ANTARES: Status, first results and multi-messenger astronomy

Manuela Vecchi for the ANTARES Collaboration
Université Aix-Marseille II and CPPM,
163, avenue de Luminy - Case 902 - 13288
Marseille cedex 09 France

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 about 2500 m deep underwater, in the Mediterranean Sea. The detection principle relies on the identification of the light produced as ultra-relativistic muons propagate in water and induce the Cherenkov effect. The main goal of the detector is the search for point-like sources of cosmic neutrinos from both galactic and extra-galactic sources. Beside 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: since the Universe is opaque to very high energy photons (E > 100 TeV), multi-messenger astronomy is thus a very promising field of research, in which photons are not the only probes, but the information coming from cosmic rays, neutrinos and gravitational waves are also used to solve this puzzle [1]. 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. The identification of sources producing neutrinos with energies bigger than some TeV could thus provide fundamental keys for the identification of CRs acceleration sites. Neutral hadrons, produced along with the charged particles generating neutrinos, are expected to decay into couples of high energy photons (γ-rays), so that astrophysical sources which are simultaneous emitters of neutrinos and γ-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 detector is an array of PMTs arranged on 12 detection lines, each comprising up to 25 triplets of PMTs (floors), regularly distributed on 350 m, the first floor being located at 100 m above the sea bed. Each line is connected to the junction box, that is 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 such a 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, so that the trigger rate is around 20 Hz.
The search for HE neutrinos is affected by a particle background, coming from the interactions of cosmic rays with the upper layers of the atmosphere, producing both neutrinos and muons, showing the same experimental signature of cosmic neutrinos. Atmospheric muons, providing

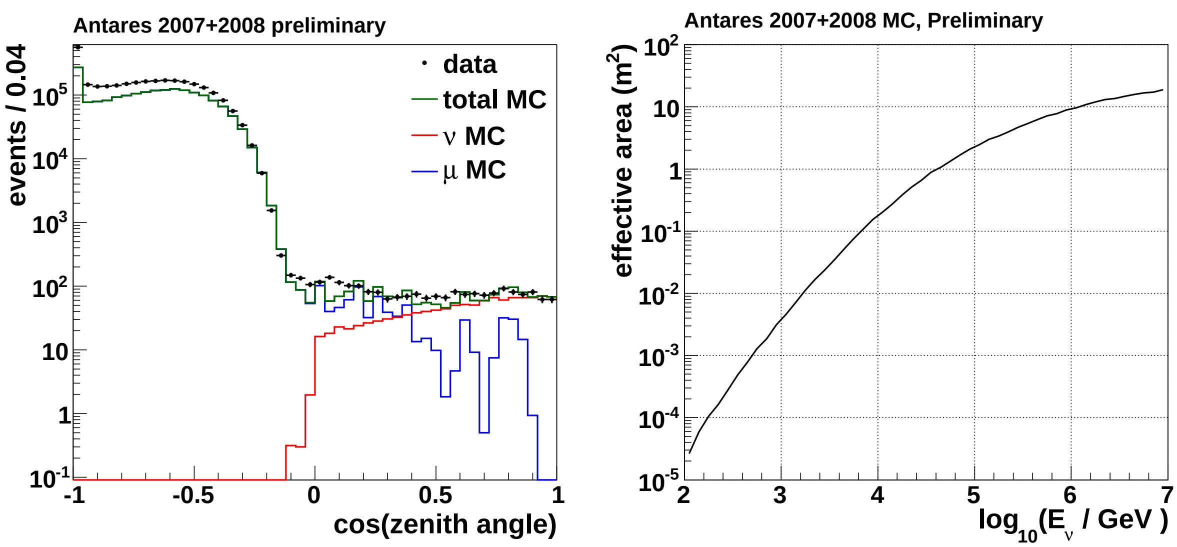

Figure 1: Left: Reconstructed arrival directions of the events detected with the ANTARES detector between 2007 and 2008. Events with cosθ <0 are reconstructed as down-going, while events with cosθ > 0 are reconstructed as up-going. Right: Effective area of the ANTARES detector, for the search for point like sources.

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, together with MonteCarlo predictions.

3 Search for neutrinos from point-like sources

A cosmic neutrino point 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 in a way 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 have been performed. The integrated live-time of the data sample is 304 days, after data quality selection and rejection of the periods of high bioluminescence and sea current. Up-going events, induced by muon neutrinos, are selected by imposing track quality requirements. Event selection criteria were optimized to achieve the best discovery potential for an assumed power-law signal with energy spectrum with spectral index $\gamma = 2$. The resulting sample, shown in figure 2, consists of 2040 neutrino candidates. Simulations indicate that the sample is composed of 60% atmospheric neutrinos, with a 40% contamination of atmospheric ... scan of the Southern ...d on the basis of HE

