A search for possible dark matter subhalos as IACT targets in the First *Fermi*-LAT Source Catalog

D. Nieto[†], V. Martínez, N. Mirabal, J. A. Barrio, K. Satalecka, S. Pardo, & I. Lozano
Dpto. Física Atómica, Facultad CC. Físicas, Universidad Complutense de Madrid, E-28040, Spain
([†]E-mail: nieto@gae.ucm.es)

We present a systematic search for potential dark matter subhalos in our Galaxy among the 630 unassociated sources included in the First *Fermi*-LAT Source Catalog. Assuming a hypothetical dark matter particle that could generate observable gamma-ray photons beyond the *Fermi* energy range through self-annihilation, we look for reasonable targets for ground-based Imaging Atmospheric Cherenkov Telescopes at energies $E > 100$ GeV. In order to narrow the origin of these enigmatic sources, we look for their possible counterparts in other wavelengths including X-ray, radio, and optical spectroscopy. We find that the synergy between *Fermi* and Cherenkov telescopes, along with multiwavelength observations, could play a key role in indirect searches for dark matter.

1. Introduction

A gamma-ray signal in the very high energy (VHE) regime from dark matter (DM) particle annihilation would be characterized by a very distinctive spectral shape due to features such as lines [Bertone et al. 2009], and internal bremsstrahlung [Bringmann et al. 2008], as well as a characteristic cut-off at the DM particle mass. The DM spectrum must be universal; hence a possible smoking-gun for DM would be the detection of several gamma-ray sources, all of them sharing identical spectra [Lee et al. 2009]. No DM signal has been detected so far in any of the most promising DM targets, including dSph galaxies [Aleksic et al. 2011], the Galactic Center [Abramowski et al. 2010], and clusters of galaxies [Aleksić et al. 2010]. Yet, there might be additional regions with high DM density.

High resolution simulations indicate that DM halos must exhibit a wealth of substructure on all resolved mass scales [Diemand et al. 2008, Stadel et al. 2008] (see Figure 1). These subhalos could be too small to have attracted enough baryonic matter to start star-formation and would therefore be invisible to past astronomical observations [Pieri et al. 2008] but most probably visible at HE and VHE via annihilation of weakly interacting massive particles (WIMP). Since DM emission is expected to be non variable in time, such hypothetical sources would appear in the all-sky monitoring programs [Kamionkowski et al. 2010], and thus could be detected by the *Fermi* satellite telescope as unassociated *Fermi* objects (UFOs) not detected at any other wavelengths. As mentioned above, a potential indicator of DM detection could be a distinct cut-off close to the DM particle mass. In the neutralino framework [Jungman et al. 1996], such a cut-off would be likely located at energies where *Fermi* is not sensitive enough [Amsler et al. 2008]. Therefore, the synergy between *Fermi* and imaging atmospheric Cherenkov telescopes (IACTs) appears as a natural way to attack this problem, since IACTs are more sensitive at VHE.

Figure 1: Via Lactea II simulation of a Milky Way-sized DM halo where rich DM substructure emerges. DM subhalos could be close enough to be detectable in the gamma-ray range. Extracted from Diemand et al. [2008]

2. Selection of Dark Matter Subhalo Candidates

The First *Fermi*-LAT catalog [1FGL Abdo et al. 2010] consists of 1451 sources with 630 unassociated with any known type of feasible gamma-ray emitter (see Figure 2). The collection of possible DM subhalo candidates out of the 1FGL starts with a selection of UFOs based on spectral characteristics, time variability, possible associations, and location in the sky. To qualify as a candidate, the sources are required to meet the following criteria:

- A location outside the Galactic Plane.
  The majority of the UFOs are located in the

