KM3NET E I NEUTRINI ASTROFISICI

R. Coniglione for KM3NeT

KM3NeT is a research infrastructure in the Mediterranean Sea hosting two neutrino detectors

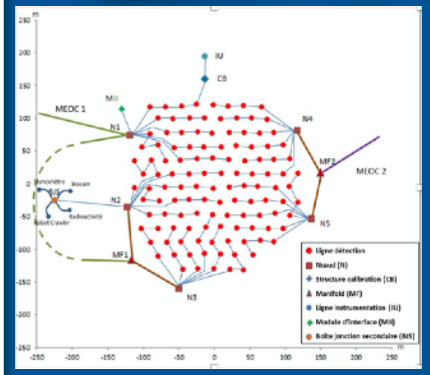
KM3NeT/ORCA: Study of the physical properties of the neutrino – neutrino mass ordering

KM3NeT/ARCA: Discovery and observation of cosmic neutrino sources

Two different detectors but based on the same technology and operated by the same collaboration

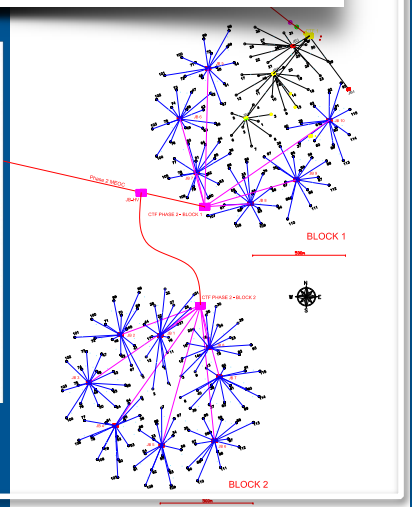
ORCA (Oscillation Research with Cosmic in the Abyss)

- Depth ~2500 m
- One block of 115 Detection Units
- Average distance between Detection Units ~20 m
- Average vertical distance between DOMs ~9 m
- Volume ≈ 7 Mton



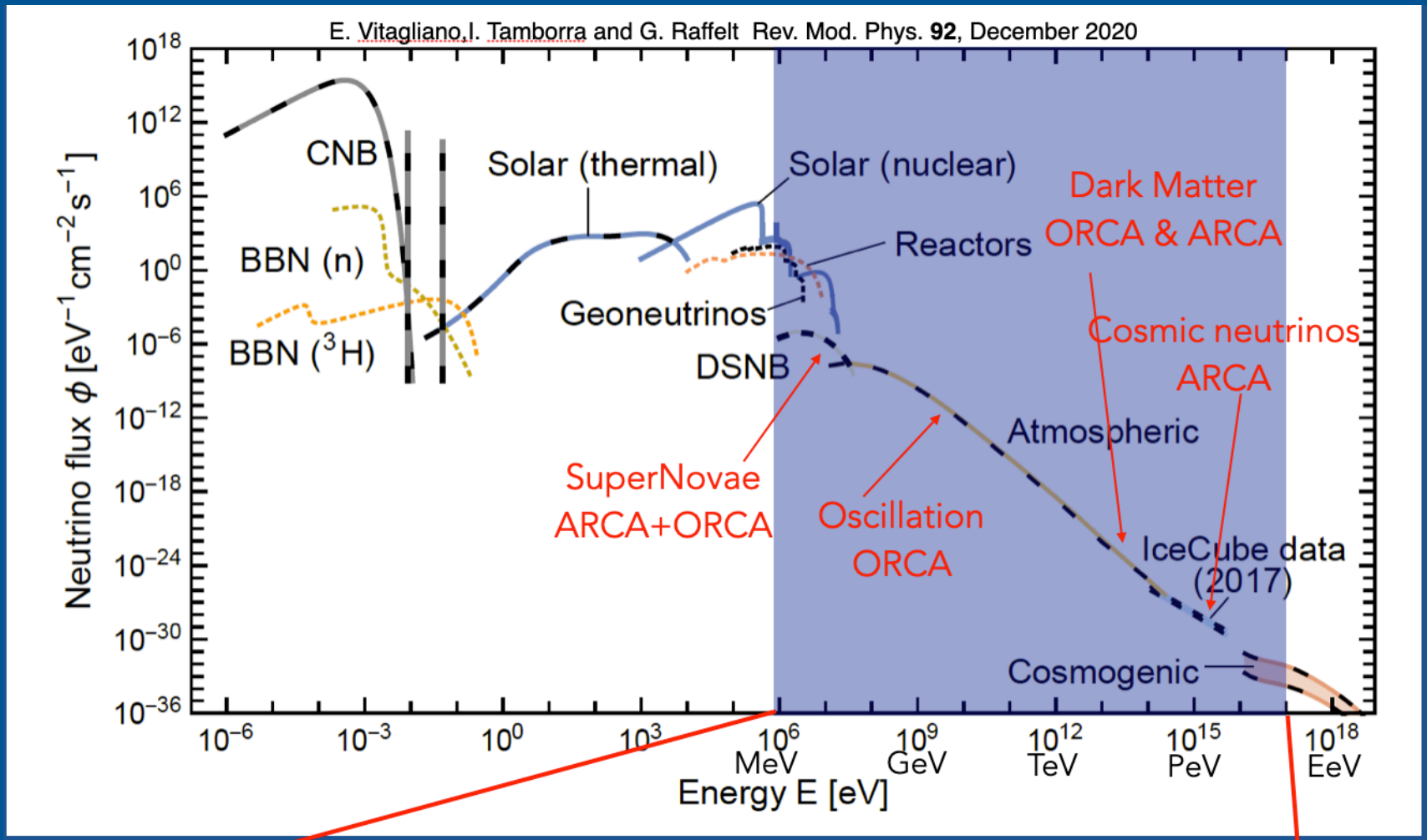
ARCA (Astroparticle Research with Cosmic in the Abyss)

- Depth ~3500 m
- Two blocks of 115 Detection Units each
- Average distance between Detection Units ~90 m
- Vertical distance between DOMs ~36 m
- Volume (0.5 × 2) km³ ≈1 Gton



THE KM3NET PHYSICS

Grand Unified neutrino spectrum



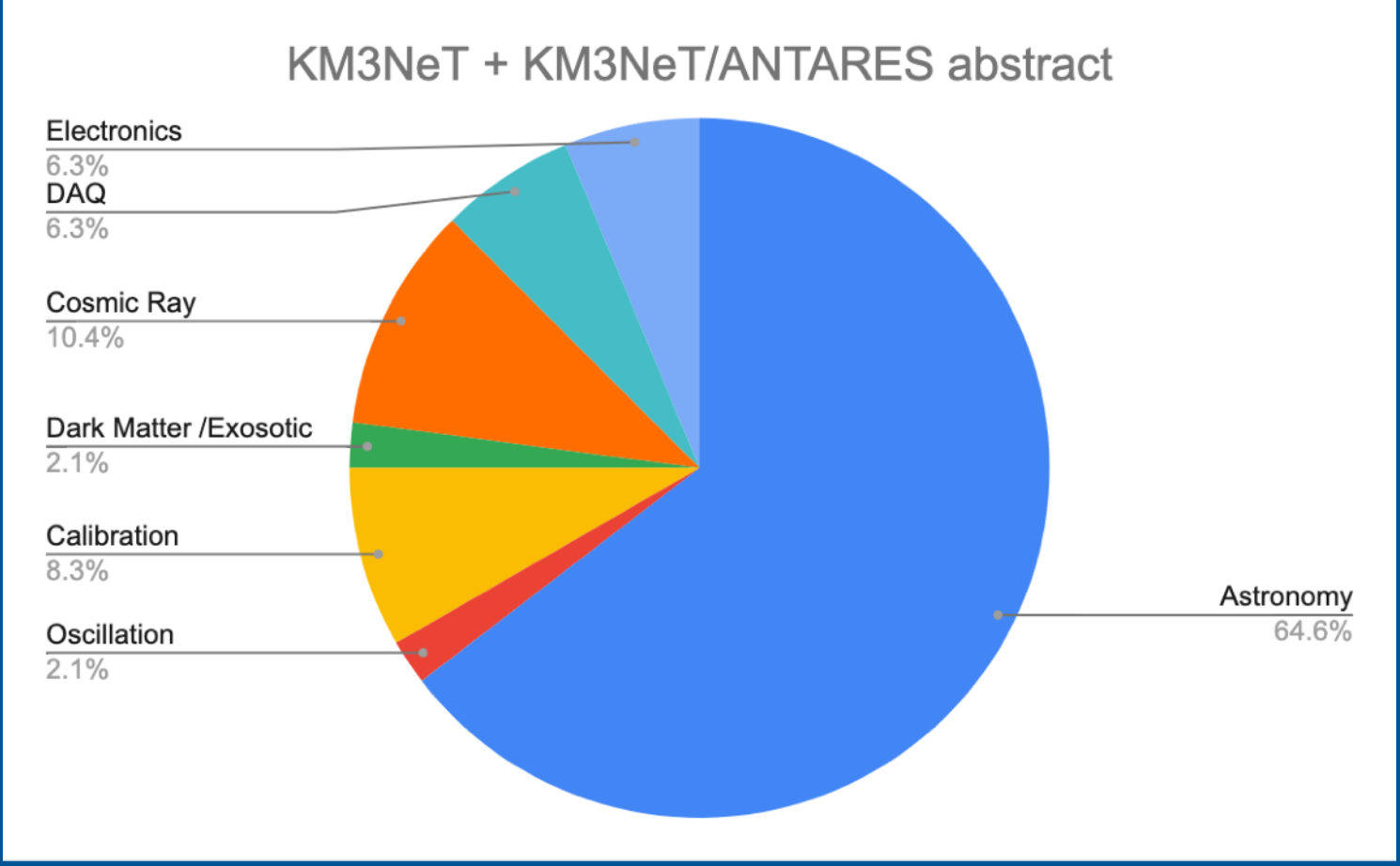
KM3NeT detects neutrinos from MeV to PeV

