Neutrino Oscillation measurements and BSM physics searches with Neutrino Telescopes in the Mediterranean

Paschal Coyle

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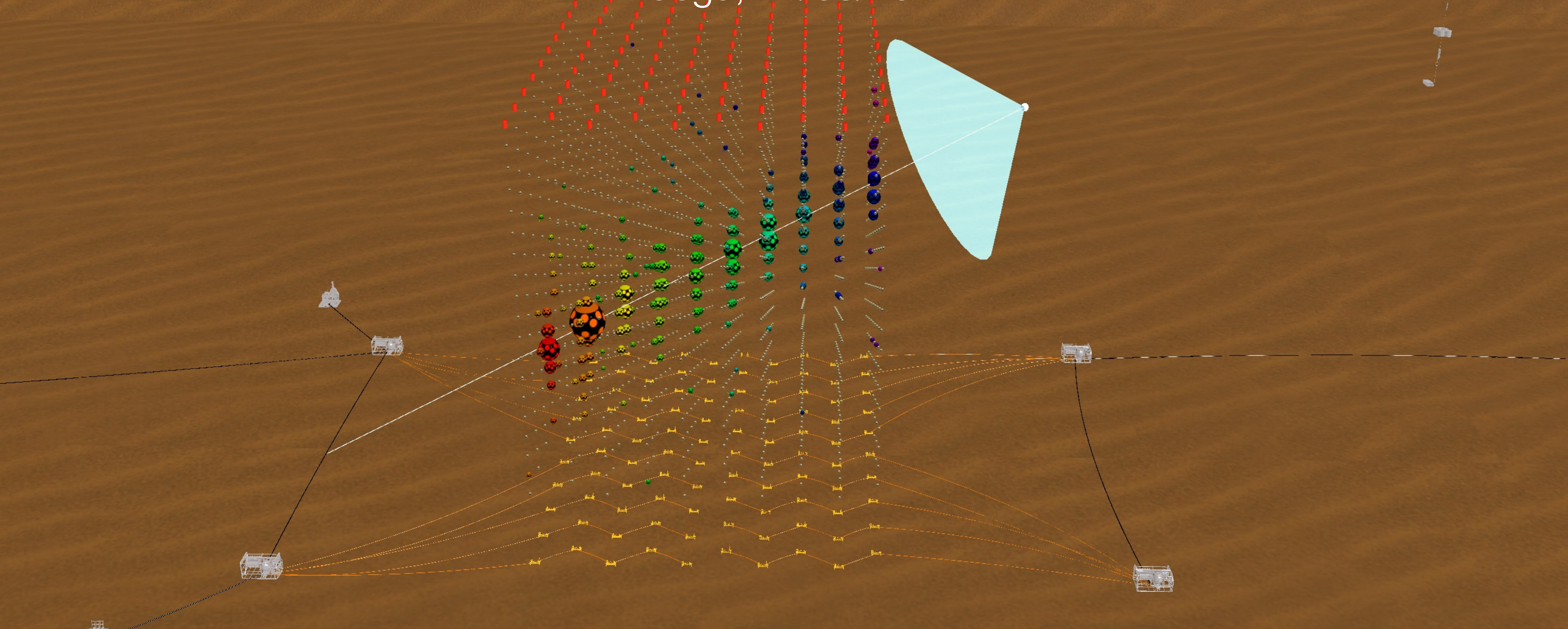
Oscillation measurements and BSM physics searches with neutrino telescopes in the Mediterranean Sea

Paschal Coyle on behalf of the ANTARES and KM3NeT Collaborations

NUFACT19
Daegu, 27/08/19



Large Volume Neutrino Telescopes

ANTARES & KM3NeT

ANTARES

KM3NeT

BAIKAL & GVD

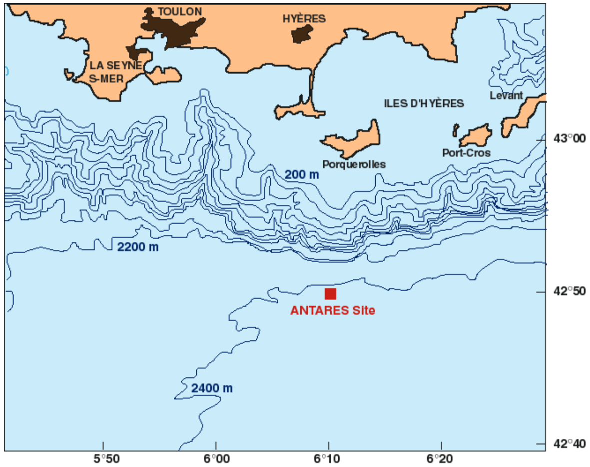
THE LAKE BAIKAL NEUTRINO TELESCOPE

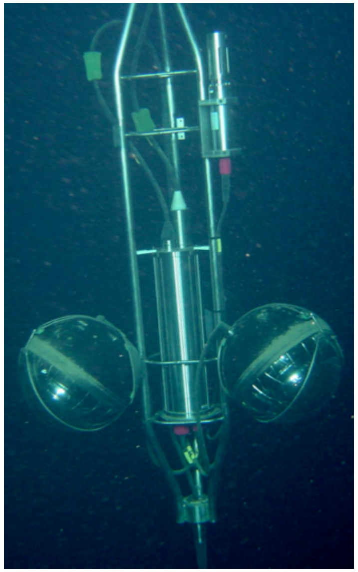
ICECUBE

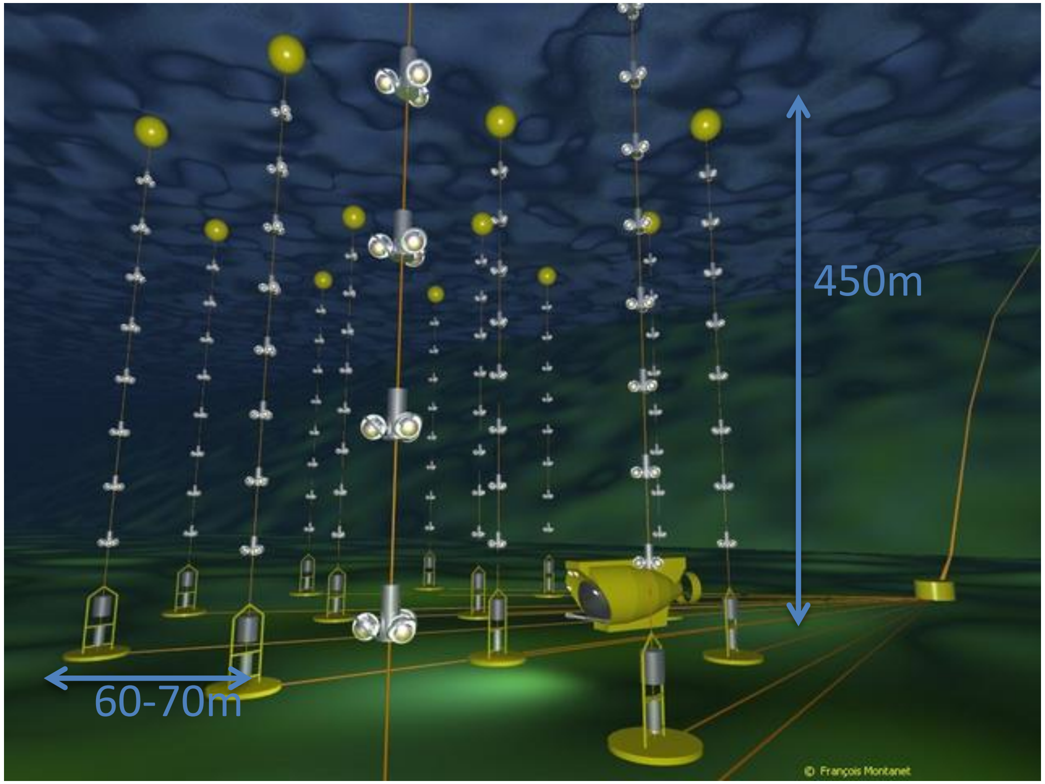
IceCube

ANTARES

- 42km offshore Toulon, depth 2475m
- Main Electro-Optic Cable/Junction Box 2001-2002
- Completed 2008
- 12 lines, ~70m spacing
- 25 storeys per line, 15m spacing
- 3x10-inch PMTs per storey
- Decommissioning 2017



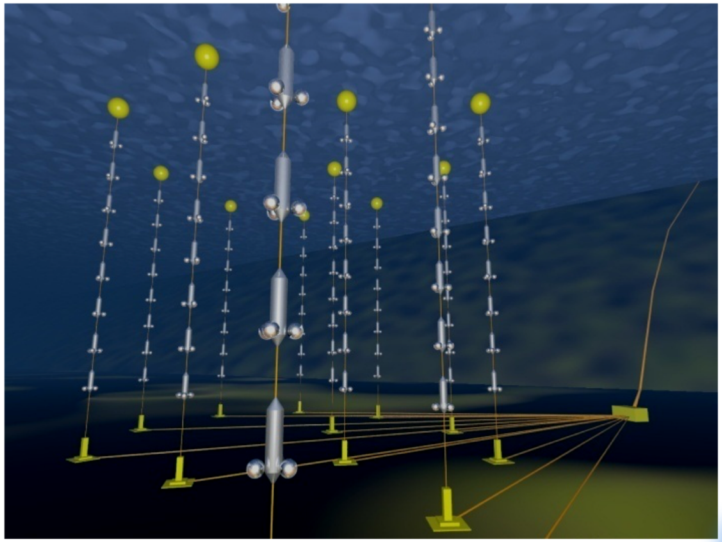


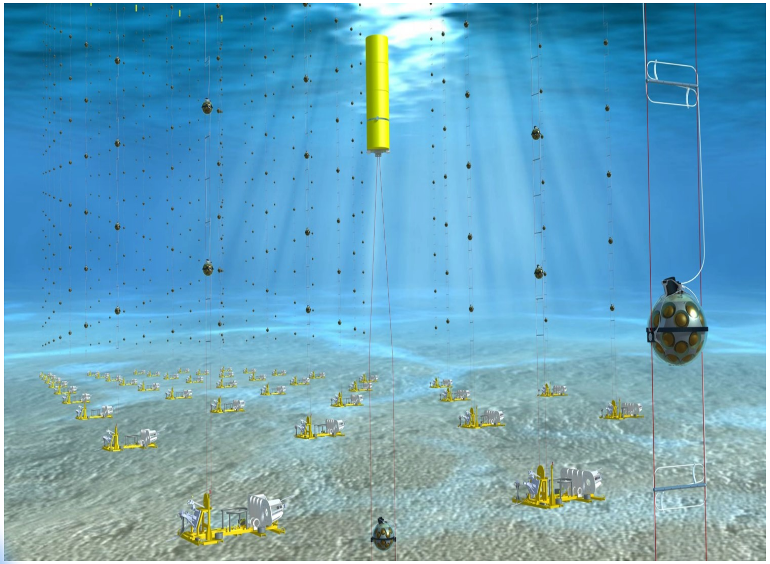


ANTARES->KM3NeT

12 lines, 900 OMs

3 Building Blocks (3*115 lines, ~3*2000 OMs)





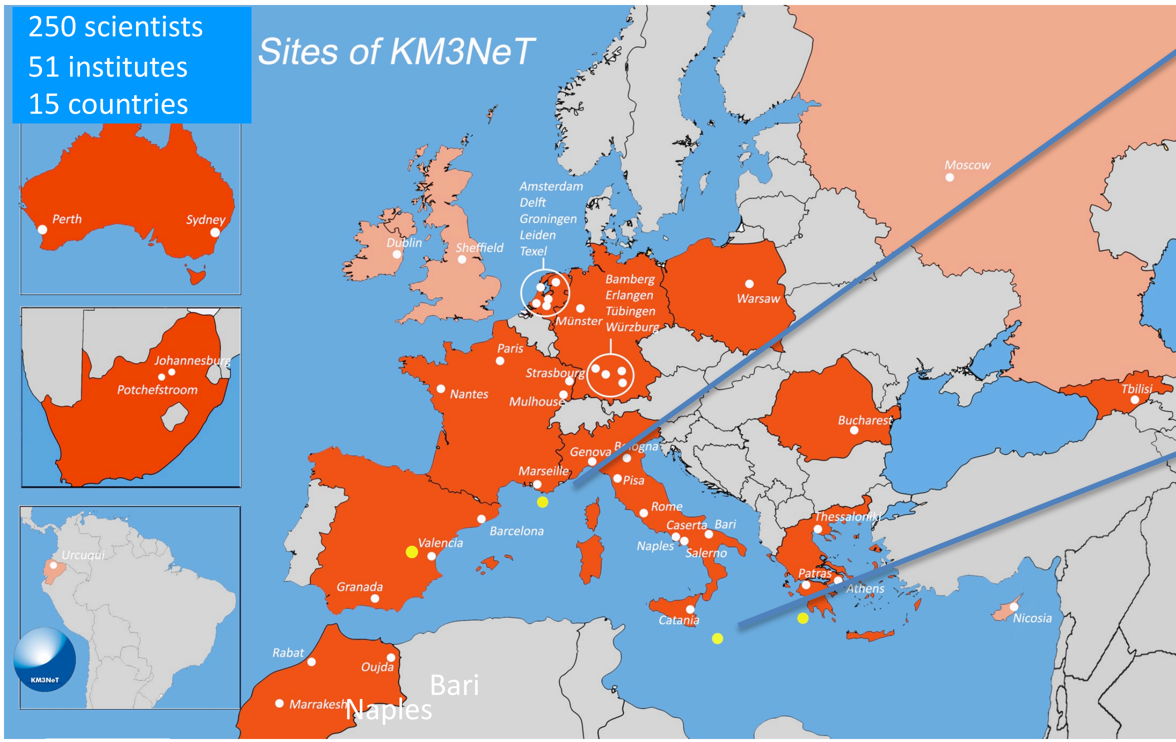
- 31 x 3” PMTs
- Uniform angular coverage
- Directional information
- Digital photon counting
- Reduced ageing
- All data to shore

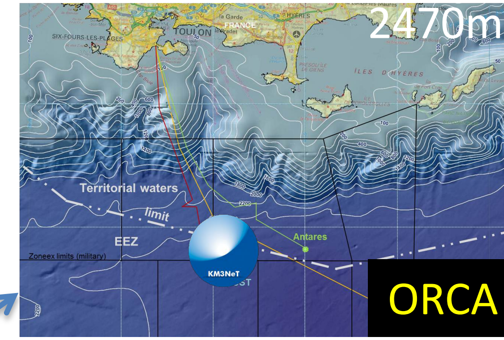
KM3NeT

Multi-site, deep-sea infrastructure

Selected by ESFRI roadmap

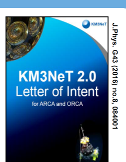
Single collaboration, Single technology





Oscillation **R**esearch with **C**osmics In the **A**byss

Astroparticle **R**esearch with **C**osmics In the **A**byss



[KM3NeT 2.0: Letter of Intent](http://dx.doi.org/10.1088/0954-3899/43/8/084001)

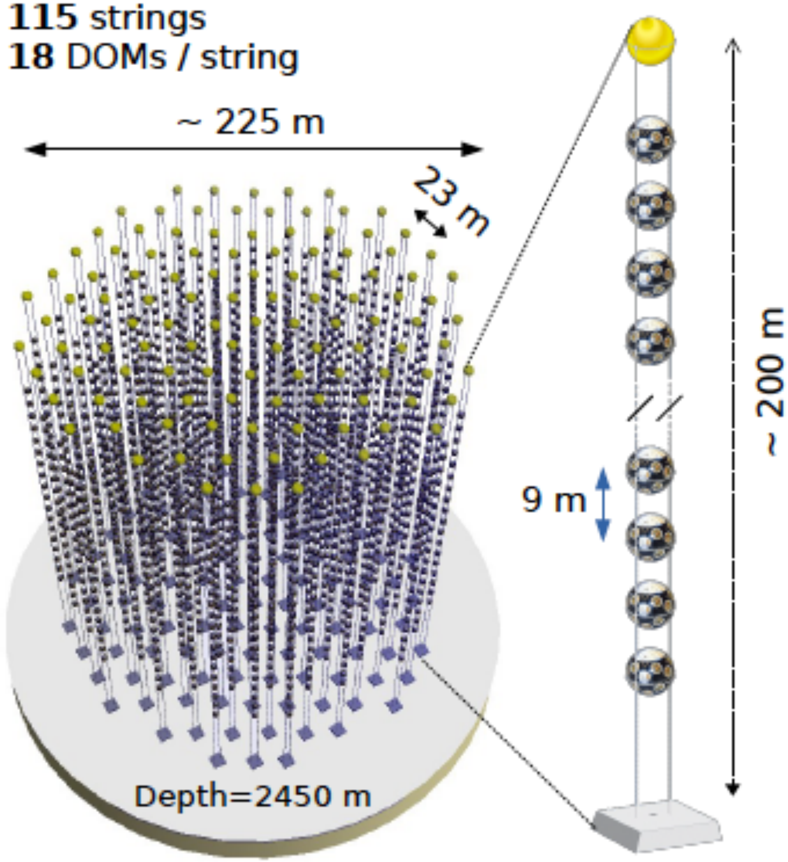
http://dx.doi.org/10.1088/0954-3899/43/8/084001

