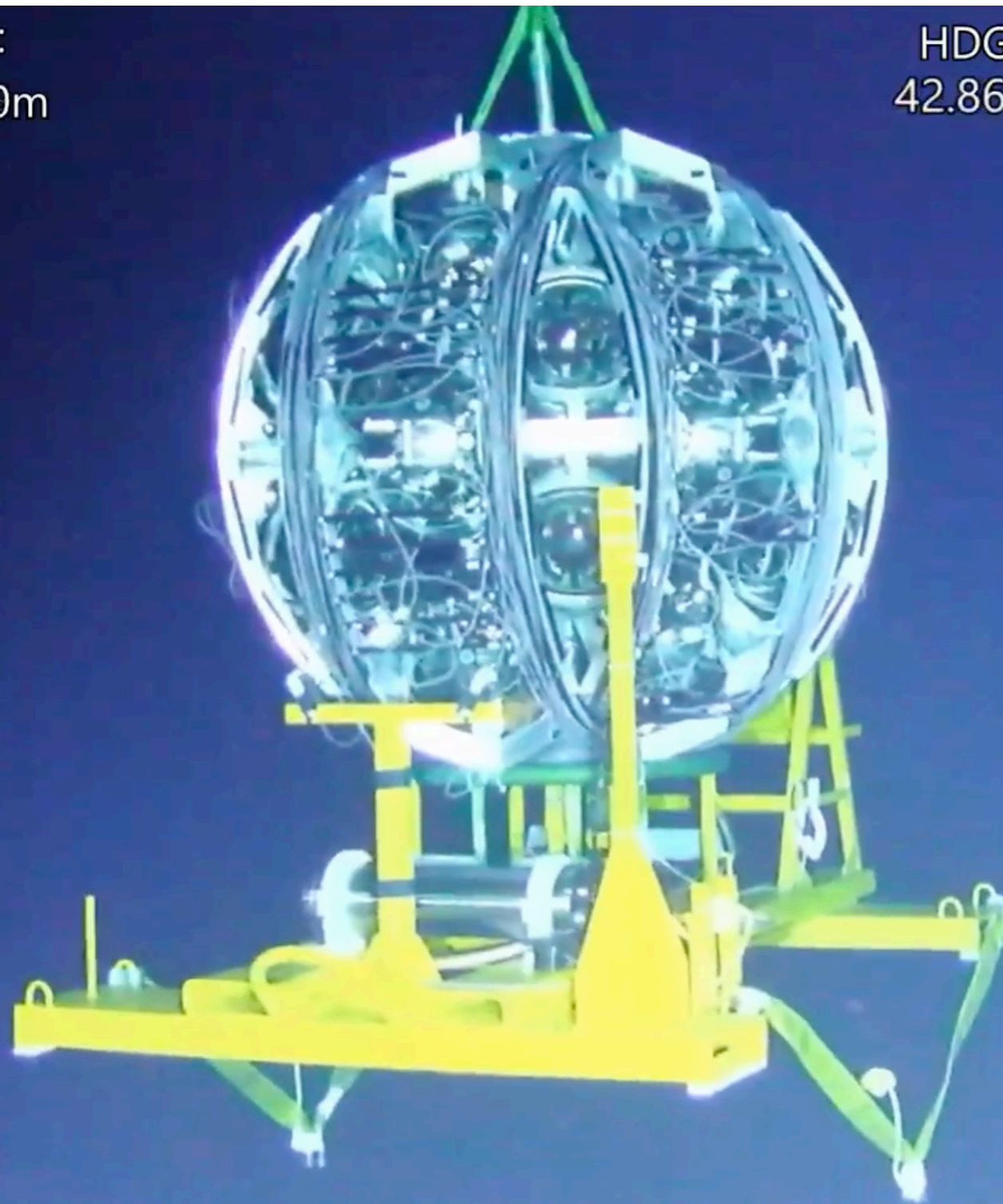




Depth:
3451.00m

HDG:
42.86°



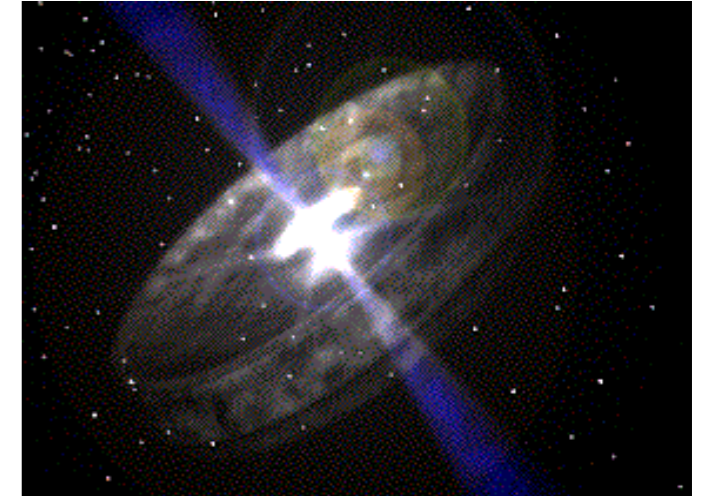
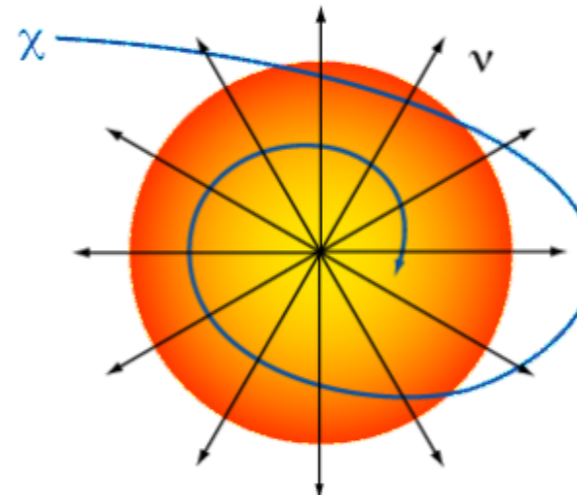
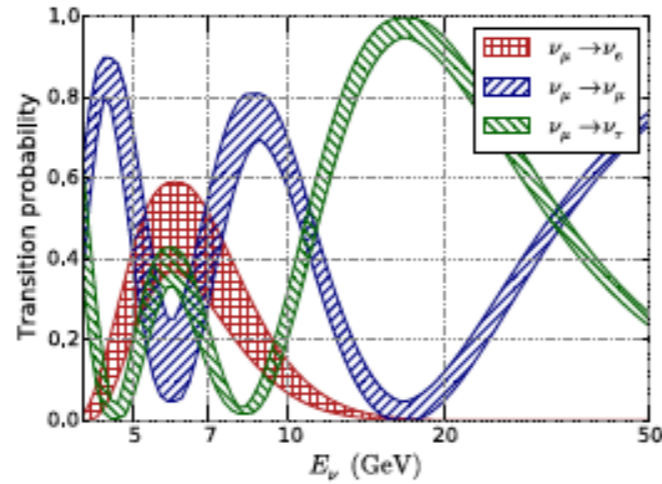
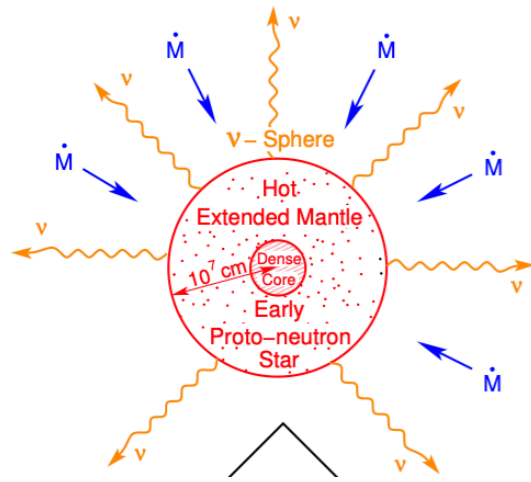
Physics results of KM3NeT and update on the construction phase



Simone Biagi *on behalf of the KM3NeT Collaboration*
INFN — LNS



The physics case



Super Novae explosion
MeV

Neutrino oscillation
GeV

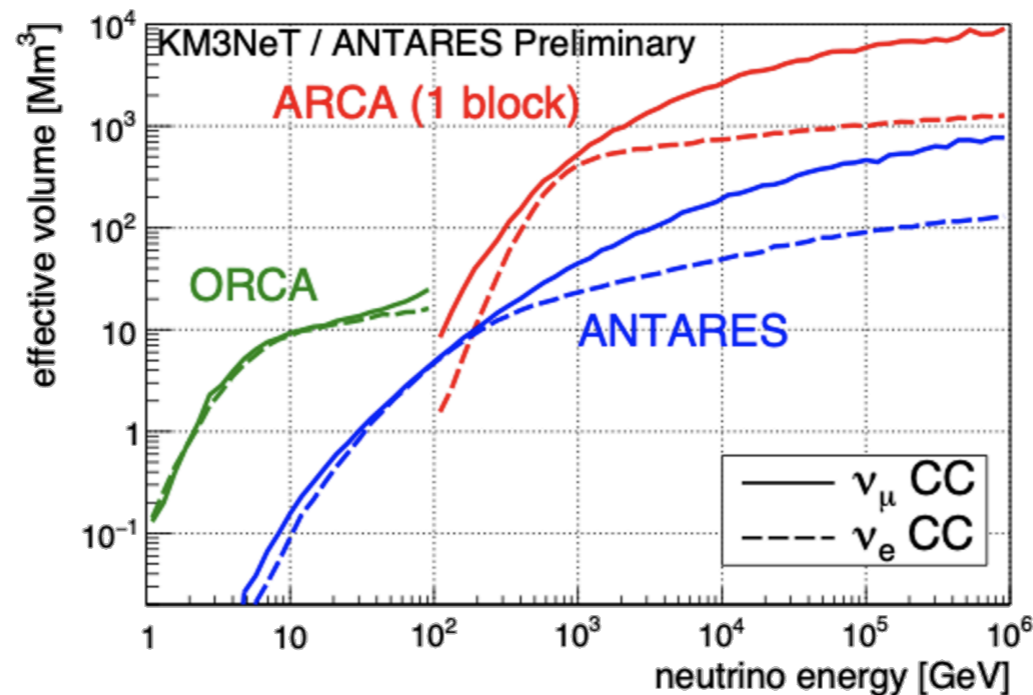
Dark Matter
TeV

HE neutrinos
Multi-messenger program
PeV

ORCA

ARCA

ARCA

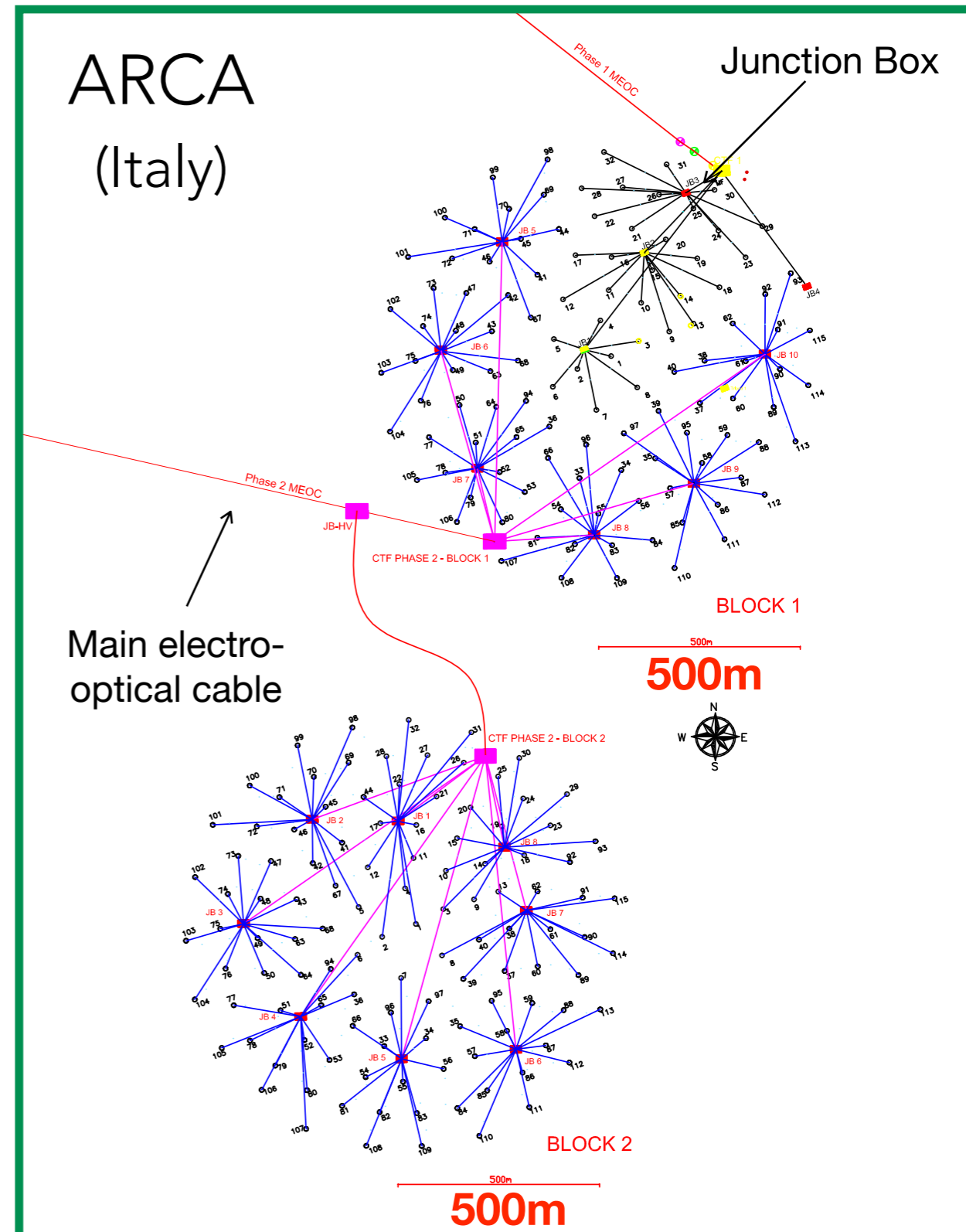
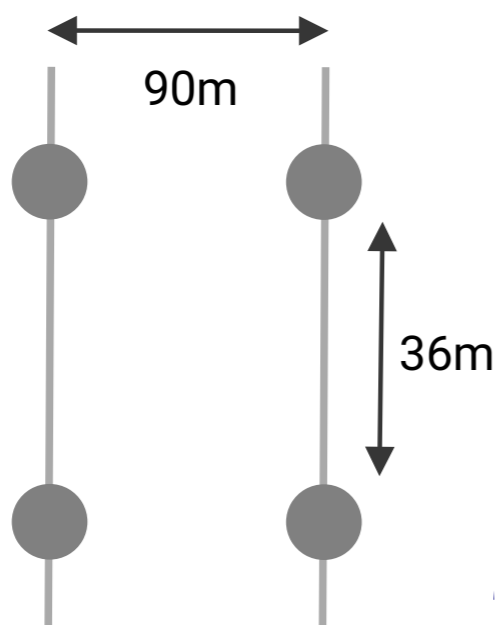


Neutrino Energy from **MeV** to **PeV**

The neutrino telescopes of KM3NeT

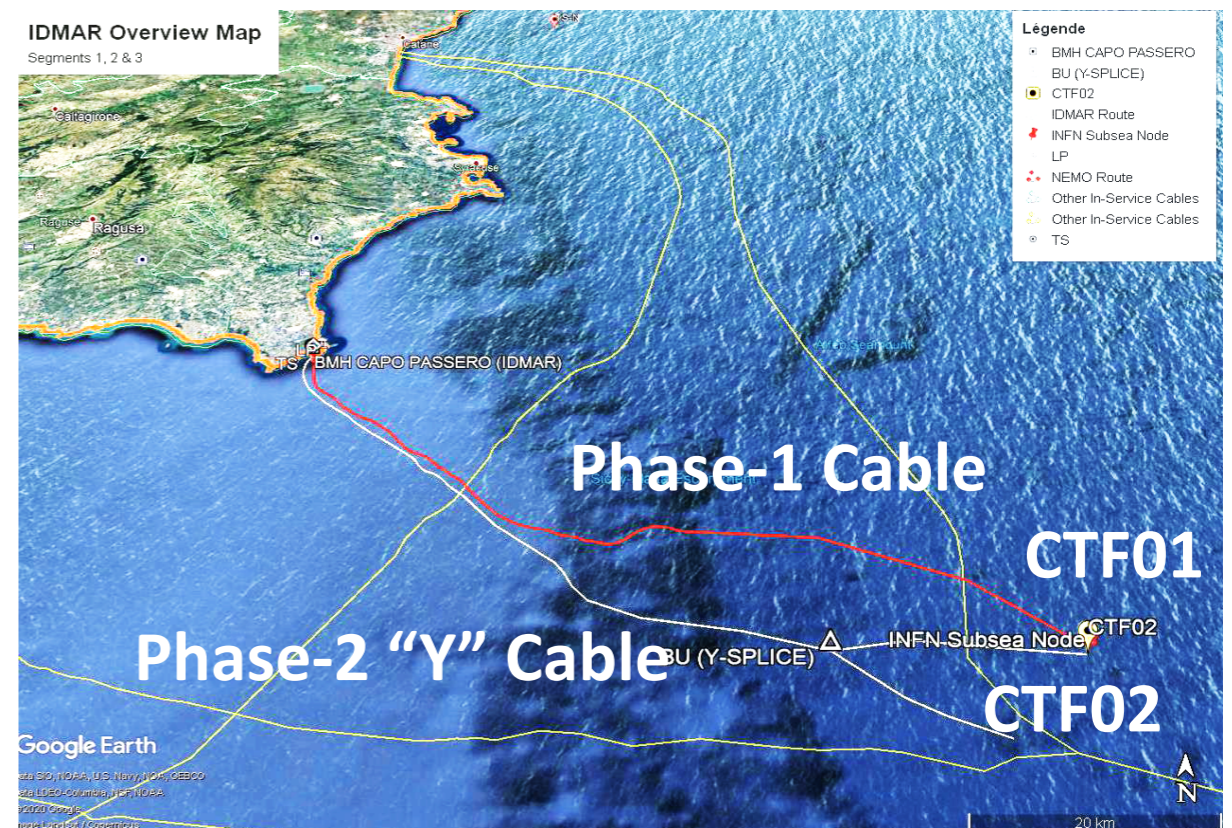
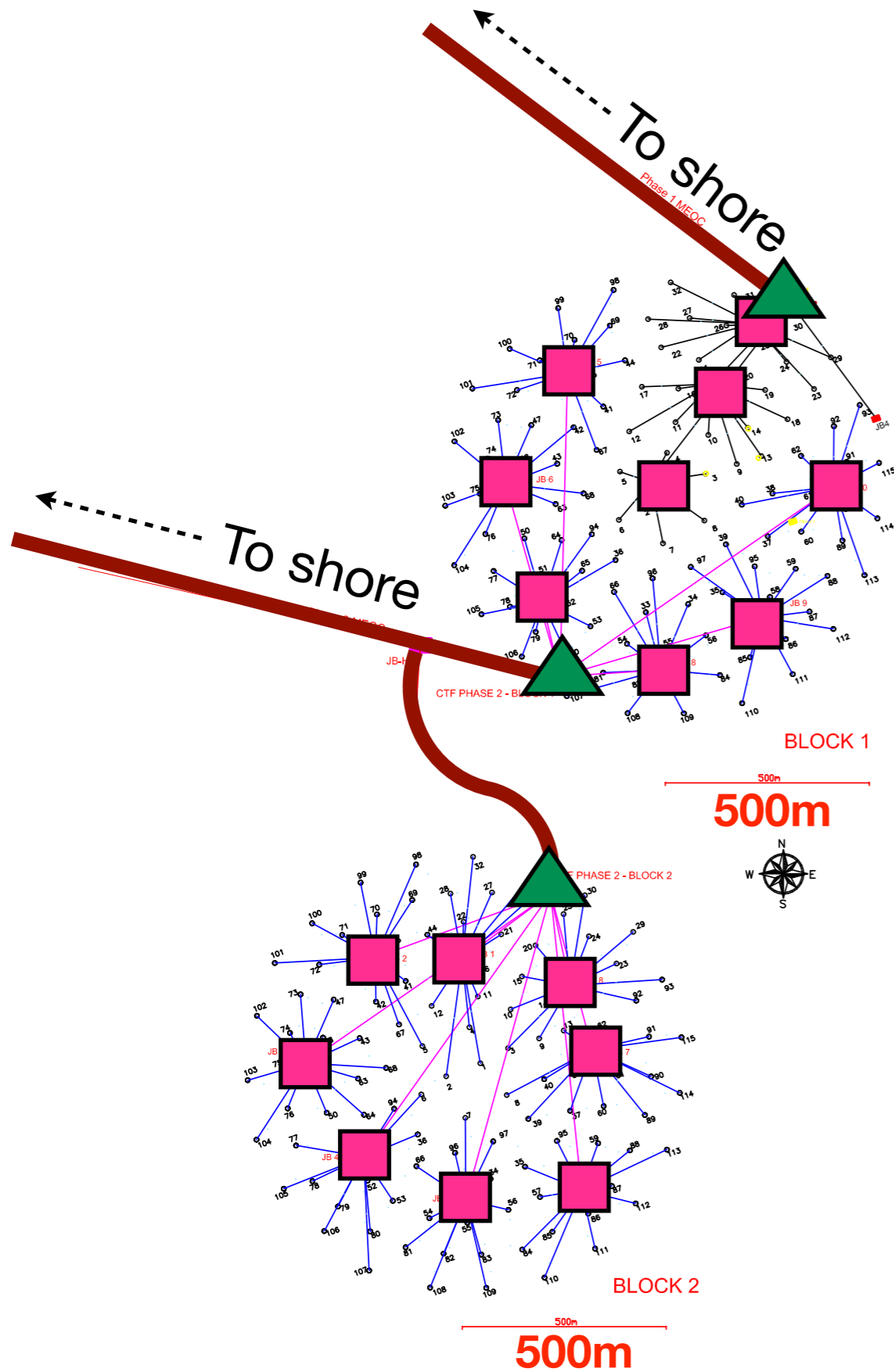
ARCA: Astroparticle Research with Cosmics in the Abyss

- 2 Building Blocks
- 115 Detection Units each, interspacing ~90 m
- 18 Digital Optical Modules (DOM) per DU, inter-DOM spacing 36 m
- Total active volume 1 km³, ≈ 500 Mton/block
- 3500 m depth, SE the Sicilian coasts
- 2 Main Electro-Optical Cables (MEOC) for connection to shore of a network of 9+8 junction boxes and inter-link cables



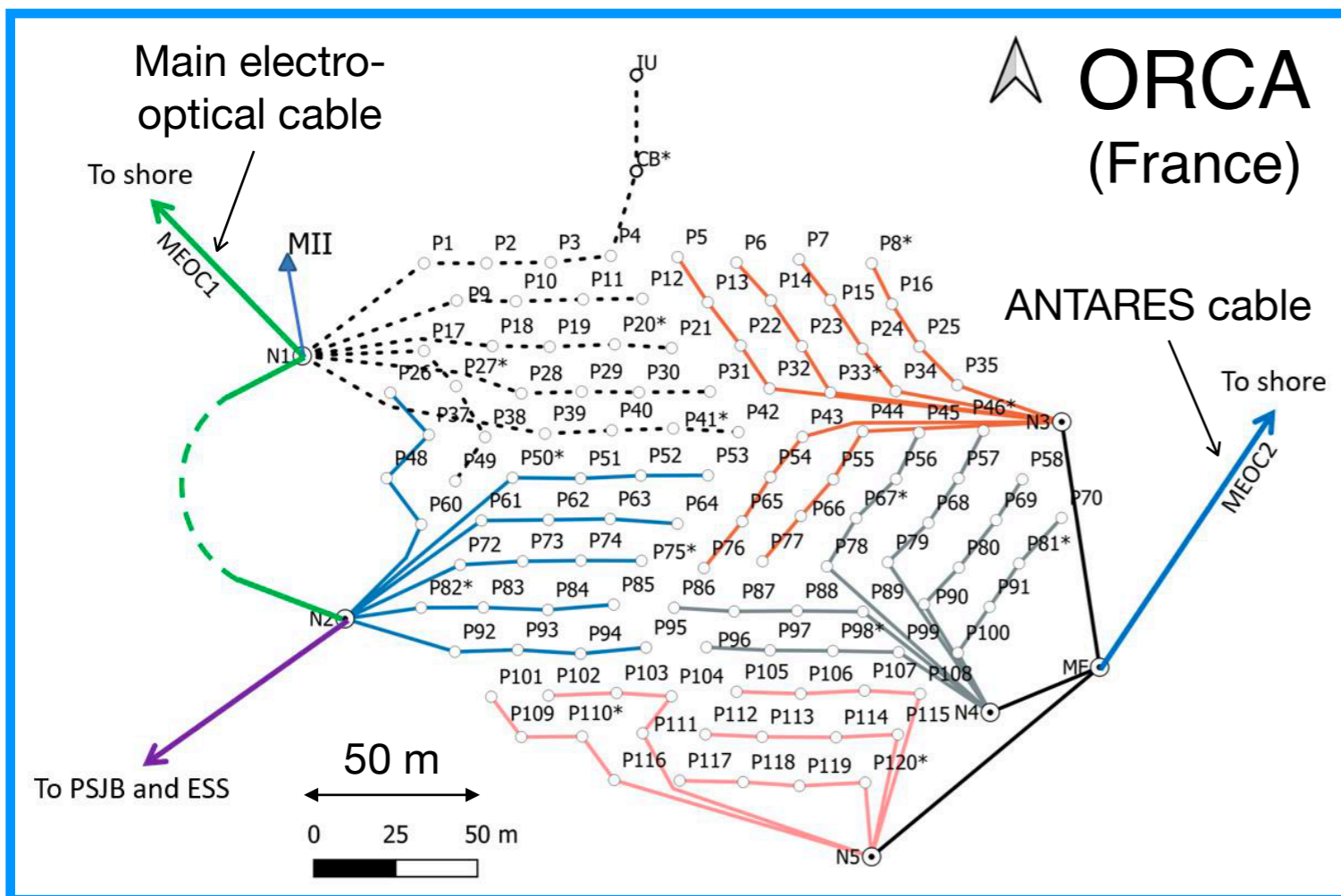
The elements of the infrastructure

- 2 Main Electro-Optical Cables (MEOC)
- 3 Cable Termination Frames (CTF)
- 9 + 8 Junction Boxes (JB)
- A network of Interlink cables
 - ◆ JB to CTF
 - ◆ DU to JB

