tau\bar{\tau}$,
801 $t\bar{t}$, W^+W^- , and ZZ . A summary of all sources, with a description of each experiments' sensitivity

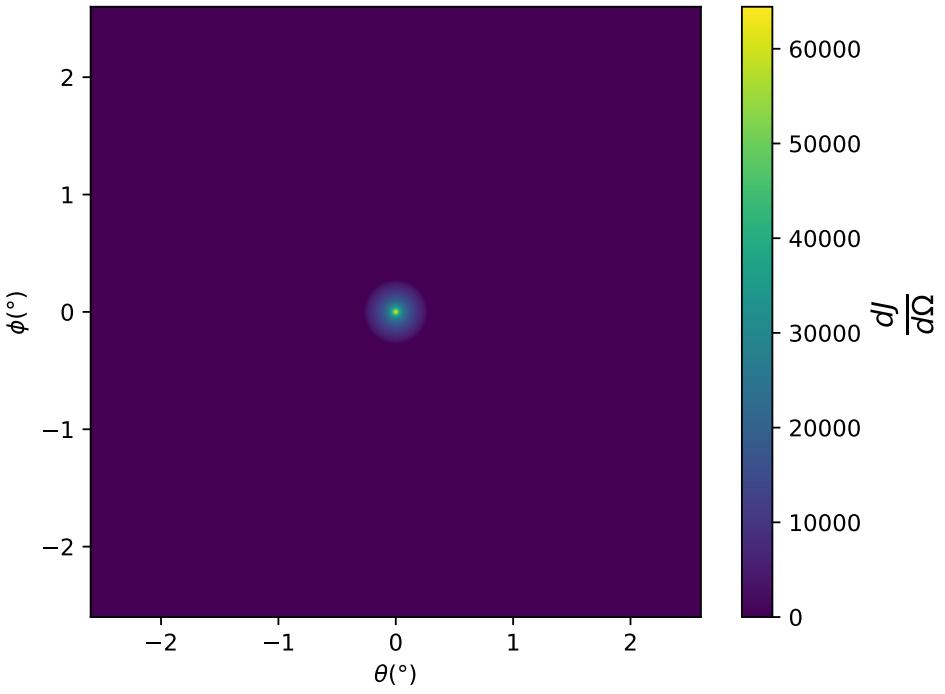
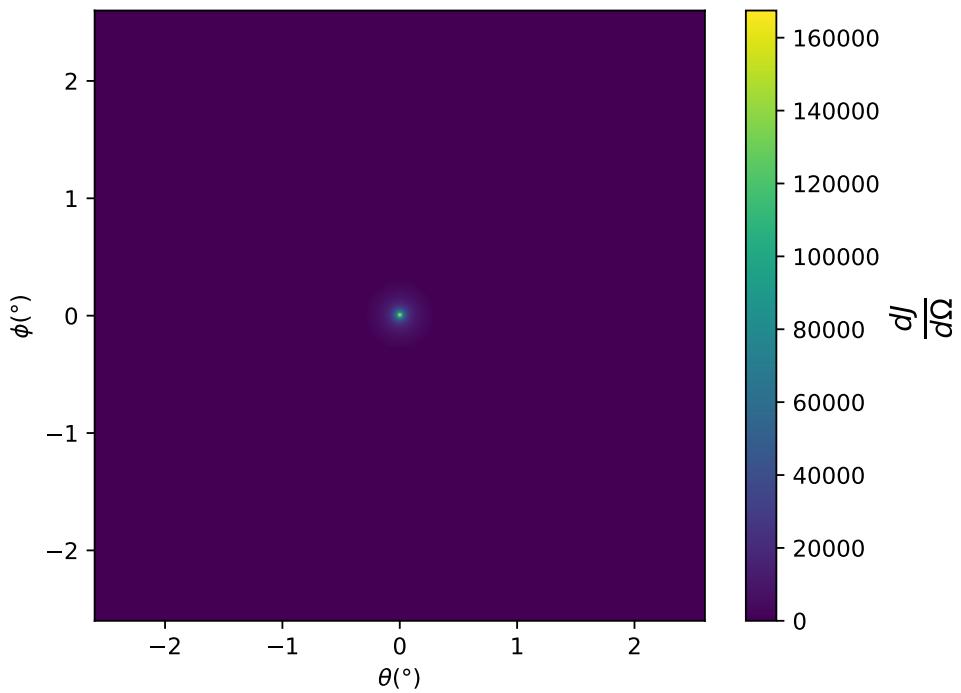


Figure 6.3 $\frac{dJ}{d\Omega}$ maps for Segue1 (top) and Coma Berenices (bottom). Origin is centered on the specific dwarf spheroidal galaxies (dSph). X and Y axes are the angular separation from the center of the dwarf. Plots of the remaining 11 dSph HAWC studied are linked in Fig. A.1.

Table 6.1 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) [45] 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) [47] 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 ($^{\circ}$)	$\log_{10} J$ (\mathcal{GS} set) $\log_{10}(\text{GeV}^2 \text{cm}^{-5} \text{sr})$	$\log_{10} J$ (\mathcal{B} set) $\log_{10}(\text{GeV}^2 \text{cm}^{-5} \text{sr})$
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	$18.95^{+0.26}_{-0.18}$	$19.08^{+0.21}_{-0.13}$

802 to the source, is provided in Table 6.2.

803 6.4 Likelihood Methods

804 6.4.1 HAWC Likelihoods

805 For every analysis bin in energy, f_{hit} bins (1-9), and location, we can expect N signal events and
806 B background events. The expected number of excess signal events from dark matter annihilation,

Table 6.2 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 .

Source name	Fermi-LAT	HAWC	H.E.S.S, MAGIC, VERITAS						
	Exposure (10^{11} s m 2)	$ \Delta\theta $ ($^\circ$)	IACT	Zenith ($^\circ$)	Exposure (h)	Energy range (GeV)	θ ($^\circ$)	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
Draco	3.8	38.1	MAGIC	5 – 37	49.5	60 – 10000	0.17	1.0	–
			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

807 S , is estimated by convolving Equation (6.1) with HAWC's energy response and pixel point spread
 808 functions. I then compute the test statistic (TS) with the log-likelihood ratio test,

$$\text{TS} = -2 \ln \left(\frac{\mathcal{L}_0}{\mathcal{L}^{\max}} \right) \quad (6.6)$$

810 where \mathcal{L}_0 is the null hypothesis, or no DM emission, likelihood. \mathcal{L}^{\max} is the best fit signal
 811 hypothesis where $\langle \sigma v \rangle$ maximizes the likelihood. We calculate the likelihood of each source and
 812 model, assuming events are Poisson distributed, with

$$\mathcal{L} = \prod_i \frac{(B_i + S_i)^{N_i} e^{-(B_i + S_i)}}{N_i!} \quad (6.7)$$

813 where S_i is the sum of expected number of signal counts. B_i is the number of background counts
 814 observed. N_i is the total number of counts.

815 I also calculate an upper limit on $\langle \sigma v \rangle$ by calculating the 95% confidence level (CL). For the
 816 CL, we define a parameter, TS_{95} , as

$$\text{TS}_{95} \equiv \sum_{\text{bins}} \left[2N \ln \left(1 + \frac{\epsilon S_{\text{ref}}}{B} \right) - 2\epsilon S_{\text{ref}} \right] \quad (6.8)$$

817 where the expected signal counts from a dSph is scaled by ϵ . S_{ref} is the expected number of excess
 818 counts in a bin from DM emission from a dSph with a corresponding annihilation cross-section,
 819 $\langle \sigma v \rangle$. We scan ϵ such that

$$2.71 = \text{TS}_{\max} - \text{TS}_{95} \quad (6.9)$$

820 6.4.2 Glory Duck Joint Likelihood

821 The joint likelihood for the 5-experiment combination was done similarly as Section 6.4.1. We
 822 calculate upper limits on $\langle \sigma v \rangle$ from the TS, Eq. (6.6), and define the likelihood ratio more generally

$$\lambda(\langle \sigma v \rangle | \mathcal{D}_{\text{dSphs}}) = \frac{\mathcal{L}(\langle \sigma v \rangle; \hat{\nu} | \mathcal{D}_{\text{dSphs}})}{\mathcal{L}(\widehat{\langle \sigma v \rangle}; \hat{\nu} | \mathcal{D}_{\text{dSphs}})} \quad (6.10)$$

823 $\mathcal{D}_{\text{dSphs}}$ is the totality of observations across experiments and dSphs. ν are the nuisance parameters
 824 which are the J factors in this study. $\widehat{\langle \sigma v \rangle}$ and $\hat{\nu}$ are the respective estimate that maximize \mathcal{L}
 825 globally. Finally, $\hat{\nu}$ is the set of nuisance parameters that maximize \mathcal{L} for a fixed value of $\langle \sigma v \rangle$.

826 The *complete* joint likelihood, \mathcal{L} that encompasses all observations from all instruments and
 827 dSphs can be factorized into *partial* functions for each dSph l (with $\mathcal{L}_{\text{dSph},l}$) and its J factor (\mathcal{J}_l):

$$\mathcal{L} (\langle \sigma v \rangle; \nu | \mathcal{D}_{\text{dSphs}}) = \prod_{l=1}^{N_{\text{dSphs}}} \mathcal{L}_{\text{dSph},l} (\langle \sigma v \rangle; J_l, \nu_l | \mathcal{D}_l) \times \mathcal{J}_l (J_l | J_{l,\text{obs}}, \sigma_{\log J_l}). \quad (6.11)$$

828 For this study, $N_{\text{dSphs}} = 20$ is the number of dSphs studied. \mathcal{D}_l are the gamma-ray observations
 829 of dSph, l . ν_l are the nuisance parameters modifying the gamma-ray observations of dSph, l ,
 830 but excludes \mathcal{J}_l . \mathcal{J}_l is the J factor for dSph, l , as defined in Equation (6.2), and it is a nuisance
 831 parameter whose value is unknown. $\log_{10} J_{l,\text{obs}}$ and $\sigma_{\log J_l}$ are obtained from fitting a log-normal
 832 function of $J_{l,\text{obs}}$ to the posterior distribution of J_l [48]. $\log_{10} J_{l,\text{obs}}$ and $\sigma_{\log J_l}$ values are provided
 833 in Table 6.1. The term \mathcal{J}_l constraining J_l is written as:

$$\mathcal{J}_l (J_l | J_{l,\text{obs}}, \sigma_{\log J_l}) = \frac{1}{\ln(10) J_{l,\text{obs}} \sqrt{2\pi} \sigma_{\log J_l}} \exp\left(-\frac{(\log_{10} J_l - \log_{10} J_{l,\text{obs}})^2}{2\sigma_{\log J_l}^2}\right). \quad (6.12)$$

834 Both the \mathcal{GS} and \mathcal{B} , displayed in Table 6.1, sets of J factors are used in this analysis. Equation (6.12)
 835 is also normalized, so it can also be interpreted as a probability density function (PDF) for $J_{l,\text{obs}}$.
 836 From Equation (6.1), we can also see that $\langle \sigma v \rangle$ and J_l are degenerate when computing $\mathcal{L}_{\text{dSph},l}$.
 837 Therefore, as noted in [49], it is sufficient to compute $\mathcal{L}_{\text{dSph},l}$ versus $\langle \sigma v \rangle$ for a fixed value of J_l .
 838 We used $J_{l,\text{obs}}(\mathcal{GS})$ reported in Tab. 6.1, in order to perform the profile of \mathcal{L} with respect to J_l .
 839 The degeneracy implies that for any $J'_l \neq J_{l,\text{obs}}$ (in practice in our case we used $J'_l = J_{l,\text{obs}}(\mathcal{B})$ to
 840 compute results from a different set of J factors):

$$\mathcal{L}_{\text{dSph},l} (\langle \sigma v \rangle; J'_l, \nu_l | \mathcal{D}_l) = \mathcal{L}_{\text{dSph},l} \left(\frac{J'_l}{J_{l,\text{obs}}} \langle \sigma v \rangle; J_{l,\text{obs}}, \nu_l | \mathcal{D}_l \right), \quad (6.13)$$

841 which is a straightforward rescaling operation that reduces the computational needs of the profiling
 842 operation since:

$$\mathcal{L} (\langle \sigma v \rangle; \hat{\nu} | \mathcal{D}_{\text{dSphs}}) = \prod_{l=1}^{N_{\text{dSphs}}} \max_{J_l} \left[\mathcal{L}_{\text{dSph},l} (\langle \sigma v \rangle; J_l, \hat{\nu}_l | \mathcal{D}_l) \times \mathcal{J}_l (J_l | J_{l,\text{obs}}, \sigma_{\log J_l}) \right]. \quad (6.14)$$

843 In addition, Eq. (6.13) enables the combination of data from different gamma-ray instruments and
 844 observed dSphs via tabulated values of $\mathcal{L}_{\text{dSph},l}$, or equivalently of λ from Eq. (6.10) as was done in

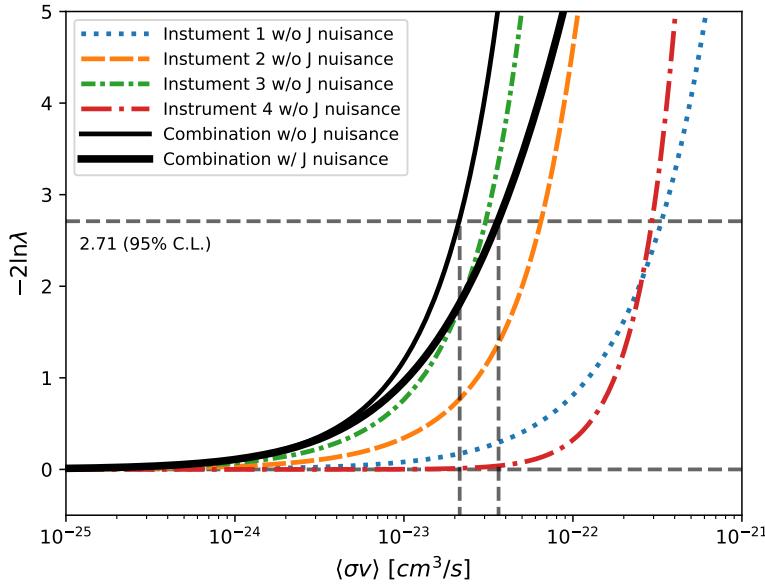


Figure 6.4 Illustration of the combination technique showing a comparison between $-2 \ln \lambda$ provided by four instruments (colored lines) from the observation of the same dSph without any J nuisance and their sum, *i.e.* the resulting combined likelihood (thin black line). According to the test statistics of Equation (6.6), 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 how the uncertainties on the J factor effects 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.

845 this work, versus $\langle \sigma v \rangle$. $\mathcal{L}_{dSph,l}$ is computed for a fixed value of J_l and profiled with respect to all
 846 instrumental nuisance parameters ν_l , these nuisance parameters are discussed in more detail below.
 847 These values are produced by each detector independently and therefore there is no need to share
 848 sensitive low-level information used to produce them, such as event lists. Figure 6.4 illustrates the
 849 multi-instrument combination technique used in this study with a comparison of the upper limit
 850 on $\langle \sigma v \rangle$ obtained from the combination of the observations of four experiments towards one dSph
 851 versus the upper limit from individual instruments. It also shows graphically the effect of the
 852 J -factor uncertainty on the combined observations.

853 The *partial* joint likelihood function for gamma-ray observations of each dSph ($\mathcal{L}_{dSph,l}$) is

written as the product of the likelihood terms describing the $N_{\text{exp},l}$ observations performed with any of our observatories:

$$\mathcal{L}_{\text{dSph},l} (\langle \sigma v \rangle; J_l, \nu_l | \mathcal{D}_l) = \prod_{k=1}^{N_{\text{exp},l}} \mathcal{L}_{lk} (\langle \sigma v \rangle; J_l, \nu_{lk} | \mathcal{D}_{lk}), \quad (6.15)$$

where each \mathcal{L}_{lk} term refers to an observation of the l -th dSph with associated k -th instrument responses. $N_{\text{exp},l}$ varies from dSph to dSph and can be inferred from Table 6.2.

Each collaboration separately analyzes their data for \mathcal{D}_{lk} corresponding to dSph l and gamma-ray detector k , using as many common assumptions as possible in the analysis. HAWC's treatment was described earlier in Section 6.4.1 whereas the specifics of the remaining experiments is left to the publication. We compute the values for the likelihood functions \mathcal{L}_{lk} (see Eq. (6.15)) for a fixed value of J_l and profile over the rest of the nuisance parameters ν_{lk} . Then, values of λ from Eq. (6.10) are computed as a function of $\langle \sigma v \rangle$, and shared using a common format. Results are computed for seven annihilation channels, W^+W^- , ZZ , $b\bar{b}$, $t\bar{t}$, e^+e^- , $\mu^+\mu^-$, and $\tau^+\tau^-$ over 62 m_χ values between 5 GeV and 100 TeV provided in [44]. The $\langle \sigma v \rangle$ range is defined between 10^{-28} and $10^{-18} \text{ cm}^3 \cdot \text{s}^{-1}$, with 1001 logarithmically spaced values. The likelihood combination, i.e. Equation (6.11), and profile over the J -factor to compute the profile likelihood ratio λ , Equation (6.10), are carried out with two different public analysis software packages, namely `gLike` [50] and `LklCom` [51], that provide the same results [52].

As mentioned previously, each experiment computes the \mathcal{L}_{lk} from Equation (6.10) 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 \mathcal{D}_{lk} of a given dSph l carried out using a given gamma-ray detector k , the binned likelihood function is:

$$\mathcal{L}_{lk} (\langle \sigma v \rangle; J_l, \nu_{lk} | \mathcal{D}_{lk}) = \prod_{i=1}^{N_E} \prod_{j=1}^{N_P} \left[\mathcal{P}(s_{lk,ij}(\langle \sigma v \rangle, J_l, \nu_{lk}) + b_{lk,ij}(\nu_{lk}) | N_{lk,ij}) \right] \times \mathcal{L}_{lk,\nu} (\nu_{lk} | \mathcal{D}_{\nu_{lk}}) \quad (6.16)$$

where N_E and N_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 $N_{lk,ij}$

877 observed in the i -th bin in energy and j -th bin in arrival direction, when the expected number is
 878 the sum of the expected mean number of signal events s_{ij} (produced by DM annihilation) and of
 879 background events b_{ij} ; $\mathcal{L}_{lk,\nu}$ is the likelihood term for the extra ν_{lk} nuisance parameters that vary
 880 from one instrument k to another. The expected counts for signal events s_{ij} for a given dSph l and
 881 detector k is given by:

$$s_{ij}(\langle\sigma\nu\rangle, J) = \int_{E'_{\min,i}}^{E'_{\max,i}} dE' \int_{P'_{\min,j}}^{P'_{\max,j}} d\Omega' \int_0^\infty dE \int_{\Delta\Omega_{tot}} d\Omega \int_0^{T_{\text{obs}}} dt \frac{d^2\Phi(\langle\sigma\nu\rangle, J)}{dEd\Omega} \text{IRF}(E', P' | E, P, t) \quad (6.17)$$

882 where E' and E are the reconstructed and true energies, P' and P the reconstructed and true
 883 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
 884 energy bin and the j -th arrival direction bin; T_{obs} is the (dead-time corrected) total observation
 885 time; t is the time along the observations; $d^2\Phi/dEd\Omega$ is the DM flux in the source region (see
 886 Equation (6.1)); and $\text{IRF}(E', P' | E, P, t)$ is the IRF, which can be factorized as the product of the
 887 effective collection area of the detector $A_{\text{eff}}(E, P, t)$, the PDFs for the energy estimator $f_E(E' | E, t)$,
 888 and arrival direction $f_P(P' | E, P, t)$ estimators. Note that for Fermi-LAT, HAWC, MAGIC, and
 889 VERITAS the effect of the finite angular resolution is taken into account through the convolution
 890 of $d\Phi/dEd\Omega$ with f_P in Equation (6.17), whereas in the cases of H.E.S.S. f_P is approximated by a
 891 delta function. This approximation has been made in order to maintain compatibility of the result
 892 with what has been previously published. The difference introduced by this approximation is $< 5\%$
 893 for all considered dSphs. A more comprehensive review of the differences between the analyses of
 894 different instruments can be found in [25].

