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ANTARES and Baikal: Recent results from underwater neutrino telescopes

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Abstract. Two Northern hemisphere neutrino telescopes are currently searching for astrophysical neutrinos in the TeV/PeV range: ANTARES and Baikal. Both observatories utilize various signatures like a high energy excess over the atmospheric neutrino flux, searches for localized neutrino sources of various extensions and multi-messenger analyses based on time and/or space coincidences with other cosmic probes. We here review the status of both experiments and discuss a selection of recent results.

1. Introduction

The quest for the origin of cosmic rays (CRs) is, a century after their discovery, still ongoing. Despite tremendous theoretical and experimental efforts over several decades we still haven't located the astrophysical sources able to accelerate hadronic particles to energies surpassing all man-made accelerators. Various techniques are being employed for this search: from studies of clustering in the CR arrival directions to the analysis of secondary particles like gamma rays and neutrinos. Over 150 TeV gamma-ray sources have been detected over the last decade. Unfortunately the emission of most of them can be modeled equally well by leptonic (accelerating mainly electrons) as well as hadronic (accelerating predominantly hadronic CRs) scenarios. This ambiguity does not exist for high-energy neutrinos as they can be created efficiently only in hadronic interactions via the decay of charged pions. The detection of a high-energy astrophysical neutrino source would therefore be the tell-tale sign of accelerated hadrons and would be a major breakthrough in the century old cosmic ray puzzle. In addition neutrinos interact only weakly with matter, which makes them insensitive to radiation fields and provides access to cosmological distance scales. Unfortunately the low cross-section is at the same time making their detection challenging. In addition, high-energy neutrinos are produced copiously in the Earths atmosphere via CR induced extensive air showers. These "atmospheric neutrinos" are an important background for the search of astrophysical neutrino sources. In the following we'll discuss various attempts to reduce this background and the status of the searches for astrophysical neutrinos and their sources.

2. Underwater neutrino telescopes

Several very sensitive instruments searching for astrophysical neutrino sources are currently in operation: IceCube at the South Pole [1], ANTARES in the Mediterranean Sea and Baikal-NT200+ in Lake Baikal.

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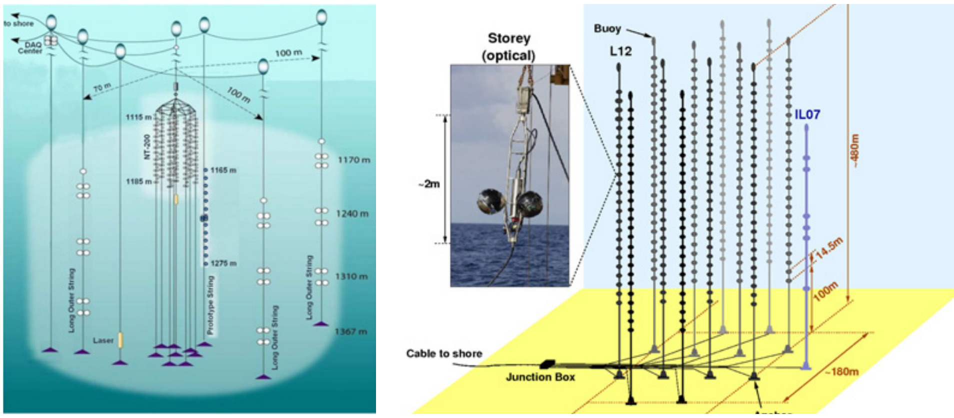

Figure 1. Left panel: layout of the Baikal-NT200+ detector. Right panel: layout of the ANTARES detector. The inset shows a photograph of one of the optical storeys holding 3 optical modules.

The fundamental building blocks of all (underwater) neutrino telescopes are similar: highly sensitive optical detectors called *optical modules* (OMs) are attached to a backbone cable providing the electrical supply and the readout of the data. These *strings* are anchored at the sea bottom and hold in an upright positions by buoys. The neutrino detection relies on the emission of Cherenkov light by high energy muons originating from charged current neutrino interactions or from electromagnetic cascades induced by interactions of electron and tau neutrinos inside or near the instrumented volume. All detected signals are transmitted via an optical cable to a shore station, where a farm of CPUs filters the data for coincident signals or *hits* in several adjacent OMs. The muon direction is then determined by maximising a likelihood which compares the timing of the hits with the expectation from the Cherenkov signal of a muon track or an electromagnetic cascade. The angular uncertainties for the track reconstructions are at the order of 0.3−0.5 deg.

