PROCEEDINGS OF SCIENCE

Energy-Dependent Expectations for the Full KM3NeT/ARCA Detector: Application to Starburst Galaxies

W. I. Ibnsalih,[b,*] **A. Ambrosone,**[a,b] **A. Marinelli,**[a,b,e] **G. Miele,**[a,b,d] **P. Migliozzi**[b] **and M. R. Musone**[b,c] **for the KM3NeT collaboration**

[a] *Dipartimento di Fisica "Ettore Pancini", Università degli studi di Napoli "Federico II", Complesso Univ. Monte S. Angelo, I-80126 Napoli, Italy*
[b] *INFN - Sezione di Napoli, Complesso Univ. Monte S. Angelo, I-80126 Napoli, Italy*
[c] *Università degli studi della Campania Luigi Vanvitelli*
[d] *Scuola Superiore Meridionale, Università degli studi di Napoli "Federico II", Largo San Marcellino 10, 80138 Napoli, Italy*
[e] *INAF-Osservatorio Astronomico di Capodimonte, Salita Moiariello 16, I-80131 Naples, Italy*

E-mail: walid.idrissiibnsalih@unicampania.it, aambrosone@km3net.de

The energy-dependent expectations for the full KM3NeT/ARCA detector, both for diffuse and point-like signals are presented. For the diffuse analysis, the 90% C.L. quasi-differential sensitivity for 10 years of the full detector operations is computed, and compared with the IceCube measured diffuse spectrum. The whole energy range observable by ARCA $\sim$ (1 TeV $-$ 100 PeV) is taken into account, selecting upgoing track-like as well as all-sky cascade-like events. For the point-like analysis, the differential sensitivity for several declinations is computed, selecting upgoing tracks ν_μ and $\bar{\nu}_\mu$ charge-current interactions. Some particular starburst galaxies (SBGs) are considered such as NGC 1068, the Small Magellanic Cloud (SMC) and Circinus Galaxy. The resulting sensitvities demonstrate the importance of KM3NeT/ARCA to link star-forming processes with high-energy neutrino production within a few years of operation.

38th International Cosmic Ray Conference (ICRC2023)
26 July - 3 August, 2023
Nagoya, Japan

*Speaker

https://pos.sissa.it/

PoS(ICRC2023)1150

1. Introduction

The KM3NeT/ARCA is a water Cherenkov neutrino telescope under construction in the Mediterranian sea [1]. It will consist of two building blocks with 115 detector units each, with a total effective volume of $\sim 1\,\mathrm{Km}^3$. Given its median-latitude position, the detector will provide a complementary view of the sky with respect to IceCube. KM3NeT is expected to have full visibility for the southern hemispher and therefore for the galactic center [2]. In this proceeding, the energy-dependent expected sensitivities of the full KM3NeT/ARCA are reported, both for diffuse and point-like spectra after 10 years of operation. For the diffuse spectrum analysis, a binned likelihood ratio technique is employed in order to compute the 90% C.L. quasi-differential sensitivity, considering both upgoing tracks and all-sky cascades. A dedicated boosted decision trees (BDTs) is used in order to reject the background from atmospheric muons. All the neutrino flavours are taken into account for charged and neutral current interactions (see [2, 3] for details). For the point-like analysis, a cut & count technique is used to calculate the 90% C.L. quasi-differential sensitivity for sources on several declinations, showing the potential of KM3NeT/ARCA to constrain neutrino emission from point-like and extended SBG emission. In order to reach such a purpose, only upgoing ν_μ and $\bar{\nu}_\mu$ events are considered. Finally, some particular sources such as Starburst Galaxies are considered. Indeed, the expectations are presented for NGC 1068, whose neutrino emission evidence has recently increased up to 4.2σ over the null hypothesis [4]. Also, the Small Magellanic Cloud (SMC) and the Circinus Galaxy are considered, since they are situated in positions of the sky where KM3NeT/ARCA has full visibility and expected neutrino fluxes constrainable by KM3NeT/ARCA [5]. The resulting sensitivity demonstrate that KM3NeT/ARCA, in few years of operation, will be able to constrain the considered scenarios.

2. Diffuse Analysis: Simulations and Event-Selection

The analysis is based on the latest simulations of the Full KM3NeT/ARCA detector Monte Carlo files. In particular, neutrino simulations are performed through the gSeaGen code [6] and muons through the MuPage code [7]. The generated events are subject to the simulation of the light generation and the response of the detector and are reconstructed with the same algorithm used for actual data (see also [8] for further details). For the track-like and cascade events, the same selection explained in Ref. [3] are employed. In particular, for the tracks only those with reconstructed zenith angle $\theta \leq 100°$ are selected, in order to use the Earth as a shield to reduce the contamination of downgoing atmospheric muons. Furthermore, a dedicated BDT is employed in order to reduce the contamination of mis-reconstructed muons (muons which are downgoing but which are mis-reconstructed as upgoing). This allows for a selection with a reliable track reconstruction (see [8] for details about the performance of the event selection). For the the full-sky cascade selection, events satisfying the track selection requirement are removed and, in addition, only events contained withn the instrumented volume of the detector are considered(containment). A BDT has been employed also for the final step of the cascade selection (see [3] for details) in order to obtain a sample of events which are reliably reconstructed.

