

1 LEVERAGING MULTI-MESSENGER ASTROPHYSICS FOR DARK MATTER SEARCHES

By

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Today

ABSTRACT

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

4 Copyright by
5 DANIEL NICHOLAS SALAZAR-GALLEGOS
6 Today

7

ACKNOWLEDGMENTS

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

TABLE OF CONTENTS

12	LIST OF TABLES	vi
13	LIST OF FIGURES	vii
14	CHAPTER 1 INTRODUCTION	1
15	CHAPTER 2 DARK MATTER IN THE COSMOS	2
16	2.1 Introduction	2
17	2.2 Dark Matter Basics	3
18	2.3 Evidence for Dark Matter	4
19	2.4 Searching for Dark Matter	12
20	2.5 Multi-Messenger Dark Matter	19
21	2.6 Search Targets for Dark Matter	22
22	CHAPTER 3 DETECTING HIGH ENERGY NEUTRAL MESSENGERS	24
23	3.1 Cherenkov Radiation	24
24	3.2 HAWC	24
25	3.3 IceCube	24
26	3.4 Opportunities to Combine for Dark Matter	24
27	CHAPTER 4 HIGH ALTITUDE WATER CHERENKOV (HAWC) OBSERVATORY .	25
28	4.1 The Detector	25
29	4.2 Events Reconstruction and Data Acquisition	25
30	4.3 Remote Monitoring	25
31	CHAPTER 5 ICECUBE NEUTRINO OBSERVATORY	26
32	5.1 The Detector	26
33	5.2 Events Reconstruction and Data Acquisition	26
34	5.3 Northern Test Site	26
35	CHAPTER 6 COMPUTATIONAL TECHNIQUES IN PARTICLE ASTROPHYSICS .	27
36	6.1 Neural Networks for Gamma/Hadron Separation	27
37	6.2 Parallel Computing for Dark Matter Analyses	27
38	CHAPTER 7 GLORY DUCK	28
39	CHAPTER 8 NU DUCK	29
40	BIBLIOGRAPHY	30

41

LIST OF TABLES

42 Proof I know how to include

LIST OF FIGURES

43

44	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	5
45			
46			
47			
48			
49	Figure 2.2	Light from distant galaxy is bent in different way depending on the distribution of mass between the galaxy and Earth. Yellow dashed lines indicate where the light would have gone if the matter was not present.	7
50			
51			
52	Figure 2.3	Woowow	8
53	Figure 2.4	TODO: bullet cluster photo.[NEEDS A SOURCE][FACT CHECK THIS] . . .	9
54	Figure 2.5	TODO: CMB photo[NEEDS A SOURCE][FACT CHECK THIS]	11
55	Figure 2.6	TODO: Planck harmonics of CMB[NEEDS A SOURCE][FACT CHECK THIS] .	12
56	Figure 2.7	TODO: Planck harmonics vs DM content CMB[NEEDS A SOURCE][FACT CHECK THIS]	13
57			
58	Figure 2.8	TODO: Standard model. Square or Circle?[NEEDS A SOURCE][FACT CHECK THIS]	14
59			
60	Figure 2.9	TODO: Shake it, break it, make it[NEEDS A SOURCE][FACT CHECK THIS]	15
61	Figure 2.10	TODO: windy dark matter. Look at Jodi's DM lectures[NEEDS A SOURCE][FACT CHECK THIS]	16
62			
63	Figure 2.11	TODO: A particle event in CMS/ATLAS with Missing E[NEEDS A SOURCE][FACT CHECK THIS]	17
64			
65	Figure 2.12	TODO: particle cascade from DM[NEEDS A SOURCE][FACT CHECK THIS]	18
66	Figure 2.13	TODO: HDMSpectra: bb, tautau, WW[NEEDS A SOURCE][FACT CHECK THIS]	19
67			
68	Figure 2.14	TODO: Line spectra, nu and gamma[NEEDS A SOURCE][FACT CHECK THIS]	20
69	Figure 2.15	TODO: multimessenger sectors from the NSF[NEEDS A SOURCE][FACT CHECK THIS]	21
70			
71	Figure 2.16	TODO: Milky way at different wavelengths[NEEDS A SOURCE][FACT CHECK THIS]	22
72			

CHAPTER 1

73

INTRODUCTION

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

CHAPTER 2

DARK MATTER IN THE COSMOS

2.1 Introduction

I'll attempt to explain the dark matter problem at an entry level with the following thought experiment. Let's say you're the teacher for an elementary school classroom. You take them on a field trip to your local science museum and among exhibits is one for mass and weight. The exhibit has a gigantic scale, and you come up with a fun problem for your classroom.

