Neutrino oscillation studies and cosmic neutrino searches with KM3NeT

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$$P_{\nu_\alpha \to \nu_\beta}(t) = \sum_{k,j} V^*_{\alpha k} V_{\beta k} V_{\alpha j} V^*_{\beta j} \exp\left(-i\frac{\Delta m^2_{kj} L}{2E}\right)$$

Elements of the PMNS Matrix

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PMNS Matrix Unitary Matrix

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$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{pmatrix}$$

$$c_{ab} \equiv \cos\vartheta_{ab} \qquad s_{ab} \equiv \sin\vartheta_{ab}$$

What do we know about neutrinos today?

A 3x3 unitary matrix as the PMNS has

$$\begin{cases} \dfrac{N\,(N-1)}{2} = 3 & \text{mixing angles}\,, \\ \dfrac{(N-1)\,(N-2)}{2} = 1 & \text{physical phase}\,. \end{cases}$$

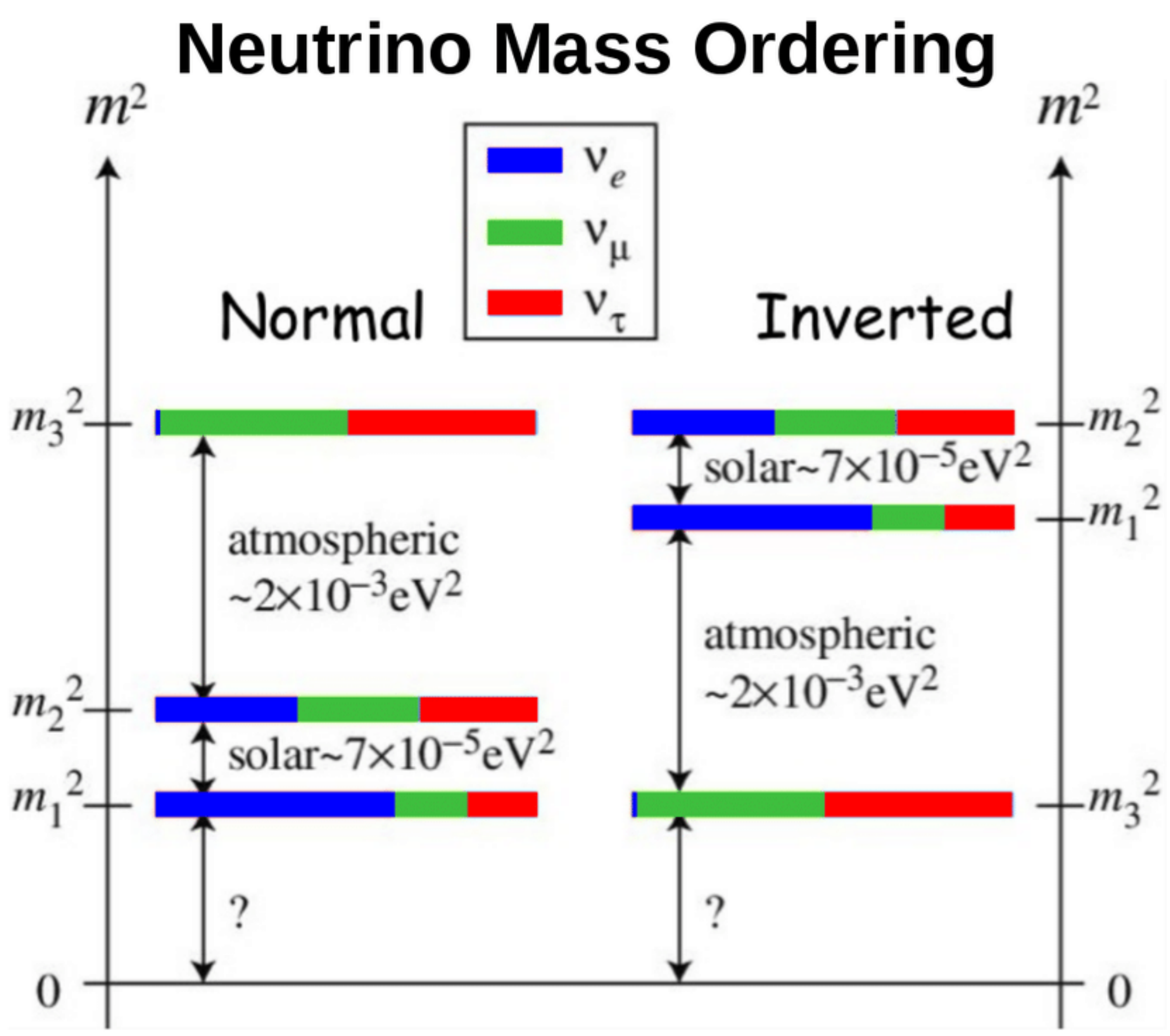
With 3 mixing angles (θ_{12}, θ_{13}, θ_{23}), 2 mass square differences (Δm^2_{12}, Δm^2_{13}) and 1 CP phase δ_{CP} there is a total of **6** parameters testable with oscillation experiments.

What is still missing?

- The value of neutrino masses.
- Neutrino oscillation experiments can not directly constrain the neutrino masses but the mass squared differences.

$$P_{\nu_\alpha \to \nu_\beta}(t) = \sum_{k,j} V^*_{\alpha k} V_{\beta k} V_{\alpha j} V^*_{\beta j} \exp\left(-i\frac{\Delta m^2_{kj} L}{2E}\right)$$

- If we assume that one of the three masses is the lightest one we get **two** mass orderings:



What is still missing?

- Neutrino nature: Dirac or Majorana?
- Neutrino masses.
- Neutrino mass ordering.
- The information of the CP violating phase is still lacking.

Studying neutrinos with neutrino telescopes

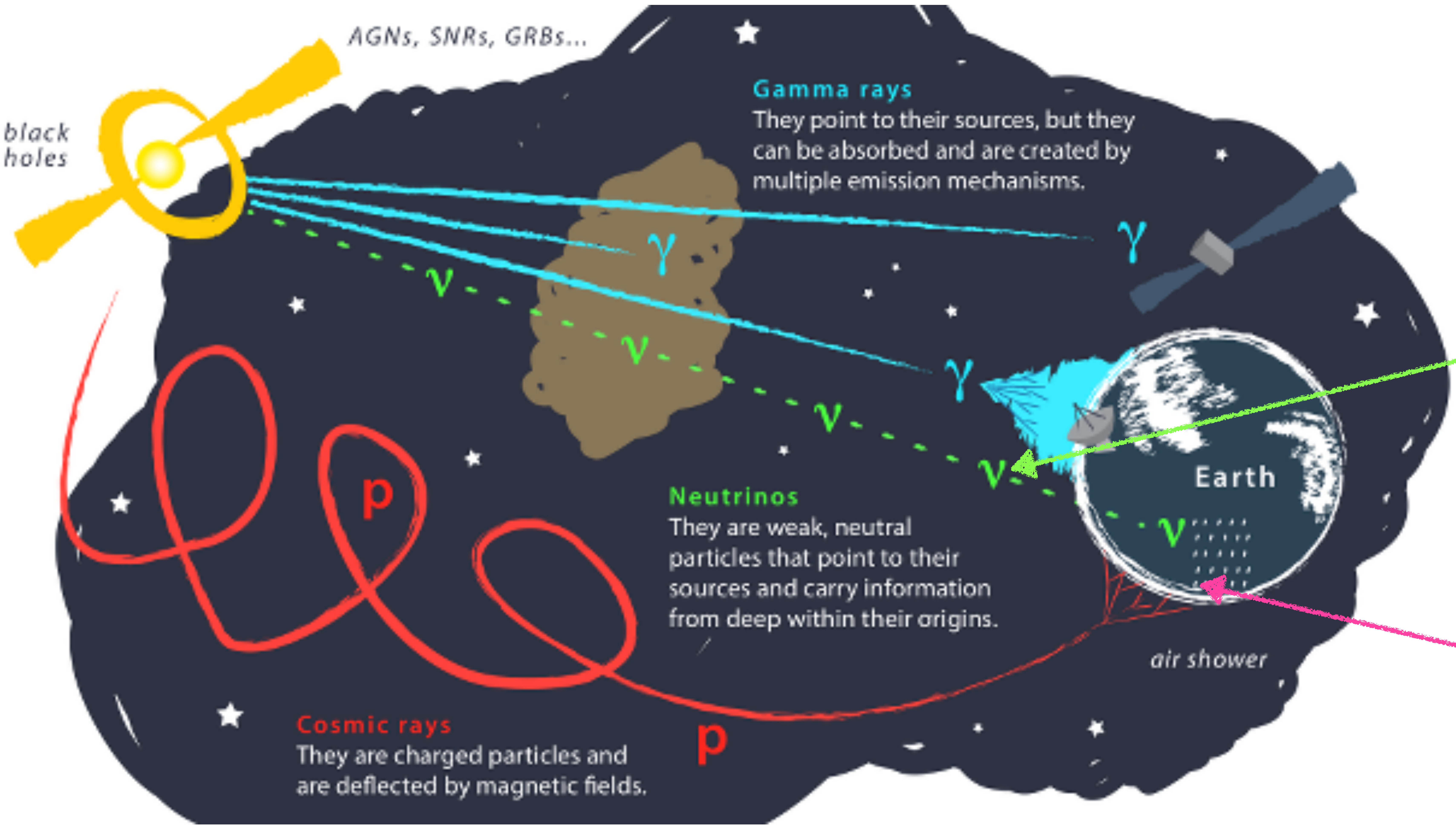
Studying neutrinos with neutrino telescopes

- 1960 - Markov has the idea to detect high energy neutrinos by exploiting huge volumes of transparent medium (water/ice).

- 1980 - Search for proton decay was the main reason for developing large detectors and underground laboratories.

- **The era of neutrino telescopes is therefore quite new!**

Basic Idea



Neutrino telescopes can analyse:

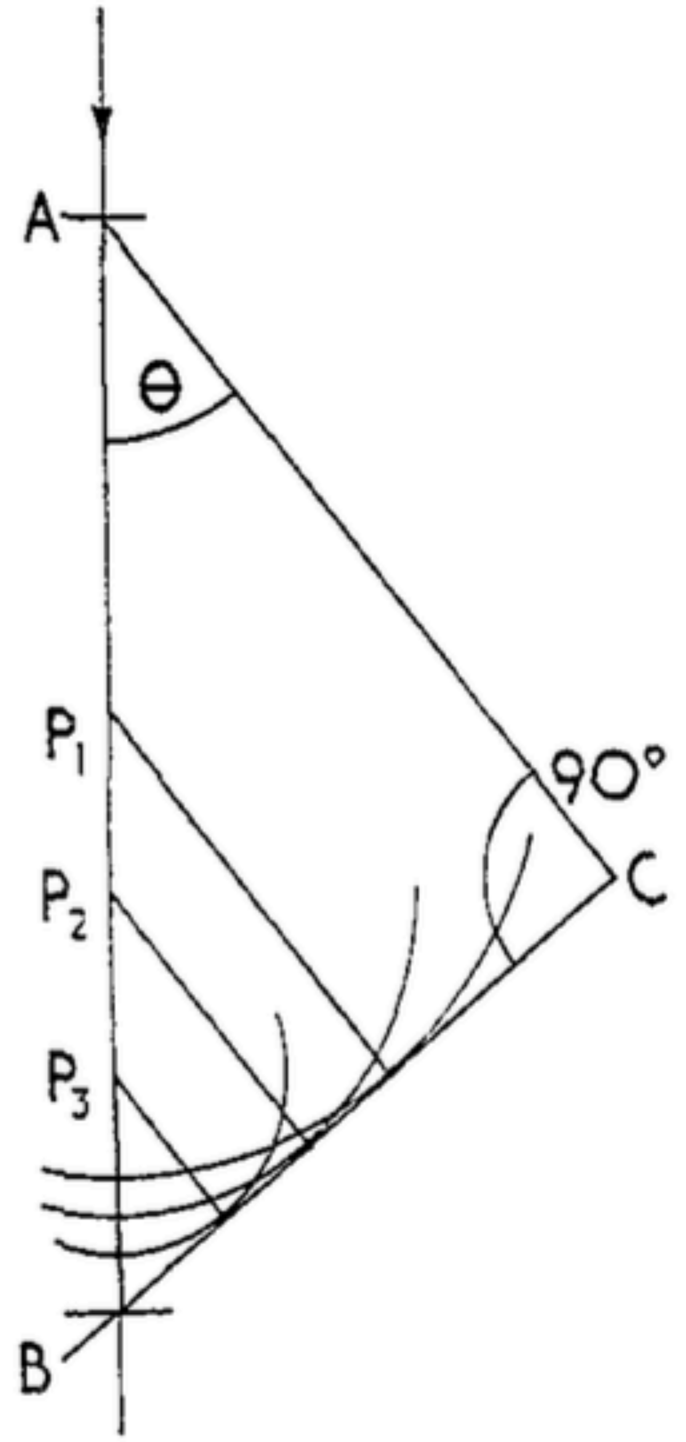
- **Astrophysical neutrinos**: directly coming from astrophysical sources.
- **Atmospheric neutrinos**: produced by interactions of primary cosmic rays with the atmosphere elements.

Neutrino Interactions

- Neutrinos can interact with ordinary matter ONLY via WEAK INTERACTIONS.
- The probability of a neutrino to interact with matter is hence **really small!**
- If we want to increase the interaction probability **we need huge volumes of matter (of the order ok km^3)!**
- However, building them artificially is **extremely expensive.**
- **But we are lucky!** Our Hearth has a lot of water (seas/oceans) and Ice (South Pole).

Neutrino Detection Principle

Cherenkov photon emission by charged particles



$\theta \sim 42°$ in water

Cherenkov photons detected by Photomultiplier Tubes!

We need many arrays of PMTs distributed in a large volume

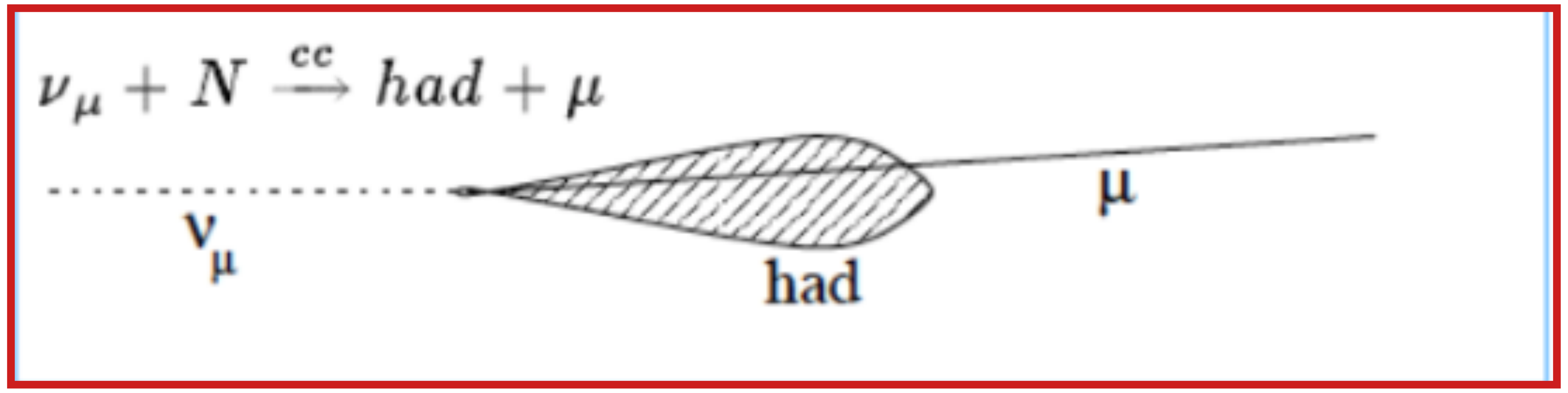
Neutrino Detection Principle

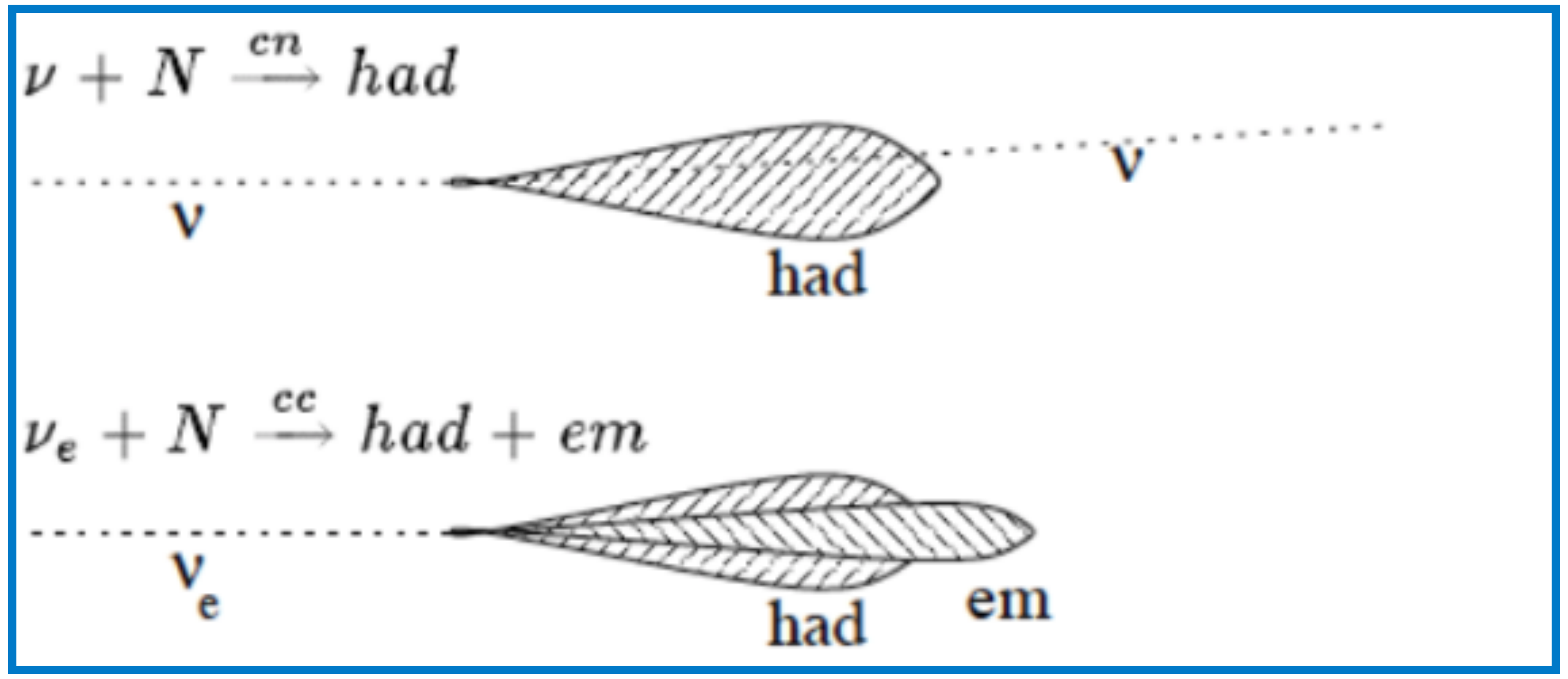
Neutrinos → very low interaction cross section → we need big volumes of material to make them interact

Interactions and event topologies

Tracks: ν_μCC, ν_τCC ($\tau \rightarrow \mu$)

