Sotto il mare e sotto il ghiaccio:

ORCA/ARCA/KM3/IceCube

Giacomo Cuttone

INFN – LNS

Per la Collaborazione KM3NeT

Giornate di Studio sul Piano Triennale INFN 2026-2028

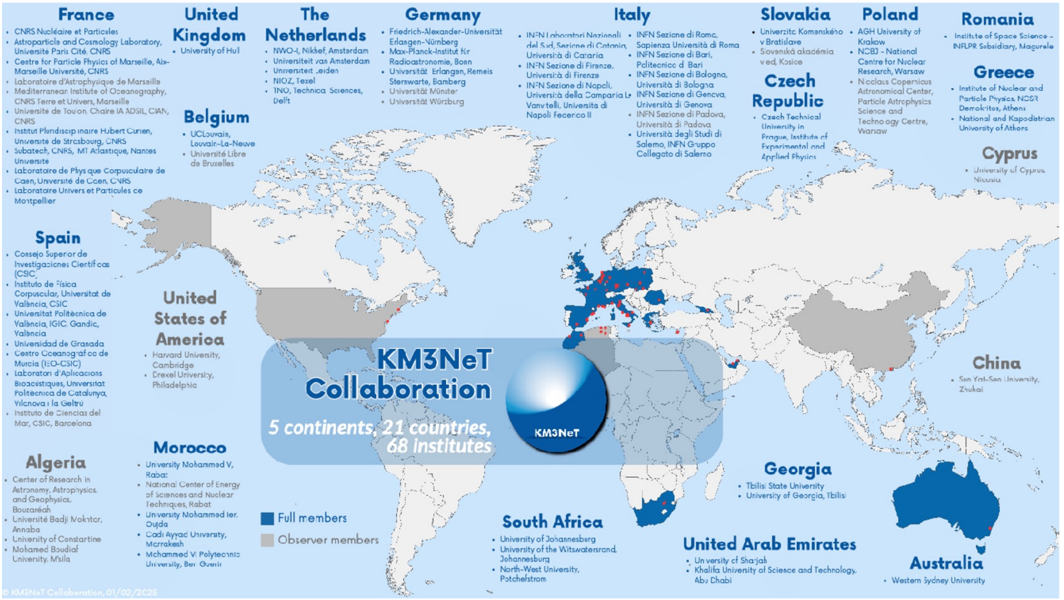
The KM3NeT project

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

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

www.km3net.org

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

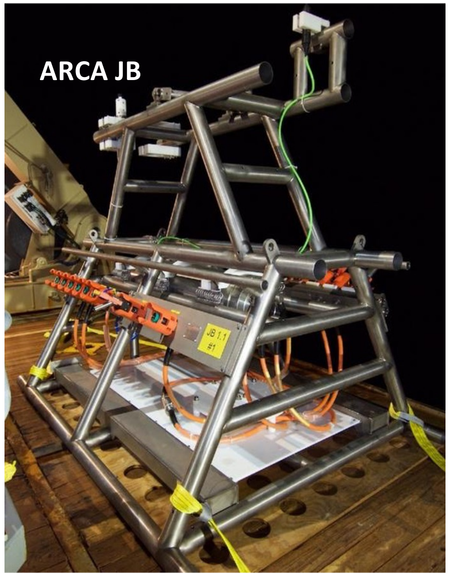
2 copper wires (375VDC)

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



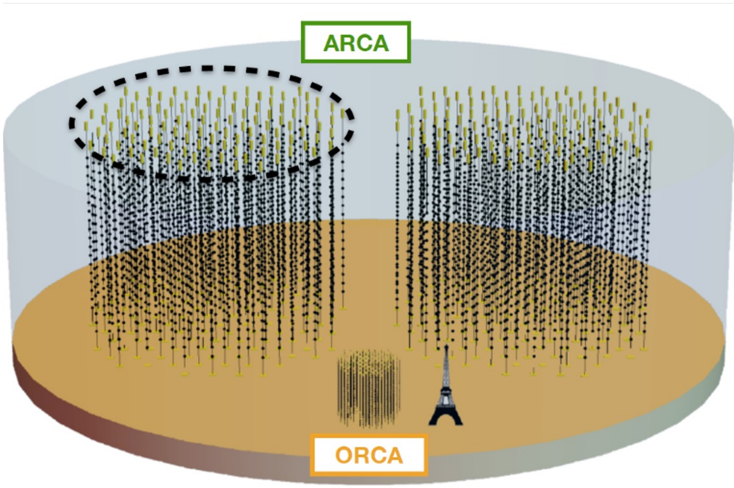
- Electro-optical cables from deep sea to the shore station
- Junction boxes (JB) to distribute power and optical fibres
- Interlink cables for connection of DUs to JBs and JBs to the main cable

Detector layouts

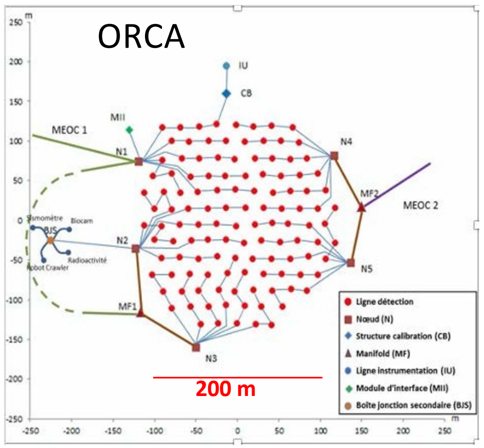
Energy optimization:

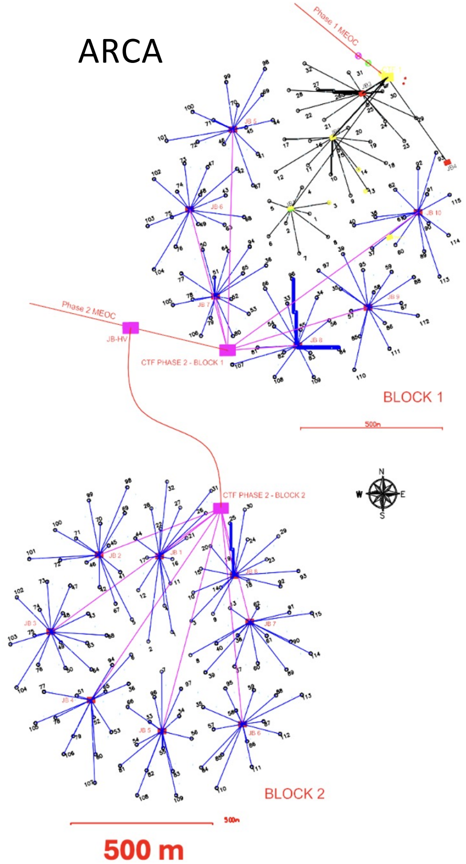
ORCA: 1-100 GeV

ARCA: E > 100 GeV



	ORCA	ARCA
DOM spacing	9 m	36 m
String height	200 m	700 m
String spacing	20 m	90 m
Strings	115	230
Building Blocks	1	2
Instrumented mass	7 Mton	500*2 Mton





