PROCEEDINGS OF SCIENCE

Model-agnostic interpretation of the first KM3NeT Ultra-High-Energy event within the Global Neutrino Landscape

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On February 13th, 2023, the KM3NeT/ARCA telescope detected a neutrino candidate with an estimated energy in the hundreds of PeVs. We review the observation of this ultra-high-energy neutrino in light of observations above tens of PeV from the IceCube and Pierre Auger observatories. Furthermore, we discuss how the ultra-high-energy data were fit together with the IceCube measurements at lower energies, either with a single power law or with a broken power law, allowing for the presence of a new component in the spectrum. Finally, we present the prospects that may lead to resolving this apparent discrepancy and better characterise the neutrino landscape at ultra-high energies.

39th International Cosmic Ray Conference (ICRC2025)
15–24 July 2025
Geneva, Switzerland

ICRC 2025
The Astroparticle Physics Conference
Geneva July 15-24, 2025

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PoS(ICRC2025)1117

1. Introduction

KM3NeT [1, 2] is an underwater neutrino telescope that is currently being deployed at the bottom of the Mediterranean Sea. It detects neutrinos via the Cherenkov light emitted by the products of the neutrino interactions with seawater. The detector consists of two separate arrays: KM3NeT/ORCA, located off-shore Toulon, France, and optimised for detecting GeV – TeV neutrinos; and KM3NeT/ARCA, off-shore from Portopalo di Capo Passero, Italy, optimised for TeV – PeV neutrinos.

On the 13th of February 2023, KM3NeT/ARCA detected a muon with an estimated energy of 120^{+110}_{-60} PeV, which most probably originated from the interaction of an astrophysical neutrino within or close to the detector volume. Assuming an E^{-2} astrophysical neutrino spectrum, the energy of the primary neutrino is estimated to be 220^{+570}_{-110} PeV, making it the most energetic neutrino observed to date [3]. This surpasses the previous highest-energy detection, made by IceCube [4], by more than one order of magnitude. Interpreting this event (denoted KM3-230213A) as a probe of the diffuse astrophysical neutrino flux suggests a tension with the non-observations of IceCube and Auger in the PeV range, especially due to KM3NeT/ARCA's shorter observation time and instrumented volume. In these proceedings, we describe how this tension is quantified using a goodness-of-fit test, following what has been presented in [5].

Since KM3-230213A is the first measurement performed in the ultra-high-energy (UHE) region, it is combined with previous measurements of the high-energy (HE) diffuse astrophysical neutrino flux performed by IceCube. This allows an investigation into whether the UHE measurement is consistent with a continuation of the lower-energy flux or indicates the emergence of an additional spectral component in the PeV range.

The latter scenario is particularly compelling, as cosmogenic neutrinos—neutrinos produced in the interaction between cosmic rays and the cosmic microwave background—are expected to dominate the flux at these energies. Moreover, new populations of astrophysical neutrino sources are expected to emerge.

To explore these possibilities in a model-independent manner, the HE and UHE observations are jointly analysed under two hypotheses: a Single Power Law (SPL) and a Broken Power Law (BPL) spectrum extending from TeV to EeV energies. These hypotheses are compared using a Likelihood Ratio (LR) test and, alternatively, by computing the Bayes factor.

2. Combination of Ultra-High-Energy datasets

As illustrated in Fig. 1 and described in [3], assuming an E^{-2} energy dependence of the neutrino flux, KM3-230213A corresponds to a per-flavour isotropic diffuse flux of $E^2\Phi^{1\mathrm{f}}_{\nu+\bar{\nu}}(E) = 5.8^{+10.1}_{-3.7} \times 10^{-8}\,\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$ in the 90% confidence level (CL) interval of 72 PeV – 2.6 EeV. Although such a high flux would be inconsistent with the non-observation of UHE neutrinos from IceCube [6] and the Pierre Auger Observatory (Auger) [7], the compatibility of the three measurements can be quantified by means of a parameter-goodness-of-fit (PG) test [8], or alternatively, through a Bayesian posterior predictive check (PPC) [9].

To do so, it is assumed that the neutrino flux follows a SPL over the 90% CL energy range of KM3-230213A, defined as:

$$\Phi^{1\mathrm{f}}_{\nu+\bar{\nu}}(E) = \phi \times \left(\frac{E}{100\,\mathrm{TeV}}\right)^{-\gamma_1}, \tag{1}$$

where $\Phi^{1\mathrm{f}}_{\nu+\bar{\nu}}$ indicates a per-flavour neutrino plus antineutrino flux, ϕ is the normalisation constant, and γ_1 is the spectral index. For the PPC analysis, uniform priors on the flux normalization and the spectral index are assumed. The PG test and PPC yield Z-scores of 2.5 σ and 1.8 σ respectively, where a high Z-score indicates disagreement between the samples.

