The KM3NeT underwater neutrino telescopes: status, latest results and outlook

LA THUILE 2024 - Les Rencontres de Physique de la Vallée d'Aoste
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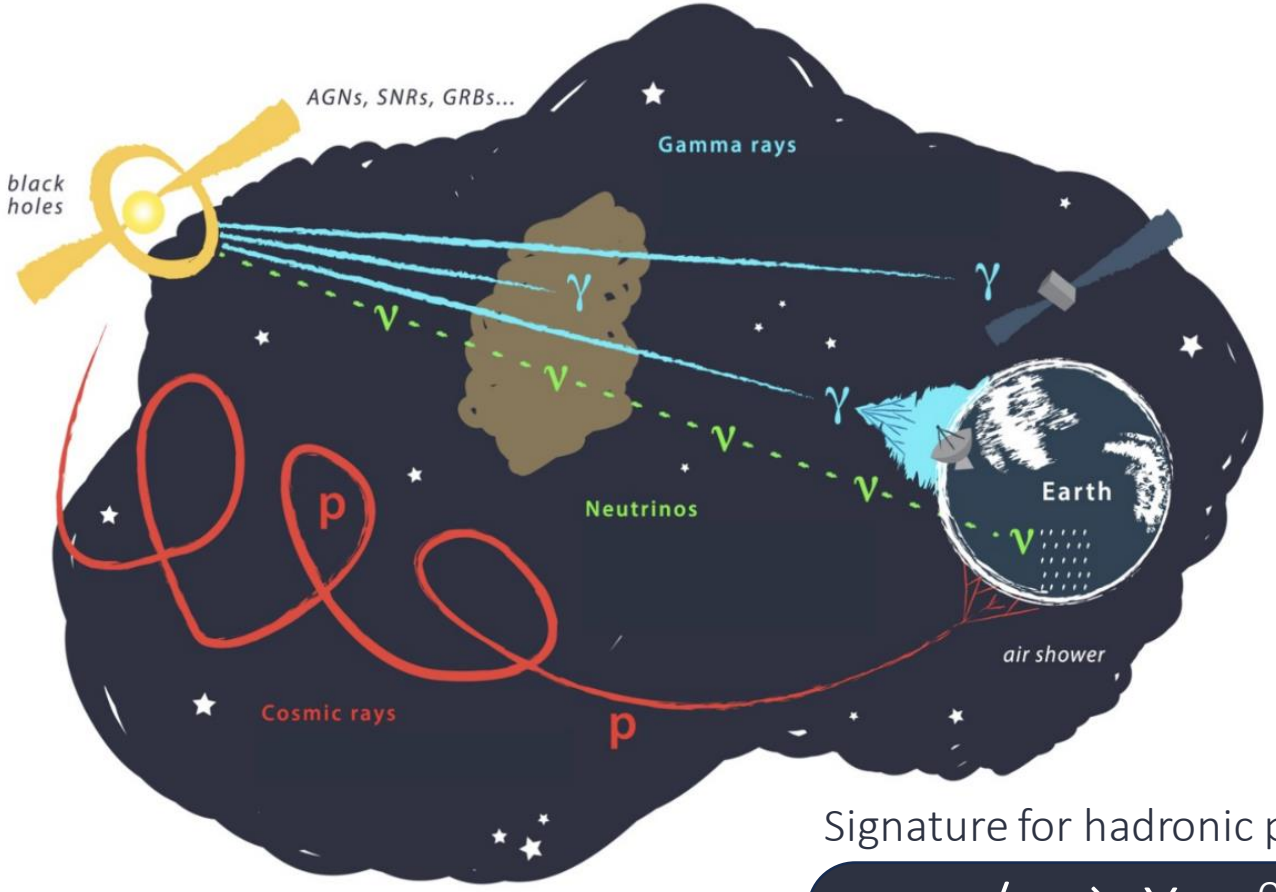
Outline

- Neutrino astronomy
- The KM3NeT neutrino telescopes
- ARCA/ORCA selected recent results
- ARCA/ORCA perspectives

Neutrino astronomy



Neutrinos are electrically neutral, stable, and weakly interacting particles.

NO deflection by magnetic fields

LOW absorption (ISM/CMB)

Travel through dense environments over cosmological distances

Ideal messengers from astrophysical sources!

Signature for hadronic processes

$$p+p/\gamma \rightarrow X+\pi^0 \rightarrow \gamma\,\gamma$$
$$\rightarrow X+\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}$$
$$\mu^{\pm} \rightarrow e^{\pm} + \overset{(-)}{\nu}_e + \overset{(-)}{\nu}_{\mu}$$

Expected correlation between HE photons and neutrino production

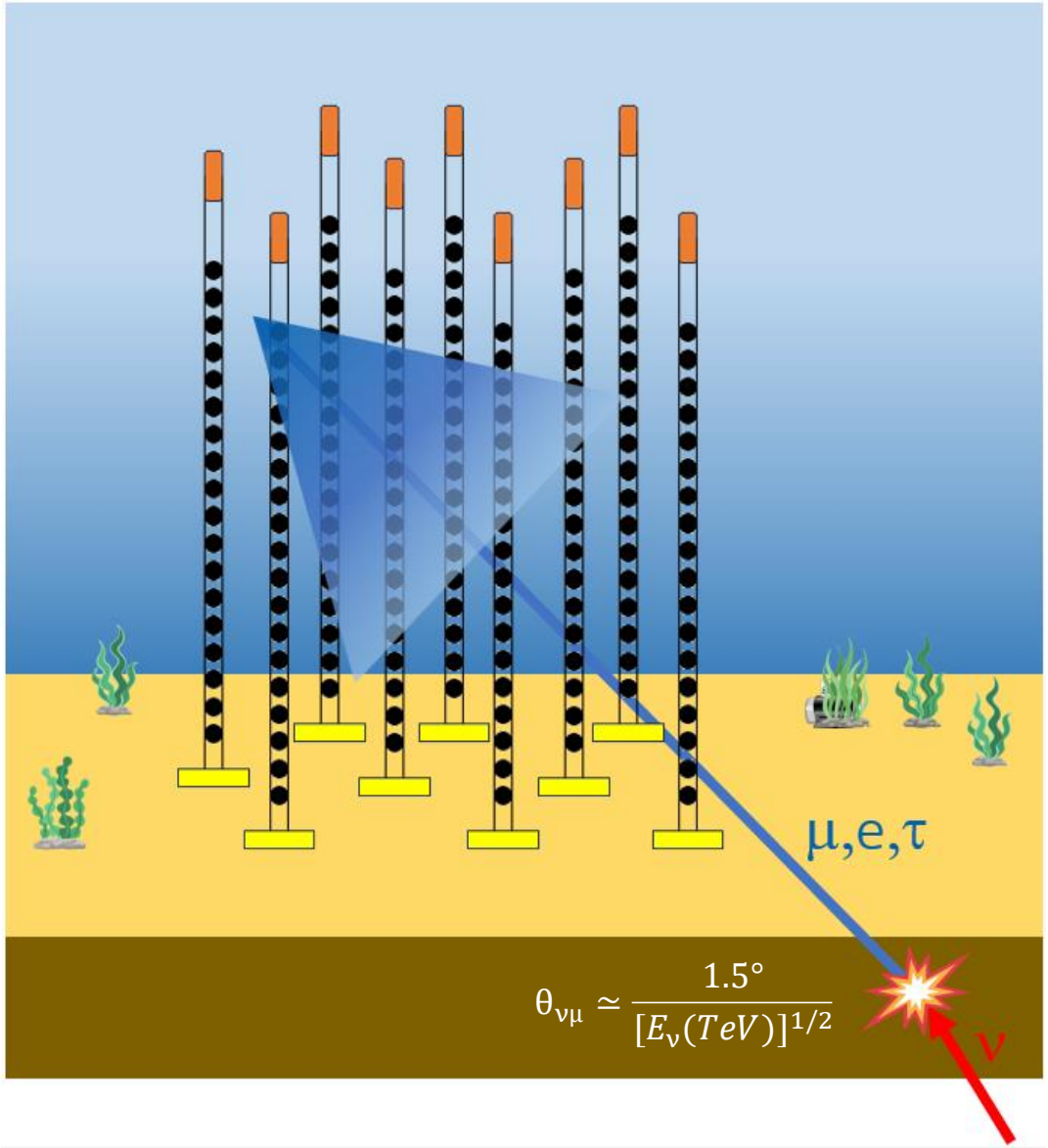
Detection principle

"We propose setting up apparatus in an underground lake or deep in the ocean in order to separate charged particle directions by Cerenkov radiation."

Moisey Markov (1960) - Proceedings of the 1960 Annual International Conference on High-Energy Physics

Neutrino telescopes

- Large volumes of water/ice instrumented with 3-dimensional arrays of photodetectors arranged in optical modules
- Vertical string-like structures, distributed in specific geometries, optimized for the targeted energy region
- Detection of Cherenkov photons emitted by relativistic charged secondary leptons from ν interactions
- Time, position, and amplitude of photon pulses are used to reconstruct ν direction and energy



Detection principle

Same paper, reply by G. Bernardini:

“I want to object a little bit to your optimism although I myself am very optimistic. […] Some new detector should be developed in which you use 10 tons of material and in which you are able to realize an appreciable amount of information. My optimism is concentrated on the possibility of developing such a detector.”

The neutrino telescopes World map

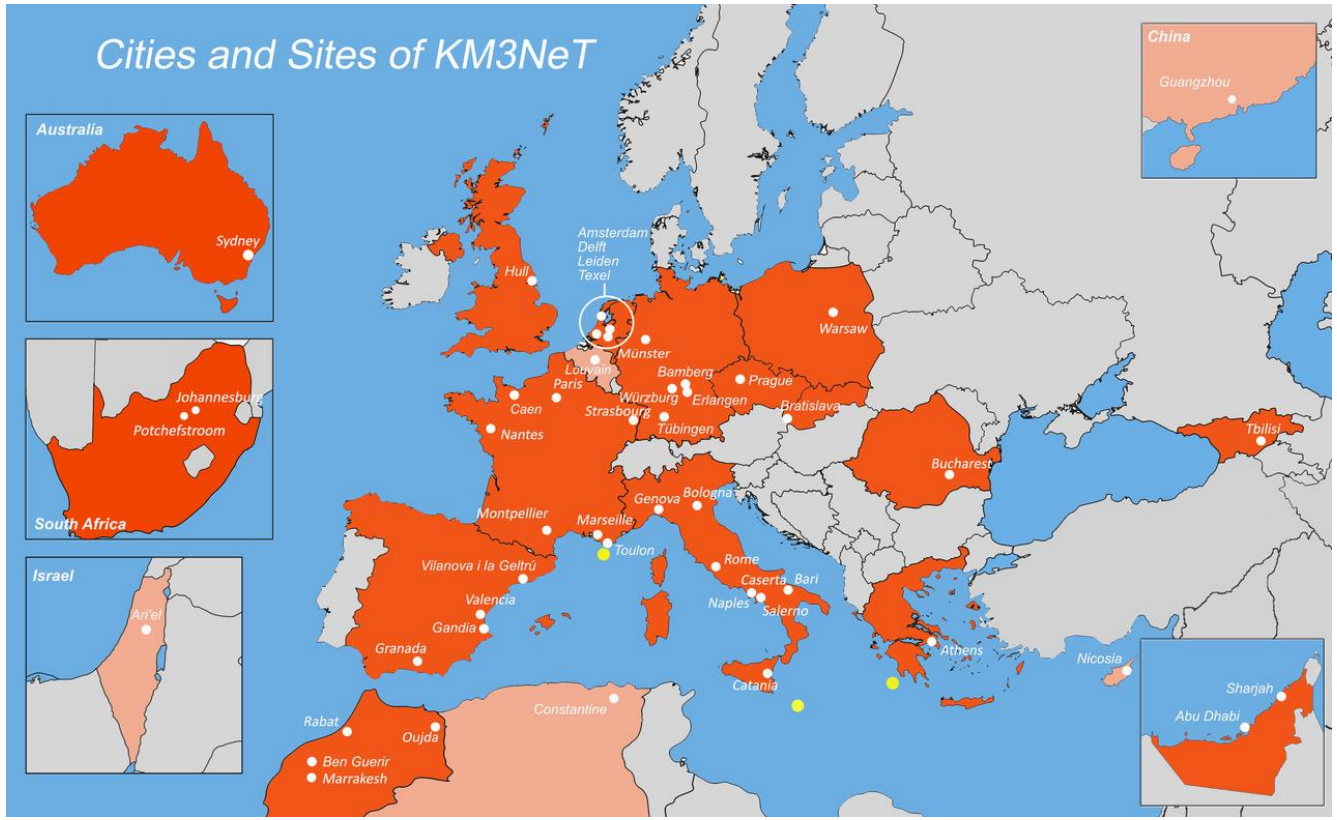
THE KM3NeT

NEUTRINO TELESCOPES

KM3NeT

KM3NeT is a multi-site, deep-sea infrastructure. Two telescopes are currently under construction in the Mediterranean Sea:

- **ORCA** (**O**scillation **R**esearch with **C**osmics in the **A**byss, France)
- **ARCA** (**A**stroparticle **R**esearch with **C**osmics in the **A**byss, Italy)



Harvard University recently joined!

