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Status and first results of the Antares neutrino telescope

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The ANTARES detector is the most sensitive neutrino telescope observing the southern sky and the world's first particle detector operating in the deep sea. It is installed in the Mediterranean Sea at a depth of 2475 m. As example for the first results, the determination of the atmospheric muon flux is discussed; a fair agreement with previous measurements is found. Furthermore, the results of a search for high-energy events in excess of the atmospheric neutrino flux are reported and significant limits are set on the diffuse cosmic neutrino flux in the multi-TeV to PeV energy range. Using data taken during the construction phase, a first analysis searching for point-like excesses in the neutrino sky distribution has been performed. The resulting sensitivity of ANTARES is reported and compared to measurements of other detectors.

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1. Introduction

The goal of high-energy neutrino astronomy is to provide a new view of the Universe by detecting the messengers emitted from its most violent regions. The emission of high energy neutrinos necessarily implies the presence of highly relativistic baryons at the acceleration sites and consequently provides incontrovertible evidence for the acceleration of cosmic rays [1]. The observable neutrino flux is expected to be generated mainly through charged pion production in collisions of high energy protons from the cosmic ray accelerators with the ambient gas or with radiation fields. These neutrinos will point back to even very distant sources, as they are neither absorbed nor deflected, a property that makes these particles unique astronomical messengers. High-energy neutrinos can be of galactic and extragalactic origin. Supernova remnants and micro-quasars are examples for candidate sources in our Galaxy, while gamma-ray bursts and active galactic nuclei represent promising potential extragalactic sources. Due to the extremely low cross section of neutrino interactions, neutrino detectors need to instrument very large volumes and should be built in a low background environment. The current neutrino telescopes exploit the idea, proposed by Markov [2], of instrumenting a large volume of water or ice, in order to detect the charged leptons (in particular muons) emerging from charged-current neutrino-nucleon interactions.

2. The ANTARES detector

The ANTARES detector, see Fig. 1 for a schematic view, is located at a depth of 2475 m in the Mediterranean Sea (42°48′ N, 6°10′ E), 42 km from the French city of Toulon. It is equipped with 885 optical sensors arranged on 12 flexible lines. Each line comprises up to 25 detection storeys, each equipped with three downward-looking 10-inch photomultipliers (PMTs), oriented at 45° relative to the vertical. Each PMT is installed in an Optical Module (OM) that consists of a 17-inch glass sphere in which the optical connection between the PMT and the glass is assured by an optical gel. Each line is roughly 450 m long and is held tight by a buoy at its top. The spacing between storeys is 14.5 m. The distance between adjacent lines is of the order of $60-70$ m. ANTARES contains in addition a line (IL07) with oceanographic sensors dedicated to the measurement of environmental parameters. It therefore represents an important multidisciplinary deep-sea research infrastructure delivering unique data to marine biologists and oceanographers. The construction of the ANTARES detector took place in several sea campaigns starting in the year 2006 and has been completed in May 2008 with the deployment and connection of the last 2 lines. Due to this long construction phase and the modularity of the detector, the commissioning phase comprised several detector configurations with different numbers of active lines.

The neutrino detection relies on the emission of Cherenkov photons by high-energy muons originating from charged-current neutrino-nucleon interactions in or around the instrumented volume. From the PMT positions and the relative arrival times of the Cherenkov photons at the PMTs, and making use of the characteristic emission angle of Cherenkov radiation, the trajectory of the muon can be reconstructed. The direction of the incident neutrino can be inferred with an energy dependent precision that is expected to be better than 0.3 degrees for $E_\nu > 10\,\mathrm{TeV}$.

As the detector lines move with the deep-sea current, the position of the OMs need to be monitored to ensure this excellent angular resolution. The position of the OMs is determined every

