Available online at www.sciencedirect.com

ScienceDirect

Nuclear and Particle Physics Proceedings 273–275 (2016) 419–424

www.elsevier.com/locate/nppp

Recent Results of the ANTARES Neutrino Telescope

Giulia De Bonis*

Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Roma
1

Abstract

The discovery of cosmic neutrinos of astrophysical origin by IceCube has started a new chapter in the field of Neutrino Astronomy. Noticeably, a small accumulation of events in the region near the Galactic Centre has been observed: a telescope in the Mediterranean Sea constitutes a great opportunity for the physics quest, since it offers a perfect complementarity to IceCube and, in particular, a better visibility of the Galactic Centre. ANTARES (Astronomy with a Neutrino Telescope and Abyss Environmental RESearch) is the first operational Cherenkov neutrino telescope in the Mediterranean Sea and the largest neutrino detector in the Northern hemisphere, covering an area of about 0.1 km^2; located 40 km offshore Toulon, France, at a depth of 2475 m, it has been completed in June 2008 and it is currently taking data. It consists of a tri-dimensional array of 885 photo-multipliers tubes (PMTs), distributed in 12 lines. ANTARES has recently performed a search for an excess of high energy neutrinos in the direction of the Galactic Centre, close to the accumulation of the IceCube events, assuming both the hypotheses of a point-like and an extended neutrino source. The results of this search will be discussed in this contribution, together with other recent achievements of the experiment, as the search for point-like sources, the results on the diffuse flux of cosmic neutrino signal and the search for neutrino emission from the Fermi bubbles. ANTARES offers a first view of the Neutrino Sky from the Northern hemisphere; its successful operation and its promising results make more compelling the expectations for KM3NeT, the next generation neutrino experiment in the Mediterranean Sea.

Keywords: Neutrino Astronomy, Neutrino Telescopes, Cherenkov Detectors, Cosmic Rays, Galactic Centre

---

1. Introduction

Neutrino astronomy is a field of investigation of the astrophysical research that uses cosmic neutrinos as probes of astrophysical processes in the Universe. Indeed, as neutral weakly interacting particles, neutrinos are not absorbed during propagation nor deflected by magnetic fields. Retaining the directional information, they offer excellent pointing capabilities; travelling unperturbed, they have the potential for looking further away at cosmological distances, and deeper inside into astrophysical objects opaque to photons and protons.

Several astrophysical models predict the emission of high-energy and ultra-high-energy ($E_\nu < 10^5$ GeV) neutrinos. Neutrino fluxes are expected from cosmic accelerators in which particles are trapped by magnetic fields and gain energy in shock fronts ("bottom-up") via the so-called *Fermi mechanism* [1]. If hadrons are present (i.e. the astrophysical site is a source of cosmic rays), they can interact with matter and radiation in the source and produce neutral and charged pions. The pion decay gives gamma-rays and neutrinos and the flux predictions for neutrinos can be computed given

---

*on behalf on the ANTARES Collaboration

Email address: `giulia.debonis@roma1.infn.it` (Giulia De Bonis)

URL: `http://www.roma1.infn.it/people/debonis/` (Giulia De Bonis)

[1] Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Roma, Piazzale Aldo Moro 2, 00185 Roma, Italy

http://dx.doi.org/10.1016/j.nuclphysbps.2015.09.061

the observations of the gamma-ray spectra. The conditions for particle acceleration can be realized in several classes of astrophysical objects, that are thus included in the list of candidate neutrino sources [2]. Among them, Supernovae Remnants (SNRs) are the most accredited steady sources in the Galaxy; Micro-Quasars are taken into account as galactic flaring emitters; Active Galactic Nuclei (AGNs) are expected as the most important extragalactic sources of cosmic rays and neutrinos; Gamma Ray Burst (GRBs) are the most powerful explosive events in the Universe and can be associated with neutrino emissions. In addition, cosmic neutrinos are a key ingredient also in Cosmology: high-energy neutrinos are predicted in so-called top-down models that have neutrinos at the end of a variety of decay chains of standard (and beyond the standard) model particles. The most important class of models of this kind regards dark matter, and neutrinos in the $GeV \div TeV$ range are expected in the self-annihilation of the hypothetical weakly interacting massive particles. See [3] for a discussion of the latest results of the ANTARES neutrino telescope in the indirect search for dark matter.

