# Atmospheric neutrino oscillations with the KM3NeT/ORCA detector and synergies with reactor neutrinos

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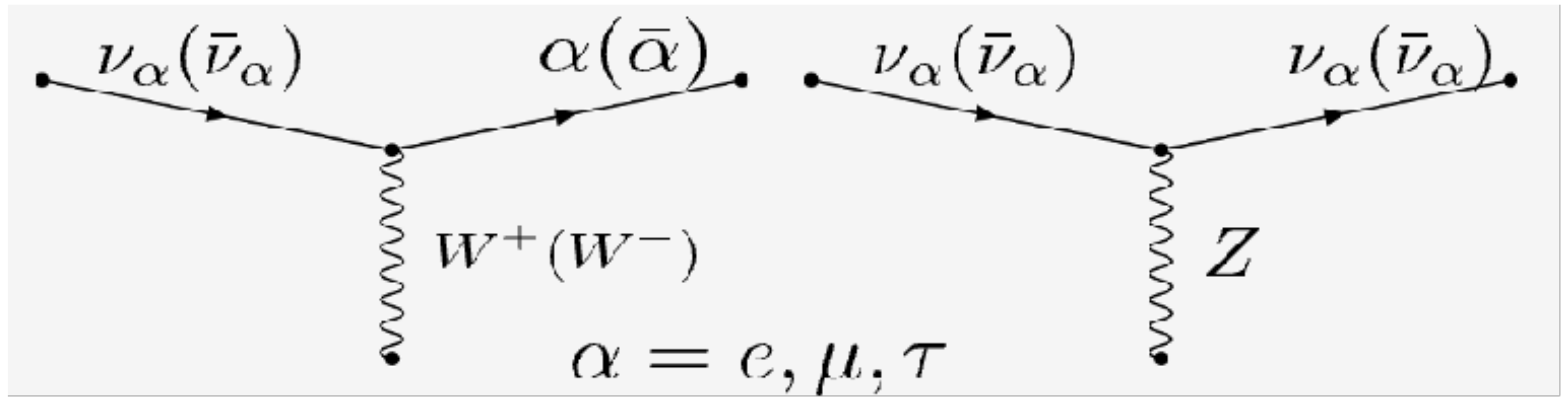
# Outlines

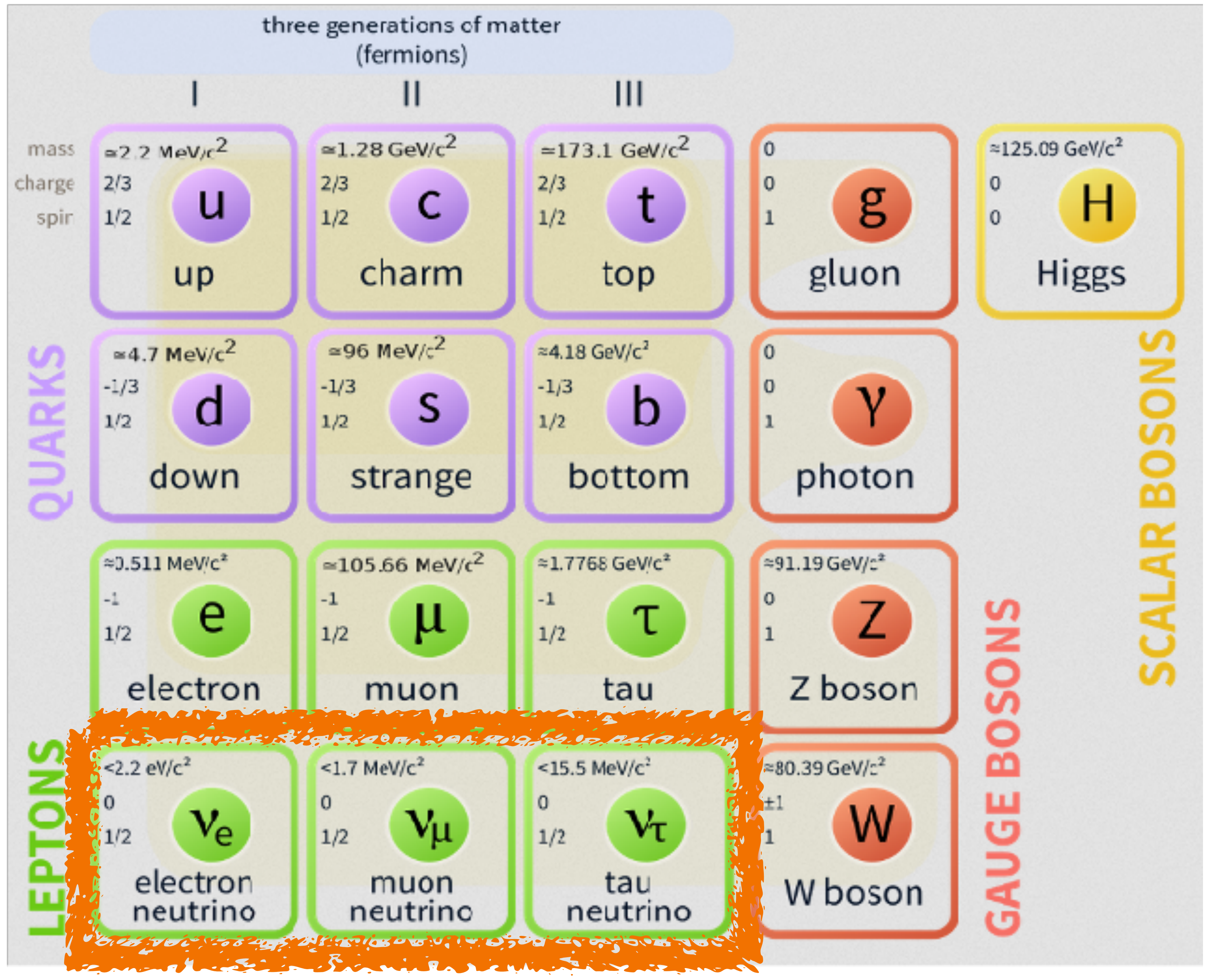
- 3-neutrino oscillations
- The KM3NeT/ORCA detector
- Neutrino mass ordering determination and combination with JUNO
- First oscillation measurement with ORCA6
- Conclusions

# 3-neutrino oscillations

# Neutrino in the Standard Model

- Neutrino - a fundamental particle:
  - In the SM: massless and neutral
  - 3 flavours (generation)
  - Only participate to weak interactions

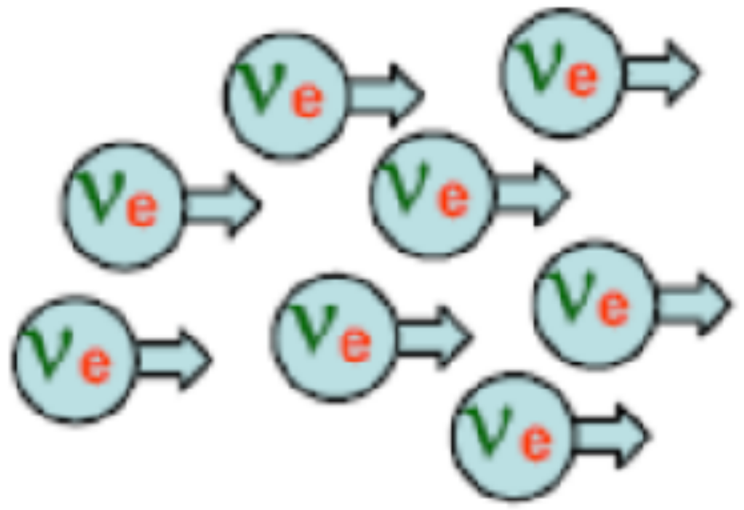


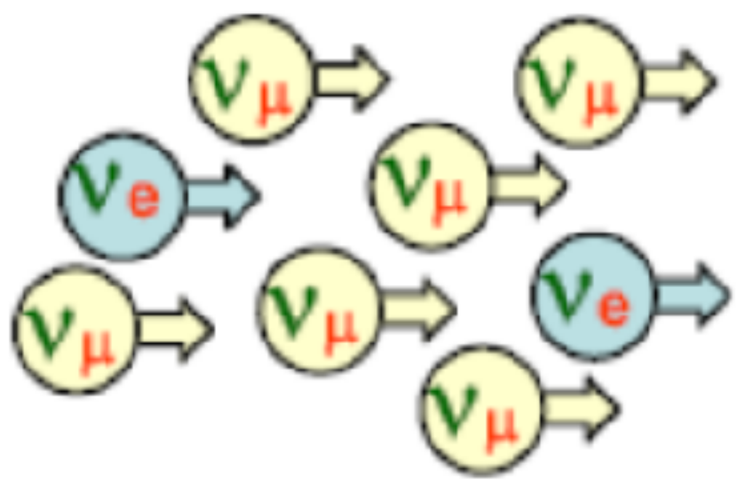




- Neutrino oscillation: neutrino changes their flavour while propagating

→ Implies non-zero mass

(hint for physics beyond SM)





