

Seyfert Hot-Coronae Stacking Analysis with the KM3NeT and ANTARES telescopes

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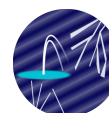
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ANTARES and KM3NeT are two Cherenkov neutrino telescopes deployed in the Mediterranean Sea. ANTARES accumulated a data sample spanning 15 years until its shutdown in 2022. KM3NeT/ARCA is currently in construction off the shore of Sicily, but already taking data in evolving detector configurations. A binned likelihood stacking framework is presented combining the data from 15 years of ANTARES and different KM3NeT/ARCA configurations (6, 8, 19 and 21 lines) data. It is applied to Seyfert hot-coronae neutrino emission, both in a model-dependent and model-independent approach. For the former, state-of-the-art hot corona models for 9 local Seyfert Galaxies are tested. For the latter, a sample of 30 Seyfert Galaxies using the BASS AGN catalogue has been constructed. No signal excess is found above the background-only hypothesis. Therefore, the results of this analysis are useful to constrain theoretical models of neutrino emission of this class of astrophysical sources.

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1. Introduction

The ANTARES detector has been the first operating Cherenkov Neutrino telescope in seawater and it has constrained the properties of astrophysical neutrinos for more than ~ 15 yr [1]. Its legacy has paved the way for the advent of a new infrastructure of two bigger Cherenkov Neutrino telescopes in the Mediterranean Sea [2]: KM3NeT/ORCA, devoted to low-energy neutrino physics and KM3NeT/ARCA, devoted to the study of astrophysical neutrinos. Given the properties of the seawater and the fact the KM3NeT/ARCA (hereafter simply denominated ARCA) is situated at a larger depth in water with respect to ANTARES, the detector is expected to have an unprecedented sensitivity for the detection of neutrino emission from several astrophysical source classes [3]. Currently, the ARCA detector is taking data with a partial configuration of 33 detection units.

In this contribution, a 2D binned likelihood ratio framework is presented that combines the experimental datasets obtained with 15 years of operation with ANTARES, and with KM3NeT in different configurations (6,8, 19 and 21 lines). The framework searches for neutrino emission within a catalogue of sources and performs a stacking analysis. In particular, the framework is applied to the specific source class of Seyfert Galaxies, i.e. Active Galactic Nuclei (AGNi) without any strong jet activity but with a hot corona surrounding the central super massive black hole (SMBH) [4]. The hot corona is a very compact region with an high x-ray density which could constitute a site of important cosmic ray acceleration [5, 6]. Recently, this class of sources has raised increased interest as the IceCube Collaboration reported compelling evidence from some of these sources [7–9].

In this contribution, both a model-independent and a model-dependent search are reported. For the former, a subsample of Seyfert Galaxies is selected from the BASS catalogue [10] which is one of the most comprehensive catalogues of local AGNi¹. For the latter case, 9 local sources have been tested against the model proposed in [11, 12]. These sources and models have also been previously studied by the IceCube Collaboration [13, 14]. The analysis yields no signal excess over the background-only hypothesis. Therefore, 90% Confidence Level (CL) upper limits are evaluated for both analyses and compared with theoretical predictions in order to show how the ANTARES and ARCA detectors can jointly probe the neutrino emission from Seyfert Galaxies.

2. Data Samples

This analysis exploits the official full ANTARES dataset including track and shower events, with a total lifetime of 4541 days [1, 15]. Tracks are events where the production of a muon is involved. They are mainly caused by charged-current interactions of muon neutrinos or tau neutrinos. Showers, instead, are mainly caused by neutrinos neutral-current interactions and by charged-current interactions of electron neutrinos [3]. For the ARCA detectors, several configurations (with 6, 8, 19 and 21 lines) are exploited. The global period under study, hereafter denoted as ARCA6-21, has a total lifetime of 640 days, considering only tracks with reconstructed zenith angle $\theta \leq 100^\circ$, where $\theta = 0$ corresponds to completely down-going events. This allows for reducing the background of down-going atmospheric muons.

