Searching for Dark Matter with Cosmic Gamma Rays

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Preface

> *The hardest thing of all is to find a black cat in a dark room, especially if there is no cat.*
>
> Confucius

In our case, we know there is dark matter, but its particle nature has remained elusive. Detecting something for the first time requires cutting edge instruments and a deep understanding of background uncertainties. I hope this can serve as an introduction to an exciting field that is always in need of new, innovative ideas. Happy hunting!

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Author biography

Andrea Albert

Andrea first became interested in particle astrophysics while studying at Rice University. She earned her doctorate at The Ohio State University where she performed searches for dark matter signals using the *Fermi* Large Area Telescope. While a postdoc at SLAC National Accelerator Laboratory, she was tapped to be the Dark Matter and New Physics working group coordinator within the *Fermi* LAT Collaboration. She is currently the Marie Curie Distinguished Postdoctoral Fellow at Los Alamos National Laboratory where she continues the hunt for dark matter signals using both the *Fermi* LAT and the HAWC Observatory. Andrea also enjoys Jazzercise and hanging out at home with her husband Dylan and their two cats Ben and Marty.

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Chapter 1

Introduction

What is the Universe made of? This is perhaps the most fundamental scientific question. Physicists have made tremendous progress identifying and characterizing the basic building blocks of the world we live in. The Standard Model of particle physics describes the particles and interactions that govern the physical processes we encounter every day. However, overwhelming evidence suggests that 95% of the energy density of the Universe is governed by physics beyond the Standard Model of particle physics. It seems that most of the cosmos is filled with elusive dark matter and dark energy. Dark energy is driving the exponential expansion of the Universe and is a topic for another book. The focus here will be on dark matter—the dominant source of mass, creating the large scale structure that is the framework for objects like galaxies and galaxy clusters.

It has been almost 100 years since Fritz Zwicky first detected hints that the dominant component of matter in the Universe does not emit or reflect light. Since then, the observational evidence for dark matter has continued to grow. Dark matter literally holds galaxies together and forms the framework that all structure in the Universe is built on. So far, all of this observational evidence has come from space. Dark matter has only been detected through its gravitational influence on objects that do emit or reflect light like stars. Even with this limitation, we now know that there is approximately five times more dark matter than atomic matter (e.g. rocks, hydrogen gas).

We have been able to rule out the simple hypothesis that the dark matter is a large abundance of particles we already know about and have studied in the laboratory. Dark matter is likely a new kind of particle that is governed by physics beyond our Standard Model of particle physics. The Standard Model contains six quarks (up, down, charm, strange, bottom, top), six leptons (electron, muon [μ], tau [τ], and their associated neutrinos), four force-carrying bosons (Z, W^+, W^-, gluon), and the Higgs boson. It does an excellent job describing the fundamental forces and particles[1] that affect our everyday lives.

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[1] Atoms are composed of electrons and protons, protons are composed of quarks.

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There are still unanswered questions such as ‘what mechanism gives neutrinos their mass?’ and ‘why is the Higgs boson mass stable?’. Many theoretical extensions of the Standard Model have been proposed to answer such questions and several new models predict viable dark matter candidates that can explain our cosmic observations. Terrestrial laboratories, like those detecting collisions at the Large Hadron Collider, are currently searching for new particles predicted by these theories. Any detection of dark matter beyond its gravitational influence will give us insight into new fundamental laws of physics. Therefore, searching for signatures of particle dark matter interactions in space is a crucial complement to terrestrial searches for new physics.

I’ll be focusing on dark matter searches with instruments that are sensitive to γ-rays with energies from about 100 MeV to 100 TeV. A variety of particle dark matter candidates have been proposed, and I’ll focus on heavy candidates ($m_{\rm DM} > 1\,{\rm GeV}$) that could produce γ-rays in that range. When describing the energies of the particles produced during dark matter interactions, it is useful to use mass units in electronvolts (eV). As we’ll see, our current evidence suggests that dark matter is cold, meaning the particles are non-relativistic ($v_{\rm DM} \ll c$). Therefore, the total energy in each annihilation or decay will be the total rest mass energy of the initial dark matter particles. In standard units, the rest mass energy is in eV/c^2. However, when referring to the mass in eV we are using natural units where $c = 1$, as is typical in the particle physics community.

A promising class of candidates is the weakly interacting massive particle (WIMP). These particles are theorized to have interactions on the scale of nuclear weak interactions and typically have masses ranging from ~10 GeV to 100 TeV. No WIMP candidates are predicted by the Standard Model, which would make the detection of WIMPs evidence of a new physics sector. We will briefly discuss a few other dark matter candidates besides WIMPs, but γ-ray searches for dark matter have typically focused on testing the WIMP paradigm.

WIMP models we can test with γ-ray observations predict that dark matter particles will annihilate with each other. Since particle dark matter candidates are typically heavy (contain a large amount of rest-mass energy), then we would expect high-energy particles to be produced during annihilations. Assuming the annihilation products are Standard Model particles like b quarks or τ leptons, we expect the subsequent particle decays and interactions to produce stable high-energy particles like γ-rays. The expected intensity of a dark matter γ-ray signal depends on the particle physics model assumed and the model of the distribution of dark matter in the region of interest. A large variety of models have been proposed for both pieces and physicists are still working hard to constrain these. Consequently, there are a number of signatures to search for and many different targets in the sky; each have their pros and cons.

