ANTARES Constrains a Blazar Origin of Two IceCube PeV Neutrino Events

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Abstract

The source(s) of the neutrino excess reported by the IceCube Collaboration is unknown. The TANAMI Collaboration recently reported on the multiwavelength emission of six bright, variable blazars which are positionally coincident with two of the most energetic IceCube events. Such objects are prime candidates to be the source of the

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highest-energy cosmic rays, and thus of associated neutrino emission. We present an analysis of neutrino emission from the six blazars using observations with the ANTARES neutrino telescope. The standard methods of the ANTARES candidate list search are applied to six years of data to search for an excess of muons — and hence their neutrino progenitors — from the directions of the six blazars described by the TANAMI Collaboration, and which are possibly associated with two IceCube events. Monte Carlo simulations of the detector response to both signal and background particle fluxes are used to estimate the sensitivity of this analysis for different possible source neutrino spectra. A maximum-likelihood approach, using the reconstructed energies and arrival directions of through-going muons, is used to identify events with properties consistent with a blazar origin.Both blazars predicted to be the most neutrino-bright in the TANAMI sample ($1653-329$ and $1714-336$) have a signal flux fitted by the likelihood analysis corresponding to approximately one event. This observation is consistent with the blazar-origin hypothesis of the IceCube event IC14 for a broad range of blazar spectra, although an atmospheric origin cannot be excluded. No ANTARES events are observed from any of the other four blazars, including the three associated with IceCube event IC20. This excludes at a 90% confidence level the possibility that this event was produced by these blazars unless the neutrino spectrum is flatter than -2.4.

1 Introduction

Since the initial report of the observation of two high-energy ($\sim$PeV) neutrino-induced cascades by the IceCube Collaboration [Aartsen et al., 2013], further observations using the high-energy starting-event (HESE) analysis have revealed an excess of events consistent with an isotropic, flavour-uniform flux of astrophysical neutrinos [IceCube Collaboration, 2013, Aartsen et al., 2014b,a]. The small number of excess events (37 total, with an estimated background of 15), and directional resolution of typically $10°$ or worse for cascades, makes it difficult to resolve potential features of this flux, such as a spectral downturn above PeV energies, a steeper spectral index, and/or a contribution from one or more point-like sources of neutrinos. Consequently, many suggestions for the nature and origin(s) of this flux have been put forward. Of particular note is the suggestion of a point-source near the Galactic Centre producing the observed excess in that region [Razzaque, 2013], a hypothesis already constrained by the ANTARES Collaboration [Adrián-Martínez et al., 2014a].

The TANAMI Collaboration has recently reported observations of six

bright, variable blazars (see Table 2) in positional coincidence with the range of possible arrival directions of the two PeV IceCube events IC14 and IC20 [Krauß et al., 2014][1]. Using a simple calculation based on the observed 1 keV to 10 GeV photon flux, the authors estimate that 1.9 ± 0.4 electron neutrino events at PeV energies would be expected in 662 days of IceCube data. This estimate compares well with the two observed events IC14 and IC20. Even taking this only as an order-of-magnitude indication of the expected event rate, a higher-resolution follow-up study of these objects is of great interest. Here, we present such an analysis using six years of data from the ANTARES neutrino telescope.

2   Target blazars and possible neutrino fluxes

The six blazars associated with the IC14 and IC20 fields by Krauß et al. [2014] are listed in Table 2. All exhibit prominent high-energy photon emission, and all but one are classified as flat-spectrum radio quasars (FSRQs) [Véron-Cetty and Véron, 2006][2]. The predictions of the expected number of detected electron neutrino events were made by assuming a neutrino energy $E_\nu = 1$ PeV and a flavour-uniform flux, with total energy flux equal to that in high-energy photons. Active galactic nuclei (AGN) of all classes have long been proposed as sites of hadronic interaction, and are potential sources of the highest-energy cosmic rays and, hence, neutrinos [Berezinskii and Smirnov, 1975, Hillas, 1984, Stecker and Salamon, 1996, Padovani and Resconi, 2014]. Predictions for the neutrino flux depend on the nature of the AGN considered, the cosmic-ray composition and flux, and the assumed densities of target hadronic matter and photon fields [Mannheim, 1995, Becker, 2008, Becker Tjus et al., 2014].