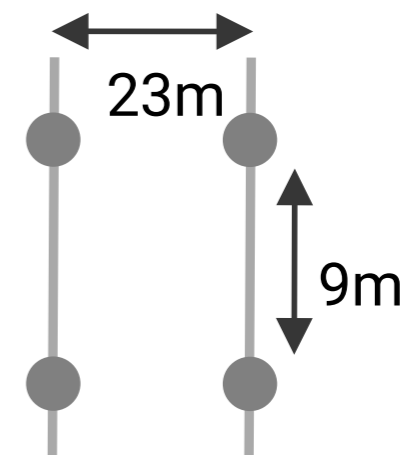


The neutrino telescopes of KM3NeT

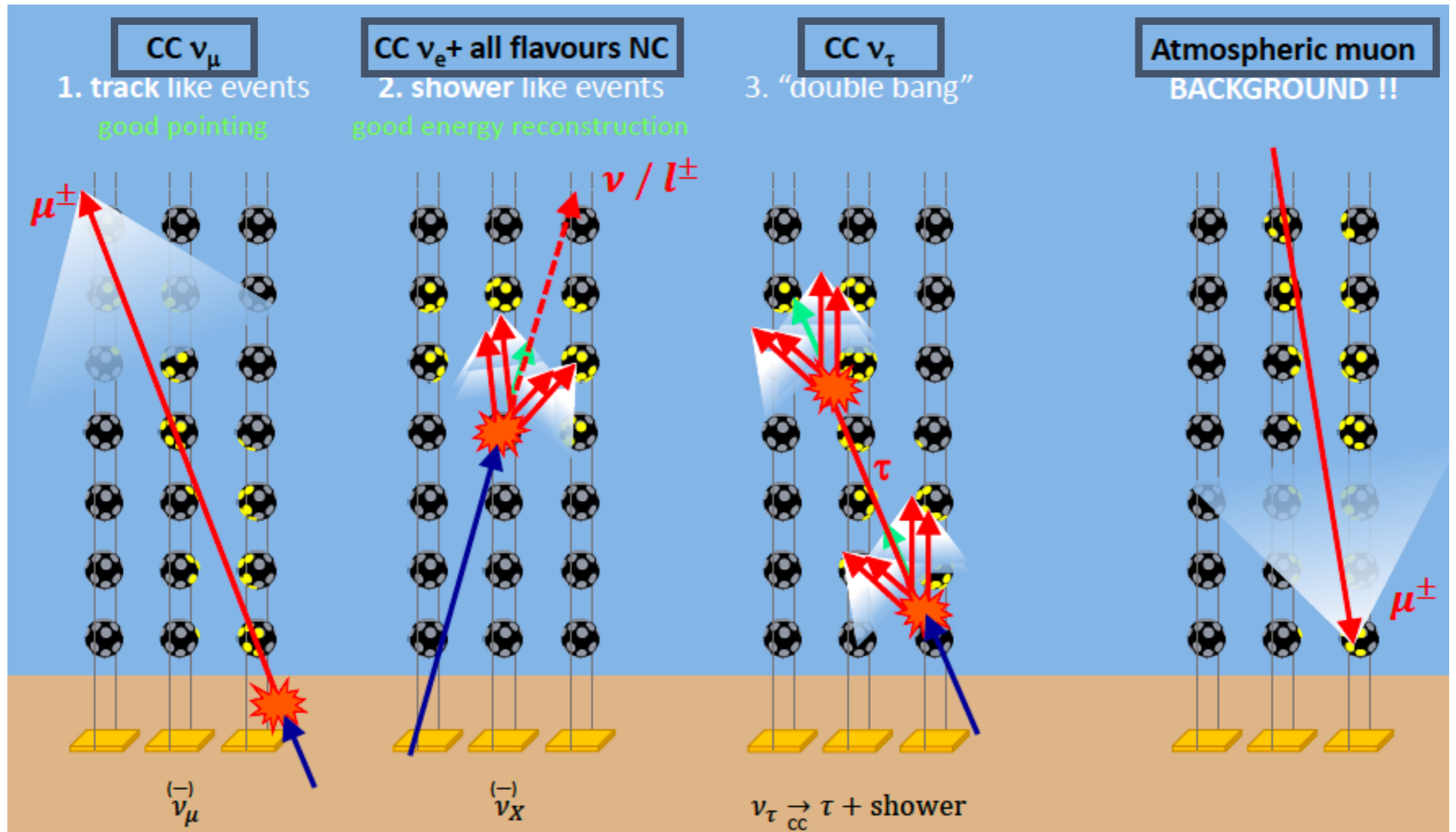
ORCA: Oscillation Research with Cosmics in the Abyss



- 1 Building Block
- 115 Detection Units (DU), interspacing ~ 20 m
- 18 Digital Optical Modules (DOM) per DU, inter-DOM spacing 9 m
- Active volume ≈ 7 Mton
- 2500 m depth, close to Toulon



Neutrino event topologies



Tracks

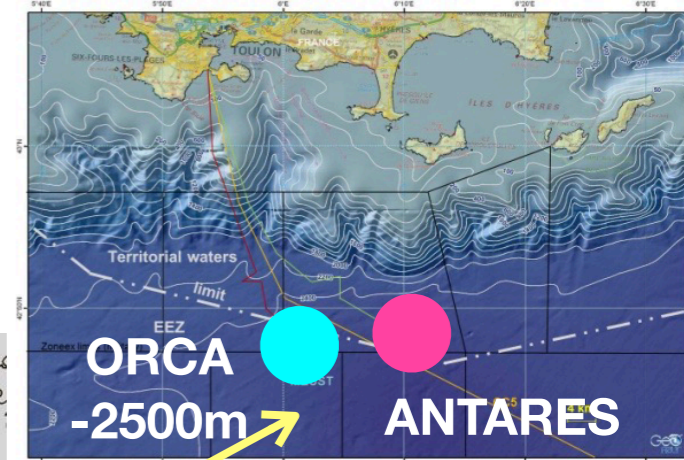
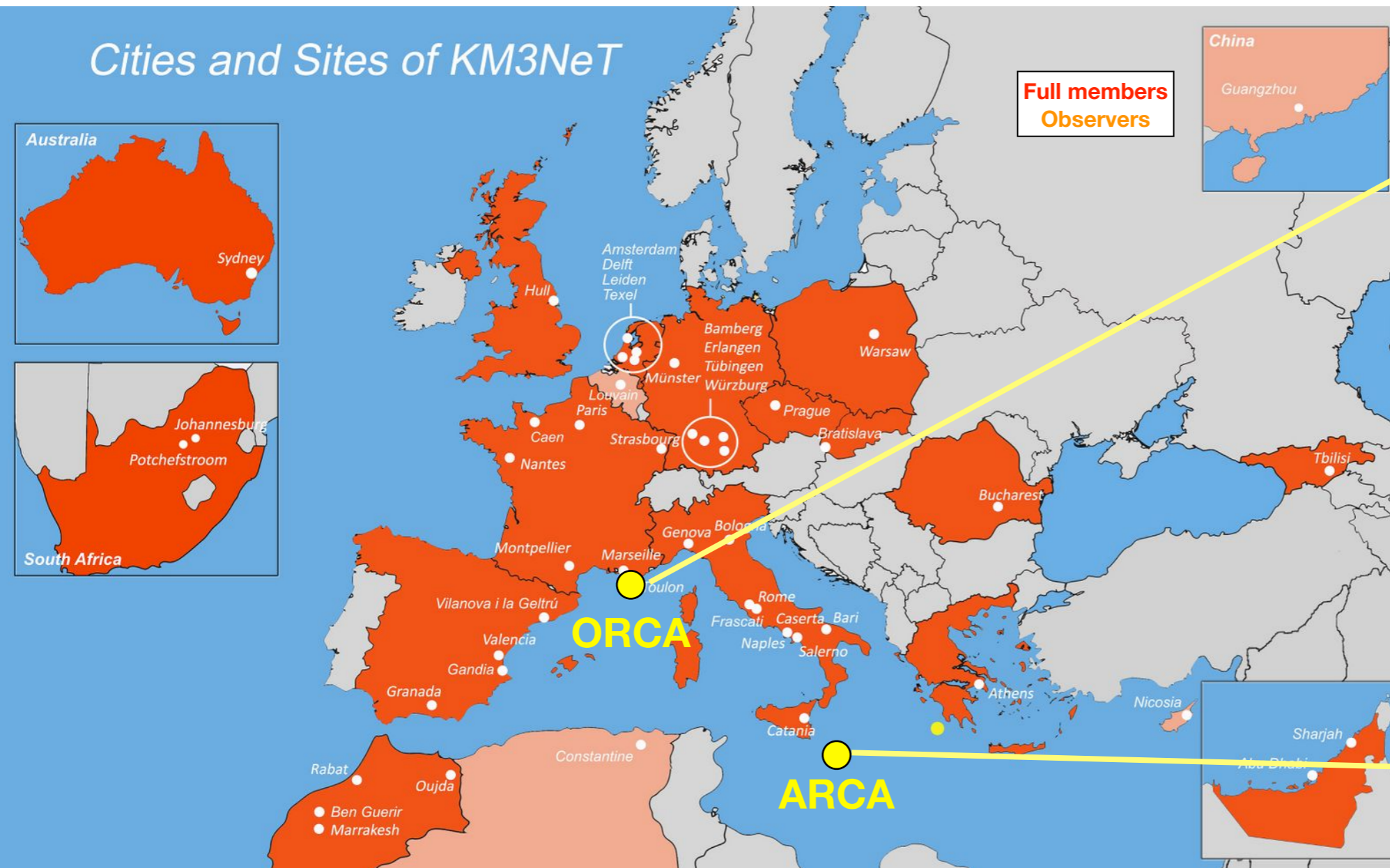
Showers

Background

The KM3NeT collaboration

63 institutes in 22 countries
4 continents – 2 detectors

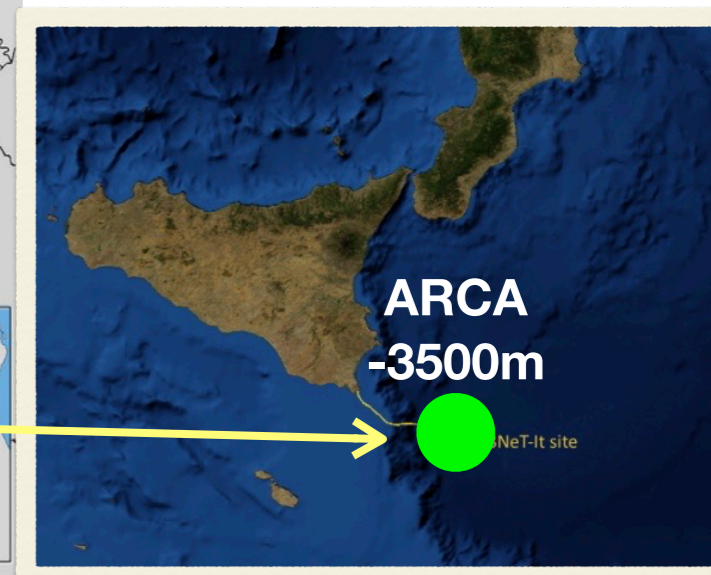
Cities and Sites of KM3NeT



ANTARES operated in
2008-2022

First-generation neutrino
telescope

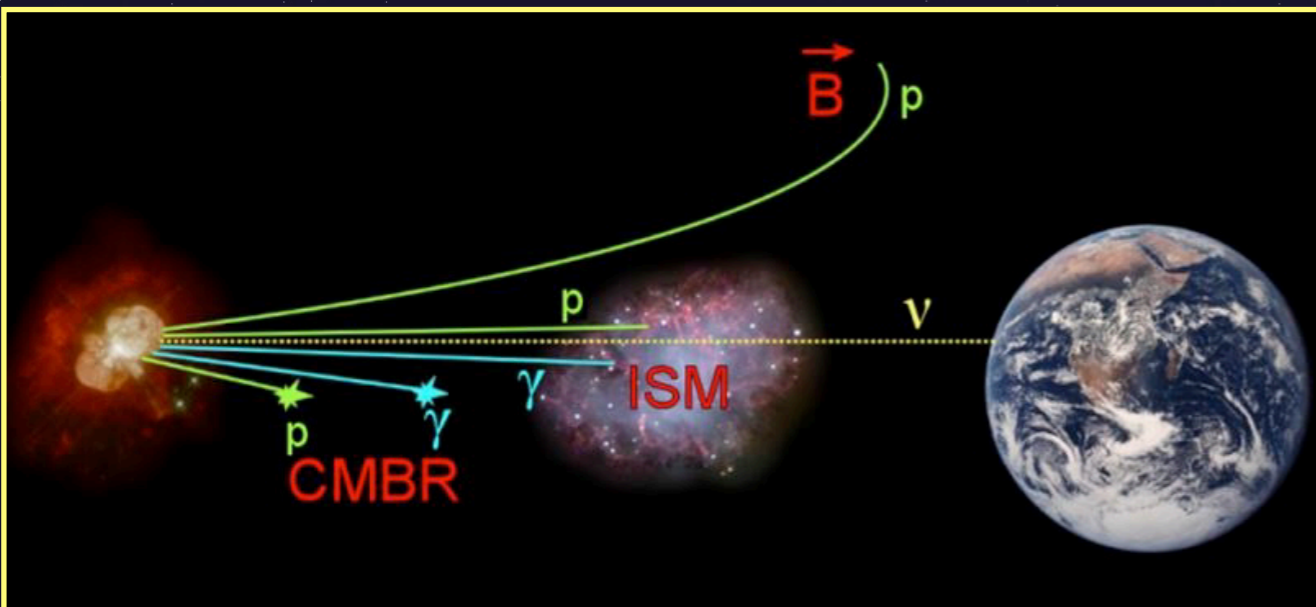
Instrumented volume
~10 Mton



➔ Tuesday 9th, h 15:00: G. Illuminati, Results from ANTARES

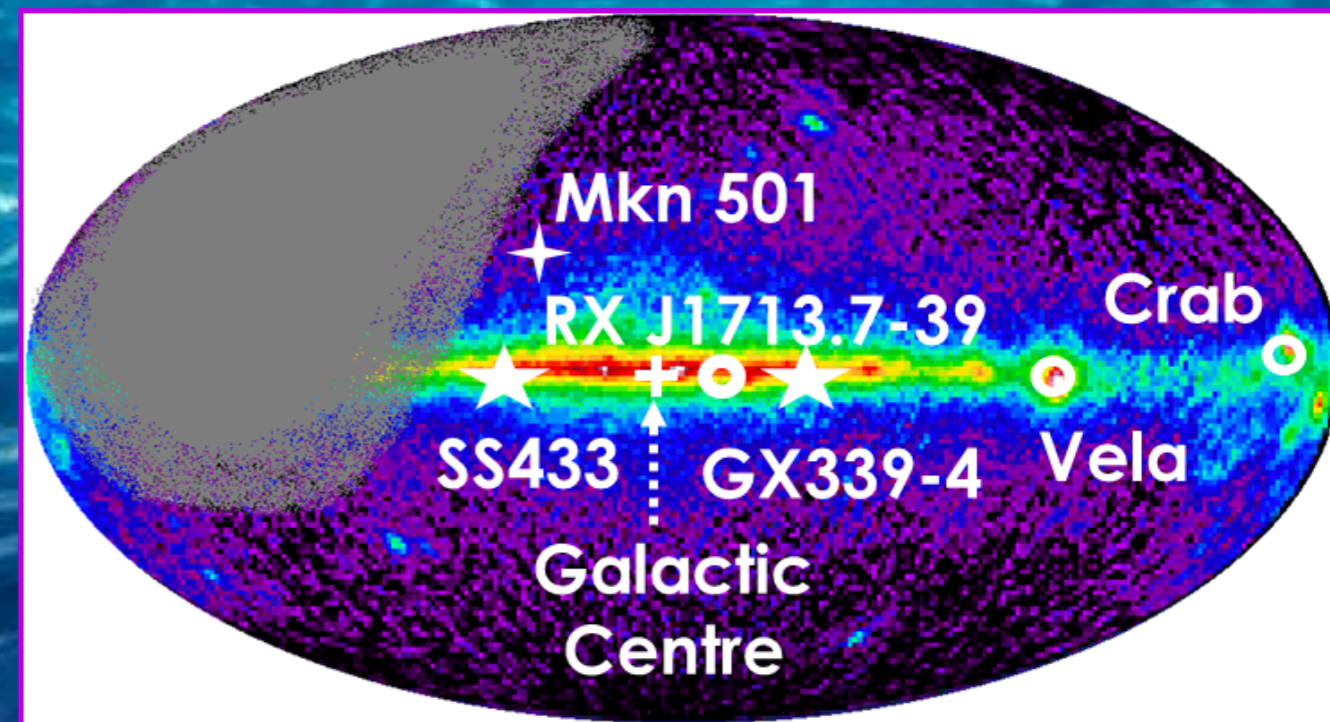
➔ Thursday 11th, h 15:00: Parallel session, ANTARES – 15 years of multi-messenger astronomy

Neutrino Astrophysics in the Mediterranean Sea



- Origin of Cosmic Rays
- Neutral messengers point back to their sources
 - Neutrons are short-lived, photons are likely to interact \Rightarrow Neutrinos as cosmic probe
- Neutrinos are produced at sources via hadronic interactions
 - Cosmic diffuse flux
 - Point-like sources
 - Multi-messenger approach

- Detection principle: large volume of transparent medium instrumented with PMTs
- Located in the Northern Hemisphere
 - Complementary to IceCube
 - Southern sky sources, "Milky-Way optimised"
- Medium: Deep Sea Water
 - Very small light scattering = good angular resolution
 - Natural background (^{40}K and bioluminescence) taken into account.



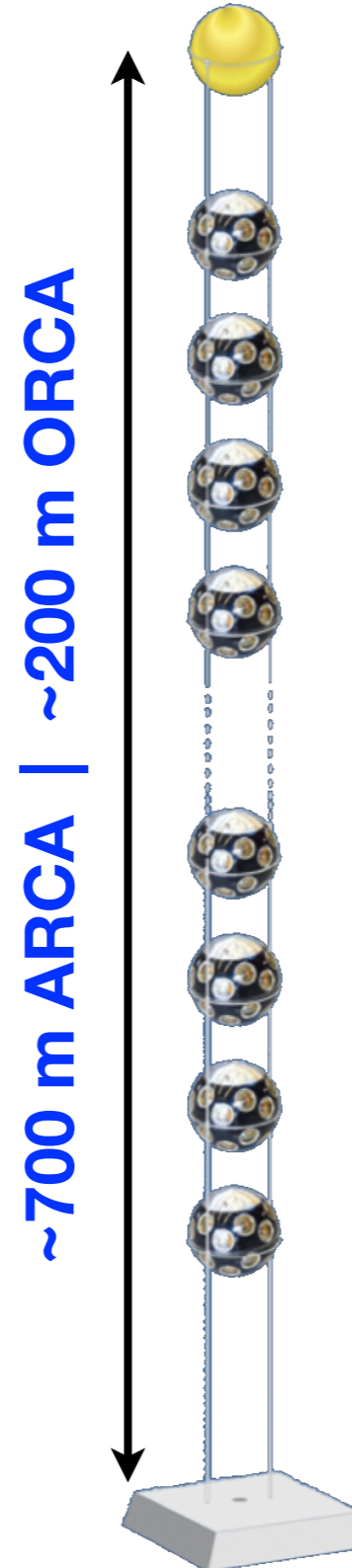
KM3NeT Technology in a nutshell

Digital Optical Module

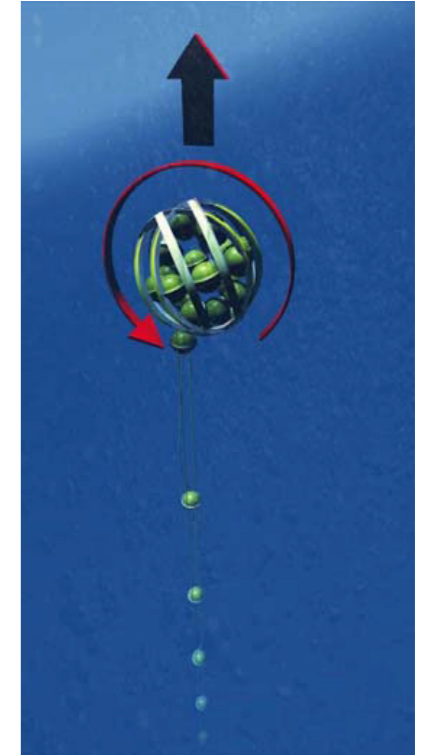
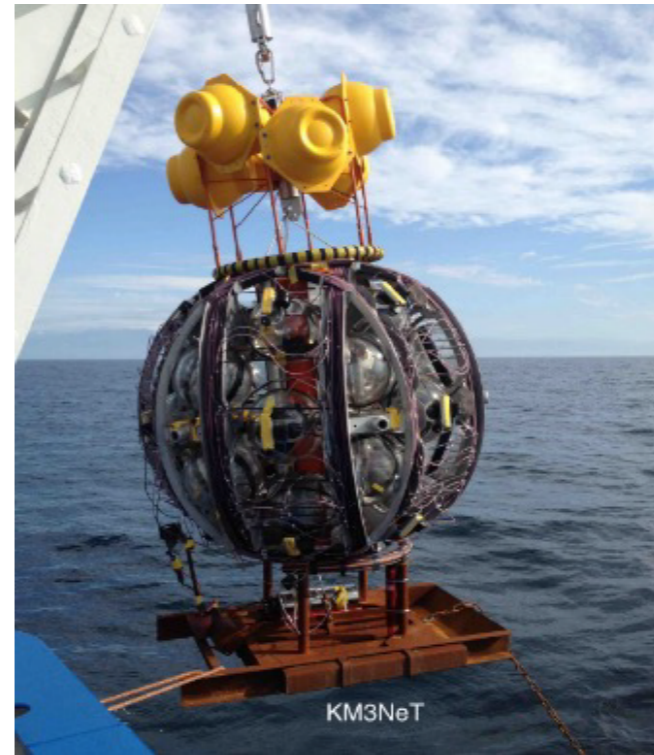


- DOM: 31 x 3" PMTs
- Digital photon counting
- Directional information
- Wide acceptance angle
- All data to shore
- Gbit/s on optical fiber
- Custom White Rabbit
- 18 DOMs / String

Detection Unit (string)

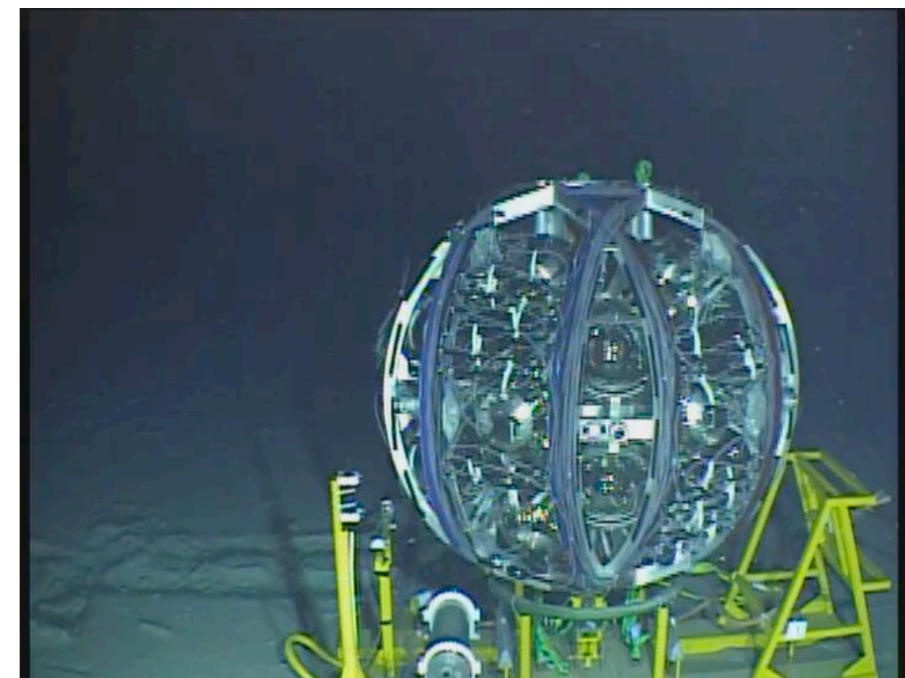


- Unfurling by autonomous ROV
- Rapid deployment
- Multiple strings in one sea campaign



