

1 LEVERAGING MULTI-MESSENGER ASTROPHYSICS FOR DARK MATTER SEARCHES

By

Daniel Nicholas Salazar-Gallegos

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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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⁶ Today

ACKNOWLEDGMENTS

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

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LIST OF ABBREVIATIONS

- 110 **MSU** Michigan State University
111 **LANL** Los Alamos National Laboratory
112 **DM** Dark Matter
113 **SM** Standard Model
114 **HAWC** High Altitude Water Cherenkov Observatory

115

CHAPTER 1

INTRODUCTION

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

CHAPTER 2

117

DARK MATTER IN THE COSMOS

118 2.1 Introduction

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

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

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

126 The students are ecstatic to hear this, and they get to work. The solution is some variation of
127 the following strategy. The students should give each other their weight or best guess if they do
128 not know. Then, all they must do is add each student's weight and get a grand total for the class.
129 The measurement on the giant scale should show the true weight of the class. When comparing
130 the measured weight to your estimation, multiply the measurement by 1.0 ± 0.1 in order to get the
131 $\pm 10\%$ tolerances for your estimation.

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

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

135 You estimated 1,900 lbs. assuming the average weight of a student in your class was 60 lbs.
136 So, you are pleased with Sandra's and Mario's answer. You instruct your students to all gather on
137 the giant scale and read off the weight together. To all your surprise, the scale reads *10,000 lbs.*!
138 10,000 is significantly more than a 10% error from 2,000. In fact, it is approximately 5 times more
139 massive than either your or your students' estimates. You think to yourself and conclude there
140 must be something wrong with the scale. You ask an employee to check the scale and verify it is
141 calibrated well. They confirm that the scale is in working order. You weigh a couple of students
142 individually to test that the scale is well calibrated. Sandra weighs 59 lbs., and Mario weighs 62

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

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

153 This chapter is organized like the following... **TODO: Text should look like ... Chaper x has**
154 **blah blah blah.**

155 2.2 Dark Matter Basics

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

162 DM is dark; it does not interact readily with light at any wavelength. DM also does not interact
163 noticeably with the other standard model forces (Strong and Weak) at a rate that is readily observed
164 [3]. DM is cold, which is to say that the average velocity of DM is below relativistic speeds [1].
165 'Hot' DM would not likely manifest the dense structures we observe like galaxies, and instead
166 would produce much more diffuse galaxies than what is observed [3, 1]. DM is old; it played a
167 critical role in the formation of the universe and the structures within it [1, 2].

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

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

173 **2.3 Evidence for Dark Matter**

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

186 **2.3.1 First Clues: Stellar Velocities**

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

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

189 Where T is the kinetic energy and V is the potential energy in a self-gravitating system. The
190 potential was defined as the classical Newton's law of gravity from stars and gas contained in the
191 observed galaxies

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

192 Zwicky et. al. measured just the velocities of stars apparent in optical wavelengths [5]. Rubin et.
193 al. added by measuring the velocity of the hydrogen gas via the 21 cm emission line of Hydrogen

194 [6]. The velocities of the stars and gas are used to infer the total mass of galaxies and galaxy clusters
 195 via Eq. (2.1). An inferred mass is also obtained from the luminosity of the selected sources. The
 196 two inferences are compared to each other as a luminosity to mass ratio and typically yields [1]

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

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

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

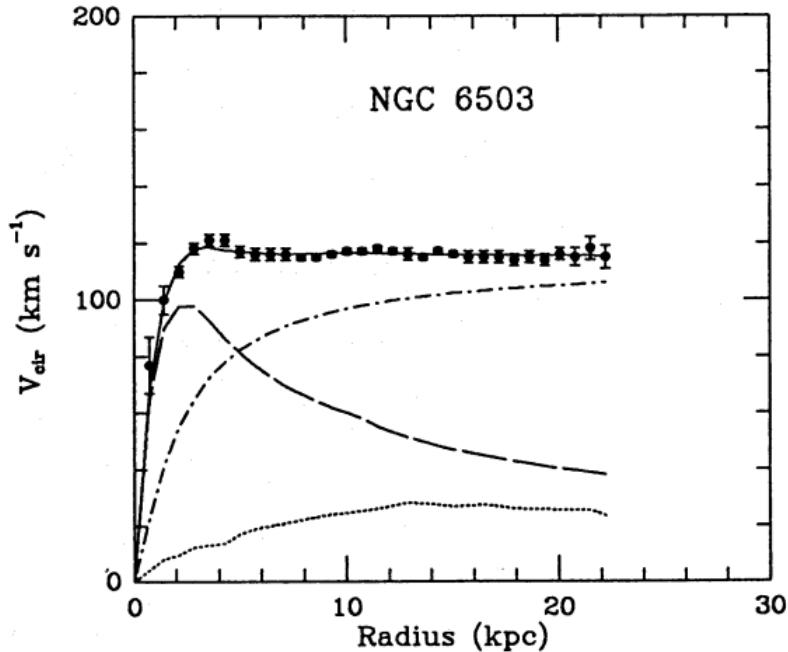


Figure 2.1 Rotation curve fit to NGC 6503 from [7]. Dashed line is the contribution from visible matter. Dotted curves are from gas. Dash-dot curves are from dark matter (DM). Solid line is the composite contribution from all matter and DM sources. Data are indicated with bold dots with error bars. Data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

202 Figure 2.1 features one of many observations made on the stellar velocities within galaxies.
 203 The measured rotation curves mostly feature a flattening of velocities at higher radius which is
 204 not expected if the gravity was only coming from gas and luminous matter. The extension of

205 the flat velocity region also indicates that the DM is distributed far from the center of the galaxy.
206 Modern velocity measurements include significantly larger objects, galactic clusters, and smaller
207 objects, dwarf galaxies. Yet, measurements along this regime are leveraging the Virial theorem
208 with Newtonian potential energies. We know Newtonian gravity is not a comprehensive description
209 of gravity. New observational techniques have been developed since 1978, and those are discussed
210 in the following sections.

211 **2.3.2 Evidence for Dark Matter: Gravitational Lensing**

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

218 Gravitational lensing provides additional compelling evidence for DM. The observation of two
219 merging galactic clusters in 2006, shown in Fig. 2.3, provided a compelling argument for DM
220 outside the Standard Model. These clusters merged recently in astrophysical time scales. Their
221 recent merger separated the stars and galaxies are separated from the intergalactic gas. For these
222 clusters, the hot, intergalactic gas is responsible for most of the baryonic mass in the systems [4].
223 The hot gas is observed from the cluster's x-ray emmision. Two observations of the clusters were
224 made independently of each other. The first was the lensing of light around the galaxies due to
225 their gravitational influences. When celestial bodies are large enough, the gravity they exert bends
226 space and time itself. These bending effects light and will deflect light an analogous way to how
227 lenses will bend light. With a sufficient understanding of light sources behind a celestial body, we
228 can reconstruct the contours of the gravitational lenses. The gradient of the contours then indicates
229 how dense the matter is and where it is.