Showers: ν_eCC, νNC



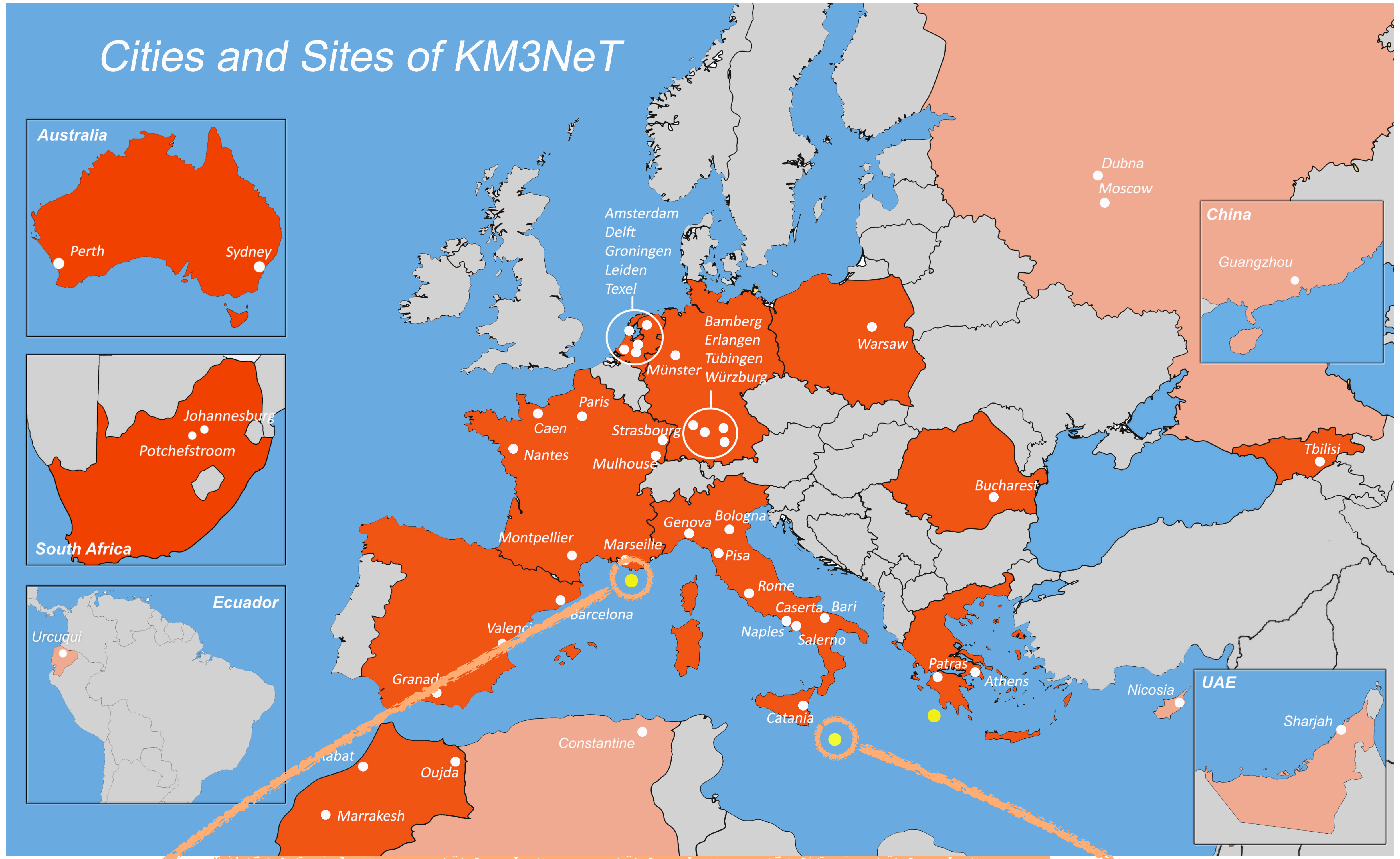


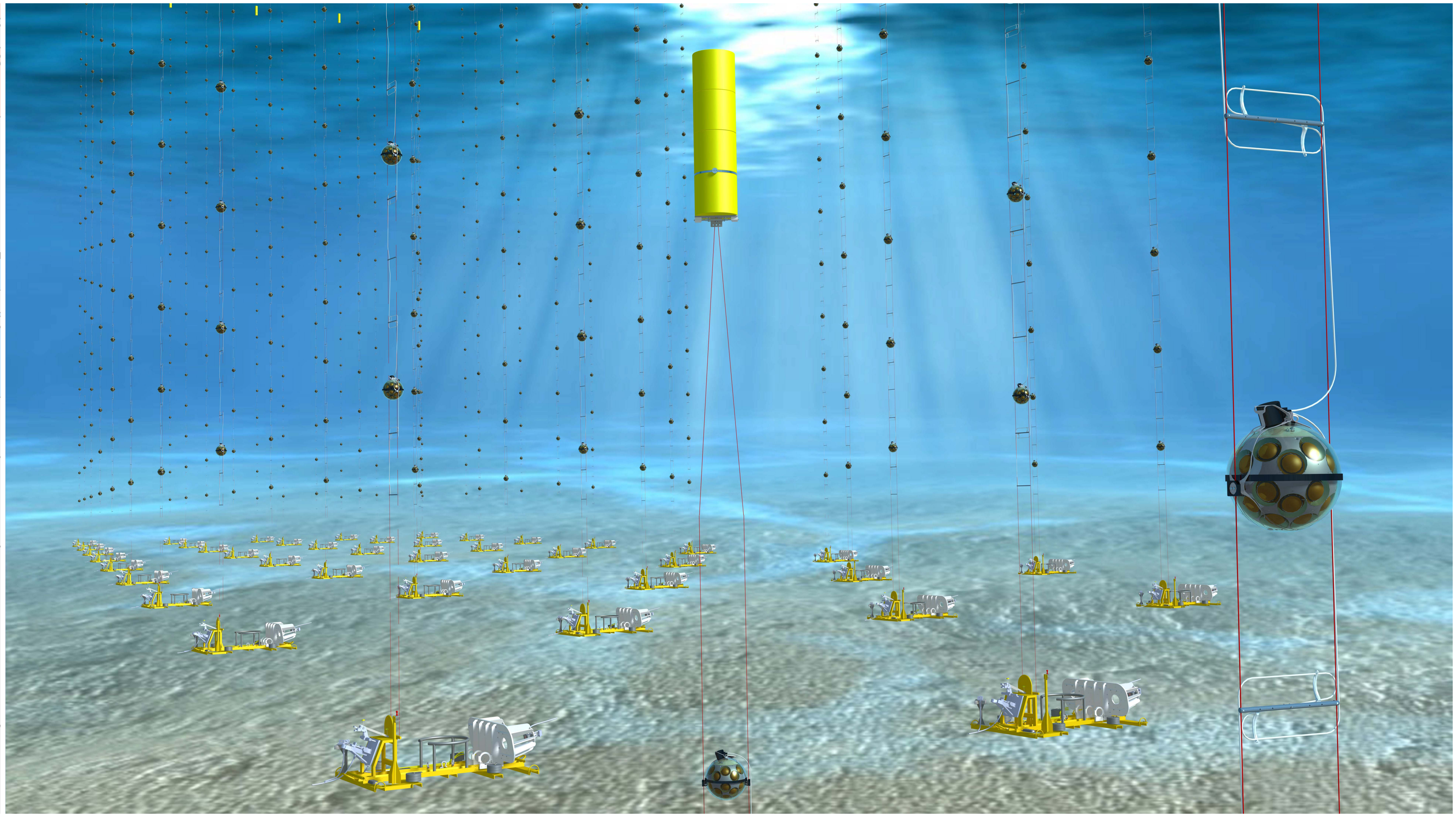
L ~ 4 m x E/GeV

L ~ 0.9 + 0.36 ln(E/GeV) m

KM3NeT Neutrino Telescope

18 DOMS with 31 3" PMTs FOR EACH LINE





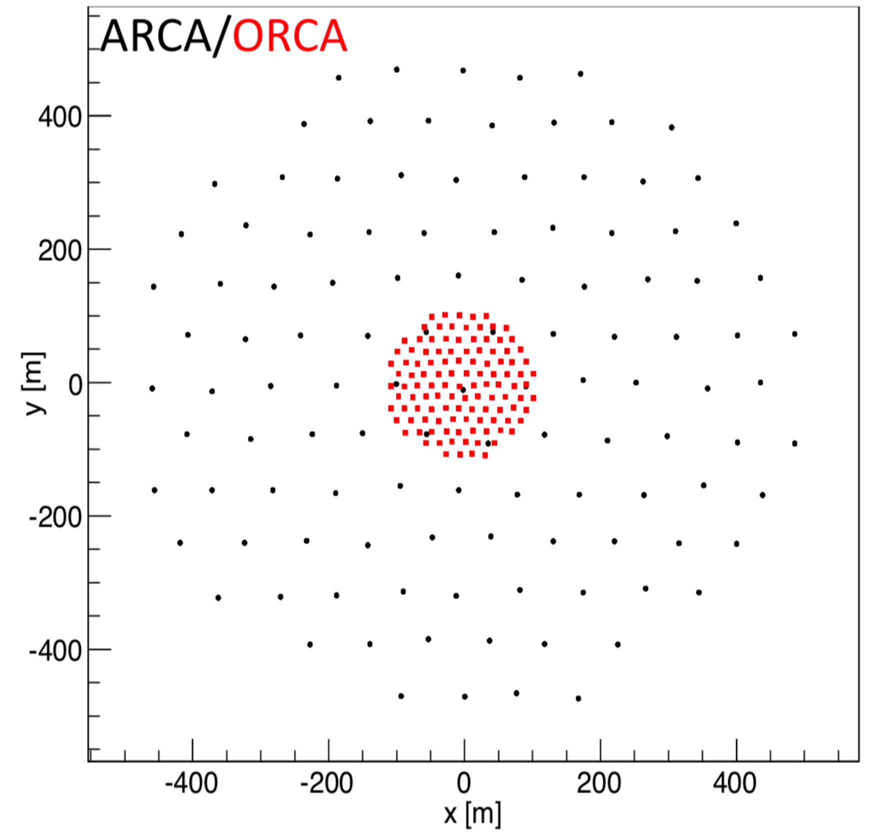
ORCA:

1 DENSE BUILDING BLOCK OPTIMISED FOR INTERMEDIATE ENERGIES (1-100 GEV)

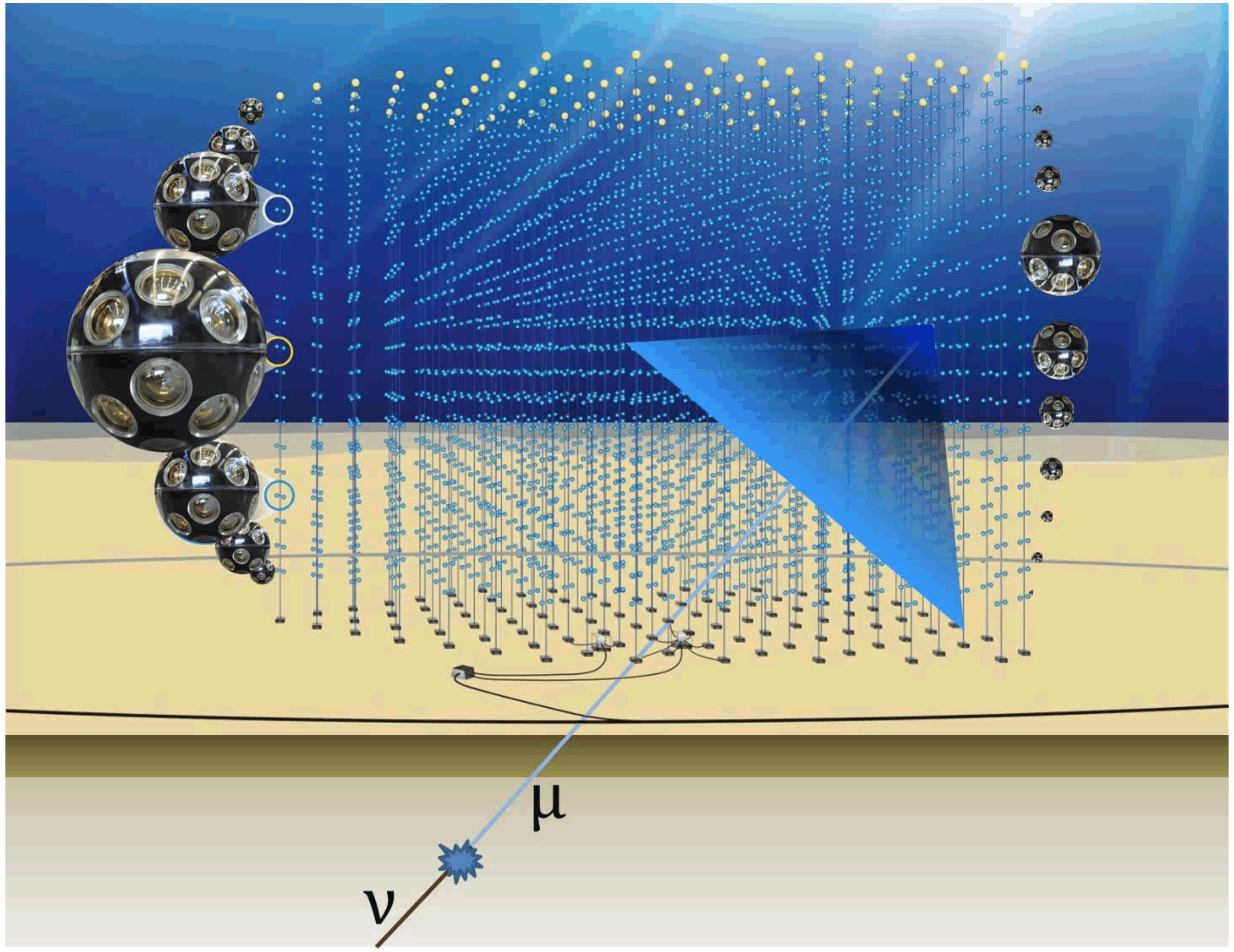
ARCA:

2 SPARSE BUILDING BLOCKS OPTIMISED FOR HIGH ENERGIES (>1 TEV)

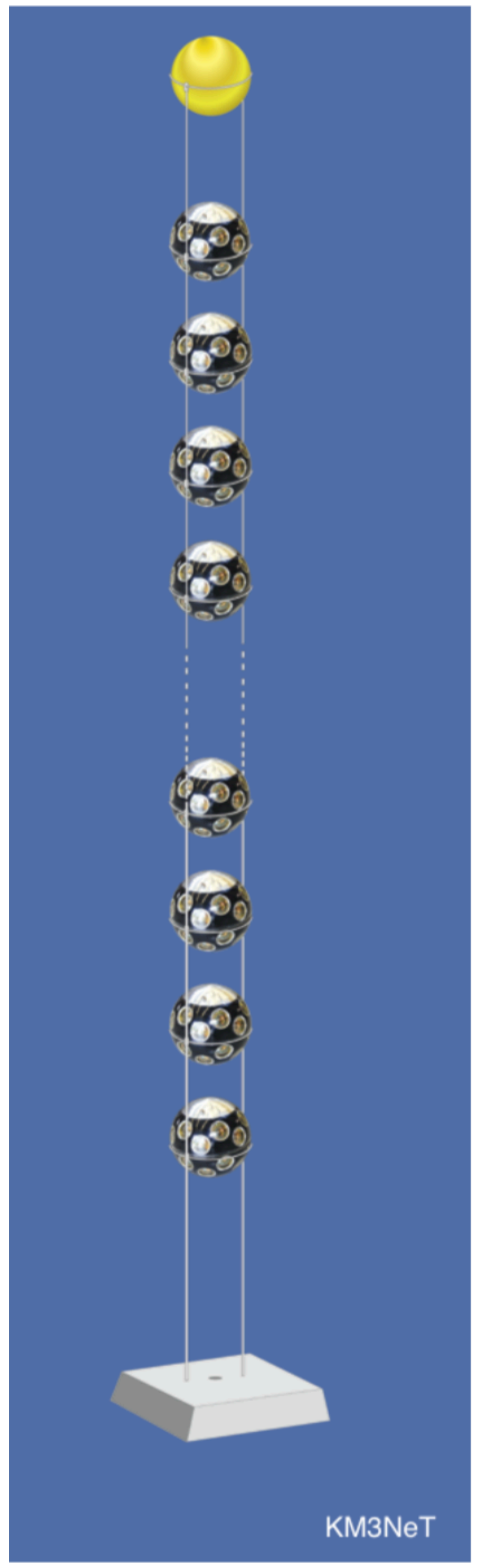
	ORCA	ARCA
String spacing	20 m	90 m
Vertical spacing	9 m	36 m
Depth	2470 m	3500 m



KM3NeT Detection Technology



115 Detection Units (DUs) per Building Block



DU: 18 DOMS

ORCA - h 200 m
ARCA - h 750 m

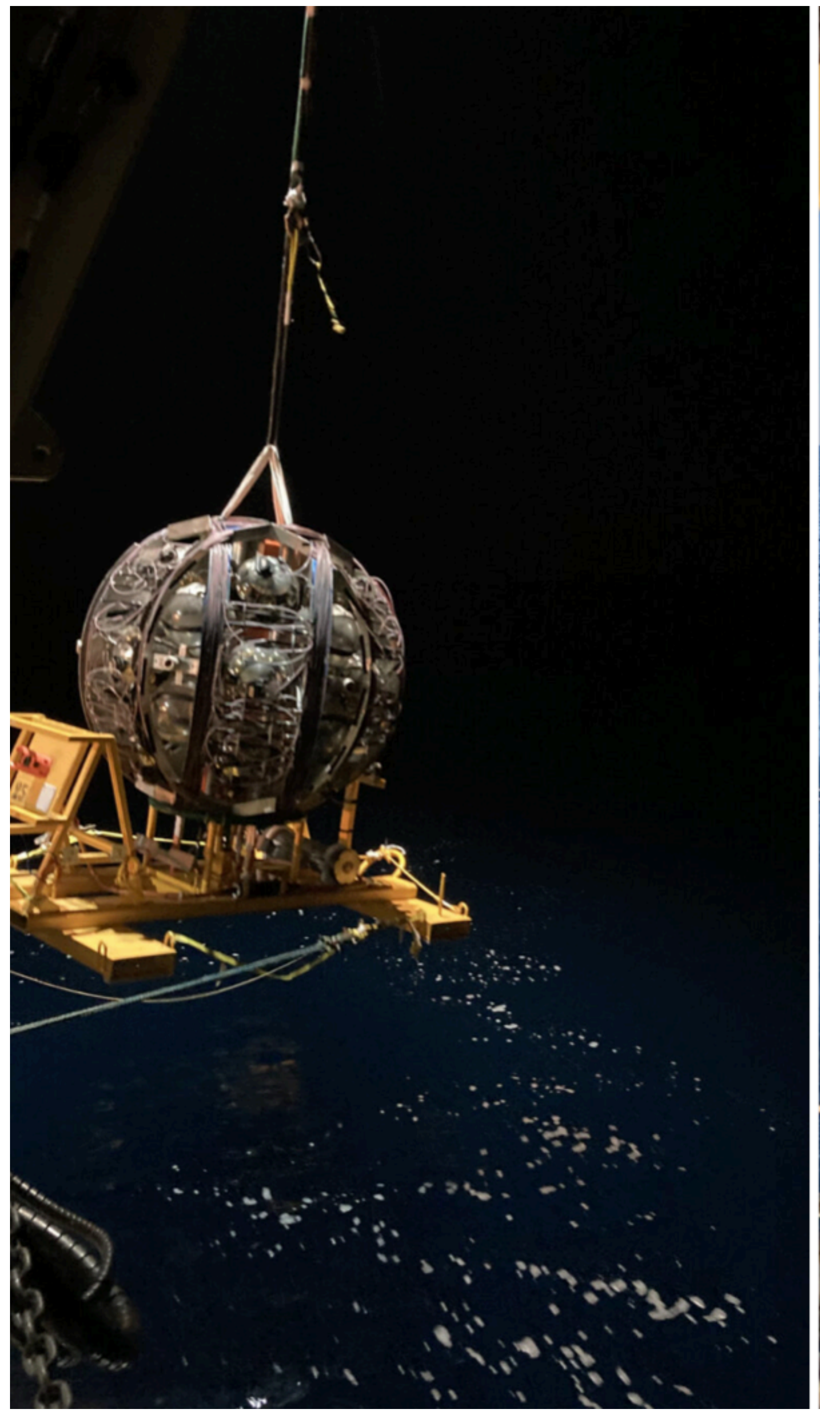
MULTI-PMT DOM: 31 PMTs 3"

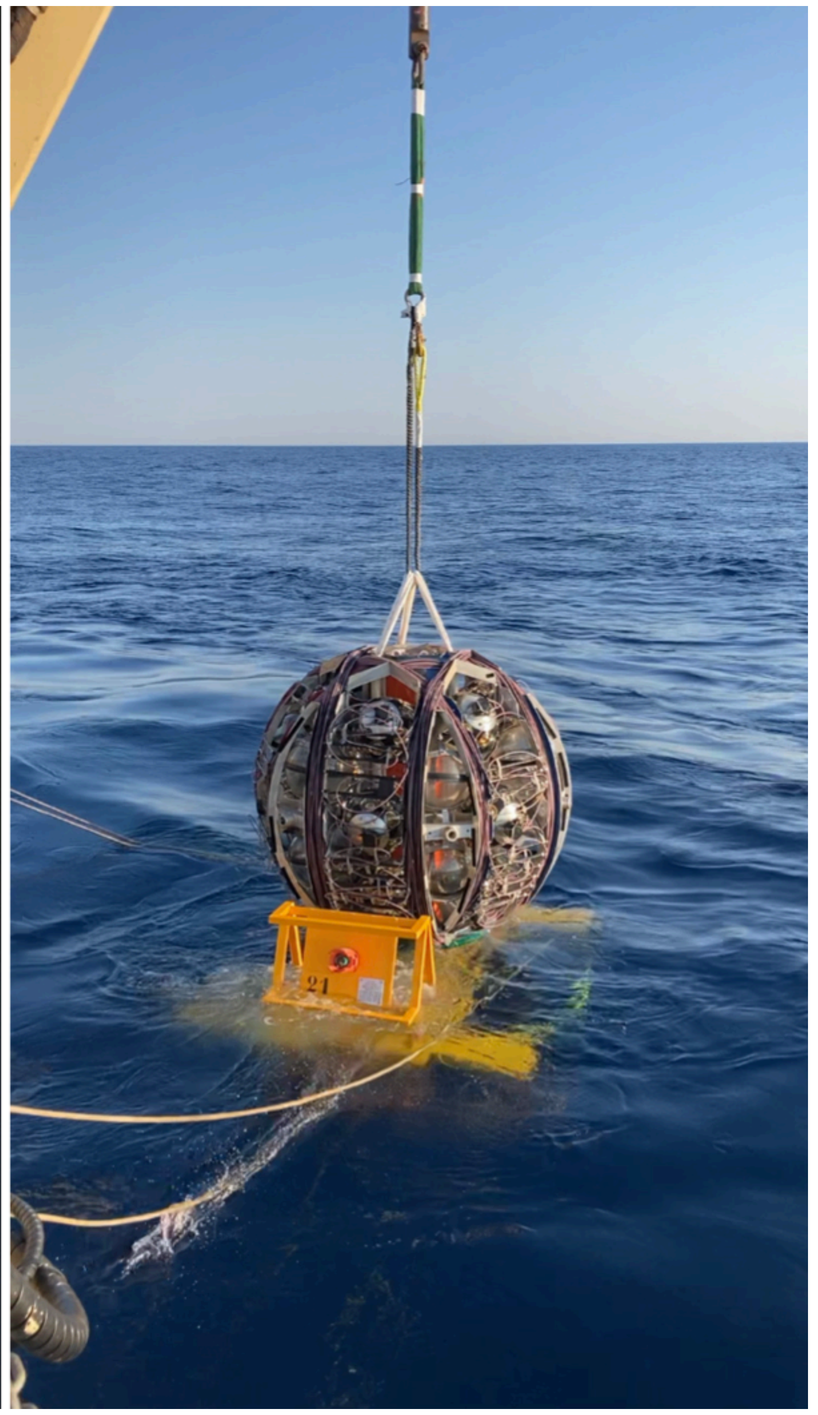
KM3NeT

DETECTOR STATUS

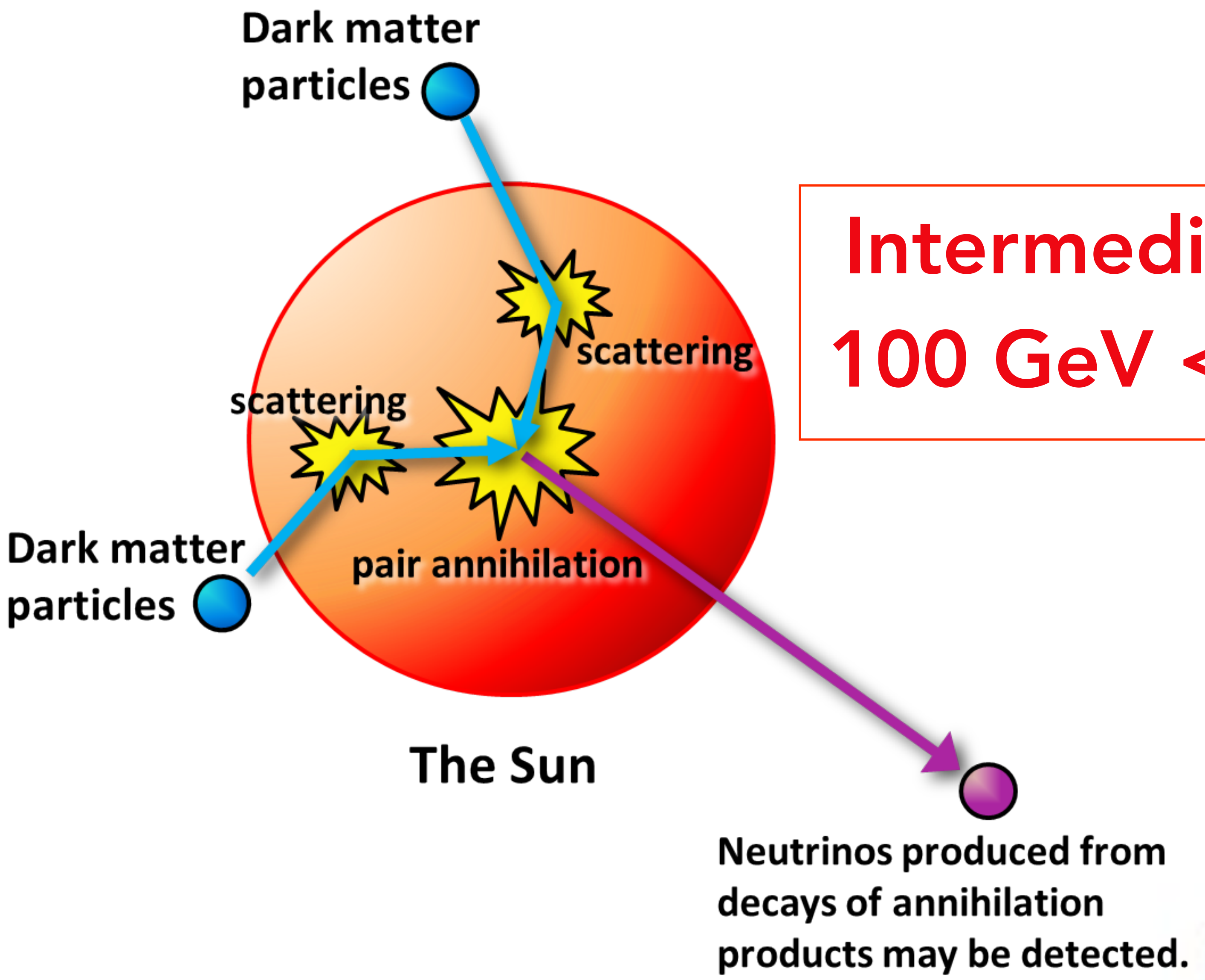
ARCA-19 DUs ready to take data in the sea!

