



Constraining Dark Matter hypothesis through Diffuse Source observations with the GLAST-LAT detector

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Abstract: The Gamma-Ray Large Area Space Telescope (GLAST), scheduled to be launched in Fall 2007, is a next generation high energy gamma-ray observatory. The Large Area Telescope (LAT) instrument on-board GLAST with a wide field of view (> 2 sr), large effective area and 20 MeV to > 300 GeV energy range, will provide excellent opportunity for future Dark Matter studies. We present an overview of the GLAST Dark Matter and New Physics Working Group efforts in the study of the LAT capability to detect a gamma-ray flux coming from WIMP pair annihilations in diffuse astrophysical sources. Particular attention will be given to extragalactic diffuse gamma-ray radiation and line searches from annihilation into gamma-gamma and/or gamma-Z final states.

Introduction

The nature of the Cold Dark Matter (CDM) has been a subject of special interest to high-energy physicists, astrophysicists and cosmologists for many years. It is probably one of the most outstanding open questions in present day Cosmology.

The existence of Dark Matter is required from galactic scale up to cosmological scale by a wealth of observations and arguments such as rotation curve data, cluster dynamics or gravitational arcs. At the same time, the Cosmic Microwave Background measurements limit the contribution from ordinary baryons so that non-baryonic matter has to make up most of the matter in the Universe.

Virtually all potential dark matter candidates require physics beyond the standard model of particle physics. One of the most widely studied model is supersymmetric extensions of the standard model which provides a natural candidate for CDM in the form of a stable Weakly Interacting Massive Particle (WIMP), the Neutralino.

The mutual annihilation of these WIMPs would yield (among a few other indirect signatures like energetic neutrinos, antiprotons or positrons) many high energy gamma rays (≥ 1 GeV) that can be well measured in the GLAST LAT. WIMP annihilation into $\gamma\gamma$ and or γZ final states would give

monochromatic gamma rays with an energy $E_\gamma \sim m_\chi$ and $E_\gamma \sim m_\chi (1 - m_Z^2/4m_\chi^2)$. Since these gamma rays are monochromatic and have high energy, they would constitute a spectacular signature of annihilating dark matter.

The LAT Dark Matter and New Physics Working group has been developing approaches for the indirect detection of both diffuse and point like [1] source observations with the GLAST-LAT detector [2]. We will focus here on diffuse source observations and, as an example, particular attention will be given to extragalactic diffuse gamma-ray radiation [3] and line searches [4].

Extragalactic diffuse gamma-ray radiation

It has been first pointed out by Bergström et al. [5] that the integrated signal of WIMP annihilations into high energy photons over all cosmological dark matter halos at all redshifts might contribute to the extragalactic diffuse gamma-ray radiation.

The resulting differential energy flux per unit area-time-energy and solid angle on the sky can be written as [6]:

$$\frac{d\Phi_\gamma}{dE_0} = \frac{\sigma v}{8\pi} \frac{c}{H_0} \frac{\bar{\rho}_0^2}{m_\chi^2} \times \int dz (1+z)^3 \frac{\Delta^2(z)}{h(z)} \frac{dN_\gamma(E_0(1+z))}{dE} e^{-\tau(z, E_0)}$$

where we can distinguish contributions from particle physics, astrophysics and cosmology.

The particle physics contribution lies in the annihilating cross section σ , the WIMP mass m_χ , and the differential gamma-ray yield per annihilation :

$$\frac{dN_\gamma}{dE} = \frac{dN_{cont}}{dE}(E) + b_{\gamma\gamma} \delta(m_\chi - E)$$

Here, dN_{cont}/dE is the mean number of photons due to WIMP annihilations summed over all relevant channels and gives rise to a continuous energy spectrum. This term is reduced to a delta function in the case of monochromatic photons as expressed in the second term where $b_{\gamma\gamma}$ is the branching ratio into $\gamma\gamma$.

As the annihilation rate is proportional to the dark matter density squared ($\bar{\rho}_0$ being the present day mean density), it depends strongly on how dark matter is distributed on small, galactic and subgalactic scale. This question is still a matter of debate however N-body simulations show that large structures formed by the successive merging of small substructures, with smaller objects which are usually more dense [7]. The ‘‘clumpiness’’ of dark matter can then significantly boost the annihilation signal from cosmological WIMPs. The quantity Δ^2 describes the average of over density squared in haloes, as a function of redshift.

Since we consider contributions from annihilations at high redshifts, the extragalactic gamma-ray signal is strongly affected by absorption in the intergalactic medium, especially at high energies. The term $e^{-\tau(z, E_0)}$ accounts for absorption of gamma-rays along the line of sight where the absorption is parameterized by the optical depth τ . We include the effect of absorption using parameterizations of the optical depth as function of both redshift and observed energy [8]. More recent calculation of the optical depth [9] do not alter our results significantly.

