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Search for neutrino emission from binary mergers with neutrino telescopes in the depths of the Mediterranean Sea

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Marion Pillas,[a,b,*] **Pierre-Alexandre Duverne,**[c] **Mathieu Lamoureux,**[d] **Iara Tosta E Melo**[e] **and Gwenhaël de Wasseige**[d] **for the ANTARES and KM3NeT Collaborations**

[a] *Institut d'Astrophysique de Paris, Sorbonne Université & CNRS, UMR 7095, 98 bis bd Arago, 75014 Paris, France*
[b] *STAR Institute, University of Liege, Belgium*
[c] *APC, Paris Cité University, France*
[d] *Centre for Cosmology, Particle Physics and Phenomenology - CP3,*
Université Catholique de Louvain, B-1348 Louvain-la-Neuve, Belgium
[e] *University of Catania, Italy*

Astrophysical neutrinos may be produced during the coalescence of compact objects, in particular those involving neutron stars. Such mergers have been observed through gravitational wave detections by the LIGO-Virgo-KAGRA interferometers. The ANTARES and KM3NeT deep-sea neutrino telescopes are sensitive to neutrino interactions in a wide range of energies, from MeV to PeV. In this contribution, recent searches for correlation in time and space between neutrinos and gravitational wave signals are reviewed. In particular, the results of follow-ups with the KM3NeT real-time system for alerts from the fourth observing run of LIGO-Virgo-KAGRA will be reported for the first time. Additionally, prospects for future studies using archival data from both neutrino and gravitational wave detectors will be outlined.

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[*] Speaker

1. Introduction

Since 2015, the LIGO, Virgo, and KAGRA interferometers (LVK) have been detecting gravitational waves (GWs) emitted by coalescing binaries of compact objects - either black holes or neutron stars. Additionally, searches for other astrophysical GW sources, such as core-collapse supernovae (SN), are conducted in the LVK data. In 2017, the joint detection of a binary neutron star merger by LIGO and Virgo - the GW170817 event [1] - and several electromagnetic (EM) counterparts over the whole spectrum [2–5] - the gamma-ray burst (GRB) GRB170817A [6, 7] and the kilonova AT2017gfo [8] in the optical wavelengths in particular - opened a new window for multi-messenger astronomy. Moreover, high-energy neutrinos (HEN) in the GeV-PeV energy range may also be produced via hadronic processes in the source's circumstellar environment. This allows for possible coincident detection of the same source in both the GW and the HEN regimes with a high potential for breakthroughs in various domains, such as cosmology, by providing an independent measurement of the H_0 constant or by constraining the equation of state of nuclear matter. The LVK collaboration has conducted three observing runs since 2015: O1, O2, and O3. The fourth run, O4, started on 24^{th} May 2023, is ongoing and will stop on 18^{th} November 2025. The ANTARES detector was a neutrino detector located at 2500 m depth in the Mediterranean Sea, offshore Toulon, France. The detector was optimized for the detection of neutrinos in the 100 GeV-100 PeV. ANTARES was decommissioned in February 2022 after 15 years of observation. The KM3NeT Observatory is currently under construction in the Mediterranean Sea with two neutrino detectors: the ORCA detector is located close to the former ANTARES site offshore Toulon, France, at a depth of about 2500 m; the ARCA detector is situated near Sicily, Italy, at a depth of about 3500 m. In this contribution, three analyses are presented aiming at finding statistically significant coincidences between LVK GW candidates and HEN candidates observed by KM3NeT and ANTARES during the O3 and O4 runs. In Section 2, a search for HEN counterparts of significant GW signals is presented, while in Section 3, a search is described for GW counterparts of significant HEN candidates. The idea behind the search described in Section 4 is that weak signals in GW or HEN channels can still create strong coincidences, provided that the source candidates are spatially and temporally close. Finally, in Section 5, concluding remarks are presented.

2. Follow-ups of significant GW detections with neutrinos

Searches for neutrino emission from significant binary mergers, with a probability of being of astrophysical origin of 0.5, reported in the GWTC-3 LVK catalogue [9], have been conducted using the data from ANTARES and KM3NeT [10, 11]. For each binary merger, a ±500 s time window centred on the GW time t_{GW} [12] is used to select GeV–TeV neutrino candidates in time and spatial coincidence with the detected GW signal. In KM3NeT, an additional search for a prompt signal of MeV neutrinos is performed by looking for a global increase of the detector counting rates in the two seconds following t_{GW}.

Since 2022, the KM3NeT Collaboration has also developed a system to perform quick follow-ups of interesting alerts reported by the community through GCN notices [13]. In this context, significant GW triggers are followed using the online data from ARCA and ORCA. Currently, the results are not reported in real time to the community, but will be in the future for interesting alerts.

To date, no significant GW-HEN coincidences have been reported in both offline and real-time searches. The observations are converted to constraints on the neutrino emission from compact binary mergers, either in terms of the flux at Earth or the total energy emitted in neutrinos by the source. In addition to individual limits for each merger, population studies have been performed, stacking O3 observations to constrain the typical neutrino emission, $E_{\text{iso},\nu}$ or $f_\nu = E_{\text{iso},\nu}/E_{\text{GW}}$, from these objects. The 90% confidence level upper limits for the stacking of 44 (72) binary black hole mergers are $E_{\text{iso},\nu} < 3.2 \times 10^{54}$ erg (3.0×10^{55} erg) and $f_\nu < 2.4$ (12) with ANTARES [10] (KM3NeT [11]). For the seven (six) detected neutron star - hole mergers, the obtained limits are $E_{\text{iso},\nu} < 3.2 \times 10^{53}$ erg (1.9×10^{55} erg) and $f_\nu < 0.88$ (46) for ANTARES (KM3NeT).

