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Constraints on the energy spectrum of the diffuse cosmic neutrino flux from the ANTARES neutrino telescope

Luigi Antonio Fusco[1,2,*] on behalf of the ANTARES Collaboration

[1]Dipartimento di Fisica dell'Università di Salerno
[2]INFN - Sezione di Napoli, Gruppo Collegato di Salerno

Abstract. The high-purity all-flavour neutrino sample collected with the ANTARES neutrino telescope over 15 years of data taking in the Mediterranean Sea, from 2007 to 2022, has been used to search for a diffuse cosmic neutrino signal. No statistically-significant observation of this signal has been obtained, so constraints on its spectral properties have been extracted from the ANTARES data, as reported in this contribution.

1 Introduction

Neutrino telescopes are three-dimensional arrays of photosensors located at large depths under water or ice. These detectors aim at observing the Cherenkov photons induced by the relativistic charged particles coming out of a neutrino interaction. The pattern of detected photons in the apparatus can then be used to determine the direction and energy of the incoming neutrino [1]. The ANTARES neutrino telescope [2] took data from 2007 to 2022, being for a large fraction of this time the largest underwater neutrino detector in the world.

The interactions of cosmic ray protons and nuclei with matter or radiation fields near their sources can produce short-lived mesons. The energy spectrum of the neutrinos coming from their decays will generally follow that of the primary cosmic ray population: in standard scenarios for the acceleration of cosmic rays [3], this will be a power law $dN_p/dE_p \propto E_p^{-\gamma_p}$, with a spectral index γ_p between 2.0 and 2.4. A high-energy ($\gg$TeV) diffuse flux of cosmic neutrinos may originate from the ensemble of all cosmic ray sources in the Universe. This diffuse cosmic neutrino signal will appear as an excess of high-energy events in neutrino telescopes with respect to those of terrestrial origin — atmospheric muons and neutrinos produced by cosmic rays interacting in the Earth's atmosphere. The high-energy diffuse neutrino energy spectrum is often modelled as a single unbroken power law for one flavour $(1f)$

$$\frac{\Phi^{1f}_{\rm astro}(E_\nu)}{C_0} = \phi_{\rm astro} \times \left(\frac{E_\nu}{E_0}\right)^{-\gamma} \tag{1}$$

with normalisation $\phi_{\rm astro}$ and spectral index γ. The normalisation constant in equation 1 is here set to $C_0 = 10^{-18}$ (GeV cm^2 s sr)$^{-1}$, with a pivot energy $E_0 = 100$ TeV.

The IceCube Collaboration [4] has measured the properties of the high-energy cosmic diffuse flux in several analyses [5–8]. The Baikal-GVD Collaboration has also reported a mildly-significant observation of the diffuse cosmic neutrino flux in their neutrino data [9].

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[*] e-mail: lfusco@unisa.it

The ANTARES neutrino telescope provides a complementary view on this cosmic flux: its efficiency for the detection of neutrinos in the 10 – 50 TeV energy range arising from the Southern Sky is similar to that of IceCube even though ANTARES is much smaller in volume.

2 Data analysis

Two main event topologies can be observed in neutrino telescopes: *tracks*, produced by the long-lived and penetrating muons induced by charged current ν_μ weak interactions, and *showers*, produced by electromagnetic and hadronic cascades coming out of the interaction vertex in all-flavour neutrino weak interactions (both charged and neutral current). An optimal directional reconstruction and a large effective volume characterises the sample of tracks collected in ANTARES; energy reconstruction is instead optimal for showers, but the volume in which neutrino interactions produce detectable events is smaller. Both event topologies convey relevant information in the study of the diffuse flux of cosmic neutrinos. As described in [10], three event samples have been defined to search for the high-energy diffuse neutrino signal:

- *Tracks:* Upgoing track-like events for which the track reconstruction algorithm [11] provides an excellent reconstruction quality;
- *Showers:* Upgoing shower-like events with an interaction vertex — as reconstructed by the shower reconstruction algorithm [12] — close to the instrumented volume and with an excellent reconstruction quality;
- *Low-Energy Showers:* An additional sample of upgoing shower-like events that have been selected using a Boosted Decision Tree algorithm following the strategy described in [13].

In each sample, high-purity has been achieved, with a contamination from atmospheric muons below at amost a few percent in all cases, to reduce systematic uncertainties in the analysis.

Binned distributions of the reconstructed energy have been defined for each sample. A Bayesian analysis [10, 14] has been carried out to extract the power-law energy spectrum (as in equation 1) that best described the properties of the cosmic neutrino flux, accounting for systematic uncertainties in the detector response and in the signal and background fluxes. Given the optimal energy resolution for showers-like events, which allows for a proper discrimination between low-energy atmospheric backgrounds and high-energy cosmic signals, the two shower samples provide most of the sensitivity of the analysis.

3 Results

No excess of high-energy neutrinos has been observed in either of the three samples [10], and in all cases the observed distributions of the reconstructed energy show compatibility at 1σ level with the expectations from the atmospheric neutrino flux [15]. As a consequence, upper limits on the energy spectrum of high-energy cosmic neutrinos have been obtained. These are reported — at 95% Bayesian profiled posterior probability — in figure 1 and compared to the measurements of the high-energy cosmic neutrino flux from the IceCube Collaboration. These upper limits are compatible with the current uncertainties of the IceCube measurements.

