KM3NeT neutrino observatory

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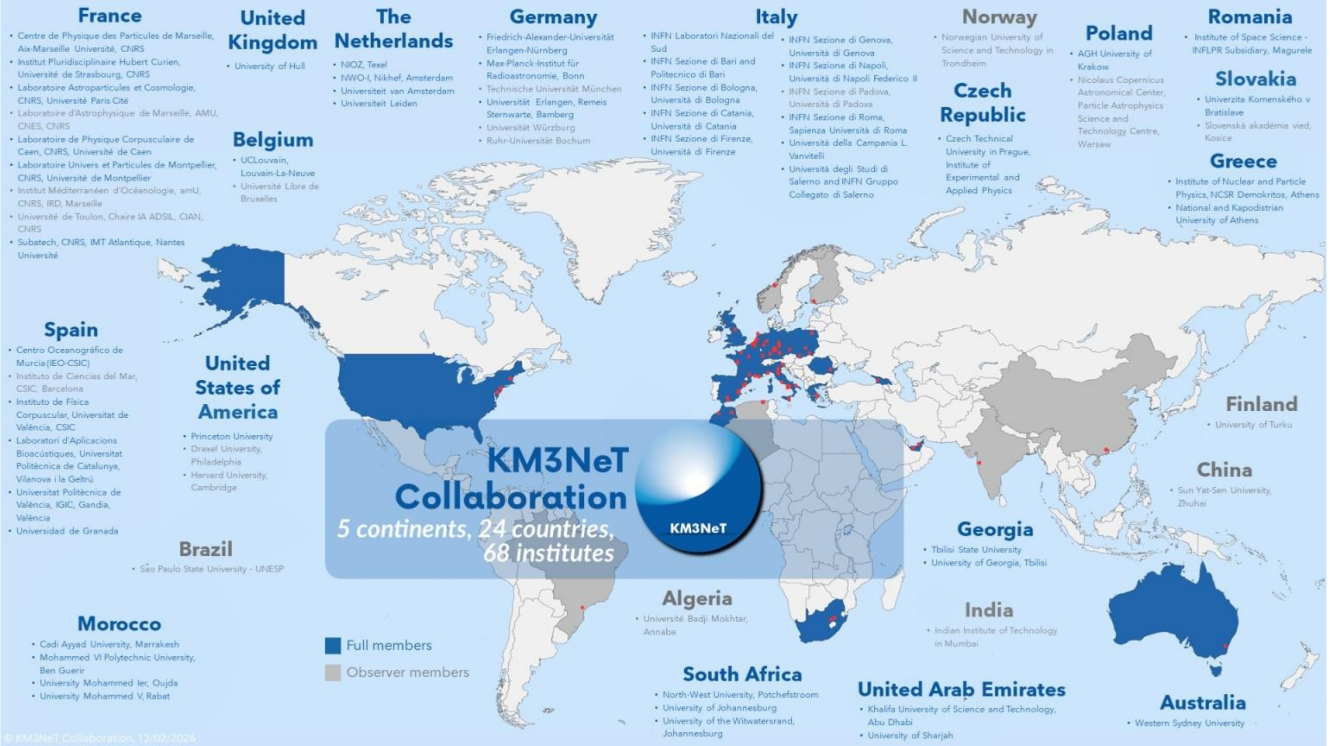
The KM3NeT project

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

KM3NeT/ORCA: Study of atmospheric neutrino oscillations

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 **R**esearch
with **C**osmics in the **A**byss

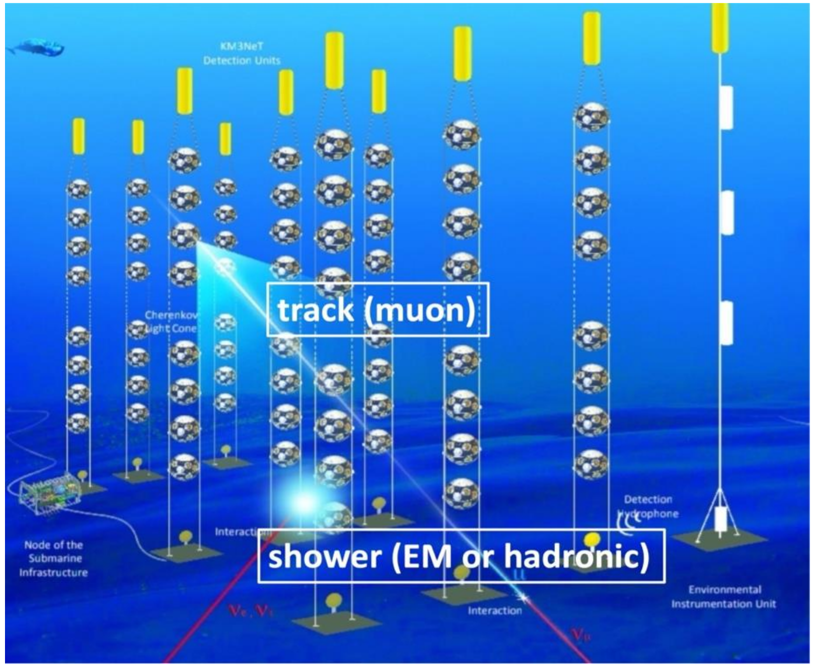
ARCA:
Astroparticle **R**esearch
with **C**osmics in the **A**byss

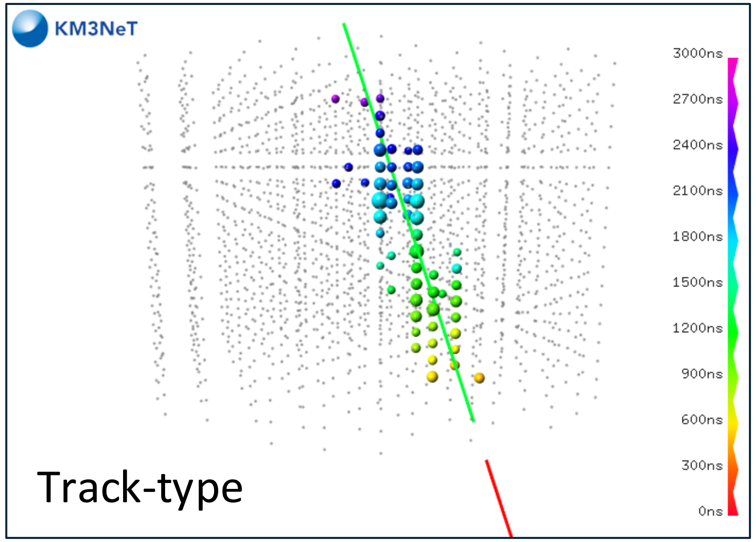
www.km3net.org

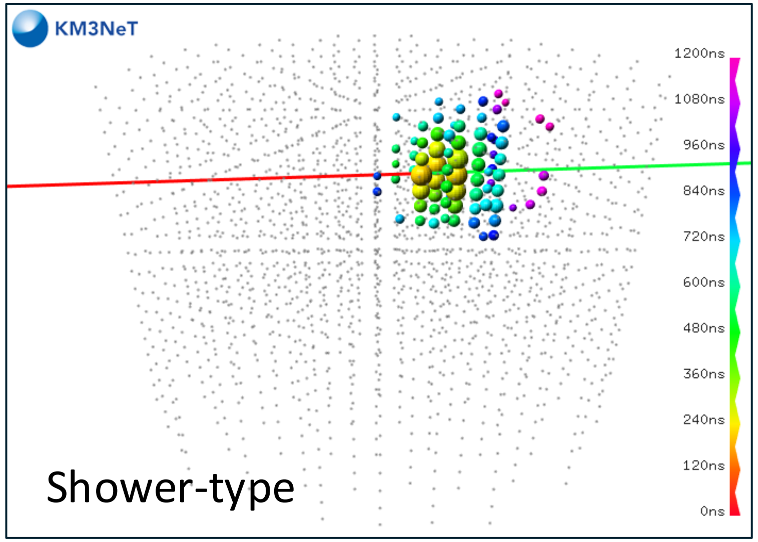
Detection principle

Detection of Cherenkov light emitted by neutrino induced charged particles

Neutrino event reconstruction and type discrimination based on event topologies







(KM3NeT, E_ν>100 TeV)

Tracks	Ang. res. below 0.1°	-	Energy res. ~ factor 2
Shower	Ang. res. below 2°	-	Energy res. ~6%

KM3NeT technology in a nutshell

Digital Optical Module (DOM)

JINST 17 (2022) P07038

- 31 x 3” PMTs in a 17” glass sphere
- LED beacon and acoustic piezoelectric
- Tiltmeter/compass
- Gbit/s fibre for data transmission
- White Rabbit for time synchronization

- Digital photon counting
- Directional information
- Wide angle of view
- Improved background rejection
- Compact and cost-effective design

Detection Unit (DU)

JINST 15 (2020) P11027

String:

1 Buoy

2 Dyneema ropes

18 DOMs

Electro-optical backbone:

Flexible hose 7mm

Oil-filled

18 fibres

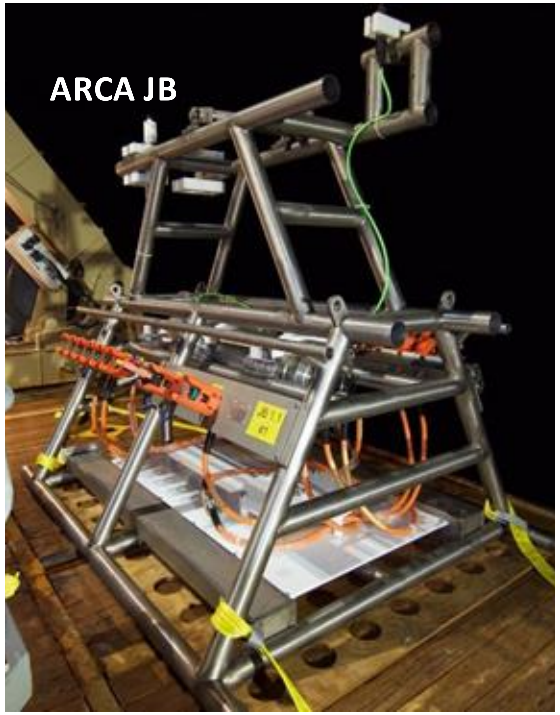
2 copper wires (375VDC)

Base:

- Anchor with electro-optical connector
- Base Module:
  - Central Logic Board (CLB, white rabbit timing)
  - Power control board
  - Optical amplifier
  - Hydrophone
  - LBL beacon

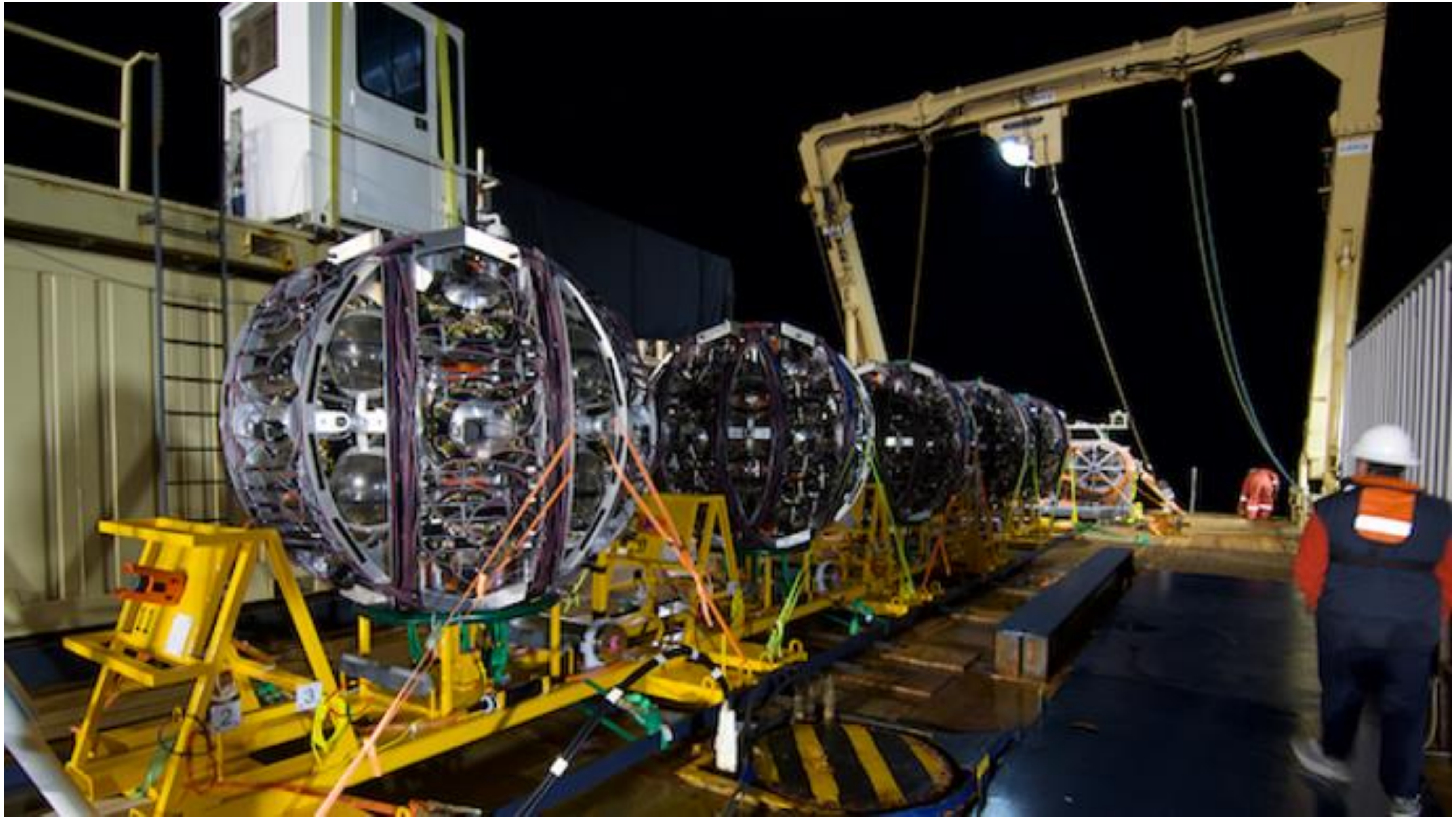
Seafloor network

JINST 18 (2023) T02001



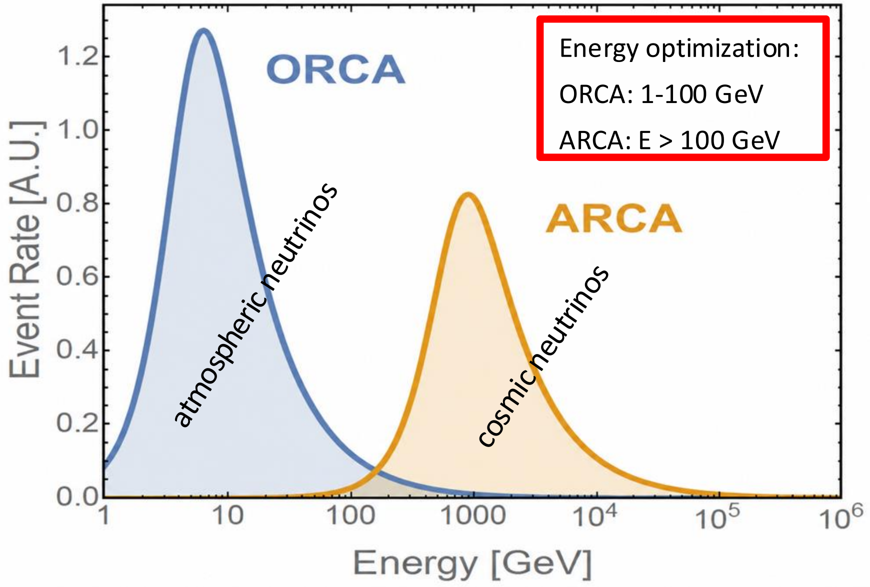
- Electro-optical cables from deep sea to the shore station
- Junction boxes (JB) to distribute power and optical fibres
- Interlink cables for connection of DUs to JBs and JBs to the main cable