3. Follow-ups of neutrino alerts with GW interferometers

In this section, a HEN-triggered search for a GW signal is described. HEN candidates from ANTARES with a strong probability of being of astrophysical origin are used as a trigger for a deep search for a GW signal in a [-500, +500] s time window centred around the HEN trigger time [12]. The search is performed using `X-Pipeline` [14], which is designed to find GW signals without making any assumption about the GW signal morphology or the GW progenitor. This agnostic approach allows for searching for generic GW transient signals emitted by a large range of sources, such as SN, but also compact binary coalescences (CBC). This type of algorithm is usually called *un-modelled*, as opposed to *modelled* searches that aim at finding CBC signals only by correlating the data with a template GW waveform, as described in Section 4. `X-Pipeline` coherently combines the interferometers' data into a time-frequency map and looks for power excess in the map's pixels. Then, the loudest pixels are clustered to identify the GW candidates, allowing finding strong statistical association. The selected neutrino candidates from ANTARES reported during the O3 run are reconstructed events with a zenith angle cos (theta) above -0.1, with log10(dEdX) > 1.6, with the reconstruction quality parameter [15] $\Lambda_\nu > -5.2$ and an error estimate β on the direction extracted from the error matrix of the fit $0 < \beta < 1$.

In addition, the metric *signalness* is defined as:

$$\text{Signalness}(E, \Lambda_\nu) = \frac{N_{\text{signal}}(E, \Lambda_\nu)}{N_{\text{signal}}(E, \Lambda_\nu) + N_{\text{background}}(E, \Lambda_\nu)}, \tag{1}$$

where E is the reconstructed event energy and $N_{\text{signal}}(E, \Lambda_\nu)$ and $N_{\text{background}}(E, \Lambda_\nu)$ are the expected number of signal and background events above energy E and Λ from simulations. The signalness allows for evaluating whether the HEN candidates are of astrophysical origin. Its computation is based on a method proposed by the IceCube collaboration [16] and relies on Monte Carlo simulations of astrophysical/atmospheric neutrinos and muons. These quantities depend on a chosen astrophysical neutrino spectrum. An $E^{-2.58}$ spectrum is chosen with a normalization of 1.68×10^{-18}. Reconstructed events with a signalness above 0.3 are selected and tagged as **Gold** when they are upgoing and **Bronze** when they are not. The results are shown in Fig. 1

This choice leads to a selection of two Gold events, the first one with a reconstructed energy of $\sim 1.5 \times 10^5$ GeV and a signalness of 0.54; the second one has a reconstructed energy of $\sim 4.7 \times 10^4$ GeV and a signalness of 0.30. Two Bronze events were selected: one with a reconstructed energy of $\sim 4.7 \times 10^5$ GeV and a signalness of 0.69; and the other with a reconstructed energy of

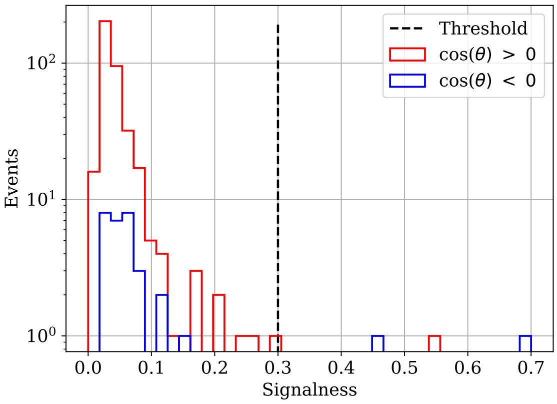

Figure 1: Signalness distribution of ANTARES upgoing (*black*) and downgoing (*blue*) reconstructed events reported during O3.

$\sim 1.6 \times 10^5$ GeV and a signalness of 0.47. Finally, a targeted analysis for GWs associated with these reconstructed HEN events has been conducted. The search returned no significant GW candidate associated to the individual HEN triggers with a p-value consistent with the signal hypothesis.

4. Joint sub-threshold analysis with a GW modelled search

In this section, a symmetric joint analysis between sub-threshold candidates in both GW and HEN regimes is described. Even for these marginally significant triggers, a statistically significant coincidence can be found in cases where the HEN and GW triggers are close in time and have a good spatial overlap. The analysis is based on the method described in [17, 18] for a joint sub-threshold search for GW and GRB associations in LVK and Fermi/GBM data, adapted for ORCA6 and ANTARES data. HEN and GW triggers that could have the same progenitor are paired; pairs are ranked with a test statistic and are assigned a false alarm rate (FAR). HEN data from ANTARES and ORCA6 - the KM3NeT detector configuration with six active detection units - are used. The ANTARES data cover the whole O3 run; the ORCA6 data cover the last 45.5 days of O3. For ORCA6, we use the upgoing - with cos(zenith angle) > 0 - track events with reconstructed energy above 1 GeV. In addition, we use the score from the Boosted Decision Tree (BDT) trained over 20 variables to keep the best reconstructed events [19]. Eventually, only the track events with BDT score higher than 1 are kept. For ANTARES, we keep reconstructed events reported during O3 with a cos(zenith angle) above -0.1, $\Lambda_\nu > -5.5$ and $\log_{10}(dEdX) > 1.6$. On the GW side, we use GWTC-3 [20] released (with a FAR < 2/day) triggers produced by `PyCBC` [21], a modelled search pipeline designed to find CBC GW signals.

