Measuring the Neutrino Mass Hierarchy with the KM3NeT/ORCA Detector

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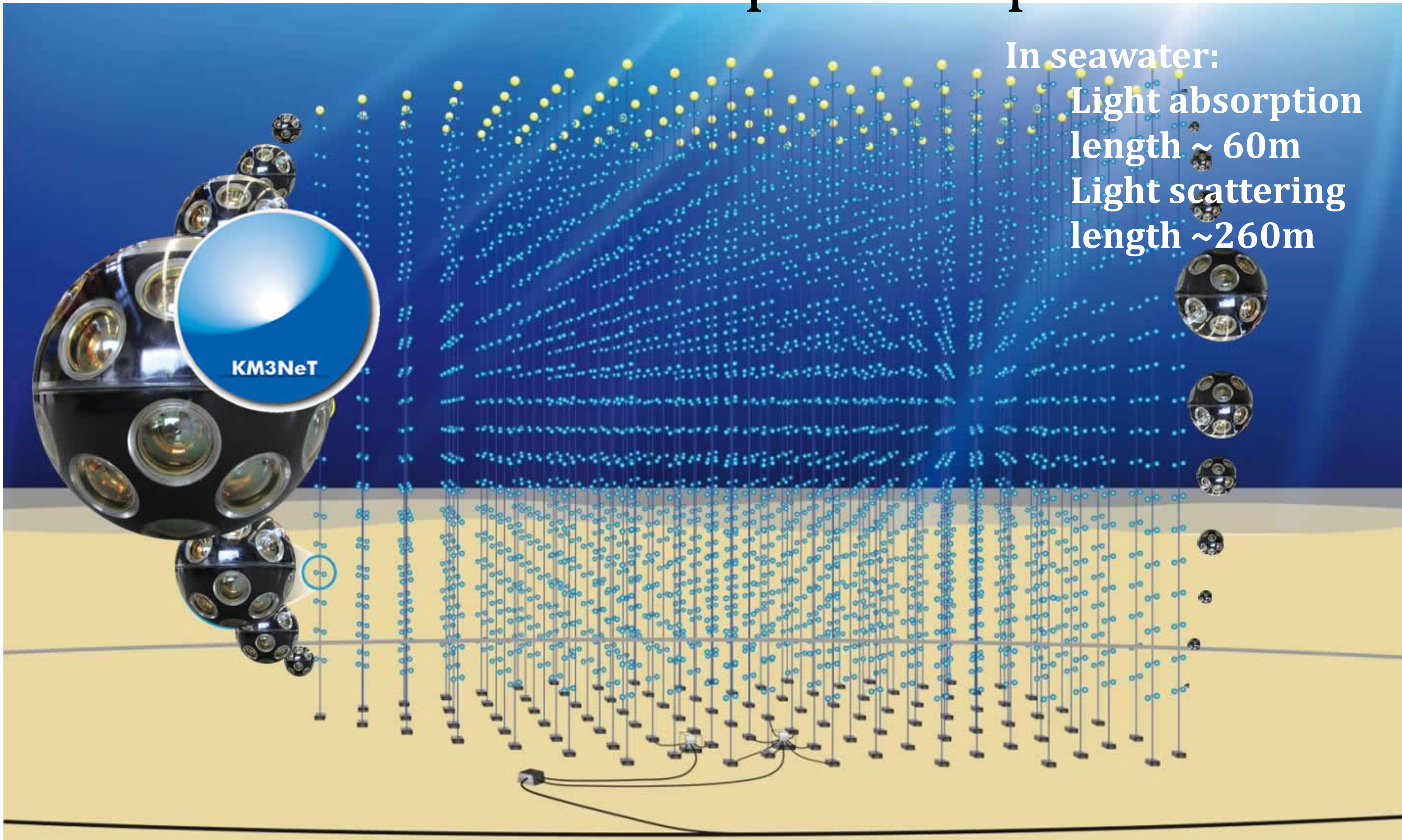
Overview

- Neutrino Telescopes and the KM3NeT Experiment
- Signal and Reconstruction at ORCA
- Physics Potential
- Latest Data and Current Status

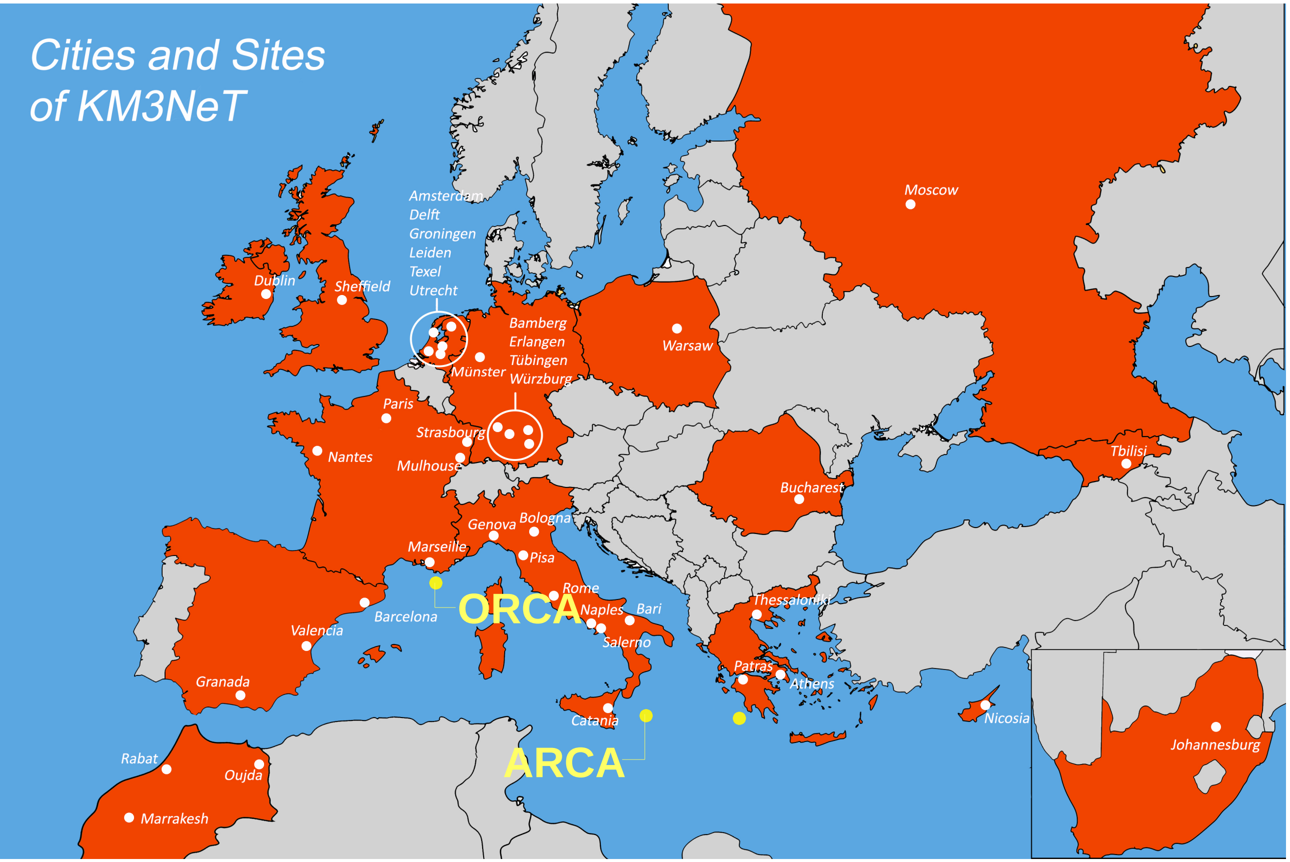
Neutrino Telescope Principles

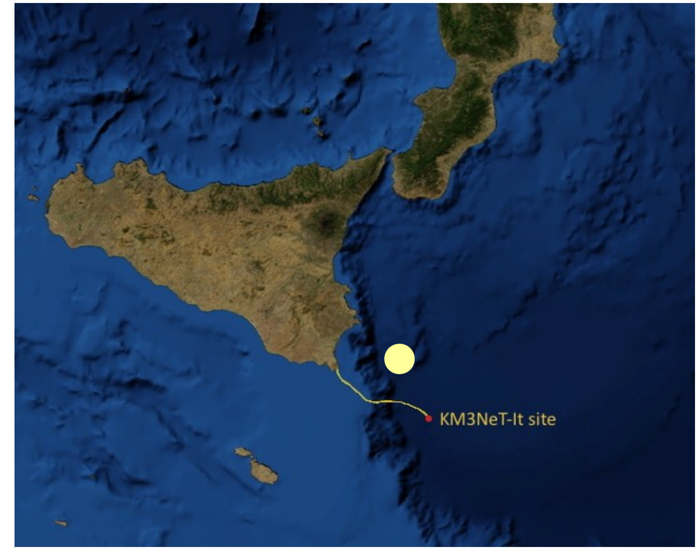


Basic principle: look for Cherenkov tracks in large instrumented volume
Similar to other Cherenkov detectors, but on a much larger scale

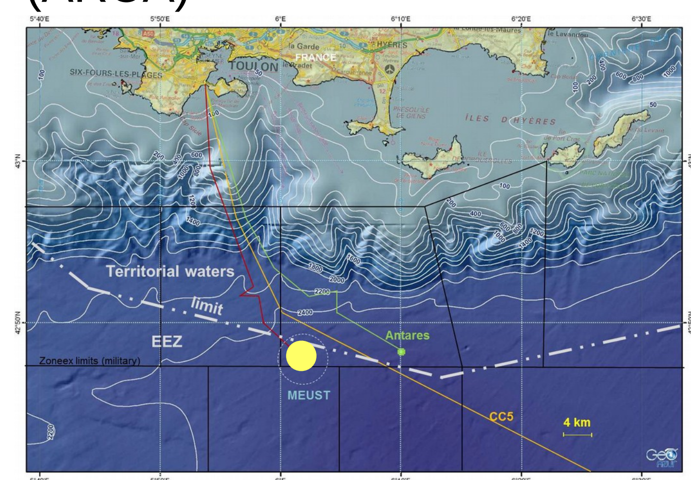
The KM3NeT Experiment

km³ Neutrino **T**elescope





Astroparticle Research with Cosmics in the Abyss (ARCA)



Oscillation Research with Cosmics in the Abyss (ORCA)

Two sites:

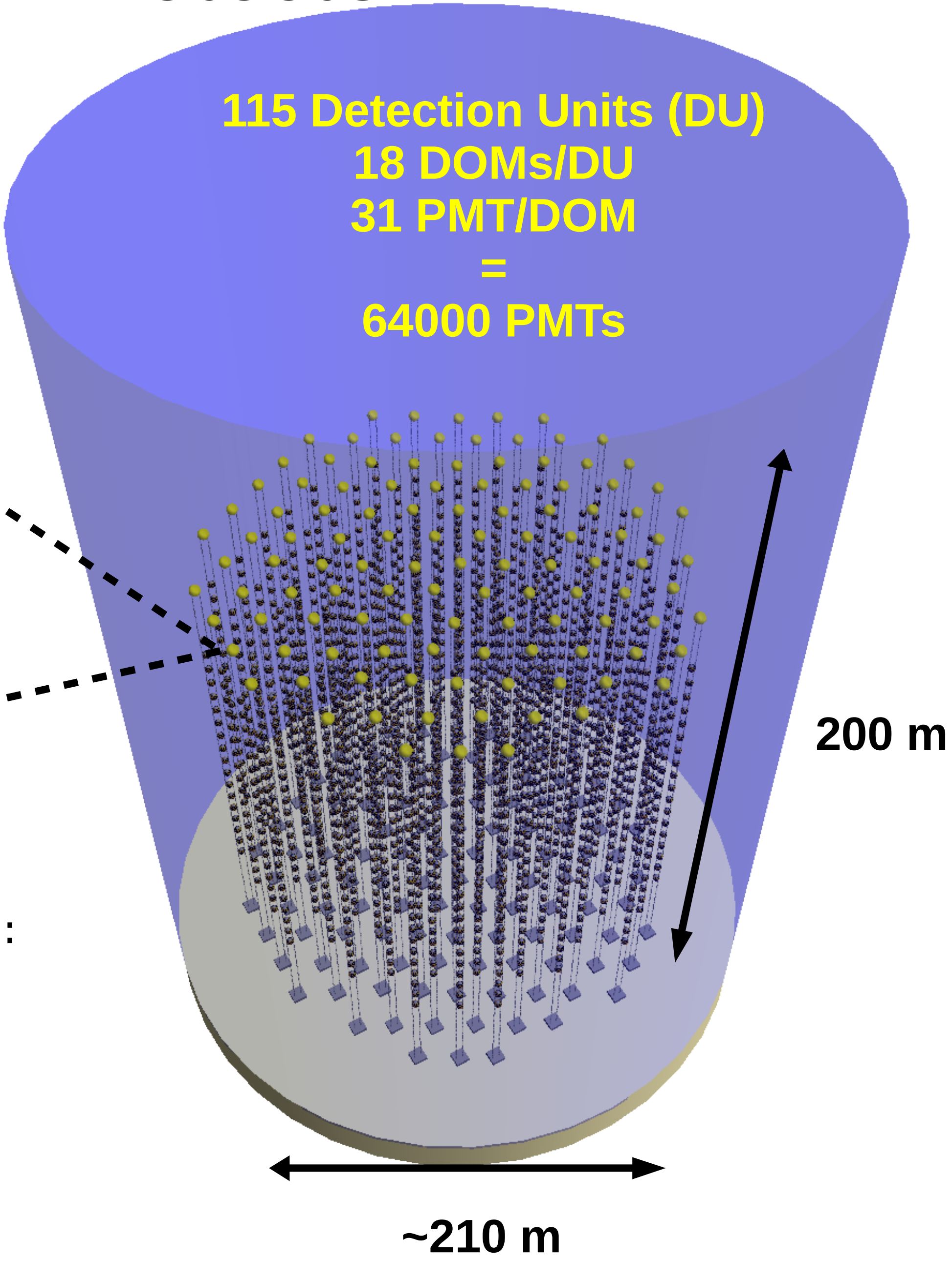
ARCA – High energy

ORCA – Low Energy

Same technology and collaboration

The ORCA Detector

Digital Optical Module (DOM)



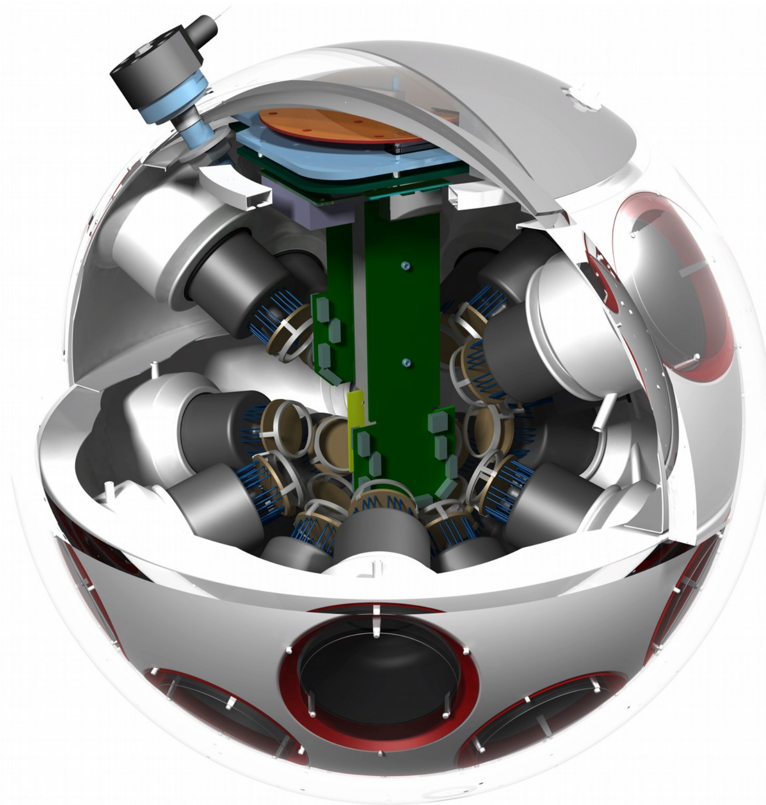
ORCA looks at lower energies (10s of GeV):

- 8 Mton instrumented
- Densely instrumented (23m spacing between lines)

Depth: 2435 m

The Digital Optical Module

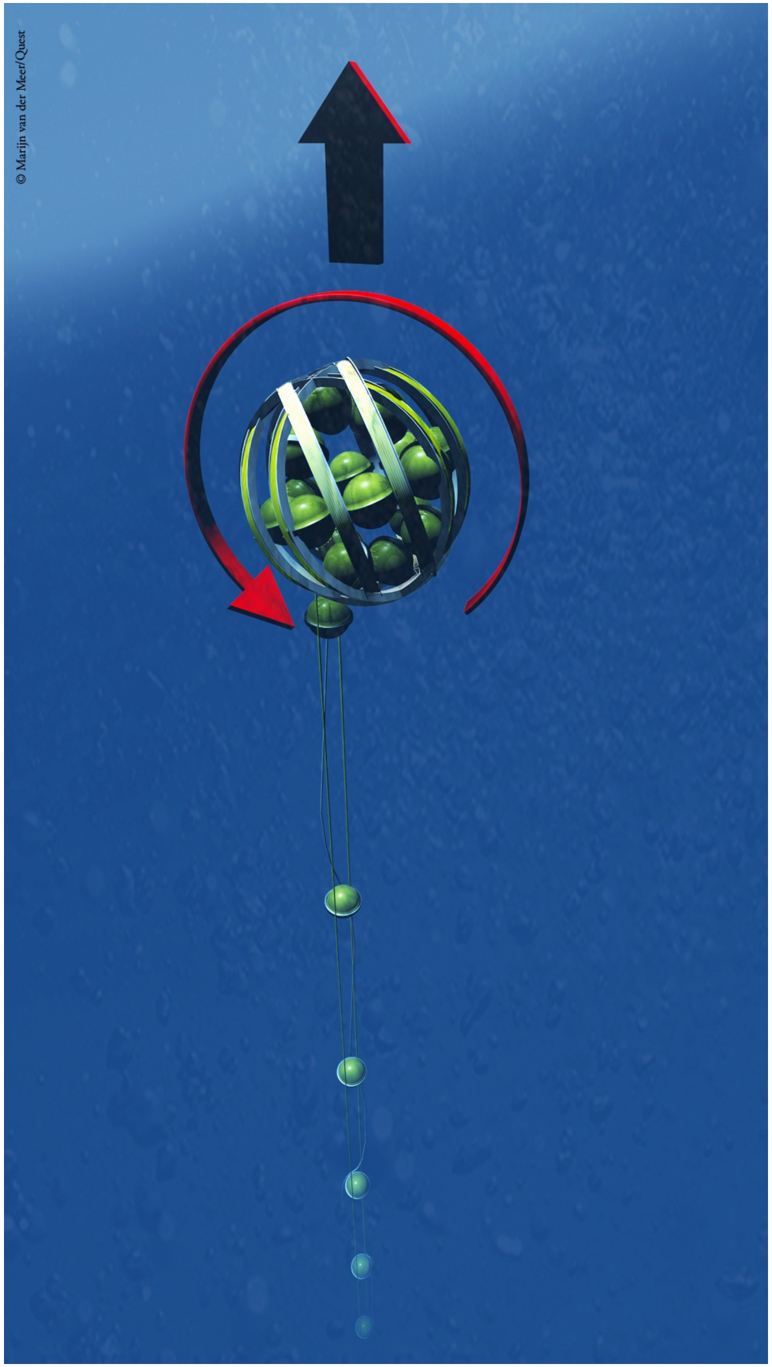
- 17” diameter
- 31 x 3” PMTs per module
- Line spacing optimized for low energy physics



This design allows for:

- Uniform angular coverage – and therefore direction reconstruction
- Digital photon counting

