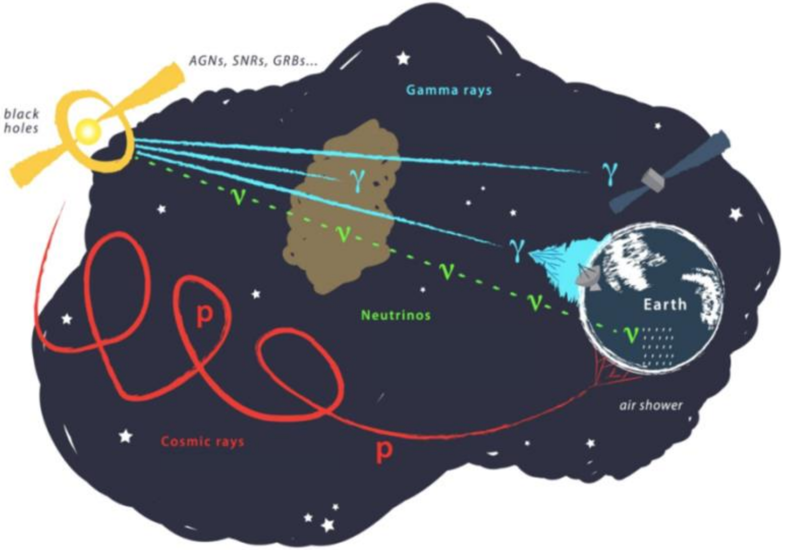
KM3NeT: Neutrino Telescopy in the Abyss

Christos Markou

Institute of Nuclear and Particle Physics, NCSR 'Demokritos', Athens

APCTP, 25/8/2025

Why neutrinos?



Photons are absorbed by interstellar matter

Charged particles (protons) are affected by magnetic fields and interact with CMB

Neutrinos are the ideal messengers from astrophysical sources

→ **Neutrino Astronomy!**

High-energy neutrino production via

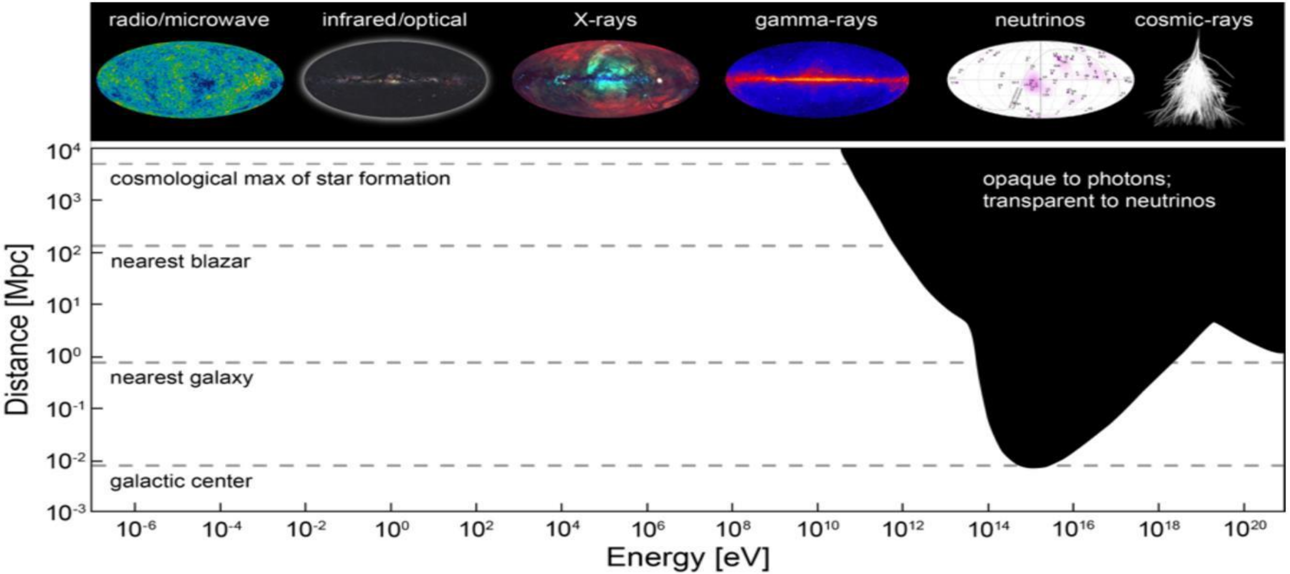
$$\begin{aligned} p + p/\gamma &\rightarrow X + \pi^0 \rightarrow \gamma\gamma \\ &\rightarrow X + \pi^\pm \rightarrow \mu^\pm + \overset{(-)}{\nu}_\mu \\ &\qquad\qquad \mu^\pm \rightarrow e^\pm + \overset{(-)}{\nu}_e + \overset{(-)}{\nu}_\mu \end{aligned}$$

Correlations between HE photons and neutrinos, ‘Smoking gun’ for hadronic processes

Neutrino Sources

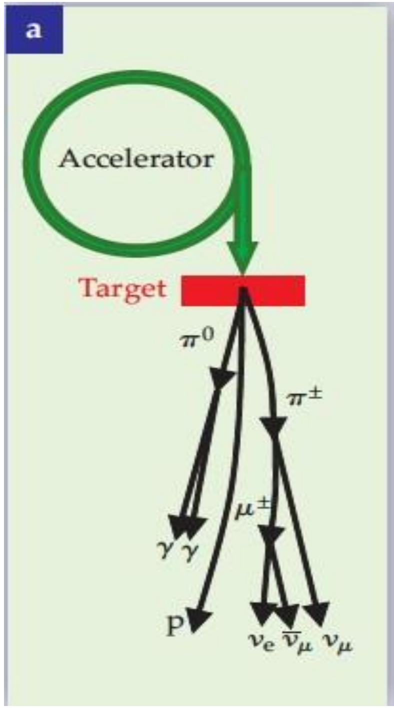
Galactic		Extra-galactic
Supernovae, SN relics, Dark Matter, Nebulae, …		AGNs, Blazars, Black Hole mergers, Quasars, …

Access to the high energy / distant universe

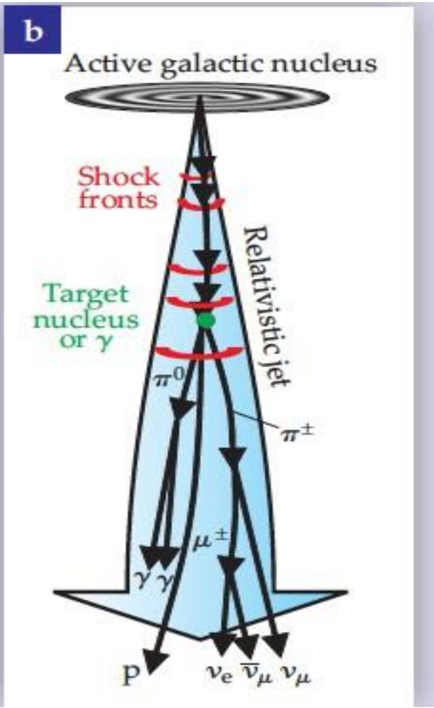


The Universe is opaque to EM radiation above 10-100 TeV, but not to neutrinos

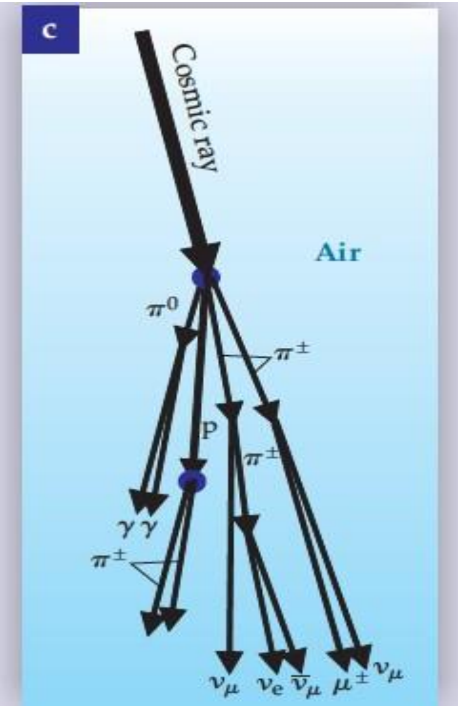
Neutrino Production mechanisms



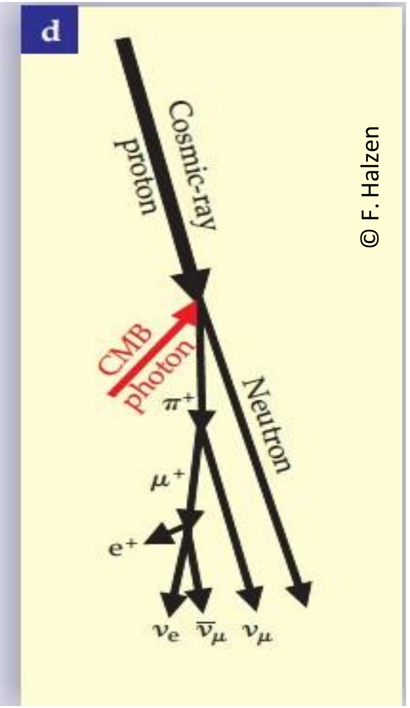
Neutrino beam



Cosmic neutrinos



Atmospheric neutrinos



Cosmogenic neutrinos

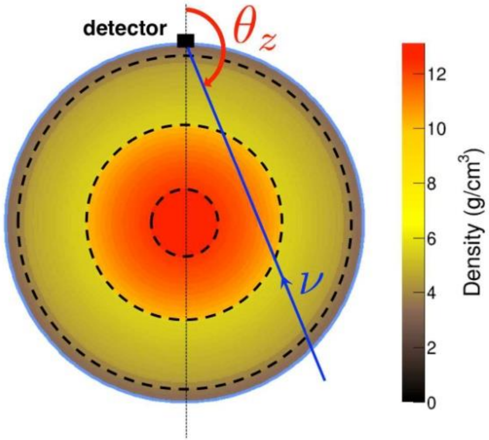
© F. Halzen

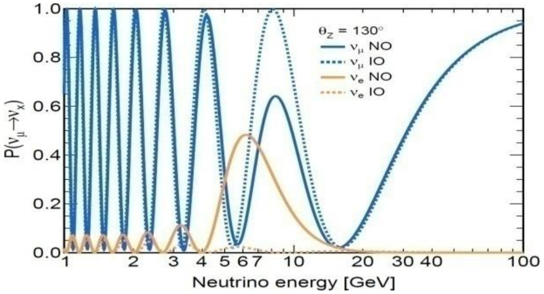
Neutrino physics

Atmospheric neutrinos are produced by the interaction of cosmic rays in the atmosphere

$p+N \rightarrow X+K^+,\pi^+ \rightarrow \ldots + \mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$

$p+N \rightarrow X+K^-, \pi^- \rightarrow \ldots + \mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$



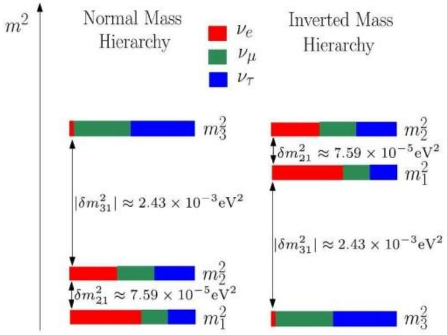


Exploit the variable path length and energy of the incoming neutrino through the Earth to study neutrino properties

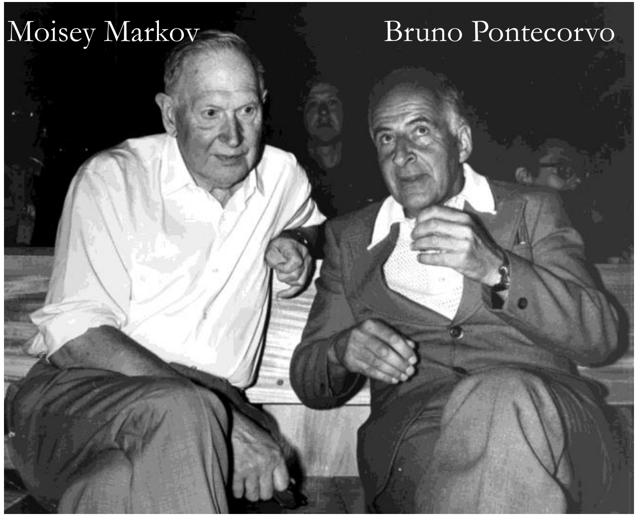
Matter effects sensitive to Δm^2_{31}

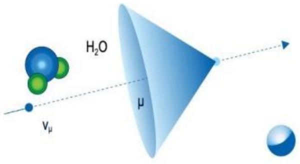
Normal vs Inverted Mass Ordering (excess of ν_e vs $\bar{\nu}_e$)

Also Sterile neutrinos,
Oscillations, ν_τ appearance,
Non Standard Interactions,…

