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The Impact of Southern-Hemisphere Radio Blazar Observations on Neutrino Astronomy

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The origin of high-energy cosmic neutrinos detected by the IceCube observatory is a hotly debated topic in astroparticle physics. There is growing evidence that some of these neutrinos can be associated with active galactic nuclei (AGN) and especially with blazars. Several recent studies have revealed a statistical correlation between radio-bright AGN samples and IceCube neutrino event catalogs. In addition, a growing number of individual high-energy neutrinos have been found to coincide with individual radio-flaring blazars. These observational results strongly call for high-quality, high angular-resolution radio observations of such neutrino-associated blazars to study their parsec-scale jet structures. TANAMI is the only large and long-term VLBI monitoring program focused on the Southern sky. Within TANAMI, we put an emphasis on Southern IceCube neutrino candidate blazars at 2.3 GHz and 8.4 GHz. Here we present first results of the first high-quality, high angular-resolution VLBI observations of nine Southern-Hemisphere blazars that were associated to IceCube neutrino hotspots in the Southern sky. In the near future, the rapidly growing KM3NeT will complement IceCube by being sensitive to high-energy neutrinos mainly from the Southern Hemisphere. This will increase the importance of Southern-Hemisphere radio monitoring programs of neutrino-associated blazars, like TANAMI.

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1. Introduction

In recent years, there has been increasing evidence that some high-energy cosmic neutrinos detected by the IceCube observatory can be associated with active galactic nuclei (AGN), especially with blazars. The IceCube Collaboration [1] reported a correlation of neutrinos with known γ-ray emitters at a significance of $3.3\,\sigma$ with the largest contributions from the nearby active galaxy NGC 1068 and the three blazars TXS 0506+056, PKS 1424+240 and GB6 J1542+6129. In addition, significant correlations have been claimed both between IceCube neutrinos and blazars from the Roma-5BZCat[1] catalog [2, 3], and with radio catalogs [4–7]. However, it has long been shown that known γ-ray blazars can contribute only a limited fraction to the observed diffuse neutrino flux [8]. A recent study [9] found that this fraction might be as small as $< 1\,\%$ and that the same is true for γ-undetected but radio-bright blazars from the radio fundamental catalog[2] (RFC). However, there are still associations between high-energy cosmic neutrinos and individual flaring blazars. Indeed, in 2017 an association of the track-like muon neutrino event IC 170922A with the γ-ray blazar TXS 0506+056 was found with a significance of $\sim 3\sigma$ [10]. Another example for such an association is the Southern-Hemisphere blazar PKS 1424−418 which was found to be associated with the IceCube neutrino event IC 35 (also known as 'BigBird') with a significance of $\sim 2\sigma$ [11].

Blazars are radio-loud AGN hosting relativistic jets pointed close to our line of sight. Their emission is highly beamed and Doppler-boosted, making them variable broadband emitters from radio to γ-ray energies. Their spectral energy distribution (SED) shows a double-humped spectrum. While the first component corresponds to synchrotron radiation, there are two different types of models that are used to explain the high-energy emission of blazars: inverse Compton scattering and hadronic emission models. In the latter, the high-energy emission is produced by the interactions of relativistic protons in the jet with soft ambient seed photons [12], and neutrino emission is naturally expected. The origin and properties of the seed photon fields are major open questions. On the one hand, the seed photon fields may originate from external regions of the AGN. On the other hand, an attractive model [13, 14] suggests that the high-energy protons of the fast inner spine of the blazar jet interact with soft target photons of the sheath, a slower jet layer surrounding the spine. Such spine-sheath structures can be revealed by radio observations using the technique of very-long-baseline interferometry (VLBI). Indeed, previous VLBI observations of the neutrino-associated blazars PKS 1424-418, TXS 0506+056 and PKS 1502+106 have found indications of a limb-brightend structure, as predicted by such spine-sheath models [11, 15, 16].

In this study we analyze 2.3 GHz VLBI observations of a sample of nine Southern-Hemisphere blazars that are associated with IceCube neutrino hotspots, according to [2], to search for properties that might be characteristic for neutrino-emitting AGN. These observations represent the first high-quality, high angular-resolution VLBI observations of these nine blazars at 2.3 GHz.

