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The Candidate Blazar Counterparts of the Ultra-High-Energy Event KM3-230213A

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The detection by the KM3NeT experiment of the ultra-high-energy event KM3-230213A marks a milestone in neutrino astrophysics. With an energy estimated of $\sim$ 220 PeV, it is the most energetic cosmic neutrino observed to date, opening the question of its astrophysical origin. Blazars, among the most powerful cosmic accelerators, have been proposed as promising sources of both astrophysical neutrinos and ultra-high-energy cosmic rays. In this contribution, seventeen candidate blazars are identified in the 3° radius error region of KM3-230213A through their multiwavelength signatures. Using archival data and dedicated observations, their properties are characterised throughout the whole electromagnetic spectrum, from radio to gamma rays. Three sources exhibit flaring behaviour in one of the examined bands, in coincidence with the neutrino arrival time. While none of these can be unequivocally associated with the KM3-230213A event, the implications of a possible blazar origin of the KM3NeT event are discussed.

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1. Introduction

KM3NeT is a research infrastructure consisting of two Cherenkov neutrino detectors under constructions in the depths of the Mediterranean sea. The KM3NeT/ARCA detector, offshore Portopalo di Capo Passero, Italy, when completed, it will instrument one cubic kilometre of seawater with several thousands digital optical modules [1]. In its partial configuration, with 21 lines deployed, KM3NeT/ARCA has observed a muon neutrino candidate, KM3-230213A. The energy of the detected muon is 120^{+110}_{-60} PeV, translating for an assumed E^{-2} flux, to a best-fit neutrino energy of $\sim$ 220 PeV with a 90% confidence interval of 72 PeV − 2.6 EeV (ultra-high energy, UHE).

The KM3NeT event is the most energetic neutrino observed to date, its nature being most likely astrophysical. Its exact origin remains, however, unknown. The production of neutrinos at these energies requires the acceleration of cosmic rays to EeV scales, that cannot be produced on a Galactic scale [2]. Extragalactic cosmic accelerators are, therefore, the most promising candidate sources [3]. Production of neutrinos above the PeV scale can be attributed to interactions of accelerated ions with photon fields (often referenced to as p-γ). Blazars and their relativistic jets are natural candidates for ultra-high-energy emission, with spectra peaked above the PeV scale [4]. Following the association of a gamma-ray flare in TXS 0506+056 with a high-energy neutrino detected by IceCube [5], further evidence has emerged connecting astrophysical neutrinos to blazars [6] and their electromagnetic flares [7]. The lack of a significant low-energy neutrino signal in the direction of KM3-230213A [8] may be an indication of its transient nature, or point to a steady source with no strong neutrino emission below the PeV scale.

The sky localisation of KM3-230213A presents a 99% confidence region of 3° radius centred at RA 94.3°, Dec −7.8° (J2000) [8]. Seventeen extragalactic objects, that exhibit distinctive multiwavelength features compatible with a blazar nature, are found to be positionally consistent with the KM3NeT event [3].

2. Identification of blazars through their multiwavelength properties

The multiwavelength emission of blazars is characterised by a spectral energy distribution with a typical *double-bump* feature, with two peaks arising from electron synchrotron and inverse Compton processes. These result in strong emission in the infrared/optical and X-ray/gamma-ray bands, respectively. In addition, blazars exhibit compact radio emission at the parsec-scale that can be probed with very long baseline interferometry (VLBI, [9]). A sample of seventeen candidate blazar counterparts of KM3-230213A has been compiled following four complementary criteria:

1. radio, X-ray and infrared properties: cross correlation of the NVSS catalogue, the eROSITA Sky Survey and the WISE infrared catalogue; further selection of blazar-like objects from the WISE colour-colour diagrams;
2. parsec-scale radio emission detected from VLBI through a dedicated observation conducted with the Very Large Baseline Array (VLBA), complementing existing VLBI measurements from the Radio Fundamental Catalogue;
3. objects previously classified as blazars in the Roma 5th Catalogue (5BZCAT, [10]);

4. gamma-ray sources observed by the Large Area Telescope (LAT) on board the *Fermi* Gamma-ray Space Telescope [11], reported in the 4FGL-DR4 catalogue, the *Fermi* Long-Term Transient Sources catalogue (1FLT) or the incremental version (iFLT).