895 6.5 HAWC Results

896 13 of the 20 dSphs considered for the Glory Duck analysis are within HAWC's field of view.
 897 These dSph are analyzed for emission from DM annihilation according to the likelihood method
 898 described in Section 6.4. The 13 likelihood profiles are then stacked to synthesize a combined
 899 limit on the dark matter cross-section, $\langle\sigma\nu\rangle$. This combination is done for the 7 SM annihilation
 900 channels used in the Glory Duck analysis. Figure 6.5 shows the combined limit for all annihilation
 901 channels with HAWC only observations. We also perform 300 studies of Poisson trials on the

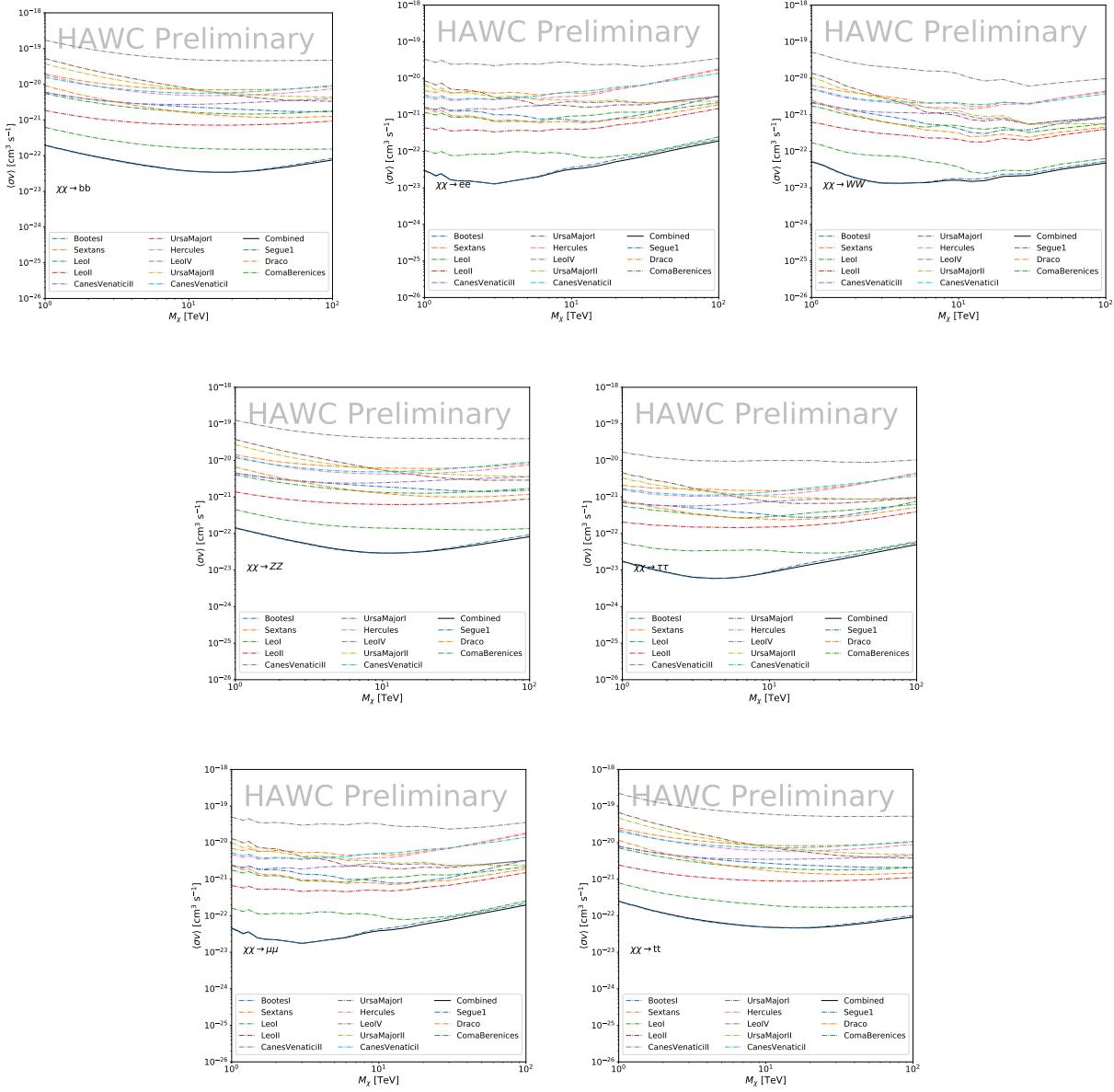


Figure 6.5 HAWC upper limits at 95% confidence level on $\langle\sigma v\rangle$ versus DM mass for seven annihilation channels, using the set of J -factors from Ref. [53]. The solid line represents the observed combined limit. Dashed lines represent limits from individual dSphs.

background. These trials are used to produce HAWC Brazil bands which were shared with the other collaborators for combined Brazil Bands. The results on fitting to HAWC's Poisson trials of the DM hypothesis is shown in Figure 6.7 for all the DM annihilation channels studied for Glory Duck.

No DM was found in HAWC observations. HAWC's limits are dominated by the dSphs Segue1

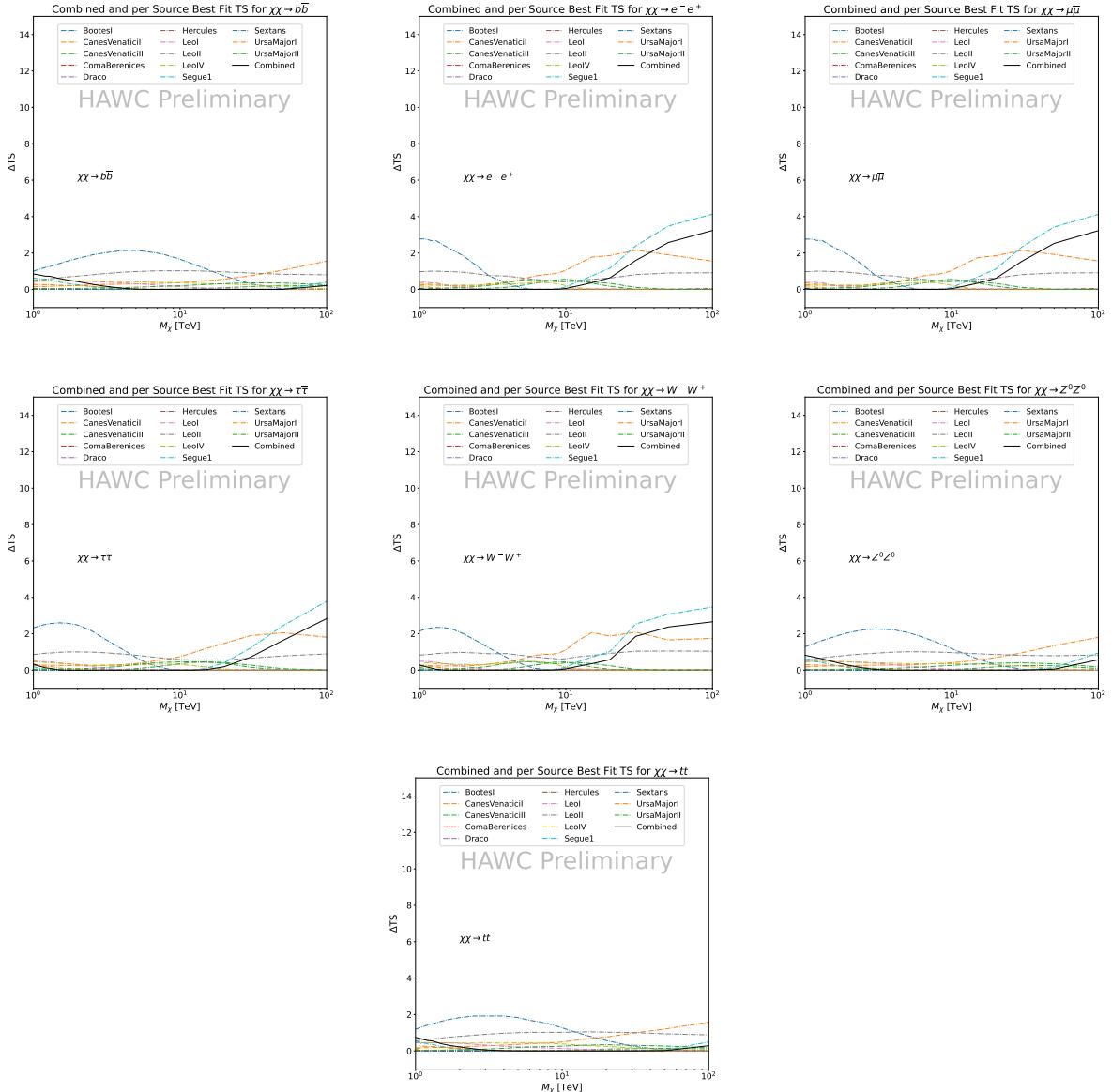


Figure 6.6 HAWC TS values for best fit $\langle \sigma v \rangle$ versus m_χ for seven SM annihilation channels with J factors from \mathcal{GS} . The solid black line shows the combined best fit TS values. The colored, dashed lines are the TS values for each of the 13 sources HAWC studied.

and Coma Berenices. The remaining 11 dSphs do not contribute significantly to the limit because they are at high zenith and/or have much smaller J factors. Even though some remaining dSphs have large J factors, they are towards the edge of HAWC's field of view where HAWC analysis is less sensitive.

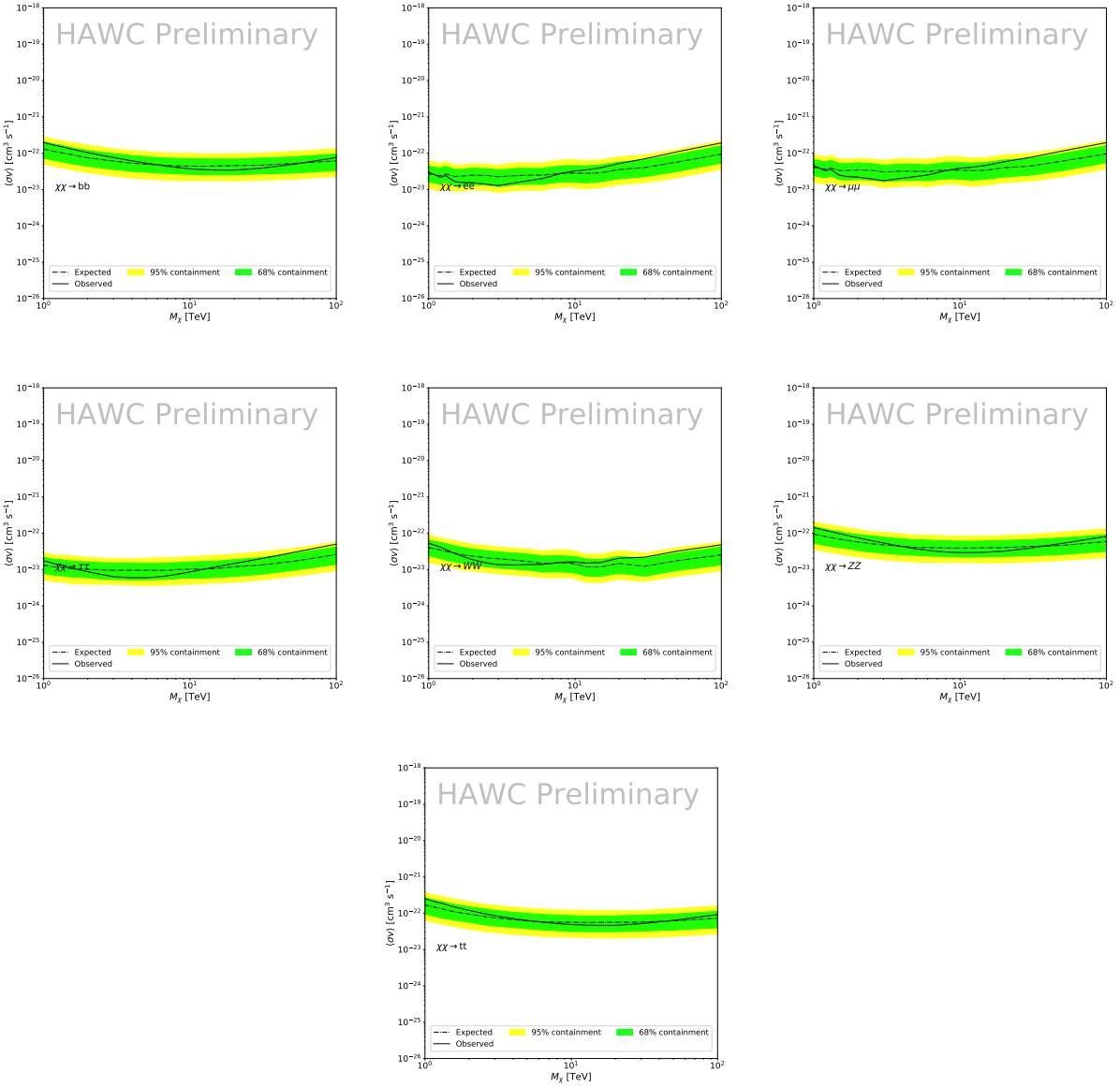


Figure 6.7 HAWC Brazil bands at 95% confidence level on $\langle\sigma v\rangle$ versus DM mass for seven annihilation channels with J -factors from \mathcal{GS} [53]. The solid line represents the combined limit from 13 dSphs. The dashed line is the expected limit. The green band is the 68% containment. The yellow band is the 95% containment.

911 6.6 Glory Duck Combined Results

912 The crux of this analysis is that HAWC's results are combined with 4 other gamma-ray observa-
 913 tories: Fermi-LAT, H.E.S.S., MAGIC, and VERITAS. No significant DM emission was observed
 914 by any of the five instruments. We present the upper limits on $\langle\sigma v\rangle$ assuming seven independent
 915 DM self annihilation channels, namely W^+W^- , Z^+Z^- , $b\bar{b}$, $t\bar{t}$, e^+e^- , $\mu^+\mu^-$, and $\tau^+\tau^-$. The 68%

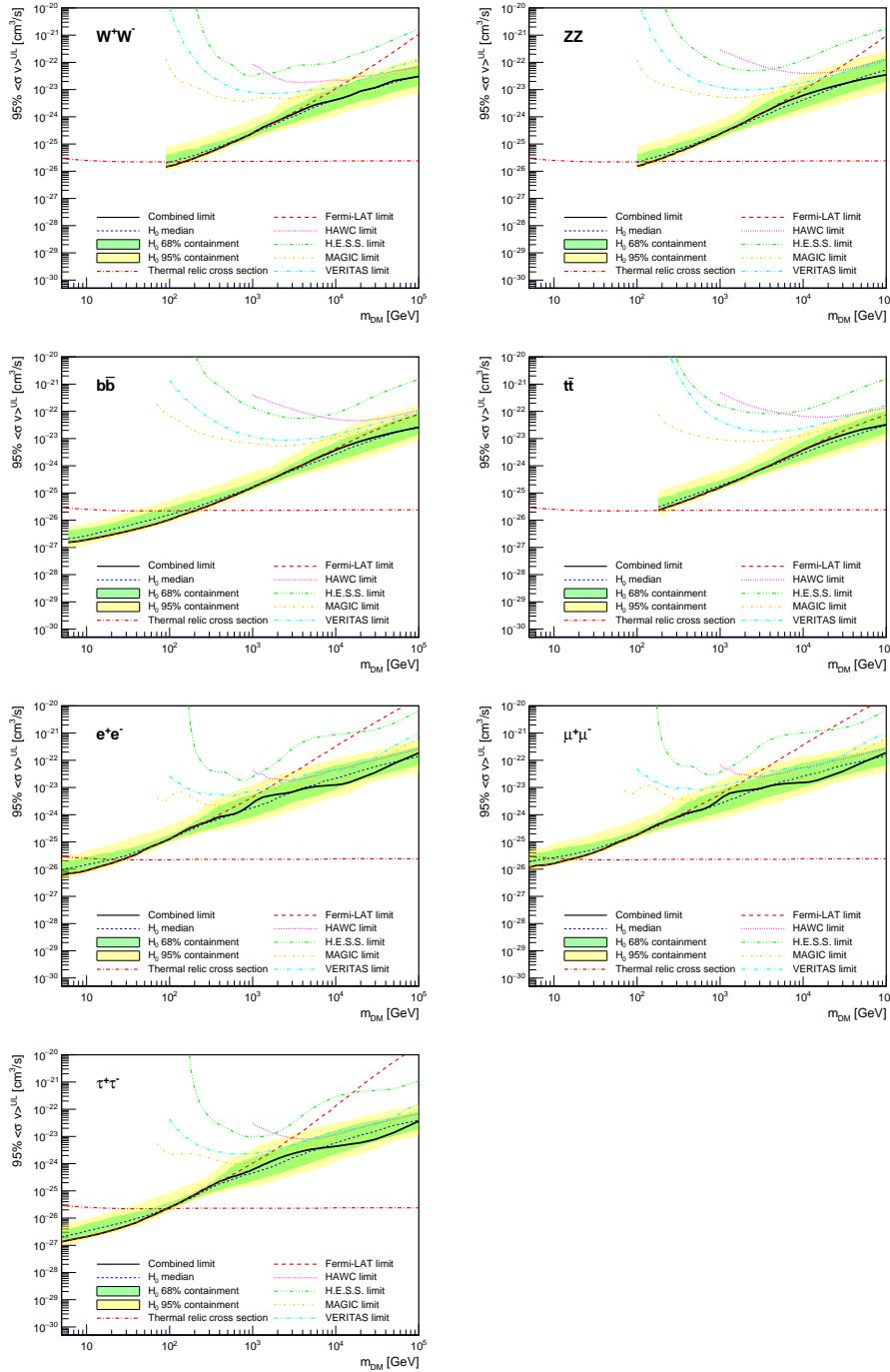


Figure 6.8 Upper limits at 95% confidence level on $\langle\sigma v\rangle$ in function of the DM mass for eight annihilation channels, using the set of J factors from Ref. [53] (\mathcal{GS} set in Table 6.1). The black solid line represents the observed combined limit, the black dashed line is the 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 [54].

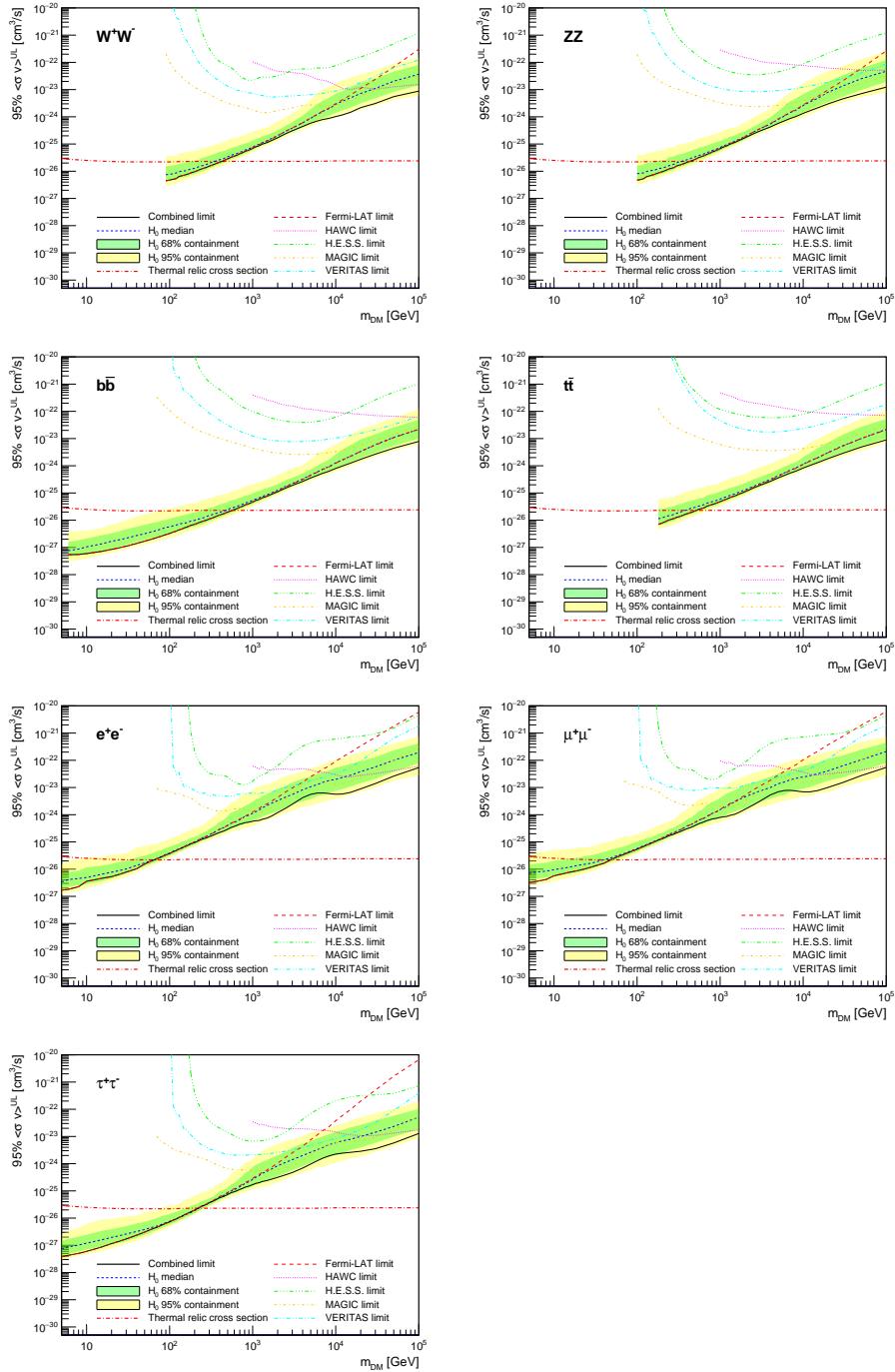


Figure 6.9 Same as Fig. 6.8, using the set of J factors from Ref. [47, 55] (\mathcal{B} set in Table 6.1).