THE KM3NET PHYSICS

Many analysis ongoing

New results are expected at ICRC 2025 and other summer conferences

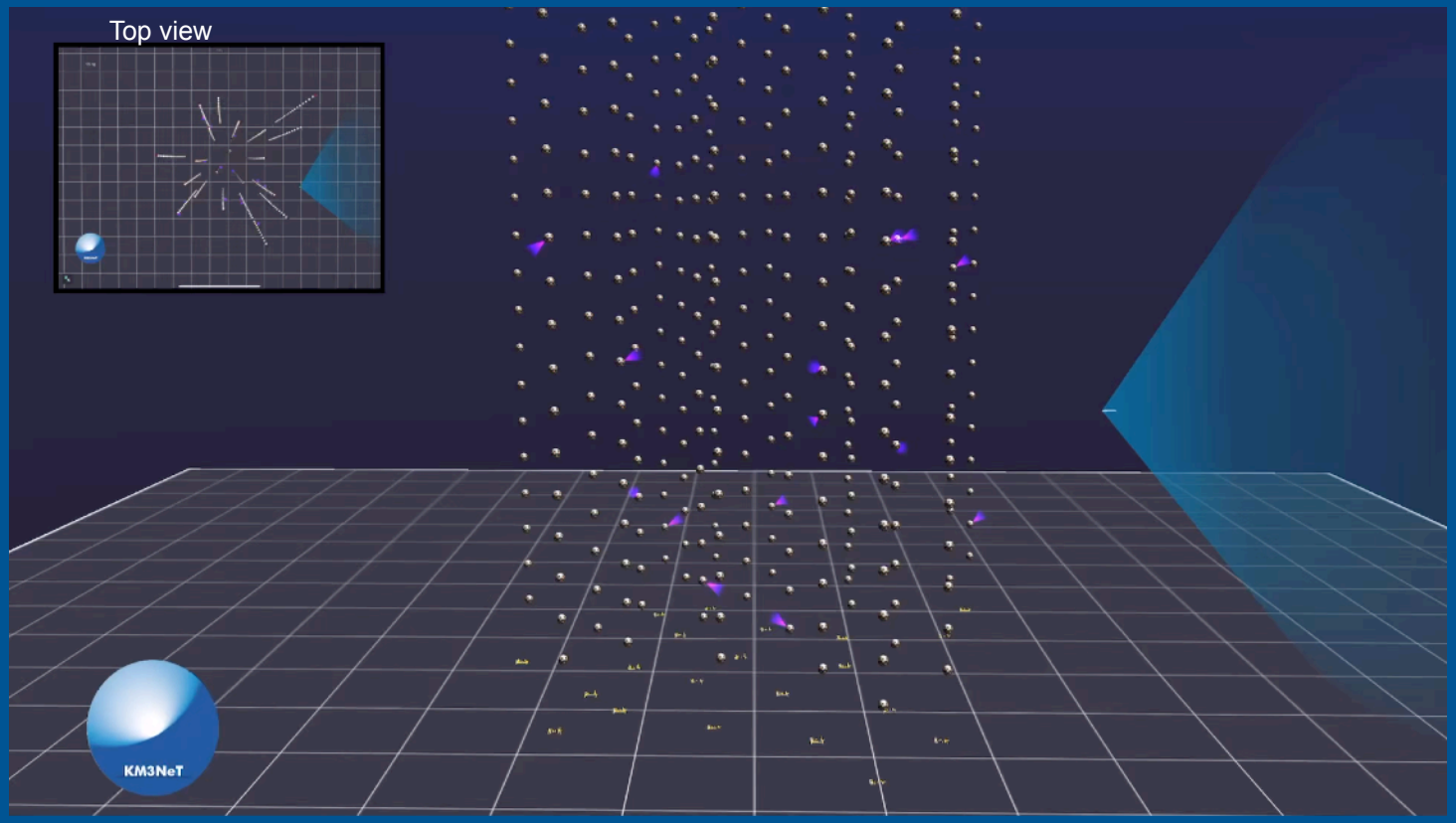
48 abstracts presented @ICRC2025



THE UHE KM3NET EVENT: KM3-230213A

The February 13 2023 an event with the highest energy ever seen has been detected with ARCA when it consisted of 21 Lines

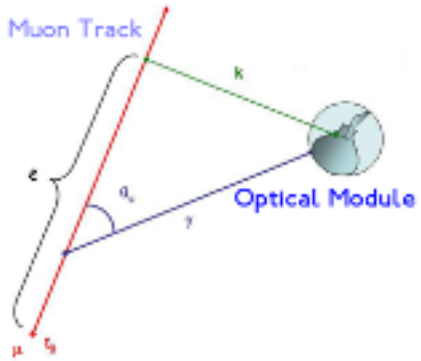
Huge amount of light detected 👉 35% of the total number of PMTs were triggered



Publication on Nature the 12 of February 2025 - Nature 638, 376–382 (2025) and public announcement on youtube (https://www.youtube.com/watch?v=2jgyZlBpkl8)

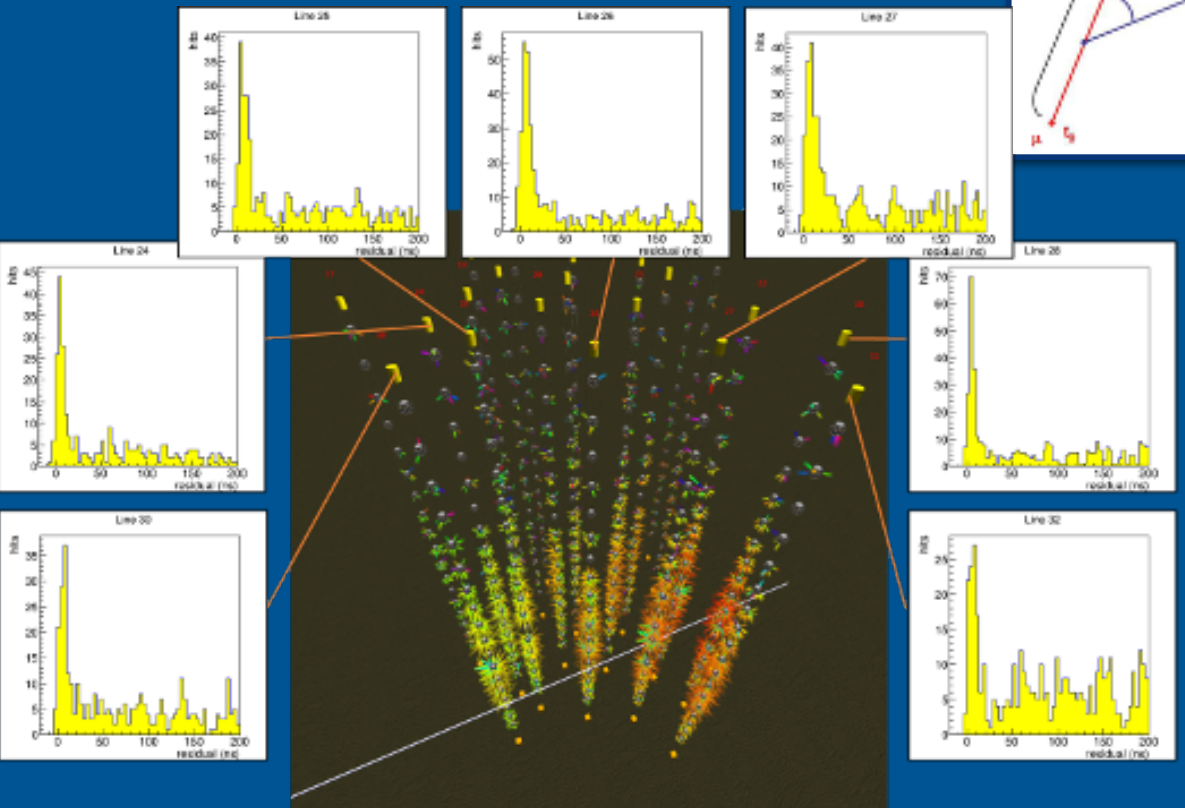
- The event is fully compatible with a muon track

$$t_{th} = t_0 + \frac{1}{c}\left(\ell - \frac{k}{\tan\theta_C}\right) + \frac{1}{v_g}\left(\frac{k}{\sin\theta_C}\right)$$



