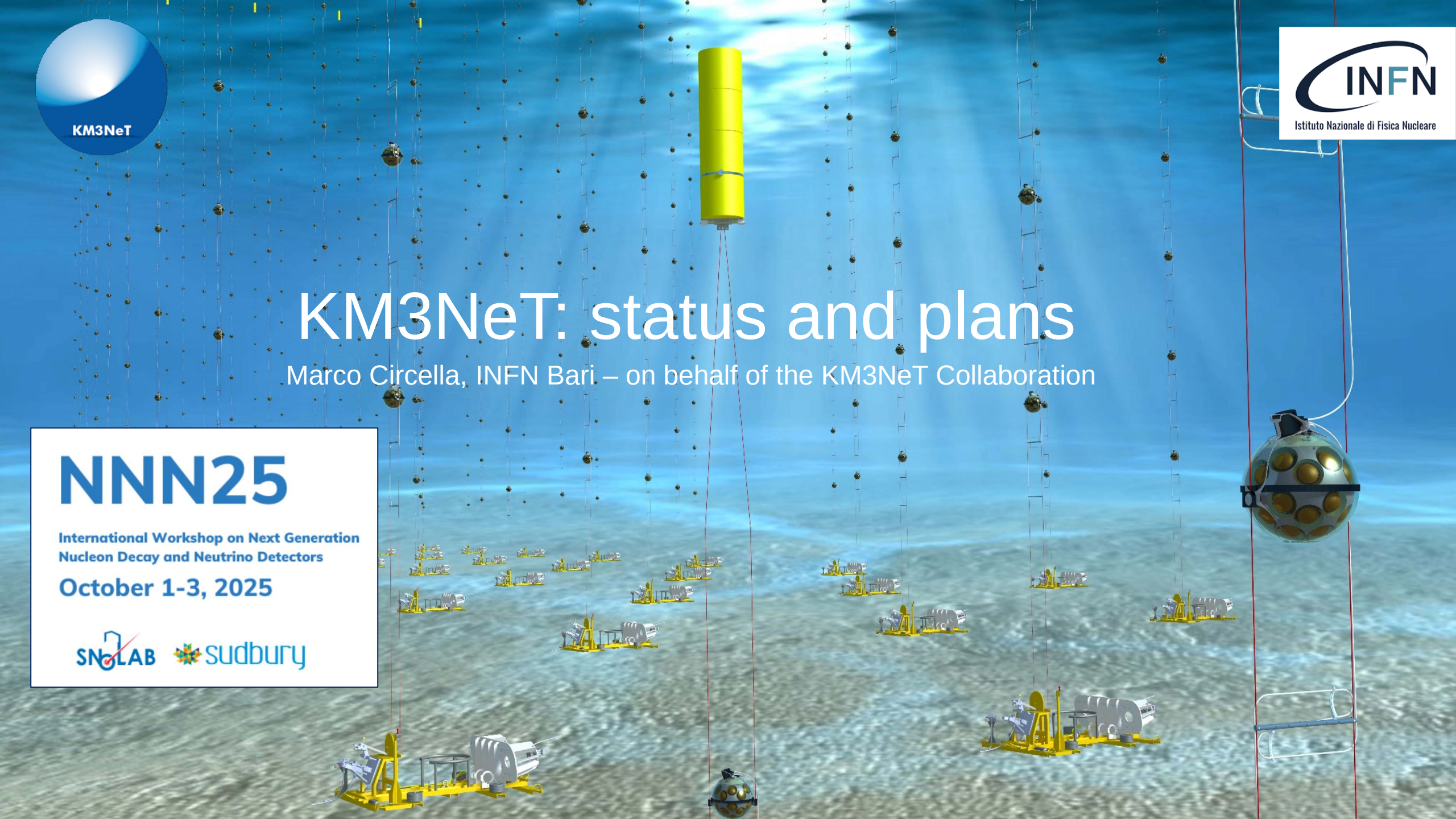


KM3NeT: status and plans

Marco Circella, INFN Bari – on behalf of the KM3NeT Collaboration

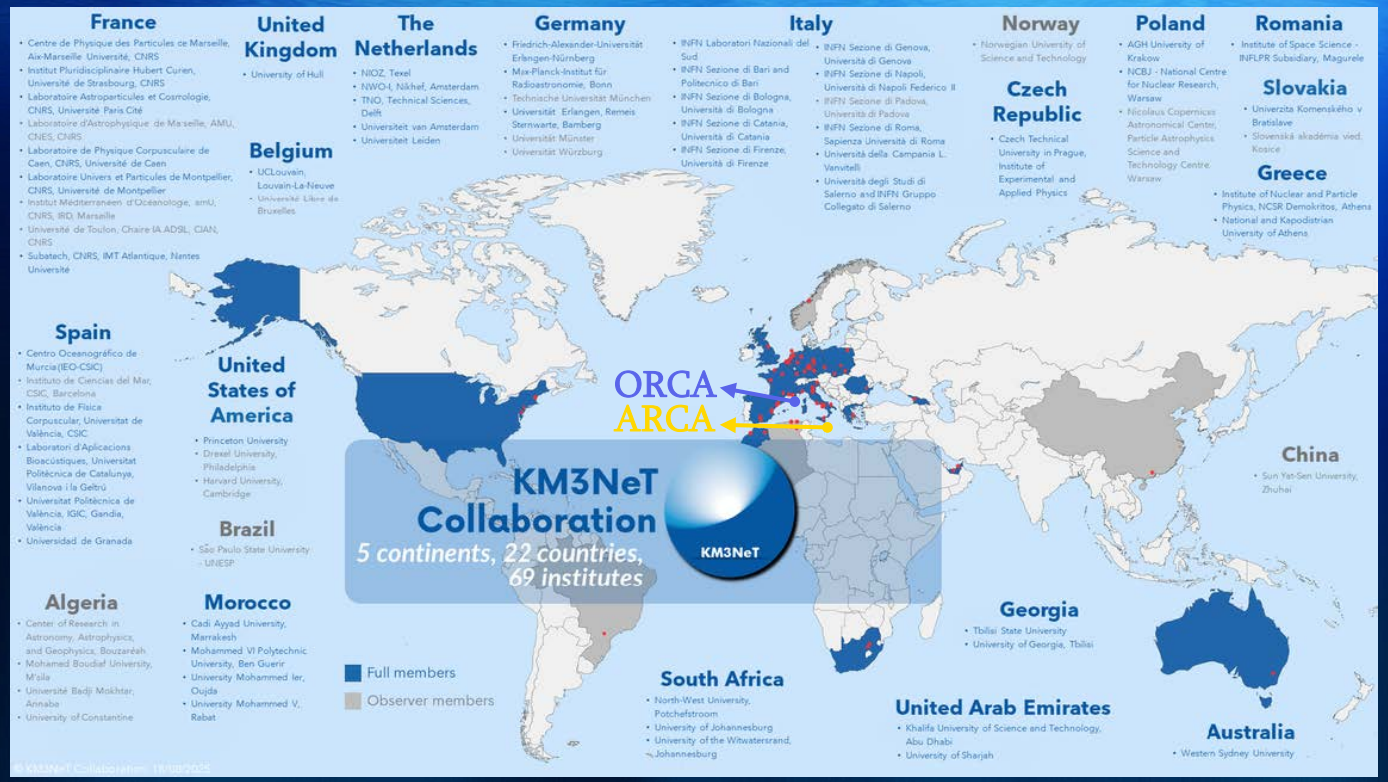
NNN25

International Workshop on Next Generation Nucleon Decay and Neutrino Detectors

October 1-3, 2025

SNOLAB sudbury

KM3NeT is a Mediterranean research infrastructure hosting two neutrino detectors and instrumentation for Earth and sea sciences



More than 65 institutes
in 22 countries in 5 continents

Same technology for:

KM3NeT/ARCA (Astroparticle Research with Cosmics in the Abyss) - Observation of high energy (GeV ÷ PeV) neutrino sources with a telescope offshore Capo Passero (Sicily-Italy) at a depth of ~3500 m

KM3NeT/ORCA (Oscillation Research with Cosmics in the Abyss) - Determination of the neutrino mass hierarchy with a detector offshore Toulon (France) able to detect neutrinos of tens of GeV at a depth of ~ 2500 m

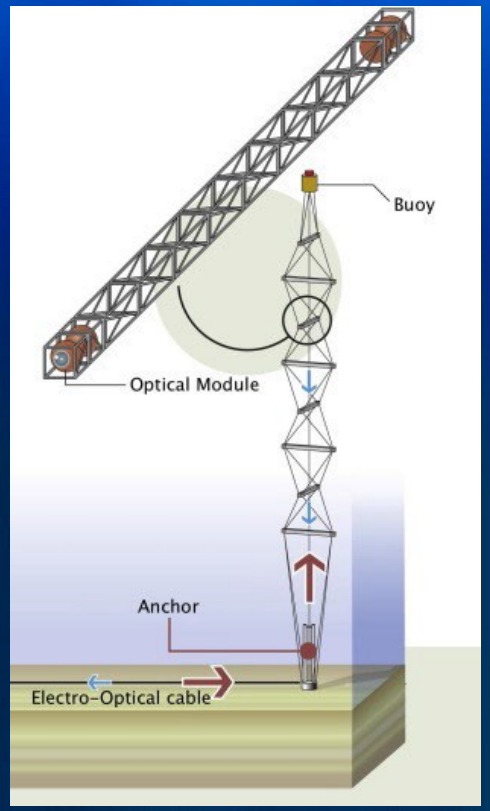
KM3NeT vs. the other neutrino astronomy initiatives in the Mediterranean

ANTARES – first undersea neutrino telescope ever built – operated from 2006 to 2022 (see Sara Rebecca Gozzini's talk)

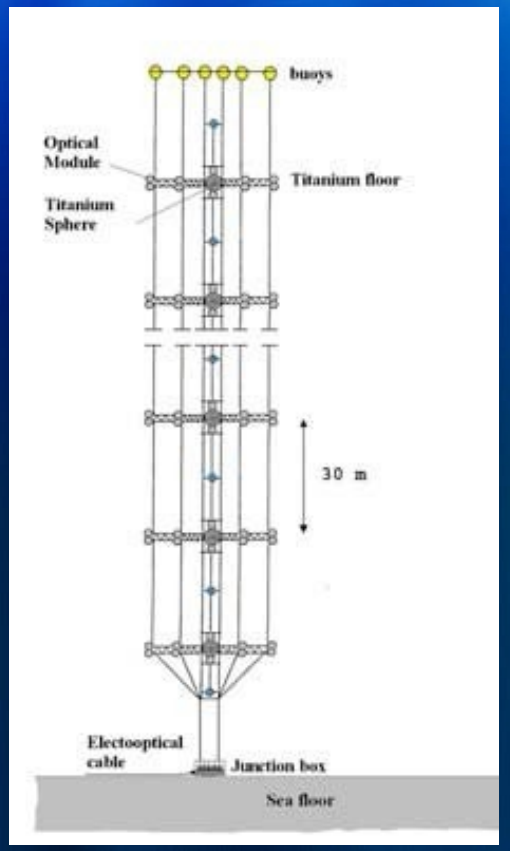
NEMO and **NESTOR** – extensive R&D programs carried out in Italy and Greece

KM3NeT – based on the experience from those three pilot projects - construction of ARCA and ORCA ongoing

Assembly of one ANTARES 'storey'



A NEMO 'tower'



A NESTOR 'tower'

A KM3NeT 'detection unit' (DU)

A game changer: the KM3NeT DOM

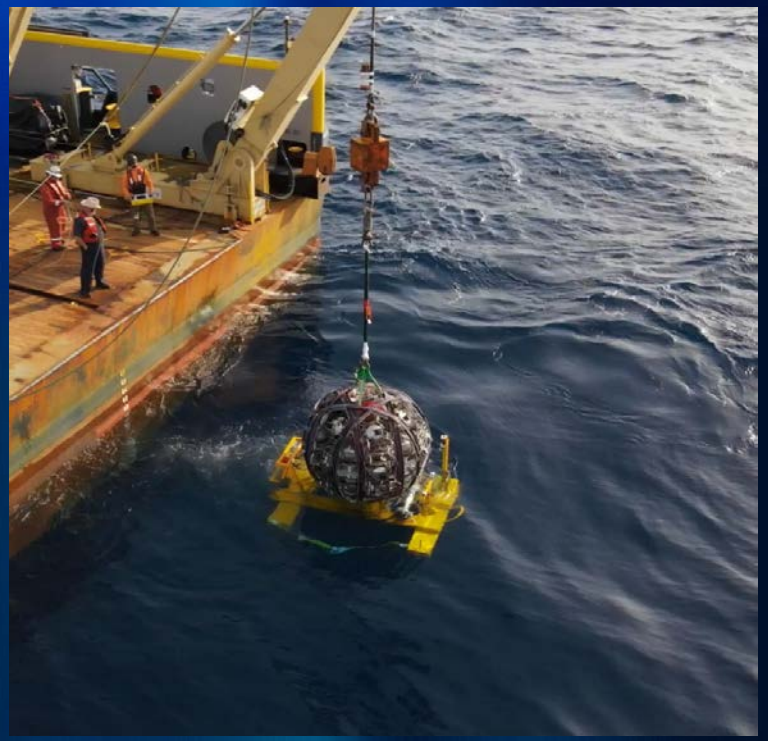
The multi-PMT Digital Optical Module (DOM) of KM3NeT – bottom view

Principles of the KM3NeT design (to scale up the ANTARES size):

- Push performance and reliability
- Simplify the mechanics: reduce the number of containers and interfaces
- Go for a lean detection unit structure, easy to transport and deploy

KM3NeT blooming on ANTARES…

The pre-production DOM of KM3NeT, installed on the instrumentation line of ANTARES in 2013



Deployment of a KM3NeT Detection Unit (DU)