ORCA-10 DUs taking data in the sea!

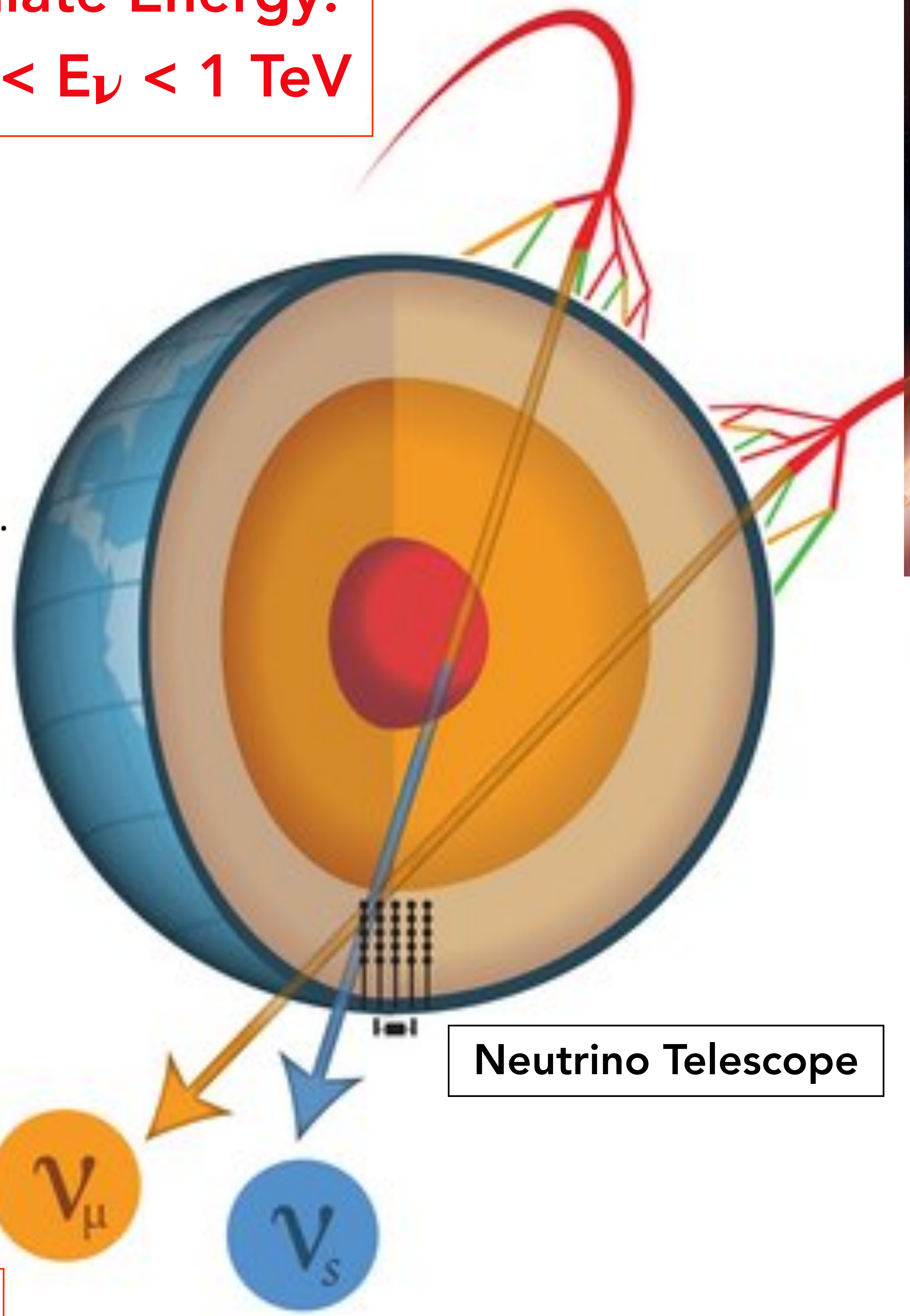




Neutrino Telescopes: science scope



Intermediate Energy:
100 GeV < E_ν < 1 TeV



Neutrino Telescope

High Energy:
E_ν > 1 TeV

High energy processes in the Universe

Dark Matter, Monopoles...

ARCA + ORCA & ANTARES

ORCA

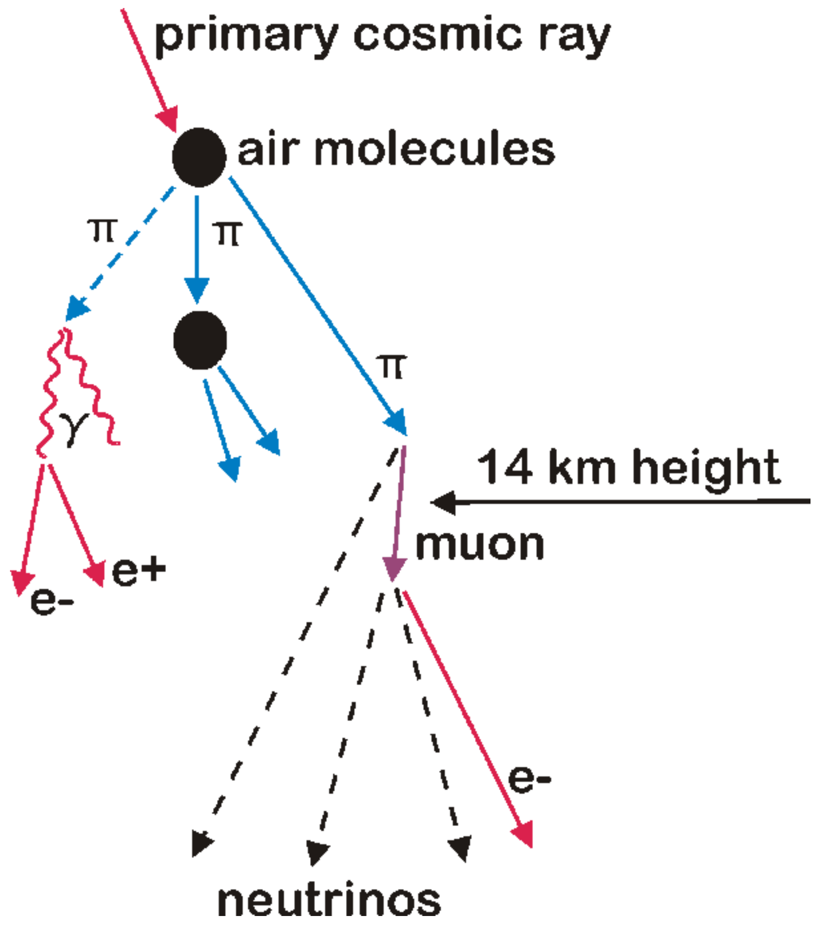
ARCA & ANTARES

Low Energy:
MeV < E_ν < 100 GeV

Neutrino properties, fundamental physics...

KM3NeT: Background in deep sea

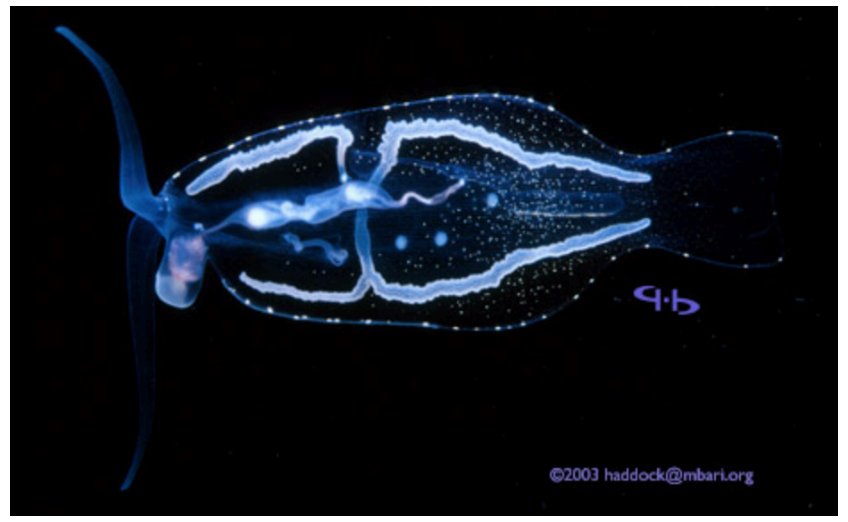
- Atmospheric muons



- K40 decay: most abundant radioactive isotope in sea water.

$$
\begin{aligned}
{}^{40}K &\rightarrow {}^{40}Ca + e^- + \overline{\nu}_e && (89.3\%)\\
{}^{40}K + e^- &\rightarrow {}^{40}Ar^* + \nu_e && (10.7\%)\\
&\quad \hookrightarrow {}^{40}Ar + \gamma
\end{aligned}
$$

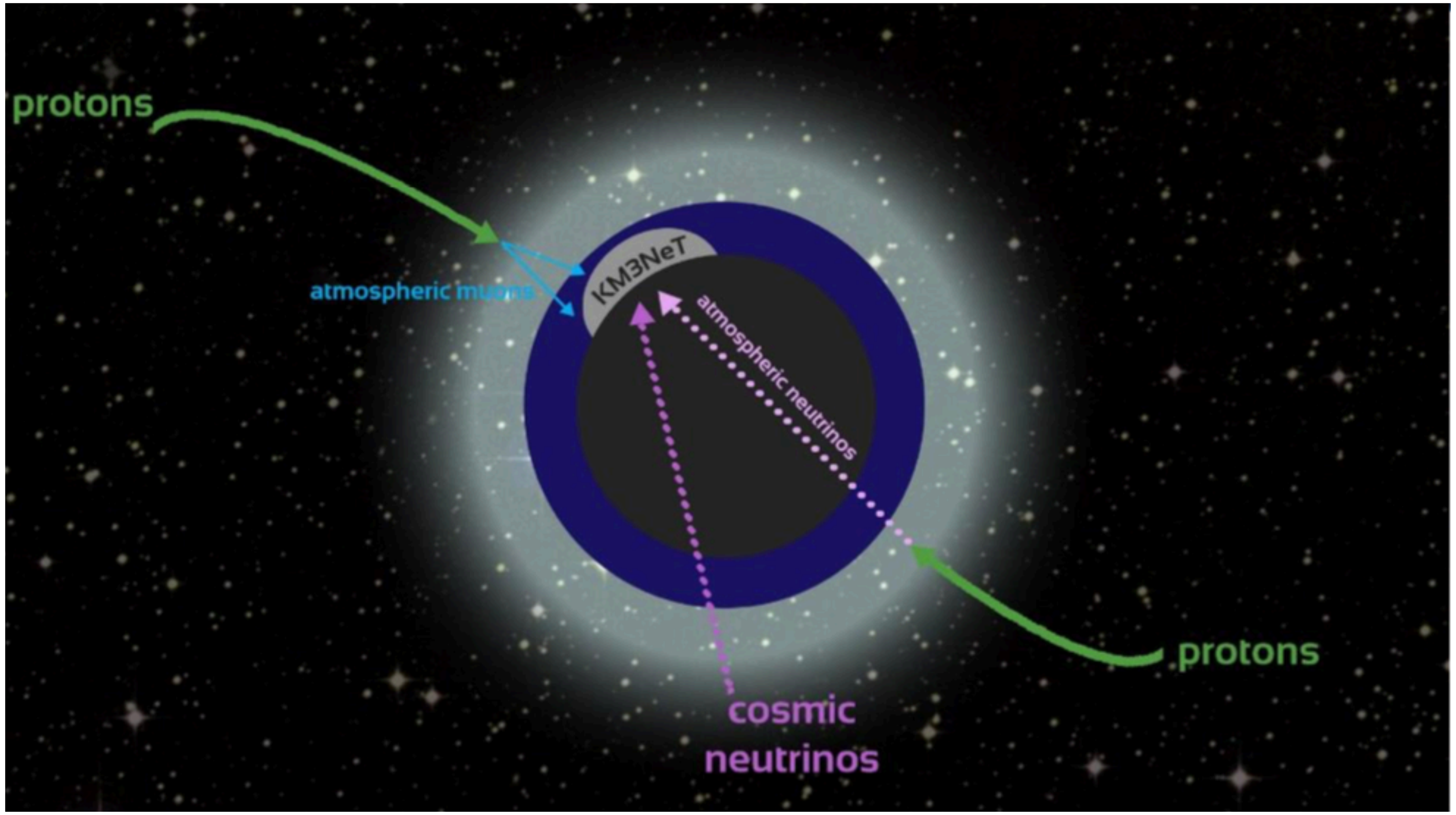
- Bioluminescence: macro organisms, bacteria.



MEASURE OF NEUTRINO PARAMETERS

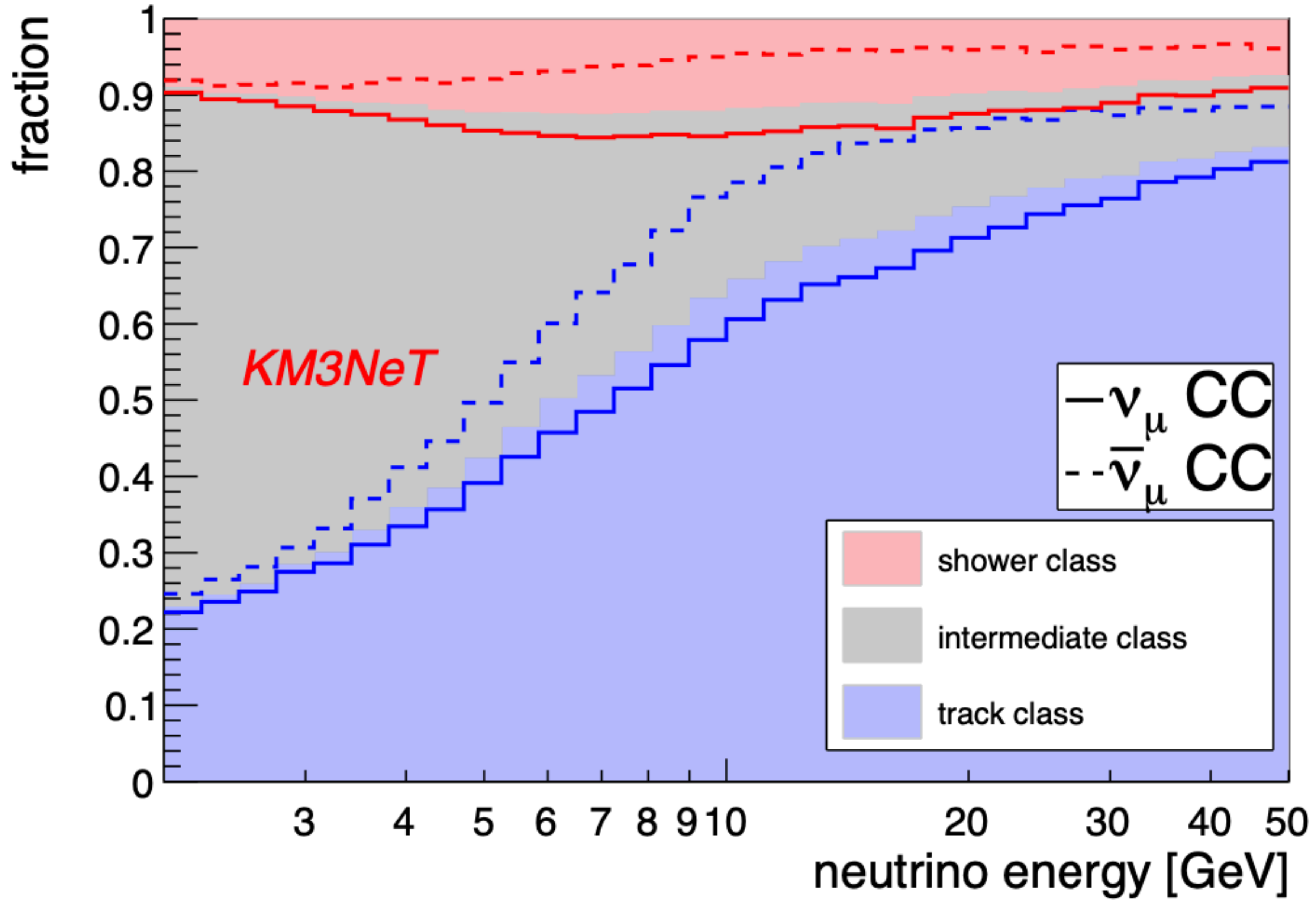
SOURCE: Atmospheric neutrinos

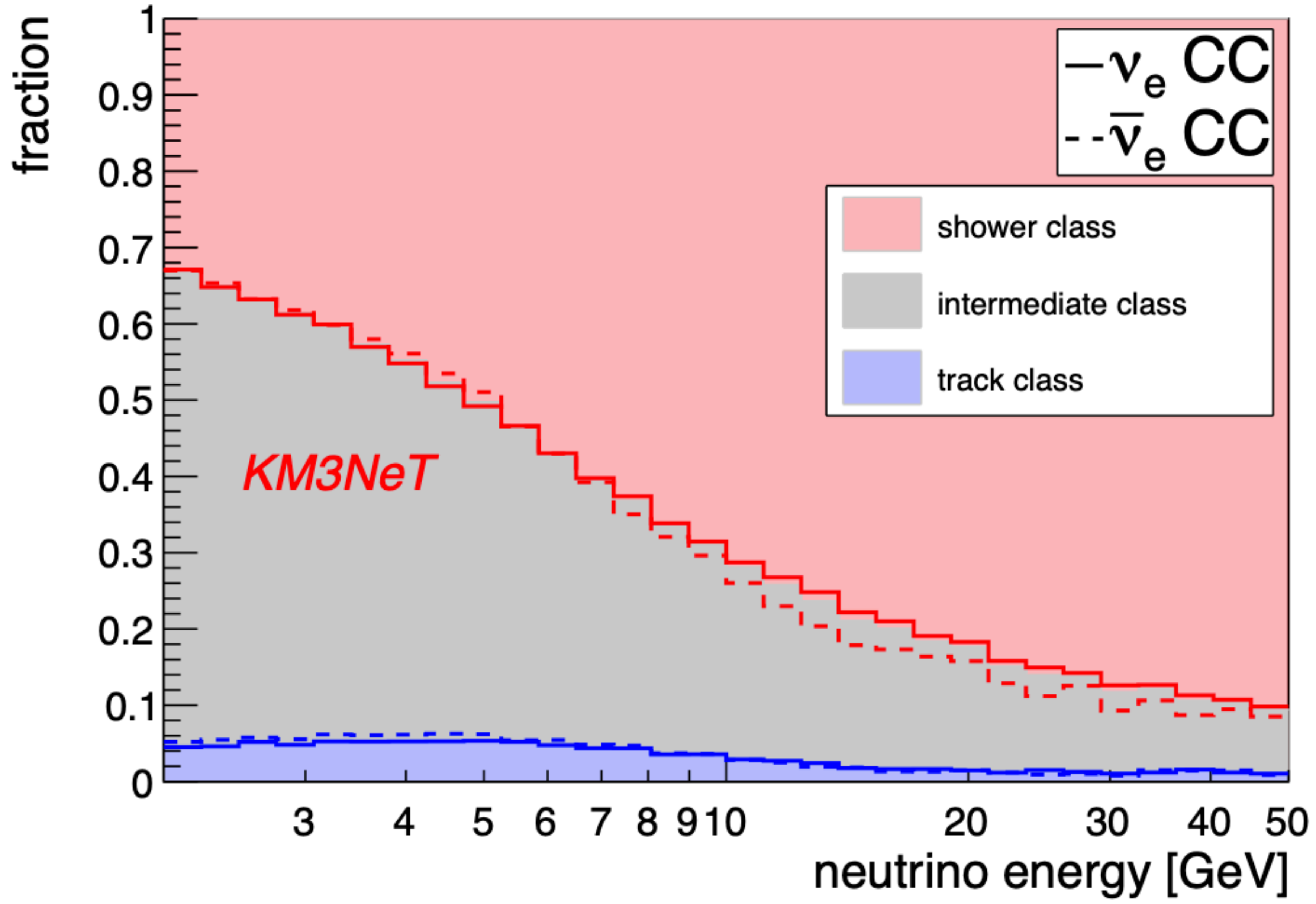
Free, natural beam of known composition.



Event Reconstruction & Selection

- Triggered events are reconstructed with track and shower reconstructions.
- Features extracted from reconstructions (likelihood, energy, direction, etc) are the input of binary random decision forests (RDF):
  - nu/mu classification: muon_score
  - noise classification: noise_score
  - track/shower classification -> 3 classes are identifies at the end: track, intermediate, shower.



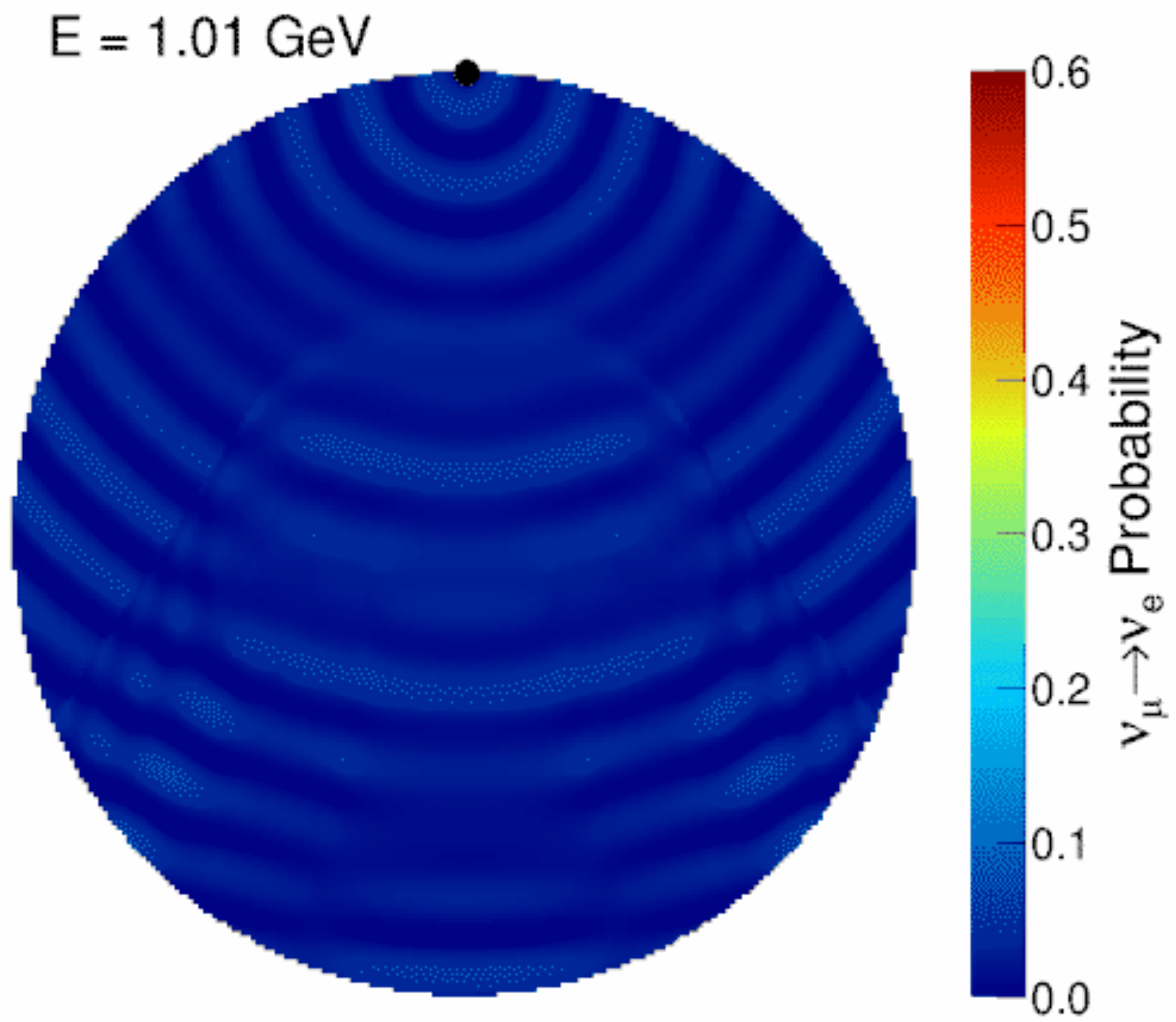


Why is neutrino mass ordering important?