- ✓ 62 Institutes
- ✓ 22 Countries
- ✓ 5 Continents

KM3NeT ARCA

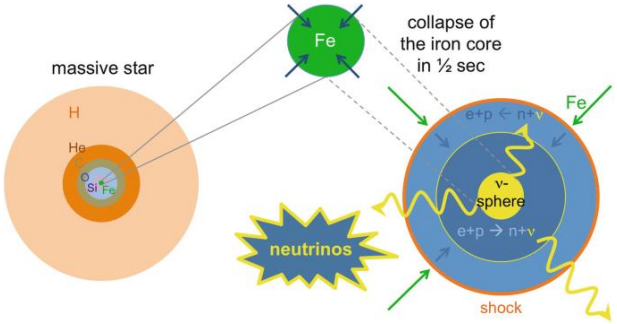
high-energy range, detection of HE cosmic neutrino sources (E_ν ~GeV-PeV) → GOAL: 1 km^3 of instrumented water (1 Gton)
ARCA = 2 BB = 230 DUs → 128340 PMTs

KM3NeT ORCA

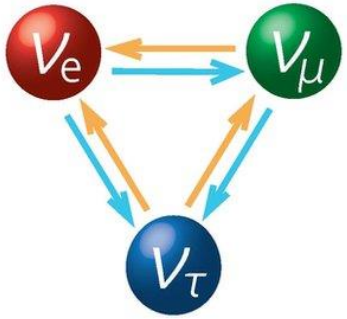
lower energy, main science goal: neutrino oscillations (E_ν ~MeV - GeV) → GOAL: 7 Mton of instrumented water
ORCA = 1 BB = 115 DUs → 64170 PMTs

The KM3NeT multi-energy scale science program

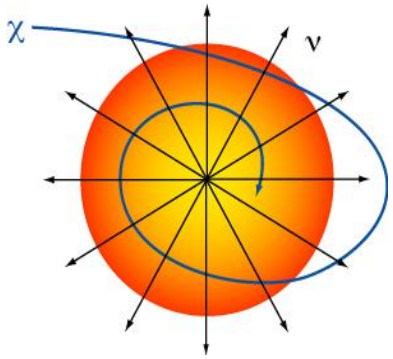
Supernova explosion



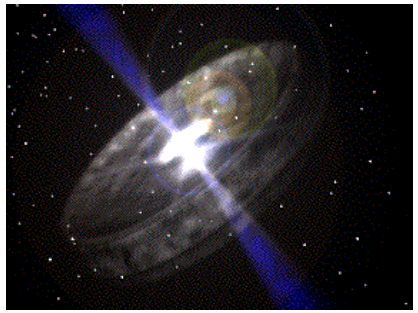
Neutrino oscillations



Dark matter



High-Energy neutrinos



MeV GeV TeV PeV

ORCA

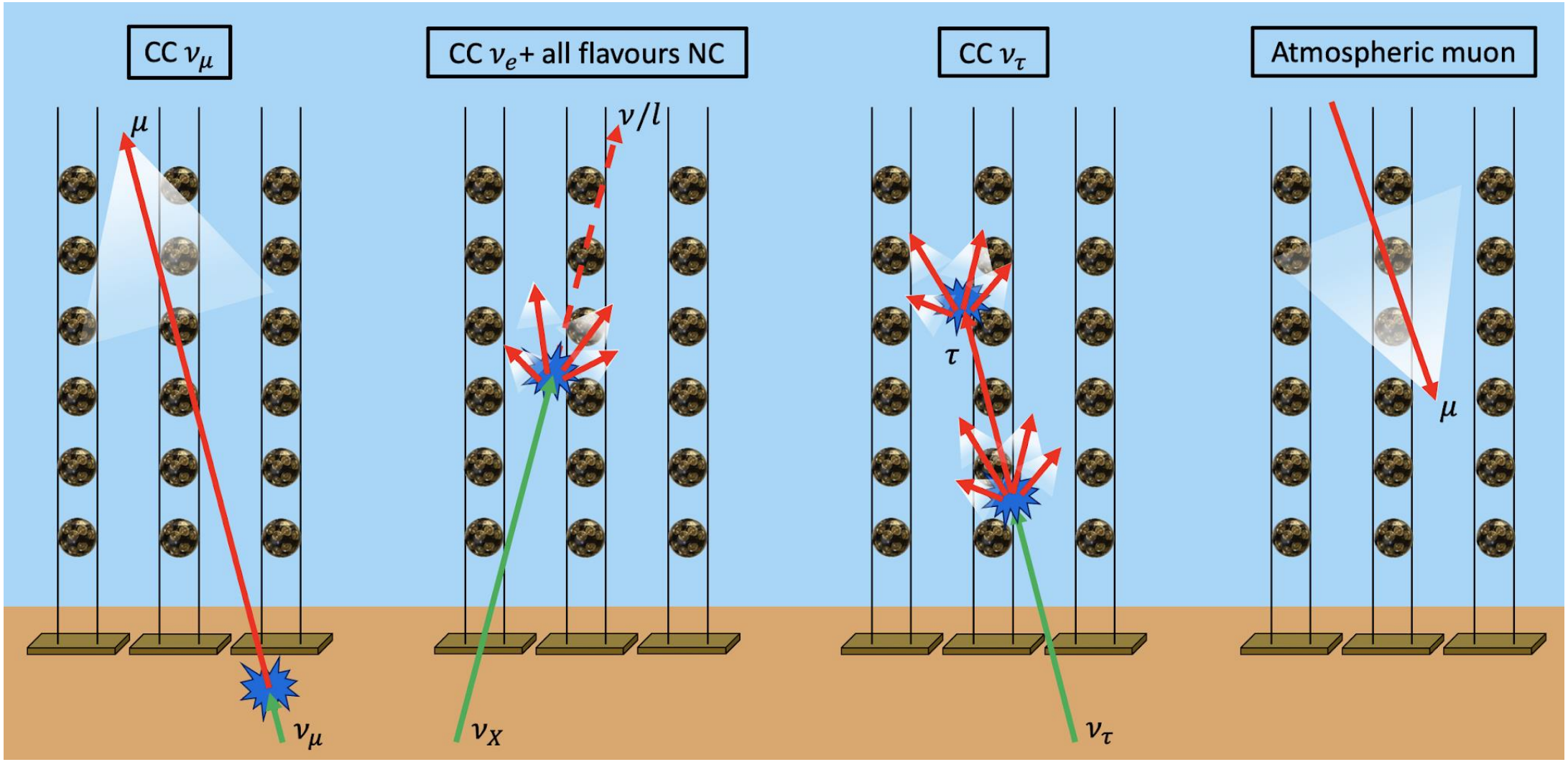
ARCA ARCA

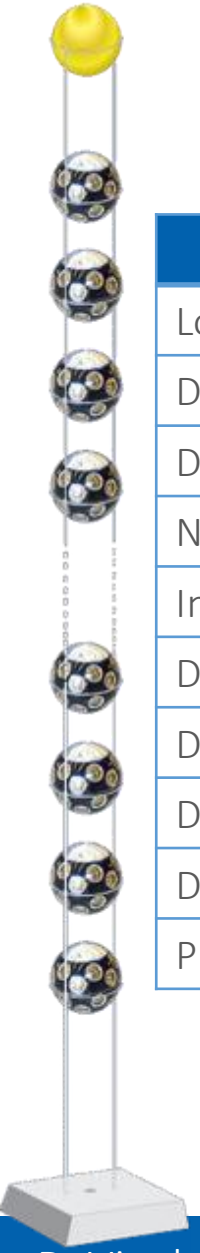
Complementary science goals, same technology!

Event topologies

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

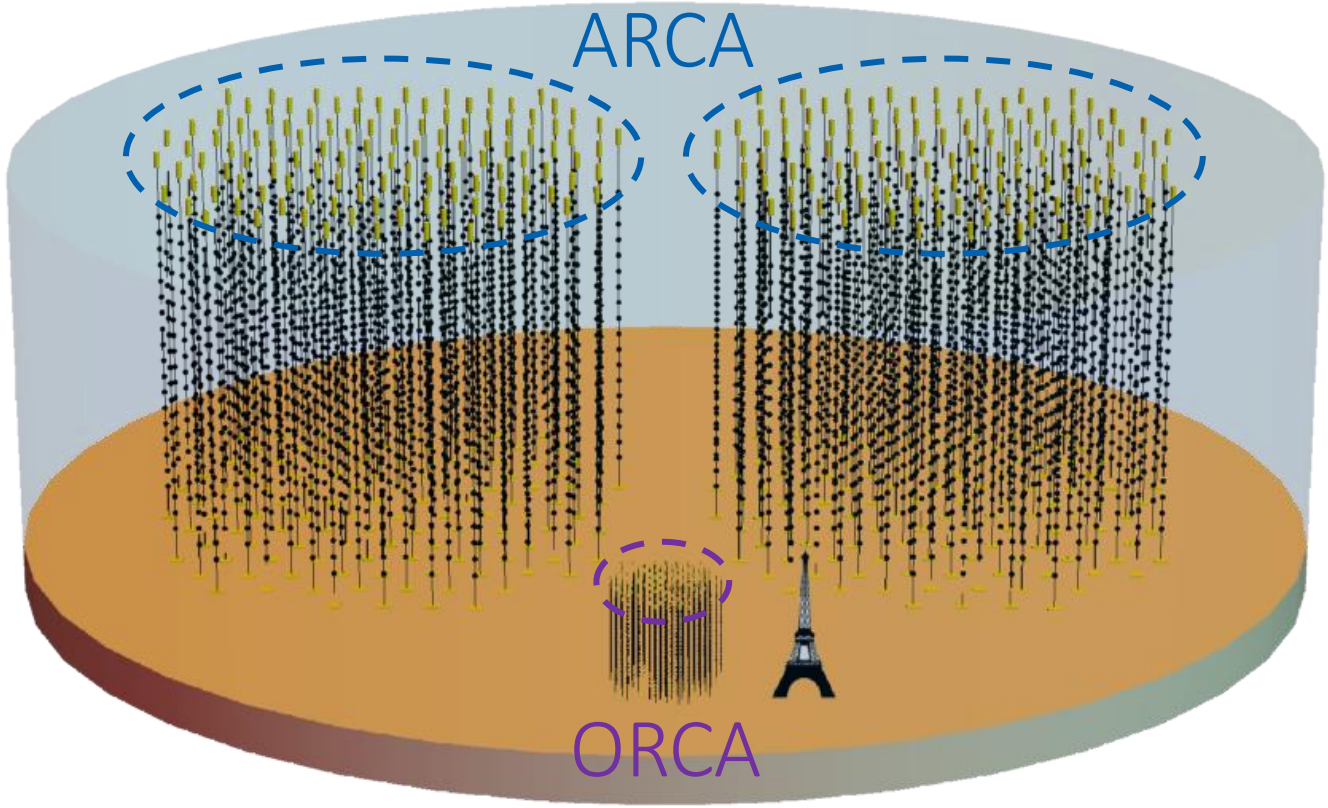
Showers: @E_ν>100 TeV Angular resolution below 2° - Energy resolution ~6%



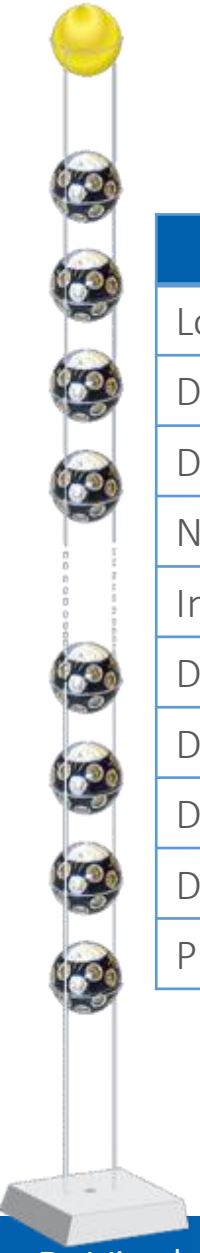


KM3NeT in numbers

	ARCA	ORCA
Location	Italy (Sicily)	France (Toulon)
Depth	3450 m	~2500m
Distance from shore	~100 km	40 km
Number of DUs	230 (115 x 2)	115
Instr. water volume	1 Gton	0.7 Mton
DU height	~700 m	~200 m
DU horizontal spacing	90 m	20 m
DU vertical spacing	37 m	9 m
DOMs/DU	18	18
PMTs/DOM	31	31



