Report on the Status of KM3NeT for the IN2P3 Scientific Council

Paschal Coyle (CPPM) on behalf of the KM3NeT groups of
APC, CPPM, IPHC, LPC, Subatech

January 4, 2017

1 Introduction

The main objectives of the KM3NeT[1] Collaboration are *i)* the discovery and subsequent observation of high-energy neutrino sources in the Universe and *ii)* the determination of the mass hierarchy of neutrinos. These objectives are strongly motivated by two recent important discoveries, namely: *1)* The high-energy astrophysical neutrino signal reported by IceCube and *2)* the sizable contribution of electron neutrinos to the third neutrino mass eigenstate as reported by Daya Bay, Reno and Double Chooz.

To meet these objectives, the KM3NeT Collaboration is in the process of building a new research infrastructure consisting of a network of deep-sea neutrino telescopes in the Mediterranean Sea. A phased and distributed implementation is pursued which maximises the access to regional funds, the availability of human resources and the synergetic opportunities for the earth and sea sciences community. Three suitable deep-sea sites are identified, namely off-shore Toulon (France), Capo Passero (Italy) and Pylos (Greece).

The KM3NeT Phase 2 (KM3NeT 2.0) infrastructure will consist of three so-called "building blocks". A building block comprises 115 detection strings, each string comprises 18 optical modules and each optical module comprises 31 photo-multiplier tubes (PMTs). Each building block thus constitutes a 3-dimensional array of photo sensors that can be used to detect the Cherenkov light produced by relativistic particles emerging from neutrino interactions.

Two building blocks will be configured to fully explore the IceCube diffuse signal for cosmic neutrinos with different methodology, improved resolution and complementary field of view, including the Galactic plane. Collectively, these building blocks are referred to as ARCA (Astroparticle Research with Cosmics in the Abyss). ARCA will be realised at the Capo Passero site in Sicily, Italy.

One building block will be configured to precisely measure atmospheric neutrino oscillations. This building block is referred to as ORCA (Oscillation Research with Cosmics in the Abyss). ORCA will be realised at the Toulon site in Southern France. Due to KM3NeT's flexible design, the technical implementation of ARCA and ORCA is almost identical. The Letter of Intent for the Phase 2 of KM3NeT describes the physics opportunities and detector design [1].

The KM3NeT 2.0 project is on the French roadmap of Research Infrastructures and was recently selected for the 2016 roadmap of the European Strategy Forum on Research Infrastructures (ESFRI). It is strongly supported by the APPEC roadmap.

---

[1] http://www.km3net.org

2 ARCA Science

2.1 High energy neutrino astronomy

For neutrino astronomy, the main objective of KM3NeT 2.0 is the detection of high-energy neutrinos of cosmic origin. Since neutrinos propagate directly from their sources to the Earth, even modest numbers of detected neutrinos will be of utmost scientific relevance since they are the unambiguous 'smoking gun' signature for hadronic acceleration, thus indicating the astrophysical objects in which cosmic rays are accelerated.

The interacting neutrinos essentially produce two patterns in the telescope: cascades and tracks. Cascades mainly originate from electrons and hadronic showers from the nucleon fragmentation. So charged-current (CC) ν_e interaction and all-flavour neutral current interactions contribute to this topology (as well as a large fraction of ν_τ's), while searches for tracks apply mainly to CC ν_μ interactions. These two events classes produce very different time-space hit patterns in the detector. The cascade-like events are characterised by a dense hit pattern close to the neutrino interaction point, thus allowing for a good estimate of the neutrino energy. A track-like event is characterised by the Cherenkov light emission all along the trajectory of the emerging muon, thus allowing for a precise measurement of its direction.

Recently, the IceCube experiment at the South Pole has reported the discovery of a diffuse flux of high-energy cosmic neutrinos with energies up to PeV. This represents a major breakthrough and strongly motivates an independent confirmation and precision studies of the origin of this flux. The IceCube so-called High Energy Starting Events (HESE) [2] used selection criteria in a restricted fiducial volume. The largest fraction of HESE are cascade events for which the angular determination is rather poor (10-20°). The HESE flux (with best fit spectral index $\Gamma \sim 2.5$) is compatible with a diffuse origin and flavour ratios $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$, as expected from charged meson decays in CR accelerators after oscillation on their way to the Earth. However, recent results with the upgoing muon neutrino flux, using six years of IC data [3], reveal some tensions with the HESE measurements, which could be explained by the presence of several components of extraterrestrial neutrinos. In particular, a non negligible contribution from point-like or extended Galactic sources has been advocated (e.g. Refs [4, 5, 6]). The poor angular resolution of the IceCube data does not allow for the identification of one or more point sources.

The ARCA telescope will detect the neutrino flux reported by IceCube and will provide essential data concerning its origin, energy spectrum and flavour composition. Due to its location in the Northern hemisphere and excellent visibility of the Galactic Plane, the ARCA information will be complementary to the IceCube measurements: ARCA will observe the same sources at different energies; it will observe sources that are not visible to IceCube; and, due to the smaller light scattering in water as compared to ice, it will be able to measure the direction and energy of electron and tau neutrinos with much better precision.

Algorithms have been developed to reconstruct tracks and cascades incorporating the directional information provided by the multi-PMT OM. The parameters quantifying the quality of the each reconstruction are used to select events and reject the background from mis-reconstructed atmospheric muons. The median angular resolutions achieved in the track and cascade channels (at 100 TeV) are better than 0.1° and 2° respectively. For the cascade channel, thanks to the reduced scattering of light in seawater, this is almost by an order of magnitude better than that achieved by IceCube. The neutrino energy resolution in the cascade channel is better than 10% and greatly surpasses that achieved in the track channel (0.27 on the log of the muon energy).

The sensitivity of the ARCA detector to the diffuse neutrino flux measured by IceCube has been evaluated using both track-like events reconstructed up to 10° above the horizon and cascade-like events in the full angular range. The results of this analysis are summarised in Fig.1 Left. A significance of 5 sigma can be reached in less than one year.

The sensitivity to potential Galactic point-like neutrino source has been studied using upgoing muon neutrino tracks. The Galactic sources that are the most intense high-energy gamma-ray sources and possible neutrino emitters, are the SuperNova Remnants RXJ1713 and Vela Junior, and the Pulsar Wind Nebula VelaX. The RXJ1713 and the Vela X neutrino spectrum have been estimated considering the hypothesis of transparent sources and a fully hadronic production mechanism. The measured extension of the source in

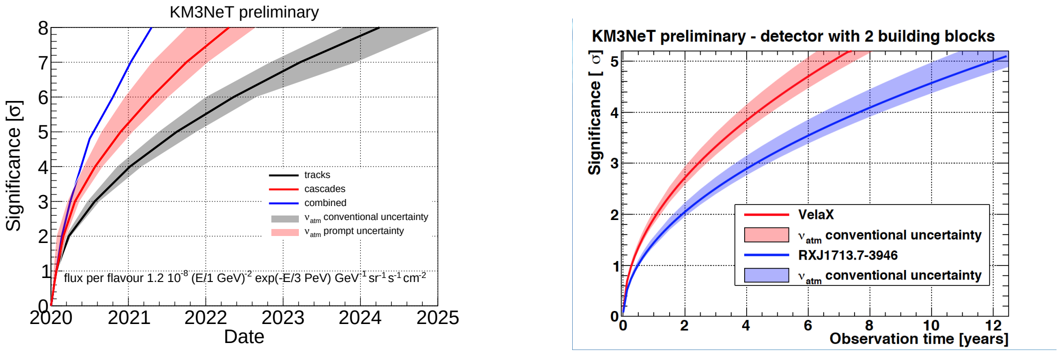


Figure 1: *Significance as a function of the observation time for the detection of: (Right) a diffuse flux of neutrinos corresponding to the signal reported by IceCube for the cascade channel (red line) and muon channel (black line). The black and red bands represent the uncertainties due to the conventional and prompt component of the neutrino atmospheric flux. The blue line represents the results of the combined analysis. (Left) the Galactic sources RXJ1713 and Vela-X. The bands represent the uncertainties due to the conventional component of the atmospheric neutrino flux.*

gamma-rays has been taken into account in the simulation. A significance of about 3 sigma is reached in 3 years (Fig.1 Right).

2.2 Additional ARCA physics

In addition to the central science targets of neutrino astronomy, i.e. investigating high-energy cosmic neutrinos and identifying their astrophysical sources, KM3NeT/ARCA will offer a wide spectrum of further physics opportunities, of which a selection is sketched in the following. Corresponding physics analyses have been pioneered by the IceCube and ANTARES Collaborations.

- **Gamma-ray bursts (GRB)**

  There is strong evidence that long-duration gamma-ray bursts (GRBs) are produced from relativistic jets formed in the collapse of a massive star [7]. Shocks generated either within the jet, or when the jet collides with surrounding material, are potential cosmic ray acceleration sites, with an associated neutrino flux from subsequent interactions and decays [8]. The short duration of GRBs (seconds to minutes) allows a narrow neutrino-search time-window, effectively reducing the background when compared to a standard point-source search. This has allowed ANTARES and IceCube to constrain the properties of GRB jets [9, 10]. KM3NeT/ARCA will increase the sensitivity of such searches similarly to that for E^{-2} point-sources.

- **Multimessenger studies:**

  KM3NeT/ARCA will be part of a global alert system able to tag synchronous observations of different experiments, observing e.g. γ rays or gravitational waves. Another branch of multimessenger studies is the creation of alerts for optical, radio or X-ray telescopes to follow up "interesting" neutrino observations, such as a doublet of events from the same celestial direction during a short time period. As for the ANTARES TAToO program [11], KM3NeT/ARCA will monitor more than half the sky, and will be able to generate alerts with high angular precision within seconds. As ultra-high-energy cosmic rays are also expected to retain some directional information, correlation studies with the arrival directions of events detected by e.g. the Pierre Auger Observatory will also be possible.

- **Cosmic ray physics:**

  KM3NeT/ARCA will register a huge number of high-energy atmospheric muons that reflect the direction of impact of the primary cosmic-ray (CR) particle with sub-degree precision. This data set will allow us to investigate inhomogeneities of the CR flux and to complement the corresponding sky maps by IceCube and dedicated CR experiments.

A further opportunity might be the detailed investigation of muon bundles that could, via their multiplicity and divergence, be related to the chemical composition of CRs.

- **Particle physics with atmospheric muons and neutrinos:**

  The high-energy end of the atmospheric muon and neutrino spectra are expected to be dominated by prompt processes, i.e. the production of charm or bottom hadrons in the primary CR reactions in the atmosphere and their subsequent fast decay to leptons. Little is experimentally known about these reactions, and theoretical modelling is difficult since it involves QCD processes at the border line of the non-perturbative regime. Identifying and measuring the muons and neutrinos from these processes would shed light on the underlying reaction mechanisms.

- **Tau neutrinos:**

  The capability to identify tau neutrino reactions at energies beyond a few 100 TeV will not only allow for constraining the flavour composition of high-energy cosmic neutrino fluxes, but might also provide an additional handle to investigate prompt neutrino fluxes (see above), which are the only CR reactions for which a significant production probability for tau neutrinos is expected.

  A further interesting phenomenon of tau neutrinos is their regeneration after CC reaction in the Earth through the subsequent tau decay (relevant for energies above a few 10 TeV). The observation of this phenomenon would be interesting in itself, but might in addition signal new particle physics, e.g. in the context of supersymmetry.

- **Dark matter:**

  Should Dark Matter particles have masses in the TeV range or above, neutrinos from self-annihilation reactions could be the first Dark Matter signal to be detected. ANTARES and IceCube have already proven the ability of neutrino telescopes to significantly constrain Dark Matter properties, with searches targeting accumulations in the Sun [12, 13] and the Galactic Centre [14, 15]. The corresponding investigations with KM3NeT/ARCA data will – as with all indirect searches – be particularly sensitive to Dark Matter particles with spin-dependent scattering cross sections on nuclei.