The emphasis on the two PeV events (IC14 and IC20; see Aartsen et al. [2014a] for a full list) comes from the fact that these two highest-energy events have only a negligible probability for an atmospheric origin. Moreover, Dermer et al. [2014] calculated that for typical FSRQs, the neutrino flux resulting from cosmic ray p-γ interactions should peak near a few PeV, with the primary target photon field being Lyman-series emission from the broad-line region. Other calculations of a neutrino flux from p-γ interactions

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[1]The paper was released before the third PeV event, IC35 ('Big Bird'), was made public. A search for possible blazar associations with this event is in preparation by the TANAMI Collaboration.

[2]The exception is the source $1714-336$, which has been classified as a BL Lac object. However, Krauß et al. [2014] find a prominent UV excess suggesting a possible reclassification as a FSRQ.

Source	Cat. Name	R.A. [°]	Dec. [°]	Class	z	F_γ [GeV cm^{-2} s^{-1}]	N_{ν_e}	IC
0235−618	PKS 0235−618	39.2218	−61.6043	Q	0.47^a	$(6.2^{+3.1}_{-3.1}) \times 10^{-8}$	$0.19^{+0.04}_{-0.04}$	20, 7
0302−623	PKS 0302−623	45.9610	−62.1904	Q	1.35^a	$(2.1^{+0.4}_{-0.4}) \times 10^{-8}$	$0.06^{+0.01}_{-0.01}$	20
0308−611	PKS 0308−611	47.4838	−60.9775	Q	1.48^a	$(4.7^{+1.8}_{-1.8}) \times 10^{-8}$	$0.14^{+0.05}_{-0.05}$	20
1653−329	Swift J1656.3−3302	254.0699	−33.0369	Q	2.40^b	$(2.8^{+0.3}_{-0.3}) \times 10^{-7}$	$0.86^{+0.10}_{-0.10}$	14, 2, 25
1714−336	TXS 1714−336	259.4001	−33.7024	B/Q	?	$(1.5^{+0.3}_{-0.4}) \times 10^{-7}$	$0.46^{+0.10}_{-0.12}$	14,2,25
1759−396	MRC 1759−396	270.6778	−39.6689	Q	1.32^c	$(7.5^{+1.9}_{-1.9}) \times 10^{-8}$	$0.23^{+0.50}_{-0.40}$	14, 2, 15, 25

Table 1: Basic data on the six blazars studied in this analysis. Columns: (1) IAU B1950 name; (2) Common catalog name; (3,4) J2000 coordinates; (5) Classification: Q – Flat Spectrum Radio Quasar, B – BL Lac object; (6) Redshift: [a] Healey et al. [2008], [b] Cutri et al. [2003], [c] Massaro et al. [2009]; (7) Total high-energy photon flux from Krauß et al. [2014]; (8) Estimated number N_{ν_e} of ν_e events in the IceCube 662-day analysis [IceCube Collaboration, 2013]; (9) IC gives the IceCube event IDs from Aartsen et al. [2014a] with which the blazars are positionally consistent within the angular error range from IceCube Collaboration [2013].

in blazars however have produced less-peaked spectra, e.g., that by Atoyan and Dermer [2001], who show that external radiation fields in 3C 279 can produce a flux of neutrinos slightly harder than E_ν^{-2} in the approximate range of 30 TeV–1 EeV.

Including p-p interactions can also lead to a neutrino flux at sub-PeV energies, which is expected to closely follow the cosmic-ray spectrum. In the case of a pure power-law proton spectrum $dN_p/dE_p \propto E_p^{-s_p}$, the pion, and hence — in a diffuse environment — neutrino spectrum reduces approximately to $dN_\nu/dE_\nu \propto E_\nu^{-s_\nu}$, with $s_\nu = \frac{4}{3}(s_p - \frac{1}{2})$ [Mannheim and Schlickeiser, 1994, Kelner et al., 2006]. Thus the simple Fermi acceleration model with $s_p = 2$ produces $s_\nu = 2$. More-detailed modelling of shock acceleration processes in AGN by Meli and Biermann [2012] has suggested that an initial accelerating shock in an AGN jet might produce an index of $s_p = 2.7$ ($s_\nu = 2.93$), while further shock acceleration leads to a flattening of the spectrum, producing $s_p = 2.4$ ($s_\nu = 2.53$) — which is nonetheless softer than the default $s_\nu = 2$ advocated by, e.g., Waxman and Bahcall [1999]. The incorporation of both p-p and p-γ interactions into full Monte Carlo calculations of particle interactions in a blazar environment confirms these expectations of a neutrino flux at sub-PeV energies [Szabo and Protheroe, 1994].

