KM3NeT: an Infrastructure for Underwater Cherenkov Neutrino Telescopes

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for the KM3NeT Collaboration

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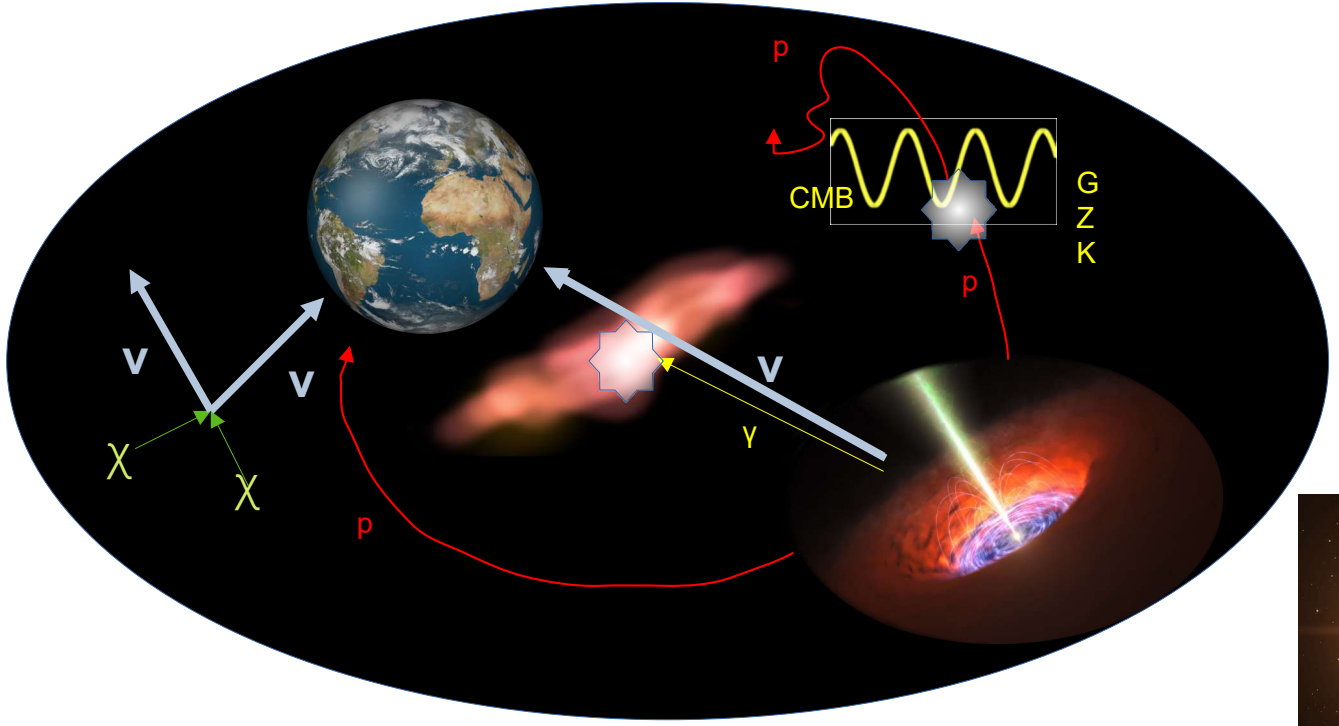
Physics programme and goals

Neutrinos from astrophysical sources



Photons can be absorbed by interstellar matter

Charged particles can travel long ranges but are affected by magnetic fields and interact with Cosmic Microwave Background

Neutrinos: messengers from deep space

Neutrino astronomy!

Neutrino sources:

Galactic

Supernovae, SN relics, Pulsar Wind Nebulae, Dark Matter particle annihilation?

Extragalactic

Active Galactic Nuclei, Black hole mergers?

High-energy neutrino production:

$p+p/\gamma \rightarrow X+\pi^0 \rightarrow \ldots+\gamma\gamma$

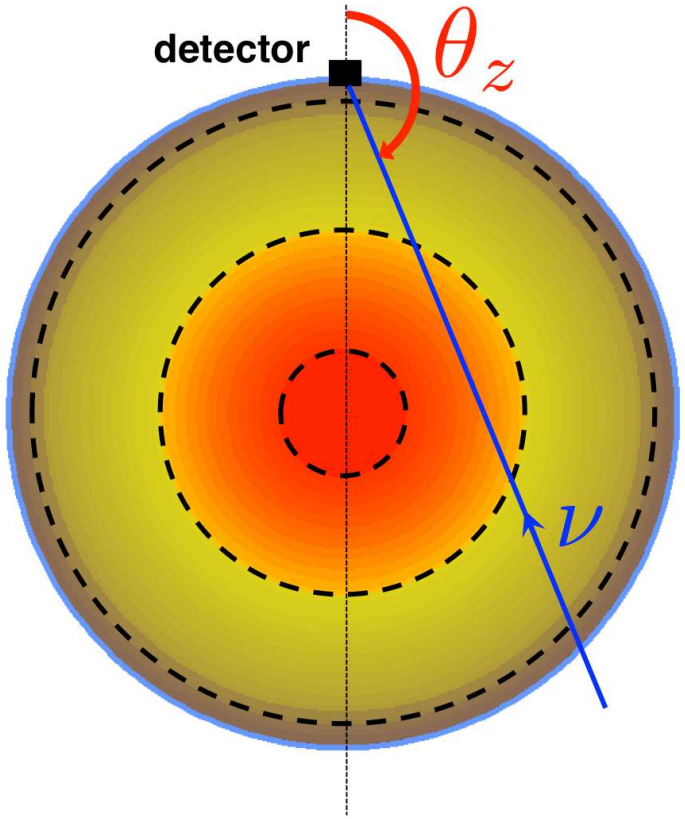
$p+p/\gamma \rightarrow X+\pi^{+/-} \rightarrow \ldots+ \mu \rightarrow e + \nu + \nu$

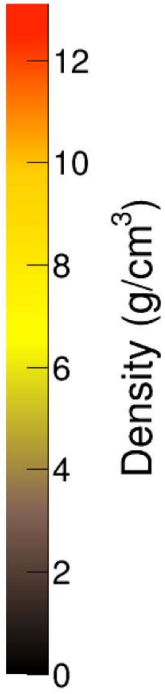
Expect correlation between HE photon and neutrino production

Tag for ongoing hadronic processes

Physics programme and goals

Atmospheric neutrinos & oscillations





Neutrinos produced by interactions of cosmic rays in atmosphere

$p+N \rightarrow X+K^+,\pi^+ \rightarrow ... + \mu \rightarrow e^+ + \nu_\mu + \nu_e$

$p+N \rightarrow X+K^-,\pi^- \rightarrow ... + \mu^- \rightarrow e^- + \nu_\mu + \nu_e$

Oscillation + propagation in Earth matter

Matter-enhanced oscillation

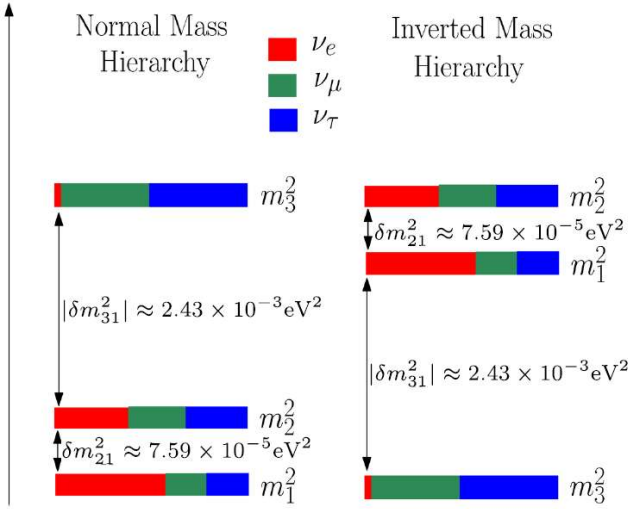
Probing different regions of Length/Energy depending on the inclination (Nadir angle) of the incoming neutrino

Matter effects sensitive to sign of Δm^2_{31}

Normal Ordering: excess ν_e

Inverted Ordering: excess $\bar{\nu}_e$

Resonance energy:
7 GeV in Mantle
3 GeV in Core



Physics programme and goals

Physics programme with ARCA and ORCA

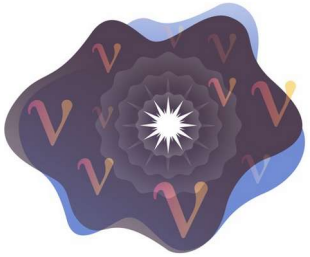
Supernovae

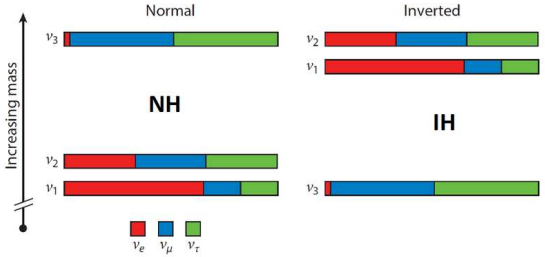
ν oscillations
ν mass ordering

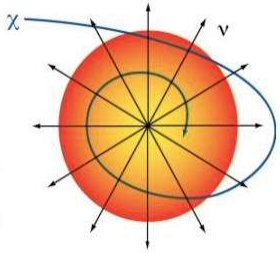
Dark Matter searches
Exotics searches

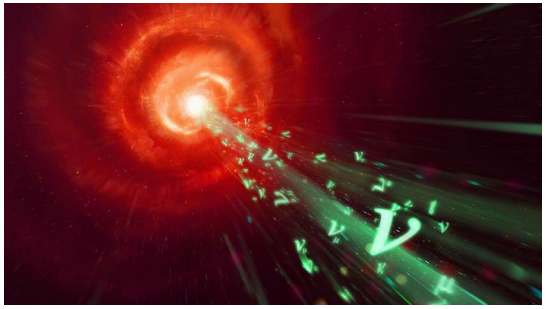
Cosmic neutrinos
Multimessenger Astronomy

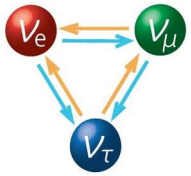
MeV GeV TeV PeV











ORCA

ARCA

Despite the naming, we can also do astronomy with ORCA (GW, AGN, SN, solar flares, GRB follow-up) and particle physics with ARCA (DM, exotics, …)

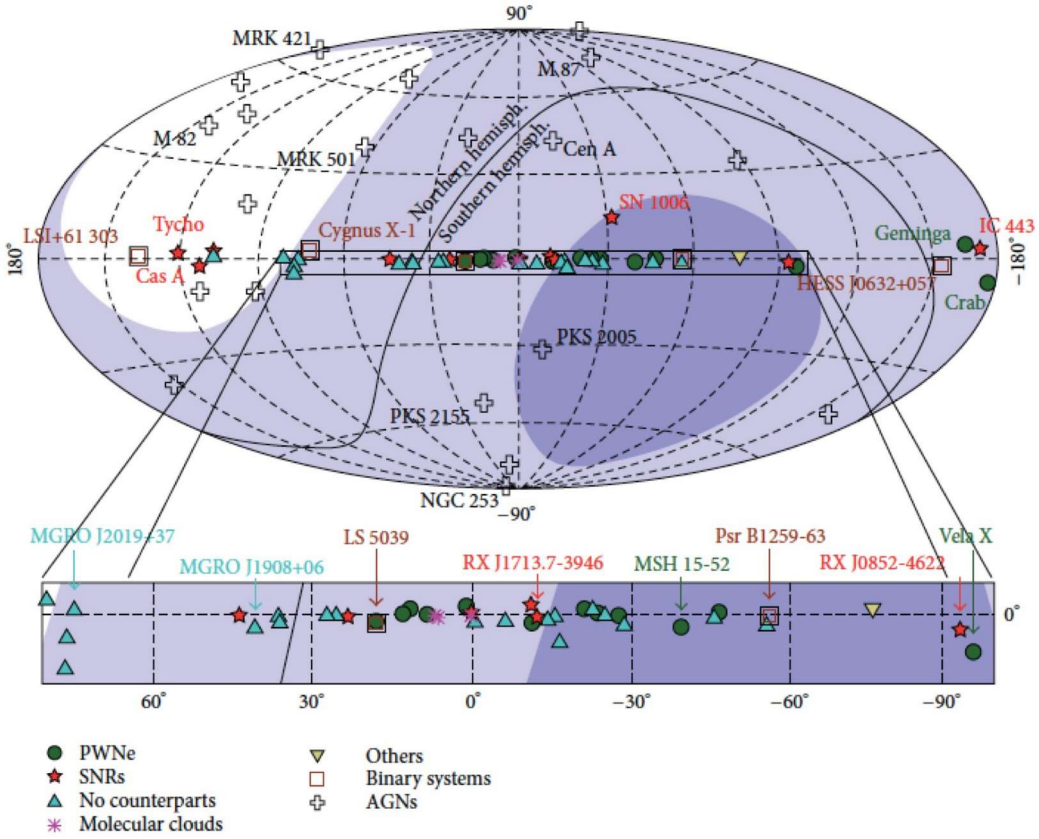
Physics programme and goals

Observing the Galactic centre

> 75% visibility

5% ÷ 75% visibility

<5% visibility

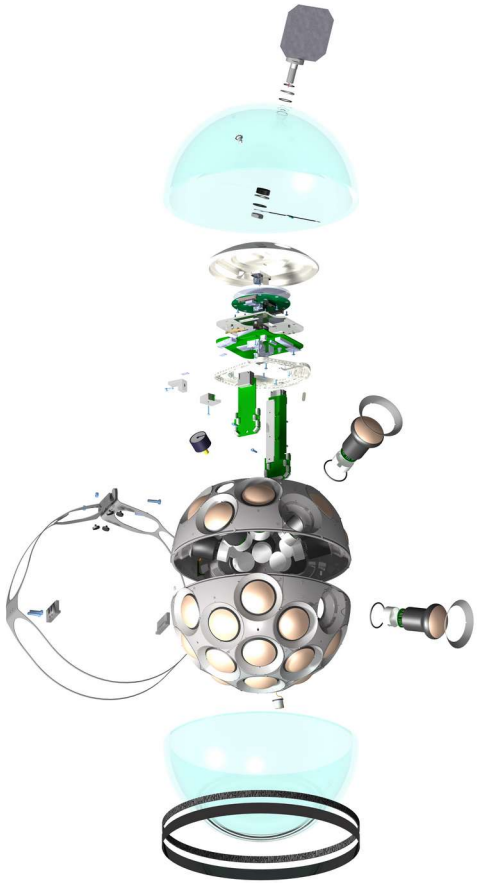


The Mediterranean is almost ideal for observing galactic sources

Technology foundation: the DOM

KM3NeT water Cherenkov telescopes: 3D arrays of Digital Optical Modules (DOM)

- *31 Photomultipliers (3 in. Hamamatsu)*
  - *12 up-pointing*
  - *19 down-pointing*
- *Central Logic Board*
  - *Compass/Tiltmeter chip*
- *Power Board*
- *Piezo Acoustic Sensor*
- *Optical transceivers*
- *Mechanical structure*
- *Cooling Mushroom*
- *High pressure – resistant glass sphere (350 bar)*



Each DOM is a complete photodetector, with directional capabilities and large photocatode area

Detection Units

Instrumenting 1 km^3 of seawater:

