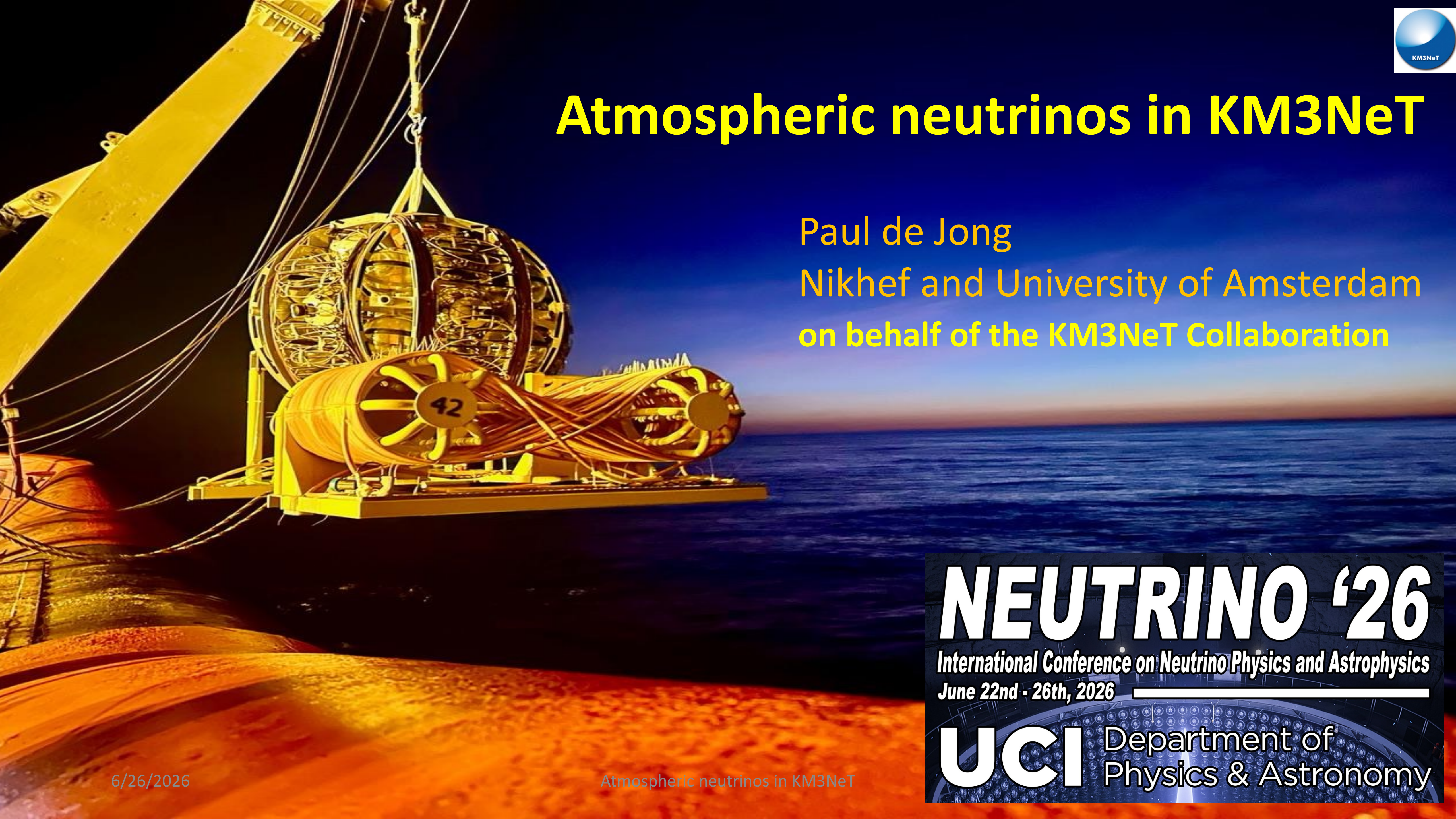


Atmospheric neutrinos in KM3NeT

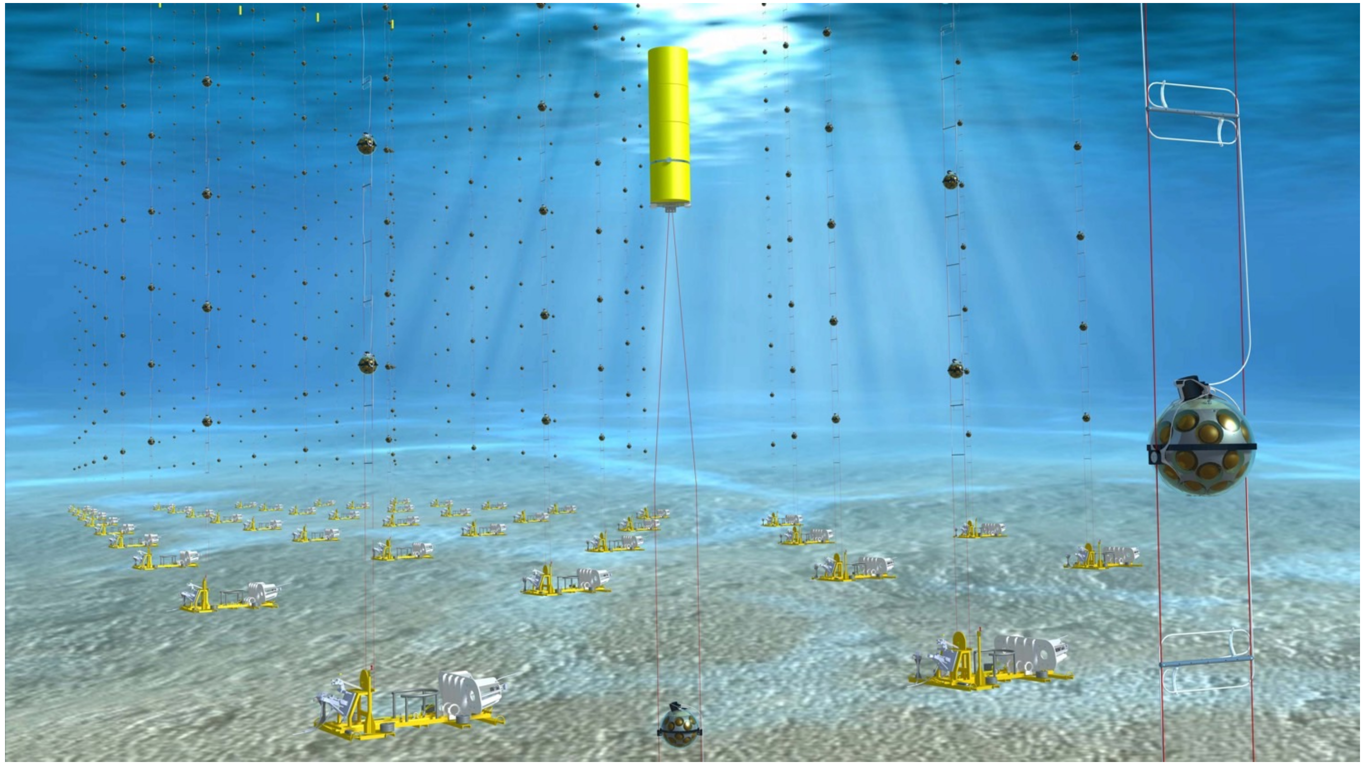
Paul de Jong
Nikhef and University of Amsterdam
on behalf of the KM3NeT Collaboration

NEUTRINO '26
International Conference on Neutrino Physics and Astrophysics
June 22nd - 26th, 2026
UCI Department of Physics & Astronomy

KM3NeT: research infrastructure in the Mediterranean Sea

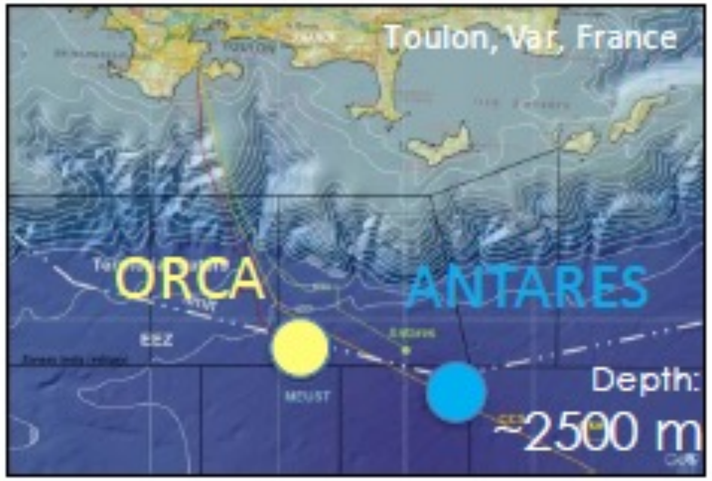
Two neutrino telescopes + portal for earth/sea sciences and marine biology

km^3 Neutrino Telescope

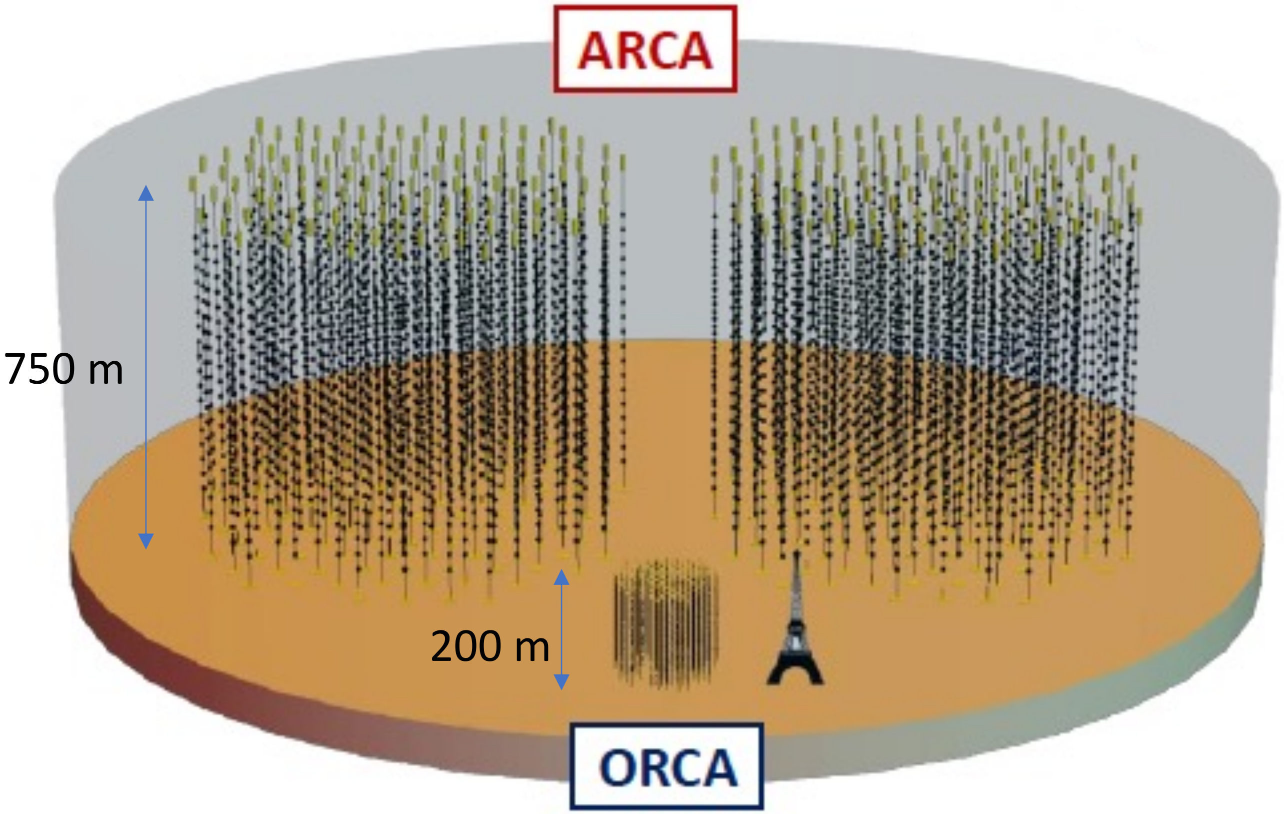


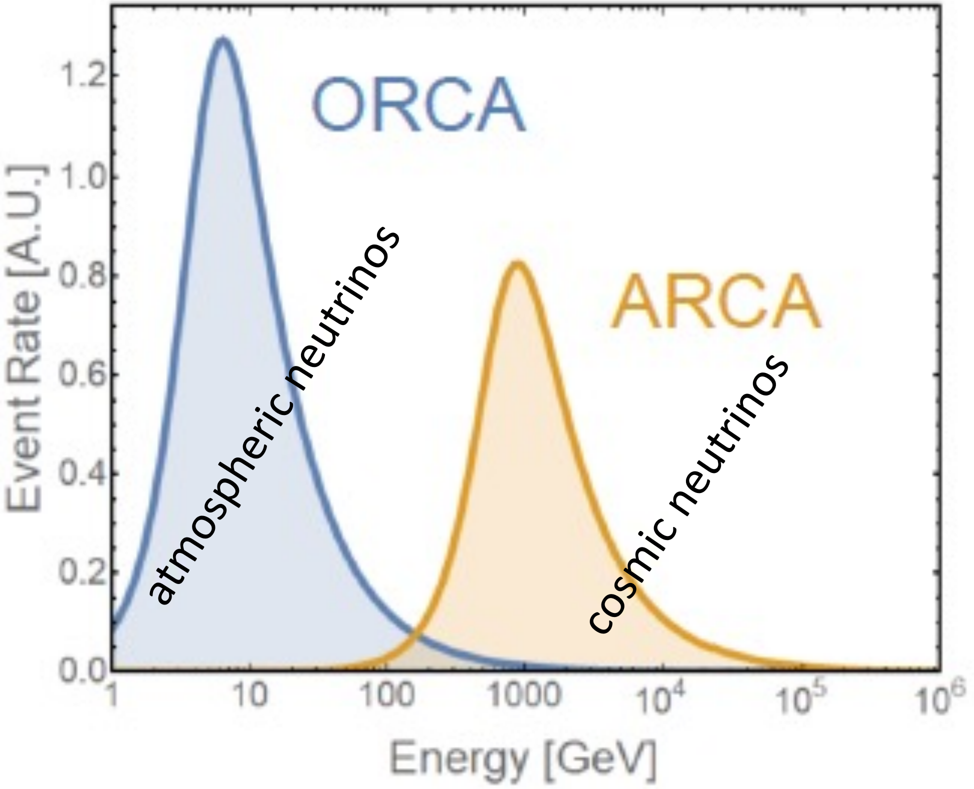
3D array of light sensors in glass spheres at large depth.
Lines connected to sea-floor network, real-time data to shore station.

Uses Cherenkov light: single photon sensitivity, precise timing.



KM3NeT: two detectors, one technology





ORCA: 108 detection units, dense spacing (20m between lines), 6.5 Mton fiducial mass

ARCA: 198 detection units, sparse layout (90m between lines), 1 Gton (1 km^3)

Detector layout

Hamamatsu R14374-02 3-inch PMT
Dark count rate ~ 500 c.p.s.
Transit time spread < 1 ns
Only few afterpulses/delayed pulses
JINST **20** (2025) P07054

+ piezo sensor,
LED nanobeacon,
accelerometer,
compass

Digital Optical Module
JINST 17 (2022) P07038

31 PMTs per DOM

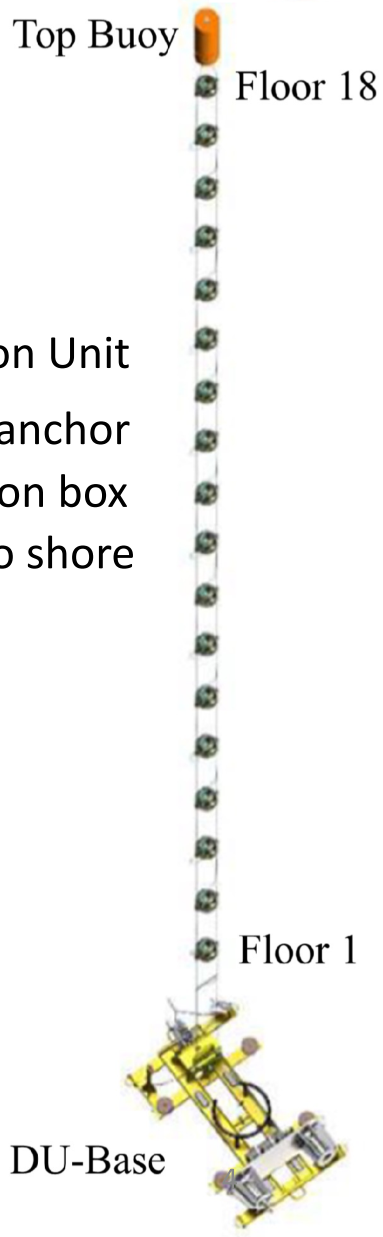
18 DOMs per Detection Unit

connected to base module on anchor
base module connected to junction box
junction box connected to cable to shore

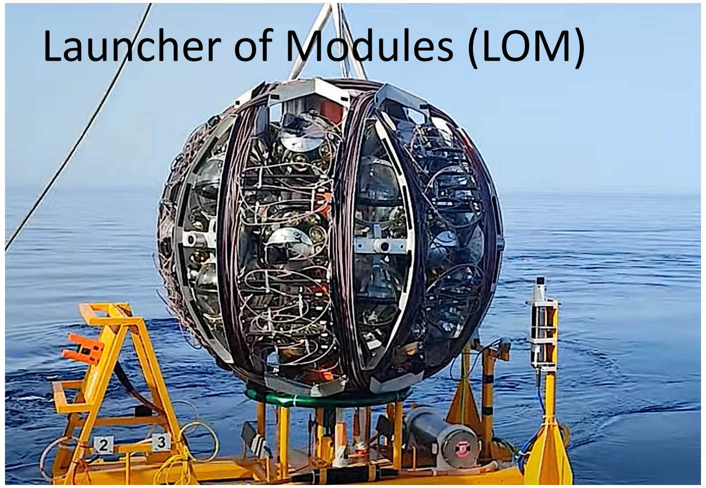
Hits: PMT ID
Time at passing of threshold
Time-over-threshold

All hits sent to shore-station
Causal trigger at shore-station

NIM A1083 (2025) 171097

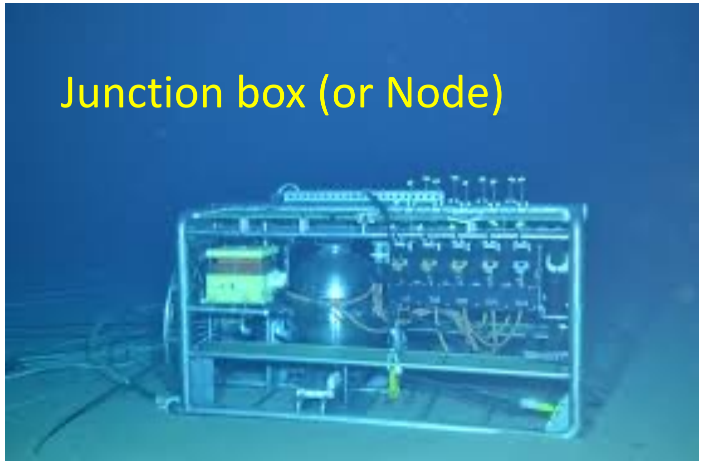


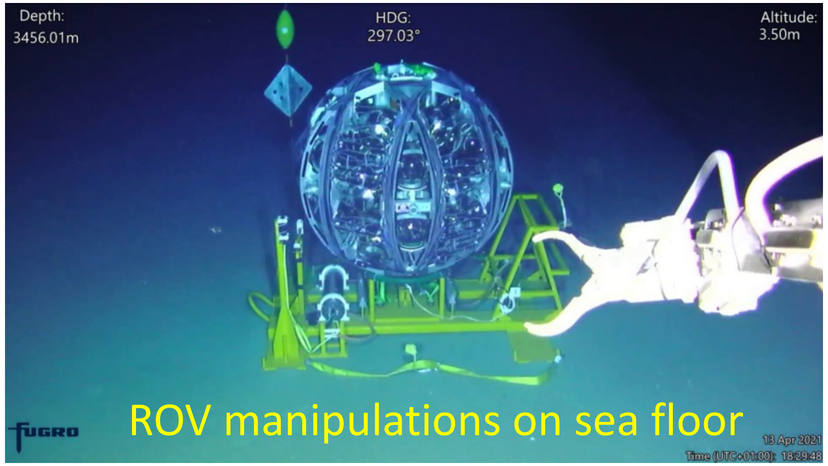
Deployment of Detection Units


Launcher of Modules (LOM)


Sea operation


unfurling


Junction box (or Node)

