Search for Galactic Primordial Black Holes with Fermi

1 Introduction

We propose to increase the sensitivity of the search for femtolensing of $\gamma-$ray bursts (GRB) [1, 2] by Compact Intermediate Mass Dark Matter Objects (CIMDMO) using GBM and LAT (Pass-8) data. The origin of cold dark matter (CDM) is one of the outstanding mysteries of astronomy and astrophysics, which has polarized around two types–weakly interacting massive particles (WIMP) in the gaseous state and massive compact halo objects (MACHO) usually thought of as stellar mass black holes that are detected indirectly by their microlensing effect. This does not exhaust other possibilities, for example, a large size range of CIMDMO with masses comparable to that of primordial black holes (PBH). Despite being more numerous, CIMDMO remain invisible to astronomy. Numerous techniques have been employed to search for these CIMDMO, but an important region of phase space (mass vs. cross-section or density$^{-2/3}$) remains undetectable by all these optical methods [3, 4].

What CIMDMO candidates cannot hide is their gravitational lensing effect, where large lenses generate multiple images ("Einstein ring"), microlenses generate brightness fluctuations. But the aberrations caused by femtolenses are so small that they only diffract light from distant point sources without changing the spectrum. When the wavelength of light is comparable to the Schwarzschild radius, $\lambda \sim GM/c^2$, then the lens generates chromatic aberration, such as the blue "fringe" around the border of the image. If the point source has a wide spectral range, multiple fringes can appear as ripples on the spectra, as described below. Since GRBs are extremely bright point sources of γ-rays with wide spectral range, the *Fermi* dataset can be searched for the telltale chromatic aberration caused by CIMDMO gravitational femtolenses in our galaxy. Unlike other MACHO searches, this technique is sensitive to smaller($10^{17} - 10^{20}$g) masses. The technique has been used to exclude about 20% of the phase space in this intermediate mass range, and we propose to more than double this coverage by including the energy range and sensitivity of the LAT Pass-8 data. The left panel of Figure 1 is a cross-section vs mass log-log plot of the excluded CIMDMO regions, showing the important role of femtolensing. The yellow shaded region is the region of increased sensitivity provided by this proposal. The labelled ovals locate some familiar astronomical objects for reference.

The diagonal black line in Figure 1 corresponds to CIMDMO with a molecular density of 1g/cc, so that only a small sliver of phase space need be searched to exclude "ordinary" small bodies, making this study specially important for closing "loopholes" in the common assumption that dark matter is not baryonic. The lower diagonal green line corresponds to nuclear densities, bracketting CIMDMO moons between femtolensing and microlensing exclusion areas to provide another significant "macro" region. These unexamined regions in phase space are important since the lack of experimental WIMP detection is necessitating a revision of the Big Bang Nucleosynthesis (BBN) models [5]. Irrespective of the baryonic makeup of the mass, CIMDMO would generate a gravitational lensing that is below the threshold of optical detection but not below the threshold of GBM+LAT femtolensing detection in γ-rays from GRBs.