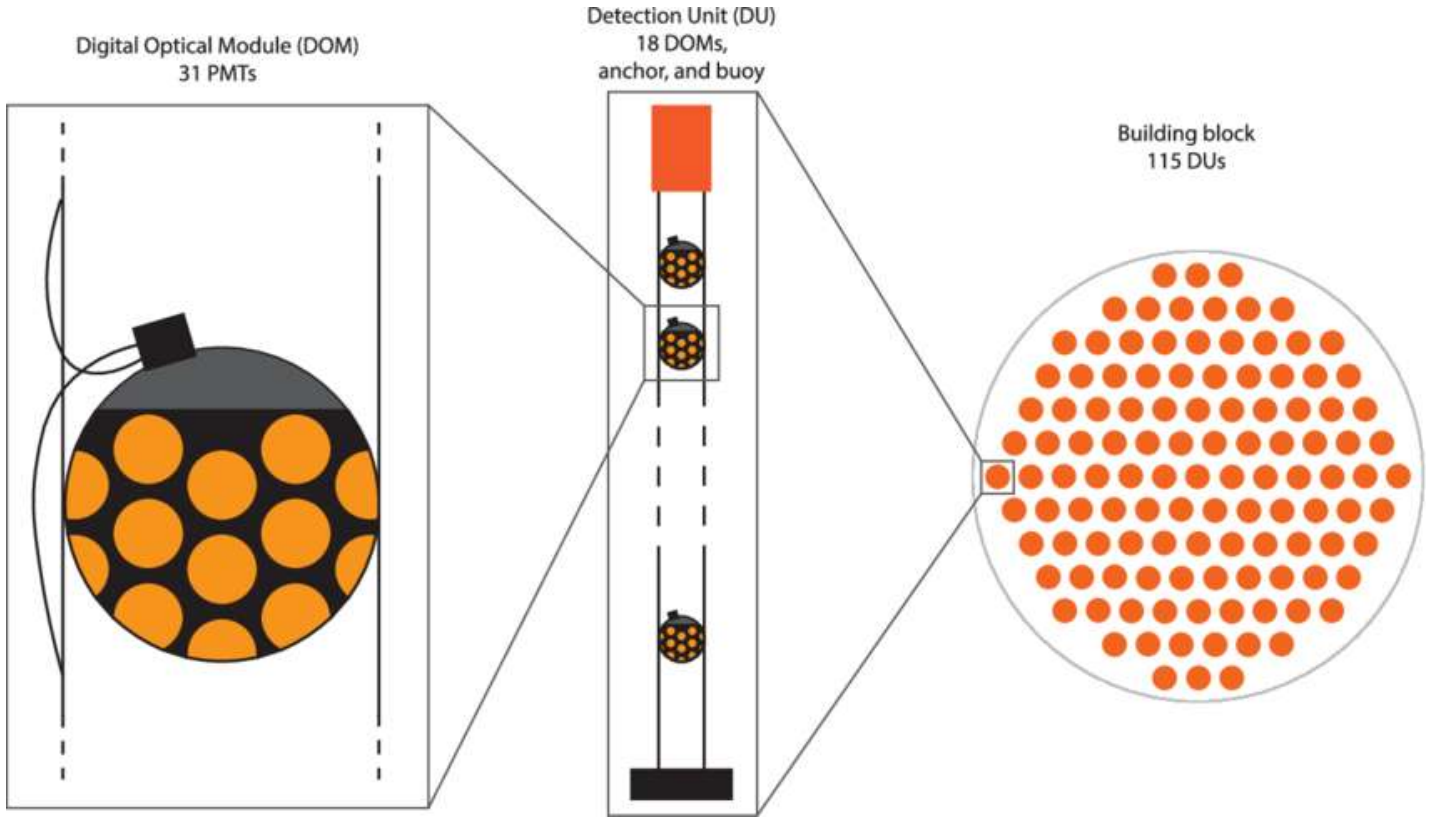
DOMs connected with ropes to anchor and buoy

DOM self-buoyancy: ~ 180 N

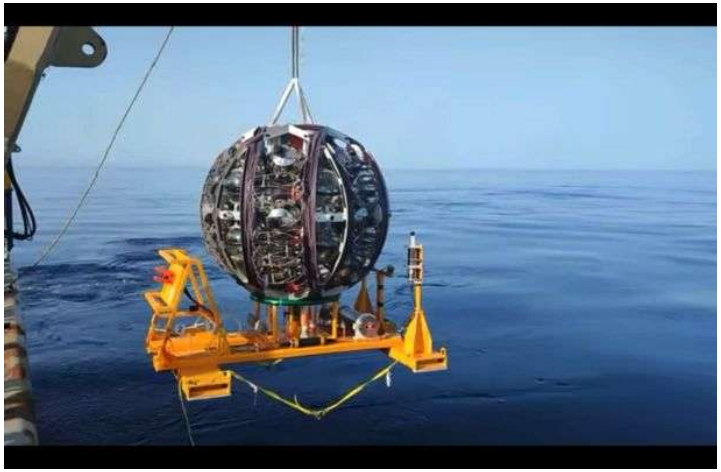
A Vertical Electro Optical Cable carries power and inbound / outbound signals

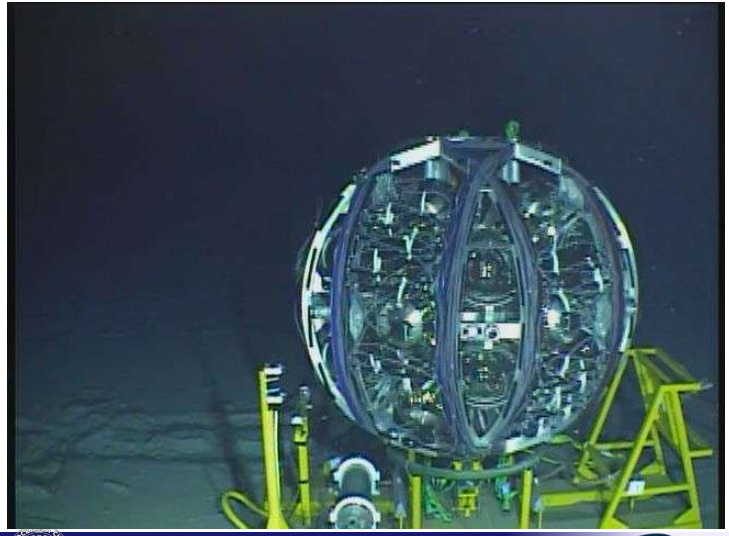
Detection Unit (DU):
- *18 DOMs*
- *1 Base Module (not shown here):*
  - *Power control*
  - *Communications*
  - *Instruments*

Building Block:
roughy cylindrical arrangement of 115 DUs on a hexagonal lattice



Full blocks and detectors



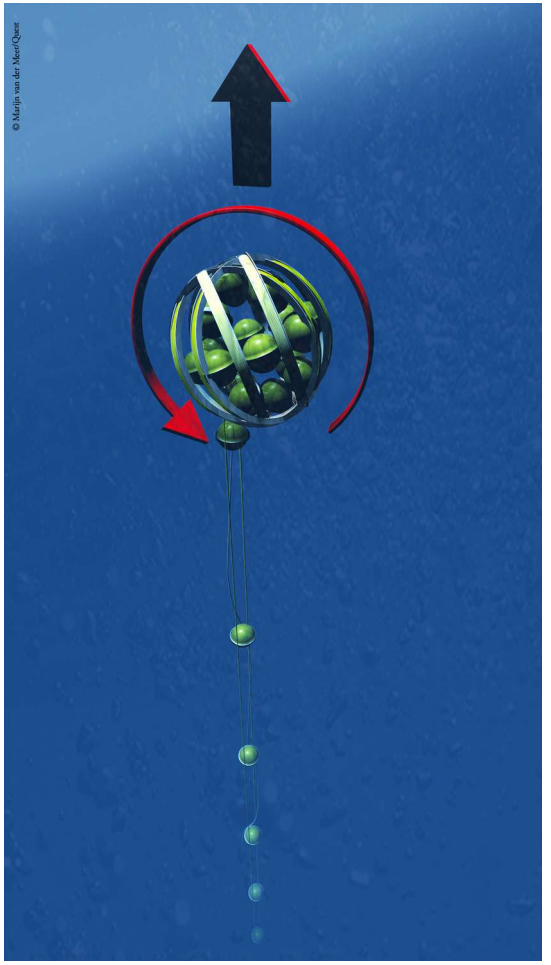


A Detection Unit is wound on a launching device (LOM)

Deployed on the seafloor

Unfurled to reach the vertical configuration

The LOM is recovered and reused for another operation



Neutrino flavour and interactions

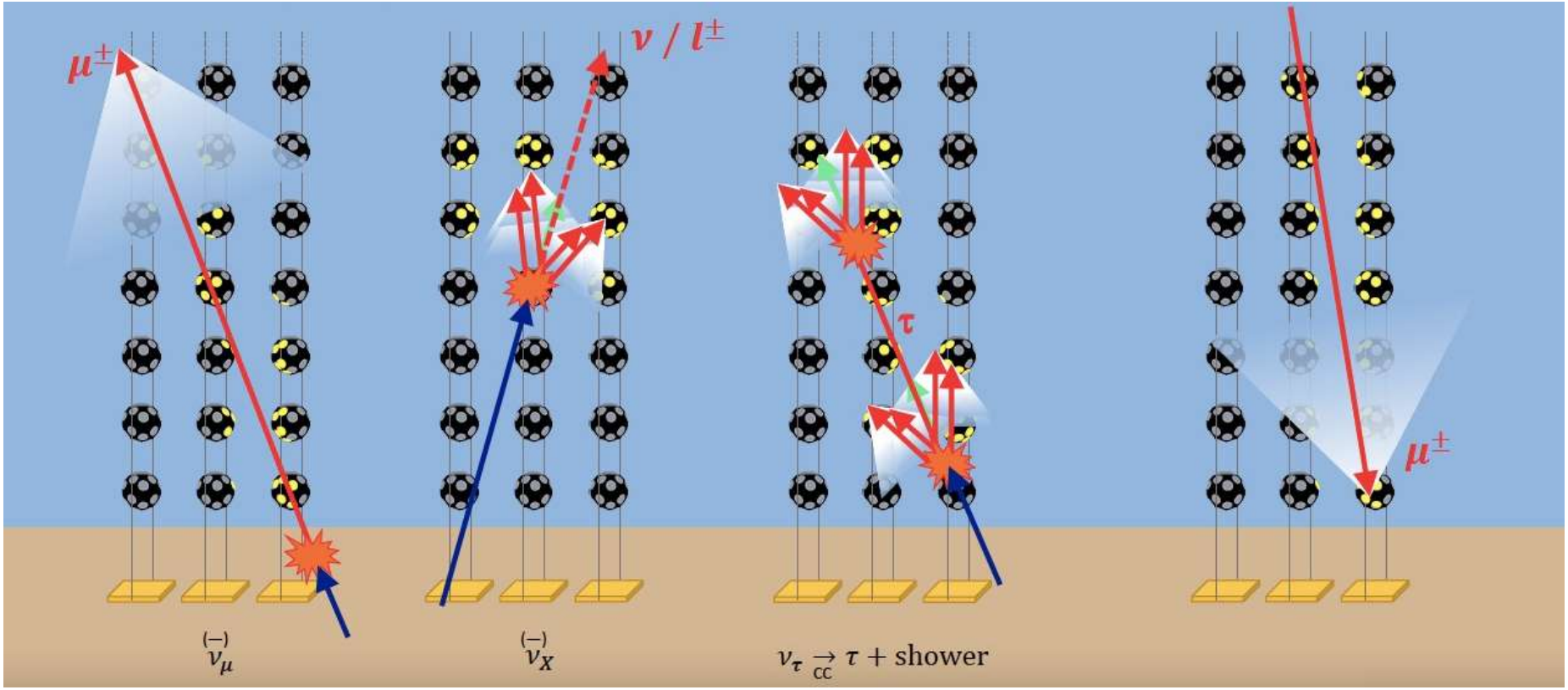
Neutrino signals in KM3NeT

ν_μ CC "track-like"
good pointing

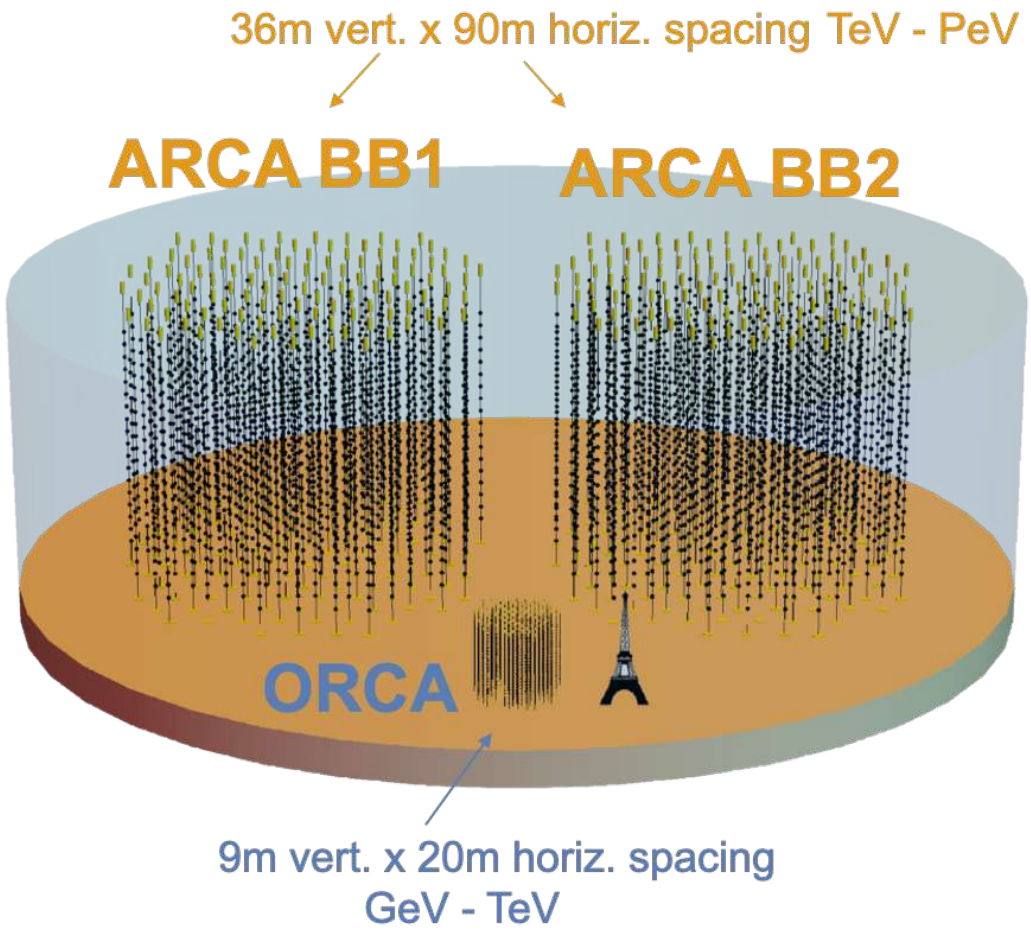
ν_e CC or any ν NC
"shower-like"
good energy resolution

ν_τ CC "double-bang"

