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The Search for Dark Matter via Gamma Rays from Astronomical Sources Using EGRET and GLAST[1]

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EGRET, aboard NASA's CGRO satellite, has made important contributions to establishing limits on WIMP dark matter in the galaxy. This paper will review these EGRET results. Based on past limits and theoretical estimates, future potential dark matter results from GLAST are projected.

1. Introduction

NASA's Compton Gamma Ray Observatory, CGRO, was launched in April 1991, and deorbited on June 4, 2000 due to a fear of loosing one more satellite gyro that would have made a controlled reentry very difficult. During those 9 years, EGRET collected considerable data concerning the diffuse background of the galaxy, and the galactic center region. Figure 1 shows the EGRET instrument. EGRET consists of a monolithic dome made of scintillator to suppress the charged particle backgrounds, a magnetostrictive wire chamber array interleaved with tantalum plates to convert the gamma rays and track the resulting e^+e^- pair, and finally a transversely segmented NaI(*tl*) array calorimeter with no longitudinal segmentation that measures the energy of the photon shower. Beside the scintillator anticoincidence dome, EGRET used the tracker and calorimeter to reject the cosmic ray hadrons. Reference [1] gives the details of the EGRET detector and its calibration.

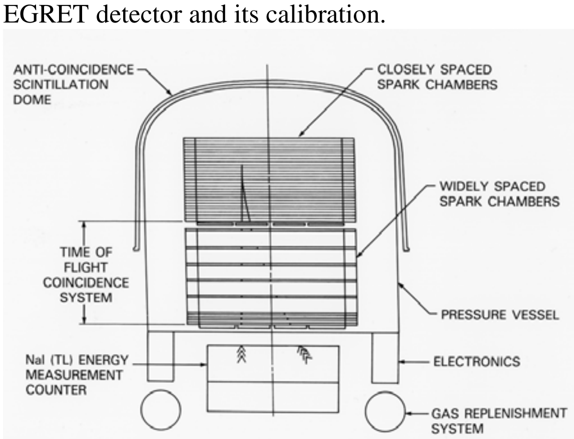

Figure 1. The EGRET detector schematically. The spark chambers were multiwire magnetostrictive chambers with "magnetic core" readout. A difficult technology to use on the ground, and these chambers worked very well in space. Ultimately, the gas supply to the chambers limited EGRET's operational lifetime.

In principle, many aspects of GLAST are similar to the EGRET instrument. Both have scintillator charged particle vetoes, a tracker and a calorimeter. GLAST does not have a time of flight system, and this allowed a much more squat geometry that opened up the field of view of the instrument. In addition, GLAST has no consumables, has a much larger effective area, and has a multi-segment charged particle veto system. The later avoids the self-veto problem that led to a dramatic loss of effective area for EGRET above ~10 GeV.

The GLAST mission has two instruments. The main instrument is the Large Area Telescope (LAT), [2], and the P.I. for the LAT is Peter Michelson of Stanford University. The other, much smaller, instrument is a context instrument that adds considerable depth to the LAT gamma ray burst program and is called the GLAST Burst Monitor (GBM), [3]. The P.I. for the GBM is Charles Meegan of the Marshall Space Flight Center**.** Figure 2 shows the GLAST LAT instrument.

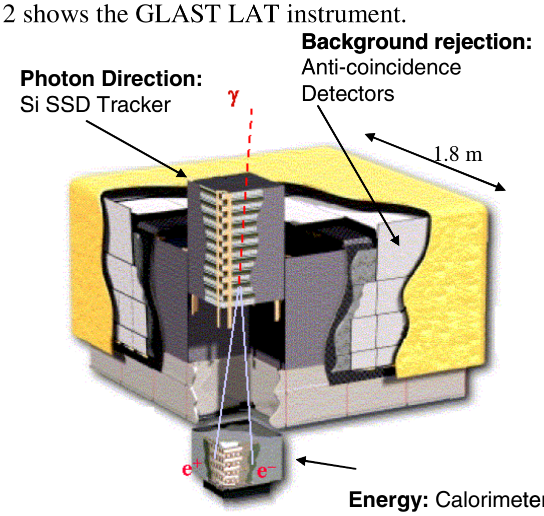

Figure 2. A CAD drawing of the GLAST LAT. The instrument is made up of 16 towers, one of which is shown in exploded view in the figure. The 16 towers are covered on 5 sides by an anti-coincidence shield. See text for further description.