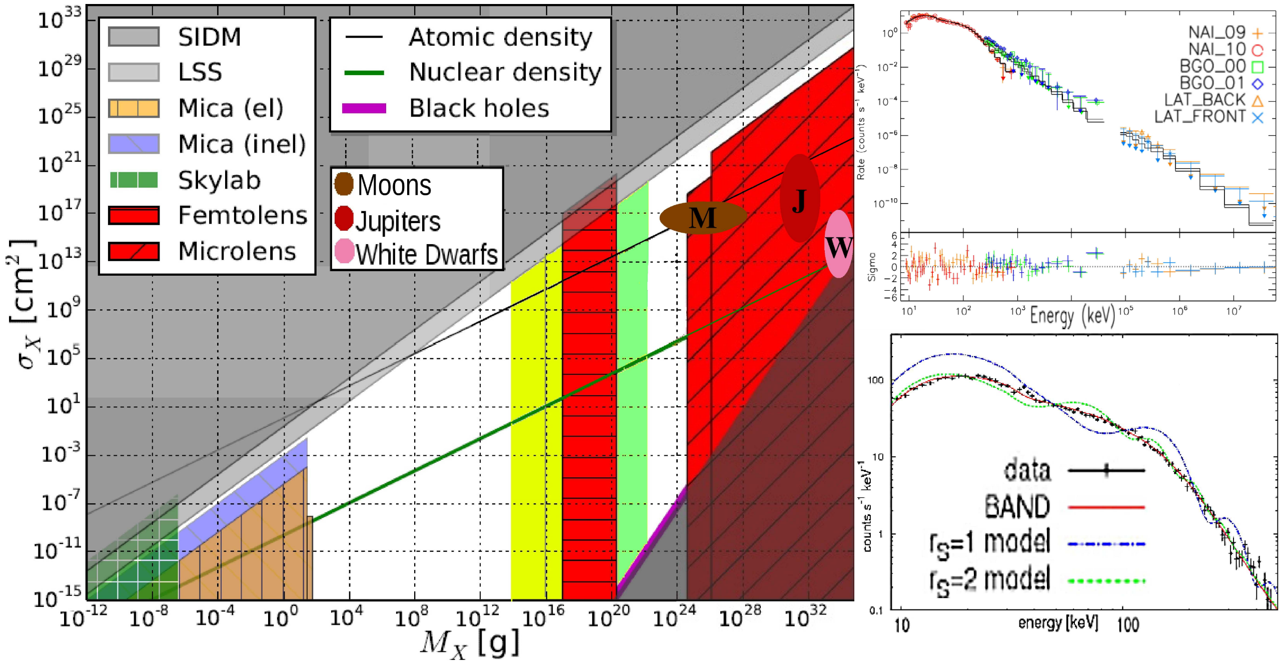

Figure 1: Left: CIMDMO excluded regions of mass-σ space. Top-Right: GRB spectral fit with Band function displaying oscillating residuals. Bottom-Right: Simulated spectrum of a femtolensed GRB superposed on the actual GBM spectrum of GRB090424 [6].

2 Femtolensing Procedure and Sensitivity

Barnacka's thesis [6] describes in greater detail the geometry of a gravitational lens and how it diffracts a wideband gamma-ray source such as a GRB. The principle effect is to superpose ripples on the spectrum of a GRB. In the top right panel of Figure 1 the GRB GBM and LAT spectra are fit simultaneously to a Band-function,[7] so that potential ripples in the residual (shown at the bottom of the plot) can be fit with the diffraction pattern of a femtolensing object. The lower right panel shows a simulated spectrum of femtolensed GRB superposed on a GBM spectrum of GRB090424. The diffraction fringes can be characterized by variable amplitude and frequency, which correspond roughly to the size (or mass) and image distance of the gravitational femtolens.

Barnacka and colleagues have made a preliminary search for signatures of femtolensing by galactic Primordial Black-holes using the GBM data only from a sample of 20 of the brightest GRBs (with known red-shift) during the first two years of the Fermi mission [2]. We propose to improve the sensitivity of such a search by including LAT pass-8 data resulting in a three-fold improvement: (i) wider spectral range of the LAT+GBM (ii) increase in the sample size and (iii) additional search for similar spectral wiggles in γ-ray sources such as AGNs, using a sliding window technique to search for fluctuation in power at the expected 100 sec interaction time. The interaction time arises from the requirement that dark matter have a slightly higher kinetic temperature than the galactic disk stars, $v_T \sim$70 km/s, which transits the source in $r_E/v_T \sim 100$s, where r_E is the Einstein radius of the gravitational lens (eq. 3.23 in [6]):

$$r_E^2 = \frac{4GM}{c^2}\frac{D_{OL}D_{LS}}{D_{OS}} \approx (c \times 0.3s)^2 \left(\frac{D_{OL}D_{LS}}{D_{OS}1Gpc}\right)\left(\frac{M}{10^{19}g}\right) \tag{1}$$

where D_{OL} is the distance between observer and the lens; D_{LS} is the distance between lens

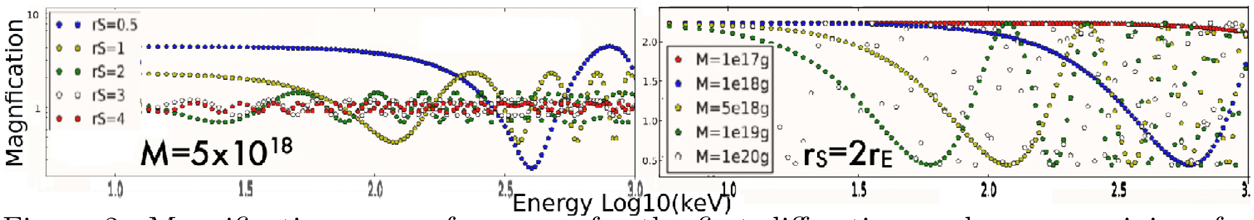

Figure 2: Magnification versus frequency for the first diffraction peak energy minima for various distances (R. panel); for differing masses, which give different focal lengths (L. panel).

and source, and D_{OS} is the distance between observer and source. Since the lens is in our galaxy, and the source is extra-galactic, then the only important variables are $r_S = D_{OL}$ and M, the lens mass.