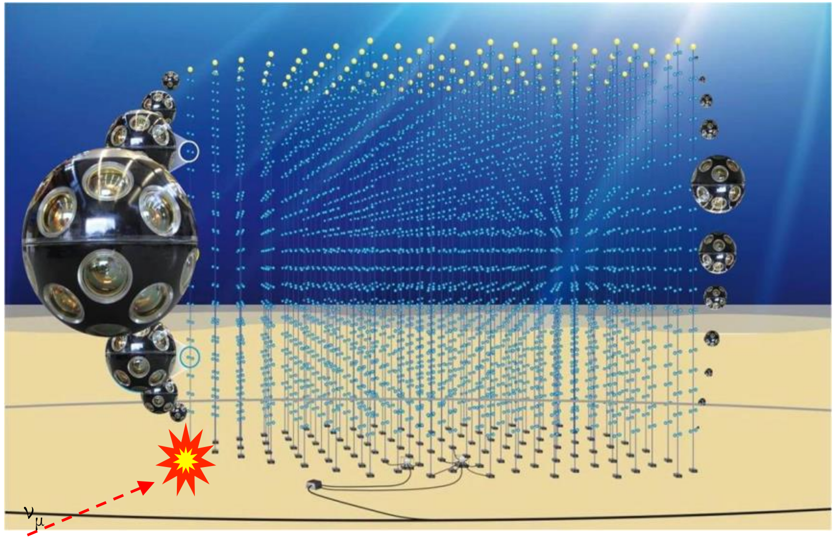


The Concept of Cherenkov Neutrino Telescopes





Cherenkov: v>c/n
Cos(angle)=1/n



1960 Rochester Conference

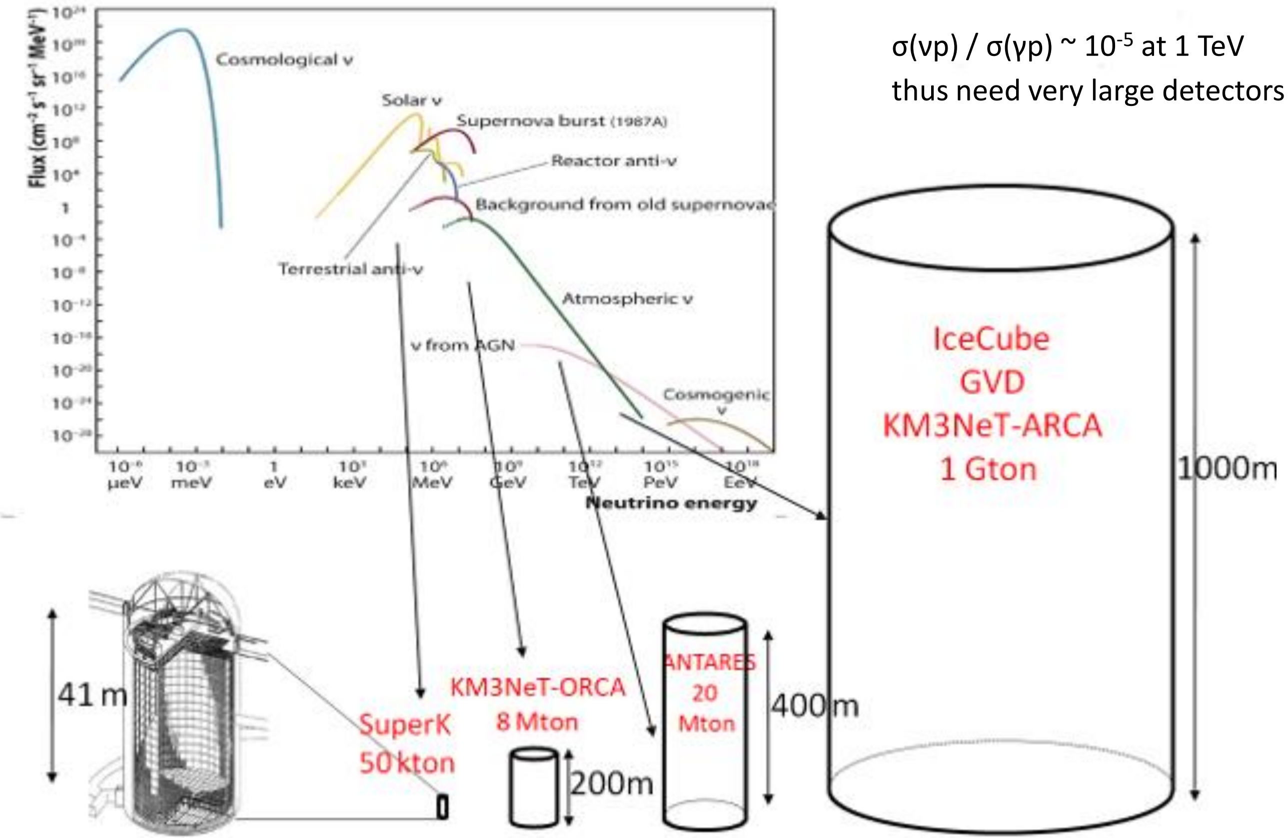
"… we propose to install detectors deep in a lake or in the sea and to determine the direction of charged particles with the help of Cherenkov radiation."

- Low interaction cross-section means **huge detection volumes**
- **Up-going** (through the Earth) ν events
- 3D lattice of photomultipliers collecting Cherenkov photons due to relativistic charged particles from ν interactions
- ν direction reconstructed using photon time & position

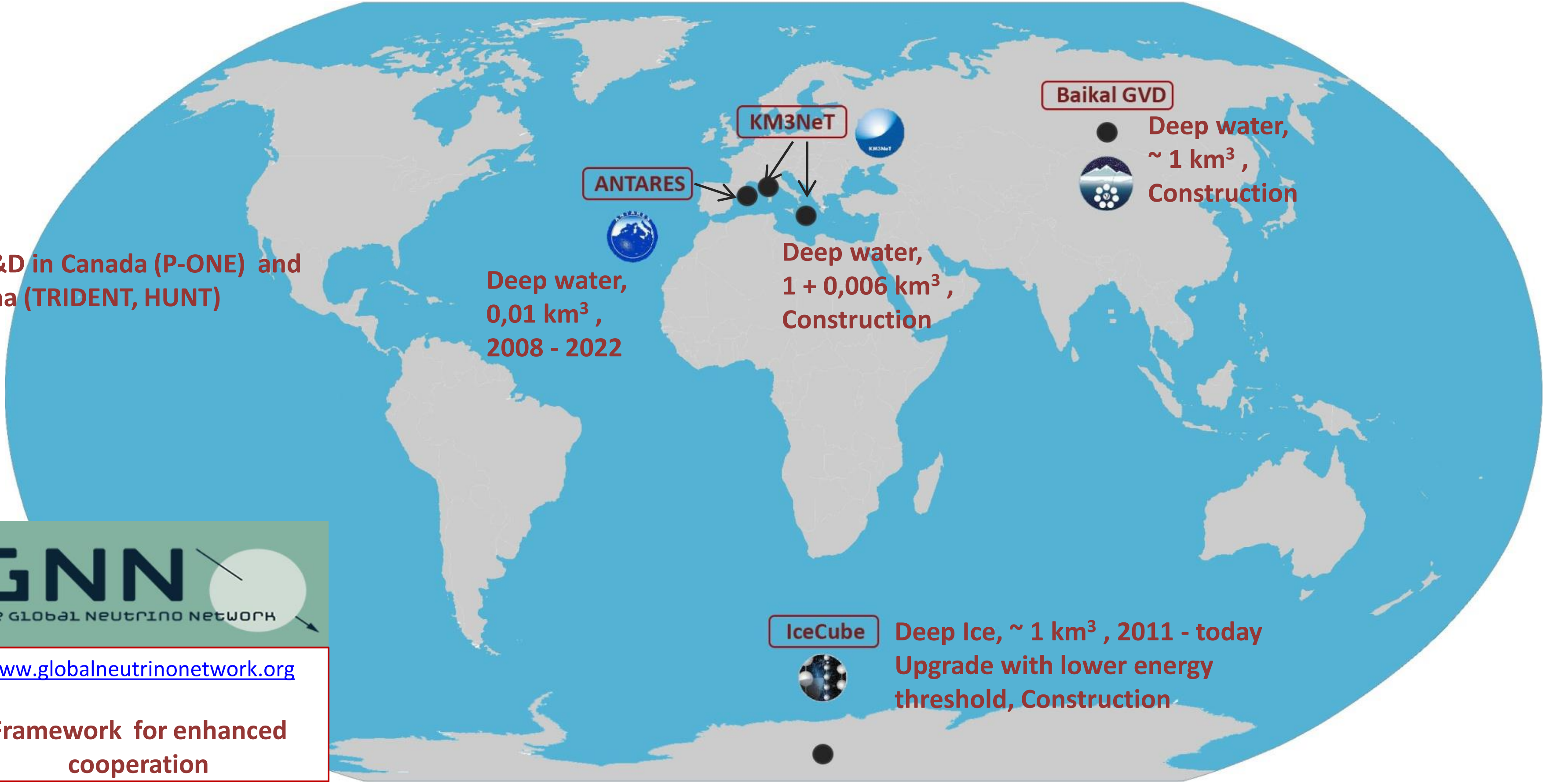
Neutrino fluxes and detector sizes

σ(νp) / σ(γp) ~ 10^{-5} at 1 TeV

thus need very large detectors



The Global Neutrino Network



Baikal GVD

Deep water,
~ 1 km^3 ,
Construction

KM3NeT

Deep water,
1 + 0,006 km^3 ,
Construction

ANTARES

Deep water,
0,01 km^3 ,
2008 - 2022

+ R&D in Canada (P-ONE) and China (TRIDENT, HUNT)

IceCube

Deep Ice, ~ 1 km^3 , 2011 - today
Upgrade with lower energy threshold, Construction

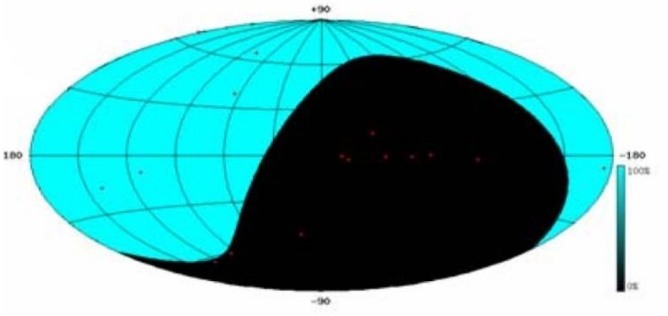
GNN
The Global Neutrino Network

www.globalneutrinonetwork.org

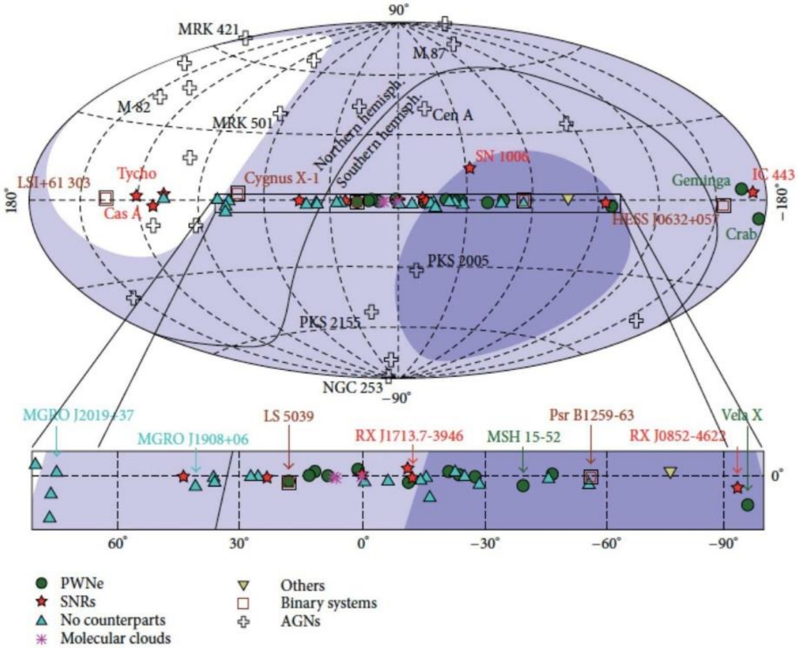
Framework for enhanced cooperation

The Mediterranean Viewpoint

- Visibility of the Galactic region ➔ ~ 70 % for the Galactic Centre
- Optical properties of water ➔ Mapping the **Southern sky** with unprecedented angular resolution

