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SEARCHING FOR NEW PHYSICS WITH *FERMI*-LAT

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Abstract

Searching for New Physics with *Fermi*-LAT

by

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Theses have elements. Isn't that nice?

To myself,

Perry H. Disdainful,

the only person worthy of my company.

Acknowledgments

I want to “thank” my committee, without whose ridiculous demands, I would have graduated so, so, very much faster.

Chapter 1

Introduction

The Standard Model of particle physic has enjoyed an unprecedented level of success since its completion in the late 1960s. Together with Einstein's theory of general relativity, today's physicists possess the ability to understand Nature on both the smallest and largest of scales. The legacy of the Standard Model has been bolstered in recent years by several experimental achievements. The discovery of the Higgs boson by the ATLAS [7] and CMS [8] teams at the Large Hadron Collider in the summer of 2012 completed the Standard Model's last missing link. Further analyses by ATLAS and CMS have since confirmed that the discovered Higgs boson has exactly the predicted properties and couplings to other particles. The discovery of gravitational waves in 2015 by the LIGO experiment [12] provided spectacular confirmation of one of the most intriguing predictions of general relativity. Our understanding of the Universe has never been on such sure footing. And yet for all its successes, the Standard Model remains at best frustratingly incomplete. Astronomical observations indicate the presence of large amounts of dark matter, whose mass dwarfs that of the Standard Model components. And although no experiment to date has seen significant deviations from the predictions of general relativity or the Standard Model, the two theories are known to be incompatible on a fundamental level. With careful experimentation, physicists can study these problems head-on, and perhaps make progress towards addressing them.

1.1 Dark Matter

Multiple lines of inquiry have firmly established that a majority of the mass-energy density of the Universe is composed of a component which is neither baryonic nor luminous. The first indications of what we now call dark matter (DM) were Zwicky's observations in 1933 that the velocity dispersion of galaxies in the Coma Cluster was far higher than the escape velocity predicted from the mass of the luminous galaxies [1]. Later observations of galaxy clustering, for example Kahn & Woltjer's analysis of the motion of Andromeda [11], further indicated that galaxies were far more massive than conventionally expected. The evidence continued to mount in the 1970s as work done by Rubin & Ford [17] and Roberts & Rots [15] showed that the rotation curve of Andromeda was flat out to large distances (30 kpc) from the galactic center, indicating that the mass-to-light ratio at large radii was far larger than that of a typical star. Further data from Rubin [16] subsequently confirmed that the same result held true for a nearly all spiral galaxies she considered.

The mystery deepened as it became clear that the dark matter could not be composed of traditional baryonic matter. The most visceral indication of this fact comes from a comparison of the gravitational lensing by merging galaxies in the Bullet Cluster to an X-ray tracer of the gas content [5]. The data shows conclusively that although the gas dominates the visible mass of the cluster, the lion's share of the mass undergoes little self-interaction. Moreover, Big Bang nucleosynthesis (BBN) constrains the baryonic density of the the Universe to be less than about one twentieth of the critical density, but the astronomical observations indicate that the DM density is approximately a quarter of the critical density. The scale of temperature fluctuations in the CMB is also too small to account for the observed density clustering in today's Universe, but the problem can be resolved if the Universe has a large nonbaryonic component [10].

Today, DM plays a key role in the successful ΛCDM model of the Universe by seeding density fluctuations around which galaxies grow. N-body simulations of galaxy formation with cold dark matter have shown great success at reproducing the observed structure [2]. The exact nature of the DM, however, remains unkown. The known massive neutral particles in the Standard Model (e.g. the Higgs or Z bosons, the neutron) all decay too quickly to account for the presence of DM at the current time. Of the remaining neutral particles, the only plausible candidates are the neutrinos, but their low mass precludes them from moving slowly enough to form structures as small as galaxies [10].

A variety of candidates for the identity of dark matter have been proposed, most of which require extensions to the Standard Model. These extensions invariably predict the existence of new neutral, stable particles, of which the most widely studied are axions and WIMPs.