Detector status

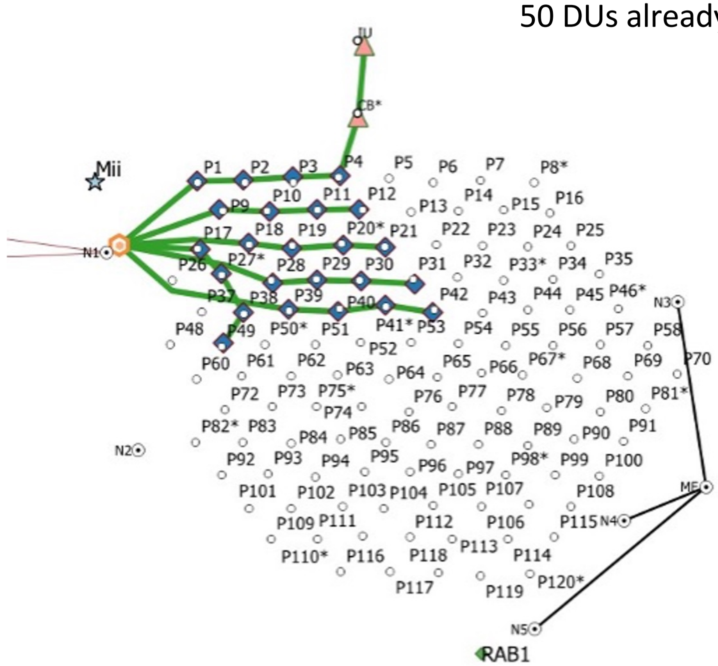
ORCA

28 DUs deployed

4 new DUs deployed in May

DU integration rate: 20/year

50 DUs already funded



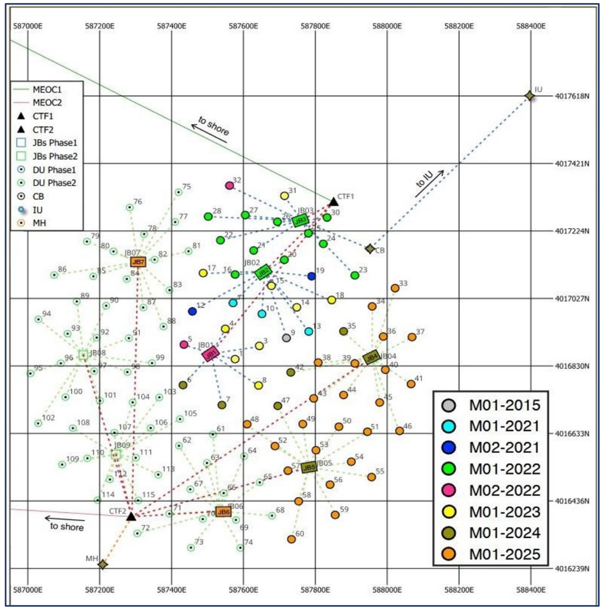
ARCA

33 DUs deployed

19 new DUs to be deployed in July

DU integration rate: 35/year

130 DUs already funded



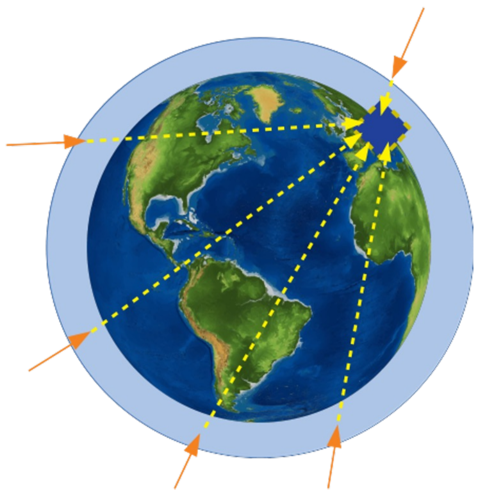
Completion of ORCA/ARCA DUs production: 2030

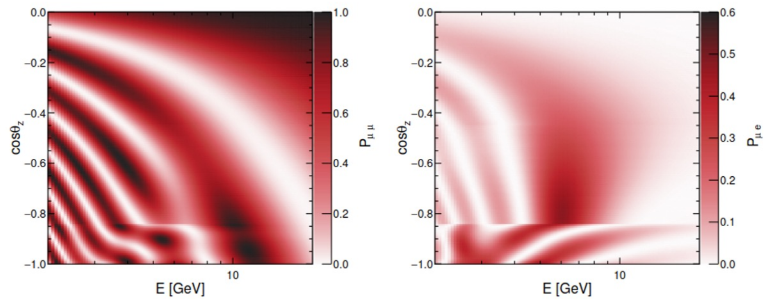
Oscillations with neutrino telescopes

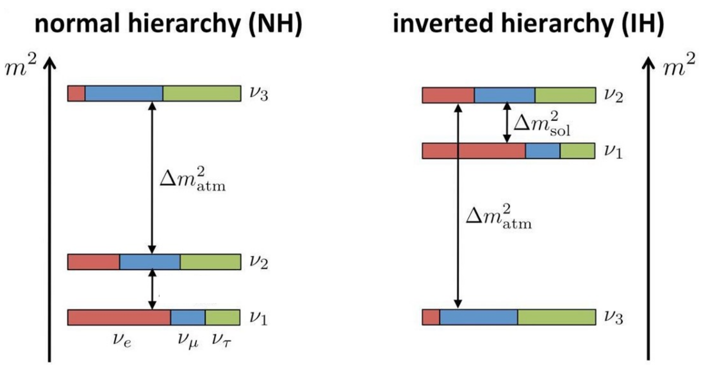
Access **Neutrino Mass Ordering**, unitarity, Beyond Standard Model physics

How to do the measurement? muon neutrino disappearance + tau appearance + matter effects

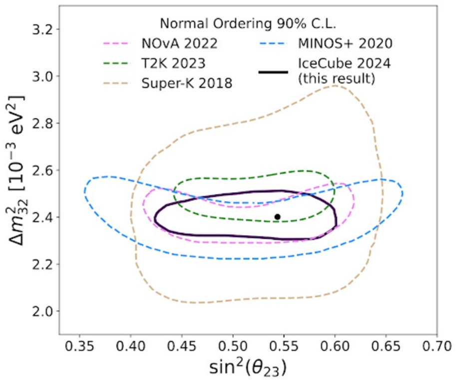
Energy and zenith dependent effects from oscillations