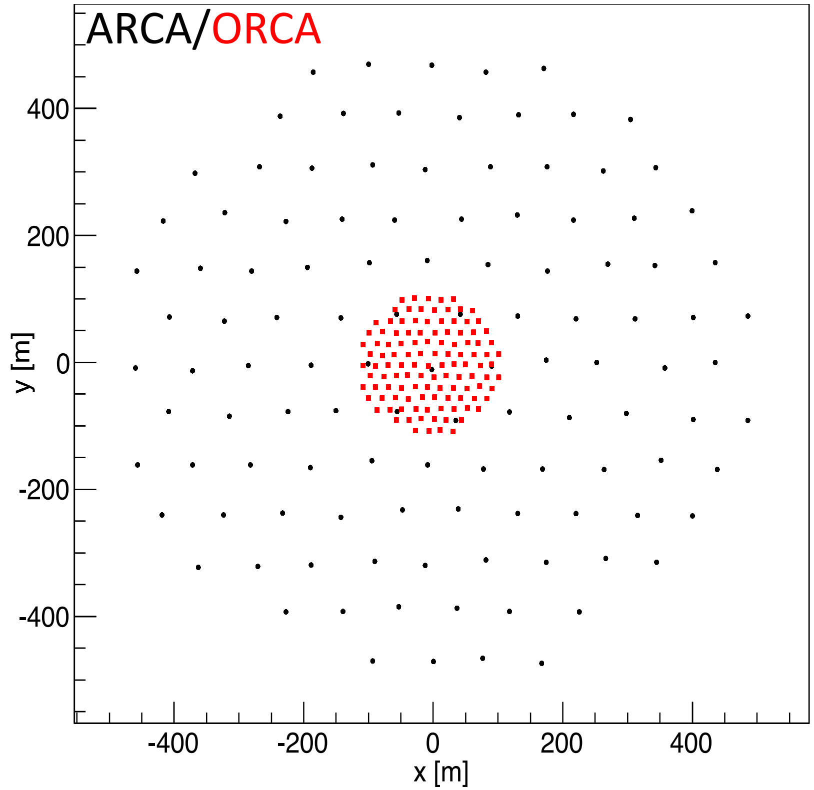
J. Phys. G: Nucl. Part. Phys. 43 (2016) 084001

Connection nodes of

european multidisciplinary seafloor & water column observatory emso

The KM3NeT Building Block



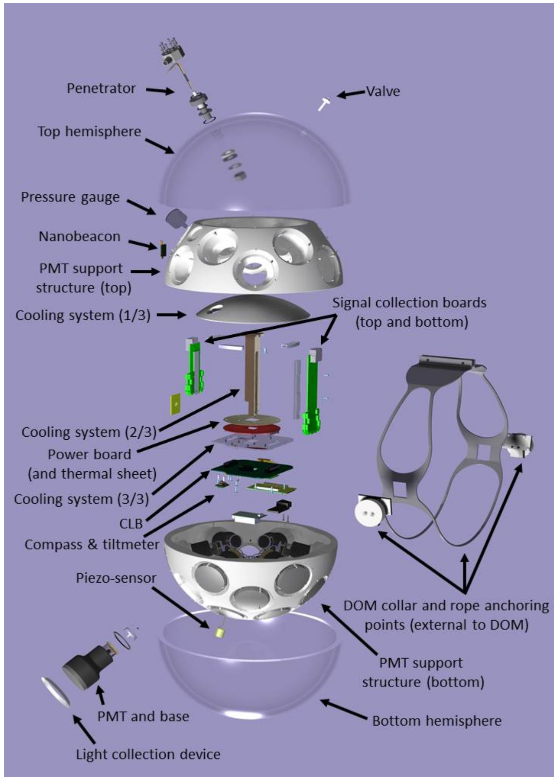


- **31** PMTs / DOM
- Total: **64k*3¨ PMTs**

	ORCA	ARCA
String spacing	20 m	90 m
OM spacing	9 m	36 m
Instrumented mass	8 Mton	500*2 Mton

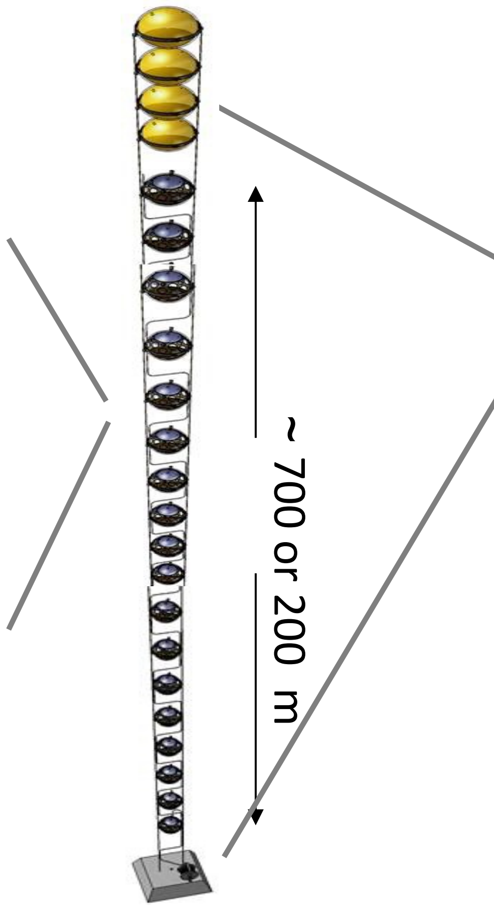
KM3NeT Technology

Digital Optical Module



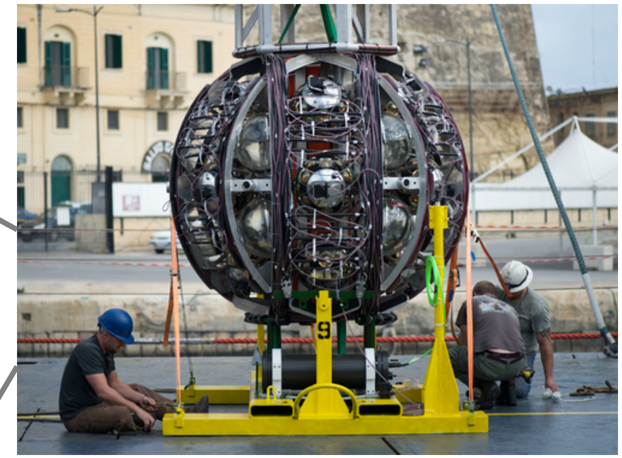
- 31 x 3” PMTs
- Gbit/s on optical fibre
- Hybrid White Rabbit
- LED flasher & acoustic piezo
- Tiltmeter/compass

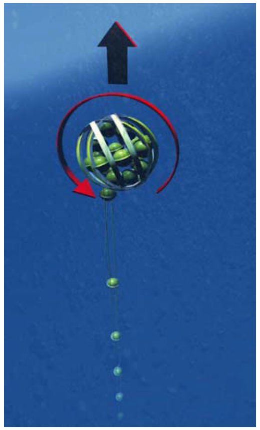
Detection unit



- 2 dyneema ropes
- Oil filled PVC tube
- Low drag
- Low cost

Deployment Vehicle



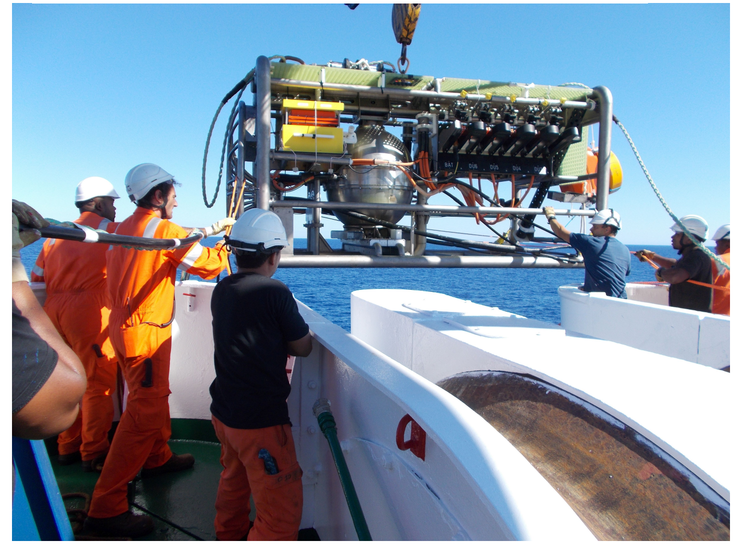


- Rapid deployment
- Multiple strings/sea campaign
- Autonomous/ROV unfurling
- Reuseable