These procedures are meant to test how unlikely it is that the positive observation performed by KM3NeT and the non-observations of IceCube and Auger are compatible with the same astrophysical flux. Accordingly, the most likely underlying flux is obtained by maximizing the product of the individual Poisson likelihoods in the 90% CL energy range of KM3-230213A, under the assumption of zero background contribution. This best-fit flux, shown in Fig. 2, is approximately equivalent to the flux that would produce one expected event over the sum of the exposures of the three detectors.

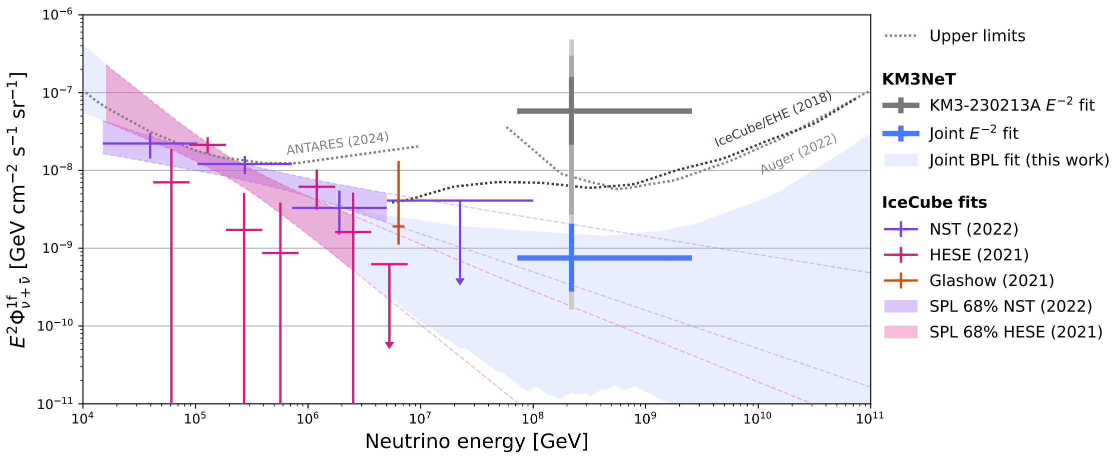

Figure 1: Per-flavour energy-squared diffuse astrophysical neutrino flux, assuming flavour equipartition. Measurements based on the KM3-230213A observation are compared with existing limits at ultra-high energies and measurements at lower energies. The KM3NeT-only measurement [3] and the joint flux including as well IC-EHE and Auger non-observations, in the central 90% neutrino energy range associated with KM3-230213A, are shown with the grey and blue crosses, respectively. The purple- and pink-filled regions represent the 68% CL contours of the IC single-power-law fits, NST [10] and HESE [11], respectively. The segmented fits from the same analyses are shown with purple and pink crosses, while the orange cross corresponds to the IC Glashow resonance event [12]. The dotted lines correspond to upper limits from ANTARES (95% CL [13]), Auger (90% CL [7]) and IC-EHE (90% CL [6]). The blue-filled region shows the 1σ envelope of the broken power law fit, using the HESE constraint below the break, as detailed in the text. The vertical spans of all crosses represent the 1σ uncertainties, and the $2-3\sigma$ ones for the KM3NeT-only point, in lighter shades. Figure and caption from [5]

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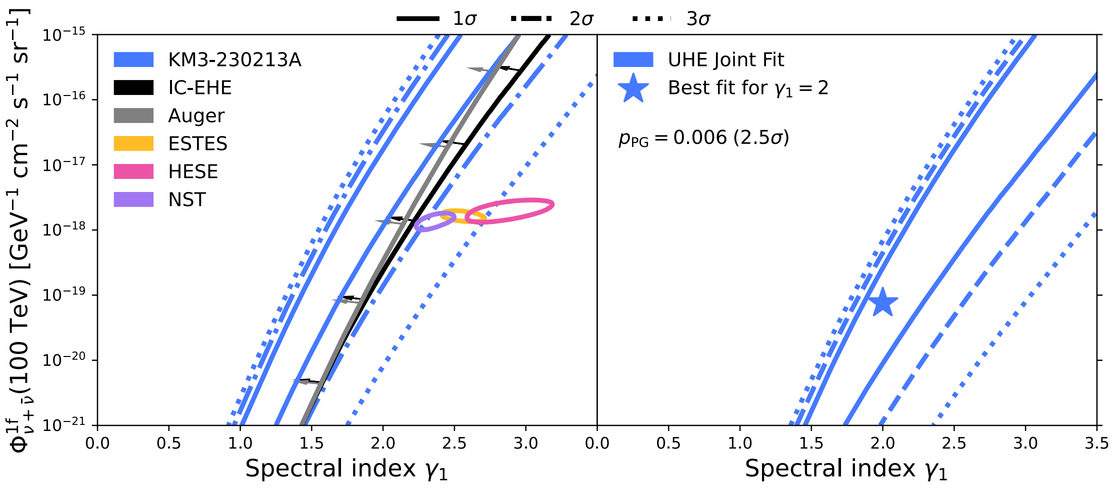