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 simu-

920 lations of the OFF observations, for H.E.S.S., MAGIC, VERITAS, and HAWC, or taken from real
921 observations of empty fields of view in the case of Fermi-LAT [48, 56, 57].

922 The obtained limits are shown in Figure 6.8 for the $\mathcal{G}\mathcal{S}$ set of J -factors [53] and in Figure 6.9
923 for the \mathcal{B} set of J -factors [47, 55]. The combined limits are presented with their 68% and 95%
924 containment bands, and are expected to be close to the median limit when no signal is present.
925 We observe agreement with the null hypothesis for all channels, within 2σ standard deviations,
926 between the observed limits and the expectations given by the median limits. Limits obtained from
927 each detector are also indicated in the figures, where limits for all dSphs observed by the specific
928 instrument have been combined.

929 Below ~ 300 GeV, the *Fermi*-LAT dominates the DM limits for all annihilation channels. From
930 ~ 300 GeV to ~ 2 TeV, *Fermi*-LAT continues to dominate for the hadronic and bosonic DM channels,
931 yet the IACTs (H.E.S.S., MAGIC, and VERITAS) and *Fermi*-LAT all contribute to the limit for
932 leptonic DM channels. For DM masses between ~ 2 TeV to ~ 10 TeV, the IACTs dominate leptonic
933 DM annihilation channels, whereas both the *Fermi*-LAT and the IACTs dominate bosonic and
934 hadronic DM annihilation channels. From ~ 10 TeV to ~ 100 TeV, both the IACTs and HAWC
935 contribute significantly to the leptonic DM limit. For hadronic and bosonic DM, the IACTs and
936 *Fermi*-LAT both contribute strongly.

937 We notice that the limits computed using the \mathcal{B} set of J -factor are always better compared to the
938 ones calculated with the $\mathcal{G}\mathcal{S}$ set. For the W^+W^- , Z^+Z^- , $b\bar{b}$, and $t\bar{t}$ channels, the ratio between the
939 limits computed with the two sets of J -factor is varying between a factor of ~ 3 and ~ 5 depending
940 on the energy, with the largest ratio around 10 TeV. For the channels e^+e^- , $\mu^+\mu^-$, and $\tau^+\tau^-$, the
941 ratio lies between ~ 2 to ~ 6 , being maximum around 1 TeV. Examining Figure 6.16 and Figure 6.17
942 in Section 6.8, these differences are explained by the fact that the \mathcal{B} set provides higher J -factors
943 for the majority of the studied dSphs, with the notable exception of Segue I. The variation on the
944 ratio of the limits for the two sets is due to different dSph dominating the limits depending on the
945 energy. This pushes the range of thermal cross-section which can be excluded to higher mass. This
946 comparison demonstrates the magnitude of systematic uncertainties associated with the choice of

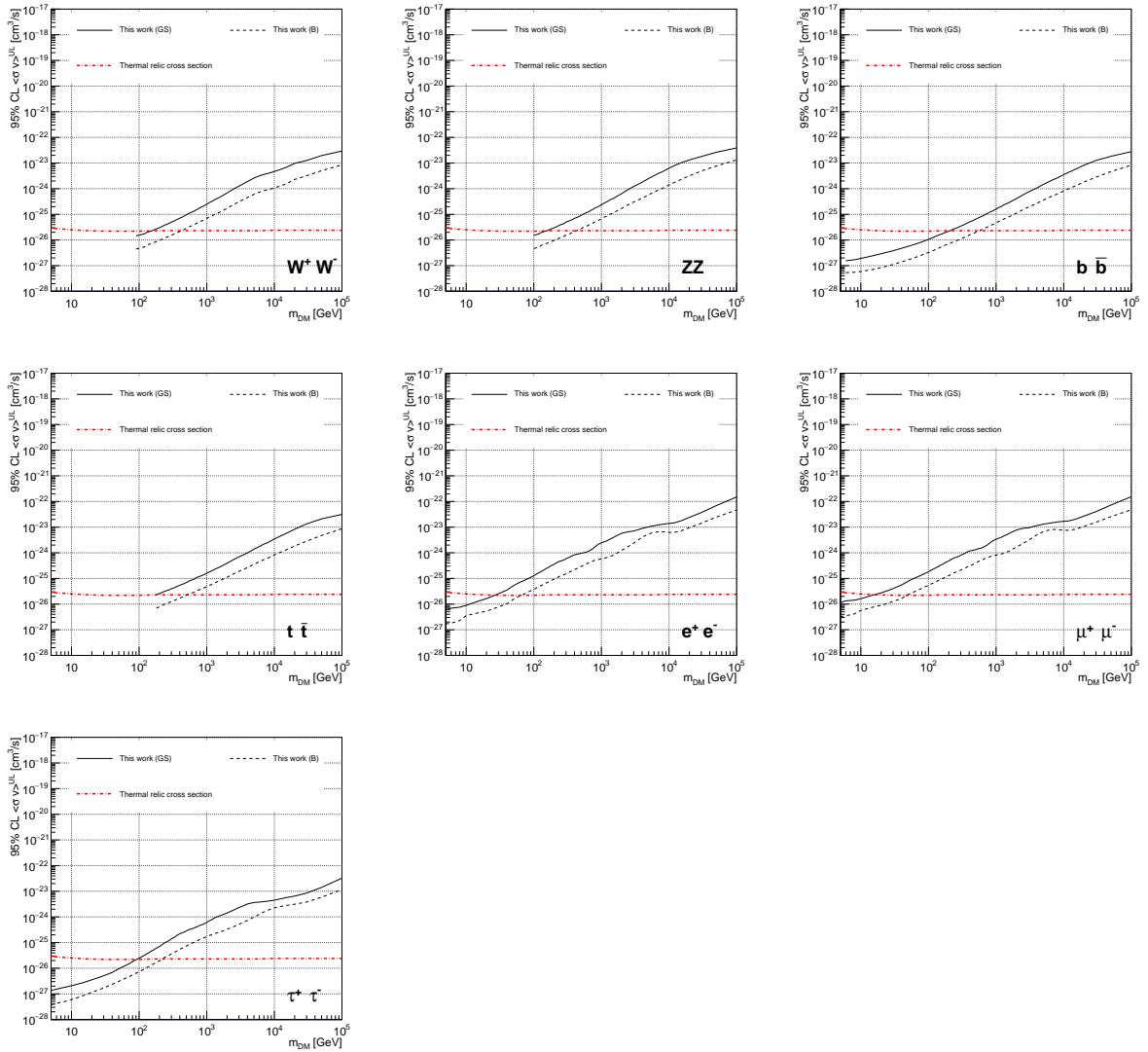


Figure 6.10 Comparisons of the combined limits at 95% confidence level for each of the eight annihilation channels when using the J factors from Ref. [53] (\mathcal{GS} set in Table 6.1), plain lines, and the J factor from Ref. [47, 55] (\mathcal{B} set in Table 6.1), dashed lines. The cross-section given by the thermal relic is also indicated [54].

947 the J -factor

948 This comparison demonstrates the magnitude of systematic uncertainties associated with the
 949 choice of the J -factor calculation. The \mathcal{GS} and \mathcal{B} sets present a difference in the limits for all
 950 channels of about This difference is explained, see Figure 6.16 and Figure 6.17 in Appendix, by the
 951 fact that the \mathcal{B} set provides higher J factors for all dSph except for Segue I. This pushes the range
 952 of thermal cross-section which can be excluded to higher mass.

953 **6.7 HAWC Systematics**

954 **6.7.1 Inverse Compton Scattering**

955 The DM-DM annihilation channels produce many high energy electrons regardless of the
956 primary annihilation channel. These high energy electrons can produce high energy gamma-rays
957 through Inverse Compton Scattering (ICS). If this effect is strong, it would change the morphology
958 of the source and increase the total expected gamma-ray counts from any source. The PPPC [44]
959 provides tools in Mathematica for calculating the impact of ICS for an arbitrary location in the
960 sky for a specified annihilation channel. We calculated the change in gamma-ray counts for DM
961 annihilation to primary $e\bar{e}$ for RA and Dec corresponding to Segue1 and Coma Berenices. These
962 dSphs were chosen because they are the strongest contributors to the limit. $e\bar{e}$ was selected because
963 it would have the largest number of high energy electrons. The effect was found to be on the order
964 of 10^{-7} on the gamma-ray spectrum. As a result, this systematic is not considered in our analysis.

965 **6.7.2 Point Source Versus Extended Source Limits**

966 The previous DM search toward dSph approximated the dSphs as point sources [46]. In
967 this analysis, the dSphs are implemented as extended with J-factor distributions following those
968 produced by [53]. The resolution of the cited map is much finer than HAWC's angular resolution.
969 The vast majority of the J-factor distribution is represented on the central HAWC pixel of the dSph
970 spatial map. However, the neighboring 8 pixels are not negligible and contribute to our limit.

971 Figure 6.11 shows a substantial improvement to the limit for Segue1. Fig. 6.12 however showed
972 identical limits. These disparities are best explained by the relative difference in their J-Factors.
973 Both dSphs pass almost overhead the HAWC detector, however Segue1 has the larger J-Factor
974 between the two. Adjacent pixels to the central pixel will therefore contribute to the limits. This is
975 the case for other dSph that are closer to overhead the HAWC detector.

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

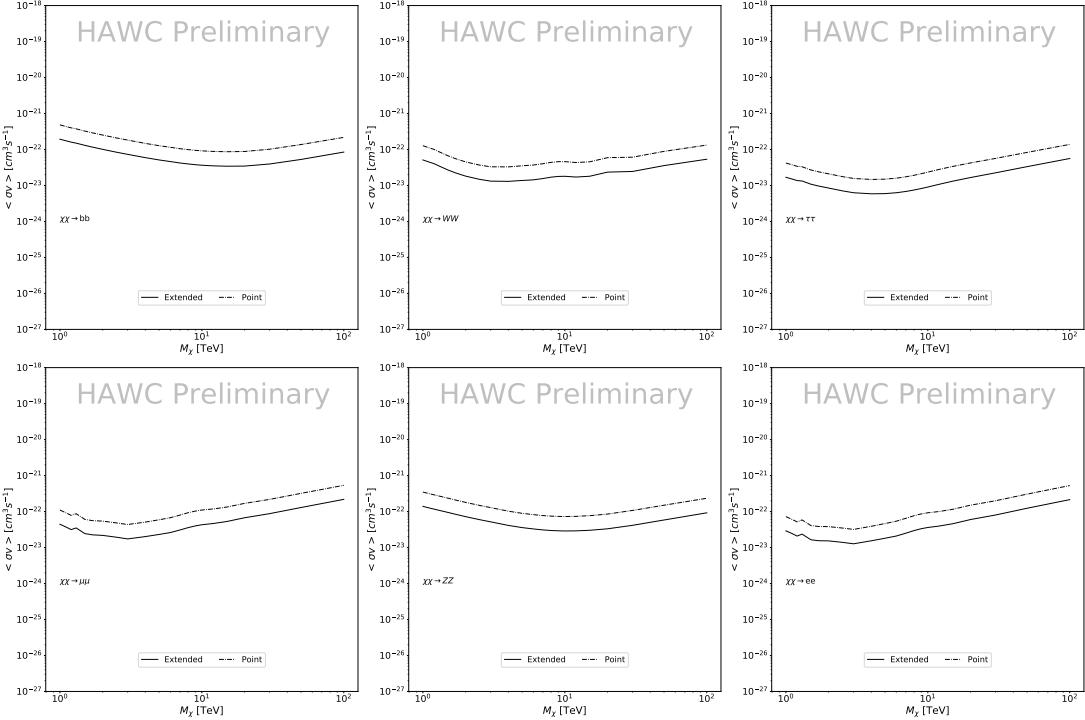


Figure 6.11 Comparisons of the combined limits at 95% confidence level for a point source analysis and extended source using [53] \mathcal{GS} J-factor distributions and PPPC [44] annihilation spectra. Shown are the limits for Segue1 which will have the most significant impact on the combined limit. 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.

978 6.7.3 Impact of Pointing Systematic

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

983 Section 6.7.3 demonstrates the impact of this systematic for all DM annihilation channels
 984 studied by HAWC. The impact is a tiny improvement, yet mostly identical, to the combined limits.

985 6.8 J-factor distributions

986 6.8.1 Numerical integration of \mathcal{GS} maps

987 It was discovered well after the HAWC analysis was completed that the published tables from
 988 \mathcal{GS} [45] quoted median J-factors were computed in a non-trivial manner. The assumption myself

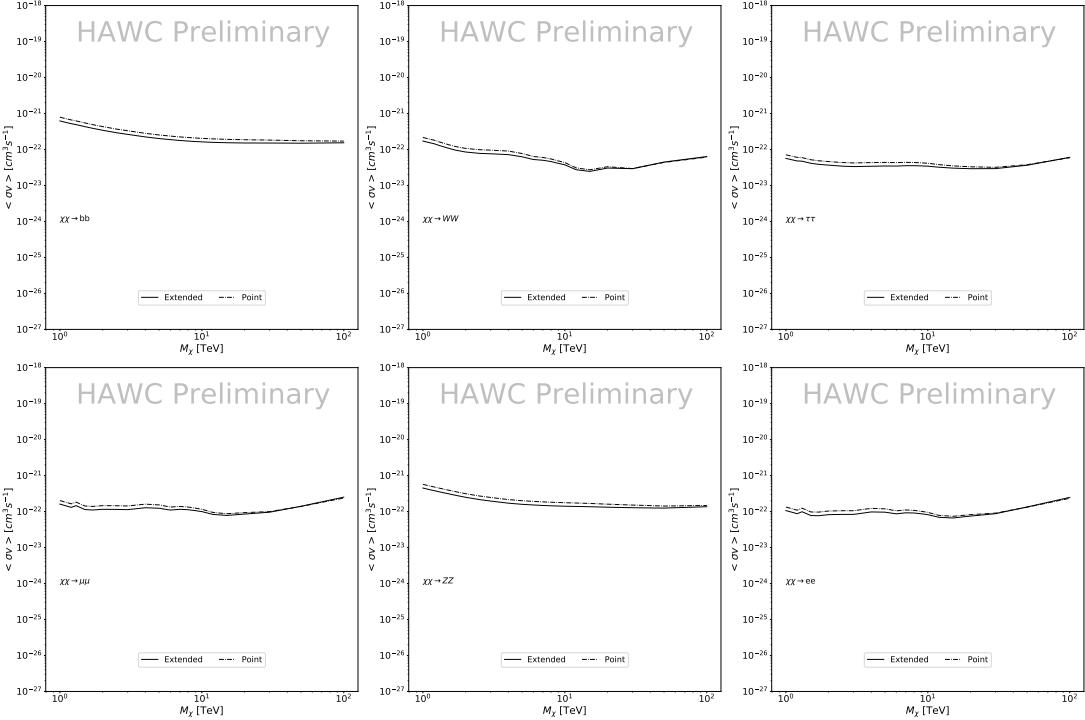


Figure 6.12 Same as Fig. 6.11 on Coma Berenices. This dSph also contributes significantly to the limit. The limits are identical in this case.

and collaborators had been that the published tables represented the J -factor as a function of θ for the best global fit model on a per-source basis. However, this is not the case. Instead, what is published are the best fit model for each dwarf that only considers stars up to the angular separation θ . Therefore, the model is changing for each value of θ for each dwarf. Yet, the introduced features from unique models at each θ are much smaller than the angular resolution of HAWC. It is not expected for these effects to impact the limits and TS greatly as a result.

Median J -factor model profiles were provided by the authors. New maps were generated and analyzed for Segue1 and Coma Berenices. Figure 6.14 shows the differential between maps generated with the method from Section 6.8.1 and from the authors of [45]. These maps were reanalyzed for all SM DM annihilation channels. Upper limits for these channels are shown in Figure 6.15

From Figure 6.15, we can see that the impact of these model difference was no substantial. The observed impact was a fractional effect which is much smaller than the impact from selecting another DM spatial distribution model as was shown in Figure 6.10.

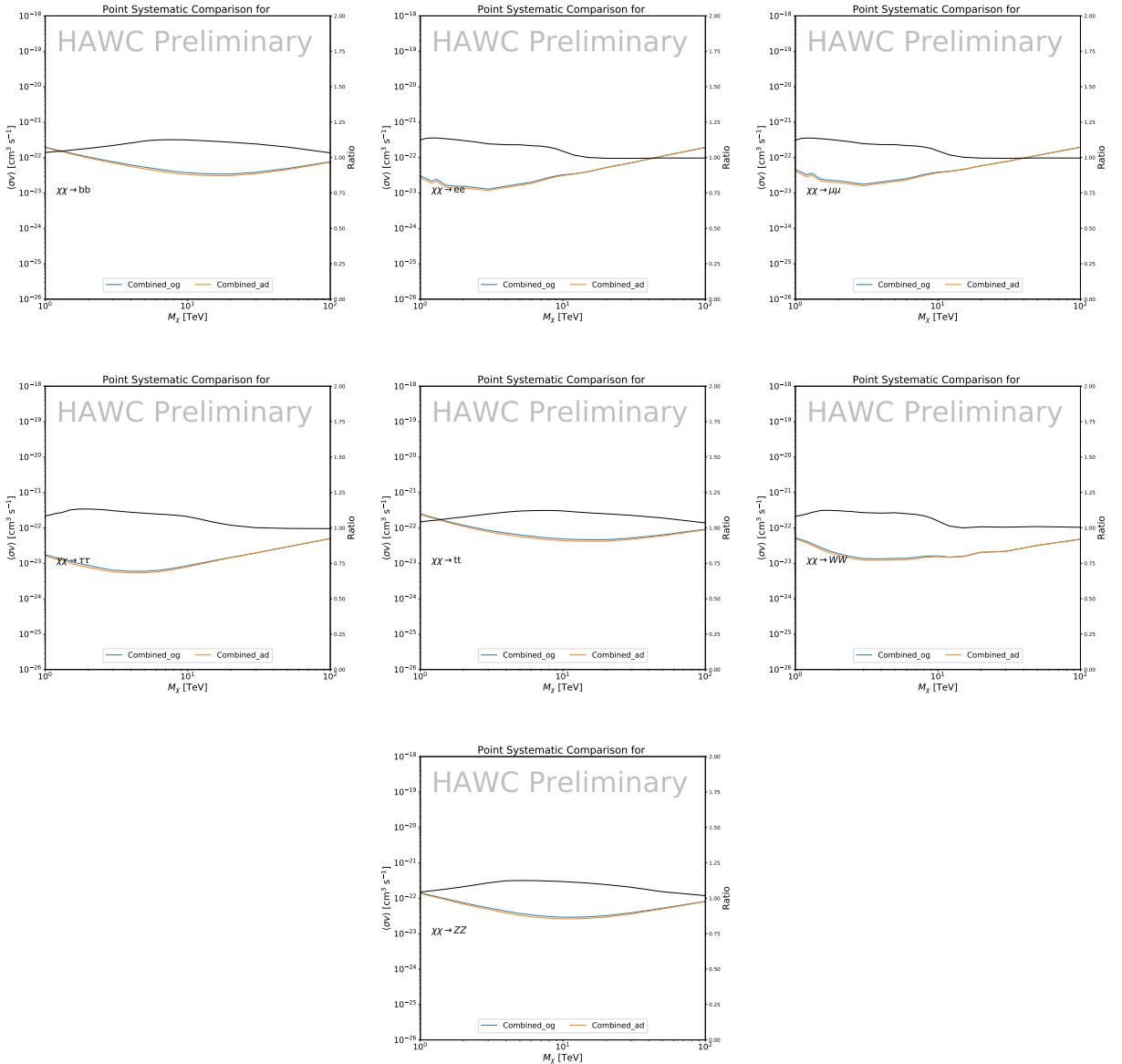


Figure 6.13 Comparison of combined limits when correcting for HAWC's pointing systematic. All DM annihilation channels are shown. The solid black line is the ratio between published limit to the declination corrected limit. The blue solid line or "Combined_og" represented the limits computed for Glory Duck. The solid orange line or "Combined_ad" represented the limits computed after correcting for the pointing systematic.

