

1 LEVERAGING MULTI-MESSENGER ASTROPHYSICS FOR DARK MATTER SEARCHES

By

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Today

2

ABSTRACT

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

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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

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Proof I know how to include

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INTRODUCTION

16 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 ... Chaper x has blah blah blah.**

2.2 Dark Matter Basics

Dark Matter (DM) has been a looming problem in physics for almost 100 years. Anamolies have been observed in galactic dynamics as early as 1933 when Fritz Zwicky noticed unusually large velocity dispersions in the Coma cluster. Zwicky's measurement was the first recorded to use the virial theorem to measure the mass fraction of visible and invisible matter in celestial bodies. **[DMHistory]** It's kind of a big deal because we have no idea what the nature of this stuff and there's a lot of it. According to Lambda CDM, the most legit model, **[NEEDS A SOURCE]**DM is about 85% **[FACT CHECK THIS]**, of all mass in the universe. It's called dark in fact because we cannot see it. **[NEEDS A SOURCE]**Finding out what the hell it is, is an active field of research and hopefully it interacts with the standard model.

Here's what we do know about DM so far. . . DM is dark, it doesn't interact readily with light. DM also doesn't interact noticably with the other standard model forces (EM, Strong, Weak) at a rate that matters **[NEEDS A SOURCE]**. DM is cold. By cold I mean that it is most likely not moving at relativisic speeds like neutrinos and photons. **[NEEDS A SOURCE]**If it was moving that fast, the structures we see like galaxies would be much more diffuse than what is observed. **[NEEDS A SOURCE]**DM is old. DM played a critical role in the formation of the universe and the

70 structure within it. [NEEDS A SOURCE] We know this from Cosmology and computer universe
71 simulations [NEEDS A SOURCE].

72 The search for DM is basically summarized by trying a bunch of different models and performing
73 measurements of all kinds to test them. These models of course have to nominally agree with the
74 known observations seen over the last century. Whenever we perform a test and don't see anything,
75 the parameter spaces gets more constrained. I discuss some of the ideas and approaches further on. I
76 Especially discuss the models that are relevant to my thesis.

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

80 **2.3 Evidence for Dark Matter**

81 Let me show you why we're pretty sure DM is a thing and why it might be particle like in
82 nature. My thesis focuses on WIMP dark matter which is one of the better motivated things out
83 there There were some weird as fuck anomalies early in the last century but we weren't 100% that
84 it was legit. Then some great scientists made some keen measurements of stars and their minds
85 were blown. Read more to see what we know now. I promise you're about to get mind fucked.

86 **2.3.1 First Clues: Stellar Velocities**

87 Ok so someone [FACT CHECK THIS][NEEDS A SOURCE] started taking measurements with
88 at. They were curious about what speed stars were orbiting the galaxies they were contained in.
89 These measurements were done for things close by. At the time we were even that sure galaxies
90 were a thing. But with the basic knowledge we had we used the virial theorem with the velocities
91 of the stars to measure the mass indirectly of the galaxies.

$$INSERT The Virial Eqn HERE. \quad (2.1)$$

92

93 **TODO: explain the virial equation**[NEEDS A SOURCE] you probably want to source the theory
94 behind why this important

95 The verdict wasn't clear however until Vera Rubin made some awesome discoveries with more
96 precise equipment and 21cm lines of Hydrogen gas in the galaxies. This really showed that
97 there was some unexplained discrepancy between how much mass we were seeing in the stars
98 and the mass measured indirectly. The issue is that we're pretty sure now that we're not just
99 under-estimating the mass of the stars [NEEDS A SOURCE]. The difference in mass was up to 5x
100 which is way way too much for what our uncertainties were (somewhere around 20%)[NEEDS A
101 SOURCE].



Figure 2.1 TODO: velocity dispersion old here.[NEEDS A SOURCE][FACT CHECK THIS]

102 Nowadays we have more measurements of the stellar velocities and have even discovered small
103 DM dense bodies called dwarf spheroidals (dSph) These measurements have been made by the
104 community [FACT CHECK THIS] and there are compiled lists of how much DM these objects
105 have. Most of these measurements are made from newtonian virial theorem measurements. There
106 has since emerged new evidence. These innovative techs are discussed in the following sections.