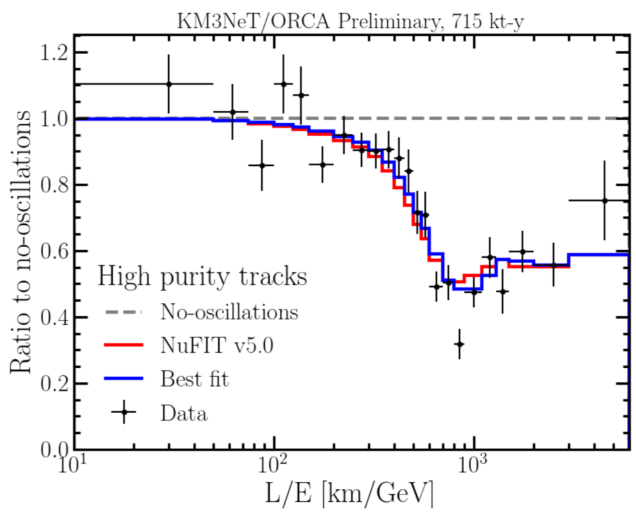


Current status before ORCA

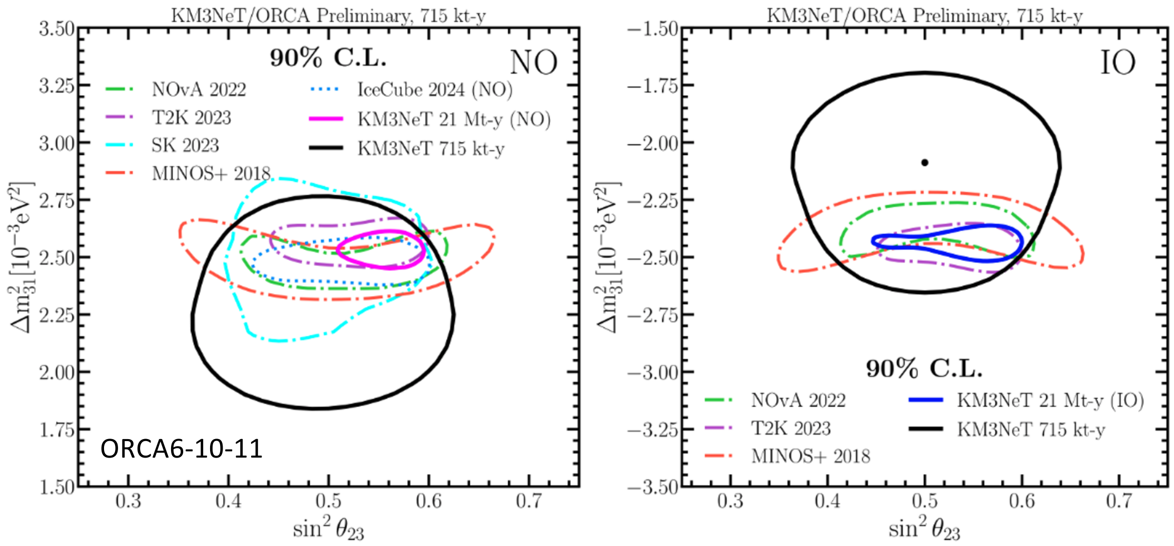


Oscillation results from ORCA

Clear oscillation signal
with 2 years of data
ORCA 11



Best oscillation measurements with atmospheric
neutrinos with the full detector

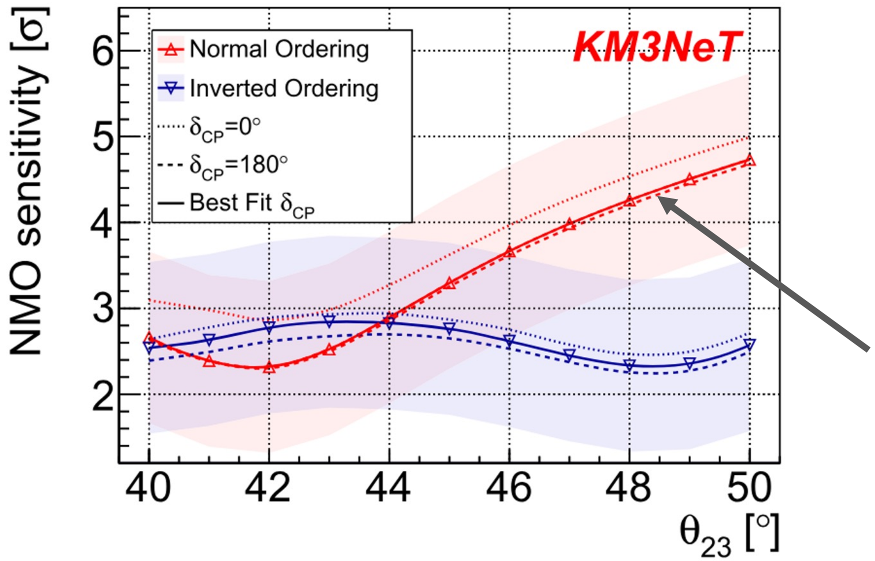


Results from Neutrino 2024: next round at Neutrino 2026 with 2x more events

Oscillations with full ORCA

Full detector results

- **Neutrino Mass Ordering** determined at ~3 sigma in 3 years from completion over the parameter space
- Final sensitivity will depend on the parameters chose by nature

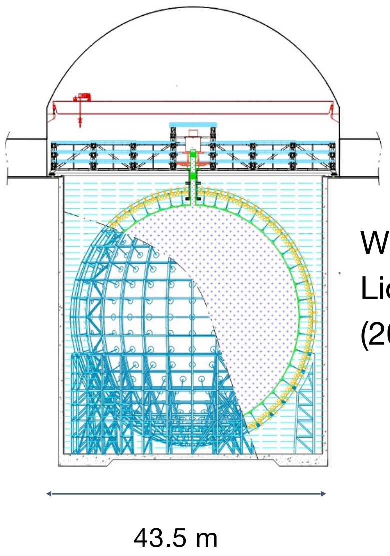


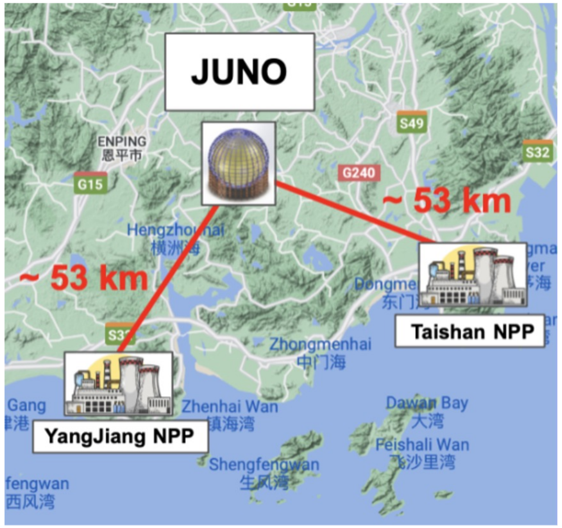
Current global best fit

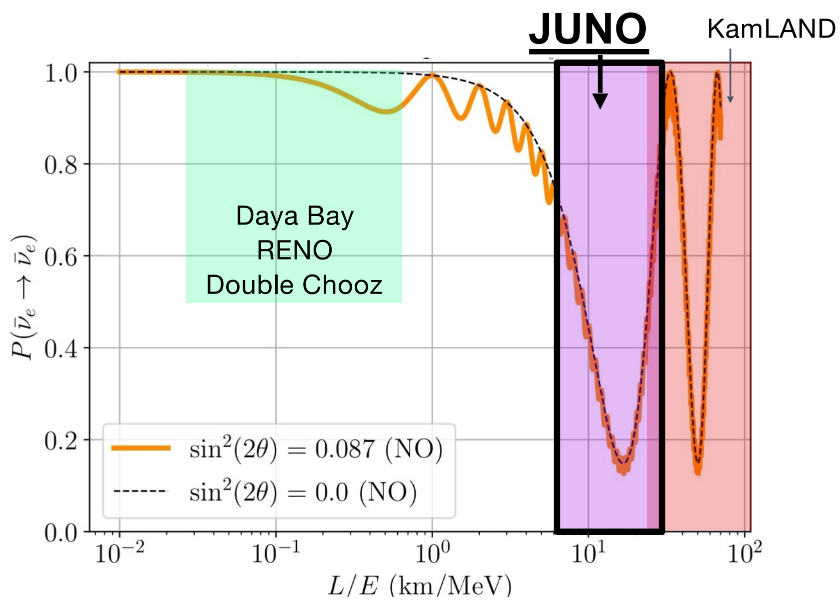
Eur. Phys. J. C 82, 26 (2022)

NMO with JUNO

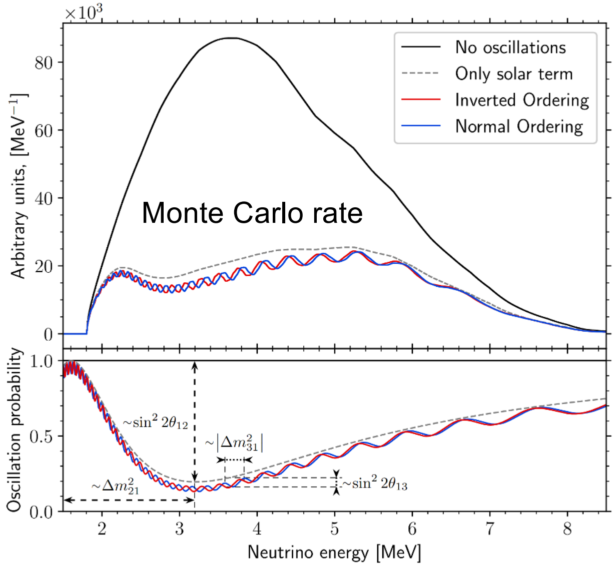
- NMO from near/far detector rates
- Requires precise measurement of the neutrino energy

