High Energy Neutrino Astronomy and Neutrino Telescopes

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Abstract. Neutrinos constitute a unique probe since they escape from their sources, travel undisturbed on cosmological distances and are produced in high-energy (HE) hadronic processes. In particular they would allow a direct detection and unambiguous identification of the acceleration sites of HE baryonic cosmic rays (CR), which remain unknown. Recent results from the icecube collaboration present the first highly significant indication for the detection of high-energy extraterrestrial neutrinos, after several decades of instrumental efforts. We briefly report on this important results which open the route for the high-energy neutrino astronomy era. We then focus on the antares detector, which despite its modest size with respect to icecube is the largest deep-sea neutrino telescope in the world. The primary goal is to search for astrophysical neutrinos in the TeV-PeV range. This comprises generic searches for any diffuse cosmic neutrino flux as well as more specific searches for astrophysical sources such as active galactic nuclei or Galactic sources. The search program also includes multi-messenger analyses based on time and/or space coincidences with other cosmic probes. The antares observatory is sensitive to a wide-range of other phenomena, from atmospheric neutrino oscillations to dark matter annihilation or potential exotics such as nuclearites and magnetic monopoles. The most recent results are reported.

1. Neutrino Astronomy
Neutrino astronomy has a key role to play towards a multi-messenger coverage of the high-energy (HE) sky, as HE neutrinos provide a unique tool to observe the non thermal Universe. Their main characteristic is that they can travel over cosmological distances without being absorbed or deflected.
The detection of a HE astrophysical neutrino source would in particular unambiguously identify one of the so far unknown acceleration sites of HE cosmic rays. Indeed, HE neutrinos ($\nu$) are produced in a beam dump scenario via meson (pion $\pi$ and mainly kaon at high energy) decay, when the accelerated hadrons (protons $p$ or nuclei $A$) interact with ambient matter or dense photon fields ($\gamma$):

$$p/A + A/\gamma \rightarrow \pi^0 + \pi^\pm + \mu^\pm + \nu_\mu (\bar{\nu}_\mu) + e^\pm + \nu_e (\bar{\nu}_e) + N + \ldots$$

In this so-called “bottom-up” scenario, the production of HE neutrinos is associated with the acceleration of nuclei through Fermi-like mechanisms, and with the production of HE gamma-
rays, through $\pi^0$ decays. Following this association, various authors have inferred benchmark fluxes of cosmic neutrinos based on the observed ultra HE cosmic rays (e.g. the so-called Waxman-Bahcall (WB) bound [1]). These neutrino fluxes essentially set the size of neutrino telescopes (NT) to the kilometer scale. From the above relation, it is also expected that ultra HE $\nu (>\text{PeV})$ would arise from the interaction of the UHECR with the relic radiation fields. These are called cosmogenic neutrinos [2].

HE neutrinos can also be produced by more exotic processes such as the decay of massive particles ("top down" scenarios, currently not favoured) or the annihilation of dark matter (DM) gravitationally trapped inside massive objects like the Sun, the Earth or the Galactic centre [4].

Detection principle If the weak interaction of neutrinos with matter is an asset for astronomy, it also makes the detection challenging. This requires the instrumentation of large volumes of water (or ice) with photomultipliers (PMTs) to detect the Cherenkov radiation induced by charged leptons (mainly muons, but also electron- or tau-induced showers) produced by cosmic neutrino interactions with the target transparent medium, inside or near the instrumented volume. PMT signals (timing and amplitude) are used to reconstruct the muon trajectory and the energy of the neutrino. In order to reduce the background due to the intense flux of down-going atmospheric muons present at ground, such detectors are buried deep under the surface. Moreover, since the Earth acts as a shield against all particles but neutrinos, their design is optimized for the detection of up-going muons produced by neutrinos which have traversed the Earth and interacted in the vicinity of the detector, with the consequence that one neutrino telescope can efficiently monitor one half of the sky in the TeV-PeV range.

Atmospheric neutrinos produced in the atmospheric cascades can also travel through the Earth and interact close to the detector, producing an irreducible background with typical energy spectrum $dN/dE \propto E^{-3.7}$. A so-called “prompt” component originating from charmed mesons [3] is also expected in the highest energy range. To discover extraterrestrial neutrinos, one searches for an excess of events above a certain energy (diffuse flux, § 2.1, 2.2, 2.3 and 3.2) and/or in a given direction (point sources, § 3.3). Another possible way to claim the discovery of cosmic neutrinos is to observe events in coincidence (in direction and/or time) with other messengers. This multi-messenger approach allows to strongly reduce the background by looking in a known direction for the reduced period of time, making the detection of a few events enough to claim a signal (see § 3.4).

A generic HE NT consists of a 3D grid of $O(10^3)$ detection units called Optical Modules (OMs). These OMs basically comprise one or several photomultipliers embedded in a pressure-proof glass sphere. They are arranged with a 10-30m spacing on vertical cable strings typically distant of 60-100m. This spacing has an impact on the energy threshold of the detector: the sparser the lines, the higher the threshold. The detector design is therefore a matter of trade-off between low energy physics such as DM searches (<TeV) and ultra HE physics like search for cosmogenic neutrinos (>PeV). NTs are usually optimised for the detection of astrophysical bodies (TeV-PeV). The first attempt to build a NT was made by the DUMAND (Deep Underwater Muon And Neutrino Detector) collaboration [5], off the Hawaiian coast. In 1987, the collaboration deployed a prototype string tied to a ship and performed some first measurements. After this success a proposal for an array of 9 strings anchored to the sea bed at 4800 m from the surface was submitted. Only the first line could be deployed. It was operational for several hours only before a leak occurred. The project was finally canceled in 1995. New projects were born since then, some in the ice (e.g. § 2) providing the detector with mechanical stability and avoiding leakage problems, others persevering with water (e.g. § 3).
2. The IceCube Neutrino Telescope

The IceCube detector is the successor to the AMANDA (Antarctic Muon and Neutrino Detector Array) experiment. The AMANDA project started in the 90’s. The collaboration chose the approximately 3 km thick Antarctic ice cap at the South Pole to deploy the detector. The deployment technique was to lower OMs attached on cables into holes drilled by hot water. Once the structures are deployed, the water freezes, mechanically fixing the OMs. Deployment of the first four strings with 86 OMs took place in 1993/94 down to 900 m depth. At such a depth, the ice layer was found comprising many air bubbles, inducing a strong scattering of the light, detrimental to the reconstruction of the muon trajectories. The detector was subsequently extended deeper in the ice (less bubbles) with longer strings (AMANDA-II). The total amount of OMs was then 676 OMs spread over 19 strings commissioned in January 2000. After 7 years of data taking, 6595 neutrino candidates were cumulated with energies up to 100 TeV. This led to a limit on the diffuse flux of astrophysical neutrinos (indicated in Fig. 8) and to the rejection of some production models.

