PROCEEDINGS OF SCIENCE

ANTARES searches for neutrinos from the direction of radio-bright blazars

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An observational evidence for a directional correlation between high-energy neutrinos detected by IceCube and radio-bright blazars has been reported in the recent years. The targeted radio catalog is given by an all sky complete sample of 3411 blazars with an average parsec-scale flux density higher than 150 mJy at 8 GHz. In view of this intriguing results, several searches for association between the data collected by the ANTARES neutrino telescope in 13 years of operation and the same blazar catalog have been performed. The hypothesis of directional correlation is tested by means of a neutrino-blazar pair counting analysis, as well as of a complementary time-integrated likelihood-based approach. Moreover, in order to search for a time clustering of the ANTARES events coming from the blazar directions, a time-dependent likelihood scan is also performed. Finally, a follow-up search for multi-messenger time flare associations is conducted. The results of these analyses are presented and discussed in this contribution.

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1. Introduction

Although high-energy astrophysical neutrinos were discovered almost ten years ago by the IceCube Collaboration, their origin is still not fully uncovered. Blazars, which have their jets pointed towards us, represent a very promising type of neutrino source candidates. In particular, synchrotron radiation from blazar jets, detected on Earth in the radio band, could likely be a good tracer of neutrino emission as it indicates relativistic beaming and activity happening close to the jet origin. Here, a search for a possible neutrino-blazar association with data collected by the ANTARES telescope is presented, targeting the same catalog of radio-bright blazars for which a promising directional correlation with IceCube tracks was reported [1, 2]. A neutrino-blazar pair counting method, as well as a complementary time-integrated likelihood-based approach are used to test the hypothesis of directional association between neutrinos and blazars. Additionally, a time-dependent likelihood scan is performed to search for a time clustering of ANTARES events coming from the blazar directions. Finally, a follow-up search for multi-messenger time flare associations is conducted. This contribution updates the results presented in [3, 4] using data reconstructed with recently improved calibrations. The employed data set includes events recorded by ANTARES between January 29, 2007 and February 29, 2020 (3845 day livetime) and selected using the criteria defined in [5]. A total of 10504 track-like and 227 shower-like events survive the selection. Only the track channel is employed in the search for directional correlations, while the search for neutrino temporal flares makes use of both tracks and showers. As for the source catalog, a complete flux-limited sample of blazars observed by VLBI is selected using the same criteria as in [1, 2]. Of the 3411 blazars with historical average flux density above 150 mJy, 3051 fall into the ANTARES field of view and are targeted by the searches for directional correlations. As for the time-dependent scan, the sources with low visibility, i.e. located below 40° in declination, are excluded from the search, leading to 2774 targeted blazars.

2. Counting method

The counting method analysis counts the neutrino-blazar pairs separated by an angular distance Ψ less than $x \cdot \beta$, with β being the angular uncertainty of the neutrino reconstruction, and x a free parameter that varies in the interval $[0.1; 2]$. Moreover, since in [1], the blazars associated to IceCube neutrinos are found to have a radio-flux density higher than the average, an additional scan on the radio-flux density $S_{8\mathrm{GHz}}$ is performed. In particular, VLBI blazars are kept in the sample if they satisfy $S_{8\mathrm{GHz}} > S_{\mathrm{min}}$, with the value of S_{min} varying in the range $[0.15 - 5]$ Jy. The results of the one-dimensional scan (over x) are shown in Figure 1. The analysis finds an absolute minimum for $x = 0.82$, with $n_{\mathrm{obs}} = 469$ pairs observed in data and $n_{\mathrm{exp}} = 410.4$ expected on average from random simulations, corresponding to an excess of 59 pairs. The associated pre-trial p-value is $p = 2.5 \times 10^{-3}$ $(3.0\,\sigma)$, leading to a post-trial p-value of $P = 3.0 \times 10^{-2}$ $(2.2\,\sigma)$ after correction. These results are very close to the previous findings of [3], as the data set used is very similar. The results of the two-dimensional scan (x, S_{min}) are shown in Figure 2. The absolute minimum is found for $x = 0.82$ and $S_{\mathrm{min}} = 0.15$ Jy, with a pre-trial p-value of $p(S > 0.15\,\mathrm{Jy}) = 2.5 \times 10^{-3}$, and a post-trial $P(S > 0.15\,\mathrm{Jy}) = 0.26$. This minimum corresponds to the findings of the one dimensional scan. It is obtained for the lowest value of the flux density cut, i.e. when the whole VLBI blazar catalog is included. In Figure 2, a local minimum is also visible. It is found for $x = 0.42$ and $S_{\rm min} = 3.68$ Jy and has a pre-trial p-value of $p(S > 3.68\,\text{Jy}) = 2.7 \times 10^{-3}$. This excess is mainly driven by three blazars: J0609-1542, J1743-0350, and J0538-4405. The significance of this excess becomes $P(S > 3.68\,\text{Jy}) = 0.28$ when accounting for the trial factors. Furthermore, the dashed line of Figure 1 shows that, when excluding the blazars with $S > 3.68$ Jy, the position of the minimum does not change, and the pre-trial p-value only slightly increases to $p = 4.5 \times 10^{-3}$. These results indicate that a small number of very high flux sources in the VLBI catalog is not inducing most of the excess in the neutrinos-blazar pair counting.