¹<https://www.bass-survey.com/dr1.html>

3. Source Selection

Sources from the BASS catalogue have been selected assuming a direct proportionality between their intrinsic 2–10KeV flux ($\phi_{[2-10] \text{ KeV}}$) and their neutrino emission [5]. Only the 32 most luminous sources in this energy band are considered in this analysis (see Tab. 1).

Source	RA (°)	Dec (°)	Redshift	$\phi_{[2-10] \text{ KeV}} [10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}]$
Circinus Galaxy	213.2913	-65.3390	0.00145	984.4
ESO 138-G001	253.8456	-59.2354	0.00914	671.3
NGC 7582	349.5979	-42.3706	0.00488	507.6
NGC 6240	253.2454	2.4009	0.02386	411.1
Cen A	201.3651	-43.0191	0.00136	347.3
NGC 1068	40.6696	-0.0133	0.00303	268.3
NGC 424	17.8650	-38.0830	0.01088	188.1
CGCG 164-019	221.4035	27.0348	0.02959	179.5
NGC 7212 NED02	331.7582	10.2334	0.02667	157.5
NGC 4945	196.3645	-49.4682	0.00188	149.4
NGC 1275	49.9507	41.5117	0.01658	132.8
NGC 3783	174.7572	-37.7386	0.00965	128.7
IC 4329 A	207.3303	-30.3094	0.01591	118.9
NGC 1194	45.9546	-1.1037	0.01357	117.8
3C 273	187.2779	2.0524	0.15869	117.6
NGC 5506	213.3119	-3.2075	0.00609	115.6
MRK 3	93.9015	71.0375	0.01344	113.6
NGC 4507	188.9026	-39.9093	0.01169	104.0
MCG 05-23-016	146.9173	-30.9489	0.00831	100.0
MCG+08-03-018	20.6435	50.0550	0.02058	99.4
4C 50.55	321.1643	50.9735	0.01536	97.0
ESO 201-4	57.5957	-50.3026	0.03499	92.2
QSO B1959+650	299.9994	65.1485	0.04700	91.5
NGC 4151	182.6357	39.4057	0.00314	84.8
2MASX J20145928+252301	303.7470	25.3836	0.04522	78.6
QSO B0033+595	8.9694	59.8346	0.08600	75.9
NGC 5643	218.1699	-44.1746	0.00418	75.9
AX J1737.4-2907	264.3681	-29.1340	0.02140	72.2
NGC 4388	186.4448	-12.6621	0.00834	71.7
ESO 005-G004	91.4235	-86.6319	0.00601	71.3
MCG+08-11-011	88.7234	46.4393	0.02019	65.1
3C 111.0	64.5887	38.0266	0.05001	61.5

Table 1: Seyfert catalogue considered in this study: RA = right ascension, Dec = declination, $\phi_{[2-10] \text{ KeV}}$ is the 2 – 10 KeV flux. Data extracted from the BASS catalogue [10].

For the model-dependent search, Tab. 2 summarises the properties of the 9 sources considered [13, 14].

4. Analysis Framework

A binned likelihood ratio test is developed to search for neutrino emission among the sources of the catalogue. The event rates are binned in reconstructed energy (E_{rec}) and angular distance to the source (α) within a region of interest (RoI) of 5° (see [3] for details). For the stacking analysis, each RoI and detector configuration is treated as independent, so that the total likelihood reads

$$\mathcal{L}_{\text{stack}}(\lambda) = \prod_{j,k} \mathcal{L}_{j,k}(\lambda) = \prod_{i,j,k} P(n_{i,j,k}, \lambda w_j \mu_s^{i,j,k} + \mu_b^{i,j,k}) \quad (1)$$