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

The students are ecstatic to hear this, and they get to work. The solution is some variation of the following strategy. The students should give each other their weight or best guess if they don't know. Then, all they have to do is add each students' weight and get a grand total for the class. The measurement on the giant scale should show the true weight of the class. When comparing the measured weight, multiply the observation by 1.1 and 0.9 in order to get the +/- 10% tolerance respectively.

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

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

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

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

This thought experiment serves as an analogy to the Dark Matter problem. The important substitution to make however is to replace the students with stars and classroom with a galaxy, say the Milky Way. Individually the mass of stars is well measured and defined with the Sun as our nearest test case. However, when we set out to measure the mass of a collection of stars as large as galaxies, our well motivated estimation is wildly incorrect. There simply is not way to account for this discrepancy except without some unseen, or dark, contribution to mass and matter in galaxies. I set out in my thesis to narrow the possibilities of what this Dark Matter could be.

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

2.2 Dark Matter Basics

Presently, the most compelling Dark Matter (DM) model is Λ Cold Dark Matter, or Λ CDM. I present the evidence supporting Λ CDM in 2.3, yet discuss the conclusions of the Λ CDM model here. According to Λ CDM fit to observations on the Cosmic Microwave Background (CMB), DM is 26.8% of the universe's current energy budget Baryonic matter, stuff like atoms, gas, and stars, contributes to 4.9% of the universe's current energy budget [1–3].

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

Observations of DM has so far been only gravitational. The parameter space available to what DM could be therefore is very broad. Searches for DM are summarized by supposing a hypothesis that has not yet been ruled out, and performing measurements to test them. When the observations yield a null result, the parameter space is further constrained. I present some approaches for DM

128 searches in Section 2.4.

129 **2.3 Evidence for Dark Matter**

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

142 **2.3.1 First Clues: Stellar Velocities**

143 Zwicky's, and later Rubin's, measurement of the stellar velocities were built upon the Virial
144 theorem, shown as

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

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

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

148 Zwicky et. al. measured just the velocities of stars apparent in optical wavelengths [5]. Rubin et.
149 al. added by measuring the velocity of the hydrogen gas via the 21 cm emission line of Hydrogen
150 [6]. The velocities of the stars and gas are used to infer the total mass of galaxies and galaxy clusters
151 via Eq. (2.1). An inferred mass is also made from the luminosity of the selected sources. The two

152 inferences are compared to each other as a luminosity to mass ratio and typically yields [1]