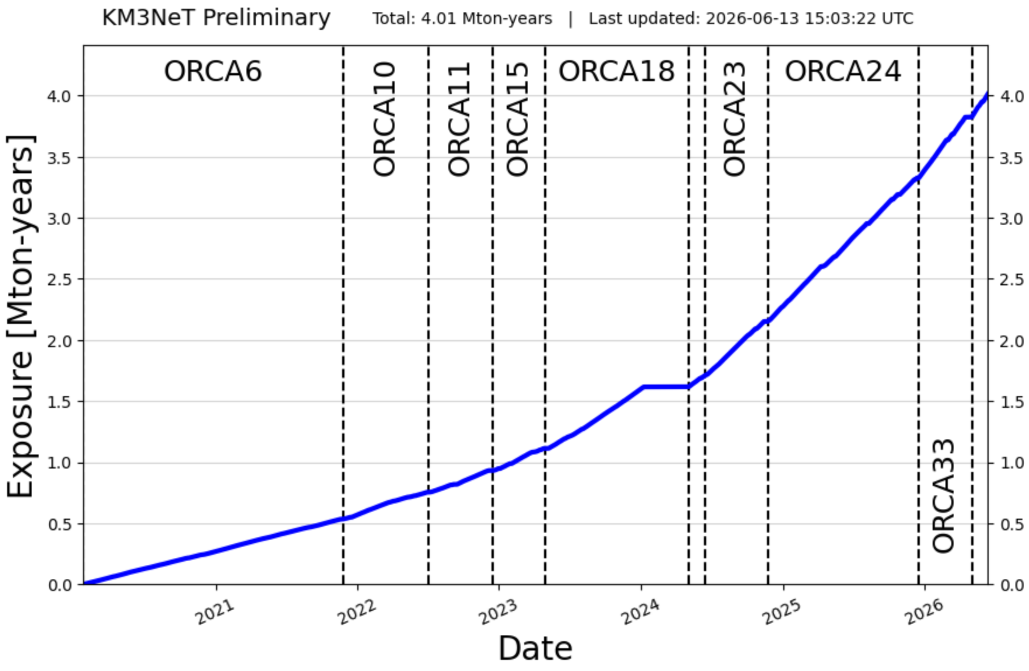

ROV manipulations on sea floor

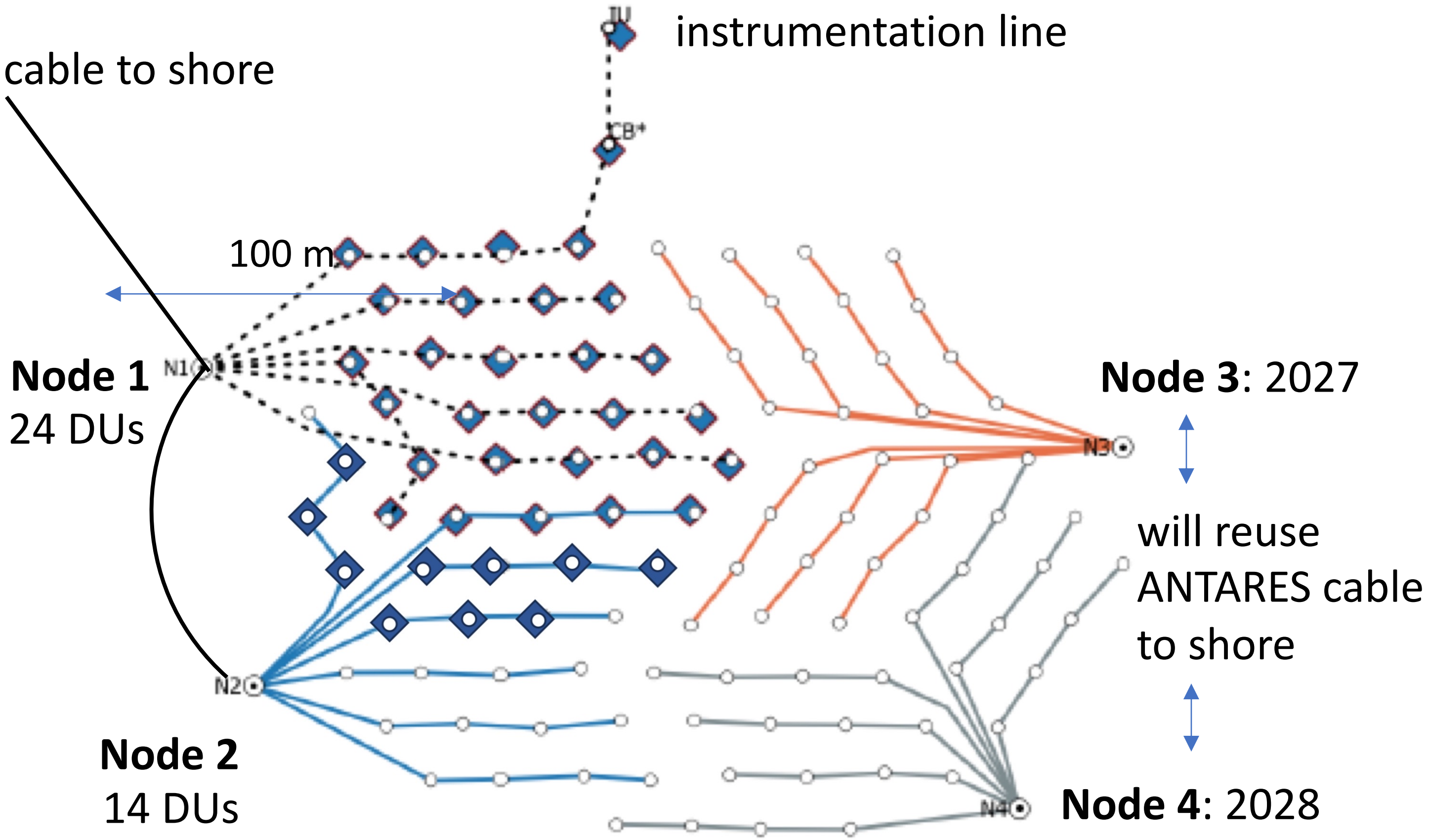
JINST 15 (2020) P11027

KM3NeT/ORCA status and evolution

Distributed construction in Europe and Morocco

D. Vivolo





instrumentation line

cable to shore

100 m

Node 1
24 DUs

Node 2
14 DUs

Node 3: 2027

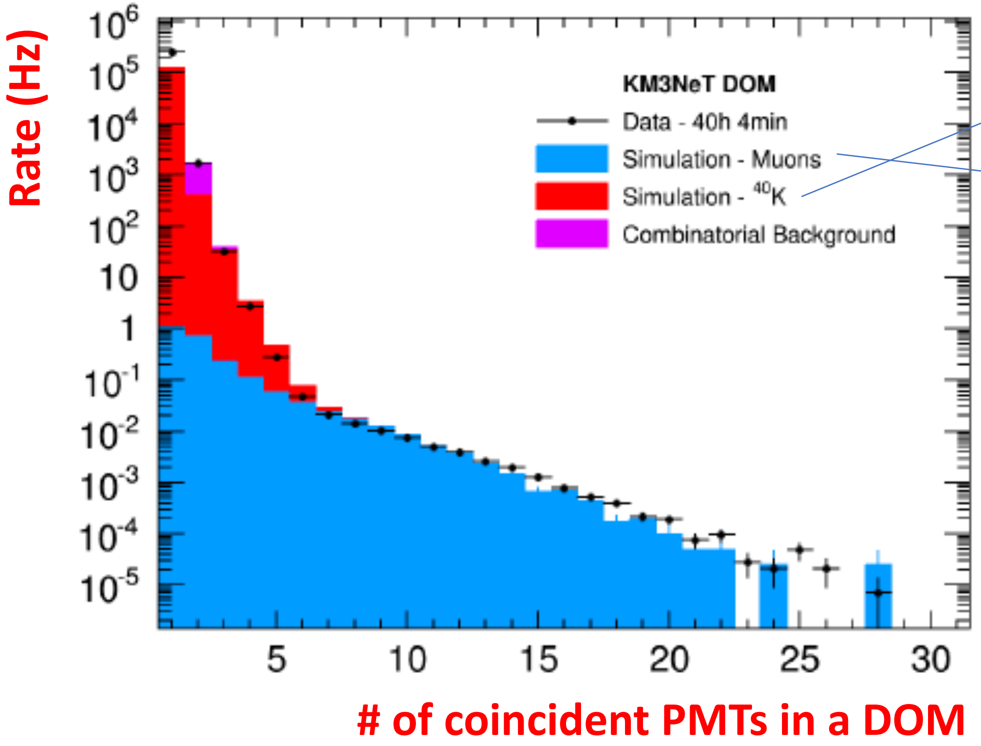
will reuse ANTARES cable to shore

Node 4: 2028

ORCA is currently taking data with 38 DUs

What do you see when you switch on?

Eur. Phys. J. C (2014) 74: 3056



^{40}K: few kHz per DOM, not a problem, great calibration source!

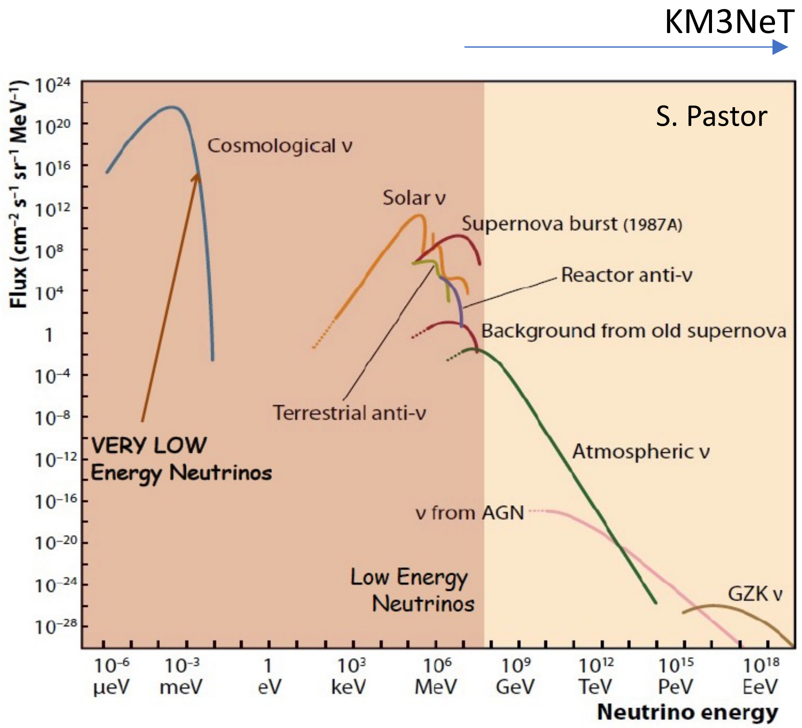
cosmic ray muons, even at 2.5 km depth

background to neutrino analyses (good tracks!)
source of calibration (stopping muons)
signal for cosmic ray physics analyses

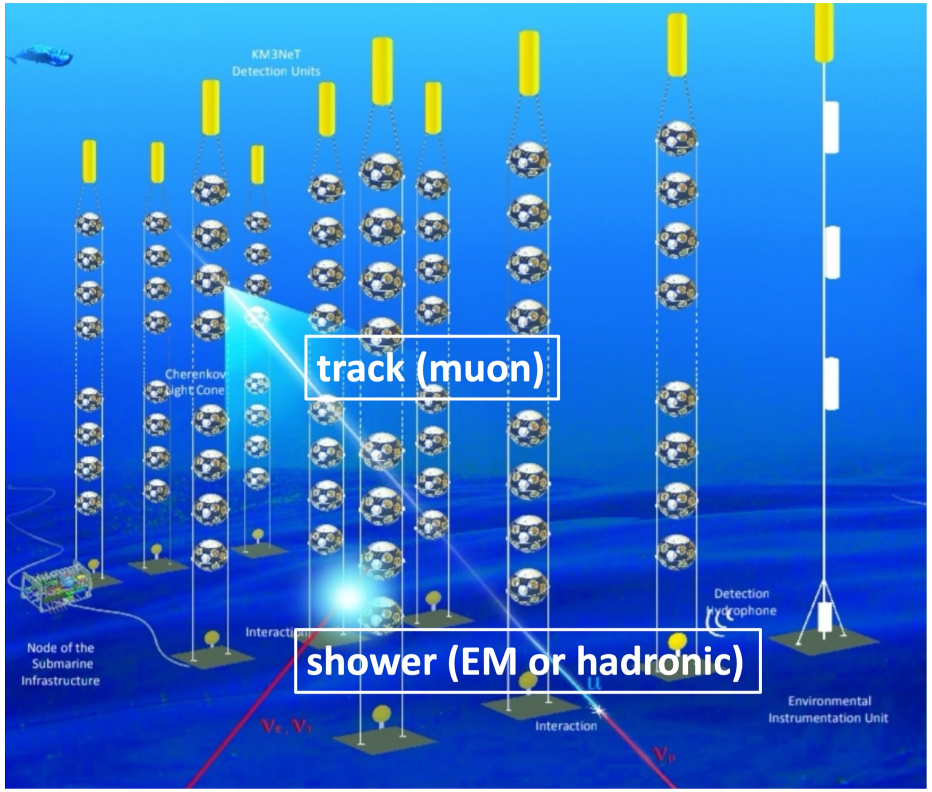
Bioluminescence:

- Not an issue for neutrino analyses
  (no correlations mimicking neutrinos or muons)
- Bursts: occasional PMT high-rate veto
- Signal for marine biology!

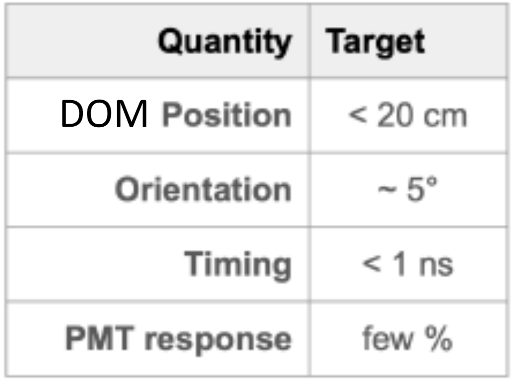
And in the end…
neutrinos!



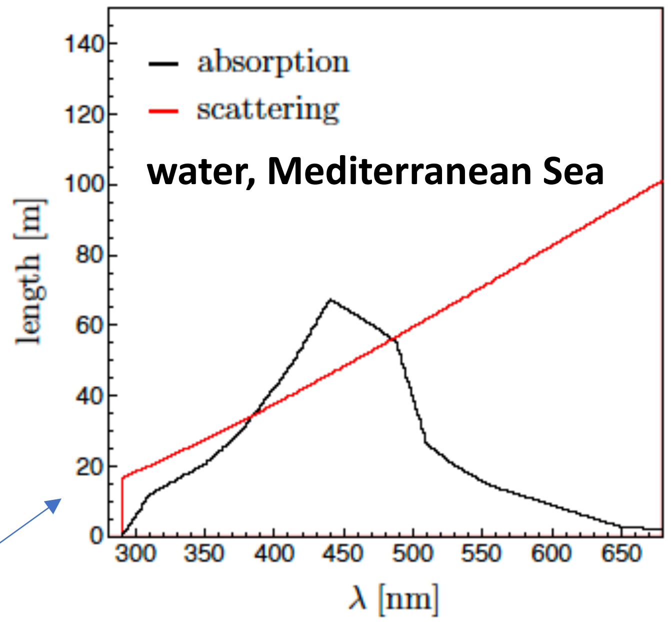
Tracks and showers



Event reconstruction uses precise (ns) timing of PMT signals, under track- or shower hypothesis



Quantity	Target
DOM Position	< 20 cm
Orientation	~ 5°
Timing	< 1 ns
PMT response	few %



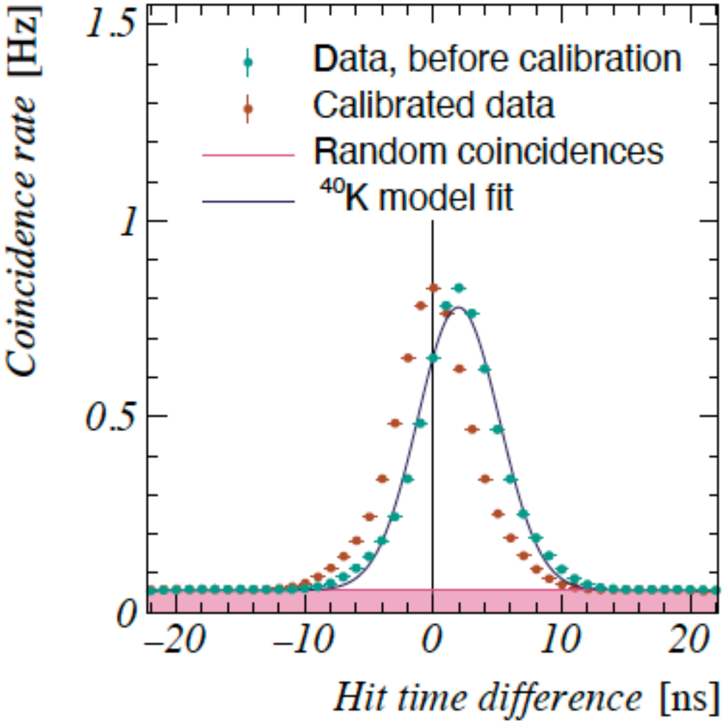
Differences with respect to IceCube:
- water versus ice
- detector layout and technology
- location

Water: absorption length ↘ scattering length ↗

ORCA tuned for atmospheric neutrinos 2 GeV and up, multi-PMT DOMs

42°50′ N, 6° E, Complementary to IceCube for sky surveys

Calibration



^{40}K decays in sea water:

$$^{40}K \rightarrow {}^{40}Ca + e^- + \bar{\nu}_e$$

$$^{40}K + e^- \rightarrow {}^{40}Ar + \gamma + \nu_e$$

Correlated signals in ≥ 2 PMTs:

- Intra-DOM PMT timing
- PMT efficiency

Stopping atmospheric muons inside ORCA: measurement of water properties.

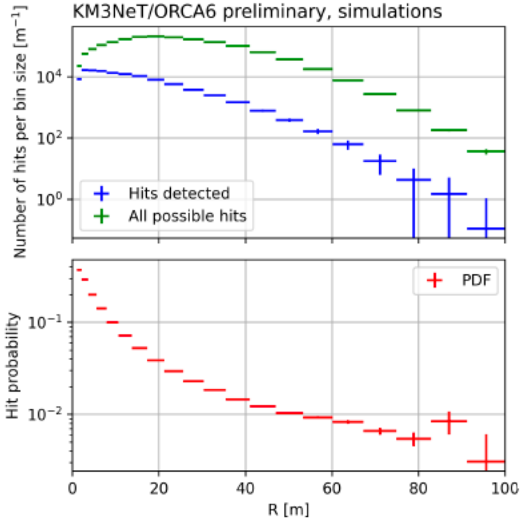
In-situ: absorption length determined to be within a few percent of values used in sim/reco.