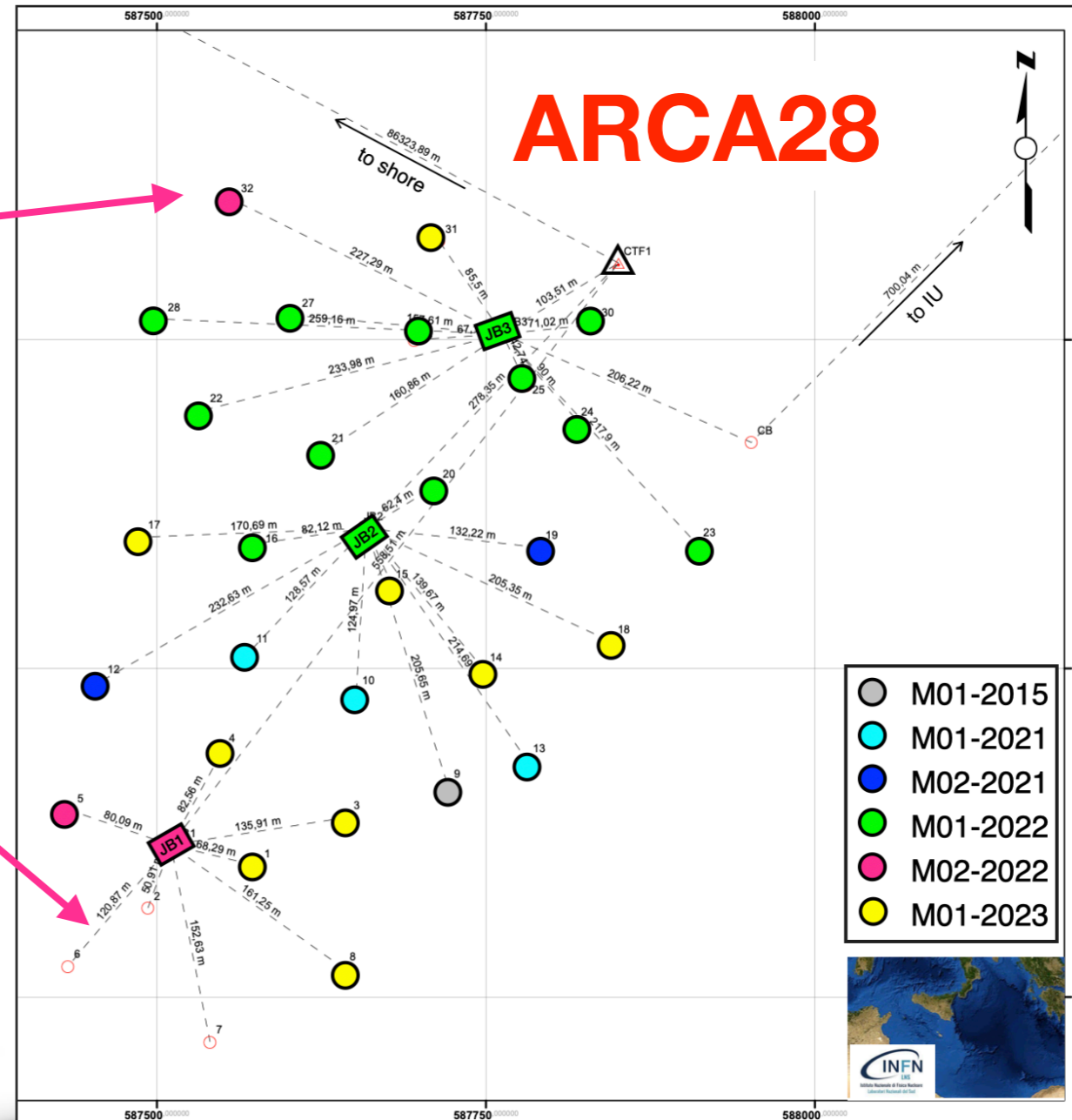
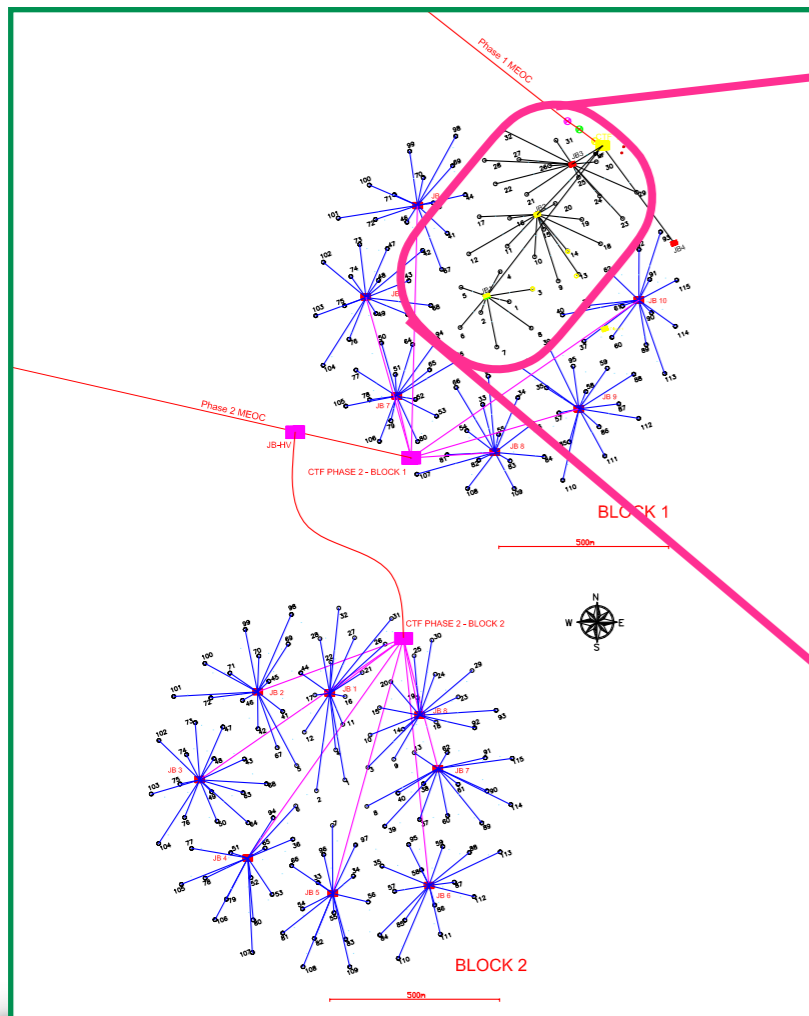
DOM: JINST 17 (2022) P07038

Unfurl: JINST 15 (2020) P11027



ARCA: Current configuration

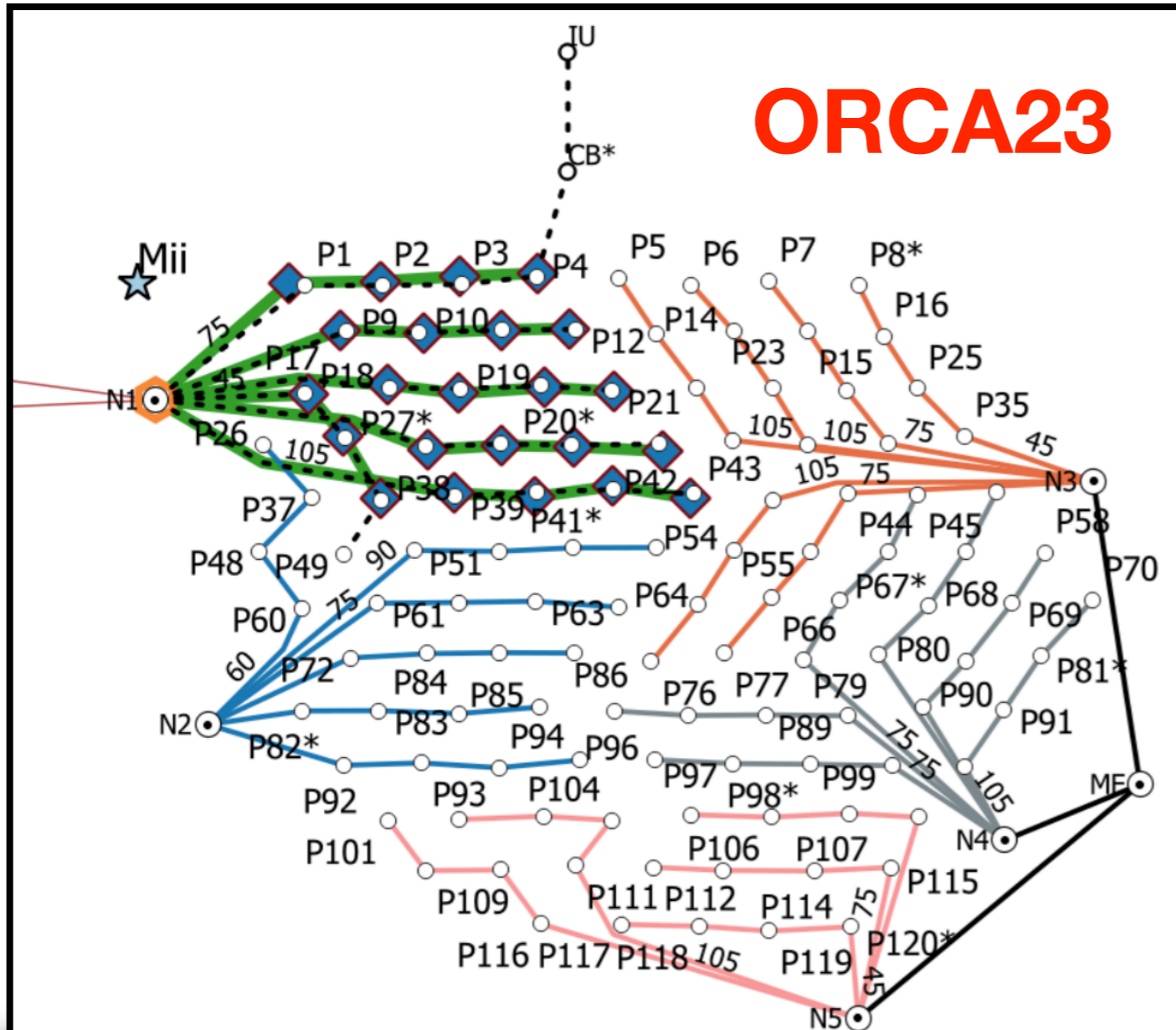
First DU deployed in December 2015



- Next campaign in Sept/Oct 2024 to install:
 - ➔ 2 Junction Boxes + 16–20 Detection Units + 1 Calibration Unit
- Before the end of the year, expecting to complete ~45% of Building Block 1

ORCA: Current configuration

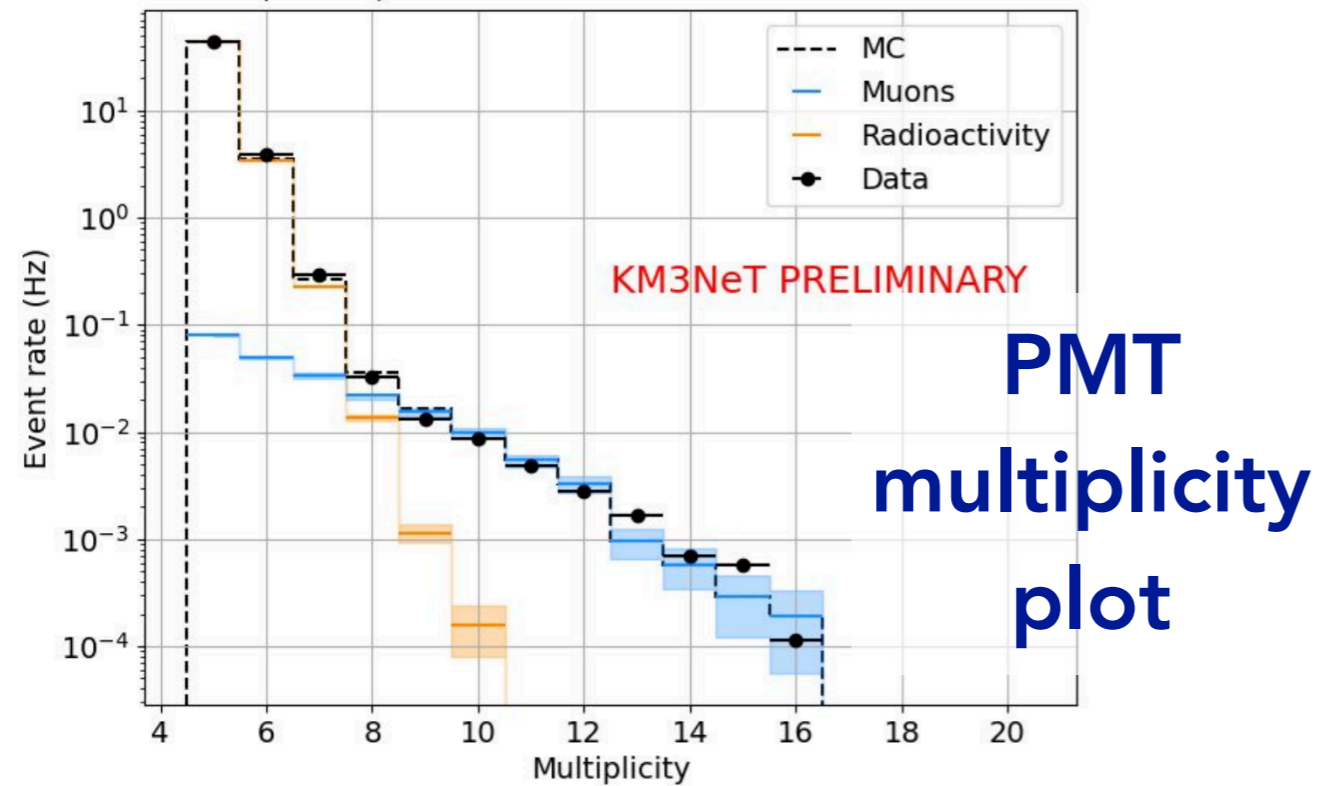
First DU deployed in 2016



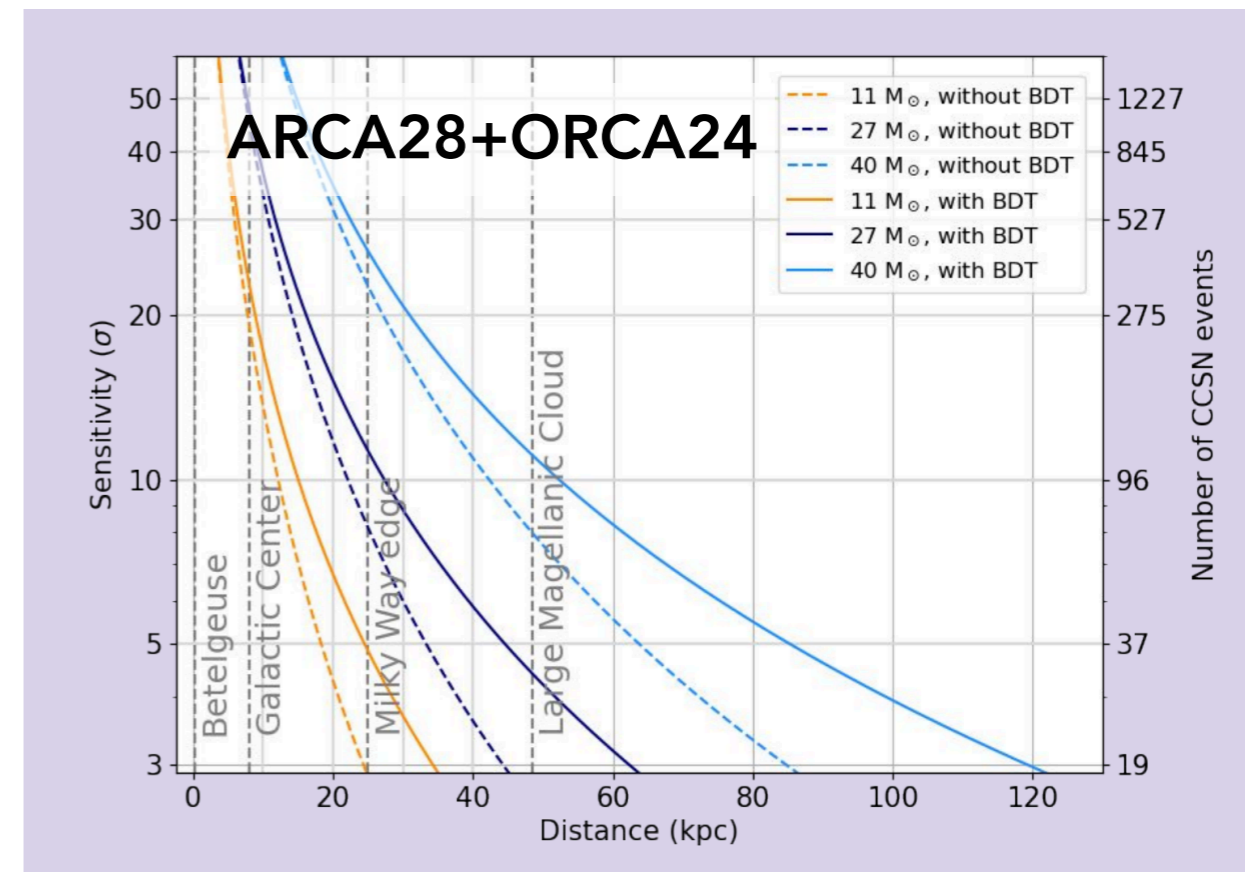
- Next campaign before the end of the year to install:
 - ➔ Node-2 + 5–6 Detection Units, depending on weather conditions
- 20% of detector active, Node-1 almost completed!

Core Collapse Supernovae

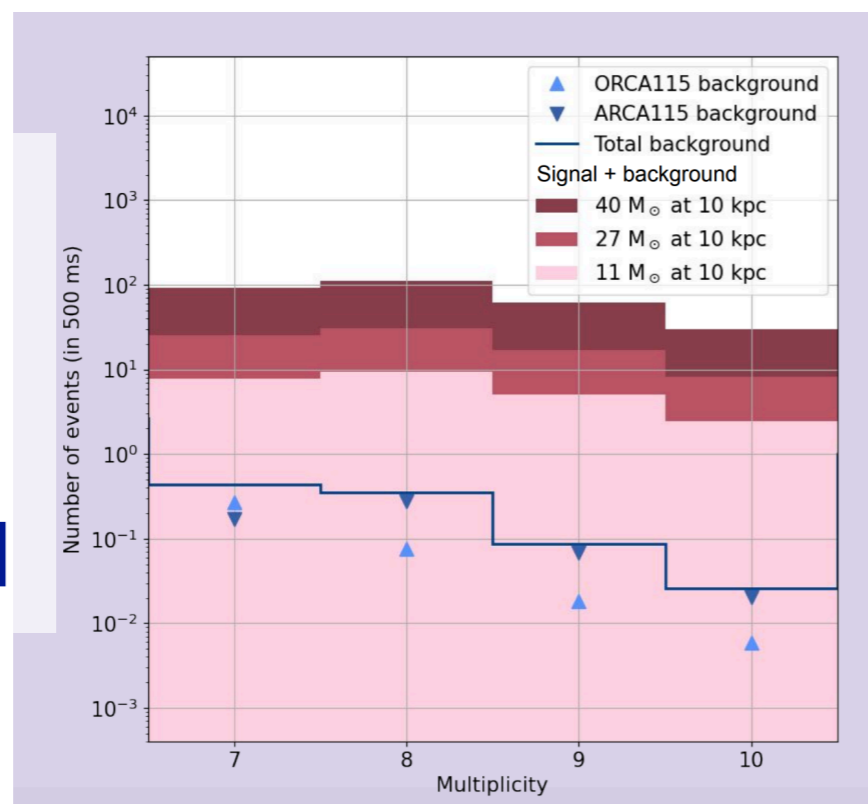
KM3NeT/ORCA6, 6 hours run



Significance



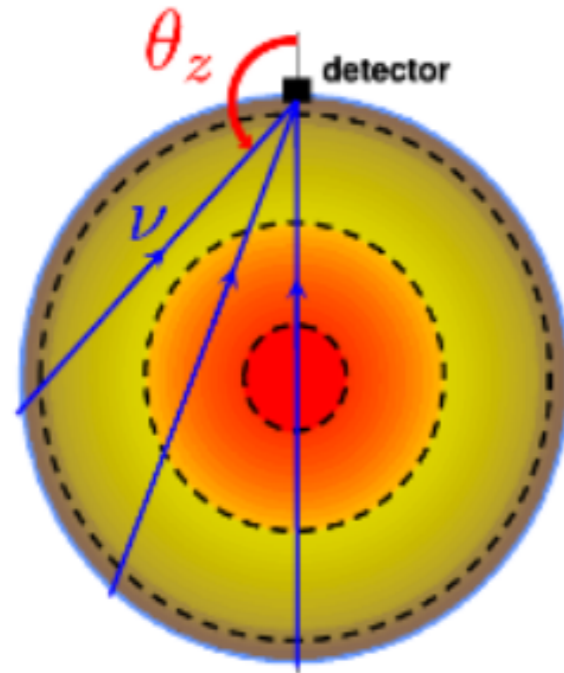
Signal expected above background



**An on-line alert system for CCSN already implemented
Integrated in SNEWS**

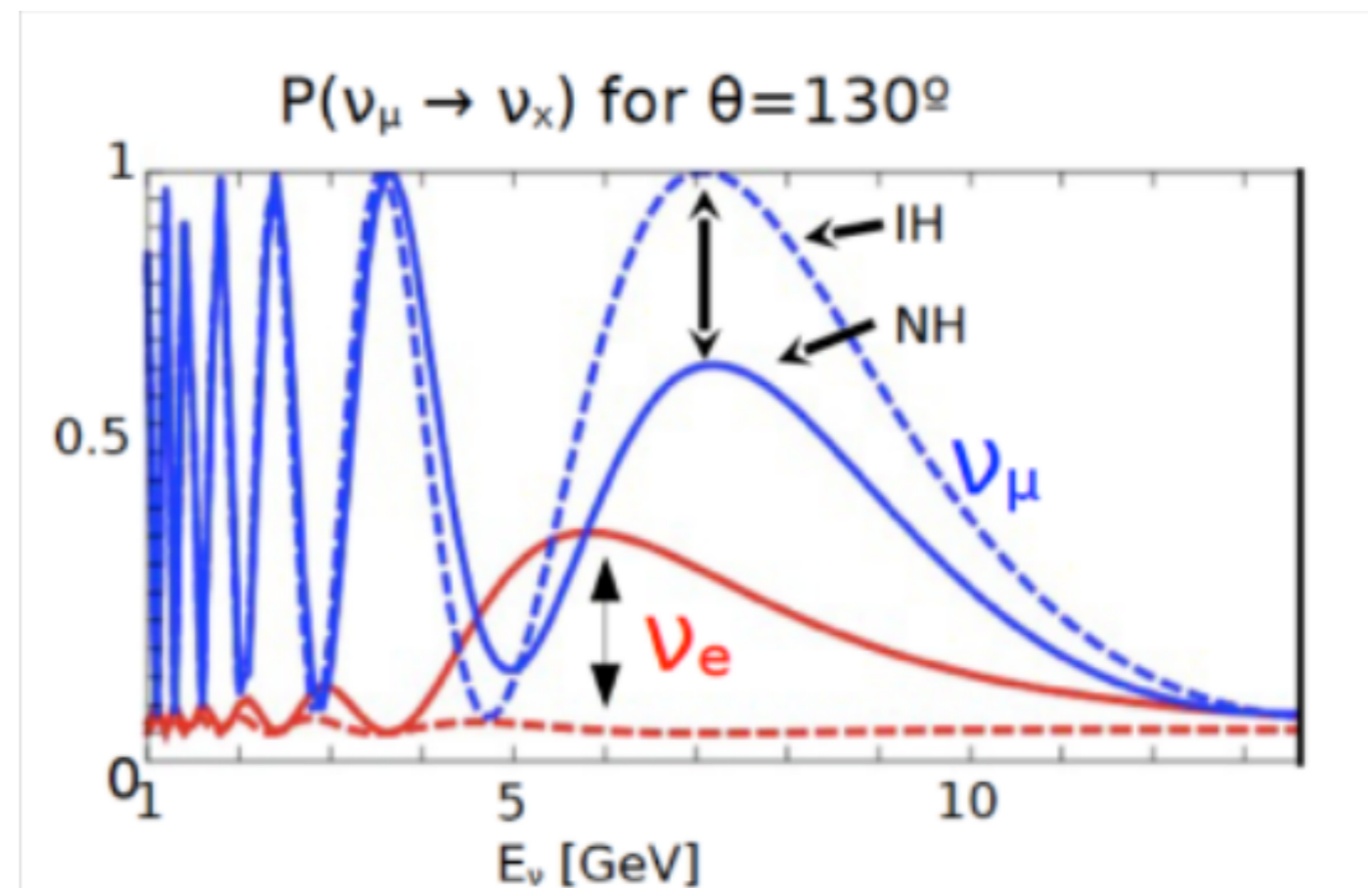
Neutrino Oscillations (ORCA)

Baseline from 50 to
12800 km



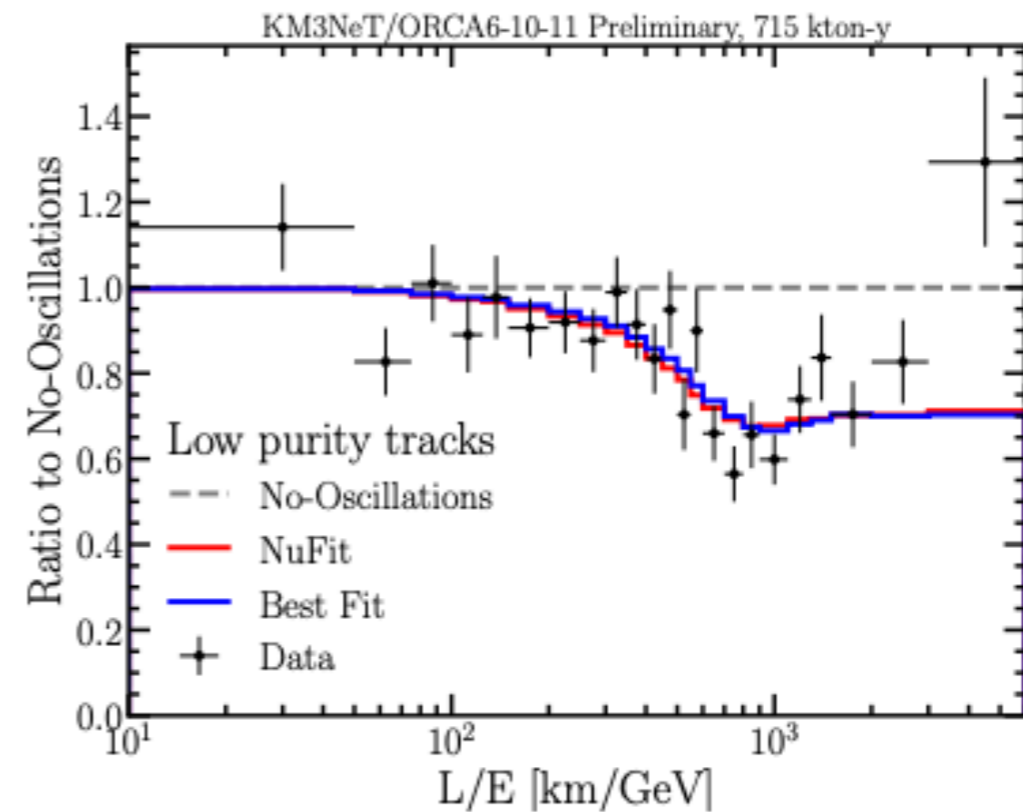
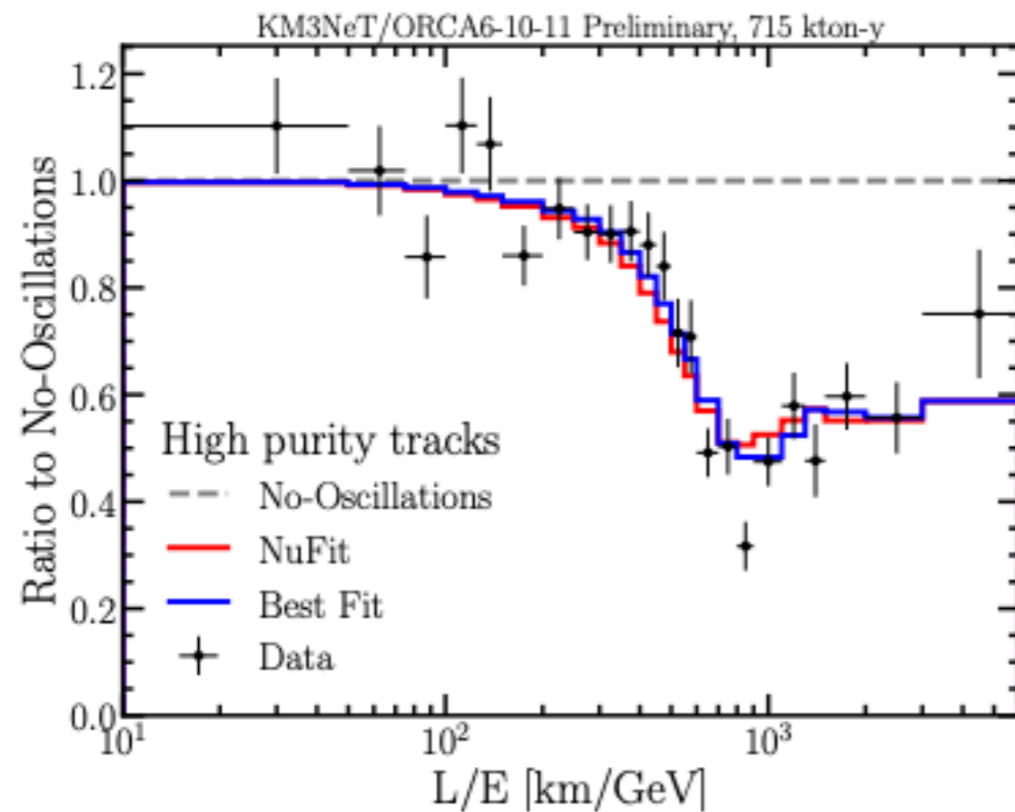
Neutrino Mass Ordering
measuring atmospheric
neutrinos crossing the Earth