2. TANAMI

TANAMI (Tracking Active galactic Nuclei with Austral Milliarcsecond Interferometry) is the only large and long-term VLBI and multi-wavelength blazar monitoring program in the Southern

[1] https://www.ssdc.asi.it/bzcat5/
[2] http://astrogeo.org/rfc/

Hemisphere. It originally started in 2007 as a VLBI program observing extragalactic jets south of $-30°$ declination [17] and was then complemented with multi-wavelength observations at IR, optical/UV, X-ray and γ-ray energies and an additional radio flux density monitoring program using the Australian Telescope Compact Array (ATCA)[18]. There was also a close collaboration with the ANTARES neutrino telescope which was located in the Mediterranean Sea and therefore reached its highest sensitivity at declinations south of $-30°$, corresponding to the TANAMI sky [18]. From 2007 to 2020, TANAMI VLBI observations were performed at 8.4 GHz and 22.3 GHz using an array consisting of the five Australian Long Baseline Array (LBA) antennas, Parkes, ATCA, Hobart, Mopra and Ceduna, and an antenna in Hartebeesthoek, South Africa, as well as the 34 m and 70 m telescopes of the NASA Deep Space Network in Tidbinbilla. This array was further complemented by two German International VLBI Service (IVS) antennas, GARS at O'Higgins, Antarctica, and TIGO which was first at Concepción, Chile, and later was moved to La Plata, Argentina [18]. Since 2020 the TANAMI sky has been extended to the entire Southern sky, which means that also blazars between $0°$ and $-30°$ declination are included in the TANAMI sample. Furthermore, to detect faint TeV-detected sources and neutrino candidate blazars, 2.3 GHz observations, using an array consisting of the five LBA antennas, the Hartebeesthoek telescope, the Tidbinbilla stations and three IVS antennas, Katherine and Yarragadee in Australia and Warkworth in New Zealand, have been added to the monitoring program.

3. The Sample

In 2022, a sample of ten Southern-Hemisphere blazars from the Roma-5BZCat catalog were associated with IceCube neutrino hotspots in the Southern sky [2]. This sample includes five quasars, three BL Lac objects, and two blazars of uncertain classification (BZU). One source, 1814−637 (5BZU J1819−6345), has already been observed at 8.4 GHz with TANAMI in 2008 and its morphology shows a compact symmetric structure [17] (see also [19, 20]). The other nine sources are likely blazars which we observed in August 2022 for the first time at VLBI resolutions at 2.3 GHz using the TANAMI array. These nine sources are listed in Table 1 and their high-image-fidelity brightness distributions on parsec scales are presented in this study (see Fig. 1).

4. TANAMI Observations at 2.3 GHz

To study the jet morphology and brightness temperature distribution of the nine sample sources presented in Sect. 3, we observed them with the TANAMI array at 2.3 GHz on August 6 and 7, 2022. The data were calibrated and imaged using the programs `AIPS` [21] and `DIFMAP` [22], respectively, in a similar way as presented in [17]. The resulting naturally weighted images are shown in Fig. 1 and their image parameters are listed in Table 1. The relative uncertainties of the flux densities are estimated to be 20 % [17]. Most of the sources are relatively faint with total integrated flux densities of around 100 – 200 mJy or below and are very compact showing a bright core component and faint jets. The quasar 2000−330 is the brightest source with an integrated flux density of $\sim$ 600 mJy and a prominent jet to the northwest.

To study the distribution of the sources' core brightness temperatures, we fitted 2D Gaussian components to the fully imaged and self-calibrated visibilities using the `modelfit` command in

