PROCEEDINGS OF SCIENCE

Search for a diffuse astrophysical neutrino flux from the Galactic Ridge using KM3NeT/ARCA data

Francesco Filippini[a,b,*] **on behalf of the KM3NeT collaboration**

[a] *Università di Bologna, Dipartimento di Fisica e Astronomia, v.le C. Berti-Pichat, 6/2, Bologna, 40127, Italy*

[b] *INFN, Sezione di Bologna, v.le C. Berti-Pichat, 6/2, Bologna, 40127, Italy*

E-mail: francesco.filippini9@unibo.it

Several theoretical models predict and describe the properties of part of the diffuse neutrino flux, originating from the interaction of Galactic cosmic rays with the interstellar medium matter located in the centre of our Galaxy. This neutrino flux is expected to be of the same order of magnitude as the diffuse γ-ray flux measured by Fermi-LAT, close to the Galactic plane. Recently hints by the ANTARES Collaboration, at a significance level over 2 σ, and the observation by the IceCube Collaboration, at a significance level of 4.5 σ, of a high-energy neutrino emission from the Galactic plane have been reported. For these reasons, and considering the privileged position of the KM3NeT/ARCA telescope, being located in the Northern hemisphere, data have been analysed searching for a possible excess of events coming from an extended region, with Galactic coordinates $|l| < 30°$ and $|b| < 2°$, namely the Galactic Ridge. In this contribution, the result of the analysis exploiting data gathered with KM3NeT/ARCA in the period in which comprises 6, 8, 19 or 21 active detection units is presented, showing the capabilities and performance of KM3NeT.

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

*Speaker

https://pos.sissa.it/

PoS(ICRC2023)1190

1. Introduction

1.1 Diffuse neutrino emission from the Galactic Ridge

The Galactic plane is the most evident source in the sky in all the electromagnetic wavelengths. These photons can be produced either in specific point sources, positioned on the Galactic plane, or by the interaction of cosmic rays (CRs) with the interstellar medium matter (ISM), located in the center of our Galaxy. A significant fraction of energy released during these interaction processes is transformed into short living particles, that can decay into γ-rays and neutrinos. While photons can be produced by energy-losses of electrons, interacting with magnetic fields or ISM, neutrinos can be produced only in the decays of particles produced in hadronic interactions, representing therefore a unique probe of acceleration and interaction sites of CRs. Several theoretical models have been developed in the past years, to try to constrain the flux of neutrinos originated inside the Galactic plane [1–3]. The strict relation that link γ-rays and neutrinos, produced via hadronic interactions, allows to constrain the expected neutrino fluxes thanks to measured CRs local properties and to γ-rays measurements themselves, performed both by space-based telescopes and by detectors located on Earth. In the specific, the predicted neutrino flux is expected to be of the same order of the γ-ray one, and in the innermost part of the Galactic plane, defined here $|l| < 30°$ and $|b| < 2°$, namely the Galactic Ridge, the CRs spectrum should be described by a harder spectral index with respect to the one locally measured at Earth. The ANTARES Collaboration reported an excess of events coming from the Galactic Ridge incompatible with the background expectation at $\sim 96\%$ confidence level [4], and at the end of June 2023, IceCube Collaboration has reported the first observation of high-energy neutrinos from the Galactic plane, with a statistical significance of 4.5 σ [5].

1.2 KM3NeT neutrino telescope

KM3NeT[1] is the next-generation neutrino telescope project that will instrument, in its final configuration, an overall volume of several cubic kilometres of sea water [6]. KM3NeT comprise two different instrumented regions, placed in separate locations: KM3NeT/ARCA[2], off-shore the Sicilian coast at a depth of about 3500 m, optimised for searching of neutrinos from astrophysical sources, and KM3NeT/ORCA[3], off-shore the French south coast, that will study neutrino properties exploiting atmospheric neutrinos. The two detectors share the same technology and neutrino detection principle: namely a 3D array of photosensors, called digital optical modules (DOM) [7], capable to detect the Cherenkov light produced by relativistic particles emerging from neutrino interactions. The main difference between the two detectors consists in the density of photosensors, which is optimised for the study of neutrinos in the few-GeV region for ORCA and the TeV-PeV energy range for ARCA. The detectors are built with detection units (DUs), which stand on the sea bottom and comprise 18 DOMs each. In its final configuration the KM3NeT/ARCA telescope will consist of two building blocks of 115 vertical detection units each. Both sites however are in the Northern hemisphere at a latitude between 36° and 43° North, allowing to observe upgoing events coming from most of the sky. In fact, looking at the KM3NeT sky coverage, reported in Figure 1,

[1]KM3NeT is an acronym for 'Cubic Kilometre Neutrino Telescope'
[2]ARCA stands for Astroparticle Research with Cosmics in the Abyss
[3]ORCA stands for Oscillation Research with Cosmics in the Abyss

we can see that most of the galactic plane, including the Galactic Ridge, is fully visible through upgoing events.