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The LAT is modular with 16 towers in a 4x4 array. Each tower is made of a multi-layer silicon strip based tracker, a multi-layered CsI calorimeter and associated electronics.

The tracker contains 18 x-y layers of single sided silicon strip detectors with 228 μm pitch, each with > 98% efficiency. The ~ 80 m^2 of silicon in this tracker make it one of the largest silicon trackers yet constructed. The first 12 x-y layers each have 0.03 X0 tungsten converters, which contribute minimal multiple scattering , while the rear 4 x-y layers have 0.18 X0 tungsten converters to increase the LAT sensitivity for greater than 1 GeV photons. Behind the converting layers are 2 x-y layers that have no tungsten converter, and are designed to locate the calorimeter entry position of the particles.

The 16 Calorimeter modules each contain 96 CsI(Tl) crystals in 4 x-y layers, for a total of 1536 crystals in the whole array. The crystals are read out on both ends by two pin diodes on each end. This readout plus the custom designed electronics allows a very wide energy range for the LAT from 20 MeV to over 300 GeV. The 8 layers of calorimeter have 8.5 X0 of CsI(Tl), and the tracker has another 1.5 X0 of mainly tungsten. The multilayers of the system allow for energy correction to the photon shower yielding σ_E/E <~ 0.1 over much of the LAT's energy range.

The Anti-Coincidence shield, ACD, covers the LAT tower array on five sides. In order to avoid "backsplash" self-vetoing from high-energy photons interacting in the detector, the ACD is segmented into 89 plastic scintillator tiles. Monte Carlo studies indicate that this level of segmentation does not appreciably affect the LAT's photon acceptance due to "backsplash" over its entire energy range. The charged particle efficiency of the ACD is >0.9997, and it has redundant phototube and electronic readout of the scintillator tiles. The ACD, together with the pattern recognition of the tracker and calorimeter x-y array, yields a cosmic ray background contamination of high latitude diffuse photon sample in any decade of energy for >100 MeV of less than 10%, with a goal of 1%.

The LAT's data acquisition system is designed to have a dead time of ~20 μsec, as compared to the 0.1 second for EGRET. This relatively short dead time for the LAT, together with the GBM, and GLAST's wide field of view, will allow unprecedented observations of gamma ray bursts from ~5 keV to over 300 GeV.

Table 1 shows CGRO/EGRET performance vs. GLAST/LAT requirements for a number of the requirements.

GLAST is a Multi-Agency and International Mission with contributions from France, Germany, Italy, Japan, Sweden, and the USA. In the US, GLAST sponsorship is a partnership between the DoE and NASA. The LAT construction project is managed at SLAC-Stanford University, while the GBM is managed at Marshall Space Flight Center. The GLAST mission is managed at Goddard Space Flight Center. The current schedule has flight hardware construction beginning this year (2004), and the GLAST launch on a delta class launch vehicle in 2007.

The overall GLAST science objective is to explore the high-energy universe with unprecedented sensitivity. One can relate this overall goal of the mission to a number of specific studies:

- Understanding the mechanisms of particle acceleration in astrophysical environments such as active galactic nuclei, pulsars and supernova remnants
- Determining the high-energy behavior of gamma-ray bursts and other transients
- Resolving and identifying point sources with known objects
- Probing the extra-galactic background light in the early universe
- Searching for large extra dimensions
- Searching for the nature of dark matter

This paper will focus on the last of these studies in comparing the Search for dark matter via gamma rays from astronomical sources using EGRET and GLAST.