4.1 Method

For identifying statistically significant HEN-GW associations, a ranking metric defined as follows has been used:

$$\Lambda = \frac{I_{\Delta t} I_{\Omega}}{1 + Q_g + Q_\nu + Q_g Q_\nu}. \tag{2}$$

Here Q_g and Q_ν are the single-instrument Bayes factors comparing the noise-only and noise+signal hypotheses in the GW and ORCA6 data, respectively. $I_{\Delta t}$ and I_Ω quantifies the temporal and spatial overlap, respectively. The metric is constructed by adapting the methods proposed in [17, 18, 22]. More details about the hypotheses underlying the derivation of Λ can be found in those references.

Neutrino trigger significance: Similar to the GBM trigger significance Bayes factor in [18], the neutrino trigger significance Bayes factor Q_ν is computed from a Kernel Density Estimation-based (KDE) method. Simulated signals and background are used to train the KDE in the $\log_{10}$(Recovered Energy [GeV]) – X observable plane, where X represents either the BDT score (ORCA6) or the Λ_ν observable. Then Q_ν is retrieved from ORCA6 data. The signal sample is composed of Monte Carlo (MC) astrophysical neutrinos, while the background sample includes Monte Carte atmospheric neutrinos and muons. The three neutrino flavours are included, and we assume here a $E^{-2.5}$ spectrum, which is consistent with the best fit from the last Diffuse Neutrino Flux IceCube publication [23].

GW trigger significance: Similarly to Pillas et al, 2023 [18], Q_g is chosen as the BCI provided in the skymaps, which compares the probability of being a *Coherent* signal in the entire network versus an *Incoherent* signal (most likely being a single-detector signal).

Time offset prior: For a pair formed by a GW trigger and a HEN trigger (ν) $I_{\Delta t}$ quantifies the probability that they are separated in time by$\Delta t = t_\nu - t_{\mathrm{GW}}$. Following [17, 18], an on-source window is chosen that allows the HEN and GW candidates to be separated by 30 s with a triangular-shaped time-offset prior centered on 0. This configuration allows for looking for neutrinos emitted from short GRB sources associated to CBC progenitors. GW and neutrino data are analysed with a ±500 seconds on-source window to cover other emission models [12], using a uniform prior. The window width is chosen consistently with other neutrino searches targeting GW sources [24].

Sky overlap: The sky overlap Bayes factor [22] is written as $I_\Omega = \int \frac{P(\Omega|D_g)P(\Omega|D_\nu)}{P(\Omega)} d\Omega$. ORCA6 and ANTARES sky localisation maps are generated as Gaussian, energy-dependent skymaps based on MC astrophysical neutrino simulations.

Foreground generation: Once the metric in Eq. 2 is estimated for all the HEN-GW associations, which are referred to as the *foreground distribution*, a FAR is estimated by comparing it to a background sample. The latter is generated by shifting the HEN and GW triggers in time by an amount that is large enough to ensure that the two are unrelated. Then Λ is computed for this fake set of coincidences. The process is repeated for several shift values to increase the background distribution. Eventually, the FAR is assigned by calculating the rate of background coincidences with Λ equal to or higher than the foreground associations.

4.2 Simulated associations

To check the performance of the method, we simulated a set of 150 associated HEN/GW triggers. The MC astrophysical HEN triggers are generated assuming an $E^{-2.5}$ spectrum, and the 150 GW CBC signals are injected at the same sky position. Two time windows are used for the delay between GW and HEN, ±30 s and the ±500 s, to check each time prior. Finally, the simulated associations are compared with the background without including the simulated associations in the background sample to retrieve the *exclusive IFAR* distribution. In Fig. 2, the results are shown for the simulated associations using ORCA6 (left) and ANTARES (right). The majority of the injections are recovered with a satisfying IFAR. An IFAR threshold of 1 yr is established, below

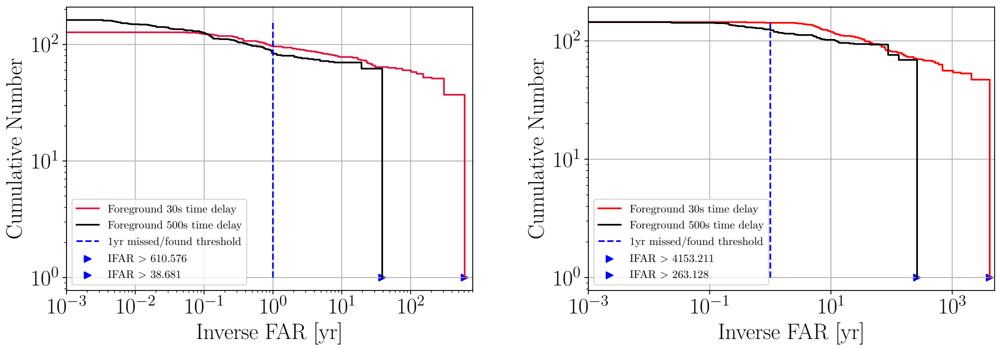

Figure 2: Cumulative number of simulated associations as a function of their IFAR [yr], for the 30 s maximum time offset prior (red), the 500 s maximum time offset prior (black), with ORCA6 (*left*) and ANTARES (*right*).

which we consider that the injection is missed. This is mostly caused by glitches in the GW data at the injection time that degrade the GW sky localisation, leading to small I_Ω values.