- Mass ordering allows to constrain unification theories, which allow to investigate the early universe.
- Mass ordering has high impact in ββ-decay investigations, whose goal is to determine the neutrino nature (is the neutrino its own antiparticle?).
- Mass ordering strongly influences the number and type of isotopes produced in a supernova explosion.
- An unknown mass ordering can obscure the differences in neutrino vs antineutrino oscillations, whose study can help in solving the mystery on why our universe is filled with particles and almost no antiparticles.

Measure Neutrino Mass Ordering

- ν_e interaction with electrons.
- Oscillation pattern distorted by Earth's matter effects:
  - Resonance in the oscillation probabilities in the few-GeV range.
  - **Earth Model:** PREM Model [1] with 42 layers and realistic Z/A values.

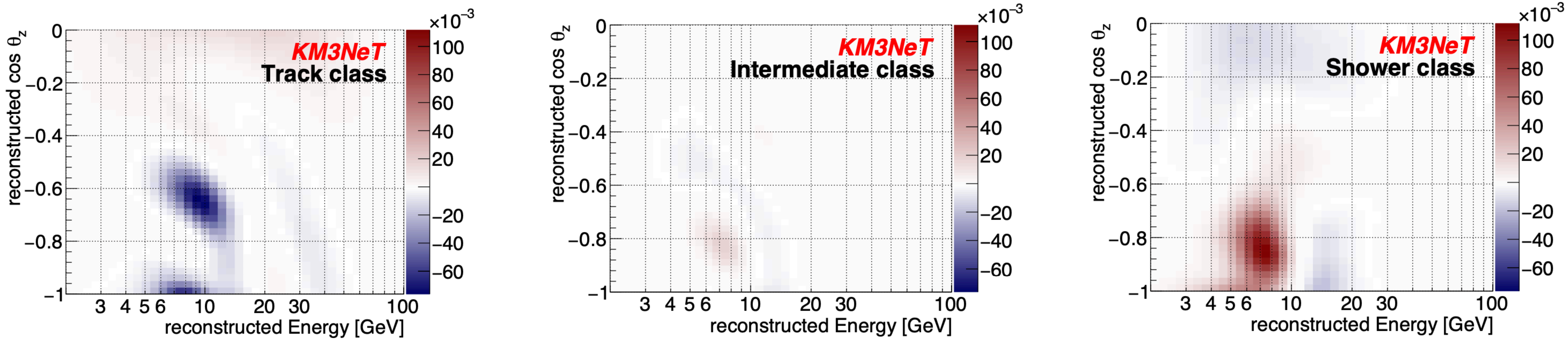


Animation Ref: J. Coelho - http://www.apc.univ-paris7.fr/Downloads/antares/Joao/animations/

[1] Adam M. Dziewonski and Don L. Anderson. Preliminary reference Earth model. Physics of the Earth and Planetary Interiors, 25(4):297–356, 1981.

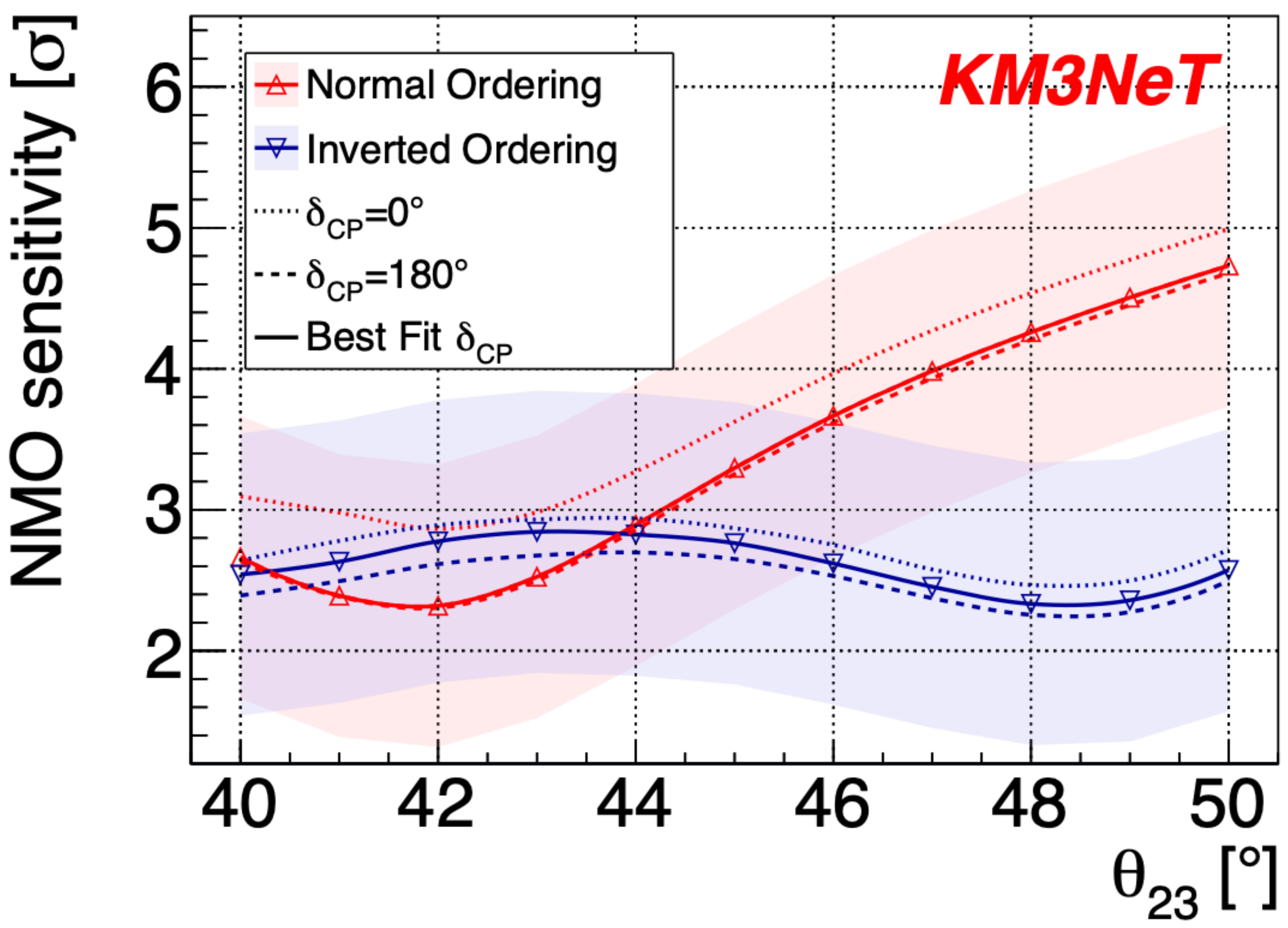
Measure Neutrino Mass Ordering

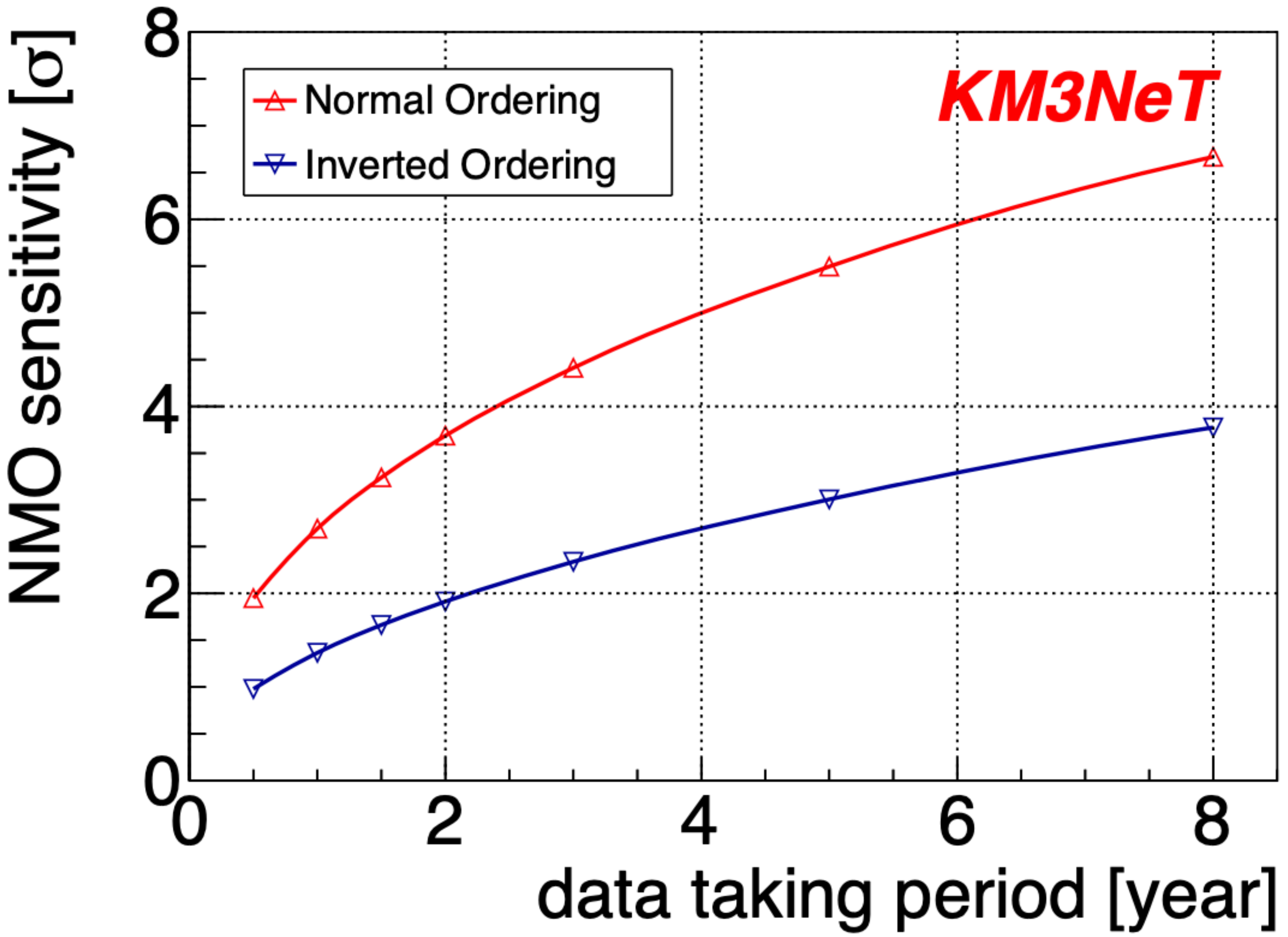
$\chi^2 \sim (N_{NO}-N_{IO})|N_{NO}-N_{IO}|/N_{NO}$



Neutrino mass ordering

FULL-ORCA, 3 years of assumed data taking

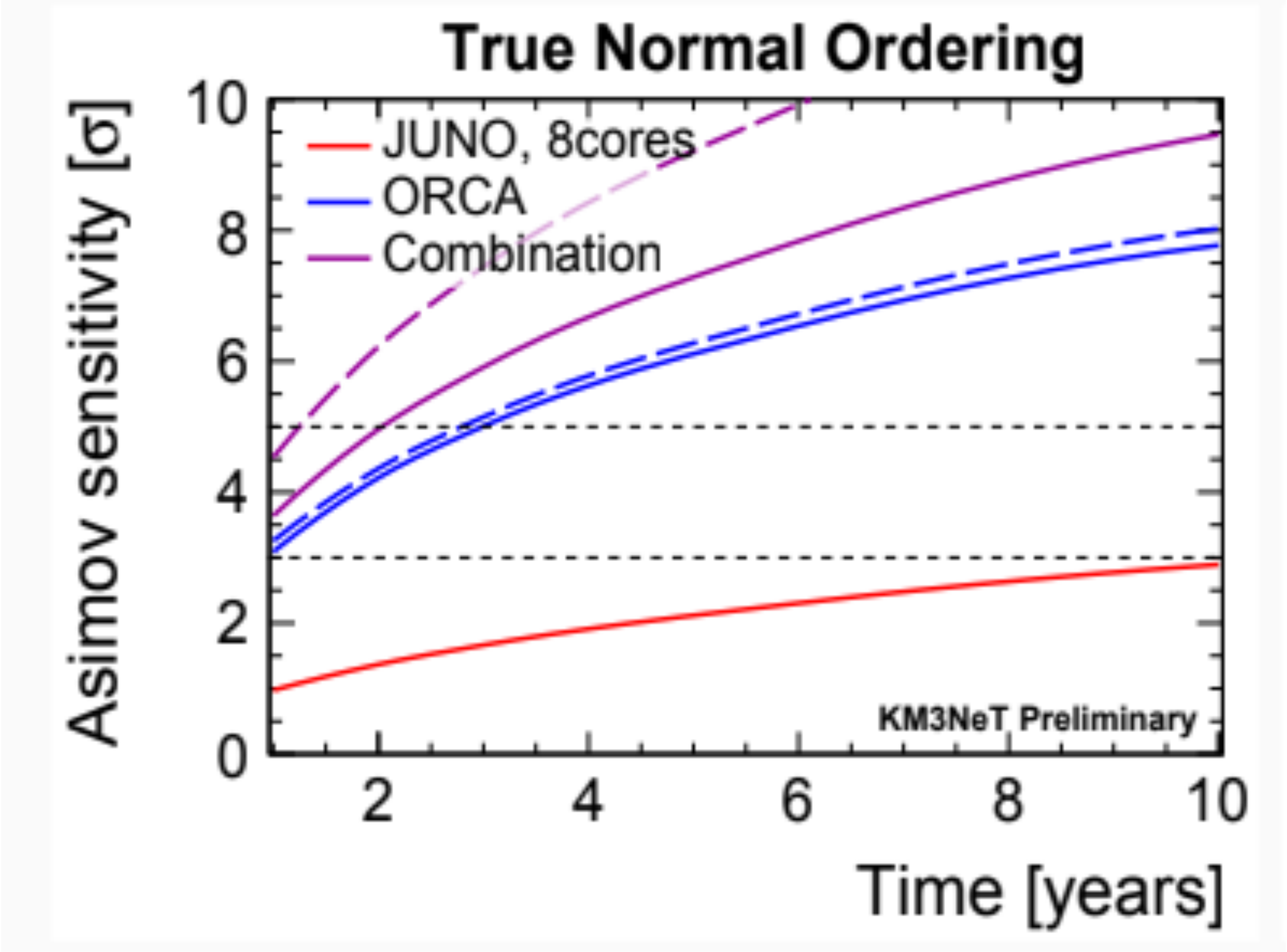


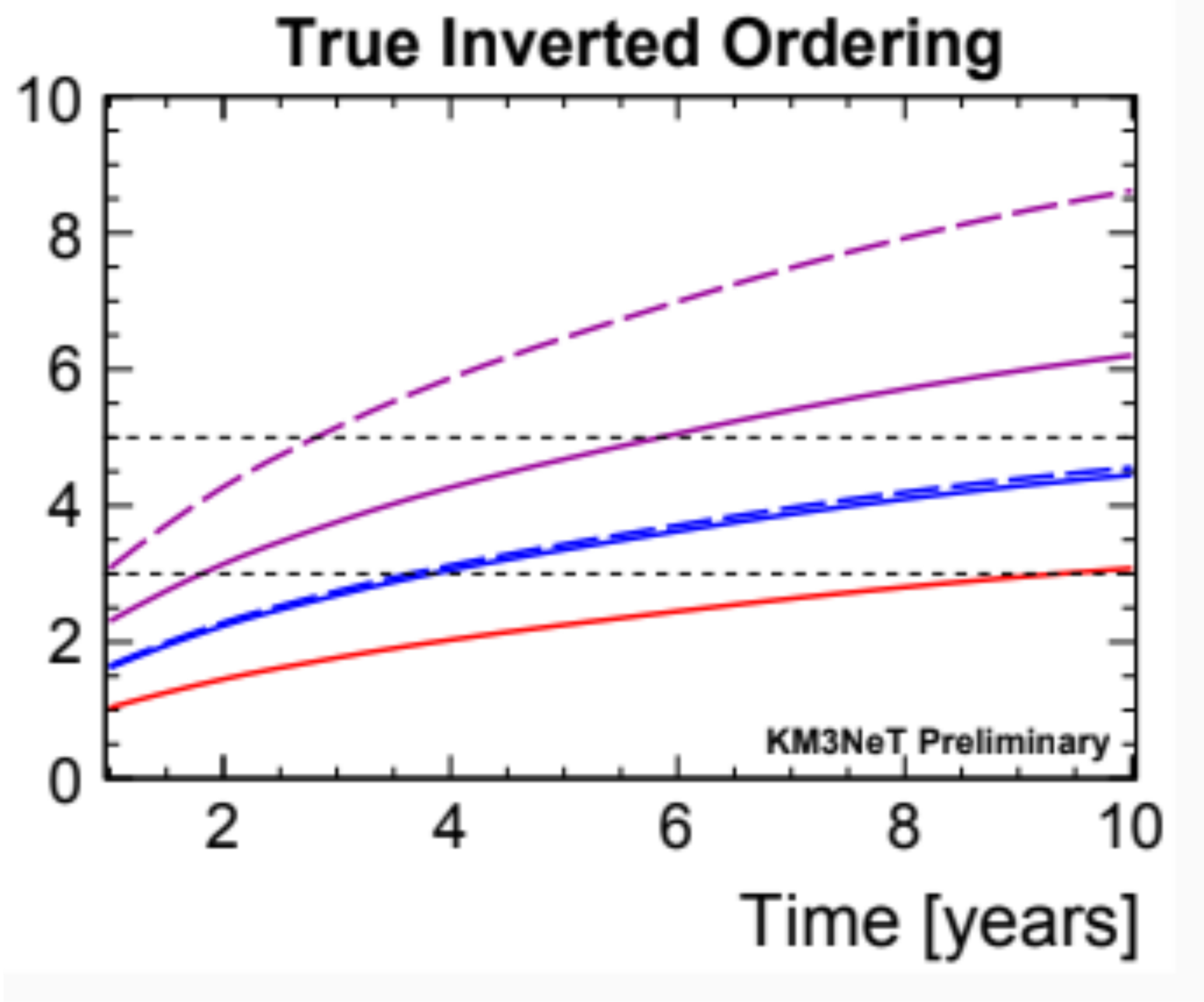


Neutrino mass ordering

KM3NeT/ORCA + JUNO

Huge increase of sensitivity to NMO determination with combined ORCA+JUNO analysis!





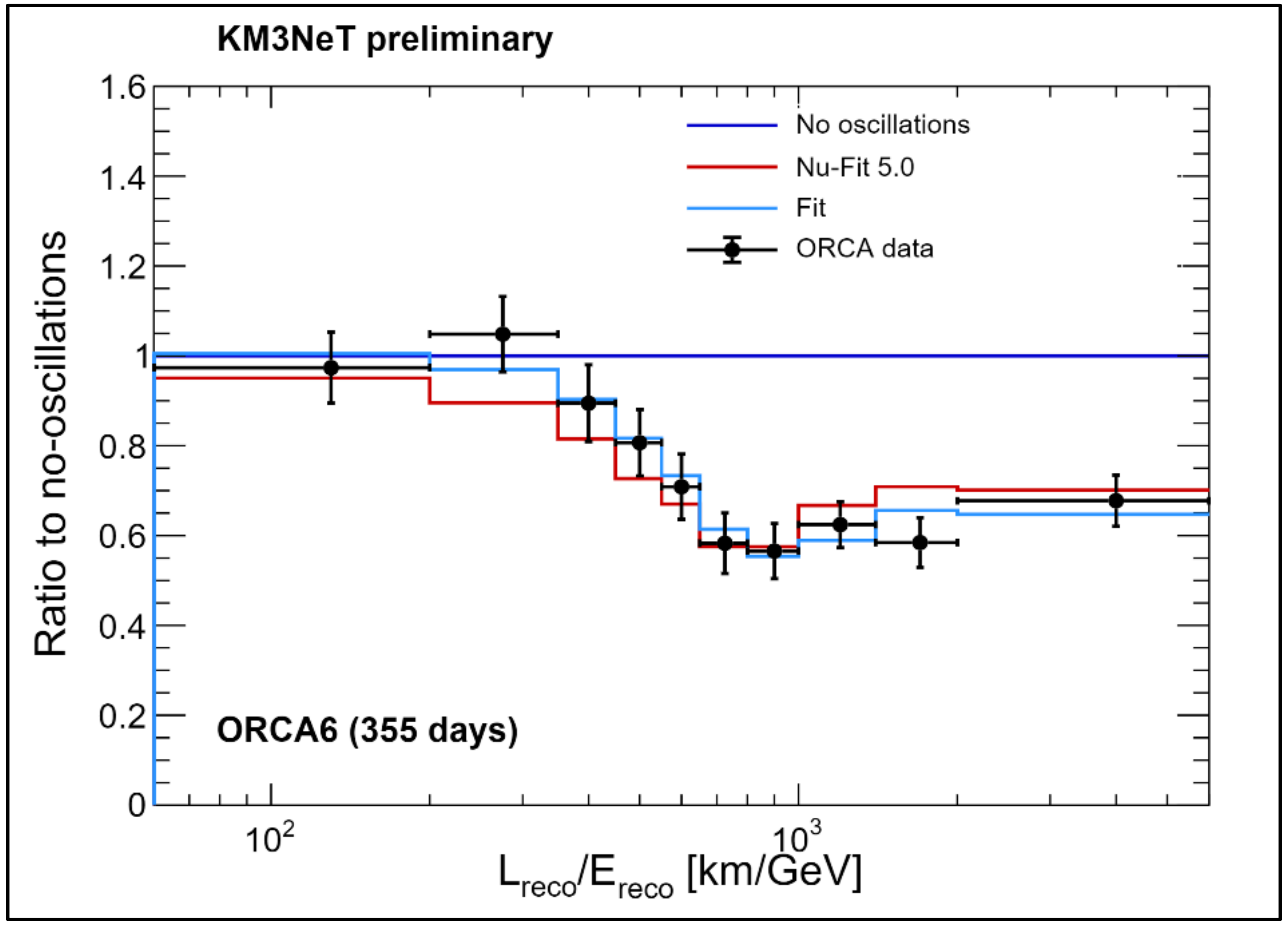
Dashed: Optimistic, Solid: Conservative

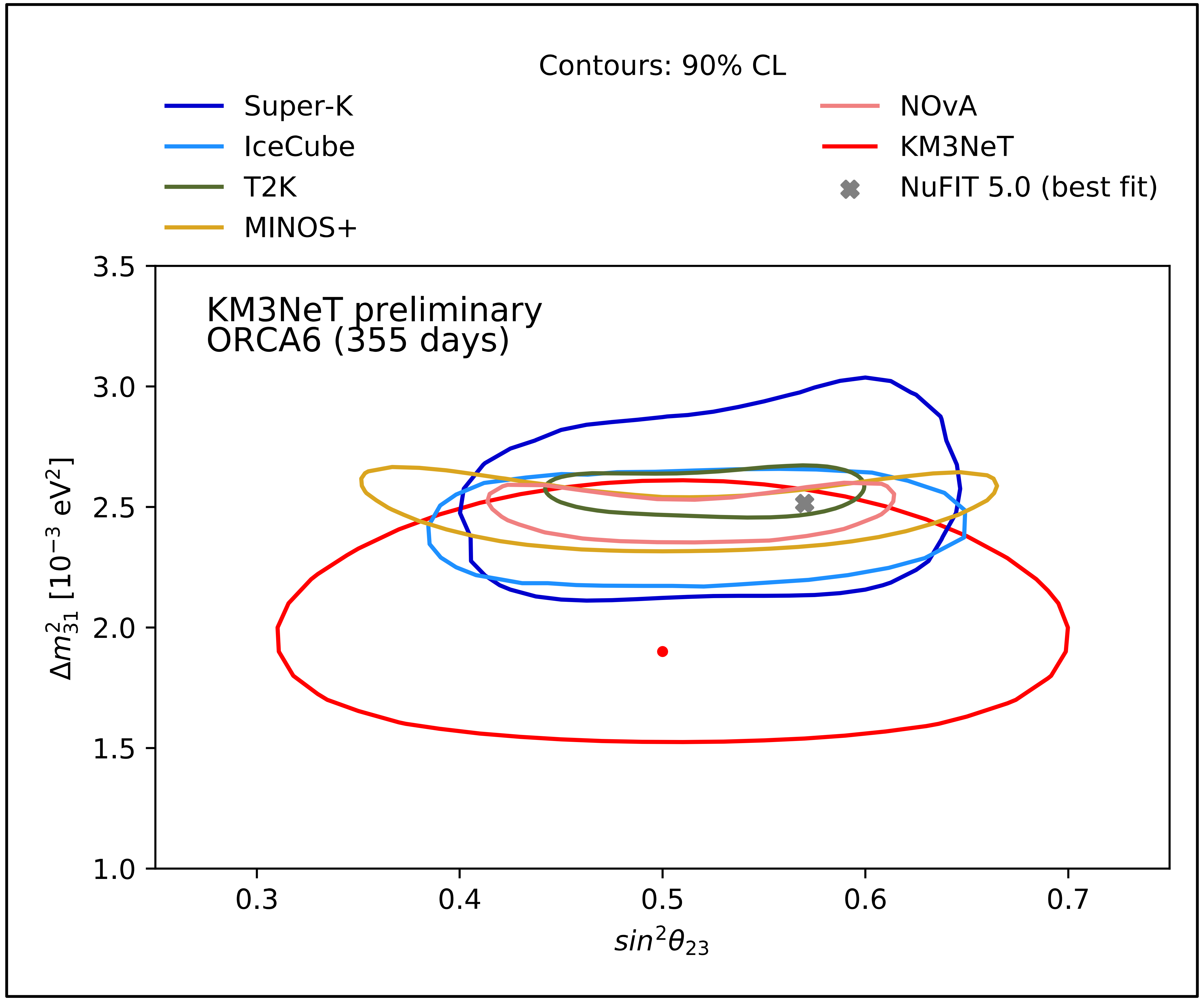
Phys. Rev. D, 101:032006, Feb 2020.