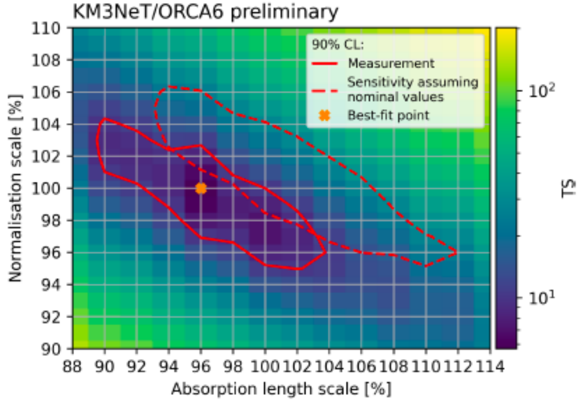
Inter-DOM and Inter-DU timing:

Laser calibration before deployment + in-situ atmospheric muons

DOM orientation:

Compasses inside DOMs + in-situ atmospheric muons





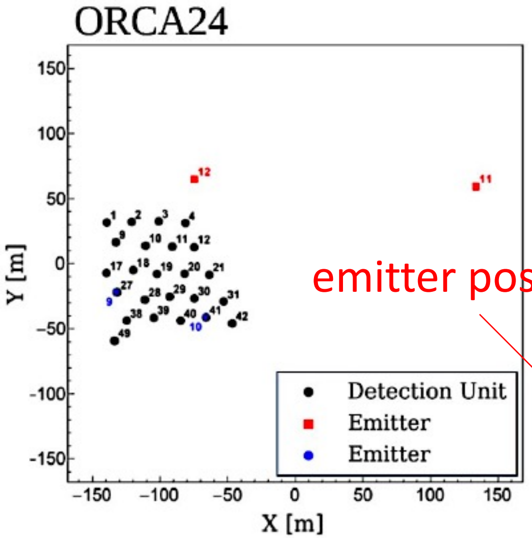
PoS ICRC2025 (2025) 1158

Calibration

Detection lines move with variable sea current: DOM positions need to be calibrated

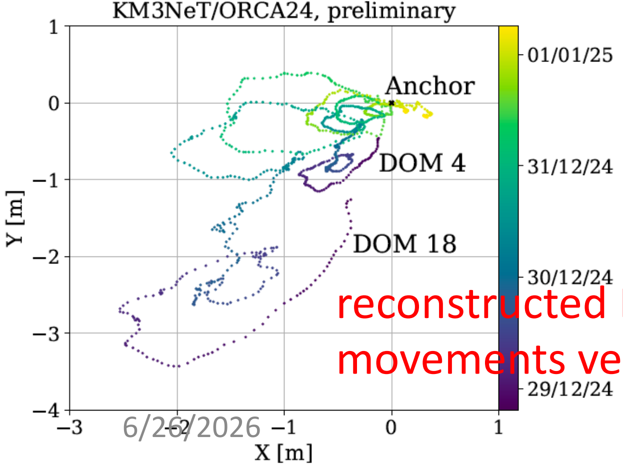
Positioning: acoustic triangulation using autonomous and DU-base emitters

PoS ICRC2025 (2025) 1095

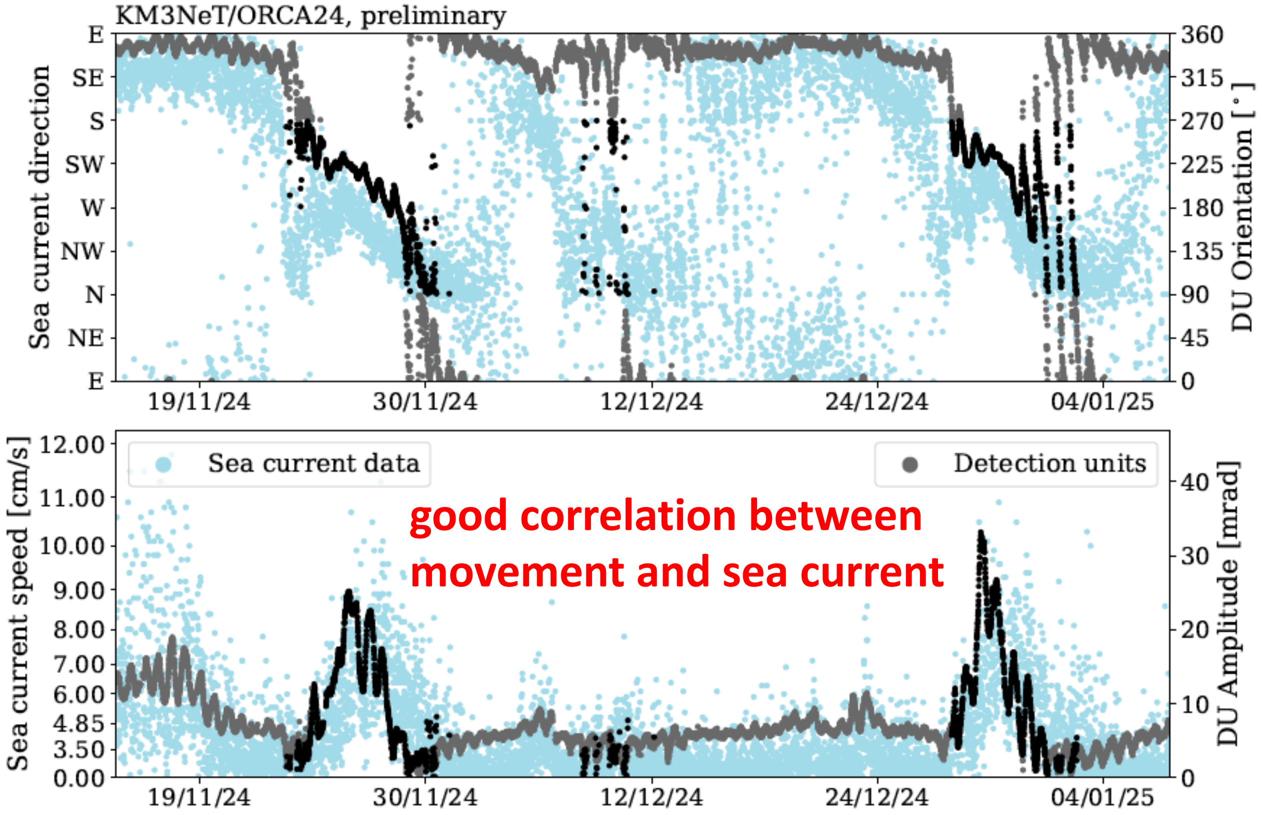


emitter positions

each DOM records sound



reconstructed DOM movements versus time

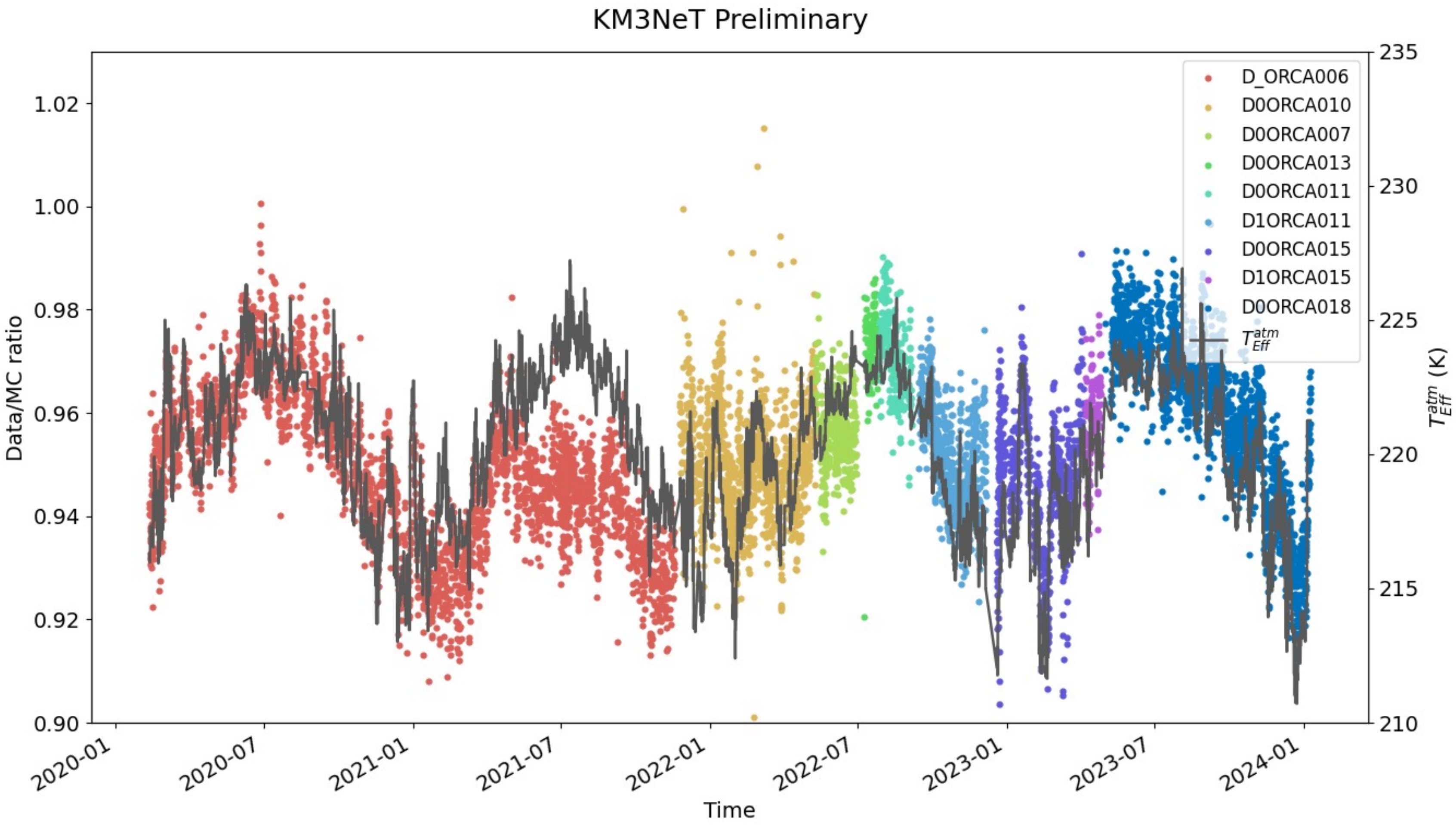


good correlation between movement and sea current

Cross-check: cosmic ray shadow of sun and moon)

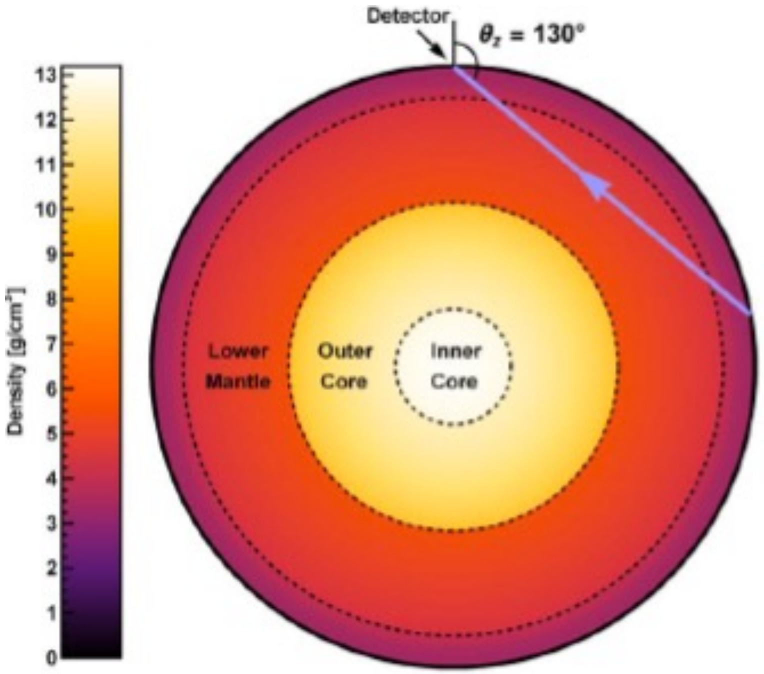
Data/MC muon rates after calibration

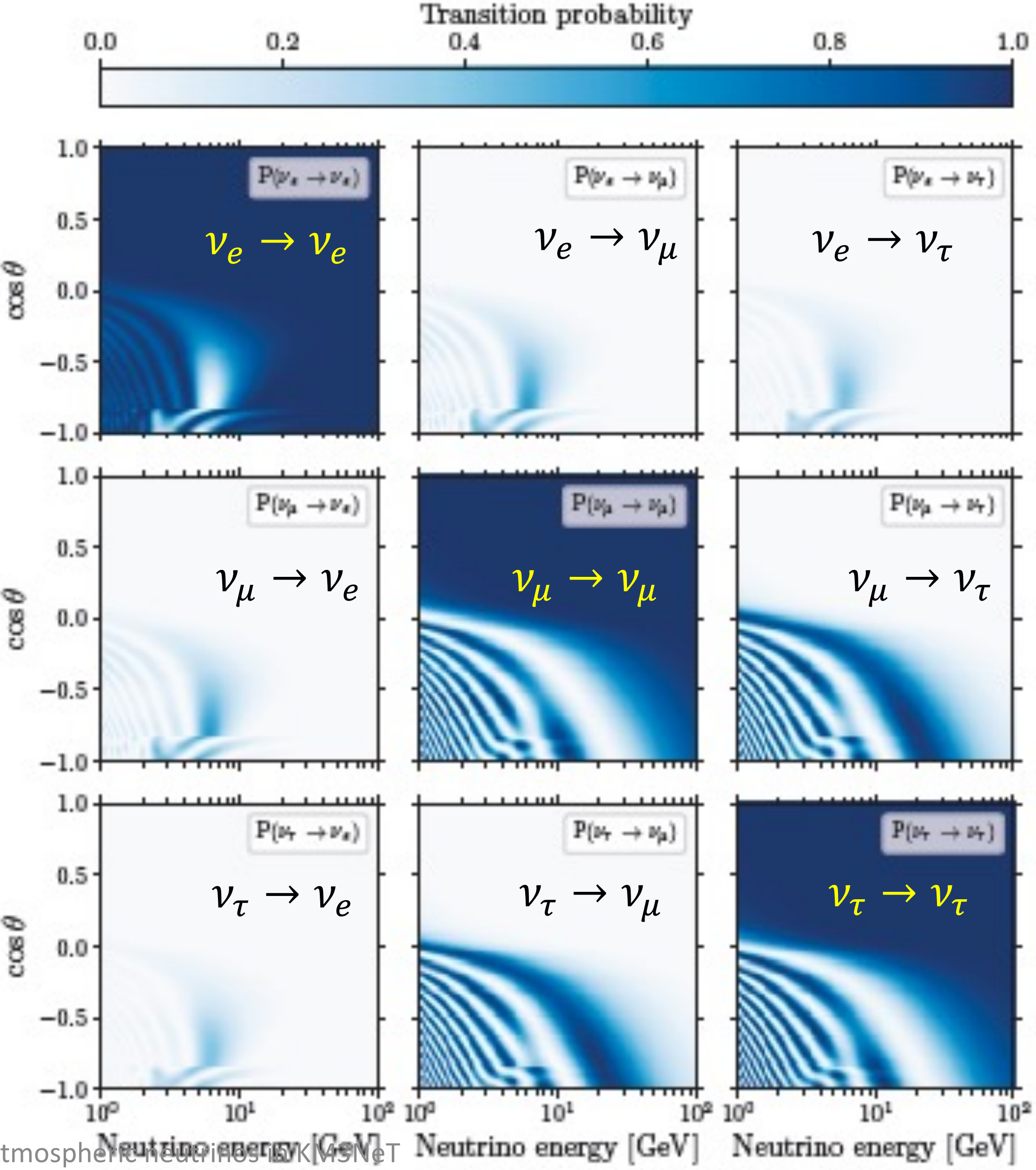
MC has all known detector calibrations implemented, but not the yearly flux changes due to atmospheric temperature variations.



Data/MC ratio follows annual cycle well

Oscillation physics with atmospheric neutrinos





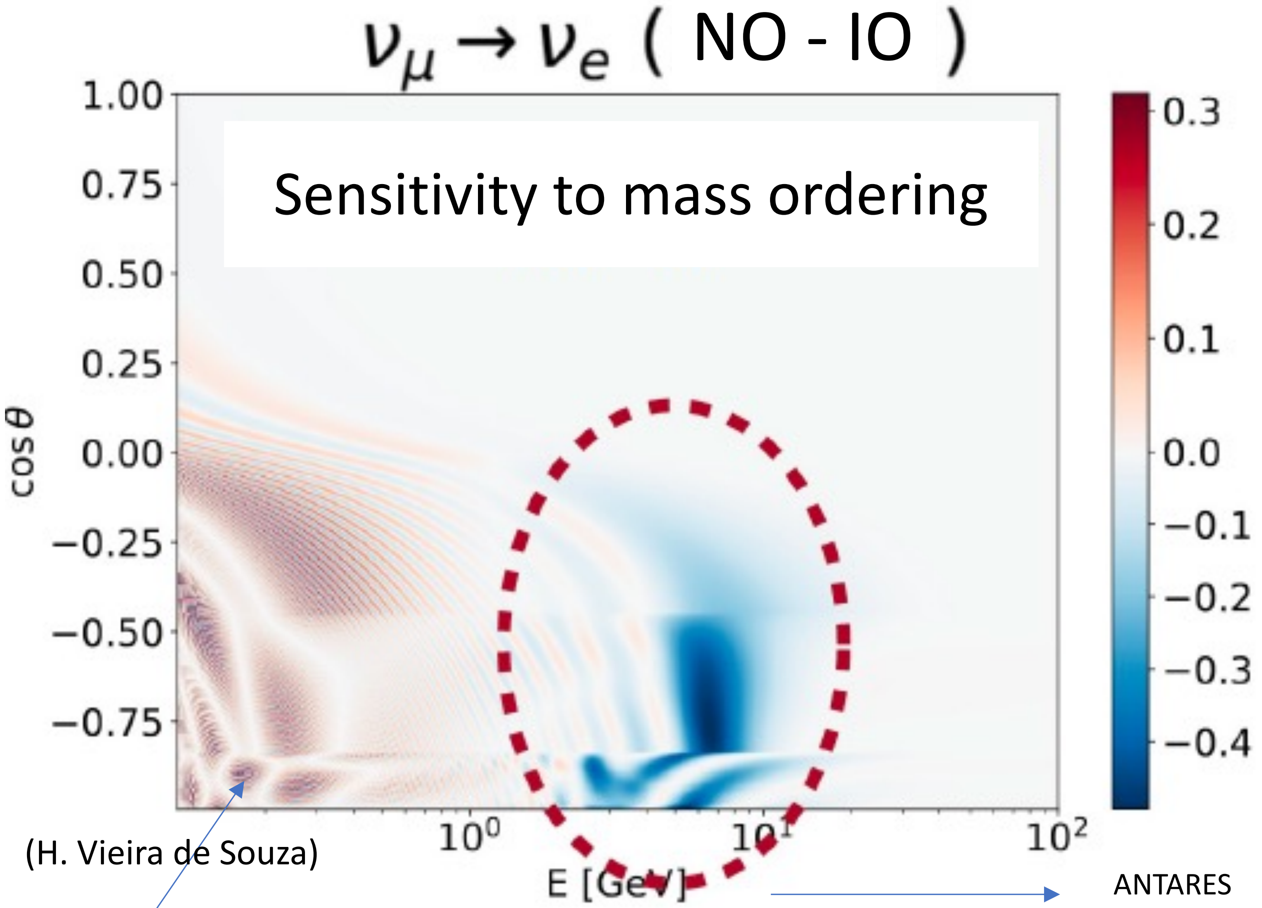
downgoing ↓

upgoing ↑

Long baselines: 10-12700 km
Baseline fully correlated with $\cos\theta$

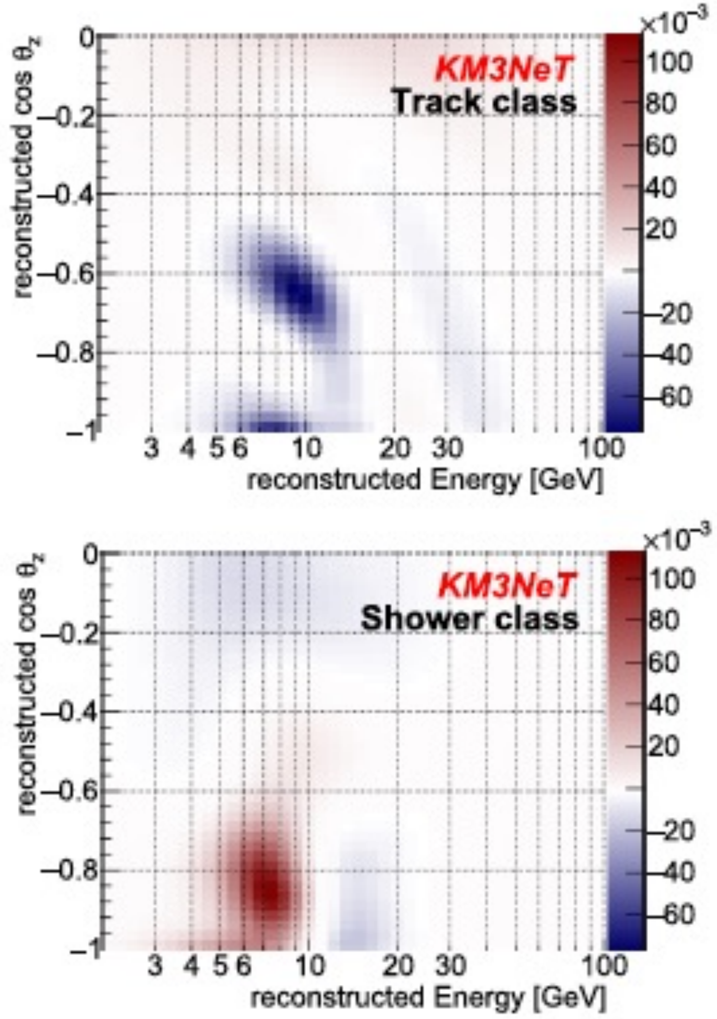
Matter effect: opportunity to measure the neutrino mass ordering

Relevant neutrino energy range (mass ordering)



(H. Vieira de Souza)

where do NO-IO differ?



