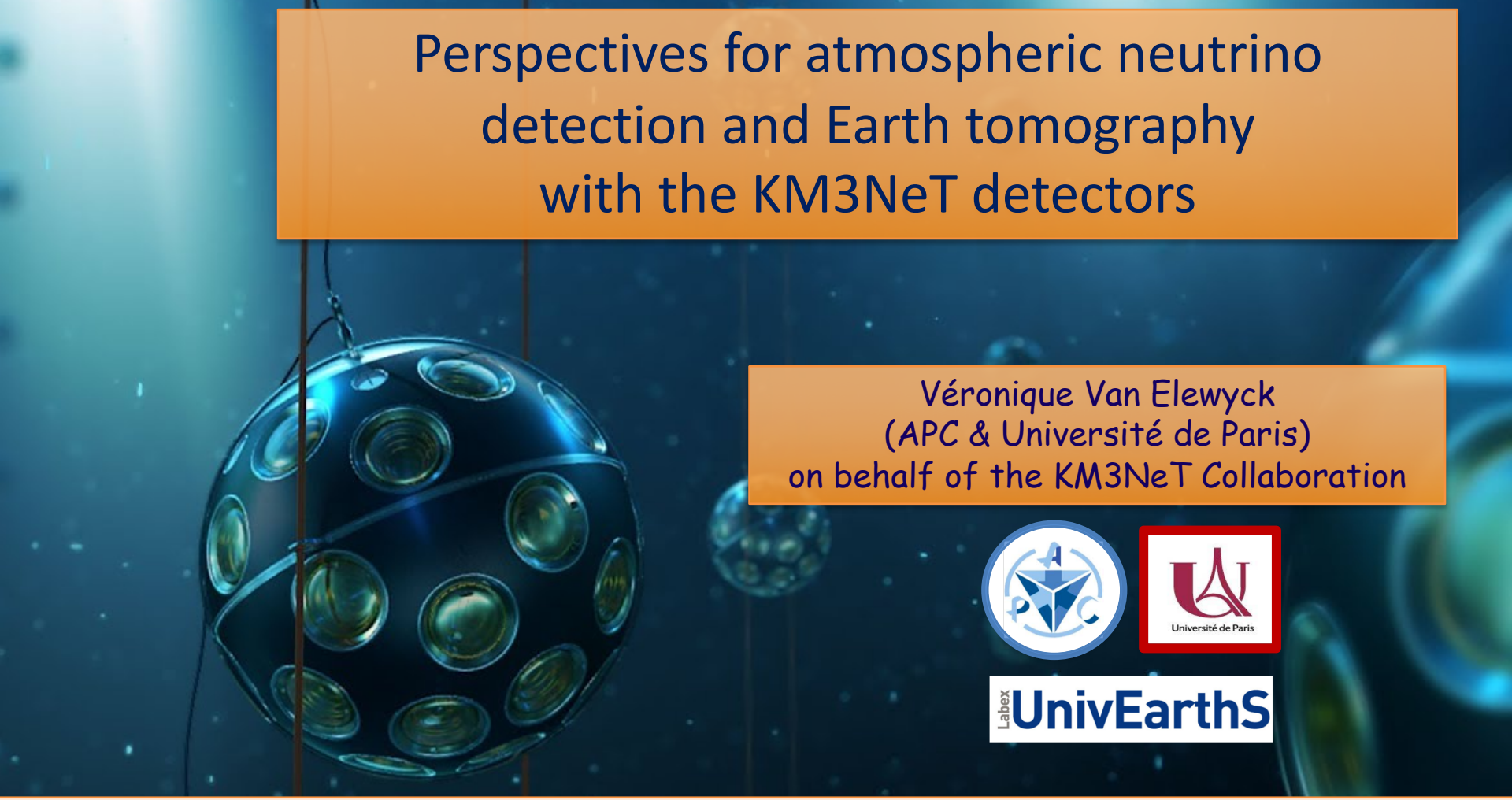
Perspectives for atmospheric neutrino detection and Earth tomography with the KM3NeT detectors

Véronique Van Elewyck
(APC & Université de Paris)
on behalf of the KM3NeT Collaboration

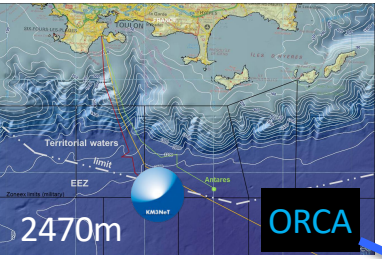


2d workshop on Multi-messenger Tomography of the Earth, Paris, July 4-7 2023

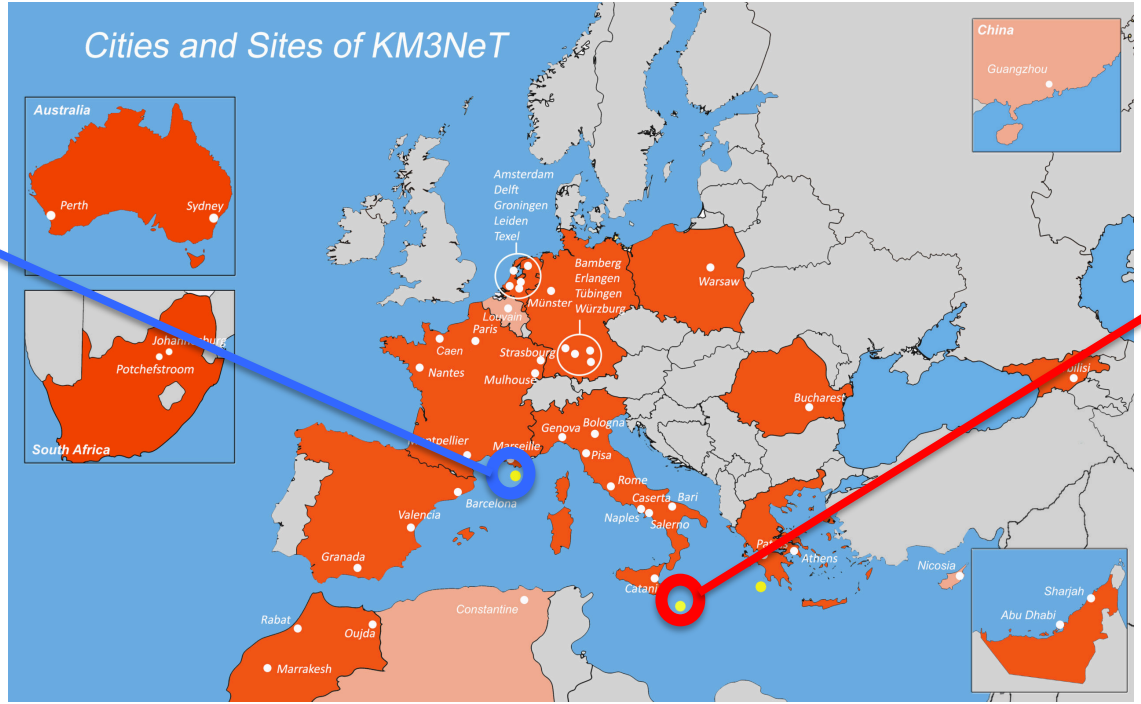
The KM3 Neutrino Telescope

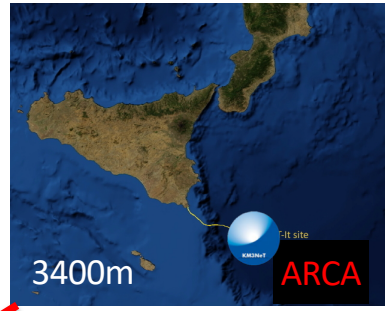
KM3NeT is a distributed research infrastructure with 2 main physics topics:

Oscillations and Astroparticle Research with Cosmics in the Abyss



~40 km offshore
Toulon (France)
close to ANTARES



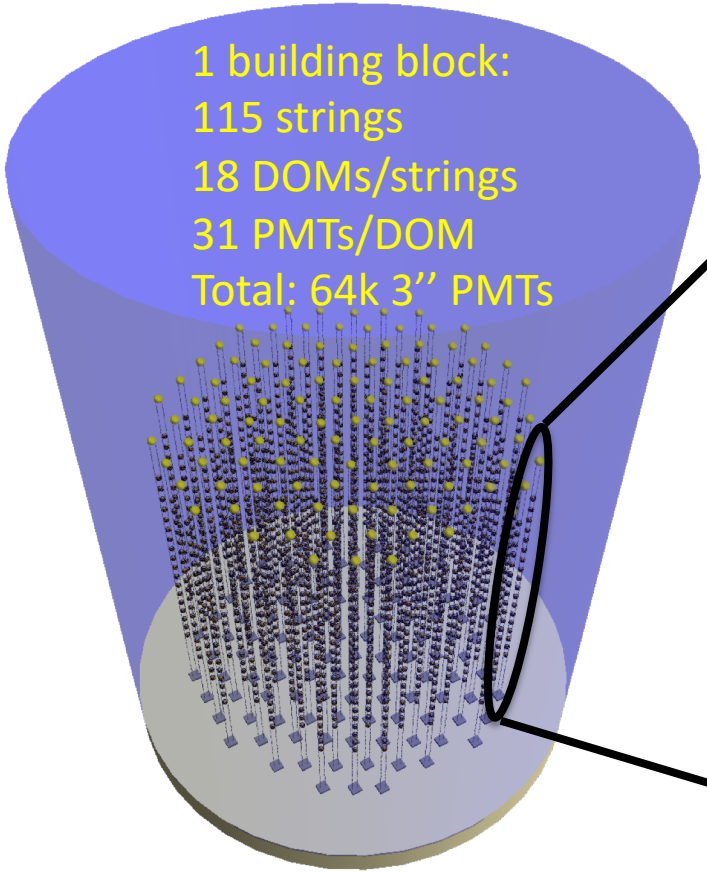


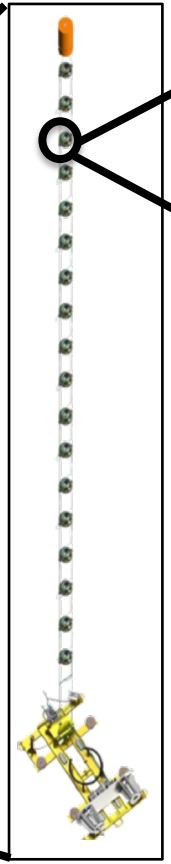
~100 km offshore
Capo Passero
(Sicily)

📖 *KM3NeT LoI:*
J.Phys.G 43 (2016) 8, 084001

1collaboration, 1 technology, 2 detectors

The KM3NeT technology





- multi-PMT Digital Optical Module

- 31 x 3" PMTs
- Enhanced detection & reconstruction performances:

~4 π sr coverage

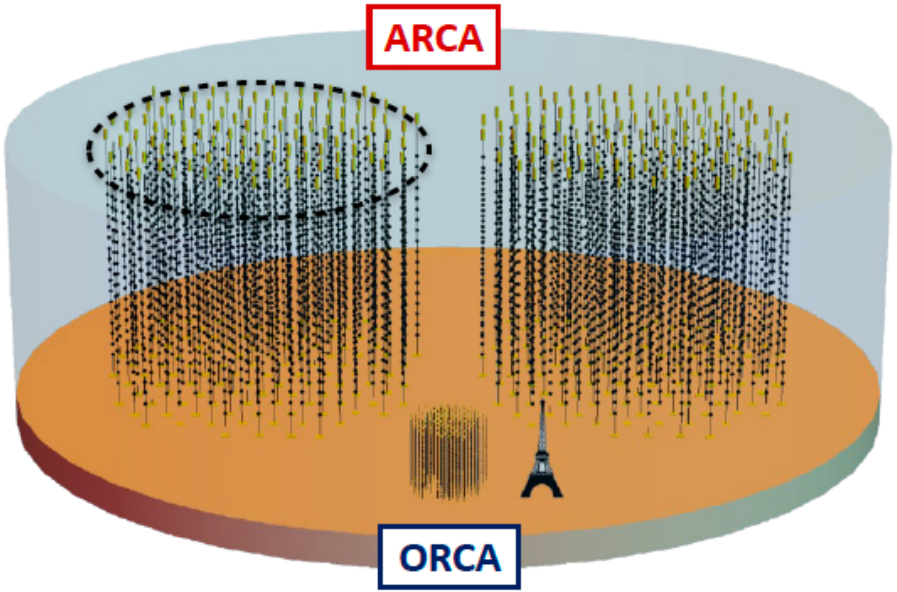
photon counting

directional information

atmospheric muon detection at single – DOM level

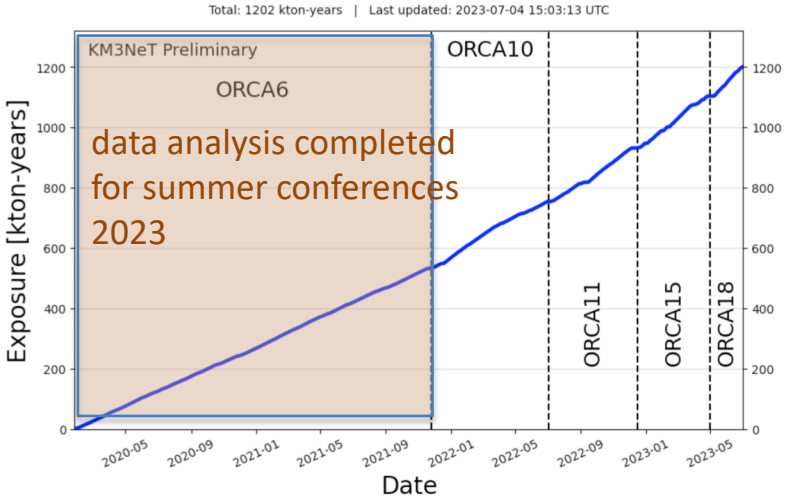
The KM3NeT detectors

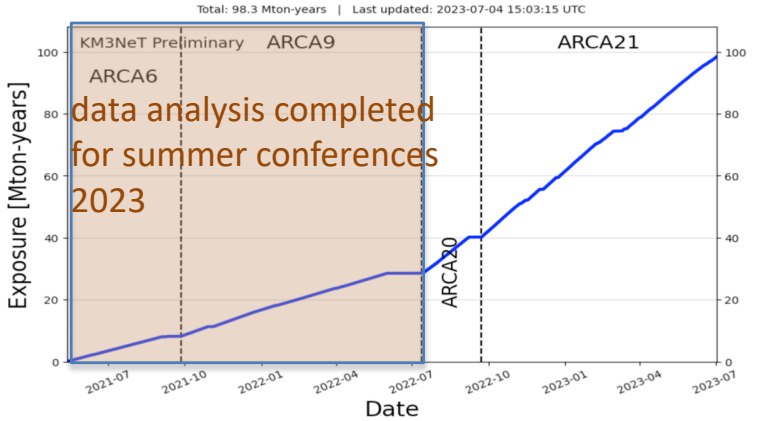
Same technology for both detectors (multi-PMT DOM)
Layout optimised for specific neutrino energy ranges/science goals:
ARCA → high-energy (> TeV) neutrino astronomy
ORCA → neutrino physics at the GeV: oscillations & mass hierarchy



	ARCA	ORCA
Location	Italy (Sicily)	France (Toulon)
Depth	3450 m	2450 m
Distance from shore	100 km	40 km
Number of DUs	115 x 2 (2 BB)	115 (1 BB)
DU horizontal spacing	90 m	20 m
DOM vertical spacing	36 m	9 m
#DOMs/DU	18	18
#PMTs/DOM	31	31
Instrumented volume	~ 1 Gton	~ 7 Mton
	> 1km^3 neutrino telescope	
Deployed DUs	21	18

The KM3NeT detectors





~10% of the detectors deployed so far, already producing meaningful physics results

Expected Completion 2027-2028

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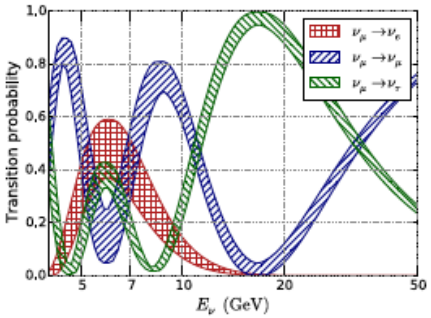
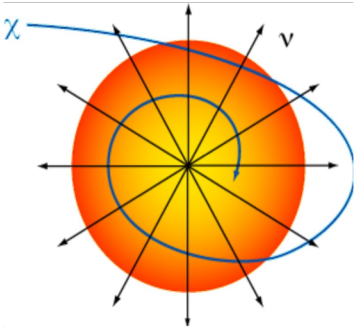
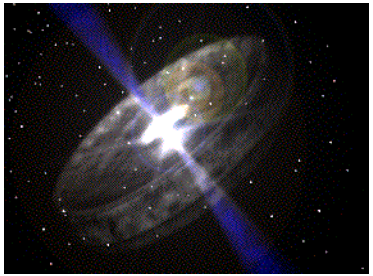
The KM3NeT Science