Neutrino Oscillations

KM3NeT/ORCA-6 DUs

1 year of data with ORCA-6 DUs

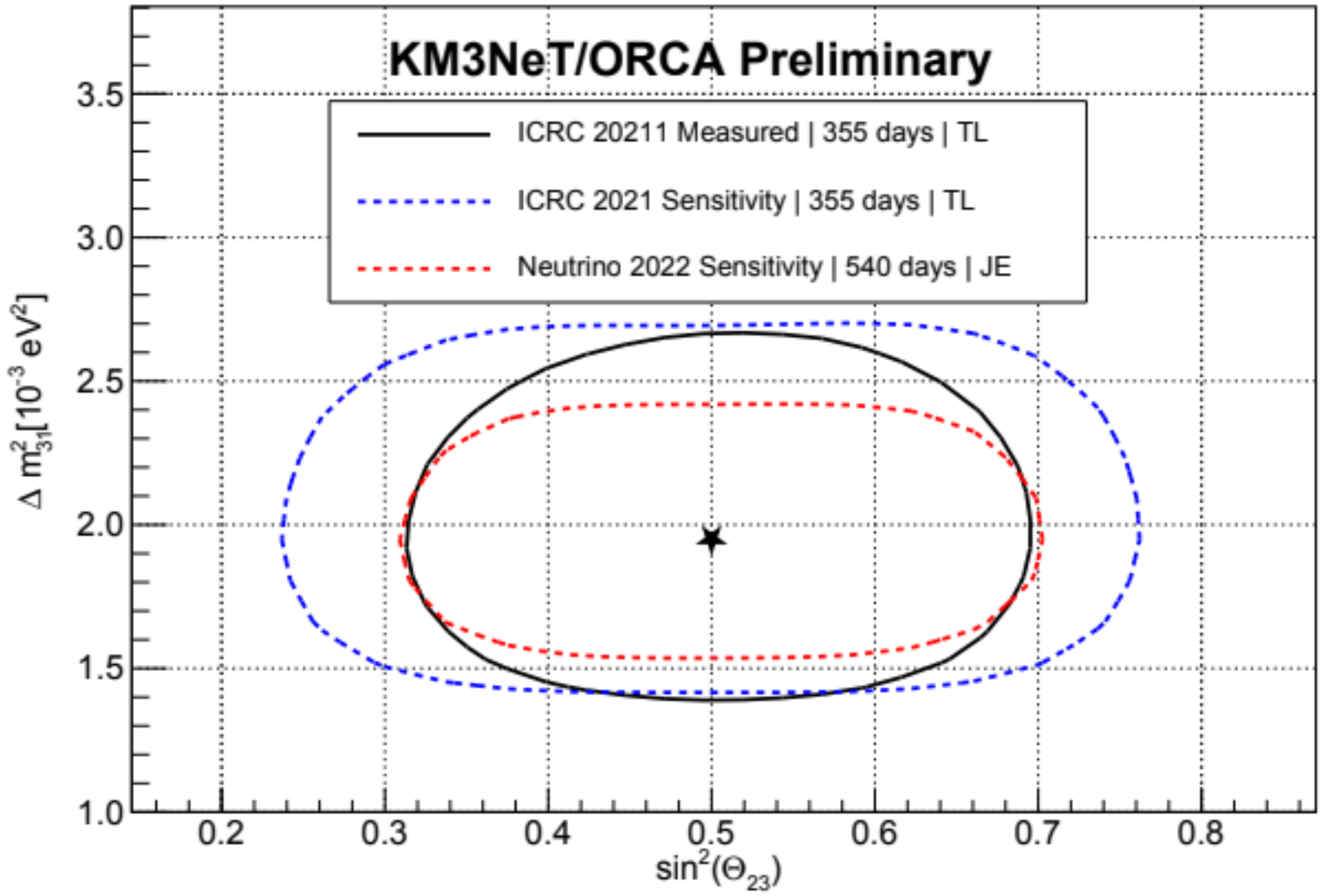




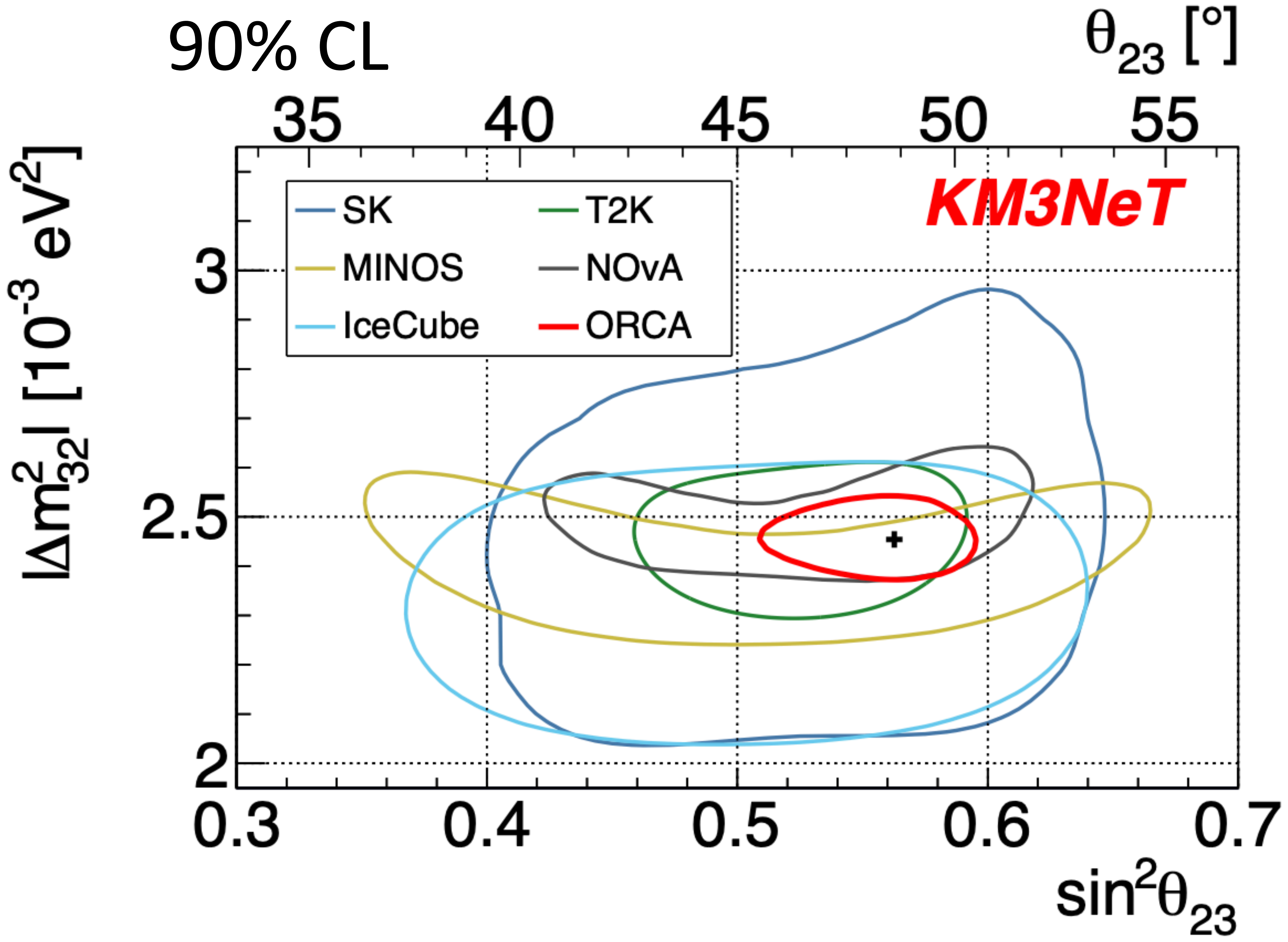
Neutrino Oscillations

ORCA-6 DUs vs FULL-ORCA

ORCA-6 DUs, 355 days

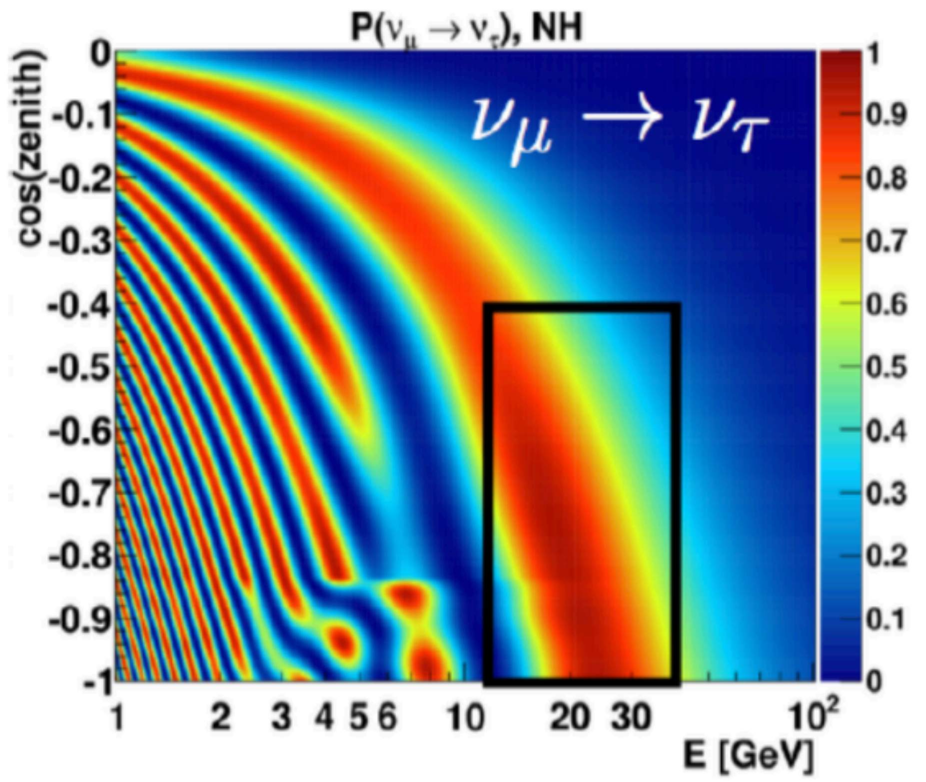


FULL-ORCA, 3 years of assumed data taking

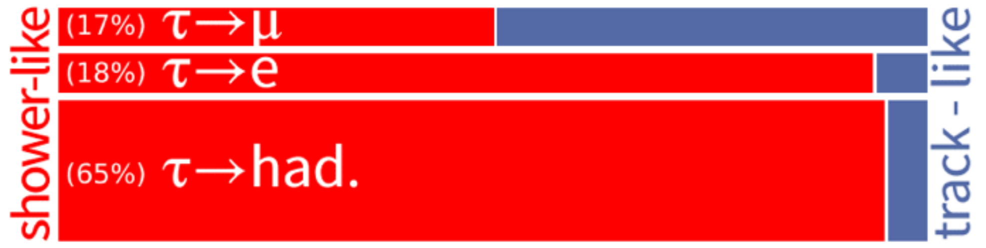


- Soon:
  - More data 355 -> 540 days
  - Better selection & particle identification
  - Sample increased by a factor 5
  - Unblind in next months

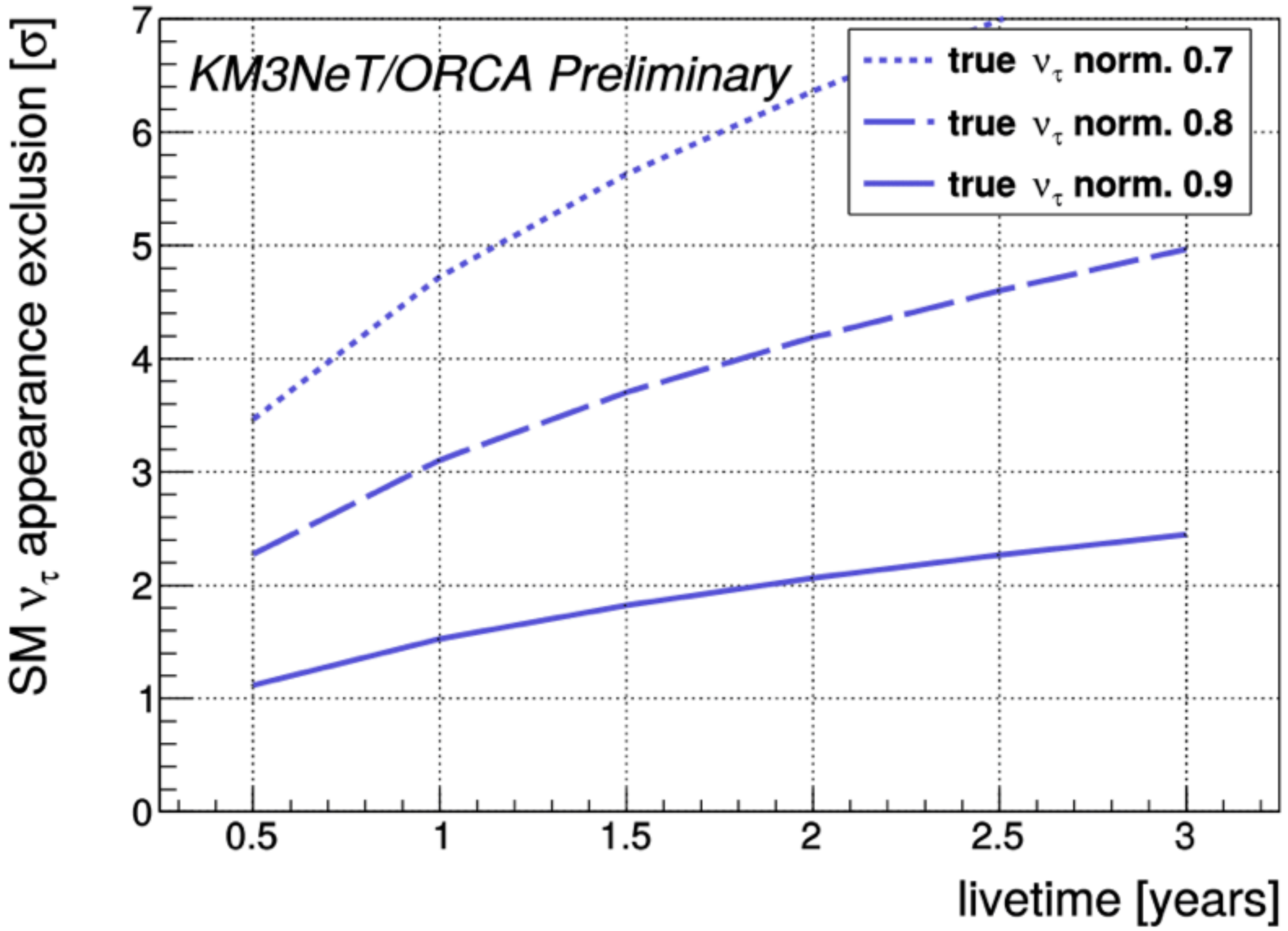
Tau neutrino searches

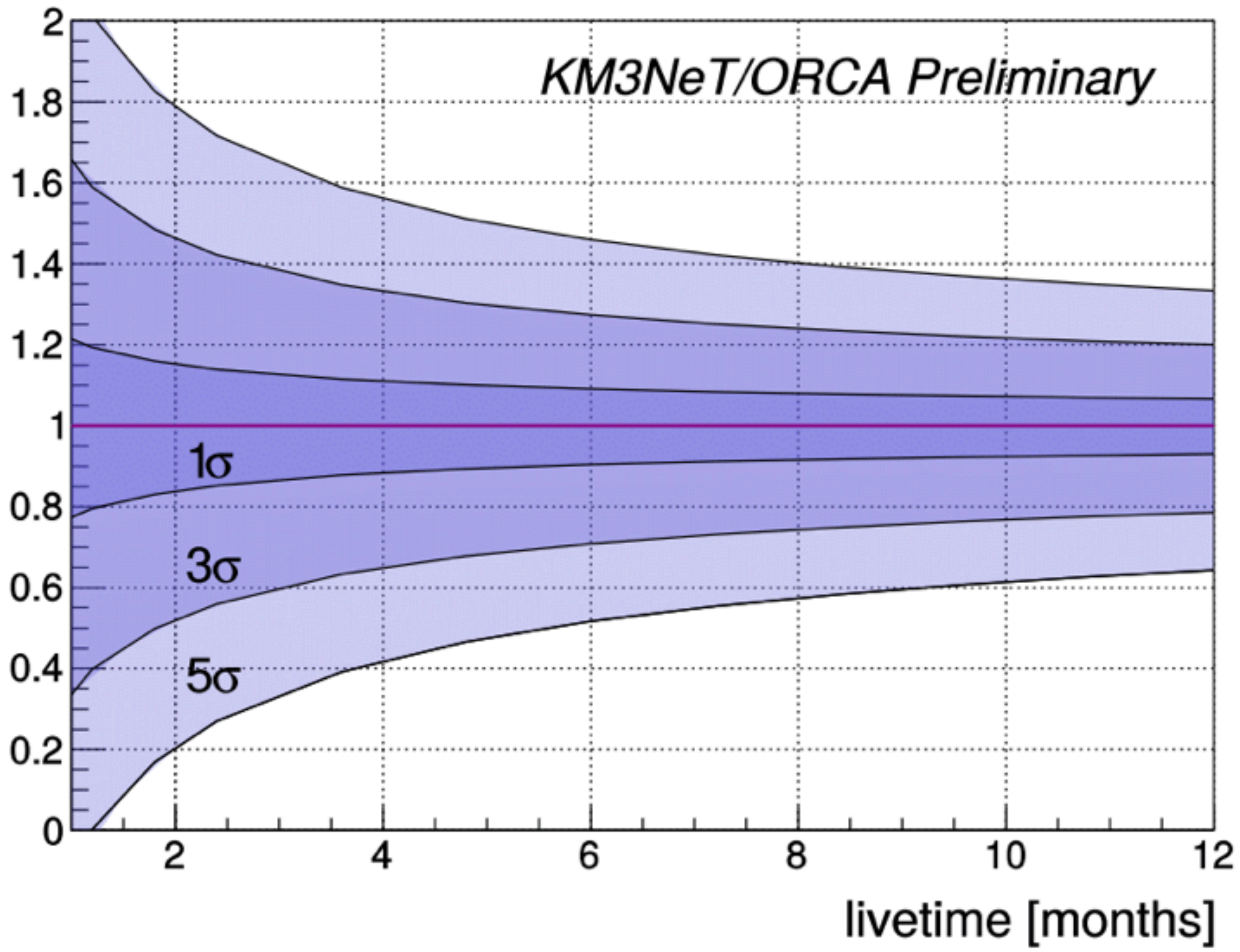


- ν_τ appearance tests unitarity of 3ν mixing matrix and BSM theories.
- 20% deviation from unitarity can be detected with 5σ in 5 years.
- ~3000 ν_τ^{CC} events/year with full ORCA.
- ν_τ events predominantly shower-like.



- Confirm exclusion of non-appearance (=0) already with 2 months of data





Sterile Neutrino Parameters

- In the standard 3 neutrino scenario there are 6 free parameters testable by oscillation experiments.

- Adding one sterile neutrino introduces **6 more free parameters**: Δm^2, 3 mixing angles ($\theta_{14},\theta_{24},\theta_{34}$) and 2 more CP phases ($\delta_{14}$, δ_{24}).

