PROCEEDINGS OF SCIENCE

Search for signal emission from unresolved point sources with the ANTARES neutrino telescope

Rodrigo G. Ruiz
IPHC Strasbourg
E-mail: rodrigo.gracia-ruiz@iphc.cnrs.fr

Bruny Baret
APC Paris
E-mail: baret@in2p3.fr

Antoine Kouchner
APC Paris
E-mail: kouchner@apc.univ-paris7.fr

On behalf of the ANTARES collaboration

We use an autocorrelation analysis to look for inhomogeneities in the arrival directions of the high energy muon neutrino candidates detected by the ANTARES neutrino telescope. This approach is complementary to a point source likelihood-based search, which is mainly sensitive to one bright point like source and not to collective effects. We present the results of a search based on this two-point correlation method, providing constraints on models of a population of Active Galactic Nuclei (AGN) too faint to be detected by the likelihood-based method.

35th International Cosmic Ray Conference — ICRC2017
10–20 July, 2017
Bexco, Busan, Korea

PoS(ICRC2017)949

1. Introduction

The origin of cosmic rays (CR) is still an open question and major efforts are ongoing to identify the CR sources and the physical mechanisms by which the CR are accelerated up to energies of the order of $\sim 10^{20}$eV. The magnetic fields in the galactic and intergalactic space deflect the CRs during their propagation, making it difficult to derive the possition of the sources from the CR arrival direction. The interactions of accelerated CR with radiation fields present in their acceleration sources lead to the production of neutrinos and gamma rays via the decay of charged and neutral pions. Unlike CR, gamma rays and neutrinos are electrically neutral and they point back to their sources. However, gamma rays cannot be used to unambiguously identify CR sources, since they can also be produced in the absence of accelerated hadrons (for instance, by synchrotron emission by accelerated electrons). In addition, gamma rays produced in dense regions cannot be directly observed because they get absorbed and reprocessed to lower energies. On the other hand neutrinos can only be produced in the presence of accelerated protons, and their low interaction cross section allows them to escape from dense regions. Therefore, neutrinos constitute a unique messenger which allows to unambiguously identify CR sources and to probe astrophysical environments that are not accessible with other messengers.

Theoretical arguments strongly suggest that Active Galactic Nuclei (AGN) are potential CR accelerators, and therefore sources of high energy neutrinos. Indeed, high energy neutrino emission from AGN jets has been the subject of theoretical discussions, and experimental analyses carried out by neutrino telescopes such as ANTARES and IceCube. In this contribution we present a new experimental analysis where we use the ANTARES neutrino telescope together with AGN luminosity functions inferred from the observations performed by Swift in the X-ray band. We evaluate the discovery power of the ANTARES telescope to populations of AGN that follow those luminosity functions, and constrain the neutrino emission from these objects in terms of two quantities: the fraction of X-ray emitting AGN that are also neutrino emitters, and the neutrino luminosity expressed as a fraction of the X-ray luminosity.

The ANTARES telescope aims to detect the Cherenkov light caused by charged leptons resulting from the interaction of cosmic neutrinos with the matter in and around the instrumented volume. The interaction of high energy cosmic rays with the Earth's atmosphere induces air showers in which among other particles, muons and neutrinos are present. These so called atmospheric muons and atmospheric neutrinos constitute the two main sources of background for the ANTARES detector. The Earth is opaque to all particles with the exception of neutrinos, because they interact only weakly with matter. Thus the atmospheric muon background can be reduced by selecting only those events that are reconstructed with an upwards direction with respect to the ANTARES neutrino telescope. Nevertheless, some muon tracks coming from above can be reconstructed as upward going. The amount of wrongly reconstructed muons can be reduced by means of quality cuts in the muon tracks reconstruction parameters. On the other hand, atmospheric neutrinos remain as an irreducible source of background. Its good angular resolution (better than 0.4 for energies above 10 TeV) for muon tracks allows ANTARES for the search of small scale anisotropies within the isotropic background produced by atmospheric events. One way of doing this is by means of an autocorrelation analysis, which is well suited for the search of anisotropies produced by the collective effect of an ensemble of point-like sources, such as the AGN populations that we want to study.

