PROCEEDINGS OF SCIENCE

Hunting for cosmic neutrinos deep under the sea: The ANTARES experiment. Some selected results

Annarita MARGIOTTA* **on behalf of the ANTARES Collaboration**
Dipartimento di Fisica dell'Università and Sezione INFN - Bologna, viale C. Berti Pichat, 6/2, 40127 Bologna, Italy
E-mail: margiotta@bo.infn.it

More than one hundred years after the first observations of cosmic rays, problems connected with their origin and propagation have not been completely solved. Astrophysical objects such as supernova remnants, active galactic nuclei, Quasars and microquasars, which are likely sources of high energy cosmic rays and gamma rays, could emit high energy neutrinos as well. The detection and the study of their properties would shed light on production and acceleration mechanisms acting inside possible cosmic accelerators.
Measuring the arrival direction and energy of such neutrinos requires very massive targets, whose size is far beyond those of present, conventional underground detectors. A possible solution is the use of the sea as a Cerenkov target-detector. ANTARES is the first undersea neutrino telescope. It has been built in the Mediterranean Sea by a large European collaboration and has been in data taking since 2008, demonstrating the feasibility of this technique. The detection principle and some selected results obtained so far are presented.

The European Physical Society Conference on High Energy Physics -EPS-HEP2013
18-24 July 2013
Stockholm, Sweden

*Speaker.

PoS(EPS-HEP 2013)404

1. Introduction

High energy neutrinos are a perfect probe to explore the far Universe. They can escape undeflected and almost unaffected from their production regions thanks to weak interaction cross section, carrying information on the mechanisms acting inside astrophysical objects. This characteristic makes their detection a challenging task, as it requires very large volume detector. Following the suggestion of Markov [1], underwater (underice) neutrino telescopes have been built, which make huge amount of natural (sea or lake) water (or polar ice) sensitive to the passage of Cherenkov photons. A neutrino telescope is a 3 dimensional array of optical sensors (photomultipliers - PMTs), which collect Cherenkov photons emitted along the path of charged particles created in neutrino interactions, in the proximity of the detector. Using charge, time and position information the arrival direction and energy of neutrinos can be reconstructed. The main scientific goal of neutrino telescopes is the search for Galactic and extra-Galactic neutrino sources. A privileged channel, in particular for underwater arrays, is the charged current muon neutrino interaction: $\nu_\mu + N \rightarrow \mu + X$. Thanks to the long scattering length of sea water, a very good angular resolution on the neutrino arrival direction can be reached. Diffuse cosmic neutrino flux can also be studied originated by the interaction of high energy cosmic rays with the cosmic background.

2. The ANTARES detector

The ANTARES ((Astronomy with a Neutrino Telescope and Abyss environmental RESearch) detector was completed in 2008 [2]. It has been deployed at a depth of 2475 m, $\sim$ 40 km off La-Seyne-sur-Mer (French Riviera). It is presently the largest neutrino telescope in the Northern hemisphere, with the best sensitivity to the central region of the Galaxy. It hosts 885 PMTs distributed along 12 lines. The horizontal distance between lines is about 60-70 m, while the vertical spacing between the 25 stories on each line is 14.5 m. Each storey carries 3 optical modules (OMs) downward looking, at 45^o with respect to the vertical direction and a titanium box (the Local Control Module) containing the main electronic boards for a correct positioning of the storey and the first treatment of data. Each OM is made by a 17" pressure resistant glass sphere, hosting a 10" PMT with its base. The strings are connected via a Mechanical Electrical Optical Cable to a Junction Box and from this to a shore station where data are collected and, through dedicated trigger algorithms, reduced and stored on disk. The infrastructure is completed by an Instrumented Line (IL07) hosting several environmental and oceanographic instruments and part of the AMADEUS system [3]. This is a test tool for the acoustic detection of ultra-high energy neutrinos. Fig. 1 shows a scheme of the ANTARES detector configuration. Since April 2013, the IL07 hosts a complete prototype of the multi PMT OM that will be used on the future KM3NeT detection units. The performances of the ANTARES detector are well within the expectations, in particular the angular resolution is $< 0.5^\circ$ and guarantees a high sensitivity to point like sources of neutrinos, see sect. 5.2.

