Observations of Dwarf Spheroidal galaxies with the Fermi-LAT detector and preliminary constraints on Dark Matter hypothesis.

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***Abstract*. Measurement of γ-rays from dark matter annihilations is perhaps one of the most challenging tasks for future γ-ray observatories. With the successful launch of the *Fermi* Gamma-Ray Space Telescope observatory on June 11, 2008, we have a new opportunity to constrain the dark matter hypothesis from the high energy γ-ray signal. Dwarf spheroidal galaxies, the largest galactic substructures predicted by the cold dark matter scenario, are attractive targets for indirect searches for dark matter because they are amongst the most extreme dark matter dominated environments. We report here on the observation of the sky region around a selection of 10 dwarf spheroidal galaxies performed with Fermi during the first 3 months of data taking. No significant γ-ray emission was found above 100 MeV. Preliminary upper limits of the order of 10^{-9}ph cm^{-2}s^{-1} on the integral flux above 100 MeV are given and compared with predictions of γ-ray fluxes from WIMP pair annihilations in the standard $mSUGRA$ scheme.**

***Keywords*: Dark Matter, Gamma-ray's, Fermi**

I. Introduction

There is a wealth of experimental evidence and arguments accumulated in recent years in favor of a non-baryonic cold dark matter (CDM) to explain the observed structure in the universe. According to the most recent estimates, CDM comprises approximately one-fourth of the total energy density of the universe. However, very little is known about the underlying nature of this dark matter, despite the efforts of high-energy physicists, astrophysicists and cosmologists over many years. This question remains one of the most fascinating and intriguing issues in present day cosmology. One appealing possibility is that CDM consists of a new type of weakly interacting massive particle (WIMPS), that are predicted by theories beyond the Standard Model of particle physics. This scenario includes several candidates which satisfy both experimental constraints and theoretical arguments [1]. One of the most widely studied candidates is the neutralino, a stable uncharged Majorana fermion that arises in supersymmetric extensions of the Standard Model. Such a particle has an annihilation cross section at freeze-out time of $\sim 3 \times 10^{-26}$ cm^3 s^{-1} and, for a mass range from about 1 GeV to 10 TeV, this would naturally yield the correct relic abundance observed today. The mutual annihilation of this WIMP would yield, among a few other indirect signatures like energetic neutrinos, antiprotons or positrons, many high energy γ-rays ($\geq$1 GeV) and may give rise to a detectable signal in the γ-ray spectra from many cosmic sources. The main emission comes from secondary products of hadronization processes and from final state radiation [2][3].

Cosmological N-body simulations of structure formation show that WIMPs are expected to form a large amount of substructures [4][5][6]. Dwarf spheroidal galaxies (dSphs), the largest clumps predicted by the CDM scenario, are ideal laboratories for indirect search for DM for the following reasons. First, baryon interactions with dark matter are not expected to play a significant role in the DM distribution. Second, the uncertainties in the DM distribution can be better quantified and understood and their DM distribution can often be inferred directly from stellar kinematics. And third, the mass-to-light ratios in dSphs can be very large $\mathcal{O}(100-1000)$, showing that they are largely DM dominated systems. For example, the mass-to-light ratio of Draco is ~ 250 in Solar units [7], while it is ~ 100 for the Sagittarius dwarf [8]. In addition, dSphs are expected to be relatively free from intrinsic γ-ray emission from other astrophysical sources as they have little warm or hot gas, minimal amount of dust, and no magnetic field [9], thus eliminating contaminating background that may hinder the interpretation of any detection. Their relative proximity and high Galactic latitude makes some of them ideal for high signal-to-noise detection.

In recent years the Sloan Digital Sky Survey (SDSS) [10] has led to the discovery of a new population of Milky Way satellites, comprising about as many (new) objects as were previously known [11][12][13][14][15]. This new population of extremely low-luminosity galaxies can be very interesting for DM searches.

