

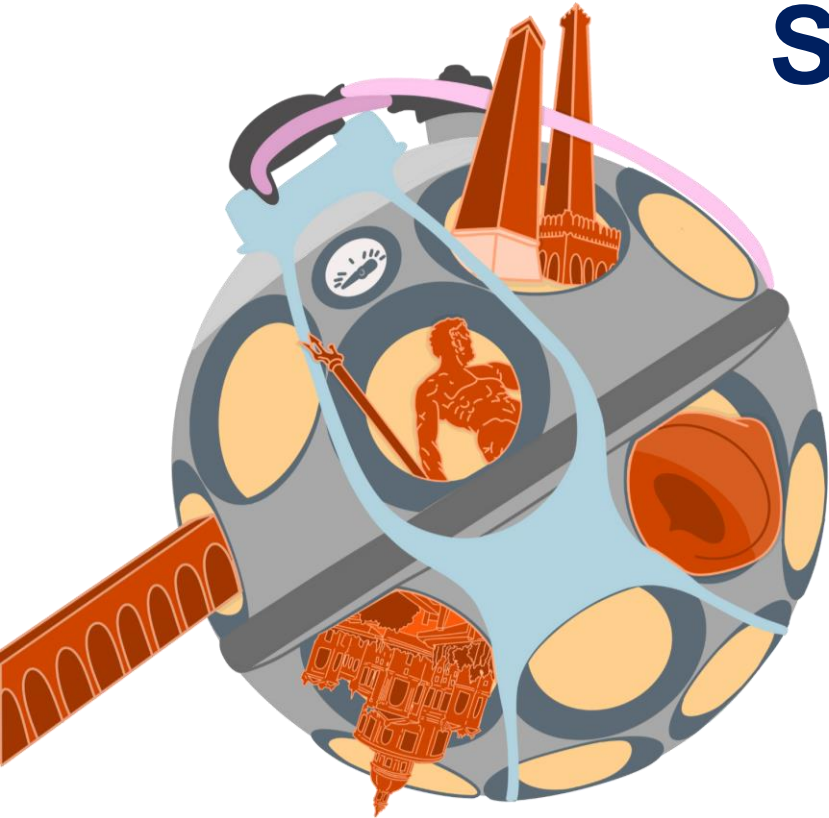


Status and results of KM3NeT

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Dipartimento di Fisica e Astronomia
Alma Mater Studiorum – Università di Bologna

on behalf of the
KM3NeT Collaboration



The KM3NeT Research Infrastructure

Mediterranean research infrastructure: two neutrino detectors and instrumentations for Earth and Sea sciences

KM3NeT/ARCA – **A**stroparticle **R**esearch with **C**osmics in the **A**byss

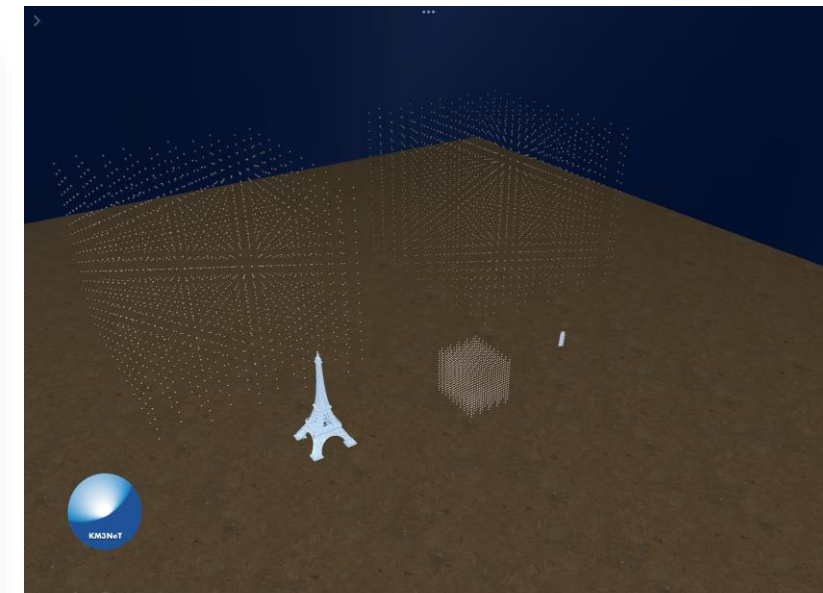
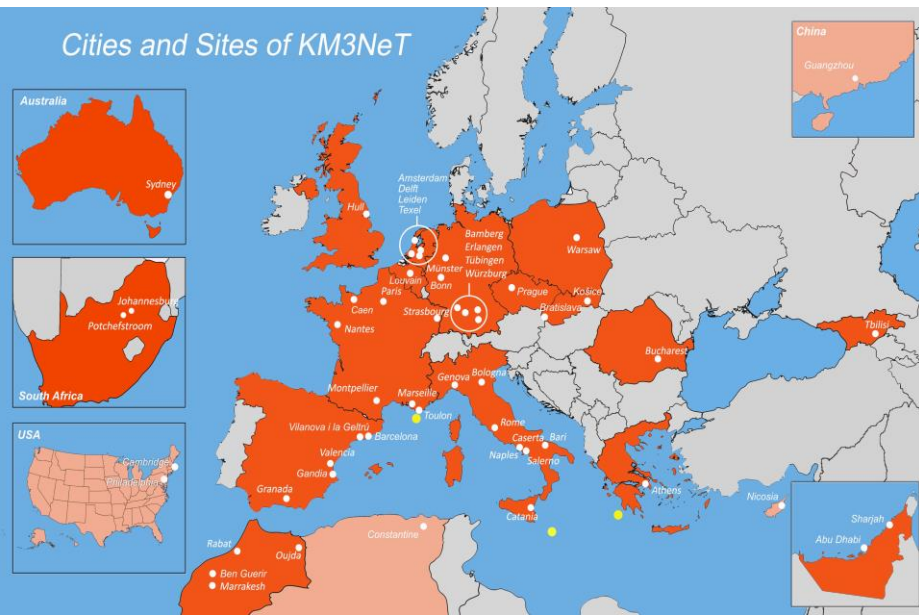
High energy astrophysical neutrinos → offshore Portopalo di Capo Passero (Sicily) – depth 3500m – 115 DUs * 2 Building Blocks - vertical spacing ~ 36 m; horizontal distance ~90 m → ~ 1 Gton = 1 km³

KM3NeT/ORCA – **O**scillation **R**esearch with **C**osmics in the **A**byss

Oscillation studies & Neutrino mass hierarchy → offshore Toulon (France) – depth 2500m – 115 DUs = 1 Building Block - vertical spacing ~ 9 m; horizontal distance ~20 m → ~ 8 Mton

1 collaboration: 62 institutes - 22 countries – 5 continents

2 sites - 2 detectors with the same technology



Natural radiators: low cost and huge instrumented volumes in dark and transparent media → water, ice

Detection of Cherenkov light induced by relativistic charged particles produced in neutrino interactions using a 3D array of PMTs

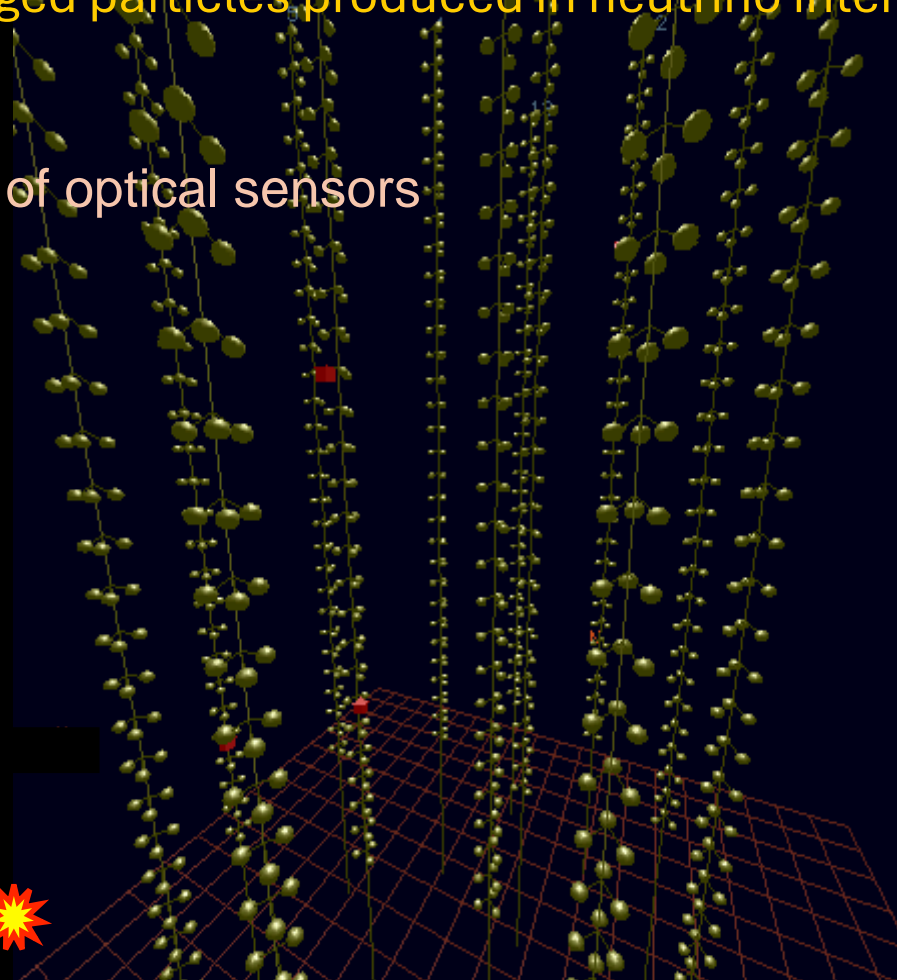
Parent ν direction reconstructed using time & position of optical sensors