3. Atmospheric Neutrino Energy Spectrum

Analyzing the data sample collected from December 2007 to December 2011, corresponding to 855 days of ANTARES livetime, the first measurement of the atmospheric neutrino energy

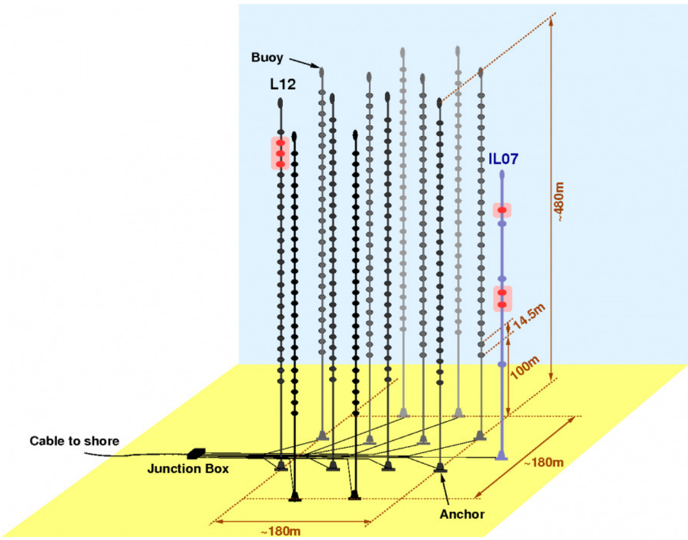

Figure 1: The ANTARES detector configuration.

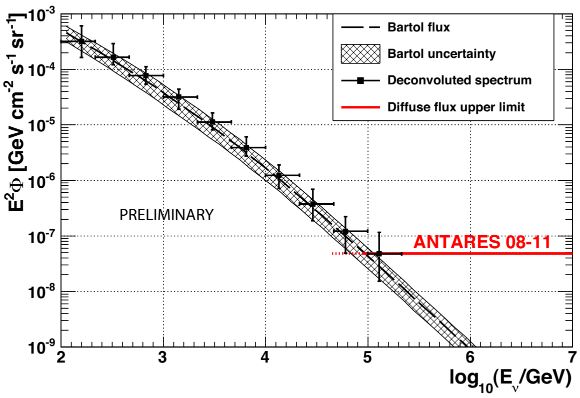

Figure 2: Atmospheric neutrino energy spectrum as measured by ANTARES. The flux is compared with the expectations from [6] while the grey band corresponds to the uncertainty in the flux calculation [7].

spectrum with an under seawater telescope has been performed, [4]. While crossing the detector, muons lose energy via ionization and radiative processes. The relative importance of the two mechanisms depends on the energy of the muon, with a dominance of the latter at higher energy. The light collected in the detector can be used to infer the energy of the muon and to estimate the energy of the parent neutrino. In this analysis two different muon energy estimators have been used. The "energy loss" method estimates the muon energy loss per track length inside the sensitive volume of the detector, considering the detected charge on the OMs and the photon detection efficiency. The "energy likelihood method" maximizes the agreement between the observed and expected amount of light on each OM, taking the muon energy as a free parameter. The stochastic nature of the muon energy loss, detector inefficiencies and its limited size require the use of unfolding procedures [5]. In Fig. 2 the results of the present measurements are shown. The ν_μ energy spectrum is averaged over all upward going track directions (zenith angle between 90^o and 180^o). Black line in the figure is the conventional Bartol flux, [6]. The ANTARES measurement is compatible with the results of the under ice detectors, considering that the latter extend on a slightly smaller angular region. The spectral index obtained with this analysis is $\gamma_{meas} = 3.58 \pm 0.12$, the flux normalization is 25% higher than Bartol flux expectations, in agreement with what found by the MACRO detector at the Gran Sasso Laboratory, [8].

4. Atmospheric Neutrino Oscillations

Data collected between 2007 and 2010 have been used to measure atmospheric neutrino oscillation parameters. Considering a simplified scheme of two flavors oscillations, the ν_μ survival probability is

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta_{23} \sin^2 \frac{1.27 \Delta m^2_{23} L}{E_\nu} \tag{4.1}$$

$$= 1 - \sin^2 2\theta_{23} \sin^2 \frac{16200 \Delta m^2_{23} \cos\theta}{E_\nu}, \tag{4.2}$$

where L is the neutrino path length, θ the zenith angle, Δm^2_{23} the difference of the squares of the mass eigenstates, m_2 and m_3, and θ_{23} the corresponding mixing angle.
Assuming $\Delta m^2_{23} = 2.43 \times 10^{-3} \mathrm{eV}^2$ and $\sin^2 2\theta_{23} = 1$, [9], the first oscillation maximum is expected at $E_\nu = 24$ GeV, for vertical up going neutrinos. Muons produced in this case can travel about 120 m in water and can be reconstructed in ANTARES, though with a reduced efficiency. The neutrino energy is estimated considering the muon range in the detector. A variable $E_R = S \cdot 0.2$ GeV/m is defined, with $S = (z_{max} - z_{min})/cos(\Theta_R)$, where z_{max} and z_{min} are the vertical coordinates of the uppermost and lowermost hits and Θ_R is the reconstructed zenith angle of the track. Fig. 3