Main features of the DOMs

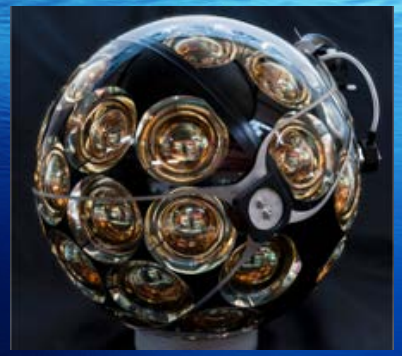
- Each DOM is equipped with 31 PMTs (3” photocathode): Hamamatsu R12199 and R14374
- Each DOM includes the opto-electronics for data collection and transmission + all needed calibration devices
- Each DOM works as an autonomous detection node

Advantages compared to single-PMT modules:

- Maximal sensor area (equivalent to 3 PMTs of 10” photocathode)
- Improved photon counting
- Directional sensitivity
- Possibility of local triggers, cross-calibration and background suppression
- Large angular acceptance
- Cost-effectiveness!
- It allows to simplify the detection unit structure

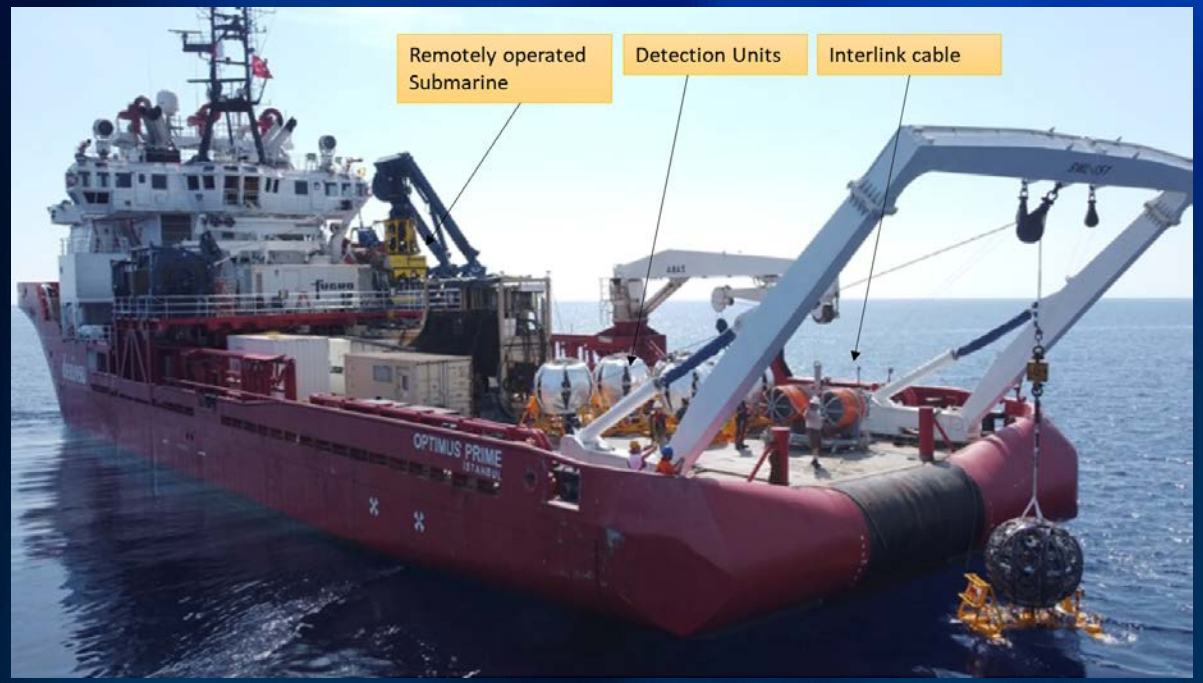
*(Ref.: Eur. Phys. J. C (2014) 74: 3056 & JINST (2022) **17** P0703)*

In a summary:

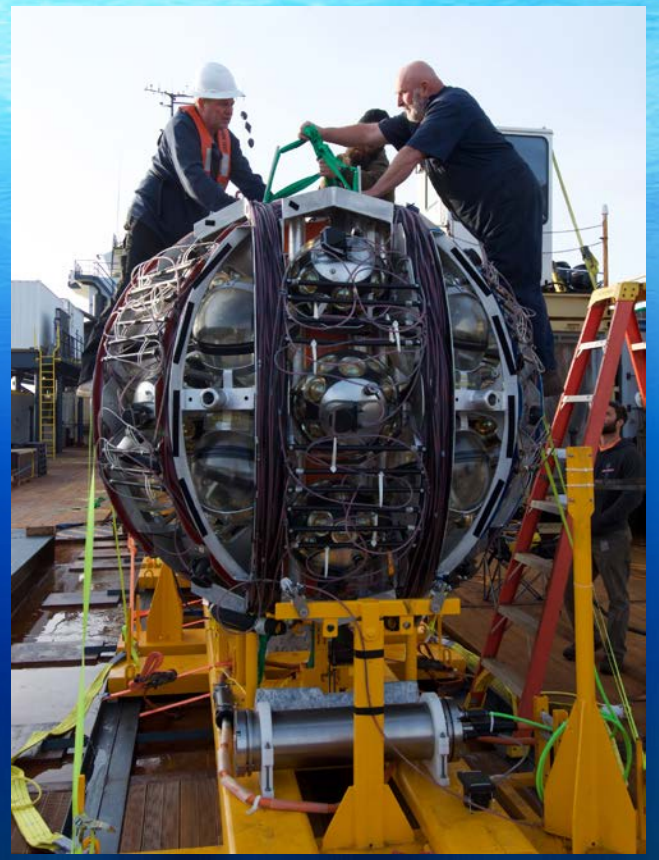


Multi-PMT DOM (Digital Optical Module)

- 31 PMTs (3” photocathode)
- Maximal sensor area
- Photon counting
- Directional sensitivity



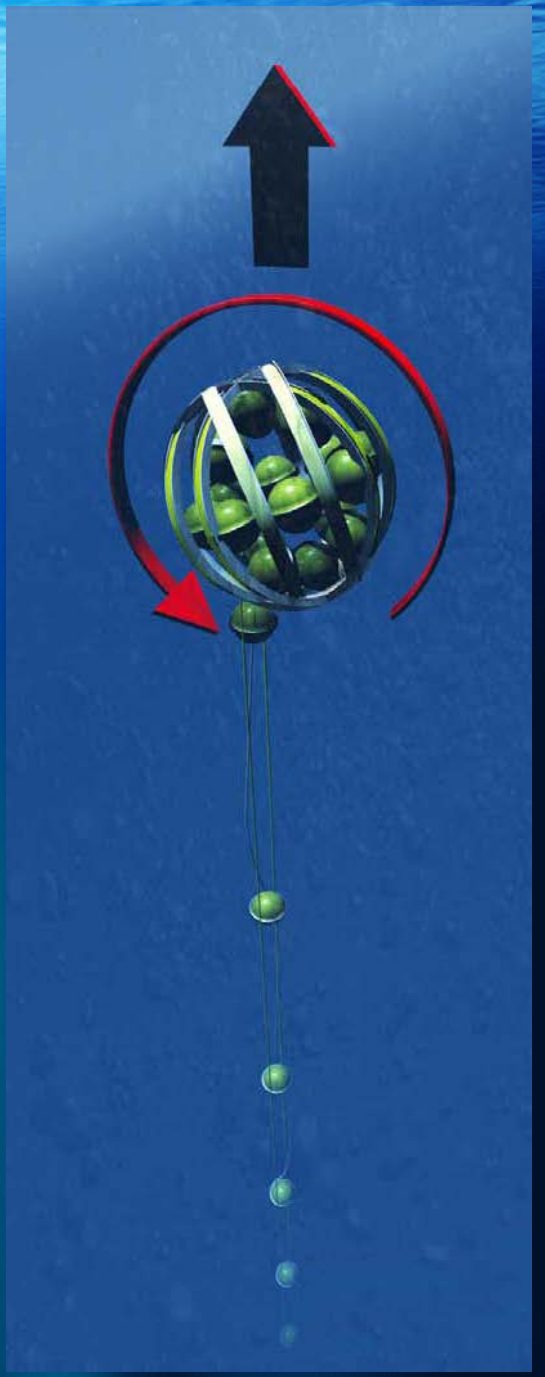
Several DUs can be installed in the same sea operation

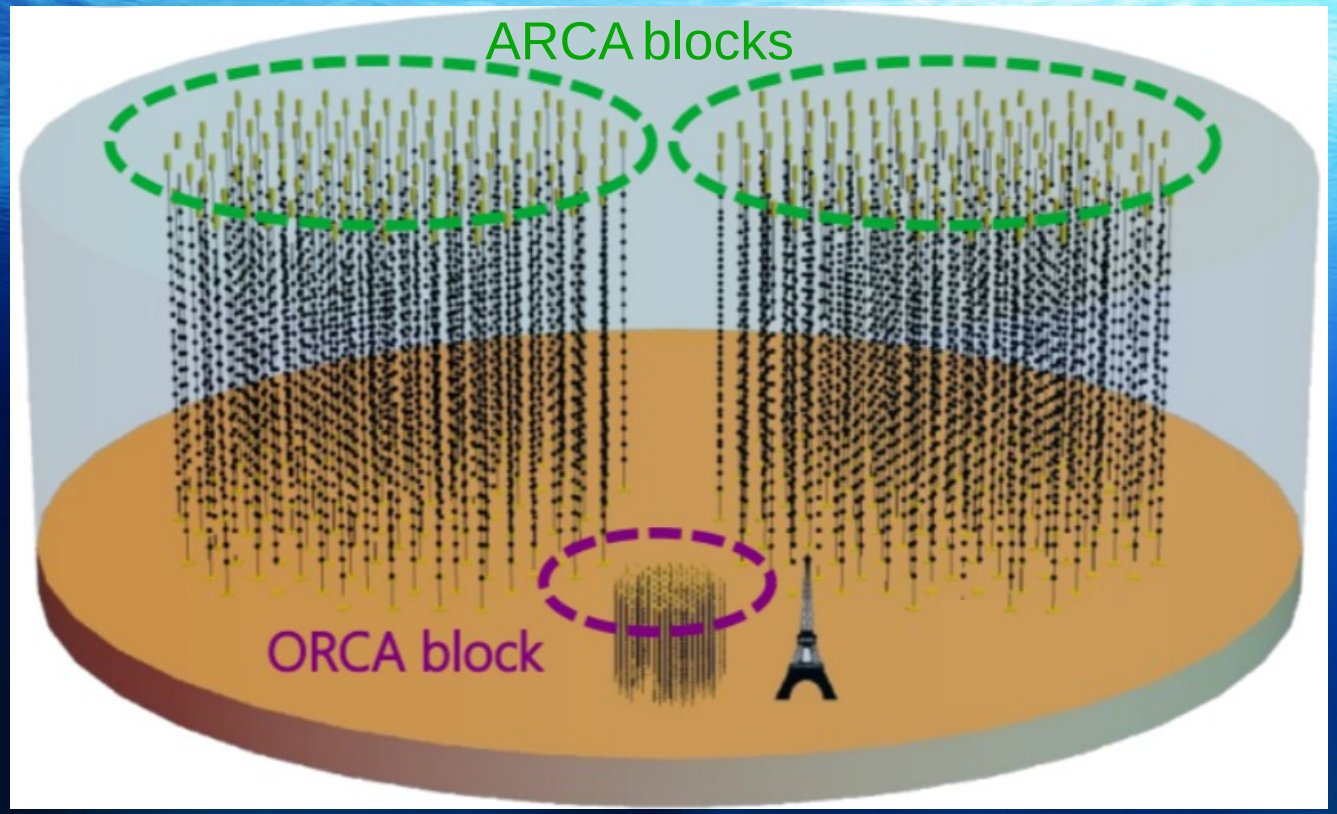


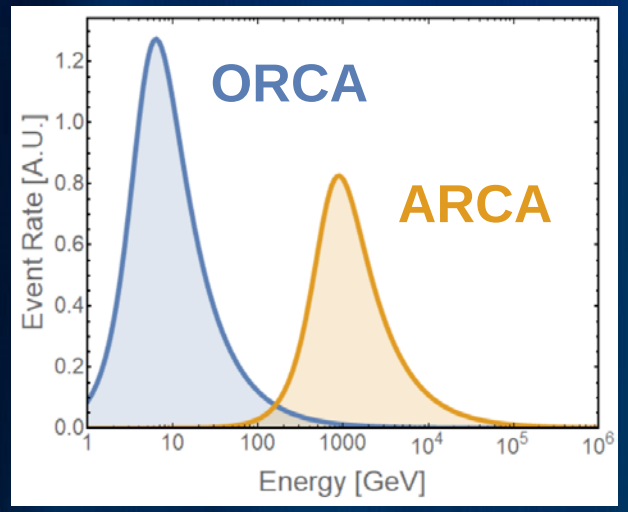
18 DOMs are installed in a DU (Detection Unit)

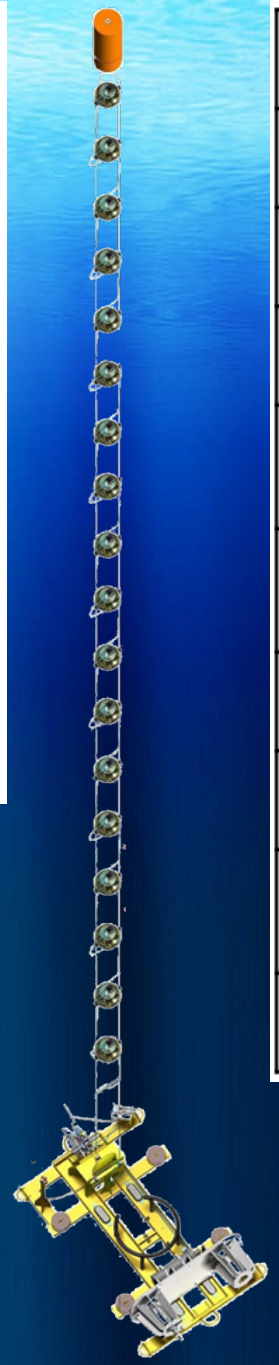
The DU is packed on a spherical launcher vehicle for installation, from which it will unfurl after deployment on sea bottom

