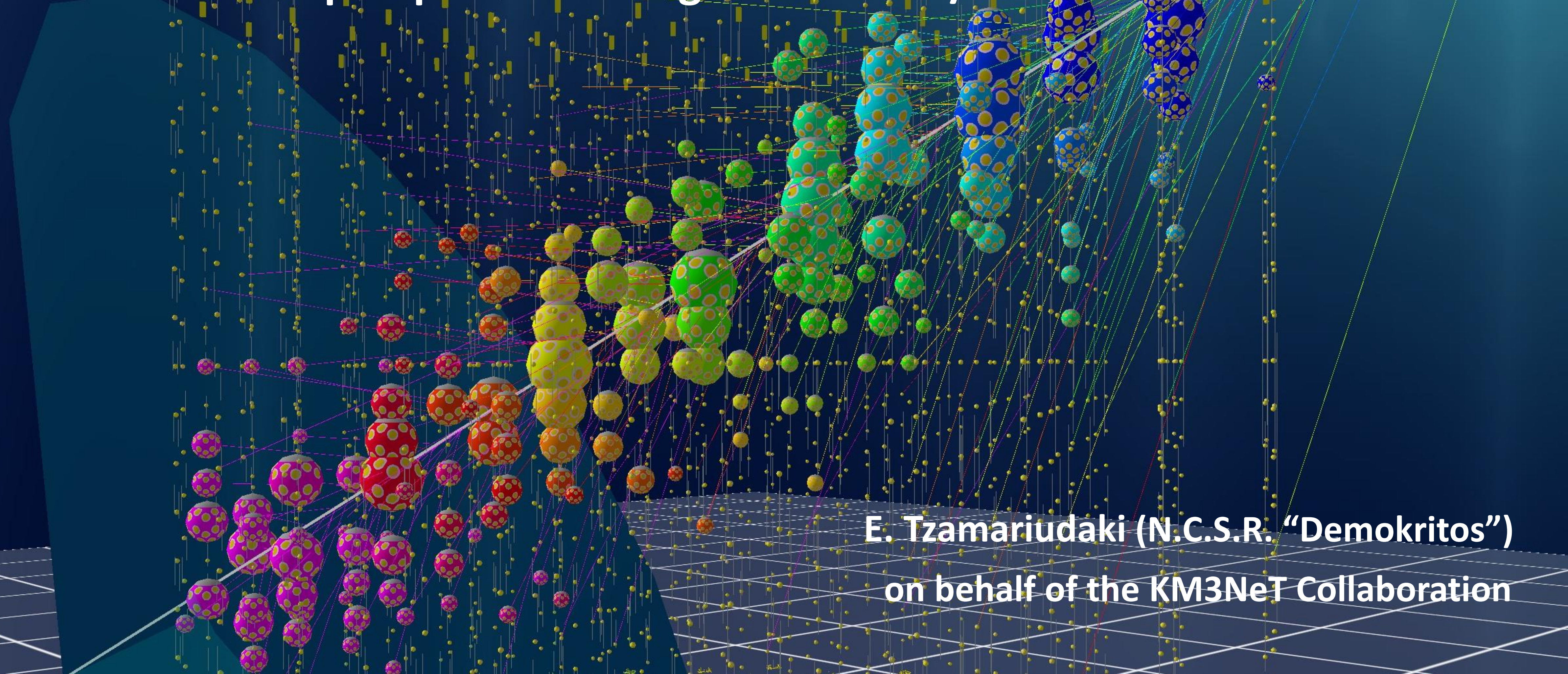
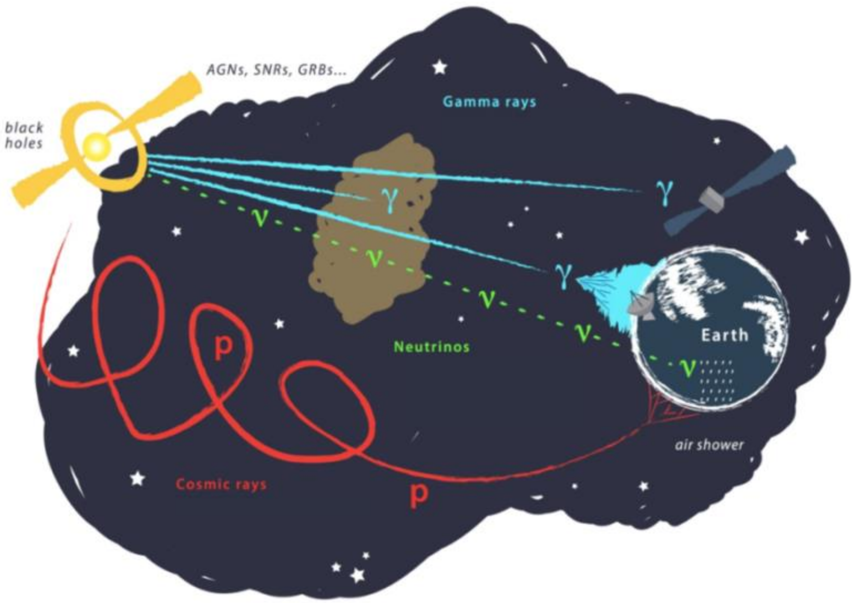
22nd Conference on Flavor Physics and CP Violation (FPCP2024)
May 27 – 31, 2024

The KM3NeT neutrino telescopes in the Mediterranean Sea: Current status and prospects focusing on KM3NeT/ORCA



E. Tzamariudaki (N.C.S.R. “Demokritos”)
on behalf of the KM3NeT Collaboration

Science Objectives: Astroparticle



Explore the High Energy Universe

Current knowledge about the Universe comes mostly from photons and cosmic rays

neutrinos: unique messengers

- no interactions with ambient matter or radiation
- no deflection by magnetic fields
- information on the internal processes of the astrophysical sources inaccessible through photons or cosmic rays

neutrinos: probe of fundamental processes

- origin of UHE cosmic rays
- production mechanism of HE gamma-rays (hadronic / leptonic)

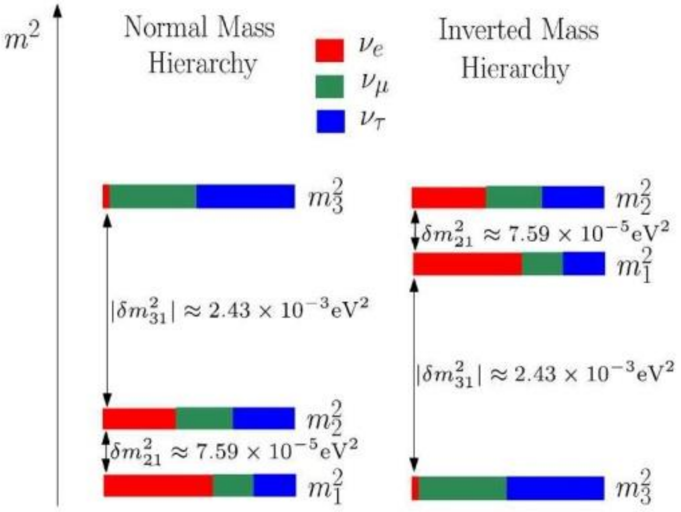
High-energy neutrino production via

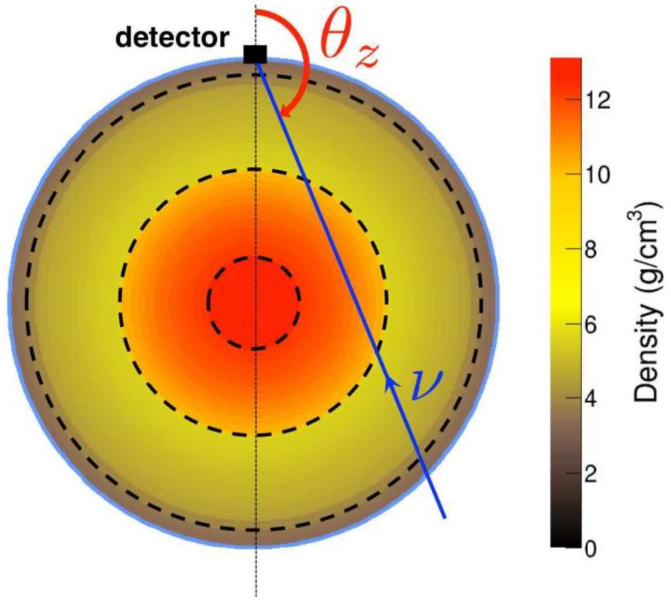
$$p + p/\gamma \rightarrow X + \pi^0 \rightarrow \gamma\gamma$$
$$\rightarrow X + \pi^\pm \rightarrow \mu^\pm + \overset{(-)}{\nu}_\mu$$
$$\mu^\pm \rightarrow e^\pm + \overset{(-)}{\nu}_e + \overset{(-)}{\nu}_\mu$$

Correlations between HE photons and neutrinos, ‘Smoking gun’ for hadronic processes

KM3NeT/ARCA for Neutrino Astronomy

Science Objectives: Study atmospheric neutrino oscillations





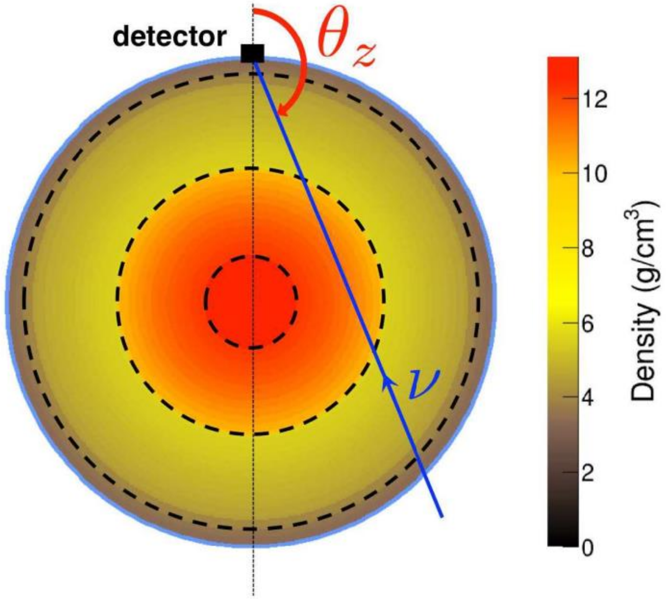
KM3NeT/ORCA

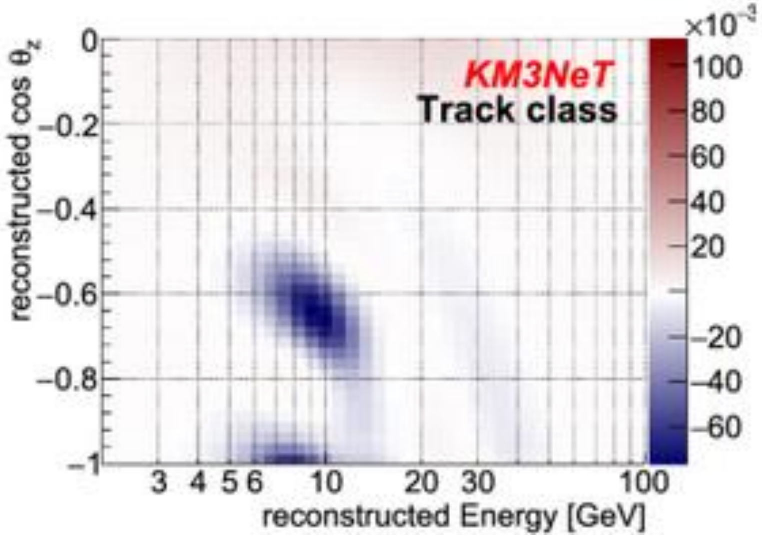
Neutrino properties through atmospheric neutrino oscillation studies

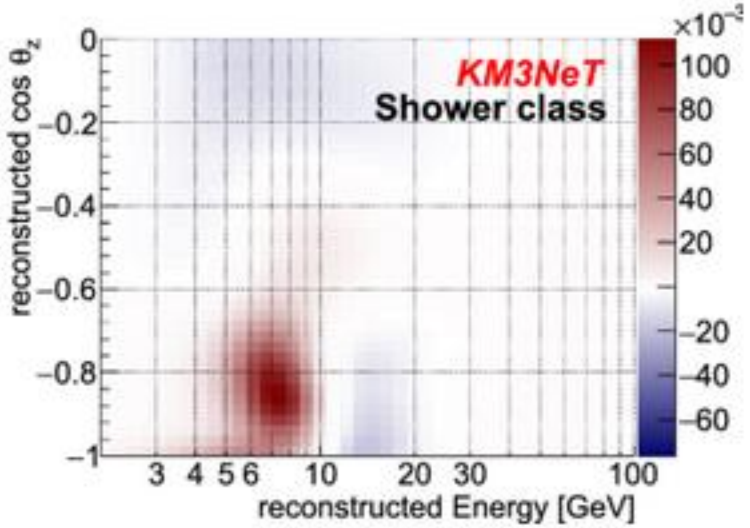
- neutrino mass ordering
- measure oscillation parameters
- New physics (sterile neutrinos, NSI & other)