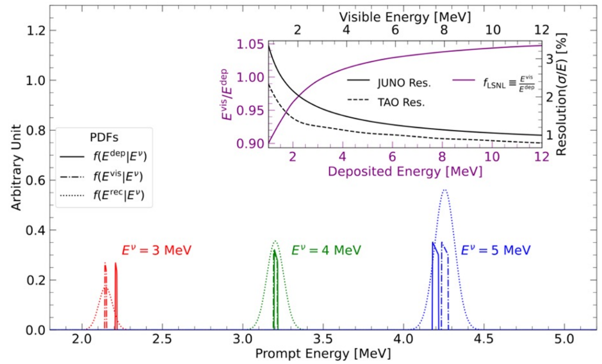




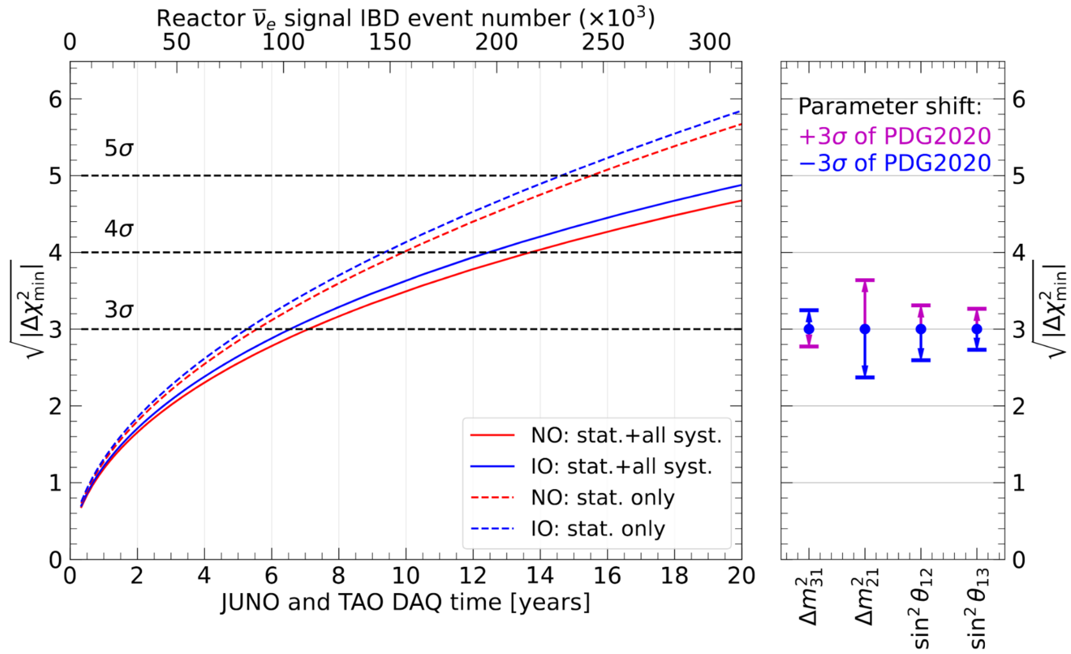


NMO with JUNO





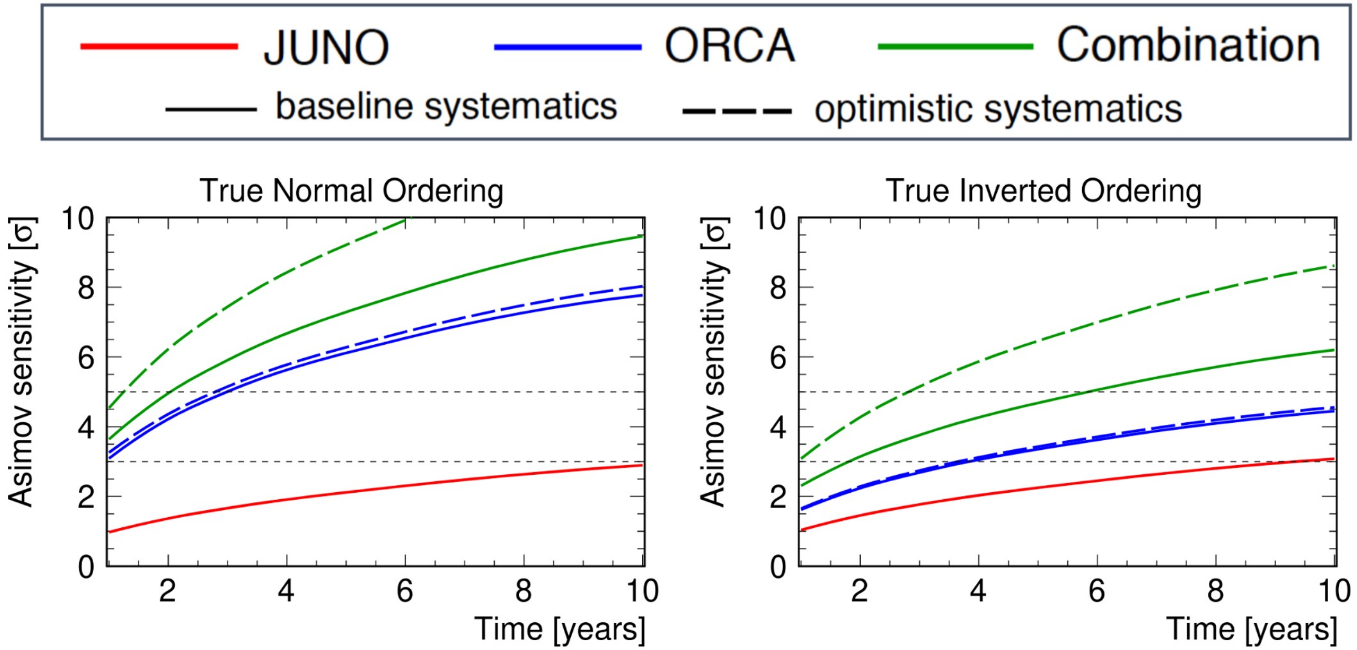
Chinese Physics C, **49,** 033104, 2025



NMO sensitivity with near and far detector

NMO with JUNO + ORCA

- No experiment alone can provide **NMO** within 10 years at 5 sigma over the full parameter space
- Need to combine simultaneous constraints: determination of Δm_{31} from ORCA and JUNO simultaneously breaks the degeneracy between the two experiments when assuming the wrong ordering
- Large boost in the sensitivity