(Ref.: JINST (2020) 15, P11027)







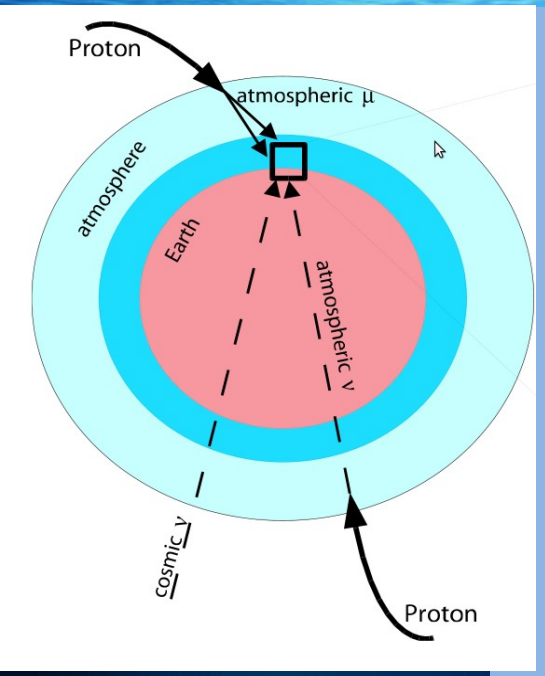


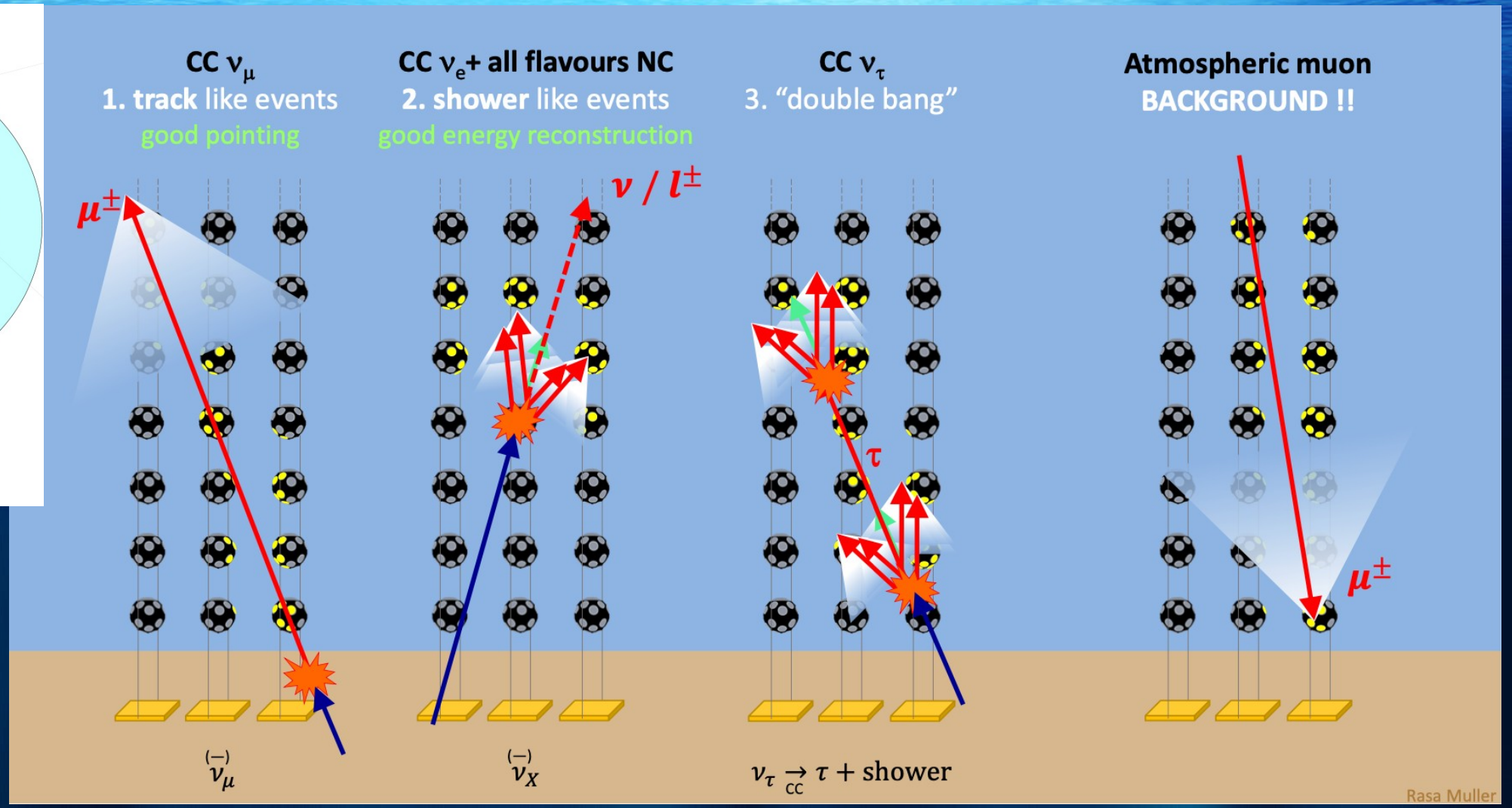
	ARCA	ORCA
Location	Sicily (IT)	Toulon (FR)
Depth	3450m	2450m
No. of DUs	2 x 115	115
DU horizontal spacing	90 m	20 m
DOM Vertical Spacing	36 m	9 m
DOMs/DU	18	18
PMTs/DOM	31	31
Instrumented water mass	1 Gton	7 Mton
DUs deployed	51	28

DU height is ~700 m in ARCA,
~200 m in ORCA

(Ref.: LoI, *J. Phys. G:**43 (2016)** 084001*)

Equipped for detection of all neutrino flavours!

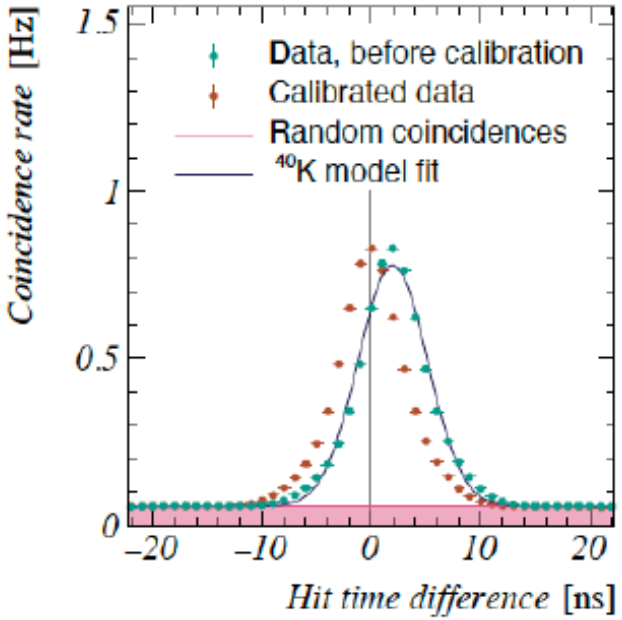




Tracks: @E_ν>100 TeV Angular resolution below 0.1° - Energy resolution ~factor 2

Shower: @E_ν>100 TeV Angular resolution below 2° - Energy resolution ~6%

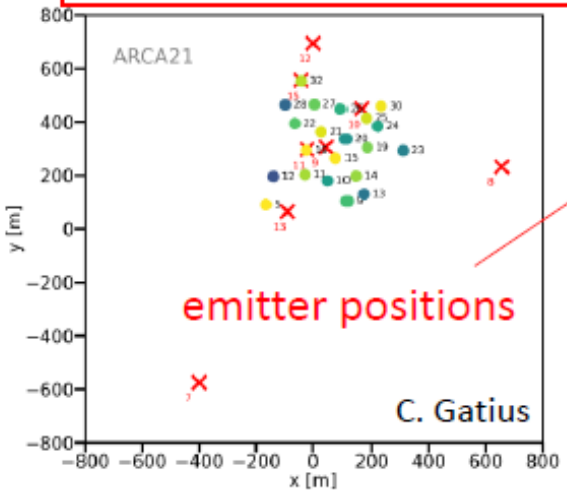
Calibration



^{40}K decays: correlated photons

Detector Timing
PMT efficiency

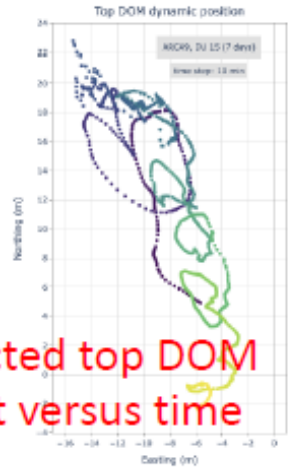
Positioning: acoustic triangulation using autonomous emitters



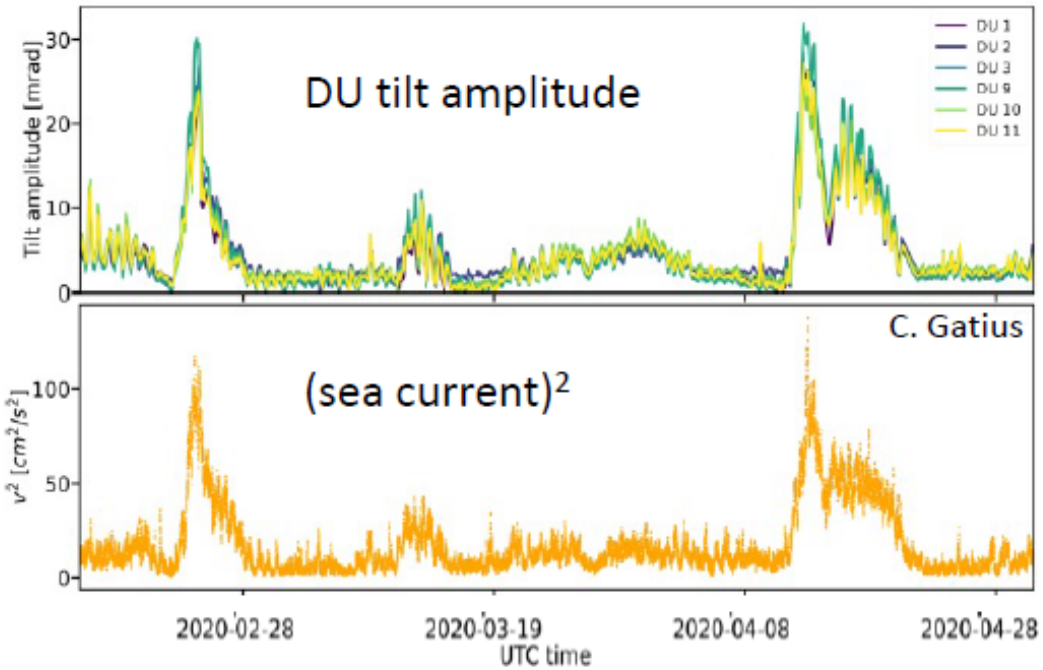
emitter positions

each DOM records sound

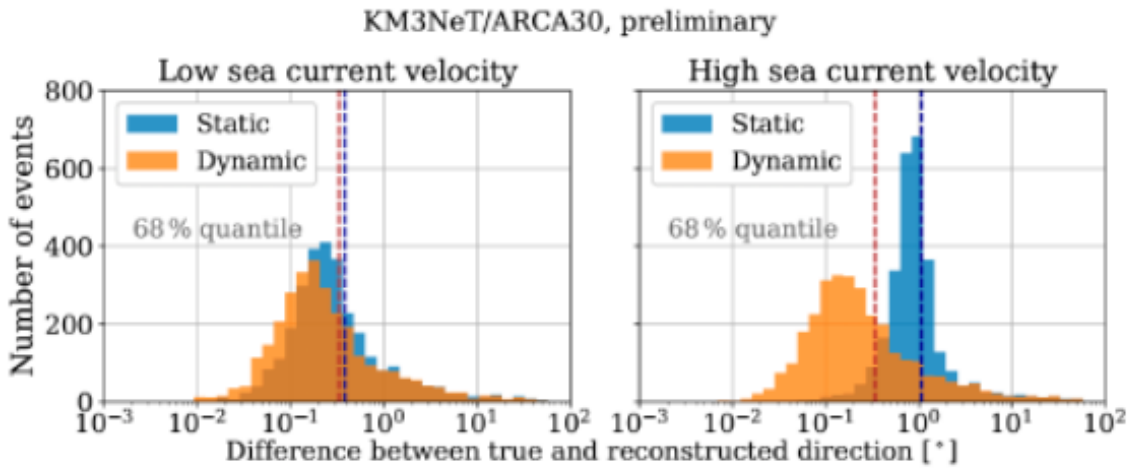
reconstructed top DOM movement versus time