4.3 Foreground associations

In Fig. 3, the blue curve shows the cumulative rate as a function of the IFAR for the foreground associations in the ± 500 s on-source window analysis. The orange regions show the 1, 2, and 3-σ deviation; the foreground distribution does not show any statistically significant association. For the ±30 s maximum time delay analysis, only the significance of the top foreground association is considered, as only 2 (ORCA6) and 3 (ANTARES) foreground associations were found. The most significant ones for ORCA6 and ANTARES have an IFAR of 0.23 and 0.81 years, respectively.

In general, all these top foreground associations are composed of a signal-like GW trigger, despite a favoured terrestrial origin in coincidence with an upgoing, uninformative neutrino candidate, because of their Q_ν close to 1. Moreover, the sky overlap is quite small due to the large sky localization uncertainty on the ORCA6 side, and the sky overlap of the most significant foreground association with the 30 s maximum time offset search for ANTARES kills the significance of the association. Therefore, it is concluded that the two candidates of each of these four associations are unlikely to be real signals coming from a common source.

5. Conclusion and outlook

In this contribution, three different multi-messenger analyses aiming at detecting GW-HEN associations are presented. None of the searches led to plausible joint detections. However, they allowed for constraining the total energy emitted in neutrinos for each GW source considered. These searches will also be conducted using the data from O4, for which ORCA6 covered a longer period than during O3. A sub-threshold analysis similar to the one developed in Sec.4 using un-modelled GW triggers is ongoing for targeting more GW-HEN sources, such as core-collapse supernovae.

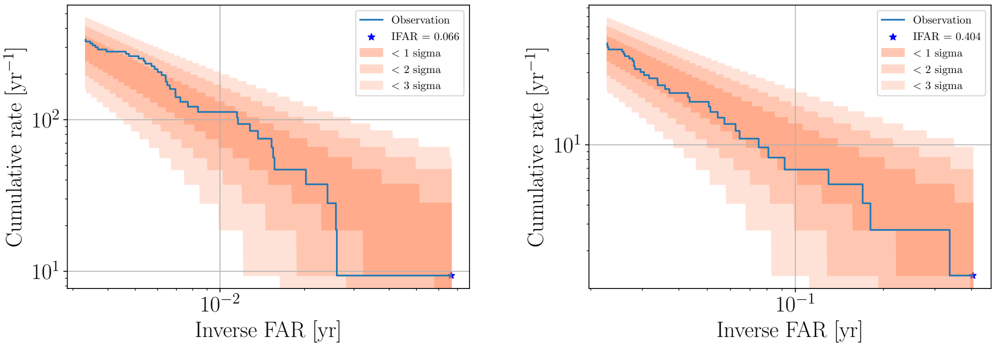

Figure 3: Cumulative rate as a function of the IFAR [yr] for the foreground associations in the ±500 s on-source window analysis with ORCA6 (*left*) and ANTARES (*right*).

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Full Authors List: The ANTARES Collaboration

