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A VLBI investigation of high-energy neutrino emitter candidates

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High angular resolution observations with the very long baseline interferometry (VLBI) provide crucial tests for the association of neutrinos with blazars. The VLBI follow-up observations have led to the unveiling of VLBI-scales properties potentially linked to the neutrino production in the jet of the blazar TXS 0506+056, the first source associated with a neutrino event. In order to collect new pieces of evidence on the connection between radio properties in blazars and neutrino production, we performed a VLBI investigation of gamma-ray blazars observed in spatial coincidence with four neutrino events, detected by the IceCube observatory between 2019 and 2020. We compared our new observations with archival data for selected candidate counterparts with the aim of searching for hints of a possible connection between the neutrino events and those sources. This contribution presents some of the results of the first exploratory VLBI follow-up campaign, with a focus on the results of the most promising targets. A brief summary of the new follow-up observations for IceCube events carried out during 2022 is also given. Among these, there are two events, IC 211208A and IC 220205A, the candidate counterparts of which are flaring at the neutrino detection. They are the blazar PKS 0735+038 and the extremely peculiar source PKS B1413+135, respectively.

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1. Introduction

High-energy (HE) neutrinos, with energies in the TeV regime, are products of the interactions of very high-energy cosmic-ray protons with the surrounding photon fields and particles. These interactions can only occur in astrophysical environments. The population of HE neutrinos is distributed uniformly in the sky [1], leading to the connection between neutrinos and extragalactic sources. According to theoretical studies (e.g., [3, 29]), among the most probable candidates as astrophysical counterparts of HE neutrinos, there is the class of blazars, radio-loud active galactic nuclei (AGN) with the jet being aligned with the observer's line of sight. It is expected that the very energetic processes occurring in blazar jets can accelerate cosmic rays up to the energies required for HE neutrino production [26]. However, testing this connection by direct observations is not trivial. The IceCube observatory, located at the South Pole, is the largest neutrino detection nowadays. Its 1 cubic kilometre structure in the ice provides a collecting area large enough to detect tens of neutrino events per year. However, the arrival directions of the events are limited within error areas from a few degrees to tens of square degrees. The association between neutrinos and their emitting source is then extremely challenging.

Thanks to multi-wavelength (MWL) follow-up observations, it is possible to investigate these associations by studying the behaviour of the sources co-spatial with the events. The most important example of the crucial role of prompt MWL observations in this context was the case of the IceCube neutrino event IC 170922A[1]. The follow-up campaign started soon after the neutrino detection allowed the identification of a highly probable counterpart of the event, the gamma-ray blazar TXS 0506+056. Lying within the relatively small error region of the event (~1 square degree), this source was detected in a flaring state at the time of the neutrino arrival [17]. The flaring activity is proof of the acceleration mechanism occurring in the source. In addition, the inspection of the IceCube archival data, performed after the IC 170922A event, revealed an excess of neutrino signal coming from the direction of TXS 0506+056 across 2014 and 2015 [18].

The high angular resolution of very long baseline interferometry (VLBI) observations is a powerful tool in studying the parsec-scale regions of blazar's jets, which are thought to be where particle acceleration happens. Crucial information on neutrino production in TXS 0506+056 resulted from VLBI studies on the source. Two NRAO Very Long Baseline Array (VLBA) follow-up observations at 43 GHz were conducted after the neutrino event. Comparing the two epochs, [27] observed that the radio flux density of the source grew by a factor of about 1.5 at the parsec-scale region of TXS 0506+056. Also, they observed jet structures as limb-brightening in the jet and an apparent superluminal expansion of the core. Similar features can be interpreted as indications of efficient particle accelerations in the jet (e.g., [33]). The kinematics and morphology of the jet of TXS 0506+056 were analysed thanks to archival VLBI data [5, 11, 21, 23]. Among several results, a helical trajectory of the jet was determined by following the changes in the position angle of the source. Also, by core-shift and variability analysis, [23] measured a decreased magnetic field strength after the neutrino detection and interpreted these results as a conversion of magnetic energy into particle energy. All these findings could significantly contribute to the understanding

[1]The IceCube events are reported with the acronym IC for *IceCube* followed by the year, month and day of the detection. The letter is added to discriminate between events that occurred on the same day: 'A' for the first event and so on in alphabetical order

PoS(EVN2022)016

of the processes involved in neutrino production. Another detailed study of the jet kinematic and the possible connection with the neutrino emission using VLBI data was dedicated to the source PKS 1502+106 [6]. In this work also the gamma-ray emission of the source has been analyzed in the context of neutrino production. In addition, population studies suggest HE neutrinos are produced in the parsec-scale regions of blazars. In two key works, a correlation has been shown between the positions of a sample of VLBI sources and IceCube neutrino events and a significant increase in the mean VLBI flux density of the blazars in temporal coincidence with the neutrinos arrival time [31, 32].