- **Exotics:**

  There is a variety of hypothesised stable or quasi-stable particles that would leave an identifiable, characteristic signature when crossing the detector. Amongst these are magnetic monopoles (for which ANTARES and IceCube have already performed a search [16, 17]), strangelets, Q-balls, and nuclearites.

- **Violation of Lorentz invariance:**

  Violation of Lorentz invariance (LIV) could lead to oscillation-like interference patterns of atmospheric neutrinos in the energy range of TeV and above. Additionally, LIV would produce a time-delay between neutrinos and photons from distant, time-variable sources (in particular, GRBs), allowing LIV to be tested by multimessenger studies.

3 ORCA Science: neutrino studies with atmospheric neutrinos

In the standard 3-neutrino scheme, the PMNS mixing matrix, which relates the neutrino flavour eigenstates to the mass eigenstates (ν_1, ν_2, ν_3), can be parameterised in terms of 3 mixing angles θ_{12} θ_{13} θ_{23}, and a CP-violating phase δ. Oscillation experiments are not sensitive to the absolute value of neutrino masses but do provide measurements of the squared-mass splittings $\Delta m^2_{ij}(i, j = 1, 2, 3)$. The values of all these mixing parameters are now extracted from global fits of available data with a reasonable precision. Despite this tremendous progress, many fundamental properties of the neutrino have yet to be determined: the octant

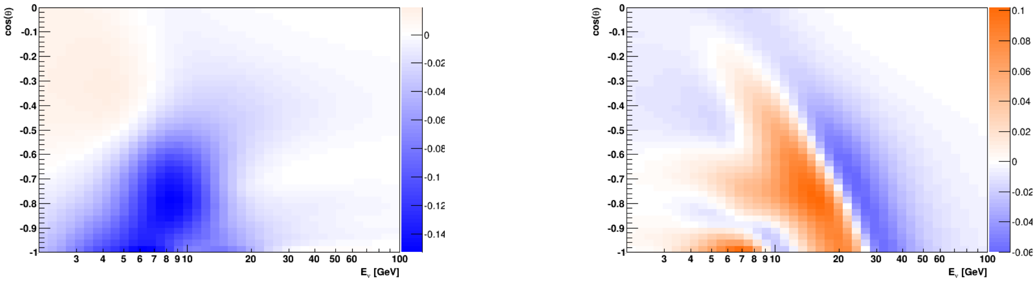


Figure 2: *The NMH asymmetry, defined as $(N_{IH} - N_{NH})/N_{NH}$, for ν and anti-ν charged current interactions as a function of neutrino energy and cosine zenith angle. Electron neutrinos are on the left and muon neutrinos are on the right. Here the neutrino energy has been smeared by 25% and the zenith angle is smeared by $\sqrt{(}M_p/E_\nu)$.*

of θ_{23}, the absolute masses, whether they are their own anti-particle (i.e. Majorana or Dirac type), the value of CP phase and finally the neutrino mass hierarchy (NMH).

3.1 Neutrino Mass Hierarchy

The NMH is termed "normal" (NH) if $\nu_1 < \nu_2 < \nu_3$ or "inverted" (IH) if $\nu_3 < \nu_1 < \nu_2$. Knowledge of the NMH is an important discriminant between theoretical models of the origin of mass. The NMH serves as an input to cosmological models and neutrino flavour conversion in supernovae explosions. Furthermore, the rates of neutrinoless double beta decay depend strongly on the NMH. Finally, the NMH has a significant impact on the precision determination of the PMNS parameters.

ORCA relies on the presence of matter effects that modify the ν_μ survival probability and the rate of $\nu_\mu \rightarrow \nu_e$ appearance at the atmospheric mass scale. The matter effects arise from the ν_e component of the "beam" undergoing charged-current elastic scattering interactions with the electrons in the matter. This effectively modifies the observed mixing angles and mass differences in a way that depends on the NMH [18].

Fig.2 shows the expected rate asymmetry, $(N_{IH} - N_{NH})/N_{NH}$, between the NH and IH cases as a function of the energy and cosine of the zenith angle (related to the baseline through the Earth) for both the ν_μ and ν_e events. Detector resolution effects on the reconstructed energy and direction are included. At certain energies and angles the relative flux differences can be as large as 10%; the electron neutrino channel being the most robust against resolution effects.

Fig.3 (Left), shows the expected performance of ORCA to determine the NMH as a function of the assumed θ_{23} and CP phase. For a true IH the significance is essentially independent of θ_{23}. For a true NH, the significance improves as θ_{23} increases. If the current value of θ_{23} from the global fits of around 42° is assumed, ORCA will determine the hierarchy with a median significance of 3 sigma in approximately three years. The ORCA data are relatively insensitive to the CP phase, the significance being reduced by at most 20-30% depending on the true value of δ_{23}. Fig.3 (Right), shows the median significance as a function of time for a variety of assumptions. As detailed in Ref. [1] many of the possible systematic uncertainties (oscillation parameters, CP phase, overall flux factor, NC scaling, ν/anti-ν skew, μ/e skew, energy slope) are actually fitted from the data itself when determining the NMH.

Fig.4 compares the performance of ORCA with other experimental facilities that aim to address the neutrino mass hierarchy: the medium baseline reactor experiment JUNO, the atmospheric neutrino experiments INO (cavern) and PINGU (deep ice), and the Fermilab long-baseline beam experiments NOVA and LBNE/DUNE.

On the long term, DUNE could make a 3σ determination of the hierarchy for all values of δ CP with less than 10 years of operation, while JUNO in China and RENO-50 in South Korea are proposed to exploit reactor neutrino oscillations at medium scale baselines of about 50-60 km to measure the hierarchy above

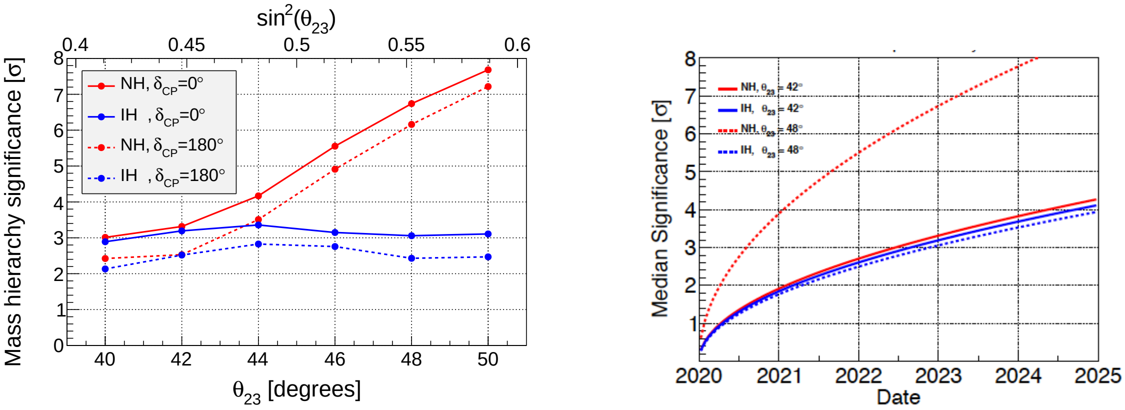


Figure 3: *The projected NMH sensitivity for a 115 string ORCA detector. (Left) after 3 years, as a function of θ_{23}. (Right) as a function of time for the indicated scenarios.*

3σ with 6 years of operation. The ICAL at INO proposes to use charge discrimination to distinguish between neutrinos and anti-neutrinos to determine the hierarchy with between 2.2-2.8 σ significance using 10 years of data with a 50 kton detector. Measurements of neutrinos from a nearby supernova, the CMB polarization and neutrinoless double beta decay may also each provide indirect sensitivity to the hierarchy.

In the case of long baseline experiments (NOVA, DUNE-10 kt and DUNE-34 kt), the sensitivity mainly depends on the value of the CP-violating phase. In the case of ORCA, PINGU and INO, the most relevant parameter is θ_{23}. For the case of JUNO it is somewhat different; the uncertainties on the oscillation parameters do not have a big impact on the results; instead, the energy resolution is the parameter expected to have the greatest impact. Therefore, in this case, the width of the band shows the change on the results when the energy resolution is changed from 3% to 3.5%.

The PINGU experiment [19] has a similar performance to ORCA (an independent confirmation of the physics capabilities of the deep-sea/deep-ice approach). On 18 Nov 2016, the IceCube/PINGU/Gen2 Collaboration submitted a proposal for a Phase-I towards IceCube-Gen2 to NSF. It envisages deployment of seven additional strings in the bottom center of IceCube. From a technological point, the purpose is three-fold: 1) to build and integrate parts to obtain a new drill 2) to test new sensors and 3) to deploy novel calibration devices. For what concerns physics, the dense instrumentation matches the requirements of PINGU (of course with limited capabilities due to the lower number of strings - 7 instead of 26). The new strings are envisioned to use multi-PMT optical modules, similar to those invented by KM3NeT. The timeline is five years, with deployment in the 4th year. In the most optimistic case (approval and funding in October 2017) the deployment could be in the 2020/2021 polar season.This 'downscaling' puts the NMH determination beyond the reach of PINGU in a reasonable timescale.

The ORCA experiment offers the possibility of a rapid construction and speedy determination of the mass hierarchy well in advance of the other experiments and via an alternative method with very different systematics.

As explained in Ref.[20] there is a synergy between the ORCA and JUNO approaches based on the fact that when data are analysed with the wrong neutrino mass ordering the best fit occurs at different values of Δm^2_{31}. Hence, the wrong mass ordering can be excluded by a mismatch of the values inferred for Δm^2_{31}, thanks to the excellent accuracy for Δm^2_{31} of both experiments. The synergy effect may lead to a high significance determination of the mass ordering even in situations where the individual experiments obtain only poor sensitivity.

Throughout the full range of neutrino oscillation parameter space, the complementarity of ORCA, beam and reactor experiments provides the surest path to determining the NMH, with synergistic effects that can improve the combined significance beyond purely statistical addition of results. Consistency of the results obtained from several of these experiments would provide assurance that our interpretation of the results in the three-flavour neutrino paradigm is indeed correct.

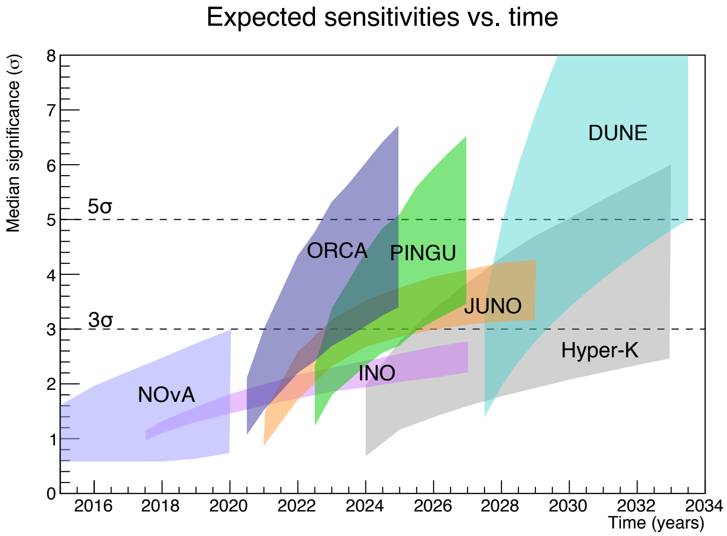


Figure 4: *(Adapted from Blennov, arXiv:1311.1822). The median sensitivity to reject the IH, if the true hierarchy is NH, for the different facilities as a function of date. The width of the bands correspond to different true values of the CP phase for NOVA and DUNE, different true values of θ_{23} between 40 and 50 for INO, ORCA, PINGU (27 strings), and energy resolution between 3% sqrt(1MeV/E) and 3.5% sqrt(1MeV/E) for JUNO.*

3.2 Oscillation parameters

Despite providing the first evidence for "atmospheric" neutrino oscillation, the mixing between the second and third neutrino mass eigenstates is currently the least well measured of the oscillation parameters in the neutrino sector. ORCA will measure $\sin^2\theta_{23}$ and Δm^2_{32} parameters via the disappearance of ν_μ in the atmospheric flux. Fig.5 shows the expected precision after three years and compares it with current measurements and the expectation from T2K and NOVA at the end of their anticipated data taking in 2020. The precision of ORCA is comparable or better, and is obtained at much higher energies and longer baselines and with very different systematic uncertainties.