Atmospheric ν_μ disappearance



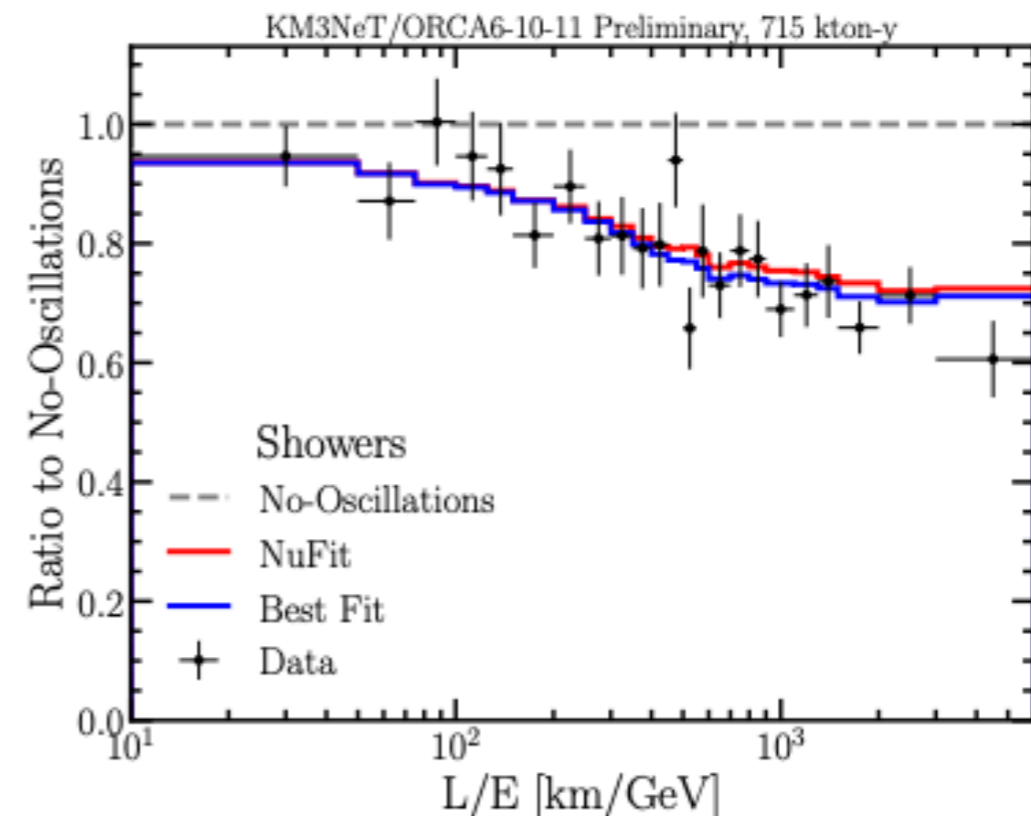
Energy range of interest 5-15 GeV

Neutrino Oscillations (ORCA)



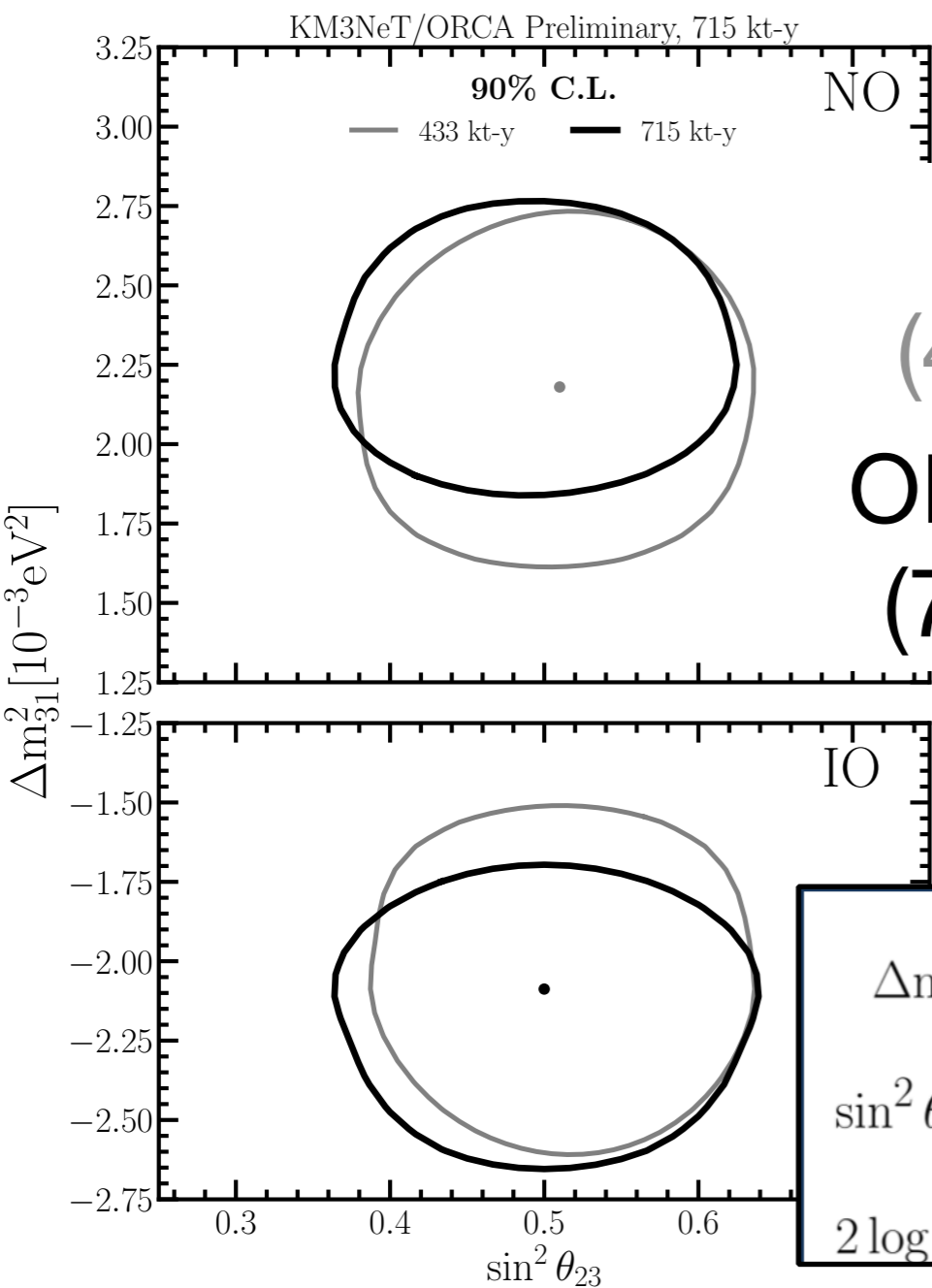
ORCA6-10-11 data

*Oscillations clearly seen both
in track and shower events*



Neutrino Oscillations (ORCA)

Δm_{32}^2 vs $\sin^2 \theta_{23}$

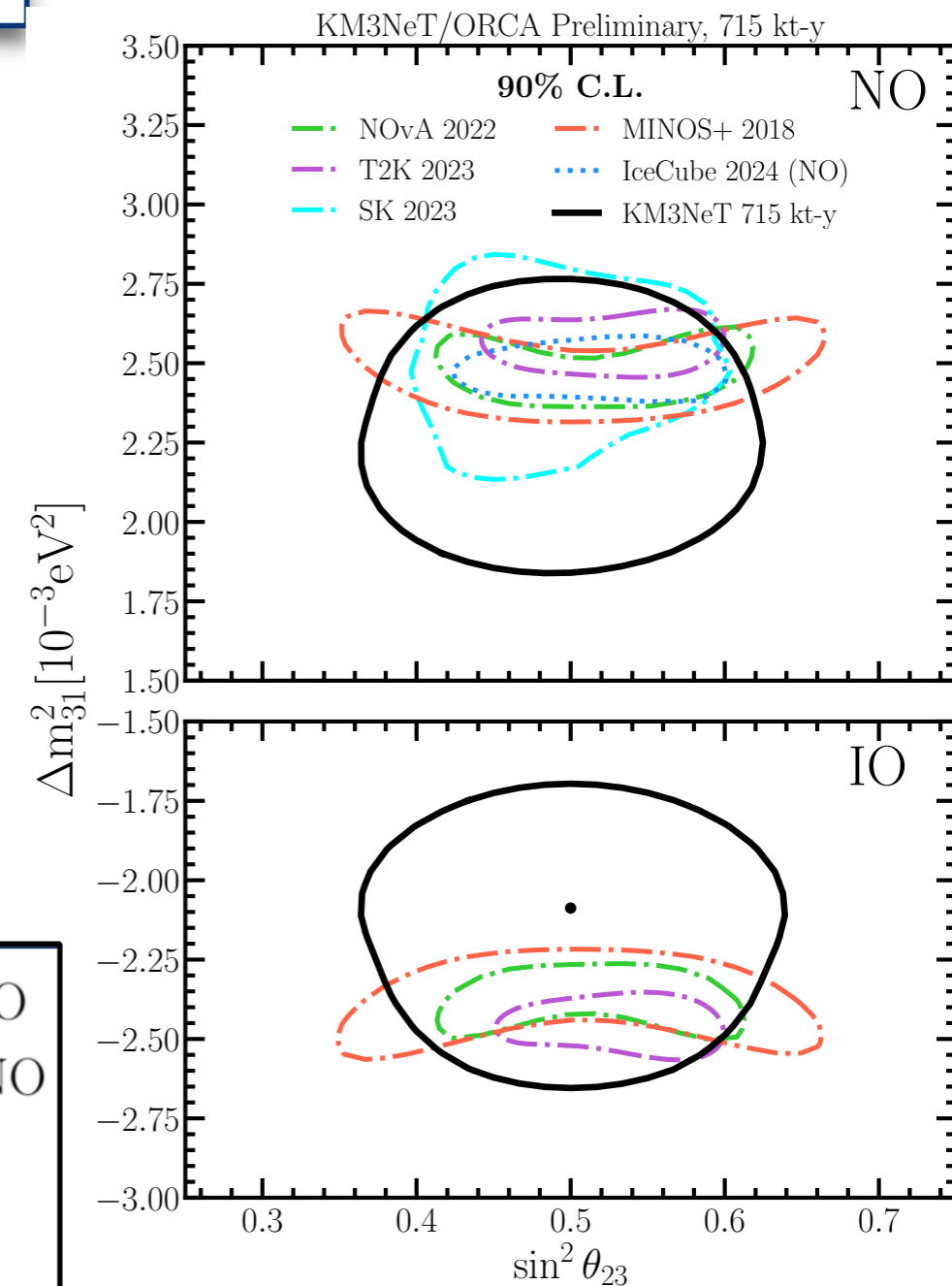


ORCA6
(433 kton-yr)
ORCA6-10-11
(715 kton-yr)

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

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

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

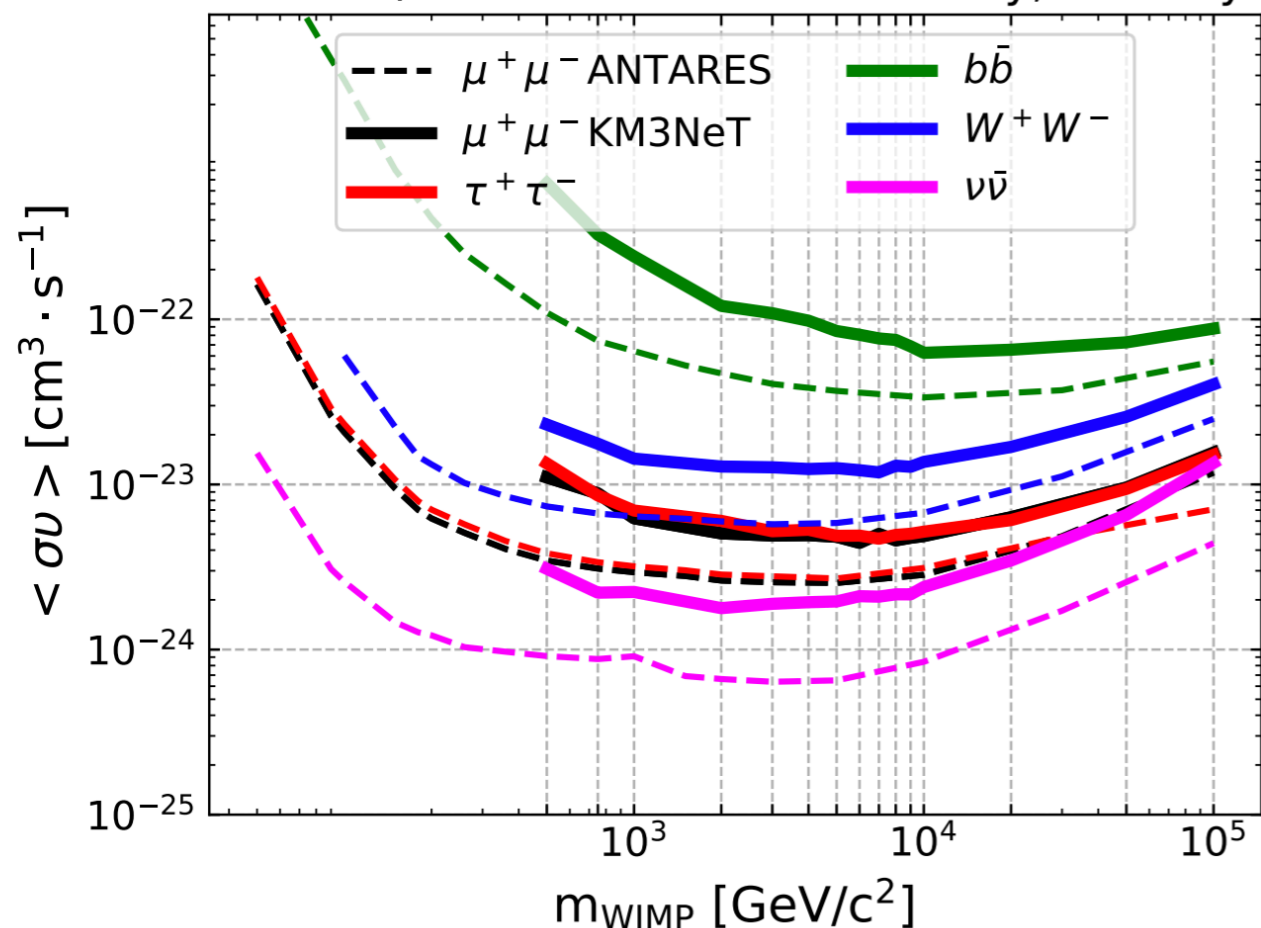


KM3NeT/ORCA competitive

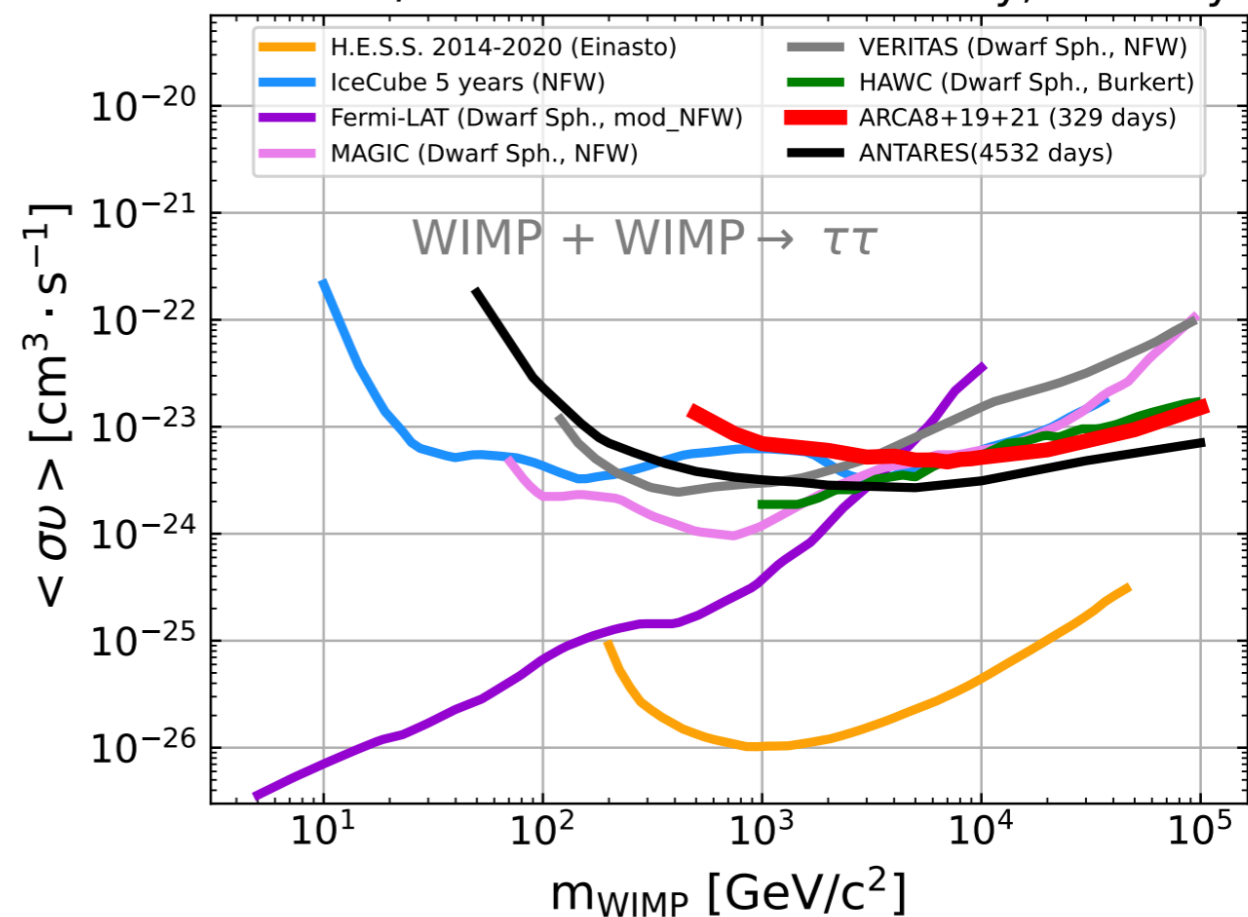
Dark Matter

Galactic Centre

KM3NeT/ARCA8+19+21 Preliminary, 329 days



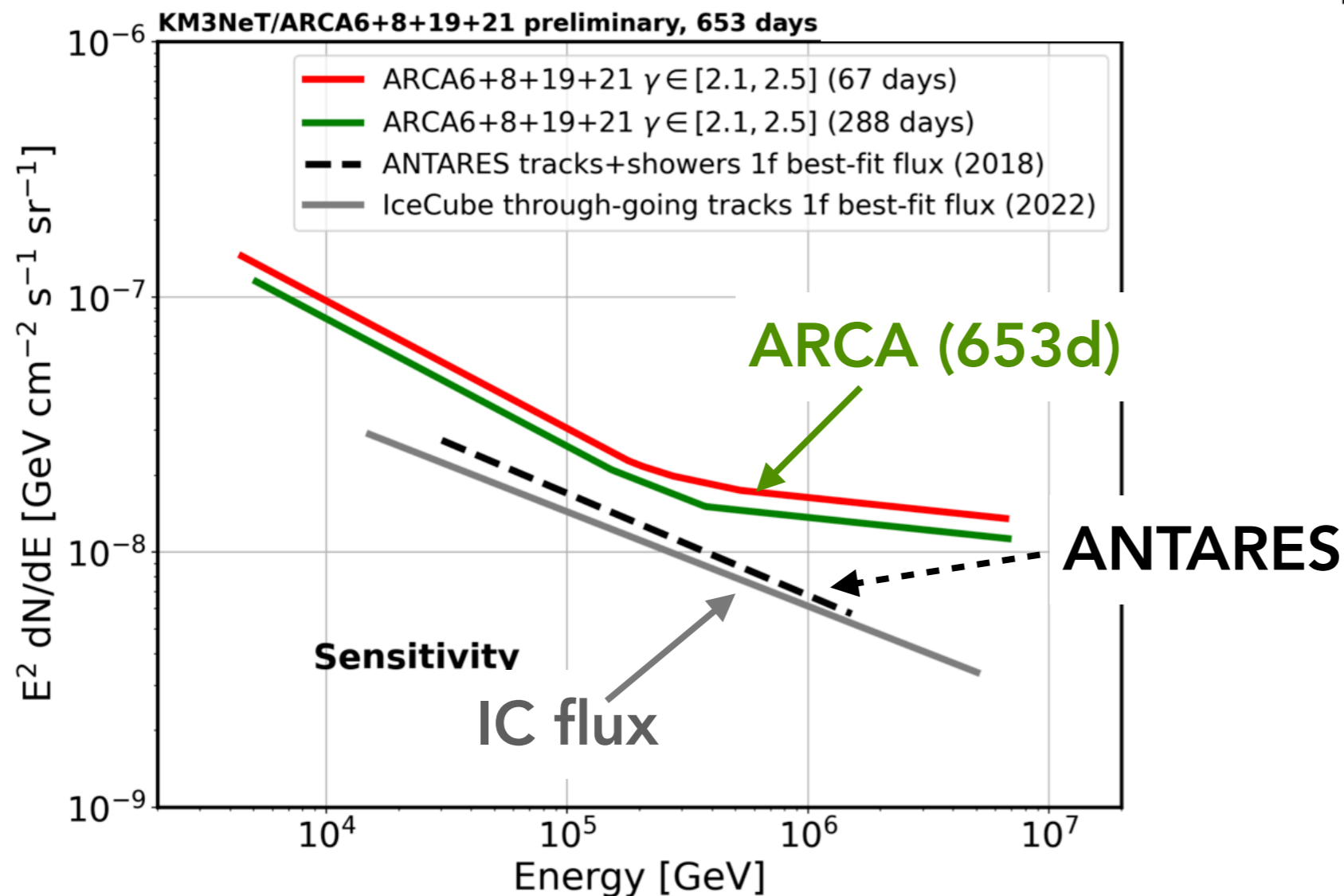
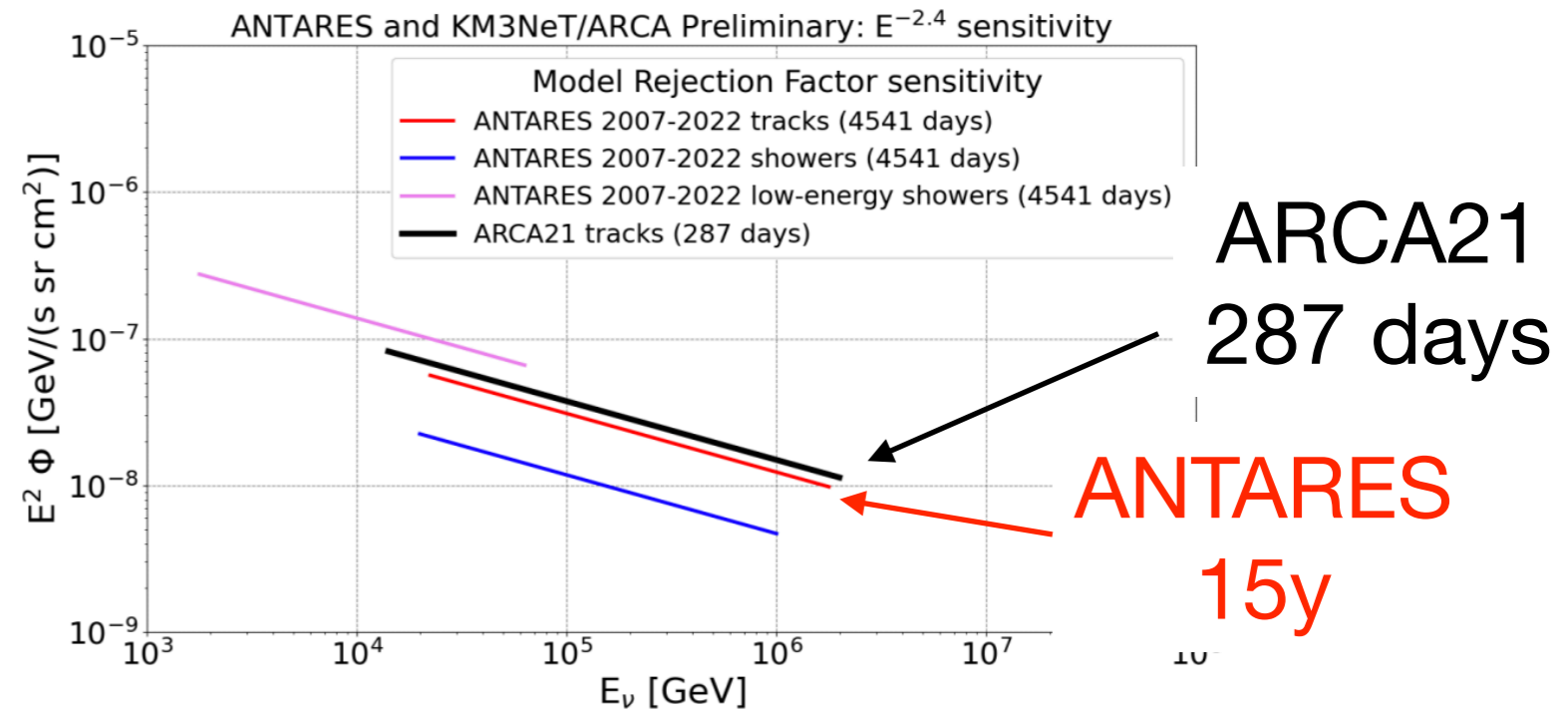
KM3NeT/ARCA8+19+21 Preliminary, 329 days