# Neutrino mixing and oscillation

- Oscillations can arise from the mismatch between flavour states and mass states

Flavour states (Weak interaction)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Mass states (Propagation)

PMNS matrix
(Pontecorvo - Maki - Nakagawa - Sakata)

- Neutrinos created at the initial flavour state $\nu_\alpha$: $|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$

- In propagation, mass states evolve as: $|\nu_i(t)\rangle = e^{-iE_i t} |\nu_i(0)\rangle$

- The probability for transition into flavour $\nu_\beta$:

$$P(\nu_\alpha \to \nu_\beta) = |\langle \nu_\beta | \nu_\alpha(t) \rangle|^2$$

$\beta = \alpha$: disappearance channel, $\beta \neq \alpha$: appearance channel

# Neutrino mixing and oscillation

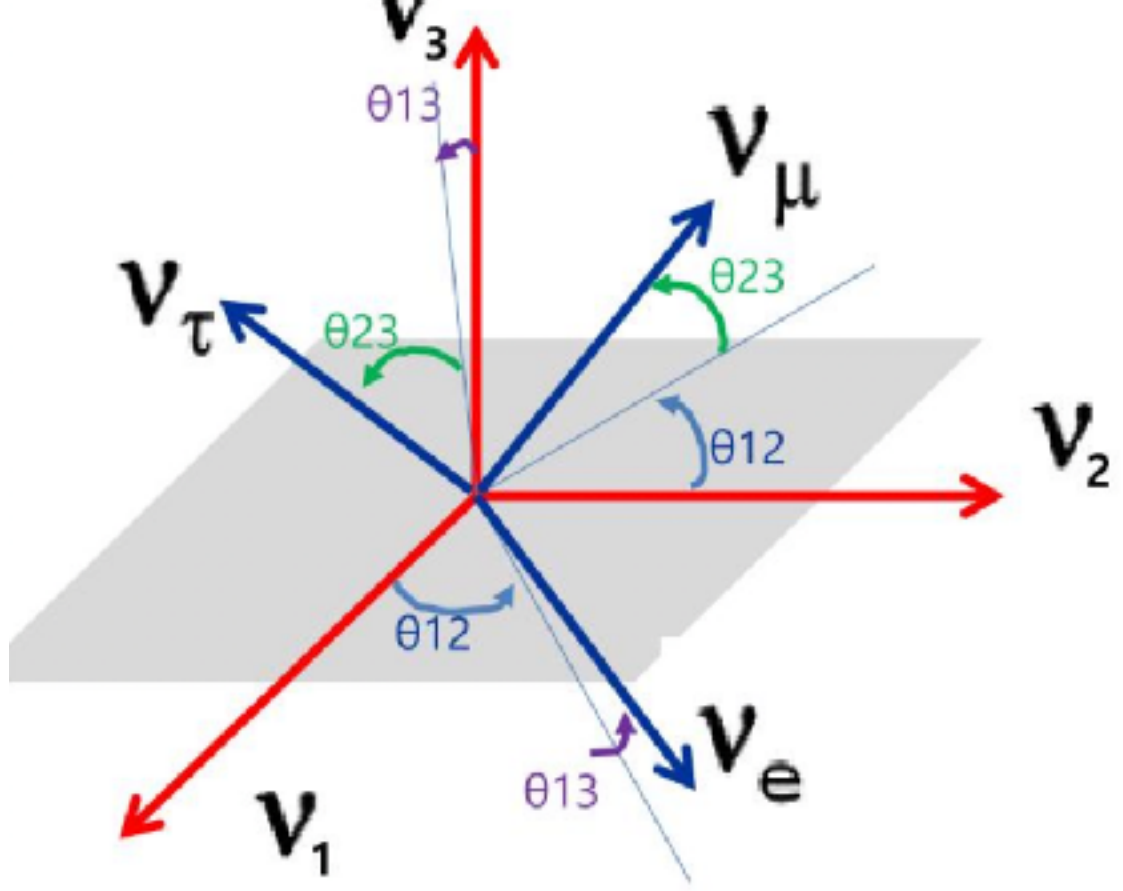
$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i<j} \mathrm{Re}\left[U_{\alpha i}U^*_{\beta i}U^*_{\alpha j}U_{\beta j}\right] \sin^2\left(\frac{\Delta m^2_{ji}L}{4E}\right) + 2\sum_{i<j} \mathrm{Im}\left[U_{\alpha i}U^*_{\beta i}U^*_{\alpha j}U_{\beta j}\right] \sin\left(\frac{\Delta m^2_{ji}L}{2E}\right)$$

- Parametrization of PMNS matrix:

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & e^{-i\delta}s_{13} \\ 0 & 1 & 0 \\ e^{-i\delta}s_{13} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

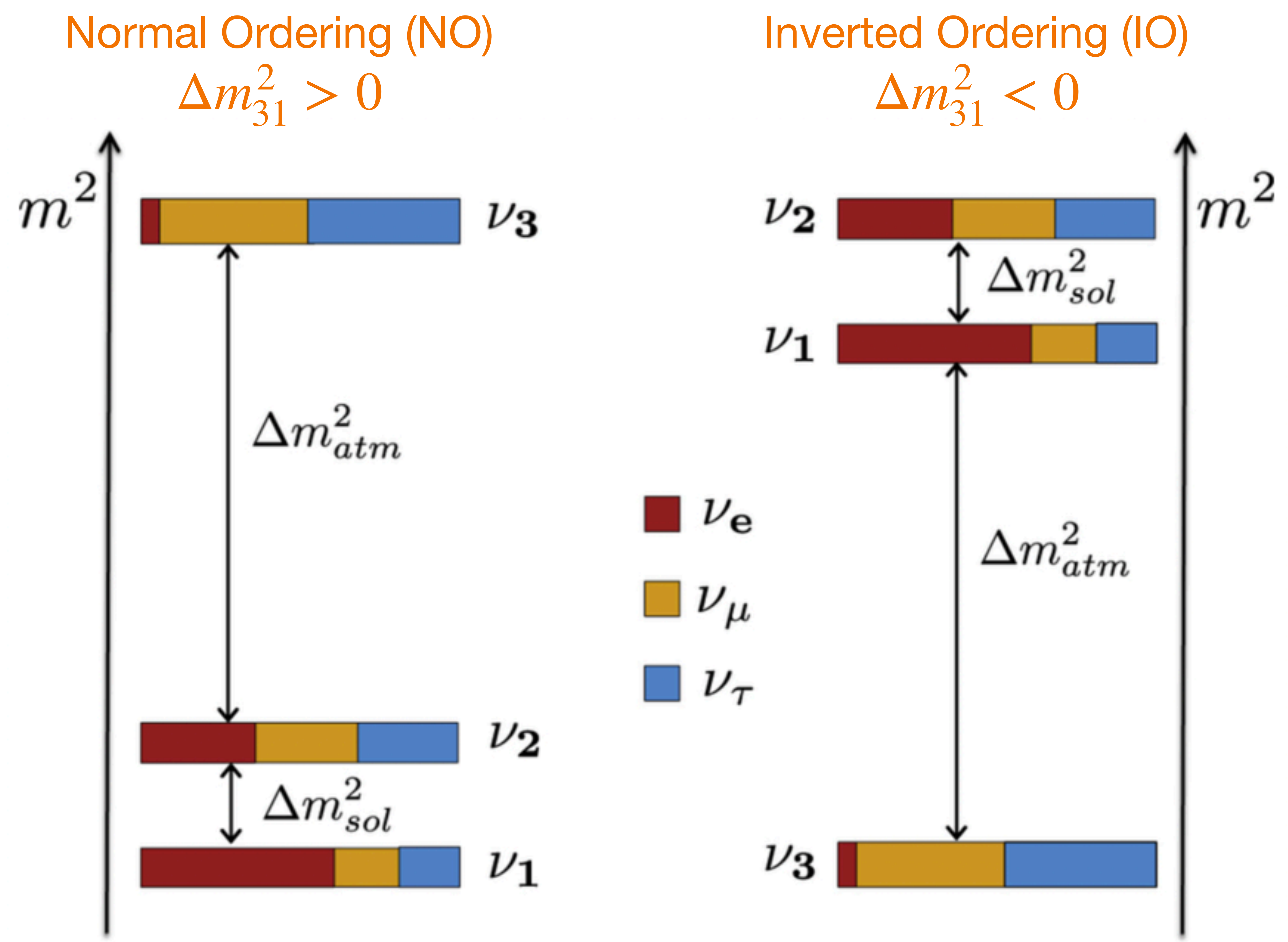
- Oscillation governed by:
  - 3 mixing angles $(\theta_{12}, \theta_{13}, \theta_{23})$
  - 2 independent squared-mass splitting $(\Delta m^2_{31}, \Delta m^2_{21})$
  - 1 CP-violation phase $(\delta)$
- *L/E* dependence