2. The Search for the Nature of Dark Matter Using EGRET and GLAST

This section will focus on the high-energy gamma ray galactic center (GC) source first seen by EGRET, [4]. In this section, I quote freely from reference [4]. The EGRET instrument on the Compton Gamma-Ray Observatory has observed the Galactic Center (GC) region with good coverage at a number of epochs. Figure 3a,b shows a strong excess of emission that is observed, with E^2 x I(E) peaking at energies ~ 2 GeV in an error circle of 0.2 degree radius including the position $l = 0^{\circ}$ and $b = 0^{\circ}$. The close coincidence of this excess with the GC direction and the fact that it is the strongest emission maximum within 15 degrees from the GC is taken as compelling evidence for the source's location in the

	CGRO/EGRET	GLAST/LAT	Change
Energy Range	30 MeV - 30 GeV	20 MeV - > 300 GeV	20-30 MeV, 30-300 GeV
Energy Resolution ($\Delta E/E$)	10% on axis.	10% on axis:100 MeV- 10 GeV, 20% on axis:10 GeV – 300 GeV 6% > 60º: >10 GeV	Similar for normal incidence
Peak Effective Area	1500 cm²	>8,000 cm²	> 5.3
Field of View	0.5 sr	>2.0 sr	> 4
Angular Resolution	5.8° @ 100 MeV 0.5° @ 10 GeV	< 3.5° @ 100 MeV < 0.15° @ 10 GeV	Area = 1/2.7 Area = 1/11
Point Source Sensitivity (> 100 MeV)*	~ 10^{-7} cm^{-2} s^{-1}	6×10^{-9} cm^{-2} s^{-1}	1/17
Dead time	100 ms	<100 μs (Currently 20 μs)	> 1000 (5000)
Mass	1810 kg	3000 kg	1190 kg
Lifetime	1991 – 1997 Gas Limited	2007 - 2017	x2

* 1 year survey at high latitudes

Table 1. CGRO/EGRET performance vs. GLAST/LAT requirements for many requirements. For a complete discussion of the GLAST mission science requirements see reference [5].

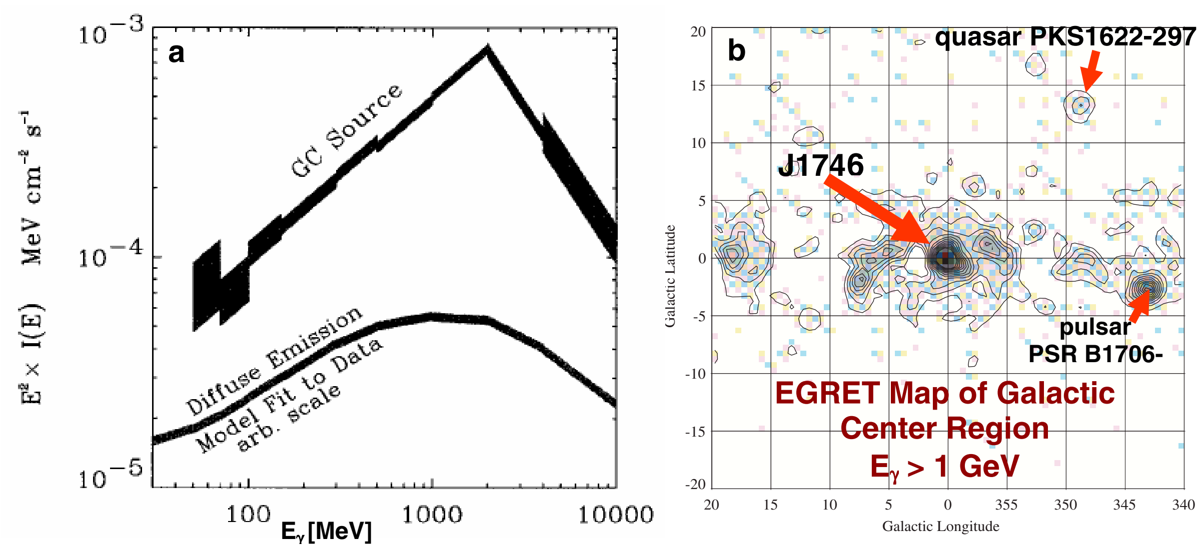

Figure 3. Part **a** shows the modified energy spectrum of the EGRET galactic center source [4], the top curve in the figure, $E_\gamma^2 \times I(E_\gamma)$ vs. E_γ, compared to the shape of the similarly modified energy spectrum of the diffuse emission as seen by EGRET. In reference [4] the authors state that the galactic center source spectrum is not consistent with the spectrum of the diffuse emission. The background subtracted intensity of the source for $E_\gamma > 1$ GeV is $(49 \pm 3) \times 10^{-8}$ ph/cm^2/s. Part **b** shows the EGRET map of the galactic center region in photons with $E_\gamma >$ 1 GeV, [4]. This figure shows that the region is complex with a number of bright sources near the galactic center source, J1746.

