KM3NeT and the ORCA Neutrino Telescope at IPHC

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Abstract

Neutrino Telescopes have two distinct scientific goals. Using astrophysical neutrinos in the MeV-PeV energy range, they allow the identification of the sources of cosmic rays, which are still unknown. Using atmospheric neutrinos in the GeV energy range, they give the opportunity to determine the ordering of the neutrino masses, which is still unconstrained.

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, targetting both cosmic neutrinos (with the ARCA Telescope, off-shore Sicily, in Italy) and the neutrino mass hierarchy with atmospheric neutrinos (with the ORCA Telescope, off-shore Toulon, in France). The Letter of Intent for the Phase 2 of KM3NeT describes the physics opportunities and detector design [1].

This document summarizes the scientific objectives of these telescopes, together with the technical and scientific contributions that IPHC has initiated and is willing to develop with the support of IPHC Scientific Council, essentially within ORCA.

1 Neutrino Telescopes and past contributions from IPHC

The low flux of extra-terrestrial neutrinos of energies above $E_\nu \approx$ GeV combined with their low interaction cross section, implies the use of large volume detectors deployed in natural and transparent media, such as ice or sea water. Their detection principle relies on the interaction of the neutrino in rock or ice/water, producing secondary particles which induce Cerenkov radiation. The emitted photons are then detected by a 3D array of photo-sensors deployed in the ice/sea; the light pattern allows in turn to estimate the energy of the primary neutrino and its arrival direction, hence the generic name of *Neutrino Telescopes* for such detectors. The neutrinos of interest here are produced in astrophysical sources (« cosmic » neutrinos) or in the Earth atmosphere (« atmospheric » neutrinos): their study is motivated by two reasons.

1.1 « Cosmic » neutrinos, from MeV-GeV to PeV

Cosmic radiation is mainly composed of hadrons, i.e. protons or nuclei. Their sources is still unknown, but they must be astrophysical objects with extreme power (e.g. compact objects with relativistic jets), to explain the acceleration of these hadrons up to macroscopic energies, of the order of 100 J. Cosmic rays being charged, their direction gives no information about their origin. But these hadrons, close to their sources, must interact and produce neutrinos, with energies ranging from MeV up to PeV-EeV ($10^{15} - 10^{18}$ eV). The detection of these (neutral) neutrinos would unambiguously identify the sources of the cosmic radiation. This is one of the objective of Neutrino Telescopes : to identify the sources at the origin of cosmic rays, by determining the origin of cosmic neutrinos.

In 2013, the IceCube neutrino telescope, embedded in the Antarctic ice, revealed the existence of such cosmic neutrinos [2], but was unable to unambiguously locate their origin. This is the objective of the ANTARES and ARCA telescopes. ANTARES, a telescope of reduced size (about of $1/10^{\text{th}}$ of IceCube), is in operation in the Mediterrean Sea since 2006 and will be dismantled in late 2017/early 2018. ARCA (**A**stroparticle **R**esearch with **C**osmics in the **A**byss), of the KM3NeT Collaboration, is under construction. Its size will be comparable to IceCube, but with a much better angular resolution, allowing to pinpoint the origin of cosmic neutrinos on the sky. Both telescopes target the TeV-PeV energy range, and the identification of neutrino sources is their primary goal. Such cosmic neutrinos can also be detected in the MeV-GeV energy range with the future ORCA Telescope (**O**scillation **R**esearch with **C**osmics in the **A**byss) of the KM3NeT Collaboration, under construction, although this is not its primary goal.

Building on past experience : Contributions of IPHC to ANTARES

IPHC joined ANTARES shortly after its initial proposal [3]. Its contributions were both technical and scientific :

- conception of the front-end electronics board, and production/characterization of the 900 boards that still equip the telescope today (2002-2008) ;
- participation to the time and charge calibration of the instrument, necessary to achieve the target angular resolution ($\approx 0.2^\circ$ above 10 TeV), using the first lines deployed (2006-2010) ;
- understanding of the bioluminescence, the main optical background on the ANTARES site, through modelling and data analysis, using data obtained with prototype lines (2002-2006) ;
- Initiation and supervision of searches for coincident signals between ANTARES and the gravitational wave detectors Virgo/Ligo, with the objective to confirm the cosmic origin of a concomitant neutrino/gravitational wave signal through multi-messenger analyses (ongoing activity, since 2008).

