# ANTARES: Status, first results and multi-messenger astronomy

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The ANTARES Collaboration has completed in 2008 the deployment of what is currently the largest high energy neutrino detector in the Northern hemisphere, covering a volume of about 0.01 km$^3$. The search for cosmic neutrinos in the energy range between tens of GeV and tens of PeV is performed by means of a three dimensional array of photomultiplier tubes (PMTs), arranged on 12 vertical structures (strings) located in the Mediterranean Sea at a depth of about 2500 meters. The detection principle relies on the identification of the Cherenkov light produced as ultra-relativistic muons propagate in water. The main goal of the detector is the search for point-like sources of cosmic neutrinos from both Galactic and extra-Galactic sources. Besides the search for point sources, other analysis topics are strongly pursued and will be described in the following.

## 1 Introduction

Cosmic rays (CRs) were discovered a century ago, but it is still uncertain where or how they are accelerated: multi-messenger astronomy[1] could solve this *puzzle*, combining the information coming from $\gamma$-rays, cosmic rays, neutrinos and gravitational waves. Charged particles, whose paths are deflected by magnetic fields, cannot carry the information on the arrival direction up to ultra high energies, so that a close look at production and acceleration sites of cosmic rays is only possible with neutral particles. Neutrinos are thought to be produced by the interaction of accelerated particles (protons and nuclei) with matter and radiation surrounding the sources. In these interactions a massive production of hadrons with short lifetime (mostly pions and kaons, both charged and neutral) is expected to take place, high energy neutrinos being their decay products. Neutral hadrons, produced along with the charged particles generating neutrinos, are expected to decay into couples of high energy $\gamma$-rays, so that simultaneous emitters of neutrinos and $\gamma$-rays are very likely to exist.

## 2 Operation of the ANTARES Neutrino Telescope

Cosmic neutrinos can be detected via the identification of the charged particles, in particular muons, that are produced as a consequence of charged current interactions of neutrinos with the target matter. Relativistic muons propagating in a transparent medium, can induce the Cherenkov effect, i. e. the emission of coherent electromagnetic radiation along the surface of a cone, whose aperture is a function of the refraction index of the medium itself (about 42° for deep sea water). The detection technique relies on the observation of Cherenkov radiation in the visible range, by means of a tridimensional array of photomultiplier tubes (PMTs).

The ANTARES Collaboration has completed the deployment of a neutrino telescope[2] that is located about 2500 meters deep, offshore Toulon, France. The PMTs are arranged on 12 detection lines, each comprising up to 25 triplets of PMTs (floors), regularly distributed on 350 m, the lowest floor being located at 100 m above the sea bed. Each line is connected to a junction box, which is itself connected to the shore station by a 40 km long electro-optical cable. The data collected on shore are then processed by a PC farm running several trigger algorithms looking for signals compatible with the ones produced by charged particles propagating through the detector. The counting rate of the detector, of the order of 100 kHz, is dominated by light emitted by bioluminescent bacteria and by the Cherenkov light that is emitted by electrons created as a decay product of radioactive elements present in sea water, such as $^{40}$K. Environmental background hits are mostly uncorrelated, and can be easily rejected by the trigger algorithm, which selects about 20 Hz of data.

The search for HE neutrinos is affected by a particle background, coming from the interactions of CRs with the upper layers of the atmosphere, producing both neutrinos and muons, showing the same experimental signature of cosmic neutrinos. Atmospheric muons, providing the most abundant flux, propagate downward through the detector, while atmospheric neutrinos contribute providing an isotropic flux that is several orders of magnitude less abundant, as can be seen in figure 1-*Left*, showing the distribution of reconstructed arrival directions of the events detected with the ANTARES detector between 2007 and 2008, together with background expectations from simulations.

