

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

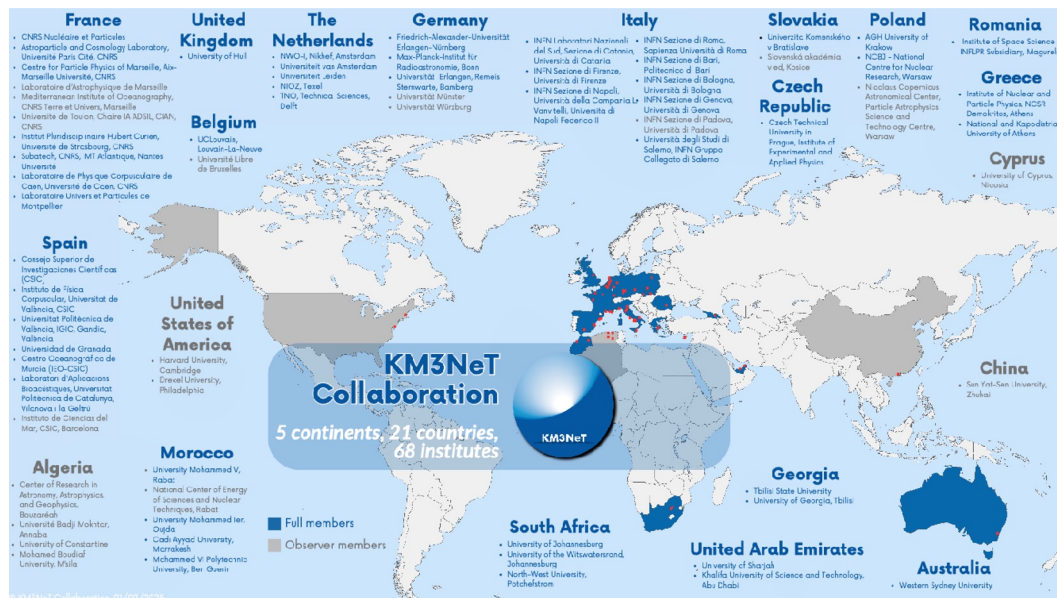


KM3NeT is a research infrastructure in the Mediterranean Sea hosting two neutrino detectors:

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 Research
with Cosmics in the Abyss



ARCA:
Astroparticle Research
with Cosmics in the Abyss

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

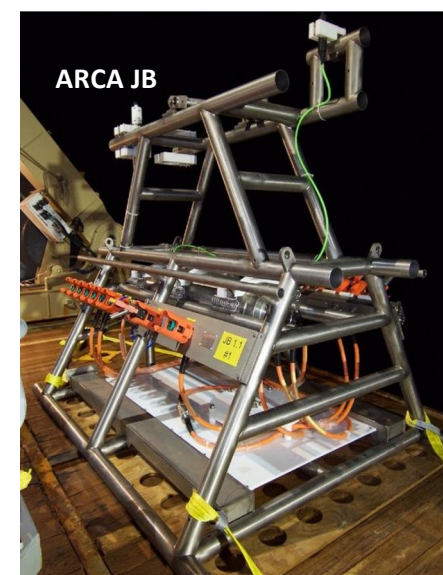
(375VDC)

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



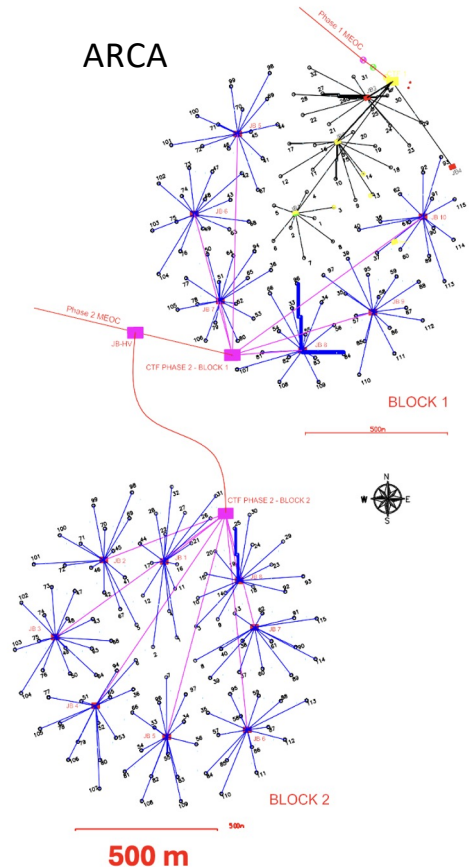
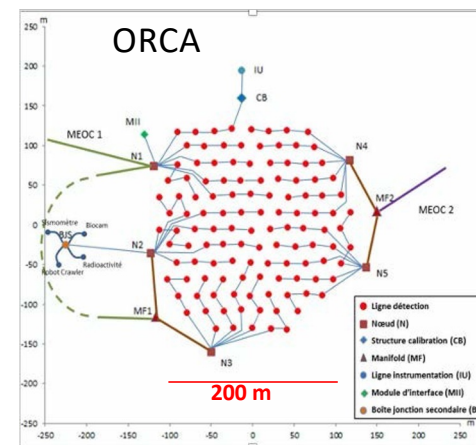
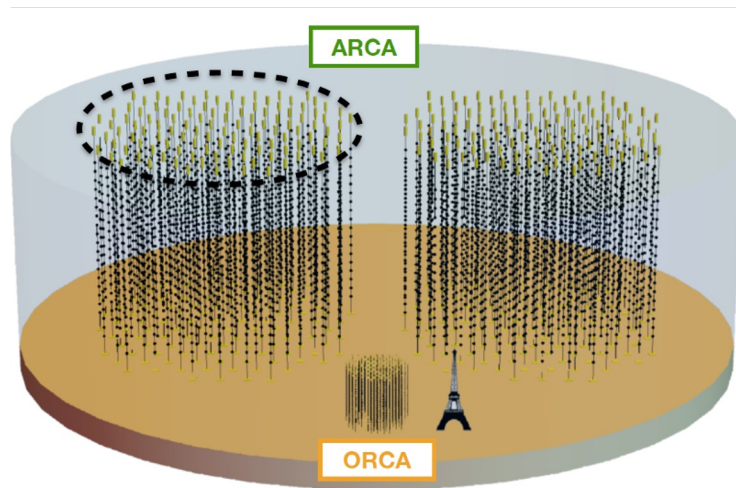
- Electro-optical cables from deep sea to the shore station
- Junction boxes (JB) to distribute power and optical fibres
- Interlink cables for connection of DUs to JB and JB to the main cable