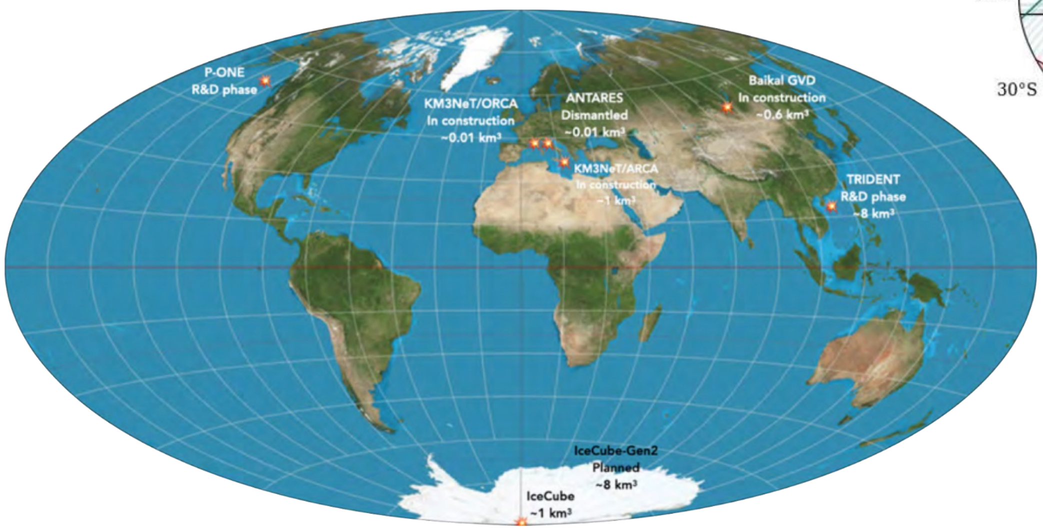


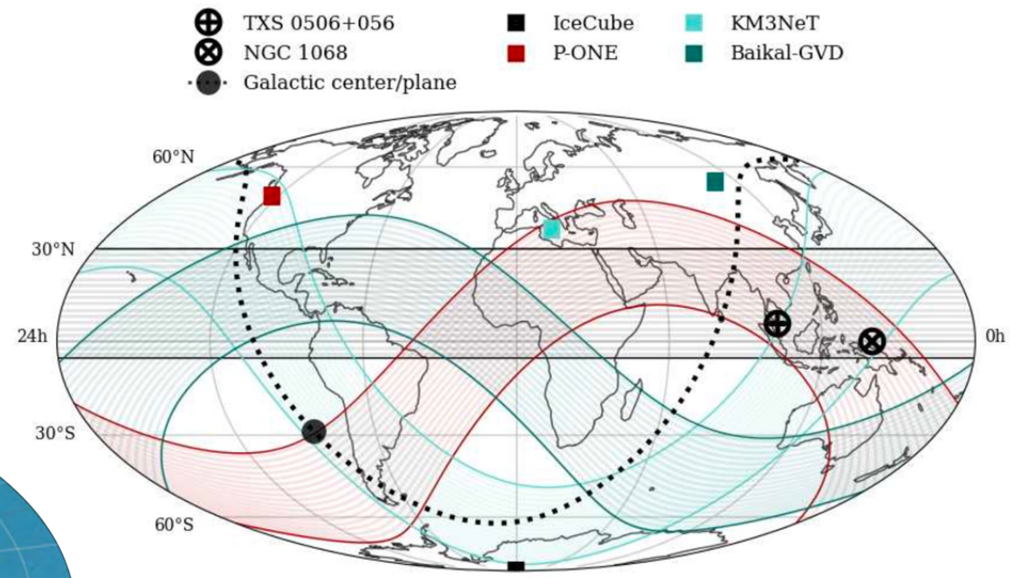
JHEP 03 (2022) 055

Neutrino telescopes

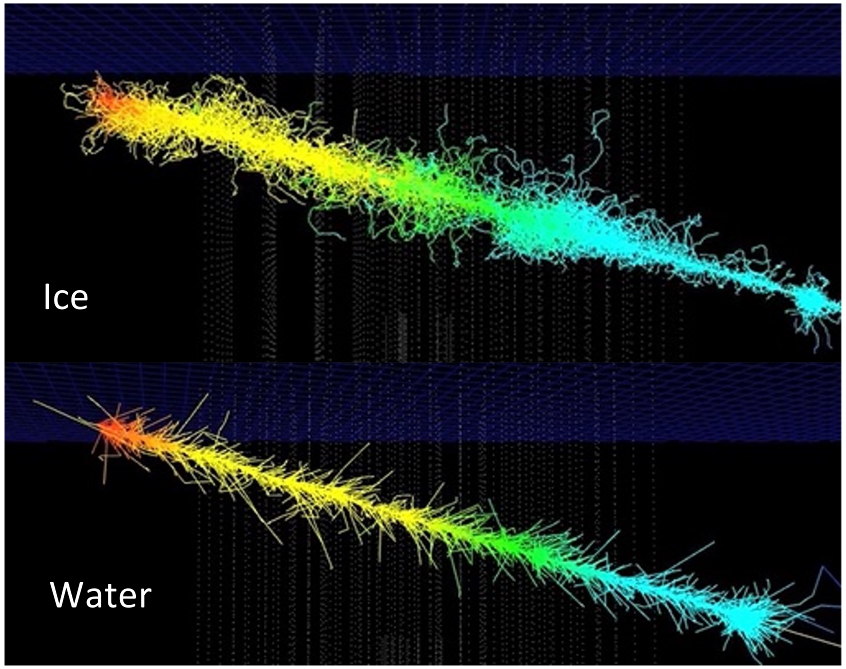
A km³ telescope in the Mediterranean sea means:

- full sky coverage
- 1.5 sr common sky with IceCube
- visibility of Galactic Plane + Galactic Center





Water vs Ice



Ice: less absorption -> more light

Water: less scattering -> more direct light
Better pointing accuracy in water

Angular resolution (@100 TeV)

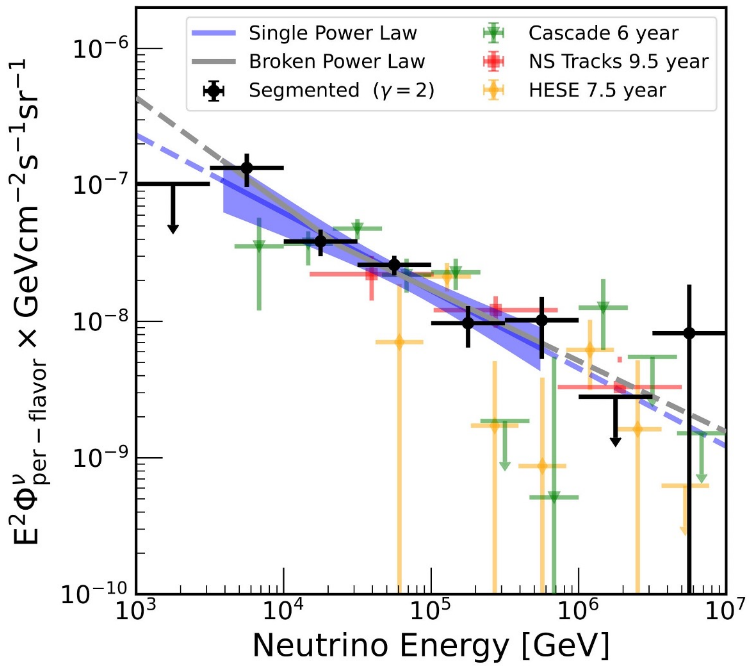
	Tracks	Showers
ANTARES	0.3°	3°
KM3NeT	0.1°	1.5°
IceCube	0.3°	7° - 8°
BAIKAL-GVD	0.25°	3° - 3.5°

Energy resolution

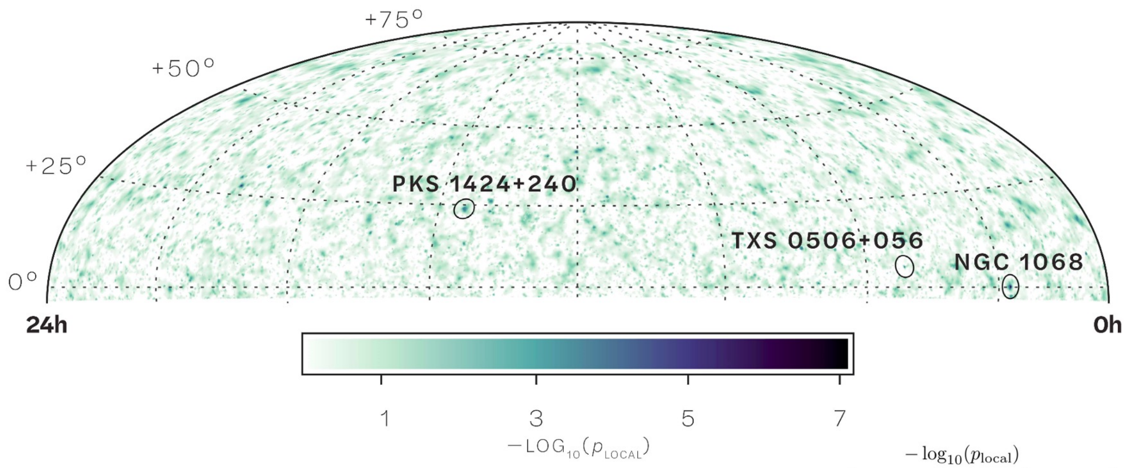
	Tracks in Log(E)	Showers in E
ANTARES	35%	5%
KM3NeT	27%	5%
IceCube	~ 30%	10%
BAIKAL-GVD		

Main results from IceCube

Phys. Rev. D 110, 022001 (2024)

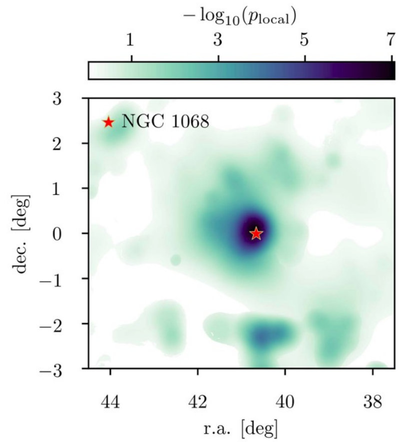


Multiple, high-significance observation of an all-sky flux of neutrinos



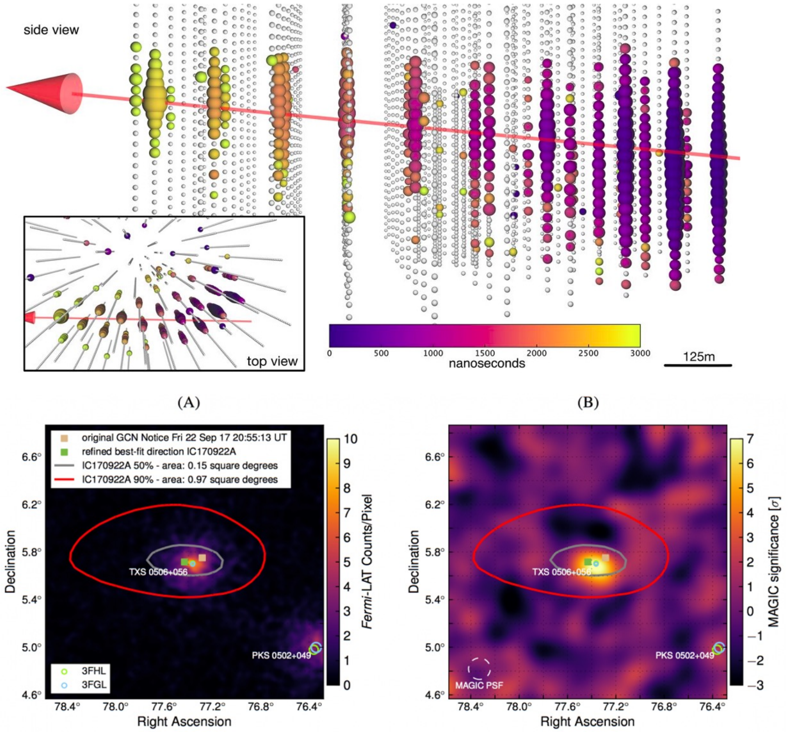
First indications of point-like sources of neutrinos towards Active Galactic Nuclei (around 3-4 sigma)