1.1.1 Axions

The motivation for axions comes from the strong CP problem- the question of why CP symmetry is conserved to a high degree in the strong interaction despite the O(1) CP-violating phase in the weak interaction. Assuming the Universe is not fine-tuned, CP violation in QCD can be made small dynamically by the introduction of a new U(1) symmetry (the Peccei-Quinn symmetry). The Nambu-Goldstone bosons of this new symmetry are the axions, in much the same way as the photon is the Goldstone boson of the U(1) symmetry associated with the electromagnetic interaction. If they exist, axions must have extremely small masses and low couplings to Standard Model particles. Constraints from beam-dump experiments and astrophysical searches require the axion mass to be less than approximately 10^{-3} eV. On the other hand, the axion mass must be greater than approximately 10^{-6} eV in order to not overclose the Universe [2]. If the axion mass is near its lower bound, axions are a plausible DM candidate. Although lighter than neutrinos, the density fluctuations in the axion field are localized enough to reproduce the DM substructure that we observe. A variety of experiments to search for them are underway, which generally seek to excite the axion field and produce resonant photons via the Primakoff process.

1.1.2 WIMPs

Weakly Interacting Massive Particles (WIMPs) are a class of particle which generally possess masses and coupling strengths on the order of the electroweak scale (roughly 100 GeV). Such particles would have been in thermal equilibrium with the rest of the matter at moments shortly after the Big Bang, but as the Universe expanded and cooled, the WIMPs would have ceased to be in equilibrium when the Hubble rate exceeded the interaction rate. As it turns out, a weak-scale cross-section yields dark matter that ”freezes out” from the rest of the Universe at precisely the correct time to yield the observed relic abundance, a coincidence which has been dubbed the ’WIMP miracle’ [2].

Generally speaking, there are three paradigms through which to search for WIMP dark matter. WIMPs can be produced in collisions at high-energy particle accelerators like the LHC. In this case, the stable and neutral WIMPs will escape the detector apparatus, leading to ”missing” transverse momentum in the reconstructed final state of particles. The scattering of WIMPs off of nucleons can also be searched for by low-background counting experiments. These experiments are typically performed deep underground to avoid contamination by showers from cosmic rays. Finally, WIMPs may annihilate or decay to Standard Model particles, which we can detect by looking at areas in the Universe where we know high concentrations of dark matter exists. WIMP annihilation in the context of such ’indirect detection’ experiments will be the focus of Sections X & Y.

1.1.3 PBHs

Unlike many other dark matter candidates, primordial black holes (PBHs) are attractive as dark matter candidates because they require little in the way of new physics beyond the Standard Model (theories of the early Universe notwithstanding). They also present straightforward detection strategies- heavy PBHs can in principle be detected via the gravitational wave events from their mergers; intermediate-mass PBHs can be constrained by their accretion onto neutron stars and white dwarfs [14] or potentially detected via microlensing events [4]. Low-mass PBHs can be detected by their Hawking radiation; a more detailed discussion of PBHs as dark matter candidates and the prospects for detecting low-mass PBHs will follow in Section X.

1.2 Quantum Field Theory in Curved Spacetime

Although general relativity and the Standard Model excel at describing Nature on large and small scales, respectively, a complete theory of quantum gravity remains unknown. Theorists have had some success (see the results in Section X, for instance) in describing quantum field theories in a background of curved spacetime, but generally these models neglect perturbative interactions in favor of free fields. As noted in Wald [19], the source of the difficulty in constructing a completely satisfactory theory of quantum gravity is rooted in the fact that the metric $g_{\mu\nu}$ is both the dynamical variable of general relativity and the description of the spacetime in which the quantum theory lives. Attempts to construct perturbative theories of gravitation via Einstein's equation for a massless spin-2 field have failed due to the fact that these theories are generally nonrenormalizable.

In the face of these theoretical challenges, unfortunately, experiments also offer little guidance. The problem for experimentalists is essentially one of mismatched scales: gravitation is extraordinarily weak on the scale of a typical quantum system (a rough sense of the mismatch is given by the fact that Newton's gravitational constant is some 42 orders of magnitude weaker than the Coulomb constant). The Planck scale (roughly 10^{18} GeV), where GR effects become important, is far beyond the reach of even the most ambitious particle accelerator designs. Only a handful of instances exist where general relativity can conceivably be applied to a quantum system- the Big Bang, for instance. Observing the Big Bang directly in the electromagnetic spectrum is made difficult by the presence of the cosmic microwave background (CMB). Future experiments, however, may be able to detect primordial gravitational waves (either directly or via B-mode polarizations in the CMB) that are predicted to arise from models of inflation and thus provide a crucial test of theories of the Big Bang. Alternatively, PBHs provide a natural laboratory for observing physics at the Planck scale: as PBHs evaporate, their temperature diverges towards the Planck scale and necessarily new physics will describe their dynamics. A search for PBHs in this context is described in Sections X &Y.