→ different *L/E* ranges (experiments) give different parameter sensitivity



# Current status

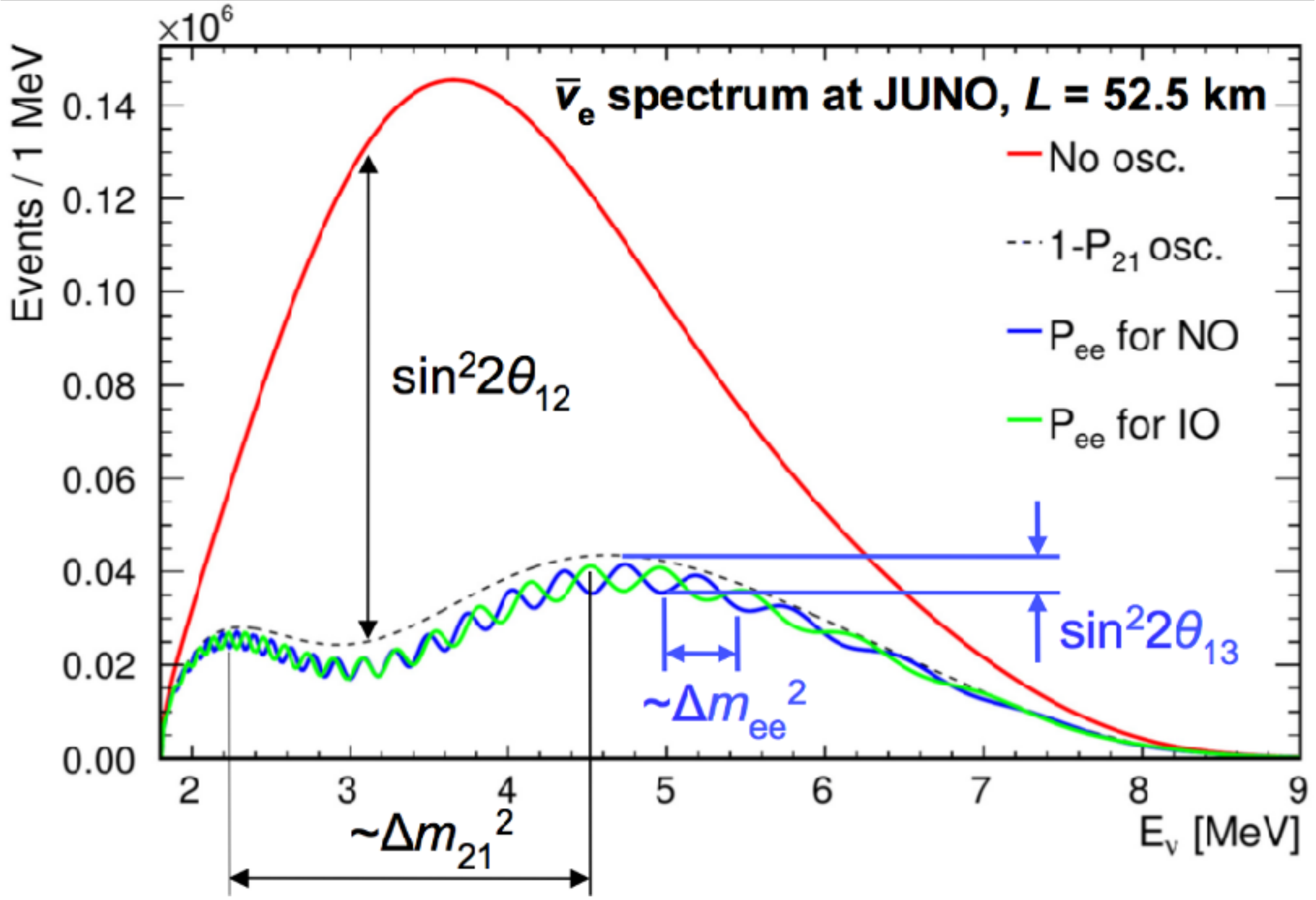
- $\theta_{13}$ and $\Delta m^2_{31}$ are measure to a very good precision
- Three main tasks: the precise measurement of $\theta_{23}$, the measurement of CP violation phase $\delta_{CP}$, and the determination of neutrino mass ordering (NMO).



# NMO determination

## Reactor neutrinos with medium baseline

- Reactor experiment ($\bar{\nu}_e \to \bar{\nu}_e$) at medium baseline (~ 53 km - JUNO)
- NMO determination using interplay between fast oscillation driven by $\Delta m^2_{31}$ and $\Delta m^2_{32}$
- Require very good energy resolution



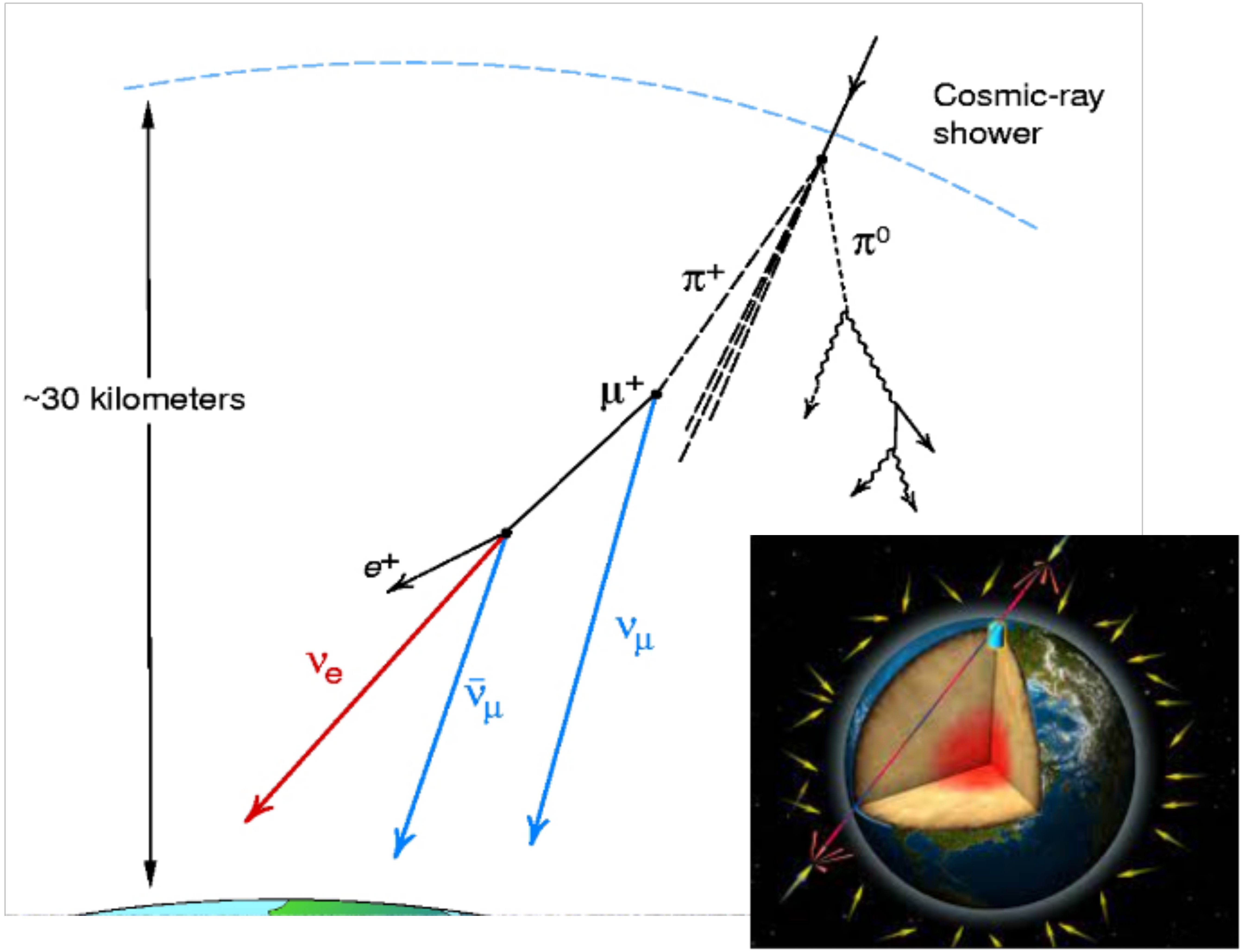
# NMO determination

## Atmospheric neutrinos

- Atmospheric neutrinos created in cosmic-ray induced air showers
  - $\pi^-/K^- \rightarrow \mu^- + \bar{\nu}_\mu$