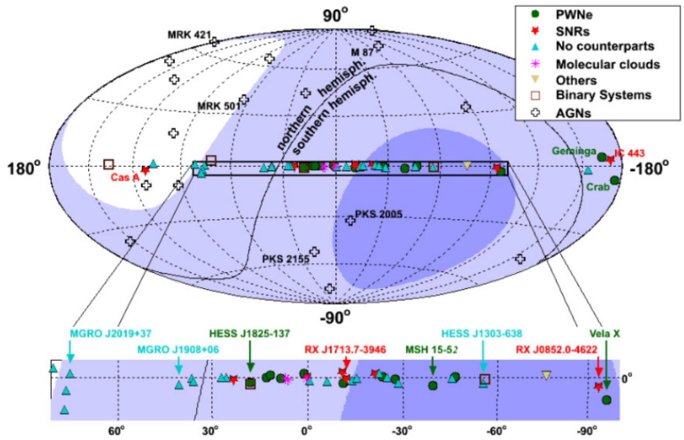

Figure 1: Sky coverage of a neutrino telescope located in the Mediterranean sea, in galactic coordinates. Dark (light) blue shaded areas represent visibility over 75% (25%). Some known astrophysical objects are marked. Figure taken from [6].

2. Analysis

In the following sections, a data analysis to search for a diffuse neutrino flux coming from the Galactic Ridge is reported. In the specific, data gathered with 6, 8, 19 and 21 active DUs of the KM3NeT/ARCA detector have been exploited, for a total lifetime of 432 days.

2.1 Event selection

The events considered in the analysis are track candidate events, generated by ν_μ charged-current interactions, that have passed quality selection criteria. To further reduce the surviving background, represented by atmospheric muons, Boost Decision Trees (BDTs) have been trained on the different detector configurations, in order to classify and reject these events (developed in synergy with [8]). In Figure 2 the BDT score data-Monte Carlo distribution is shown, evaluated in this specific case on KM3NeT/ARCA8 data. An optimal event selection is then derived, through the minimization of the Model Rejection Factor (MRF) [9], specifically for a signal flux with spectral index $\Gamma_\nu = 2.4$. The optimal region, from which to require that reconstructed directions of the track events should come from, has been found to be $|l| < 31°$ and $|b| < 5°$ for KM3NeT/ARCA6-8 and $|l| < 31°$ and $|b| < 4°$ for KM3NeT/ARCA19-21, due to the angular resolution of the detector in the considered configurations. The whole event selection has been carried out following the blinding policies of the KM3NeT Collaboration.

2.2 Method

The methodology adopted for the analysis is an on-off technique, similarly to what has been done in [4] and [10]. The on-region is defined for each detector configuration from the optimization

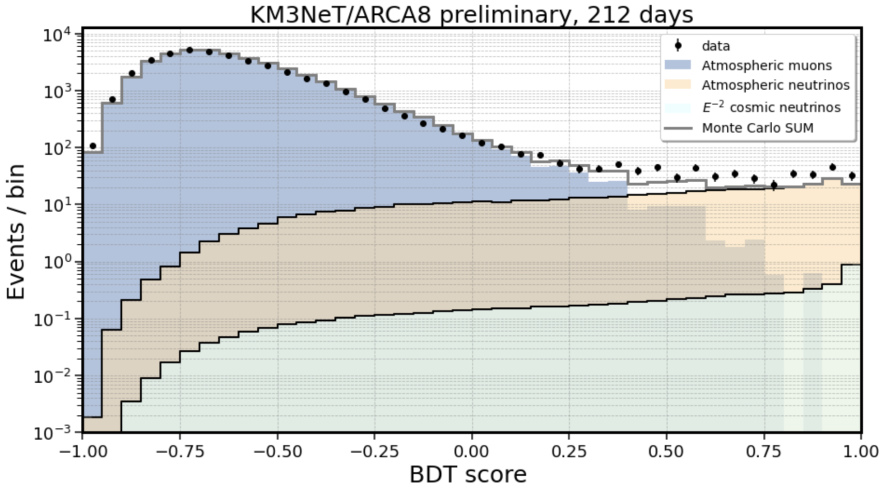

Figure 2: Data-Monte Carlo comparison for Boost Decision Tree output score, evaluated on test sample. Classification among atmospheric muons (blue shaded distribution) and neutrinos (orange and green shaded area).