Science 378 (2022) no. 6619, 538



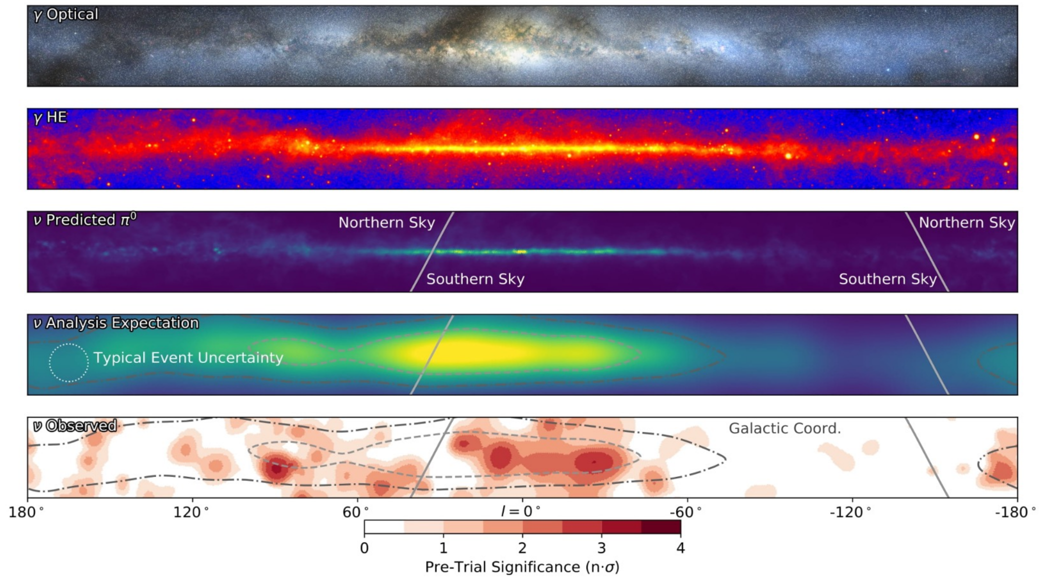
Main results from IceCube

Science 361 (2018) no. 6398, eaat1378



Neutrinos from TXS-0506+056 with Gamma-Ray counterpart

Science 380, 6652, 2023

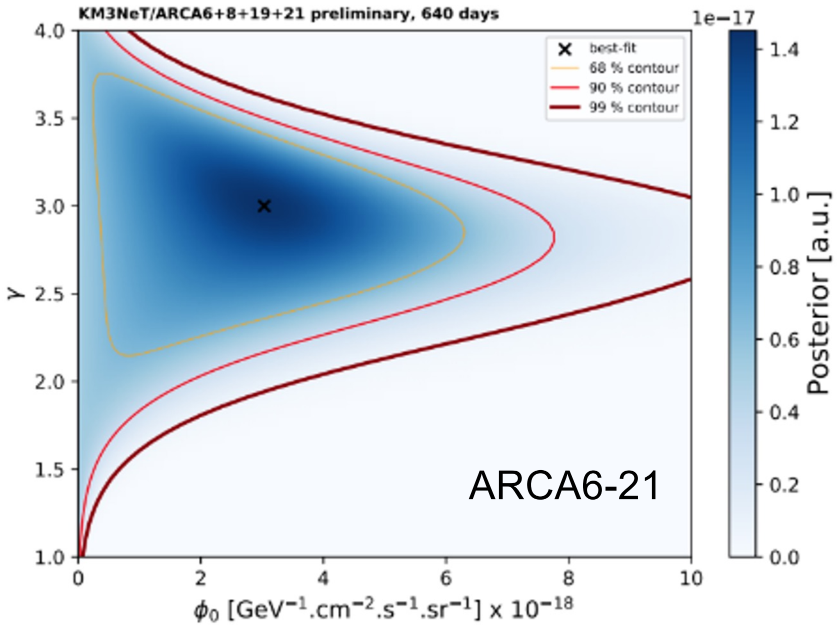


Model-dependent observation of neutrinos from the Galactic Plane (3-4 sigma)

First ARCA data analyses

Diffuse analysis

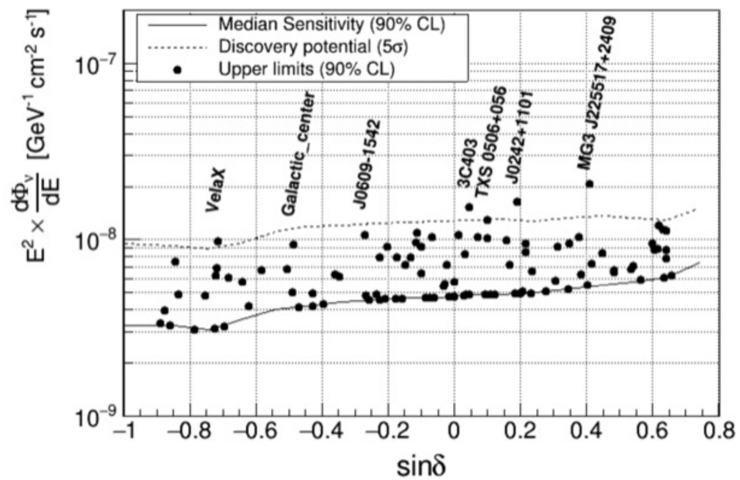
Results just unblinded, Preliminary results (Tracks only)



Best estimated points for the cosmic parameters are a normalisation of ϕ_0 = 3.03 and a spectral index of γ = 3.0

Search for point-like sources

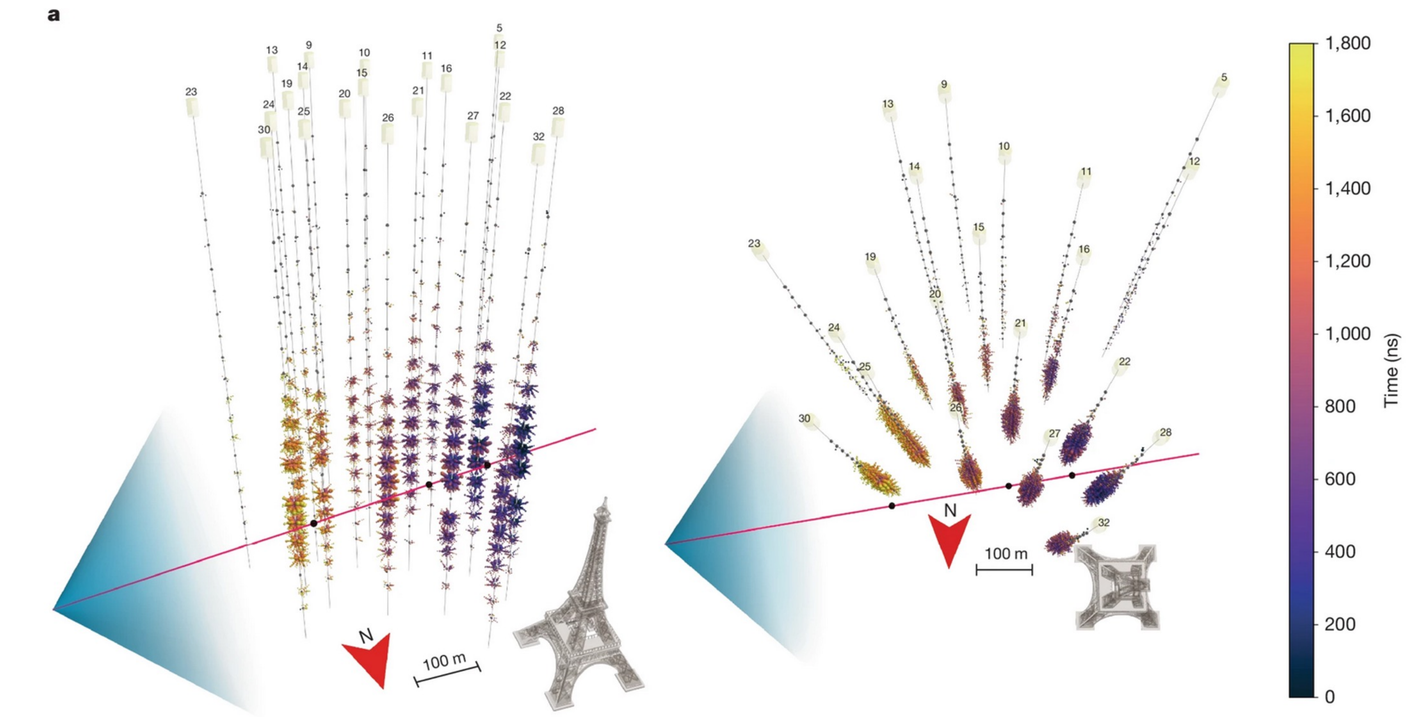
Results just unblinded, Very preliminary results



