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Multi-Messenger observations of the γ-ray blazar 4FGL J0658.6+0636 consistent with an IceCube high-energy neutrino

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The detection of cosmic neutrinos has raised many new questions in astroparticle physics, among the most compelling of which is the identification of cosmic neutrino emitters. After more than a decade of IceCube operations, the most promising neutrino astrophysical association remains the very-high-energy (VHE, > 100 GeV) blazar TXS 0506+056. Recently, on November 14, 2020 the IceCube observatory reported the detection of a well-reconstructed high-energy neutrino event, IceCube-201114A, with a high probability of being astrophysical. Within the 90% IceCube-201114A localization region only one known γ-ray (> 100 MeV) source is found. This is 4FGL J0658.6+0636, associated with the blazar NVSS J065844+063711. In these proceedings we present results from the rich multi-messenger campaign triggered by the IceCube-201114A neutrino detection, which has allowed us to collect simultaneous and quasi-simultaneous data for the γ-ray source potentially associated with the neutrino. NVSS J065844+063711 is a previously-known blazar with broadband properties resembling a high-synchrotron-peaked object, making it a promising TeV emitter. Indeed, the detection of very high-energy (VHE) photons (i.e., > 100 GeV) by the *Fermi* Large Area Telescope provides the first evidence of such emission from this object. It makes NVSS J065844+063711 the second VHE object found within the 90% confidence region of a well-reconstructed, high-energy IceCube event.

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1. Introduction

The detection of a diffuse background of astrophysical neutrinos with the IceCube Neutrino Observatory in 2013 opened a new window to the sky [1, 2]. Neutrinos are unambiguous tracers of cosmic-ray acceleration sites, as they are able to escape unimpeded from dense astrophysical environments generally opaque to other particles [3]. The interactions of relativistic protons and heavier nuclei with the gas and background light near these sites can produce unstable particles, like pions and kaons, which quickly decay into secondary particles, including neutrinos [2].

In 2017, an IceCube neutrino (IceCube-170922A) of high probability of being astrophysical was detected in both spatial and temporal coincidence with the γ-ray flaring blazar TXS 0506+056 [4], providing the first direct evidence of cosmic-ray acceleration in blazars' jets. This discovery prompted a search in the archival IceCube data revealing an excess of low-energy neutrinos with respect to the atmospheric background positionally consistent with IceCube-170922A. The low-energy neutrino excess was observed $2 \sim 3$ years before the detection of IceCube-170922A and is likely associated with the γ-ray blazar, i.e., with a significance of $\sim 3.5\sigma$ [5]. However, during the epoch of the neutrino excess, the blazar displayed an electromagnetic emission compatible with a low activity state in radio, optical and even the GeV energy bands [6, 7]. The putative detection of neutrino emission suggests the presence of hadronic γ-ray emission from blazars, which can be generated by synchrotron radiation of relativistic protons [8] or photo-hadronic interactions with the ambient photon field [9]. The spectral energy distribution (SED) of TXS 0506+056is fairly well described by leptonic models, suggesting that if hadronic processes are at work, their contribution to the overall observed emission is not dominant [10, 11].

On November 14, 2020, the IceCube observatory reported the detection of another well-reconstructed high-energy neutrino, IceCube-201114A, which was found to be spatially consistent with the γ-ray blazar 4FGL J0658.6+0636, associated with the high-synchrotron-peaked object NVSS J065844+063711 [12]. The γ-ray observations performed with the *Fermi* Large Area Telescope (LAT) show no enhanced activity of this blazar during the neutrino arrival time. In this contribution, we present the ensemble of the multimessenger observations of NVSS J065844+063711. We include archival and new observations quasi-simultaneous to the neutrino arrival, spanning several energy bands from radio to VHE γ-rays.

2. IceCube-201114A

On November 11, 2020, at 15:05:31.96 UTC, the IceCube observatory reported the detection of a "gold" neutrino[1], i.e. a high-energy neutrino track event (IceCube-201114A) with a >50% likelihood to be of astrophysical origin. It had a reconstructed direction of right ascension (RA) = $105.25^{\circ}{}^{+1.28^{\circ}}_{-1.12^{\circ}}$ and declination (Dec) = $6.05^{\circ}{}^{+0.95^{\circ}}_{-0.95^{\circ}}$ (90% containment, statistical errors only). Its estimated energy is $\sim$ 214 TeV[2]. No neutrino candidate events were recorded by the ANTARES observatory within the 90% error box of the IceCube event during a +/- one day time-window centered on the IceCube event time [30].