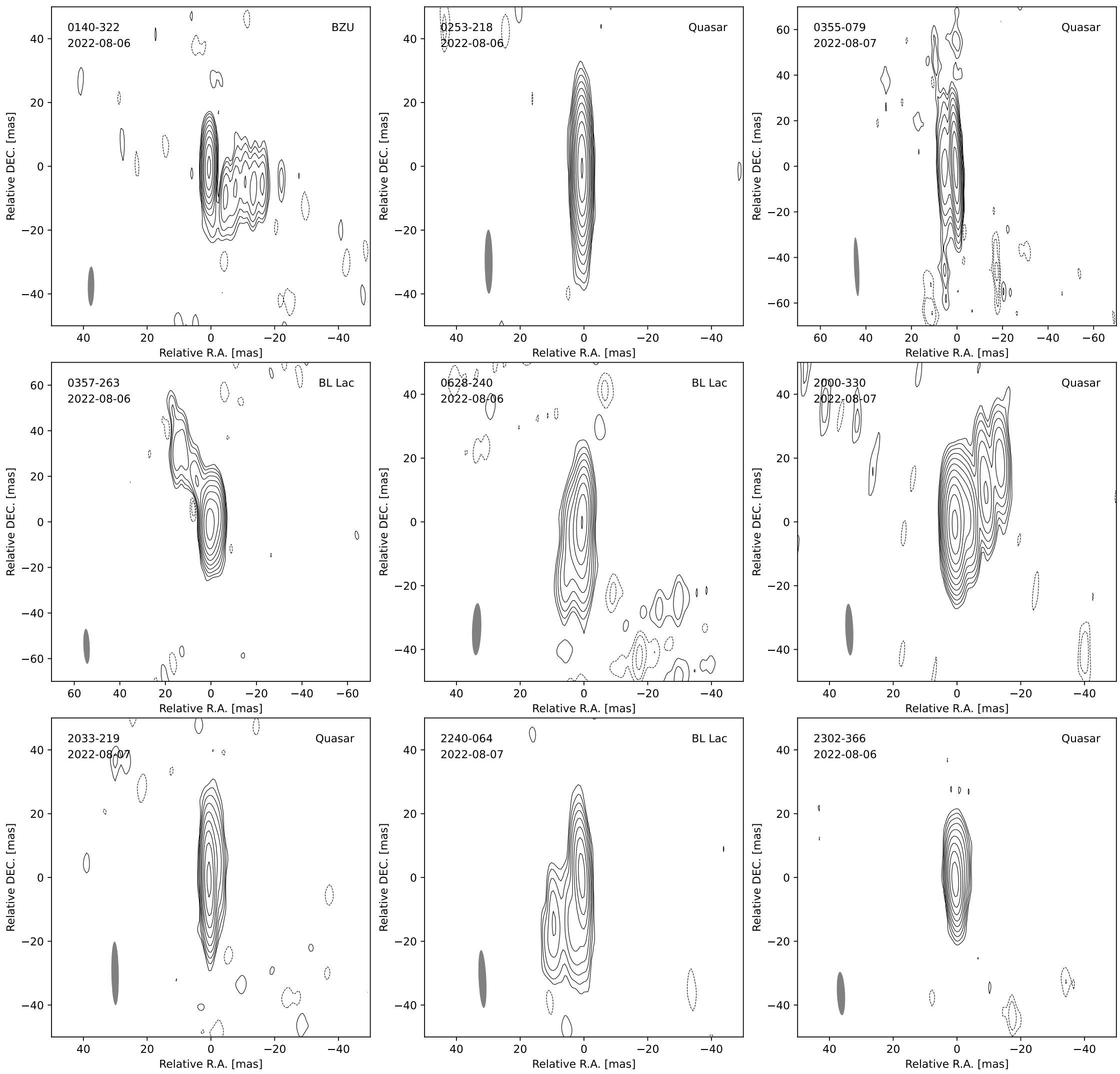

Figure 1: *Preliminary naturally weighted* 2.3 *GHz TANAMI images of Southern-Hemisphere blazars associated with IceCube neutrino hotspots according to* [2]*. The contours start at* 3σ *and increase logarithmically by factors of* 2*. The grey ellipse in the bottom left corner of each image corresponds to the size of the beam. The beam parameters are listed in Table* 1.

DIFMAP. Based on the parameters of these Gaussian components we calculated the brightness temperatures of the core in the source's rest frame using Eq. 3 of [26]. We also calculated the resolution limit of the core components based on Eq. 2 of [26]. Whenever an axis of the fitted Gaussian components was smaller than the corresponding resolution limit, we considered that component to be unresolved and used the corresponding resolution limit as an upper limit of its size to calculate a lower limit of the brightness temperature. However, the brightness temperatures of resolved core components should also be treated as lower limits, since even smaller structures inside the VLBI cores could dominate their emission [17]. The derived brightness temperatures of the core components are listed in Table 1 and their distribution is shown in Fig. 2. It can be seen that the brightness temperatures of the three BL Lac objects in the sample are all below the equipartition

