

1 LEVERAGING MULTI-MESSENGER ASTROPHYSICS FOR DARK MATTER SEARCHES

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Today

**ABSTRACT**

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

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<sup>6</sup> Today

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8 I love my friends. Thanks to everyone that helped me figure this out. Amazing thanks to the people  
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**LIST OF ABBREVIATIONS**

- 407 **MSU** Michigan State University  
408 **LANL** Los Alamos National Laboratory  
409 **DM** Dark Matter  
410 **SM** Standard Model  
411 **HAWC** High Altitude Water Cherenkov Observatory  
412 **dSph** Dwarf Spheroidal Galaxy

## CHAPTER 1

### INTRODUCTION

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

## CHAPTER 2

415

### DARK MATTER IN THE COSMOS

416 **2.1 Introduction**

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

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

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

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

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

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

433 You estimated 1,900 lbs. assuming the average weight of a student in your class was 60 lbs.  
434 So, you are pleased with Sandra's and Mario's answer. You instruct your students to all gather on  
435 the giant scale and read off the weight together. To all your surprise, the scale reads *10,000 lbs.*!  
436 10,000 is significantly more than a 10% error from 2,000. In fact, it is approximately 5 times more  
437 massive than either your or your students' estimates. You think to yourself and conclude there  
438 must be something wrong with the scale. You ask an employee to check the scale and verify it is  
439 well calibrated. They confirm that the scale is in working order. You weigh a couple of students  
440 individually to assess that the scale is well calibrated. Sandra weighs 59 lbs., and Mario weighs

441 62 lbs., typical weights for their age. You then weigh each student individually and see that their  
442 weights individually do not deviate greatly from 60 lbs. So, where does all the extra weight come  
443 from?

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

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

453 **2.2 Dark Matter Basics**

454 Presently, a more compelling theory of cosmology that includes Dark Matter (DM) in order  
455 to explain a variety of observations is  $\Lambda$  Cold Dark Matter, or  $\Lambda$ CDM. I present the evidence  
456 supporting  $\Lambda$ CDM in Section 2.3 yet discuss the conclusions of the  $\Lambda$ CDM model here. According  
457 to  $\Lambda$ CDM fit to observations on the Cosmic Microwave Background (CMB), DM is 26.8% of the  
458 universe's current energy budget. Baryonic matter, stuff like atoms, gas, and stars, contributes to  
459 4.9% of the universe's current energy budget [1, 2, 3].

460 DM is dark; it does not interact readily with light at any wavelength. DM also does not interact  
461 noticeably with the other standard model forces (Strong and Weak) at a rate that is readily observed  
462 [3]. DM is cold, which is to say that the average velocity of DM is below relativistic speeds [1].  
463 'Hot' DM would not likely manifest the dense structures we observe like galaxies, and instead  
464 would produce much more diffuse galaxies than what is observed [3, 1]. DM is old; it played a  
465 critical role in the formation of the universe and the structures within it [1, 2].

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

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

471 **2.3 Evidence for Dark Matter**

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

485 **2.3.1 First Clues: Stellar Velocities**

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

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

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

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

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

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

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

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

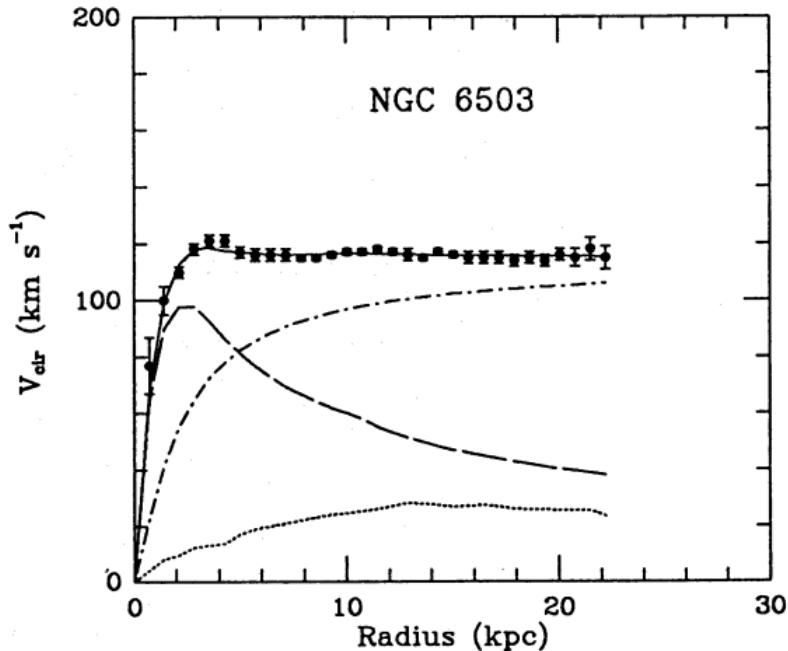


Figure 2.1 Rotation curve fit to NGC 6503 from [7]. Dashed line is the contribution from visible matter. Dotted curves are from gas. Dash-dot curves are from dark matter (DM). Solid line is the composite contribution from all matter and DM sources. Data are indicated with bold dots with error bars. Data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

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

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

510 **2.3.2 Evidence for Dark Matter: Gravitational Lensing**

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

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

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

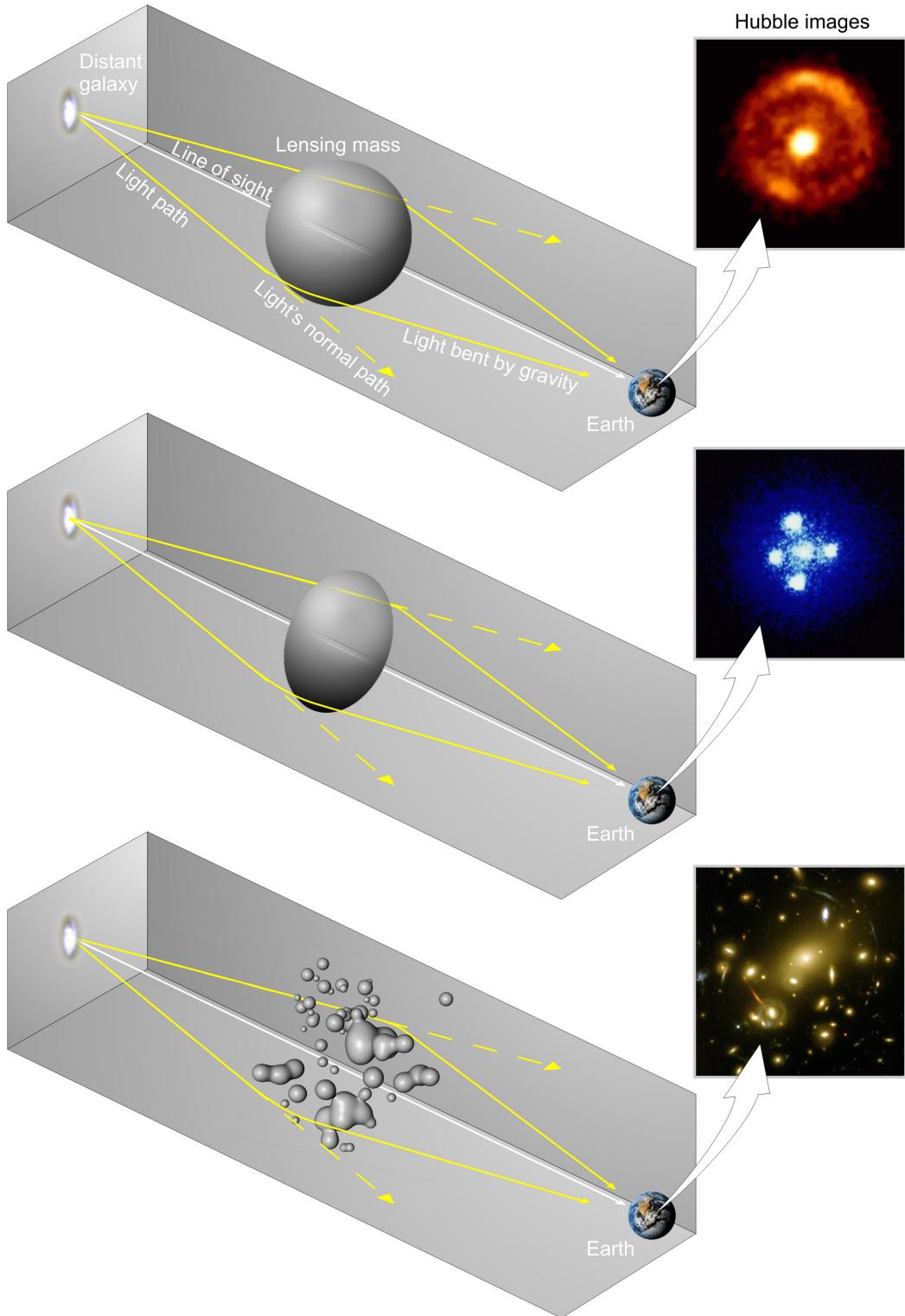


Figure 2.2 Light from distant galaxy is bent in unique ways depending on the distribution of mass between the galaxy and Earth. Yellow dashed lines indicate where the light would have gone if the matter were not present [8].

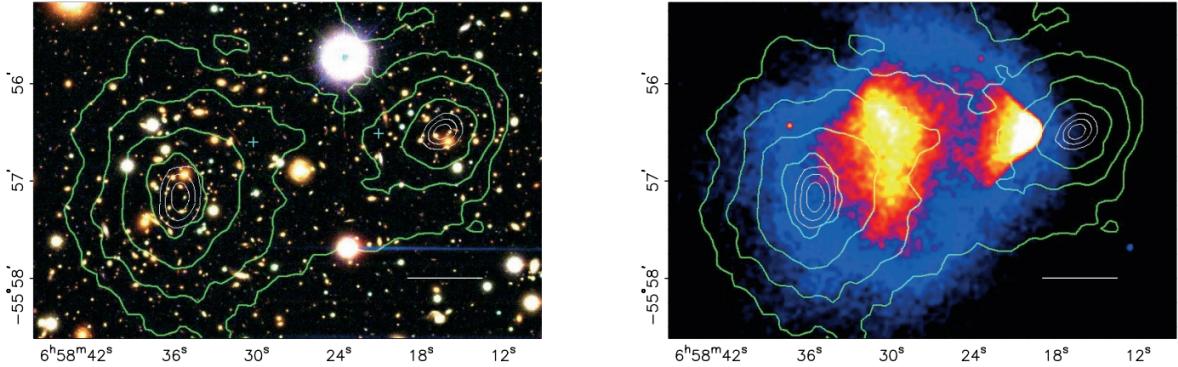


Figure 2.3 (left) Optical image of galactic cluster 1E0657-558. (right) X-ray image of the cluster with redder meaning hotter and higher baryon density. (both) Green contours are reconstruction of gravity contours from weak lensing. White rings are the best fit mass maxima at 68.3%, 95.5%, and 99.7%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

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

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

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

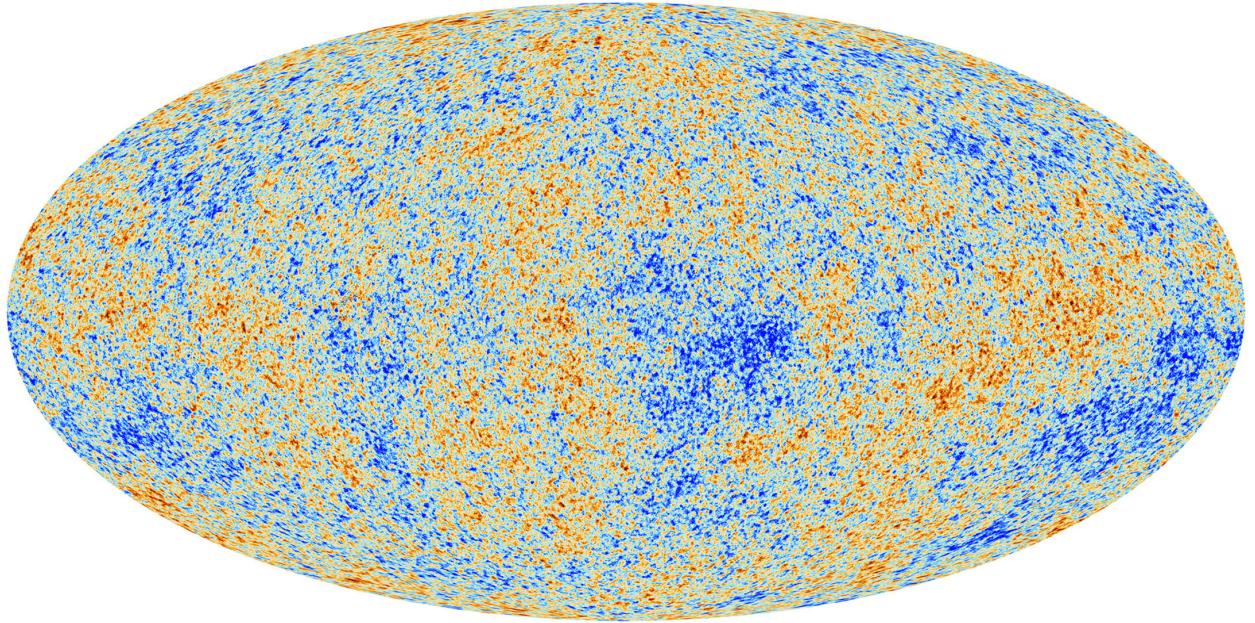


Figure 2.4 Plank CMB sky. Sky map features small variations in temperature in primordial light. These anisotropies are used to make inferences about the universe’s energy budget and developmental history. [10]

545 **2.3.3 Evidence for Dark Matter: Cosmic Microwave Background**

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

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

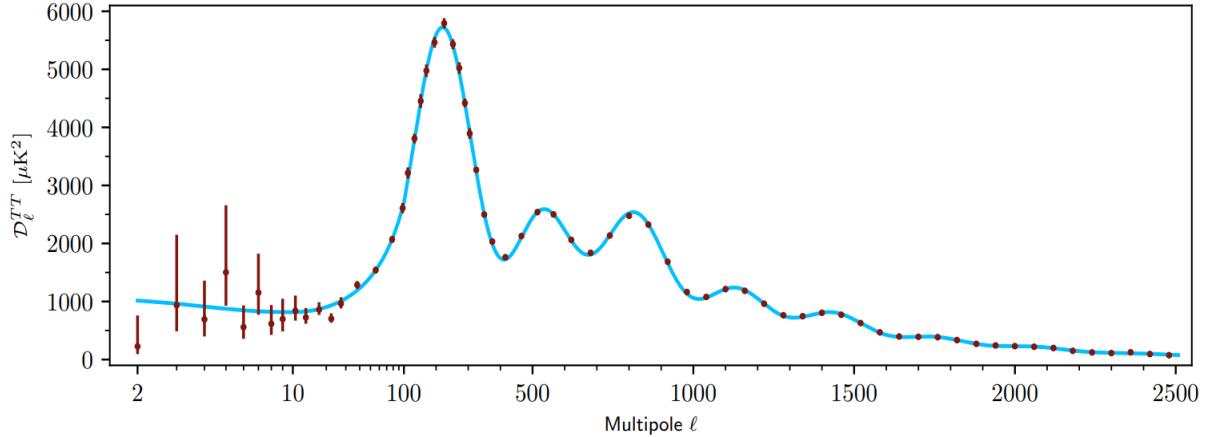


Figure 2.5 Observed Cosmic Microwave Background power spectrum as a function of multipole moment from Plank [10]. Blue line is best fit model from  $\Lambda$ CDM. Red points and lines are data and error, respectively.

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

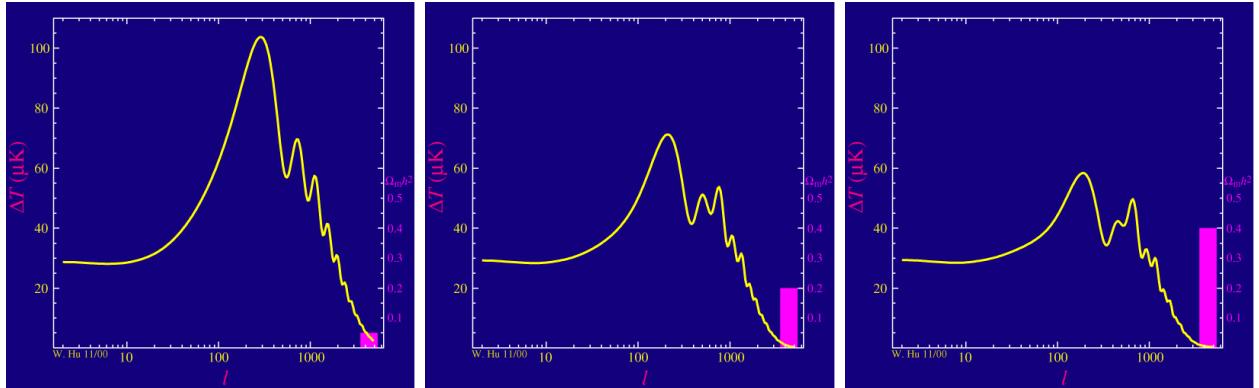


Figure 2.6 Predicted power spectra of CMB for different  $\Omega_m h^2$  values for fixed baryon density from [11]. (left) Low  $\Omega_m h^2$  increases the prominence of first and second peaks. (middle)  $\Omega_m h^2$  is most similar to the observed power spectrum. The second and third peaks are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

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

568 past decade that continues to deepened with observations from instruments like the James Webb  
569 Telescope [12, 13]. As Hubble tensions deepen, we may find that perhaps  $\Lambda$ **CDM**, despite its  
570 successes, is missing some critical physics.

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

580 **2.4 Searching for Dark Matter: Particle DM**

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

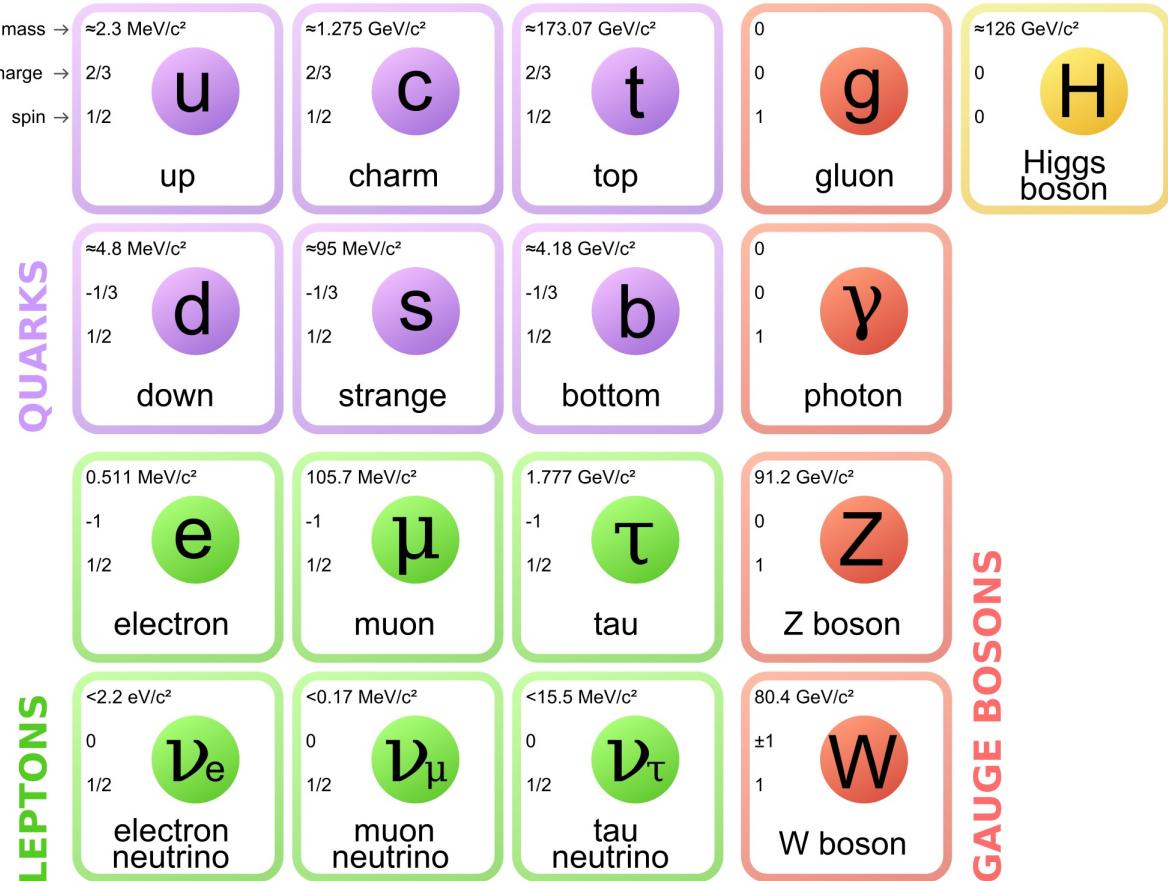


Figure 2.7 The Standard Model (SM) of particle physics. Figure taken from <http://www.quantumdiaries.org/2014/03/14/the-standard-model-a-beautiful-but-flawed-theory/>

### 593 2.4.1 Shake it, Break it, Make it

594 When considering DM that couples in some way with the SM, the interactions are roughly  
 595 demonstrated by interaction demonstrated in Figure 2.8. The figure is a simplified Feynman  
 596 diagram where the arrow of time represents the interaction modes of: **Shake it, Break it, Make it**.  
 597 **Shake it** refers to the direct detection of dark matter. Direct detection interactions start with  
 598 a free DM particle and an SM particle. The DM and SM interact via elastic or inelastic collision  
 599 and recoil away from each other. The DM remains in the dark sector and imparts some momentum  
 600 onto the SM particle. The hope is that the momentum imparted onto the SM particle is sufficiently  
 601 high enough to pick up with extremely sensitive instruments. Because we cannot create the DM in  
 602 the lab, a direct detection experiment must wait until DM is incident on the detector. Most direct  
 603 detection experiments are therefore placed in low-background environments with inert detection

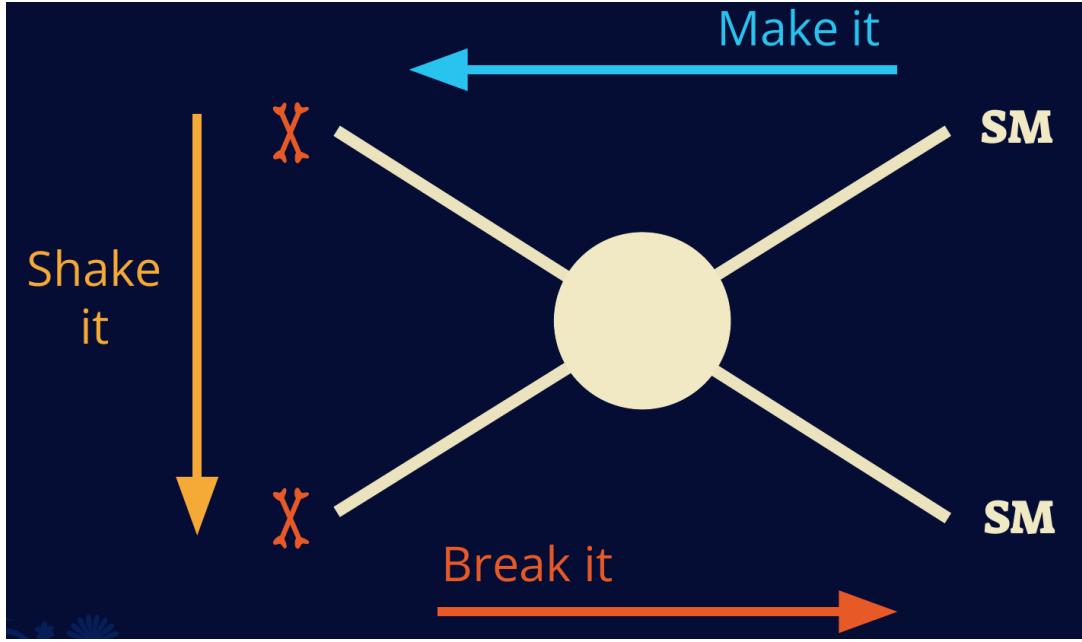


Figure 2.8 Simplified Feynman diagram demonstrating different ways DM can interact with SM particles. The 'X's refer to the DM particles whereas the SM refer to fundamental particles in the SM. The large circle in the center indicates the vertex of interaction and is purposely left vague. The colored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

604 media like the noble gas Xenon. [14]

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

617 momentum. [15]

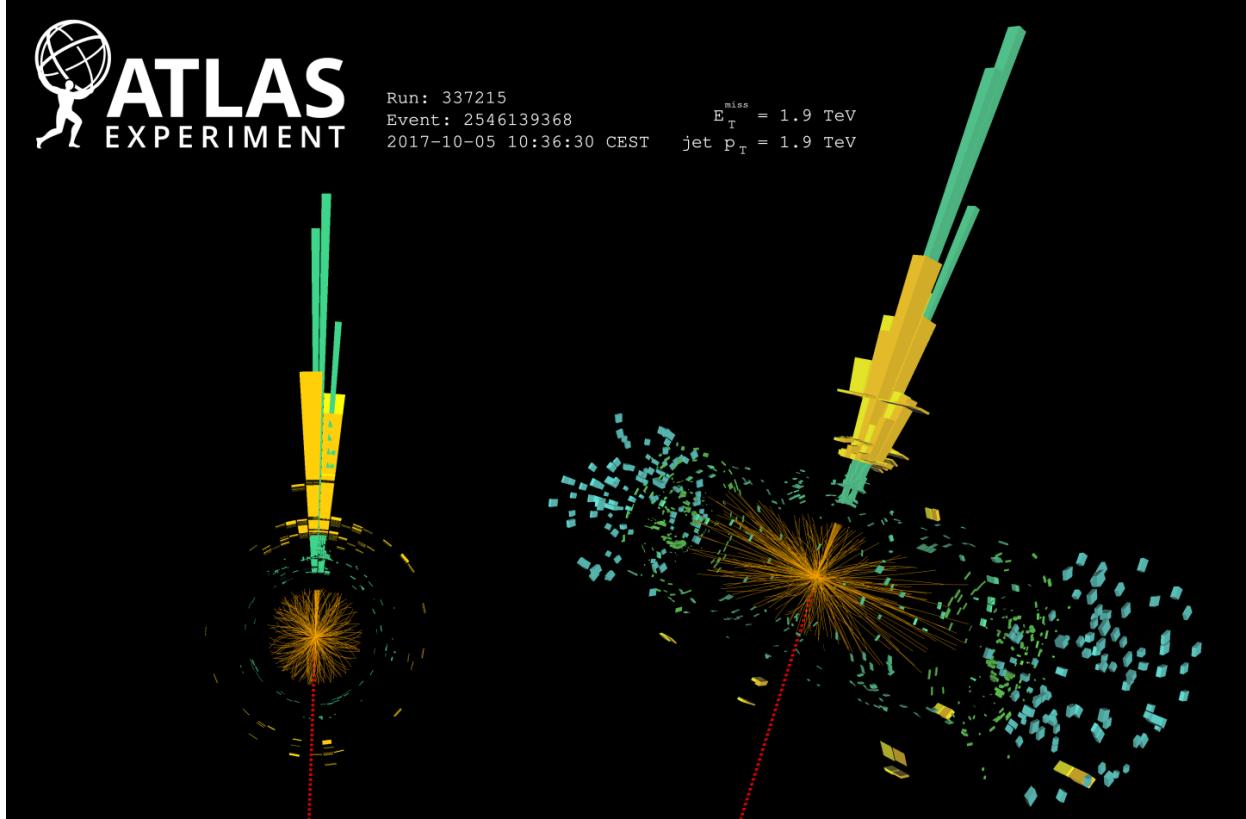


Figure 2.9 A single jet event in ATLAS detector from 2017 [16]. Jet momentum was observed to be 1.9 TeV. Missing transverse momentum was observed to be 1.9 TeV compared to the initial transverse momentum of the event was 0. Implied MET is traced by a red dashed line in event display.

#### 618 2.4.2 Break it: Standard Model Signatures of Dark Matter through Indirect Searches

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

627 the problem of DM in the first place.

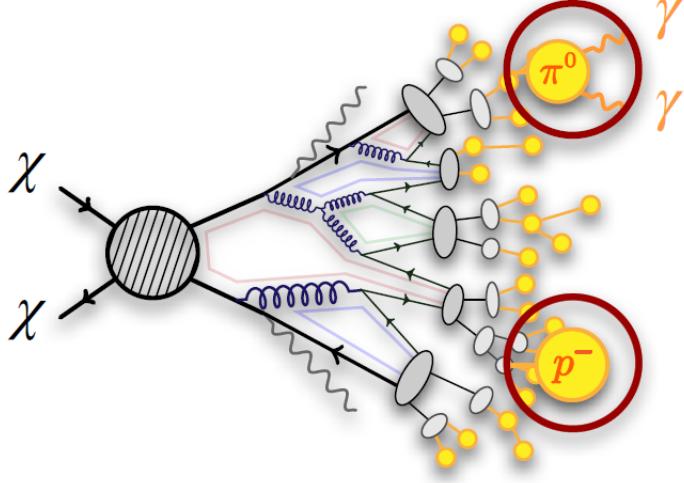


Figure 2.10 More detailed pseudo-Feynman diagram of particle cascade from dark matter annihilation into 2 quarks. The quarks hadronize and down to stable particles like  $\gamma$  or the anti-proton ( $p^-$ ). Diagram pulled from ICRC 2021 presentation on DM annihilation search [17].

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

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

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

642 interaction. For any arbitrary DM source and stable SM particle, the SM flux from DM annihilating  
 643 to a neutral particle in the SM,  $\phi$ , from a region in the sky is described by the following.

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

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

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

651 In Equation (6.1),  $\tau$  is the decay lifetime of the DM. Just as in Equation (7.1), the left and right  
 652 terms are the particle physics and the astrophysical components respectively. The integrated  
 653 astrophysical component of Equation (7.1) is often called the J-Factor. Whereas the integrated  
 654 astrophysical component of Equation (6.1) is often called the D-Factor.

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

## 662 2.5 Sources for Indirect Dark Matter Searches

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

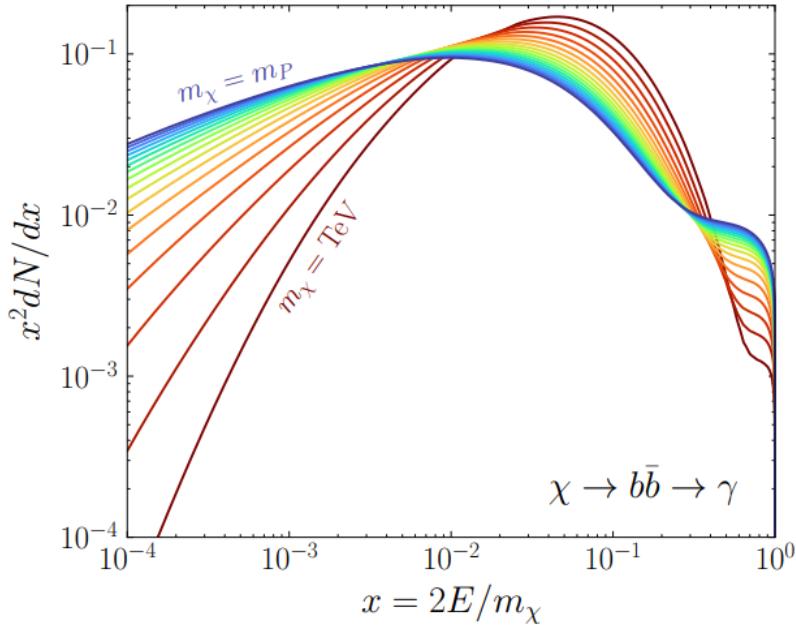


Figure 2.11 Dark Matter (DM) decay spectrum for  $b\bar{b}$  initial state and  $\gamma$  final state. Redder spectra are for larger DM masses. Bluer spectra are light DM masses.  $x$  is a unitless factor defined as the ratio of the mass of DM,  $m_\chi$ , and the final state particle energy  $E_\gamma$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

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

Searches toward Dwarf Spheroidal Galaxies (dSph's) suffer from uncertainties in the DM density less than the galactic center studies. This is mostly from their diminutive size being smaller than the angular resolution of most  $\gamma$ -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

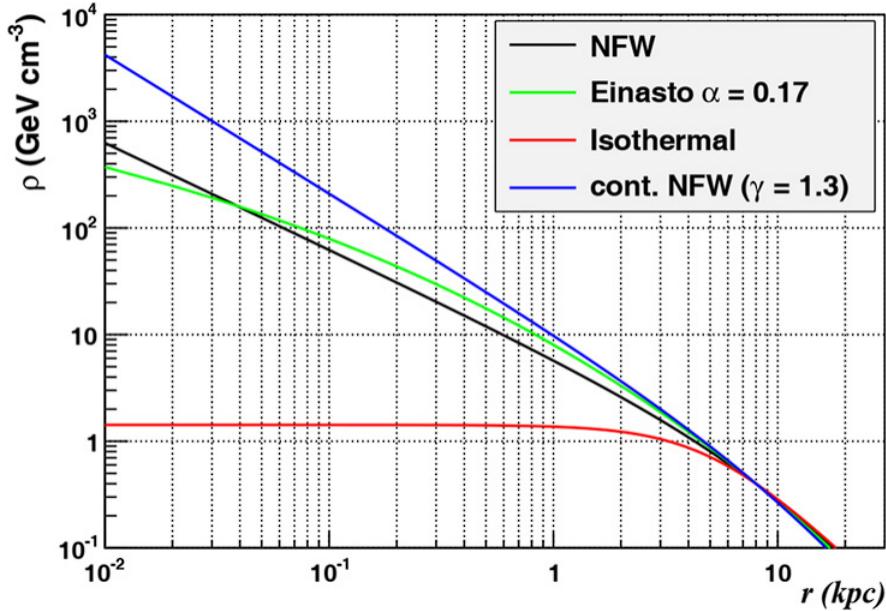


Figure 2.12 Different dark matter density profiles compared. Some models produce exceptionally large densities at small  $r$  [20].

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

## 684 2.6 Multi-Messenger Dark Matter

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

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

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

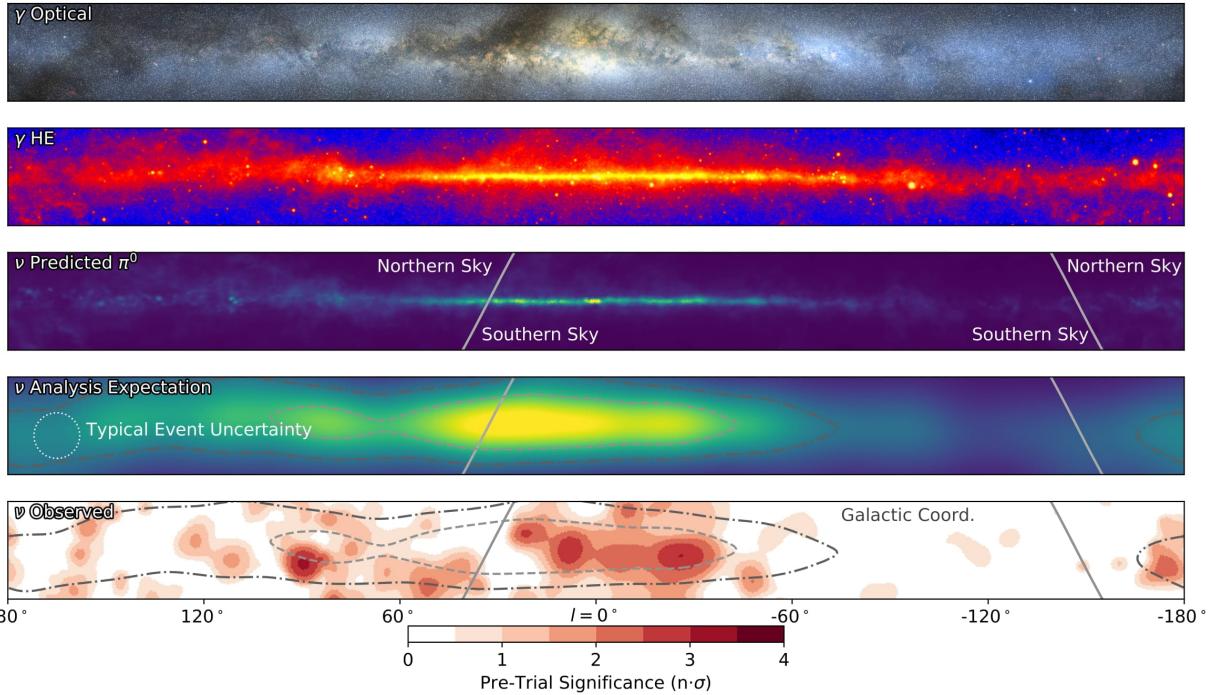


Figure 2.13 The Milky Way Galaxy in photons ( $\gamma$ ) and neutrinos ( $\nu$ ) [22]. The Galactic center is at  $l=0^\circ$  and is the brightest region in all panels. (top) An Optical color image of the Milky Way galaxy seen from Earth. Clouds of gas and dust obscure some light from stars. (2nd down)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

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

706 energy particles are produced. For example, the fit to IceCube data prefers neutrino production  
 707 from the decay of  $\pi^0$  [22].

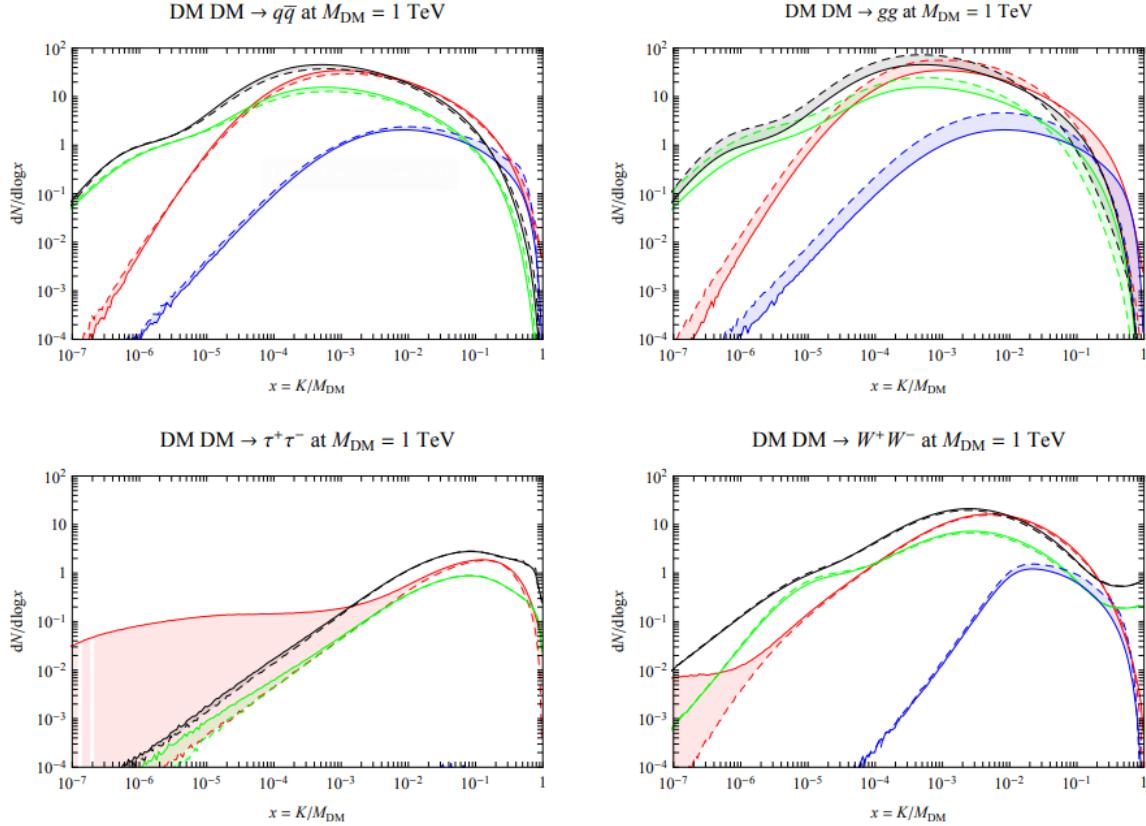


Figure 2.14 Dark Matter annihilation spectra for different final state particle and standard model annihilation channels [24]. Photons (red),  $e^\pm$  (green),  $\bar{p}$  (blue),  $\nu$  (black).

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

## CHAPTER 3

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

715   **3.1 The Detector**

716   **3.2 Events Reconstruction and Data Acquisition**

717   **3.2.1 G/H Discrimination**

718   **3.2.2 Angle**

719   **3.2.3 Energy**

720   **3.3 Remote Monitoring**

721   **3.3.1 ATHENA Database**

722   **3.3.2 HOMER**

723

## CHAPTER 4

### ICECUBE NEUTRINO OBSERVATORY

724 **4.1 The Detector**

725 **4.2 Events Reconstruction and Data Acquisition**

726 **4.2.1 Angle**

727 **4.2.2 Energy**

728 **4.3 Northern Test Site**

729 **4.3.1 PIgeon remote dark rate testing**

730 **4.3.2 Bulkhead Construction**

## CHAPTER 5

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

#### 5.1 Introduction

The field of astrophysics now has several instruments and observatories sensitive to high energy gamma-rays. The energy sensitivity for the modern gamma-ray program spans many orders of magnitude. Figure 5.1 demonstrates these similar sensitivities across energies for the five experiments: Fermi-LAT, HAWC, HESS, MAGIC, and VERITAS.

Each of the five experiments featured in Figure 5.1 have independently searched for DM annihilation from dwarf spheroidal galaxies (dSph) and set limits. Intriguingly, there are regions of substantial overlap in their energy sensitivities. This clearly motivates an analysis that combines data from these five. Each experiment has unique gamma-ray detection methods and their weaknesses and strengths can be leveraged with each other. The HAWC gamma-ray observatory is extensively introduced in chapter 3, so it is not introduced here. A brief description of the remaining experiments are in the following paragraphs.

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

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

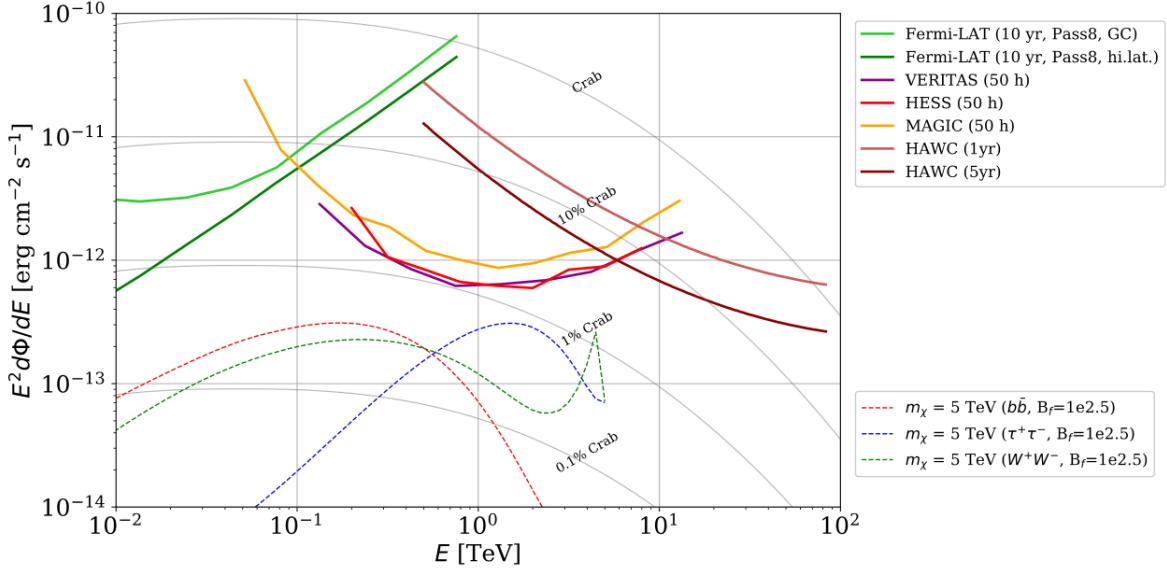


Figure 5.1 Sensitivities of five gamma-ray experiments compared to percentages of the Crab nebula’s emission and dark matter annihilation. Solid lines present estimated sensitivities to power law spectra [FACT CHECK THIS] for each experiment. Green lines are Fermi-LAT sensitivities where lighter green 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]

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

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

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

769 **5.2 Dataset and Background**

770 This section enumerates the data and background methods used for HAWC’s study of dSphs.  
771 Section 5.2.1 and Section 5.2.2 are most useful for fellow HAWC collaborators looking to replicate  
772 the Glory Duck analysis.