IPHC's objective is of course to carry on these pioneering multi-messenger searches using ORCA and ARCA data.

1.2 « Atmospheric » neutrinos

Atmospheric neutrinos are produced by the interaction of cosmic rays in the upper atmosphere. Their detection and study by, e.g. Super Kamiokande, have proved their *oscillations*, i.e. the change of neutrino flavour with propagation, which is only possible if neutrinos have distinct non-zero masses. Oscillations from one flavour to another occur because the neutrino flavour eigenstates $\nu_{e,\mu,\tau}$ are linear combinations of the three mass (propagation) eigenstates $\nu_{1,2,3}$. This mixing is completely known : the last mixing angle has been measured by the Daya Bay and RENO experiment in 2012 [4]. What is still unknown is the exact ordering of the neutrino masses, the *Neutrino Mass Hierarchy* (NMH), i.e. $m_{\nu_1} < m_{\nu_3}$ (*Normal* Hierarchy) or $m_{\nu_1} > m_{\nu_3}$ (*Inverted* Hierarchy): current oscillation experiments have little sensitivity to the sign of the mass differences. Also the absolute mass scale is not known, i.e. the mass of the lightest neutrino mass-eigenstate.

The oscillation probability of GeV atmospheric neutrinos crossing the Earth depends on their energy, the distance traveled, but also on the NMH. Hence, the distribution of atmospheric neutrinos of all flavours as a function of energy and arrival direction allows to constrain the hierarchy. This determination is the primary goal of ORCA, using GeV atmospheric neutrinos.

The ORCA concept was born in 2012, shortly after the measurement of the last mixing angle $\theta_{13} \approx 9°$ which made possible the ORCA approach : to use a dense neutrino telescope, optimized for GeV neutrinos, to determine the NMH[1].

Building on past experience : Contributions of IPHC to ORCA during the Feasibility Study

IPHC is involved in ORCA since its early proposal in 2012. Together with APC (Paris) and IPHC physicists from Double-Chooz/JUNO, its main contributions were in the early stage (2012-2015) essentially related to the assessment of the feasibility of the determination of the NMH with a dense underwater telescope :

- Derivation of scaling laws to relate the characteristic dimensions of the telescope (inter-line and inter-storey distances) to its performances, namely its energy and angular resolutions [5], using "first principles" estimates ;
- First estimate of the sensitivity of ORCA to the NMH [6], with results very close to the performances recently published in the KM3NeT 2.0 Letter of Intent [1] - namely about 3 sigma in 3 years with a 115-lines telescope.

The objective of IPHC, as developed later in this document, is now to contribute significantly to the building of ORCA, and to improve its ability to determine the NMH.

2 Science with the KM3NeT Telescopes

The KM3NeT Collaboration is then building a new research infrastructure consisting of a network of deep-sea neutrino telescopes in the Mediterranean Sea. The KM3NeT Phase 2 (KM3NeT 2.0) infrastructure will consist of three so-called « building blocks ». A building block comprises 115 detection strings (or Detection Units, DU), each string with 18 optical modules and each optical module hosting 31 photo-multiplier tubes (PMTs).

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, which 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, which will be realised at the Toulon site in Southern France. Figure 1 shows a 3D view of one building block, together with the footprint of ORCA, with 20m spacing between strings.

A staging approach is pursued : Phase-1 consists in the deployment of 24 ARCA strings and 6 ORCA strings in 2017/early 2018. Phase-2 will consist in the completion of the 2 blocks for ARCA, and 1 block for ORCA, to be fully deployed before 2020-2021.

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) [7], and approved by the IN2P3 Scientific Council (February 2017) [8].

2.1 ARCA *Science and Performances*

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

[1] ORCA relies on the presence of matter effects that modify the ν_μ survival probability and the rate of $\nu_\mu \to \nu_e$ appearance at the atmospheric mass scale. The matter effects arise from the ν_e component of the atmospheric "beam" undergoing charged-current elastic scattering interactions with the electrons in the matter.