PMNS Parameters

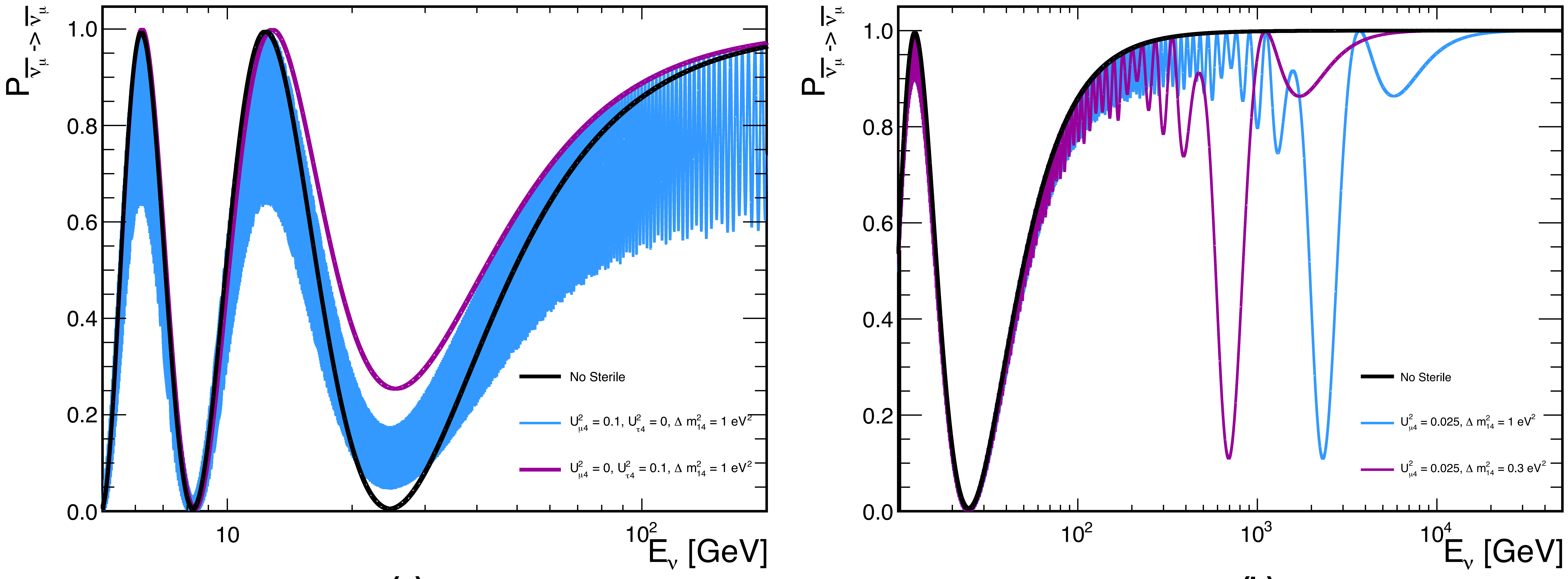
A 3x3 unitary matrix as the PMNS has

$$\begin{cases} \dfrac{N(N-1)}{2} = 3 & \quad \text{mixing angles}\,, \\ \dfrac{(N-1)(N-2)}{2} = 1 & \quad \text{physical phase}\,. \end{cases}$$

With 3 mixing angles (θ_{12}, θ_{13}, θ_{23}), 2 mass square differences (Δm^2_{12}, Δm^2_{13}) and 1 CP phase δ_{CP} there is a total of **6** parameters testable with oscillation experiments.

Sterile Neutrino Parameters

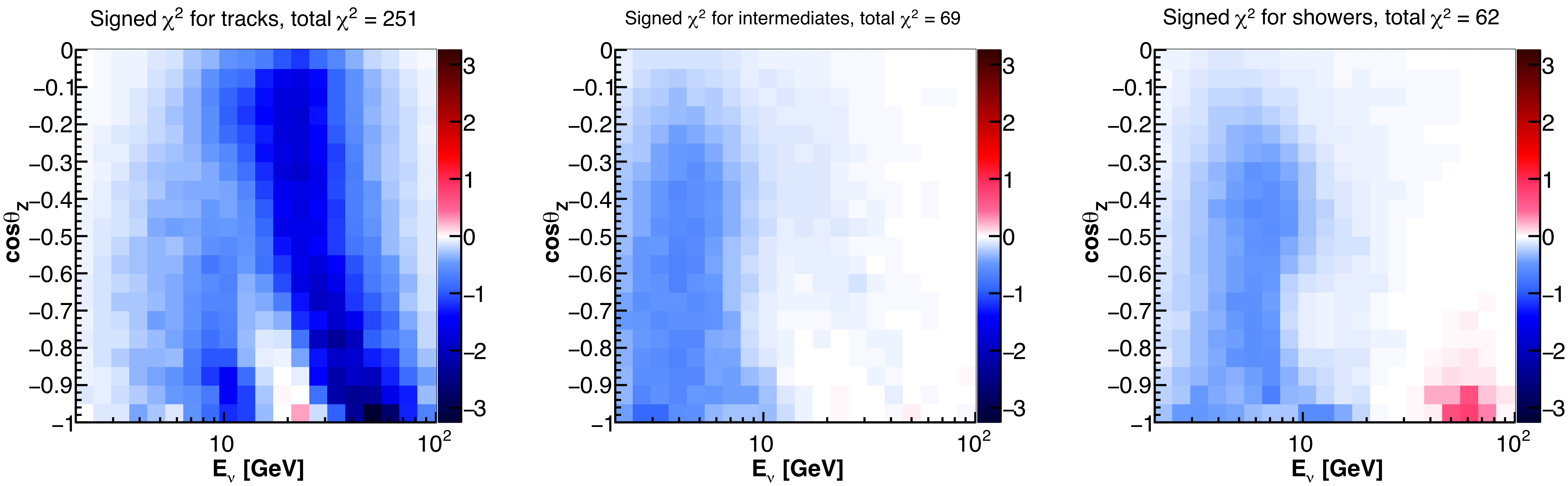
- In the ORCA energy range (< 100 GeV) and with a baseline of the order of the Earth's diameter we are sensitive to the 3 sterile-active mixing angles and to low values of Δm^2_{14} .
- With the same baseline but in the energy range ≳ 1 TeV (ARCA) we are also sensitive to high values of Δm^2_{14} .



Sterile Neutrino: Impact on event distributions

Example plots for KM3NeT/ORCA

$$\text{signed-}\chi^2 = \frac{(N_{\text{Sterile}} - N_{\text{Standard}})|N_{\text{Sterile}} - N_{\text{Standard}}|}{N_{\text{Sterile}}}$$



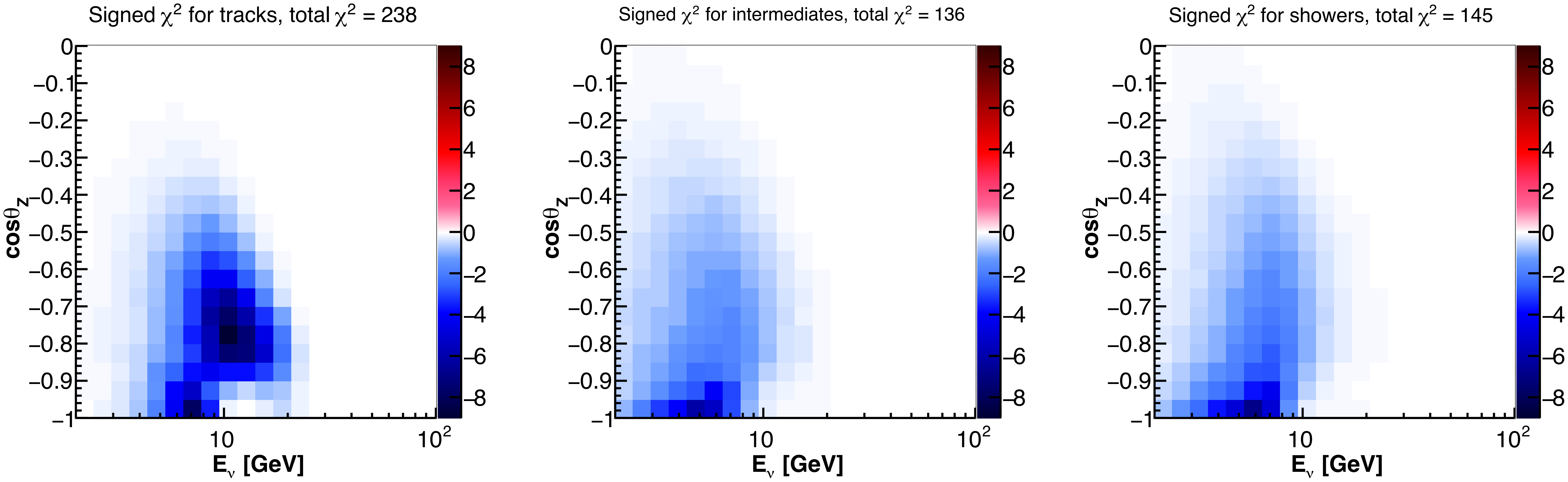
active-sterile parameters: $\sin^2\theta_{24} = 0.03,\ \sin^2\theta_{34} = 0.05,\ \Delta m^2_{41} = 1\,\mathrm{eV}^2$

Sterile Neutrino: Impact on event distributions

Example plots for KM3NeT/ORCA

$$\text{signed-}\chi^2 = \frac{(N_{\text{Sterile}} - N_{\text{Standard}})|N_{\text{Sterile}} - N_{\text{Standard}}|}{N_{\text{Sterile}}}$$

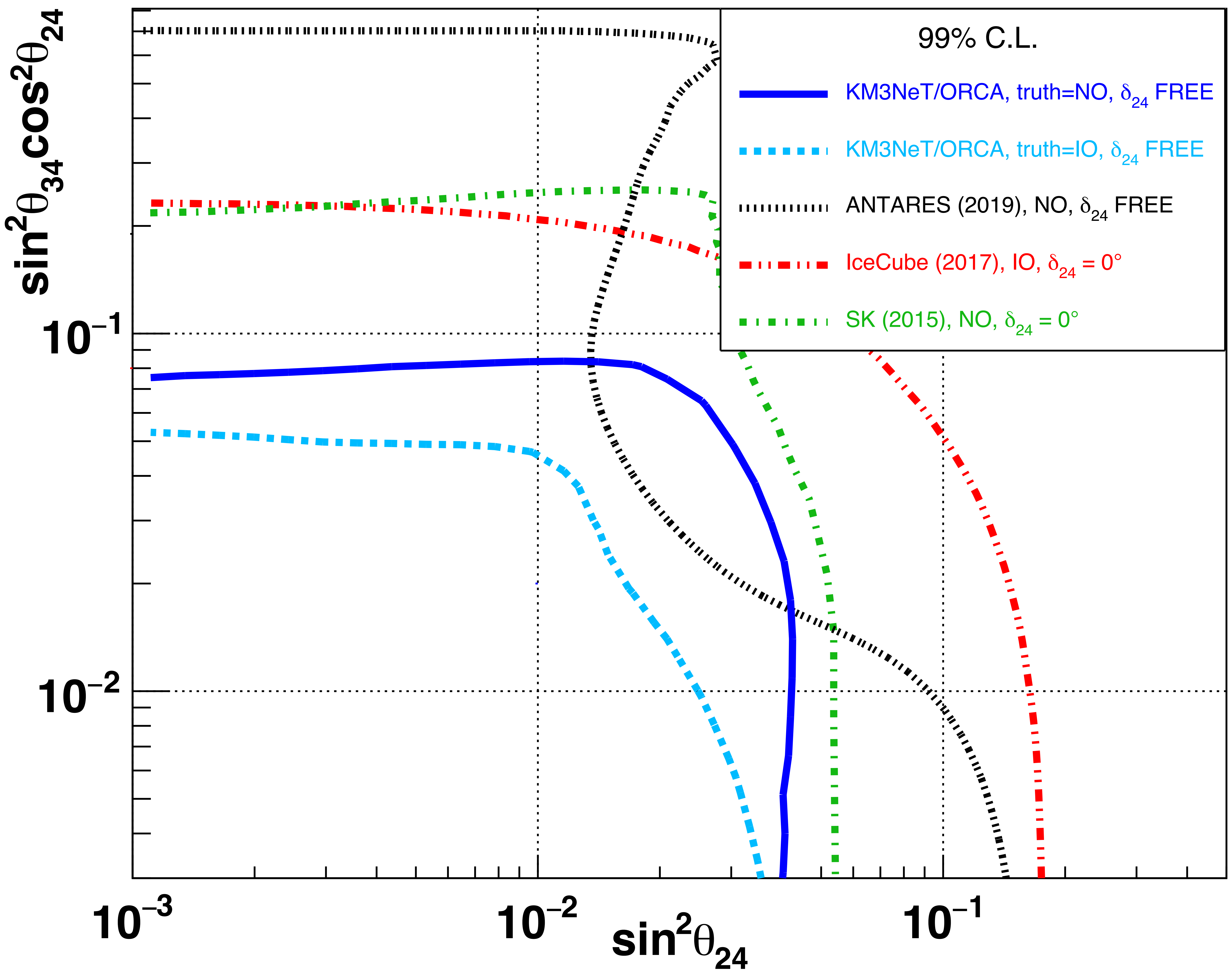
Majority of the impact below ANTARES energy threshold (~20 GeV)!



active-sterile parameters: $\sin^2\theta_{14} = \sin^2\theta_{24} = \sin^2\theta_{34} = 0.01,\ \Delta m^2_{41} = 10^{-4}\,\text{eV}^2$

KM3NeT/ORCA: Sensitivity to θ_{24}-θ_{34} in the large Δm_{41}^2 limit

3 years of data taking

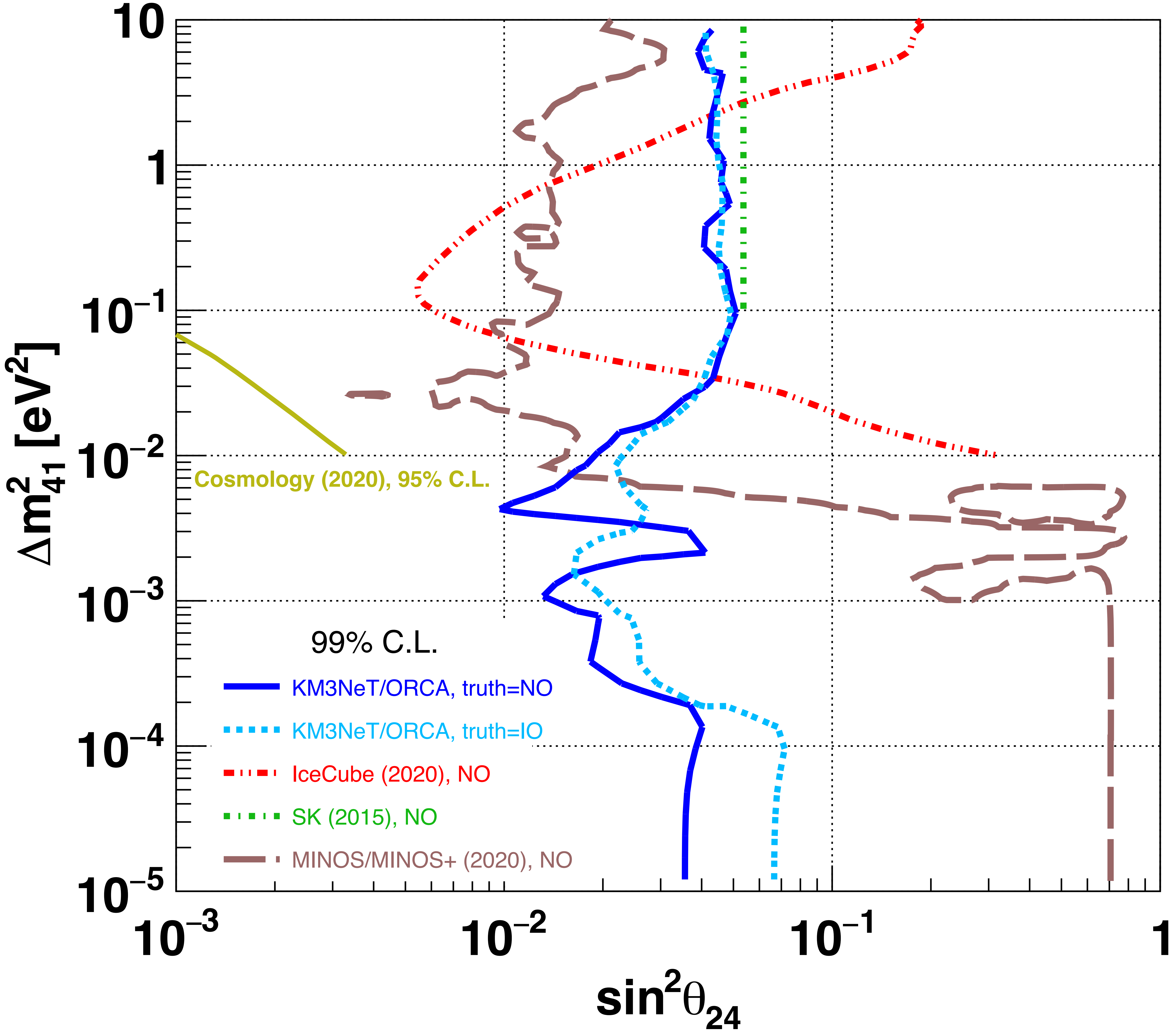


LETTING δ_{24} FREE WORSENS THE SENSITIVITY.

δ_{24} and NMO degeneracy allows for direct comparison between NO & δ_{24} FREE with IO & $\delta_{24} = 0$

KM3NeT/ORCA: Sensitivity to θ_{24} for different $\Delta m_{41}{}^2$ values

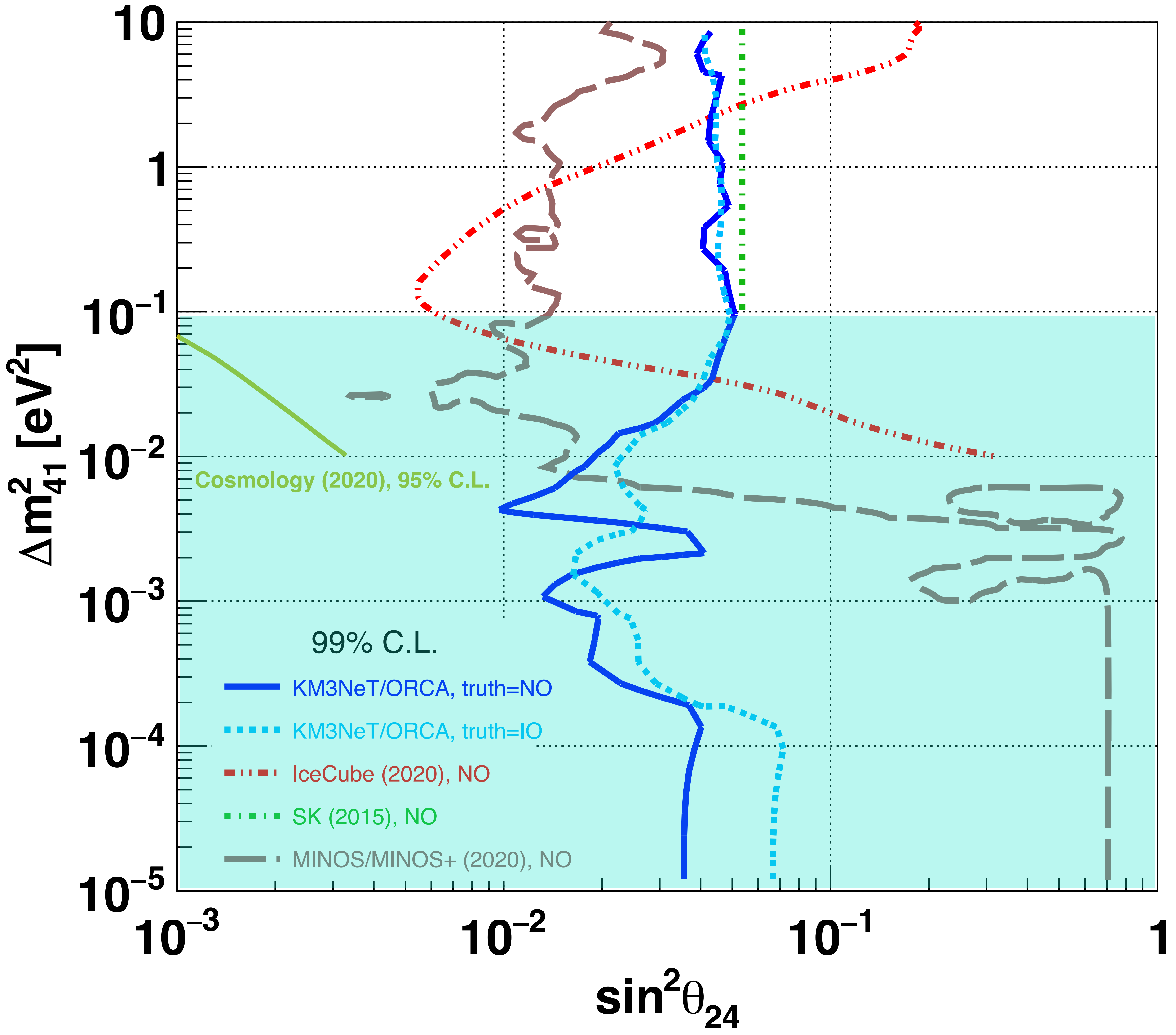
3 years of data taking



θ_{14}, θ_{34}, δ_{24}, δ_{34} FREE IN THE ANALYSIS.