Moisej Markov

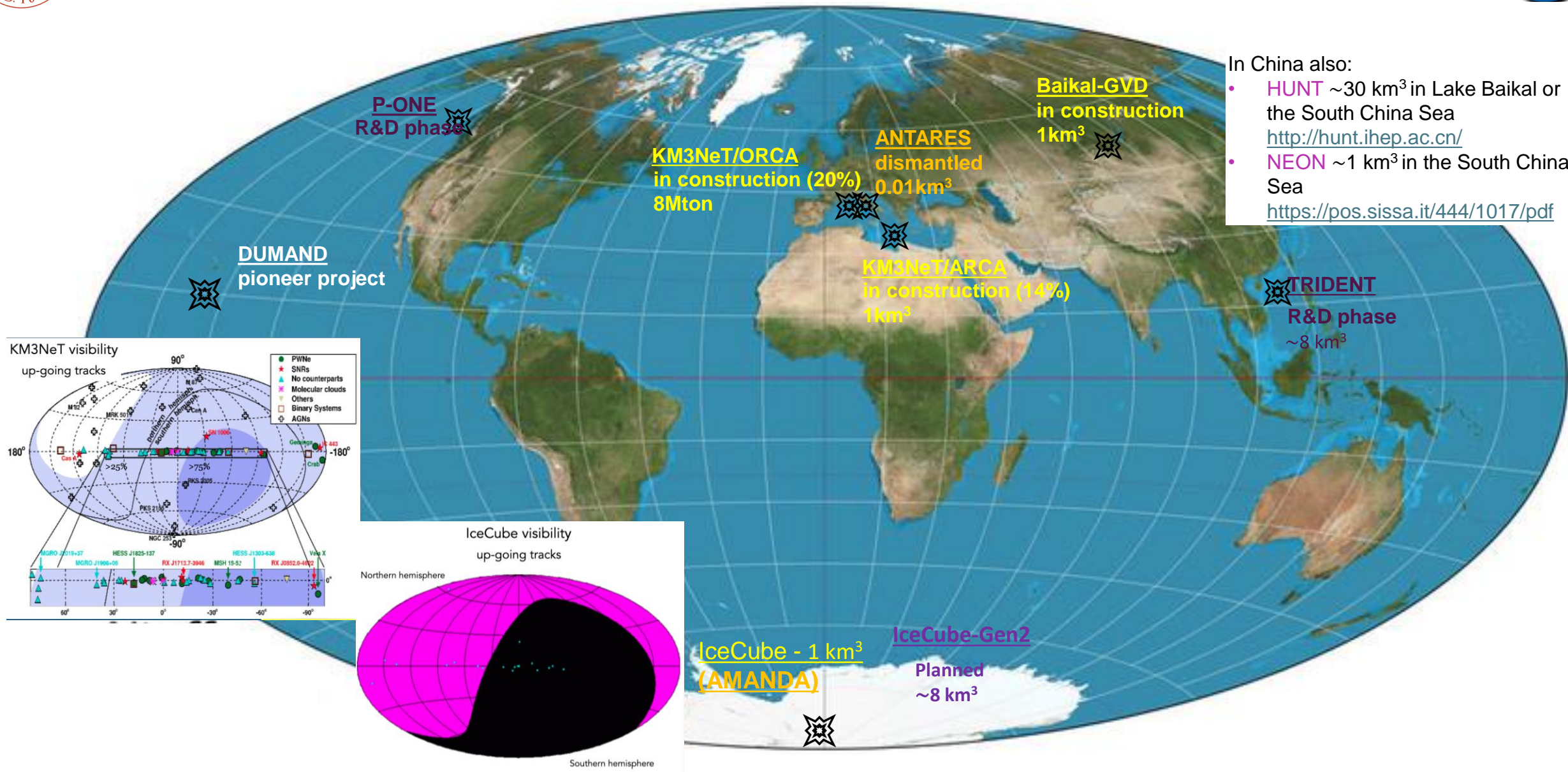
Bruno Pontecorvo

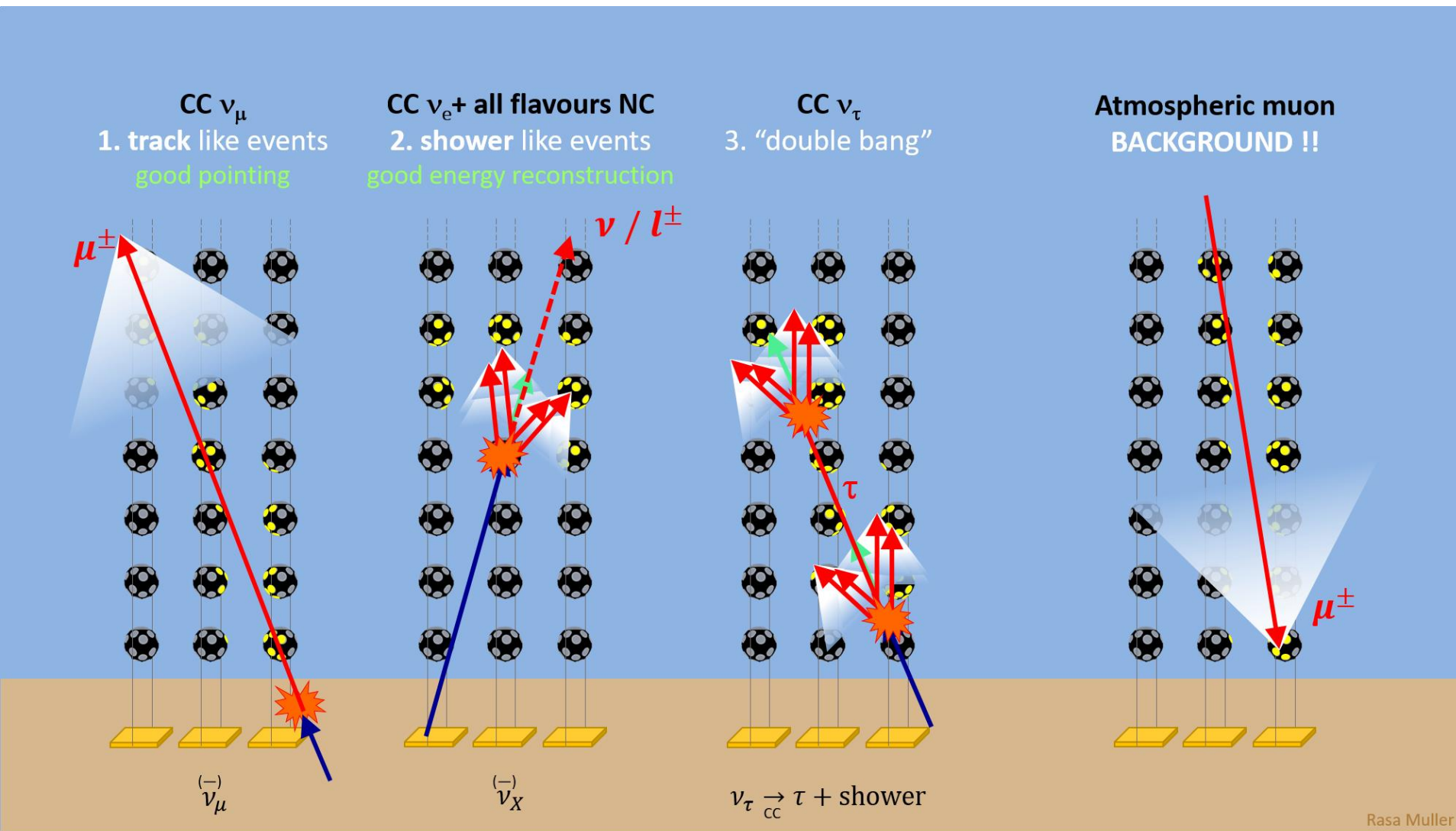


Detection technique
1960, Rochester Conference
M.Markov,
We propose to install detectors deep in a lake or in the sea and to determine the direction of charged particles with the help of Cherenkov radiation

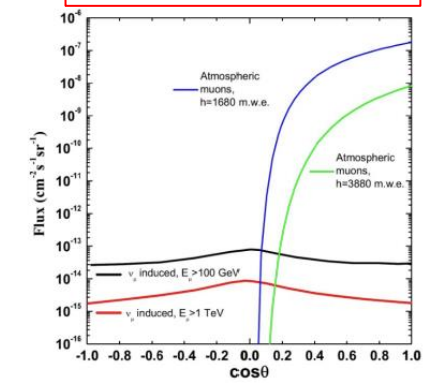


Underwater neutrino telescopes in the world



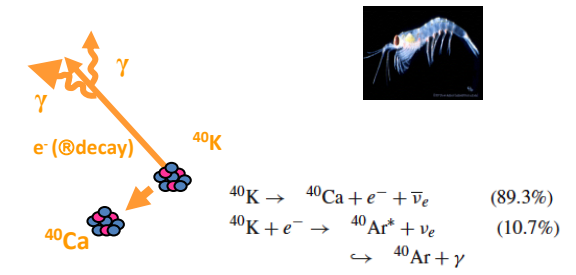


Physics background atmospheric muons



Earth as a shield \rightarrow upgoing events only
 EPJ C 84 (2024) 696

Environmental optical background ^{40}K decay & bioluminescence



causal correlation of the signals

\rightarrow GOLDEN CHANNEL for point sources

Track-like events \rightarrow angular resolution $< 0.1^\circ$ at $E_\nu > 100 \text{ TeV}$ energy resolution \sim factor 2
 Shower-like events \rightarrow angular resolution $< 2^\circ$ at $E_\nu > 100 \text{ TeV}$ energy resolution $\sim 6\%$

	ARCA	ORCA
Location	Italy	France
Site depth	3450 m	2450 m
from shore	100 km	40 km
DU distance	90 m	20 m
DOM spacing	36 m	9 m
DU height	~ 800 m	~ 200 m
Nb. of DUs	2*115	115
Instrum.mass	2*500 Mt	7 Mt
Depth	3500 m	2500 m

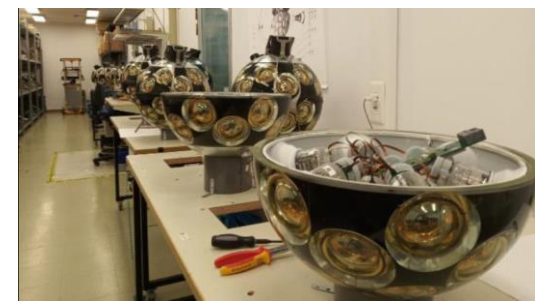
Detection Unit

18 DOMs/DU



Digital Optical Module (DOM)

JINST 17 (2022) P0703



17" glass sphere with

- 31x 3" PMTs $\approx 3 \times 10$ " PMTs photocathode area
- LED, Piezo (acoustic positioning), system sensors (monitoring)
- Front-end electronics -> FPGA



Acoustic beacon



Hydrophone



DU Base Module



Acoustic beacon



The technology

The LOM
(Launcher of Optical Modules)

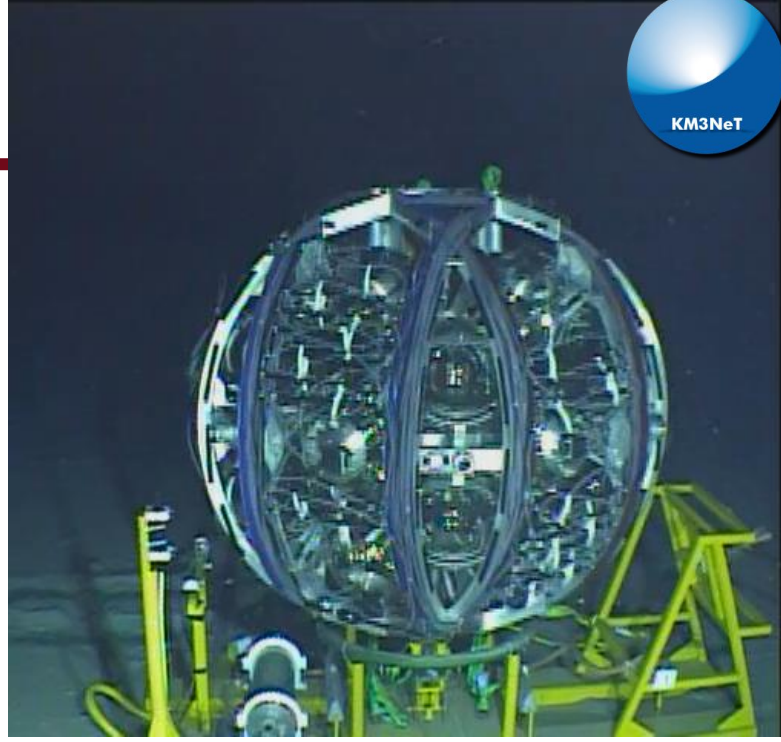
JINST 15 (2020) P11027



The sea floor network:

- **Electro-optical cables** from shore to the deep sea
- **Junction boxes/nodes** to distribute power and optical fibers
- **Cable Termination Frames (ARCA)**
- **Interlink cables** for connection of DU to JB and JB to the main cable

The deployment and the connection

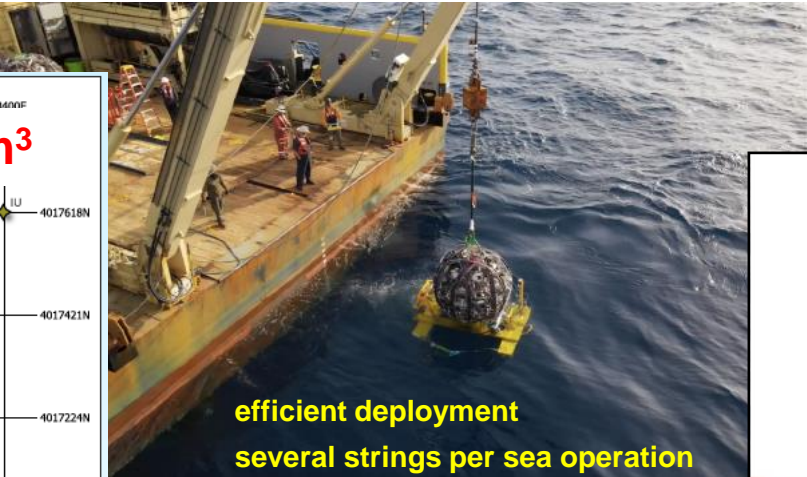
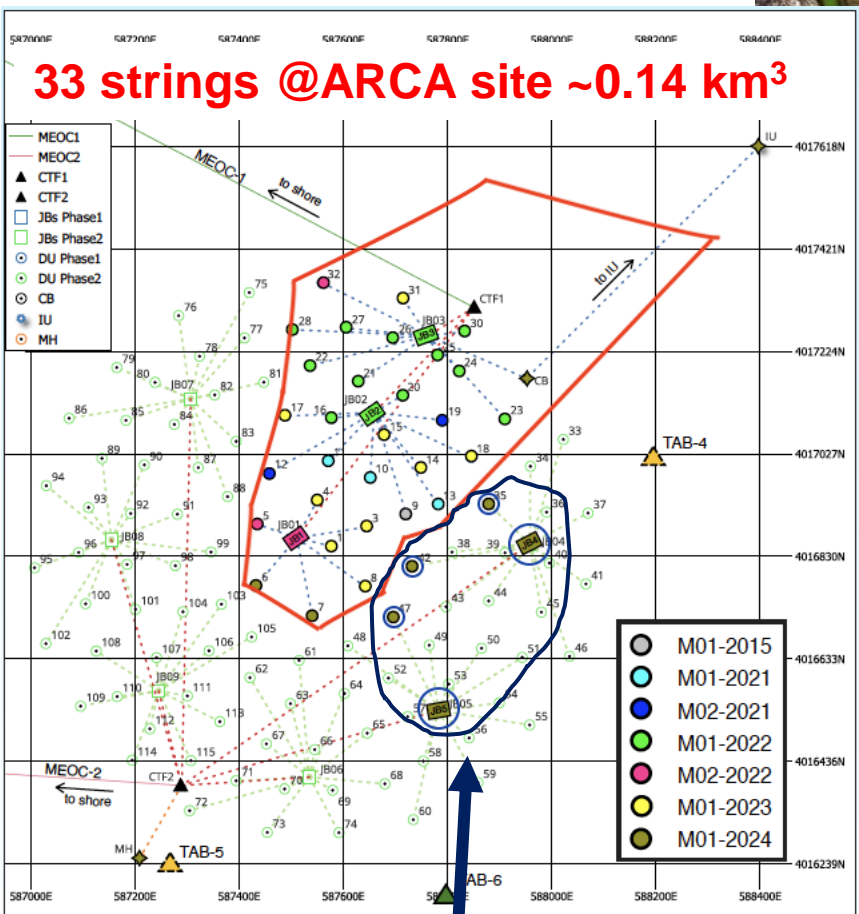