The results achieved with IceCube detector now supersede the ones obtained with AMANDA. The first IceCube detector string was deployed in January 2005, followed by 8 more in the austral summer 2005/2006, 13 in 2006/2007 (IC22 configuration), 18 in 2007/2008 (IC40), 19 in 2008/2009 (IC59), 20 in 2009/2010 (IC79). The detector was then completed in Dec 2011 with the deployment of 7 additional strings for a total of 86 lines (IC86) carrying 60 digital OMs each spread over depths between 1450 m and 2450 m with vertical separation of 17 m. For 78 strings, the horizontal spacing is 170 m, while 8 inner strings (together with 7 surrounding IceCube strings) form a denser instrumented volume dubbed as DeepCore. On top of the telescope a large air-shower array named ICETOP has been installed. It is designed to detect the...
Cherenkov light inside ice tanks of charged particles reaching the Earth surface: it can be used for calibration purposes and for studies of mass composition of primary CRs up to $10^{17}$ eV [6]. The overall detector layout is sketched in Fig. 1.

In the following, we focus on the recent icecube results in the search for a HE cosmic neutrino flux. For results on atmospheric neutrino oscillations and dark matter search, the reader is respectively referred to sections (references) § 3.1.1 ([7]) and § 3.5.1 ([8]). Comprehensive reviews on recent icecube results related to point source searches, atmospheric and diffuse UHE neutrino searches, cosmic ray studies, exotic searches and supernova searches can be found in [9].

2.1. First searches for a diffuse astrophysical neutrino flux

In this section we briefly summarized the most recent searches for a diffuse cosmic neutrino flux performed by the icecube collaboration. The interacting neutrinos essentially produce two patterns: cascades and tracks. Cascades mainly originate from electrons and hadronic showers from the nucleon fragmentation. So charged-current (CC) $\nu_e$ interaction and all-flavor neutral current interactions contribute to this topology (as well as a large fraction of $\nu_\tau$’s), while searches for tracks apply mainly to CC $\nu_\mu$ interactions.

The latest dedicated search in the cascade channel was made with the first 40 string configuration of the detector [10]. The used data for this search was collected between April 2008 and May 2009 with a total livetime of 367.1 days. Three different data selections were performed to study 3 different energy regimes from 2 TeV to hundreds of TeV. Each time, the analysis was conducted in a blind way. Only a 10% subset of the experimental data, sampled uniformly over the year was used for comparison with Monte Carlo. Optimized cuts were simply applied on the remaining 90%. Even though the search focuses on cascade-like events, the selected event can be reconstructed in parallel under the assumption of a muon track. In such case, events reconstructed as down-going with zenith angles below $80^\circ$ are rejected. The search in the lowest energy range provides sensitivity to atmospheric neutrinos and hence allows for consistency checks of the background assumptions of the 2 other selection strategies. In this low-energy band, a total of 67 events were found for a total expected background of 71 events.

The selection strategy of the 2 other samples is optimized for the detection of an astrophysical $\frac{dN}{dE} \propto E^{-2}$ flux. The analysis with an intermediate threshold of 25 TeV lead to the observation of 14 cascade-like events, again consistent with the predicted background of 10.7 events. From this, assuming an equipartition of the neutrino flavors at the Earth, an upper limit (90% C.L.) of $E^2 \phi_{\nu_e+\nu_\mu+\nu_\tau} = 7.46 \times 10^{-8}$ GeV sr$^{-1}$ s$^{-1}$ cm$^{-2}$ was placed on the diffuse flux from astrophysical neutrinos of all neutrino flavors. This limit applies to the energy range 25 TeV to 5 PeV. The energy threshold of the third study reported in [10] is of the order 100 TeV. Three events were found for a background 0.04 atmospheric muon events and 0.21 events from atmospheric neutrinos (both conventional and prompt components). Including systematic errors this corresponds to a $2.7\sigma$ excess and can be seen as a first indication of an excess (though it was formally published after the results presented in § 2.2 and §2.3).

In reference [11], the icecube collaboration reports for a search for high-energy neutrinos using data collected between May 2009 and May 2010, corresponding to the IC59 configuration. The events searched for are through-going muons originating from neutrino interactions in or around the detector. The selected data are analyzed with a global likelihood fit to search for possible contributions of prompt atmospheric and astrophysical neutrinos, which exhibit a harder spectrum than conventional atmospheric neutrinos. One important source of background originates from coincident atmospheric muons (from distinct air showers) in the detector. Severe quality cuts must be applied to get a high-purity muon neutrino sample. A first selection is to
restrict to upward-going muons with zenith angles above $90^\circ$. Then cuts concentrate on the quality of the reconstructed tracks. Variables such as the log-likelihood or the estimated error on the track direction are used, as well as specific topological cuts. Details are given in [11]. With such a selection, an astrophysical flux at the level of the WB upper bound would yield $\sim 50$ events in this data sample. Monte Carlo simulations indicate that the associated atmospheric neutrino purity of $99.85\% \pm 0.06\%(\text{stat.}) \pm 0.04\%(\text{sys.})$, corresponding to a muon background of $\sim 30$ events. But these muons are rather low in energy and can be removed by a further cut on the reconstructed energy, which is based on the measurement of the amount of light deposited along the track in the detector. A global fit of the remaining data sample is then performed accounting for an astrophysical contribution and atmospheric backgrounds. A small excess of events is found in the final sample, which leads to a p-value of 0.032, corresponding to a 1-sided significance of $1.8\sigma$. Because of this small excess, the derived experimental limit at 90\% confidence level is quite high (a factor of 1.5 above the WB prediction) compared to the sensitivity: $E^2 \phi_{\nu \mu} = 1.44 \times 10^{-8}$ GeV sr$^{-1}$ s$^{-1}$ cm$^{-2}$. This limit is shown in Fig. 8 and compared to other results.