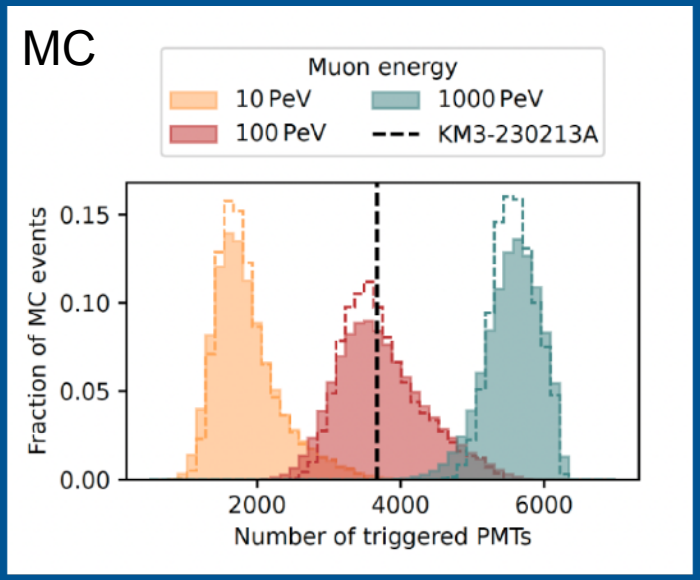
$$t_{res} = t_{det} - t_{th}$$

Time residuals



It is a **cosmic neutrino**

- With a very high energy
  - the muon energy is estimated by counting the number of PMTs participating at the triggering of the event



- **Energy is measured from the amount of light:**

$$E_\mu = 120^{+110}_{-60}\ \text{PeV}$$

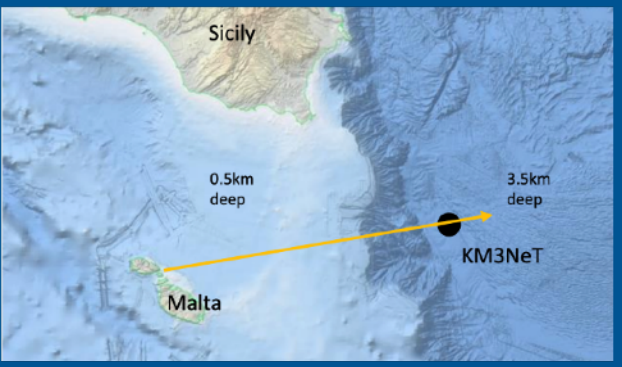
(10 000 times the energy of the LHC)

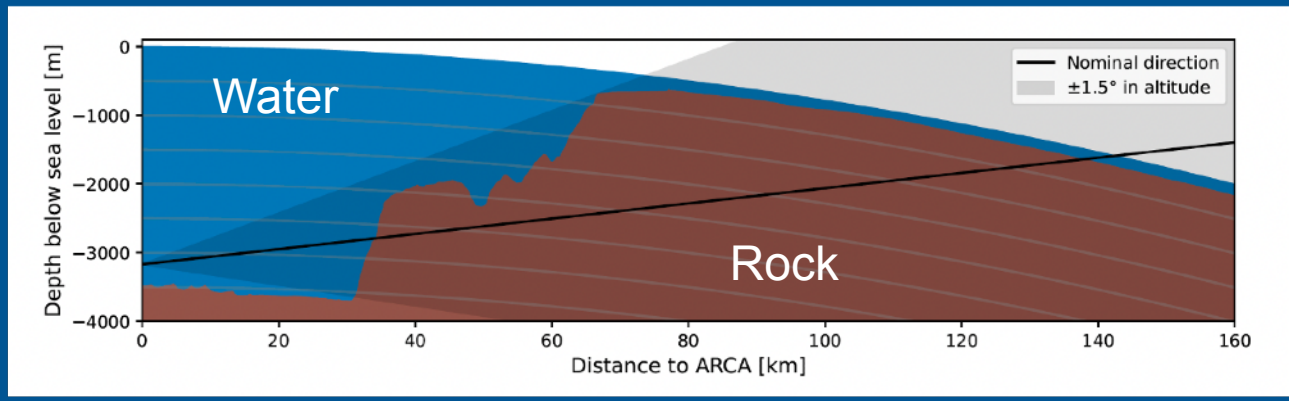
- **The neutrino Energy is higher:**

$$E_\nu = 220^{+570}_{-100}\ \text{PeV}$$

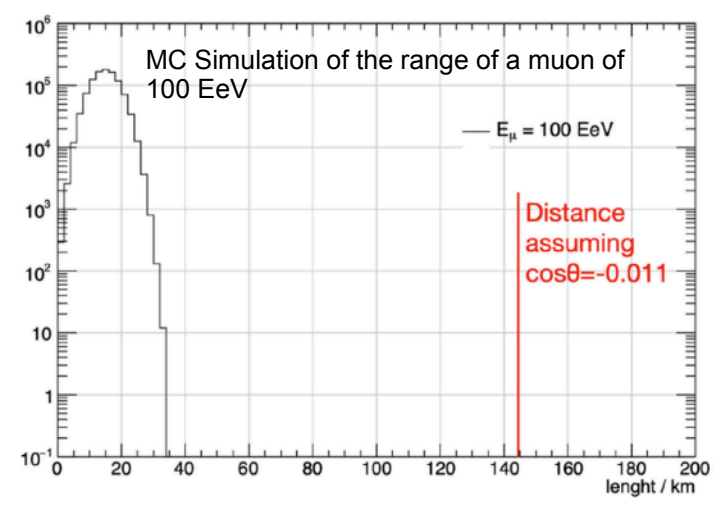
Assuming a E^{-2} muon neutrino spectrum

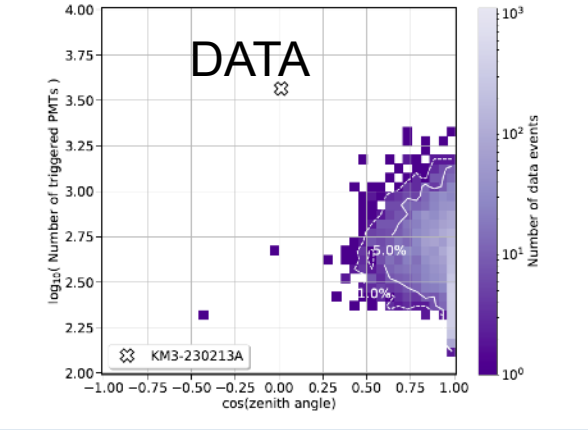
- It is a horizontal event (0.6° above the horizon) traversing ~140km of rock&water