Atmospheric μ
background for ν
signal for Cosmic Ray studies



ARCA & ORCA



Full ORCA: 7 Mton

Currently deployed: 28/115 DUs

Full ARCA (2 building blocks): 1 Gton ~ 1 km³

Currently deployed: 51/230 DUs

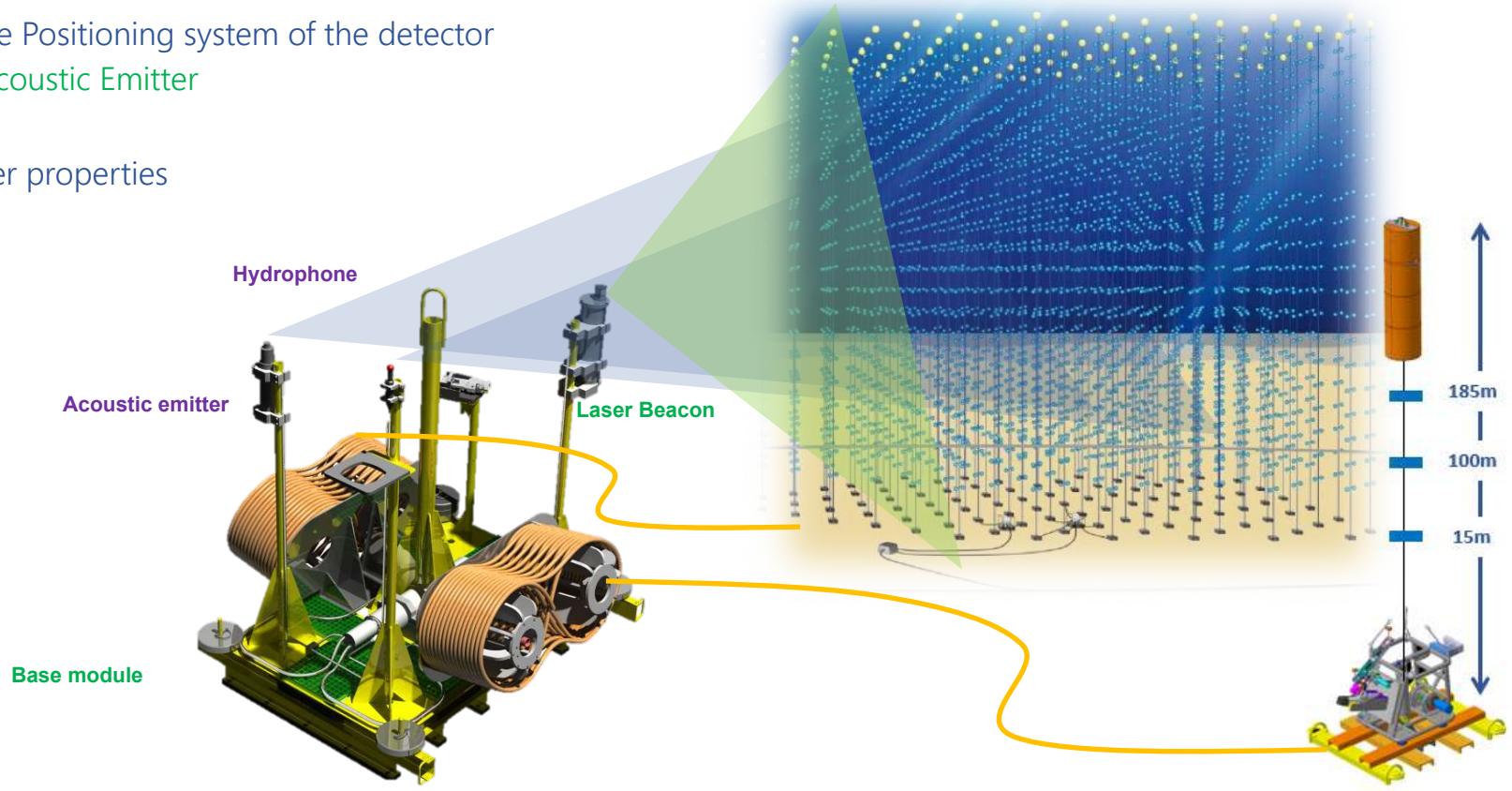
ARCA & ORCA

Calibration base :

- InterDU Complementary Time calibration method
  - Laser Beacon
- Part of the Long Base Line Positioning system of the detector
  - Hydrophone and Acoustic Emitter

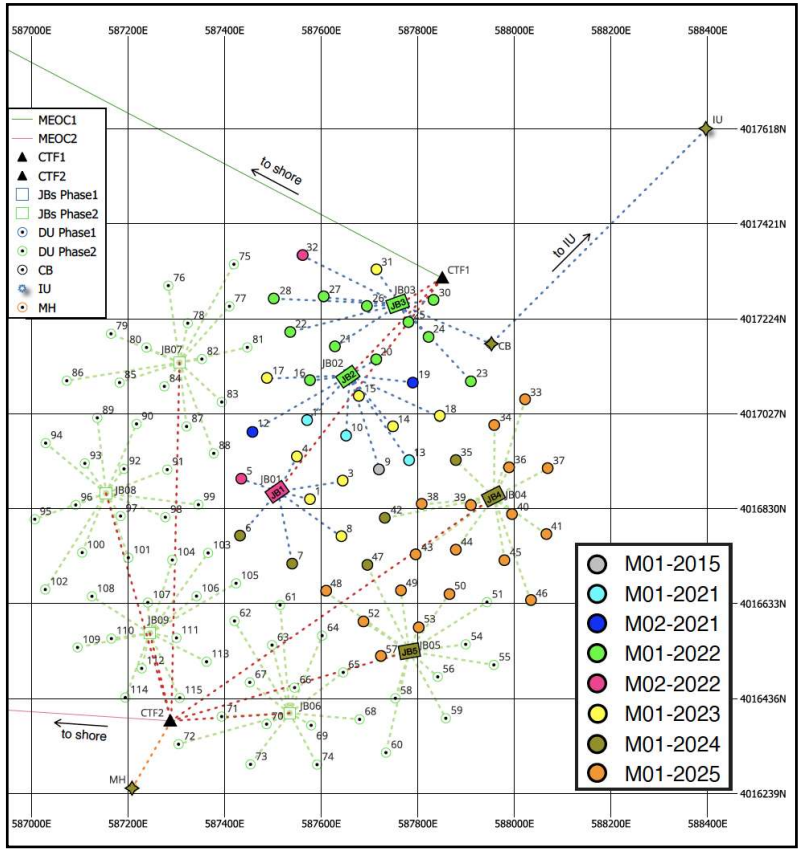
Instrumentation Unit :

- Used to monitor sea water properties
- Instruments:
  - Conductivity
  - Pressure
  - Temperature,
  - Salinity
  - Current profiler
  - Sound velocity

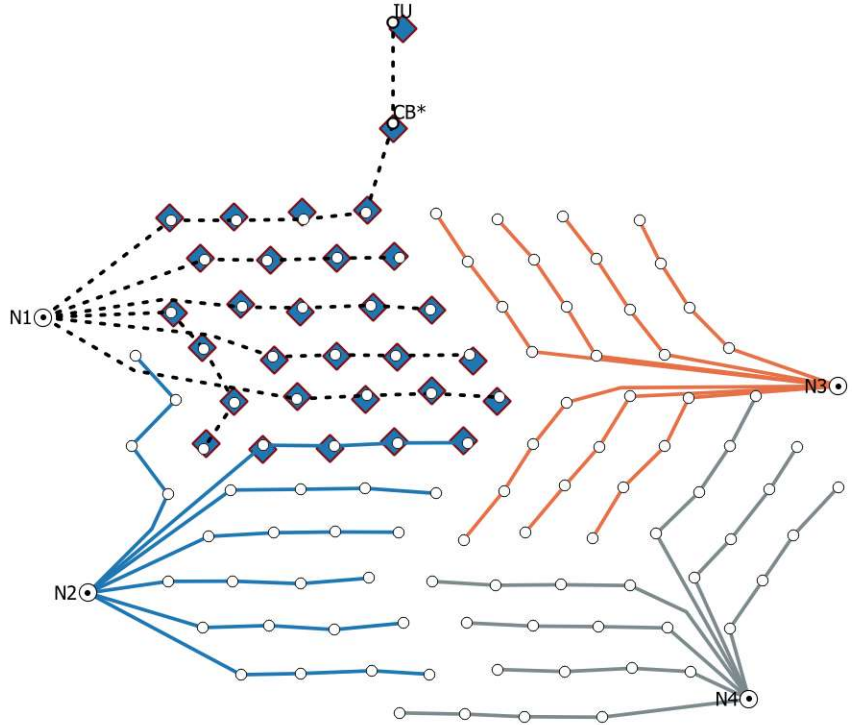


ARCA & ORCA

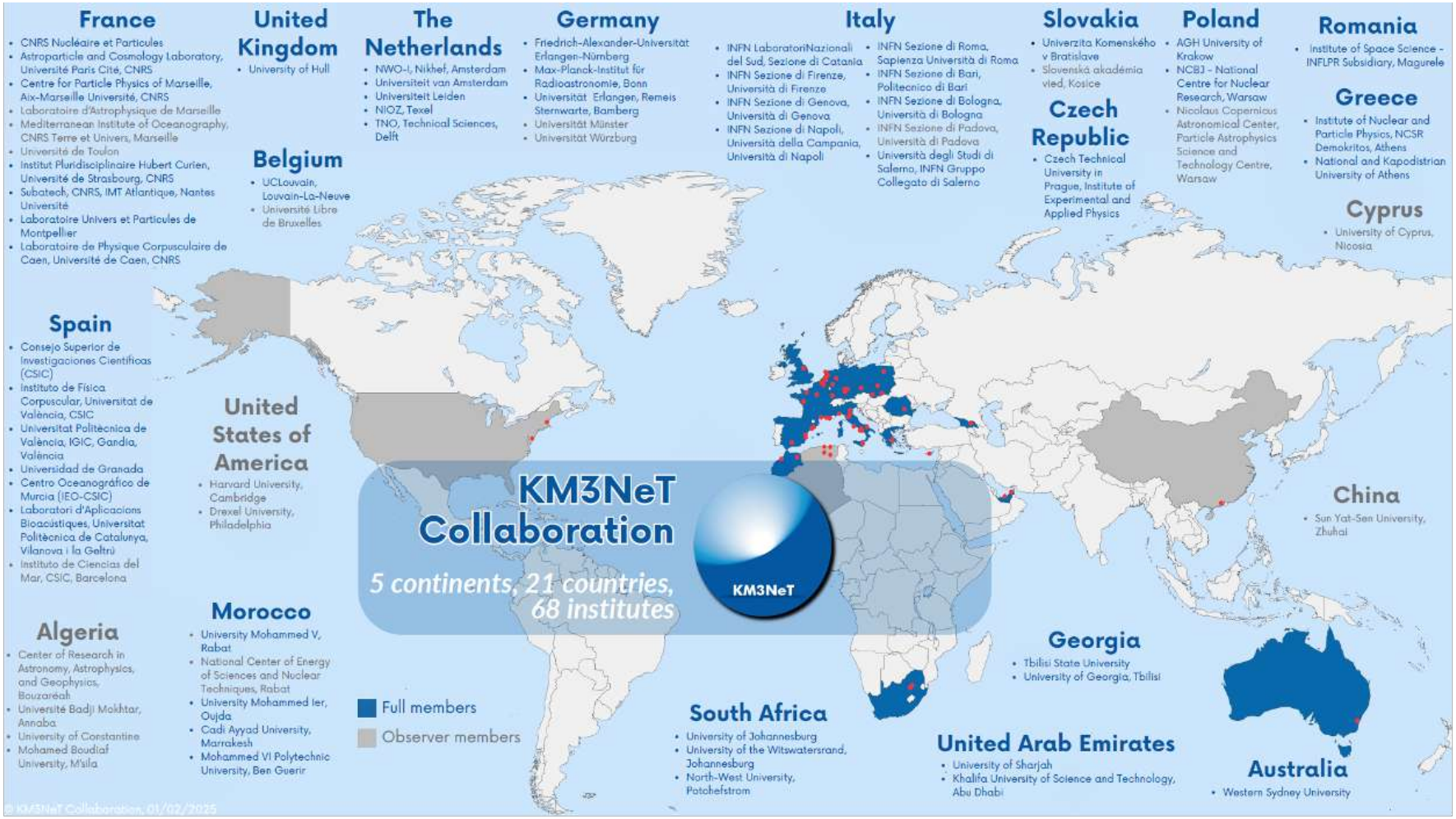
Current ARCA footprint on the seabed



Current ORCA footprint on the seabed



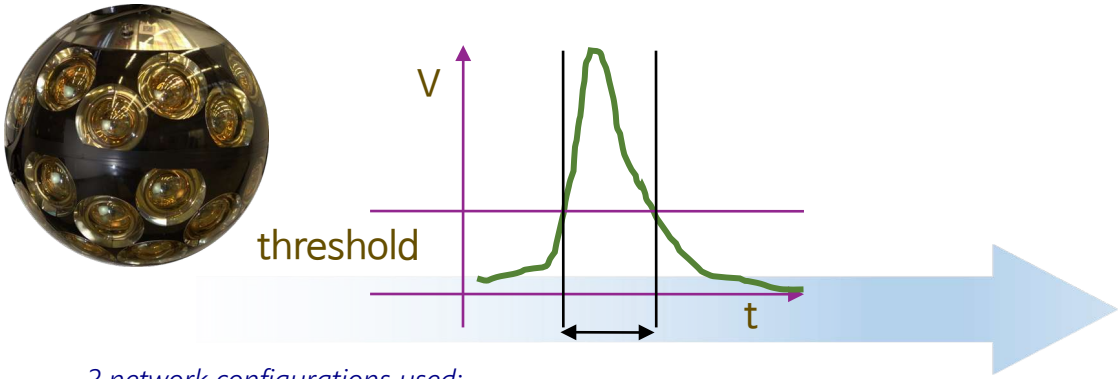
The Collaboration



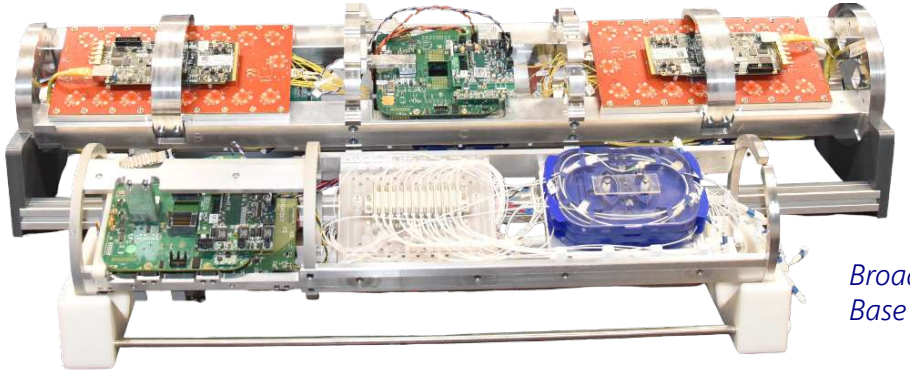
Data acquisition: all data to shore

PMT pulses are encoded by timestamping the crossing of a threshold and the time over threshold

All data are sent to shore for triggering, filtering and processing

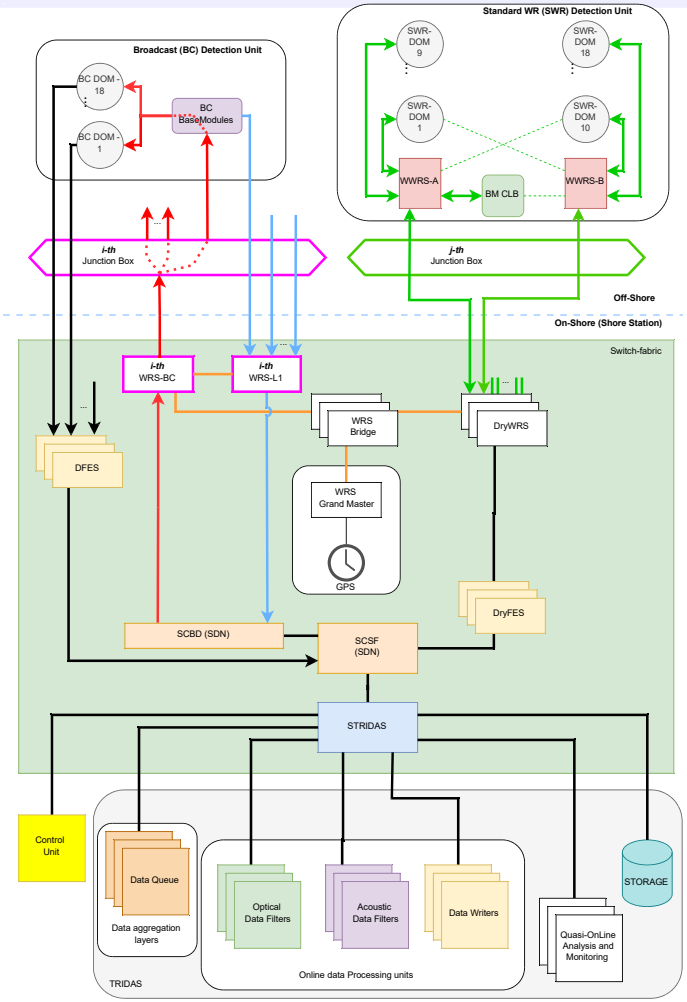


2 network configurations used:
ORCA: Broadcast White Rabbit
ARCA: 30 DUs in Broadcast mode, all others in Standard White Rabbit



Standard White Rabbit Base Module

Broadcast White Rabbit Base Module



Acoustic Positioning

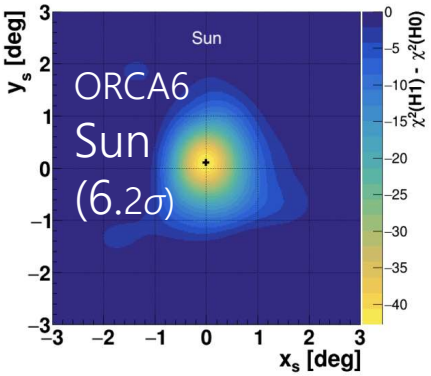
DUs sway and change their shape under the action of currents

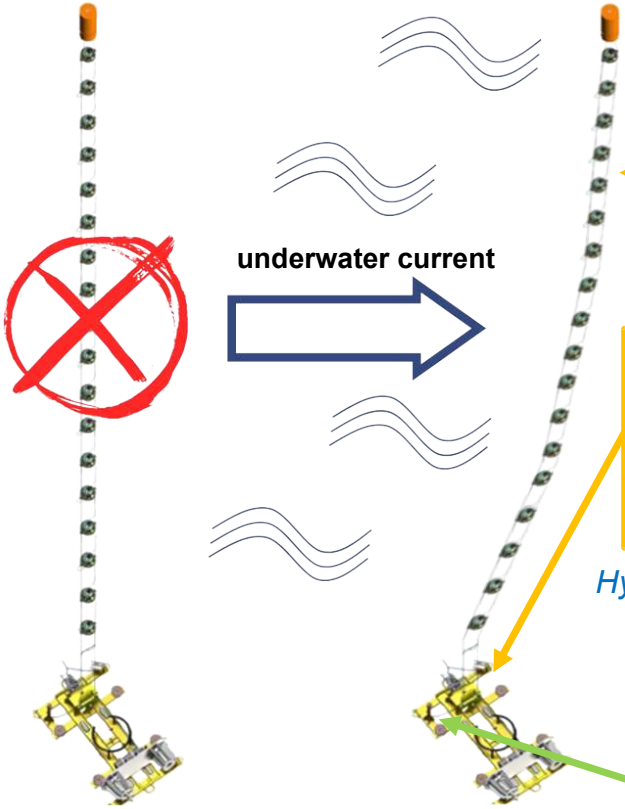
Acoustic beacons in known positions emit signals with characteristic waveforms

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

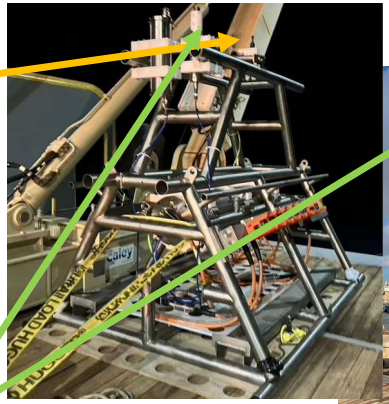
We need pointing accuracy ~ 0.1° or better!