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

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

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

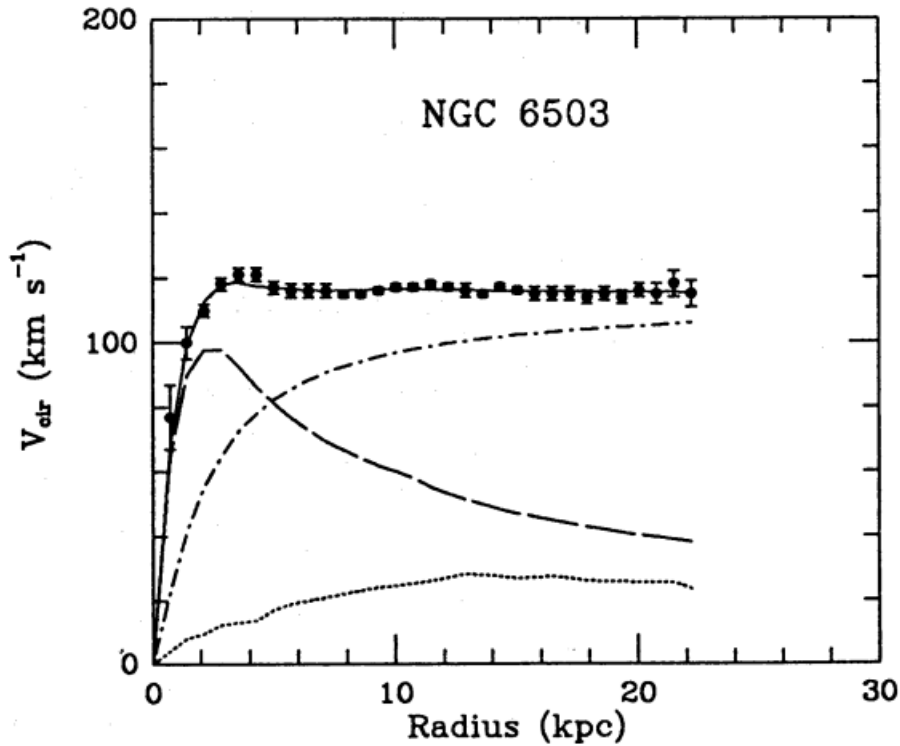


Figure 2.1 Rotation curve fit to NGC 6503 from [7]. Dashed line is the contribution from visible matter. Dotted curves are from gas. Dash-dot curves are from dark matter (DM). Solid line is the composite contribution from all matter and DM sources. Data are indicated with bold dots with error bars. Data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

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

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

2.3.2 Mounting Evidence for Dark Matter

Modern evidence for dark matter comes from new avenues beyond stellar velocities. Gravitational micro-lensing from DM is a new channel from general relativity. The Cosmic Microwave Background shows that the universe had DM in it from a very early stage. Computational resources have expanded greatly in recent decades enabling universe models that again support the need for DM in the evolution of the universe.

General relativity predicts aberrations in light caused by massive objects. In recent decades we have been able to measure the lensing effects from compact objects and DM haloes. Fig. 2.2 shows how different compact bodies change the final image of a far away galaxy resulting from gravitational lensing. Gravitational lensing developed our understanding of dark matter in two important ways.

First, micro-lensing observations, or the lack of them, of our Milky Way halo resulted in a conspicuous absence of massive astrophysical compact halo objects (MACHOs). The hypothesis was that 'dark matter' could be accounted for by sufficiently dim compact objects. Such objects include things like planets, brown dwarves, black holes, or neutron stars. Whenever these objects passed in front of a large luminous source, such as the Large Magellenic Clouds, a variation in light should be observed [4]. The MACHO and EROS collaborations performed this observation and did not find a substantial contribution to the DM Milky Way halo from MACHOs. They measured that MACHOs of mass range 0.15 to $0.9 M_{\odot}$ contributes to an upper limit of 8% of the DM halo mass [8].

Gravitational lensing can also be applied towards galaxy clusters for DM searches. The ob-