773 **5.2.1 Itemized HAWC files**

- 774 • Detector Resolution: `response_aerie_svn_27754_systematics_best_mc_test_no`  
775 `broadpulse\_10pctlogchargesmearing_0.63qe_25kHzNoise_run5481_curvatu`  
776 `re0_index3.root`
- 777 • Data Map: `maps-20180119/liff/maptree_1024.root`
- 778 • Spectral Dictionary: `DM_CirrelliSpectrum_dict_gammas.npy`
- 779 • Analysis wiki: [https://private.hawc-observatory.org/wiki/index.php/Glory\\_Duck\\_Multi-Experiment\\_Dark\\_Matter\\_Search](https://private.hawc-observatory.org/wiki/index.php/Glory_Duck_Multi-Experiment_Dark_Matter_Search)

781 **5.2.2 Software Tools and Development**

782 This analysis was performed using HAL and 3ML [42, 43] in Python version 2. I built software  
783 to implement the *A Poor Particle Physicist Cookbook for Dark Matter Indirect Detection* (PPPC)  
784 [44] DM spectral model and dSphs spatial model from [45] for HAWC analysis. A NumPy version  
785 of this dictionary was made for both Py2 and Py3. The code base for creating this dictionary is  
786 linked on my GitLab sandbox:

- 787 • Py2: [Dictionary Generator \(Deprecated\)](#)
- 788 • Py3: [PPPC2Dict](#)

789 The analysis was performed using the  $f_{\text{hit}}$  framework performed in the HAWC Crab paper  
790 [42]. The Python2 NumPy dictionary file for gamma-ray final states is `dmCirSpecDict.npy`. The  
791 corresponding Python3 file is `DM_CirrelliSpectrum_dict_gammas.npy`. These files can also

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

795 **5.2.3 Data Set and Background Description**

796 The HAWC data maps used for this analysis contain 1017 days of data between runs 2104  
797 (2014-11-26) and 7476 (2017-12-20). They were generated from pass 4.0 reconstruction. The  
798 analysis is performed using the  $f_{hit}$  energy binning scheme with bins (1-9) similar to what was done  
799 for the Crab and previous HAWC dSph analysis [42, 46]. Bin 0 was excluded as it has substantial  
800 hadronic contamination and poor angular resolution.

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

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

808 Therefor we make no additional assumptions on the background from our sources and use  
809 HAWC’s standard direct integration method for background estimation [42]. It is possible for  
810 gamma rays from DM annihilation to scatter in transit to HAWC via Inverse Compton Scattering  
811 (ICS). This was investigated and its impact on the flux is basically zero. Supporting information  
812 on this is in Section 5.7.1

813 **5.3 Analysis**

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

$$\frac{d\Phi_\gamma}{dE_\gamma} = \frac{\langle\sigma v\rangle}{8\pi m_\chi^2} \frac{dN_\gamma}{dE_\gamma} \times \int_{\text{source}} d\Omega \int_{l.o.s} \rho_\chi^2 dl(r, \theta') \quad (5.1)$$

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

$$J = \int d\Omega \int_{l.o.s} dl \rho_\chi^2(r, \theta') \quad (5.2)$$

819  $l$  is the distance to the source from Earth.  $r$  is the radial distance from the center of the source.  $\theta'$  is  
 820 the half angle defining a cone containing the DM source. How each component is synthesized and  
 821 considered for HAWC's analysis is presented in the following sections. Section 5.3.1 presents the  
 822 particle physics model for DM annihilation. Section 5.3.2 presents the spatial distributions built  
 823 for each dSph.

824 **5.3.1  $\frac{dN_\gamma}{dE_\gamma}$  - Particle Physics Component**

825 For these spectra, we import the PPPC with Electroweak (EW) corrections [44]. The spectrum  
 826 is implemented as a model script in astromodels for 3ML. The EW corrections were previously not  
 827 considered for HAWC and are significant for DM annihilating to EW coupled SM particles such  
 828 as all leptons, and the  $\gamma$ ,  $Z$ , and  $W$  bosons [46]. Figure 5.2 demonstrates the significance of EW  
 829 corrections for W boson annihilation. Across EW SM channels, the gamma-ray spectra become  
 830 harder than spectra without EW corrections. Tables from the PPPC were reformatted into Python  
 831 NumPy dictionaries for collaboration-wide use. A class in astromodels was developed to include  
 832 the EW correction from the PPPC and is aptly named `PPPCSpectra` within `DM_models.py`.

833 **5.3.2  $J$ - Astrophysical Component**

834 The J-factor profiles for each source are imported from Geringer-Sameth (referred to with  $\mathcal{GS}$ )  
 835 [45]. These were pulled from the publication as  $J(\theta)$ , where  $\theta$  is the angular separation from the  
 836 center of the source. HAWC requires maps in terms of  $\frac{dJ}{d\Omega}$ , so the conversion from the maps was  
 837 done in the following way...

838 First, convert the angular distances to solid angles

$$\Omega = 2 \cdot \pi(1 - \cos(\theta)) \quad (5.3)$$

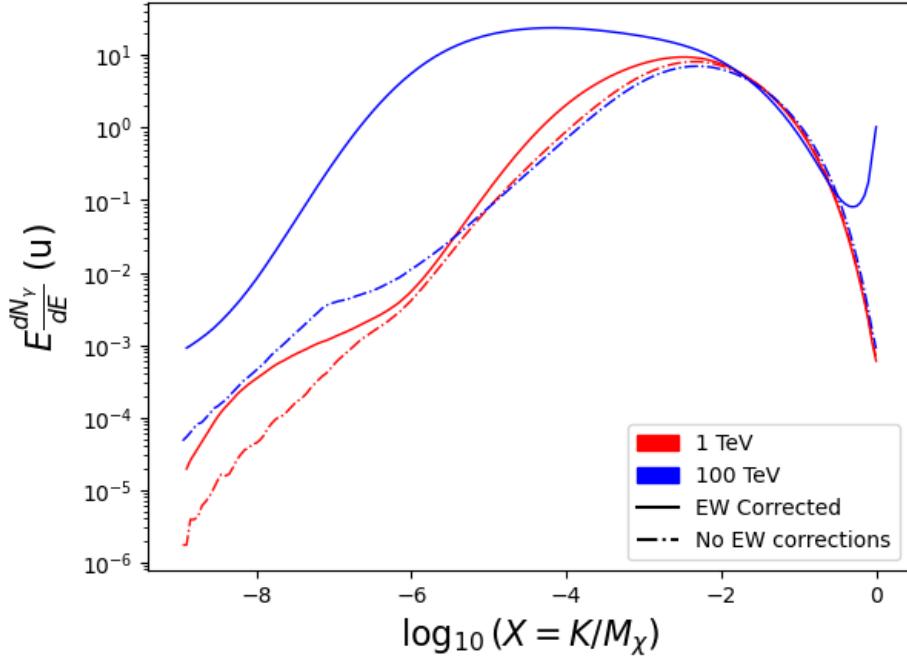


Figure 5.2 Effect of Electroweak (EW) corrections on expected DM annihilation spectrum for  $\chi\chi \rightarrow W^-W^+$ . Solid lines are spectral models that consider EW corrections. Dash-dot lines are spectral models without EW corrections. Red lines are models for  $M_\chi = 1$  TeV. Blue lines represent models for  $M_\chi = 100$  TeV. All models are sourced from the PPPC4DMID [44].

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

$$\Delta\phi_i = \phi_{i+1} - \phi_{i-1} \quad (5.4)$$

841 Where  $\phi$  is either  $\Omega$  or  $J$ . These were done separately in case the grid spacing in  $\theta$  was not uniform.  
 842 Finally, these lists are divided so that we are left with an approximation of the  $dJ/d\Omega$  profile that  
 843 is a function of  $\theta$ . Admittedly, this is an approximation method for the map which introduces small  
 844 errors compared to the true profile estimate. This was checked as a systematic against the author's  
 845 profiling of the spatial distribution and is documented in Section 5.8.1.

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

849 of bins, Newton’s integral:

$$p^2 \cdot \sum_{i,j=0}^{N,M} \frac{dJ}{d\Omega}(\theta_{i,j}, \phi_{i,j}) \quad (5.5)$$

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

851 Another DM spatial distribution model from Bonnivard ( $\mathcal{B}$ ) [47] was used for the Glory Duck  
852 study. However, to save computational time, limits from  $\mathcal{GS}$  were scaled to  $\mathcal{B}$  instead of each  
853 experiment performing a full study a second time. How these models compare is demonstrated  
854 for each dSph in Figure 5.16 and Figure 5.17 Plots of these maps are provided for each source  
855 in chapter A Examples of the two most impactful dSphs derived from  $\mathcal{GS}$ , Segue1 and Coma  
856 Berenices are featured in Figure 5.3

### 857 5.3.3 Source Selection and Annihilation Channels

858 We use many of the dSphs presented in HAWC’s previous dSph DM search [46]. HAWC’s  
859 sources for Glory Duck include Boötes I, Coma Berenices, Canes Venatici I + II, Draco, Hercules,  
860 Leo I, II, + IV, Segue 1, Sextans, and Ursa Major I + II. A full description of all sources used  
861 in Glory Duck is found in Table 5.1. Triangulum II was excluded from the Glory Duck analysis  
862 because of large uncertainties in its  $J$  factor. Ursa Minor was excluded from HAWC’s contribution  
863 to the combination because the source extension model extended Ursa Minor beyond HAWC’s field  
864 of view. Ursa Minor was not expected to contribute significantly to the combined limit, so work  
865 was not invested in a solution to include Ursa Minor.

866 This analysis improves on the previous HAWC dSph paper [46] in the following ways. Pre-  
867 viously, the dSphs were treated and implemented as point sources. For this analysis, dSphs are  
868 modeled and treated as extended source. The impact of this change with respect to the upper limit  
869 is source dependent and is explored in Section 5.7.2. Previously, the particle physics model used for  
870 gamma-ray spectra from DM annihilation did not have EW corrections where the PPPC includes  
871 them. Finally, the gamma-ray ray dataset is much larger. The study performed here analyzes over  
872 1000 days of data compared to 507.

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

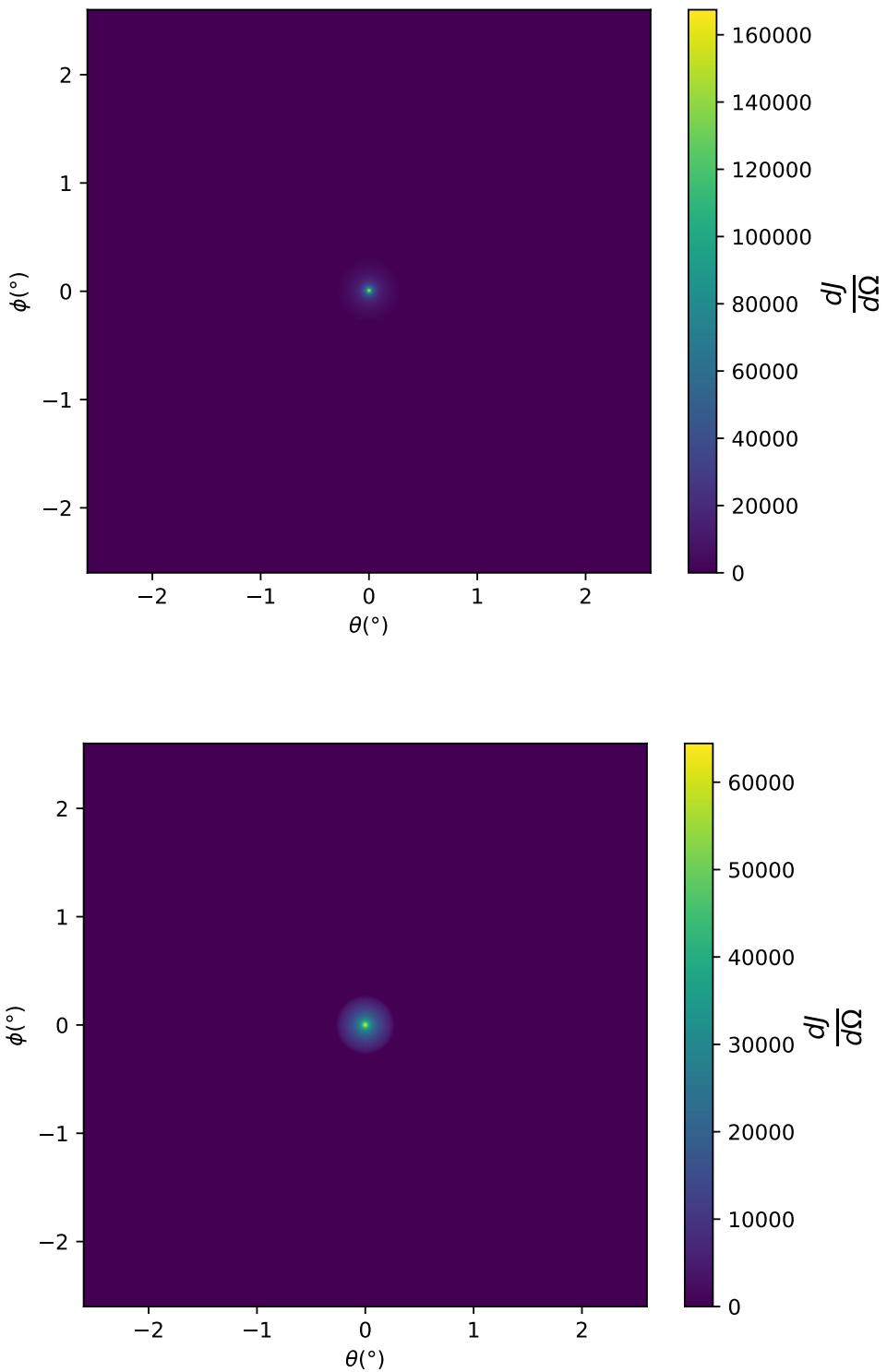


Figure 5.3  $\frac{dJ}{d\Omega}$  maps for Segue1 (top) and Coma Berenices (bottom). Origin is centered on the specific dwarf spheroidal galaxies (dSph). X and Y axes are the angular separation from the center of the dwarf. Plots of the remaining 11 dSph HAWC studied are linked in Fig. A.1.

Table 5.1 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) $\log_{10}(\text{GeV}^2 \text{cm}^{-5} \text{sr})$
<b>Boötes I</b>	66	358.08, 69.62	$18.24^{+0.40}_{-0.37}$	$18.85^{+1.10}_{-0.61}$
<b>Canes Venatici I</b>	218	74.31, 79.82	$17.44^{+0.37}_{-0.28}$	$17.63^{+0.50}_{-0.20}$
<b>Canes Venatici II</b>	160	113.58, 82.70	$17.65^{+0.45}_{-0.43}$	$18.67^{+1.54}_{-0.97}$
Carina	105	260.11, -22.22	$17.92^{+0.19}_{-0.11}$	$18.02^{+0.36}_{-0.15}$
<b>Coma Berenices</b>	44	241.89, 83.61	$19.02^{+0.37}_{-0.41}$	$20.13^{+1.56}_{-1.08}$
<b>Draco</b>	76	86.37, 34.72	$19.05^{+0.22}_{-0.21}$	$19.42^{+0.92}_{-0.47}$
Fornax	147	237.10, -65.65	$17.84^{+0.11}_{-0.06}$	$17.85^{+0.11}_{-0.08}$
<b>Hercules</b>	132	28.73, 36.87	$16.86^{+0.74}_{-0.68}$	$17.70^{+1.08}_{-0.73}$
<b>Leo I</b>	254	225.99, 49.11	$17.84^{+0.20}_{-0.16}$	$17.93^{+0.65}_{-0.25}$
<b>Leo II</b>	233	220.17, 67.23	$17.97^{+0.20}_{-0.18}$	$18.11^{+0.71}_{-0.25}$
<b>Leo IV</b>	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	$18.57^{+0.07}_{-0.05}$	$18.63^{+0.14}_{-0.08}$
<b>Segue I</b>	23	220.48, 50.43	$19.36^{+0.32}_{-0.35}$	$17.52^{+2.54}_{-2.65}$
Segue II	35	149.43, -38.14	$16.21^{+1.06}_{-0.98}$	$19.50^{+1.82}_{-1.48}$
<b>Sextans</b>	86	243.50, 42.27	$17.92^{+0.35}_{-0.29}$	$18.04^{+0.50}_{-0.28}$
<b>Ursa Major I</b>	97	159.43, 54.41	$17.87^{+0.56}_{-0.33}$	$18.84^{+0.97}_{-0.43}$
<b>Ursa Major II</b>	32	152.46, 37.44	$19.42^{+0.44}_{-0.42}$	$20.60^{+1.46}_{-0.95}$
Ursa Minor	76	104.97, 44.80	$18.95^{+0.26}_{-0.18}$	$19.08^{+0.21}_{-0.13}$

875 to the source, is provided in Table 5.2.

## 876 5.4 Likelihood Methods

### 877 5.4.1 HAWC Likelihoods

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

Table 5.2 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  $\theta$  of the signal or ON region, the ratio of exposures between the background-control (OFF) and signal (ON) regions ( $\tau$ ), and the significance of gamma-ray excess in standard deviations,  $\sigma$ .

Source name	Fermi-LAT	HAWC	H.E.S.S, MAGIC, VERITAS						
	Exposure ( $10^{11}$ s m $^2$ )	$ \Delta\theta $ (°)	IACT	Zenith (°)	Exposure (h)	Energy range (GeV)	$\theta$ (°)	$\tau$	$S$ ( $\sigma$ )
Boötes I	2.6	4.5	VERITAS	15 – 30	14.0	100–41000	0.10	8.6	-1.0
Canes Venatici I	2.9	14.6	–	–	–	–	–	–	–
Canes Venatici II	2.9	15.3	–	–	–	–	–	–	–
Carina	3.1	–	H.E.S.S.	27 – 46	23.7	310 – 70000	0.10	18.0	-0.3
Coma Berenices	2.7	4.9	H.E.S.S.	47 – 49	11.4	550 – 70000	0.10	14.4	-0.4
			MAGIC	5 – 37	49.5	60 – 10000	0.17	1.0	–
			MAGIC	29 – 45	52.1	70 – 10000	0.22	1.0	–
Draco	3.8	38.1	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

880  $S$ , is estimated by convolving Equation (7.1) with HAWC's energy response and pixel point spread  
 882 functions. I then compute the test statistic (TS) with the log-likelihood ratio test,

$$\text{TS} = -2 \ln \left( \frac{\mathcal{L}_0}{\mathcal{L}^{\max}} \right) \quad (5.6)$$

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

$$\mathcal{L} = \prod_i \frac{(B_i + S_i)^{N_i} e^{-(B_i + S_i)}}{N_i!} \quad (5.7)$$

886 where  $S_i$  is the sum of expected number of signal counts.  $B_i$  is the number of background counts  
 887 observed.  $N_i$  is the total number of counts.

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

$$\text{TS}_{95} \equiv \sum_{\text{bins}} \left[ 2N \ln \left( 1 + \frac{\epsilon S_{\text{ref}}}{B} \right) - 2\epsilon S_{\text{ref}} \right] \quad (5.8)$$

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

$$2.71 = \text{TS}_{\max} - \text{TS}_{95} \quad (5.9)$$

### 893 5.4.2 Glory Duck Joint Likelihood

894 The joint likelihood for the 5-experiment combination was done similarly as Section 5.4.1. We  
 895 calculate upper limits on  $\langle \sigma v \rangle$  from the TS, Eq. (5.6), and define the likelihood ratio more generally

$$\lambda(\langle \sigma v \rangle | \mathcal{D}_{\text{dSphs}}) = \frac{\mathcal{L}(\langle \sigma v \rangle; \hat{\nu} | \mathcal{D}_{\text{dSphs}})}{\mathcal{L}(\widehat{\langle \sigma v \rangle}; \hat{\nu} | \mathcal{D}_{\text{dSphs}})} \quad (5.10)$$

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

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

$$\mathcal{L}(\langle\sigma v\rangle; \nu | \mathcal{D}_{\text{dSphs}}) = \prod_{l=1}^{N_{\text{dSphs}}} \mathcal{L}_{\text{dSph},l}(\langle\sigma v\rangle; J_l, \nu_l | \mathcal{D}_l) \times \mathcal{J}_l(J_l | J_{l,\text{obs}}, \sigma_{\log J_l}). \quad (5.11)$$

901   For this study,  $N_{\text{dSphs}} = 20$  is the number of dSphs studied.  $\mathcal{D}_l$  are the gamma-ray observations  
902   of dSph,  $l$ .  $\nu_l$  are the nuisance parameters modifying the gamma-ray observations of dSph,  $l$ ,  
903   but excludes  $\mathcal{J}_l$ .  $\mathcal{J}_l$  is the  $J$  factor for dSph,  $l$ , as defined in Equation (5.2), and it is a nuisance  
904   parameter whose value is unknown.  $\log_{10} J_{l,\text{obs}}$  and  $\sigma_{\log J_l}$  are obtained from fitting a log-normal  
905   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  
906   in Table 5.1. The term  $\mathcal{J}_l$  constraining  $J_l$  is written as:

$$\mathcal{J}_l(J_l | J_{l,\text{obs}}, \sigma_{\log J_l}) = \frac{1}{\ln(10)J_{l,\text{obs}}\sqrt{2\pi}\sigma_{\log J_l}} \exp\left(-\frac{(\log_{10} J_l - \log_{10} J_{l,\text{obs}})^2}{2\sigma_{\log J_l}^2}\right). \quad (5.12)$$

907   Both the  $\mathcal{GS}$  and  $\mathcal{B}$ , displayed in Table 5.1, sets of  $J$  factors are used in this analysis. Equation (5.12)  
908   is also normalized, so it can also be interpreted as a probability density function (PDF) for  $J_{l,\text{obs}}$ .  
909   From Equation (7.1), we can also see that  $\langle\sigma v\rangle$  and  $J_l$  are degenerate when computing  $\mathcal{L}_{\text{dSph},l}$ .  
910   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  $J_l$ .  
911   We used  $J_{l,\text{obs}}(\mathcal{GS})$  reported in Tab. 5.1, in order to perform the profile of  $\mathcal{L}$  with respect to  $J_l$ .  
912   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  
913   compute results from a different set of  $J$  factors):

$$\mathcal{L}_{\text{dSph},l}(\langle\sigma v\rangle; J'_l, \nu_l | \mathcal{D}_l) = \mathcal{L}_{\text{dSph},l}\left(\frac{J'_l}{J_{l,\text{obs}}}\langle\sigma v\rangle; J_{l,\text{obs}}, \nu_l | \mathcal{D}_l\right), \quad (5.13)$$

914   which is a straightforward rescaling operation that reduces the computational needs of the profiling  
915   operation since:

$$\mathcal{L}(\langle\sigma v\rangle; \hat{\nu} | \mathcal{D}_{\text{dSphs}}) = \prod_{l=1}^{N_{\text{dSphs}}} \max_{J_l} \left[ \mathcal{L}_{\text{dSph},l}(\langle\sigma v\rangle; J_l, \hat{\nu}_l | \mathcal{D}_l) \times \mathcal{J}_l(J_l | J_{l,\text{obs}}, \sigma_{\log J_l}) \right]. \quad (5.14)$$

916   In addition, Eq. (5.13) enables the combination of data from different gamma-ray instruments and  
917   observed dSphs via tabulated values of  $\mathcal{L}_{\text{dSph},l}$ , or equivalently of  $\lambda$  from Eq. (5.10) as was done in

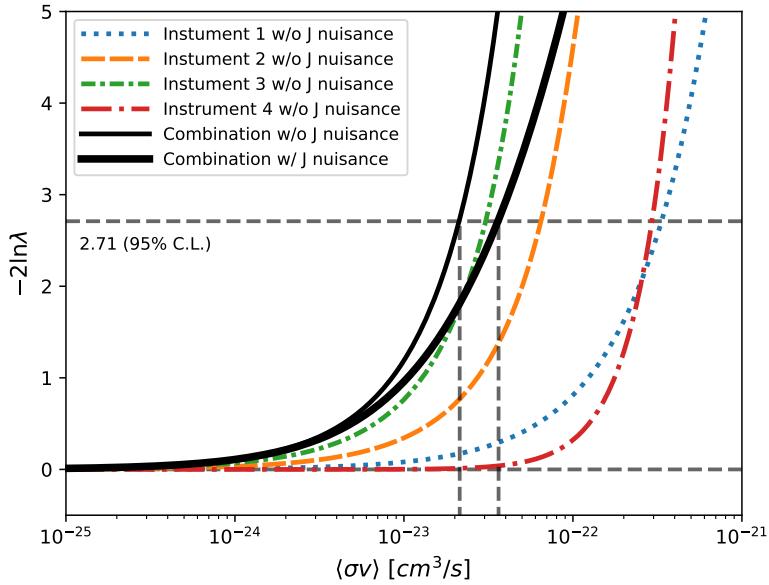


Figure 5.4 Illustration of the combination technique showing a comparison between  $-2 \ln \lambda$  provided by four instruments (colored lines) from the observation of the same dSph without any  $J$  nuisance and their sum, *i.e.* the resulting combined likelihood (thin black line). According to the test statistics of Equation (5.6), 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.

918 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  
 919 instrumental nuisance parameters  $\nu_l$ , these nuisance parameters are discussed in more detail below.  
 920 These values are produced by each detector independently and therefore there is no need to share  
 921 sensitive low-level information used to produce them, such as event lists. Figure 5.4 illustrates the  
 922 multi-instrument combination technique used in this study with a comparison of the upper limit  
 923 on  $\langle \sigma v \rangle$  obtained from the combination of the observations of four experiments towards one dSph  
 924 versus the upper limit from individual instruments. It also shows graphically the effect of the  
 925  $J$ -factor uncertainty on the combined observations.

926 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:

$$\mathcal{L}_{\text{dSph},l} (\langle \sigma v \rangle; J_l, \nu_l | \mathcal{D}_l) = \prod_{k=1}^{N_{\text{exp},l}} \mathcal{L}_{lk} (\langle \sigma v \rangle; J_l, \nu_{lk} | \mathcal{D}_{lk}), \quad (5.15)$$

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 5.2.

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 5.4.1 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. (5.15)) for a fixed value of  $J_l$  and profile over the rest of the nuisance parameters  $\nu_{lk}$ . Then, values of  $\lambda$  from Eq. (5.10) 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  $m_\chi$  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 (5.11), and profile over the  $J$ -factor to compute the profile likelihood ratio  $\lambda$ , Equation (5.10), 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 (5.10) 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:

$$\mathcal{L}_{lk} (\langle \sigma v \rangle; J_l, \nu_{lk} | \mathcal{D}_{lk}) = \prod_{i=1}^{N_E} \prod_{j=1}^{N_P} \left[ \mathcal{P}(s_{lk,ij}(\langle \sigma v \rangle, J_l, \nu_{lk}) + b_{lk,ij}(\nu_{lk}) | N_{lk,ij}) \right] \times \mathcal{L}_{lk,\nu} (\nu_{lk} | \mathcal{D}_{\nu_{lk}}) \quad (5.16)$$

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  $N_{lk,ij}$

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

$$s_{ij}(\langle\sigma\nu\rangle, J) = \int_{E'_{\min,i}}^{E'_{\max,i}} dE' \int_{P'_{\min,j}}^{P'_{\max,j}} d\Omega' \int_0^\infty dE \int_{\Delta\Omega_{tot}} d\Omega \int_0^{T_{\text{obs}}} dt \frac{d^2\Phi(\langle\sigma\nu\rangle, J)}{dEd\Omega} \text{IRF}(E', P' | E, P, t) \quad (5.17)$$

955 where  $E'$  and  $E$  are the reconstructed and true energies,  $P'$  and  $P$  the reconstructed and true  
 956 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  
 957 energy bin and the  $j$ -th arrival direction bin;  $T_{\text{obs}}$  is the (dead-time corrected) total observation  
 958 time;  $t$  is the time along the observations;  $d^2\Phi/dEd\Omega$  is the DM flux in the source region (see  
 959 Equation (7.1)); and  $\text{IRF}(E', P' | E, P, t)$  is the IRF, which can be factorized as the product of the  
 960 effective collection area of the detector  $A_{\text{eff}}(E, P, t)$ , the PDFs for the energy estimator  $f_E(E' | E, t)$ ,  
 961 and arrival direction  $f_P(P' | E, P, t)$  estimators. Note that for Fermi-LAT, HAWC, MAGIC, and  
 962 VERITAS the effect of the finite angular resolution is taken into account through the convolution  
 963 of  $d\Phi/dEd\Omega$  with  $f_P$  in Equation (5.17), whereas in the cases of H.E.S.S.  $f_P$  is approximated by a  
 964 delta function. This approximation has been made in order to maintain compatibility of the result  
 965 with what has been previously published. The difference introduced by this approximation is  $< 5\%$   
 966 for all considered dSphs. A more comprehensive review of the differences between the analyses of  
 967 different instruments can be found in [25].

## 968 5.5 HAWC Results

969 13 of the 20 dSphs considered for the Glory Duck analysis are within HAWC's field of view.  
 970 These dSph are analyzed for emission from DM annihilation according to the likelihood method  
 971 described in Section 5.4. The 13 likelihood profiles are then stacked to synthesize a combined  
 972 limit on the dark matter cross-section,  $\langle\sigma\nu\rangle$ . This combination is done for the 7 SM annihilation  
 973 channels used in the Glory Duck analysis. Figure 5.5 shows the combined limit for all annihilation  
 974 channels with HAWC only observations. We also perform 300 studies of Poisson trials on the

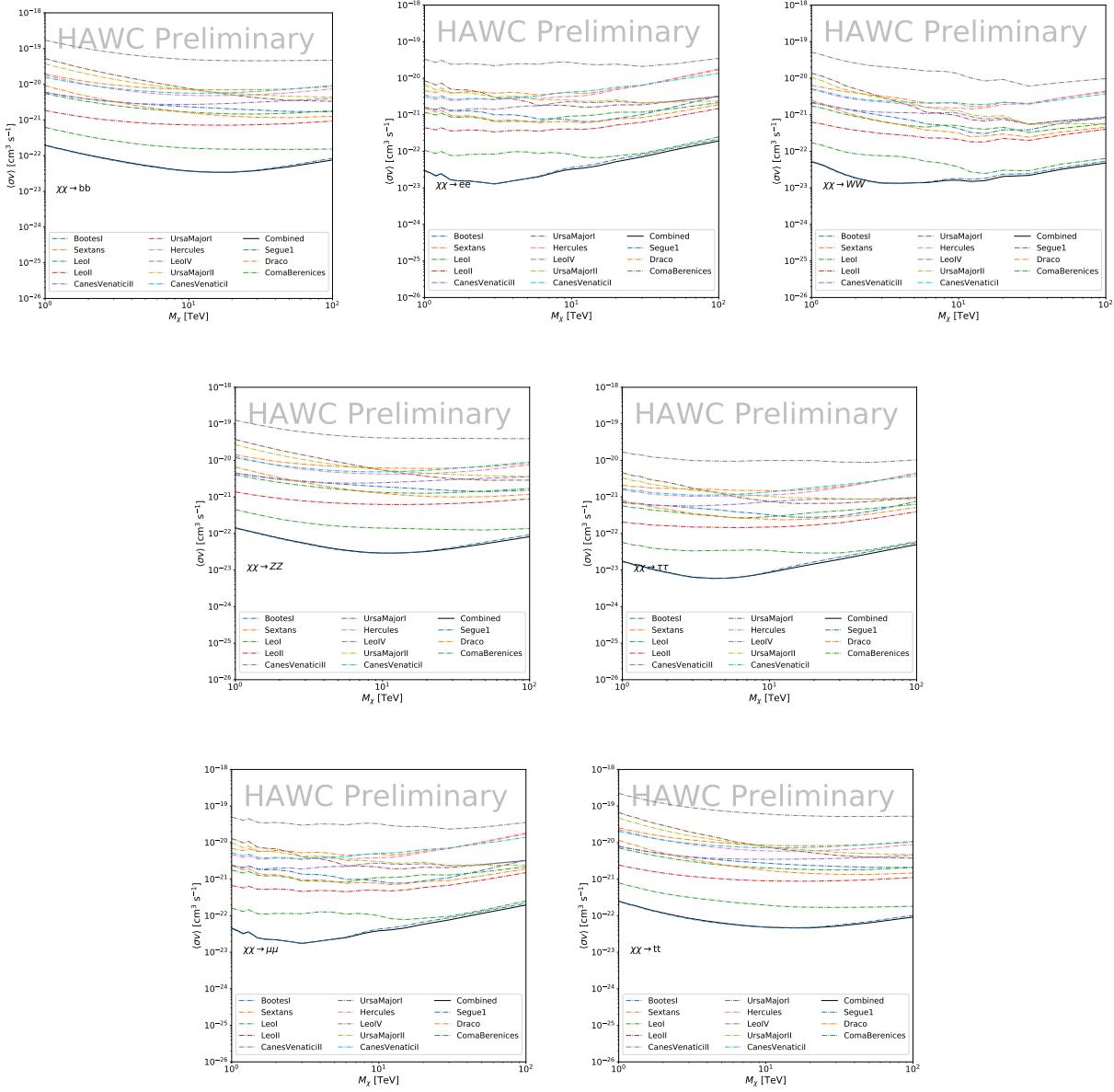


Figure 5.5

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 5.7 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 and Coma Berenices. The remaining 11 dSphs do not contribute significantly to the limit because

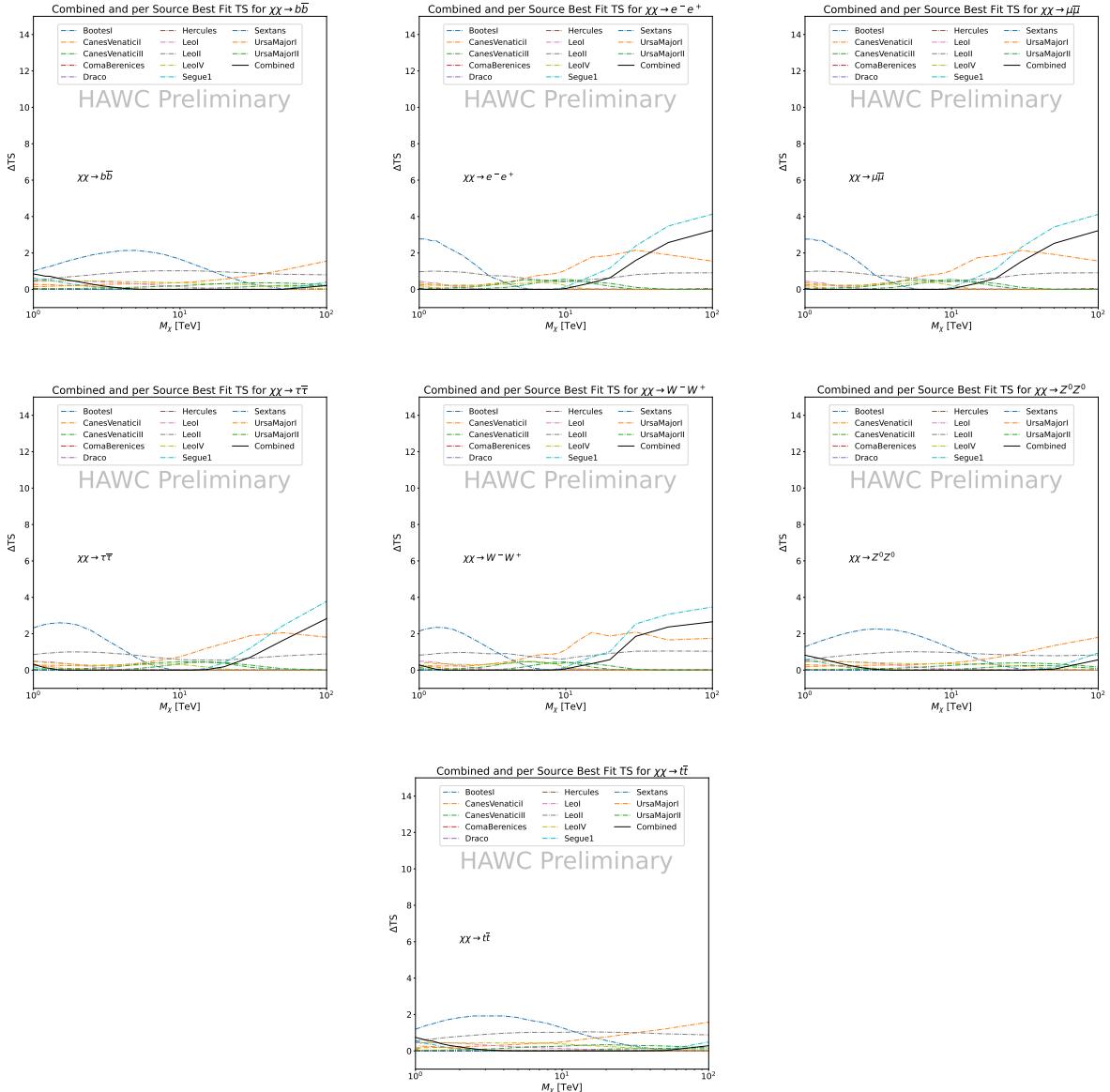


Figure 5.6 HAWC TS values for best fit  $\langle\sigma v\rangle$  versus  $m_\chi$  for seven SM annihilation channels with  $J$  factors from  $\mathcal{GS}$ . The solid black line shows the combined best fit TS values. The colored, dashed lines are the TS values for each of the 13 sources HAWC studied.

981 they are at high zenith and/or have much smaller  $J$  factors. Even though some remaining dSphs  
 982 have large  $J$  factors, they are towards the edge of HAWC's field of view where HAWC analysis is  
 983 less sensitive.

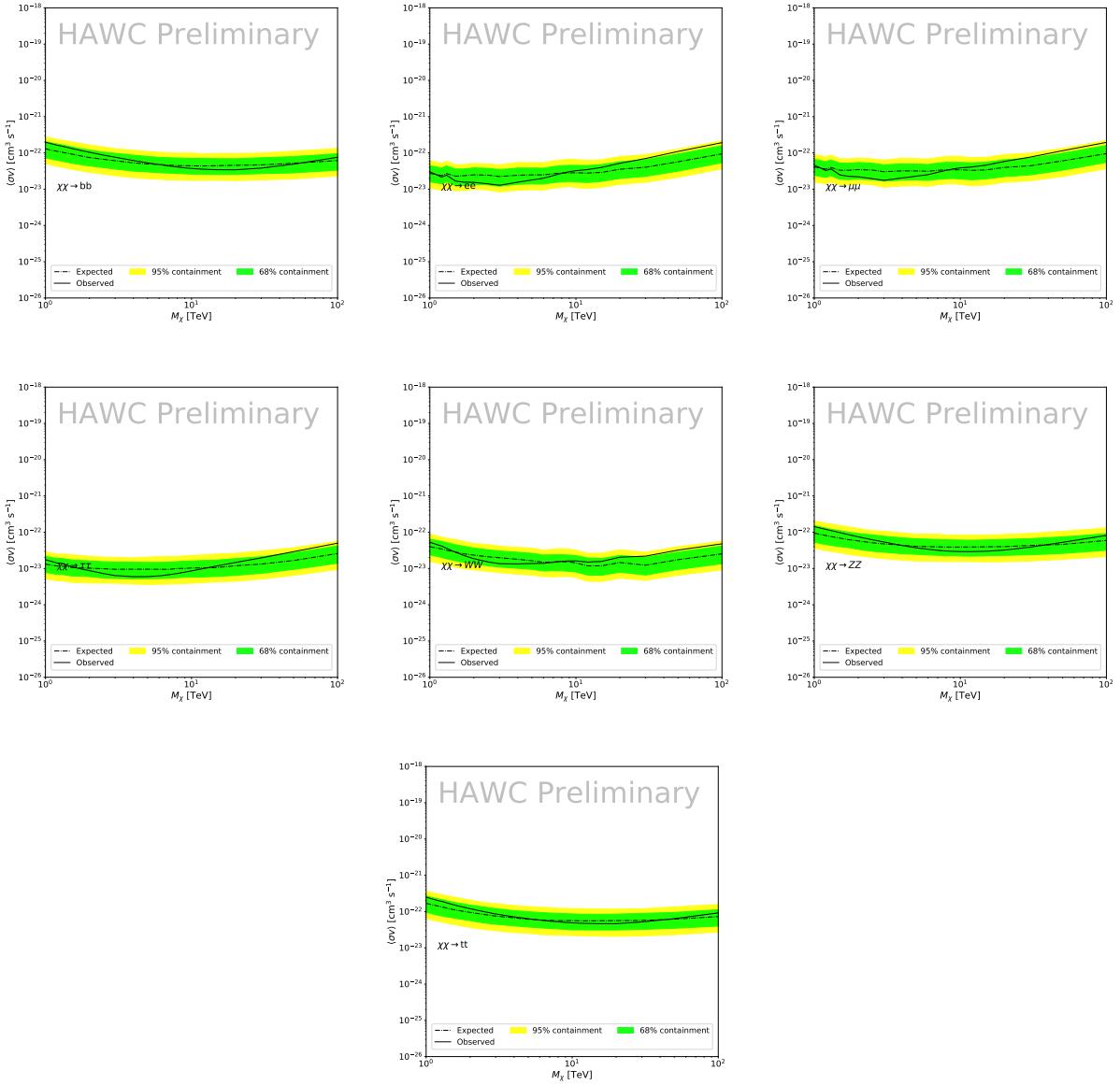


Figure 5.7 HAWC Brazil bands at 95% confidence level on  $\langle\sigma v\rangle$  versus DM mass for seven annihilation channels with  $J$ -factors from  $\mathcal{GS}$  [53]. The solid line represents the combined limit from 13 dSphs. The dashed line is the expected limit. The green band is the 68% containment. The yellow band is the 95% containment.

## 984 5.6 Glory Duck Combined Results

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

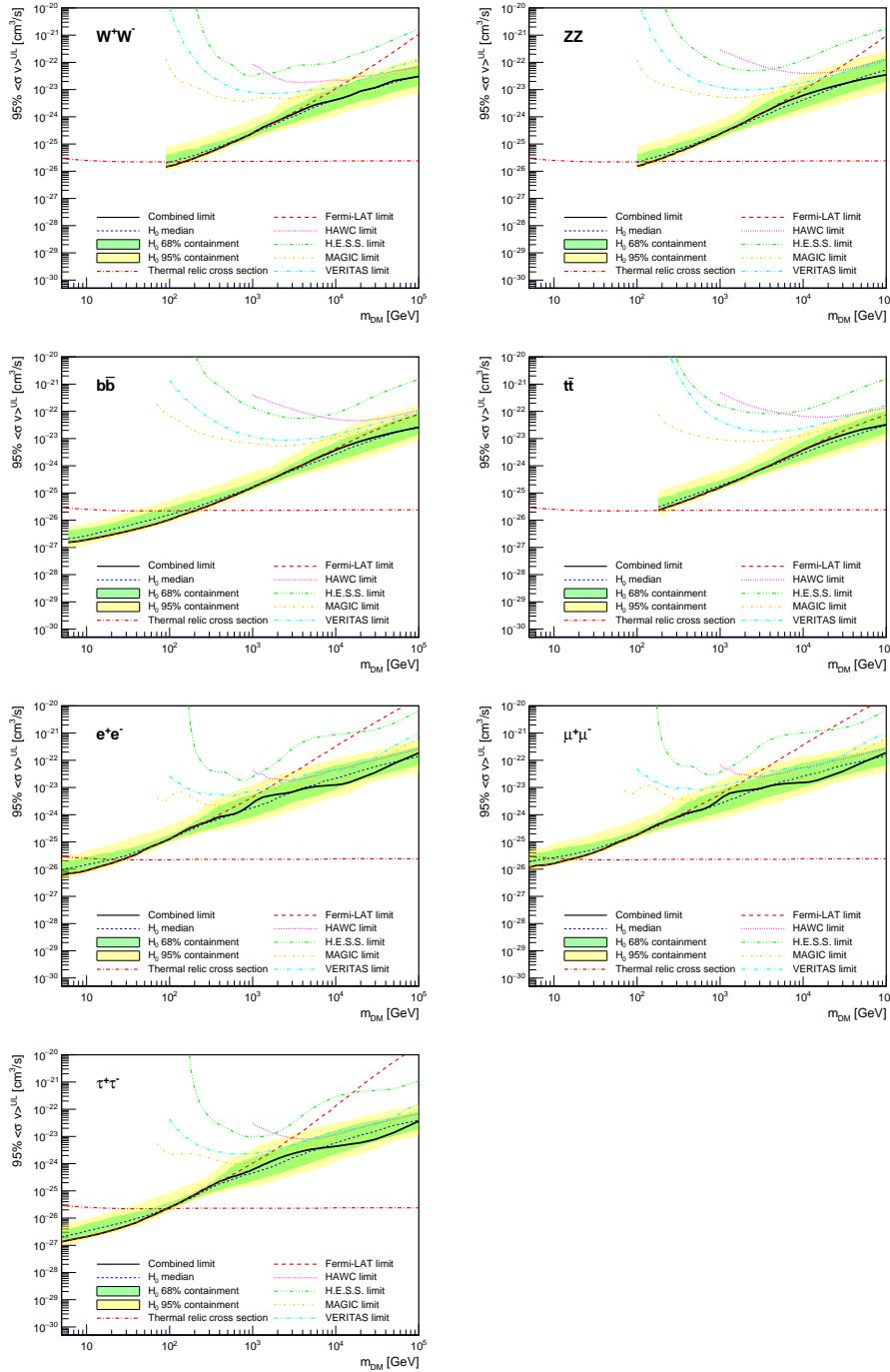


Figure 5.8 Upper limits at 95% confidence level on  $\langle\sigma v\rangle$  in function of the DM mass for eight annihilation channels, using the set of  $J$  factors from Ref. [53] ( $\mathcal{GS}$  set in Table 5.1). The black solid line represents the observed combined limit, the black dashed line 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].