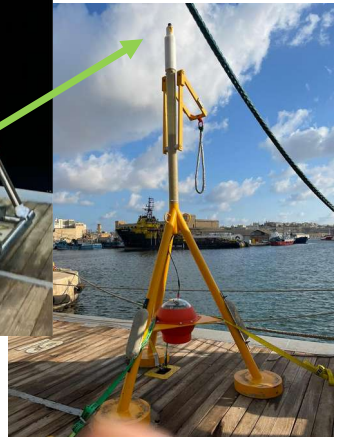
Piezoelectric sensor on DOM

Hydrophone



Junction Box

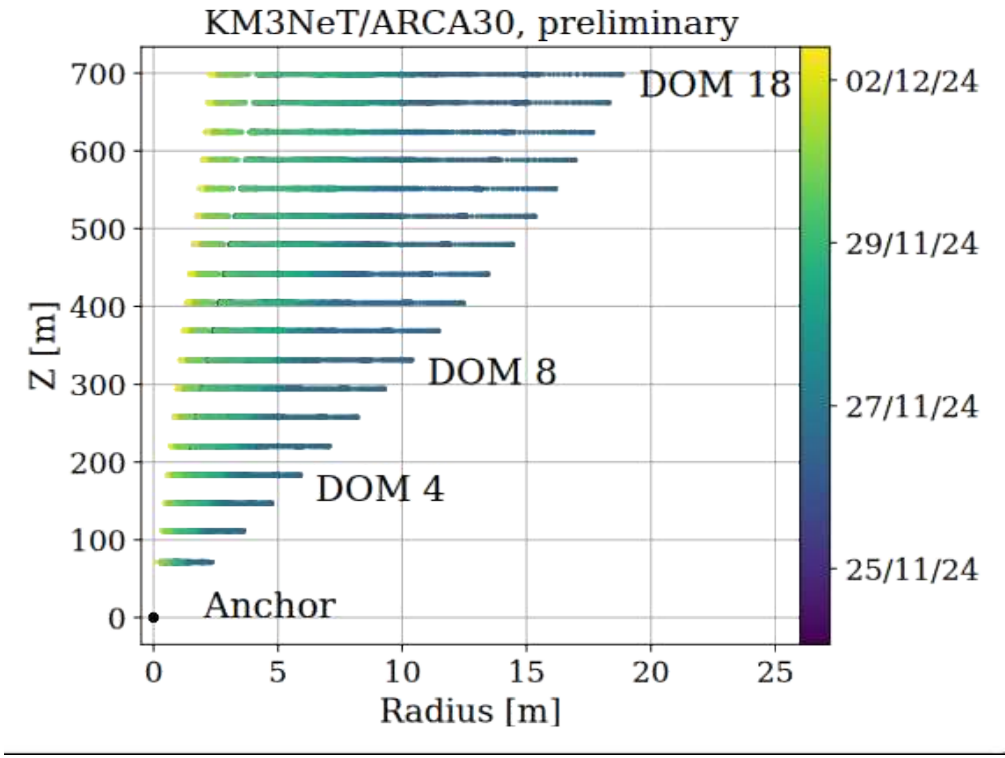
Acoustic Beacon



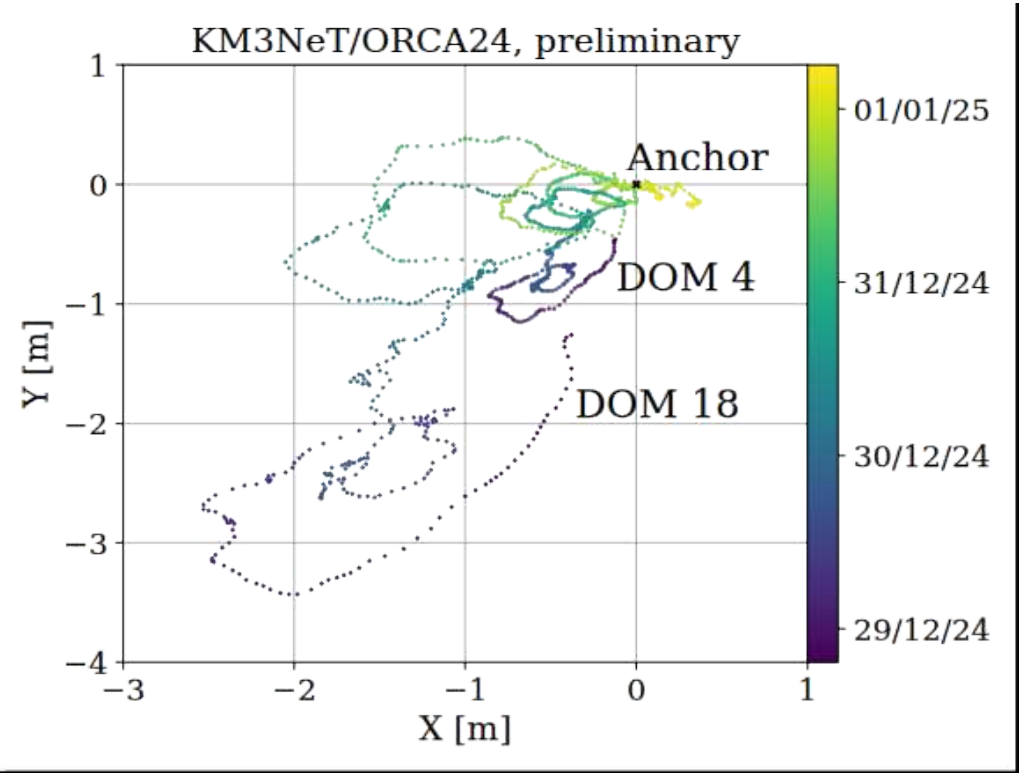
External tripod

Acoustic Positioning

Reconstructed deviation of a DU in ARCA in 7 days



Reconstruction DOM position shifts in ORCA in 4 days



DAQ software: TriDAS and Control Unit

Slow Control data

Optical Acoustic data

Database Interface
Detector Manager
Dynamic Provisioning and Authentication

Master Control Program
TriDAS Manager
Dynamic Provisioning and Authentication

Optical Data Queue
Optical Data Queue
Optical Data Queue
Dynamic Provisioning and Authentication

Optical Data Queue
Optical Data Queue
Optical Data Queue
Dynamic Provisioning and Authentication

Data Filter (×6)
Dynamic Provisioning and Authentication

Data Filter (×6)
Dynamic Provisioning and Authentication

Data Filter (×6)
Dynamic Provisioning and Authentication

Data Dispatcher
Data Writer
Dynamic Provisioning and Authentication

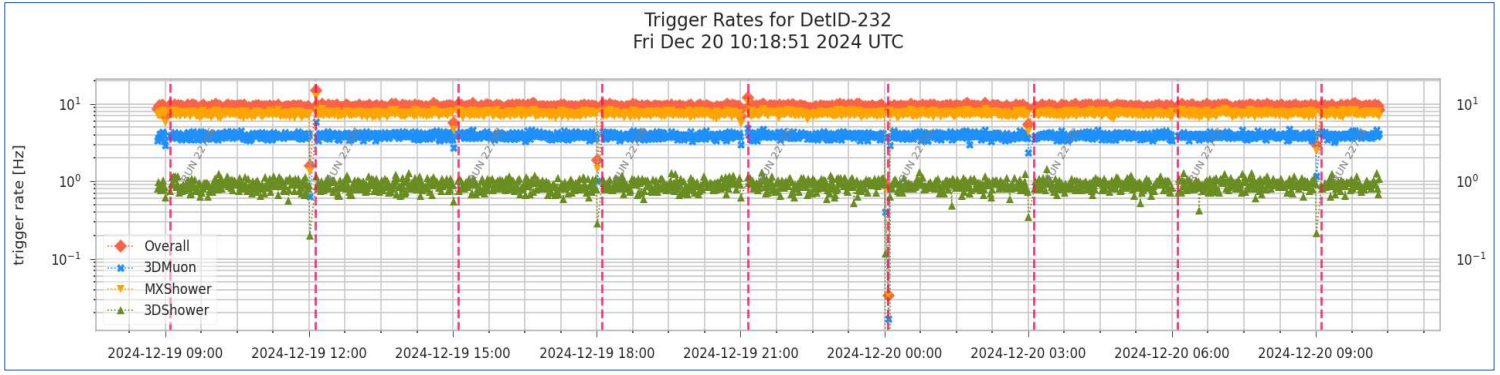
*The components of the **Triggering and Data Acquisition System (TriDAS) Control Unit** receive timeslices from each DOM, build timeslices for the full telescope, then apply triggering algorithms and provide partial reconstructions and write triggered events to storage*

*The **Control Unit (CU)** is a modular software suite that defines the current task and operating parameters of the telescope*

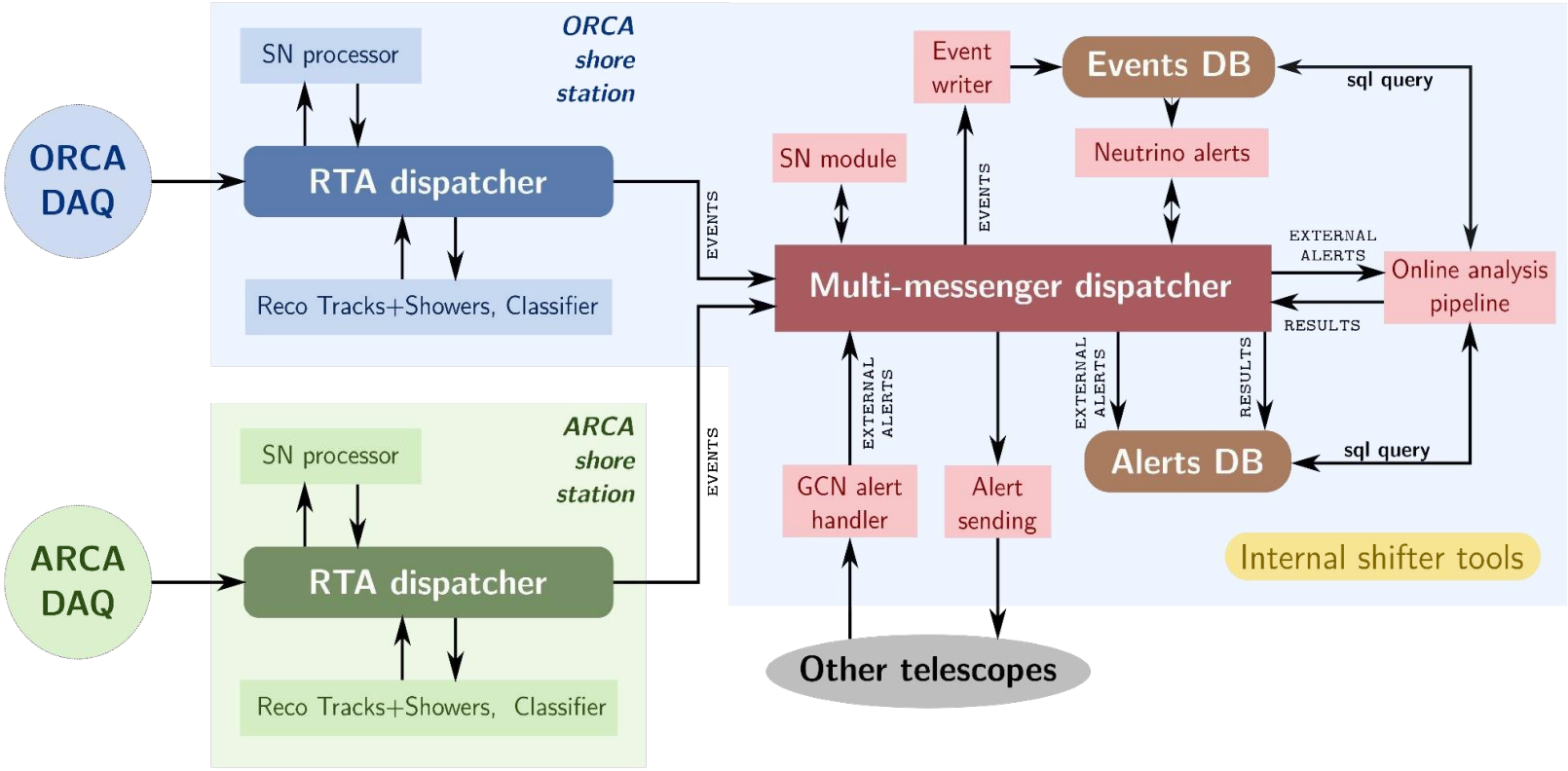
CU processes can run on different servers

It can work without connection to the central database and can reconfigure itself in case of hardware failures

Regular and steady data taking



The Realtime Reconstruction System

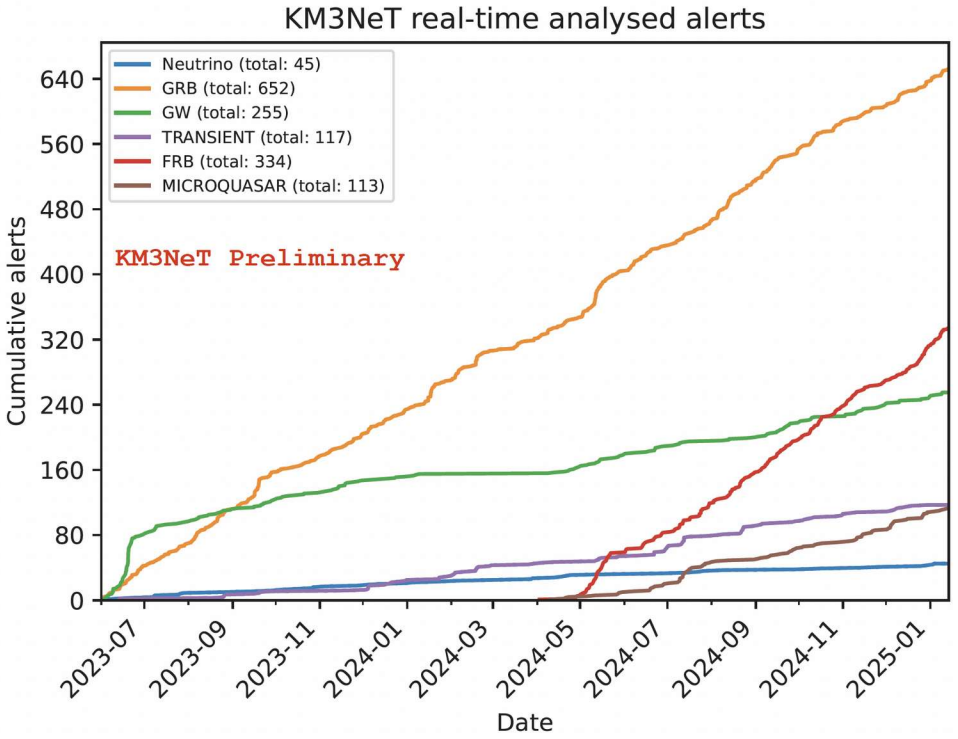


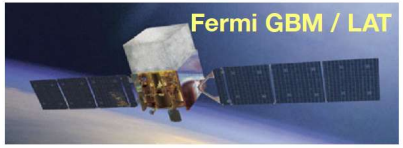
A Realtime Reconstruction System provides fast reconstruction for Supernova signals and quickly reconstructs tracks and showers to detect correlation with external alerts

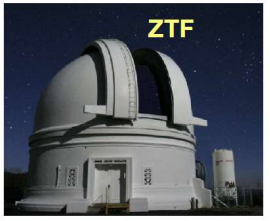
KM3NeT also starting to provide alerts itself!