20 m



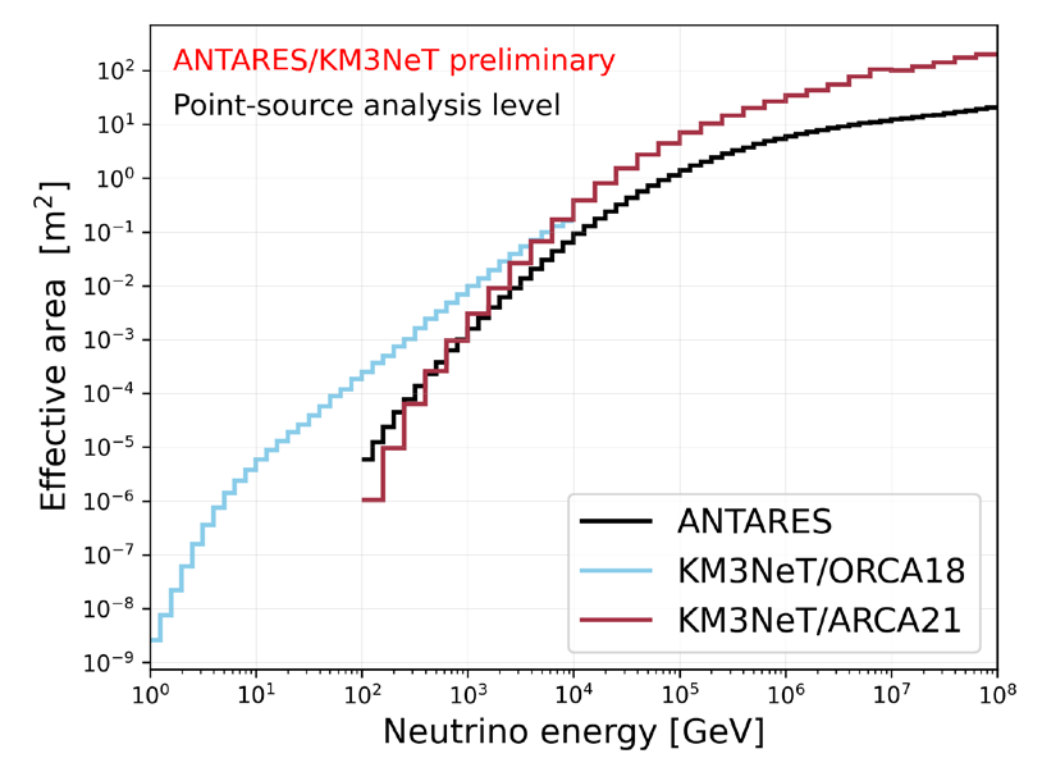
Comparison static/dynamical positioning

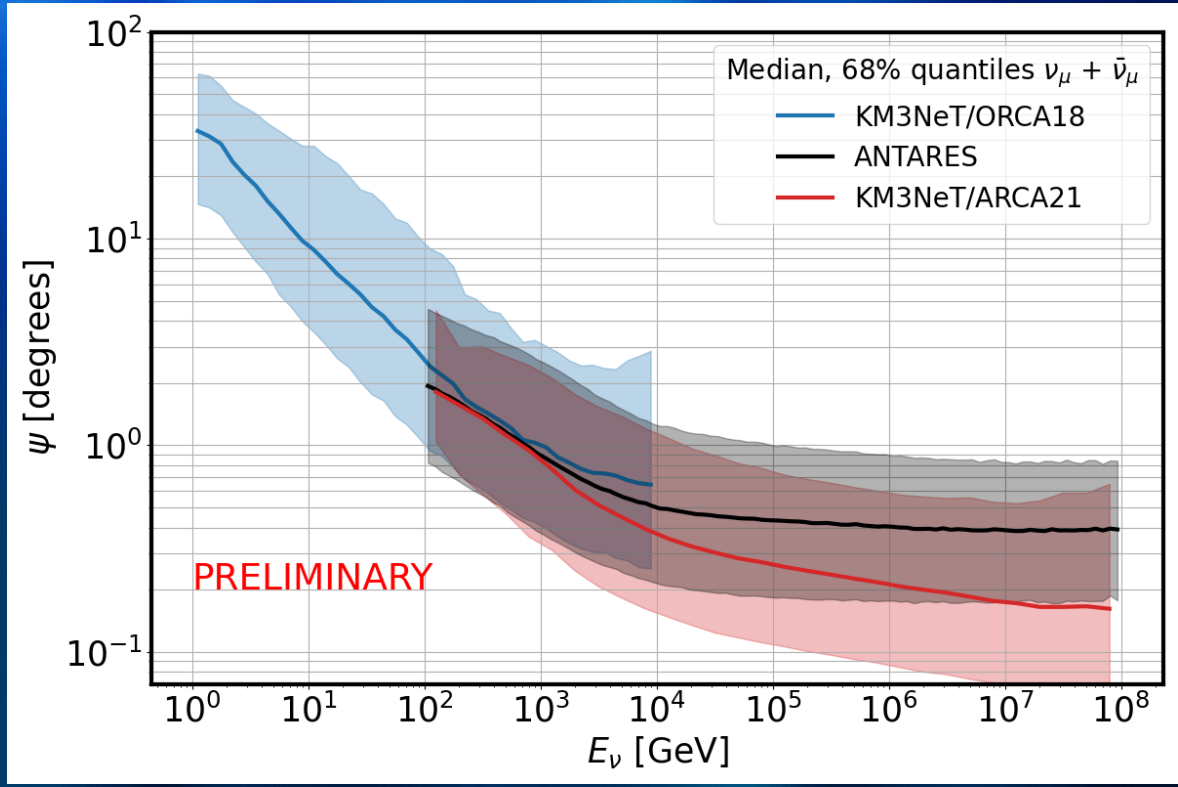


Cross-check: stopping cosmic muons, cosmic ray shadow sun/moon)

How KM3NeT (ARCA+ORCA) compares to ANTARES

Improvement in effective area and angular resolution over full energy range

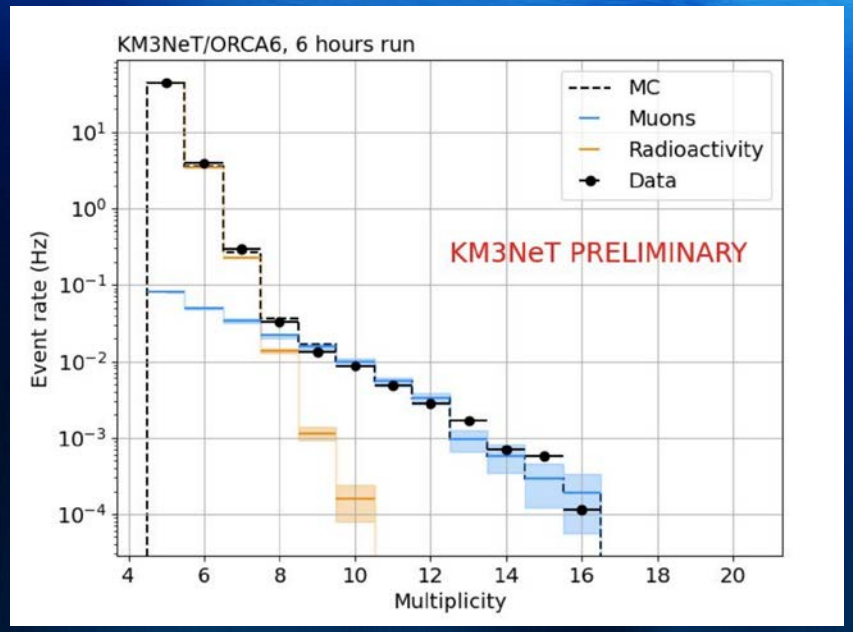




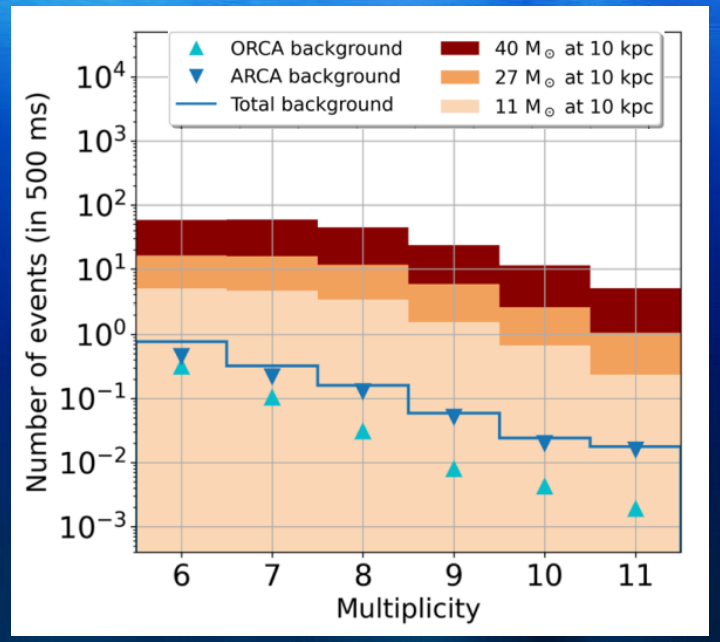
Core-Collapse Supernova neutrinos

Based on detection of collective increase of signal rates in DOMs

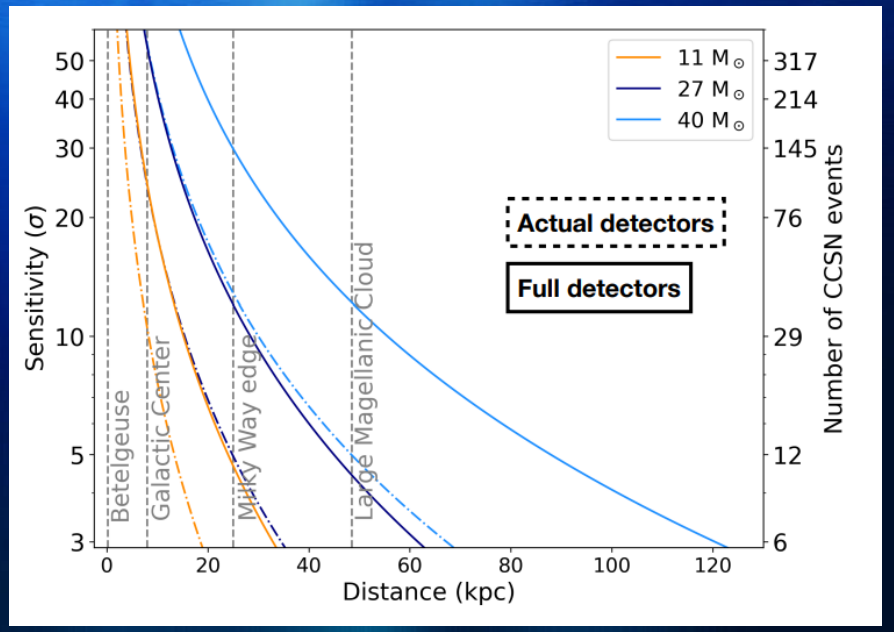
PMT multiplicity plot

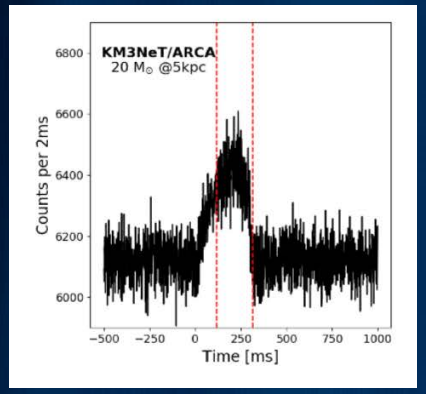


Expected signal



Significance

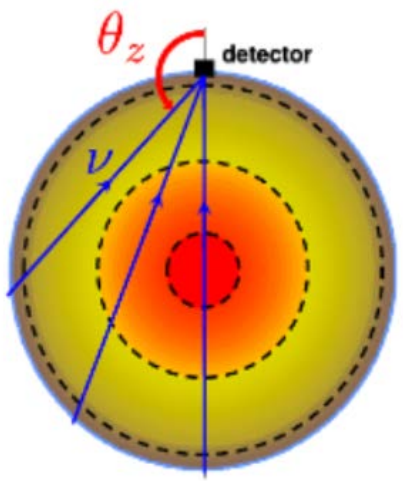




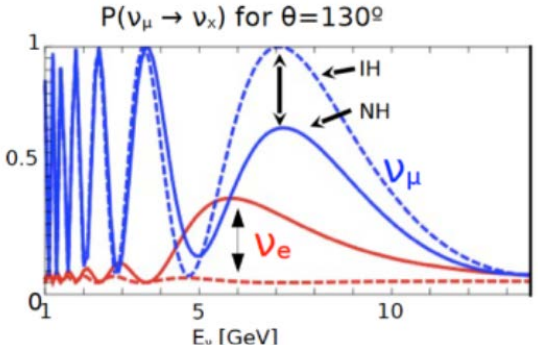
On-line alert system for CCSN Integrated in SNEWS2.0