    $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$
  - $\pi^+/K^+ \rightarrow \mu^+ + \nu_\mu$

    $\mu^+ \rightarrow e^+ + \bar{\nu}_e + \bar{\nu}_\mu$

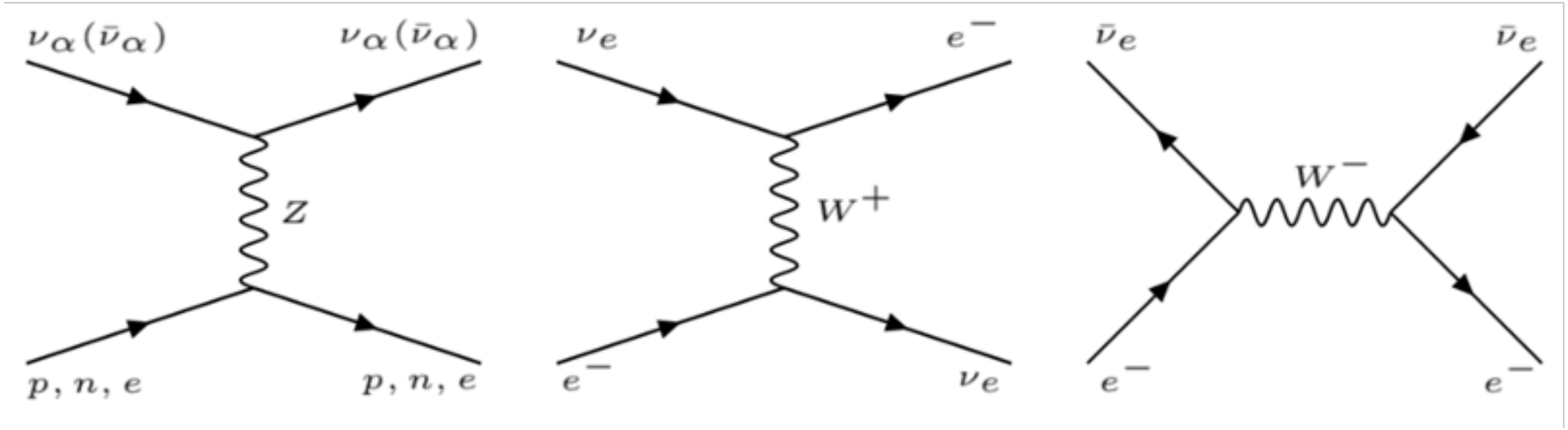


# NMO determination

## Atmospheric neutrinos

- Vacuum oscillation is hard to determine NMO: $P(\nu_\alpha \to \nu_\beta) \sim \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$

- In matter, forward elastic weak scattering modify the oscillation



# NMO determination

## Atmospheric neutrinos

- Matter effect can modify the oscillation:

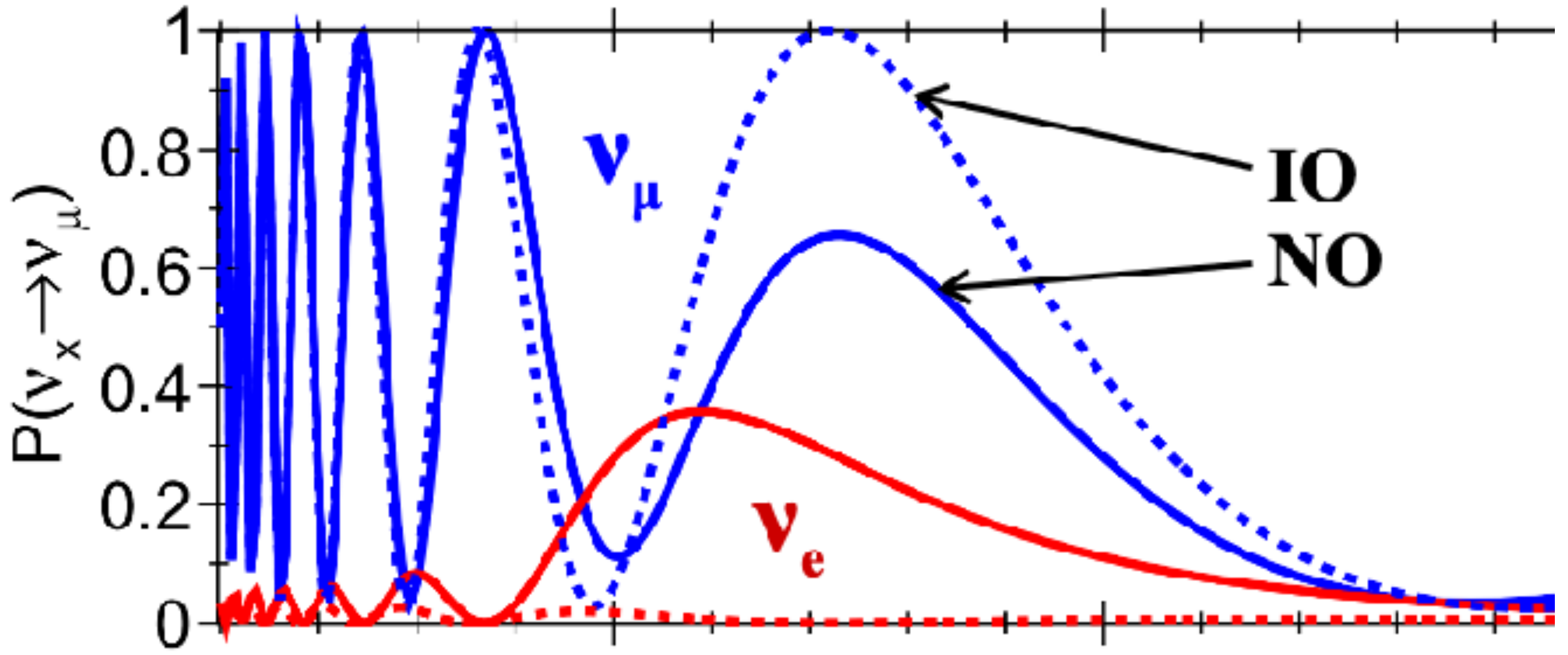
$$P^m(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23} \sin^2 2\theta_{13}^m \sin^2\left(\frac{\Delta^m m_{31}^2 L}{4E_\nu}\right)$$

$$\sin^2\theta_{13}^m = \sin^2 2\theta_{13}\left(\frac{\Delta m_{31}^2}{\Delta^m m^2}\right)^2$$

with $\Delta^m m^2 = \sqrt{(\Delta m_{31}^2 \cos 2\theta_{13} - 2E_\nu A) + (\Delta m_{31}^2 \sin 2\theta_{13})^2}$, $A = +(-)\sqrt{2}G_F N_e$ for $\nu(\bar{\nu})$

- MSW resonance for neutrinos (antineutrinos) in case of NO (IO)

→ NMO determination with atmospheric neutrino traversing the Earth (PINGU, Hyper-K, KM3NeT/ORCA)



# The KM3NeT/ORCA detector

# The KM3NeT detectors

Next generation of large-volume water-Cherenkov neutrino telescopes in the Mediterranean Sea