The IceCube observations allow for the possibility of a sub-PeV flux of neutrinos from the sample blazars, in that four other events are positionally associated with the blazar sample (see Table 2). This is also consistent with the prediction of two ν_e charged-current (CC) events, since the low flavour-dependence of the IceCube HESE effective area at the highest energies means an equal number of ν_μ and ν_τ events would be expected, but with a lower deposited energy. While these additional four events do not represent a significant excess above a diffuse background, the possibility that they may originate from the blazars in question should also be tested.

3 ANTARES candidate list search and expected sensitivity

ANTARES is an underwater neutrino telescope located in the Mediterranean Sea off the coast of Toulon, at $42°48'$ N, $6°10'$ E [Ageron et al., 2011]. Consisting of an array of photomultiplier tubes, it is designed to record the induced Cherenkov light from the passage of energetic charged particles to infer the interactions of neutrinos.

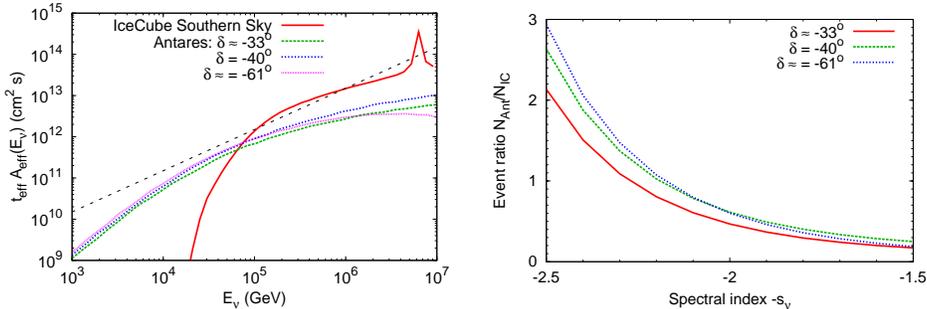The ANTARES candidate list search (CLS) methodology is described in

Figure 1: (left) Relative exposures of the ANTARES CLS [Adrián-Martínez et al., 2012] to a flavour-uniform neutrino flux from the characteristic declinations of the six blazars of Table 2, and the Southern-Sky-average of the IceCube HESE analysis [Aartsen et al., 2014a] (exposures from IceCube Collaboration [2013]). The black dashed line, included for reference purposes, is proportional to E_ν. (right) Expected number of ANTARES events per detected IceCube event for power-law spectra (Eq. 1) as a function of the neutrino spectral index $-s_\nu$, calculated using the relative exposures.

Adrián-Martínez et al. [2012], with the latest results using six years of data (1338 days effective livetime) presented in Adrián-Martínez et al. [2014a]. The search uses only up-going muons (i.e., those originating from below the horizon), with cuts placed on the fit-quality of the muon track reconstruction and the estimated angular error. The long range of relativistic muons in seawater and the Earth's crust extends the effective detection volume to well beyond the physical size of the detector, in contrast with a HESE-like analysis. The six-year sample consists of 5516 events, with an estimated atmospheric muon contamination of 10%, and an estimated median angular resolution of $0.38°$. A maximum-likelihood method is then used to estimate the relative contributions of signal and background fluxes, based on both the reconstructed event arrival directions and the fitted number of photon hits (a robust proxy for energy). Note that this method results in a non-integer number of signal events N_{sig} being estimated, since the signal and background fluxes maximising the likelihood of a given observation can take any normalisation. Note also that it is optimised assuming an E_ν^{-2} source spectrum, and it is sensitive almost exclusively to muon neutrinos.