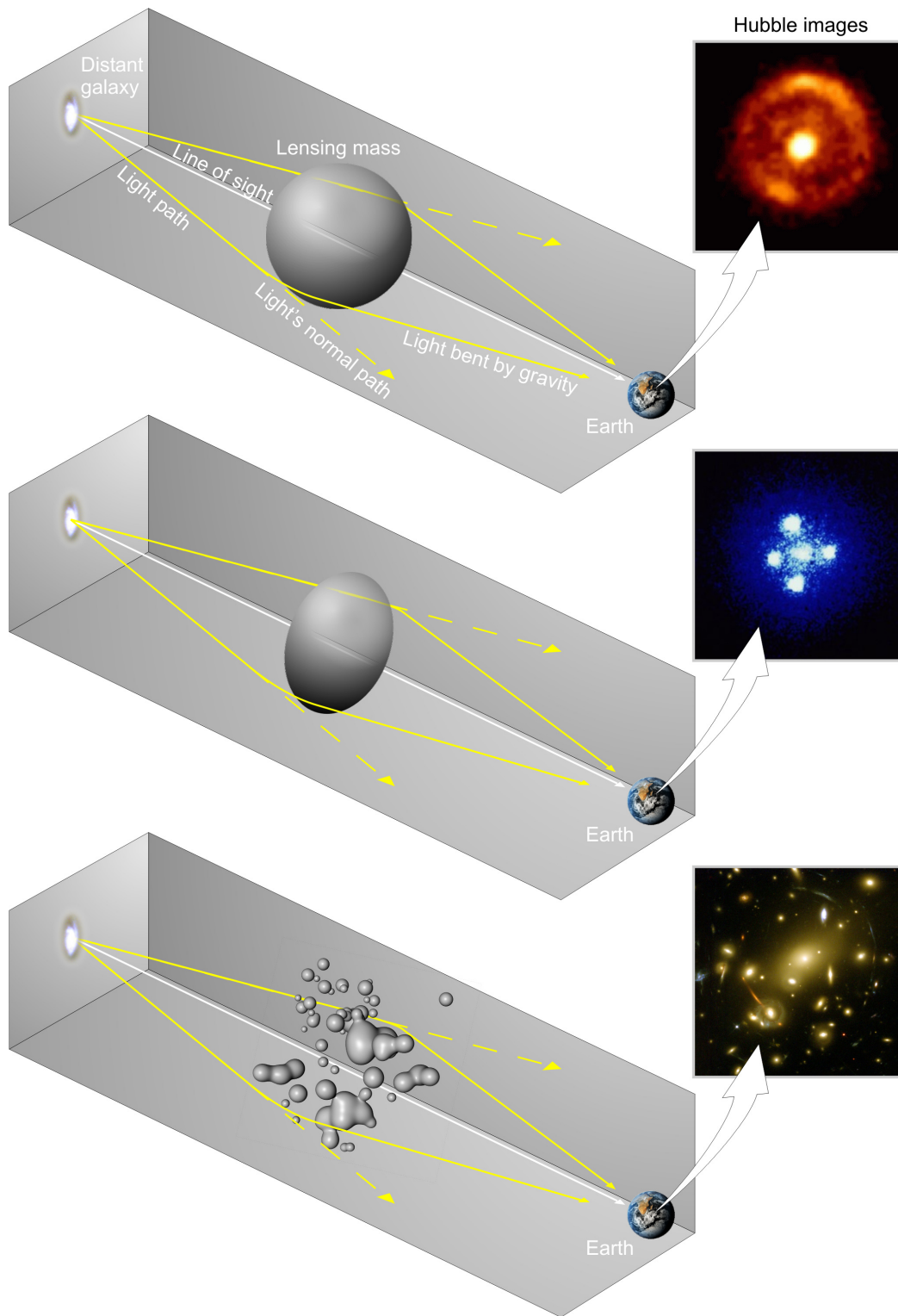


Figure 2.2 Light from distant galaxy is bent in different way depending on the distribution of mass between the galaxy and Earth. Yellow dashed lines indicate where the light would have gone if the matter was not present.

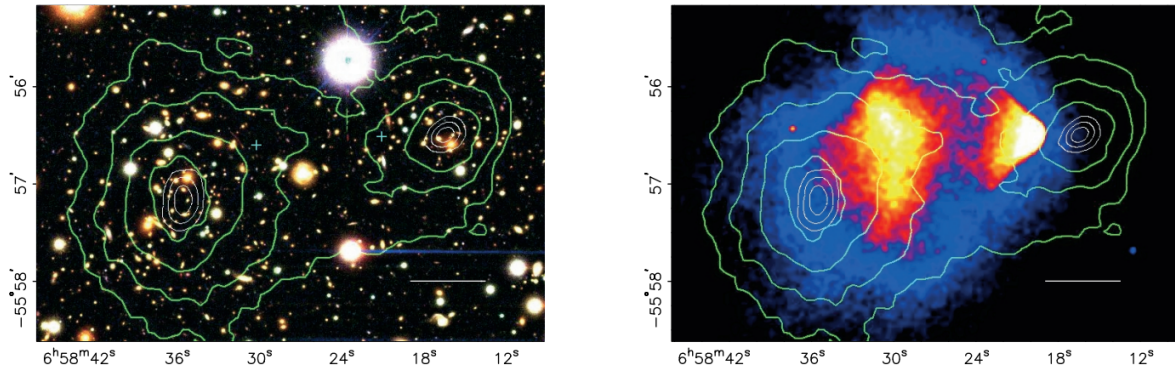


Figure 2.3 Wooooow

servation of two merging galactic clusters in 2006 provided a compelling argument for particle DM outside the Standard Model. These clusters merged recently in astrophysical time scales. As a result of their recent merge, the stars and galaxies are separated from the intergalactic gas. For these clusters, the hot, intergalactic gas is responsible for most of the mass in the systems [4]. The hot gas emits x-rays we observe at Earth.

passed through each other at some point in the past and are in the process of merging [NEEDS A SOURCE]. Two observations of the clusters were made independently of each other. The first was the microlensing of light around the galaxies due to their gravitational influences. When celestial bodies are large enough, the gravity they exert bends space and time itself. This bending effects light and will deflect light in a similar way to how lenses will bend light.

With a sufficient understanding of light sources behind a celestial body, you can reconstruct the contours of the gravitational lenses. The gradient of the contours then tells you how dense the matter is and where it is.

They then made measurements of the x-ray emission from the clusters. The idea is that since these galaxies are mostly gas and are merging, then they should be getting hotter. If they're merging, the x-ray emissions should be the strongest where the gas is mostly moving through each other. The x-rays basically map out where the gas is in these merging galaxies.