ORCA: Some construction milestones

Main Cable: dec 2015, sept 2018

Node 1: sept 2016, sept 2018

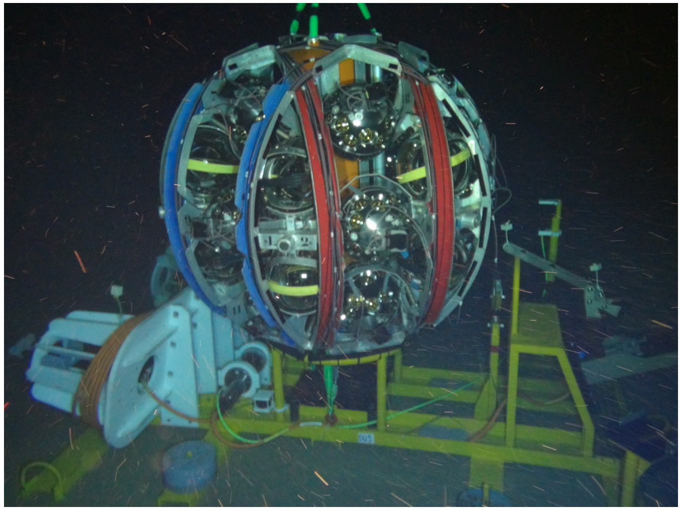


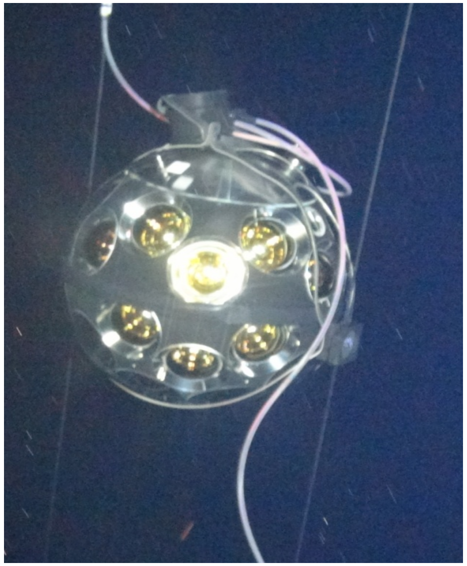
DUs: feb(1), may(1), july(2) 2019

Instrumentation module: may 2019

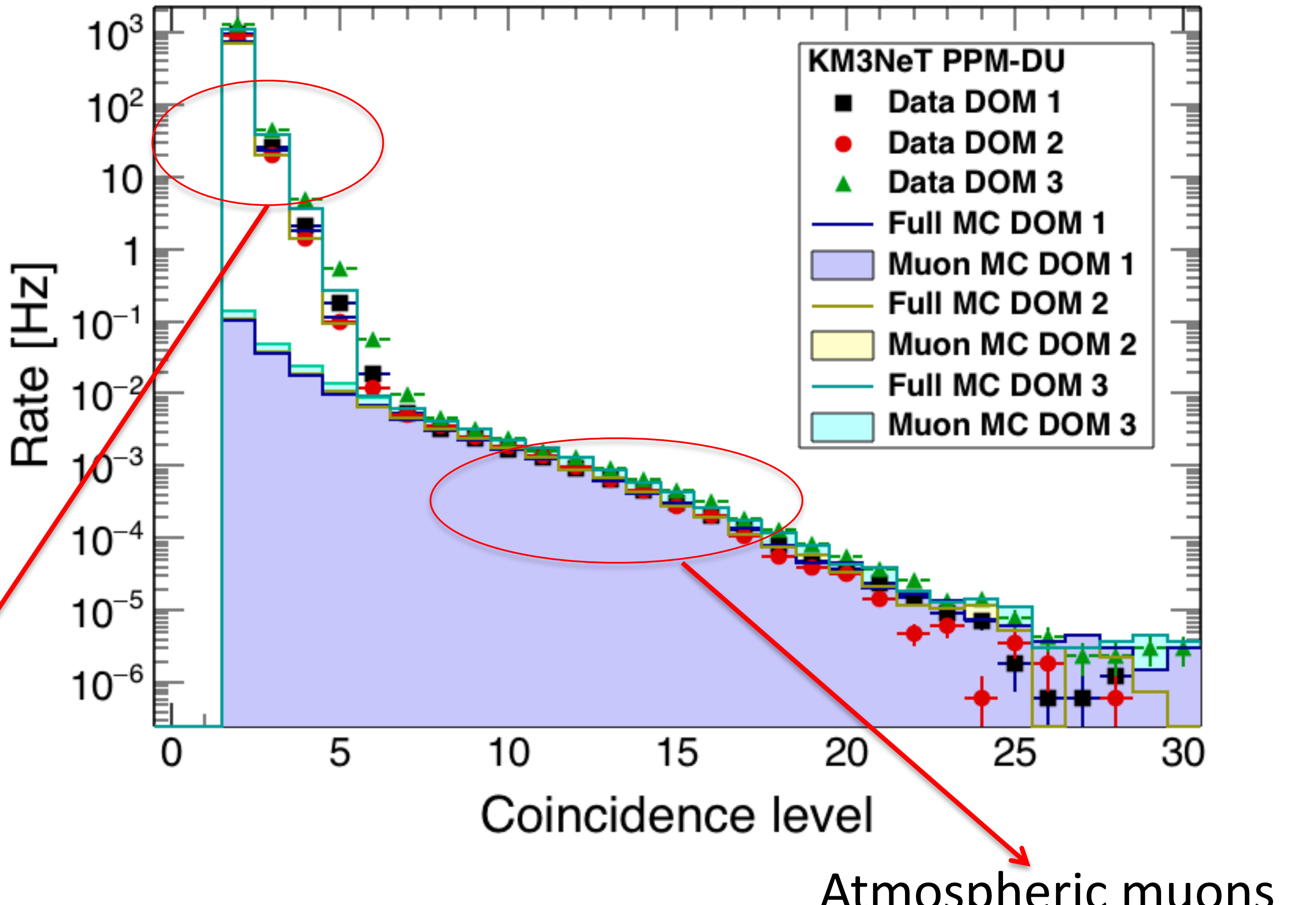
detection unit deployment/connection

https://youtu.be/dMjN93H7Nvo

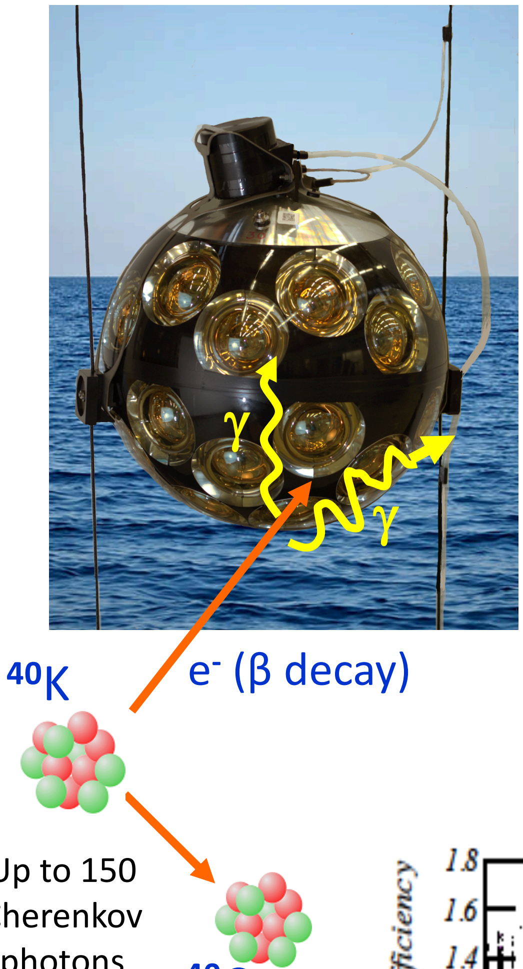




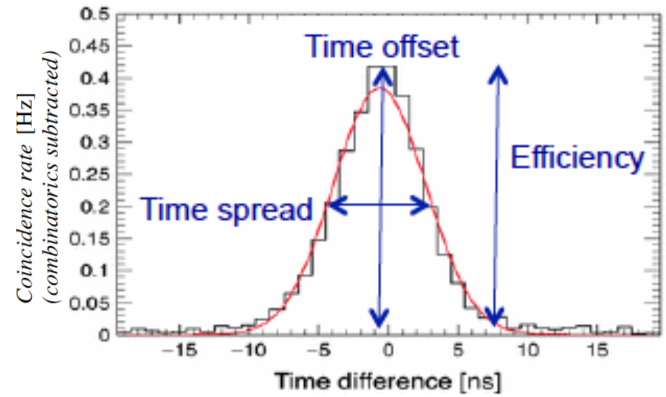
DOM coincidences

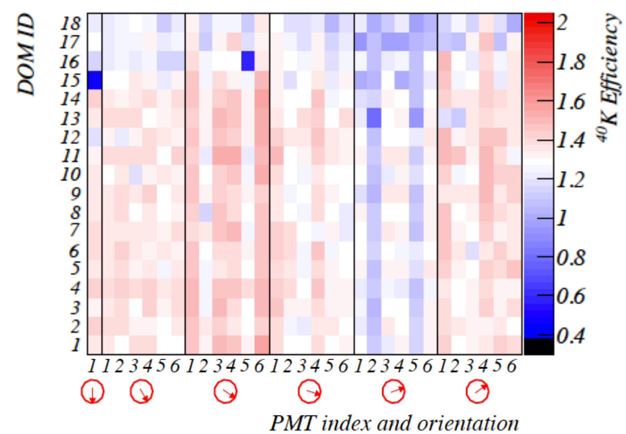


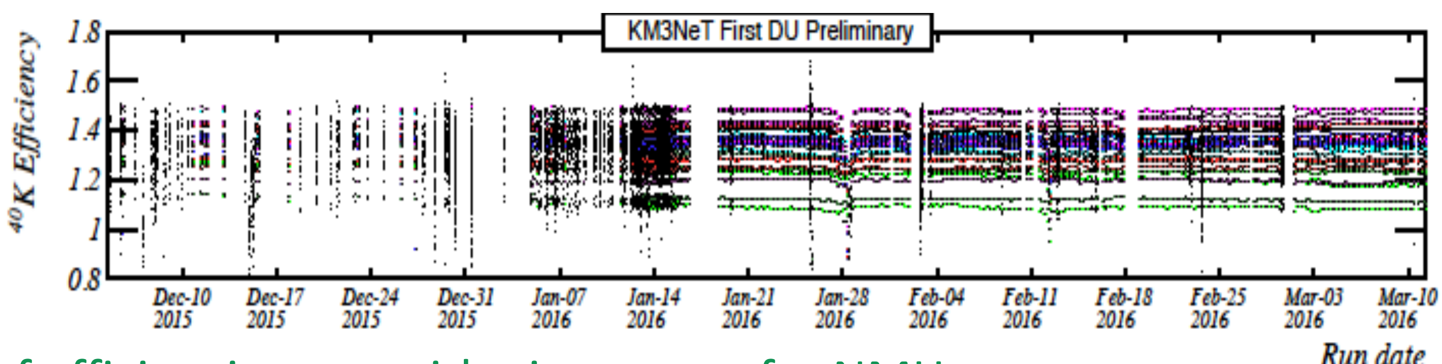
^{40}K: Inter-PMT Calibration



Up to 150 Cherenkov photons per decay; stable ^{40}K concentration



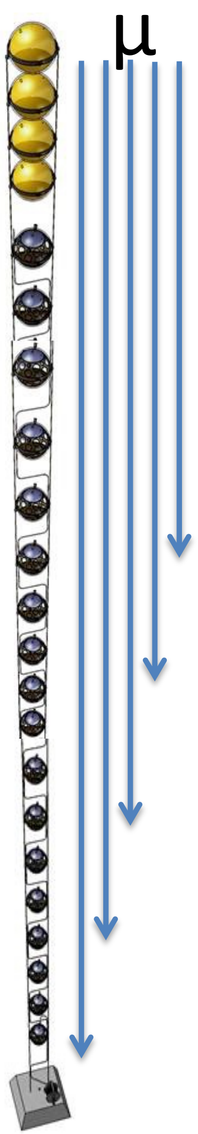


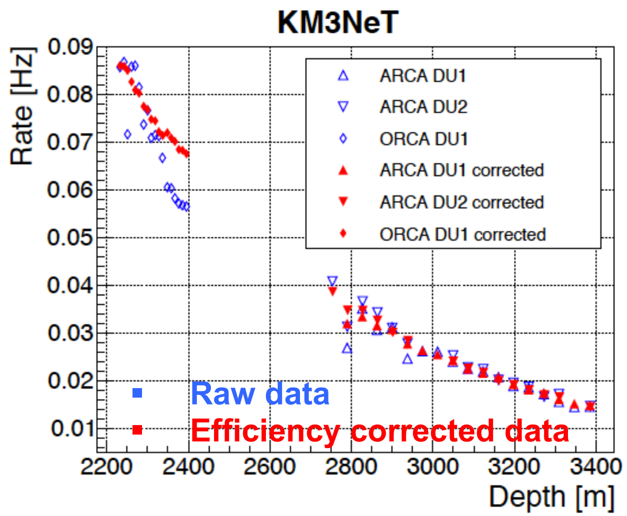


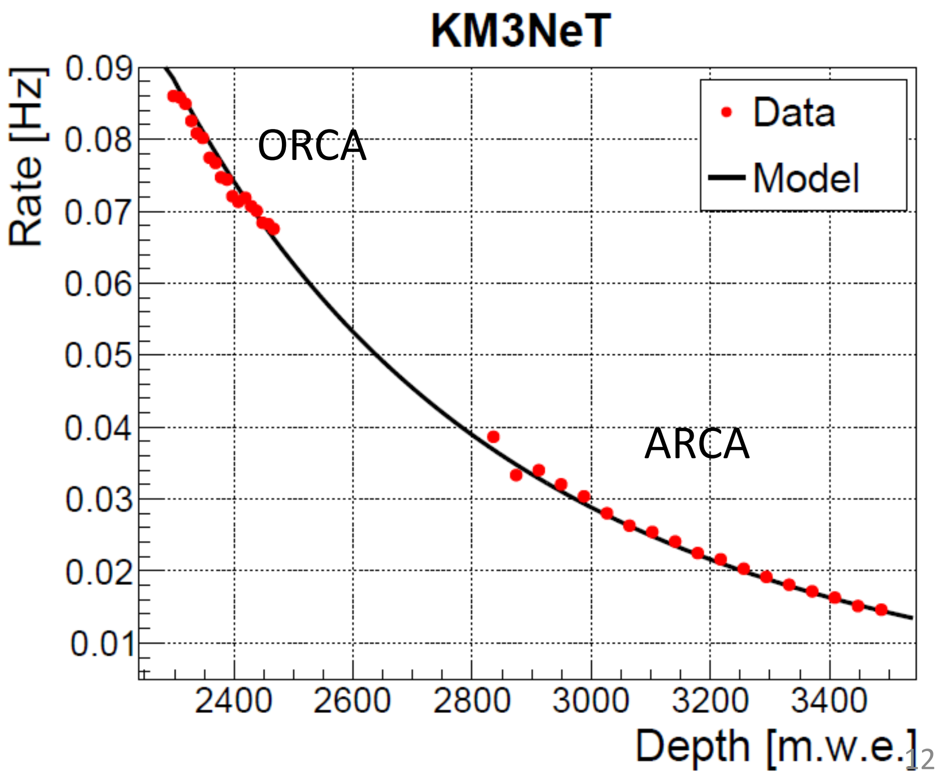
Knowledge of efficiencies vs zenith - important for NMH measurement

ARCA + ORCA Muon Depth Dependence

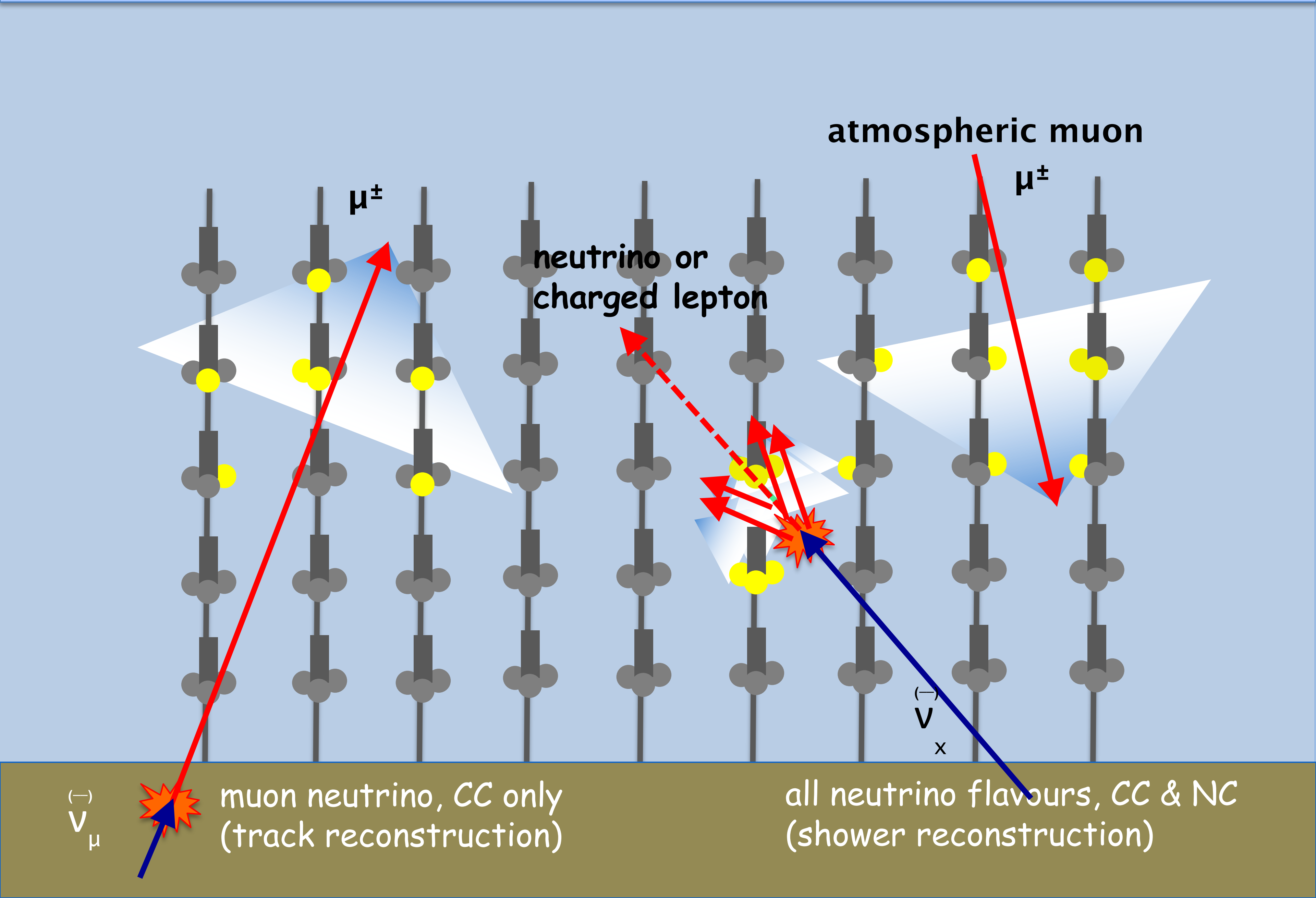
Joint ARCA/ORCA analysis measures the muon flux attenuation over > 1 km length
e-Print: arXiv:1906.02704