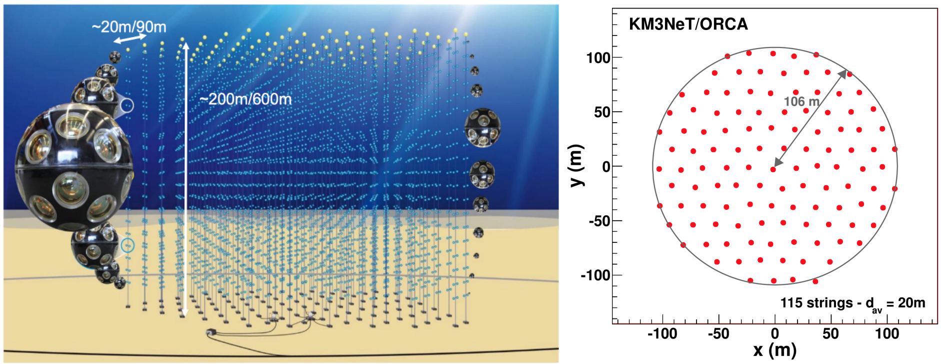

Figure 1: Left : 3D view of 1 KM3NeT block of 115 strings. ARCA and ORCA differ from their inter-line and inter-storey distances. Right : Footprint of the ORCA reference detector (top view), with 115 strings (20 m spacing) with 18 OMs each.

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.

The sensitivity of the ARCA detector to the diffuse neutrino flux measured by IceCube has been evaluated : the results of this analysis are summarised in Figure 2. A significance of 5 sigma can be reached in less than one year.

The sensitivity to potential Galactic point-like neutrino source has also been studied. 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 Vela-X. The RXJ1713 and the Vela-X neutrino spectrum have been estimated considering the hypothesis of transparent sources and a fully hadronic production mechanism. A significance of about 3 sigma is reached in 3 years, as seen in Figure 2.

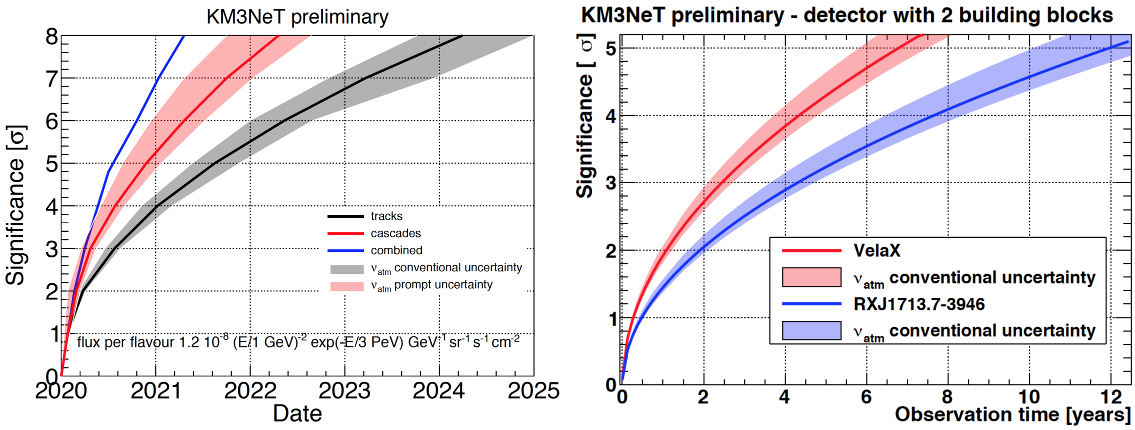

Figure 2: Significance as a function of the observation time for the detection of: (Left) a diffuse flux of neutrinos corresponding to the signal reported by IceCube for the cascade channel (red line, produced by charged-current ν_e interactions and all-flavour neutral current interactions) and muon channel (black line). The blue line represents the results of the combined analysis. (Right) the Galactic sources RXJ1713 and Vela-X.

2.2 ORCA *Science and Performances*

Knowledge of the NMH is an important discriminant between theoretical models of the origin of mass, and serves as an input to cosmological models and neutrino flavour conversion in supernovae explosions. The NMH also has a strong impact on the potential performances of next-generation experiments aiming at the determination of the CP phase (responsible for matter-antimatter asymmetry).

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 for atmospheric neutrinos. Figure 3 shows the expected rate asymmetry, $(N_{IH} - N_{NH})/N_{NH}$, between the Normal (NH) and Inverted (IH) Hierarchy cases as a function of the energy and cosine of the zenith angle (related to the baseline through the Earth) for both atmospheric 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%.