1003 6.8.2 $\mathcal{G}\mathcal{S}$ Versus \mathcal{B} spatial models

1004 We show in this appendix a comparison between the J -factors computed by Geringer-Sameth
 1005 *et al.* [53] (the $\mathcal{G}\mathcal{S}$ set) and the ones computed by Bonnivard *et al.* [47, 55] (the \mathcal{B} set). The
 1006 $\mathcal{G}\mathcal{S}$ J -factors are computed through a Jeans analysis of the kinematic stellar data of the selected

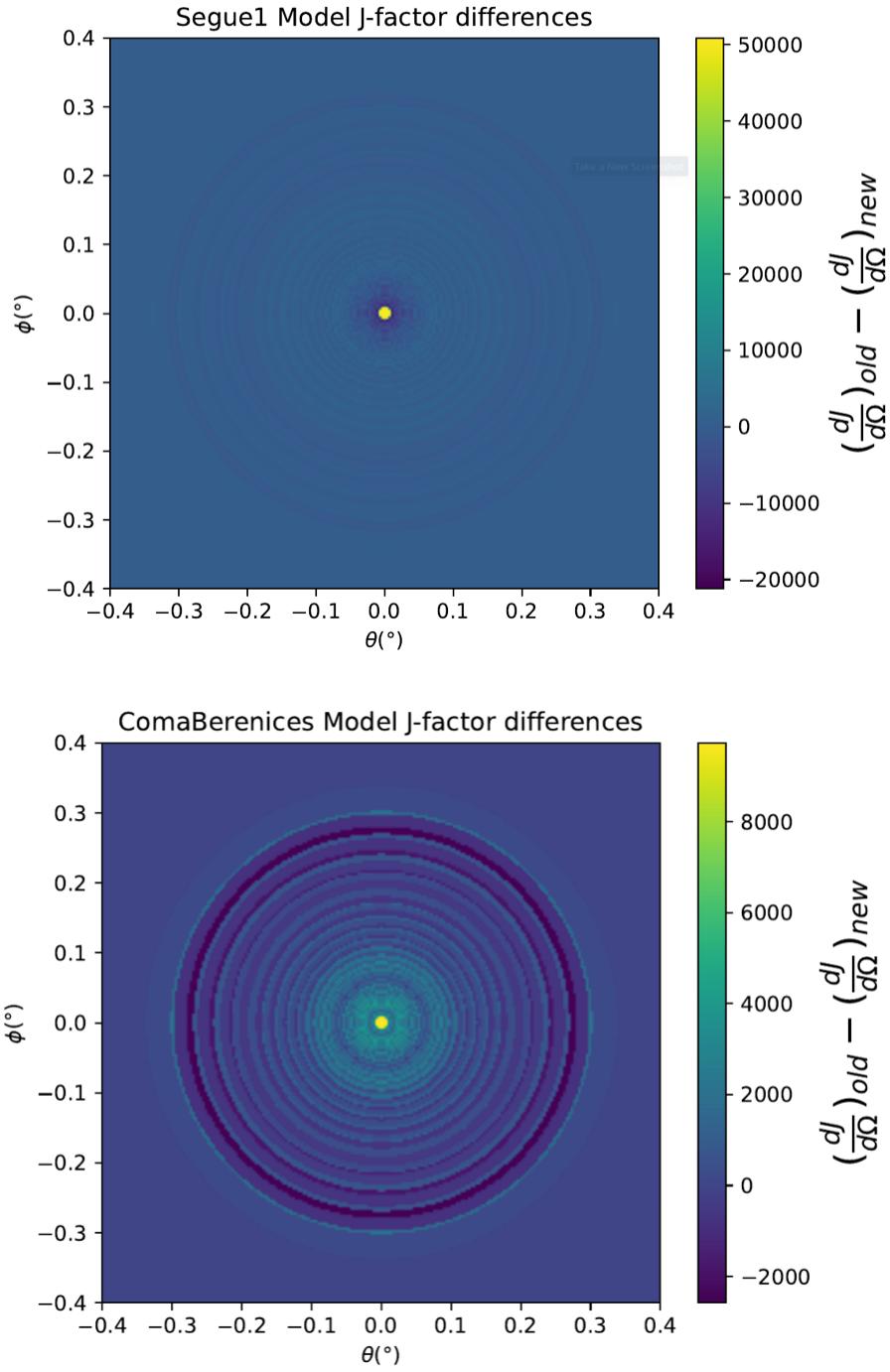


Figure 6.14 Differential map of dJ/Ω from model built in Section 6.8.1 and profiles provided directly from authors. (Top) Differential from Segue1. (bottom) Differential from Coma Berenices. Note that their scales are not the same. Segue1 shows the deepest discrepancies which is congruent with its large uncertainties. Both models show anuli where unique models become apparent.

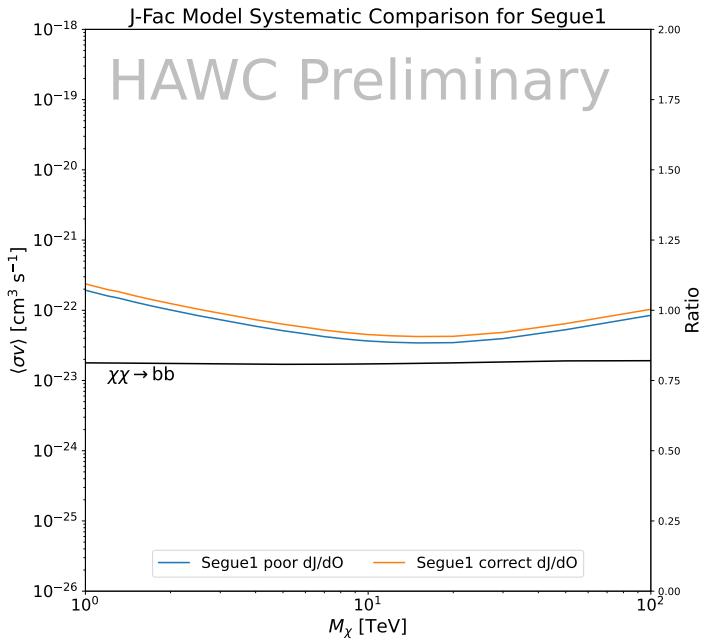
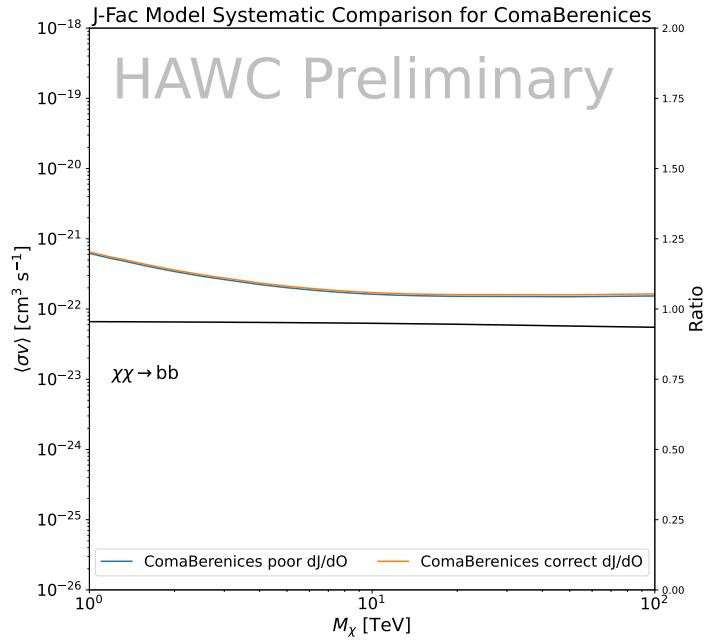


Figure 6.15 HAWC limits for Coma Berenices (top) and Segue1 (bottom) for two different map sets. Blue lines are limits calculated on maps with poor model representation. Orange lines are limits calculated on spatial profiles provided by the authors of [45]. Black line is the ratio of the poor spatial model limits to the corrected spatial models. The left y-axis measures $\langle \sigma v \rangle$ for the blue and orange lines. The right y-axis measures the ratio and is unitless.

1007 dSphs, assuming a dynamic equilibrium and a spherical symmetry for the dSphs. They adopted
1008 the generalized DM density distribution, known as Zhao-Hernquist, introduced by [58], carrying
1009 three additional index parameters to describe the inner and outer slopes, and the break of the
1010 density profile. Such a profile parametrization allows the reduction of the theoretical bias from
1011 the choice of a specific radial dependency on the kinematic data. In other words, the increase of
1012 free parameters with the use of the Zhao-Hernquist profile allows a better description of the mass
1013 density distribution of dark matter.

1014 In addition, a constant velocity anisotropy profile and a Plummer light profile [59] for the stellar
1015 distribution were assumed. The velocity anisotropy profile depends on the radial and tangential
1016 velocity dispersion. However, its determination remains challenging since only the line-of-sight
1017 velocity dispersion can be derived from velocity measurements. Therefore, the parametrization of
1018 the anisotropy profile is obtained from simulated halos (see [60] for more details). They provide the
1019 values of the J -factors of regions extending to various angular radius up to the outermost member
1020 star.

1021 The \mathcal{B} J -factors were computed through a Jeans analysis taking into account the systematic
1022 uncertainties induced by the DM profile parametrization, the radial velocity anisotropy profile, and
1023 the triaxiality of the halo of the dwarf galaxies. They performed a more complete study of the dSph
1024 kinematics and dynamics than \mathcal{GS} for the determination of the J -factor. Conservative values of the
1025 J -factors where obtained using an Einasto DM density profile [61], a realistic anisotropy profile
1026 known as the Baes & Van Hese profile [62] which takes into account that the inner regions can be
1027 significantly non-isotropic, and a Zhao-Hernquist light profile [58].

1028 For both sets, J -factor values are provided for all dSphs as a function of the radius of the
1029 integration region [53, 47, 55]. Table 6.1 shows the heliocentric distance and Galactic coordinates
1030 of the twenty dSphs, together with the two sets of J -factor values integrated up to the outermost
1031 observed star for \mathcal{GS} and the tidal radius for \mathcal{B} . Both J -factor sets were derived through a Jeans
1032 analysis based on the same kinematic data, except for Draco where the measurements of [63] have
1033 been adopted in the computation of the \mathcal{B} value. The computations for producing the \mathcal{GS} and \mathcal{B}

1034 samples differ in the choice of the DM density, velocity anisotropy, and light profiles, for which the
1035 set \mathcal{B} takes into account some sources of systematic uncertainties.

1036 Figure 6.16 and Figure 6.17 show the comparisons for the J -factor versus the angular radius
1037 for each of the 20 dSphs used in this study. The uncertainties provided by the authors are also
1038 indicated in the figures. For the \mathcal{GS} set, the computation stops at the angular radius corresponding
1039 to the outermost observed star, while for the \mathcal{B} set, the computation stops at the angular radius
1040 corresponding to the tidal radius.

1041 6.9 Discussion and Conclusions

1042 In this multi-instrument analysis, we have used observations of 20 dSphs from the gamma-ray
1043 telescopes Fermi-LAT, H.E.S.S., MAGIC, VERITAS, and HAWC to perform a collective DM
1044 search annihilation signals. The data were combined across sources and detectors to significantly
1045 increase the sensitivity of the search. We have observed no significant deviation from the null, no
1046 DM hypothesis, and so present our results in terms of upper limits on the annihilation cross-section
1047 for seven potential DM annihilation channels.

1048 Fermi-LAT brings the most stringent constraints for continuum channels below approximately
1049 1 TeV. The remaining detectors dominate at higher energies. Overall, for multi-TeV DM mass,
1050 the combined DM constraints from all five telescopes are 2-3 times stronger than any individual
1051 telescope for multi-TeV DM.

1052 Derived from observations of many dSphs, our results produce robust limits given the DM
1053 content of the dSphs is relatively well constrained. The obtained limits span the largest mass
1054 range of any WIMP DM search. Our combined analysis improves the sensitivity over previously
1055 published results from each detector which produces the most stringent limits on DM annihilation
1056 from dSphs. These results are based on deep exposures of the most promising known dSphs with
1057 the currently most sensitive gamma-ray instruments. Therefore, our results constitute a legacy of
1058 a generation of gamma-ray instruments on WIMP DM searches towards dSphs. Our results will
1059 remain the reference in the field until a new generation of more sensitive gamma-ray instruments
1060 begin operations, or until new dSphs with higher J -factors are discovered.

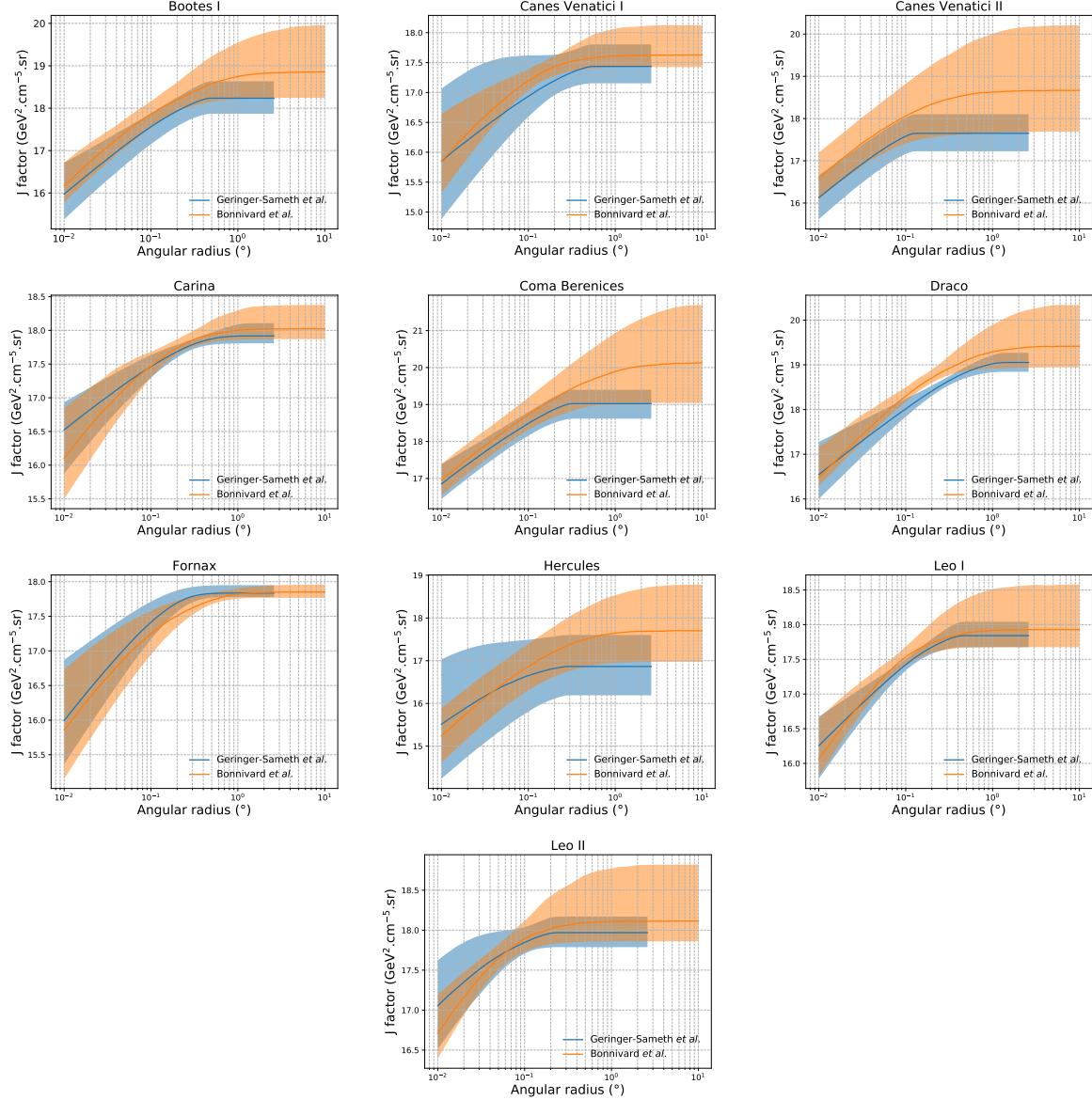


Figure 6.16 Comparisons between the J -factors versus the angular radius for the computation of J factors from Ref. [53] (\mathcal{GS} set in Table 6.1) in blue and for the computation from Ref. [47, 55] (\mathcal{B} set in Tab. 6.1) in orange. The solid lines represent the central value of the J -factors while the shaded regions correspond to the 1σ standard deviation.

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

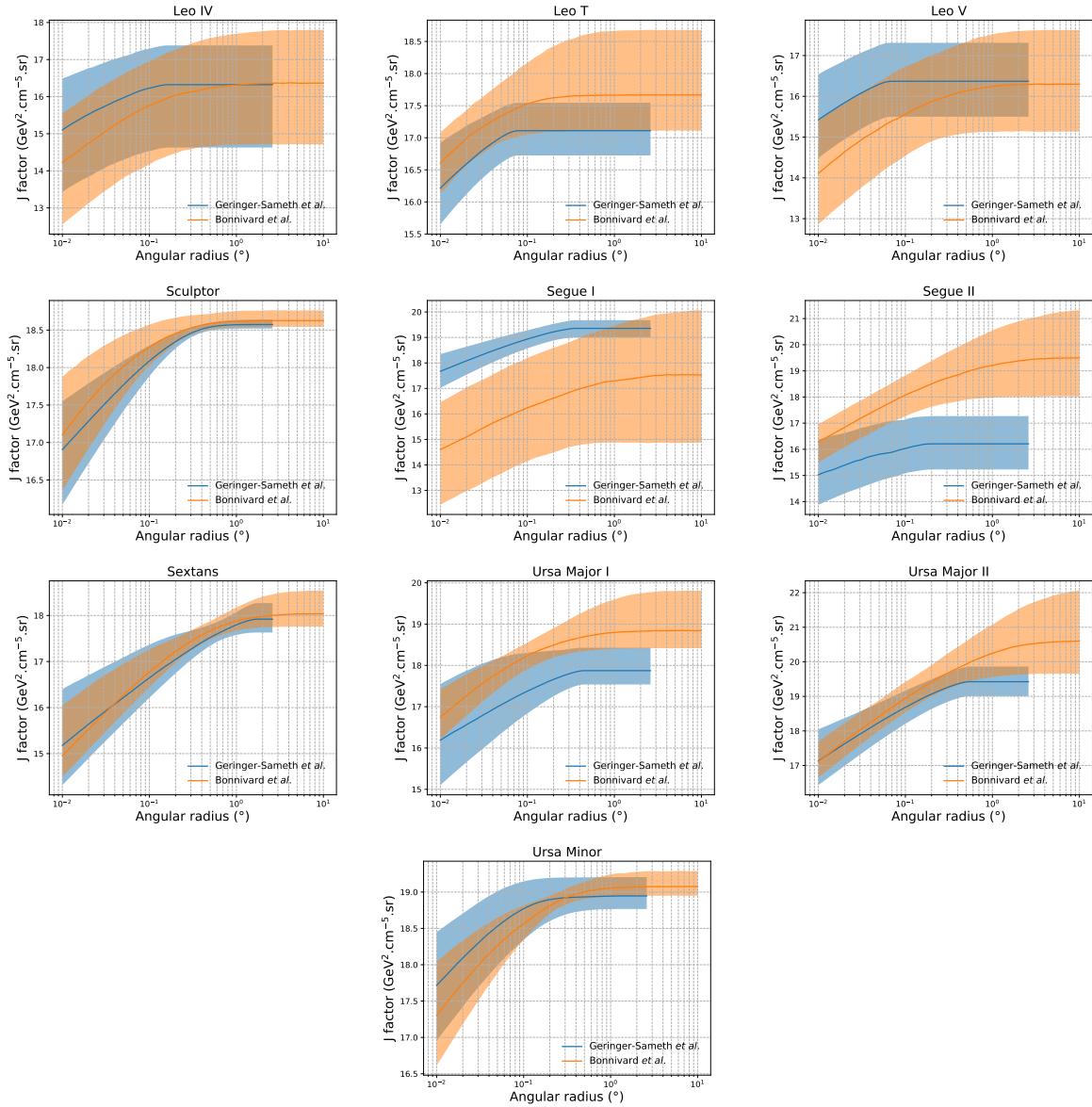


Figure 6.17 Comparisons between the J -factors versus the angular radius for the computation of J factors from Ref. [53] (\mathcal{GS} set in Tab. 6.1) in blue and for the computation from Ref. [47, 55] (\mathcal{B} set in Tab. 6.1) in orange. The solid lines represent the central value of the J -factors while the shaded regions correspond to the 1σ standard deviation.