**2.2. The IceCube PeV events**

In this section, we briefly report on a search performed by the IceCube collaboration for very high energy ($E > $ PeV) cosmogenic neutrinos [12]. Data from May 2010 until May 2012, corresponding to an effective livetime of 615.9 days were analyzed from all directions. A total of 54.2 days of the sample was used for the optimization of the analysis. The used detector configuration is thus a mixture of IC79 and IC86. Neutrino candidates are calorimetrically selected via the total number of observed photo-electrons in each event (NPE) which is used as a proxy for the deposited energy. A minimal condition of NPE $\geq$ 1000 is required for the data filtering, but a tighter selection asking for events with at least 300 hits and NPE $\geq$ 3200 is used to reject downward-going atmospheric muons. To further reduce this background, the directions of the remaining events are reconstructed with a track hypothesis and a stricter NPE criterion is applied for events reconstructed as down-going. Muon tracks are reconstructed with a zenith angle resolution of $1^\circ$ or better. Cascade events which pass the initial hit and NPE selection criteria are also considered as signal events for this search.
The final selection is determined by optimizing the NPE-threshold values for each of the IC79 and IC86 samples separately with the aim to maximize the signal from the cosmogenic neutrino model [2] applying the so-called MRF method [31]. With the final selection, the search begins to be sensitive around 1 PeV with growing sensitivity for higher energies. Below 10 PeV the analysis is more sensitive to \( \nu_e \)'s than to \( \nu_\mu \)'s or \( \nu_\tau \)'s. The conventional atmospheric background is expected to amount to 0.038 \( \pm \) 0.004 (stat) \( +0.023 \) \( -0.038 \) (syst) and 0.012 \( \pm \) 0.001 (stat) \( +0.010 \) \( -0.007 \) (syst), for muons and neutrinos respectively. Adding the prompt atmospheric neutrino component, the total number of background events increases to 0.082 \( \pm \) 0.004 (stat) \( +0.041 \) \( -0.057 \) (syst). After unblinding, two events were observed, dubbed as Ernie and Bert. Both events are found in the IC86 sample. They are shown in Fig. 2. Their topology is that of a spherical cascade without indication, two events were observed, dubbed as Ernie and Bert. Both events are found in the IC86 sample. They are shown in Fig. 2. Their topology is that of a spherical cascade without indication. As a consequence, they are most likely induced by either CC interactions of \( \nu_e \) or NC interactions of \( \nu_e, \nu_\mu \) or \( \nu_\tau \). The reconstructed deposited energies of the two cascades are 1.04 PeV and 1.14 PeV, respectively, with combined statistical and systematic uncertainties of \( \pm 15 \% \) each. This is assuming that the observed cascades are the result of a CC \( \nu_e \) interactions. The observed cascades are unlikely to originate from the Glashow resonance (\( \bar{\nu}_e + e^{-} \rightarrow W^{-} \)) as only about 10\% of these interactions will deposit 1.2 PeV or less in the detector in cascade-like signatures. The final distributions of NPE for data, signal models and background simulations is presented in Fig. 3. It is striking that the two events are near the NPE analysis threshold, while signals from a cosmogenic neutrino flux would rather be expected at higher NPE values. On the plot is also shown the result of an astrophysical neutrino flux with an all-flavor normalization of \( E^2 \phi_{\nu_e+\nu_\mu+\nu_\tau} = 3.6 \times 10^{-8} \text{ GeV sr}^{-1} \text{s}^{-1} \text{cm}^{-2} \).

The two PeV neutrino events observed are often considered as the first hint of an astrophysical high-energy neutrino flux. Indeed, the probability that such two events could be produced by a background fluctuation was estimated to \( 2.9 \times 10^{-3} \) (equivalent to a 2.8\( \sigma \) deviation from the null hypothesis). Despite the relative moderate significance of the 2 events, the icecube collaboration decided to concentrate on a follow-up search with the idea that an astrophysical neutrino flux with the above mentioned normalization should yield to an excess of events below the threshold of the present study.

2.3. Follow-Up and Evidence for High-Energy Extraterrestrial Neutrinos

Following the discovery of the 2 PeV events presented in section 2.2, the icecube collaboration developed a dedicated strategy to improve the sensitivity to this type of events lowering the energy threshold of the search. The search is conducted during the first season running with the completed IceCube array (IC86, between May 2011 and May 2012) and the preceding construction season (IC79, between May 2010 and May 2011), with a total combined live time of 662 days. The results are presented in [13].

The events are searched with a vertex inside the instrumented volume and discarding the possibility of a muon track originating from outside the detector. The detector boundary is used to detect and veto entering muon tracks. This strategy offers the advantage of strongly suppressing the atmospheric background (neutrinos and muons). Indeed, the cosmic-ray interactions in the atmosphere produce secondary muons reaching the detector from above as well as atmospheric neutrinos. This event selection strongly reduces the effective volume, but rejects 99.999\% of the muon background and 70\% of down-going atmospheric neutrinos. The selection preserves nearly all cosmic neutrino events above a few hundred TeV and allows for an almost equal sensitivity to neutrinos from all directions. Some sensitivity to neutrino energies as low as 30 TeV is preserved.

At the relevant energies cascades can be seen as point sources of light extending inside the detector, while muon track dimensions are larger than the detector size. It is important to notice that, for a flux made of an equal number of neutrinos of each species (as expected for a cosmic
neutrino flux due to oscillations), cascades are expected to contribute for \( \sim 80\% \) of the observed events. The analysis is therefore sensitive to all neutrino flavors but favors the detections of cascade-like events, and in particular of electron neutrinos.

In spite of the approximately spherical distribution of hit for cascade events, a careful (but CPU extensive) timing study of the PMT waveforms allows for some sensitivity to the initial direction of the incoming neutrinos. Simulation studies indicate an median angular resolution of the order of 10° to 15°. The resolution on the deposited energy is as good as 10 to 15% for cascades. When a track is present in the event topology the angular resolution improves greatly to less than 1°, but the energy estimate deteriorates due to the escaping muon track. The amount of remaining background still passing the veto condition is estimated from the data themselves by implementing a two-layer anti-coincidence detector. Incoming events are flagged by the outer layer of the detector. Their capacity to pass the next veto layer is then studied: 6.0 ± 3.4 veto-penetrating muon events are expected in the analysis. The rest of the background for this search comes from atmospheric neutrinos, including the charmed component. Simulations predict an amount of \( 4.6^{+3.7-1.2} \) events, close to the energy threshold.

The analysis has led to the observation of 28 events, so about 17 events in excess with respect to the background expectations. The two most energetic events are the ones reported in § 2.2. Seven events contain identifiable muon tracks, whereas the remaining are cascade-like. The time distribution of the events show no evidence of a significant time clustering. The distributions of the deposited energy in the detector and the arrival direction of the events are shown Fig. 4. A display, together with the features of each event, is presented in [13]. The excess related to the additional 26 events represent a significance of 3.3σ (one-sided) only, but the combination with the 2.8σ observation mentioned in § 2.2 amount to a final significance of 4.1σ. The same calculation performed a posteriori on all 28 events gives 4.8σ. A global fit
of the events of Fig. 4 has been performed taking into account one component of conventional atmospheric neutrino background, atmospheric neutrinos from charmed meson decays, and an isotropic equal-flavor astrophysical power-law flux. All normalizations are let free. The fit applies to the energy range $60 \text{ TeV} < E_{\text{dep}} < 2 \text{ PeV}$, leading to an $E^{-2}$ neutrino spectrum with a per-flavor normalization of $E^2 \Phi(E) = (1.2 \pm 0.4) \cdot 10^{-8} \text{ GeV cm}^{-2} \text{s}^{-1} \text{ sr}^{-1}$ (see figure 8 - right panel). With such a flux 3 to 6 additional events should be seen in the 2-10 PeV range, which may indicate the presence of cutoff at PeV energies.