The KM3NeT detectors



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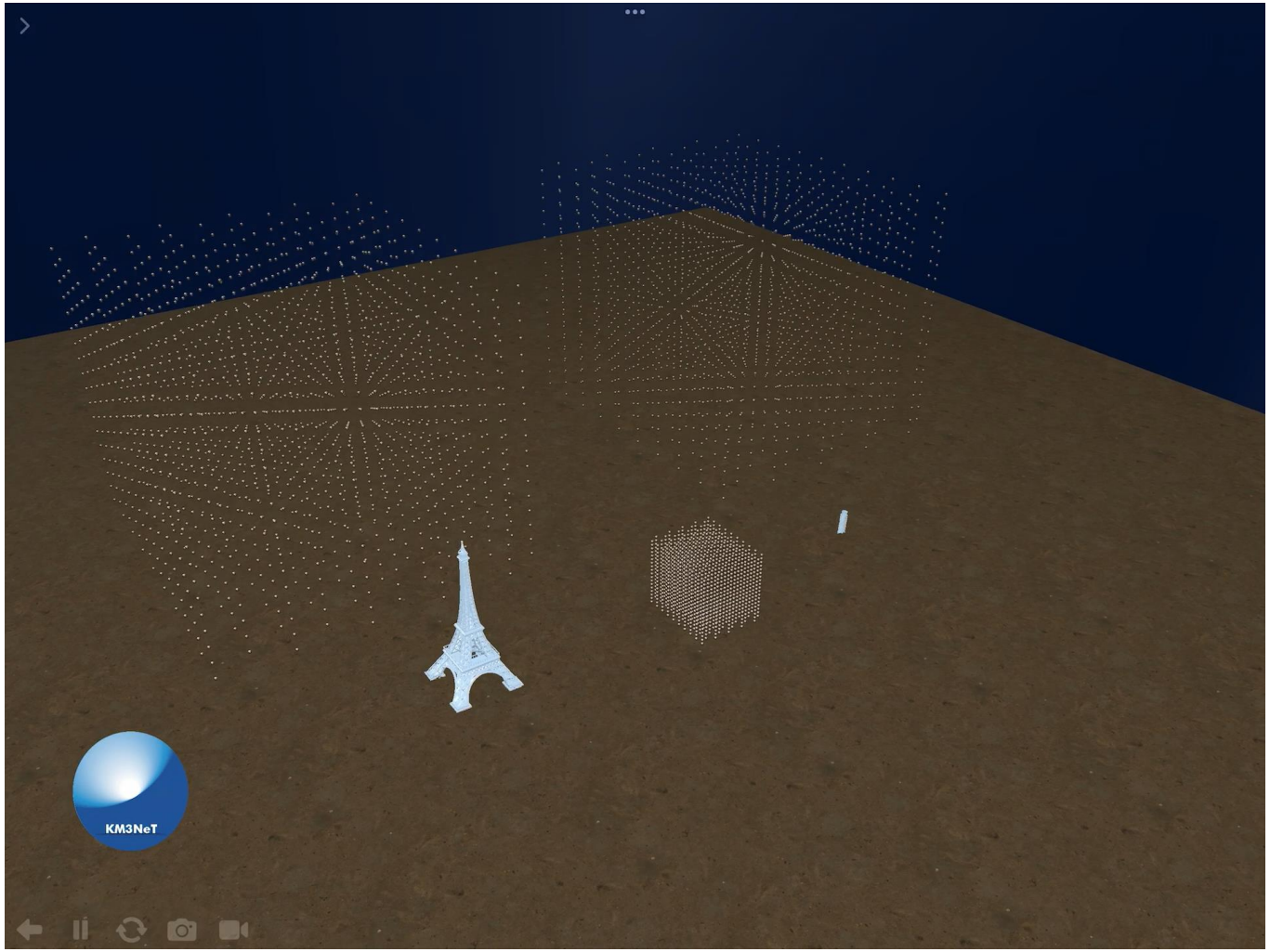
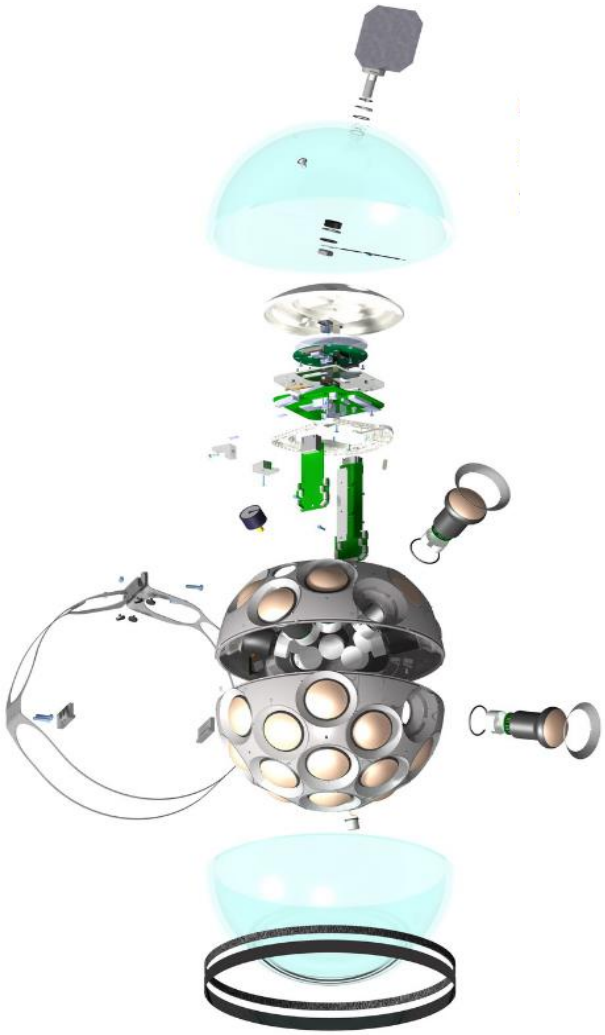


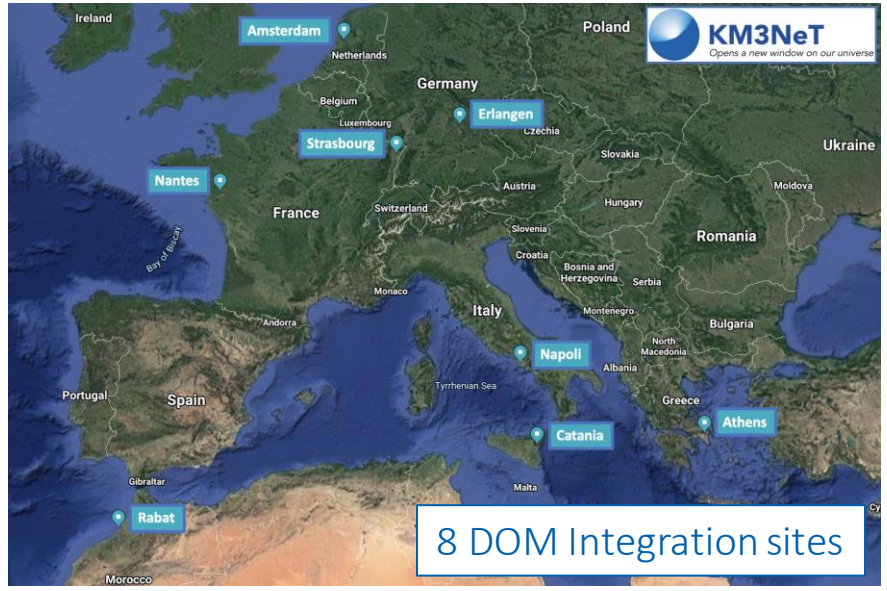
The KM3NeT Digital Optical Module



17'' high-pressure-resistant glass sphere containing

- 31 three-inches photomultiplier tubes (12 in the top hemisphere, 19 in the bottom)
- Readout electronics
- Gbit/s optical fiber transmission (all data to shore)
- White Rabbit time synchronisation
- LED beacon for auto-calibration
- Acoustic sensor for position reconstruction
- Tiltmeter/compass chip

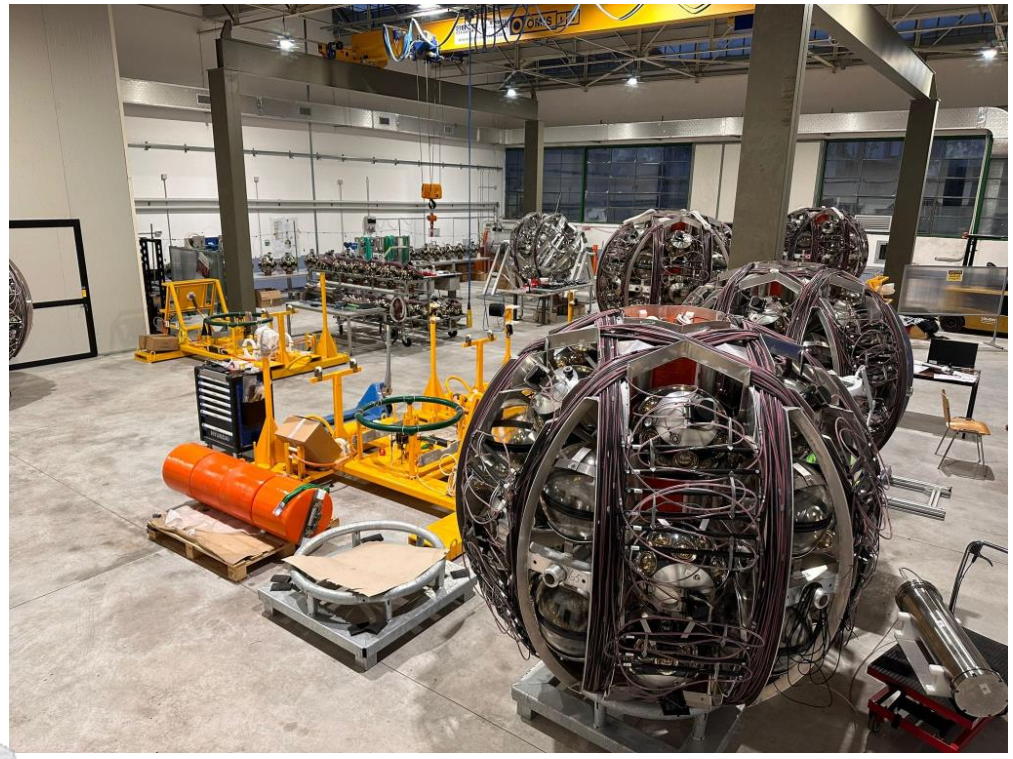
1400 DOMs integrated!

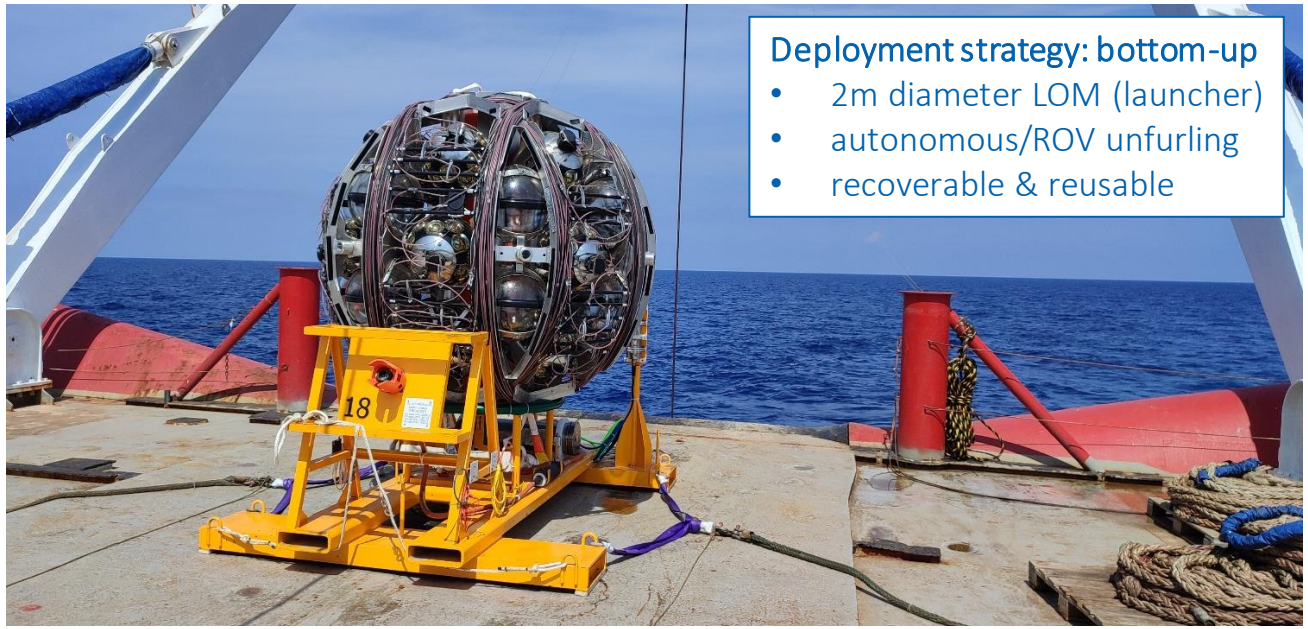


The KM3NeT Detection Unit

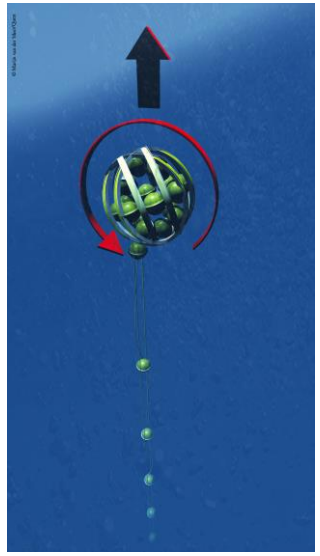
- 18 DOMs per DU
- Base Module
- Anchor
- Vertical Electro-Optical Cable
- Buoy

Assembly, calibration and test in 6 DU Integration sites

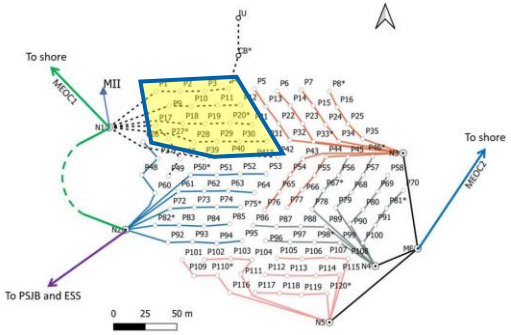




Deployment strategy: bottom-up
- 2m diameter LOM (launcher)
- autonomous/ROV unfurling
- recoverable & reusable