ANTARES

ICECUBE/DEEPCORE

KM3NeT/ORCA

ICECUBE/UPGRADE

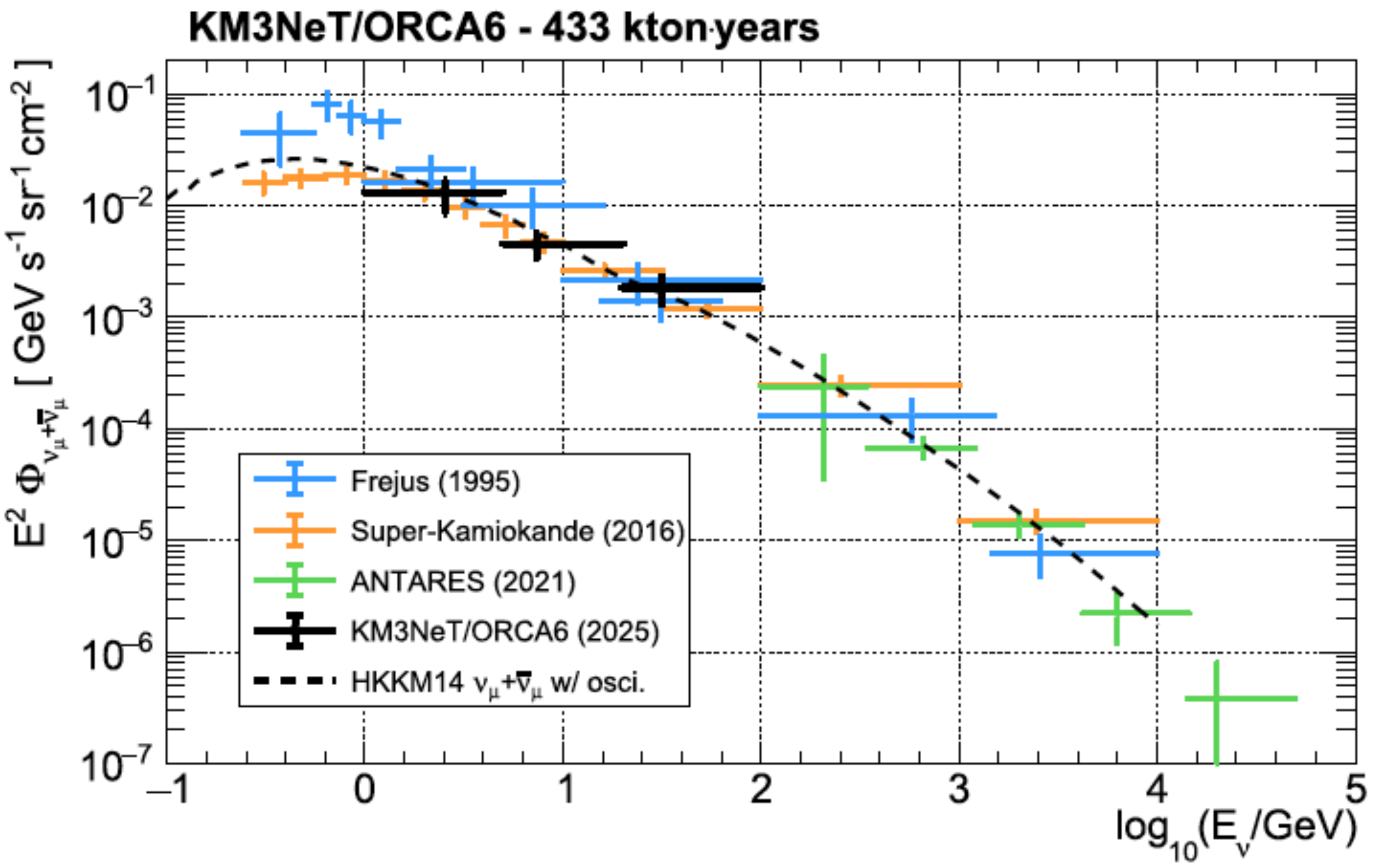
SUPER-K/HYPER-K/DUNE

some sensitivity to δ_{CP}

Atmospheric neutrino flux

Measurement of the atmospheric ν_μ flux with six detection units of KM3NeT/ORCA

Eur. Phys. J. C **85** (2025) 871



Measured flux is consistent with Honda HKKM14 model, but error bars still sizable.

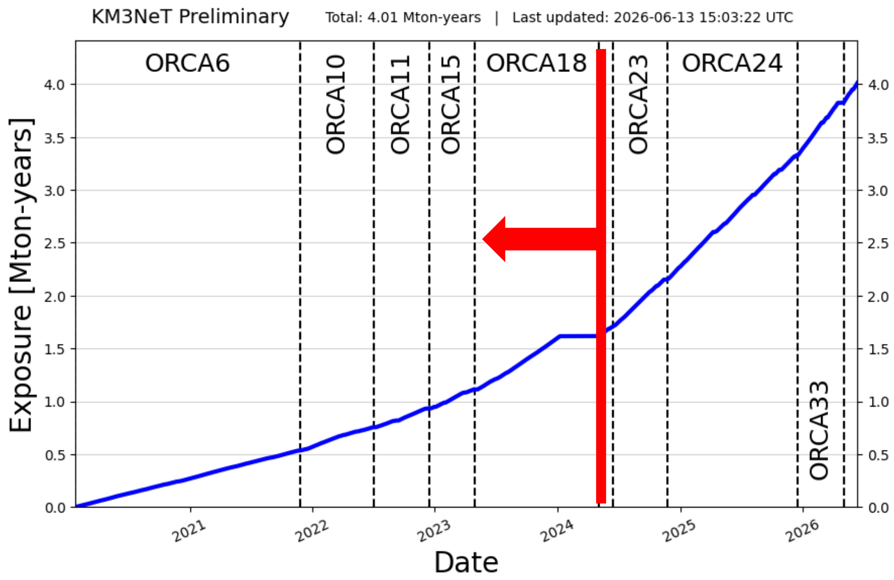
For this ORCA6-18 analysis:

We also tested an alternative flux model, based on DaemonFlux but not tuned for ORCA location, no geomagnetic effects, overshoot at low energies (HybridFlux). Parameters varied in flux systematics.

New Results for Neutrino 2026

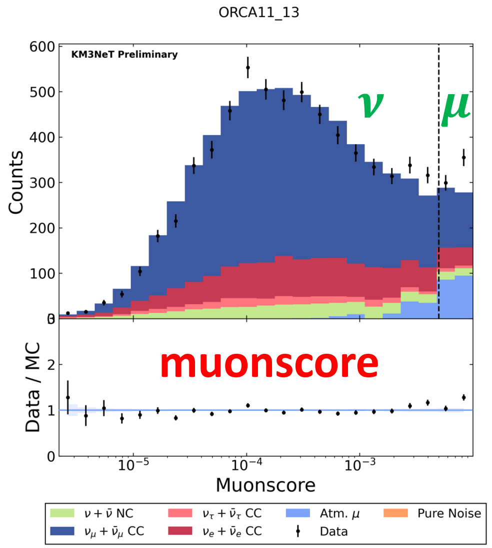
ORCA 6-18 (~4 years data)

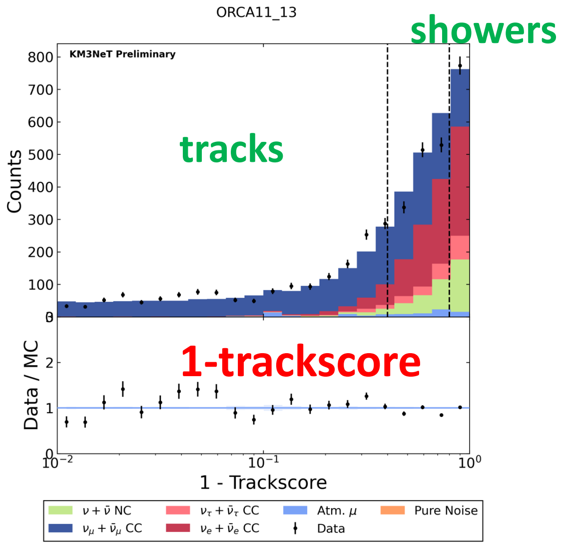
- Neutrino oscillations in 3-generation framework
- Tau neutrino production
- Limits on sterile neutrinos



Selection:

- basic quality criteria
- upgoing events
- noise rejection (random and sparks)
- atmospheric muon rejection (muonscore BDT)
- classification: track/shower/intermediate (BDT)





ORCA6-7 and ORCA11-18: exposure 1.4 Mton-years

ORCA data selection

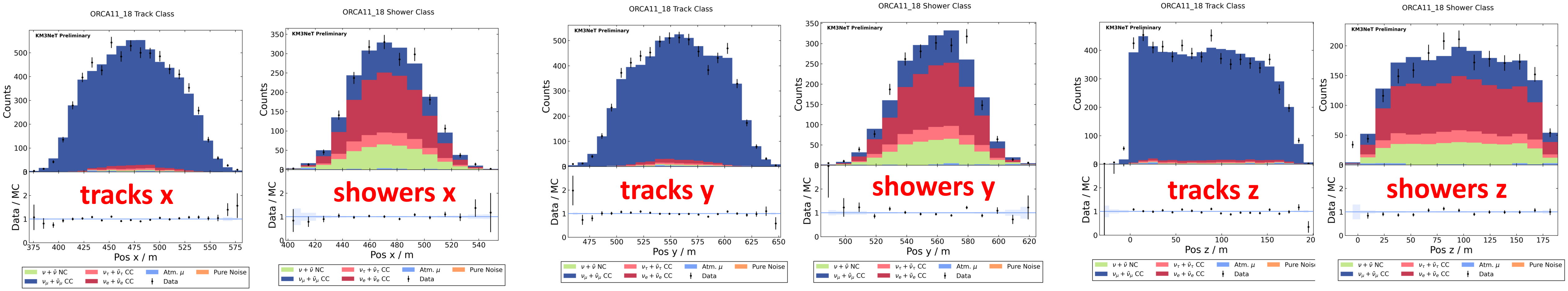
Event Type	ORCA6/7 tracks	ORCA6/7 interm.	ORCA6/7 showers	ORCA11–18 tracks	ORCA11–18 interm.	ORCA11–18 showers
$\nu_e \mathrm{CC} + \bar{\nu}_e \mathrm{CC}$	50	336	682	87	646	911
$\nu_\mu \mathrm{CC} + \bar{\nu}_\mu \mathrm{CC}$	3869	748	493	5641	1151	557
$\nu_\tau \mathrm{CC} + \bar{\nu}_\tau \mathrm{CC}$	36	80	176	53	141	212
$\nu \mathrm{NC} + \bar{\nu} \mathrm{NC}$	19	112	276	31	219	430
atmospheric $\mu + \bar{\mu}$	29	22	30	31	20	21
Total MC	4003	1298	1657	5843	2176	2131
Total Data	4098	1361	1586	6329	2236	2016

- pre-fit
- Honda flux

(μ contamination 0.9%)

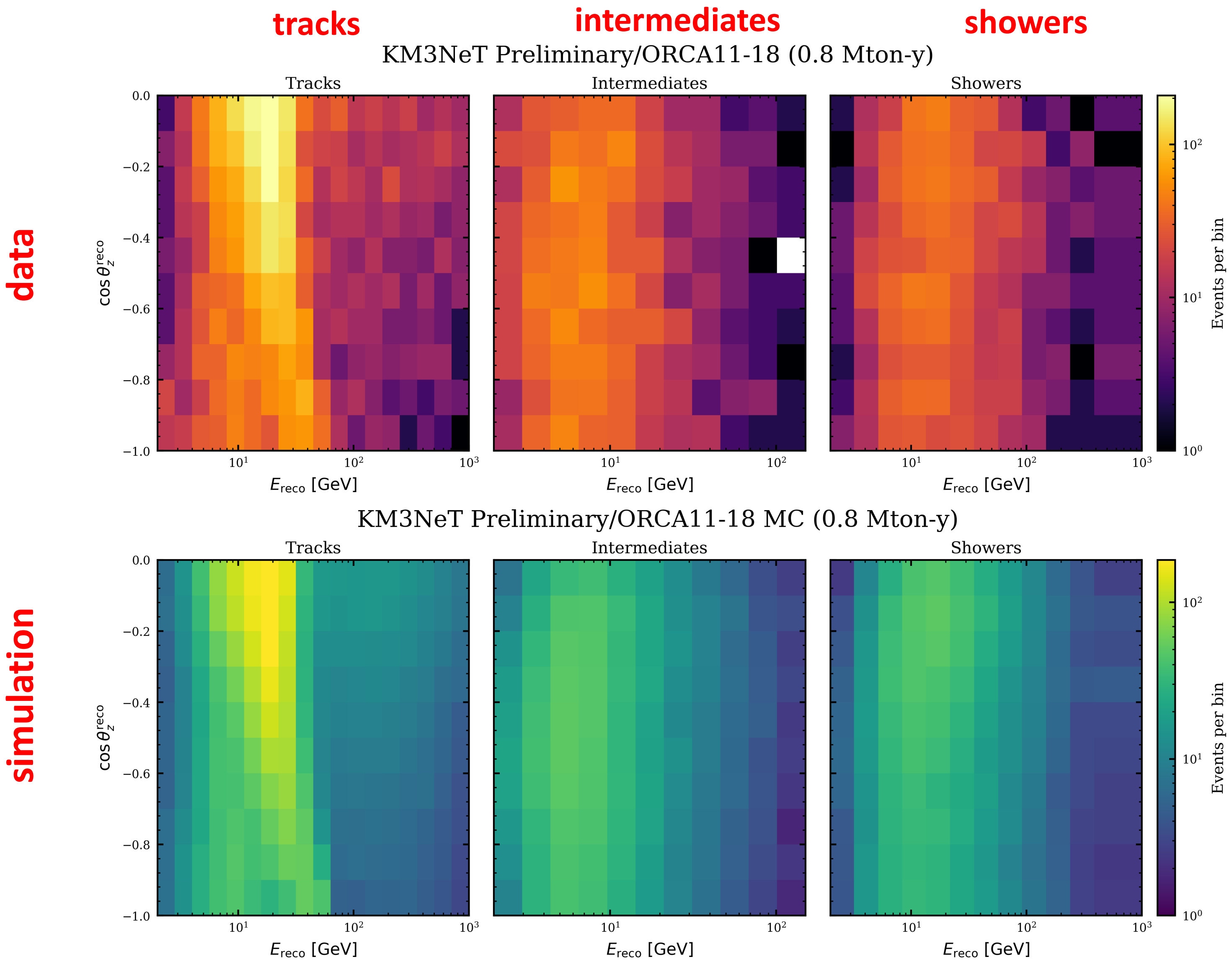
$\Sigma = 17108$ MC

$\Sigma = 17626$ Data



ORCA15-18, physical distributions of events in the detector

Oscillations fit procedure



Oscillations fit is performed on these 2D distributions of cos θ versus E

We split the data set in ORCA6-7 and ORCA11-18, with different reponse functions.

Systematics:

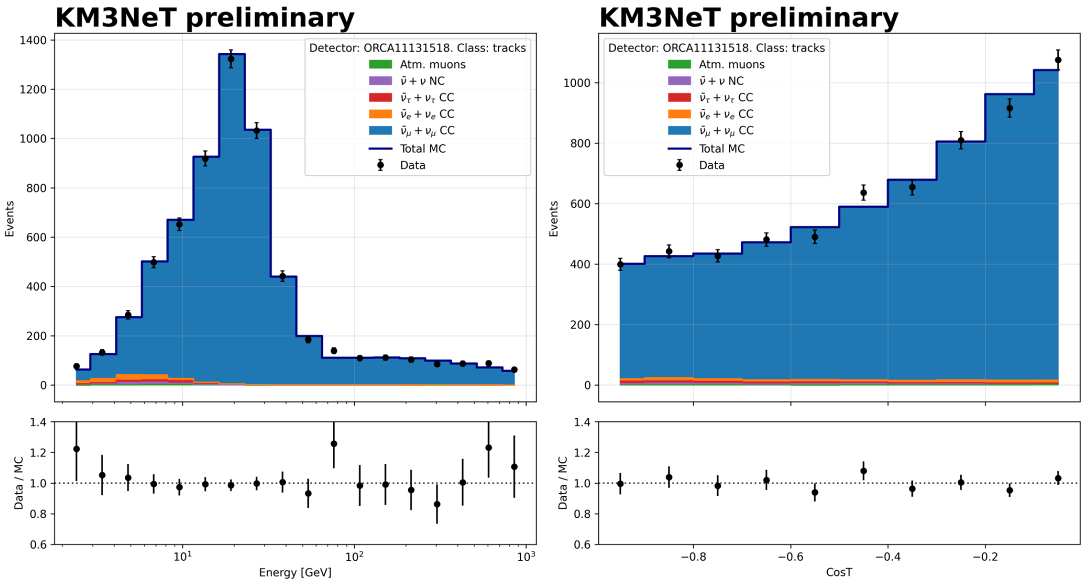
- Flux: HybridFlux parameter variation (also implemented for Honda flux)
- Cross sections: rescale QE, RES, NC, τ
- Detector: trigger efficiency, energy scale (including PMT QE and water properties)

The fit prefers the Honda flux over the HybridFlux by $\Delta\chi^2 = 3.6$

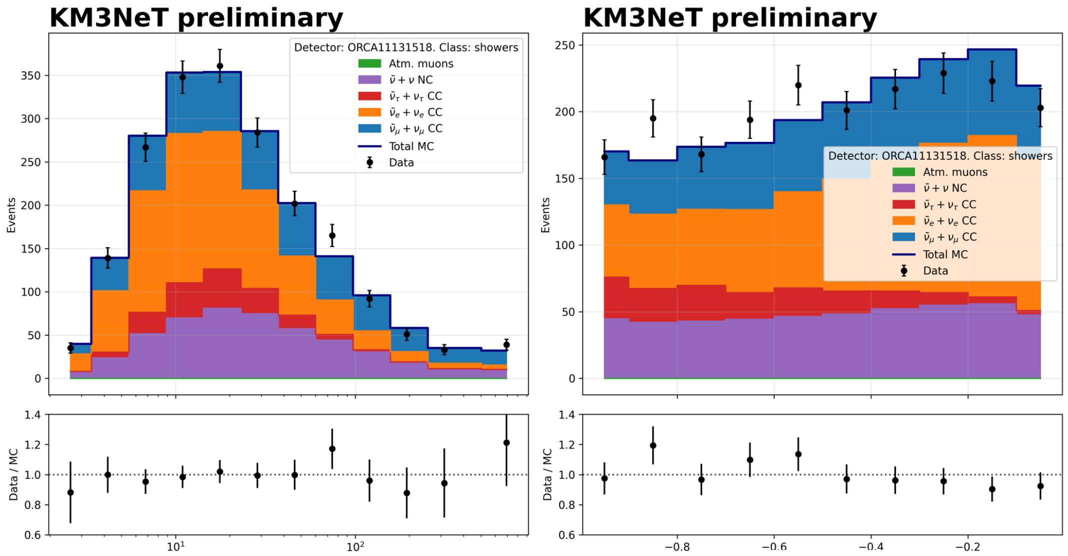
Results are quoted with the Honda flux.