The skymap of the 28 events is given in Fig. 5. In order to quantify the significance of possible clusters of events, a maximum likelihood point source analysis was performed. The values of the used Test Statistic ($TS = 2 \log(L/L_0)$, where $L$ is the maximized likelihood and $L_0$ the likelihood under the null hypothesis), is also shown. No significant clustering is found. In the case of the shower events, the coordinates of the most significant cluster are at RA=281°, dec=−23°. Five events, including the second highest energy event in the sample, contribute to the main part of the excess with two others nearby. The post-trial p-value associated to the cluster is 8%. This degree of clustering may be compatible with a source or sources in the galactic center region. The authors of [28] have envisaged that the cluster could be associated to a point source of $E^2 \Phi(E) = 6 \cdot 10^{-8} \text{ GeV cm}^{-2} \text{s}^{-1}$. While such hypothesis cannot be discarded by the ICENU data due to the poor angular resolution of cascades, it appears very unlikely in view of the recent results from the ANTEARES experiment (see § 3.3).

3. The ANTEARES Neutrino Telescope
The ANTEARES (Astronomy with a Neutrino Telescope and Abyss environmental RESearch) Collaboration started in March 2006 the deployment of a large scale detector ~ 40 km off La-Seyne-sur-Mer (French Riviera), at a depth of 2475 m. The construction phase ended in May 2008. Since then, ANTEARES is the largest neutrino telescope constructed in the Northern hemisphere, providing unprecedented sensitivity to the central region of our Galaxy.
Figure 5. Skymap in equatorial coordinates of the Test Statistic value (TS) from the maximum likelihood point-source analysis. The most significant cluster consists of five events—all showers and including the second-highest energy event in the sample—with a final significance of 8%. This is not sufficient to identify any neutrino sources from the clustering study. The galactic plane is shown as a gray line with the galactic center denoted as a filled gray square. Best-fit locations of individual events are indicated with vertical crosses (+) for showers and angled crosses (×) for muon tracks. Taken from [13].

The full detector [14] comprises 885 photomultipliers distributed in a three dimensional array on twelve 450 m high vertical detection lines (Fig.6). The lines are separated with a typical interline spacing of 60-70m and each line comprises 25 storeys, separated by 14.5 m. A storey hosts a triplet of Optical Modules (OM) orientated at 45 degrees with respect to the vertical, in order to maximise the sensitivity to Cherenkov light from upcoming neutrinos. The OMs contain a 10 inch PMT protected in a 17 inch pressure resistant glass sphere. The lines are connected to a junction box, via interlink cables on the seafloor. It provides electrical power and gathers together the optical fibres from each line into a single electro-mechanical fibre optic cable for transmission of the data to and from the shore station.

The infrastructure also hosts a thirteenth line, the instrumentation line (labelled as IL07 in Fig. 6), which provides measurement of environmental parameters such as sea current, temperature and also hosts a part of the AMADEUS system [15], a test bed for the acoustic detection of ultra-high energy neutrinos. The line now also hosts a fully functional prototype OM designed for the next generation telescope KM3NeT, housing 31 3" PMTs (see § 4.1). In December 2010, a secondary junction box, dedicated to host sensors for various Earth and Marine science projects, was also connected to the main junction box.

Timing calibration [16] is ensured by a dedicated network of laser and LED beacons, and line motions are monitored by acoustic devices and by inclinometers regularly spread along the line, allowing redundancy. The angular resolution is within design expectations (< 0.5°) and allows to look for point sources with high sensitivity, as reported in section 3.3.

3.1. Atmospheric Neutrino Studies
Atmospheric neutrinos represent a background in the search for astrophysical neutrinos. Nevertheless their study offers some intrinsic interest for particle physics, in particular at low energy ($O(\text{GeV})$), where the mixing of flavors can be observed (see § 3.1.1). At higher energies, the measurement of the spectrum is a demonstration of the good understanding of the detector behaviour (see § 3.1.2).
3.1.1. Neutrino Oscillations

A measurement of the neutrino mixing parameters in the atmospheric sector has been performed with the data taken from 2007 to 2010 [17], for an overall live time of 863 days. In the simplified framework of vacuum oscillations between two flavours ($\nu_\mu$ to $\nu_\tau$), the $\nu_\mu$ survival probability can be written as

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

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta_{23} \sin^2 \frac{16200 \Delta m_{23}^2 \cos \theta}{E_\nu}, \quad (2)$$

where $L$ and $\theta$ are respectively the neutrino path length and zenith angle, $\Delta m_{23}^2$ is the difference of the squares of the mass eigenstates $m_2$ and $m_3$ and $\theta_{23}$ is the corresponding mixing angle. Considering values of $\Delta m_{23}^2 = 2.43 \times 10^{-3}\text{eV}^2$ and $\sin^2 2\theta_{23} = 1$, as reported by the MINOS experiment [18], the first oscillation maximum is found for vertical upgoing neutrinos at $E_\nu = 24\text{ GeV}$, leading to a suppression of vertical upgoing muon neutrinos around this energy.

The oscillation parameters are thus inferred by fitting the event rate as a function of the ratio of the neutrino energy and the reconstructed incoming zenith angle (eq. 2), the energy being estimated from the observed muon range in the detector. Assuming a maximal mixing, a mass difference of $\Delta m_{23}^2 = (3.1 \pm 0.9) \times 10^{-3}\text{eV}^2$ is found. The corresponding contour plot for different confidence levels is shown in Fig. 7, together with measurements by other experiments for comparison.

The compatibility of the ANTAOES measurement with the world data gives confidence in the understanding of the detector, even close to the detection threshold. This, in addition, paves the way to additional measurements of the neutrino fundamental parameters by neutrino telescopes, such as the mass hierarchy, which has been recently put forward (e.g [20, 21]) thanks to the large measured value of the mixing angle $\theta_{13}$. A feasibility study, dubbed ORCA, for such a measurement with a deep-sea detector is presently being performed in the framework of the KM3NeT Collaboration [22].

3.1.2. Measurement of the Atmospheric Neutrino Spectrum

At higher energy, where oscillations are suppressed, the neutrino energy cannot be estimated based on the muon path length, since

\[ \text{Figure 6. The ANTARES detector configuration.} \]
the latter generally exceeds the dimension of the detector. The method used to reconstruct the muon energy relies instead on the total amount of detected light knowing the event geometry and the water properties. The event-by-event energy reconstruction is nevertheless not sufficient to derive the energy spectrum of the detected atmospheric neutrinos. The fact that only the induced muon is observed, the stochastic nature of muon energy losses, the limited energy resolution and the detection inefficiencies have to be accounted for in an unfolding procedure [23].