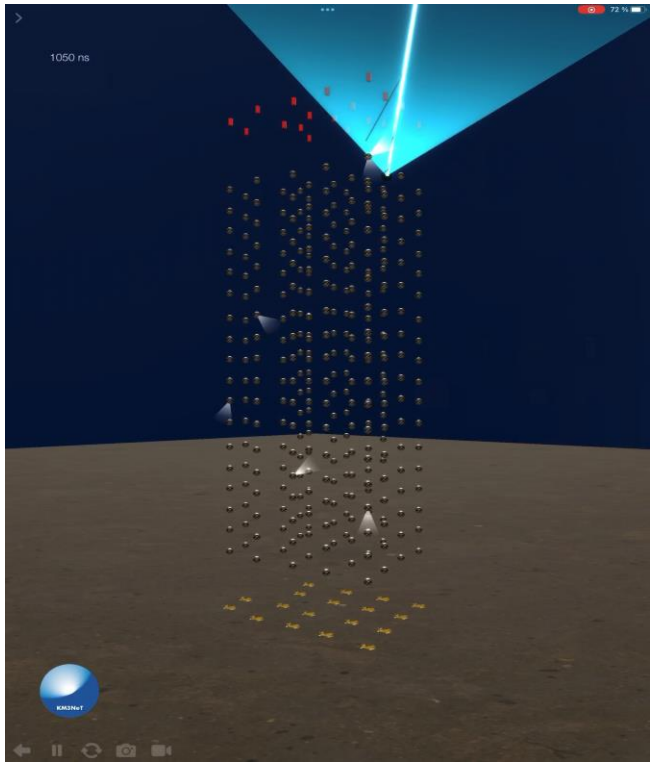


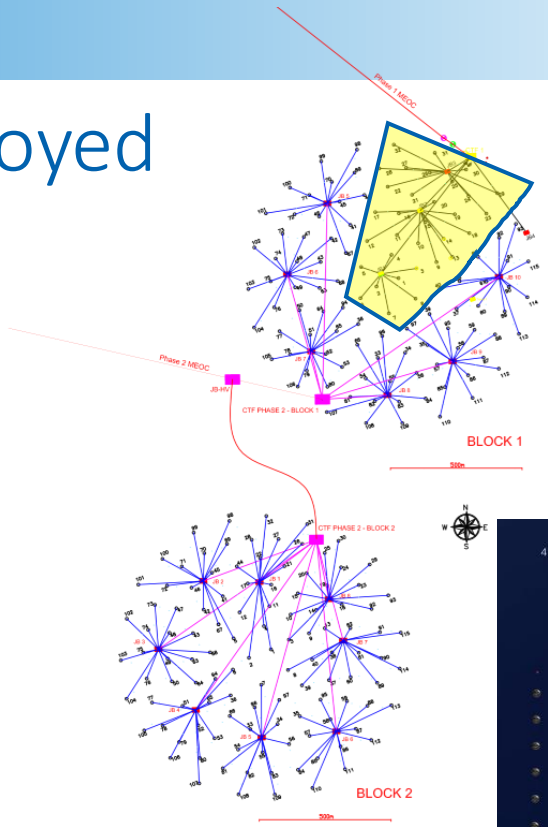
46 KM3NeT Detection Units deployed



ORCA: 18 DUs

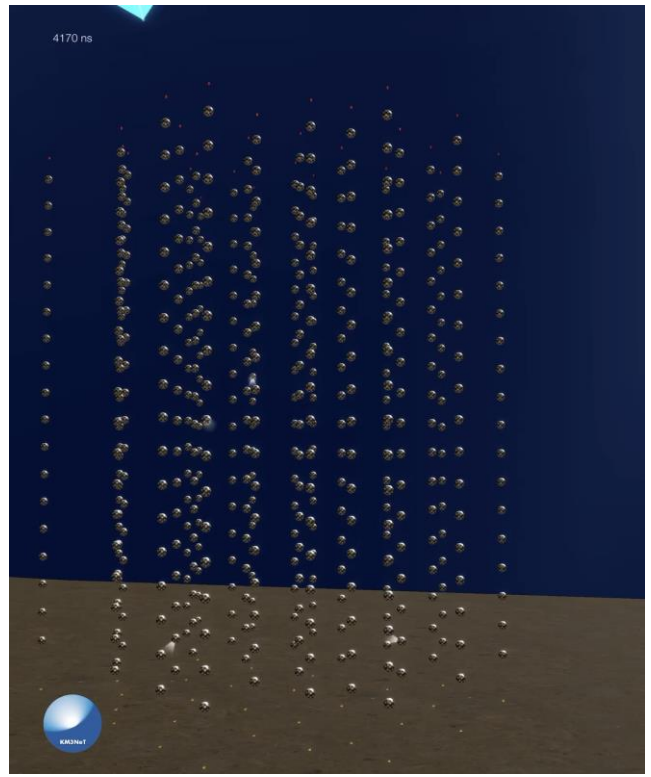
(15% of the full detector)





ARCA: 28 DUs

(12% of the full detector)



Upcoming sea campaigns:

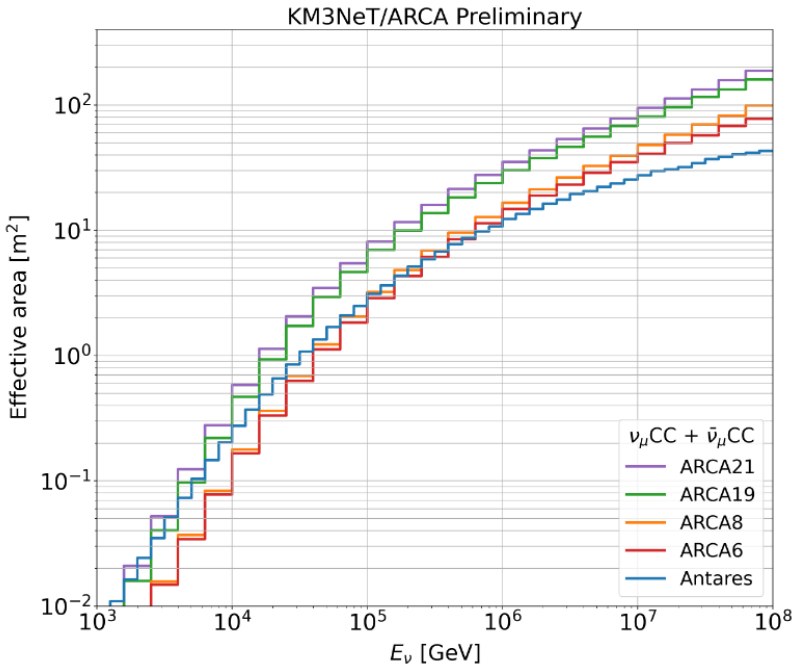
- ORCA (spring 2024):
  from 7 to 10 additional DUs
- ARCA (summer 2024):
  from 20 to 24 additional DUs

STAY TUNED!

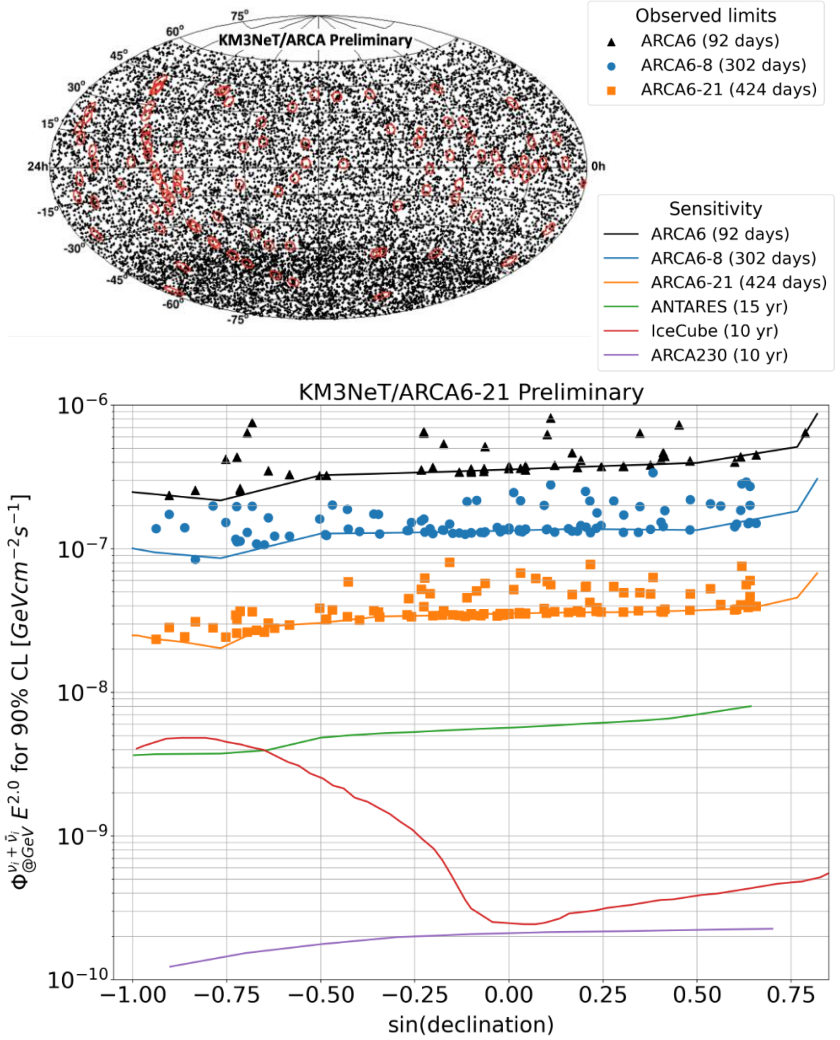
KM3NeT ARCA/ORCA
SELECTED RECENT RESULTS

Point-like sources

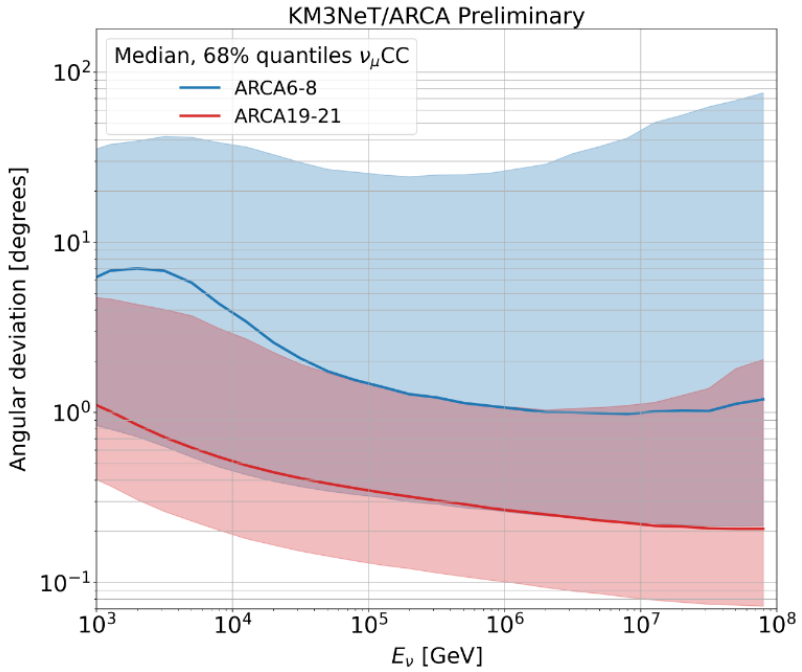
[PoS(ICRC2023)1018]



Effective area at selection level for the different ARCA detectors for a flux of $\nu_\mu + \bar{\nu}_\mu$ in the CC interaction.



Observed limits on the flux for the ARCA6-21 point source analysis assuming an E^{-2} source spectrum



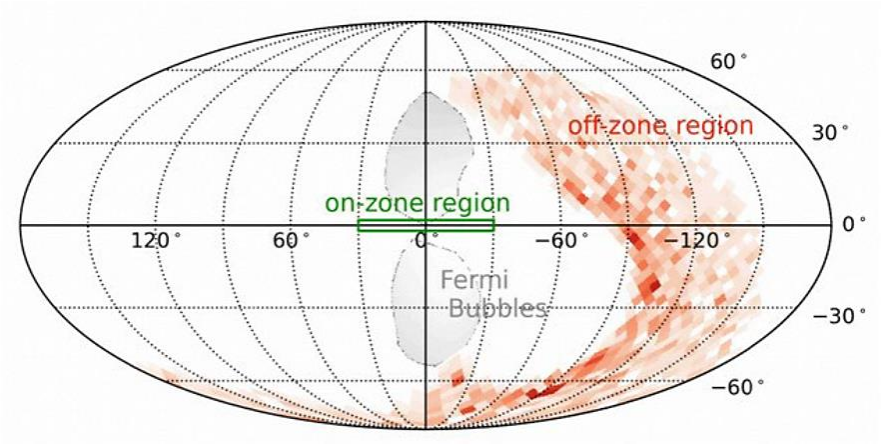
Angular deviation for the ARCA6-8 and ARCA19-21 periods