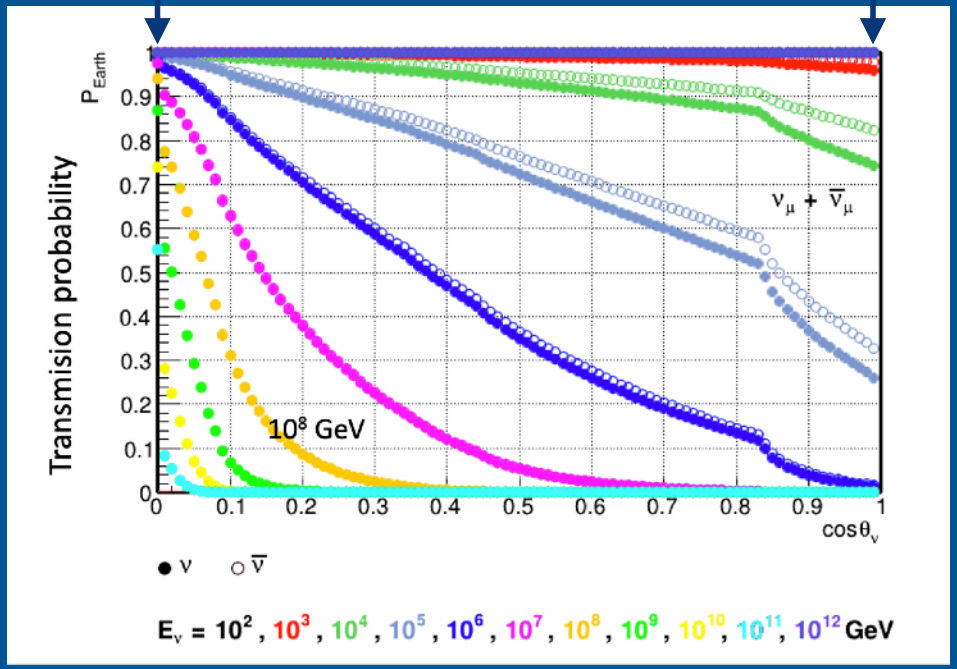




- It is not an atmospheric neutrino or atmospheric muon background
  - Given the detected energy and direction the expected rate of atmospheric muon is « 10^{-10} per year.
  - At this energies (>100 PeV) the expected rate of an atmospheric neutrino (prompt component) is of $1-5\ 10^{-5}$ events per year







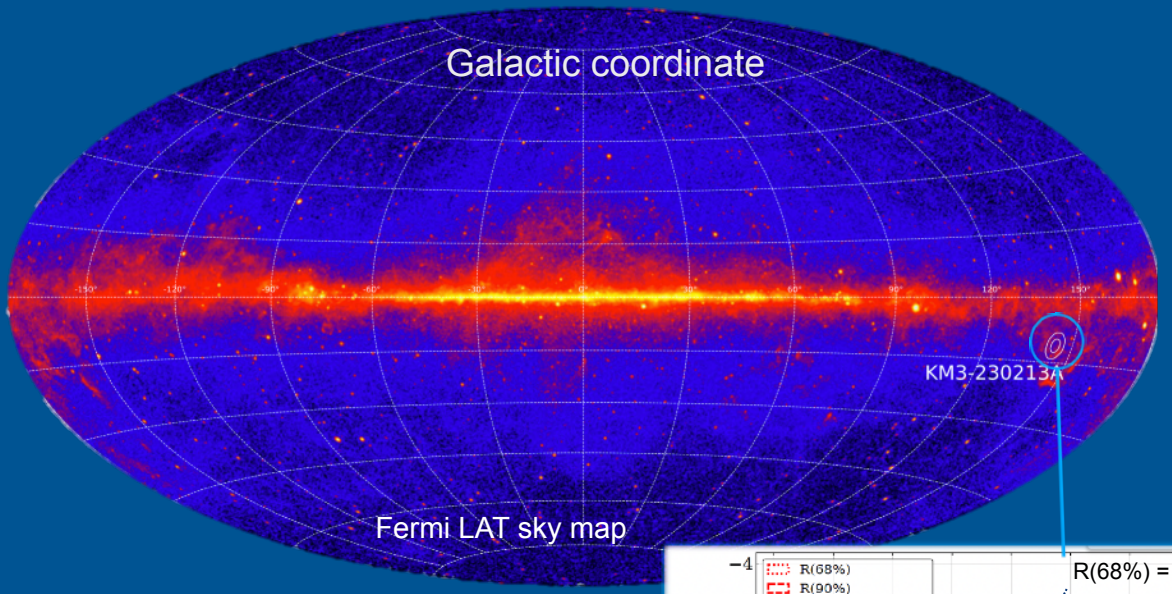
THE UHE KM3NET EVENT: KM3-230213A

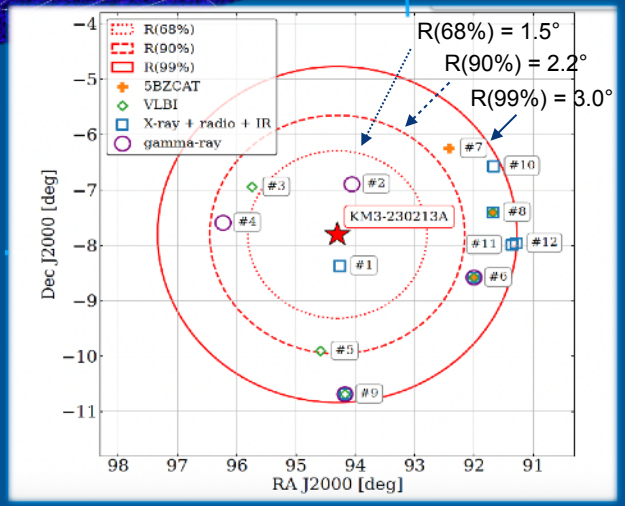
- Celestial coordinate

Equatorial coordinate

- **Approximate celestial origin:**

$RA = 94.3°, Dec = -7.8°$
with 1.5° error circle





Angular uncertainties dominated by the systematics on the absolute orientation of the detector

- A measurement in planned (Exail system) to have a measurement of the absolute position at a precision of ~1m -> the first measurement with this high precision at 3500m
- Cross check with the moon shadow

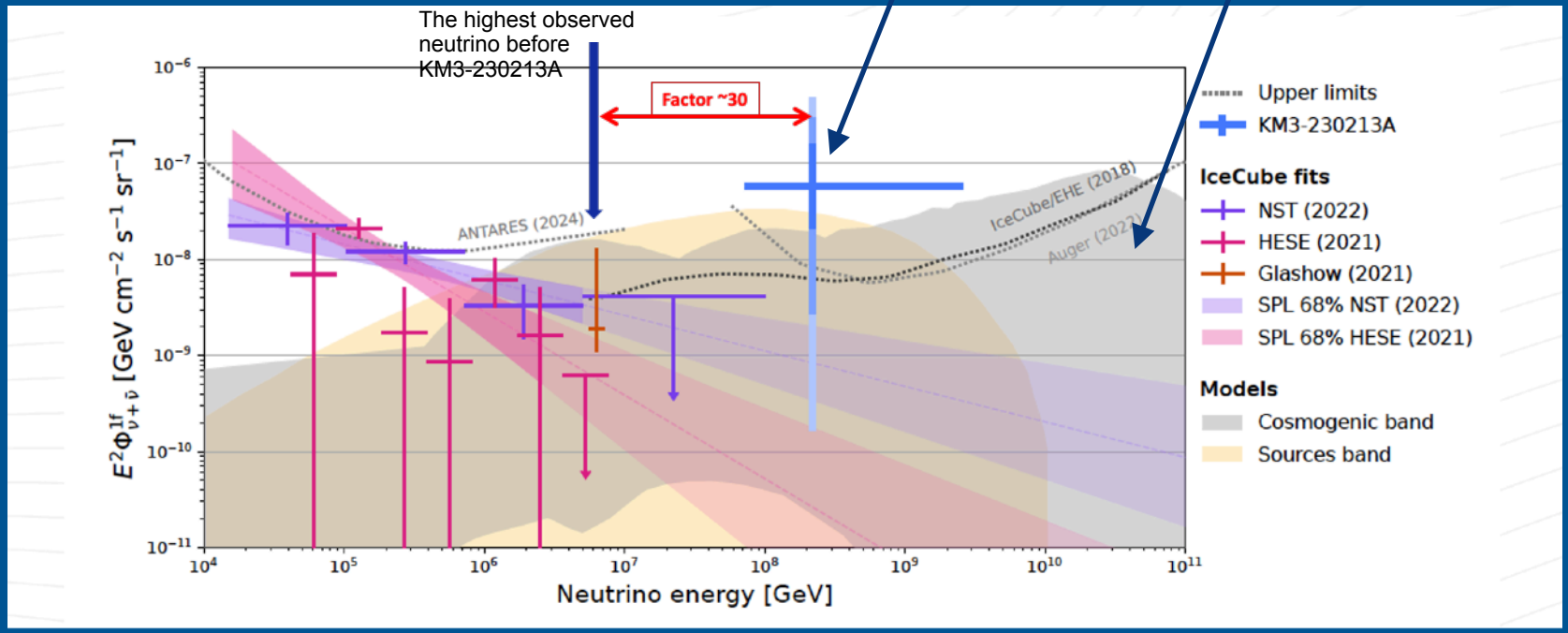
12 AGN sources found in region of 3° around the estimated direction