A. Albert[a,b], S. Alves[c], M. André[d], M. Ardid[e], S. Ardid[e], J.-J. Aubert[f], J. Aublin[g], B. Baret[g], S. Basa[h], Y. Becherini[g], B. Belhorma[i], F. Benfenati[j,k], V. Bertin[f], S. Biagi[l], J. Boumaaza[m], M. Bouta[n], M.C. Bouwhuis[o], H. Brânzaş[p], R. Bruijn[o,q], J. Brunner[f], J. Busto[f], B. Caiffi[r], D. Calvo[c], S. Campion[s,t], A. Capone[s,t], F. Carenini[j,k], J. Carr[f], V. Carretero[c], T. Cartraud[g], S. Celli[s,t], L. Cerisy[f], M. Chabab[u], R. Cherkaoui El Moursli[m], T. Chiarusi[j], M. Circella[v], J.A.B. Coelho[g], A. Coleiro[g], R. Coniglione[l], P. Coyle[f], A. Creusot[g], A. F. Díaz[w], B. De Martino[f], C. Distefano[l], I. Di Palma[s,t], C. Donzaud[g,x], D. Dornic[f], D. Drouhin[a,b], T. Eberl[y], A. Eddymaoui[m], T. van Eeden[o], D. van Eijk[o], S. El Hedri[g], N. El Khayati[m], A. Enzenhöfer[f], P. Fermani[s,t], G. Ferrara[l], F. Filippini[j,k], L. Fusco[z], S. Gagliardini[s,t], J. García-Méndez[e], C. Gatius Oliver[o], P. Gay[aa,g], N. Geißelbrecht[y], H. Glotin[ab], R. Gozzini[c], R. Gracia Ruiz[y], K. Graf[y], C. Guidi[r,ac], L. Haegel[g], H. van Haren[ad], A.J. Heijboer[o], Y. Hello[ae], L. Hennig[y], J.J. Hernández-Rey[c], J. Hößl[y], F. Huang[f], G. Illuminati[j,k], B. Jisse-Jung[o], M. de Jong[o,af], P. de Jong[o,q], M. Kadler[ag], O. Kalekin[y], U. Katz[y], A. Kouchner[g], I. Kreykenbohm[ah], V. Kulikovskiy[r], R. Lahmann[y], M. Lamoureux[g], A. Lazo[c], D. Lefèvre[ai], E. Leonora[aj], G. Levi[j,k], S. Le Stum[f], S. Loucatos[ak,g], J. Manczak[c], M. Marcelin[h], A. Margiotta[j,k], A. Marinelli[al,am], J.A. Martínez-Mora[e], P. Migliozzi[al], A. Moussa[n], R. Muller[o], S. Navas[an], E. Nezri[h], B. Ó Fearraigh[o], E. Oukacha[g], A.M. Păun[p], G.E. Păvălaş[p], S. Peña-Martínez[g], M. Perrin-Terrin[f], P. Piattelli[l], C. Poirè[z], V. Popa[p], T. Pradier[a], N. Randazzo[aj], D. Real[c], G. Riccobene[l], A. Romanov[r,ac], A. Sánchez Losa[c], A. Saina[c], F. Salesa Greus[c], D. F. E. Samtleben[o,af], M. Sanguineti[r,ac], P. Sapienza[l], F. Schüssler[ak], J. Seneca[o], M. Spurio[j,k], Th. Stolarczyk[ak], M. Taiuti[r,ac], Y. Tayalati[m], B. Vallage[ak,g], G. Vannoye[f], V. Van Elewyck[g,ao], S. Viola[l], D. Vivolo[ap,al], J. Wilms[ah], S. Zavatarelli[r], A. Zegarelli[s,t], J.D. Zornoza[c], J. Zúñiga[c].
[a] Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France
[b] Université de Haute Alsace, F-68100 Mulhouse, France
[c] IFIC - Instituto de Física Corpuscular (CSIC - Universitat de València) c/ Catedrático José Beltrán, 2 E-46980 Paterna, Valencia, Spain
[d] Technical University of Catalonia, Laboratory of Applied Bioacoustics, Rambla Exposició, 08800 Vilanova i la Geltrú, Barcelona, Spain
[e] Institut d'Investigació per a la Gestió Integrada de les Zones Costaneres (IGIC) - Universitat Politècnica de València. C/ Paranimf 1, 46730 Gandia, Spain
[f] Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France
[g] Université Paris Cité, CNRS, Astroparticule et Cosmologie, F-75013 Paris, France
[h] Aix Marseille Univ, CNRS, CNES, LAM, Marseille, France
[i] National Center for Energy Sciences and Nuclear Techniques, B.P.1382, R. P.10001 Rabat, Morocco
[j] INFN - Sezione di Bologna, Viale Berti-Pichat 6/2, 40127 Bologna, Italy
[k] Dipartimento di Fisica e Astronomia dell'Università di Bologna, Viale Berti-Pichat 6/2, 40127, Bologna, Italy
[l] INFN - Laboratori Nazionali del Sud (LNS), Via S. Sofia 62, 95123 Catania, Italy
[m] University Mohammed V in Rabat, Faculty of Sciences, 4 av. Ibn Battouta, B.P. 1014, R.P. 10000 Rabat, Morocco
[n] University Mohammed I, Laboratory of Physics of Matter and Radiations, B.P.717, Oujda 6000, Morocco
[o] Nikhef, Science Park, Amsterdam, The Netherlands
[p] Institute of Space Science - INFLPR subsidiary, 409 Atomistilor Street, Măgurele, Ilfov, 077125 Romania
[q] Universiteit van Amsterdam, Instituut voor Hoge-Energie Fysica, Science Park 105, 1098 XG Amsterdam, The Netherlands
[r] INFN - Sezione di Genova, Via Dodecaneso 33, 16146 Genova, Italy
[s] INFN - Sezione di Roma, P.le Aldo Moro 2, 00185 Roma, Italy
[t] Dipartimento di Fisica dell'Università La Sapienza, P.le Aldo Moro 2, 00185 Roma, Italy
[u] LPHEA, Faculty of Science - Semlali, Cadi Ayyad University, P.O.B. 2390, Marrakech, Morocco.
[v] INFN - Sezione di Bari, Via E. Orabona 4, 70126 Bari, Italy
[w] Department of Computer Architecture and Technology/CITIC, University of Granada, 18071 Granada, Spain
[x] Université Paris-Sud, 91405 Orsay Cedex, France
[y] Friedrich-Alexander-Universität Erlangen-Nürnberg, Erlangen Centre for Astroparticle Physics, Erwin-Rommel-Str. 1, 91058 Erlangen, Germany

[z] Università di Salerno e INFN Gruppo Collegato di Salerno, Dipartimento di Fisica, Via Giovanni Paolo II 132, Fisciano, 84084 Italy
[aa] Laboratoire de Physique Corpusculaire, Clermont Université, Université Blaise Pascal, CNRS/IN2P3, BP 10448, F-63000 Clermont-Ferrand, France
[ab] LIS, UMR Université de Toulon, Aix Marseille Université, CNRS, 83041 Toulon, France
[ac] Dipartimento di Fisica dell'Università, Via Dodecaneso 33, 16146 Genova, Italy
[ad] Royal Netherlands Institute for Sea Research (NIOZ), Landsdiep 4, 1797 SZ 't Horntje (Texel), the Netherlands
[ae] Géoazur, UCA, CNRS, IRD, Observatoire de la Côte d'Azur, Sophia Antipolis, France
[af] Huygens-Kamerlingh Onnes Laboratorium, Universiteit Leiden, The Netherlands
[ag] Institut für Theoretische Physik und Astrophysik, Universität Würzburg, Emil-Fischer Str. 31, 97074 Würzburg, Germany
[ah] Dr. Remeis-Sternwarte and ECAP, Friedrich-Alexander-Universität Erlangen-Nürnberg, Sternwartstr. 7, 96049 Bamberg, Germany
[ai] Mediterranean Institute of Oceanography (MIO), Aix-Marseille University, 13288, Marseille, Cedex 9, France; Université du Sud Toulon-Var, CNRS-INSU/IRD UM 110, 83957, La Garde Cedex, France
[aj] INFN - Sezione di Catania, Via S. Sofia 64, 95123 Catania, Italy
[ak] IRFU, CEA, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France
[al] INFN - Sezione di Napoli, Via Cintia 80126 Napoli, Italy
[am] Dipartimento di Fisica dell'Università Federico II di Napoli, Via Cintia 80126, Napoli, Italy
[an] Dpto. de Física Teórica y del Cosmos & C.A.F.P.E., University of Granada, 18071 Granada, Spain
[ao] Institut Universitaire de France, 75005 Paris, France
[ap] Dipartimento di Matematica e Fisica dell'Università della Campania L. Vanvitelli, Via A. Lincoln, 81100, Caserta, Italy