In the work that follows I present two analyses that make use of data from the Fermi Large Area Telescope (Fermi-LAT) to search for evidence of dark matter and PBHs. I will show that the capabilities of *Fermi*-LAT allow it to test models of physics that cannot be studied with other means. Gamma-ray astrophysics remains one of the best available probes of physics beyond the Standard Model.

Chapter 2

Fermi-LAT and the γ-Ray Sky

In this chapter I provide an overview of the design and analysis abilities of the Large Area Telescope on board the *Fermi* Gamma Ray Space Telescope (otherwise known as *Fermi*-LAT). *Fermi*-LAT is a whole-sky imaging gamma-ray telescope currently in low-Earth orbit which is capable of detecting photons from about 10 MeV to more than 1 TeV in energy. For a more in-depth description of the LAT design, the *Fermi*-LAT collaboration provides technical paper [6].

2.1 History

The field of gamma ray astronomy begins in earnest with a paper by Morrison in 1958 [13] which lays out the motivation for making astronomical observations at high energies. The crux of Morrison's argument is that visible light from high-energy processes is only created indirectly- for example, the nuclear reactions that power stars are screened by huge amounts of stellar medium. High-energy cosmic rays are directly produced by energetic processes, but their origins are obscured by the presence of magnetic fields. On the other hand, gamma rays are produced directly in high-energy processes and are unaffected by magnetic fields, therefore providing a window into new physical processes. Morrison's ideas influenced a number of balloon-based gamma ray instruments, as well as the space-based telescopes Agile and EGRET. A proposal for the telescope that would eventually become *Fermi* was first put together in 1994. During the next 14 years, an international collaboration of scientists and engineers, primarily from the United States, Italy, Japan, and Sweden worked together to build *Fermi* . On June 11, 2008, the *Fermi* satellite was successfully launched into low-Earth orbit aboard a Delta II Heavy launch vehicle. In its ten years in orbit, *Fermi* has successfully measured the angular positions, energies, and arrival times of over 1 billion photons.

2.2 Design

The design of *Fermi*-LAT is informed by the fact that gamma rays cannot be focused or reflected in the same manner as visible light, as their wavelength is far smaller than typical atomic spacing. Instead of measuring the gamma rays directly, *Fermi*-LAT causes incident gamma rays to pair-convert into electrons and positrons whose momenta are then measured. Pair-conversion is an important background rejection feature, as only e+/e- pairs that originate from within the LAT are eligible gamma-ray candidates. The measurement of the e+/e- momenta takes place in two stages- directional information is reconstructed from hits in silicon strip sensors in the tracker, while energies are measured via detection of scintillation light in the calorimeter.

2.2.1 Tracker

There are 16 individual tracker towers on the LAT, arranged in a 4x4 grid. Each tower has 18 layers of two silicon strip detectors laid in an orthogonal X-Y configuration. 16 layers of a high-Z material (tungsten foil) are placed in front of each of the first 16 pairs of silicon strip detectors, providing a location where the gamma rays can pair-convert into an electron and positron. Electron/hole pairs are created in the silicon detectors as the pair-produced electrons and positrons pass through them, which are then read out by electronics. The recorded positions of the electron/positron pair are recorded at subsequent tracker layers and a track reconstruction algorithm (generally based on a Kalman filter) is used to find the path of the e+ or e-. As the e+/e- pairs traverse the tracker layers, they undergo multiple scattering (especially by the tungsten foils), which limits the angular resolution available. On the other hand, the probability of a gamma ray conversion event depends on the thickness of the tungsten, so a compromise between the two goals (good angular resolution and high conversion efficiency) must be reached. In the LAT, the compromise made was to separate the tungsten into two groups: the first 12 layers are thin (the ”front”) while the last 4 layers (”back”) are approximately 6 times thicker. The total number of radiation lengths is approximately equal in the ”front” and ”back” segments, though the front-converting photons have somewhat better angular resolution (by roughly a factor of two). The angular resolution of *Fermi*-LAT for ”front”- and ”back”- converting photons is represented in Figure X by the 68% containment radius. Notably, the resolution improves dramatically as the energy of the incident photon increases- this is a consequence of the fact that a typical multiple scattering angle is inversely proportional to the energy of a particle.