Deployment

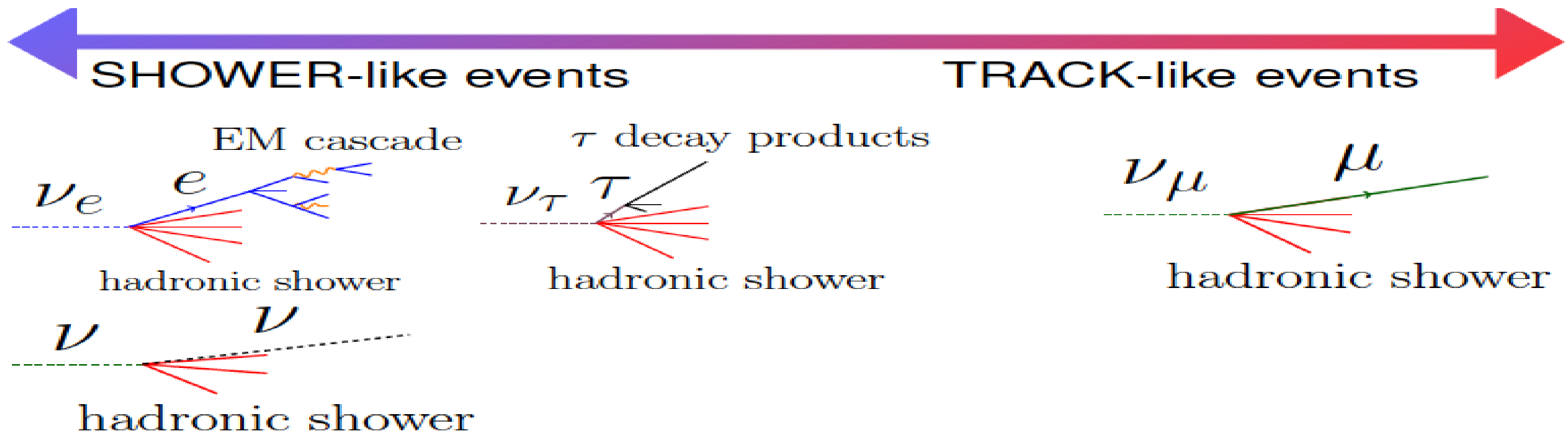


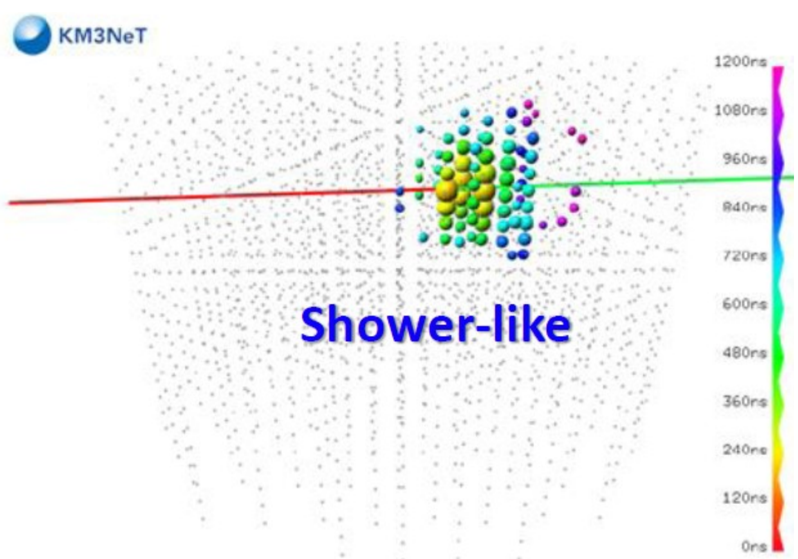
Rapid deployment possible

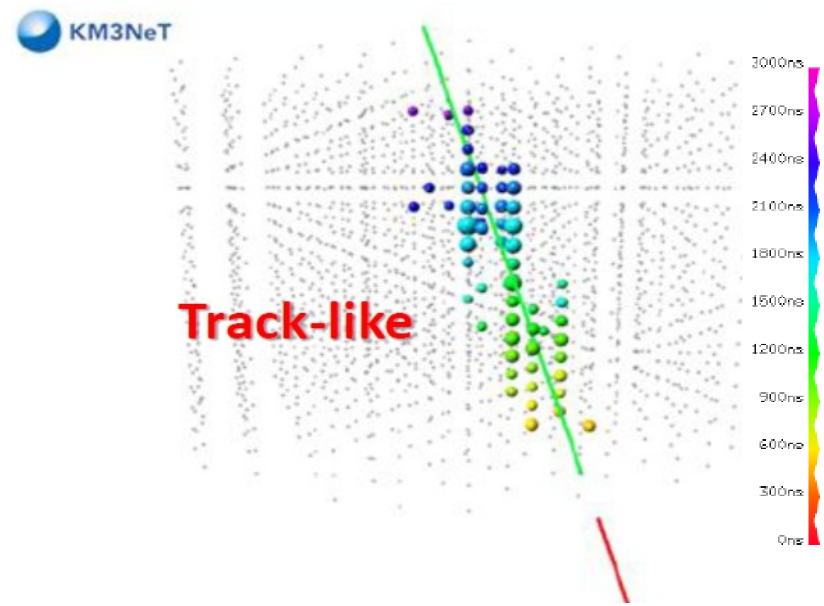
- Autonomous unfurling for each string

Can deploy multiple strings per sea operation

Signal at ORCA

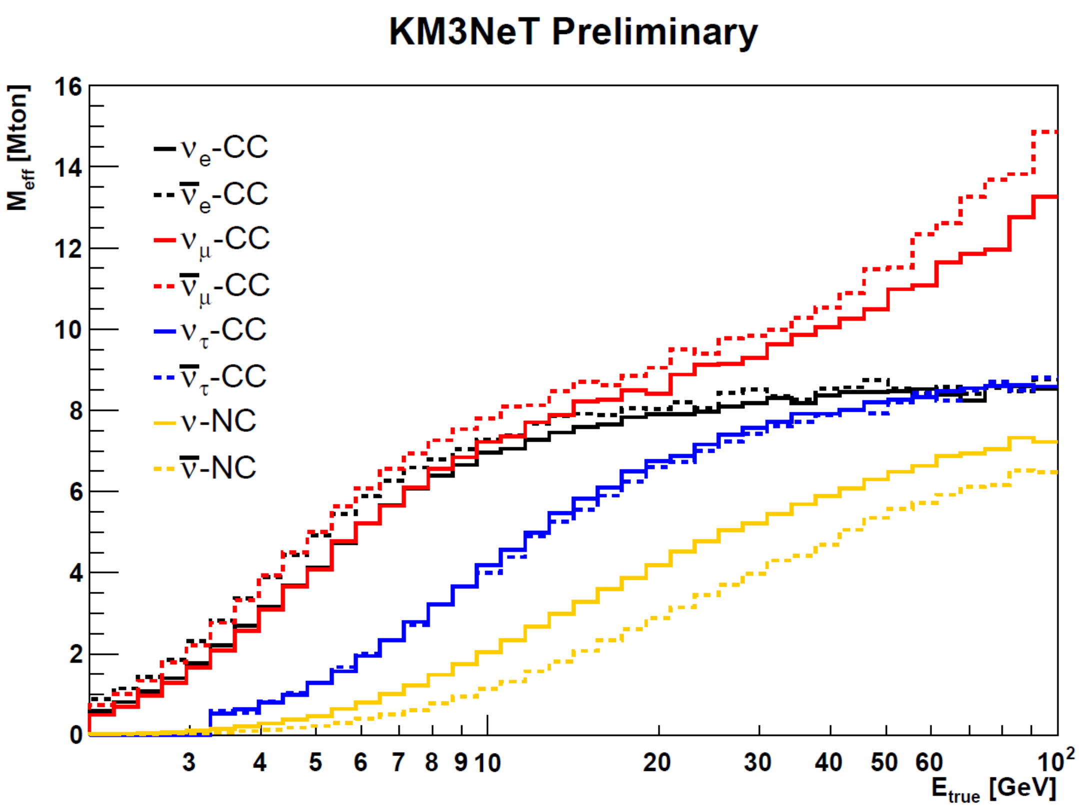






The main signal at ORCA comes from ν_μ and ν_e CC in the 10GeV region

ORCA Effective Mass



Effective mass after triggering, background rejection and containment cuts

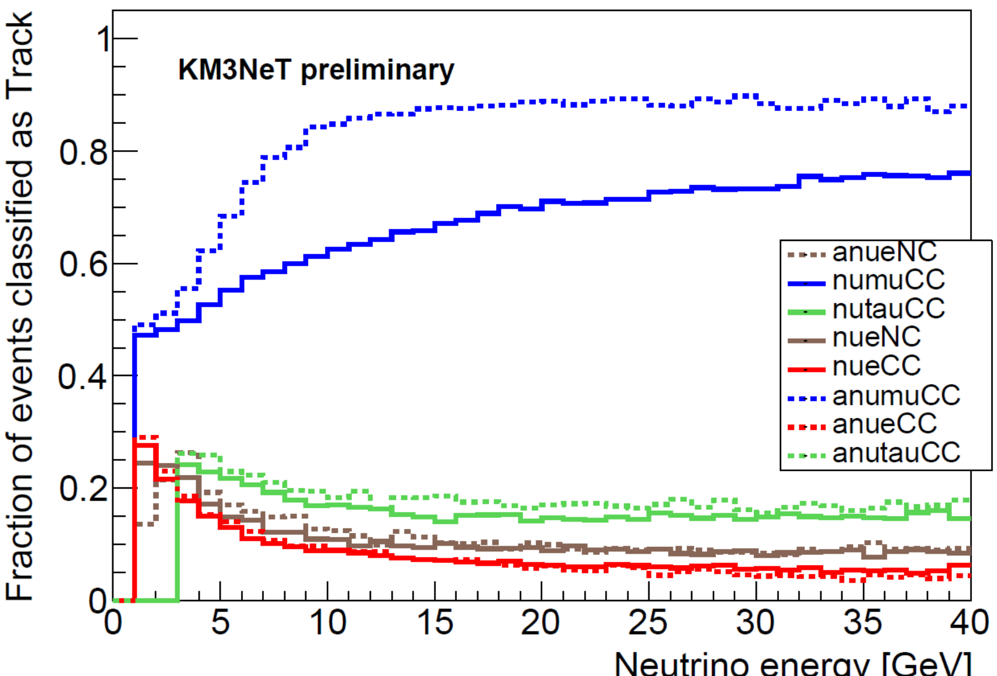
- Threshold dependent on DOM spacing

channel	events/y	channel	events/y
ν_e CC	14700	ν_τ CC	2900
$\bar{\nu}_e$ CC	5700	$\bar{\nu}_\tau$ CC	1300
ν_μ CC	21300	ν NC	5300
$\bar{\nu}_\mu$ CC	9900	$\bar{\nu}$ NC	1500

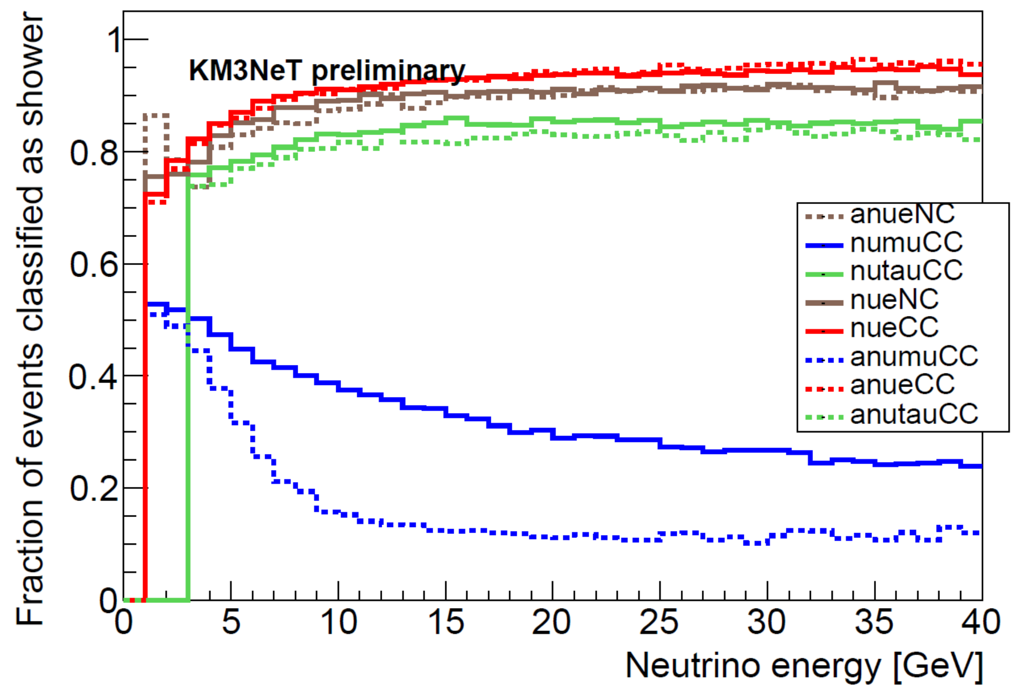
Particle ID at ORCA

Random decision forest technique to both identify atmospheric muons and perform track-shower separation