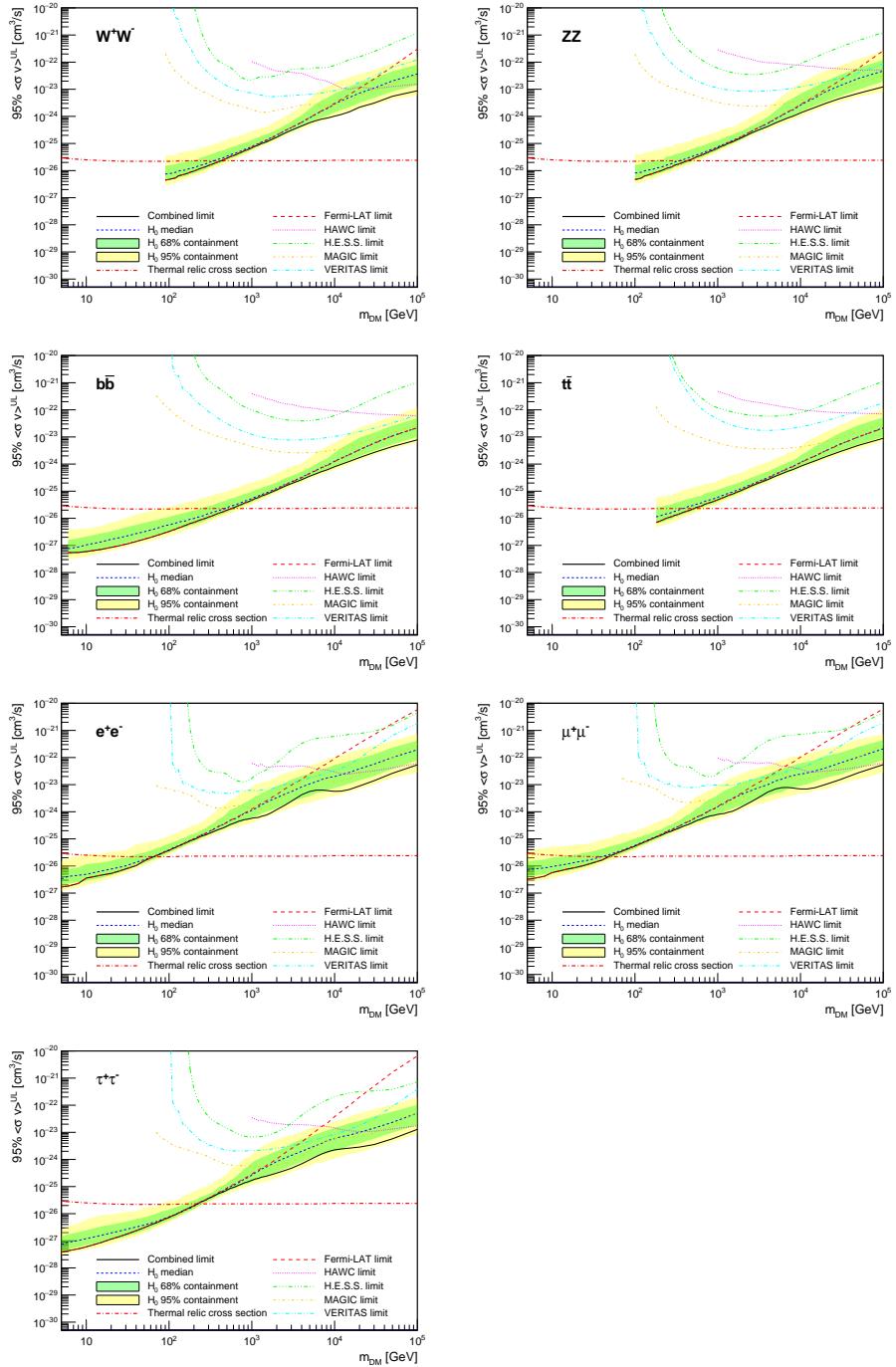


Figure 5.9 Same as Fig. 5.8, using the set of  $J$  factors from Ref. [47, 55] ( $\mathcal{B}$  set in Table 5.1).

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-

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

995 The obtained limits are shown in Figure 5.8 for the  $\mathcal{G}\mathcal{S}$  set of  $J$ -factors [53] and in Figure 5.9  
996 for the  $\mathcal{B}$  set of  $J$ -factors [47, 55]. The combined limits are presented with their 68% and 95%  
997 containment bands, and are expected to be close to the median limit when no signal is present.  
998 We observe agreement with the null hypothesis for all channels, within  $2\sigma$  standard deviations,  
999 between the observed limits and the expectations given by the median limits. Limits obtained from  
1000 each detector are also indicated in the figures, where limits for all dSphs observed by the specific  
1001 instrument have been combined.

1002 Below  $\sim 300$  GeV, the *Fermi*-LAT dominates the DM limits for all annihilation channels. From  
1003  $\sim 300$  GeV to  $\sim 2$  TeV, *Fermi*-LAT continues to dominate for the hadronic and bosonic DM channels,  
1004 yet the IACTs (H.E.S.S., MAGIC, and VERITAS) and *Fermi*-LAT all contribute to the limit for  
1005 leptonic DM channels. For DM masses between  $\sim 2$  TeV to  $\sim 10$  TeV, the IACTs dominate leptonic  
1006 DM annihilation channels, whereas both the *Fermi*-LAT and the IACTs dominate bosonic and  
1007 hadronic DM annihilation channels. From  $\sim 10$  TeV to  $\sim 100$  TeV, both the IACTs and HAWC  
1008 contribute significantly to the leptonic DM limit. For hadronic and bosonic DM, the IACTs and  
1009 *Fermi*-LAT both contribute strongly.

1010 We notice that the limits computed using the  $\mathcal{B}$  set of  $J$ -factor are always better compared to the  
1011 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  
1012 limits computed with the two sets of  $J$ -factor is varying between a factor of  $\sim 3$  and  $\sim 5$  depending  
1013 on the energy, with the largest ratio around 10 TeV. For the channels  $e^+e^-$ ,  $\mu^+\mu^-$ , and  $\tau^+\tau^-$ , the  
1014 ratio lies between  $\sim 2$  to  $\sim 6$ , being maximum around 1 TeV. Examining Figure 5.16 and Figure 5.17  
1015 in Section 5.8, these differences are explained by the fact that the  $\mathcal{B}$  set provides higher  $J$ -factors  
1016 for the majority of the studied dSphs, with the notable exception of Segue I. The variation on the  
1017 ratio of the limits for the two sets is due to different dSph dominating the limits depending on the  
1018 energy. This pushes the range of thermal cross-section which can be excluded to higher mass. This  
1019 comparison demonstrates the magnitude of systematic uncertainties associated with the choice of

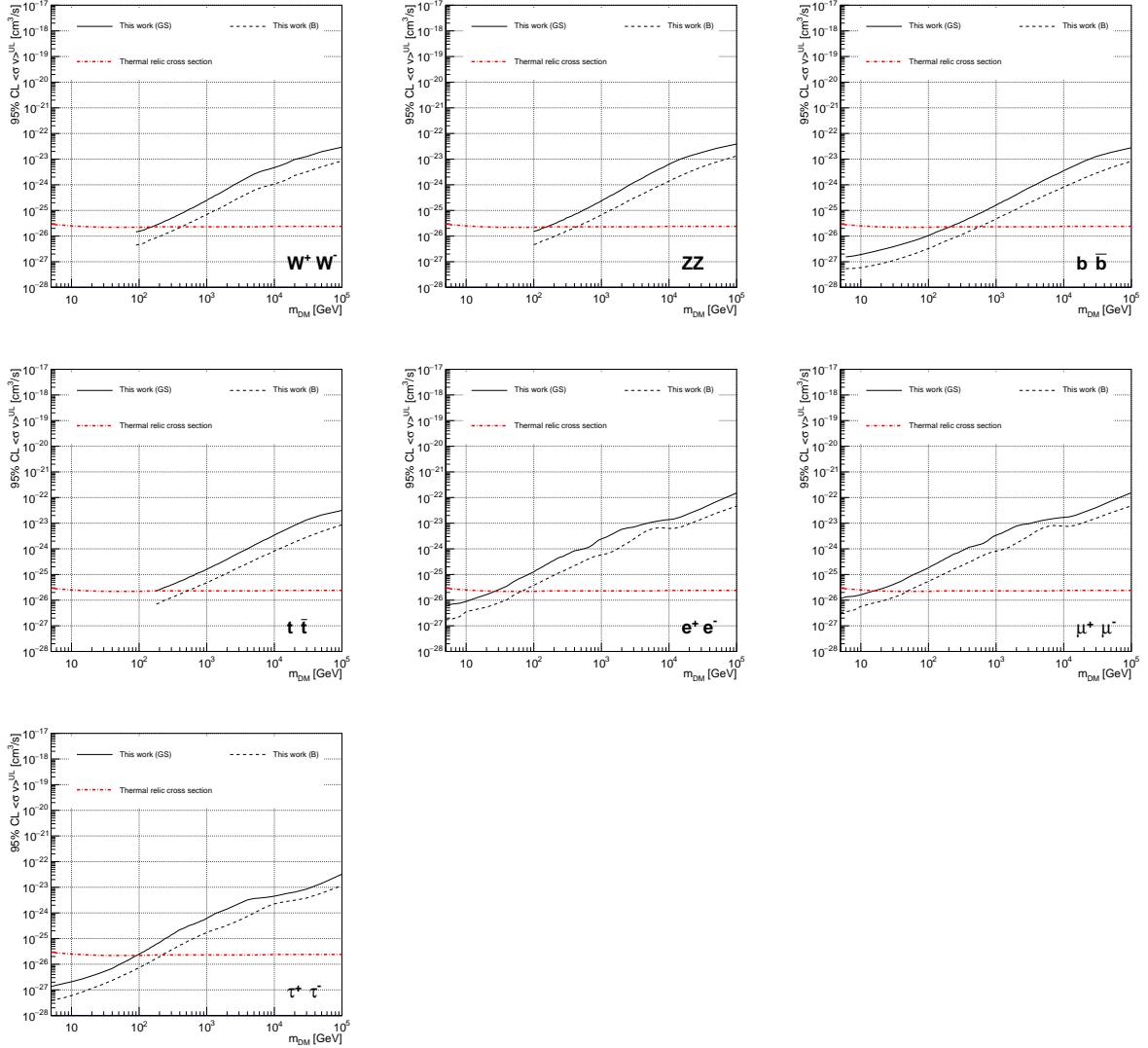


Figure 5.10 Comparisons of the combined limits at 95% confidence level for each of the eight annihilation channels when using the  $J$  factors from Ref. [53] ( $\mathcal{GS}$  set in Table 5.1), plain lines, and the  $J$  factor from Ref. [47, 55] ( $\mathcal{B}$  set in Table 5.1), dashed lines. The cross-section given by the thermal relic is also indicated [54].

1020 the  $J$ -factor

1021 This comparison demonstrates the magnitude of systematic uncertainties associated with the  
1022 choice of the  $J$ -factor calculation. The  $\mathcal{GS}$  and  $\mathcal{B}$  sets present a difference in the limits for all  
1023 channels of about This difference is explained, see Figure 5.16 and Figure 5.17 in Appendix, by the  
1024 fact that the  $\mathcal{B}$  set provides higher  $J$  factors for all dSph except for Segue I. This pushes the range  
1025 of thermal cross-section which can be excluded to higher mass.

1026 **5.7 HAWC Systematics**

1027 **5.7.1 Inverse Compton Scattering**

1028     The DM-DM annihilation channels produce many high energy electrons regardless of the  
1029     primary annihilation channel. These high energy electrons can produce high energy gamma-rays  
1030     through Inverse Compton Scattering (ICS). If this effect is strong, it would change the morphology  
1031     of the source and increase the total expected gamma-ray counts from any source. The PPPC [44]  
1032     provides tools in Mathematica for calculating the impact of ICS for an arbitrary location in the  
1033     sky for a specified annihilation channel. We calculated the change in gamma-ray counts for DM  
1034     annihilation to primary  $e\bar{e}$  for RA and Dec corresponding to Segue1 and Coma Berenices. These  
1035     dSphs were chosen because they are the strongest contributors to the limit.  $e\bar{e}$  was selected because  
1036     it would have the largest number of high energy electrons. The effect was found to be on the order  
1037     of  $10^{-7}$  on the gamma-ray spectrum. As a result, this systematic is not considered in our analysis.

1038 **5.7.2 Point Source Versus Extended Source Limits**

1039     The previous DM search toward dSph approximated the dSphs as point sources [46]. In  
1040     this analysis, the dSphs are implemented as extended with J-factor distributions following those  
1041     produced by [53]. The resolution of the cited map is much finer than HAWC's angular resolution.  
1042     The vast majority of the J-factor distribution is represented on the central HAWC pixel of the dSph  
1043     spatial map. However, the neighboring 8 pixels are not negligible and contribute to our limit.

1044     Figure 5.11 shows a substantial improvement to the limit for Segue1. Fig. 5.12 however showed  
1045     identical limits. These disparities are best explained by the relative difference in their J-Factors.  
1046     Both dSphs pass almost overhead the HAWC detector, however Segue1 has the larger J-Factor  
1047     between the two. Adjacent pixels to the central pixel will therefore contribute to the limits. This is  
1048     the case for other dSph that are closer to overhead the HAWC detector.

1049     Comparison plots for all sources and the combined limit can be found in the sandbox for the  
1050     Glory Duck project.

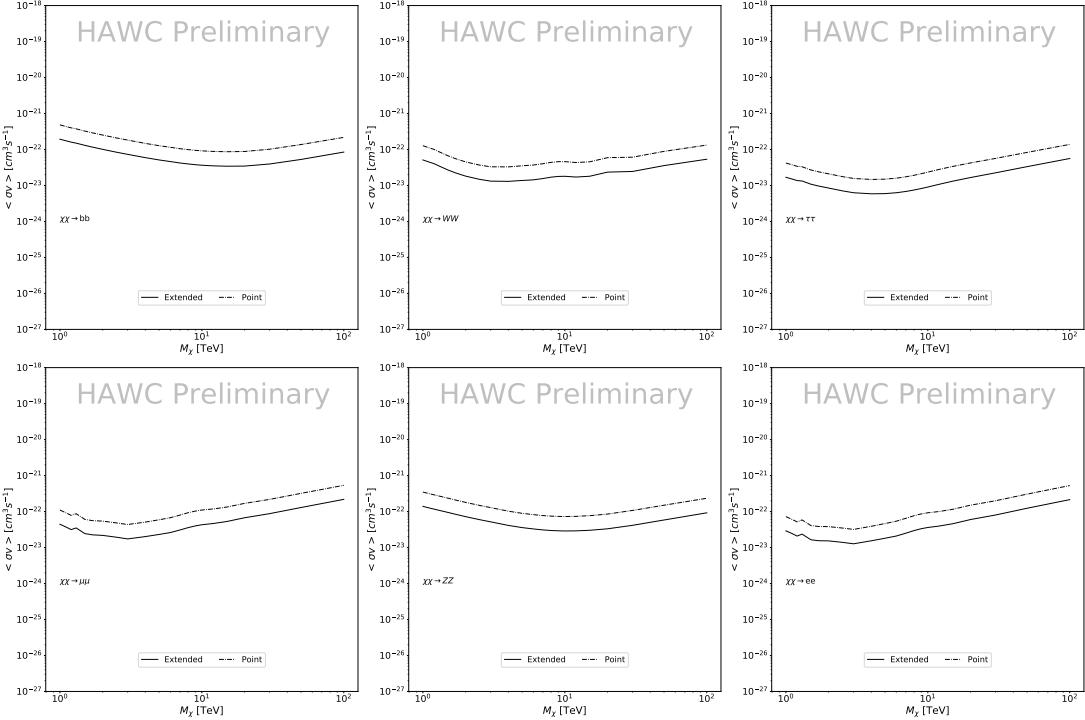


Figure 5.11 Comparisons of the combined limits at 95% confidence level for a point source analysis and extended source using [53]  $\mathcal{GS}$  J-factor distributions and PPPC [44] annihilation spectra. Shown are the limits for Segue1 which will have the most significant impact on the combined limit. 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.

### 1051 5.7.3 Impact of Pointing Systematic

1052 During the analysis it was discovered that reconstruction of gamma-rays. Slides describing this  
 1053 systematic can be found [here](#). Shown on the presentation is dependence on the pointing systematic  
 1054 on declination. New spatial profiles were generated for every dSph and limits were computed for  
 1055 the adjusted declination.

1056 Section 5.7.3 demonstrates the impact of this systematic for all DM annihilation channels  
 1057 studied by HAWC. The impact is a tiny improvement, yet mostly identical, to the combined limits.

## 1058 5.8 J-factor distributions

### 1059 5.8.1 Numerical integration of $\mathcal{GS}$ maps

1060 It was discovered well after the HAWC analysis was completed that the published tables from  
 1061  $\mathcal{GS}$  [45] quoted median J-factors were computed in a non-trivial manner. The assumption myself

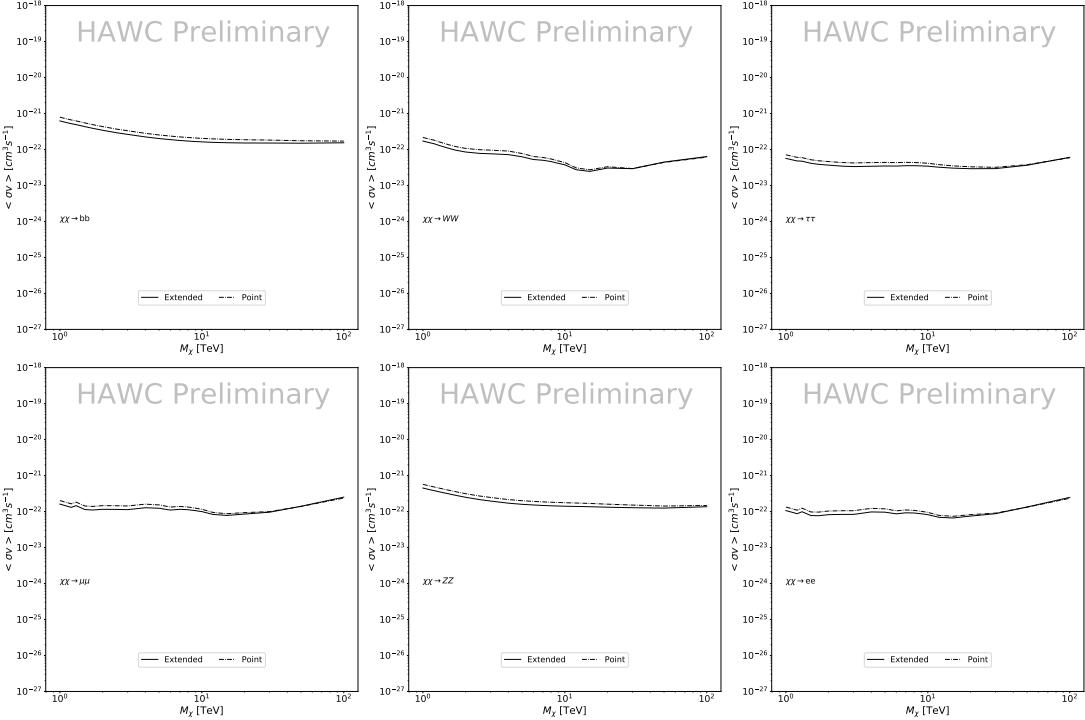


Figure 5.12 Same as Fig. 5.11 on Coma Berenices. This dSph also contributes significantly to the limit. The limits are identical in this case.

and collaborators had been that the published tables represented the  $J$ -factor as a function of  $\theta$  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  $\theta$ . Therefore, the model is changing for each value of  $\theta$  for each dwarf. Yet, the introduced features from unique models at each  $\theta$  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 5.14 shows the differential between maps generated with the method from Section 5.8.1 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 5.15

From Figure 5.15, 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 5.10.

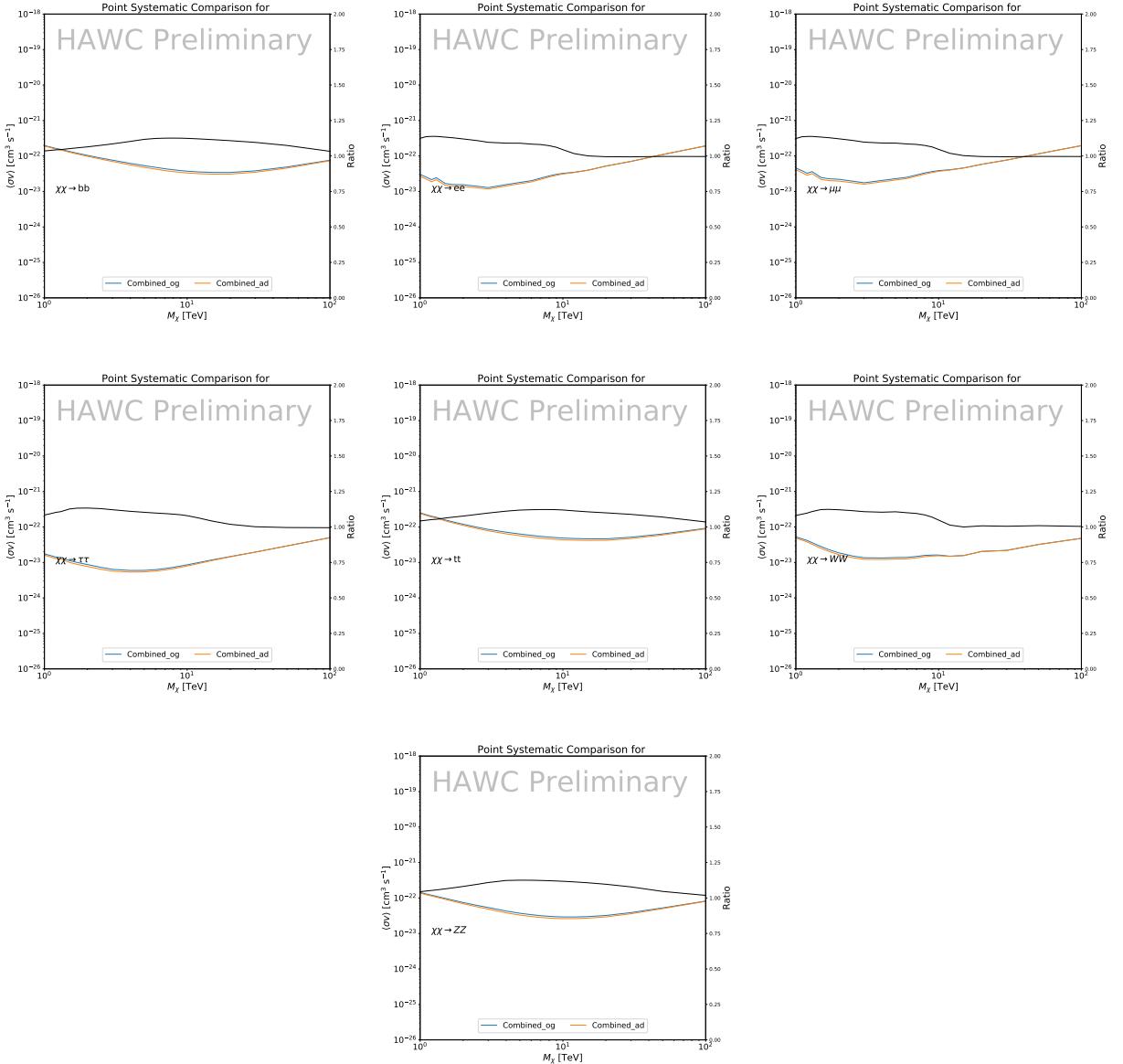


Figure 5.13 Comparison of combined limits when correcting for HAWC's pointing systematic. All DM annihilation channels are shown. The solid black line is the ratio between published limit to the declination corrected limit. The blue solid line or "Combined\_og" represented the limits computed for Glory Duck. The solid orange line or "Combined\_ad" represented the limits computed after correcting for the pointing systematic.

## 1076 5.8.2 $\mathcal{G}\mathcal{S}$ Versus $\mathcal{B}$ spatial models

1077 We show in this appendix a comparison between the  $J$ -factors computed by Geringer-Sameth  
 1078 *et al.* [53] (the  $\mathcal{G}\mathcal{S}$  set) and the ones computed by Bonnivard *et al.* [47, 55] (the  $\mathcal{B}$  set). The  
 1079  $\mathcal{G}\mathcal{S}$   $J$ -factors are computed through a Jeans analysis of the kinematic stellar data of the selected

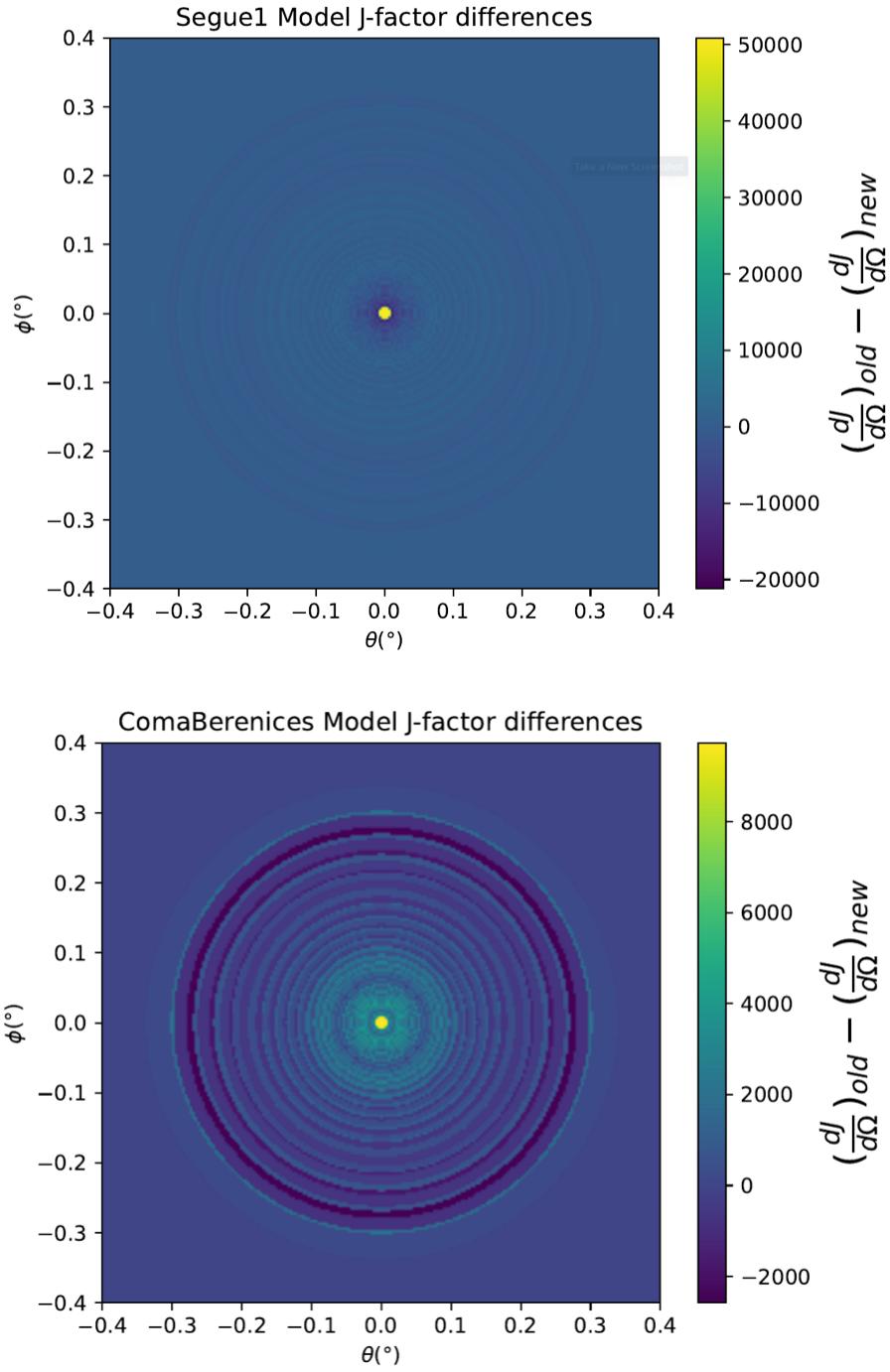


Figure 5.14 Differential map of  $dJ/\Omega$  from model built in Section 5.8.1 and profiles provided directly from authors. (Top) Differential from Segue1. (bottom) Differential from Coma Berenices. Note that their scales are not the same. Segue1 shows the deepest discrepancies which is congruent with its large uncertainties. Both models show anuli where unique models become apparent.

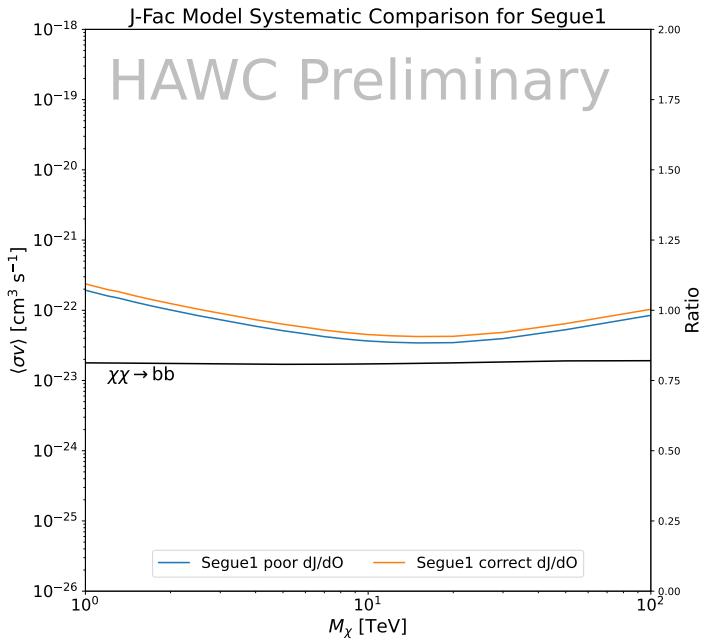
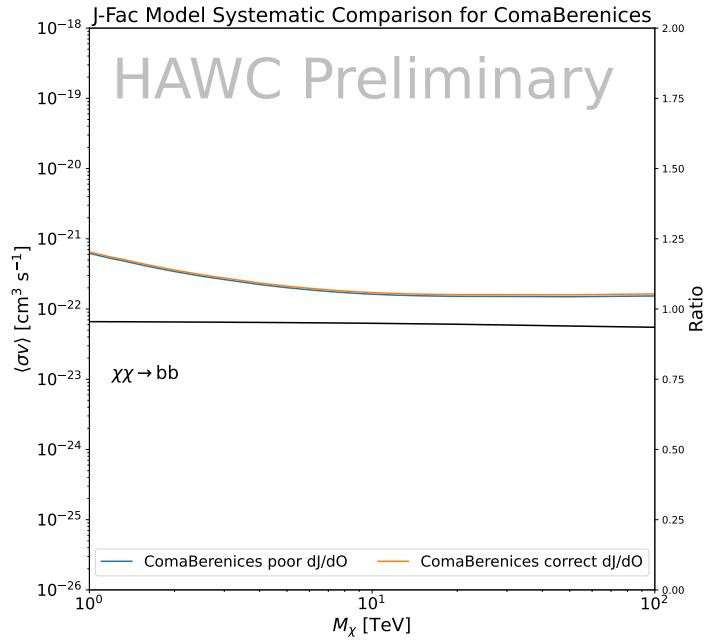


Figure 5.15 HAWC limits for Coma Berenices (top) and Segue1 (bottom) for two different map sets. Blue lines are limits calculated on maps with poor model representation. Orange lines are limits calculated on spatial profiles provided by the authors of [45]. Black line is the ratio of the poor spatial 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.

1080 dSphs, assuming a dynamic equilibrium and a spherical symmetry for the dSphs. They adopted  
1081 the generalized DM density distribution, known as Zhao-Hernquist, introduced by [58], carrying  
1082 three additional index parameters to describe the inner and outer slopes, and the break of the  
1083 density profile. Such a profile parametrization allows the reduction of the theoretical bias from  
1084 the choice of a specific radial dependency on the kinematic data. In other words, the increase of  
1085 free parameters with the use of the Zhao-Hernquist profile allows a better description of the mass  
1086 density distribution of dark matter.

1087 In addition, a constant velocity anisotropy profile and a Plummer light profile [59] for the stellar  
1088 distribution were assumed. The velocity anisotropy profile depends on the radial and tangential  
1089 velocity dispersion. However, its determination remains challenging since only the line-of-sight  
1090 velocity dispersion can be derived from velocity measurements. Therefore, the parametrization of  
1091 the anisotropy profile is obtained from simulated halos (see [60] for more details). They provide the  
1092 values of the  $J$ -factors of regions extending to various angular radius up to the outermost member  
1093 star.

1094 The  $\mathcal{B}$   $J$ -factors were computed through a Jeans analysis taking into account the systematic  
1095 uncertainties induced by the DM profile parametrization, the radial velocity anisotropy profile, and  
1096 the triaxiality of the halo of the dwarf galaxies. They performed a more complete study of the dSph  
1097 kinematics and dynamics than  $\mathcal{GS}$  for the determination of the  $J$ -factor. Conservative values of the  
1098  $J$ -factors where obtained using an Einasto DM density profile [61], a realistic anisotropy profile  
1099 known as the Baes & Van Hese profile [62] which takes into account that the inner regions can be  
1100 significantly non-isotropic, and a Zhao-Hernquist light profile [58].

1101 For both sets,  $J$ -factor values are provided for all dSphs as a function of the radius of the  
1102 integration region [53, 47, 55]. Table 5.1 shows the heliocentric distance and Galactic coordinates  
1103 of the twenty dSphs, together with the two sets of  $J$ -factor values integrated up to the outermost  
1104 observed star for  $\mathcal{GS}$  and the tidal radius for  $\mathcal{B}$ . Both  $J$ -factor sets were derived through a Jeans  
1105 analysis based on the same kinematic data, except for Draco where the measurements of [63] have  
1106 been adopted in the computation of the  $\mathcal{B}$  value. The computations for producing the  $\mathcal{GS}$  and  $\mathcal{B}$

1107 samples differ in the choice of the DM density, velocity anisotropy, and light profiles, for which the  
1108 set  $\mathcal{B}$  takes into account some sources of systematic uncertainties.

1109 Figure 5.16 and Figure 5.17 show the comparisons for the  $J$ -factor versus the angular radius  
1110 for each of the 20 dSphs used in this study. The uncertainties provided by the authors are also  
1111 indicated in the figures. For the  $\mathcal{GS}$  set, the computation stops at the angular radius corresponding  
1112 to the outermost observed star, while for the  $\mathcal{B}$  set, the computation stops at the angular radius  
1113 corresponding to the tidal radius.

## 1114 5.9 Discussion and Conclusions

1115 In this multi-instrument analysis, we have used observations of 20 dSphs from the gamma-ray  
1116 telescopes Fermi-LAT, H.E.S.S., MAGIC, VERITAS, and HAWC to perform a collective DM  
1117 search annihilation signals. The data were combined across sources and detectors to significantly  
1118 increase the sensitivity of the search. We have observed no significant deviation from the null, no  
1119 DM hypothesis, and so present our results in terms of upper limits on the annihilation cross-section  
1120 for seven potential DM annihilation channels.

1121 Fermi-LAT brings the most stringent constraints for continuum channels below approximately  
1122 1 TeV. The remaining detectors dominate at higher energies. Overall, for multi-TeV DM mass,  
1123 the combined DM constraints from all five telescopes are 2-3 times stronger than any individual  
1124 telescope for multi-TeV DM.

1125 Derived from observations of many dSphs, our results produce robust limits given the DM  
1126 content of the dSphs is relatively well constrained. The obtained limits span the largest mass  
1127 range of any WIMP DM search. Our combined analysis improves the sensitivity over previously  
1128 published results from each detector which produces the most stringent limits on DM annihilation  
1129 from dSphs. These results are based on deep exposures of the most promising known dSphs with  
1130 the currently most sensitive gamma-ray instruments. Therefore, our results constitute a legacy of  
1131 a generation of gamma-ray instruments on WIMP DM searches towards dSphs. Our results will  
1132 remain the reference in the field until a new generation of more sensitive gamma-ray instruments  
1133 begin operations, or until new dSphs with higher  $J$ -factors are discovered.

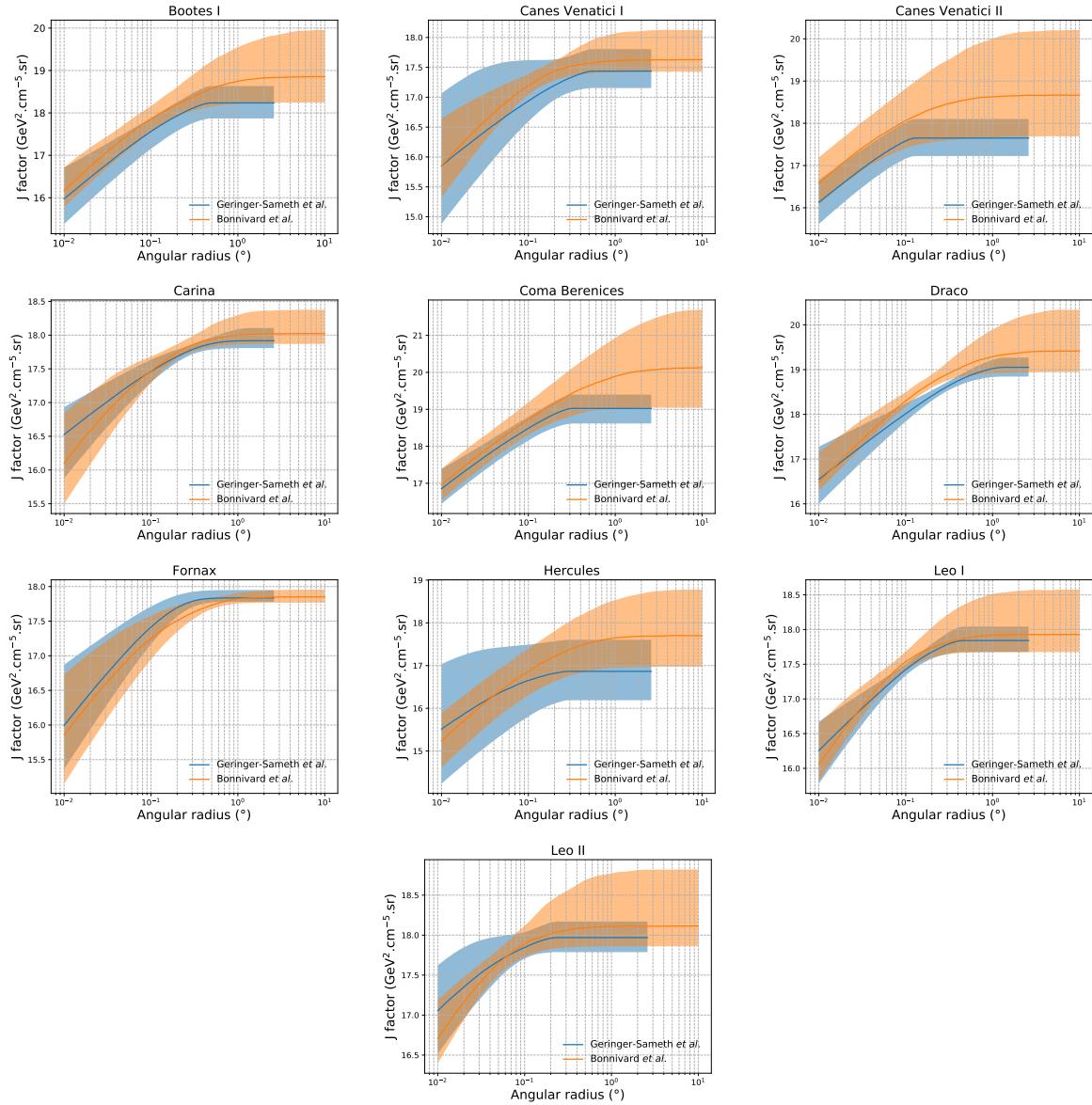


Figure 5.16 Comparisons between the  $J$ -factors versus the angular radius for the computation of  $J$  factors from Ref. [53] ( $\mathcal{GS}$  set in Table 5.1) in blue and for the computation from Ref. [47, 55] ( $\mathcal{B}$  set in Tab. 5.1) in orange. The solid lines represent the central value of the  $J$ -factors while the shaded regions correspond to the  $1\sigma$  standard deviation.

1134 This analysis serves as a proof of concept for future multi-instrument and multi-messenger

1135 combination analyses. With this collaborative effort, we have managed to sample over four orders

1136 in magnitude in gamma-ray energies with distinct observational techniques. Determining the nature

1137 of DM continues to be an elusive and difficult problem. Larger datasets with diverse measurement

1138 techniques could be essential to tackling the DM problem. A future collaboration using similar

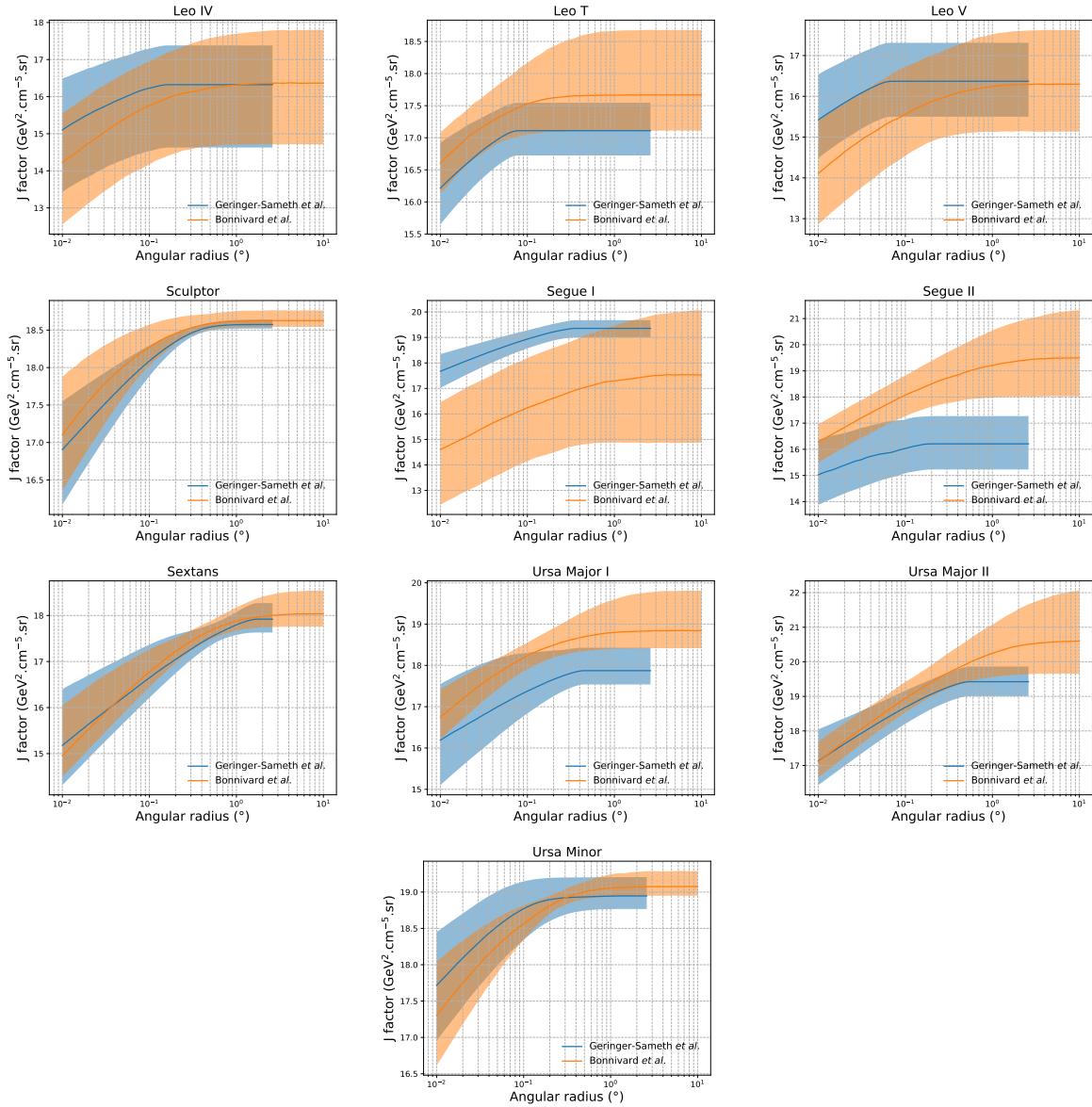


Figure 5.17 Comparisons between the  $J$ -factors versus the angular radius for the computation of  $J$  factors from Ref. [53] ( $\mathcal{GS}$  set in Tab. 5.1) in blue and for the computation from Ref. [47, 55] ( $\mathcal{B}$  set in Tab. 5.1) in orange. The solid lines represent the central value of the  $J$ -factors while the shaded regions correspond to the  $1\sigma$  standard deviation.

