Diffuse flux results from the ANTARES neutrino telescope

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Abstract. The ANTARES neutrino telescope is located in the Mediterranean Sea off the coast of France and offers a high visibility of the Galactic plane. Its main scientific goal is the detection of cosmic neutrinos, which is achieved by measuring the Cherenkov light emitted by the products of neutrino interactions. A limit on the all-sky diffuse neutrino flux has been set using muon-neutrinos, and a new analysis provides an improved sensitivity by also using showers created in electron- and tau-neutrino interactions. In addition, the high visibility of the Galactic plane is exploited in a dedicated analysis focusing on the Galactic plane. In this analysis the diffuse muon-neutrino flux of a region around the Galactic plane is compared with the flux from multiple equivalent off-source regions. Results of these analyses using five years of data will be reported.

1. Introduction
The recent observation of a cosmic neutrino flux by the IceCube neutrino telescope [1] is the start of a new era in neutrino astronomy. Due to the low amount of detected neutrinos and also due to the limited angular resolution of IceCube, the origin of this flux of neutrinos is not yet clear. Measurements of the neutrino flux with other detectors would help in better understanding the emission origin. The ANTARES detector [2] is currently the largest deep-sea neutrino telescope in the Northern Hemisphere and will be succeeded by the next generation Mediterranean Neutrino Telescope, KM3NeT (see also the contribution of R. Coniglione at this conference).

Neutrinos only interact via the weak interaction by exchanging a weak boson with a target nucleus. Neutrino telescopes detect neutrinos indirectly through the interaction products created in these interactions. The exact signature that is produced in the detector depends on the flavour of the neutrino and the type of the interaction, which can be either charged current (CC) or neutral current (NC). In a neutral current interaction, the neutrino breaks up the nucleon (N), resulting in a hadronic shower (X) and a lower energy neutrino:

$$\nu_l(\bar{\nu}_l) + N \rightarrow \nu_l(\bar{\nu}_l) + X,$$

(1)

with \( l = e, \mu, \tau \) the neutrino flavour. In a charged current interaction, a relativistic charged lepton is produced in addition to a hadronic shower:

$$\nu_l(\bar{\nu}_l) + N \rightarrow l^- (l^+) + X.$$

(2)

The emerging lepton inherits the flavour of the incident neutrino.
In a charged current interaction of an electron-neutrino, an electron is produced, which in turn produces an electromagnetic shower by bremsstrahlung and pair production. In a CC muon-neutrino interaction a muon is produced, which can travel a considerable distance before decaying. Around an energy of 1 TeV, the typical track length in water is a few kilometres, providing a long lever arm for direction reconstruction. In a CC interaction of a tau-neutrino a tau is produced, which predominantly decays to hadrons, producing a second hadronic shower.

In transparent media, like water or ice, the light produced in each of the interactions described above can be detected with an array of sensitive optical sensors. Since neutrinos only interact via the weak interaction (and thus have a low interaction cross section), large detector volumes are required.

In order to reduce the background from atmospheric muons, which are produced in cosmic ray interactions with the Earth’s atmosphere, neutrino telescopes are hosted in deep water or in deep Antarctic ice, where several thousands of metres of water (ice) reduce the flux of atmospheric muons by several orders of magnitude. Also, since neutrinos are the only particles that can pass through the whole Earth, neutrino telescopes mainly use upgoing neutrinos originating from the opposite hemisphere to remove the remaining atmospheric muon background.

In addition to atmospheric muons, also neutrinos are produced when cosmic rays interact with our atmosphere. These upgoing atmospheric neutrinos constitute an unavoidable background, since an atmospheric neutrino by itself can not be distinguished from a cosmic one. However, the energy spectrum of atmospheric neutrinos is softer than the expected spectrum of cosmic neutrinos, which can be used to discriminate between them by reconstructing the energy of the neutrinos.

First the ANTARES neutrino telescope will be described in section 2, after which the results of recent diffuse flux analyses will be presented in sections 3, 4 and 5. A conclusion is given in section 6.