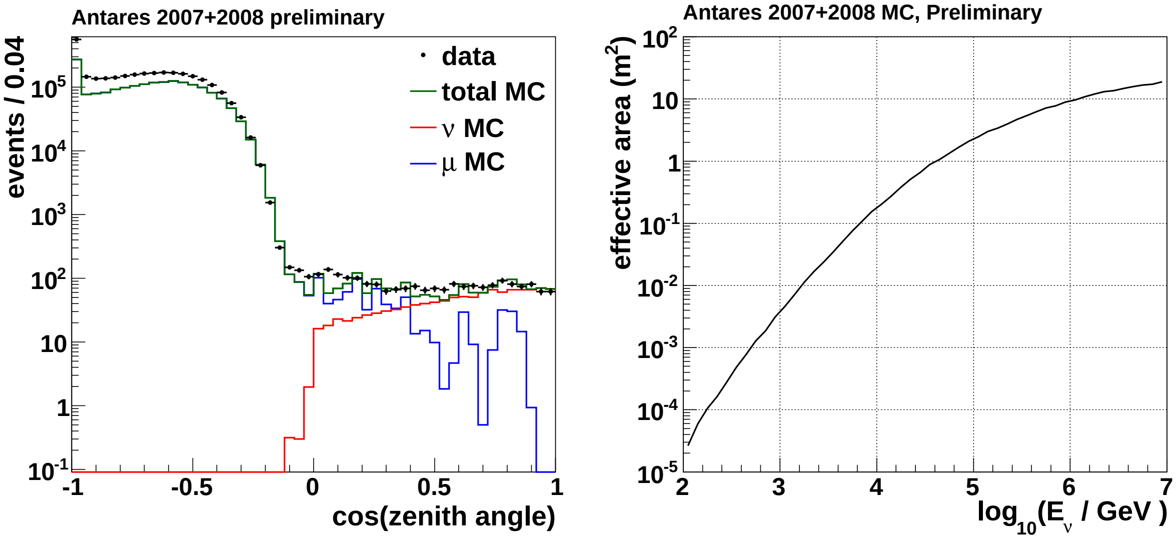

Figure 1: *Left*: Reconstructed arrival directions of the events detected with the ANTARES detector between 2007 and 2008. Events with $\cos\theta < 0$ are reconstructed as down-going, while events with $\cos\theta > 0$ are reconstructed as up-going. *Right*: Effective area of the ANTARES detector as a function of the neutrino energy, for an analysis optimized for point-like sources search.

## 3 Search for neutrinos from point-like sources

A cosmic neutrino point-like source would manifest itself as a localized excess of events on top of the background.

To ensure a high signal-to-noise ratio, the event reconstruction[3] and selection are optimized to provide tracks with good angular resolution, in a wide energy range: the detector effective area is shown in figure 1-*Right.* Using data collected between 2007 and 2008, a search for point-like sources has been performed. The integrated live-time of the data sample is 295 days, after data quality selection and rejection of the periods of high bioluminescence and high sea current. Up-going events, induced by muon neutrinos, are selected by imposing track quality criteria. The event selection was optimized to achieve the best discovery potential for an assumed power-law signal with energy spectrum with spectral index $\gamma = 2$. Figure 2-*Left* shows the preliminary sample of selected events: 2040 neutrino candidates have been identified. Simulations indicate that this sample is contaminated by a 40% of misreconstructed atmospheric muons. Based on these events, a dedicated search for candidate sources, already known as HE gamma-rays emitters, was performed. This search was also completed by a full scan of the Southern sky. Preliminary results find GX 339 as the most likely candidate source, where two events have been found within 1 degree of its position. The probability to observe this or a larger excess due to a statistical fluctuation of the background is 7%. It can be concluded therefore that all observed excesses are compatible with the background hypothesis, and 90% C.L. upper limits on the neutrino flux from the considered sources have been set. Figure 3 shows ANTARES upper limits as function of the declination, together with the expected sensitivity for 1 year of data taking. Results from both previous and current experiments are shown for comparison. The ANTARES experiment is currently providing the more stringent upper limits on the Southern sky sources, moreover these limits are in good agreement with the expected sensitivity.