2.1 Likelihood Framework and Results

In order to evaluate the sensitivity, a binned maximum likelihood ratio framework is used. The likelihood is defined following Ref. [9] as:

$$\mathcal{L}(\lambda) = \prod_i P\left(n_i; \lambda\mu_i^{\text{Sig}} + \mu_i^{\text{Back}}\right) \tag{1}$$

where i runs over the 140 reconstructed energy bins. $P(n, \mu)$ is the Poisson PDF to observe n events with an expected value μ [9]. λ is a free-parameter which represents the signal strength (or normalization), μ_i^{Sig} is the expected number of signal events for a given i^{th} bin (in the case $\lambda = 1$) and finally μ_i^{Back} represents the expected number of background events for each bin. 10^4 pseudo experiments (PEs) are generated for different signal strengths and the test-statistics (TS) is defined as:

$$\text{TS} = \log \frac{\mathcal{L}(\tilde{\lambda})}{\mathcal{L}(\lambda = 0)} \tag{2}$$

where $\tilde{\lambda}$ is the signal strength which maximizes the likelihood for each pseudo experiment. We determine the PDF distribution of the TS for each signal strength. The Model rejection factor (MRF) is defined as the value of the signal strength λ_{90} for each:

$$\int_{TS_m}^{+\infty} d(\text{TS}|\lambda_{90})\text{dTS} = 90\% \tag{3}$$

where TS_m is the median distribution in the null hypothesis (only background) and $d(\text{TS}|\lambda_{90})$ is the PDF distribution for the TS for a given λ_{90} value. In other words, the sensitivity is defined as the signal strength for which 90% of the signal is above the median of the background-only distribution [9]. The TS is corrected (allowing for negative values of $\tilde{\lambda}$) in order to get always TS > 0. The final sensitivity is given by:

$$\phi_{90}(E) = \lambda_{90} \cdot \phi^{\text{Sig}}(E) \tag{4}$$

where $\phi^{\text{Sig}}(E)$ is the signal flux corresponding to $\lambda = 1$ (the final sensitivity does not depend on the normalization of the input signal spectrum, but only on its shape). For this contribution, the signal is considered as a E^{-2} spectrum binned over half-decade true energy bins. Fig. 1 shows the differential sensitivity after 10 years of operation for 2BB both for upgoing tracks and all-sky cascades. The sensitivities refer to one flavour of neutrinos + antineutrinos. They are compared with the corresponding IceCube measured spectra. In particular, the track sensitivity is compared with the 9.5 yr through-going muon flux [10] and the cascade sensitivity is compared with the 6 yr cascade flux [11]. Interestingly, the track sensitivity peaks around 1 PeV where there is a significant contribution from horizontal events. On the other hand, the cascade sensitivity peaks at 100 TeV, since the containment requirement harshly reduces the amount of signal events above this energy. For this reason, at high energies a better sensitivity is obtained for tracks compared to cascades, while at low energies the sensitivity is better for cascades due to the reduced background rate. The Result demonstrates the potential of KM3NeT/ARCA to constrain a diffuse spectrum outside the energy ranges where IceCube has measured it. Indeed, the spectrum is not well known below $\sim 10 - 15$ TeV and above ~ 1 PeV. Therefore, it is crucial to understand if it can be extrapolated also for lower energies as well as if it changes its shape. Indeed, as highlighted in Ref. [12], some tension is reported between the gamma-ray and neutrino data have tension due to the electromagnetic cascade contribution.

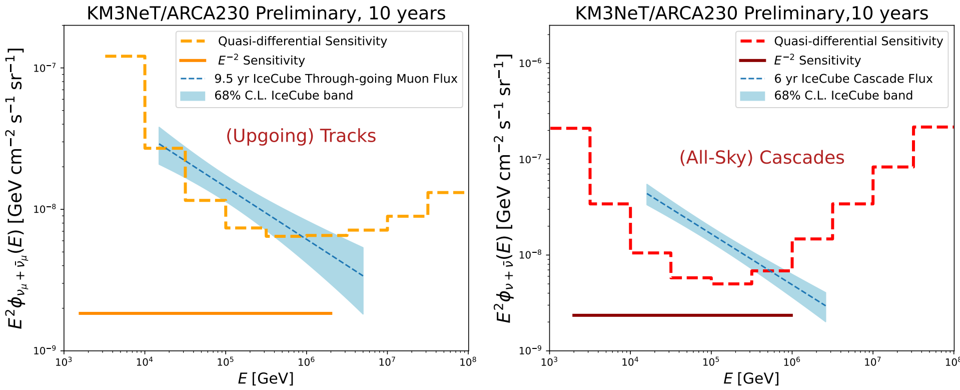

Figure 1: Left: 90% C.L. quasi-differential sensitivity (per neutrino flavour) for KM3NeT/ARCA after 10 years of operation and 2BB for a diffuse spectrum for upgoing tracks (dashed orange line). The continuous orange line shows the integrated sensitivity for a E^{-2} diffuse spectrum. The sensitivities are compared with the corresponding 9.5 yr diffuse spectrum measurement by the IceCube Collaboration in the through-going muon channel [10]. **right**: 90% C.L. quasi-differential sensitivity (per neutrino flavour) for KM3NeT/ARCA after 10 years of operation and 2BB for a diffuse spectrum for the all-sky contained cascades (dashed red line). The integrated sensitivity for a E^{-2} diffuse spectrum is shown with the continuous dark red line. The sensitivities are compared with the corresponding 6 yr cascade flux measured by the IceCube collaboration [11].