Post-fit data

Tracks



Showers

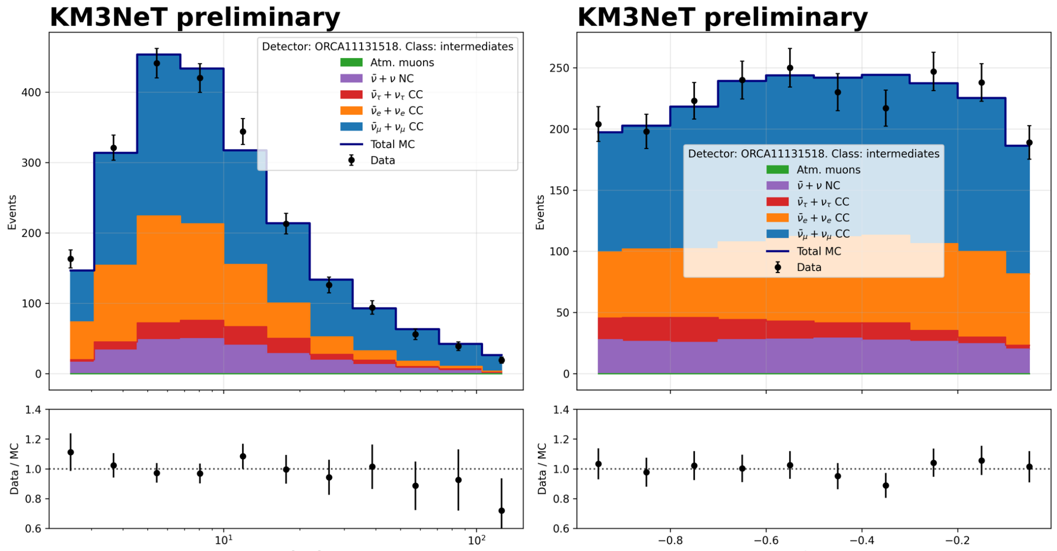


Energy [GeV]

$\cos\theta$

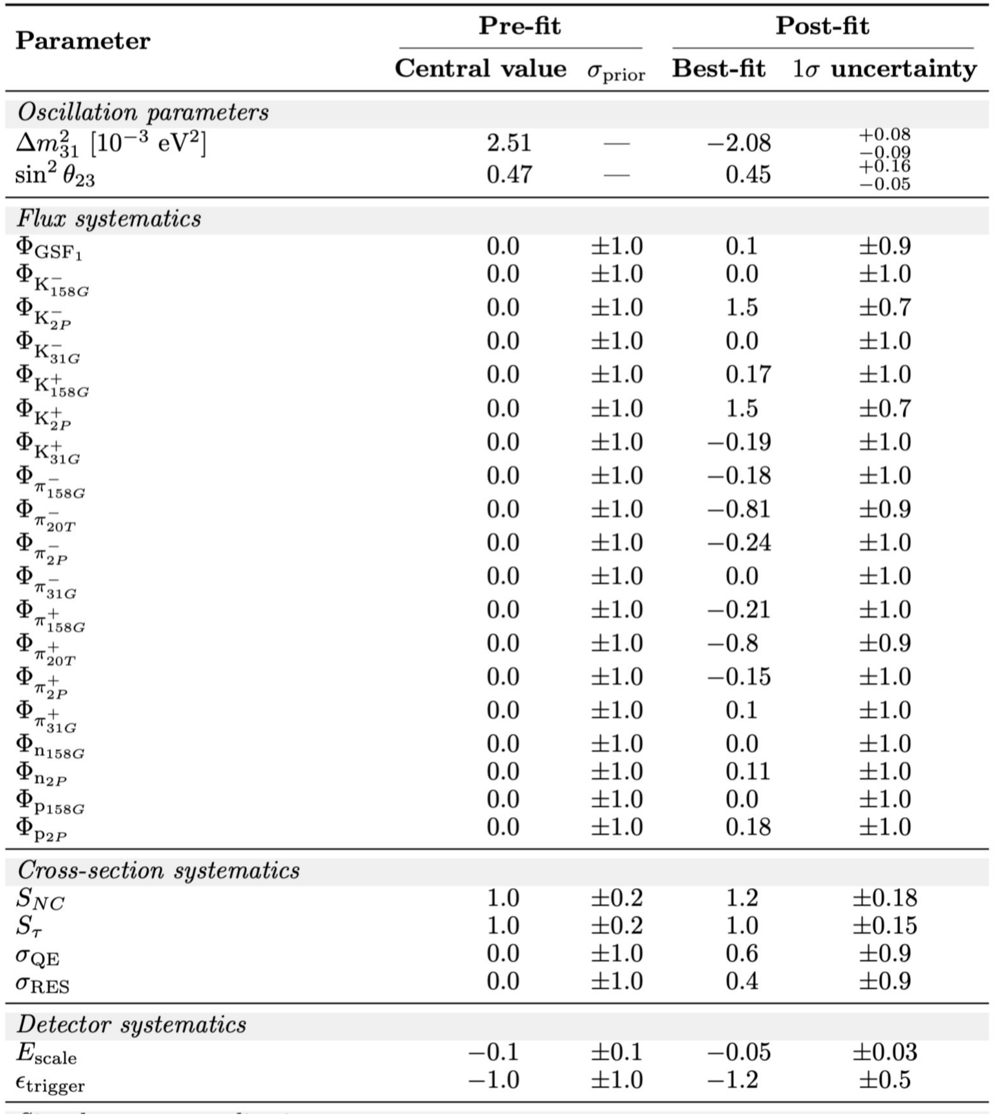
ORCA 11-18

Post-fit Energy and $\cos\theta$ distributions for tracks, showers, and intermediates



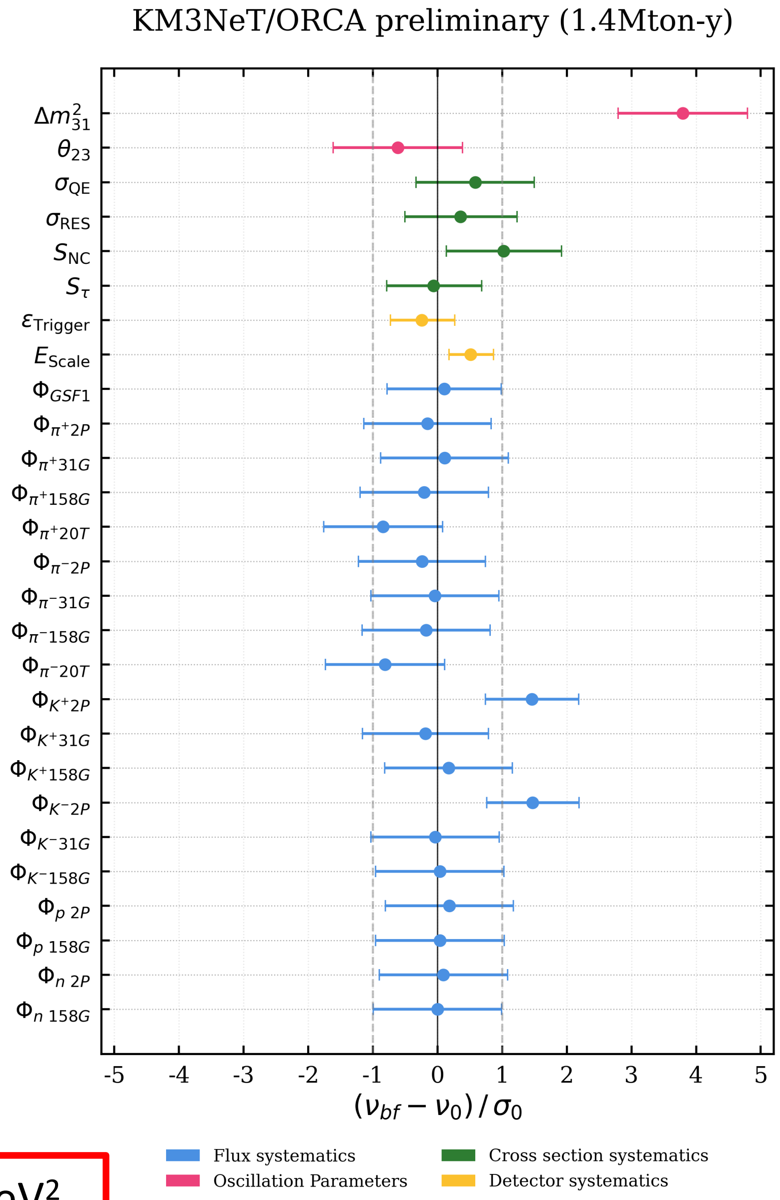
Intermediates

ORCA6-18 oscillations fit result, 1.4 Mton-year



Parameter	Pre-fit		Post-fit	
	Central value	σ_{prior}	Best-fit	1σ uncertainty
Oscillation parameters				
Δm^2_{31} $[10^{-3}\ \text{eV}^2]$	2.51	—	−2.08	$^{+0.08}_{-0.09}$
$\sin^2\theta_{23}$	0.47	—	0.45	$^{+0.16}_{-0.05}$
Flux systematics				
Φ_{GSF_1}	0.0	±1.0	0.1	±0.9
$\Phi_{\text{K}^-_{158G}}$	0.0	±1.0	0.0	±1.0
$\Phi_{\text{K}^-_{2P}}$	0.0	±1.0	1.5	±0.7
$\Phi_{\text{K}^-_{31G}}$	0.0	±1.0	0.0	±1.0
$\Phi_{\text{K}^+_{158G}}$	0.0	±1.0	0.17	±1.0
$\Phi_{\text{K}^+_{2P}}$	0.0	±1.0	1.5	±0.7
$\Phi_{\text{K}^+_{31G}}$	0.0	±1.0	−0.19	±1.0
$\Phi_{\pi^-_{158G}}$	0.0	±1.0	−0.18	±1.0
$\Phi_{\pi^-_{20T}}$	0.0	±1.0	−0.81	±0.9
$\Phi_{\pi^-_{2P}}$	0.0	±1.0	−0.24	±1.0
$\Phi_{\pi^-_{31G}}$	0.0	±1.0	0.0	±1.0
$\Phi_{\pi^+_{158G}}$	0.0	±1.0	−0.21	±1.0
$\Phi_{\pi^+_{20T}}$	0.0	±1.0	−0.8	±0.9
$\Phi_{\pi^+_{2P}}$	0.0	±1.0	−0.15	±1.0
$\Phi_{\pi^+_{31G}}$	0.0	±1.0	0.1	±1.0
$\Phi_{\text{n}_{158G}}$	0.0	±1.0	0.0	±1.0
$\Phi_{\text{n}_{2P}}$	0.0	±1.0	0.11	±1.0
$\Phi_{\text{p}_{158G}}$	0.0	±1.0	0.0	±1.0
$\Phi_{\text{p}_{2P}}$	0.0	±1.0	0.18	±1.0
Cross-section systematics				
S_{NC}	1.0	±0.2	1.2	±0.18
S_τ	1.0	±0.2	1.0	±0.15
σ_{QE}	0.0	±1.0	0.6	±0.9
σ_{RES}	0.0	±1.0	0.4	±0.9
Detector systematics				
E_{scale}	−0.1	±0.1	−0.05	±0.03
$\epsilon_{\text{trigger}}$	−1.0	±1.0	−1.2	±0.5

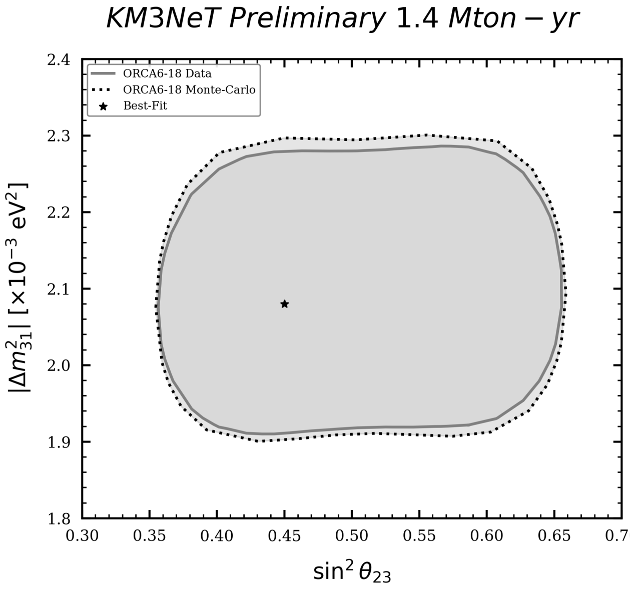
$$\sin^2\theta_{23} = 0.45^{+0.16}_{-0.05}, \Delta m^2_{31} = (-2.08^{+0.08}_{-0.09}) \cdot 10^{-3}\ \text{eV}^2$$



No large pulls in nuisance parameters.

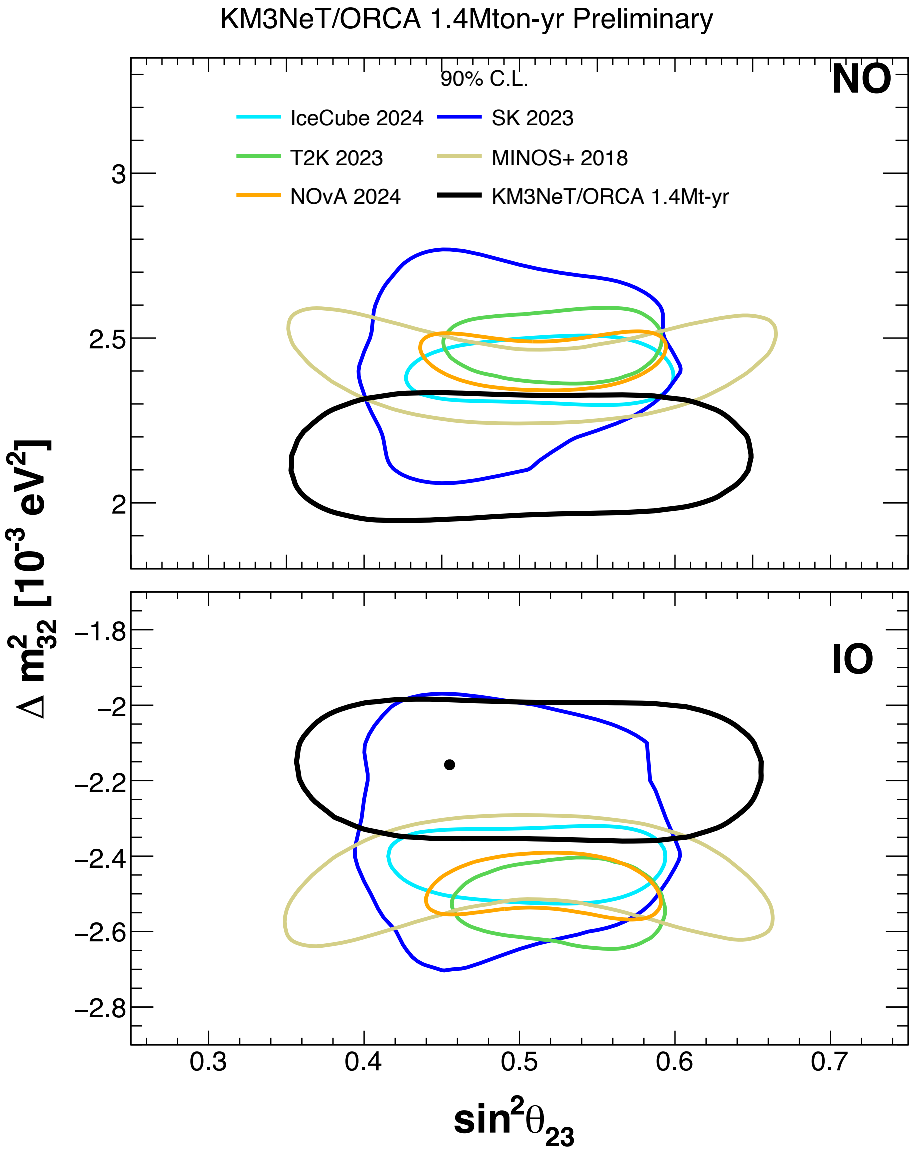
Largest pull in Δm^2_{31}

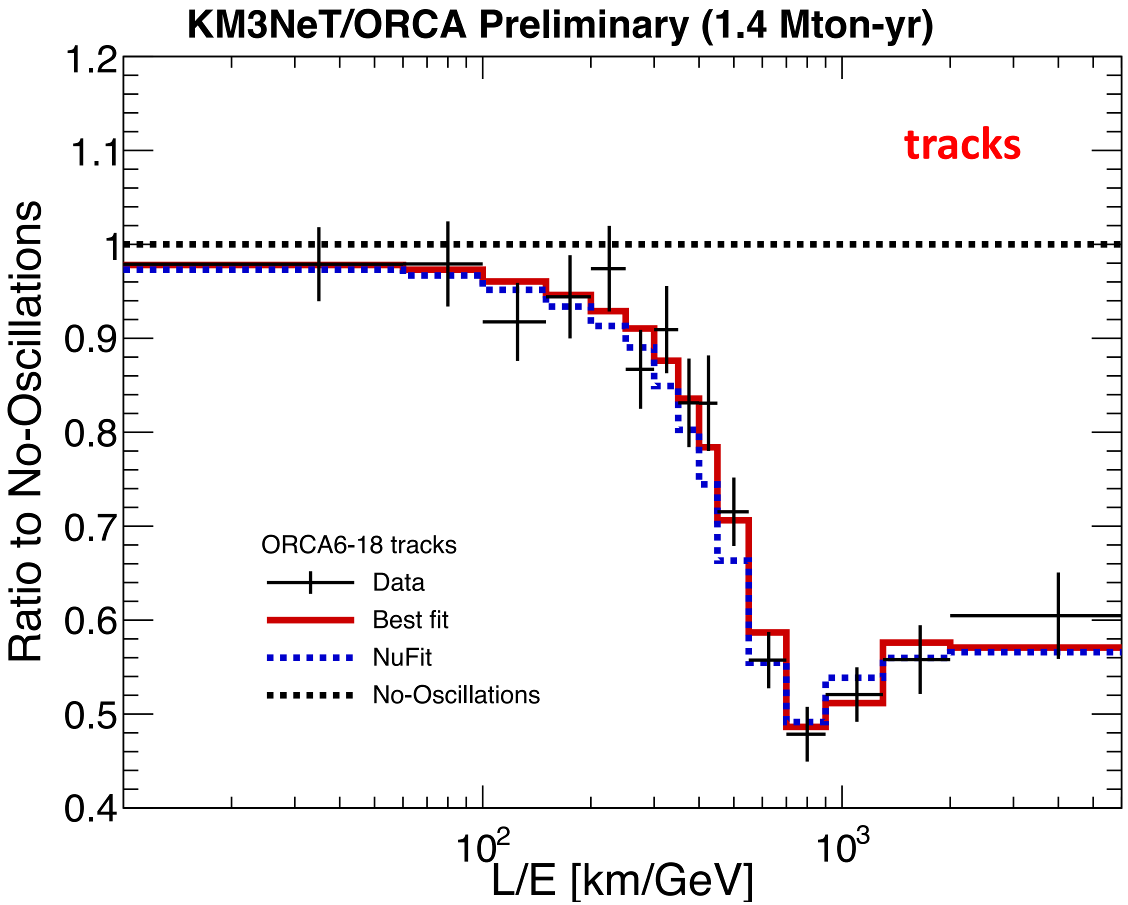
90% CL contour in data on top of expectation



Poster #97, V. Kueviakoe

ORCA6-18 oscillations fit result, 1.4 Mton-year



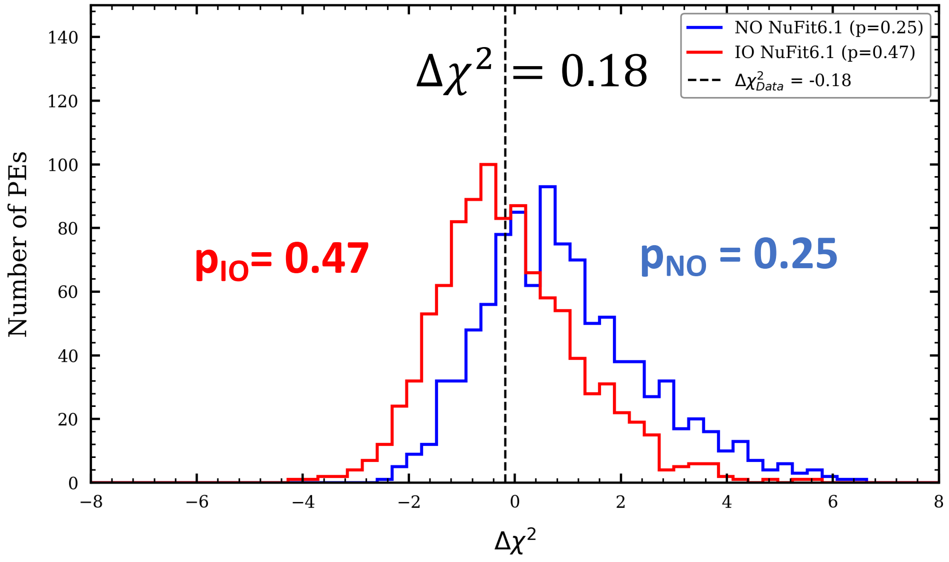


ORCA6-18 oscillations fit result, 1.4 Mton-year

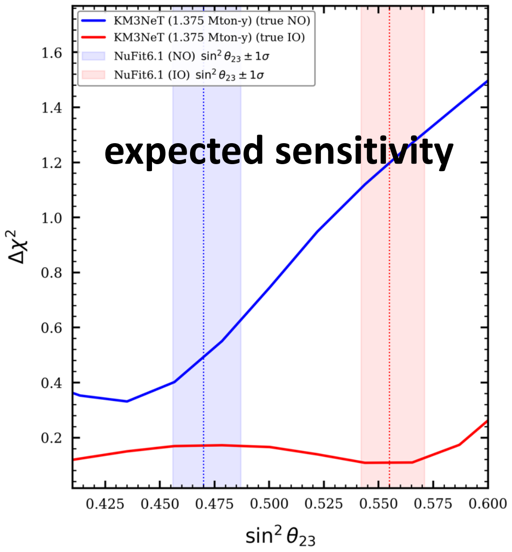
Neutrino Mass Ordering

We strive towards a single-experiment determination of the NMO

KM3NeT Preliminary



KM3NeT Preliminary



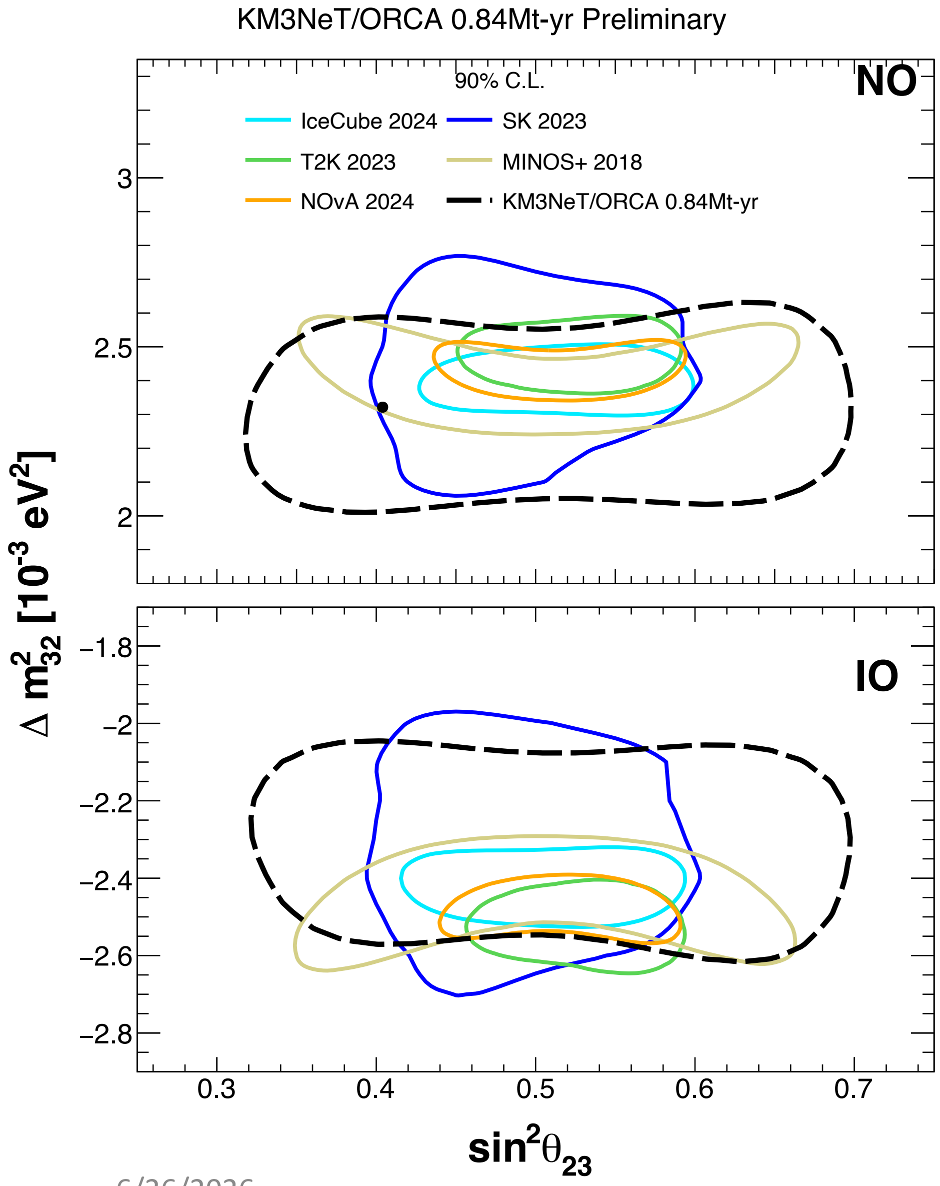
However, with external input from reactor expts. (Daya Bay and JUNO, **very very preliminary**):