Despite the promising results on the link between neutrinos production and parsec-scale radio emission, a reasonable number of observational tests and a larger number of reliable associations are still missing to strengthen the hypothesis. Then we started to follow neutrino events with multi-epoch and multi-frequency VLBI observations to confirm the connection between neutrino detections and recurring radio properties in the candidate counterparts. Our main goals are to *(i)* characterize the sources co-spatial with the events, with a focus on their parsec scale regions, *(ii)* search for enhanced activity in these sources, as observed in TXS 0506+056, by comparing our data with archival VLBI data, and *(iii)* test the presence of recurring radio properties possibly linked to the neutrino production in their jets, following the works on TXS 0506+056.

2. The sample

Between 2019 and 2020, we collected four VLBI follow-up observations of IceCube neutrino events. The detection of these events is promptly circulated by the IceCube collaboration via the gamma-ray burst (GRB) Coordinates Network[2] (GCN). Usually, the GCN circulars are followed by related Astronomer's Telegrams[3] (ATels), reporting the observations of the candidate counterparts by facilities working at different wavelengths. In light of the limited pieces of evidence and the still open debate on the astrophysical sources associated with HE neutrinos, this first collection includes different kinds of sources and event types. At this stage, we still cannot build a homogeneous sample according to well-defined selection criteria. Our aim now is rather to start our collection by focusing on the most promising candidate leads. Indeed, the candidate counterparts-events selection mainly reflects the interest of the MWL community which simultaneously carried out follow-up observations on these sources and events and shared the results via ATels. As a result of the poor spatial resolution of neutrino events, several candidate sources lie within their localization regions. In addition, sometimes sources slightly outside the 90% IceCube error region are pointed out as good candidate counterparts in dedicate ATels. Then, for each event, more than one source has been identified as a possible neutrino source. We observed a total of ten radio sources associated with the four events.

We followed both *gold* and *bronze* IceCube events. According to the IceCube alerts classification, gold events have a higher probability of being of astrophysical origin than bronze ones[4]. The classification of each event is reported in the dedicated GCN. The candidate counterparts are both extended and compact radio sources. They come either from different sub-classes of blazars

[2]https://gcn.gsfc.nasa.gov/gcn/gcn3_archive.html.
[3]https://www.astronomerstelegram.org/
[4]https://gcn.gsfc.nasa.gov/doc/IceCube_High_Energy_Neutrino _Track_Alerts_v2.pdf

or from other classes of AGN, in some cases, they have not been classified yet. Most of them are associated with a gamma-ray counterpart from the Fourth *Fermi*-LAT Fourth Source Catalogue (4FGL and its second data release, 4FGL-DR2, [2]), however, there are also two sources unrelated to gamma-ray sources that are part of the sample. In a few cases, the gamma-ray sources were detected for the first time by a dedicated *Fermi*-LAT analysis performed after the neutrino alerts. The new detections from the *Fermi*-LAT analysis are reported by the *Fermi* collaboration in dedicated ATels (see Tab. 1). On the basis of theoretical studies (e.g. [34]) and observational suggestions (limited to the case of TXS 0506+056 up to now) gamma-ray blazars are favoured neutrino counterparts among the AGN classes. Then, among the ten radio sources, we analysed in detail the ones with a gamma-ray counterpart and showing blazar-like properties. We ended up with a sample of five good candidates. We relied on the NASA/IPAC Extragalactic Database (NED), the 4FGL and 4FGL-DR2 and the dedicated ATels to retrieve information on the sources, for example, their redshift and classification. Tab. 1 reports the basic properties of each event and the gamma-ray and other wavelength counterparts. In the following, we use the MWL counterpart name to refer to the radio sources that we targeted. The candidates to which we dedicated the detailed analysis are highlighted in bold in Tab. 1. The error regions of the four events and the relative radio candidate counterparts are shown in Fig. 1.

Table 1: IceCube neutrino events and candidate counterparts.