The last contribution comes from cosmological model : the Hubble parameter at the present day

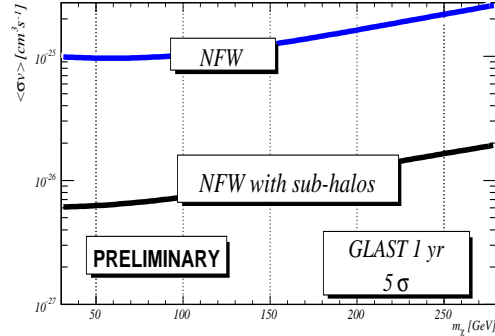


Figure 1:

value H_0 , and the dimensionless quantity $h(z)$, which depends on the energy content of the universe at a given redshift. For the fractions of critical density given by matter, vacuum energy and curvature, we used the results from the WMAP three-year data [10].

To compute the GLAST LAT sensitivity to Dark Matter contribution to the extragalactic diffuse gamma-ray radiation, we used the Observation Simulator (ObsSim) [11]. LAT photons for a generic model of WIMPs annihilating into $b\bar{b}$ and into 2γ were generated for different WIMP masses ranging from 50 GeV to 250 GeV.

Assuming that the background consists of unresolved blazars [6], a χ^2 analysis was performed, to obtain a 3σ exclusion curves in the σv vs m_χ plan for one year of simulated data (fig. 1).

Two different halo profiles have been considered for the normalization : the Navarro Franck White smooth profile [12] (NFW) and NFW profile where we also have included the effect of substructures. We assumed that substructures constitute 5% of the mass and have three times the concentration parameter of the parent halo. The concentration parameters, as a function of halo mass, is distributed according to [13].

As shown in fig. 1, depending on the Dark Matter halo model, the GLAST LAT would be sensitive to annihilating cross-sections from few 10^{-26} up to $10^{-25} cm^3 s^{-1}$.

One should note that this estimate neglects contributions of instrumental background, uncertainties

introduced by the analysis (where point-sources and galactic diffuse emission have to be taken into account) and finally that the extragalactic background spectrum from astrophysical sources is very uncertain, especially at high energies.

Line searches from WIMP annihilation into $\gamma\gamma$ and/or γZ final states

The detection of monoenergetic photons from mutual annihilation of WIMPs would be a very distinct “smoking gun” signal of Dark Matter content in the Universe. These processes are however loop suppressed and, in popular SUSY models, these lines only occur at the $\sim 10^{-4}$ to $\sim 10^{-2}$ branching ratio level, leading to a great challenge in detection.

The LAT Dark Matter and New Physics Working group computed a preliminary estimate of the LAT sensitivity at 5σ above background and 95% upper limits confidence level (ULCL) to these WIMP lines. Two cases have been investigated, the first being when the line energy is known (e.g. supplied by SUSY searches at the LHC). The second case, when energy is unknown, is less constraining as further statistical treatment is needed to account for the number of energy bins searched over the range of interest.

The gamma-ray line signal depends strongly on Dark Matter halo and on the diffuse background models. The best signal-to-noise is expected [14] for an observation of a galactic centered broad broken annulus ($r \in [25^\circ, 35^\circ]$), which excludes the region within 10° from the galactic plane.

For this study we estimated the galactic diffuse background in this annulus from Galprop [15] which is based on EGRET and other data in the EGRET energy range. The high energy range (up to 150 GeV), for which the line sensitivity is computed in this proceeding, has been obtained from extrapolations provided by the Galprop team.

To estimate the LAT sensitivities to known line energy, we first considered a point source at high latitude ($l = -76^\circ$, $b = 26^\circ$) with a narrow Gaussian energy distribution ($\sigma/E_0 = 10^{-3}$). The Instrument Response Functions (IRFs) from the LAT Data Challenge-2 (DC-2) [16] were used, and LAT resolved lines were simulated with ObsSim for a

55 day full sky scanning mode exposure (uniform all-sky coverage for the LAT in scanning mode). Energies of 25, 50, 75, 100, 125, and 150 GeV were considered. NB: The DC-2 version of the LAT IRFs cut off at 200 GeV, the currently available LAT IRF version extends beyond 300 GeV.

The ObsSim results for the all-sky scan were well fit to a double Gaussian distribution, Φ_1 :

$$\Phi_1(E, E_0, N_T, r, \sigma_1, \sigma_2) = \frac{N_T}{\sqrt{2\pi}} \left[\frac{1-r}{\sigma_1} e^{-\frac{(E-E_0)^2}{2\sigma_1^2}} + \frac{r}{\sigma_2} e^{-\frac{(E-E_0)^2}{2\sigma_2^2}} \right]$$

where $N_T = N_1 + N_2$, and $r = N_2/N_T$.