The dope super interesting thing is that the map of the x-ray emissions totally doesn't align with the gravitational contours from the microlensing. This incongruence is really telling that there is



Figure 2.4 **TODO: bullet cluster photo.**[NEEDS A SOURCE][FACT CHECK THIS]

207 a lot of matter somewhere that we jsut cannot see. Moreover this matter is NOT BARYONIC. So
 208 then what is it? This measurement didn't really tell us what exactly, but it did suggest that this DM
 209 also doesn't interact with itself very strongly. If it did, then it would have been more aligned with
 210 where the x-ray emmision was. There's been other studies of galaxies with similar results altho
 211 there are a handful that resemble something we expect for strongly self-interacting DM. [NEEDS
 212 A SOURCE]. This result really makes it hard to argue that DM is somehow something amiss in our
 213 gravitational theories.

214 The CMB is the primordial light from the young universe. Basically a baby photo. Then we
 215 look at how the simulated universes look like compared to what we see. From those simulations
 216 we infer how much dark matter is in the universe. The fuller explanations and shortcoming of each
 217 of these methods is explained further in this section.

218 we got the CMB and geometry of the universe. So there's this thing called the cosmic Microwave

219 Background (CMB). It's the universe's baby photo from when all of the hydrogen de-ionized to form
220 atoms. This happened because it was cold enough finally from the expansion of the universe. The
221 recombination happened sometime around less than 1 million years after the universe was born [FACT
222 CHECK THIS][NEEDS A SOURCE]. when hydrogen absorbs an electron, it releases a photon of
223 a specific wavelength. This wavelength amounts to 13 eV or so according to the QM eqn. . .

$$\text{INSERT hydrogen energy level HERE.} \quad (2.4)$$

224

225 However the universe has been expanding since its creation. In fact the time and space itself is
226 expanding away from us for as long as the universe is old. This red-shifts the combination light into
227 the Microwave frequencies. This is the light we can detect with microwave observatories and is
228 what was first detected by so and so in the 19?? [NEEDS A SOURCE][FACT CHECK THIS] This
229 makes a microwave image seen below after we subtract the average of the image.

230 We can do a funny thing with the photo but it's fairly straightforward. Shove the photo into a
231 spherical harmonic decomposition. This gives you the vibrational modes of the CMB and therefore
232 the early universe. The important thing to note is that the harmonics are based on primordial
233 baryonic acoustic oscillations [FACT CHECK THIS] This is directly linked with the energy density
234 of the universe and how these couple. It's a cosmology and geometry thing.

235 The harmonics would look very different for a universe with less Ω_m (see fig bla) or a lot more
236 Ω_m (see fig bla)

237 The observations fit well with the Lambda CDM model and we derive the primordial Ω_m
238 concentration to be XX% and primordial DM to be XX%. **TODO: What are the shortcomings?** I
239 think the most obvious argument is simply that this is very old light, up to 13.6 billion years old.
240 It's not at all necessary that the universe shares the exact same DM, matter ratio. There is a poor fit
241 in the lower region of the graph and this is unexplained. The way we measure distance can be
242 really fucked sometimes so maybe that's a problem too.

243 Finally we have universe simulations like the Millennium simulation and more [FACT CHECK



Figure 2.5 TODO: CMB photo[NEEDS A SOURCE][FACT CHECK THIS]

244 THIS[NEEDS A SOURCE]. These are computer simulations of the universe with different fractions
 245 of DM and baryonic matters. Additionally hypotheses are tested like how hot the DM is and how
 246 strongly it interacts with itself and with baryonic matter. These simulations are also done for smaller
 247 scales like galactic formation and galaxy clustering. In all cases the simulations most resemble
 248 out universe for a Lambda CDM like universe.

249 The main issues with the simulations is mostly that we cant perfectly simulate the universe.
 250 They are often incomplete with how they treat baryonic matter and make big assumptions about
 251 dark matter. These simulations also have to contend with very real computational limitations. The
 252 resolution of some of the universe simulations are as large at XX's of solar masses. There's reason
 253 to beleive that the resolution might really matter as well. [NEEDS A SOURCE][FACT CHECK
 254 THIS]

255 Overall this forms a compelling arguement for dark matter. However, these observations really



Figure 2.6 **TODO: Plan harmonics of CMB[NEEDS A SOURCE][FACT CHECK THIS]**

only confirm that DM is there. It takes another leap of theory to make observations of DM that are nongravitational. One of which is the emergence of the Weakly Interacting Massive Particle hypothesis of DM. This DM candidate theory is discussed further in the next section.