The Realtime Reconstruction System

KM3NeT is participating in several multimessenger alert programmes

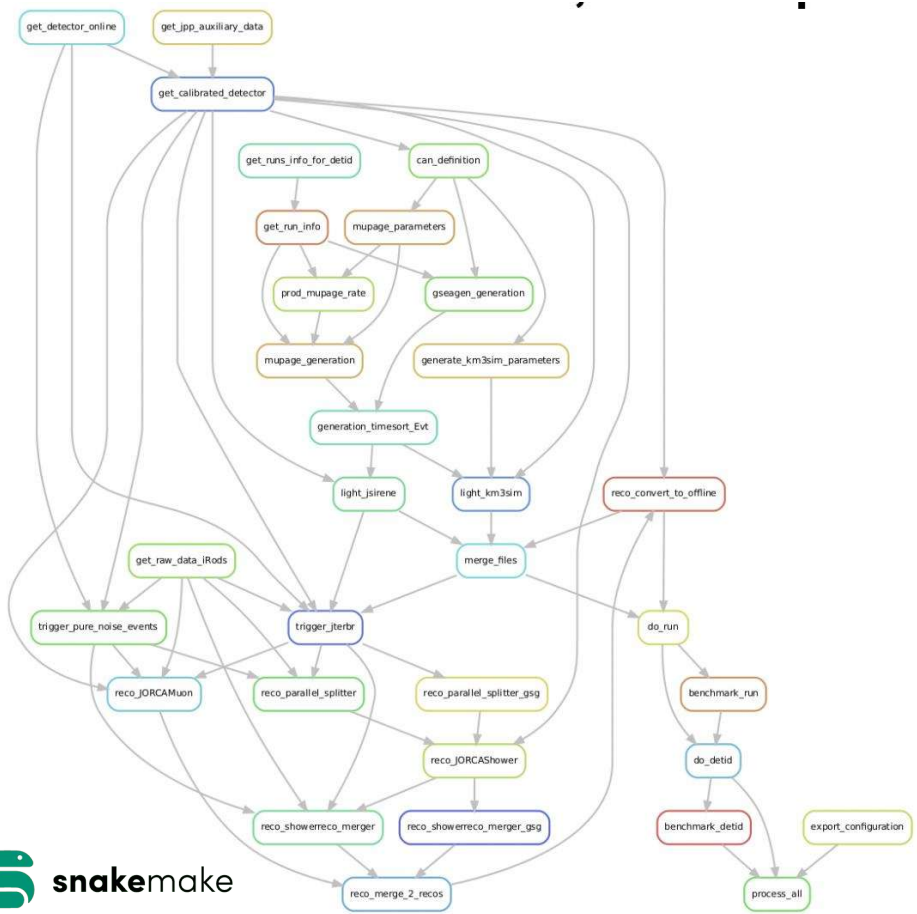




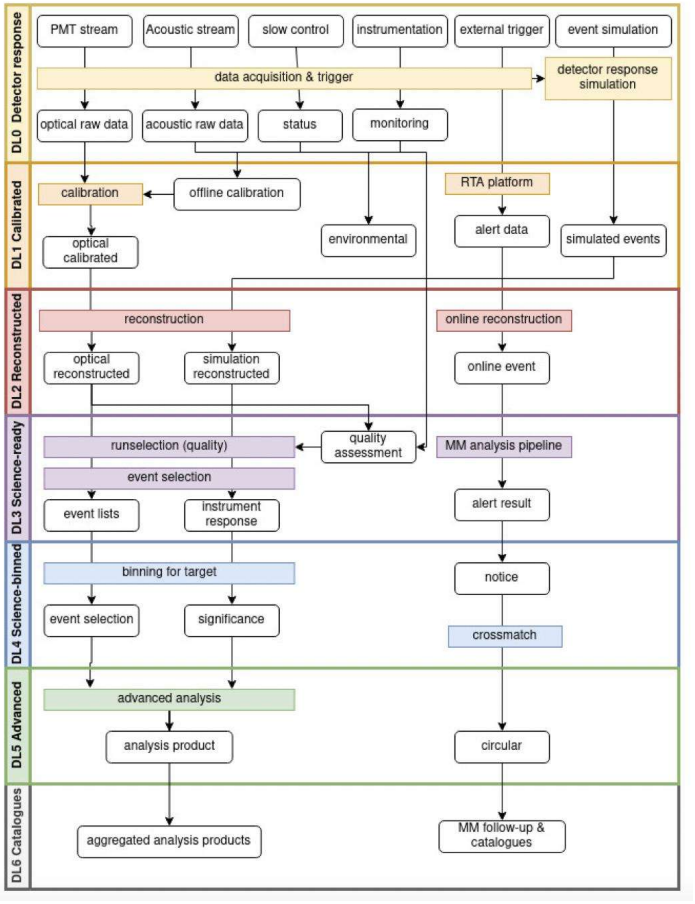


Alerts from satellites, observatories and detectors

Data flow and processing



Data processing with Snakemake-defined workflow on the GRID: optimising computation and resource usage

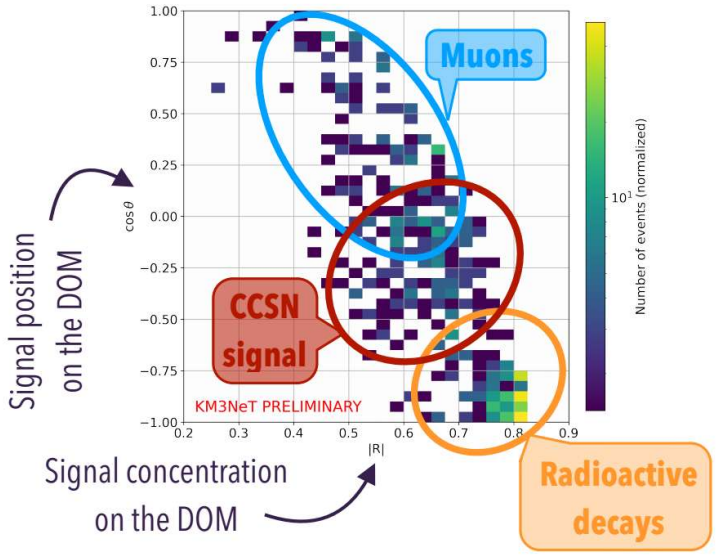


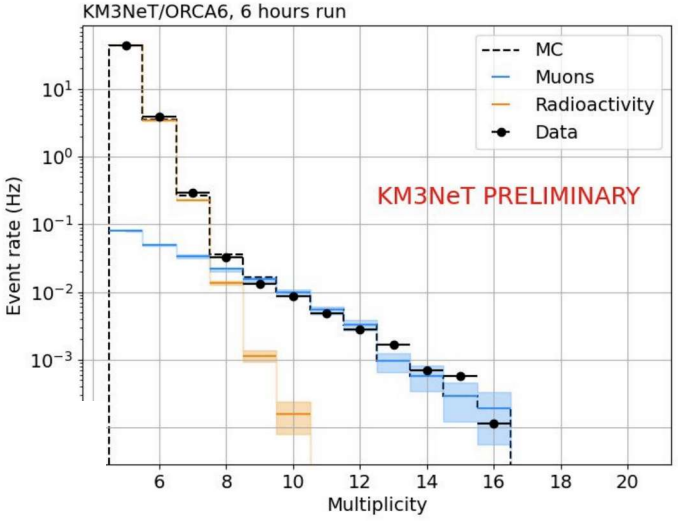
Data filtering and processing levels: "regular" and online flows Storage using RUCIO

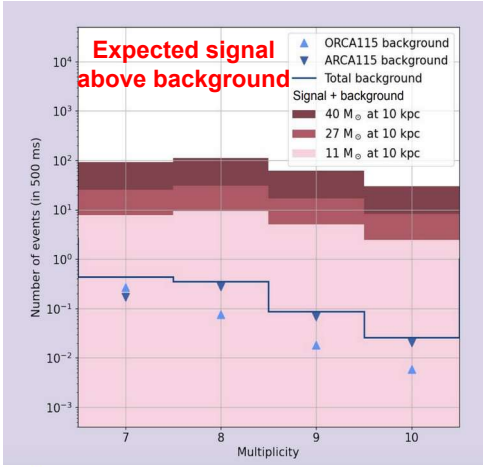
Results: supernovae

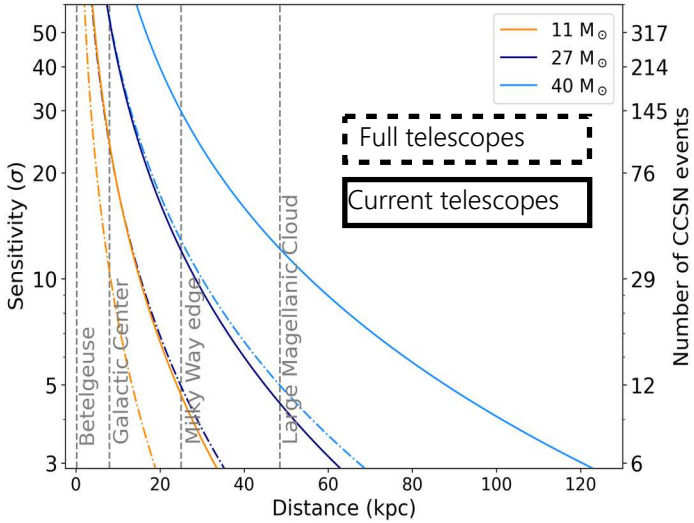
A single DOM is itself a detector suitable for Supernova neutrinos

Low energy neutrinos
Multiple signals in a single DOM
Competition with ^{40}K in seawater, atmospheric muons,
muons from neutrino interactions



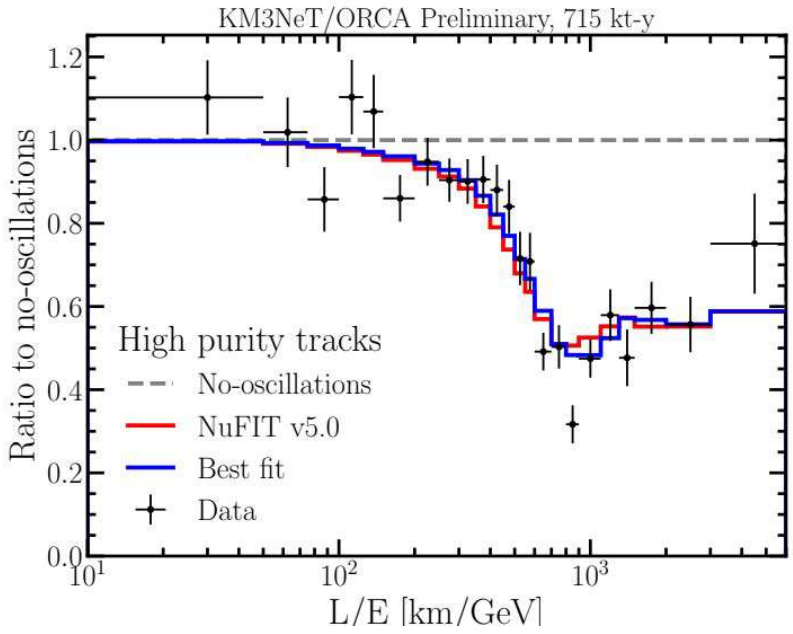






Results: oscillations

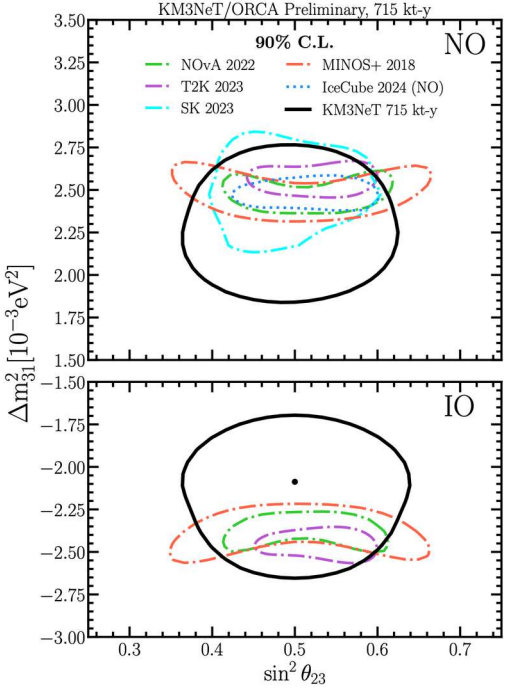
Neutrino oscillations in the Earth: status and outlook

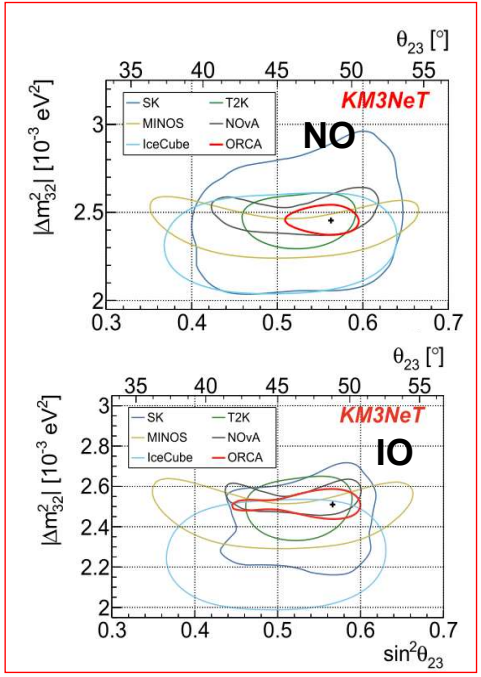


$$\Delta m^2_{31} = \begin{cases} -2.09^{+0.17}_{-0.21} \times 10^{-3}\text{eV}^2, & \text{IO} \\ [2.10, 2.37] \times 10^{-3}\text{eV}^2, & \text{NO} \end{cases}$$