$$\chi^2_{IO} - \chi^2_{NO} \approx 4.0$$

(preference for NO)

Slight preference for the IO, not statistically significant (as expected)

New data of ORCA11-18 only



In this analysis, ORCA6 data was reanalysed as part of the ORCA6-18 sample, with re-optimised selection criteria.

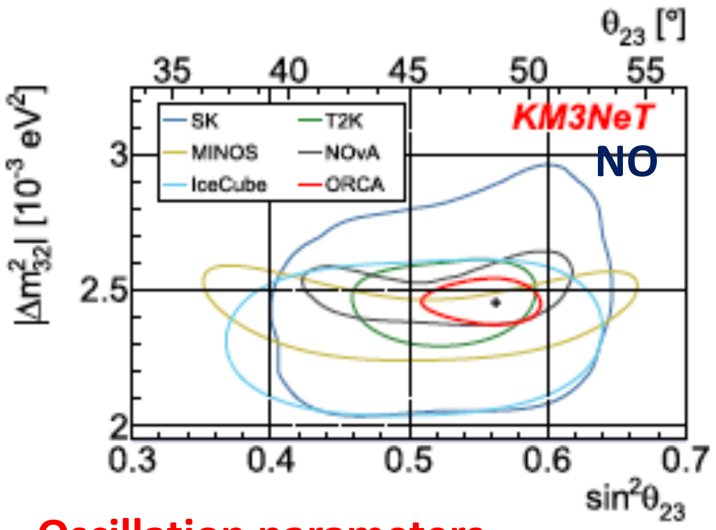
Results are consistent with earlier ORCA6 publication.
J. High Energ. Phys. **2024**, 206 (2024)

We also fit new data ORCA11-18, 0.84 Mton-year, alone

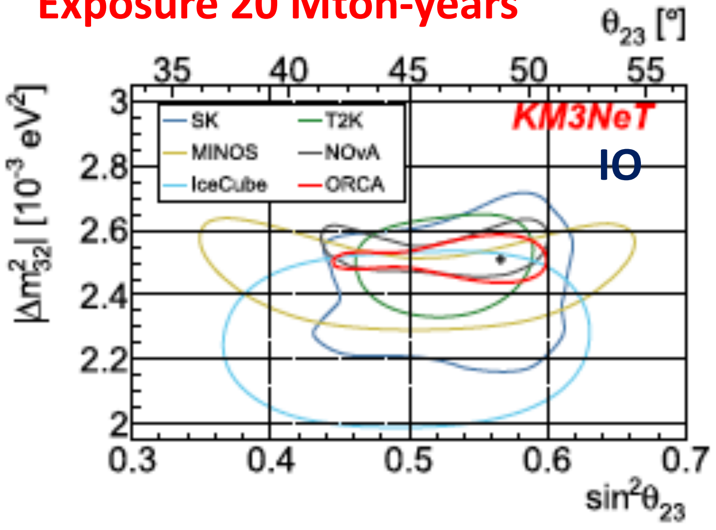
Within uncertainties, ORCA6-7 and ORCA11-18 are statistically consistent.

ORCA11-18 alone prefers somewhat higher Δm^2_{32} than ORCA6-7, and prefers NO over IO

Outlook to growing ORCA detector



Oscillation parameters
Exposure 20 Mton-years

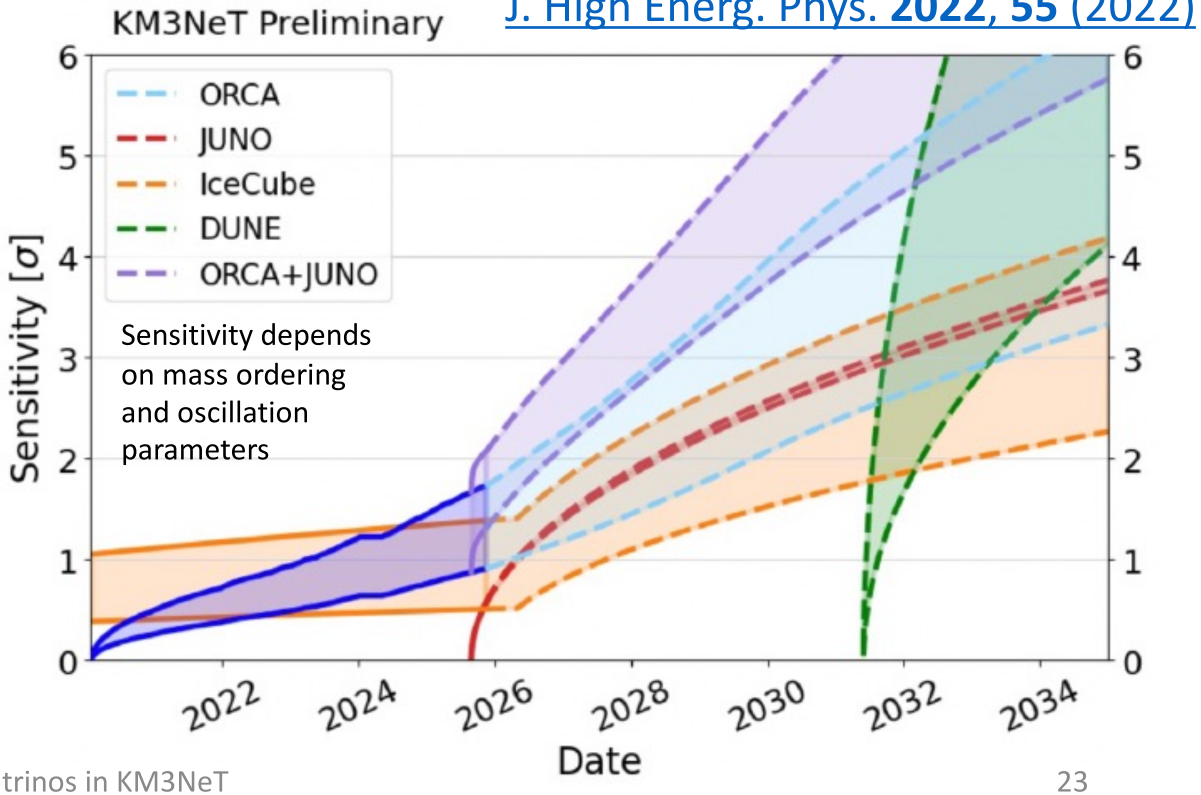


Eur. Phys. J. C **82,** 26 (**2022**)

ORCA keeps growing, from 38 DUs now, to 52 DUs (node 2 filled, 2027), to 80 DUs (node 3 filled, 2028/2029), to 108 DUs (node 4 filled, 2030) (roughly: 2.3 Mton → 3.1 Mton → 4.8 Mton → 6.5 Mton)

Sensitivity to mass ordering with realistic detector growth:

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

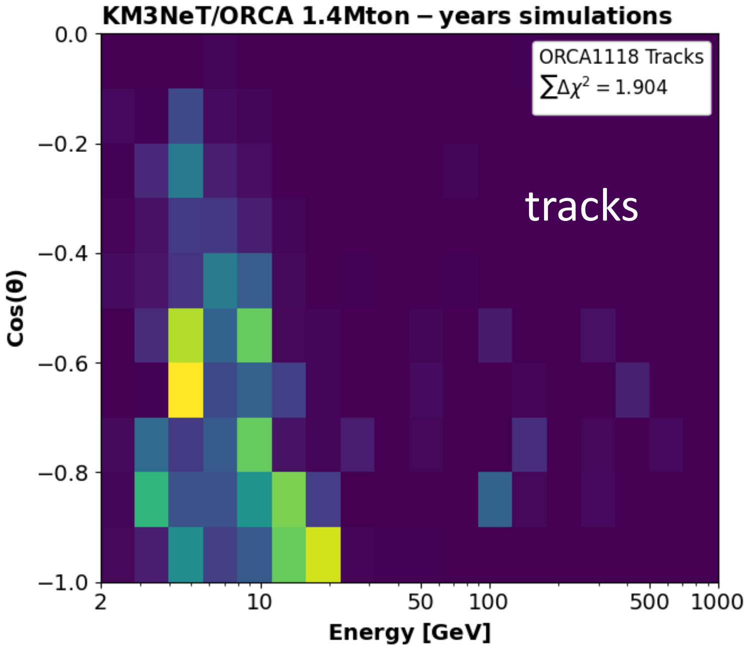


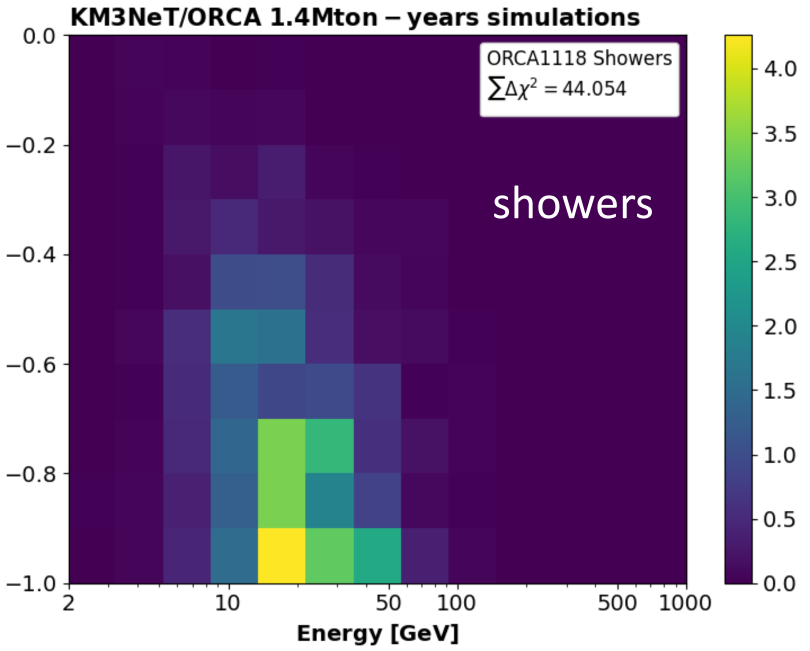
Sensitivity depends on mass ordering and oscillation parameters

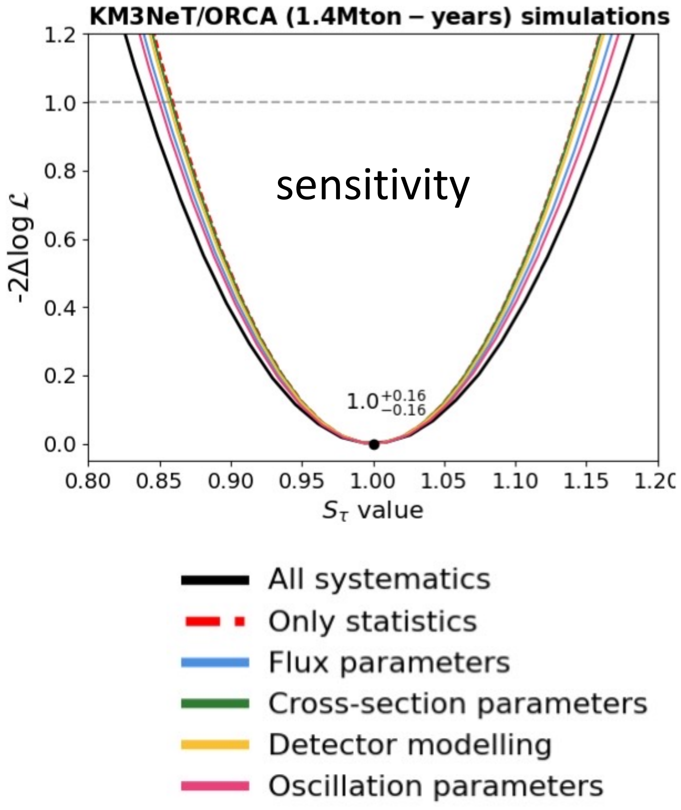
Tau neutrino appearance

Tau neutrinos mostly originate from oscillations of muon neutrinos.
We leave the tau neutrino normalisation S_τ free in the fit.
Tau neutrinos are best visible in the shower sample.

Simulations: where does S_τ sensitivity come from?