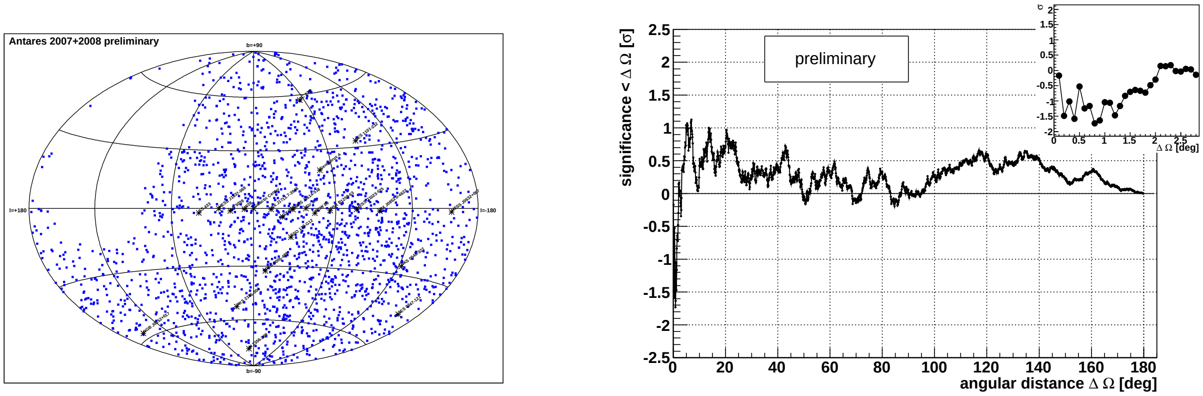

Figure 2: *Left*: Skymap of the 2040 neutrino candidates selected for the point source search. Stars indicate the 24 sources of the candidate list. *Right*: Autocorrelation significance as a function of the cumulative angular scale. A maximum significance of 1.13 sigma is found for angular scales smaller than 7 degrees.

In a complementary analysis, the two point autocorrelation of the selected dataset has been studied. The applied method is independent on MonteCarlo simulations and it is sensitive to a larger variety of source morphologies. The reference autocorrelation distribution is determined by scrambling the data itself, so that randomized sky maps are obtained. The final comparison between the data and the reference distributions yields the significance of the differences, as a function of the cumulative angular scale, as shown in figure 2-*Right.* The maximum significance is of 1.3 sigma, and it corresponds to angular bins smaller than 7 degrees.

## 4 Search for diffuse neutrino flux

The search for a diffuse neutrino flux, i.e. unresolved (neither in time nor in space) neutrino sources, is based on the search for an excess of high energy (TeV ÷ PeV) events above the irreducible background of atmospheric neutrinos, whose flux is described by a power law with

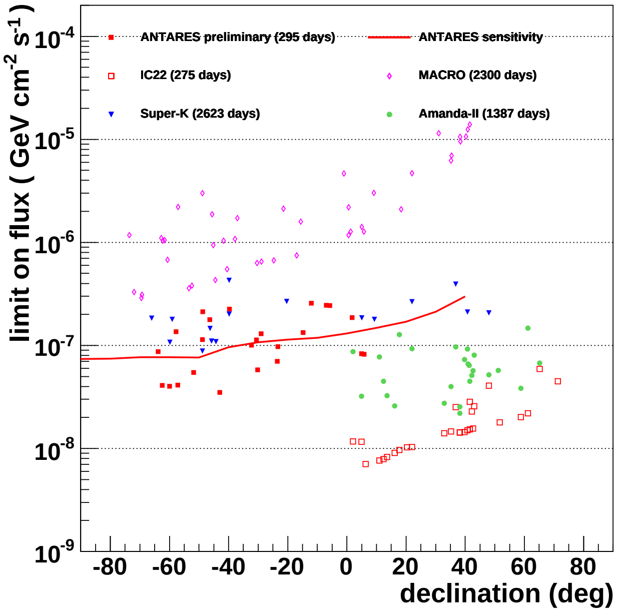

Figure 3: Upper limits on the flux of HE neutrinos, assuming an E$^{-2}$ spectrum, for selected sources. The expected sensitivity of the ANTARES detector for a full year of data taking is also shown for comparison. Limits set by MACRO, AMANDA II, Super-K and IC22 [4] are superposed.