MeV **GeV** **TeV** **PeV**

Neutrino energy

Supernova ν

ν Oscillations, Mass ordering

Dark matter, exotics

HE neutrino astronomy
Cosmic accelerators

ORCA

ARCA

ORCA

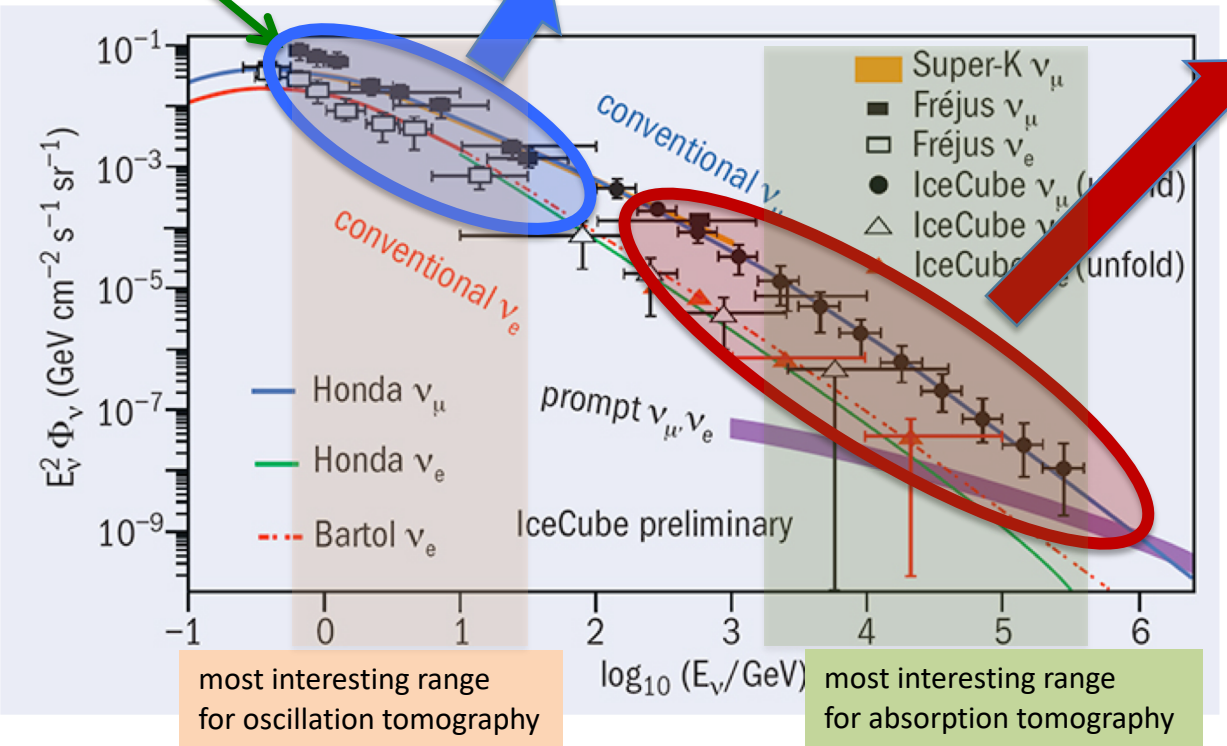
ARCA

Atmospheric neutrinos in KM3NeT

ORCA:
~ 30 000 $(\nu_e + \nu_\mu)$/year
with energy in [1, 10^2] GeV

ARCA:
~ 80 000 $(\nu_e + \nu_\mu)$/year
with energy in [10^2, 10^6] GeV

at 1 GeV: ~1 ν_μ cm^{-2} s^{-1}

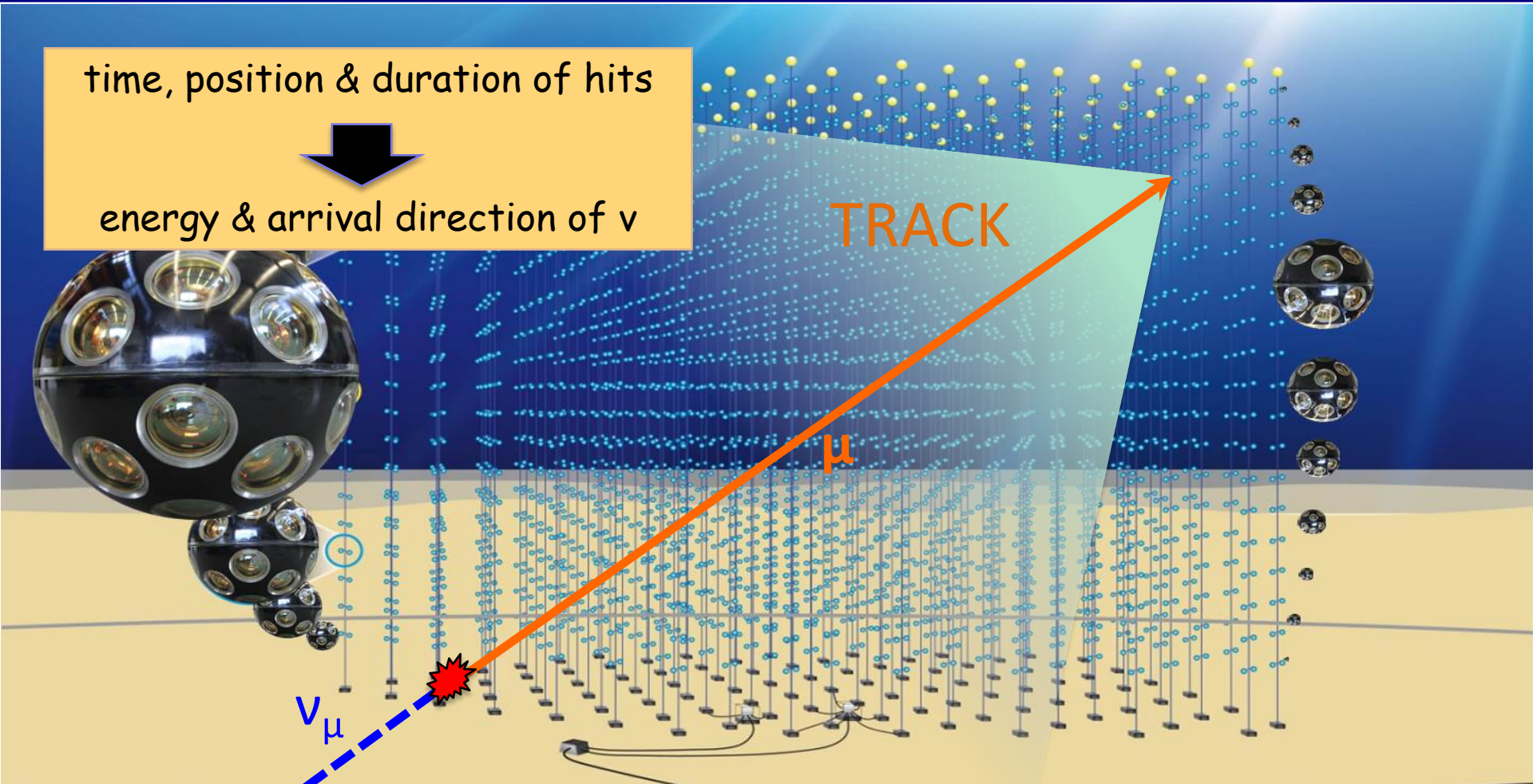


most interesting range
for oscillation tomography

most interesting range
for absorption tomography

→ KM3NeT can perform both oscillation and absorption tomography

Detection principle: Cherenkov telescope



Detection principle: Cherenkov telescope

time, position & duration of hits

↓

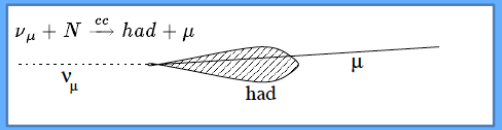
energy & arrival direction of ν

TRACK

μ

ν_μ

TRACK TOPOLOGY



Large lever arm
→ Good angular resolution
<0.4° @ 10 TeV (ARCA)
~ 7° @ 10 GeV (ORCA)

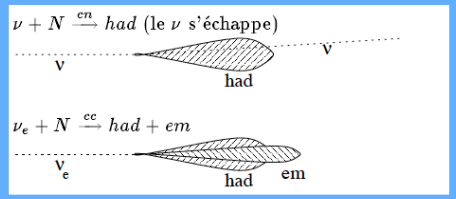
→ Limited energy resol.
$\Delta E/E_\mu$~30% (ARCA)
$\Delta E/E_\mu$~35% (ORCA)

Detection principle: Cherenkov telescope

time, position & duration of hits

energy & arrival direction of ν

SHOWER TOPOLOGY



→ Angular resolution
< 1° @ 30 TeV (ARCA)
~ 7° @ 10 GeV (ORCA)

→ Energy resolution
ΔE/E~5% (ARCA)
ΔE/E~25% (ORCA)

TRACK

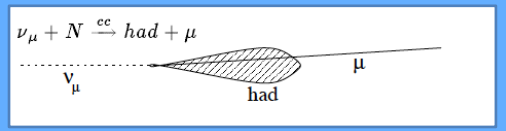
μ

SHOWER

e

ν_e

TRACK TOPOLOGY



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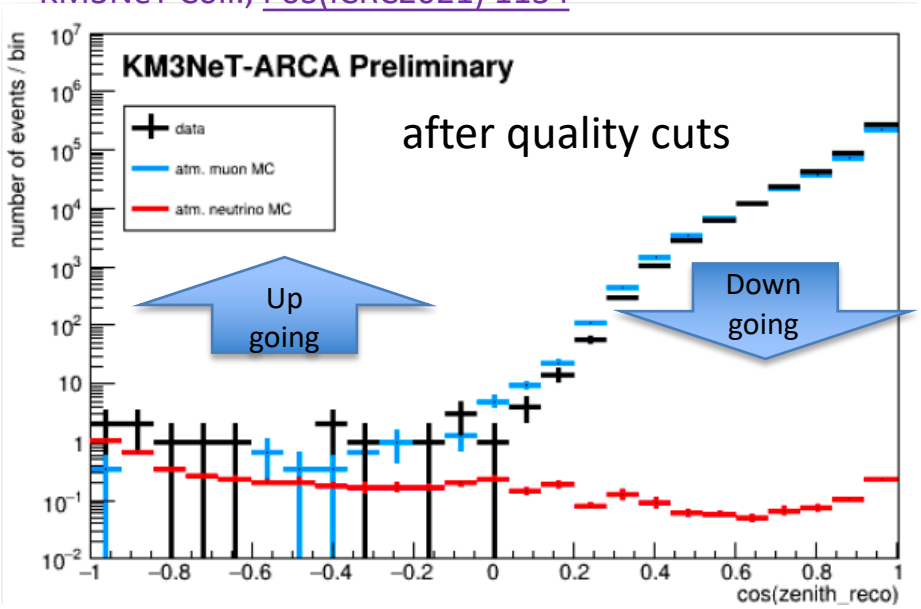
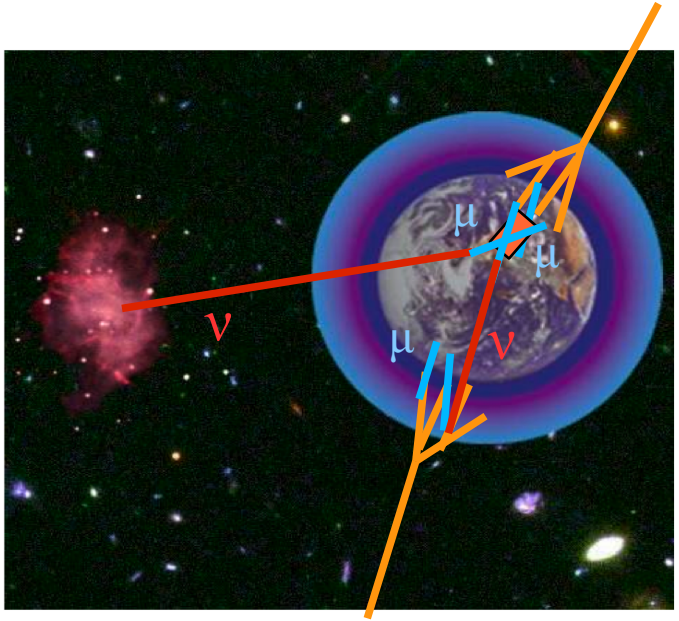
ARCA atmospheric neutrino studies

First data with ARCA6 – 20 days:

KM3NeT Coll., PoS(ICRC2021) 1134



Main background: down-going atmospheric muons (some reconstructed as up-going)



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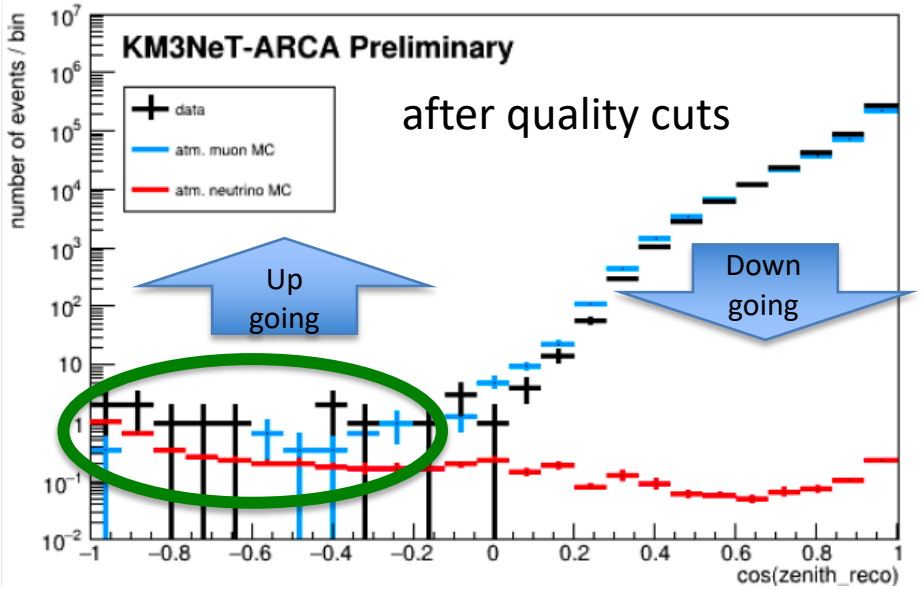
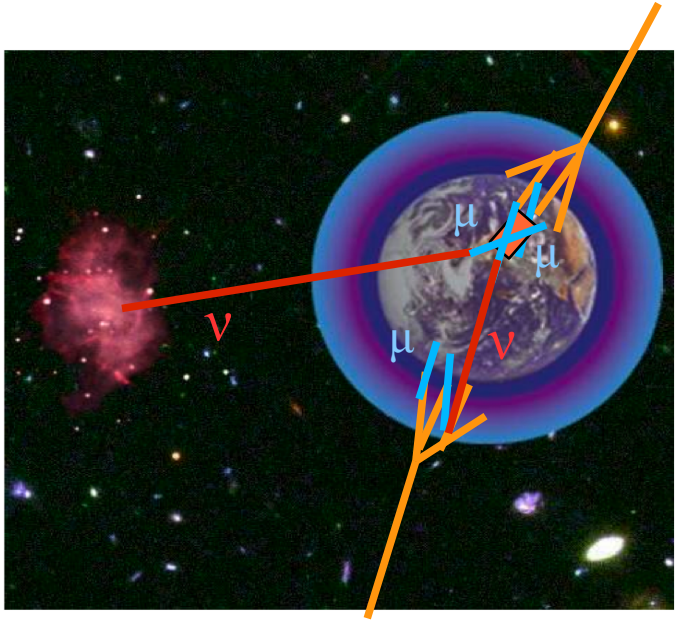


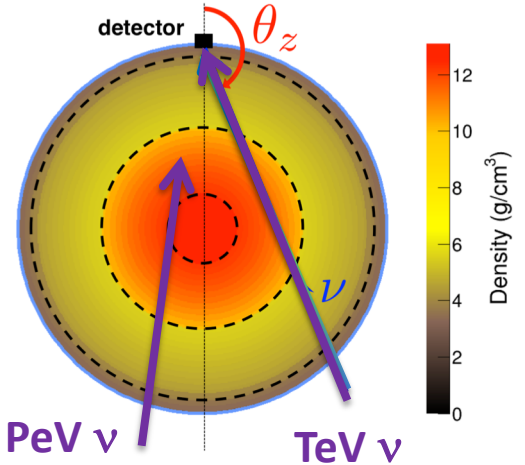
15 upgoing track events(expected: 7 μ_{atm} + 4 ν_{atm})

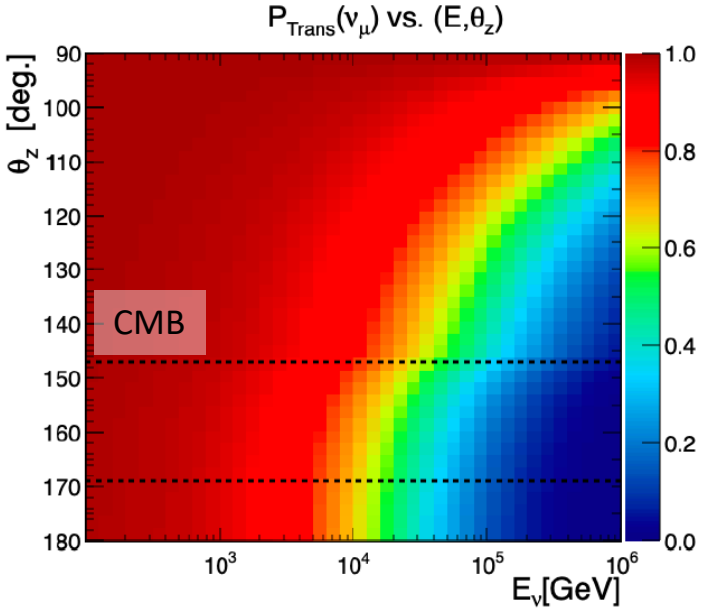
- ✓ Good data/Monte Carlo agreement
- ✓ validation of technology
- ➢ More results with ARCA6+9 to be presented at summer conferences (ICRC2023)