Science Objectives: Study atmospheric neutrino oscillations

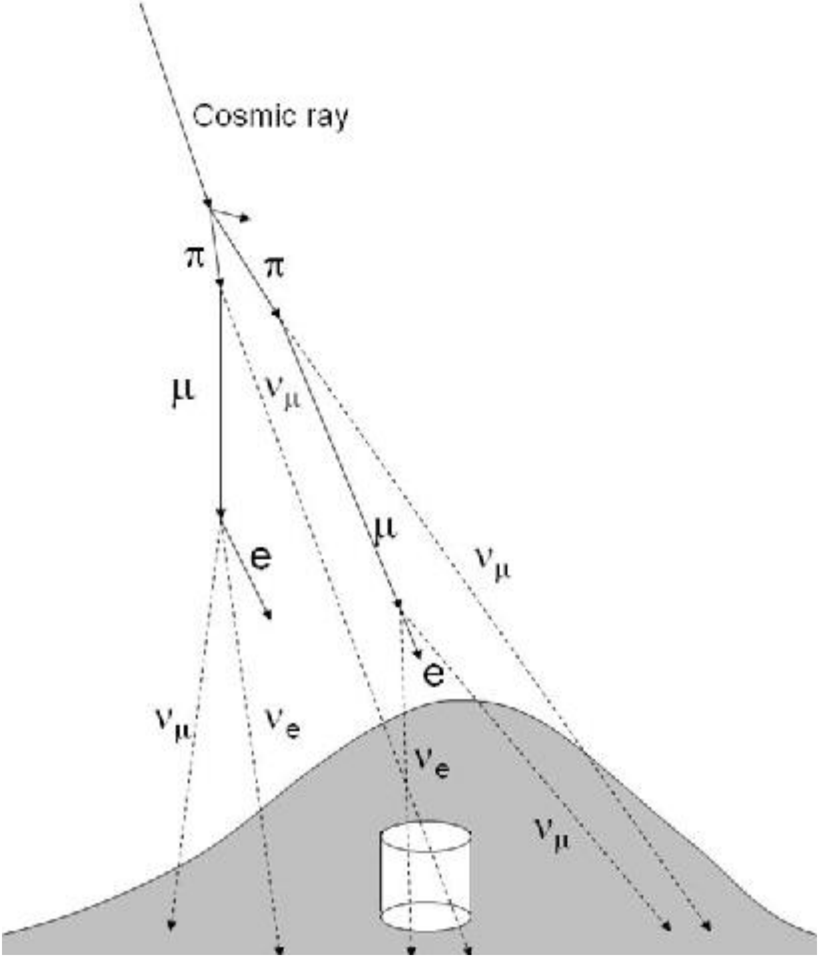
- Study atmospheric neutrino oscillations (few GeV energy regime)
- Oscillation pattern distorted by Earth matter effects leading to an enhancement of the $\nu_\mu/\bar{\nu}_\mu \leftrightarrow \nu_e/\bar{\nu}_e$ transition. Largest effects for ~7 GeV neutrinos passing through the Earth mantle. Allows for determination of mass ordering because of different behaviour of neutrinos/antineutrinos
- KM3NeT: no event-by-event $\nu/\bar{\nu}$ separation, but event rates affected by differences in flux/kinematics/cross-section



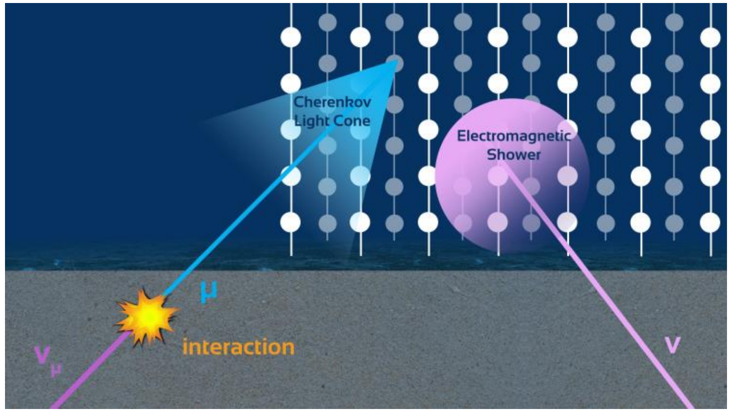




Neutrino telescopes: Detection principle

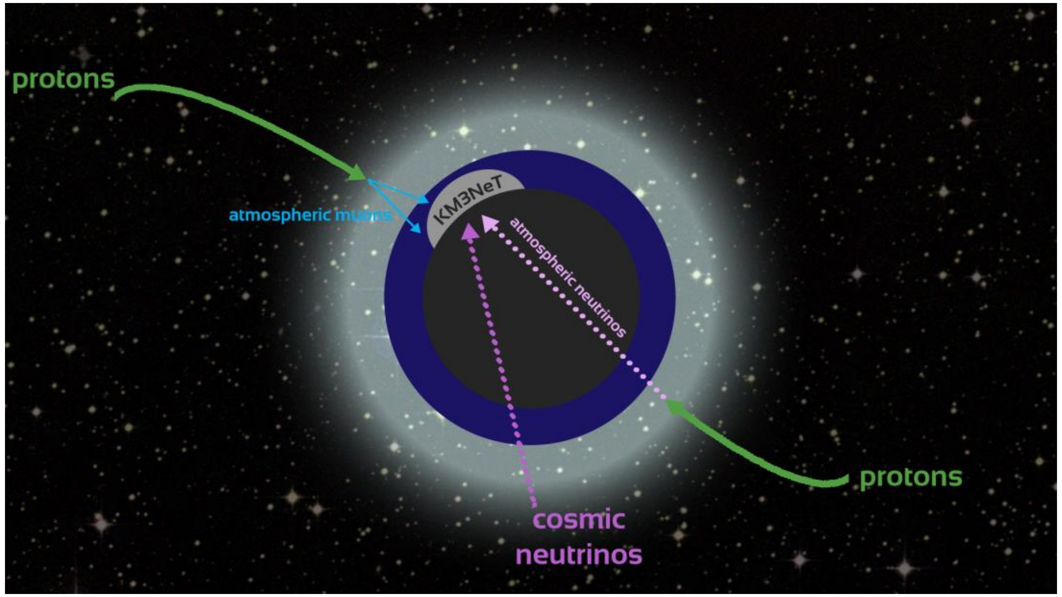


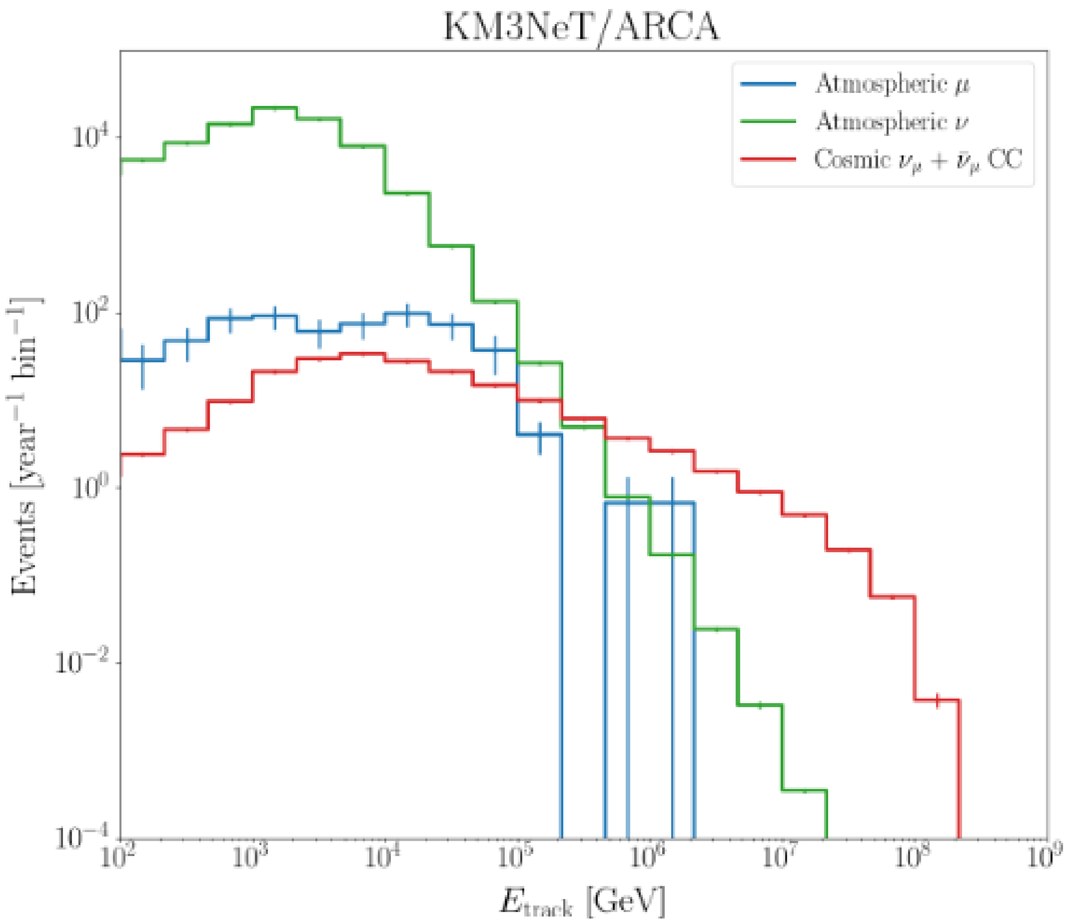
- Upward-going neutrinos interact in rock or water
- charged particles (in particular muons) produce Cherenkov light in water at 43° with respect to the neutrino direction
- light is detected by array of photomultipliers
- muon direction is reconstructed using PMT positions and photon arrival times



cosmic ray interactions in the atmosphere produce $\pi^{\pm}$ and $K^{\pm}$ whose decays produce neutrinos and muons

Neutrino telescopes: Signal and background sources





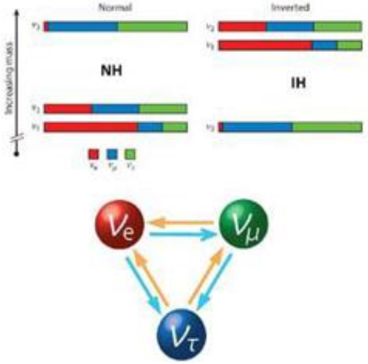
Suppress atmospheric muons: selection of up-going events as the Earth provides screening against all particles except neutrinos

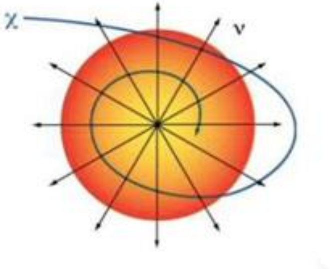
<u>noise:</u> background from ^{40}K decays and from bioluminescence (life forms in the deep sea emitting light)

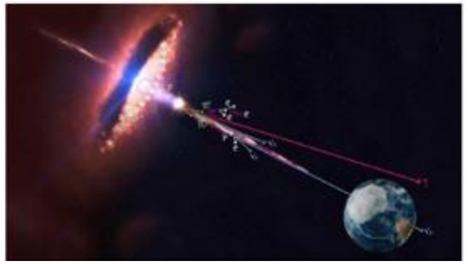
e-Print: 2402.08363 astro-ph.HE

Science Objectives: from MeV to PeV neutrinos

MeV	GeV	TeV	PeV
Supernova explosions Solar Flares	Neutrino oscillations Neutrino mass hierarchy	Dark matter Exotic searches	Cosmic neutrinos Multi-messenger astronomy