In this study, the analysed data sample covers acquisitions from December 2007 to December 2011, corresponding to an equivalent live time of 855 days. For each data run a Monte Carlo counterpart is available, reproducing acquisition conditions of the detector. All the cuts to select a pure sample of atmospheric neutrinos were optimised with this Monte Carlo. A 10% fraction of the data was initially used to check the agreement between the observed and expected quantities. The inferred neutrino energy spectrum, averaged over zenith angles larger than $90^\circ$, is shown as a function of the energy in Fig. 8 (left panel). The measured spectrum spans a range from 100 GeV to 200 TeV. It is 25% higher than the prediction from the Bartol group (but still within uncertainties) and intermediate between that measured by the AMANDA-II [26] and IC40 [27] Antarctic neutrino telescopes. This good overall agreement demonstrates the proper understanding of the energy scale of the detector.

3.2. Searches for Diffuse Fluxes

3.2.1. Search for a Cumulative Flux from Unresolved Astrophysical Sources

The measurement in the highest energy region of the atmospheric neutrino spectrum presented in the previous section has been used to put a constraint on the diffuse flux of cosmic neutrinos. Indeed, a harder spectrum (typically $\frac{dN}{dE} \propto E^{-\alpha}$ with $\alpha = 1 - 2$), is expected for neutrinos of astrophysical origin, as mentioned in section 1. After a critical value of the energy, which depends on the absolute normalization of the cosmic neutrino flux, an excess of events over the atmospheric background is expected.

The same statistical method as the one described in reference [29], which presents the first ANTARES limit based on the 2008-2009 data set, was used. The main difference arises from the new energy estimator employed. Here the muon energy deposit per unit path length is approximated by an estimator which can be derived from measurable quantities such as the
amplitude of the hit PMTs. To remove the contribution from background light, only the hits used by the final tracking algorithms (filtered out following strict causality criteria) are used. The energy estimator was then used to determine the cut yielding the best sensitivity, applying the Model Rejection Factor (MRF) procedure [31]. In the considered live time and with the track quality cuts applied, the conventional atmospheric neutrinos revealed a 28% deficit, well within uncertainties, with respect to the data. Therefore the predicted background from the simulation is normalised to the data. After normalization, 8.4 atmospheric events were expected and 8 events were observed in the high energy region ($2.3$ signal events were expected from a test flux $E^{-2}$). This translates into a 90% C.L. upper limit of

$$E^2 \frac{dN}{dE} = 4.8 \times 10^{-8} \text{GeVcm}^{-2}\text{s}^{-1}\text{sr}^{-1}$$

in the energy range 45 TeV - 10 PeV, as indicated in Fig. 8 (left panel). As can be seen in Fig. 8, this updated result of ANTARES is close to the WB predictions. It is only a factor $\sim 4$ above the signal measured by ICECUBE and applies complementarily to the Southern Hemisphere.

3.2.2. Fermi Bubbles The Fermi-LAT data has revealed a large ($\sim 10$kpc) bilateral structure originating from the Galactic Centre and perpendicular to the Galactic plane (and therefore, visible mostly in the southern hemisphere). This structure is generally referred to as “Fermi Bubbles” (FBs). A possible explanation of the observed gamma-rays (which have an almost uniform $E^{-2}$ spectrum, with a normalisation uncertainty of a factor of $\sim 2$ [32]) is the presence of a Galactic wind in which accelerated cosmic rays interact with an interstellar medium producing pions [33]. In such a scenario, neutrinos would be naturally produced. A dedicated search with the ANTARES data from May 2008 to December 2011 (806 days) has thus been performed by comparing the rate of HE events observed in the region of the FBs (ON zone) to that observed in equivalent areas of the Galaxy excluding the FBs (OFF zones). A small excess of events (1.2$\sigma$) was observed in the ON region above the chosen energy cut. Limits were placed on possible fluxes of neutrinos for various assumptions on the energy cutoff at the source (Fig. 9). These limits are close to the theoretical expectations, meaning that the hadronic origin of the observed
Figure 9. Upper limits on the neutrino flux from the Fermi Bubbles, estimated for different source cutoffs: no cutoff (black solid), 500 TeV (red dashed), 100 TeV (green dot-dashed), 50 TeV (blue dotted) together with the theoretical predictions for the case of a pure hadronic model (the same colours, areas filled with dots, inclined lines, vertical lines and horizontal lines respectively). The limits are drawn for the energy range where 90% of the signal is expected.

gamma-rays from the FBs could be probed with the full ANTARES data set, or after one year of data taking with the next generation neutrino telescope to be built in the Mediterranean (see § 4.2).

3.3. Searches for Sources of Cosmic Neutrinos

For the search of resolved sources of cosmic neutrinos, several approaches were followed. The studies presented below have been first applied to the 2007-2010 data (for a total live time of 813 days), corresponding to 3058 events passing the optimised selection criteria [34]. A recent update, based on data from the 31st of January 2007 until the 31st of December 2012 is also presented [36], corresponding to a total live time of ~1334 days of which 183 days correspond to the period when the detector was working with the first 5 deployed lines. After the quality cuts, a total of 5516 neutrino candidates are selected, of which 90 % should be atmospheric neutrinos and the rest is composed of misreconstructed muons. The median uncertainty on the reconstructed neutrino direction, assuming an $E^{-2}$ neutrino energy spectrum, is $0.4^\circ \pm 0.1^\circ$. Almost 90% of the events are reconstructed within $1^\circ$ from their true direction. With the selected events, a time-integrated full-sky search was performed, which is presented in section 3.3.1. Another search focused on ~50 neutrino source candidates of various types (section 3.3.2). Special attention was also paid to the case of some extended sources (section 3.3.3). It is also worth mentioning that a two-point autocorrelation method was also applied to the 2007-2010 data sample [35]). Such method offers the advantage of being sensitive to a large variety of cluster morphologies and does not depend on Monte Carlo simulations.

3.3.1. Full Sky Search

In the full-sky search an excess of events over the atmospheric muon and neutrino backgrounds is looked for in the declination range $[-90^\circ; +48^\circ]$. The algorithm used 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 included. 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 with the position of every selected point in the sky is shown in equatorial coordinates in Fig. 10. The most significant cluster is located at (R.A=-47.8°; $\delta$=-64.9°), containing 14 events. This
Figure 10. 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.

corresponds to a fitted number of signal events of 6.3 on top of the expected background. The post-trial p-value is 2.1%, equivalent to $2.3\sigma$. It is worth noticing that this is the same most significant cluster as found in the 2007-2010 data set, plus 6 additional events. Nonetheless, this ”warm spot” was searched for counterparts in the electromagnetic band with data from other instruments, without success [37].