The Fermi Gamma-Ray Space Telescope (in short *Fermi*) [16][17], which is part of the NASA's office of Space and Science strategic plan, is a next generation space observatory designed to explore the high-energy γ-ray sky[1]. This mission, realized as a close collaboration between the astrophysics and particle physics communities (including institutions in the USA, Japan, France, Germany, Italy and Sweden), was successfully launched on June 11th 2008 and is operating in nominal science configuration. The

[1]For more details, see the Fermi website at: http://glast.gsfc.nasa.gov/

Large Area Telescope (LAT), the main instrument on-board *Fermi* is an electron-positron pair production telescope [16] sensitive to photon energies from 20 MeV to $>$ 300 GeV. It is made of a silicon tracker, a calorimeter and an anticoincidence system to reject the charged particle background. The LAT takes much of its basic design concept from its predecessor EGRET but the energy range (over more than four energy decades), field-of-view ($>$ 2 sr), angular resolution and large effective area, provide the LAT with unprecedented sensitivity and resolution, including the largely unexplored energy window above 10 GeV. Moreover, the LAT is filling the gap between the previous generation of γ-ray space missions and the ground based Cerenkov detectors. This improvement has already allowed the LAT to detect several hundreds of new high-energy sources and to shed light on many issues left open by EGRET. During the first 8 months of operation, the LAT produced a deeper and better resolved map of the γ-ray sky than any previous space mission and provided excellent high-energy γ-ray observations for DM searches.

Several studies have been performed to determine the sensitivity of Fermi to a DM annihilation signal [18] and the Fermi-LAT collaboration currently explores different complementary searches for a DM signal [19][20][21][22]. For this analysis, we will focus on the Fermi-LAT observation of a selection of 10 dSphs of the local group listed in Table I. These 10 dSphs have been selected based on their proximity, high Galactic latitude and their DM content which have been estimated in the literature from the most recent measurements of their velocity dispersion profiles. Preliminary constraints on DM hypothesis derived from these data are given in Section III. LAT results with an updated dataset will be presented and discussed at the conference.

II. FERMI/LAT DATA ANALYSIS

The dataset used for this proceeding has been collected during the first three months of nominal sky survey operation (August 4 to October 30 2008), and will be updated for the conference. The LAT is observing the whole sky every 3 hours, the overall coverage of the sky in this dataset is fairly uniform.

The data have been analyzed using the `Science Tools version 9.11`, a software package dedicated to the *Fermi*/LAT data analysis [2]. The standard onboard filtering, event reconstruction, and classification were applied to the data (see [26] for an extended discussion). For this analysis, the events that have the highest probability of being photons and that come from zenith angles $< 105°$ (to avoid Earth's albedo) were selected.

For each dSph, photons were extracted from a region of interest (ROI) typically $10°$ in radius and centered on the coordinates of the expected dwarf position, as given in Table I. Because of calibration uncertainties at low energies, data were selected with energies above 100 MeV. As an example, the smoothed count map in the Willman 1 region is shown in Fig.1.

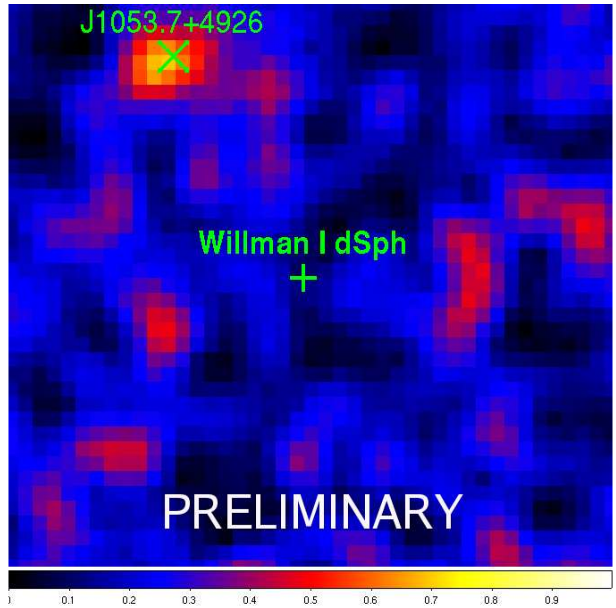

Fig. 1: Measured smoothed count map ($E_\gamma > 100$ MeV) in the Willman 1 dwarf region. Binning is $0.1^o \times 0.1^o$. The bright source J1053.7+4926 at the upper left corner of the figure has been reported in the bright source list published in [26].

Data were analyzed with an binned likelihood [23][24], which is implemented in the `LAT Science Tools` as the `gtlike` task. `gtlike` uses maximum likelihood to fit source spectral parameters such as flux and power-law spectral index, though more complex spectral models are available. Since the detected counts for sources near the detection limit will be fairly low, `gtlike` calculates a likelihood function based on the Poisson probability using the source model folded through the LAT instrument response functions [25] to provide the expected model counts.