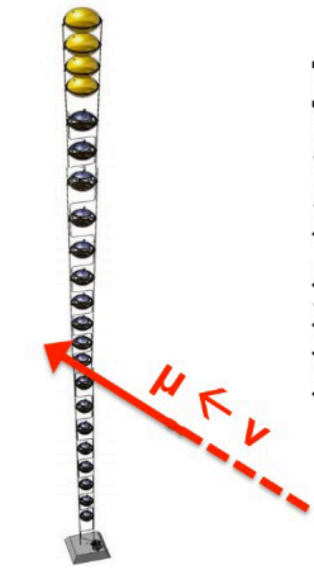




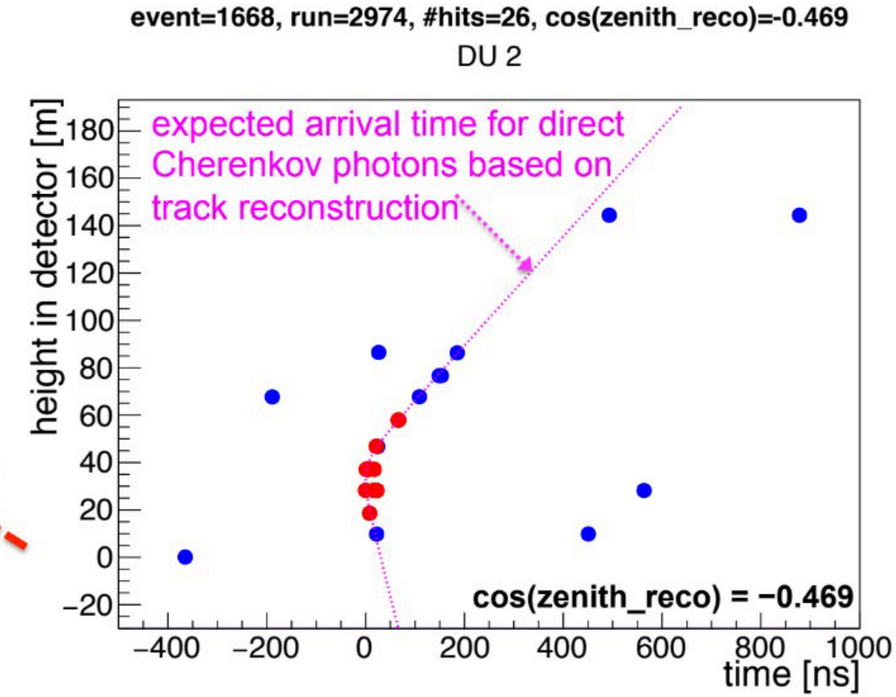
Neutrino signatures

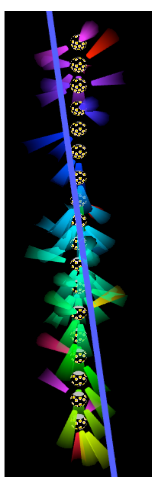


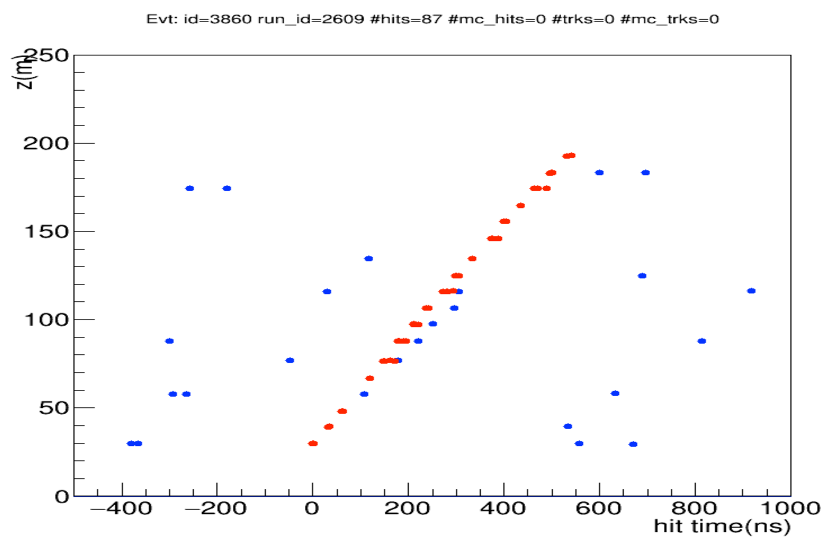
ORCA1: neutrinos



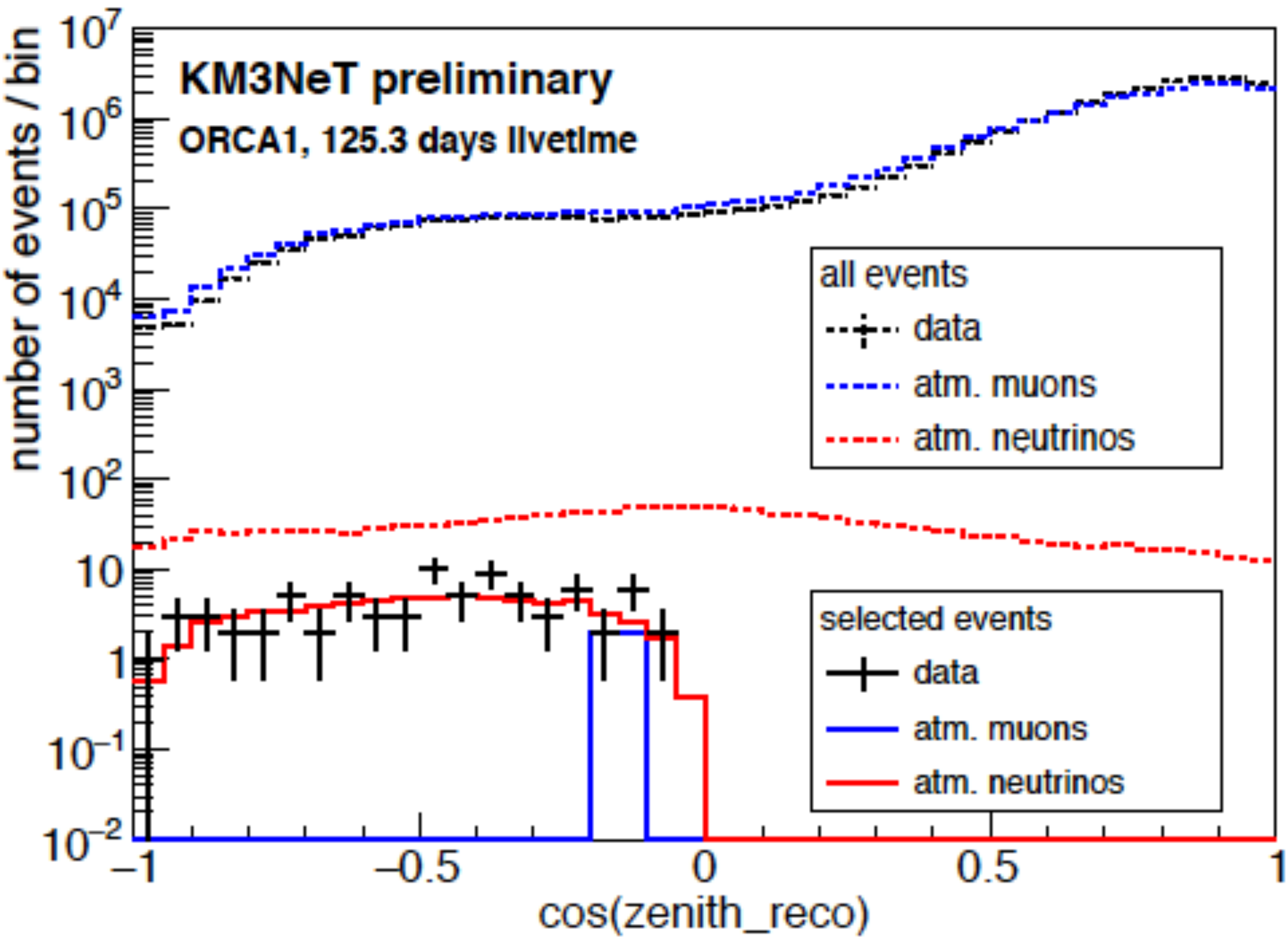
ORCA1





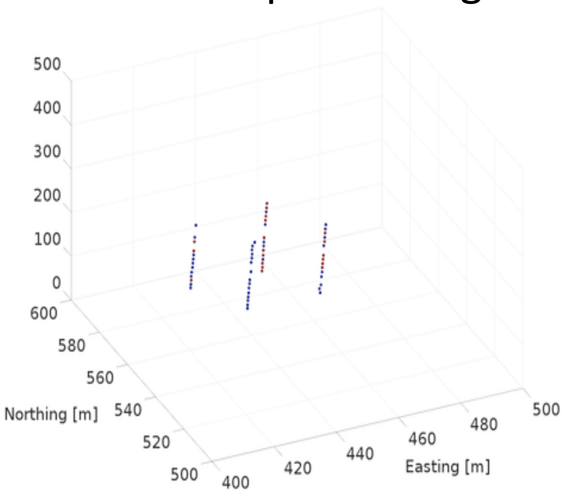


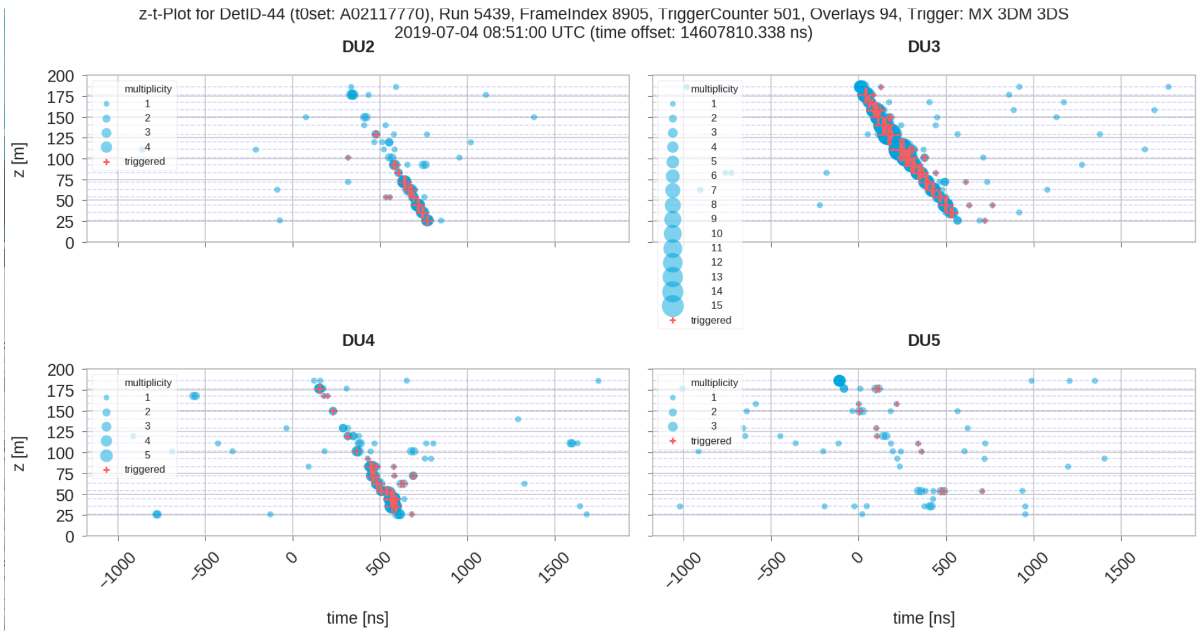
ORCA1: neutrinos

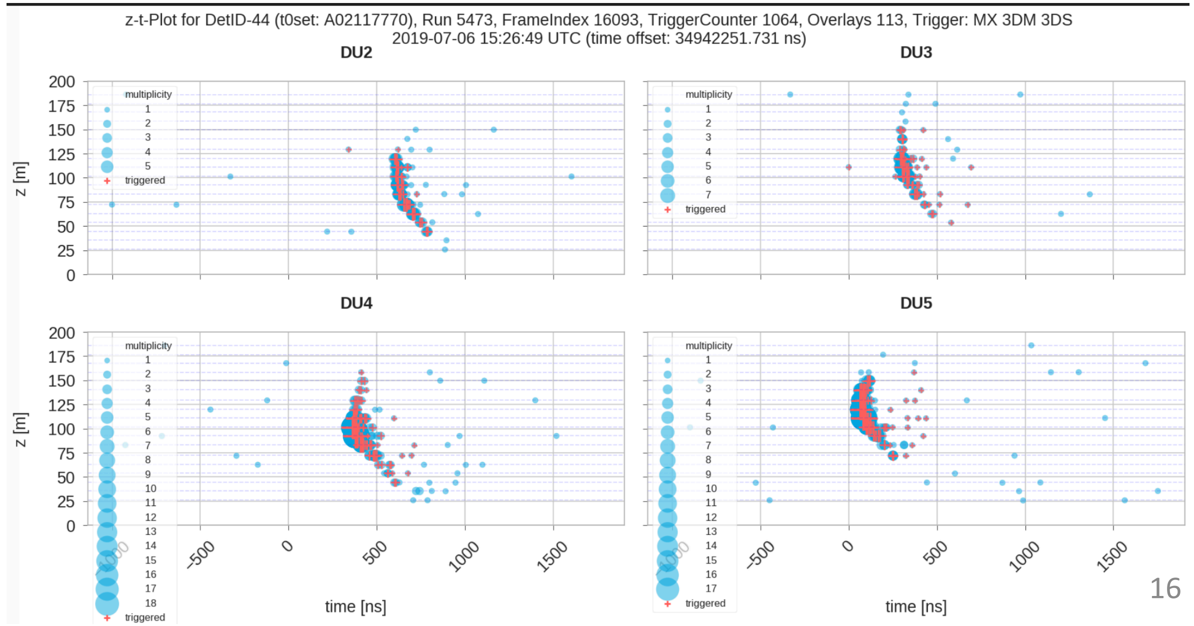


ORCA4: atmospheric muons

Acoustic positioning



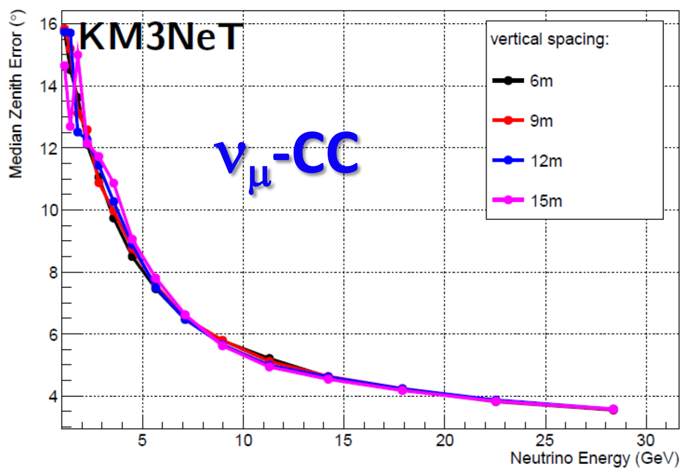




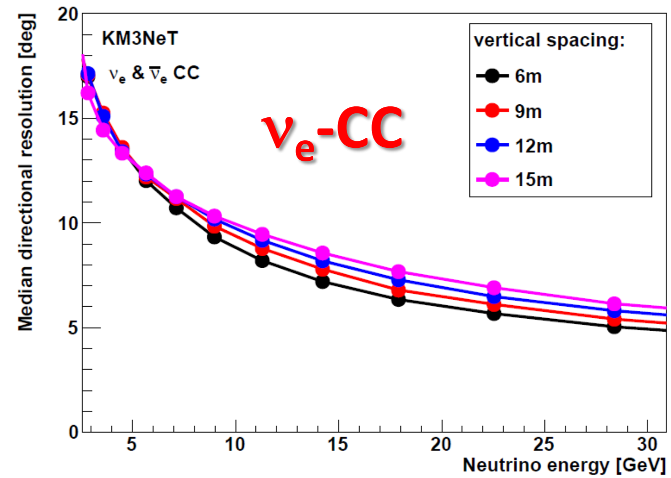
ORCA: reconstruction performance

- Angular resolution: Better than 10 degrees at relevant energies
- Energy resolution: ~25% (Close to intrinsic limit arXiv:1612.05621)

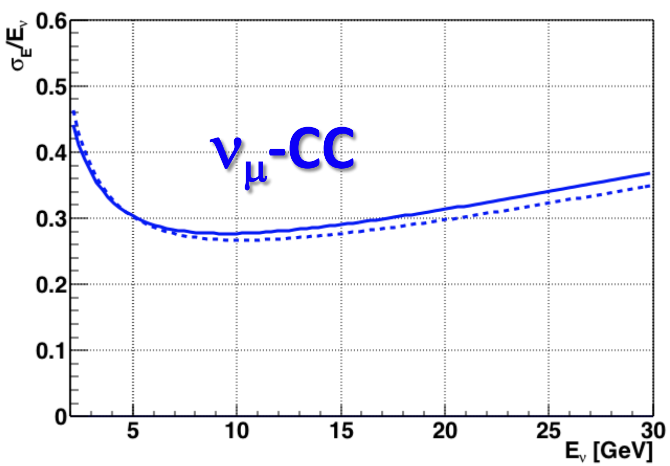
θ Res.



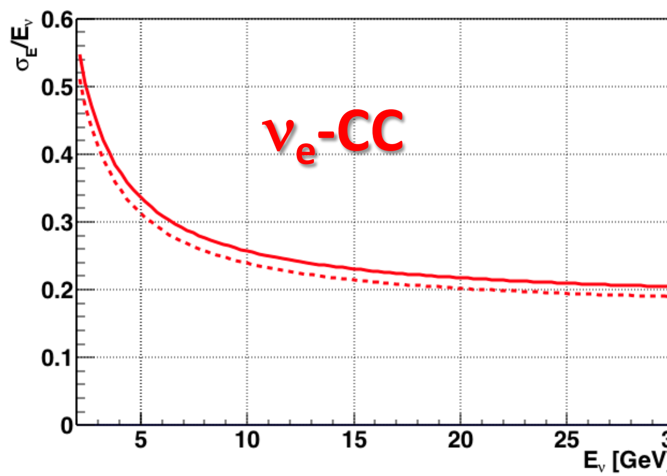
θ Res.



E Res.

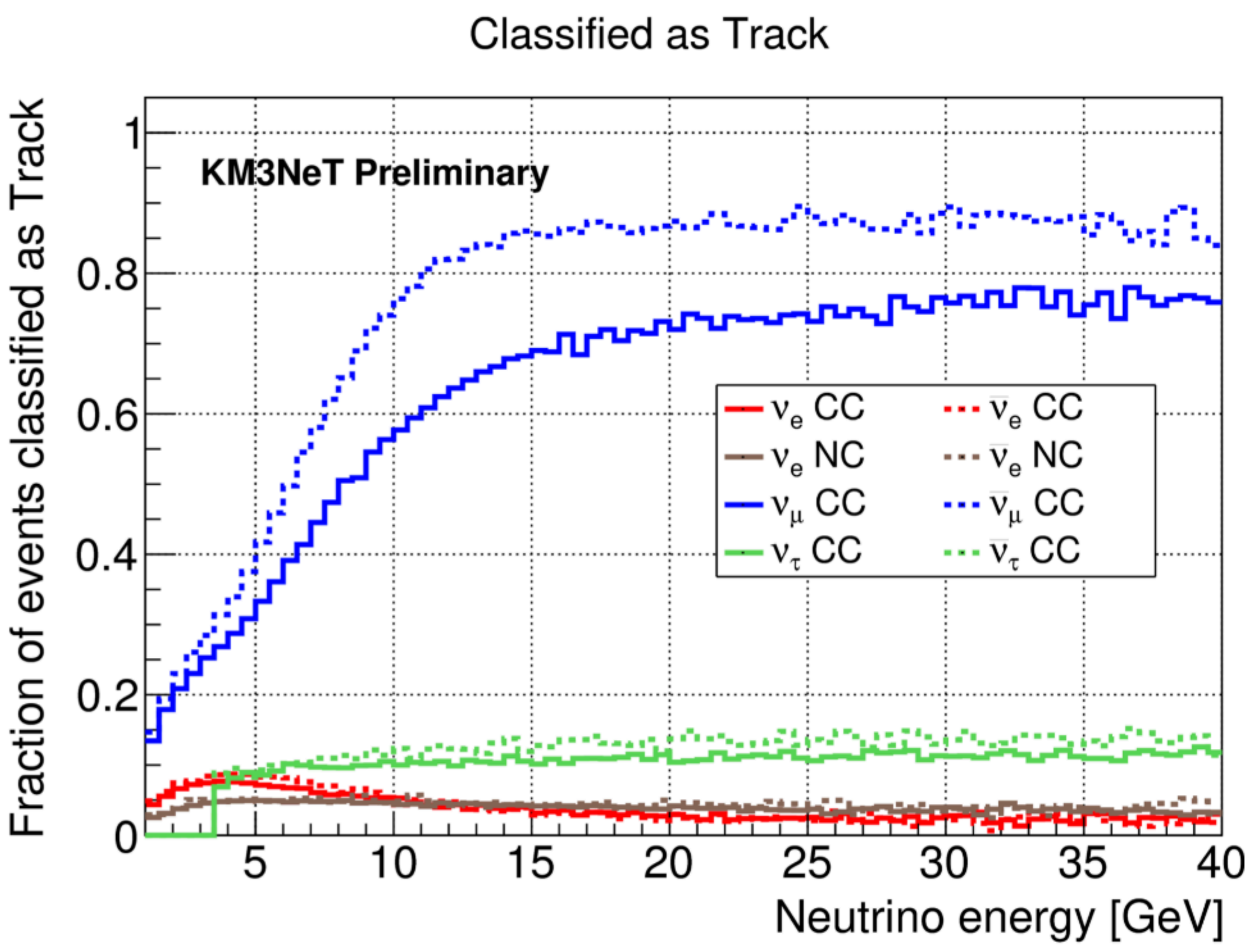


E Res.