Deployment of Detection Units

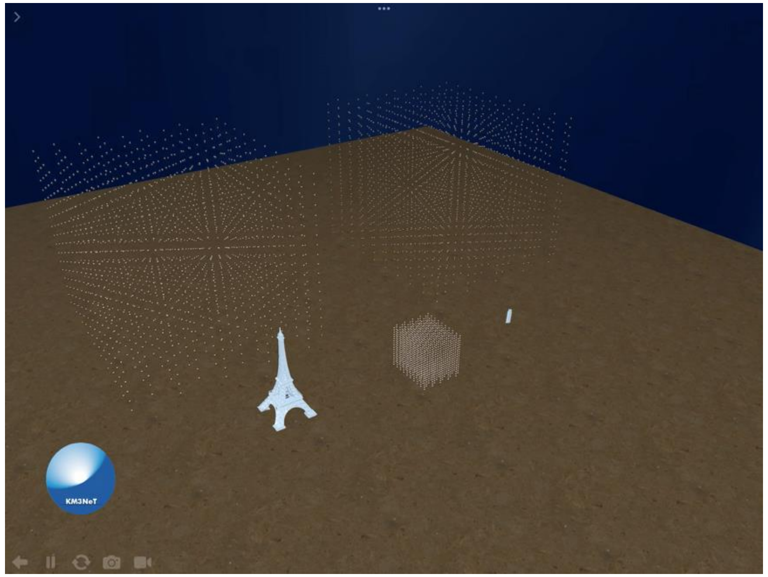


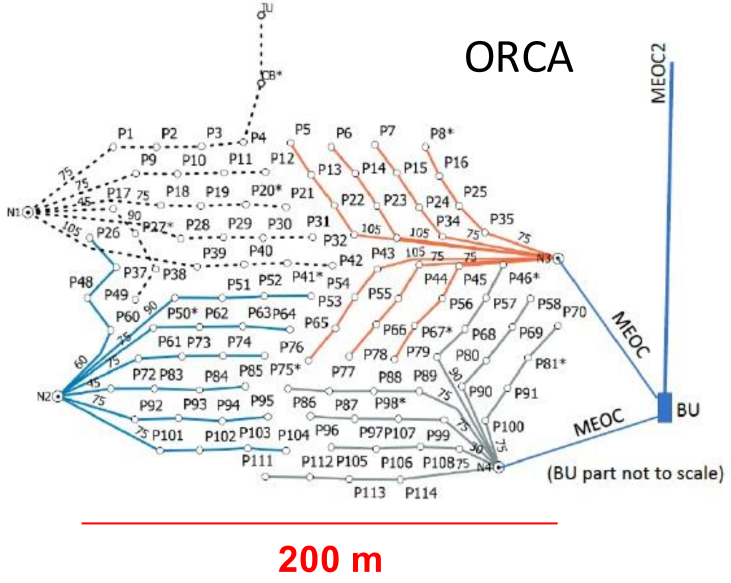
JINST 15 (2020) P11027

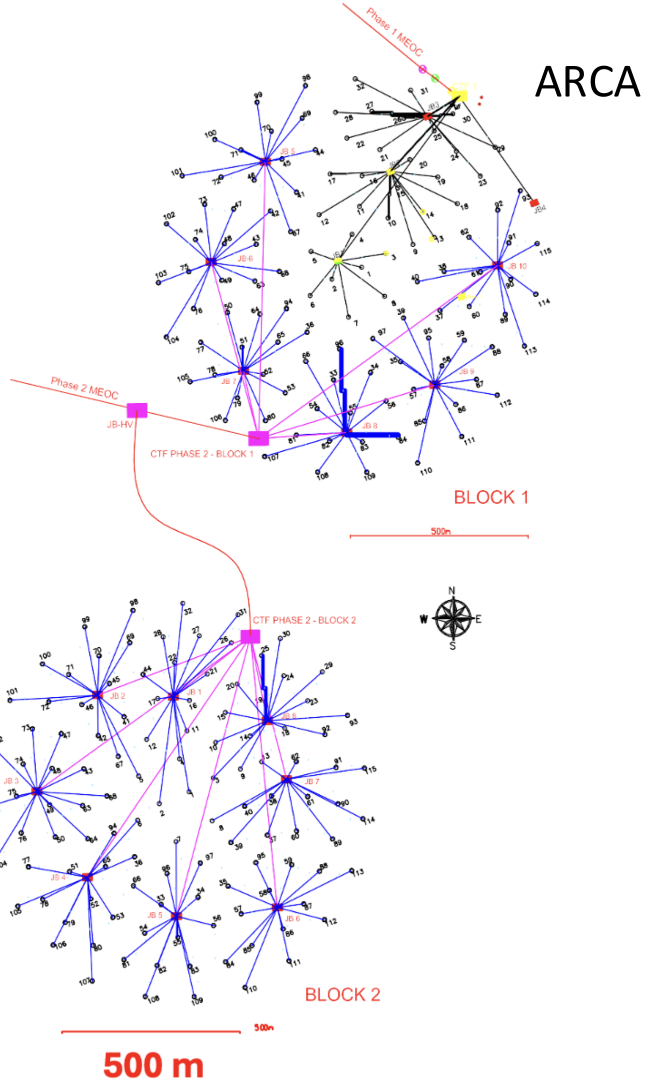
Detector layouts



	ORCA	ARCA
DOM spacing	9 m	36 m
String height	200 m	700 m
String spacing	20 m	90 m
Strings	108	198
Building Blocks	1	2
Instrumented mass	6.5 Mton	1 Gton

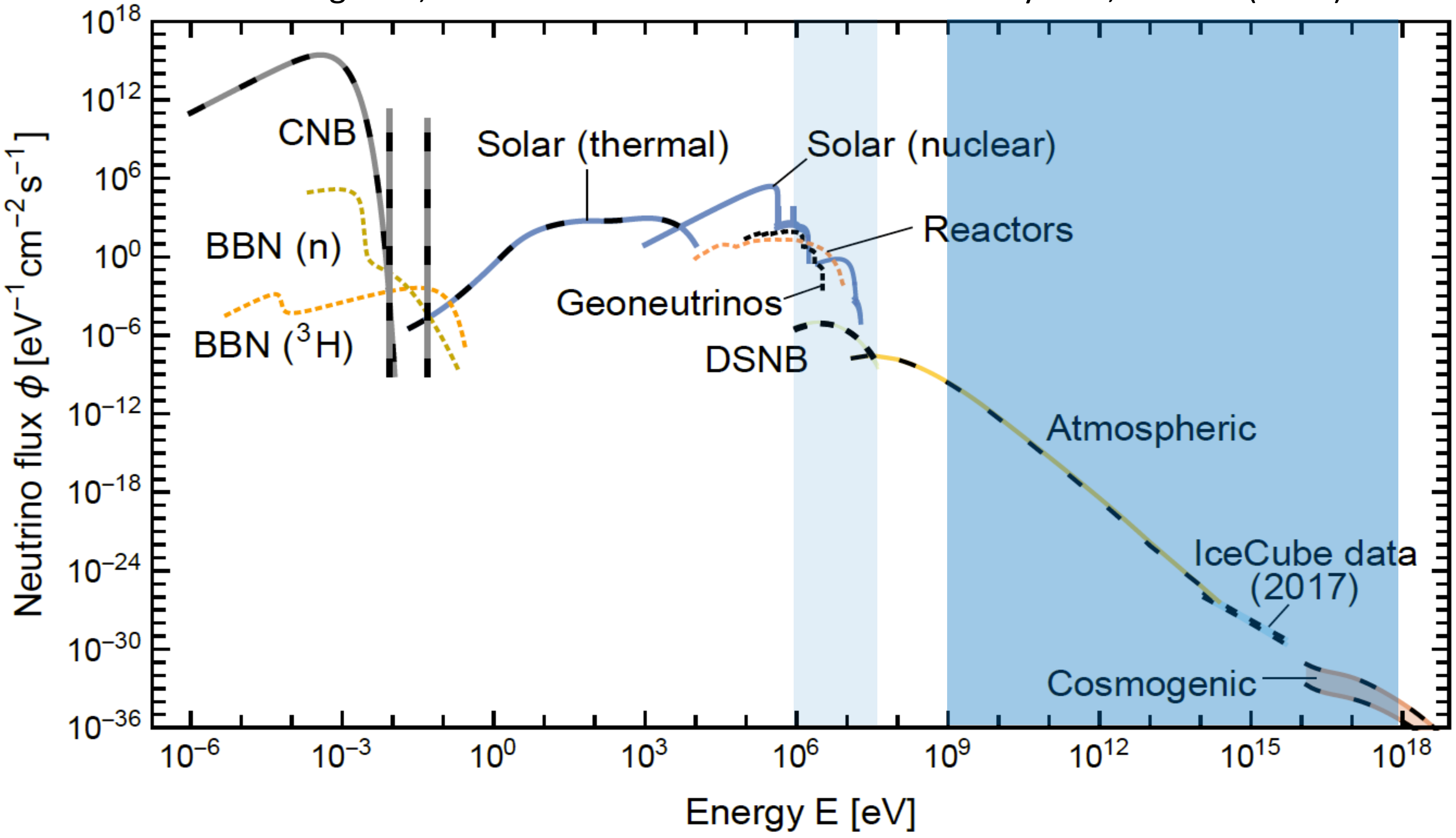






Grand Unified Neutrino Spectrum at Earth

E. Vitagliano, I. Tamborra and G. Raffelt Rev. Mod. Phys. **92**, 045006 (2020)



Detector status

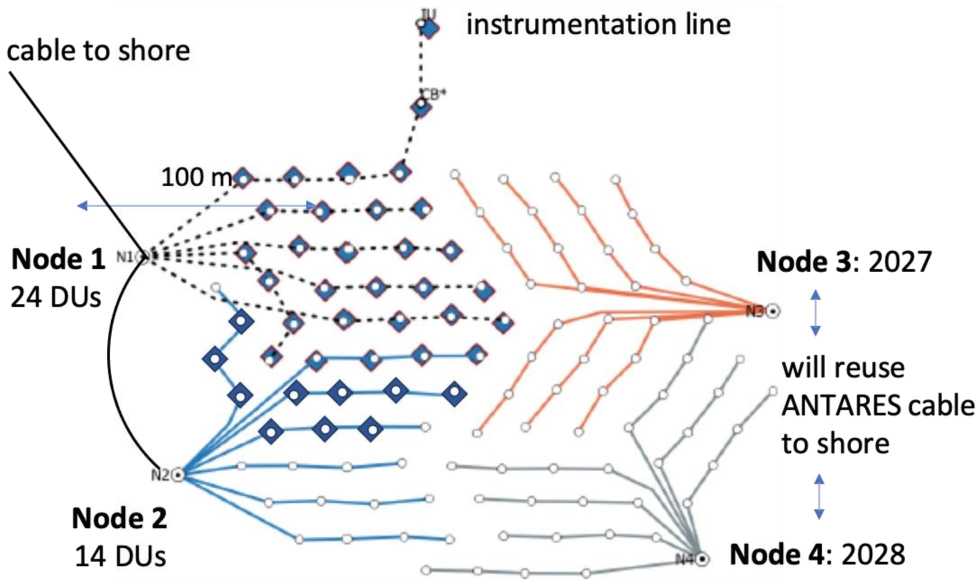
ORCA

42 DUs deployed

4 new DUs deployed in July

DU integration rate: 20/year

90% of the detector already funded



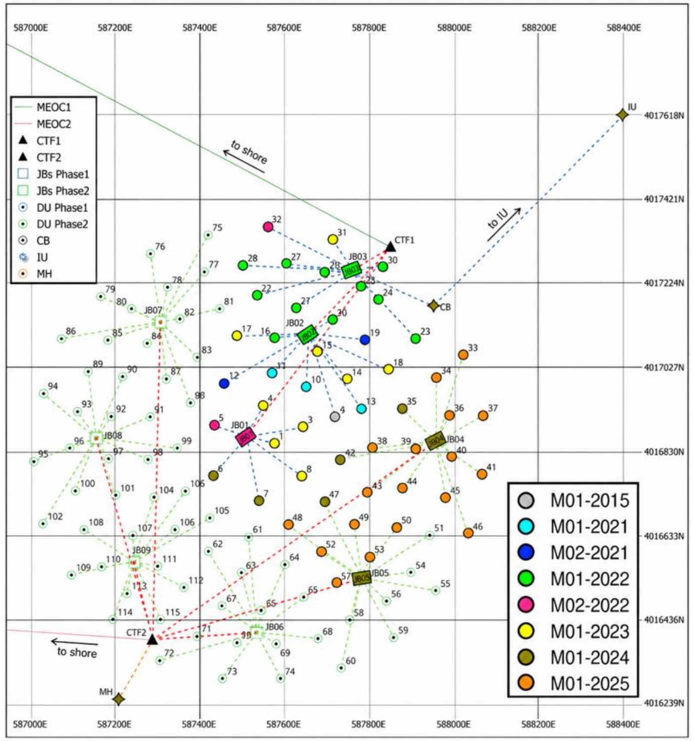
ARCA

51 DUs deployed

12 new DUs to be deployed in September

DU integration rate: 35/year

80% of the detector already funded



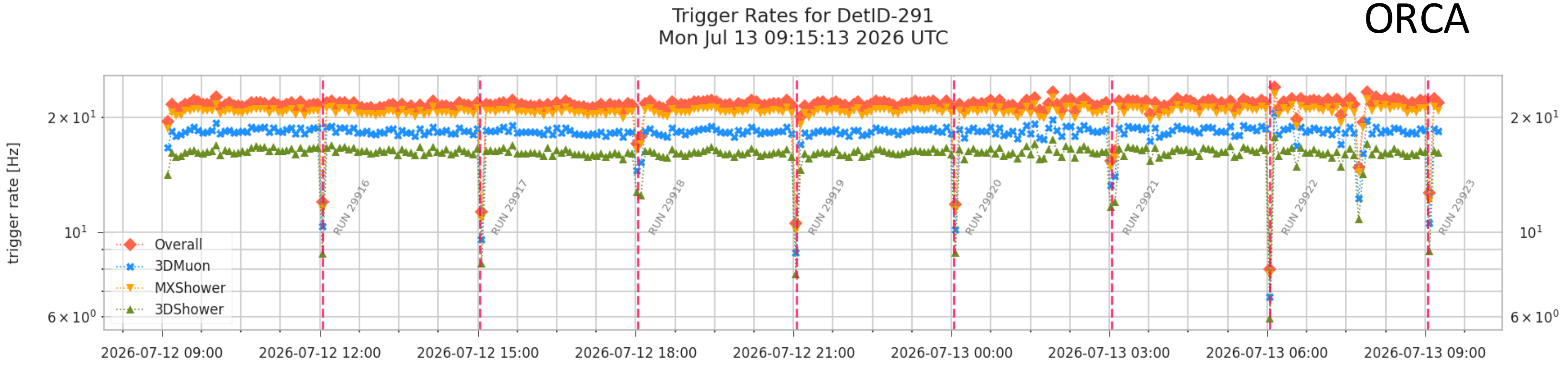
Completion of ORCA/ARCA DUs production: 2030

All digital PMT data are sent to shore and processed in real time on a computing cluster

Set of trigger algorithms searching different event topologies

Data rate per building block amounts to about 25 Gb/s, reduced by a factor of 10^4 at the trigger level

ORCA

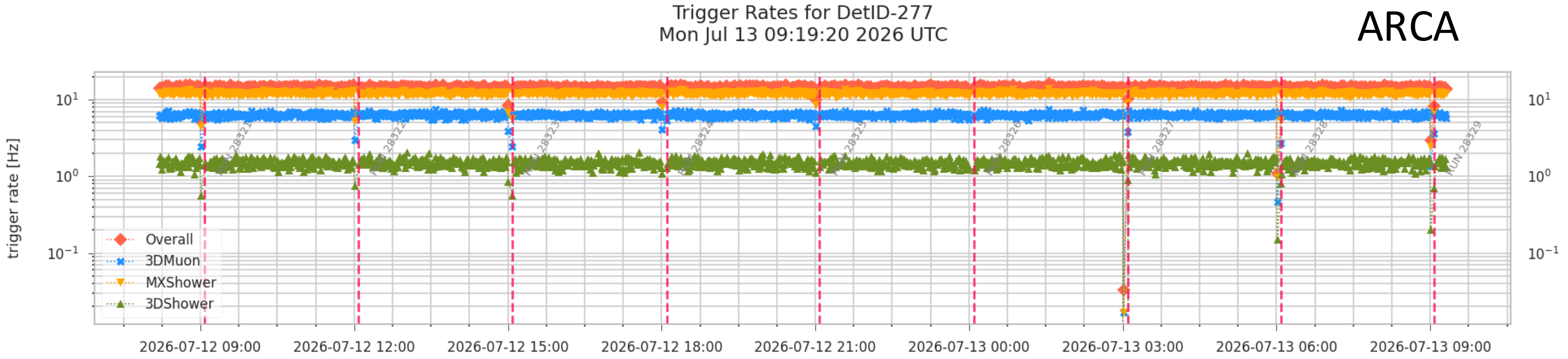


Post-trigger processing:

Online: real-time event selection for transient and multi-messenger searches

Offline: precision event reconstruction and physics analyses

ARCA

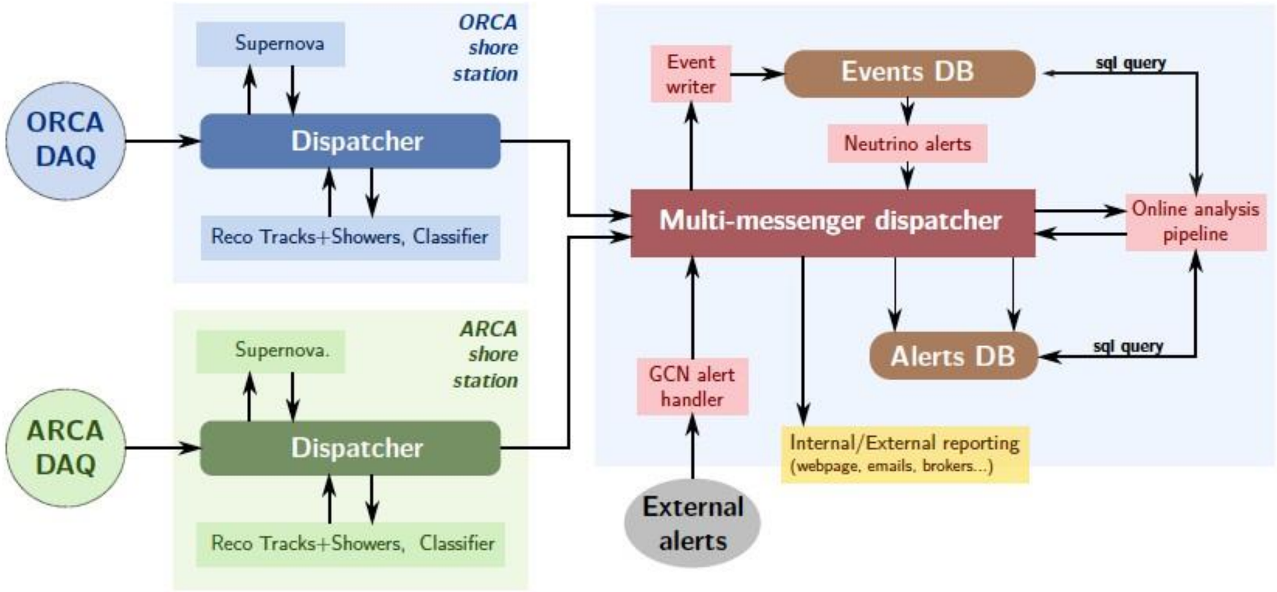


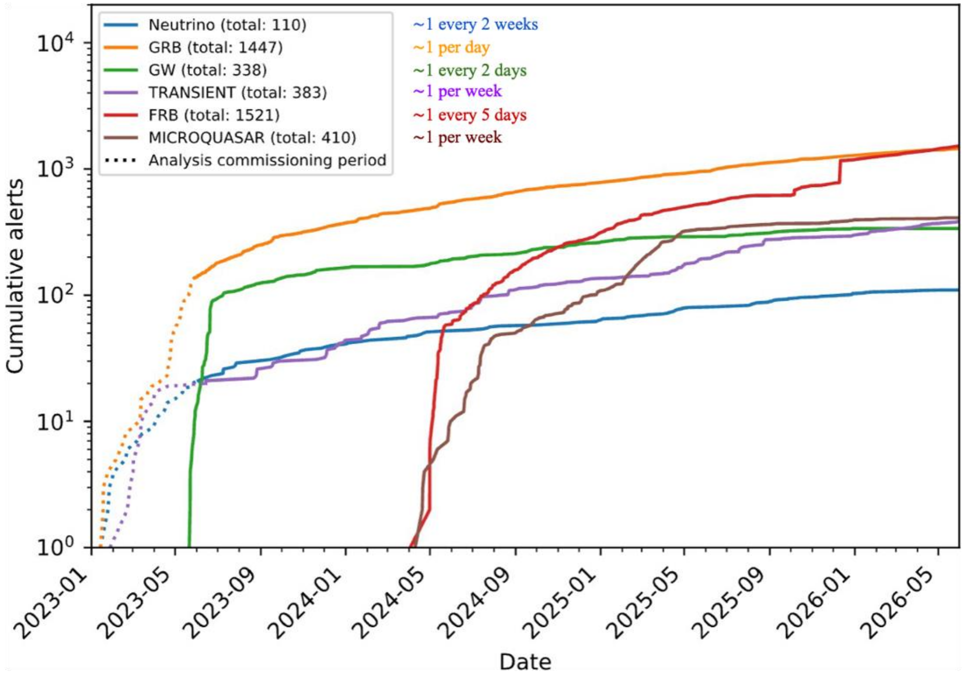
NIMA 1083 (2026) 171097

KM3NeT real-time analysis system

KM3NeT Online Platform: real-time event reconstruction + multi-messenger dispatcher + analysis module