3. Point-Like Analysis

Regarding the Point-Like Analysis, particular SBGs are considered in order to to evaluate the KM3NeT/ARCA expectations: NGC 1068, SMC and Circinus Galaxy. For such a purpose, a simple cut & count technique is used in order to optimize the event selection. The same event selection explained in Ref. [3] is employed. In particular, the sensitivity is defined as the average upper limit evaluated through the 90% C.L. Felmand and Cousins upper limits [13]. Given an astrophysical flux ϕ^{Sig}, the sensitivity is

$$\phi_{90} = \frac{\mu_{90}}{n_s} \cdot \phi^{\text{Sig}} \tag{5}$$

where n_s is the expected number of signal events induced by the astrophysical flux and μ_{90} is the average upper limit. μ_{90}/n_s is defined as the Model Rejection Factor (MRF). The minimization of the MRF is performed over the cone angle (α) and track reconstruction related variables such as the likelikood (Λ), the angular error (β) and the track length (Len). A final optimization over a reconstructed energy range $[E_{\text{min}}, E_{\text{max}}]$ is used to further optimize the selection of signal events.

NGC 1068

NGC 1068 is a nearby SBG located 10 – 14 Mpc [15] away from the Earth and it also shows Seyfert Galaxy activity [16]. The IceCube collaboration has recently found compelling evidence for neutrino emission along the direction of this source measuring 79 astrophysical neutrino events with a significance at 4.2σ [4]. The sensitivity and the discovery potential for this source is shown in Fig. 2.

Firstly, on the left, the 90% C.L. quasi-differential sensitivity (orange line) is compared with the IceCube measured band [4]. Given the importance of this source, the model discovery potential

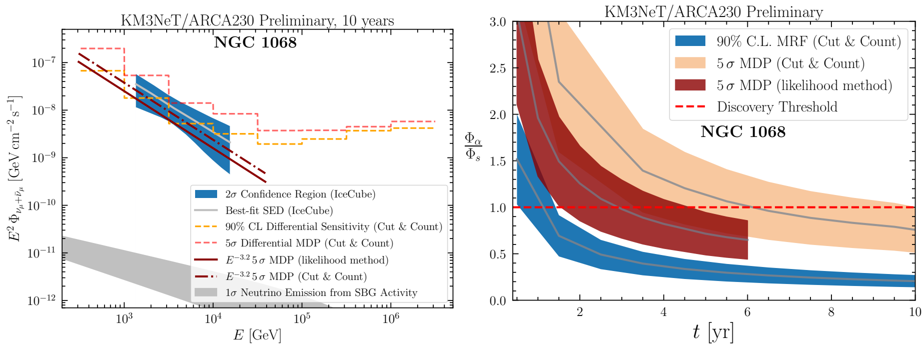

Figure 2: Left: 90% C.L. quasi-differential sensitivity (dashed orange line), the 5σ differential MDP (dashed red line) and finally the integrated 5σ MDP for a $E^{-3.2}$ spectrum, obtained both with the Cut & count approach (dashed dotted dark red line) and with the Binned Likelihood Ratio (continous dark red line). It is also shown the the IceCube 2σ region [4]. Furthermore, the neutrino expectations from SBG activity are shown according to the analysis of Ref. [5]. **Right**: The integrated MRF (blue band) and the MDP (orange band for cut & count and dark red band for the Binned likelihood ratio) are shown as functions of the KM3NeT/ARCA operation time. The bands correspond to the 1σ uncertainty provided by the normalization uncertainty provided by the IceCube fit ([4]).

(MDP) is reported, defined as the minimum flux needed for a 5σ discovery in the 50% of cases (see [2] for more details). In order to compute it, the event selection is optimized in order to produce the minimum MDP for each bin. The integrated MDP for a $E^{-3.2}$ spectrum (dashed dotted dark red line) is reported. For this particular quantity, it has been calculated both with Cut & Count and binned likelihood ratio (see [14] for details). The integrated MRF and MDP are shown as functions of the KM3NeT/ARCA operation time. The result demonstrates that, after few years, KM3NeT/ARCA is expected to discover the IceCube flux. Indeed, the binned likelihood ratio method provides a strong improvement with respect to the cut & count method. So, further improvements are also expected for the energy-dependent sensitivity. Finally, the result shows that the energy-dependent sensitivity peaks at ~ 100 TeV for this particular position in the sky.

The Small Magellanic Cloud (SMC)

SMC is a very nearby star-forming galaxy which exhibits a hard gamma-ray spectrum up to 1 TeV, which could be attributed to its star forming activity [16]. The importance for studying this source with KM3NeT/ARCA and the potential to significantly constrain the theoretical models has been pointed out in Ref. [5]. In this contribution, in order to evaluate the sensitivity, the source is simulated as a disk of radius $r = 0.5°$ (therefore a total extension of $\sim 1°$) which is consistent also with the Fermi-LAT observations [16]. The expected sensitivity is shown in Fig. 3 (for 2 BB after 20 years of operation) compared with theoretical neutrino expectations according to [5]. The integrated MRF is shown as a function of time. In this case, it will take a couple of decades in order to produce an upper limit. It is worth mentioning that if the neutrino emission is concentrated in a smaller region of the galaxy effectively, the expectations will improve. Even in case no neutrino excess will be found, it will be important to constrain the hadronic budget of this source at 1 – 10 TeV.

