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## The search for galactic dark matter clump candidates with Fermi and MAGIC

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**Abstract:** We present a systematic search for potential dark matter clumps in our Galaxy among the 630 unassociated sources included in the LAT 1-year Point Source Catalog. Assuming a dark matter particle that generates observable gamma-ray photons beyond the Fermi energy range through self-annihilation, we compile a list of reasonable targets for the MAGIC Imaging Atmospheric Cherenkov Telescopes. In order to narrow down the origin of these enigmatic sources, we summarize ongoing multiwavelength studies including X-ray, radio, and optical spectroscopy. We report on observations of two of these candidates using the MAGIC Telescopes. 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.

**Keywords:** Indirect dark matter searches. Very high energy gamma-rays. MAGIC. Unassociated Fermi Objects.

## 1 Introduction

The concordance cosmological model, thoroughly validated by measurements, requires 83% of the total mass density in the Universe to be non-baryonic [1]. Thus, the identification of this so-called *dark matter* (DM) is one of the most relevant issues in Physics today. Assuming that DM is composed by weakly interacting massive particles (WIMP), which could annihilate or decay into standard model particles, its nature can be unraveled by the detection of these by-products. This is the principle of indirect detection searches carried out in the  $\gamma$ -ray regime.

A  $\gamma$ -ray signal from DM annihilation would be characterized by a very distinctive spectral shape due to features such as annihilation lines [2] and internal bremsstrahlung [3], as well as a characteristic cut-off at the DM particle mass. In order to shed light over the nature of the DM constituent the detection of several sources sharing the same DM-like spectrum is mandatory, since the DM spectrum must be universal [4]. Astrophysical regions where high DM density is foreseen are the best candidates to search for DM originated  $\gamma$ -ray emission. No DM signal has been detected so far in any of the most promising targets, including dwarf spheroidal galaxies [5], galaxy clusters [6] or the Galactic Center [7].

Yet, there exist other possible regions of high DM density. Most recent cosmological N-body high-resolution simulations [8] indicate that DM halos should not be smooth but must exhibit a wealth of substructure on all resolved mass scales [9]. These subhalos could be too small to have attracted enough baryonic matter to start star-formation and would therefore be invisible to past and present astronomical observations. Overdensities or clumps are foreseen into these subhalos which can be nearby in our galaxy and therefore bright at  $\gamma$ -rays [10]. Also DM high density regions can develop around intermediate massive black holes where a rather peaked  $\gamma$ -ray emission is predicted [11]. These clumps would most probably only be visible at very high energies (VHE) and therefore may not have shown up in any catalog yet.

Since  $\gamma$ -ray emission from DM annihilation is expected to be constant, DM clumps would pop-up in all-sky monitoring programs [12]. This can be best provided by the Fermi satellite telescope<sup>1</sup> as *unassociated Fermi objects* (UFOs) not detected at any other wavelengths. Very likely, the distinct spectral cut-off at the DM particle mass is located at too high an energy (see, e.g. the *neutralino* mass lower limits in [13]) to be measurable by Fermi within reasonable time and can only be limited by IACT observations.

1. <http://fermi.gsfc.nasa.gov/>

## 2 Candidates Search

The First Fermi-LAT Catalog (1FGL) contains 1451 high energy  $\gamma$ -ray sources detected by the LAT instrument after the first 11 months of the science phase of the mission [14]. For each source, positional and spectral information are provided as well as identification or possible associations with cataloged sources at other wavelengths. Although Fermi-LAT has a good angular resolution, a firm identification based on positional coincidence alone is not always feasible. Thus, 630 sources in the 1FGL lack any clear association. These are the so-called unassociated Fermi objects (UFOs), a population among which DM clumps might be represented [15].

### 2.1 Selection Criteria

In order to extract possible DM clump candidates out of the 1FGL UFOs the following selection criteria were required:

- To lay outside the Galactic Plane.

A noteworthy fraction of galactic baryonic objects are found in the Galactic Plane, unlikely the galactic dark matter substructures whose galactic latitude distribution is homogeneous [9]. Source association in a very crowded environment is more difficult for the Fermi association algorithms. Thus associations due to an excess of candidates are more likely. Moreover, the galactic diffuse  $\gamma$ -ray background is much stronger at low galactic latitudes. Consequently, UFOs with galactic latitudes  $|b| < 10^\circ$  were discarded.

- To be a hard source.

The expected spectrum from WIMP annihilation essentially follows the shape of the annihilation photon yield, which has been shown to be hard up to the WIMP mass cut-off [16, 17]. Additionally, 1FGL sources showing hard spectra are more likely to be detected by IACTs beyond the Fermi upper energy threshold. Therefore only hard sources were selected, meaning that 1FGL sources whose spectral fitting power law index was above 2 were discarded.

- To be non-variable.

The photon flux from dark matter annihilation must be constant, thus variable sources were rejected. Sources with a 1FGL *variability index* showing the lightcurve to deviate from a flat one were discarded.

- To follow a power law spectra.