- Real-time processing of data with online calibration: **track** & **cascades** reconstruction + **classification**
- Triggered events are processed in real-time in **less than 7 s** for both ARCA and ORCA
- **Main analysis functionalities**: follow-up of external triggers (active), Supernovae alert pipeline (active), sending alerts (work in progress)





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PoS(ICRC2025)1115

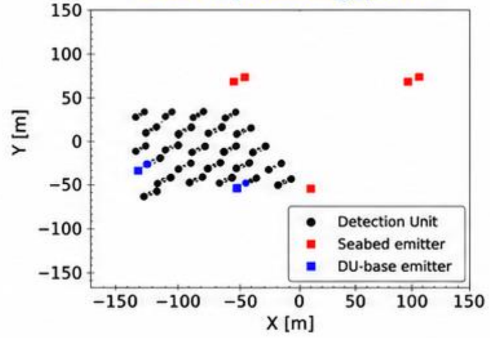
Detector calibration

POSITION CALIBRATION

Detection Units bend under sea currents, making the detector geometry time dependent.

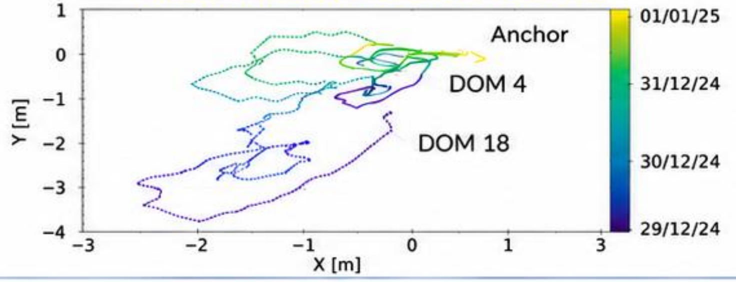
- **Acoustic triangulation** using seabed and DU-base emitters, with hydrophones on each DOM
- **Compass** and **tiltmeter** measurements
- Continuous reconstruction of the **3D position** and **orientation** of each DOM
- Geometry known with **~10 cm** precision

Acoustic positioning system

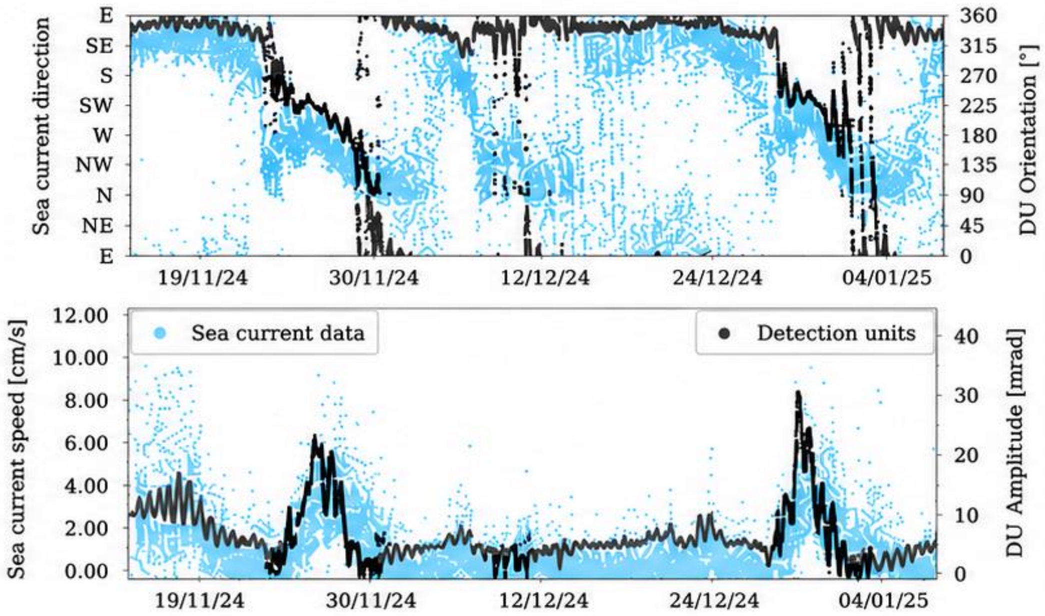


Each DOM records sound signals and its position is reconstructed in time

Reconstructed DOM movements versus time



Sea currents drive DU movements



Strong correlation between sea current and DU orientation/amplitude

DETECTOR CALIBRATION

POSITION (Geometry)
- Acoustic system (seabed & DU-base emitters)
- Compass
- Tiltmeter

Output: detector geometry

TIME (Timing)
- ^{40}K coincidences (intra-DOM timing)
- Nanobeacons (inter-DOM timing)

Output: time offsets

PMT RESPONSE
- Gain
- Efficiency
- Angular acceptance

Output: PMT parameters

OUTPUT

detx

Detector calibration constants

(geometry + timing + PMT parameters)

EVENT RECONSTRUCTION

The calibrated detector geometry, timing and charge response provide the detector conditions used for event reconstruction.

Monte Carlo simulation and data processing

MONTE CARLO CHAIN

EVENT GENERATION
- Neutrino events with gSeaGen
- Atmospheric muons with MUPAGE/CORSIKA

LIGHT GENERATION
Propagation of Cherenkov light in seawater

DETECTOR RESPONSE SIMULATION
Interaction of light with the sensors and response of the front-end electronics

REAL DATA

DATA ACQUISITION
Signals from the detector are digitized and time-stamped by the acquisition system

DETECTOR CALIBRATION
- Position calibration (acoustic, compass, tilt)
- Time calibration (^{40}K, nanobeacons)
- Charge calibration (ToT, gain, HV)

Output: detector calibration constants

EVENT RECONSTRUCTION AND ANALYSIS
The same reconstruction algorithms and tools are applied to Monte Carlo simulations and real data to reconstruct particle tracks and energies and perform physics analyses.

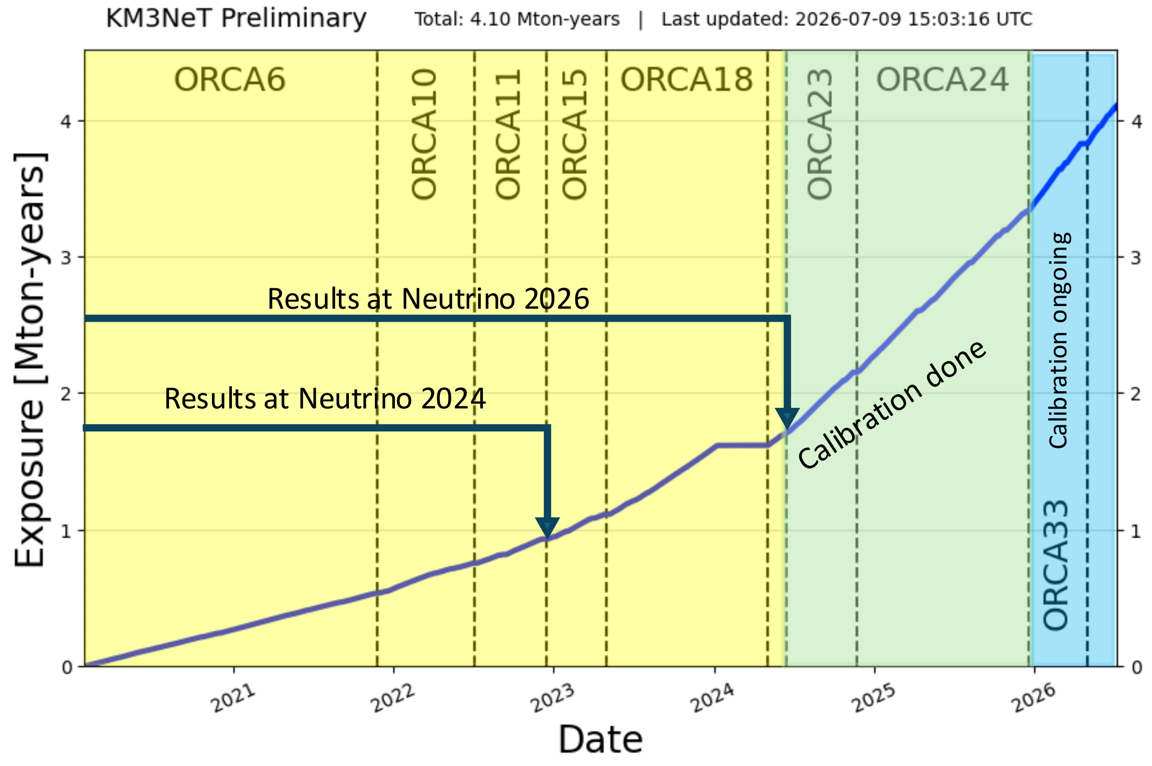
RUN-BY-RUN DETECTOR SIMULATIONS
For each data run, dedicated atmospheric muon and neutrino simulations are produced using the corresponding detector and environmental conditions.

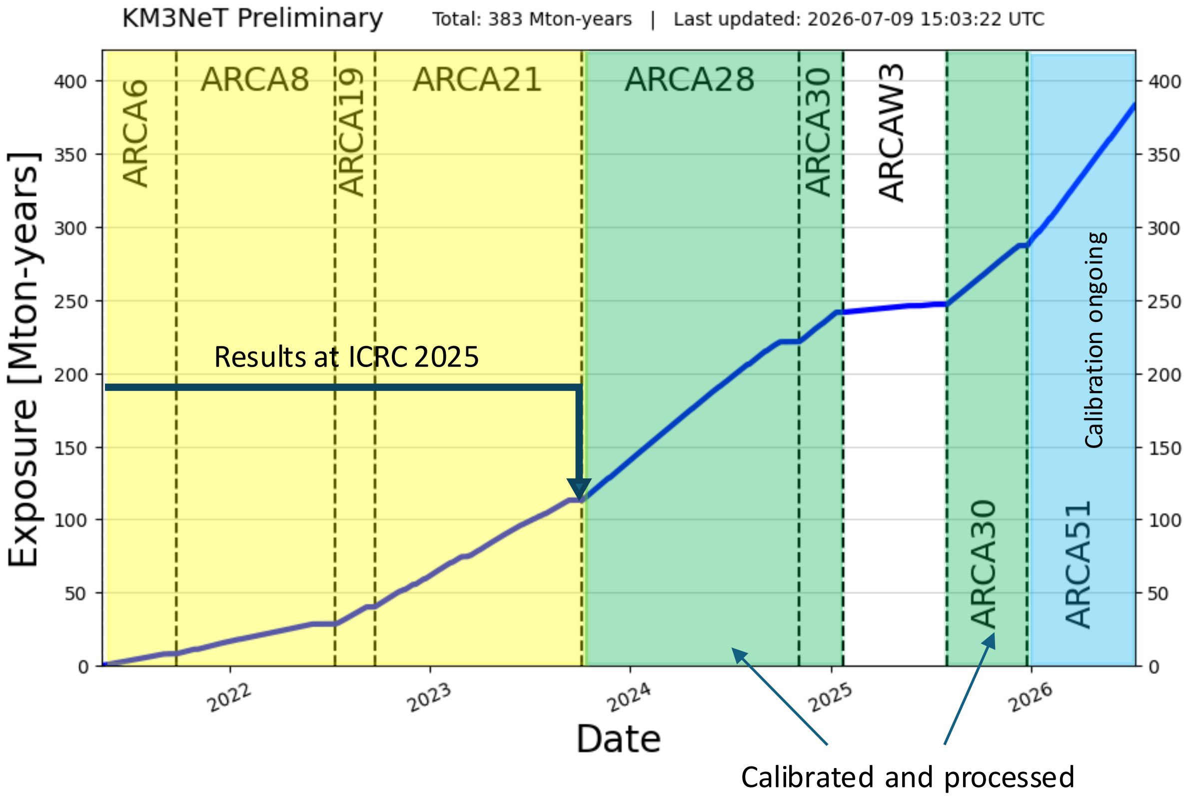
WHY DO WE SIMULATE?

Data - MC agreement is important for:

- Good understanding of the detectors
- Optimization of selection criteria for background rejection
- Neural network training for PID
- Application of statistical tests to evaluate the significance of a signal
- Estimate of the detector response for the flux measurements

Offline data analysis status



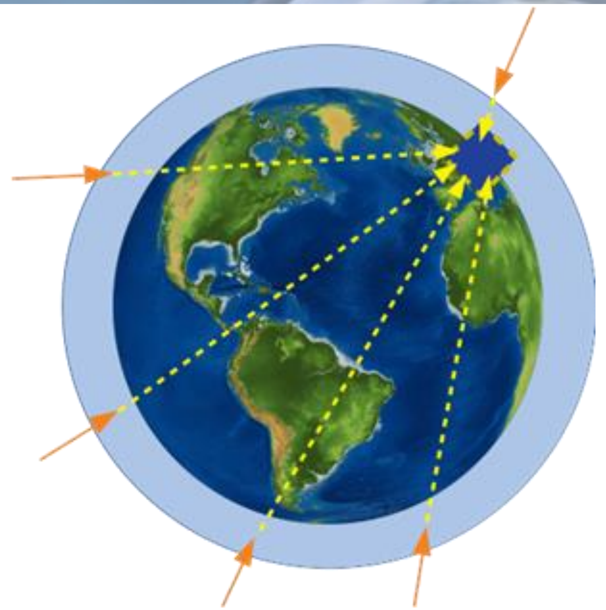


ORCA6-18 results presented at Neutrino 2026

ARCA19-30 results will be presented at ICRC 2027

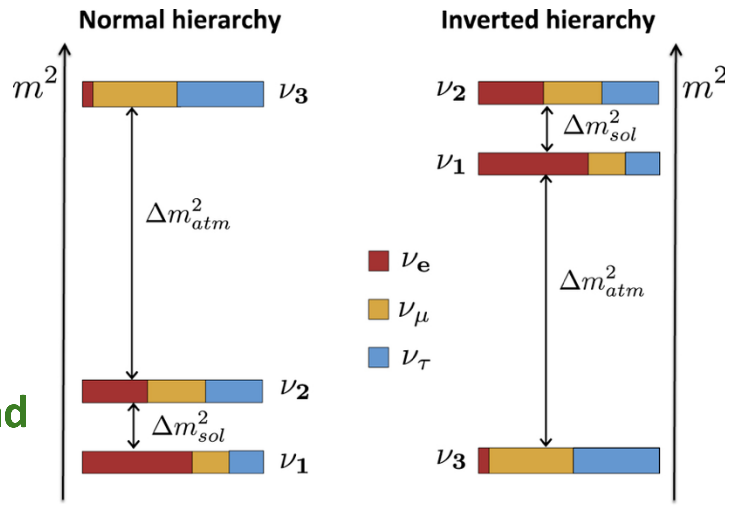
Neutrino oscillation with ORCA

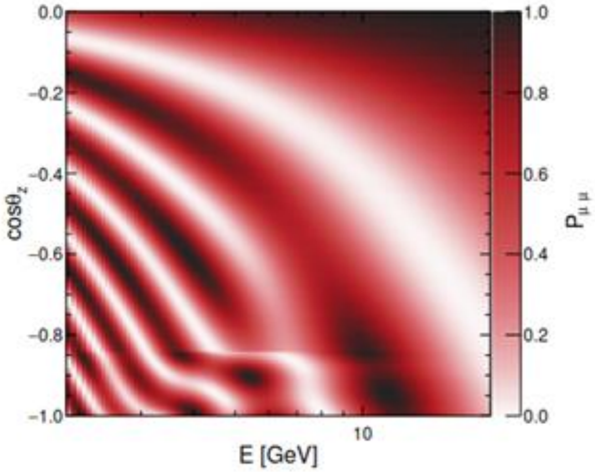
- Atmospheric flux of ν_e and ν_μ well known
- Wide range of neutrino energies
- Wide range of zenith angles -> baselines (50 – 12,800 km)
- Distortion of the oscillation pattern due to matter effects in the Earth