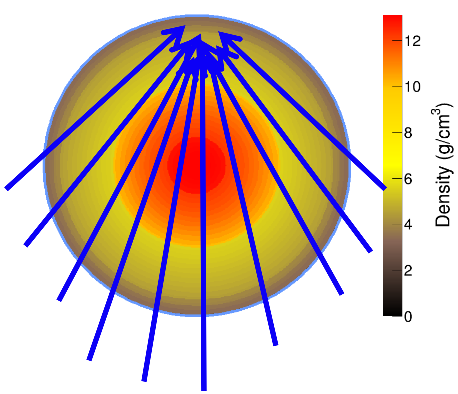
ORCA: shower/track identification

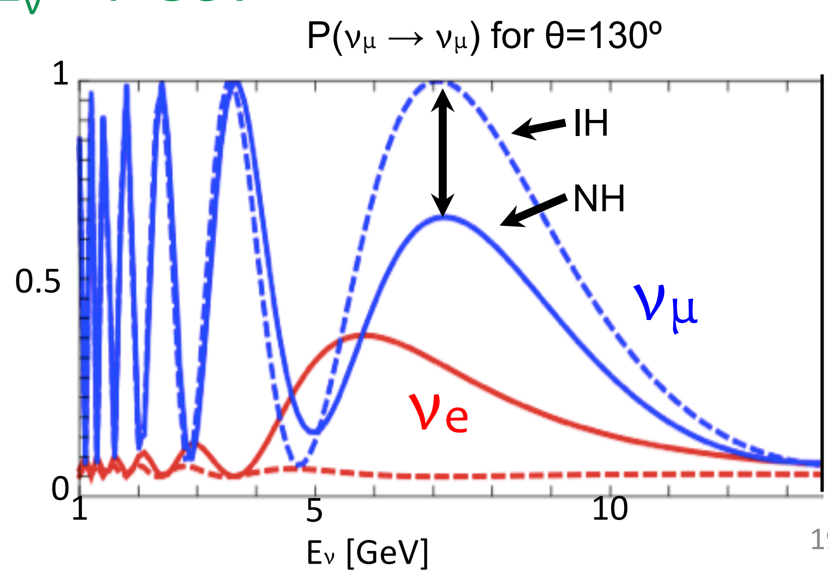
Discrimination of track-like and shower-like events via Random Decision Forest



Oscillations with atmospheric neutrinos

- A ¨free beam¨ of known composition (ν_e, ν_μ)
- A ¨free cavern¨ of known/uniform composition
- Wide range of baselines and energies
- Oscillation pattern distorted by Earth matter effects maximum difference IH ⍰ NH for resonance in Earth mantle: θ=130° (7645 km) and E_ν = 7 GeV

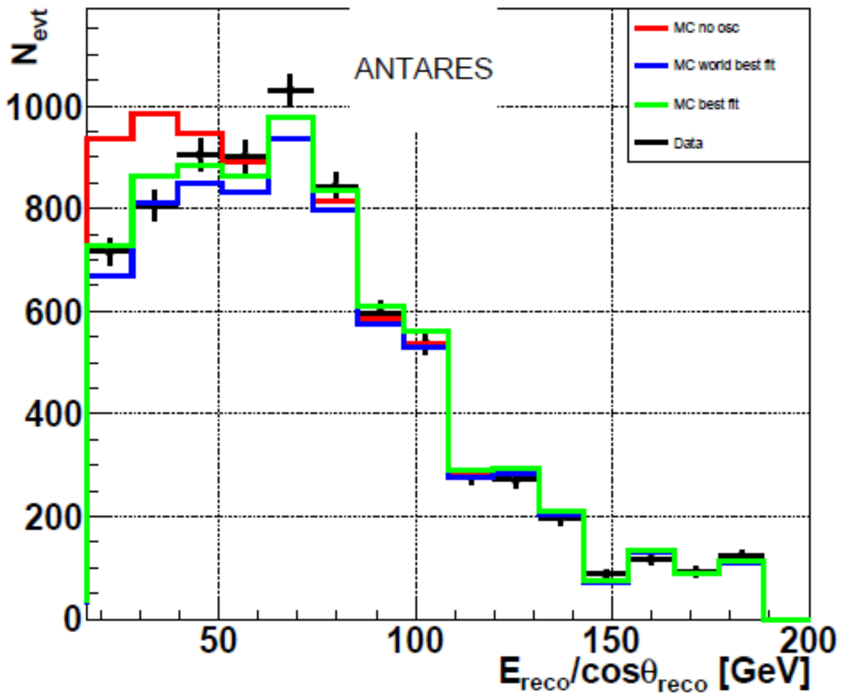


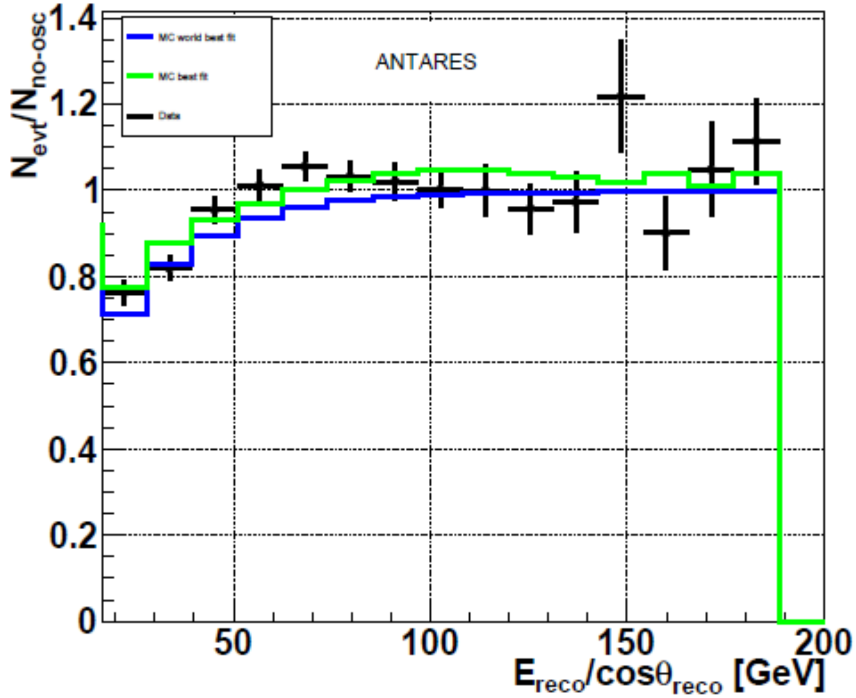


ANTARES neutrino oscillations

arXiv:1812.08650v3 [hep-ex] 21 May 2019

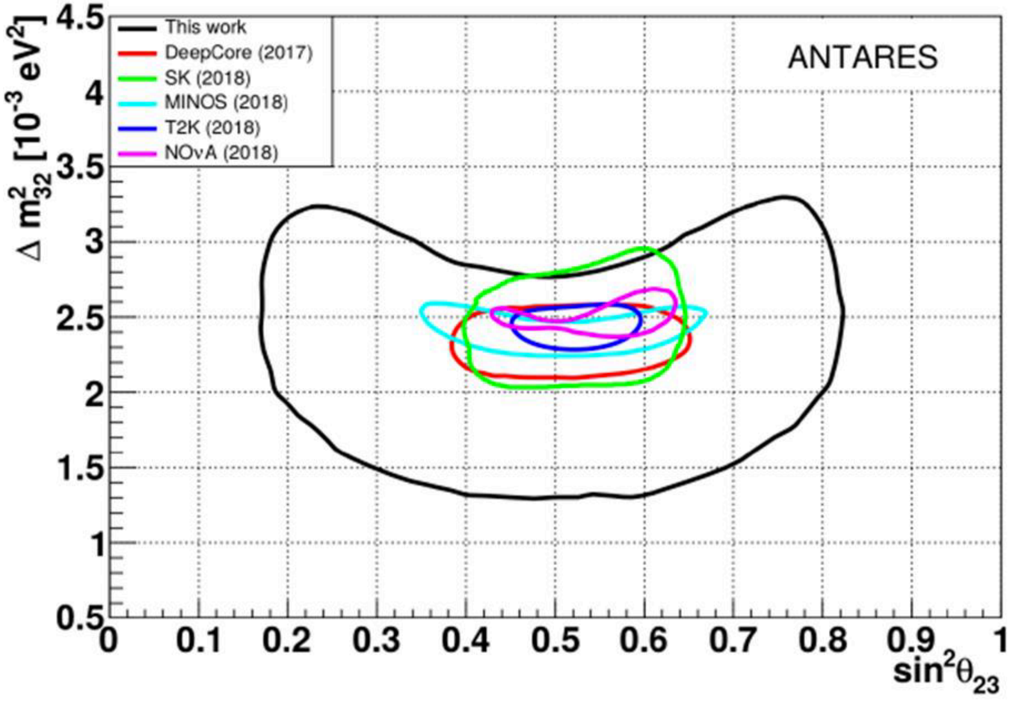
Data sample: 9 years (2007-2016) -2830 days lifetime
7710 events selected: Tracks only
A binned likelihood fit is performed in two dimensions (E_{reco}, $\cos\theta_{reco}$)





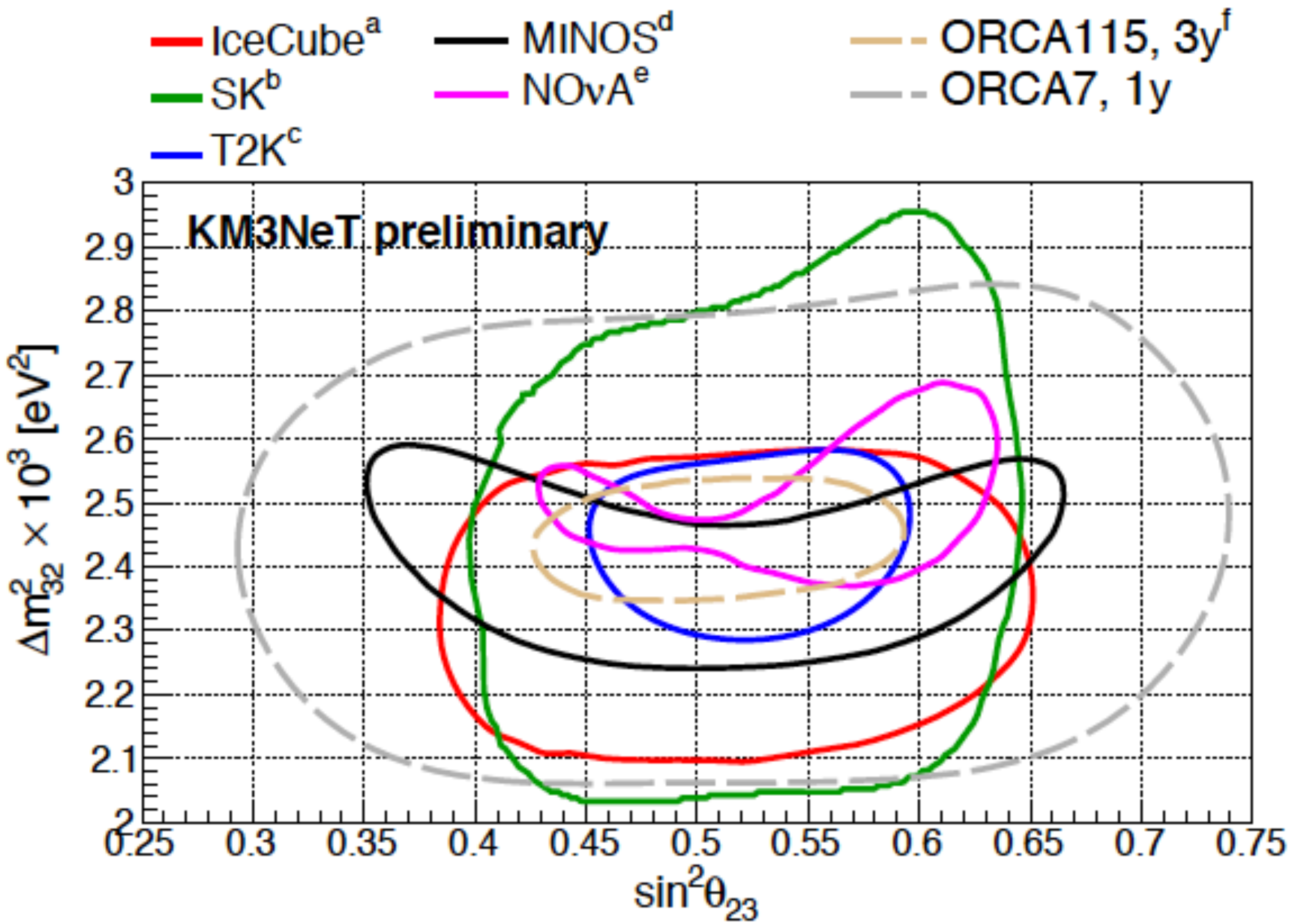
ANTARES: oscillations parameters

Parameter	Prior	Fit result
Δm^2_{32} [10^{-3} eV^2]	none	$2.0^{+0.4}_{-0.3}$
θ_{23} [°]	none	45^{+12}_{-11}
n_ν	none	$0.81^{+0.10}_{-0.09}$
$\nu/\bar{\nu}$ [σ]	0.0 ± 1.0	$1.10^{+0.64}_{-0.56}$
$\Delta\gamma$	0.00 ± 0.05	-0.003 ± 0.036
N_μ	740 ± 120	414^{+48}_{-24}
θ_{13} [°]	8.41 ± 0.28	8.41 ± 0.28
M_A [σ]	0.0 ± 1.0	0.0 ± 1.0