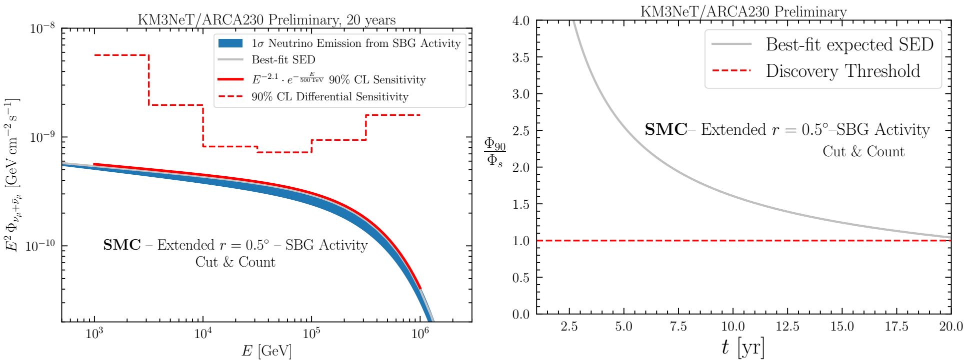

Figure 3: Left: Theoretical neutrino expectations according to Ref. [5] with the corresponding integrated and differential sensitivity after 20 years of operation with 2BB. **Right**: The integrated MRF is shown as a function of the KM3NeT/ARCA operation time (for 2BB).

Furthemore, further analysis using a likelihood framework is also expected to significantly improve the expectations.

Circinus Galaxy

Circinus Galaxy is a nearby SBG situated 4 Mpc away from the Earth [15] in a region of the sky where KM3NeT/ARCA is expected to have full visibility [3]. It has also AGN actvity just like NGC 1068 with Seyfert Galaxy activity. Therefore, it might be the perfect candidate not only to study SBG emissions, but also to understand if other seyfert galaxies have similar emission as NGC 1068. It is also noteworthy to remark that this particular source is nearer than NGC 1068, thereby providing better prospects for future discovery for this source. The resulting sensitivity is shown in Fig. 4. Analogously to SMC, the neutrino expectations from SBG activity ([5]) are compared

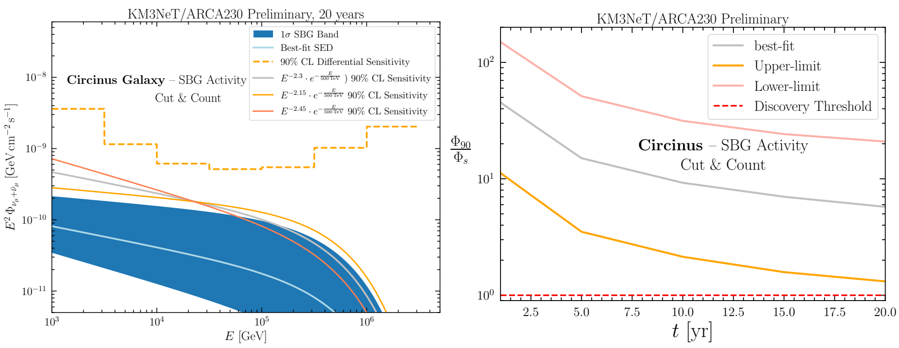

Figure 4: Left: Theoretical neutrino expectations from the SBG activity according to Ref. [5] compared with the corresponding integrated and differential sensitivity after 20 years and 2BB. **Right**: The integrated MRF is shown as a function of the KM3NeT/ARCA operation time (for 2BB).

with the corresponding integrated and differential sensitivities. The expectations are less promising since this source has a lower flux compared to SMC. However, a potential AGN component might significantly increase the normalization of the flux, leading to much better expectations.

3.1 Sensitivities for Different Positions in the Sky

The differential sensitivity after 10 years and 2BB for different declinations is shown in Fig. 5. The result highlights how the KM3NeT/ARCA expectations vary along different position in the sky.

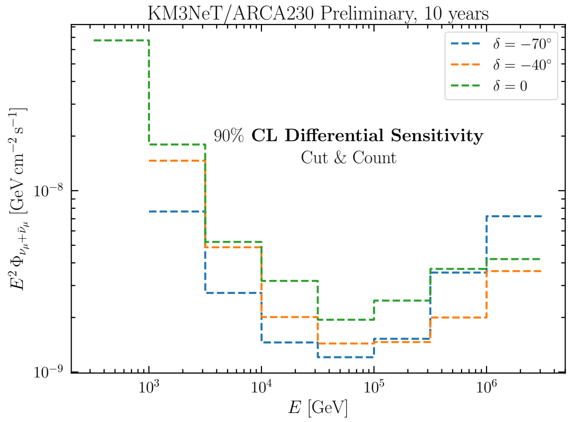

Figure 5: 90% C.L. Quasi-differential sensitivity for point-like emission for several positions in the sky. The cut & count method is used and the sensitivity refers to one flavour of neutrinos and antineutrinos.