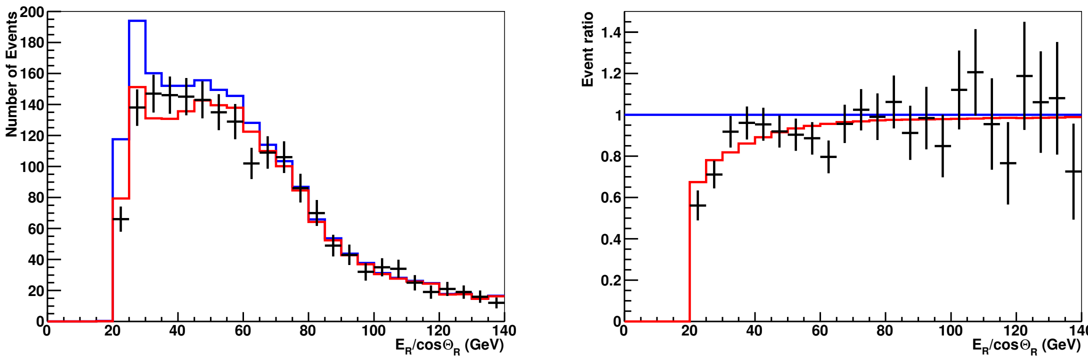

Figure 3: Left: Distribution of $E_R/\cos\Theta_R$ for selected events. Black crosses are data with statistical uncertainties, whereas the blue histogram shows simulations of atmospheric neutrinos without neutrino oscillations plus the residual background from atmospheric muons. The red histogram shows the result of the fit. **Right**: The ratio of data and simulated events with respect to the non-oscillation hypothesis. Same color code as for the left figure.

(left) shows the comparison between data (black crosses) and MC expectations without oscillations (blue line) as a function of $E_R/cos(\Theta_R)$. Fig. 3 (right) shows the ratio between data and simulated events with respect to the non oscillation hypothesis. A deficit is clearly visible for $E_R/cos(\Theta_R) < 60$ GeV. Assuming maximal mixing, a value $\Delta m^2_{23} = 3.1 \times 10^{-3} \mathrm{eV}^2$ is obtained.

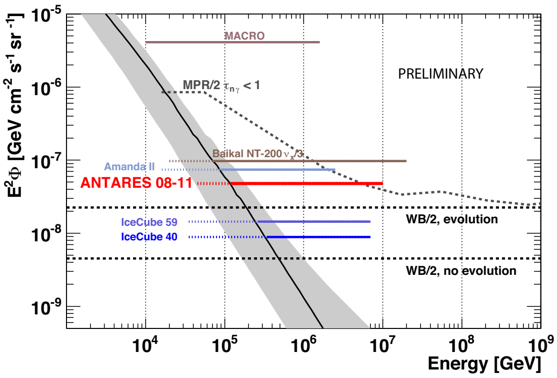

Figure 4: The updated ANTARES upper limit (90% C. L.) for an E^{-2} spectrum compared to 90% C.L. upper limits from other experiments, all for single neutrino flavour.

The good agreement with current world data shows the understanding of the detector even at the lowest accessible energies and suggests the possibility of measuring the neutrino fundamental parameters with an underwater neutrino telescope, in particular the mass hierarchy. The KM3NeT Collaboration has been carrying on a feasibility study for such a measurement (the ORCA project, [11]).