230 The x-ray emission can then be observed from the clusters. Since these galaxies are mostly gas
231 and are merging, then the gas should be getting hotter. If they are merging, the x-ray emissions

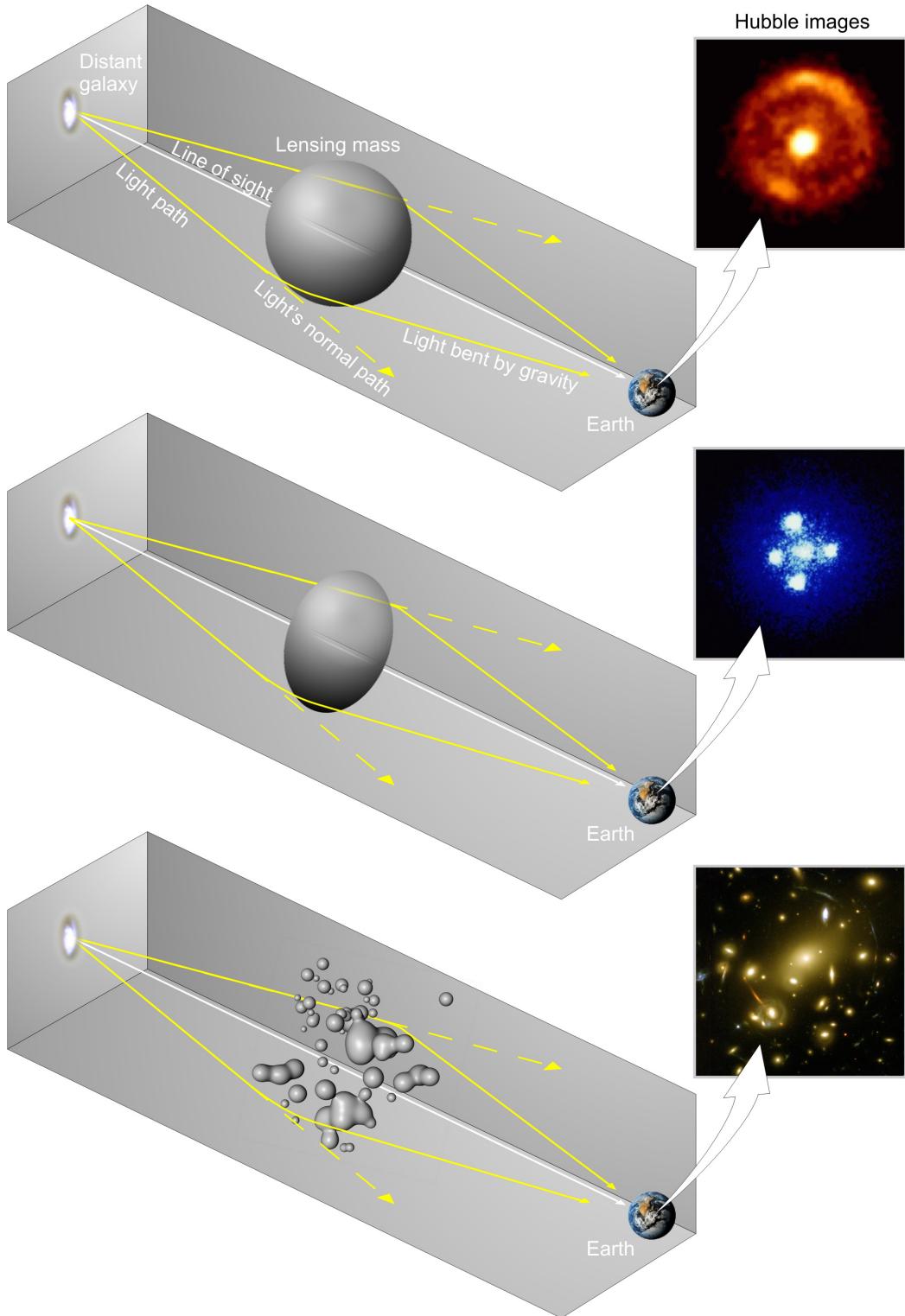


Figure 2.2 Light from distant galaxy is bent in unique ways depending on the distribution of mass between the galaxy and Earth. Yellow dashed lines indicate where the light would have gone if the matter were not present [8].

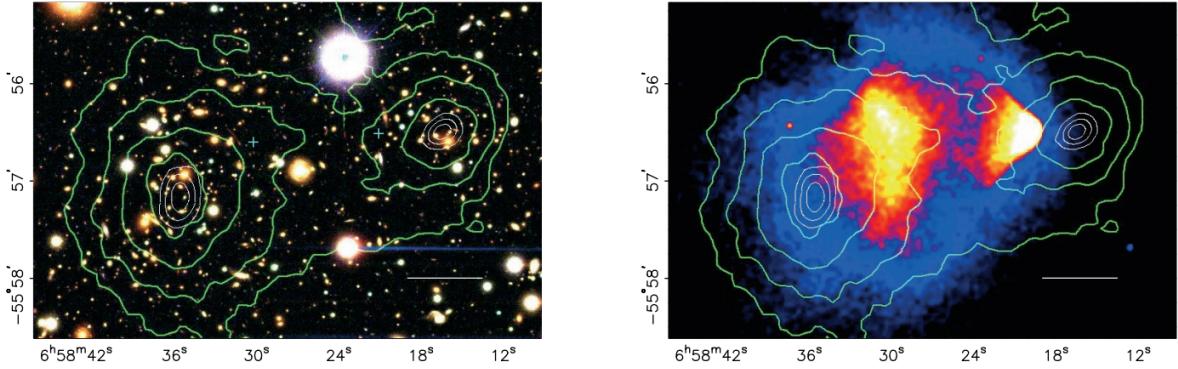


Figure 2.3 (left) Optical image of galactic cluster 1E0657-558. (right) X-ray image of the cluster with redder meaning hotter and higher baryon density. (both) Green contours are reconstruction of gravity contours from lensing. White rings are the best fit mass maxima at 68.3%, 95.5%, and 99.7% confidence.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

232 should be the strongest where the gas is mostly moving through each other. Hence, X-ray emission
 233 maps out where the gas is in the merging galaxy cluster.

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

243 **2.3.3 Evidence for Dark Matter: Cosmic Microwave Background**

244 The Cosmic Microwave Background (CMB) is the primordial light from the early universe
 245 when Hydrogen atoms formed from the free electron and proton soup in the early universe. The
 246 CMB is the earliest light we can observe; released when the universe was about 380,000 years old.
 247 Then we look at how the simulated universes look like compared to what we see. Fig. 2.4 is the
 248 most recent CMB image from the Plank observatory [10]. Redder regions indicate a slightly hotter

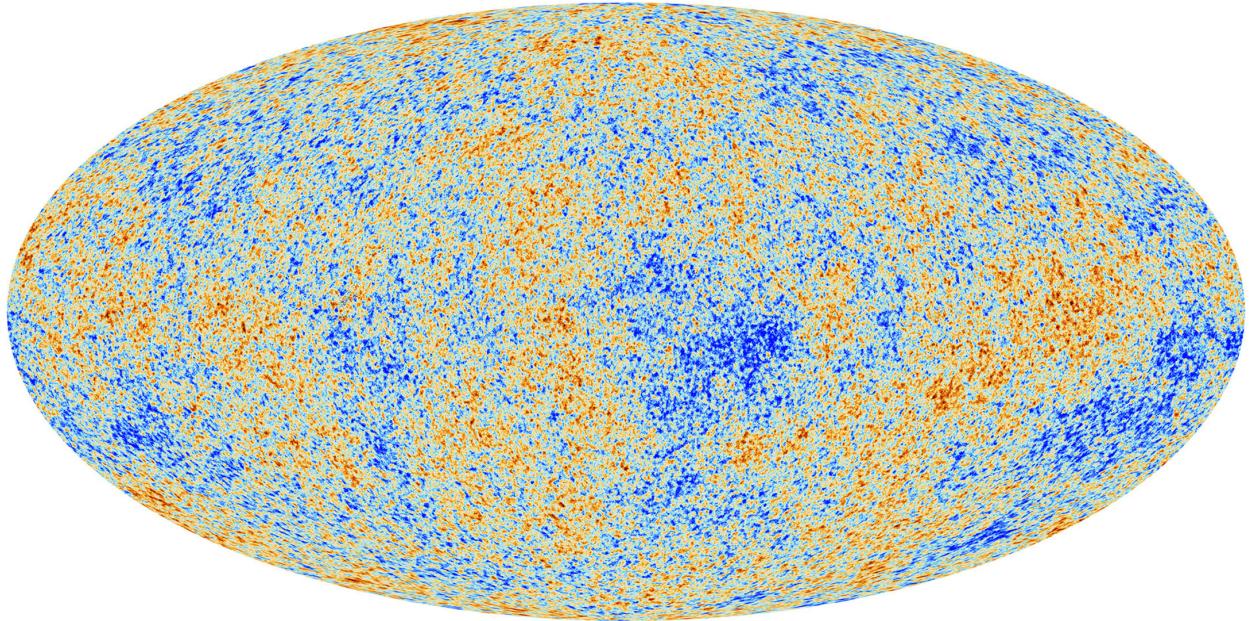


Figure 2.4 Plank CMB sky. Sky map features small variations in temperature in primordial light. These anisotropies can be used to make inferences about the universe's energy budget. [10]

249 region of the early universe and blue indicates colder.