GC region. The history of the emission intensity, observed over 5 years, leaves room for possible time variation; however, it does not provide evidence. The angular extent of the excess appears only marginally compatible with the signature expected for a single compact object. The emission therefore may stem from one or more compact objects or may originate from diffuse interactions within 85 pc from the center of the Galaxy at 8.5 kpc distance. The spatial distribution of the emission does not correlate with the details of the CO-line surveys. Thus, in spite of the existence of a strong emission peak, earlier conclusions based on an apparent 'gamma-ray deficit', postulating the masses of the 'wide-line' clouds in the GC area to be an order of magnitude lower than indicated by naive CO interpretation, are supported. However, the total gas mass in the Nuclear Bulge (NB) derived from the gamma-ray emission is found to be in agreement with the mass that in recent studies has been derived from molecular-line and FIR surveys. The γ-ray emission spectrum is peculiar and different from the spectrum of the large-scale galactic diffuse emission. A diffuse emission scenario requires an enhanced and peculiar Cosmic Ray (CR) spectrum as suggested for the electrons in the 'Radio Arc'. A compact sources model hints at an origin in pulsars. While the spectrum suggests middle-aged pulsars like Vela, too many are required to produce the observed flux. The only detected very young pulsar, the Crab pulsar, has an incompatible spectrum. However, it is not proven that the Crab spectrum is characteristic for all young pulsars: thus, a single or a few very young pulsars (at the GC not detectable in radio emission), provided their gamma-ray emission is larger than that of the Crab pulsar by a factor of 13, are likely candidates. Alternatively, more exotic scenarios, related to the postulated central black hole or dark matter (neutralino) annihilation, may be invoked The background subtracted intensity for the source for >1 GeV is $(49 \pm 3) \times 10^{-8}$ ph/cm^2/s.

There has been additional work on the EGRET GC source, 2EG J1746-2852, since the publication of reference [4] in 1998. More recently, Nolan, et al. 2003, [6] indicate that EGRET systematic errors do not allow a firm statement on variability of the source. This specialized study of the variability of EGRET sources is in agreement with reference [4].

The reanalysis of EGRET data in Reference [7] indicate that source is off the CG. However, their result is consistent, within 2 σ, with the source being at the GC and is consistent with reference 4. GLAST should provide much better data to decide this issue as the GLAST LAT PSF is projected to yield 10 arc sec location information for bright sources. Figure 4 shows a comparison of the EGRET diffuse emission observations to that expected from GLAST (Monte Carlo).

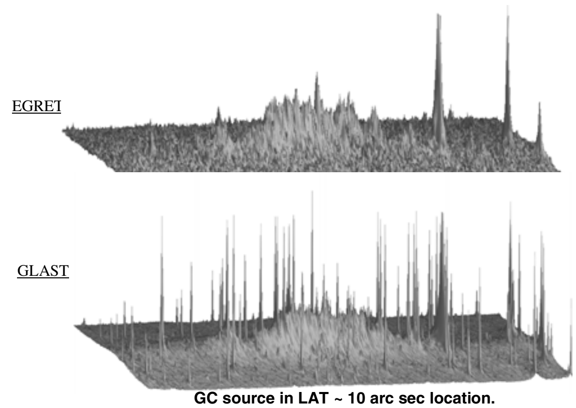

Figure 4. Top part of the figure shows EGRET results on the galactic diffuse background. The bottom part of the figure shows GLAST LAT MC estimates of what the LAT will observe. The brighter sources, including the galactic center source are located to 10 arc sec.

Whipple has reported [8] a 3.7σ excess at the galactic center (E>~2 TeV, 26 hrs observation). Further observations and analysis are underway.