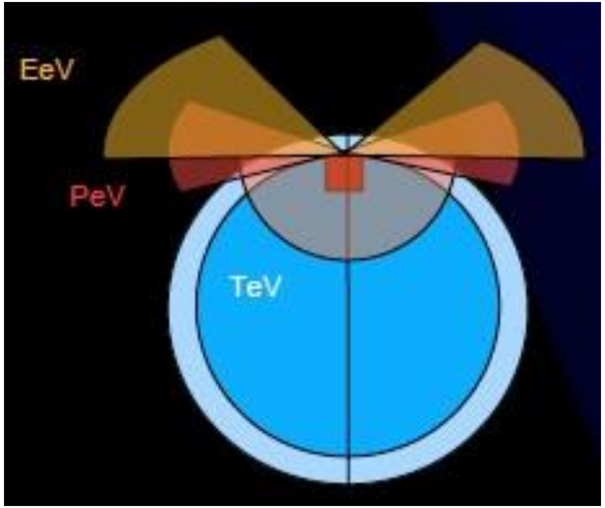


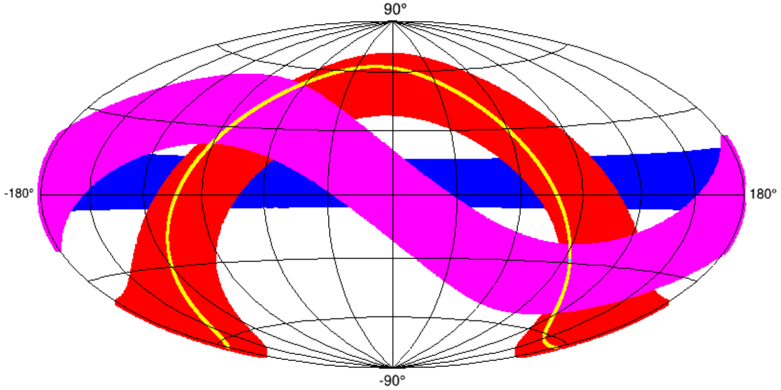
From the South Pole



Visibility for up-going neutrinos E<~100TeV

The Mediterranean Viewpoint



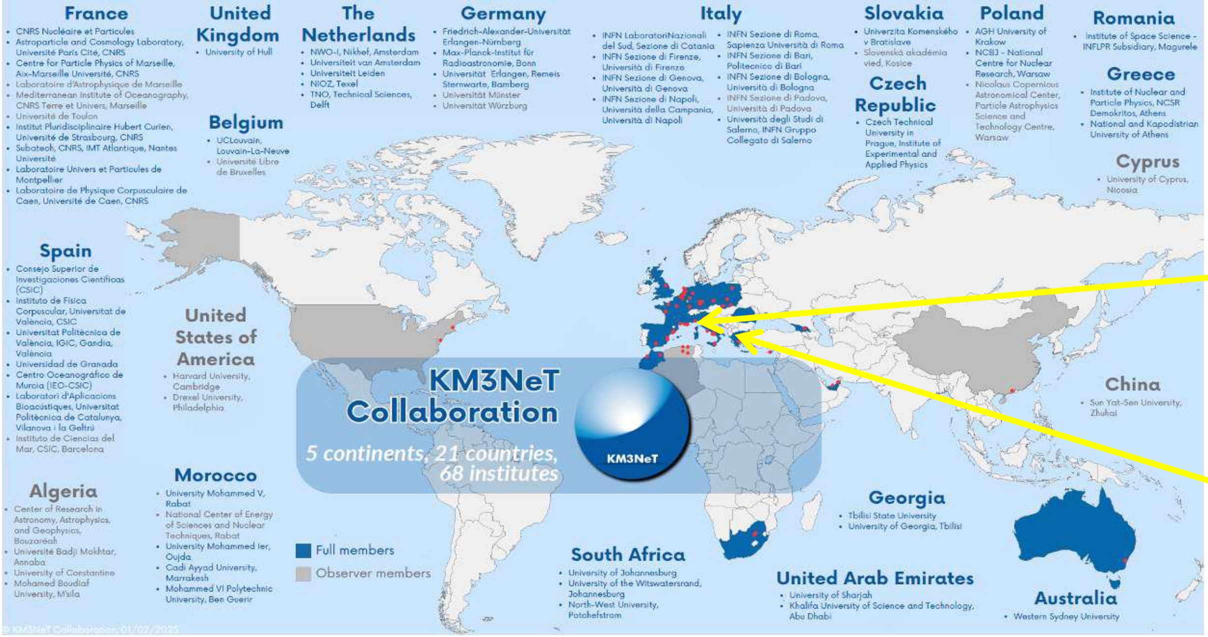


Instantaneous
FoV at 100 PeV

Lake Baikal
South Pole
Mediterranean

The KM3NeT Collaboration

Distributed infrastructure in the ESFRI Roadmap



France
- CNRS Nucléaire et Particules
- Astroparticle and Cosmology Laboratory, Université Paris Cité, CNRS
- Centre for Particle Physics of Marseille, Aix-Marseille Université, CNRS
- Laboratoire d'Astrophysique de Marseille
- Mediterranean Institute of Oceanography, CNRS Terre et Univers, Marseille
- Université de Toulon
- Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, CNRS
- Subatech, CNRS, IMT Atlantique, Nantes Université
- Laboratoire Univers et Particules de Montpellier
- Laboratoire de Physique Corpusculaire de Caen, Université de Caen, CNRS

United Kingdom
- University of Hull

Belgium
- UCLouvain, Louvain-La-Neuve
- Université Libre de Bruxelles

The Netherlands
- NWO-I, Nikhef, Amsterdam
- Universiteit van Amsterdam
- Universiteit Leiden
- NIOZ, Texel
- TNO, Technical Sciences, Delft

Germany
- Friedrich-Alexander-Universität Erlangen-Nürnberg
- Max-Planck-Institut für Radioastronomie, Bonn
- Universität Erlangen, Remeis Sternwarte, Bamberg
- Universität Münster
- Universität Würzburg

Italy
- INFN LaboratoriNazionali del Sud, Sezione di Catania
- INFN Sezione di Firenze, Università di Firenze
- INFN Sezione di Genova, Università di Genova
- INFN Sezione di Napoli, Università della Campania, Università di Napoli
- INFN Sezione di Roma, Sapienza Università di Roma
- INFN Sezione di Bari, Politecnico di Bari
- INFN Sezione di Bologna, Università di Bologna
- INFN Sezione di Padova, Università di Padova
- Università degli Studi di Salerno, INFN Gruppo Collegato di Salerno

Slovakia
- Univerzita Komenského v Bratislave
- Slovenská akadémia vied, Kosice

Czech Republic
- Czech Technical University in Prague, Institute of Experimental and Applied Physics

Poland
- AGH University of Krakow
- NCBJ - National Centre for Nuclear Research, Warsaw
- Nicolaus Copernicus Astronomical Center, Particle Astrophysics Science and Technology Centre, Warsaw

Romania
- Institute of Space Science - INFLPR Subsidiary, Magurele

Greece
- Institute of Nuclear and Particle Physics, NCSR Demokritos, Athens
- National and Kapodistrian University of Athens

Cyprus
- University of Cyprus, Nicosia

Spain
- Consejo Superior de Investigaciones Científicas (CSIC)
- Instituto de Física Corpuscular, Universitat de València, CSIC
- Universitat Politècnica de València, IGIC, Gandia, València
- Universidad de Granada
- Centro Oceanográfico de Murcia (IEO-CSIC)
- Laboratori d'Aplicacions Bioacústiques, Universitat Politècnica de Catalunya, Vilanova i la Geltrú
- Instituto de Ciencias del Mar, CSIC, Barcelona

United States of America
- Harvard University, Cambridge
- Drexel University, Philadelphia

China
- Sun Yat-Sen University, Zhuhai

Algeria
- Center of Research in Astronomy, Astrophysics, and Geophysics, Bouzaréah
- Université Badji Mokhtar, Annaba
- University of Constantine
- Mohamed Boudiaf University, M'sila

Morocco
- University Mohammed V, Rabat
- National Center of Energy of Sciences and Nuclear Techniques, Rabat
- University Mohammed Ier, Oujda
- Cadi Ayyad University, Marrakesh
- Mohammed VI Polytechnic University, Ben Guerir

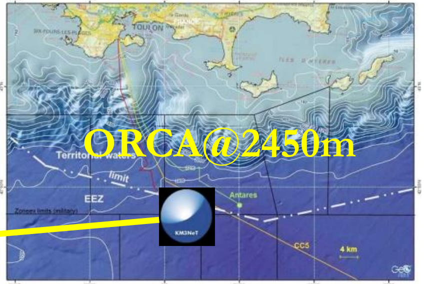
South Africa
- University of Johannesburg
- University of the Witswatersrand, Johannesburg
- North-West University, Potchefstrom

Georgia
- Tbilisi State University
- University of Georgia, Tbilisi

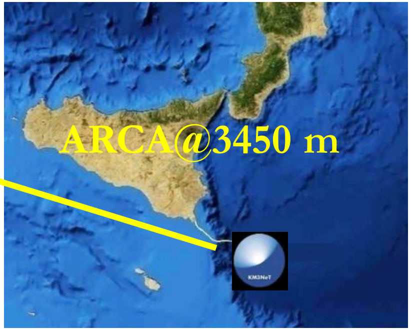
United Arab Emirates
- University of Sharjah
- Khalifa University of Science and Technology, Abu Dhabi

Australia
- Western Sydney University

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



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



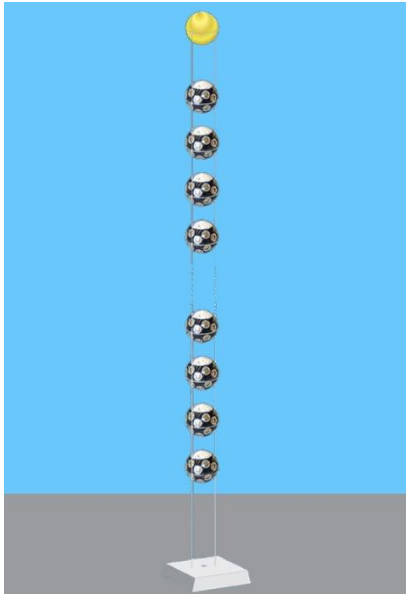
22 countries, 61 institutions, ~300 physicists

The KM3NeT Detectors

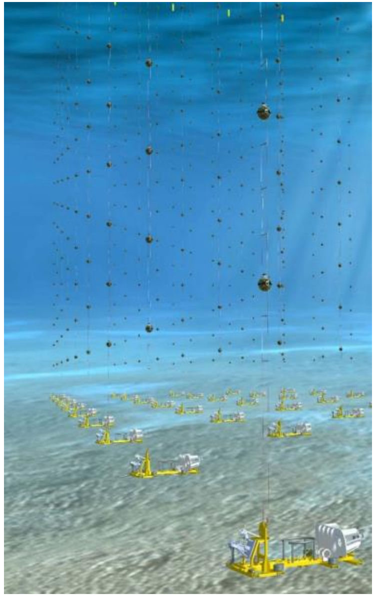
Common, modular design for both ARCA and ORCA

71 Unique Components

1 Digital Optical Module = 31 PMTs + electronics

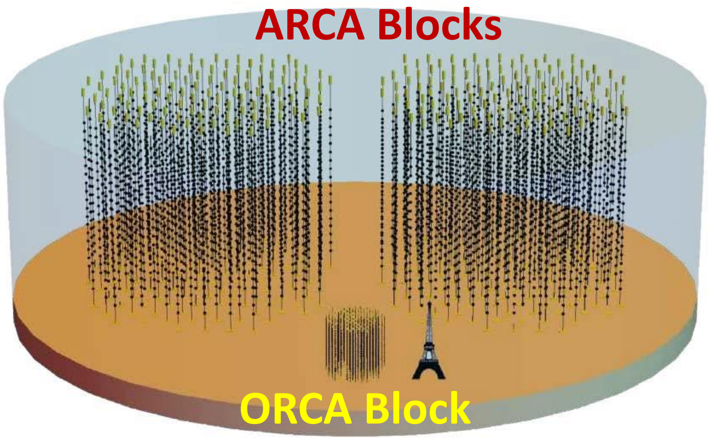


1 Detection Unit = 18 Digital Optical Modules

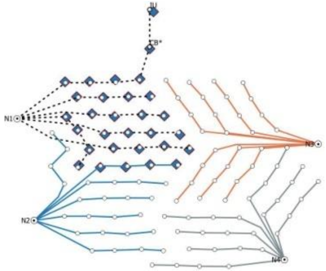


1 Building Block = 115 Detection Units

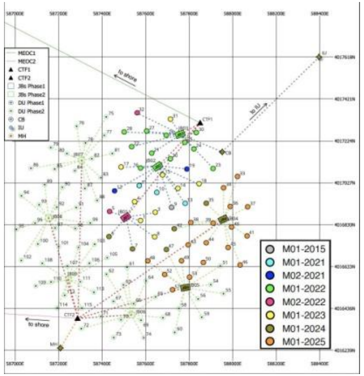
The KM3NeT Detectors



ORCA Footprint



ARCA Footprint



	ARCA	**ORCA**
Location	Sicily (IT)	Toulon (FR)
Depth	3450m	2450m
No. of DUs	2 x 115	115
DU horizontal spacing	90 m	20 m
DOM Vertical Spacing	36 m	9 m
DOMs/DU	18	18
PMTs/DOM	31	31
Instrumented water mass	1 Gton	7 Mton
DUs deployed	**51**	**28**

Detector construction


Amsterdam


Athens


Bologna


Erlangen

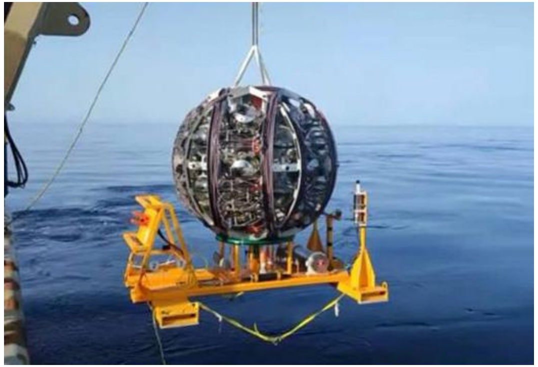

Catania


Caen


Marseille


Caserta

Deployment Strategy



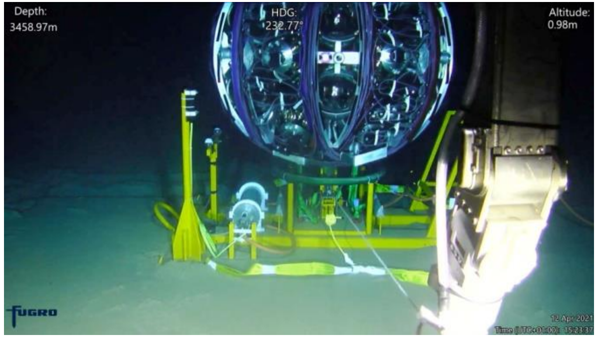
DUs are furled onto reusable launchers

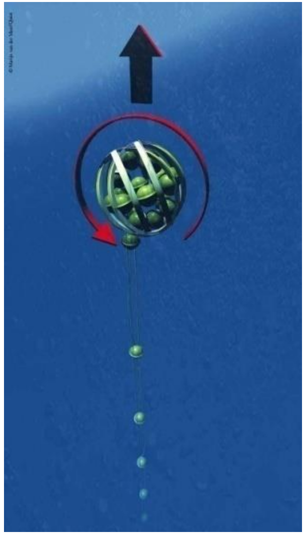
Upon lowered to the seabed via a ship crane, a ROV connects power and network cables

The launcher unfurls allowing the DU to achieve its final position

Typically, multiple DUs are installed in each sea campaign.