Main background: down-going atmospheric muons (some reconstructed as up-going)



Absorption tomography with ARCA





Transmission probability after path length L:

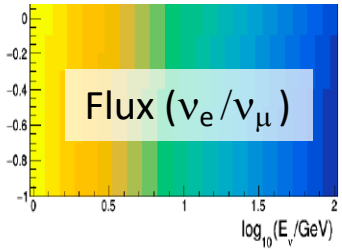
$$P(L) = 1 - \int_0^L \frac{dx}{L} \exp\left(-\frac{x m_N}{\sigma_{\nu N}\,\rho_m}\right)$$

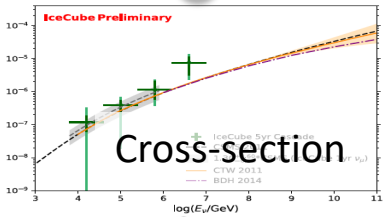
Neutrino-nucleon cross-section: increases with E

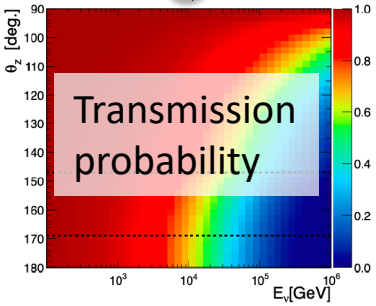
matter density (default: PREM)

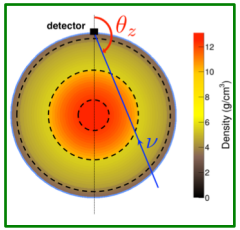
Absorption tomography with ARCA

Full simulation chain:

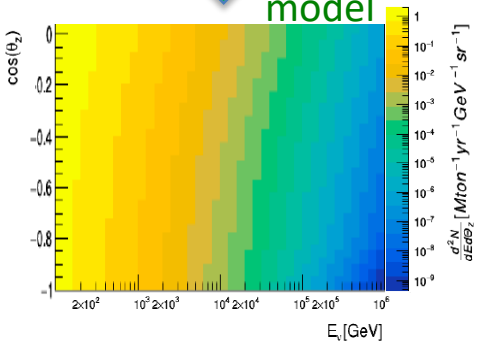








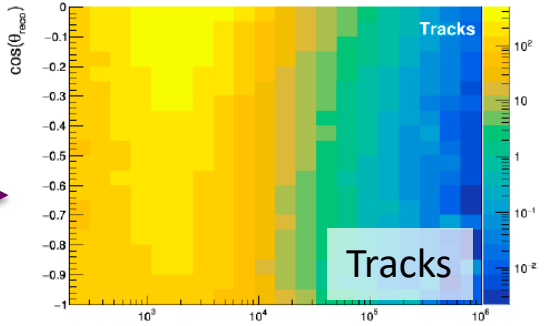
Input: Earth model



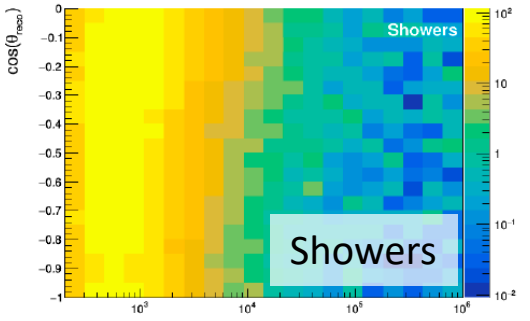
Interacting events at the detector (ν_e/ν_μ)

Detector response: reconstruction & classification

(MC-based response matrix)



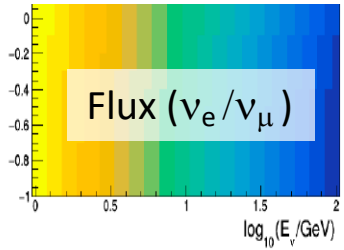
~60 kevents/yr (full ARCA 2 BB)



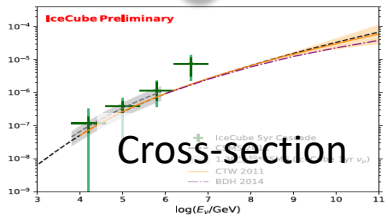
~20 kevents/yr (full ARCA 2 BB)

Absorption tomography with ARCA

Full simulation chain:



⊗



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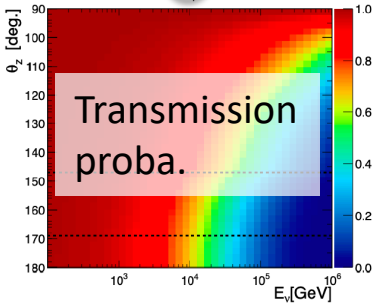

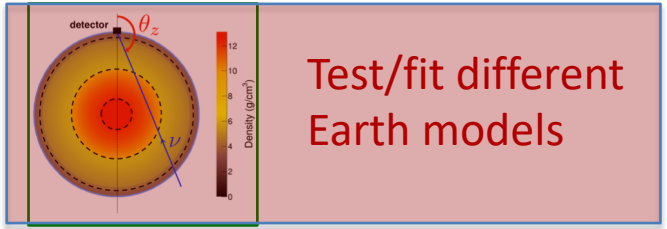

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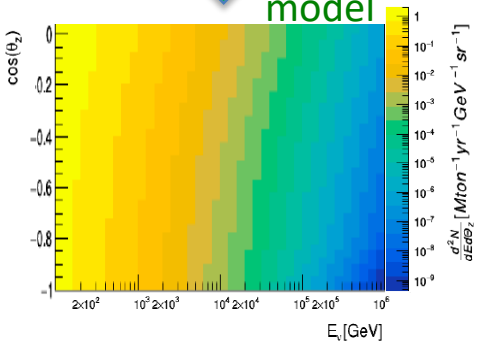

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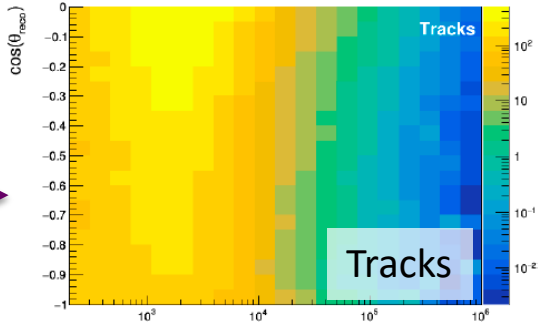

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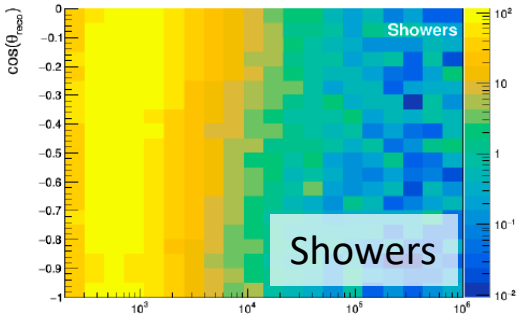


~20 kevents/yr (full ARCA 2 BB)

Absorption tomography with ARCA

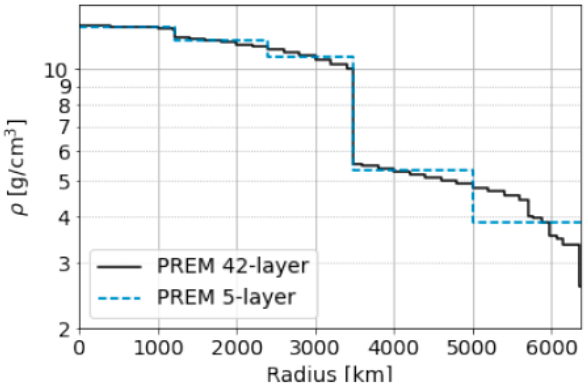
Preliminary studies (all based on simulations w/full detector) :

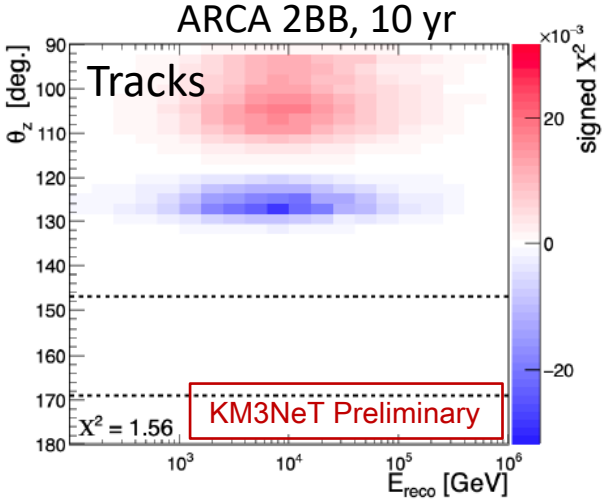
L. Maderer, Ph. D thesis (link)

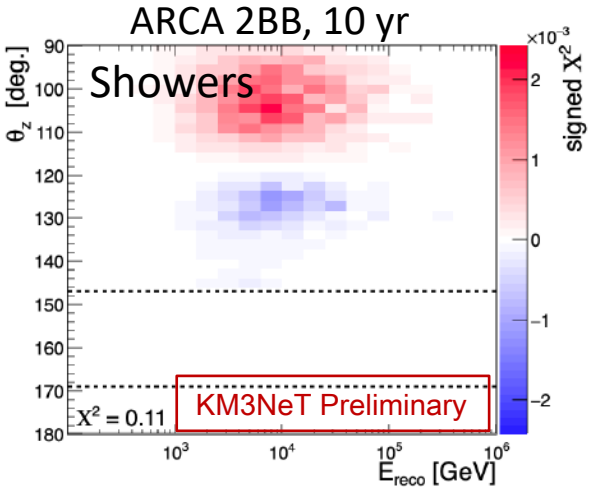
- Hypothesis testing: PREM 5-layers vs 42-layers

signed chi2 maps:

$$\text{signed } \chi^2 = \sum_i \frac{(n_A^i - n_B^i) \times |n_A^i - n_B^i|}{n_A^i}$$







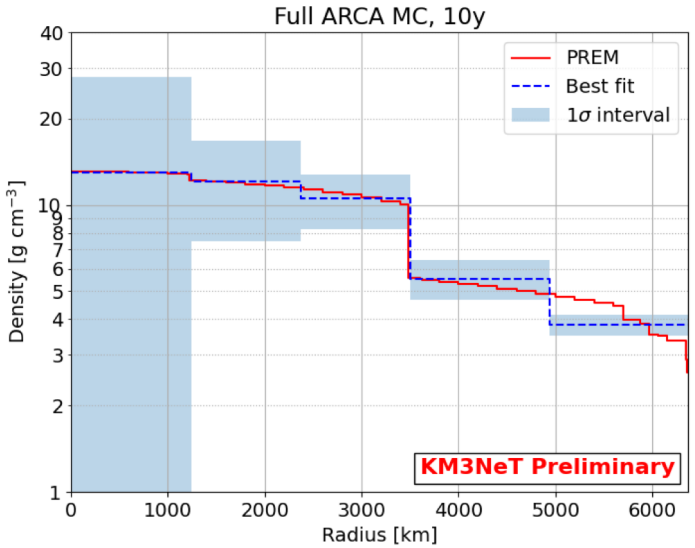
- Most sensitivity from energy range [20-500] TeV
- Dominant contribution from track channel

