

LEVERAGING MULTI-MESSENGER ASTROPHYSICS FOR DARK MATTER SEARCHES

By

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Today

## **ABSTRACT**

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

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## **ACKNOWLEDGMENTS**

I love my friends. Thanks to everyone that helped me figure this out. Amazing thanks to the people at LANL who supported me. Eames, etc Dinner Parties Jenny and her child Kaydince Kirsten, Pat, Andrea Family. Roommate

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## **CHAPTER 1**

### **INTRODUCTION**

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. You see the gigantic scale and come up with a fun problem.

You say to your class, "What is the weight of the classroom? Give me your guess 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 have a movie day tomorrow with a movie of your choice."

The kids are ecstatic to hear this, and they get to work. The solution is straight forward. 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 student's weight and get a grand total for the class.

Alice and Bob 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's 30 of us, and we got 2000 lbs! That a ton!"

You estimated 1900 lbs assuming the average weight of a student in your class was ~60 lbs. So you're pleased with this 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 thousand lbs*! This is way more than a 10% error. In fact this is 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 fact in working order. You then weigh a couple students individually, maybe the scale is not properly calibrated. Alice weighs 59 lbs, and Bob 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 is in essence 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 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 can 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 whispering problem in physics for almost 100 years. Anomalies have been detected by way of weird galaxy behaviour, budding Cosmology, and more **[NEEDS A SOURCE]**. It was sometime in 1930's when the super duper smart Zwicky measured that it was defintely there. 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 structure within it. **[NEEDS A SOURCE]**We know this from Cosmology and computer universe simulations **[NEEDS A SOURCE]**.

The search for DM is basically summarized by trying a bunch of different models and performing measurements of all kinds to test them. These models of course have to nominally agree with the

known observations seen over the last century. Whenever we perform a test and don't see anything, the parameter spaces gets more constrained. I discuss some of the ideas and approaches further on. I Especially discuss the models that are relevant to my thesis.

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

## 2.3 Evidence for Dark Matter

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

### 2.3.1 First Clues: Stellar Velocities

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

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

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

The verdict wasn't clear however until Vera Rubin made some awesome discoveries with more precise equipment and 21cm lines of Hydrogen gas in the galaxies. This really showed that there was some unexplained discrepancy between how much mass we were seeing in the stars and the mass measured indirectly. The issue is that it we're pretty sure now that we're not just

under-estimating the mass of the stars [NEEDS A SOURCE]. The difference in mass was up to 5x which is way way too much for what our uncertainties were (somewhere around 20%)[NEEDS A SOURCE].



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

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

### 2.3.2 Mounting Evidence for Dark Matter

Modern evidence for dark matter comes from new avenues. We got microlensing which supports DM in the general relativity sector. The Cosmic Microwave Background shows that the universe

has DM in it from a very early stage. The CMB is the primordial light from the young universe. Basically a baby photo. Then we have computational models where we model the universe. Then we look at how the simulated universes look like compared to what we see. From those simulations we infer how much dark matter is in the universe. The fuller explanations and shortcoming of each of these methods is explained further in this section.

someone took a an observation of the bullet cluster. The microlensing of galaxy clusters are some of the most damning evidence that DM is actually matter and not just a flaw in our gravitational theories. There were two galaxy clusters [FACT CHECK THIS]. They clearly 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 independantly 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 smilar way to how lenses will bend light.

With a sufficient understanding of light sources behind a celestial body, you can reconstruct the countours 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 emmision from the clusters. The idea is that since these galaxies are mostly gass and are merging, then they should be getting hotter. If they're merging, the x-ray emmisions 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 emmisions totally doesnt align with the gravitational countours from the microlensing. This incongruence is really telling that there is a lot of matter somewhere that we jsut cannot see. Moreover this matter is NOT BARYONIC. So 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 emmision was. There's been other studies of galaxies with similar results altho there are a handful that resemble something we expect for strongly self-interacting DM. [NEEDS



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

**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. . .

$$\text{INSERT hydrogen energy level HERE.} \quad (2.2)$$

However the universe has been expanding since its creation. In fact the time and space itself is





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

expanding away from us for as long as the universe is old. This red-shifts the combination light into the Microwave frequencies. This is the light we can detect with microwave observatories and is what was first detected by so and so in the 19?? [NEEDS A SOURCE][FACT CHECK THIS] This make a microwave image seen below after we subtract the average of the image.

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

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

The observations fit well with the Lambda CDM model and we derive the primordial dm



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

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

Finally we have universe simulations like the millenium simulation and more [FACT CHECK THIS][NEEDS A SOURCE]. These are computer simulations of the universe with different fractions of DM and baryonic matters. Additionally hypotheses are tested like how hot the DM is and how strongly it interacts with itself and with baryonic matter. These simulations are also done for smaller scales like galactic formation and galaxy clustering. In all cases the simulations most resemble our universe for a Lambda CDM like universe.

The main issues with the simulations is mostly that we can't perfectly simulate the universe.





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

They are often incomplete with how they treat baryonic matter and make big assumptions about dark matter. These simulations also have to contend with very real computational limitations. The resolution of some of the universe simulations are as large as  $10^{15}$  solar masses. There's reason to believe that the resolution might really matter as well. **[NEEDS A SOURCE]****[FACT CHECK THIS]**

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



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

## **2.4 Searching for Dark Matter**

### **2.4.1 Shake it, Break it, Make it**

### **2.4.2 Break it: Standard Model Signatures of Annihilating Dark Matter**

## **2.5 Multi-Messenger Dark Matter**

## **2.6 Search Targets for Dark Matter**

### **2.6.1 Dwarf Spheroidal Galaxies**

## **CHAPTER 3**

### **DETECTING HIGH ENERGY NEUTRAL MESSENGERS**

#### **3.1 Cherenkov Radiation**

#### **3.2 HAWC**

#### **3.3 IceCube**

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

## **CHAPTER 4**

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

#### **4.1 The Detector**

#### **4.2 Events Reconstruction and Data Acquisition**

##### **4.2.1 G/H Discrimination**

##### **4.2.2 Angle**

##### **4.2.3 Energy**

#### **4.3 Remote Monitoring**

##### **4.3.1 ATHENA Database**

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## **CHAPTER 5**

### **ICECUBE NEUTRINO OBSERVATORY**

#### **5.1 The Detector**

#### **5.2 Events Reconstruction and Data Acquisition**

##### **5.2.1 Angle**

##### **5.2.2 Energy**

#### **5.3 Northern Test Site**

##### **5.3.1 Pigeon remote dark rate testing**

##### **5.3.2 Bulkhead Construction**

## **CHAPTER 6**

### **COMPUTATIONAL TECHNIQUES IN PARTICLE ASTROPHYSICS**

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

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

**CHAPTER 7**  
**GLORY DUCK**

## **CHAPTER 8**

### **NU DUCK**