2.4 Searching for Dark Matter

We've explored any options for what dark matter could be now. The remainder of this thesis I will focus only on a particle dark matter hypothesis. I will not be discussing alternative gravitational theories such as Modified Newtonian Dynamics. I am also ignoring composite dark matter discussion like primordial black holes, dark atoms, or dark bound states of baryonic matter. For this thesis I focus on the hypothesis that DM is a weakly interacting and massive particle (WIMP).

The current status of the standard model does not have a WIMP candidate. When looking at the standard model, we can immediately exclude any charged particle. This is because charged particles interact with light and so much DM would be immediately visible if it had the same



Figure 2.7 **TODO: Plank harmonics vs DM content CMB[NEEDS A SOURCE][FACT CHECK THIS]**

charge as SM particles. Specifically this will rule out the following charged, fundamental particles:
 $e, \mu, \tau, W, u, d, s, c, t, b$ and their corresponding antiparticles. Recalling from earlier that DM must
 be long lived and stable over the age of the universe. This would exclude all SM particles with
 decay half-lives at or shorter than the age of the universe. This constraint eliminates the Z , and
 H bosons. Finally, the candidate DM needs to be somewhat massive. This follows from the DM
 needing to be cold or not relativistic through the universe. This eliminates the remaining SM
 particles: $\nu_{e, \mu, \tau}, g, \gamma$. This indicates the SM that is likely not the full story and hints to physics
 beyond the standard model (BSM).

2.4.1 Shake it, Break it, Make it

The above figure demonstrates the different interaction modes possible with particle DM and the
 DM. The figure is a simplified Feynman diagram where the arrow of time represents the interaction
 modes of: **Shake it, Break it, Make it.**



Figure 2.8 **TODO: Standard model. Square or Circle?****[NEEDS A SOURCE]****[FACT CHECK THIS]**

280 **Shake it** refers to the direct detection of dark matter. Direct detection interactions start with a
 281 free DM particle and some SM particle. The DM and SM interact under some elastic or inelastic
 282 collision and recoil away from each other. The DM remains in the dark sector and imparts some
 283 momentum onto the SM particle. The hope is that the momentum imparted onto the SM particle
 284 is sufficiently high enough to ick up with highly sensitive instruments. Because we cannot create
 285 the DM in the lab, we have to wait until it is incident on the detector. We do this by increasing
 286 the interaction volume of the detector with some inert chemical. We then leverage the hypothesis
 287 that the DM is everywhere around us and Earth's motion through the cosmos creates a sort of DM
 288 wind. Direct detectors are live now and taking data. Some active experiments include XENON
 289 **TODO: look up and name direct DM experiments.**

290 **Make it** refers to the production of DM from SM initial states. The experiment starts with
 291 particles in the SM. These SM particles are accelerated to incredibly high energies and then collided



Figure 2.9 **TODO: Shake it, break it, make it**[NEEDS A SOURCE][FACT CHECK THIS]

with each other. In the confluence of energy DM emerges as a byproduct of the SM annihilation. Often it is the collider experiments that are able to generate energies high enough to probe DM. These experiments include the renown ATLAS and CMS collaborations at CERN where protons are collided together at extreme energies. The DM searches however are complex. DM likely does not interact with the detectors and lives long enough to escape the detection apparatus of CERN's colliders. This means any DM search with production searches for an excess of events with missing energy in the events. The missing energy with no particle tracks implies a neutral particle carried the energy out of the detector. However, there are other neutral particles in the SM and so any analysis have to discriminate between SM signatures of missing energy and a potential DM candidate.

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

Break it refers to the creation of SM particles from the dark sector, and it is the primary concern of this thesis. The interaction begins with dark matter or in the dark sector. The hypothesis is that



Figure 2.10 **TODO: windy dark matter. Look at Jodi's DM lectures[NEEDS A SOURCE][FACT CHECK THIS]**

304 this DM will either annihilate with itself or decay and produce a SM byproduct which we can detect.
 305 This method is often referred to the Indirect detection of DM because we have no lab to directly
 306 control or manipulate the DM. Therefore most DM primary observations will be performed from
 307 observations of known DM densities among the cosmos. The strength is that we have the entirety
 308 of the universe and its lifespan to use as the detector or particle accelerator. Additionally, locations
 309 of dark matter are also well understood since it was astrophysical observations that presented the
 310 problem of DM in the first place.