The current measurements of θ_{23} indicate that the angle is close to maximal mixing. If θ_{23} is not maximal, determining its value and its "octant" is of importance for understanding the origin of neutrino masses and mixing. Although in two-flavour models, values of θ_{23} above and below 45° produce identical transition probabilities, this is no longer true for three-flavour oscillation in the presence matter effects. By comparing the rates for neutrinos passing the Earth's core/mantle, ORCA can determine the octant for a wide range of θ_{23}. Unlike the case of T2K and NOVA, the measurement is essentially insensitive to the assumed CP phase.

3.3 Tau Appearance

The unitarity of the PMNS matrix is currently only tested at the 20%-40% level. Many beyond the Standard Model theories, with an extended mixing matrix, could modify the rate of ν_τ appearance relative to Standard Model expectations. For vertically upgoing neutrinos, with a baseline of the Earth's diameter, the ν_μ disappearance into ν_τ is maximum around 24 GeV, well above the ORCA energy threshold. ORCA will detect around 3,000 ν_τ CC interactions per year. As shown in Fig.6, this yields a better than 10% precision on the ν_τ appearance rate with one year of data taking.

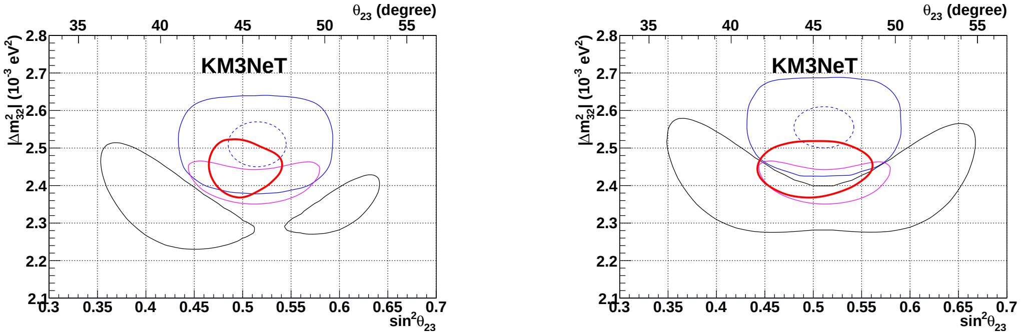


Figure 5: *ORCA one sigma contours, after three years, of the atmospheric neutrino oscillation parameters for the NH (Left) and IH (Right) scenarios (red). The current contours for MINOS (Grey), T2K (blue solid) are indicated, as well as the projected 2020 contours for T2K (blue dotted) and NOVA (pink).*

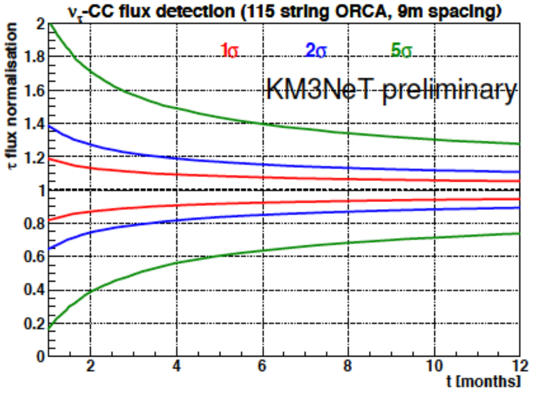


Figure 6: *Precision on the rate of ν_τ appearance as a function time. The true value is assumed to be the Standard Model expectation (1.0). The corresponding 1, 2, 5 sigma regions are indicated.*

3.4 Sterile neutrinos and non-standard interactions

Phenomenological extensions of the standard 3ν oscillation framework can include non-standard interactions (NSI) that behave as four-fermion point interactions at low energies. For the sterile neutrino case, the Hamiltonian is extended to four neutrinos and the 4th neutrino is assumed not to interact. Fig.7, shows the preliminary estimate of the ORCA sensitivity to sterile neutrinos in the $|U_{\mu 4}|^2 - |U_{\tau 4}|^2$ parameter space and to NSI in the $\epsilon_{\tau\tau} - \epsilon_{e\tau}$ parameter space, under some simplified assumptions [21]. They improve on current limits by an order of magnitude in the NSI parameters and about a factor 5 in the $|U_{\tau 4}|$ mixing.

3.5 Dark matter, Tomography

Observations in astronomy and cosmology provide irrefutable evidence that the vast majority of the matter in the Universe comprises of non-luminous "dark matter" the nature of which is completely unknown. A theoretically well-motivated candidate is a Weakly Interacting Massive Particle (WIMP), but theory gives little guidance for the mass or whether their interaction with matter is dominantly spin-dependent or spin-independent. WIMPs could be captured in the Sun after scattering off nuclei, accumulate and self-annihilate producing a flux of neutrinos, whose flux and maximum energy depends on the WIMP mass. Since the Sun is primarily made of protons, ORCA can place strong constraints on the spin-dependent WIMP-proton scattering cross-section (Fig.8 (Left)), thereby extending the limits provided by ANTARES, IceCube and Super-Kamiokande to lower WIMP masses.

ORCA will also provide tomographic information on the electron density of the Earth interior [22]. This

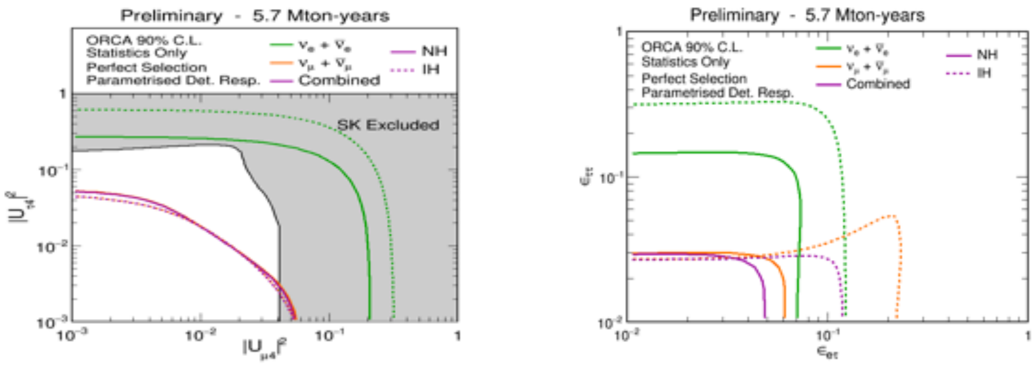


Figure 7: *Preliminary one-year sensitivity of ORCA to sterile neutrinos (left) and NSI (Right) in selected slices of the multi-dimensional parameter space. The regions on top-right of the curves are excluded. Limits from Super-Kamiokande are shown for sterile neutrinos.*

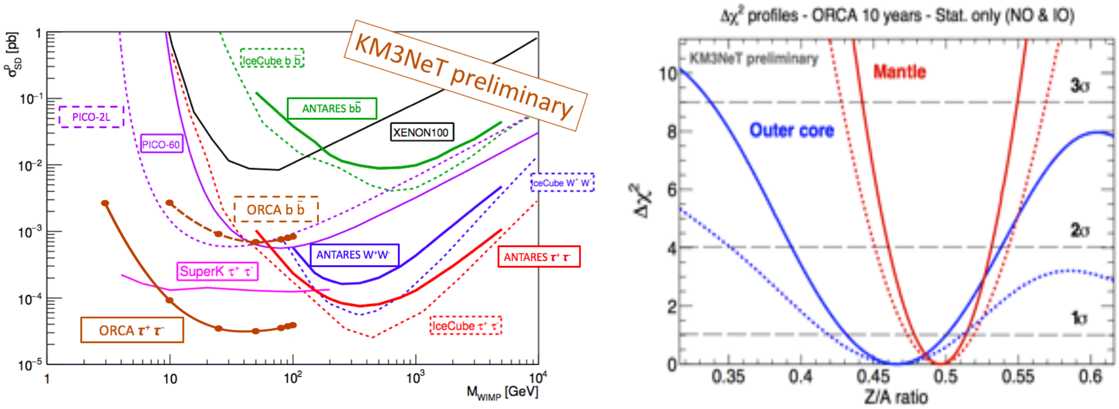


Figure 8: *(Left) 90% C.L. limits on the spin-dependent WIMP-proton cross-section after 3 years of data taking, based on counting both ν_μ and ν_e events coming from the direction of the Sun. (Right) Ten year $\Delta\chi^2$ profiles for mantle and outer core for NH (Solid lines) and IH (Dotted lines).*

new technique is complementary to standard geophysical methods that probe mass density. As shown in Fig.8 (Right) after 10 years of operation, ORCA can measure the electron density in the Earth mantle to an accuracy of $\pm 3.6\%$ ($\pm 4.6\%$) at 1σ confidence level, assuming normal (inverted) mass hierarchy. Here only statistical uncertainties are quoted.

3.6 Supernova neutrinos

A supernova explosion in the close-by Universe will produce a enormous number of MeV anti-ν_e neutrinos. The signal can be statistically extracted from the coherent count rate increase in all the PMTs induced by Cherenkov photons emitted from the neutrino-induced positrons. Thanks to the new OM geometry, it is possible to reduce significantly the dark noise rate and the ^{40}K decay rate. Combining both the ORCA and ARCA arrays, the detection is significant for SN explosions for distance up to the Large Magellanic Cloud.

3.7 CP violation?

Studies indicate that the current unknown value of the Dirac CP violating phase in the neutrino sector only mildly impacts the ORCA sensitivity to the neutrino mass hierarchy. However, if the mass hierarchy is known, significantly improved sensitivity to the CP phase with atmospheric neutrinos can be obtained in the (0.2 –

1) GeV energy regime [23]. This would imply a denser instrumentation than what is currently envisaged for ORCA, but considering the importance of measuring the CP phase could be interesting. In the same spirit, sensitivity studies for both the NMH and the CP phase have been performed for an upgraded neutrino beam to be sent to ORCA from Protvino [24, 25]. Such a strategy would in particular allow for a confirmation of ORCA-only results on the NMH with high statistical power on a short (< 1 yr) timescale [26]. It would require a new beamline to be setup but would offer the advantage to rely on an already built detector. Similar ideas to implement ORCA-like detectors at deep sea locations along the Fermilab and J-PARC neutrinos beams are also under consideration.

4 Earth and Sea Sciences

Measurements in the deep sea are typically performed by deploying and recovering autonomous devices that record data intermittently over a period of months to years. This method is severely constrained by power and bandwidth limitations, by the absence of real-time interaction with the measurement devices and by the delayed access to the data. A cabled observatory like KM3NeT remedies these disadvantages by providing continuous, high frequency, access to real-time measurements in situ. Further the large concentration of different sensors at the same location facilitates the study of time and spatial correlations between sensors. This is an important and unique opportunity for performing deep-sea research, e.g. by scientists from the fields of marine biology, oceanography, environmental sciences, geosciences or seismology.