Figure 2: Fit results of the KM3NeT / IC / Auger data to a single-power-law flux model. Left: preferred regions and constraints from each dataset individually. The UHE datasets are all fit within the 90% CL energy range of KM3-230213A, while the lower energy IC datasets are fit within their own defined energy ranges, always below that of the UHE datasets. The KM3-230213A contours are shown at the $1-2-3\sigma$ CLs (solid, dash-dotted and dotted lines, respectively), while all other contours are shown at the 1σ CL. Right: result of a joint fit to the UHE datasets. The star indicates the best-fit point for $\gamma_1 = 2$. The resulting tension from the PG test, detailed in the text, is also reported. Figure and caption from [5]

3. Global fit of the diffuse astrophysical neutrino flux

In addition to investigating how KM3-230213A fits in the UHE region, it is also informative to contextualize this measurement with respect to previous observations of the diffuse astrophysical neutrino flux at lower energies (TeV – PeV), measured by IceCube. Therefore, we investigate two scenarios: a SPL spectrum extending continuously from TeV to EeV energies, and a two-component BPL with a spectral hardening in the PeV region, defined as

$$\Phi^{1\mathrm{f}}_{\nu+\bar{\nu}}(E) = \phi \times \begin{cases} \left(\dfrac{E}{100\,\mathrm{TeV}}\right)^{-\gamma_1} & ;\ E \leq E_\mathrm{b}, \\ \left(\dfrac{E}{E_\mathrm{b}}\right)^{-\gamma_2} \left(\dfrac{E_\mathrm{b}}{100\,\mathrm{TeV}}\right)^{-\gamma_1} & ;\ E > E_\mathrm{b}, \end{cases} \tag{2}$$

where two additional parameters are introduced compared to Eq. 1: the break energy E_b, and the spectral index of the second component γ_2.

Under these two hypotheses, we combine the measurements in the UHE region introduced in Sec. 2 with each of the following IceCube's HE samples: High-Energy Starting Events (HESE, [11]), Enhanced Starting Track Event Selection (ESTES, [14]), and Northern-Sky Tracks (NST, [10]). The results of these joint fits are shown in Fig. 3. Under the SPL hypothesis, the inclusion of the UHE measurements leads to smaller 1σ contours, with both the contours and best-fit points shifting slightly closer together. The BPL joint fits assume a uniform prior on the logarithm of E_b, and a uniform prior between 1 and γ_1 on the spectral index γ_2. This ensures that only a hardening of the spectrum is probed, since a broader exploration of other possible shapes of the diffuse flux is beyond the scope of this work. The most significant indication of a hardening is found in the joint