ARCA
Junction Box



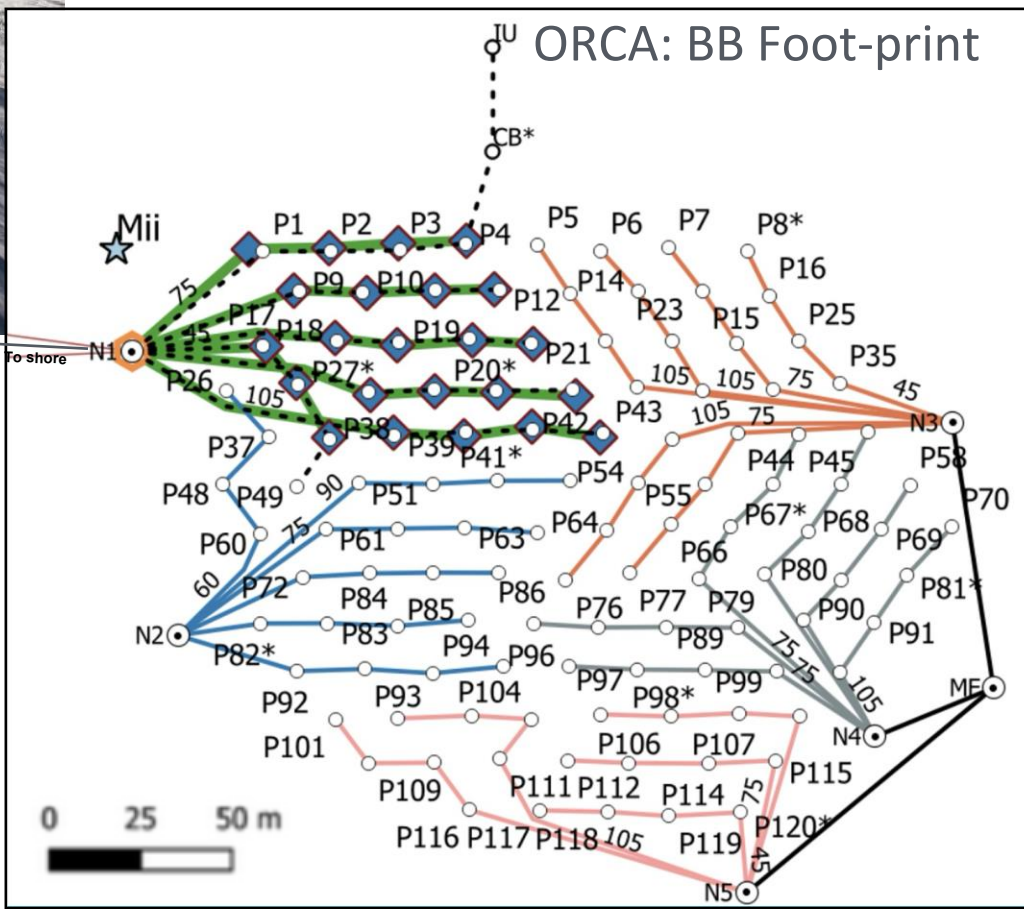
Status of the construction

1 long sea operation/year



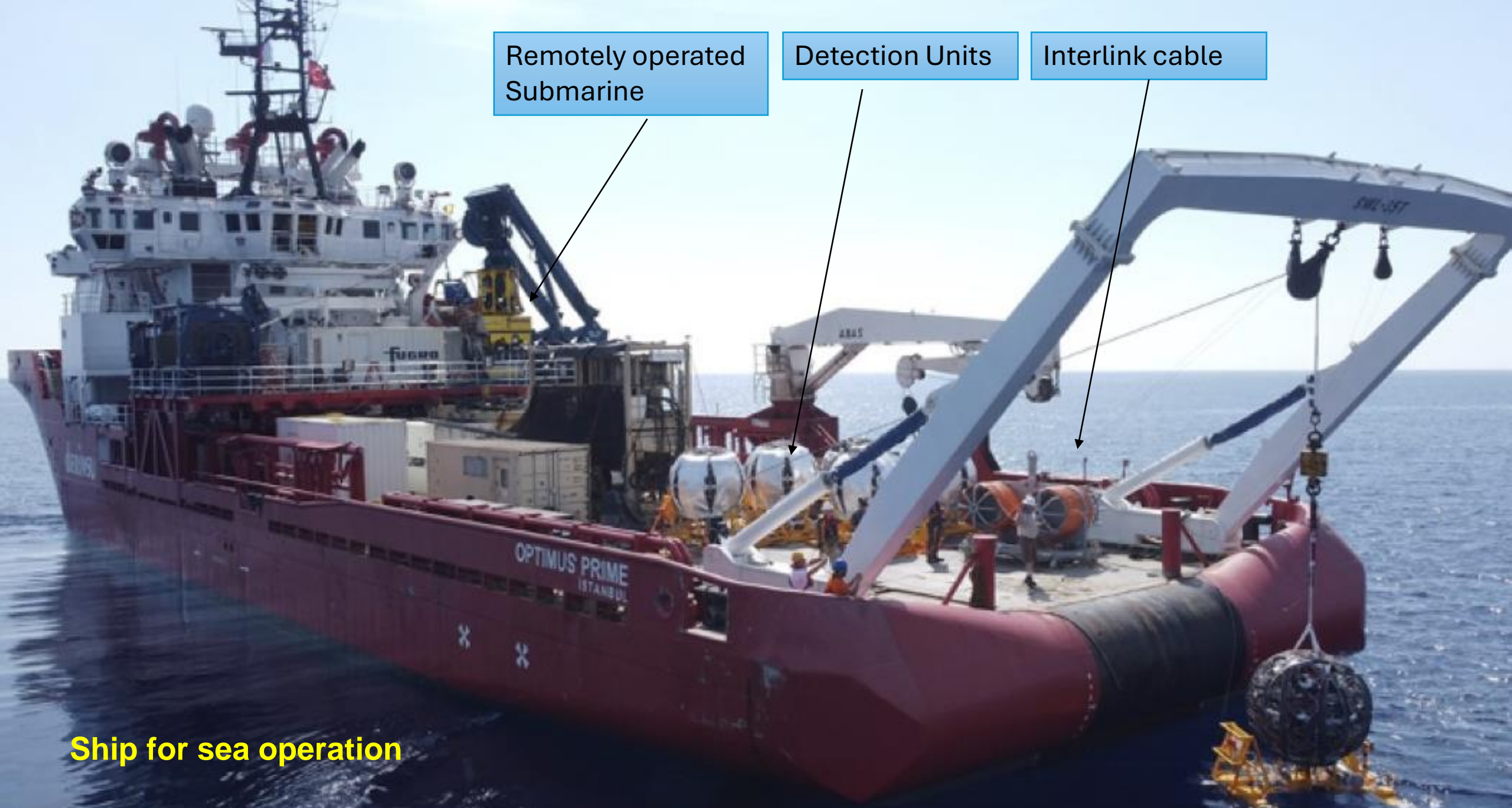
The DUs on board, furling around the LOM

24 strings @ORCA site



Almost completed the first node ~ 20% ORCA
several short sea operations/year

ARCA Phase-2 started: 3 DUs + 2JBs
New DAQ architecture → “Wet” White Rabbit



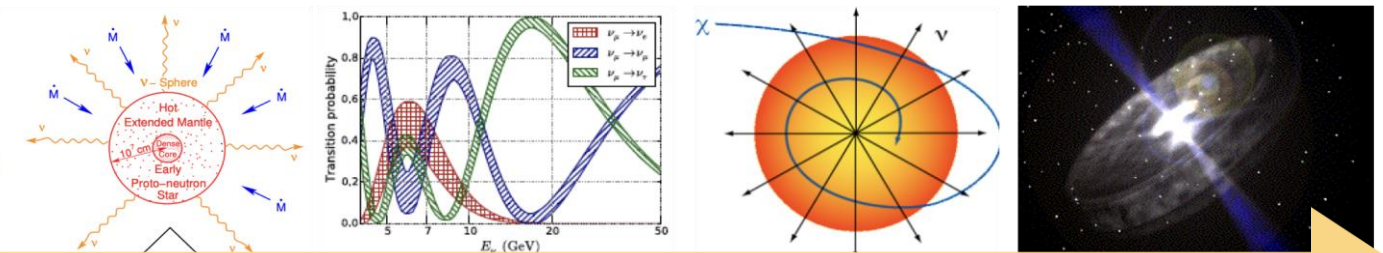
Remotely operated
Submarine

Detection Units

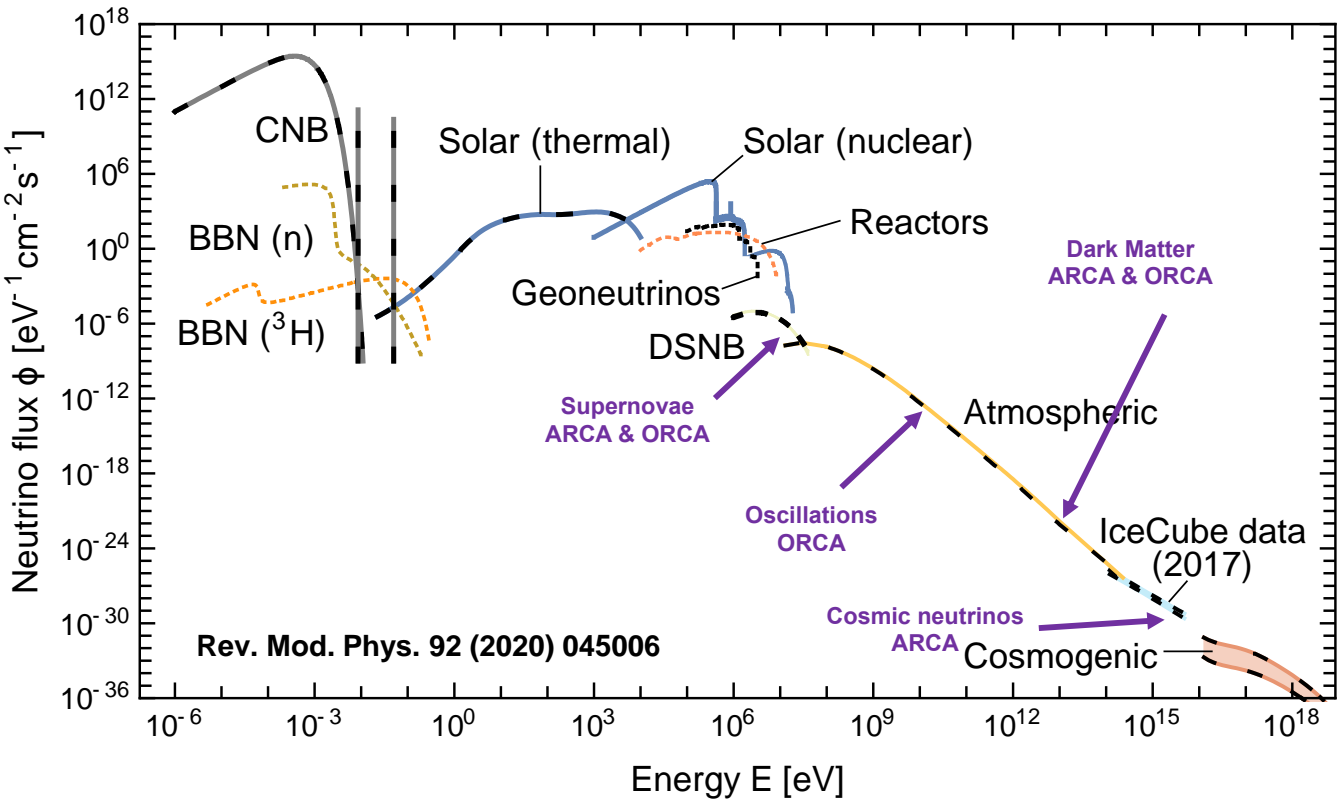
Interlink cable

Ship for sea operation

Super Novae explosion Neutrino oscillation Dark Matter HE neutrinos Multi-messenger program



Neutrino Energy from MeV to PeV



Wide physics program

- Cosmic neutrinos
- Intense multimessenger activity
- Atmospheric neutrino oscillations:
 - Oscillation parameters
 - Neutrino mass hierarchy
 - Non-standard physics
 - Particle physics properties
- Indirect search of Dark Matter
- Exotic particles
- Beyond the Standard Model Physics

Exploration of a large energy range

Supernova Explosion

Each DOM used as a single detector – multiplicity = nb of hit PMTs in a single DOM

>5 σ for ARCA+ORCA for 27M $_{\odot}$ at a distance <50kpc

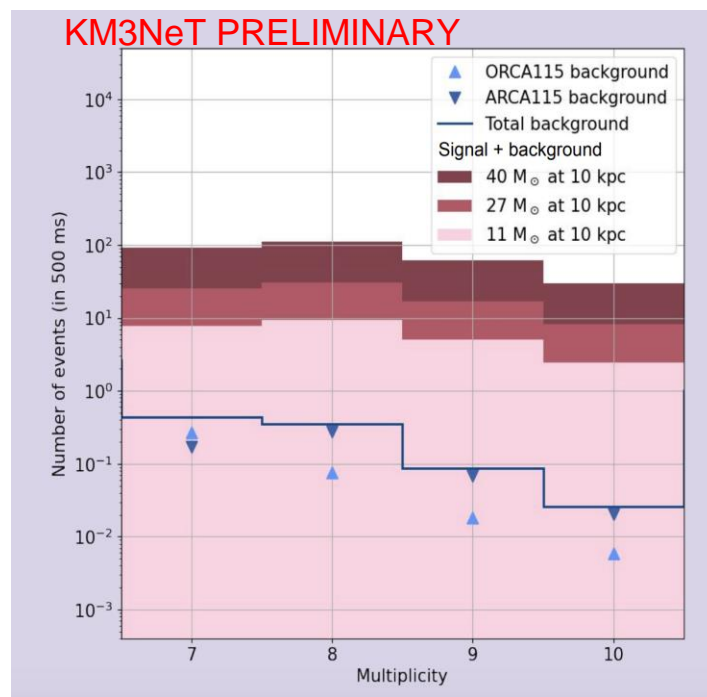
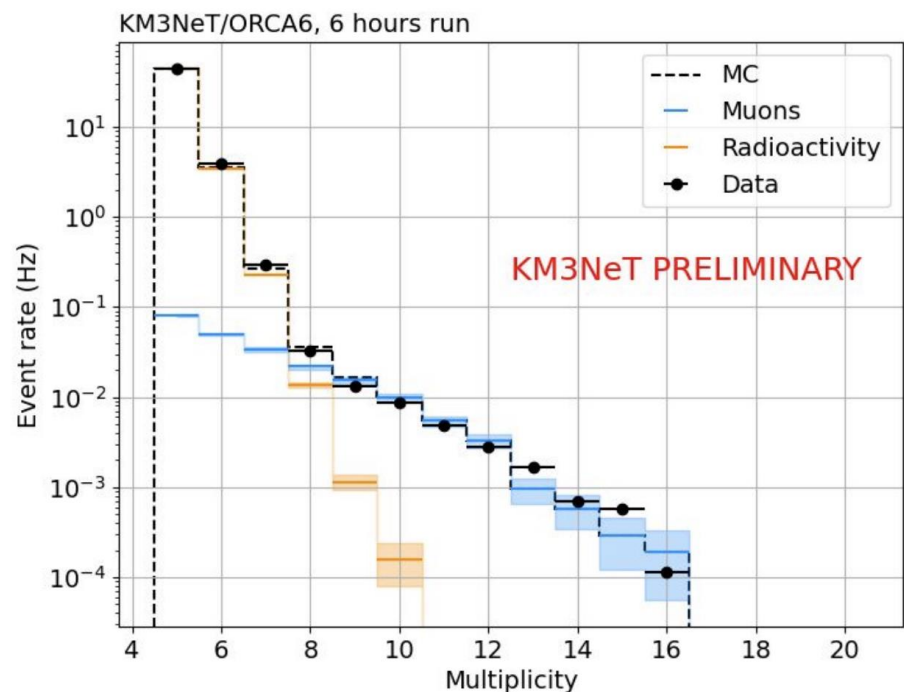
EPJ C81 (2021) 445