A permanent deep sea observatory in the Ligurian Sea is of specific interest for several reasons detailed below. The Ligurian Basin is a passageway for several water masses: the modified Atlantic Waters as the surface layer, the Leventine Intermediate Water, the Dense Tyrrhenian Water and the Western Mediterranean Deep Water on the deepest layer, into the Gulf of Lion. The Ligurian sea is therefore a key area to monitor the hydrodynamics of the Western Mediterranean Basin. During wintertime, the unstable Ligurian current develops a strong activity that induces extremely large variability. Vertical velocity changes have been deduced from patterns in phytoplankton biomass, salinity, and temperature, and may result from changes in the local climate (evaporation/precipitation) that affect surface waters, which then sink as dense waters form in the winter. Available time-series data indicate that these changes in temperature and salinity occur at a range of timescales and result in density changes that must impact the circulation of water masses and the biochemical budget (nutrients, dissolved oxygen, organic carbon).

Convergence between Africa and Europe causes the Ligurian region to undergo a weak tectonic compression, generating seismic activity, both on-land and at sea. While this deformation is moderate, the East Ligurian region is one of the most seismically active in France. The West Ligurian site is seismically quieter, but cabled seismometers will contribute to a better understanding of active tectonics and seismic hazard in the region, as well as to alert systems for earth quakes and tsunamis.

The KM3NeT instruments will allow monitoring the deep sea biodiversity on all scales, from micro-organisms up to the largest marine mammals, which is of utmost societal importance. Most of deep-sea living organisms are bioluminescent, either continuously or in specific circumstances, with light emission patterns dependent on the species. Bioluminescence can thus be used to monitor biological activity, and particularly planktonic diversity in deep waters. The biggest organisms like marine mammals can be studied from the distinctive sounds they emit, using hydrophones placed in the water column. Coupling hydrophone tracking results with the hydrodynamic and biochemical data collected at the same site will allow studying the behaviour, physiology, and ecology of marine mammals, and the anthropogenic impact on these communities.

Cooperation with the Earth and Sea Science community has been established over the last decade in the ANTARES and NEMO projects and has led to a number of publications. It is a declared objective of KM3NeT 2.0 to intensify and extend this cooperation. The KM3NeT sites are nodes of the European Multidisciplinary Seafloor and water column Observatory (EMSO).

The KM3NeT-France infrastructure foresees the incorporation of a number of sensors for ESS studies:

- **Photosensors:** The PMTs are sensitive to single photons and thus ideal sensors for bioluminescence studies throughout the instrumented volume.

- **Hydrophones:** For bioacoustic studies, each optical modules incorporates an acoustic piezo sensor and the anchor of each detection string hosts a high sensitivity hydrophone.
- **Instrumentation Unit:** This line has sensors intended to provide information needed for the neutrino studies, these include, pressure, temperature, velocity of sound, salinity, sea current velocity. The Instrumentation Unit will be connected at the periphery of the array at the end of one of the daisy-chains.
- **Albatross line:** The Albatross line, developed by MIO-INSU, hosts various oceanographic sensors (ADCP, CTD, O_2, ...) to instrument the full water column. It will transfer data via an acoustic modem to a receiver connected to the first node.
- **Secondary Junction Box:** once ANTARES is decommissioned, its 'so-called' Secondary Junction Box (SJB) will be transferred to the Junction Box 2 of ORCA.
- **Seismograph:** a seismograph will be connected to the SJB. The seismo is provided by Geo-science Azur.
- **Radioactivity monitor:** a Germanium gamma detector will be connected to the SJB.
- **Biocamera:** two ultrafast, single photon biocameras will be operated in stereo, connected to the SJB. The cameras have been developed by Remi Barbier (IPNL);
- **Wally crawler:** this benthic robot can move along the seafloor under remote control. It incorporates a camera, lights and a plethora of sensors (temperature, O_2, CO_2, CH_4, benthic chamber) that can probe the seafloor sediments. It will be connected to the SJB.

5 KM3NeT/ORCA deep sea and onshore Infrastructures

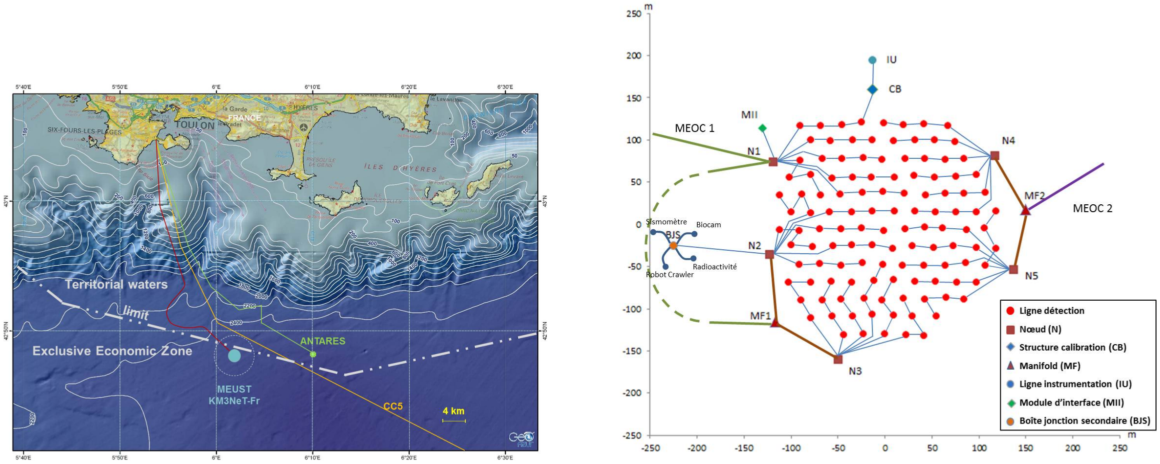


Figure 9: *(Left) Map of the Mediterranean Sea south of Toulon, France. The location of the KM3NeT-France and ANTARES installations are indicated. (Right) Layout of the full ORCA array.*

The KM3NeT-France infrastructure is located at 42° 48' N 06° 02' E at a depth of 2450 m, about 40 km offshore from Toulon, France (see Fig.9, left). The site is outside of the French territorial waters and about 10 km west of the site of the existing ANTARES telescope.

Fig.9 right illustrates the layout of the full ORCA array; a single KM3NeT building block of 115 strings with a horizontal spacing between strings of about 20m and a vertical spacing between optical modules of 9m.. The power/data are transferred to/from the infrastructure via two main electro-optic cables (MEOC) each

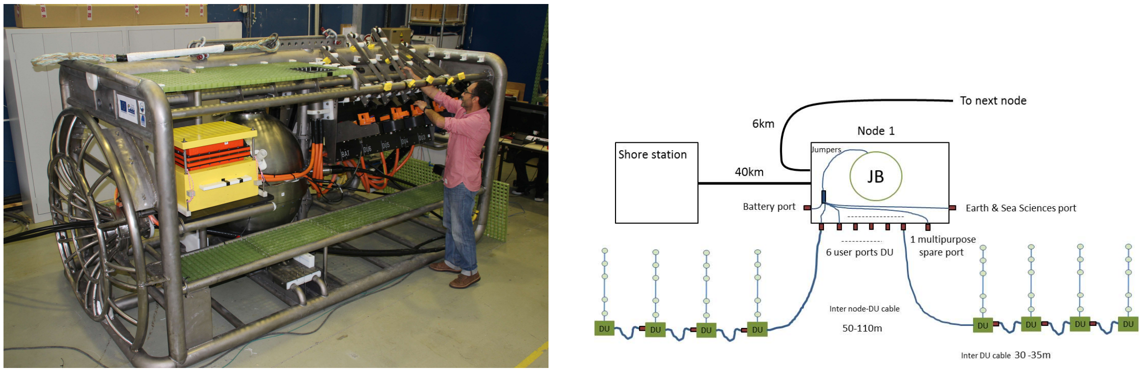


Figure 10: *(Left) Photograph of a KM3NeT-France Junction Box. (Right) Schematic of the connections to the Junction Box .*

comprising 36/48 optical fibres and a single power conductor (the return is via the sea). Once ANTARES is decommissioned, its main electro-optic cable will be reused as the second MEOC of ORCA.

The strings are connected to five Junction Boxes (JB) (Fig.10, left), located on the periphery of the array. Each JB has eight connectors, each of which can power four strings daisy chained in series (Fig.10, right). One daisy chain includes an Instrumentation Unit, which incorporate a laser beacon and acoustic emitter. In the baseline design, six connectors on the JB are dedicated for the neutrino array and one is dedicated for Earth and Sea science sensors and one is spare. The underwater connection of the strings to the JB is via interlink cables running along the seabed. The Apache light-class ROV of COMEX is currently used for the various deep sea manipulations and connections.

Due to the short distance (42 km) from shore to the ORCA site, it is feasible to transfer power in Alternating Current (as used in ANTARES). The power station, dimensioned for a single building block (92 KVA) is located at the shore end of the main cable near the 'Les Sablettes' beach, La Seyne-sur-Mer. Power is transferred at 3500 VAC. The offshore JBs use a step-down AC transformer to convert this to 400 VAC for transmission along the interlink cables to the strings. The control room is located at the Institute Michel Pacha, La Seyne-sur-Mer, and hosts the data acquisition electronics and a commodity PC farm used for data filtering. In 2019 the control room will be transferred to a new CNRS building (MEUST) close to the Ifremer campus at Bregaillon, La Seyne-sur-Mer.

The KM3NeT-Italy seafloor infrastructure, although similar to that of ORCA has some important differences; two building blocks with a sparser configuration (90 m string spacing and 36 m vertical spacing), DC power transmission and no-daisy chain. The adoption of DC power transmission is necessary due to the further distance from shore (80 km). The availability of a work-class ROV makes possible the deployment of long interlink cables.

On the ORCA site, in December, 2014, the first MEOC was successfully deployed by Orange Marine. The first JB was connected in Spring 2015. After a few days of operation a non-fatal fault developed in one of the SEACON HV/fibre-optic penetrators. Then, after a month of nominal operation, an electrical short developed in the MEOC cable close to the JB. In June 2015, the JB was recovered in order to replace the faulty penetrator. On 29 September 2016, the JB with new penetrators was redeployed and at the same time the MEOC was repaired. After a week of nominal operation another electrical short developed about halfway along the MEOC. On 8 Nov 2016, a repair operation on the MEOC was successfully performed. A few days after this repair yet another short in the MEOC developed, this time at a distance of about 38 km from shore. A hopefully last repair cable operation is planned in early 2017. The difficulties experienced by Orange Marine with the MEOC deployment most likely have two origins; damage of the cable due to movement on the seafloor during the JB deployment and/or entanglement with fishing lines. For the next cable repair operation preventative actions will be taken to avoid both these possibilities.

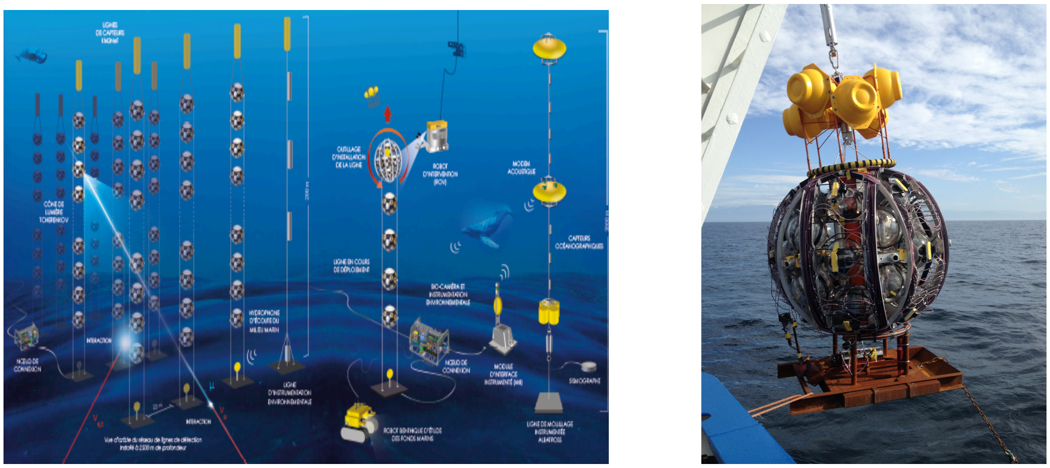


Figure 11: *(Left) Artist impression of the KM3NeT/ORCA infrastructure. (Right) The spherical frame upon which the detection strings are furled for deployment.*

6 Detector Technology

To maximise the sensitivity the detector should be capable to distinguish track-like topologies (ν_μ-CC) from shower-like topologies (ν_e-CC, ν_τ-CC and neutral current), provide adequate energy and angular resolutions, should be capable to reject the background from downgoing atmospheric muons and large enough to acquire sufficient statistics.