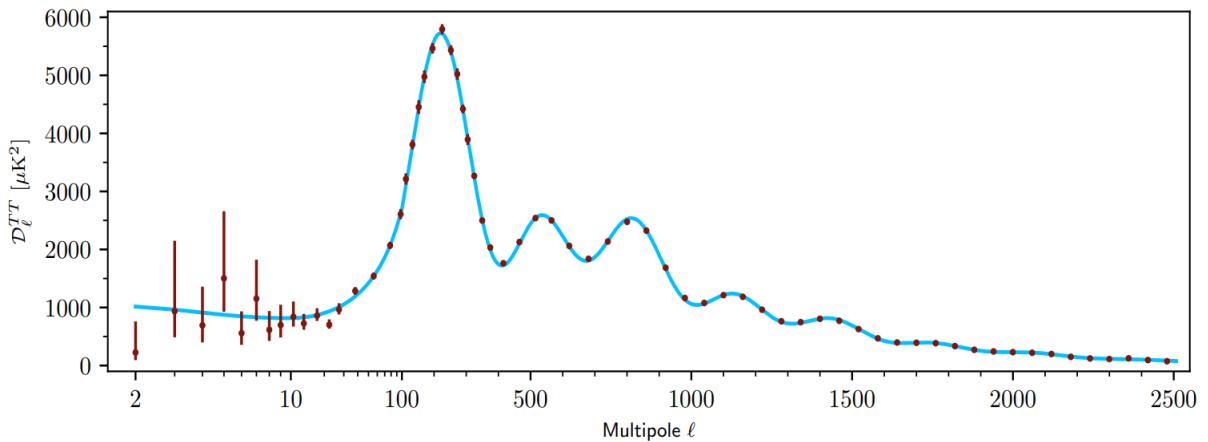


Figure 2.5 Observed Cosmic Microwave Background power spectrum as a function of multipole momentfrom Plank [10]. Blue line is best fit model from Λ CDM. Red points and lines are data and error respectively.

250 The Cosmic Microwave Background shows that the universe had DM in it from an incredibly
 251 early stage. To measure the DM, Dark Energy, and matter fractions of the universe from the CMB,
 252 the image is deconstructed into a power spectrum, which shows the amplitude of the fluctuations as
 253 a function of spherical multipole moments. Λ CDM provides the best fit to the power spectra of the

254 CDM as shown in Fig. 2.5. The CMB power spectrum is very sensitive to the fraction of each energy
 255 contribution in the early universe. Low l modes are dominated by variations in gravitational potential.
 256 Intermediate l emerge from oscillations in photon-baryon fluid from competing baryon pressures
 257 and gravity. High l is a damped region from the diffusion of photons during electron-proton
 258 recombination. [1]

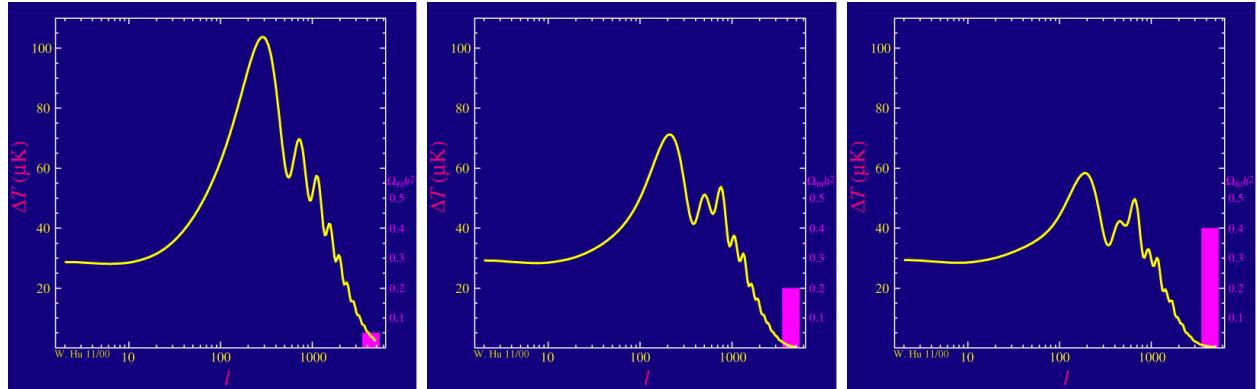


Figure 2.6 Predicted power spectra of CMB for different $\Omega_m h^2$ values. (left) Low $\Omega_m h^2$ increases the prominence of first and second peaks. (middle) $\Omega_m h^2$ is most similar to the observed power spectrum. The second and third peaks are similar in height. (right) $\Omega_m h^2$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

259 The harmonics would look very different for a universe with less DM. Fig. 2.6 shows the
 260 differences expected in the power spectrum for different matter fractions of the universe's energy
 261 budget. The observations fit well with the Λ CDM model and the derived fractions are as follows.
 262 The matter fraction: $\Omega_m = 0.3153$; and the baryon fraction: $\Omega_b = 0.04936$ [10]. These findings
 263 do rely however on a few assumptions and the precision of the Hubble constant, H_0 . H_0 especially
 264 has seen a growing tension in recent decades that continues to deepened with observatories like the
 265 James Webb Telescope [11, 12]

266 Overall these observations form a compelling body of research in favor of dark matter. However,
 267 these observations really only confirm that DM is there. It takes another leap of theory and
 268 experimentation to make observations of DM that are non-gravitational in nature. One hypothesis
 269 is the Weakly Interacting Massive Particle DM. This DM candidate theory is discussed further in
 270 the next section and is the hypothesis to this thesis.

271 **2.4 Searching for Dark Matter**

272 **TODO: Start section that needs adoption**

273 First, micro-lensing observations, or the lack of them, of our Milky Way halo resulted in a
274 conspicuous absence of massive astrophysical compact halo objects (MACHOs). The hypothesis
275 was that 'dark matter' could be accounted for by sufficiently dim compact objects. Such objects
276 include things like planets, brown dwarves, black holes, or neutron stars. **TODO: End section**
277 **that needs adoption**

278 Whenever these objects passed in front of a large luminous source, such as the Large Magellenic
279 Clouds, a variation in light should be observed [4]. The MACHO and EROS collaborations
280 performed this observation and did not find a substantial contribution to the DM Milky Way halo
281 from MACHOs. They measured that MACHOs of mass range 0.15 to $0.9 M_{\odot}$ contributes to an
282 upper limit of 8% of the DM halo mass [13]. There remains many options available to what Dark
283 Matter could be. For a particle dark matter hypothesis, we assume that DM interacts in some way,
284 even if very weakly, with the Standard Model (SM), see Section 2.4. The current status of the SM
285 does not have a viable DM candidate. When looking at the standard model, we can immediately
286 exclude any charged particle. This is because charged particles interact with light. If DM is
287 charged, it would be immediately visible if it had similar charge to many SM particles. Specifically
288 this will rule out the following charged, fundamental particles: $e, \mu, \tau, W, u, d, s, c, t, b$ and their
289 corresponding antiparticles. Recalling from earlier that DM must be long lived and stable over the
290 age of the universe, this would exclude all SM particles with decay half-lives at or shorter than the
291 age of the universe. The lifetime constraint additionally eliminates the Z and H bosons. Finally,
292 the candidate DM needs to be somewhat massive. Recall from Section 2.2 that DM is cold or not
293 relativistic through the universe. This eliminates the remaining SM particles: $\nu_{e,\mu,\tau}, g, \gamma$ as DM
294 candidates. Because there are no DM candidates within the SM, the DM problem strongly hints to
295 physics beyond the SM (BSM).