procedure described in section 2.1. The background expectation instead is directly estimated from off-regions in the data, which have been selected so as to have the same sky coverage of the on-region and are shifted in right ascension, while avoiding also the region of the Fermi Bubbles. The expected neutrino signal has been simulated following the standard Monte Carlo chain developed within the KM3NeT collaboration [11], assuming the signal to be originated inside the Galactic Ridge. Each simulated event has been then weighted assuming a single power-law spectrum, of the form $\Phi_\nu(E) = \frac{dN_\nu}{dE_\nu} = \Phi_0 \times \left(\frac{E_\nu}{E_0}\right)^{-\Gamma_\nu}$ with a normalization energy E_0 set at 40 TeV, for convenience. The selected events are binned in function of the reconstructed energy, and the statistical analysis, based on the same procedure developed in [4], adopts the following binned likelihood approach:

$$\mathcal{L}(N_i; S_i^{\Gamma_\nu}, B_i, \Phi_0) = \prod_{i=1}^{12} Poisson(N_i, B_i + S_i^{\Gamma_\nu}) \quad (1)$$

where N_i is the number of events observed in the on-region in each energy bin, B_i the background derived from the off-regions and $S_i^{\Gamma_\nu}$ is the signal expectation, derived from Monte Carlo simulations for a given spectral index Γ_ν and normalization flux Φ_0. A posterior probability distribution is derived, following a Bayesian approach, in order to include statistical and systematic uncertainties, and assuming a flat prior for the two parameter of interest: the neutrino spectral index Γ_ν and normalization flux Φ_0. The combination of different detector configurations is performed multiplying the respective posterior probabilities. From the profiled posterior probability then upper limits and sensitivities are derived.

2.3 Results

In Figure 3 the unblinded energy distributions are shown for respectively KM3NeT/ARCA6, KM3NeT/ARCA8, KM3NeT/ARCA19 and KM3NeT/ARCA21.