Classified as Track



Classified as shower (9m Spacing)



At 10 GeV:
90% correct ID for ν_e CC
70% correct ID for ν_μ CC

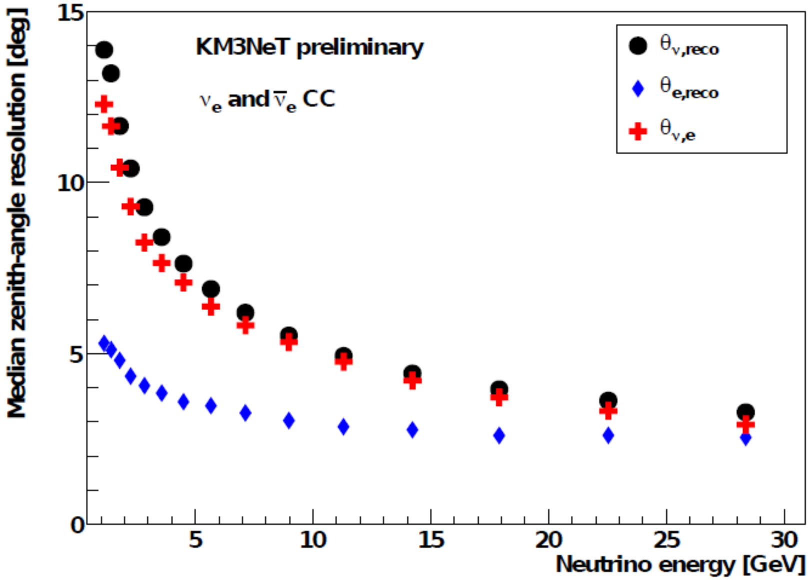
Able to suppress atmospheric muon background and noise to the 3% level

- Still preserves 95% of the neutrino signal

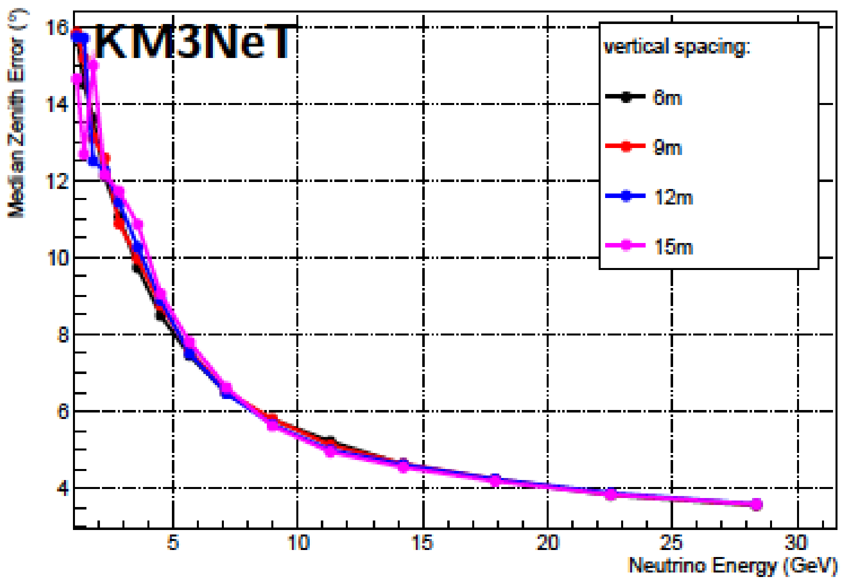
Deep-learning based efforts currently underway as well

Zenith Angle Reconstruction

Showers



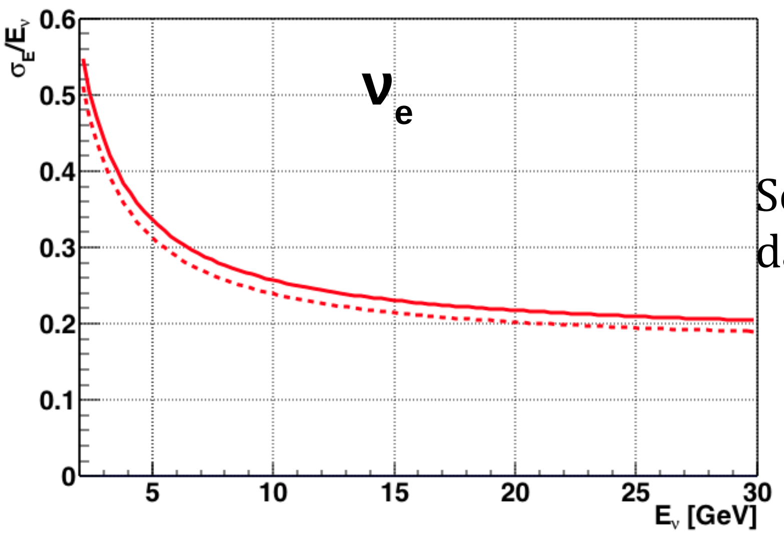
Tracks



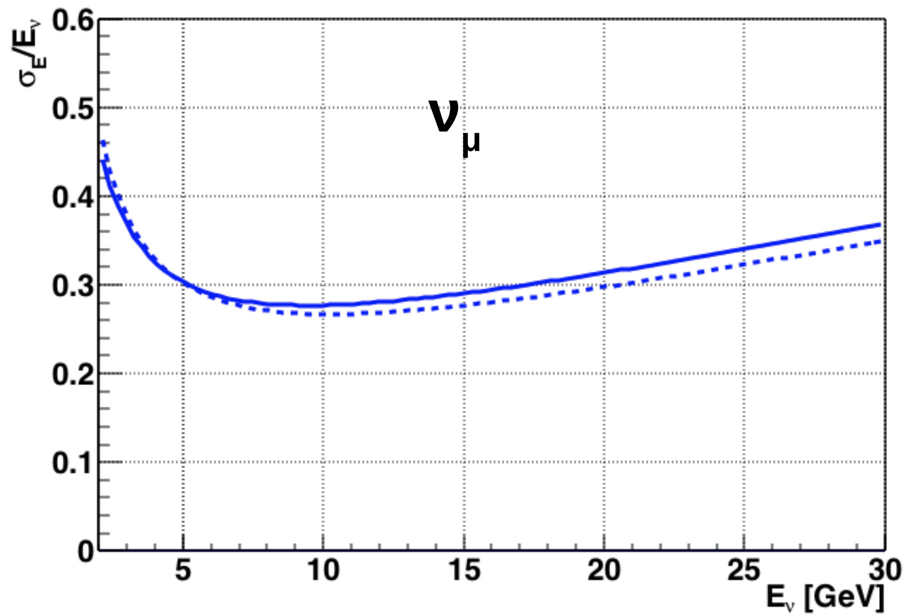
Median zenith angle resolution of 5° at 10 GeV for both track and shower channels.

- Dominated by the intrinsic ν-lepton scattering angle

Energy Reconstruction

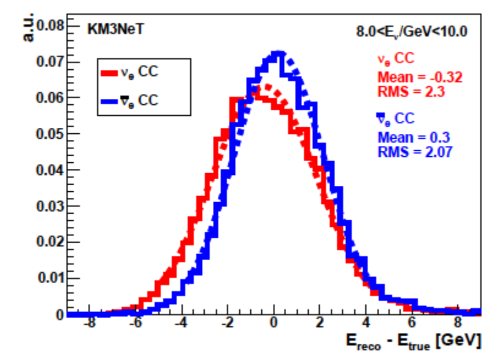


Solid – ν,
dashed - $\bar{\nu}$



Energy resolution is better than 30% in the relevant E range

Distribution close to Gaussian



ORCA Physics Goals

Primary goal: Measuring the neutrino mass hierarchy

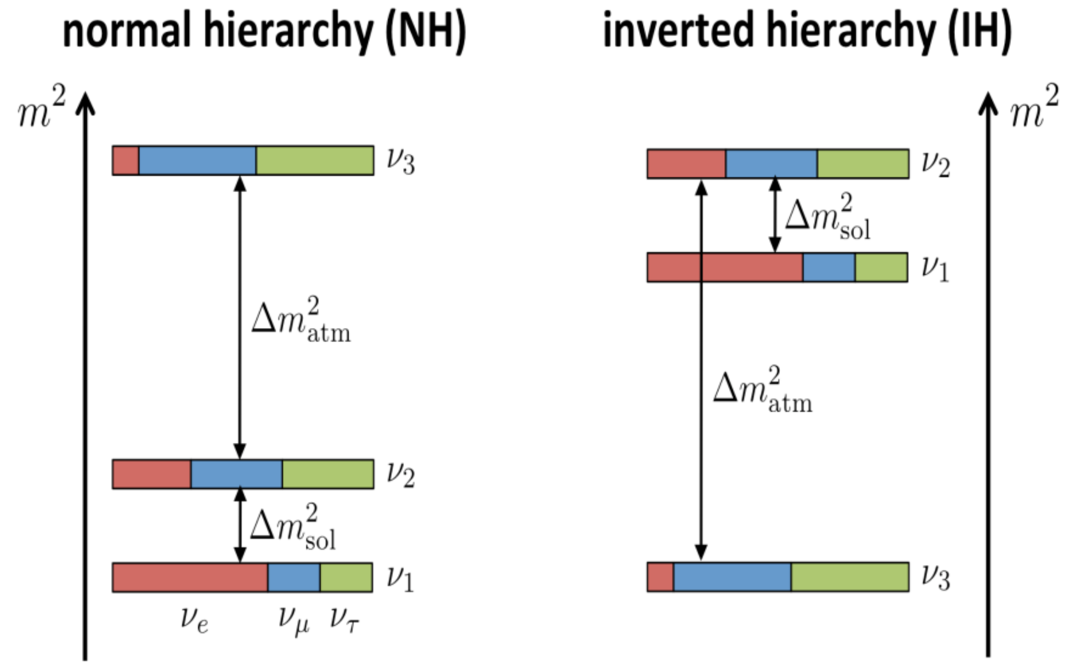
Other potential physics avenues:

- ν_τ appearance to test PMNS unitarity
- Neutrino tomography of the Earth's core
- Further constraints on neutrino oscillation measurements
- Sterile neutrino searches

Neutrino Mass Hierarchy

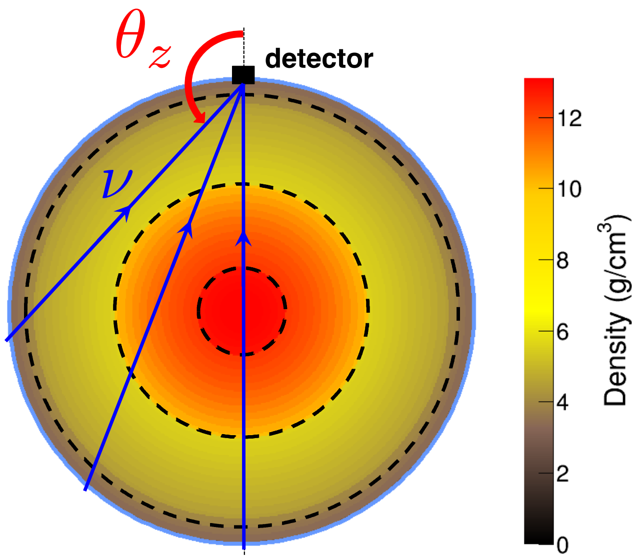
We need to know the sign of the neutrino mass splittings to resolve many neutrino unknowns:

- Dirac vs Majorana
- Absolute mass scale



Δm^2_{21}, $|\Delta m^2_{32}|$ measured... but the sign of Δm^2_{32} is still unknown.

Atmospheric Neutrinos

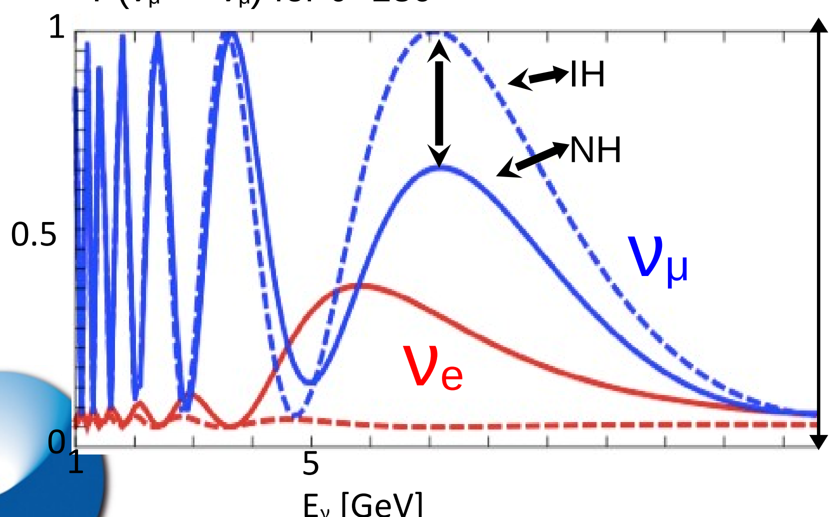


Atmospheric flux gives known ν_e and ν_μ composition
Wide range of zenith angles and neutrino energies

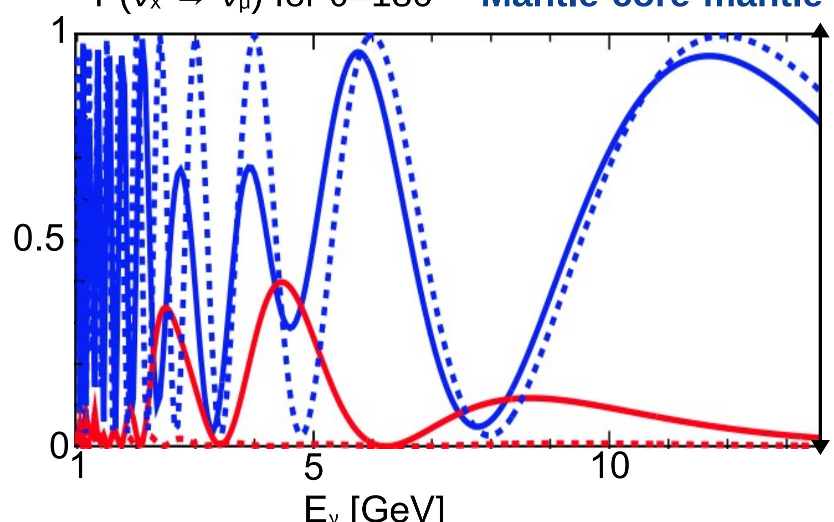
Matter effects in the earth distort the neutrino oscillation pattern

- Maximum difference between IH/NH occurs at θ = 130 E_ν = 7 GeV

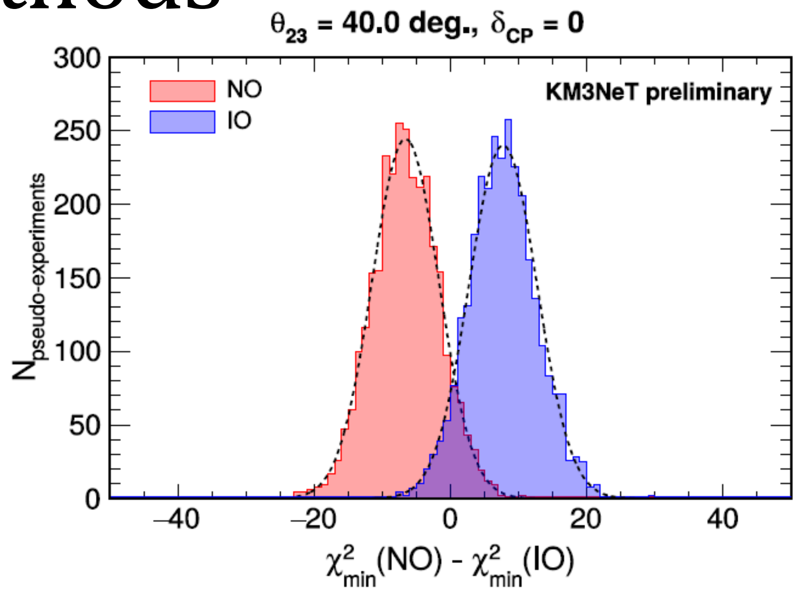
P($\nu_\mu \rightarrow \nu_\mu$) for θ=130º



P($\nu_x \rightarrow \nu_\mu$) for θ=180º - **Mantle-core-mantle**



Statistical methods



Generate psuedo-experiments to calculate the LLR test statistic:

$$\boxed{TS = -2 \cdot \ln \frac{\max \mathcal{L}_{\mathrm{NO}}}{\max \mathcal{L}_{\mathrm{IO}}} = \chi^2_{\min}(\mathrm{NO}) - \chi^2_{\min}(\mathrm{IO})}$$

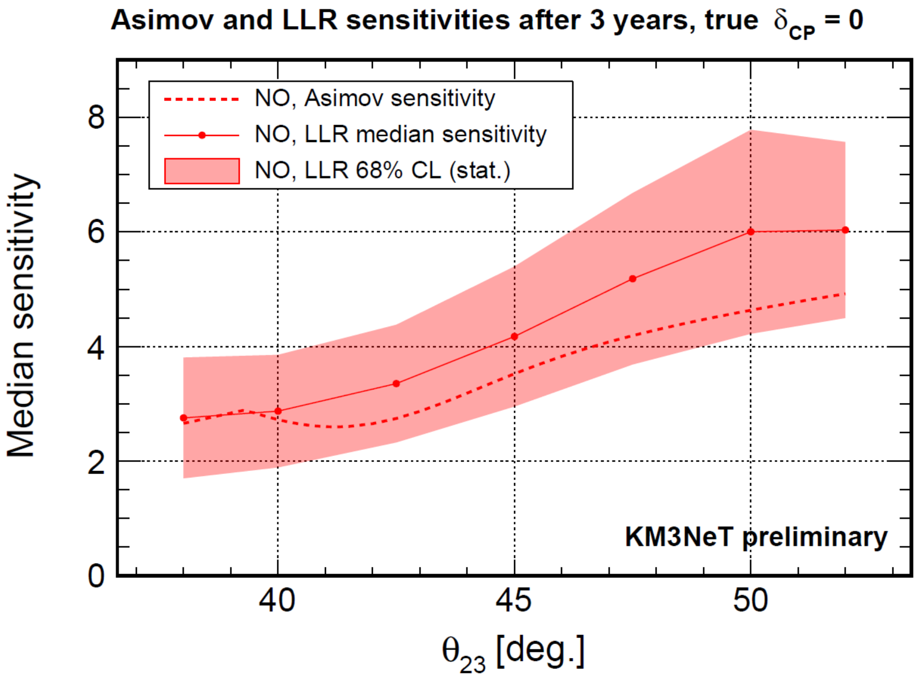
This gives sensitivity to exclude the wrong hierarchy.

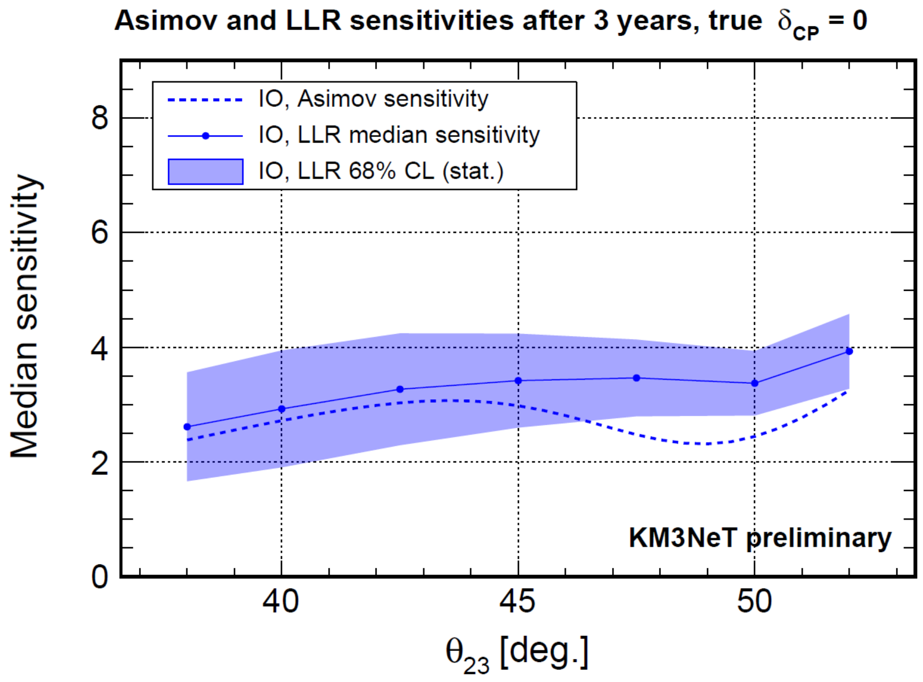
parameter	*treatment*	*true value*	*prior*
$\lvert\Delta M^2\rvert$ (eV^2)	fitted	$2.48\,10^{-3}$	free
$\Delta m^2{}_{21}$ (eV^2)	fix	$7.53\,10^{-5}$	–
θ_{13} (°)	fitted	8.42	0.26
θ_{12} (°)	fix	33.4	–
θ_{23} (°)	fitted	38 – 52	free
δ_{CP}	fitted	$0 - 2\pi$	free
Flux spectral tilt	fitted	0	free
$\nu/\bar{\nu}$ skew	fitted	0	0.03
Tracks normalisation	fitted	1	free
Cascades normalisation	fitted	1	free
NC events normalisation	fitted	1	0.10