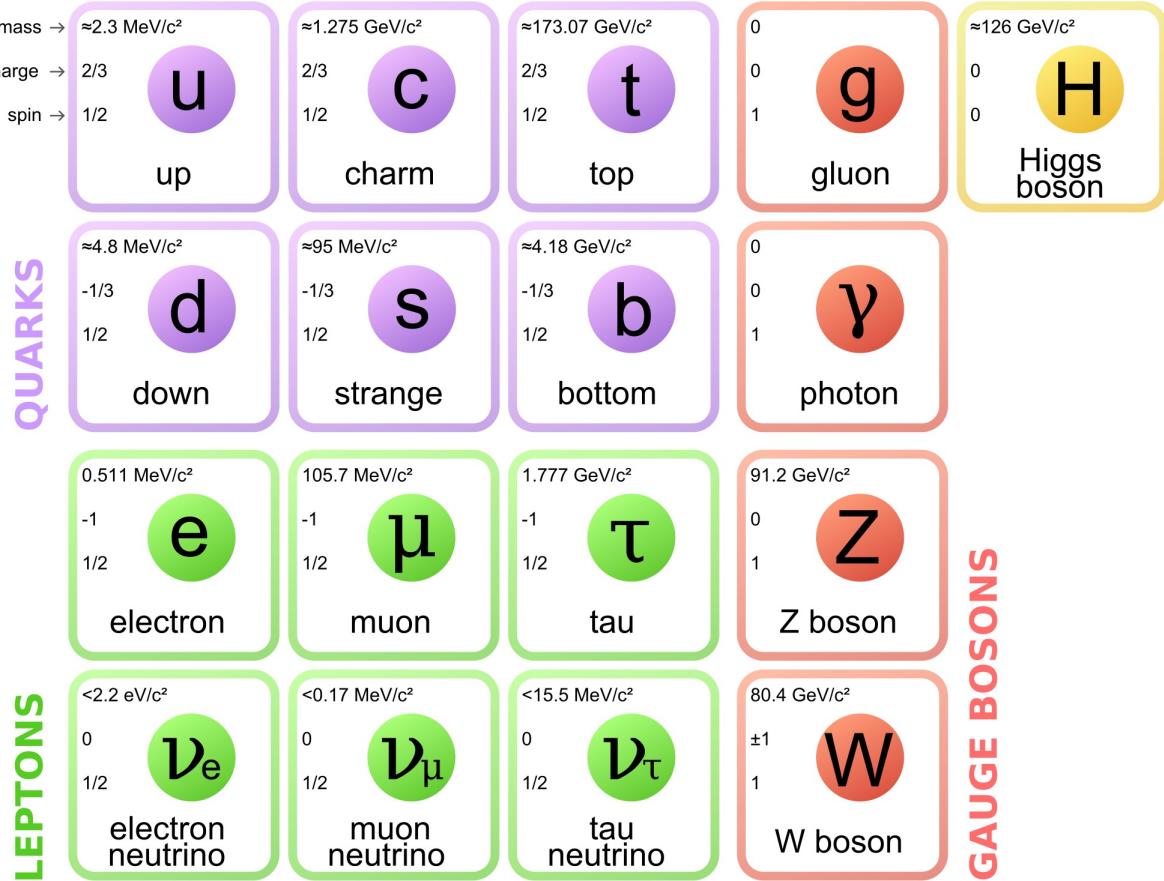


Figure 2.7 The Standard Model (SM) of particle physics. Figure taken from <http://www.quantumdiaries.org/2014/03/14/the-standard-model-a-beautiful-but-flawed-theory/>

296 2.4.1 Shake it, Break it, Make it

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

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

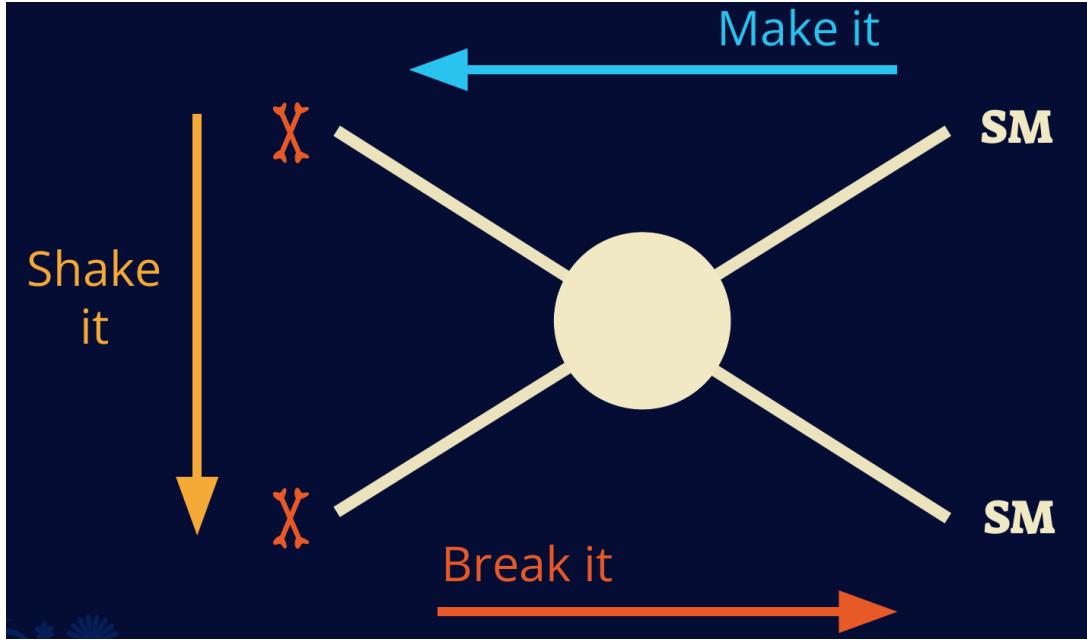


Figure 2.8 Simplified Feynman diagram demonstrating different ways DM can interact with SM particles. The 'X's refer to the DM particles whereas the SM refer to fundamental particles in the SM. The large circle in the center indicates the vertex of interaction and is purposely left vague. The colored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

307 detection media like the noble gas Xenon. [14]

308 **Make it** refers to the production of DM from SM initial states. The experiment starts with
 309 particles in the SM. These SM particles are accelerated to incredibly high energies and then collided
 310 with each other. In the confluence of energy, DM hopefully emerges as a byproduct of the SM
 311 annihilation. Often it is the collider experiments that are able to generate energies high enough
 312 to probe DM production. These experiments include the world-wide collaborations ATLAS and
 313 CMS at CERN where protons are collided together at extreme energies. The DM searches however
 314 are complex. DM likely does not interact with the detectors and lives long enough to escape the
 315 detection apparatus of CERN's colliders. This means any DM production experiment searches for an
 316 excess of events with missing momentum or energy in the events. An example event with missing
 317 transverse momentum is shown in Fig. 2.9. The missing momentum with no particle tracks implies
 318 a neutral particle carried the energy out of the detector. However, there are other neutral particles
 319 in the SM, like neutrons or neutrinos, so any analysis have to account for SM signatures of missing

320 momentum. [15]