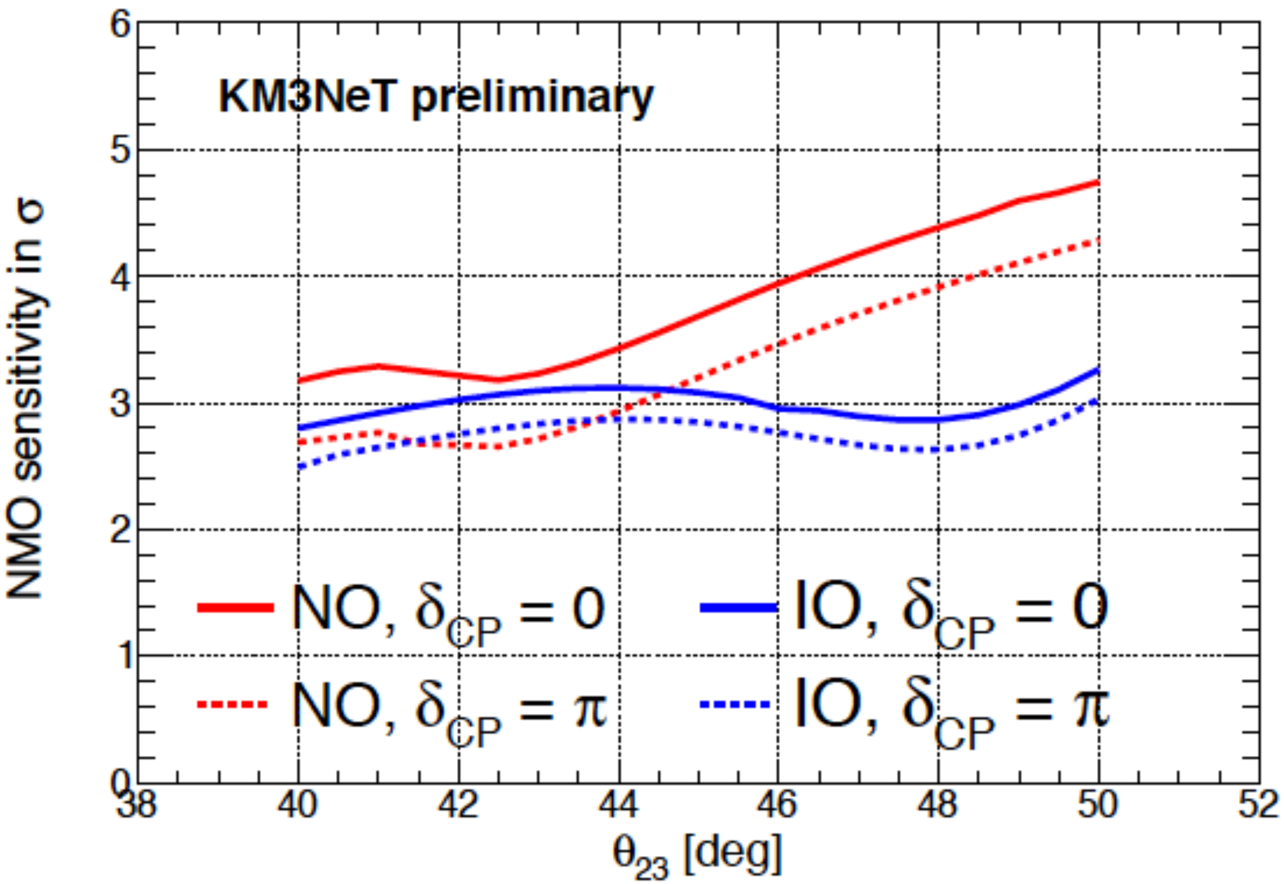


The non-oscillation hypothesis rejected at 4.6 sigma

KM3NeT/ORCA: oscillation parameters



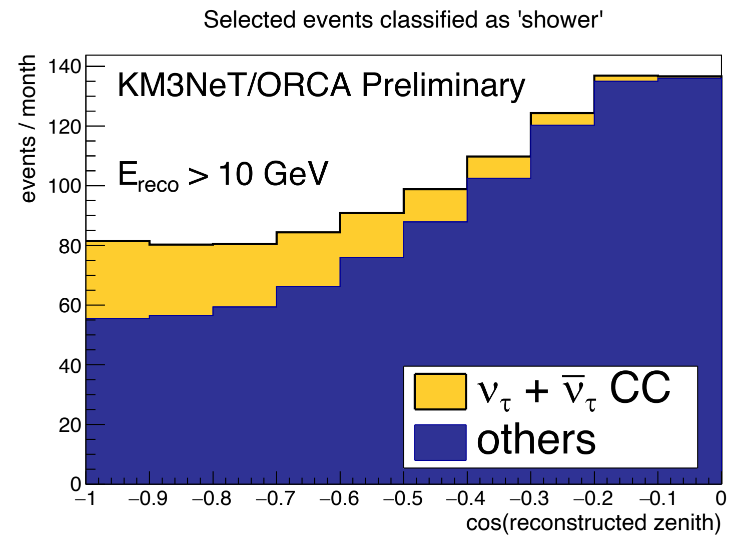
Sensitivity to neutrino mass hierarchy

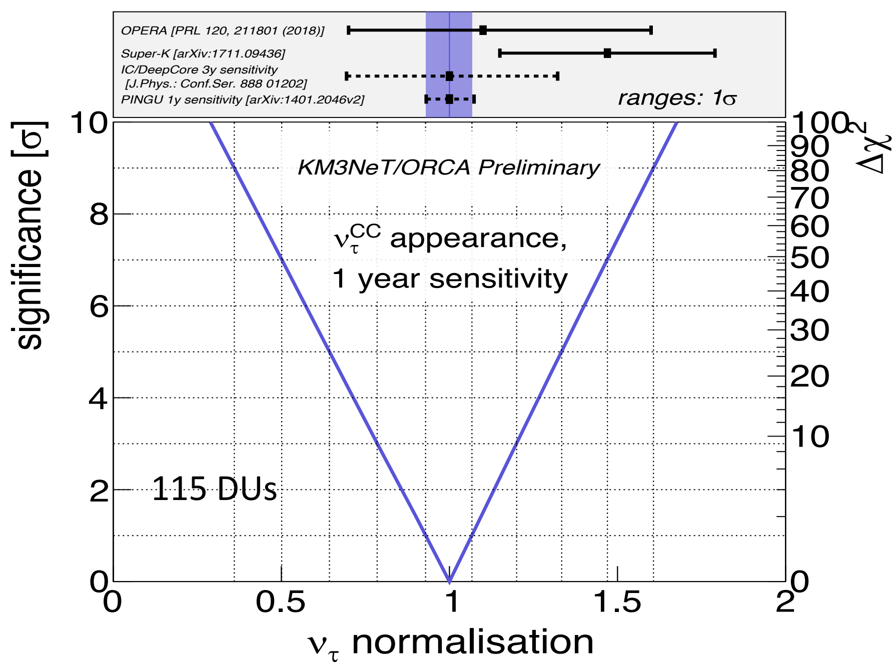


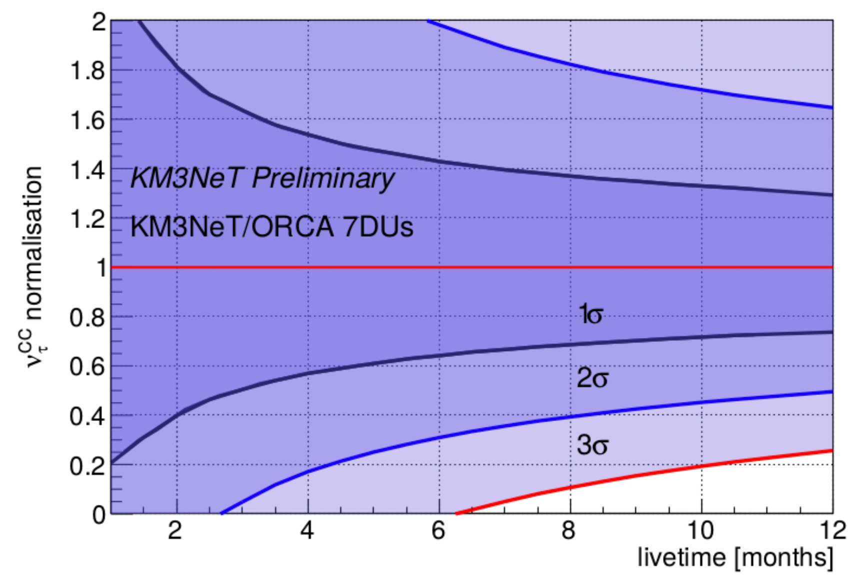
- ~3σ MH sensitivity in 3 years
- The combination of NH and upper octant of θ_{23} gives improved sensitivity
- The value of δ_{cp} has small but non-negligible impact on sensitivity

KM3NeT/ORCA: Tau neutrino appearance

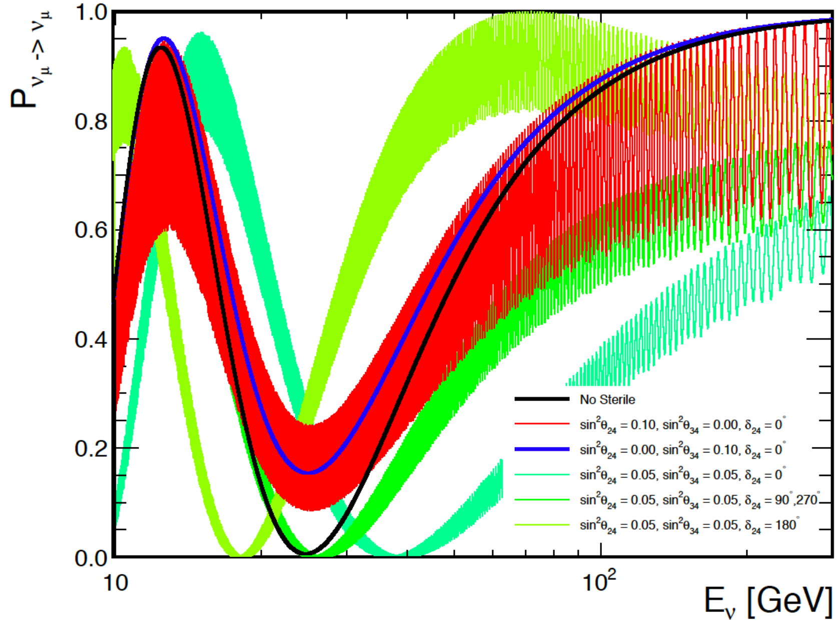
- ν_τ appearance tests PMNS unitarity and BSM theories
- 30% deviations allowed by world data
- ≈3k ν_τ CC events/year with full ORCA
- Rate constrained within ≈5 (25)% for 115 (7) DUs in 1 year

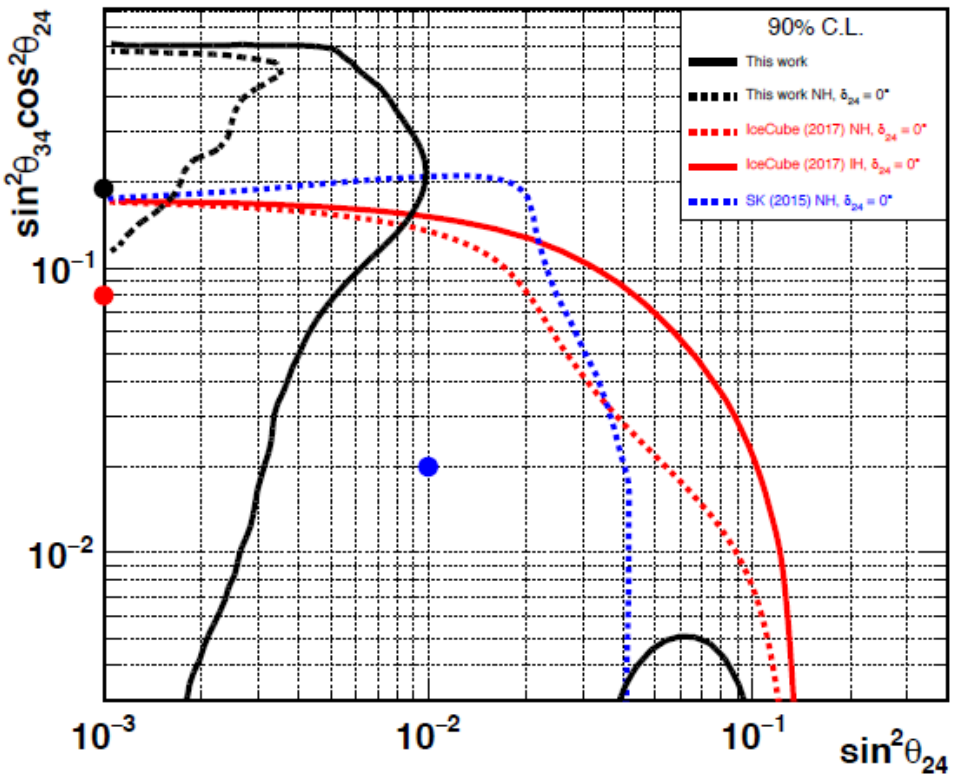






Presence of sterile neutrino modify significantly the oscillation pattern



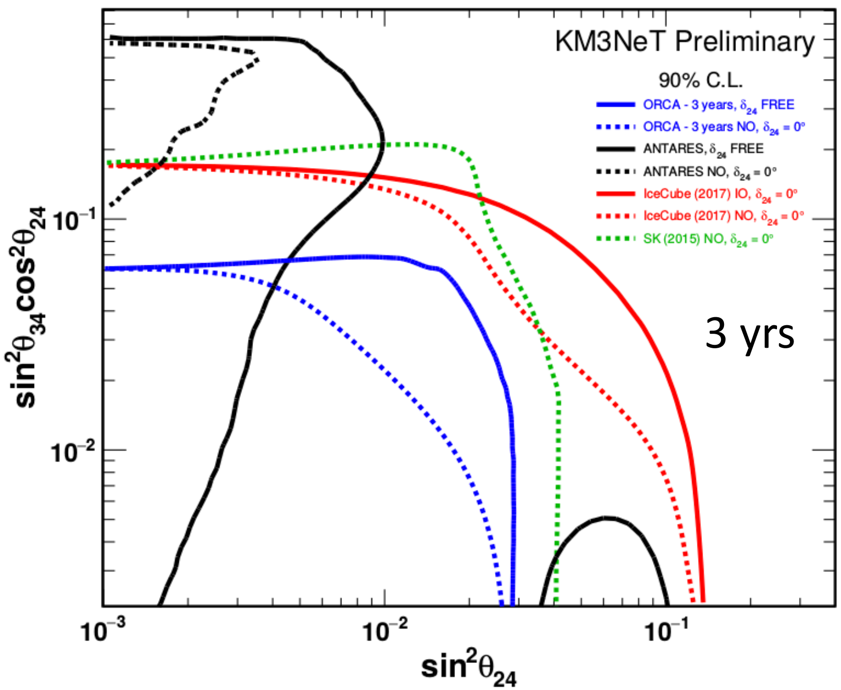


Parameter	Prior	Fit NH	Fit IH
θ_{24} [°]	none	$1.5^{+2.0}_{-5.0}$	$1.5^{+2.0}_{-5.0}$
θ_{34} [°]	none	$25.9^{+5.1}_{-4.2}$	$25.9^{+5.1}_{-4.2}$
δ_{24} [°]	none	180 ± 71	0 ± 72
n_ν	none	$0.84^{+0.10}_{-0.09}$	$0.84^{+0.10}_{-0.09}$
$\nu/\overline{\nu}$ [σ]	0.0 ± 1.0	$1.07^{+0.63}_{-0.55}$	$1.07^{+0.63}_{-0.55}$
$\Delta\gamma$	0.00 ± 0.05	-0.011 ± 0.036	-0.011 ± 0.036
Δm^2_{32} [10^{-3} eV^2]	none	$3.0^{+0.8}_{-0.6}$	$-3.0^{+0.6}_{-0.8}$
θ_{23} [°]	none	52 ± 8	52 ± 8
θ_{13} [°]	8.41 ± 0.28	8.41 ± 0.28	8.41 ± 0.28
M_A [σ]	0.0 ± 1.0	$0.11^{+0.93}_{-0.97}$	$0.11^{+0.93}_{-0.97}$

$$|U_{\mu 4}|^2 < 0.007\ (0.13) \text{ at } 90\%\ (99\%) \text{ CL},$$
$$|U_{\tau 4}|^2 < 0.40\ (0.68) \text{ at } 90\%\ (99\%) \text{ CL}.$$

KM3NeT/ORCA: sterile neutrino (3+1)

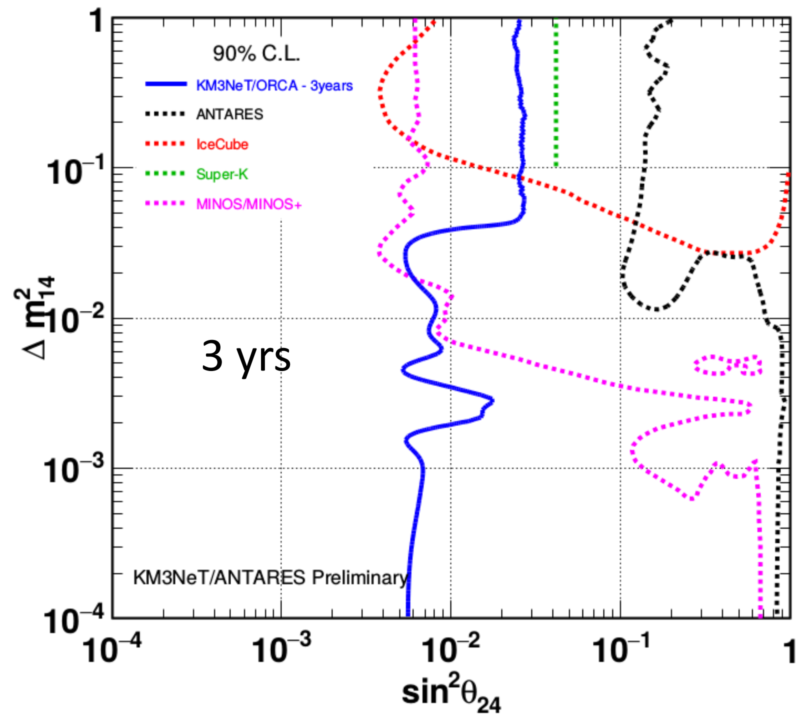
$\Delta m_{41}^2 > 0.1\ \mathrm{eV}^2$



Dependence on δ_{24}

Factor of two better sensitivity on $U_{\tau 4}$ than current limits from SK and IC

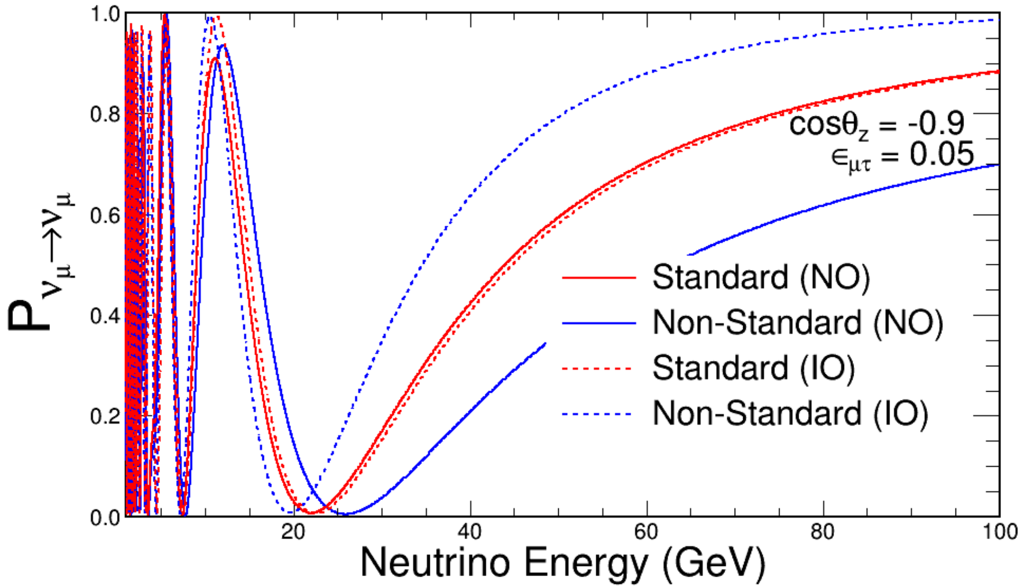
$\Delta m_{41}^2 < 0.1\ \mathrm{eV}^2$



Due to longer & multiple baselines improve on MINOS/MINOS+ limits by 2 orders of magnitude

KM3NeT/ORCA: non-standard interactions

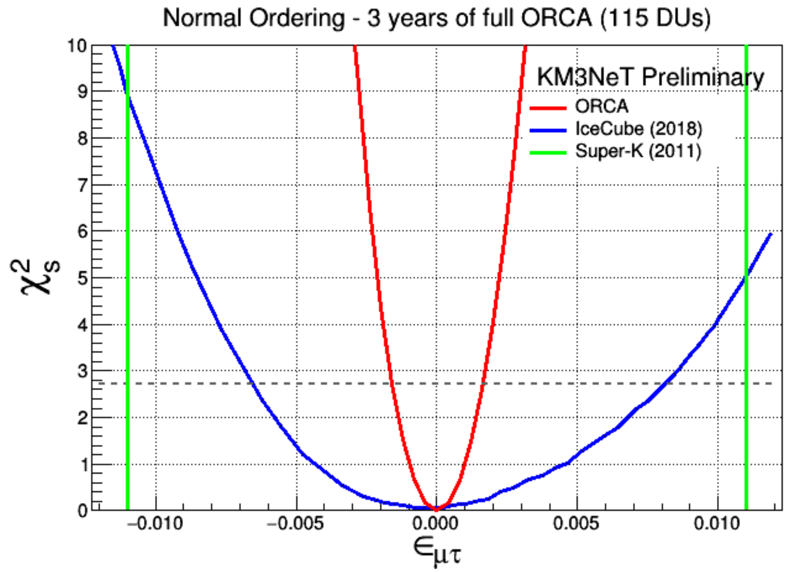
- ORCA sensitive to NSI effects of order 10% of the Fermi int.