Two detectors with the same technology

- ORCA: Oscillation Research with Cosmic in the Abyss

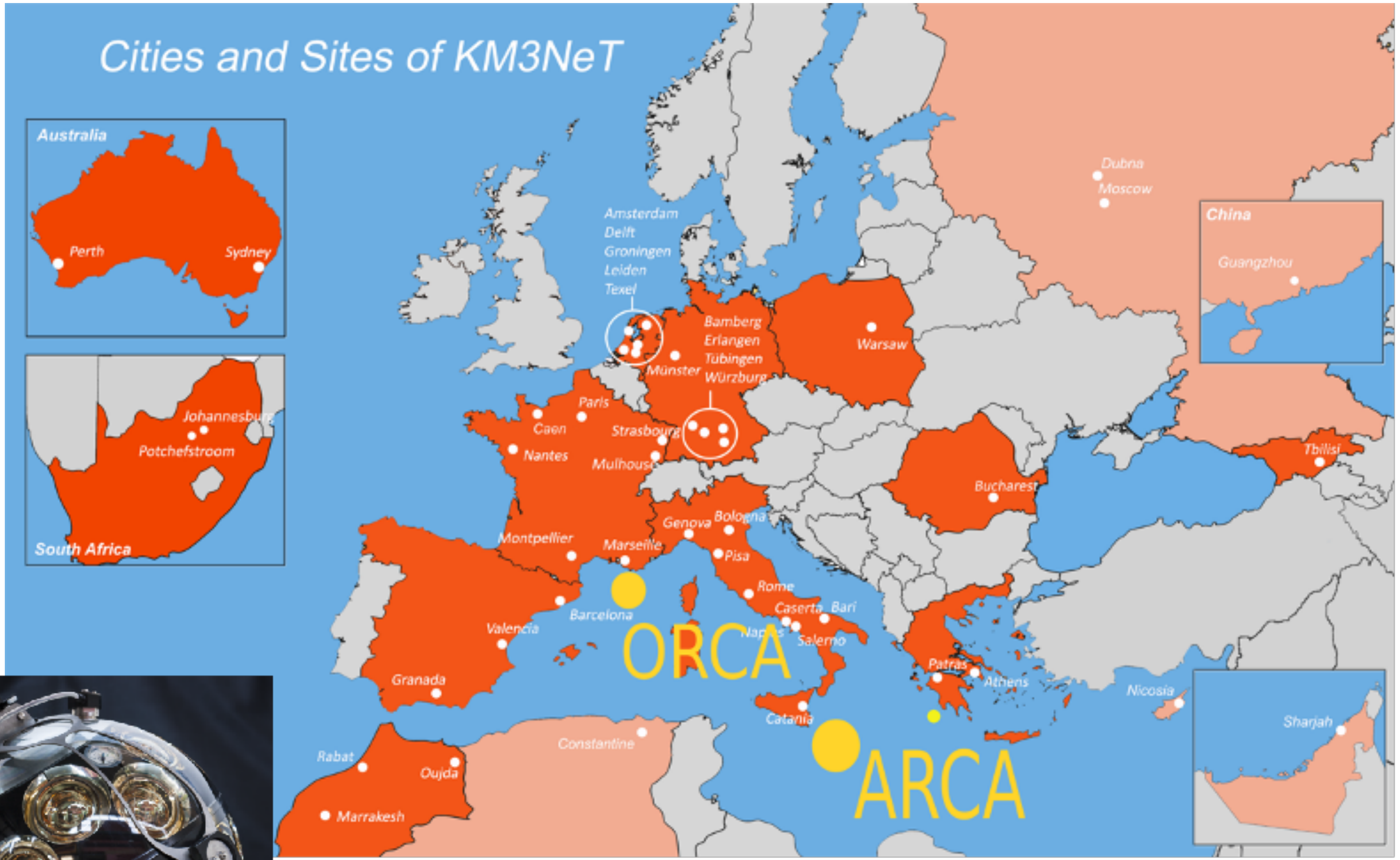
    *Smaller and denser array*

    *GeV-TeV*

- ARCA: AstroParticle Research with Cosmic in the Abyss

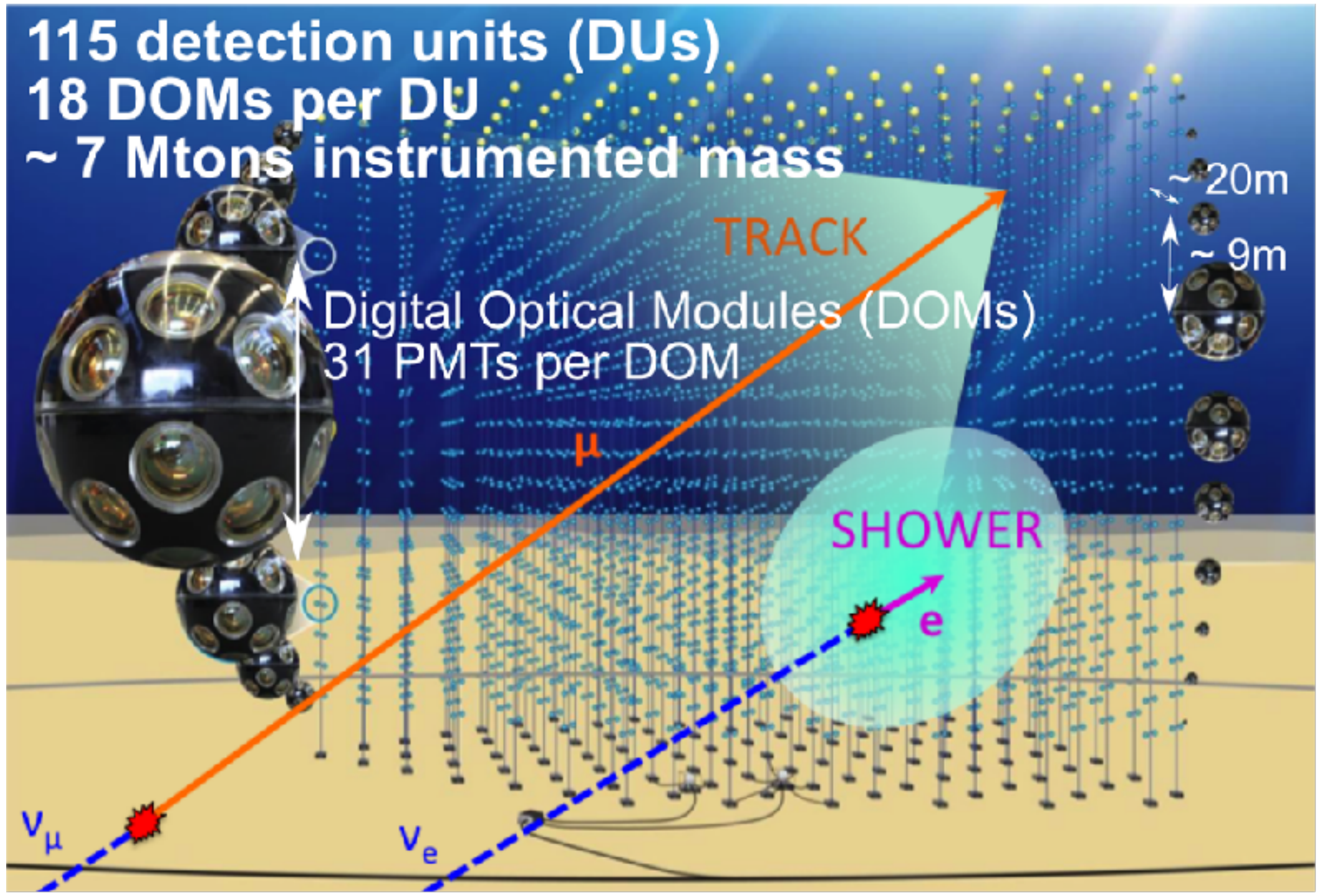
    *Larger and sparser array*

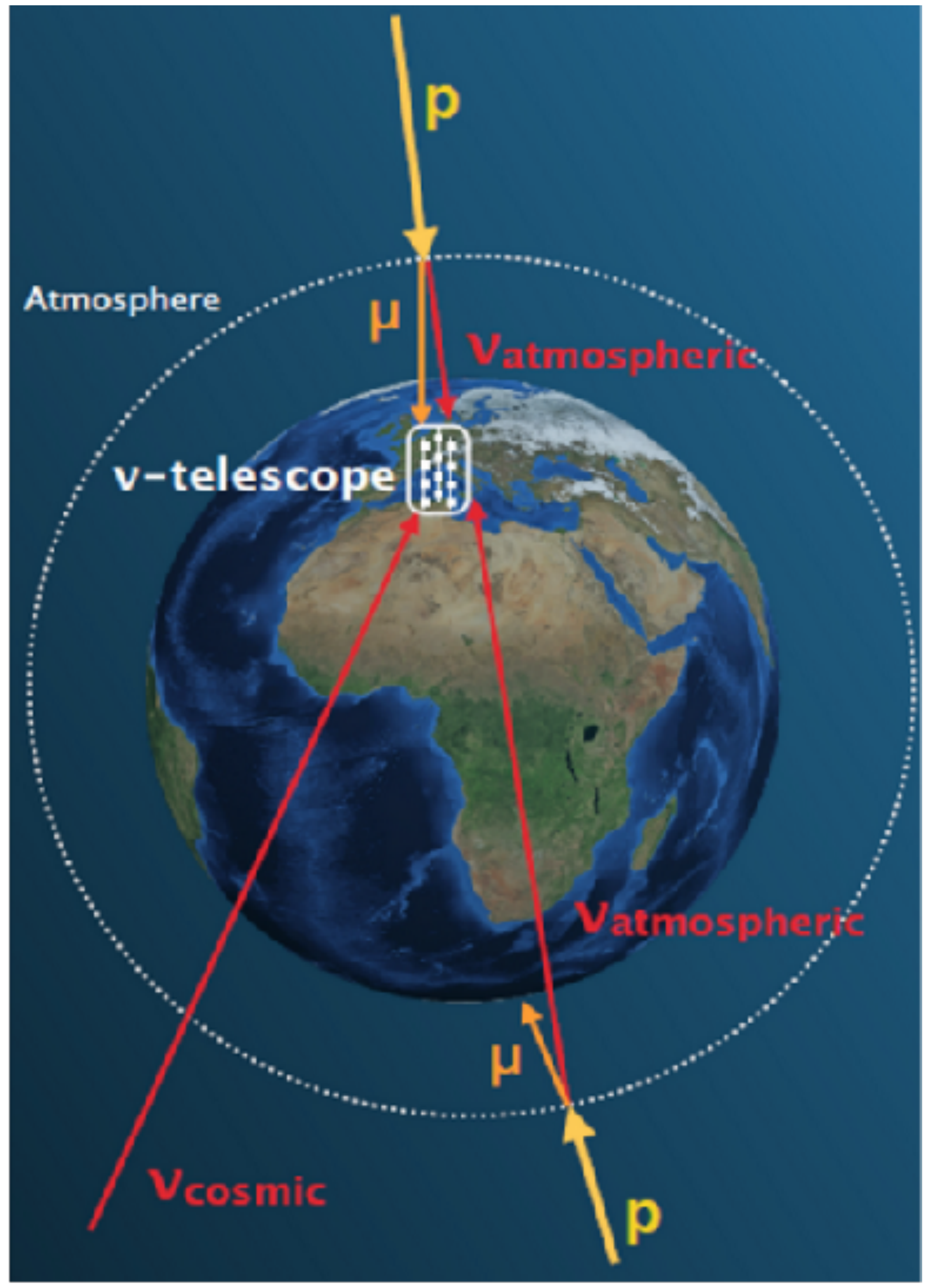
    *TeV-PeV*



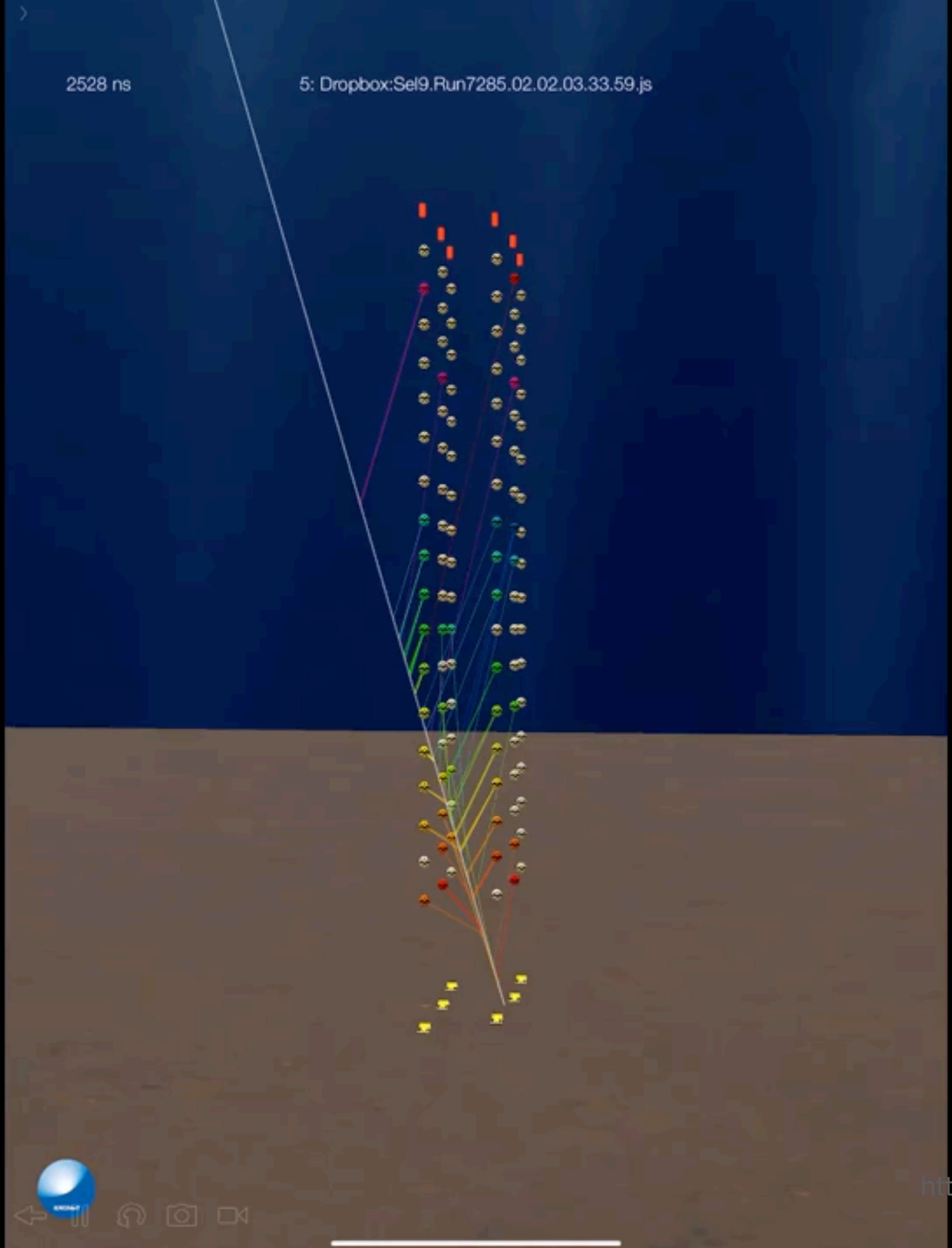

A KM3NeT Digital Optical Module (DOM)

# The KM3NeT/ORCA detector




- ORCA: optimized for atmospheric neutrino detection above 1 GeV.
- Events can be reconstructed in energy, direction (zenith angle) and classified into topology classes.
- 11 lines deployed and will continue growing!
- Rich physics programs including not only Neutrino Oscillation but also other topics: Neutrino Astronomy, indirect Dark Matter Search, Sterile Neutrino, Non-Standard Interaction,…