EPJ C82 (2022) 317

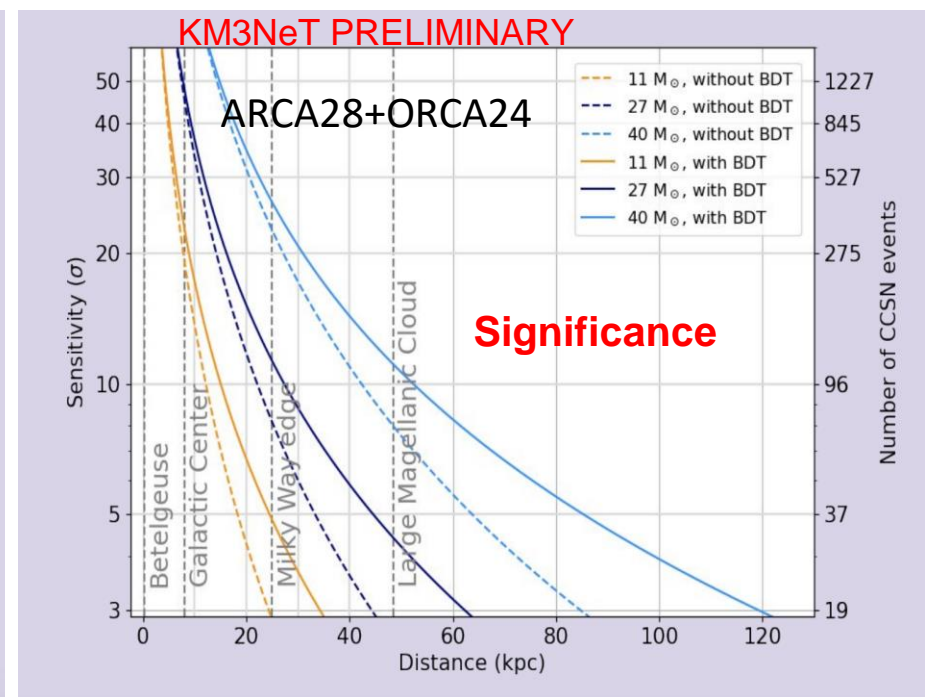


on-line alert system for CCSN integrated in SNEWS

PMT multiplicity plot

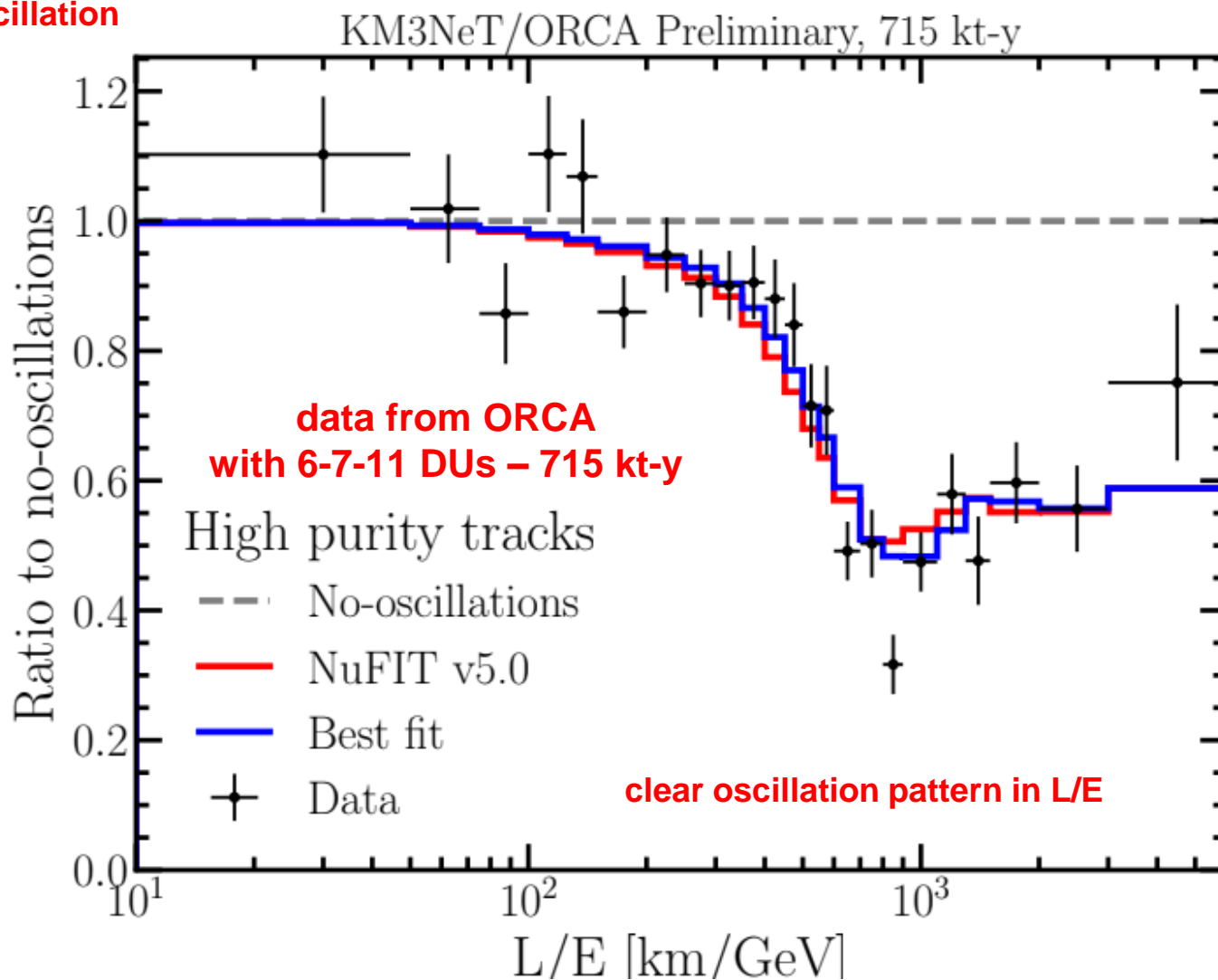
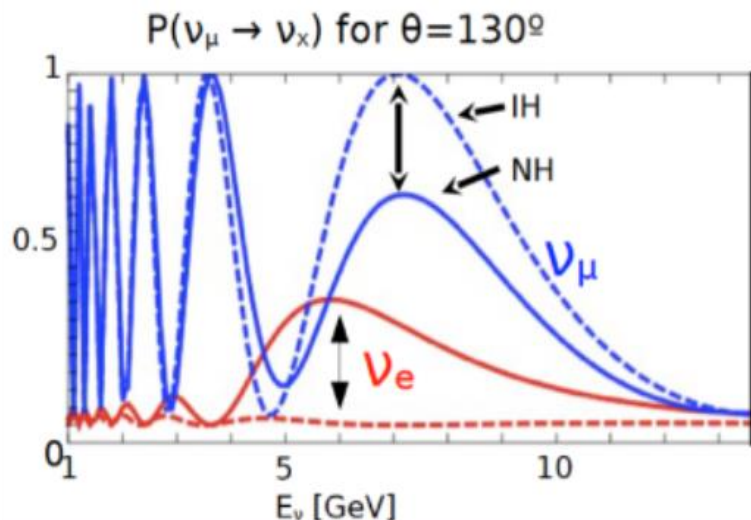
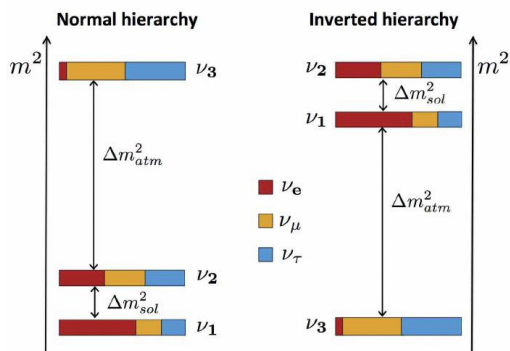
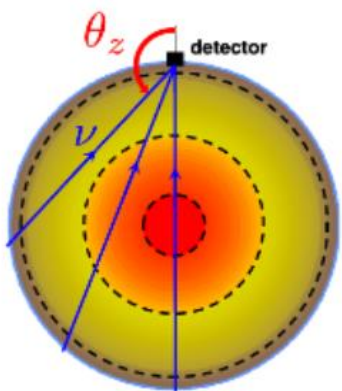


Expected signal above background



Determination of Neutrino Mass Ordering comparing oscillation patterns of atmospheric neutrinos crossing the Earth

Baseline from 50 to 12800 km



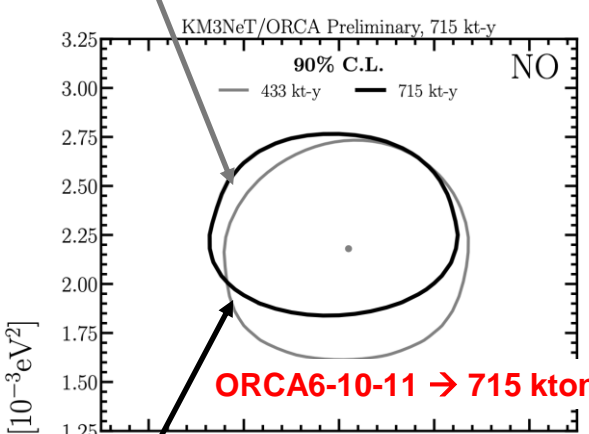
JHEP10(2024)206 - ORCA 6 only

Neutrino oscillations with ORCA

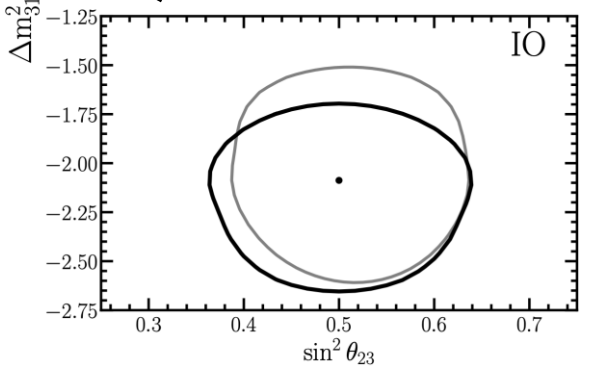
- JHEP10 (2021)180
- Eur. Phys. J. C82 (2022)26
- JHEP03 (2022)55
- arXiv: 2411.19078

New analysis - increased exposure: 433kt-yr (ORCA6) → 715 kt-yr (ORCA6-7-11)

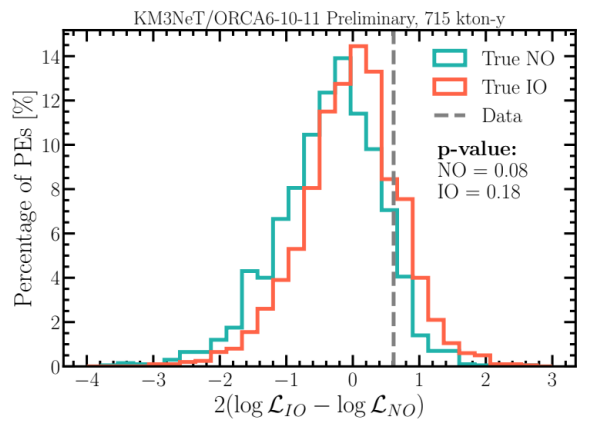
ORCA6 → 433 kton-yr



ORCA6-10-11 → 715 kton-yr



Δm^2_{31} vs $\sin^2 \theta_{23}$

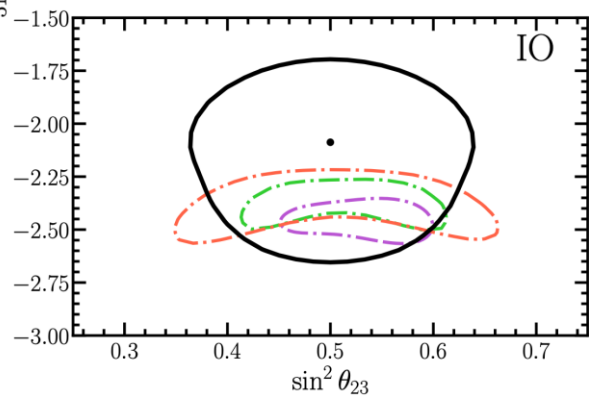
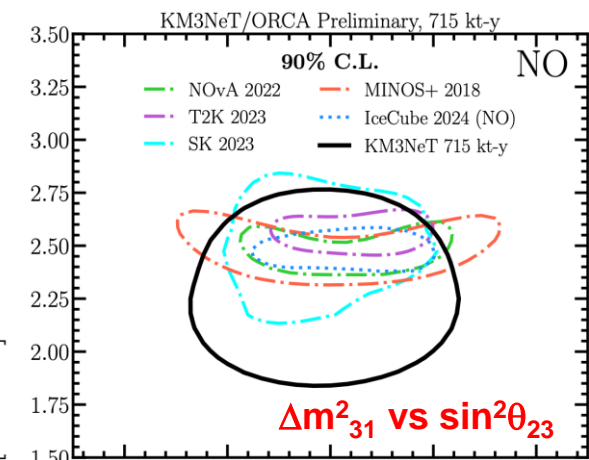


Fully consistent with world data
NO hypothesis disfavoured at 1.7σ
IO preference slightly stronger than expected