4. Conclusions

The potential of the full KM3NeT/ARCA to discover diffuse and point-like spectra has been presented in this contribution. The result highlights that the upcoming detector will be able to strengthen IceCube's observations, confirming measured spectral features in few years of operation. KM3NeT/ARCA will also be able to detect neutrinos from nearby starburst galaxies. It is worth emphasizing that the expectations are going to improve with future event selections able to better reject the background and with more sophisticated statistical treatment of the data. For instance, a maximum likelihood ratio framework might improve the point-like sensitivity, thereby reducing the time needed for discovery for NGC 1068 and for constraints on the other sources. Nonetheless, already with cut & count method, it is clear that KM3NeT/ARCA will pave the way for a new era of the multi-messenger astronomy.

References

[1] S. Adrian-Martinez *et al.* [KM3Net], J. Phys. G **43**, no.8, 084001 (2016) doi:10.1088/0954-3899/43/8/084001 [arXiv:1601.07459 [astro-ph.IM]].

[2] S. Aiello *et al.* [KM3NeT], Astropart. Phys. **111**, 100-110 (2019) doi:10.1016/j.astropartphys.2019.04.002 [arXiv:1810.08499 [astro-ph.HE]].

[3] A. Ambrosone, W. I. Ibnsalih, A. Marinelli, G. Miele, P. Migliozzi and M. R. Musone, EPJ Web Conf. **280**, 03001 (2023) doi:10.1051/epjconf/202328003001

[4] R. Abbasi *et al.* [IceCube], Science **378**, no.6619, 538-543 (2022) doi:10.1126/science.abg3395 [arXiv:2211.09972 [astro-ph.HE]].

[5] A. Ambrosone, M. Chianese, D. F. G. Fiorillo, A. Marinelli and G. Miele, Astrophys. J. Lett. **919**, no.2, L32 (2021) doi:10.3847/2041-8213/ac25ff [arXiv:2106.13248 [astro-ph.HE]].

[6] Aiello, S., Albert, A., Garre, S. A., et al. 2020, Computer Physics Communications, 256, 107477. doi:10.1016/j.cpc.2020.107477

[7] G. Carminati, A. Margiotta and M. Spurio, Comput. Phys. Commun. **179**, 915-923 (2008) doi:10.1016/j.cpc.2008.07.014 [arXiv:0802.0562 [physics.ins-det]].

[8] A. G. Soto *et al.* [KM3NeT], JINST **16**, no.09, C09030 (2021) doi:10.1088/1748-0221/16/09/C09030 [arXiv:2107.13050 [astro-ph.IM]].

[9] M. G. Aartsen *et al.* [IceCube], Phys. Rev. D **98**, no.6, 062003 (2018) doi:10.1103/PhysRevD.98.062003 [arXiv:1807.01820 [astro-ph.HE]].

[10] R. Abbasi *et al.* [IceCube], Astrophys. J. **928**, no.1, 50 (2022) doi:10.3847/1538-4357/ac4d29 [arXiv:2111.10299 [astro-ph.HE]].

[11] M. G. Aartsen *et al.* [IceCube], Phys. Rev. Lett. **125**, no.12, 121104 (2020) doi:10.1103/PhysRevLett.125.121104 [arXiv:2001.09520 [astro-ph.HE]].

[12] K. Fang, J. S. Gallagher and F. Halzen, Astrophys. J. **933**, no.2, 190 (2022) doi:10.3847/1538-4357/ac7649 [arXiv:2205.03740 [astro-ph.HE]].

[13] G. J. Feldman and R. D. Cousins, Phys. Rev. D **57**, 3873-3889 (1998) doi:10.1103/PhysRevD.57.3873 [arXiv:physics/9711021 [physics.data-an]].

[14] Thijs Juan van Eeden [KM3NeT], "Astronomy potential of KM3NeT/ARCA," PoS(ICRC2023)1075

[15] P. Kornecki, L. J. Pellizza, S. del Palacio, A. L. Müller, J. F. Albacete-Colombo and G. E. Romero, Astron. Astrophys. **641**, A147 (2020) doi:10.1051/0004-6361/202038428 [arXiv:2007.07430 [astro-ph.HE]].

[16] M. Ajello, M. Di Mauro, V. S. Paliya and S. Garrappa, Astrophys. J. **894**, no.2, 88 (2020) doi:10.3847/1538-4357/ab86a6 [arXiv:2003.05493 [astro-ph.GA]].