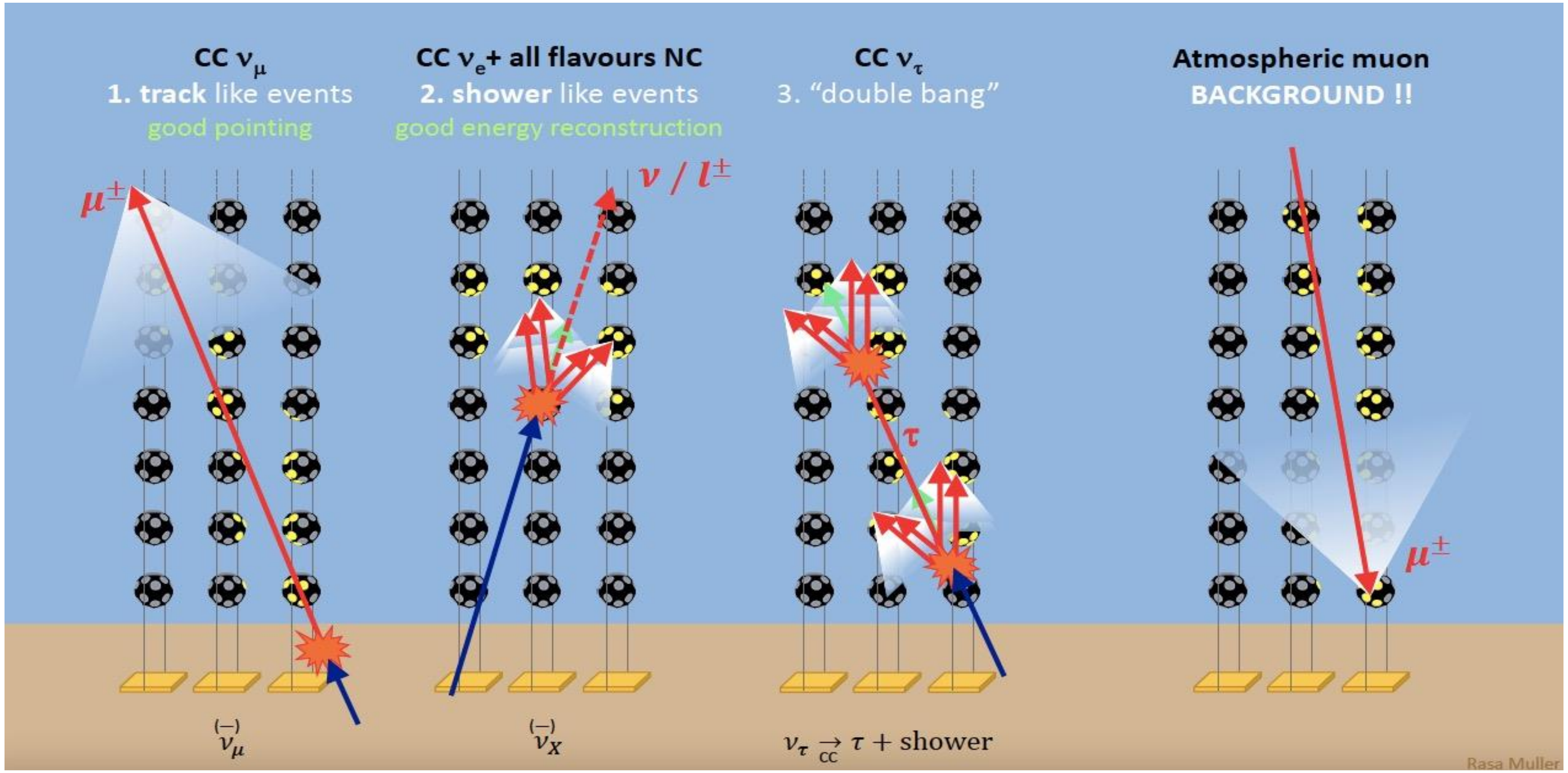


KM3NeT/ORCA ⟷ KM3NeT/ARCA

Direction and energy resolution are of primary importance

Neutrino telescopes and detection principle

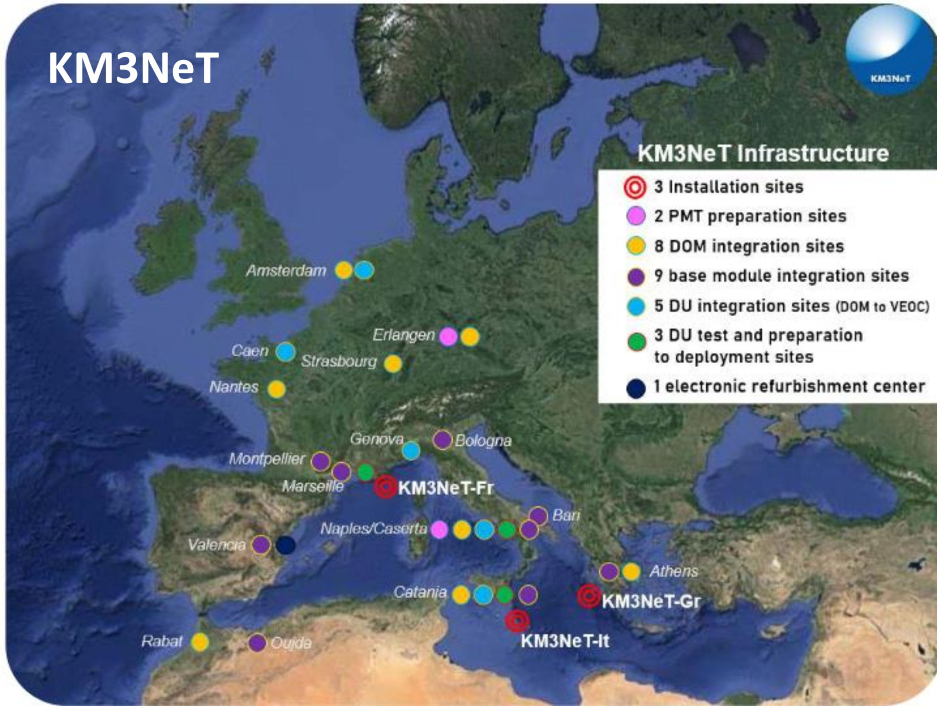
Cherenkov light emitted by charged particles produced when neutrinos interact



- Large volume detectors
- Deployment at great depth to reduce background from muons produced by cosmic ray interactions

❑ down-going: dominated by atmospheric muons
❑ up-going: atmospheric ν and astrophysical ν

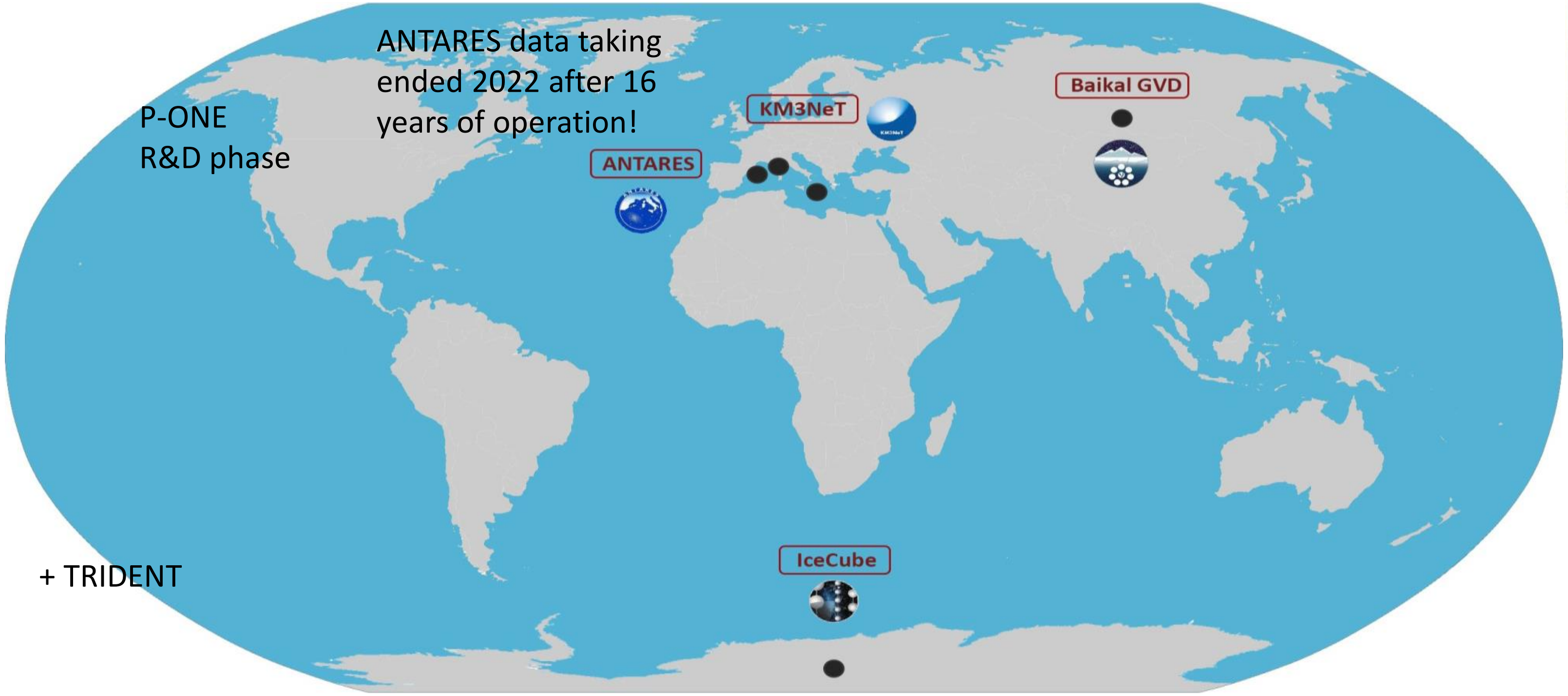
Neutrino telescopes



Neutrino telescopes around the world

ANTARES data taking ended 2022 after 16 years of operation!

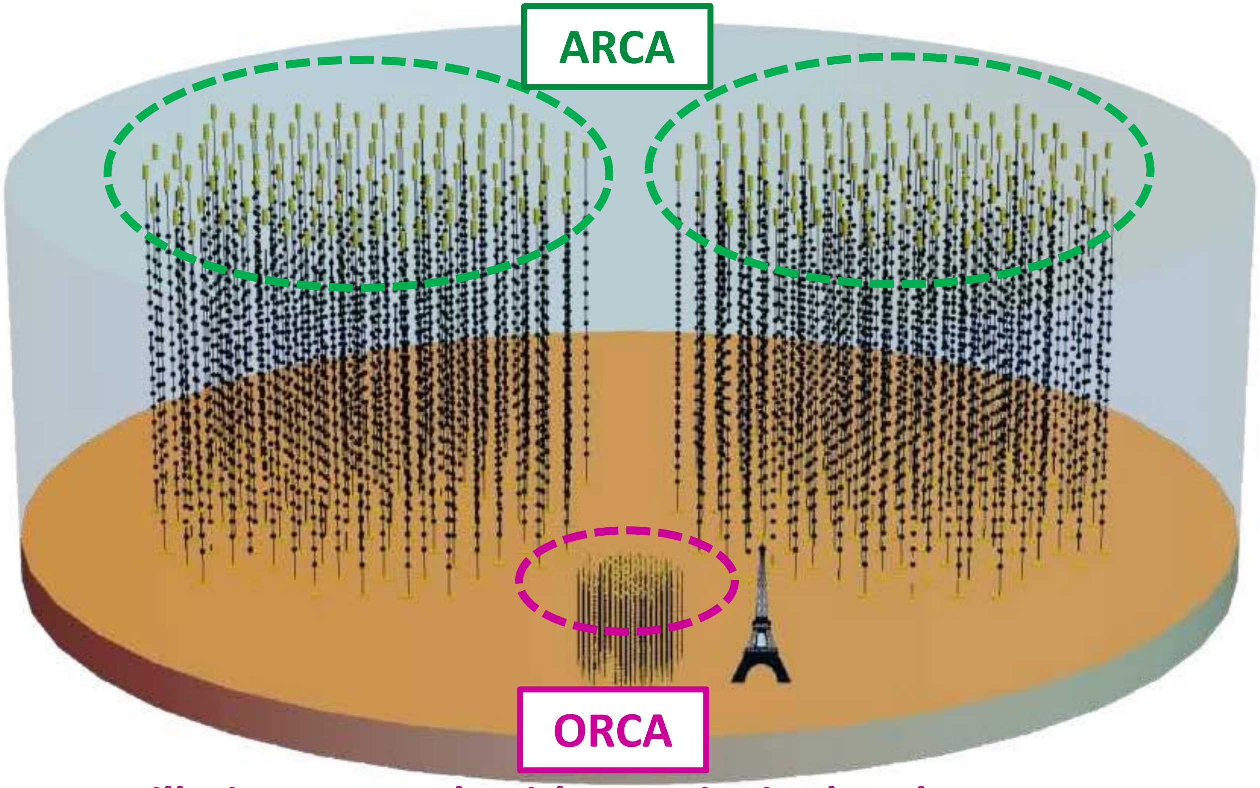
P-ONE
R&D phase



+ TRIDENT

The KM3NeT detectors

Astroparticle Research with Cosmics in the Abyss



Oscillation Research with Cosmics in the Abyss

ARCA ✓ **Currently 28 DUs deployed**

ORCA ✓ **Currently 18 DUs deployed**

ARCA:

- ✓ KM3NeT-It site; 3400 m; Capo Passero, Italy.
- ✓ Astrophysical Neutrinos (TeV-PeV Energies).
- ✓ 2 blocks of 115 DUs each: Volume (0.5 * 2) km^3
- ✓ Each DU is ~ 700 m in height, with 18 DOMs 36 m vertically spaced; DU horizontal spacing ~ 90 m.
- ✓ Sparsely instrumented.

ORCA:

- ✓ KM3NeT-Fr site; 2475 m; Toulon, France.
- ✓ Atmospheric neutrinos (GeV Energies).
- ✓ 1 block of 115 DUs : Volume ≈ 7 Mton.
- ✓ DUs are 200 m in height with 18 DOMs vertically spaced by ~ 9 m. DU horizontal spacing ~ 20 m.
- ✓ More densely instrumented.