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

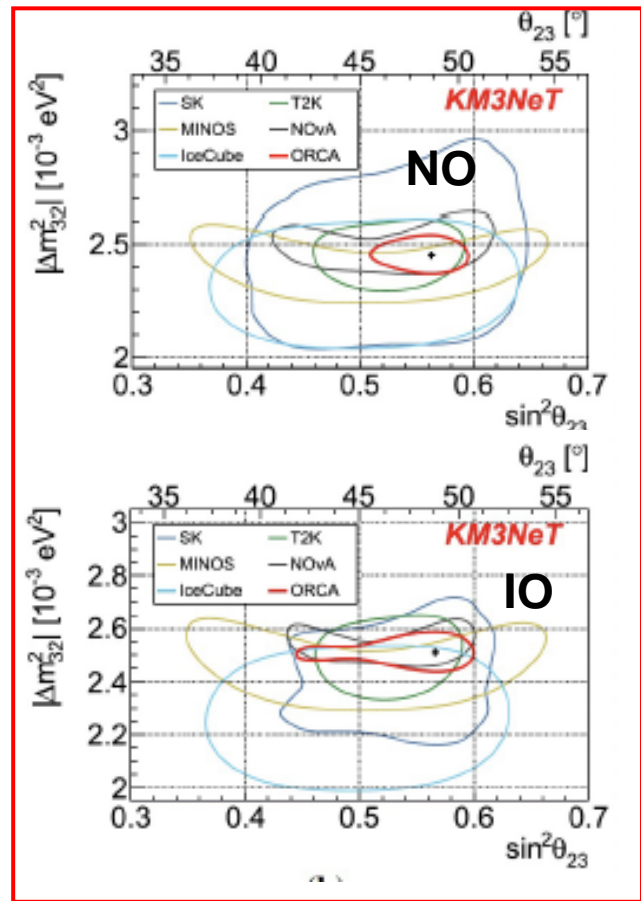
$$\sin^2 \theta_{23} = 0.50 \pm 0.07$$

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



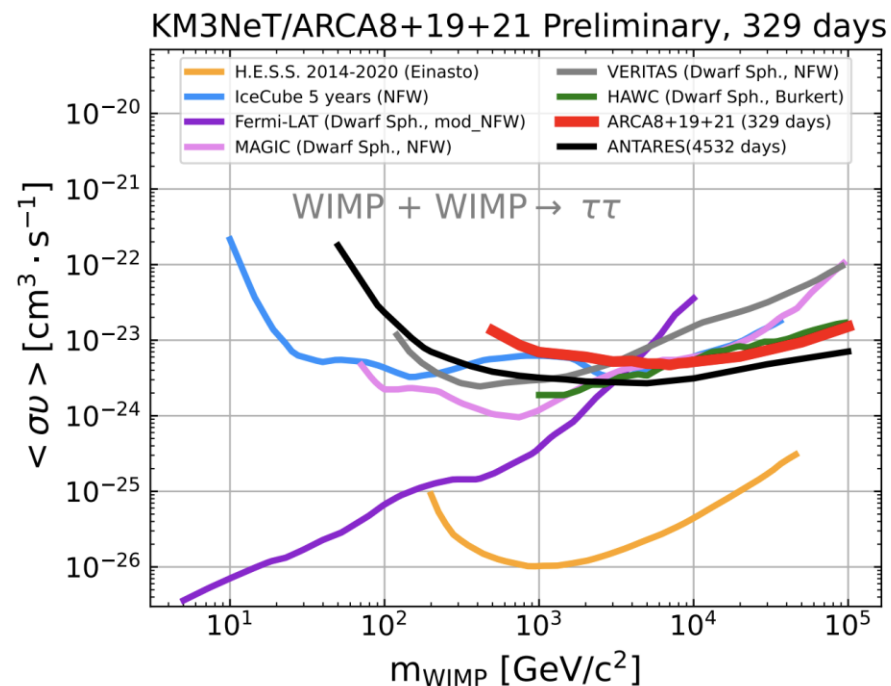
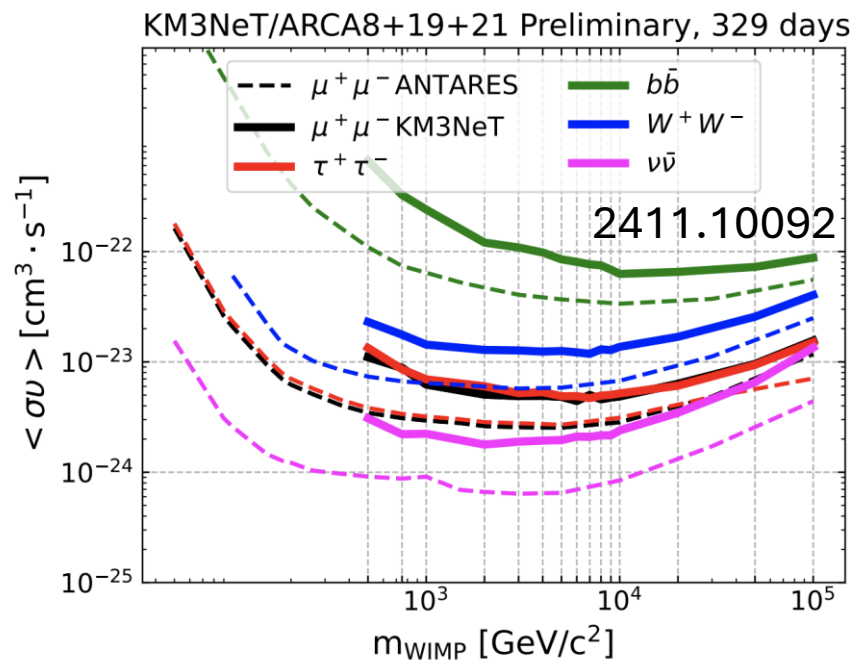
More details on physics BSM
talk of Rebecca Gozzini

Full detector expectations



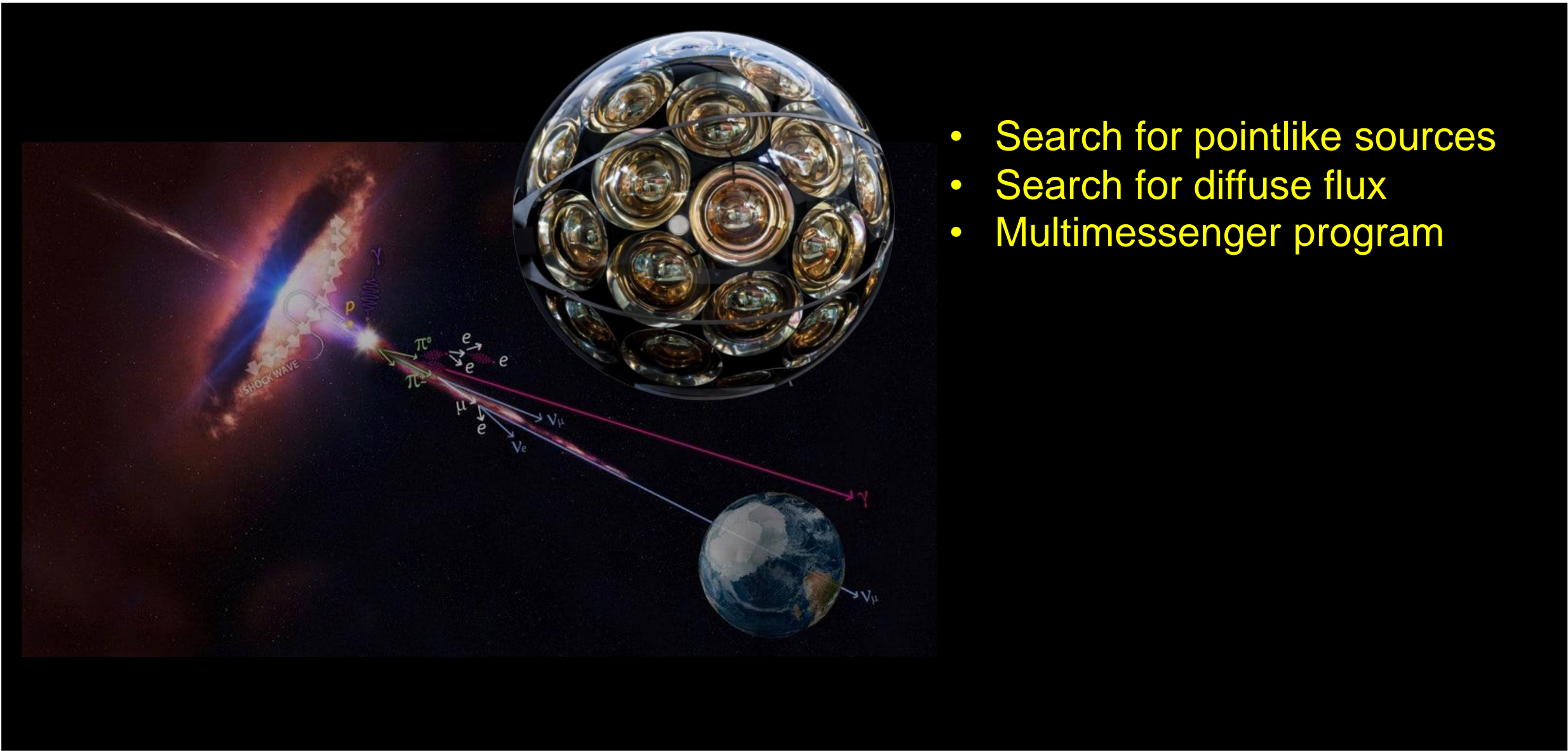
- JHEP04 (2023) 090
- arXiv: 2411.19078
- arXiv: 2410.01388

Neutrinos from the annihilation of Dark Matter particles (WIMPs) trapped in the centre of Galaxy, Sun



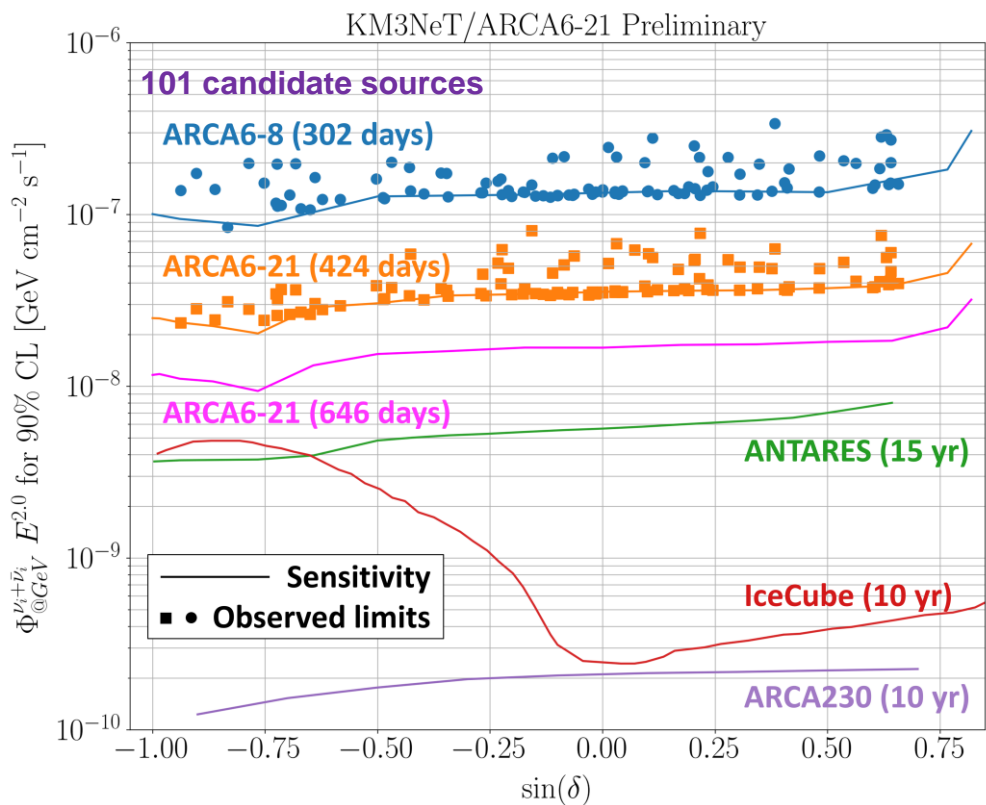
More details on Dark Matter talk of Rebecca Gozzini

arXiv: 2411.10092

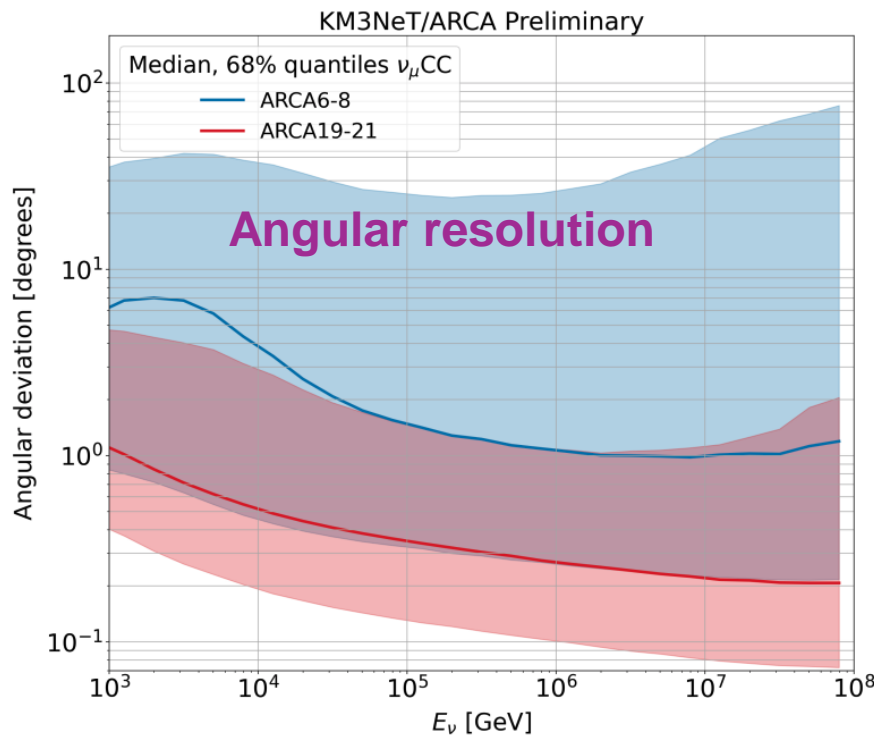


- Search for pointlike sources
- Search for diffuse flux
- Multimessenger program

Search for pointlike sources



- Search for an excess of events from the direction of a list of 101 candidate sources
- **ARCA upper limits quickly improving**
- Data collected with ARCA21 only partially exploited.
- Full ARCA21 soon available, together with ARCA28 (data taking from September 2023) and ARCA33 (from October 2024)