3.3.2. Candidate-list Search Good candidates for HE \( \nu \) production are active galactic nuclei (AGN) where the accretion of matter by a supermassive black hole may lead to relativistic ejecta [38, 39]. TeV activity from our Galaxy has also been reported by ground based gamma-ray telescopes. Many of the observed Galactic sources [40] are candidates of hadron acceleration and subsequent neutrino production. This includes, among others, supernovae remnants, pulsar wind nebulae or microquasars. A list of \( \sim 50 \) sources of interest has been established for a search in the corresponding specific directions. No significant excess was found. Upper limits on the neutrino flux from these sources were derived as shown in Fig.11. In addition to the above mentioned sources, cosmic neutrinos were also looked for in the direction of a selected sample of gravitational lenses, with the same method. The results of this specific study, applied to the 2007-2010 data set, are presented in [41].

For TeV-PeV sources, these limits are the best for the Southern hemisphere since, for this region of the sky, the IceCube limits are relevant above \( \sim 1 \text{ PeV} \), an energy threshold applied in order to mitigate the downgoing muon background.

3.3.3. Extended Sources Several of the sources included in the candidate source list are not point-like, but have an intrinsic spatial structure that can be resolved by ANTARES. This applies to sources such as the shell-type supernova remnant RX J1713.7-3946 and the pulsar wind nebula Vela X. For these sources, the assumption of point-like sources is not optimal and may be improved. Assuming the neutrino flux to be related to the gamma-ray flux and taking
Figure 11. 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.

into account the measured extensions, special studies were made for these two sources. Upper limits (90% C.L.) on the flux normalisation were computed, as well as the corresponding model rejection factor (MRF). For RX J1713.7-3946 the upper limit is a factor 6.4 higher than the theoretical prediction. For Vela X the upper limit is a factor 9.7 higher than the model, which is slightly worse than previously obtained with the 2007-2010 data set, because of the presence of 4 additional events. In both cases ANTARES limits are the most restrictive ones for the emission models considered (see [36] for more details).

3.4. Searches for Transient Sources

Other potential sources of extra-galactic HE neutrinos are transient sources like gamma ray bursts (GRBs, section 3.4.1). The flux of HE neutrinos from GRBs [42] is lower than the one expected from steady sources, but the background can be dramatically reduced by requiring a directional and temporal coincidence with the direction and time of a GRB detected by a satellite. Similar studies can also be applied to AGNs or microquasars while observed in high flaring periods (section 3.4.2).

3.4.1. GRB

A first search for neutrino-induced muons in correlation with a selection of 40 GRBs that occurred in 2007, while the detector was in its 5-line configuration, is reported in [43]. A second search, based on the 2008 - 2011 data sample, was recently performed, corresponding to an analysed set of 296 GRBs, representing a total equivalent live time of 6.6 hours. In contrast to the previous searches, this study has been optimised for a fully numerical neutrino-emission model, based on [44]. The optimisation relied on an Extended Maximum Likelihood Ratio built with an a priori knowledge of the background estimated from real data from the whole data sample period, in the GRB direction, adjusted to match the detector efficiency at the respective trigger time.

In both cases, no significant number of events was found in correlation with the prompt photon emission of the GRBs and upper limits were placed on the total fluence from the whole sample as well as on the inferred quasi-diffuse flux of neutrinos for different models, as shown in Fig. 12. Although not competitive with the IceCube limits, the ANTARES results are obtained on a 90% different sample of GRBs, thus offering some complementarity.

On April 27th, 2013, the brightest GRB of the last 29 years has been detected by five $\gamma$-ray telescopes simultaneously, with the highest-energy photon detected by Fermi-LAT reaching a
record-holding energy of 94 GeV. Consequently, a dedicated search for neutrino emission from this exceptionally nearby GRB130427A has been conducted. No excess over background has been found in coincidence with the electromagnetic signal, thus the first limits have been placed on the neutrino emission from this burst\cite{45}, as shown in Fig. 12 (right panel).

The above mentioned studies are triggered searches based on external alerts. Reversely, ANTARES can also send alerts thanks to the ability of its data acquisition system to rapidly filter and reconstruct events in real-time\cite{46}. In this context, the $2\pi$ instantaneous sky coverage and the high duty cycle of the detector are relevant assets. Alerts consist either of doublets occurring within 15 minutes and separated by $3^\circ$ or of HE events (typically above 5 TeV). Recently, a third criterion has been implemented: events closer than $0.3^\circ$ from a local galaxy (within 20 Mpc) generate an alert as well. Since 2009, alerts have been sent on a regular basis to a network of fast-response, wide field of view ($1.9^\circ \times 1.9^\circ$) robotic telescopes (TAROT, ROTSE, ZADKO) and more recently also to the SWIFT/XRT telescope. The rapid response of the system ($\sim 20s$) is particularly well suited for the detection of optical afterglows from GRBs. Up to now, no optical counterpart associated with a neutrino alert was observed and limits on the magnitude of a possible GRB afterglow were derived\cite{47}.

3.4.2. Flaring Sources To further improve the sensitivity, specific searches have been performed during reported period of intense activity of some sources. This approach enhances the sensitivity by a factor 2-3 with respect to a standard time-integrated search, for a flare duration of 1-100 days. The first analysis of this kind was made with a total of ten blazars selected based on their Fermi-LAT light curve profiles in the last four months of 2008. In this method, the assumed neutrino time distribution is directly extracted from the gamma-ray light curve. The search for a signal is performed using an unbinned likelihood ratio maximisation, where the data are parameterised as a two components mixture of signal and background. For one of these AGNs (3C279), one neutrino candidate was found to be in spatial ($0.56^\circ$) and time coincidence with the flare. The post-trial probability for this to occur randomly in the only-background hypothesis was evaluated as 10%. The 90% C.L. upper limits derived on the neutrino fluence for these AGNs are presented in\cite{48}. An extension of the search was recently done with data till December 31st, 2011 (750 live time days). A total of 86 flaring periods from 41 blazars was studied with an
improved likelihood incorporating the number of hits as an energy proxy, yielding an additional improvement of about 25%. Again, the most significant flare, with a post trial p-value of 12%, is found for 3C279 with a second event passing the selection. More details are given in [49].

Another search of this kind has been conducted with a list of 6 microquasars with x-ray or gamma-ray outbursts in the 2007-2010 satellite data (RXTE/ASM, Swift/BAT and Fermi/LAT). No significant excess of neutrino events in spatial and time coincidence with the flares was found. The inferred limits on the neutrino flux are close to theoretical predictions [50] which may be reached by ANTARES in the following years, in particular for what concerns GX339-4 and CygX-3.