3. Observational strategy

To compile a complete survey of the candidate blazar counterparts of KM3-230213A, public and archival data have been collected from a wide-range of surveys: Owens Valley Radio Observatory, RATAN-600, ALMA (radio); WISE/ALLWISE (infrared); ZTF, Gaia, ATLAS, ASAS-SN (optical); eROSITA [12], Chandra, ROSAT, *Swift*-XRT, SVOM-MXT and -ECLAIR (X-ray) *Fermi*-LAT (gamma). Complete documentation of the data reduction and analysis, and a complete set of references for the facilities, can be found in [3].

In addition, dedicated observations have been conducted:

Radio VLBI survey The VLBA has been used to observe all the objects in the 99% error region with a flux density in VLASS above 50 mJy (about 50 objects).

SVOM tiling The MXT and ECLAIR instruments onboard the SVOM spacecraft [13] have been exploited to observe the 95% error region in a tiling pattern. No source has been detected in the X-ray band. While being the most recent, the SVOM upper limits are less constraining compared to previously existing eROSITA observations.

Swift ToO The X-ray telescope onboard the *Swift* mission [14] has been used to observe the two X-ray brightest candidates in order to characterise their X-ray properties with dedicated target of opportunity observations.

4. Summary of candidate blazar counterparts

With the exception of 4FGL J0616.2-0653, all the other sources are detected both in radio and infrared, with only three lacking a VLBI detection. Three objects, classified in the 5BZCAT as flat-spectrum radio quasars (FSRQs), have a measured redshift: 0605-085 (#6, 5BZQ J0607-0834), PMN J0609-0615 (#7, 5BZQ J0609-0615) and PMN J0606-0724 (#8, 5BZQ J0606-0724). A single source is only detected in gamma-rays, without associated point-like counterparts in other wavelengths. The nature of this object is unclear, and, while a point source cannot be excluded with high confidence, such a signature may arise from mismodelled diffuse Galactic foregrounds. A summary of the seventeen candidates and their key multiwavelength properties is given in Table 1.

4.1 Flaring sources

High-energy neutrinos have been tentatively associated with major electromagnetic flares, notably in the gamma-ray and radio bands. Systematic studies of associations with X-ray flares are more difficult due to the sparse coverage of available facilities. However, several studies have highlighted X-ray activity as a good tracer of environment favouring neutrino emission in blazars. In this study of the positional uncertainty region of KM3-230213A, three blazars positionally

Table 1: Summary of the seventeen candidate blazar counterparts. Positions are provided in equatorial (J2000) coordinates, with the primary name (in bold) of each source corresponding to either a common name or the name in the first survey reporting the object. The listed coordinates prioritize counterparts in the following order: Radio Fundamental Catalog (VLBI), infrared surveys, VLASS, and *Fermi*-LAT analysis for the single gamma-ray-only detection (#2). Radio fluxes (8 GHz) and intrinsic, time-averaged X-ray fluxes in the 0.2 keV to 2.3 keV band are reported in the respective columns.