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

1144 From this work, a selection of the best candidates for observations, according to the latest  
1145 knowledge on stellar dynamics and modelling techniques for the derivation of the  $J$ -factors on  
1146 the potential dSphs targets, is highly desirable at the time that new experiments are starting their  
1147 dark matter programs using dSphs. Given the systematic uncertainty inherent to the derivation of  
1148 the  $J$ -factors, an informed observational strategy would be to select both objects with the highest  
1149  $J$ -factors that could lead to DM signal detection, and objects with robust  $J$ -factor predictions, i.e.  
1150 with kinematic measurements on many bright stars, which would strengthen the DM interpretation  
1151 reliability of the observation outcome.

1152 This analysis combines data from multiple telescopes to produce strong constraints on astro-  
1153 physical objects. From this perspective, these methods can be applied beyond just DM searches.  
1154 Almost every astrophysical study can benefit from multi-telescope, multi-wavelength gamma-ray  
1155 studies. We have enabled these telescopes to study the cosmos with greater precision and detail.  
1156 Many astrophysical searches can benefit from multi-instrument gamma-ray studies, for which our  
1157 analysis lays the foundation.

## CHAPTER 6

### MULTITHREADING HAWC ANALYSES FOR DARK MATTER SEARCHES

#### 6.1 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 multicore processors. The analysis described in chapter 5 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,  $f_{\text{hit}}$  and NN, the time needed to compute 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 multicore 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.

#### 6.2 Dataset and Background

This section enumerates the data and background methods used for HAWC's multithreaded study of dSphs. Section 6.2.1 and Section 6.2.2 are most useful for fellow HAWC collaborators looking to replicate a multithreaded dSph DM search.

##### 6.2.1 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`

##### 6.2.2 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*

1182 *the Electroweak to the Planck Scale* (HDM) [64] and dSphs spatial model from [65] for HAWC  
1183 analysis. A NumPy dictionary of HDM was made for Py3. The corresponding Python3 file is  
1184 `HDMspectra_dict_gamma.npy`. These files can also be used for decay channels and tools are  
1185 provided in HDM’s [git repository](#) [64]. The analysis was performed using the Neural Network  
1186 energy estimator for Pass 5.F. A description of this estimator was provided in chapter 3. **TODO:**  
1187 **Define a subsection when it’s written**, and its key improvements are an improved energy estimation  
1188 and improved sensitivities at higher zenith angles. All other software used for data analysis, DM  
1189 profile generation, and job submission to SLURM are also kept in my sandbox in the [Dark Matter](#)  
1190 [HAWC](#) project. The above repository also incorporates the model inputs used previously in Glory  
1191 Duck, described in chapter 5

1192 **6.2.3 Data Set and Background Description**

1193 The HAWC data maps used for this analysis contain 2565 days of data between runs 2104 (   
1194 **TODO: Day start**) and 7476 ( **TODO: Day end**). They were generated from pass 5.f reconstruction.  
1195 The analysis is performed using the NN energy estimator with bin list:

1196     B1C0Ea, B1C0Eb, B1C0Ec, B1C0Ed, B1C0Ee, B2C0Ea, B2C0Eb, B2C0Ec, B2C0Ed, B2C0Ee,  
1197     B3C0Ea, B3C0Eb, B3C0Ec, B3C0Ed, B3C0Ee, B3C0Ef, B4C0Eb, B4C0Ec, B4C0Ed, B4C0Ee,  
1198     B4C0Ef, B5C0Ec, B5C0Ed, B5C0Ee, B5C0Ef, B5C0Eg, B6C0Ed, B6C0Ee, B6C0Ef, B6C0Eg,  
1199     B6C0Eh, B7C0Ee, B7C0Ef, B7C0Eg, B7C0Eh, B7C0Ei, B8C0Ee, B8C0Ef, B8C0Eg, B8C0Eh,  
1200     B8C0Ei, B8C0Ej, B9C0Ef, B9C0Eg, B9C0Eh, B9C0Ei, B9C0Ej, B10C0Eg, B10C0Eh,  
1201     B10C0Ei, B10C0Ej, B10C0Ek, B10C0El

1202 Bin 0 was excluded as it has substantial hadronic contamination and poor angular resolution.

1203 Background considerations and source selection was identical to Section 5.2, and no additional  
1204 arguments are provided here. Many of the HAWC systematics explored in Section 5.7 also apply  
1205 for this DM search and are not added upon here.

1206 **6.3 Analysis**

1207 The analysis and its systematics are almost identical to Section 5.3. Importantly, we use the  
1208 same Equation (7.1) and Equation (5.2) for estimating the gamma-ray flux at HAWC from our  
1209 sources. We add on to the previous study with a search for DM decay. The flux equations for DM  
1210 decay are

$$\frac{d\Phi_\gamma}{dE_\gamma} = \frac{1}{4\pi\tau m_\chi} \frac{dN_\gamma}{dE_\gamma} \times \int_{\text{source}} d\Omega \int_{l.o.s} \rho_\chi dl(r, \theta') \quad (6.1)$$

1211 with a new quantity, the  $D$  factor, defined as

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

1212 Software was written to accommodate DM decay from dSphs, however decay profiles were not  
1213 received from  $\mathcal{L}\mathcal{S}$  by the time of writing this thesis.

1214 **6.3.1  $\frac{dN_\gamma}{dE_\gamma}$  - Particle Physics Component**

1215 For these spectra, we import HDM with Electroweak (EW) corrections and additional correc-  
1216 tions for neutrinos above the EW scale [64]. The spectrum is implemented as a model script in  
1217 astromodels for 3ML. A comprehensive description of EW corrections and neutrino considerations  
1218 are provided later in [TODO: refeance MM nu duck](#).

1219 Figure 6.1 demonstrates the impact of changes from HDM on DM annihilation to W bosons.  
1220 A class in astromodels was developed to include HDM and is aptly named `HDMspectra` within  
1221 `DM_models.py`. The SM DM annihilation channels studied here are  $\chi\chi \rightarrow$ :

1222  $e^+e^-$ ,  $\mu^+\mu^-$ ,  $\tau^+\tau^-$ ,  $b\bar{b}$ ,  $t\bar{t}$ ,  $gg$ ,  $W^+W^-$ ,  $ZZ$ ,  $c\bar{c}$ ,  $u\bar{u}$ ,  $d\bar{d}$ ,  $s\bar{s}$ ,  $\nu_e\bar{\nu}_e$ ,  $\nu_\mu\bar{\nu}_\mu$ ,  $\nu_\tau\bar{\nu}_\tau$ ,  $\gamma\gamma$ ,  $hh$ .

1223 For  $\gamma\gamma$  and  $ZZ$ , a substantial fraction of the signal photons are expected to have total energy equal  
1224  $m_\chi$  [64]. This introduces a  $\delta$ -function that is much narrower than the energy resolution of the  
1225 HAWC detector. To ensure that this feature is not lost in the likelihood fits, the 'line' feature is  
1226 convolved with a Gaussian kernel with a  $1\sigma$  width of  $0.05 \cdot m_\chi$  and total kernel window of  $\pm 4\sigma$ .  
1227 This differs from HAWC's previous line study where 30% of HAWC's energy resolution was used  
1228 for the kernel [66]. The NN energy estimator's strength compared to  $f_{\text{hit}}$  at low gamma-ray energy

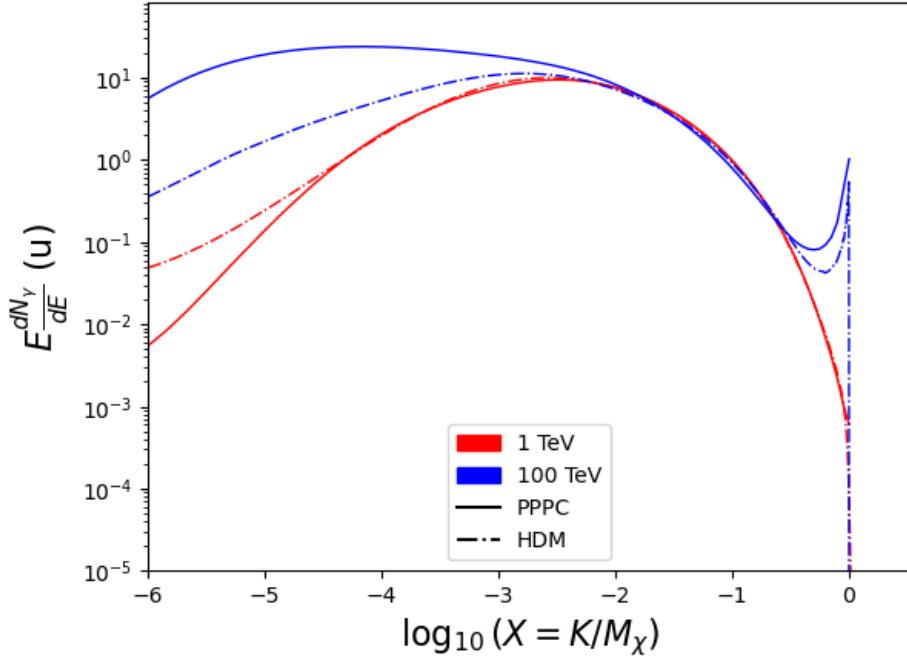


Figure 6.1 Difference between spectral hypotheses from PPPC [44] and HDM [64]. Shown is the expected DM annihilation spectrum for  $\chi\chi \rightarrow W^-W^+$ . Solid lines are spectral models with EW corrections from the PPPC. Dash-dot lines are spectral models from HDM. Red lines are models for  $M_\chi = 1$  TeV. Blue lines represent models for  $M_\chi = 100$  TeV.

enables smaller resolutions in addition to low energy tails in the spectral models [64].  $\chi\chi \rightarrow \gamma\gamma$  and ZZ spectral hypotheses are shown in Figure 6.2. Spectral models for the remaining annihilation channels are plotted for each  $m_\chi$  in Figure B.1.

### 6.3.2 J and D- Astrophysical Components

The J-factor profiles for each source are imported from Louis Strigari et al. (referred to with  $\mathcal{LS}$ ) [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 5.3.2 except that a higher order trapezoidal integral was used for the normalization of the square, uniformly-spaced map:

$$p^2 \cdot \sum_{i=0}^N \sum_{j=0}^M w_{i,j} \frac{d\mathcal{K}}{d\Omega}(\theta_{i,j}, \phi_{i,j}) \quad (6.3)$$

$\mathcal{K}$  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

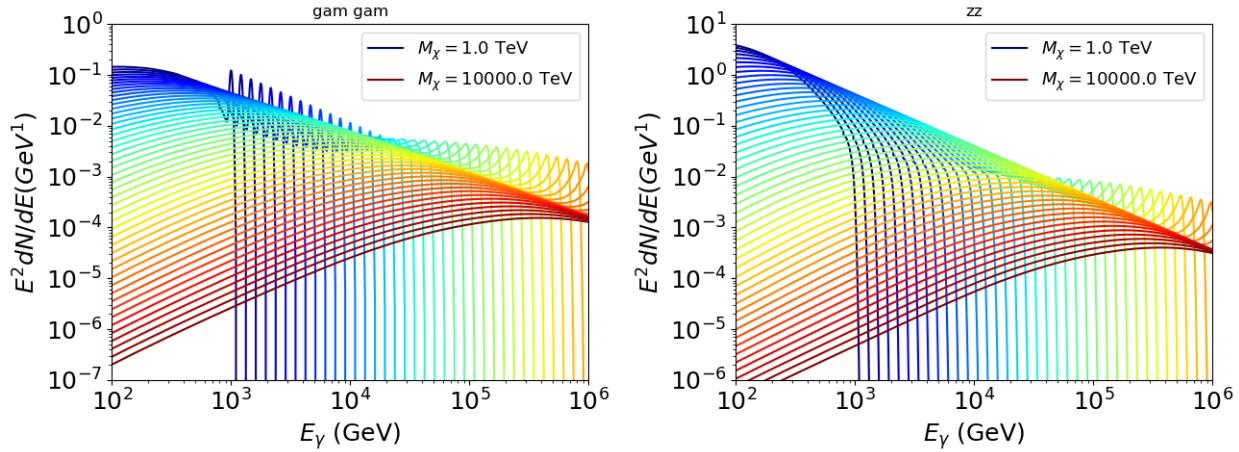


Figure 6.2 Photon spectra for  $\chi\chi \rightarrow \gamma\gamma$  (left) and  $\chi\chi \rightarrow ZZ$  (right) after Gaussian convolution of line features. Both spectra have  $\delta$ -features at photon energies equal to the DM mass. Bluer lines are annihilation spectra with lower DM mass. Redder 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.

1240        $w_{i,j} = 1/2$  if  $(\theta_{i,j}, \phi_{i,j})$  is on an edge of the region of integration

1241        $w_{i,j} = 1/4$  if  $(\theta_{i,j}, \phi_{i,j})$  is on a corner of the region of integration

1242   Figure 6.3 shows the median and  $\pm 1\sigma$  maps used as input for DM annihilation studied by  $\mathcal{LS}$ .

### 1243   **6.3.3 Source Selection and Annihilation Channels**

1244   HAWC's sources for this multithreaded analysis include Coma Berenices, Draco, Segue 1, and  
 1245   Sextans  $\mathcal{LS}$  observes up to 43 sources in its publication, however only 4 of the best fit profiles were  
 1246   provided at the time this thesis was written. A full description of each source used in this analysis  
 1247   is found in Table 6.1.

1248   This analysis improves on chapter 5 in the following ways. Previously, the particle physics  
 1249   model used for gamma-ray spectra from DM annihilation was from the PPPC [44] which missed  
 1250   important considerations relevant for the neutrino sector. HDM is used to account for this shortfall  
 1251   [64]. HDM also models DM to the Planck scale which permits HAWC to probe PeV scale DM.  
 1252   For this study, we sample DM masses: 1 TeV - 10 PeV with 6 mass bins per decade in DM mass.  
 1253   In the case of line spectra ( $\chi\chi \rightarrow \gamma\gamma$ , or  $ZZ$ ), we double the mass binning to 12 DM mass bins  
 1254   per decade in DM mass. A larger source catalog is used that uses a Navarro–Frenk–White (NFW)

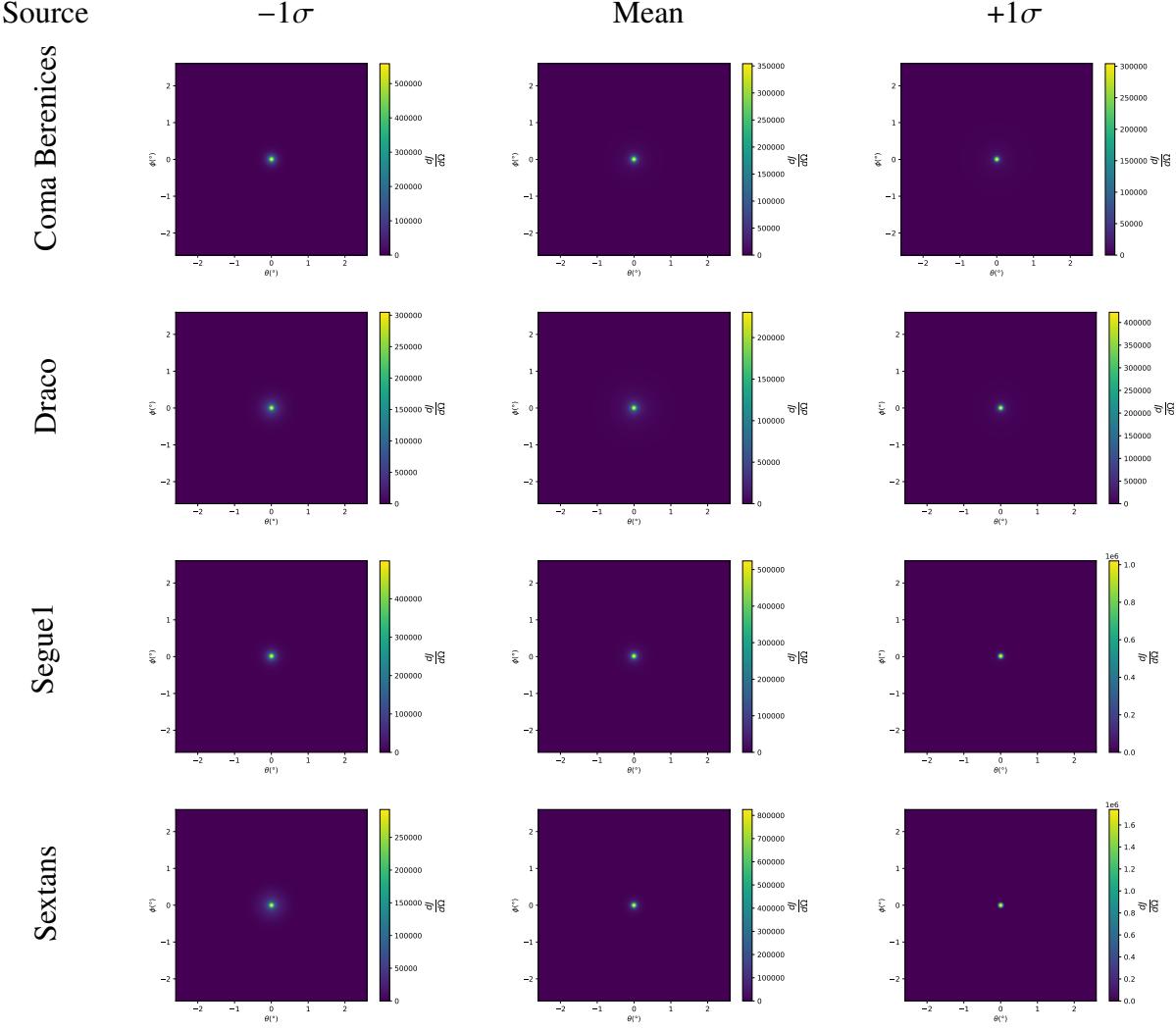


Figure 6.3  $\frac{dJ}{d\Omega}$  maps for Coma Berenices, Draco, Segue1, and Sextans. Columns are divided for the  $\pm 1\sigma$  uncertainties in  $dJ/d\Omega$  around the mean value from  $\mathcal{LS}$  [65]. Origin is centered on the specific dwarf spheroidal galaxies (dSph).  $\theta$  and  $\phi$  axes are the angular separation from the center of the dwarf

1255 spatial DM distribution from  $\mathcal{LS}$  [65]. Because NFW has fewer parameters than what is used  
 1256 for  $\mathcal{GS}$ ,  $\mathcal{LS}$  is able to fit ultra-faint dwarves, expanding the number of sources available for DM  
 1257 searches. Finally, the gamma-ray ray dataset is much larger. The study performed here analyzes  
 1258 2565 days of data compared to 1017 days analyzed in chapter 5.

## 1259 6.4 Likelihood Methods

1260 These are identical to Section 5.4.1 and no additional changes are made to the likelihood. Bins  
 1261 in this analysis are expanded to include HAWC’s NN energy estimator.

1262 **6.5 Computational Methods: Multithreading**

1263 Previously, as in Section 5.3, the likelihood was minimized for one model at a time. One  
 1264 model in this case representing a DM annihilation channel, DM mass, and dSph. In an effort  
 1265 to conserve human and CPU time, jobs submitted for high performance computing contained a  
 1266 list of DM masses to iterate over for likelihood fitting. Jobs were then trivially parallelized for  
 1267 each permutation of the two lists: CHANS (SM annihilation channel) and SOURCES (dSph spatial  
 1268 templates). The lists for CHANS and SOURCES are found in Section 6.3.1 and Table 6.1, respectively.  
 1269 Initially, 11 DM mass bins were serially sampled for one job defined by a [SM channel, dSph] set.  
 1270 Computing the likelihoods would take between 1.5 to 2 hrs, stochastically, for a job. We expect to  
 1271 compute likelihoods for data and 300 Poisson background trials. The estimated CPU time based on  
 1272 the above for all SM annihilation channels (17) and 25 sources (all  $\mathcal{LS}$  sources within HAWC's  
 1273 field of view) amounted to 127,925 jobs. In total, 1,407,175 likelihood fits and profiles would  
 1274 be computed for the 11 mass bins we wished to study. The estimated CPU time ranged between  
 1275 10k CPU days - 8k CPU days. Human time is more challenging to estimate as job allocation is  
 1276 stochastic and highly dependent on what other users are submitting, yet it is unlikely that all jobs  
 1277 would run simultaneously. Therefore, we can expect human time to be about as long as was seen  
 1278 in chapter 5 which was on the order of months to fully compute on a smaller analysis. A visual aid  
 1279 to describe how jobs were organized is provided in Figure 6.4.

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 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. 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  $0.5^{\circ}$ .

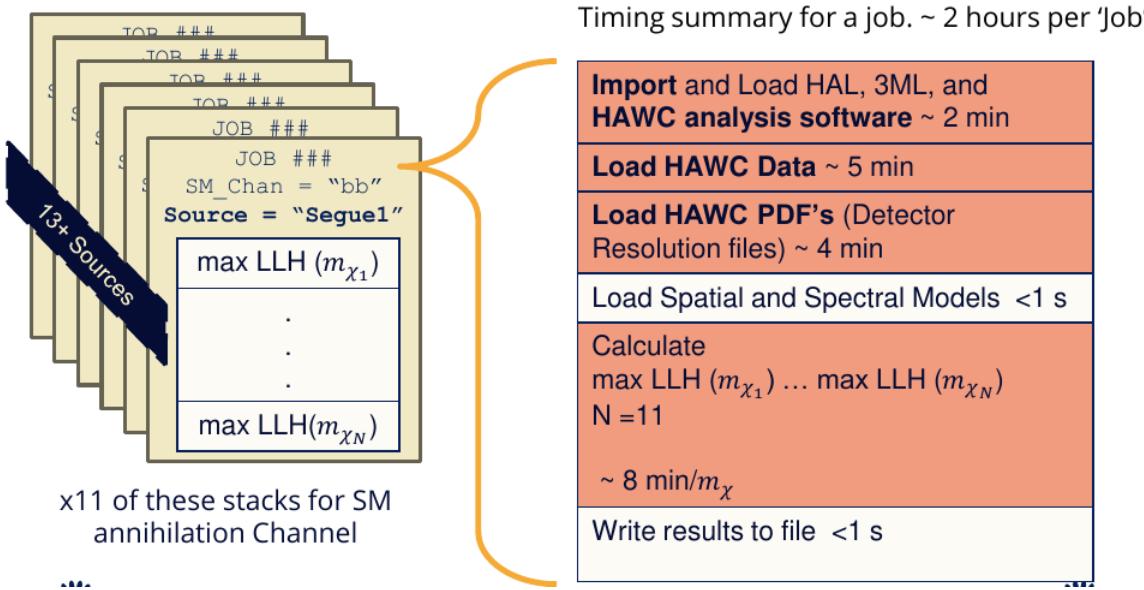


Figure 6.4 Infographic on how jobs and DM computation was organized in Section 5.3. Jobs were built for each permutation of CHANS and SOURCES shown by the left block in the figure. Each job, which took on the order 2 hrs to compute, had the following work flow: 1. Import HAWC analysis software, 2 min 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.

1280     The computational needs for this next generation DM analysis are extreme and is unlike other

1281   analyses performed on HAWC. It became clear that there was a lot to gain from optimizing how  
1282   the likelihoods are computed. This section discusses how multi-threading was applied to solve and  
1283   reduce HAWC’s computing of likelihoods for large parameter spaces like in DM searches.

### 1284 6.5.1 Relevant Foundational Information

1285     The profiling of the likelihood for HAWC is done via gradient descent where the normalization

1286   of Equation (7.1) (linearly correlated with  $\langle \sigma v \rangle$ ) is rescaled in the descent. Additionally, we sample  
1287   the likelihood space for a defined list of  $\langle \sigma v \rangle$ ’s described in Section 5.4.2. The time to compute  
1288   these values is not predictable or consistent because many variables can change across the full  
1289   model-space. Comprehensively, these variables are:

- 1290     •  $m_\chi$  : DM rest mass

- 1291     • CHAN : DM SM annihilation channel.

1292 • SOURCE : dSph within HAWC's field of view. This involves a spatial template AND coordinate  
1293 in HAWC data.

1294 •  $\langle\sigma v\rangle$ : Effectively the flux normalization and free parameter in the likelihood fit.

1295 Therefore, we develop an asynchronous, functional-parallel coding pattern. Asynchronous mean-  
1296 ing that the instructions and computing within a function are independent and permitted to be out  
1297 of sync with sibling computations. Functional-parallel meaning that instructions are the subject of  
1298 parallelization rather than threading the likelihood computation. This is close to trivial parametriza-  
1299 tion seen in Figure 6.4 except that we seek to consolidate the loading stages (software, data, and  
1300 detector resolution loading). Reducing the total instances of loading stages and distributing access  
1301 to the reduced loads across multiple asynchronous threads is expected to reduce serial processing  
1302 time and the overhead implicit to each job in addition to saving human time.

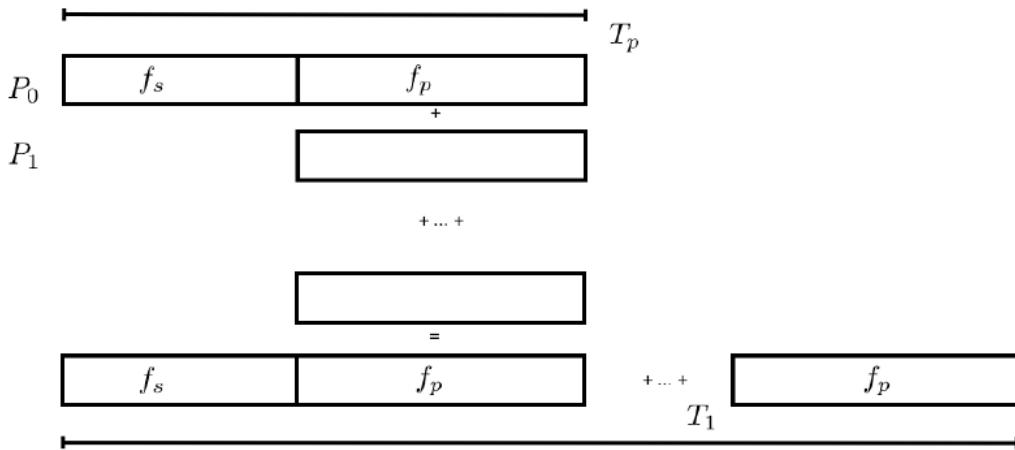


Figure 6.5 Graphic of Gustafson parallel coding pattern.  $f_s$  is the fraction of a program, in time, spent on serial computation.  $f_p$  is the fraction of computing time that is parallelizable.  $T_p$  is the total time for a parallel program to run.  $T_1$  is the total time for a parallel program 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].

1303 We need a way to measure and compare the expected speedup and efficiency gain for this  
1304 asynchronous coding pattern. I pull inspiration for timing measurement from [67] and use *Amdahl's  
1305 law with hybrid programming*. Hybrid programming meaning that the computation is a mix of

1306 distributed and shared memory programming. If we assume the code is fully parallelizable over  $p$   
1307 processors and  $c$  threads, the ideal speedup is simply  $pc$  and ideal run-time is  $T_1/(pc)$ .  $T_1$  is the  
1308 total time for a parallel program to run if only 1 processor is allocated. However, the coding pattern  
1309 contains some amount of unavoidable serial computation, as shown in Figure 6.5. In our case, the  
1310 run time is estimated to be

$$T_{p,c} = \frac{T_1}{pc} (1 + F_s(c - 1)). \quad (6.4)$$

1311  $F_s$  is the fraction of CPU time dedicated to serial computation. The expected speedup is

$$S_{p,c} \equiv \frac{T_1}{T_{p,c}} = \frac{pc}{1 + F_s(c - 1)}. \quad (6.5)$$

1312 From Equation (6.5), we can see that the speed-up scales with  $p/F_s$ . We are free to minimize  
1313  $F_s$  asymptotically by enlarging the total models that are submitted to the thread pool, thereby  
1314 shrinking the CPU fraction dedicated to serial operation. We are also free to define exactly how  
1315 many threads and processors we utilize, yet eventually hit a hard cap at the hardware available on  
1316 our computing cluster. HAWC uses Intel Xeon processors with 48 cores and 96 threads. This  
1317 means when N-threads ( $c$ ) are defined,  $N \bmod 2$  cores ( $p$ ) are needed. We see that a successful  
1318 code scales well as the expected speedup is inversely correlated with  $F_s$ . As the total number of  
1319 models sampled grows, the speedup will also.

### 1320 6.5.2 Implementation

1321 The multithreaded code was written in Python3 and is documented in the `dark_matter_hawc`  
1322 [repository](#) within the script named `mpu_analysis.py`. A version of the script as of April 25  
1323 **TODO: make sure to update on this date** is also provided in Section B.2 It has many dependencies  
1324 including the HAWC analysis software. Figure 6.6 displays the workflow of a job with 3 threads.  
1325 Within a job, SOURCE is kept fixed . CHAN(S) remains 17 elements long. More  $m_\chi$  are sampled  
1326 from 11 bins up to 49 (for  $\gamma\gamma$  and ZZ) and 25 (for remaining CHANS) which amounts to 12 or 6  
1327 mass bins per decade. The DM mass,  $m_\chi$ , and SM annihilation channels, CHANS, are permuted into  
1328 a 473 element list which is split evenly across N threads where N ranges between 5 - 16. Within a  
1329 thread, for each  $m_\chi$ -CHAN tuple, 1001  $\langle\sigma v\rangle$  values are sampled in the likelihood, and the value of

Timing summary for a multi-threaded job.

Import and Load HAL, 3ML, and <b>HAWC analysis software</b> ~ 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, $m_{\chi_1}$ ) ... max LLH (Chan_?, $m_{\chi_N}$ ) N = TOTAL/N_THREADS  ~ 8 min/Spec_model	Calculate max LLH (Chan_?, $m_{\chi_1}$ ) ... max LLH (Chan_?, $m_{\chi_N}$ ) N = TOTAL/N_THREADS  ~ 8 min/Spec_model	Calculate max LLH (Chan_?, $m_{\chi_1}$ ) ... max LLH (Chan_?, $m_{\chi_N}$ ) 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 6.6 Task chart for one multithreaded 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  $m_{\chi}$ , CHAN, and  $\langle \sigma v \rangle$  variables are entered into the thread pool and allocated as evenly as possible across the threads.

1330  $\langle \sigma v \rangle$  that maximizes the likelihood is found. Although rare, fits that failed are handled on a case  
1331 by case basis.

### 1332 6.5.3 Performance

M Tasks	$T_{p,c}$ (hr:min:s)			
	$T_{1,1}$	$T_{1,2}$	$T_{1,8}$	$T_{1,16}$
50	1:40:37.5	0:52:43.7	0:19:13.8	0:13:44.0
74	2:22:30.0	1:15:00.6	0:25:21.3	0:15:49.8
100	(3:07:51.9)	1:40:10.5	0:30:44.4	0:20:01.4
200	(6:02:20.6)	-	1:00:32.0	0:30:35.0
473	(13:58:40.3)	-	2:01:41.4	1:07:53.2

Table 6.2 Timing summaries for analyses for serial and multithreaded processes. M tasks is the number of functional-parallel tasks ran for the computation.  $T_{p,c}$  is a single run time in hours:minutes:seconds for runs utilizing  $p$  nodes and  $c$  threads. Runs are run interactively on the same computer to maximize consistency. Empty entries are indicated with '-'. (·) entries are estimated entries extrapolated from data earlier in the column.

1333 We see a tremendous reduction to human time waiting for our dSph analyses to run. Table 6.2

1334 shows the timing summaries for analyses of different sizes and thread counts. Additionally, the  
 1335 efficiency gained when consolidating the serial loading of data is also apparent in our ability to  
 1336 study many more tasks in about the same amount of wall time as a smaller serial computation. Trials  
 1337 represented in the table were run on an AMD Opteron® processor 6344 with 48 cores, 2 threads  
 1338 per core; 2.6 GHz clock. This is not the same architecture used for analysis on the computing  
 1339 cluster however they are similar enough that results shown here are reasonably representative of  
 1340 computing on the HAWC computing cluster. I use the Tab. 6.2 for the inferences and conclusions  
 1341 in the following paragraphs.

1342 First, we want to find  $T_s$ , the time of serial computation. From Fig. 6.5, the timing for our  
 1343 coding pattern can be written as

$$T_s + Mt_p = T_{1,1}^M. \quad (6.6)$$

1344  $M$  is the number of functional-parallel tasks (represented as column 1 of Tab. 6.2), and  $t_p$  is the  
 1345 average time to complete a single parallel task.  $T_{1,1}^M$  is the total time for a parallel program to run if  
 1346 only 1 processor is allocated for  $M$  parallel task. With two runs of different  $M$  ( $M1$  and  $M2$ ), we  
 1347 can use a system of equations to derive

$$T_s = T_{1,1}^{M1} - M1 \left( \frac{T_{1,1}^{M1} - T_{1,1}^{M2}}{M1 - M2} \right). \quad (6.7)$$

1348 We also extract  $t_p$  using the same methods:

$$t_p = \frac{T_{1,1}^{M1} - T_{1,1}^{M2}}{M1 - M2}. \quad (6.8)$$

1349 From Tab. 6.2, we set  $M1 = 50$  and  $M2 = 74$  and take their corresponding  $T_{1,1}$  from the table to  
 1350 calculate  $T_s$  and  $t_p$ .

$$T_s = 803.1\text{s} \text{ and } t_p = 104.6\text{s} \quad (6.9)$$

1351 Now, we have specific estimation for the fraction of serial computing time,  $F_s$ :

$$F_s = \frac{803.1}{803.1 + 104.6 \cdot M}. \quad (6.10)$$

1352 The maximum  $M$  for this study is 473 which evaluates using Eq. (6.10):  $F_s = 0.016$  or 1.6% of  
 1353 computing time. Table 6.3 shows the resulting speedups.

M Tasks	$F_s$	$S_{1,2}$	$S_{1,8}$	$S_{1,16}$
50	1.33 E-1	1.90 [1.76]	5.23 [4.14]	6.35 [5.34]
74	9.40 E-2	1.90 [1.83]	5.62 [4.82]	9.00 [6.64]
100	7.13 E-2	1.88 [1.87]	6.11 [5.34]	9.38 [7.73]
200	3.70 E-2	- [1.93]	5.98 [6.36]	11.85 [10.29]
473	1.60 E-2	- [1.97]	6.89 [7.20]	12.35 [12.91]

Table 6.3 Speed up summaries for analyses for serial and multithreaded processes. M tasks is the number of functional-parallel tasks ran for the computation.  $S_{p,c}$  is a single speedup comparison for runs utilizing  $p$  nodes and  $c$  threads. [·] are the estimated speedups calculated from Tab. 6.2, Eq. (6.10), and Eq. (6.5). Empty entries are indicated with '-'.

1354 We see a speedup that generally exceeds expectations from Eq. (6.5) for real trail runs. We also  
 1355 see that there are diminishing returns as the number of threads increases. For small jobs with large  $c$ ,  
 1356 both the expected and observed speedup are significantly smaller than  $c$ . One thing not considered  
 1357 in Eq. (6.5) is the time incurred via communication latency. Communication latency increases  
 1358 with the number of threads and contributes to diminishing returns. Additionally, these values are  
 1359 for single runs and do not consider the stochastic variation expected in a shared high performance  
 1360 computing resource. Therefor, these results are not strictly conclusive, yet demonstrate the merits  
 1361 of multi-threading. We see very clearly that there is a lot to gain, and this new coding pattern will  
 1362 expand HAWC's analysis capabilities.

## 1363 6.6 Analysis Results

1364 3 of the 43  $\mathcal{LS}$  dSphs considered for the multithreaded analysis. These dSph are analyzed for  
 1365 emission from DM annihilation according to the likelihood method described in Section 5.4. The 3  
 1366 likelihood profiles are then stacked to synthesize a combined limit on the dark matter cross-section,  
 1367  $\langle\sigma v\rangle$ . This combination is done for the 17 SM annihilation channels. Figure 6.7 and Fig. 6.8 show  
 1368 the combined limits for all annihilation channels with HAWC's observations. Test statistics of the  
 1369 best fit  $\langle\sigma v\rangle$  values for each DM mass and SM annihilation channels are shown in Fig. 6.9 and  
 1370 Fig. 6.10. We also compare these limits to HAWC's Glory Duck limits shown in Section 5.5. The  
 1371 comparison to Glory Duck are featured in Fig. 6.11 for all the DM annihilation channels studied  
 1372 for Glory Duck. A full comparison is provided in the appendix in Fig. B.2, Fig. B.3, and Fig. B.4.  
 1373 Here, we show updated limits for  $\chi\chi \rightarrow b\bar{b}, e\bar{e}, \mu\bar{\mu}, \tau\bar{\tau}, t\bar{t}, W^+W^-$ ,  $\gamma\gamma$  and  $ZZ$ . For the first time

ever, we show limits for  $\chi\chi \rightarrow c\bar{c}$ ,  $s\bar{s}$ ,  $u\bar{u}$ ,  $d\bar{d}$ ,  $\nu_e\bar{\nu}_e$ ,  $\nu_\mu\bar{\nu}_\mu$ ,  $\nu_\tau\bar{\nu}_\tau$ ,  $gg$ , and  $hh$ .

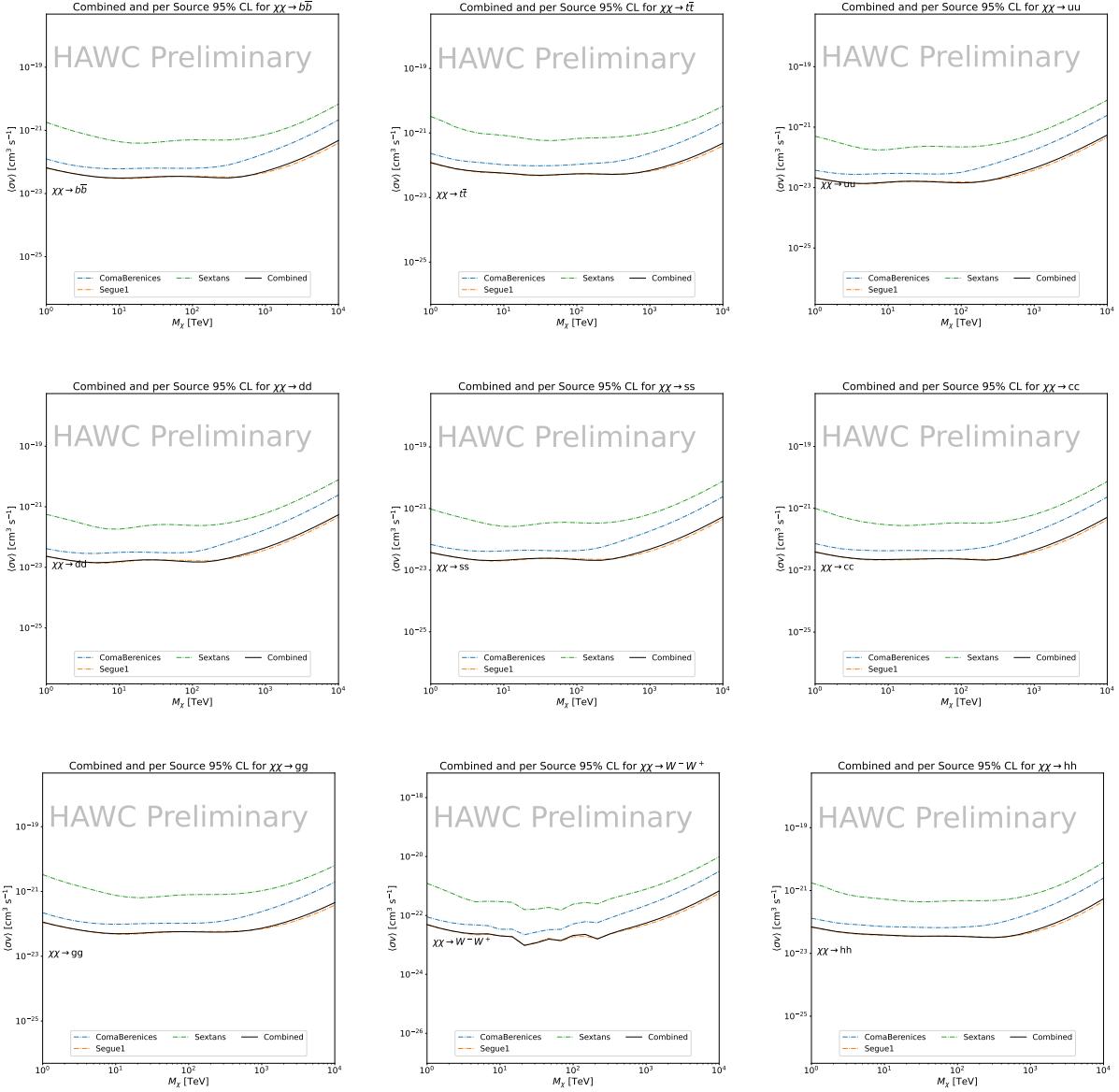


Figure 6.7 HAWC upper limits at 95% confidence level on  $\langle\sigma v\rangle$  versus DM mass for  $\chi\chi \rightarrow b\bar{b}$ ,  $t\bar{t}$ ,  $u\bar{u}$ ,  $d\bar{d}$ ,  $s\bar{s}$ ,  $c\bar{c}$ ,  $gg$ ,  $W^+W^-$ , and  $hh$ . Limits are with  $\mathcal{LS}$   $J$ -factors [65]. The solid line represents the observed combined limit. Dashed lines represent limits from individual dSphs.