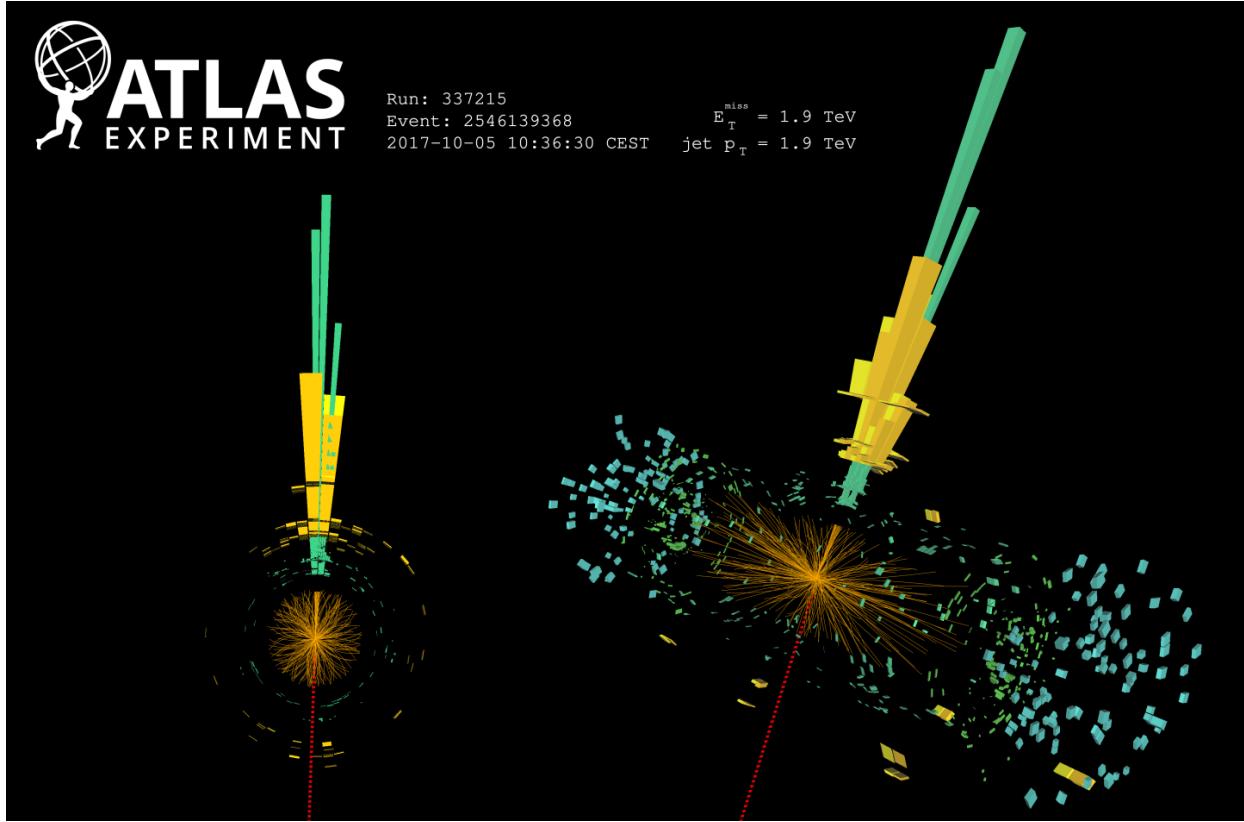


Figure 2.9 A single jet event in ATLAS detector from 2017 [16]. Jet momentum observed to be 1.9 TeV. Missing transverse momentum observed to be 1.9 TeV as the initial momentum of the event was 0. Implied MET is shown as a red dashed line in event display.

321 2.4.2 Break it: Standard Model Signatures of Indirect Dark Matter Searches

322 **Break it** refers to the creation of SM particles from the dark sector, and it is the primary focus
323 of this thesis. The interaction begins with DM or in the dark sector. The hypothesis is that this
324 DM will either annihilate with itself or decay and produce a SM byproduct. This method is often
325 referred to the Indirect Detection of DM because we have no lab to directly control or manipulate the
326 DM. Therefor most DM primary observations will be performed from observations of known DM
327 densities among the astrophysical sources. The strength is that we have the whole of the universe
328 and it's 13.6 billion year lifespan to use as the detector or particle accelerator. Additionally, locations
329 of dark matter are also well understood since it was astrophysical observations that presented the
330 problem of DM in the first place.

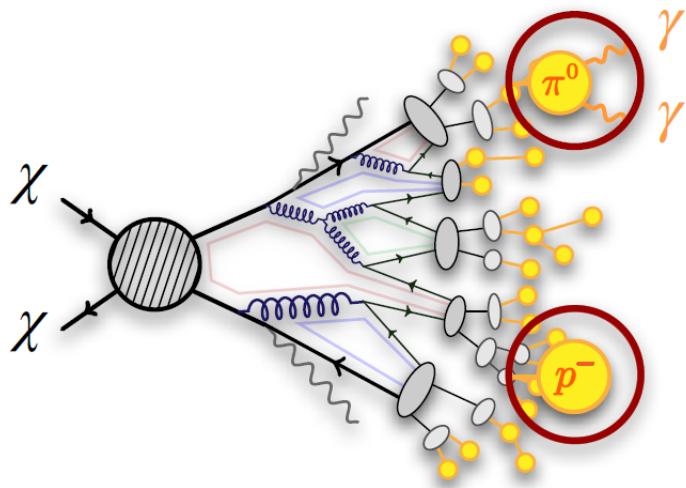


Figure 2.10 More detailed pseudo-Feynman diagram of particle cascade from dark matter annihilation into 2 quarks. The quarks hadronize and down to stable particles like γ or the anti-proton (p^-). Diagram pulled from ICRC 2021 presentation on DM annihilation search [17].

331 However, anything can happen in the universe. There are many difficult to deconvolve back-
 332 grounds when searching for DM. One prominent example is the galactic center. There's a lot of
 333 DM there since the Milky Way definitely has a lot of DM. But any signal coming from there is hard
 334 to parse apart from the extreme environment of our supermassive black hole, Sagittarius A* [18]
 335 Despite the challenges, any DM model that yields evidence in the other observation two methods,
 336 **Shake it or Make it** must be corroborated with indirect observations of the known DM sources.
 337 Without corroborating evidence, DM observation in the lab is hard-pressed to demonstrate that it
 338 is the model contributing to the DM seen at the universal scale.

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

342 Fig. 2.10 shows the quagmire of SM particles that emerges from SM initial states that are not
 343 stable [17]. There are many different particles with varying energies that can be produced in such an
 344 interaction. For any arbitrary DM source and stable SM particle, the SM flux from DM annihilating

345 to some neutral particle in the SM, ϕ , from a region in the sky is described by the following

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

346 In Eq. (2.4), $\langle\sigma v\rangle$ is the velocity-weighted annihilation cross-section of DM to the SM. m_χ refers
347 to the mass of DM, noted with greek letter χ . $\frac{dN_\phi}{dE_\phi}$ is the N particle flux weighted by the particle
348 energy. An example is provided in Fig. 2.11 for the γ final state. The integrated terms are performed
349 over the solid angle, $d\Omega$, and line of sight, l.o.s. ρ is the density of DM for a location (r, θ') in the
350 sky. The terms left of the '×' are often referred to as the particle physics component. The terms on
351 the right are referred to as the astrophysical component. For decaying DM, the equation changes
352 to...

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

353 In Eq. (2.5), τ is the decay lifetime of the DM. Just as in Eq. (2.4), the left and right terms are
354 the particle physics and the astrophysical components respectively. The integrated astrophysical
355 component of Eq. (2.4) is often called the J-Factor. Whereas the integrated astrophysical component
356 of Eq. (2.5) is often called the D-Factor.