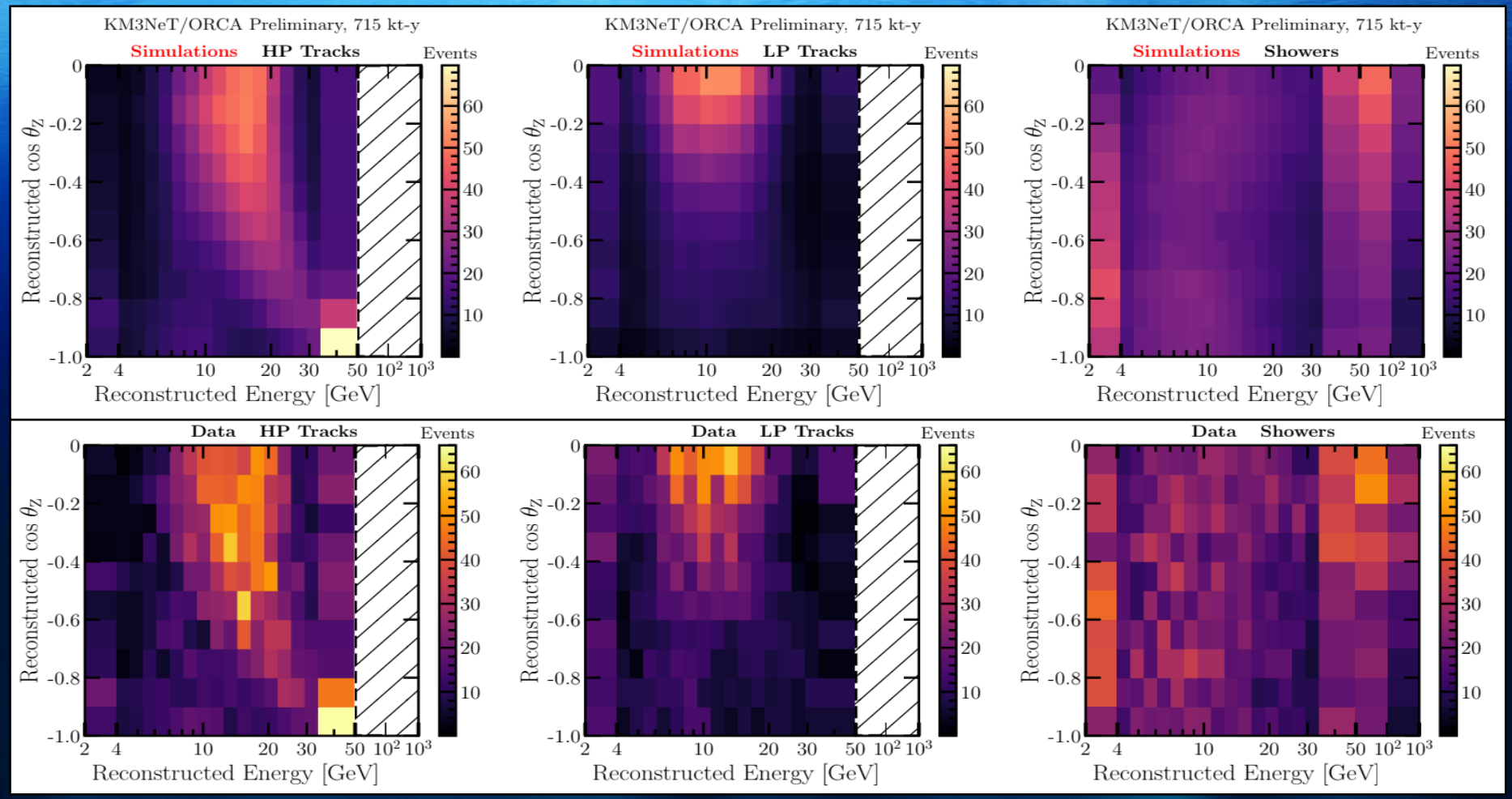
ν oscillation patterns in ORCA

Baseline from 50 to 12800 km



Energy range of interest 5-15 GeV





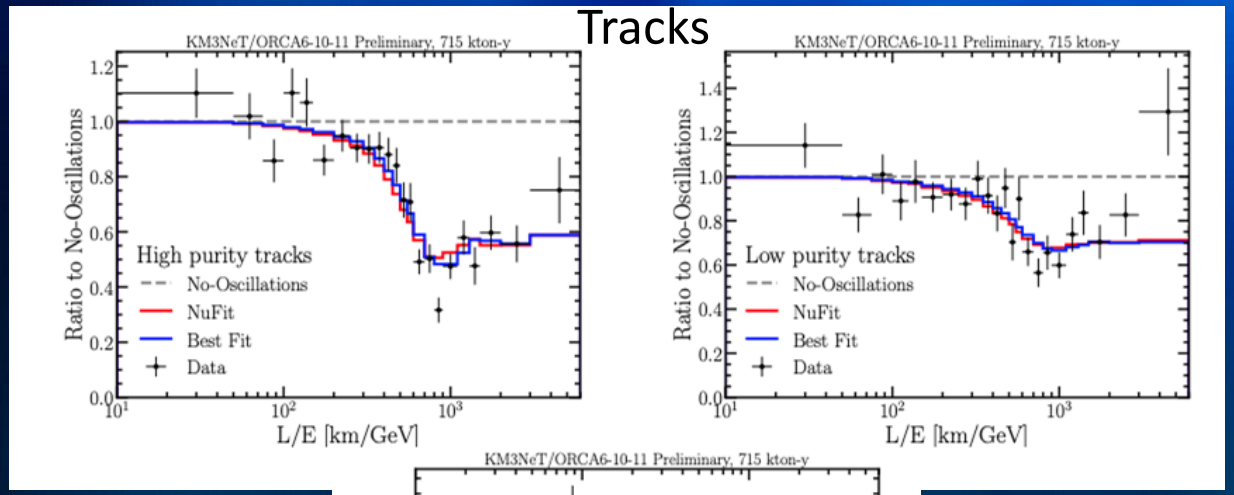
3 classes of events

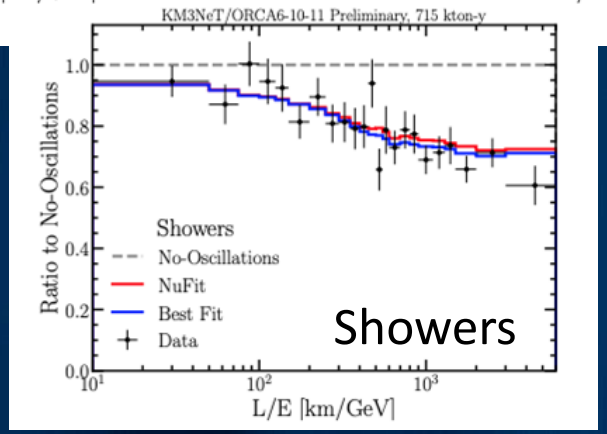
(see Jürgen Brunner's talk for more details)

Neutrino oscillation results

- Already providing relevant information with reduced exposure (715 kt-y analyzed, with 3 Mt-y on disk)
- Fully consistent with world data
- Slight IO preference

Tracks

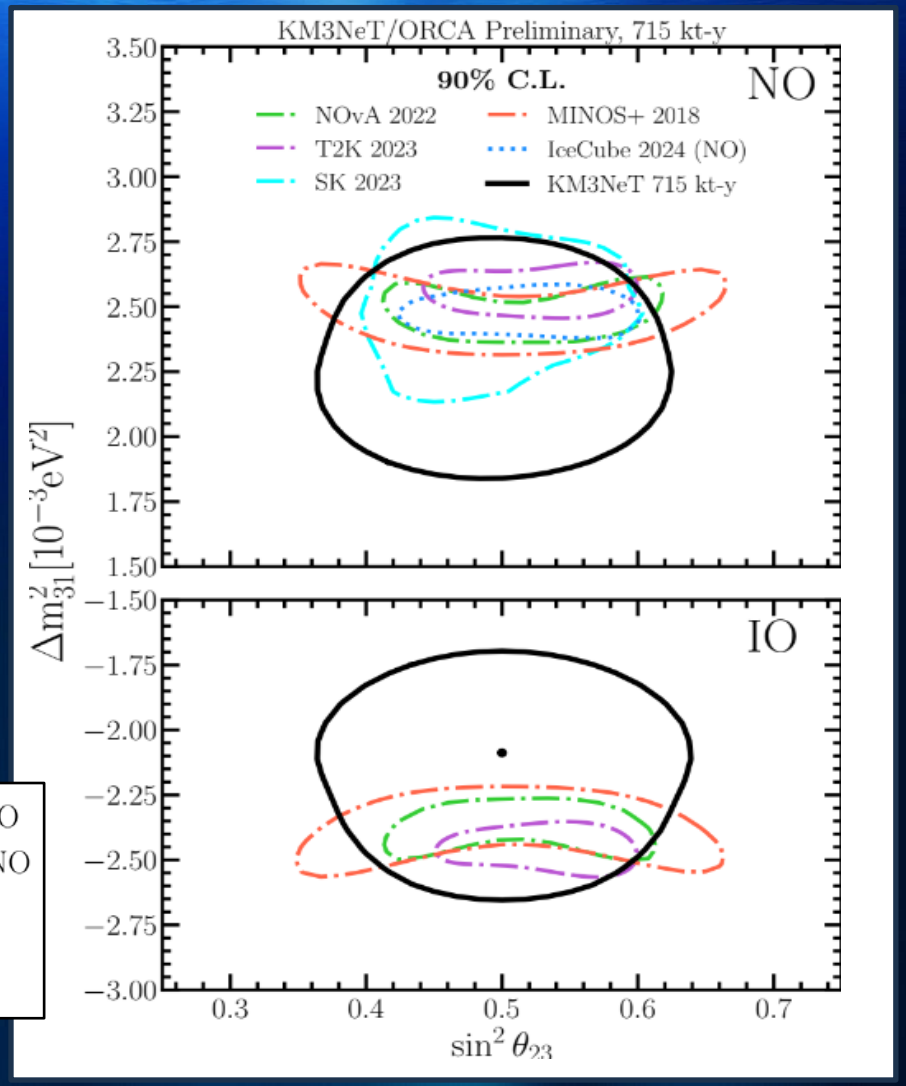




$$\Delta m^2_{31} = \begin{cases} -2.09^{+0.17}_{-0.21} \times 10^{-3}\text{eV}^2, & \text{IO} \\ [2.10, 2.37] \times 10^{-3}\text{eV}^2, & \text{NO} \end{cases}$$

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

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



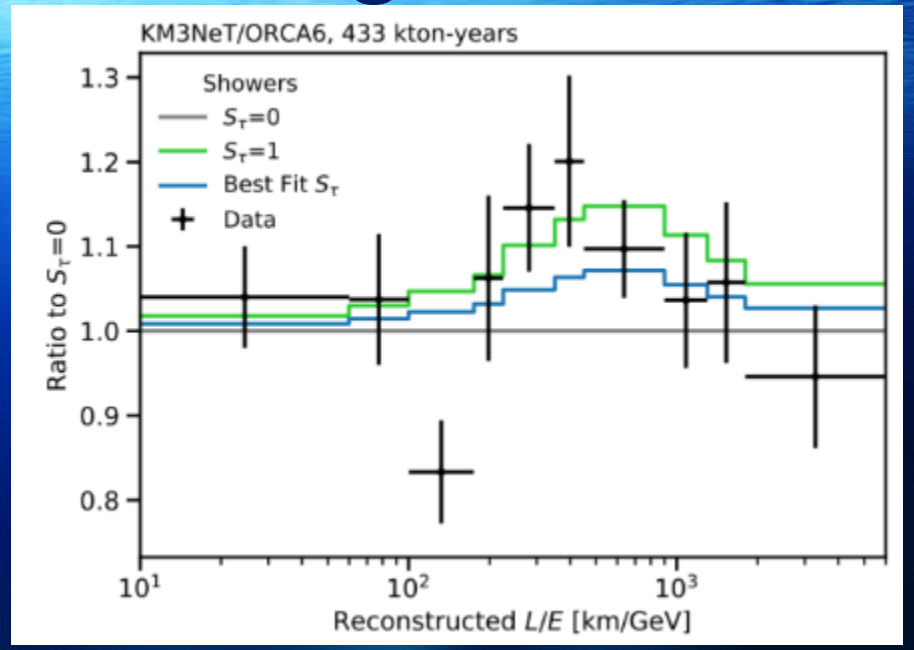
Neutrino oscillation and BSM investigations

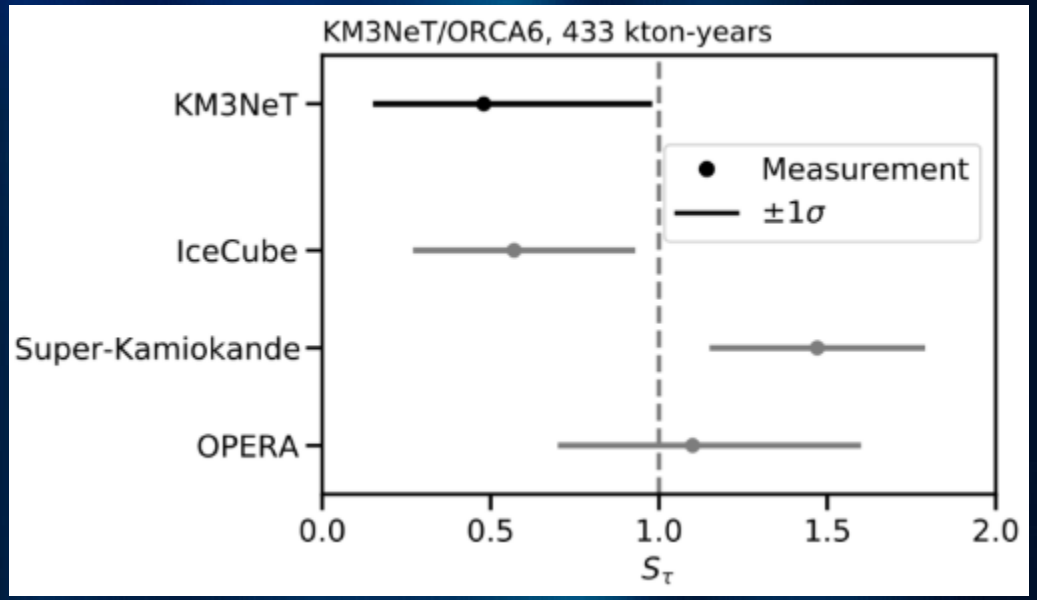
Thanks to large data sample we can investigate:

- Oscillation parameters (Δm^2_{31} - $sin^2\theta_{23}$) & neutrino mass ordering
- Tau appearance and unitarity of the neutrino mixing matrix

(Ref. J. High Energ. Phys. 2025, 213 /2025))

- Sterile neutrinos
- Non-standard neutrino interactions *(Ref. JCAP 02 (2025) 073)*
- Quantum decoherence and invisible decay *(Ref. JCAP 03 (2025) 039 & JCAP 02 (2025) 073)*
- Lorentz invariance violation *(Ref. arXiv: 2502.12070)*