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Full Authors List: The KM3NeT Collaboration

O. Adriani[b,a], A. Albert[c,be], A.R. Alhebsi[d], S. Alshalloudi[d], M. Alshamsi[e], S. Alves Garre[f], F. Ameli[g], M. Andre[h], L. Aphecetche[i], M. Ardid[j], S. Ardid[j], J. Aublin[k], F. Badaracco[m,l], L. Bailly-Salins[n], B. Baret[k], A. Bariego-Quintana[f], M. Barnard[o], Y. Becherini[k], M. Bendahman[p], F. Benfenati Gualandi[r,q], M. Benhassi[s,p], D.M. Benoit[t], Z. Beňušová[v,u], E. Berbee[w], E. Berti[b], V. Bertin[e], P. Betti[b], S. Biagi[x], M. Boettcher[o], D. Bonanno[x], M. Bondì[y], S. Bottai[b], A. B. Bouasla[bf], J. Boumaaza[z], M. Bouta[e], M. Bouwhuis[w], C. Bozza[aa,p], R.M. Bozza[ab,p], H. Brânzaş[ac], F. Bretaudeau[i], M. Breuhaus[e], R. Bruijn[ad,w], J. Brunner[e], R. Bruno[y], E. Buis[w,ae], R. Buompane[s,p], I. Burriel[f], J. Busto[e], B. Caiffi[m], D. Calvo[f], A. Capone[g,af], F. Carenini[r,q], V. Carretero[ad,w], T. Cartraud[k], P. Castaldi[ag,q], V. Cecchini[f], S. Celli[g,af], L. Cerisy[e], M. Chabab[ah], A. Chen[ai], S. Cherubini[aj,x], T. Chiarusi[q], W. Chung[ak], M. Circella[al], R. Clark[am], R. Cocimano[x], J. A. B. Coelho[k], A. Coleiro[k], A. Condorelli[k], R. Coniglione[x], P. Coyle[e], A. Creusot[k], G. Cuttone[x], R. Dallier[i], A. De Benedittis[s,p], G. De Wasseige[am], V. Decoene[i], P. Deguire[e], I. Del Rosso[r,q], L.S. Di Mauro[x], I. Di Palma[g,af], A.F. Díaz[an], D. Diego-Tortosa[x], C. Distefano[x], A. Domi[ao], C. Donzaud[k], D. Dornic[e], E. Drakopoulou[ap], D. Drouhin[c,be], J.-G. Ducoin[e], P. Duverne[k], R. Dvornický[v], T. Eberl[ao], E. Eckerová[v,u], A. Eddymaoui[z], T. van Eeden[w], M. Eff[k], D. van Eijk[w], I. El Bojaddaini[aq], S. El Hedri[k], S. El Mentawi[e], V. Ellajosyula[m], A. Enzenhöfer[e], M. Farino[ak], G. Ferrara[aj,x], M. D. Filipović[ar], F. Filippini[q], D. Franciotti[x], L. A. Fusco[aa,p], T. Gal[ao], J. García Méndez[j], A. Garcia Soto[f], C. Gatius Oliver[w], N. Geißelbrecht[ao], E. Genton[am], H. Ghaddari[aq], L. Gialanella[s,p], B. K. Gibson[t], E. Giorgio[x], I. Goos[k], P. Goswami[k], S. R. Gozzini[f], R. Gracia[ao], B. Guillon[n], C. Haack[ao], C. Hanna[ak], H. van Haren[as], E. Hazelton[ak], A. Heijboer[w], L. Hennig[ao], J.J. Hernández-Rey[f], A. Idrissi[x], W. Idrissi Ibnsalih[p], G. Illuminati[q], R. Jaimes[f], O. Janik[ao], D. Joly[e], M. de Jong[at,w], P. de Jong[ad,w], B.J. Jung[w], P. Kalaczyński[bg,au], U.F. Katz[ao], J. Keegans[t], V. Kikvadze[av], G. Kistauri[aw,av], C. Kopper[ao], A. Kouchner[ax,k], Y. Y. Kovalev[ay], L. Krupa[u], V. Kueviakoe[w], V. Kulikovskiy[m], R. Kvatadze[aw], M. Labalme[n], R. Lahmann[ao], M. Lamoureux[am], A. Langella[ak], G. Larosa[x], C. Lastoria[n], J. Lazar[am], A. Lazo[f], G. Lehaut[n], V. Lemaître[am], E. Leonora[y], N. Lessing[f], G. Levi[r,q], M. Lindsey Clark[k], F. Longhitano[y], S. Madarapu[f], F. Magnani[e], L. Malerba[m,l], F. Mamedov[u], A. Manfreda[p], A. Manousakis[az],