Name B1950 (1)	z (2)	$S_{\rm tot}$ [Jy] (3)	$S_{\rm peak}$ [Jy/beam] (4)	$\sigma_{\rm rms}$ [mJy/beam] (5)	$b_{\rm maj}$ [mas] (6)	$b_{\rm min}$ [mas] (7)	P.A. [deg] (8)	$T_{\rm B}$ [K] (9)
0140−322	0.375	0.101	0.074	0.077	12.4	2.06	-0.552	$> 1.30 \cdot 10^{10}$
0253−218	1.47	0.144	0.138	0.042	20.1	2.50	0.457	$9.01 \cdot 10^{10}$
0355−079	1.05	0.176	0.142	0.129	25.9	2.25	2.42	$> 4.63 \cdot 10^{11}$
0357−263	1.47^a	0.277	0.138	0.111	15.4	2.80	2.41	$8.57 \cdot 10^{9}$
0628−240	$>1.239^b$	0.057	0.041	0.051	16.3	2.89	-2.04	$> 4.66 \cdot 10^{9}$
2000−330	3.78^c	0.594	0.365	0.096	16.2	2.48	2.21	$1.44 \cdot 10^{12}$
2033−219	2.299	0.170	0.155	0.163	19.9	2.33	0.971	$1.57 \cdot 10^{11}$
2240−064	0.30	0.098	0.063	0.112	18.2	2.42	2.66	$3.67 \cdot 10^{9}$
2302−366	0.962	0.034	0.030	0.025	13.6	2.56	2.70	$9.24 \cdot 10^{9}$

Table 1: *Image parameters and brightness temperatures of the observed neutrino candidate blazars. Col.(1): B1950 name; Col.(2): Redshift taken from [2], ^{a}redshift taken from [23], ^{b}redshift taken from [24], ^{c}redshift taken from [25]; Col.(3): Integrated total flux density; Col.(4): Highest flux density per beam; Col.(5): Noise level per beam; Col.(6): FWHM of the major axis of the beam; Col.(7): FWHM of the minor axis of the beam; Col.(8): Position angle of the major axis of the beam with respect to the beam's centroid (measured north through east); Col.(9): Brightness temperature of the core component.*

value of $T_{\rm eq} \approx 5 \cdot 10^{10}$ K [27], while four out of five quasars show brightness temperatures above the equipartition value and only one of these four quasars exceeds the inverse Compton limit of $\approx 10^{12}$ K [28]. Interestingly, this brightness temperature distribution is similar to that found for TeV-detected blazars observed at 2.3 GHz within the TANAMI program (Benke et al. in prep.).

5. Conclusion and Outlook

We have for the first time observed a sample of nine blazars associated with IceCube neutrino hotspots by [2] at 2.3 GHz in the TANAMI program at parsec-scale resolutions and calculated the brightness temperatures of their core components. The resulting distribution of these brightness temperatures is similar to the brightness temperature distribution of TeV-bright blazars observed with the TANAMI array at 2.3 GHz (Benke et al. in prep.). TeV-detected high-peaked BL Lac objects tend to show low brightness temperatures, indicating low Doppler factors of the radio-emitting plasma. To explain this, and at the same time the high Doppler factors inferred for the same sources from higher energy observations, models suggesting separate emission regions with different Doppler factors are discussed [e.g., 29]. The comparability of the neutrino candidate blazars in this sample with respect to TeV blazars opens the interesting possibility to interpret neutrino production models in a similar scenario [e.g., 13, 14]. However, we need to observe a larger sample of neutrino candidate blazars to test this hypothesis in more detail. In the future, the rapidly growing KM3NeT neutrino telescope in the Mediterranean Sea could provide such a sample of Southern-Hemisphere neutrino-associated blazars, since it is particularly sensitive to neutrino-emitting sources in the Southern sky [30]. This underlines the importance of Southern-Hemisphere radio monitoring programs such as TANAMI.