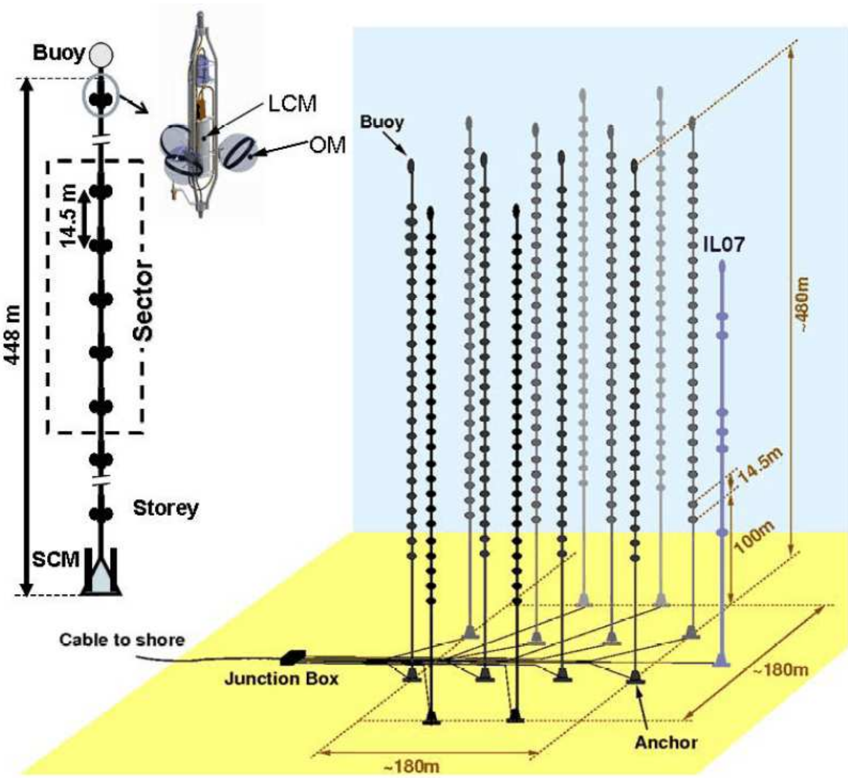

Figure 1: Schematic view of the ANTARES detector.

2 minutes by means of an acoustic triangulation system, while the orientation of each storey is measured with a compass and a tiltmeter. The timing calibration, which is also crucial for the angular resolution and very stable in time, is monitored regularly in-situ with dedicated pulsed light sources distributed along the lines.

3. Atmospheric muon flux

The main goal of a neutrino telescope is to detect high-energy neutrinos from extraterrestrial sources. However, the signal observed by ANTARES is dominated by muons that are generated in cosmic ray interactions in the atmosphere above the detector and which have sufficient energy to reach the detector at its average installation depth of 2200 m below sea surface. The muon flux measured at the ANTARES site is an important test beam to study detector systematics and to validate the reconstruction algorithms employed. Two different studies of the depth-intensity relation for muons have been carried out. In the first, the attenuation of the muon flux as a function of depth is observed as a reduction in the rate of photon coincidences between adjacent storeys along the detection lines [3]. This method has the advantage that it does not rely on any track reconstruction method and therefore allows for testing directly the response of the detector. The second method is based on a standard tracking algorithm that allows for reconstructing the (average) zenith angle of the incident muon (bundle) which is then used to compute the track length from the sea surface

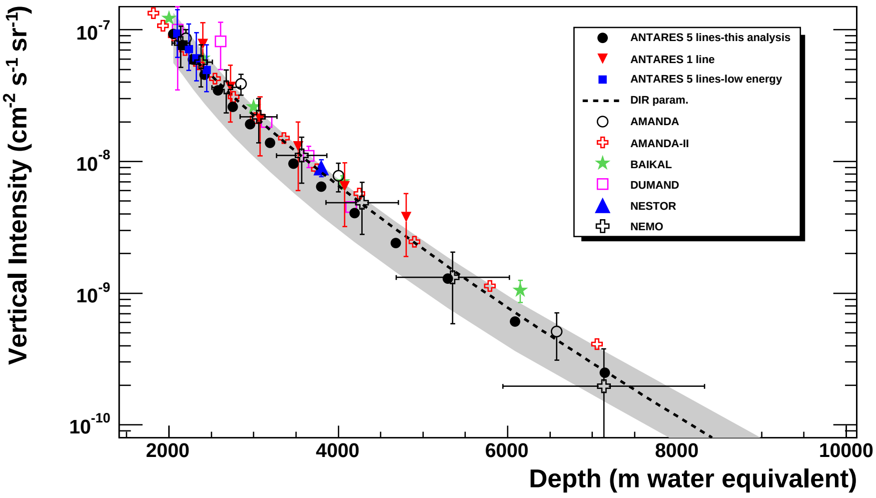

Figure 2: Vertical flux of atmospheric muons as a function of the equivalent slant depth (taken from [4]), measured with 5 lines of the ANTARES detector during the construction phase.