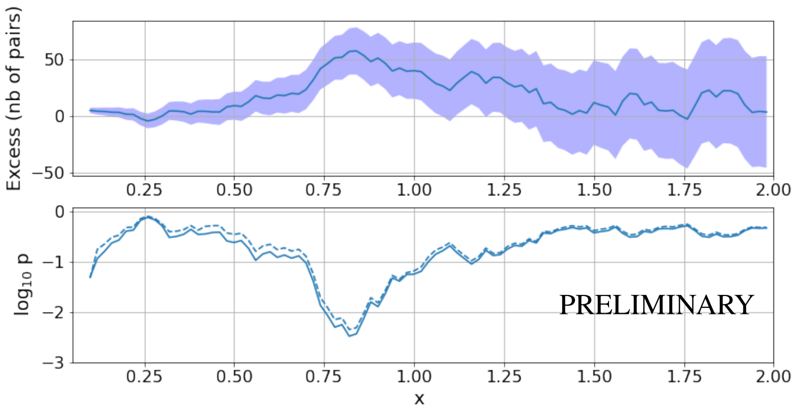

Figure 1: Result of the counting analysis. The top and bottom panels show, as a function of the parameter x (defined in the text), the observed excess of pairs relative to random expectations, and the pre-trial p-value respectively. In the top panel, the blue band shows the $\pm 1\,\sigma$ confidence interval. In the bottom panel, the dashed curve shows the p-value obtained when excluding blazars with $S > 3.68$ Jy from the catalog.

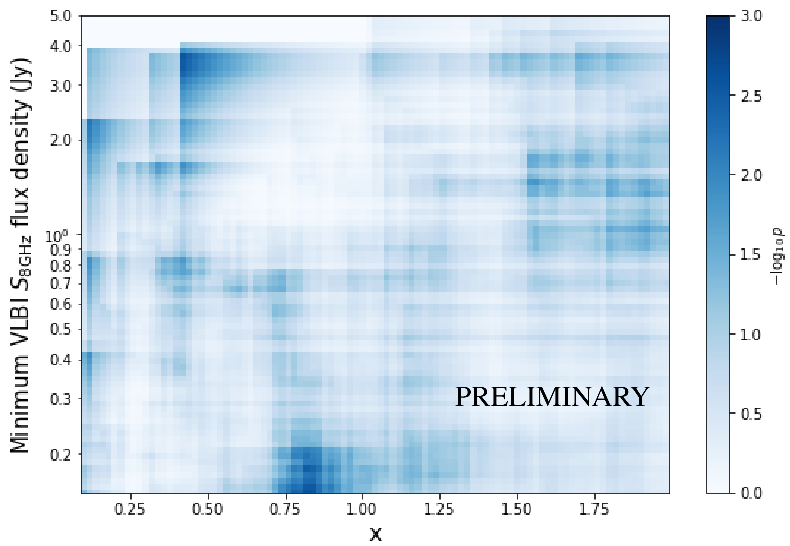

Figure 2: Result of the two-dimensional scan over the radio-flux density $S_{\rm 8GHz}$ and parameter x. The color code indicates the pre-trial p-value with the transformation $-\log_{10}(p)$.