2. The ANTARES detector
The ANTARES neutrino telescope is located 40 km offshore from the French city of Toulon, at a depth of 2475 metre below sea level. It is the first operational neutrino telescope in the Mediterranean Sea and was completed in May 2008. The detector consists of 12 vertical detection lines, which each contain 25 storeys with a triplet of so-called Optical Modules (OMs), except for line number 12 which contains only 20 storeys. The top 5 spots of this line contain acoustic detection devices, which are used for the acoustic detection of very high energy neutrinos. The distance between storeys is 14.5 m, with the first storey being located 100 m above the sea floor. The OMs look downward under an angle of 45° in order to optimise the detection of light from upgoing muons. A schematic overview of the detector is shown in figure 1.

An OM consists of a glass sphere, which contains a 10 inch PhotoMultiplier Tube (PMT) that detects photons via the photo-electric effect. The PMT is magnetically shielded against the Earth’s magnetic field using a µ-metal cage. The PMT and the µ-metal cage are held in place in the OM with special optical gel. A schematic view of an OM is shown in figure 2.

In addition to three OMs, a storey also contains the Local Control Module (LCM), which houses the offshore electronics. Each line is anchored by the Bottom String Socket (BSS) and held vertical by a buoy. The BSS consists of a dead weight which acts as an anchor, and contains the String Control Module (SCM), which contains the electronics steering the LCMs.

An interlink cable links each line to the Junction Box (JB), which in turn is connected to the shore station by the Main Electro-Optical Cable (MEOC). The MEOC is a standard telecommunications cable and provides the electrical power link and the optical data link between the detector and the shore station.

All data that is recorded by the OMs is sent to shore, where a PC farm runs the trigger algorithms responsible for selecting interesting physics events.
3. Muon-neutrino diffuse flux analysis

The goal of diffuse flux analyses is to look for an excess of events in the flux integrated over the full field of view. The excess would become apparent above a certain energy threshold, which depends on the spectral index of the cosmic flux and its size compared to the atmospheric neutrino background. The first ANTARES analysis in which a search for a diffuse flux of cosmic neutrinos is performed used data taken during 2008 and 2009 [3]. In the updated analysis two more years of data are used, giving a total livetime of 885 days [4].

In this analysis only muon-neutrino events are considered, which are reconstructed using the track fitting algorithm described in [5]. This algorithm provides the quality parameter Λ, which is derived from the likelihood and the uncertainty β on the reconstructed track direction. These parameters can be used to select well reconstructed events. To reduce the atmospheric muon background and reject badly reconstructed tracks, only upgoing events are considered which have β < 0.5°. After these cuts are applied, the muon background is reduced to below the 1% level using a combined cut on Λ and the number of hits correlated with the track (N_{hit}). Applying these cuts to the data shows a 28% deficit compared to the simulated atmospheric neutrino flux (using the Bartol flux [6]). The shape of the two distributions is the same (see also [7]) and the deficit is well within the systematic uncertainties on the theoretical expectation. For these reasons the simulation is thus normalised to the data.

The muon energy is reconstructed based on an estimation of the muonic energy loss by using the number of detected hits and the reconstructed track length (dE/dX-estimator [8]). The cut on the reconstructed energy is then optimised to obtain the best flux sensitivity using the Model Rejection Factor (MRF) technique [9]. After normalisation, 8.4 atmospheric events are expected for the optimised cut (E_{dE/dX} > 1.4 TeV) and 8 events are observed in data after unblinding. Using the method described in [10] this translates into a 90% CL flux upper limit of:

$$\Phi_{\nu_\mu + \bar{\nu}_\mu}^{90\%} = 5.1 \cdot 10^{-8} \left( E_\nu [\text{GeV}] \right)^{-2} \text{GeV}^{-1} \text{cm}^{-2} \text{sr}^{-1} \text{s}^{-1},$$

in the energy range from 45 TeV to 10 PeV (containing the central 90% of the signal). The uncertainties on the signal and background estimation are taken into account in the limit as a systematic error. The upper limit is shown in figure 4 (blue dashed line) and is compared to the atmospheric neutrino flux predictions, upper limits from other experiments and a fit to the neutrino flux measured by IceCube.
4. All flavour diffuse flux analysis using showers

