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AGILE γ-ray sources coincident with cosmic neutrino events

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Abstract. Using data obtained by the γ-ray imager on board of the AGILE satellite, we systematically searched for transient γ-ray sources above 100 MeV in temporal and spatial coincidence with high-energy neutrino IceCube events. We found some significant γ-ray transients possibly associated with HESE neutrinos recently detected by the IceCube experiment. In this talk, we review the AGILE results and we will show that the probability of this association to be by chance is very low. One of the sources detected by AGILE is related to the blazar AGN TXS 0506+056. For the other sources, there are no obvious known counterparts.

1 Introduction

The clear observation of an isotropic flux of very high energy (VHE) neutrinos by the IceCube experiment [1] has opened the quest for the identification of their possibile electro-magnetic (EM) counterparts. Up to now, only two extra-terrestrial sources of neutrinos have been clearly identified: the Sun and SN1987a.

Theoretically, it is expected that VHE neutrinos with energies above 10 TeV are produced in cosmic beam dumps where cosmic rays (protons and heavy ions), accelerated via Fermi mechanisms in regions very near to compact objects or at the shock fronts of expanding supernova shells, collide with matter or radiation fields surrounding the central engine or filling an ejected jet of plasma (see [2] for a review). High-energy γ-ray photons above MeV–GeV are expected from neutral pions' decays produced in these proton-proton ($p - p$) or proton-photon ($p - \gamma$) collisions, with flux intensities that may vary depending on the source characteristics and its environment [3].

Active Galactic Nuclei (AGNs) of the blazar category are considered as the main cosmic neutrino source candidates [4]. Contribution from other types of active galaxies (starburst galaxies, radio-galaxies) [5, 6], AGN winds [7] as well as Galactic sources (supernovae remnants expanding in dense molecular clouds, microquasars, hidden compact objects) should also be also taken into account [8].

Observation of transient EM emission, spatially and temporally compatible with the IceCube neutrinos, is crucial to identify their possible counterpart. Since April 2016, the

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IceCube Collaboration alerts the astronomical community whenever a high-energy single neutrino-induced event (HESE/EHE)[1] is detected [9].

Thanks to the IceCube real time system and the fast space- and ground-based observations which followed the alert, a neutrino event recorded by IceCube on Sept. 22nd, 2017, has been significantly associated for the first time to a quasi-simultaneous γ-ray flare from the AGN blazar TXS 0506+056 [10]. Using IceCube archival data, a second strong neutrino flare was observed from the same direction between 2014 and 2015 [11]: the BL Lac TXS 0506+056 has thus been suggested as the first most-likely extra-galactic neutrino source ever observed.

The AGILE γ-ray mission [12] is also contributing to the new-born multi-messenger neutrino astronomy. Thanks to the very large field of view of its main detector, the γ-ray imager GRID, and the spinning observation mode, AGILE is a very suitable instrument for performing searches for short transient γ-ray counterparts to multi-messenger events like the neutrino observed on Sept. 2017.

In what follows, we report about the results of the AGILE search for transient γ-ray sources consistent *in time* and *space* with publicly announced IceCube HESE starting events.

2 AGILE search for γ-ray transient emission consistent with recent public IceCube events

The *AGILE* space mission is devoted to high-energy γ-ray astrophysics in the 30 MeV—30 GeV energy range. After an initial period of pointed observations, since 2009 the satellite has been put in spinning observation mode. In this way, AGILE is capable to image about 70-80% of the whole sky every day, with good sensitivity and angular resolution to γ-rays above 100 MeV[2].

One of the AGILE main astrophysical goal is the rapid identification of transient γ-ray sources over time-scales of a few days. To accomplish this issue, the AGILE Team has developed a very fast ground segment alert system and a robust Quick Look (QL) scientific analysis, which allows to automatically detect significant γ-ray excesses above 100 MeV over time-scales of 1-2 days [14]. This automatic procedure routinely runs daily over predefined AGILE count maps covering 48-hrs of data.

To find γ-ray signals consistent with a sample of 10 public IceCube events published since Apr. 2016[3], we have explored the database of automatic AGILE QL detections searching for transient γ-ray emission with the following characteristics: 1) positionally compatible, within the AGILE angular resolution, with the reconstructed arrival directions of the IceCube HESE/EHE neutrinos; 2) temporally occurring within a fixed search time window of ±4 days around the neutrino event time T_0.