[1] https://gcn.gsfc.nasa.gov/doc/IceCube_High_Energy_Neutrino_Track_Alerts.pdf

[2] Astrophysical signalness = 0.56. More details about this event can be found here: https://gcn.gsfc.nasa.gov/notices_amon_g_b/134698_40735501.amon

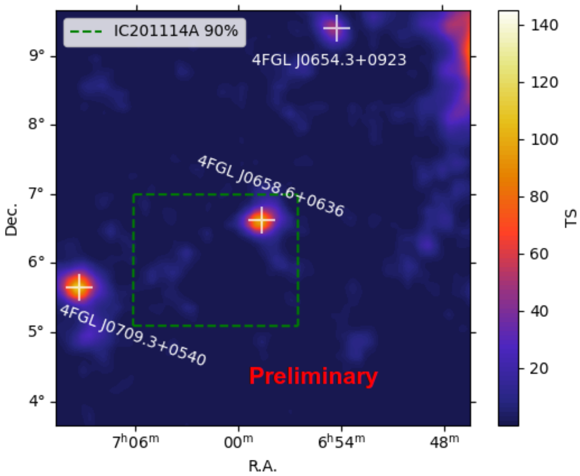

Figure 1: *Fermi*-LAT TS map centered on 4FGL J0658.6+0636 (a.k.a. NVSS J065844+063711), which is the only γ-ray source within the ~ 90% containment region of IceCube-201114A, given by the dashed contour. This map is based on γ-ray observations in the energy range 0.1–500 GeV, integrating LAT data from August 2008 to February 2021. Only the extended sources and diffuse background are modelled, hence the point-sources in the region are highlighted.

At γ-ray energies, the continuous all-sky monitoring by *Fermi*-LAT revealed only one γ-ray source significantly ($> 5\sigma$) detected within the IceCube-201114A error region [12], as shown in Figure 1. According to the *Fermi*-LAT Fourth Source Catalog [4FGL; 14] this is the γ-ray object 4FGL J0658.6+0636, associated with the blazar NVSS J065844+063711. The well-reconstructed neutrino event prompted several follow-up observations in the very-high-energy (VHE) γ-ray [29], X-ray, optical, and radio bands focused on the candidate neutrino γ-ray counterpart. In §3 we summarize initial results from this multi-messenger campaign, while the full information will be reported in [22].

3. Observations

We collected archival data from the ASI Space Science Data Center (SSDC)[3] and performed new observations of NVSS J065844+063711 at γ-ray, X-ray, ultraviolet, optical, and radio wavelengths, quasi-simultaneous with the neutrino arrival time. In the following section we describe the observations at VHE by H.E.S.S., MAGIC and VERITAS and at MeV-GeV energies by *Fermi*-LAT. For a description of the full acquired dataset we refer the reader to [22].

3.1 Very high-energy γ rays

The H.E.S.S. observations presented here were obtained in two epochs to increase the overlap with the MWL campaign. The first observation period took place between the 19th to 26th November 2020, while the second period covered the 10th to 12th December 2020. After data and calibration quality selection a total of 14.5 hours of data are available for analysis. Here we combined the full dataset and reconstruct the arrival direction and energies of the γ-ray events using a log-likelihood optimization comparing the shower images recorded by the four 12-meter telescopes to a semi-analytical model of air showers [23]. A cross-check with an independent calibration and analysis chain, using the Image Pixel-wise fit for the Atmospheric Cherenkov Telescopes *ImPACT* reconstruction method [24], shows consistent results. We define a circular region-of-interest with a radius of 0.12° centered on the optical position of NVSS J065844+063711. The background level in this region was determined using the standard "ring background" technique [25] allowing the background level to be derived from the data itself.

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

MAGIC observed NVSS J065844+063711 from the 16th to the 25th November 2020, for a total exposure of 7.5 hours. After quality cuts, two nights (16th and 20th) were excluded from the data set, resulting in 6.3 hours of available data. The analysis was performed using MARS, the MAGIC Analysis and Reconstruction Software [26]. No signal was detected either for any single night of observation or for the whole stacked data sample. During the computation of upper limits no negative fluctuations were allowed [4].

VERITAS observed NVSS J065844+063711 from the 15th to the 19th November 2020 for a total exposure of approximately 8 hours. After quality cuts, 7 hours of data were available. The analysis was performed using Eventdisplay [27] with the background estimated through the standard "ring background" technique. Cross-check analysis was performed with an independent software package (VEGAS) [28].