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

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





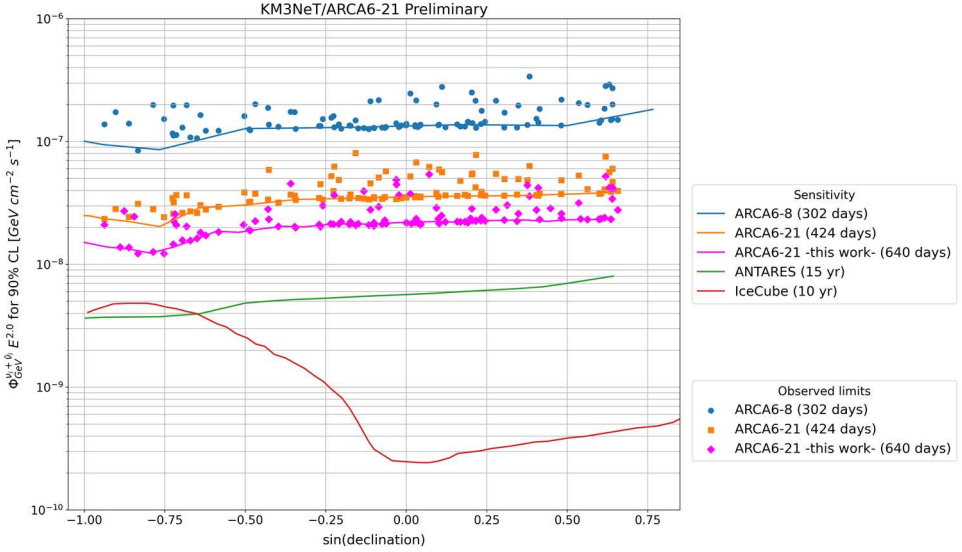
Full detector expectation

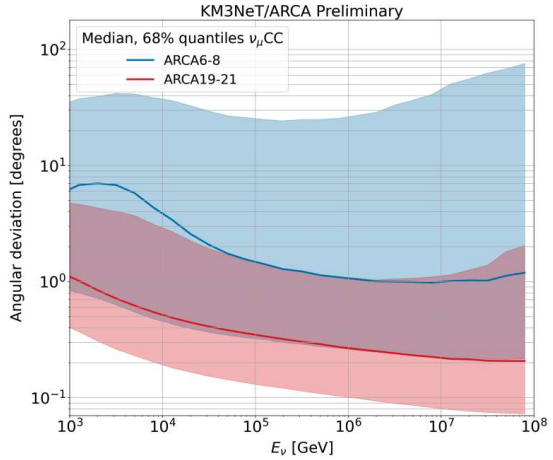
Results: point sources

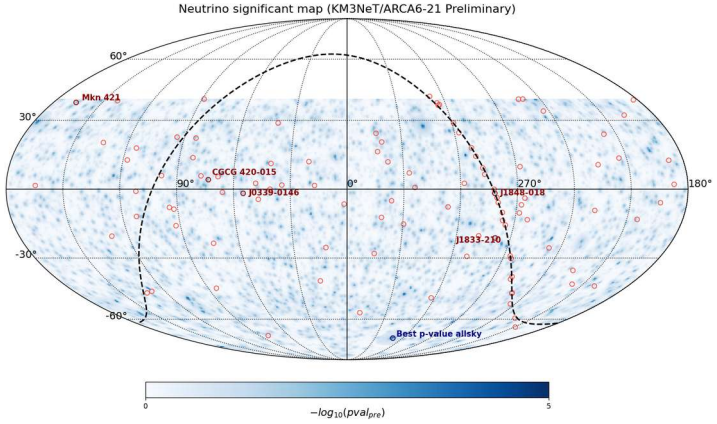
Pointing capability improving with increasing telescope size

No point sources observed yet (101 candidate sources)

Sensitivity quickly improving: telescope growth, time integration, data processing (part of ARCA21 dataset used, full ARCA21, ARCA28 and ARCA33 coming)

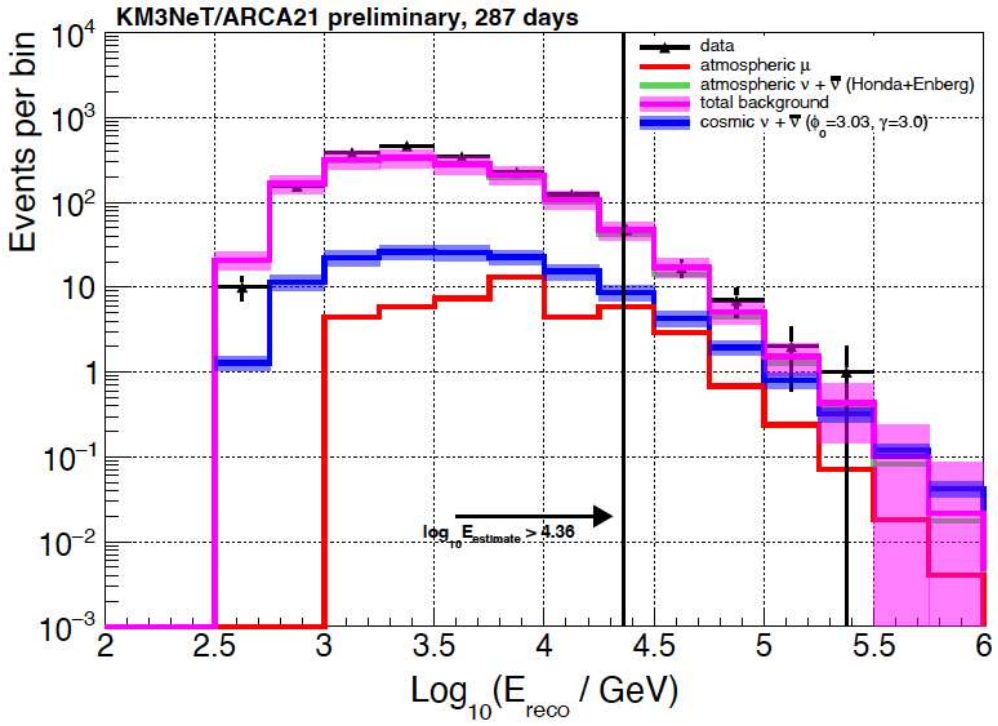


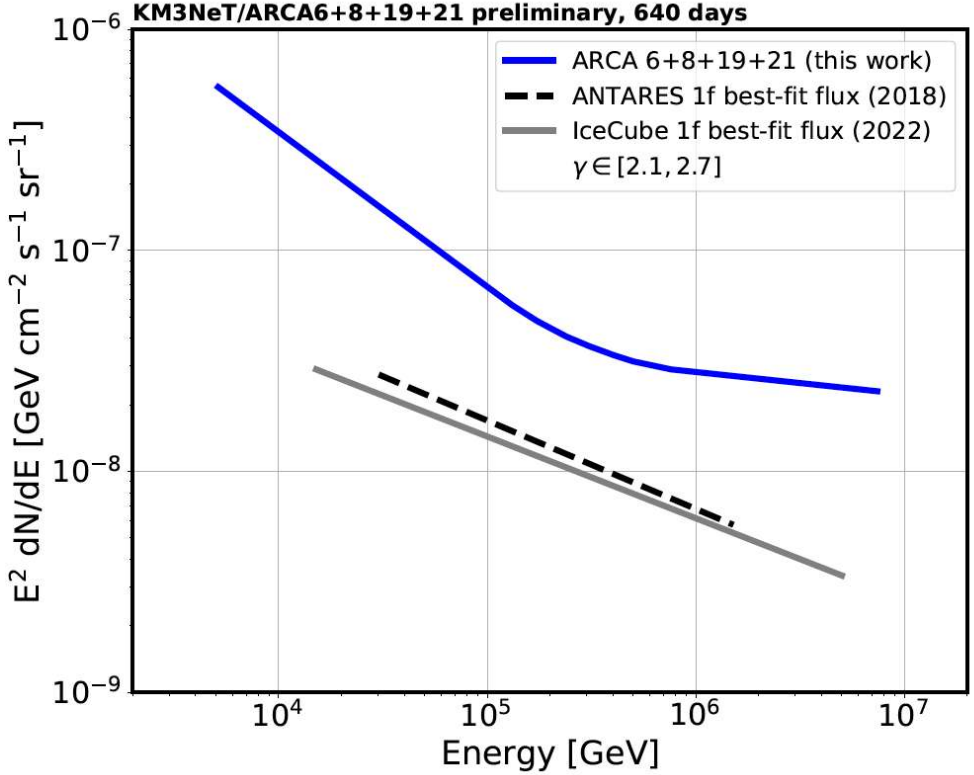




Results: diffuse flux

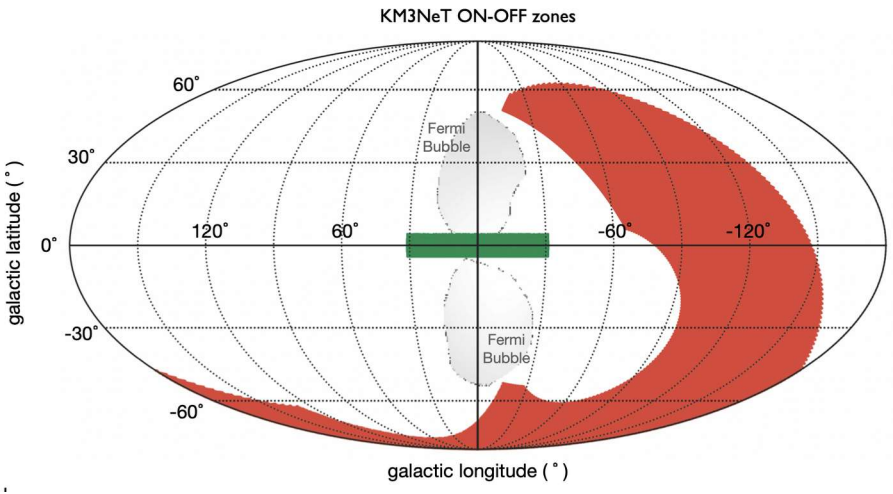
All-sky diffuse flux detection

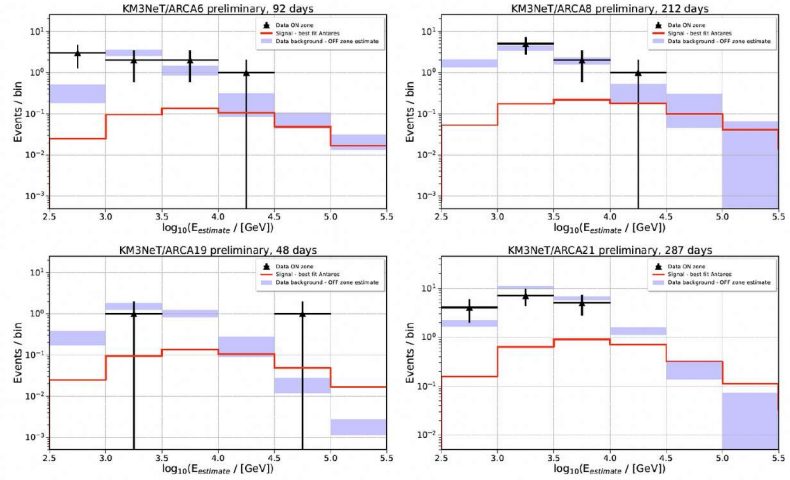




No observation yet, sensitivity improving

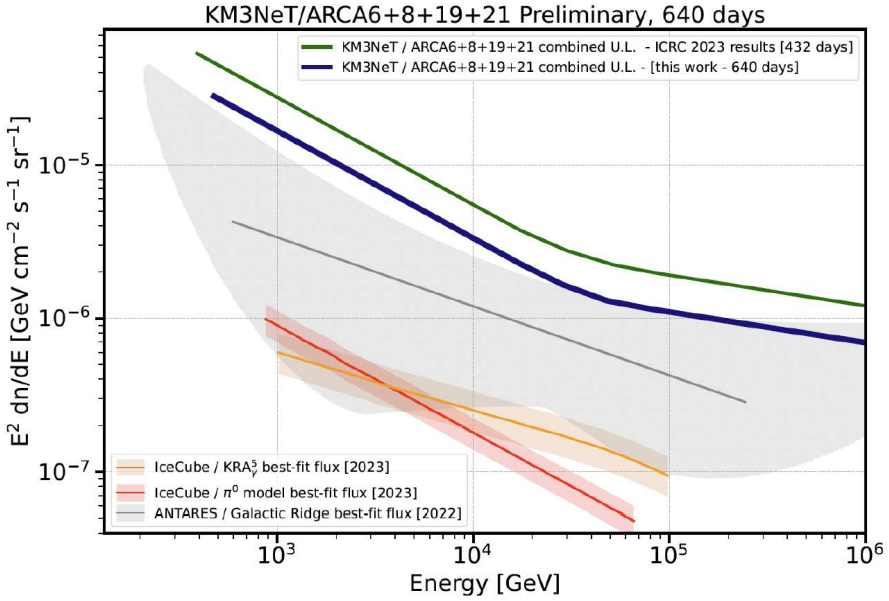
Results: Galactic ridge





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

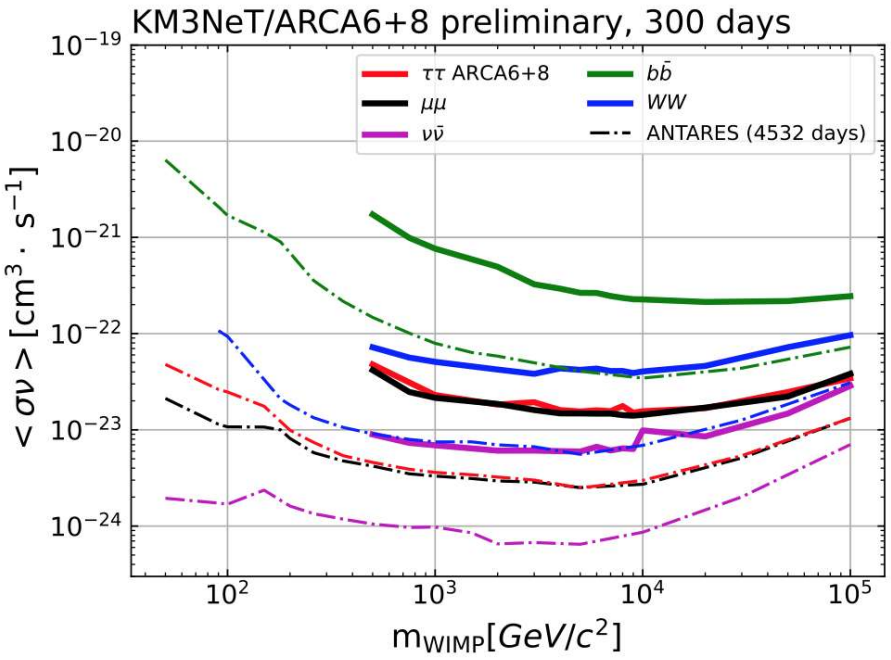
$\mathbf{p+N \rightarrow X+K^+,\pi^+ \rightarrow ...+ \mu \rightarrow e^+ + \nu_\mu + \nu_e}$
$p+N \rightarrow X+K^-,\pi^- \rightarrow ...+ \mu^- \rightarrow e^- + \nu_\mu + \nu_e$



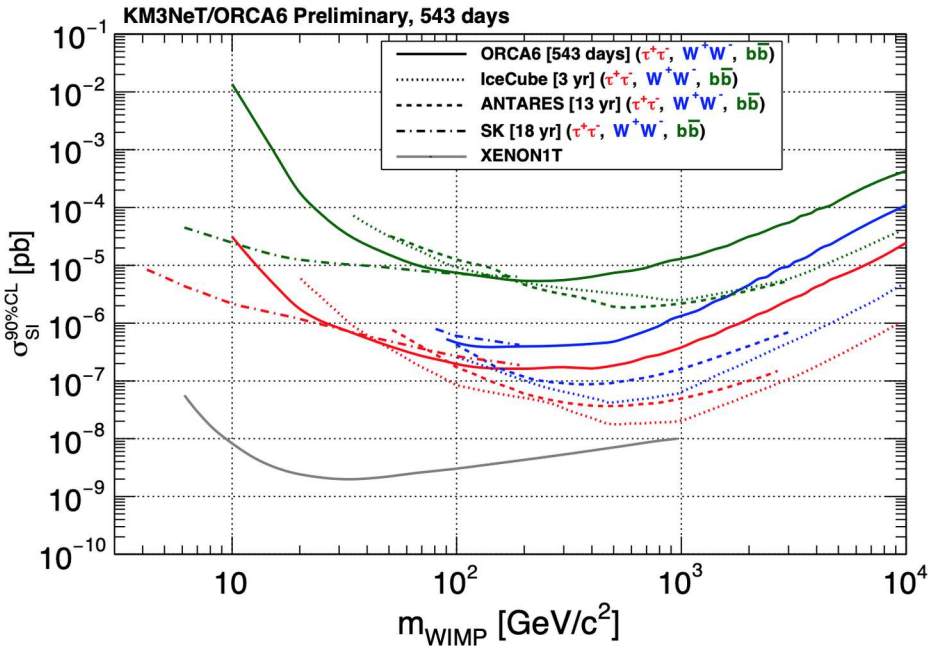
KM3NeT approaching the "measurement ballpark"