Increased Spectral Range: Large femtolenses generate large amplitude fringes but are less numerous, so that the upper mass limit of the exclusion band is limited by event statistics. By increasing the size of the data set using more GRBs detected by GBM and LAT, as well as LAT data from monitoring of AGNs. The improved statistics raises the upper limit on large lenses, moving the high-mass bound of the excluded femtolensing region closer to moon-sized objects. Small lenses have small amplitude fringes and can only be seen in close proximity. Unfortunately at close ranges, the diffraction ripples widen in spectral range so that the "first null" that delimits the first diffraction peak moves toward higher energy (Left panel of figure 2), where the poor statistics make it hard to observe. Therefore adding the LAT data set to the analysis increases the upper energy limit by five orders of magnitude over that with GBM data alone, which permits a thousand-fold reduction in the distance D_{LS}, and a million-fold increase in the amplitude. This increased volume of real space translates into an improved statistics, a higher high-mass detection region, and more importantly, a detection of small lenses with weak aberration.

Increased Temporal Range: Barnacka's analysis of 20 GRBs corresponds to about 1000 seconds of observation. But LAT records about 1800 seconds of observation of a single AGN per *Fermi* orbit, and orbits 16 times a day. Treating non-identical orbits as separate observations, we can monitor ∼30 high-E AGN per day for 7 years or 1800*30*365*7∼0.14Gs of observation, or dividing by Barnacka's 1000s and taking the square root, ∼400 times better statistics at the high-mass CIMDMO limit, which we indicate with the shaded light-green region in the left panel of figure 1.

Increased Proximity: Small femtolenses are amplitude limited, which is improved by reducing the lens distance, but which simultaneously moves the diffraction fringes to higher energy. Detecting the first minima of the diffraction pattern in the spectra, we find it is correlated to the mass, so that every order of magnitude increase in spectral range corresponds to a reduction of an order of magnitude in mass. From the right panel of Figure 2, a lens mass of $5{\cdot}10^{18}$g and a source distance $r_S = 2r_E$ has a minima at 100 keV, so the 10 GeV upper range of LAT corresponds to a minima at $5{\cdot}10^{13}$g.

Likewise, r_S, the lens-observer distance, also changes the location of the first minima. The left panel of figure 2 with $5 \cdot 10^{18}$g at $r_S = 0.5r_E$ has the first minimum at about 400 keV. If the energy of the first minima shifts downwards by about half an order of magnitude for every doubling of distance, then 4 orders of magnitude range increase to 10 GeV would correspond to 8 halvings, or about $r_S \sim 0.002r_E$. Since both r_S and M drive the minima in the same direction, it would appear that the lower mass limit for LAT observation of diffraction fringes is about $5 \cdot 10^{14}$g, albeit with a greater range of r_S probed.

3 Science Objectives

Some have argued that if Hawking's calculations are correct[8], PBH $< 10^{15}$ grams would have already evaporated, making this search unnecessary. We argue that Hawking radiation remains to be confirmed by experiment, and other theorists have contested Hawking's model[9]. Our primary goal here is to detect the mysterious source of CDM in our galaxy, which will change our understanding of the BBN as well as particle and theoretical physics.

For almost two decades, particle physicists have invoked cosmology as justification for the search of exotic physics, which has paradoxically allowed cosmology to drift free of observational constraints. By pinning down the source of CDM in our own galaxy, cosmology will no longer be dominated by speculative physics. By putting limits on the BBN, we provide a complementary data set to the "precision cosmology" of the Planck satellite, enabling many of the free parameters of the current "baryon acoustic modulation" fit to be removed. This will then make the models not just polynomially but observationally precise, putting stringent limits on inflationary models. If a CIMDMO femtolensing event is found, it will impact on the types of instruments proposed for the Dark Matter mission, which in turn will affect the next decade of instrument building. On the other hand, an absence of CIMDMO femtolensing will exclude a large region of phase space from consideration, which strengthens the case for exotic particle physics and Dark Matter missions, as well as pushes BBN models in the opposite direction toward baryon-free CDM. So whether CIMDMO are found or excluded, this study will have important implications for the next decade of astronomy.

4 NASA Relevance and management plan

NASA is committing to several Dark Matter searches, towards which this study is highly relevant. We expect our total level of effort for this proposal to be equivalent to about 0.5 FTE for 1 year. We have requested funding of 70 k$. Funded personnel will include a member of University of Alabama in Huntsville (UAH, N.Bhat), and Grassmere Dynamics (R. Sheldon). R. Sheldon (0.25 FTE) will lead the data analysis, N. Bhat (0.25 FTE) will help with the analysis code and interpretation of results, M. Briggs will assist the rest of us in interpretation of results and writing papers.

References

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