The ability of the ANTARES CLS to probe the PeV-neutrino blazar-origin hypotheses of Krauß et al. [2014] can be seen from Fig. 1, which compares the time-integrated, flavour-averaged exposures of the ANTARES CLS

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(Adrián-Martínez et al. [2014a]; 1338 days, using one third of the effective area to muon neutrinos) at the characteristic declinations of the six blazars considered here, to that of the IceCube HESE analysis, averaged over the Southern Hemisphere (IceCube Collaboration [2013]; now updated to 998 days by Aartsen et al. [2014a], averaged over all three neutrino flavours). It can be seen that below approximately 100 TeV, ANTARES has a greater sensitivity to a neutrino flux from the six blazars at the given southern declinations than the recent IceCube HESE analysis. Due to the greater size of the IceCube detector, the effects of Earth absorption, and its sensitivity to all three neutrino flavours, the IceCube analysis has a significantly greater sensitivity at the highest energies. In particular, at an energy of 1 PeV, the exposure of IceCube to a flavour-uniform flux is approximately four times that of ANTARES. Therefore, the relative utility of an ANTARES analysis of the neutrino emission of these blazars will depend strongly on the energy spectrum of that flux.

The predictions for the number of IceCube-detected PeV neutrino events by Krauß et al. [2014], shown in Table 2, were based on equating the neutrino flux at 1 PeV to the integrated photon flux between 1 keV and 10 GeV. While — as discussed in Sect. 2 — the expected neutrino-flux shape is highly model-dependent, the prediction that the total neutrino energy flux F_ν (GeV cm^{-2} s^{-1}) is approximately equal to the total high-energy photon flux F_γ is relatively robust, at least when attributing this emission to a 100% hadronic origin. The black-dashed line in Fig. 1 is proportional to neutrino energy E_ν and normalised to the IceCube exposure at 1 PeV, i.e., it is a line of equal sensitivity to a neutrino flux F_ν. For constant F_ν, it is clear that the IceCube HESE analysis is most sensitive to a flux at a few hundred TeV, while the ANTARES CLS is most sensitive near 30 TeV.

A range of potential neutrino fluxes, $\Phi_\nu(E_\nu)$ (defined as the differential number-density flux dN_ν/dE_ν), can be characterised by generic power-law spectra of the form:

$$\Phi_\nu(E_\nu) \;\; = \;\; \Phi_0 \left(\frac{E_\nu}{1\ \mathrm{GeV}} \right)^{-s_\nu} \quad [\mathrm{GeV}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}]. \qquad (1)$$

The relative numbers of events expected to be observed by ANTARES compared to IceCube for such spectra are shown in Fig. 1 (right). For a spectral index $-s_\nu < -2.2$, ANTARES is expected to observe more events, while IceCube would observe more for $-s_\nu > -2.2$.

For each spectral index $-s_\nu$ and source declination δ, the required neutrino flux $\Phi_\nu^*(E_\nu, \delta)$ expected to produce a single ANTARES event can be
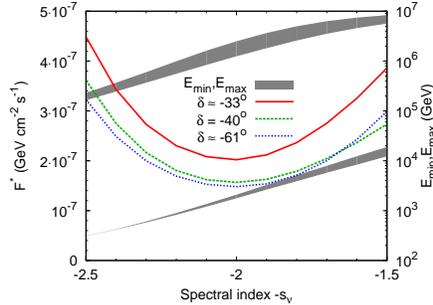
Figure 2: Neutrino flux F_ν^* required to produce one neutrino event in ANTARES as a function of spectral index s_ν (Eq. 4). The corresponding energy ranges of integration $E_{\min}$ and $E_{\max}$ (Eq. 3) are shown as lower and upper shaded regions respectively — the shading covers the variation due to declination.

found from the following expression:

$$\int_0^\infty t_{\text{eff}}\, A_{\text{eff}}(E_\nu)\, \Phi_\nu^*(E_\nu, \delta)\, dE_\nu \quad = \quad 1, \tag{2}$$

where $A_{\text{eff}}(E_\nu, \delta)$ and t_{eff} are respectively the ANTARES effective area and observation time. While the total energy in such a flux is infinite, the energy over the sensitive range of ANTARES can be calculated by defining characteristic energies $E_{\min}(\delta, s_\nu)$ and $E_{\max}(\delta, s_\nu)$ such that:

$$\int_{E_{\min}}^{E_{\max}} t_{\text{eff}}\, A_{\text{eff}}(E_\nu, \delta)\, \Phi_\nu^*(E_\nu, \delta)\, dE_\nu \quad = \quad 0.9, \tag{3}$$

with 0.05 below $E_{\min}$ and 0.05 above $E_{\max}$. The total neutrino energy flux $F_\nu^*(\delta, s_\nu)$ in the range $E_{\min} \leq E_\nu \leq E_{\max}$ required to produce one event can then be calculated from $\Phi_\nu^*(E_\nu, \delta)$ as:

$$F_\nu^*(\delta, s_\nu) \quad = \quad \frac{1}{0.9} \int_{E_{\min}}^{E_{\max}} \Phi_\nu^*(E_\nu, \delta)\, E_\nu\, dE_\nu \quad [\text{GeV cm}^{-2}\text{ s}^{-1}]. \tag{4}$$