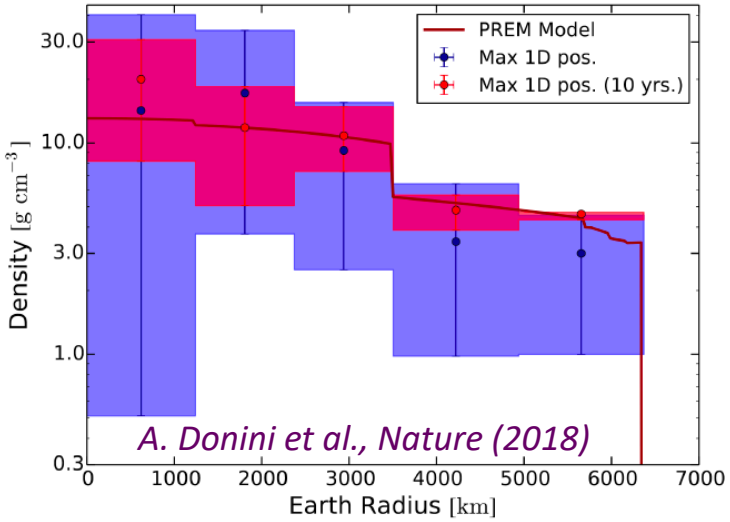
Absorption tomography with ARCA

Preliminary studies (all based on simulations w/full detector) :

L. Maderer, Ph. D thesis (link)

- fit of 5-layer density model





Compatible with 10 yr projections for IceCube (from Donini et al.)

→ Provides a complementary measurement of the matter content/profile of Earth

→ (much) more statistics needed to reach < few % uncertainty level

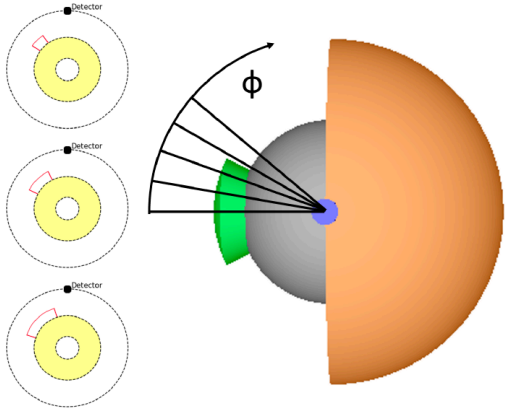
→ main systematics: neutrino flux & cross-section, detector effects

Absorption tomography with ARCA

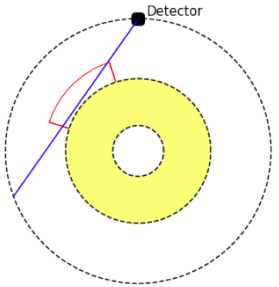
Preliminary studies (all based on simulations w/full detector) :

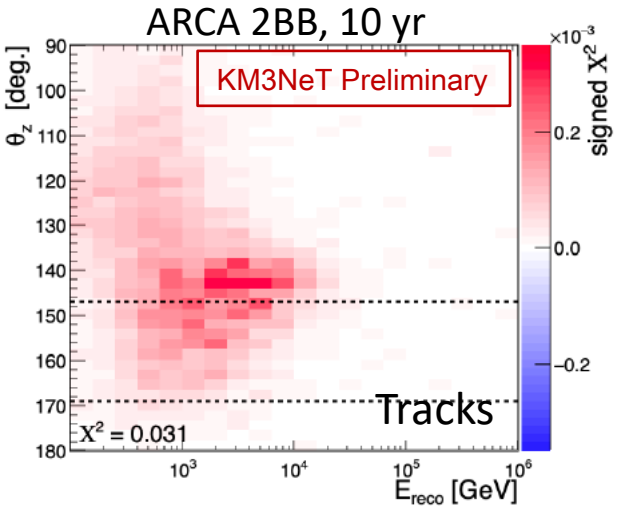
- LLSVP-like inhomogeneity in the mantle

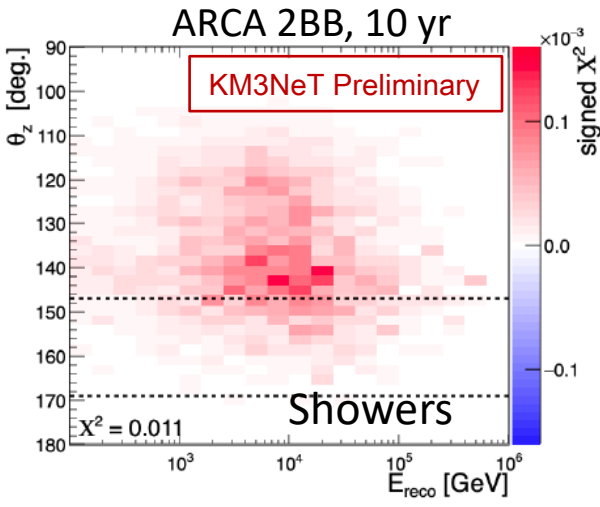
L. Maderer, Ph. D thesis (link)



For 10% overdensity in LLSVP, most favourable azimuth:

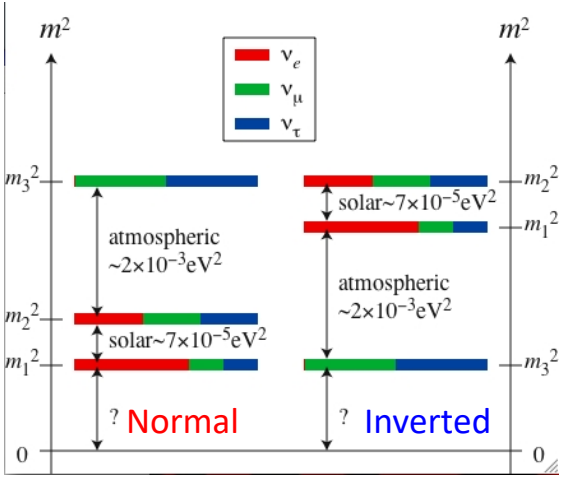






ORCA atmospheric neutrino studies

Atmospheric neutrino measurement above 1 GeV:



❖ Probe neutrino oscillations in the atmospheric sector:
sensitivity to mixing angle θ_{23} and $\Delta m^2_{31} = m^2_3 - m^2_1$ (+ θ_{13} , δ_{CP})

❖ Determine the neutrino mass ordering (inverted/normal)
by exploiting matter effects in neutrino oscillations:

→ extra potential proportional to electron density in medium:

$$A \equiv \pm\sqrt{2} G_F N_e$$

→ Resonance energy for neutrino oscillations:

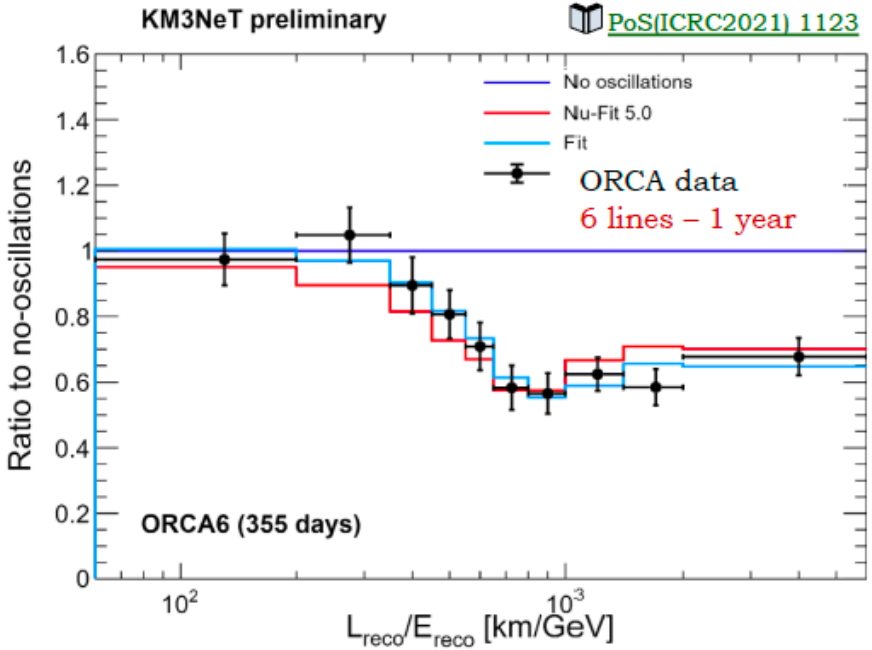
$$E_{\text{res}} \equiv \frac{\Delta m^2_{31} \cos 2\theta_{13}}{2\sqrt{2}\, G_F\, N_e} \simeq 7\,\text{GeV} \left(\frac{4.5\,\text{g/cm}^3}{\rho}\right) \left(\frac{\Delta m^2_{31}}{2.4 \times 10^{-3}\,\text{eV}^2}\right) \cos 2\theta_{13}$$

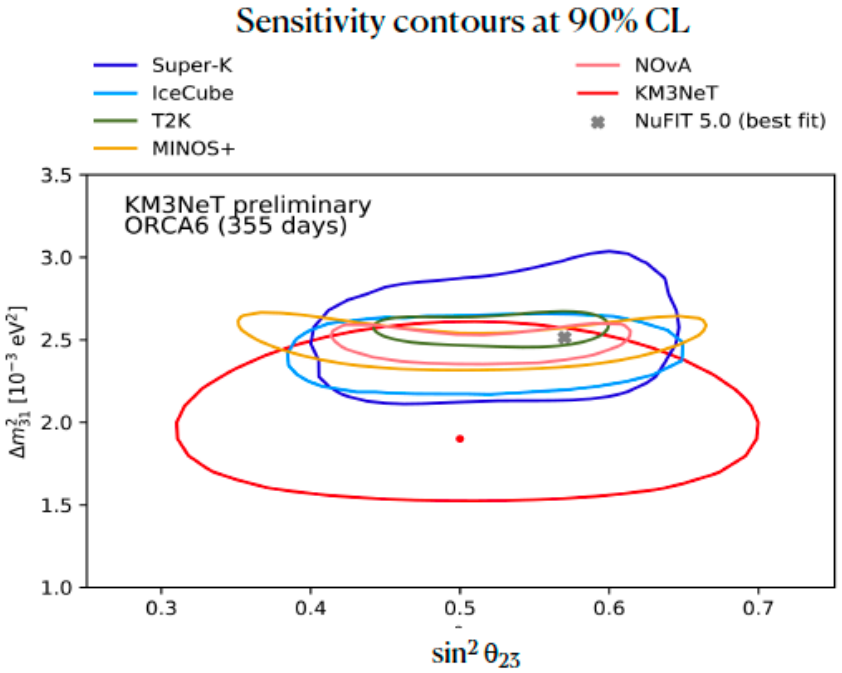
≅ 3 GeV (core)
≅ 7 GeV (mantle)

for neutrinos if $\Delta m^2_{13} > 0$ / antineutrinos if $\Delta m^2_{13} < 0$
→ depends on the neutrino mass hierarchy – not yet measured…