IC event	GCN id.	Alert type	Loc. area (90%) (deg^2)	Energy (TeV)	*Fermi*-LAT id.	Other wavelength Counterpart
(1)	(2)	(3)	(4)	(5)	(6)	(7)
190704A	24981	Bronze	20.1	155	J1045.3+2751	**1WHSP J104516.2+275133**
					J1049.8+2741	NVSS J104938+274212
200109A	26696	Gold	26.6	375	J1103.0+1157	**TXS 1100+122**
					J1114.6+1225	*WISEA J111439.67+122503.7*
					J1055.8+1034[a]	WISEA J105553.74+103446.5
201021A	28715	Bronze	5.98	105	*J1728.0+1216*[b]	***1RXS J172314.4+142103***
					J1725.5+1312	**PKS 1725+123**
201114A	28887	Gold	3.66	214	J0658.6+0636	**NVSS J065844+063711**
						WISEA J065633.43+053922.7
						NVSS J065916+055252

Notes: (1) IceCube event; (2) GCN Circular identification number; (3) IceCube classification of the event; (4) Localization area (90% PSF containment); (5) Event energy; (6) 4FGL or 4FGL-DR2 identifier of candidate counterparts; (7) Candidate counterparts from other-wavelength catalogues. Information in columns (3), (4), and (5) are retrieved from the GCN dedicated to the event. All the sources in column (7) are associated with the gamma-ray sources in column (6) in the same row. The last two sources in column (7) are not associated with a gamma-ray source in the *Fermi* catalogue, however, they have been proposed as candidate counterparts in a dedicated Atel [15]. In bold are the sources on which we focused the analysis, and in italics are the ones lying outside the IceCube error regions. [a] new gamma-ray detection reported by [12]. [b] new gamma-ray detection reported by [9], the X-ray associated source, 1RXS J172314.4+142103, is suggested by the *Fermi* collaboration and reported in the dedicated ATel.

3. The observations

The VLBI follow-up observations have been conducted within a few days to one month after the detections. The VLBI networks employed for carrying out the observations are the

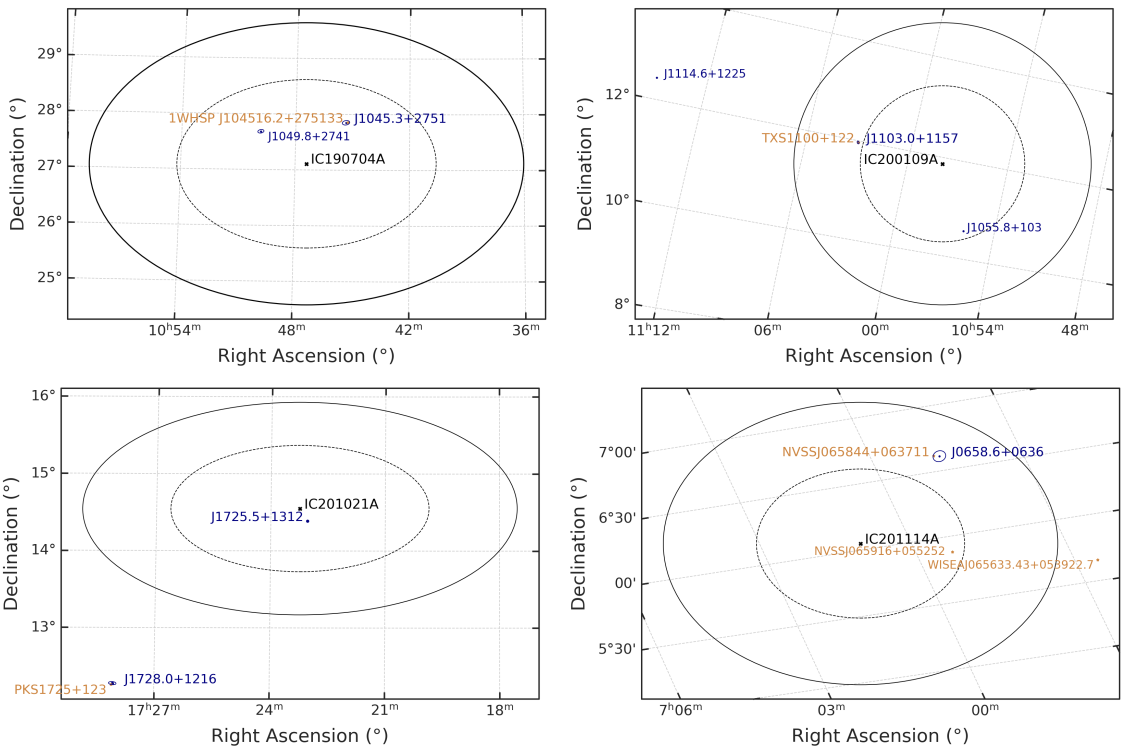

Figure 1: Localization regions of the IceCube neutrino events analysed in this work. The ellipses drawn with the continuous lines mark the 90% error region, while the dashed-line ellipses mark the 50% error region (error regions are taken from the GCNs of the events). In blue are reported the gamma-ray candidate counterparts within their error regions (small blue circles, 68% *Fermi*-LAT localization regions) of the events and in gold the other-wavelength candidate counterparts (and associated with the gamma-ray ones).