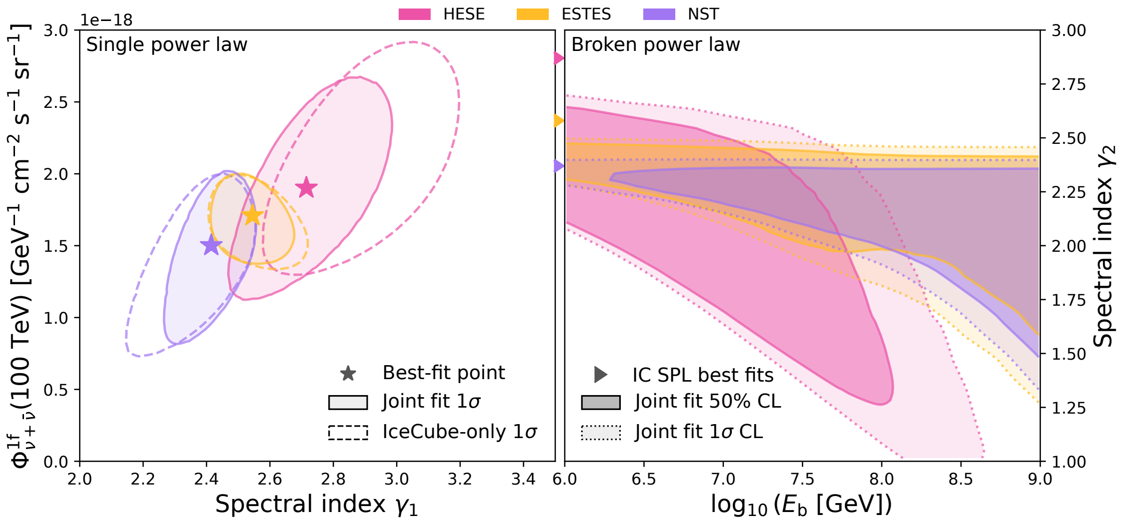

Figure 3: Joint fit of IC measurements in the TeV–PeV region, and KM3NeT / IC / Auger UHE measurements. Left: Bayesian fit with a single power law in the (γ_1, ϕ) plane. Right: broken power law fit in the $(\log_{10} E_b, \gamma_2)$ plane, after marginalising over ϕ and γ_1. The different colours correspond to different IC measurements: HESE in pink, ESTES in orange, and NST in purple. The filled regions indicate the 1σ contours (as well as the 50% contours in the right panel). On the left panel, the star markers are the best-fit points and the 1σ contours from IC priors are also shown in dashed lines. On the right panel, the triangles on the left axis represent the value of the spectral indices corresponding to the IC SPL best fits. Figure and caption from [5]

fit with the HESE sample, which is also the IceCube sample that measures the softest spectrum in the TeV – PeV region.

4. Evidence of a break

Finally, we test whether the recent measurement of KM3-230213A provides statistical evidence for a break in the astrophysical neutrino spectrum. To do so, we use two complementary statistical tests: a frequentist likelihood ratio (LR) test, and a bayesian model comparison via the Bayes factor. Both tests are suited to quantify the preference for a more complex model (i.e., with more parameters), in this context a BPL flux, against a simpler model, here a SPL flux.

The LR test statistic is defined as:

$$t_{\rm LR}^{(a)} = 2\log\frac{\mathcal{L}_{\rm BPL}^{(a)}(\hat{\Theta}_{\rm BPL})}{\mathcal{L}_{\rm SPL}^{(a)}(\hat{\Theta}_{\rm SPL})}, \tag{3}$$

here the likelihoods are constructed from the product of Poisson likelihoods in UHE region, and the public likelihood maps for a given IceCube HE sample a. In the BPL case, the IceCube HE likelihoods depend only on the parameters ϕ and γ_1, while the additional parameters Eb and γ_2 influence only the UHE part of the likelihood. The symbols $\hat{\Theta}_{\rm SPL}$ and $\hat{\Theta}_{\rm BPL}$ indicate the parameters that maximise the respective likelihoods. From Eq. 3 a p-value can be extracted using Wilk's theorem [15] for two degrees of freedom, which is the number of additional parameters introduced in the BPL model. A low p-value indicates a preference for a break in the neutrino spectrum.

Table 1: Obtained preferences for a broken-power-law spectrum versus the single-power-law hypothesis.

HE Sample	HESE	ESTES	NST
Bayes factor $\mathcal{B}$	1.2	0.6	0.3
LR p-value	0.33	0.86	1

Similarly, the Bayes factor is defined as the ratio of the evidences $\mathcal{B} = \mathbb{E}_{\mathrm{BPL}}/\mathbb{E}_{\mathrm{SPL}}$, where each evidence is computed as the integral of the product of the model likelihood and its associated priors over the full parameter space. According to Jeffrey's scale [16], a Bayes factor $\mathcal{B} > 3.2$ ($\mathcal{B} < 0.3$) corresponds to a strong preference for BPL (SPL).

The results of both the LR test and Bayes factor analysis are summarised in Table 1, a mild preference for the BPL hypothesis is found with both tests in the combination with the HESE measurement, while no such preference is found in the case of ESTES or NST.

5. Conclusions

The compatibility of the recent KM3NeT observation KM3-230213A, with the non-observations reported by IceCube and Auger in the UHE range has been addressed. Assuming that KM3-230213A is a probe of the diffuse astrophysical neutrino flux with flavour composition of (1:1:1), we evaluated the consistency of the three experiments using both a PG test and a PPC. The resulting compatibility levels, corresponding to 2.5 σ and 1.8 σ respectively, are consistent with a statistical upward fluctuation.