The model of the ROI used to fit the data was built taking into account all the sources detected within a given ROI. The isotropic background and Galactic diffuse background models used in the fit are fully discussed in [26]. We model the Galactic diffuse emission using GALPROP, described in [27][28] and [29], which uses a realistic large scale representation of cosmic-ray propagation in the Galaxy to compute the resulting γ-ray emission. For this work, the GALPROP package has been updated to include recent HI and CO surveys, more accurate decomposition into Galactocentric rings, and many other improvements, including analysis of the LAT data. The isotropic component of the diffuse emission (extragalactic + residual backgrounds) is modeled by a simple power law.

[2]http://fermi.gsfc.nasa.gov/ssc/data/analysis/software/

Name	Distance (kpc)	year of discovery	M/L	l	b	ρ_s ($M_\odot\ pc^{-3}$)	r_s (kpc)	J^{NFW} ($10^{19}\ GeV^2\ cm^{-5}$)	References
Segue 1	23± 3	2007	1320 ± 2680	220.48	50.42	1.65	0.05	0.97	1
Ursa Major II	30± 5	2006	1722 ± 1226	152.46	37.44	0.17	0.25	0.57	2,3
Segue 2	35	2009	650^{+1300}_{-380}	149.4	-38.01	0.61	0.06	0.1	4
Willman 1	38± 7	2004	$\sim$500	158.57	56.78	0.417	0.17	0.84	2
Coma Berenices	44± 4	2006	448 ± 297	241.9	83.6	0.232	0.22	0.42	2,3
Usra Minor	66± 3	1954	275 ± 35	104.95	44.80	0.04	0.97	0.35	5,6
Sculptor	79± 4	1937	158 ± 33	287.15	-83.16	0.063	0.52	0.12	5,6
Draco	76± 5	1954	290 ± 60	86.37	34.72	0.13	0.50	0.43	5,6
Sextans	86± 4	1990	70 ± 10	243.4	42.2	0.079	0.36	0.057	5,6
Fornax	138± 8	1938	14.8 ± 8.3	237.1	-65.7	0.04	1.00	0.11	5,6

TABLE I: Properties of the dwarf Spheroidals used in this study. References: (1) Geha et al. [30], (2) Strigari et al. [31], (3) Simon and Geha [32], (4) Belokurov et al. [33], (5) Peñarrubia et al. [34], (6) Mateo et al. [9]

To compute upper limits, the profile likelihood method was used [35]. The model that was input to the likelihood included Galactic and extragalactic (isotropic) diffuse components and a point source with power-law spectrum ($\gamma = 2$) at the dwarf location. The normalizations of the Galactic and extragalactic components were left free so as to allow for model uncertainties and also to account for possible instrumental background. Results are gathered in Table II. Because γ-ray sources are seen against a background of diffuse gamma radiation, which is highly non-uniform across the sky, the limiting flux for a given statistical significance varies with position of the considered dSph.

Name	Flux UL (95%)($E > 100\ MeV$) in units of 10^{-9} ph cm^{-2} s^{-1}
Segue 1	3.13
Ursa Major II	7.55
Segue 2	4.22
Willman 1	3.81
Coma Berenices	2.80
Ursa Minor	2.23
Sculptor	7.93
Draco	2.31
Sextans	11.2
Fornax	3.84

TABLE II: Priliminary 95% upper limit flux obtained for each dwarf. UL are given in units of 10^{-9} ph cm^{-2} s^{-1} and for γ-ray energies $E > 100\ MeV$.

III. Discussion

At a given photon energy E, the γ-ray flux originating from WIMP particle annihilations with a mass m_{WIMP} can be factorized into two contributions: the "astrophysical factor" $J(\psi)$ related to the morphology of the emission region and the "particle physics factor" Φ^{PP} which depend on the candidate particle characteristics :

$$\phi_{WIMP}(E, \psi) = J(\psi) \times \Phi^{PP}(E) \quad (1)$$

where ψ is the angle under which the observation is performed with respect to the source localization. Following notations of [18], $J(\psi)$ and Φ^{PP} are defined as

$$\Phi^{PP}(E) = \frac{1}{2} \frac{< \sigma v >}{4\pi\ m_{WIMP}^2} \sum_f \frac{dN_f}{dE} B_f \quad (2)$$