ARCA 19-21 + ANTARES 15 years

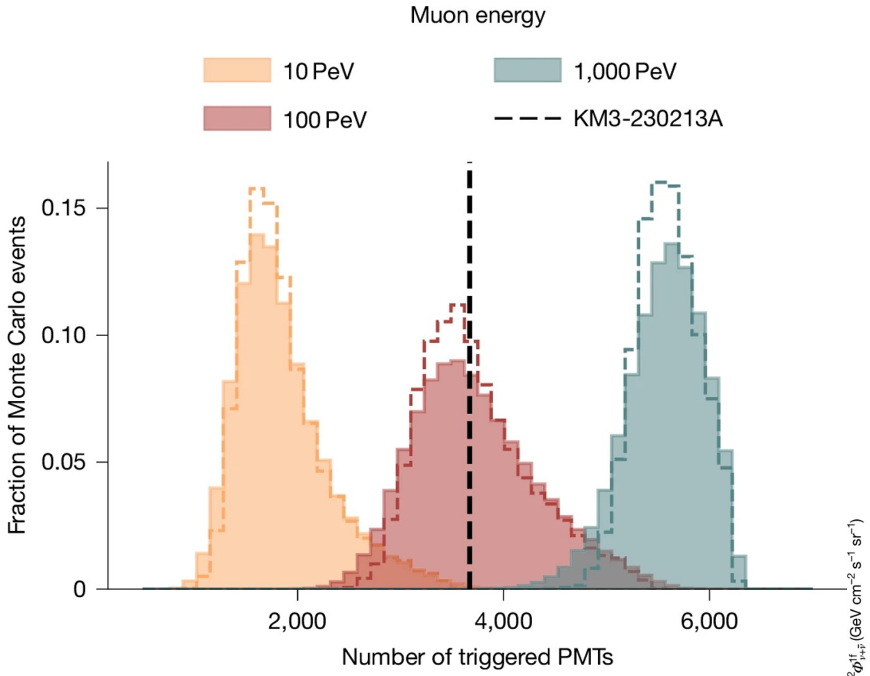
- ANTARES sensitivities improved of about 20% adding ARCA 19-21
- Several sources start to have an interesting p-value

KM3-230213A



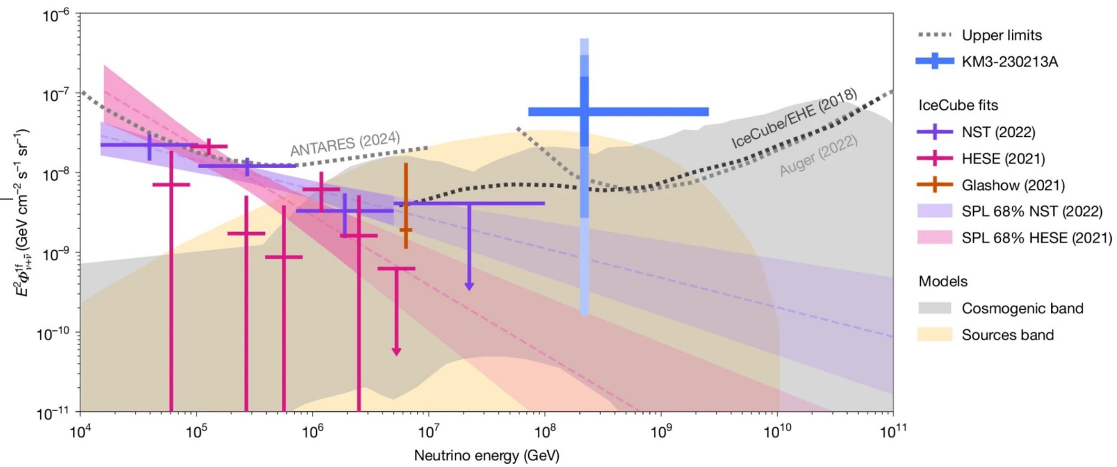
Nature **638**: 376–382 (2025)

KM3-230213A

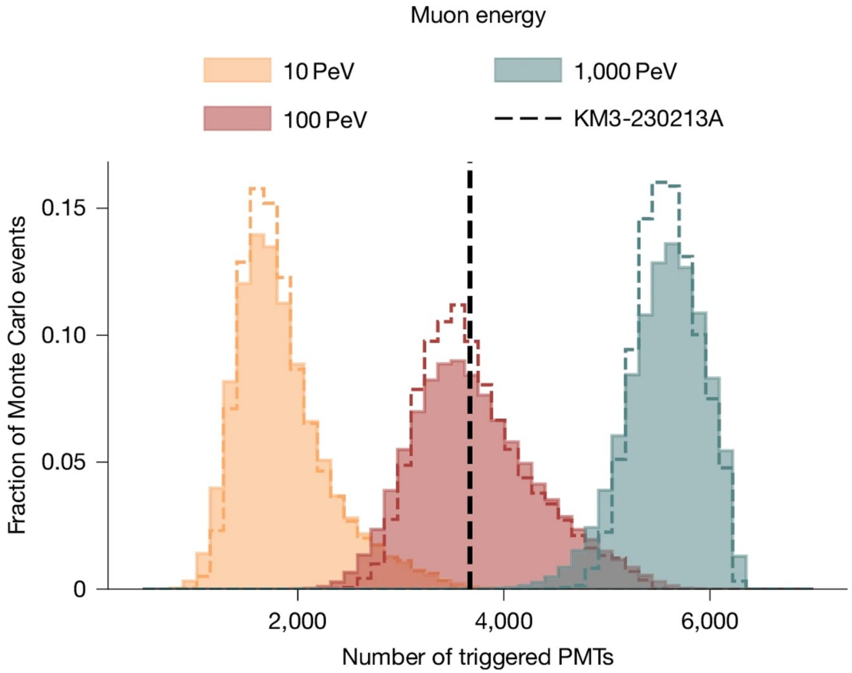


Highest energy neutrino ever observed (220 PeV, 68% c.l. 110 – 790 PeV)

Completely unexplored region: new source population? cosmogenic? Beyond Standard Model?



KM3-230213A



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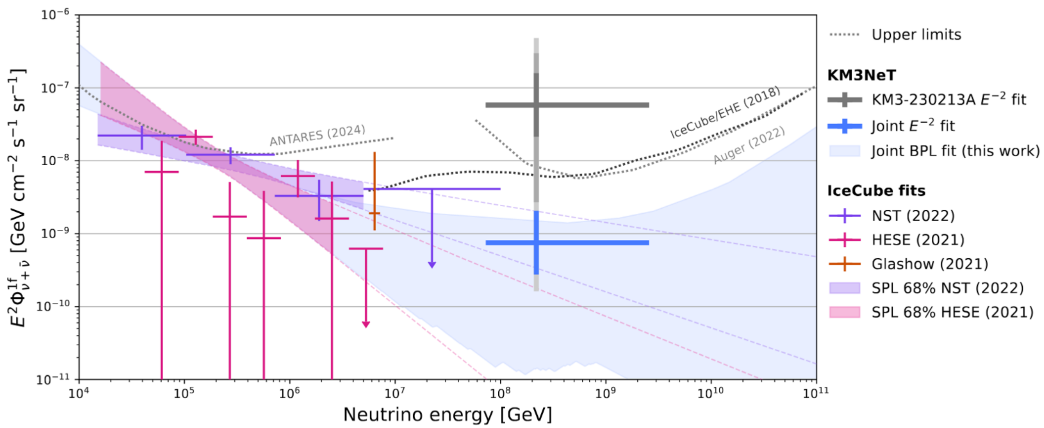
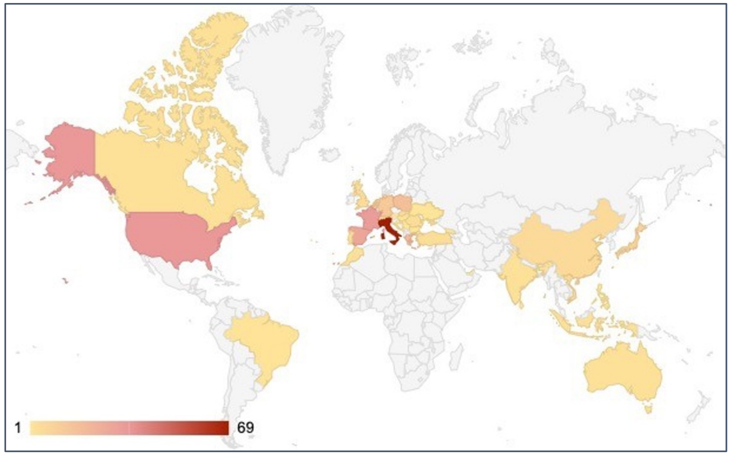