1066 techniques as the ones described in this paper could grow even beyond gamma rays. The models we
 1067 used for this study include annihilation channels with neutrinos in the final state. Advanced studies
 1068 could aim to merge our results with those from neutrino observatories with large data sets. Efforts
 1069 are already underway to add data from the IceCube, ANTARES, and KM3NeT observatories to
 1070 these gamma-ray results.

1071 From this work, a selection of the best candidates for observations, according to the latest
1072 knowledge on stellar dynamics and modelling techniques for the derivation of the J -factors on
1073 the potential dSphs targets, is highly desirable at the time that new experiments are starting their
1074 dark matter programs using dSphs. Given the systematic uncertainty inherent to the derivation of
1075 the J -factors, an informed observational strategy would be to select both objects with the highest
1076 J -factors that could lead to DM signal detection, and objects with robust J -factor predictions, i.e.
1077 with kinematic measurements on many bright stars, which would strengthen the DM interpretation
1078 reliability of the observation outcome.

1079 This analysis combines data from multiple telescopes to produce strong constraints on astro-
1080 physical objects. From this perspective, these methods can be applied beyond just DM searches.
1081 Almost every astrophysical study can benefit from multi-telescope, multi-wavelength gamma-ray
1082 studies. We have enabled these telescopes to study the cosmos with greater precision and detail.
1083 Many astrophysical searches can benefit from multi-instrument gamma-ray studies, for which our
1084 analysis lays the foundation.

CHAPTER 7

MULTITHREADING HAWC ANALYSES FOR DARK MATTER SEARCHES

7.1 Introduction

HAWC's current software suite, plugins to 3ML, does not fully utilize computational advancements of recent decades. Said advancements include the proliferation of Graphical Processing Units (GPUs), and multithreading on multi-core processors. The analysis described in chapter 6 took up to 3 months of human time waiting for the full gambit of data analysis and simulation of background to run. Additionally, with the addition of a 2D binning scheme, f_{hit} and NN, the compute time is expected to grow. Although excessive computing time was, in part, from an intense use of a shared computing cluster, it was evident that there was room for improvement. In HAWC's next generation dSph DM search, I decided to develop codes that would utilize the multi-core processors on modern high performance computing clusters. The results of this work are featured in this chapter and brought a human timing improvement to computation that scales as $1/N$ where N is the number of threads.

7.2 Dataset and Background

This section enumerates the data and background methods used for HAWC's multi-threaded study of dSphs. Section 7.2.1 and Section 7.2.2 are most useful for fellow HAWC collaborators looking to replicate a multithreaded dSph DM search.

7.2.1 Itemized HAWC files

- Detector Resolution: `refit-Pass5-Final-NN-detRes-zenith-dependent.root`
- Data Map: `Pass5-Final-NN-maptree-ch103-ch1349-zenith-dependent.root`
- Spectral Dictionary: `HDMspectra_dict_gamma.npy`

7.2.2 Software Tools and Development

This analysis was performed using HAL and 3ML [42, 43] in Python version 3. I built software in collaboration with Michael Martin and Letrell Harris to implement the *Dark Matter Spectra from*

1109 *the Electroweak to the Planck Scale* (HDM) [64] and dSphs spatial model from [65] for HAWC
1110 analysis. A NumPy dictionary of HDM was made for Py3. The corresponding Python3 file is
1111 `HDMspectra_dict_gamma.npy`. These files can also be used for decay channels and tools are
1112 provided in HDM’s [git repository](#) [64]. The analysis was performed using the Neural Network
1113 energy estimator for Pass 5.F. A description of this estimator was provided in chapter 4. **TODO:**
1114 **define a subsection when it’s written** All other software used for data analysis, DM profile generation,
1115 and job submission to SLURM are also kept in my sandbox in the [Dark Matter HAWC](#) project.
1116 The above repository also incorporates the model inputs used previously in Glory Duck, described
1117 in chapter 6

1118 7.2.3 Data Set and Background Description

1119 The HAWC data maps used for this analysis contain 2565 days of data between runs 2104 (

1120 **TODO: Day start**) and 7476 (**TODO: day end**). They were generated from pass 4.0 reconstruction.

1121 The analysis is performed using the NN energy estimator with bin list:

1122 B1C0Ea, B1C0Eb, B1C0Ec, B1C0Ed, B1C0Ee, B2C0Ea, B2C0Eb, B2C0Ec, B2C0Ed, B2C0Ee,
1123 B3C0Ea, B3C0Eb, B3C0Ec, B3C0Ed, B3C0Ee, B3C0Ef, B4C0Eb, B4C0Ec, B4C0Ed, B4C0Ee,
1124 B4C0Ef, B5C0Ec, B5C0Ed, B5C0Ee, B5C0Ef, B5C0Eg, B6C0Ed, B6C0Ee, B6C0Ef, B6C0Eg,
1125 B6C0Eh, B7C0Ee, B7C0Ef, B7C0Eg, B7C0Eh, B7C0Ei, B8C0Ee, B8C0Ef, B8C0Eg, B8C0Eh,
1126 B8C0Ei, B8C0Ej, B9C0Ef, B9C0Eg, B9C0Eh, B9C0Ei, B9C0Ej, B10C0Eg, B10C0Eh,
1127 B10C0Ei, B10C0Ej, B10C0Ek, B10C0El

1128 Bin 0 was excluded as it has substantial hadronic contamination and poor angular resolution.

1129 Background considerations and source selection was identical to Section 6.2, and no additional
1130 arguments are provided here. Many of the HAWC systematics explored in Section 6.7 also apply
1131 for this DM search and are not added upon here.

1132 7.3 Analysis

1133 The analysis and its systematics are almost identical to Section 6.3. Importantly, we use the
1134 same Equation (6.1) and Equation (6.2) for estimating the gamma-ray flux at HAWC from our

1135 sources. We add on to the previous study with a search for DM decay. The flux equations for DM
1136 decay are

$$\frac{d\Phi_\gamma}{dE_\gamma} = \frac{1}{4\pi\tau m_\chi} \frac{dN_\gamma}{dE_\gamma} \times \int_{\text{source}} d\Omega \int_{l.o.s} \rho_\chi dl(r, \theta') \quad (7.1)$$

1137 with a new quantity, the D factor, defined as

$$D = \int d\Omega \int_{l.o.s} dl \rho_\chi(r, \theta') \quad (7.2)$$

1138 Software was written to accomodate DM decay from dSphs, however decay profiles were not
1139 received from $\mathcal{L}\mathcal{S}$ by the time of writing this tehsis.

1140 **7.3.1 $\frac{dN_\gamma}{dE_\gamma}$ - Particle Physics Component**

1141 For these spectra, we import HDM with Electroweak (EW) corrections and additional correc-
1142 tions for neutrinos above the EW scale [64]. The spectrum is implemented as a model script in
1143 astromodels for 3ML. A comprehensive description of EW corrections and neutrino considerations
1144 are provided later in [TODO: refeance MM nu duck](#).

1145 Figure 7.1 demonstrates the impact of changes from HDM on DM annihilation to W bosons.
1146 A class in astromodels was developed to include HDM and is aptly named `HDMspectra` within
1147 `DM_models.py`. The SM DM annihilation channels studied here are $\chi\chi \rightarrow$:

1148 e^+e^- , $\mu^+\mu^-$, $\tau^+\tau^-$, $b\bar{b}$, $t\bar{t}$, gg , W^+W^- , ZZ , $c\bar{c}$, $u\bar{u}$, $d\bar{d}$, $s\bar{s}$, $\nu_e\bar{\nu}_e$, $\nu_\mu\bar{\nu}_\mu$, $\nu_\tau\bar{\nu}_\tau$, $\gamma\gamma$, hh .

1149 For $\gamma\gamma$ and ZZ , a substantial fraction of the signal photons are expected to have total energy equal
1150 m_χ [64]. This introduces a δ -function that is much narrower than the energy resolution of the
1151 HAWC detector. To ensure that this feature is not lost in the likelihood fits, the 'line' feature is
1152 convolved with a gausian kernel with a 1σ width of $0.05 \cdot m_\chi$ and total kernel window of $\pm 4\sigma$.
1153 This difers from HAWC's previous line study where 30% of HAWC's energy resolution was used
1154 for the kernel [66]. The NN energy estimator's strength compared to f_{hit} at low gamma-ray energy
1155 enables smaller resolutions in addition to low energy tails in the spectral models [64]. $\chi\chi \rightarrow \gamma\gamma$
1156 and ZZ spectral hypotheses are shown in Figure 7.2. Spectral models for the remaining annihilation
1157 channels are plotted for each m_χ in Figure B.1.

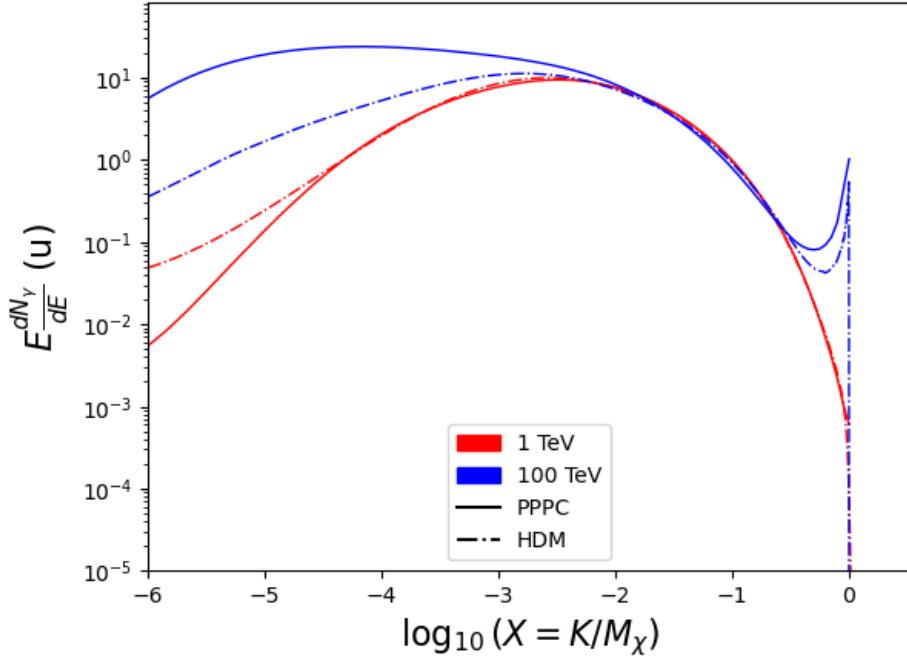


Figure 7.1 Difference between spectral hypotheses from PPPC [44] and HDM [64]. Shown is the expected DM annihilation spectrum for $\chi\chi \rightarrow W^-W^+$. Solid lines are spectral models with EW corrections from the PPPC. Dash-dot lines are spectral models from HDM. Red lines are models for $M_\chi = 1$ TeV. Blue lines represent models for $M_\chi = 100$ TeV.

7.3.2 *J* and *D*- Astrophysical Components

The J-factor profiles for each source are imported from Louis Strigari et al. (referred to with

$\mathcal{L}S$) [65]. Profiles in $\frac{dJ}{d\Omega}(\theta)$ up to $\theta = 0.5^\circ$ were provided directly from the authors. Map generation from these profiles were almost identical to Section 6.3.2 except that a higher order trapezoidal integral was used for the normalization of the square, uniformly-spaced map:

$$p^2 \cdot \sum_{i=0}^N \sum_{j=0}^M w_{i,j} \frac{d\mathcal{K}}{d\Omega}(\theta_{i,j}, \phi_{i,j}) \quad (7.3)$$

\mathcal{K} is either *J* or *D* for the spatial distributions of annihilation or decay respectively. *p* is the angular side of one pixel in the map. $w_{i,j}$ is a weight assigned the following ways:

$w_{i,j} = 1$ if $(\theta_{i,j}, \phi_{i,j})$ is fully within the region of integration

$w_{i,j} = 1/2$ if $(\theta_{i,j}, \phi_{i,j})$ is on an edge of the region of integration

$w_{i,j} = 1/4$ if $(\theta_{i,j}, \phi_{i,j})$ is on a corner of the region of integration

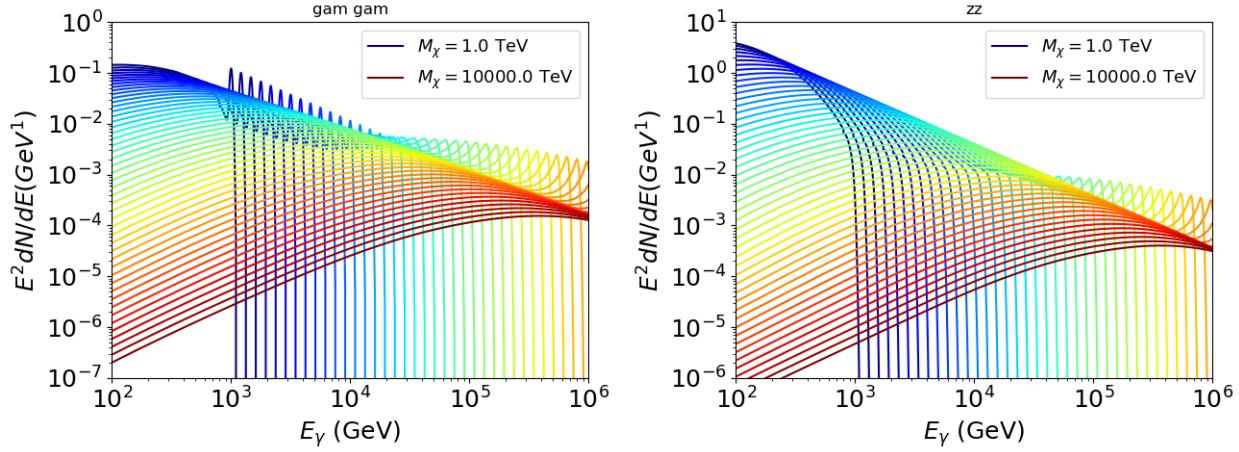


Figure 7.2 Photon spectra for $\chi\chi \rightarrow \gamma\gamma$ (left) and $\chi\chi \rightarrow ZZ$ (right) after gaussian convolution of line features. Both spectra have δ -features at photon energies equal to the DM mass. Bluer lines are annihilation spectra with lower DM mass. Redder lines are spectra from larger DM mass. All Spectral models are sourced from the Heavy Dark Matter models [64]. Axes are drawn roughly according to the energy sensitivity of HAWC.

1168 Figure 7.3 shows the median and $\pm 1\sigma$ maps used as input for DM annihilation studied by \mathcal{LS} .

1169 **7.3.3 Source Selection and Annihilation Channels**

1170 HAWC's sources for this multithreaded analysis include Coma Berenices, Draco, Segue 1, and
 1171 Sextans. \mathcal{LS} observes up to 43 sources in its publication, however only 4 of the best fit profiles were
 1172 provided at the time this thesis was written. A full description of each source used in this analysis
 1173 is found in Table 7.1.

1174 This analysis improves on chapter 6 in the following ways. Previously, the particle physics

Name	Distance (kpc)	l, b ($^\circ$)	$\log_{10} J$ (\mathcal{LS} set) $\log_{10}(\text{GeV}^2 \text{cm}^{-5} \text{sr})$
Coma Berenices	44	241.89, 83.61	$19.00^{+0.36}_{-0.35}$
Draco	76	86.37, 34.72	$18.83^{+0.12}_{-0.12}$
Segue I	23	220.48, 50.43	$19.12^{+0.49}_{-0.58}$
Sextans	86	243.50, 42.27	$17.73^{+0.13}_{-0.12}$

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. Column 4 reports the J -factors of each source given from the \mathcal{LS} studies and estimated $\pm 1\sigma$ uncertainties. The values $\log_{10} J$ (\mathcal{LS} set) [65] correspond to the mean J -factor values for a source extension truncated at 0.5° .

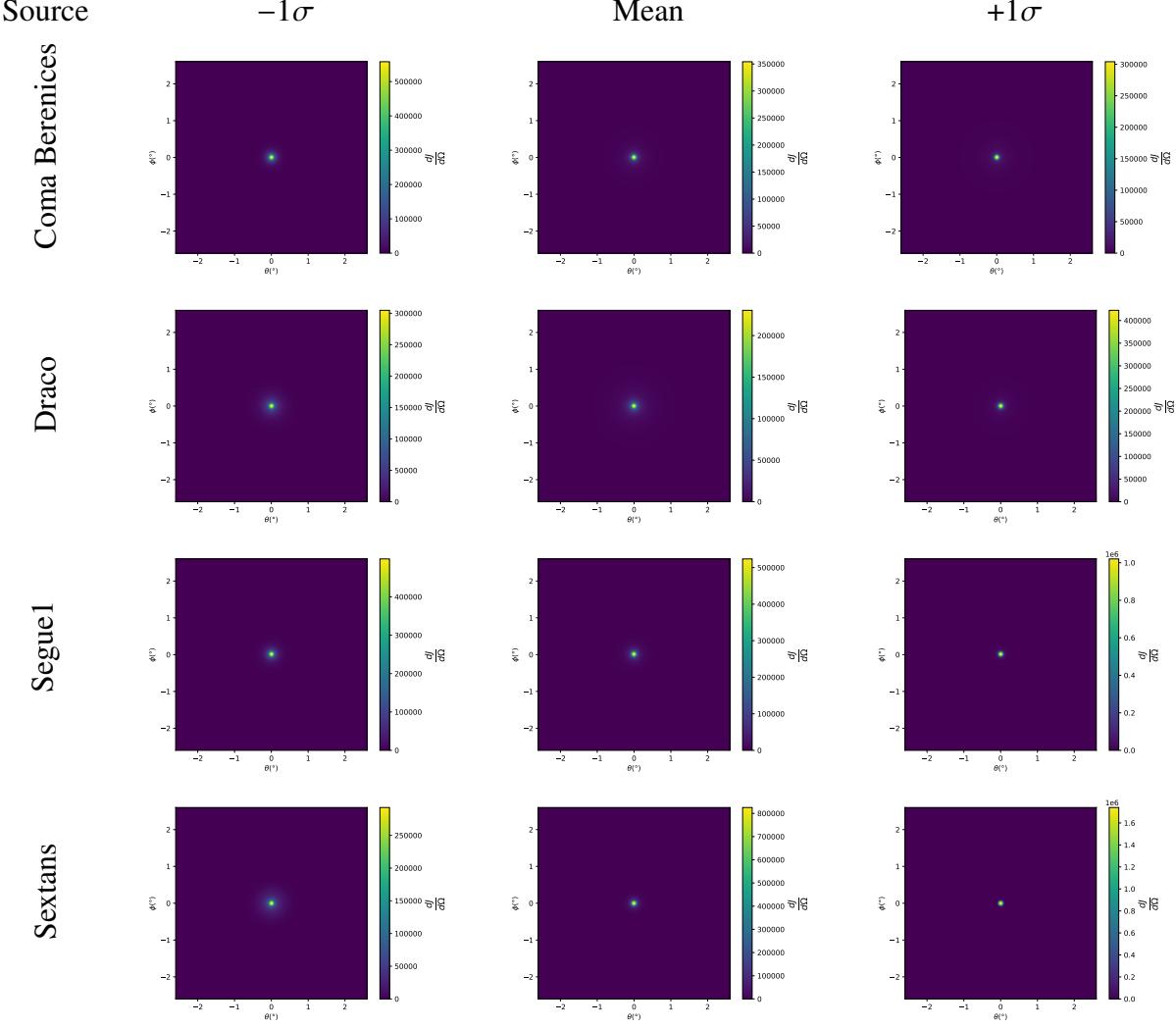


Figure 7.3 $\frac{dJ}{d\Omega}$ maps for Coma Berenices, Draco, Segue1, and Sextans. Columns are divided for the $\pm 1\sigma$ uncertainties in $dJ/d\Omega$ around the mean value from \mathcal{LS} [65]. Origin is centered on the specific dwarf spheroidal galaxies (dSph). θ and ϕ axes are the angular separation from the center of the dwarf

model used for gamma-ray spectra from DM annihilation was from the PPPC [44] which missed important considerations relevant for the neutrino sector. HDM is used to account for this shortfall [64]. HDM also models DM to the Planck scale which permits HAWC to probe PeV scale DM. For this study, we sample DM masses: 1 TeV - 10 PeV with 6 mass bins per decade in DM mass. In the case of line spectra ($\chi\chi \rightarrow \gamma\gamma$, or ZZ), we double the mass binning to 12 DM mass bins per decade in DM mass. A larger source catalog is used that uses a Navarro–Frenk–White (NFW) spatial DM distribution from \mathcal{LS} [65]. Because NFW has fewer parameters than what is used

1182 for \mathcal{GS} , \mathcal{LS} is able to fit ultra-faint dwarves, expanding the number of sources available for DM
1183 searches. Finally, the gamma-ray ray dataset is much larger. The study performed here analyzes
1184 2565 days of data compared to 1017 days analyzed in chapter 6.