The ORCA array (Fig.11 (Left)) comprises 115 detection strings and each string comprises 18 optical modules (OMs). The vertical spacing is 9 m and the strings are located about 20 m from each other on the seafloor. The total instrumented volume is about 6 Mton.

The OMs [27] are distributed in space along flexible strings, one end of which is anchored to the sea floor and the other end is held close to vertical by a submerged buoy. The string comprises two thin parallel ropes that hold the optical modules in place. Attached to the ropes is the vertical electro-optical cable (VEOC), an oil filled plastic tube which contain the electrical wires and optical fibres used for the power and data transmission. The strings are initially coiled around a spherical frame (Fig.11 (Right)) and deployed by a surface vessel. A remotely operated submersible is used to deploy and connect interlink cables from the string base container to a Junction Box. An acoustic signal from the boat triggers autonomous unfurling of the string from the sea bottom.

An OM (Fig.12) is a pressure resistant, 17-inch glass sphere containing a total of 31 3-inch PMTs and their associated electronics. The design offers a number of improvements compared to previous designs based on a single large area PMT, most notably: larger photocathode area, digital photon counting, directional information, wider field of view and reduced ageing effects. A position calibration device (acoustic piezo sensor) and a time calibration device (nano-beacon) are also housed inside each sphere. The read-out electronics features low power consumption (7 W), high-bandwidth (Gb/s) data transmission using dense wavelength division multiplexing (DWDM), time over threshold measurement of each PMT signal and precision time synchronisation via a White Rabbit protocol.

Simulation studies indicate that the ORCA array provides an effective detector mass of about 6 Mton for ν_e charged current interactions; being fully efficient above 10 GeV and 50% efficient at 4 GeV. It will provide data samples of about 50,000 reconstructed upgoing neutrinos per year for energies below 100 GeV. Reconstruction algorithms applied to ν_μ-CC and ν_e-CC events yield a Gaussian energy resolution of better than 30% in the range 5-10 GeV. The median angular resolutions on the zenith angle are better than 8° above 5 GeV for both the muon and electron channels; being limited by the kinematic smearing. Discrimination between track and shower topologies is 90% (70%) at 10 GeV for ν_e-CC (ν_μ-CC). A downgoing muon contamination at the few % level is achieved, while retaining an efficiency of about 80% for the signal.

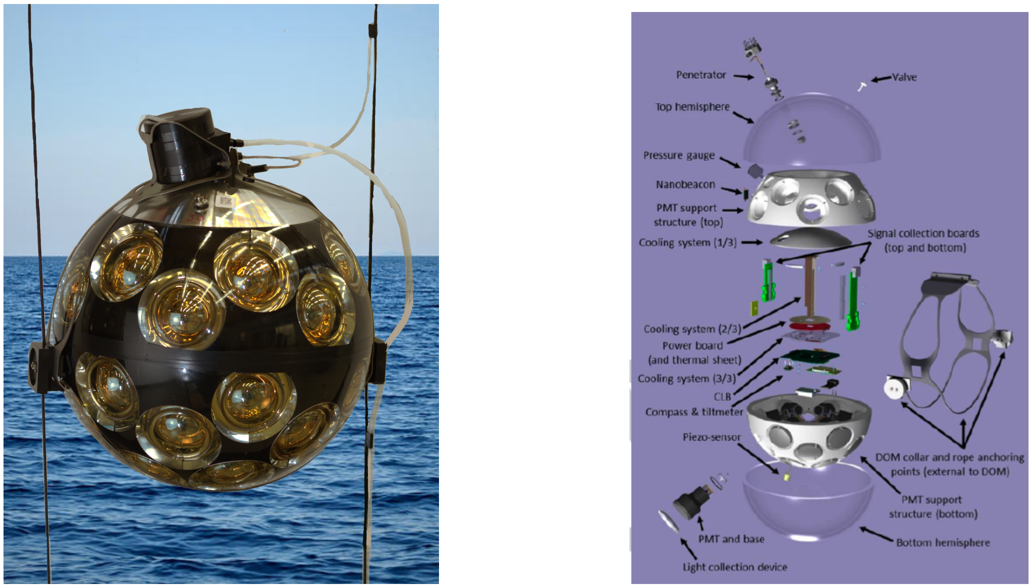


Figure 12: *(Left) photo of a KM3NeT optical module and breakout box of the VEOC. (Right) exploded view of an optical module interior.*

6.1 Prototype results

The development plan of KM3NeT included a successful test of a single KM3NeT OM hosted on an ANTARES line in 2013 [28] and the operation of a short prototype string with three OMs in 2014 [29]. In early 2016, three full-length ARCA style strings (vertical spacing 36 m) have been deployed at the KM3NeT-Italy site in Capo Passero. Two of these strings continue to provide high quality data, while the third (ARCA-DU3) developed a power issue just after deployment. In August 2016, the ARCA-DU3 was recovered to understand the origin of its failure. The post-mortem showed that one of the breakout boxes of the VEOC had developed a small leak, resulting in an electrical short. As a consequence of this, the design of the VEOC/breakout box interface has been improved and the quality control of the VEOC production at the external supplier reinforced.

A shallow water test of the deployment of a 'mechanical' ORCA-style string (vertical spacing 9 m) was successfully performed in 2016. The first ORCA string is planned to be connected in Spring 2017, once the MEOC has been repaired. It will make use of the improved VEOC design.

Fig.13 (Left) shows the observed in-situ counting rate versus the multiplicity of PMTs of a single OM having a hit within a 20 ns time window. At low multiplicities, the counting rate is dominated by light from ^{40}K decays from the salt in the seawater. The ^{40}K coincidences provide a powerful method to calibrate the time offsets of the PMTs within an OM and extract the absolute PMT efficiencies, as well as continuously track its dependence as a function of time. At high PMT multiplicities only the Cherenkov light from downgoing muons remain. Fig.13 (Right), shows the rate of 10-fold coincidences as a function of the height of the OM on the string; the expected muon attenuation as the depth increases is clearly visible.

7 International Collaboration

KM3NeT federates and unifies the various smaller European efforts in the field of Neutrino Astronomy. The process of convergence was supported by an EU funded Design Study (2008–2009) and Preparatory Phase (2008–2012). In 2013 the KM3NeT consortium made the transition to a collaboration with an elected management. The funding agencies involved have installed the Resources Review Board (RRB) which oversees the project. The RRB is advised by an international Scientific and Technical Advisory Committee (STAC) with as Michel Spiro the current chairperson. A project organisation is setup with the objective to

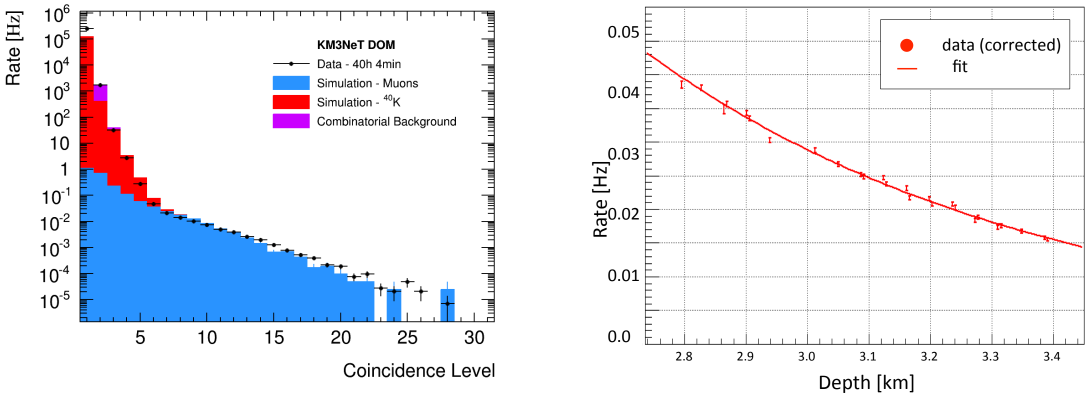


Figure 13: *(Left) The rate of events as a function of the coincidence level (number of PMTs with signal in a 20 ns time window). Black dots correspond to data while coloured histograms represent simulations (muons in blue, ^{40}K in red and accidental coincidences in purple). (Right) The rate of 10-fold coincidences as a function of the OM depth for two strings.*

implement the first phase (Phase-1) of the KM3NeT Research Infrastructure. To this end, a Memorandum of Understanding (MoU), covering the Phase-1 budget of about 31 MEuro, has been signed by the members of the RRB. The purpose of this MoU is to define the programme of work to be carried out for this phase and the distribution of charges and responsibilities among the Parties and Institutes for the execution of this work. The MoU sets out i) the organisational, managerial and financial guidelines to be followed by the Collaboration, ii) the external scientific and technical review processes and iii) the user access policy.

At present, the Collaboration consists of more than 240 persons from 52 institutes from 12 countries (Cyprus, France, Germany, Greece, Ireland, Italy, Morocco, Netherlands, Romania, Russia, Spain, Poland, United Kingdom) plus Canada if their funding request is successful. The first phase has already started and comprises the final prototyping and preproduction, engineering, construction, calibration, transportation, assembly, installation and commissioning of the elements which form the basis of the KM3NeT neutrino detector and the seafloor and shore station infrastructures as well as the operation of the installed neutrino detectors. The installation is proceeding in two places, off-shore Toulon, France and off-shore Capo Passero, Italy. A third suitable site is available off-shore Pylos, Greece.

The Collaboration will offer open access for external users to the KM3NeT Research Infrastructure. The KM3NeT Research Infrastructure will also provide user ports for continuous Earth and Sea science measurements in the deep-sea environment. The needs for the Earth and Sea sciences are partly incorporated in the present KM3NeT MoU and other needs will be detailed in designated MoUs between KM3NeT and individual Earth and Sea science groups or more generally with EMSO.

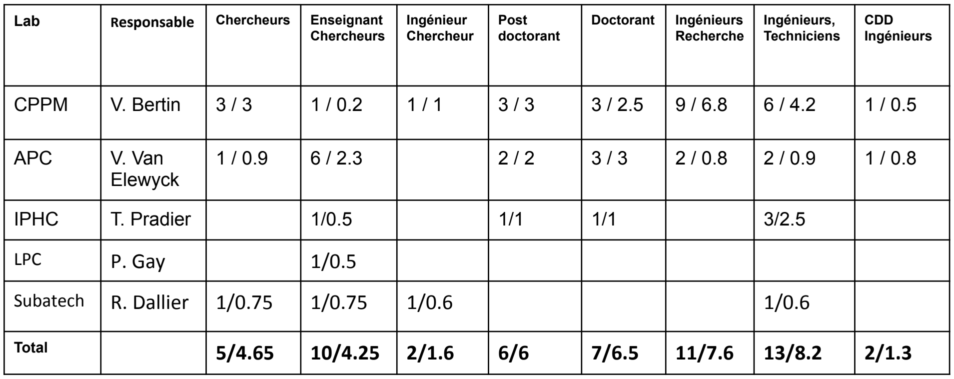
The Phase-1 MoU is a first step towards the intended establishment of a European Research Infrastructure Consortium (ERIC). The Collaboration has agreed to host the KM3NeT ERIC in the Netherlands.