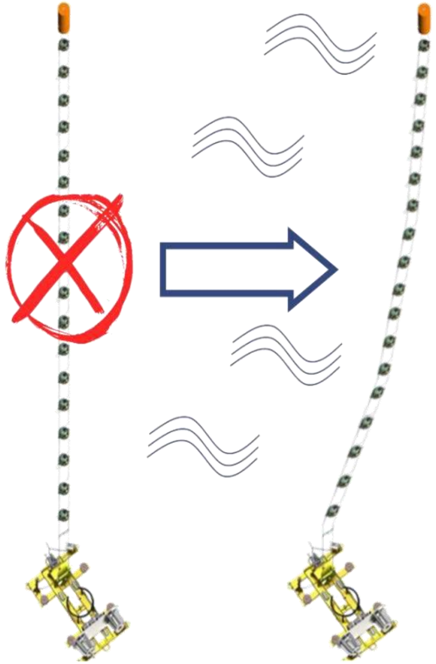
Video





Detector Calibration

- Timing calibration
    - LED pulsers (nanobeacon) for inter-DOM calibration (NIM.A 1040 (2022) 167132)
    - < 1ns precision for relative timing between DOMs
    - individual control for each DOM, each DU base and slow control for the junction boxes at the seabed



- Position calibration
    - Tilt and heading in each DOM via tiltmeter and compass
    - Acoustic positioning system
    - Precision better than 10 cm

- results in < 0.1° precision for neutrino direction at high energy (>100TeV)

Acoustic positioning

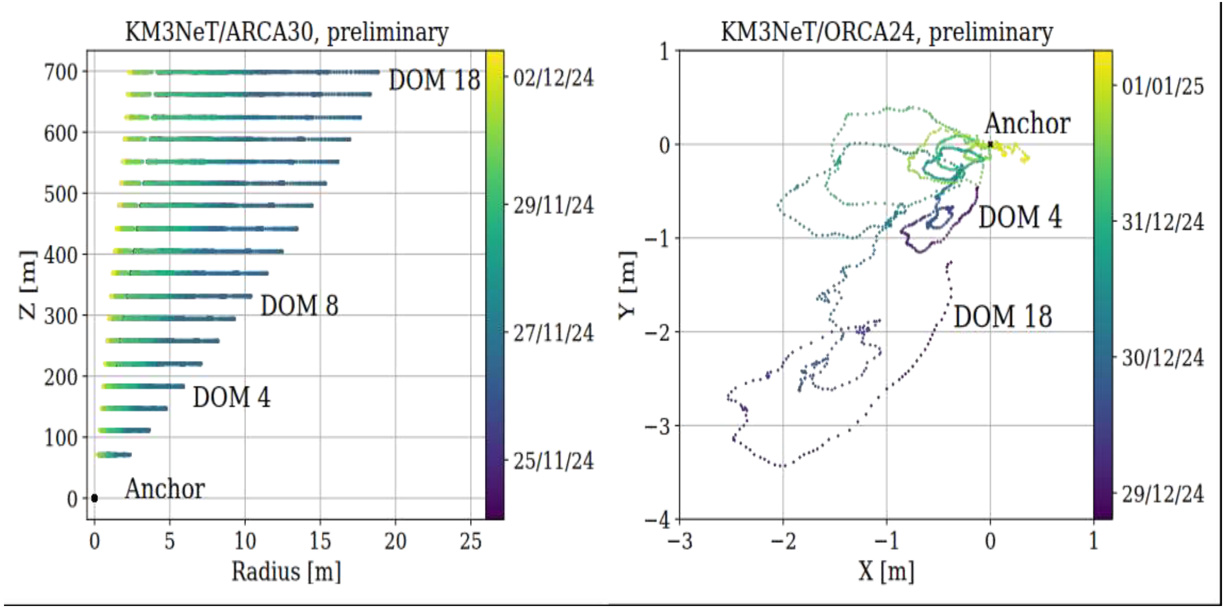
DUs sway and change their shape under the action of currents

Acoustic beacons in known positions emit signals with characteristic waveforms

Piezo sensors on DOMs and base modules detect the signals

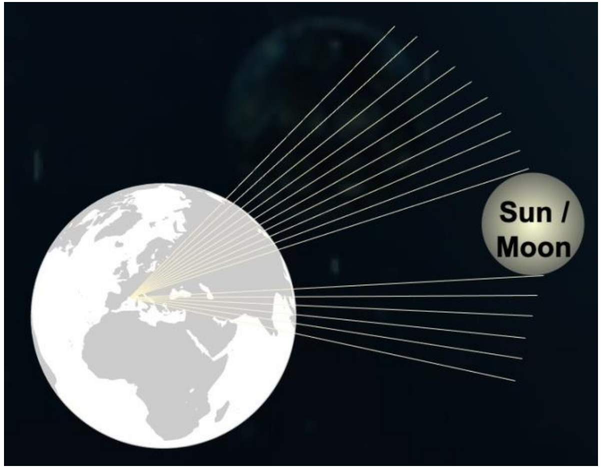
The map of the times of arrival of the acoustic signals is inverted to work out the current geometry of the telescope

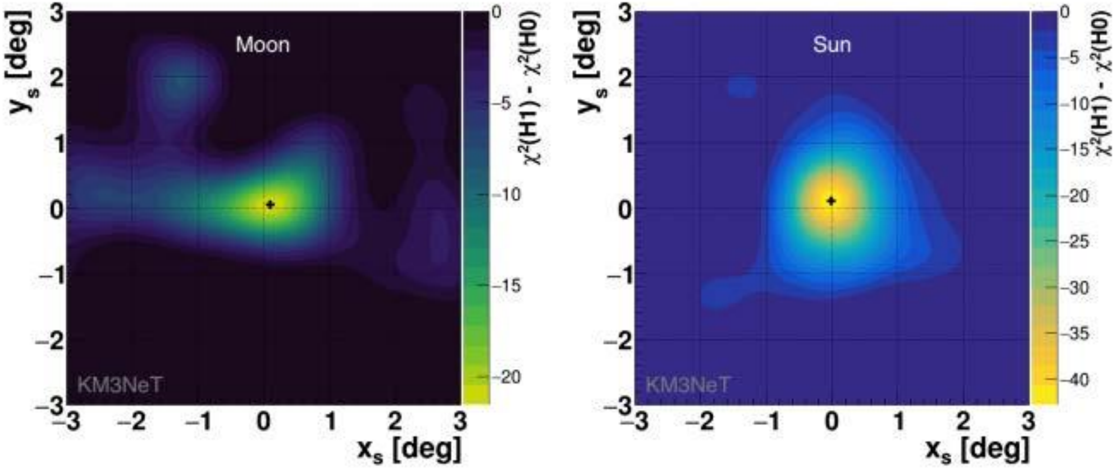
We need pointing accuracy ~ 0.1° or better!



Pointing Accuracy

Exploit the deficit of the *atmospheric muon flux* in the direction of the Moon & Sun induced by the *absorption of cosmic rays (G.W. Clark, 1957)*





ORCA6 (500 days) Eur. Phys. J. C 83 (2023) 4, 344	**Sun**	**Moon**
Statistical Significance	6.2 σ	4.2 σ
Resolution	0.65° ± 0.13°	0.49° ± 0.15°

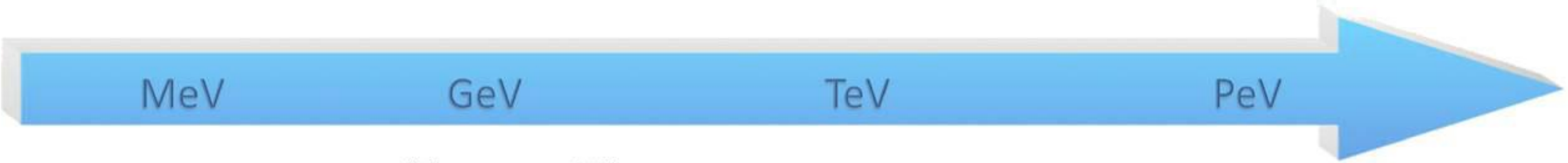
Physics Program with ORCA and ARCA

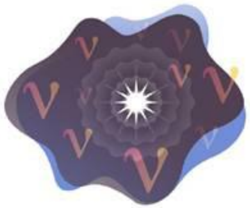
Supenovae
Solar Flares

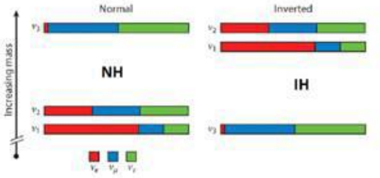
ν oscillations
ν mass ordering

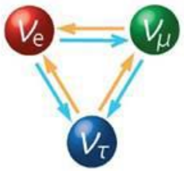
Dark matter searches
Exotics searches

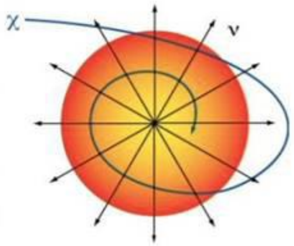
Cosmic neutrinos
Multi-messenger Astronomy