Figure 4 (left), shows the expected performance of ORCA to determine the NMH as a function of the assumed mixing parameter θ_{23} and CP phase. If the current value of θ_{23} from the global fits of around 42° is assumed, ORCA will determine

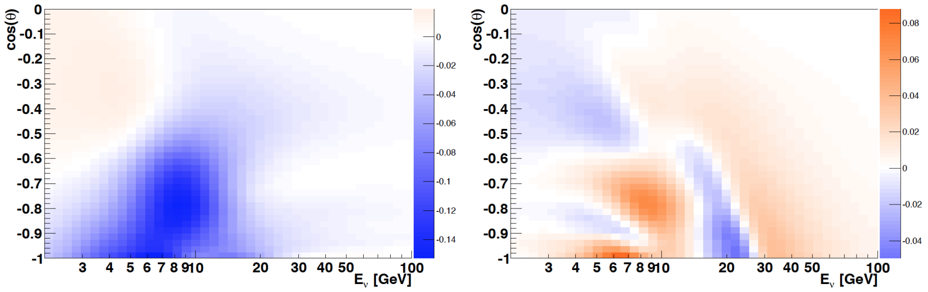

Figure 3: The NMH asymmetry $(N_{IH} - N_{NH})/N_{NH}$ for ν and anti-ν charged current interactions as a function of neutrino energy and cosine zenith angle. Electron neutrinos are on the left and muon neutrinos are on the right. Here the neutrino energy has been smeared by 25% and the zenith angle is smeared by $\sqrt{m_p/E_\nu}$, where m_p is the target nucleon mass.

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 θ_{23}. Figure 4 (middle) shows the median significance as a function of time for a variety of assumptions.

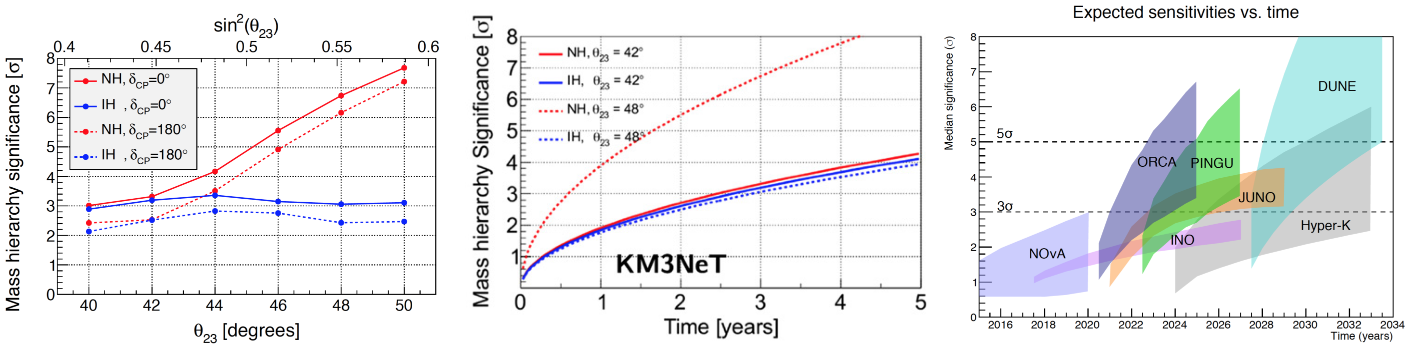

Figure 4: The projected NMH sensitivity for a 115 string ORCA detector. (Left) after 3 years, as a function of θ_{23}. (Middle) as a function of time for the indicated scenarios. (Right) The median sensitivity to reject the IH, if the true hierarchy is NH, for the different facilities as a function of 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 $3\%\sqrt{(1\text{MeV}/E)}$ and $3.5\%\ \sqrt{(1\text{MeV}/E)}$ for JUNO.

Figure 4 (right, adapted from [9]) compares the performance of ORCA with other experimental facilities that aim to address the neutrino mass hierarchy: the medium baseline reactor experiment JUNO (in China, see [10], with IPHC contributions), the atmospheric neutrino experiments INO (cavern) and PINGU (deep ice), and the Fermilab long-baseline beam experiments NOVA and LBNE/DUNE. 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.