Source	RA (rad)	Dec (rad)
Cen A	3.51	-0.75
Circinus	3.72	-1.14
ESO 138-1	4.41	-1.03
NGC 7582	6.10	-0.74
NGC 1068	0.71	$-2.0 \cdot 10^{-4}$
NGC 4945	3.43	-0.86
NGC 6240	4.42	0.042
NGC 4388	3.25	0.22
NGC 4151	3.19	0.69

Table 2: Properties of the 9 sources included in the model-dependent analysis: source name, declination, right ascension [13, 14]

$P(n, \mu)$ is the Poissonian probability of observing n events given a $\mu = \lambda\mu_s + \mu_b$ expected events, where μ_s and μ_b are respectively the expected number of background and signal events, j and k run over each source RoI and detector configuration, and i runs over each bin of a given RoI. The signal strength λ represents the overall normalisation of the catalogue total flux and it is left as a free parameter. In the model-independent search, each source emission is assumed to be a power-law ($E^{-\gamma}$) weighted by $w_j = \phi_{[2-10] \text{ KeV}}^j / \sum_j \phi_{[2-10] \text{ KeV}}^j$. By contrast, for the model-dependent search, w_j is set to 1 but each source flux is modelled according to [11, 12]. The test statistics (TS) reads

$$\text{TS} = \ln \left(\frac{\mathcal{L}_{\text{stack}}(\tilde{\lambda})}{\mathcal{L}_{\text{stack}}(\lambda = 0)} \right) \quad (2)$$

where $\tilde{\lambda}$ is the signal normalisation required to fit the data. The sensitivity is defined in a frequentist approach using pseudo-datasets generated according to the expected distributions of signal and background [3]. The range $[0, 6]$ of λ is discretized in steps of 0.1. For each value of λ , the distribution of the test statistic, $d(TS|\lambda)$, is determined, and the model rejection factor (MRF) λ_{90} is defined as

$$\int_{\text{TS}_m}^{+\infty} d(TS|\lambda_{90}) d\text{TS} = 90\% \quad (3)$$

where TS_m is the median TS distribution for the background-only hypothesis.

The sensitivity is defined as $\phi_{90}(E) = \lambda_{90}\phi_s(E)$ where $\phi_s(E)$ is the total flux injected corresponding to $\lambda = 1$.

5. Results

The stacking searches yield no neutrino signal excess over the background-only hypothesis. Therefore, 90% confidence level (CL) upper limits are set according to Eq. 3 by substituting TS_m with TS_{obs} , namely the observed TS on the unblinded dataset. Fig. 1 shows the results for the BASS catalogue stacking analysis, combining data from the ARCA and ANTARES detectors. In particular, on the left, the upper limit at a pivot energy $E_0 = 10 \text{ TeV}$ is shown as a function of several spectral indexes tested. On the right, the upper limit for an E^{-2} source emission is shown in the