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



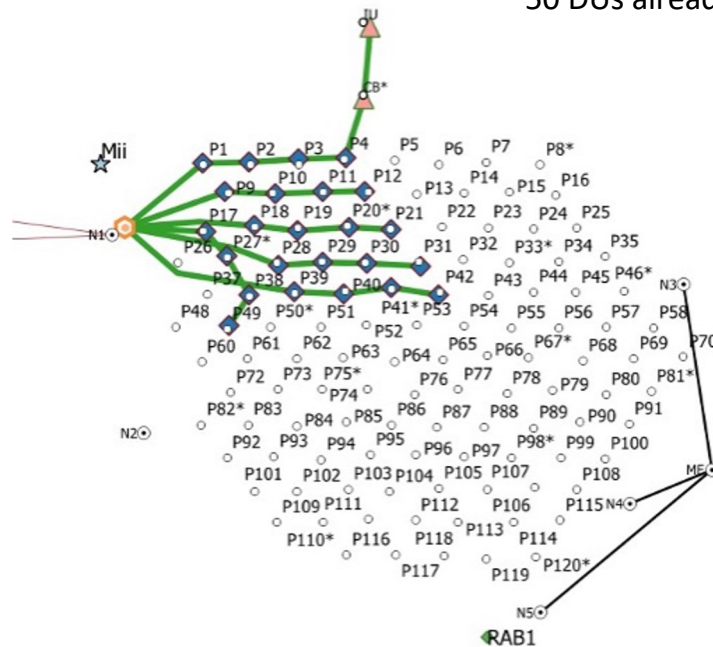
ORCA

28 DUs deployed

4 new DUs deployed in May

DU integration rate: 20/year

50 DUs already funded



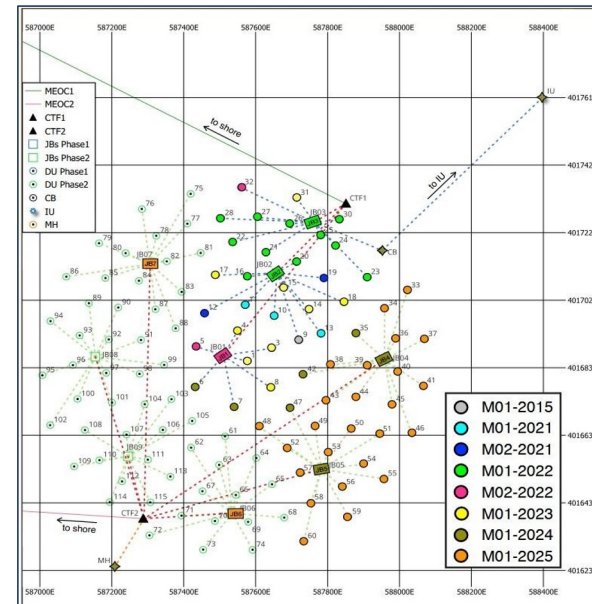
ARCA

33 DUs deployed

19 new DUs to be deployed in July

DU integration rate: 35/year

130 DUs already funded

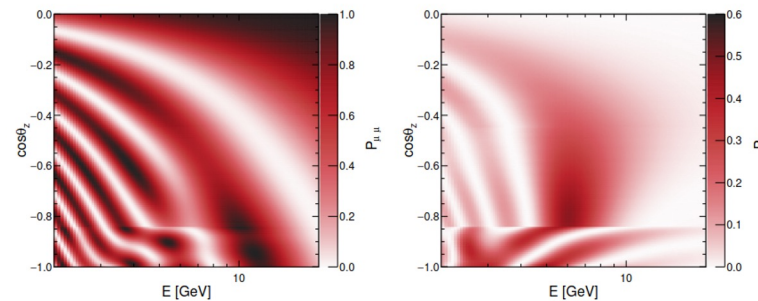
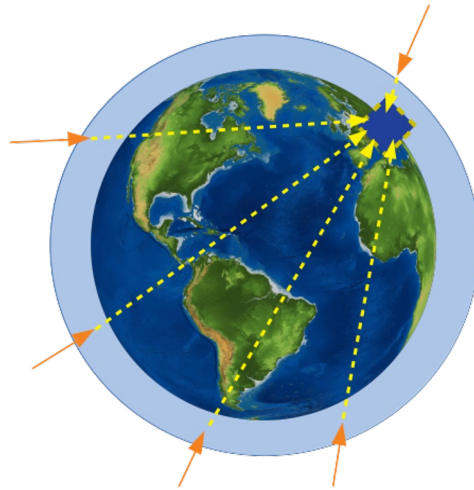


Completion of ORCA/ARCA DUs production: 2030

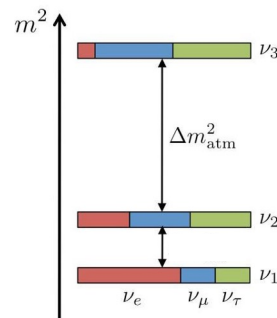
Access **Neutrino Mass Ordering**, unitarity, Beyond Standard Model physics

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

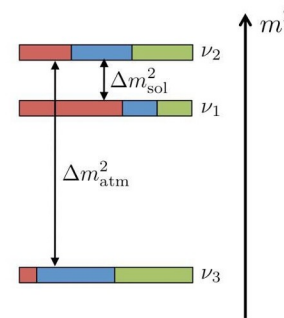
Energy and zenith
dependent effects from
oscillations



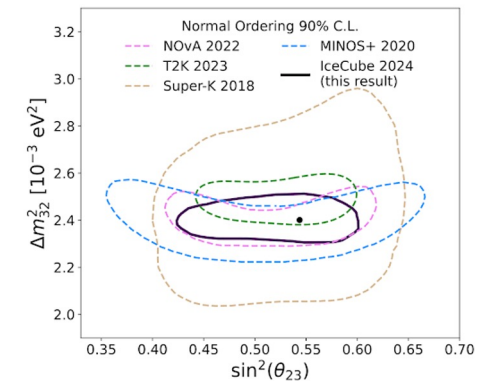
normal hierarchy (NH)



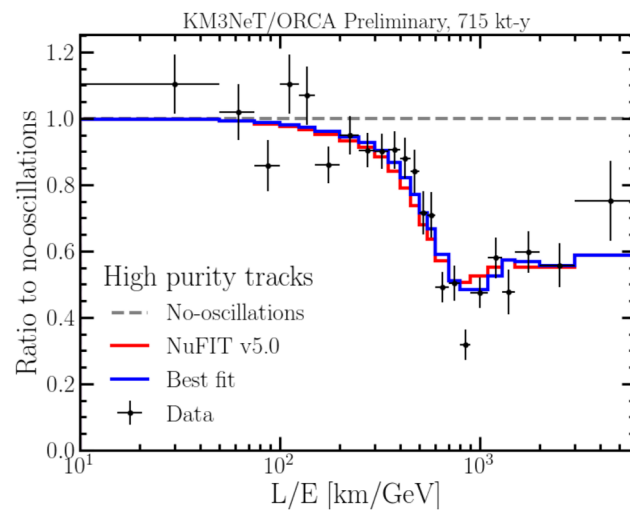
inverted hierarchy (IH)