311 However, anything can happen in the universe. So there are many difficult to deconvolve
 312 backgrounds when searching for a DM signal. One prominent example is the galactic center.
 313 There's a lot of DM there since the Milky Way definitely has a lot of DM. But any signal coming
 314 from there is hard to parse apart from the extreme environment of our supermassive black hole,
 315 Sagittarius A* In fact, there has been known γ -ray excesses from the galactic center **[NEEDS A**



Figure 2.11 **TODO: A particle event in CMS/ATLAS with Missing E[NEEDS A SOURCE][FACT CHECK THIS]**

316 **SOURCE]**, yet the environment presents a difficult problem in sussing out what the fuck is actually
 317 going on. Despite the challenges, any DM model that yields evidence in the other observation
 318 two methods, **Shake it or Make it** must be corroborated with indirect observations of the known
 319 DM overdensities. Without corroborating Evidence, DM observation in the lab is hard pressed to
 320 demonstrate that it is the model contributing to the DM seen at the universal scale.

321 In the case of WIMP DM, signals are typically described in terms of primary SM particles
 322 produced from a DM decay or annihilation. These particles are then simulated to stable final states
 323 such as: γ , ν , p , or e which can traverse galactic lengths to reach the earth.

324 The figure shows the quagmire of SM particles that emerges from SM initial states that are not
 325 stable. There's a lot of different things with different energies that can pop out.

326 For any neutral messenger, the DM flux from DM annihilating to some particle in the SM, ϕ ,
 327 from a region in the sky is



Figure 2.12 **TODO: particle cascade from DM****[NEEDS A SOURCE]****[FACT CHECK THIS]**

$$INSERTDMannfluxequationHERE. \quad (2.5)$$

328

329 **TODO: explain the equation**And for decay it is . . .

$$INSERTDMdecayfluxeqHERE. \quad (2.6)$$

330

331 **TODO: explain the equation**

332 The integral over a line of sight is a simplification made because we mostly observe a 2d
 333 surface with our Astrophysics experiments. This also translates the equation into observables in
 334 our detector like solid angle. The spectral shape is mostly determined by the SM primary products.
 335 From HDMSpectra, they look like the following figures for the bb, tau, and Z spectra.



Figure 2.13 **TODO: HDMSpectra: bb, tautau, WW[NEEDS A SOURCE][FACT CHECK THIS]**

336 Additionally, when DM primarily goes into one of the neutral messengers (nu or gamma), the
 337 spectra will typically have a line feature. These messengers are very unlikely to be attenuated in
 338 any way from their primary state. These line spectra are usually considered smoking gun signals
 339 as their energy will be half the COM of the DM \rightarrow SM process. For DM in the GeV+ scale, there
 340 is no similar SM process and so seeing the signal would almost certainly be an indication of the
 341 presence of dark matter.

342 We fortunately have the largest volume and lifetime ever for a particle physics experiment in the
 343 universe. This means we can do some pretty cool shit very efficiently. The drawn back are the
 344 backgrounds.

345 **2.5 Multi-Messenger Dark Matter**

346 Astrophysics entered a dope as fuck new phase in the past few decades that leverages our new
 347 knowlledge of the SM and general relativity. Up until the 21st century, astrophysical observations



Figure 2.14 **TODO: Line spectra, nu and gamma****[NEEDS A SOURCE]****[FACT CHECK THIS]**

348 were done with photons. At first, observations were optical in nature. You can confirm this yourself
 349 by going outside at night. The moon and constellations are observabke to the naked eye. In darker
 350 places on Earth, celestial bodies like our Milky Way galaxy become visible. Novel observations
 351 of the universe have since only adjusted the sensitivity of the wavelength of light that's observed.
 352 Gems like the CMB, MEERkat, **[NEEDS A SOURCE]** and more have ultimately been observations
 353 of different wavelengths of light. Light can also be thought of as a particle in the SM is referred to
 354 as a photon, or a packet of light.