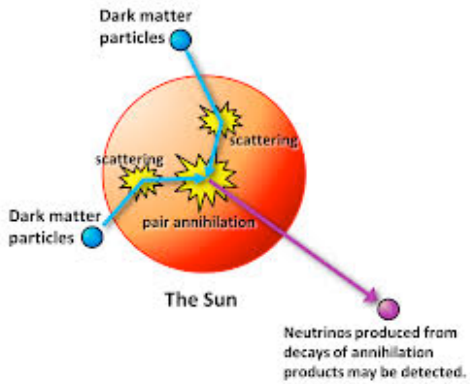
- Two-flavour hybrid model:

$$\varepsilon_{\mu\mu} = \varepsilon_{\tau\tau} = 0$$

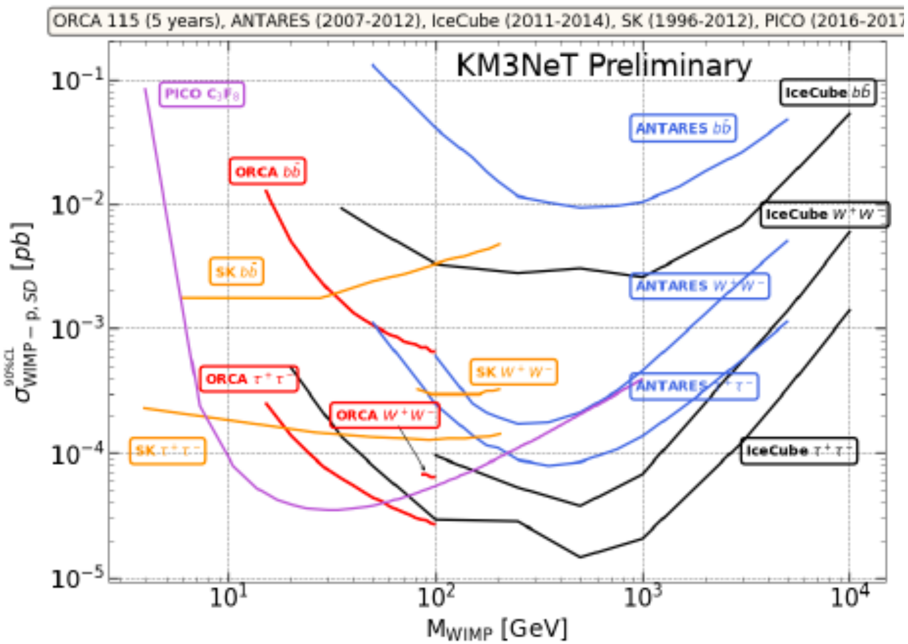
- ORCA improves significantly over current atmospheric bounds



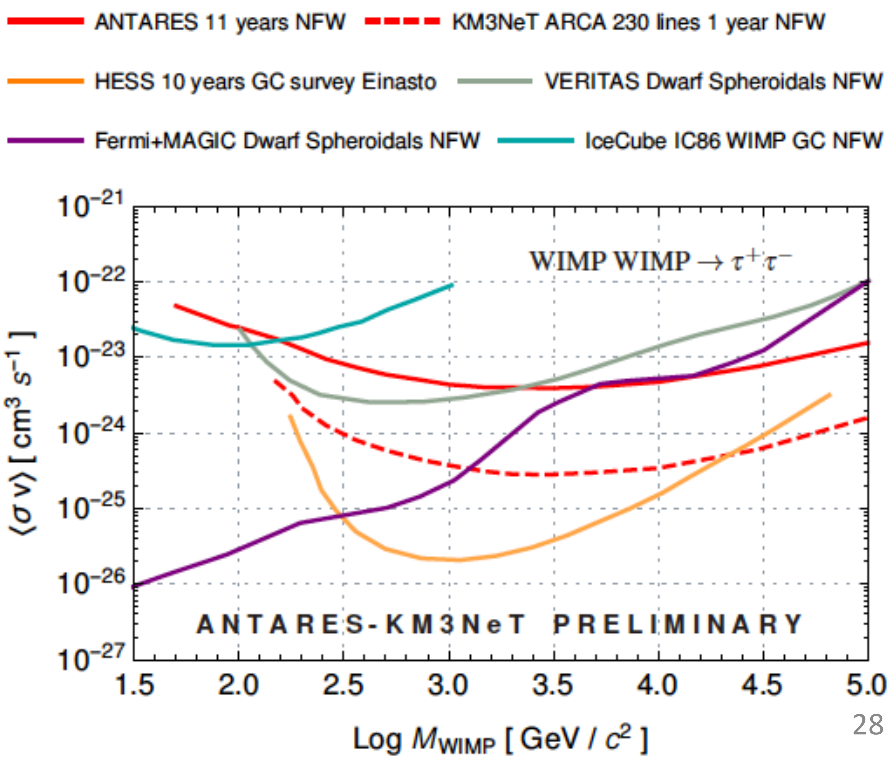
Dark Matter



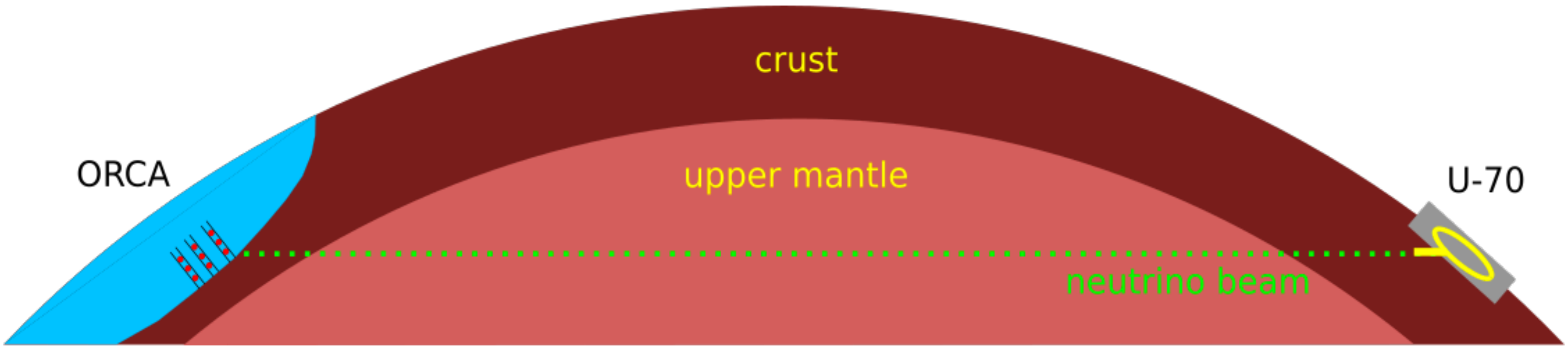
Sun: ORCA115



Galactic Centre: ARCA230



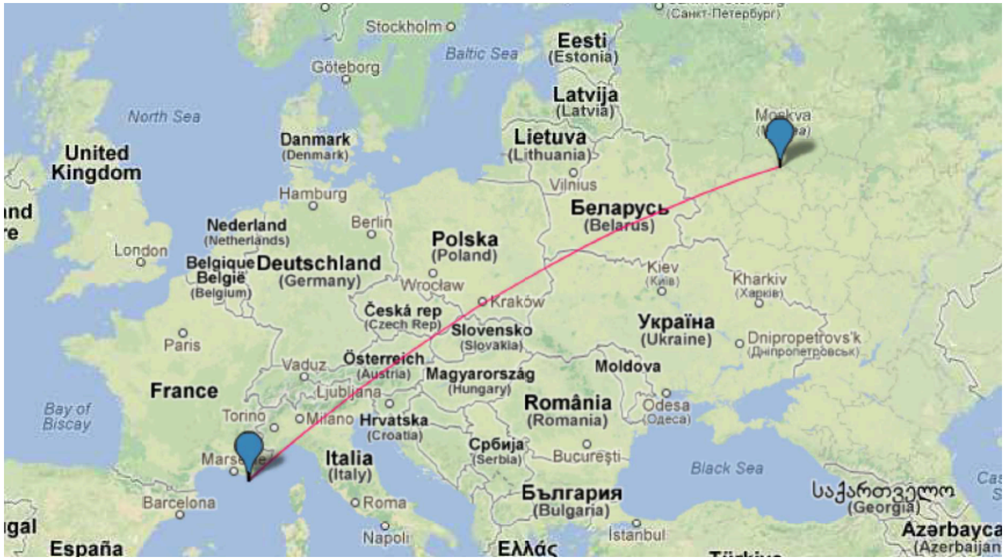
Protvino to ORCA (P2O)



Big detector -> lower beam power

- Baseline 2588 km
- Beam inclination : 11.7˚ (cos θ = 0.2)
- Deepest point : 134 km (3.4 g/cm^3)
- First oscillation maximum 5.1 GeV

-> Sensitivity to mass hierarchy
and CP violation

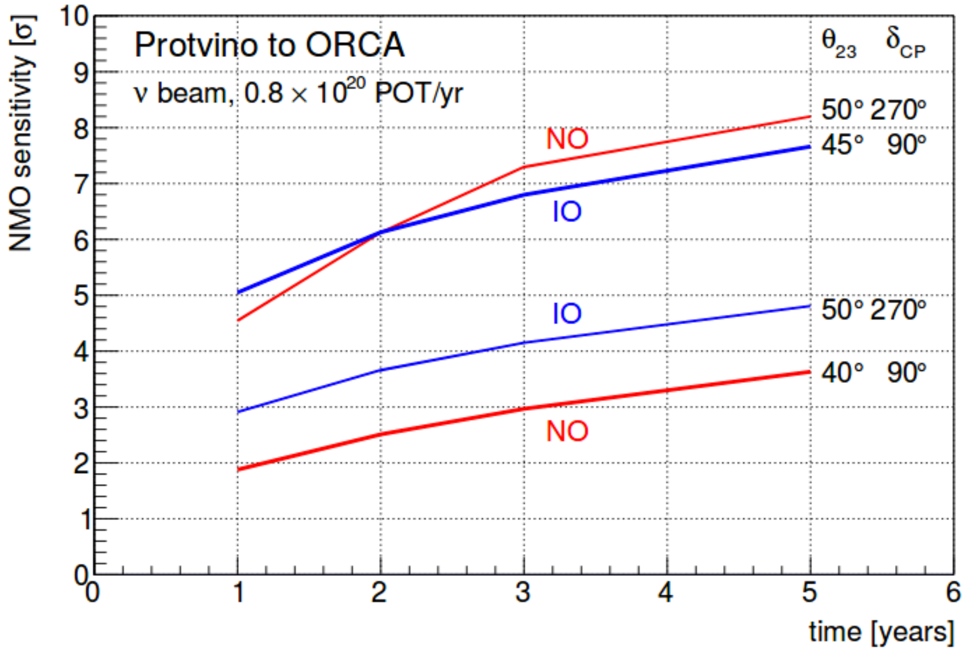


LoI published as arXiv:1902.06083

Protvino to ORCA (P2O): prelim. study

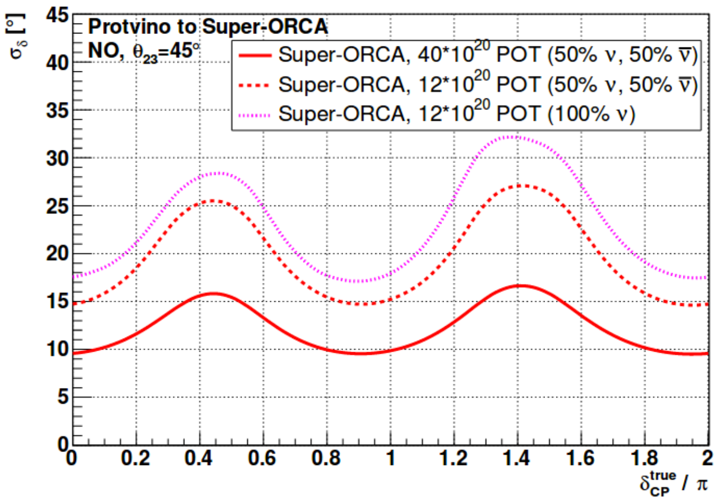
Phase 1: Mass Hierarchy

ORCA detector +
1 (5) years with 450 (90) kW



Phase 2: CP Violation

10x denser detector (Super ORCA)
450 kW
Measure CP Phase to 10-16 degrees in 10 years



Summary and Perspectives

ANTARES: Demonstration of potential of deep sea neutrino telescopes

KM3NeT: phased construction of a next-generation neutrino telescope
Developed novel and performant multi-PMT technology
interest from IC-Gen2, CHIPs, NuPrism, HyperK,…

ARCA-high energy:

- unprecedented angular resolution/multi-flavour astronomy
- investigation of diffuse cosmic flux, galactic sources,…

ORCA-low energy:

- NMH at 3 sigma level in 3 years (IH, NH/first octant). Much quicker if NH/second octant
- Competitive measurements of Δm^2_{32} and $\sin^2\theta_{23}$, tau appearance, sterile neutrinos, NSI, DM, tomography,…

CP Violation?:

- P2O: Protvino beam to (Super) ORCA

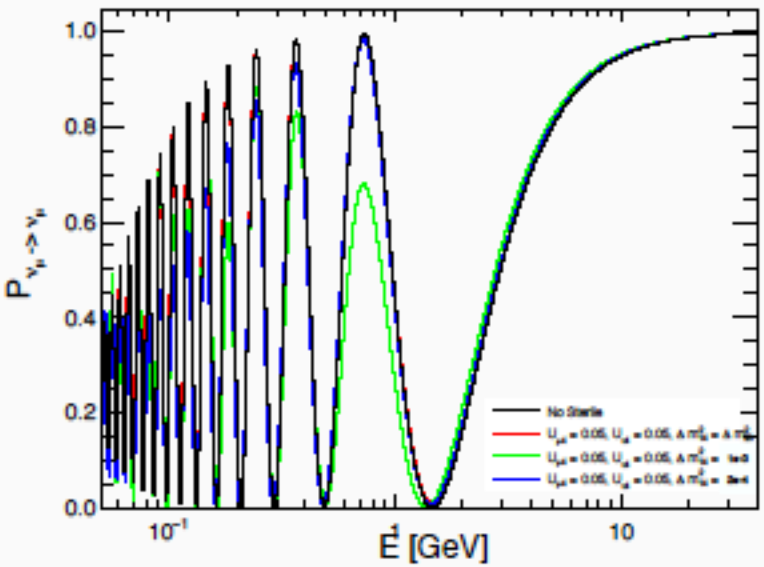
Exciting times ahead- please come and join us!


Thanks!

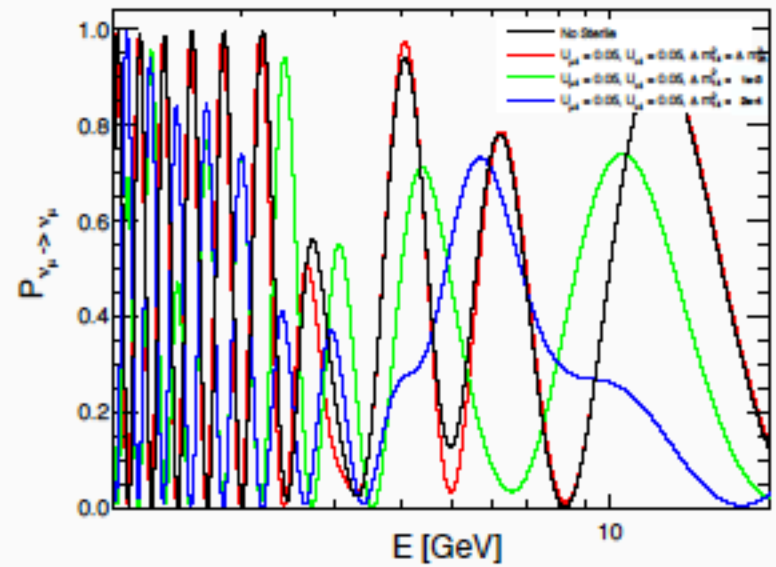
BACKUPS

ORCA vs MINOS

MINOS baseline + Vacuum



ORCA baseline + Matter

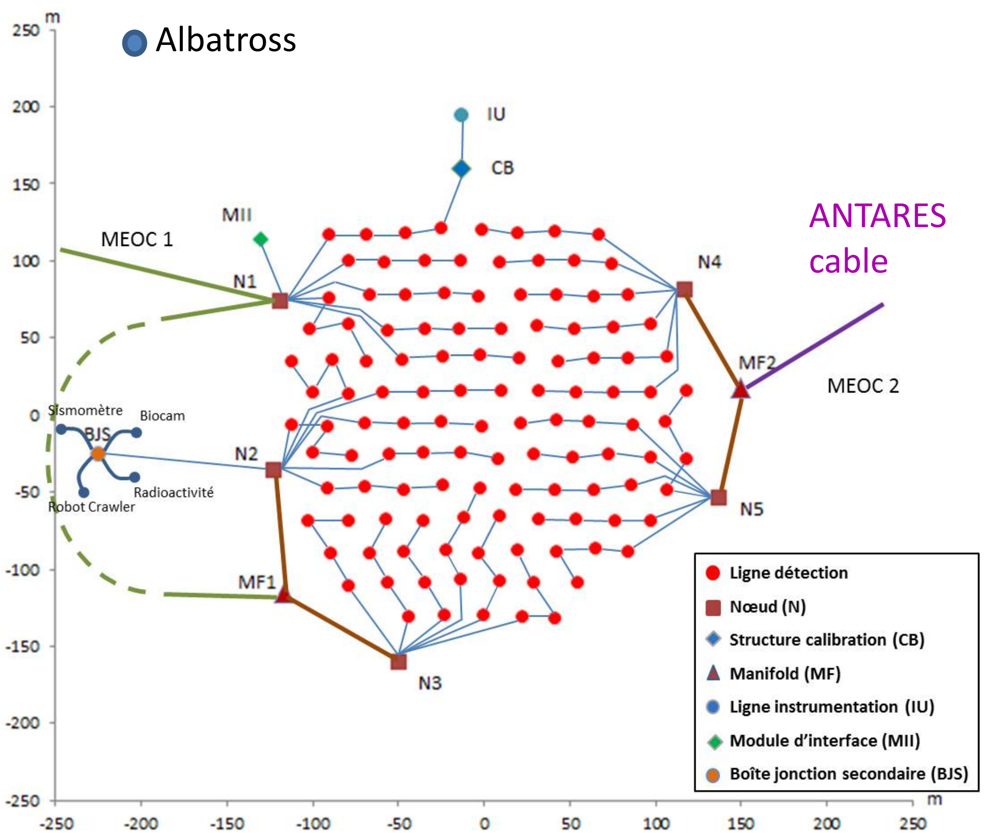


- We should expect a better sensitivity of ORCA wrt MINOS in the low sterile mass range.