Following a sequence of joint meetings between ANTARES (Mediterranean Sea), IceCube (South Pole), Lake Baikal (Russia) and KM3NeT (Mediterranean Sea), a Memorandum of Understanding for a Global Neutrino Network (GNN) has been signed on 15 October 2013 by the representatives of each project. This step formalised the active collaboration between these projects. Once infrastructures of similar scale are operational on the three continents, the stated aim of the GNN is a worldwide Global Neutrino Observatory.

8 French Contributions

Fig.14 summarise the anticipated manpower of the currently involved IN2P3 laboratories (APC, CPPM, IPHC, LPC, Subatech) for 2017.

The APC group is responsible for the Calibration Unit. It is hoped they will be able to take responsibility for the pre-integration of the base containers for the ORCA detection strings. APC is in the process of



Lab	Responsable	Chercheurs	Enseignant Chercheurs	Ingénieur Chercheur	Post doctorant	Doctorant	Ingénieurs Recherche	Ingénieurs, Techniciens	CDD Ingénieurs
CPPM	V. Bertin	3 / 3	1 / 0.2	1 / 1	3 / 3	3 / 2.5	9 / 6.8	6 / 4.2	1 / 0.5
APC	V. Van Elewyck	1 / 0.9	6 / 2.3		2 / 2	3 / 3	2 / 0.8	2 / 0.9	1 / 0.8
IPHC	T. Pradier		1/0.5		1/1	1/1		3/2.5	
LPC	P. Gay		1/0.5						
Subatech	R. Dallier	1/0.75	1/0.75	1/0.6				1/0.6	
Total		**5/4.65**	**10/4.25**	**2/1.6**	**6/6**	**7/6.5**	**11/7.6**	**13/8.2**	**2/1.3**

Figure 14: *Anticipated manpower (Number, FTE) for KM3NeT and ANTARES in 2017.*

characterising a complete OM using muon track passing through a large water filled tank. They also have facilities to characterise single PMTs. The permanent researchers are V. Van Elewyck (group leader), A. Kouchner (ORCA Physics Coordinator), B. Baret, A. Creusot, C. Donzaud, P. Gay (associate, LPC), C. Lachaud, S. Loucatos, B. Vallage (associate, CEA).

The CPPM group is responsible for the ORCA seafloor infrastructure, the onshore string calibration, the string deployment and connection, the Instrumentation Unit, the Shore Station and the day-to-day detector operation. The permanent researchers are Vincent Bertin (group leader), Jurgen Brunner (ORCA Detector Operation Manager). Jose Busto, Paschal Coyle (initiated the ORCA concept [30], KM3NeT-Fr scientific coordinator, outgoing KM3NeT Deputy Spokesperson (2013-2016), incoming Physics and Software Coordinator), Damien Dornic (coordinator of the KM3NeT Multi-Messenger Astronomy group) and Patrick Lamare (ORCA Site Representative for KM3NeT and the Technical Coordinator of KM3NeT-Fr).

The IPHC group with GRPHE, is in the process of setting up a OM integration site. This may later evolve to include the DOM+VEOC integration. IPHC is investigating the potential of incorporating wavelength shifter in the OM to increase the number of detected photons. The permanent researchers are Thierry Pradier (group leader), Arnaud Albert (GRPHE), Doriane Drouhin (GRPHE).

The request of the Subatech group to join the KM3NeT Collaboration was endorsed by the laboratory Scientific Council in December 2016. They plan to investigate anti-biofouling techniques in collaboration with Ifremer-Brest. On the longer term they will also become an OM integration site. The permanent researchers involved are Richard Dallier (group leader) and Lilian Martin.

On top of hardware contributions the IN2P3 institutes play an important role on software, simulation and data analysis.

The Lyon computing centre is the principle data repository and analysis centre for all of KM3NeT.

For the ESS activities, scientists from MIO-Marseille (AMU/INSU), Toulon University, DT/INSU-La Seyne-sur-Mer, Geoscience-Azur (INSU), IPGP (INSU) and Ifremer are involved through the framework of EMSO-France.

9 Planning

It is expected that the issues with the ORCA deep sea infrastructure construction will be resolved early 2017. A total of 155 OMs have been already been assembled by the production sites at Nikhef, Naples, Catania and Erlangen. It has been decided that the first ORCA string will adopt an improved VEOC design, that benefits from the return of experience of the ARCA-DU3 post-mortem. In this case, it could be deployed in April 2017. Once the production readiness review are completed, the rest of the six Phase-1 strings would then follow by the end of 2017.

For Phase-2, the aim is to construct the 115 strings of ORCA in about three years. If not limited by funds, this implies the deployment of about 40 strings per year. As the deployment surface vessel can deploy four strings per cruise, a rhythm of a single cruise per month for 10 months a year is required. The Phase-1 experience shows that a single OM integration site can produce 4-5 OMs per week once in steady production, thus 4-5 DOM integration sites would be needed to produce DOMs at the required rate. This rate could be satisfied with the OM integration sites at Strasbourg/Nantes, Nikhef, Morocco, Erlangen and Canada. The base containers, VEOCs and JBs can be constructed at a matching rate. The ORCA detector could therefore be completed by the end of 2020.

The biggest challenge will be to ensure a consistent and high level of quality control across all the OM integration sites. Logistics will also be an important issue, in order to ensure that the integration sites are not halted due to lack of materials.

Note that physics studies would already be possible as the array is being constructed, thus reducing the overall time needed to obtain a specified precision.

10 Cost and Funding

The investment budget for the construction of the first phase (Phase-1) of the KM3NeT research infrastructure, which is fully funded, amounts to about 31 MEuro. This will allow during 2015-2017, 31 (7 ORCA, 24 ARCA) strings, equipped with 558 optical modules, to be assembled and deployed at the French and Italian sites.

The completion of the full ORCA array requires an additional 40 MEuros above the Phase-1 investment. The cost estimates are based on the actual prices obtained for Phase-1 and thus can be considered accurate. They are consistent with the estimations stated in the KM3NeT Technical Design Report published in 2011 and represent a factor of four cost reduction compared to that previously achieved for the ANTARES detector. The cost of a single KM3NeT string is about 230 kEuro, an additional 90 kEuro is needed for the interlink cable, the string deployment and the ROV connection.

The cost for operation and decommissioning of the ORCA infrastructure have been evaluated and amount to about 0.7 MEuro per year and 1 MEuro, respectively.

In France, the project is a national IR and has strong regional support from the Pole Mer Mediterranee. The funding for Phase-1 (MEUST, 2011-2015) amounted to 7 MEuro (CNRS: 3.5 MEuro/FEDER: 3.5 MEuro). The funding for Phase-2 (NUMerEnv, 2016-2020) amounts to 8.35 MEuro (CNRS: 4.95 MEuro, CPER: 2.0 MEuro, DRRT-PACA: 0.5 MEuro, FEDER: 0.9 MEuro). In the framework of PIA3, support for investment to consolidate Research Infrastructures on the French roadmap is envisaged.

At the international level, Canada have made a request to the CFI for 225 OMs (13 strings) for ORCA, this is about 2.2 MEuro, with the anticipation that additional requests will be possible. The Netherlands will be making a funding request of 13 MEuro for 2018, of which half would be dedicated to ORCA. Germany have made a request to the DFG of 1.2 MEuro for ORCA strings. Italy will apply for significant regional funds (70 MEuro) mainly for ARCA, but most likely a small fraction will become available for ORCA. Discussion with other groups in the UK, Korea, Australia, etc. are ongoing.

In the framework of the H2020 Infra-Dev program, restricted to ESFRI selected projects, the European Commission approved the KM3NeT proposal to prepare the establishment of a legal entity for the KM3NeT research infrastructure. The grant will also make it possible to prepare services covering multi-messenger physics, communication and training activities, open data access policies and implementation, as well as environmental impact studies. The allocated budget is 3.8 MEuro.

The French groups are also supported by an ANR grant (DAEMONS) of 450 KEuro.

11 Transition ANTARES to KM3NeT

The ANTARES Collaboration is operating the first neutrino telescope (NT) ever built in the deep sea [31]. The detector was gradually deployed between 2006 and 2008 and is, as of today, the largest NT in the Northern Hemisphere. The reliable operation of ANTARES for more than ten years has convincingly demonstrated the feasibility of constructing complex instrumentation in the unforgiving deep sea environment. The

KM3NeT design has benefited tremendously from the experience gained with ANTARES. The decommissioning of ANTARES is foreseen by the end of 2017, at which point KM3NeT-ARCA will supersede its sensitivity. No operating funds have been requesting for ANTARES in 2017.

Most of the ANTARES collaborators are also members of the KM3NeT Collaboration. The simulation and event reconstruction software of ANTARES has formed the basis of much of the KM3NeT software. Since 2013, the ANTARES and KM3NeT Collaboration have held joint collaboration meetings (3 times a year), this has facilitated the scientific progress and the exchange of know-how and reduces the travel time and expenses.

The French groups initiated ANTARES and were/are the main driving-force of the experiment. Some have major responsibilities, for example, Antoine Kouchner is the ANTARES Spokesperson and Jurgen Brunner the ANTARES Technical Coordinator. All the researchers are cognisant that ANTARES data taking comes to an end soon and that a gradual transition fully to KM3NeT activities is desirable. Nevertheless, it is expected that two more years of data analysis will be needed to finalise the ANTARES analyses with the full dataset and latest event reconstruction.

12 Conclusions

Capitalising on the twenty years of experience acquired with the pioneering ANTARES neutrino telescope and many years of R&D effort, the KM3NeT Collaboration has developed a cost effective and performant technology to instrument large volumes of the deep sea. The technical implementation have been successfully demonstrated and once the production readiness reviews are completed, the large scale production of detection strings and the corresponding extension of the sea floor infrastructures will commence. The infrastructure will offer innovative and synergetic opportunities for Earth and Sea Science studies. Using this technology two major physics questions will be addressed, namely the astrophysical origin of cosmic rays and the fundamental properties of the neutrino. In particular, the ORCA array, located in France, will allow the IN2P3 to play a leading role at the forefront of neutrino physics over the next decade.

References

[1] KM3NeT Collaboration, "KM3NeT 2.0 Letter of Intent for ARCA and ORCA", J. Phys. G: Nucl. Part. Phys. 43 (2016) 084001.

[2] M. G. Aartsen et al., Phys. Rev. Lett. 111 (2013)021103.

[3] M. G. Aartsen et al., arXiv:1607.08006.

[4] M.C. Gonzalez-Garcia et al. Astropart.Phys. 57-58 (2014) 39-48.

[5] D. Gaggero et al., JCAP 12 (2015) 056.

[6] A. Neronov & D.V. Semikoz, Phys. Rev. D 93 (2016) 123002.

[7] P. Meszaros and M. J. Rees, "Relativistic fireballs and their impact on external matter - Models for cosmological gamma-ray bursts", Astrophys. J. 405, 278 (1993).

[8] E. Waxman and J. Bahcall, "High energy neutrinos from cosmological gamma-ray burst fireballs", Phys. Rev. Lett. 78, 2292 (1997), [arXiv:astro-ph/9701231].

[9] M. G. Aartsen et al., IceCube Coll., "Search for prompt neutrino emission from Gamma-Ray Bursts with IceCube. Astrophys", J. 805, L 5 (2015), [arXiv:1412.6510 [astro-ph.HE]].

