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Search for Gamma-Ray Counterparts of IceCube Neutrino Events in the AGILE Public Archive

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The search for gamma-ray counterparts of IceCube neutrino events is relevant for understanding the role of blazars as possible sources of cosmic neutrinos. We searched for the counterparts of the IceCube neutrinos events observed in the period 2018-2020 in the AGILE gamma-ray satellite public archive. We present the AGILE candidate gamma-ray counterparts found within the IceCube 90% location regions centered on the best-fit neutrino candidate position. We show a selection of light curves and spectral energy distributions, and provide estimates of the gamma-ray flux above 100 MeV for the AGILE candidate detections. The possible associations with blazars are discussed.

Multifrequency Behaviour of High Energy Cosmic Sources XIV (MULTIF2023)
12-17 June 2023
Palermo, Italy

*Speaker

PoS(MULTIF2023)003

1. Introduction

High-energy astrophysical neutrinos, with energies above 10 TeV, are produced in the interaction of cosmic rays through proton-photon (pγ) or proton-proton (pp) processes [1], in association with energetic gamma-rays [2]. Astrophysical high-energy neutrinos have been detected by the IceCube Collaboration [3–10]. The detection of association between the IceCube IC-170922A neutrino event with the blazar TXS 0506+056 [11, 12] has started additional searches for electromagnetic counterparts of high-energy neutrinos.

The favoured candidate sources of high-energy neutrinos are blazars [13–18], contributing to a fraction of the diffuse neutrino flux [19]. Blazars are a subclass of Active Galactic Nuclei where strong and energetic non-thermal radiation is generated [20, 21]. In addition to TXS 0506+056, some other blazars have been suggested as high-energy neutrino sources: PKS 1424+240, GB6 J1542+6129 [22], PKS 0735+178 [23], as well as the nearby active galaxy NGC 1068 [24]. The different blazar sub-classes, LBL, IBL, HBL and extreme blazars [25, 26], are not expected to contribute at the same level [27]. The debate about the neutrino contribution from the sub-classes is still open [18, 28, 29].

The possible correlation of high-energy neutrinos with blazars has been addressed by several authors, see e. g. [28, 30–34]. The emission of high-energy neutrinos is not necessarily associated to a flaring state of the system, as observed in TXS 0506+056, where neutrinos were detected both when the source was undergoing a gamma-ray flare [11, 35, 36] or in a normal state [12]. It has been suggested that the gamma-ray emission could be reduced during neutrino production due to the large $\gamma\gamma$ opacity [37]. Some investigations have performed targeted searches of electromagnetic counterparts of specific neutrino events [38–43]. Other investigations have studied the correlation between neutrino events and source catalogs over different regions of the electromagnetic spectrum, mainly the radio and gamma-ray regions. Some authors have studied the possible association between IceCube neutrinos and radio loud blazars. Radio loud blazars in temporal and spatial coincidence with neutrino emission often show an increase in the radio flux above 10 GHz around the epoch of the neutrino event [44–46]. Radio sources consistent with the direction of neutrino events were found by [47], without being associated to radio flares and often not detected in gamma-rays. The search of gamma-ray counterparts has involved several catalogs: 2FHL [28, 48], 2LAC [29], 3LAC [49], 4LAC [50], 4FGL [51]. A multi-messenger search in the BZCAT and RFC catalogs as been performed by [52].

The present work reports about the search for high energy counterparts of a sample of IceCube neutrino events in the public data archive of the gamma-ray mission AGILE. We will present the neutrino sample in Section 2, followed by a summary of the AGILE mission in Section 3. The analysis tools will be presented in Section 4. The candidate counterparts for a neutrino of the sample will be presented in Section 5.

2. The IceCube neutrino sample

The IceCube detector [53] of high energy neutrinos is located at the Amundsen-Scott base at the South Pole. IceCube is composed of 5160 Optical Modules installed with a spacing of 17 m along 86 strings, with 125 m spacing.