No DM was found in HAWC observations. The largest excess found in HAWC data was for DM annihilating to  $W$ -bosons for  $m_\chi = 10 \text{ TeV}$  at  $2\sigma$ . HAWC's limits and excesses are dominated by Segue1. Coma Berenices shows excess at higher DM mass, yet no similar excesses were observed in Segue1. Sextans did not contribute significantly to signal excess or the combined limit as it is

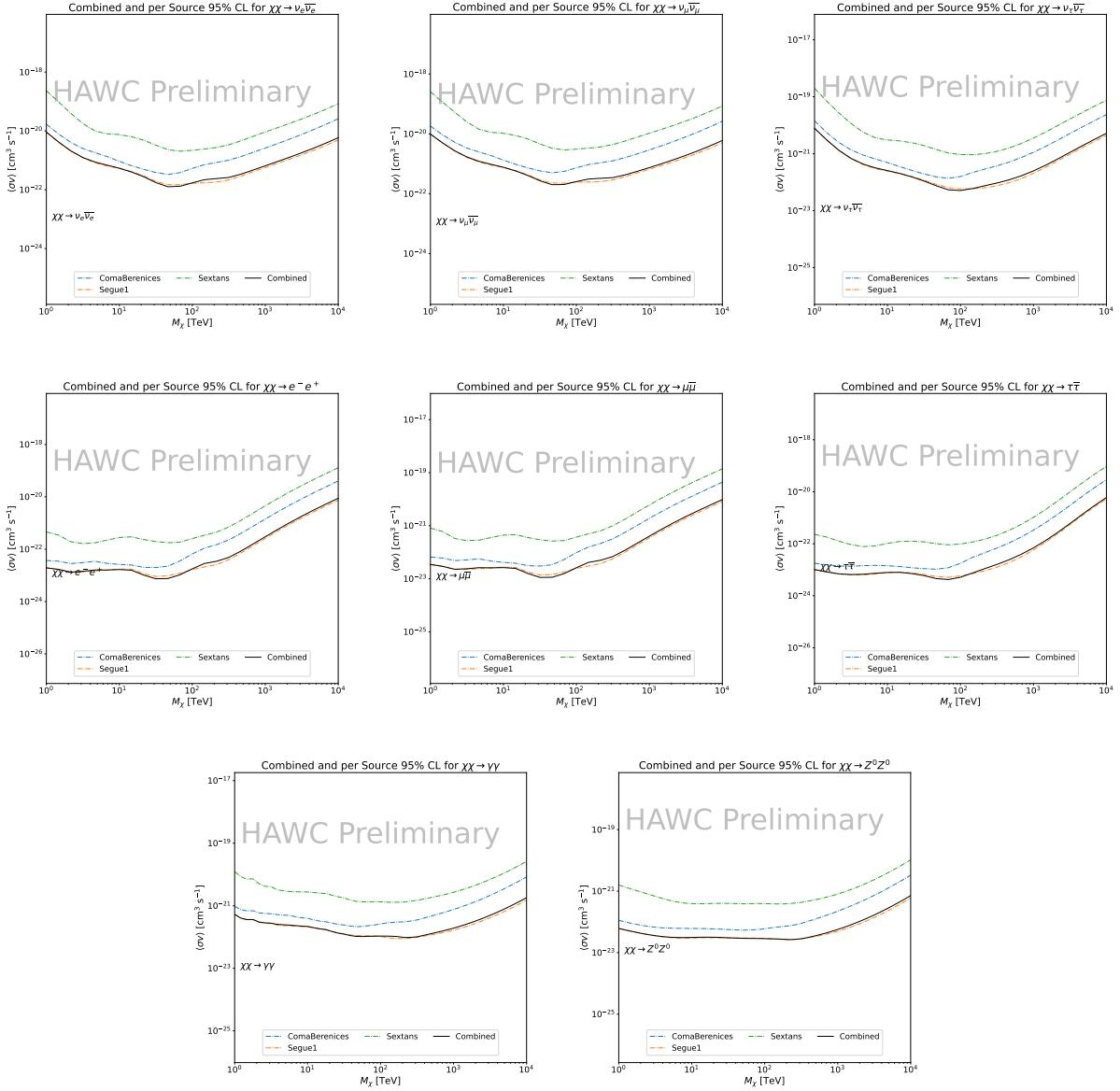


Figure 6.8 HAWC upper limits at 95% confidence level on  $\langle\sigma v\rangle$  versus DM mass for  $\chi\chi \rightarrow \nu_e \bar{\nu}_e$ ,  $\nu_\mu \bar{\nu}_\mu$ ,  $\nu_\tau \bar{\nu}_\tau$ ,  $e^- e^+$ ,  $\mu \bar{\mu}$ ,  $\tau \bar{\tau}$ ,  $\gamma\gamma$  and  $ZZ$ . Limits use  $\mathcal{L}S J$  factors [65]. The solid line represents the observed combined limit. Dashed lines represent limits from individual dSphs.

at high zenith. Draco was not included as the PDF of some of our analysis bins were wider than what is reasonable for a point source analysis. Draco is at a high zenith for HAWC, so the effort required to include it was not justified by the benefits.

We were not able to generate background trials in time of writing this thesis. These are not shown and are an immediate next step for this analysis before publication.

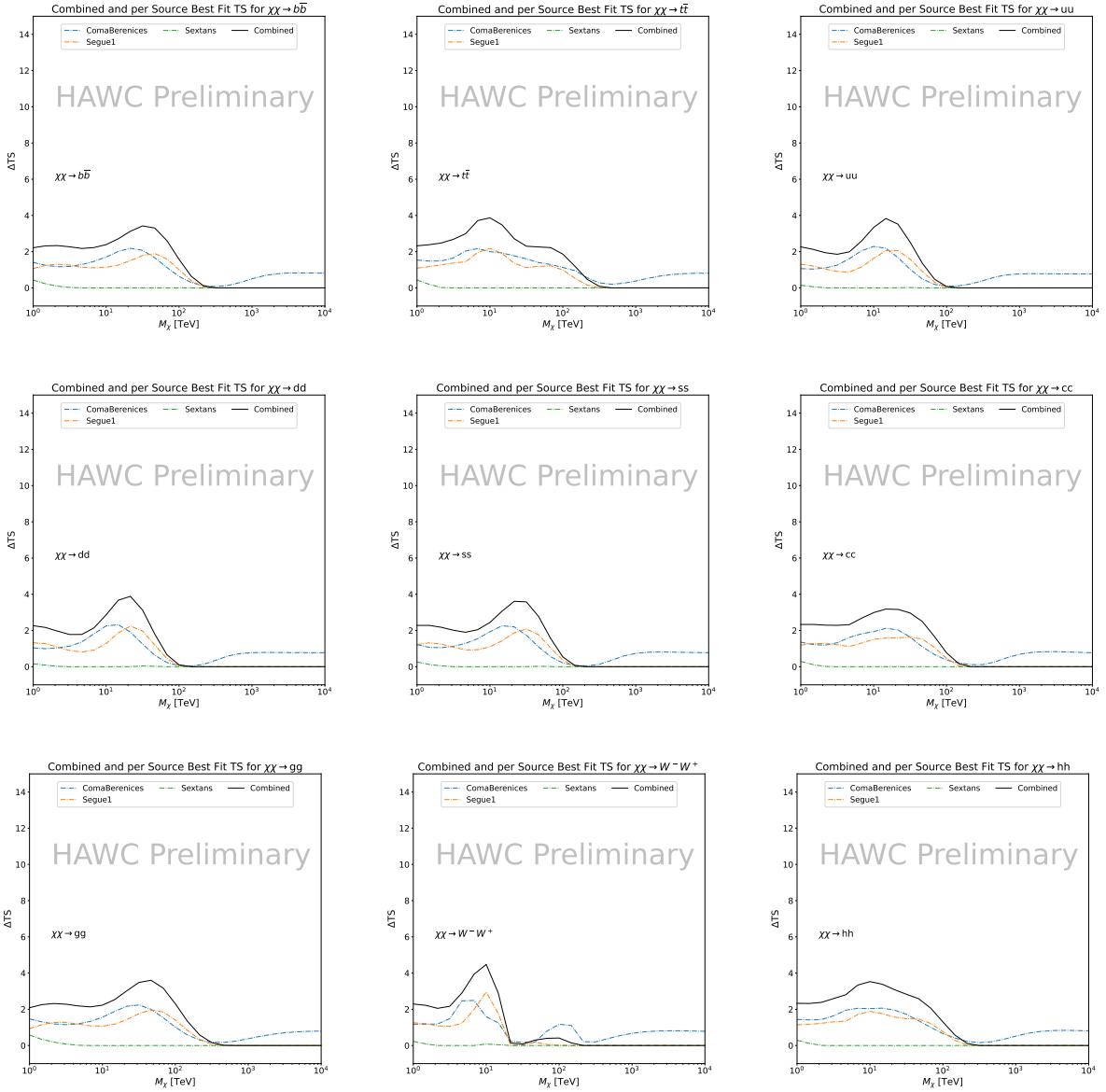


Figure 6.9 HAWC TS values for best fit  $\langle\sigma v\rangle$  versus  $m_\chi$  for SM annihilation channels:  $\chi\chi \rightarrow b\bar{b}$ ,  $t\bar{t}$ ,  $u\bar{u}$ ,  $d\bar{d}$ ,  $s\bar{s}$ ,  $c\bar{c}$ ,  $gg$ ,  $W^-W^+$ , and  $hh$ . Limits use  $\mathcal{L}\mathcal{S} J$  factors. The solid black line shows the combined best fit TS values. The colored, dashed lines are the TS values from each dSph.

When comparing these results to Section 5.5, we see an overall decrease to the confidence limit therefore improvement to HAWC's expected sensitivity. This improvement is generally stronger than a doubling of data, or a factor  $\sqrt{2}$  decrease. The comparison is somewhat complex and dependent on the dSph and SM annihilation channel. Figure 6.11 shows the comparisons of limits calculated for this analysis and Glory Duck (Section 5.5). Segue 1 and Coma Berenices are low

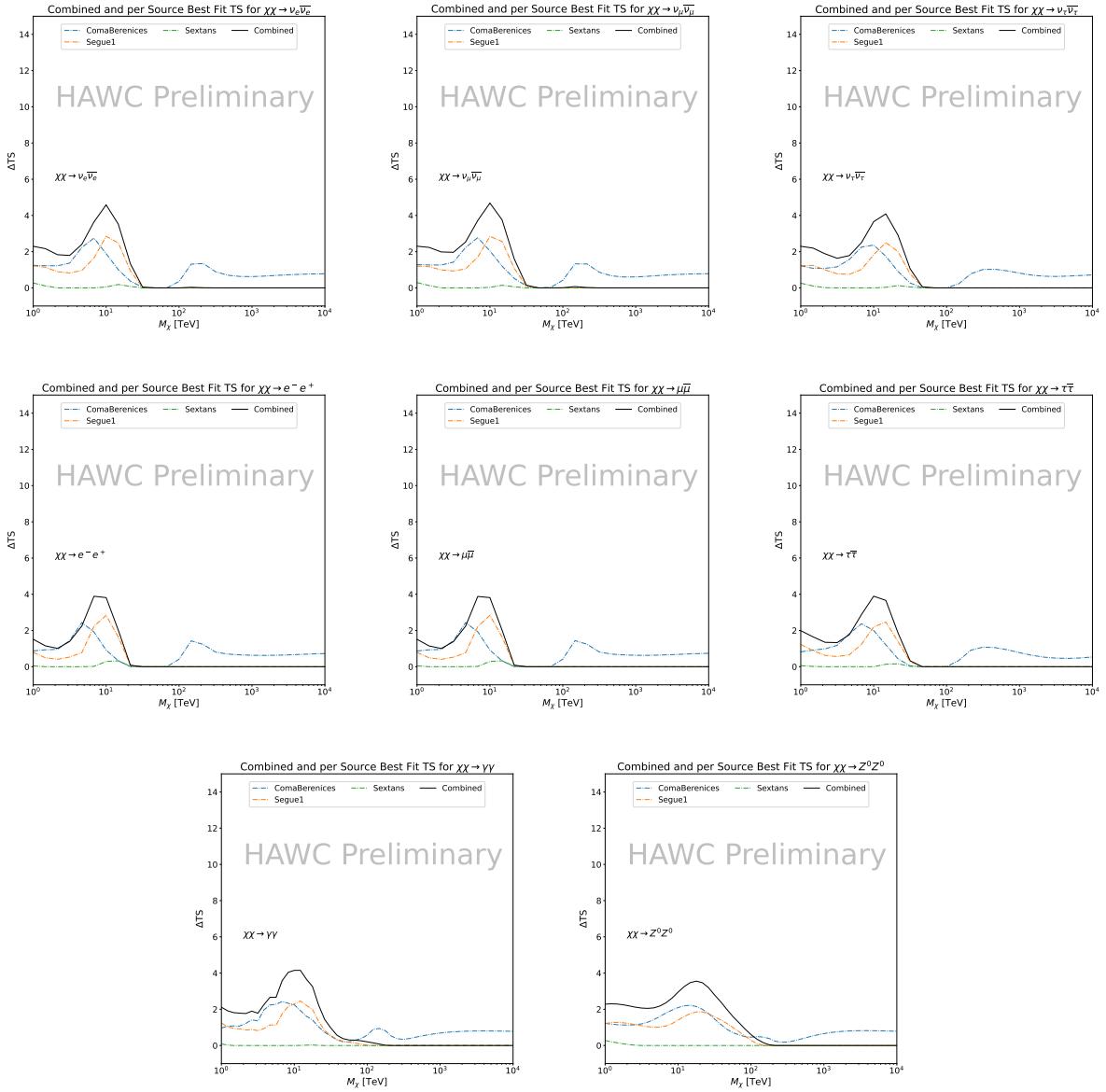


Figure 6.10 HAWC TS values for best fit  $\langle\sigma v\rangle$  versus  $m_\chi$  for SM annihilation channels:  $\chi\chi \rightarrow \nu_e \bar{\nu}_e$ ,  $\nu_\mu \bar{\nu}_\mu$ ,  $\nu_\tau \bar{\nu}_\tau$ ,  $e^- e^+$ ,  $\mu \bar{\mu}$ ,  $\tau \bar{\tau}$ ,  $\gamma\gamma$  and  $ZZ$ . Limits use  $\mathcal{L}\mathcal{S} J$  factors. The solid black line shows the combined best fit TS values. The colored, dashed lines are the TS values from each dSph.

zenith where improvements to HAWC's analysis come only from energy estimation. Differences between these two are dominantly from their differences in  $J$ -factor, half-light radii of the dSphs, and the particle physics inputs. Substantial gains in HAWC's analysis methods (pass 5.F) were made at high zenith which is important for sources like Sextans. The HDM particle physics model produces almost identical spectra to the PPPC for  $\chi\chi \rightarrow e^- e^+$ , so can be used to compare limits

1394 between dSph. Overhead sources see minimal improvement to the limits, while high zenith sources  
1395 see an order of magnitude improvement for all DM masses. Softer SM annihilation channels see  
1396 broad improvements to the limit compared to harder channels.

1397 **6.7 Systematics**

1398 These are identical to what was performed earlier in Glory Duck, Section 5.7. We are also  
1399 sensitive to the choice in spatial template, and this was explored in Section 5.7.2 and Section 5.8.2.

1400 **6.8 Conclusion and Discussion**

1401 In this multithreaded analysis, we have used observations of 3 dSphs from HAWC to perform  
1402 a collective DM search for annihilation signals. The data were combined across sources to signifi-  
1403 cantly increase the sensitivity of the search. Advanced computational techniques were deployed to  
1404 accelerate wall-time spent analyzing by an order of magnitude. We have observed no significant  
1405 deviation from the null, no DM, hypothesis, and so present our results in terms of upper limits on  
1406 the annihilation cross-section for seventeen potential DM annihilation channels across four decades  
1407 of DM mass.

1408 This analysis serves as a proof of concept for multithreaded HAWC analyses with large parameter  
1409 spaces. Larger datasets with fast techniques will be essential to tackling the DM problem. The  
1410 models we used for this study include annihilation channels with neutrinos in the final state.  
1411 Advanced studies could aim to merge our results with those from neutrino observatories with large  
1412 data sets.

1413 A full HAWC analysis will include systematic studies of the  $J$ -factor distributions. Additionally,  
1414 because of the timing reduction, the study can be doubled in size to include DM decay. We have no  
1415 yet received the remaining spatial profiles to the  $\mathcal{L}\mathcal{S}$  catalog, and limits can be quickly computed  
1416 once these are received. Finally, statistical studies with Poisson variation of HAWC’s background  
1417 are essential to a comprehensive understanding of our observed excesses.

Segue1

Coma Berenices

Sextans

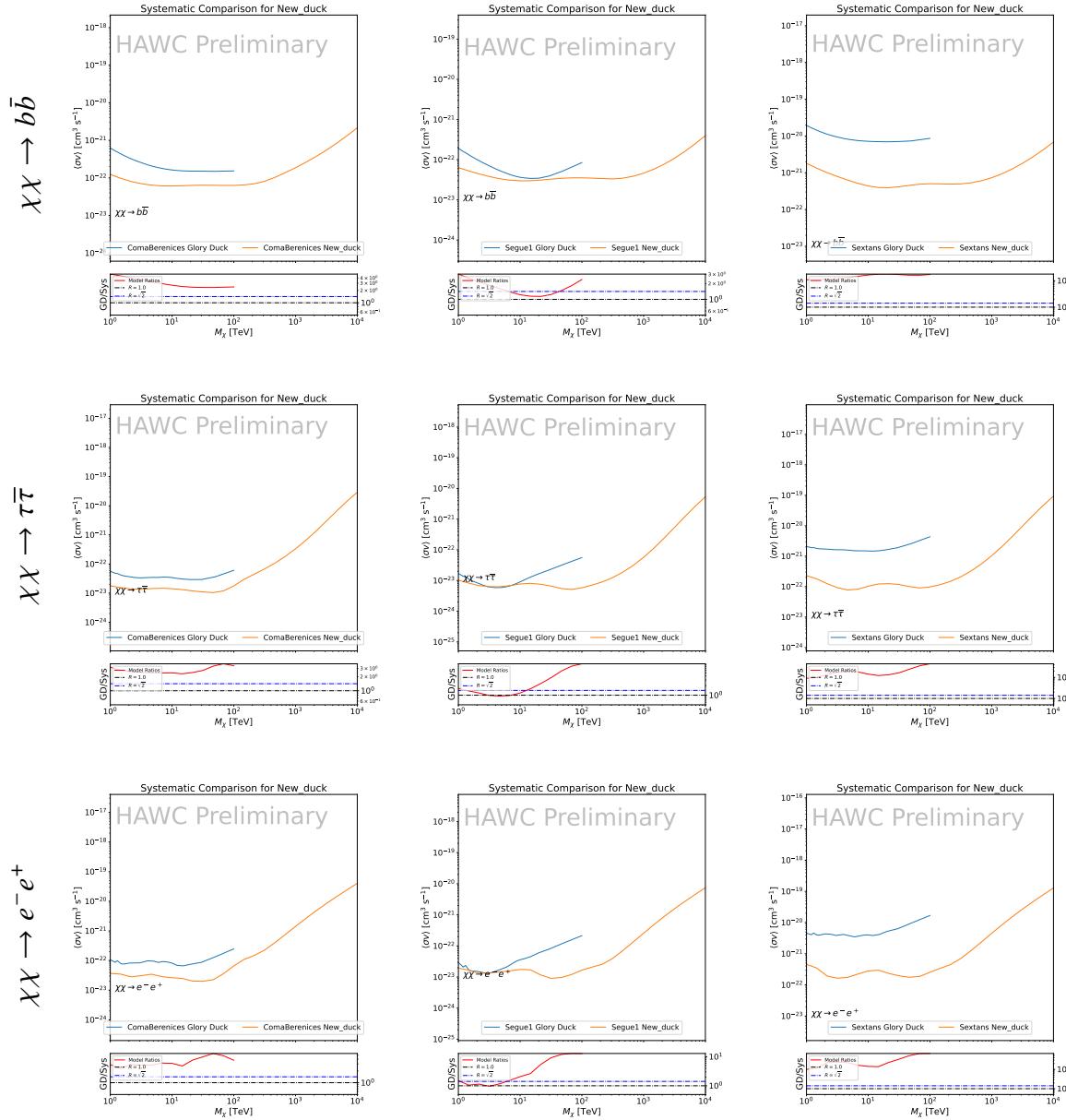


Figure 6.11 Comparison of HAWC limits from this analysis to Glory Duck (Fig. 5.5) for 3 dSphs and 3 SM annihilation channels:  $b\bar{b}$ ,  $\tau\bar{\tau}$ , and  $e\bar{e}$ . Each sector shows the 95% confidence limit from Glory Duck (blue line) and this analysis (orange line) in the top plot. The lower plot features the ratio in log scale of Glory Duck to this analysis in a red solid line. Horizontal dashed lines are for ratios of 1.0 (black) and  $\sqrt{2}$  (blue). Ratios larger than 1.0 are for limits smaller, or stricter, than Glory Duck. Ratios larger than  $\sqrt{2}$  indicates limits are stricter than a simple doubling of the Glory Duck data.

## CHAPTER 7

### 1418 HEAVY DARK MATTER ANNIHILATION SEARCH WITH ICECUBE'S NORTH SKY 1419 TRACK DATA

#### 1420 7.1 Introduction

1421 Neutrinos are another astrophysical messenger than can travel long distances without interaction.  
1422 Uniquely, they interact less readily than photons especially above PeV energies. Neutrinos thereofre  
1423 provide another window through which we can perform dark matter searches. Neutrinos come in  
1424 three flabors and so this triples the multiplicity of the particles we are searching for.

1425 Icecube has not done a DM annihilation analysis towards dwarf galaxies for a while. **TODO:**  
1426 [cite 2013 paper](#). This is in spite of the potentially crucial sensitivity afforded from neutrino spectral  
1427 lines [TODO: cite dan hooper and neutrino lines](#). A lot has changed in IC3 since that last analysis (we  
1428 have more strings, we have much more sophisticated analysis methods, and the theory modeling  
1429 has made significant leaps.) Therefore it is time to finally do a DM search toward dSphs. The hope  
1430 is that by laying down the important statistical foundation as well, that this work can be meshed  
1431 with gamma-ray data. IceCube is sensitive to annihilating DM to the DM ranges above 1 TeV  
1432 and can produce competitive results relative to gamma ray observatories in spectral models that  
1433 produce sharp neutrino features. The goal of this analysis is to perform a DM annihilation search  
1434 using the new datasets NST. The search will only be towards dwarf spheroidal galaxies (dSph).  
1435 These sources are known for their low backgrounds and high DM contents. Since the dataset is  
1436 sensitive to the north and south, as many dSph as possible will be included. Additionally, with  
1437 annihilation, these sources can be treated as point sources with little loss to sensitivity or model  
1438 dependence on how the DM is distributed. DM masses from 500 GeV to 100 PeV are considered  
1439 for this analysis. All standard model annihilation channels available from the HDMspectra are  
1440 studied in this analysis.

1441 Additional work is done to extract the Likelihood profiles for each DM, source hypothesis so  
1442 that these data can be combined with gamma-ray observatories. This work is considered a separate  
1443 project as the statistical treatment is unique from many IceCube analyses. The wiki for [ the

1444 combined analysis] **TODO: instead point to chapter**This chapter presents the analysis work for  
1445 IC3 for DM searches toward dSphs. This section describes the various steps and features of the  
1446 analysis. It is structure first introduces the data and how it is treated, then systematic studies of the  
1447 dwarves individually. Finally, the stacked analysis and results are presented.

1448 **7.2 Dataset and Background**

1449 This section enumerates the data and background methods used for IceCube's study of dSphs.  
1450 Section 7.2.1 and Section 7.2.2 are most useful for fellow IceCube collaborators looking to replicate  
1451 this analysis.

1452 **7.2.1 Itemized IceCube files**

- 1453 • Software Environment: CVMFS Py3-v4.1.1
- 1454 • Data Sample: Northern Tracks NY86v5p1
- 1455 • Analysis Software: cksy ([nu\\_dark\\_matter](#))
- 1456 • Analysis wiki: [https://wiki.icecube.wisc.edu/index.php/Dark\\_Matter\\_Annihilation\\_Search\\_towards\\_dwarf\\_spheroidals\\_with\\_NST\\_and\\_DNN\\_Cascades](https://wiki.icecube.wisc.edu/index.php/Dark_Matter_Annihilation_Search_towards_dwarf_spheroidals_with_NST_and_DNN_Cascades)
- 1458 • Project repository

1459 **7.2.2 Software Tools and Development**

1460 This analysis was performed inside IceCube's CVMFS (3.4.1.1) software environment using  
1461 csky for likelihood calculations. Csky did not come with dark matter spectral models nor could  
1462 accomodate custom flux models. We developed these capacities for single source and stacked  
1463 source studies for this analysis. The analysis code is held in a separate repository from csky. The  
1464 [nu\\_dark\\_matter](#) branch of csky manages the input of custom dark matter spectra and accompanied  
1465 DM astrophysical source then calculates likelihoods with a selected data sample. The [IceCube Dark](#)  
1466 [Matter dSph repository](#) manages the generation of spectral models for neutrinos, physics parameter  
1467 extraction from  $n_{\text{sig}}$ ,  $J$ -factor per source inputs, and bookkeeping for the large parameter space.  
1468 The project repository required a secondary software environment for neutrino oscillations. How

1469 to launch and run those calculations are documented in the project repository and the Docker image  
1470 is additionally saved in Section C.1

### 1471 **7.2.3 Data Set and Background Description**

1472 For this analysis, I use the Northern Sky Tracks (NST) Sample (Version V005-P01). The sample  
1473 contains up-going track-like events, usually from  $\nu_\mu$  and  $\nu_\tau$  and has a superior angular resolution  
1474 compared to the cascade dataset. This sample covers 10.4 years of data (IC86\_2011-2021). The  
1475 accepted neutrino energy range used for the analysis is unique from most other IceCube searches  
1476 because DM spectra are very hard. The sampled energy range is  $1 < \log(E_\nu/\text{GeV}) < 9.51$  with  
1477 step size 0.125.

1478 The strength of a dwarf analysis is that there is no additional background consideration beyond  
1479 nominal, baseline background estimations. For NST, the nominal contribution comes from atmo-  
1480 spheric neutrinos and isotropic astrophysical neutrinos. We estimate the background by scrambling  
1481 NST data along Right Ascension.

## 1482 **7.3 Analysis**

1483 The expected differential neutrino flux from DM-DM annihilation to standard model particles,  
1484  $d\Phi_\nu/dE_\nu$ , over solid angle,  $\Omega$  is described by the familiar equation.

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

1485 This is identical to past examples except that there are 3 neutrino flavors, so there are a corresponding  
1486 3 flux equations. Section 5.3 has a complete description of all the terms. Additionally, neutrinos  
1487 oscillate between flavors which needs to be considered for the expected neutrino flux at Earth.  
1488 Section 7.3.1 presents the particle physics model for DM annihilation. Section 7.3.2 presents the  
1489 spatial distributions built for each dSph.

### 1490 **7.3.1 $\frac{dN_\nu}{dE_\nu}$ - Particle Physics Component**

1491 Neutrino spectra from heavy dark matter annihilation were generated using HDMSSpectra [64]  
1492 and  $\chi$ arrov [68]. HDMSSpectra simulates the decay and annihilation of heavy dark matter, for  
1493 different dark matter masses and SM primary annihilation channels. The simulation includes

1494 electroweak radiative corrections and higher order loop corrections with quarks. This publication  
1495 also pushes the simulated DM mass to the Plank scale (1 EeV), however this study will not explore  
1496 that high.

1497 An important novel feature in the spectra is that neutrino line channels will be accompanied  
1498 with a low energy tail. Thus the earth will not fully attenuate a neutrino SM channel signal from  
1499 high declination sources where the neutrino flux must first traverse through the Earth. The SM  
1500 annihilation channels that feature lines include all leptonic channels. ( $\nu_{e,\mu,\tau}$ ,  $e$ ,  $\mu$ , and  $\tau$ ) We use  
1501 [χarov](#) to propagate and oscillate the neutrinos from the source to Earth. Because these sources are  
1502 quite large in absolute terms, and also far (order 10 kpc or more), the resulting flavor spectra are  
1503 the averages of the transition probabilities [68]:

$$P(\nu_\alpha \rightarrow \nu_\beta) \approx \begin{bmatrix} 0.55 & 0.18 & 0.27 \\ 0.18 & 0.44 & 0.38 \\ 0.27 & 0.38 & 0.35 \end{bmatrix} \quad (7.2)$$

1504 When calculating the expected contribution to  $n_s$ , only  $\nu_\mu$ ,  $\nu_\tau$  are considered as NST's effective  
1505 area to  $\nu_e$  is essentially 0 [69]. With these consideration, the expected composite neutrino spectrum  
1506 is sum of the two flavors:  $\nu_\mu + \nu_\tau$ . The spectral tables are then converted to splines to condense  
1507 information, enable random sampling of the spectra, and enable faster computation times. The  
1508 spectral splines are finally implemented as a DM class in csky. Examples of the spectra before and  
1509 after propagation are shown in Fig. 7.1.

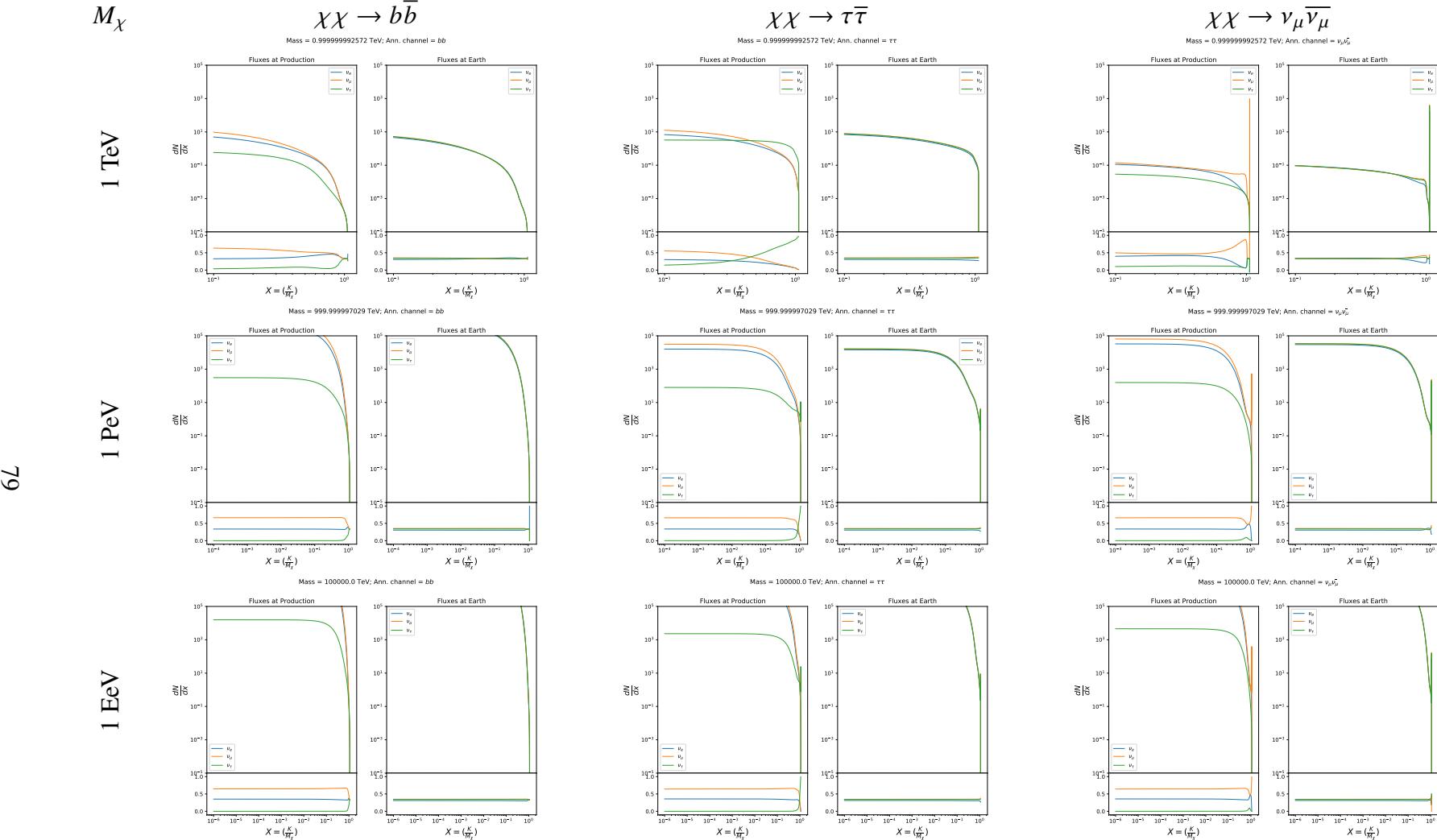


Figure 7.1 Neutrino spectra at production (left panels) and after oscillation at Earth (right panels). Blue, orange, and green lines are the  $\nu_e$ ,  $\nu_\mu$ , and  $\nu_\tau$  spectra respectively. Top panels show the spectra in  $\frac{dN}{dE}$ . Lower panels plot the flavor ratio to  $\nu_e + \nu_\mu + \nu_\tau$ . SM annihilation channels  $b\bar{b}$ ,  $\tau\bar{\tau}$ , and  $\nu_\mu \bar{\nu}_\mu$  are shown for  $M_\chi = 1 \text{ PeV}$ ,  $1 \text{ TeV}$ , and  $1 \text{ EeV}$ .

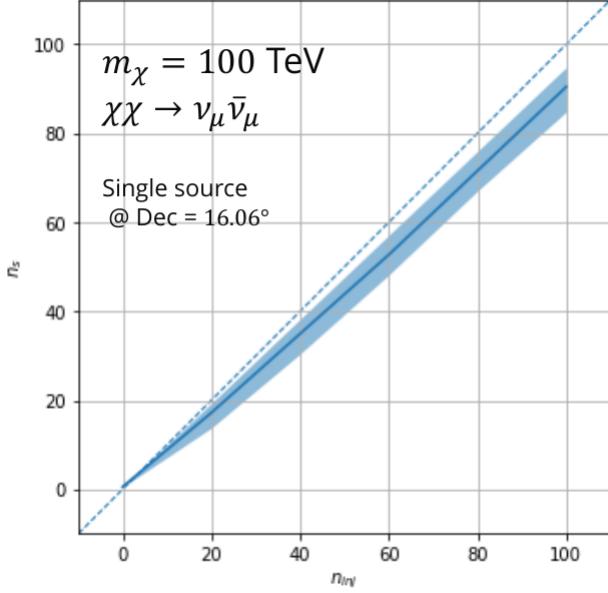


Figure 7.2 Signal recovery for 100 TeV DM annihilation into  $\nu_\mu \bar{\nu}_\mu$  for a source at Dec = 16.06°.  $n_{\text{inj}}$  is the number of injected signal events in simulation.  $n_s$  is the number of reconstructed signal events from the simulation. Although the uncertainties are small and tight, the reconstructed  $n_s$  are systematically underestimated.

### 1510 7.3.1.1 Treatment of Neutrino Line Features

1511 All leptonic DM annihilation channels  $\chi\chi \rightarrow [\nu_{e,\mu,\tau}, e, \mu, \tau]$  develop a prominent and narrow  
 1512 spectral line feature. For all neutrino flavors, this line is visible and prominent in all mass models  
 1513 studied for this analysis. For charged leptons, the feature only really shows up at the larger DM  
 1514 mass models. Examples for lines in both neutrinos and charged leptons annihilation are provided  
 1515 in Fig. 7.1. This line feature is so narrow relative the sampled energy range that the MC rarely  
 1516 samples within the neutrino line. As a result, often the best fit to simulation of background will  
 1517 always floor to TS = 0 and the signal recovery tends to be conservative.

1518 To remedy this, a similar approach to the IceCube’s decay analysis [TODO: refer to Minjin’s](#)  
 1519 [page](#). 2 kernels were tested (Gaussian, uniform (flat)) to smooth out the line feature. The widths  
 1520 were tuned such that the signal recovery approached unity for DM mass 100 TeV to 1 PeV.  
 1521 Additionally, the tuning was performed only for a source at declination 16.06 (Segue 1). This is  
 1522 to avoid confusion loss in signal recovery from too narrow a line and from Earth’s attenuation of  
 1523 high energy neutrinos. The convolution also needed to as close as possible preserve the integrated  
 1524 counts of neutrinos. The optimized kernel window for all lines is summarized as:

- 1525 • Gaussian kernel w/ $2\sigma$  width =  $3.5E-3 \cdot m_\chi$
- 1526 • Minimum energy included in convolution =  $\text{MIN}[0.995 \cdot m_\chi, En(\nu_{line}) - 4\sigma]$
- 1527 • Maximum energy included in convolution =  $\text{MAX}[1.005 \cdot m_\chi, En(\nu_{line}) + 4\sigma]$

1528 where  $En(\nu_{line})$  is the neutrino energy where the neutrino line is at the maximum.

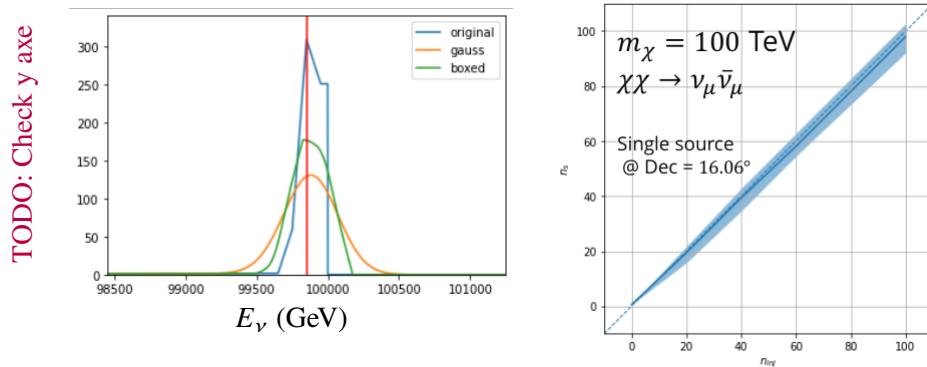


Figure 7.3 Top left panel shows the two kernels overlaid the original spectrum from Charon. delta I is the difference in the integral of the peaks with respect to the original spectrum. The vertical red line indicated where the original neutrino line is maximized. Lower right shows the signal recoveries of the DM model using the Gaussian kernel with parameters enumerated above.

1529 These parameters broadly improved the signal recovery of the line spectra. An example is  
1530 provided below. Signal recovery plots of the full analysis are provided much further down.

### 1531 7.3.1.2 Spline Fitting

1532 In an effort to reduce computational work, memory burden, and align with point source methods  
1533 used for NGC1068 and Seyfert analyses, spectral splines were created and adopted for estimating  
1534 the neutrino flux for the different annihilation. Software was written to generate, handle, and  
1535 calculate values on the splines. When using splines, one has to be careful of the goodness to fit.  
1536 There are critical caveats when testing the goodness to fit to MC generated above for all channels.

- 1537 • The splines must be Log10(\*) in Energy and dN/dE to account for the exponential nature of  
1538 the flux
- 1539 • The fidelity of the fit matters more at  $E_\nu \approx m_\chi$  where the model uncertainties are minimal  
1540 and physical considerations (like the cut-off) are most apparent.

- 1541 • The fidelity of the fit matters less at low  $E_\nu$  as the model uncertainties are large AND  
 1542 IceCube's sensitivity diminishes significantly below 500 GeV

- 1543 • Total integrated counts should be well preserved, however, the resolution of the MC is much  
 1544 higher than IceCube's energy resolution.

1545 – Meaning over several steps in E, the integral is preserved

1546 – the step size enters the cost function

1547 – Oscillating residuals, so long as they are very small and well centered, are not penalized  
 1548 as this gets averaged out.

1549 The resulting cost function to evaluate the goodness of fit was used to account for the above  
 1550 considerations.

$$e_i = x_i \cdot \left( \frac{dN_i}{dE_i} - 10^{\hat{e}_i} \right) \quad (7.3)$$

1551 Where  $\hat{e}_i$  is the spline estimator's value for  $x_i$ .  $x_i = E_{\nu_i}/m_\chi$ .  $\frac{dN_i}{dE_i}$  is the flux value from MC.

$$\text{err} = \sqrt{\frac{1}{x_{\max} - x_{\min}} \int_{x_{\min}}^{x_{\max}} e^2 dx} \quad (7.4)$$

1552 I then take the RMS of the error distribution and the resulting value (err) is used to evaluate  
 1553 the fidelity of the spectral spline. Each SM channel had different tolerances for 'err'. Channels  
 1554 with very hard cut-offs had looser tolerance for err because a lot of error would be generated from  
 1555 the cut-off being estimated to occur slightly early or late. Soft channels don't have this issue and  
 1556 therefore the tolerance is very strict. The table blow summarizes the tolerances for the SM channels.

1557  
 1558 The errors are then plotted in two ways. First, FAIL and OK are directly plotted with  $e_i$  as a  
 1559 function of x, and the full spline and MC. Second, a summary plot of all the splines is plotted and  
 1560 colors coded.

1561 Figure C.1 are the spline summaries and represent the current, up-to-date status of the splines.  
 1562 The goal broadly is to eliminate all red and inspect yellow.  $\nu_e$  is not considered in this analysis  
 1563 among the neutrino final states and so no work was done to converge the spline fits for this flavor.

$\chi\chi \rightarrow$	GOOD	OK	FAIL	Limits of err calc [ $X_{min}, X_{max}$ ]
$Z^0 Z^0, W^+ W^-$	1.0E-3	1.0E-3, 1.0E-2	1.0E-2	MAX[100GeV/ $m_\chi$ , $10^{-6}$ ], 1.0
$t\bar{t}, hh$	1.0E-5	1.0E-5, 1.0E-4	1.0E-4	MAX[100GeV/ $m_\chi$ , $10^{-6}$ ], 1.0
$b\bar{b}, d\bar{d}, u\bar{u}$	9.0E-7	9.0E-7, 9.0E-6	9.0E-6	MAX[100GeV/ $m_\chi$ , $10^{-6}$ ], 1.0
$\nu\bar{\nu}_{e,\mu,\tau}$	1.0E-3	1.0E-3, 1.0E-2	1.0E-2	MAX[100GeV/ $m_\chi$ , $10^{-6}$ ], MIN[0.995, ( $E_n(\nu_{line}) - 4\sigma$ ) / $M_\chi$ ]
$e\bar{e}, \mu\bar{\mu}, \tau\bar{\tau}$	1.0E-3	1.0E-3, 1.0E-2	1.0E-2	MAX[100GeV/ $m_\chi$ , $10^{-6}$ ], MIN[0.995, ( $E_n(\nu_{line}) - 4\sigma$ ) / $M_\chi$ ]

Table 7.1 TODO: fill me daddy

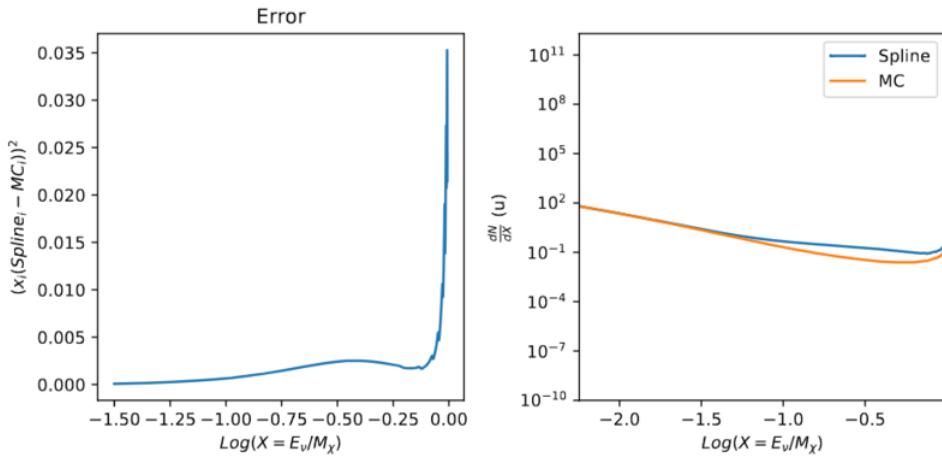


Figure 7.4 Example spline that failed the fit. Failed splined are corrected on a case by case basis unless the SM channel has a systematic problem fitting the splines. In this case, I made a bookkeeping error and loaded the incorrected neutrino flavor

1564     A Final inspection of the splines by eye was done to verify that the spline fitting did not introduce  
 1565     spurious features into the distribution that would corrupt the LLH fitting.