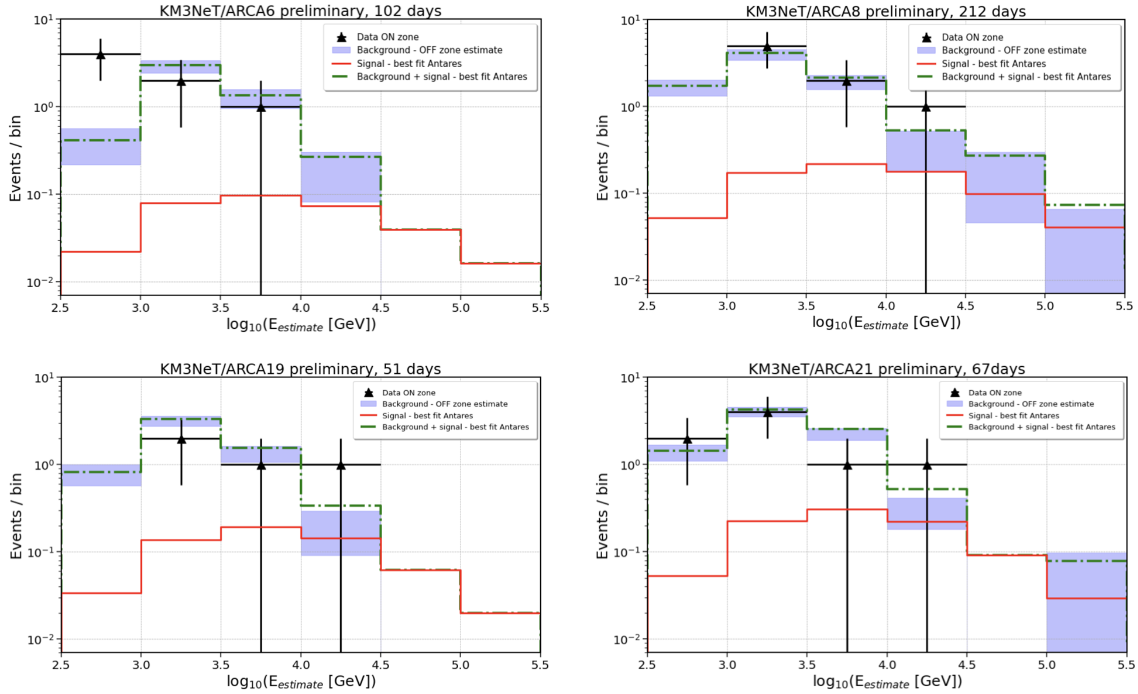

Figure 3: Energy distribution of selected events for KM3NeT/ARCA with 6 (**top left**), 8 (**top right**), 19 (**bottom left**) and 21 (**bottom right**) active detection units. The blue bands represent the background estimation derived from the off-regions, with the associated statistical error. The black points represent the data found in the on-region while the red solid lines represent the numbers of events expected in each data sets, assuming the ANTARES best-fit flux found in [4]. The green dashed lines show the sum of the expected signal and background.

No excess of events has been found with respect to the background expectation. Therefore the 90% C.L. upper limits have been calculated and reported in Table 1. Limits for each single detector configuration and for the combination KM3NeT/ARCA6+8 and KM3NeT/ARCA6+8+19+21 are reported, in order to highlight the impact of including data sets gathered with 19 and 21 DUs, despite the limited lifetime.

90% C.L. upper limits						
Γ_ν	ARCA6	ARCA8	ARCA6+8	ARCA19	ARCA21	ARCA6+8+19+21
2.2	8.6×10^{-5}	4.5×10^{-5}	3.4×10^{-5}	4.9×10^{-5}	3.4×10^{-5}	1.9×10^{-5}
2.3	2.7×10^{-4}	1.3×10^{-4}	1.1×10^{-4}	1.5×10^{-5}	1.0×10^{-4}	5.8×10^{-5}
2.4	8.2×10^{-4}	3.9×10^{-4}	3.0×10^{-4}	4.1×10^{-4}	2.8×10^{-4}	1.7×10^{-4}
2.5	2.3×10^{-3}	1.1×10^{-3}	9.0×10^{-4}	1.1×10^{-3}	7.8×10^{-4}	4.8×10^{-4}
2.6	6.5×10^{-3}	2.9×10^{-3}	2.5×10^{-3}	2.8×10^{-3}	2.1×10^{-3}	1.3×10^{-3}
2.7	1.7×10^{-2}	7.4×10^{-3}	6.8×10^{-3}	7.1×10^{-3}	5.5×10^{-3}	3.5×10^{-3}

Table 1: 90% C.L. upper limits under a single power-law assumption, referred to in the text as Φ_ν, for a reference energy $E_0 = 1$ GeV and with spectral indices Γ_ν ranging from 2.2 to 2.7 for KM3NeT/ARCA6, KM3NeT/ARCA8, KM3NeT/ARCA19, KM3NeT/ARCA21 and the combined data sets. All the results are expressed in units of GeV^{-1} cm^{-2} s^{-1} sr^{-1}.

In Figure 4 the best-fitting flux obtained from the IceCube Collaboration [5] for two templates models is reported, together with the ANTARES results [4] and KM3NeT upper limits. Since the analysis methodology adopted by IceCube is based on a full-sky template search, the ANTARES and KM3NeT limits has been integrated over the solid angle extension of the Galactic Ridge.