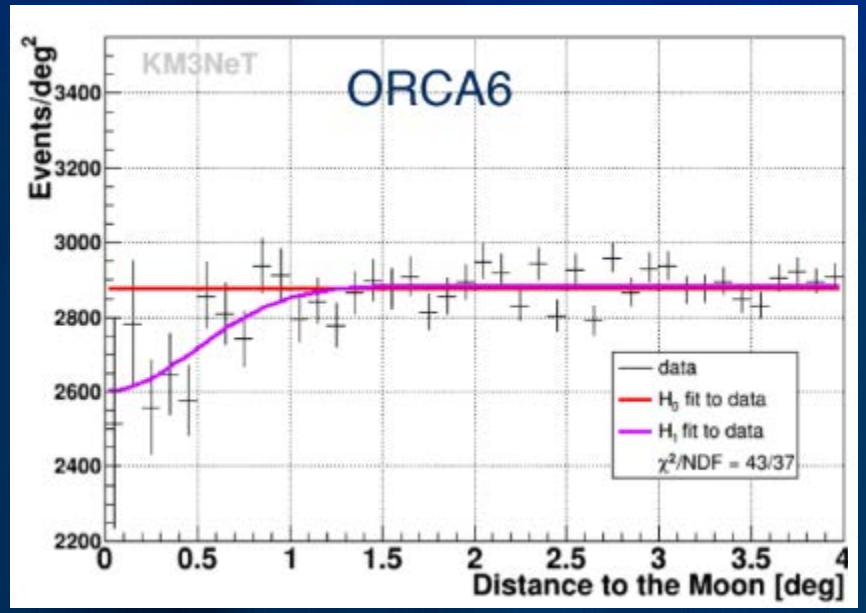


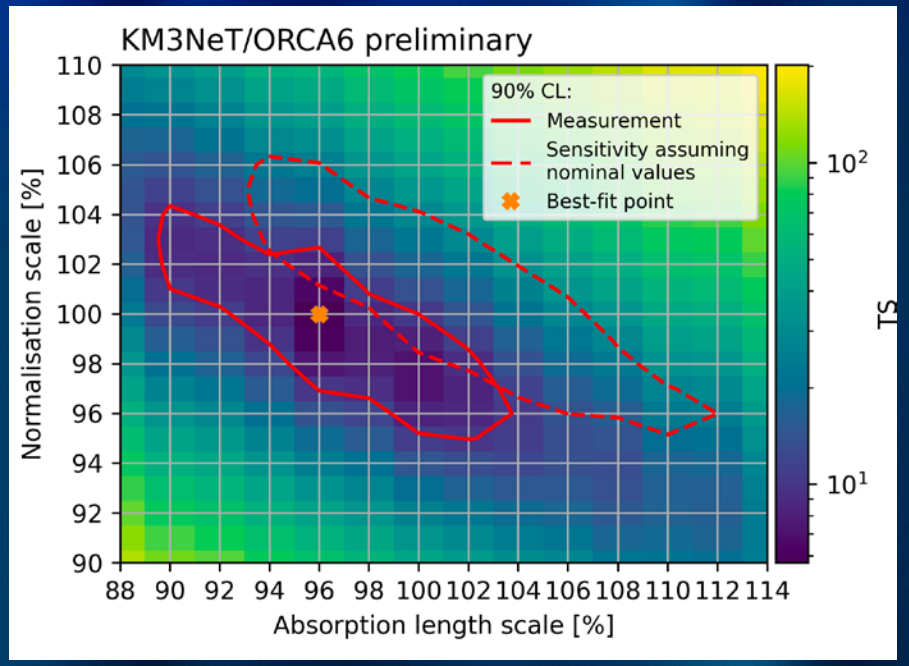


Measurements of atmospheric particles

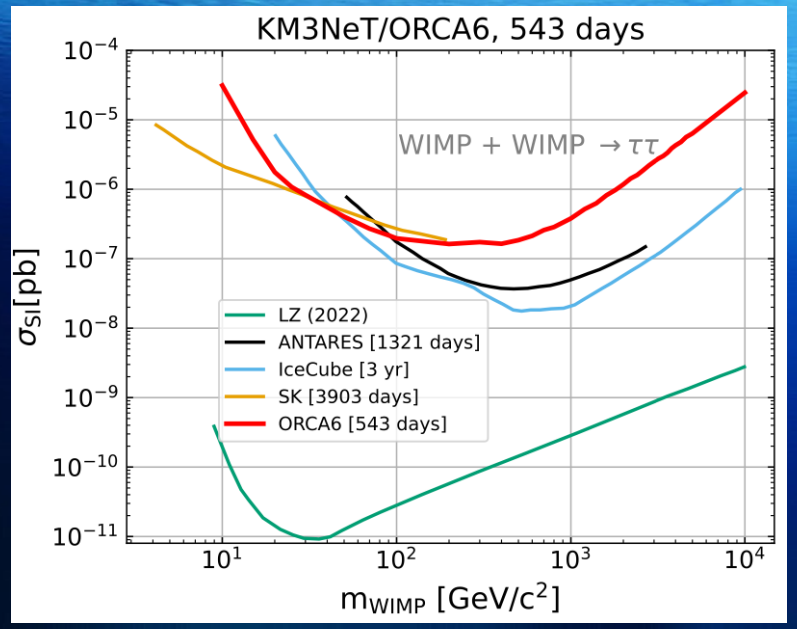
The very large data sample allows to:

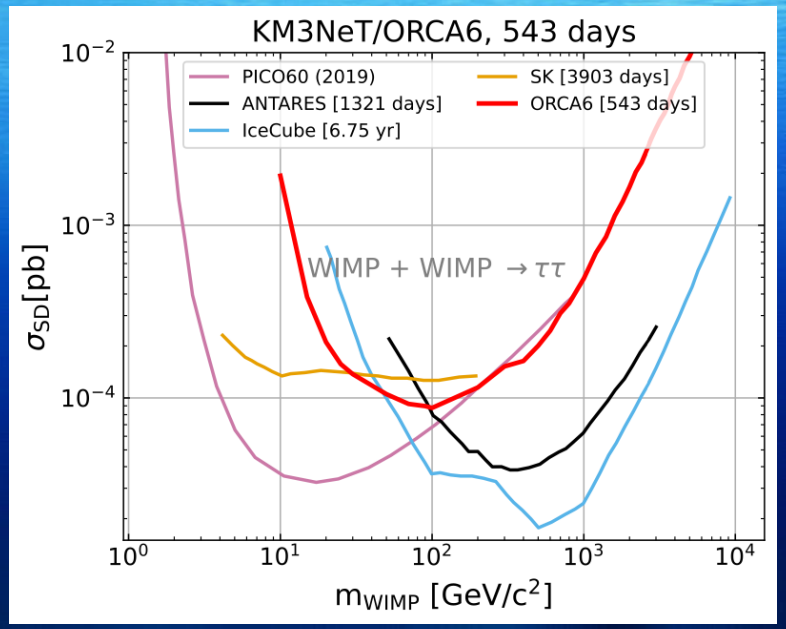
- Measure the muon spectrum, studying anisotropies and seasonal variations, and searching for prompt component
- Measure the atmospheric neutrino spectrum *(Ref. Eur. Phys. J. C **85**, 871 (2025))*
- Improve calibration
- Infer the water properties through detection of stopping muons

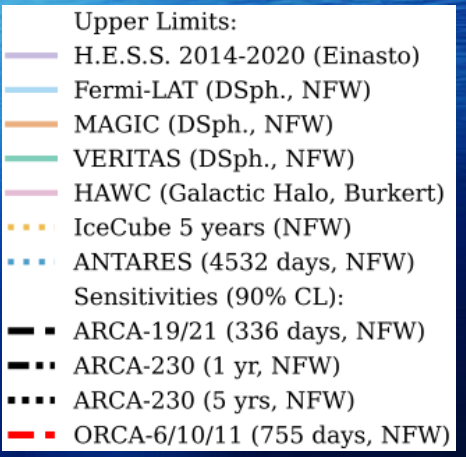


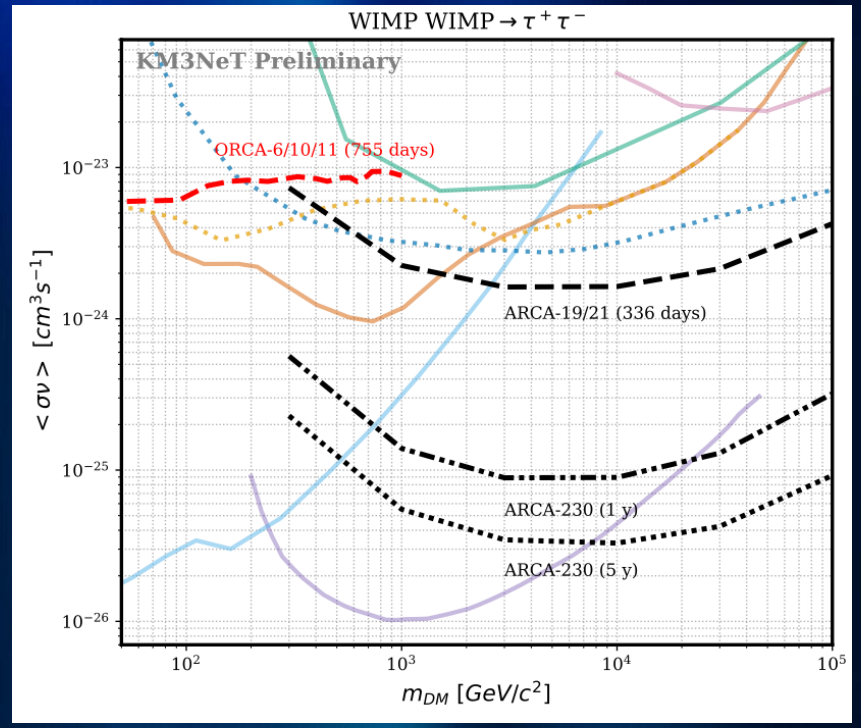


Search for dark matter in the Sun and the Galactic Center





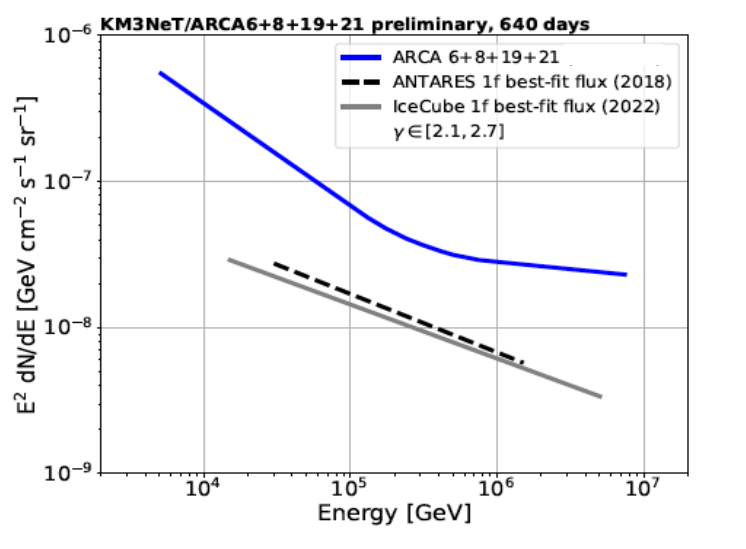


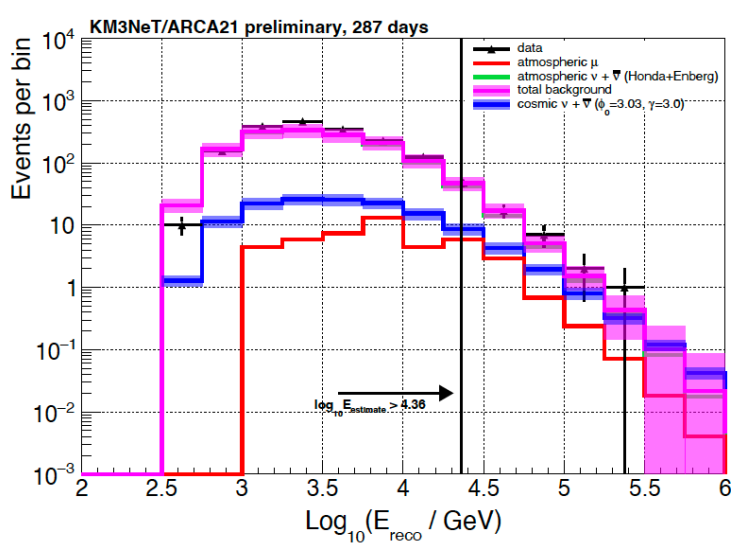


No evidence found yet,
but… already competitive with ANTARES and IceCube

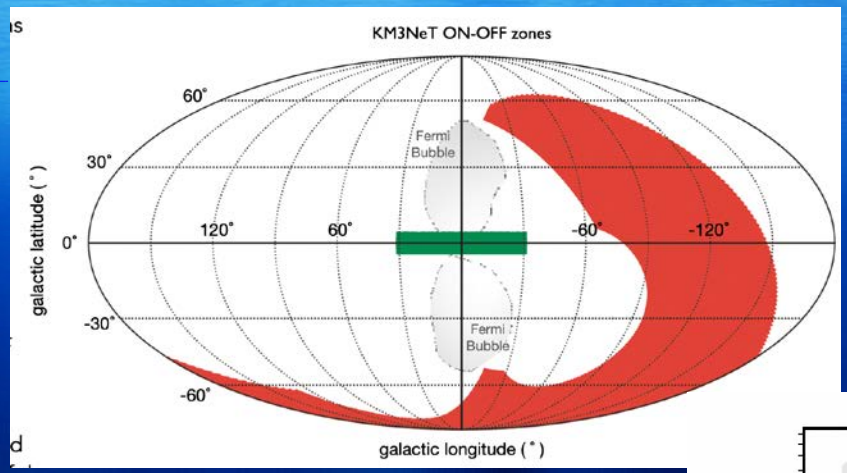
Search for a cosmic diffuse neutrino flux