Neutrino astronomy aims at identifying cosmic neutrino sources in the Sky, providing a map with neutrino "hot spots". Such locations, if confirmed (and unambiguous identification can profit from the multi-messenger approach), will offer a crucial contribution in astrophysics, for the understanding of the nature and behaviour of cosmic engines and of explosive events in the Universe. The discovery of neutrino sources can also help in discriminating between different acceleration mechanisms (hadronic *versus* leptonic) and can solve the puzzle of the origin (sites of production and acceleration) of cosmic rays. Other impacts of neutrino astronomy include cosmology and particle physics (interaction cross section above the threshold that can be explored with particle accelerators; neutrino oscillations; hints of new physics beyond the standard model).

Weak interaction is a great opportunity for discovery, but also a challenge for detection. A cubic-kilometre scale detector is required, to offer a significant target for neutrino interactions and to collect a valid statistics of events (expected event rate at $E_\nu = 10^5$ GeV is some tens in a year on a surface of 1 km^2). To fulfil the requirements, neutrino telescopes are submarine or in-ice apparata: the oceanic mass operates, at the same time, as the target for neutrino interactions, the medium for signal generation and transmission and the shielding for the reduction of the background of atmospheric muon flux. Water and ice are indeed an effective medium for Cherenkov technique: the detection principle is based on the measurement of Cherenkov light emitted as a consequence of the propagation in water of ultra-relativistic (super-luminal) charged particles produced in neutrino interactions. Cherenkov photons are detected with a three-dimensional grid of light collectors, or photo-multipliers tube (PMTs). The geometry of the emission is fixed by the refractive index of the medium; particle tracks are reconstructed from the measurement of the times of arrival of photons at the PMTs; the energy in estimated from the collected charge. Muon tracks are the result of charge-current interactions of muon neutrinos; particle showers originate in charged-current interactions of electron and tau neutrinos and in all-flavour neutral-current interactions. The evaluation of the neutrino direction is more accurate if muon tracks are reconstructed; on the other hand, the energy estimate is more precise for shower events. Atmospheric muons (i.e. muons produced as secondaries in interactions of cosmic rays with the atmosphere) are the main source of background for neutrino telescopes. To prevent atmospheric muon contamination, an optimal installation site is at large depth; in addition, a further background reduction is gained rejecting down-going events. An irreducible and isotropic source of background is given by atmospheric neutrinos; the discrimination of the potential signal is performed using statistical arguments (looking for excesses or event above the expected background level) and isolating an high-energy component in the sample of neutrino candidates. Indeed, the atmospheric flux is expected to fade away at energies larger than $E_\nu = 10^6$ GeV; at about the same energies, because of the increase of the neutrino cross section with energy, the Earth becomes opaque to up-going neutrinos and the sky above the detector becomes visible.

The latest IceCube results [4][5] have started a new era in Neutrino Astronomy. The IceCube experiment, deployed in-ice in Antarctica, has announced the observation of several tens of high-energy neutrino events with energy spectrum harder than any expected atmospheric background, so that any association with the atmospheric neutrino flux can be excluded. The measured event sample is compatible with an isotropic neutrino flux (diffuse flux), meaning that no statistically significant cluster has been found, and thus no candidate point source of neutrinos can be claimed so far.