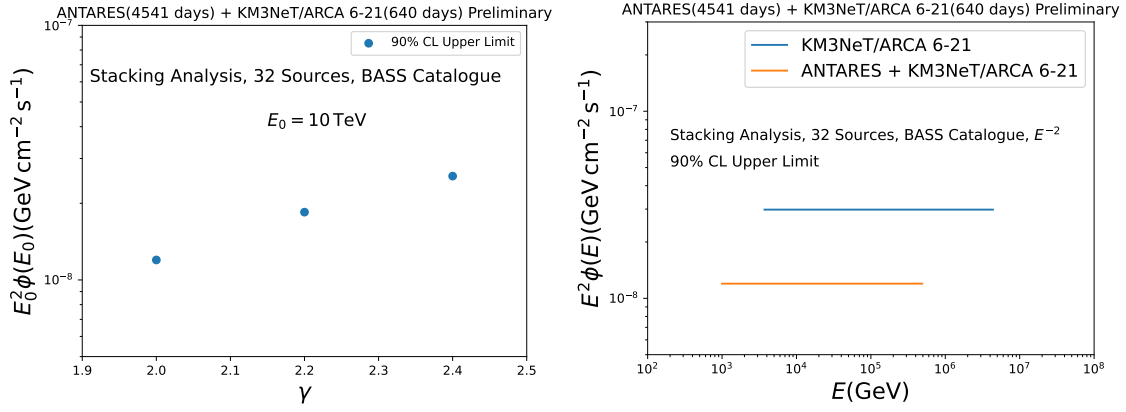


Figure 1: **Left:** BASS stacking catalogue sensitivity at a pivot energy $E_0 = 10$ TeV for different spectral indexes (γ), for the combined analysis ANTARES and ARCA 6-21. **Right:** The sensitivity for E^{-2} as a function of the energy for the ARCA 6-21 detectors (blue line) and the combined sensitivity ARCA plus ANTARES (orange line). The sensitivities are shown in the 90% central energy range.

90% central energy range, in terms of energy. The blue line refers to the ARCA 6-21 only case, while the orange line refers to the combination of ARCA and ANTARES detectors.

Fig. 2 presents the 90% CL upper limit obtained for the model-dependent stacking of the 9 sources listed in Tab. 2, also compared with the total neutrino flux predicted by [11, 12]. The figure also reports the 3σ Model discovery potential (MDP) flux obtained with the method described in [3]. Interestingly, the 90% CL upper limit on the flux lies below the theoretical prediction, meaning that the combination of current ARCA and ANTARES datasets already constrains the theoretical scenario proposed in [11, 12].

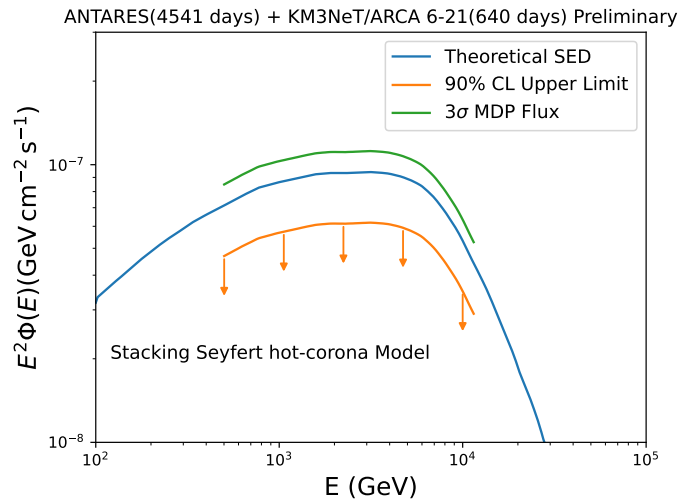


Figure 2: 90% CL upper limit (orange line) and the 3σ MDP flux (green line) for the model-dependent stacking search as functions of the energy, compared with the predicted spectral energy distribution (blue line) [11, 12]. The upper limit and the MDP fluxes are shown in the 90% central energy range.

6. Conclusions

In this contribution, a 2D binned likelihood ratio analysis has been applied to the datasets of the ANTARES and ARCA 6-21 detectors in order to search for neutrino emission from a predefined catalogue of sources. Furthermore, this method has been extended to search for a combined emission of several sources within a catalogue (stacking analysis). The framework has been applied to Seyfert Galaxies. The IceCube collaboration has reported compelling evidence for neutrino emission along the direction of several of these sources (for instance see [5] for more details), making this study of the utmost importance. Two catalogues have been scrutinised: one constructed from the BASS AGN catalogue selecting sources with the highest 2 – 10 KeV flux and another comprising 9 sources with a very high theoretically predicted neutrino flux. The presented analysis shows no signal excess over the background-only hypothesis. Interestingly, the 90% CL upper limit lies below the theoretical predictions from [11, 12], indicating that the combined observations of ANTARES and ARCA severely constrain this scenario.

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The KM3NeT Collaboration

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