2.1 Baikal

Pioneering the neutrino detection in water, the Baikal collaboration is operating a neutrino telescope in the worlds deepest body of freshwater, Lake Baikal in Siberia. The deployed detector underwent several phases and consecutive enhancements. One of the main building blocks is the Baikal-200 detector which is in operation since 1998. Is is comprised of 192 OMs on 8 strings of 72 m height which cover a circular footprint with a radius of 20 m. This setup has been extended to the current Baikal-200+ setup by adding 3 additional lines (each 200 m in height and holding 36 OMs) at a distance of 100 m around the original telescope. The layout is shown in the left panel of Fig. 1. This latest stage is in operation since 2005 and has mainly been used as testbed for the next phase, Baikal-GVD [2].

2.2 ANTARES

Whereas physics data taking started already during the deployment phase, the ANTARES detector [3] became fully equipped and operational in 2008. The detector is composed of 12 detection lines anchored at a depth of 2475 m off the French coast near Toulon. The detector lines are about 450 m long and hold a total of 885 OMs, consisting in 17″ glass spheres housing each a 10″ photomultiplier tube. The OMs look downward at 45° in order

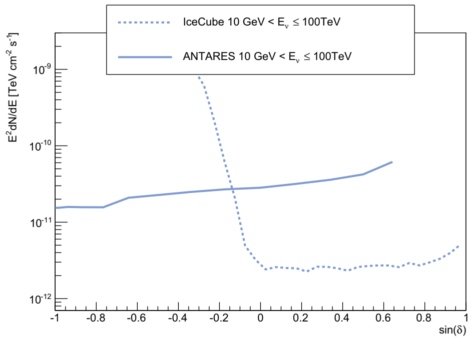

Figure 2. Sensitivity of ANTARES and IceCube to neutrino induced muon tracks following an E^{-2} energy spectrum within the range 10 GeV−100 TeV.

to optimize the detection of upgoing, i.e. neutrino induced, events. The geometry and size of the detector make it sensitive to extraterrestrial neutrinos in the TeV-PeV energy range. A schematic layout of the detector is shown in the right panel of Fig. 1.

2.3 Comparison with IceCube

In terms of its instrumented volume the IceCube detector at the South Pole is significantly larger than the neutrino telescopes on the Northern hemisphere, but for a direct comparison other effects have to be taken into account: the underwater detectors benefit for example from an improved angular resolution due to the reduced light scattering in water and their denser line spacing increases the sensitivity towards lower energies. In addition, their location provides a high sensitivity towards the bulk of the Galactic Plane, i.e. towards the region containing most high-energy gamma-ray sources. In Fig. 2 the sensitivities of IceCube and ANTARES are compared for events induced by charged current muon neutrino interactions. The simulated neutrinos follow an E^{-2} energy spectrum in the interval between 10 GeV−100 TeV as function of the declination. As can be seen, ANTARES is providing a better sensitivity to these track-like events for a significant part of the sky.

3. Diffuse flux searches

The main backgrounds for the search for astrophysical neutrinos are of atmospheric origin: downgoing atmospheric muons, which have been mis-reconstructed as upgoing, and atmospheric neutrinos originating in cosmic ray induced air showers at the opposite side of the Earth. Depending on the requirements of the analysis both backgrounds can at least partially be discriminated using various parameters like the quality of the event reconstruction or an estimator of the energy of the muon or the electromagnetic cascade. Especially the latter, being strongly correlated with the energy of the original neutrino, allows good discrimination of atmospheric origin from neutrinos produced in astrophysical sources. Atmospheric neutrinos have a much softer energy spectrum ($\propto E^{-3.7}$) compared to the generic E^{-2} spectrum expected from Fermi acceleration in astrophysical sources.

3.1 Atmospheric neutrinos

A precise measurement of the energy spectrum of atmospheric neutrinos is therefore an important pre-requisite for searches trying to detect an excess over this flux at high-energies.