2.3 *Earth & Sea Sciences*

A cabled observatory like KM3NeT provides continuous, high frequency access to real-time measurements in situ. Furthermore 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.

Details on these topics are beyond the scope of this short document. Locally, let us mention the contacts with IPHC/DEPE for the bioacoustics studies of sea turtles, or the use of ARCA/ORCA to put constraints on the density and composition of the Earth Core (with IPGS, Institut de Physique du Globe de Strasbourg).

3 Planning and French contributions

Planning : The first ORCA string will be deployed during summer 2017, while the rest of the six Phase-1 strings would follow by the end of 2017/early 2018.

For Phase-2, the aim is to construct the 115 strings of ORCA in about three years. 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. Once in steady production, a single DOM[2] integration site can produce 4-5 DOMs per week once in steady production : thus 4-5 integration sites would be needed to produce DOMs at the required rate. This rate could be satisfied with integration sites at IPHC, Nantes, Nikhef, Morocco, Erlangen and Canada. The ORCA detector could therefore be completed by the end of 2020. Physics studies would already be possible as the array is being constructed, thus reducing the overall time needed to obtain a specified precision.

French IN2P3 Contributions : 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 detector operation.

The APC group is responsible for the Calibration Unit (which incorporates laser beacons and hydrophone acoustic emitters). APC is in the process of characterising a complete DOM using muon track passing through a large water filled tank. They also have facilities to characterise single PMTs.

Subatech has recently joined the KM3NeT Collaboration. They plan to investigate anti-biofouling techniques in collaboration with Ifremer-Brest. On the longer term they will also become a DOM integration site.

4 Proposed contributions to ORCA from IPHC

The primary objective of IPHC contributions is to participate to the building of the ORCA telescope, with the aim of determining the NMH. This can be achieved both through technical and scientific contributions, some of which are briefly presented here for what concerns ORCA[3]. As of May 2017, the people involved are :

- Physicists : T. Pradier - R. Gracia-Ruiz (Post-doc ANR)[4] - M. Organokov (PhD) [+ GRPHE[5] : A. Albert, D. Drouhin];
- Technical Staff : S. Kihel (supervision of DOM production), C. Weber (integration) + S. Suzanne (Quality)

4.1 *Building* ORCA *: DOM production*

In late 2016, IPHC has officially become a production site for *Digital Optical Modules*, the elementary photo-sensor brick of the detector. Already 15k€ have been invested in the purchase of furnitures and storage facilities to integrate DOMs, mainly on IPHC internal funds, but also using IN2P3 funds (AP for ORCA). An engineer (S. Kihel) is in charge of supervising the production, and one person has been identified to participate to the integration. S. Kihel has recently participated to the Review of DOM production, with other members of the KM3NeT Collaboration. She was closely involved in defining the basic requirements that production sites have to fulfill in order to integrate DOMs. The integration room (Building 25) is in the process of being installed, and dedicated equipments are being purchased, using NUMerEnv funds at CPPM (for a total of $\approx$ 35k€).

The technical staff will be trained for the DOM production in a KM3NeT lab with an existing and functional integration site in the forthcoming months (probably at NIKHEF, the Netherlands) - training under the responsability of the KM3NeT Collaboration. The DOM integration activity properly speaking will begin after summer 2017. The objective is to reach a rate of 5 DOMs/week as soon as possible, so that ORCA can be completed by the end of 2020. This steady-production rate is achievable only with a technical reinforcement of the integration team.

KM3NeT has requested that integration sites should also consider the possibility to integrate DOMs on the Vertical Electro-Optical Cable (VEOC), so that cable-integrated DOMs could be directly sent to CPPM for DU integration, calibration and deployment. This technical activity is only possible with a technical reinforcement of the integration team. Should this solution be adopted, the DOM production rate would be accordingly decreased, to allow for this new activity, unless the reinforcement compensates for this new need.

4.2 *Determining the NMH and improving the sensitivity - synergy with JUNO*

Once the deployment of the telescope has started, the primary objective is to determine the NMH. This implies simulation studies, for instance to reconstruct individual particles in the neutrino interaction, for an accurate estimate of the inelasticity of the reactions, allowing the discrimination between neutrinos and antineutrinos on a statistical basis.