VLBA, the European VLBI network (EVN) and the enhanced Multi Element Remotely Linked Interferometer Network (e-MERLIN) array. We performed multi-frequency observations, with frequencies spanning from 1.5 GHz to 23.5 GHz, for each event, except for the IC 201021A event for which we have e-MERLIN observations at 5 GHz only. The data reduction and imaging are described in Ref. [25]. The final VLBA and EVN images are produced with angular resolutions of about 0.8 to 12 mas and about 35 to 84 mas for e-MERLIN images.

To test the state of the sources at the time of neutrino arrival we compared the results of the follow-up observations with archival VLBI data. These are mainly taken from the Radio Fundamental Catalogue (RFC). Archival data of PKS 1725+123 presented in this work are from the Monitoring Of Jets in Active galactic nuclei with VLBA Experiments (MOJAVE) [24]. For the characterization of the sources at the arcseconds scale we used surveys data from the NRAO VLA Sky Survey (NVSS, [10]) and the Faint Images of the Radio Sky at Twenty-cm (FIRST, [8]) survey, at 1.4 GHz, and the VLA Sky Survey (VLASS, [22]) at 3 GHz. The image angular resolutions go from 45 arcsec and 5.4 arcsec for NVSS and FIRST, respectively, to 3 arcsec for the VLASS. VLBI Archival data have been re-imaged while the survey images have been retrieved using the CIRADA tool[5] [16].

[5]www.cirada.ca/catalogues

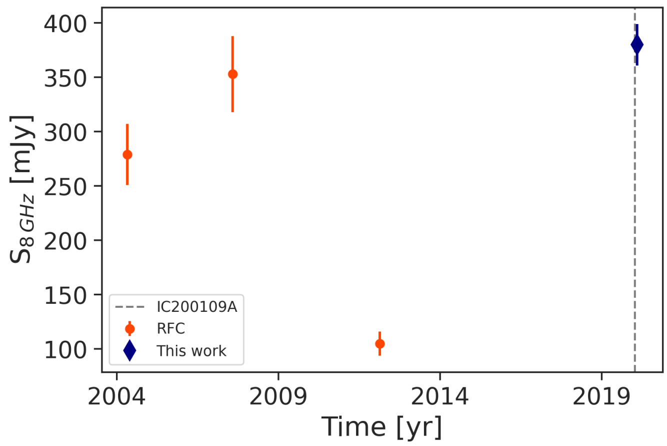

Figure 2: Total flux density at 15 GHz of PKS 1100+122 as a function of time. The red points are taken from the RFC observations of the source. The blue point shows the flux density from our VLBA observation. The grey dashed line indicates the neutrino's arrival.

4. Analysis and results

The study of the neutrinos candidate counterparts includes the comparison of the large-scale VLA data with the small-scale VLBI data to discriminate between extended and compact structures. The sources are then characterized in terms of their luminosity, spectral properties and morphology. This analysis has been carried out for each of the ten observed sources and the results are presented in detail in Ref. [25].

For the five best candidates we further investigated the milliarcsecond (i.e. parsec at the redshift of these sources) observations. We compared our VLBI data with RFC and MOJAVE data with the aim of measuring the activity levels and constraining the overall radio properties of the jets in these regions. We observed the blazar **1WHSP J104516.2+275133**, associated with the IC 190704A event, for the first time with VLBI. In this case, the comparison with archival data was not possible but our data provide reference images for any future comparison. The candidate counterpart of the IC 200109A event, **TXS 1100+122** showed hints of enhanced activity in coincidence with the neutrino detection. Figure 2 shows the flux density of the source at 8 GHz as a function of time. Moreover, [20] reported RATAN-600 observations between 2 and 22 GHz, also confirming the high state in the radio band with respect to the past RFC observations. Despite the RFC data having been taken more than ten years before our observations, it is still possible to recognize a possible high state with respect, for example, to the very low state in 2012. The large time gap however does not allow us to determine when the raise occurred and the actual duration of this high state.