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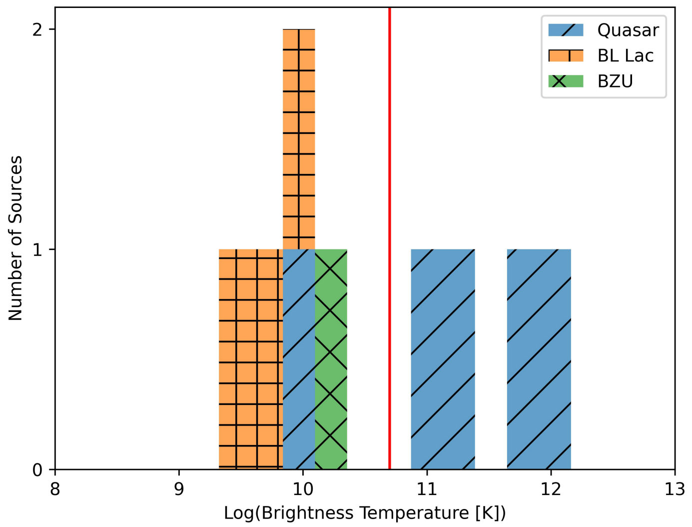

Figure 2: *Distribution of the brightness temperatures of the core components of the observed neutrino-associated blazars. The red line indicates the equipartition value of* $T_{\mathrm{eq}} \approx 5 \cdot 10^{10}$ K [27].

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References

[1] IceCube Collaboration, R. Abbasi, M. Ackermann, J. Adams, J.A. Aguilar, M. Ahlers et al., *Evidence for neutrino emission from the nearby active galaxy NGC 1068*, *Science* **378** (2022) 538 [2211.09972].

[2] S. Buson, A. Tramacere, L. Pfeiffer, L. Oswald, R. de Menezes, A. Azzollini et al., *Beginning a Journey Across the Universe: The Discovery of Extragalactic Neutrino Factories*, ApJ **933** (2022) L43 [2207.06314].

[3] S. Buson, A. Tramacere, L. Oswald, E. Barbano, G. Fichet de Clairfontaine, L. Pfeiffer et al., *Extragalactic neutrino factories*, *arXiv e-prints* (2023) arXiv:2305.11263 [2305.11263].

[4] T. Hovatta, E. Lindfors, S. Kiehlmann, W. Max-Moerbeck, M. Hodges, I. Liodakis et al., *Association of IceCube neutrinos with radio sources observed at Owens Valley and Metsähovi Radio Observatories*, A&A **650** (2021) A83 [2009.10523].

[5] A. Plavin, Y.Y. Kovalev, Y.A. Kovalev and S. Troitsky, *Observational Evidence for the Origin of High-energy Neutrinos in Parsec-scale Nuclei of Radio-bright Active Galaxies*, ApJ **894** (2020) 101 [2001.00930].

[6] A.V. Plavin, Y.Y. Kovalev, Y.A. Kovalev and S.V. Troitsky, *Directional Association of TeV to PeV Astrophysical Neutrinos with Radio Blazars*, ApJ **908** (2021) 157 [2009.08914].

[7] A.V. Plavin, Y.Y. Kovalev, Y.A. Kovalev and S.V. Troitsky, *Growing evidence for high-energy neutrinos originating in radio blazars*, MNRAS **523** (2023) 1799 [2211.09631].

[8] M.G. Aartsen, K. Abraham, M. Ackermann, J. Adams, J.A. Aguilar, M. Ahlers et al., *The Contribution of Fermi-2LAC Blazars to Diffuse TeV-PeV Neutrino Flux*, ApJ **835** (2017) 45 [1611.03874].

[9] R. Abbasi, M. Ackermann, J. Adams, S.K. Agarwalla, J.A. Aguilar, M. Ahlers et al., *Search for correlations of high-energy neutrinos detected in IceCube with radio-bright AGN and gamma-ray emission from blazars*, *arXiv e-prints* (2023) arXiv:2304.12675 [2304.12675].

[10] IceCube Collaboration, M.G. Aartsen, M. Ackermann, J. Adams, J.A. Aguilar, M. Ahlers et al., *Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A*, *Science* **361** (2018) eaat1378 [1807.08816].

[11] M. Kadler, F. Krauß, K. Mannheim, R. Ojha, C. Müller, R. Schulz et al., *Coincidence of a high-fluence blazar outburst with a PeV-energy neutrino event*, *Nature Physics* **12** (2016) 807 [1602.02012].

[12] K. Mannheim, *The proton blazar.*, A&A **269** (1993) 67 [astro-ph/9302006].

[13] F. Tavecchio, G. Ghisellini and D. Guetta, *Structured Jets in BL Lac Objects: Efficient PeV Neutrino Factories?*, ApJ **793** (2014) L18 [1407.0907].