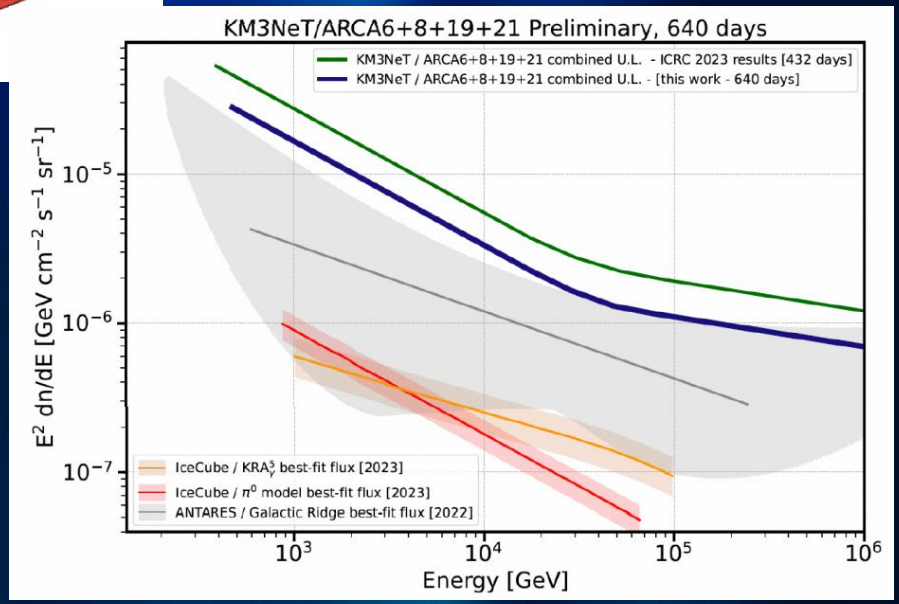
Full sky





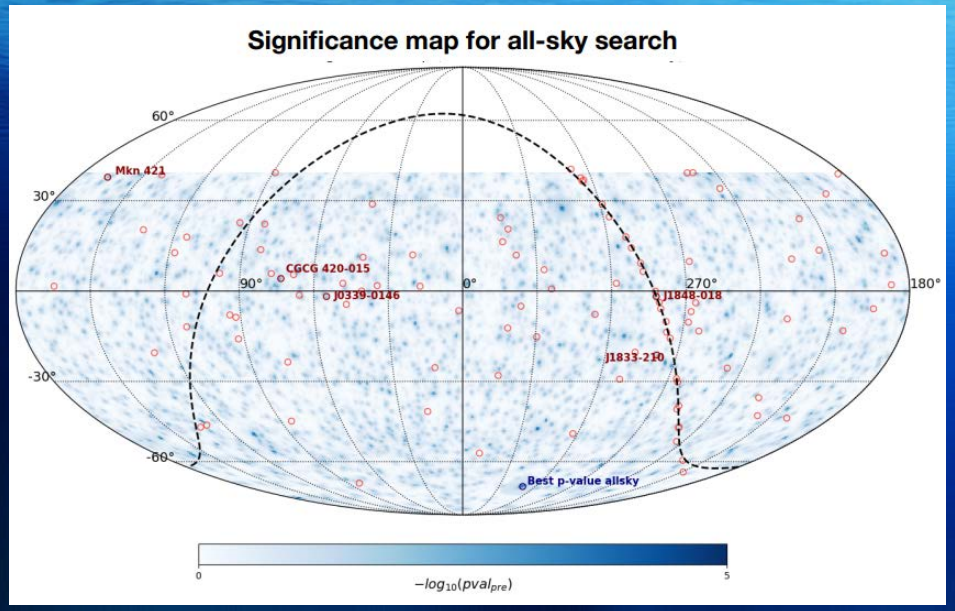
Galactic ridge

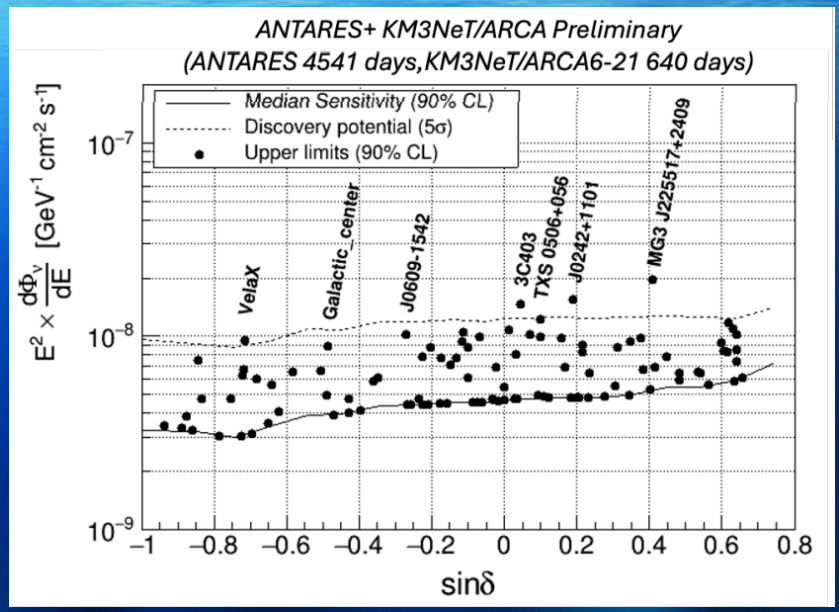




No signal found yet, but rapidly approaching the ANTARES sensitivity

Search for cosmic (point) sources of neutrinos





- **Best source: MG3 J225517+2409 (as in ANTARES): Fermi 3LAC Blazar**
- **Pre-trial p-value: 4.0 10^{-5} (0.03 with ARCA)**

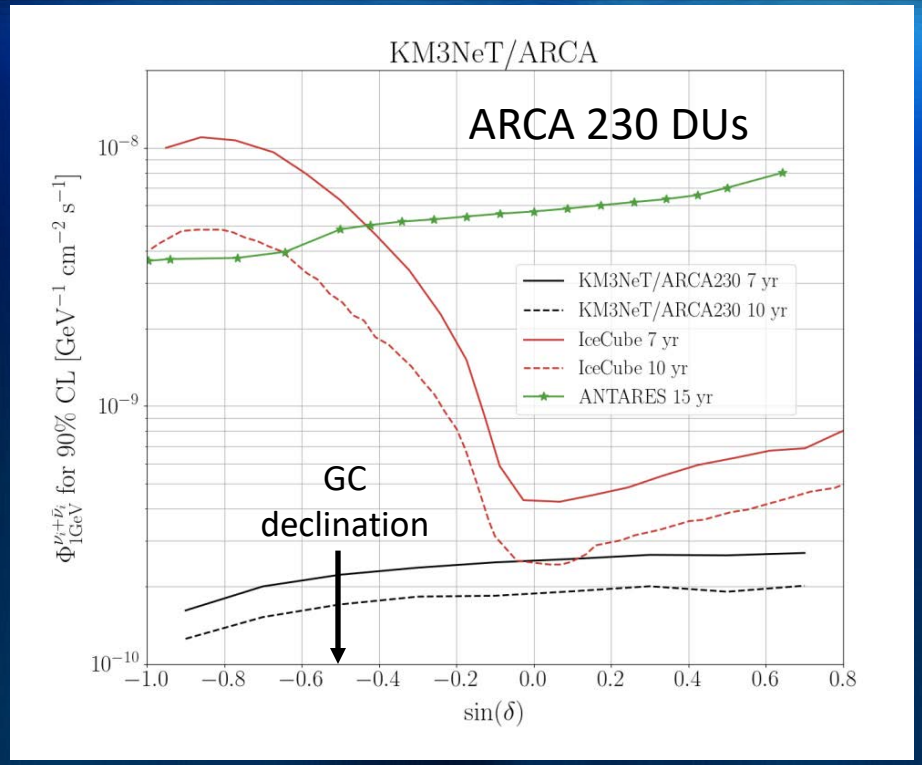
(Gain compared to ANTARES only)

- Post trial calculation under evaluation

- Accumulating more and more data
- Angular resolution improves as detector grows
- Combined search of ANTARES+KM3NeT improves the ANTARES sensitivity by 20%

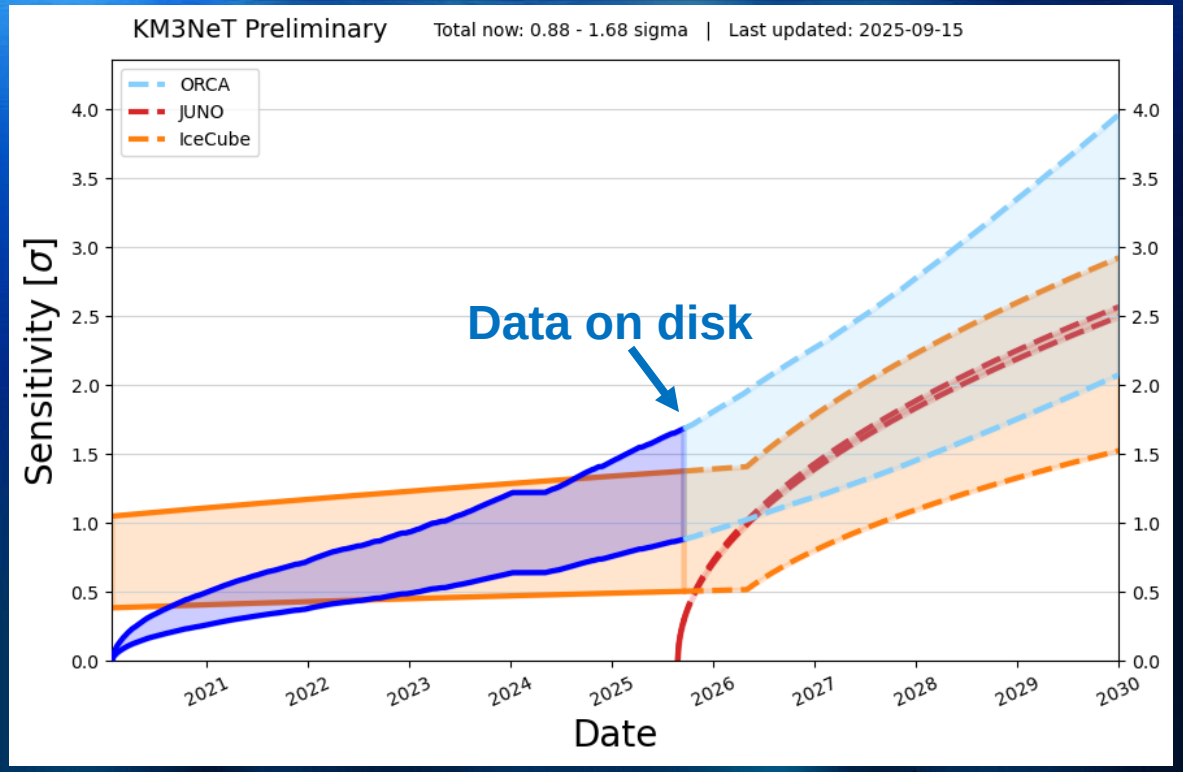
KM3NeT perspectives

ARCA - Sensitivity for point-like searches



https://arxiv.org/abs/2402.08363

ORCA - Neutrino mass ordering

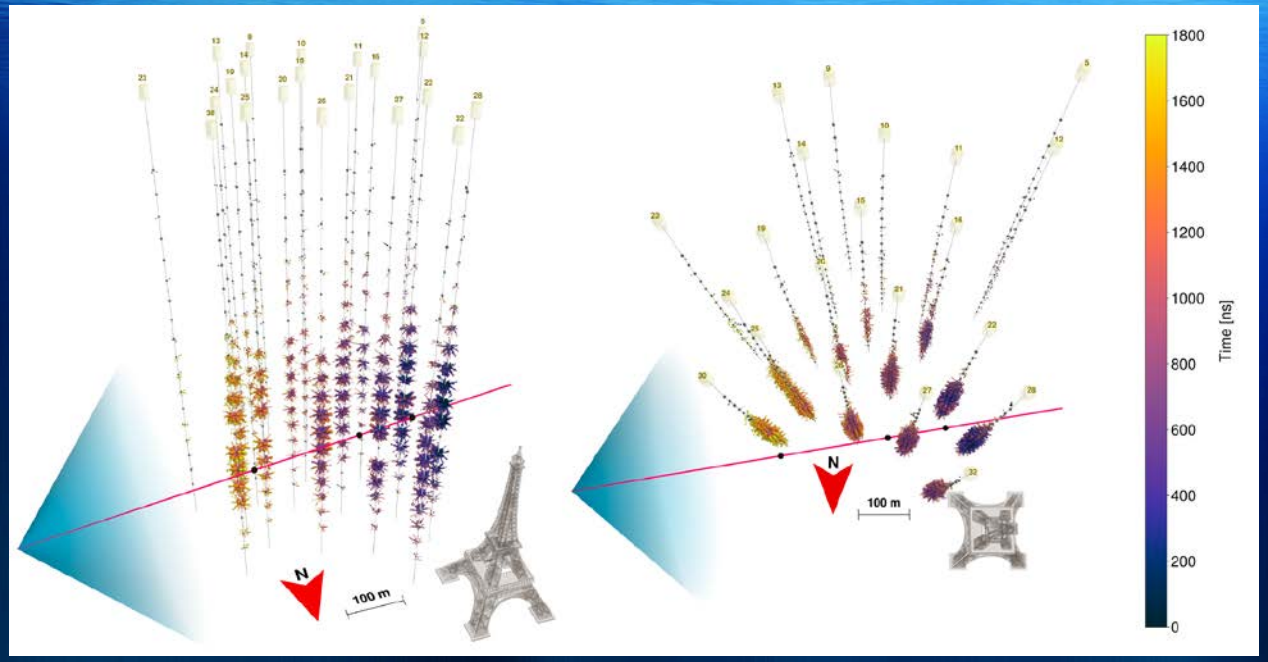


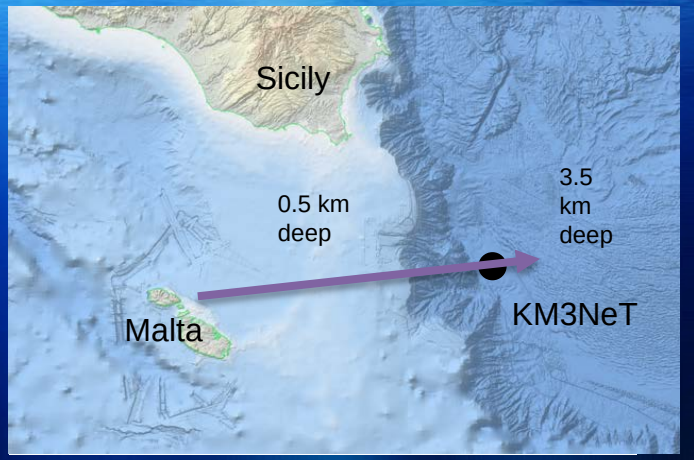
2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 **2030**

- 2022: ANTARES decommissioning
- 2025: ARCA 51 DUs, ORCA 28 DUs
- 2030: ARCA & ORCA completion

KM3-230213A: the first UHE neutrino!