2. The ANTARES Detector

ANTARES (Astronomy with a Neutrino Telescope and Abyss environmental RESearch) [6], deployed in the Mediterranean Sea, is the largest neutrino telescope in operation in the Northern hemisphere. The detector is located 40 km offshore Toulon, France, at a depth of about 2500 m. It consists in 885 PMTs, arranged in triplets to make a storey. The detection unit is the string (or line), composed of 25 storeys; the distance between storeys along the string is 14.5 m; the total length of the string is 450 m, including the length of 100 m between the bottommost storey and the seabed. The detector is made up with 12 strings; the distance between string is about 70 m. ANTARES PMTs are downward-looking, with the axis of the photocatode at an angle of 45° to the vertical, aiming at maximising the capabilities of detecting up-going tracks. The deployment of the telescope and the data taking started in 2007 with the first 5 lines; the detector has reached its final configuration (12 lines) in May 2008. Data taking is continuosly on-going and will be on up to end of 2016. The location of the telescope in the Northern hemisphere makes it perfectly complementary to IceCube; in particular ANTARES visibility for up-going events covers a large portion of the Galactic Plane and the Galactic Centre, allowing the inspection of the IceCube ”hot spots“ at a lower energy threshold (see Figure 1).

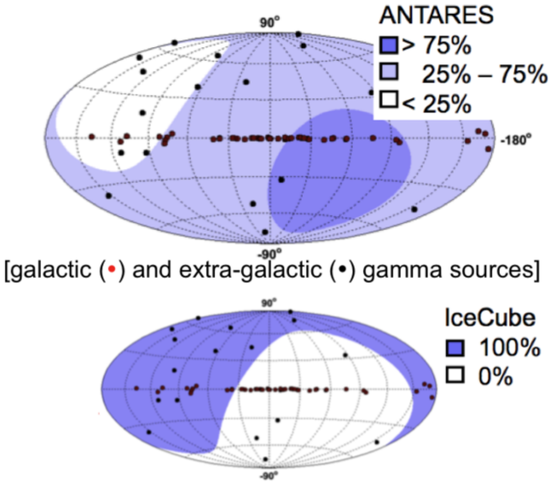

Figure 1: Sky coverage in Galactic coordinates for a detector located in the Mediterranean Sea (ANTARES) and at the South Pole (IceCube) with a 2π downward exposure. The figure points out the complementarity of the two installations. A telescope in the Mediterranean Sea assures a good coverage of the Galactic Centre (the ”hottest“ cluster in the IceCube data set) and of the Galactic Plane (where most of gamma-ray emitters, indicated by dots in the figure, have been observed).

3. ANTARES Selected Results

In the following, the latest results of the ANTARES detector will be illustrated, paying attention in particular to the outcomes for astronomy and astrophysics.

3.1. Point-Like Sources

The most recent search for neutrino point sources in ANTARES [7] has considered data taken in the period 2007-2012, for an integrated live time of 1340 days and a total number of 5516 neutrino candidates. The search focuses on muon neutrinos, since selection cuts have been optimized for muon tracks. following a blind-strategy approach. The track reconstruction algorithm is likelihood-based; parameter Λ measures the quality of the reconstruction. Only good quality (large Λ) up-going tracks with low angular error are selected for the analysis; these cuts allow to discard most of the atmospheric muon background (Figure 2).

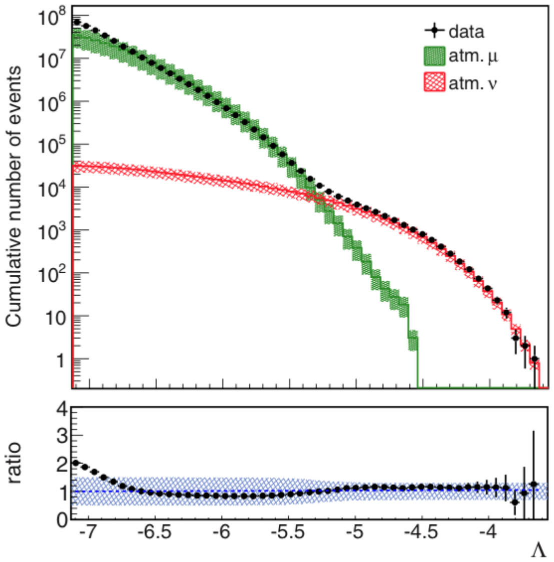

Figure 2: Distribution of the quality parameter Λ for up-going tracks with low angular error estimate. Results are compared for data, Monte Carlo simulation of atmospheric neutrinos and of atmospheric muons (down-going muon tracks mis-reconstructed as up-going). The bottom panel shows the ratio between data and simulation; a good agreement is achieved.