This work is organised as follows. In section 2 the analysis method using an autocorrelation function is explained, and the data set used for this analysis is presented. In section 3, details on the simulation of AGN populations are given and the discovery power of the autocorrelation analysis is tested with those populations. Finally, the results after applying the autocorrelation analysis to the ANTARES data set are shown in section 4. Since we didn't find any significant excess with respect to the background only expectation, upper limits on the AGN populations are also shown.

2. Analysis method and data set

We use the autocorrelation analysis, which allows to find inhomogeneities within a discrete data set by studying the autocorrelation distribution. This is defined as the distribution of the number of pairs of events as a function of their mutual angular distance $\Delta\Omega$. A comparison of the autocorrelation distribution resulting from the observed events with the one representing pure background samples, allows to detect possible clusters if a significant excess with respect to the pure background is present in the data. In this work we apply this method based on the description given in references [2] and [4].

For the present analysis, a data set recorded by the ANTARES neutrino telescope between 2007 and 2012 has been used. The sample contains 5243 neutrino candidates that have been selected using criteria optimized to obtain the best average upper limit on the flux of neutrinos coming from point like sources. These selection criteria consist in a cut on the reconstructed zenith angle $\theta > 90°$, a cut on the angular uncertainty in the track reconstruction $\beta < 1°$, and a cut on the reconstruction quality parameter $\Lambda > -5.2$. A cut is also applied on the N_{hit} energy estimator, which is defined as the number of Optical Modules (OMs) used in the reconstruction of a track. The cut $N_{hit} > 50$ has been applied. After applying this cut, a total of 1555 events remain in the sample.

3. Autocorrelation analysis and populations of AGN

In this work, we use the autocorrelation analysis to constrain the neutrino emission from populations of AGN. We model AGN populations by defining two parameters. One related to the possible number of AGN that are neutrino emitters, and another related to the mean number of neutrinos that are reconstructed by the ANTARES telescope for each AGN.

3.1 Number of neutrino-emitter AGN

Observations across the electromagnetic spectrum have allowed to infer information on the abundance of AGN and to build phenomenological models that describe the astrophysical processes within. For instance, observations in the X-ray band by the Swift and Chandra satellites, have allowed to estimate the distribution of X-ray emitting AGN in the Universe. Such distribution is given by the so-called X-ray Luminosity Function (XLF), which is defined as

$$\mathrm{XLF} \equiv \frac{d^2N}{dL_X dz} \tag{3.1}$$

where L_X is the amount of energy emitted per unit time in the X-ray band, and z is the redshift. Here we use the results from [6], where the XLF is computed for four different AGN classes (BL

Lac, FSRQ, Blazars and Radio Galaxies) in the ranges $0 < z < 10$ and $10^{44}\mathrm{erg/s} < L_X < 10^{48}\mathrm{erg/s}$. A graphical representation of the XLF for Blazars is shown in figure 1 left. The total number of AGN emitting in X-rays in the considered (L_X, z) range N_X, can be found by integrating the XLF over all the phase space.

In this work we have considered that a fraction of the AGN that are X-ray emitters are also neutrino emitters, $N_\nu = \eta \cdot N_X$, where η is left as a free parameter that allows to explore populations with different numbers of AGN.