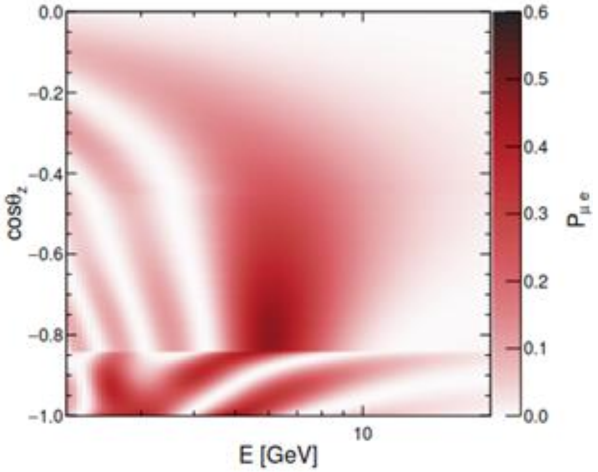


Primary goal:
neutrino mass hierarchy

But also, unitarity, Beyond Standard Model physics

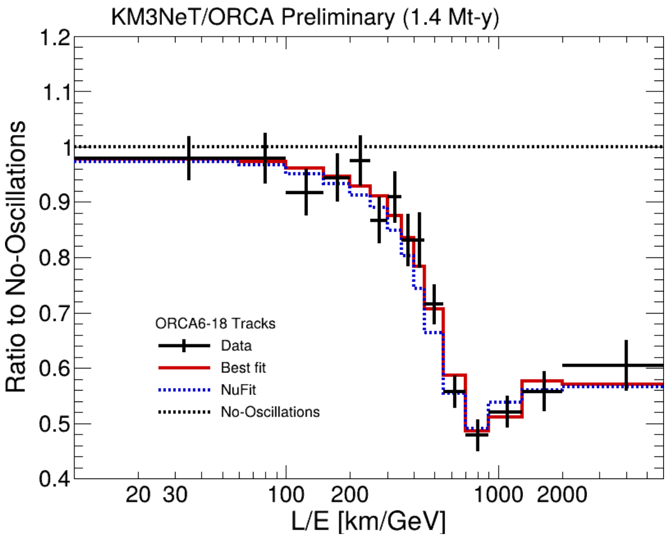




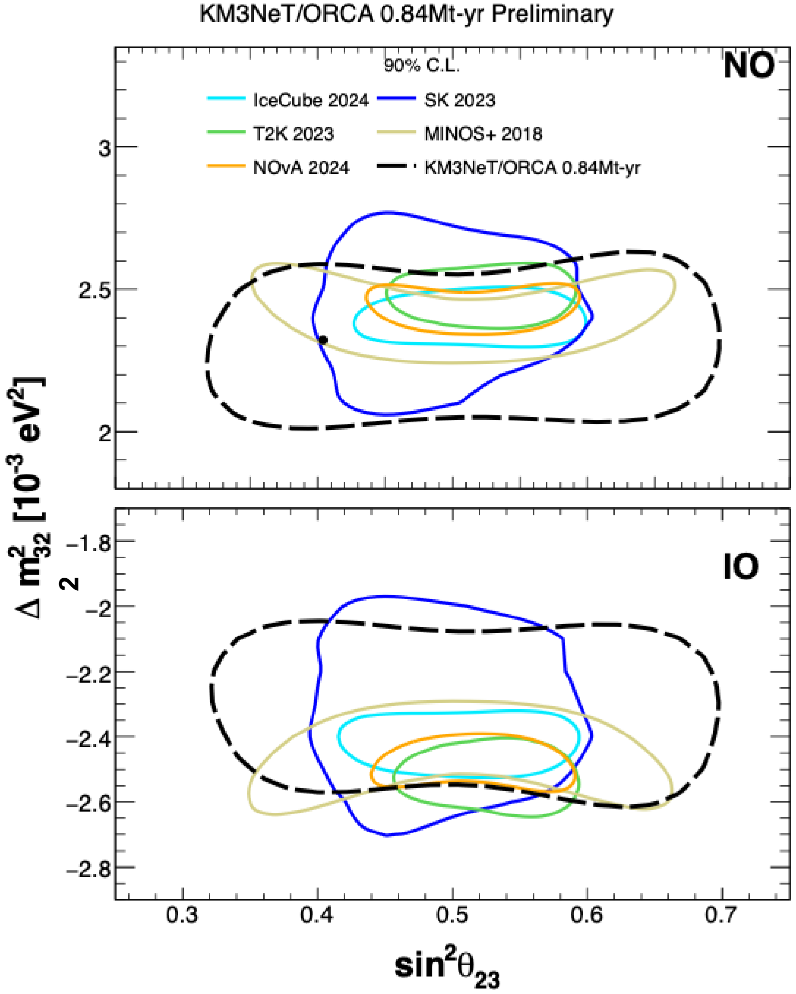


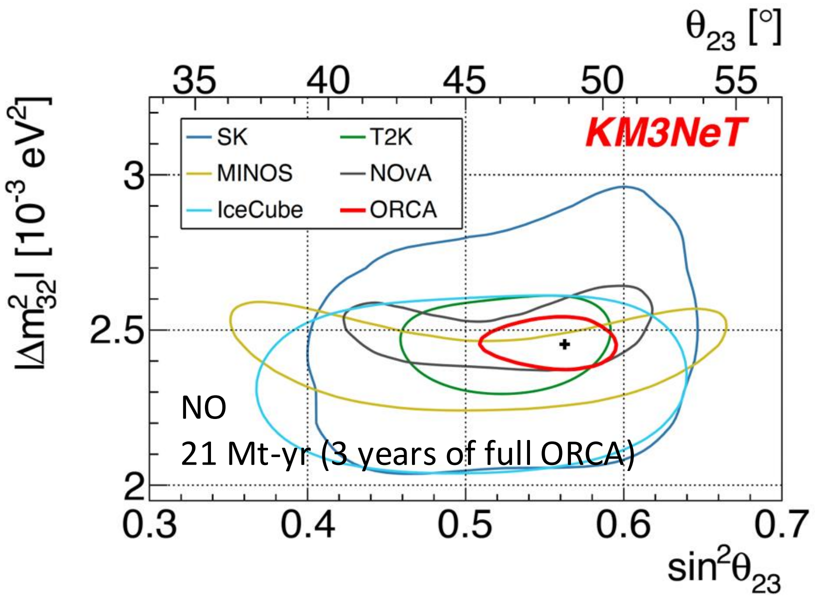
ORCA data analysis and perspectives

ORCA6-18

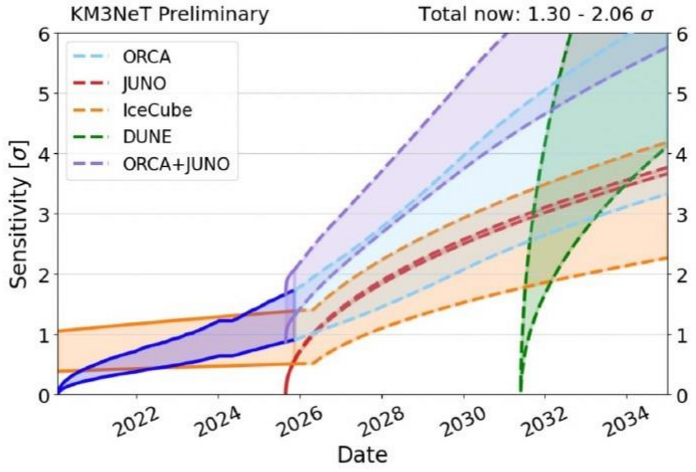


ORCA11-18





Eur. Phys. J. C 82, 26 (2022)



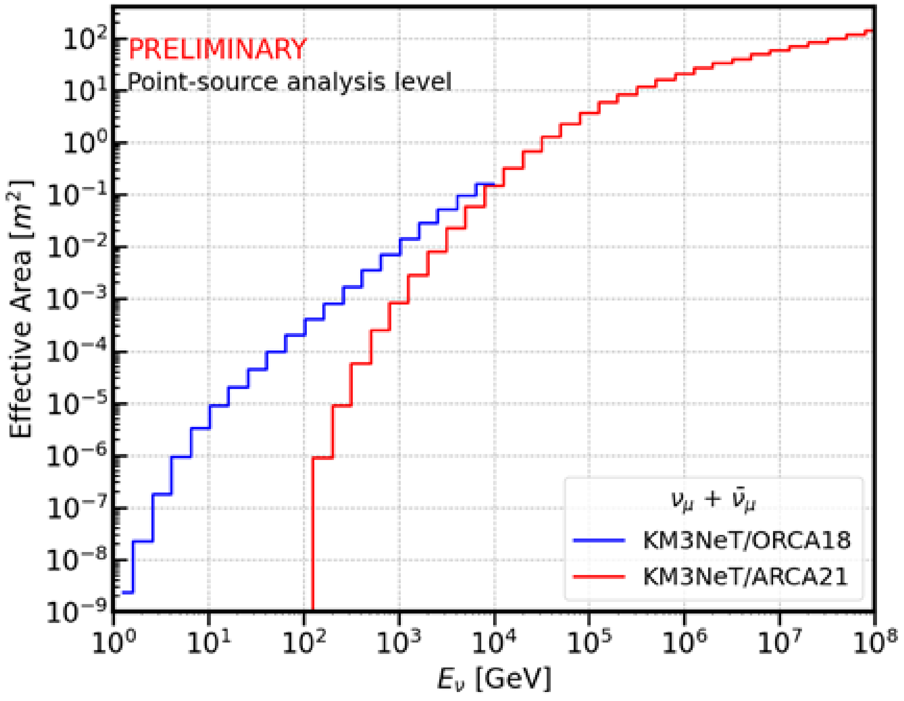
J. High Energ. Phys. 2022, 55 (2022)

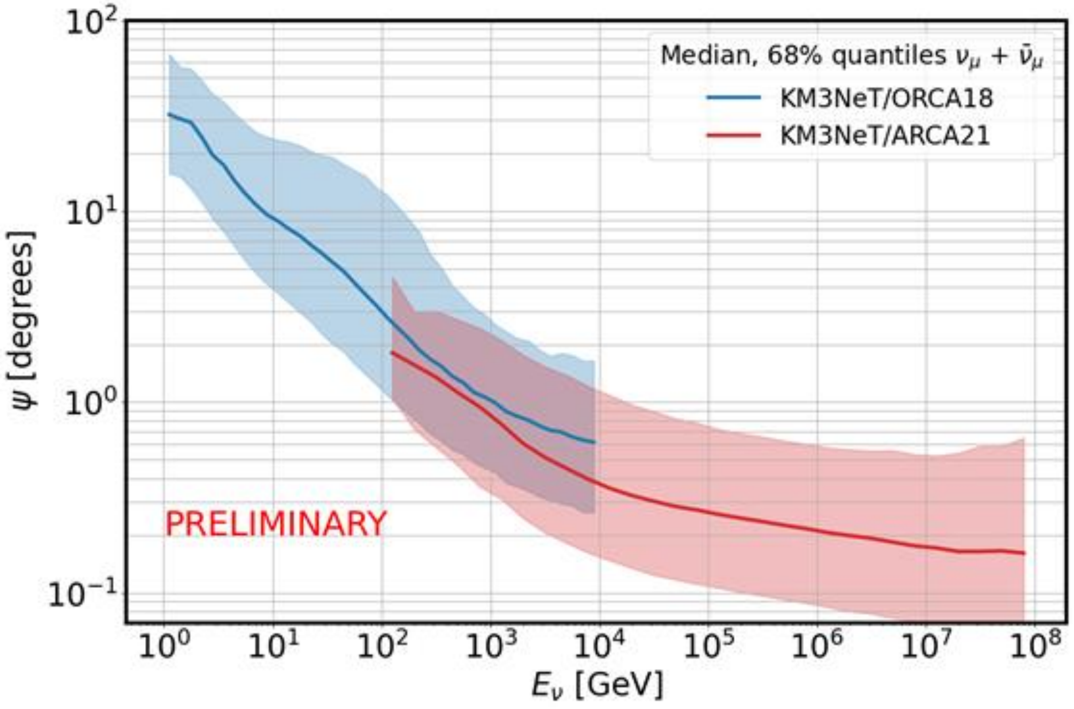
Results from Neutrino 2026

Astronomy program in KM3NeT

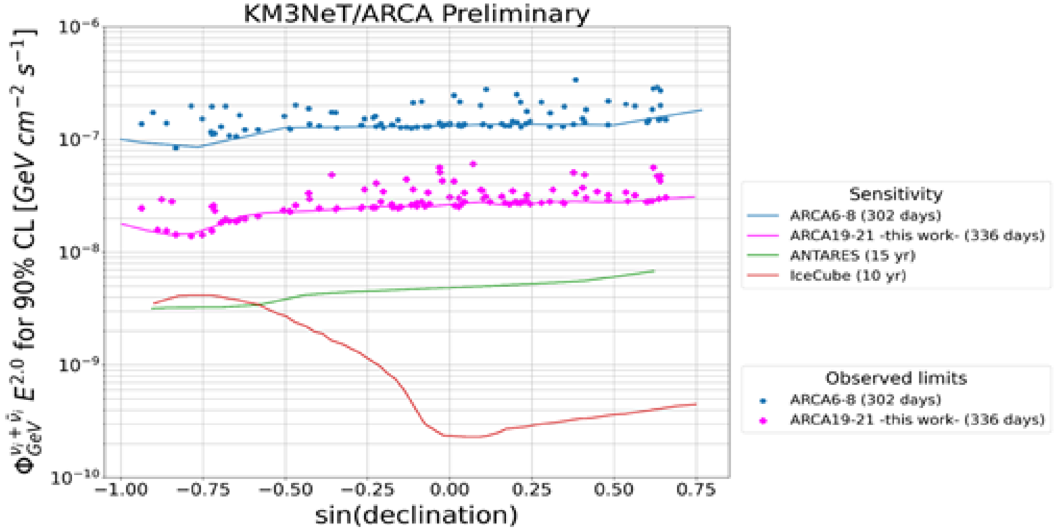
The KM3NeT astronomy program spans a broad range of analyses, including searches for point-like and extended sources, diffuse neutrino fluxes, source populations, and time-dependent or multi-messenger signals

Although ARCA is optimized for high-energy neutrino astronomy, ORCA complements the program by extending the sensitivity towards lower energies

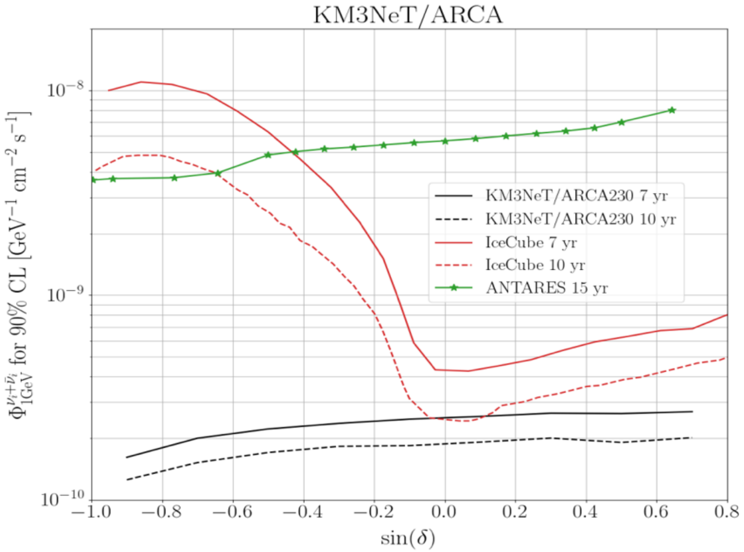




Point source search



- The current ARCA detector already demonstrates the rapid increase in sensitivity as the detector grows.
- After 7–10 years of operation, the full ARCA detector is expected to achieve a point-source sensitivity about two orders of magnitude better than the current ARCA19–21 performance.
- ARCA and ORCA provide complementary sensitivity, with ORCA being particularly competitive for very soft neutrino spectra.