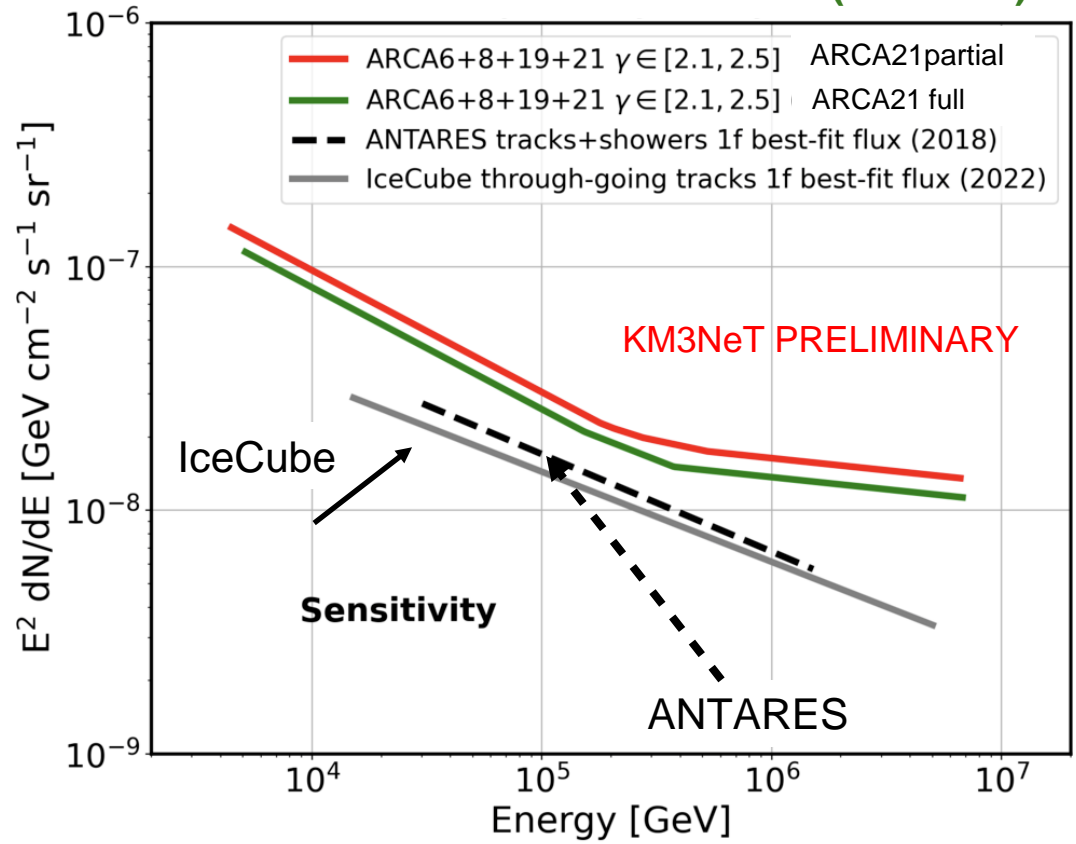


Joint ARCA-ANTARES point-like searches on going.

ANTARES (15y) contributes most significantly, enhancement by 10% observed adding ARCA data (424d)

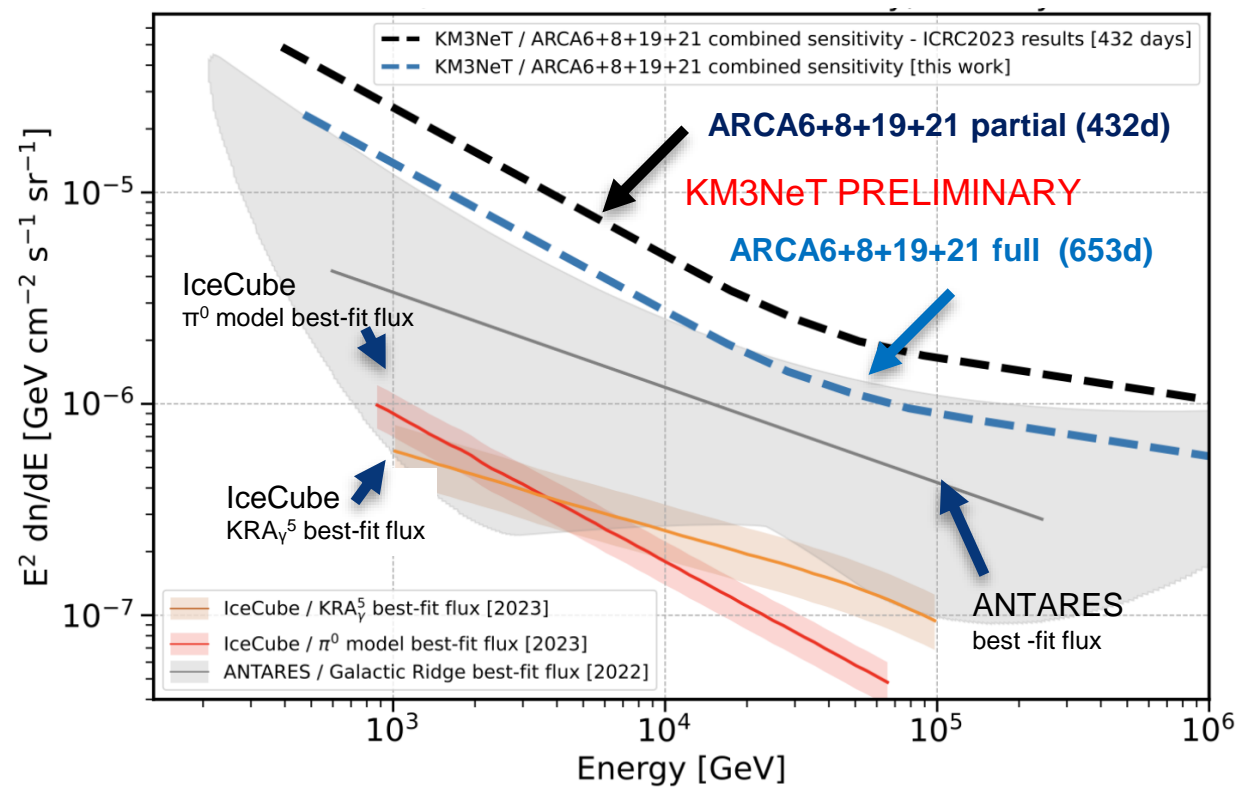
From the full sky

KM3NeT/ARCA6+8+19+21partial (LT=432d)
KM3NeT/ARCA6+8+19+21full (LT=653d)



From the Galactic plane

KM3NeT/ARCA6+8+19+21partial (LT=432d)
KM3NeT/ARCA6+8+19+21full (LT=653d)



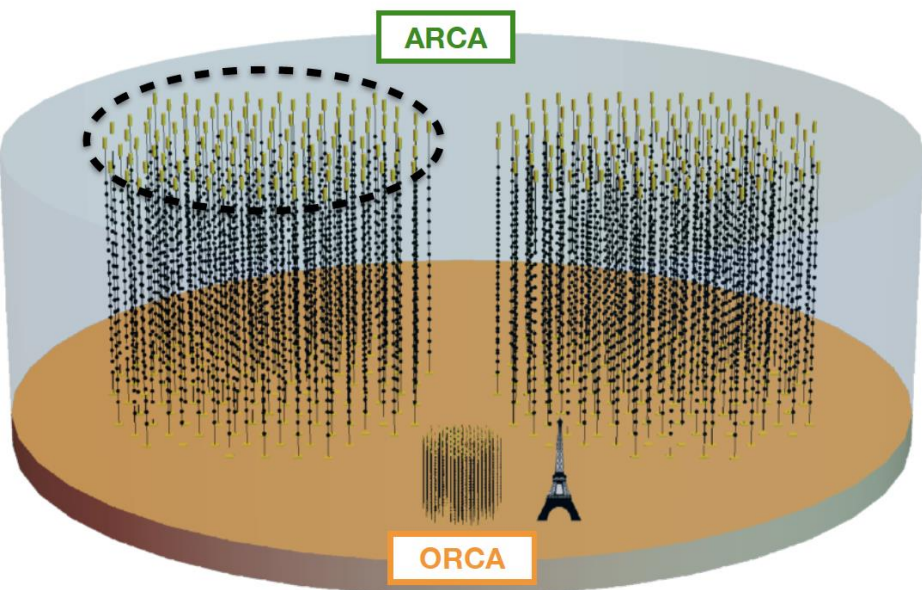
$|| < 31^\circ$ and $|b| < 5^\circ$ for ARCA6-8 & $|| < 31^\circ$ and $|b| < 4^\circ$ for ARCA19-21

Neutrino searches in space-time coincidence with other cosmic messengers: photons, gravitational waves,...

A dedicated software already available at the shore stations for **Real-Time Analysis (RTA)**

from November 2022 ARCA and ORCA detectors receiving alerts
end 2024 ARCA and ORCA will be also sending high-energy neutrino alerts

📖 ICRC2023 PoS 1125
📖 ICRC2023 PoS 1521

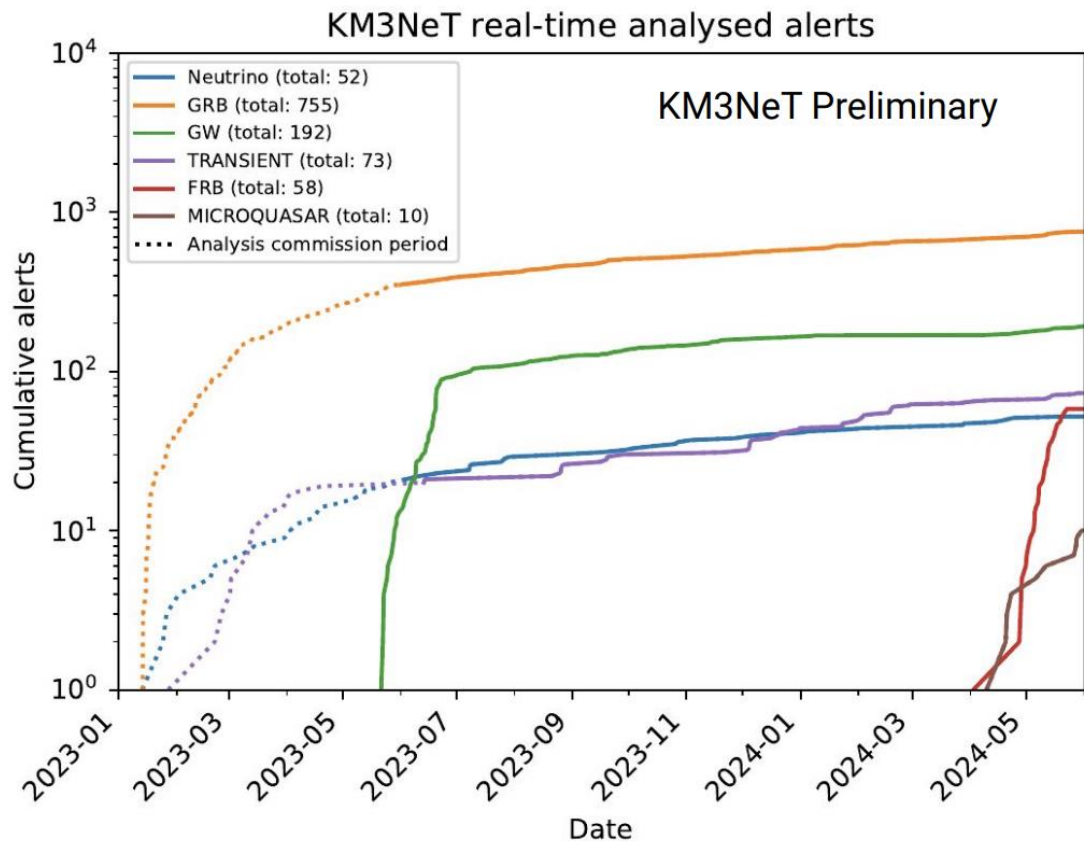


Receiving alerts - on-line analysis and follows ups
active since Nov 2022

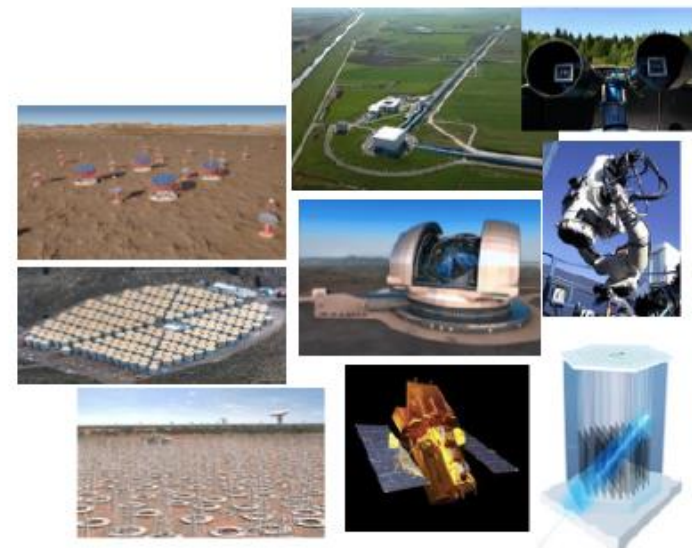


Sending alerts to astrophysical community
will be active by end 2024





EM/MM external communities



Several thousands of alerts received and analyzed in real time → so far no significant excess found in any alert

Not only online alerts, several offline analyses published and in progress:

📖 JCAP04(2024)026 (Gravitational Waves – O3 Virgo/Ligo)