KM3NeT quickly reaching
the ANTARES limits

Diffuse fluxes

Full sky



Using data collected until Sept. 2023, same ANTARES sensitivity for track events 15yr

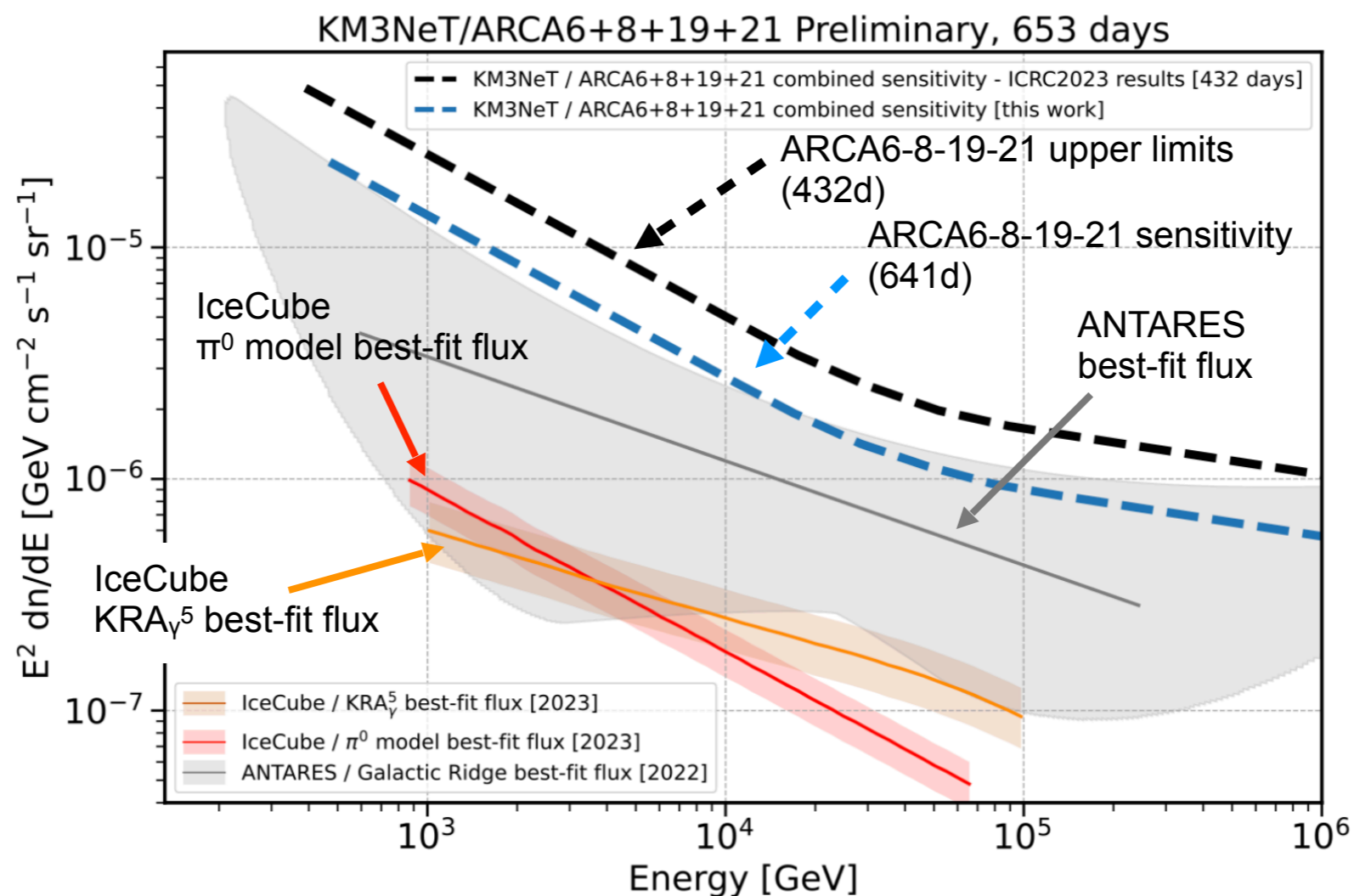
ARCA reaching ANTARES sensitivity!

Diffuse fluxes

Galactic Plane

On-Off zone
analysis

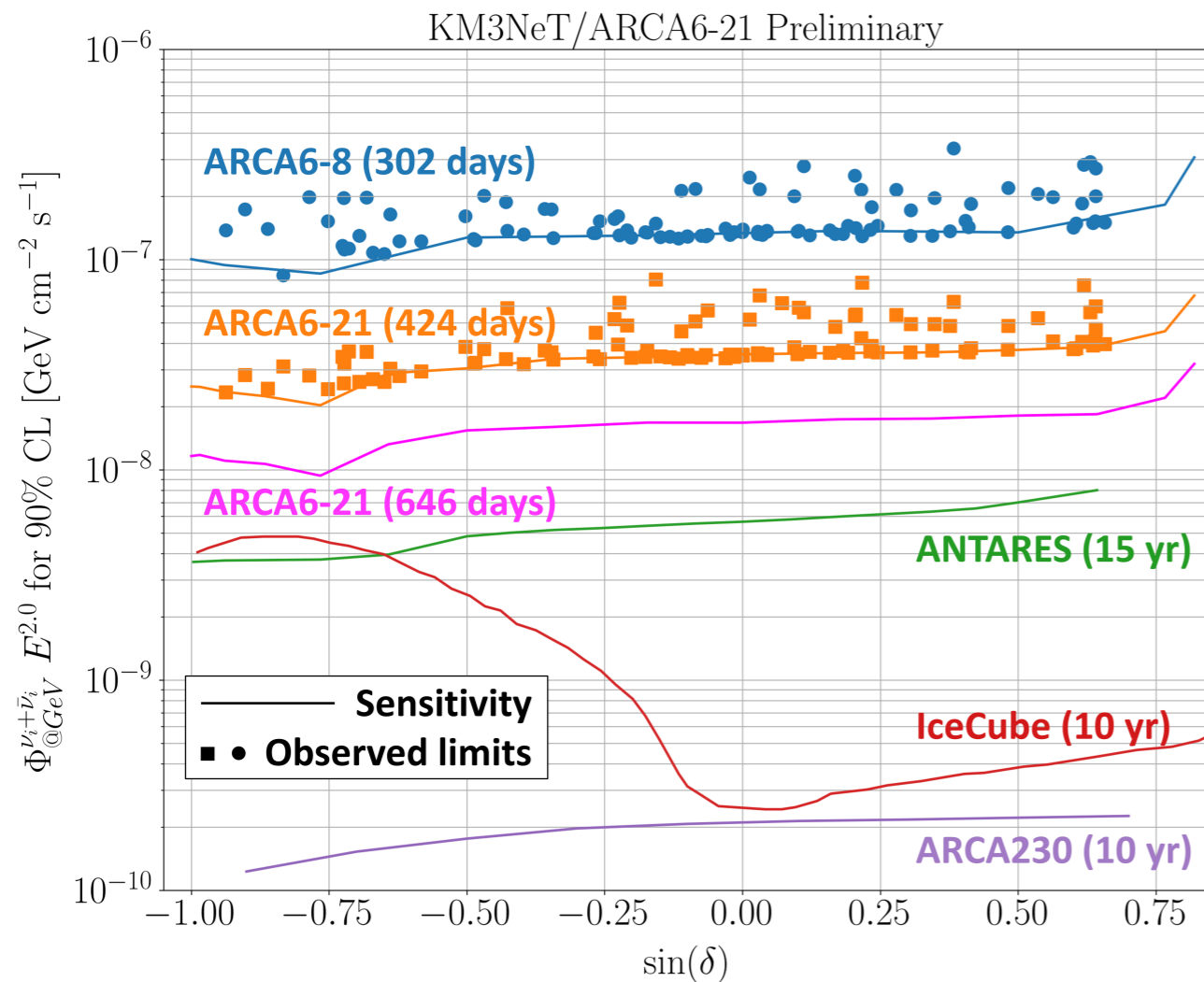
$|l| < 31^\circ$ and $|b| < 5^\circ$ for KM3NeT/ARCA6-8 and
 $|l| < 31^\circ$ and $|b| < 4^\circ$ for KM3NeT/ARCA19-21



ARCA6 & ARCA8 & ARCA19 full dataset
 ARCA21 partially included (until Dec 2022)

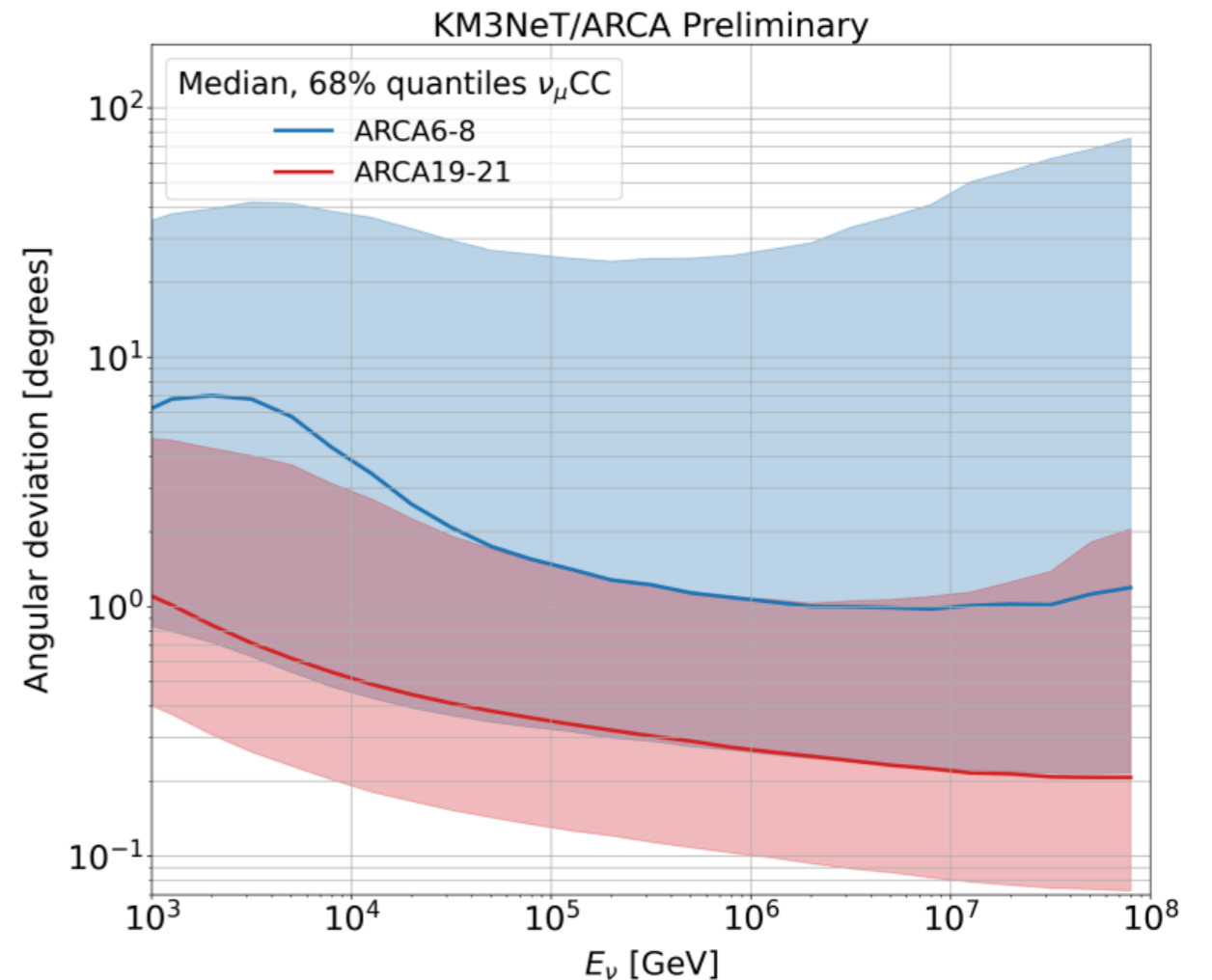
Point-like Sources

ARCA21 until December 2022
101 candidate sources



Large improvement in sensitivity is expected with data from substantially extended active volumes resulting from the sea operations in September 2023 and September 2024

Angular resolution

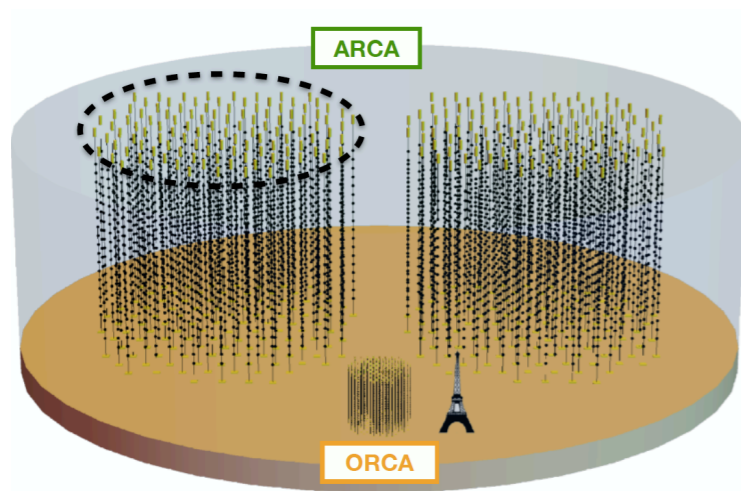


KM3NeT upper limits will soon improve the ANTARES 15yr limits

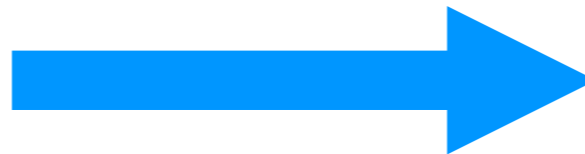
Angular resolution improved

Multi-messenger program

A dedicated software is installed at the shore stations for Real-Time Analysis (RTA)



Send neutrino alerts to external communities



Receive alerts from external communities
➤ On-line analysis and follow-up



EM/MM external communities



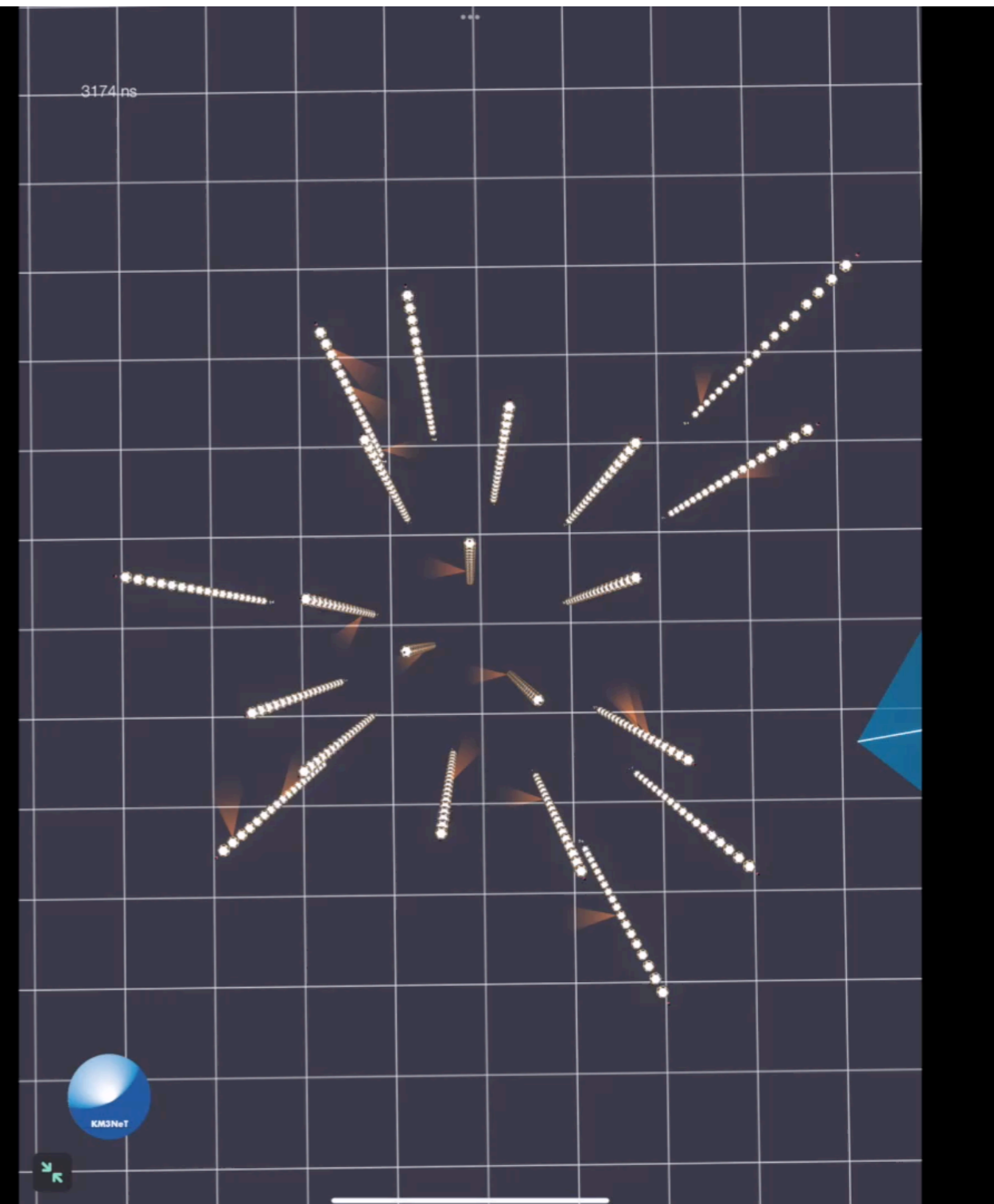
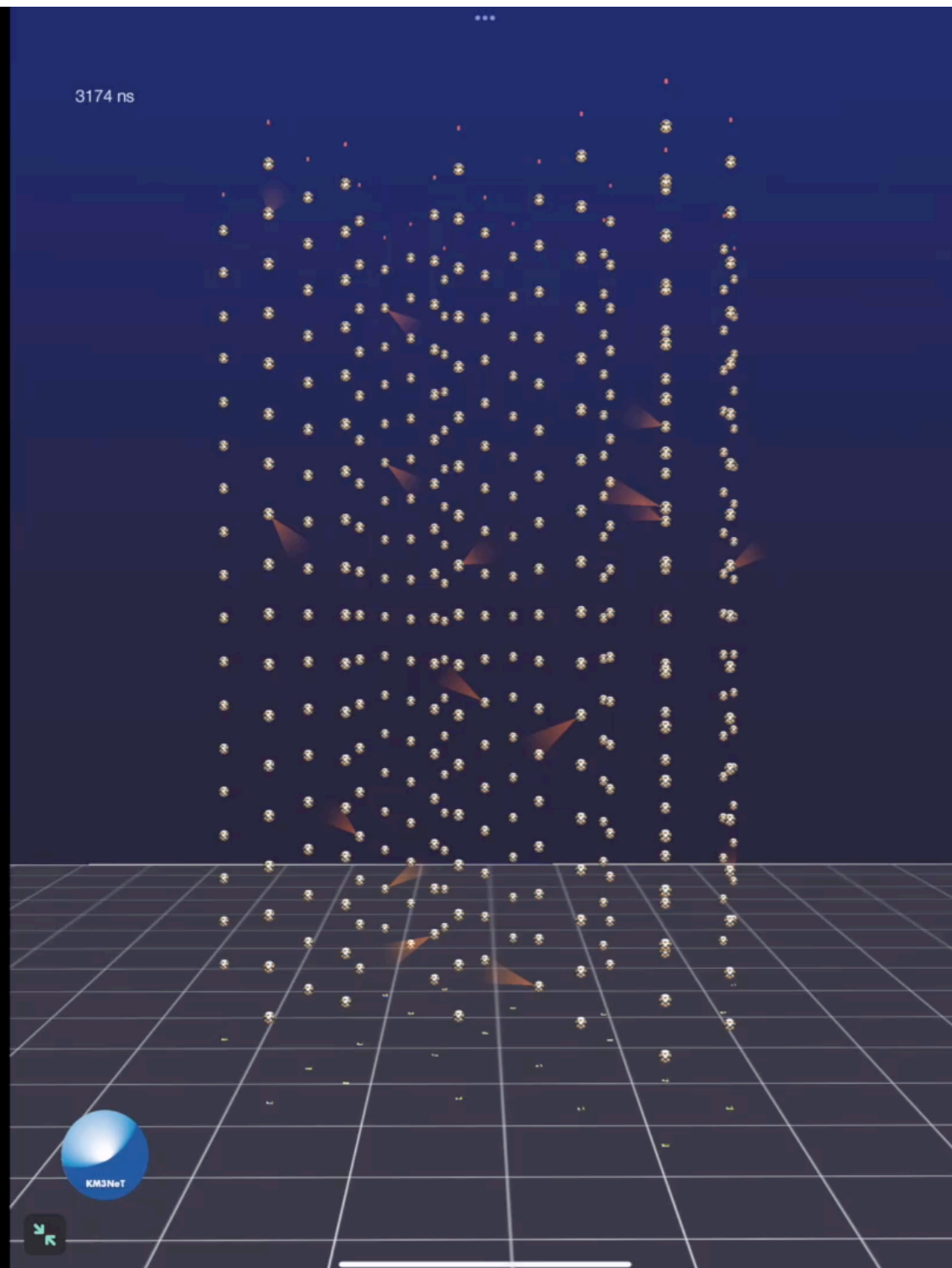
Receiving alert system operative: RTA platform active from November 2022 in ARCA and ORCA.

Sending alert system to be finalised: High-energy neutrino alerts will be sent in real-time by end-2024.

- ➔ Tuesday 9th, h 15:50: A. Veuro, Online event reconstruction and classification in KM3NeT
- ➔ Tuesday 9th, h 16:10: M. Mastrodicasa, Neutrino real-time follow-ups with KM3NeT

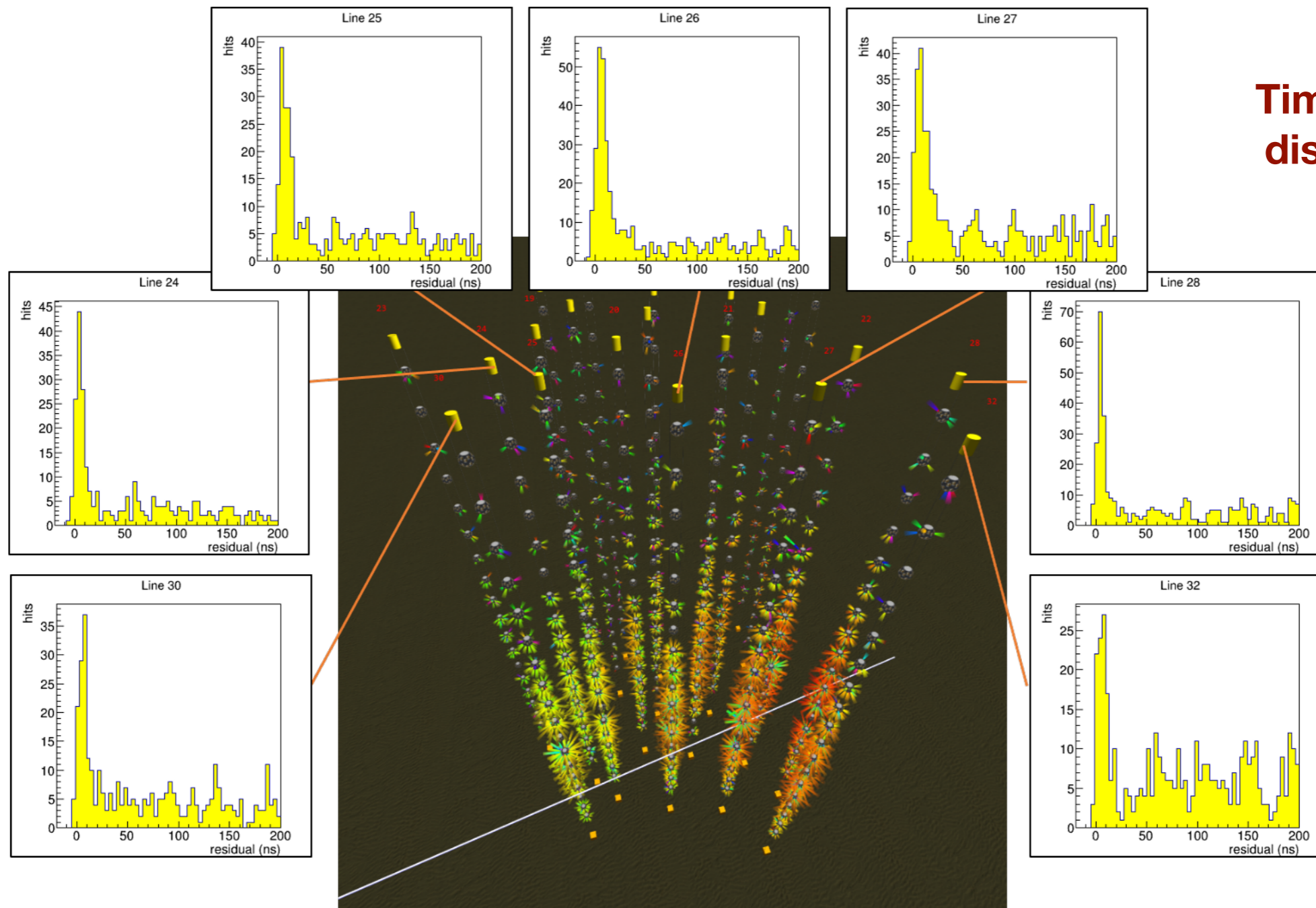
Something unexpected...

A very-high energy cosmic event detected!



Something unexpected...