[10] S. Adrin-Martnez et al., ANTARES Coll., "Search for muon neutrinos from gamma-ray bursts with the ANTARES neutrino telescope using 2008 to 2011 data", Astron. Astrophys. 559, A 9 (2013), [arXiv:1307.0304 [astro-ph.HE]].

[11] S. Adrin-Martnez et al., ANTARES Coll., "Optical and X-ray early follow-up of ANTARES neutrino alerts", 2015. arXiv:1508.01180 [astro-ph.HE].

[12] S. Adrin-Martnez et al., ANTARES Coll., "First results on dark matter annihilation in the Sun using the ANTARES neutrino telescope", JCAP 1311, 032 (2013), [arXiv:1302.6516 [astro-ph.HE]].

[13] M. G. Aartsen et al., IceCube Coll., "Search for dark matter annihilations in the Sun with the 79-string IceCube detector", Phys. Rev. Lett. 110, 131302 (2013), [arXiv:1212.4097 [astro-ph.HE]].

[14] S. Adrin-Martnez et al., ANTARES Coll., "Search of dark matter annihilation in the Galactic Centre using the ANTARES neutrino telescope", JCAP 10, 068 (2015), [arXiv:1505.04866 [astro-ph.HE]].

[15] M. G. Aartsen et al., IceCube Coll., "Search for dark matter annihilation in the Galactic Center with IceCube-79", Eur. Phys. J. C 75, 492 (2015), [arXiv:1505.07259 [astro-ph.HE]].

[16] S. Adrin-Martnez et al., ANTARES Coll., "Search for relativistic magnetic monopoles with the ANTARES neutrino telescope", Astropart. Phys. 35, 634 (2012), [arXiv:1110.2656 [astro-ph.HE]].

[17] M. G. Aartsen et al., IceCube Coll., "Searches for Relativistic Magnetic Monopoles in IceCube", 2015. arXiv:1511.01350 [astro-ph].

[18] Akhmedov E K, Razzaque S and Smirnov Yu, "Mass hierarchy, 2-3 mixing and CP-phase with huge atmospheric neutrino detectors", JHEP 02 (2013) 082. Erratum: JHEP07,026(2013).

[19] IceCube PINGU Collaboration, Aartsen M G, et al., "Letter of Intent: the Precision IceCube Next Generation Upgrade (PINGU)", arXiv: 1401.2046.

[20] M. Blennow and T. Schwetz, "Determination of the neutrino mass ordering by combining PINGU and Daya Bay II", JHEP 09, 089 (2013), [arXiv:1306.3988 [hep-ph]].

[21] Coelho J A B, "Probing new physics with atmospheric neutrinos at KM3NeT-ORCA", Neutrino 2016.

[22] Bourret S, Coelho J A B and Van Elewyck V, "Neutrino Oscillation Tomography of the Earth with KM3NeT-ORCA", Neutrino 2016.

[23] S. Razzaque and A. Yu. Smirnov, "Super-PINGU for measurement of the leptonic CP-phase with atmospheric neutrinos", JHEP 05, 139 (2015), [arXiv:1406.1407 [hep-ph]].

[24] J. Brunner, "Counting electrons to probe the neutrino mass hierarchy", 2013. arXiv:1304.6230 [hep-ex].

[25] J. Brunner, "Measurement of neutrino oscillations with neutrino telescopes", Adv. High Energy Phys. 2013, 782538 (2013).

[26] S. Bourret, "Sensitivity to the neutrino mass hierarchy and discovery of CP violation with the Protvino-to-ORCA proposal", 2015. M. Sc. Thesis, ETH Zrich (Switzerland) and Ecole Polytechnique (France).

[27] R. Bruijn, "The KM3NeT DOM", Neutrino 2016.

[28] KM3NeT Collaboration, Adrian-Martinez S, et al., "Deep sea tests of a prototype of the KM3NeT digital optical module", Eur. Phys. J. C (2014) 74: 3056.

[29] KM3NeT Collaboration, Adrian-Martinez S, et al., "The prototype detection unit of the KM3NeT detector", Eur. Phys. J. C (2016) 76: 54.

[30] P. Coyle, contribution to the European Strategy Preparatory Group Symposium, September 2012 Krakow, Poland.

[31] ANTARES Collaboration, Ageron M et al.,"ANTARES: the first undersea neutrino telescope", Nucl. Instr. and Meth. A (2011), doi:10.1016/j.nima.2011.06.103.

Report on the Status of ANTARES for the IN2P3 Scientific Council

Antoine Kouchner (APC) on behalf of the ANTARES groups of
APC, CPPM, IPHC, LPC

January 4, 2017

1 Introduction

The ANTARES Collaboration is operating the first neutrino telescope (NT) ever built in the deep sea. The detector was gradually deployed between 2006 and 2008 and is, as of today, the largest NT in the Northern Hemisphere. The detector is still working in good conditions but its decommission is foreseen by the end of 2017 when KM3NeT-ARCA will have acquired superseding sensitivity.

In light of the recent results from the IceCube Collaboration which report several indications of a cosmic neutrino component, yet without a clear identification of the sources, ANTARES makes a valuable contribution thanks to its excellent angular resolution in both the muon channel and the cascade channel (induced by all neutrino flavours). While the ANTARES sensitivity to an all-sky diffuse flux just touches the IceCube measured flux (section 3.1), it is sufficient to constrain the origin of the IceCube excess from regions extended up to 0.2 sr in the Southern sky (section 3.2). Assuming various spectral indexes for the energy spectrum of neutrino emitters, the Southern sky and in particular central regions of our Galaxy, are studied searching for extended regions of emission as well as for point-like objects (section 3.3). By adopting a multi-messenger approach, based on time and/or space coincidences with other cosmic probes, the sensitivity can be considerably augmented (section 3.4). Finally ANTARES provides various constraints on Dark Mater through indirect searches for WIMP annihilation, with limits that are the most restrictive in some WIMP mass intervals (section 3.5).

2 Detector design

The ANTARES (Astronomy with a Neutrino Telescope and Abyss environmental RESearch) Collaboration started in March 2006 the deployment of a first-generation detector ~ 40 km off La-Seyne-sur-Mer (French Riviera), at a depth of 2475 m. The construction phase ended in May 2008. The full detector comprises 885 photomultipliers distributed in a three dimensional array on twelve 450 m high vertical detection lines (Fig.1). 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 OMs 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 single 10-inch PMT protected in a 17 inch pressure resistant glass sphere. The lines are connected to a junction box (in constant reliable operation since 2001), 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. 1), which provides measurement of environmental parameters such as sea current, temperature and also hosts a part of the AMADEUS system, a test bed for the acoustic detection of ultra-high energy neutrinos. 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. ANTARES is therefore a multi-disciplinary observatory providing results in several scientific domains including Sea Science.

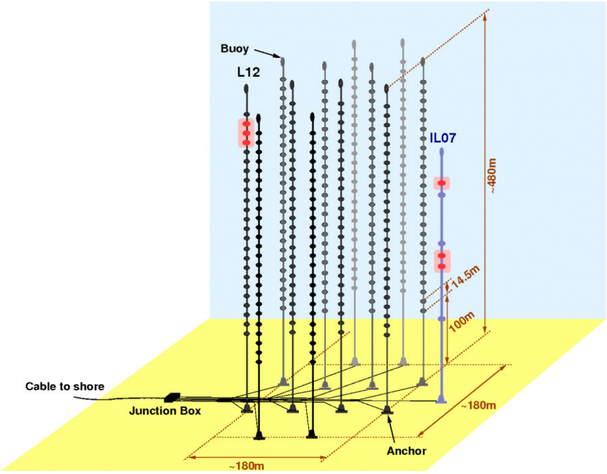


Figure 1: *The ANTARES detector configuration.*

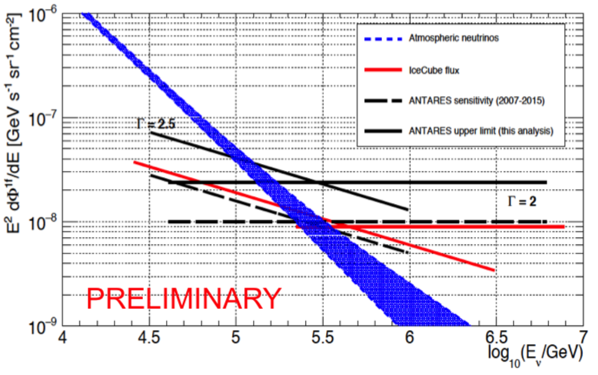


Figure 2: *Upper limits (at 90% C.L.) on the diffuse neutrino fluxes (black thick lines) for 2 spectral indices* ($\Gamma = 2; 2.5$) *for the combination of the track and shower analyses, compared to the sensitivity achievable with the entire ANTARES 2007-2015 data set (dashed lines) and the IceCube measured flux (red).*

3 Physics Studies

A primary goal of deep-sea NT is the search for astrophysical neutrinos in the TeV-PeV range. This covers generic searches for any diffuse cosmic neutrino flux as well as more specific searches for astrophysical sources such as Active Galactic Nuclei and Gamma-Ray Bursts or close-by Galactic sources.

The IceCube Collaboration (operating a detector ∼50 times larger than ANTARES) has recently discovered a cosmic neutrino flux component with energy up to the PeV range, using selection criteria in a restricted fiducial volume resulting in the so-called High Energy Starting Events (HESE) [1]. The largest fraction of HESE are cascades for which the angular determination is poor (10-20°). The HESE flux (with best fit spectral index $\Gamma \sim 2.5$) is compatible with a diffuse origin and flavour ratios $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$, as expected from charged meson decays in CR accelerators after oscillation on their way to the Earth. ANTARES, thanks to its location in the Northern Hemisphere and its excellent pointing capabilities is well suited to constrain potential galactic components. For instance, the hypothesis of a point source producing more than 6 HESE events in a 20° region around the Galactic Center has promptly been excluded by ANTARES.

Following this line, the subsequent text presents the current constraints from ANTARES in the assumptions of large scale sources to smaller scale sources.

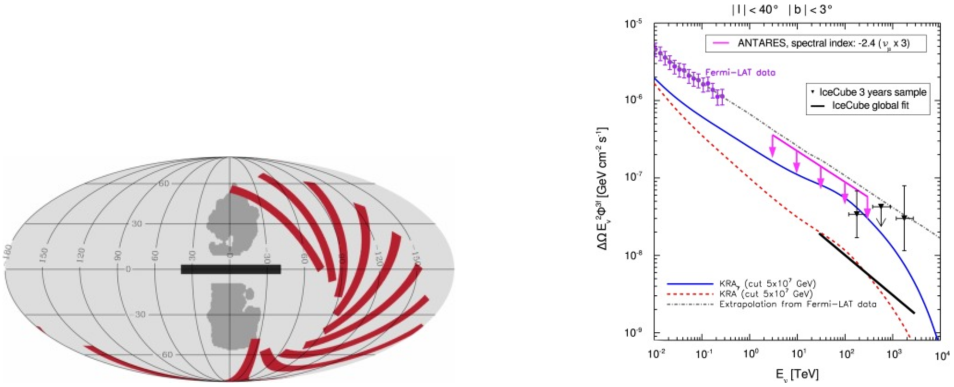


Figure 3: *Left: Illustration of the "off-zone" (in red) – "on-zone" (in black) search method for the Galactic Ridge. The area in grey indicate the Fermi Bubbles. Overlap with those are avoided.Right:* antares *90% C.L upper limit (magenta) for the search for an excess of events from the central Galactic region, compared to expectations from [5].*

3.1 Diffuse Fluxes

The current results from ANTARES are based on two independent analyses, searching for tracks and cascades separately. In the latter case, the good energy resolution achieved allows rejecting atmospheric neutrinos with a cut on the estimated energy, which is optimized to obtain the best upper limit. After the unblinding of data collected from 2007 to 2013, 7 events are observed, while 5 ± 2 are expected from atmospheric backgrounds and ~ 1.5 events from the cosmic signal observed by IceCube depending on the best fit spectral index. In the track channel, reconstruction quality parameters, coupled to an energy estimator based on the number of selected hits, are used to reduce the contamination from atmospheric muons below 0.5%. Data from two more years (2014 and 2015) than in the cascade channel were analysed yielding 19 observed events for an expectation of 13^{+3}_{-4} from the background and ~ 3 from the IceCube flux (see Fig. 2). As can be seen on the figure, the combined sensitivity is very close to IceCube signal. If no excess were to be observed in the final sample, ANTARES could in fact exclude the iceCube with 90% C.L. at least for soft spectral indices. But the small excesses (not significant by their own) observed so far are rather compatible with the IceCube signal. In any case, a final analysis is expected once the detector is decommissioned. Stronger constraints can be obtained for smaller scale searches.