M. Marconi[l,m], A. Margiotta[r,q], A. Marinelli[ab,p], C. Markou[ap], L. Martin[i], M. Mastrodicasa[af,g], S. Mastroianni[p], J. Mauro[am], K.C.K. Mehta[au], G. Miele[ab,p], P. Migliozzi[p], E. Migneco[x], M.L. Mitsou[s,p], C.M. Mollo[p], L. Morales-Gallegos[s,p], N. Mori[b], A. Moussa[aq], I. Mozun Mateo[n], R. Muller[q], M.R. Musone[s,p], M. Musumeci[x], S. Navas[ba], A. Nayerhoda[al], C. A. Nicolau[g], B. Nkosi[ai], B. Ó Fearraigh[m], V. Oliviero[ab,p], A. Orlando[x], E. Oukacha[k], L. Pacini[b], D. Paesani[x], J. Palacios González[f], G. Papalashvili[al,av], P. Papini[b], V. Parisi[l,m], A. Parmar[n], C. Pastore[al], A. M. Păun[ac], G. E. Păvălaş[ac], S. Peña Martínez[k], M. Perrin-Terrin[e], V. Pestel[n], M. Petropavlova[u,bh], P. Piattelli[x], A. Plavin[ay,bi], C. Poirè[aa,p], V. Popa†[2][ac], T. Pradier[c], J. Prado[f], S. Pulvirenti[x], C.A. Quiroz-Rangel[j], N. Randazzo[y], A. Ratnani[bb], S. Razzaque[bc], I. C. Rea[p], D. Real[f], G. Riccobene[x], J. Robinson[o], A. Romanov[l,m,n], E. Ros[ay], A. Šaina[f], F. Salesa Greus[f], D. F. E. Samtleben[at,w], A. Sánchez Losa[f], S. Sanfilippo[x], M. Sanguineti[l,m], D. Santonocito[x], P. Sapienza[x], M. Scaringella[b], M. Scarnera[am,k], J. Schnabel[ao], J. Schumann[ao], J. Seneca[w], P. A. Sevle Myhr[am], I. Sgura[al], R. Shanidze[av], Chengyu Shao[bj,e], A. Sharma[k], Y. Shitov[u], F. Šimkovic[v], A. Simonelli[p], A. Sinopoulou[y], B. Spisso[p], M. Spurio[r,q], O. Starodubtsev[b], D. Stavropoulos[ap], I. Štekl[u], D. Stocco[i], M. Taiuti[l,m], Y. Tayalati[z,bb], H. Thiersen[o], I. Tosta e Melo[y,aj], B. Trocmé[k], V. Tsourapis[ap], C. Tully[ak], E. Tzamariudaki[ap], A. Ukleja[au], A. Vacheret[n], V. Valsecchi[x], V. Van Elewyck[ax,k], G. Vannoye[l,m], E. Vannuccini[b], G. Vasileiadis[bd], F. Vazquez de Sola[w], A. Veutro[g,af], S. Viola[x], D. Vivolo[s,p], A. van Vliet[d], E. de Wolf[ad,w], I. Lhenry-Yvon[k], S. Zavatarelli[m], D. Zito[x], J. D. Zornoza[f], and J. Zúñiga[f].