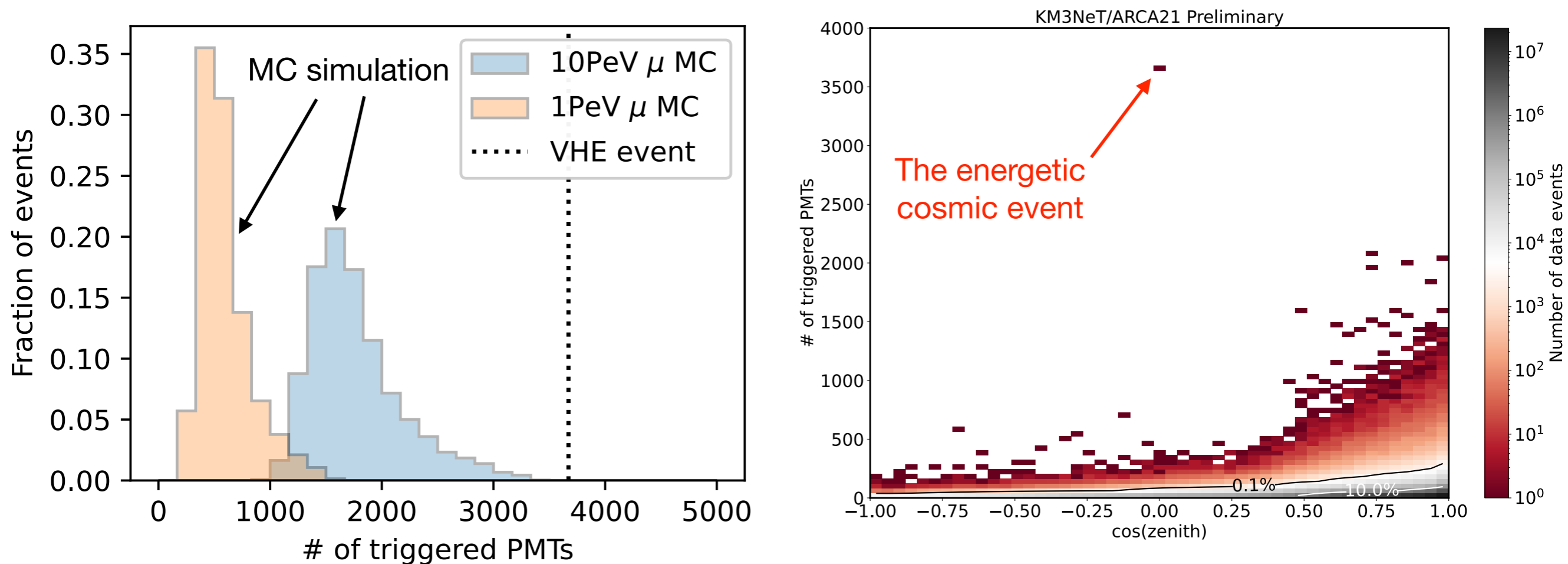
A very-high energy cosmic event detected!



The event is well reconstructed as a track

Something unexpected...

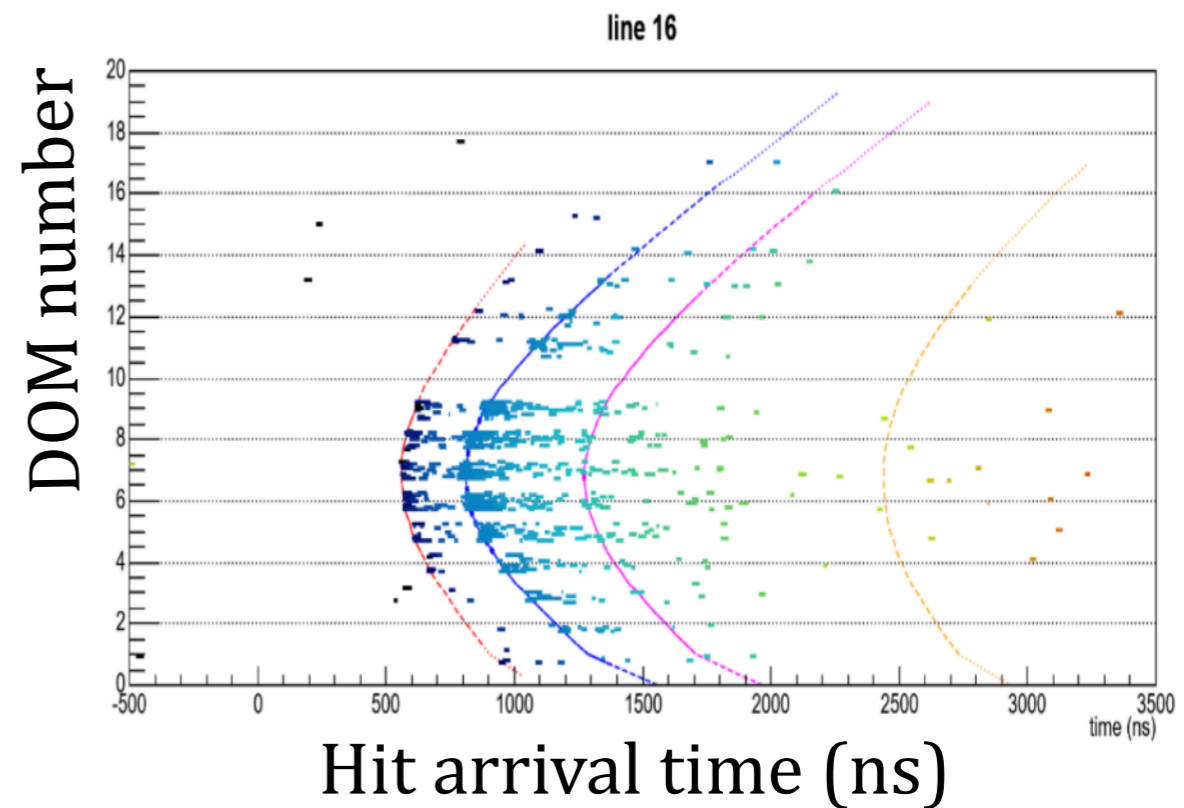
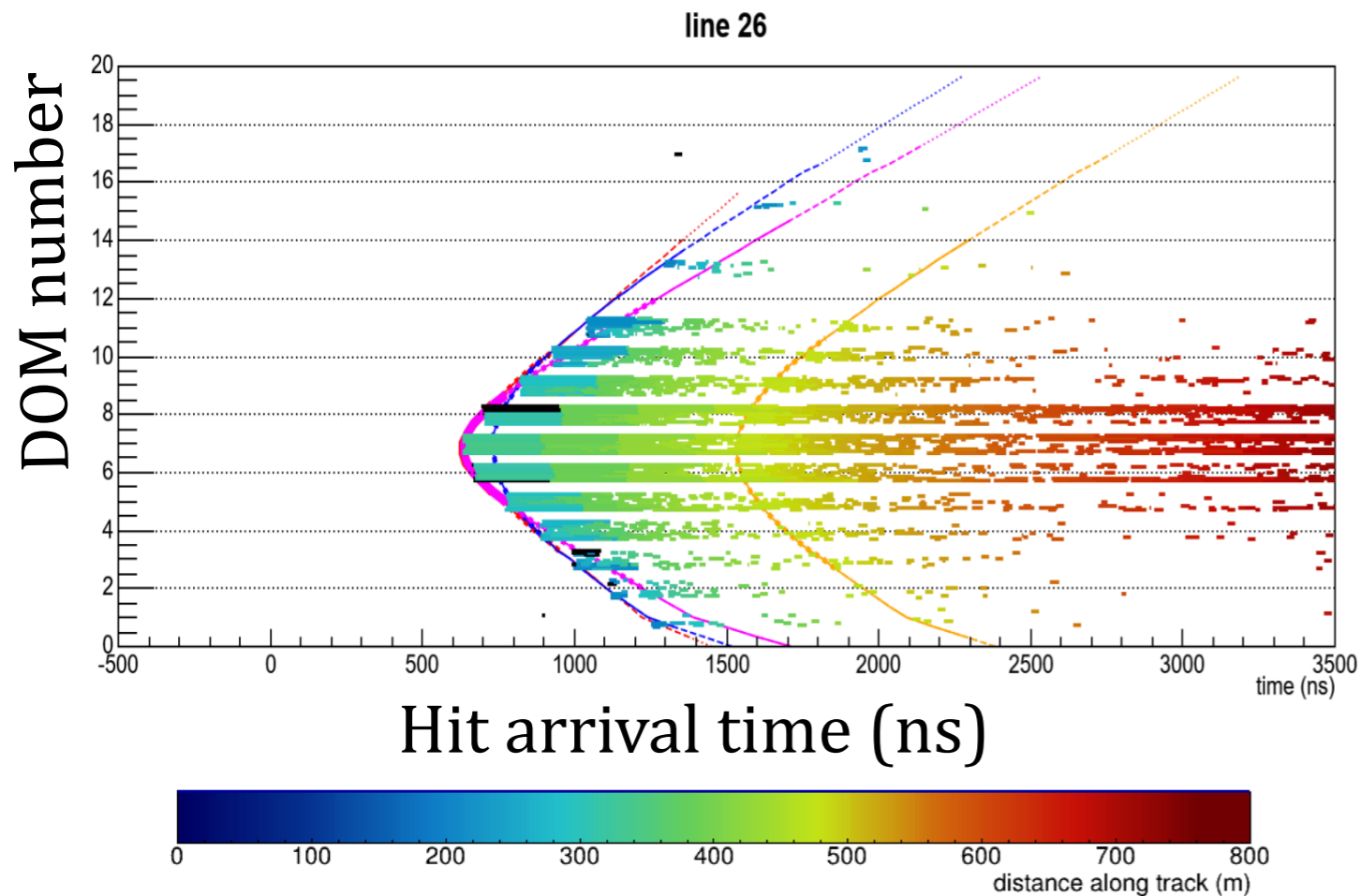
A very-high energy cosmic event detected!



The event is a horizontal event (1° above the horizon) with energy above 10 PeV

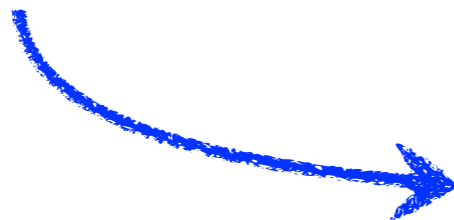
Huge amount of light detected \Rightarrow 35% of the total number of PMTs were triggered

Very-high energy cosmic event



Hit times are fully consistent with photons from Cherenkov emission

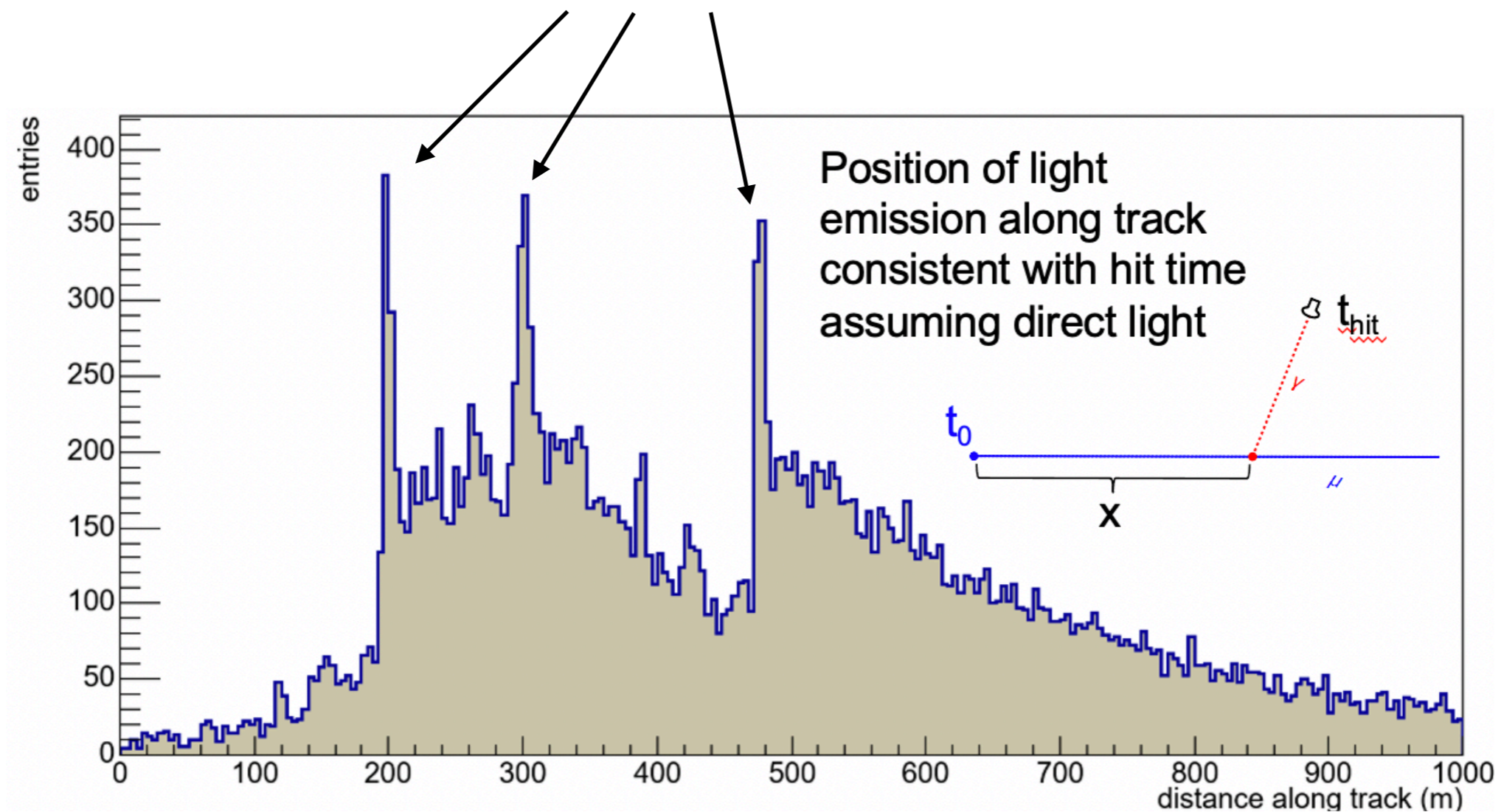
From the track and shower reconstructions



A muon track and three showers detected

Very-high energy cosmic event

Hit times consistent with the emission from three points along the track



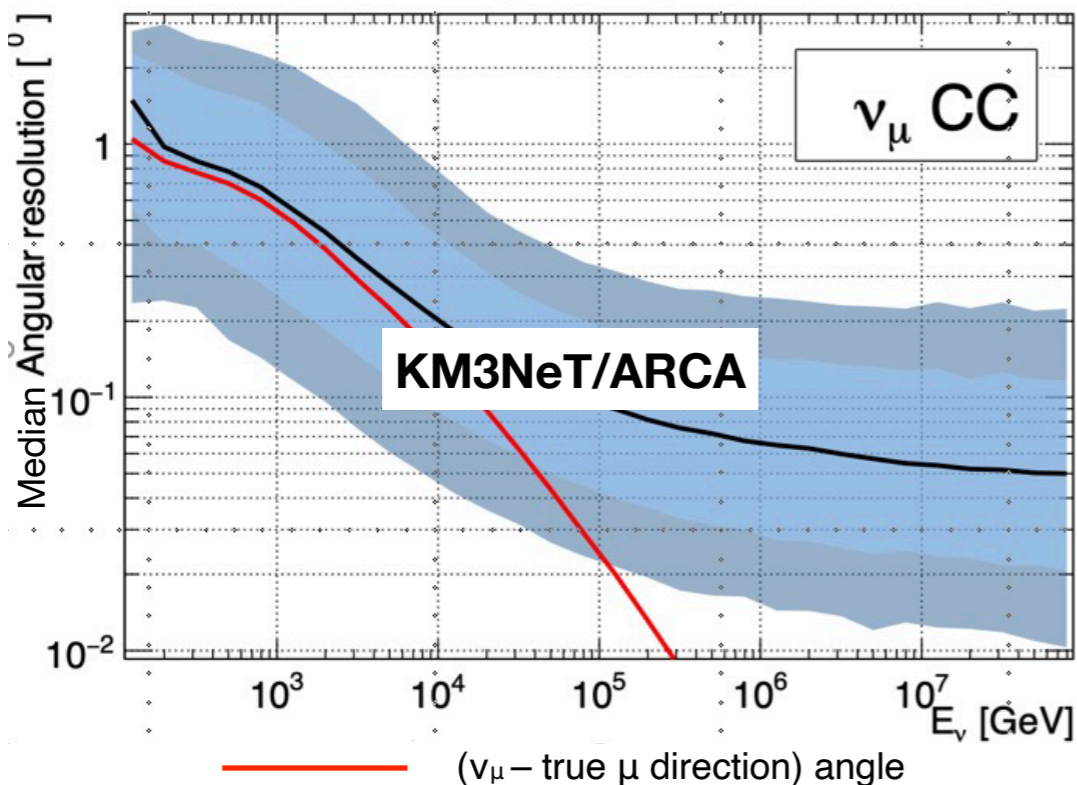
Stochastic light emission

ARCA Reconstruction Performances

Track-like and shower-like events

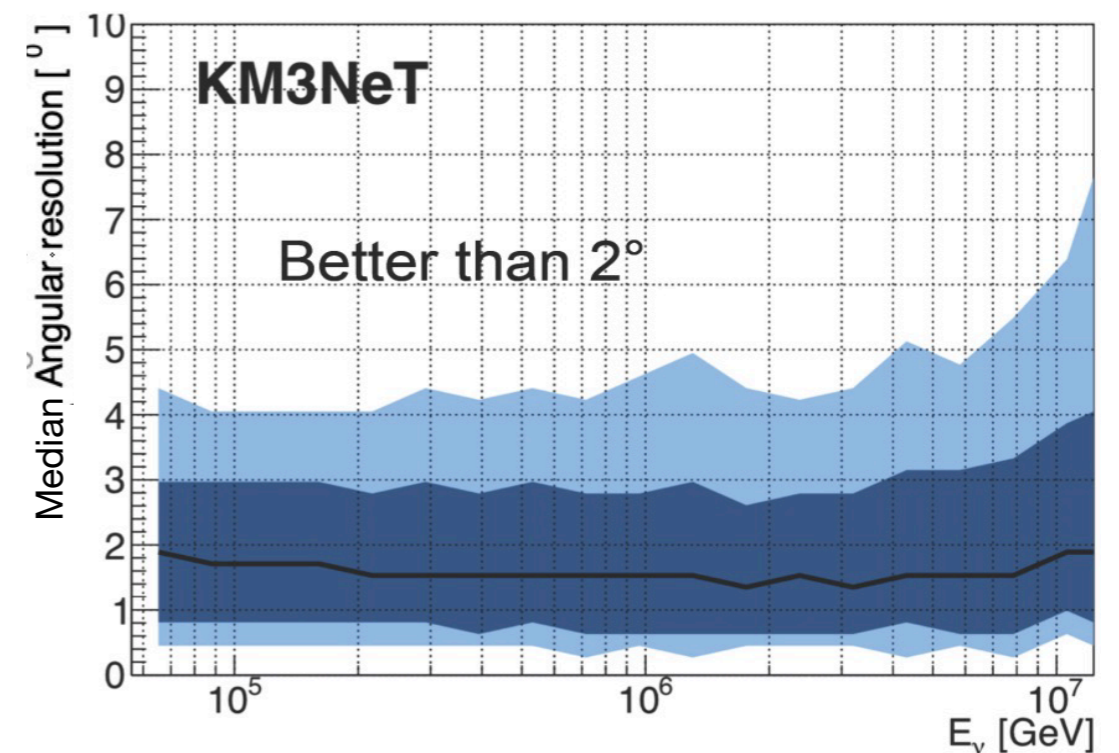
Tracks (ν_μ CC) ideal tool for astronomy

- **Ang. Resol.** $< 0.2^\circ$ above 10 TeV
- **Energy Resol.** ~ 0.27 in $\log_{10}(E_{\text{reco}}/E_\mu)$
(10 TeV $< E_\mu < 10$ PeV)



Shower (ν_x NC + ν_e CC) contained events

- **Ang. Resol.** $< 2^\circ$ above 50 TeV
- **Energy Resol.** $< 5\%$

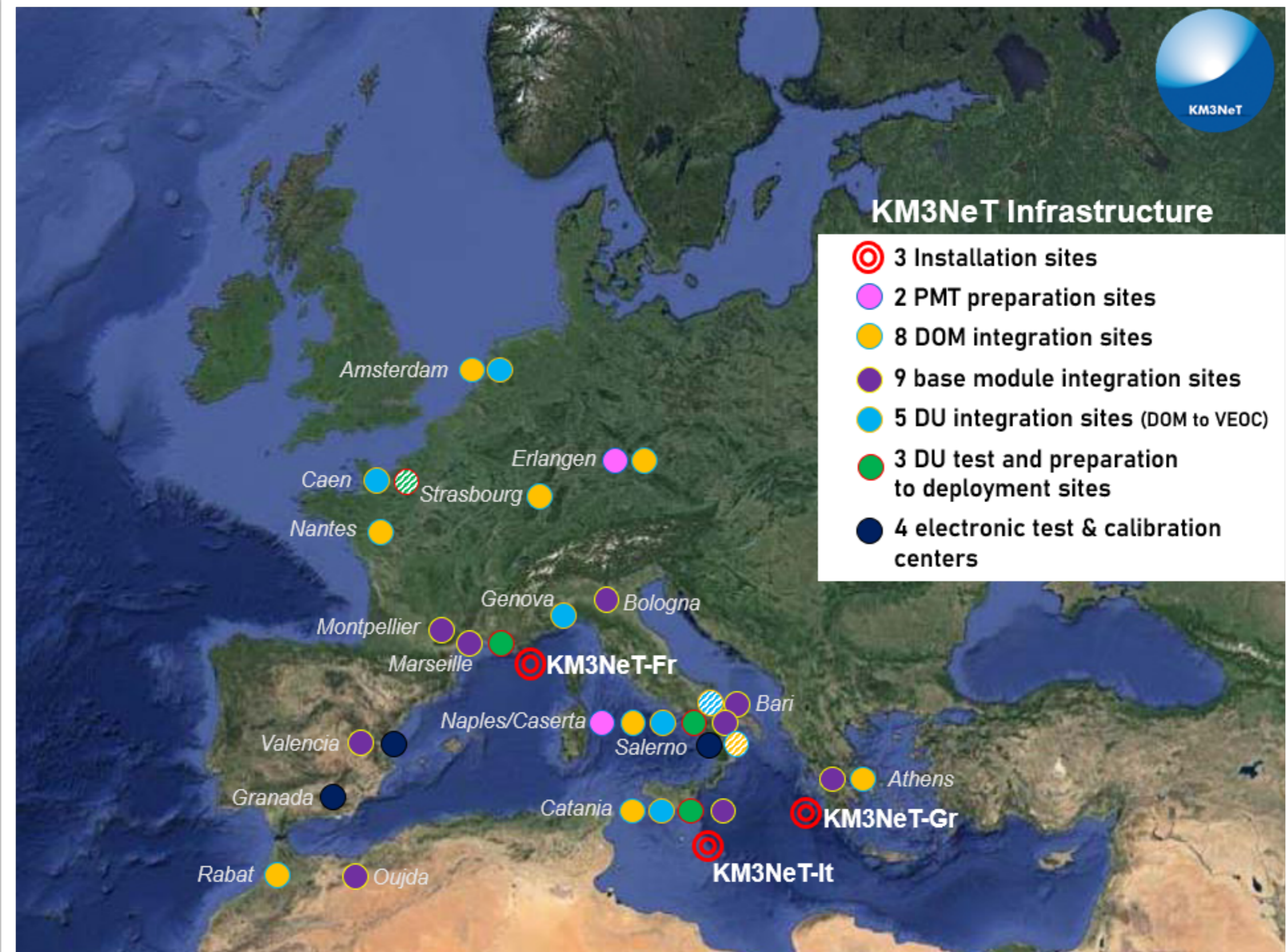


KM3NeT vs IceCube:

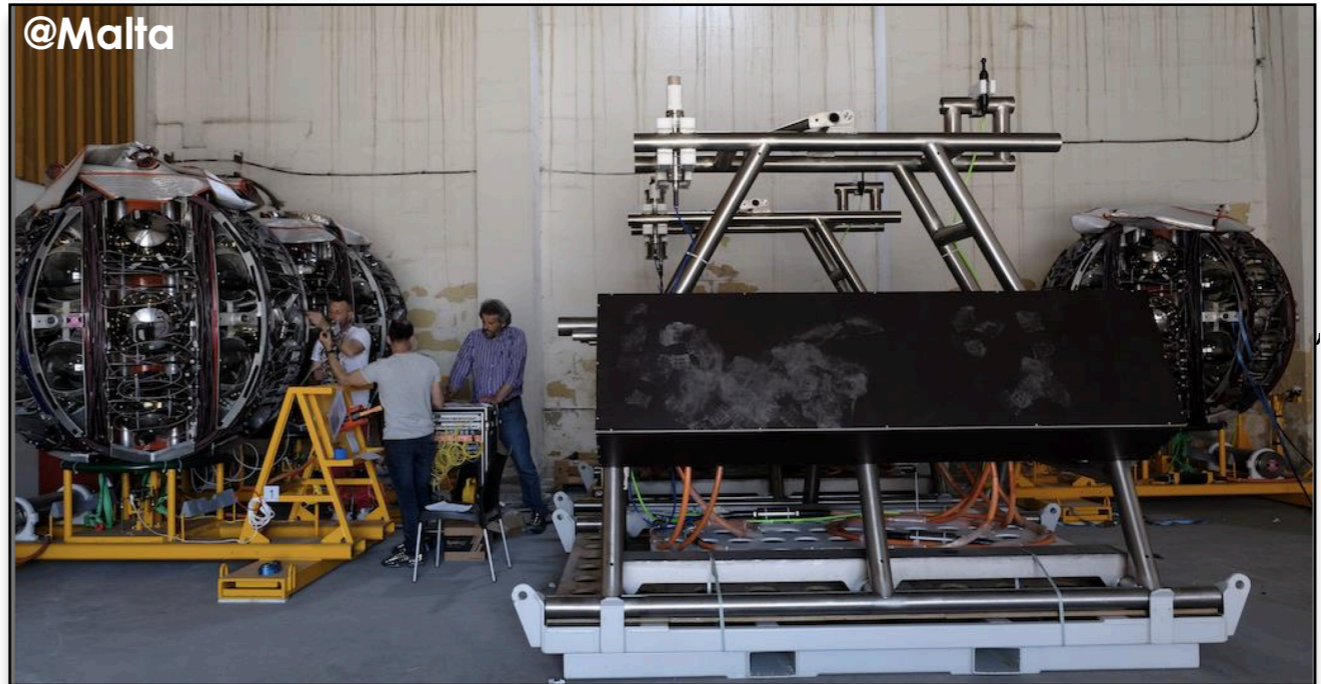
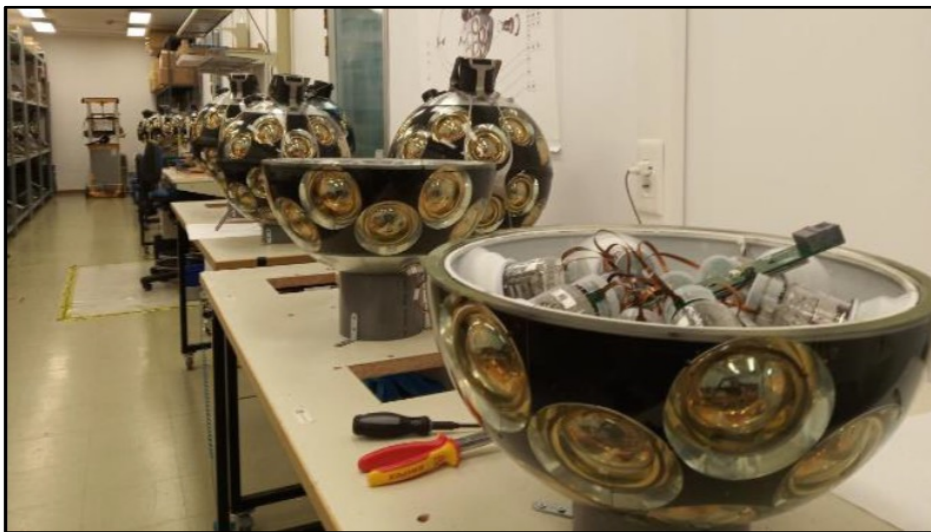
Con: ^{40}K background, bioluminescence, need for real-time positioning, deep-sea operations

Pro: ^{40}K calibration, better view of the galactic center, no bubbles/dust \rightarrow better angular resolution

Detector construction



Detector construction: a collaboration effort!