and

$$J(\psi) = \int_{\mathrm{l.o.s}} dl(\psi) \rho(l)^2 \quad (3)$$

where $< \sigma v >$ is the total mean annihilation cross-section σ multiplied by the relative velocity of the particles (in the limit of $v \rightarrow 0$) and dN_f/dE the sum of all the photon yields for each annihilation channel weighted by the corresponding branching ratio B_f. The integral in Eq.(3) is the integral along the line of sight (l.o.s) of the assumed density squared, $\rho(l)^2$, of WIMPs. For each galaxy, the line of sight integral in Eq.(3) is computed from the kinematic data of the dwarf galaxy. As described in [36], a very common modeling of the DM distribution in the dSphs is given by radial density profiles of the form

$$\rho(r) = \frac{\rho_s}{\tilde{r}(1+\tilde{r})^{3-\gamma}} \quad (4)$$

where ρ_s is the characteristic density, $\tilde{r} = r/r_s$ and r_s is the scale radius. For this analysis, we will only consider the case of a moderate Navarro-Frenk-White (NFW) [37] cuspy profile given by $\gamma = 1$. To compute the astrophysical factor for each dwarf, we substitute the values of r_s and ρ_s as given in Table I into Eq.(4) and compute $J^{NFW}(\Delta\Omega = 8.6\ 10^{-5}\mathrm{sr})$ from Eq.(3). Here $\Delta\Omega = 8.6\ 10^{-5}$ sr corresponds to a solid angle of 0.3^o from which the main DM signal is expected from the selected dSphs.

Using the DarkSUSY package [38], Eq.(1) and 95% upper limits given in Section III, upper limits on the annihilating cross sections $< \sigma v >$ have been derived for each dSph. Fig.2 shows how our sensitivity can be compared with the mSUGRA predictions in the (m_{wimp},$< \sigma v >$) plane. All plotted models are consistent with all accelerator constraints and red points are also compatible with WMAP data. Fixing a 1/E spectrum in the upper limit determination, as suggested in [39], dramatically improves the flux limits for 3 months of data by about a factor of 10 over what is shown in Table II.

IV. Conclusions and final remarks

Fermi has been in routine science operations since August 11th, 2008. In this letter, we have reported the observations of γ-ray emission from 10 known dwarf

spheroidal galaxies by Fermi/LAT. No excesses have been observed in LAT data and preliminary upper limits have been derived.
Flux boost factors of the models shown in Fig.2 of about two orders of magnitude are required even in the most optimistic scenario to match our upper limits. However, uncertainties in the DM distributions (e.g., presence of substructure in the halo) may significantly reduce this boost estimate. Future observations will likely allow us to slightly improve the derived upper limits and updated results will be presented at the conference.

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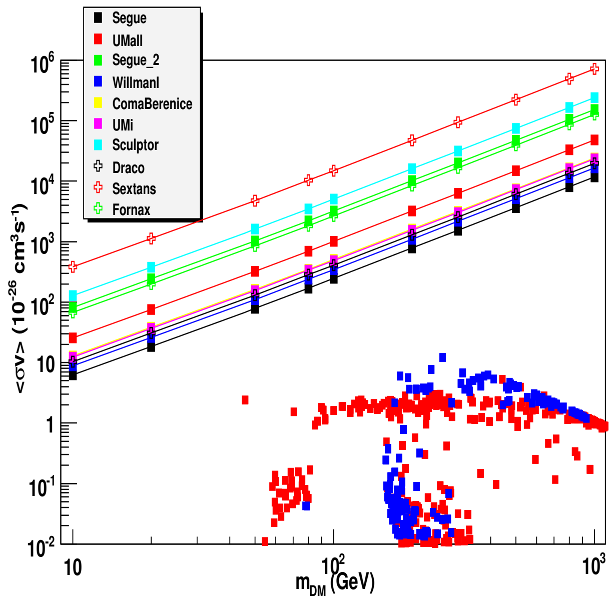

Fig. 2: mSUGRA models in the ($m_{\rm wimp}$,$<\sigma v>$) plane. All plotted models are consistent with all accelerator constraints and red points are also compatible with WMAP data. The lines indicate the Fermi 95% upper limits obtained from likelihood analysis on the selected dwarfs given in Table I.

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