From the DB search[4], we found three significant AGILE detections which satisfy the temporal and spatial association criteria defined above in correspondence of the following three IceCube events: IC-160731, IC-170321, and IC-170922.

Table 1 reports the three AGILE detections and the corresponding identification IceCube parameters (ID and occurence date). For each of them, we estimated the *post-trial probability*

[1]The events are announced through the GCN/AMON network and published at https://gcn.gsfc.nasa.gov/amon_hese_events.html (HESE events) or at gcn.gsfc.nasa.gov/amon_ehe_events.html for the highest energy events (EHE events).

[2]Sensitivity (at 5σ detection level) to γ-ray fluxes above 100 MeV: $(2 \div 3) \times 10^{-6}$ ph cm^{-2} s^{-1} over 2-day integration time intervals. Mean angular resolution (FWHM): 2.5° in the 100—400 MeV energy range; 1.2° in the 400 MeV—1 GeV band [13].

[3]The IceCube neutrinos considered to be most likely background events have been discarded from the search.

[4]Based on the typical AGILE angular resolution, we used the values of 1.0, 1.5, and 2.0 degrees for the database search radius around the initial IceCube input sky positions.

Table 1. The three AGILE QL detections close in time and space to IceCube HESE/EHE neutrinos. Column 1 displays the AGILE name assigned to the transient. Columns 2 and 3 show the main parameters of the corresponding IceCube event (event ID, neutrino event time T_0). Columns 4 to 6 show, respectively, the AGILE γ-ray flux (above 100 MeV) estimated over the QL 2-day integration time bin, the distance in time Δt from the QL detection centroid and T_0, the false alarm rate (FAR) expected for each detection, and the corresponding *post-trial* false alarm probability P_i.

AGILE source	IceCube event	T_0 (MJD)	$F_\gamma(E > 100\ MeV)$ $\times 10^{-6}$ (ph cm^{-2} s^{-1})	Δt (days)	FAR	P_i *post-trial*
A (AGL J1418+0008)	IC–160731	57600.079	(1.8 ± 0.7)	-2.0	5.9×10^{-4}	2.0×10^{-3}
B (AGL J0634–1504)	IC–170321	57833.314	(1.5 ± 0.6)	-2.2	1.5×10^{-3}	5.7×10^{-3}
C (AGL J0508+0459)	IC–170922	58018.871	(1.7 ± 0.7)	-2.8	1.0×10^{-3}	5.0×10^{-3}

that the proximity *in time* and *space* of the AGILE and IceCube events is *by chance*, taking into account the distance in time between the two detections and the AGILE occurence of false detections due to background noise (*false alarm rate* - FAR) [15], directly estimated from ten years of data [16].

Each detection results to have a post-trial false alarm probability P_i of the order of 3 Gaussian equivalent standard deviations. If we calculate the *joint* post-trial probability for the three detection as $P_{joint}(\mathrm{post-trial}) = 1 - (1 - \mathrm{P_A} * \mathrm{P_B} * \mathrm{P_C})^N$ [5], we find that the chance probability to observe an AGILE/IceCube correlation for 3 out of 10 events is around 1.7×10^{-6} (~ 4.7 Gaussian equivalent one-sided standard deviations).

3 Summary

In this contribution, we presented the results of the AGILE observations of the uncertainty regions of a selected sample of IceCube HESE neutrinos announced since April 2016 through the GCN/AMON system. Searching the database of automated AGILE QL detections, we found three significant γ-ray detections above 100 MeV within 1.5 degrees from the IceCube best-fit centroids, occurring within two days from the neutrino event time T_0. We showed that the global post-trial false alarm probability to find 3 out of 10 AGILE/IceCube correlations is quite low ($\sim 10^{-6}$), and significantly hints towards an astrophysical connection between the γ-ray and neutrino events.