Diffuse sources

KM3NeT ICRC2023 PoS 1190

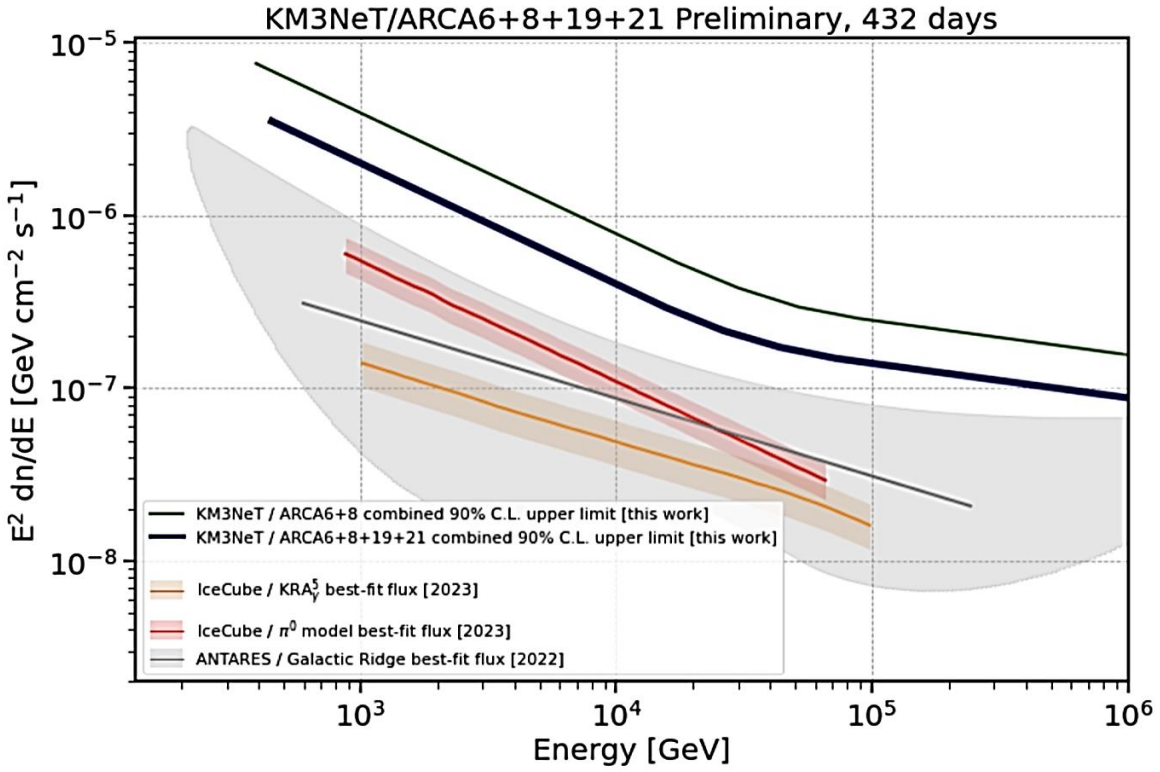
- Multiple sources of high-energy Cosmic Rays in the centre of the Milky Way
- High-energy neutrinos should be produced via interaction of CR with the interstellar medium

- ON region: the Galactic ridge |Lgal|<30°, |Bgal|< 2°
- OFF region obtained by shifting the ON region and avoiding the Fermi Bubbles



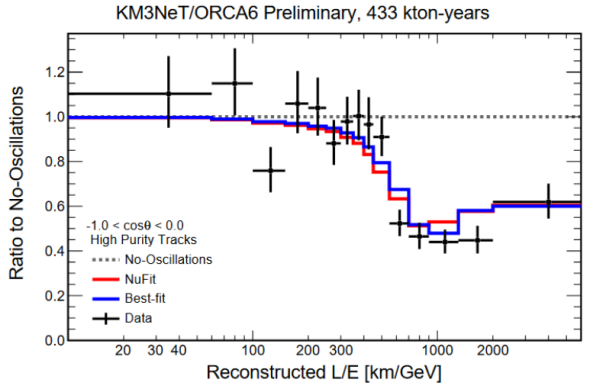
NO statistical effects found yet

ARCA6 & ARCA8 & ARCA19 fully analyzed
ARCA21 partially analyzed (until December 2022)

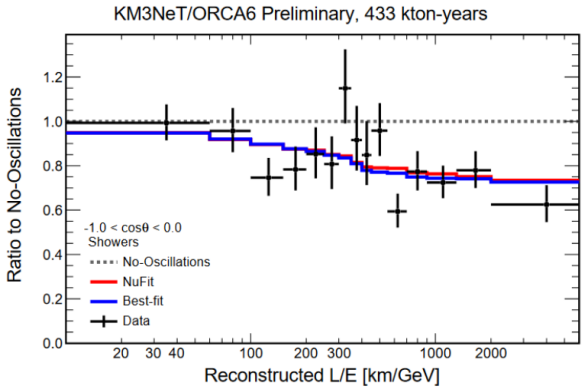


KM3NeT/ARCA6+8+19+21 combined (blue solid line) 90% C.L. upper limits to a diffuse neutrino emission from the Galactic Ridge, for a range of spectral indices $\Gamma_\nu \in [2.2, 2.7]$

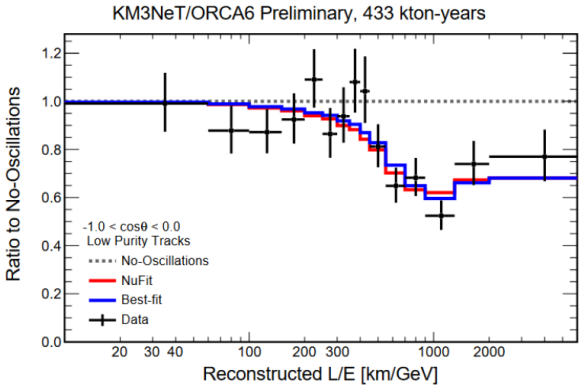
KM3NeT ORCA recent results



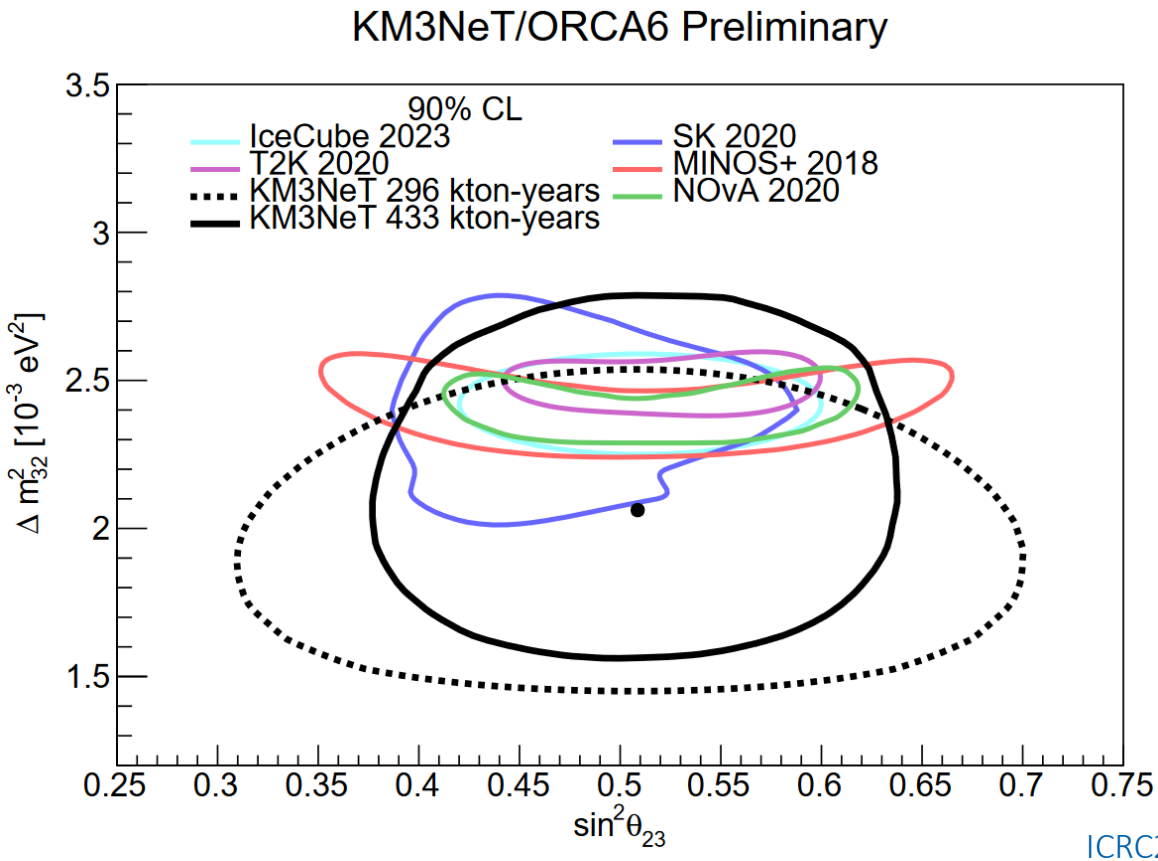
High purity tracks



Low purity tracks



Showers



ICRC2023 PoS 996

- Best-fit: $\sin^2\theta_{23} = 0.51^{+0.06}_{-0.07}$

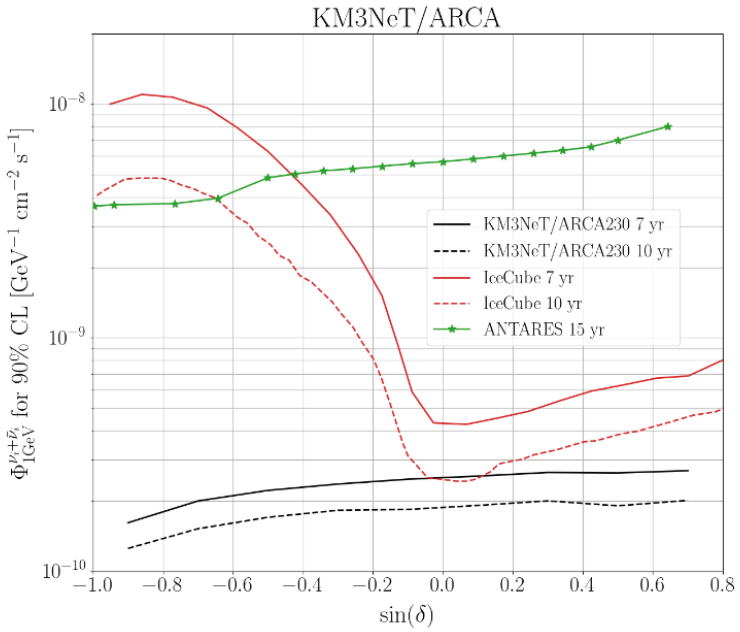
and $\Delta m^2_{32} = 2.14^{+0.36}_{-0.25} \cdot 10^{-3}\mathrm{eV}^2$.

Normal Ordering favoured at delta_chi2=0.9

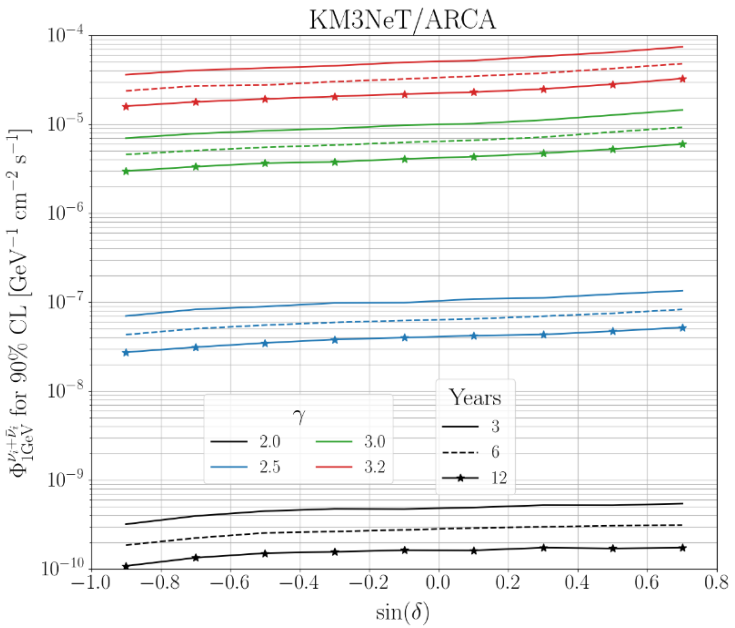
KM3NeT ARCA/ORCA
EXPECTED PERFORMANCE
FULL-DETECTOR CONFIGURATION

Point-like sources

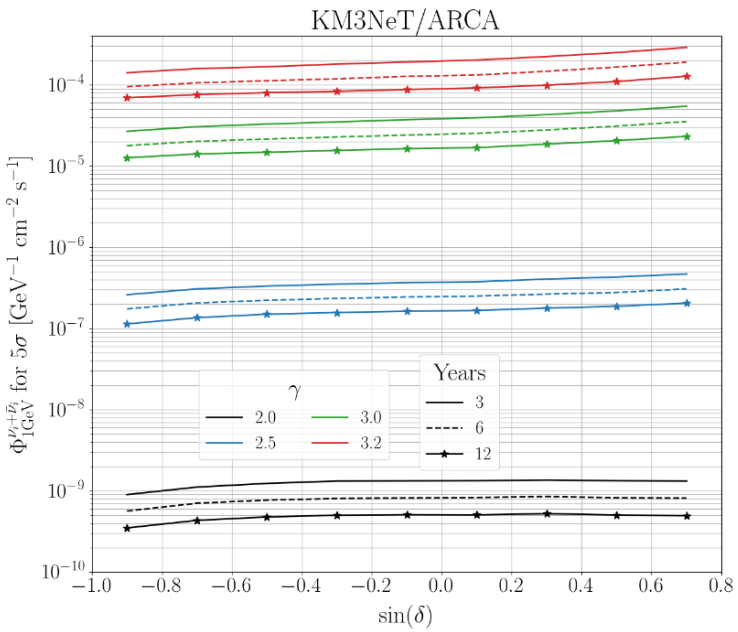
arXiv:2402.08363 - submitted to Eur. Phys. J. C