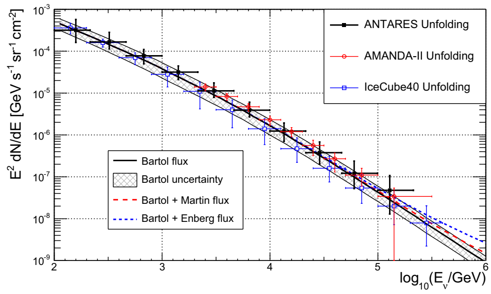

Figure 3. The energy spectrum of atmospheric neutrinos measured by ANTARES compared with earlier measurements and theoretical predictions [5].

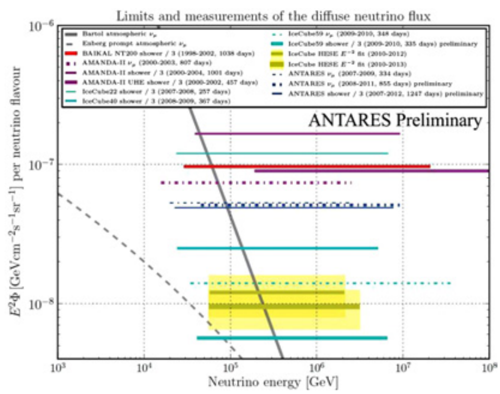

Figure 4. Summary of searches for diffuse, high-energy neutrino fluxes.

A recent measurement by the ANTARES collaboration is relying on several algorithms to estimate the energy of the events (e.g. [4]) and is employing unfolding algorithms to correct for biases induced by the limited resolution of these estimators. The resulting energy spectrum (cf. Fig. 3 and Ref. [5]) shows good agreement with previous in-ice measurements and a 25% higher normalization than the conventional model based on the flux and mass composition of cosmic rays [6].

3.2 Shower-like events

Recently the IceCube collaboration reported the observations of a high-energy excess over the atmospheric backgrounds at the level of 5.6 σ and with a flux at the level of $E^2\Phi = 0.95 \cdot 10^{-8}$ GeVcm^{-2}s^{-1}sr^{-1} [7]. The majority of the detected events are induced by electromagnetic cascades. Similarly 5 years (1247 effective days) of data recorded with the ANTARES telescope have been recently used to search for similar events. A dedicated reconstruction algorithm has been developed and extensive Monte Carlo simulations where used to optimize the event selection criteria. The number of background events has been estimated to $4.9^{+2.9}_{-3}$. After un-blinding the data set, 8 events have been found and an upper limit of $E^2\Phi_{90\%} = 4.9 \cdot 10^{-8}$ GeVcm^{-2}s^{-1}sr^{-1} could be derived. Details of this result and further searches for diffuse emission from interesting regions like the Galactic Plane and the Fermi Bubbles are discussed in [8]. An overview over the recent status of searches for a diffuse flux of high-energy neutrinos is shown in Fig. 4.

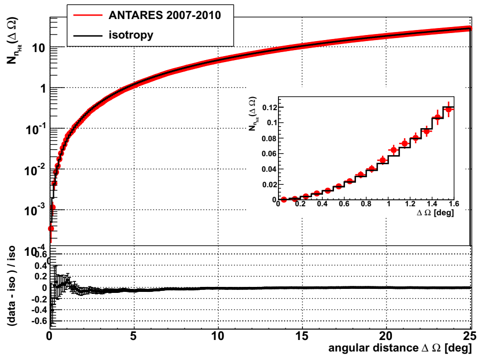

Figure 5. Autocorrelation analysis [12]: ANTARES data (red markers) compared to the reference distribution expected for an isotropic dataset (black histogram).

4. Searches for clusters

In addition to exploiting the different energy spectra, one can use the reconstructed arrival directions of the recorded events to search for an excess over the uniform atmospheric backgrounds. Exploiting a combination of both features, an enhanced two-point correlation method has been used recently to search for clusters in the arrival directions of neutrinos observed by ANTARES. The introduced novel method exploits the energy of the individual events and searches for the cumulative signal from clusters over the full accessible sky. No a-priori assumption on the underlying source morphologies are required. The method has been applied to 4 years of ANTARES data (813 days of effective lifetime; 3058 events) without the detection of a significant excess [12] (cf. Fig. 5).

Complementing the analysis, the developed two-point correlation method has also been used to search for multi-messenger cross-correlations. The ANTARES data set has been correlated with high energy gamma-ray sources given in the 2nd Fermi-LAT source catalog [9], massive black holes [10] and nearby galaxies [11]. None of these searches showed a significant excess.