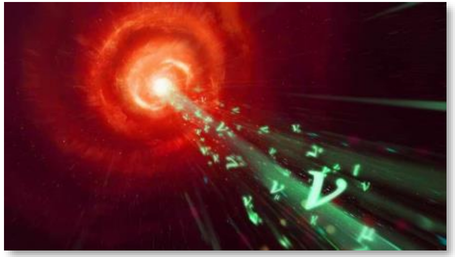




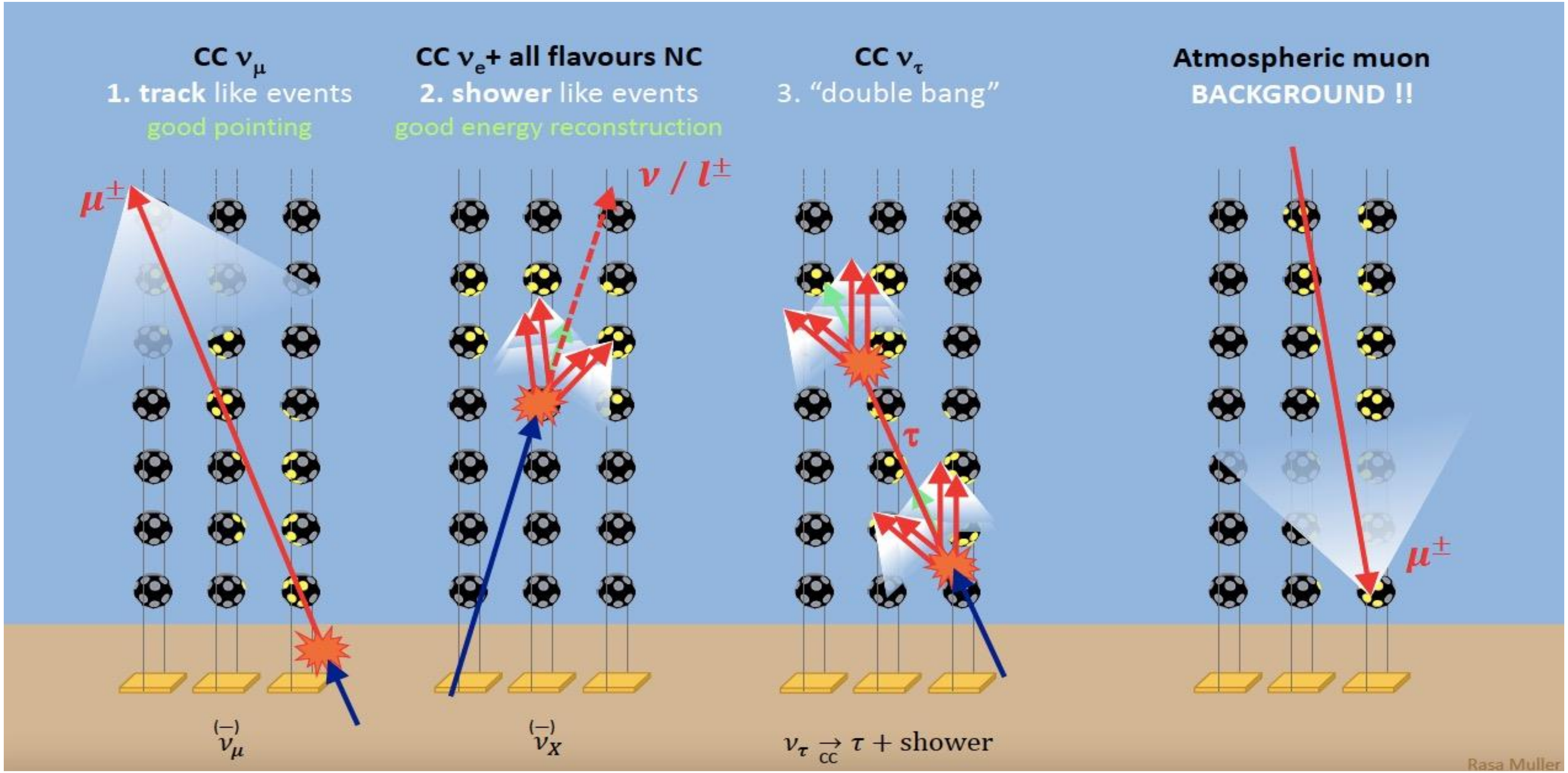








Event Topologies

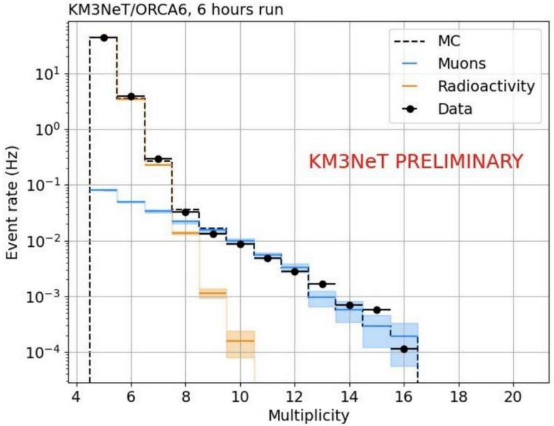


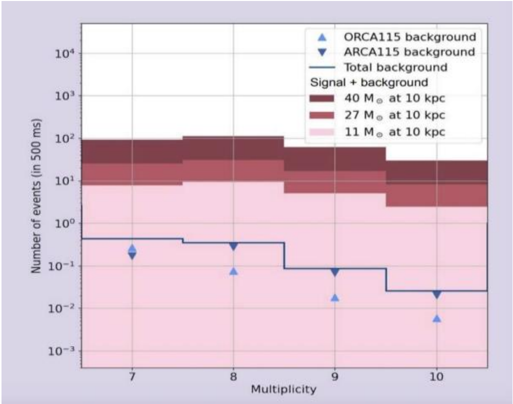
Tracks @Eᵥ>100 TeV Ang. res. below 0.1° - Energy res. ~ factor 2

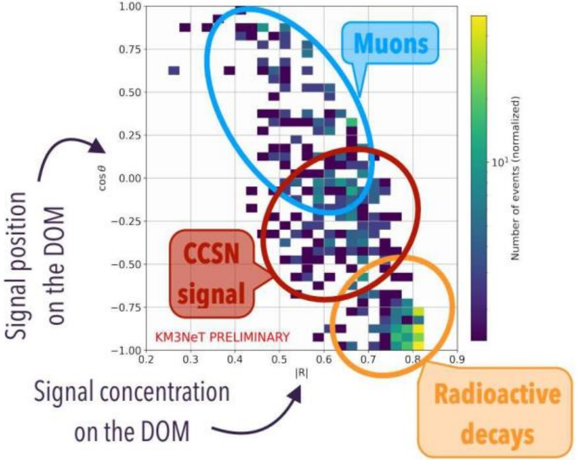
Shower @Eᵥ>100 TeV Ang. res. below 2° - Energy res. ~6%

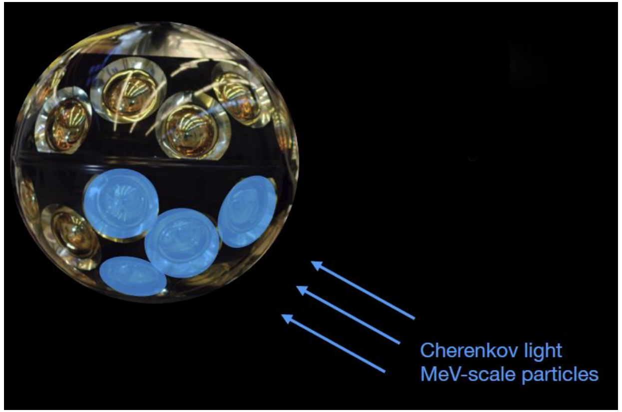
Physics Performance: Supernovae

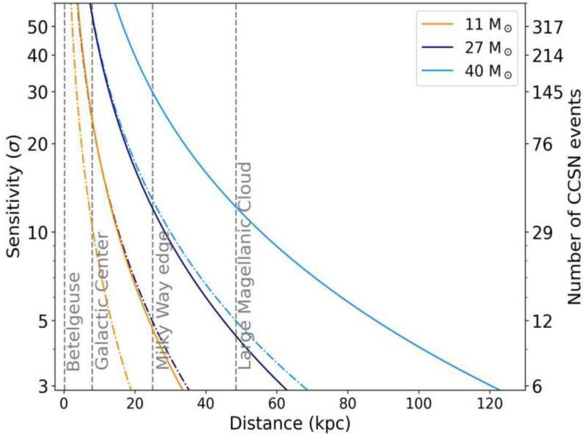
- Neutrinos with E<100 MeV expected at several stages of core collapse
- Low-energy neutrino detection is based on the coincidences in single DOMs thanks to the multi-PMT DOM configuration
- Background from ^{40}K decays, atmospheric muons and muons from ν.



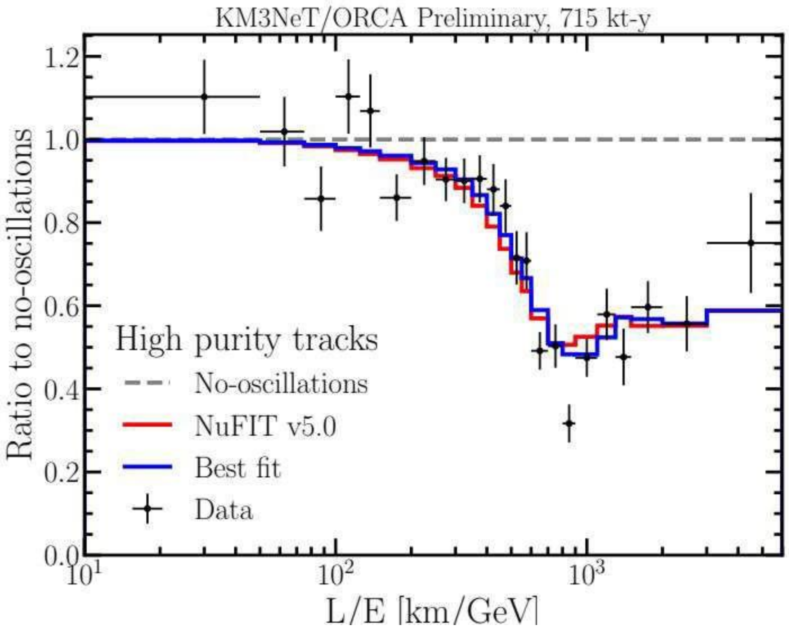








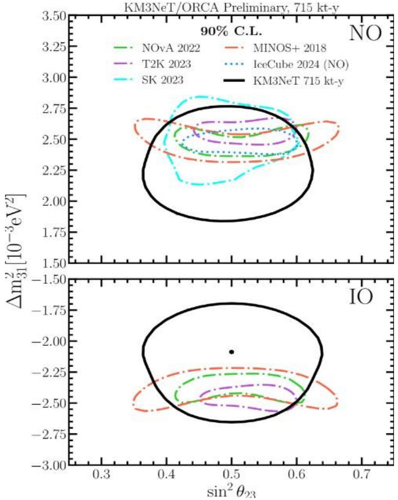
Physics Performance: Oscillation results with ORCA6 - 11



$$\Delta m^2_{31} = \begin{cases} -2.09^{+0.17}_{-0.21} \times 10^{-3}\text{eV}^2, & \text{IO} \\ [2.10, 2.37] \times 10^{-3}\text{eV}^2, & \text{NO} \end{cases}$$

$$\sin^2 \theta_{23} = 0.50 \pm 0.07$$

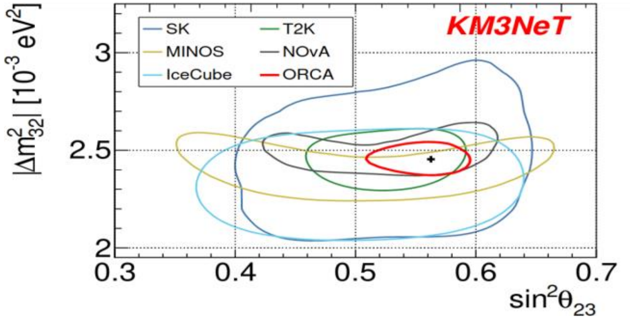
$$2\log(\mathcal{L}_{IO}/\mathcal{L}_{NO}) = 0.61$$



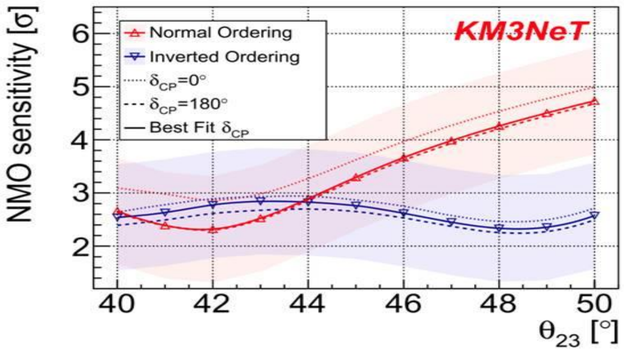
Slight preference for IO,
but not significant

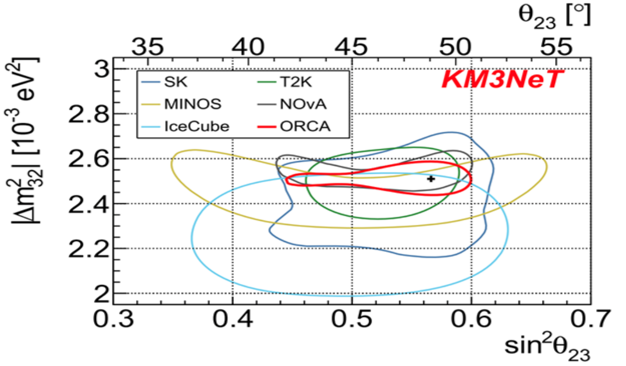
Physics Performance: Oscillation prospects

3 years of ORCA 115



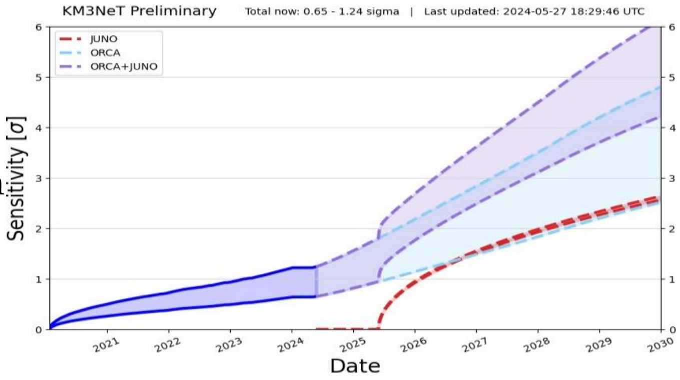
Normal Ordering





Inverted Ordering

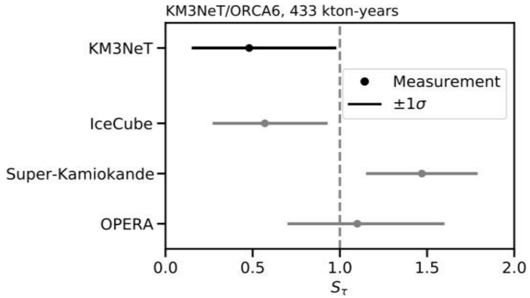
> 4σ NMO determination in reach within this decade when combined with JUNO