The KM3NeT technology

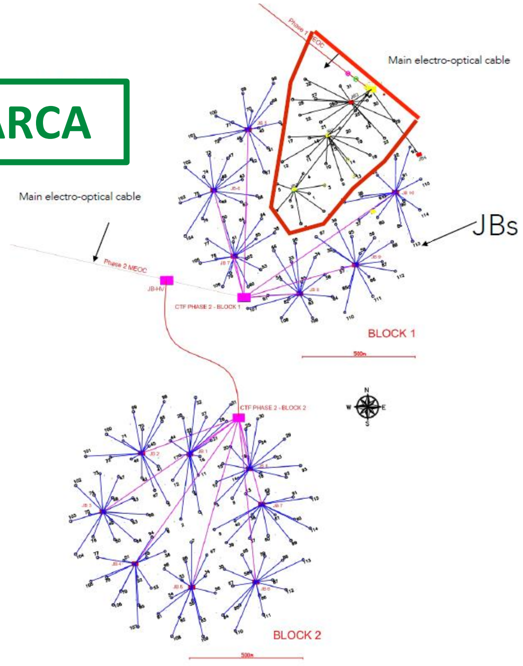
The Digital Optical Module (DOM)

31 3” PMTs

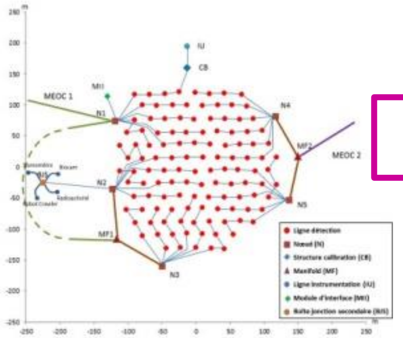
JINST 17 (2022) 07, (P07038)

The detector footprints

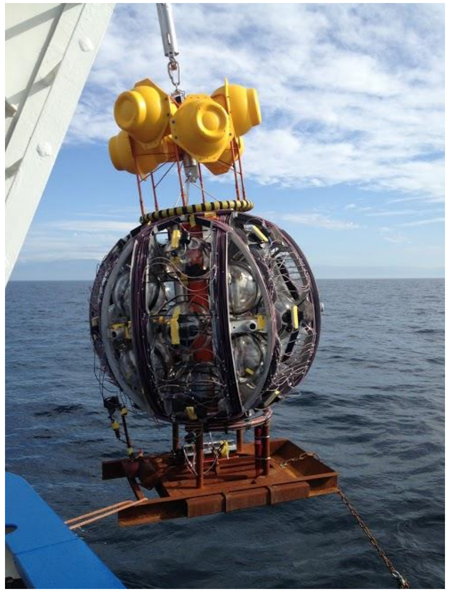
ARCA



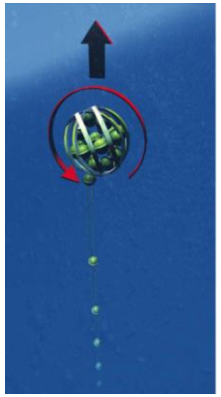
ORCA



Launching the Detection Unit (DU)



each DU is equipped with 18 DOMs



From triggering to sensitivity: Analysis strategy

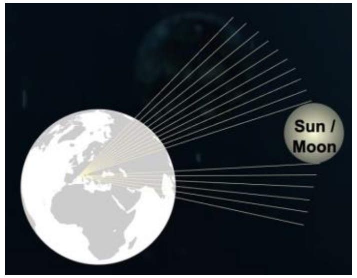
trigger (ORCA: atmospheric muons ~50 Hz, noise ~54 Hz, atmospheric neutrinos ~8 mHz)

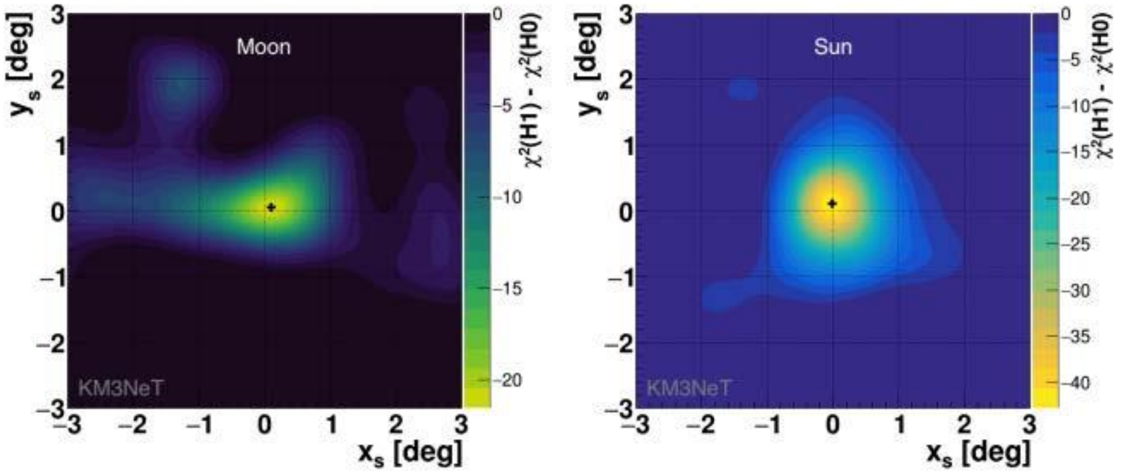
calibration (atmospheric muons, LED beacons, acoustic emitters), **reconstruction**

classification, background suppression -> event selection

test different hypotheses (MC) to obtain the detector sensitivity

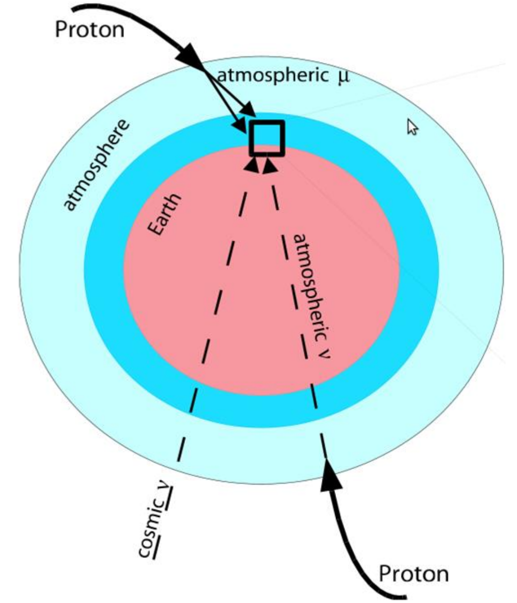
compare with data





ORCA6 (500 days) *Eur. Phys. J. C 83 (2023) 4, 344*	Sun	Moon
Statistical Significance	6.2 σ	4.2 σ
Resolution	0.65° ± 0.13°	0.49° ± 0.15°

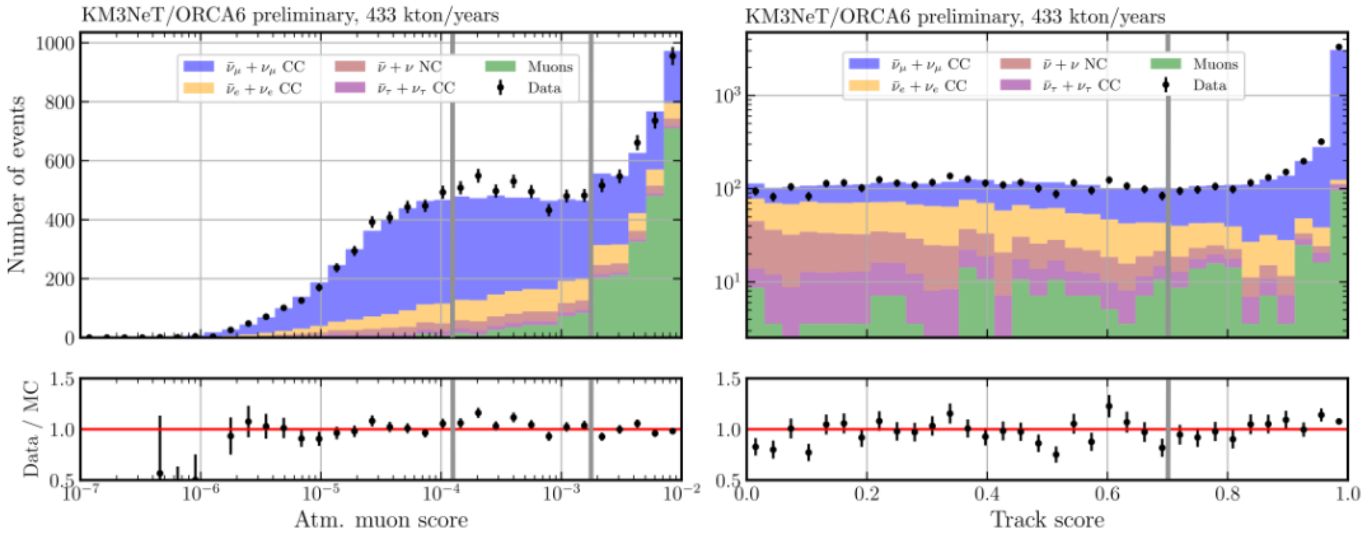
Neutrino oscillations with KM3NeT/ORCA6



- Energy range optimized to 2 – 100 GeV
- Event topologies: track-like for muons, shower-like for all other flavours
- Majority of recorded events are atmospheric muons or due to pure noise
- Request events to be reconstructed as up-going
- BDT to differentiate neutrinos from atmospheric muons (removing atmospheric muons)
- BDT for separating the track/shower topologies (three classes of events: High purity tracks, Low purity tracks and Showers)

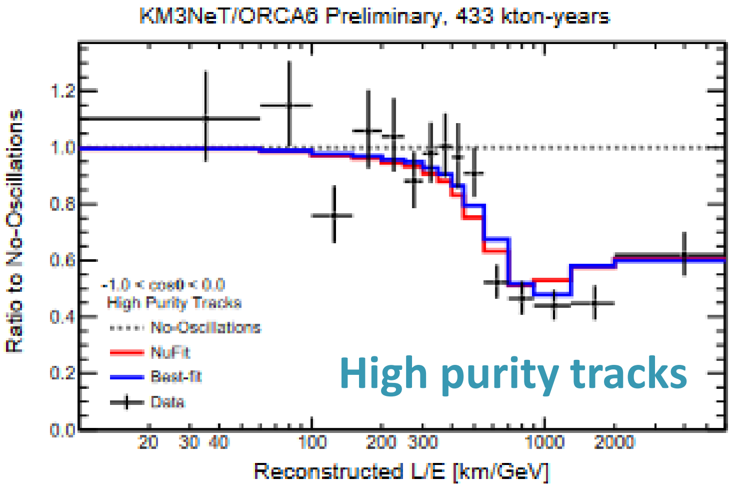
down-going: dominated by atmospheric muons
up-going: atmospheric ν and astrophysical ν

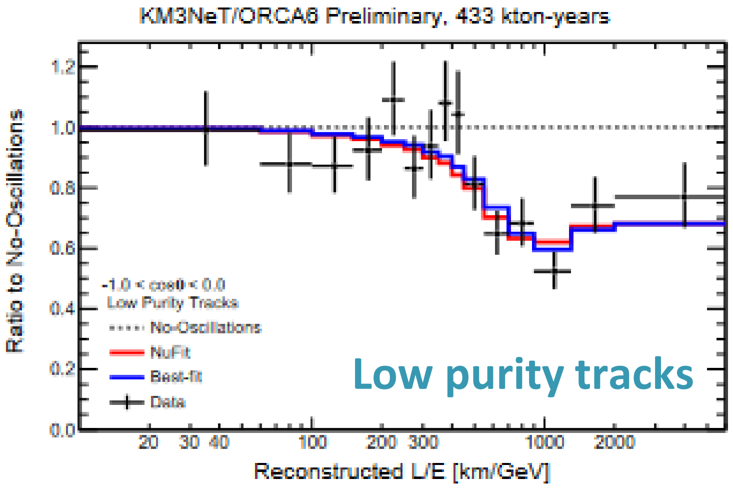
- Constrain oscillation parameters based on the likelihood maximization for the 2D binned distribution of events in log(E_{reco}) and cos θ_{reco} comparing data to a model prediction

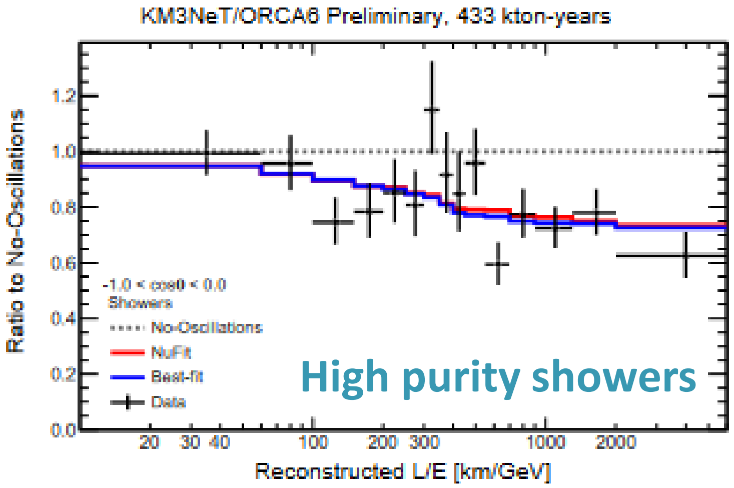


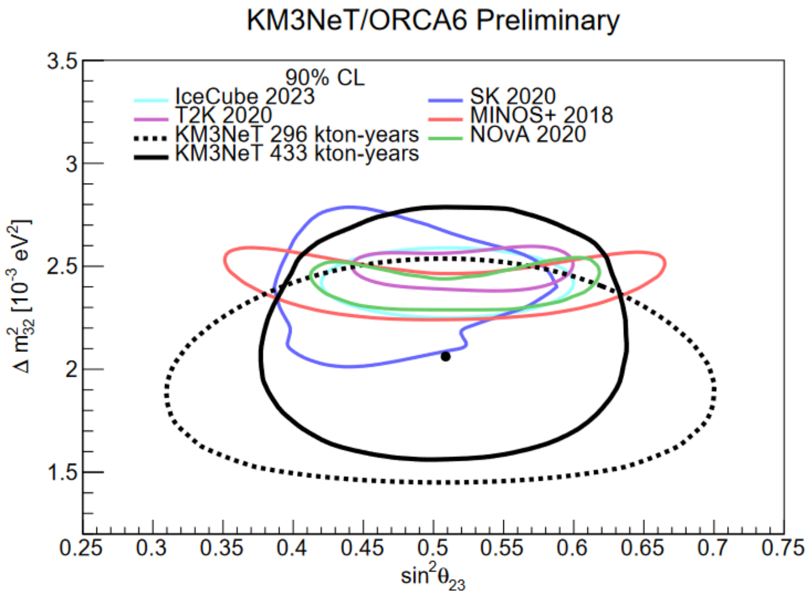
ICRC2023 PoS 1191

Neutrino oscillations with KM3NeT/ORCA6









best-fit values:

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

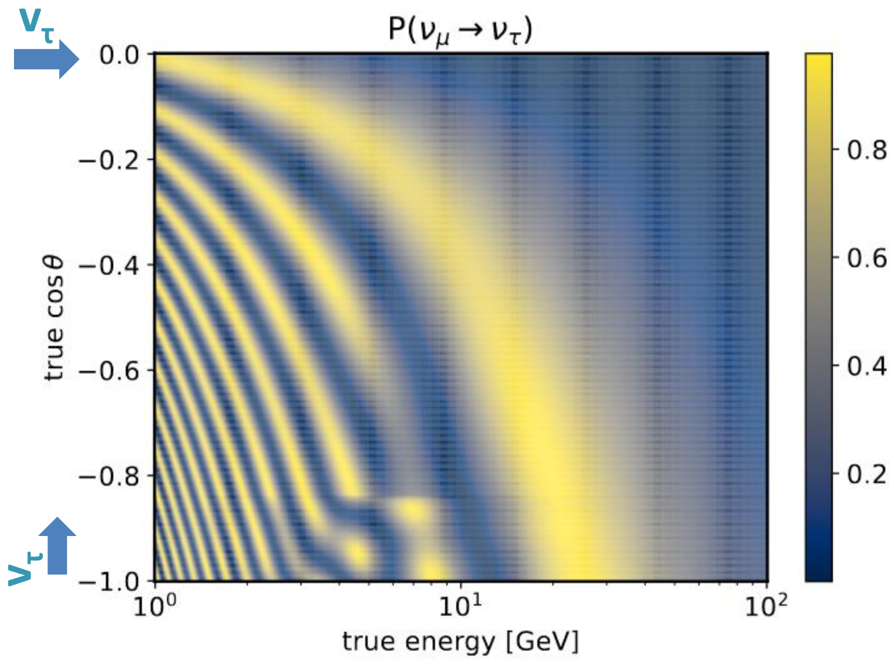
$$\Delta m^2_{31} = 2.14^{+0.36}_{-0.25} \cdot 10^{-3}\ \mathrm{eV}^2$$

Normal Ordering favoured at $\Delta_{\chi^2} = 0.9$

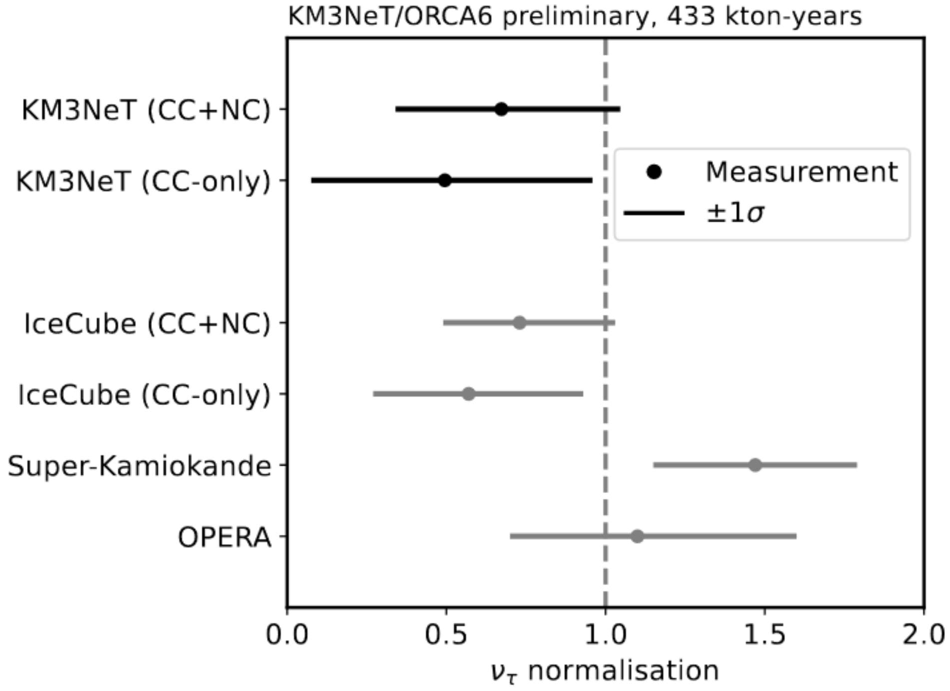
ICRC2023 PoS 996

Tau appearance with KM3NeT/ORCA6

ν_τ produced through the transition: $\nu_\mu \rightarrow \nu_\tau$



ICRC2023 PoS 1107



- Most prominent oscillation maximum for vertically up-going neutrinos with E between 20 and 30 GeV
- ν_τ appearance observed as an excess of shower-like events
- expect ~ 200 ν_τ CC interactions

ν_τ normalisation: ratio of measured ν_τ flux to the one expected in the std 3-flavour oscillation scenario

- CC-only: related to ν_τ CC cross section
- CC+NC: related to unitarity of PMNS matrix

NSI studies with KM3NeT/ORCA6

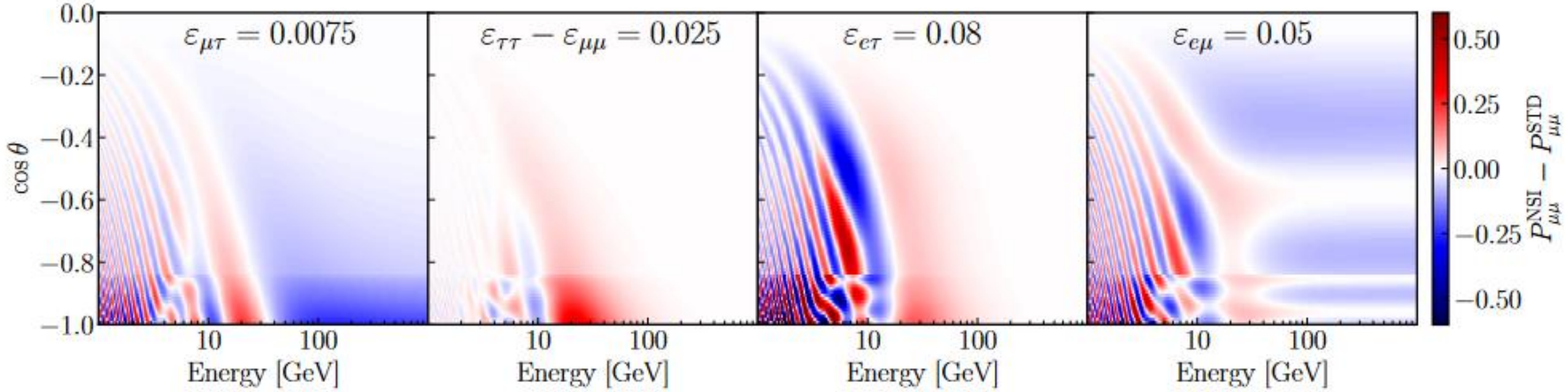
ICRC2023 PoS 998

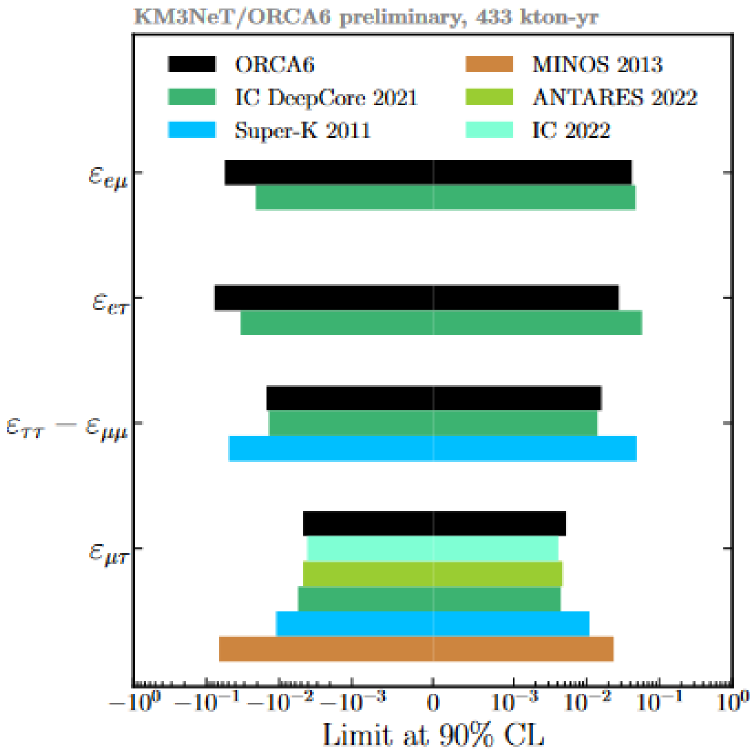
Non-standard interactions

- appear in several extensions of the SM proposing mechanisms for the origin of neutrino masses
- lead to modifications of neutrino oscillation probabilities in matter

$$A(x)\begin{bmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon_{e\mu}^{*} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon_{e\tau}^{*} & \varepsilon_{\mu\tau}^{*} & \varepsilon_{\tau\tau} \end{bmatrix}$$

- non-zero NSI parameters change the ν_μ survival probabilities
- difference in the ν_μ survival probabilities between std and different NSIs hypothesis

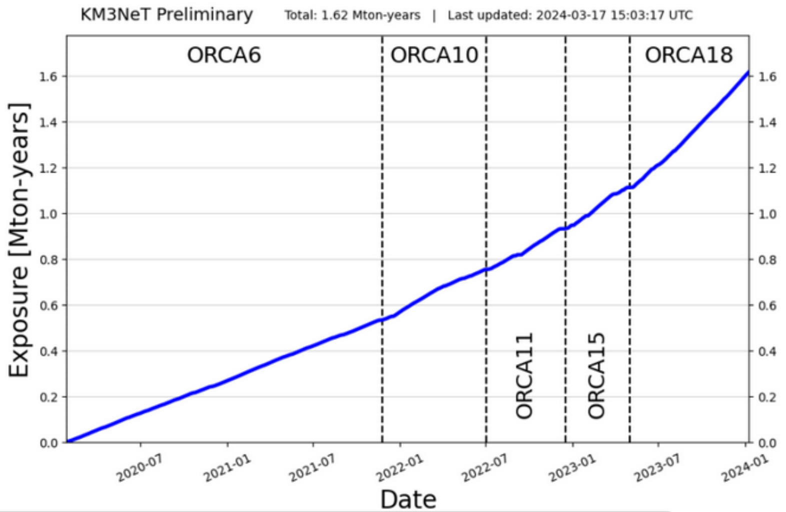




- No significant deviation from SI found
- Competitive results, to be improved as ORCA is growing

What's next?

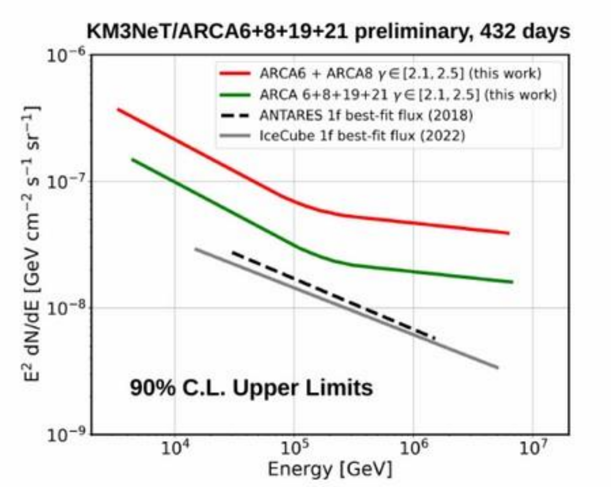
- Detector construction is ongoing
- KM3NeT/ORCA6 configuration up to Nov. 2021
- Improvements for energy estimation, event selection, classification underway
- Analyses extended to include data from the more recent detector configurations (now ORCA18)
- Similarly for KM3NeT/ARCA: reported results use data up to Dec. 2022 with ARCA21 (now ARCA28)



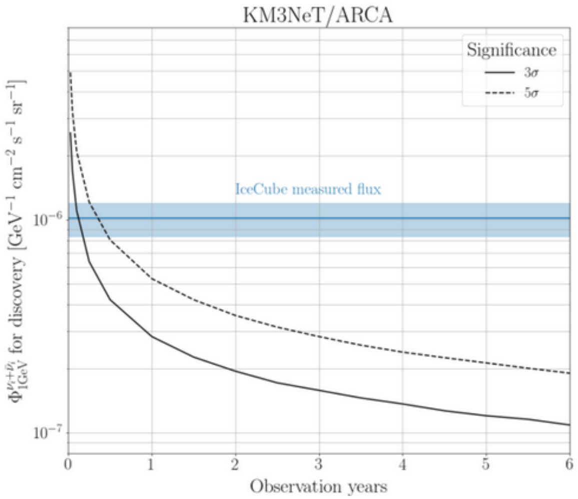
- ➢ direction and energy resolution very important both for neutrino astronomy and for neutrino oscillation studies
- ➢ Larger detector configuration ➞ improved direction and energy resolution!