ARCA point-like source sensitivity as a function of sin(δ) for γ = 2.0



ARCA point-like source sensitivity for different γ

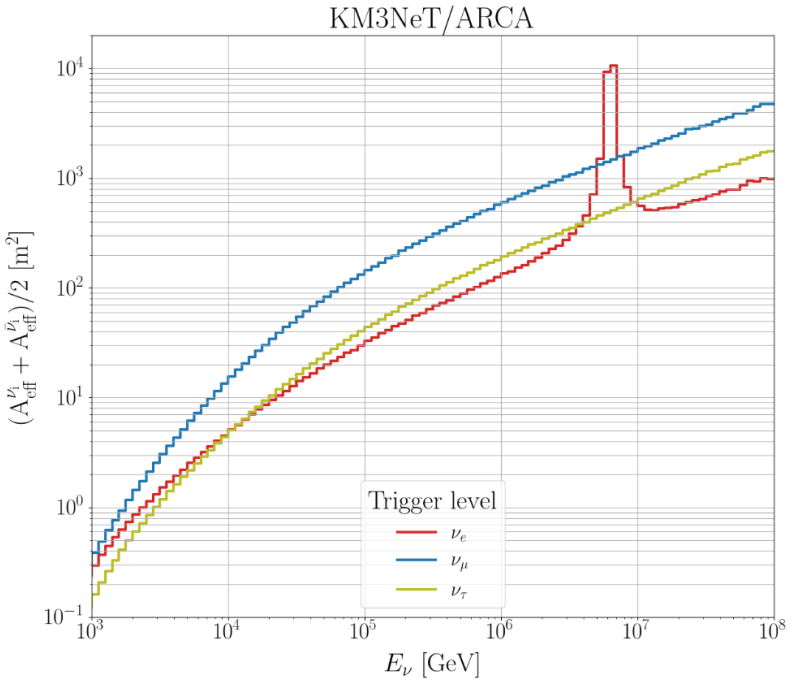


5σ discovery flux for point-like sources for different spectral indices

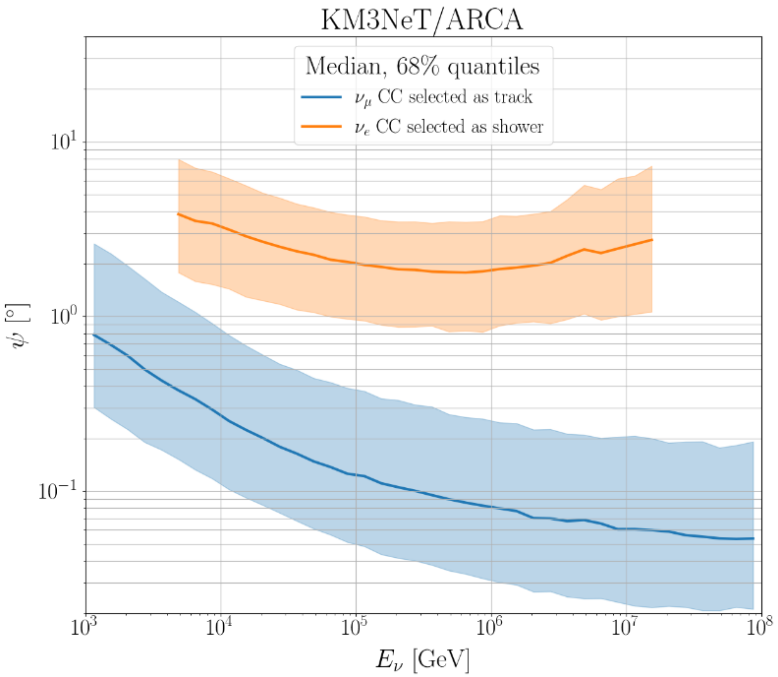
The better sensitivity of ARCA in the Southern Sky is due to the visibility of the Galactic Plane.
In the Northern Sky, the enhanced performance of ARCA is attributed to its angular resolution.

Astronomy potential

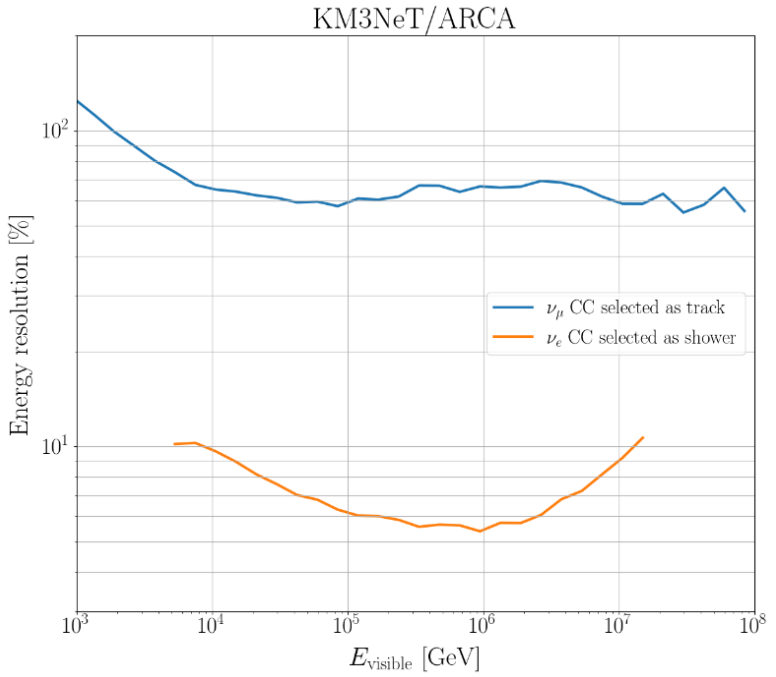
arXiv:2402.08363 - submitted to Eur. Phys. J. C



The ARCA effective area for a flux of $\nu_i + \bar{\nu}_i$ at trigger level for all neutrino flavors and interactions



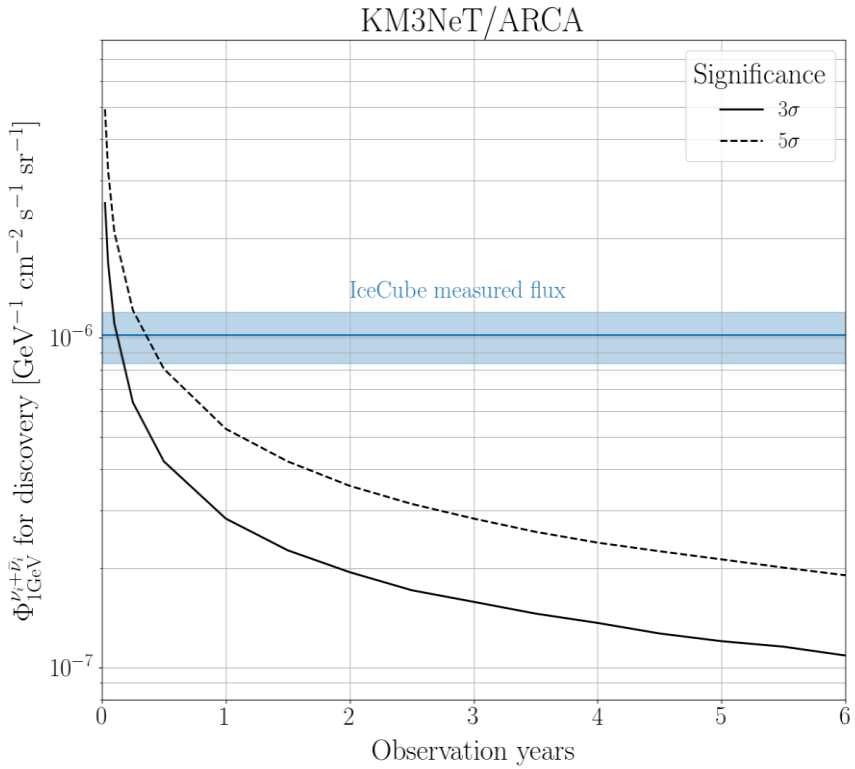
ARCA angular deviation for ν_μ CC events selected as track and for ν_e CC events selected as shower.



ARCA energy resolution for ν_μ CC events selected as track and for ν_e CC events selected as shower.

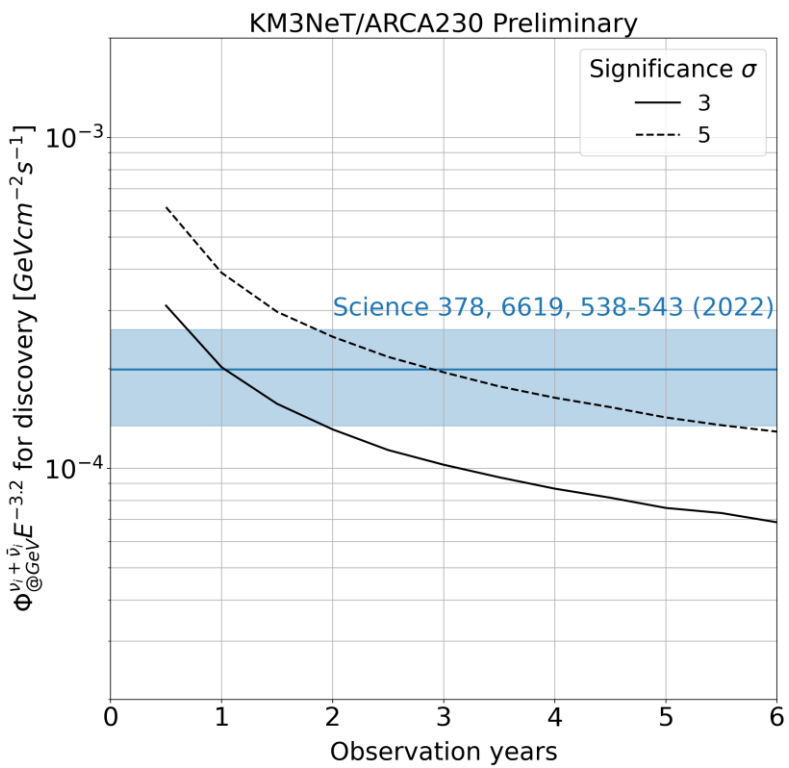
Expected sensitivities

Diffuse flux



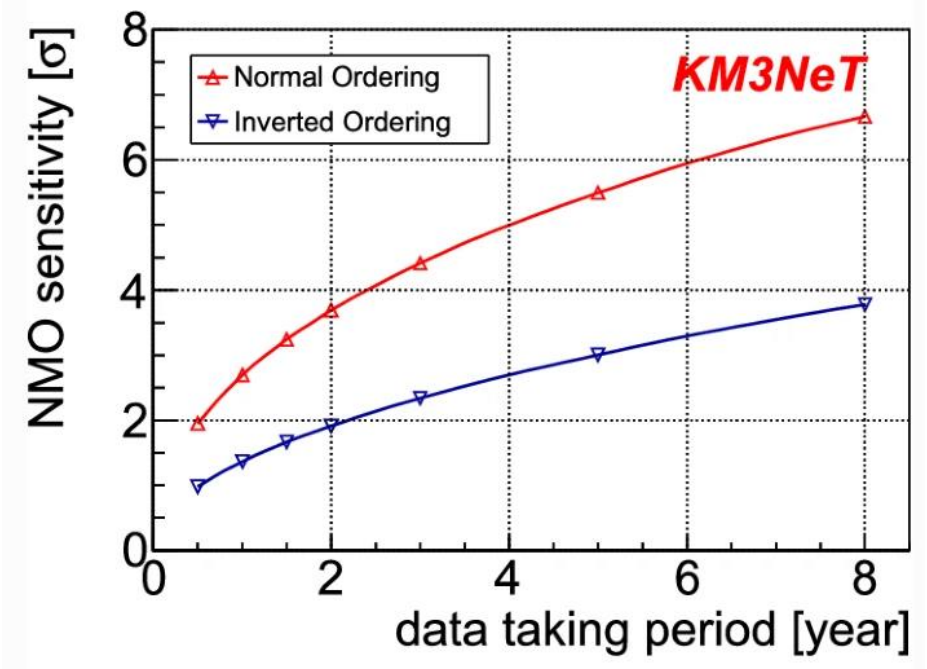
5σ in ~ 0.5 year for the full detector (230 DUs)

NGC1068



3σ in one year

NMO sensitivity

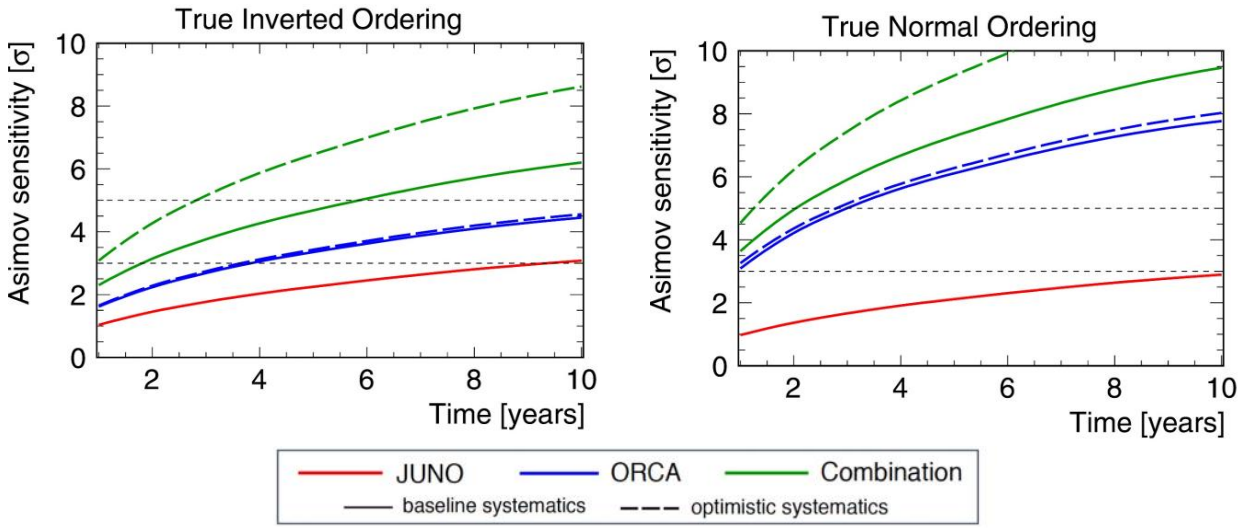


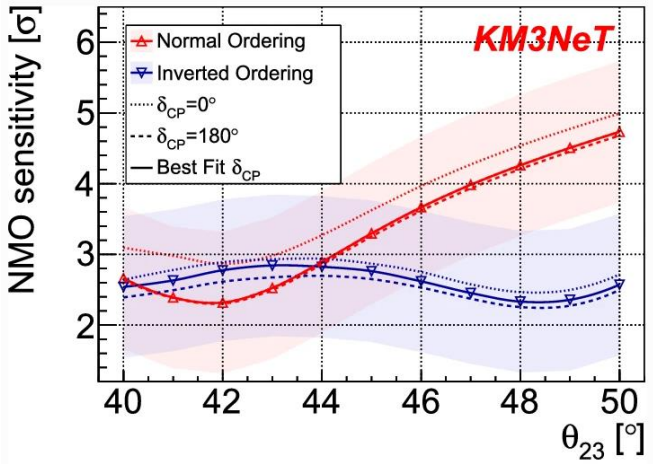
After 3 years of data taking with the full ORCA detector:

- expected sensitivity for neutrino mass hierarchy 4.4σ (NO) and 2.3σ (IO)
- competitive measurements for Δm^2_{32} and θ_{23}

Exploiting synergies with reactor experiments can boost the measurement

📖 J. High Energ. Phys. 2022, 55 (2022)





Sensitivity to NMO after 3 years of data taking, as a function of the true θ_{23} value

Earth matter affects the oscillation pattern depending on NMO

📖 Eur. Phys. J. C 82, 26 (2022)

SUMMARY

KM3NeT is building two deep-sea underwater neutrino telescopes in the Mediterranean Sea: **KM3NeT/ORCA** (Toulon, France) and **KM3NeT/ARCA** (Capo Passero, Italy)

- ✓ Rich combined neutrino physics and astrophysics scientific program, ranging from MeV to PeV energies
- ✓ Good angular resolution + Galactic center visibility → precision multi-flavour astronomy
  - the diffuse flux observed by IceCube will be observed, by the full ARCA detector, with 5σ significance in less than one year
  - sensitivity to astrophysical sources in the Southern Hemisphere will be improved by a factor 2
  - multi-messenger program

KM3NeT is taking data and growing rapidly:

- ✓ 46 Detection Units are currently deployed (28 in ARCA, 18 in ORCA)
- ✓ First measurement of neutrino oscillation parameters
- ✓ Succesful measurements of μ, ν fluxes
- ✓ Upper limits quickly reaching the ANTARES limits

KM3NeT

THANKS FOR THE ATTENTION!

BACKUP SLIDES

Event type and angular resolution

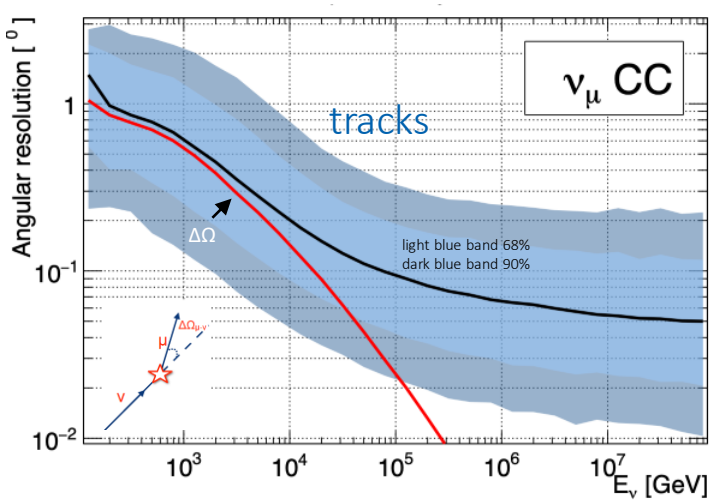
	TRACK*	CASCADE*
ANTARES	0.3°	3°
KM3NET	0.1°	1.5°
ICECUBE	0.3°	7°-8°
BAIKAL-GVD	0.25°	3° - 3.5°

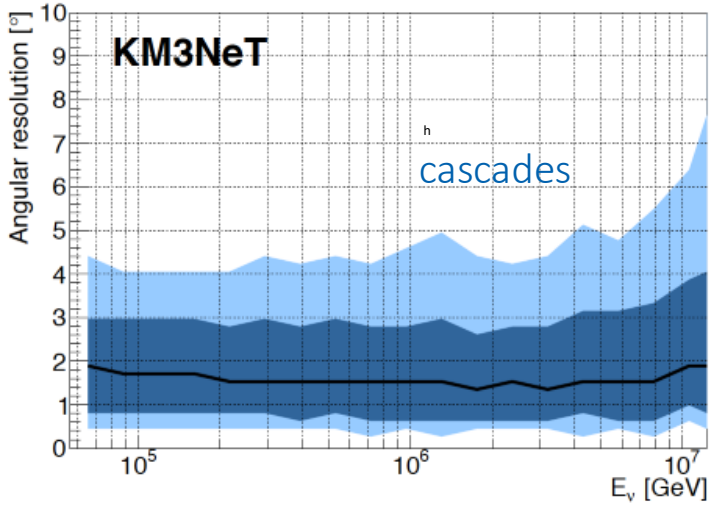
*Resolution at 100 TeV

Tracks: very long path (E_μ>1TeV several km)
Big lever arm
- Good angular resolution

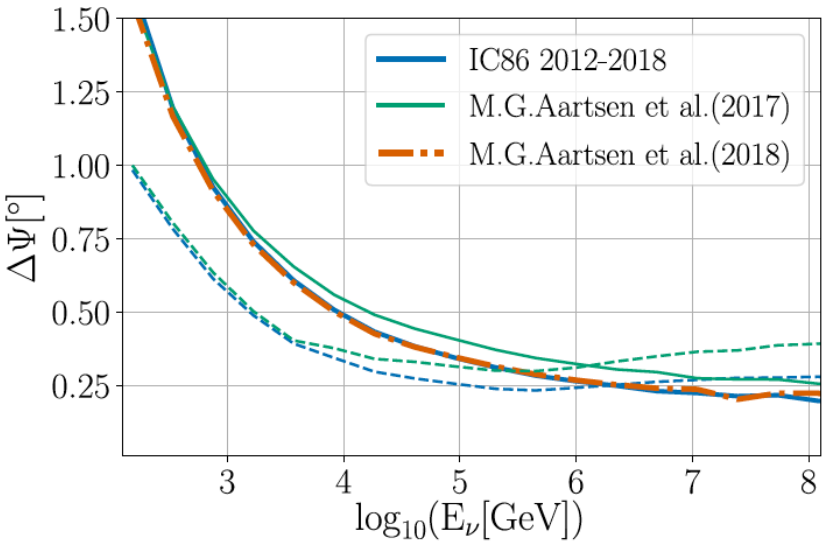
Cascades: small path (E_{casc} >1TeV some tens of meters)
- Modest angular resolution

KM3NeT





IC resolution for tracks
from arXiv:1910.08488, 15 October 2019



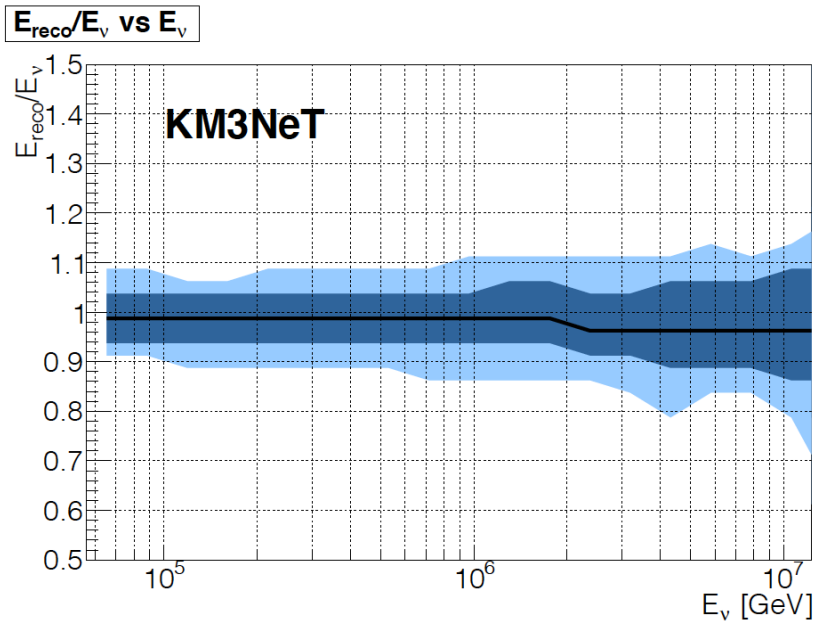
Event type and energy resolution

	TRACK*	CASCADE
ANTARES	35%	5%
KM3NET	27%	5%
ICECUBE	30%	10%
BAIKAL - GVD		

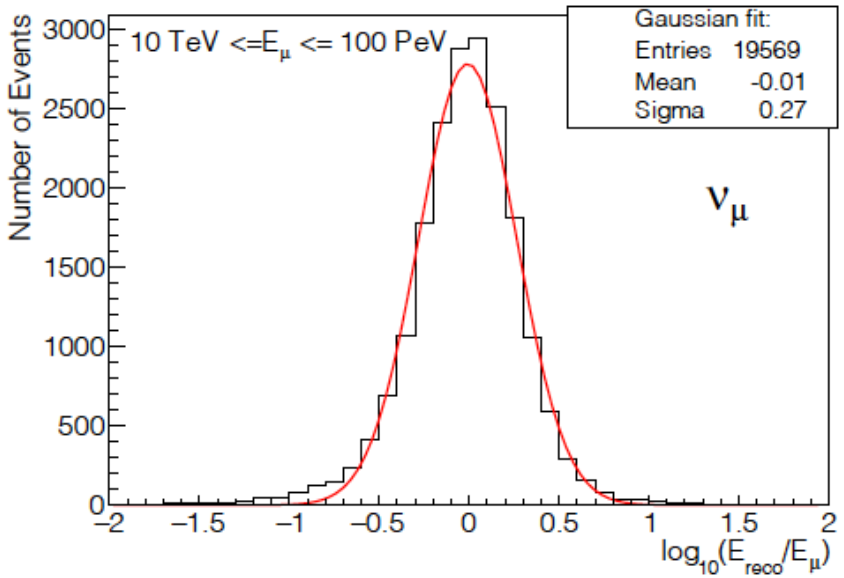
*in Log(E)

Tracks: very long path (E_μ>1TeV several km)
Neutrino interaction vertex far from the detector
Modest energy resolution

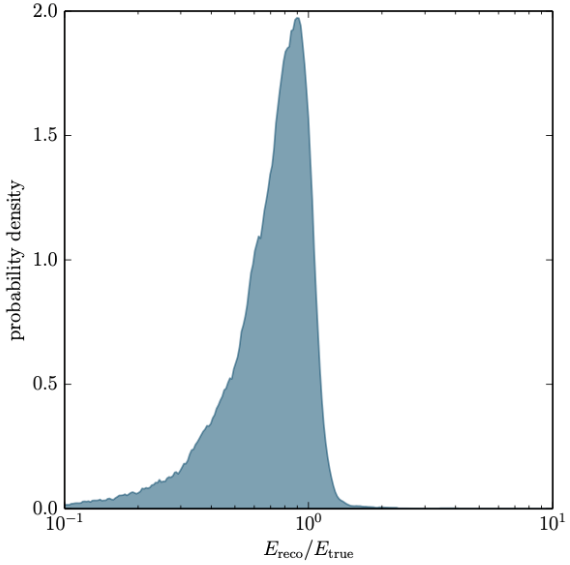
Cascades: small path (E_{casc} >1TeV some tens of meters)
All the energy released inside the detector
Good energy resolution



KM3NeT



IC resolution for cascades
from ArXiv:1705.02383

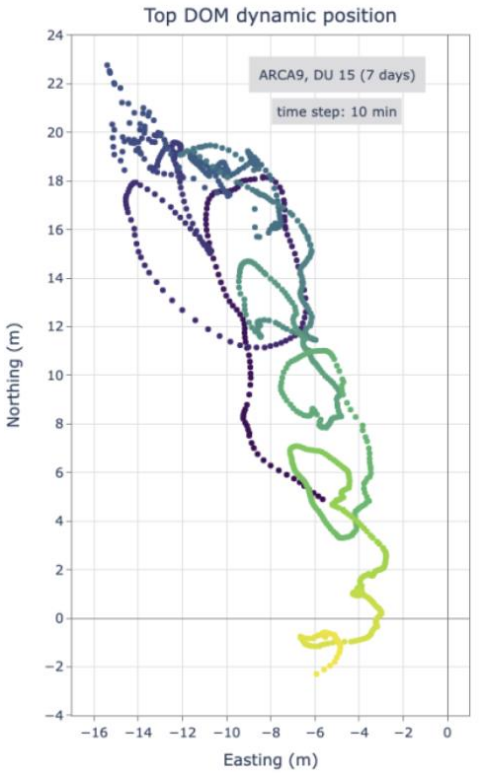


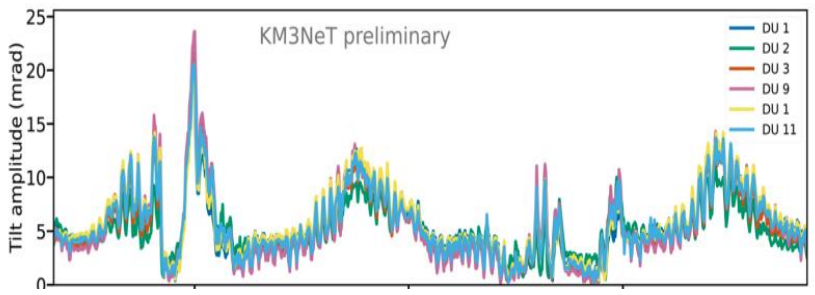
Detector calibration

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

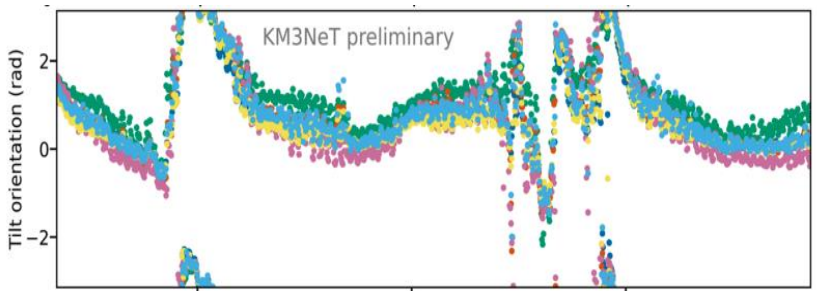
- Position calibration
  - Acoustic positioning system:
    - Receivers are located in each DOM (Piezo-electric acoustic sensors)
    - Emitters are located in autonomous tripods, Junction Boxes and some DUs
  - Tilt and heading in each DOM via tiltmeter and compass
  - → Precision better than 10 cm