https://www.youtube.com/watch?v=AjQx8NpQJ8Y

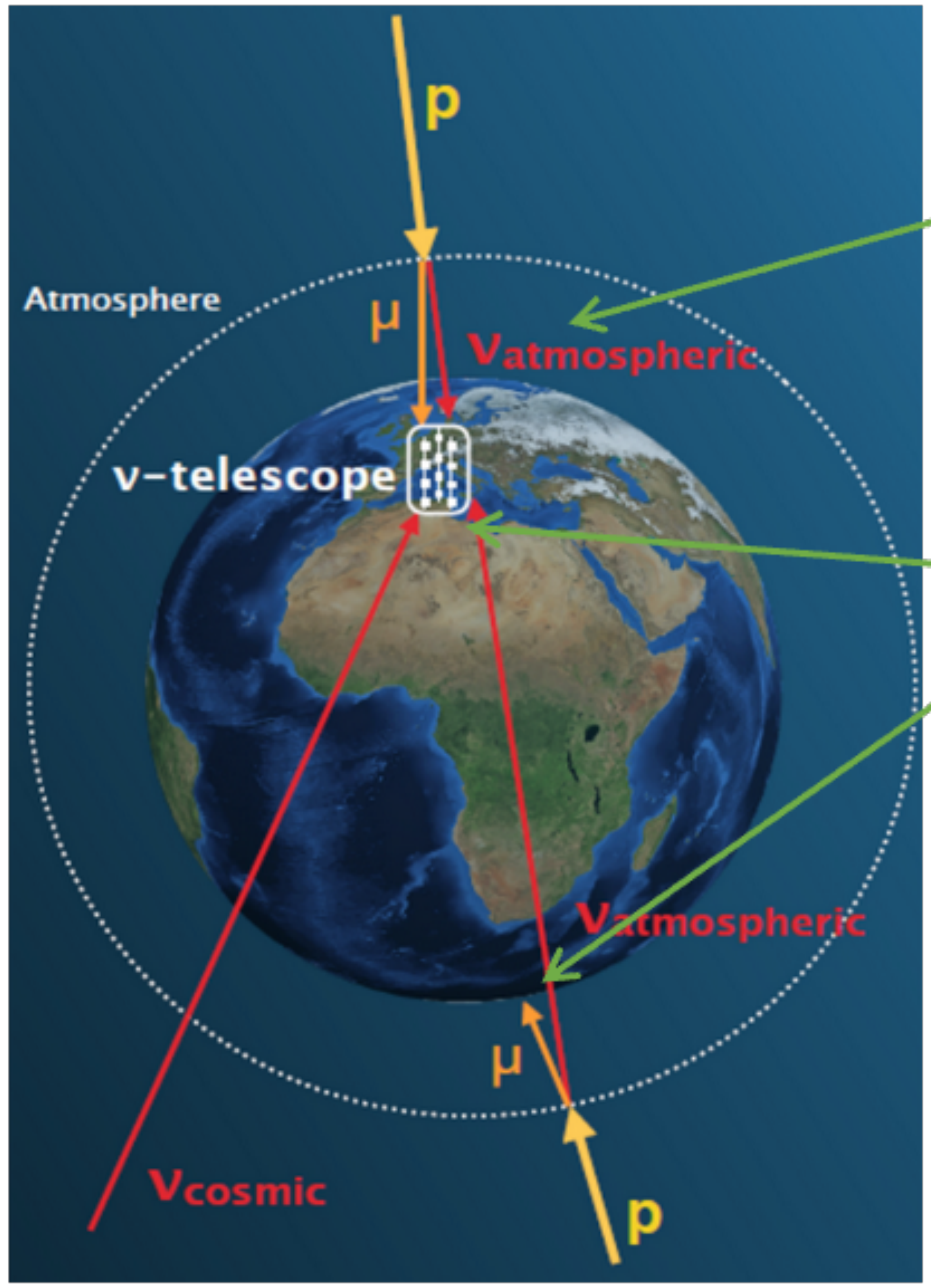
# Oscillation analysis in ORCA

- Selecting up-going events (high purity sample of atmospheric neutrinos crossing the Earth)

- Event distribution as the histogram in energy ($E_\nu$), cosine zenith ($\cos\theta_z = L/R_{Earth}$) for each topology or PID (~ flavour)

    - Reminding: $P^m(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\sin^2 2\theta_{13}^m \sin^2\left(\frac{\Delta^m m_{31}^2 L}{4E_\nu}\right)$

# Oscillation analysis in ORCA




Atmospheric neutrino fluxes

↓

Oscillation, Earth Model, Cross Section

↓

Interaction Rates at Detector

↓

Detector Response (Effective Mass, PID, Resolutions)

↓

Reconstructed and Classified Events

$i$

$[E_{true}, \cos\theta_{true}]$

*Polarity:* $\nu/\bar{\nu}$

*Flavour:* $\nu_e/\nu_\mu/\nu_\tau$

*Interaction: CC, NC*

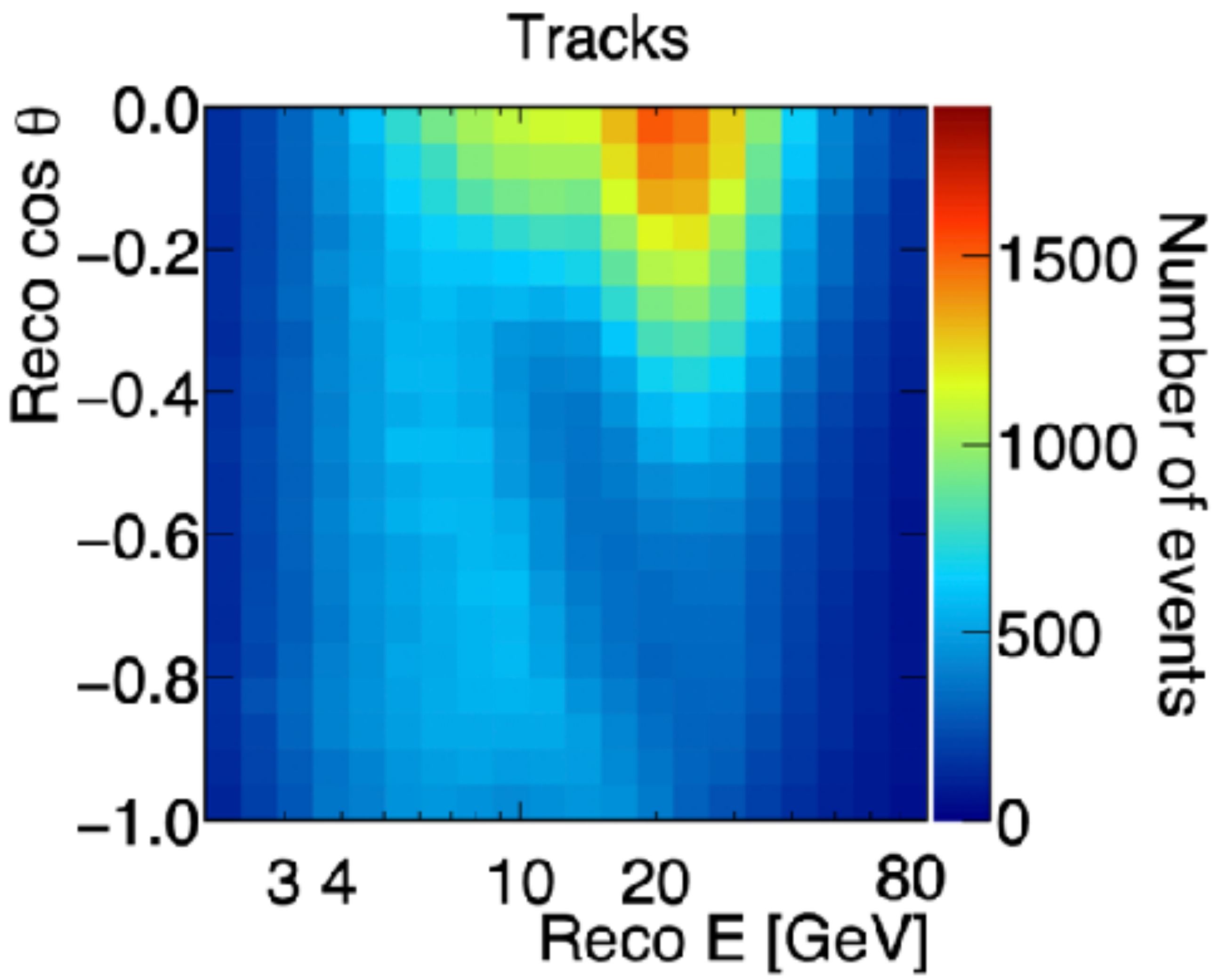
$R_{ij}$

$j$

$[E_{reco}, \cos\theta_{reco}]$

*Topology classes*

$$N_j^{reco} = \sum_i R_{ij} N_i^{true}$$



# Oscillation analysis in ORCA

- Different oscillation hypothesis leads to different expected distributions.

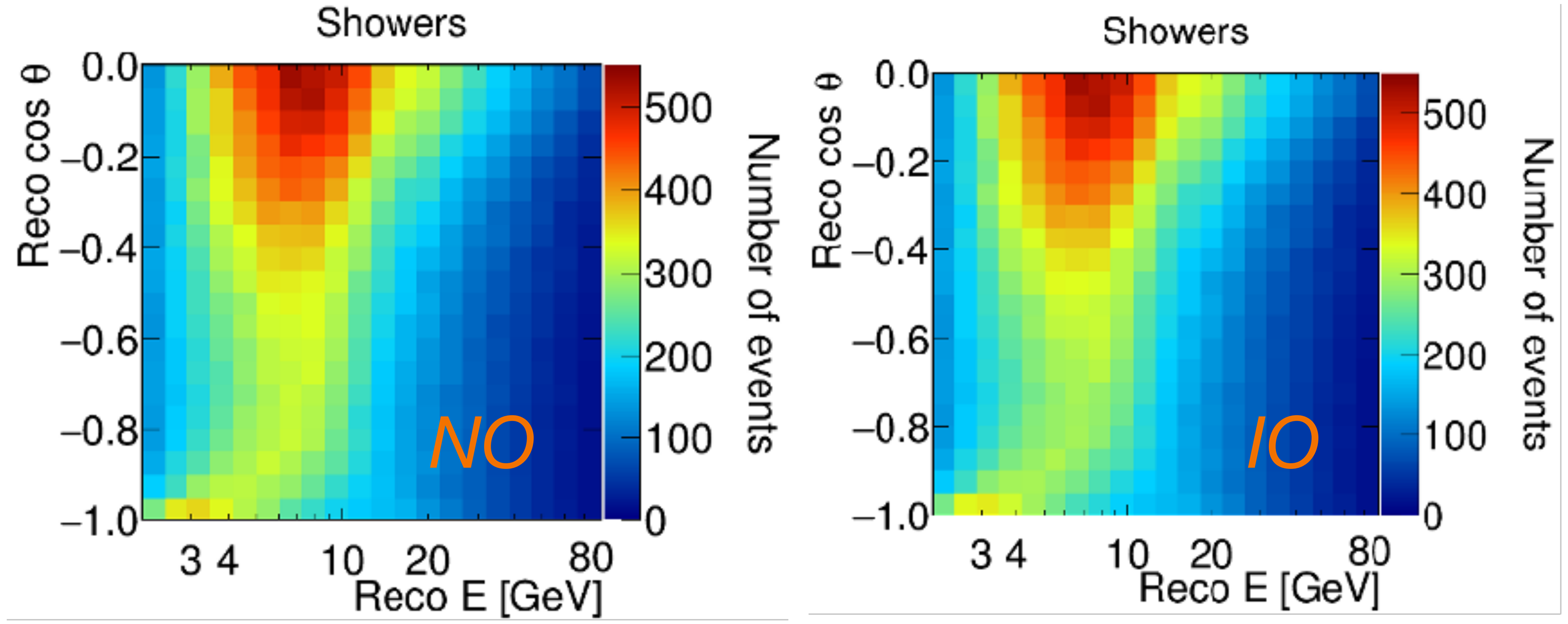
- A test statistic ( $\chi^2$) is constructed to tell the compatibility between data and hypothesis