The sensitivity to a diffuse flux can be improved by using electron- and tau-neutrino interactions in addition to muon-neutrinos. As described before, the signature of these types of neutrino interactions is different, since they create hadronic/electromagnetic showers. In the all flavour diffuse flux analysis, the shower reconstruction method described in [21] is used. The reconstruction is a two-step maximum likelihood fit that makes use of simulated likelihood tables. In the first step the shower vertex is reconstructed, after which this is used as input for a second likelihood fit reconstructing the energy and direction of the incoming neutrino. In the (shower) energy range from 1 TeV to 1 PeV the algorithm achieves 0.2-0.3 resolution in $\log_{10}(E_{\text{shower}})$ with a slight underestimation. The median direction resolution for neutrinos is about 6° for showers below 100 TeV and about 25° for 1 PeV showers. The worsening of the direction resolution at the highest energies has to do with the spatial extension of the shower compared to the size of the ANTARES detector. The numbers quoted here are for well reconstructed events that pass an upper cut on the vertex log-likelihood, with an efficiency ranging from 10% at 1 TeV to 60% at 1 PeV.

For the analysis data from 2007 to 2012 were used, with a total livetime of 1247 days. The background of atmospheric muons and track like events (from charged current muon-neutrino interactions) is reduced by using a cut on the vertex log-likelihood and requiring that at least 3 detector lines were used by the reconstruction algorithm. Additionally, it was required that the reconstructed vertex position was not closer than 15 m to any of the OMs to exclude events that are produced by sparks in the OMs.

The cuts on the reconstructed zenith angle $\theta_{\text{rec}}$ and the shower energy are optimised by again using the MRF technique, resulting in $\theta_{\text{rec}} > 94^\circ$ and $E_{\text{shower}} > 10$ TeV. After unblinding of the data 8 events were observed, where 5 ± 3 were expected from the atmospheric background simulation (atmospheric muons, conventional atmospheric neutrinos using the Bartol flux and prompt atmospheric neutrino using the Enberg flux [11]). The measurement corresponds to an excess over the background of 1.5σ.

The observed number of events can again be translated into a 90% CL flux upper limit of:

$$\Phi_{\nu_{\mu}+\bar{\nu}_{\mu}}^{90\%} = 4.9 \cdot 10^{-8} (E_{\nu}[\text{GeV}])^{-2} \text{GeV}^{-1} \text{cm}^{-2} \text{sr}^{-1} \text{s}^{-1},$$

Figure 3. ANTARES 90% CL flux upper limits for an $E_{\nu}^{-2}$ spectrum versus neutrino energy (shown in blue). Also shown are the atmospheric neutrino flux predictions by Bartol [6] and Enberg [11] (in grey), the fits to the neutrino flux measured by IceCube [1,12] (in yellow) and upper limits from other experiments: AMANDA [13–15] (in purple), Baikal [16] (in red) and IceCube [17–20] (in cyan).
per neutrino flavour, in the energy range from 23 TeV to 7.8 PeV. Again, the systematic uncertainties on signal and background estimation are taken into account. This upper limit is shown in figure 4 as the solid blue line.

5. Galactic plane diffuse flux analysis
In addition to the all sky diffuse flux searches, there are analyses which focus on specific regions on the sky from which a higher diffuse flux is expected. An example of such an analysis is the Fermi Bubble analysis that is described in [22]. Here, the results are reported for another analysis of this kind, which focusses on the Galactic plane region. Since only a part of the sky is used as signal region, multiple equivalent background regions can be defined which can be used to also perform a measurement of the background from the data.