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

364 **2.5 Sources for Indirect Dark Matter Searches**

365 We of course have to know where to look. Thankfully, we have a good idea of where. The
366 first detection of DM relied on optical observations. Since then, we've developed new techniques
367 to find DM dense regions. As described in Section 2.3.1, many DM dense regions were through
368 observing galactic rotation curves. Our Milky Way galaxy is among DM dense regions discovered,

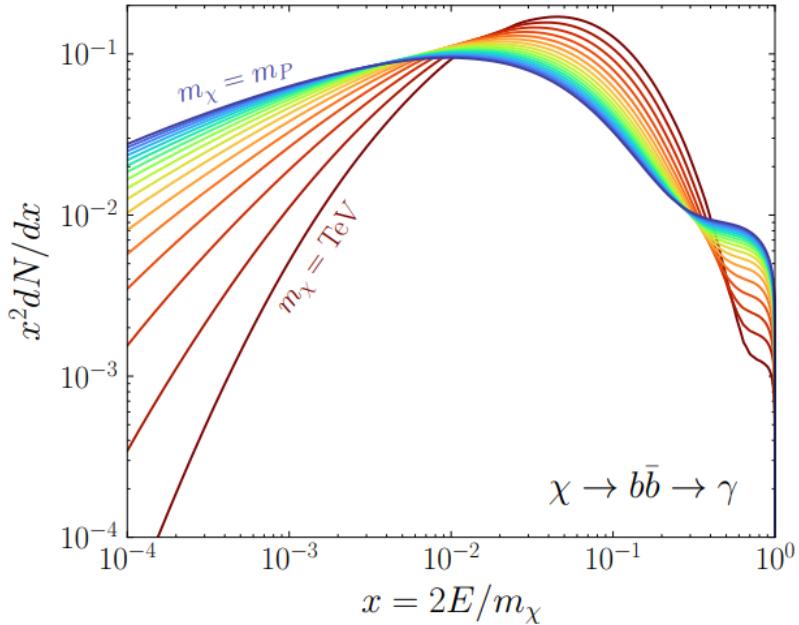


Figure 2.11 Dark Matter (DM) decay spectrum for $b\bar{b}$ initial state and γ final state. Redder spectra are for larger DM masses. Bluer spectra are light DM masses. x is a unitless factor defined as the ratio of the mass of DM, m_χ , and the final state particle energy E_γ . Figure from [19].

and it is the largest nearby DM dense region to look at. Additionally, the DM halo surrounding the Milky Way is somewhat clumpy [18]. There are regions in the DM halo of the Milky Way that have more DM than others they have captured gas over time. In some cases these sub-haloes were dense enough to host stars. These apparent sub galaxies are known was 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 assume distribution of DM. The central DM density can very substantially as demonstrated in Fig. 2.12. At small r, the differences in DM densities can be 3-4 orders of magnitude.

Dwarf Spheroidal Galaxies (dSph's) studies suffer from uncertainties in the DM density less than the galactic center studies. This is mostly from their diminutive size being smaller than the angular resolution of most γ -ray observatories [18]. The DM content dSph's are typically determined with the virial theorem, Eq. (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 fairly quiet with little

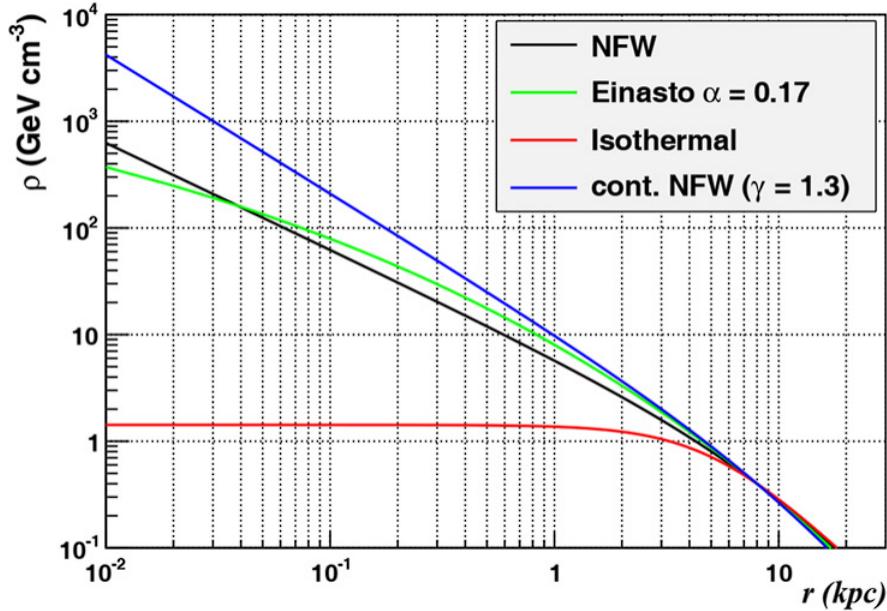


Figure 2.12 Different dark matter density profiles compared. Some models produce very large densities at small r [20].

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

386 2.6 Multi-Messenger Dark Matter

387 Astrophysics entered a new phase in the past few decades that leverages our increasing sensitivity
 388 to SM channels and general relativity (GR). Up until the 21st century, astrophysical observations
 389 were done with photons (γ) only. Astrophysics with this 'messenger' is fairly mature now. Novel
 390 observations of the universe have since only adjusted the sensitivity of the wavelength of light
 391 that's observed. Gems like the CMB [10], and more have ultimately been observations of different
 392 wavelengths of light. Multi-messenger astrophysics proposes using other SM particles such the
 393 $p^{+/-}$, or ν or gravitation waves predicted by general relativity.

394 The experiments LIGO had a revolutionary discovery in 2016 with the first detection of a binary
 395 black hole merger [21]. This opened the collective imagination entirely to observing the universe

396 through gravitational waves. There's also been a surge of interest in the neutrino (ν) sector. IceCube
 397 demonstrated that we are sensitive to neutrinos in regions that correlate with significant photon
 398 emmission like the galactic plane [22]. Neutrinos, like gravitational waves and light, travel mostly
 399 unimpeded from their source to our observatories. This makes pointing to the oringinating source
 400 of the these messengers much easier than it is for cosmic rays that are almost always deflected from
 401 their source.