DM spectra show prominent cut-offs at the DM particle mass. Sufficiently away from the cut-off the spectra can be well described by a power law (see *e.g.* the asymptotic behavior of spectra in [16]). Thus, assuming that the cut-off lays beyond Fermi energy range, sources departing from a power law spectral fit (information which is provided by the 1FGL *curvature index*) were rejected.

- Not to have possible counterparts.

An extensive and independent search for possible associations was performed for each UFO through the NASA's

High Energy Astrophysical Archive<sup>2</sup>. The main astronomical catalogs and missions archives, from  $\gamma$ -ray to radio, were explored around the sources 1FGL nominal positions with a 20' conservative search radius corresponding to twice Fermi PSF at 10 GeV [18], and UFOs with possible counterparts were discarded. Also Swift-XRT data from several high galactic latitude UFOs [19] were made public recently. After analyzing these data, UFOs containing Swift-XRT X-ray sources within their Fermi error contour were consequently discarded. The purpose of this search was not to associate nor to identify counterparts for 1FGL sources, but to conservatively discard objects whose Fermi  $\gamma$ -ray flux could be eventually attributed to an already detected source.

After all these criteria, the candidate search finally provided 10 possible DM clumps out of the 630 initial UFOs.

### 2.2 IACTs Detection Prospects

A signal detection in the IACT context is defined as a more than  $5\sigma$  deviation of the excess events over the background events. If the total number of observed events is expressed in terms of their rates as  $N_{on} = (R_{exc} + R_{bkg})t$  and  $N_{off} = \kappa R_{bkg}t$ , were  $t$  is the observation time, and the on-off ratio is assumed to be  $\kappa = 1$ , the detection time can then be estimated working out Eq. 5 from Li and Ma [20]. The excess rate  $R_{exc}$  over a certain energy threshold  $E_{th}$  can be computed from the effective area of the instrument, and the differential spectrum of the source. The characteristic background rate of the instrument is computed from Monte Carlo simulations.

For this work, the MAGIC Telescopes<sup>3</sup> effective area and background rate were considered. The very high energy UFO spectra were directly extrapolated from the 1FGL Catalog, evaluating also the impact of the uncertainties in the Fermi spectral parameters over the detection time. The adopted  $E_{th}$  was 100 GeV, a conservative one already achieved by MAGIC single telescope observations.

Fermi data were studied for all these 10 sources using the latest version of the Fermi `ScienceTools` [21]. The total number of high energy photons (HE,  $E_\gamma > 10$  GeV) is a determinant quantity since it provides an evidence of the validity of the Fermi spectra extrapolation. Therefore, HE photons from a circular region of 1.5 times Fermi PSF radius ( $0.15^\circ$ ) were extracted in order to get the events likely to have been emitted by the source (the contribution from diffuse HE  $\gamma$ -ray background in each source position was estimated from actual data to be almost negligible).

Finally, the estimated detection time, and the list of Fermi HE photons, were used to sort the 10 candidates attending to their feasibility of detection: sources were ordered as a function of their estimated detection time, although the effect of the spectral parameters uncertainties was taken into consideration, giving lower priority to those whose uncer-

2. <http://heasarc.gsfc.nasa.gov/>

3. <http://wwwmagic.mppmu.mpg.de/>

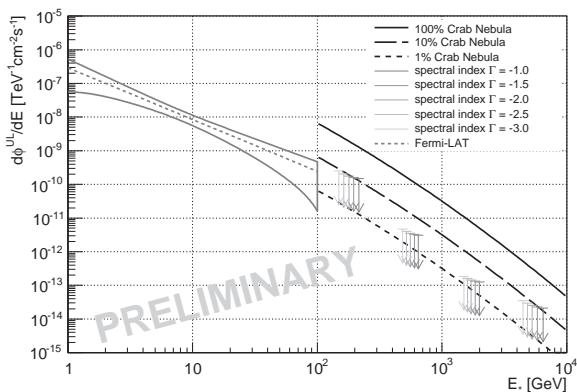


Figure 1: 1FGL J2347.3+0710 Fermi-LAT differential spectrum and preliminary MAGIC differential spectrum upper limits. MAGIC Crab Nebula spectrum [24] is depicted as reference.

tainties were larger; in case of similar estimated detection times, sources with a larger Fermi HE photons population were given higher priority.

### 3 MAGIC Observations

MAGIC consists of a system of two telescopes operating in stereoscopic mode since fall 2009 at the Canary Island of La Palma (28.8° N, 17.8° W, 2200 m a.s.l.). Only 6 out of the 10 selected DM clump candidates can be observed from MAGIC latitude under reasonable zenith angle conditions. So far, the two best candidates, namely, 1FGL J2347.3+0710 and 1FGL J0338.8+1313, have been observed under dark night conditions and lowest zenith angle range possible. Both conditions are needed when the sensitivity at low energies is pursued. The sources were surveyed in false tracking mode [22]. In the two cases, data were analyzed in the MARS analysis framework by means of the standard stereoscopic analysis routines [23]. Contemporaneous Crab Nebula data were used to verify the proper performance of the telescopes and analysis routines.