	Name	Sep.	RA	Dec	z	$S^{8\,\mathrm{GHz}}_{VLBI}$	X-ray (0.2–2.3 keV)
		[°]	[°] J2000	[°] J2000		[mJy]	[10^{-13} erg cm^{-2} s^{-1}]
#1	**MRC 0614-083**	0.6	94.2623	-8.3749	–	–	$5.58^{+1.16}_{-0.99}$
#2	**4FGL J0616.2-0653**	0.9	94.06	-6.90	–	–	≤ 0.89
#3	**PMN J0622-0657**	1.7	95.7419	-6.9478	–	87 ± 9	$0.62^{+1.48}_{-0.39}$
#4	**NVSS J062455-073536**	1.9	96.2306	-7.5936	–	50 ± 5	$0.37^{+1.82}_{-0.21}$
#5	**PMN J0618-0954**	2.1	94.5861	-9.9071	–	100	≤ 0.93
#6	**0605-085**	2.4	91.9987	-8.5805	0.87	2240 ± 226	$11.6^{+9.25}_{-2.89}$
#7	**PMN J0609-0615**	2.4	92.41656	-6.25163	2.219	48 ± 5	≤ 1.45
#8	**PMN J0606-0724**	2.6	91.68144	-7.40840	1.277	306 ± 31	$0.09^{+0.53}_{-0.06}$
#9	**PMN J0616-1040**	2.9	94.17420	-10.68568	–	248 ± 25	$2.82^{+1.5}_{-0.89}$
#10	**NVSS J060639-063421**	2.9	91.6667	-6.5721	–	–	$0.23^{+0.65}_{-0.09}$
#11	**PMN J0605-0759**	2.9	91.35911	-7.99216	–	67 ± 7	$1.99^{+1.04}_{-0.67}$
#12	**NVSS J060509-075747**	3.0	91.28843	-7.96308	–	–	$1.93^{+1.94}_{-0.88}$
#13	**PMN J0612-0700**	1.5	93.02018	-7.00635	–	62 ± 7	≤ 0.98
#14	**PMN J0614-0918**	1.7	93.52517	-9.31053	–	55 ± 6	≤ 0.85
#15	**PMN J0622-0846**	1.7	95.65833	-8.77174	–	109 ± 12	≤ 1.13
#16	**NVSS J061237-055244**	2.2	93.15567	-5.87900	–	45 ± 5	≤ 1.17
#17	**NVSS J061050-095934**	2.7	92.71130	-9.99277	–	94 ± 10	$0.19^{+0.75}_{-0.09}$

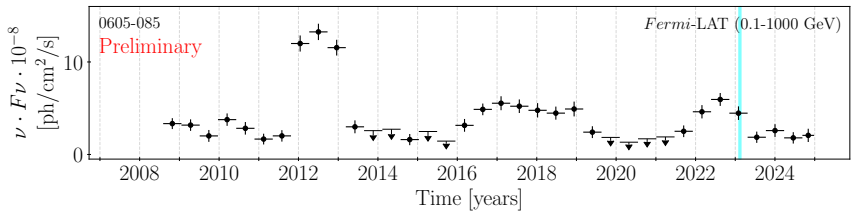
consistent with the event have been found to exhibit flaring or enhanced emission around the neutrino arrival time.

Thanks to the continuous, all-sky coverage granted by the *Fermi*-LAT instrument, the gamma-ray variability of all the candidate sources has been studied. Among them, 0605-085 exhibits a year-long gamma-ray flare, peaking about 180 days before the detection of KM3-230213A. Such a temporal coincidence may, however, arise by chance. This source is notably the brightest in radio, being among the top fifty brightest objects in the sky when ranked by VLBI flux.

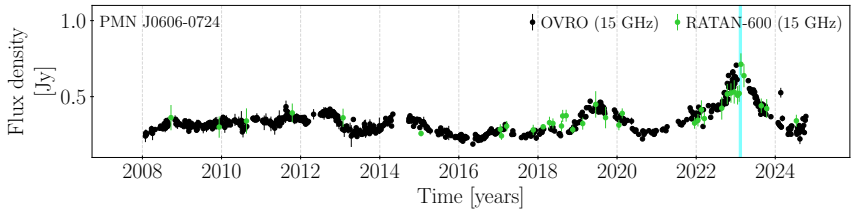
For three radio-bright candidate sources in the region, continuous radio coverage is available from the OVRO monitoring program of the Candidate Gamma-Ray Blazar Survey Source Catalog (CGRaBS), complemented by RATAN-600 observations. Among them, PMN J0606-0724 presents a major flare in close coincidence with the neutrino arrival time, occurring five days after the largest historical peak. From the full sample of $\sim$ 3000 OVRO CGRaBS lightcurves, the pre-trial chance probability of obtaining a coincidence with a time difference equal or smaller to the observed one is estimated at $p = 0.26\%$.