KM3NeT/ORCA: Sensitivity to θ_{24} for different Δm_{41}^2 values

3 years of data taking

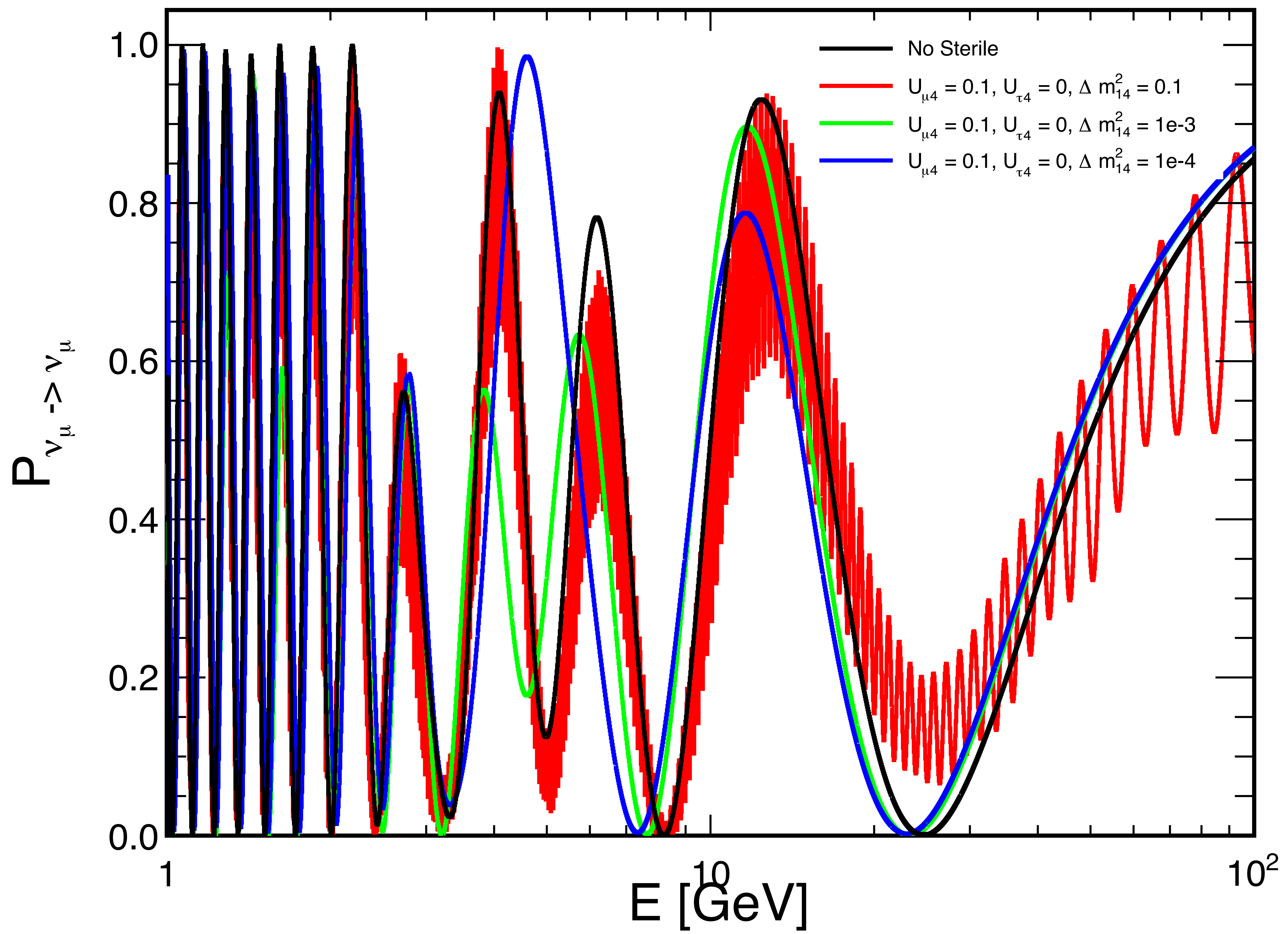


Low frequency (LF) region

KM3NeT/ORCA: LF region

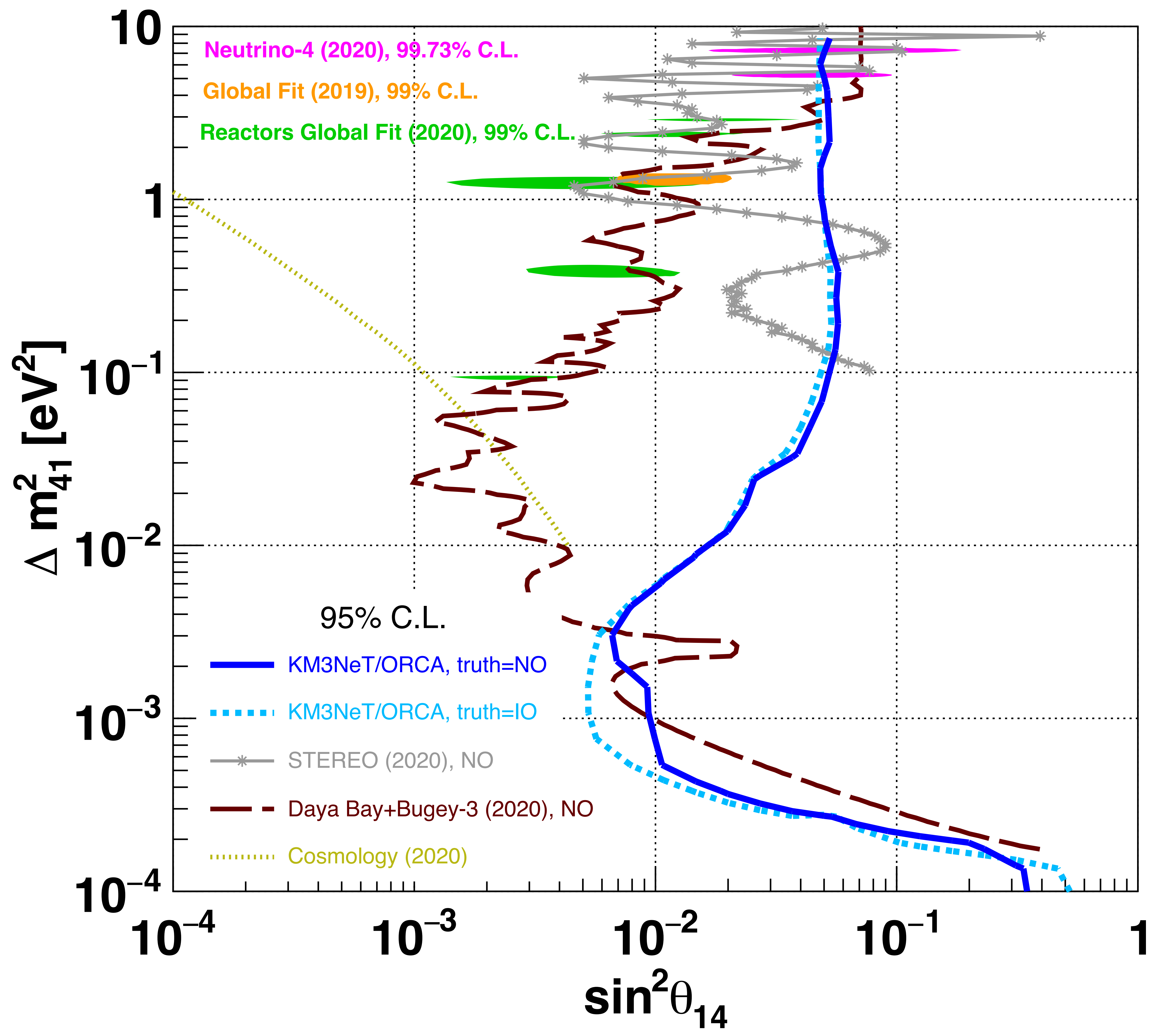
With ORCA we have 2 advantages with respect to MINOS:

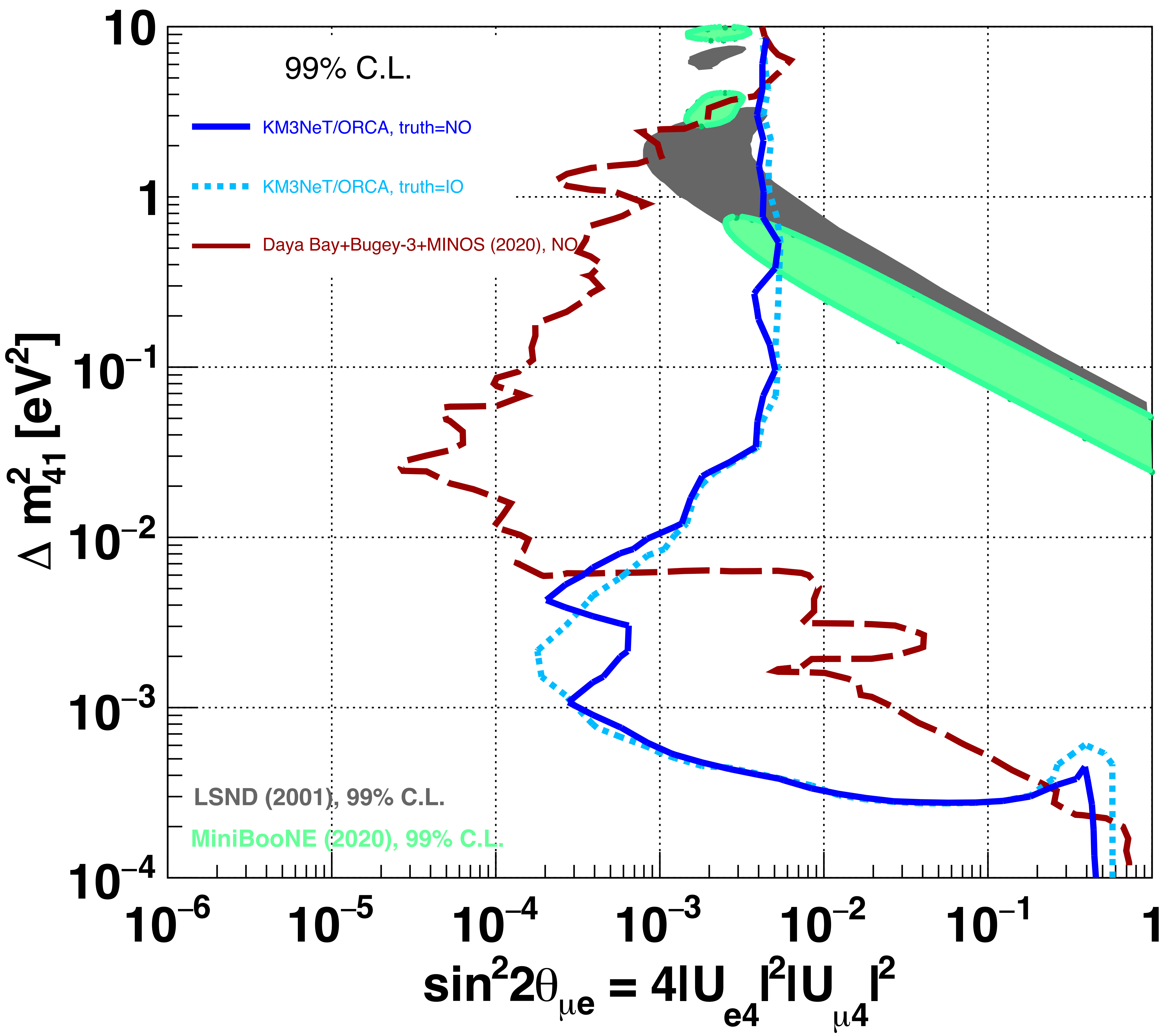
- **longer baseline.**
- Earth's **matter effects can not be neglected.**



KM3NeT/ORCA: Sensitivity to θ_{14} and $|U_{\mu e}|^2$ for different Δm_{41}^2 values

3 years of data taking



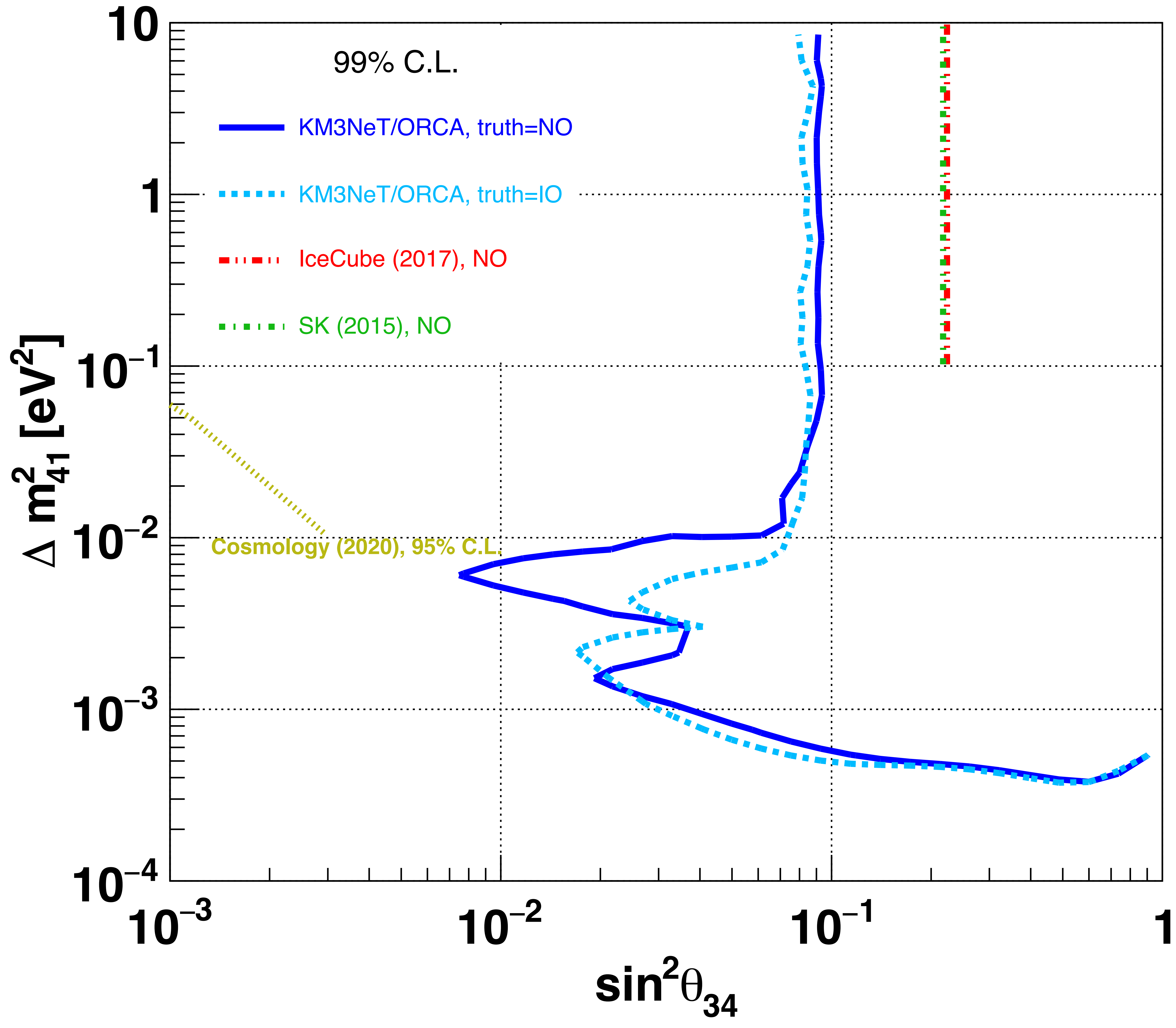


$\theta_{24}, \theta_{34}, \delta_{24}, \delta_{34}$ **FREE**

$\theta_{34}, \delta_{24}, \delta_{34}$ **FREE**

KM3NeT/ORCA: Sensitivity to θ_{34} for different Δm_{41}^2 values

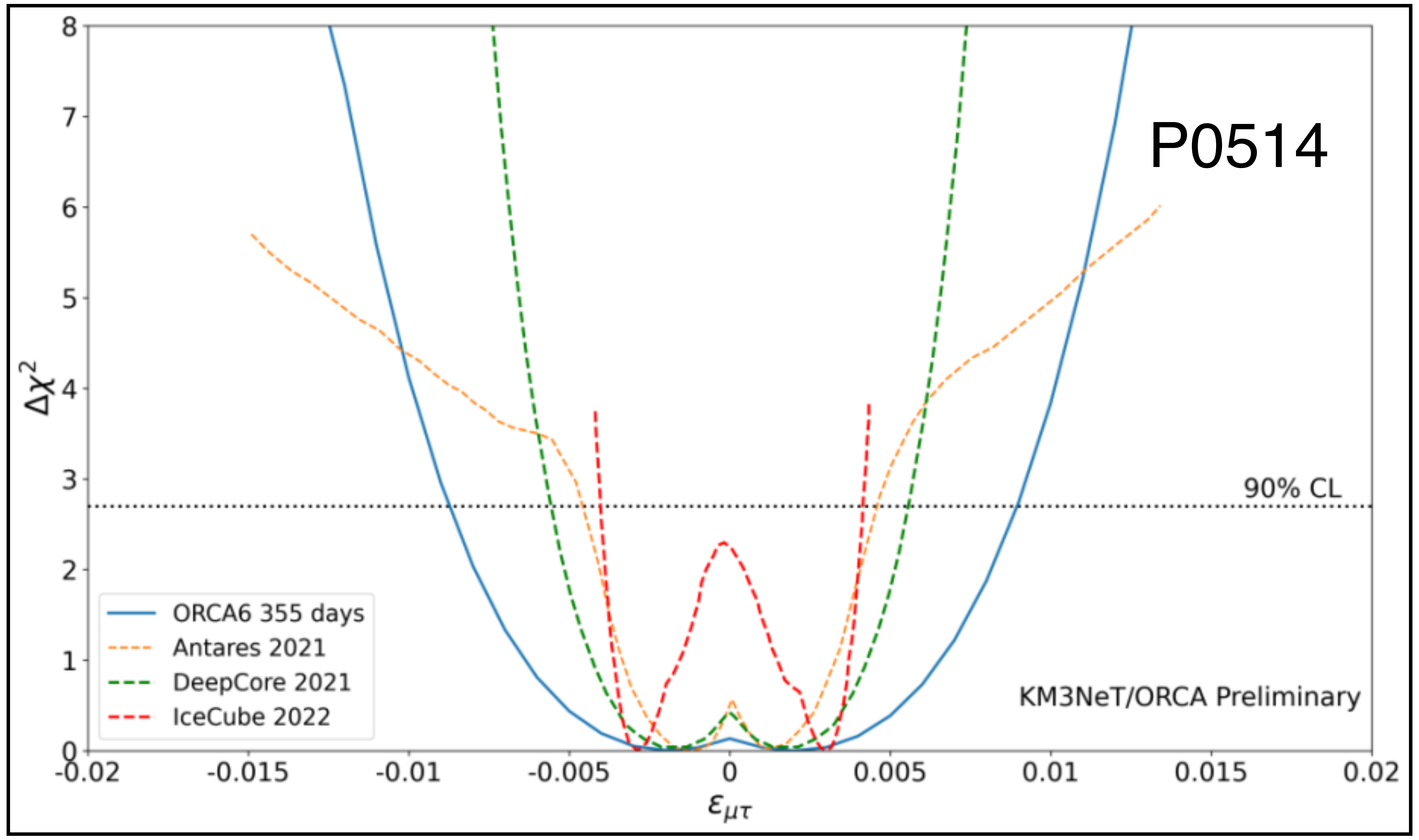
3 years of data taking

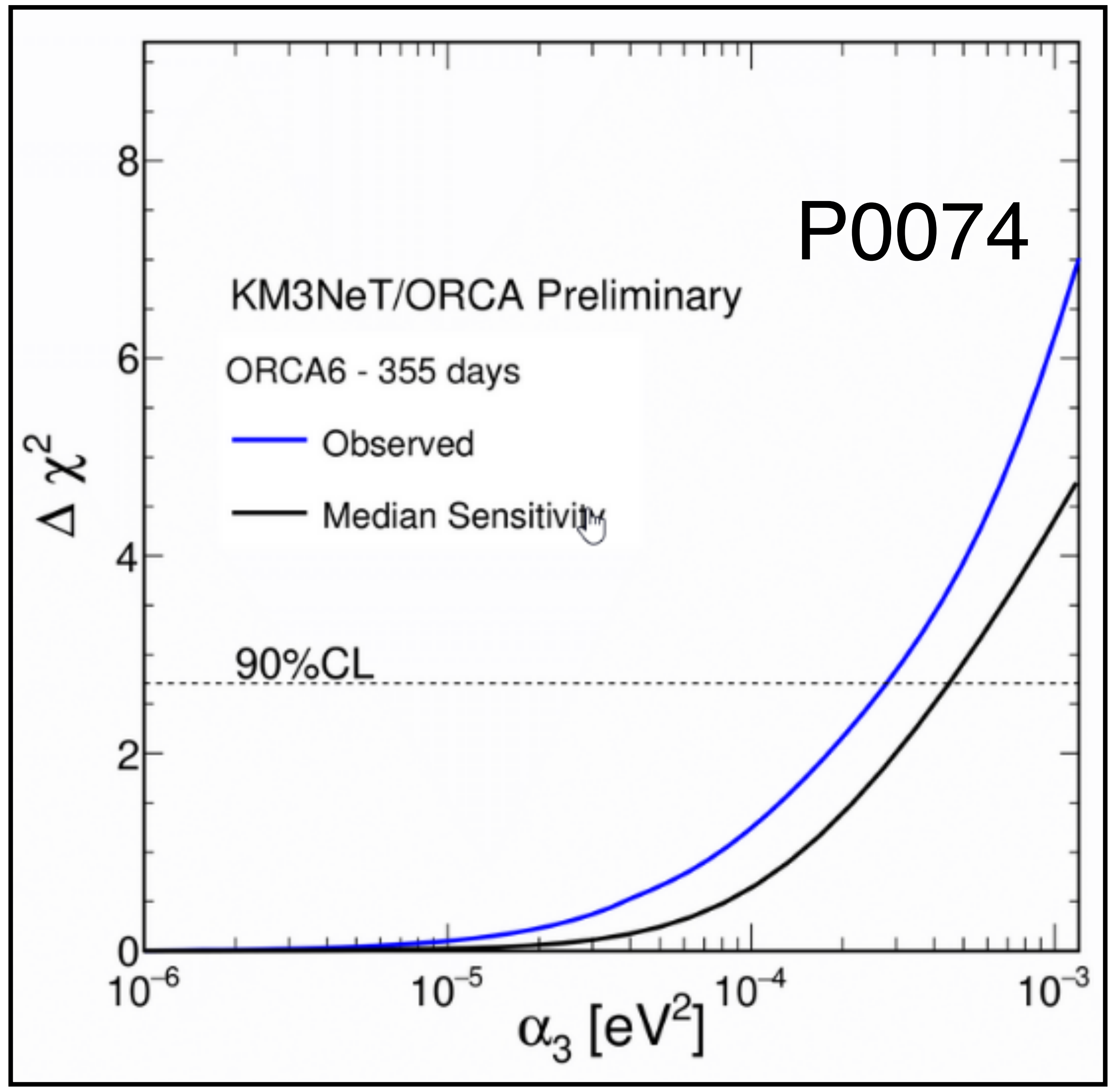


θ_{14}, θ_{24}, δ_{24}, δ_{34} FREE

Non standard interactions & Neutrino decay

ORCA-6, 355 days-data sample





Experiment	L.L.(90%CL) (ps/eV)
ORCA6	2.4
ORCA115 (10y)	180
T2K, NOvA	1.5
T2K, MINOS	2.8
K2K, MINOS, SK I+II	290