5. Searches for point-like sources

The main goal of neutrino telescopes is the localization of astrophysical sources of high-energy neutrinos. Typically the data quality selection criteria are optimized on simulated data sets injecting point-like sources in addition to the atmospheric backgrounds and assuming an E^{-2} energy spectrum. Within the ANTARES collaboration these Monte Carlo simulations reproduce the actual, time-dependent data taking conditions and allow to describe the real data very accurately. Extensive comparison between data and Monte Carlo simulations are performed using blinded events where the relevant information for the final analysis (e.g. the arrival directions of the events) is hidden. Only once the data selection procedure is finalized, the data is unblinded and a skymap of the neutrino arrival directions is build. An example of such a map showing 5 years of data (1038 effective days) from the Baikal-200 detector is shown in Fig. 6 [13, 14].

The search for localized excesses is then using maximum likelihood algorithms taking into account the estimated energy of the events to further suppress the influence of atmospheric backgrounds. Monte Carlo pseudo-experiments are used to derive the probability of the analyzed cluster to originate from background only. Based on six years of data from

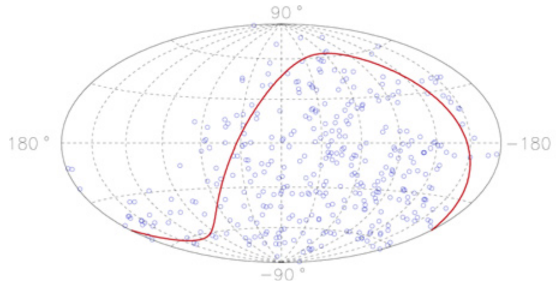

Figure 6. Arrival directions in galactic coordinates of neutrino candidates observed in 5 years of data from the Baikal-NT200 detector [13, 14].

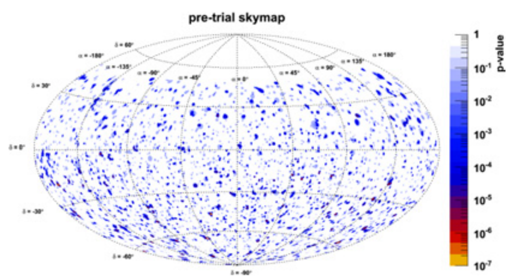

Figure 7. Sky map in equatorial coordinates showing the pre-trial p-values obtained searching for point-like clusters in 6 years of data from the ANTARES detector [15].

the ANTARES telescope which corresponds to 1338 live days and 5516 selected neutrino candidates, an example for such a distribution is shown in Fig. 7. It should be noted that the shown p-values are not corrected for the trial factors related to the scanning of large areas of the sky. Using pseudo-experiments to do so, the most significant cluster of events has been found around $(\alpha, \delta) = (-46^\circ.8, -64^\circ.9)$ with a post-trial p-value of 2.7% (significance of 2.2σ using the two-sided convention) [15].

This region has shown an increased number of neutrino candidates already in searches using an earlier subset of the data [16]. Although not significant on its own, it does currently constitute the *hottest* region in the neutrino sky and has therefore triggered multi-messenger follow-up analyses and observations. Analyzing 4 years of GeV gamma-ray data from Fermi-LAT and 2 hours of dedicated observations of TeV gamma rays obtained with the H.E.S.S. observatory, no source could be found within the region identified by ANTARES [17].

The current status of searches for a point-like high-energy neutrino excess is summarize in Fig. 8 where the obtained upper limits on the neutrino flux are shown. In addition to the all-sky limits, the ANTARES collaboration also searched for extended sources in the region around the Galactic Center [15]. None has been found and the derived limits are able to exclude the possibility that the accumulation of seven events reported by IceCube near the Galactic Center is produced by a single point-like or slightly extended source (cf. [18]).