Full Authors List: The KM3NeT Collaboration

S. Aiello[a], A. Albert[b,bd], S. Alves Garre[c], Z. Aly[d], A. Ambrosone[f,e], F. Ameli[g], M. Andre[h], E. Androutsou[i], M. Anguita[j], L. Aphecetche[k], M. Ardid[l], S. Ardid[l], H. Atmani[m], J. Aublin[n], L. Bailly-Salins[o], Z. Bardačová[q,p], B. Baret[n], A. Bariego-Quintana[c], S. Basegmez du Pree[r], Y. Becherini[n], M. Bendahman[m,n], F. Benfenati[t,s], M. Benhassi[u,e], D. M. Benoit[v], E. Berbee[r], V. Bertin[d], S. Biagi[w], M. Boettcher[x], D. Bonanno[w], J. Boumaaza[m], M. Bouta[y], M. Bouwhuis[r], C. Bozza[z,e], R. M. Bozza[f,e], H.Brânzaş[aa], F. Bretaudeau[k], R. Bruijn[ab,r], J. Brunner[d], R. Bruno[a], E. Buis[ac,r], R. Buompane[u,e], J. Busto[d], B. Caiffi[ad], D. Calvo[c], S. Campion[g,ae], A. Capone[g,ae], F. Carenini[t,s], V. Carretero[c], T. Cartraud[n], P. Castaldi[af,s], V. Cecchini[c], S. Celli[g,ae], L. Cerisy[d], M. Chabab[ag], M. Chadolias[ah], A. Chen[ai], S. Cherubini[aj,w], T. Chiarusi[s], M. Circella[ak], R. Cocimano[w], J. A. B. Coelho[n], A. Coleiro[n], R. Coniglione[w] P. Coyle[d], A. Creusot[n], A. Cruz[al], G. Cuttone[w], R. Dallier[k], Y. Darras[ah], A. De Benedittis[e], B. De Martino[d], V. Decoene[k], R. Del Burgo[e], U.M. Di Cerbo[e], L.S. Di Mauro[w], I. Di Palma[g,ae], A.F. Díaz[j], C. Diaz[j], D. Diego-Tortosa[w], C. Distefano[w], A. Domi[ah], C. Donzaud[n], D. Dornic[d], M. Dörr[am], E. Drakopoulou[i], D. Drouhin[b,bd], R. Dvornický[q], T. Eberl[ah], E. Eckerová[q,p], A. Eddymaoui[m], T. van Eeden[r], M. Eff[n], D. van Eijk[r], I. El Bojaddaini[y], S. El Hedri[n], A. Enzenhöfer[d], G. Ferrara[w], M. D. Filipović[an], F. Filippini[t,s], D. Franciotti[w], L.A. Fusco[z,e], J. Gabriel[ao], S. Gagliardini[g], T. Gal[ah], J. García Méndez[l], A. Garcia Soto[c], C. Gatius Oliver[r], N. Geißelbrecht[ah], H. Ghaddari[y], L. Gialanella[e,u], B. K. Gibson[v], E. Giorgio[w], I. Goos[n], D. Goupilliere[o], S.R. Gozzini[c], R. Gracia[ah], K. Graf[ah], C. Guidi[ap,ad], B. Guillon[o], M. Gutiérrez[aq], H. van Haren[ar], A. Heijboer[r], A. Hekalo[am], L. Hennig[ah], J. J. Hernández-Rey[c], F. Huang[d], W. Idrissi Ibnsalih[e], G. Illuminati[s], C. W. James[al], M. de Jong[as,r], P. de Jong[ab,r], B. J. Jung[r], P. Kalaczyński[at,be], O. Kalekin[ah], U. F. Katz[ah], N. R. Khan Chowdhury[c], A. Khatun[q], G. Kistauri[av,au], C. Kopper[ah], A. Kouchner[aw,n], V. Kulikovskiy[ad], R. Kvatadze[av], M. Labalme[o], R. Lahmann[ah], G. Larosa[w], C. Lastoria[d], A. Lazo[c], S. Le Stum[d], G. Lehaut[o], E. Leonora[a], N. Lessing[c], G. Levi[t,s], M. Lindsey Clark[n], F. Longhitano[a], J. Majumdar[r], L. Malerba[ad], F. Mamedov[p], J. Mańczak[c], A. Manfreda[e], M. Marconi[ap,ad], A. Margiotta[t,s], A. Marinelli[e,f], C. Markou[i], L. Martin[k], J. A. Martínez-Mora[l], F. Marzaioli[u,e], M. Mastrodicasa[ae,g], S. Mastroianni[e], S. Micciché[w], G. Miele[f,e], P. Migliozzi[e], E. Migneco[w], M.L. Mitsou[e], C.M. Mollo[e], L. Morales-Gallegos[u,e], C. Morley-Wong[al], A. Moussa[y], I. Mozun Mateo[ay,ax], R. Muller[r], M.R. Musone[e,u], M. Musumeci[w], L. Nauta[r], S. Navas[aq], A. Nayerhoda[ak], C.A. Nicolau[g], B. Nkosi[ai], B. Ó Fearraigh[ab,r], V. Oliviero[f,e], A. Orlando[w], E. Oukacha[n], D. Paesani[w], J. Palacios González[c], G. Papalashvili[au], V. Parisi[ap,ad], E.J. Pastor Gomez[c], A. M. Păun[aa], G. E. Păvălaş[aa], S. Peña Martínez[n], M. Perrin-Terrin[d], J. Perronnel[o], V. Pestel[ay], R. Pestes[n], P. Piattelli[w], C. Poirè[z,e], V. Popa[aa], T. Pradier[b], S. Pulvirenti[w], G. Quéméner[o], C. Quiroz[l], U. Rahaman[c], N. Randazzo[a], R. Randriatoamanana[k], S. Razzaque[az], I.C. Rea[e], D. Real[c], S. Reck[ah], G. Riccobene[w], J. Robinson[x], A. Romanov[ap,ad], A. Šaina[c], F. Salesa Greus[c], D. F. E. Samtleben[as,r], A. Sánchez Losa[c,ak], S. Sanfilippo[w], M. Sanguineti[ap,ad], C. Santonastaso[ba,e], D. Santonocito[w], P. Sapienza[w], J. Schnabel[ah], J. Schumann[ah], H. M. Schutte[x], J. Seneca[r], N. Sennan[y], B. Setter[ah], I. Sgura[ak], R. Shanidze[au], Y. Shitov[p], F. Šimkovic[q], A. Simonelli[e], A. Sinopoulou[a], M.V. Smirnov[ah], B. Spisso[e], M. Spurio[t,s], D. Stavropoulos[i], I. Štekl[p], M. Taiuti[ap,ad], Y. Tayalati[m], H. Tedjditi[ad], H. Thiersen[x], I. Tosta e Melo[a,aj], B. Trocmé[n], V. Tsourapis[i], E. Tzamariudaki[i], A. Vacheret[o], V. Valsecchi[w], V. Van Elewyck[aw,n], G. Vannoye[d], G. Vasileiadis[bb], F. Vazquez de Sola[r], C. Verilhac[n], A. Veutro[g,ae], S. Viola[w], D. Vivolo[u,e], J. Wilms[bc], E. de Wolf[ab,r], H. Yepes-Ramirez[l], G. Zarpapis[i], S. Zavatarelli[ad], A. Zegarelli[g,ae], D. Zito[w], J. D. Zornoza[c], J. Zúñiga[c], and N. Zywucka[x].