to the detector. This track length is usually called “equivalent slant depth”. Taking into account the known angular distribution of the incident muons, a depth-intensity relation can be extracted [4]. The results are in fair agreement with previous measurements as can be seen from Fig. 2. The rather large error band is mainly due to the systematic uncertainty on the determination of the absorption length of light in water and of the angular acceptance of the OMs at large angles, which becomes important for muons traversing the detector from above due to the downward-pointing setup of the OMs.

4. Diffuse flux of astrophysical neutrinos

The prediction of a neutrino flux from extraterrestrial sources is a direct consequence of the observation of high-energy particle and gamma radiation impinging on the Earth’s atmosphere. While both electrons and charged hadrons can be present at cosmic acceleration sites, only in the case of hadron acceleration will the energy escaping from the source be distributed between the cosmic ray component, gamma rays and neutrinos. A spatially unresolved, hence diffuse, flux of such high-energy neutrinos resulting from different cosmic sources has been predicted by various authors. There are two relevant upper bound estimates: Waxman and Bahcall (W&B) [5, 6] use as a constraint the cosmic ray flux measurements at energies $E_{\mathrm{CR}} \approx 10^{19}$ eV; Mannheim, Protheroe and Rachen [7] consider the diffuse γ-ray flux in addition. For sources that are assumed to be transparent to neutrons, the resulting upper limits are shown in Fig. 3. The search method for the diffuse neutrino flux exploits the fact that the atmospheric neutrino flux, which constitutes the main background in this search, has been measured to exhibit a $E^{-3.7}$ dependence at high energies. The predicted diffuse flux of cosmic neutrinos, however, is expected to follow the much harder energy spectrum of its parent hadron distribution, i.e. a spectrum with a spectral index close to -2. This

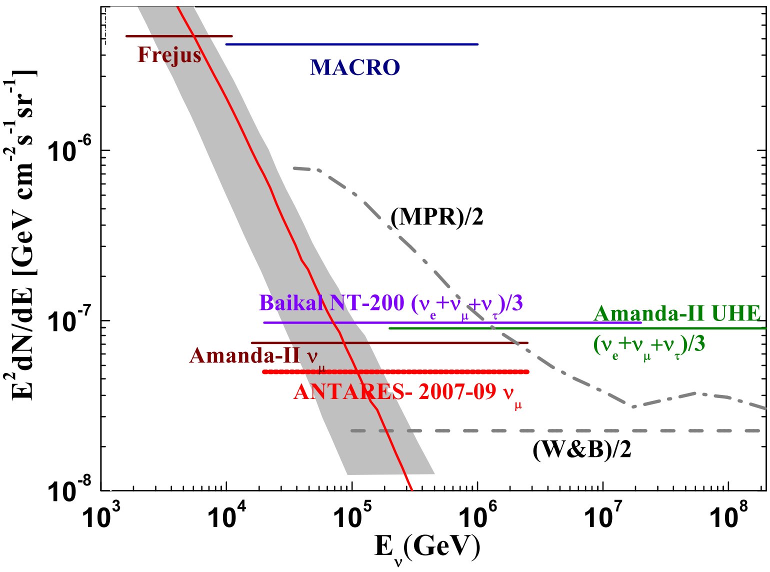

Figure 3: The ANTARES upper limit (90% C.L.) for a E^{-2} diffuse high-energy $\nu_\mu + \overline{\nu}_\mu$ flux (taken from [12]), compared with limits from other experiments and theoretical predictions for transparent sources. The factor 1/2 for the W&B and the MPR model accounts for neutrino oscillations. While the central red line represents the average atmospheric neutrino flux, the grey band denotes the uncertainty due to incident angle and different neutrino production channels [9].