[14] F. Tavecchio and G. Ghisellini, *High-energy cosmic neutrinos from spine-sheath BL Lac jets*, MNRAS **451** (2015) 1502 [1411.2783].

[15] E. Ros, M. Kadler, M. Perucho, B. Boccardi, H.M. Cao, M. Giroletti et al., *Apparent superluminal core expansion and limb brightening in the candidate neutrino blazar TXS 0506+056*, A&A **633** (2020) L1 [1912.01743].

[16] V. Karamanavis, L. Fuhrmann, T.P. Krichbaum, E. Angelakis, J. Hodgson, I. Nestoras et al., *PKS 1502+106: A high-redshift Fermi blazar at extreme angular resolution. Structural dynamics with VLBI imaging up to 86 GHz*, A&A **586** (2016) A60 [1511.01085].

[17] R. Ojha, M. Kadler, M. Böck, R. Booth, M.S. Dutka, P.G. Edwards et al., *TANAMI: tracking active galactic nuclei with austral milliarcsecond interferometry . I. First-epoch 8.4 GHz images*, A&A **519** (2010) A45 [1005.4432].

[18] M. Kadler, R. Ojha and TANAMI Collaboration, *TANAMI: Multiwavelength and multimessenger observations of active galaxies*, Astronomische Nachrichten **336** (2015) 499 [1506.03947].

[19] A. Tzioumis, E. King, R. Morganti, D. Dallacasa, C. Tadhunter, C. Fanti et al., *A sample of southern Compact Steep Spectrum radio sources: The VLBI observations*, A&A **392** (2002) 841 [astro-ph/0207495].

[20] R. Morganti, J. Holt, C. Tadhunter, C. Ramos Almeida, D. Dicken, K. Inskip et al., *PKS 1814-637: a powerful radio-loud AGN in a disk galaxy*, A&A **535** (2011) A97 [1109.0630].

[21] E.W. Greisen, *AIPS, the VLA, and the VLBA*, in *Information Handling in Astronomy - Historical Vistas*, A. Heck, ed., vol. 285 of *Astrophysics and Space Science Library*, p. 109, Mar., 2003, DOI.

[22] M.C. Shepherd, T.J. Pearson and G.B. Taylor, *DIFMAP: an interactive program for synthesis imaging.*, in BAAS, vol. 26, pp. 987–989, May, 1994.

[23] M.J. Drinkwater, R.L. Webster, P.J. Francis, J.J. Condon, S.L. Ellison, D.L. Jauncey et al., *The Parkes Half-Jansky Flat-Spectrum Sample*, MNRAS **284** (1997) 85 [astro-ph/9609019].

[24] M.S. Shaw, R.W. Romani, G. Cotter, S.E. Healey, P.F. Michelson, A.C.S. Readhead et al., *Spectroscopy of the Largest Ever γ-Ray-selected BL Lac Sample*, ApJ **764** (2013) 135 [1301.0323].

[25] B.A. Peterson, A. Savage, D.L. Jauncey and A.E. Wright, *PKS 2000-330 : a quasi-stellar radio source with a redshift of 3.78.*, ApJ **260** (1982) L27.

[26] Y.Y. Kovalev, K.I. Kellermann, M.L. Lister, D.C. Homan, R.C. Vermeulen, M.H. Cohen et al., *Sub-Milliarcsecond Imaging of Quasars and Active Galactic Nuclei. IV. Fine-Scale Structure*, AJ **130** (2005) 2473 [astro-ph/0505536].

[27] A.C.S. Readhead, *Equipartition Brightness Temperature and the Inverse Compton Catastrophe*, ApJ **426** (1994) 51.

[28] K.I. Kellermann and I.I.K. Pauliny-Toth, *The Spectra of Opaque Radio Sources*, ApJ **155** (1969) L71.

[29] G. Ghisellini, F. Tavecchio and M. Chiaberge, *Structured jets in TeV BL Lac objects and radiogalaxies. Implications for the observed properties*, A&A **432** (2005) 401 [astro-ph/0406093].

[30] S. Adrián-Martínez, M. Ageron, F. Aharonian, S. Aiello, A. Albert, F. Ameli et al., *Letter of intent for KM3NeT 2.0*, *Journal of Physics G Nuclear Physics* **43** (2016) 084001 [1601.07459].