3. Halo WIMP annihilations

Particle theory has proposed interesting candidates for galactic halo dark matter. GLAST can observe some of candidates in principle. Two examples are:

a) The ever-popular SUSY lightest stable particle the neutralino, χ^0. $\chi^0 \chi^0$ annihilations to jets, produce an extra component of multi-GeV γ flux that follows the halo density (not isotropic) peaking at $E_\gamma \sim 0.1\ M\chi^0$. A major background to detecting these decay is the galactic γ ray diffuse. [9] There are also γ lines that may result from the annihilation, but these are, at best, a small fraction of the decays, have been discussed extensively in the literature[10], and won't be discussed in this paper.

b) Heavy right-handed neutrinos. Leptonic dark matter is not totally hopeless from the viewpoint of detection via the annihilation channels $L_R L_R \rightarrow l^+ l^- \gamma$, $\gamma\gamma$. [11]

a) In general, the γ ray flux from WIMP annihilation is given by,

$\Phi(E, \Delta\Omega) \sim (\sigma v/M^2_{WIMP}) \times (\int_{los} \int_{\Delta\Omega} \rho^2(\lambda) d\lambda d\Omega)$.

The expression for σ in the first set of parentheses depends upon the particular theory of WIMP annihilation being considered, σ being the cross section for same, v the relative speed of the 2 annihilating WIMPs in their CM ($v/c << 1$), and M_{WIMP} its mass. The expression in the second set of parentheses gives the path length integral of the square of the WIMP particle density along the line of sight (los) from the source to the instrument and over the acceptance solid angle of the instrument. $\rho(\lambda)$ is the density of the dark matter halo, assumed spherically symmetric in this formula. The annihilation rate is proportional to $\rho(\lambda)^2$. A frequently used approximation for $\rho(r)$ is,

$\rho(r) = \rho_c /[(r/a)^\gamma(1+(r/a)^\alpha)^{(\beta-\gamma)/\alpha})]$.

r is the distance from the center of the galaxy, **a** is the model dependent radius of the core of the galaxy, ρ_c normalizes the dark matter distribution to the dark matter density at the earth. (The local dark matter density is inferred from rotation curve measurements of the galactic dark matter halo, and is ~ 0.3- 0.5 GeV cm^{-3} if the dark matter halo is assumed to be spherical [12].) α, β, γ are model dependent constants. Table 2 gives values for these constants that come from various currently popular models. Clearly, depending on which model one selects, there is a very different halo density, and hence a different predicted photon flux.

α	β	γ	Model
2	2	0	[13]
1	3	1	[14]
1.5	3	1.5	[15]
2	3	0.2	[16]
2	3	0.4	[16]

Table 2. Model dependent constants for some popular phenomenological dark matter halo models of the Milky Way galaxy.

In addition to the galactic halo uncertainty, there is the uncertainty of the WIMP annihilation modes one uses to calculate the expected observational results. A number of decay modes are listed below and their relative strengths in the annihilation depend on the mass of the WIMP and the MSSM model used. $\phi^{\chi\chi}_\gamma(E_\gamma)$ is the total photon yield at E_γ from WIMP annihilation derived from the decay mix and the other factors mentioned above..

$$\chi\chi \to \left\{ \begin{array}{l} b\bar{b} \\ c\bar{c} \\ t\bar{t} \\ W^+W^- \\ Z^0Z^0 \\ \text{(light quarks)} \\ \text{(Higgs)} \end{array} \right\} \to \ldots\gamma \quad \Rightarrow \phi_\gamma^{\chi\chi}(E_\gamma)$$

Figure 5 shows the γ yield per annihilation for a number of possible decay channels for M_{WIMP} = 200 GeV [17].

A popular approach used to estimate the γ yield from $\chi\chi$ annihilation has been to use MSSM through the Dark SUSY Monte Carlo [18] to calculate the single annihilation normalized energy dependent photon spectrum from the annihilation final state mix. One then multiplies this spectrum by the integral of the WIMP halo density integrated along the line of sight to the galactic center to give the expected continuum gamma ray flux from a small region around the galactic centre (~ 2 degrees) due to neutralino-neutralino annihilations. Figure 6 shows a spectrum, determined from EGRET, obtained in this general fashion from reference [17].