Name	T_0 (MJD)	Type	RA (deg)	DEC (deg)	Energy (10^2 TeV)	Signalness	l (deg)	b (deg)	GCN
IC-180908A	58369	EHE	$144.58^{+1.55}_{-1.45}$	$-2.13^{+0.9}_{-1.2}$	1.1998	0.34364	237.2	35.1	[55]
IC-181023A	58414	EHE	$270.18^{+2.00}_{-1.70}$	$-8.57^{+1.25}_{-1.30}$	1.1998	0.28016	19.4	7.2	[56]
IC-190503A	58606	EHE	$120.28^{+0.57}_{-0.77}$	$6.35^{+0.76}_{-0.70}$	1.0000	0.36266	215.2	18.4	[57]
IC-181014A	58405	HESE	$225.15^{+1.40}_{-2.85}$	$-34.80^{+1.15}_{-1.85}$	-	0.10	331.0	20.9	[58]
IC-190104A	58487	HESE	$357.98^{+2.3}_{-2.1}$	$-26.65^{+2.2}_{-2.5}$	-	0.35	31.6	-76.7	[59]
IC-190124A	58504	HESE	$307.40^{+0.8}_{-0.9}$	$-32.18^{+0.7}_{-0.7}$	-	0.91	10.8	-33.8	[60]
IC-190221A	58535	HESE	$268.81^{+1.2}_{-1.8}$	$-17.04^{+1.3}_{-0.5}$	-	0.37	11.4	4.2	[61]
IC-190331A	58573	HESE	$337.68^{+0.23}_{-0.34}$	$-20.70^{+0.30}_{-0.48}$	-	0.57	36.6	-57.3	[62]
IC-190504A	58607	HESE	65.79	-37.44	-	0.63	239.9	-44.7	[63]
IC-190619A	58653	GOLD	$343.26^{+4.08}_{-2.63}$	$10.73^{+1.51}_{-2.61}$	1.9870	0.54551	81.8	-42.5	[64]
IC-190730A	58694	GOLD	$225.79^{+1.28}_{-1.43}$	$10.47^{+1.14}_{-0.89}$	2.9881	0.67158	11.1	54.8	[65]
IC-190922A	58748	GOLD	$167.43^{+3.40}_{-2.63}$	$-22.39^{+2.88}_{-2.89}$	31.139	0.20165	274.1	34.7	[66]
IC-190922B	58748	GOLD	$5.76^{+1.19}_{-1.37}$	$-1.57^{+0.93}_{-0.82}$	1.8737	0.50501	106.8	-63.6	[67]
IC-191001A	58757	GOLD	$314.08^{+6.56}_{-2.26}$	$12.94^{+1.50}_{-1.47}$	2.1742	0.58898	60.2	20.3	[68]
IC-191119A	58806	GOLD	$230.10^{+4.76}_{-6.48}$	$3.17^{+3.36}_{-2.09}$	1.7648	0.44999	5.5	47.1	[69]
IC-200109A	58857	GOLD	$164.49^{+4.94}_{-4.19}$	$11.87^{+1.16}_{-1.36}$	3.7523	0.76931	237.2	59.3	[70]

Table 1: Public IceCube alerts for EHE, HESE and GOLD candidates issued through the AMON and GCN: candidate id, MJD of event, event type, right ascension, declination, signalness, Galactic longitude and latitude, GCN reference.

The neutrino events detected by Icecube are classified into different categories. The classification started in 2016 devised the EHE (Extremely High Energy) events, with E=500 TeV-10 PeV, and the HESE (High Energy Starting Event) ones, track-like events with interaction vertex inside the detector and E=100 TeV-1 PeV [54]. The updated alert system introduced the GOLD and BRONZE events, according to the value of the signalness, above 50% and above 30%, respectively. The signalness is the probability that the neutrino is of astrophysical origin:

$$Signalness(E, \delta) = \frac{N_{signal}(E, \delta)}{N_{signal}(E, \delta) + N_{background}(E, \delta)} \tag{1}$$

where δ is the declination of the source.