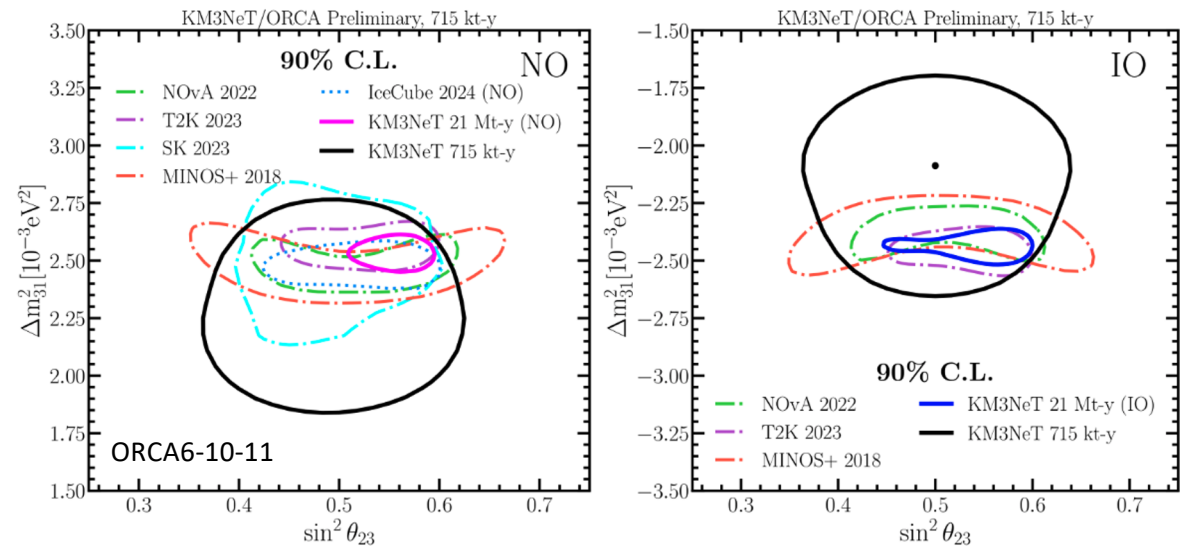
Current status before ORCA



Clear oscillation signal
with 2 years of data
ORCA 11



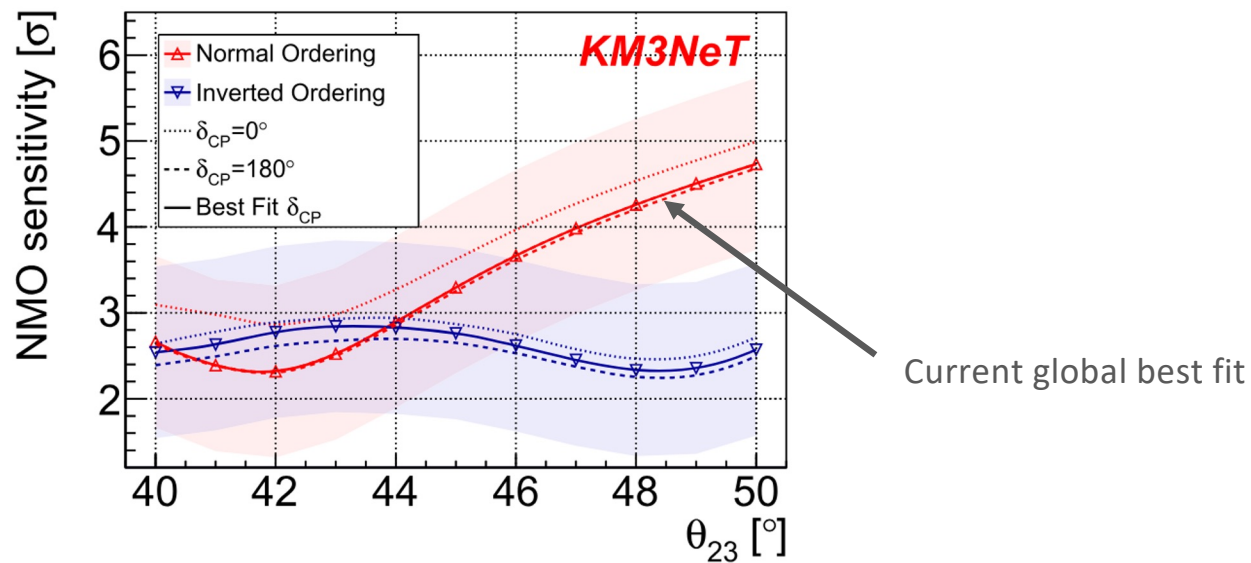
Best oscillation measurements with atmospheric
neutrinos with the full detector



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

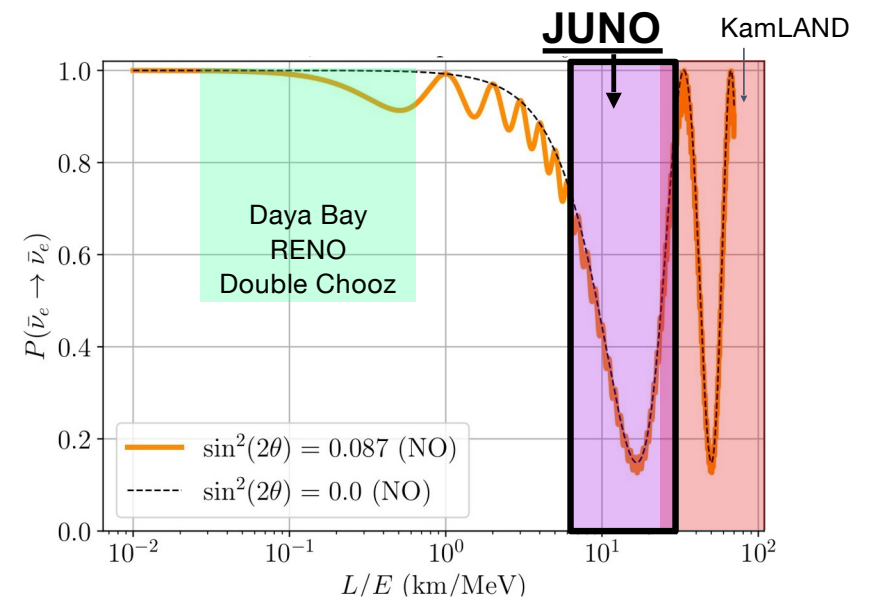
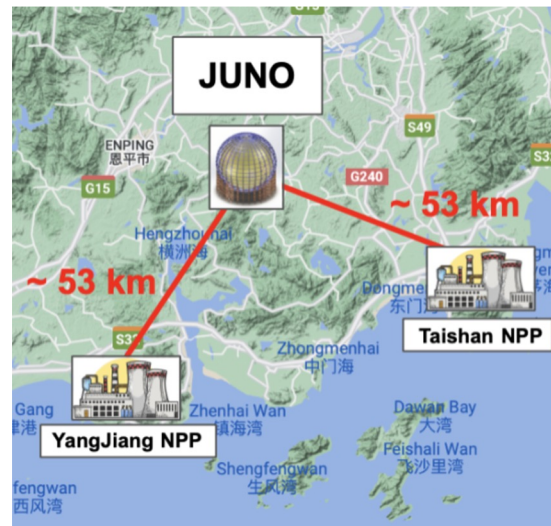
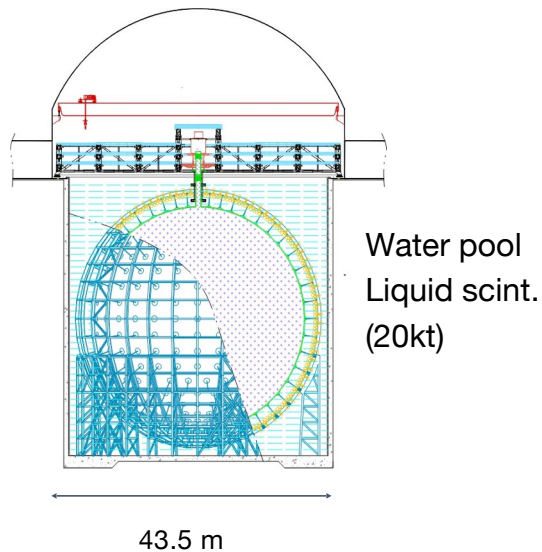
Full detector results

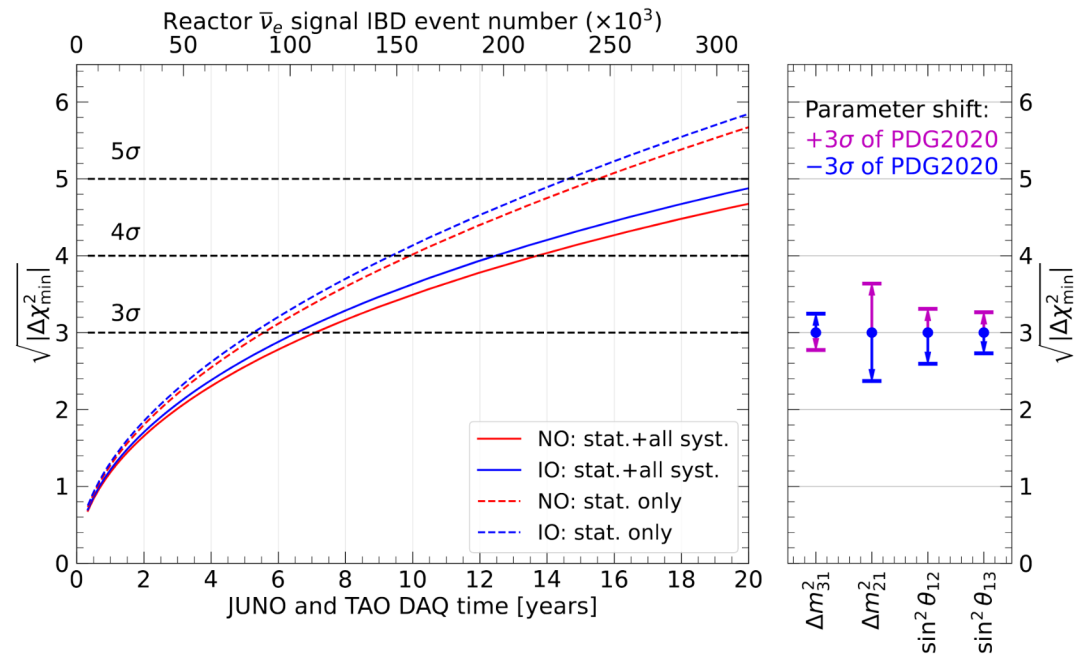
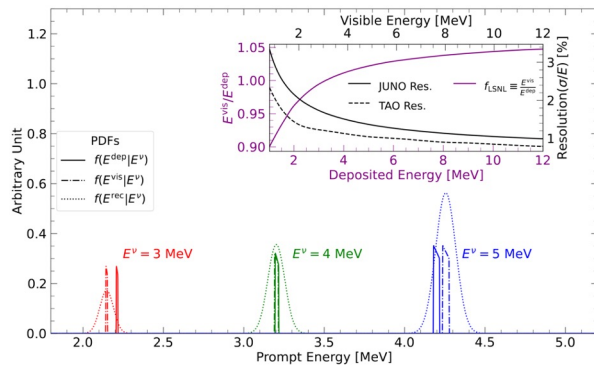
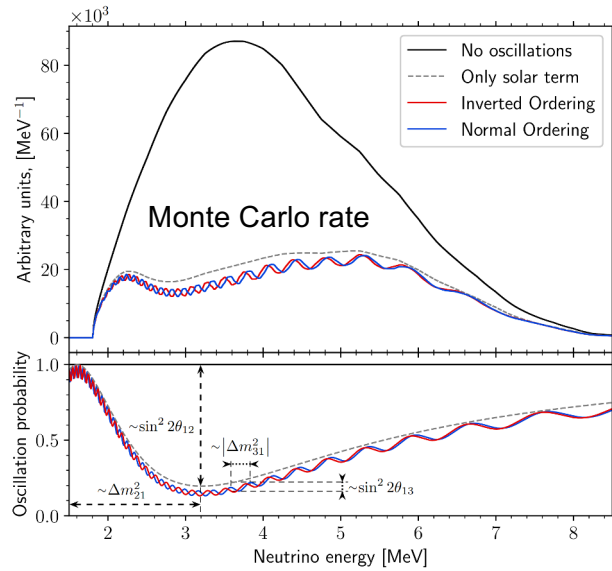
- **Neutrino Mass Ordering** determined at ~ 3 sigma in 3 years from completion over the parameter space
- Final sensitivity will depend on the parameters chose by nature