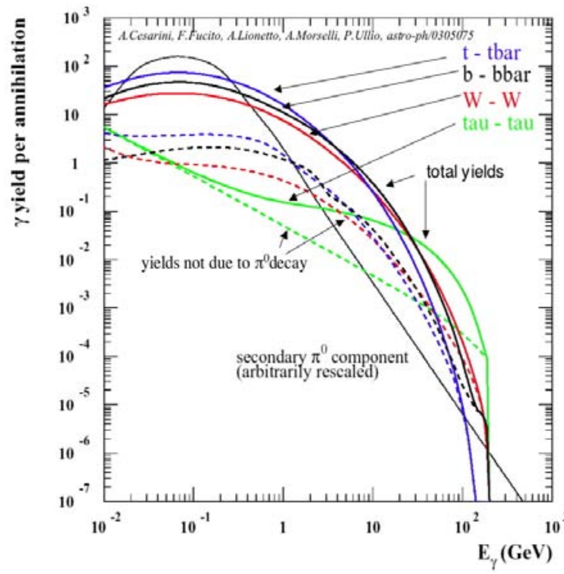

Figure 5. Differential yield for a number of annihilation channels, WIMP Mass = 200 GeV. The solid lines are the total yields, while the dashed lines are components not due to π^0 decays. The spectra are calculated using Dark SUSY in reference [17].

In addition to the photon signal from WIMP annihilation, the figure indicates that there is a very large background to this potential channel coming from cosmic ray interactions with the galactic medium and magnetic field, i.e., the galactic diffuse gamma ray background. The model of the diffuse galactic background emanating along the line of sight to the center of the galaxy is at the heart of the extraction of a putative WIMP annihilation signal at the center of the galaxy. This source of uncertainty currently represents a large systematic error compared to the statistical errors shown in the plot.

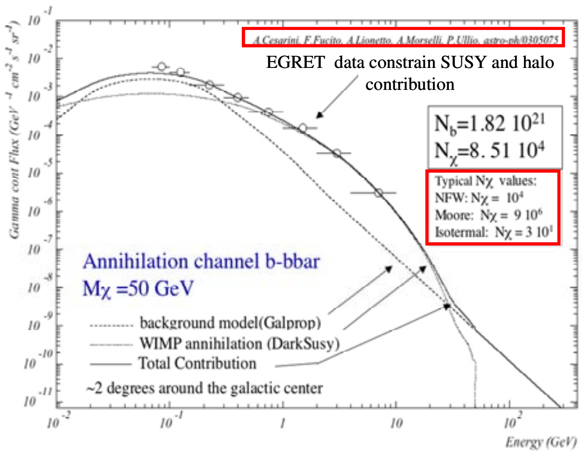

Figure 6. Fit of the EGRET galactic center γ-ray data for a sample WIMP model from ref. [17]. In this case, they fix the $WIMP_{mass}$ = 50 GeV and select a single annihilation channel (b-bbar). Signal and background components are indicated separately, while their sum is shown with a solid line.

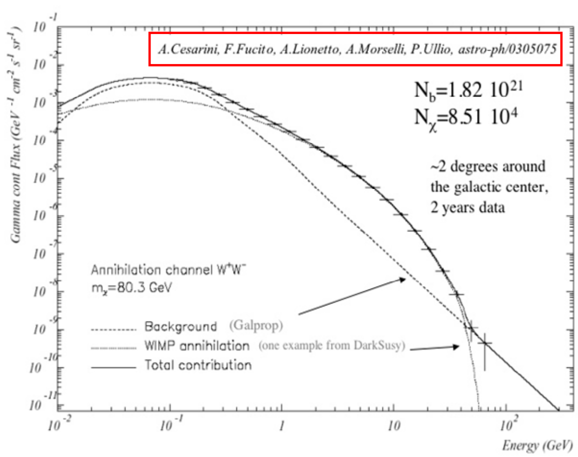

Figure 7. Simulation of the data set to be obtained with GLAST in 2 years of scanning observations, assuming the EGRET galactic center excess is due to a WIMP-induced flux. This case is another chosen in ref. [17] for $WIMP_{mass}$ = 80.3 GeV, and dominated by W decay. The value of the parameters N_b and N_χ are the same as obtained for the similar fit to EGRET data in the reference. The error bars refer to statistical errors for the chosen energy binning and for the angular acceptance $\Delta\Omega = 10^{-3}$ sr.