The IceCube neutrino sample considered in this work includes 16 events, from September 2018 to March 2020, including all EHE (3), HESE (6) and GOLD (7) events that have the highest energy and signalness. The neutrino events and the relevant parameters, including the epoch T_0, are reported in Table 1. The order of magnitude of the uncertainty on the position is generally about 90 arcmin, similar to the size of the AGILE Point Spread Function.

In the following, we will discuss in detail a specific event; the full paper is in preparation.

3. The AGILE mission

AGILE (Astrorivelatore Gamma ad Immagini LEggero) is an Italian scientific space mission for high-energy astrophysics funded by the Italian Space Agency (ASI) with scientific and programmatic participation by INAF, INFN, several Italian universities and industrial companies [71]. AGILE, launched on April 23, 2007 is now completing its 16th years of operations in orbit, with satellite operations and all payload functions working nominally.

The AGILE scientific payload is a cube of ~60 cm side, weighting only about 100 kg. It consists of four instruments with independent detection capability: 1) the Gamma Ray Imager Detector (GRID), an imaging gamma-ray silicon tracker sensitive in the energy range 30 MeV–30 GeV; 2) SuperAGILE (SA), a coded mask X-ray imager on top, sensitive in the energy range 18–60 keV; 3) a non-imaging Mini-CALorimeter (MCAL), sensitive in the energy range 350 keV to 100 MeV, that works both as a subsystem for the GRID and as an autonomous detector for transient events; and 4) an Anti-Coincidence system (AC), sensitive in the energy range 50–200 keV, composed of five independent plastic scintillation panels (four lateral and one top).
AGILE is a low-Earth orbit (LEO) satellite in a quasi-equatorial orbit (2.5° inclination), with initial altitude of $\sim$ 500 km. The AGILE data are downloaded at the ASI Ground Station in Malindi (Kenya) and then processed at the AGILE ASI Space Science Data Center (SSDC) [72], delivering data and scientific alerts for transients within 25 minutes - 2 hours since the onboard acquisition.

4. Data analysis tools

4.1 AGILE-LV3

The AGILE public data archive can be accessed using the AGILE-LV3 tool at SSDC[1]. The tool is built on top of the command-line version of the AGILE-GRID standard software package and interactively uses the official on-line Maximum Likelihood analysis on the LV3 data archive. The AGILE data analysis method for detections and upper limits in light curves is based on the Test Statistic (TS) of Maximum Likelihood ratio (ML) used to compare null hypothesis (diffuse background only) with presence of a source. The asymptotic distribution of TS follow the Wilks' theorem [73] and, for N>10-20, the significance of a detection is the number of standard deviations $\sigma = \sqrt{TS}$ [74]. The analysis is performed on pre-compiled maps of exposure, counts and diffuse background integrated over one day. The AGILE analysis produces light curves with bin durations of 2, 4, 7 and 28 days, and the significance of the candidate detections with their Modified Julian Date and flux (photons s^{-1} cm^{-2}). In our work, we have selected detections with significance $\sqrt{TS} \geq 3$.

4.2 VOU-Blazars

The VOU-Blazars Tool [75] is part of the Open Universe Initiative [76] targeted to search blazars in selected sky regions. The tool builds the Spectral Enegry Distribution (SED) and light curves of the found blazars using multi-frequency data from more than fifty catalogs, providing their classification into the HBL, IBL, LBL categories.

5. Results

We have built the AGILE light curves around the neutrino coordinates using the four binning choices (2, 4, 7, 28 days) and searching for candidate detections with $\sqrt{TS}$ >3. We have analyzed the

[1]https://www.ssdc.asi.it/mmia/index.php?mission=agilelv3mmia

light curves around the event T_0 exploring different time intervals: ± 1 month, ± 1 year, full mission, with the purpose of studying the gamma-ray history measured by AGILE and other observatories in that particular sky direction.