The sample on neutrino candidates passing the selection cuts is analysed aiming at the identification of clusters of events; the statistical significance of any excess over the expected amount of atmospheric background is evaluated with a maximum-likelihood approach that been applied in three different studies: 1) the full-sky search; 2) the search for neutrinos from selected sources (taken from a list of gamma-ray sources assumed as candidate neutrino emitters); 3) the search in the region of the Galactic Centre, aiming at having an ANTARES view of the IceCube most significant cluster.

The first search looks for an excess of events over the background expectations anywhere in the ANTARES visible sky. Results are shown in Figure 3 and claim no statistically significant excess; the most significant spot is located at $(\alpha, \delta) = (46.8°, -64.9°)$, with a post-trial p-value of 2.7%, corresponding to a signal significance of 2.2 σ, and consistent with the most significant spot found in the previous analysis [8].

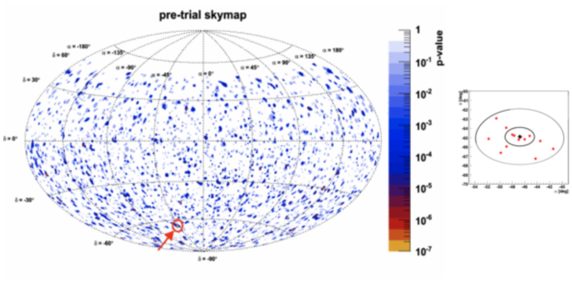

Figure 3: Sky-map in equatorial coordinates of the pre-trial p-value. The arrow points at the most significant excess, shown on the right.

The second search is motivated by the assumption that gamma-rays and neutrinos have common sources, therefore a list of 50 candidate emitters is taken into account and the likelihood is evaluated at the source positions. The most significant result is obtained at the position of HESS J0632+057, with a post-trial p-value of 6.1 %, corresponding to a significance of 1.9 σ. Figure 4 sums up the results of the full-sky search and of the search for the list of candidate sources. The noteworthy fact that can be extracted from the comparison with IceCube results is that ANTARES has the best sensitivity in the Southern Sky for $E_\nu < 100 TeV$, i.e. for potential Galactic sources, since a cut-off in energy is expected for accelerators in the Galaxy because of the magnetic confinement of particles in the galactic accelerators.

Finally, the last study focuses on the interpretation of the IceCube results. The starting point is a publication by González-Garcìa *et al.* [10] that, in the light of the IceCube results, advances the hypothesis of a point source around the position of the Galactic Centre (at $(\alpha, \delta) = (-79°, -23°)$), with an expected flux normalization of $\Phi = 6 \times 10^{-8} GeV cm^{-2} s^{-1}$. ANTARES has investigated a region of 20° around the proposed location, testing both the point-like source and the extended source hypotheses (the direction of IceCube events is reconstructed with large uncertainty, since most of them are shower-like events). The results of this search are illustrated in Figure 5. The presence of a point-like source at the proposed location compatible with the flux measured by IceCube is excluded by ANTARES.