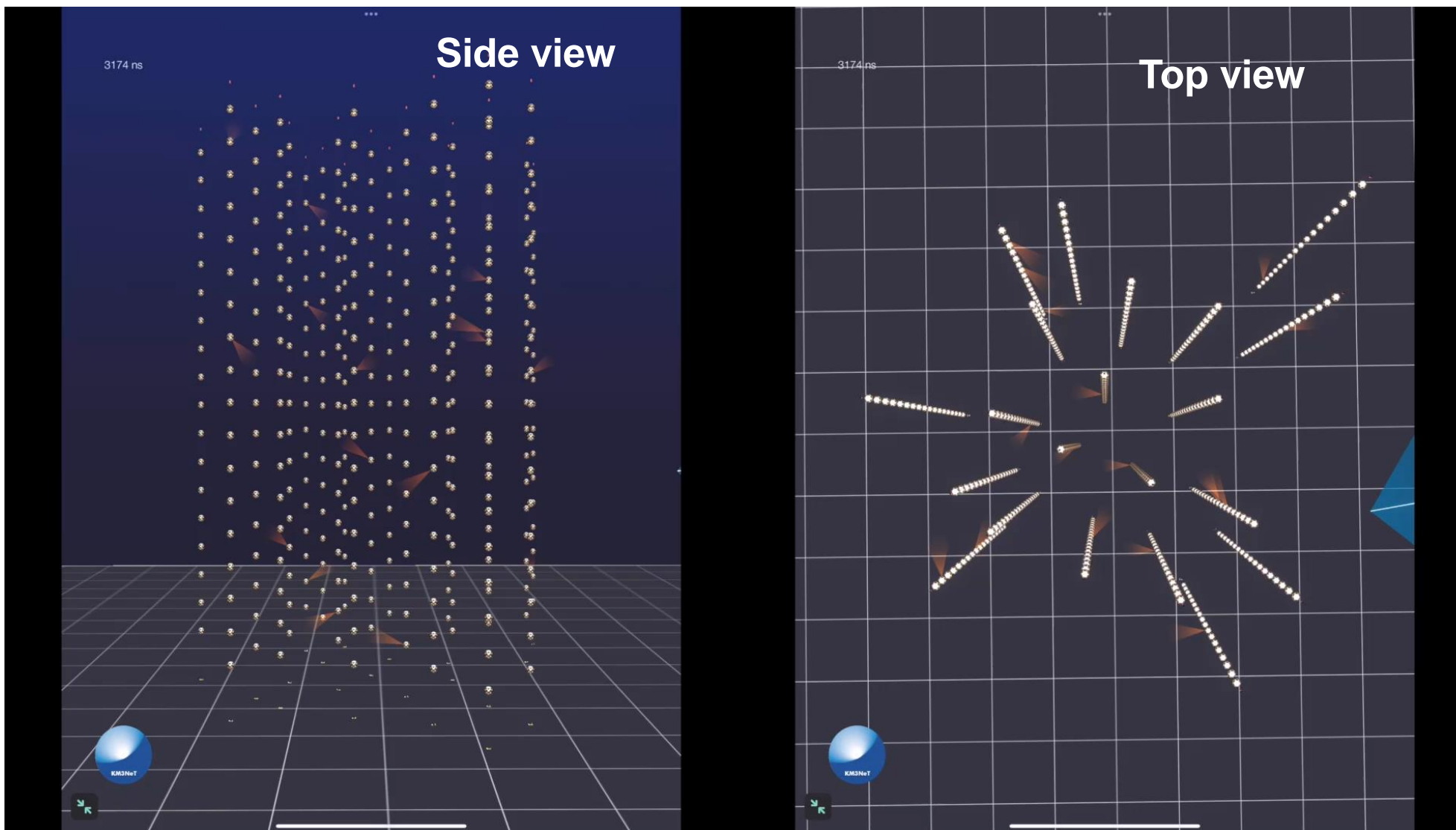
📖 JCAP08(2024)006 (GRB 221009A)

If on a winter's night a traveler (I. Calvino)



A very special encounter...

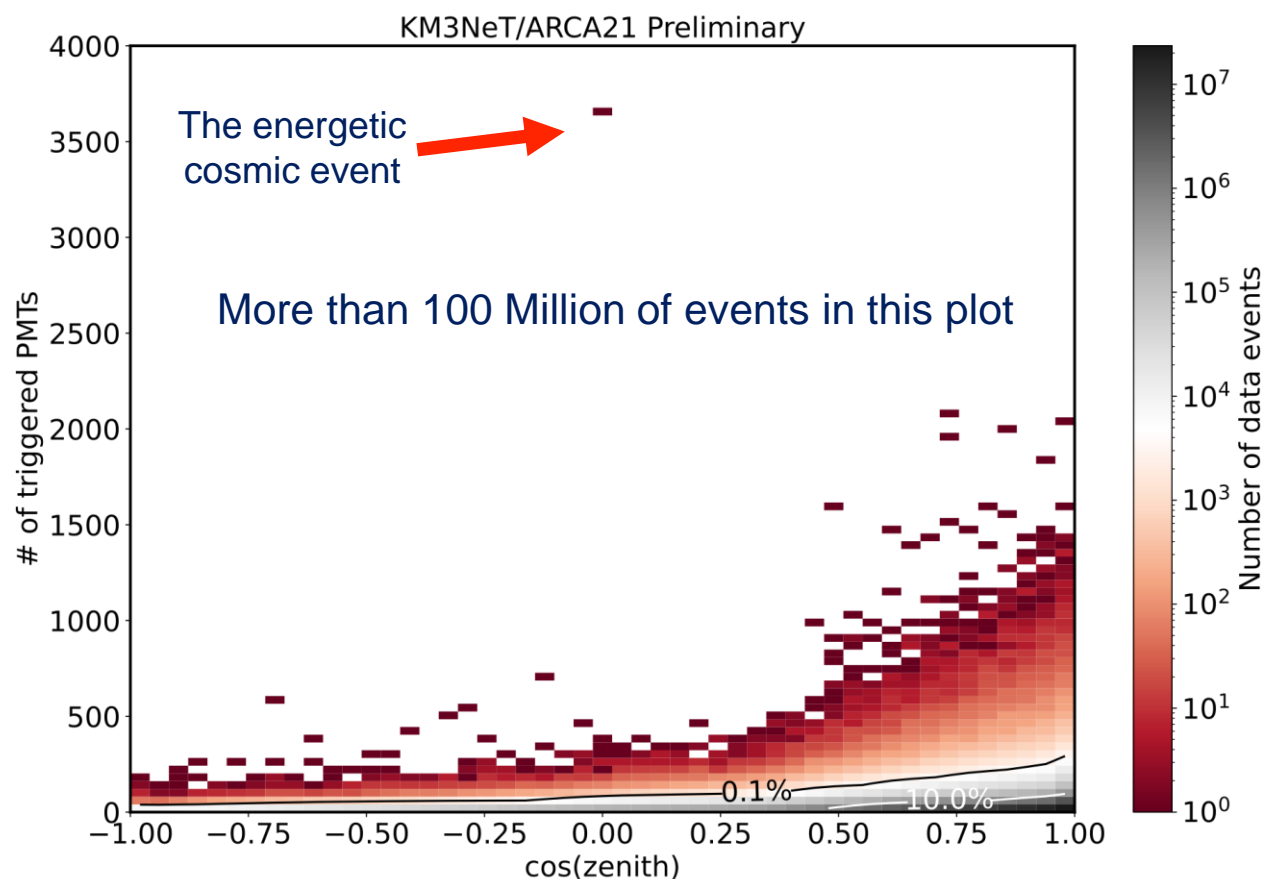
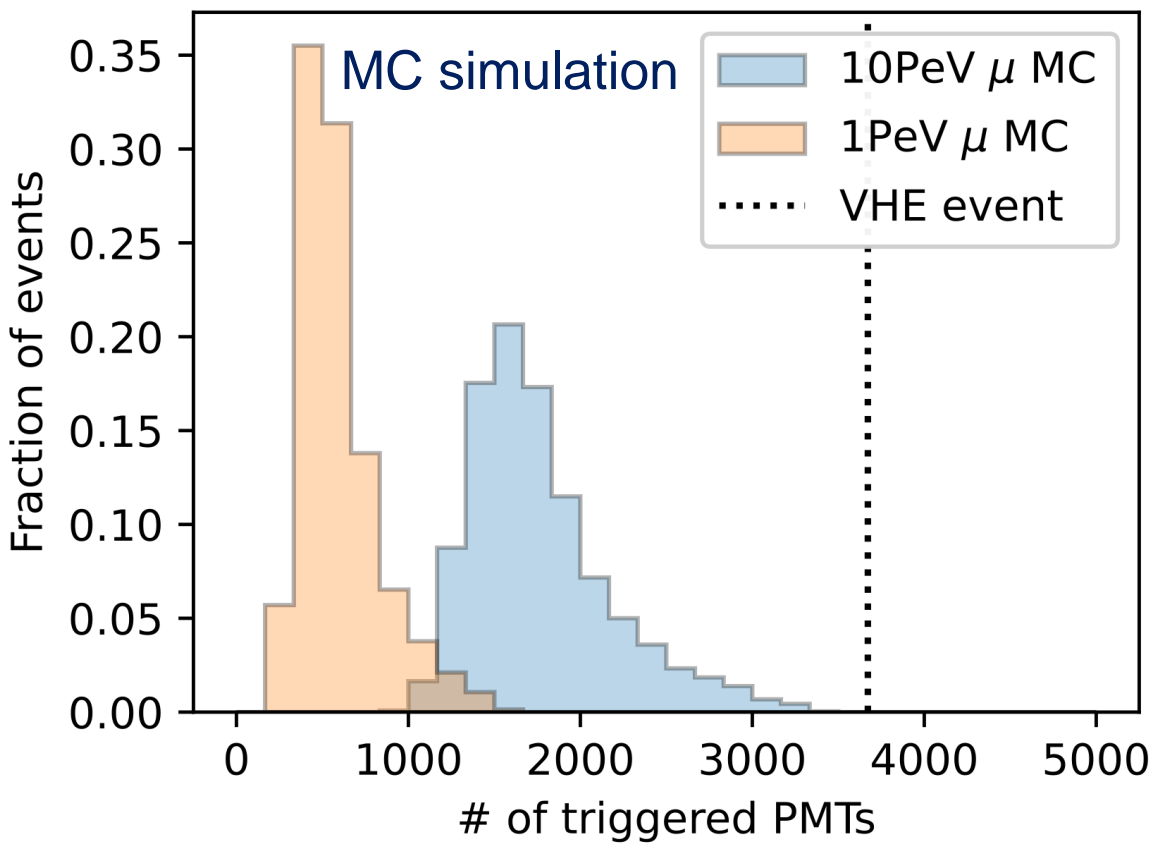
The most energetic neutrino event so far



The most energetic neutrino event so far

Huge amount of light detected → 3672 PMTs were triggered = 35% of the total

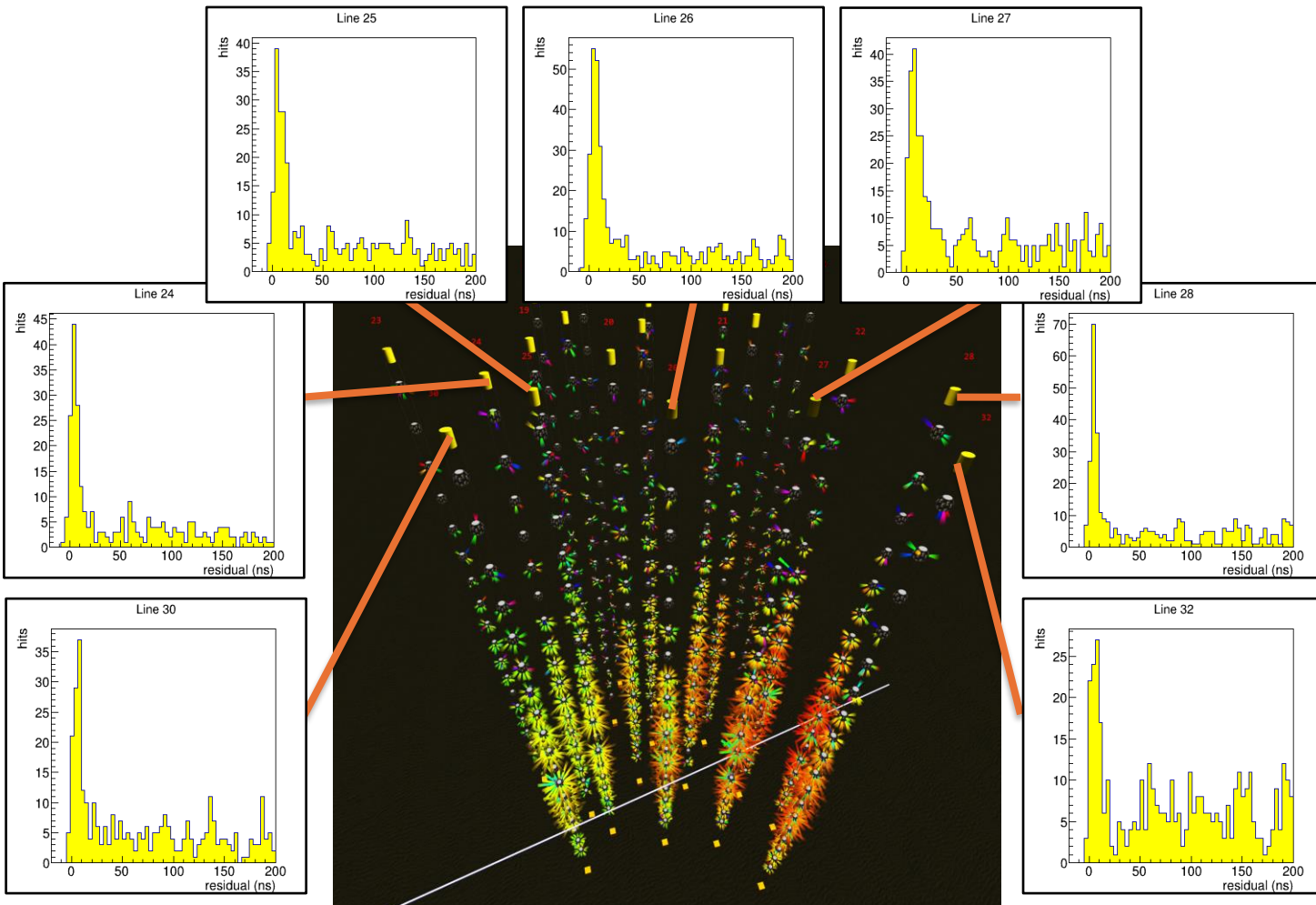
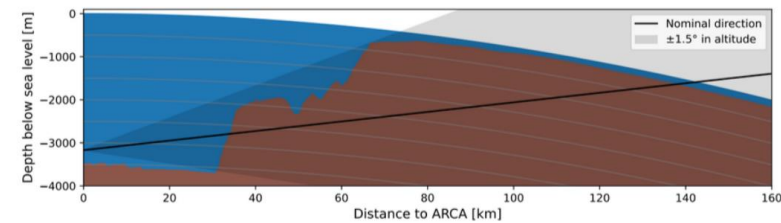
Almost horizontal event (1° above the horizon) with energy above 10 PeV



The most energetic neutrino event so far

Event is well reconstructed as a high energy muon crossing entire ARCA21 detector

Unlikely for atmospheric muon to travel through that much water/ground -> neutrino



nature

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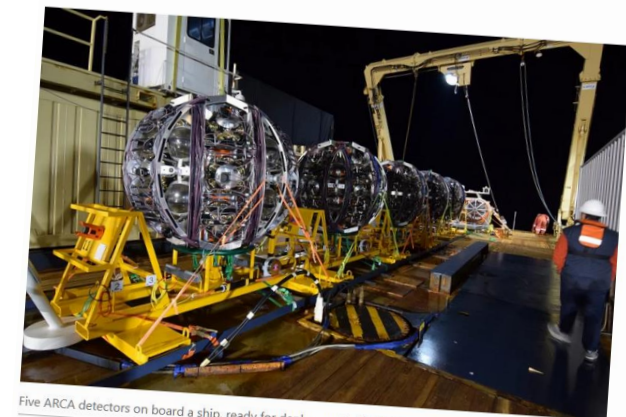
[nature](#) > [news](#) > article

NEWS | 21 June 2024

'Fantastic' particle could be most energetic neutrino ever detected

The ultra-high-energy neutrino was spotted by deep-sea detectors and could point to a massive cosmic event.