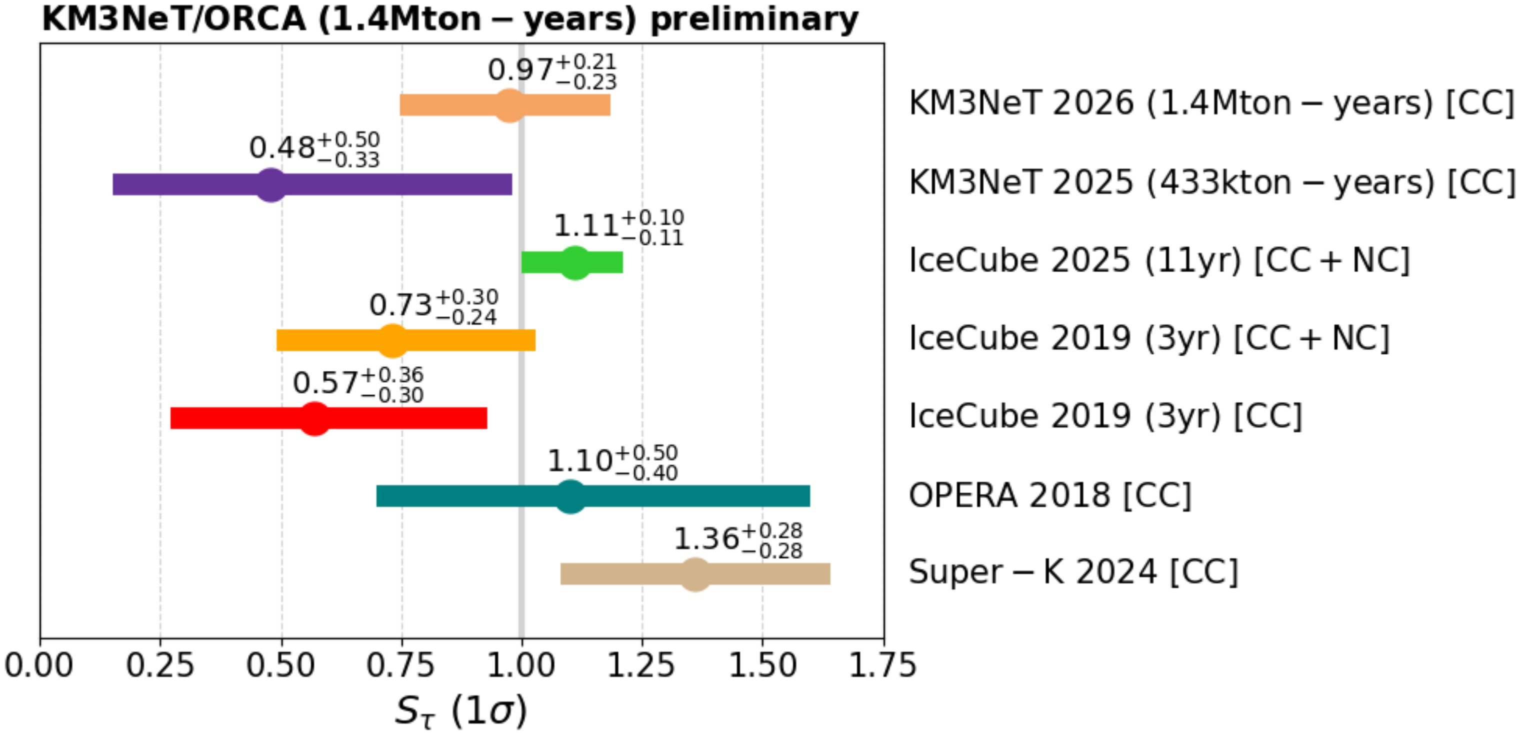


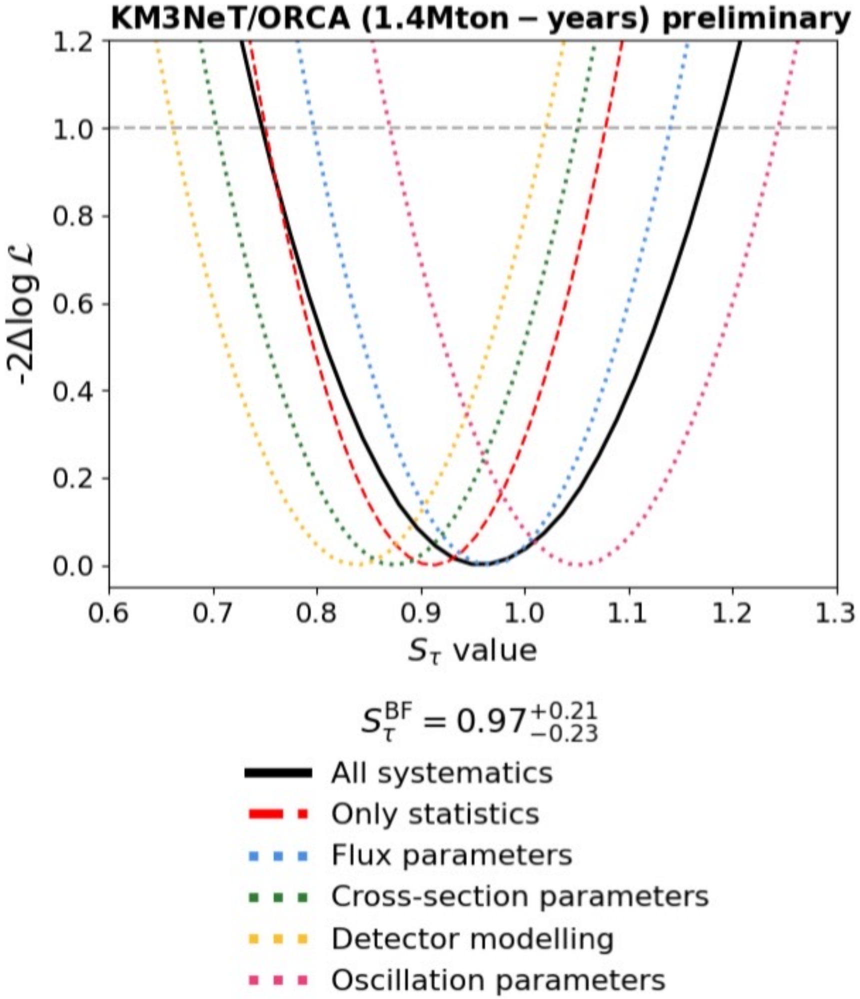


Tau neutrino appearance

Result: $S_\tau = 0.97^{+0.21}_{-0.23}$

$N_\tau = 680 \pm 150$



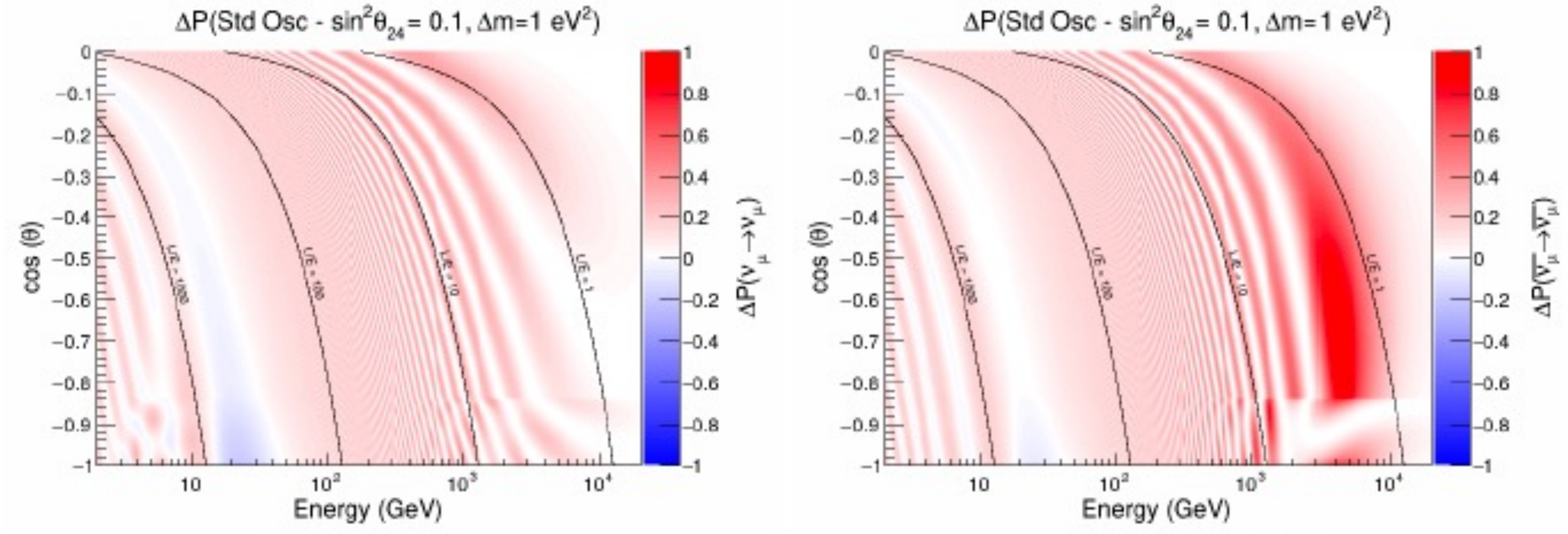


Sterile neutrinos

GeV-range atmospheric neutrinos have the right E/L to also show sensitivity to modifications of oscillations arising from a 3+1 neutrino model, with $\Delta m^2_{41} \approx 1$ eV^2

ORCA sensitivy is fairly constant for Δm^2 between 0.2 and 10 eV^2, we assume 1 eV^2 in this analysis.
Under that assumption, and assuming $\theta_{14} = 0$, we fit $|U_{\mu 4}|^2 = \sin^2\theta_{24}$ and $|U_{\tau 4}|^2 = \cos^2\theta_{24}\sin^2\theta_{34}$

Expected difference with standard oscillations for $\sin^2\theta_{24} = 0.1$



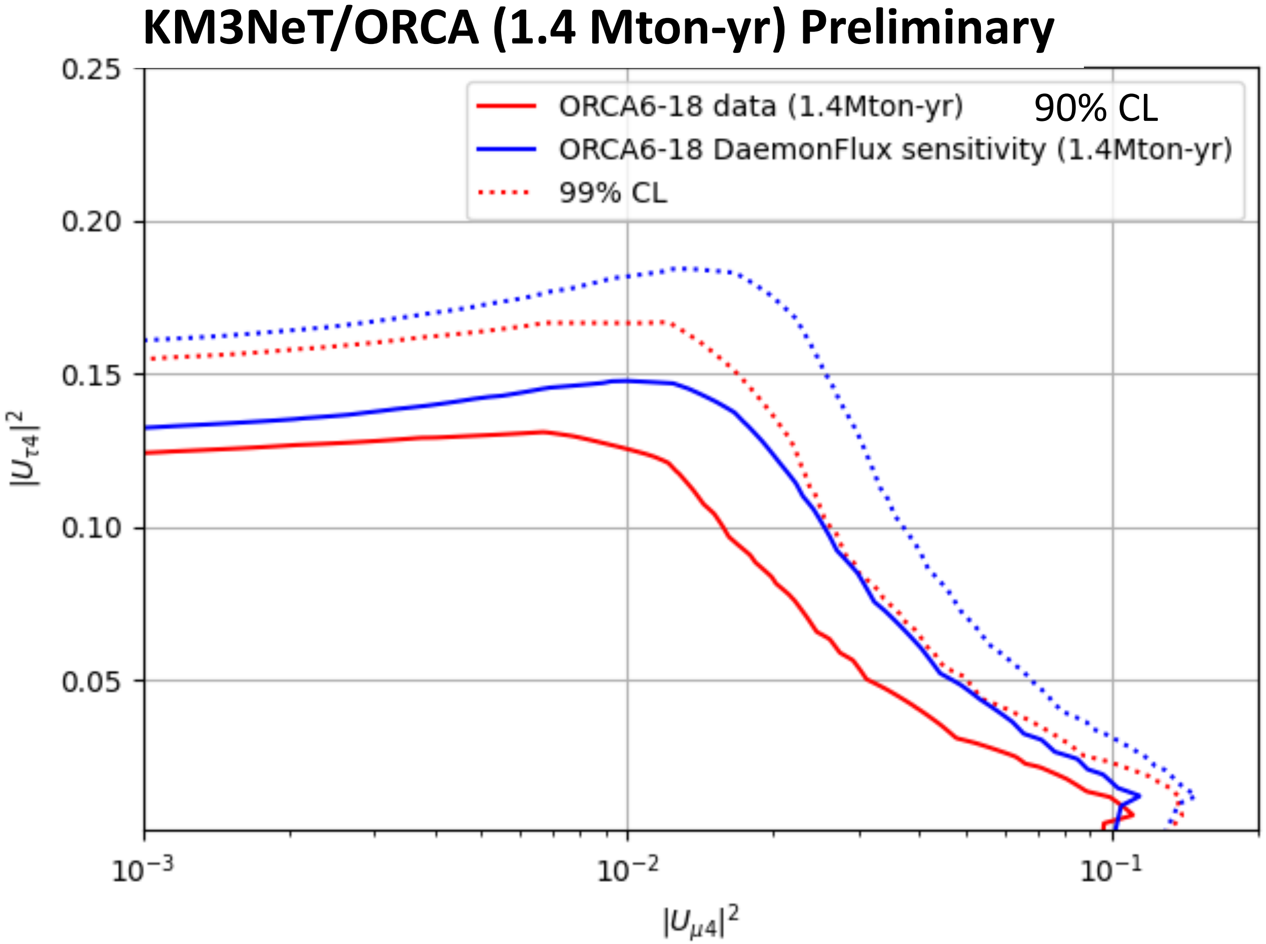
(a) $P(\nu_\mu \rightarrow \nu_\mu)$

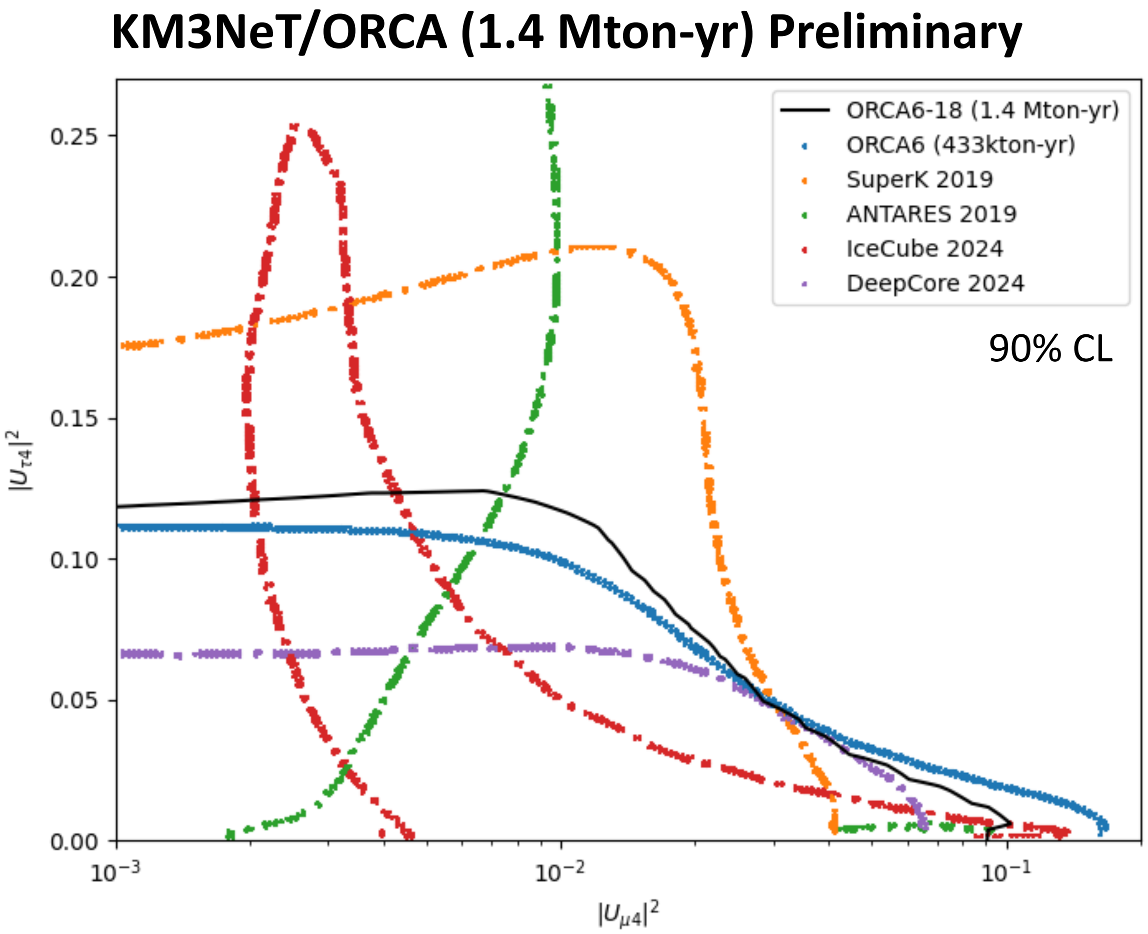
(b) $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu)$

Sterile neutrinos

Poster #112, R. Clark

Data: no evidence for sterile neutrinos: limits set on $|U_{\mu 4}|^2$ and $|U_{\tau 4}|^2$





Results on ORCA6 only

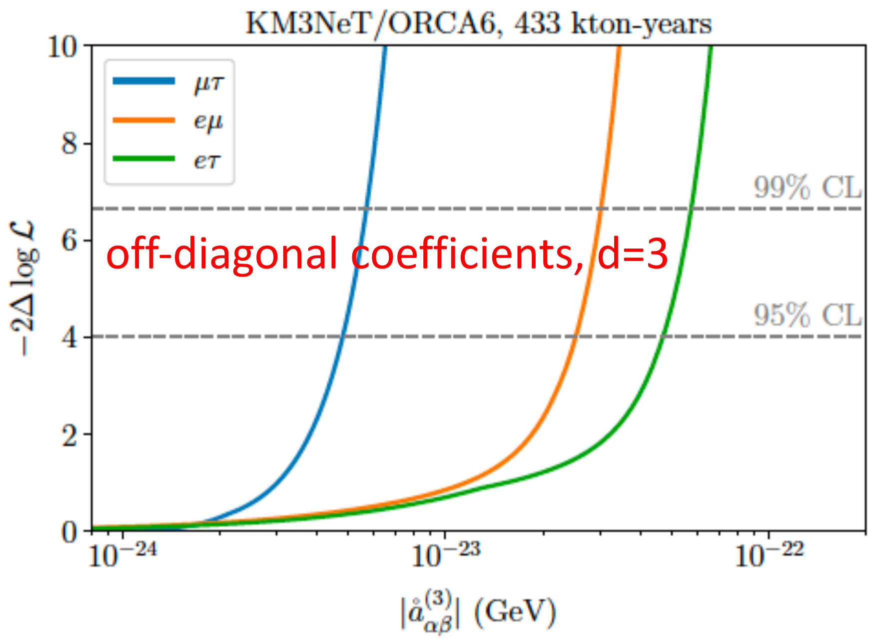
Published earlier: - *Limits on Invisible Neutrino Decay* [*J. High Energ. Phys.* **2025**, 105 (2025)]
- *Limits on Non-Standard Interactions* JCAP 02 (2025) 073
- *Limits on Quantum Decoherence* JCAP 03 (2025) 039

New: arxiv:2603.04264

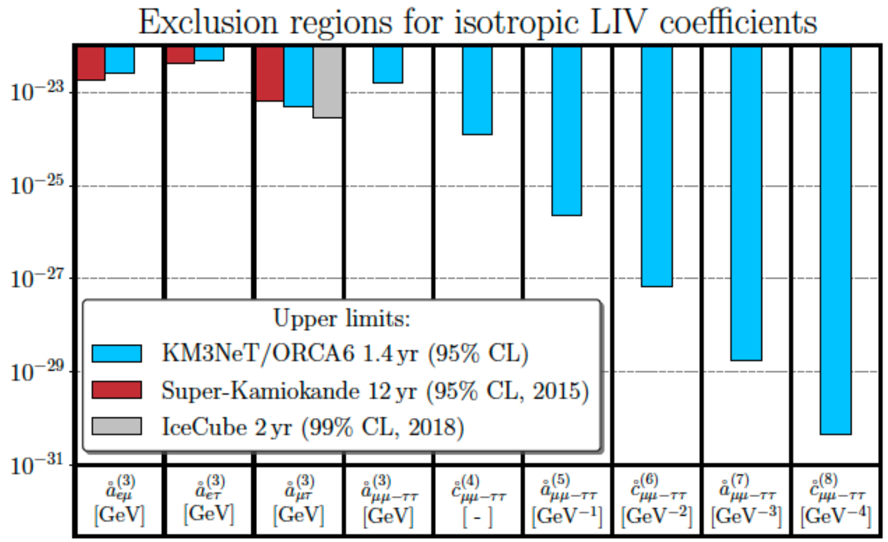
Atmospheric neutrino constraints on Lorentz Invariance Violation with the first six detection units of KM3NeT/ORCA

Within Standard Model Extension framework (EFT), we investigate isotropic LIV.

Limits are set on a number of coefficients corresponding to operators of dimensions d = 3-8.



off-diagonal coefficients, d=3



KM3NeT/ORCA6, 433 kton-years

off-diagonal and diagonal, d=3-8

Summary and conclusions

KM3NeT provides an infrastructure at two locations in the Mediterranean Sea
for neutrino physics and astronomy, for earth and sea sciences and marine biology.

KM3NeT/ORCA is currently a 2.3 Mton water Cherenkov neutrino detector for atmospheric neutrinos with energies above 2 GeV, and will grow to 6.5 Mton in 2030.

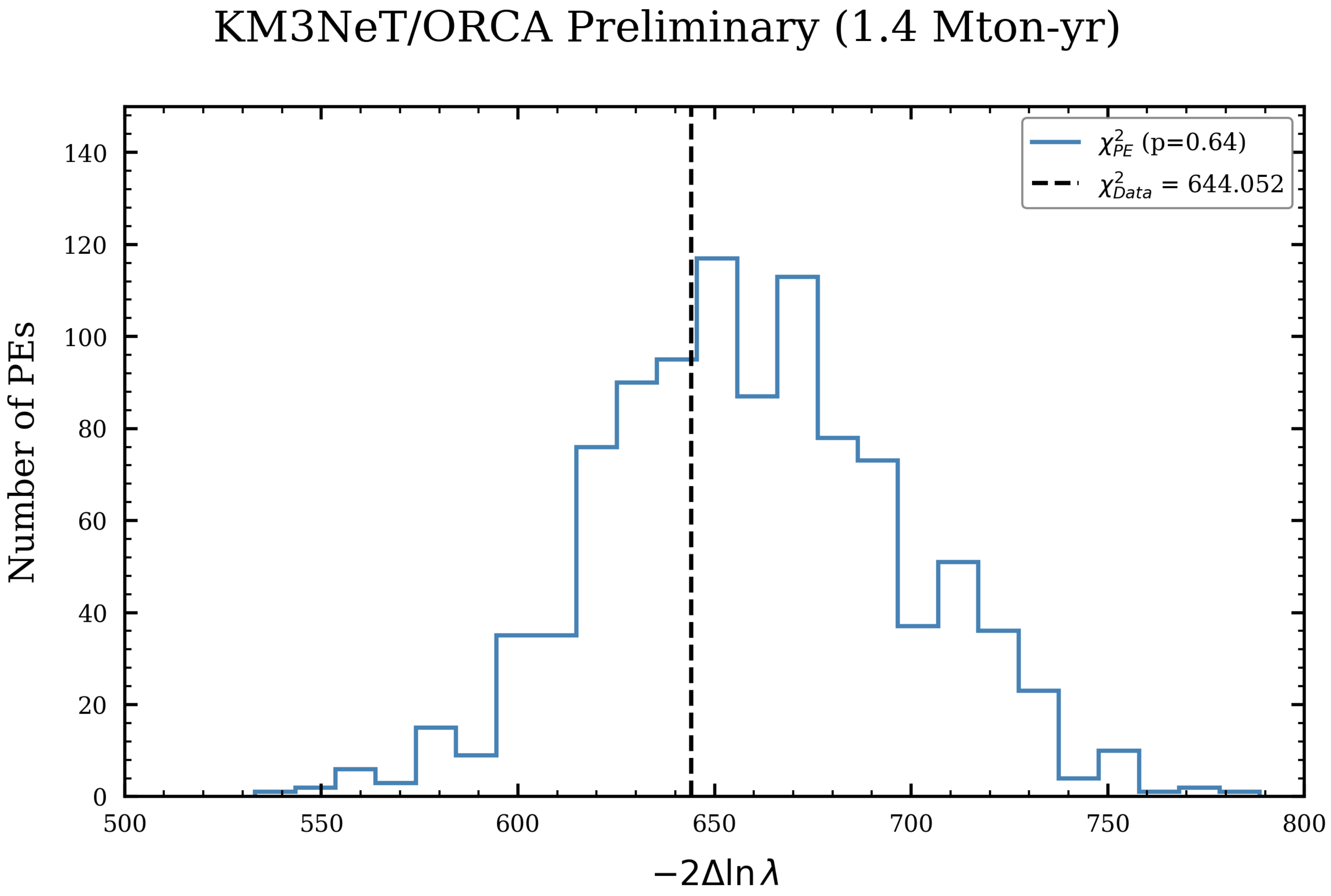
ORCA measures oscillations of atmospheric neutrinos, and is sensitive to the Neutrino Mass Ordering, as well as physics beyond the Standard Model.