5. Neutrino Astronomy

5.1 Search for a Diffuse Flux of Cosmic Neutrinos

Neutrinos of astrophysical origin are expected to have a harder spectrum than the atmospheric neutrinos. An excess of events over the atmospheric neutrino flux should be measured above a critical value of energy, which is dependent on the absolute normalization of fluxes. A first search for high energy neutrinos from unresolved astrophysical sources was published in [12]. Recently a new measurement has been performed using a larger data sample (2008-2011 data, 855 days LT) and a new energy estimator. In this second analysis the muon energy loss per unit path length is estimated by measurable quantities like the amplitude of the hits. To improve the rejection of background light, only hits considered for the reconstruction track algorithm are accounted for. Finally, using the energy estimator, the value of the energy cut producing the best sensitivity was evaluated, according to the Model Rejection Factor procedure. After reconstruction quality cuts, the simulated atmospheric neutrino flux shows a deficit of about 28% with respect to data. The discrepancy is well within uncertainties and the MC expectation is normalized to the data. At the end of the analysis, 8 events are observed in the high energy region when 8.4 atmospheric neutrino events are expected. This implies an upper limit of

$$E^2\frac{dN}{dE} = 4.8\times 10^{-8}\mathrm{GeV cm^{-2} s^{-1} sr^{-1}}$$

in the energy range 45 TeV - 10 PeV at 90%C.L., as shown in fig. 4.

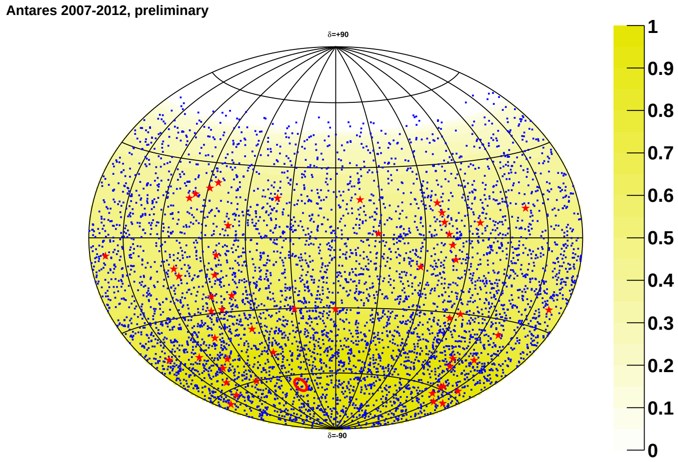

Figure 5: Sky map in equatorial coordinates showing the 5516 selected data events. The position of the most signal-like cluster is indicated by the red circle. The red stars denote the position of the candidate sources.

5.2 Search for Neutrino Point Sources

Searches for cosmic neutrino sources have been performed following different approaches. Point like sources were searched for, using 2007-2010 data, LT of 813 days, with 3058 events passing the selection criteria, [13]. Recently, data collected until the end of 2012 were analyzed. The corresponding LT is ~1334 days, with 5516 neutrino events. About 90% of the events are reconstructed within 1° from their true direction, with a median uncertainty on the reconstructed neutrino direction of $0.4^{\circ} \pm 0.1^{\circ}$, for a E^{-2} neutrino energy spectrum. A 10% contamination of misreconstructed atmospheric muons is estimated. Starting from this sample a full-sky scanning has been performed searching for an excess over expected background of atmospheric muons and neutrinos, in the declination range $[-90^{\circ}; +48^{\circ}]$. The algorithm is based on the likelihood of the observed events, where the knowledge of the point spread function, of the expected background rate as a function of the declination and of the number of hits used in the reconstruction are accounted for. The error estimate on the track direction, as given by the fit procedure, is also included in the likelihood on an event-by-event basis. A skymap, in equatorial coordinates, with the position of every selected point in the sky is shown in Fig. 5. The most significant cluster is located at (R.A=-47.8°; δ=-64.9°). The post-trial p-value is 2.1%, equivalent to 2.3σ. This "warm spot" does not correspond to any counterparts in the electromagnetic band.
A second analysis identified $\sim$ 50 potential sources of neutrinos. The list includes some extra Galactic objects, like Active Galactic Nuclei (AGN), and several Galactic sources, whose activity in the TeV gamma ray region has been reported. No statistically significant excess was found. Upper limits were calculated, see Fig.6.