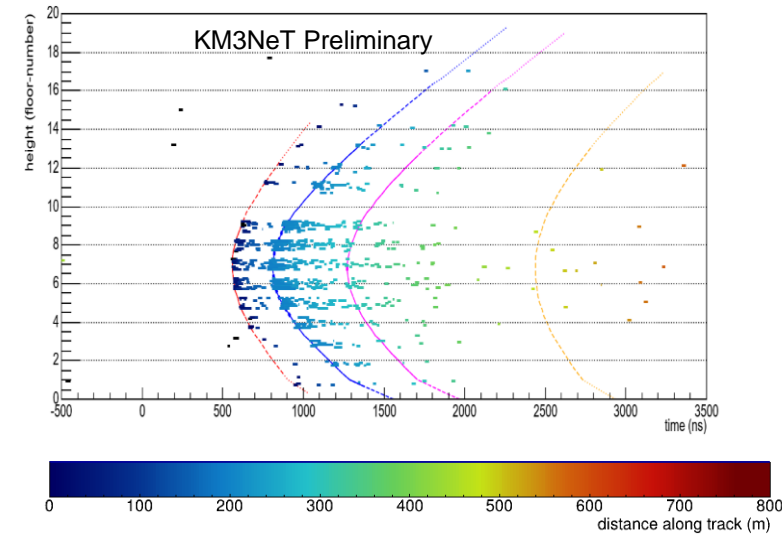
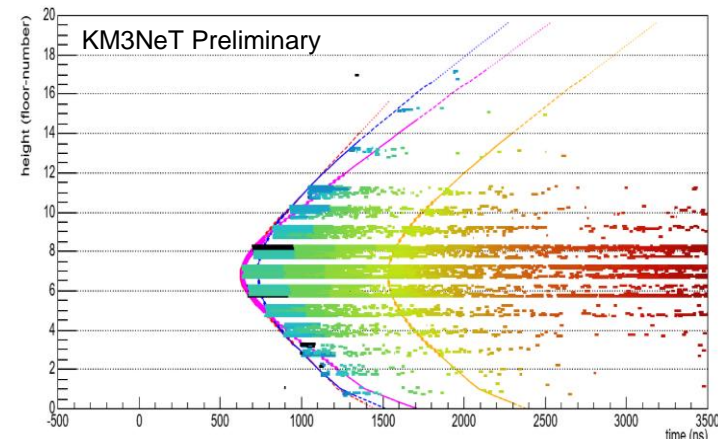
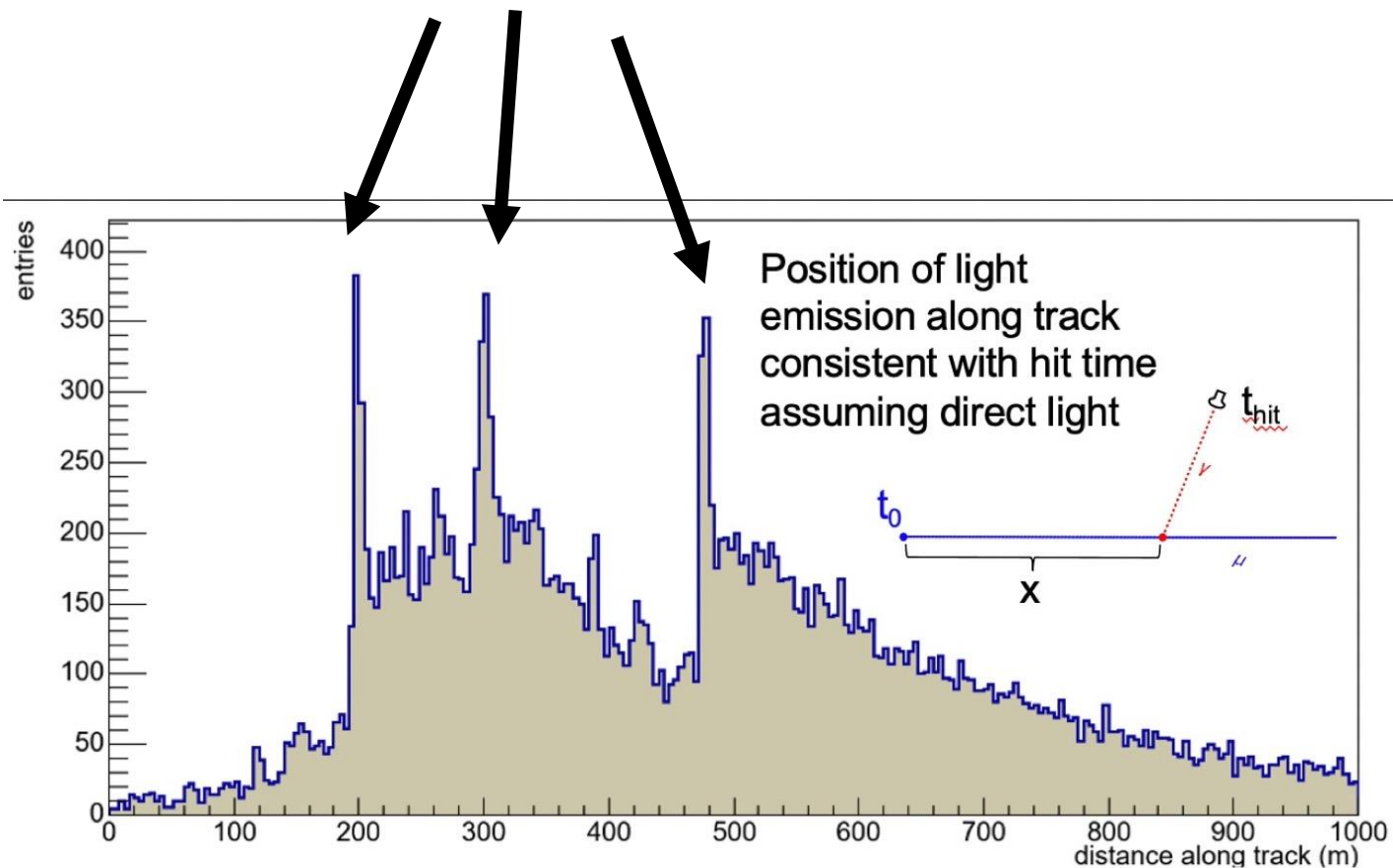
By [Davide Castelvecchi](#)



Five ARCA detectors on board a ship, ready for deployment. Credit: KM3NeT Collaboration

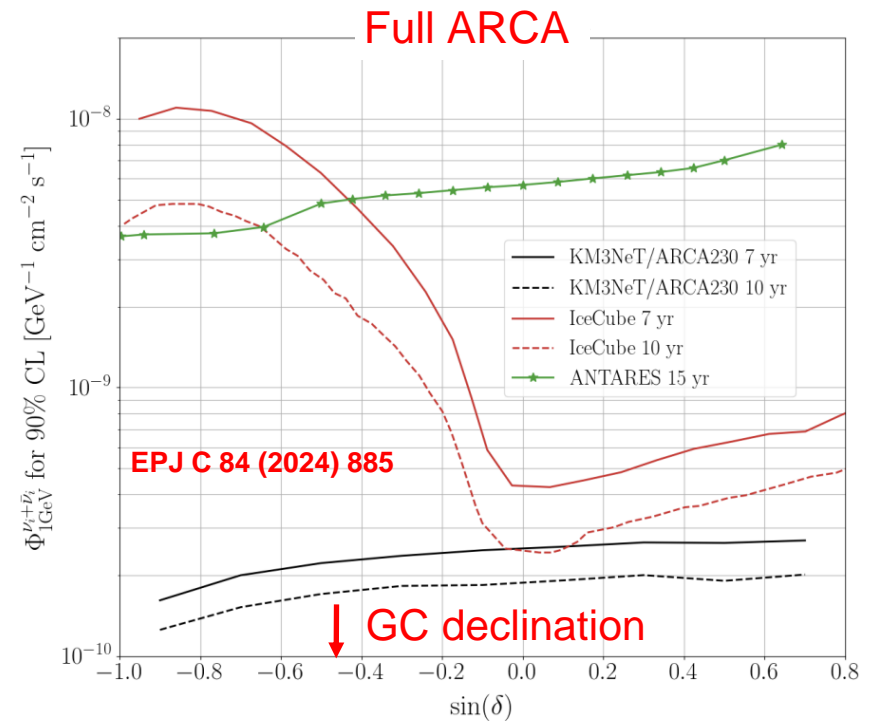
The most energetic neutrino event so far

- Hit times consistent with the light emission from three points along the track → stochastic interactions



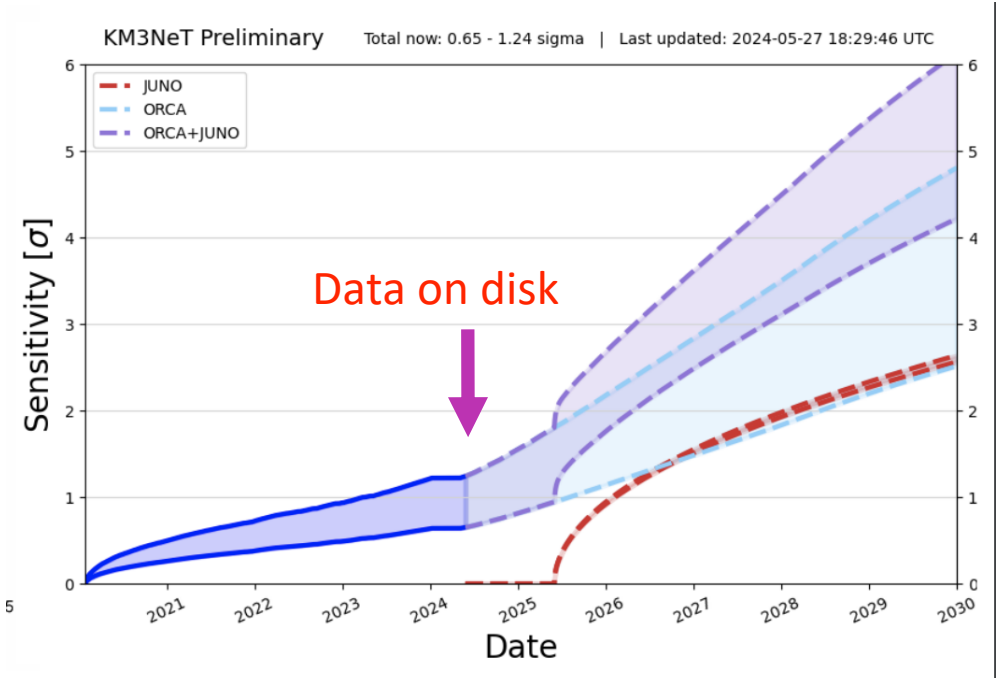
The future: ARCA 230 DUs + ORCA 115 DUs

ARCA - Sensitivity to point-like sources



Unprecedented performance for the southern sky

ORCA - Neutrino mass ordering



5σ can be reached in the next 5-6 years if combined with Juno
Predictions based on the current construction plan.



↑
full
ANTARES

↑
ARCA 6 DUs
ORCA 6 DUs

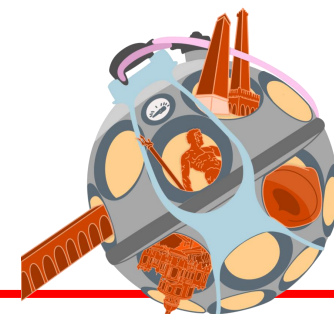
↑
ANTARES stop
ARCA 21 DUs
ORCA 10 DUs

↑
ARCA 33 DUs
ORCA 24 DUs

↑
Full ARCA & ORCA

- **KM3NeT**: research infrastructure under construction at the bottom of the Mediterranean Sea
- present status: ARCA 33 DUs (14% of full detector) and ORCA 24 DUs (20% of the full detector)
- modular design → Detectors in data taking from the first strings deployed
- ARCA sensitivity quickly approaching ANTARES
- exciting results expected in a few years especially in the exploration of the southern sky
- promising results also in neutrino oscillations → ORCA in the race for mass hierarchy determination

- an exceptionally high-energy event detected → horizontal event with energy above several tens of PeV
- detailed event description thanks to the design of the Digital Optical Module
- more public information arriving soon



Follow us on social media and keep updated on the development of the detector construction and on our results.



<https://www.km3net.org/>



<https://www.facebook.com/KM3NeT>



<https://www.youtube.com/user/KM3NeTneutrino>



<https://www.instagram.com/km3net/>



<https://x.com/km3net>