6. Correlations in space and time

The use additional, complementary information helps to increase the sensitivity of the searches for neutrinos of astrophysical origin. On of the most promising attempts is to narrow

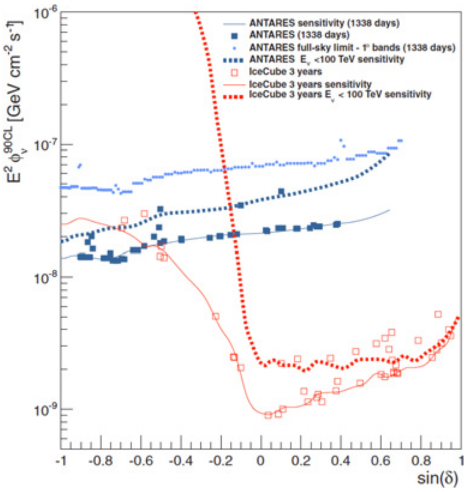

Figure 8. Limits on the high-energy flux obtained in searches for point-like sources [15].

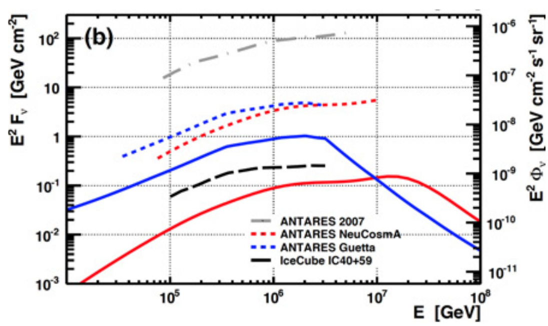

Figure 9. Expected total muon neutrino flux from 296 individual gamma-ray-bursts (solid lines) and upper limits derived from observations by the ANTARES telescope (dashed lines) [22].

down the time window of the searches. This can be done very effectively by analyzing coincidences with transient phenomena detected with other messengers.

6.1 Gamma ray bursts

Gamma ray bursts (GRBs) are one of the prime candidates of transient sources of high-energy cosmic rays (e.g. [19]) and are therefore candidates for searches of contemporaneous emission of high-energy neutrinos. In these searches neutrino events are typically selected in a time window around the detection time of the GRBs and spatial coincident with its location, information provided by X and gamma-ray satellites. All neutrinos telescopes are actively performing these searches, but so far no significant detection has been made. For example data from the Baikal-NT200 detector has been scanned for coincidences with 303 GBRs detected by the BATSE instrument between 1998 and 2000 [20]. Recently the ANTARES collaboration performed an analysis based on 296 GRBs detected by the Swift and Fermi satellites [22]. This analysis used for the first time a novel full Monte Carlo simulation [21] to derive the expected neutrino flux from each individual GRB. The results are summarized in Fig. 9.

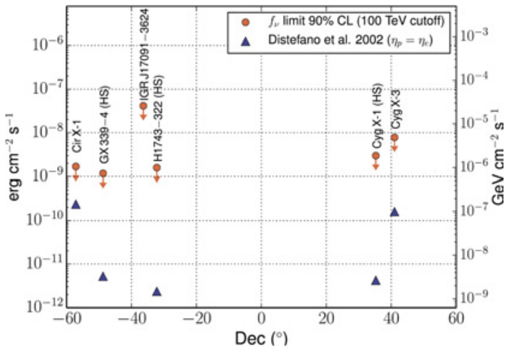

Figure 10. Upper limits on the neutrino flux from microquasars derived from ANTARES observations (red arrows) compared to model predictions (blue triangles) [23].

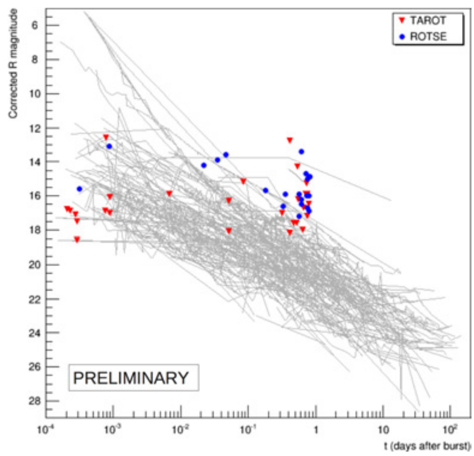

Figure 11. Limits on the optical magnitude of optical data obtained after a neutrino trigger sent by ANTARES (colored triangles) in comparison with the optical afterglows of detected GRBs (gray lines).