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

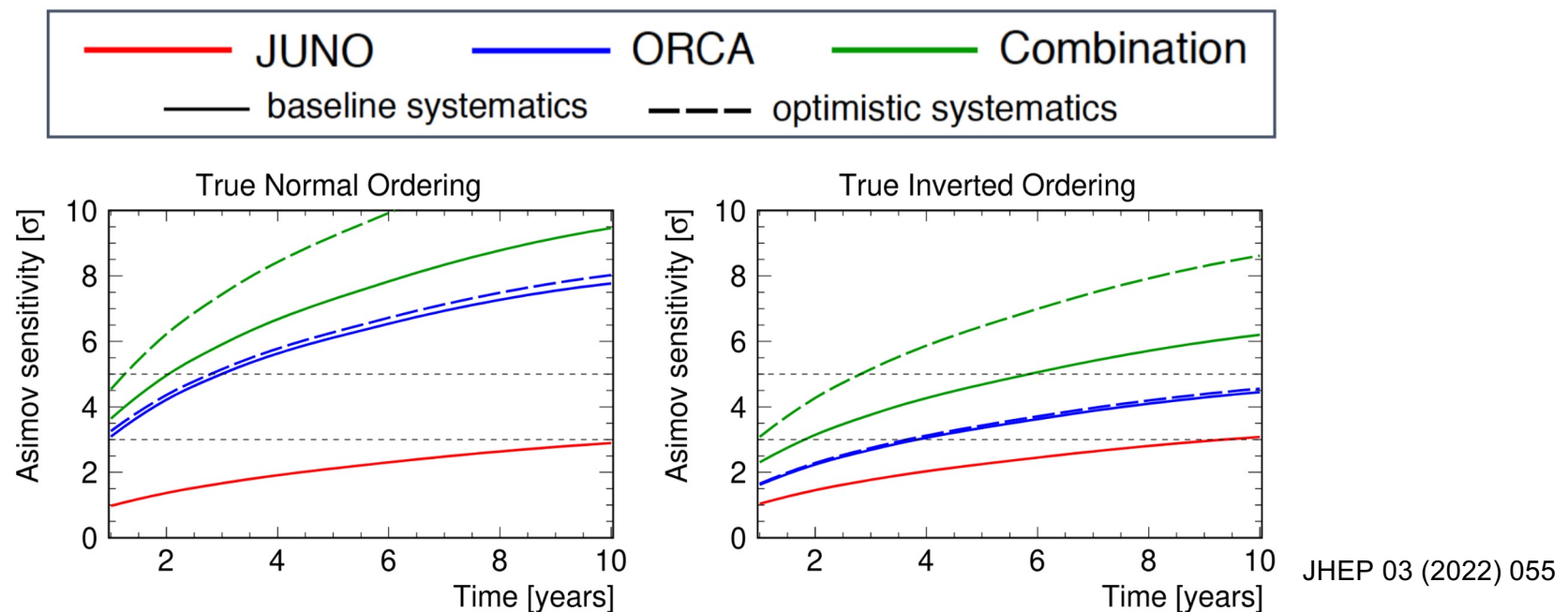
- NMO from near/far detector rates
- Requires precise measurement of the neutrino energy





NMO sensitivity with near and far detector

- 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}^2 from ORCA and JUNO simultaneously breaks the degeneracy between the two experiments when assuming the wrong ordering
- Large boost in the sensitivity



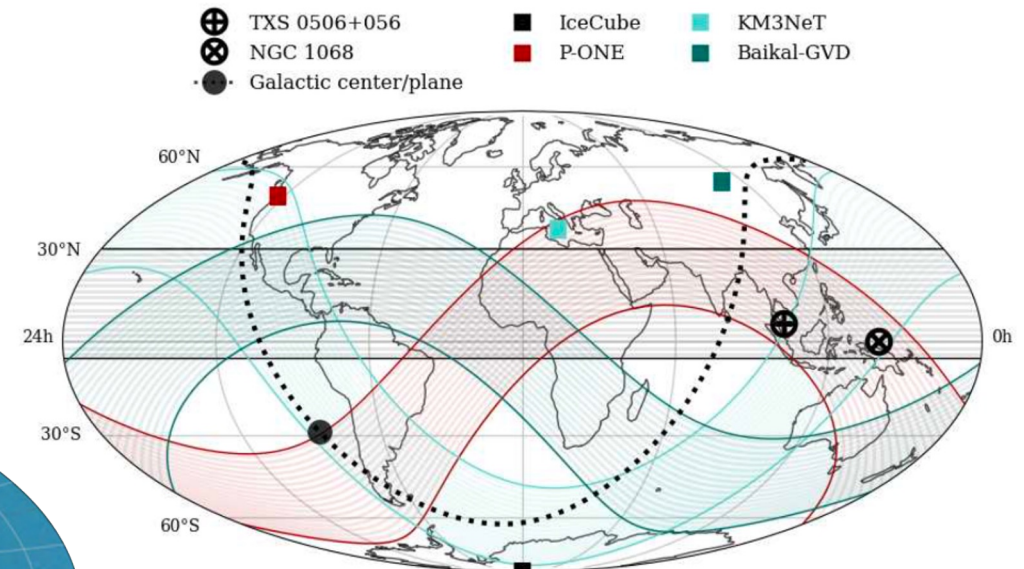


Neutrino telescopes



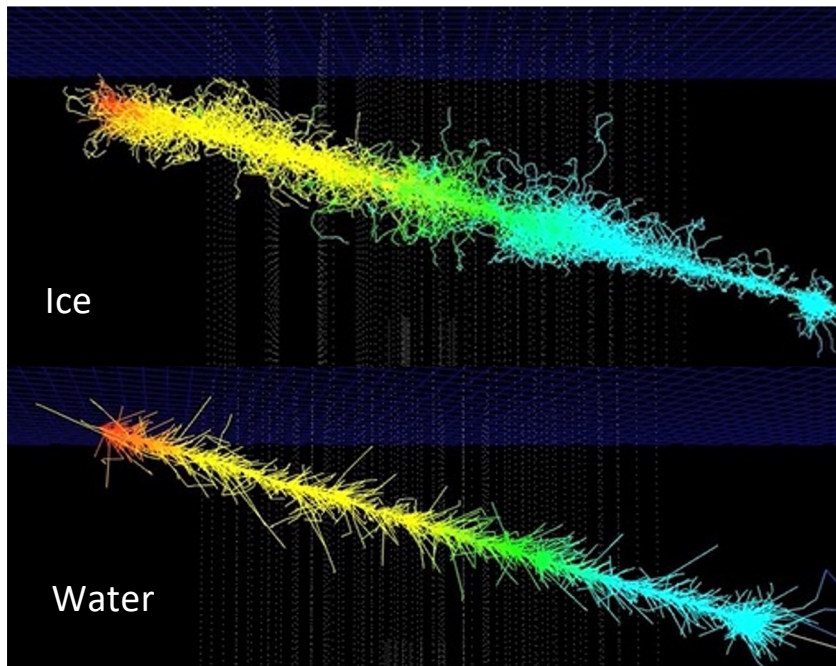
A km³ telescope in the Mediterranean sea means:

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





Water vs Ice



Ice: less absorption \rightarrow more light

Water: less scattering \rightarrow more direct light

Better pointing accuracy in water

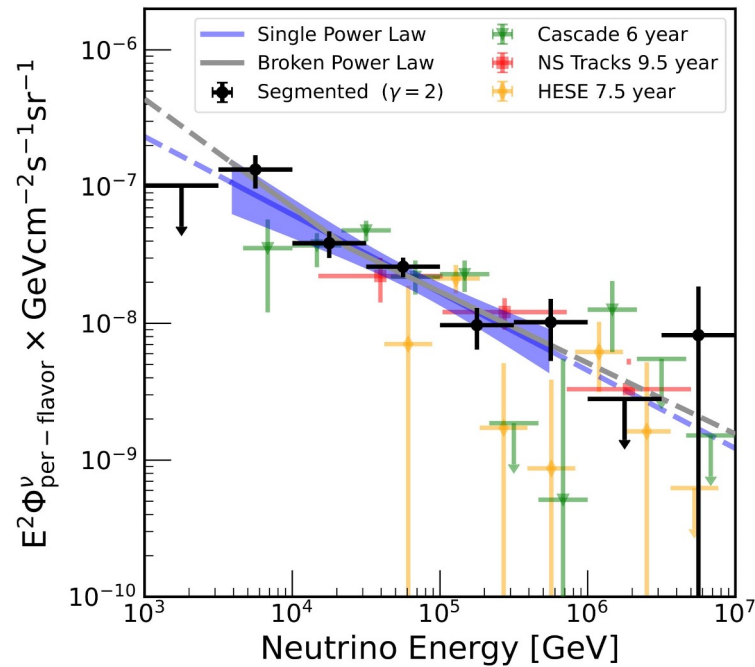
Angular resolution (@100 TeV)

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

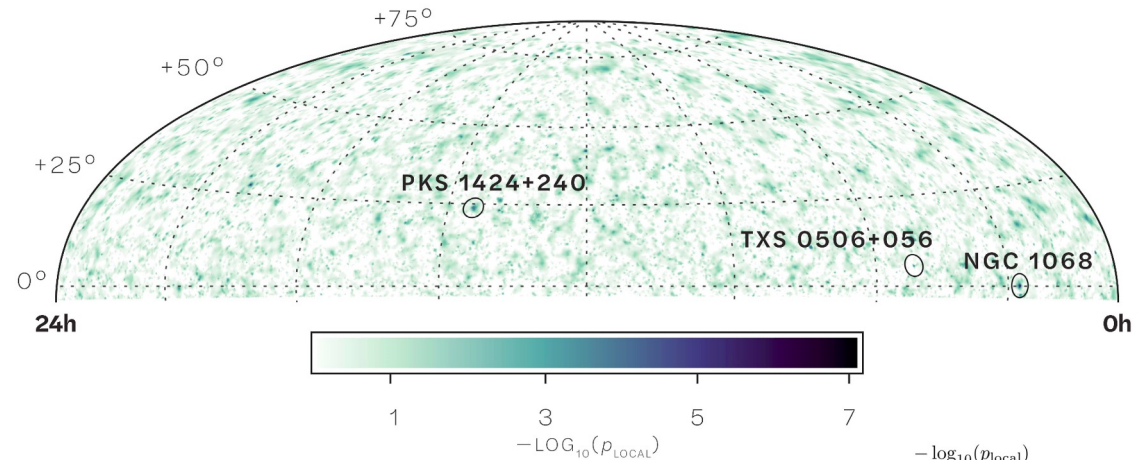
Energy resolution

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

Phys. Rev. D 110, 022001 (2024)