3.2 Reducing the Search Window

Taking advantage of the mild latitude of the Mediterranean Sea, reducing the search window allows developing search methods which rely much less on the Monte Carlo simulation than in the aforementioned study. This is achieved exploiting *off-zones* which are then compared to *on-zones* of the same size and shape, but offset in right ascension. Such an approach was followed for the Galactic Ridge as illustrated in Fig. 3 (left). The search concentrated on a region of galactic longitude $|l| < 40°$ and latitude $|b| < 3°$. No excess could be found in the data sample from May 2007 to Dec 2013 using tracks only, excluding that more than 2 HESE events of the IceCube 3 yr sample could originate from this region for spectral indices softer than ~ 2.3. The resulting limits are shown in Fig. 3 (right), excluding the simplistic hypothesis of a one-to-one relation between γ-ray (Fermi) and neutrinos from the inner galactic plane. Fainter predictions such as Ref [5] (also shown in blue on Fig. 3 [right] and referred to as the $\mathrm{KRA_{fl}}$ flux) are tackled with more sophistical approaches. Very recently unblinding of a larger data set 2007-2015 was granted to a likelihood based search incorporating both tracks and showers. No significant excess could be observed yielding an upper limit at $1.2 \times$ the $\mathrm{KRA_{fl}}$ flux. The ANTARES and IceCube sensitivities being of similar order, a combined analysis is being planned to further probe this model.

Another *on-off* search was performed, with 3 off-zones, to search for an excess from the Fermi-Bubbles (indicated in Fig. 3). Only the track channel was investigated but with data up to 2015. The study revealed

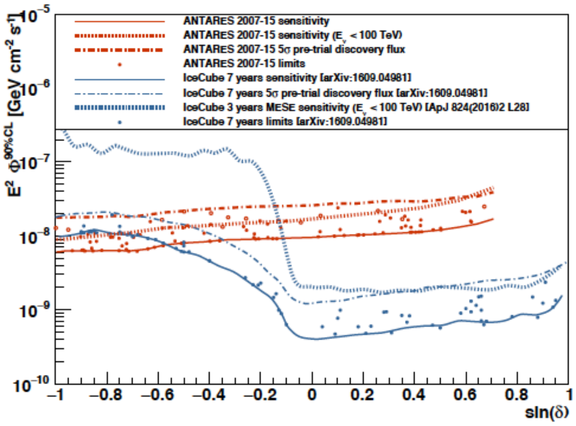


Figure 4: *Upper limits (at 90% C.L.) on the E^{-2} neutrino flux from selected candidate sources as function of their declination (blue squares). The continuous red line shows the ANTARES sensitivity, the blue line the sensitivity of the seven years point-source analysis by the IceCube Collaboration for comparison [7]. The curves for the discovery flux and the sensitivity for neutrino energies under 100 TeV are also included. The IceCube curves for energies under 100 TeV are obtained from the 3 years MESE analysis [8].*

a 1.5σ excess in the on-zone. Follow-up searches will be made including the cascade topology.

3.3 Point Sources

The good angular resolution achieved with cascade reconstructions in seawater, allows including this topology in searches for point-like sources. A point source with a flavour uniform flux and with a E_ν^{-2} spectrum is expected to produce a cascade-to-track ratio of 3 to 10. Nine years of data (2007-2015, 2423.6 days livetime) have been recently unblinded. No significant excess was found in the all-sky search, nor in the dedicated search in the Galactic center region. The most signal-like cluster of events is located at $(\alpha,\delta)=(-16.2°; 23.5°)$ with a significance 1.9σ. A pre-defined list of sources was also used, including 13 track-like events from IceCube's HESE sample (4 years) and yielding no significant excess. The sensitivity of the analysis is well below $\sim 10^{-8}\text{GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}$ for an E^{-2} spectrum, in the Southern Sky (see Fig. 4). Below $\sim$ 100 TeV, the ANTARES limits are the best in the world in a large region of the Southern Sky. As already done with the (2007-2012) data set, a combination of those results with IceCube is foreseen.

3.4 The Multi-messenger Program

Because of its large field of view (2π sr) and high duty cycle, ANTARES is well designed to look for neutrinos emitted by transient astrophysical sources. Searches for neutrino candidates coincident with multi-wavelength and multi-messenger transient phenomena are performed by triggering optical, X-ray and radio observations immediately after the detection of an interesting event and also by looking for neutrino emission spatially and temporally coincident with transient astrophysical events detected across the electromagnetic spectrum or via new messengers such as gravitational-wave signals.
The multi-wavelength follow-up program of alerts, dubbed TAToO (Telescopes-ANTARES Target of Opportunity) has been operating since 2009. It triggers optical and/or X-ray observations within a few seconds after the detection of selected high energy neutrino candidates. More than 230 alerts have been sent to optical robotic telescopes (TAROT, ROTSE and MASTER) since mid-2009 while 12 X-ray targets of opportunity have been sent to the XRT instrument on board Swift satellite since mid-2013. From January 2010 to January 2016, 93 alerts with early optical follow-up have been analyzed. No optical counterparts were found and upper limits on the R-band magnitude of a transient astrophysical source have been derived. Follow-up observations of neutrino candidates are now performed over a broad range of the electromagnetic spectrum. Recently, the Murchinson Widefield Array (MWA), a low frequency (80 - 300 MHz) precursor

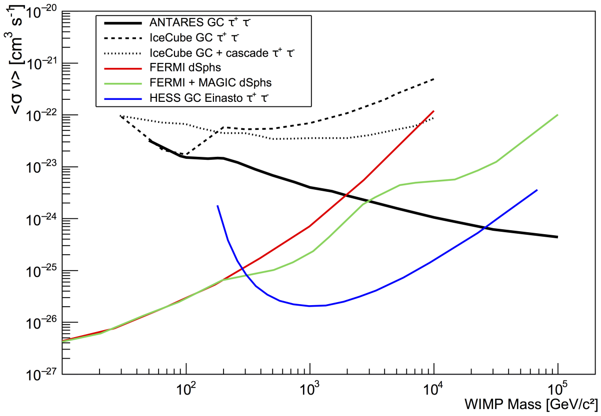


Figure 5: *Limit on the velocity averaged self-annihilation cross section* $\sigma_A v$ *compared to other detectors.*

of the Square Kilometre Array, searched for radio counterpart of two candidate high-energy neutrino events consistent with the locations of galaxies within 20 Mpc of Earth. Likewise, two ANTARES alerts have been followed by H.E.S.S. and 36 by HAWC since November 2014.

Specific strategies are also developed to look for neutrino events in both time and space coincidence with transient events announced by an alert distributed through the Gamma-ray Coordinated Network (GCN). Various searches for neutrinos counterparts to Gamma-ray Bursts have been reported. More recently a joint follow-up search with IceCube was made upon detection of the first gravitational-wave event by LIGO/Virgo in September 2015, with ANTARES providing the most stringent limit up to 100 TeV. A similar follow-up search for 2 other GW events should be soon made public. For the second scientific run of LIGO, antares will receive triggers in real-time, offering the possibility to drastically reduce the size of the region of interest in case of a matching neutrino detection.

Since 2016, ANTARES is also receiving alerts from IceCube distributed by the Astrophysical Multi-messenger Observatory Network (AMON [9]). Similar searches are conducted after the observation of Fast radio bursts (FRBs). Those are very energetic sources only seen in radio during few tens of milliseconds. Six alerts from the PARKES telescope in Australia (project SUPERB) have been analysed so far.

In general, the interest for receiving/sending alerts to/from ANTARES by the astrophysical community has kept growing in the last years, illustrating the importance and credibility of ANTARES on the international scientific stage.

3.5 Dark Matter Searches

Neutrino telescopes contribute to the world wide efforts to search for Dark Matter in the form of Weakly Interactive Massive Particles (WIMP). Scenarios involving the production of high-energy neutrinos involve dense sources in the Universe, such as the Sun, the Centre of the Earth, the Galactic Centre (GC), dwarf galaxies and galaxy clusters. Thanks to their good angular pointing capabilities and their geographical location Mediterranean detectors offer particularly good prospects for the Sun and the GC. While the ANTARES results for the Sun and the Center of the Earth are comparable to the Icecube ones, those obtained from the direction of the Galactic Center with 2007- 2015 data are significantly better (see Fig. 5), given the better visibility of the GC compared to the South Pole. Contacts are made with the IceCube Collaboration for combined analyses.

4 Publications and Conferences

Since 2012, about 40 contributions[1] from the ANTARES Collaboration are presented every year at international conferences. In particular 24 presentations (oral or poster) have been given at the 34^{th} International Cosmic Ray Conference (ICRC) held at The Hague, Netherlands (including a High-Light talk) and 12 at the 7^{th} Very Large Volume Neutrino Telescopes (VLVνT) Workshop in Rome, Italy. Last summer, 9 posters were presented at the Neutrino 2016 conference. The most recent results were presented in an specific oral contribution and reported in topical reviews on multi-messengers and Dark Matter.

For what publications are concerned, ANTARES has now significantly contributed to Astroparticle physics. The list of publications in peer-reviewed journals is available at `http://antares.in2p3.fr/Publications/index.html`. In 2016, the collaboration has published 9 papers; 7 are under review by different journals, and many others under the review of the ANTARES Publication Committee, which has just been renewed last November, together with the Conference Committee.

5 Conclusions

The high quality of the data provided by ANTARES and the competitiveness of the results achieved, despite the modest size of the detector, demonstrate the tremendous potential of Deep Sea Neutrino Telescopes for high-energy neutrino astronomy. 2017 will be the last year of data taking of ANTARES, with KM3NeT taking up the torch in monitoring the High-Energy Neutrino Southern Sky from the Deep Mediterranean Sea. The amount and quality of the data collected, together with the rich multi-messenger program setup, naturally call for great expectations. The hope for discoveries is also enhanced by the perspective of several combined searches, within the framework of the Global Neutrino Network.

References

[1] M. G. Aartsen et al., Phys. Rev. Lett. 111 (2013)021103.

[2] M. G. Aartsen et al., arXiv:1607.08006.

[3] M. Spurio, Phys. Rev. D90, 103004 (2014).

[4] M.C. Gonzalez-Garcia et al. Astropart.Phys. 57-58 (2014) 39-48.

[5] D. Gaggero et al., JCAP 12 (2015) 056.

[6] A. Neronov & D.V. Semikoz, Phys. Rev. D 93 (2016) 123002.

[7] Aartsen et al., arXiv:1609.04981

[8] Aartsen et al. ApJL, 824, L28.

[9] M.W. E. Smith et al., Astroparticle Physics, 45:56-70 (2013).

---

[1] With values above the average in odd years due to the presence of ICRC conferences (Lodz in 2009; Beijing in 2011; Rio de Janeiro in 2013; The Hague in 2015)