Conclusion



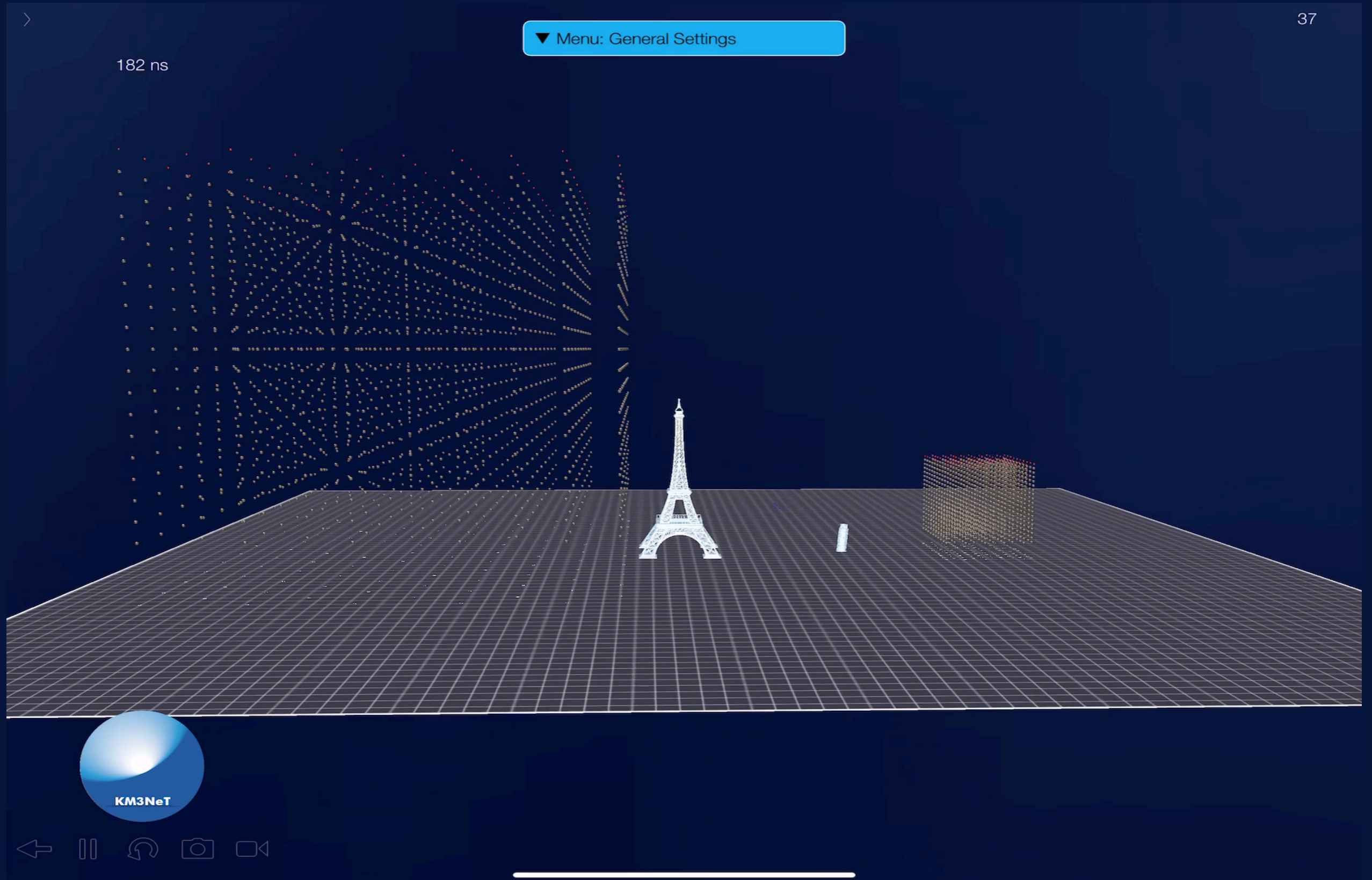
- KM3NeT is active and taking (good!) data
- Detector performance as good as expected. First physics results with partial detector configurations.
- ORCA currently taking data with 23 Detection Units.
 - ◆ Funding assured, procurement and construction in progress, for ~50 DUs
- ARCA taking data with 28 Detection Units —> substantially more in October!
 - ◆ Funding assured, procurement and construction in progress, for ~130 DUs
- Detector mass production in regime stage. Production rate will increase in the next years
- Stay tuned!



Simone Biagi



Why don't you join KM3NeT?

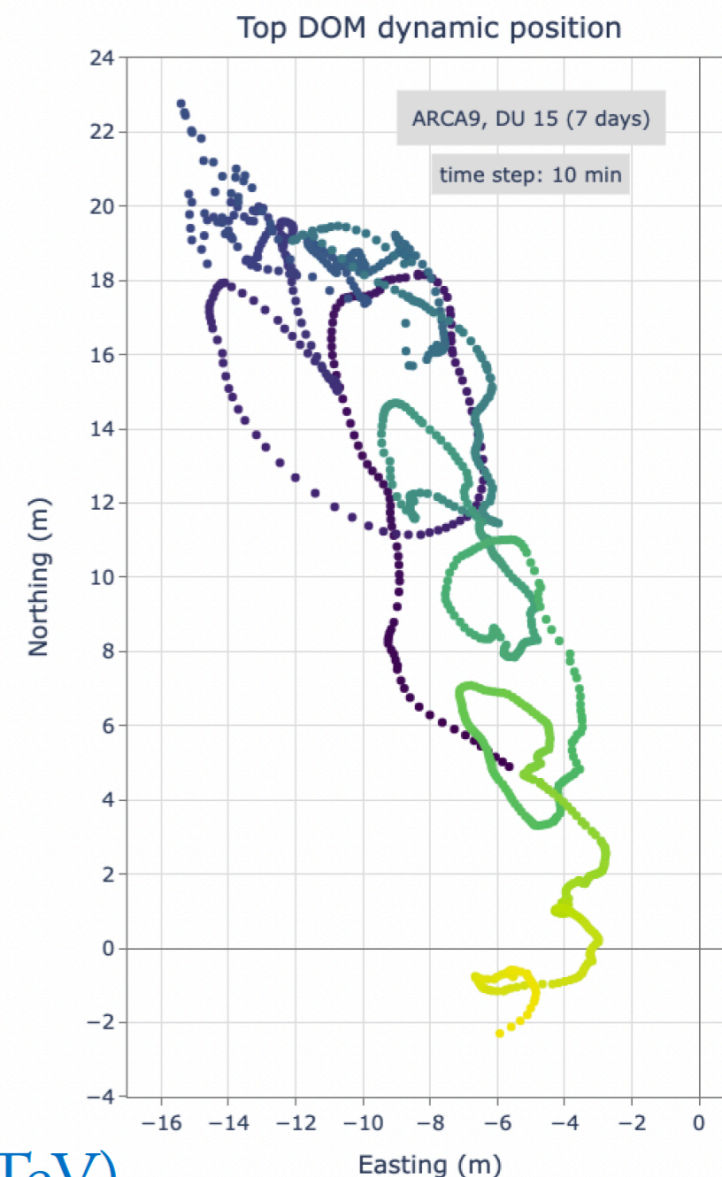


ARCA and ORCA Building Blocks

Spare

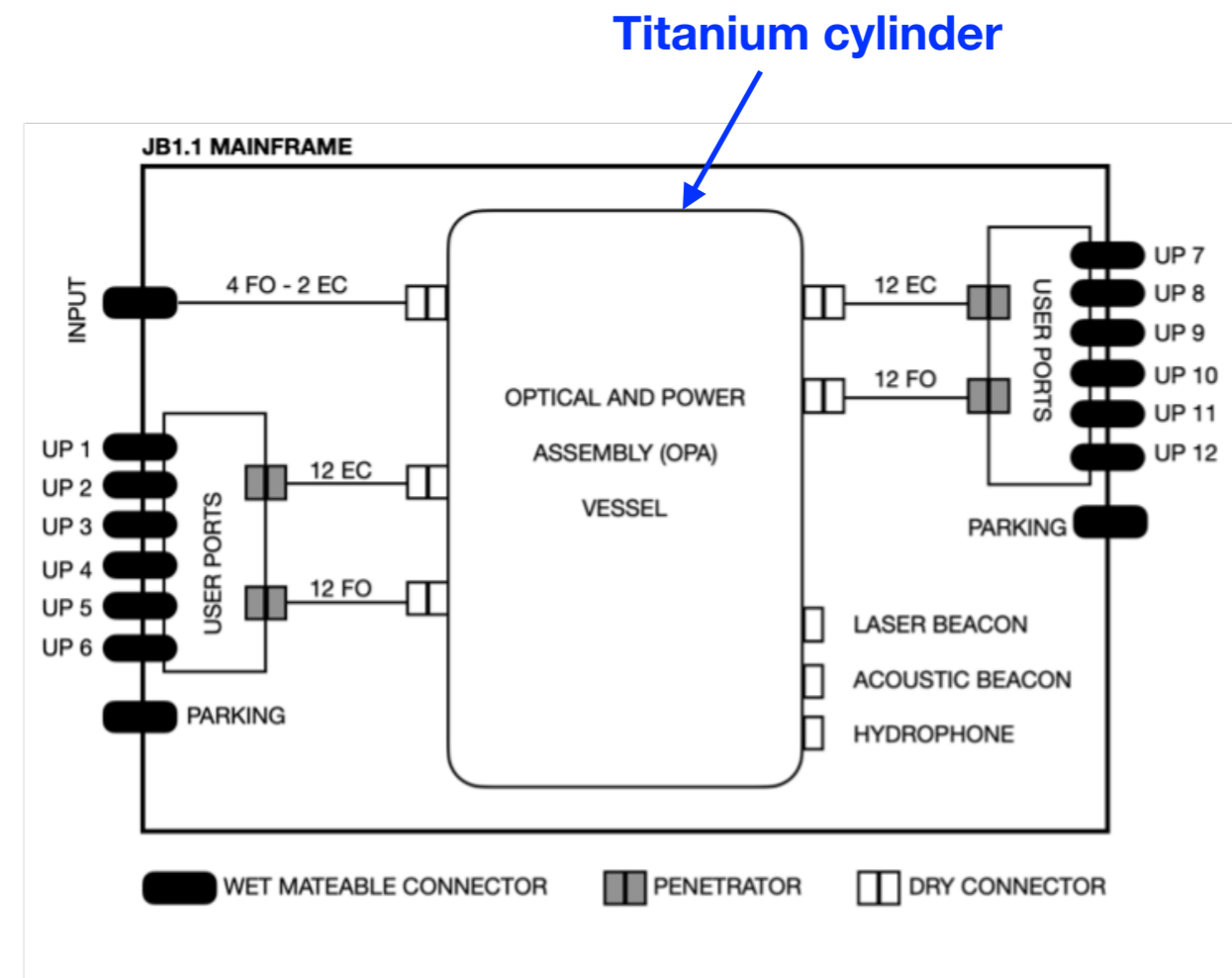
Detector calibration

- Timing calibration
 - LED pulsers (nanobeacon) for inter-DOM calibration (NIM.A 1040 (2022) 167132)
 - < 1 ns 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 $< 0.1^\circ$ precision for neutrino direction at high energy (> 100 TeV)

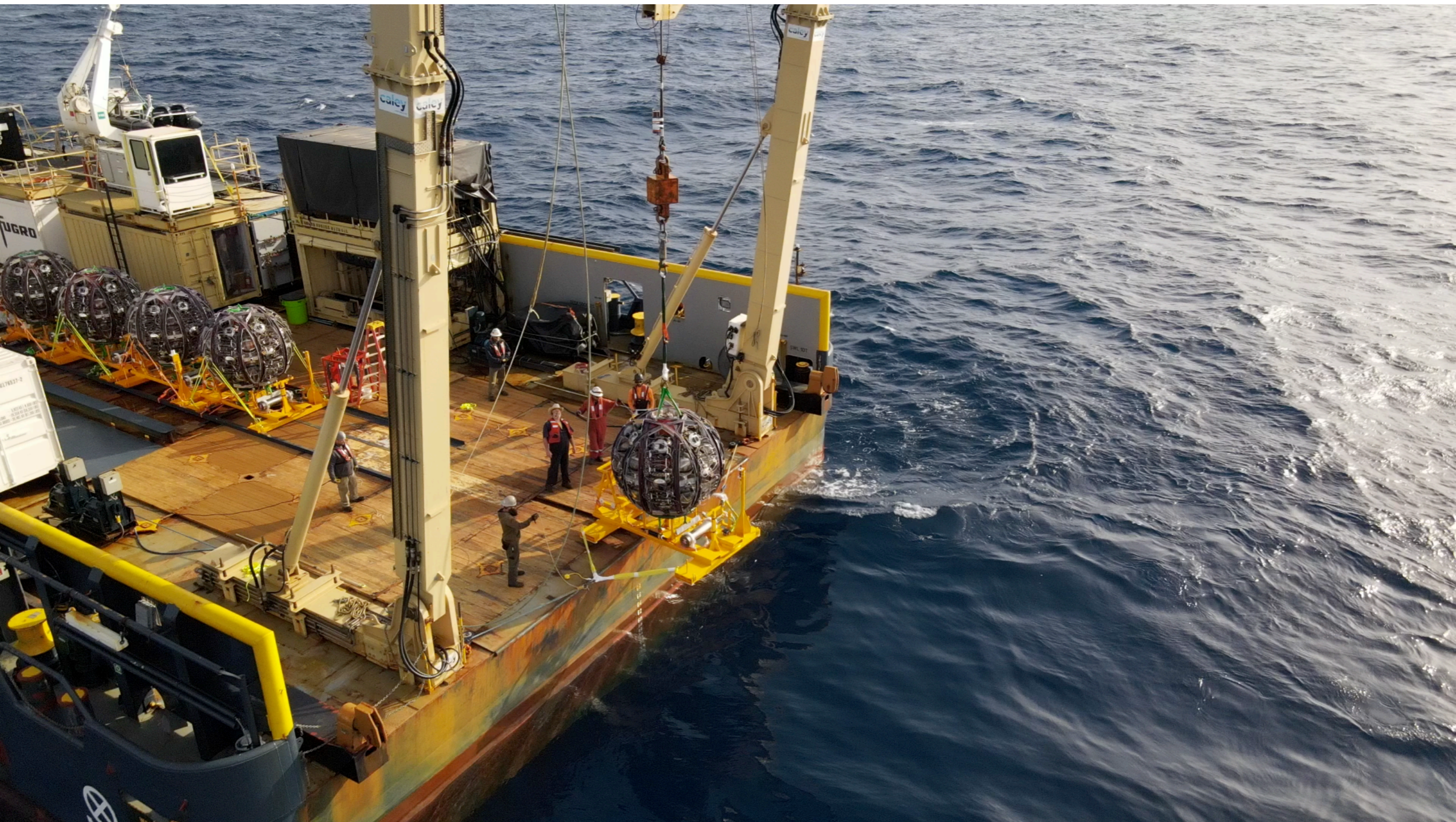


Junction Boxes

- Technology developed with external companies, from oil&gas
- Electronics intrinsically redundant, every component is duplicated in case of breaking
- Boards and components produced with military/space standard
- This junction box meets the requirement of a 20-year lifetime at 3500m sea depth
- With a reliable infrastructure, DU mass production can start

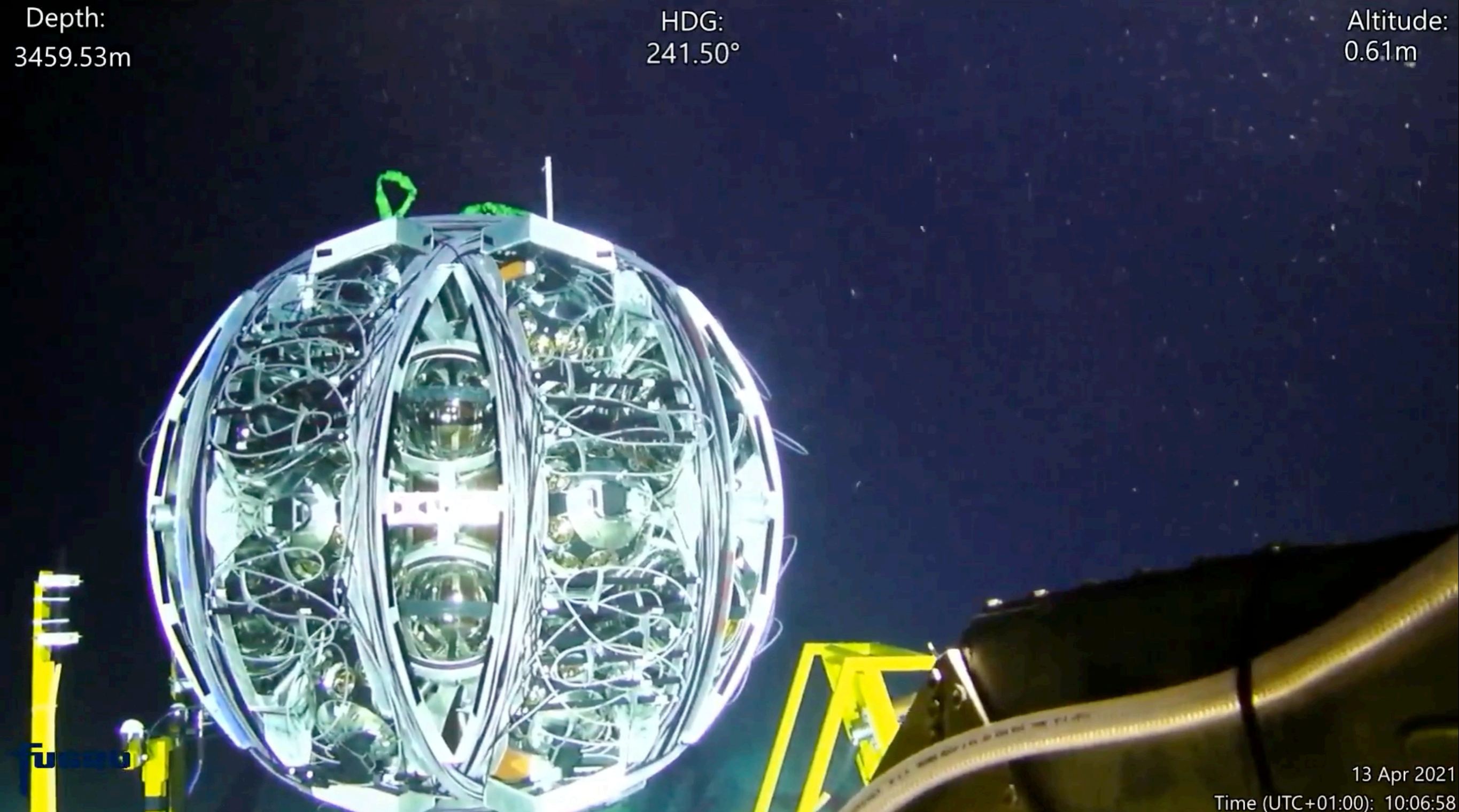


Detection Unit deployment



Deployments: **launcher module (LOM)** with anchor, lower to sea floor, connect, test, unfurl, retrieve LOM₃₄

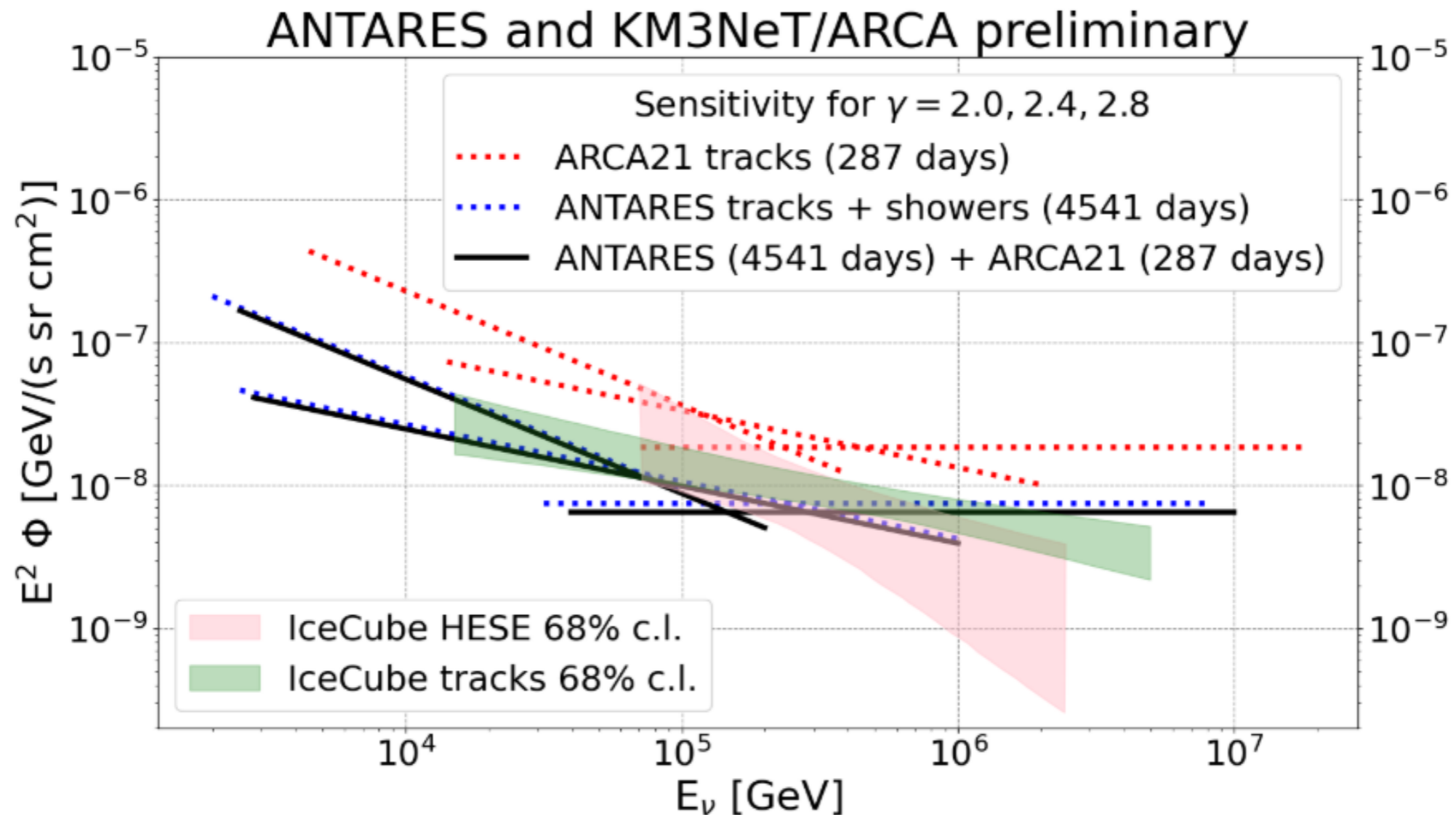
Detection Unit unfurling, triggered by ROV



Deployments: launcher module (LOM) with anchor, lower to sea floor, connect, test, **unfurl**, retrieve LOM 35

Diffuse Analysis

- Overall, on the lack of any particular sources we can explore the highest energy tail
- Atmospheric neutrinos expected to taper off above 100 TeV scale
- Diffuse flux already observed by IceCube
- ARCA and ANTARES joining forces to confirm the full sky flux