Towards detecting a diffuse flux of astrophysical neutrinos

Data up to Dec. 2022 (ARCA21)

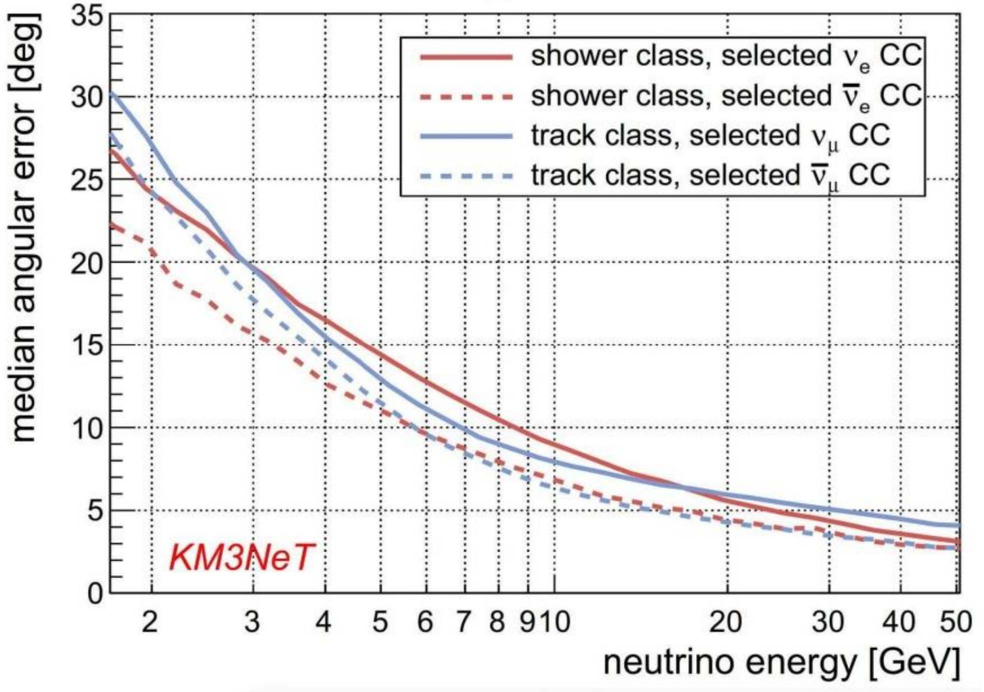


Full ARCA: 5σ measurement of the diffuse flux after 6 months



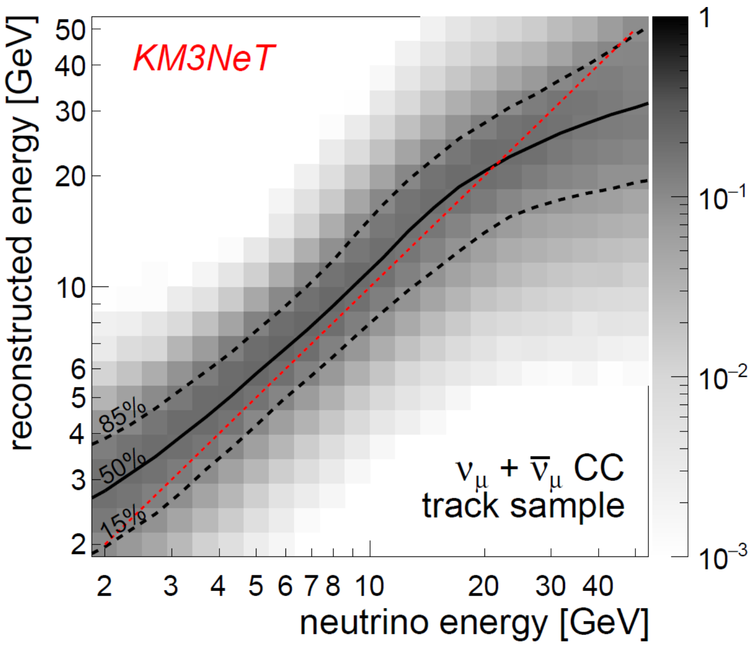
KM3NeT/ORCA performance

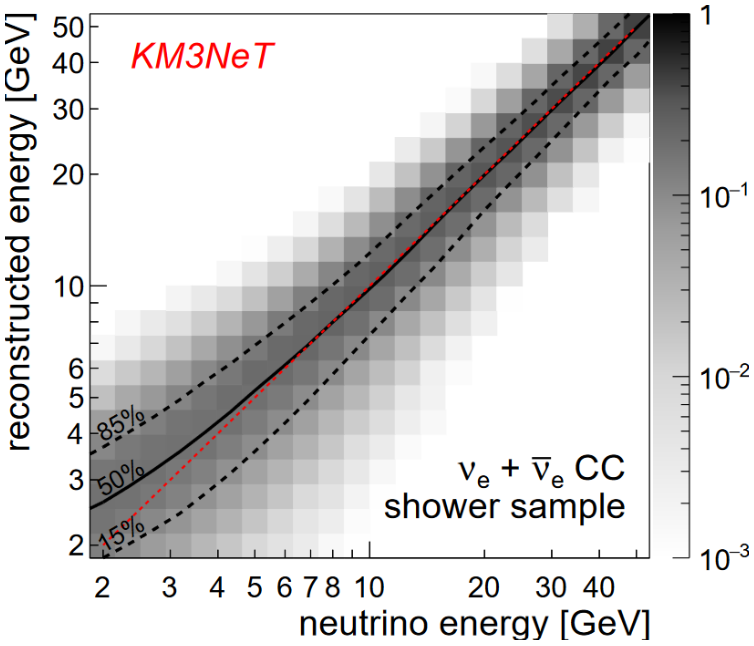
Angular resolution



Pointing accuracy dominated by neutrino kinematics

Energy resolution



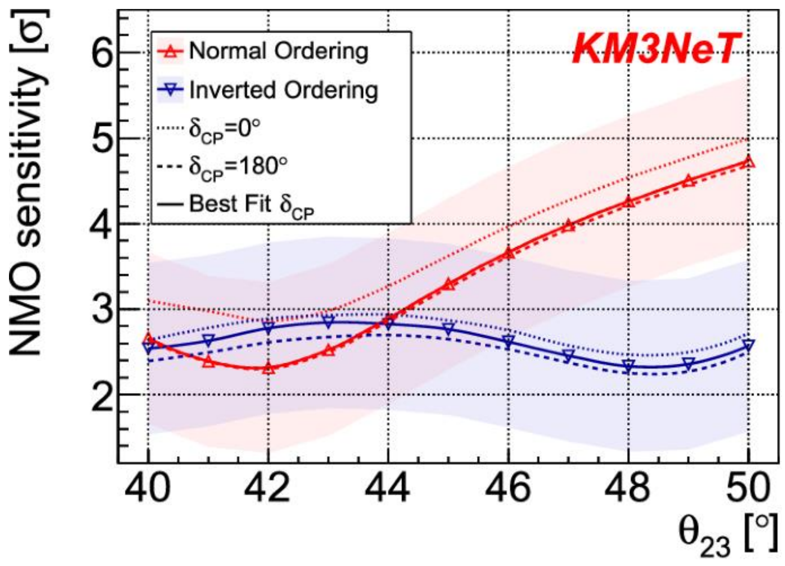


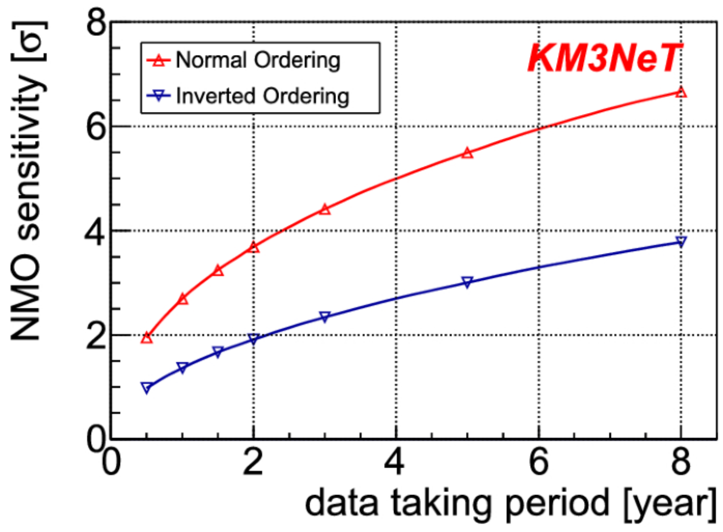
- Direction resolution better than 15° at relevant energies
- Energy resolution: ~ 25%

Neutrino oscillations with KM3NeT/ORCA

Completed KM3NeT/ORCA (115 strings) after 3 years of data taking

Eur. Phys. J. C 82, 26 (2022)



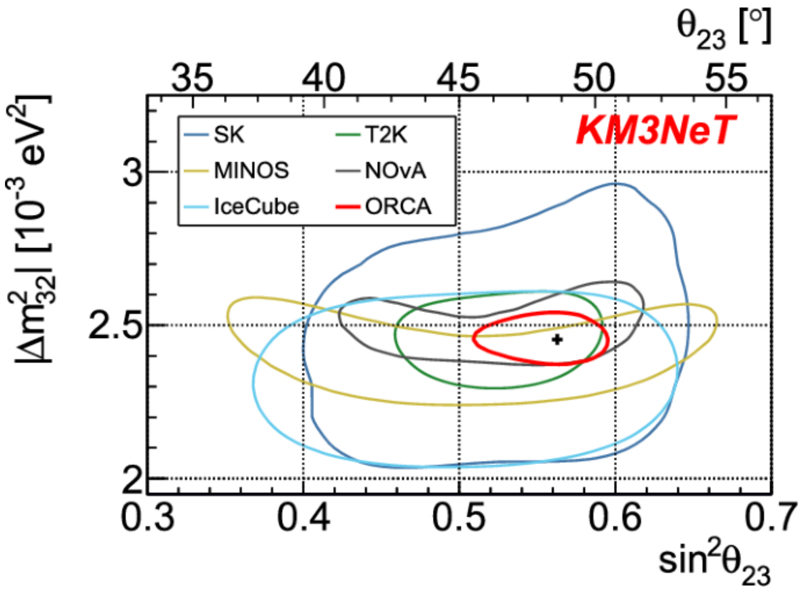


4.4σ (2.3σ) determination of neutrino mass ordering if Normal (Inverted) after 3 years of data taking

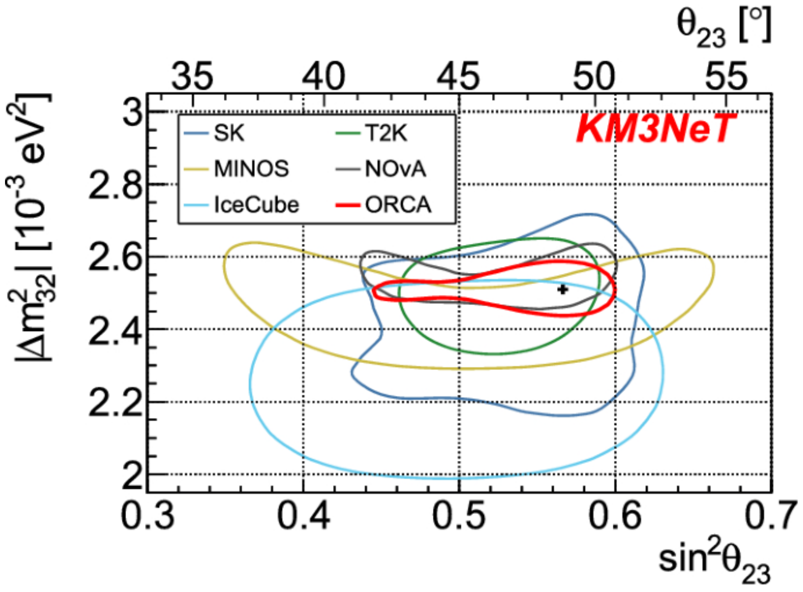
Neutrino oscillations with KM3NeT/ORCA

Eur. Phys. J. C 82, 26 (2022)