107 The evidence culminates into a story of particle dark matter.

108 **2.3.2 Mounting Evidence for Dark Matter**

109 Modern evidence for dark matter comes from new avenues. We got microlensing which supports
110 DM in the general relativity sector. The Cosmic Microwave Background shows that the universe
111 has DM in it from a very early stage. The CMB is the primordial light from the young universe.
112 Basically a baby photo. Then we have computational models where we model the universe. Then
113 we look at how the simulated universes look like compared to what we see. From those simulations
114 we infer how much dark matter is in the universe. The fuller explanations and shortcoming of each
115 of these methods is explained further in this section.

116 someone took a an observation of the bullet cluster. The microlensing of galaxy clusters are
117 some of the most damning evidence that DM is actually matter and not just a flaw in our gravitational
118 theories. There were two galaxy clusters [FACT CHECK THIS]. They clearly passed through each
119 other at some point in the past and are in the process of merging [NEEDS A SOURCE]. Two
120 observations of the clusters were made independantly of each other. The first was the microlensing
121 of light around the galaxies due to their gravitational influences. When celestial bodies are large
122 enough, the gravity they exert bends space and time itself. This bending effects light and will
123 deflect light in a smilar way to how lenses will bend light.

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

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

131 The dope super interesting thing is that the map of the x-ray emmissions totally doesnt align with
132 the gravitational countours from the microlensing. This incongruence is really telling that there is
133 a lot of matter somewhere that we jsut cannot see. Moreover this matter is NOT BARYONIC. So



Figure 2.2 **TODO: gravitational lensing figure compared to glass lensing.**[NEEDS A SOURCE][FACT CHECK THIS]

then what is it? This measurement didn't really tell us what exactly, but it did suggest that this DM also doesn't interact with itself very strongly. If it did, then it would have been more aligned with where the x-ray emission was. There's been other studies of galaxies with similar results although there are a handful that resemble something we expect for strongly self-interacting DM. [NEEDS A SOURCE]. This result really makes it hard to argue that DM is somehow something amiss in our gravitational theories.

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



Figure 2.3 **TODO: bullet cluster photo.**[NEEDS A SOURCE][FACT CHECK THIS]

INSERThydrogenenergylevelHERE. (2.2)

146

147 However the universe has been expnding since it's creation. In fact the time and space itself is
 148 exanding away from us for as long as the universe is old. This red-shifts the combination light into
 149 the Microwave frequencies. This is the light we can detect with microwave observatories and is
 150 what was first detected by so and so in the 19?? [NEEDS A SOURCE][FACT CHECK THIS]This
 151 make a microwave image seen below after we subtract the average of the image.

152 We can do a funny thing with the photo but it's fairly straight forward. Shove the photo into a
 153 spherical harmonic decomposition. This gives you the vibrational modes of the CMB and therefore
 154 the early universe. The important thing to note is that the harmoincs are based on primordial
 155 baryonic acoustic oscillations [FACT CHECK THIS]This is directly linked with the energy density



Figure 2.4 **TODO: CMB photo****[NEEDS A SOURCE]****[FACT CHECK THIS]**

156 of the universe and how these couple. It's a cosmology and geometry thing.

157 The harmonics would look very different for a universe with less dmm (see fig bla) or a lot more
158 dm (see fig bla)

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

165 Finally we have universe simulations like the millenium simultation and more **[FACT CHECK**
166 **THIS]****[NEEDS A SOURCE]**. These are computer simulations of the universe with different fractions
167 of DM and baryonic matters. Additionally hypotheses are tested like how hot the DM is and how



Figure 2.5 TODO: Plan harmonics of CMB[NEEDS A SOURCE][FACT CHECK THIS]

168 strongly it interacts with itself and with baryonic matter. These simulations are also done for smaller
 169 scales like galactic formation and galaxy clustering. In all cases the simulations most resemble
 170 out universe for a Lambda CDM like universe.

