A Search for Femtolensing Dark Matter w/ GBM+LAT

1 Introduction

We propose to increase the sensitivity of previous femtolensing $\gamma-$ray burst (GRB) searches [1, 2, 3] for Intermediate Mass Dark Matter Objects (IMDMO) by adding the LAT Pass-7/8 high energy spectral 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 (MACHOs), usually thought of as black holes. This does not exhaust the possibilities, however, for a large range of IMDMO may exist that may not be black holes but are otherwise undetectable. Numerous techniques have been employed to look for these IMDMO, but an important region of phase space (mass vs. cross-section or density$^{-2/3}$) remains undetectable by all these optical methods [4].

For what all IMDMO candidates cannot hide is their gravitational lensing effect. Large lenses cause multiple images ("Einstein ring") and microlenses cause brightness changes, but femtolens are so small they only chromatically aberrate distant point light sources. That is, when the wavelength of light is comparable to the effective Schwarzschild radius of the small lensing object (treating all the mass as if concentrated at a point), then the high curvature of these tiny lens generates chromatic aberration, such as a blue "fringe" around the border of the image. If the background point light source has a wide spectral range, multiple energy fringes can appear as ripples on the spectra, as described below. Since GRBs are extremely bright point sources of light with wide spectral range, the *Fermi* dataset can be searched for the telltale ripples on the γ-ray spectra caused by the high curvature of the small IMDMO gravitational femtolens in our galaxy. Unlike other MACHO searches, this technique is sensitive to smaller, $10^{17} - 10^{20}$-gram masses that are more massive than comets but less massive than the Moon. The technique has been used to exclude about 20% of the log-log phase space in this intermediate mass range, and we propose to extend the coverage to nearly 40% by including the energy range and sensitivity of the LAT Pass-7/8 data. The left panel of Figure 1 is a cross-section vs mass log-log plot of the excluded IMDMO regions, showing the important role of femtolensing. The yellow and orange shaded region is the region of increased sensitivity provided by this proposal. The ovals locate some typical astronomical objects for reference.

IMDMO grams	Eros #/yr	Moon #/yr	Earth #/yr	Jupiter #/yr	Sun #/yr	Mars Orbit #/yr
10^{12}	10^{-8}	$3{\cdot}10^{-4}$	$4{\cdot}10^{-3}$	$4{\cdot}10^{-1}$	50	$1{\cdot}10^{4}$
10^{15}	10^{-11}	$3{\cdot}10^{-7}$	$4{\cdot}10^{-6}$	$4{\cdot}10^{-4}$	$5{\cdot}10^{-2}$	10
10^{18}	10^{-14}	$3{\cdot}10^{-10}$	$4{\cdot}10^{-9}$	$4{\cdot}10^{-7}$	$5{\cdot}10^{-5}$	$1{\cdot}10^{-2}$

This search is relevant, because several astronomical constraints on DM suggest IMDMO. If they have a galactic velocity ($\sim$300 km/s) then the collection efficiency of astronomical bodies with cross-sectional radii is estimated in Table 1.[5] For example, if IMDMO are comet-like with masses $\sim 10^{17}$g, then when they approach the Sun closer than Mars (2AU), the emit gas and dust that can be observed as a comet on a hyperbolic trajectory. A century of observations reveal that such comets arrive at a rate of $\sim$0.6/yr but perhaps only $\sim$0.1/yr are from outside the Oort Cloud in approximate agreement with estimated IMDMO rate.[6]