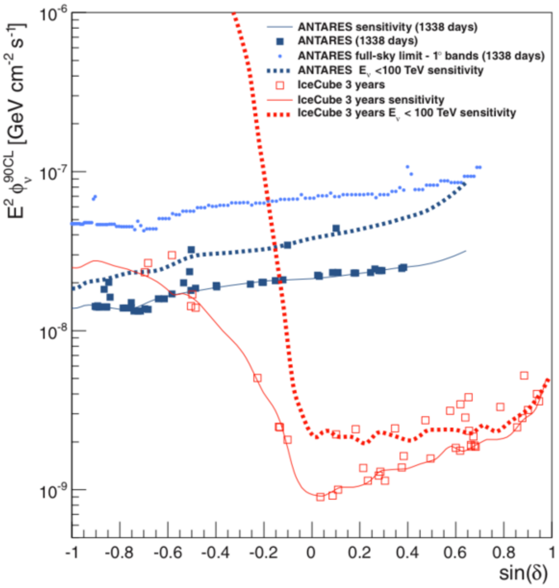

Figure 4: 90% C.L. flux upper limits and sensitivities on the muon neutrino flux for six years of ANTARES data, as a function of declination. IceCube results, in red, are shown for comparison (taken from [9]). The result of the full-sky search (light-blue markers) is given in terms of the upper limit for any point source located in the ANTARES visible sky in declination bands 1°. The blue markers represent the upper limits for the candidate sources in the list under study. The solid line is the sensitivity for point-like sources, assuming an E^{-2} spectrum; the dashed line is the sensitivity computed for neutrino energies lower than 100 TeV.

3.2. *Fermi Bubbles*

Fermi bubbles are extended gamma-ray emitting regions above and below the Galactic Centre discovered with Fermi-LAT data. The spectrum follows a power law (E^{-2}); an exponential energy cutoff is expected. The origin of the ”bubbles“ is still unclear, but some models assume the presence of hadrons and thus predict an associated neutrino flux [11]. The bubbles are in the field of view of ANTARES, thus a dedicated search has been carried on to evaluate the presence of a neutrino signal from the regions of interest [12]. The study has been performed using ANTARES data collected in the period 2008-2011, for an integrated live time of 806 days. Only good quality, up-going, track-like events with low angular errors are selected, to reject the contamination of atmospheric muons. An energy estimator is used to identify high-energy neutrino candidates and discriminate atmospheric neutrinos. A blind strategy is adopted for the optimizations of the cuts on the quality parameter (Λ, see Section 3.1) and on the energy estimator. The background of atmospheric neutrinos is estimated from data, averaging the information taken from three non-overlapping ”off-zones“ having the same size, shape and

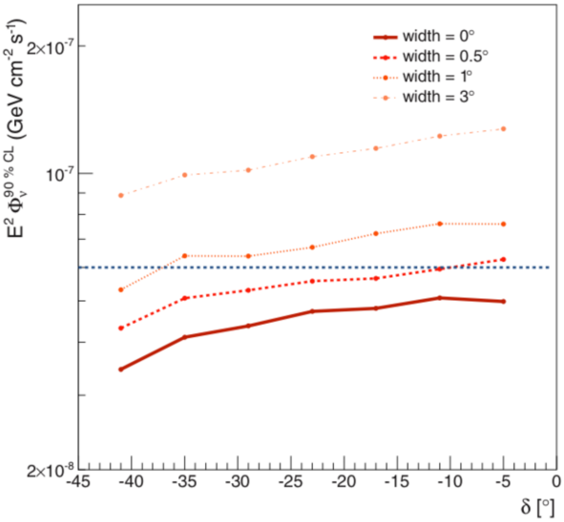

Figure 5: C.L. upper limits obtained for different source widths as a function of the declination, compared with the theoretical expectation on the flux (dashed line).

detector efficiency of the on-zone region (Figure 6).

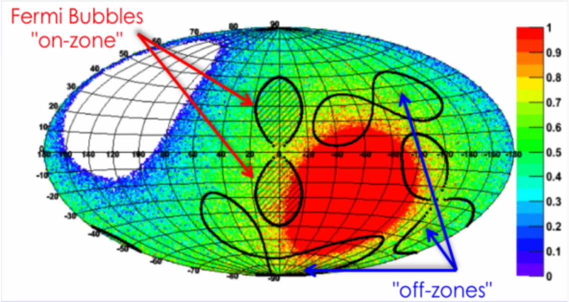

Figure 6: Sky-map in galactic coordinates; the ANTARES visibility of the "on-zone" (the region where the neutrino signal is looked for in the Fermi bubble search) is comparable to the visibility of the "off-zones" (defined for the evaluation of the atmospheric background in the on-zone).

After applying the cuts on the un-blinded data sample, 16 events are observed in the on-zone, to be compared with 11 events observed in the off-zones (average value). The observed excess is no statistically significant (it corresponds to 1.2 σ) and allows to set upper limits on the theoretical models for the neutrino emission from the Fermi bubbles (Figure 7).