a spectral index $\alpha \sim -3.5$, while several theoretical models have foreseen an E$^{-2}$ spectrum for astrophysical neutrinos. Atmospheric and astrophysical neutrinos can be therefore distinguished statistically on the basis of the particle energy. The energy estimator, called $R$, is based on hit repetitions on the PMTs, due to the different arrival time of Cherenkov photons produced directly by the muon, and by delayed Cherenkov photons from secondary electrons and positrons dressing up the HE muon tracks. The average number of hit repetitions in the event is defined as the number of hits in the same PMT, within 500 ns from the earliest hit selected by the reconstruction algorithm. A complete analysis has been performed on data collected from December 2007 to December 2009 for a total live-time of 334 days [5]. Figure 4-*Left* shows the distribution of the $R$ parameter for the 134 candidate neutrino events found in the data sample, together with simulation for both background and signal neutrino events. The number of selected events was found to be compatible with the expected background, so that the 90% C.L. upper limit on the diffuse $\nu_\mu$ flux with a $E^{-2}$ spectrum is set at $E^2\Phi_{90\%} = 5.3 \times 10^{-8}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ for the energy range between 20 TeV and 5 PeV, where the energy estimator is approximately linear with log E$_\mu$. This result is shown in figure 4-*Right*: the upper limit is competitive with upper limits set by other neutrino telescopes of comparable size and is compared to theoretical predictions [6].

## 5 ANTARES as an observatory for physics beyond the Standard Model

Neutrino telescopes could also probe physics beyond the Standard Model, by detecting neutrinos from the annihilation of Dark Matter (DM) particles, or exotic particles [7] such as magnetic monopoles (MM) and slow nuclearites.

Neutrinos with energies of the order of tens of GeV could be produced in the annihilation of Weakly Interacting Massive Particles, e.g. neutralinos, which become gravitationally trapped in celestial bodies, like the Galactic Center or the Sun. The existence of magnetic monopoles

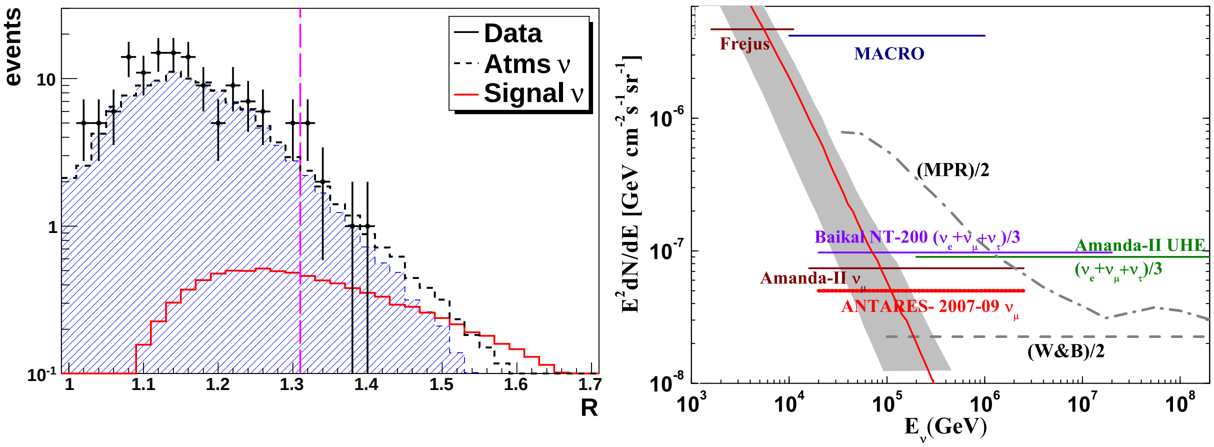

Figure 4: *Left*: Distribution of the energy estimator $R$ for the 134 candidate neutrino events found in the 2007-2009 ANTARES data [5], together with MonteCarlo predictions. Points represent data, the filled histogram and the dashed line represents simulated atmospheric neutrinos. The signal, normalized at the upper limit, is shown as a full line. The optimized value $R = 1.31$, that is used to discriminate between signal and background event, is indicated as a vertical line. *Right*: Upper limit on the diffuse neutrino flux of HE neutrinos obtained from the 2007-2009 ANTARES data [5], compared to theoretical predictions [6] and to limits set by other neutrino telescopes. See the paper for more references.