Physics performance: Testing new physics models with ORCA6

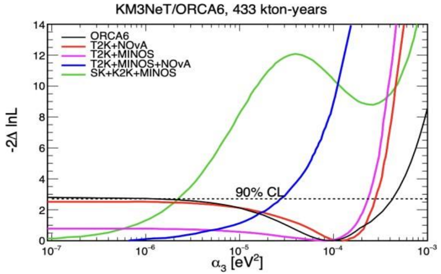
ν_τ appearance

arXiv:2502.01443



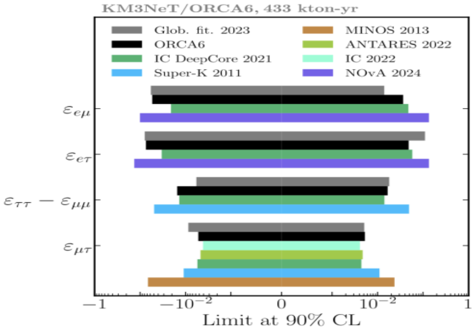
Neutrino decay

arXiv:2501.11336



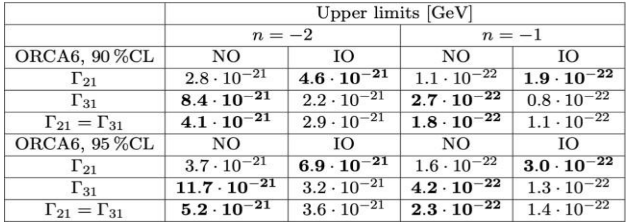
Non-standard interactions

arXiv:2411.19078



Quantum decoherence

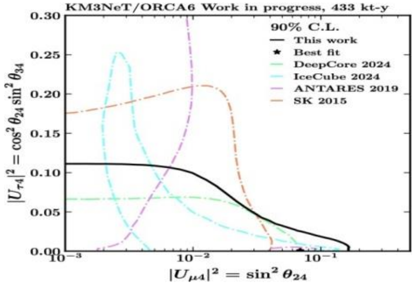
arXiv:2410.01388



	Upper limits [GeV]			
	$n=-2$		$n=-1$	
ORCA6, 90 %CL	NO	IO	NO	IO
Γ_{21}	$2.8\cdot10^{-21}$	$\mathbf{4.6\cdot10^{-21}}$	$1.1\cdot10^{-22}$	$\mathbf{1.9\cdot10^{-22}}$
Γ_{31}	$\mathbf{8.4\cdot10^{-21}}$	$2.2\cdot10^{-21}$	$\mathbf{2.7\cdot10^{-22}}$	$0.8\cdot10^{-22}$
$\Gamma_{21}=\Gamma_{31}$	$\mathbf{4.1\cdot10^{-21}}$	$2.9\cdot10^{-21}$	$\mathbf{1.8\cdot10^{-22}}$	$1.1\cdot10^{-22}$
ORCA6, 95 %CL	NO	IO	NO	IO
Γ_{21}	$3.7\cdot10^{-21}$	$\mathbf{6.9\cdot10^{-21}}$	$1.6\cdot10^{-22}$	$\mathbf{3.0\cdot10^{-22}}$
Γ_{31}	$\mathbf{11.7\cdot10^{-21}}$	$3.2\cdot10^{-21}$	$\mathbf{4.2\cdot10^{-22}}$	$1.3\cdot10^{-22}$
$\Gamma_{21}=\Gamma_{31}$	$\mathbf{5.2\cdot10^{-21}}$	$3.6\cdot10^{-21}$	$\mathbf{2.3\cdot10^{-22}}$	$1.4\cdot10^{-22}$

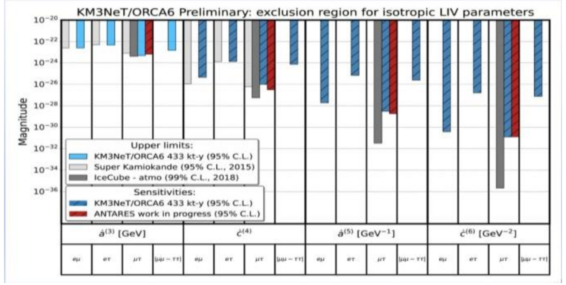
Sterile neutrinos

10.22323/1.476.0155



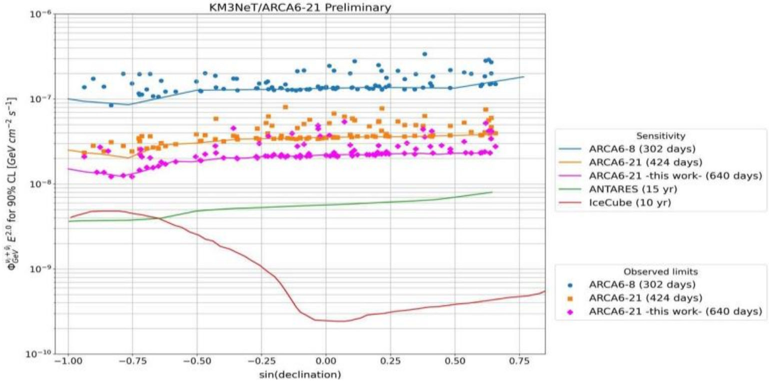
Lorentz Invariance Violation

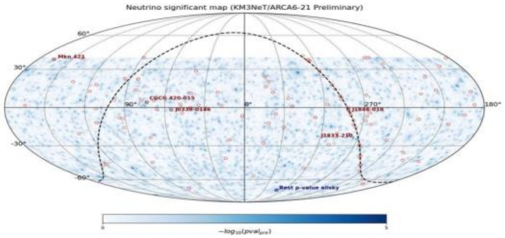
ICRC 2023

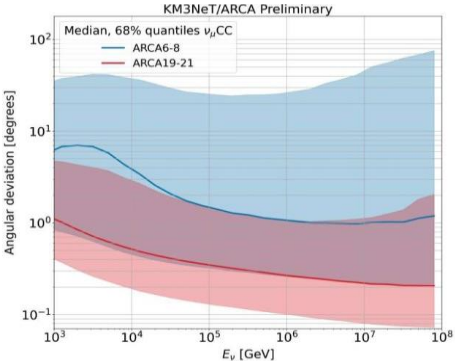


Physics performance: Point sources

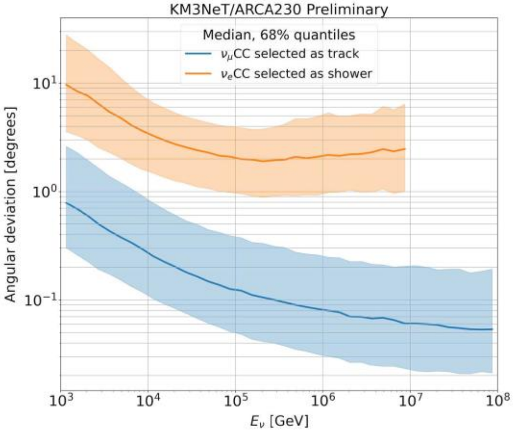
Pointing capability improving with increasing telescope size
No point sources observed yet (101 candidate sources)
Sensitivity quickly improving





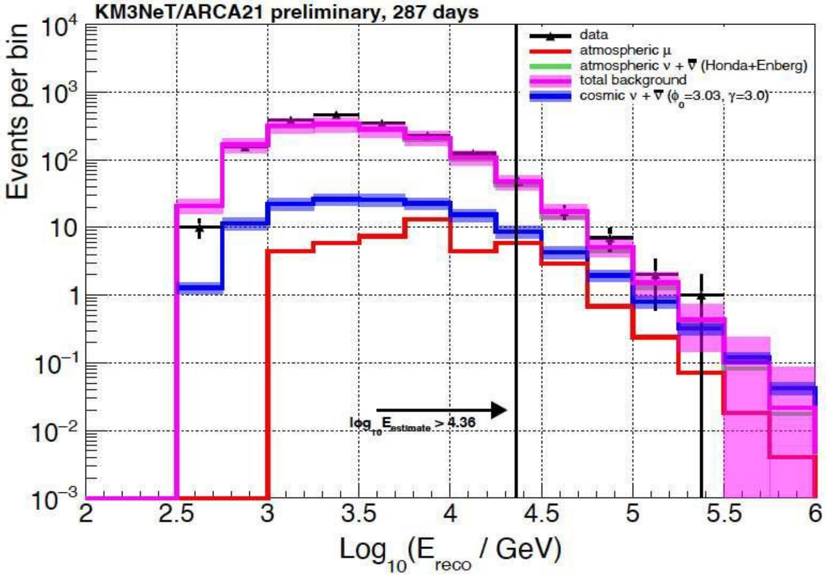


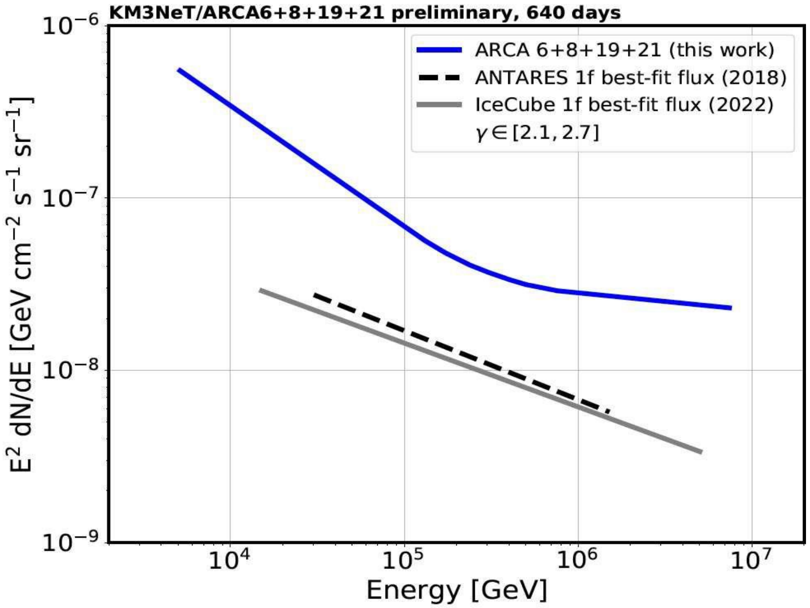
Pointing accuracy expectation with the full ARCA Detector



Physics performance: Diffuse flux

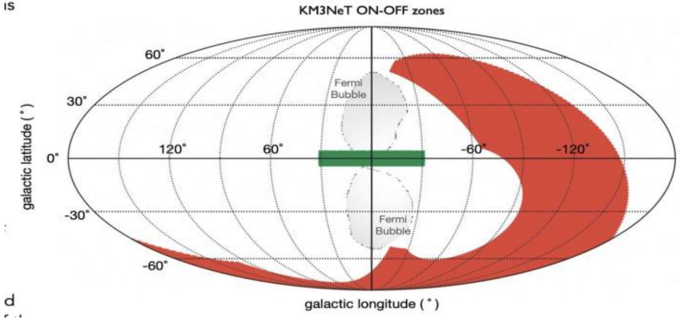
All-sky diffuse flux detection

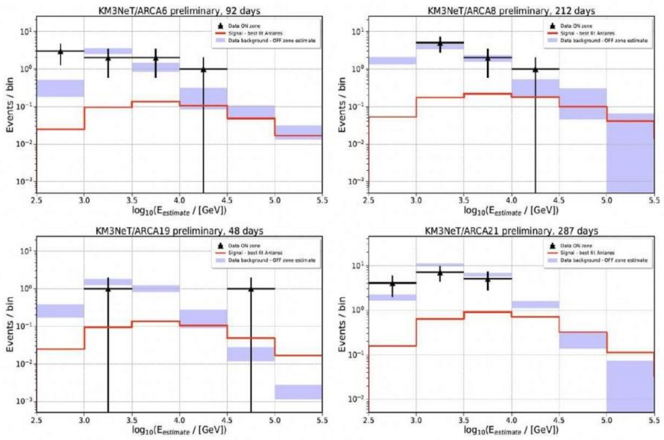




No observation yet, sensitivity improving

Physics performance: Galactic Ridge



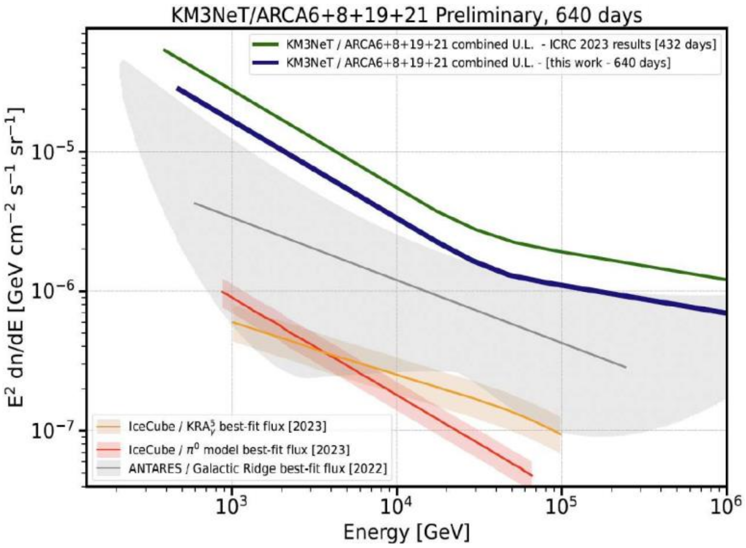


Multiple sources of high-energy CR (Cosmic Rays) in the plane of the Milky Way

High-energy neutrinos should be produced via interaction of CR with the interstellar medium

$$p+N \rightarrow X+K^{+},\pi^{+} \rightarrow \ldots + \mu \rightarrow e^{+} + \nu_{\mu} + \nu_{e}$$