THE UHE KM3NET EVENT: KM3-230213A

- The estimated flux

KM3-230213A event

Grey band - Cosmogenic neutrino models



It falls in an unexplored energy region where neutrinos are expected but never observed

With the KM3NeT flux the average number of expected events in IceCube and Auger are of 0.59 and 0.4 respectively. In KM3NeT 0.013 are expected

KM3NeT observation is an upper fluctuation at 2.2σ level

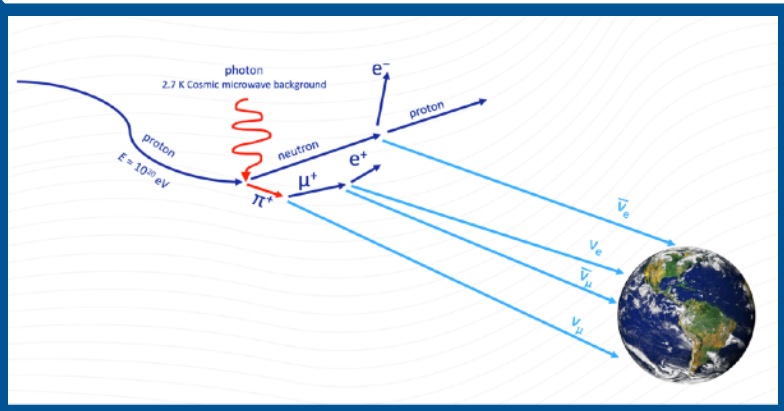
At the date of the official announcement 4 KM3NeT companion papers were published on arXiv

- On the potential cosmogenic origin of the ultra-high-energy event, arXiv:2502.08508
  Submitted on Astrophysical Journal Letters. Positive referee answers
- The ultra-high-energy event KM3-230213A within the global neutrino landscape, arXiv:2502.08173
  Submitted to Physical Review X. Positive referee answers
- On the Potential Galactic Origin of the Ultra-High-Energy Event KM3-230213A, arXiv:2502.08387
- Characterising Candidate Blazar Counterparts of the Ultra-High-Energy Event KM3-230213A, arXiv:2502.08484

Published just after on arXiv

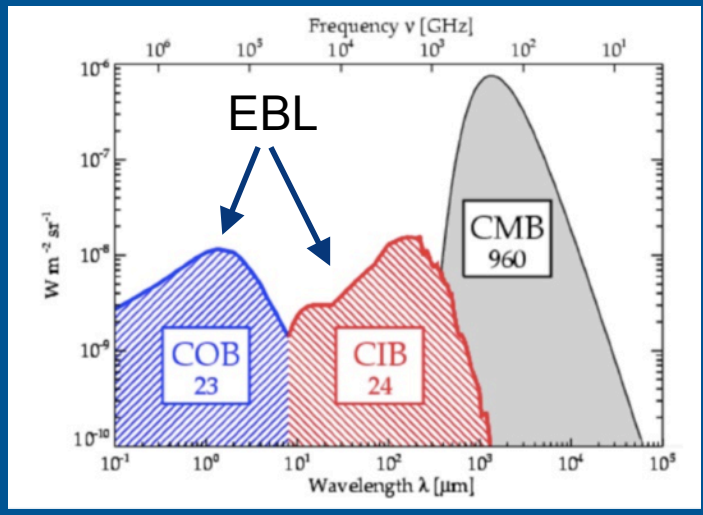
- KM3NeT Constraint on Lorentz-Violating Superluminal Neutrino Velocity arXiv:2502.12070
  Submitted to Communications Physics

On the potential cosmogenic origin of the ultra-high-energy event, arXiv:2502.08508



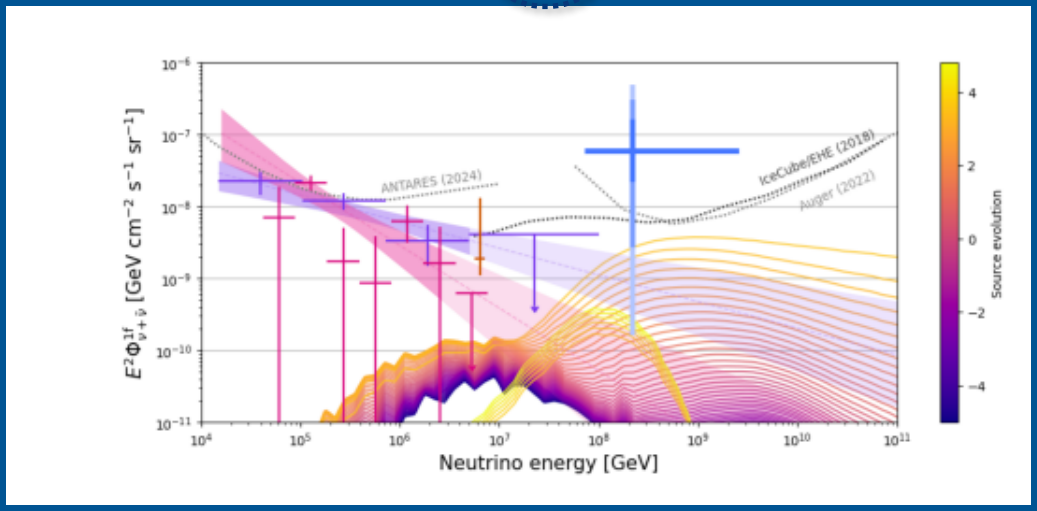
Cosmogenic neutrinos:

Ultra high energy comic-rays that interact with intergalactic Cosmic Microwaves Background (CMB) & Extragalactic Background Light (EBL) produce high energy neutrinos



The cosmogenic neutrino flux is strongly dependent on

- the cosmic-ray mass composition above 5 x 10^{19} eV.
- the maximum acceleration energy ($\propto Z$ of each element)
- the shape of the particle energy spectrum
- the source density $S(z) \propto (1+z)^m$ ◀ ..... Source evolution model

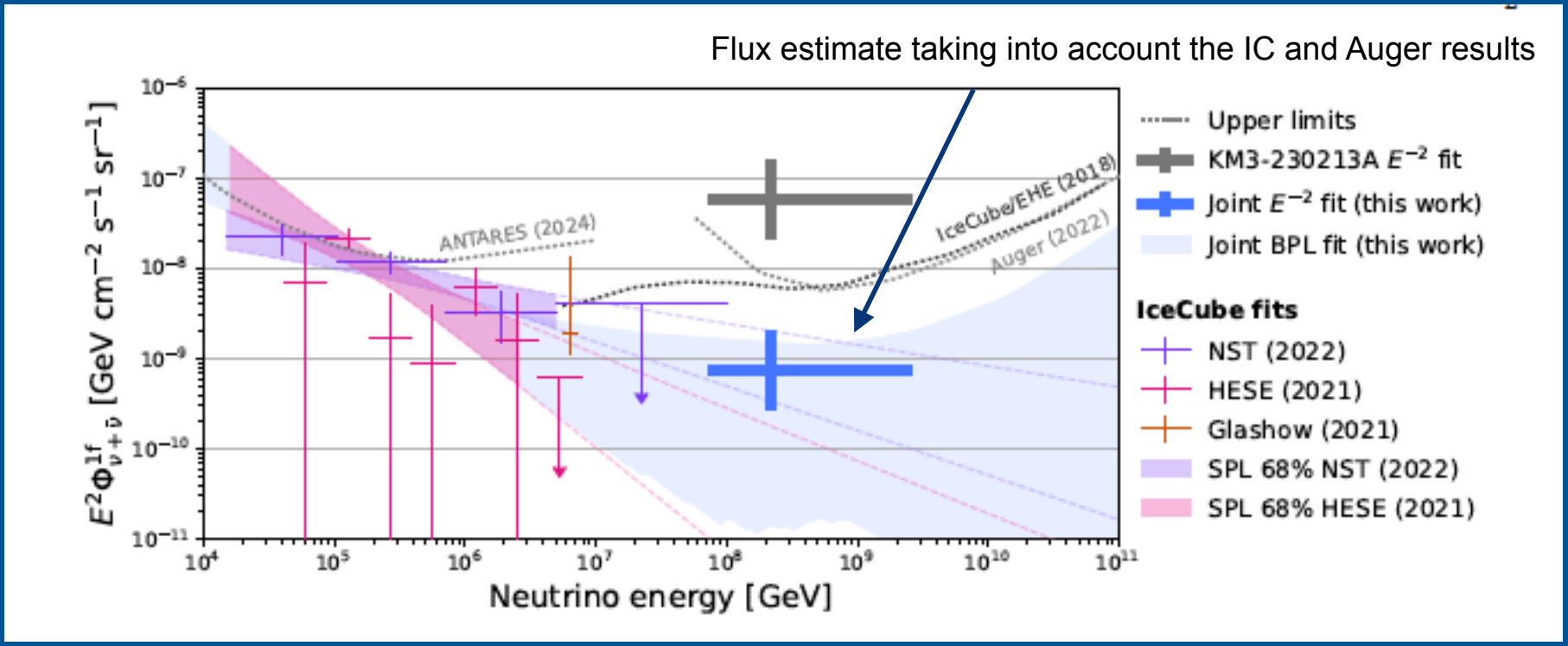


Strong source evolutions and a non-negligible proton fraction produced at the highest energies are the model parameters preferred