3. Time-integrated likelihood analysis

In order to make use of more information about the ANTARES detector response than the one used in the simple counting method, a time-integrated likelihood analysis very similar to the one reported in [6] is performed. The likelihood is defined as:

$$\ln \mathcal{L}_{\text{s+b}} = \sum_{i}^{N} \ln\left(\mu_s S_i + \mu_b B_i\right) - \mu_s - \mu_b, \tag{1}$$

where N is the total number of observed track-like events, S_i is the probability density function (PDF) of the signal and B_i the background one. The free parameters are the estimated number of signal μ_s and background μ_b events. The analysis is performed for a fixed value of the spectral index γ, and repeated for values $\gamma \in [1.8, 2.6]$ in 0.1 steps. The test statistics Q is defined as a likelihood ratio, $Q = 2\ln\left[\frac{\max(\mathcal{L}_{\text{s+b}})}{\max(\mathcal{L}_{\text{b}})}\right]$, where the likelihoods defined in Equation 1 are maximized with respect to the free parameters. The signal and background PDF are given by the product of a spatial and an energy terms, using the same definition as in [6]. In particular, as for the spatial signal term, this is obtained by summing over all the individual blazars contributions, and by associating to the j^{th} blazar a weight proportional to its measured flux density $w_j^{\text{model}} = S_{8\text{GHz}}$, corrected by the declination-dependent acceptance of the ANTARES neutrino track sample. Moreover, a basic scenario in which the same weight $w_j^{\text{model}} = 1$ is assigned to all blazars is considered.

The smallest p-value obtained with the time-integrated likelihood analysis is $p = 2.6 \times 10^{-2}$ ($2.2\,\sigma$), for a $E^{-2.3}$ neutrino energy spectrum and with the radio-flux weight hypothesis. Upper limits (UL) at 90% confidence level are reported in Figure 3. When comparing the best fit flux from the ANTARES diffuse analysis [7] (best-fit spectral index of $\gamma = 2.3$) with the blazar upper limit for the same γ, a ratio between the latter and the former of ~ 0.2 is found, implying that the VLBI blazars could not contribute to more than $\sim 20\%$ of our estimated total diffuse flux of cosmic neutrinos. However, when considering the 68% confidence interval on the ANTARES diffuse flux estimation, the total VLBI upper-limit only weakly constrains our measurement. Moreover, the total neutrino upper limit mildly constrains the first data point above 100 TeV of the IceCube HESE measurement, where the VLBI blazars would contribute to $\sim 50\%$ of the flux.

4. Time-dependent likelihood scan

The time-dependent scan looks for neutrino flares from the direction of the selected radio-bright blazars. It also relies on an unbinned maximum likelihood method as the time-integrated analysis, with the difference that a time-dependent term multiplies the signal and background PDFs and that the likelihood is maximised independently at the position of each investigated source, meaning that each source is analysed separately. As for the signal time PDF, two generic time profiles describing a temporary increase in neutrino emission are tested, a Gaussian profile and a box profile:

$$\mathcal{S}_{\text{Gaussian}}^{\text{time}}(t_i) = \frac{1}{\sqrt{2\pi}\sigma_t} e^{-\frac{(t_i - T_0)^2}{2\sigma_t^2}}, \qquad \mathcal{S}_{\text{box}}^{\text{time}}(t_i) = \begin{cases} \frac{1}{2\sigma_t}, & \text{if } [T_0 - \sigma_t] \le t_i \le [T_0 + \sigma_t]; \\ 0, & \text{otherwise;} \end{cases}, \tag{2}$$

In Equation 2, t_i is the detection time of the neutrino candidate event i, and T_0 and σ_t are the unknown central time and duration of the flaring emission, respectively, both fitted in the likelihood