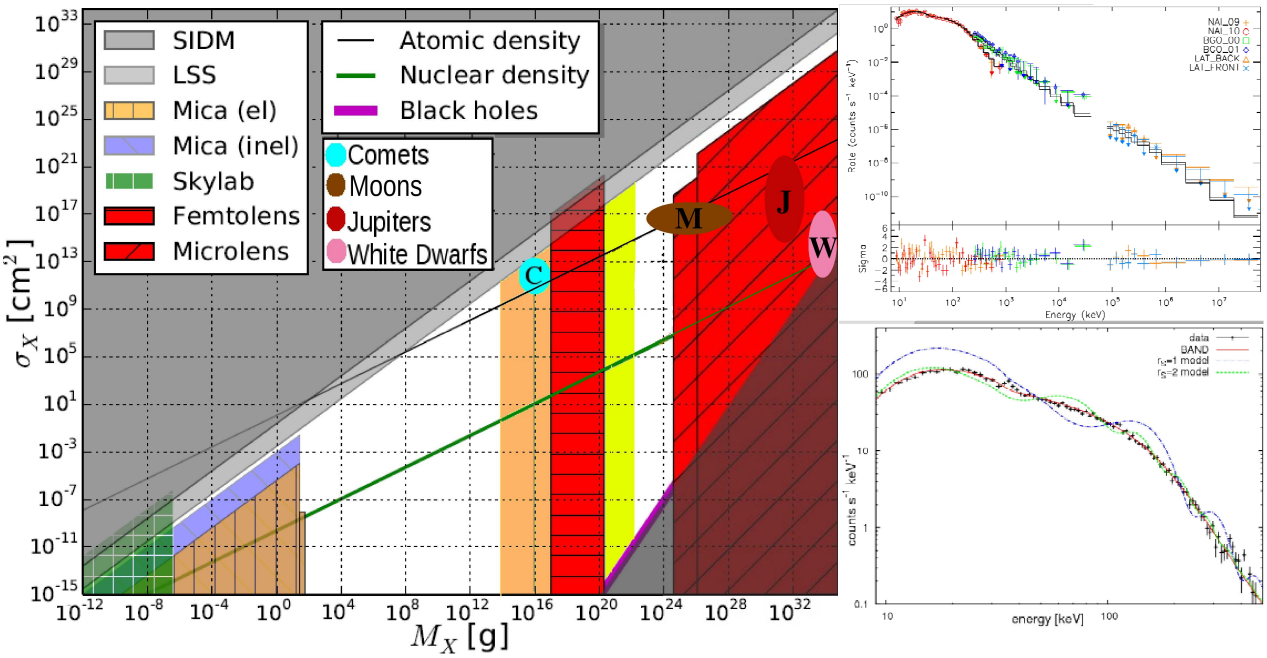

Figure 1: L: IMDMO excluded regions of mass-σ phase space. Red indicates previous lensing exclusion regions. Yellow and orange is this proposal. TR: GRB fit with Band function displaying oscillating residuals. BR: Simulated femtolensing superposed on GBM spectrum.

This is also in agreement with recent observations of primordial deuterium in ice grains of planetary disks [7], which suggest abundant primordial oxygen such that a large component of the Big Bang Nucleosynthesis (BBN) baryon production may be locked up in icy comets. Finally, comets also have the unique property that they outgass as they approach a star, which gives them a "negative-viscosity" to counteract their gravitational clumping and create a flat density profile that matches the dark matter distribution within galaxies.[8]

The diagonal black line in Figure 1 corresponds to IMDMO with an atomic or water density of 1g/cc, so that only a small sliver of phase space needs to be searched for comet-sized IMDMO, making this study especially fruitful in finding/excluding "ordinary" small bodies. The lower diagonal green line corresponds to nuclear densities, bracketting moon-sized IMDMO between femtolensing and microlensing exclusion areas, which is a second significant search region. A completely baryonic CDM is not considered possible with current BBN models, but there is a growing consensus that a revision of the 1-D, homogeneous, isotropic BBN model is necessary to explain the lack of direct WIMP detection by experiment.[9] Irrespective of the composition of the matter, IMDMO would cause gravitational lensing that is below the threshold of optical detection but not below the threshold of GBM+LAT femtolensing detection.

2 Femtolensing Procedure and Sensitivity

In top-right panel of Figure 1, the GRB GBM+LAT spectra is fit to a smooth Band-function and subtracted,[10] revealing potential ripples in the residual that can be fit with the pattern of a femtolensing object. The bottom-right panel shows a simulated femtolensing event superposed on the GBM spectrum of GRB090424.[3] The spectral fringes can be characterized by a variable amplitude and frequency, which correspond roughly to the size (or mass) and image distance of the femtolens, as shown in Figure 2. Barnacka and colleagues have made a