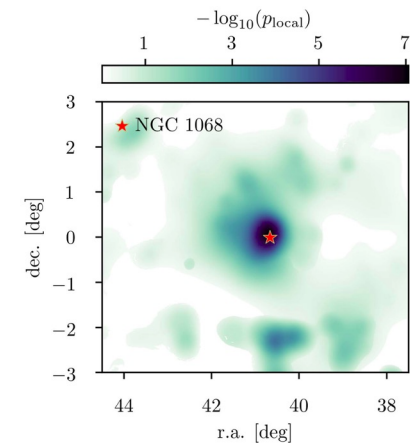


Multiple, high-significance observation of an all-sky flux of neutrinos



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

Science 378 (2022) no. 6619, 538

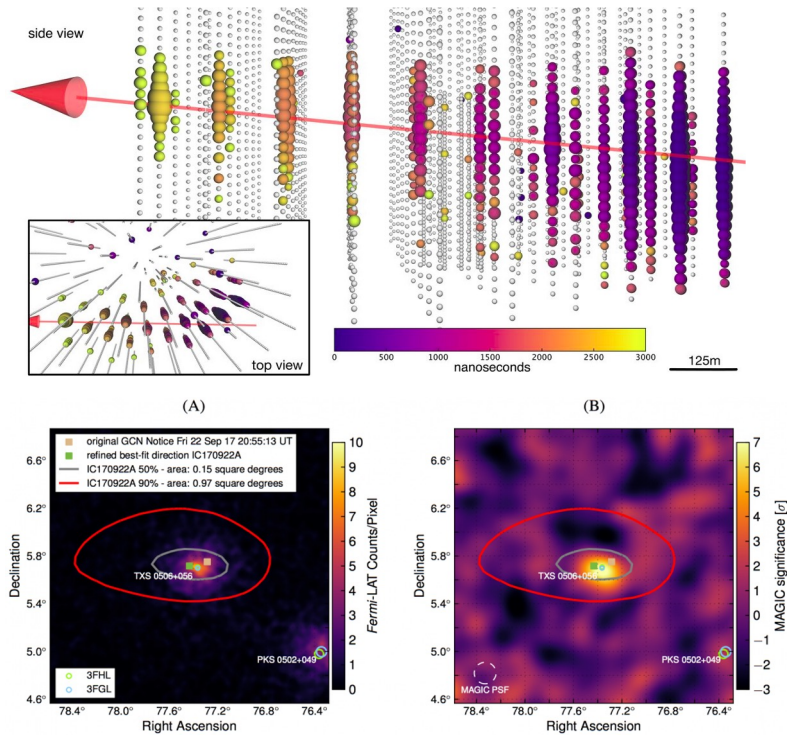




Main results from IceCube

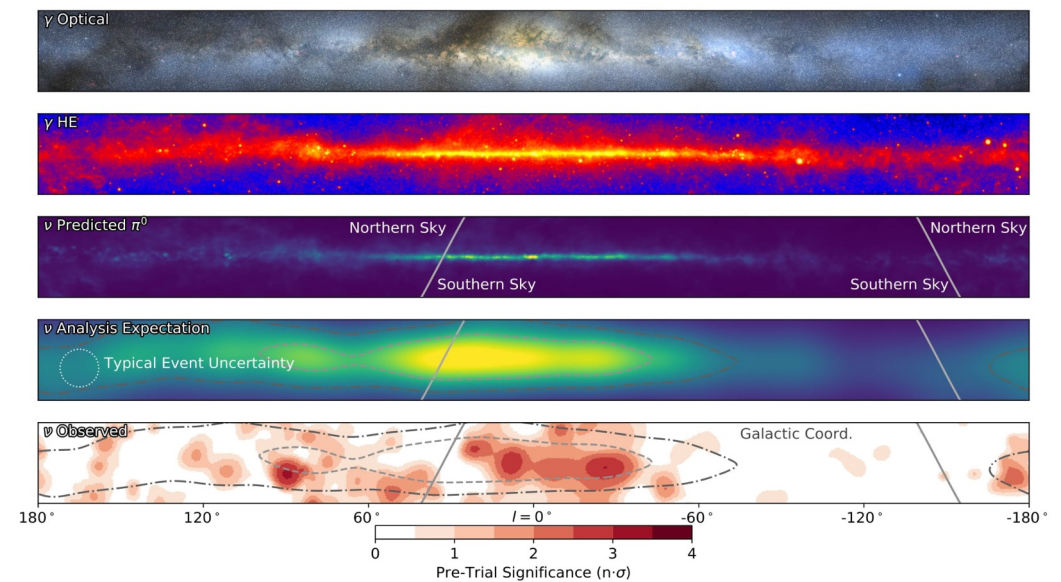


Science 361 (2018) no. 6398, eaat1378



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

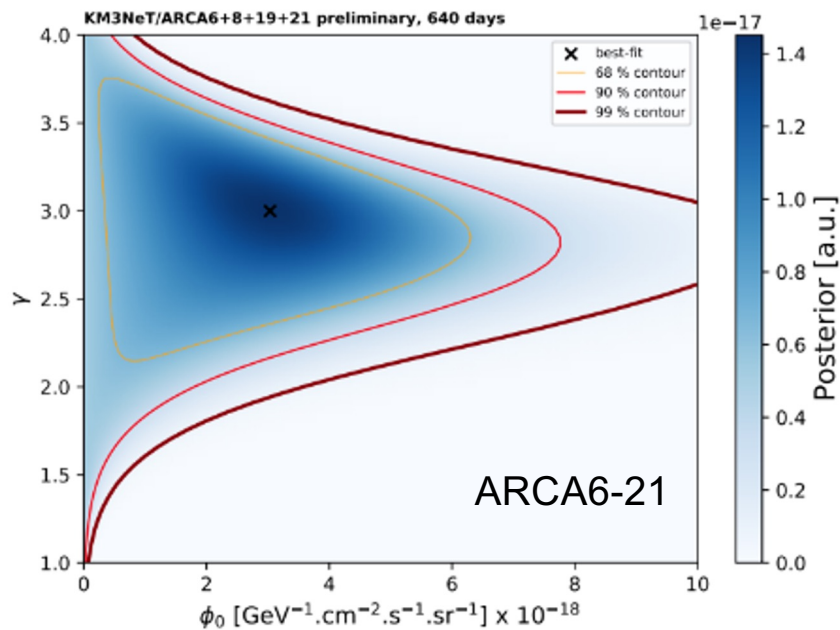
Science 380, 6652, 2023



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

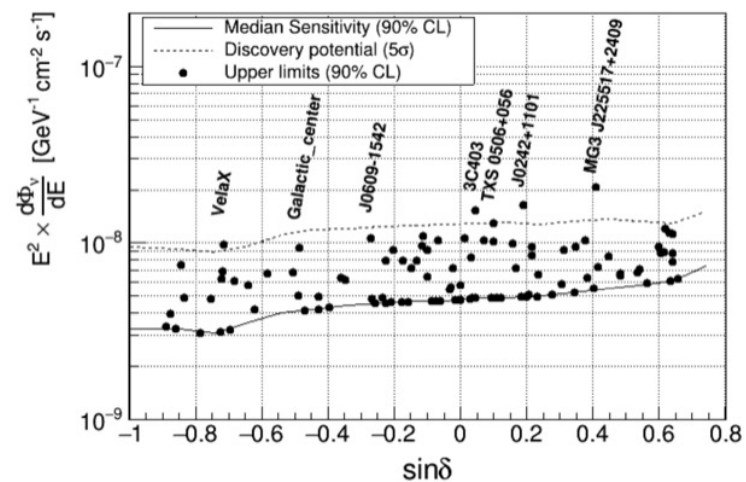
Diffuse analysis

Results just unblinded, Preliminary results (Tracks only)



Search for point-like sources

Results just unblinded, Very preliminary results

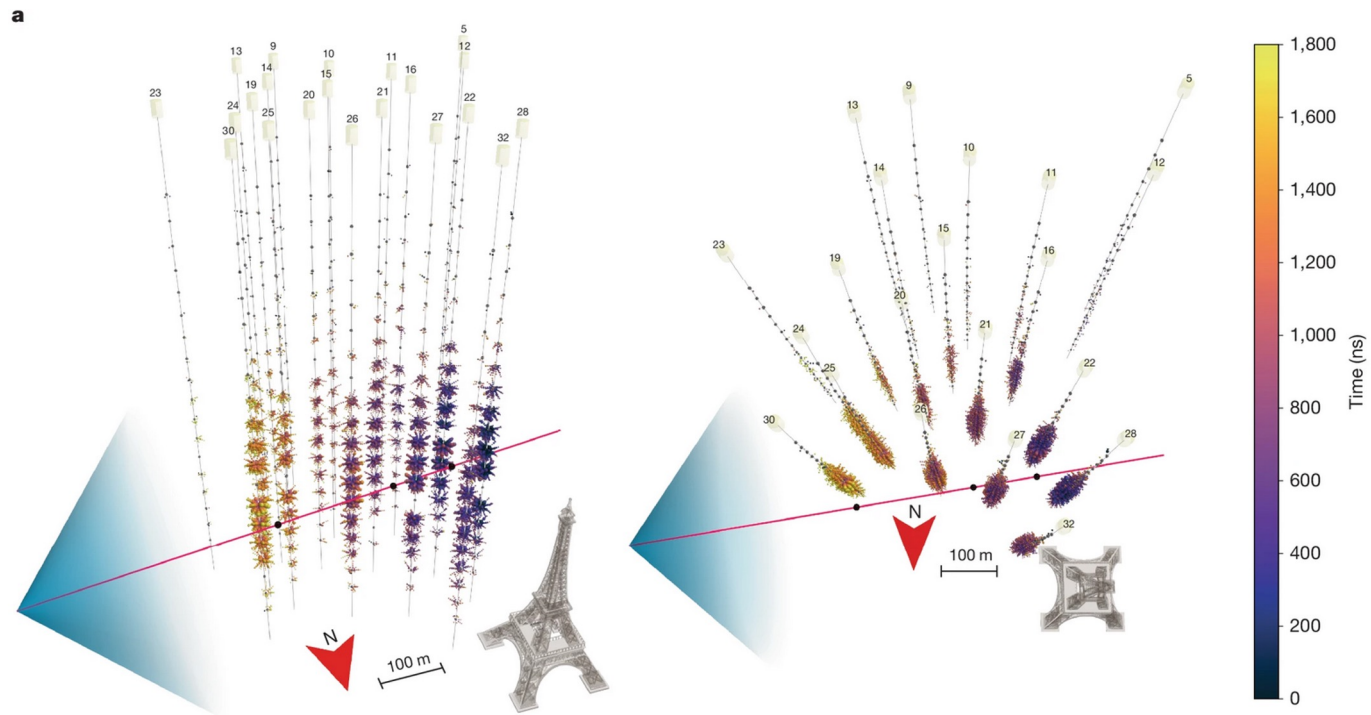


ARCA 19-21 + ANTARES 15 years

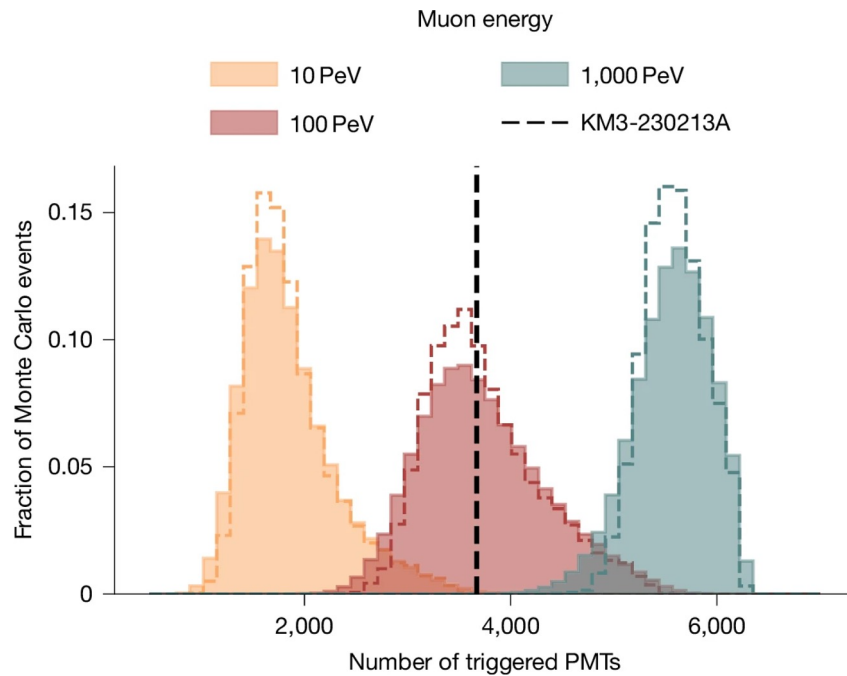
- ANTARES sensitivities improved of about 20% adding ARCA 19-21
- Several sources start to have an interesting p-value