1185 **7.4 Likelihood Methods**

1186 These are identical to Section 6.4.1 and no additional changes are made to the likelihood. Bins
1187 in this analysis are expanded to include HAWC’s NN energy estimator.

1188 **7.5 Computational Methods: Multithreading**

1189 Previously, as in Section 6.3, the likelihood was minimized for one model at a time. One
1190 model in this case representing a DM annihilation channel, DM mass, and dSph. In an effort
1191 to conserve human and CPU time, jobs submitted for high performance computing contained a
1192 list of DM masses to iterate over for likelihood fitting. Jobs were then trivially parallelized for
1193 each permutation of the two lists: CHANS (SM annihilation channel) and SOURCES (dSph spatial
1194 templates). The lists for CHANS and SOURCES are found in Section 7.3.1 and Table 7.1, respectively.
1195 Initially, 11 DM mass bins were serially sampled for one job defined by a [SM channel, dSph] set.
1196 Computing the likelihoods would take between 1.5 to 2 hrs, stocastically, for a job. We expect to
1197 compute likelihoods for data and 300 Poisson background trials. The estimated CPU time based on
1198 the above for all SM annihilation channels (17) and 25 sources (all \mathcal{LS} sources withing HAWC’s
1199 field of view) amounted to 127,925 jobs. In total, 1,407,175 likelihood fits and profiles would be
1200 computed for the 11 mass bins we wished to study. The estimated CPU time ranged between 10k
1201 CPU days - 8k CPU days. Human time is more challenging to estimate as job allocation is stochastic
1202 and highly dependant on what other users are submitting, yet it is unlikely that all jobs would run
1203 simultaneously. Therefore we can expect human time to be about as long as was seen in chapter 6
1204 which was on the order of months to fully compute on a smaller analysis. A visual aid to describe
1205 how jobs were organized is provided in Figure 7.4.

1206 The computational needs for this next generation DM analysis are extreme and is unlike other
1207 analyses performed on HAWC. It became clear that there was a lot to gain from optimzing how
1208 the likelihoods are computed. This section discusses how multi-threading was applied to solve and

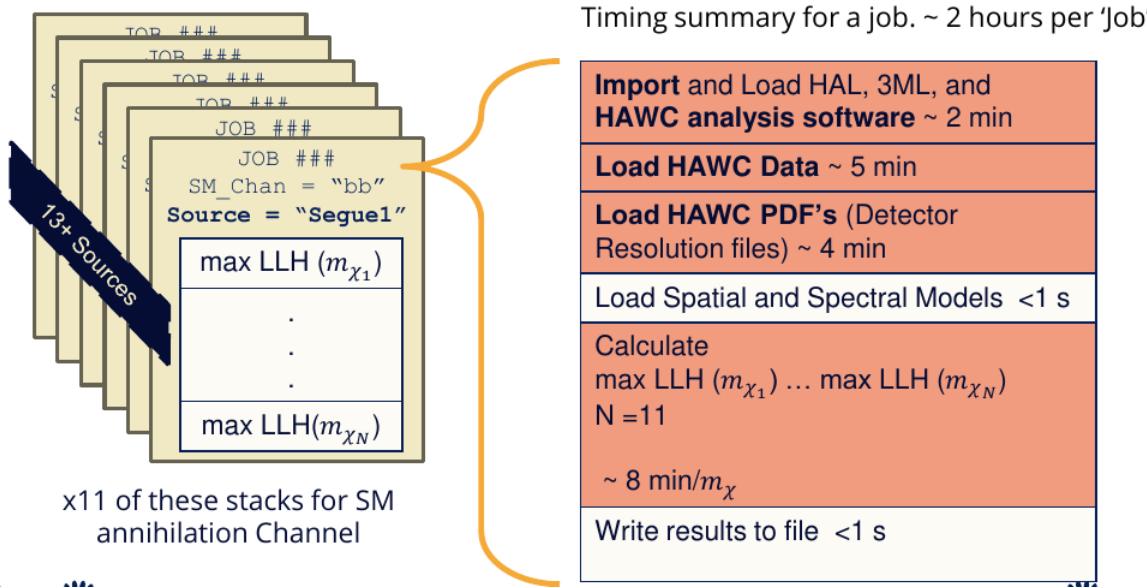


Figure 7.4 Infographic on how jobs and DM computation was organized in Section 6.3. Jobs were built for each permutation of CHANS and SOURCES shown by the left block in the figure. Each job, which took on the order 2 hrs to compute, had the following work flow: 1. Import HAWC analysis software, 2 min to run. 2. Load HAWC count maps, 5 min to run. 3. Load HAWC energy and spatial resolutions, 4 min. 5. Load DM spatial source templates and spectral models, less than 1 s. 6. Perform likelihood fit on data and model, about 8 min per DM mass. 7. Write results to file, less than 1s.

1209 reduce HAWC's computing of likelihoods for large parameter spaces like in DM searches.

1210 7.5.1 Relevant Foundational Information

1211 The profiling of the likelihood for HAWC is done via gradient descent where the normalization
 1212 of Equation (6.1) (linearly correlated with $\langle \sigma v \rangle$) is rescaled in the descent. Additionally, we sample
 1213 the likelihood space for a defined list of $\langle \sigma v \rangle$'s described in Section 6.4.2. The time to compute
 1214 these values is not predictable or consistent because many variables can change across the full
 1215 model-space. comprehensively, these variables are:

- 1216 • m_{χ} : DM rest mass
- 1217 • CHAN : DM SM annihilation channel.
- 1218 • SOURCE : dSph within HAWC's field of view. This involves a spatial template AND coordinate
 1219 in HAWC data.

1220 • $\langle \sigma v \rangle$: Effectevly the flux normalization and free parameter in the likelihood fit.
 1221 Therefore, we develop an asynchronous, functional-parallel coding pattern. Asyncronous meaning
 1222 that the instructions and computing within a function are independent and permitted to be out of sync
 1223 with sibling computations. Functional-parallel meaning that instructions are the subject of parral-
 1224 lelization rather than threading the likelihood computation. This is close to trivial parametrization
 1225 seen in Figure 7.4 except that we seek to consolidate the loading stages (software, data, and detector
 1226 resolution loading). Reducing the total instances of loading stages and distributing access to the
 1227 reduced loads across multiple asynchronous threads is expected to reduce serial processing time and
 1228 the overhead implicit to each job in addition to saving human time.

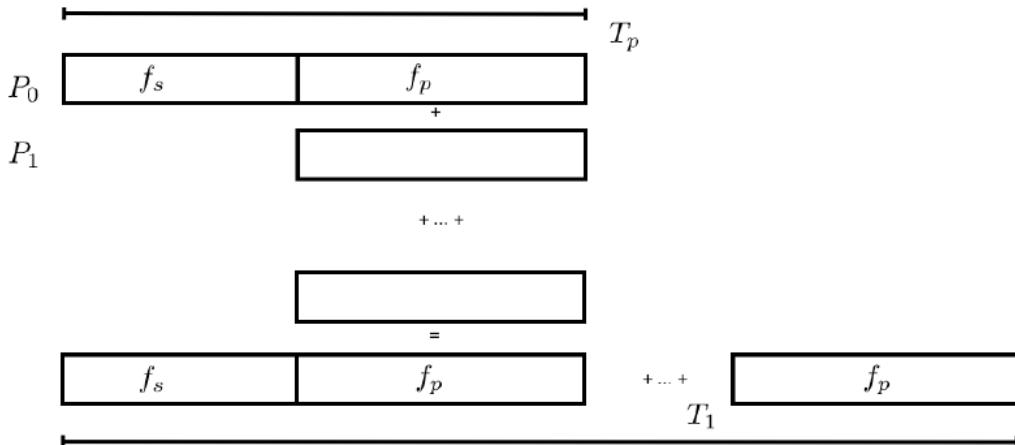


Figure 7.5 Graphic of Gustafson parallel coding pattern. f_s is the fraction of a program, in time, spent on serial computation. f_p is the fraction of computing time that is parallelizable. T_p is the total time for a parallel program to run. T_1 is the total time for a parallel program to run if only 1 processor is allocated. P_N is the N -th processor where it's row is the computation the processor performs. The Gustafson pattern is most similar to what is implemented for this analysis. Figure is pulled from [67].

1229 We need a way to measure and compare the expected speedup and efficiency gain for this
 1230 asynchronous coding pattern. I pull inspiration for timing measurement from [67] and use *Amdahl's law with hybrid programming*. Hybrid programming meaning that the computation is a mix of
 1231 distributed and shared memory programming. If we assume the code is fully parallelizable over p
 1232 processors and c threads, the ideal speedup is simply pc and ideal run-time is $T_1/(pc)$. T_1 is the
 1233

1234 total time for a parallel program to run if only 1 processor is allocated. However, the coding pattern
1235 contains some amount of unavoidable serial computation, as shown in Figure 7.5. In our case, the
1236 run time is estimated to be

$$T_{p,c} = \frac{T_1}{pc} (1 + F_s(c - 1)). \quad (7.4)$$

1237 F_s is the fraction of CPU time dedicated to serial computation. The expected speedup is

$$\frac{T_1}{T_{p,c}} = \frac{pc}{1 + F_s(c - 1)}. \quad (7.5)$$

1238 From Equation (7.5), we can see that the speed up scales with p/F_s . We are free to minimize
1239 F_s asymptotically by enlarging the total models that are submitted to the thread pool, thereby
1240 shrinking the CPU fraction dedicated to serial operation. We are also free to define exactly how
1241 many threads and processors we utilize, yet eventually hit a hard cap at the hardware available on
1242 our computing cluster. HAWC uses Intel Xeon processors with 48 cores and 96 threads. This
1243 means when N-threads (c) are defined, $N \bmod 2$ cores (p) are needed. We see that a successful
1244 code scales well as the expected speedup is inversely correlated with F_s . As the total number of
1245 models sampled grows, the speedup will also.

1246 7.5.2 Implementation

1247 The multithreaded code was written in Python3 and is documented in the `dark_matter_hawc`
1248 `repository` within the script named `mpu_analysis.py`. A version of the script as of April 25
1249 `TODO: make sure to update on this date` is also provided in Section B.1 It has many dependancies
1250 including the HAWC analysis software. Figure 7.6 displays the workflow of a job with 3 threads.
1251 Within a job, SOURCE is kept fixed. CHAN(S) remains 17 elements long. More m_χ are sampled
1252 from 11 bins up to 49 (for $\gamma\gamma$ and ZZ) and 25 (for remaining CHANS) which amounts to 12 or 6
1253 mass bins per decade. The DM mass, m_χ , and SM annihilation channels, CHANS, are permuted into
1254 a 473 element list which is split evenly across N threads where N ranges between 5 - 16. Within a
1255 thread, for each m_χ -CHAN tuple, 1001 $\langle\sigma v\rangle$ values are sampled in the likelihood, and the value of
1256 $\langle\sigma v\rangle$ that maximizes the likelihood is found. Although rare, fits that failed are handled on a case
1257 by case basis.

Timing summary for a multi-threaded job.

Import and Load HAL, 3ML, and HAWC analysis software ~ 2 min		
Load HAWC Data ~ 5 min		
Load HAWC PDF's (Detector Resolution files) ~ 4 min		
Load Spatial Model < 1s		
Load Spectra Models <1 s	Load Spectra Models <1 s	Load Spectra Models <1 s
Calculate max LLH (Chan_0, m_{χ_1}) ... max LLH (Chan_?, m_{χ_N}) N = TOTAL/N_THREADS ~ 8 min/Spec_model	Calculate max LLH (Chan_?, m_{χ_1}) ... max LLH (Chan_?, m_{χ_N}) N = TOTAL/N_THREADS ~ 8 min/Spec_model	Calculate max LLH (Chan_?, m_{χ_1}) ... max LLH (Chan_?, m_{χ_N}) N = TOTAL/N_THREADS ~ 8 min/Spec_model
Write results to file <1 s	Write results to file <1 s	Write results to file <1 s
Join Threads and terminate < 1s		

Figure 7.6 Task chart for one multi-threaded job developed for this project. Green blocks indicate a shared resource across the threads AND computation performed serially. Red blocks indicate functional parallel processing within each thread. 3 threads are represented here, yet many more can be employed during the full analysis. Jobs are defined by the SOURCE as these require unique maps to be loaded into the likelihood estimator. The m_{χ} , CHAN, and $\langle \sigma v \rangle$ variables are entered into the thread pool and allocated as evenly as possible across the threads.

CHAPTER 8

1258 **HEAVY DARK MATTER ANNIHILATION SEARCH WITH ICECUBE'S NORTH SKY**
1259 **TRACK DATA**

CHAPTER 9

1260

NU DUCK

MULTI-EXPERIMENT SUPPLEMENTARY FIGURES

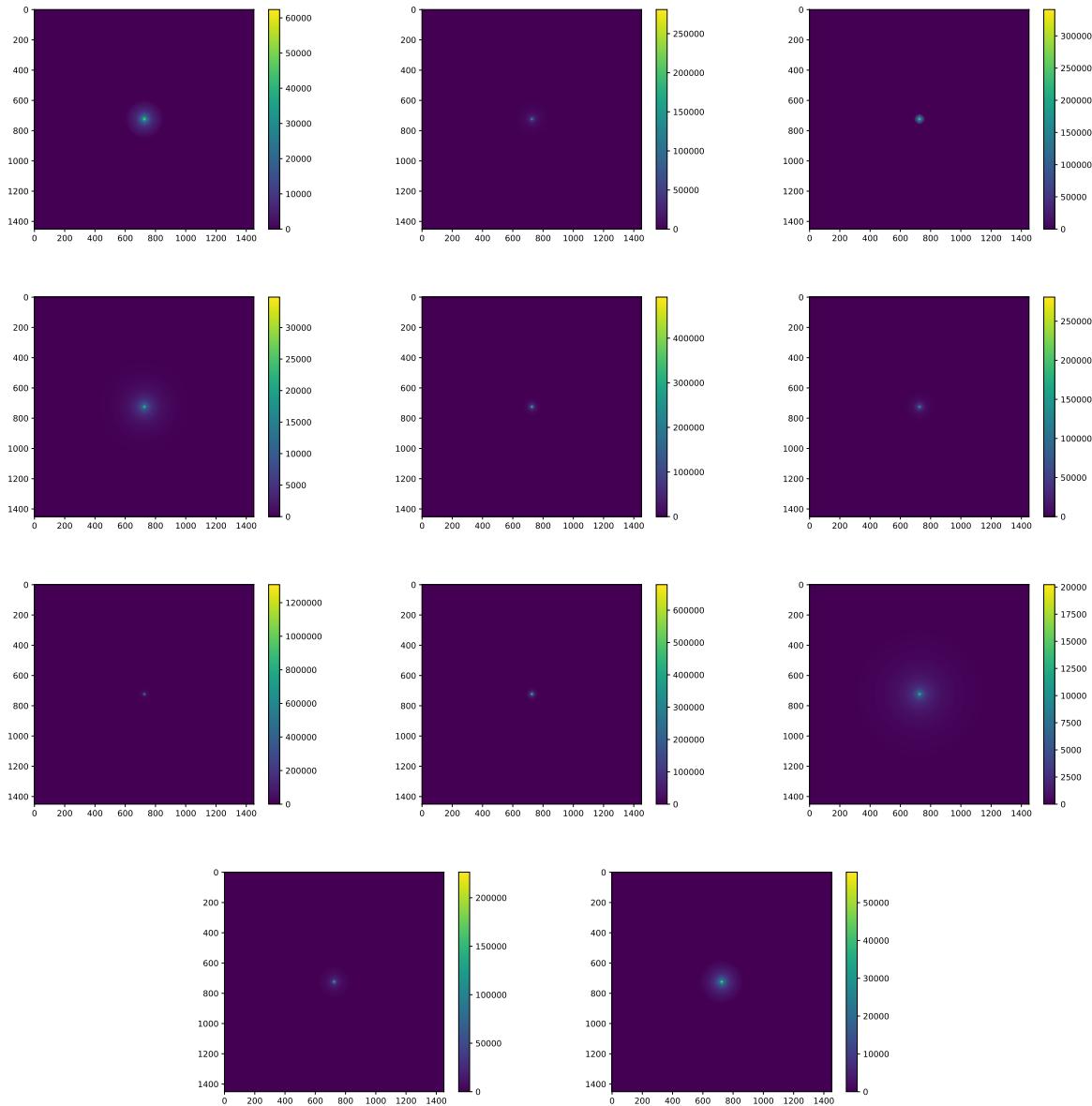


Figure A.1 Sister figure to Figure 6.3. Sources in the first row from left to right: Bootes I, Canes Venatici I, II. In second row: Draco, Hercules, Leo I. In the first row: Leo II, Leo IV, Sextans. In the final row: Ursa Major I, Ursa Major II.

APPENDIX B

MULTITHREADING SUPPLEMENTARY FIGURES

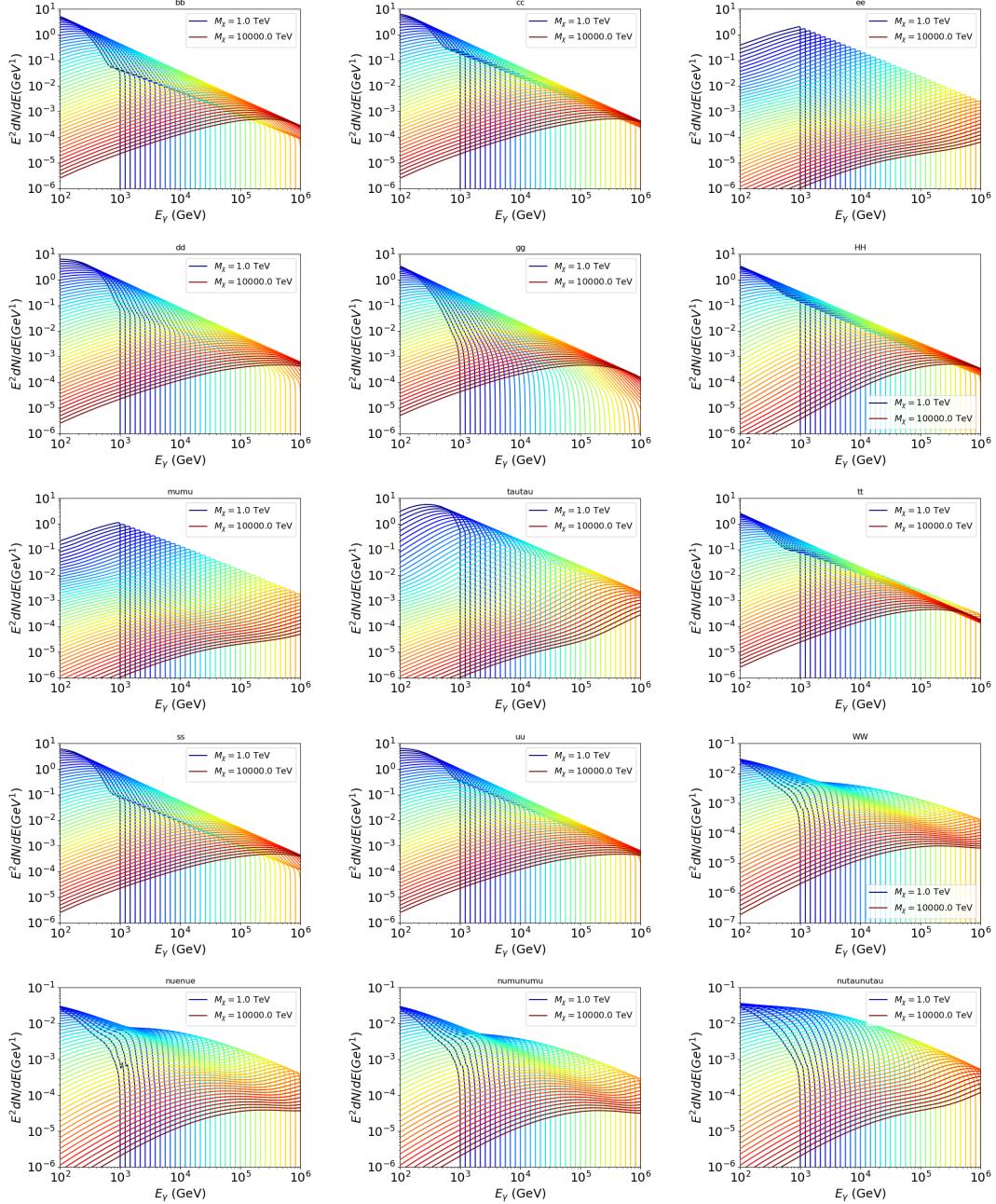


Figure B.1 Sister figure to Figure 7.2 for remaining SM primary annihilation channels studied for this thesis. These did not require any post generation smoothing and so are directly pulled from [64] with a binning scheme most helpful for a HAWC analysis.