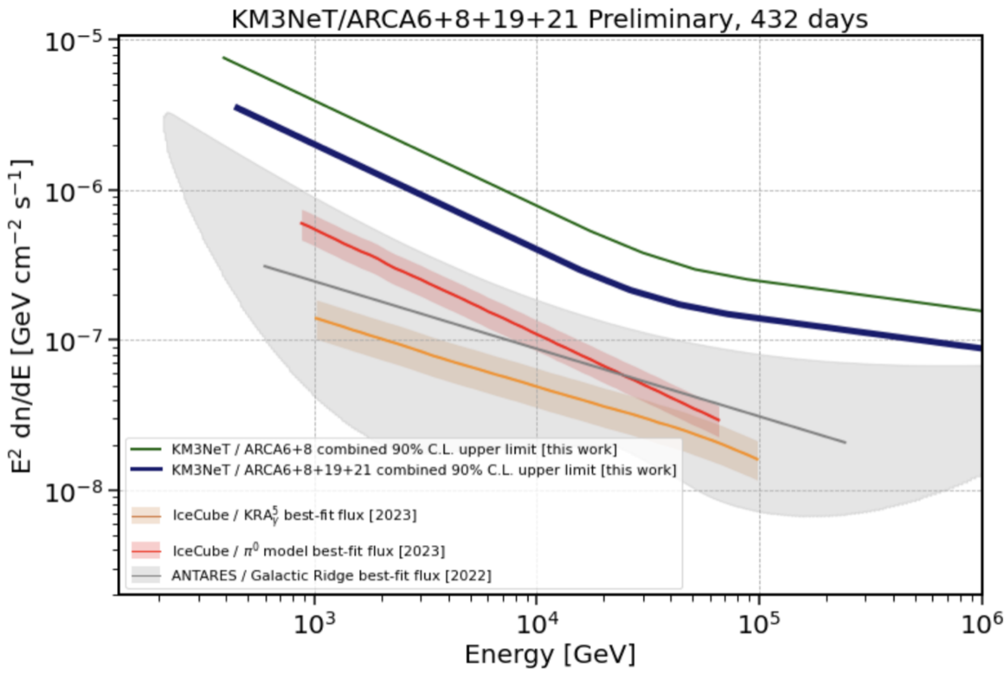

Figure 4: KM3NeT/ARCA6+8 combined (green solid line) and KM3NeT/ARCA6+8+19+21 combined (blue solid line) 90% C.L. upper limits to a diffuse neutrino emission from the Galactic Ridge, for a range of spectral indices $\Gamma_\nu \in [2.2, 2.7]$. The ANTARES limits and best-fitting flux are also reported (grey shaded area and grey solid line) for the same type of search, derived from [4]. The KM3NeT and ANTARES limits have been integrated over the solid angle, spanned by the Galactic Ridge, to be compared to the best fitting fluxes (red and orange lines) reported by IceCube analysis, which are based on full-sky template method [5].

2.4 Conclusions and outlook

The discovery of a neutrino emission, recently reported by IceCube collaboration, following a hint reported by the ANTARES Collaboration, has opened a new perspective on the possibility to study the properties of our Galaxy through neutrinos [12]. The analysis illustrated in this contribution, searching for a diffuse neutrino flux originated from the Galactic Ridge region, has been performed exploiting data collected by KM3NeT/ARCA with 6, 8, 19 and 21 active detection units, for a total lifetime of 432 days. No excess of events has been found with respect to the background estimation. Currently the KM3NeT/ARCA detector comprises 21 active detection units, for an effective area which is three times higher than the one of ARCA6/8. The first period of KM3NeT/ARCA21 has been included in this analysis, but further 6 months of data gathered with this configuration geometry are currently under analysis. A further expansion of the detector with ~ 10 more detection units is planned for the coming autumn. The limits shown in this work for this type of search are not yet competitive with the results reported by ANTARES and IceCube, but the fast growth planned for the KM3NeT detectors in the near future will allow soon to complement those observations and to further constrain the neutrino emission from the center of our Galaxy. Moreover multi-messenger observations, combining information from gamma-rays observatories like CTA, LHAASO, SWGO and from second generation neutrino telescopes (KM3NeT, GVD, IceCube Gen-2, P-One, TRIDENT) will be fundamental to identify individual sources of CRs and to deeply study the CR properties inside our galaxy.

A. Evaluation of systematic uncertainties

In order to evaluate the systematic uncertainties on the signal acceptance, dedicated Monte Carlo simulations have been performed, allowing to identify a limited number of parameters as the main contributors to the systematic uncertainties. In order to disentangle the different contributions to the overall uncertainty, a dedicated simulation has been produced, in which only one parameter was varied at a time. In Figure 5 the relative difference of the modified Monte Carlo production with respect to the standard one has been calculated in bins of reconstructed neutrino energy. This percentage variation is assumed to be the systematic uncertainty associated with the specific parameter variation. The PMT quantum efficiency has been modified by a 5% (*red dotted line*), while the uncertainty on the water properties are taken into account by modifying the light absorption length by a factor 10%, coherently to what was previously done by ANTARES Collaboration [13] (*green line*). These two different contributions are then summed in quadrature (*blue solid line*) to derive an overall uncertainty, which has been added to the statistical analysis described in section 2.2.