An additional galactic component is not excluded

The ultra-high-energy event KM3-230213A within the global neutrino landscape, arXiv:2502.08173

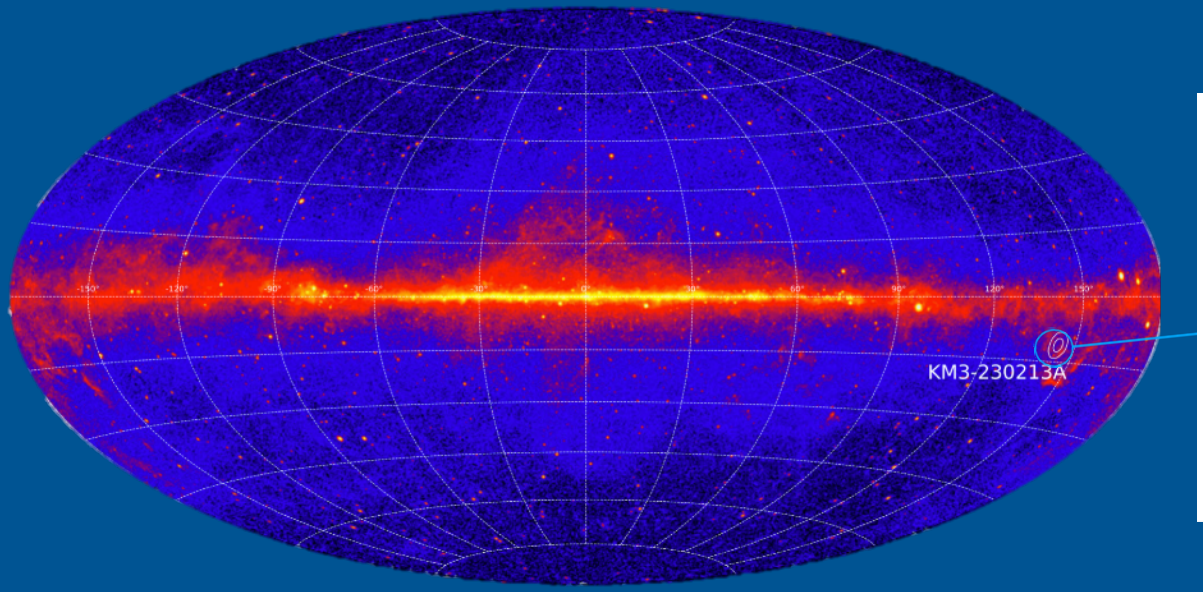
- IceCube and Auger non observation at the KM3NeT event energy taken into account
- Global fit with low energy IceCube events. Single Power Law (SPL) and Broken Power Law (BPL) fits taken into account



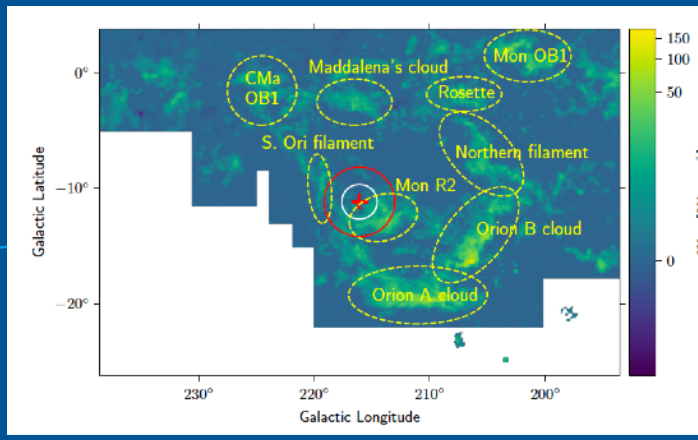
A preference for a SPL or BPL is not clear

A stronger preference for a break appears if only the KM3NeT data is considered in the ultra-high-energy region

On the Potential Galactic Origin of the Ultra-High-Energy Event KM3-230213A, arXiv:2502.08387



CO map

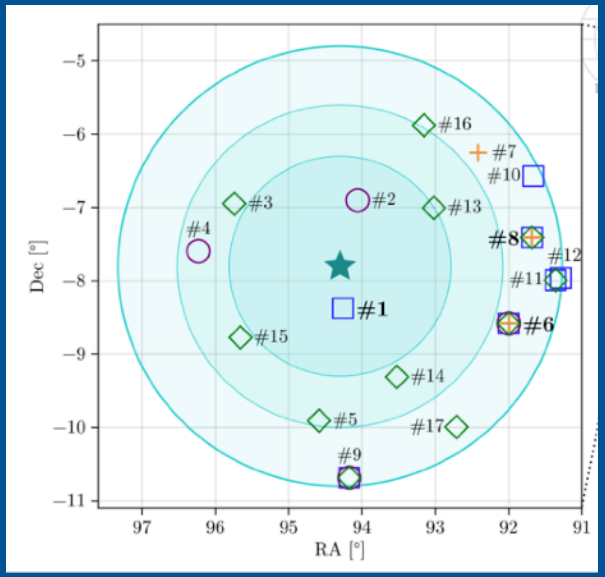


- Searches for production
  - Potential gas targets (Diffuse Galactic flux)
  - Nearby cosmic accelerators (Fermi gamma sources investigated and HAWC and LHAASO upper limits evaluated)

Very unlike that it is of Galactic origin

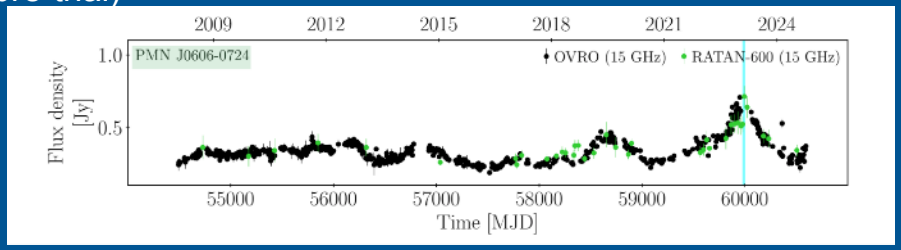
Characterising Candidate Blazar Counterparts of the Ultra-High-Energy Event KM3-230213A, arXiv:2502.08484 many collaborations involved KM3NeT, MessMapp, Fermi-LAT, OVRO 40-m Telescope, SVOM

Looked at archival data and dedicated observation in Xray, radio, IR and gamma
Found in the search cone of 3° 17 sources

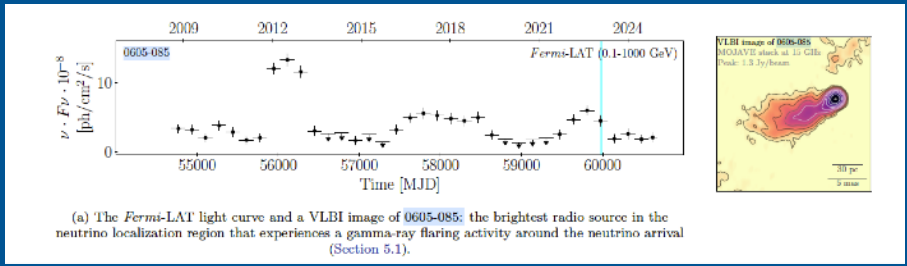


The most intriguing ones:

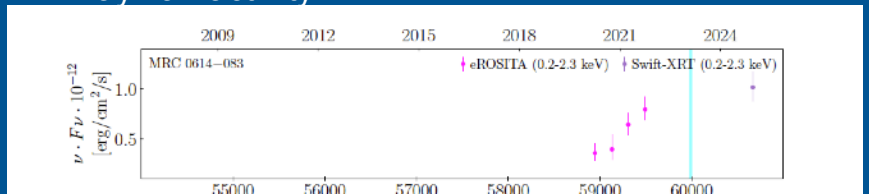
#8 fast radio flair in coincidence with the KM3-230212A event - value (0.26% pre-trial)



#6 gamma-ray activity in 1 year around the KM3-230212A event. It is among the fifty most intense radio blazars

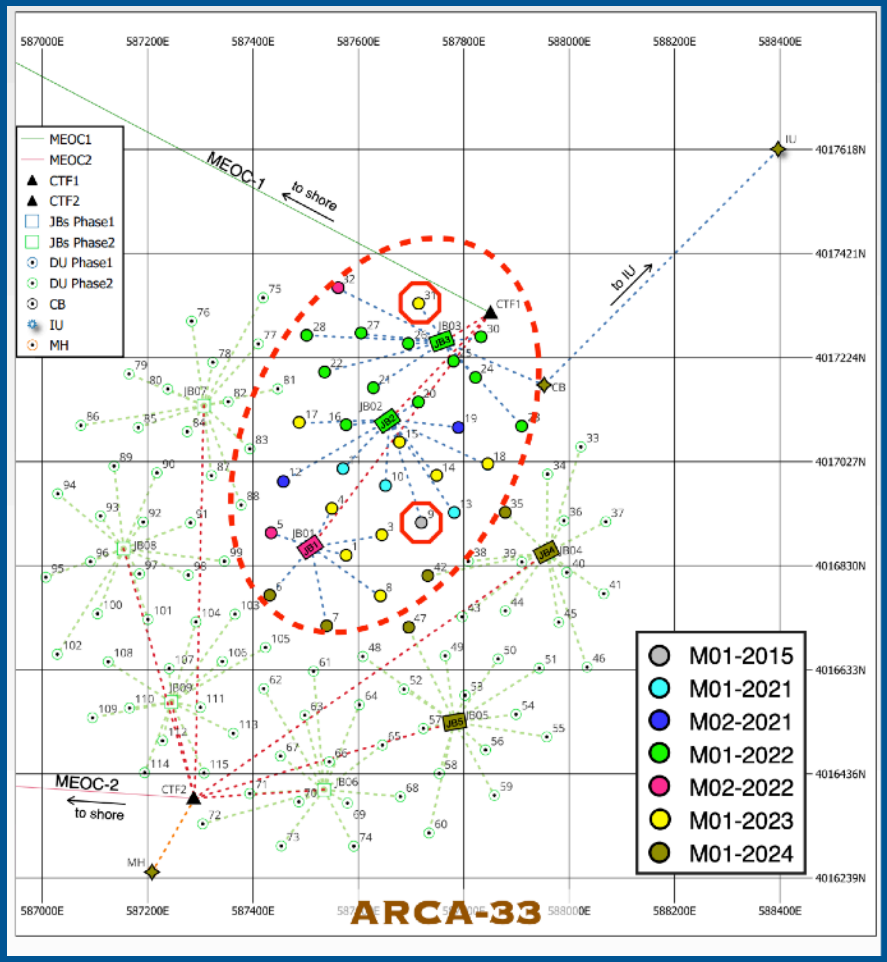


#1 X-ray flair activity

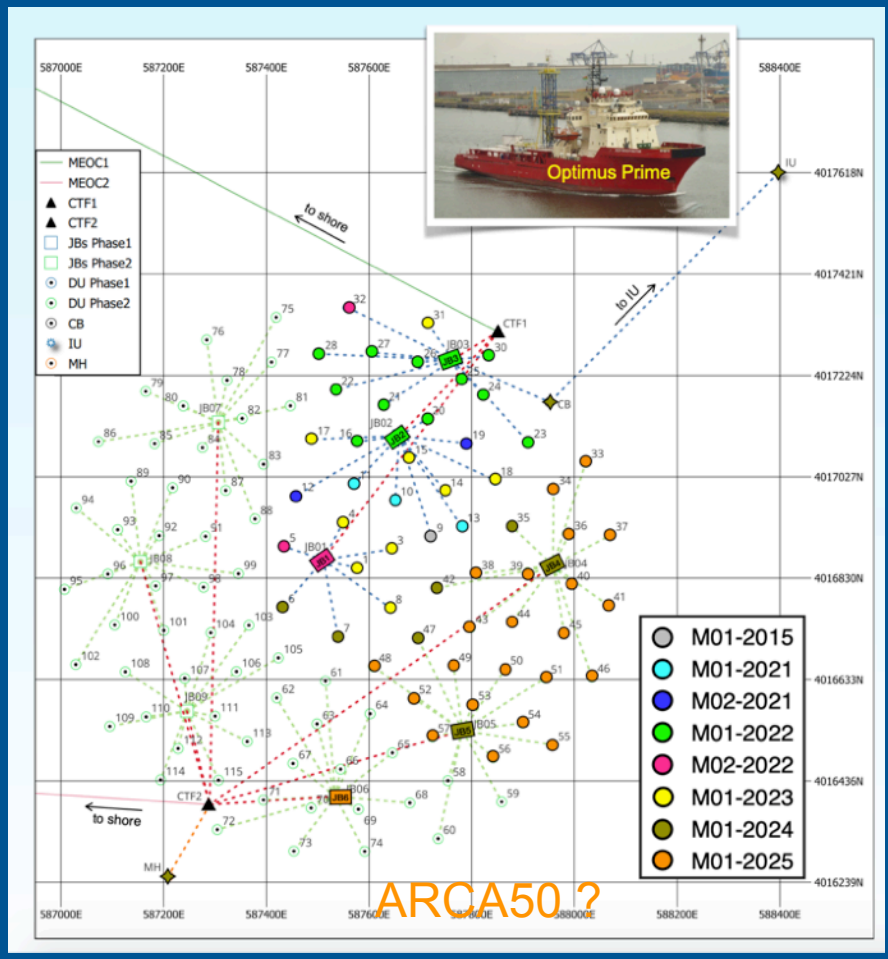


KM3NET NEXT SEA CAMPAIGN

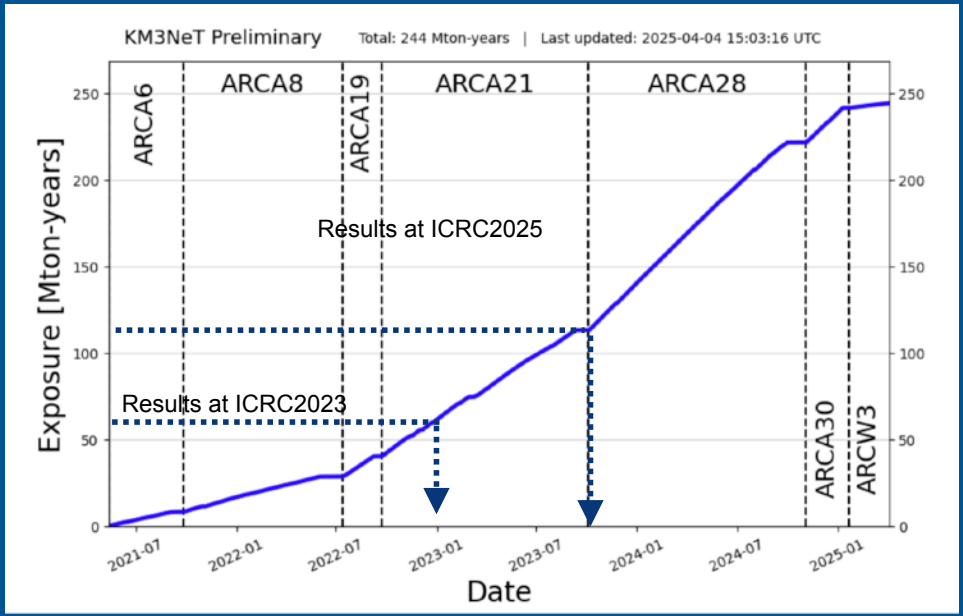
Present status



Next sea campaign in July ?!?
About 20 additional DU in water



KM3NET ANALYSIS STATUS AND NEAR FUTURE



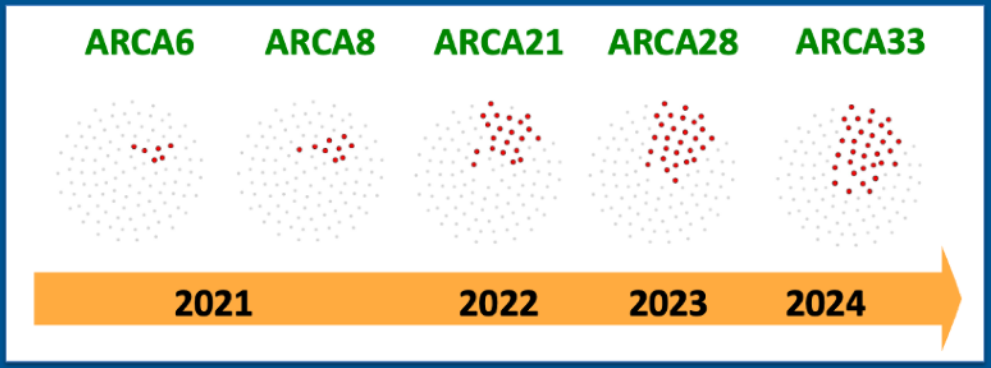
Unblinding of data Data of ARCA6-8-21 soon.
Results @ICRC2025

Problems with ARCA28 data

Bugs in the firmware caused:

- a temporal misalignment (-16ns) of about 20% of DOMs. The DOM misaligned changed randomly at each reboot.
- missing also compasses data for many DOMs.