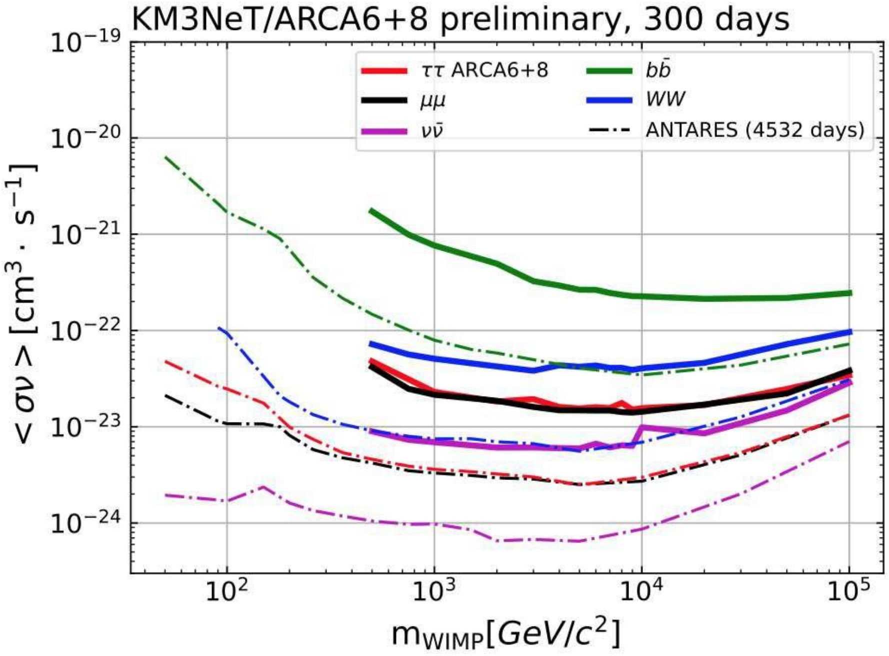
$$p+N \rightarrow X+K^{-},\pi^{-} \rightarrow \ldots + \mu^{-} \rightarrow e^{-} + \nu_{\mu} + \nu_{e}$$

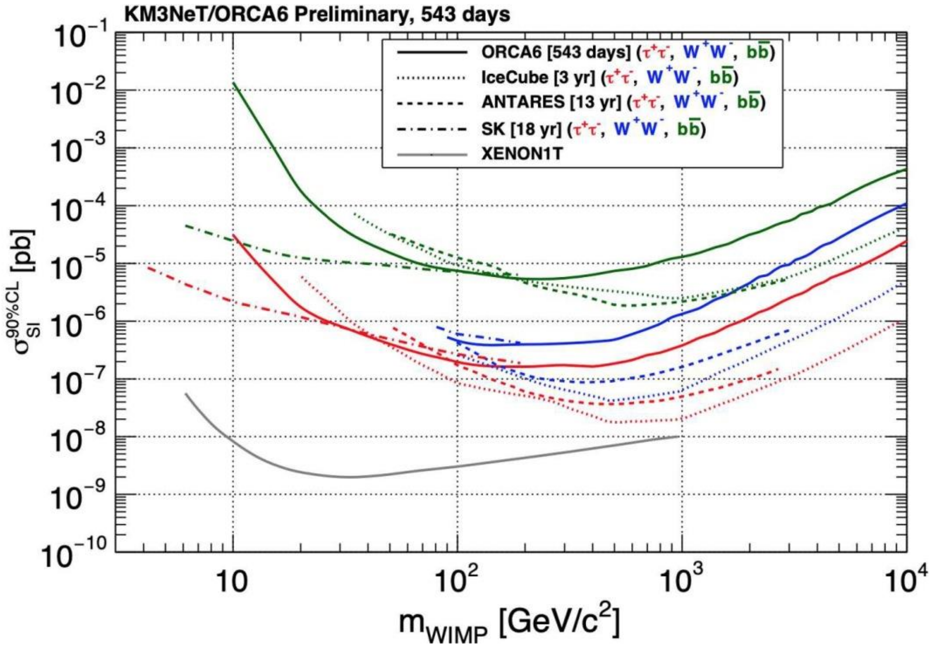


Physics performance: Dark Matter

Sensitivity to signals from WIMP-WIMP annihilation in the Galactic centre

Sensitivity to signals from WIMP-WIMP annihilation in the Sun





Nature 638 (2025) 8050, 376-382

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
[redacted]
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], 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.

Open Data: https://zenodo.org/records/14860165

Event display 1, 2, 3

Companion papers

The ultra-high-energy event KM3-230213A within the global neutrino landscape
KM3NeT Coll., arXiv:2502.08173

On the Potential Galactic Origin of the Ultra-High-Energy Event KM3-230213A
KM3NeT Coll., arXiv:2502.08387

Characterizing candidate blazar counterparts of the ultra-high-energy event KM3-230213A
KM3NeT Coll., arXiv:2502.08484

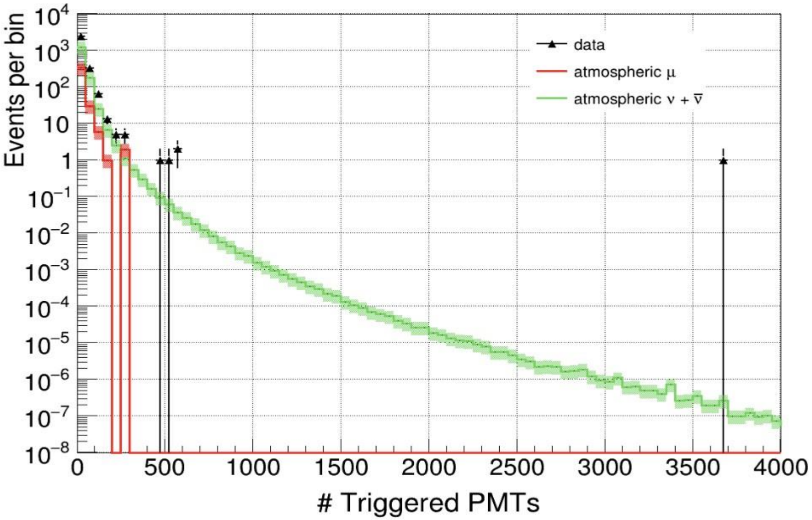
On the potential cosmogenic origin of the ultra-high-energy event KM3-230213A
KM3NeT Coll., arXiv:2502.08508

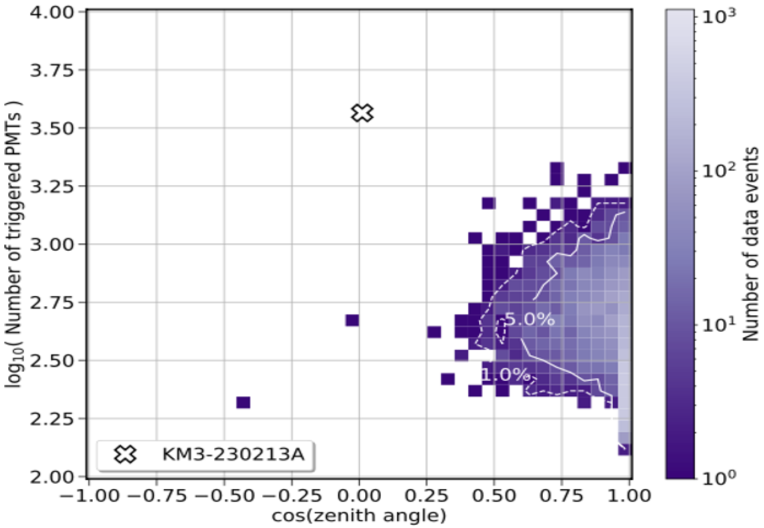
KM3NeT constraint on lorentz-violating superluminal neutrino velocity
KM3NeT Coll., arXiv:2502.12070

+ more in the pipe-line…

KM3-230213A: An exceptionally high energy event

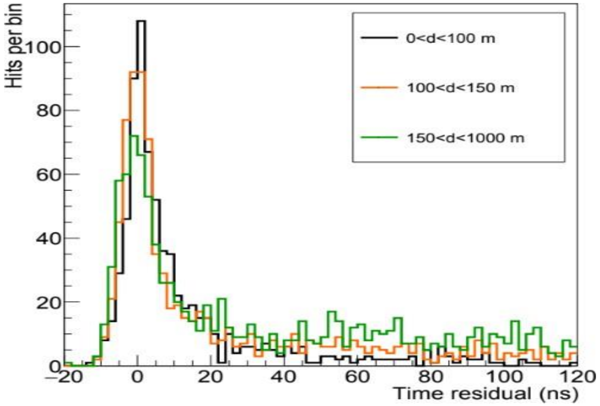
~28,000 photons, 3,672 PMTs (35% of the ARCA21 detector)

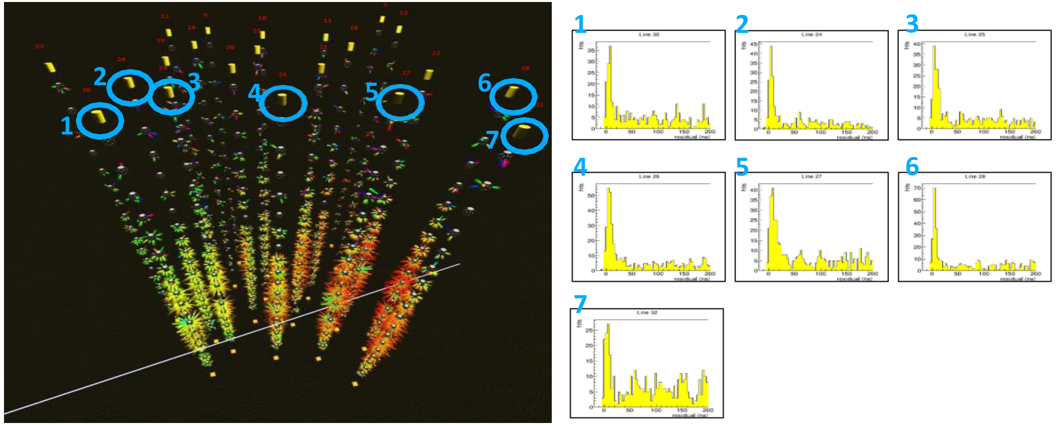




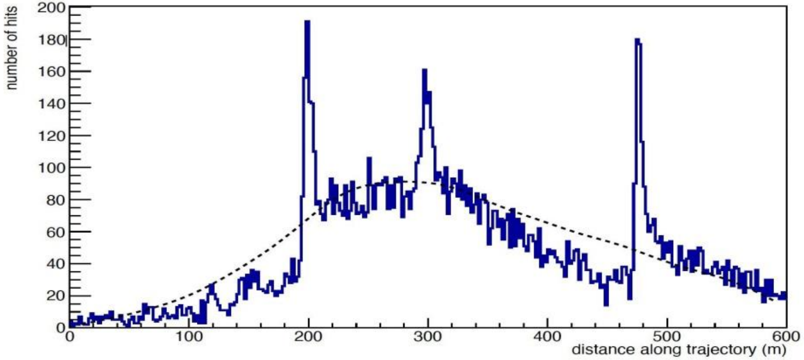
- Expected atmospheric muon contamination @ 100 PeV: << 10^{-10} event/year within 2σ of reconstructed direction
- Expected rate of atmospheric neutrinos >100 PeV: << (1-5) x 10^{-5} event/year

KM3-230213A: Very well reconstructed muon

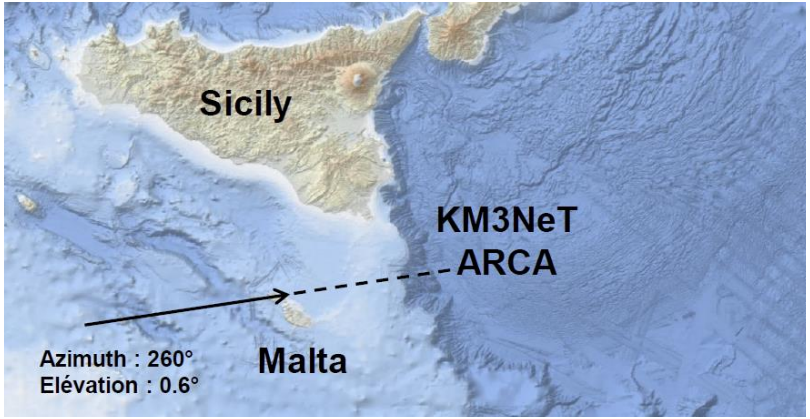


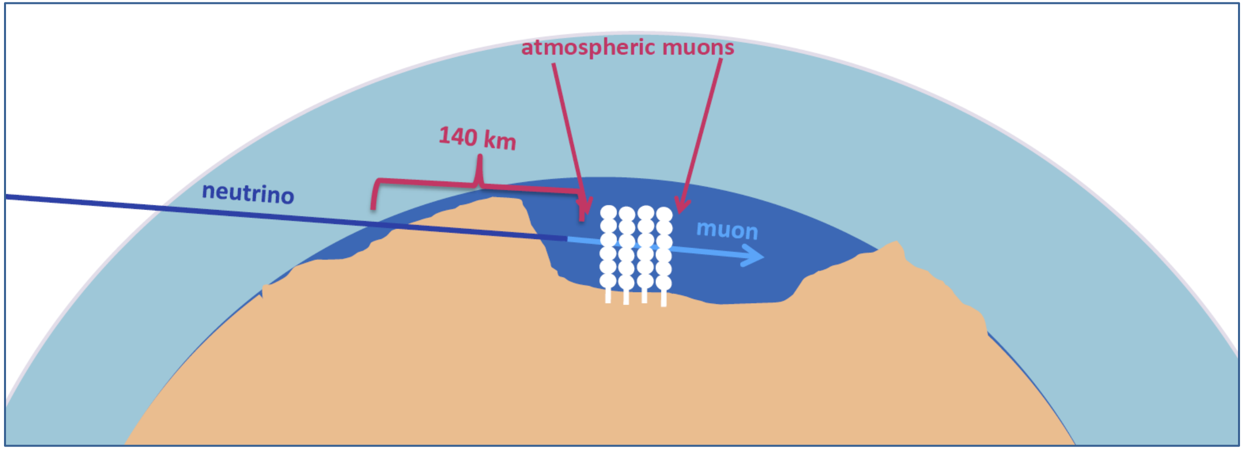


- Light profile consistent with at least 3 large energy depositions along the muon track
- Characteristic of stochastic losses from very high energy muons