Normal Ordering



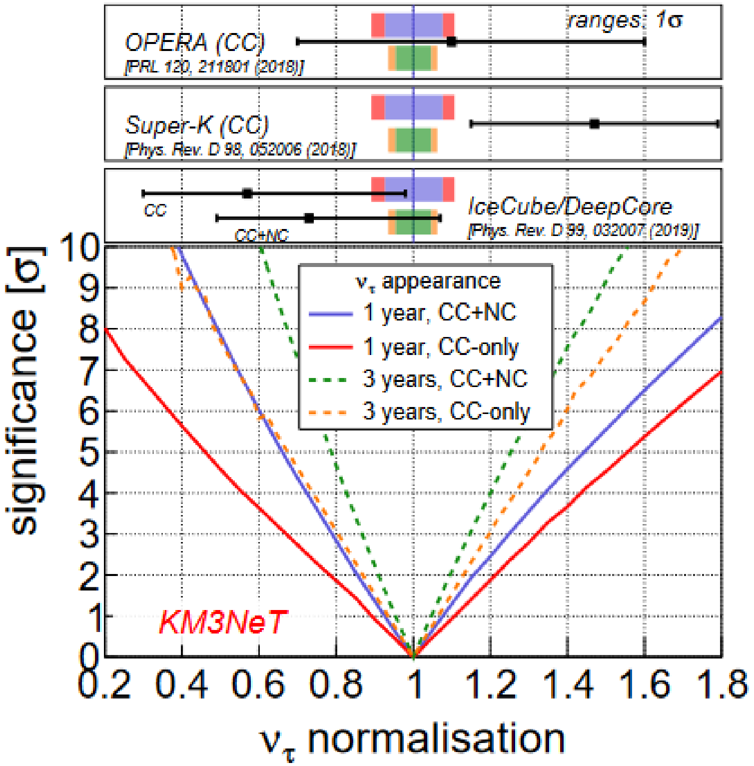
Inverted Ordering

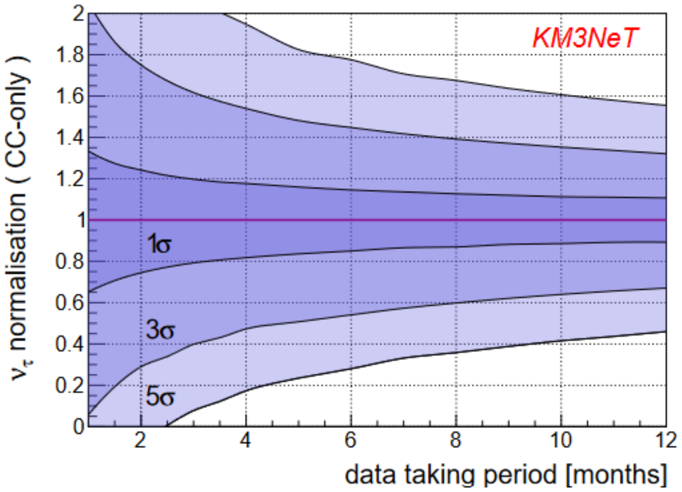


Precision measurements of $\sin^2 \theta_{23}$ and Δm^2_{23} after 3 years of data taking

Tau appearance with KM3NeT/ORCA

Eur. Phys. J. C 82, 26 (2022)

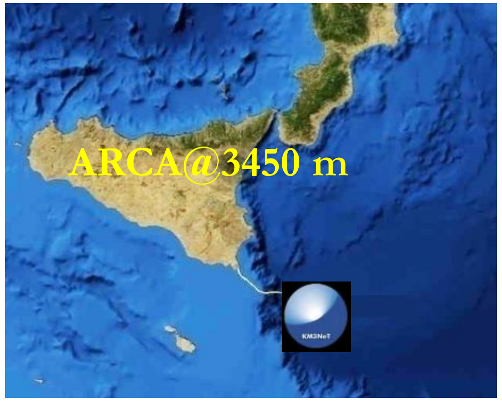




A ν_τ $(\overline{\nu_\tau})$ event rate variation larger than 20% can be excluded at the 3σ level after 3 years of data taking

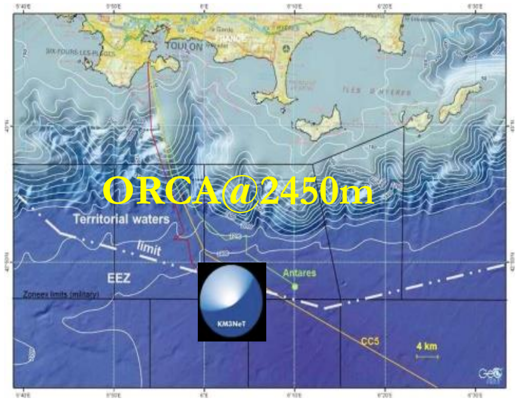
ARCA

- Smooth data taking > 95% uptime
- Sea operation planned in fall 2024 ~20 additional DUs and upgrade of the seabed infrastructure
- Funding secured for one building block and 10 additional DUs (and the corresponding infrastructure)

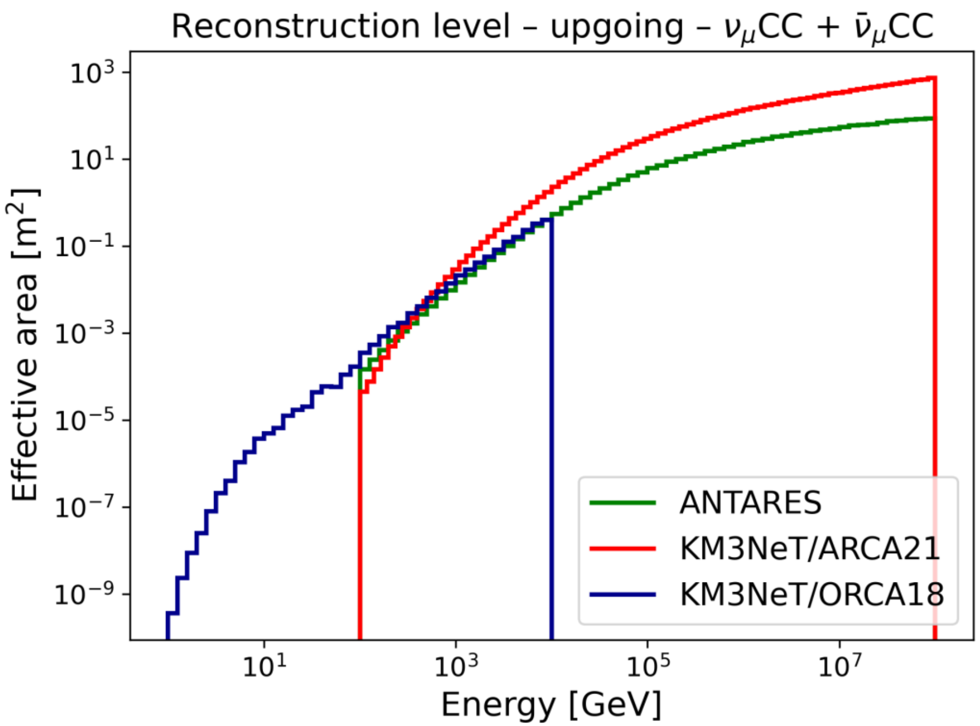


ORCA

- Smooth data taking > 95% uptime
- About 10 additional DUs ready to be deployed at the next sea operation
- Funding secured for ~50 DUs



KM3NeT status



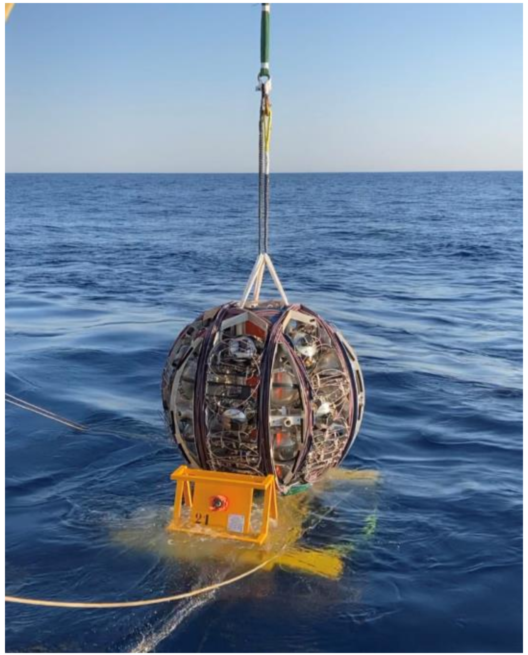
- Rich physics program while the detector construction is ongoing
- Physics analyses progressing and results delivered using the early detector configurations both for ARCA and ORCA

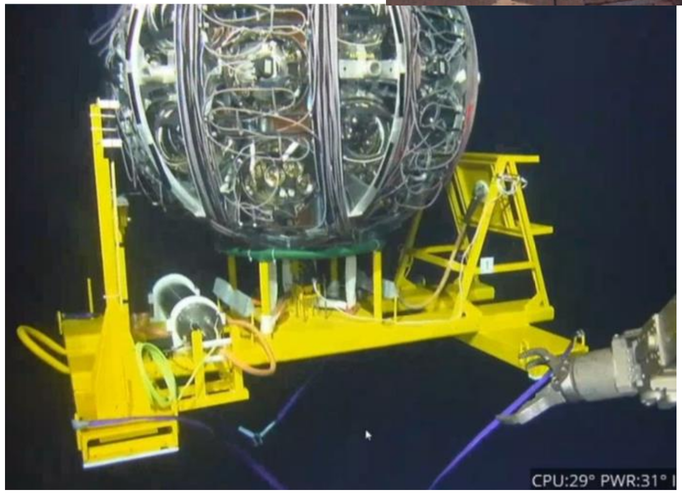
  - Neutrino oscillations
  - Neutrino astronomy

    point-sources, extended sources, diffuse astrophysical neutrino flux all sky and from the Galactic Ridge, Core-Collapse Supernova neutrinos
  - Cosmic ray physics

    atmospheric muon neutrino flux, atmospheric muon flux
  - Multi-messenger
  - Dark matter and exotics

Thank you for your attention!





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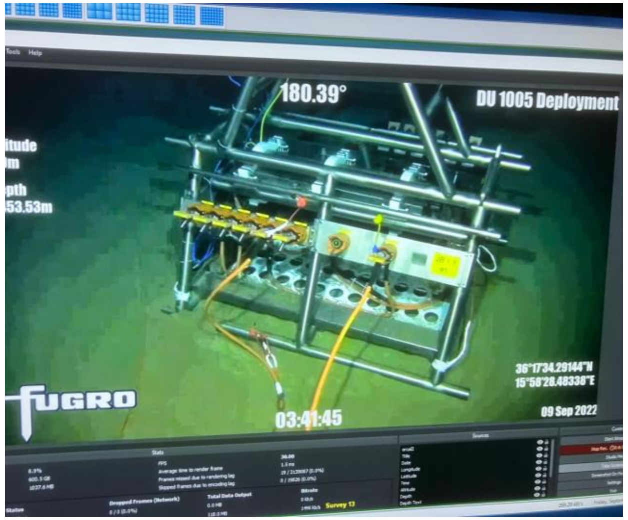


Backup

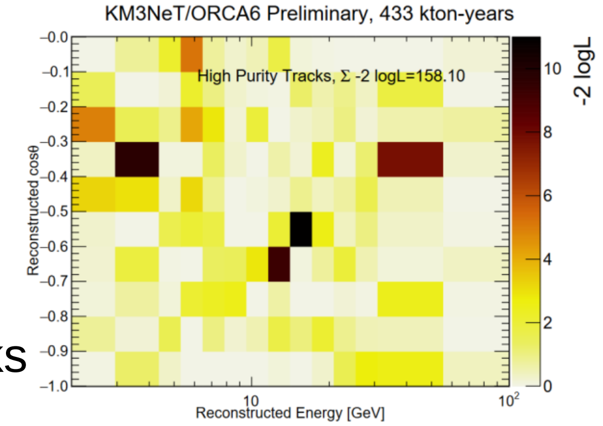
Neutrino oscillations with KM3NeT/ORCA6

Poisson log-likelihood and gaussian penalties for the nuisance parameters

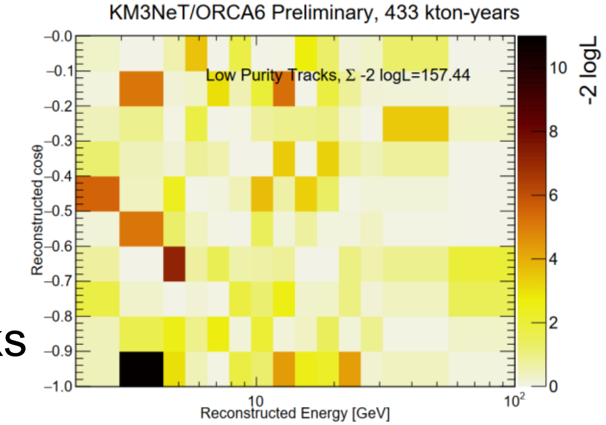
$$-2\log L = 2\sum_{i,j}\left[\left(N_{ij}^{\text{model}} - N_{ij}^{\text{dat}}\right) + N_{ij}^{\text{dat}}\log\left(\frac{N_{ij}^{\text{dat}}}{N_{ij}^{\text{model}}}\right)\right] + \sum_{k}\left(\frac{\epsilon_k - \mu_k}{\sigma_k}\right)^2$$