Results: Dark Matter

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

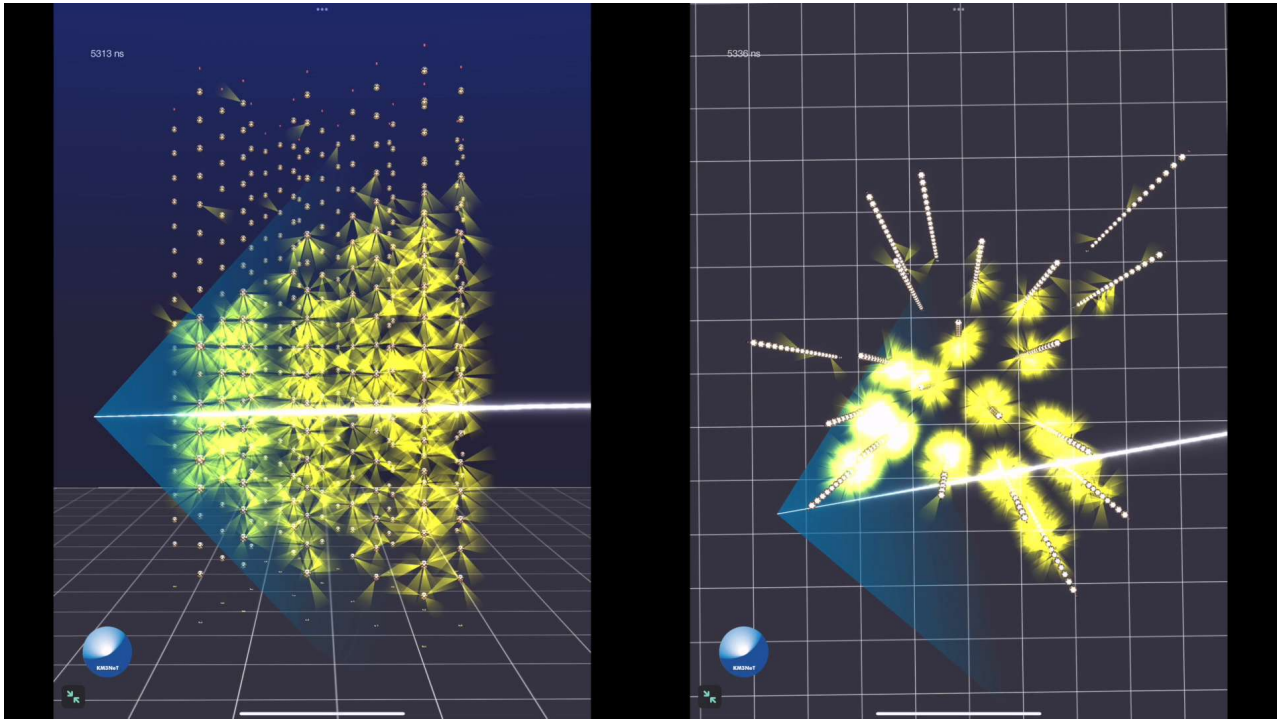


Sensitivity to signals from WIMP-WIMP annihilation in the Sun



KM3-230213A

THE BIGGEST MOVING THING UNDERWATER

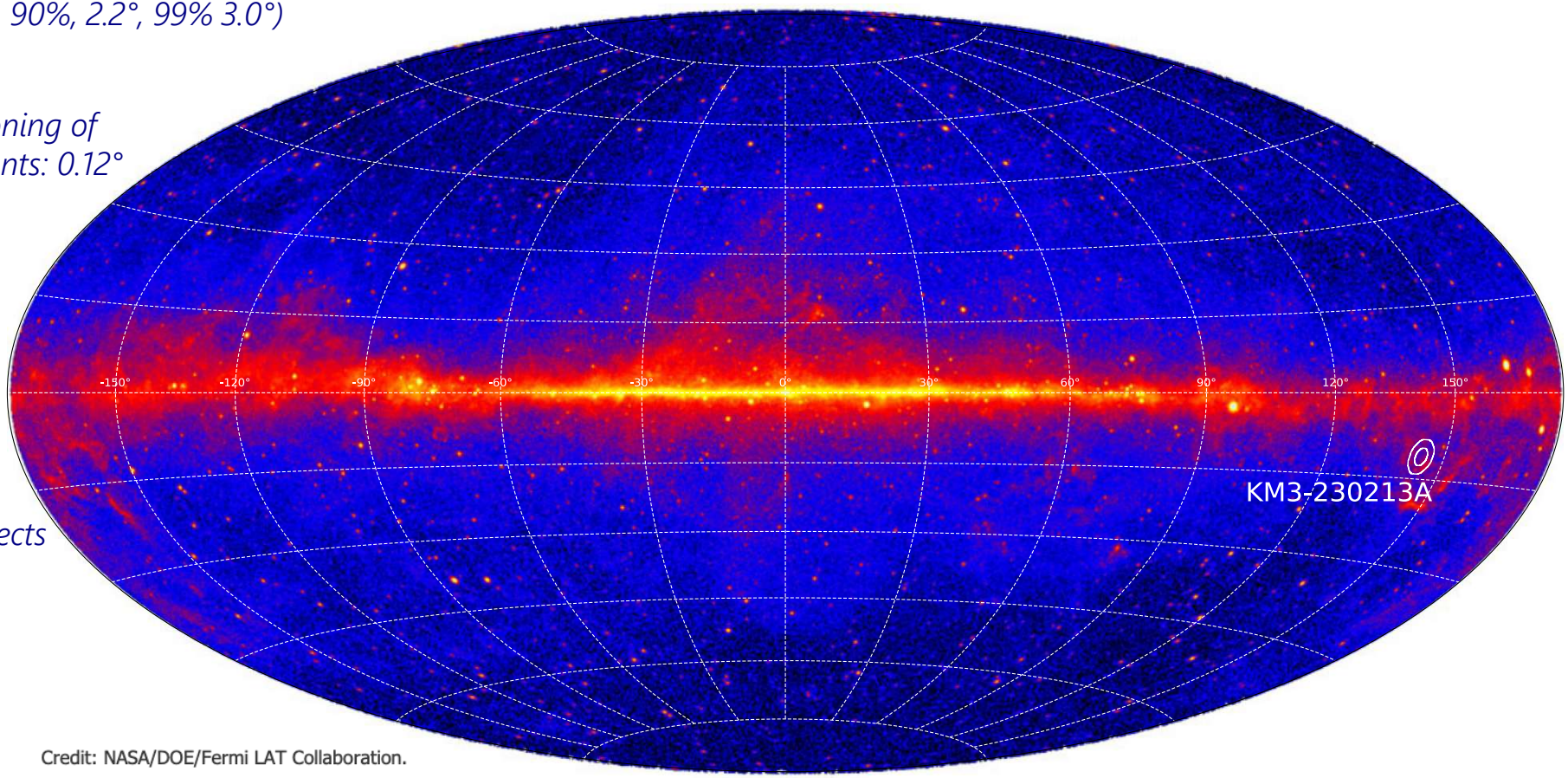


KM3-230213A

Local coordinates: (zenith, azimut) = (89.4°, 259.8°)
Celestial coordinates: (RA, dec) = (94.3°, -7.8°)
Error (68%, 1.5°, 90%, 2.2°, 99% 3.0°)

Absolute positioning of detection elements: 0.12°

Sea campaign to improve position measurement of reference objects



Credit: NASA/DOE/Fermi LAT Collaboration.

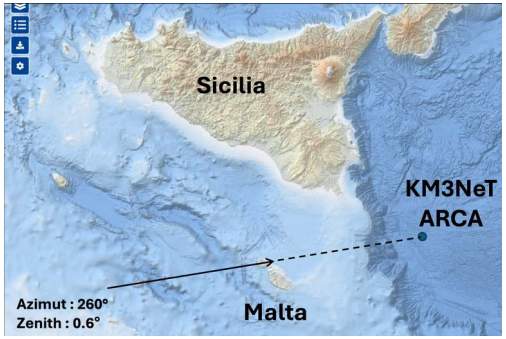
KM3-230213A

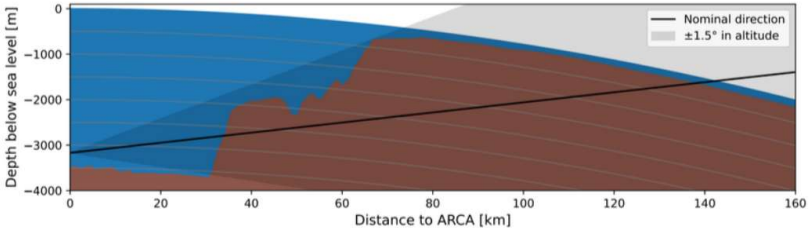
Event reconstructed as a track

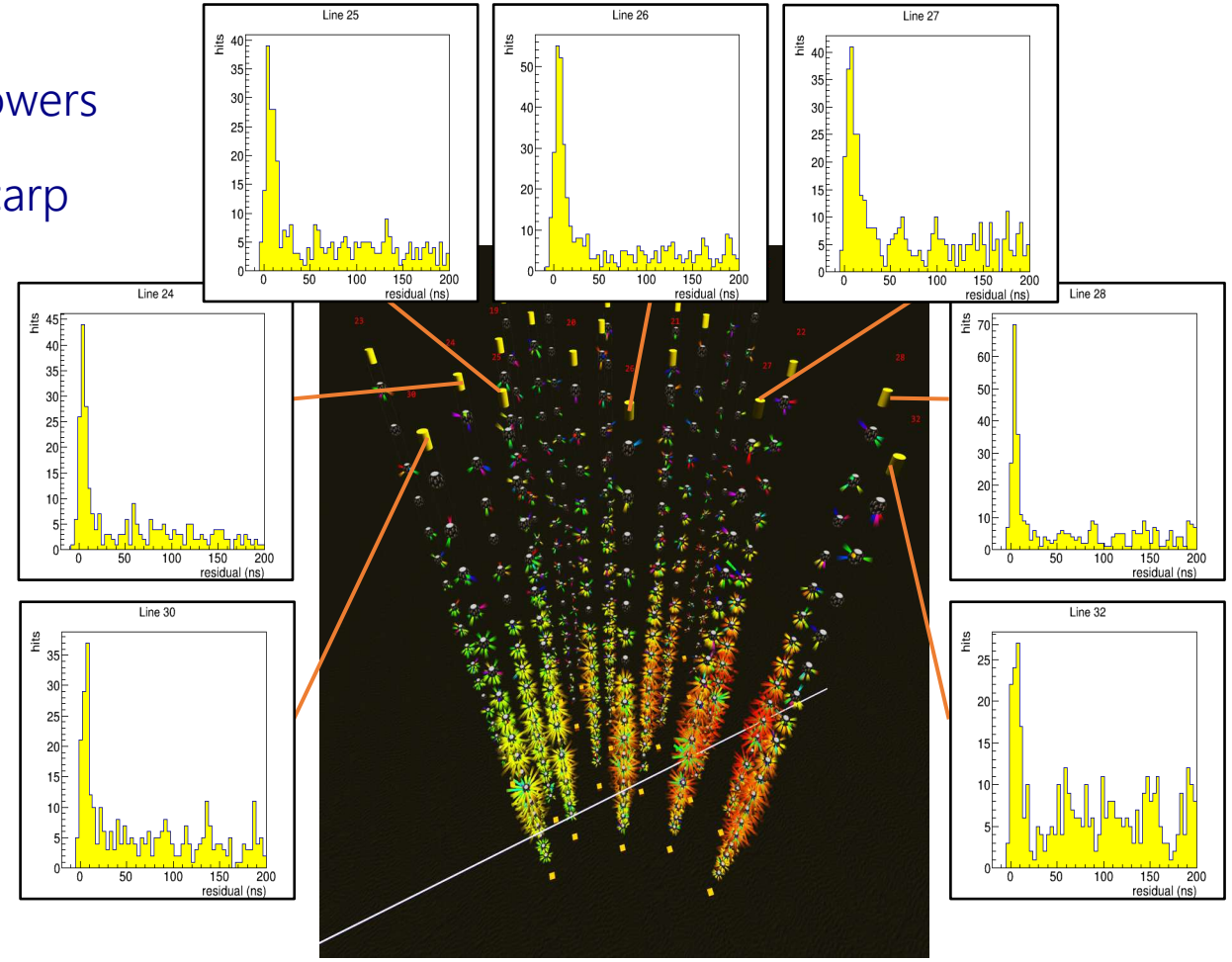
Additional excitation due to trailing showers