### 1566 7.3.1.3 Composite Neutrino Spectra

1567     With all of the previously mentioned pieces, we are ready to fully assemble a comprehensive  
 1568     description of the particle physics term  $dN/dE$  in Eq. (7.1).

$$\frac{dN_\nu}{dE_{\nu \oplus}} = \left( \frac{dN_{\nu_e}}{dE_{\nu_e}} + \frac{dN_{\nu_\mu}}{dE_{\nu_\mu}} + \frac{dN_{\nu_\tau}}{dE_{\nu_\tau}} \right)_{\text{src}} \cdot \mathbf{P}(\nu_\alpha \rightarrow \nu_\beta) \quad (7.5)$$

1569     Figure 7.5 shows the spectral models that required Gaussian smoothing, the leptonic annihilation  
 1570     channels. The remaining models where the only processing was the spline fitting are documented  
 1571     in the TODO: refer to apdxNotice that the different neutrino flavors are unique, especially in their  
 1572     low energy tails. Therefore, this analysis will be sensitive to DM annihilating to the distinct neutrino

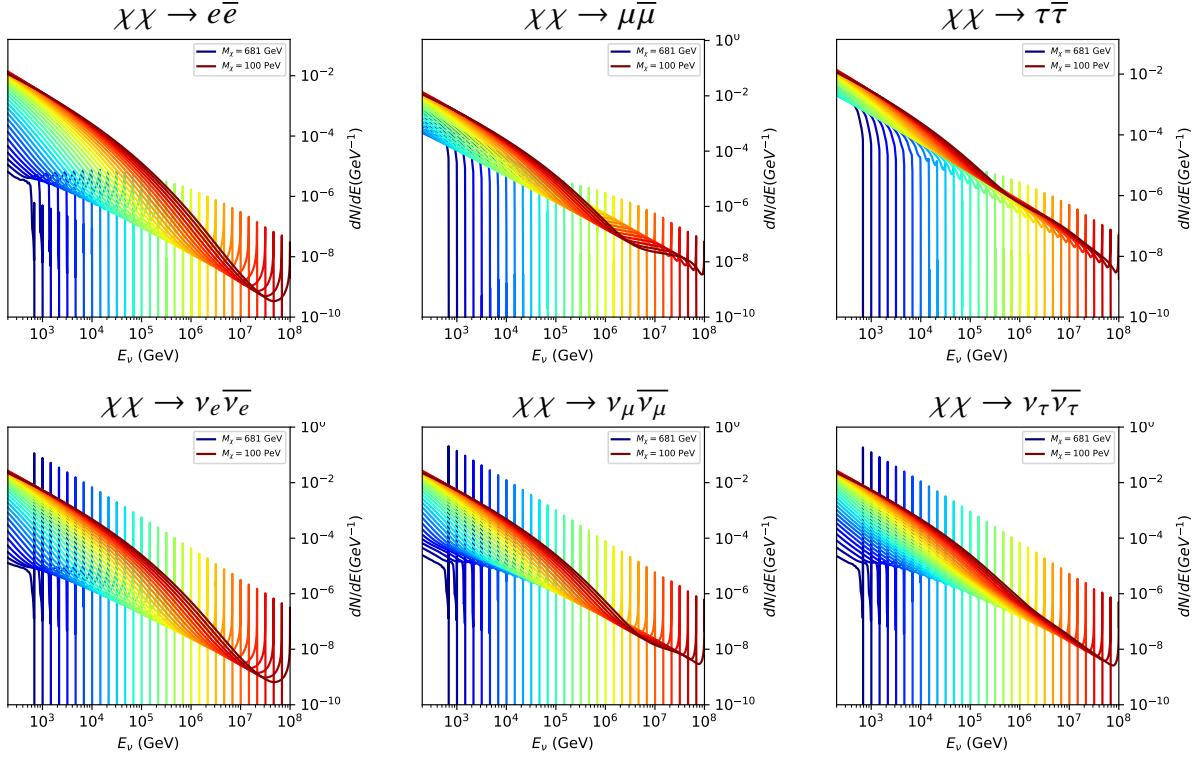


Figure 7.5 Summary of input spectral models that were smoothed with Gaussian kernel. Spectral models are for  $\chi\chi \rightarrow e\bar{e}$ ,  $\mu\bar{\mu}\tau\bar{\tau}$ ,  $\nu_e\bar{\nu}_e$ ,  $\nu_\mu\bar{\nu}_\mu$ , and  $\nu_\tau\bar{\nu}_\tau$ . These spectra are the composite ( $\nu_\mu + \nu_\tau$ ) of neutrino flavors. Every spectral model used for this analysis is featured as a colored solid line. Bluer lines are for lower DM mass spectral models. DM masses range from 681 GeV to 100 PeV. HDM [64],  $\chi$ arov [68], and Photospline [70] are used to generate these spectra. Energy (x-axis) was chosen to roughly represent the energy sensitivity of NST.

1573 flavors. All leptonic channels show prominent, hard features around  $E_\nu = m_\chi$ .

### 1574 7.3.2 J- Astrophysical Component

1575 The expected neutrino counts from a dwarf spheroidal galaxy depends also on the the 'astro-  
 1576 physical factor'. The value for this (in our specific case) J-factor for a target depends on its dark  
 1577 matter density distribution,  $\rho_\chi$  and how far it is  $l$ . For this analysis, we adopt the  $\mathcal{GS}$  model used  
 1578 in Sec. 5 for dSph from [45]. These models are based on a modified Navarro-Frenk-White (NFW)  
 1579 profile where the indices of the NFW (traditionally 1,3,1) are allowed to float. More specifically,  
 1580 these DM distributions are described using the Zhao profile. The Zhao profile is written as:

1581 where  $\theta$  is the angular distance from the center of the source. For the case annihilation, the  
 1582 source diameter, [[https://iopscience.iop.org/article/10.1088/0004-637X/801/2/74 here](https://iopscience.iop.org/article/10.1088/0004-637X/801/2/74)] defined as

1583 the  $2\theta_{\max}$ , of these dwarves is typically under  $1^\circ$  with the largest in the catalog, Fornax, extending  
 1584 to  $2.61^\circ$ . Fornax is not in the northern sky and the remaining sources are notably below this angular  
 1585 size. Therefore, the sources are treated as point sources because the typical source diameter is under  
 1586 1 degree. The J-factor used for the point source assumption is the total J emitted from  $\theta_{\max}$ . These  
 1587 values are enumerated in Geringer-Sameth 2015 and again in the table below with their coordinates.  
 1588 Coordinates are given in J200.0 equatorial coordinates. IceCube uses identical sources to Tab. 5.1  
 1589 except we analyze source with declinations above  $0.0$  degrees.

### 1590 7.3.3 Source Selection and Annihilation Channels

1591 We use all of the dSphs presented in IceCube's previous dSph DM search [69]. IceCube's  
 1592 sources for these simulation studies include Bootes I, Canes VenaticiI, Canes Venatici II, Coma  
 1593 Berenices, Draco, Hercules, Leo I, Leo II, Leo V, Leo T, Segue 1, Segue 2, Ursa Major I, Ursa Major  
 1594 II, and Ursa Minor. A full description of all sources used in Table 5.1. Sources with declinations  
 1595 less than  $0.0$  are excluded from this analysis.

1596 This analysis improves on the previous IceCube dSph paper [69] in the following ways. Pre-  
 1597 viously, the IceCube detector was not yet completed to the 86 string configuration. Many more  
 1598 dSphs will be observed, from 4 to 15. Previously, the particle physics model used for neutrino-ray  
 1599 spectra from DM annihilation did not have EW corrections where they are now included [64]. The  
 1600 spectral models also predict substantial differences between the neutrino flavors, so this analysis  
 1601 will be the first DM dwarf analysis to discriminate between primary neutrino flavors. The study  
 1602 performed here studies 10.4 years of data.

1603 The SM annihilation channels probed for this study include  $b\bar{b}$ ,  $t\bar{t}$ ,  $u\bar{u}$ ,  $d\bar{d}$ ,  $e\bar{e}$ ,  $\mu\bar{\mu}$ ,  $\tau\bar{\tau}$ ,  $ZZ$ ,  
 1604  $W^+W^-$ ,  $\nu_e\bar{\nu}_e$ ,  $\nu_\mu\bar{\nu}_\mu$ , and  $\nu_\tau\bar{\nu}_\tau$ .

### 1605 7.4 Likelihood Methods

1606 I use the Point-Source search likelihood which is widely used in IceCube analyses. The  
 1607 likelihood function is defined as the following:

$$L(n_s) = \prod_{i=1}^N \left[ \frac{n_s}{N} S_i + \left(1 - \frac{n_s}{N}\right) B_i \right] \quad (7.6)$$

1608 where  $i$  is an event index,  $S$  and  $B$  are the signal PDF and background PDF respectively. For a joint  
1609 analysis where the sources are stacked the likelihood is expanded in the simplified way:

$$L(n_s) = \prod_{i=1}^{N_{\text{sources}}} L_i(n_s) \quad (7.7)$$

1610 Where  $L_i$  is the likelihood from the  $i$ -th source in the stacked analysis. The test statistic definition  
1611 remains the same as Eq. (5.6)

## 1612 7.5 Background Simulation

1613 Before we look at data, we must first analyze background and signal injection to validate our  
1614 analysis. The following sections show the results of the likelihood fitting for a suite of background  
1615 trials for the DM models we set out to study in [TODO: refer to the section](#). We study the TS  
1616 distributions first for each source, then for the stacked analysis.

1617 The TS distributions are not expected to behave according to a chi-squared distribution with 1  
1618 degree of freedom. This is in large part due to the distinct spectral shapes demonstrated earlier.  
1619 These can vary significantly between DM mass and annihilation models. Therefore, Wilks' theorem  
1620 may not be applicable to the analysis. Instead, a critical value is defined from a large number of  
1621 background trials.

1622 I assume that TS values are physical:  $\text{TS} \geq 0$ .  $\eta$  denotes the fraction of positive TS values  
1623 above the threshold and written in the legend.  $\epsilon[x]$  indicate the fraction of events where  $\text{TS} < x$ .  
1624 For TS plots shown here, the decimal values of  $x$  are 1.0e-2 and 1.0e-3. The following plots show  
1625 the background TS distributions obtained from Segue1, a source with little Earth attenuation and  
1626 large J-factor, assuming that dark matter annihilates into  $b\bar{b}$ . I also show the 15 source stack TS  
1627 distributions with identical DM models.

### 1628 7.5.1 TS per Source

1629 Below I present the TS distributions for Segue1 and  $\chi\chi \rightarrow b\bar{b}$ . All remaining channels and  
1630 source TS panels are hosted on [TODO: Change this text, it will all be here](#).

1631 Although it was not expected, almost every distribution produced follows a chi2 distribution  
1632 with 1 degree of freedom. This is important for future assumptions made (in multi-messenger) and

1633 may justify statistical calculations assuming Wilk's theorem is valid.

1634 TODO: add text saying that you show: bb, numu, and tau??? specs for Seg1 and UMa2?

1635 **7.5.2 Stacked TS**

1636 The presentation of these plots are identical to the previous 'per Source' section. I use csky  
1637 source software to calculate the TS distributions. Bugs were found when implementing, however  
1638 were rectified. Warning to future users performing a stacked analysis with custom spectra. In  
1639 using the above, I am making the implicit assumption that the primary/only cause to a difference in  
1640 neutrino counts from the sources is accounted for through the J-factors. The J-factors are therefor  
1641 used as weights for the stacking where an individual source's weight is defined as:

1642 Each subplot, except the final, is the TS distribution for a specific DM mass listed in the subplot.  
1643 The final subplot plots the all DM spectral models used as input for the TS distribution calculations  
1644 with bluer lines indicating lower DM mass and redder indicating higher DM mass. Below is an  
1645 image of bb. The full resolution pdfs were provided in links above.

1646 **7.6 Signal Recovery**

1647 **7.6.1 Sensitivities**

1648 In IceCube, we usually define the 90% confidence level (CL), as the minimum number of signal  
1649 events ( $n_s$ ) required to have a Type I error rate smaller than 0.5 and Type II error rate of 0.1. Csky  
1650 performs the sweep to find  $n_s$  that satisfies the previous condition, and from  $n_s$  I use the following  
1651 equation

$$n_s = T_{live} \int_0^{\Delta\Omega} d\Omega \int_{E_{min}}^{E_{max}} dE_\nu A_{eff}(\hat{n}, E_\nu) \frac{d\Phi_\nu}{d\Omega dE_\nu}(\hat{n}, E_\nu), \quad (7.8)$$

1652 to extract the sensitivity on the dark matter annihilation cross-section.  $T_{live}$  is the detector  
1653 livetime,  $A_{eff}$  is the effective area of the detector, and  $E_{min}$ ,  $E_{max}$  are the minimum, maximum  
1654 energies of the expected neutrinos, respectively.

1655 Sensitivities are calculated for each source individually as if they were the only source and as  
1656 a stack. Example plots of these plots are shown below and organized by the single source/stacked  
1657 studies. Finally, I generated a plot with all hypotheses which is presented at the very end.

1658 **7.7 Systematics**

1659     Lol What Systematics. Beside signal recovery we don't have many additional studies for here.  
1660     The current analysis plan is to compare these sensitivities to another  $J$ -factor catalog such as  $\mathcal{LS}$   
1661     [65]. Additionally, we set out to perform a standard suite of IceCube systematic studies which  
1662     include: **TODO: THE BIG 4: ICE MODEL ETC**

1663 **7.8 Conclusions**

1664     We built many things for this analysis. We utilized advanced computing techniques like  
1665     parallel programming and spline fitting of particle physics Monte Carlo to greatly expand and  
1666     refine IceCube's sensitivity to DM annihilation from dSphs. We imported updated astrophysical  
1667     and particle physics models that better represent what we believe neutrino signals from DM  
1668     annihilation should look like. We, for the first time, build an analysis that is sensitivity to PeV DM  
1669     annihilation.

1670     When we compare to previous IceCube publications of dSphs [69], we see an order of magnitude  
1671     improvement to our sensitivity. This analysis has been working group approved within IceCube and  
1672     has begun the unblinding process. This processes did not complete in time for this dissertation.  
1673     Therefor we do not show data for this thesis and is the clear next step.

1674     The test statistic distributions in this analysis also demonstrate more characteristic behaviour  
1675     compared to previous DM analyses. With a 10 year dataset, we finally have enough statistics to  
1676     almost trivially combine with other photon observatories, such as HAWC. The first ground work for  
1677     a multi-messenger DM search is provided with concluding remarks in Sec. 8.

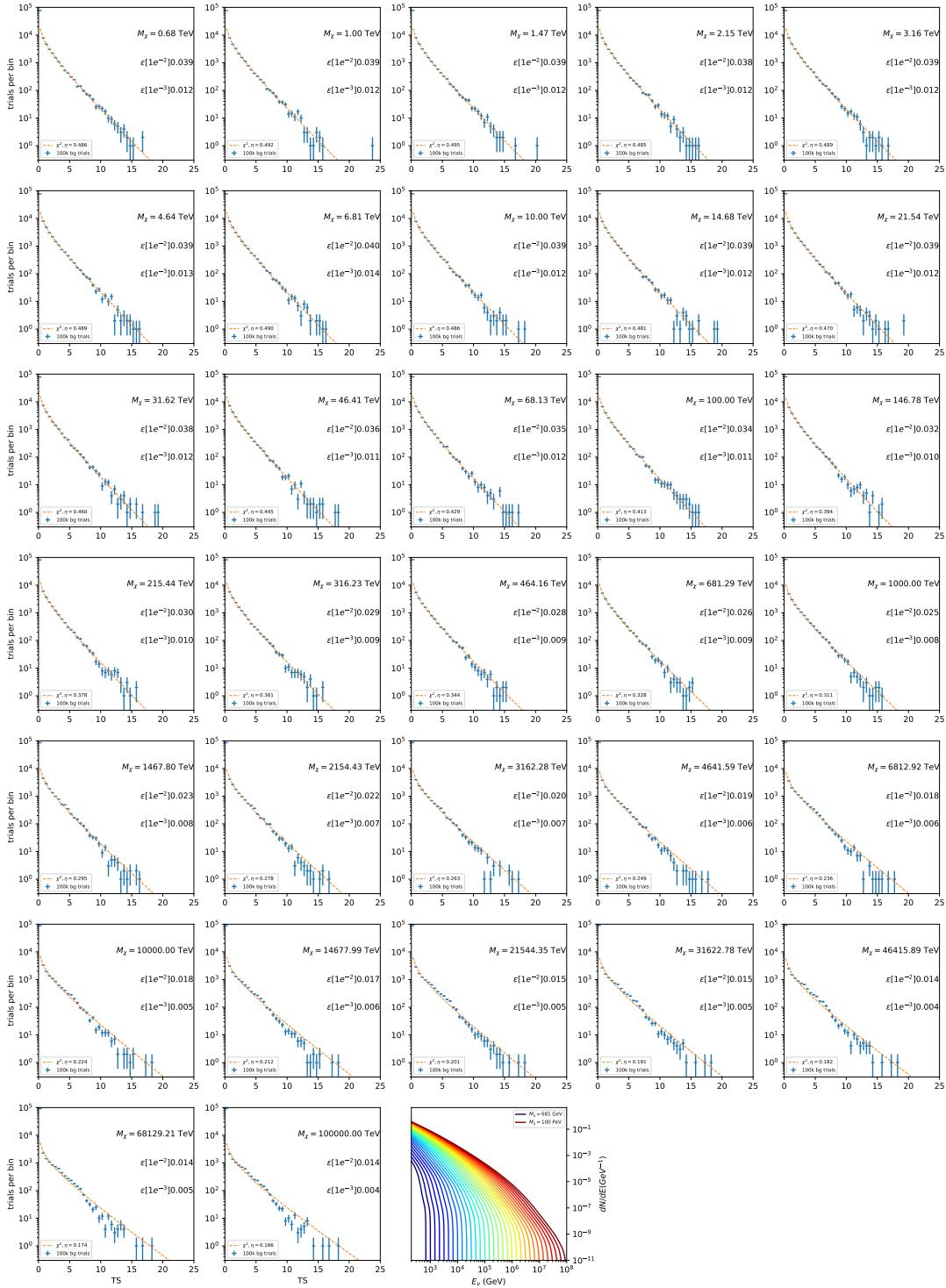


Figure 7.6 Test statistic (TS) distributions for Segue 1 and  $\chi\chi \rightarrow b\bar{b}$ . Each subplot, except the final, is the TS distribution for a specific DM mass listed in the subplot. Orange dashed lines are the traces for a  $\chi^2$  distribution with 1 degree of freedom.  $\epsilon[\cdot]$  is the fraction of trials smaller than the bracketed value. The final subplot plots the all DM spectral models, similar to Fig. 7.5, used as input for the TS distributions.

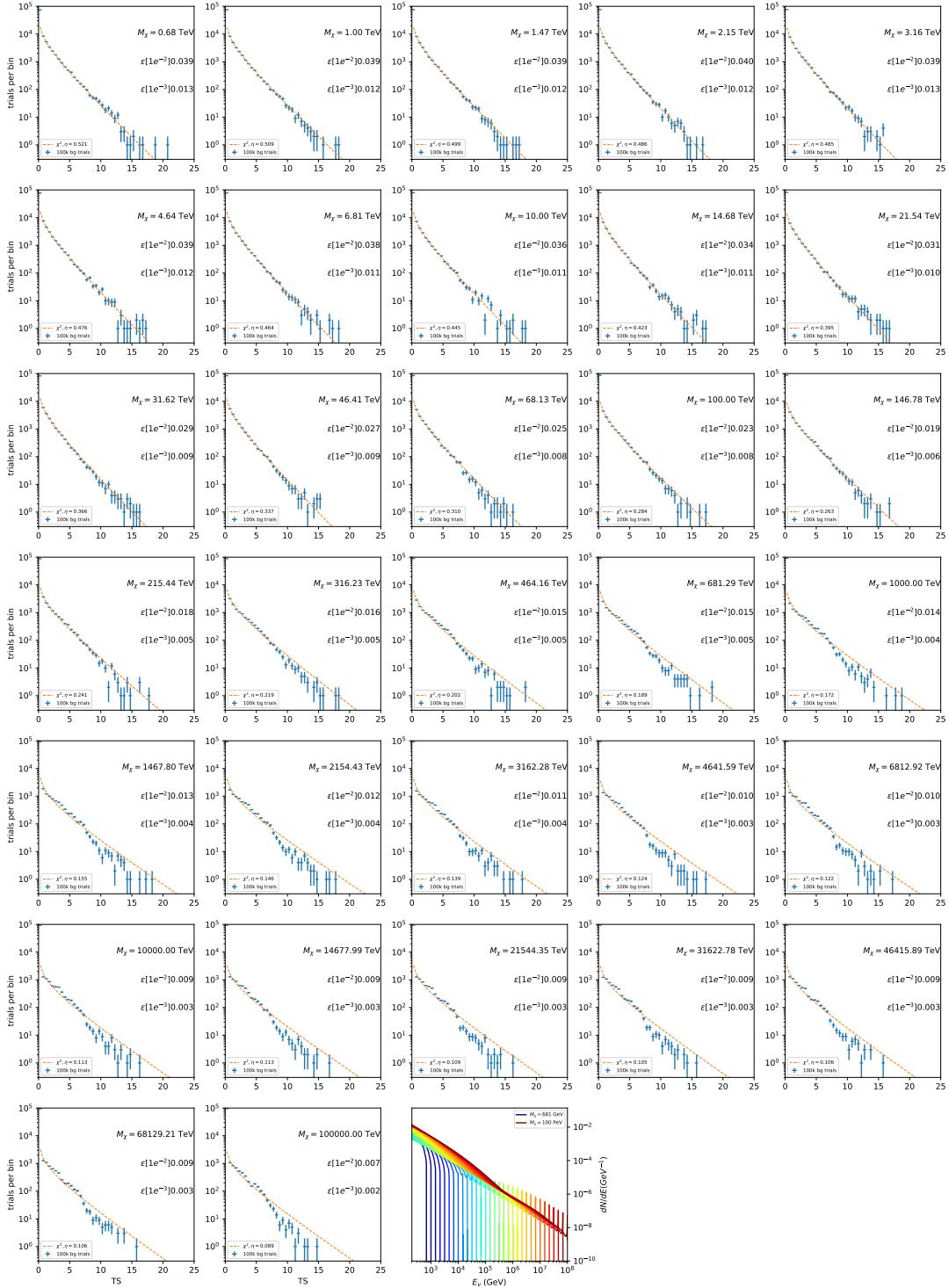


Figure 7.7 Same as Fig. 7.6 for Segue 1  $\chi\chi \rightarrow \tau\bar{\tau}$ .

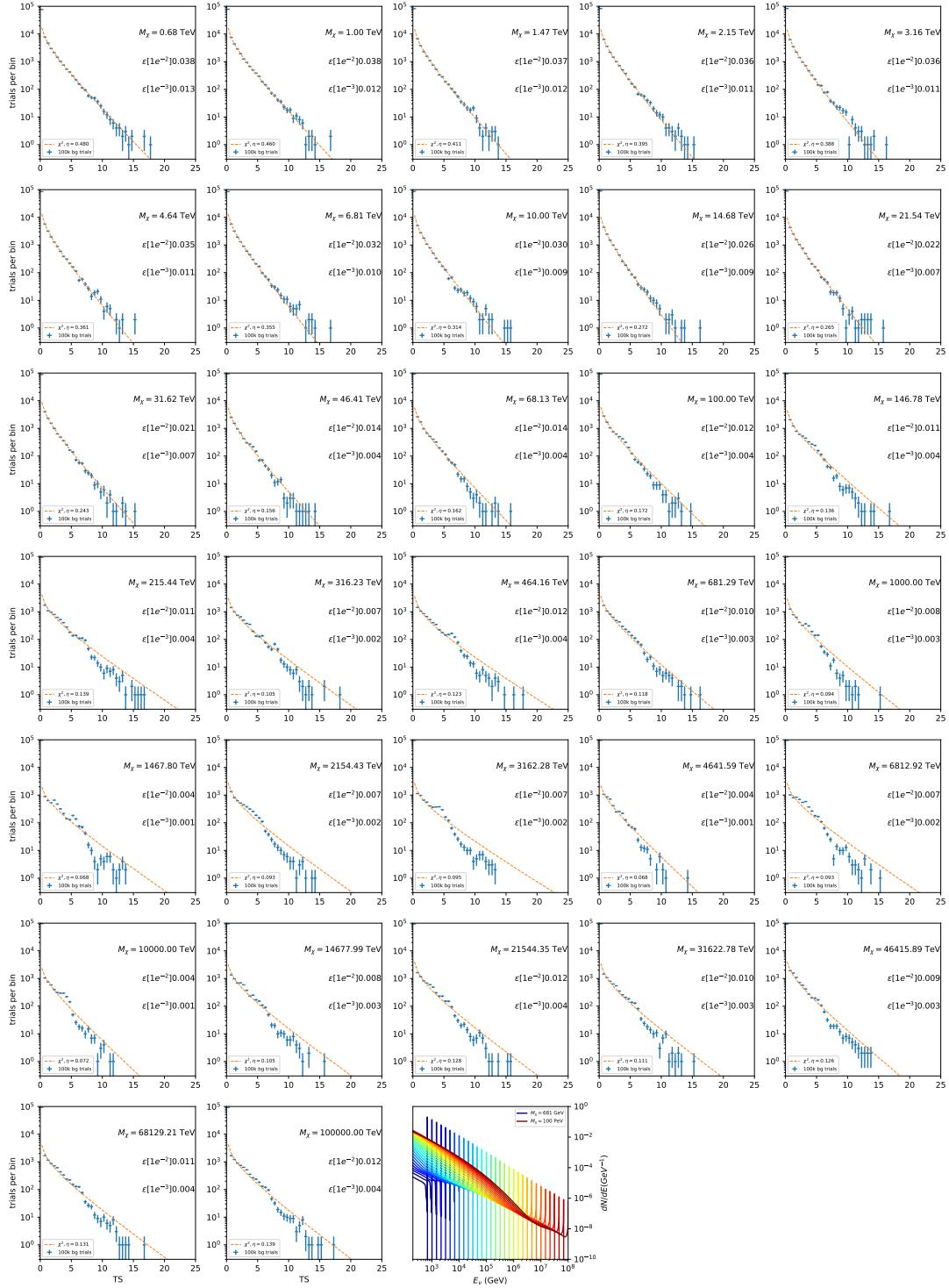


Figure 7.8 Same as Fig. 7.6 for Segue 1  $\chi\chi \rightarrow \nu_\mu\bar{\nu}_\mu$ .

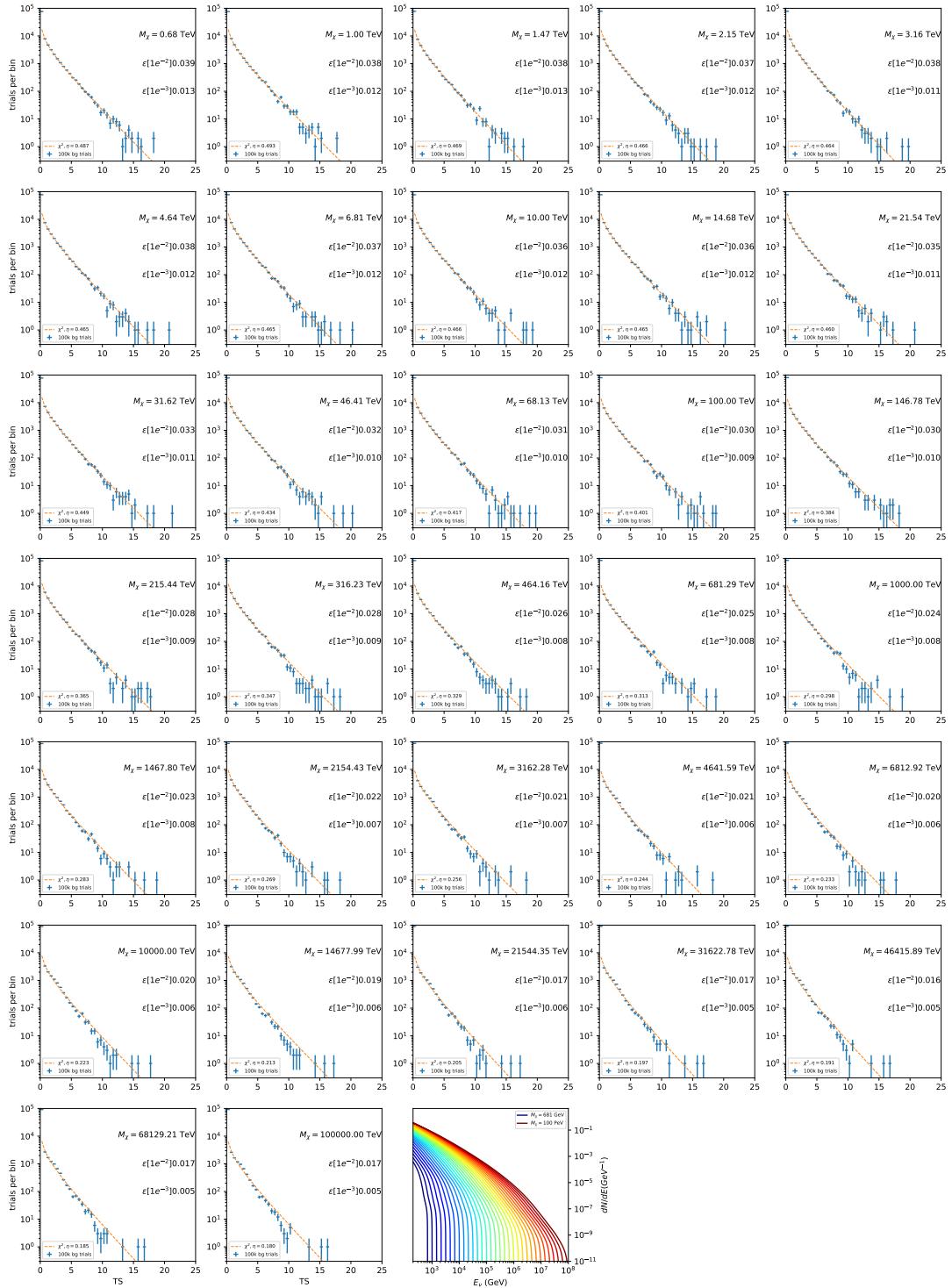


Figure 7.9 Same as Fig. 7.6 for Ursa Major II 1  $\chi\chi \rightarrow b\bar{b}$ .

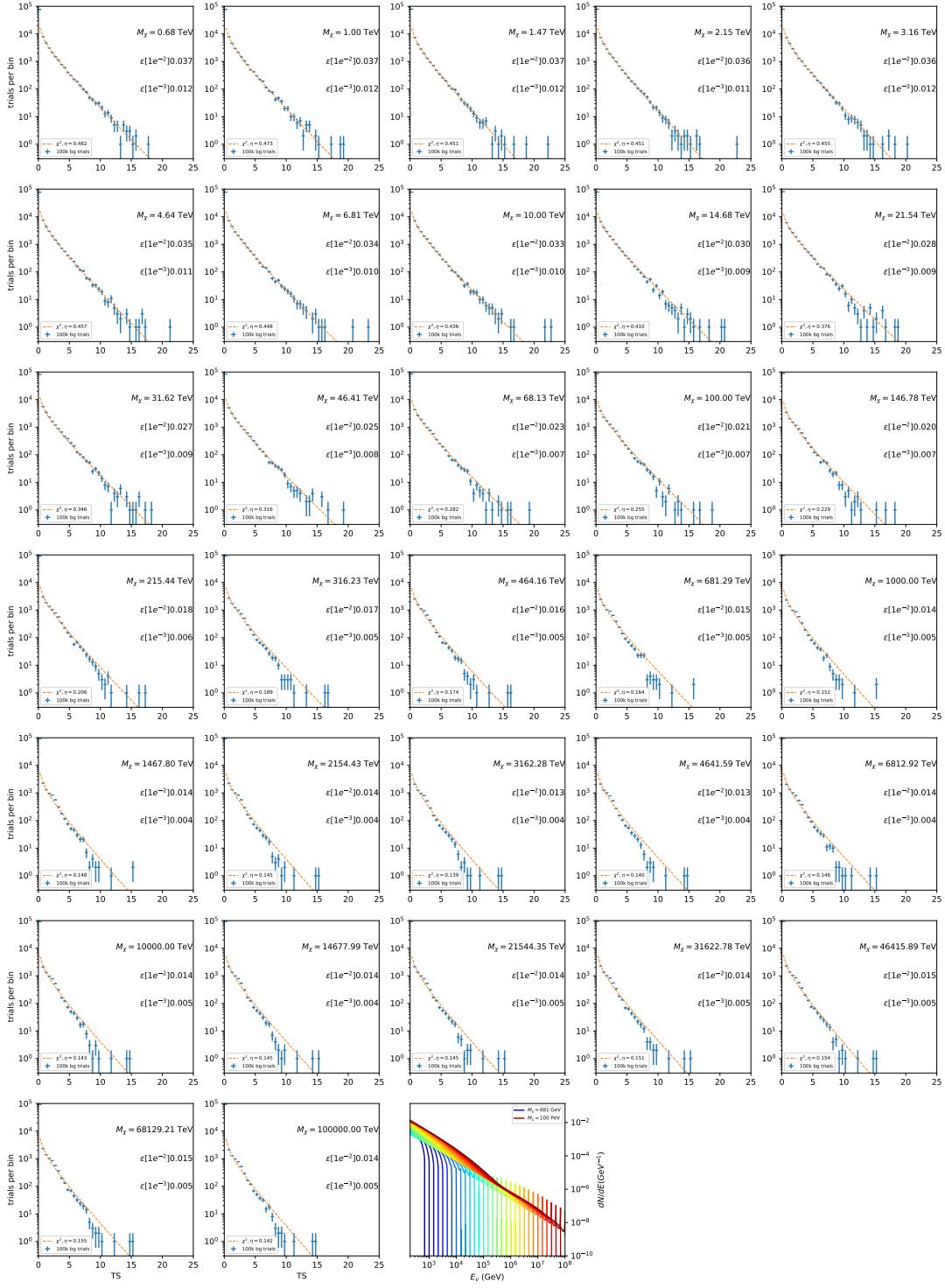


Figure 7.10 Same as Fig. 7.6 for Ursa Major II 1  $\chi\chi \rightarrow \tau\bar{\tau}$ .

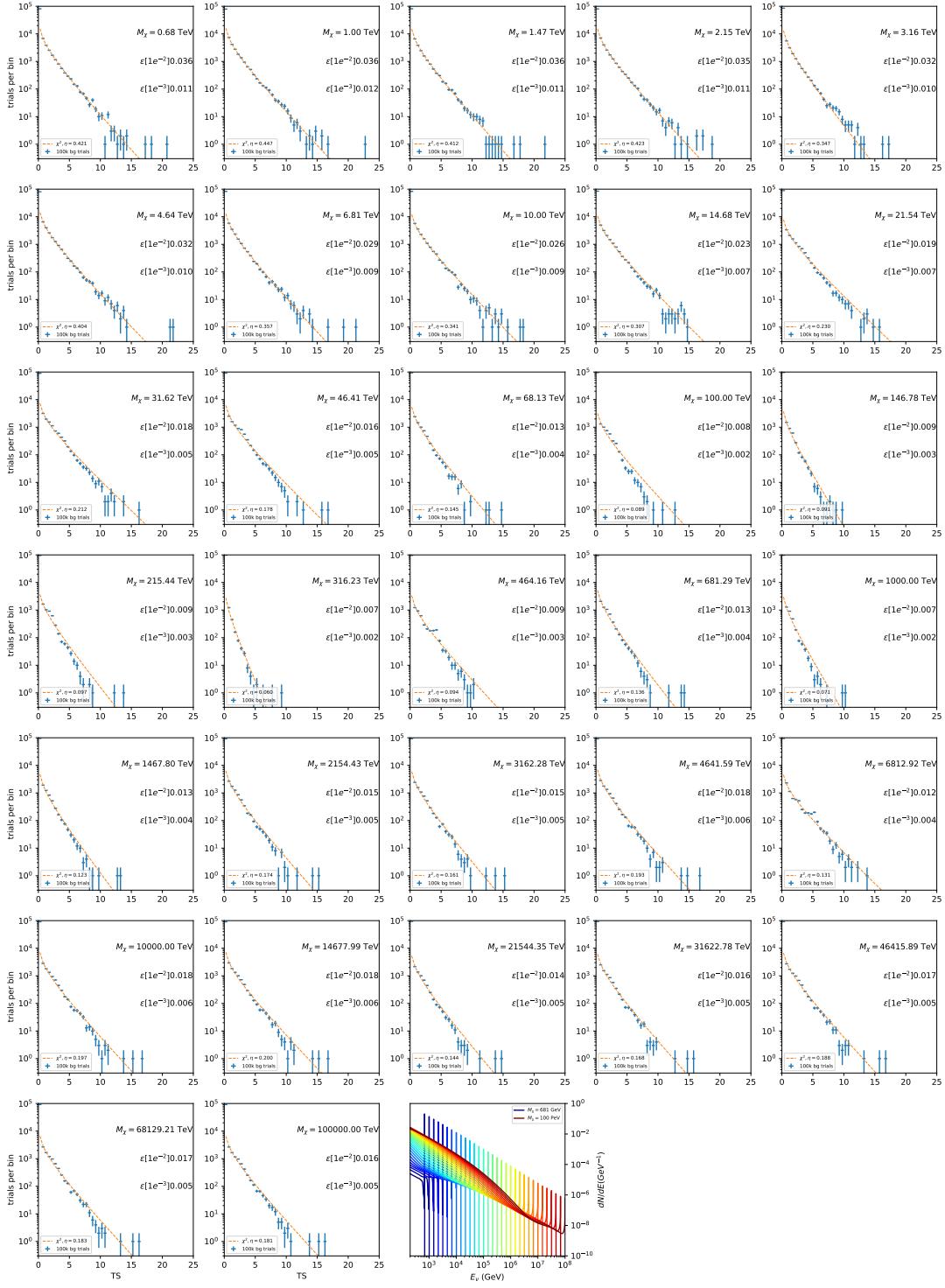


Figure 7.11 Same as Fig. 7.6 for Ursa Major II 1  $\chi\chi \rightarrow \nu_\mu\bar{\nu}_\mu$ .

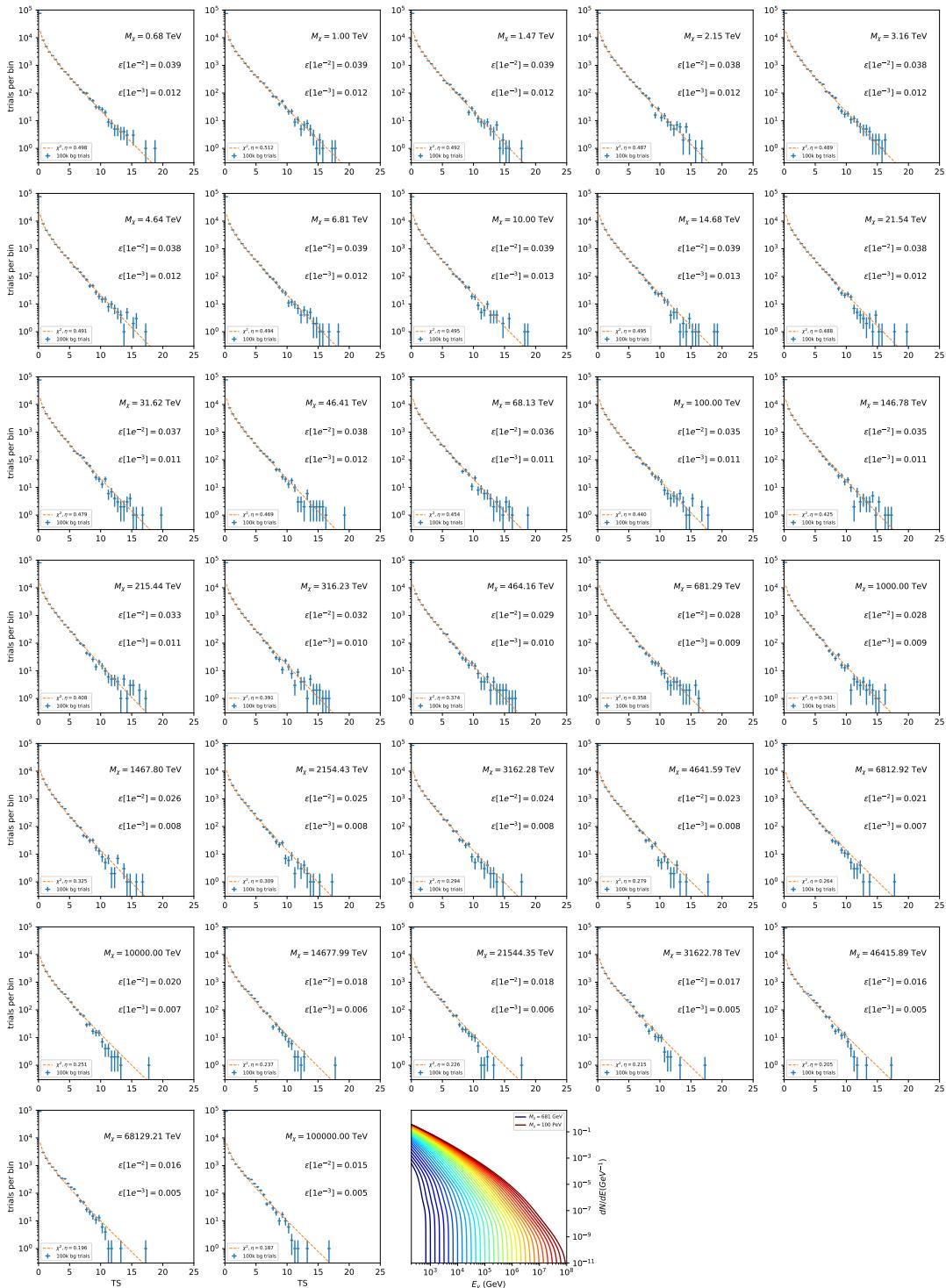


Figure 7.12 Same as Fig. 7.6 for 15,  $\mathcal{G}\mathcal{S}$  J-factor, stacked sources and  $\chi\chi \rightarrow b\bar{b}$ .

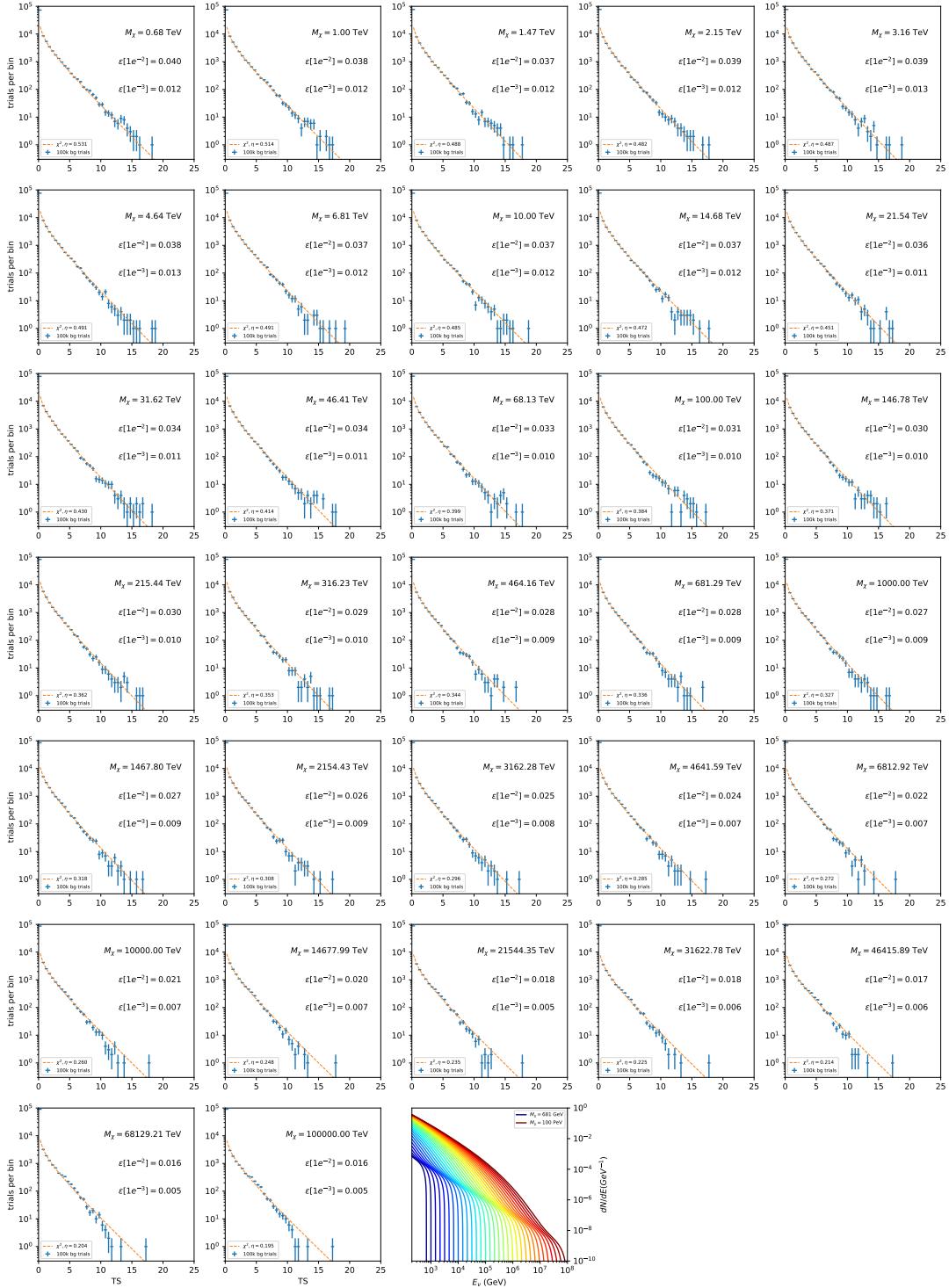


Figure 7.13 Same as Fig. 7.6 for 15,  $\mathcal{GS}$  J-factor, stacked sources and  $\chi\chi \rightarrow t\bar{t}$ .