ORCA Seafloor

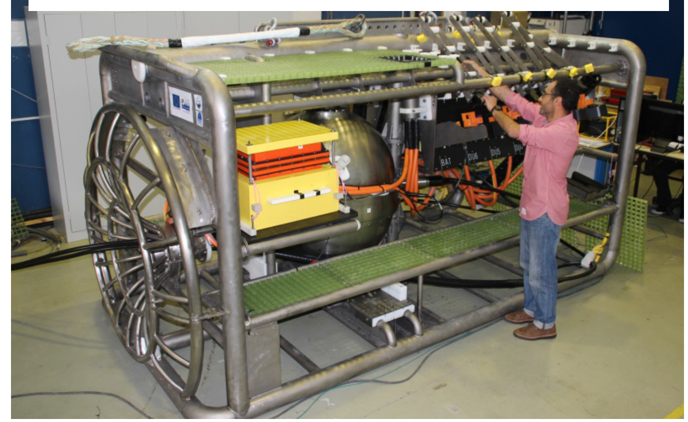
Phase 1: 6 string array at KM3NeT-France site to demonstrate technology/detection methods in the GeV range

Phase 2: Deploy 1 building block (115 strings)-2024

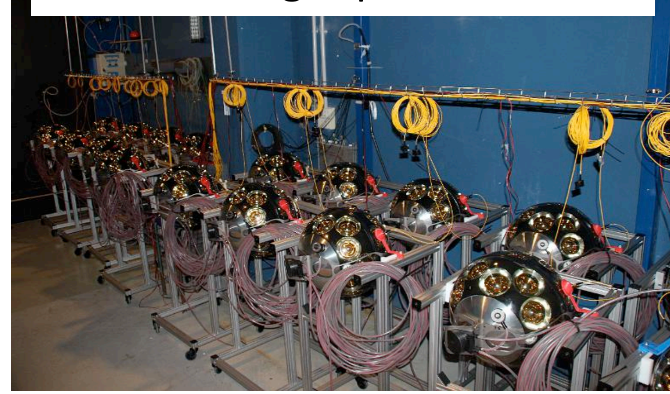


MEOC: Dec 2015, March 2017

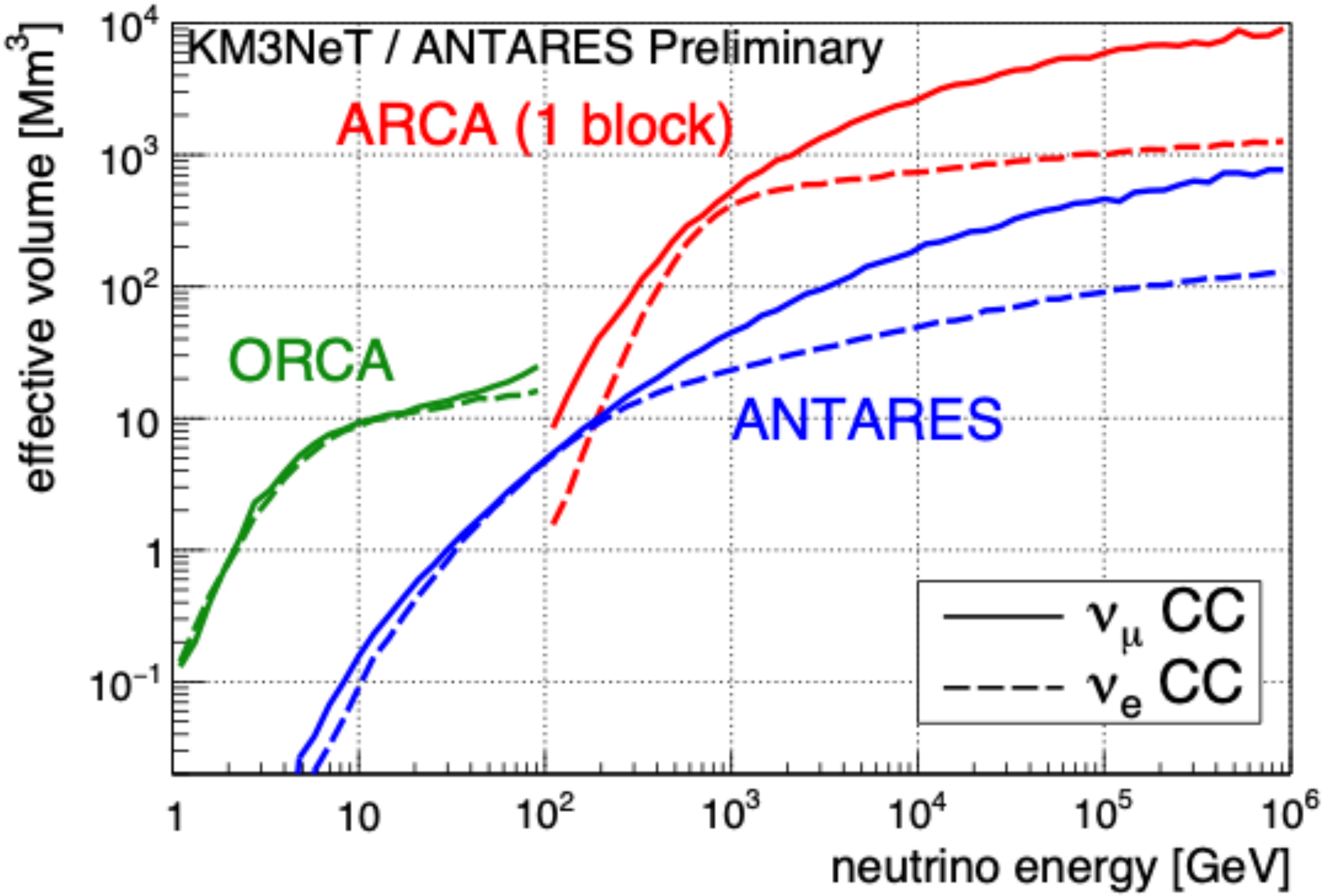
1st node: Sept 2016, Sept 2018



ORCA string: April 2017



ANTARES/ORCA/ARCA: Effective volumes



approved: ICRC2017, S. Hallmann

Oscillation of massive neutrinos

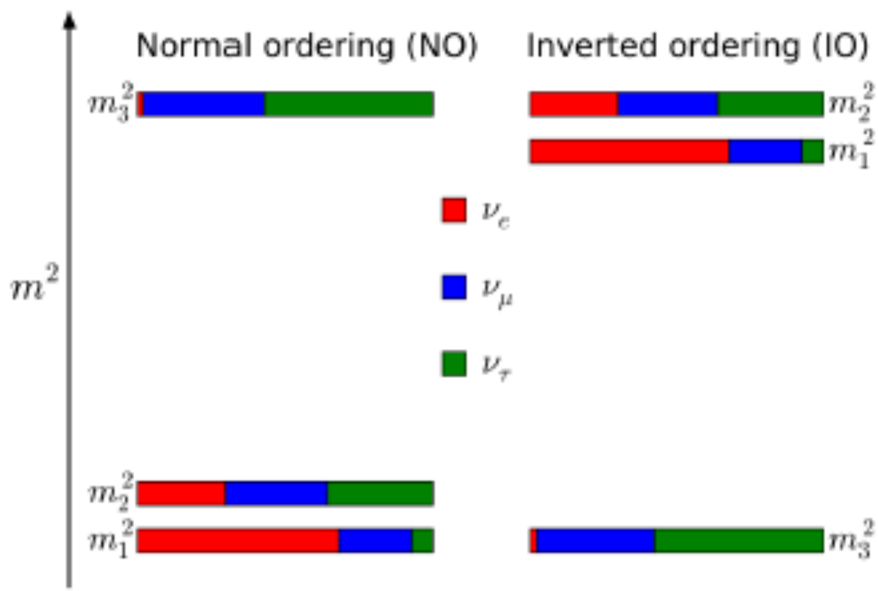
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} e^{i\eta_1} & 0 & 0 \\ 0 & e^{i\eta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Atmospheric **θ_A~45°** | Reactor θ_{13}~9° | Solar $\theta_\odot$~30° | Majorana

Reactor ↓ CP violating phase δ_{CP}

All parameters measured to fair precision except:

mass ordering
octant of θ_{23}
CP phase
Absolute masses
Majorana/Dirac

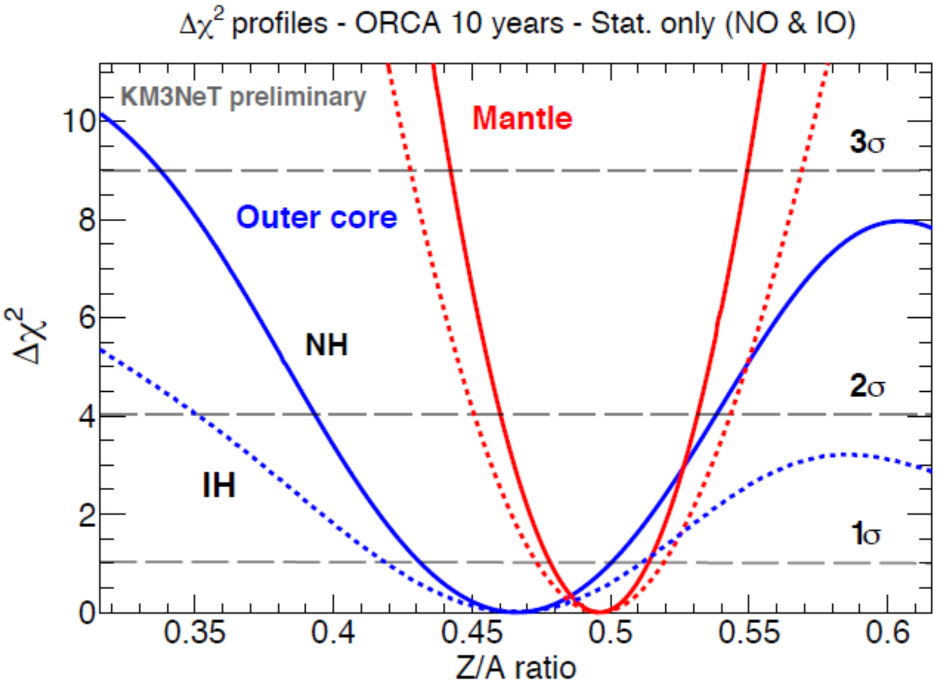


$$m_1^2 < m_2^2$$

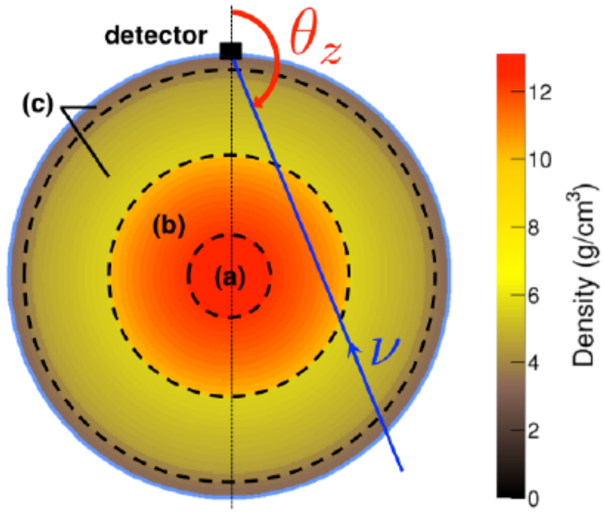
$$m_2^2 - m_1^2 \ll |m_3^2 - m_{1,2}^2|$$

Earth Tomography

- ORCA is sensitive to the electron density N_e while geophysics measure ρ_m
- 1σ stat. uncertainty after 10 years for NH:
  - ~ 4% in the whole mantle (c)
  - ~ 7% in the whole outer core (b)



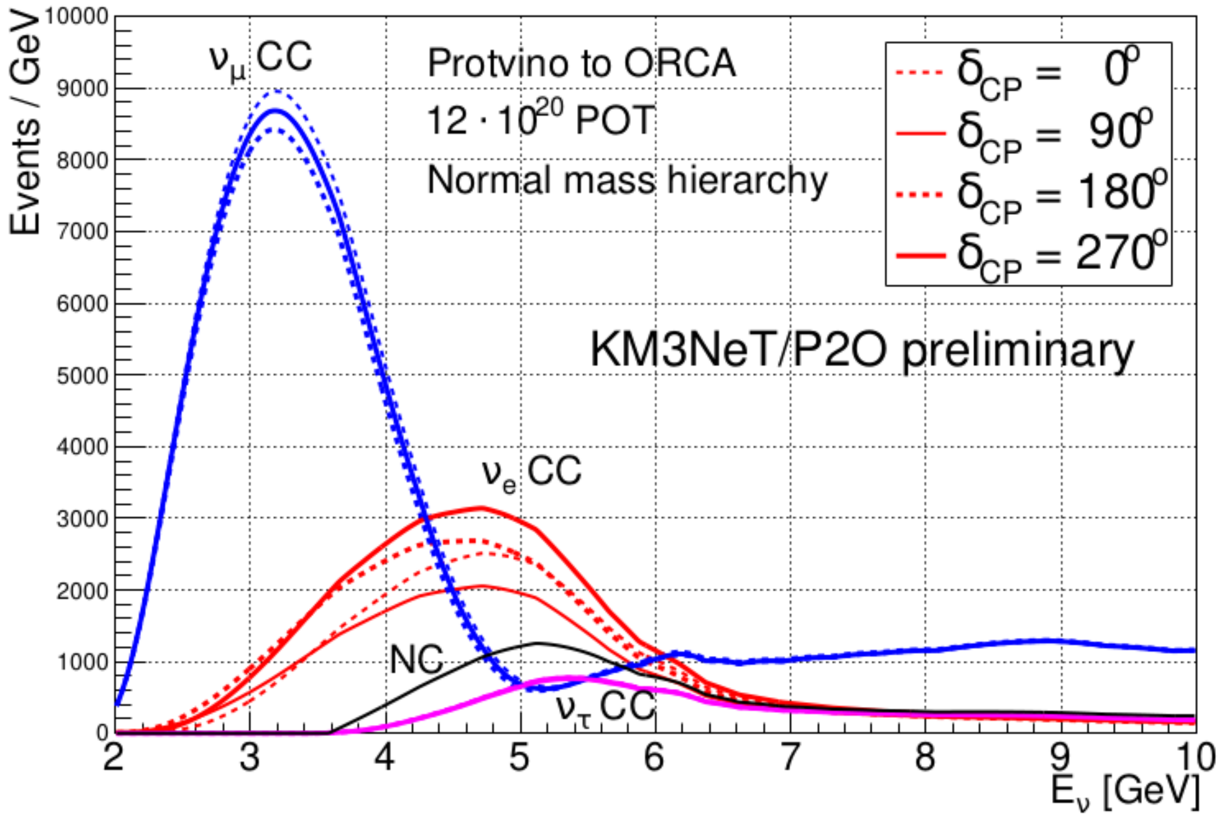
S Bourret et al (KM3NeT) 2016
J. Phys.: Conf. Ser. [Neutrino2016]



$$\frac{N_e}{\rho_m} \propto \sum_i w_i \frac{Z_i}{A_i}$$

- PREM model basis for ρ_m
- uniform Z/A rescaling in layer
- Monte Carlo response & PID
- statistical uncertainty only

P2O: Expected rates in ORCA (NH)



After 3 yr of 450 kW beam:

ν_μ CC: ~ 30000 events
ν_e CC: ~ 8000 events
ν_τ CC: ~ 3500 events
NC: ~ 6000 events

For comparison:
DUNE: ~ 750 ν_e / 3 yr

Vacuum oscillation maximum at E = 5.1 GeV
Most ν_μ convert to ν_τ which remains largely invisible (CC reaction suppressed by τ mass)

$\nu_\mu \rightarrow \nu_e$ transitions are enhanced by the matter effect, resonance energy 3.8 GeV