Signs of enhanced activity in VLBA data can be observed for the blazar **PKS 1725+123**, one of the candidate counterparts of the IC 201021A event. The source is located about 2.6 degrees from the neutrino best-fit position, slightly outside the event error region. However, taking into account the relatively small error area of localization for the event (systematics are not included) and the significantly enhanced activity of the source at the neutrino detection, PKS 1725+123 is still a good candidate counterpart (see [25] for more details). The VLBA data of the source come from the MOJAVE monitoring, as shown in Fig. 3, left panel. In this case we provided an e-MERLIN

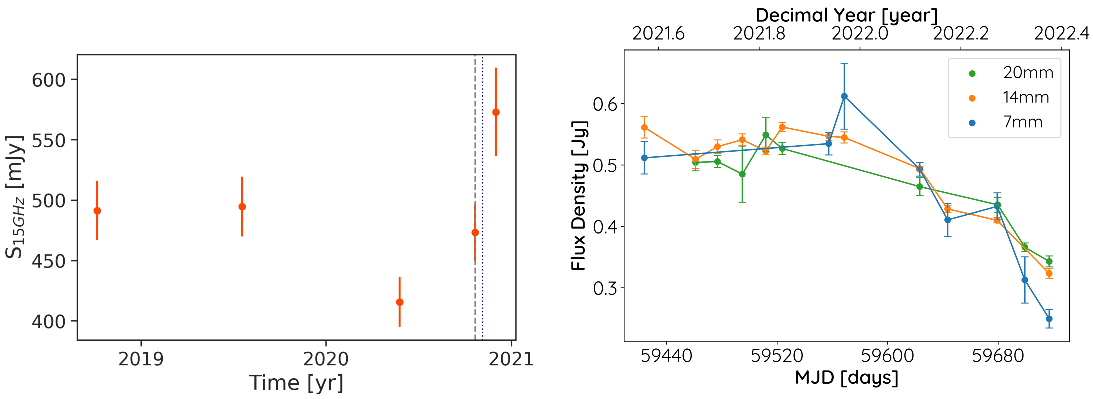

Figure 3: *Left:* VLBI total flux density at 15 GHz of PKS 1725+123 as a function of time. Data are from the MOJAVE monitoring of the source. The neutrino arrival time is indicated by the grey dashed line. The blue dotted line marks when our e-MERLIN observation at 5 GHz was carried out (see [25] for the results). *Right:* Multi-frequency Effelsberg single-dish monitoring of the source up to six months after the neutrino detection as part of the TELAMON program.

follow-up that allowed us to characterize the source also at a much larger scale, up to a few kpc, soon after the neutrino detection. Remarkably, the monitoring of the source with the TeV Effelsberg Long-term AGN MONitoring (TELAMON, [19]) program gives a further confirmation of the high state after the neutrino detection since the single-dish flux density level started to decrease about six months after the neutrino detection (Fig. 3, right).

We also modelled our data and archival VLBI data with Gaussian components. We aim to measure kinematic and morphological parameters as velocities and position angles of the components, and their changes after the neutrino detection. By monitoring the components of the jets over time, it is possible to spot newly ejected knots which are sites of particle acceleration processes. Core-shift measurements provide estimations of magnetic field energy density over several months and brightness temperatures allow us to determine upper limits on Doppler factors. These parameters will be compared with the ones retrieved from the modelling of the spectral energy distribution of the sources, allowing a comprehensive understanding of the emission mechanisms acting during and after the neutrino detections. In order to perform this analysis we monitor the sources with two or three epochs of VLBI observations, and the results of the first epoch are presented in Ref. [25].

5. New VLBI follow-up

In the past year, we continued monitoring three sources with VLBA and the KaVA combined array, which involves the Korean VLBI Network (KVN) and the VLBI Exploration of Radio Astrometry (VERA) facilities. Meanwhile, we collected VLBI follow-up observations for new IceCube neutrino events.