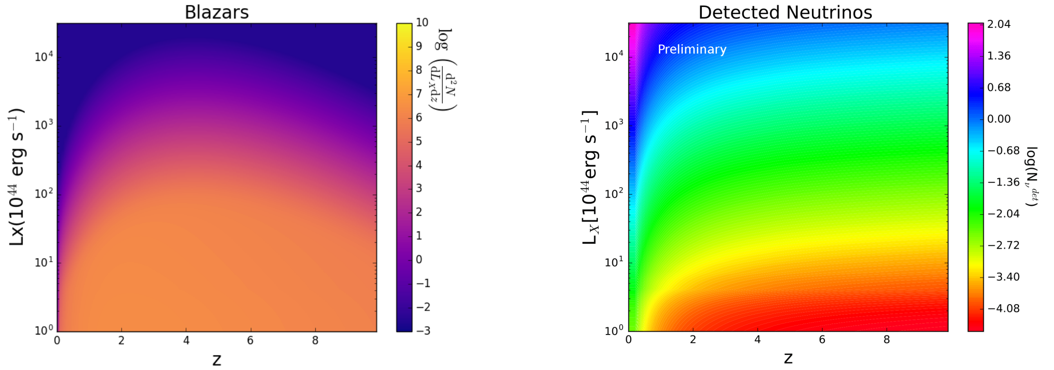

Figure 1: Left: The XLF for Blazars as defined by equation 3.1, as a function of the X-ray luminosity L_X and redshift z. Right: Number of neutrinos that ANTARES would detect from an AGN assuming $L_X = L_\nu$, as a function of z and L_X.

3.2 Neutrinos from AGN in ANTARES

Here we assume that the sources emit neutrinos with a spectral energy distribution given by an E^{-2} power law. In that case the neutrino flux at the Earth can be written as $\phi_\nu = \phi_0 \cdot E^{-2}$, where ϕ_0 is called the normalization flux of the source at the Earth and has units of $(GeV \cdot cm^{-2} \cdot s^{-1})$. The number of detected neutrinos that a source is expected to produce in ANTARES can be found through its acceptance A_δ as a function of the declination δ, as

$$N_\nu^{\mathrm{det}} = \phi_0 \cdot A_\delta \tag{3.2}$$

where A_δ has units of $(GeV^{-1} \cdot cm^2 \cdot s)$. N_ν^{det} can be computed as a function of the intrinsic properties of a source by relating ϕ_0 with the source luminosity. For an AGN at a luminosity distance $d_L(z)$ from the Earth and characterized by a neutrino luminosity L_ν, the amount of energy arriving at the Earth per unit time can be written as $\varepsilon = L_\nu/(4\pi d_L^2(z))$. If the source emits neutrinos with an $\sim E^{-2}$ spectrum, ε can be rewritten as

$$\frac{L_\nu}{4\pi d_L^2(z)} = \int_{E_{\mathrm{min}}}^{E_{\mathrm{max}}} E\phi_\nu dE = \int_{E_{\mathrm{min}}}^{E_{\mathrm{max}}} E\phi_0 E^{-2} dE = \phi_0 \log\left(\frac{E_{\mathrm{max}}}{E_{\mathrm{min}}}\right) \tag{3.3}$$

Assuming that the neutrino luminosity relates to the X-ray luminosity by a proportionality constant as $L_\nu = k \cdot L_X$, the expected average of the number of detected events for a source at redshift z and with X-ray luminosity L_X can be written as

$$N_\nu^{\mathrm{det}}(L_X, z) = \frac{kL_X}{4\pi r_L^2(z)} \langle A \rangle \left[\log\left(\frac{E_{\mathrm{max}}}{E_{\mathrm{min}}}\right)\right]^{-1} \tag{3.4}$$

where $\langle A \rangle$ is the acceptance averaged over all the declinations and integrated over the energy range 1GeV$< E <$ 1PeV. Figure 1 right shows N_ν^{det} in the (z, L_X) plane for $k = 1$.