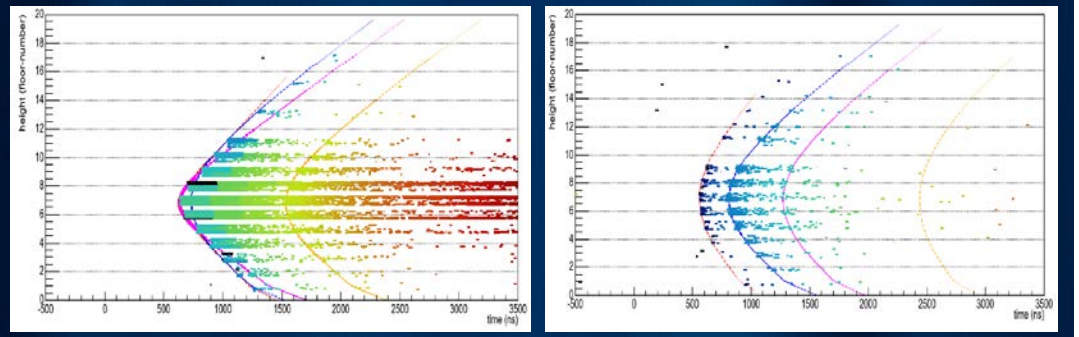
Single muon crossing almost horizontally the entire ARCA21 detector, releasing a never-observed-before amount of signal (photons detected by more than 1/3 of the PMTs, 25% of which reached saturation!)

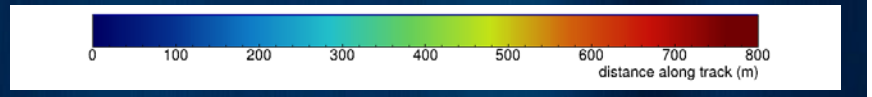


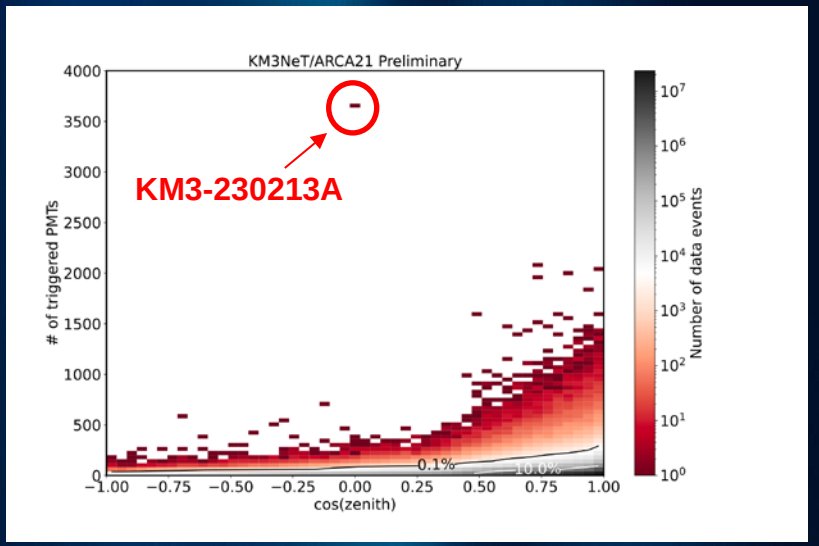


The almost horizontal direction, crossing the Malta escarpment, combined with the enormous signal released allowed to identify the highest-energy neutrino ever detected (220 PeV)

- More than 28,000 photons detected by 3,742 PMTs
- Evidence for three localized energy releases



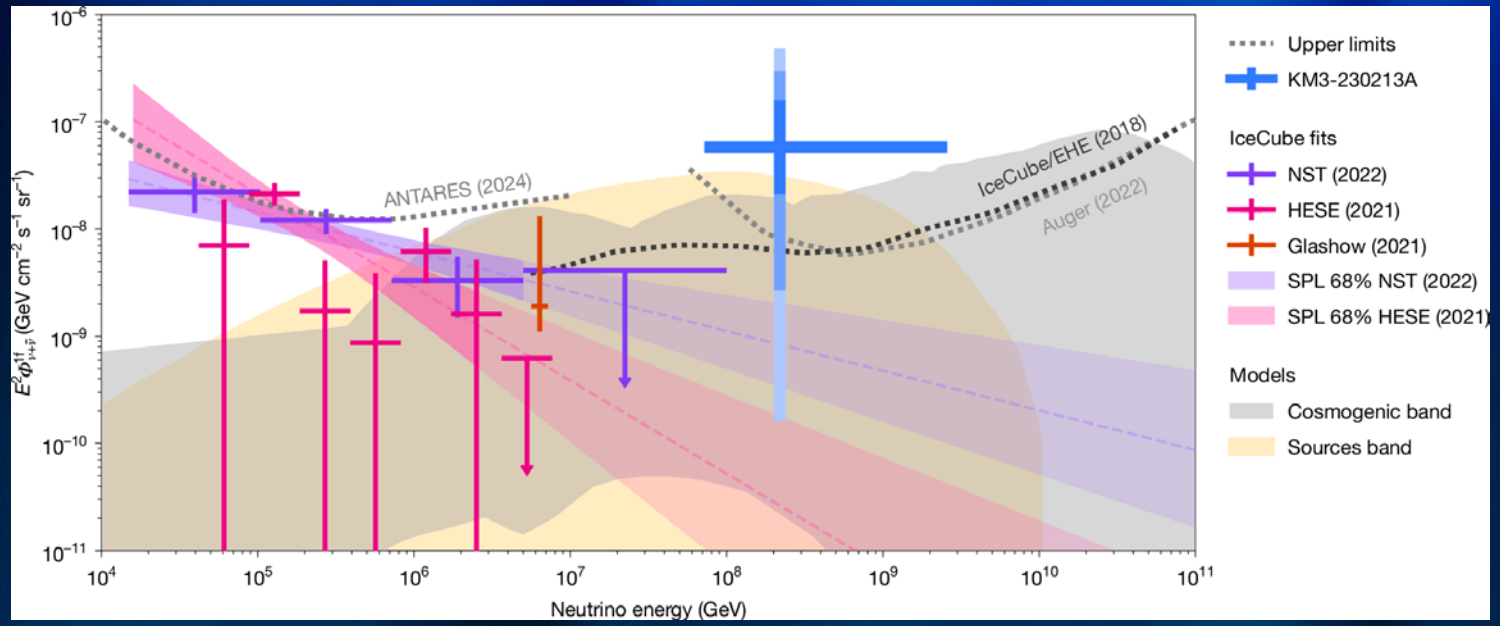


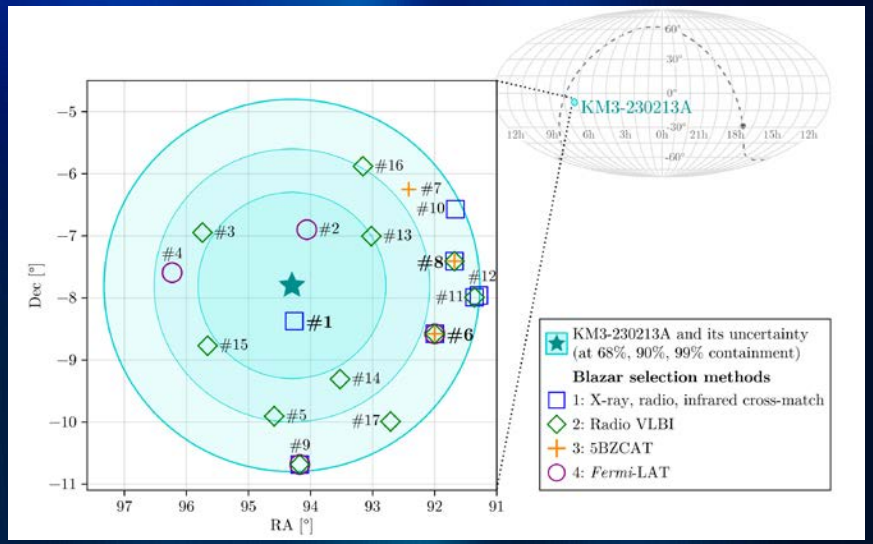


(Ref. Nature 638, 376-382 (2025))

Quest for origin of KM3-230213A is continuing

- Not incompatible with expectations from existing measurements and limits — *Phys. Rev. X **15**, 031016 (2025)*
- No obvious source found, either in Galaxy or beyond — *https://arxiv.org/abs/2502.08387*
- Cosmogenic hypothesis scrutinized — *ApJL **984**, L41 (2025)* — *https://arxiv.org/abs/2502.08484*
- Working on improving the direction accuracy



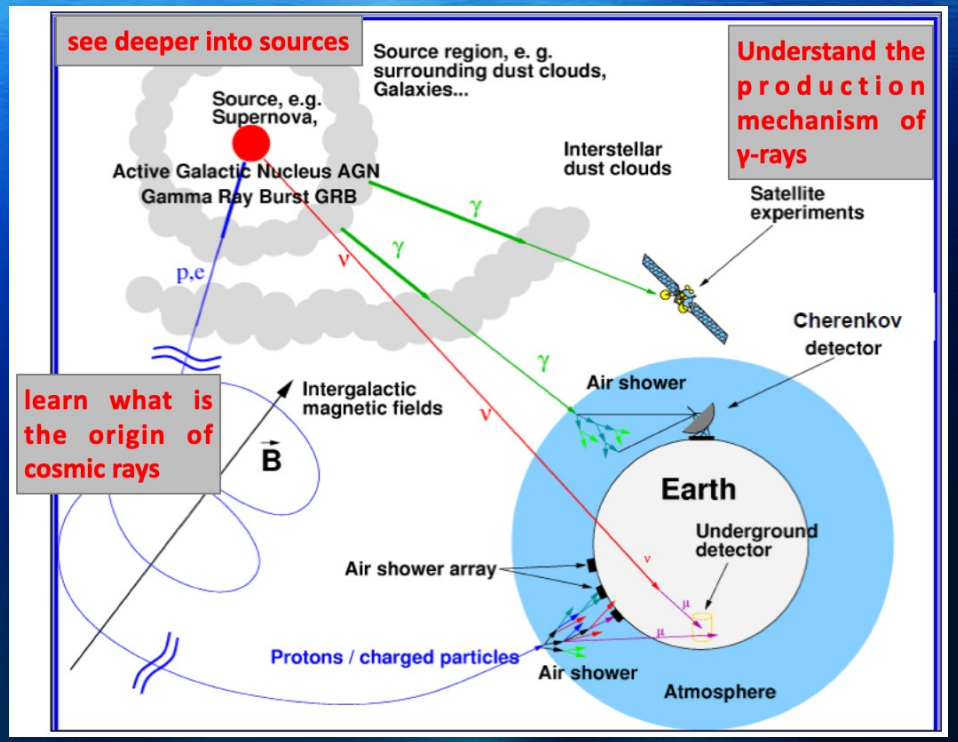


Multi-messenger approach

Multi-messenger astronomy is becoming the most sensitive approach to astrophysical event detection, especially for transient events

Multi-messenger framework developed in KM3NeT

KM3NeT actively monitors and analyses a variety of external triggers in real-time, including alerts due to IceCube neutrinos, Fermi/Swift GRB, HAWC gamma-ray transients, LIGO-Virgo-KAGRA gravitational waves, SNEWS neutrino alerts, and others



- Receiving alert system operative → Real Time Analysis platform active since Nov. 2022 in ARCA & ORCA
- Several thousands of alerts received and analyzed in real time → no significant excess found in any such alert so far
- Sending alert system being set up → High-energy neutrino alerts will be sent in real-time by end of 2025

Outlook and conclusions

The KM3NeT detectors ARCA and ORCA exploit a novel multi-PMT Optical Module design to explore from the deep sea the frontiers of the cosmos and to investigate the neutrino properties

KM3NeT has been taking high-quality data already during its construction phase

New results available about neutrino oscillations, search for cosmic neutrinos and a variety of other topics (atmospheric muons and neutrinos, search for new physics, etc.) – with much more to come!

Highest-ever-energy event, KM3-230213A, observed in rich details

Detector construction is well proceeding:

- effective integration and deployment procedures are in place
- integration facilities are being further extended
- funding secured for ~2/3 ARCA and ~1/2 ORCA, new requests for funds submitted

Aiming at completing both ARCA and ORCA during this decade