KM3-230213A

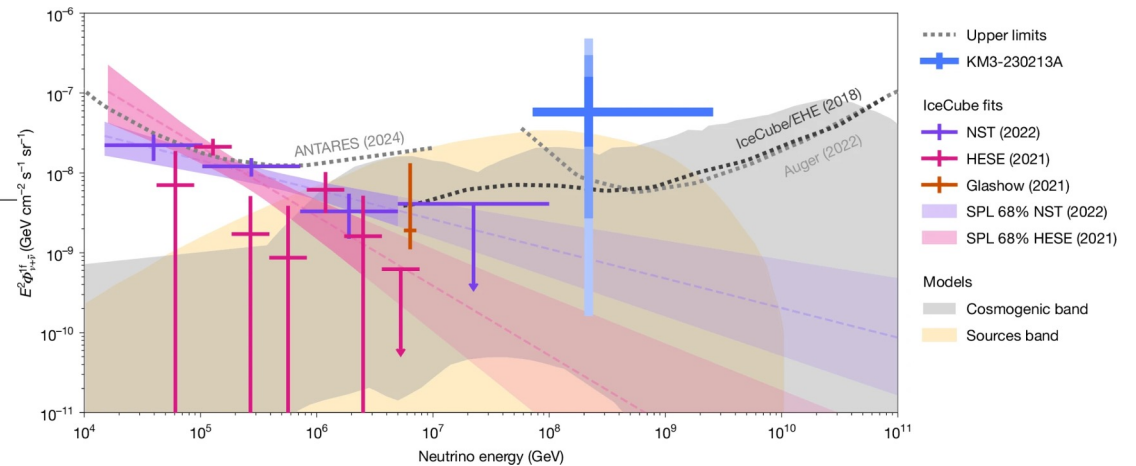


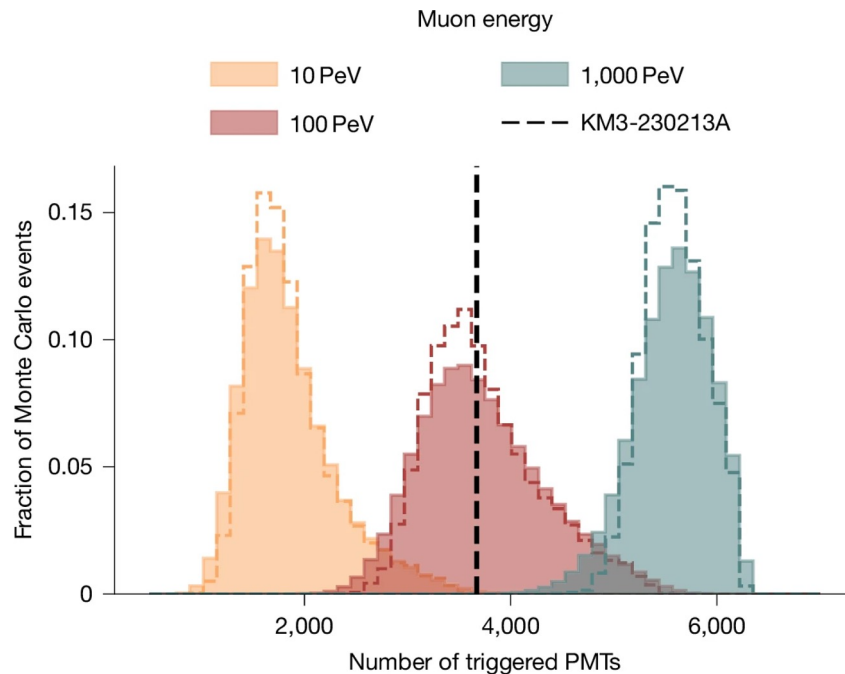
Nature **638**: 376–382 (2025)



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

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

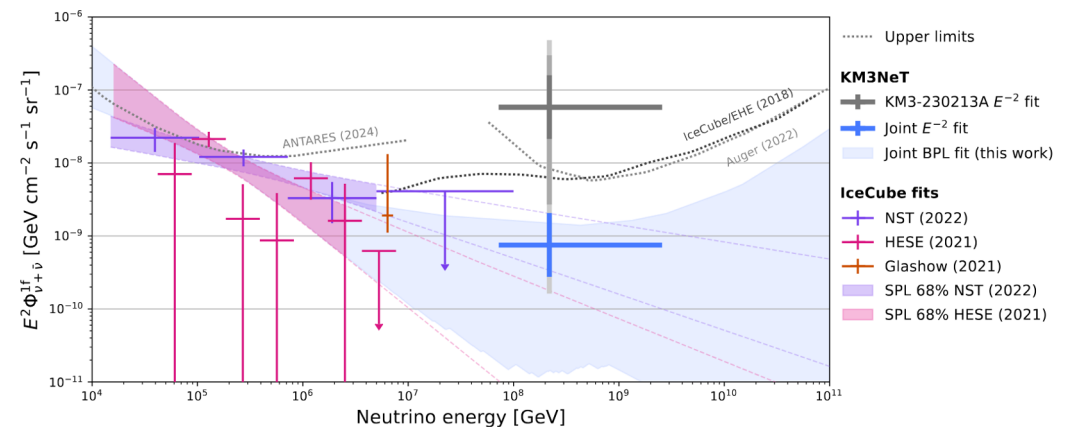




Observation of 1 event in KM3NeT suggests a 2.2σ upward fluctuation with a tension of $\sim 2.5\sigma$ with the null observation from other experiments combined

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

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



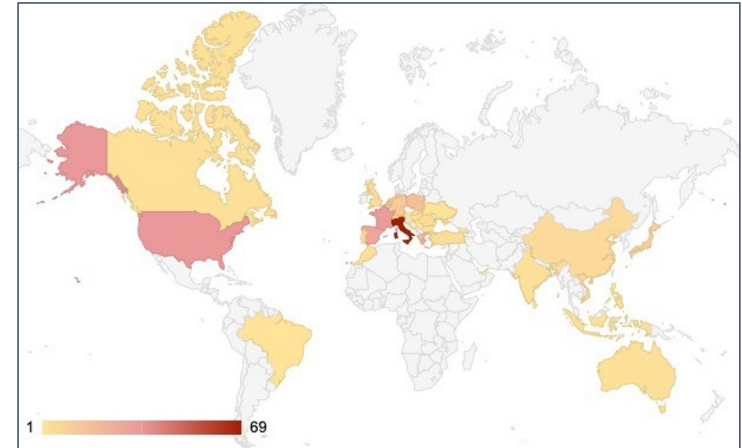
Phys. Rev. X - Accepted 22 May, 2025



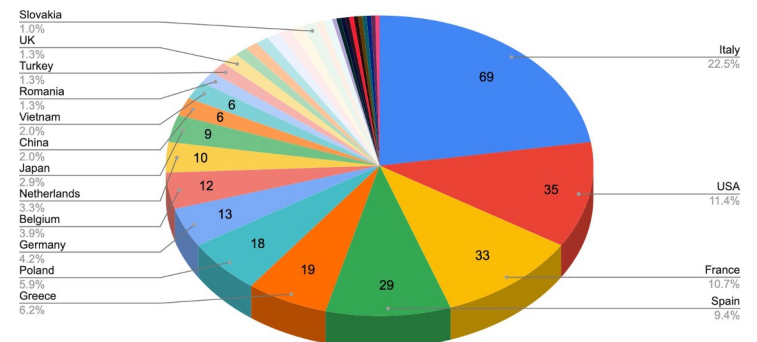
February 12, 2025



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





Article

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

<https://doi.org/10.1038/s41586-024-08543-1>

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Open access

Check for updates

The KM3NeT Collaboration^{1,2}

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 Sea⁴, which we associate with a cosmic neutrino detection. We detect a muon with an estimated energy of 120^{+100}_{-40} 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^{5,6} 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 neutrino⁷, 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 Sea⁴. 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 coverage⁸. 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 photoneuclear 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 resonance²³ and a muon neutrino above 10 PeV from the observation of a 4.4-PeV muon²⁴.

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.