Neutrino coming through steep rock scarp

Natural filter for cosmic rays







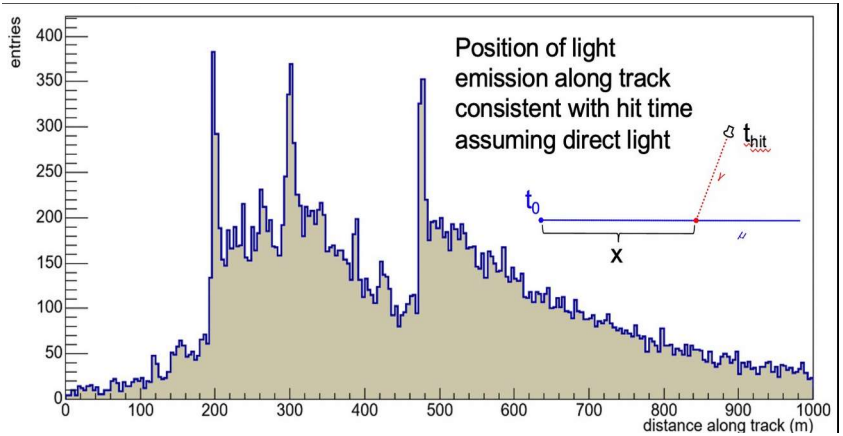
KM3-230213A

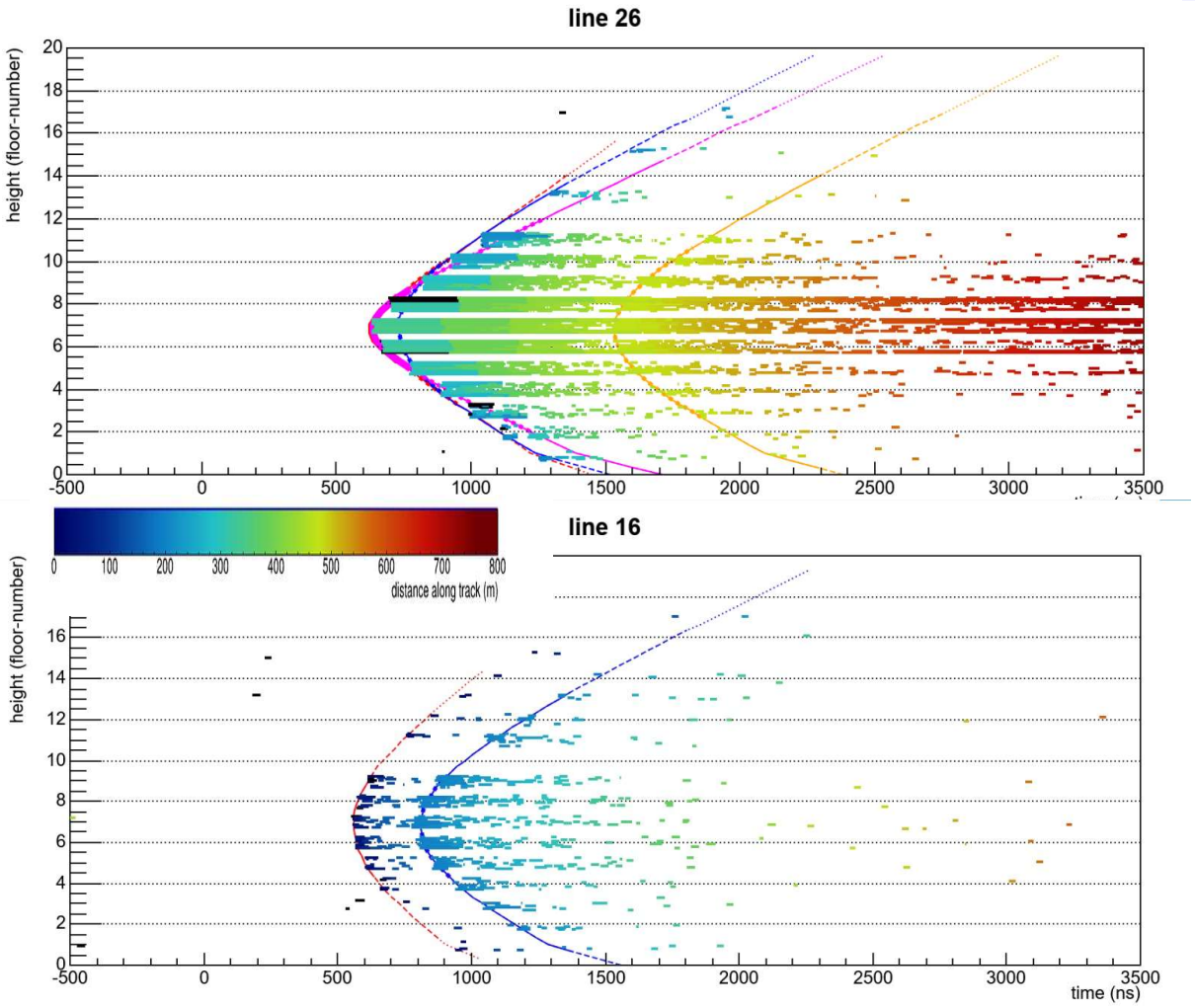
Cherenkov emission from muon

+

Three trailing showers

3672 (35% of total) PMTs triggered



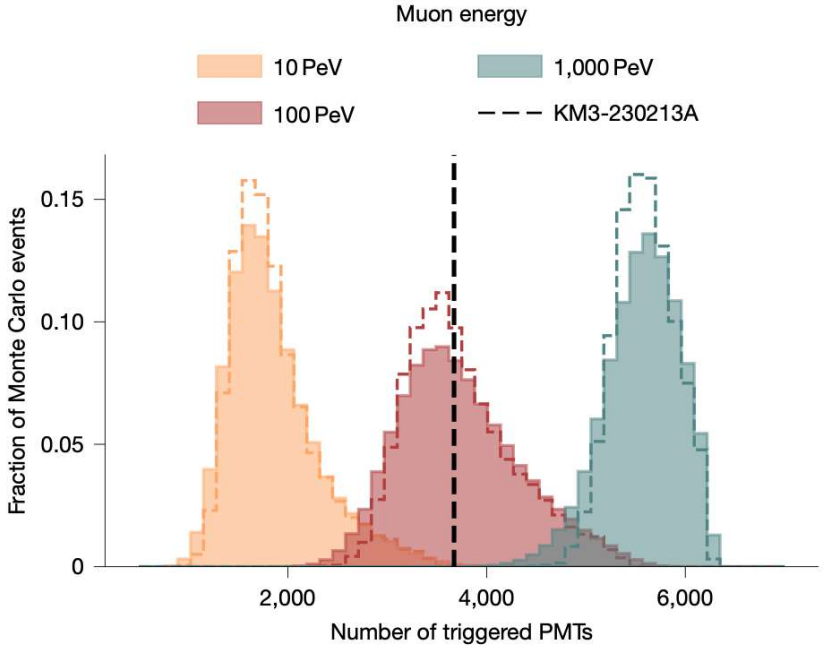


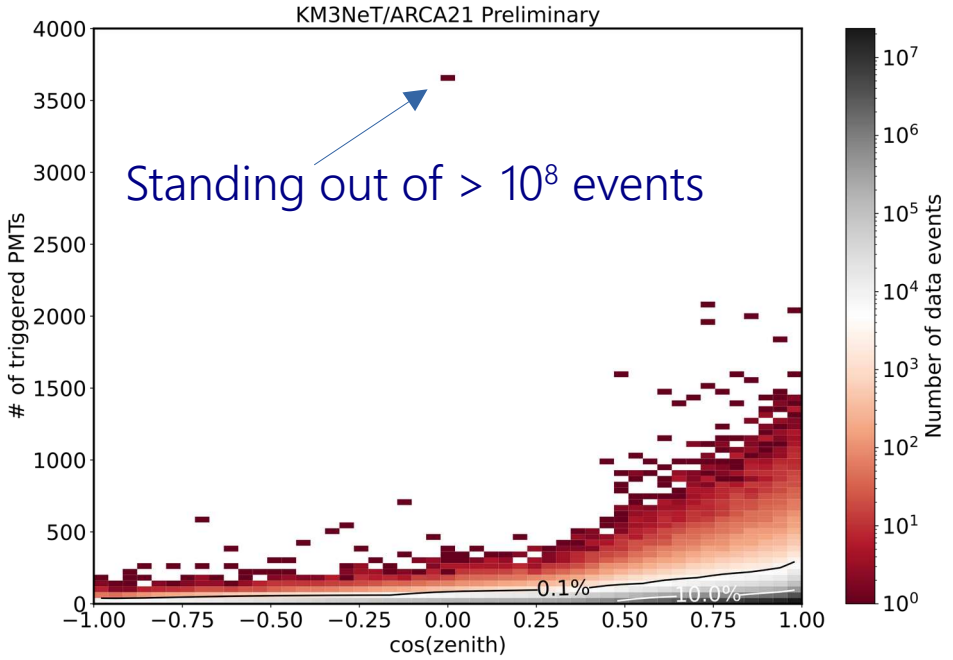
KM3-230213A

Robust energy estimate from the number of triggered PMTs

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

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





KM3-230213A

Four main hypotheses for KM3-230213A

1 diffuse flux

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

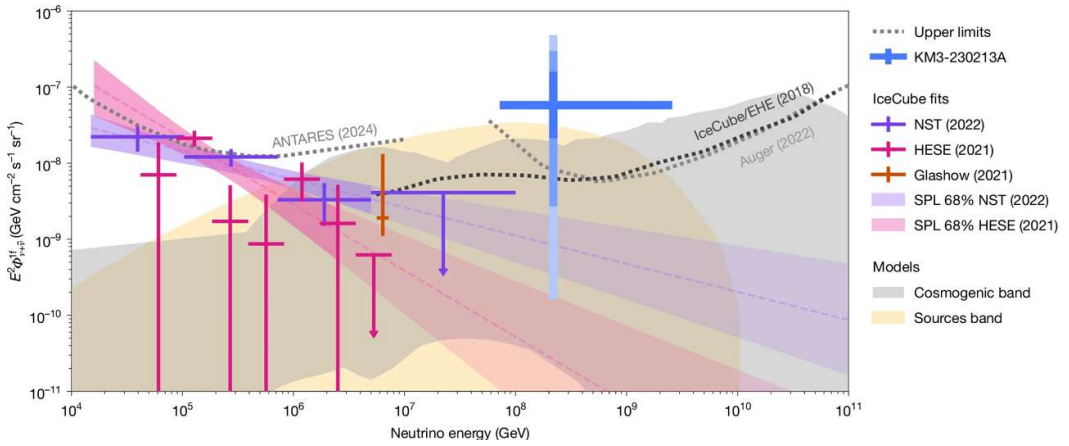
$$E^2 \Phi^{1f}_{\nu+\bar{\nu}} = 5.8^{+10.1}_{-3.7} \times 10^{-8}\, GeV\, cm^{-2}\, s^{-1}\, sr^{-1}$$

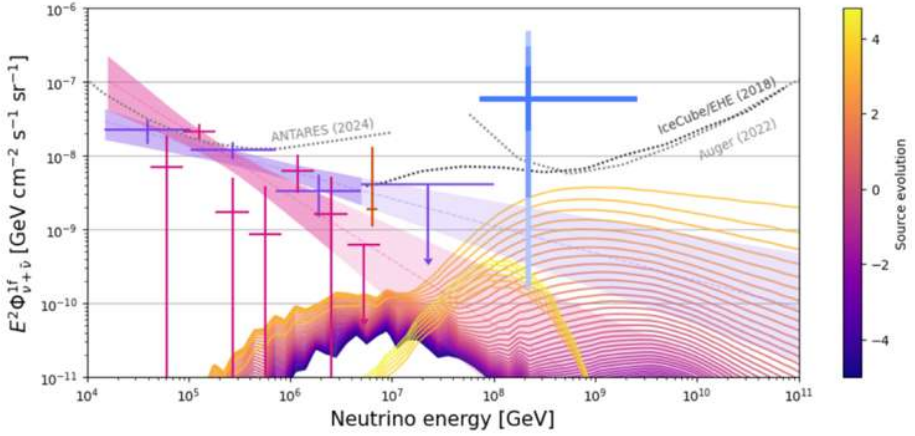
2 Galactic – **unlikely**

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

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

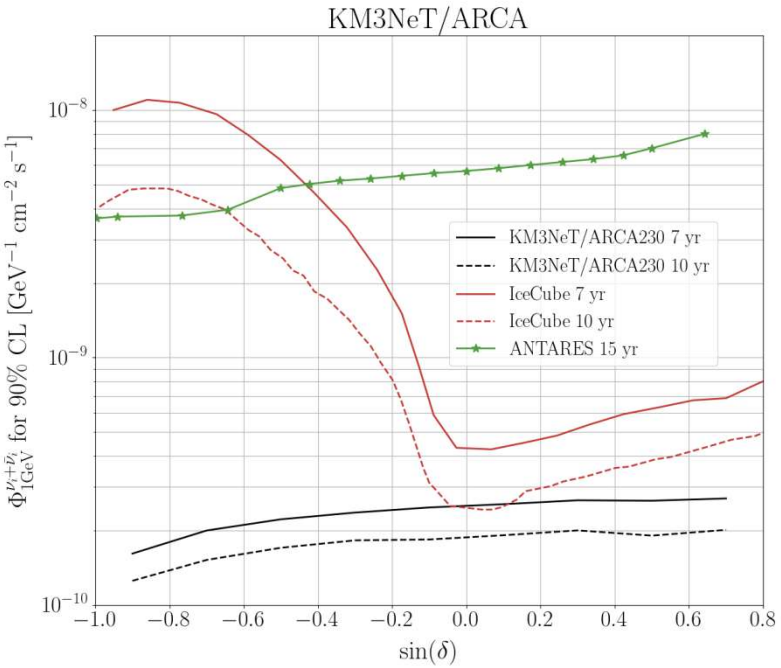
+ many others!

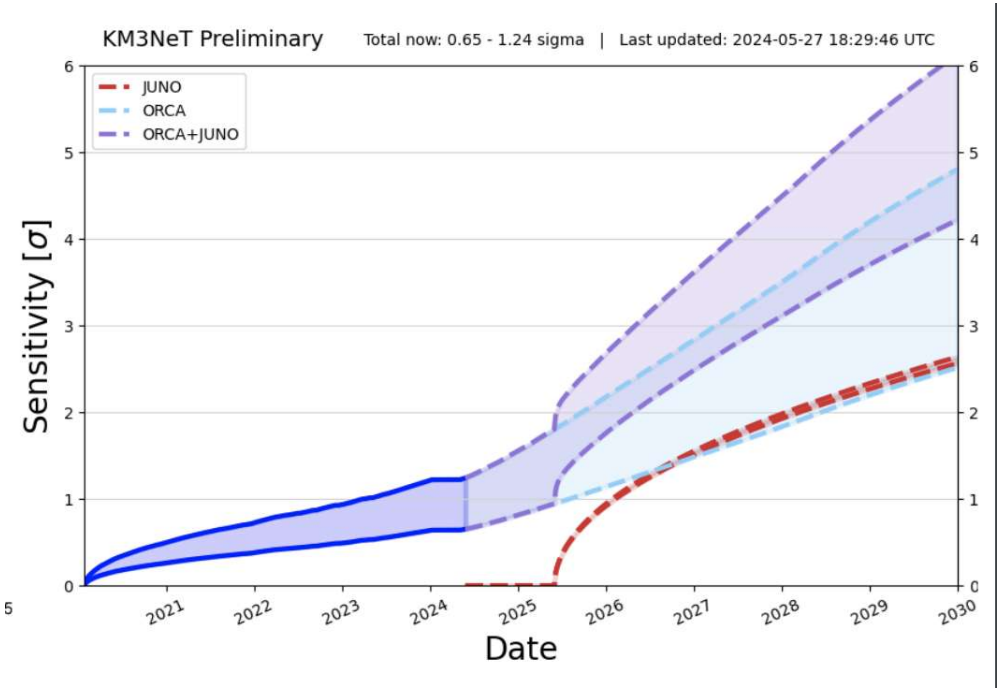




Outlook

Outlook

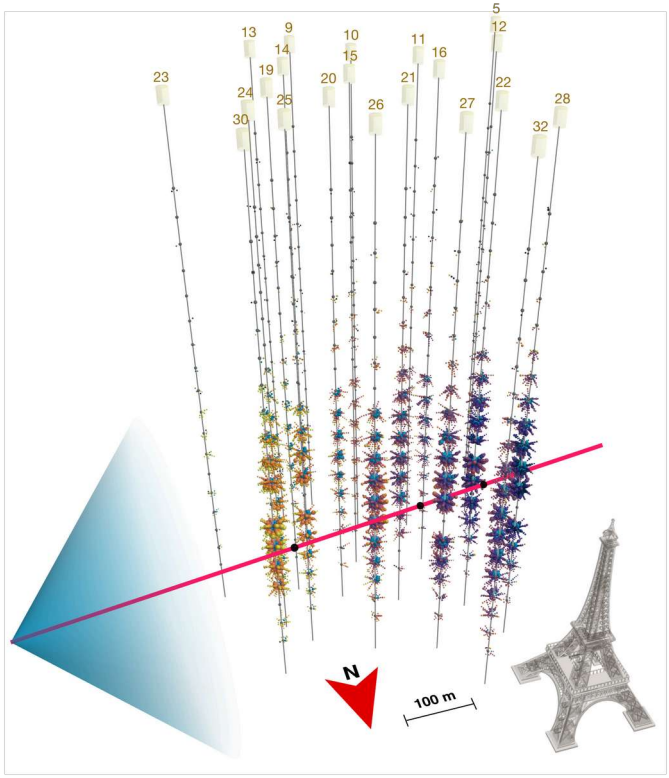


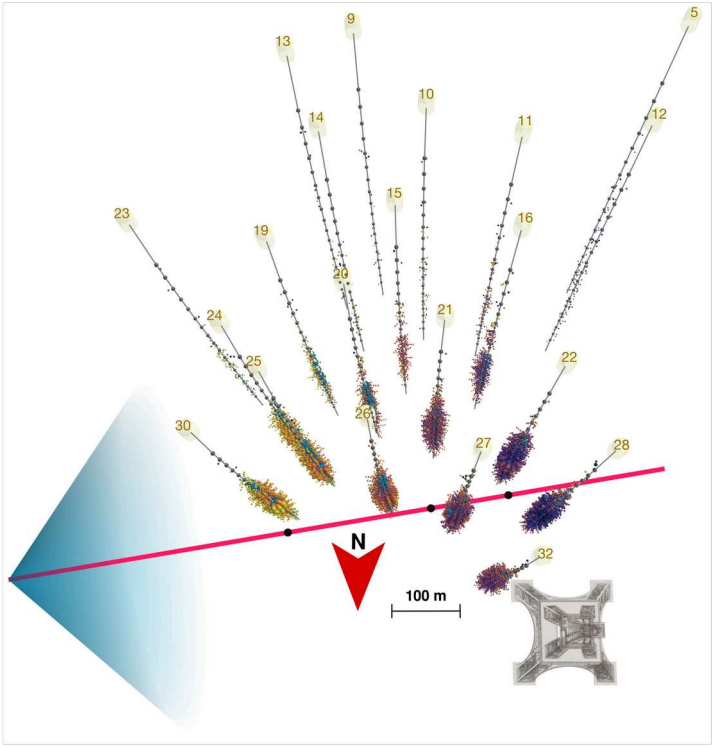


Combined performance ORCA + JUNO
Band: NO+IO+θ_{23} allowed values

Outlook

… and maybe more such stuff!





Thanks!