2.2.2 Calorimeter

Below each tracker tower lies a calorimeter module containing 96 scintillating thallium-doped cesium iodide crystals, read out by PIN photodiodes. The crystals are oriented in 8 rows of 12 crystals in a hodoscopic array, yielding a total calorimeter depth of 8.6 radiation lengths. As the primary high-energy electrons and positrons from the tracker encounter the dense calorimeter medium, they radiate secondary photons which can themselves pair-produce electron-positron pairs. The process continues until the energy of the gamma rays in the shower falls below the rest energy of an electron, yielding a shower shape that is sensitive to the total energy of the incident electron or positron. With its segmented array, the LAT calorimeter modules are capable of measuring both the energy and shape of the electromagnetic shower. The reconstructed energy is simply the sum of all the collected energy in the scintillators, subject to corrections (estimated from Monte Carlo studies) for showers that are large enough to escape the detector volume. The eigenvectors of the shower shape are then computed and used to guess a preliminary track direction to seed the track reconstruction algorithm.

2.2.3 Anticoincidence Detector

Surrounding the tracker and calorimeter is a segmented anti-coincidence detector composed of scintillating plastic, whose purpose is the rejection of charged particle backgrounds from cosmic rays. The material of the ACD is chosen to be low-Z so as to not absorb any gamma-rays, and to not provide a location for incident protons to generate pions (which would generate a substantial background by subsequent decay to two gamma rays). Events are vetoed only if the ACD triggers at a position consistent with reconstructed track, which prevents spurious vetos from ’backsplash’- an effect that happens when the EM shower in the calorimeter causes the emission of secondary particles that strike the ACD. By segmenting the ACD into 89 tiles, these self-veto events are present for less than 20% of the photons at 300 GeV, compared to 50% at 10 GeV for the non-segmented EGRET.

2.2.4 Data

Fermi most often operates in ’survey mode’, during which it scans the entire sky with roughly equal exposure on a time scale of 3 hours. However, alternate observing patterns are relatively common, such as when *Fermi* reorients itself to observe the afterglow of a LIGO event. Other interruptions to regular data collection include the times *Fermi* traverses the South Atlantic Anomaly (during which the event rate becomes extremely high), and the handful of orbits during which *Fermi* has faced the Earth in order to detect terrestrial gamma-ray flashes from lightning.

Data collected by *Fermi*-LAT is downloaded via radio link to NASA’s Goddard Space Flight Center, and sent on to SLAC National Accelerator Laboratory for processing. Photons detected by *Fermi*-LAT are typically available for download from the GSFC within 8 hours of their arrival.

2.3 γ-Ray Sky

A typical *Fermi*-LAT gamma ray has an energy of GeV scale. An approximate measure for the corresponding temperature of such a photon is given by E/k= $10^{1}3$ K, for comparison, the temperature at the center of the Sun is approximately 10^{7} K. Therefore gamma rays are generally produced by a handful of well-known non-thermal processes. Relativistic charged particles can emit synchrotron radiation in the presence of magnetic fields, and bremsstrahlung radiation upon interactions with matter. Neutral pions decay to two gamma rays, and excited nuclei can de-excite via the emission of a gamma ray. In Chapter 6, I will discuss the potential for dark matter to annihilate to final states that include gamma rays. With this in mind, it is not surprising that the gamma-ray sky looks rather different from the sky in the optical band- see Figure X. A number of features are readily apparent from the whole-sky image:

2.3.1 Diffuse emission

Much of the sky's gamma ray emission is in the Galactic plane, and is due to highly energetic charged particles interacting with the interstellar medium. These interaction generally produce neutral pions which then decay to two gamma rays, the energy of which depends on the energy of the initial cosmic ray. The origin of high-energy cosmic rays was a mystery for some time, as 2nd-order *Fermi* acceleration seemed insufficient to produce particles with energy ¿10 GeV. A number of authors in the 1970s, however, discovered that collisionless shock boundary of supernova remnants could sufficiently energize charged particles. At the shock boundary, the magnetic field is nearly discontinuous, and 1st order *Fermi* acceleration is sufficient to produce charged particles in the many-GeV energy range. Models of the galactic diffuse emission are generated by the *Fermi*-LAT collaboration by fitting templates of interstellar emission at several wavelengths to observed regions of the γ-ray sky [**?**].