[a] INFN, Sezione di Catania, Via Santa Sofia 64, Catania, 95123 Italy
[b] Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France
[c] IFIC - Instituto de Física Corpuscular (CSIC - Universitat de València), c/Catedrático José Beltrán, 2, 46980 Paterna, Valencia, Spain
[d] Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France
[e] INFN, Sezione di Napoli, Complesso Universitario di Monte S. Angelo, Via Cintia ed. G, Napoli, 80126 Italy
[f] Università di Napoli "Federico II", Dip. Scienze Fisiche "E. Pancini", Complesso Universitario di Monte S. Angelo, Via Cintia ed. G, Napoli, 80126 Italy
[g] INFN, Sezione di Roma, Piazzale Aldo Moro 2, 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] NCSR Demokritos, Institute of Nuclear and Particle Physics, Ag. Paraskevi Attikis, Athens, 15310 Greece
[j] University of Granada, Dept. of Computer Architecture and Technology/CITIC, 18071 Granada, Spain
[k] Subatech, IMT Atlantique, IN2P3-CNRS, Université de Nantes, 4 rue Alfred Kastler - La Chantrerie, Nantes, BP 20722 44307 France
[l] Universitat Politècnica de València, Instituto de Investigación para la Gestión Integrada de las Zonas Costeras, C/ Paranimf, 1, Gandia, 46730 Spain
[m] University Mohammed V in Rabat, Faculty of Sciences, 4 av. Ibn Battouta, B.P. 1014, R.P. 10000 Rabat, Morocco
[n] Université Paris Cité, CNRS, Astroparticule et Cosmologie, F-75013 Paris, France
[o] LPC CAEN, Normandie Univ, ENSICAEN, UNICAEN, CNRS/IN2P3, 6 boulevard Maréchal Juin, Caen, 14050 France
[p] Czech Technical University in Prague, Institute of Experimental and Applied Physics, Husova 240/5, Prague, 110 00 Czech Republic
[q] Comenius University in Bratislava, Department of Nuclear Physics and Biophysics, Mlynska dolina F1, Bratislava, 842 48 Slovak Republic
[r] Nikhef, National Institute for Subatomic Physics, PO Box 41882, Amsterdam, 1009 DB Netherlands
[s] INFN, Sezione di Bologna, v.le C. Berti-Pichat, 6/2, Bologna, 40127 Italy
[t] Università di Bologna, Dipartimento di Fisica e Astronomia, v.le C. Berti-Pichat, 6/2, Bologna, 40127 Italy
[u] Università degli Studi della Campania "Luigi Vanvitelli", Dipartimento di Matematica e Fisica, viale Lincoln 5, Caserta, 81100 Italy
[v] E. A. Milne Centre for Astrophysics, University of Hull, Hull, HU6 7RX, United Kingdom