3.4.3. Sources emitting Gravitational Waves
Another example of a multi-messenger search with ANTARES candidate events used as a trigger, is the search for joint sources of HE neutrinos and Gravitational Waves (GWs) with the VIRGO and LIGO interferometers. In addition to already known type of sources, the association of HE neutrino candidates with GWs could reveal new, hidden sources that are not observed by conventional photon astronomy (e.g. failed GRBs) [51, 52]. This has motivated the signature of an agreement for data exchange between the ANTARES Collaboration, the LIGO Scientific Collaboration and the Virgo Collaboration. Two common data set exists. The first one covers the period from January to September 2007 which coincides with the fifth and first science runs of LIGO and Virgo, respectively, and with data from the 5 first ANTARES lines. This common data set was jointly analysed. No significant number of coincident event was observed and limits on the density of joint HE neutrino - GW emission events in the local universe were placed [53].

An additional data set corresponding to the second VIRGO-LIGO common science data sample (from July 2009 to October 2010) and to the full ANTARES configuration is currently being analysed with improved methods on both sides.

3.5. Beyond Astrophysics
The ANTARES detector offers the possibility to study a broad field of physics, beyond astrophysics. Here we briefly report on searches for DM in the form of Weakly Interacting Massive Particles (WIMPs, section 3.5.1) and further exotic physics such as magnetic monopoles and nuclearites (section 3.5.2).

3.5.1. Dark Matter Searches
WIMPs are advocated in many theoretical models to explain the missing matter in the Universe. As massive particles, they are gravitationally trapped in dense bodies such as the Sun, the Earth or the Galactic centre, where they can subsequently self-annihilate. As by-product of the annihilation process, neutrinos can be produced, which may be the only particles able to escape, with an energy of the order of the mass of the WIMP. A signature for DM would therefore be an excess of neutrinos in the direction of such bodies in the ~10 GeV - 1 TeV energy domain.

A first search in the direction of the Sun has been performed using the data recorded by ANTARES during 2007 and 2008, corresponding to a total live time of 294.6 days. For each WIMP mass and each annihilation channel envisaged, the quality cuts were chosen to minimise the average 90% C.L. upper limit on the DM induced neutrino flux. No excess above atmospheric background was found. The results are reported in [54].

An improved analysis has been recently unblinded, relying on 1321 effective days from the 2007-2012 data set. Improvements arise at low energy from the addition of events reconstructed with only one line (offering poor azimuth accuracy but valuable zenith information). Another source of improvement comes from the use of 2 independent track reconstructions, the best one being kept for each tested WIMP mass. Again, no significant number of event was found over background and upper limits were derived on the flux of neutrinos from the Sun (see Fig. 13 - left panel). Additionally, in Fig. 13 (right panel), the 90% C.L. upper limits in terms of
Figure 13. Left: 90% C.L. upper limit on the muon neutrino flux as a function of the WIMP mass for the three self-annihilation channels $b\bar{b}$ (green), $W^+W^-$ (blue) and $\tau^+\tau^-$ (red).

Right: ANTARES limits on the spin-dependent cross-section of WIMPS on protons inside the Sun. Non-excluded MSSM-7 models from a scan over its parameter space are indicated. The results from Baksan 1978-2009 (dash-dotted lines), SuperKamiokande 1996-2008 (dotted lines) and IceCube-79 2010-2011 (dashed lines) are also shown, with the addition of the direct detection limits from KIMS 2007 (dashed-dotted black line) and COUP 2011 (dashed black line).

spin-dependent WIMP-proton cross-sections are derived and compared to predictions of the MSSM-7 [55] model, a simplified version of the Minimal SuperSymmetric Model containing a neutralino as lightest stable particle.

3.5.2. Exotic Searches

Magnetic Monopoles  Magnetic monopoles are predicted by various gauge theories to have been produced in the early universe. Their predicted signature in a neutrino telescope is quite visible, as the intensity of the light they emit in the detector is $O(10^4)$ times greater than the Cherenkov light, depending on the velocity $\beta$. A search for relativistic upgoing magnetic monopoles was performed with 116 days live time of ANTARES 2007-2008 data [56]. In order to improve the sensitivity for low velocity monopoles, the tracking algorithm has been modified so as to leave the velocity as a free parameter to be fitted. One event was observed, compatible with the background only hypothesis. The derived limits on the upgoing magnetic monopole flux above the Cherenkov threshold for $0.625 \leq \beta \leq 0.995$ are shown in Fig. 14.

Nuclearites  Nuclearites are hypothetical massive stable particles made of lumps of up, down and strange quarks [58]. They could be present in the cosmic radiation, either as relics of the early Universe or as debris of supernovae or strange star collisions. They could be detected in a neutrino telescope through the blackbody radiation emitted by the expanding thermal shock wave along their path.

A dedicated search was performed with data collected in 2007 and 2008. The study was optimized for non relativistic nuclearites. Assuming a velocity $\beta = 10^{-3}$ outside the atmosphere, the nuclearite should have a mass larger than $\sim 10^{22}$ GeV in order to cross the Earth. Since the nuclearite flux is expected to decrease with the nuclearite mass, only downgoing nuclearites were considered in the analysis. As for monopoles, the light yield in the detector depends on the nuclearite mass. It is expected to be much greater than for relativistic muons for nuclearite masses larger than few $10^{13}$ GeV. After unblinding, no significant excess of nuclearite-like events
was found. Upper limits on the flux of downgoing nuclearites were established between $7.1 \times 10^{-17}$ and $6.7 \times 10^{-18} \text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$, for the mass range $10^{14} \leq M_N \leq 10^{17} \text{GeV}$.

4. The km3net project

km3net is a project for a deep-sea research facility to be installed in the Mediterranean Sea and comprising the next-generation neutrino telescope. The infrastructure will gather several other instruments for sea science and geophysics. After the completion of the EU funded Design Study and the Preparatory Phase Study and thanks the acquisition about 20% of the envisaged total budget (estimated to be 220-250 M€), the project has entered the "phase-1" early 2013. A cost-effective design have been adopted in the final layout which is presented in § 4.1. The detector will be distributed over 3 possible sites in France, Italy and Greece. The construction has already started at the French and Italian sites. The expected performances and prospects for science are briefly discussed in § 4.2.