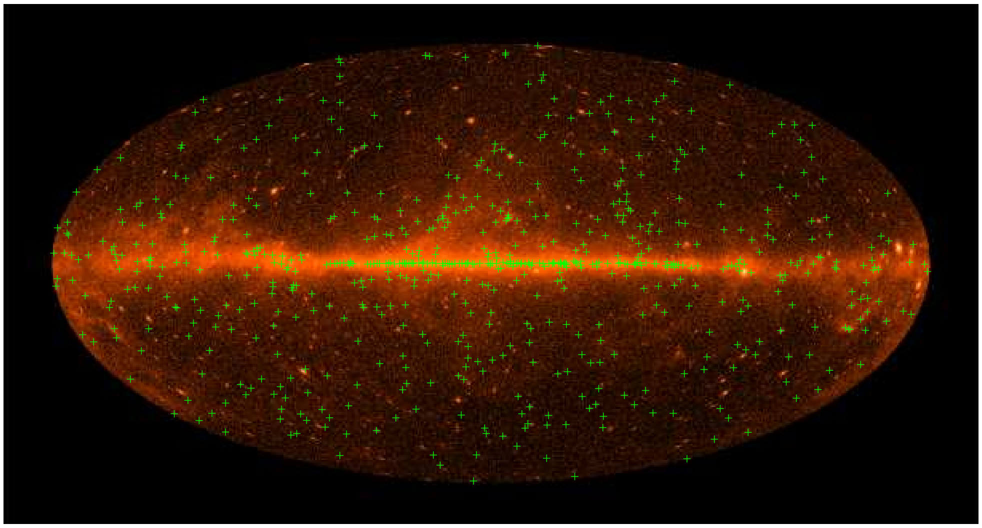

Figure 2: All-sky *Fermi* Aitoff projection of photons above 10 GeV (Galactic coordinates). Green crosses indicate the nominal position of the 630 UFOs. As clearly seen, the bulk of UFOs is located in the Galactic plane.

Galactic plane, where an overwhelming fraction of conventional galactic objects are found (pulsars, pulsar wind nebulae, supernova remnants, binary systems, etc). On the other hand, the galactic DM substructures present an homogeneous distribution in galactic latitude [Diemand et al. 2008, Springel et al. 2008]. The association algorithms are not very efficient in very crowded environments and unassociations due to an excess of candidates are likely. On top of that, the galactic diffuse gamma-ray background is stronger close to the Galactic plane, making *Fermi* data analysis much difficult up to the extent that the statement of detection of some faint UFOs, nearby or within the Galactic Plane, depends on the assumed galactic gamma-ray background model. Consequently, in case some UFOs are actual DM clumps, the chances of ordinary object contamination in the final selection would be much higher if low galactic coordinate objects are considered. As a conclusion, UFOs with galactic latitudes $|b| < 10\,\mathrm{deg}$ were rejected.

- Hardness.
  The expected spectral shape from WIMP annihilation, which essentially follow the shape of the annihilation photon yield, is hard until the WIMP mass cut-off [Cembranos et al. 2011]. Moreover, 1FGL sources presenting hard spectra are more likely to be detected by IACTs. Therefore, only hard sources were selected, meaning that 1FGL sources with spectral fitting power law indices $\Gamma < 2$ were considered.

- Non variability.
  The photon flux from DM annihilation must be constant over time, thus variable sources must be rejected. The 1FGL provides a *variability index* for each source. The corresponding light curve is significantly different from a flat one if that index is greater than 23.21. Therefore, sources whose *variability index* surpasses that limit were discarded.

- Spectral behavior.
  In the SUSY DM framework, the neutralino has a mass lower limit of ~ 50 GeV [Jungman et al. 1996]. Thus, the energy cut-off of its annihilation spectrum must lay above that energy. As such, the spectrum within the *Fermi* energy range must be well described by a single power law [Bertone et al. 2006]. In order to quantify departures from a power law spectra, the 1FGL includes the so called *curvature index*. When the value of that index is greater than 11 it means that the spectrum of the source deviates from a power law. Consequently, sources with a *curvature index* surpassing that limit were discarded.

Out of the total 630 UFOs only 93 of them fulfilled the before mentioned criteria.

3. Possible counterpart search

For each candidate from the above mentioned subset of sources, we conducted an extensive counterpart search for possible associations. The main astronomical catalogs and mission archives were explored around the 1FGL nominal positions with a conservative 20 search radius, corresponding to twice the *Fermi* PSF at 10 GeV [Burnett et al. 2009]. The search, performed with the help of the NASA's High Energy

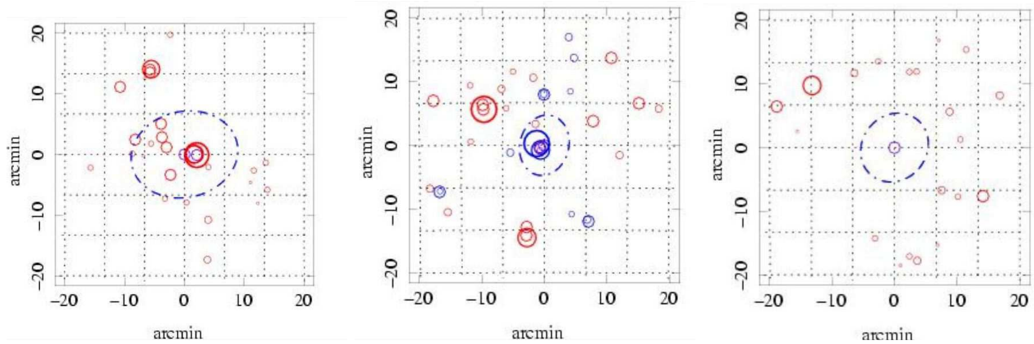

Figure 3: $40' \times 40'$ regions centered in some representative sample of unassociated *Fermi* objects out of the catalog selection. The purple circles are centered in *Fermi* nominal position, surrounded by a dot-dashed line representing its 95% error region. Left-most and center sources were discarded since bright radio or X-ray sources were present within their error regions. The right-most field qualifies it as a candidate. Red, blue, and purple circles depict radio, X-ray and gamma-ray sources respectively. The maps, in equatorial coordinates, were generated with the ASDC Data Explorer [ASI 2011].