prediction results from the fact that the only known mechanism that can accelerate cosmic ray particles up to the highest observed energies is the so called Fermi acceleration expected to occur in hydrodynamical shock fronts. To separate atmospheric and diffuse cosmic neutrino fluxes, a robust energy estimator for high-energy muon neutrino events has been developed for ANTARES. The algorithm is based on the average number of hit repetitions (R) in the OMs due to the different arrival times of so called direct and delayed photons. The number of hit repetitions for a specific OM in a single event is defined as the number of hits measured in a time interval up to 500 ns after and including the first hit that is used for the muon track reconstruction. The estimator R is calculated as the average number of repetitions, dividing the sum of the number of repetitions in the individual OMs by the number of all OMs that contribute at least one hit selected by the track reconstruction algorithm. Direct photons reach an OM without being scattered on their way from their Cherenkov vertex along the muon track, whereas scattered Cherenkov photons or photons induced by electromagnetic showers along the muon track are referred to as delayed with arrival time differences up to hundreds of nanoseconds with respect to direct photons. For high muon energies ($E_\mu > 1$ TeV) energy loss contributions due to radiative processes start to dominate and increase linearly with the muon energy, thus leading to additional delayed light in the detector due to electromagnetic showers. This is exploited to select neutrino events and to finally discriminate between atmospheric background and cosmic neutrinos. Using a large set of atmospheric muon and neutrino Monte

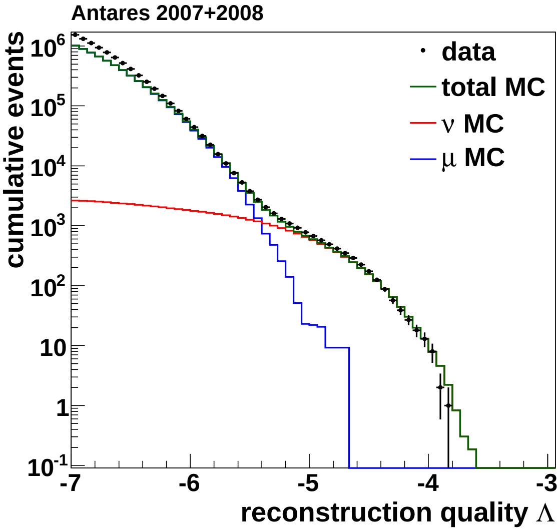

Figure 4: Comparison of data and Monte-Carlo simulation for the cumulative event distribution as a function of the reconstruction quality parameter Λ.

Carlo events, for which the detector response was fully simulated, the event selection has been optimised before the signal region was uncovered for the data. The atmospheric neutrino background was modelled following the Bartol flux parametrisation [11] with an additional high-energy component induced by the decay of charmed mesons (prompt component)[10]. The signal neutrino flux Φ was modelled with a E^{-2} spectral shape. The discrimination of signal and background neutrinos is achieved by a single cut on the hit repetition value R of the above defined energy estimator. This cut has been optimised to maximise the detector sensitivity using Monte-Carlo events only. The expected number of remaining atmospheric neutrino events is 10.7 ± 2. The systematic uncertainties are dominated by the uncertainty on the atmospheric neutrino flux and the detector acceptance including its dependence on environmental parameters. Data taken during the years 2007 to 2009 with an equivalent lifetime of 334 days and with several different detector configurations are used for the analysis. After applying the same cut on the data, 9 neutrino candidate events remain, in full agreement with the background assumption. This result translates into an upper limit (90% C.L.) for the diffuse cosmic neutrino flux of:

$$E^2\Phi_{90\%} = 5.3 \times 10^{-8}\,\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}} \tag{4.1}$$

This limit [12] holds for an assumed E^{-2} signal spectrum and in a neutrino energy range $20\,\mathrm{TeV} < E_\nu < 2.5\,\mathrm{PeV}$. Models yielding spectral shapes different from the generic E^{-2} have been tested and some of them could be excluded (cf. [12] and ref. therein) at the 90% confidence level.