Some diffuse emission extends beyond the Galactic plane, and appears to be isotropic across the sky. Most of this isotropic component is believed to originate from unresolved point sources (see below), though some backgrounds of cosmic rays and improperly reconstructed photons from the Earth limb also contribute.

2.3.2 Point Sources

Blazars

Most large galaxies contain a rapidly rotating supermassive black hole at their center, some of which actively accrete material. These so-called "active galaxies" possess two main features- a thermal accretion disk, and a relativistic jet aligned along the black hole's rotation axis. When the Earth lies in the direction of a jet axis, the active galaxy is called a blazar and they are bright sources of gamma rays.

The highly relativistic particles in the jet are believed to derive their power directly from the supermassive black hole. Via the Blandford-Znajek process [**?**], magnetic fields from the accretion disk which reach inside the black hole's ergosphere can extract rotational energy from the black hole, and the subsequent rotation of the magnetic field causes charged particles to be accelerated to high speeds along the jets. These relativistic particles can then emit gamma rays via synchrotron radiation, bremsstrahlung, or inverse Compton scattering.

Pulsars

Rapidly rotating neutron stars known as pulsars are one of the most numerous point sources in the gamma-ray sky. Surrounded by extraordinarily powerful and rapidly rotating magnetic fields, pulsars emit gamma rays as electrons stripped from their surface emit synchrotron radiation. A small number of pulsars have periods smaller than 1 second, and are referred to as millisecond pulsars. A novel population of millisecond pulsars may exist near the galactic center and contribute to the gamma-ray excess that has been observed there by a number of authors (e.g. [3]).

Galactic Center

The brightest source in the gamma-ray sky by far is the Galactic center, containing the supermassive black hole at the center of the Milky Way located at Sag A*. A number of models have been proposed to explain the gamma-ray emission at Sag A*, generally involving charged particles interacting with the surrounding medium [18]. These particles may be injected into the region by tidal disruption of stars. As discussed in Chapter 6, some DM models predict annihilation to occur in the region surrounding Sag A* as well, which may lead to gamma-ray emission.

2.4 Analysis Tools

Fermi-LAT data and LAT-specific analysis tools are publicly available for download from the *Fermi* Science Support Center at NASA's Goddard Space Flight Center [1]. Processing *Fermi*-LAT data for analysis begins by removing photons (via the tool `gtselect`) that are incident from near the Earth limb, as these mostly originate from cosmic ray interactions with the atmosphere. For a typical analysis, the photons are then binned (with the use of the tool `gtbin`) in angular position and energy. The LAT effective area is convolved (by use of the tool `gtltcube`) with its pointing history over the time period considered to produce an exposure map binned in energy and angular position. Typical *Fermi*-LAT analyses make use of maximum likelihood techniques to test differing hypotheses (spectral features, location, etc) about sources in question. The process begins by defining a model of the region of interest (ROI). A model is composed of a list of sources, each of which is defined by its spectral shape, position on the sky, and spatial appearance. With a model and the exposure map, the expected number of photons μ_i in each bin i can be computed and compared to the actual counts n_i. The value of the likelihood for the model is then given by the product of Poisson factors over the number of bins N:

$$\mathcal{L} = \prod_{i=1}^{N} \frac{\mu_i^{n_i}}{n_i!} e^{-\mu_i} \tag{2.1}$$

By varying the parameters in the model, the likelihood can be maximized. In cases with sufficient statistics and where the parameters satisfy Wilks criteria, the value of the delta log-likelihood between two hypotheses follows a χ^2 distribution [**?**]. If this is the case, the signifi-

[1] `https://fermi.gsfc.nasa.gov/ssc/`

cance of the varied parameter can be determined; if this is not the case, the significance can be determined through a Monte Carlo study.

The *Fermi*-LAT collaboration has successfully used these techniques to compile several catalogs of gamma-ray sources. The most current catalog is the Third *Fermi* Source Catalog [9] (hereafter referred to as 3FGL). The 3FGL composed of 3033 sources, of which a majority (3008) of which are point sources and 25 of which are modeled as extended. A large fraction of the sources are pulsars or active galaxies, but a sizable component (1010) are unassociated with any known sources. I make use of the 3FGL in Chapter 4 to identify potential PBH candidates, and to place limits on their presence.

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