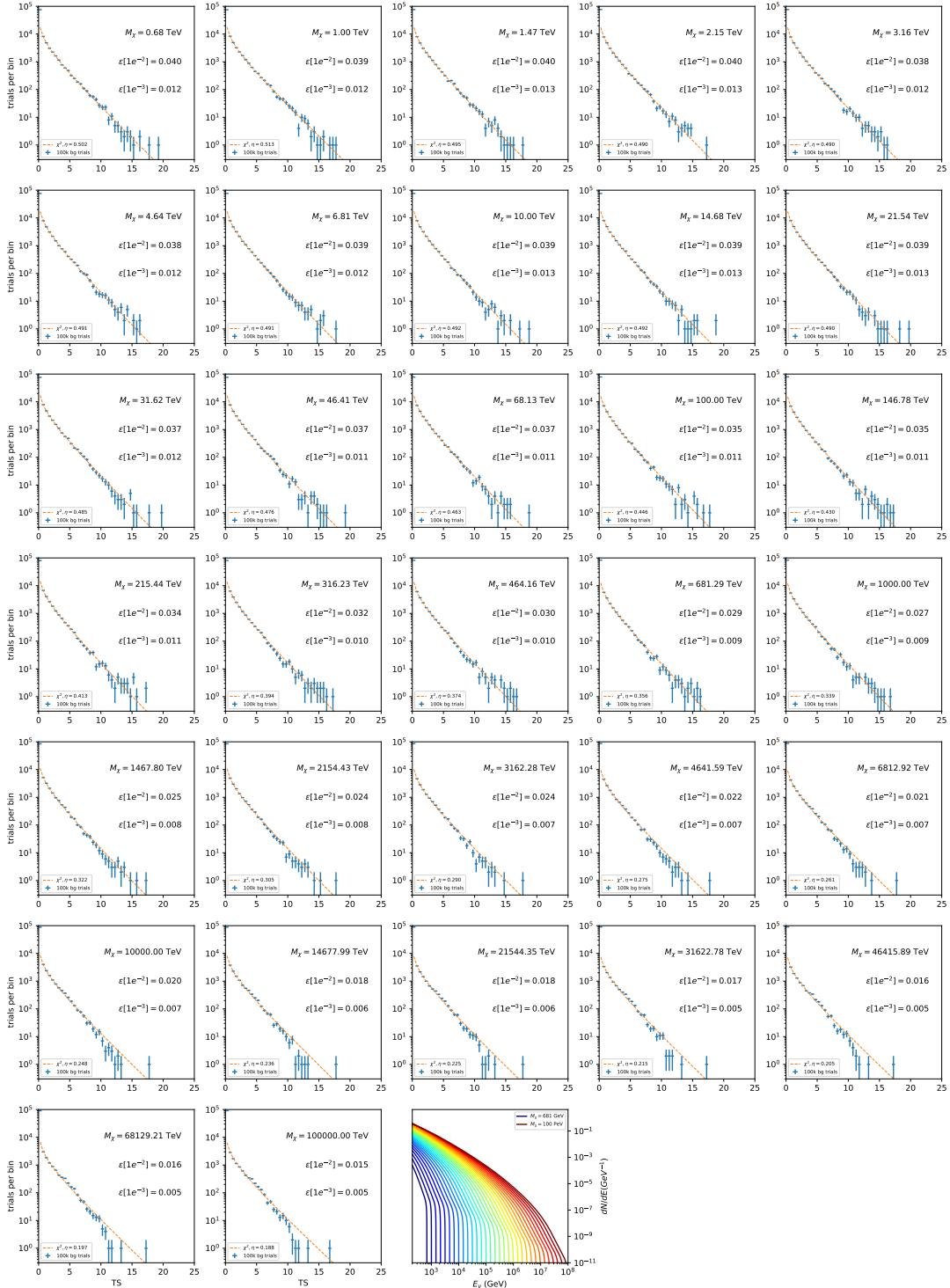


Figure 7.14 Same as Fig. 7.6 for 15,  $\mathcal{GS}$   $J$ -factor, stacked sources and  $\chi\chi \rightarrow u\bar{u}$ .

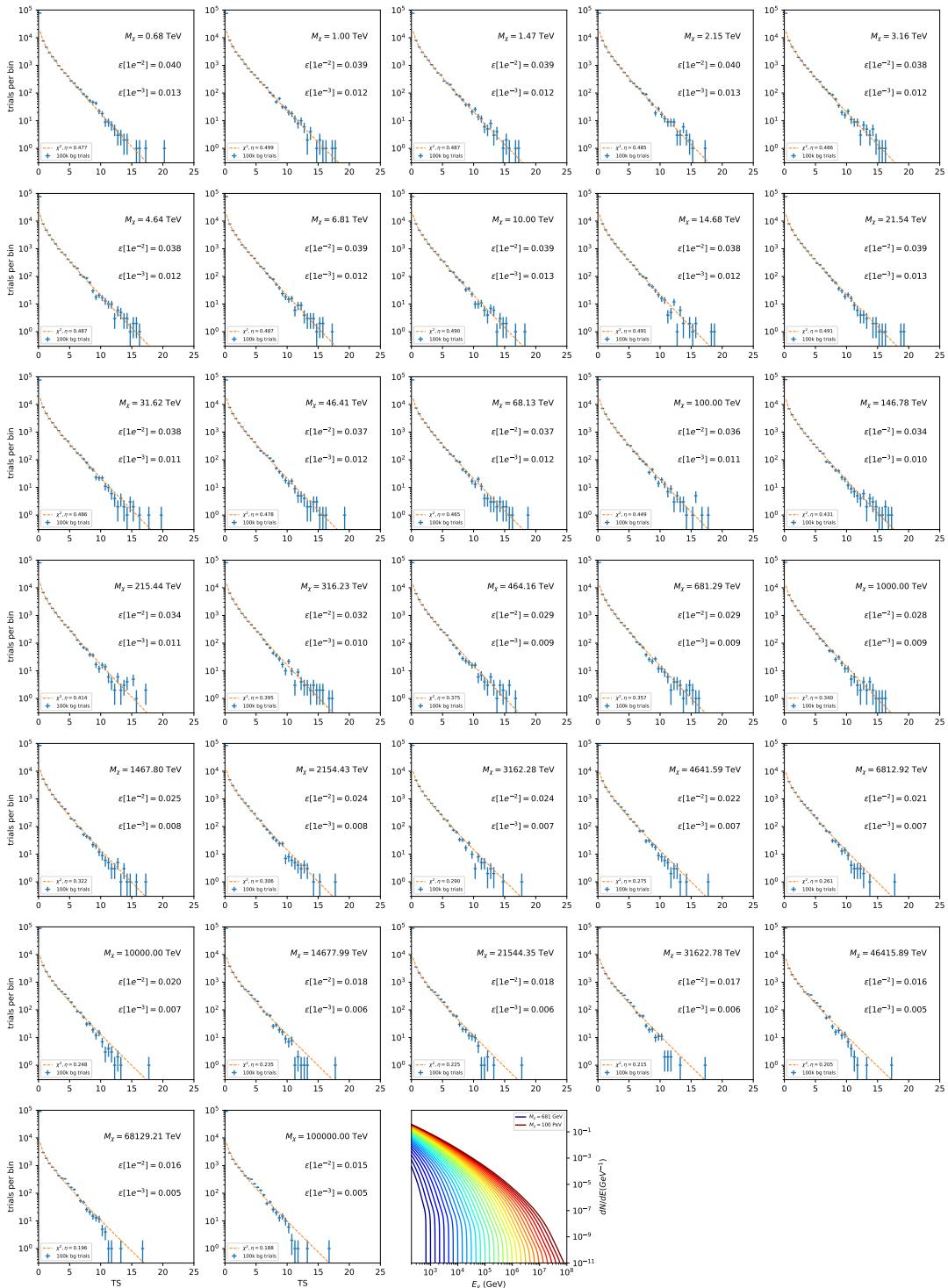


Figure 7.15 Same as Fig. 7.6 for 15,  $\mathcal{GS}$  J-factor, stacked sources and  $\chi\chi \rightarrow d\bar{d}$ .

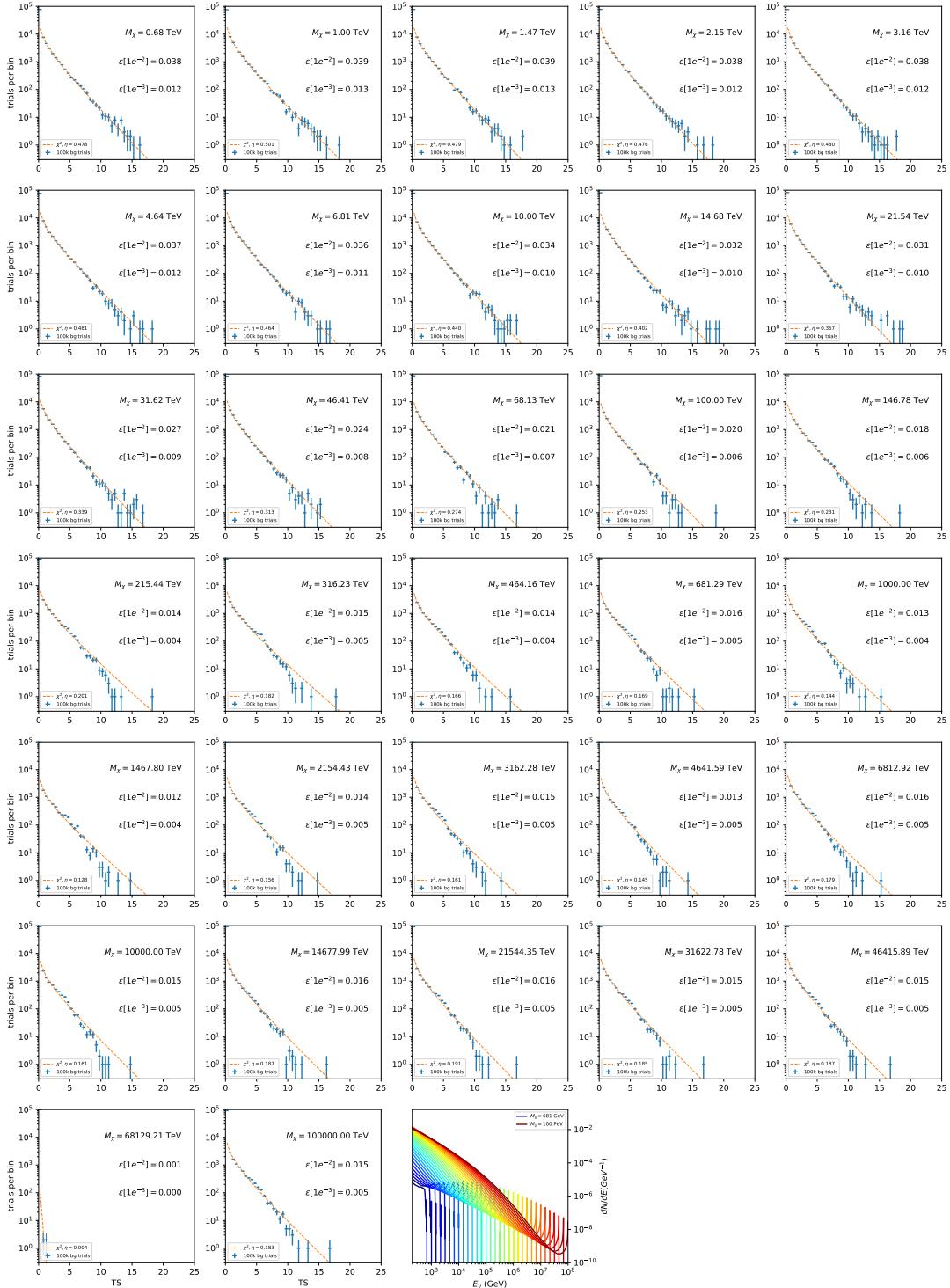


Figure 7.16 Same as Fig. 7.6 for 15,  $\mathcal{GS}$  J-factor, stacked sources and  $\chi\chi \rightarrow e\bar{e}$ .

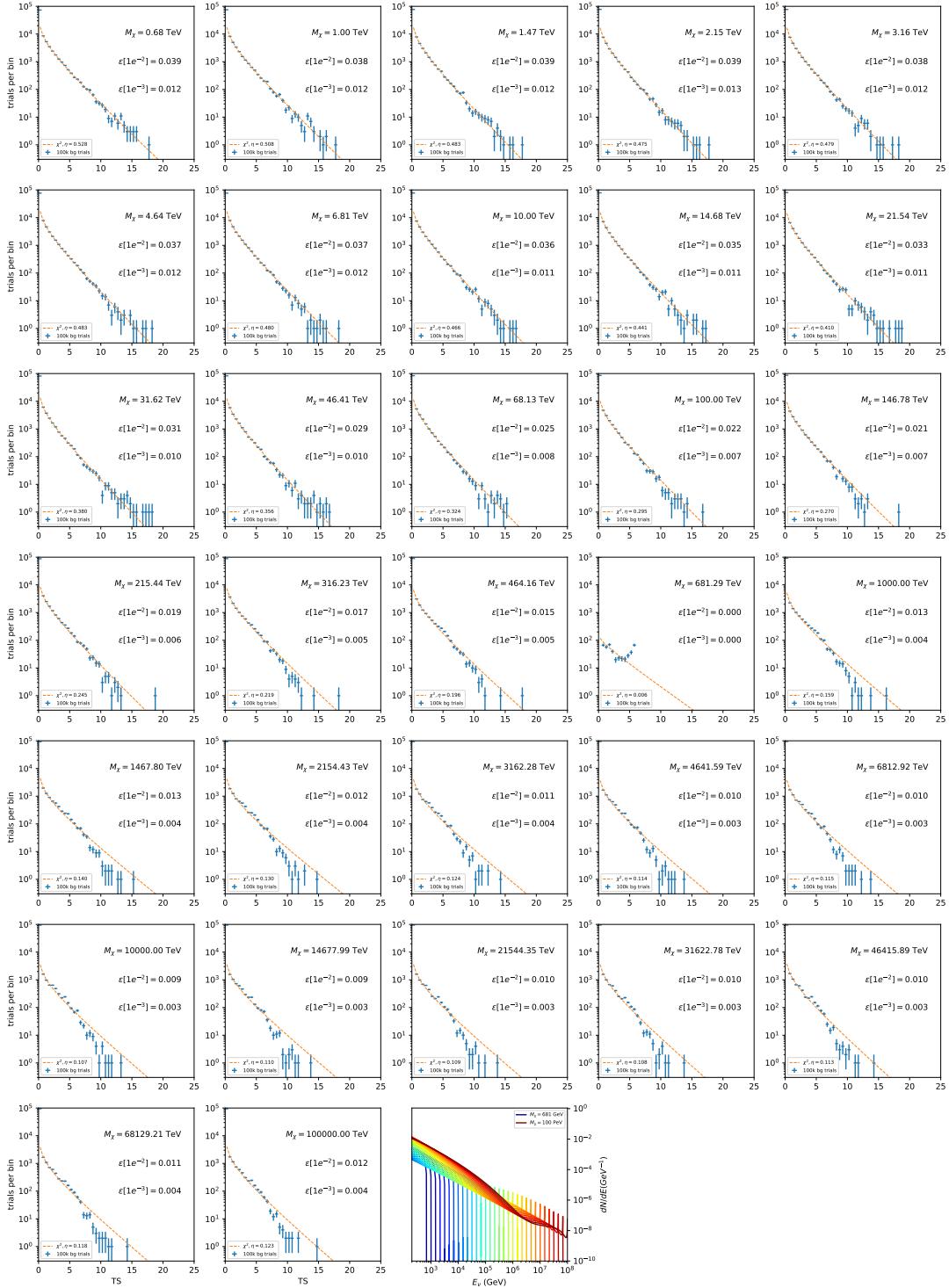


Figure 7.17 Same as Fig. 7.6 for 15,  $\mathcal{GS}$   $J$ -factor, stacked sources and  $\chi\chi \rightarrow \mu\bar{\mu}$ .

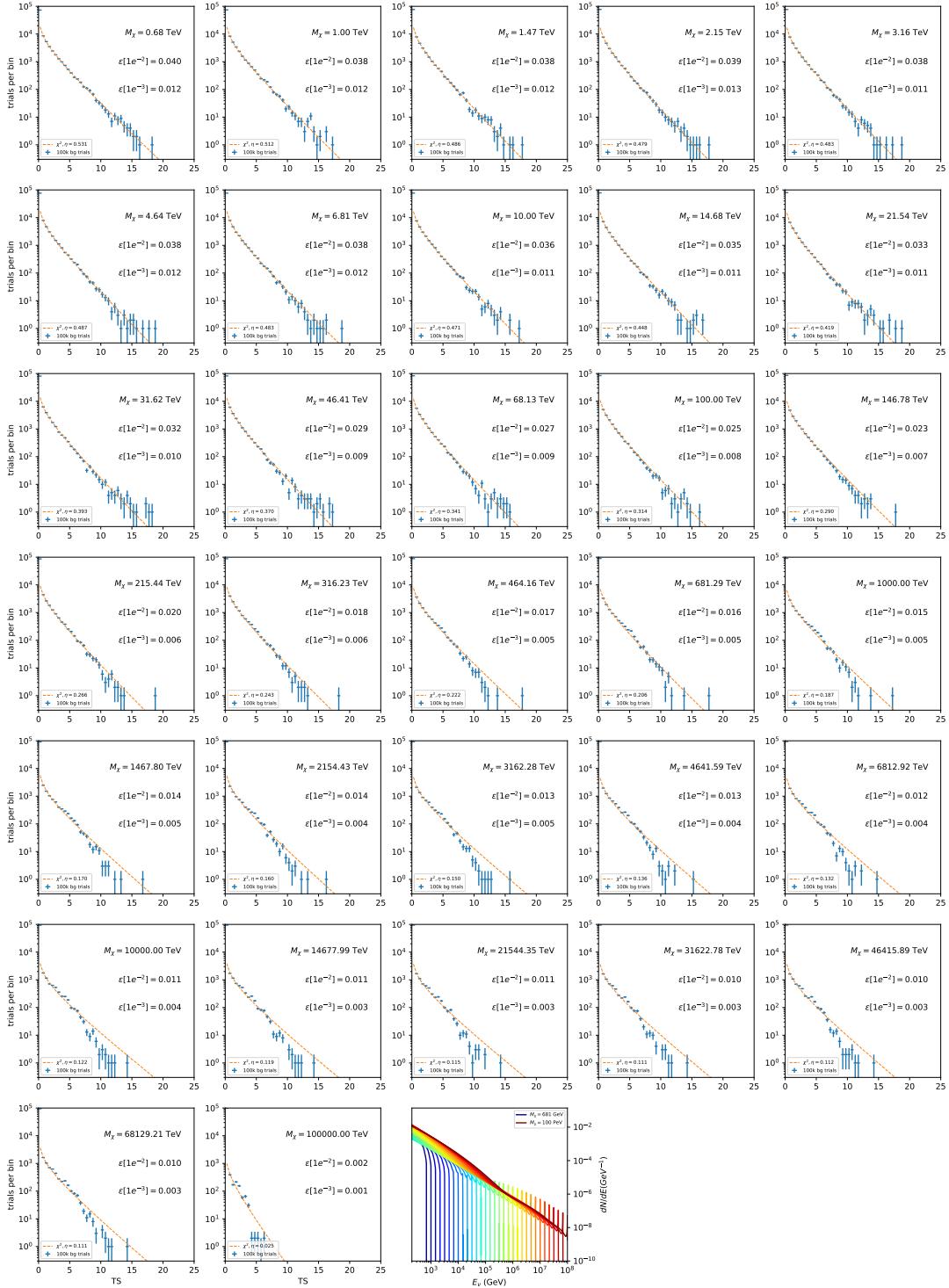


Figure 7.18 Same as Fig. 7.6 for 15,  $\mathcal{GS}$   $J$ -factor, stacked sources and  $\chi\chi \rightarrow \tau\bar{\tau}$ .

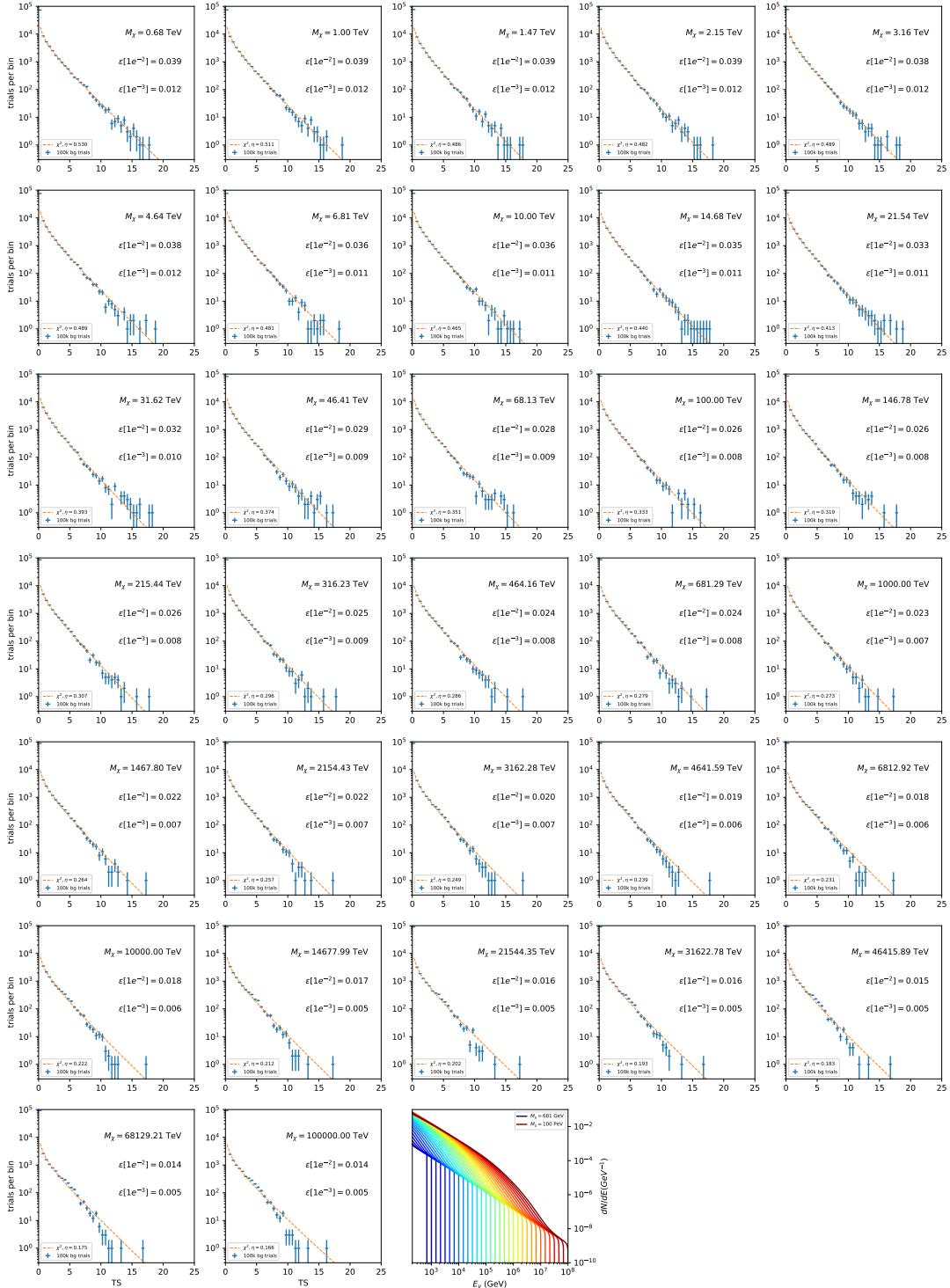


Figure 7.19 Same as Fig. 7.6 for 15,  $\mathcal{GS}$  J-factor, stacked sources and  $\chi\chi \rightarrow W^+W^-$ .

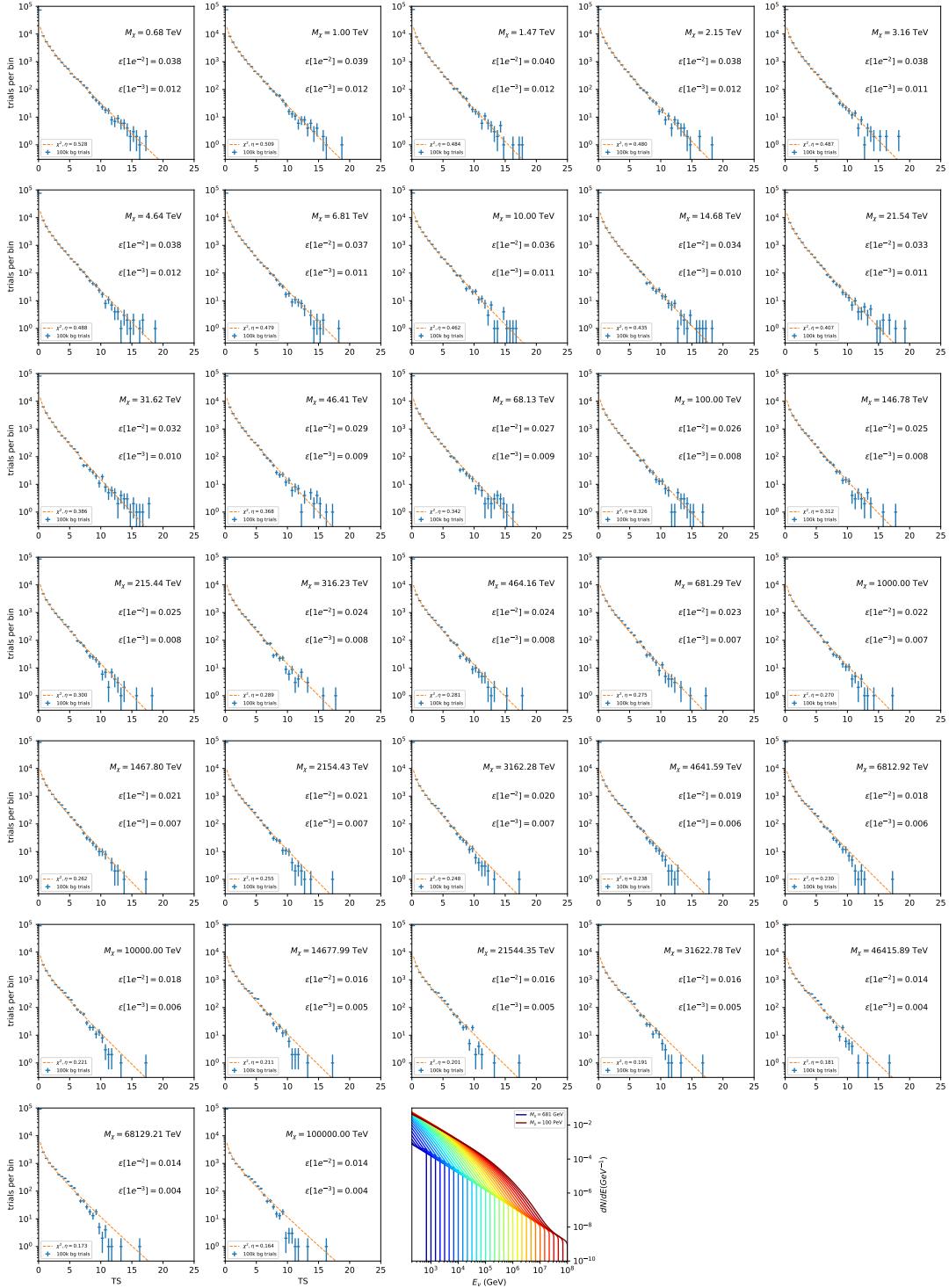


Figure 7.20 Same as Fig. 7.6 for 15,  $\mathcal{GS}$  J-factor, stacked sources and  $\chi\chi \rightarrow ZZ$ .

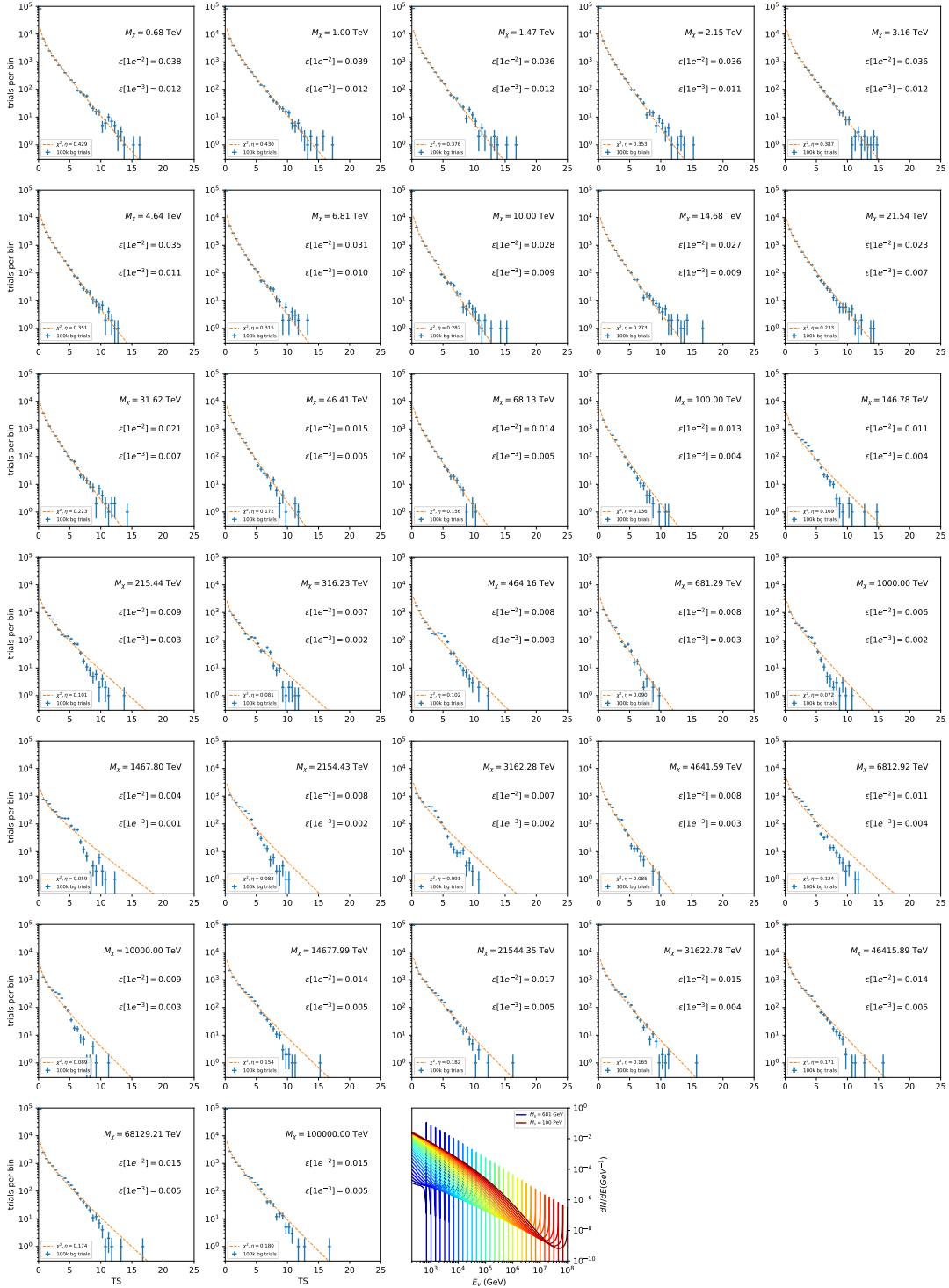


Figure 7.21 Same as Fig. 7.6 for 15,  $\mathcal{GS}$   $J$ -factor, stacked sources and  $\chi\chi \rightarrow \nu_e \bar{\nu}_e$ .

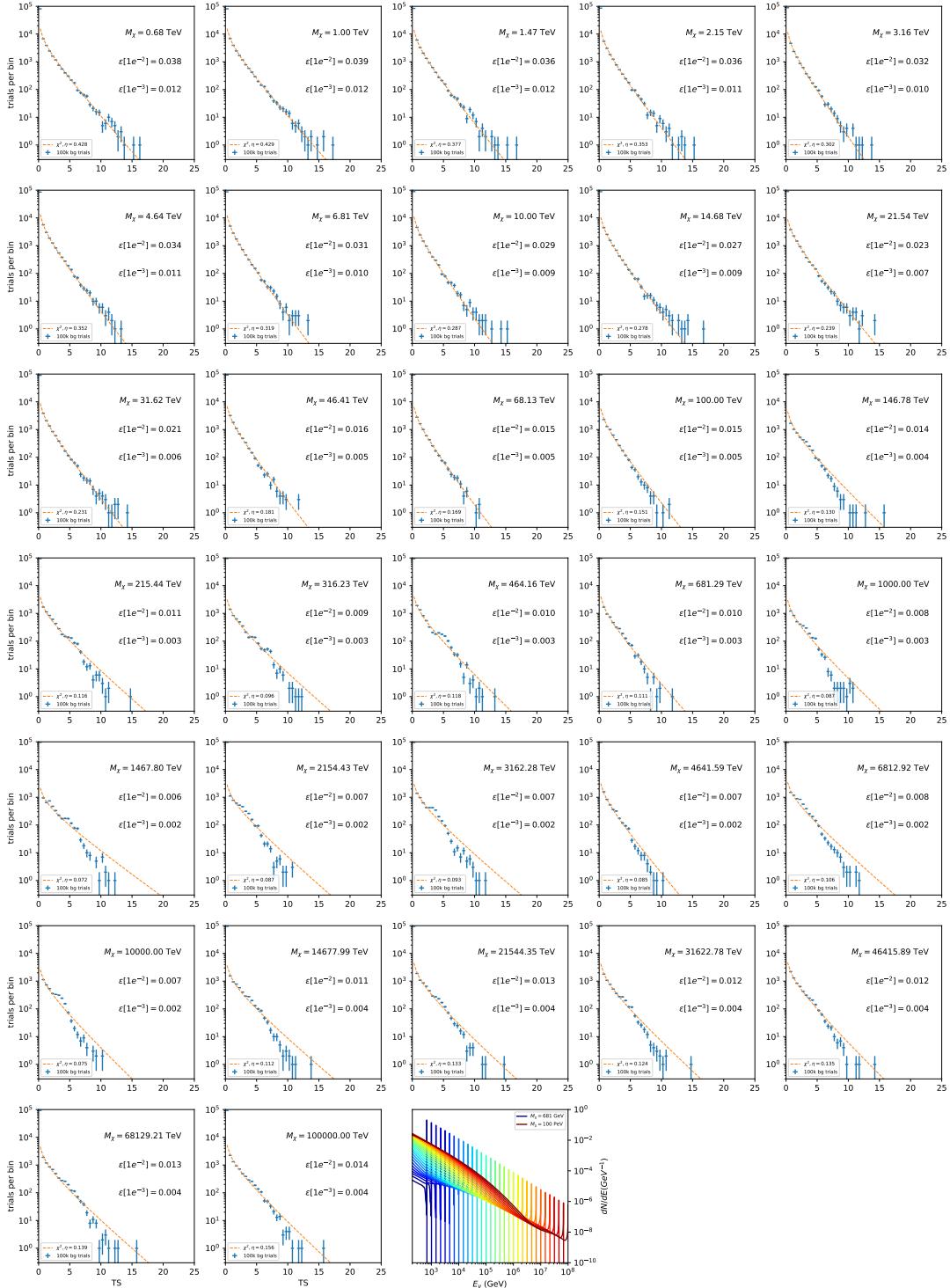


Figure 7.22 Same as Fig. 7.6 for 15, GS J-factor, stacked sources and  $\chi\chi \rightarrow \nu_\mu \bar{\nu}_\mu$ .

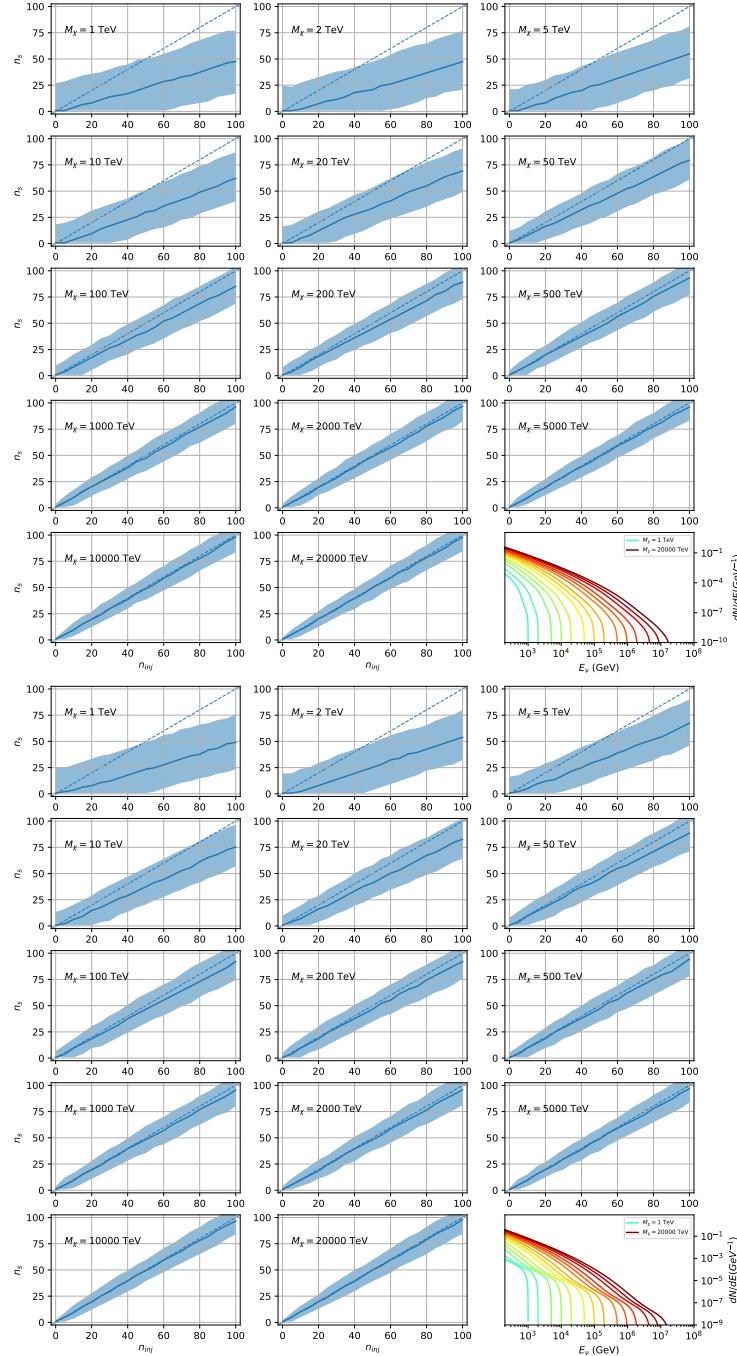


Figure 7.23 Signal Recovery study for an analysis with 15 stacked sources using the  $\mathcal{GS}$   $J$ -factors [45]. Each panel block represents 14 studies for DM mass ranging between 1 TeV and 20 PeV and one annihilation channel. Top panel block is for  $\chi\chi \rightarrow b\bar{b}$ . Bottom panel block is for  $\chi\chi \rightarrow t\bar{t}$ . Each panel block features every spectral model used as input in the bottom-right subpanel. The remaining panels show  $N_{inj}$  as the number of signal events injected into background simulation. Whereas,  $N_s$  is the number of signal events recovered from analyzing the injected simulation. Blue line represents the median values of 100 simulations. Light blue bands show the  $1\sigma$  statistical uncertainty around the median.

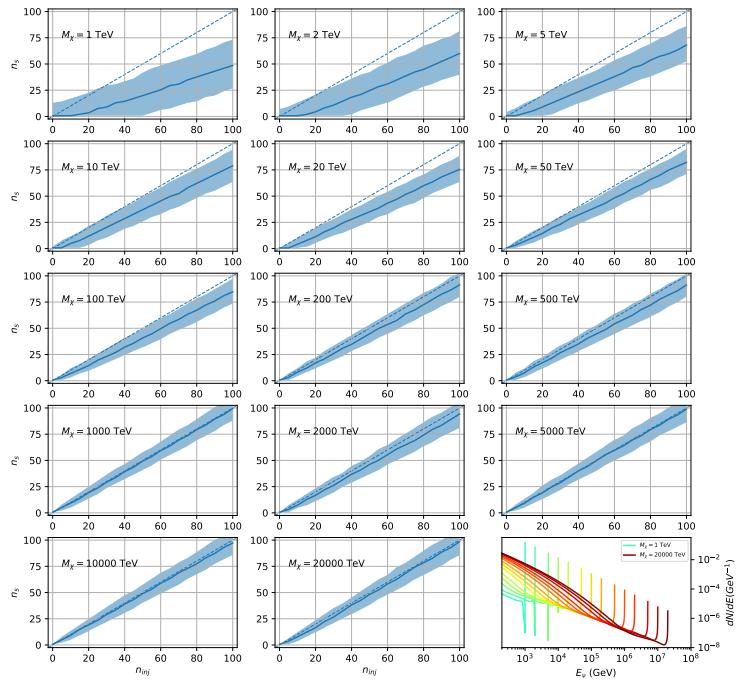


Figure 7.24 Same as Fig. 7.23 but for  $\chi\chi \rightarrow \nu_\mu\bar{\nu}_\mu$ .