Systematic	Expectation, $\langle\epsilon_k\rangle$	Std deviation, σ_k
Overall normalisation	1	No prior
Track normalisation	1	No prior
Shower normalisation	1	No prior
NC normalisation	1	20%
τ-CC normalisation	1	20%
High Energy Light Sim.	1	50%
Atm. muon normalisation	1	No prior
$\nu_\mu/\bar{\nu}_\mu$ skew	0	5%
$\nu_e/\bar{\nu}_e$ skew	0	7%
ν_μ/ν_e skew	0	2%
$\nu_{\text{hor}}/\nu_{\text{ver}}$ skew	0	2%
Spectral index	0	0.3
Energy scale	1	9%

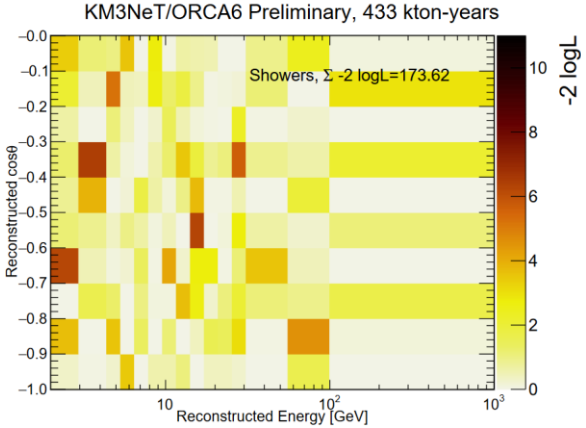
High-purity tracks



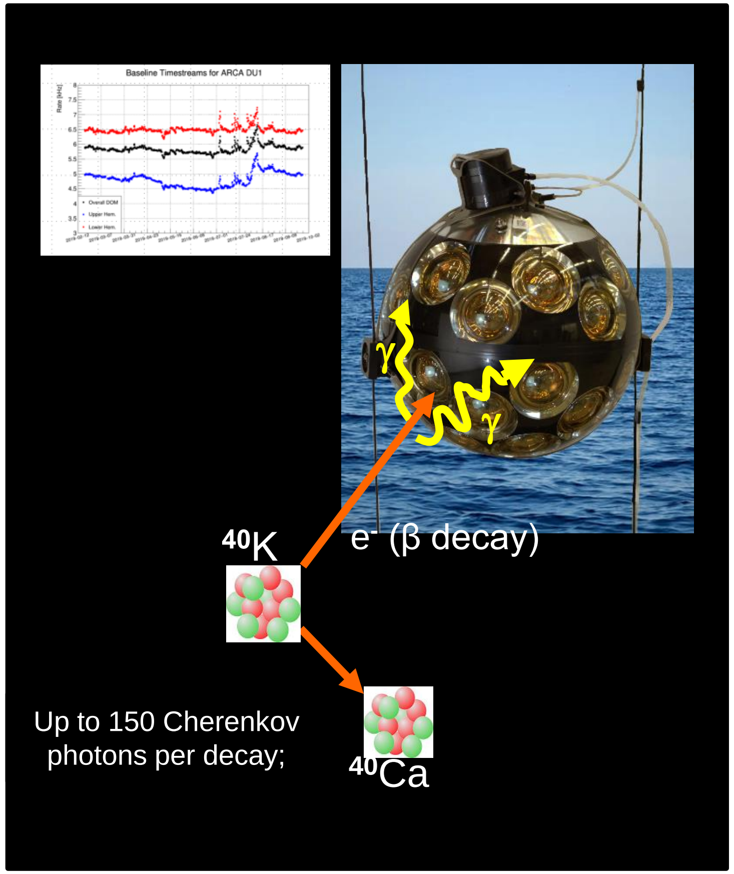
Low-purity tracks

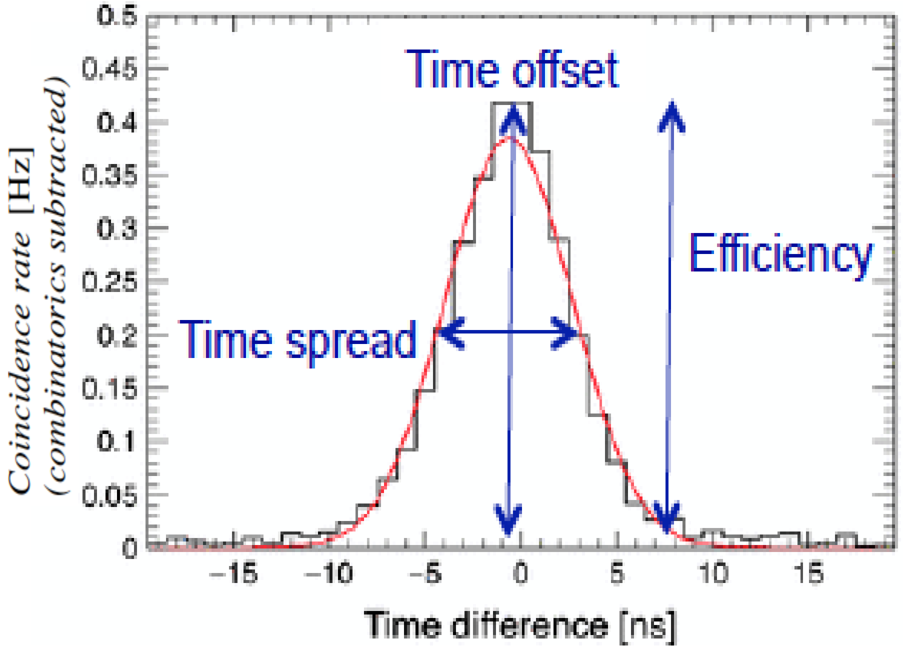


Showers



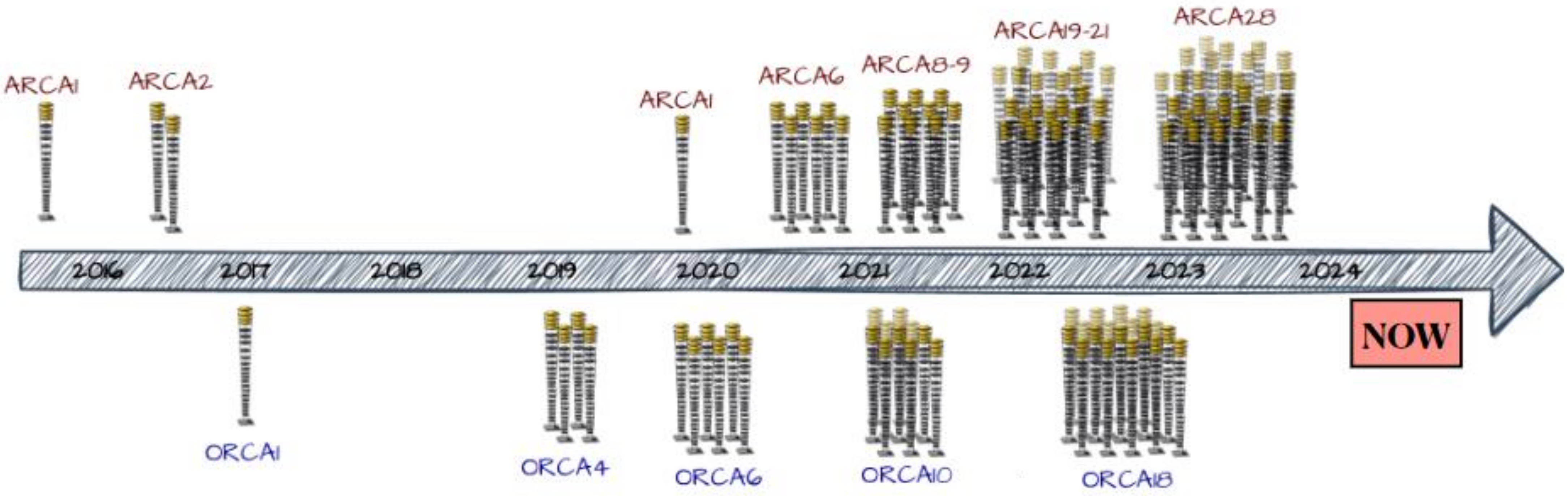
Calibration





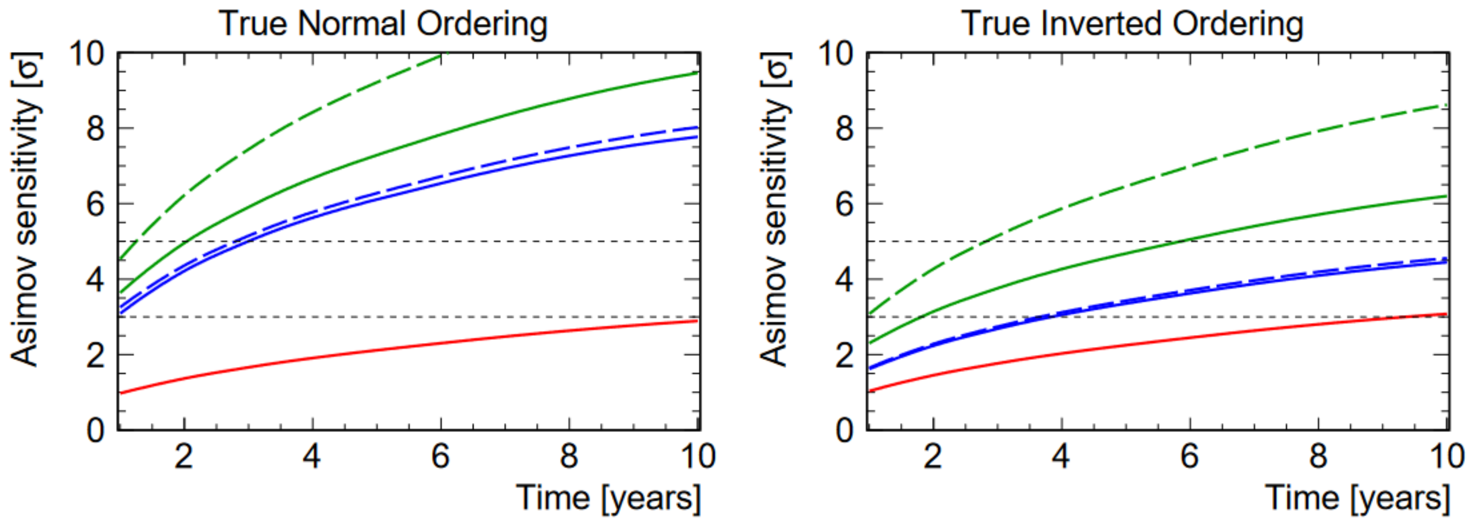
Inter-PMT: ^{40}K decays
Inter-DOM: nanobeacons, atmospheric muons

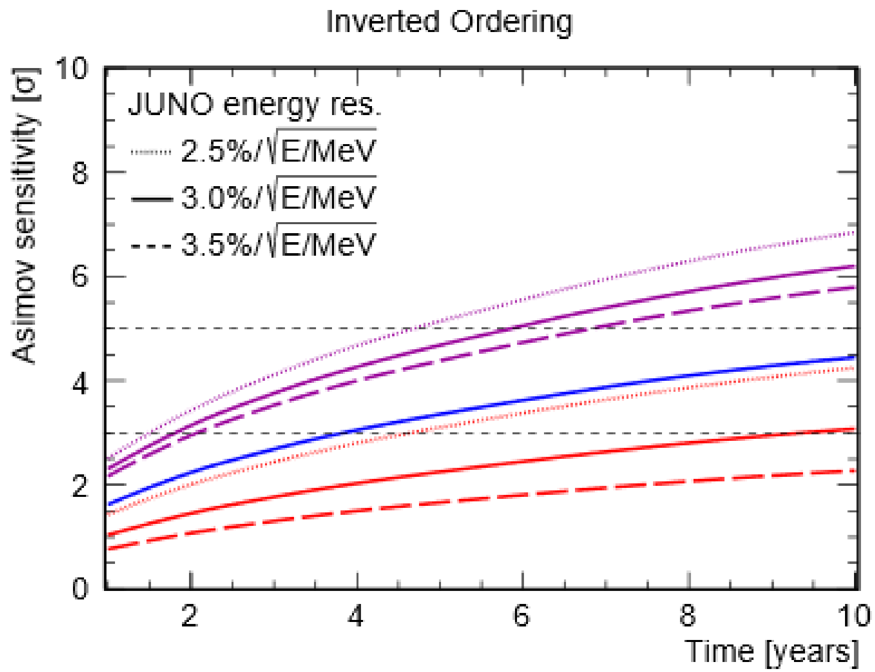
Status of KM3NeT construction



Mass ordering – combined sensitivity of ORCA with JUNO

When fitting both datasets with wrong NMO hypothesis
-> disagreement on the value of Δm_{31}





Energy-scale systematic important

Phys. Rev. D, 101:032006, Feb 2020.