We have then searched sources within a radius of 90 arcmin around the reconstructed neutrino direction using the VOU-Blazars tool. We have combined the VOU-Blazars light curves with additional multi-frequency observations to build light curves of candidate counterparts and constructed the SED for classification, to estimate the contribution of different blazar sub-classes to neutrino emission.

We report here in detail the investigation about the HESE neutrino IC-190504A. The AGILE light curves reported in Fig. 1 show the AGILE candidate detections for all time binnings. In this case the light curve is associated to a 2AGL catalog source, 2AGL J0429-3755, and the light curve with bin duration of 2 days shows several detections, including a candidate detection within a year from the arrival time of neutrino. This candidate detection is at Modified Julian Date (MJD) = 58324.5 ± 1.0, with a flux of $(1.53 \pm 0.72) \times 10^{-6}$ photons cm^{-2} s^{-1} and $\sqrt{TS} = 3.1$.

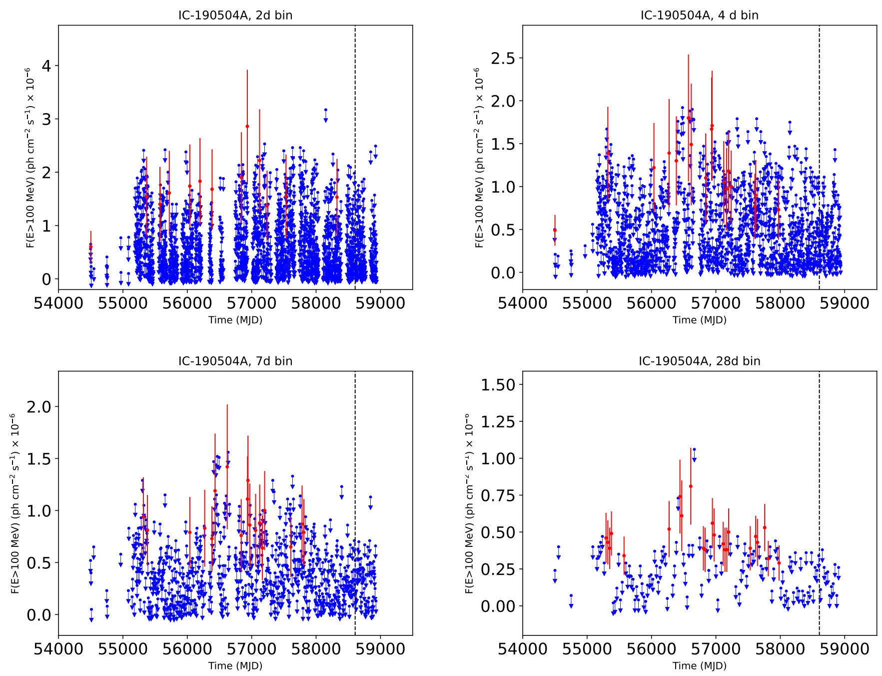

Figure 1: AGILE light curve of IC-190504A, with detections in red; the dashed line corresponds to the neutrino event T_0

The gamma-ray counterparts for IC-190504A with a radius of 90 arcmin found using the VOU-Blazars tool are reported in Table 2 and in Fig. 2. The sources 3HSP J042850.8-380550, PKS 0422-380, PKS 0422-389, 5BZQ J0422-3844 have not been previously reported, while PKS 0426-380 (also known as 2AGL J0429-3755 and 4FGL J0428.6-375) and 4LAC J0420.3-374 have been reported by [42, 77].