The all-sky diffuse background was generated for 5 years and the flux in the galactic annulus was fit with an exponential background, Φ_2 :

$$\Phi_2(E; a, b) = a \times e^{E/b} \text{ for } E \in [40, 200] \text{ GeV.}$$

For each line, the input background was bootstrapped with a MC signal 1000 times and fit to $\Phi_1 + \Phi_2$ and Φ_2 , to compute the 5σ signal sensitivity for 5 years of observations. This series of 1000 bootstraps was re-run varying only the average number of MC signal counts (constant across the series) until $\langle \Delta\chi^2 \rangle = \chi_{\Phi_1+\Phi_2}^2 - \chi_{\Phi_2}^2 \sim 25$ (corresponding to a 5σ signal over background). The average number of signal counts needed at each energy was then converted to a sensitivity using average exposures integrated over the annulus (fig 2). The LAT detection sensitivity for a line of unknown energy ($E \in [40, 150]$ GeV) for a 5σ above background signal corresponds to a confidence level of 10^{-7} . To calculate the number of counts needed at each energy in this case we used the probability of no detection in a single bin, q :

$$q = (1 - P)^{1/\#ofEnergyBins} = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\#of\sigma} e^{-x^2/2} dx,$$

where $P = 10^{-7}$ is the probability of detecting a signal greater than $\#of\sigma$, in one or more bins. A bin width of $\sigma_{fwhm}/E = 8\%$ was used based on the FWHM energy resolution of the IRFs. The error in the signal was estimated as $\sigma_{signal} = \sqrt{2B}$ where B is the number of background counts in a bin centered on E_0 with width σ_{fwhm} . The $\#of\sigma$

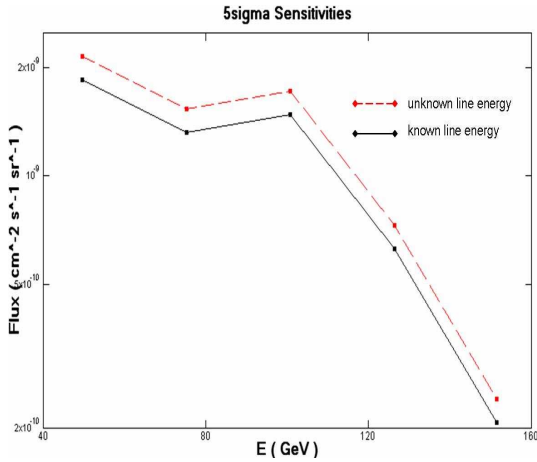


Figure 2:

signal error was converted to flux for calculation of the unknown line energy (fig. 2).

The 5 year 95% CLUL sensitivity for known line energies was obtained similarly to the 5σ case by bootstrapping the ObsSim diffuse background and fitting $\Phi_1 + \Phi_2$ with no MC generated signal. After the calculation of $N_T \pm \sigma_{NT}$, the 95% CLUL was obtained from $1.64 \sigma_{NT}$ and sensitivities calculated as in the 5σ case with $P=.05$ (fig 3). The case of unknown line energy ($E \in [40, 150]$ GeV) 95% CLUL was calculated as in the 5σ case with $P = .05$ (fig 3).

Conclusions

We presented the GLAST Dark Matter and New Physics Working Group efforts on indirect detection of Dark Matter through diffuse source observations. As an example, preliminary results on extragalactic diffuse gamma-ray radiation and line searches illustrated that the GLAST-LAT detector will provide excellent high energy gamma-ray observations for future Dark Matter searches.

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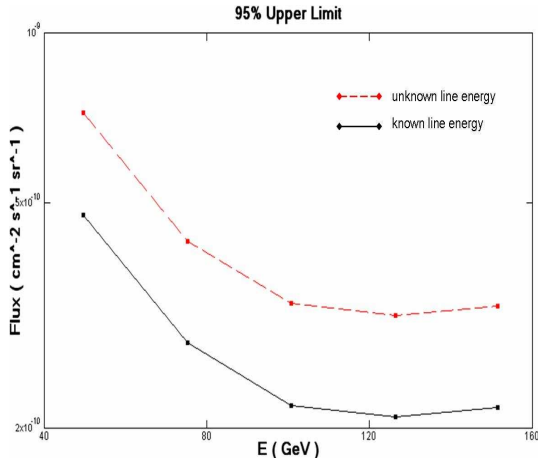


Figure 3:

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