5. Search for neutrino point sources

A search for cosmic ν_μ sources has been carried out with data collected in the years 2007

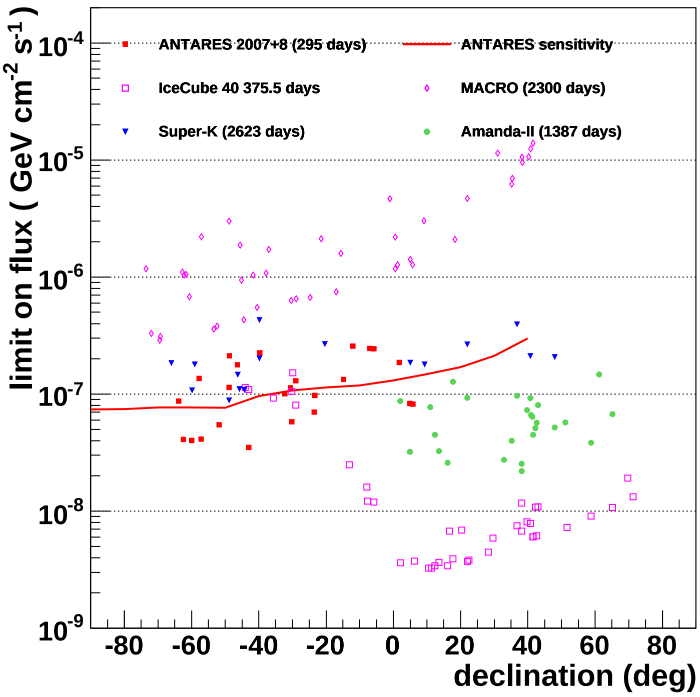

Figure 5: Preliminary flux limit (90% C.L.) vs. source declination for a list of 24 potential neutrino sources in the ANTARES field of view. The sensitivity (red line) is given as the median of the flux limits for the tested sources.

and 2008, corresponding to an integrated lifetime of 295 days. During this phase the detector was extended from a setup with 5 lines to its maximal configuration with 12 lines. The muon reconstruction algorithm employed is based on a maximum likelihood fit and yields the track direction and a fit quality parameter Λ. Using a full detector simulation, an average angular resolution of $0.5^\circ \pm 0.1^\circ$ has been determined for a E^{-2} neutrino spectrum. Optimising the limit setting and discovery potential at the same time, only upward-going events with a fit quality $\Lambda > -5.4$ are selected. The MC simulation yields 1093 upward-going neutrinos and 738 mis-reconstructed atmospheric muons (cf. Fig. 4) surviving this cut. After uncovering the data, 2040 events are selected. As the signature of a point source is a cluster of events at a given celestial position, three analyses using different methods to search for such clusters have been applied to the selected events. In each case, the likelihoods for the assumption that the cluster under inspection is induced by pure background or by an additional source contribution of unknown intensity are computed and their ratio is used to distinguish between signal-like clusters and clusters induced by background fluctuations. The first method creates a potential signal cluster from all events for an angular distance of 20° around any predefined location in the sky. With this method the sensitivity of ANTARES is determined in terms of an upper limit on the flux for a source with an E^{-2} spectrum. At the lowest declinations, which are always in the field of view of ANTARES, the sensitivity on $E^2 \times$ flux is roughly $7.5 \times 10^{-8}\,\mathrm{GeV\,cm^{-2}\,s^{-1}}$. The second method is a full sky search that preselects clusters of at least

4 events that are all within a maximal angular distance of 3° of at least one of the events. This method has the sensitivity to discover sources with a flux greater than $2.2 \times 10^{-7}\,\mathrm{GeV\,cm^{-2}\,s^{-1}}$ at the 3σ level. The largest cluster that has been found contains 8 events while only 3 events are expected from the background, i.e. the cluster has a post-trial significance of 2σ. The third method makes use of the sky coordinates of a list of 14 galactic and 10 extragalactic well known astrophysical objects that potentially could be powerful neutrino sources. As for the other 2 methods, no significant excess has been found and the derived limits together with the ANTARES sensitivity, given as the median of the individual limits, are reported in Fig. 5.

6. Conclusion and outlook

The ANTARES neutrino telescope started routine data taking in a configuration with 5 installed lines in 2007 and has recorded a large neutrino sample of high quality with different configurations during its construction phase until May 2008. The feasibility of installation and operation of a particle physics detector in the hostile environment of the deep sea has been demonstrated and first results have been obtained. The search for a cosmic diffuse high-energy neutrino flux and a point source search both resulted in very sensitive upper limits for the flux of cosmic neutrinos. Its successful operation is an important step towards KM3NeT ([8], cf. the KM3NeT contribution in these proceedings for details), a future km^3-scale high-energy neutrino observatory and marine science infrastructure proposed for construction in the Mediteranean Sea.

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