ORCA atmospheric neutrino studies

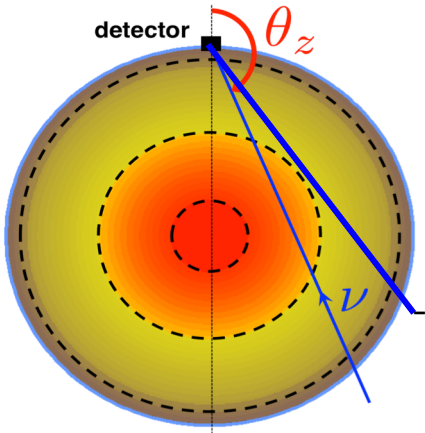
First results with ORCA6 – 1 year



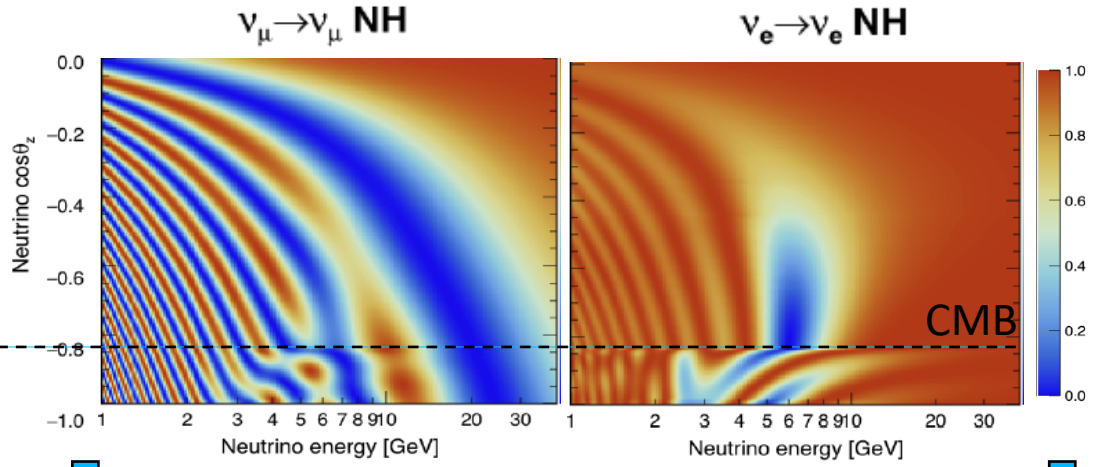


- ✓ Oscillation favoured at 5.9 σ over no-oscillations
- ✓ Sensitivity to mixing parameters already in the ballpark of other experiments
- ➢ More results with ORCA6 (full sample) to be presented at summer conferences (ICRC2023)

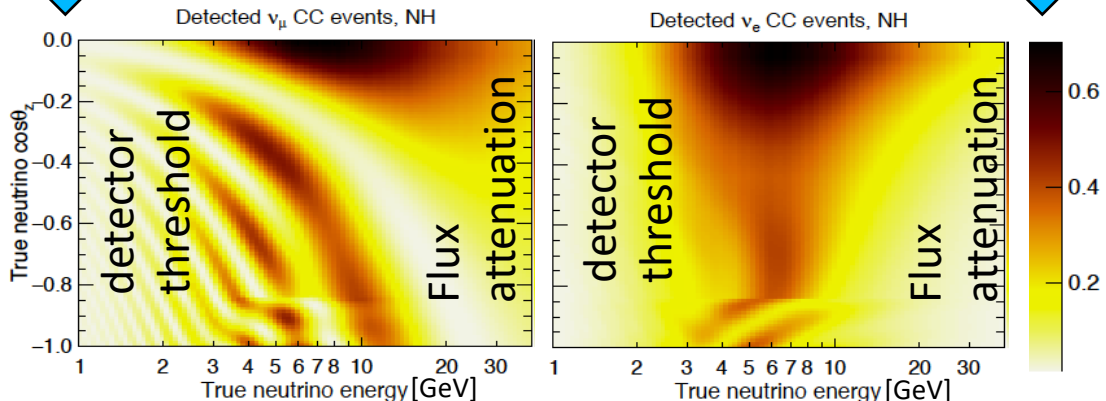
Oscillation tomography with ORCA



PREM + benchmark composition



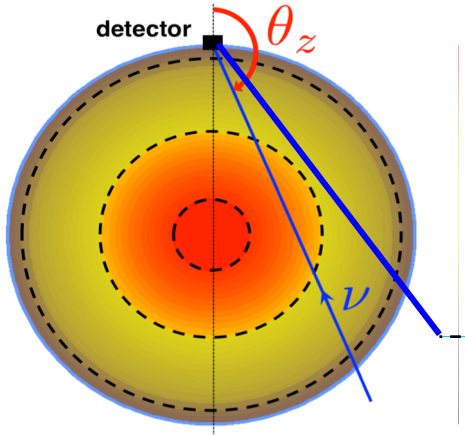
$$\times \Phi_{\nu_X}(E,\theta) \times \sigma_{\nu N}(E) \times M^{eff}_{\nu_X}(E,\theta) \times t$$



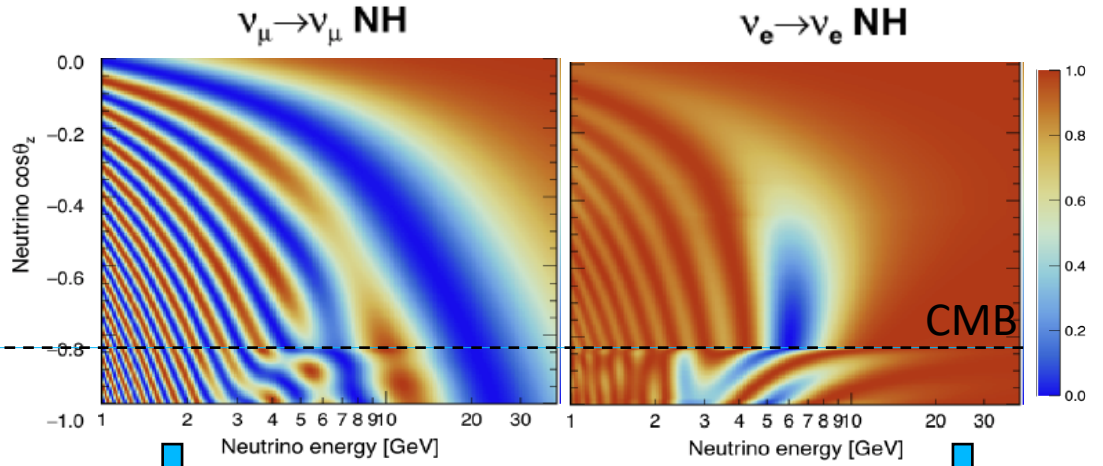
→infer the electron density by measuring the ν_e / ν_μ event rates at the detector

(here: 1 Mton yr exposure)

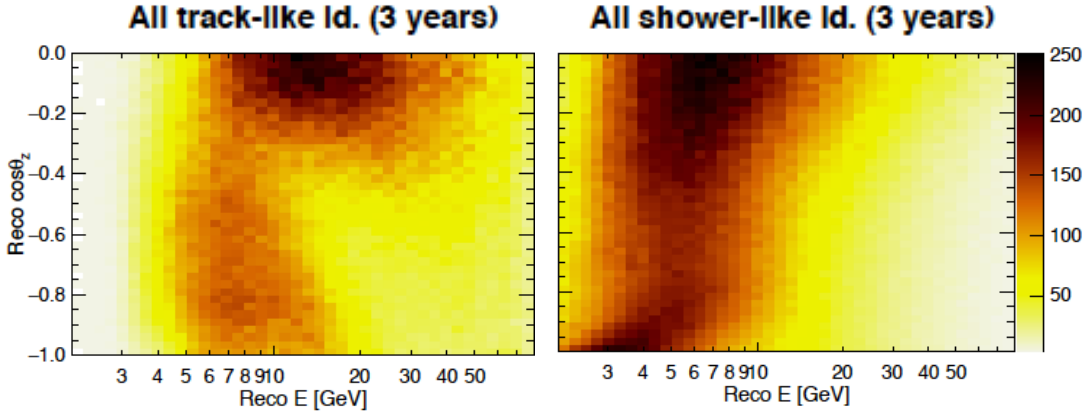
Oscillation tomography with ORCA



PREM + benchmark composition (FeNi, pyrolyte)



All detector effects included



CHALLENGE: achieve sufficient reco/classification performances in the detector !!

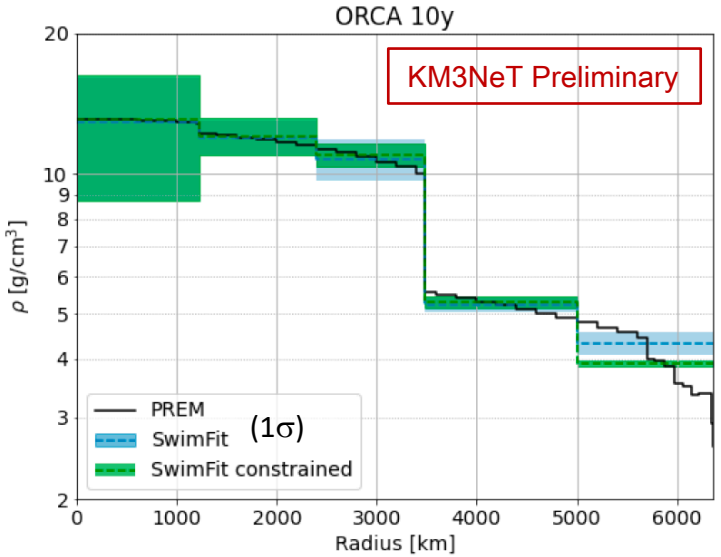
(here: ORCA 3 years)

Oscillation tomography with ORCA

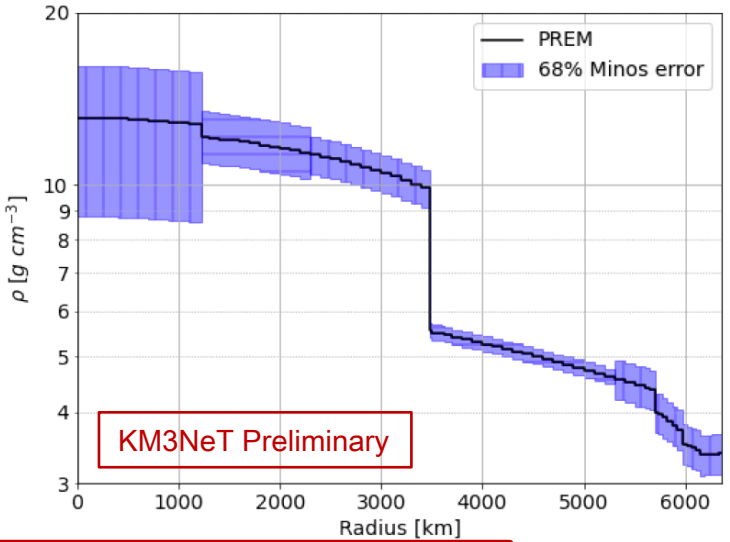
Preliminary studies (all based on simulations w/full detector) :