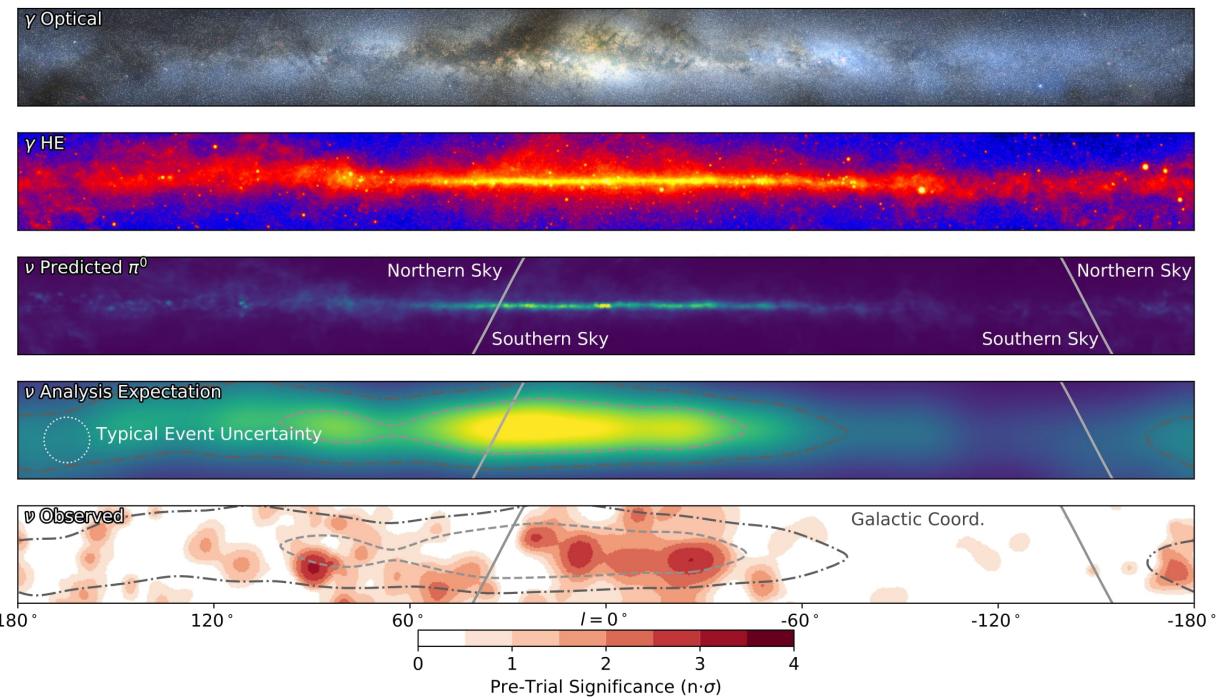


Figure 2.13 The Milky Way Galaxy in photons (γ) and neutrinos (ν) [22]. Galactic center is at $l=0^\circ$ and is the brightest region in all panels. (top) An Optical color image of the Milky Way galaxy seen from Earth. Clouds of gas and dust obscure some of the light from stars. (2nd down) Integrated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

402 The recent result from IceCube, shown in Fig. 2.13, proves that we can make obervations under
 403 different messenger regimes. The top two panels are the appearance of the galactic plane to different
 404 wavelengths of light. Some sources are more apparent in some panels, while others are not. The
 405 IceCube collaboration recently published a groundbreaking result of the Milky Way in neutrinos.

406 This new channel is potentially very powerful because neutrinos are readily able to penetrate see
 407 through gas and dust in the Milky Way. This new image also refines our understanding of how high
 408 energy particles are accelerated since the fit to IceCube data prefers one standard model process
 409 over the other [22].

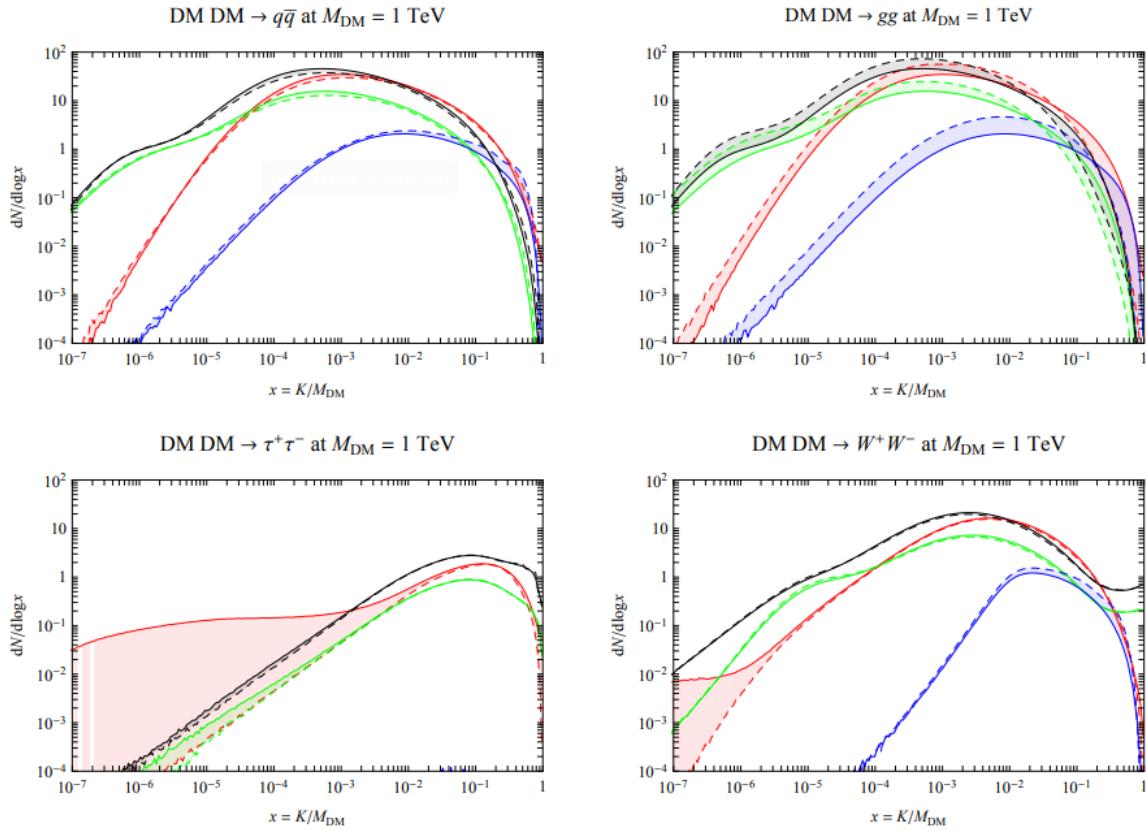


Figure 2.14 Dark Matter annihilation spectra for different final state particle and standard model annihilation channels [24]. Photons (red), e^\pm (green), \bar{p} (blue), ν (black).

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

CHAPTER 3

416 MULTIMESSENGER ASTROPHYSICS: DETECTING HIGH ENERGY NEUTRAL 417 MESSENGERS

418 3.1 Introduction

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

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

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

438 3.2 Charged Particles in a Medium

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

442 speed of light in that medium. This is similar to sonic boom where an object moves through air
443 faster than the speed of sound in air. Cherenkov radiation can therefore be thought of as an 'optic
444 boom'. Many astro-particle physics experiments will use water as the medium as because water
445 has a unique set of properties ideal for charged particle tracking.