6.2 Microquasars

Microquasars are Galactic binary objects that show variable X and gamma-ray emission related to the formation of jet-like outflows. Due to their similarity to the jet-formation around massive black holes at the center of active galactic nuclei emission of high-energy radiation and potentially of neutrinos can be expected. 4 years of data from the ANTARES neutrino telescope have been scanned in a dedicated analysis searching for coincidences between the supposed periods of jet-formation of 6 microquasars and high-energy neutrinos from the same region. No statistically significant excess has been observed, and thus upper limits on the neutrino fluences have been derived. A comparison of these limits with model predictions is shown in Fig. 10 and constraints have been put on the ratio of the proton to electron luminosity in the jets [23].

6.3 Optical and x-ray follow-up

Another very promising method in the search for transient neutrino sources is the emission of alerts from neutrino telescopes triggering follow-up observations of a variety of observatories at different wavelengths. The TAToO project [24] within the ANTARES Collaboration is sending alerts to a range of optical telescopes including the Tarot and Rotse networks and to the Swift satellite. An extension of the system to the H.E.S.S. high-energy gamma-ray observatory is in preparation. The obtained optical images are analysed in search for transient sources at various timescales (e.g. GRBs, supernovae). An example of the obtained limits on the optical magnitudes of GRB afterglows is shown in Fig. 11. Details on the ANTARES multi-messenger program are given in [25].

7. Summary and conclusion

Thanks to their good angular resolution, their location offering access to the bulk of the Galactic Plane and an extensive physics analysis program including many multi-messenger and transient searches, the current neutrino telescopes on the Northern hemisphere Baikal-NT200 and ANTARES continue to produced a wide range of significant results. Future observatories (e.g. GVD and KM3NeT whose deployment started recently) will further enhance the scientific reach and provide important information about the high-energy universe.

References

[1] C. Finley on behalf of the IceCube Collaboration, these proceedings
[2] Z. Dzhilkibaev on behalf of the GVD Collaboration, these proceedings
[3] M. Ageron et al. (ANTARES Collaboration), NIM A **656** (2011) 11–38
[4] F. Schüssler on behalf of the ANTARES Collaboration, 33rd ICRC, Rio de Janeiro (2013), ID 421
[5] S. Adrián-Martá-nez et al. (ANTARES Collaboration), Eur. Phys. J. C **73** (2013) 2606
[6] G. D. Barr et al., Phys. Rev. D **70** (2004) 023006
[7] M. G. Aartsen et al. (IceCube Collaboration), PRL **113** (2014) 101101
[8] L.A. Fusco on behalf of the ANTARES Collaboration, these proceedings
[9] P. L. Nolan et al. (Fermi-LAT Collaboration), ApJ Supplement Series **199** (2012) 31
[10] L.I. Caramete and P.L. Biermann, The mass function of nearby black hole candidates, A&A **521** (2010) A55
[11] D.J. White, E.J. Daw and V.S. Dhillon, Class. Quantum Grav. **28** (2011) 085016
[12] S. Adrian-Martinez et al. (ANTARES Collaboration), JCAP **05** (2014) 001
[13] R. Wischnewski on behalf of the Baikal Collaboration, 29th ICRC, Pune (2005)
[14] O.V. Suvorova and T.A. Ovsiannikova, arXiv:1406.2478
[15] S. Adrian-Martinez et al. (ANTARES Collaboration), ApJ Letters **786** (2014) L5
[16] S. Adrian-Martinez et al. (ANTARES Collaboration), ApJ **760** (2012) 53
[17] F. Schüssler et al. on behalf of the H.E.S.S. Collaboration, 33rd ICRC, Rio de Janeiro (2013), arXiv:1307.6074
[18] M.C. Gonzalez-Garcia, F. Halzen and V. Niro, APP **57–58** (2014) 39
[19] E. Waxmann, PRL **75** (1995) 386
[20] A.V. Avrorin et al. (Baikal Collaboration), Astro. Letters **37** (2011) 692
[21] S. Hümmer et al., ApJ **721**, (2010) 630
[22] S. Adrian-Martinez et al. (ANTARES Collaboration), A&A **559** (2013) A9
[23] S. Adrian-Martinez et al. (ANTARES Collaboration), JHEAP **3–4** (2014) 9
[24] M. Ageron et al. (ANTARES Collaboration), APP **35** (2012) 35
[25] G. de Bonis on behalf of the ANTARES Collaboration, these proceedings