The VOU-Blazars tool also provides blazar preliminary classification into LBL, IBL HBL classes and the multi-frequency data needed to obtain the Spectral Energy Distribution (SED) of the candidates. The SEDs of the identified candidate counterparts are reported in Fig. 3. In some

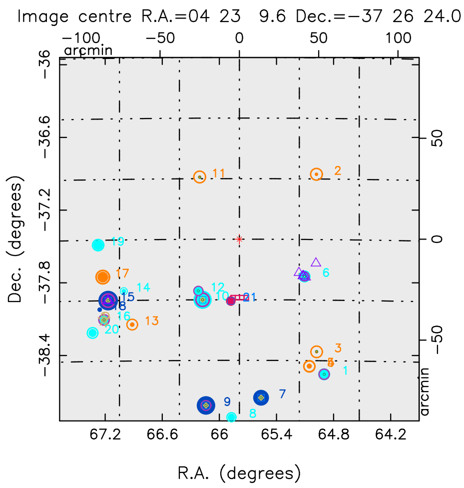

Figure 2: Map of sources within 90 arcmin from the arrival direction of the neutrino event IC-190504A. HBL candidates in orange, IBL candidate in turquoise, LBL in blue.

Table 2: Identified gamma-ray counterparts for IC-190504A within 90 arcmin from the arrival direction. The number of the candidate corresponds to the labeling in the map in Fig. 2); also reported are the source name, its classification, the equatorial coordinates, the angular distance from the reconstructed direction of the neutrino event and the gamma-ray counterpart, if any. Previously unreported candidate counterparts are in bold.

$N_{Candidate}$	Source name	Type	RA	DEC	Distance(arcmin)	γ-ray Counterpart
15	PKS 0426-380	LBL/IBL	67.17	-37.94	71.95	4FGL J0428.6-375
16	**3HSP J042850.8-380550**	IBL	67.21	-38.10	78.12	0
6	WISEA J042025.10-374445.0	IBL	65.11	-37.65	37.4	4LAC J0420.3-374
10	**PKS 0422-380**	LBL/IBL	66.17	-37.94	35.1	0
9	**PKS 0422-389**	LBL	66.14	-38.81	83.95	0
7	**5BZQ J0422-3844**	LBL/IBL	65.56	-38.75	79.2	0

cases we found data in the X-ray and radio band, making it possible to estimate the position of the synchrotron peak in order to confirm the classification in HBL, IBL and LBL provided by the VOU-Blazars tool.

We also performed additional search of multi-frequency data to build multi-frequency light curve of the candidate blazars. Figure 4 reports the multi-frequency light curve of PKS 0426-380, where the T_0 of the neutrino event is the dashed red line and the AGILE detections are the dotted lines. There are no AGILE detections around the $T_0 \pm 1$ day of the event, but the candidate detections correspond to gamma-ray flaring state in the Fermi-LAT measurements.

The analysis of our sample shows that 8 out of 16 light curves show significant detections ($\sqrt{TS} > 3$) within $T_0 \pm 1$ year. Among them, 2 out of 3 are EHE neutrinos (IC-180908A and IC-190503A), 3 out of 6 are HESE neutrinos (IC-190104A, IC-190221A, IC-190504A) and 3 out of 7 are GOLD neutrinos (IC-190619A, IC-190922A, IC-191001A). In addition, 2 out of 16 light curves are associated to 2AGL catalog blazars (IC-190504A and IC-190730A). We have found previously undetected candidates for all neutrinos.

Among the possible counterparts of our neutrino sample, HBL blazars are favourite compared to IBL, LBL ones and HESE neutrinos are associated to a larger number of possible AGILE