L. Maderer, Ph. D thesis (link)

- fit of 5-layer density model



- fit of variations to PREM with 42-layer density model



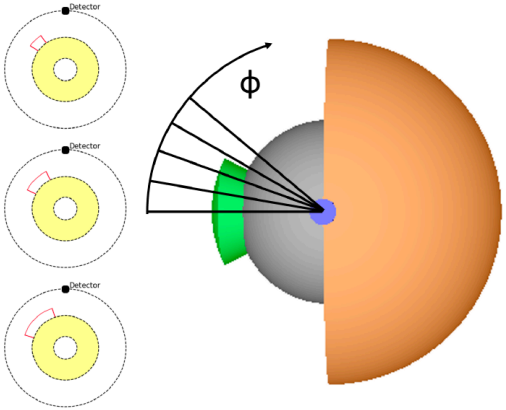
- ✓ Higher sensitivity than with absorption
- ✓ Results improve with external constraints on Earth mass & inertia
- ✓ Possibility to constrain more detailed models

Oscillation tomography with ORCA

Preliminary studies (all based on simulations w/full detector) :

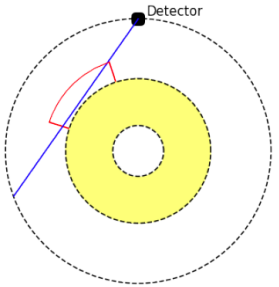
- LLSVP-like inhomogeneity in the mantle

L. Maderer, Ph. D thesis (link)

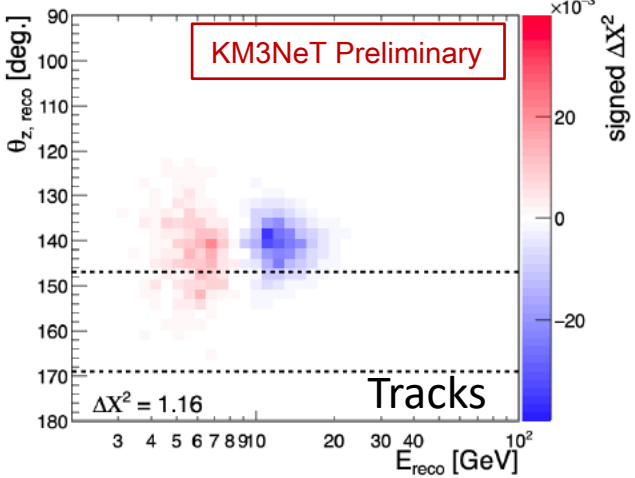


Comparable contributions of track/shower channels

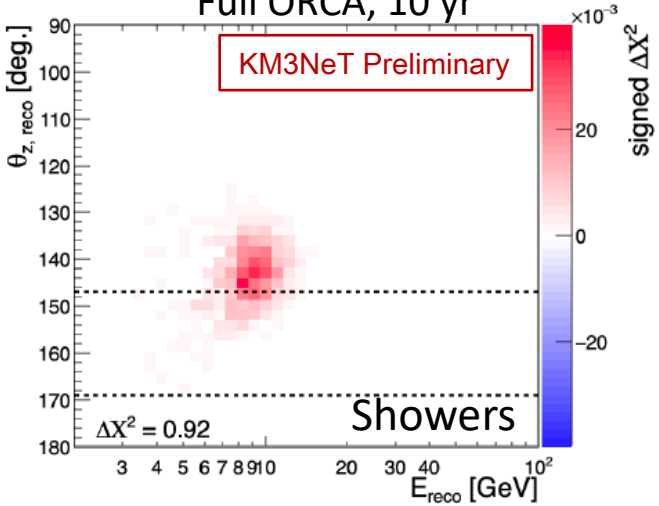
For 10% overdensity in LLSVP, most favourable azimuth:



Full ORCA, 10 yr



Full ORCA, 10 yr



Oscillation tomography with ORCA

Preliminary studies (all based on simulations w/full det.)

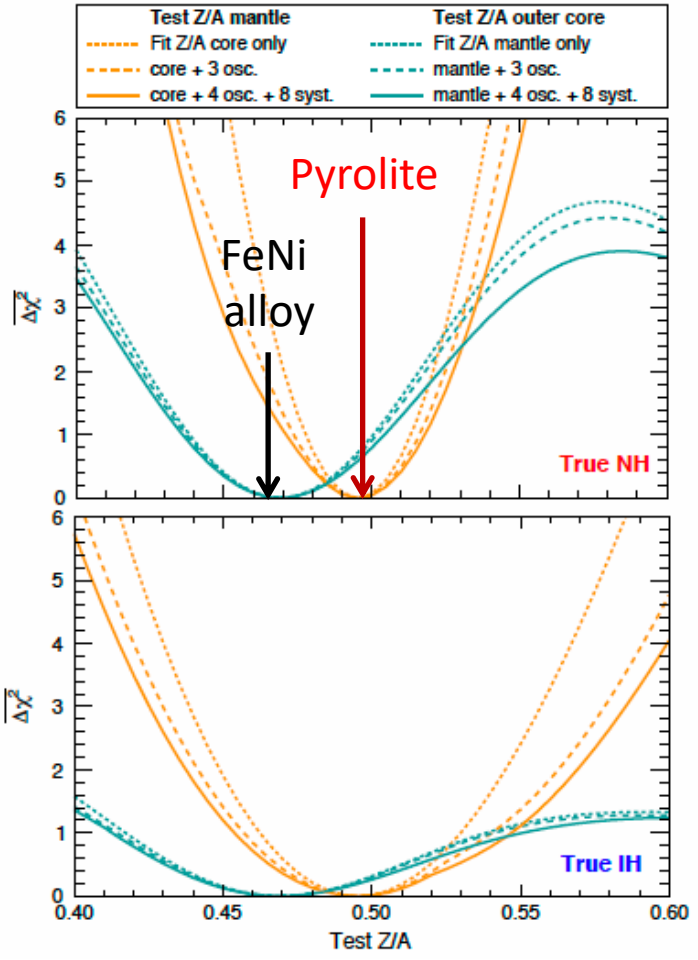
❖ Constraining the core & mantle composition

$$N_e = \frac{N_A}{m_n} \times \frac{Z}{A} \times \rho_{matter}$$

Atmospheric neutrino oscillations

assume PREM

Constrain $\frac{Z}{A} = \sum_i w_i \frac{Z_i}{A_i}$



❖ 1σ sensitivity on Z/A after 10 years:

5% in mantle

6% in outer core

assuming normal hierarchy

(systematics included, MC response & PID)

📖 *S. Bourret [KM3NeT Coll.], EPJ Web Conf. 207 (2019) 04008*

Oscillation tomography with ORCA

Preliminary studies (all based on simulations w/full detector)

❖ Constraining the core & mantle composition

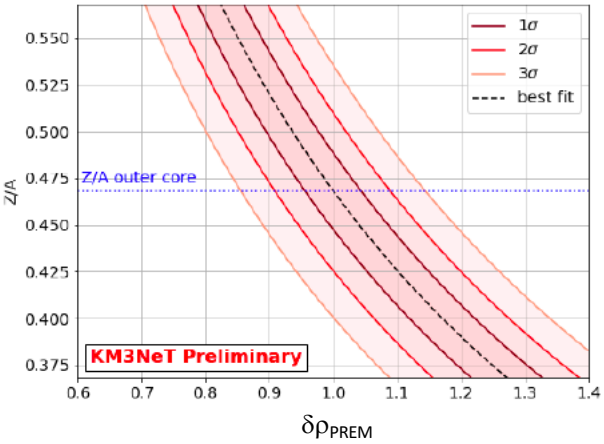
$$N_e = \frac{N_A}{m_n} \times \frac{Z}{A} \times \rho_{matter}$$

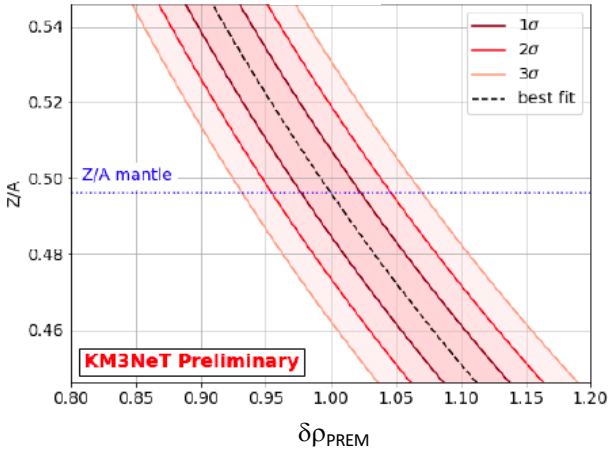
Atmospheric neutrino oscillations

assume PREM

Constrain $\frac{Z}{A} = \sum_i w_i \frac{Z_i}{A_i}$

…or directly plot constraints on the electron density N_e as contours in the ($\delta\rho_{PREM}$,Z/A) plane





📖 *L. Maderer et al. [KM3NeT Coll.], Procs(ICRC2021) 1172*

Summary and outlook

- KM3NeT now in mass production stage with stable expansion rate
  >10% of expected building blocks deployed as of Jan. 2023
- Data taking possible from the very first lines;
  Preliminary results validate the multi-PMT DOM technology
  & already bring meaninful physical results
- KM3NeT expected to bring competitive contributions on neutrino tomography:

  → ARCA-high energy (TeV-PeV)
  km^3-scale instrumented volume with unprecedented angular resolution
  neutrino absorption tomography: matter density profile, LLSVPs,…

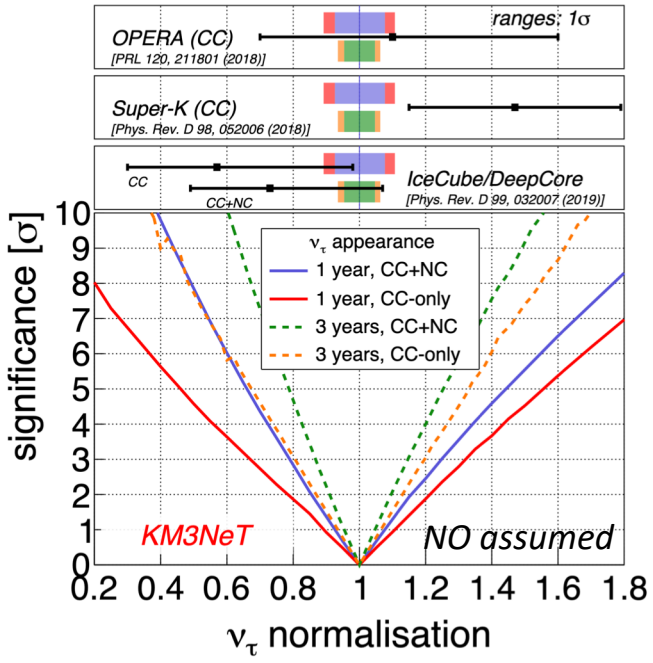
  → ORCA-low energy (1-100 GeV)
  7 Mton-detector, quick measurement of neutrino mass hierarchy (3σ in 1.5/5 yr)
  then oscillation tomography: matter density profile & composition: core, LLSVPs,…