3.3. Diffuse Flux

The first study on the diffuse neutrino flux with ANTARES [13] was performed using data collected in the period 2007-2009, corresponding to an integrated live time of 334 days. A dedicated energy estimator was developed to separate the two components of atmospheric and astrophysical neutrinos; no excess of high energy neutrinos was found over expectation from atmospheric background and results were expressed in terms of flux upper limit.

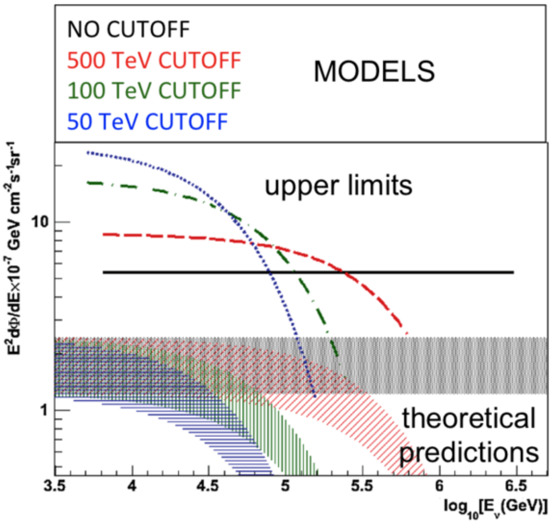

Figure 7: ANTARES Upper limits and theoretical predictions on the neutrino flux from the Fermi bubbles.

The first improvement of the above analysis has considered an extended data sample (the period under study is 2008-2011, with the 12-lines detector), for an integrated live time of 885 days. Up-going muon neutrino candidates were selected and an improved energy estimator was developed and applied to the data. No statistically significant excess has been found and the value on the flux upper limit of the previous analysis has been updated:

$$E^2 \cdot \Phi(E) < 5.1 \times 10^{-8} GeV cm^{-2} s^{-1} sr^{-1} \qquad (1)$$

valid in the energy range 45 TeV $< E <$ 10 PeV.

A further improvement is obtained enlarging the collection of neutrino candidates including not only track-like events (muon neutrinos), but also shower-like events (all-flavour neutrinos). The preliminary analysis has been completed on data collected in the period 2007-2012, corresponding to an integrated live time of 1247 days. The sensitivity per neutrino flavour has been computed for the energy range 23 TeV $< E <$ 7.8 PeV and the obtained value is

$$E^2 \cdot \Phi(E) < 2.21 \times 10^{-8} GeV cm^{-2} s^{-1} sr^{-1} \qquad (2)$$

After the un-blind, the search for an high energy component in the sample of shower-like events has produced no statistically significant excess over the expected background and results can be given in terms of flux upper limit:

$$E^2 \cdot \Phi(E) < 4.9 \times 10^{-8} GeV cm^{-2} s^{-1} sr^{-1} \qquad (3)$$

valid in the energy range 23 TeV < E < 7.8 PeV.

Figure 8 sums up ANTARES results on the search for the diffuse flux; theoretical predictions on the atmospheric flux and results from other experiments are reported for comparison.

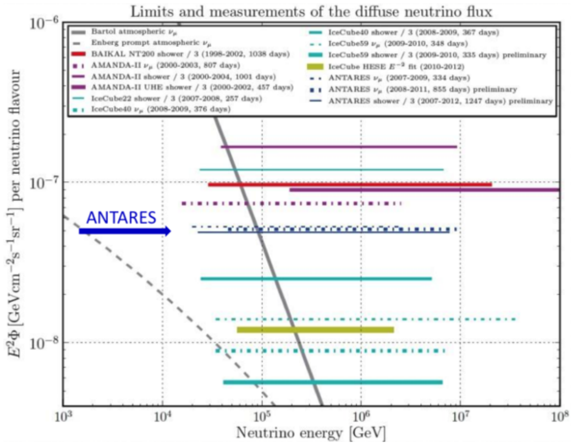

Figure 8: Limits and measurements of the diffuse neutrino flux. ANTARES results are given together with results from other experiments and theoretical predictions on the atmospheric component.