has been initially predicted by P. Dirac in 1931. Up-going magnetic monopoles with masses

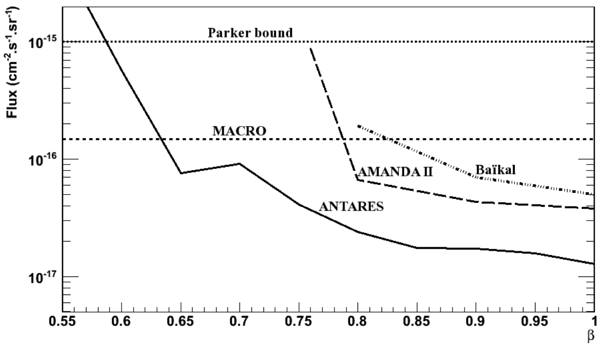

Figure 5: Upper limits at 90% C.L. on the flux of fast magnetic monopoles, as a function of the monopoles speed: solid line indicates the preliminary result from the ANTARES Collaboration.

between $10^{10}$ and $10^{14}$ GeV could be detected with the ANTARES detector, given their typical experimental signature: a very bright muon-like track, providing an amount of photons that is estimated to be more than 8000 times higher than that of a muon.

The solid line in figure 5 shows the preliminary limit set on the flux of MM by the ANTARES Collaboration, for $\beta > 0.55$. This limit is currently competitive with those previously established [8], that are also shown for comparison.

## 6 Multi-messenger approach within the ANTARES Collaboration

The search for neutrino emission from transient sources, like for example Micro-quasars, Gamma Ray Bursts (GRBs) [9] or core collapse supernovae (ccSNe) [10], is well suited for the multi-messenger strategy. Given the expected small difference in the arrival time and position between photons and neutrinos, a very efficient rejection of the associated background can be achieved. Due to the very low background rate, even the detection of a small number of neutrinos correlated with a transient source could lead to a discovery.

Two different detection methods have been implemented within the ANTARES Collaboration. The first one is the triggered search method, based on the search for neutrino candidates in conjunction with an accurate timing and positional information provided by an external source. The second one is the rolling search method, based on the search for high energy events or multiplets of neutrino events coming from the same position within a given time window,

GRBs are detected by gamma-ray satellites, which deliver in real time an alert to the Gamma-ray bursts Coordinates Network (GCN). The characteristics of this alert, mainly the direction and the time of the detection, are then distributed to the other observatories. Most gamma-ray, X-ray and optical observatories are capable of observing only a small fraction of the sky, for example Swift has a 1.4 sr field of view, while neutrino telescopes monitor essentially a full hemisphere. To avoid dependence on external triggers as well as to cover a larger region of the sky, events detected with the ANTARES telescope can be used to trigger optical follow-up observations[11], using a Target-of-Opportunity (ToO) program. This method is sensitive to all transient sources producing high energy neutrinos.

The ANTARES Collaboration has developed an alert system[12] that triggers the observation with a network of optical telescopes. The key ingredients are the use of a fast and robust reconstruction algorithm[13] and the connection with a network of robotic telescopes with large field of view (approximately 2°× 2°), with slewing times of the order of tens of seconds. This is important since a GRB afterglow requires a very fast observation strategy, in contrary to a core collapse supernovae, for which the optical signal will appear several days after the neutrino signal. To be sensitive to all these astrophysical sources, the observational strategy is composed of a real time observation, followed by several observations during the following month. The system is operational since 2009 and, since then, more than 30 alerts have been sent to optical telescopes. The analysis of the optical images is under way.

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