4.1. The km3net technology

The km3net detector [59] will consist of a large number (about 12,000) of optical modules each equipped with 31 small (3 inch) PMTs and associated electronics. Each PMT is surrounded by a light concentrator ring which increases the photon detection efficiency by a factor 1.3 to 1.5, depending on the angle of incidence of the photon. The optical module also contains instrumentation allowing for the determination of its position (acoustic sensor), orientation (compass and tilt meter), as well as a nano-beacon for time calibration purpose. The optical modules are distributed along strings called detection units (DUs). A DU consists of two vertical ropes with a length of about 1 kilometre which support up to 20 optical modules with a spacing of 30–40 metres. The DUs are anchored to the sea floor and kept vertical by buoys. They are connected to shore by an electro-optical cable. An array of DUs will constitute a detector building block, which should be considered as the smallest size detector with an optimal efficiency. A sketch of the detector, together with an exploded view of an optical module are shown in Fig. 15. Following the antares scheme, every analogue pulse from any PMT above a typical threshold of 0.3 photo-electrons is digitized and sent to shore for real-time filtering. The filtered data are then sent to various computer centers around Europe for offline analyses. Each optical module requires about 10 W of electrical power and has 1 Gb/s readout bandwidth. The different read-out channels are multiplexed using DWDM technology.

The new design of optical modules (with many small PMTs instead of a large one) offers many advantages. This will not only increases by a factor $\sim 3$ total photocathode area per OM, but
Figure 15. Left: a possible configuration of the km3net array of OMs. A zoom of one line of OMs can be seen on the right of the picture. Right: an exploded view of the multi-PMT optical module.

also improves photon counting purity: the photon counting with a multi-PMT optical module will essentially rely on counting the number of hits within a certain time window, instead of measuring the charge of an analogue pulse. Furthermore, the presence of several small PMTs in one OM should provide directional information which could be used to improve the performance of the reconstruction algorithms.

A prototype of a multi-PMT OM has been recently integrated in the ANTARES instrumentation line. It was deployed in April 16th, 2013. Data taking started the same day. The first runs were dedicated to perform calibrations of the system. The average rate per PMT is about 8 kHz. The main asset of the OM containing many PMTs is the possibility to ask for coincidences of hits within the same optical module. A $n$-fold coincidence can be defined as the occurrence of a hit in $n$ PMTs within a time window of 20 ns. In this respect, Fig. 16 (top) shows the event rate as a function of the coincidence level $n$. Above the coincidence level of 6, the signals from atmospheric muon dominate and a good agreement is seen between data and the simulation of atmospheric muons. The conclusion being that with a single OM, muons are unambiguously identified, which was not possible with the previous OMs à la ANTARES. In Fig. 16 (bottom), for which a coincidence level greater than 6 is required, the number of hits detected by each PMT is represented against their zenith position on the OM. As expected, since atmospheric muons come from above, an increase in the rate is observed as the zenith angle decreases. There is fair agreement between data and the atmospheric muon simulation. The drop in hit count in 2 PMTs in the uppermost part is attributed to a shadowing effect of the local control module of ANTARES line and should be absent in the km3net detection units. The successful operation of this first multi-PMT module demonstrates the superior capabilities of the optical modules of the future neutrino telescope.

In order to permit the deployment of several detection units in one sea campaign, new techniques have been developed. Each string is first wound on a launcher vehicle. The launcher vehicle is lowered to the seabed from a surface vessel. Once the launcher vehicle has reached the seabed, the buoy is released, the string unfurls and rises to its full height. The launcher vehicle is then recovered for subsequent deployments. Several launcher vehicles will be used to deploy several strings during a single cruise.
Figure 16. Top: the rate of events as a function of the coincidence level. Black dots correspond to data while colored histograms represent simulations. The single rate, which is very sensitive to the attenuation and scattering length in the water and also has a contribution from bioluminescence is underestimated by the simulation. Bottom: The number of hits as a function of the zenith position of the PMT for coincidence levels above 6. One PMT is looking downward (180°). The others are grouped by 6 in 5 different angles.

4.2. Expected science

The angular resolution (shown in Fig. 17), the geographical location and the size are the key element that make KM3NeT a suited instrument to search for neutrinos from Galactic sources. As a prime example, the sensitivity of the detector for an assumed flux of neutrinos from the young shell-type supernova remnant RXJ1713-39.43 has been determined [60]. Assuming a hadronic origin of the observed gamma-ray flux, which extends to several tens of TeV, the figure of merit of KM3NeT can be summarized as a 5σ discovery within five years. The observation time to get 50% probability to reach a significance of 3σ is only 2 years. A case study has also been inquired for Vela X, one of the nearest pulsar wind nebulae (PWN) associated with the energetic Vela pulsar PSR B0833-45. The source extension was simulated as a flat spatial distribution within a disk with 0.8° radius. Preliminary results with a binned analysis for a 100 m DU distance indicates that a discovery power (50% chance) at 5σ (3σ) will be possible after 3.3 (1.2) years of data taking. As in the case of the RXJ1713.7-3946 study, this value is expected to improve with unbinned analyses currently being performed.
In a similar way, if a hadronic mechanism is responsible for the emission of the observed gamma-rays from the FBs, a flux of high-energy neutrinos could be detected (see § 3.2.2). The detection capability for high-energy neutrinos from the FBs has been extensively studied in reference [61]. In order to determine the number of observation years for the discovery, the Model Discovery Potential (MDP) method was used. In Fig. 18 the number of years required to have a signal from bubbles at 3σ and 5σ of significance, with 50% probability, is shown as a function of the number of OMs. Assuming the observed gamma rays are of hadronic origin and the spectrum extends to the multi-TeV range with an exponential cutoff at 100TeV, this analysis shows that in about 2.5 years a detector made of only 6000 OM can detect this neutrino flux at a significance of 5σ with 50% probability.

Last, but not least, the KM3NET detector should be able to exclude at 90% C.L, after a few months of operation, the IceCube signal reported in [13]. A highly significant confirmation would naturally require a bit more time of data taking. The exact numbers are not available as of today, but the collaboration is now taking great care in trying to optimize the configuration of the first deployments in order possibly confirm ICECUBE’s signal (see § 2) before the completion of the detector.

5. Conclusions
Neutrino astronomy is entering a new exciting era thanks to the observation by ICECUBE of the first high-energy extraterrestrial neutrinos. Further results from ICECUBE are expected soon and should tell wether the observed excess is indeed uniformly distributed in the sky. The observation of point sources in the Southern sky may require the operation of a large neutrino telescope in the Northern Hemisphere. The ANTARES deep sea observatory is the most sensitive neutrino telescope currently in operation in the Northern Hemisphere. It has been continuously taking data since 2007. Besides atmospheric neutrino studies, several searches for neutrinos of astrophysical origin have been performed, including a rich multi-messenger program. Beyond astrophysics, competitive searches for dark matter and even more exotic particles have been carried out. All the studies presented in the proceedings will be updated with the data remaining to be analysed and/or recorded. The data acquisition is foreseen at least until the end of 2016, when the detector gets eventually superseded by the next generation KM3NET detector,
Figure 18. Time needed for discovery at 5σ of significance, 50% probability, and 3σ of significance, at 50% probability, as a function of the number of OM for a spectrum with a 100 TeV cutoff.

currently being built in the Mediterranean Sea.

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