In case of IC-170922 (AGILE Source C/AGL J0508+0459), we observed a significant temporal correlation between the neutrino event and the almost simultaneous γ-ray activity in HE and VHE bands observed from the BL Lac type blazar TXS 0506+056 [10]. This is suggestive of this AGN sub-class of blazars being one of the main VHE neutrino emitters from hadronic processes. For the other two cases of possible γ/neutrino correlation, IC-160731/AGL J1418+0008 (AGILE Source A) and IC-170321/AGL J0634–1504 (AGILE Source B), there was not any clear evidence of flaring activity from any known EM source inside the AGILE/IceCube common position uncertainty regions. Searching for possible EM counterparts from existing radio and X-ray source catalogs using the cross-search SSDC tools[6], we identified a new possible HBL candidate[7], within the IC-160731/AGL J1418+0008 error circle: the elliptical galaxy SDSS J141457.72-002058.6 (recently classified as the extreme blazar 3HSP J062753.3-151957 [21]). For IC-170321/AGL J0634–1504, several HBL candidates appear within the IceCube error box, among them the weak γ-ray source 3FGL J0627.9-1517 (also classified as the extreme blazar 3HSP J062753.3-151957 [21]).

[5] N is the number of global trials given by the product of two contributions: the total number of IceCube events considered (10), and the number (3) of optimizations of the AGILE detections DB search radius.

[6] https://tools.ssdc.asi.it

[7] A sub-class of blazars considered as one of the most promising neutrino–emitter candidates [19, 20].

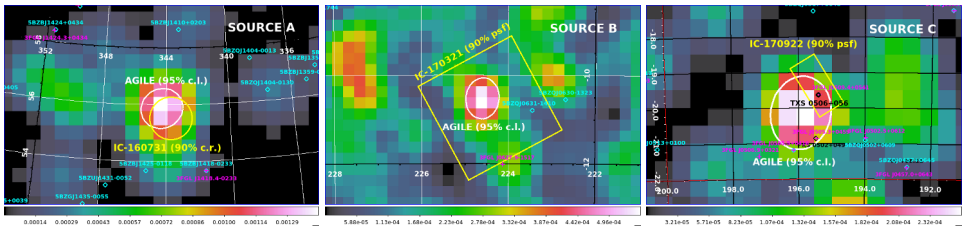

Figure 1. AGILE intensity maps above 100 MeV, in (ph cm^{-2} s^{-1} sr^{-1}) and galactic coordinates, centered at the position of the IceCube events IC-160731 (*left panel*), IC-170321 (*middle panel*), and IC-170922 (*right panel*), for the three AGILE detections A, B and C near the IceCube T_0's. The AGILE 95% confidence level location contours, obtained with the maximum likelihood AGILE analysis [17], are shown in white; the IceCube position uncertainty boxes/circles in yellow. The positions of the classified AGNs from the BZCAT Catalog [22] and the 3FGL γ-ray sources [23] are shown in cyan and magenta colors, respectively.

Given the lack of clear blazar counterparts, the IceCube/AGILE detections for Sources A and B might be explained by different classes of bursting extra-galactic sources (radio-galaxies, starburst galaxies, eruptions from AGN cores, etc.). Moreover, the IceCube neutrino fluxes can be produced by γ-ray hidden sources, where the targets for $p-p$ or $p-\gamma$ absorption processes are highly enhanced due to the high matter/radiation density surrounding the central engine. In such cases of enhanced target density, we might expect then to observe a soft γ-ray component peaking at MeV/sub-GeV due to reprocessing of VHE photons emitted by pions decay. The AGILE detections of γ-ray sources near IC-160731 and IC-170321 indicate the possibility that, from time to time, under particularly favorable conditions, the neutrino source may become transparent to these MeV/GeV γ-rays. AGILE, with its optimized sensitivity to soft γ-ray emission in the 100—400 MeV energy band and fast response to transient events, is thus particularly adapted to observe such softer spectrum sources.

To conclude, this is the first time that evidence of multiple γ-ray sources in close spatial and temporal coincidence with cosmic neutrinos is presented. More simultaneous neutrino and γ-ray events are in any cases needed to strengthen the correlation indicated in the current AGILE data analysis. Continuous blazar monitoring is also needed to confirm the association of BL Lac-type flaring sources with neutrino events. Given the low Galactic latitude of the IC-170321 event ($b = -10.75$ deg), in principle, also galactic sources should be taken into account and included in future searches of EM counterparts to neutrino-emitter.

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