A guaranteed neutrino flux is expected from cosmic ray interactions with the interstellar matter in the Milky Way, which will be maximal in a region around the Galactic Centre (GC)
since the matter density peaks there. To model the fluxes, three different theoretical models are considered, which differ in the assumptions that are made. The NoDrift_simple [23] and NoDrift_advanced [24] models assume a constant cosmic ray (CR) flux in the Galaxy and take a uniform matter density of 1 nucleon/cm$^3$. They differ in the parameterisation used for the CR flux. In the Drift model [25], the assumed magnetic field gives rise to the drift of high energy CRs to the GC, where also the matter density peaks, resulting in an enhanced neutrino flux from the GC. Besides these theoretical models, the γ-ray data as measured by Fermi-LAT [26] are used to estimate the neutrino flux based on the assumption that both originate (partly) from pion decay.

Using these signal models, the size of the signal region is optimised using the MRF technique. This results in an optimal region of 78° in Galactic longitude and 9° in Galactic latitude, centred on the GC. For this region size, 8 background regions can be defined, which trace the same path in local detector coordinates, so that the same number of events are expected in each and most systematic effects cancel out. The signal and background regions are shown in figure 5.

The background of atmospheric muons and atmospheric neutrinos is reduced by only considering upgoing events and optimising the cuts on the track parameters and the reconstructed energy using the MRF technique again. This results in an event selection with $\Lambda > -5.6$, $\beta < 8.0^\circ$ and $E_{\text{ANN}} > 350$ GeV, where the energy is estimated using Artificial Neural Networks [8]. In addition a cut has been placed on a parameter related to the clustering of the hits, which has been found to help in rejecting atmospheric muons [27].

Data from 2007 to 2012 were used, with a total livetime of 1288 days. After unblinding of the data 177 events were observed in the signal region and on average 166 events from each of the 8 background regions. Using the method described in [29] this corresponds to an excess with a significance of 0.8σ.

Since no significant excess has been observed, upper limits on the flux are placed. Following the method described in [30], the neutrino flux for a spectral index of $\gamma$ is written as:

$$\frac{E^{-\gamma}}{\lambda^{-\gamma}} \Phi_{\nu_{\mu} + \nu_{\mu}} = F \cdot (E_{\nu} \text{[GeV]})^{-2} \text{GeV}^{-1} \text{cm}^{-2} \text{sr}^{-1} \text{s}^{-1},$$

with $\lambda = 1$ GeV, so that the sensitivities and upper limits can be presented in the same units as used in equations 3 and 4. The 90% CL sensitivities (denoted with a bar) and upper limits on the flux constant $F$ are presented in table 1 for several values of the spectral index. The sensitivities and limits are shown versus Galactic longitude in figure 6, in which also the model predictions are shown.
Table 1. Sensitivities, obtained flux upper limits and energy validity range (central 90% of the signal) for different spectral indices.

| Spectral index $\gamma$ | $\mathcal{F}^{90\%}$ | $\mathcal{F}^{90\%}$ | Valid energy range [TeV] |
|--------------------------|-----------------------|-----------------------|--------------------------|
|                          | [GeV$^{-1}$ cm$^{-2}$ sr$^{-1}$ s$^{-1}$] | | |
| 2.5                      | $1.4 \cdot 10^{-4}$   | $2.0 \cdot 10^{-4}$   | 0.24 - 96                |
| 2.6                      | $3.2 \cdot 10^{-4}$   | $4.6 \cdot 10^{-4}$   | 0.18 - 71                |
| 2.7                      | $7.1 \cdot 10^{-4}$   | $1.1 \cdot 10^{-3}$   | 0.15 - 52                |

6. Conclusions

The ANTARES neutrino telescope is currently the largest neutrino telescope in the Northern Hemisphere and is in its 7th year of operation. Despite its moderate size, but thanks to its location and excellent angular resolution it is yielding competitive diffuse flux sensitivities and the best limits for the diffuse Galactic neutrino flux from the Galactic plane region. In the near future the results can be improved by adding more data and perform joint track and shower analyses. ANTARES also paves the way for the next generation neutrino telescope, KM3NeT, which will provide more than an order of magnitude improvement in sensitivity and will complement the IceCube detector located on the South Pole.

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