Projected sensitivity (full ARCA)

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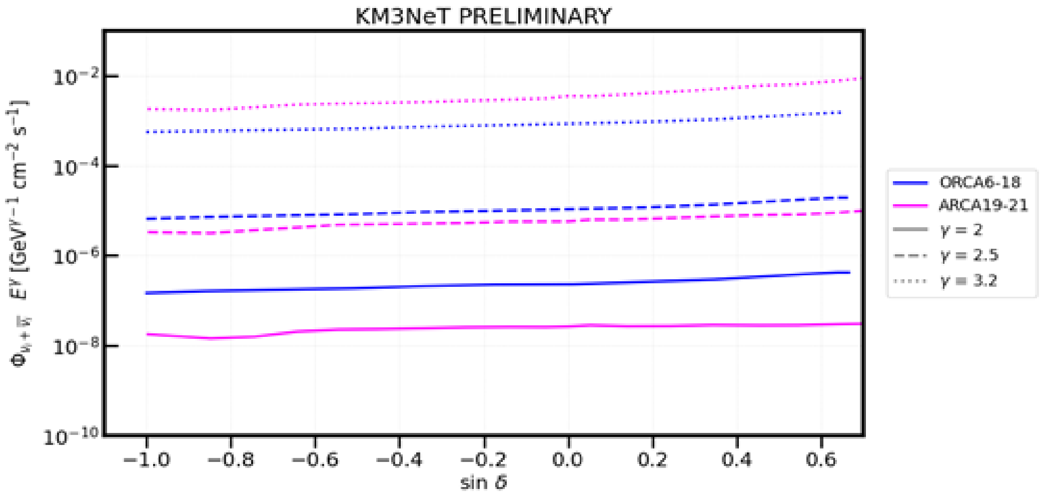


Review of KM3NeT Astrophysical Results – Neutrino 2026

The KM3-230213A event

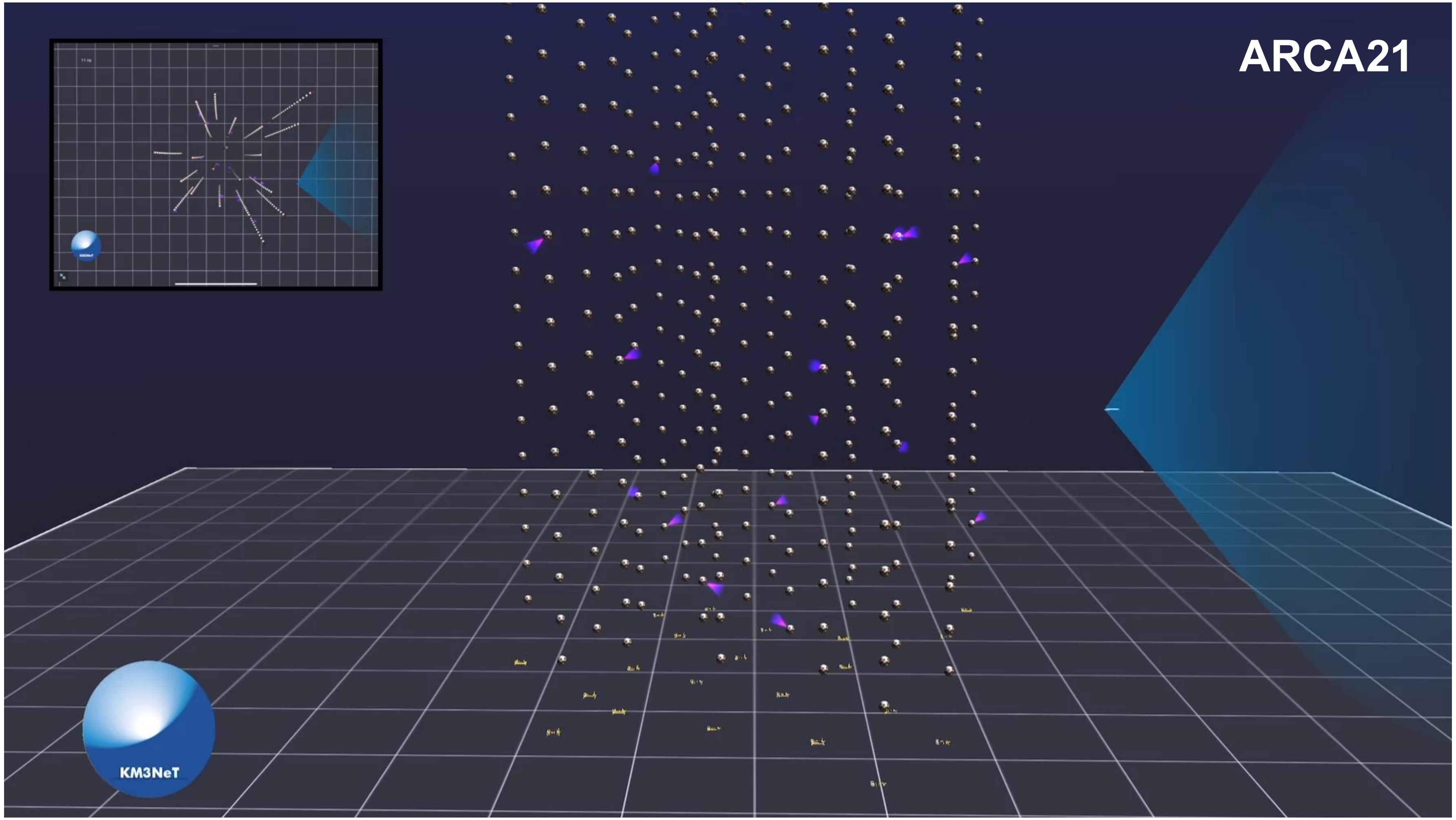
Feb 13, 2023, 01:16:47 UTC

28,086 PMT hits, recorded in all the 21 DUs

3672 PMTs (35%) participated at the triggering of the event

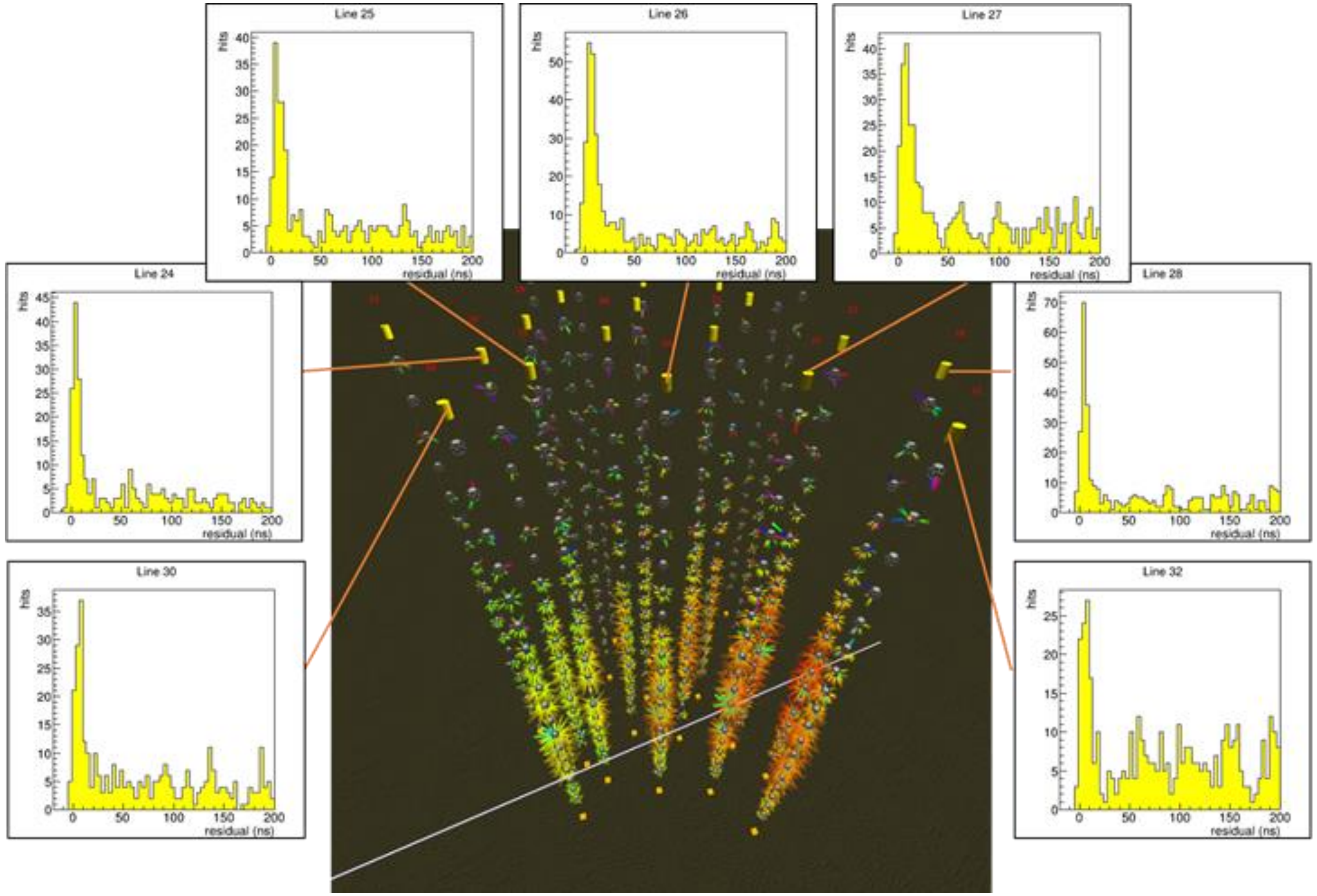
Brightest among 10^8 events collected in the 21-string configuration

Horizontal track-type event with unprecedent high energy

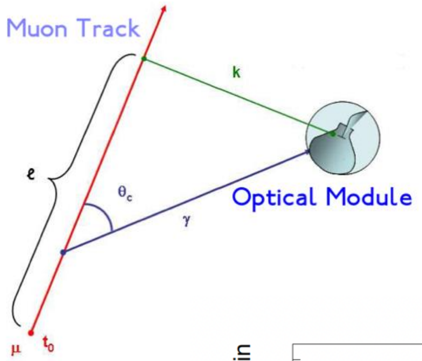


The event is well reconstructed as a muon track

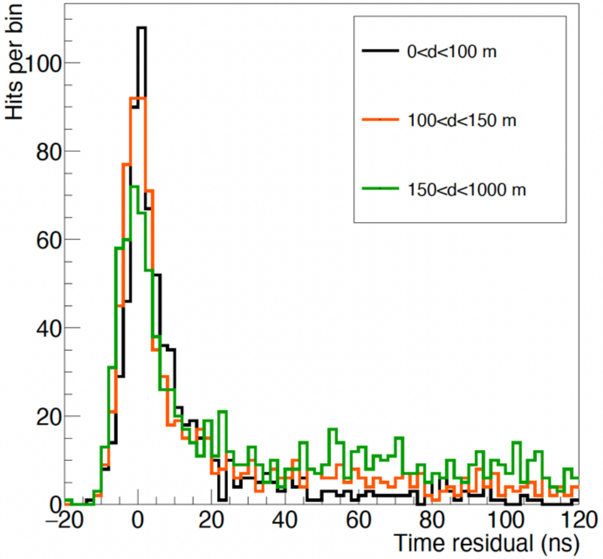
Time residuals



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

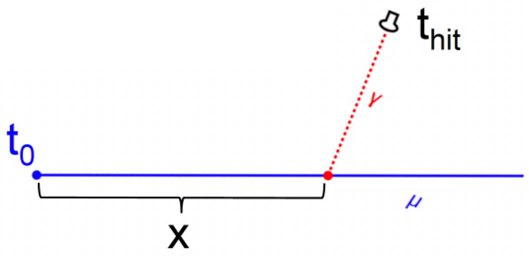


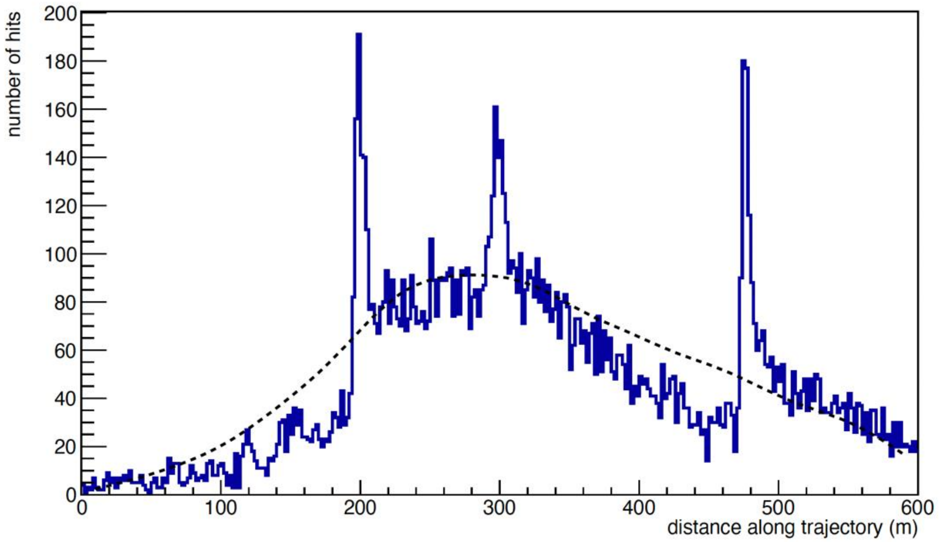
$$t_{res} = t_{det} - t_{th}$$



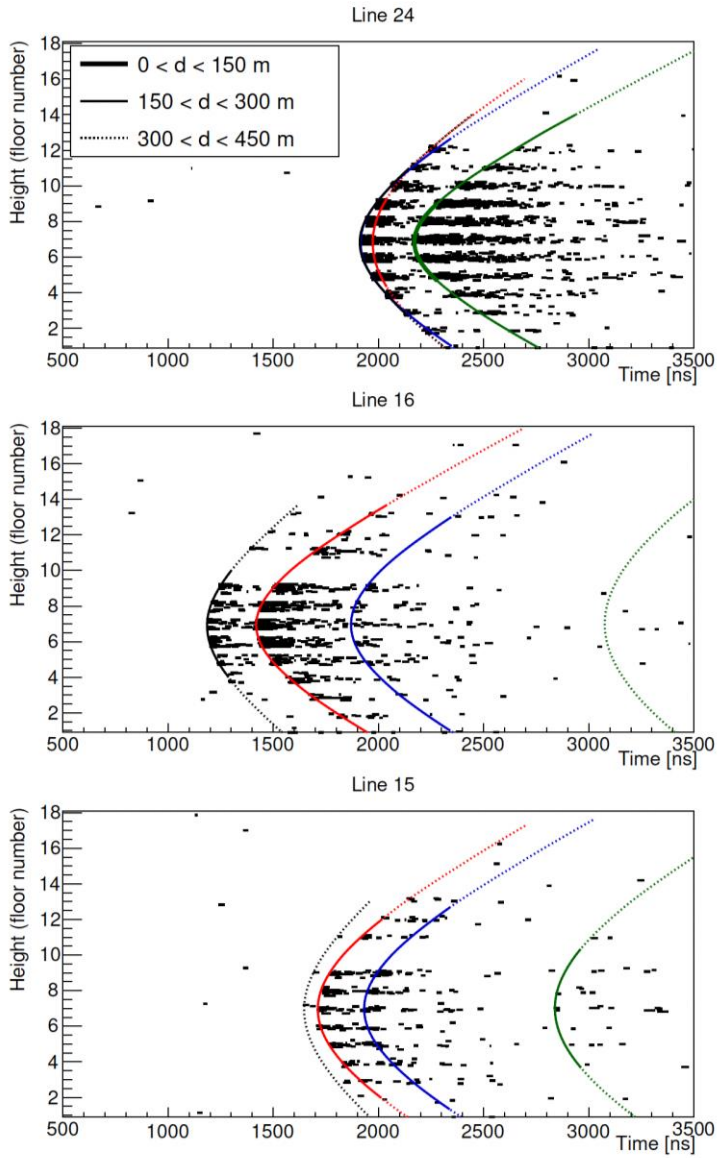
The event is well reconstructed as a muon track

- Position of light emission along track consistent with hit time assuming direct light
- Light profile consistent with at least 3 large energy depositions along the muon track
- Characteristic of stochastic losses from ultra high energy muons
- Space-time distribution of light consistent with photons from Cherenkov emission





Position of light emission along track



Event direction

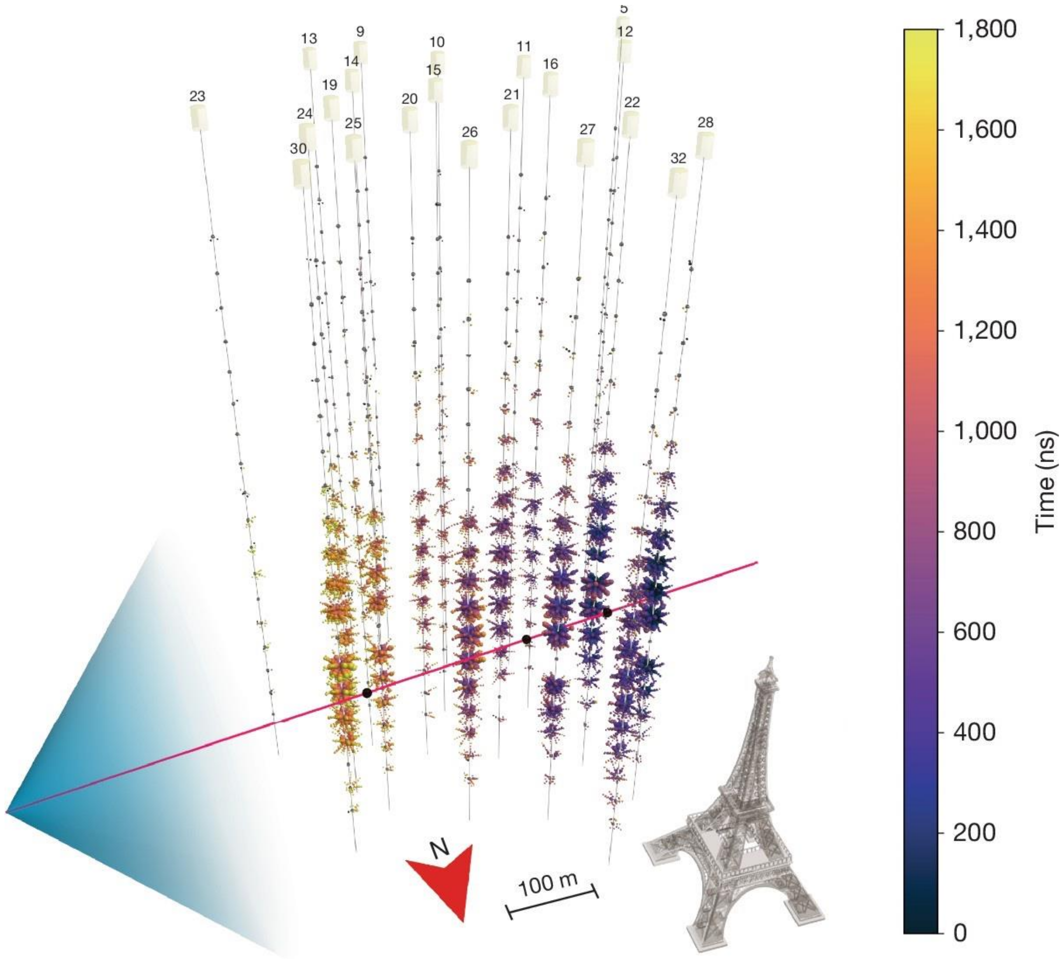
The direction of the KM3-230213A event is reconstructed as near-horizontal

Altitude: 0.6°
Azimuth: 259.8°

The uncertainty is estimated to be **1.5°** (68% c.l.), dominated by the systematic uncertainty on the absolute azimuthal orientation of the detector at the time of the analysis

Detector positioning system upgraded during the 2025 sea campaign, providing improved knowledge of the detector element positions on the seafloor