In order to simulate populations where the amount of neutrinos detected from each source remains consistent with the XLF, the results from section 3.1 and equation 3.4 can be used to build a pdf for the mean number of detected neutrinos for each AGN class which depends on the parameter k. This is done by dividing the phase space (L_X, z) into a high number of bins (in this case, $\sim 10^4$). The total number of AGN in the bin ij can be found as $(N_{\mathrm{AGN}})_{ij} = \int_{ij} XLF\, dL_x dz$, and the mean number of detected neutrinos as $\langle N_\nu^{\mathrm{det}} \rangle_{ij} \approx \frac{1}{\Delta L_X \Delta z} \int_{ij} N_\nu^{\mathrm{det}} dL_X dz$[1]. Figure 2 shows for different values of k, a pdf obtained by histogramming the quantity $\langle N_\nu^{\mathrm{det}} \rangle_{ij}$ weighted by $(N_{\mathrm{AGN}})_{ij}$ and normalising the resulting distribution to 1. These distributions are used to generate the signal neutrinos for each AGN in the population as explained in section 3.3

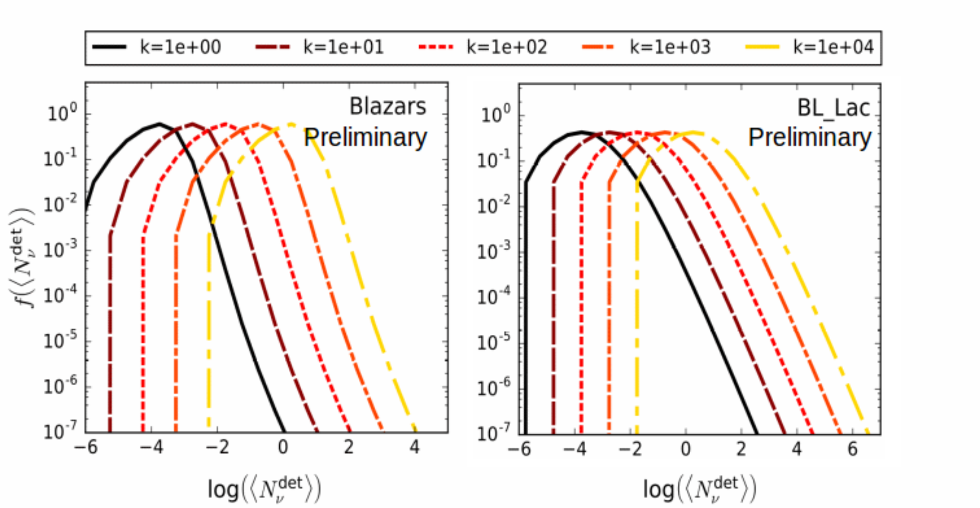

Figure 2: Probability distributions of the mean number of detected neutrinos for the different AGN families, and for different values of the parameter k.

3.3 AGN populations in ANTARES

The imprints that an AGN population characterized by the parameters (η, k) would leave in the ANTARES telescope are simulated as follows:

1. A number of sources N_S is determined by the choice of η, as a fraction of the total number of AGN that are X-ray emitters in the considered range of L_X and z.

2. A pure background data set $\mathscr{S}_{\mathrm{bg}}$ is generated as described in section 2.

3. For each source in the population,

   (a) The source location is generated from flat distributions in right ascension and declination.

[1]This expression is valid as long as the bin size is small enough to consider that the XLF is constant

(b) $\langle N_\nu^{\rm det}\rangle$ is sampled from the distribution as the ones shown in figure 2, corresponding to the choice of k.

(c) For each source, $N_\nu^{\rm det}$ is sampled from a Poisson distribution $P(\langle N_\nu^{\rm det}\rangle \cdot (\omega_\nu))$, where ω_ν is a weight based on the ANTARES visibility, which depends on the source declination.

(d) The position of each neutrino in the source is generated from a 2D Gaussian distribution centred in the source's coordinates

4. As a result from the previous steps, a collection of coordinates of the signal neutrinos is obtained, $\{(\alpha,\delta)_\nu\}$. For each of the signal neutrinos, a neutrino in $\mathscr{S}_{\rm bg}$ is removed from its position and reallocated in the signal neutrino's coordinates.