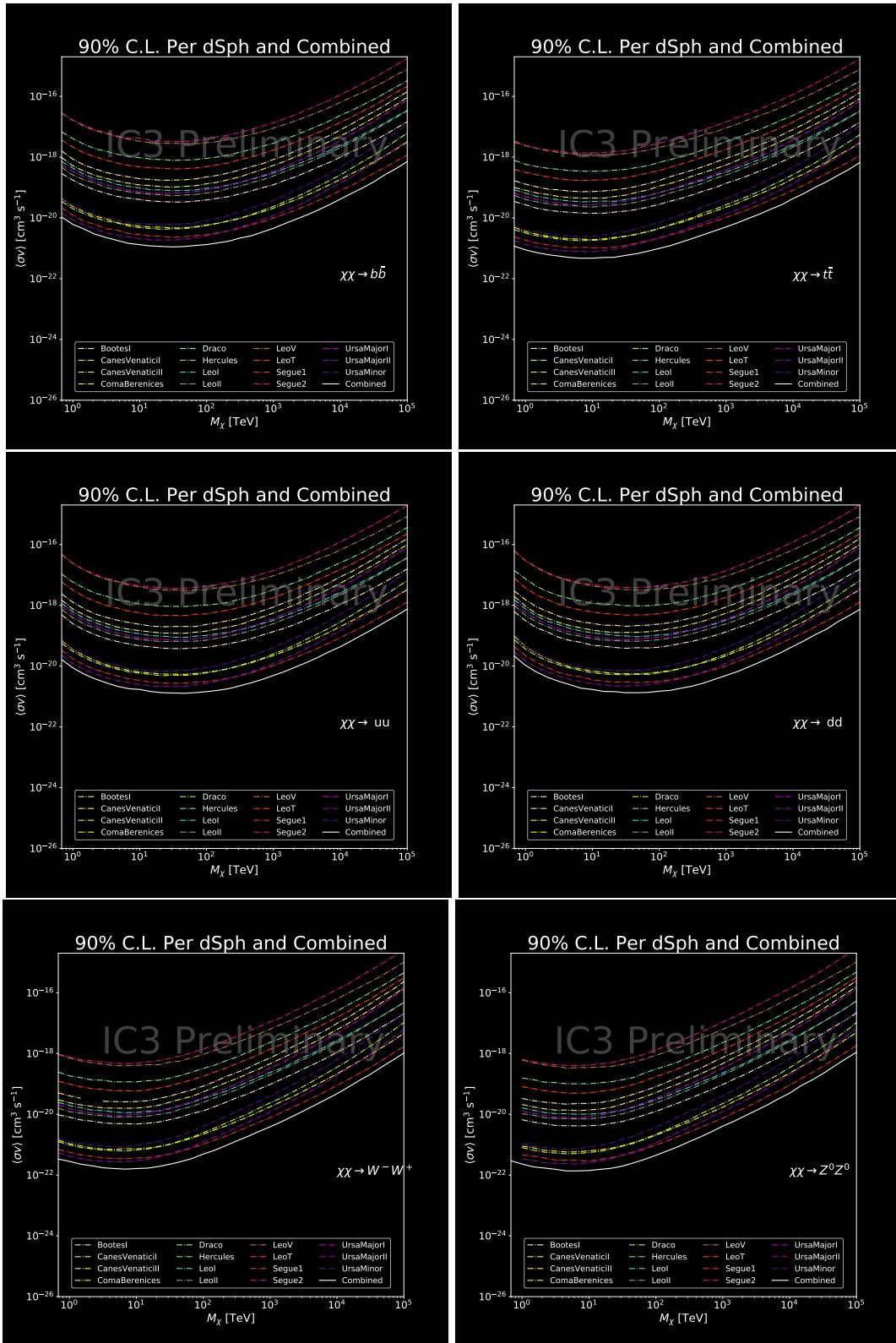


Figure 7.25 Words. I prent Icecibe Sensitivities weeee

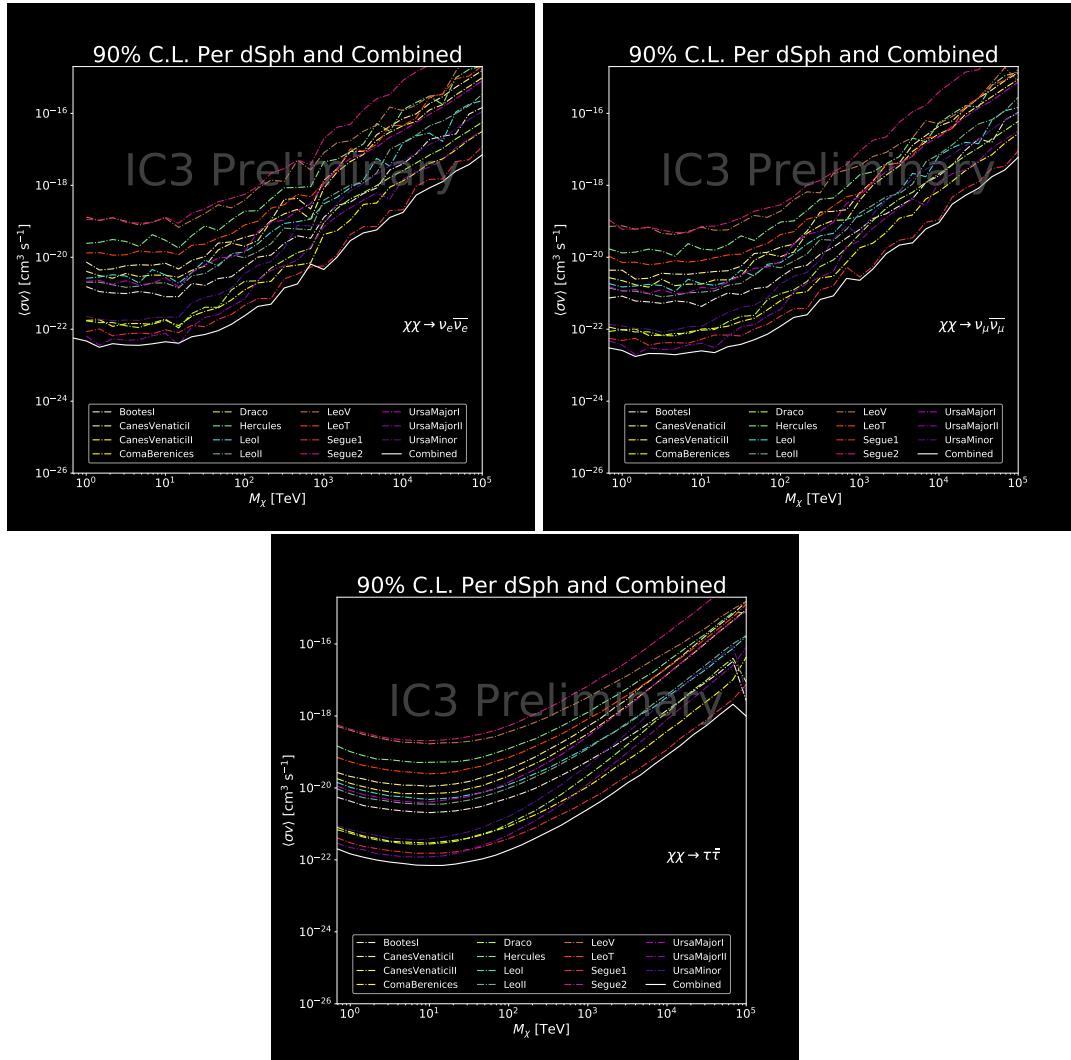


Figure 7.26 Words. I prent Icecibe Sensitivities weeee

## **CHAPTER 8**

1678

### **NU DUCK**

## APPENDIX A

### MULTI-EXPERIMENT SUPPLEMENTARY FIGURES

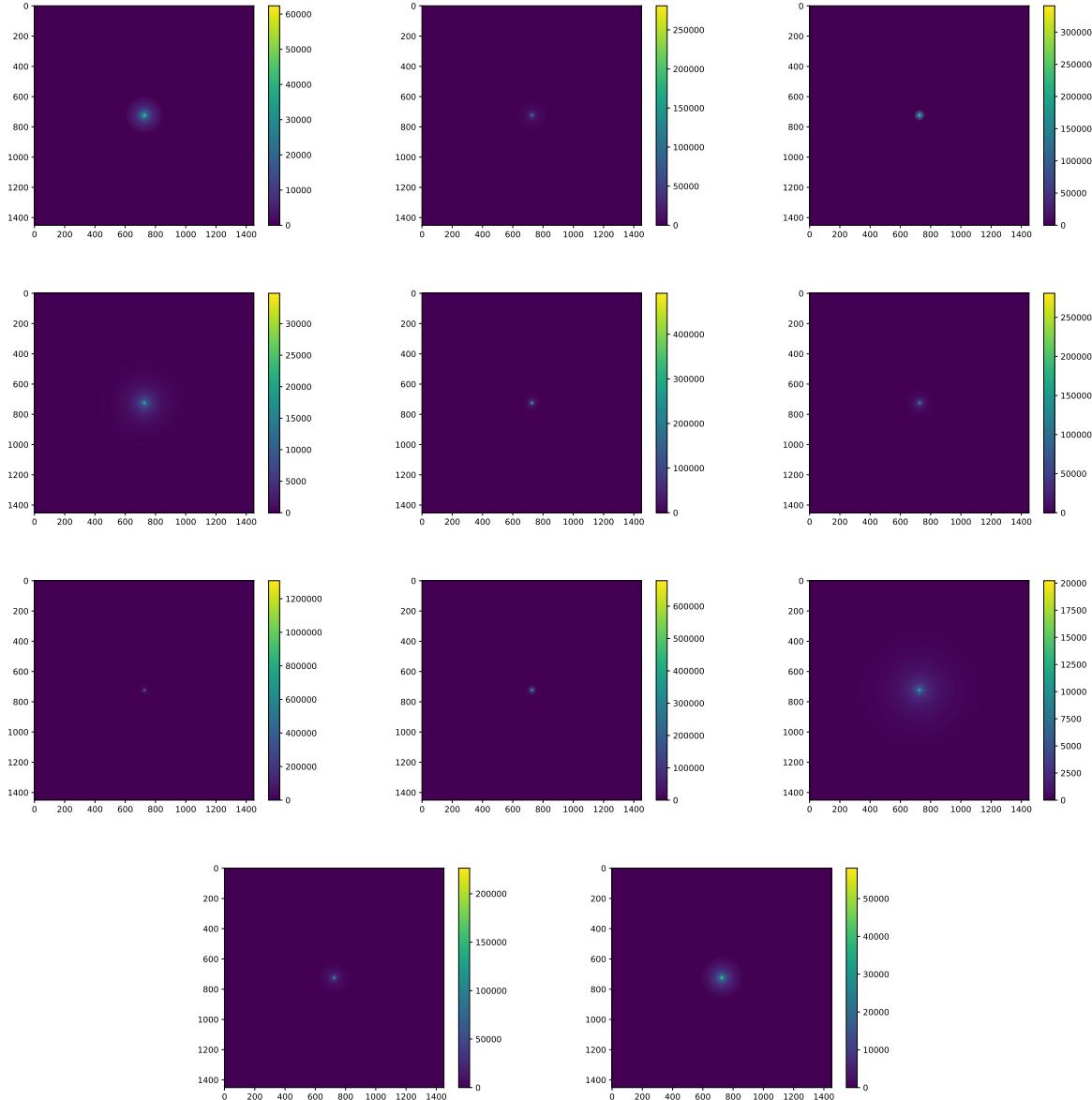


Figure A.1 Sister figure to Figure 5.3. Sources in the first row from left to right: Bootes I, Canes Venatici I, II. In second row: Draco, Hercules, Leo I. In the first row: Leo II, Leo IV, Sextans. In the final row: Ursa Major I, Ursa Major II.

## APPENDIX B

### 1680 MULTITHREADING DARK MATTER ANALYSES SUPPLEMENTARY MATERIAL

#### 1681 B.1 Remaining Spectral Models

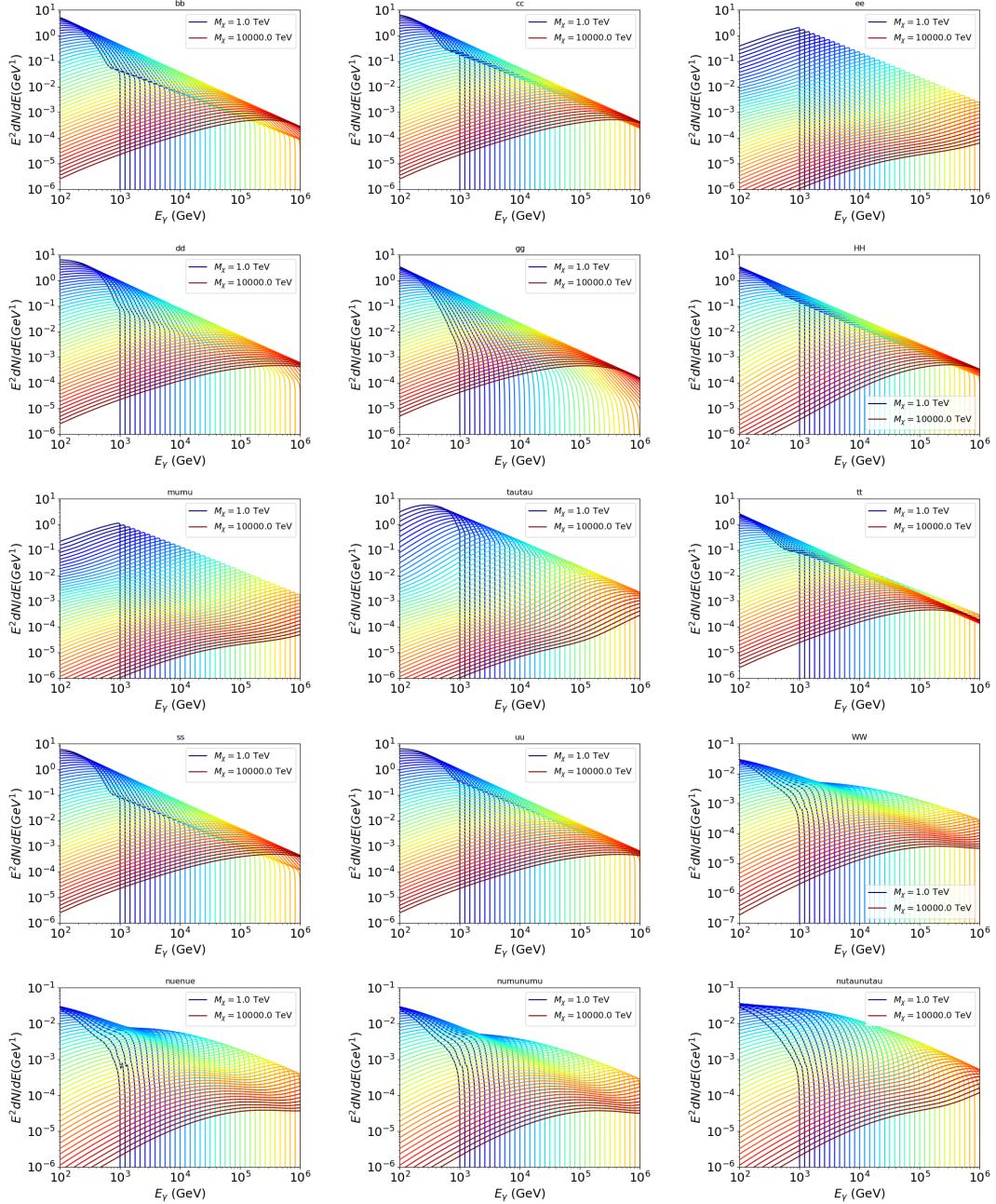


Figure B.1 Sister figure to Figure 6.2 for remaining SM primary annihilation channels studied for this thesis. These did not require any post generation smoothing and so are directly pulled from [64] with a binning scheme most helpful for a HAWC analysis.

## 1682 B.2 mpu\_analysis.py

```
16831 import warnings
16842 with warnings.catch_warnings():
16853     warnings.simplefilter("ignore")
16864 # Python base libraries
16875 import os
16886 import sys
16897 import time
16908 # Import general libraries with namespace
16919 import matplotlib
16920 # Necessary for computing on cluster
16931 matplotlib.use("agg")
16942 import numpy as np
16953 import multiprocessing as mp
16964 # Import HAWC software
16975 sys.path.insert(1, os.path.join(os.environ['HOME'], 'hawc_software', 'threeML-
1698     analysis-scripts', 'fitModel'))
16996 from analysis_modules import *
17007 from threeML import *
17018 from hawc_hal import HAL, HealpixConeROI
17029 from threeML.minimizer.minimization import FitFailed
17030 # Import Dark Matter HAWC Libraries
17041 import analysis_utils as au
17052 import spectra as spec
17063 import sources as srcs
17074
17085 #* READ ONLY PATHS This block will change eventually
17096 MASS_LIST = './plotting/studies/nd/masses.txt'
17107 CHAN_LIST = './plotting/studies/nd/chans.txt'
17118
17129 #* WRITE PATHS, default location is to scratch
17130 OUT_PATH = os.path.join(os.environ["SCRATCH"], os.environ["USER"], 'New_duck')
```

```

17141 print('Our out path is going to be {}'.format(OUT_PATH))
17152
17163 # Define parallel Function. Can also be run serially
17174 def some_mass_fit(sigVs, datalist, shape, dSph, jfactor, mass_chan,
17185                 progress=None, log_file='', queue=None, i_job=0):
17196
17207     if progress is None:
17218         progress = [0]
17229     else: # Create log files for each thread
17230         log_file = log_file.replace('.log', '_ThreadNo_')
17241         log_file = log_file + str(i_job) + ".log"
17252         sys.stdout = open(log_file, "w")
17263
17274     fits = []
17285
17296     try:
17307         for m_c in mass_chan:
17318             print(f'Mass chan tuple: {m_c}')
17329             mass = int(m_c[0])
17330             ch = m_c[1]
17341             # Build path to output files
17352             outPath = os.path.join(OUT_PATH, ch, dSph)
17363             au.ut.ensure_dir(outPath)
17374
17385             if progress[i_job] < 0:
17396                 # If the master gets a Keyboard interrupt, commit suicide.
17407                 break
17418
17429                 ### Start Model Building for DM mass and SM channel #####
17430                 spectrum = spec.DM_models.HDMSpectra()
17441                 spectrum.set_channel(ch)
17452
17463                 myDwarf = ExtendedSource(dSph, spatial_shape=shape,

```

```

17474                     spectral_shape=spectrum)

17485

17496     spectrum.J = jfactor * u.GeV**2 / u.cm**5
17507     spectrum.sigmav = 1e-24 * u.cm**3 / u.s
17518     spectrum.set_dm_mass(mass * u.GeV)

17529

17530     spectrum.sigmav.bounds = (1e-30, 1e-12)
17541     model = Model(myDwarf)
17552     ##### End model Building #####
17563
17574     jl = JointLikelihood(model, datalist, verbose=False)
17585
17596     try:
17607         result, lhdf = jl.fit(compute_covariance=False)
17618         ts = -2.* (jl.minus_log_like_profile(1e-30) - jl.
1762         _current_minimum)
17639         # Also profile the LLH vs sv
17640         ll = jl.get_contours(spectrum.sigmav, sigVs[0],
17651                         sigVs[-1], len(sigVs),
17662                         progress=False, log=['False'])
17673
17684         sigv_ll = au.ut.calc_95_from_profile(ll[0], ll[2])
17695         # Write results to file
17706         outFileLL = outPath+f"/LL_{dSph}_{ch}_mass{int(mass)}_GD.txt"
17717         np.savetxt(outFileLL, (sigVs, ll[2]),
17728                         delimiter='\t', header='sigV\tLL\n')
17739
17740         with open(outPath+f"/results_{dSph}_{ch}_mass{int(mass)}_GD.
1775 txt", "w") as results_file:
17761             results_file.write("mDM [GeV]\tsigV_95\tsigV_B.F.\n")
17772
17783             results_file.write("%i\t%.5E\t%.5E\t%.5E"%(mass, sigv_ll,
17794                                         ts, result.value[0]))

```

```

17805         # End write to file
17816     except FitFailed: # Don't kill all threads if a fit fails
17827         print("Fit failed. Go back and calculate this spectral model
1783    later")
17848         fits.append((ch, mass, -1, -1))
17859         with open(log_file+'.fail', 'w') as f_file:
17860             f_file.write(f'{ch}, {mass}\n')
17871
17882         progress[i_job] += 1
17893         matplotlib.pyplot.close() # Prevent leaky memory
17904
17915         fits.append((ch, mass, result.value[0], ts))
17926         progress[i_job] += 1
17937         matplotlib.pyplot.close()
17948     except KeyboardInterrupt:
17959         progress[i_job] = -1
17960
17971     fits = np.array(fits)
17982     if queue is None:
17993         return fits
18004     else:
18015         queue.put((i_job, fits))
18026
18037 def main(args):
18048     masses = np.loadtxt(MASS_LIST, dtype=int)
18059     chans = np.loadtxt(CHAN_LIST, delimiter=',', dtype=str)
18060     mass_chan = au.ut.permute_lists(chans, masses)
18071
18082     print(f"DM masses for this study are: {masses}")
18093     print(f"SM Channels for this study are XX -> {chans}")
18104     print(mass_chan)
18115
18126 # extract information from input argument

```

```

18137 dSph = args.dSph
18148 data_mngr = au.ut.Data_Selector('P5_NN_2D')
18159 dm_profile = srcts.Spatial_DM(args.catalog, dSph, args.sigma, args.decay)
18160
18171     ### Extract Source Information ####
18182 if dm_profile.get_dec() < -22.0 or dm_profile.get_dec() > 62.0:
18193     raise ValueError("HAWC can't see this source D: Exitting now...")
18204
18215 print(f'{dSph} information')
18226 print(f'jfac: {dm_profile.get_factor()}\tRA: {dm_profile.get_ra()}\tDec: {dm_profile.get_dec()}\n')
18247
18258 shape = SpatialTemplate_2D(fits_file=dm_profile.get_src_fits())
18269     ### Finish Extract Source Information ####
18270
18281     ### LOAD HAWC DATA ####
18292 roi = HealpixConeROI(data_radius=2.0, model_radius=8.0,
18303                         ra=dm_profile.get_ra(), dec=dm_profile.get_dec())
18314 bins = choose_bins.analysis_bins(args, dec=dm_profile.get_dec())
18325
18336 hawc = HAL(dSph, data_mngr.get_datmap(), data_mngr.get_detres(), roi)
18347 hawc.set_active_measurements(bin_list=bins)
18358 datalist = DataList(hawc)
18369     ### FINISH LOAD HAWC DATA ####
18370
18381 # set up SigV sampling. This sample is somewhat standardized
18392 sigVs = np.logspace(-28,-18, 1001, endpoint=True) # NOTE This will change
1840 with HDM
18413
18424 if args.n_threads == 1:
18435     # No need to start || programming just iterate over the masses
18446     kw_arg = dict(sigVs=sigVs, datalist=datalist, shape=shape, dSph=dSph,
18457                     jfactor=dm_profile.get_factor(), mass_chan=mass_chan,

```

```

18468                 log_file=args.log)
18479             some_mass_fit(**kw_arg)
18480         else:
18491             # I Really want to suppress TQMD output
18502             from tqdm import tqdm
18513             from functools import partialmethod
18524             tqdm.__init__ = partialmethod(tqdm.__init__, disable=True)
18535
18546             x = np.array_split(mass_chan, args.n_threads)
18557             n_jobs = len(x)
18568
18579             print("Thread jobs summary by mass and SM channel")
18580             for xi in x:
18591                 print(f'{xi}')
18602
18613             queue = mp.Queue()
18624             progress = mp.Array('i', np.zeros(n_jobs, dtype=int))
18635
18646             # Define task pool that will be split amongsts threads
18657             kw_args = [dict(sigVs=sigVs, datalist=datalist, shape=shape,
18668                             dSph=dSph, jfactor=dm_profile.get_factor(),
18679                             mass_chan=mass_chan, progress=progress,
18680                             queue=queue, i_job=i, log_file=args.log)
18691                 for i, mass_chan in enumerate(x)]
18702
18713             # Define each process
18724             procs = [mp.Process(target=some_mass_fit, kwargs=kw_args[i]) \
18735                 for i in range(n_jobs)]
18746
18757             ### Start MASTER Thread only code block ###
18768             # Begin running all child threads
18779             for proc in procs: proc.start()
18780

```

```

18791     try:
18802         # In this case, the master does nothing except monitor progress of
1881         the threads
18823         # In an ideal world, the master thread also does some computation.
18834         n_complete = np.sum(progress)
18845         while_count = 0
18856
18867         while n_complete < len(mass_chan):
18878
18889             if np.any(np.asarray(progress) < 0):
18890                 # This was no threads are stranded when killing the script
18901                 raise KeyboardInterrupt()
18912             if while_count%1000 == 0:
18923                 print(f"{np.sum(progress)} of {len(mass_chan)} finished")
18934
18945             n_complete = np.sum(progress)
18956             time.sleep(.25)
18967             while_count += 1
18978
18989         except KeyboardInterrupt:
18990             # signal to jobs that it's time to stop
19001                 for i in range(n_jobs):
19012                     progress[i] = -2
19023                     print('\nKeyboardInterrupt: terminating early.')
19034             ### End MASTER Thread only code block ###
19045
19056             fitss = [queue.get() for proc in procs]
19067             print(fitss)
19078             print(f'Thread statuses: {progress[:]}')
19089
19090             # putting results in a file
19101
19112             print("QUACK! All Done!")

```

```

19123
19134
19145 if __name__ == '__main__':
19156     import argparse
19167
19178     p = argparse.ArgumentParser(description="Run a DM annihilation analysis on
1918         a dwarf spheroidal for a specific SM channel for DM masses [1 TeV to 10
1919         PeV]")
19209
19210     # Dwarf spatial modeling arguements
19221     p.add_argument("-ds", "--dSph", type=str,
19232             help="dwarf spheroidal galaxy to be studied", required=
1924             True)
19253     p.add_argument("-cat", "--catalog", type=str, choices=['GS15', 'LS20'],
19264             default='LS20', help="source catalog used")
19275     p.add_argument("-sig", "--sigma", type=int, choices=[-1, 0, 1], default=0,
19286             help="Spatial model uncertainty. 0 corresponds to the
1929 median. +/-1 correspond to the +/-1sigma uncertainty respectively.")
19307
19318     # Arguements for the energy estimators
19329     p.add_argument("-e", "--estimator", type=str,
19330             choices=['P5_NHIT', 'P5_NN_2D'],
19341             default="P5_NN_2D", required=False,
19352             help="The energy estimator choice. Options are: P5_NHIT,
1936 P5_NN_2D. GP not supported (yet).")
19373     p.add_argument("--use-bins", default=None, nargs="*",
19384             help="Bins to use for the analysis", dest="use_bins")
19395     p.add_argument('--select_bins_by_energy', default=None, nargs="*",
19406             help="Does nothing. May fill in later once better
1941 understood")
19427     p.add_argument('--select_bins_by_fhit', default=None, nargs="*",
19438             help="Also does nothing see above")
19449     p.add_argument( '-ex', '--exclude', default=None, nargs="*",

```

```

19450         help="Exclude Bins", dest="exclude")

19461

19472 # Computing and logging arguements.

19483 p.add_argument('-nt', '--n_threads', type=int, default=1,
19494                         help='Maximum number of threads spawned by script. Default
1950      is 4')

19515 p.add_argument('-log', '--log', type=str, required=True,
19526                         help='Name for log files. Especially needed for threads')

19537

19548 p.add_argument('--decay', action="store_true",
19559                         help='Set spectral DM hypothesis to decay')

19560

19571 args = p.parse_args()

19582 print(args.decay)

19593 if args.exclude is None: # default exclude bins 0 and 1
19604     args.exclude = ['B0C0Ea', 'B0C0Eb', 'B0C0Ec', 'B0C0Ed', 'B0C0Ee']

19615

19626 if args.decay: OUT_PATH += '_dec'
19637 else: OUT_PATH += '_ann'

19648

19659 OUT_PATH = OUT_PATH + '_' + args.catalog
19660 if args.sigma != 0: OUT_PATH += f'_{args.sigma}sig'

19671

19682 main(args)

```

1969 **B.3 Comparison with Glory Duck**

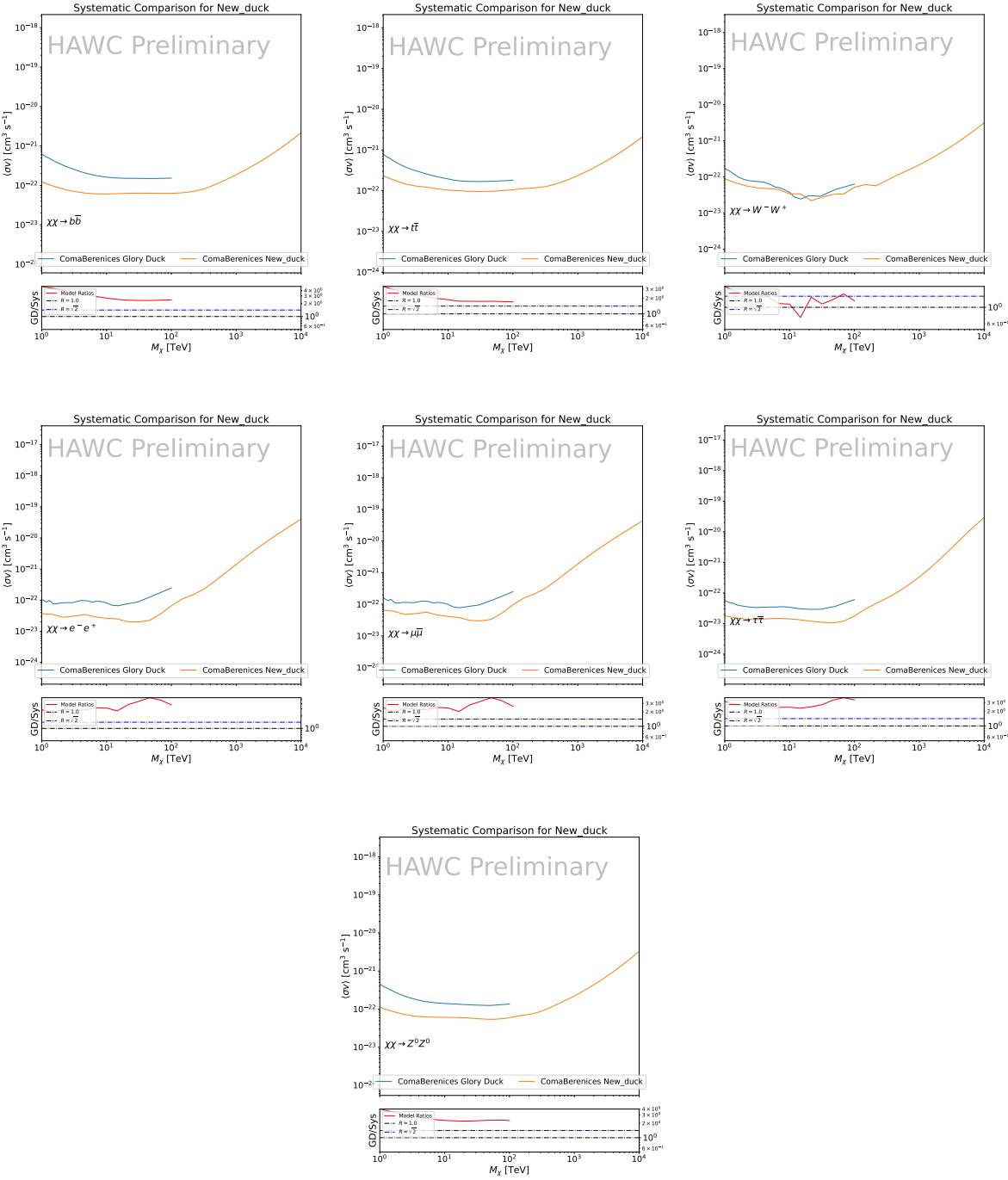


Figure B.2 TODO: fill this out

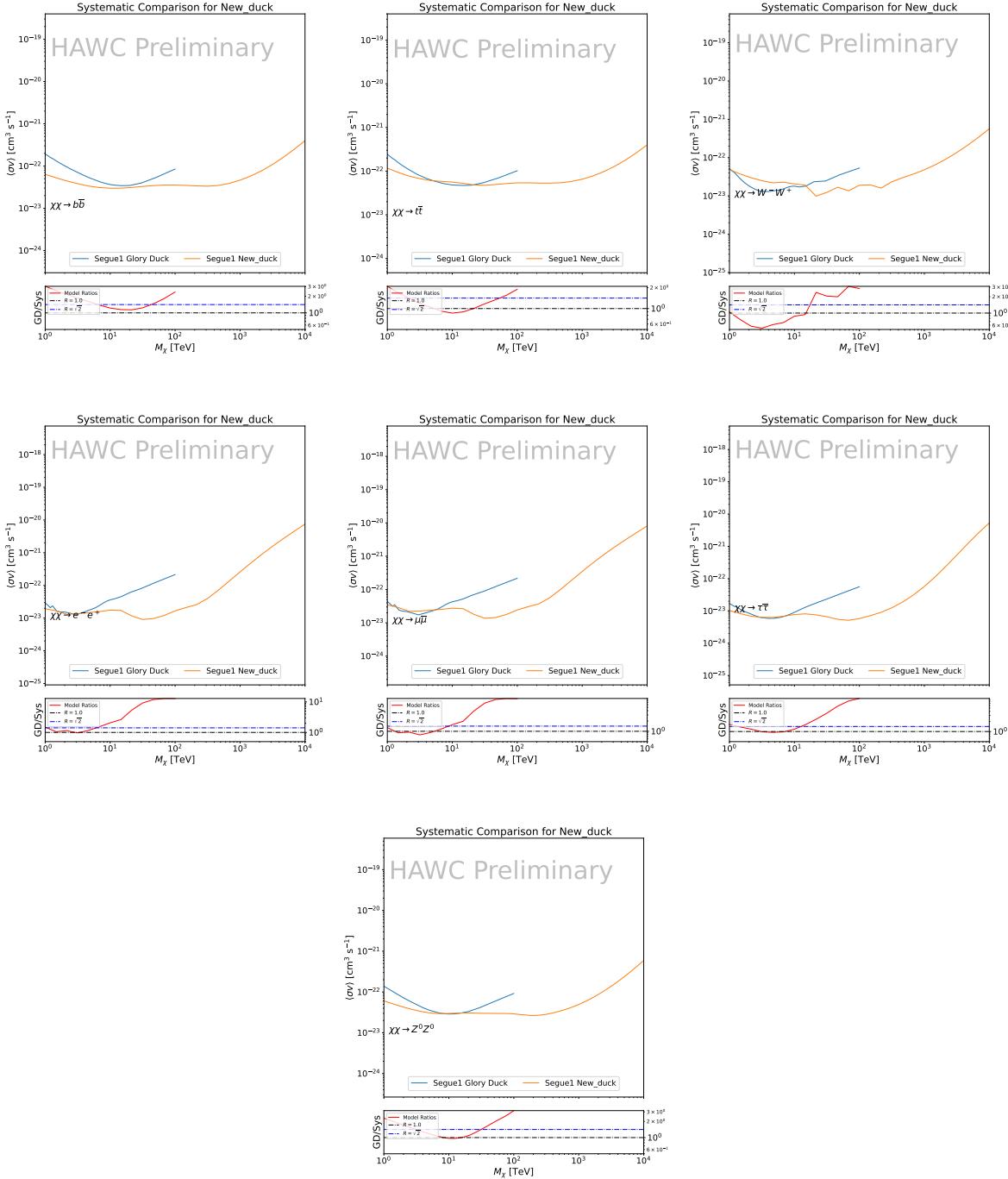


Figure B.3 TODO: fill this out

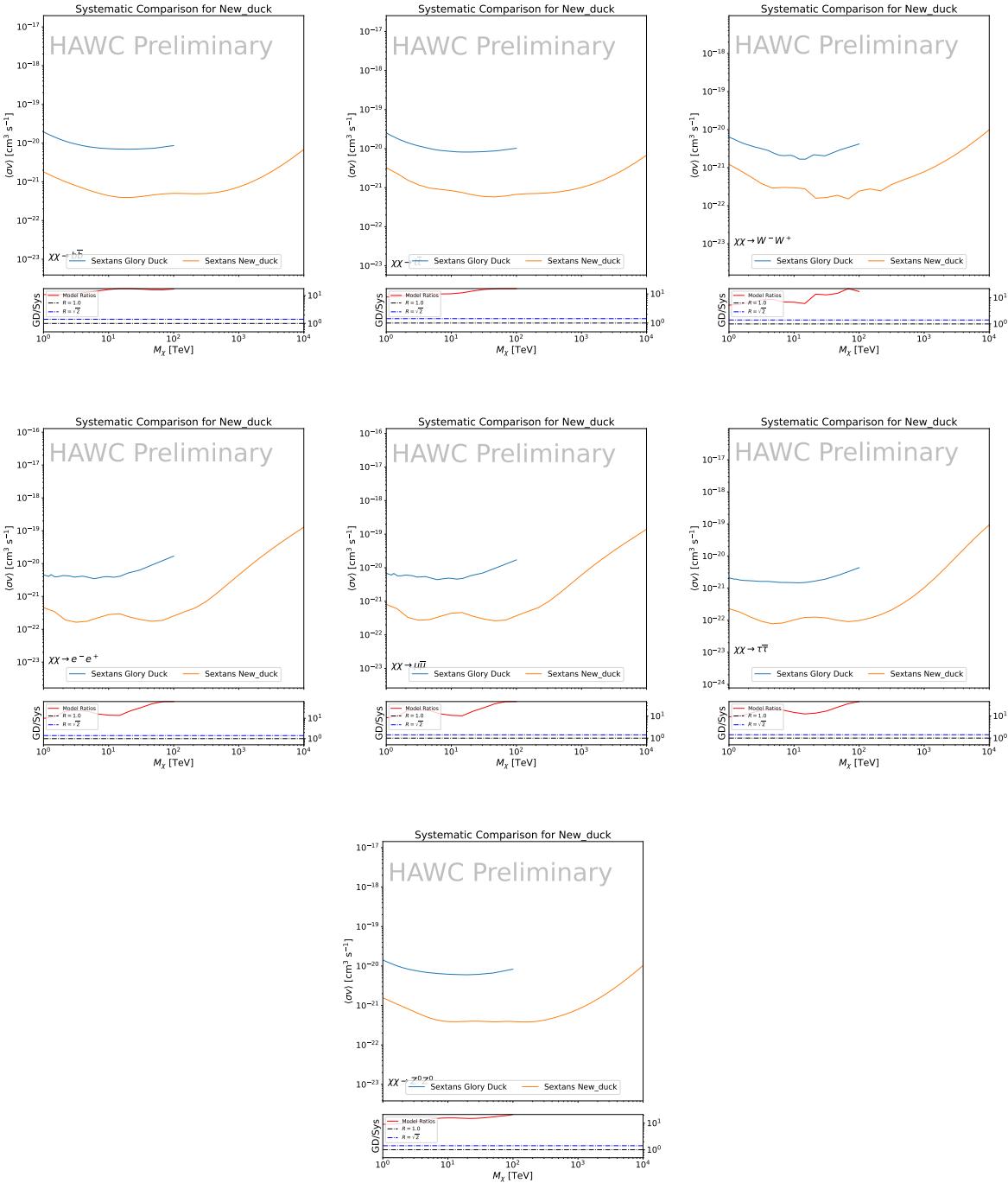


Figure B.4 TODO: fill this out

## APPENDIX C

### 1970 ICECUBE HEAVY DARK MATTER ANALYSIS SUPPLEMENTARY MATERIAL

#### 1971 C.1 Docker Image for Oscillating Neutrino Spectra

```
1972 1 FROM ubuntu:18.04
1973 2
1974 3 # Execute commands to install software packages
1975 4 RUN apt -y update
1976 5
1977 6     # Install utility programs
1978 7 RUN apt -y install vim wget git cmake
1979 8
1980 9 ARG DEBIAN_FRONTEND=noninteractive
1981 10
1982 11     # Install python
1983 12 RUN apt -y install python python-dev python-pip libjpeg-dev zlib1g-dev
1984 13
1985 14     # We need Python2 for installing Charon.
1986 15 RUN apt -y install python-numpy python-sympy python-matplotlib \
1987 16             python-sympy python-h5py python-astropy python-ipython
1988 17
1989 18     # Install dependencies of Charon : SQuIDS, NuSQuIDS
1990 19 RUN apt -y install libgsl-dev libgslcblas0 libgsl23 gsl-bin pkg-config
1991 20     # Install SQuIDS
1992 21 RUN mkdir /home/SQuIDS /home/SQuIDS_install
1993 22 WORKDIR /home/SQuIDS
1994 23 RUN git clone https://github.com/jsalvado/SQuIDS.git
1995 24 WORKDIR /home/SQuIDS/SQuIDS
1996 25 RUN git checkout 7ad9ba7c6ad06d1f0fa8418f937ebf1a403fef90
1997 26     # Before executing "make install" an environmental variable has to be set.
1998 27 ENV PKG_CONFIG_PATH=/home/SQuIDS/SQuIDS/lib
1999 28 RUN ./configure --prefix=../SQuIDS_install \
```

```

20009  && make
20010 RUN make install
20021
20032 # Set up an environmental variable that is required to install nuSQuIDS..
20043 ENV SQuIDS=/home/SQuIDS/SQuIDS
20054 ENV LD_LIBRARY_PATH=$SQuIDS/lib:$LD_LIBRARY_PATH
20065
20076 # Install NuSQuIDS
20087 RUN mkdir /home/nuSQuIDS
20098 WORKDIR /home/nuSQuIDS
20109 RUN git clone https://github.com/qrliu/nuSQuIDS.git
20110 WORKDIR /home/nuSQuIDS/nuSQuIDS
20121 RUN git checkout 072d8ef740e2fc7330f1fabaea94f0f4540c46f9
20132 RUN apt -y install libhdf5-dev hdf5-tools
20143 RUN apt -y install libboost1.65-all-dev
20154 RUN ./configure --with-squids=$SQuIDS --with-python-bindings --prefix=../
2016     nuSQuIDS_install \
20175   && make \
20186   && make install
20197
20208 # Set up an environmental variable for nuSQuIDS.
20219 ENV nuSQuIDS=/home/nuSQuIDS/nuSQuIDS
20220 ENV LD_LIBRARY_PATH=$nuSQuIDS/lib:$LD_LIBRARY_PATH
20231
20242 # Build the python bindings
20253 WORKDIR /home/nuSQuIDS/nuSQuIDS/resources/python/src
20264 RUN make
20275
20286 # Set up an environmental variable for the python bindings.
20297 ENV PYTHONPATH=$nuSQuIDS/resources/python/bindings/:$PYTHONPATH
20308
20319 # Install Charon in the /home/Charon/charon directory.
20320 RUN mkdir /home/Charon

```

```
20331 WORKDIR /home/Charon
20342 RUN git clone https://github.com/icecube/charon.git \
20353   && apt -y install unzip python-scipy
20364 WORKDIR charon
20375 RUN git checkout c531efe4e01dc364a60d1c83f950f04526ccd771
20386 RUN unzip ./charon/xsec/xsec.zip -d charon/xsec/ \
20397
20408 # Download neutrino spectra tables in the /home/Charon/charon/data directory
2041 .
20429 && mkdir ./charon/data
20430 WORKDIR ./charon/data
20441 RUN wget --no-check-certificate https://icecube.wisc.edu/~qliu/charon/
2045   SpectraEW.hdf5 \
20462 && wget --no-check-certificate https://icecube.wisc.edu/~qliu/charon/
2047   Spectra_PYTHIA.hdf5 \
20483 && wget --no-check-certificate https://icecube.wisc.edu/~qliu/charon/
2049   Spectra_noEW.hdf5
20504
20515 WORKDIR ../..
20526 RUN python setup.py install
20537 WORKDIR /home
```

2054 C.2 Spline Fitting Statuses

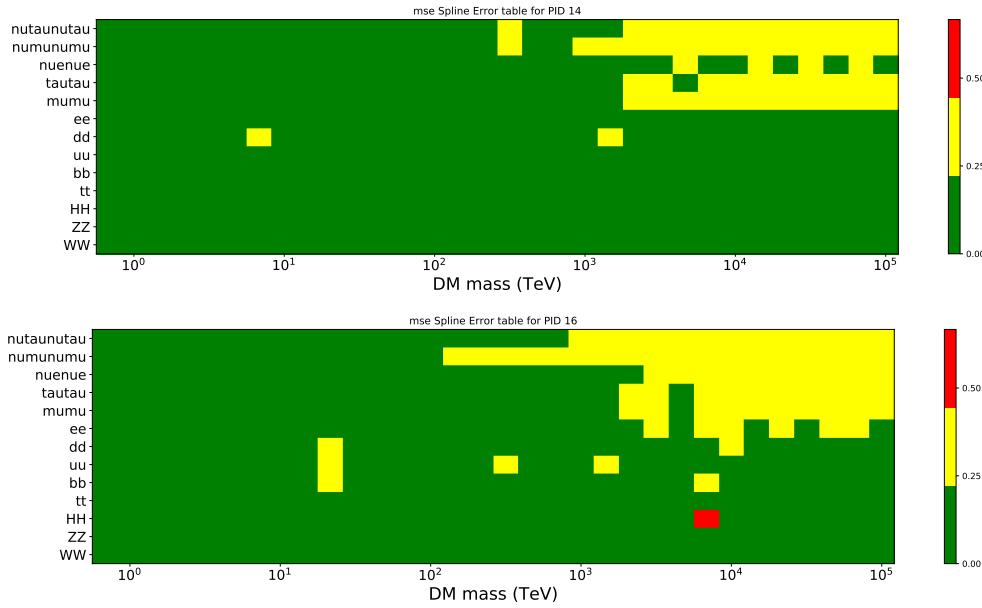


Figure C.1 TODO: fill me daddy

2055 C.3 Segue 1 And Ursa Major II Signal Recovery



Figure C.2 TODO: Fill this out eventually. I think I want all the plots generated first[NEEDS A SOURCE][FACT CHECK THIS]

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