With the data of ORCA 6-18 (1.4 Mton-year exposure) we measure:

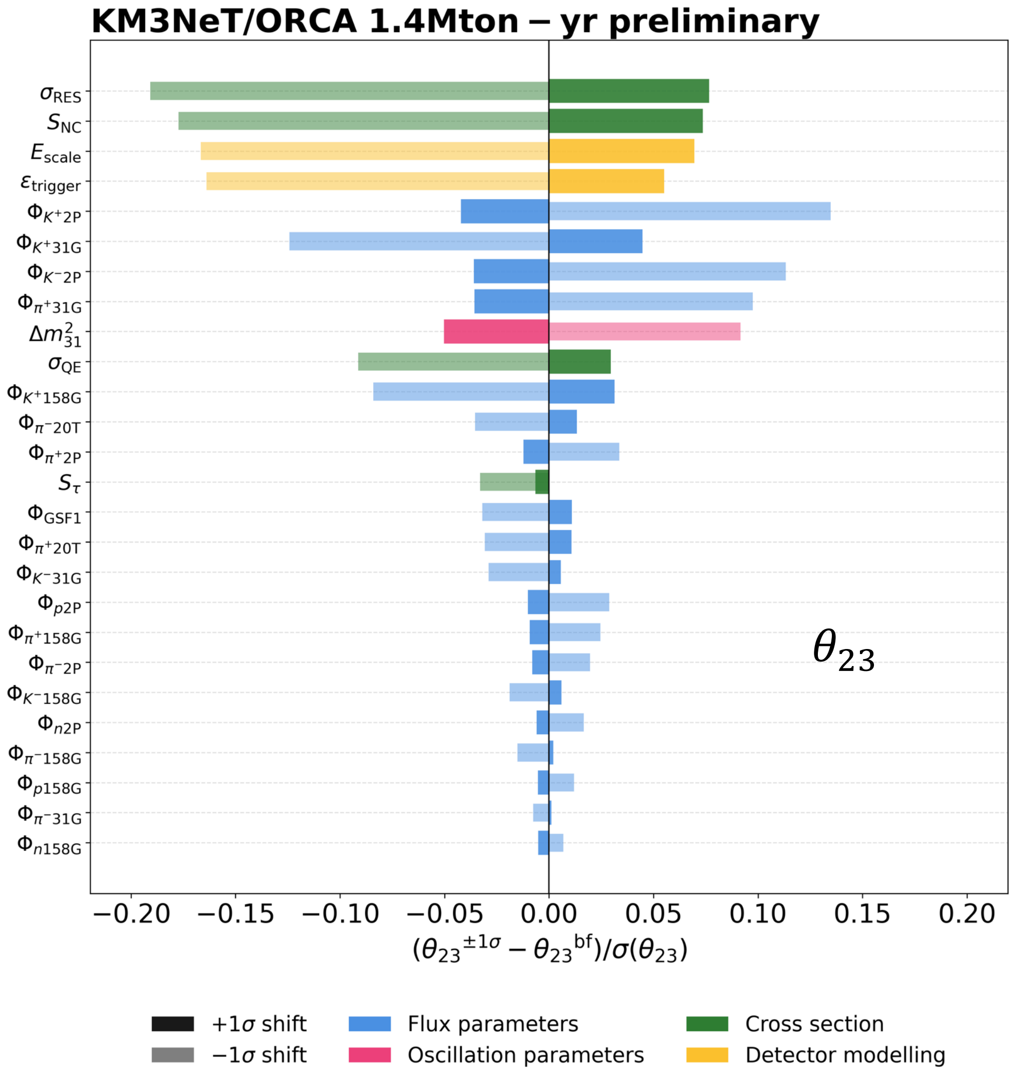
- $\sin^2\theta_{23} = 0.45^{+0.16}_{-0.05}, \Delta m^2_{31} = (-2.08^{+0.08}_{-0.09}) \cdot 10^{-3}$ eV^2
- ORCA alone: a small preference for Inverted Ordering; significance as expected for this exposure
- tau neutrino production, with scale factor $S_\tau = 0.97^{+0.21}_{-0.23}$
- no signficant evidence for a 4th generation sterile neutrino with $\Delta m^2 \geq 1$ eV^2

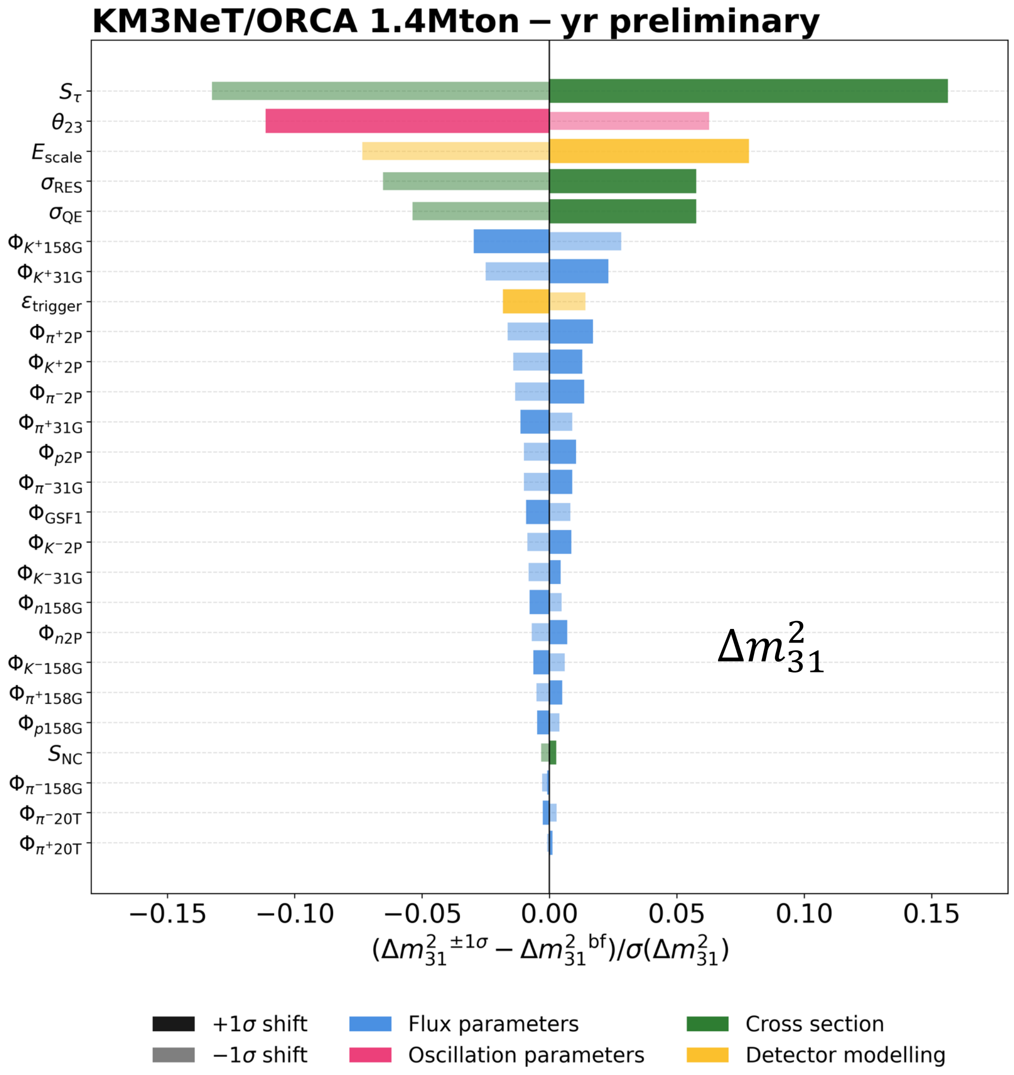
Backup Slides

Goodness of Oscillations Fit



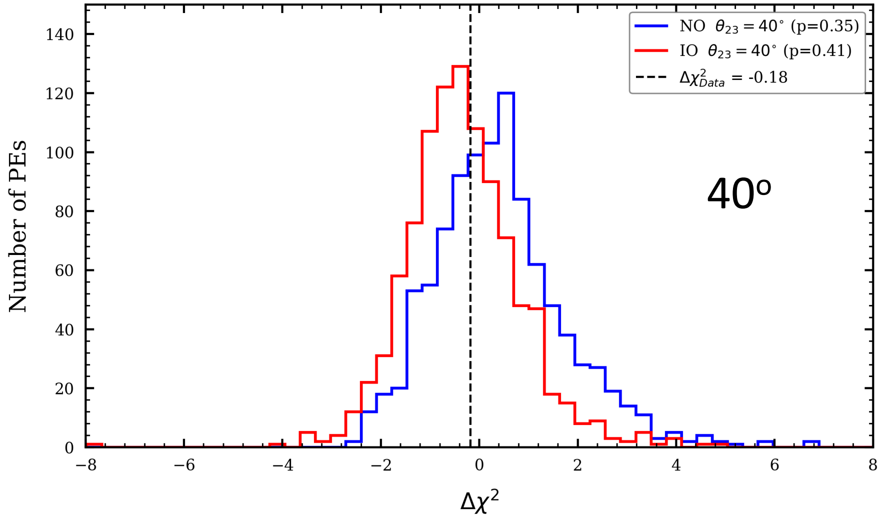
Systematics Impact



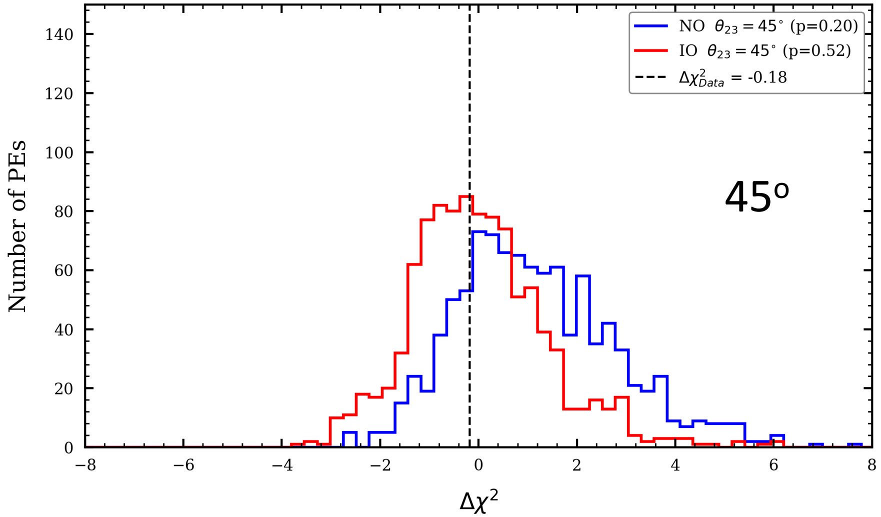


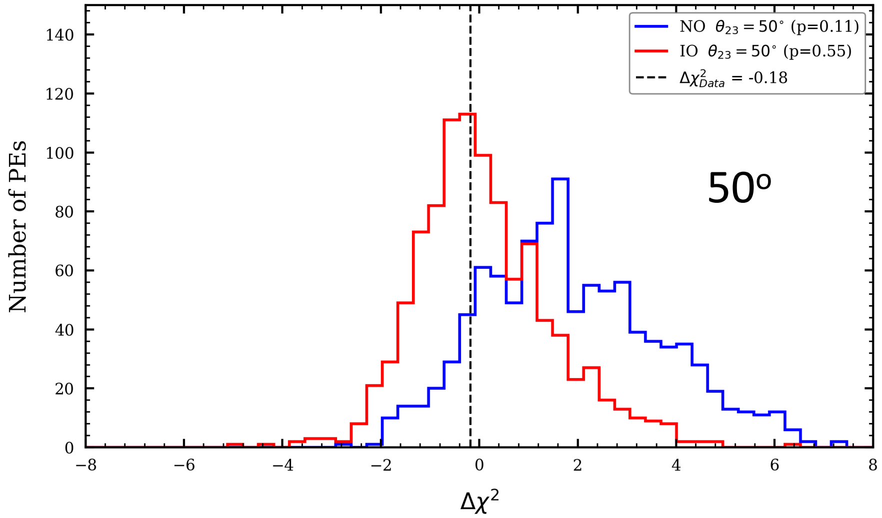
NMO sensitivity for various θ_{23}

KM3NeT Preliminary

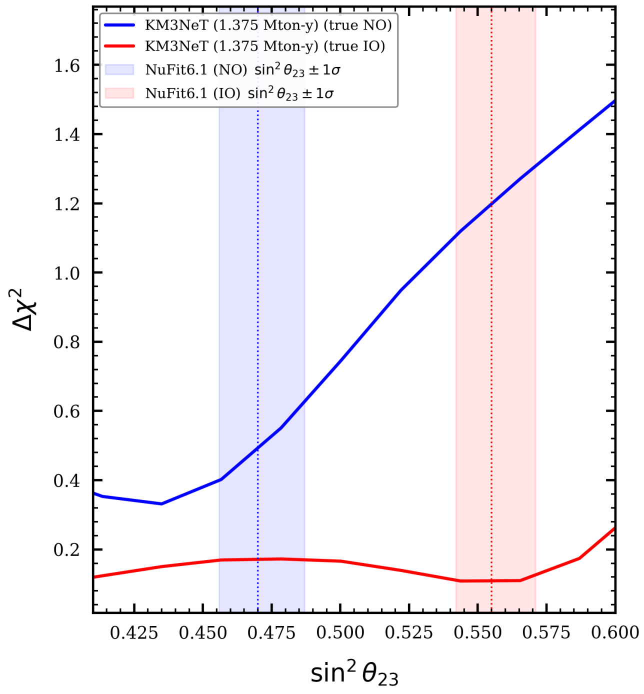


KM3NeT Preliminary





KM3NeT Preliminary

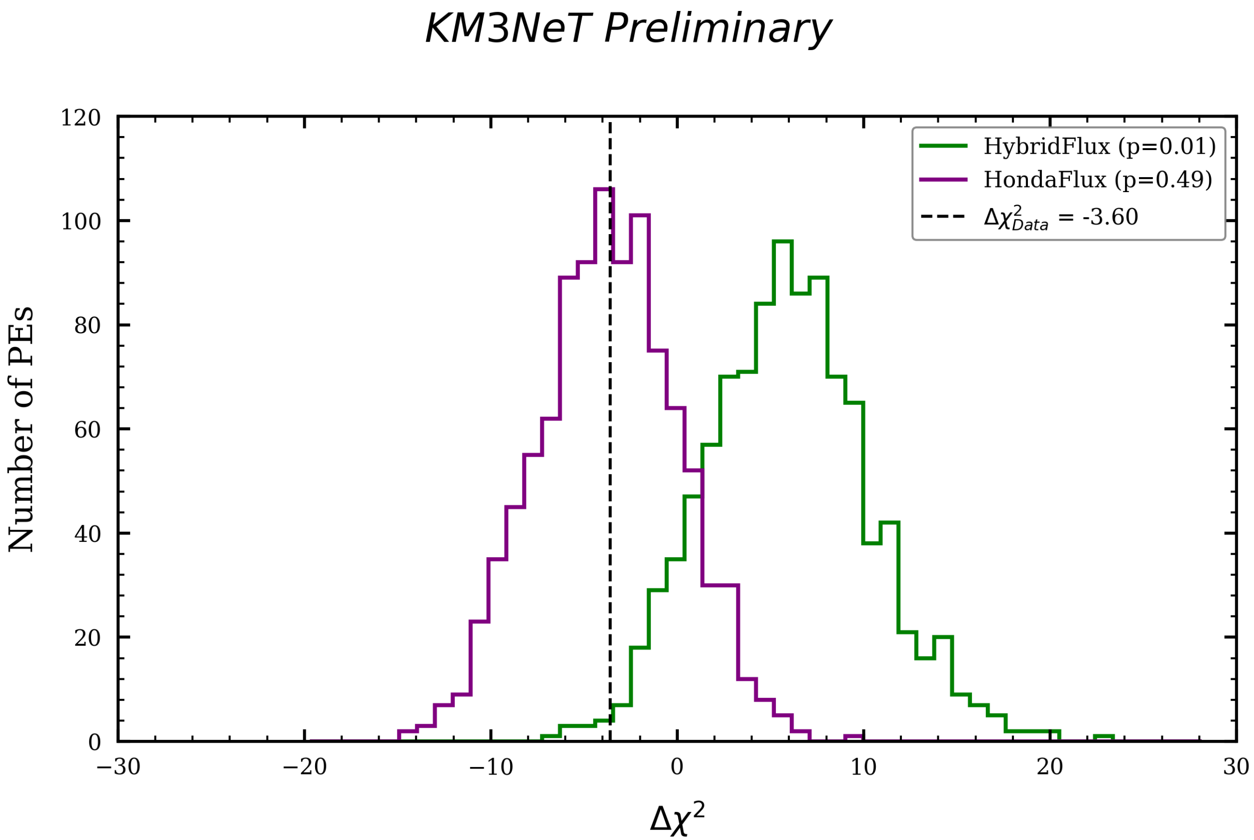


Flux preference

Fit on data prefers Honda by $\Delta\chi^2 = 3.6$

Generating pseudo-experiments with NuFit6.1 parameters, looking at $\Delta\chi^2$ between fitting with Honda and fitting with HybridFlux, and comparing with the actual fit in our data, we observe:

p(Honda flux) = 0.49
p(HybridFlux) = 0.01

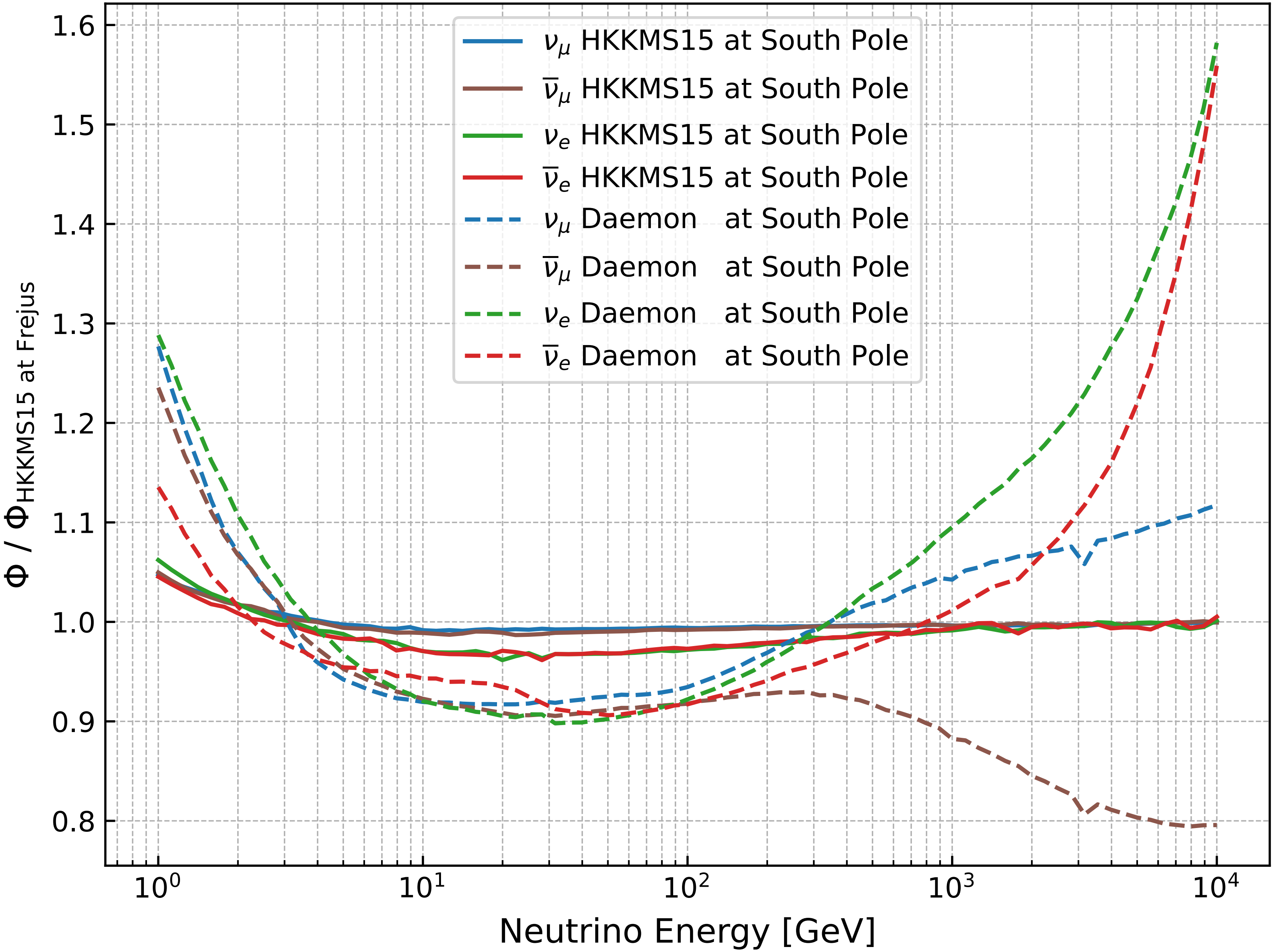


We know HybridFlux is not complete yet:

- evaluated at South Pole, not ORCA location
- no geomagnetic effects
- large difference with Honda at low energies, to be understood.

We look forward to a future DaemonFlux with all these implemented.

Flux ratios


ν_μ HKKMS15 at South Pole
$\bar{\nu}_\mu$ HKKMS15 at South Pole
ν_e HKKMS15 at South Pole
$\bar{\nu}_e$ HKKMS15 at South Pole
ν_μ Daemon at South Pole
$\bar{\nu}_\mu$ Daemon at South Pole
ν_e Daemon at South Pole
$\bar{\nu}_e$ Daemon at South Pole
Φ / $\Phi_{\mathrm{HKKMS15\ at\ Frejus}}$
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
10^0
10^1
10^2
10^3
10^4
Neutrino Energy [GeV]