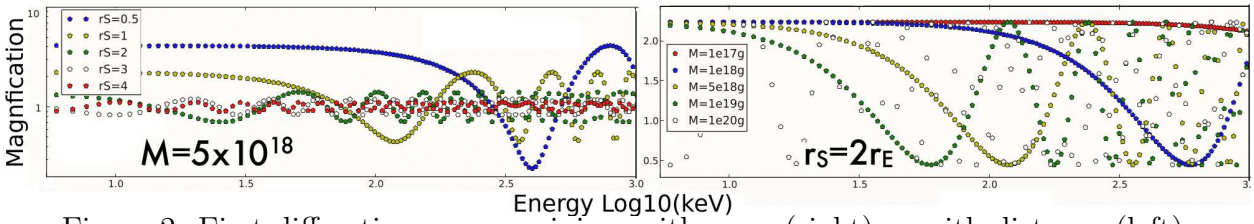

Figure 2: First diffraction energy minima with mass (right) or with distance (left).

preliminary analysis of the first two years of GBM data using 20 of the brightest GRBs with red-shift data.[2] We improve the sensitivity of their search: first, by including the wider spectral range of the LAT+GBM; second, by augmenting the number of GRB spectra both with more observations and with continuous γ-ray sources such as AGNs; and third, by using both effects together to search for nearby femtolenses.

Increased Spectral Range Large lenses have large amplitude fringes but are less numerous, so that the upper mass limit of the (yellow) exclusion band in Figure 1 is given by event statistics. Increasing the size of the data set by using more years of GBM data and LAT monitoring of AGNs, we can raise the upper limit on large lenses, moving the high-mass bound of the excluded femtolensing region closer to Jupiter. Small lenses have small amplitude and can only be seen in close proximity, however, with simultaneous motion of the first diffraction peak toward higher energy (left panel of figure 2). Adding the LAT data set to the analysis increases the upper energy limit by five orders of magnitude over GBM, which permits a thousandfold reduction in distance. This increased volume of the search-space "shell" (orange region) translates into improved statistics and more importantly, the detection of small lenses with weak aberration, which enables the detection of comets.

Increased Temporal Range Large femtolens due to IMDMO would be rare but with high amplitude, so the upper limit on excluded IMDMO mass is mostly given by the temporal statistics. From Barnacka, 20 GRB's gave about 1000 seconds of observation, while LAT achieves about 1800 seconds of observation per AGN per 2 *Fermi* orbits (= 8 orbits/day) of similar instrument orientation. Then in 7 years, we have $\sim$37 Ms of observation, or taking the square root of the ratio 37 Ms/1 ks, about 190 times better statistics at the high-mass limit, which we indicate with the yellow-shaded region in the left panel of figure 1.

Increased Proximity Small femtolenses are amplitude limited, which can be improved by reducing the object distance, but this simultaneously moves the diffraction fringe toward higher energy. So in order to observe nearby lenses, the spectral range of the detector must be increased to observe this first minima. Likewise, the first minima is also correlated to the mass, so every order of magnitude increase in spectral range corresponds to a reduction of an order of magnitude in mass. Analyzing these two effects, the right panel of Figure 2 shows a mass of 10^{18}g and $r_s = 2r_E$ with a minima at 1 MeV, so the 10 GeV upper range of LAT corresponds to a minima at 10^{14}g. The left panel of figure 2 with $5 \cdot 10^{18}$g at $r_S = 0.5r_E$ has the first minimum at about 800keV, which would permit about 1/256 smaller r_S to be observed. Since both r_S and mass drive the minima 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.

Unlike primordial black holes, these low density "baryonic" femtolenses may block more light than they transmit, since the lens is partially "filled-in" by the matter itself. This

reduces the sensitivity of the GBM at the low-mass/low-density limit, but for the long duration AGN studies, both occultation and chromatic aberration are signals that can be extracted from the data. This simultaneous detection of aberration and occultation can then provide a signature to distinguish intrinsic AGN variability from a 10,000s femtolensing event, thereby lowering the mass threshold for detection.

3 Science Objectives

We hope 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. By pinning down the source of CDM in our own galaxy and 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. Finally, if an IMDMO femtolensing candidate 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 IMDMO 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 constrains the BBN models in the opposite direction toward baryon-free CDM. So whether IMDMO are found or excluded, this study will have important implications for the next decade of astronomy.

4 NASA Relevance and management plan

We expect our total level of effort for this proposal to be equivalent to about 0.5 FTE per year for 1 year. We have requested funding of 70 k$ for an year. Funded personnel will include a member of University of Alabama in Huntsville (UAH, N.Bhat), and Grassmere Dynamics (R. Sheldon). R. Sheldon (0.4 FTE) will lead the data analysis, N. Bhat (0.1 FTE) will help with the analysis code, interpretation of results and writing papers.

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