After data recalibration, expected uncertainty close to the intrinsic statistical uncertainty on the muon direction of $\sim 0.1°$



Nature 638 (2025) 376

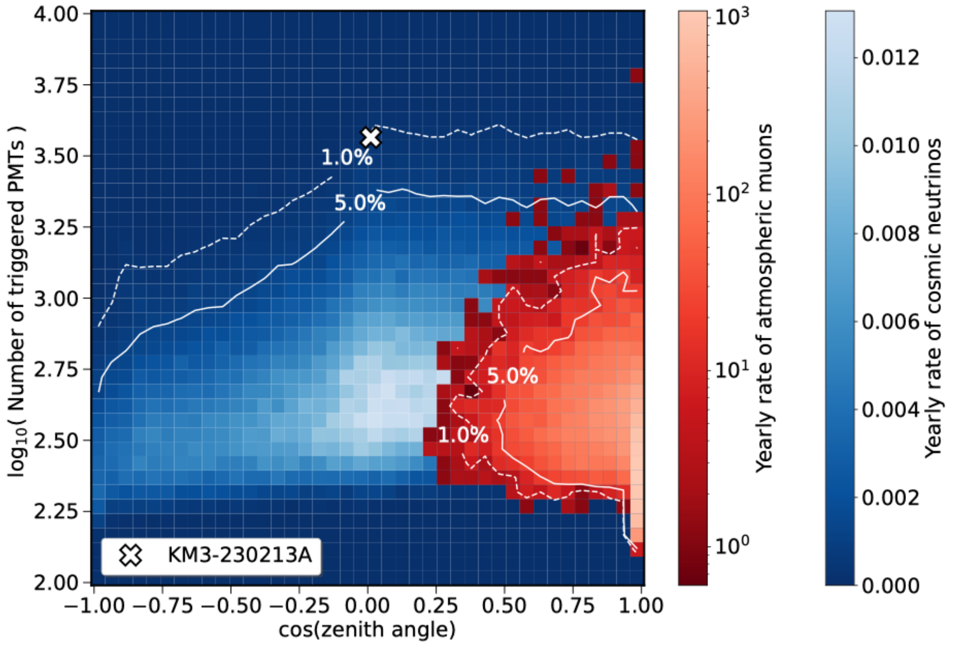
Event energy

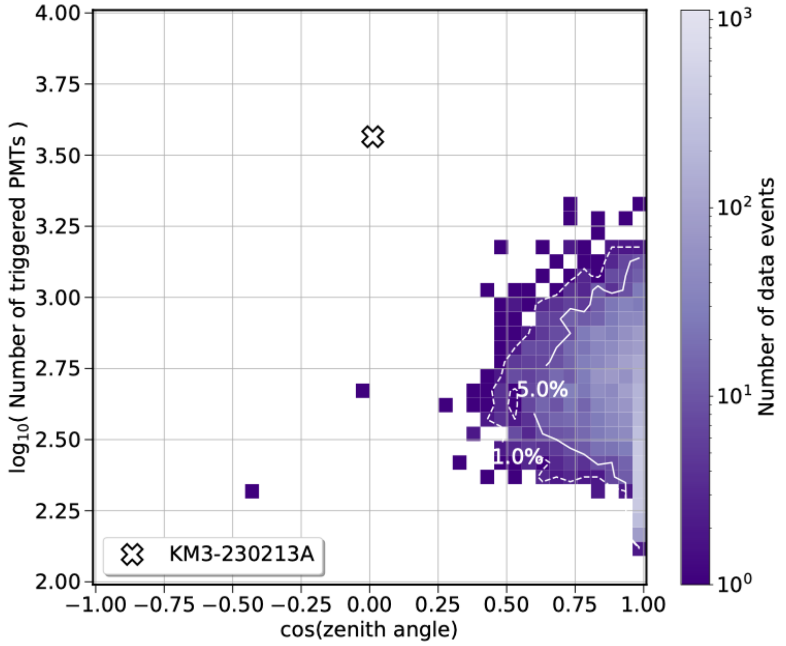
The energy of muon with E > TeV can be estimated by measuring its energy loss

A saturation effect was visible in the PMTs within 100 m from the track (over 25% of the PMTs)

The muon energy is estimated by counting the number of PMTs participating at the triggering of the event

This quantity is robust against limitations of detector simulations and contamination from the optical background





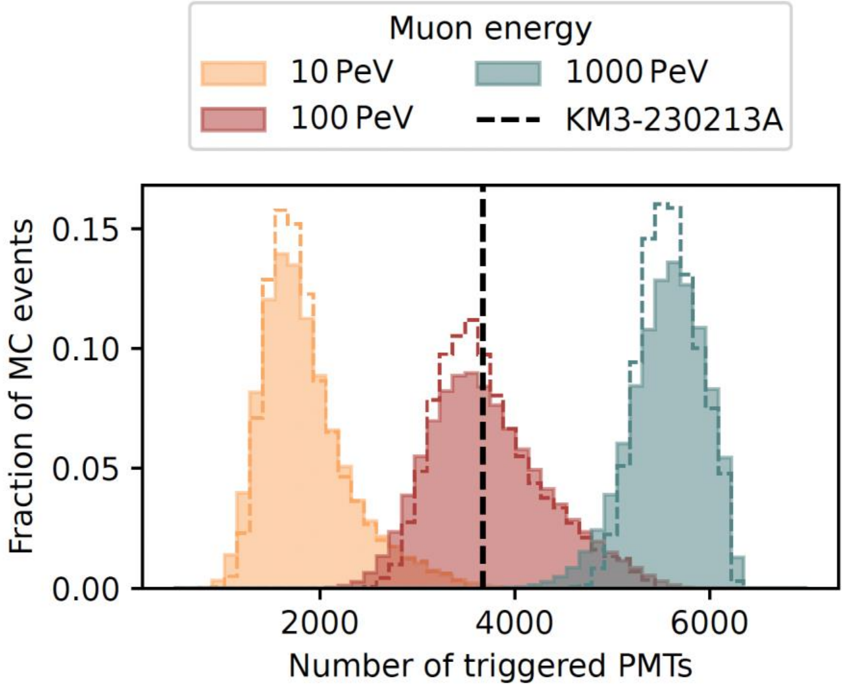
bright track event selection

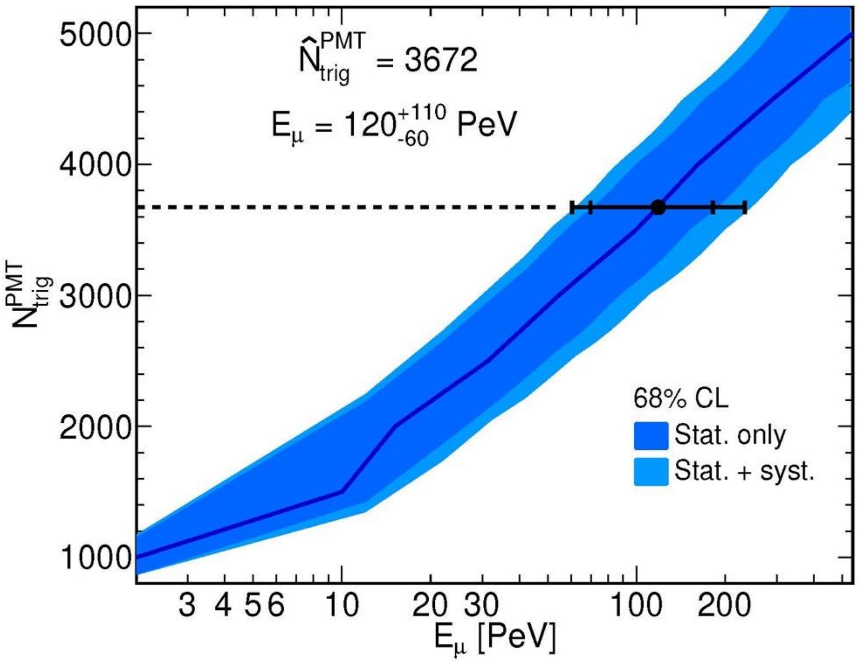
Event energy

Simulations of muons of various energies (from PeV to EeV) traversing the detector in the same direction ad location as KM3-230213A

Simulations varying light absorption and scattering, and DOM efficiency

Building of frequentist confidence intervals on the true muon energy -----> $E_\mu = 120^{+110}_{-60}\ PeV$





Nature 638 (2025) 376

Event energy

What about the neutrino energy?

We did not observe the interaction vertex: we do not know the muon energy at production or the energy transferred to the hadronic shower

We don't know where the muon originated: we do not know how much energy the muon lost before entering the detector

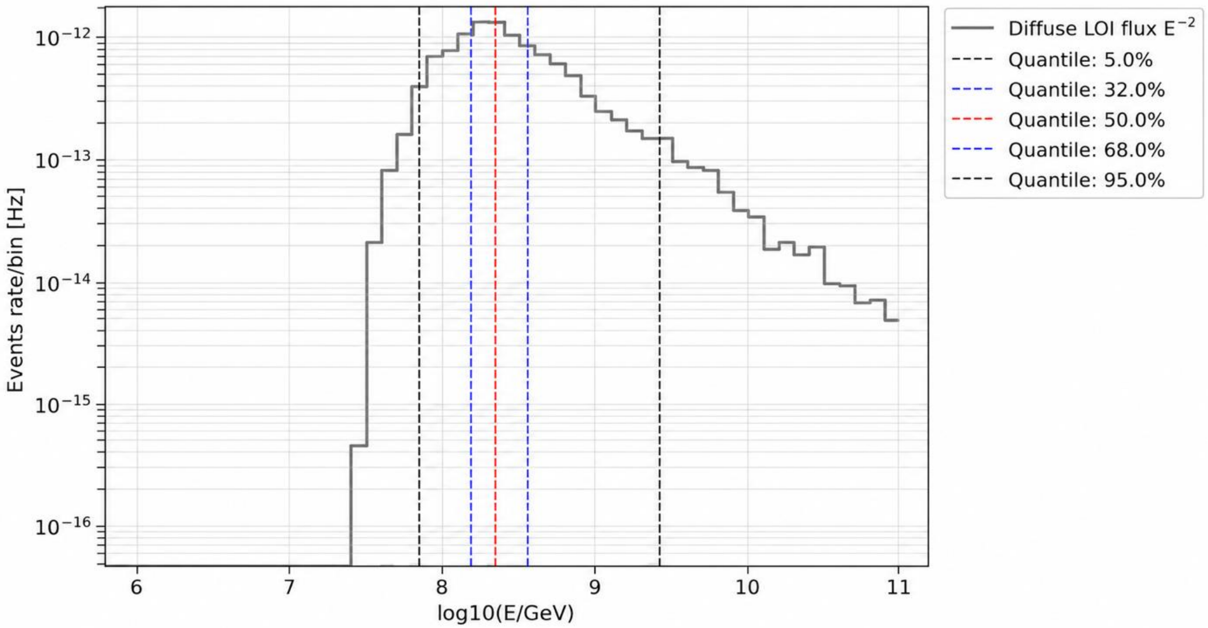
We need to assume an incoming neutrino energy spectrum:

the harder the spectrum → the more likely to have higher energy muons → they may have travelled more before we see them

Assuming muon neutrino with energy spectrum $\propto E^{-2}$:

- median neutrino energy **220 PeV**
- 68% c.l. **110 – 790 PeV**

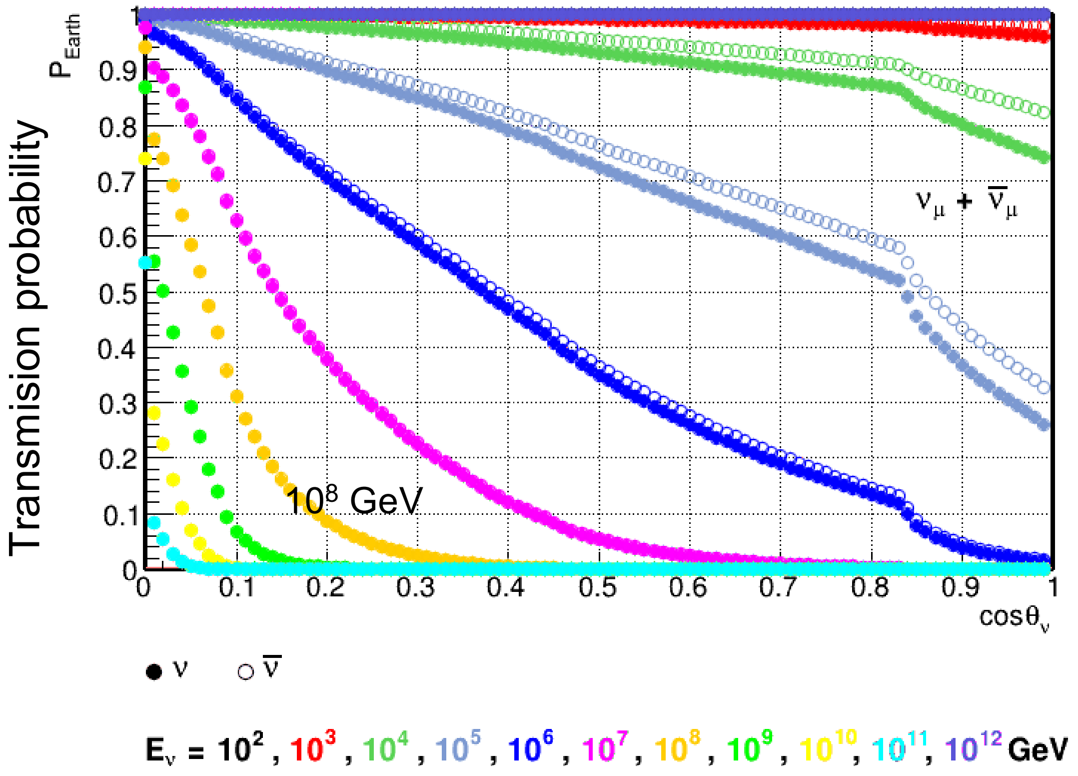
Nature 638 (2025) 376

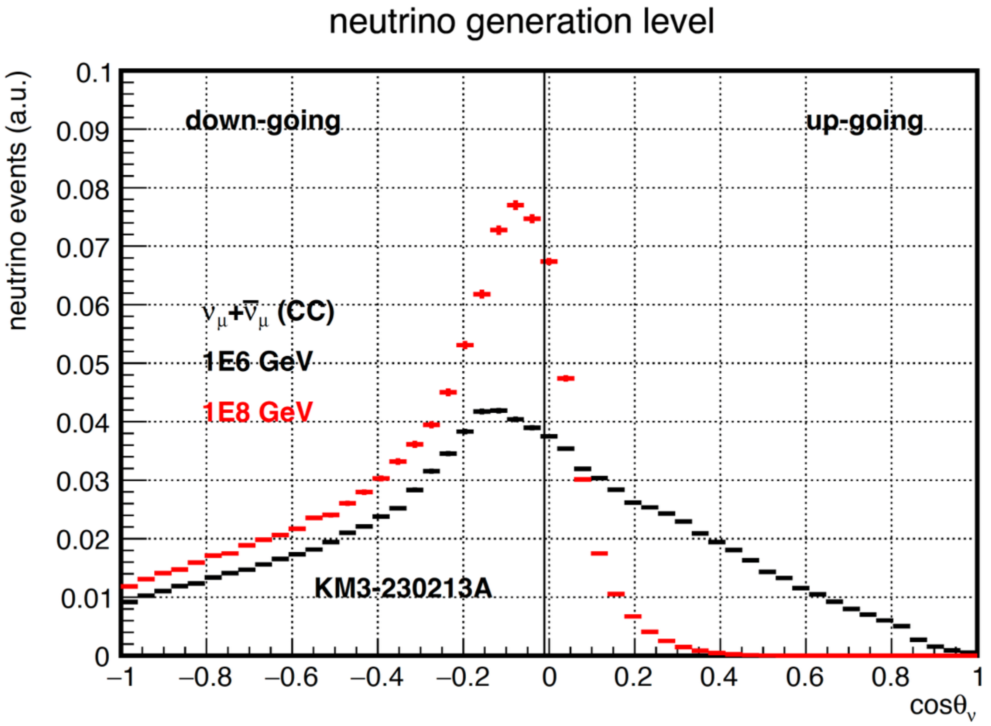


Event energy

100 PeV neutrinos are mainly expected horizontal

The Earth becomes increasingly opaque for neutrinos above ~0.1 PeV

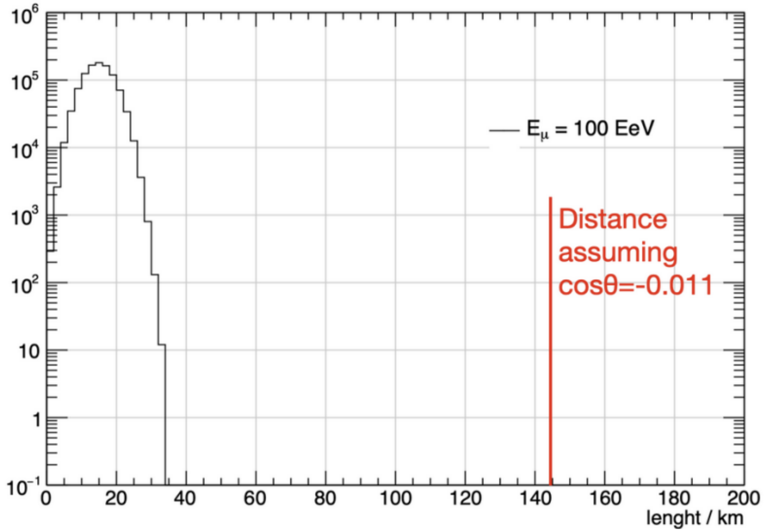




Simulations performed with the gSeaGen code

CPC 256 (2020) 107477

Upper limit on the muon background

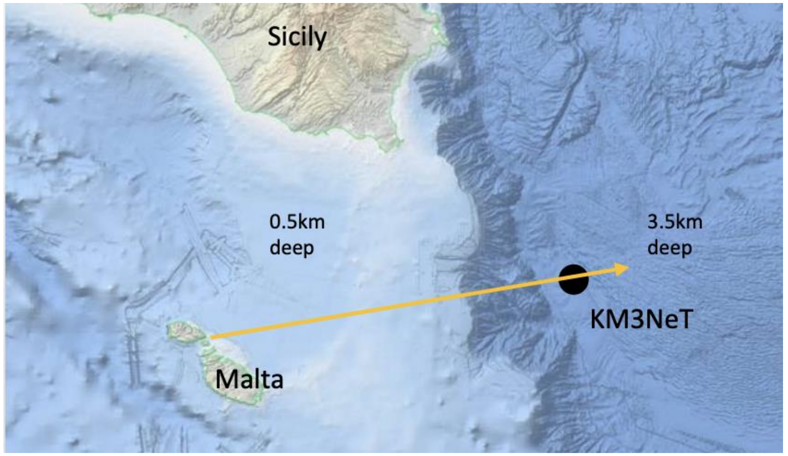


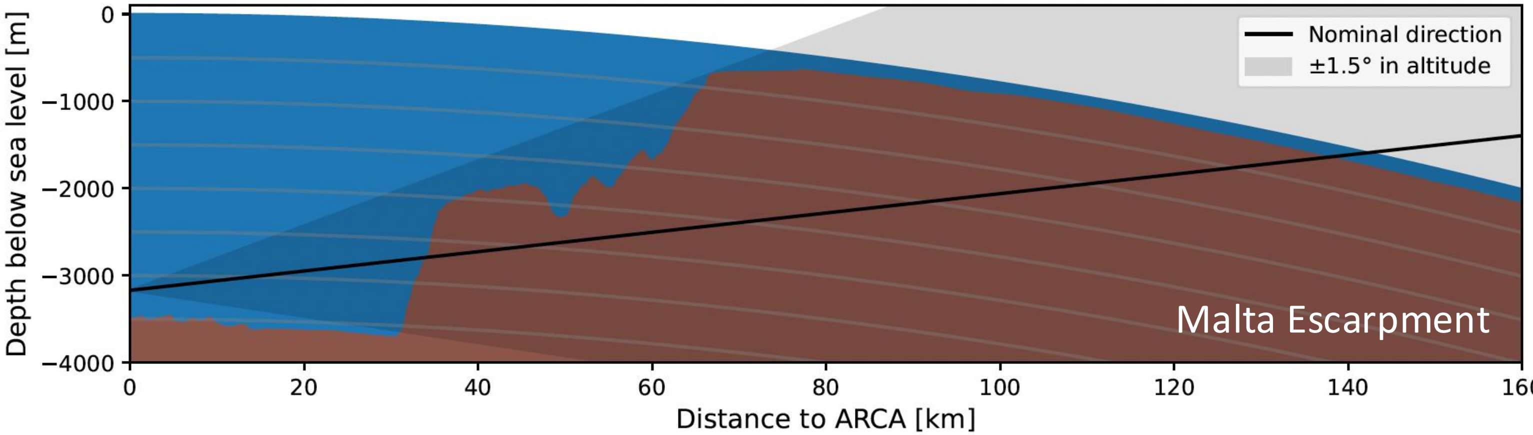
A muon with the observed direction would have traversed 300 km water equivalent of material, which exceeds the maxim range of atmospheric muons (>10 PeV at the detector)

Upper limit on muon contamination, assuming angular error of 2°
10^{-10} events/year at the event energy

10^{-4} events/year slant 28 km w.e. at 5.6° above the horizon (5σ deviation)

Expected rate of an atmospheric neutrino (prompt component) is about 10^{-5} events/year





Detector response

The effective area is the equivalent area of an ideal detector that would detect all incident neutrinos

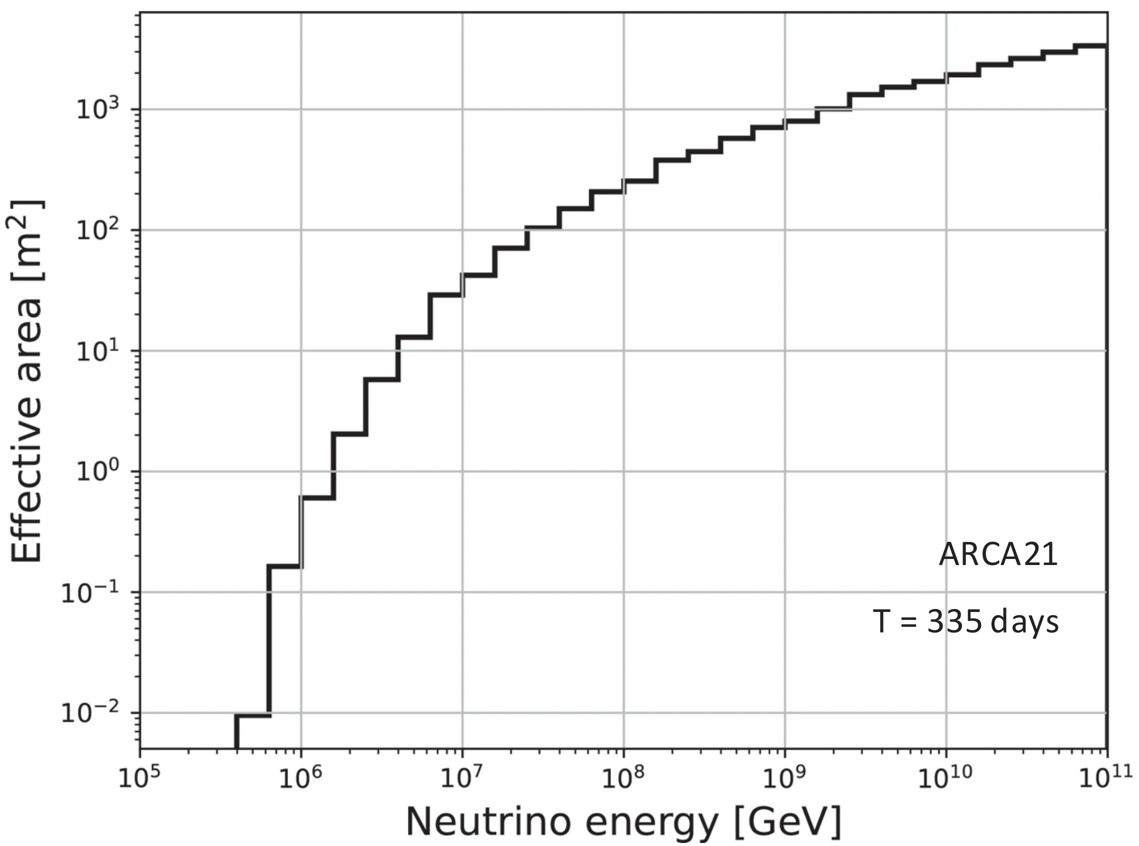
Exposure

$$\mathcal{E}(E) = 4\pi \times T \times A_{eff}(E)$$

Expected number of events

$$n_{evt} = \int_{E_{min}}^{E_{max}} \mathcal{E}(E) \times \Phi(E) dE$$

A_{eff} estimated using Monte Carlo simulations and used to evaluate the neutrino flux



The neutrino flux

- Considering the central 90% energy range [72 PeV-2.6 EeV] and assuming a steady isotropic flux E^{-2} over this energy range

$$E^2\Phi(E) = 5.8^{+10.1}_{-3.7} \times 10^{-8} GeV\,(cm^2 s\ sr)^{-1}$$

produces 1 event in the considered data. Uncertainties according to Feldman & Cousins

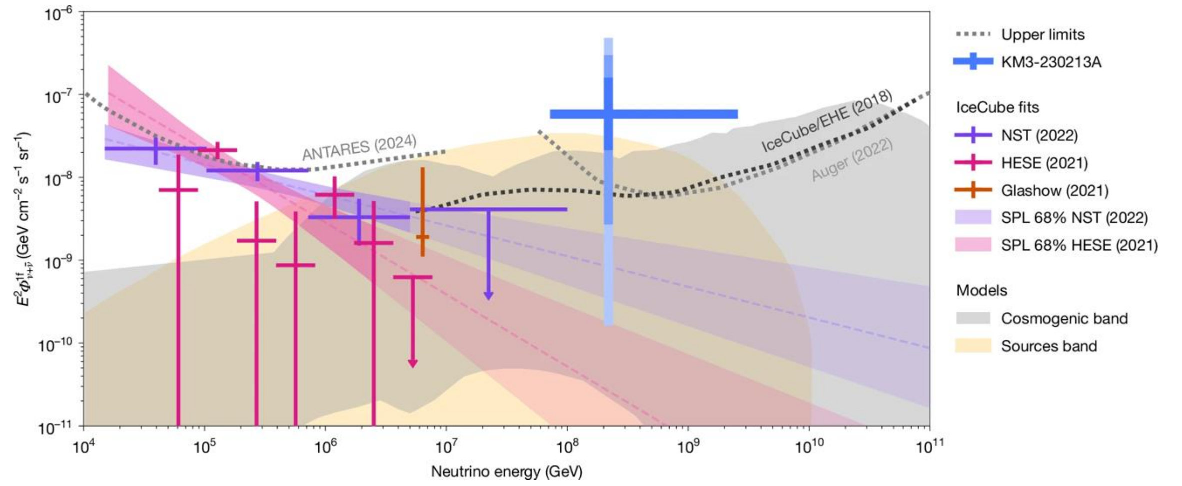
- Performing a joint fit of all experiments

$$E^2\Phi(E) = 7.5 \times 10^{-10} GeV\,(cm^2 s\ sr)^{-1}$$

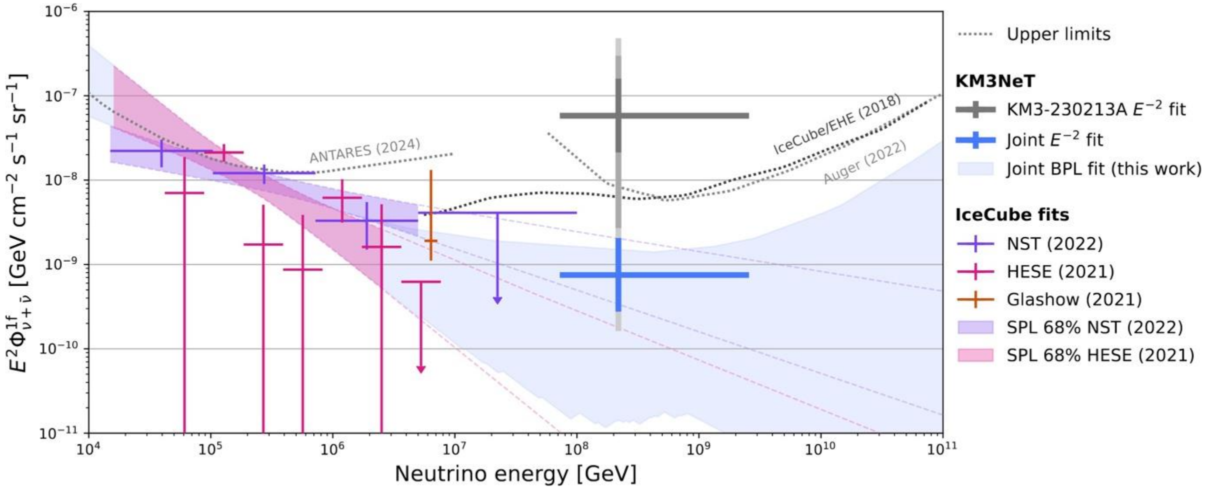
- Observed tension of ~2.5σ

- Increased statistics are required to resolve this tension and better characterise the neutrino landscape at UHE

Nature 638 (2025) 376



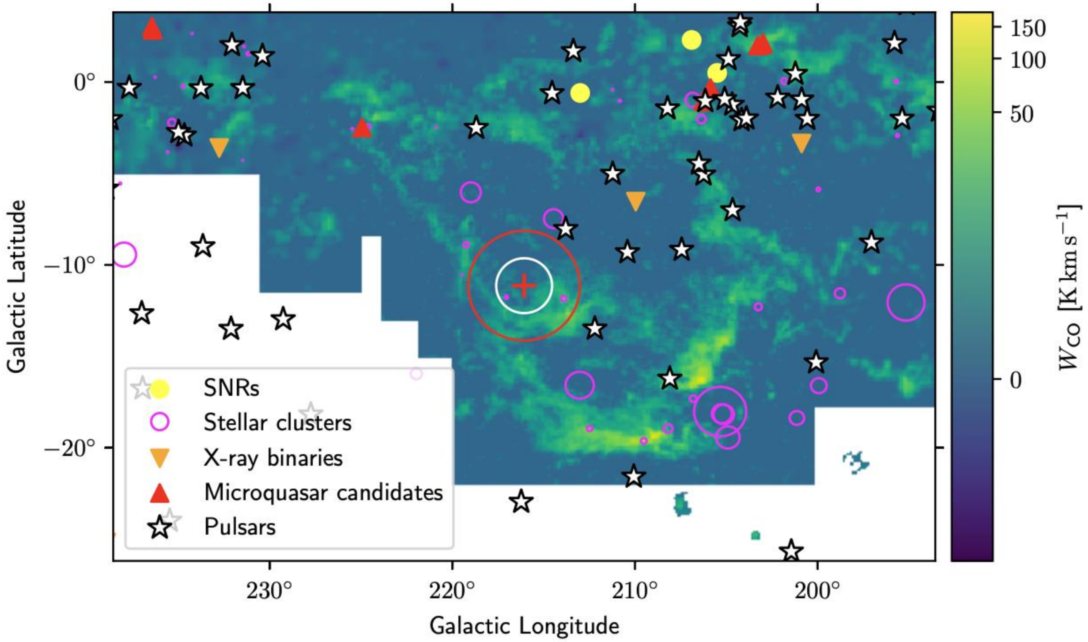
Phys. Rev. X 15 (2025) 031016

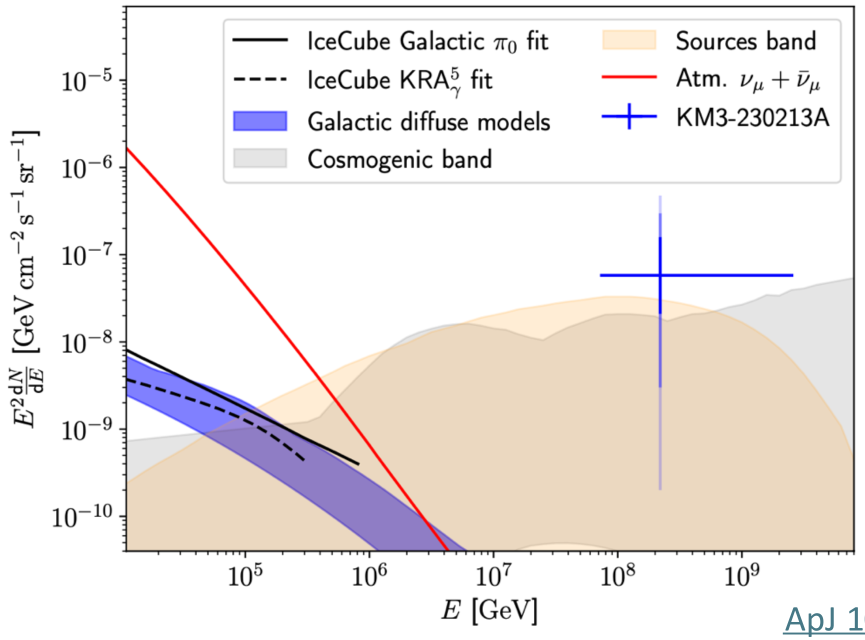


Potential galactic origin

- KM3-230213A location is far from both the galactic centre and the galactic plane (l = 216.1°, b = -11.1°)
- Too low fluxes of the Galactic diffuse emission at these energies
- Lack of a nearby potential Galactic particle accelerator in the direction of the event
- Difficulty to accelerate particles to such high energies in Galactic systems

KM3-230213A is most likely of extragalactic origin





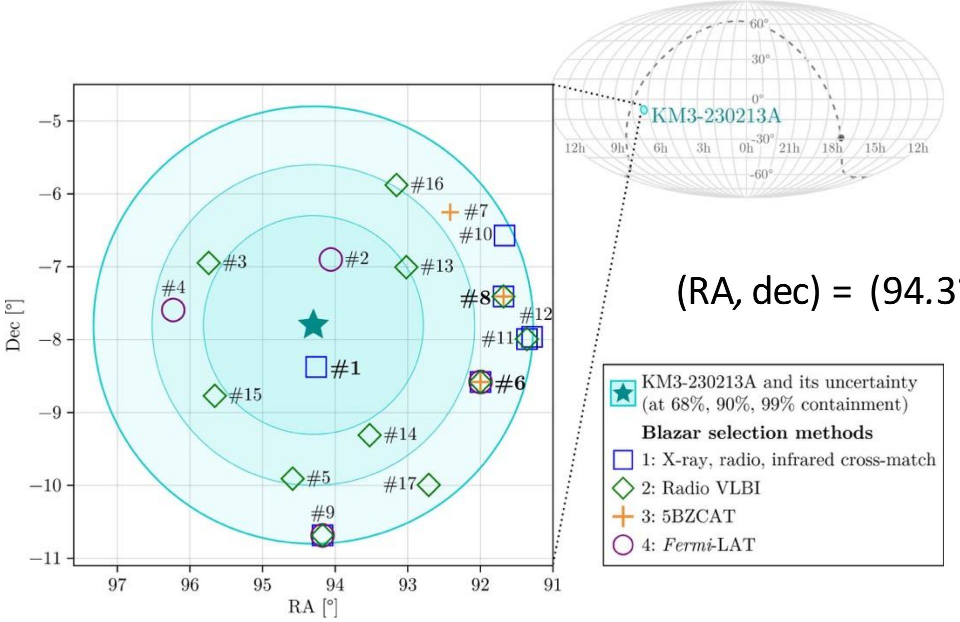
ApJ 1003 (2026) 157

Search for blazar candidates

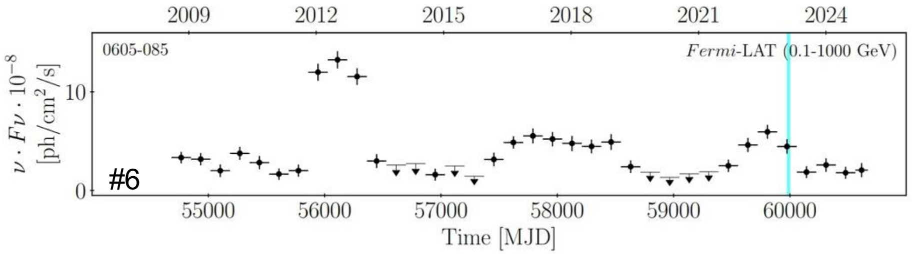
- Gamma-ray flare for the source 0605-085
- Major radio flare from PMN J0606-0724
- X-ray activity for MRC 0614-083