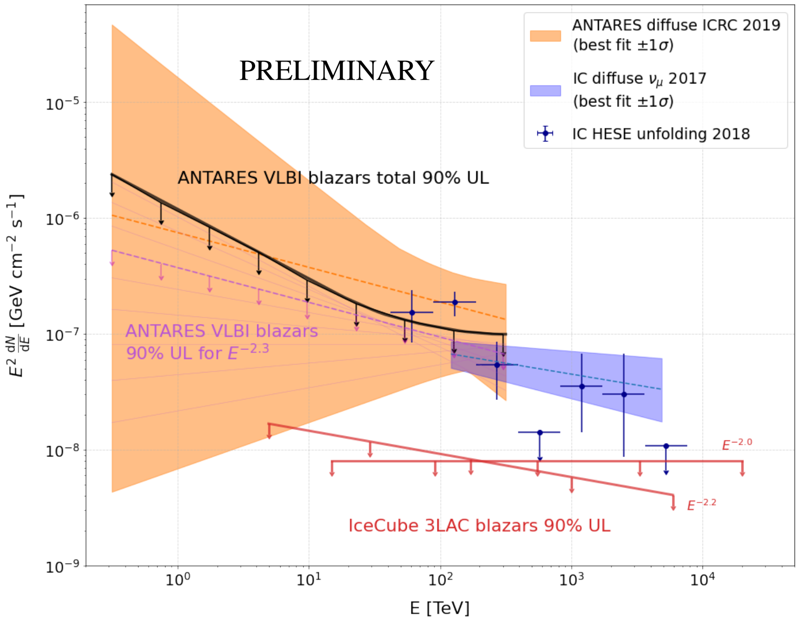

Figure 3: Upper limits on the one-flavour $(\nu_\mu + \bar{\nu}_\mu)$ total neutrino flux from the VLBI blazars obtained with the time-integrated likelihood analysis as a function of neutrino energy. The ANTARES limits for each of the spectral indices tested are represented by thin solid violet lines. For comparison, the IceCube limits [14] on *Fermi* 3LAC blazars for E^{-2} and $E^{-2.2}$ spectra are shown in red. The thick black line shows the highest values of the single spectral index limits, and provides the most conservative upper-limit curve. For comparison, the orange dashed line shows the best fit diffuse flux measured by ANTARES [7] together with its 68% confidence region (orange shaded band). The IceCube best fit to the astrophysical diffuse muon neutrino flux from [8] is displayed as a blue-shaded band, and the IceCube HESE spectrum from [9] is shown as blue markers.

maximisation. Concerning the background time profile, this PDF is built using the time distribution of data events, following the same approach as in [10]. At the location of each investigated source, the likelihood is maximised leaving as free parameters the number of signal events μ_s, the signal spectral index γ (in the range $[1.0, 3.5]$), the flare duration (in the range $[1, 2000]$ days), and the central time of the flare which can vary over the time range of the ANTARES data. The test statistic Q is defined as in the time-integrated analysis. However, in this case, the likelihood ratio is multiplied by the term $\frac{\hat{\sigma}_t}{\Delta T}$, with $\hat{\sigma}_t$ being the best-fit flare duration and ΔT the allowed time range for T_0. Its purpose is to account for the larger trial factor that should be associated to short flares since a larger number of short flares than of long ones can be accommodated in a given time range.

The search results in 18 sources showing a flare with a pre-trial significance of over 3σ for at least one of the tested time profiles. They are listed in Table 1, together with the corresponding best-fit values of the free parameters. The most significant Gaussian (box) flare is found from the direction of J1355−6326 (J1826+1831), with a pre-trial significance of 3.7σ (3.3σ) in the two-sided convention, turning into a post-trial p-value of 29% (84%). While no significant detection is found from any of the investigated source after correcting for trials, an additional study is performed to look for the presence of a cumulative excess. By performing background pseudo-experiments (PEs), i.e. targeting the same source catalog using sets of data randomised in right ascension, it is found that the probability to find 18 or more sources with a pre-trial significance greater than 3σ is 1.4% (2.5σ). This result provides an additional hint to the time-independent analysis, that a fraction of the blazars contained in the VLBI catalog could be neutrino emitters.