As pointed out in ref. [17], qualitative agreement with the data is rather good, even if the reduced χ^2 for the 6 degrees of freedom of the fit is rather large (of the order of 5). However, it is clear that adding a WIMP annihilation component in addition to the background component greatly improves the agreement between the fit and the EGRET measurement. But, it must be noted that the systematic errors coming from uncertainty in the diffuse background model likely dwarf the statistical errors. These difficult to estimate systematic errors result in the quotation of limits on WIMP signals in ref. [17], rather than a claim of a signal. For future missions to make a more significant contribution than EGRET on this topic, considerable progress is required in understanding the diffuse galactic background. This is amply demonstrated in figure 7, also from ref. [17], which shows projected results from GLAST. Statistics will most likely not be the problem.

b) Standard Model neutrinos are light and are hot dark matter. The presence of a significant amount of hot dark matter in the universe is in strong conflict with the existence of galaxies today. A right handed neutrino is very massive in see-saw models, and this is used to explain light neutrinos. Can such a heavy right handed neutrino be an acceptable dark matter candidate or LIMP? Reference [11] explores the ramifications such a model [19] where a right-handed neutrino of mass on the order of a few TeV plays a crucial role in giving mass to the otherwise massless standard model neutrinos through a high-order loop mechanism. This is a version of the Zee model [20], which has been quite successful in reproducing the observed mass and mixing pattern of solar and atmospheric neutrinos (see, e.g., [21]). The authors of [11] point out that the radiatively induced annihilation rate of these LIMPs into leptons and photons is bound to be substantial, and provides a conspicuous gamma-ray signature for annihilations in the galactic halo.

There are two related issues. First, one needs a new scale to explain standard model neutrinos, and this could be the GUT scale. Second, the very weakly interacting relic LIMP density is much too high. Reference [19] address both issues and gets a more natural standard model neutrino and a good dark matter candidate. It is a variation of the Zee model that has standard model particle content plus SU(2) singlets-two charged scalars and right-handed neutrino. The authors impose additional parity symmetry-standard model and one scalar even, others odd. The lightest odd state is stable (similar to R-parity in SUSY).

Figure 8 shows that leptonic dark matter is not totally hopeless from the viewpoint of detection by ACTs. GLAST cannot observe such small fluxes.

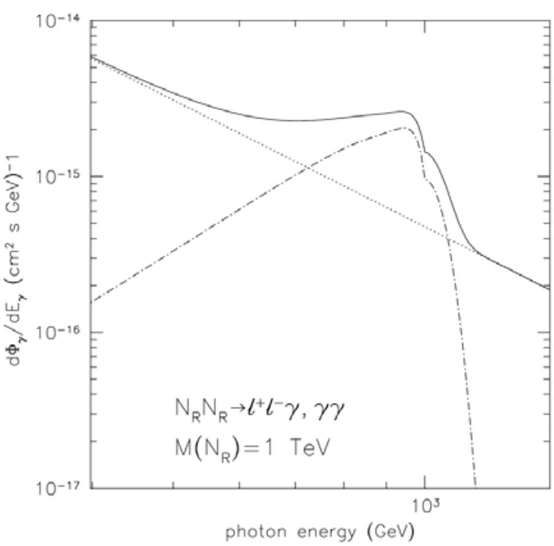

Figure 8. The total gamma-ray flux expected from a $\Delta\ \Omega=10^{-3}$ sr cone around the galactic center (solid line). The flux is composed by a power-law background extrapolated from EGRET data (dotted line) and a 1 TeV LIMP annihilating with a cusped (NFW) galactic DM density profile through a 1.1 TeV GeV scalar *S*2, giving both a continuous spectrum and a 2γ line. An energy resolution of 5% has been assumed for the line signal. Other examples are discussed in [11].

4. Conclusions

EGRET and ground based air Cherenkov telescope (ACT) results on the galactic center have generated interest concerning hits of signs of WIMPS / LIMPS. GLAST and ACTs can make significant contributions toward resolving these questions. In particular, GLAST should make significant contributions to our understanding of the nature of dark matter as well as contributing new information over a wide range of astrophysically interesting and connected topics. For example, GLAST results will be very helpful in better characterizing the diffuse galactic gamma ray emission, a major source of systematic error in understanding the nature of the excess at the galactic center observed by EGRET. At the time of this writing, GLAST is making good progress towards a launch in 2007, with the expectation of the start of integration and testing at SLAC in the summer of 2004.

5. Acknowledgements

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