The candidate blazar MRC 0614-083, the closest object to the best-fit neutrino position in the sample, exhibits an X-ray flux enhancement in the four epochs of eROSITA observations, the last occurring about two years before the KM3-230213A detection. A target of opportunity (ToO) observation conducted with the X-ray Telescope (XRT) onboard the *Swift* Neil Gehrels Telescope

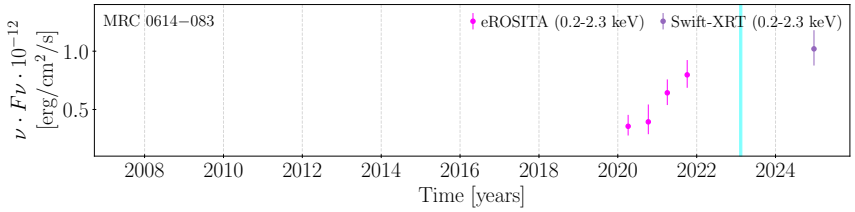
Observatory mission confirmed that the source maintained a X-ray enhanced state at the end of 2024. The multi-year gap in the data does not allow, however, to establish more in detail the time profile of the X-ray flux around the detection of the KM3NeT event. A super-Eddington accretion flare has been proposed as possible joint interpretation of the time-dependent multiwavelength signature of the object and the detection of a UHE neutrino from the source [15].



(a) The *Fermi*-LAT light curve of 0605-085, the brightest radio source in the neutrino localization region that experiences gamma-ray flaring activity around the neutrino arrival.



(b) The radio light curve for PMN J0606-0724, which shows a major flare in close coincidence with the neutrino arrival.



(c) The X-ray light curve for MRC 0614-083, indicating flaring activity around the neutrino arrival.

Figure 1: Summary of observational properties related to three notable blazars tentatively associated with the KM3-230213A event. The cyan line highlights the arrival time of KM3-230213A in each light curve.

5. Discussion

Assuming the typical relation between neutrino energy and parent proton energy, $E_p \simeq 20\, E_\nu$, the production of a neutrino at 220 PeV implies a source environment able to accelerate protons to a few EeV. AGN jets have been proposed as possible sources of ultra-high-energy cosmic rays that have been measured up to energies about two order of magnitudes larger ($\sim$ 300 EeV) [16], and theoretical models with fluxes peaking at hundreds of PeV are not uncommon for blazars [4]. The lack of a strong neutrino counterpart at lower energies appearing in time integrated searches, and the mild tension arising from the observation of KM3-230213A in KM3NeT and the upper

limits at the ultra-high-energies placed by IceCube and the Pierre Auger Observatory [8], suggest that flaring of transient phenomena may be of particular interest. It should be noted, as well, that the 220 PeV neutrino energy is estimated from the energy deposited by the outgoing muon in the KM3NeT instrumented volume, relying on an hypothetical power law flux $\propto E^{-2}$. Assuming a different spectral shape may produce a best-fit neutrino energy in excess of the quoted figure. Further considerations on the source energetics can be only of speculative nature, given that the detection of a single event does not allow to establish a lower limit on the flux of the hypothetical source. Besides the blazar hypothesis, other origins for KM3-230213A are possible, such a cosmogenic process or an otherwise undiscovered astrophysical transient.

6. Conclusion

By combining archival data and dedicated observations, seventeen candidate blazars positionally consistent with KM3-230213A have been identified and characterised in their multiwavelength and time-dependent properties. Flaring behaviour proximal to the neutrino arrival time is observed in three objects. Accounting for the a posteriori nature of the study, the number of candidates and the multiple electromagnetic bands that have been analysed, none of the observed coincidences can be claimed as statistically significant. While no object in the sample can be conclusively associated to the neutrino, blazars are among the most promising source candidates. Follow-up studies to characterise these sources by means of theoretical modelling efforts, and potential new astronomical observations, may be able to highlight the potential of specific objects as sources of ultra-high-energy neutrinos.

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