4. Conclusions and Perspectives

ANTARES is the largest neutrino telescope in the Northern hemisphere and the first undersea Cherenkov telescope in operation. Despite its reduced size, the scientific content of information produced by ANTARES is already competitive with IceCube. Indeed, the location of the telescope in the Northern hemisphere offers a perfect complementarity to the IceCube observations. Moreover, since the ANTARES detector observes the Galaxy and the Galactic Centre looking for up-ward going tracks, it can lower the energy threshold for the search of neutrino candidate events from Galactic sources. In addition, water offers a better angular resolution than ice, due to its larger scattering length, and thus great potentials for astronomy.

ANTARES results offer a precious contribution for the interpretation of the IceCube results, producing some constraints on theoretical predictions concerning in particular the presence of a point-like source at the Galactic Centre. The observation of the region of the Fermi bubbles is feasible with ANTARES and the analysis can put constraints on theoretical models; further improvements are expected with an extended data set. The analysis directed at the search of a diffuse component in the cosmic neutrino flux has improved in sensitivity including also the reconstruction of shower-like events.

After the successful results of the IceCube experiment, neutrino telescopes aim at playing a crucial role in the astrophysical research, offering a precious source of complementarity to gamma astronomy and opening new opportunities for discovery. ANTARES is working within design sepcification since 2008, data taking and data analysis are on-going and extended results are forthcoming. ANTARES is a milestone towards a km^3-scale detector in the Mediterranean sea and its inheritance in the next future will be collected by the KM3NeT experiment [14].

References

[1] R. Blandford, J. Ostriker, Particle Acceleration by Astrophysical Shocks, The Astrophysical Journal 221 (1978) L29–L32.

[2] L. Anchordoqui, et al., Cosmic neutrino pevatrons: A brand new pathway to astronomy, astrophysics, and particle physics, JHEAp 1-2 (2014) 1–30.

[3] M. Ardid, Dark Matter Searches with ANTARES Neutrino Telescope, in: this Conference, 2014.

[4] M. Aartsen, et al., Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector, Science 342 (2013) 1242856.

[5] M. Aartsen, et al., Observation of High-Energy Astrophysical Neutrinos in Three Years of IceCube Data, Phys. Rev. Lett. 113 (2014) 101101.

[6] J. Aguilar, et al., ANTARES: the first undersea neutrino telescope, Nucl. Instr. and Meth.A 656 (2011) 11–38.

[7] S. Adrián-Martínez, et al., Searches for Point-like and Extended Neutrino Sources Close to the Galactic Center Using the ANTARES Neutrino Telescope, The Astrophysical Journal Letters 786 (2014) L5.

[8] S. Adrián-Martínez, et al., Search for cosmic neutrino point sources with four year data of the ANTARES telescope, The Astrophysical Journal 760 (2012) 53.

[9] M. Aartsen, et al., Search for time-independent neutrino emission from astrophysical sources with 3 yr of IceCube data, The Astrophysical Journal 779 (2013) 132.

[10] M. González-García, et al., Reevaluation of the Prospect of Observing Neutrinos from Galactic Sources in the Light of Recent Results in Gamma Ray and Neutrino Astronomy, Astroparticle Physics 57-58 (2014) 39–48.

[11] M. Crocker, F. Aharonian, Fermi Bubbles: Giant, Multibillion-Year-Old Reservoirs of Galactic Center Cosmic Rays, Phys. Rev. Lett. 106 (2011) 101102.

[12] S. Adrián-Martínez, et al., A search for neutrino emission from the Fermi bubbles with the ANTARES telescope, Eur. Phys. J. C 74 (2014) 2701.

[13] J. Aguilar, et al., Search for a diffuse flux of high-energy muon neutrinos with the ANTARES neutrino telescope, Phys. Lett. B 696 (2011) 16–22.

[14] P. Piattelli, Status and physics goals of KM3NeT, in: this Conference, 2014.