There are a variety of instruments observing the gamma-ray sky from hundreds of keV to hundreds of TeV. Some make deep, focused observations of small regions, while others provide coverage of the entire sky. Different experiments complement each other by searching for dark matter in a variety of targets and probing different mass scales. A detection in just one region by one instrument would not be convincing evidence for dark matter, so it is critical to search with a network of γ-ray instruments. Additionally, if evidence for particle dark matter interactions were seen from space, it would be important to follow up with searches for that particle in terrestrial experiments (and vice versa).

The particle nature of dark matter remains elusive, but γ-ray experiments have just begun to test some of the most promising dark matter models put forward and there is still a lot of ground to cover. We will give an overview of the observational and theoretical motivation for dark matter. Then we will discuss the components that go into calculating the predicted γ-ray flux for a specific dark matter model and the instruments and search techniques used. In chapter 4 we summarize and discuss recent results and unexplained anomalies from the γ-ray data. Finally we look at future γ-ray instruments and the connection between γ-ray results and other dark matter search techniques.

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Chapter 2

Observational and theoretical motivation for particle dark matter

This chapter will discuss evidence that has been collected over the past century pointing toward the existence of dark matter. Dark matter plays a crucial role in the structure and formation of galaxies, galaxy clusters, and the Universe as a whole. We will also see why weakly interacting massive particles (WIMPs) are such a promising class of dark matter candidates.

2.1 Gravitational evidence for dark matter halos

2.1.1 The Coma Cluster

The very first evidence for dark matter came from Fritz Zwicky's observations of the Coma Cluster, though at the time no one realized that the missing mass couldn't be atomic matter. Let's first recall how astronomers in the early 1900s estimated the mass of systems like galaxies and galaxy clusters. Without knowledge of dark matter, they assumed galaxies are simply clusters of stars or other luminous matter. Then the mass would simply be proportional to the luminosity:

$$\frac{M}{M_\odot} = \alpha\left(\frac{L}{L_\odot}\right), \tag{2.1}$$

where $L_\odot$ and $M_\odot$ are the solar luminosity and mass, respectively. Normalizing by the solar mass and luminosity makes sense since our Sun is an average star. For stellar systems (like our solar system) α is typically between 1 and 10. It is about 1 for our solar system. Assuming that most of the mass of a galaxy comes from stars, the mass of the galaxy can be approximated using the observed luminosity and a model of the types of stars in that galaxy. This approach could be extended to also calculate the mass of galaxy clusters like the Coma Cluster.

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In 1937 Fritz Zwicky proposed an alternative method for determining the mass of gravitationally bound systems [1]. Starting with the assumption that a system (e.g. galaxy, galaxy cluster) is stable, then the average kinetic energy can be related to the average gravitational potential energy using the Virial Theorem:

$$\langle PE \rangle = -2^* \langle KE \rangle. \tag{2.2}$$

The brackets represent both an average over time and an average over the individual components of the system (e.g. stars, galaxies).

Using a Newtonian potential and assuming the components are non-relativistic and uniformly distributed inside a sphere with radius R_{sys}, the Virial theorem yields

$$M_{\text{sys}} = \frac{5R_{\text{sys}}\langle v^2 \rangle}{3G}, \tag{2.3}$$

where M_{sys} is the total mass of the system, R_{sys} is the radius of the system, $\langle v \rangle$ is the average velocity of the components in the system, and G is the gravitational constant. The factor of 5/3 comes from assuming a uniform density sphere, but making other assumptions about the mass distribution results in similar factors [1] so we would expect equation (2.3) to give us an answer at the correct order of magnitude.

When Zwicky applied this method to the Coma Cluster, he used the averaged square velocities ($\langle v^2 \rangle$) of the galaxies in the cluster to calculate the average galactic mass, and then compared it to the average luminosity of each galaxy. Using this approach, Zwicky found the mass-luminosity index (equation (2.1)) of the Coma Cluster to be $\alpha \sim 500$, which is 2 orders of magnitude larger than expected if the mass predominantly came from Sun-like stars [1]. In other words, the Coma Cluster was significantly dimmer than expected assuming all the mass inferred by the Virial Theorem came from stars.

This result suggests that there is missing non-luminous matter in the Coma Cluster, and most likely in other galaxy clusters too. At the time, no new fundamental particles were proposed to explain the missing mass in the Coma Cluster. In fact, Zwicky himself referred to a 'dark matter' component, but this was simply 'cool and cold stars, macroscopic and microscopic solid bodies, and gases' [1]. And he was correct, the luminous matter did not make up the majority of the atomic matter. We later learned that the majority of the atomic mass is in the form of interstellar gas, not stars. However, the gas, which is observed and measured using x-rays, still only accounts for about 1/6 of the total mass. Clearly the atomic matter does not account for the majority of mass in galaxy clusters, but what about smaller systems?

2.1.2 Stellar rotation curves of spiral galaxies

Evidence that the majority of the mass in galaxies is non-luminous came from studying their stellar rotation curves. These studies also showed that the dominant mass component was an extended spherical halo (see figure 2.1). If the mass of a