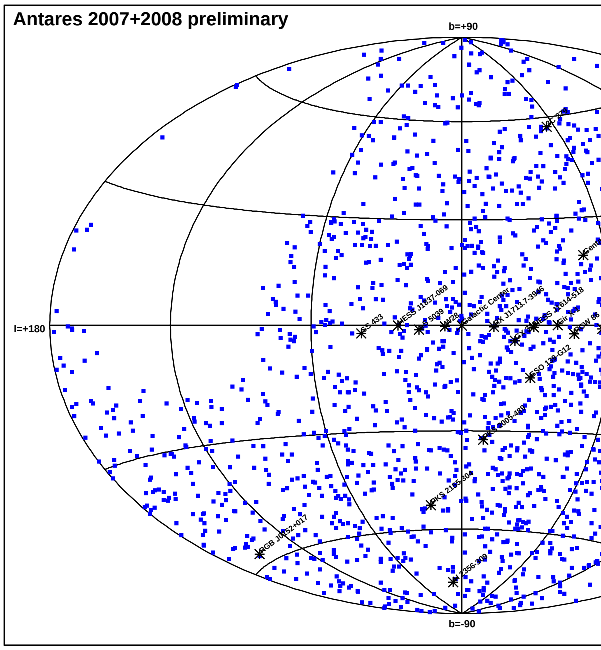

Figure 2: Skymap of the 2040 neutrino candidates selected for the point source search. The position of the most significant cluster is indicated by the circle. Stars indicate the 24 sources of the candidate list.

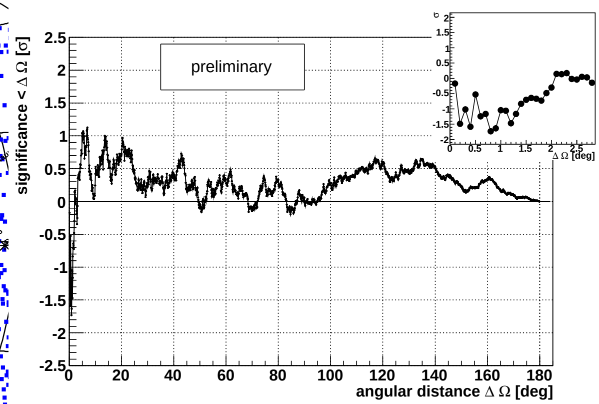

Figure 3: Autocorrelation significance as a function of the cumulative angular scale. A maximum significance of 1.13 sigma is found for angular scales smaller than 7 degrees.

gamma-ray observations. Preliminary results indicate that in both cases all observed excesses are compatible with the background hypothesis, however the most signal-like source candidate is HESS J1023-575, where 3 events have been found within 1 degree of its position. The probability to observe this excess, as due to a statistical fluctuation of the background is 55%.

As no significant excess was found corresponding to any point source, 90%C.L. upper limits on the neutrino flux from the sources of the catalogue have been set. Figure 4 shows ANTARES upper limits as function of the declination, together with the expected sensitivity for 1 year data taking. Results from both previous and current experiments are shown for comparison.

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

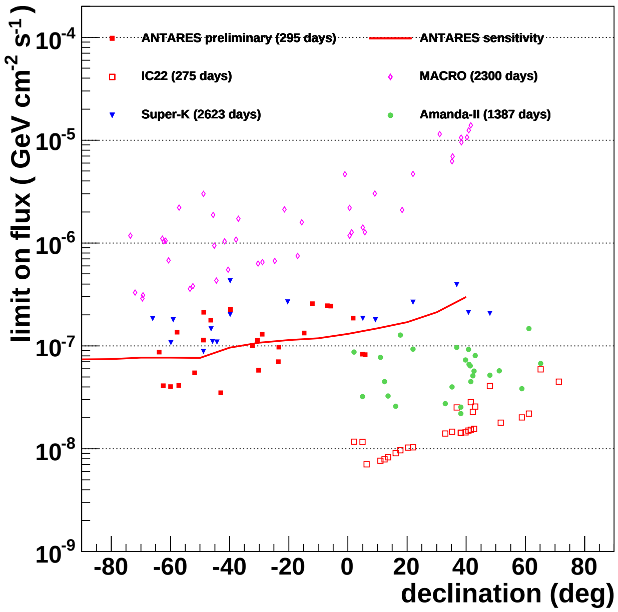

Figure 4: Upper limits on the flux of HE neutrinos, assuming an E^{-2} spectrum, for selected sources. The expected sensitivity of the ANTARES detector is also shown for comparison. Results from other experiments are also shown.

by scrambling the data itself, so that randomized sky maps are obtained. The final comparison between the data and the reference distributions yelds the significance of the differences, as a function of the cumulative angular scale, as shown in figure 3. 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 $\div$ PeV) events above the irreducible background of atmospheric neutrinos, whose flux is described by a power law with 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 distinguished on the basis of a discrimination on the particle energy. The energy estimator is based on hit repetitions in the PMTs, due to the different arrival time of direct and delayed photons [4].

The mean number of 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. The energy estimator is defined as follows: $R = \frac{R_i}{N_{PMTs}}$, where R_i is the number of repetitions in each PMT and N_{PMTs} is the number of PMTs involved in the given event. The energy estimator is approximately linear with log E_μ, in the energy range between 20 TeV and 5 PeV. Figure 5 shows the expected energy distribution for both background and signal neutrino events: the green arrow indicates the region where the 90% of the astrophysical neutrino signal is present. A complete analysis has been performed on data collected from December 2007 to December 2009 for a total live-time of 334 days. The number of observed events after the proper cuts was found to be compatible with the expected background, so that an upper limit on the diffuse neutrino flux have been set. The results are shown in figure 5, together with results from other experiments.