3.4 Discovery power of the autocorrelation analysis for AGN populations

The discovery power of the autocorrelation analysis has been computed for populations of AGN characterised by several values of the parameters η and k. The choice of the (η,k) phase space is done so that the following conditions are satisfied:

- There are no more AGN emitting neutrinos than AGN emitting X-rays.
- There is at least an AGN emitting X-rays that also emits neutrinos.
- As it was shown in [2], the autocorrelation method is less sensitive to a single point source than a likelihood based search. Since we are interested on sources that cannot be detected by the latter method, we require the sources in the population to be weak neutrino emitters.
- A sample of events containing signal from an AGN population should be background dominated. To be consistent with the uncertainties on the atmospheric background [5], AGN populations where the amount of signal exceeds 30% of the total sample are not analysed.

The first two conditions constrain the range of the parameter η, which is related to the number of sources in the population. On the other hand, the parameter k controls the mean number of signal events produced by each source, and is constrained by the two last conditions. For those couples (η,k) that satisfy the previous conditions, the discovery power is computed as the probability that a population produces a 3σ excess over the background. For each couple (η,k), this is done by finding the corresponding distribution of the test statistic λ, and comparing it to that for pure background sets. The results are shown in figure 3.1.

4. Unblinding results, and limits to AGN populations

After performing the autocorrelation analysis with the unblinded set of events introduced in section 2, a p-value of 0.49 is found which is not statistically significant to reject the background only hypothesis. When the analysis of the observed data does not produce a statistically significant result, the observed value of the test $\lambda_{\rm obs}$ can be used to exclude the existence of models of sources of signal. For the AGN populations, all the combinations (η,k) for which a value of the test higher than $\lambda_{\rm obs}$ would be observed in at least a 90% of the cases, are said to be excluded with a 90%