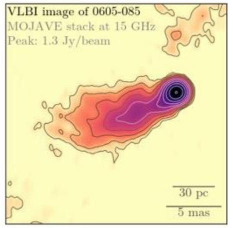
No conclusive statement given the large *R*(99%)

The hypothesis that the event originates from a blazar is still viable

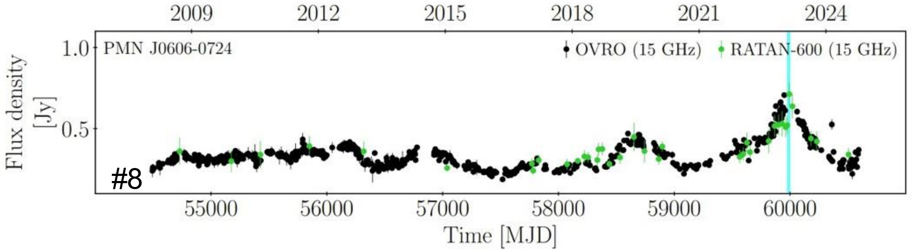


(RA, dec) = (94.3°, −7.8°)

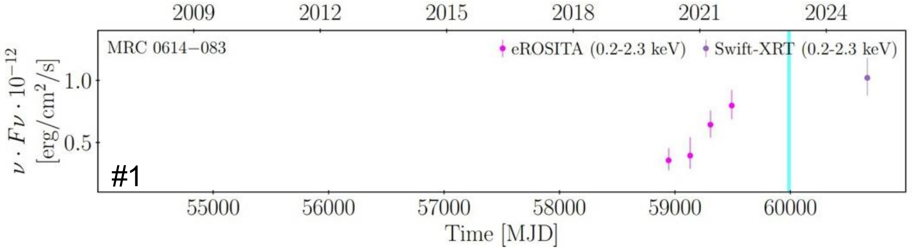




(a) The *Fermi*-LAT light curve and a VLBI image of 0605-085: the brightest radio source in the neutrino localization region that experiences a gamma-ray flaring activity around the neutrino arrival (Section 5.1).



(b) The radio light curve for PMN J0606-0724 that experiences a major flare in close coincidence to the neutrino arrival (Section 5.2).



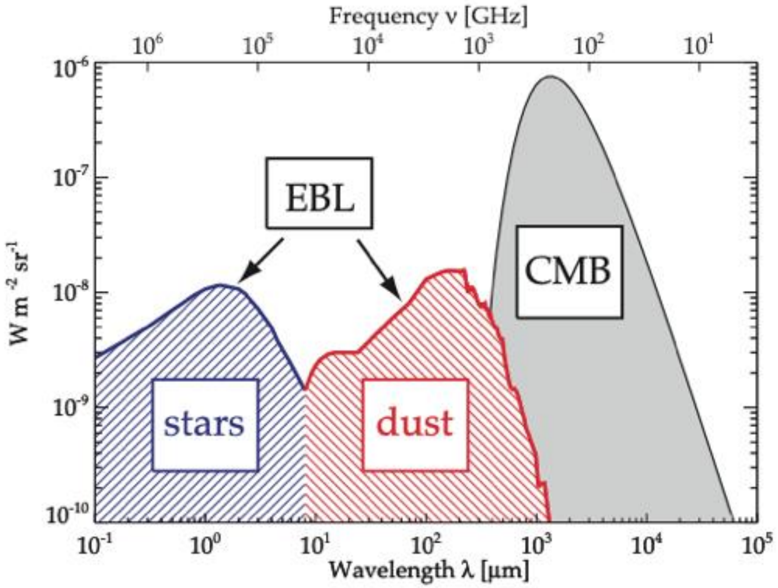
arXiv:2502.08484

JCAP03(2026)033

The first cosmogenic neutrino?

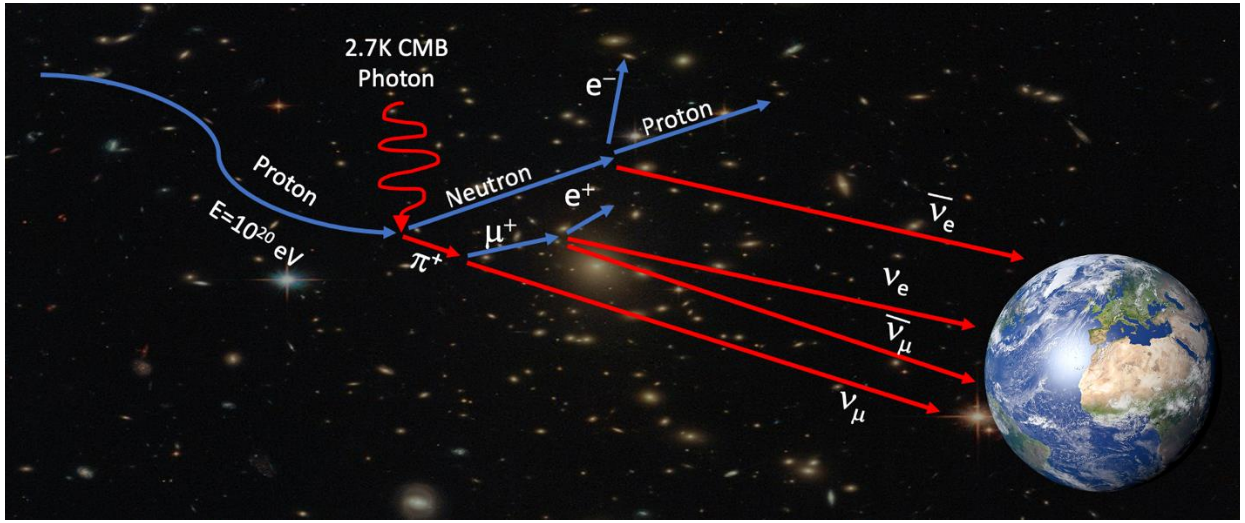
Cosmogenic neutrinos are produced by interaction of cosmic rays with extra-galactic photon backgrounds (e.g. the Cosmic Microwave Background)

Large uncertainties in the predicted fluxes due to our limited knowledge of UHECR sources, composition, and propagation.



Important astrophysical parameters determining the shape and normalization of the cosmogenic neutrino flux:

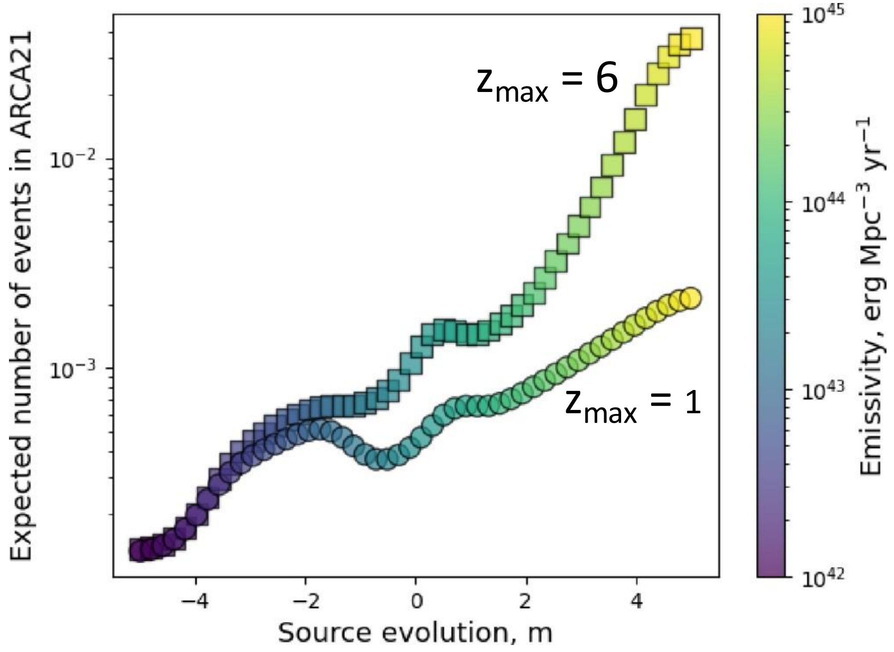
- UHECR source emissivity
- Maximum acceleration energy
- Injection energy spectrum
- Cosmological evolution of UHECR sources
- UHECR composition at injection
- Spatial distribution of UHECR sources

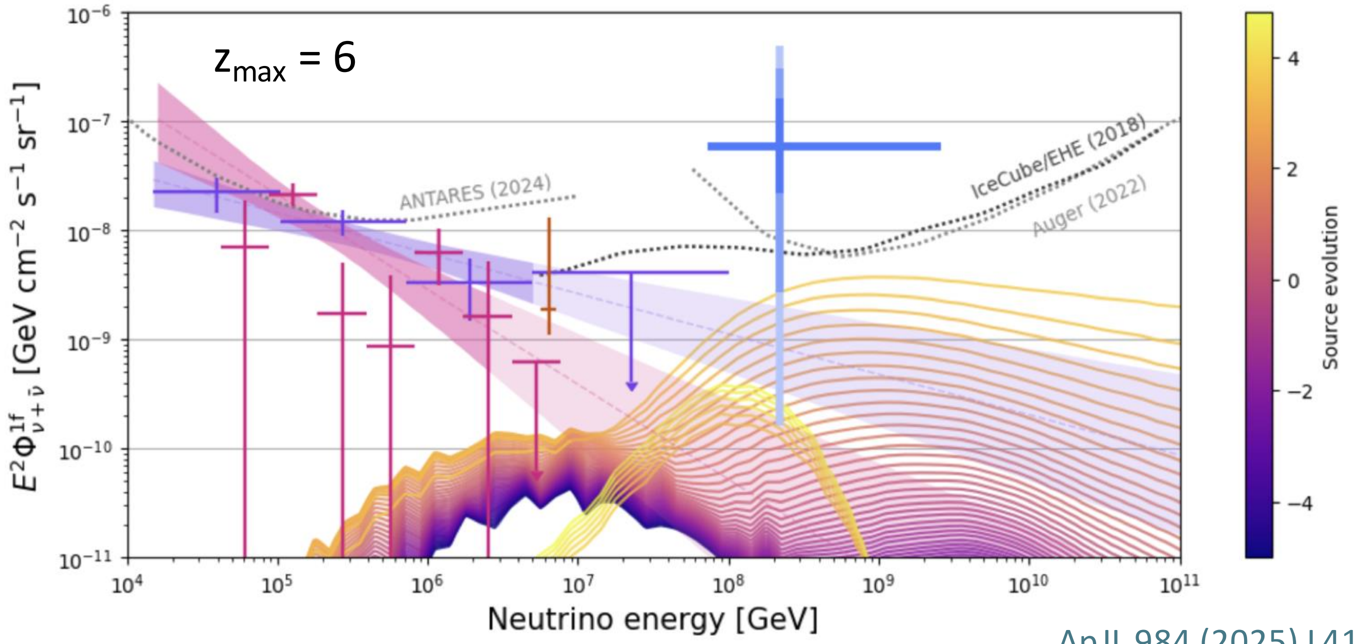


Cosmogenic origin

The cosmogenic origin of KM3-230213A is compatible when

- looking into the deep sky ($z_{max} \simeq 6$)
- at strong positive cosmological source evolution (m>3, source density $S(z) \propto (1+z)^m$)
- and allowing for a non-negligible proton fraction at the highest energies.





ApJL 984 (2025) L41

Publications

Article

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

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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[5–7] 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[8], 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[9]. 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[5].

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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Companion papers submitted/published:

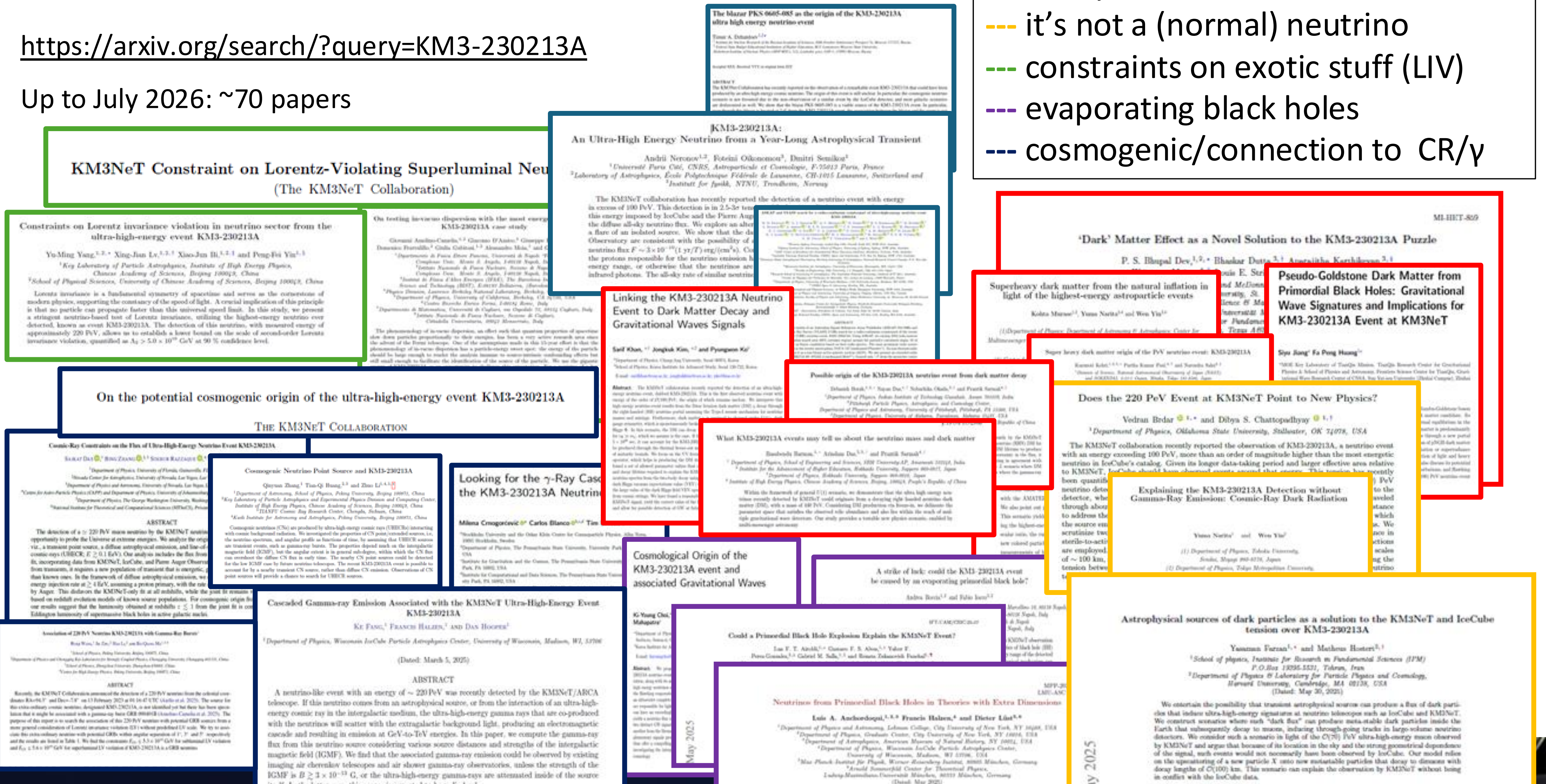
- The ultra-high-energy event KM3-230213A within the global neutrino landscape, Phys. Rev. X 15 (2025) 031016
- On the Potential Galactic Origin of the Ultra-High-Energy Event KM3-230213A, ApJ 1003 (2026) 157
- Characterising Candidate Blazar Counterparts of the Ultra-High-Energy Event KM3-230213A, arXiv:2502.08484
- On the potential cosmogenic origin of the ultra-high-energy event, ApJL 984 (2025) L41
- KM3NeT Constraint on Lorentz-Violating Superluminal Neutrino Velocity, Commun Phys 8 (2025) 457
- Constraining gamma-ray burst parameters with the first ultra-high-energy neutrino KM3-230213A A&A 710 (2026) A168
- Blazars as a Potential Origin of the KM3-230213A, JCAP03(2026)033

Scientific interest in KM3-202313A

--- astrophysical counterparts
--- heavy dark matter
--- it's not a (normal) neutrino
--- constraints on exotic stuff (LIV)
--- evaporating black holes
--- cosmogenic/connection to CR/γ

https://arxiv.org/search/?query=KM3-230213A

Up to July 2026: ~70 papers



Summary

- KM3NeT is a distributed deep-sea neutrino observatory currently under construction, already taking data in partial detector configurations (ARCA51 and ORCA42).
- Both detectors are steadily expanding, with sensitivity continuously improving as new detection units are deployed.
- The complementary capabilities of ORCA and ARCA enable a broad scientific program, spanning neutrino oscillation physics, neutrino astronomy and multi-messenger studies.
- The detection of the ultra-high-energy neutrino KM3-230213A, the highest-energy neutrino ever observed, marks a major milestone for KM3NeT and opens a new window on the high-energy Universe.
- With construction progressing and the detector performance continuously improving, KM3NeT is entering an exciting era of precision measurements and discoveries.

STAY TUNED FOR UPDATES!