355 Come the 21st century and we've started to use more of the SM and general relativity. The
 356 experiments LIGO and VIRGO had an iconic dicoverly in 2015??**[FACT CHECK THIS]** with the
 357 first chirps of black hole mergers. This opened an entirely new method of observing the universe
 358 through gravitational waves. They litterally use the bending of space-time to do astrophysics like
 359 holy shit. There's also been a surge of interested in the neutrino sector. We're now finally having



Figure 2.15 **TODO: multimessenger sectors from the NSF[NEEDS A SOURCE][FACT CHECK THIS]**

some sensitivity to neutrinos that we're able to detect them from astrophysical sources. Neutrinos, like gravitational waves and light, travels mostly unimpeded from their source to our observatories. This makes pointing to the originating source of the these messengers much each than it is for cosmic rays that are almost always deflected from their source.

Being able to see the same objects under different regimes was demonstrated already with just photons. From the previous figure you can see different ways to look at the milky way galaxy. Each panel corresponds do a different wavelength of light which has different penetrations through gas and galactic dust. Some sources are more apparent in some panels, while others are not. Recently, the IceCube collaboration published a groundbreaking result of the milky way in neutrinos. This new channel is very unique because we can really see through the galaxy. This new image also refines our understanding of how high energy particles are accelerated since the fit to IceCube data prefers one standard model process over the other.



Figure 2.16 **TODO: Milky way at different wavelengths****[NEEDS A SOURCE]****[FACT CHECK THIS]**

372 Exposing our observations to more cosmic messengers greatly increases our sensitivity to rare
 373 processes. In the case of DM, from fig (SM ann), you can see there are many SM particles at the end
 374 of the particle cascade. Among the final states are gammas and neutrinos. The charged particles
 375 however would not likely make it to earth since they'll be deflected. This means observatories that
 376 can see the neutral messengers are especially good for DM searches and for combining data for a
 377 multi-messenger search.

378 **2.6 Search Targets for Dark Matter**

379 We of course have to know where to look. Thankfully, we have a good idea of where. Our
 380 first detection of DM relied on optical observations. Since then, we've developed new techniques
 381 to find large DM dense regions. We first found out about DM through observing galactic rotation
 382 curves. This includes our nearest galaxy, the Milky Way. The Milky Way thus is the largest nearby
 383 DM dense region to look at. Additionally, the DM halo surrounding the Milky Way is somewhat

384 clumpy [NEEDS A SOURCE]. There are regions in the DM halo of the Milky Way that have more
385 DM than others and it's captured gas over time. In some cases these sub-haloes were dense enough
386 to creat stars. These apparent sub galaxies are known was dwarf spheroidal galaxies and are the
387 main sources studied in this thesis.

388 **2.6.1 Dwarf Spheroidal Galaxies**

389 The way we look for dwarf spheroidal galaxies (dSph's) is through mostly Newtonian physics.
390 We use either the virial theorem to determine the DM density of the dSph's or a Jeans analysis /ns.
391 DSphs tend to be ideal sources to look at for DM searches. The reason is that these environments
392 are fairly quiet. Unlike the galactic center, the most active components of dSph's are the stars within
393 them. There are few compact objects, like black holes, and much less gas that would contribute
394 to a large backgrounds. The DM to mass ratio here is also massive. [NEEDS A SOURCE]. The
395 signal to background ratio is really large and we expect a lot of signal from how much dark matter
396 there is. All this together means that dSph's are among the best sources to look at for indirect DM
397 searches.

CHAPTER 3

398

DETECTING HIGH ENERGY NEUTRAL MESSENGERS

399

3.1 Cherenkov Radiation

400

3.2 HAWC

401

3.3 IceCube

402

3.4 Opportunities to Combine for Dark Matter

CHAPTER 4

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

404 **4.1 The Detector**

405 **4.2 Events Reconstruction and Data Acquisition**

406 **4.2.1 G/H Discrimination**

407 **4.2.2 Angle**

408 **4.2.3 Energy**

409 **4.3 Remote Monitoring**

410 **4.3.1 ATHENA Database**

411 **4.3.2 HOMER**

CHAPTER 5

412

ICECUBE NEUTRINO OBSERVATORY

413 5.1 The Detector

414 5.2 Events Reconstruction and Data Acquisition

415 5.2.1 Angle

416 5.2.2 Energy

417 5.3 Northern Test Site

418 5.3.1 Pigeon remote dark rate testing

419 5.3.2 Bulkhead Construction

CHAPTER 6

420 COMPUTATIONAL TECHNIQUES IN PARTICLE ASTROPHYSICS

421 6.1 Neural Networks for Gamma/Hadron Separation

422 6.2 Parallel Computing for Dark Matter Analyses

CHAPTER 7

423

GLORY DUCK

CHAPTER 8

NU DUCK

424

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