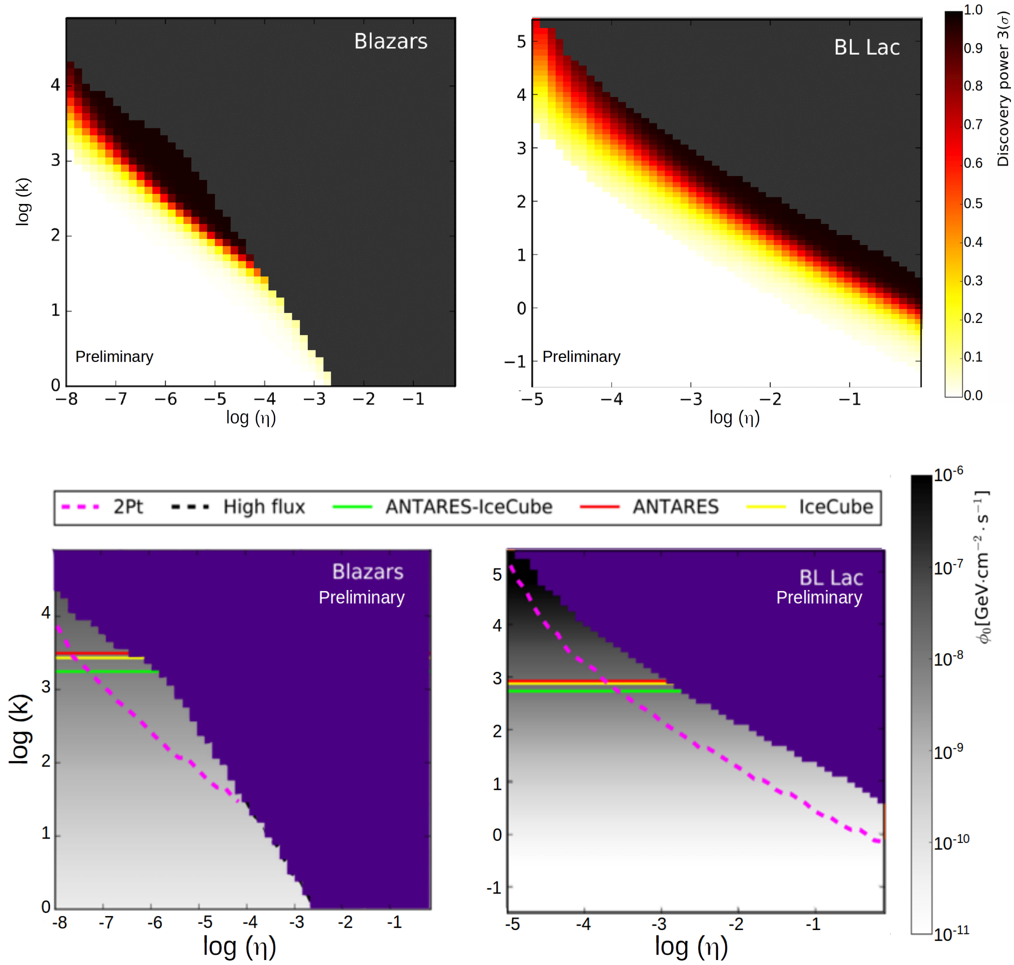

Figure 3: Top: Discovery power for blazars and radio galaxies as a function of the parameters η and k. Bottom: Limits on the (η,k) plane set by ANTARES for blazars and radio galaxies. The horizontal lines show the median upper limits from regular point source searches. Similar results were obtained for BL Lac and FSRQ.

confidence level. The values of η and k which are excluded by the autocorrelation analysis are shown in figure 3 bottom.

The color scale corresponds to the average flux per source. Additionally, upper limits on the neutrino flux from a point source are shown for IceCube (yellow), ANTARES (red) and a combined analysis using both data sets (green) are shown. These values have been extracted from reference [7], where a search for point sources is performed with the ANTARES and IceCube data sets separately, and with a combination of both. The search method consists on finding the most significant cluster in a given sky region, and the search was performed for different declination values in the range $-1.0 < sin(\delta) < 0$. The corresponding lines in figure 3 show the median values over all the declinations for each of the data sets for an E^{-2} energy spectrum. The comparison of these limits with the limits calculated here with the autocorrelation analysis, confirms some of the results shown in reference [2], where it is shown that the likelihood based search is more sensitive to a single point source than the autocorrelation analysis. This is reflected in the limits for the lowest values of the parameter η, which are less stringent for the autocorrelation analysis. In addition, this plot also shows that the autocorrelation analysis provides with much better limits for a point source flux, when populations of weak point sources are considered.

5. Conclusions

The autocorrelation analysis has been presented. Since this method is able to detect an excess of anisotropies produced by sources of different morphologies, it has been used to search for neutrinos produced by populations of different classes of AGN. These populations, which have been modelled from X-ray observations are characterized by two parameters η and k, which respectively represent the amount of X-ray emitting AGN that also emit neutrinos, and the fraction proportion between the neutrino and X-ray luminosity of the sources. The absence of a statistically significant departure from background in the ANTARES 2007-2012 data set has allowed to constrain the space defined by η and k for each AGN class.

References

[1] J.A. Aguilar et al. *ANTARES: the first undersea neutrino telescope*, Nuclear Inst. and Methods in Physics Research, A 656 (2011) pp. 11-38

[2] S. Adrián-Martínez et al. *Searches for clustering in the time integrated skymap of the ANTARES neutrino telescope*, JCAP05 (2014)0001

[3] S. Adrián-Martínez et al. *Search for cosmic neutrino point sources with four year data of the ANTARES telescope*, The Astrophysical Journal 760:53(2012)

[4] F. Schuessler on behalf of the ANTARES Collaboration in the 2013 ICRC proceedings, *2pt correlation analysis of ANTARES data*, arXiv:1312.4308 [astro-ph.HE].

[5] Agrawal et al. *Atmospheric neutrino flux above 1-GeV*, Phys. Rev. D 53, 1314-1323

[6] I. Jacobsen et al. *High-energy neutrino fluxes from AGN populations inferred from X-ray surveys.* MNRAS, 451(4): 3649 - 3663 2015.

[7] S. Adrián-Martínez et al.*First combined search for neutrino point-sources in the Southern Hemisphere with the ANTARES and IceCube neutrino telescopes*, The Astrophysical Journal 823 (2016) 65

PoS(ICRC2017)949