- Interest to combine KM3NeT data with other detectors for 3D Earth tomography

BACKUP

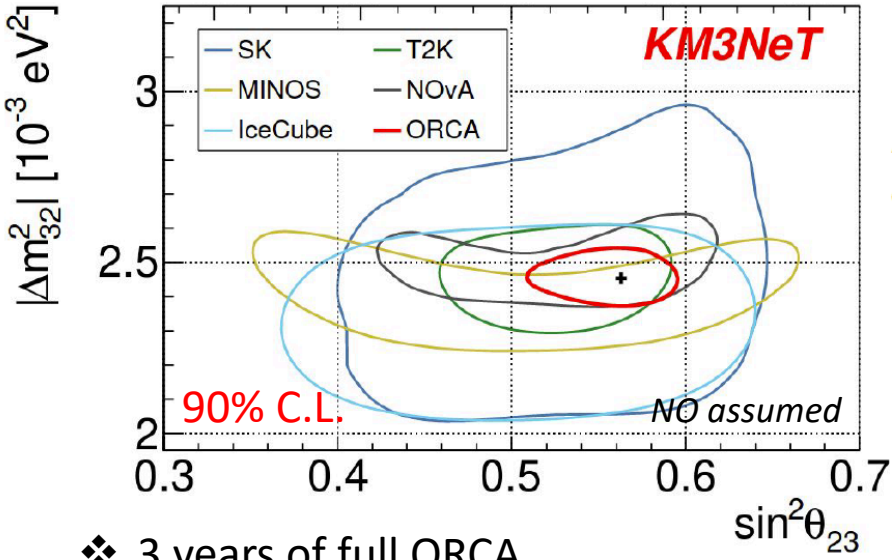
ORCA sensitivity projections

ν_τ appearance



- Confirmation possible after a few months operation with full ORCA
- Fit robust against θ_{23} and mass ordering

Oscillation parameters

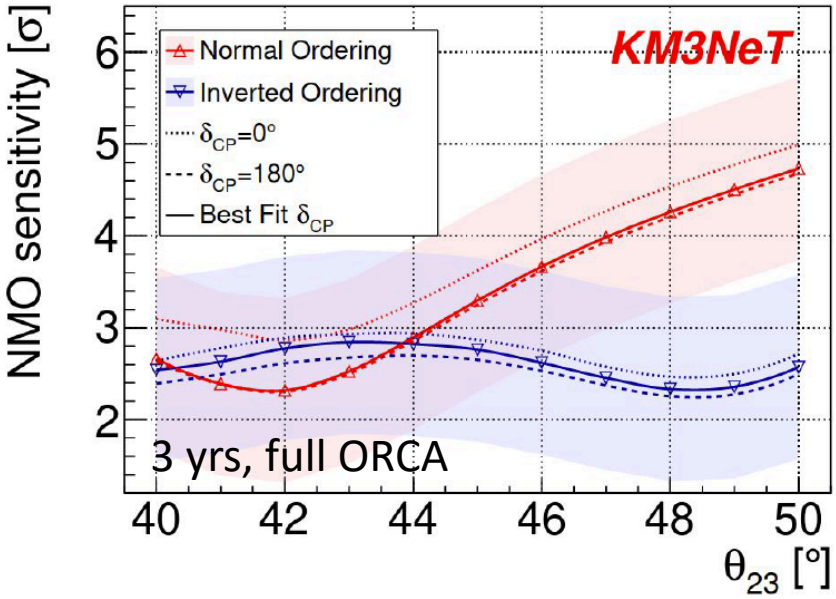


- 3 years of full ORCA
- Normal ordering, $\theta_{23} = 48.6°$ (NuFit v4.1)

📖 *KM3NeT Coll., arXiv: hep-ex/2103.09885 , submitted to EPJ C*

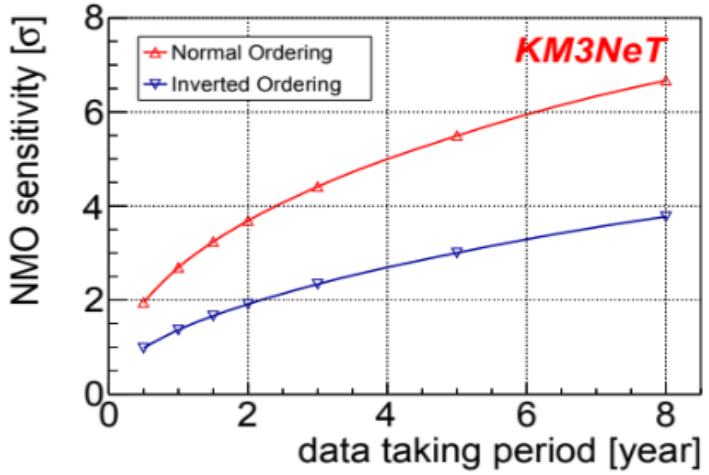
ORCA sensitivity projections

Neutrino mass ordering



68% sensitivity bands (Asimov);
Oscillation parameters from NuFit 4.1

- Favourable scenario: Normal Ordering
→ measurement at 5σ after 4 years
- For Inverted Ordering scenario:
→ measurement at 3σ after 5 years
- moderate impact of δ_{CP} on sensitivity

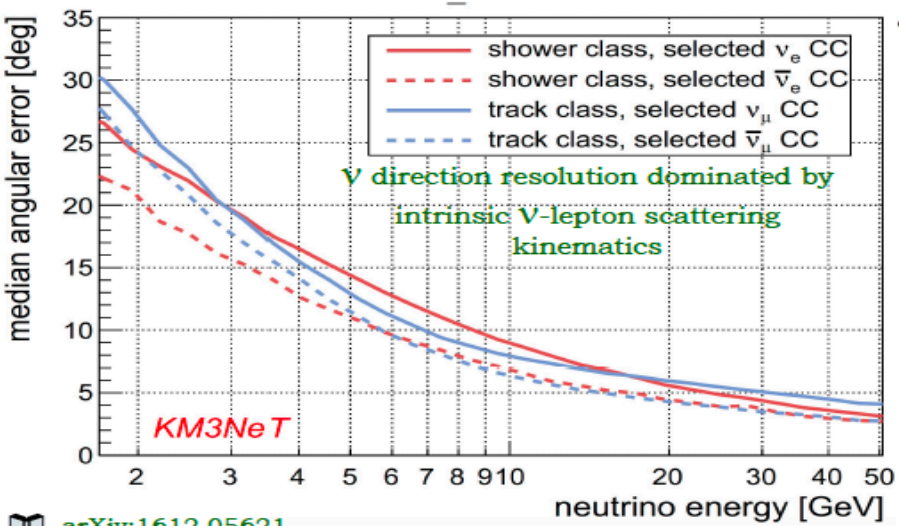


📖 *KM3NeT Coll., arXiv: hep-ex/2103.09885 , submitted to EPJ C*

ORCA Performance

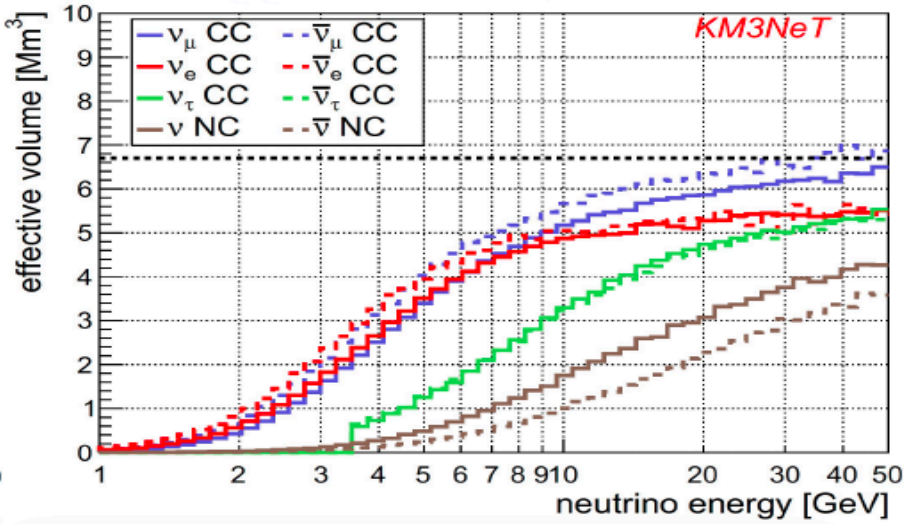
Full detector

"Angular resolution"



arXiv:1612.05621

"Effective Volume"



Energy Resolution:

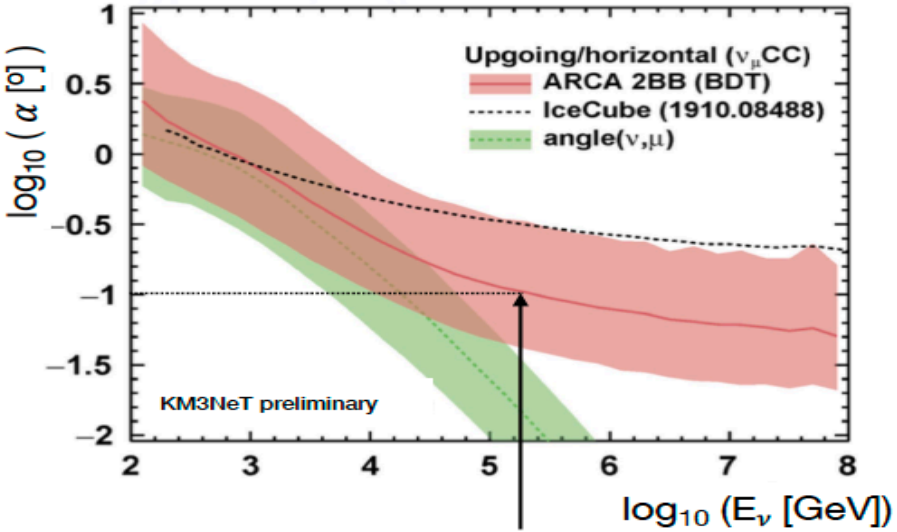
- $\Delta E/E \sim 25\%$ for ν_e CC events at E=10 GeV
  (dominated by intrinsic light yield fluctuations in hadronic shower)
- $\Delta E/E \sim 35\%$ for ν_μ CC events
  (outgoing muon often not fully contained)

ARCA Performance

Full detector

"tracks"

PoS(ICRC2021) 1077

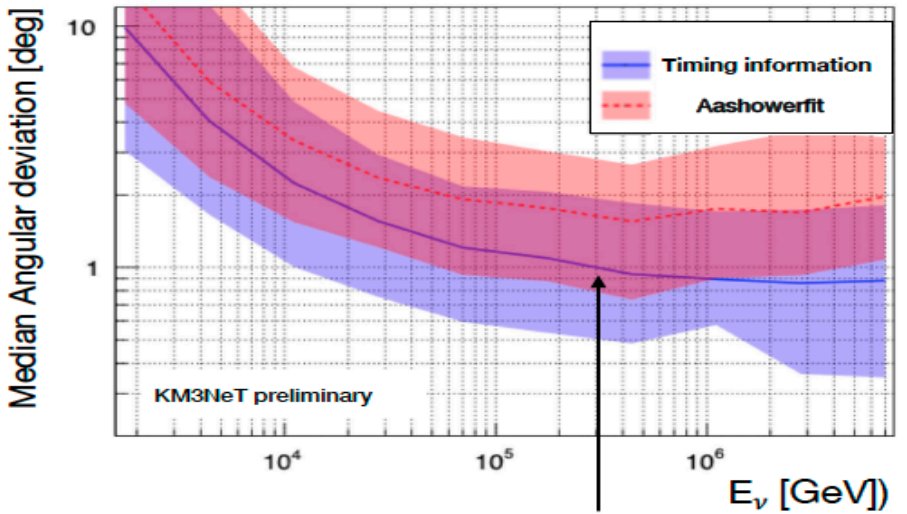


Better than 0.1° at 100 TeV

Energy Resolution ~ 0.27 in $\log_{10}(E_{reco}/E_\mu)$
(10 TeV < E_μ < 10 PeV)

"showers"

PoS(ICRC2021) 1089



Better than 1° at 30 TeV

Energy Resolution < 5%

Showers (ν_x NC + ν_e CC): contained events
Deposited energy strongly correlated with primary E_ν
Effective area smaller compared to "tracks"