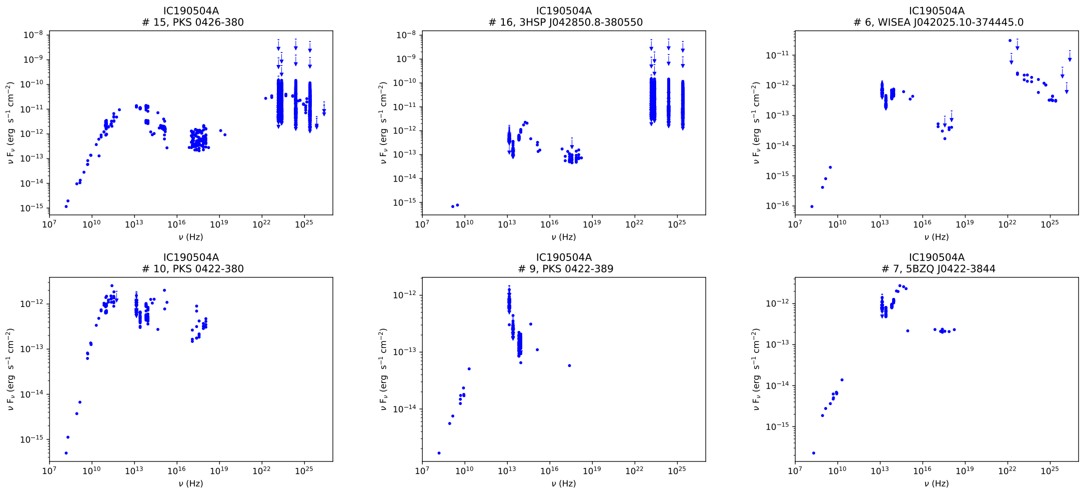

Figure 3: Spectral energy distribution of the blazar candidate counterparts of the IC-190504A IceCube neutrino event.

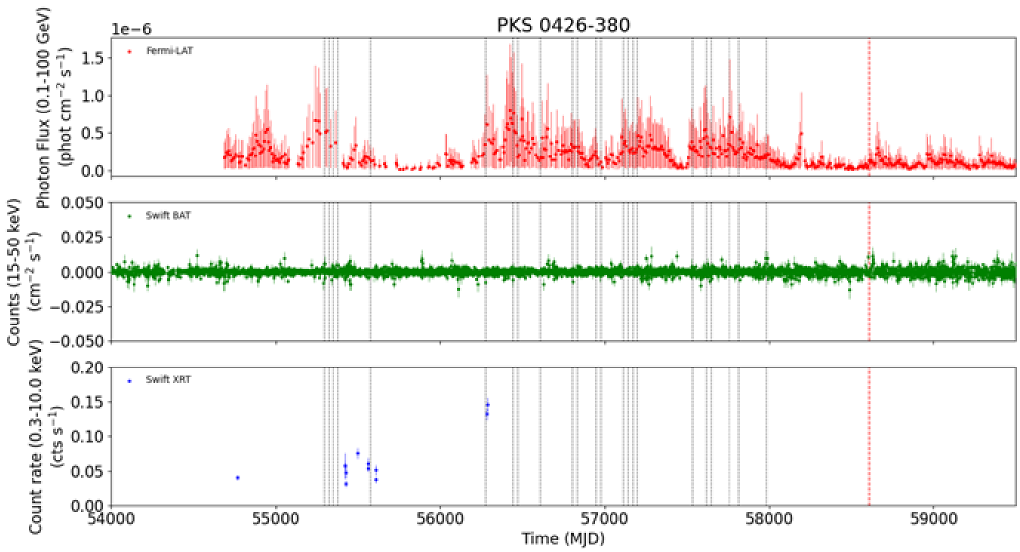

Figure 4: Multi-frequency light curve of PKS 0426-380; the T_0 of the neutrino event is the dashed red line and the AGILE detections are the dotted lines.

gamma-ray counterparts (Fig. 5).

6. Conclusions

We have analyzed a sample of 16 IceCube neutrino events in the time interval from September 2018 to March 2020, including all EHE, HESE and GOLD events. We have built the full mission AGILE light curves using the AGILE-LV3 public data archive and analysis tool, searching for candidate blazars in the neutrino error regions using the VOU-Blazars tool. We have found previously unreported sources for all neutrinos in the sample, building the multi-frequency light curves and the spectral energy distribution of the identified counterpart candidates. In the investigated

Figure 5: The left panel shows the fraction of the different class of candidate blazars counterparts; the right panel reports the AGILE candidate detections against the neutrino event type.

sample, HBL blazars appear more frequently than IBL, LBL as candidate counterparts of IceCube neutrino events, and HESE neutrinos are the most prolific producers of possible AGILE gamma-ray counterparts.

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PoS(MULTIF2023)003