¹A list of authors and their affiliations appears at the end of the paper. ²E-mail: km3net-pc@km3net.de

Companion papers submitted/published:

- The ultra-high-energy event KM3-230213A within the global neutrino landscape, [arXiv:2502.08173](https://arxiv.org/abs/2502.08173)
- On the Potential Galactic Origin of the Ultra-High-Energy Event KM3-230213A, [arXiv:2502.08387](https://arxiv.org/abs/2502.08387)
- Characterising Candidate Blazar Counterparts of the Ultra-High-Energy Event KM3-230213A, [arXiv:2502.08484](https://arxiv.org/abs/2502.08484)
- On the potential cosmogenic origin of the ultra-high-energy event, [arXiv:2502.08508](https://arxiv.org/abs/2502.08508)
- KM3NeT Constraint on Lorentz-Violating Superluminal Neutrino Velocity, [arXiv:2502.12070](https://arxiv.org/abs/2502.12070)

New companion papers under preparations:

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

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scientific interest in KM3-202313A

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

KM3NeT Constraint on Lorentz-Violating Superluminal Neutrinos (The KM3NeT Collaboration)

Constraints on Lorentz invariance violation in neutrino sector from the ultra-high-energy event KM3-230213A

Yu-Ming Yang,^{1,2,*} Xing-Jian Lv,^{1,2,†} Xiao-Jun Bi,^{1,2,‡} and Peng-Fei Yin^{1,§}
¹Key Laboratory of Particle Astrophysics, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China
²School of Physics Sciences, University of Chinese Academy of Sciences, Beijing 100049, China

Lorentz invariance is a fundamental symmetry of spacetime and serves as the cornerstone of modern physics, supporting the constancy of the speed of light. A crucial implication of this principle is that no particle can propagate faster than this universal speed limit. In this study, we present a stringent, neutrino-based test of Lorentz invariance by utilizing the highest-energy neutrino ever detected, known as event KM3-230213A. The detection of this neutrino, with measured energy of approximately 220 PeV, allows us to establish a lower bound on the scale of second-order Lorentz invariance violation, quantified as $\Delta_2 \gtrsim 5.0 \times 10^{-19}$ GeV at 90% confidence level.

On the potential cosmogenic origin of the ultra-high-energy event KM3-230213A

THE KM3NeT COLLABORATION

Cosmic-Ray Constraints on the Flux of Ultra-High-Energy Neutrino Event KM3-230213A

SARAI DUTTA¹, BING ZHANG^{2,3,†}, SOHAIL RAZZOQUE^{4,5}
¹Department of Physics, University of Florida, Gainesville, FL 32611, USA
²Graduate Center for Astrophysics, University of Florida, Los Angeles, CA 90048, USA
³Department of Physics and Astronomy, University of Florida, Los Angeles, CA 90048, USA
⁴Center for Astro-Particle Physics (CAPP) and Physics Department, University of Maryland, College Park, MD 20742, USA
⁵National Institute for Theoretical and Computational Sciences (NITCS), Physics Department, University of Maryland, College Park, MD 20742, USA

ABSTRACT
The detection of a ~ 220 PeV muon neutrino by the KM3NeT neutrino observatory provides a unique opportunity to probe the Universe at extreme energies. We analyze the origin of this event, a transient point source, a diffuse astrophysical emission, and the flux of cosmic rays (UHECRs, $E \gtrsim 1$ EeV). Our analysis includes the flux from BL, incorporating data from KM3NeT, IceCube, and Pierre Auger Observatory. From this analysis, it requires a new population of transient that is energetic, as known ones. In the framework of diffuse astrophysical emission, we energy injection rate at $z \sim 4$ EeV, assuming a proton primary, with the rest by Auger. This disfavors the KM3NeT-only fit at all redshifts, while the fit remains based on redshift evolution models of known source populations. For cosmogenic origin, our results suggest that the luminosity obtained at redshift $z \leq 1$ from the fit is consistent with the luminosity of superluminal black holes in active galactic nuclei.

Cosmogenic Neutrino Point Source and KM3-230213A

Qiyuan Zhang,^{1,2,*} Tian-Qi Huang,^{2,3,†} and Zhao Li^{1,2,§}
¹Department of Astronomy, School of Physics, Peking University, Beijing 100871, China
²Key Laboratory of Particle Astrophysics and Experimental Physics, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China
³CASTAR Cosmic Ray Research Center, Chengdu, Sichuan, China

ABSTRACT
Cosmogenic neutrinos (CNs) are produced by ultra-high-energy cosmic rays (UHECRs) interacting with cosmic background radiation. We investigate the properties of CN point sources, including the neutrino spectrum, and angular profile as functions of time, by assuming that UHECR sources are transient events, such as gamma-ray bursts. The properties depend on the intergalactic magnetic field (IGMF), but the angular profile is in general sub-degree, within which the CN flux can be searched for by the IceCube. The diffuse CN point sources could be detected by the IceCube. In the framework of diffuse astrophysical emission, we energy injection rate at $z \sim 4$ EeV, assuming a proton primary, with the rest by Auger. This disfavors the KM3NeT-only fit at all redshifts, while the fit remains based on redshift evolution models of known source populations. For cosmogenic origin, our results suggest that the luminosity obtained at redshift $z \leq 1$ from the fit is consistent with the luminosity of superluminal black holes in active galactic nuclei.

Cascaded Gamma-ray Emission Associated with the KM3NeT Ultra-High-Energy Event KM3-230213A

KE FANG,¹ FRANCIS HALZEN,¹ AND DAN HOOPER¹

¹Department of Physics, Wisconsin IceCube Particle Astrophysics Center, University of Wisconsin, Madison, WI 53706

(Date: March 5, 2025)

ABSTRACT

A neutrino-like event with an energy of ~ 220 PeV was recently detected by the KM3NeT/ARCA telescope. If this neutrino comes from an astrophysical source, or from the interaction of an ultra-high-energy cosmic ray in the intergalactic medium, the ultra-high-energy gamma rays that are co-produced with the neutrinos will scatter with the extragalactic background light, producing an electromagnetic cascade and resulting in emission at GeV-to-TeV energies. In this paper, we compute the gamma-ray flux from this neutrino source considering various source distances and strengths of the intergalactic magnetic field (IGMF). We find that the associated gamma-ray emission could be observed by existing imaging air Cherenkov telescopes and air shower gamma-ray observatories, unless the strength of the IGMF is $B \gtrsim 3 \times 10^{-13}$ G, or the ultra-high-energy gamma-rays are attenuated inside of the source.

Looking for the γ -Ray Cascade of the KM3-230213A Neutrino

Milena Craggović^{1,*} Carlos Blanco^{1,2,†} and Tim

¹Stockholm University and the Oskar Klein Centre for Cosmoparticle Physics, Alba Nova, 10033 Stockholm, Sweden
²Department of Physics, The Pennsylvania State University, University Park, PA 16802, USA
³Department of Physics, The Pennsylvania State University, University Park, PA 16802, USA
⁴Department of Physics, The Pennsylvania State University, University Park, PA 16802, USA
⁵Department of Physics, The Pennsylvania State University, University Park, PA 16802, USA

⁶Department of Physics, The Pennsylvania State University, University Park, PA 16802, USA

⁷Department of Physics, The Pennsylvania State University, University Park, PA 16802, USA

⁸Department of Physics, The Pennsylvania State University, University Park, PA 16802, USA

⁹Department of Physics, The Pennsylvania State University, University Park, PA 16802, USA

¹⁰Department of Physics, The Pennsylvania State University, University Park, PA 16802, USA

¹¹Department of Physics, The Pennsylvania State University, University Park, PA 16802, USA

¹²Department of Physics, The Pennsylvania State University, University Park, PA 16802, USA

¹³Department of Physics, The Pennsylvania State University, University Park, PA 16802, USA

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¹⁶Department of Physics, The Pennsylvania State University, University Park, PA 16802, USA

¹⁷Department of Physics, The Pennsylvania State University, University Park, PA 16802, USA

¹⁸Department of Physics, The Pennsylvania State University, University Park, PA 16802, USA

¹⁹Department of Physics, The Pennsylvania State University, University Park, PA 16802, USA

²⁰Department of Physics, The Pennsylvania State University, University Park, PA 16802, USA

²¹Department of Physics, The Pennsylvania State University, University Park, PA 16802, USA

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¹⁵⁸Department of Physics, The Pennsylvania State University, University Park, PA 16802, USA

¹⁵⁹Department of Physics, The Pennsylvania State University, University Park, PA



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).