1263 B.1 mpu_analysis.py

```
12641 import warnings
12652 with warnings.catch_warnings():
12663     warnings.simplefilter("ignore")
12674 # Python base libraries
12685 import os
12696 import sys
12707 import time
12718 # Import general libraries with namespace
12729 import matplotlib
12730 # Necessary for computing on cluster
12741 matplotlib.use("agg")
12752 import numpy as np
12763 import multiprocessing as mp
12774 # Import HAWC software
12785 sys.path.insert(1, os.path.join(os.environ['HOME'], 'hawc_software', 'threeML-
1279     analysis-scripts', 'fitModel'))
12806 from analysis_modules import *
12817 from threeML import *
12828 from hawc_hal import HAL, HealpixConeROI
12839 from threeML.minimizer.minimization import FitFailed
12840 # Import Dark Matter HAWC Libraries
12851 import analysis_utils as au
12862 import spectra as spec
12873 import sources as srcs
12884
12895 #* READ ONLY PATHS This block will change eventually
12906 MASS_LIST = './plotting/studies/nd/masses.txt'
12917 CHAN_LIST = './plotting/studies/nd/chans.txt'
12928
12939 #* WRITE PATHS, default location is to scratch
12940 OUT_PATH = os.path.join(os.environ["SCRATCH"], os.environ["USER"], 'New_duck')
```

```

12951 print('Our out path is going to be {}'.format(OUT_PATH))
12962
12973 # Define parallel Function. Can also be run serially
12984 def some_mass_fit(sigVs, datalist, shape, dSph, jfactor, mass_chan,
12995                 progress=None, log_file='', queue=None, i_job=0):
13006
13017     if progress is None:
13028         progress = [0]
13039     else: # Create log files for each thread
13040         log_file = log_file.replace('.log', '_ThreadNo_')
13051         log_file = log_file + str(i_job) + ".log"
13062         sys.stdout = open(log_file, "w")
13073
13084     fits = []
13095
13106     try:
13117         for m_c in mass_chan:
13128             print(f'Mass chan tuple: {m_c}')
13139             mass = int(m_c[0])
13140             ch = m_c[1]
13151             # Build path to output files
13162             outPath = os.path.join(OUT_PATH, ch, dSph)
13173             au.ut.ensure_dir(outPath)
13184
13195             if progress[i_job] < 0:
13206                 # If the master gets a Keyboard interrupt, commit suicide.
13217                 break
13228
13239                 ### Start Model Building for DM mass and SM channel #####
13240                 spectrum = spec.DM_models.HDMSpectra()
13251                 spectrum.set_channel(ch)
13262
13273                 myDwarf = ExtendedSource(dSph, spatial_shape=shape,

```

```

13284                     spectral_shape=spectrum)
13295
13306             spectrum.J = jfactor * u.GeV**2 / u.cm**5
13317             spectrum.sigmav = 1e-24 * u.cm**3 / u.s
13328             spectrum.set_dm_mass(mass * u.GeV)
13339
13340             spectrum.sigmav.bounds = (1e-30, 1e-12)
13351             model = Model(myDwarf)
13362             ##### End model Building #####
13373
13384             jl = JointLikelihood(model, datalist, verbose=False)
13395
13406             try:
13417                 result, lhdf = jl.fit(compute_covariance=False)
13428                 ts = -2.* (jl.minus_log_like_profile(1e-30) - jl.
1343 _current_minimum)
13449                 # Also profile the LLH vs sv
13450                 ll = jl.get_contours(spectrum.sigmav, sigVs[0],
13461                                     sigVs[-1], len(sigVs),
13472                                     progress=False, log=['False'])
13483
13494                 sigv_ll = au.ut.calc_95_from_profile(ll[0], ll[2])
13505                 # Write results to file
13516                 outFileLL = outPath+f"/LL_{dSph}_{ch}_mass{int(mass)}_GD.txt"
13527                 np.savetxt(outFileLL, (sigVs, ll[2]),
13538                               delimiter='\t', header='sigV\tLL\n')
13549
13550                 with open(outPath+f"/results_{dSph}_{ch}_mass{int(mass)}_GD.
1356 txt", "w") as results_file:
13571                     results_file.write("mDM [GeV]\tsigV_95\tsigV_B.F.\n")
13582
13593                     results_file.write("%i\t%.5E\t%.5E\t%.5E"%(mass, sigv_ll,
13604                                         ts, result.value[0]))

```

```

13615         # End write to file
13626     except FitFailed: # Don't kill all threads if a fit fails
13637         print("Fit failed. Go back and calculate this spectral model
1364     later")
13658         fits.append((ch, mass, -1, -1))
13669         with open(log_file+'.fail', 'w') as f_file:
13670             f_file.write(f'{ch}, {mass}\n')
13681
13692         progress[i_job] += 1
13703         matplotlib.pyplot.close() # Prevent leaky memory
13714
13725         fits.append((ch, mass, result.value[0], ts))
13736         progress[i_job] += 1
13747         matplotlib.pyplot.close()
13758     except KeyboardInterrupt:
13769         progress[i_job] = -1
13770
13781     fits = np.array(fits)
13792     if queue is None:
13803         return fits
13814     else:
13825         queue.put((i_job, fits))
13836
13847 def main(args):
13858     masses = np.loadtxt(MASS_LIST, dtype=int)
13869     chans = np.loadtxt(CHAN_LIST, delimiter=',', dtype=str)
13870     mass_chan = au.ut.permute_lists(chans, masses)
13881
13892     print(f"DM masses for this study are: {masses}")
13903     print(f"SM Channels for this study are XX -> {chans}")
13914     print(mass_chan)
13925
13936 # extract information from input argument

```

```

13947 dSph = args.dSph
13958 data_mngr = au.ut.Data_Selector('P5_NN_2D')
13969 dm_profile = srcts.Spatial_DM(args.catalog, dSph, args.sigma, args.decay)
13970
13981 ##### Extract Source Information #####
13992 if dm_profile.get_dec() < -22.0 or dm_profile.get_dec() > 62.0:
14003     raise ValueError("HAWC can't see this source D: Exitting now...")
14014
14025 print(f'{dSph} information')
14036 print(f'jfac: {dm_profile.get_factor()}\tRA: {dm_profile.get_ra()}\tDec: {dm_profile.get_dec()}\n')
1404
14057
14068 shape = SpatialTemplate_2D(fits_file=dm_profile.get_src_fits())
14079 ##### Finish Extract Source Information #####
14080
14091 ##### LOAD HAWC DATA #####
14102 roi = HealpixConeROI(data_radius=2.0, model_radius=8.0,
14113                         ra=dm_profile.get_ra(), dec=dm_profile.get_dec())
14124 bins = choose_bins.analysis_bins(args, dec=dm_profile.get_dec())
14135
14146 hawc = HAL(dSph, data_mngr.get_datmap(), data_mngr.get_detres(), roi)
14157 hawc.set_active_measurements(bin_list=bins)
14168 datalist = DataList(hawc)
14179 ##### FINISH LOAD HAWC DATA #####
14180
14191 # set up SigV sampling. This sample is somewhat standardized
14202 sigVs = np.logspace(-28,-18, 1001, endpoint=True) # NOTE This will change
1421 with HDM
14223
14234 if args.n_threads == 1:
14245     # No need to start || programming just iterate over the masses
14256     kw_arg = dict(sigVs=sigVs, datalist=datalist, shape=shape, dSph=dSph,
14267                     jfactor=dm_profile.get_factor(), mass_chan=mass_chan,

```

```

14278                 log_file=args.log)
14289             some_mass_fit(**kw_arg)
14290         else:
14301             # I Really want to suppress TQMD output
14312             from tqdm import tqdm
14323             from functools import partialmethod
14334             tqdm.__init__ = partialmethod(tqdm.__init__, disable=True)
14345
14356             x = np.array_split(mass_chan, args.n_threads)
14367             n_jobs = len(x)
14378
14389             print("Thread jobs summary by mass and SM channel")
14390             for xi in x:
14401                 print(f'{xi}')
14412
14423             queue = mp.Queue()
14434             progress = mp.Array('i', np.zeros(n_jobs, dtype=int))
14445
14456             # Define task pool that will be split amongsts threads
14467             kw_args = [dict(sigVs=sigVs, datalist=datalist, shape=shape,
14478                             dSph=dSph, jfactor=dm_profile.get_factor(),
14489                             mass_chan=mass_chan, progress=progress,
14490                             queue=queue, i_job=i, log_file=args.log)
14501                         for i, mass_chan in enumerate(x)]
14512
14523             # Define each process
14534             procs = [mp.Process(target=some_mass_fit, kwargs=kw_args[i]) \
14545                         for i in range(n_jobs)]
14556
14567             ### Start MASTER Thread only code block ###
14578             # Begin running all child threads
14589             for proc in procs: proc.start()
14590

```

```

14601     try:
14612         # In this case, the master does nothing except monitor progress of
1462         the threads
14633         # In an ideal world, the master thread also does some computation.
14644         n_complete = np.sum(progress)
14655         while_count = 0
14666
14677         while n_complete < len(mass_chan):
14688
14699             if np.any(np.asarray(progress) < 0):
14700                 # This was no threads are stranded when killing the script
14711                 raise KeyboardInterrupt()
14722             if while_count%1000 == 0:
14733                 print(f"{np.sum(progress)} of {len(mass_chan)} finished")
14744
14755             n_complete = np.sum(progress)
14766             time.sleep(.25)
14777             while_count += 1
14788
14799         except KeyboardInterrupt:
14800             # signal to jobs that it's time to stop
14811             for i in range(n_jobs):
14822                 progress[i] = -2
14833                 print('\nKeyboardInterrupt: terminating early.')
14844             ### End MASTER Thread only code block ###
14855
14866             fitss = [queue.get() for proc in procs]
14877             print(fitss)
14888             print(f'Thread statuses: {progress[:]}')
14899
14900             # putting results in a file
14911
14922             print("QUACK! All Done!")

```

```

14933
14944
14955 if __name__ == '__main__':
14966     import argparse
14977
14988     p = argparse.ArgumentParser(description="Run a DM annihilation analysis on
1499      a dwarf spheroidal for a specific SM channel for DM masses [1 TeV to 10
1500      PeV]")
15019
15020     # Dwarf spatial modeling arguements
15031     p.add_argument("-ds", "--dSph", type=str,
15042             help="dwarf spheroidal galaxy to be studied", required=
1505     True)
15063     p.add_argument("-cat", "--catalog", type=str, choices=['GS15', 'LS20'],
15074             default='LS20', help="source catalog used")
15085     p.add_argument("-sig", "--sigma", type=int, choices=[-1, 0, 1], default=0,
15096             help="Spatial model uncertainty. 0 corresponds to the
1510      median. +/-1 correspond to the +/-1sigma uncertainty respectively.")
15117
15128     # Arguements for the energy estimators
15139     p.add_argument("-e", "--estimator", type=str,
15140             choices=['P5_NHIT', 'P5_NN_2D'],
15151             default="P5_NN_2D", required=False,
15162             help="The energy estimator choice. Options are: P5_NHIT,
1517      P5_NN_2D. GP not supported (yet).")
15183     p.add_argument("--use-bins", default=None, nargs="*",
15194             help="Bins to use for the analysis", dest="use_bins")
15205     p.add_argument('--select_bins_by_energy', default=None, nargs="*",
15216             help="Does nothing. May fill in later once better
1522      understood")
15237     p.add_argument('--select_bins_by_fhit', default=None, nargs="*",
15248             help="Also does nothing see above")
15259     p.add_argument( '-ex', '--exclude', default=None, nargs="*",

```

```

15260         help="Exclude Bins", dest="exclude")

15271

15282     # Computing and logging arguements.

15293     p.add_argument('-nt', '--n_threads', type=int, default=1,
15304                         help='Maximum number of threads spawned by script. Default
1531                         is 4')

15325     p.add_argument('-log', '--log', type=str, required=True,
15336                         help='Name for log files. Especially needed for threads')

15347

15358     p.add_argument('--decay', action="store_true",
15369                         help='Set spectral DM hypothesis to decay')

15370

15381     args = p.parse_args()

15392     print(args.decay)

15403     if args.exclude is None: # default exclude bins 0 and 1
15414         args.exclude = ['B0C0Ea', 'B0C0Eb', 'B0C0Ec', 'B0C0Ed', 'B0C0Ee']

15425

15436     if args.decay: OUT_PATH += '_dec'
15447     else: OUT_PATH += '_ann'

15458

15469     OUT_PATH = OUT_PATH + '_' + args.catalog
15470     if args.sigma != 0: OUT_PATH += f'_{args.sigma}sig'

15481

15492     main(args)

```

BIBLIOGRAPHY

- 1551 [1] Anne M. Green. “Dark matter in astrophysics/cosmology”. In: *SciPost Phys. Lect.*
 1552 *Notes* (2022), p. 37. doi: [10.21468/SciPostPhysLectNotes.37](https://doi.org/10.21468/SciPostPhysLectNotes.37). URL: <https://scipost.org/10.21468/SciPostPhysLectNotes.37>.
- 1554 [2] Bing-Lin Young. “A survey of dark matter and related topics in cosmology”. In: *Frontiers*
 1555 *of Physics* 12 (Oct. 2016). doi: <https://doi.org/10.1007/s11467-016-0583-4>.
 1556 URL: <https://doi.org/10.1007/s11467-016-0583-4>.
- 1557 [3] Gianfranco Bertone, Dan Hooper, and Joseph Silk. “Particle dark matter: evidence,
 1558 candidates and constraints”. In: *Physics Reports* 405.5 (2005), pp. 279–390. ISSN:
 1559 0370-1573. doi: <https://doi.org/10.1016/j.physrep.2004.08.031>. URL:
 1560 <https://www.sciencedirect.com/science/article/pii/S0370157304003515>.
- 1561 [4] Gianfranco Bertone and Dan Hooper. “History of dark matter”. In: *Rev. Mod. Phys.*
 1562 90 (4 Aug. 2018), p. 045002. doi: [10.1103/RevModPhys.90.045002](https://doi.org/10.1103/RevModPhys.90.045002). URL: <https://link.aps.org/doi/10.1103/RevModPhys.90.045002>.
- 1564 [5] Fritz Zwicky. “The Redshift of Extragalactic Nebulae”. In: *Helvetica Physica Acta* 6.
 1565 (1933), pp. 110–127. doi: [10.5169/seals-110267](https://doi.org/10.5169/seals-110267).
- 1566 [6] Vera C. Rubin and Jr. Ford W. Kent. “Rotation of the Andromeda Nebula from a
 1567 Spectroscopic Survey of Emission Regions”. In: *ApJ* 159 (Feb. 1970), p. 379. doi:
 1568 [10.1086/150317](https://doi.org/10.1086/150317).
- 1569 [7] K. G. Begeman, A. H. Broeils, and R. H. Sanders. “Extended rotation curves of spiral galax-
 1570 ies: dark haloes and modified dynamics”. In: *Monthly Notices of the Royal Astronomical So-*
 1571 *ciety* 249.3 (Apr. 1991), pp. 523–537. ISSN: 0035-8711. doi: [10.1093/mnras/249.3.523](https://doi.org/10.1093/mnras/249.3.523).
 1572 eprint: <https://academic.oup.com/mnras/article-pdf/249/3/523/18160929/mnras249-0523.pdf>. URL: <https://doi.org/10.1093/mnras/249.3.523>.
- 1574 [8] *Different types of gravitational lenses*. website. Feb. 2004. URL: <https://esahubble.org/images/heic0404b/>.
- 1576 [9] Douglas Clowe et al. “A Direct Empirical Proof of the Existence of Dark Matter”. In: *apjl*
 1577 648.2 (Sept. 2006), pp. L109–L113. doi: [10.1086/508162](https://doi.org/10.1086/508162). arXiv: [astro-ph/0608407](https://arxiv.org/abs/astro-ph/0608407)
 1578 [*astro-ph*].
- 1579 [10] Planck Collaboration and N. et. al. Aghanim. “Planck 2018 results I. Overview and the
 1580 cosmological legacy of Planck”. In: *A&A* 641 (2020). doi: [10.1051/0004-6361/201833880](https://doi.org/10.1051/0004-6361/201833880). URL: <https://doi.org/10.1051/0004-6361/201833880>.
- 1582 [11] Wayne Hu. *Matter Density Animation*. web. 2024. URL: <http://background.uchicago.edu/~whu/animbut/anim2.html>.

- 1584 [12] Wenlong Yuan et al. “A First Look at Cepheids in a Type Ia Supernova Host with JWST”. in:
1585 *The Astrophysical Journal Letters* 940.1 (Nov. 2022). doi: [10.3847/2041-8213/ac9b27](https://doi.org/10.3847/2041-8213/ac9b27).
1586 URL: <https://dx.doi.org/10.3847/2041-8213/ac9b27>.
- 1587 [13] Wendy L. Freedman. “Measurements of the Hubble Constant: Tensions in Perspective”. In:
1588 *The Astrophysical Journal* 919.1 (Sept. 2021), p. 16. doi: [10.3847/1538-4357/ac0e95](https://doi.org/10.3847/1538-4357/ac0e95).
1589 URL: <https://dx.doi.org/10.3847/1538-4357/ac0e95>.
- 1590 [14] Jodi Cooley. “Dark Matter direct detection of classical WIMPs”. In: *SciPost Phys. Lect.*
1591 *Notes* (2022), p. 55. doi: [10.21468/SciPostPhysLectNotes.55](https://doi.org/10.21468/SciPostPhysLectNotes.55). URL: <https://scipost.org/10.21468/SciPostPhysLectNotes.55>.
- 1593 [15] “Search for new phenomena in events with an energetic jet and missing transverse momentum
1594 in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector”. In: *Phys. Rev. D* 103
1595 (11 July 2021), p. 112006. doi: [10.1103/PhysRevD.103.112006](https://doi.org/10.1103/PhysRevD.103.112006). URL: <https://link.aps.org/doi/10.1103/PhysRevD.103.112006>.
- 1597 [16] *Jetting into the dark side: a precision search for dark matter*. website. July 2020. URL:
1598 <https://atlas.cern/updates/briefing/precision-search-dark-matter>.
- 1599 [17] Celine Armand et. al. “Combined dark matter searches towards dwarf spheroidal galaxies
1600 with Fermi-LAT, HAWC, H.E.S.S., MAGIC, and VERITAS”. in: *Proceedings of Science*.
1601 Vol. 395. Mar. 2022. doi: <https://doi.org/10.22323/1.395.0528>.
- 1602 [18] Tracy R. Slatyer. “Les Houches Lectures on Indirect Detection of Dark Matter”. In: *SciPost*
1603 *Phys. Lect. Notes* (2022), p. 53. doi: [10.21468/SciPostPhysLectNotes.53](https://doi.org/10.21468/SciPostPhysLectNotes.53). URL:
1604 <https://scipost.org/10.21468/SciPostPhysLectNotes.53>.
- 1605 [19] Christian W Bauer, Nicholas L. Rodd, and Bryan R. Webber. “Dark matter spectra from
1606 the electroweak to the Planck scale”. In: *Journal of High Energy Physics* 2021.1029-8479
1607 (June 2021). doi: [https://doi.org/10.1007/JHEP06\(2021\)121](https://doi.org/10.1007/JHEP06(2021)121).
- 1608 [20] Riccardo Catena and Piero Ullio. “A novel determination of the local dark matter density”.
1609 In: *Journal of Cosmology and Astroparticle Physics* 2010.08 (Aug. 2010), p. 004. doi:
1610 [10.1088/1475-7516/2010/08/004](https://doi.org/10.1088/1475-7516/2010/08/004). URL: <https://dx.doi.org/10.1088/1475-7516/2010/08/004>.
- 1612 [21] B. P. Abbott et al. “Observation of Gravitational Waves from a Binary Black Hole Merger”.
1613 In: *Phys. Rev. Lett.* 116 (6 Feb. 2016), p. 061102. doi: [10.1103/PhysRevLett.116.061102](https://doi.org/10.1103/PhysRevLett.116.061102). URL: <https://link.aps.org/doi/10.1103/PhysRevLett.116.061102>.
- 1615 [22] R. Abbasi et. al. “Observation of high-energy neutrinos from the Galactic plane”. In: *Science*
1616 380.6652 (June 2023), pp. 1338–1343.