[a] Università di Firenze, Dipartimento di Fisica e Astronomia, via Sansone 1, Sesto Fiorentino, 50019 Italy
[b] INFN, Sezione di Firenze, via Sansone 1, Sesto Fiorentino, 50019 Italy
[c] Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France
[d] Khalifa University of Science and Technology, Department of Physics, PO Box 127788, Abu Dhabi, United Arab Emirates
[e] Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France
[f] IFIC - Instituto de Física Corpuscular (CSIC - Universitat de València), c/Catedrático José Beltrán, 2, 46980 Paterna, Valencia, Spain
[g] INFN, Sezione di Roma, Piazzale Aldo Moro, 2 - c/o Dipartimento di Fisica, Edificio, G.Marconi, Roma, 00185 Italy
[h] Universitat Politècnica de Catalunya, Laboratori d'Aplicacions Bioacústiques, Centre Tecnològic de Vilanova i la Geltrú, Avda. Rambla Exposició, s/n, Vilanova i la Geltrú, 08800 Spain
[i] Subatech, IMT Atlantique, IN2P3-CNRS, Nantes Université, 4 rue Alfred Kastler - La Chantrerie, Nantes, BP 20722 44307 France
[j] Universitat Politècnica de València, Instituto de Investigación para la Gestión Integrada de las Zonas Costeras, C/ Paranimf, 1, Gandia, 46730 Spain
[k] Université Paris Cité, CNRS, Astroparticule et Cosmologie, F-75013 Paris, France
[l] Università di Genova, Via Dodecaneso 33, Genova, 16146 Italy
[m] INFN, Sezione di Genova, Via Dodecaneso 33, Genova, 16146 Italy
[n] LPC CAEN, Normandie Univ, ENSICAEN, UNICAEN, CNRS/IN2P3, 6 boulevard Maréchal Juin, Caen, 14050 France
[o] North-West University, Centre for Space Research, Private Bag X6001, Potchefstroom, 2520 South Africa
[p] INFN, Sezione di Napoli, Complesso Universitario di Monte S. Angelo, Via Cintia ed. G, Napoli, 80126 Italy
[q] INFN, Sezione di Bologna, v.le C. Berti-Pichat, 6/2, Bologna, 40127 Italy
[r] Università di Bologna, Dipartimento di Fisica e Astronomia, v.le C. Berti-Pichat, 6/2, Bologna, 40127 Italy
[s] Università degli Studi della Campania "Luigi Vanvitelli", Dipartimento di Matematica e Fisica, viale Lincoln 5, Caserta, 81100 Italy
[t] E. A. Milne Centre for Astrophysics, University of Hull, Hull, HU6 7RX, United Kingdom
[u] Czech Technical University in Prague, Institute of Experimental and Applied Physics, Husova 240/5, Prague, 110 00 Czech Republic
[v] Comenius University in Bratislava, Department of Nuclear Physics and Biophysics, Mlynska dolina F1, Bratislava, 842 48 Slovak Republic
[w] Nikhef, National Institute for Subatomic Physics, PO Box 41882, Amsterdam, 1009 DB Netherlands
[x] INFN, Laboratori Nazionali del Sud, (LNS) Via S. Sofia 62, Catania, 95123 Italy
[y] INFN, Sezione di Catania, (INFN-CT) Via Santa Sofia 64, Catania, 95123 Italy
[z] University Mohammed V in Rabat, Faculty of Sciences, 4 av. Ibn Battouta, B.P. 1014, R.P. 10000 Rabat, Morocco
[aa] Università di Salerno e INFN Gruppo Collegato di Salerno, Dipartimento di Fisica, Via Giovanni Paolo II 132, Fisciano, 84084 Italy
[ab] Università di Napoli "Federico II", Dip. Scienze Fisiche "E. Pancini", Complesso Universitario di Monte S. Angelo, Via Cintia ed. G, Napoli, 80126 Italy
[ac] Institute of Space Science - INFLPR Subsidiary, 409 Atomistilor Street, Magurele, Ilfov, 077125 Romania
[ad] University of Amsterdam, Institute of Physics/IHEF, PO Box 94216, Amsterdam, 1090 GE Netherlands
[ae] TNO, Technical Sciences, PO Box 155, Delft, 2600 AD Netherlands
[af] Università La Sapienza, Dipartimento di Fisica, Piazzale Aldo Moro 2, Roma, 00185 Italy
[ag] Università di Bologna, Dipartimento di Ingegneria dell'Energia Elettrica e dell'Informazione "Guglielmo Marconi", Via dell'Università 50, Cesena, 47521 Italia
[ah] Cadi Ayyad University, Physics Department, Faculty of Science Semlalia, Av. My Abdellah, P.O.B. 2390, Marrakech, 40000 Morocco
[ai] University of the Witwatersrand, School of Physics, Private Bag 3, Johannesburg, Wits 2050 South Africa
[aj] Università di Catania, Dipartimento di Fisica e Astronomia "Ettore Majorana", (INFN-CT) Via Santa Sofia 64, Catania, 95123 Italy
[ak] Princeton University, Department of Physics, Jadwin Hall, Princeton, New Jersey, 08544 USA
[al] INFN, Sezione di Bari, via Orabona, 4, Bari, 70125 Italy

---

[2] Deceased

[am]UCLouvain, Centre for Cosmology, Particle Physics and Phenomenology, Chemin du Cyclotron, 2, Louvain-la-Neuve, 1348 Belgium
[an]University of Granada, Department of Computer Engineering, Automation and Robotics / CITIC, 18071 Granada, Spain
[ao]Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Erlangen Centre for Astroparticle Physics, Nikolaus-Fiebiger-Straße 2, 91058 Erlangen, Germany
[ap]NCSR Demokritos, Institute of Nuclear and Particle Physics, Ag. Paraskevi Attikis, Athens, 15310 Greece
[aq]University Mohammed I, Faculty of Sciences, BV Mohammed VI, B.P. 717, R.P. 60000 Oujda, Morocco
[ar]Western Sydney University, School of Science, Locked Bag 1797, Penrith, NSW 2751 Australia
[as]NIOZ (Royal Netherlands Institute for Sea Research), PO Box 59, Den Burg, Texel, 1790 AB, the Netherlands
[at]Leiden University, Leiden Institute of Physics, PO Box 9504, Leiden, 2300 RA Netherlands
[au]AGH University of Krakow, Al. Mickiewicza 30, 30-059 Krakow, Poland
[av]Tbilisi State University, Department of Physics, 3, Chavchavadze Ave., Tbilisi, 0179 Georgia
[aw]The University of Georgia, Institute of Physics, Kostava str. 77, Tbilisi, 0171 Georgia
[ax]Institut Universitaire de France, 1 rue Descartes, Paris, 75005 France
[ay]Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany
[az]University of Sharjah, Sharjah Academy for Astronomy, Space Sciences, and Technology, University Campus - POB 27272, Sharjah, - United Arab Emirates
[ba]University of Granada, Dpto. de Física Teórica y del Cosmos & C.A.F.P.E., 18071 Granada, Spain
[bb]School of Applied and Engineering Physics, Mohammed VI Polytechnic University, Ben Guerir, 43150, Morocco
[bc]University of Johannesburg, Department Physics, PO Box 524, Auckland Park, 2006 South Africa
[bd]Laboratoire Univers et Particules de Montpellier, Place Eugène Bataillon - CC 72, Montpellier Cédex 05, 34095 France
[be]Université de Haute Alsace, rue des Frères Lumière, 68093 Mulhouse Cedex, France
[bf]Université Badji Mokhtar, Département de Physique, Faculté des Sciences, Laboratoire de Physique des Rayonnements, B. P. 12, Annaba, 23000 Algeria
[bg]AstroCeNT, Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences, Rektorska 4, Warsaw, 00-614 Poland
[bh]Charles University, Faculty of Mathematics and Physics, Ovocný trh 5, Prague, 116 36 Czech Republic
[bi]Harvard University, Black Hole Initiative, 20 Garden Street, Cambridge, MA 02138 USA

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