A SEARCH FOR POSSIBLE DARK MATTER SUBHALOS AS IACTS TARGETS IN THE FIRST FERMI LAT SOURCE CATALOG

D. Nieto, V. Martínez, N. Mirabal, J.A. Barrio, S. Pardo

Dpto. Física Atómica, Facultad C.C. Físicas, Universidad Complutense de Madrid, Spain.

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. We obtain a list of reasonable targets for ground-based Imaging Atmospheric Cherenkov Telescopes at energies E > 100 GeV.

Abstract.- 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.

DARK MATTER SUBHALOS

A γ-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 [1], and internal bremsstrahlung [2], as well as a characteristic cut-off at the DM particle mass. Even if one can accommodate all these features in a single measured spectrum, not much could be said about the real nature of the DM particle. The DM spectrum must be universal; hence a possible smoking-gun for DM would be the detection of several γ-ray sources, all of them sharing identical spectra [3]. No DM signal has been detected so far in any of the most promising DM targets including dSph galaxies [4], the Galactic Center [5], and clusters of galaxies [6]. 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 [7,8] (see Fig. 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 [9] but most probably visible at HE and VHE in the context of annihilating 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 [10], and thus could be detected by the *Fermi* satellite telescope as unassociated *Fermi* objects (UFOs), *i.e.* not detected at any other wavelengths (see Fig. 2). 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 [11], such a cut-off would be likely located at energies where *Fermi* is not sensitive enough [12]. 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.

Fig 1.- Via Lactea II simulation of a Milky Way-sized DM halo where a rich substructure emerges. Subhalos could be close enough to be detectable at the γ-ray range.

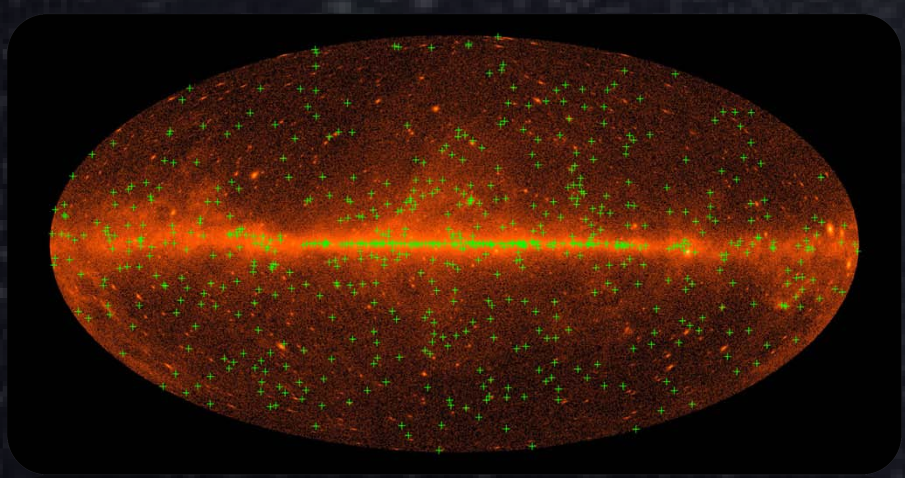

Fig 2.- All sky Fermi Aitoff projection of photons above 10 GeV (Galactic coordinates). Green crosses indicate the nominal position of the 630 unassociated Fermi objects.

SELECTION OF CANDIDATES

The collection of possible DM subhalo candidates out of the First *Fermi-LAT* Source Catalog (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.***
  Most UFOs are found in the Galactic Plane where the majority of sources are expected to be conventional baryonic sources like pulsars, pulsar wind nebulae, supernova remnants, and binary systems. Therefore, all UFOs with $|b| < 10º$ were rejected.
- ***Hardness.***
  The photon yield from *neutralino* DM annihilation is expected to follow a hard spectrum up to the *neutralino* mass cut-off [13]. Additionally, hard sources are more likely to be detected by IACTs beyond the *Fermi* upper energy threshold. Only sources with *spectral indices* < 2 were considered.
- ***Non variability.***
  The photon flux from dark matter annihilation must be constant over time, thus variable sources should be rejected. Sources with *variability index* (VI) larger than 23,21 were discarded.
- ***Spectral behavior.***
  In the SUSY DM framework, the neutralino has a mass lower limit of ~50 GeV [11] so that the energy cut-off must lay above that energy. As such, the spectrum within the *Fermi* energy range must be well described by a single power law [14]. Consequently, sources with a *curvature index* (CI) greater than 11 were discarded.

93 OUT OF 630 UFOS WERE SELECTED

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 [15]. The search, performed with the help of the *NASA's* High Energy Astrophysical Archive [16], scrutinized the archives from current and past γ-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* γ-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.