$F_\nu^*(\delta, s_\nu)$ is plotted in Fig. 2, along with $E_{\min}$ and $E_{\max}$. Comparing this with the total blazar photon flux calculated by Krauß et al. [2014] and reported in Table 2, it is clear that the detection of one or more neutrinos from power-law spectra in the range $-2.5 < -s_\nu < -1.5$ would be consistent with the observed source photon fluxes F_γ.

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Having established a wide range of plausible neutrino flux scenarios, and the sensitivity of the ANTARES CLS to neutrino fluxes over a broad range of energies, we therefore perform the standard ANTARES CLS for an excess of neutrino emission from the blazars listed in Table 2.

4   Results and discussion

The results of the ANTARES analysis of the six blazars are given in Table 4. For four of the six targets, no source-like neutrinos were identified ($N_{\mathrm{sig}} = 0$), allowing relatively strong upper limits to be placed on an E_ν^{-2} flux. The blazars $1653-329$ and $1714-336$ were each fitted as having approximately one nearby signal-like event, with N_{sig} of 1.1 and 0.9 respectively[3]. This observation is well within the expected background fluctuations however, with pre-trial p-values (probability of the likelihood procedure fitting a stronger signal flux to background-only data) of 0.10 and 0.04 respectively[4]. Nonetheless, it must be noted that these two blazars are the two with the highest predicted neutrino fluxes (see Table 2), and that from Fig. 1 (right), neutrino fluxes with spectral indices between -2.5 and -2.3 producing one IceCube event would be expected to produce between one and two ANTARES events. Therefore, when the calculation of Krauß et al. [2014] is extended to include power-law neutrino spectra, the result of the analysis is consistent with the sample blazars being neutrino sources with fluxes in proportion to their observed high-energy photon flux (F_γ in Table 2), even if the result is also consistent with background.

Limits at a 90% confidence level (C.L.), Φ_ν^{90}, on the spectra from Eq. 1 are generated from the ANTARES observations as a function of s_ν over the approximate predicted range (between 1.5 and 2.5), using the method of Neyman [1937]. These, all of which are upper limits, are given in Fig. 3 (left). Φ_ν^{90} is given at 100 TeV, because this is both the approximate energy at which the ANTARES and IceCube analyses have equal exposures, and where the flux limit is least sensitive to s_ν.

Constraints can be placed on a blazar origin of the IceCube events given in Table 2. The flux limits shown in Fig. 3 (left) correspond to a maximum expected number $N_{\nu,IC}^{90}$ of events observed by IceCube; where this number is less than the observed number of events, a blazar origin can be

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[3]The maximum-likelihood procedure estimates N_{sig} as a continuous variable, as discussed in Sect. 3.

[4]The correct penalty factor for multiple trials is 61, including the six blazars considered here, and 55 trials from other analyses using the CLS [Adrián-Martínez et al., 2014a,b]

Source	$N_{\rm sig}$	p	Limit $10^{-8}\,\mathrm{GeV^{-1}\,cm^{-2}\,s^{-1}}$	$N_{\nu,IC}=1$	$N_{\nu,IC}=2$	$N_{\nu,IC}=3$	$N_{\nu,IC}=4$
0235−618	0	1	1.3	-2.4	-2.1	-2.0	-1.9
0302−623	0	1	1.3	-2.4	-2.1	-2.0	-1.9
0308−611	0	1	1.3	-2.4	-2.1	-2.0	-1.9
1653−329	1.1	0.10	2.9	<-2.5	-2.5	-2.3	-2.2
1714−336	0.9	0.04	3.5	<-2.5	-2.5	-2.3	-2.2
1759−396	0	1	1.4	-2.4	-2.1	-2.0	-1.8