Predicted Sensitivities for NMH

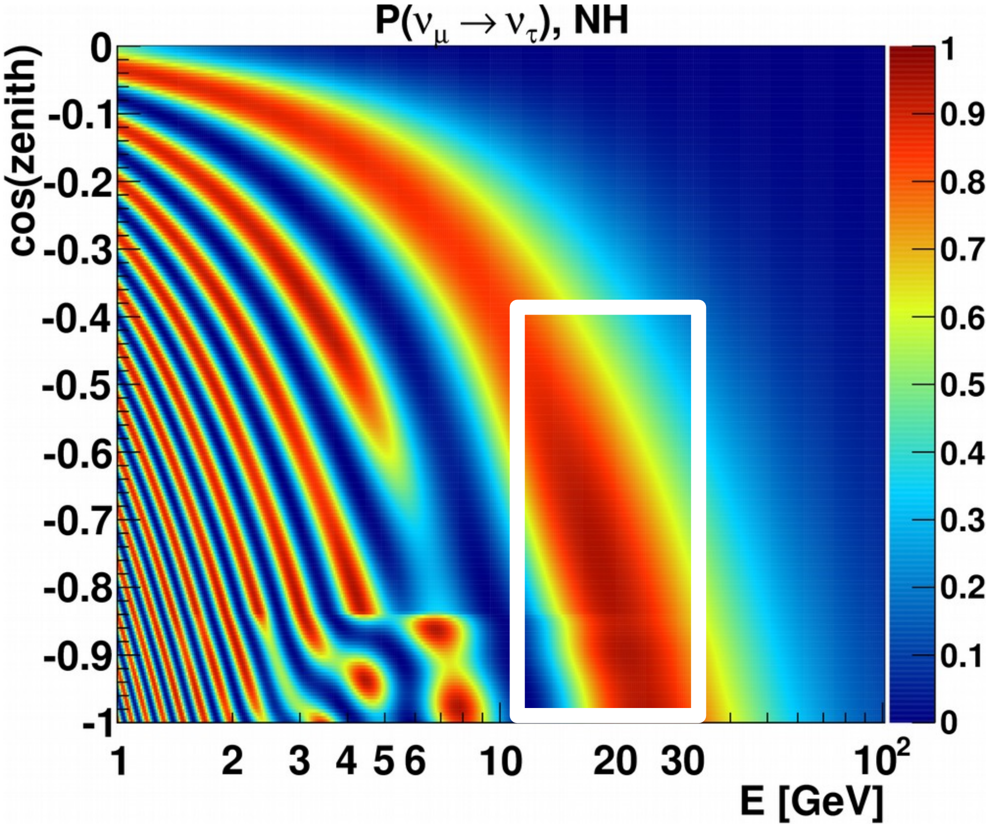
Worst case: ~3σ in 3 years

Best case: > 5 σ in 3 years – if NH & we are in upper octant of θ_{23}



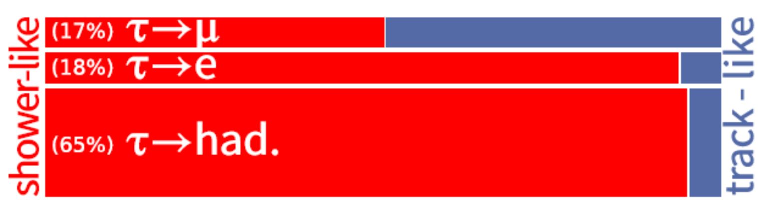


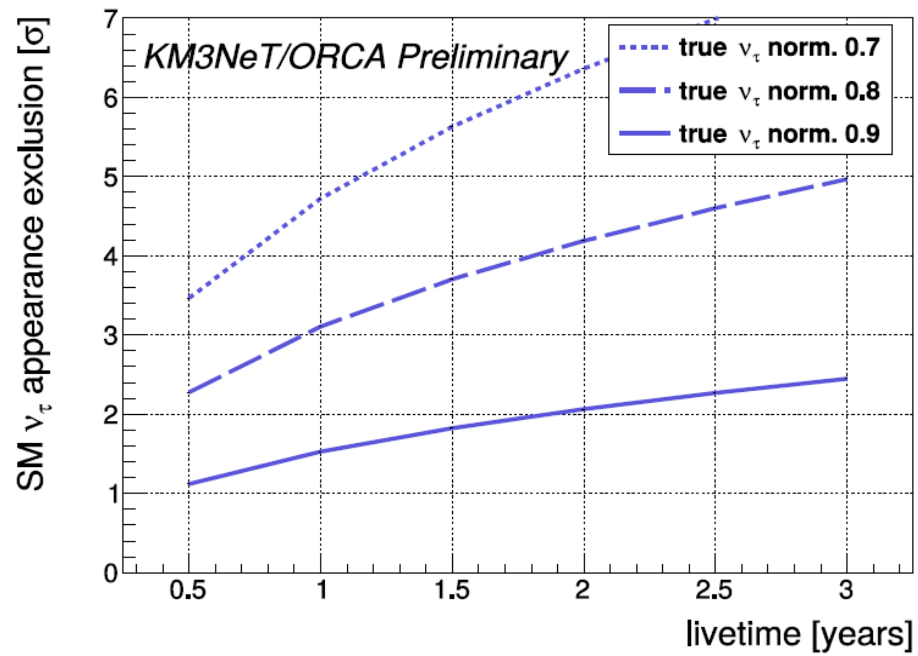
τ Neutrino Appearance



Look for ν_τ appearance to test PMNS unitarity/BSM theories

- ~3k ν_τ CC events expected per year with full ORCA

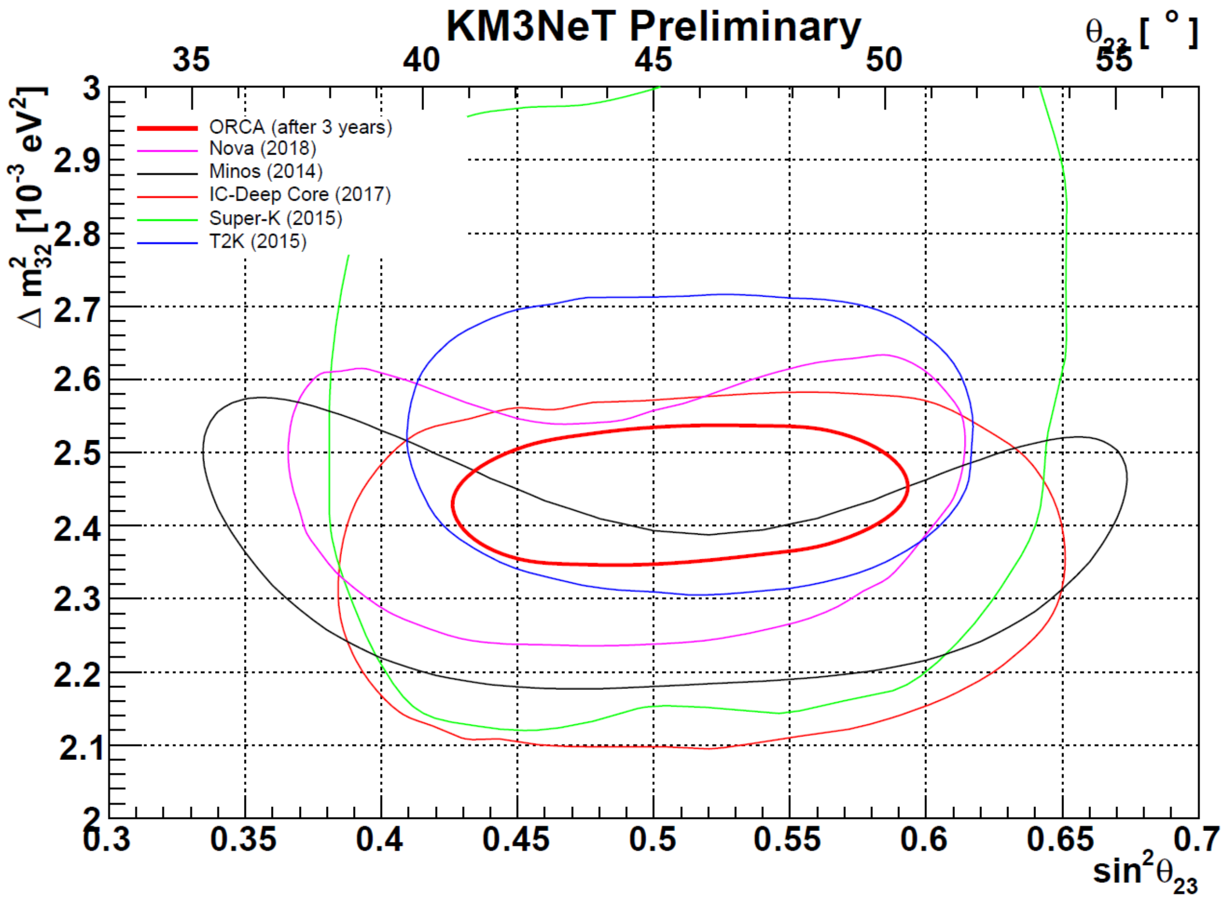




Rate constrained within ~10% in one year

Oscillation Parameter Measurements

With high statistics and resolution, ORCA can measure Δm^2_{32} and $\sin^2 \theta_{23}$:



2% projected precision in Δm^2_{32} and 5% in $\sin^2 \theta_{23}$

Fit shown uses Asimov dataset approach

Neutrino Tomography

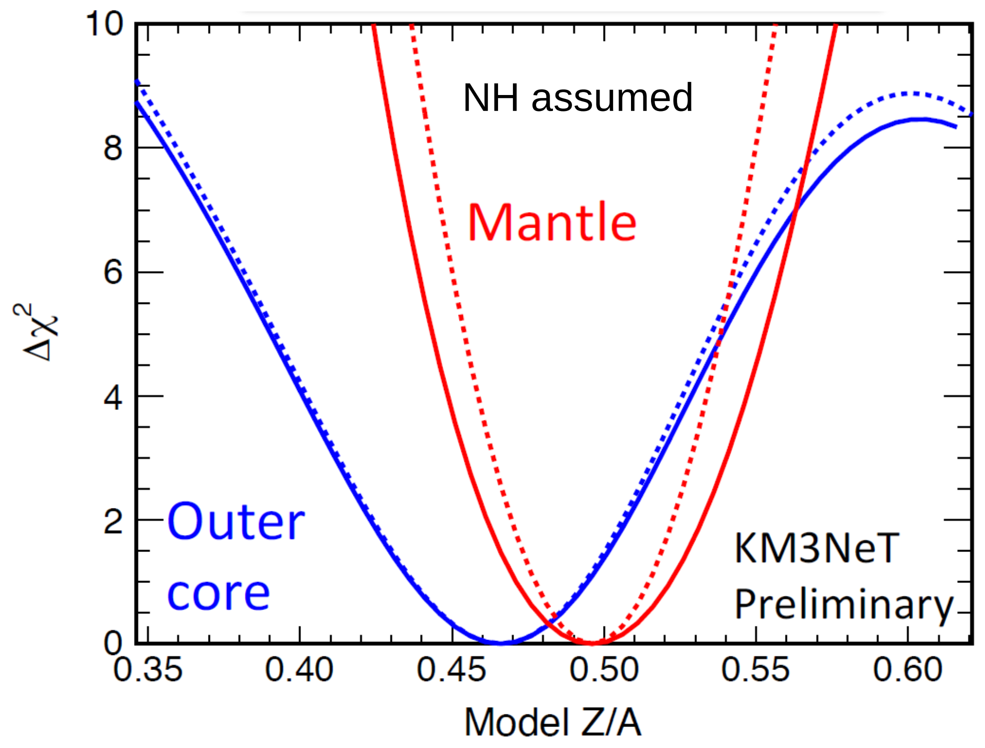
Because of matter effects, ORCA is sensitive to the electron density

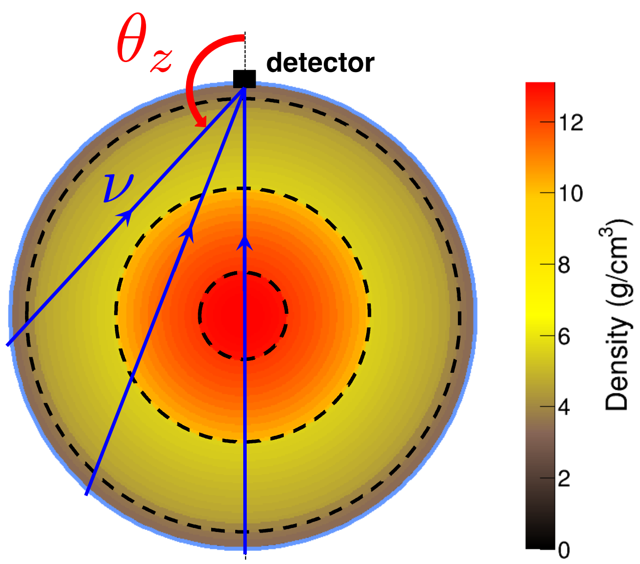
- Compare with geophysics, which measures ρ_M

1σ uncertainty after 10 years (NH)

6% core

5% mantle



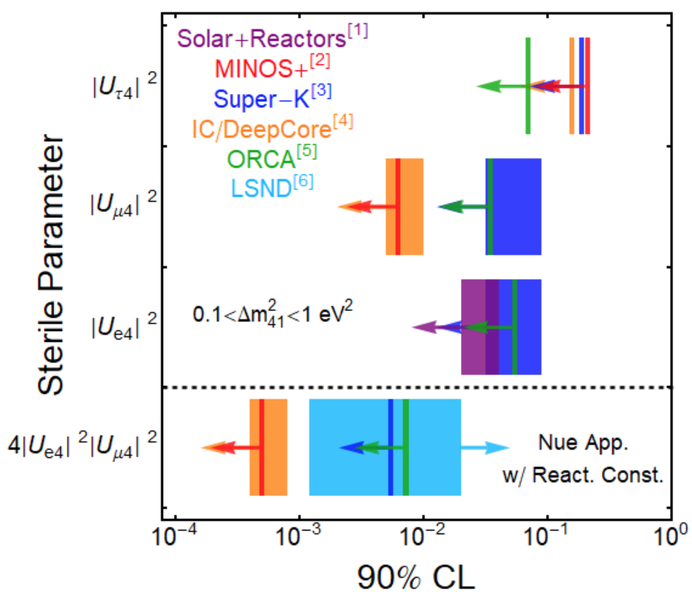


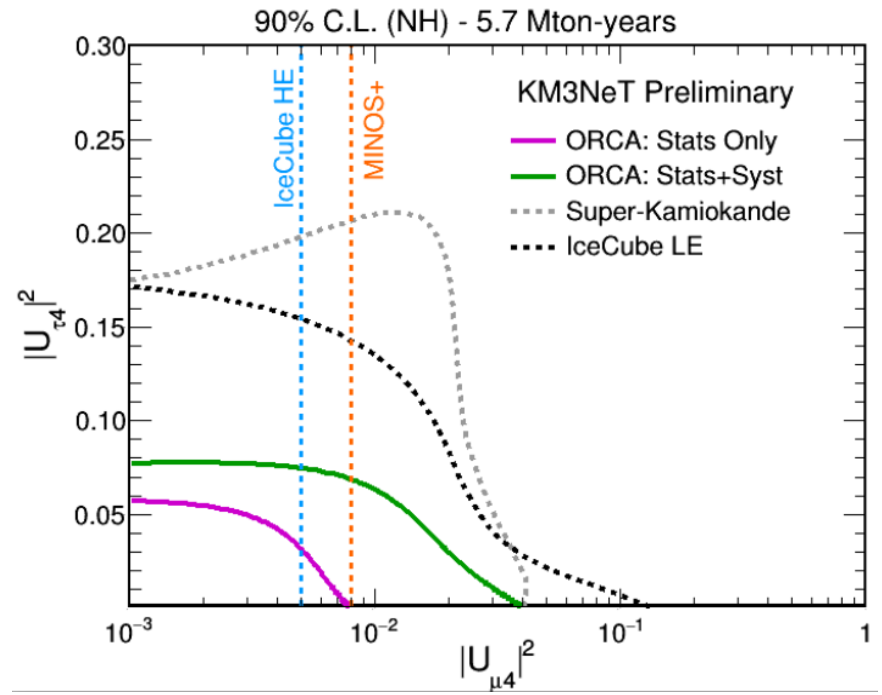
- PREM model basis for rho
- Uniform Z/A rescaling in layer

3+1 Sterile Neutrino Searches

Atmospheric neutrino oscillations have sensitivity to $|U_{\tau 4}|^2$ through $\nu_\mu \leftrightarrow \nu_\tau$ oscillation

eV-scale sterile neutrino leads to suppression at ~20GeV





[1] PRD 85, 077301 (2012); PRL 117, 151801 (2016)
[2] J. J. Evans, Neutrino 2016; PRL 117, 151803 (2016)
[3] Phys. Rev. D 91, 052019 (2015)
[4] PRL 117, 071801 (2016); arXiv:1702.05160 (2017)
[5] KM3NeT-ORCA Preliminary
[6] Phys. Rev. D 64, 112007 (2001)

Construction Status

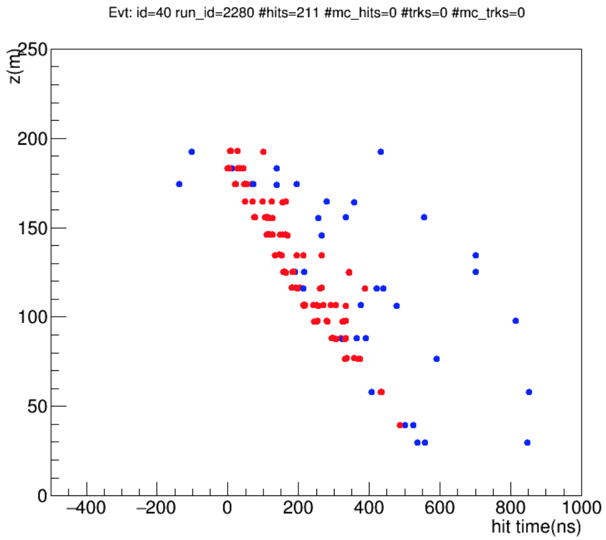
Construction has been started, with first DU deployed and data arriving in 2017

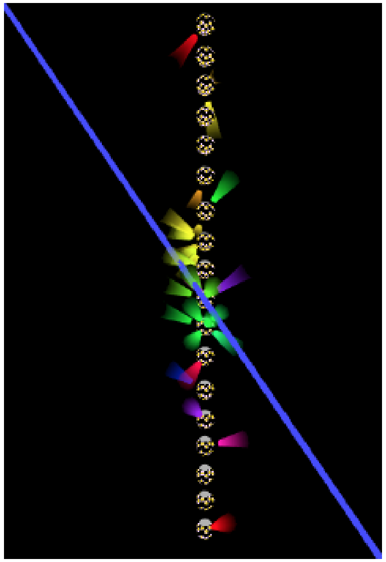
- Currently interrupted in order to replace the deep sea part of the main cable

Detection line production is still underway

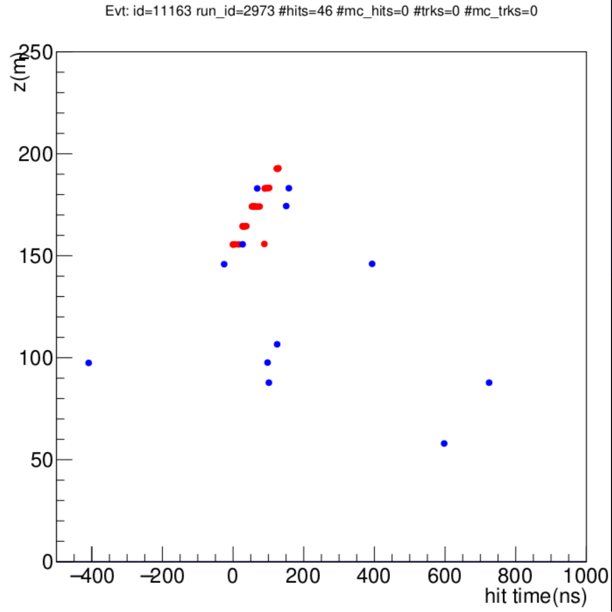
- Deployment of 4 lines planned for post-summer 2018 in a single sea operation