#### 3.1 1FGL J2347.3+0710 Observations

The observation of 1FGL J2347.3+0710 were performed during October and November 2010. The zenith angle window ranged from 21.5° to 30.0°. The total exposure time was 13.3 h. After data quality selection the exposure time reduced down to 8.3 h.

No signal was found over the background. Considering an energy threshold of 100 GeV the number of excess events was  $N_{exc}(> 100 \text{ GeV}) = 98 \pm 86$  events which translates into a significance of  $1.1\sigma$ , computed using Eq. 17 from Li and Ma [20]. Consequently, we derived upper limits (ULs) to the differential and integral spectra following the prescriptions from [5]. The integral ULs for different energy thresholds and power law spectra are found in Table 1. The

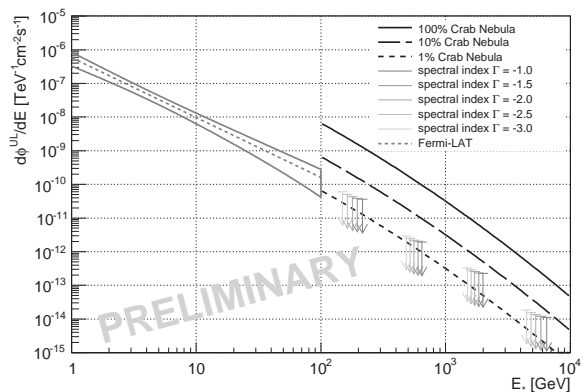


Figure 2: 1FGL J0338.8+1313 Fermi-LAT differential spectrum and preliminary MAGIC differential spectrum upper limits. MAGIC Crab Nebula spectrum [24] is depicted as reference.

differential ULs are presented in Fig. 1, together with the corresponding 1FGL Catalog Fermi spectrum and its error band (computed as in [25]).

#### 3.2 1FGL J0338.8+1313 Observations

In the case of 1FGL J0338.8+1313 the observations were performed from December 2010 to January 2011. The zenith angle window covered the interval from 15.5° to 30.5°, again ensuring a low energy threshold. Data were taken for a total observation time of 15.5 h which reduced to 10.7 h after data quality selection. As in the previous case, no signal was detected over the background. The excess events above an energy threshold of 100 GeV were  $N_{exc}(> 100 \text{ GeV}) = -81 \pm 84$ , producing a significance of  $-1.0\sigma$ . The integral ULs, extracted as already described, can be found in Table 1. MAGIC differential ULs as well as Fermi spectrum with its error band are found in Fig. 2

### 4 Discussion & Conclusions

A dedicated search designed to select possible DM clump candidates out of the 1FGL Catalog has been presented, concluding with 10 candidates out of the 630 UFOs. After studying the prospects of detection for each of these 10 sources, the two best candidates were observed by the MAGIC Telescopes.

Although no very high energy  $\gamma$ -ray signal was detected for any of them, competitive upper limits to the differential and integral spectra were obtained.

It can be seen from Fig. 1 that a direct extrapolation of 1FGL J2347.3+0710 Fermi spectrum above 400 GeV is ruled out by MAGIC observations, meaning that some kind of cut-off or spectral curvature may be taking place at energies between 100 and 400 GeV. In the case of 1FGL J0338.8+1313, as illustrated in Fig. 2, one can conservatively rule out a direct extrapolation of Fermi spectrum

Table 1: Integral upper limits.

$E_0$ [GeV]	$N_{ON}/N_{OFF}$	$\sigma_{Li, Ma}$	$N_{exc}^{UL}$ 95% C.L.	$\Phi^{UL}$ $\times 10^{-11} [\text{cm}^{-2} \text{s}^{-1}]$				
				$\Gamma = -1.0$	$\Gamma = -1.5$	$\Gamma = -2.0$	$\Gamma = -2.5$	$\Gamma = -3.0$
1FGL J2347.3+0710								
100	3744/3646	1.14	376	16.1	20.8	26.8	31.0	32.6
250	369/372	-0.11	62	2.4	2.6	3.0	3.2	3.3
500	77/92	-1.15	18	0.6	0.6	0.7	0.7	0.7
1000	18/27	-1.34	9	0.3	0.3	0.3	0.3	0.3
1FGL J0338.8+1313								
100	3494/3575	-0.96	119	4.0	5.1	6.6	7.6	8.0
250	346/350	-0.15	59	1.8	2.0	2.2	2.4	2.4
500	81/82	-0.07	30	0.9	0.9	0.9	0.9	1.0
1000	18/19	-0.16	14	0.4	0.4	0.4	0.4	0.4

above 200 GeV. This fact suggests a possible curvature or cut-off at Fermi high energy range.

Nonetheless, these conclusions should be taken *cum grano salis* since they rely on 1FGL spectral information, and must be consequently revisited once the second version of the Fermi Catalog (2FGL) is released.

We expect the synergy between deeper MAGIC observations and the incoming 2FGL Catalog will help us to reveal the actual spectral nature of these two enigmatic objects and the next-to-come in future searches of DM clump candidates.

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