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

177 Overall this forms a compelling arguement for dark matter. However, these observations really
 178 only confirm that DM is there. It takes another leap of theory to make observations of DM that
 179 are nongravitational. One of which is the emergence of the Weakly Interacting Massive Particle



Figure 2.6 **TODO: Plank harmonics vs DM content CMB[NEEDS A SOURCE][FACT CHECK THIS]**

180 hypothesis of DM. This DM candidate theory is discussed further in the next section.

181 **2.4 Searching for Dark Matter**

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

187 The current status of the standard model does not have a WIMP candidate. When looking at
 188 the standard model, we can immediately exclude any charged particle. This is because charged
 189 particles interact with light and so much DM would be immediately visible if it had the same
 190 charge as SM particles. Specifically this will rule out the following charged, fundamental particles:
 191 $e, \mu, \tau, W, u, d, s, c, t, b$ and their corresponding antiparticles. Recalling from earlier that DM must



Figure 2.7 **TODO: Standard model. Square or Circle?****[NEEDS A SOURCE]****[FACT CHECK THIS]**

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**.

Shake it refers to the direct detection of dark matter. Direct detection interactions start with a free DM particle and some SM particle. The DM and SM interact under some elastic or inelastic



Figure 2.8 **TODO: Shake it, break it, make it**[NEEDS A SOURCE][FACT CHECK THIS]

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

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



Figure 2.9 **TODO: windy dark matter. Look at Jodi's DM lectures[NEEDS A SOURCE][FACT CHECK THIS]**

These experiments include the renowned 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 this DM will either annihilate with itself or decay and produce a SM byproduct which we can detect. This method is often referred to the Indirect detection of DM because we have no lab to directly



Figure 2.10 **TODO: A particle event in CMS/ATLAS with Missing E****[NEEDS A SOURCE]****[FACT CHECK THIS]**

228 control or manipulate the DM. Therefore most DM primary observations will be performed from
 229 observations of known DM densities among the cosmos. The strength is that we have the entirety
 230 of the universe and its lifespan to use as the detector or particle accelerator. Additionally, locations
 231 of dark matter are also well understood since it was astrophysical observations that presented the
 232 problem of DM in the first place.

233 However, anything can happen in the universe. So there are many difficult to deconvolve
 234 backgrounds when searching for a DM signal. One prominent example is the galactic center.
 235 There's a lot of DM there since the Milky Way definitely has a lot of DM. But any signal coming
 236 from there is hard to parse apart from the extreme environment of our supermassive black hole,
 237 Sagittarius A*. In fact, there have been known γ -ray excesses from the galactic center **[NEEDS A**
 238 **SOURCE]**, yet the environment presents a difficult problem in sussing out what the fuck is actually
 239 going on. Despite the challenges, any DM model that yields evidence in the other observation

240 two methods, **Shake it or Make it** must be corroborated with indirect observations of the known
241 DM overdensities. Without corroborating Evidence, DM observation in the lab is hard pressed to
242 demonstrate that it is the model contributing to the DM seen at the universal scale.

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



Figure 2.11 **TODO: particle cascade from DM[NEEDS A SOURCE][FACT CHECK THIS]**

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

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

$$\text{INSERT DM ann flux equation HERE.} \quad (2.3)$$

250

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

$$\textcolor{green}{INSERT DM decay flux eq HERE.} \tag{2.4}$$

252

253 **TODO: explain the equation**

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



Figure 2.12 **TODO: HDMSpectra: bb, tautau, WW[NEEDS A SOURCE][FACT CHECK THIS]**

258 Additionally, when DM primarily goes into one of the neutral messengers (nu or gamma), the
259 spectra will typically have a line feature. These messengers are very unlikely to be attenuated in

any way from their primary state. These line spectra are usually considered smoking gun signals as their energy will be half the COM of the DM \rightarrow SM process. For DM in the GeV+ scale, there is no similar SM process and so seeing the signal would almost certainly be an indication of the presence of dark matter.