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

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

$$INSERTCherenkovwavelengthcalcHERE. \quad (3.1)$$

447 The absorption spectra is shown in the following figure:

448 **3.3 Photons (γ)**

449 **3.4 Neutrinos (ν)**

450 **3.5 Opportunities to Combine for Dark Matter**



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

CHAPTER 4

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

452 **4.1 The Detector**

453 **4.2 Events Reconstruction and Data Acquisition**

454 **4.2.1 G/H Discrimination**

455 **4.2.2 Angle**

456 **4.2.3 Energy**

457 **4.3 Remote Monitoring**

458 **4.3.1 ATHENA Database**

459 **4.3.2 HOMER**

460

CHAPTER 5

ICECUBE NEUTRINO OBSERVATORY

461 **5.1 The Detector**

462 **5.2 Events Reconstruction and Data Acquisition**

463 **5.2.1 Angle**

464 **5.2.2 Energy**

465 **5.3 Northern Test Site**

466 **5.3.1 PIgeon remote dark rate testing**

467 **5.3.2 Bulkhead Construction**

CHAPTER 6

COMPUTATIONAL TECHNIQUES IN PARTICLE ASTROPHYSICS

469 **6.1 Neural Networks for Gamma/Hadron Separation**

470 **6.2 Parallel Computing for Dark Matter Analyses**

CHAPTER 7**GLORY DUCK**

CHAPTER 8

NU DUCK

472

BIBLIOGRAPHY

- 474 [1] Anne M. Green. “Dark matter in astrophysics/cosmology”. In: *SciPost Phys. Lect.*
 475 *Notes* (2022), p. 37. doi: [10.21468/SciPostPhysLectNotes.37](https://doi.org/10.21468/SciPostPhysLectNotes.37). URL: <https://scipost.org/10.21468/SciPostPhysLectNotes.37>.
- 476
- 477 [2] Bing-Lin Young. “A survey of dark matter and related topics in cosmology”. In: *Frontiers*
 478 *of Physics* 12 (Oct. 2016). doi: <https://doi.org/10.1007/s11467-016-0583-4>.
 479 URL: <https://doi.org/10.1007/s11467-016-0583-4>.
- 480 [3] Gianfranco Bertone, Dan Hooper, and Joseph Silk. “Particle dark matter: evidence,
 481 candidates and constraints”. In: *Physics Reports* 405.5 (2005), pp. 279–390. ISSN:
 482 0370-1573. doi: <https://doi.org/10.1016/j.physrep.2004.08.031>. URL:
 483 <https://www.sciencedirect.com/science/article/pii/S0370157304003515>.
- 484 [4] Gianfranco Bertone and Dan Hooper. “History of dark matter”. In: *Rev. Mod. Phys.*
 485 90 (4 Aug. 2018), p. 045002. doi: [10.1103/RevModPhys.90.045002](https://doi.org/10.1103/RevModPhys.90.045002). URL: <https://link.aps.org/doi/10.1103/RevModPhys.90.045002>.
- 486
- 487 [5] Fritz Zwicky. “The Redshift of Extragalactic Nebulae”. In: *Helvetica Physica Acta* 6.
 488 (1933), pp. 110–127. doi: [10.5169/seals-110267](https://doi.org/10.5169/seals-110267).
- 489 [6] Vera C. Rubin and Jr. Ford W. Kent. “Rotation of the Andromeda Nebula from a Spectro-
 490scopic Survey of Emission Regions”. In: *ApJ* 159 (Feb. 1970), p. 379. doi: [10.1086/150317](https://doi.org/10.1086/150317).
- 491
- 492 [7] K. G. Begeman, A. H. Broeils, and R. H. Sanders. “Extended rotation curves of spiral galaxies: dark haloes and modified dynamics”. In: *Monthly Notices of the Royal Astronomical Society* 249.3 (Apr. 1991), pp. 523–537. ISSN: 0035-8711. doi: [10.1093/mnras/249.3.523](https://doi.org/10.1093/mnras/249.3.523). eprint: <https://academic.oup.com/mnras/article-pdf/249/3/523/18160929/mnras249-0523.pdf>. URL: <https://doi.org/10.1093/mnras/249.3.523>.
- 493
- 494 [8] *Different types of gravitational lenses*. website. Feb. 2004. URL: <https://esahubble.org/images/heic0404b/>.
- 495
- 496 [9] Douglas Clowe et al. “A Direct Empirical Proof of the Existence of Dark Matter”. In: *apjl*
 497 648.2 (Sept. 2006), pp. L109–L113. doi: [10.1086/508162](https://doi.org/10.1086/508162). arXiv: [astro-ph/0608407](https://arxiv.org/abs/astro-ph/0608407) [astro-ph].
- 498
- 502 [10] Planck Collaboration and N. et. al. Aghanim. “Planck 2018 results I. Overview and the
 503 cosmological legacy of Planck”. In: *A&A* 641 (2020). doi: [10.1051/0004-6361/201833880](https://doi.org/10.1051/0004-6361/201833880). URL: <https://doi.org/10.1051/0004-6361/201833880>.
- 504
- 505 [11] Wenlong Yuan et al. “A First Look at Cepheids in a Type Ia Supernova Host with JWST”. in:
 506 *The Astrophysical Journal Letters* 940.1 (Nov. 2022). doi: [10.3847/2041-8213/ac9b27](https://doi.org/10.3847/2041-8213/ac9b27).

- 507 URL: <https://dx.doi.org/10.3847/2041-8213/ac9b27>.
- 508 [12] Wendy L. Freedman. “Measurements of the Hubble Constant: Tensions in Perspective”. In:
509 *The Astrophysical Journal* 919.1 (Sept. 2021), p. 16. doi: [10.3847/1538-4357/ac0e95](https://doi.org/10.3847/1538-4357/ac0e95).
510 URL: <https://dx.doi.org/10.3847/1538-4357/ac0e95>.
- 511 [13] P. Tisserand et al. “Limits on the Macho content of the EROS-2
512 Survey of the Magellanic Clouds”. In: *A&A* 469.2 (2007), pp. 387–404. doi: [10.1051/0004-6361:20066017](https://doi.org/10.1051/0004-6361:20066017). URL: <https://doi.org/10.1051/0004-6361:20066017>.
- 514 [14] Jodi Cooley. “Dark Matter direct detection of classical WIMPs”. In: *SciPost Phys. Lect.
515 Notes* (2022), p. 55. doi: [10.21468/SciPostPhysLectNotes.55](https://doi.org/10.21468/SciPostPhysLectNotes.55). URL: <https://scipost.org/10.21468/SciPostPhysLectNotes.55>.
- 517 [15] “Search for new phenomena in events with an energetic jet and missing transverse momentum
518 in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector”. In: *Phys. Rev. D* 103
519 (11 July 2021), p. 112006. doi: [10.1103/PhysRevD.103.112006](https://doi.org/10.1103/PhysRevD.103.112006). URL: <https://link.aps.org/doi/10.1103/PhysRevD.103.112006>.
- 521 [16] *Jetting into the dark side: a precision search for dark matter*. website. July 2020. URL:
522 <https://atlas.cern/updates/briefing/precision-search-dark-matter>.
- 523 [17] Celine Armand et. al. “Combined dark matter searches towards dwarf spheroidal galaxies
524 with Fermi-LAT, HAWC, H.E.S.S., MAGIC, and VERITAS”. in: *Proceedings of Science*.
525 Vol. 395. Mar. 2022. doi: <https://doi.org/10.22323/1.395.0528>.
- 526 [18] Tracy R. Slatyer. “Les Houches Lectures on Indirect Detection of Dark Matter”. In: *SciPost
527 Phys. Lect. Notes* (2022), p. 53. doi: [10.21468/SciPostPhysLectNotes.53](https://doi.org/10.21468/SciPostPhysLectNotes.53). URL:
528 <https://scipost.org/10.21468/SciPostPhysLectNotes.53>.
- 529 [19] Christian W Bauer, Nicholas L. Rodd, and Bryan R. Webber. “Dark matter spectra from
530 the electroweak to the Planck scale”. In: *Journal of High Energy Physics* 2021.1029-8479
531 (June 2021). doi: [https://doi.org/10.1007/JHEP06\(2021\)121](https://doi.org/10.1007/JHEP06(2021)121).
- 532 [20] Riccardo Catena and Piero Ullio. “A novel determination of the local dark matter density”.
533 In: *Journal of Cosmology and Astroparticle Physics* 2010.08 (Aug. 2010), p. 004. doi:
534 [10.1088/1475-7516/2010/08/004](https://doi.org/10.1088/1475-7516/2010/08/004). URL: <https://dx.doi.org/10.1088/1475-7516/2010/08/004>.
- 536 [21] B. P. Abbott et al. “Observation of Gravitational Waves from a Binary Black Hole Merger”.
537 In: *Phys. Rev. Lett.* 116 (6 Feb. 2016), p. 061102. doi: [10.1103/PhysRevLett.116.061102](https://doi.org/10.1103/PhysRevLett.116.061102). URL: <https://link.aps.org/doi/10.1103/PhysRevLett.116.061102>.
- 539 [22] R. Abbasi et. al. “Observation of high-energy neutrinos from the Galactic plane”. In: *Science*
540 380.6652 (June 2023), pp. 1338–1343.

- 541 [23] NASA Goddard Space Flight Center. *Fermi's 12-year view of the gamma-ray sky*. website.
542 2022. URL: <https://svs.gsfc.nasa.gov/14090>.
- 543 [24] Marco Cirelli et al. “PPPC 4 DM ID: a poor particle physicist cookbook for dark matter
544 indirect detection”. In: *Journal of Cosmology and Astroparticle Physics* 2011.03 (Mar.
545 2011), p. 051. DOI: [10.1088/1475-7516/2011/03/051](https://doi.org/10.1088/1475-7516/2011/03/051). URL: <https://dx.doi.org/10.1088/1475-7516/2011/03/051>.
546