Astrophysical Archive [NASA 2011a], scrutinized the archives from current and past gamma-ray missions like AGILE, INTEGRAL, CGRO, HETE-2, COS-B; X-ray missions like ROSAT, *Chandra*, XMM-*Newton*, *Swift*, *Suzaku*, RXTE; and radio catalogs including the NRAO VLA Sky Survey, *Green Bank* Survey, FIRST Survey. Infrared and ultraviolet missions archives like *Spitzer*, IRAS, FUSE, and GALEX were also considered. The purpose of this search is to discard sources whose *Fermi* gamma-ray flux could be eventually attributed to an already detected conventional source. In this way a set of unassociated sources, i.e. sources with no potential counterparts in their *Fermi* error region, was obtained. In order to illustrate the results of the search some examples of $40' \times 40'$ regions centered in different UFOs are shown in Figure 3 for both selected and discarded sources.

After the dedicated search only 23 out of the previous 93 UFOs surviving the catalog selection were left. *Swift*-XRT data [Donato et al. 2010] were publicly available for all these 23 sources and were analyzed. UFOs containing X-ray sources within *Fermi* error contour in *Swift*-XRT data were consequently discarded. Finally, only 10 UFOs out of the previous 23 sources, qualified as candidates.

4. Final List

As a final step we rank the 10 sources based on the number of high-energy *Fermi* photons ($E_\gamma > 10$ GeV). This number is a crucial quantity that provides evidences for a possible extrapolation of *Fermi* fluxes beyond the IACTs energy thresholds.

Fermi data for all these 10 sources were analyzed using the latest version of *Fermi* `ScienceTools` [NASA 2011b]. The best suited event selection quality cuts for off-plane point source analysis were applied by means of the `gtselect` tool, namely, event class 3 and 4 were considered for photons below 20 GeV and class 4 beyond that energy, a maximum zenith angle cut of 105° was applied and the latest Instrument Response Functions (*Pass6_v3*) were considered. Regarding the time selection, performed with the `gtmktime`, only good time intervals were considered. On top of that, photons arriving when the satellite was crossing the South Atlantic Anomaly were discarded as well as those recorded at a rocking angle greater than 45°. Regions of interest-based zenith angle cuts were also applied. A circular region corresponding to 1.5 times the *Fermi* PSF radius at 10 GeV (0.15°) centered on the source nominal position was examined in order to get the high-energy photons likely to have been emitted by the source. The diffuse high-energy gamma-ray background at high galactic latitudes is expected to be almost negligible. The background contribution to the total number of photons extracted from the 0.15° radius region was estimated to span from ~ 0.2 to ~ 0.8 photons, depending on the source. Attending to the estimated number of background photons in the extraction region, it is clear that, for most of the selected UFOs, the majority of extracted high-energy photons are unlikely to be background photons. The list of photons per source is found in Table I.

We posit that this list can serve as a source pool for follow-up observations with IACTs. In particular, experiments such as MAGIC [The-MAGIC-Collaboration 2011] hold a clear advantage based on outstanding response at low energies (E $<$ 150 GeV) that best overlaps with the *Fermi* energy range. This list could also serve to consider the prospects with future IACT experiments.

Table I *Fermi*-LAT photons as of February 2011. Reprocessed data (P6_V3_DIFFUSE) were considered.

Candidate	*Fermi*-LAT photons over 10 GeV
UFO I	12.7, 14.0, 14.2, 18.2, 22.3, 23.7, 29.1, 133.5
UFO II	15.6, 45.7, 20.4, 29.2, 86.8, 101.1
UFO III	14.5, 14.6, 22.4, 35.4, 42.5, 58.3
UFO IV	10.6, 24.4, 25.5, 49.2
UFO V	10.0, 10.6, 12.7, 27.0
UFO VI	43.7, 45.4, 171.5
UFO VII	15.4, 18.0, 43.1
UFO VIII	18.6, 71.8
UFO IX	19.0, 25.0
UFO X	13.8, 17.0

5. Summary & Outlook

We have presented a method to select possible dark matter subhalos candidates among unassociated *Fermi* objects. While there is no guarantee that the selected candidates are *bona fide* dark matter subhalos [Mirabal et al. 2011], the method presented here will help to highlight peculiar objects in the sky.

With the recently released results by *Fermi* , the next natural step will be the application of the method to the 2FGL. We should then consider the detection prospects of these sources with current IACTs such as MAGIC and H.E.S.S. [The-H.E.S.S.-Collaboration 2011], as well as with the next generation of IACTs, namely the Cherenkov Telescope Array [The-CTA-Consortium 2010].

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