Observation of 1 event in KM3NeT suggests a 2.2σ upward fluctuation with a tension of ~2.5σ with the null observation from other experiments combined

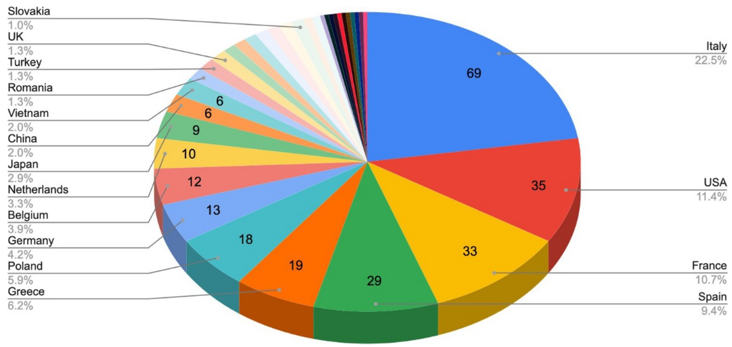
Phys. Rev. X - **Accepted** 22 May, 2025

February 12, 2025

KM3NeT shared with the world the discovery, coinciding with the publication of the result on *Nature*.



Records kept by Outreach Committee:
306 articles/media appearances in 35 countries



Publications

Article

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

https://doi.org/10.1038/s41586-024-08543-1
Received: 19 August 2024
Accepted: 18 December 2024
Published online: 12 February 2025
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[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.

*A list of authors and their affiliations appears at the end of the paper. ✉e-mail: km3net-pc@km3net.de

Companion papers submitted/published:

- The ultra-high-energy event KM3-230213A within the global neutrino landscape, arXiv:2502.08173
- 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
- On the potential cosmogenic origin of the ultra-high-energy event, arXiv:2502.08508
- KM3NeT Constraint on Lorentz-Violating Superluminal Neutrino Velocity, arXiv:2502.12070

New companion papers under preparations:

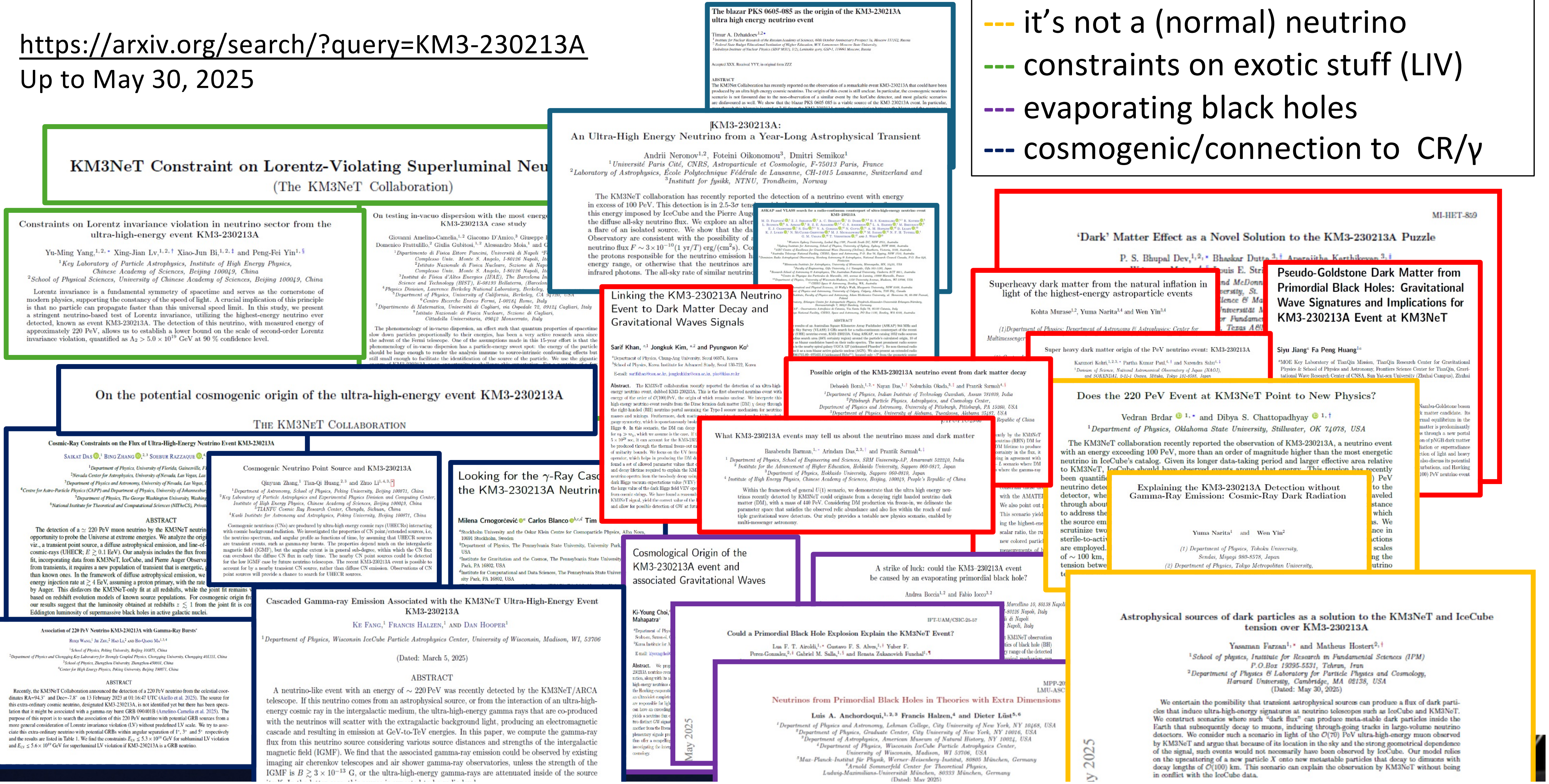
- Diffuse flux from transients (GRB, blazars)
- BSM options (e.g. heavy DM)

....

Scientific interest in KM3-202313A

https://arxiv.org/search/?query=KM3-230213A
Up to May 30, 2025

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



KM3NeT as an AISBL

On June 18, 2025, the KM3NeT Collaboration was officially established in Brussels as an *Association Internationale Sans But Lucratif*

Non-profit international association founded by INFN (Italy), Nikhef (Netherlands), IN2P3/CNRS (France), Universitat de València (Spain), and INPP/NCSR (Greece).

Summary

- KM3NeT is a cutting-edge neutrino observatory in the Mediterranean Sea, composed of ORCA and ARCA detectors, optimized respectively for neutrino oscillation studies and neutrino astronomy.
- ORCA is providing world-leading results on atmospheric neutrino oscillations, with sensitivity to the neutrino mass ordering.
- ARCA has entered the high-energy frontier with the detection of the highest-energy neutrino ever observed (KM3-230213A), opening a new window on the Universe.
- The synergy with IceCube, JUNO and other observatories enhances discovery potential and parameter sensitivity.
- With the official foundation of KM3NeT as an AISBL (June 2025), the project is entering a new phase of scientific and institutional maturity (ESFRI Landscape).