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

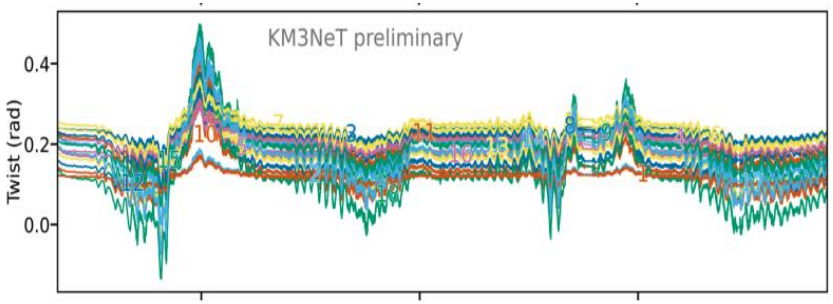




DU tilt



Tilt orientation



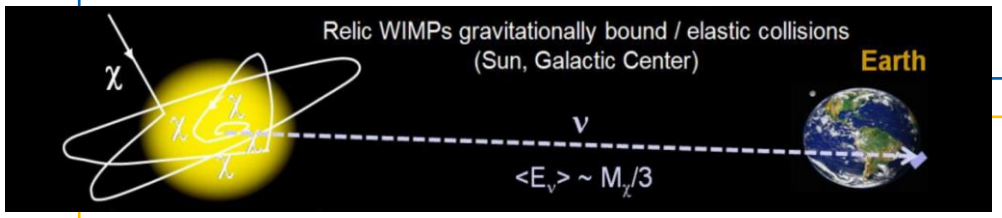
Twist

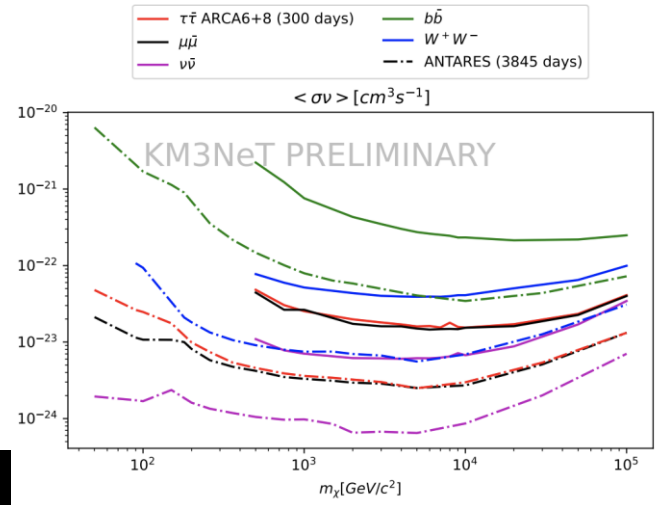
Dark matter studies

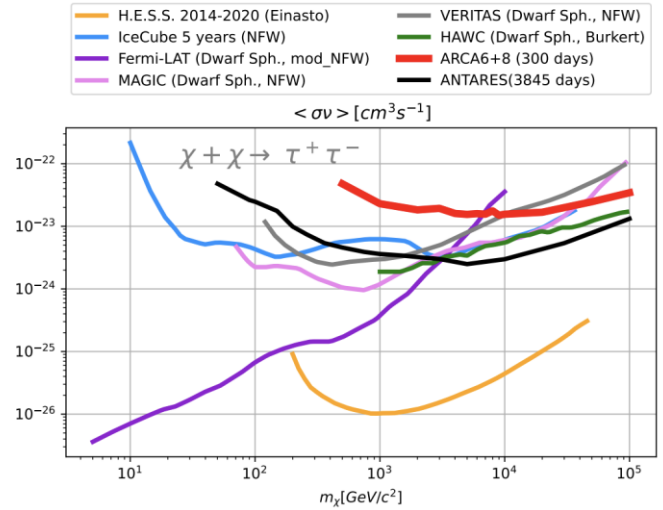
From the Galactic Center

(ARCA6 + ARCA8)

ICRC2023 PoS 1377



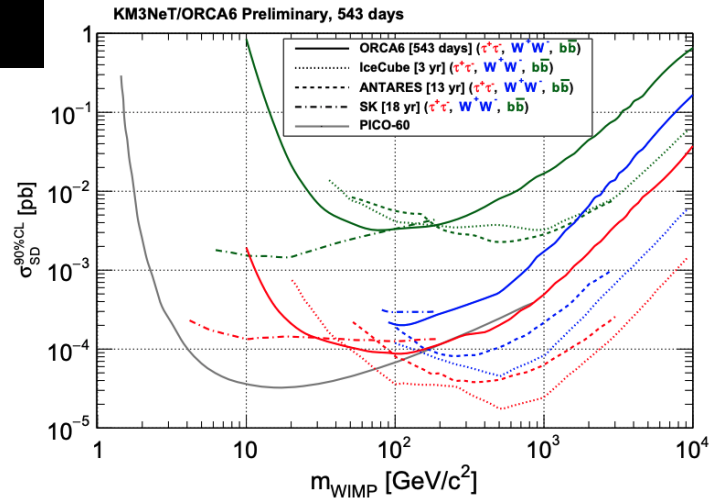


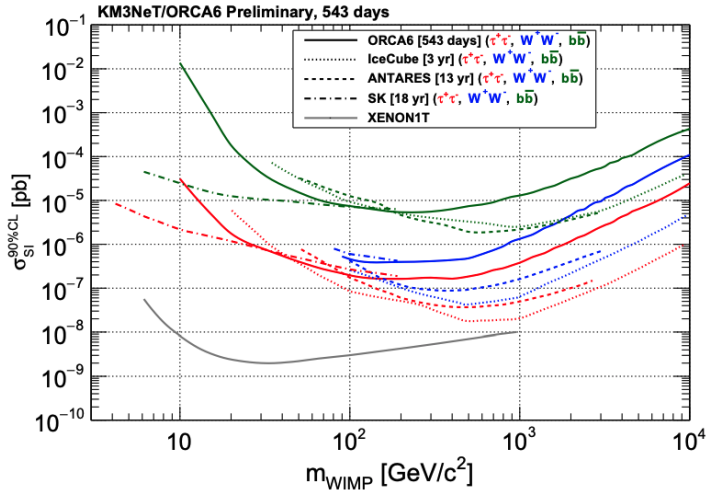


From the Sun

(ORCA6)

ICRC2023 PoS 1406



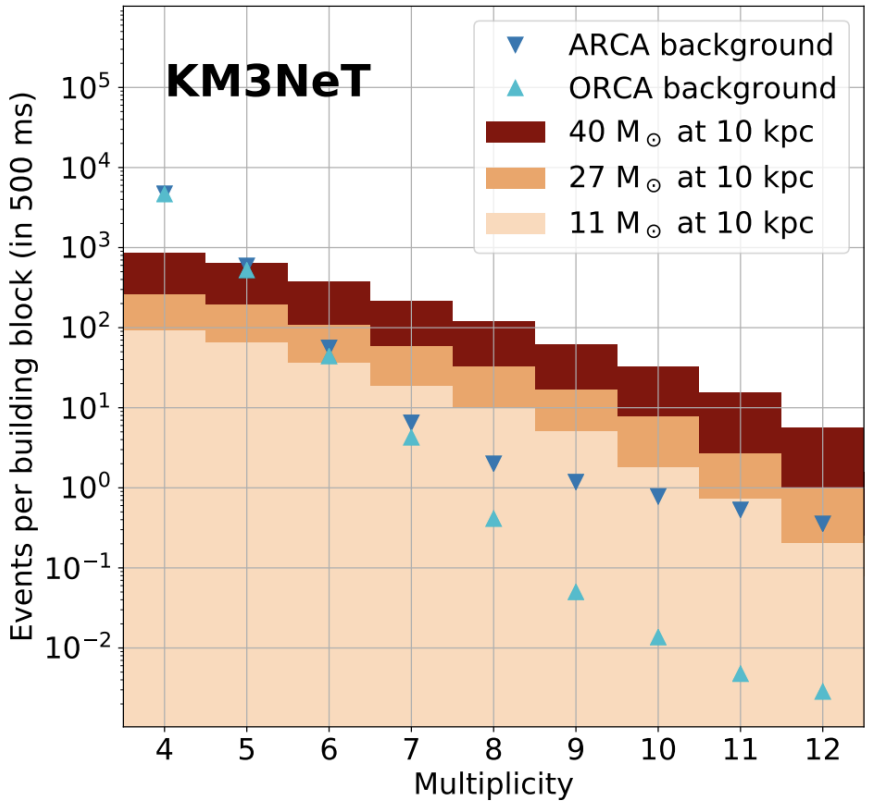


Supernova studies

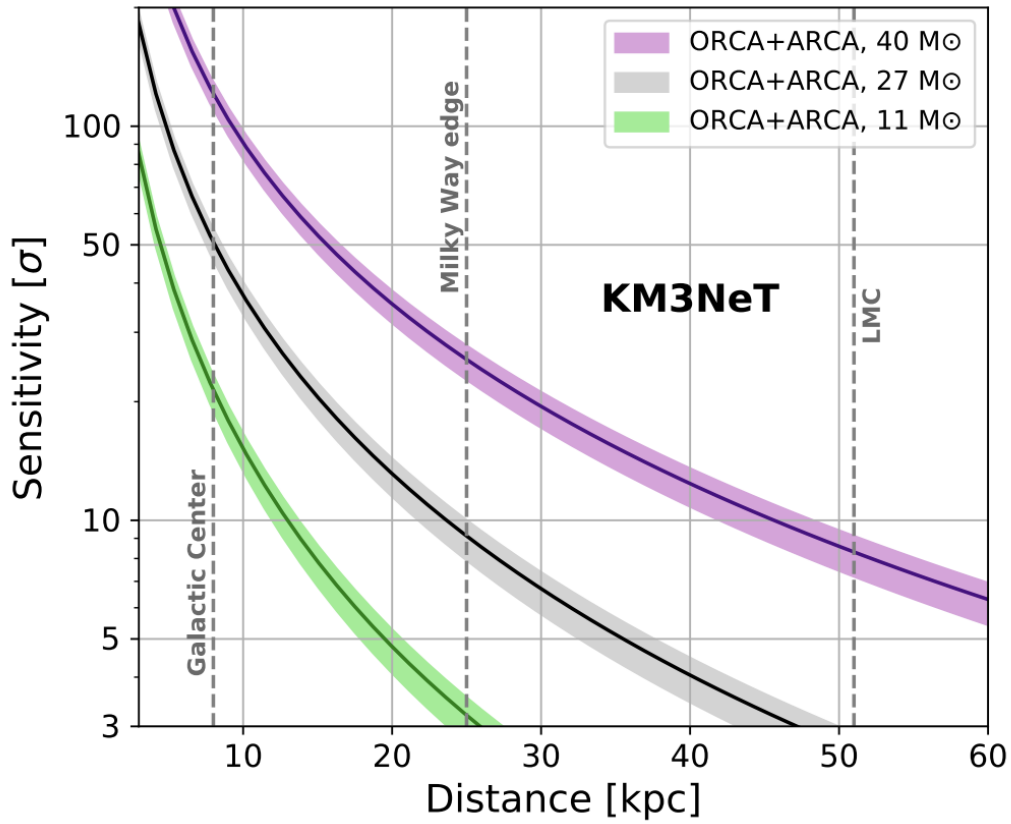
- Neutrinos with E<100 MeV expected at several stages of core collapse
- Low-energy neutrino detection is based on the coincidences in single DOMs, thanks to the multi-PMT DOM configuration
- Background from 40K decays, atmospheric muons and muons from ν.

PMT multiplicity plot

Eur. Phys. J. C 81, 445 (2021)



>5σ for ARCA+ORCA for 27M⊙ at a distance <35kpc



Real-time multi-messenger program

Goals:

- Trigger neutrino alerts to the astronomy community
- look for time/space coincidence around external electromagnetic and multi-messenger triggers

Based on:

- Fast online reconstruction
- Fast selection of high-purity neutrino sample

The event processing is done separately for ORCA and ARCA at each store station

Same processing structure but different software architectures, based on two different pipelines:

1. The MeV CCSN monitoring pipeline (ORCA)
2. The GeV-PeV neutrino alert pipeline (ARCA)

Data from each detector are transferred to a common dispatcher (MM dispatcher), where analysis pipelines are also activated