Furthermore, 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 the oscillation parameters [11]. Hence, the wrong mass ordering can be excluded by a mismatch of the values inferred for the said parameters, thanks

[2] *Digital Optical Module*, elementary brick of the KM3NeT telescopes, visible on Figure 1 (left image), composed of 31 3" photo-multiplier tubes.
[3] Time permitting, foreseen contributions to ARCA, or the possibilities offered by the combination of ORCA+ARCA data, will be developed during the oral presentation to the Scientific Council.
[4] A second post-doc, funded through the european H2020 program, will join the IPHC after summer 2017.
[5] *Groupe de Recherche en Physique des Hautes Energies*, Université de Haute Alsace. The group is hosted at IPHC for its research activities.

to the excellent accuracy for their measurements in 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. The evaluation of such a study which would combine ORCA and JUNO results has already started at IPHC (ANR post-doc), and a close collaboration with JUNO physicists at IPHC is foreseen.

4.3 *Improving the sensitivity to MeV neutrinos : R&D on UV Wavelength-Shifting DOMs*

The IPHC group has expressed its will to study the possibility to make DOMs more sensitive to UV photons, by testing different wavelength-shifting materials, to be deposited on current DOMs. Since the Cherenkov spectrum is dominated by UV photons, this would improve the energy and angular resolution of the telescope. Given the shorter absorption length of UV light in water as compared to visible light, this is only possible because ORCA is a denser telescope.

Apart from the improvement of the sensitivity of ORCA to the NMH (to be assessed in details), this modification would allow for a better detection of MeV neutrinos, for instance produced during a type II Supernova. Measuring the delay between such neutrinos and the concomitant gravitational wave burst, if detected by Virgo/Ligo, would ensure the determination of the neutrino absolute mass scale [12]. This would transform ORCA into a telescope able to measure the entire neutrino mass spectrum (hierarchy and mass scale).

5 Conclusions : expectations from IPHC Scientific Council

The DOM integration activity has already started since late 2016, and consequent funds invested. To reach the objective of a completion of ORCA by the end of 2020, a reinforcement of the technical staff involved in the DOM integration, and possibly VEOC integration, is mandatory. The endorsement of the ORCA activities by IPHC Scientific Council would without any doubt facilitate this reinforcement.

Furthermore, the scientific case of ORCA, but also of ARCA, is very rich. IPHC will concentrate on the determination of the NMH, the improvement of its sensitivity and also on multi-messenger analyses combining ORCA, ARCA, and gravitational wave observatories in operation at the completion of Phase-1. To develop these physics studies, and improve the visibility and attractivity of IPHC within the KM3NeT Collaboration, a reinforcement of the permanent physics staff is needed. Again, the official endorsement by IPHC Scientific Council of the local *Neutrino Telescope* activities would undoubtedly facilitate this future reinforcement.

References

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

[2] IceCube Collaboration - *First Observation of PeV-Energy Neutrinos with* IceCube, PRL 111 (2013) 021103

[3] ANTARES Collaboration - *A Deep Sea Telescope for High Energy Neutrinos*, https://arxiv.org/abs/astro-ph/9907432

[4] e.g. Daya Bay Collaboration - *Observation of electron-antineutrino disappearance at Daya Bay*, PRL 108 (2012) 171803

[5] T. Pradier - HDR : *Télescopes à Neutrinos, d'*ANTARES *à* ORCA*: Aspects Pluridisciplinaires & Multi-Messagers*, Université de Strasbourg (2015)

[6] D. Franco et al. - *Mass hierarchy determination with atmospheric neutrinos in large volume ice/water Cherenkov detectors*, JHEP 2013 (2014) 4

[7] ESFRI Roadmap, see here (for instance page 51)

[8] CS IN2P3, February 2017, available online (click here)

[9] M. Blennow et al. - *Quantifying the sensitivity of oscillation experiments to the neutrino mass ordering*, JHEP 03 (2014) 028

[10] JUNO Collaboration - *Neutrino Physics with JUNO*, J. Phys. G 43 (2016) 030401

[11] M. Blennow, T. Schwetz - *Determination of the neutrino mass ordering by combining PINGU and Daya Bay II*, JHEP 09 (2013) 089

[12] N. Arnaud et al. - *Gravity Wave and Neutrino Bursts from Stellar Collapse: A Sensitive Test of Neutrino Masses*, PRD 65 (2002) 033010