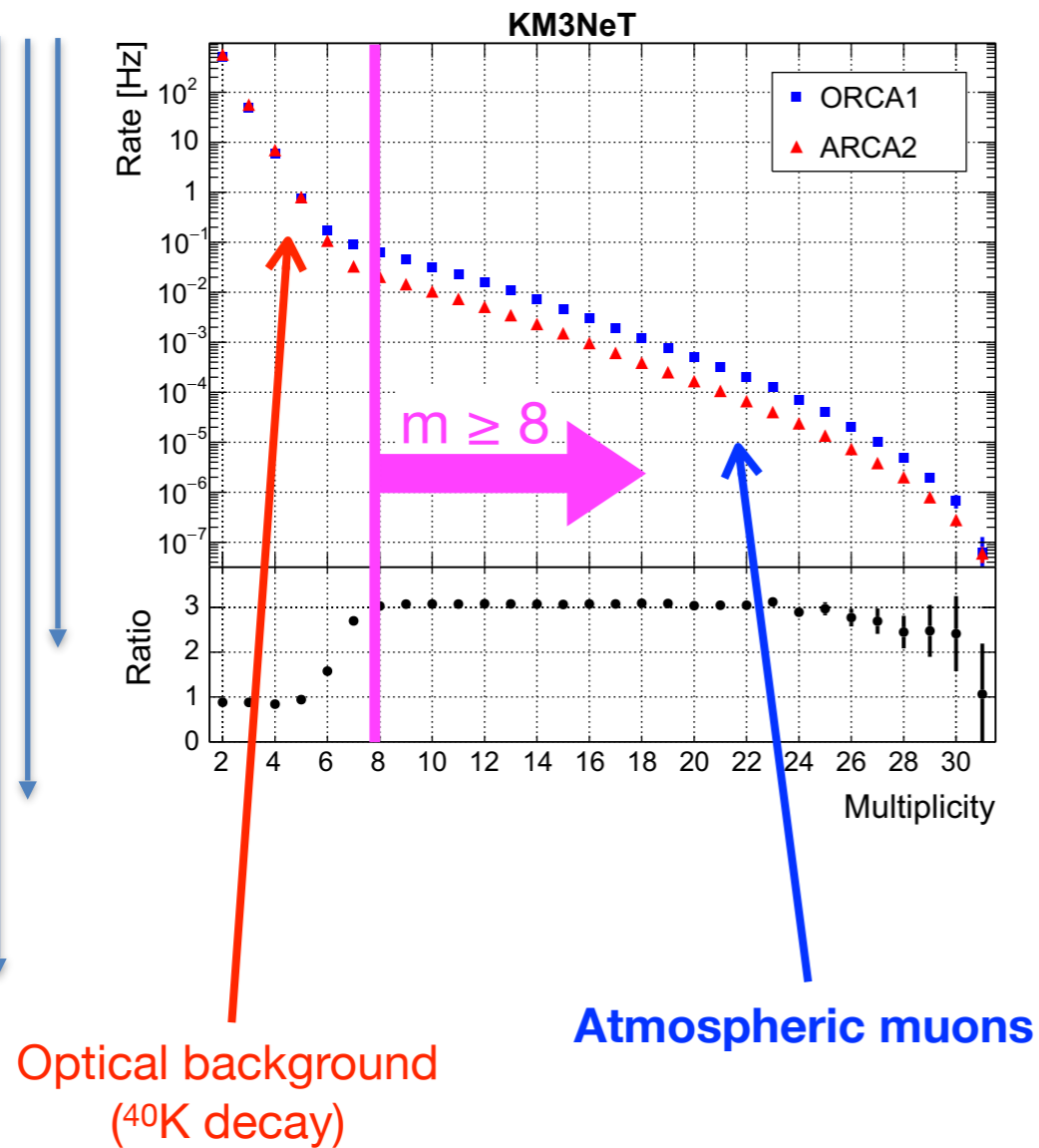


Atmospheric muon flux

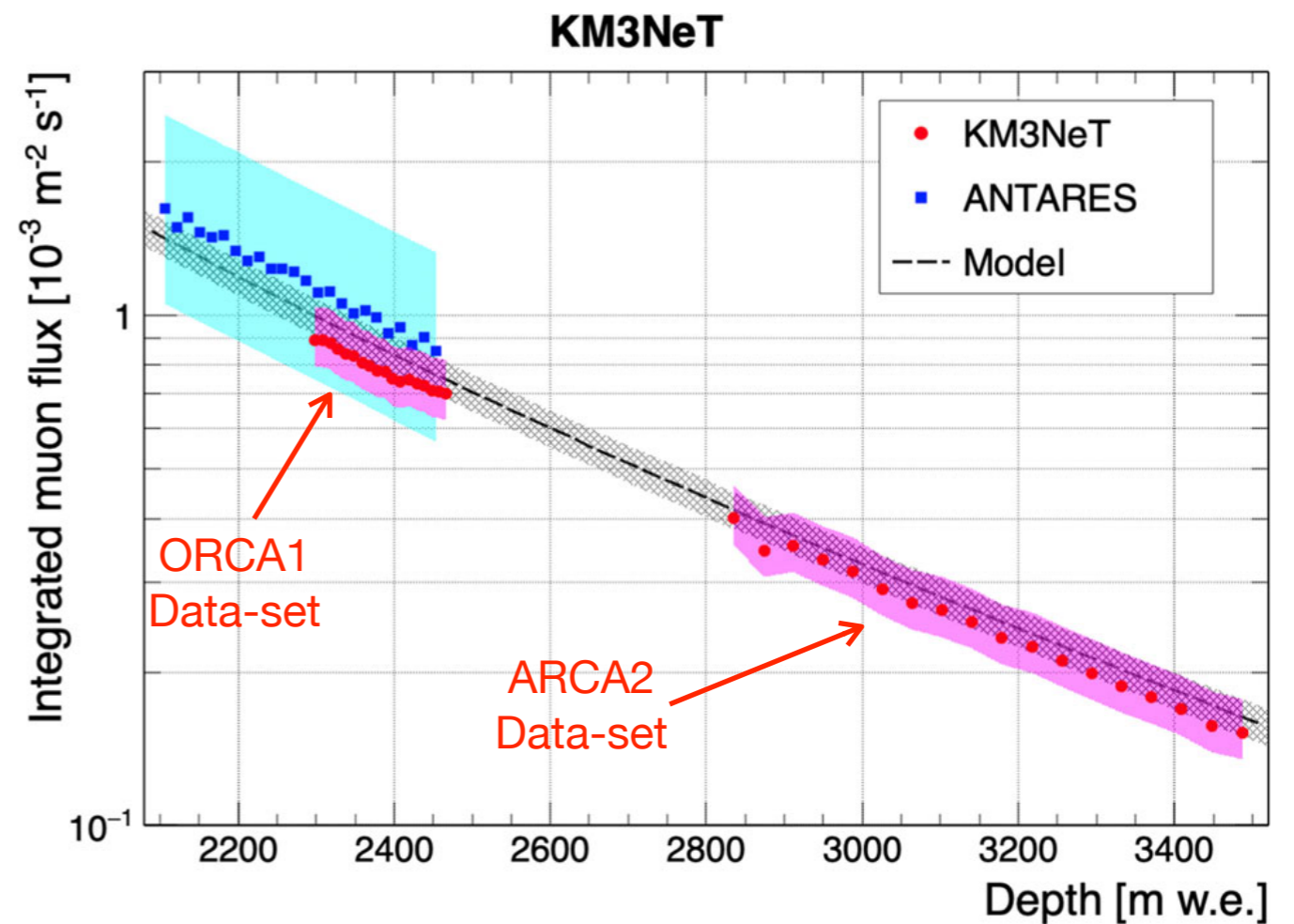
Eur. Phys. J. C 80 (2020) 99

ARCA2 + ORCA1

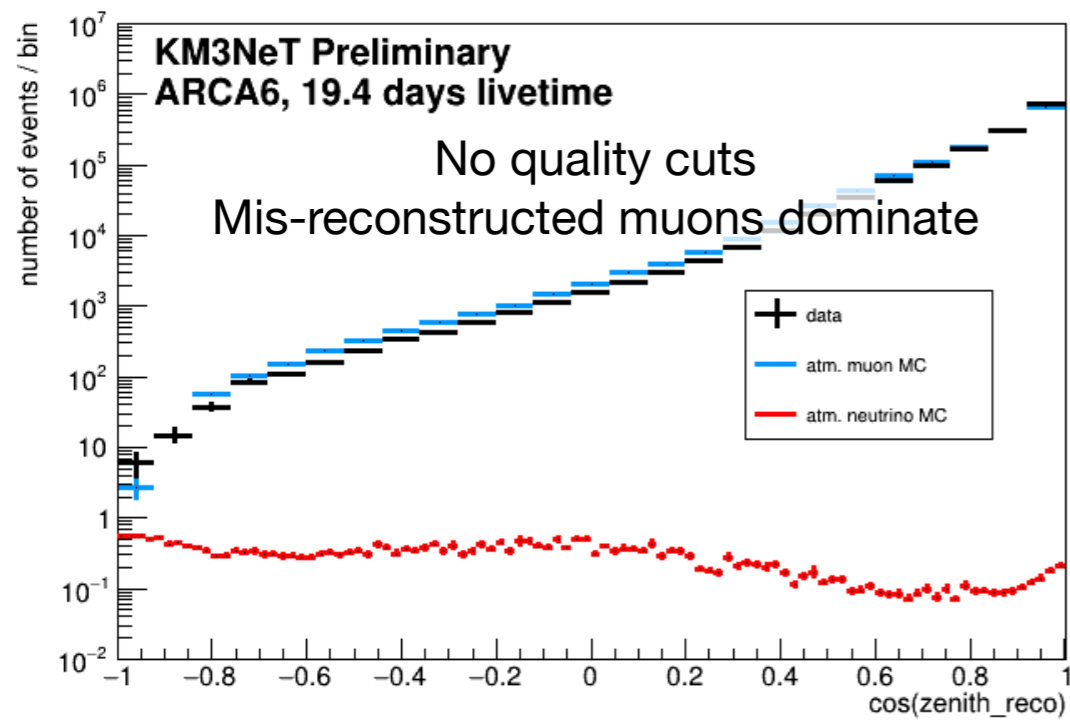
μ



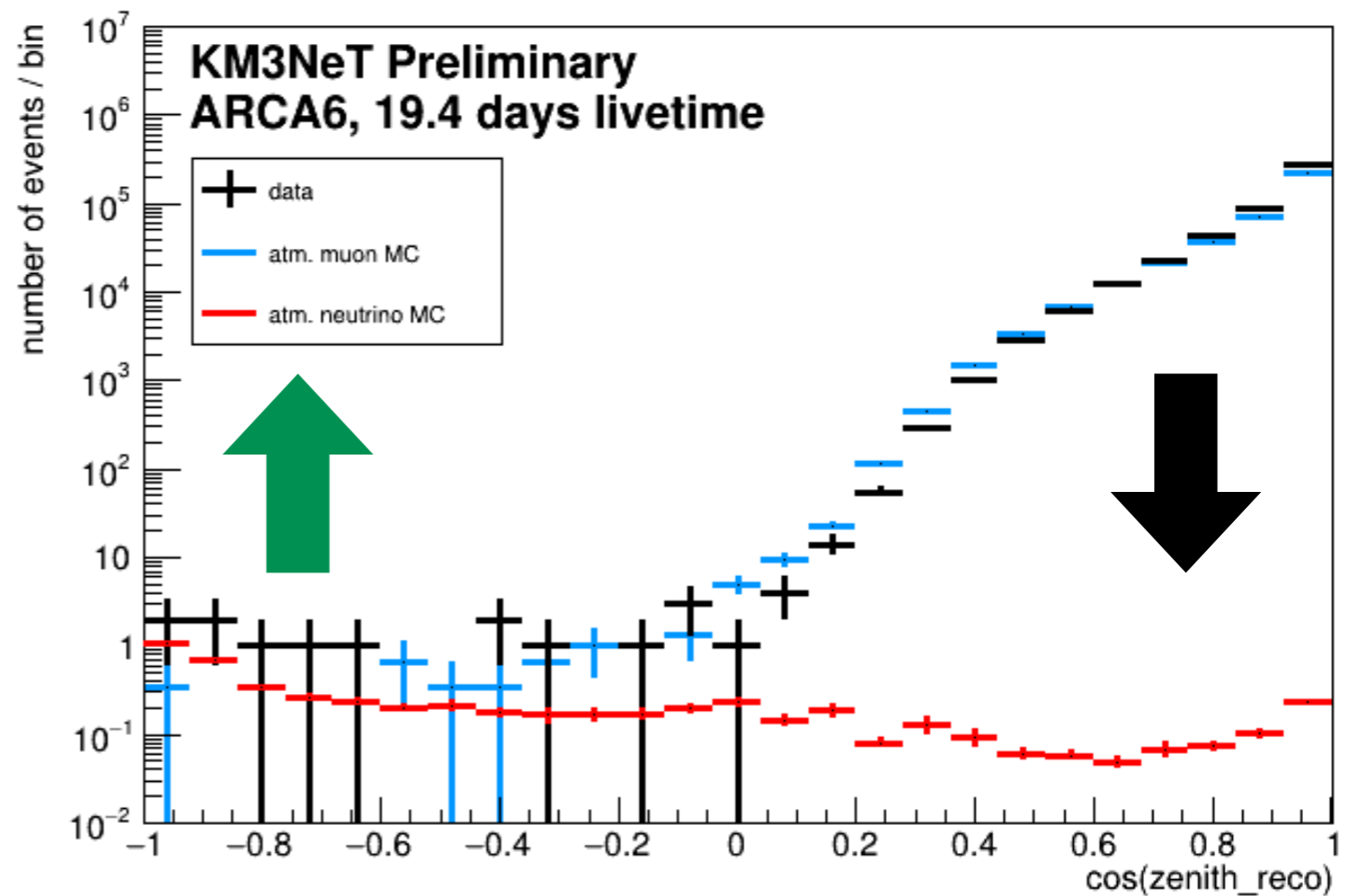
- Single-DOM measurement
- Useful to validate the calibration process
- Results compared with ANTARES and Bugaev model



Selection of atmospheric neutrinos



- Selection criteria applied to remove atmospheric muon background
- 15 events observed as up-going
- MC: 4 events from atmospheric ν
- MC: 7 events from atmospheric μ



Up-going

(only ν can travel through the Earth)

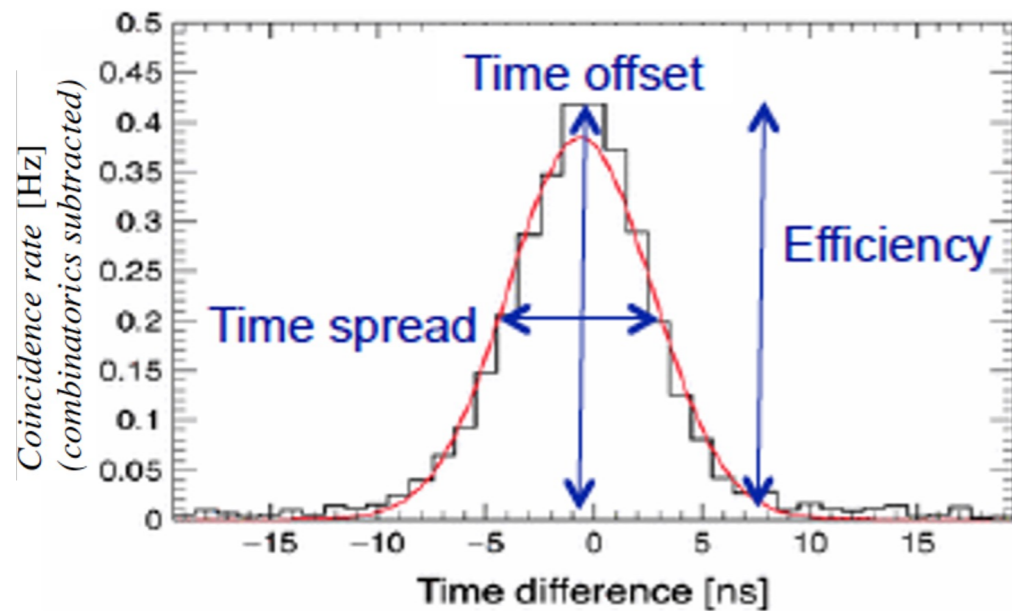
Down-going

(dominated by atmospheric μ)

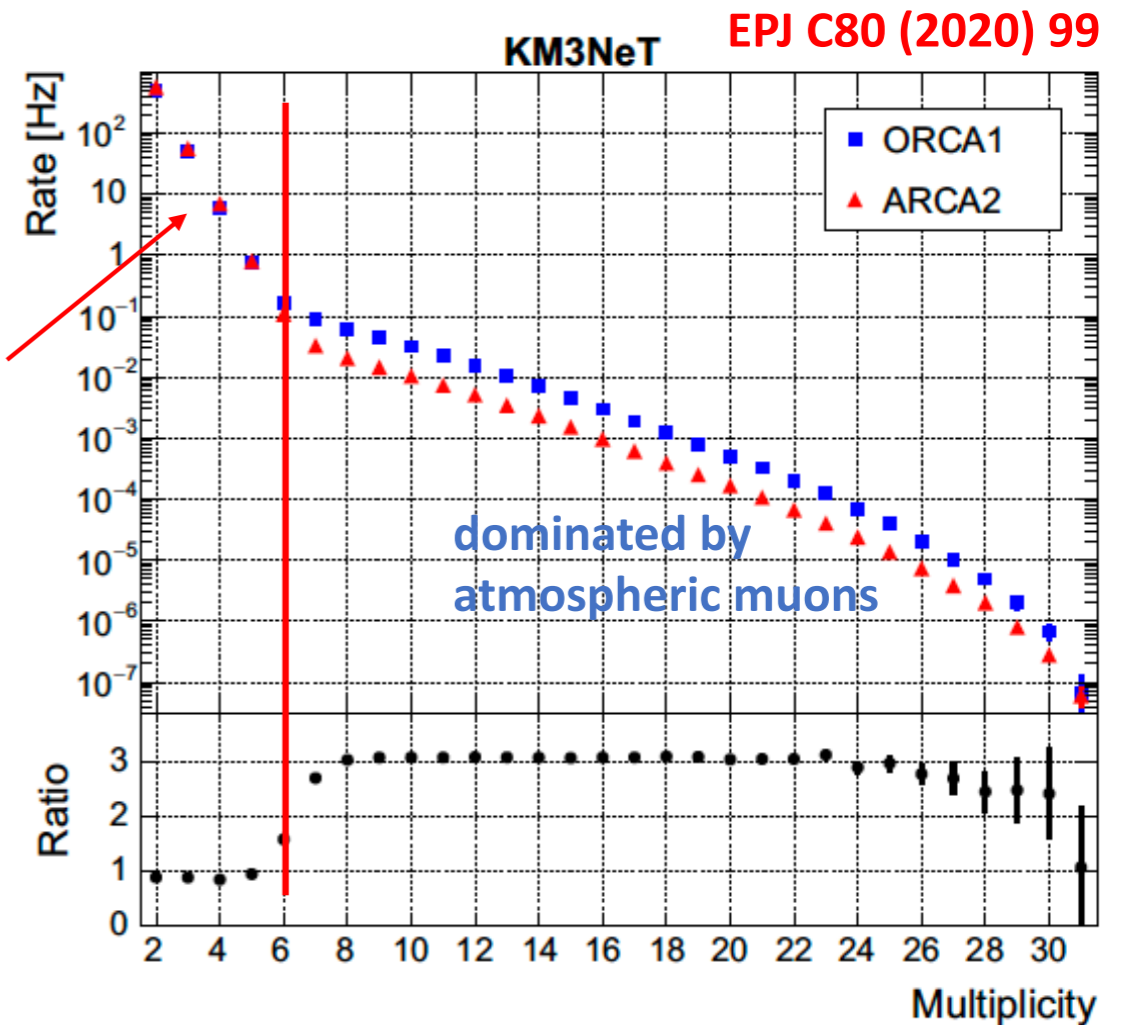
Time calibration



information from PMT coincidences



dominated by ^{40}K



Coincidence rate between PMTs on a DOM for one ORCA and one ARCA line, as a function of PMT multiplicity

Also: lab calibration of timing differences, LED flasher, timing from reconstructed tracks. Timing resolution better than 1 ns.

Positioning

Lines move with the sea current. Needs dynamic position calibration

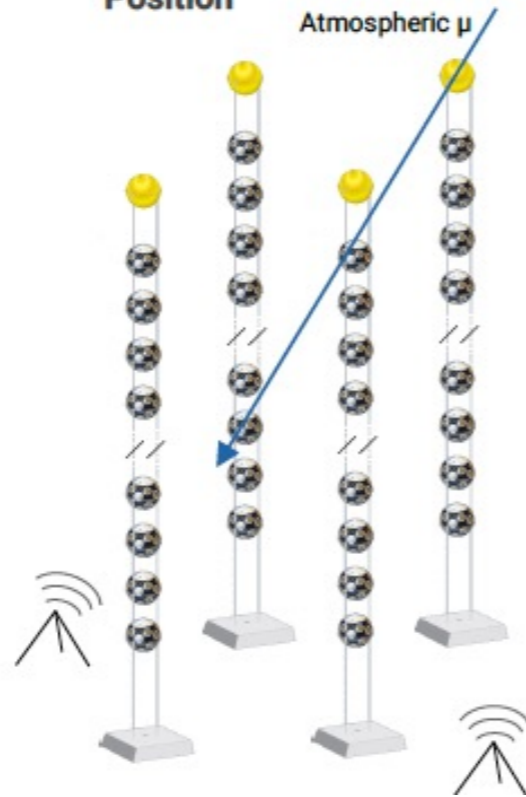
JINST 16 (2021) 09, C09023

Orientation

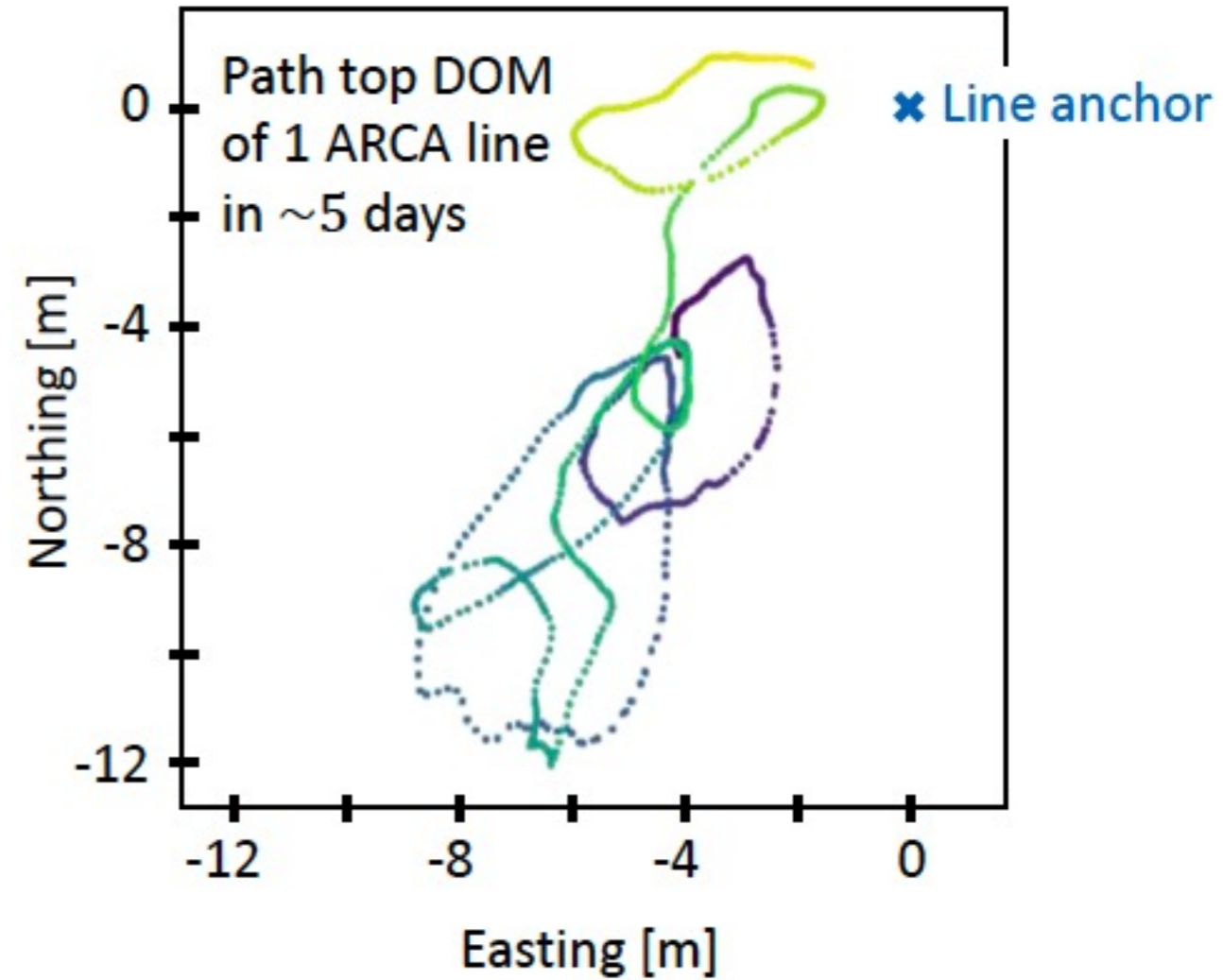


compass in DOMs

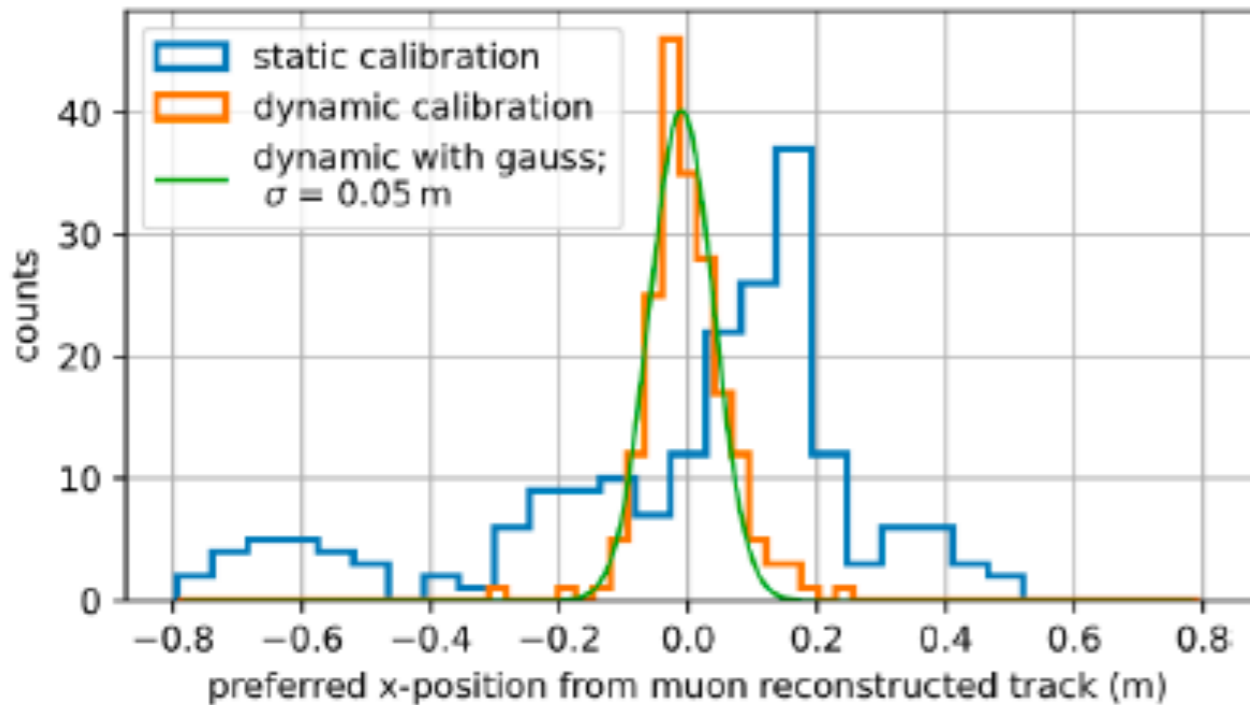
Position



acoustic emitters,
hydrophones, piezo sensors



Positioning



*Track residuals before (blue) and after (orange) dynamic position calibration.
After: 5 cm resolution.*

KM3NeT, ICHEP 2022

Independent validation: cosmic ray shadow of sun and moon