Given the lack of detection in any of the observations obtained by the VHE instruments, differential upper limits were computed according to a common configuration using the Rolke method [31], considering a confidence level of 95% and a global 30% systematic uncertainty and assuming a power law spectrum with photon index $\alpha = -2.5$.

3.2 *Fermi*-LAT

We select *Fermi*-LAT data within a $15° \times 15°$ region-of-interest (ROI) centered on the optical position of NVSS J065844+063711. The period of observations spans 12.5 years, ranging from 4th August 2008 to 10th February 2021. The energy range chosen is 100 MeV – 500 GeV, divided into 8 logarithmically spaced bins per energy decade. The γ-ray data are filtered for good time intervals with `DATA_QUAL` > 0 and the recommended instrument configuration for science `LAT_CONFIG` == 1. We use photons belonging to the `SOURCE` class (`evclass` = 128) and split the data set into three energy components: i) 100–300 MeV, ii) 300–1000 MeV, and iii) 1–500 GeV, for which we consider events belonging to different types of point spread function, given by `evtype` = 48, 56, and 3, respectively. To reduce contamination from the Earth limb, we adopt specific maximum zenith angle cuts of 85°, 90°, and 105° for components i), ii) and iii), respectively.

The Galactic and extragalactic background emissions are modeled with the latest interstellar emission model[4] *gll_iem_v07* and with the isotropic spectral template *iso_P8R3_SOURCE_V2_v1*. We perform the data analysis with `Fermitools`[5] v1.2.23 and `fermipy`[6] v0.17.4, by means of a binned likelihood analysis and using MINUIT as the minimizer. In the model of the ROI, we include γ-ray sources listed in 4FGL as well as all sources found with the `fermipy` function `find_sources()` and located up to 12° from the target. Our target is modeled with a single power law.

4. Discussion and conclusions

The blazar NVSS J065844+063711 is the only γ-ray source found within the IceCube neutrino error region. We cross-checked the WISE Blazar-Like Radio-Loud Sources catalog [15] and Roma-BZCat [16] for the presence of blazar-like sources within the neutrino 90% localization region and

[4] https://fermi.gsfc.nasa.gov/ssc/data/access/lat/BackgroundModels.html
[5] https://fermi.gsfc.nasa.gov/ssc/data/analysis/software/
[6] https://fermipy.readthedocs.io/en/latest/index.html

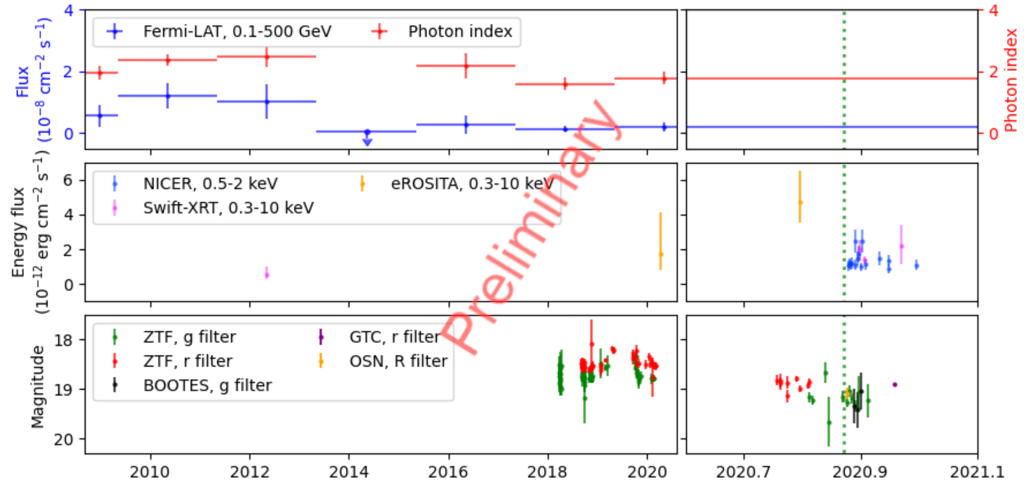

Figure 2: Multiwavelength light curves of NVSS J065844+063711. No flaring activity is observed around the neutrino arrival (green dotted line). The left panels show the observations performed between August 2008 and July 2020, while the right panels show an expanded time scale between July 2020 and February 2021. In the top panels, we show the *Fermi*-LAT fluxes and photon indexes. For the middle panels, we show the X-ray observations performed with NICER, eROSITA and Swift-XRT. In the bottom panels, we show the optical observations collected with ZTF, BOOTES, GTC and OSN. For more details on the data collection and analysis, we refer the reader to [22].

found none beside NVSS J065844+063711. This is a BL Lac object of unknown redshift[7] at coordinates R.A. = 104.6876° and Dec. = 6.6199° [18]. It lies 0.81° away from the best-fit localization of IceCube-201114A, i.e., well within the 90% neutrino positional uncertainty region.