[w] INFN, Laboratori Nazionali del Sud, Via S. Sofia 62, Catania, 95123 Italy
[x] North-West University, Centre for Space Research, Private Bag X6001, Potchefstroom, 2520 South Africa
[y] University Mohammed I, Faculty of Sciences, BV Mohammed VI, B.P. 717, R.P. 60000 Oujda, Morocco
[z] Università di Salerno e INFN Gruppo Collegato di Salerno, Dipartimento di Fisica, Via Giovanni Paolo II 132, Fisciano, 84084 Italy
[aa] ISS, Atomistilor 409, Măgurele, RO-077125 Romania
[ab] University of Amsterdam, Institute of Physics/IHEF, PO Box 94216, Amsterdam, 1090 GE Netherlands
[ac] TNO, Technical Sciences, PO Box 155, Delft, 2600 AD Netherlands
[ad] INFN, Sezione di Genova, Via Dodecaneso 33, Genova, 16146 Italy
[ae] Università La Sapienza, Dipartimento di Fisica, Piazzale Aldo Moro 2, Roma, 00185 Italy
[af] Università di Bologna, Dipartimento di Ingegneria dell'Energia Elettrica e dell'Informazione "Guglielmo Marconi", Via dell'Università 50, Cesena, 47521 Italia
[ag] Cadi Ayyad University, Physics Department, Faculty of Science Semlalia, Av. My Abdellah, P.O.B. 2390, Marrakech, 40000 Morocco
[ah] Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Erlangen Centre for Astroparticle Physics, Nikolaus-Fiebiger-Straße 2, 91058 Erlangen, Germany
[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", Via Santa Sofia 64, Catania, 95123 Italy
[ak] INFN, Sezione di Bari, via Orabona, 4, Bari, 70125 Italy
[al] International Centre for Radio Astronomy Research, Curtin University, Bentley, WA 6102, Australia
[am] University Würzburg, Emil-Fischer-Straße 31, Würzburg, 97074 Germany
[an] Western Sydney University, School of Computing, Engineering and Mathematics, Locked Bag 1797, Penrith, NSW 2751 Australia
[ao] IN2P3, LPC, Campus des Cézeaux 24, avenue des Landais BP 80026, Aubière Cedex, 63171 France
[ap] Università di Genova, Via Dodecaneso 33, Genova, 16146 Italy
[aq] University of Granada, Dpto. de Física Teórica y del Cosmos & C.A.F.P.E., 18071 Granada, Spain
[ar] NIOZ (Royal Netherlands Institute for Sea Research), PO Box 59, Den Burg, Texel, 1790 AB, the Netherlands
[as] Leiden University, Leiden Institute of Physics, PO Box 9504, Leiden, 2300 RA Netherlands
[at] National Centre for Nuclear Research, 02-093 Warsaw, Poland
[au] Tbilisi State University, Department of Physics, 3, Chavchavadze Ave., Tbilisi, 0179 Georgia
[av] The University of Georgia, Institute of Physics, Kostava str. 77, Tbilisi, 0171 Georgia
[aw] Institut Universitaire de France, 1 rue Descartes, Paris, 75005 France
[ax] IN2P3, 3, Rue Michel-Ange, Paris 16, 75794 France
[ay] LPC, Campus des Cézeaux 24, avenue des Landais BP 80026, Aubière Cedex, 63171 France
[az] University of Johannesburg, Department Physics, PO Box 524, Auckland Park, 2006 South Africa
[ba] Università degli Studi della Campania "Luigi Vanvitelli", CAPACITY, Laboratorio CIRCE - Dip. Di Matematica e Fisica - Viale Carlo III di Borbone 153, San Nicola La Strada, 81020 Italy
[bb] Laboratoire Univers et Particules de Montpellier, Place Eugène Bataillon - CC 72, Montpellier Cédex 05, 34095 France
[bc] Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Remeis Sternwarte, Sternwartstraße 7, 96049 Bamberg, Germany
[bd] Université de Haute Alsace, rue des Frères Lumière, 68093 Mulhouse Cedex, France
[be] AstroCeNT, Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences, Rektorska 4, Warsaw, 00-614 Poland

Acknowledgements

The authors acknowledge the financial support of the funding agencies: Agence Nationale de la Recherche (contract ANR-15-CE31-0020), Centre National de la Recherche Scientifique (CNRS), Commission Européenne (FEDER fund and Marie Curie Program), LabEx UnivEarthS (ANR-10-LABX-0023 and ANR-18-IDEX-0001), Paris Île-de-France Region, France; Shota Rustaveli National Science Foundation of Georgia (SRNSFG, FR-22-13708), Georgia; The General Secretariat of Research and Innovation (GSRI), Greece Istituto Nazionale di Fisica Nucleare (INFN), Ministero dell'Università e della Ricerca (MIUR), PRIN 2017 program (Grant NAT-NET 2017W4HA7S) Italy; Ministry of Higher Education, Scientific Research and Innovation, Morocco, and the Arab Fund for Economic and Social Development, Kuwait; Nederlandse organisatie voor Wetenschappelijk Onderzoek (NWO), the Netherlands; The National Science Centre, Poland (2021/41/N/ST2/01177); The grant "AstroCeNT: Particle Astrophysics Science and Technology Centre", carried out within the International Research Agendas programme of the Foundation for Polish Science financed by the European Union under the European Regional Development Fund; National Authority for Scientific Research (ANCS), Romania; Grants PID2021-124591NB-C41, -C42, -C43 funded by MCIN/AEI/ 10.13039/501100011033 and, as appropriate, by "ERDF A way of making Europe", by the "European Union" or by the "European Union NextGenerationEU/PRTR", Programa de Planes Complementarios I+D+I (refs. ASFAE/2022/023, ASFAE/2022/014), Programa Prometeo (PROMETEO/2020/019) and GenT (refs. CIDEGENT/2018/034, /2019/043, /2020/049. /2021/23) of the Generalitat Valenciana, Junta de Andalucía (ref. SOMM17/6104/UGR, P18-FR-5057), EU: MSC program (ref. 101025085), Programa María Zambrano (Spanish Ministry of Universities, funded by the European Union, NextGenerationEU), Spain; The European Union's Horizon 2020 Research and Innovation Programme (ChETEC-INFRA - Project no. 101008324).