Table 1: List of radio-bright blazars for which a pre-trial significance of over 3σ for at least one of the tested time profiles (Gaussian-shaped and box-shaped) has been obtained. The first three columns report the name and equatorial coordinates of the sources. The remaining columns summarise the results of the search in terms of best-fit central time of the flare $\hat{T}_0$, flare duration $\hat{\sigma}_t$, number of signal events $\hat{\mu}_{\rm sig}$, spectral index $\hat{\gamma}$ and pre-trial p-value, for the Gaussian-shaped and box-shaped signal time profile. The most significant flare found assuming each of the considered time shape is highlighted in bold.

Source			Results									
Name	δ	α	Gaussian-shaped time profile					box-shaped time profile				
			$\hat{T}_0$	$\hat{\sigma}_t$	$\hat{\mu}_s$	$\hat{\gamma}$	p-value	$\hat{T}_0$	$\hat{\sigma}_t$	$\hat{\mu}_s$	$\hat{\gamma}$	p-value
	[deg]	[deg]	[MJD]	[days]				[MJD]	[days]			
J0112-6634	-66.6	18.1	58215	304	4.5	2.7	0.0026	58154	305	3.8	2.7	0.0097
J1355-6326	**-63.4**	**208.9**	**56524**	**1041**	**7.9**	**2.8**	**0.00018**	56091	905	6.0	2.9	0.0048
J0359-6154	-61.9	59.7	56316	78	5.4	3.5	0.0022	56321	112	5.7	3.5	0.0013
J0522-6107	-61.1	80.6	56221	42	4.6	3.4	0.0034	56232	59	4.9	3.4	0.0023
J1220-5604	-56.1	185.1	58406	18	2.8	2.6	0.00029	58413	22	0.4	2.2	0.0032
J1825-5230	-52.5	276.3	57265	600	5.4	2.7	0.0031	57188	959	5.5	2.7	0.0027
J0641-3554	-35.9	100.3	58084	16	2.9	3.0	0.0021	58081	19	3.0	3.0	0.0018
J1418-3509	-35.2	214.7	58120	11	3.3	2.9	0.0018	58121	14	2.9	2.8	0.0021
J1500-2358	-24.0	225.2	55846	4	3.7	2.3	0.0016	55847	6	3.7	2.2	0.0015
J0521-1737	-17.6	80.3	57332	1	2.0	1.9	0.0011	57333	1	2.0	1.9	0.0023
J2345-1555	-15.9	356.3	57653	460	3.2	2.6	0.0011	57784	404	2.4	2.7	0.0030
J1537-1259	-13.0	234.3	58201	46	2.6	2.0	0.0019	58201	55	2.7	2.0	0.0016
J0933-0819	-8.3	143.3	57411	533	3.1	2.0	0.0014	57128	697	2.9	2.0	0.0017
J0732+0150	1.8	113.1	55794	82	5.0	3.5	0.0010	55854	61	2.7	3.4	0.033
J0242+1101	11.0	40.6	56676	311	5.4	2.2	0.0060	56586	451	6.6	2.6	0.0021
J1826+1831	**18.5**	**276.6**	57672	151	2.9	2.5	0.0015	**57636**	**178**	**3.0**	**2.5**	**0.0010**
J1606+2717	27.3	241.7	58793	1	1.0	1.0	0.00076	58793	1	1.0	1.0	0.0017
J1800+3848	38.8	270.1	56590	3	1.7	2.4	0.0024	56590	3	1.9	2.6	0.0021

5. Multi-messenger flares comparison

As a follow-up study of the findings of this analysis, the obtained best-fit neutrino flares of Table 1 have been compared to the radio light curves produced by the Owens Valley Radio Observatory (OVRO) [11] for those sources for which radio data are available. A noteworthy overlap in time is noticed between the best-fit neutrino flare found from the direction of J0242+1101 and its largest flare observed in radio, as shown in Figure 4. Triggered by this findings, the time distribution of the public data of the *Fermi* γ-ray telescope and of the IceCube neutrino telescope have also been studied. The adaptive binned γ-ray light curve, obtained from *Fermi* data using the method described in [12] is also reported in Figure 4. Noticeably, the most significant *Fermi* γ-ray flare for this blazar happened during the radio and neutrino flares. The time distribution of the IceCube tracks in the 10-year point-source sample [13], with direction compatible with the blazar position within the 50% angular error, is also shown. Only events with an angular uncertainty contour smaller than 10 deg^2 are depicted. While there is no evidence of time clustering, a ν_μ-induced track with the remarkable high energy of 50 TeV was detected during the flare.