Data corrections on-going
Software for the selection of DOM misaligned already in place.Checks on going.
System to roughly estimate orientation in the x-y- plan from atmospheric muon already done. Checks ongoing

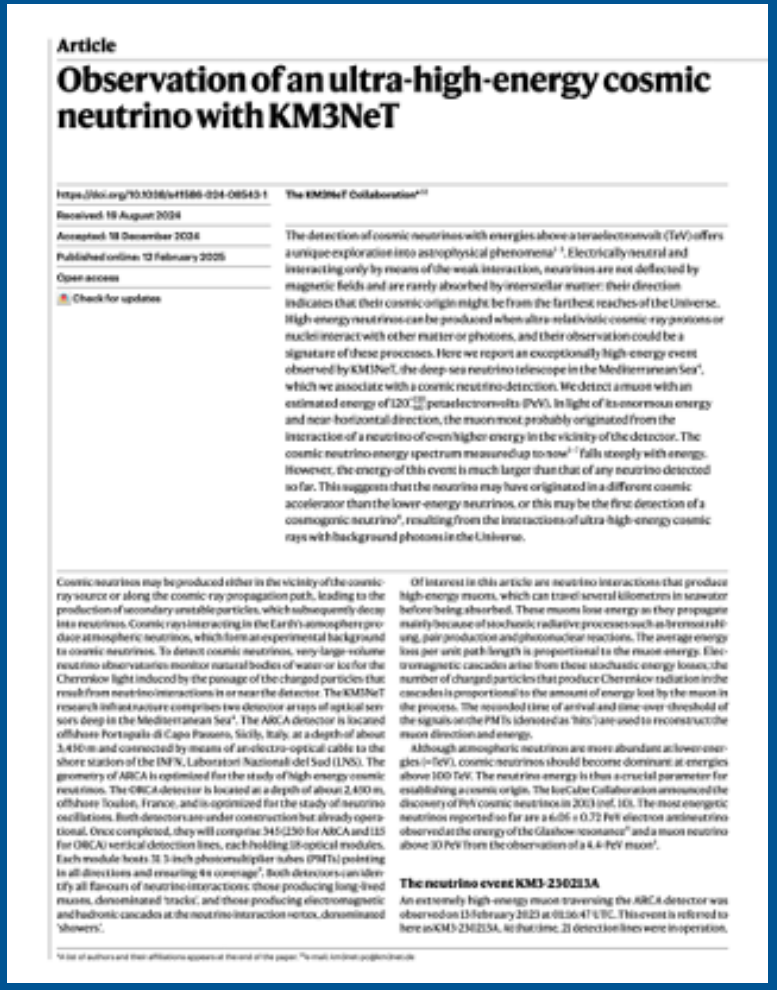


Detector calibration is a challenging task:

- Efforts to reduce the time from the first data taking to a reliable detector calibration are on-going.
- Calibration workflow already set -> speed up of the treatment of anomalies on-going
- To reduce the present angular uncertainty a high precision measurement (~1m) of the absolute positions of the detector elements is needed.

First big result already achieved

Many others will come in the next years



Article

Observation of an ultra-high-energy cosmic neutrino with KM3NeT

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Open access
Check for updates

The KM3NeT Collaboration*

The detection of cosmic neutrinos with energies above a teraelectronvolt (TeV) offers a unique exploration into astrophysical phenomena[1–3]. Electrically neutral and interacting only by means of the weak interaction, neutrinos are not deflected by magnetic fields and are rarely absorbed by interstellar matter: their direction indicates that their cosmic origin might be from the farthest reaches of the Universe. High-energy neutrinos can be produced when ultra-relativistic cosmic-ray protons or nuclei interact with other matter or photons, and their observation could be a signature of these processes. Here we report an exceptionally high-energy event observed by KM3NeT, the deep-sea neutrino telescope in the Mediterranean Sea[4], which we associate with a cosmic neutrino detection. We detect a muon with an estimated energy of 120^{+110}_{-60} petaelectronvolts (PeV). In light of its enormous energy and near-horizontal direction, the muon most probably originated from the interaction of a neutrino of even higher energy in the vicinity of the detector. The cosmic neutrino energy spectrum measured up to now[1,2] falls steeply with energy. However, the energy of this event is much larger than that of any neutrino detected so far. This suggests that the neutrino may have originated in a different cosmic accelerator than the lower-energy neutrinos, or this may be the first detection of a cosmogenic neutrino[5], resulting from the interactions of ultra-high-energy cosmic rays with background photons in the Universe.

Cosmic neutrinos may be produced either in the vicinity of the cosmic-ray source or along the cosmic-ray propagation path, leading to the production of secondary unstable particles, which subsequently decay into neutrinos. Cosmic rays interacting in the Earth's atmosphere produce atmospheric neutrinos, which form an experimental background to cosmic neutrinos. To detect cosmic neutrinos, very-large-volume neutrino observatories monitor natural bodies of water or ice for the Cherenkov light induced by the passage of the charged particles that result from neutrino interactions in or near the detector. The KM3NeT research infrastructure comprises two detector arrays of optical sensors deep in the Mediterranean Sea[4]. The ARCA detector is located offshore Portopalo di Capo Passero, Sicily, Italy, at a depth of about 3,450 m and connected by means of an electro-optical cable to the shore station of the INFN, Laboratori Nazionali del Sud (LNS). The geometry of ARCA is optimized for the study of high-energy cosmic neutrinos. The ORCA detector is located at a depth of about 2,450 m, offshore Toulon, France, and is optimized for the study of neutrino oscillations. Both detectors are under construction but already operational. Once completed, they will comprise 345 (230 for ARCA and 115 for ORCA) vertical detection lines, each holding 18 optical modules. Each module hosts 31 3-inch photomultiplier tubes (PMTs) pointing in all directions and ensuring 4π coverage[4]. Both detectors can identify all flavours of neutrino interactions: those producing long-lived muons, denominated 'tracks', and those producing electromagnetic and hadronic cascades at the neutrino-interaction vertex, denominated 'showers'.

Of interest in this article are neutrino interactions that produce high-energy muons, which can travel several kilometres in seawater before being absorbed. These muons lose energy as they propagate mainly because of stochastic radiative processes such as bremsstrahlung, pair production and photonuclear reactions. The average energy loss per unit path length is proportional to the muon energy. Electromagnetic cascades arise from these stochastic energy losses; the number of charged particles that produce Cherenkov radiation in the cascades is proportional to the amount of energy lost by the muon in the process. The recorded time of arrival and time-over-threshold of the signals on the PMTs (denoted as 'hits') are used to reconstruct the muon direction and energy.

Although atmospheric neutrinos are more abundant at lower energies (≈TeV), cosmic neutrinos should become dominant at energies above 100 TeV. The neutrino energy is thus a crucial parameter for establishing a cosmic origin. The IceCube Collaboration announced the discovery of PeV cosmic neutrinos in 2013 (ref. 10). The most energetic neutrinos reported so far are a 6.05 ± 0.72 PeV electron antineutrino observed at the energy of the Glashow resonance[11] and a muon neutrino above 10 PeV from the observation of a 4.4-PeV muon[3].

The neutrino event KM3-230213A

An extremely high-energy muon traversing the ARCA detector was observed on 13 February 2023 at 01:16:47 UTC. This event is referred to here as KM3-230213A. At that time, 21 detection lines were in operation,

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