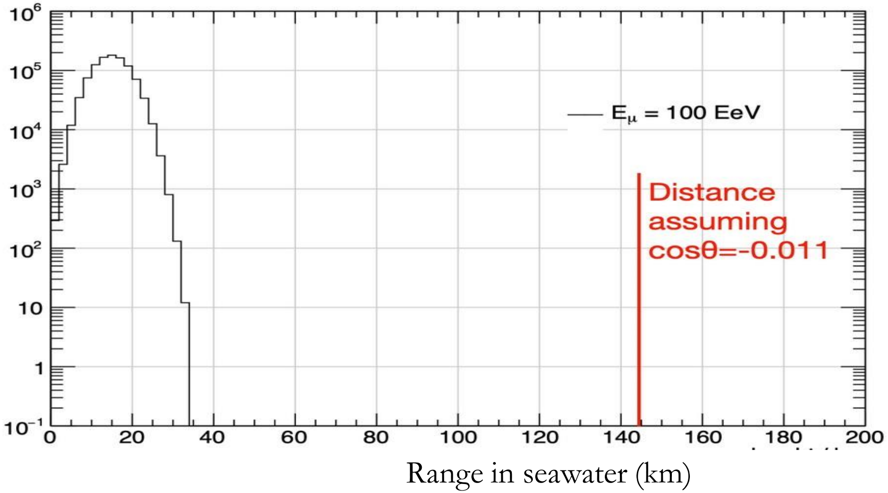


KM3-230213A: A horizontal muon

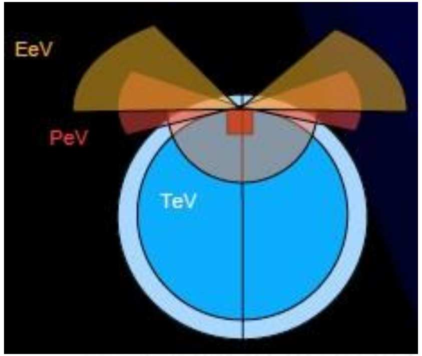


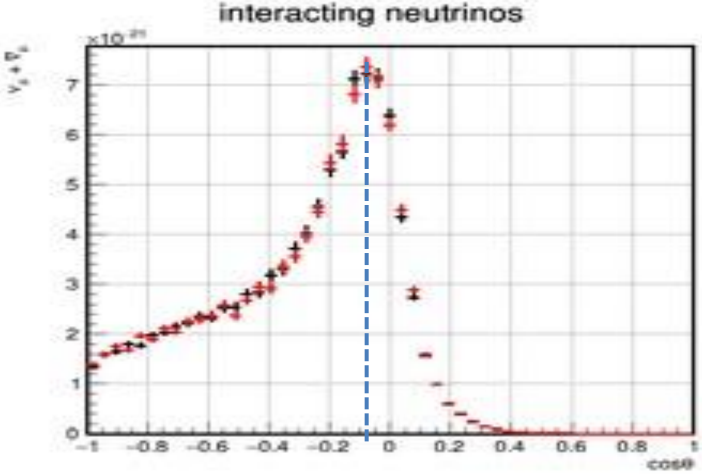


KM3-230213A: Not an atmospheric muon

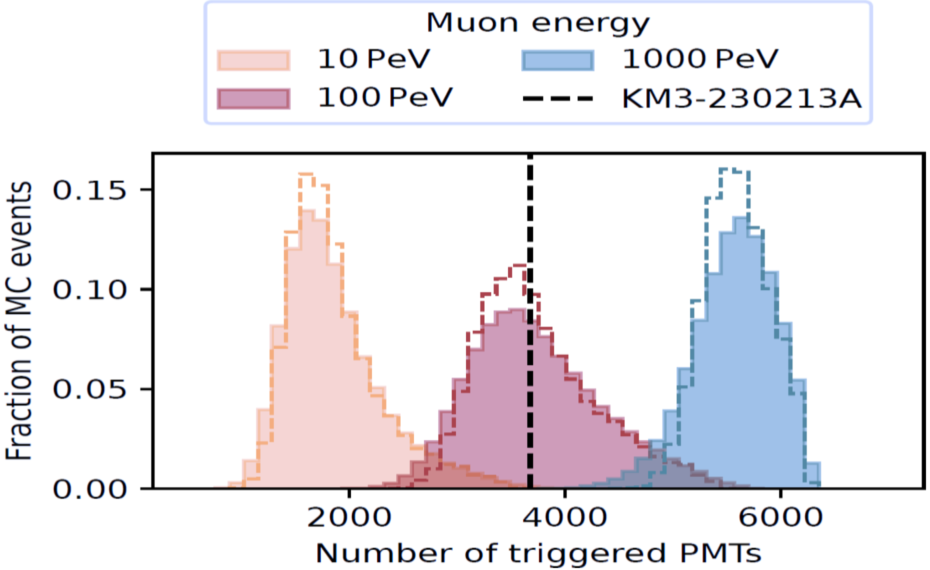


In reality, w.e. distance much larger due to Continental shelf





KM3-230213A: Energy measurement



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

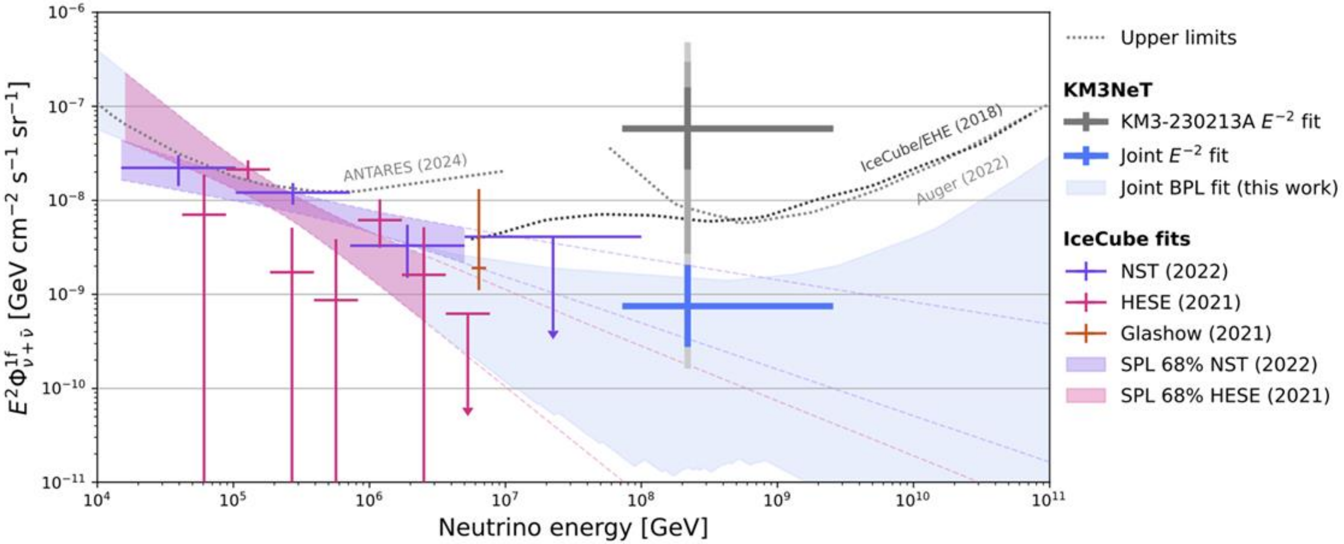
$$E_\mu = 120^{+110}_{-60}\ \mathrm{PeV}$$

- **The neutrino Energy is higher:**

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

(assuming an E^{-2} source spectrum)

KM3-230213A: Global fit



Accounting for IceCube & Auger non-observations:

$$E^2\phi_\nu = 5.7 \times 10^{-10}\,\mathrm{GeV cm^{-2} s^{-1} sr^{-1}}$$

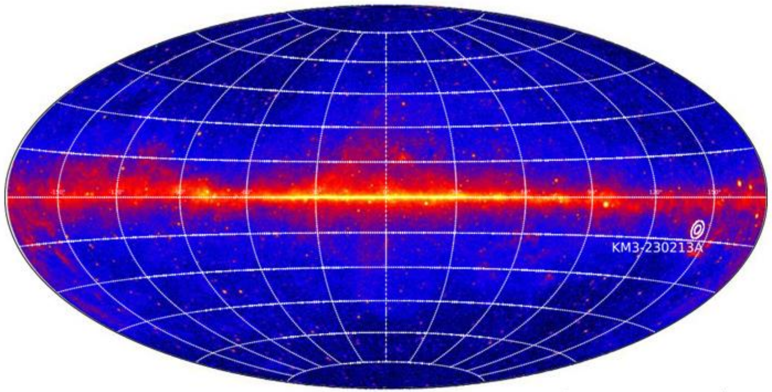
Tension at 2.5 sigma level

KM3NeT Coll., arXiv:2502.08173

KM3-230213A: Galactic?

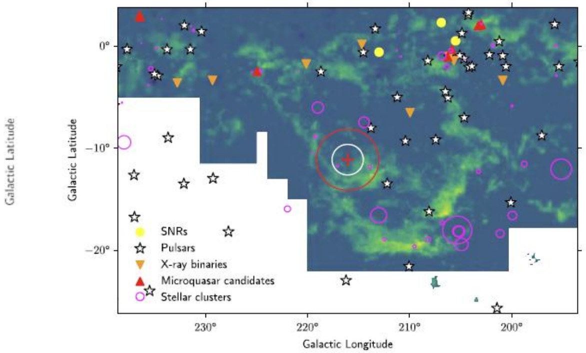
Out of galactic plane

Near Orion molecular cloud region



Galactic coords

Fermi satellite (gamma rays)



No compelling source
-> unlikely to be galactic

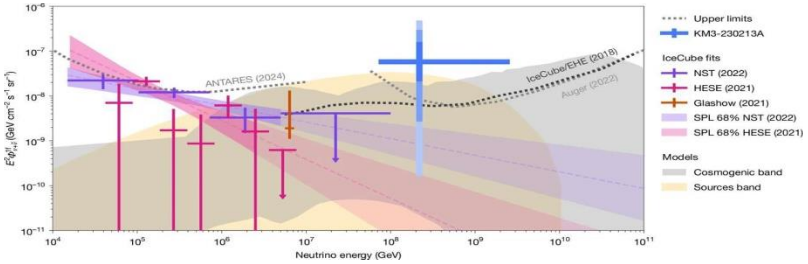
KM3-230213A: Origin

Four main hypotheses for KM3-230213A

1 diffuse flux

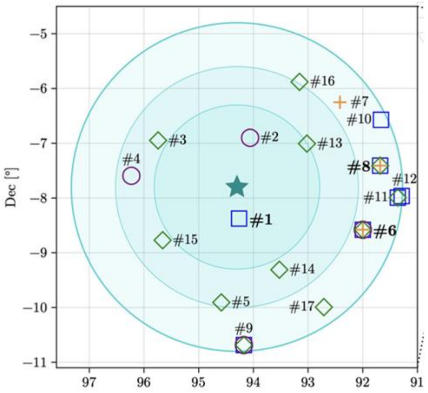
$$E_\nu = 220^{+570}_{-110}\, PeV$$

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

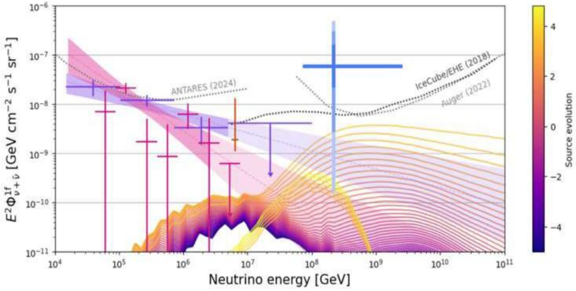


2 Galactic – **unlikely**

3 Blazar flare – **no strong evidence + requires reduction of systematic pointing errors**



4 Cosmogenic – **possible if subdominant proton acceleration is included**



+ many others!

Summary

The KM3NeT research infrastructure is being built in the Mediterranean Sea and includes two neutrino telescope: KM3NeT/ORCA (Toulon, France) and KM3NeT/ARCA (Capo Passero, Italy)

ORCA and ARCA combine a rich neutrino physics and astrophysics scientific scope, from MeV to PeV energies

- Excellent Angular resolution allows for precision multi-flavor astronomy
- Location allows for the study of galactic and extra-galactic sources
- ARCA/ORCA cover full energy range

KM3Net already has

- Competitive measurement of neutrino oscillation parameters
- First point source limits, diffuse limits
- Neutrino mass ordering towards end of the decade

Exceptional >100 PeV neutrino event detected

- Sky localization can be improved retroactively - stay tuned

Probably the most important message!

Ἐὰν μὴ ἔλπηται ἀνέλπιστον, οὐκ ἐξευρήσει.

If you do not hope for the unexpected, you will not find it!

HERACLITUS

Healthy greek snacks

Organic coffee-cocoa

-chocolate-