6. Searches for transient sources and multi messenger approach

Several analyses have been performed to search for neutrinos emitted in combination with possible transient sources like: Gamma Ray Bursters (GRB), Gravitational Wave (GW) events,

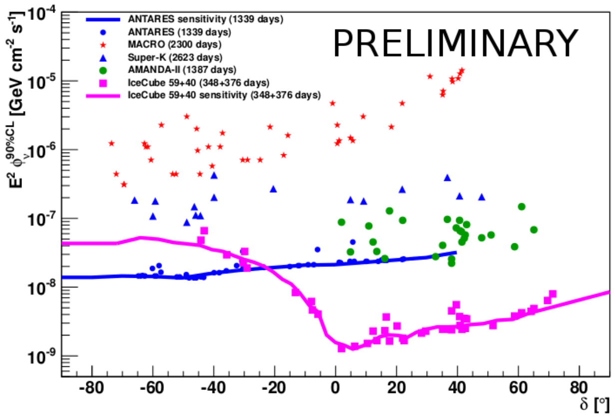

Figure 6: Upper limits (at 90% C.L.) on the E^{-2} neutrino flux from selected candidate sources as function of their declination. Upper limits from other experiments are also indicated. The lines show the expected median sensitivities.

flaring sources during their activity period (μ-quasars, AGN...). Presently ANTARES is part of an alarm system for GRBs connected to a number of telescopes. In case of particular triggers (like two neutrinos within 15 minutes and separated by less than 3^o, a high energy event, typically larger than 5 TeV or an event closer than 0.3^o from a local galaxy, within 20 Mpc) an alarm is sent to a network of robotic telescopes (TAROT, ROTSE, ZADKO) and more recently to the SWIFT/XRT telescope. This system has a fast response which would allow the detection of possible optical afterglows from GRBs. Up to now, no optical counterparts have been observed in coincidence with a neutrino alert and limits have been set on the possibility of a GRB afterglow [14].
Also an extended search for coincidence between a candidate neutrino and a GRB event, selected in a list of GRB occurred between 2007-2011, did not lead to any evidence [15]. A dedicated search has been performed in coincidence with a very bright event, GRB130427A [16]. No excess was found simultaneously with the electromagnetic signal.
Combined searches of neutrinos and GW events have been conducted in collaboration with VIRGO and LIGO interferometers. HE neutrino candidates in coincidence with GWs could reveal new, hidden sources that are not observed by conventional photon astronomy. Also in this case no significant number of coincident event was observed and limits on the density of joint HE neutrino - GW emission events in the local universe have been calculated [17].

7. Conclusions

The ANTARES neutrino telescope is the only deep sea neutrino telescope presently in operation. It has been continuously monitoring the Southern Sky with very high sensitivity since 2007. Several analyses have been developed in different energy range of atmospheric neutrinos, in the search for extra-terrestrial high energy neutrinos and following a multi messenger approach in combination with GW, GRB and other transient source detectors. In addition, a wide program of studies on dark matter and other exotic particles, like nuclearites and magnetic monopoles [18] have been performed. The data acquisition will continue at least until the end of 2016. At that time a larger detector, the KM3NeT, that is presently being built in the Mediterranean Sea, will start taking data.

References

[1] A. M. Markov, in Proceeding of the Rochester Conference, New York (1960).

[2] M. Ageron et al., Nucl. Instrum. Meth. A 656 (2011) 11.

[3] J.A. Aguilar et al., Nucl. Instrum. Meth. A 626-627 (2011) 128.

[4] S. Adrian-Martinez et al., Eur. Phys. J. C (2013) 73:2606.

[5] A. Hocker and V. Kartvelishvili, Nucl. Instr. Meth. In Phys. Res. A372(1996)469 ; G. DÕAgostini, Nucl. Instr. Meth. in Phys. Res. A362 (1995)487.

[6] G.D. Barr et al., Phys. Rev. D 70 (2004) 023006.

[7] G.D. Barr et al., Phys. Rev. D 74 (2006)094009.

[8] M. Ambrosio et al., Eur. Phys. J. C 36 (2004)323.

[9] P. Adamson et al., Phys. Rev. Lett. 101 (2008)131802.

[10] S. Adrian-Martinez et al., Physics Letters B 714 (2012) 224.

[11] P. Kooijman for KM3NeT, 33rd ICRC, id 164.

[12] J.A. Aguilar et al., Phys. Lett. B696 (2011)16.

[13] S. Adrian-Martinez et al., ApJ, 760 (2012) 53.

[14] M. Ageron et al., Astropart. Phys. 35 (2012) 530.

[15] S. Adrian-Martinez et al., JCAP 1303 (2013) 006; S. Adrian-Martinez et al., A&A 559 (2013)A9.

[16] J. Schmid for the ANTARES Coll., TeVPA 2013 proceedings.

[17] S. Adrian-Martinez et al., JCAP06(2013)008.

[18] S. Adrian-Martinez et al., Astropart. Phys. 35 (2012) 634

PoS(EPS-HEP 2013)404