Assuming a continuous diffuse neutrino flux extending from TeV to EeV energies, KM3-230213A provides critical information, since it is the first positive observation performed in the UHE region. It was shown here that, under the SPL hypothesis, combining the joint UHE flux with IceCube measurements in the TeV – PeV range leads to smaller contours in the parameter space. Alternatively, allowing for a hardening in the spectrum, we explored the preferred regions in the E_{b} and γ_2 space for each of the three IceCube HE samples considered.

We've estimated the preference for a break in the spectrum and found only a mild preference if the IceCube HESE sample is included in the fit, while no preference was found in the case of ESTES and NST. These results imply that KM3-230213A does not, on its own, provide significant statistical evidence for the emergence of a new component in the diffuse astrophysical neutrino flux. Future observations in the UHE range from the upcoming full KM3NeT/ARCA detector [17] and radio neutrino telescopes [18, 19], as well as increased exposures from IceCube and Auger, will allow us to better characterize the shape of the UHE neutrino flux and will highlight possible spectral features that remain unresolved with current statistics.

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PoS(ICRC2025)1117

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Acknowledgements for the KM3NeT Collaboration

The authors acknowledge the financial support of: KM3NeT-INFRADEV2 project, funded by the European Union Horizon Europe Research and Innovation Programme under grant agreement No 101079679; Funds for Scientific Research (FRS-FNRS), Francqui foundation, BAEF foundation. Czech Science Foundation (GAČR 24-12702S); 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, Normandy Region (Alpha, Blue-waves and Neptune), France, The Provence-Alpes-Côte d'Azur Delegation for Research and Innovation (DRARI), the Provence-Alpes-Côte d'Azur region, the Bouches-du-Rhône Departmental Council, the Metropolis of Aix-Marseille Provence and the City of Marseille through the CPER 2021-2027 NEUMED project, The CNRS Institut National de Physique Nucléaire et de Physique des Particules (IN2P3); Shota Rustaveli National Science Foundation of Georgia (SRNSFG, FR-22-13708), Georgia; This work is part of the MuSES project which has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 Research and Innovation Programme (grant agreement No 101142396). The General Secretariat of Research and Innovation (GSRI), Greece;

Istituto Nazionale di Fisica Nucleare (INFN) and Ministero dell'Università e della Ricerca (MUR), through PRIN 2022 program (Grant PANTHEON 2022E2J4RK, Next Generation EU) and PON R&I program (Avviso n. 424 del 28 febbraio 2018, Progetto PACK-PIR01 00021), Italy; IDMAR project Po-Fesr Sicilian Region az. 1.5.1; A. De Benedittis, W. Idrissi Ibnsalih, M. Bendahman, A. Nayerhoda, G. Papalashvili, I. C. Rea, A. Simonelli have been supported by the Italian Ministero dell'Università e della Ricerca (MUR), Progetto CIR01 00021 (Avviso n. 2595 del 24 dicembre 2019); KM3NeT4RR MUR Project National Recovery and Resilience Plan (NRRP), Mission 4 Component 2 Investment 3.1, Funded by the European Union – NextGenerationEU,CUP I57G21000040001, Concession Decree MUR No. n. Prot. 123 del 21/06/2022; 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 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; The program: "Excellence initiative-research university" for the AGH University in Krakow; The ARTIQ project: UMO-2021/01/2/ST6/00004 and ARTIQ/0004/2021; Ministry of Research, Innovation and Digitalisation, Romania; Slovak Research and Development Agency under Contract No. APVV-22-0413; Ministry of Education, Research, Development and Youth of the Slovak Republic; MCIN for PID2021-124591NB-C41, -C42, -C43 and PDC2023-145913-I00 funded by MCIN/AEI/10.13039/501100011033 and by "ERDF A way of making Europe", for ASFAE/2022/014 and ASFAE/2022 /023 with funding from the EU NextGenerationEU (PRTR-C17.I01) and Generalitat Valenciana, for Grant AST22_6.2 with funding from Consejería de Universidad, Investigación e Innovación and Gobierno de España and European Union - NextGenerationEU, for CSIC-INFRA23013 and for CNS2023-144099, Generalitat Valenciana for CIDEGENT/2018/034, /2019/043, /2020/049, /2021/23, for CIDEIG/2023/20, for CIPROM/2023/51 and for GRISOLIAP/2021/192 and EU for MSC/101025085, Spain; Khalifa University internal grants (ESIG-2023-008, RIG-2023-070 and RIG-2024-047), United Arab Emirates; The European Union's Horizon 2020 Research and Innovation Programme (ChETEC-INFRA - Project no. 101008324).