Table 2: ANTARES point-source analysis results. Columns: (1) IAU B1950 name; (2) Number of fitted signal events; (3) pre-trial p-value; (4) 90% upper limit on Φ_0 for $-s_\nu = -2.0$, (5)–(8): minimum spectral indicies $-s_\nu$ consistent at 90% C.L. with $N_{\nu,IC}=1\ldots4$ associated IceCube events.
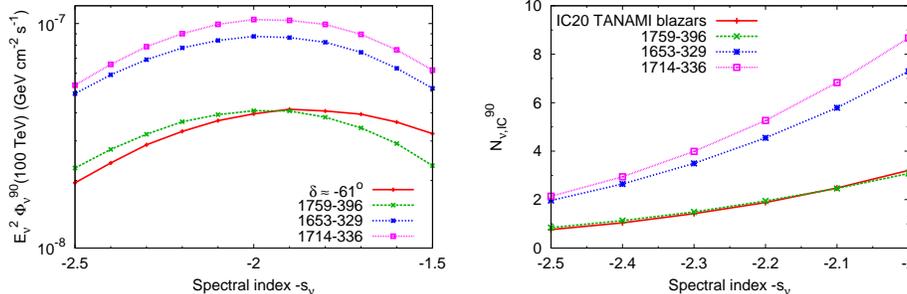
Figure 3: (left) ANTARES 90% confidence limits on a flavour-uniform neutrino flux ($\Phi_\nu \equiv \Phi_{\nu_e} + \Phi_{\nu_\mu} + \Phi_{\nu_\tau} = 3\Phi_{\nu_\mu}$) from the six blazars as a function of spectral index s_ν (Eq. 1), and (right) corresponding limits on the expected number of IceCube events of blazar origin, using the exposures shown in Fig. 1 and the limiting fluxes. Since the limits from $0235-618$, $0302-623$, and $0308-611$ are almost identical, and since no events were observed, the limits also apply to the summed flux from all three of these blazars, and hence only one line is shown, and labelled 'IC20 TANAMI blazars'.

excluded at 90% C.L. This is shown in Fig. 3 (right). Any given number of IceCube events is therefore only consistent with a blazar origin for neutrino spectral indices flatter than certain value; minimum values of $-s_\nu$ are given for 1–4 events in Table 4, and should be compared to the possible associations in Table 2. For the IC14 field for instance, the possibility that blazar $1759-396$ could be responsible for three or more associated IceCube events is excluded at 90% confidence for neutrino spectra steeper than -2.1. For spectra steeper than -2.4, we can exclude that $1759-396$ is responsible for any IceCube events. The limits for $1653-329$ and $1714-336$ are weaker, due to a possible physical association with the two signal-like ANTARES events. Regardless of the association, we can rule out the possibility that the cluster IC14, IC2, and IC25 arose from a single considered blazar with a spectrum steeper than -2.4. For the IC20 grouping, the non-observation of any event from the three candidate blazars means that the $\delta \approx -61°$ limit applies both to the individual blazars, and the group as a whole. Therefore, ANTARES observations can rule out a neutrino spectrum steeper than -2.2 as being responsible for both IC20 and IC7, and a neutrino spectrum steeper than -2.4 being responsible for only one of them. That is, if IC20 does indeed originate from the three associated TANAMI blazars, the neutrino spectral index must be flatter than -2.4.

5 Conclusion

We have tested the hypothesis of Krauß et al. [2014] that the first two PeV neutrino events observed by IceCube, IC14 and IC20, are of blazar origin, by performing a candidate list search (CLS) for an excess muon neutrino flux from the six suggested blazars using six years of ANTARES data. We are not able to either confirm or rule out a blazar origin of these events, although constraints have been placed on the range of source spectra which could have produced them, particularly in the case of IC20. While approximately two ANTARES events were fitted as being more signal-like than background-like by the maximum-likelihood analysis, such a result is completely within the expected background fluctuations, with pre-trial p-values of 10% and 4% for the blazars in question ($1653-329$ and $1714-336$). It is interesting to note though that these two blazars were predicted by Krauß et al. [2014] to have the strongest neutrino flux, and that such a result is within expectations for the ANTARES event rate for an E_ν^{-2} to $E_\nu^{-2.3}$ neutrino spectrum given that IceCube observes two such events, and $E_\nu^{-2.3}$ to $E_\nu^{-2.5}$ for a single event of blazar origin. Given these considerations, the TANAMI candidate blazars should be included in all future analyses.

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