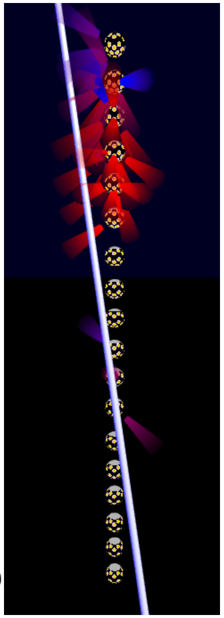
First Observed Data





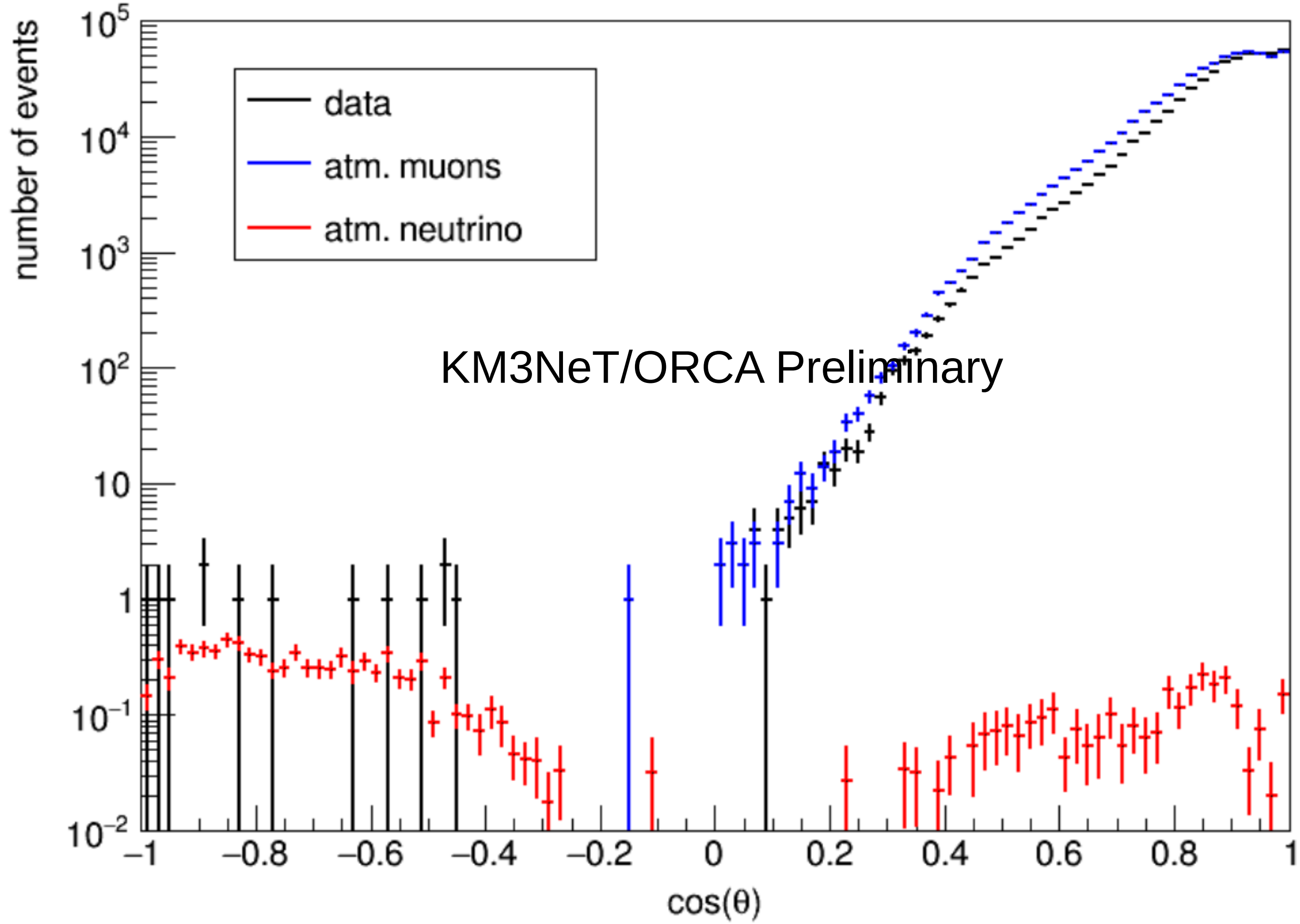
Muon bundle





Typical neutrino
candidate event

Observations from first ORCA Detection Unit



Number of upgoing events:
Atm. Nu: 8.33
Atm. Mu: ~1
Events observed: 13

Data from ORCA single DU
82 days of live time

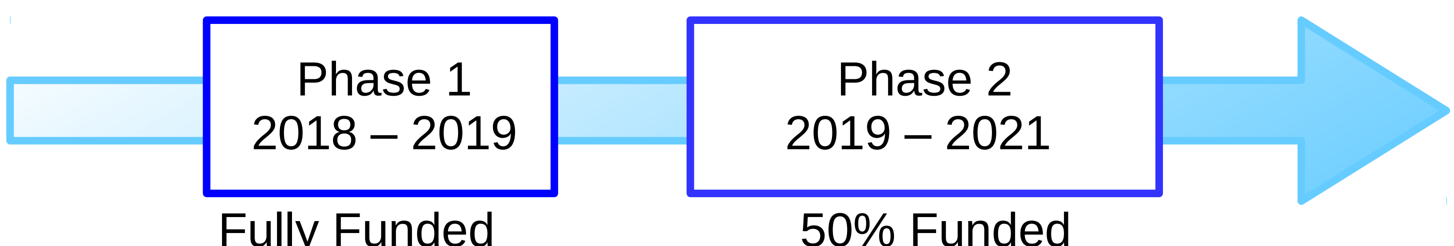
Timeline and Summary

KM3NeT/ORCA construction and deployment has started

- Multiple strings planned to be operational by end of 2018

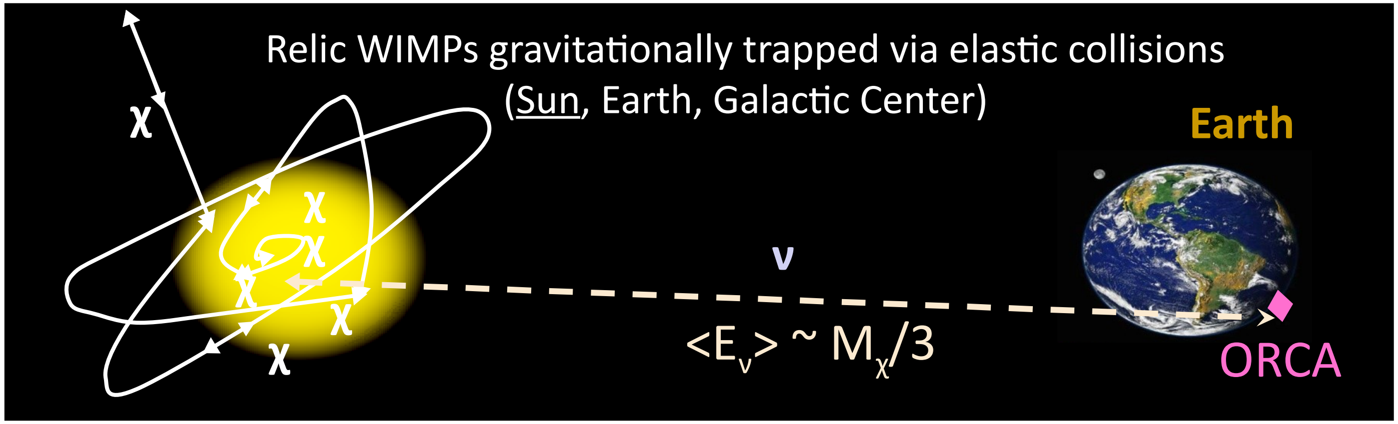
Main goal is to determine the neutrino mass hierarchy

- Aim to accomplish this after 3 years of operation
- Lots of other physics potential as well

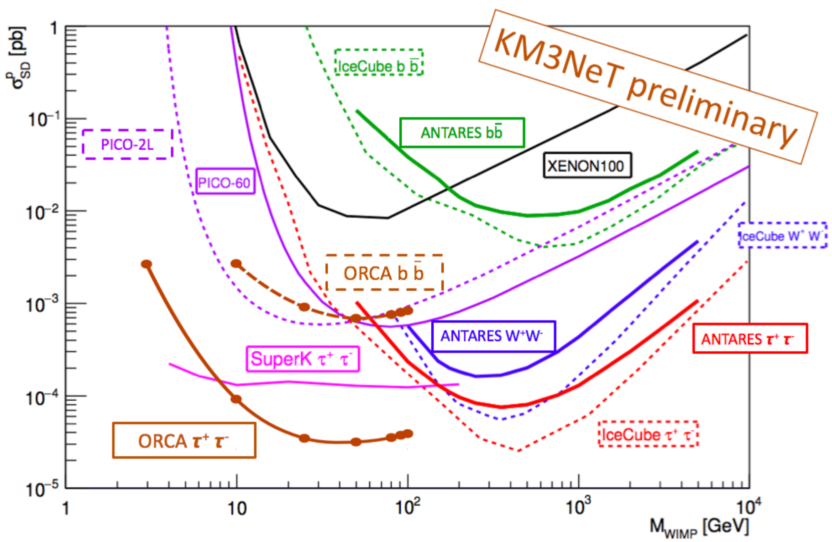


Backup

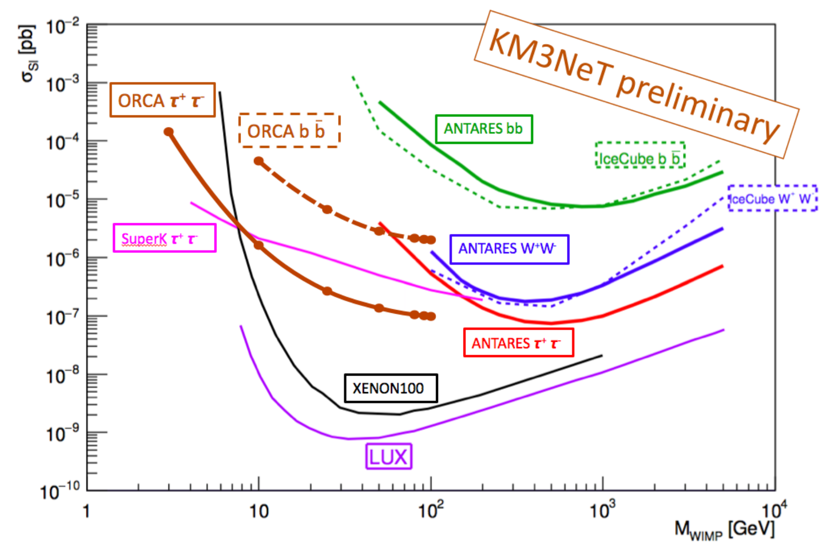
Dark Matter Searches



Spin Dependent



Spin independent



Plots show 3 years of ORCA operation