Two VLBA follow-up observations were dedicated to the IC 211208A event and IC 220205A event. The possible counterpart of the first one is the blazar PKS 0735+038. The source was in a high state at several wavelengths at the neutrino detection [28] and an enhanced activity is also ongoing on the VLBI scales (Fig. 4). The second event was detected close to a radio

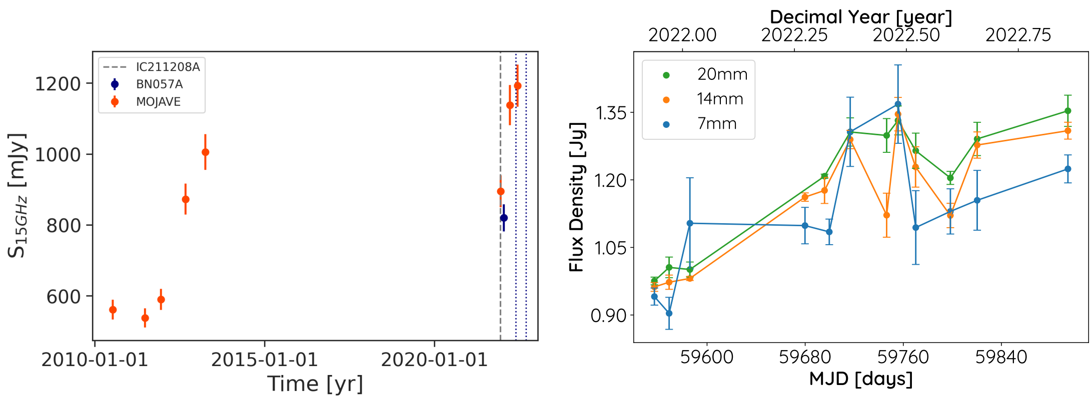

Figure 4: *Left:* Total flux density at 15 GHz of PKS 0735+038 as a function of time. The red points are taken from the MOJAVE monitoring of the source. The blue point shows the flux density measured from the first epoch of the BN057 project (BN057A, performed on 12 Jan, about one month after the neutrino detection). The grey dashed line indicates the neutrino's arrival, after which the flux is increasing. The blue dotted line marks the date of the second and the third epoch of observation (BN057A1, carried out on May 23 and BN057A2, on September 10), the data reduction of which is currently ongoing. *Right:* Multi-frequency Effelsberg single-dish monitoring of the source as part of the TELAMON program. The monitoring goes from soon after the neutrino detection up to seven months after and it shows a growth in the source flux density.

source, PKS B1413+135, also found in a high state at gamma-ray energy at the neutrino arrival time [13]. The flaring activity at high energy started in 2019 and a new episode was detected in January 2022, a few weeks before the neutrino detection [4, 14]. More intriguingly, in temporal coincidence with the January 2022 flare, the source has also been detected at very high energies ($E > 100$ GeV) by the Major Atmospheric Gamma Imaging Cherenkov (MAGIC) telescopes [7]. In addition, the peculiarity of the source makes its connection with the neutrino event even more interesting. Indeed its nature has been highly debated in the past: it shows typical blazar-like properties (compactness, core-dominance, flat spectrum) but also unique features such as emission from a counter-jet, which usually cannot be detected in blazars. Also, the monitoring of the flux density exhibits an uncommonly achromatic and symmetric variability. According to the latest interpretations, this behaviour is ascribed to the gravitationally lensed nature of this source [30]. Both sources are being monitored with three epochs of multi-frequency VLBA observations.

Two other events, IC 220205B and IC 220425A have been followed with EVN and e-MERLIN follow-up observations. The best candidate counterpart of the IC 220205B is the blazar PKS 1741−03, previously identified as one of the four most probable blazar-neutrino-emitters [31]. There are two candidates in the vicinity of the IC 220425A event, PKS 1749−101, previously associated with a 2018-neutrino event (GCN 23375), and TXS 1742−078, detected in a high state in the optical band in coincidence with the neutrino detection (GCN 31948). Two epochs of e-MERLIN observations and three epochs of EVN observations (a few of these planned for the next months) are dedicated to monitoring these sources after the neutrino detection. Over the course of the next year we plan to further enlarge our sample with VLBI follow-up observations of new possible counterparts of IceCube neutrino events.

6. Summary

We acquired VLBI observations spatially coincident with four neutrino events to investigate the possible connection between neutrinos and blazars. We collected, calibrated and analysed VLBI data of ten radio sources. Among those we selected sources similar to TXS 0506+056, the only blazar associated with a neutrino event so far, and studied radio properties related to neutrino detection. Out of the ten sources, we selected five candidate neutrino counterparts and for two of them we found hints of enhanced state of activity at the neutrino detection. We aim to characterize the kinematics of these sources with further VLBI observing epochs. We are also collecting new VLBI follow-up observations to study the kinematics of more sources and to determine the presence of recurring properties in the neutrino candidate counterparts.

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