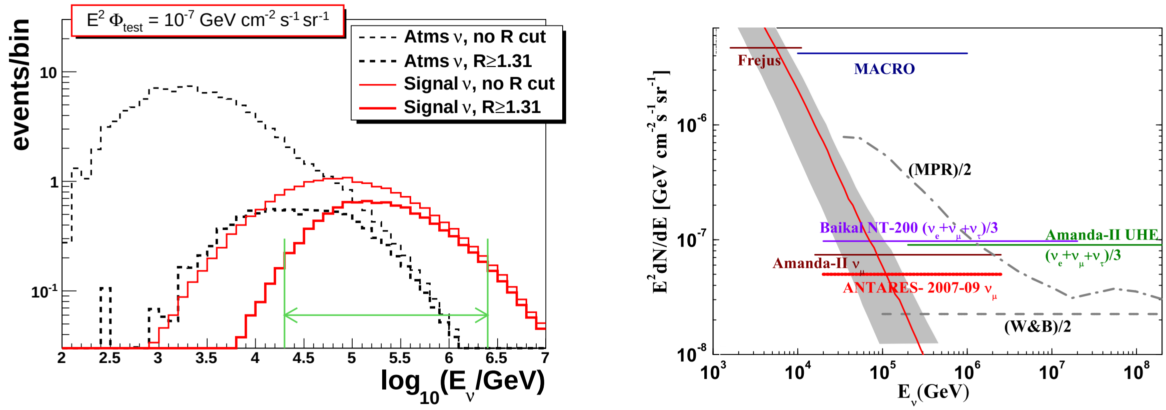

Figure 5: Left: Signal and background neutrino energy spectra as a function of the true neutrino energy (in GeV) before and after the selection of the condition R $\geq$ 1.31. It is highlighted the region where the 90% of the astrophysical neutrino signal is present. Right: Upper limit on the diffuse neutrino flux of HE neutrinos for the ANTARES detector, compared to the results of previous neutrino telescopes and to some theoretical predictions.

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 such as magnetic monopoles (MM) and slow nuclearites.
DM particles could be detected directly in underground laboratories, through elastic interactions with nuclei inside detectors, or indirectly, through the analysis of its annihilation products in massive objects like the Galactic Center or the Sun. If DM particles are WIMPs, they can undergo auto-annihilation, resulting in observable by-products such as neutrinos with energies of the order of tens of GeV, depending on the predicted DM particles mass.
The existence of intermediate mass magnetic monopoles, with masses between 10^{10} and 10^{14} GeV, have been predicted in several theoretical models. MM 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. Preliminary results on the search for fast MM performed with the ANTARES detector, are shown in as a function of the monopoles speed in figure **??**, and are compared to the results of other experiments.

6 Multimessanger approach within the ANTARES Collaboration

The search for neutrino emission from transient sources, like Micro-quasars, Gamma Ray Bursts (GRBs)[8], flares of Active Galactic Nuclei (AGNs) or core collapse supernovae (ccSNe)[9], 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 set a discovery.
Two different detection methods have been implemented within the ANTARES Collaboration. The first one is based on the search for neutrino candidates in conjunction with an accurate timing and positional information provided by an external source: the triggered search method. The second one is based on the search for high energy or multiplet of neutrino events coming from the same position within a given time window: the rolling search method.

GRBs or flares of AGNs are detected by gamma-ray satellites, which deliver in real time an alert to the Gamma-ray bursts Coordinates Network (GCN). The characteristics (mainly the direction and the time of the detection) of this alert 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 [5], using a Target-of-Opportunity (ToO) program. This method is sensitive to all transient sources producing high energy neutrinos.

The ANTARES Collaboration have developed an alert system [6] that triggers the observation with a network of optical telescopes.

The key ingredients are the use of a fast and robust reconstruction algorithm[7] and the connection with a network of robotic telescopes with large field of view (approximately $2° \times 2°$), 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 optical images is under way.

References

1. J. K. Becker, Physics Reports, 458(4-5):173-246, 2008.
2. M. Ageron *et al*, arXiv:1104.1607
3. Heijboer A, Track reconstruction and point source searches with ANTARES, PhD thesis, Universiteit van Amsterdam, 2004, http://antares.in2p3.fr/Publications.
4. J. Aguilar *et al.*, *Phys. Rev.* B **696**, 1622 (2011)
5. M. Kowalski and A. Mohr, Astropart. Phys., 27 (2007) 533-538
6. M. Ageron *et al*, arXiv:1103.4477
7. J. Aguilar *et al*, Astropart. Phys. **34 I9**, 652-662 (2011)
8. S. Razzaque, P. Meszaros, E. Waxman, Phys. Rev. Lett. 90 (2003) 241103
9. S. Ando and J. Beacom, Phys.Rev.Lett. 95 (2005) 061103