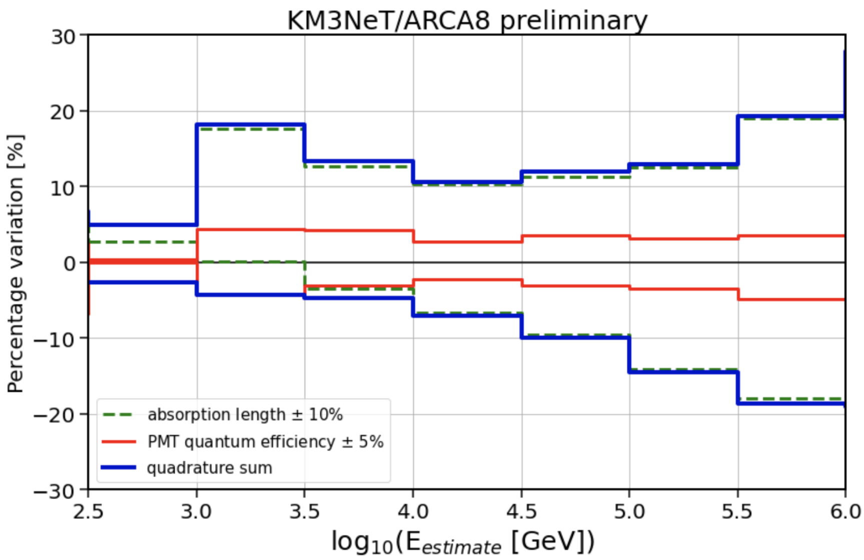

Figure 5: Percentage variation of the modified Monte Carlo simulations, for each parameter modification (specified in the legend) with respect to standard Monte Carlo simulation, as a function of reconstructed neutrino energy.

References

[1] D. Gaggero, D. Grasso, A. Marinelli, A. Urbano and M. Valli, *The gamma-ray and neutrino sky: A consistent picture of Fermi-LAT, Milagro, and IceCube results*, *Astrophys. J. Lett.* **815** (2015) L25 [1504.00227].

[2] C. Evoli, D. Grasso and L. Maccione, *Diffuse neutrino and gamma-ray emissions of the galaxy above the TeV*, *Journal of Cosmology and Astroparticle Physics* **2007** (2007) 003.

[3] A. Palladino, M. Spurio and F. Vissani, *Neutrino Telescopes and High-Energy Cosmic Neutrinos*, *Universe* **6** (2020) 30 [2009.01919].

[4] ANTARES collaboration, *Hint for a TeV neutrino emission from the Galactic Ridge with ANTARES*, *Phys. Lett. B* **841** (2023) 137951 [2212.11876].

[5] IceCube collaboration, *Observation of high-energy neutrinos from the galactic plane*, *Science* **380** (2023) 1338 [https://www.science.org/doi/pdf/10.1126/science.adc9818].

[6] KM3NeT collaboration, *Letter of intent for KM3NeT 2.0*, *J. Phys. G* **43** (2016) 084001 [1601.07459].

[7] KM3NeT collaboration, *The KM3NeT multi-PMT optical module*, *JINST* **17** (2022) P07038 [2203.10048].

[8] KM3NeT collaboration, *Search for a diffuse astrophysical neutrino flux using ARCA data*, *PoS* **ICRC2023** (these proceedings) 1195.

[9] G.C. Hill and K. Rawlins, *Unbiased cut selection for optimal upper limits in neutrino detectors: The Model rejection potential technique*, *Astropart. Phys.* **19** (2003) 393 [astro-ph/0209350].

[10] ANTARES collaboration, *Hint for a TeV neutrino emission from the Galactic Ridge with the ANTARES telescope*, *PoS* **ICRC2023** (these proceedings) 1103.

[11] KM3NeT collaboration, *Upgrading gSeaGen: from MeV to PeV neutrinos*, *JINST* **16** (2021) C09008 [2107.13880].

[12] L.A. Fusco, *Galactic neutrinos in the Milky Way*, *Science* **380** (2023) 1318 [https://www.science.org/doi/pdf/10.1126/science.adi6277].

[13] ANTARES collaboration, *Zenith distribution and flux of atmospheric muons measured with the 5-line ANTARES detector*, *Astropart. Phys.* **34** (2010) 179 [1007.1777].

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. Miccichè[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).