- 1617 [23] NASA Goddard Space Flight Center. *Fermi's 12-year view of the gamma-ray sky*. website.
1618 2022. URL: <https://svs.gsfc.nasa.gov/14090>.
- 1619 [24] Marco Cirelli et al. “PPPC 4 DM ID: a poor particle physicist cookbook for dark matter
1620 indirect detection”. In: *Journal of Cosmology and Astroparticle Physics* 2011.03 (Mar.
1621 2011), p. 051. doi: [10.1088/1475-7516/2011/03/051](https://doi.org/10.1088/1475-7516/2011/03/051). URL: <https://dx.doi.org/10.1088/1475-7516/2011/03/051>.
- 1623 [25] Javier Rico. “Gamma-Ray Dark Matter Searches in Milky Way Satellites—A Comparative
1624 Review of Data Analysis Methods and Current Results”. In: *Galaxies* 8.1 (Mar. 2020), p. 25.
1625 doi: [10.3390/galaxies8010025](https://doi.org/10.3390/galaxies8010025). arXiv: [2003.13482 \[astro-ph.HE\]](https://arxiv.org/abs/2003.13482).
- 1626 [26] W. B. Atwood et al. “The Large Area Telescope on the Fermi Gamma-Ray Space Telescope
1627 Mission”. In: *apj* 697.2 (June 2009), pp. 1071–1102. doi: [10.1088/0004-637X/697/2/1071](https://doi.org/10.1088/0004-637X/697/2/1071). arXiv: [0902.1089 \[astro-ph.IM\]](https://arxiv.org/abs/0902.1089).
- 1629 [27] M. Ackermann et al. “Searching for Dark Matter Annihilation from Milky Way Dwarf
1630 Spheroidal Galaxies with Six Years of Fermi Large Area Telescope Data”. In: *prl* 115.23,
1631 231301 (Dec. 2015), p. 231301. doi: [10.1103/PhysRevLett.115.231301](https://doi.org/10.1103/PhysRevLett.115.231301). arXiv:
1632 [1503.02641 \[astro-ph.HE\]](https://arxiv.org/abs/1503.02641).
- 1633 [28] Mattia Di Mauro, Martin Stref, and Francesca Calore. “Investigating the effect of Milky
1634 Way dwarf spheroidal galaxies extension on dark matter searches with Fermi-LAT data”.
1635 In: *Phys. Rev. D* 106 (12 Dec. 2022), p. 123032. doi: [10.1103/PhysRevD.106.123032](https://doi.org/10.1103/PhysRevD.106.123032).
1636 URL: <https://link.aps.org/doi/10.1103/PhysRevD.106.123032>.
- 1637 [29] F. et al. Aharonian. “Observations of the Crab Nebula with H.E.S.S.”. In: *Astron. Astrophys.*
1638 457 (2006), pp. 899–915. doi: [10.1051/0004-6361:20065351](https://doi.org/10.1051/0004-6361:20065351). arXiv: [astro-ph/0607333](https://arxiv.org/abs/astro-ph/0607333).
- 1640 [30] J. Albert et al. “VHE γ -Ray Observation of the Crab Nebula and its Pulsar with the MAGIC
1641 Telescope”. In: *The Astrophysical Journal* 674.2 (Feb. 2008), p. 1037. doi: [10.1086/525270](https://doi.org/10.1086/525270). URL: <https://dx.doi.org/10.1086/525270>.
- 1643 [31] N. Park. “Performance of the VERITAS experiment”. In: *Proceedings, 34th International
1644 Cosmic Ray Conference (ICRC2015): The Hague, The Netherlands, July, 30th July - 6th
1645 August*. Vol. 34. 2015, p. 771. arXiv: [1508.07070 \[astro-ph.IM\]](https://arxiv.org/abs/1508.07070).
- 1646 [32] A. Abramowski et al. “H.E.S.S. constraints on Dark Matter annihilations towards the Sculptor
1647 and Carina Dwarf Galaxies”. In: *Astropart. Phys.* 34 (2011), pp. 608–616. doi: [10.1016/j.astropartphys.2010.12.006](https://doi.org/10.1016/j.astropartphys.2010.12.006). arXiv: [1012.5602 \[astro-ph.HE\]](https://arxiv.org/abs/1012.5602).
- 1649 [33] A. Abramowski et al. “Search for dark matter annihilation signatures in H.E.S.S. observations
1650 of Dwarf Spheroidal Galaxies”. In: *Phys. Rev. D* 90 (2014), p. 112012. doi: [10.1103/PhysRevD.90.112012](https://doi.org/10.1103/PhysRevD.90.112012). arXiv: [1410.2589 \[astro-ph.HE\]](https://arxiv.org/abs/1410.2589).

- 1652 [34] H. Abdalla et al. “Searches for gamma-ray lines and ‘pure WIMP’ spectra from Dark
1653 Matter annihilations in dwarf galaxies with H.E.S.S”. in: *JCAP* 11 (2018), p. 037. doi:
1654 [10.1088/1475-7516/2018/11/037](https://doi.org/10.1088/1475-7516/2018/11/037). arXiv: [1810.00995 \[astro-ph.HE\]](https://arxiv.org/abs/1810.00995).
- 1655 [35] J. Aleksić et al. “Optimized dark matter searches in deep observations of Segue 1 with
1656 MAGIC”. in: *JCAP* 1402 (2014), p. 008. doi: [10.1088/1475-7516/2014/02/008](https://doi.org/10.1088/1475-7516/2014/02/008).
1657 arXiv: [1312.1535 \[hep-ph\]](https://arxiv.org/abs/1312.1535).
- 1658 [36] V.A. Acciari et al. “Combined searches for dark matter in dwarf spheroidal galaxies observed
1659 with the MAGIC telescopes, including new data from Coma Berenices and Draco”. In: *Physics of the Dark Universe* (2021), p. 100912. issn: 2212-6864. doi: <https://doi.org/10.1016/j.dark.2021.100912>. URL: <https://www.sciencedirect.com/science/article/pii/S2212686421001370>.
- 1663 [37] M. L. Ahnen et al. “Indirect dark matter searches in the dwarf satellite galaxy Ursa Major II
1664 with the MAGIC Telescopes”. In: *JCAP* 1803.03 (2018), p. 009. doi: [10.1088/1475-7516/2018/03/009](https://doi.org/10.1088/1475-7516/2018/03/009). arXiv: [1712.03095 \[astro-ph.HE\]](https://arxiv.org/abs/1712.03095).
- 1666 [38] S. et al. Archambault. “Dark matter constraints from a joint analysis of dwarf Spheroidal
1667 galaxy observations with VERITAS”. in: *prd* 95.8 (Apr. 2017). doi: [10.1103/PhysRevD.95.082001](https://doi.org/10.1103/PhysRevD.95.082001). arXiv: [1703.04937 \[astro-ph.HE\]](https://arxiv.org/abs/1703.04937).
- 1669 [39] Louise Oakes et al. “Combined Dark Matter searches towards dwarf spheroidal galaxies with
1670 Fermi-LAT, HAWC, HESS, MAGIC and VERITAS”. in: *Proceedings of Science*. 2019.
- 1671 [40] Celine Armand et al. on behalf of the Fermi-LAT, HAWC, HESS, MAGIC, VERITAS.
1672 “Combined Dark Matter searches towards dwarf spheroidal galaxies with Fermi-LAT,
1673 HAWC, HESS, MAGIC and VERITAS”. in: *Proceedings of Science*. 2021.
- 1674 [41] Daniel Kerszberg et al. on behalf of the Fermi-LAT, HAWC, HESS, MAGIC, and VER-
1675 TIAS collaborations. “Search for dark matter annihilation with a combined analysis of
1676 dwarf spheroidal galaxies from Fermi-LAT, HAWC, H.E.S.S., MAGIC and VERITAS”. in:
1677 *Proceedings of Science*. 2023.
- 1678 [42] A. U. Abeysekara et al. “Observation of the Crab Nebula with the HAWC Gamma-Ray
1679 Observatory”. In: *The Astrophysical Journal* 843.1 (June 2017), p. 39. doi: [10.3847/1538-4357/aa7555](https://doi.org/10.3847/1538-4357/aa7555). URL: <https://doi.org/10.3847/1538-4357/aa7555>.
- 1681 [43] Giacomo Vianello et al. *The Multi-Mission Maximum Likelihood framework (3ML)*. 2015.
1682 arXiv: [1507.08343 \[astro-ph.HE\]](https://arxiv.org/abs/1507.08343).
- 1683 [44] Marco Cirelli et al. “PPPC 4 DM ID: a poor particle physicist cookbook for dark matter
1684 indirect detection”. In: *Journal of Cosmology and Astroparticle Physics* 2011.03 (Mar.
1685 2011). issn: 1475-7516. doi: [10.1088/1475-7516/2011/03/051](https://doi.org/10.1088/1475-7516/2011/03/051). URL: <http://dx.doi.org/10.1088/1475-7516/2011/03/051>.

- 1687 [45] Alex Geringer-Sameth, Savvas M. Koushiappas, and Matthew Walker. “DWARF GALAXY
1688 ANNIHILATION AND DECAY EMISSION PROFILES FOR DARK MATTER EXPERI-
1689 MENTS”. in: *The Astrophysical Journal* 801.2 (Mar. 2015), p. 74. ISSN: 1538-4357. doi:
1690 [10.1088/0004-637X/801/2/74](https://doi.org/10.1088/0004-637X/801/2/74). URL: <http://dx.doi.org/10.1088/0004-637X/801/2/74>.
- 1692 [46] A. Albert et al. “Dark Matter Limits from Dwarf Spheroidal Galaxies with the HAWC
1693 Gamma-Ray Observatory”. In: *The Astrophysical Journal* 853.2 (Feb. 2018), p. 154. ISSN:
1694 1538-4357. doi: [10.3847/1538-4357/aaa6d8](https://doi.org/10.3847/1538-4357/aaa6d8). URL: <http://dx.doi.org/10.3847/1538-4357/aaa6d8>.
- 1696 [47] V. Bonnivard et al. “Spherical Jeans analysis for dark matter indirect detection in dwarf
1697 spheroidal galaxies - Impact of physical parameters and triaxiality”. In: *Mon. Not. Roy.
1698 Astron. Soc.* 446 (2015), pp. 3002–3021. doi: [10.1093/mnras/stu2296](https://doi.org/10.1093/mnras/stu2296). arXiv:
1699 [1407.7822 \[astro-ph.HE\]](https://arxiv.org/abs/1407.7822).
- 1700 [48] M. Ackermann et al. “Searching for Dark Matter Annihilation from Milky Way Dwarf
1701 Spheroidal Galaxies with Six Years of Fermi Large Area Telescope Data”. In: *prl* 115.23,
1702 231301 (Dec. 2015), p. 231301. doi: [10.1103/PhysRevLett.115.231301](https://doi.org/10.1103/PhysRevLett.115.231301). arXiv:
1703 [1503.02641 \[astro-ph.HE\]](https://arxiv.org/abs/1503.02641).
- 1704 [49] M. L. Ahnen et al. “Limits to Dark Matter Annihilation Cross-Section from a Combined
1705 Analysis of MAGIC and Fermi-LAT Observations of Dwarf Satellite Galaxies”. In: *JCAP*
1706 1602.02 (2016), p. 039. doi: [10.1088/1475-7516/2016/02/039](https://doi.org/10.1088/1475-7516/2016/02/039). arXiv: [1601.06590](https://arxiv.org/abs/1601.06590)
1707 [astro-ph.HE].
- 1708 [50] Javier Rico et al. *gLike: numerical maximization of heterogeneous joint
1709 likelihood functions of a common free parameter plus nuisance parameters*.
1710 <https://doi.org/10.5281/zenodo.4601451>. Version v00.09.03. Mar. 2021. doi: [10.5281/zenodo.4601451](https://doi.org/10.5281/zenodo.4601451). URL: <https://doi.org/10.5281/zenodo.4601451>.
- 1712 [51] Tjark Miener and Daniel Nieto. *LklCom: Combining likelihoods from different experiments*.
1713 <https://doi.org/10.5281/zenodo.4597500>. Version v0.5.3. Mar. 2021. doi: [10.5281/zenodo.4597500](https://doi.org/10.5281/zenodo.4597500). URL: <https://doi.org/10.5281/zenodo.4597500>.
- 1715 [52] T. Miener et al. “Open-source Analysis Tools for Multi-instrument Dark Matter Searches”.
1716 In: *arXiv e-prints*, arXiv:2112.01818 (Dec. 2021), arXiv:2112.01818. arXiv: [2112.01818](https://arxiv.org/abs/2112.01818)
1717 [astro-ph.IM].
- 1718 [53] Alex Geringer-Sameth and Matthew Koushiappas Savvas M. and Walker. “Dwarf galaxy
1719 annihilation and decay emission profiles for dark matter experiments”. In: *Astrophys.
1720 J.* 801.2 (2015), p. 74. doi: [10.1088/0004-637X/801/2/74](https://doi.org/10.1088/0004-637X/801/2/74). arXiv: [1408.0002](https://arxiv.org/abs/1408.0002)
1721 [astro-ph.CO].

- 1722 [54] Gianfranco Bertone, Dan Hooper, and Joseph Silk. “Particle dark matter: evidence, can-
1723 didates and constraints”. In: *Physics Reports* 405.5-6 (Jan. 2005), pp. 279–390. ISSN:
1724 0370-1573. doi: [10.1016/j.physrep.2004.08.031](https://doi.org/10.1016/j.physrep.2004.08.031). URL: <http://dx.doi.org/10.1016/j.physrep.2004.08.031>.
- 1726 [55] V. Bonnivard et al. “Dark matter annihilation and decay in dwarf spheroidal galaxies: The
1727 classical and ultrafaint dSphs”. In: *Mon. Not. Roy. Astron. Soc.* 453.1 (2015), pp. 849–867.
1728 doi: [10.1093/mnras/stv1601](https://doi.org/10.1093/mnras/stv1601). arXiv: [1504.02048 \[astro-ph.HE\]](https://arxiv.org/abs/1504.02048).
- 1729 [56] A. et al. Albert. “Searching for Dark Matter Annihilation in Recently Discovered Milky Way
1730 Satellites with Fermi-LAT”. in: *Astrophys. J.* 834.2 (2017), p. 110. doi: [10.3847/1538-4357/834/2/110](https://doi.org/10.3847/1538-4357/834/2/110). arXiv: [1611.03184 \[astro-ph.HE\]](https://arxiv.org/abs/1611.03184).
- 1732 [57] Mattia Di Mauro and Martin Wolfgang Winkler. “Multimessenger constraints on the dark
1733 matter interpretation of the Fermi-LAT Galactic Center excess”. In: *prd* 103.12, 123005
1734 (June 2021), p. 123005. doi: [10.1103/PhysRevD.103.123005](https://doi.org/10.1103/PhysRevD.103.123005). arXiv: [2101.11027 \[astro-ph.HE\]](https://arxiv.org/abs/2101.11027).
- 1736 [58] HongSheng Zhao. “Analytical models for galactic nuclei”. In: *Mon. Not. Roy. Astron. Soc.*
1737 278 (1996), pp. 488–496. doi: [10.1093/mnras/278.2.488](https://doi.org/10.1093/mnras/278.2.488). arXiv: [astro-ph/9509122 \[astro-ph\]](https://arxiv.org/abs/astro-ph/9509122).
- 1739 [59] H. C. Plummer. “On the Problem of Distribution in Globular Star Clusters: (Plate 8.)”
1740 In: *Monthly Notices of the Royal Astronomical Society* 71.5 (Mar. 1911), pp. 460–470.
1741 ISSN: 0035-8711. doi: [10.1093/mnras/71.5.460](https://doi.org/10.1093/mnras/71.5.460). eprint: <https://academic.oup.com/mnras/article-pdf/71/5/460/2937497/mnras71-0460.pdf>. URL:
1743 <https://doi.org/10.1093/mnras/71.5.460>.
- 1744 [60] Daniel R. Hunter. “Derivation of the anisotropy profile, constraints on the local velocity
1745 dispersion, and implications for direct detection”. In: *JCAP* 02 (2014), p. 023. doi:
1746 [10.1088/1475-7516/2014/02/023](https://doi.org/10.1088/1475-7516/2014/02/023). arXiv: [1311.0256 \[astro-ph.CO\]](https://arxiv.org/abs/1311.0256).
- 1747 [61] Barun Kumar Dhar and Liliya L. R. Williams. “Surface mass density of the Einasto family
1748 of dark matter haloes: are they Sersic-like?” In: *Mon. Not. Roy. Astron. Soc.* (2010). doi:
1749 [10.1111/j.1365-2966.2010.16446.x](https://doi.org/10.1111/j.1365-2966.2010.16446.x).
- 1750 [62] M. Baes and E. Van Hese. “Dynamical models with a general anisotropy profile”. In:
1751 *Astron. Astrophys.* 471 (2007), p. 419. doi: [10.1051/0004-6361:20077672](https://doi.org/10.1051/0004-6361:20077672). arXiv:
1752 [0705.4109 \[astro-ph\]](https://arxiv.org/abs/0705.4109).
- 1753 [63] Matthew G. Walker, Edward W. Olszewski, and Mario Mateo. “Bayesian analysis of re-
1754 solved stellar spectra: application to MMT/Hectochelle observations of the Draco dwarf
1755 spheroidal”. In: *mnras* 448.3 (Apr. 2015), pp. 2717–2732. doi: [10.1093/mnras/stv099](https://doi.org/10.1093/mnras/stv099).
1756 arXiv: [1503.02589 \[astro-ph.GA\]](https://arxiv.org/abs/1503.02589).

- 1757 [64] Nicholas L. Rodd et al. “Dark matter spectra from the electroweak to the Planck scale”. In:
1758 *J. High Energy Physics* 121.10.1007 (June 2021).
- 1759 [65] Pace, Andrew B and Strigari, Louis E. “Scaling relations for dark matter annihilation and
1760 decay profiles in dwarf spheroidal galaxies”. In: *Monthly Notices of the Royal Astronomical
1761 Society* 482.3 (Oct. 2018), pp. 3480–3496. ISSN: 0035-8711. doi: [10.1093/mnras/sty2839](https://doi.org/10.1093/mnras/sty2839).
- 1763 [66] Albert, A. et al. “Search for gamma-ray spectral lines from dark matter annihilation in
1764 dwarf galaxies with the High-Altitude Water Cherenkov observatory”. In: *Phys. Rev. D* 101 (10 May 2020), p. 103001. doi: [10.1103/PhysRevD.101.103001](https://doi.org/10.1103/PhysRevD.101.103001). URL:
1765 <https://link.aps.org/doi/10.1103/PhysRevD.101.103001>.
- 1767 [67] Victor Eijkhout and Edmund Show and Robert van de Geijn. *The Science of Computing.
1768 The Art of High Performance Computing*. Vol. 3. Open Copy published under CC-BY 4.0
1769 license, 2023, pp. 63–66.