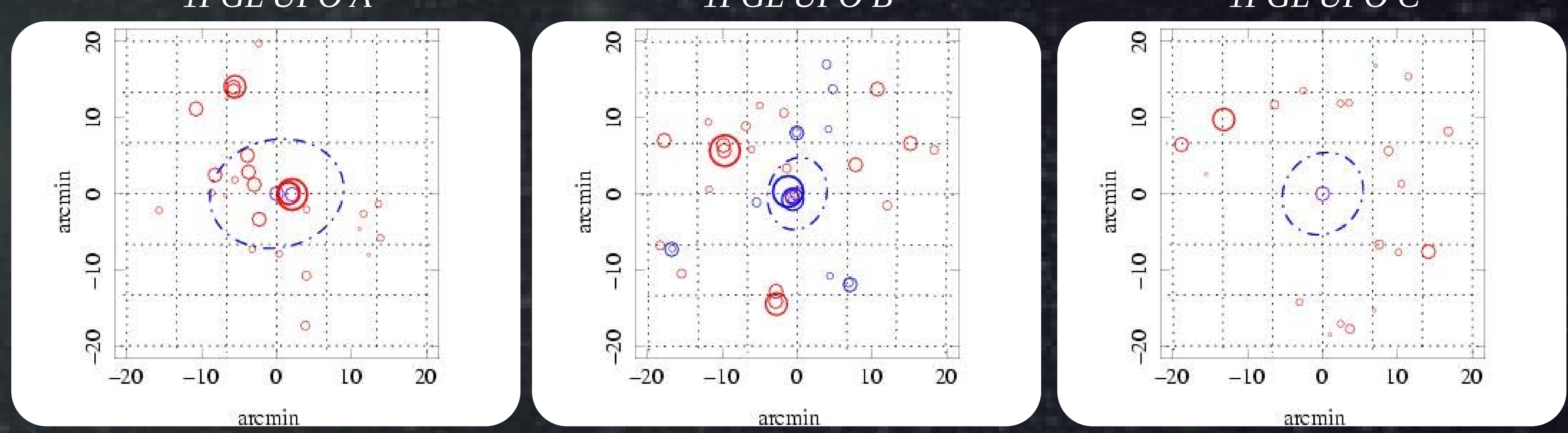

Fig. 3.- Examples of 40'x40' regions centred in three different UFOs. 1FGL UFO A and B were discarded since bright radio or x-ray sources were present within their error regions (dot-dashed lines). 1FGL UFO C qualifies as a candidate. Red , blue, and purple circles depict radio, X-ray and γ-ray sources respectively. The maps (equatorial coordinates) were generated with the ASDC Data Explorer [17].

After the dedicated search only 23 out of the previous 93 UFOs surviving the catalog selection were left. *Swift-XRT* data were publicly available for these 23 [18] 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.

10 OUT OF 93 UFOS WERE SELECTED

FINAL LIST

As a final step we rank the 10 sources based on the number of clean high energy *Fermi* events (see Table 1). We posit that this list can serve as a source pool for follow-up observations with IACTs. In particular, experiments such as *MAGIC* [19] 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.

Candidate	Fermi photons over 10 GeV
1FGL UFO I	12.7, 14.0, 14.2, 18.2, 22.3, 23.7, 29.1, 133.5
1FGL UFO II	15.6, 45.7, 20.4, 29.2, 86.8, 101.1
1FGL UFO III	14.5, 14.6, 22.4, 35.4, 42.5, 58.3
1FGL UFO IV	10.6, 24.4, 25.5, 49.2
1FGL UFO V	10.0, 10.6, 12.7, 27.0
1FGL UFO VI	43.7, 45.4, 171.5
1FGL UFO VII	15.4, 18.0, 43.1
1FGL UFO VIII	18.6, 71.8
1FGL UFO IX	19.0, 25.0
1FGL UFO X	13.8, 17.0

Table 1.- Fermi *photons as of February 2011. Reprocessed data (P6_V3_DIFFUSE) were considered.*

SUMMARY & OUTLOOK

We have presented a method to select possible DM subhalos candidates among *Fermi* UFOs. 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 *HESS* [20], as well as with the next generation of IACTs, namely the *Cherenkov Telescope Array* (*CTA*) [21].

REFERENCES

[1] Bertone *et al*., Phys.Rev. D80 (2009) 023512; [2] Bringmann *et al*., JHEP 0801 (2008) 049; [3] Lee *et al*., JCAP 0907 (2009) 007; [4] Aleksic *et al*., astro-ph.HE:1103.0477; [5] Abramowski *et al*., astro-ph.HE:1103.3266; [6] Aleksic *et al*., Astrophys. J. 710 (2010) 634-647; [7] Kuhlen *et al*., J.Phys.Conf.Ser. 125 (2008) 012008; [8] Stadel *et al*., astro-ph/0808.2981; [9] Pieri *et al*., MNRAS 384 (2008) 1627; [10] Kamionkowski *et al*., Phys.Rev. D81 (2010) 043532; [11] Jungman *et al*., Phys. Rep. 267 (1996) 195; [12] Amsler *et al*., Phys. Lett. B667 (2008) 1-1340; [13] Cembranos *et al*., Phys.Rev.D (2011) 83:083507; [14] Bertone *et al*., astro-ph/0612387; [15] Burnett *et al*., astro-ph.HE/0912.3855; [16] http://heasarc.gsfc.nasa.gov; [17] http://www.asdc.asi.it; [18] Donato et al., Bulletin of the AAS (2010) 42, 671; [19] wwwmagic.mppmu.mpg.de; [20] http://www.mpi-hd.mpg.de/hfm/HESS; [21] http://www.cta-observatory.org

The authors acknowledge the support of the Spanish MICINN Consolider-Ingenio MULTIDARK CSD2009-00064. N.M. gratefully acknowledges support from the Spanish MICINN through a Ramón y Cajal fellowship.