In order to evaluate how likely such a correlation is to arise by chance, a study is performed by running the analysis on PEs. For each set of flares with over 3σ significance found in each PE, the number of blazars with the following characteristics are counted: 1) the global maximum of their radio/gamma light curve falls within the ANTARES flare duration, $\hat{T}_0 \pm \hat{\sigma}_t$ and 2) that maximum is at least as high as for J0242+1101, compared to the median flux of the same blazar (maximum-to-median ratios above 1.6 for radio, and above 3.5 for gamma). For this study, the light curves provided by the OVRO and *Fermi* observatories were used, leading to a total of 335 blazars with data available both in radio and gamma-ray. The result indicates that the chance coincidence probability to find even a single matching blazar with the abovementioned characteristics is of 0.5% . This is an a-posteriori estimate which gives a hint for connection between neutrino and electromagnetic emission and motivates further studies when more observational data becomes available.

6. Conclusions

Several searches for association between ANTARES neutrinos and radio-bright blazars have been conducted. While not resulting in any significant excess, they provide hints of neutrino-blazar correlation which, if real, will be strengthened by the future improved data of the neutrino and radio telescopes.

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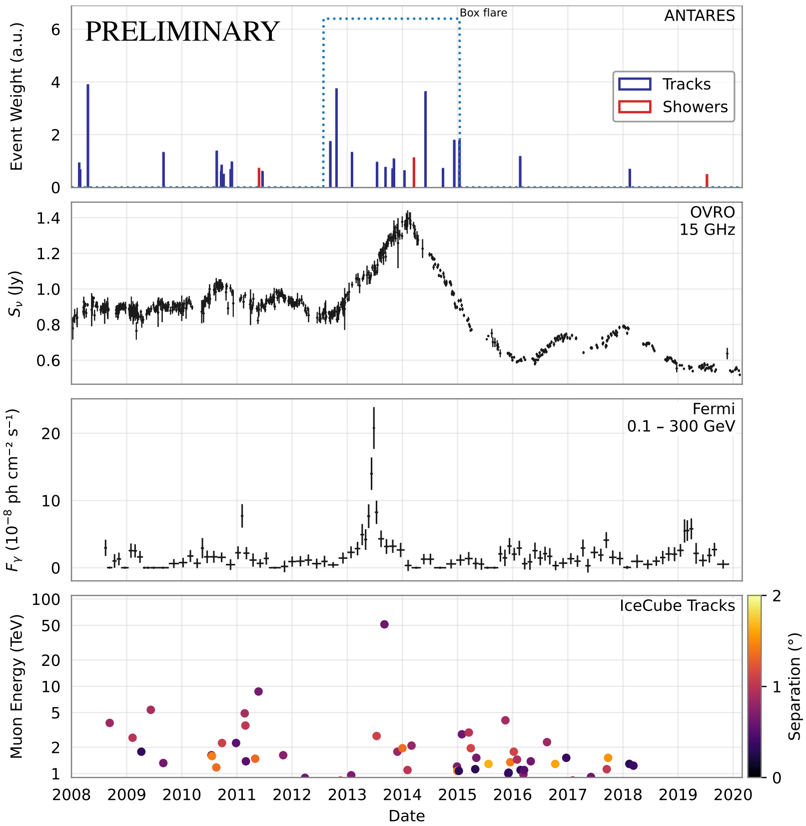

Figure 4: Multi-messenger light curves from the direction of the blazar J0242+1101 as a function of time, since 2008. Top panel: weighted time distribution of the ANTARES track-like (shower-like) events within 5° (10°) from J0242+1101. The box profile has been drawn using the best-fit values of $\hat{\sigma}_t$ and $\hat{T}_0$ found in this analysis. Second panel: OVRO radio light curve. Third panel: adaptive binned γ-ray light curve obtained from *Fermi* LAT data. Bottom panel: weighted time distribution of the IceCube tracks-like events closer to J0242+1101 than their 50% angular uncertainty. The applied weight corresponds to the energy of each event. The color scale indicates the event angular distance from the source.

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