The neutrino energy range to which ANTARES was sensitive to cosmic neutrinos extended down to the TeV region, and could provide additional information on the nature of the cosmic flux observed in IceCube. For this reason, the signal spectrum of equation 1 has been modified in the Bayesian analysis by introducing a low-energy cut. Namely, the flux has been assumed to be null below a certain $E_\nu^{\mathrm{cut}} = 10,\ 20,\ 30,\ 50$ TeV, and then to follow the same behaviour as equation 1 above E_ν^{cut}. Once the signal hypothesis has been modified, the analysis

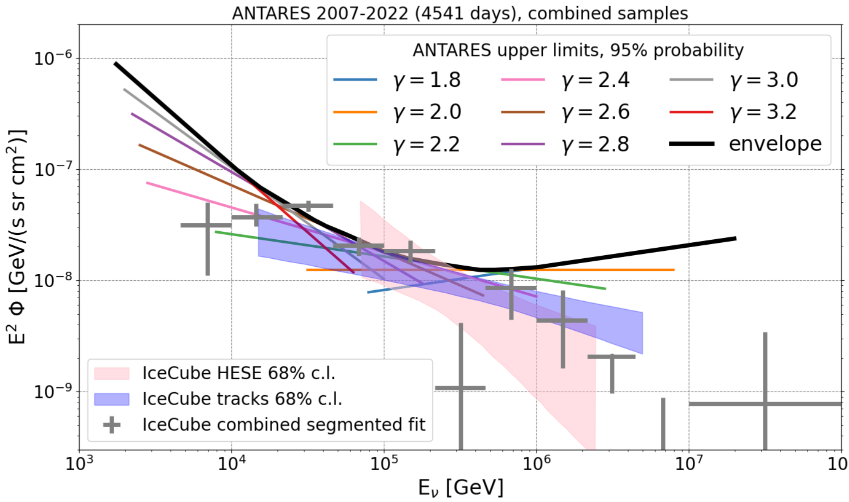

Figure 1. The ANTARES 15-years 95% Bayesian profiled probability upper limits for different spectral indexes (coloured lines in the legend) are reported in the figure. The limit for each spectral index encompasses the energy range in which the central 90% of cosmic events are expected. The envelope of the limits (in black) is taken as the least restrictive limit at every energy. The shaded areas represent the 68% confidence level intervals for the measurements obtained with the IceCube HESE sample [5] in pink and the IceCube track sample [6] in blue. The results from the E^{-2} segmented fit of the IceCube combined samples [8] are also shown in grey.

has been repeated and the Bayesian posterior distribution has been re-evaluated. The results in the $(\phi_{\text{astro}}, \gamma)$ phase-space are provided in figure 2. The consequence of the absence of a significant excess of events in the ANTARES dataset in the tens-of-TeV range is that a single power-law cosmic spectrum described by the HESE best-fit parameters is inside the 95% ANTARES Bayesian credible area only if that power law does not extend below 20 TeV. At the moment, however, these results do not allow to quantitatively state a preference for such cut-off.

These results prove the scientific potential of underwater neutrino telescopes. The KM3NeT detectors [16] have now taken the place of ANTARES in the Mediterranean Sea.

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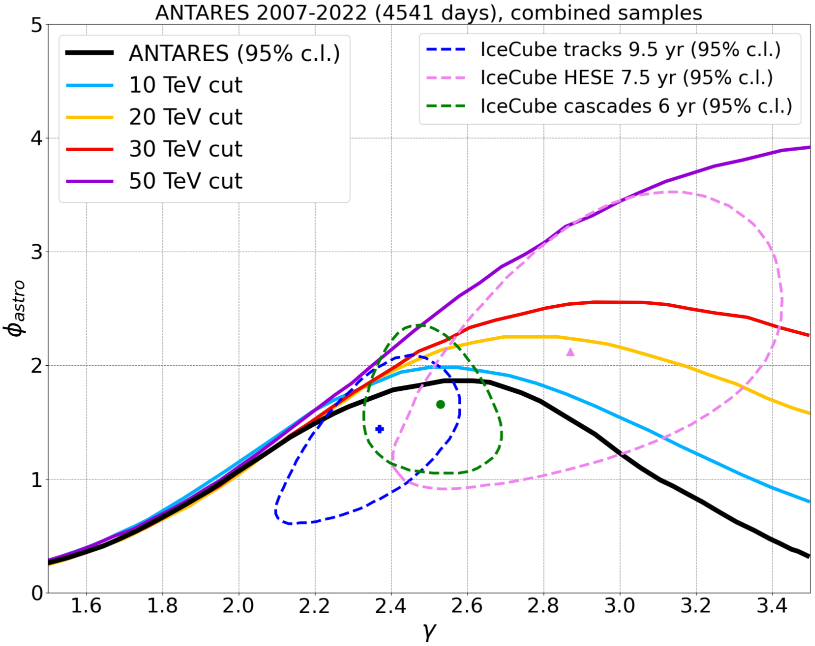

Figure 2. The 95% posterior probability credible areas obtained from the ANTARES fit assuming the single unbroken power-law hypothesis (black) and adding a low-energy cut in the spectrum from 10 to 50 TeV (coloured lines as in the legend) are compared to the 95% confidence limit contours from the IceCube HESE (pink), tracks (blue) and cascades (green) samples, shown as dashed lines together with their respective best-fit point.

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