Gamma-ray emission positionally consistent with this object was first reported in the *Fermi*-LAT First Source Catalog [1FGL J0658.5+0641; 19] as an unassociated γ-ray source. The association with NVSS J065844+063711 was established in the *Fermi*-LAT Third Source Catalog [3FGL; 17]. During the first four years of LAT operations, this source displayed a soft power-law spectrum with a photon index $\Gamma \sim 2.5 \pm 0.1$, according to the 3FGL. In the 4FGL, built integrating the first eight years of LAT data, the source displayed a somewhat harder photon index of $\Gamma \sim 2.2 \pm 0.1$ and had a variability index of 10, consistent with no significant variability detected in γ-ray on year timescales [see 4FGL; 14].

The light curves in Figure 2 show overall minor variability. The arrival time of IceCube-201114A (highlighted by the green dotted line) coincides with a quiescent state of NVSS J065844 +063711, where no remarkable enhanced activity was detected at γ-ray, X-ray or optical wavelengths. The spectral energy distribution (SED) is shown in Figure 3. It is consistent with an HSP blazar with the low-energy bump peaking at $\nu = 3 \times 10^{15}$ Hz ($\sim$ 4 eV) [20]. NVSS J065844+063711 is also included in the *Fermi*-LAT Third Hard Source Catalog, being associated with 3FHL J0658.5+0636 [21]. The highest energy photon reported in the 3FHL consistent with this object is a ~61 GeV event. In January 2018, i.e., nearly two years prior to the arrival of IceCube-201114A, a VHE photon with a 155 GeV energy was detected with a probability of ~ 95% of being associated with

[7] https://web.oapd.inaf.it/zbllac/refindex.html

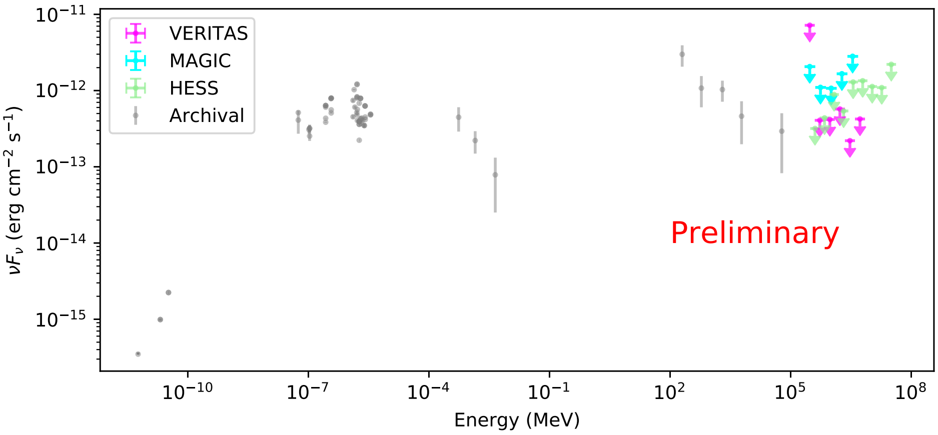

Figure 3: The spectral energy distribution of NVSS J065844+063711. Archival observations collected from the ASDC SED Builder are shown in gray and illustrate the historical flux level of this blazar. The colored data points indicate quasi-simultaneous observations collected with VHE telescopes. For more details on the data collection and analysis, we refer the reader to [22].

this blazar [13]. This VHE photon was accompanied by three other high-energy (i.e., > 10 GeV) photons within a ~ 1-year period. However, observations by the H.E.S.S., MAGIC and VERITAS telescopes did not lead to the detection of significant VHE emission from NVSS J065844+063711.

Previously, the only VHE γ-ray blazar found within the 90% confidence region of a well-reconstructed IceCube high-energy neutrino event is TXS 0506+056. NVSS J065844+063711, the second only candidate VHE emitter potentially associated with an astrophysical neutrino, may provide crucial information about the hadronic processes at work in the jets of active galactic nuclei and clues on the origin of cosmic neutrinos.

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