Constraining non-standard interactions

- 1 year ORCA6 already starting to become competitive with similar experiments

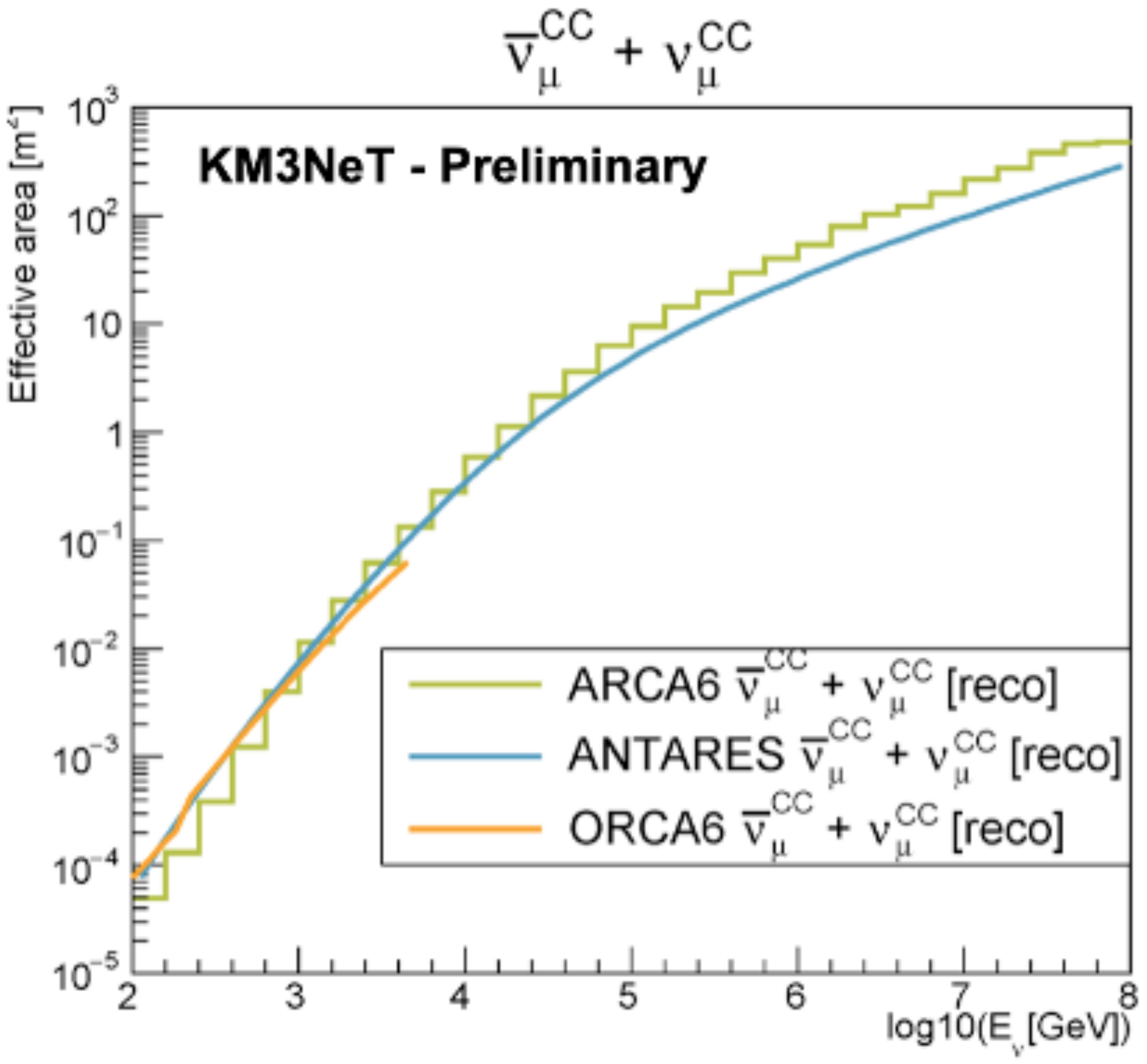
Neutrino decay / livetime

- Proof of principle
- Full ORCA detector will be world-leading

Neutrino astronomy: first results with KM3NeT data

Neutrino astronomy

ARCA+ORCA

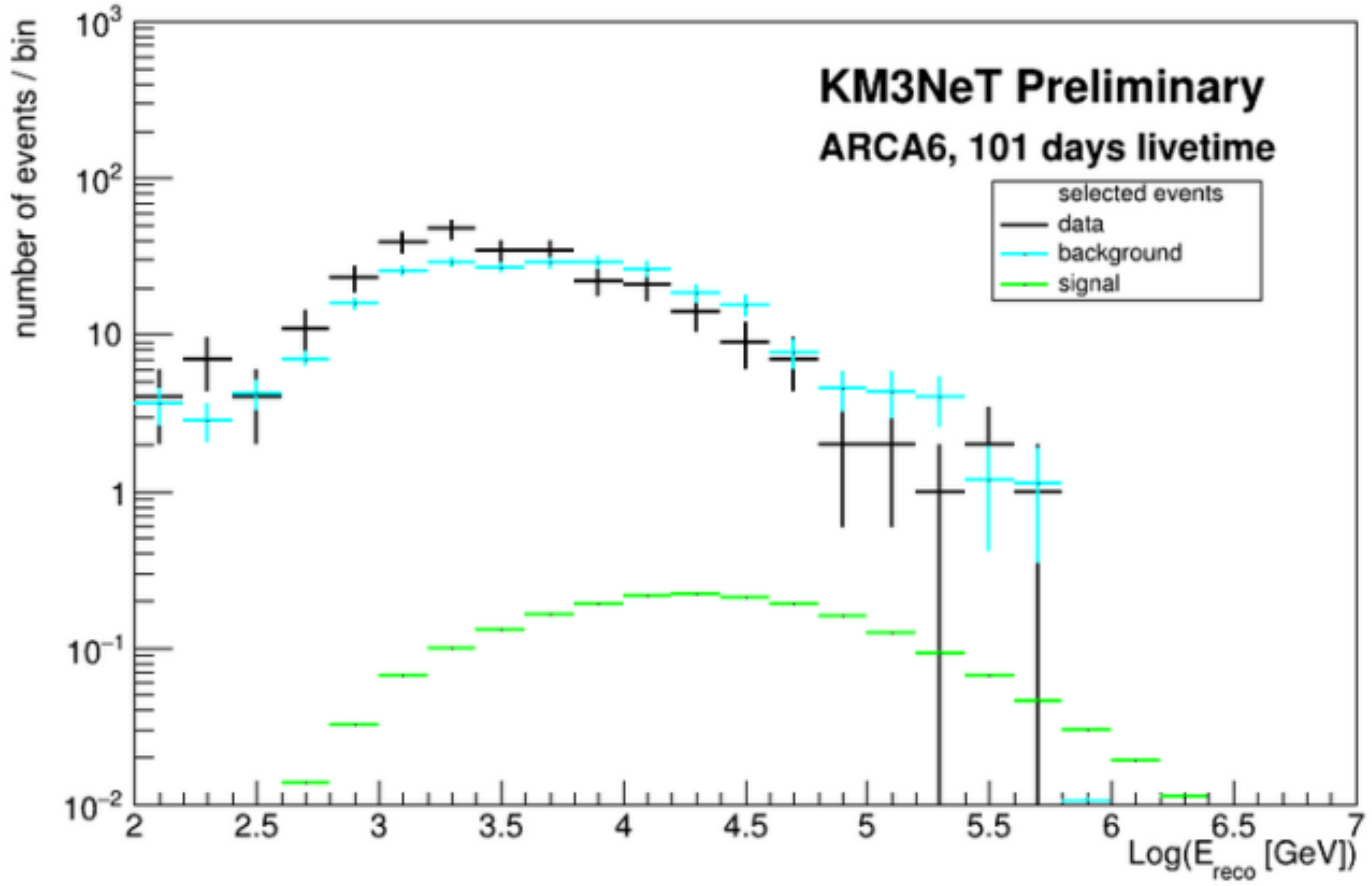


- KM3NeT today has the same acceptance as ANTARES.

- ANTARES has factor 40 more live time at the moment.

Neutrino astronomy

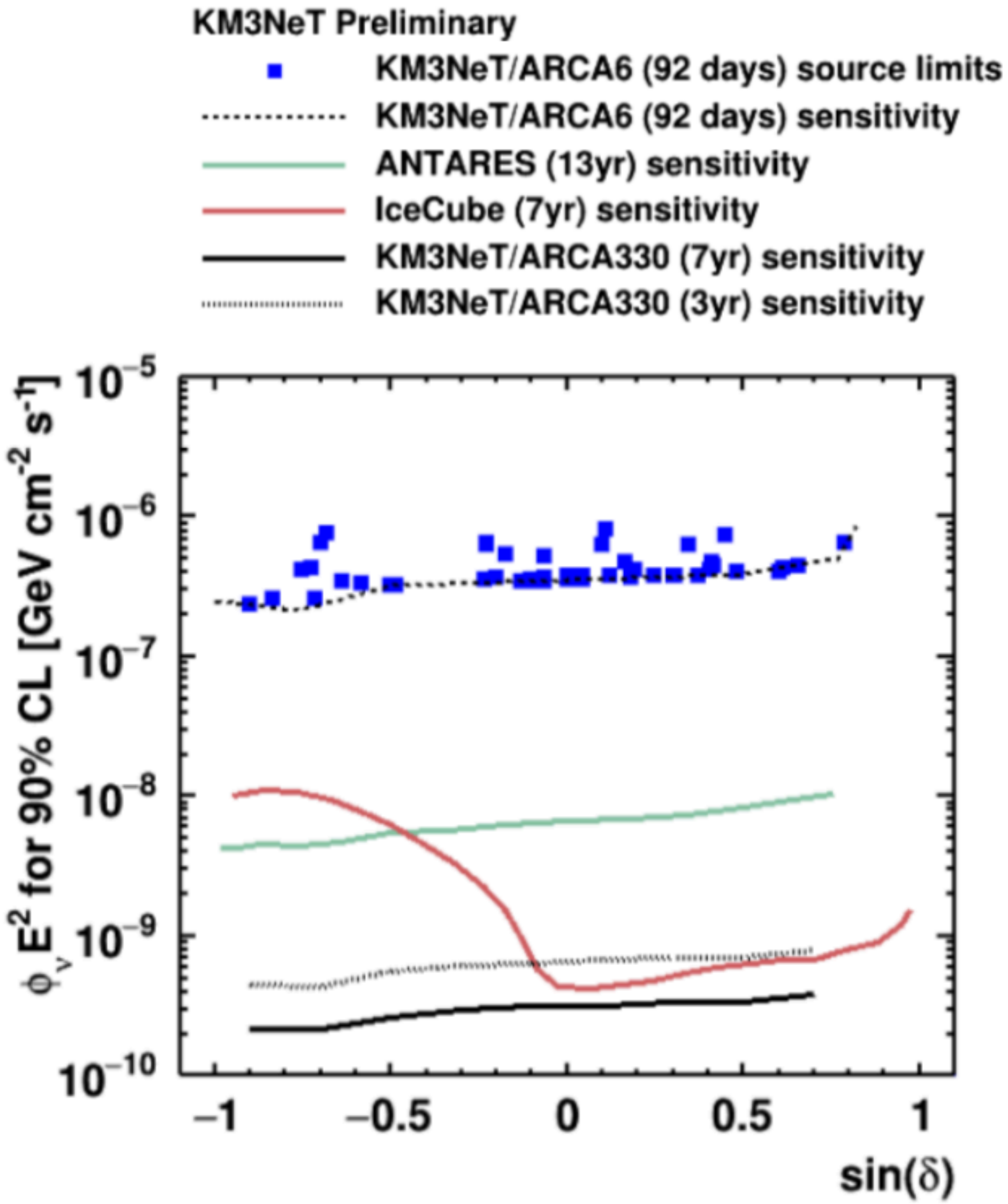
Cosmic neutrinos



For the diffuse cosmic neutrino flux of [2]: 1.44×10^{-18} $(E/100TeV)^{-2.28}$ [GeV^{-1} cm^{-2} s^{-1} sr^{-1}]		Number of events
$\Phi_{90\%CL}$ [GeV^{-1} cm^{-2} s^{-1} sr^{-1}]	$\Phi_{5\sigma}$ [GeV^{-1} cm^{-2} s^{-1} sr^{-1}]	$N_{atm.mu\&nu} = 68.4$
17.3×10^{-18}	51.4×10^{-18}	$N_{cosmic\ nu} = 1.3$

ARCA 6, 101 days

- Sample dominated by muon,
- No high-E excess due to neutrinos
- Results compatible with background

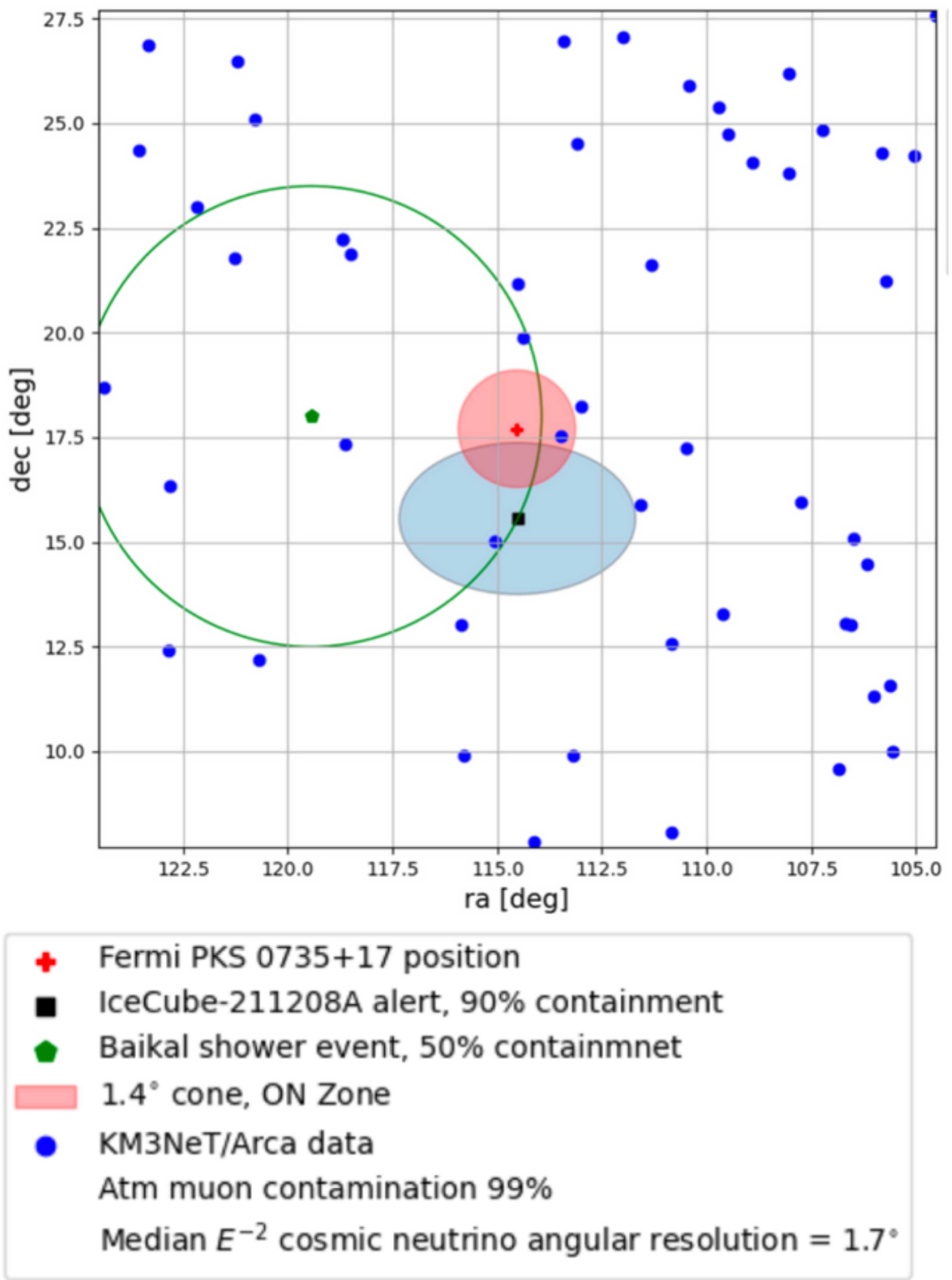


- Time integrated point source search May-Sept 2021, dynamic calibration
- Background dominated by muons
- Resolution ~1.3 degree for E^{-2}
- No significant excess observed
- Limits not yet competitive, as expected

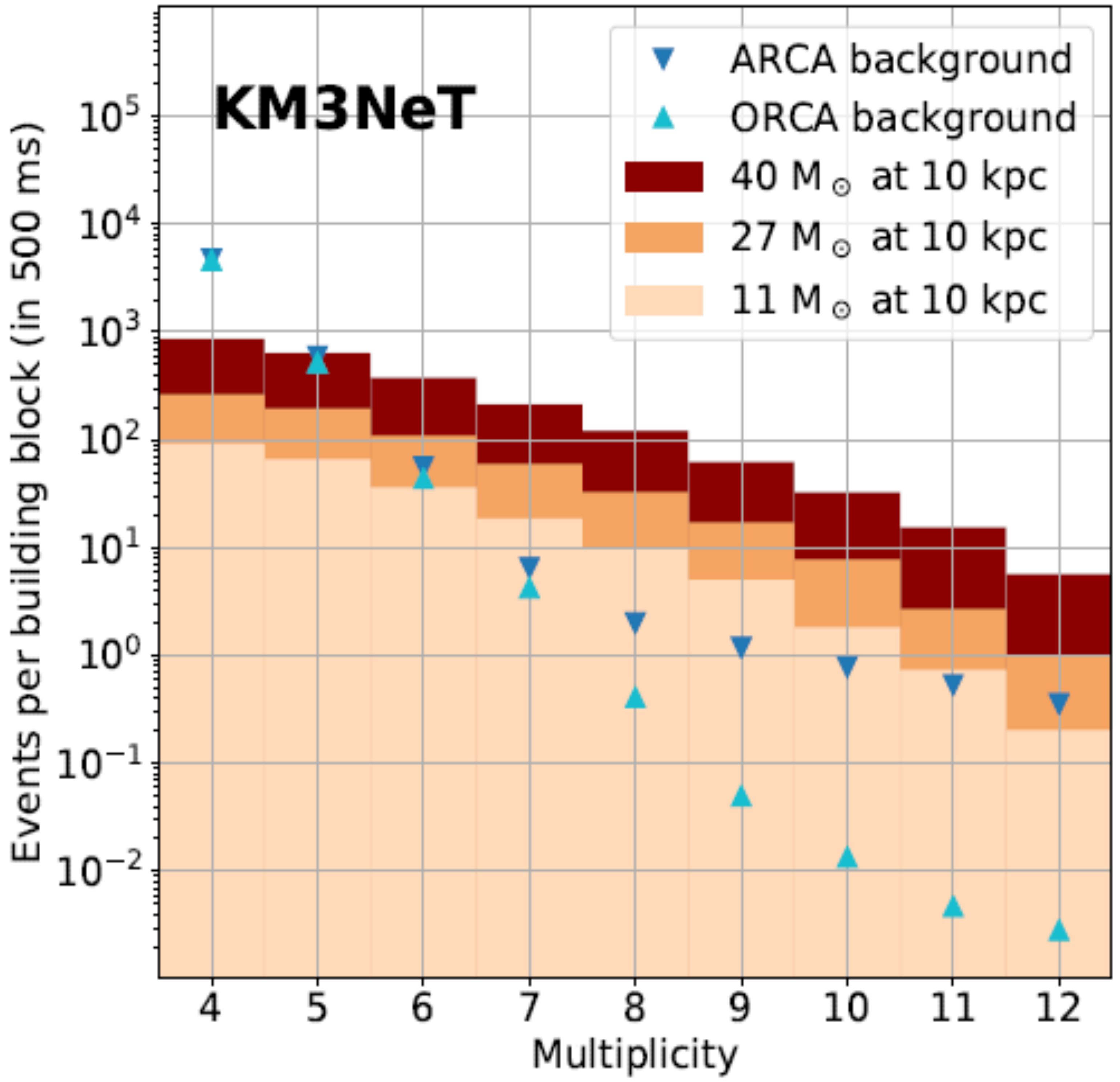
Time-dependent astronomy

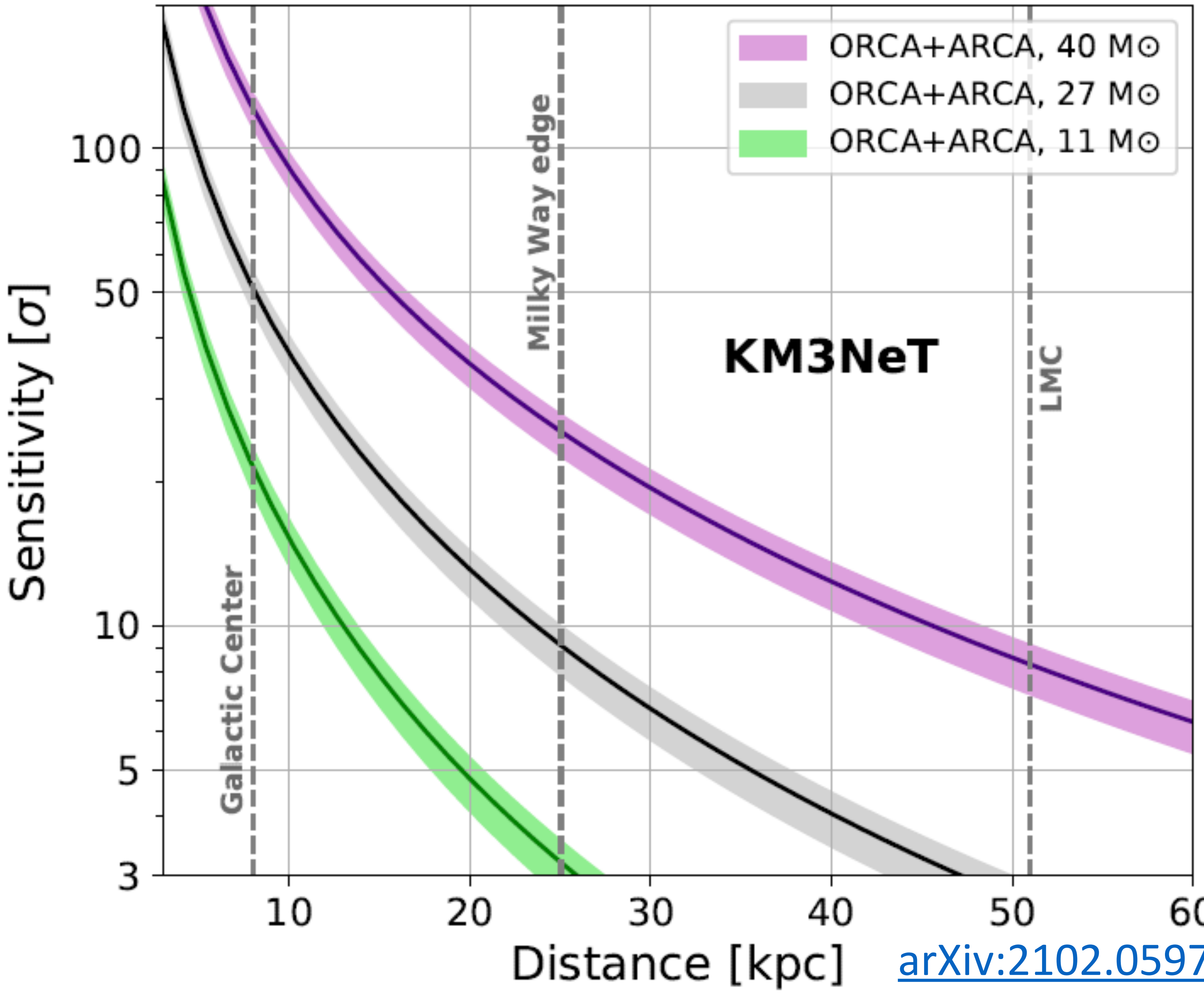
- Several recent IceCube alerts possibly associated with Blazars
- Follow up with both ORCA and ARCA, and ANTARES
- No discoveries

IC alert	Potential blazar
IC211208A	PKS 0735+17
IC220205B	PKS 1741-03
IC220225A	PKS 0215+15
IC220304A	TXS 0310+022

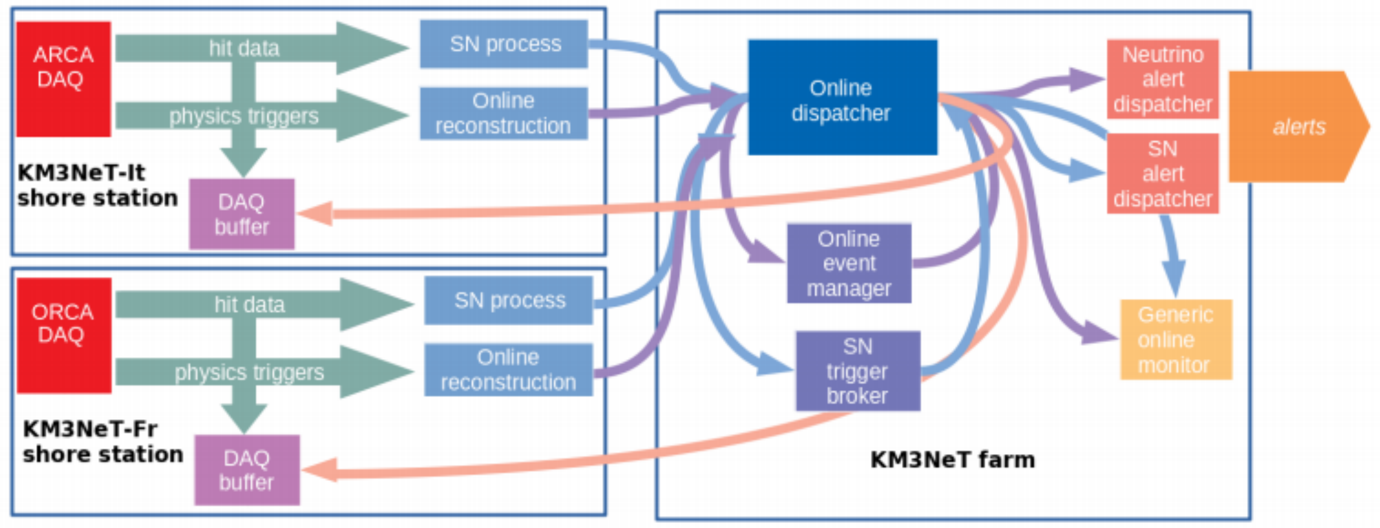


(MeV) Supernova neutrinos





arXiv:2102.05977



Alert system already operational!

Integrated in SNEWS network

Currently (ORCA6) would trigger on e.g. 27 $M_{\odot}$ at ~10 kpc

Summary

- KM3NeT is a next generation neutrino telescope under construction in the Mediterranean Sea.
- To date, 19 ARCA DUs are ready to take data and 10 ORCA DUs are taking data.
- Once completed, ORCA & ARCA will have the potential to lead particle and astroparticle physics searches.