Figure 2.13 **TODO: Line spectra, nu and gamma****[NEEDS A SOURCE]****[FACT CHECK THIS]**

2.5 Multi-Messenger Dark Matter

Astrophysics entered a dope as fuck new phase in the past few decades that leverages our new knowledge of the SM and general relativity. Up until the 21st century, astrophysical observations were done with photons. At first, observations were optical in nature. You can confirm this yourself by going outside at night. The moon and constellations are observable to the naked eye. In darker places on Earth, celestial bodies like our Milky Way galaxy become visible. Novel observations of the universe have since only adjusted the sensitivity of the wavelength of light that's observed. Gems like the CMB, MEERkat, **[NEEDS A SOURCE]** and more have ultimately been observations

272 of different wavelengths of light. Light can also be thought of as a particle in the SM is referred to
273 as a photon, or a packet of light.



Figure 2.14 **TODO: multimessenger sectors from the NSF[NEEDS A SOURCE][FACT CHECK THIS]**

274 Come the 21st century and we've started to use more of the SM and general relativity. The
275 experiments LIGO and VIRGO had an iconic discovery in 2015??[FACT CHECK THIS]with the
276 first chirps of black hole mergers. This opened an entirely new method of observing the universe
277 through gravitational waves. They literally use the bending of space-time to do astrophysics like
278 holy shit. There's also been a surge of interest in the neutrino sector. We're now finally having
279 some sensitivity to neutrinos that we're able to detect them from astrophysical sources. Neutrinos,
280 like gravitational waves and light, travels mostly unimpeded from their source to our observatories.
281 This makes pointing to the originating source of these messengers much easier than it is for
282 cosmic rays that are almost always deflected from their source.



Figure 2.15 **TODO: Milky way at different wavelengths****[NEEDS A SOURCE]****[FACT CHECK THIS]**

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

291 Exposing our observations to more cosmic messengers greatly increases our sensitivity to rare
 292 processes. In the case of DM, from fig (SM ann), you can see there are many SM particles at the end
 293 of the particle cascade. Among the final states are gammas and neutrinos. The charged particles
 294 however would not likely make it to earth since they'll be deflected. This means observatories that

295 can see the neutral messengers are especially good for DM searches and for combining data for a
296 multi-messenger search.

297 **2.6 Search Targets for Dark Matter**

298 We of course have to know where to look. Thankfully, we have a good idea of where. Our
299 first detection of DM relied on optical observations. Since then, we've developed new techniques
300 to find large DM dense regions. We first found out about DM through observing galactic rotation
301 curves. This includes our nearest galaxy, the Milky Way. The Milky Way thus is the largest nearby
302 DM dense region to look at. Additionally, the DM halo surrounding the Milky Way is somewhat
303 clumpy [NEEDS A SOURCE]. There are regions in the DM halo of the Milky Way that have more
304 DM than others and it's captured gas over time. In some cases these sub-haloes were dense enough
305 to create stars. These apparent sub galaxies are known as dwarf spheroidal galaxies and are the
306 main sources studied in this thesis.

307 **2.6.1 Dwarf Spheroidal Galaxies**

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

CHAPTER 3

317 **DETECTING HIGH ENERGY NEUTRAL MESSENGERS**

318 **3.1 Cherenkov Radiation**

319 **3.2 HAWC**

320 **3.3 IceCube**

321 **3.4 Opportunities to Combine for Dark Matter**

CHAPTER 4

322 HIGH ALTITUDE WATER CHERENKOV (HAWC) OBSERVATORY

323 4.1 The Detector

324 4.2 Events Reconstruction and Data Acquisition

325 4.2.1 G/H Discrimination

326 4.2.2 Angle

327 4.2.3 Energy

328 4.3 Remote Monitoring

329 4.3.1 ATHENA Database

330 4.3.2 HOMER

CHAPTER 5

331

ICECUBE NEUTRINO OBSERVATORY

332 **5.1 The Detector**

333 **5.2 Events Reconstruction and Data Acquisition**

334 **5.2.1 Angle**

335 **5.2.2 Energy**

336 **5.3 Northern Test Site**

337 **5.3.1 Pigeon remote dark rate testing**

338 **5.3.2 Bulkhead Construction**

CHAPTER 6

339 COMPUTATIONAL TECHNIQUES IN PARTICLE ASTROPHYSICS

340 6.1 Neural Networks for Gamma/Hadron Separation

341 6.2 Parallel Computing for Dark Matter Analyses

CHAPTER 7

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GLORY DUCK

CHAPTER 8

NU DUCK

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