$$TS(data\,|\,hypo) = \sum_{bin} TS_{bin}(N^{evt}_{data}, N^{evt}_{hyp})$$

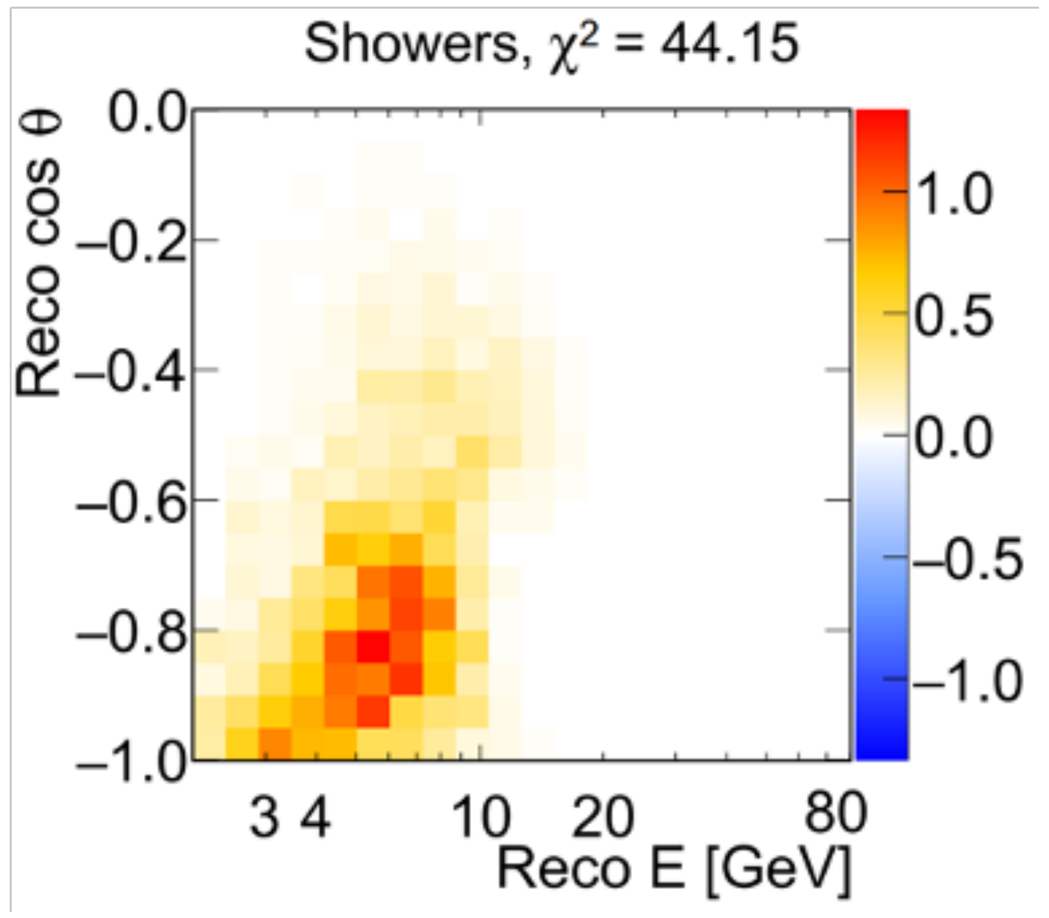
→ fit the parameters of the hypothesis to the data (find their values that minimise TS)

→ sensitivity evaluation (NMO, oscillation parameters - $\Delta m^2_{31}, \theta_{23}$)

*Event Distributions*




*TS(NO|IO)*



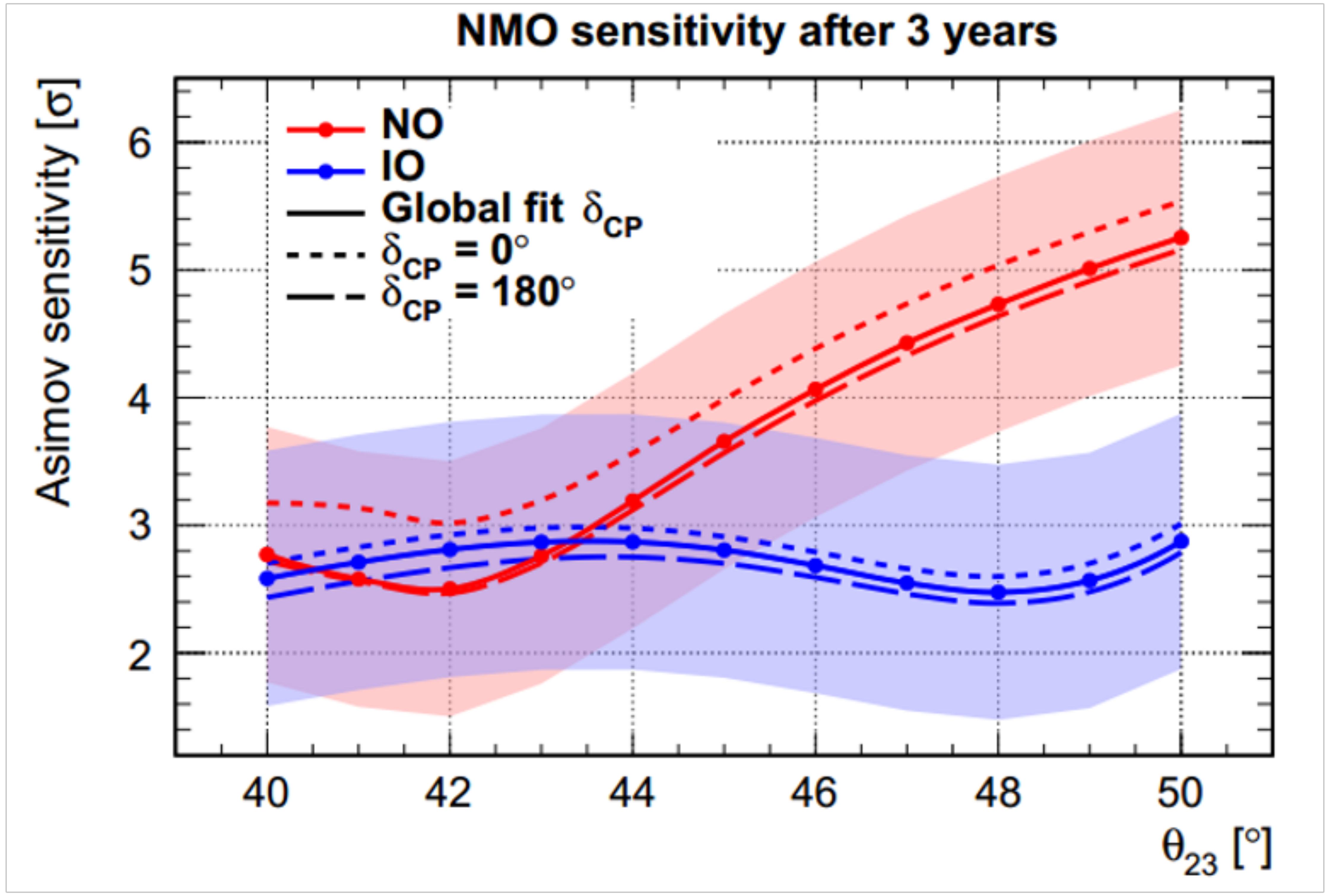
# Neutrino mass ordering determination and combination with JUNO

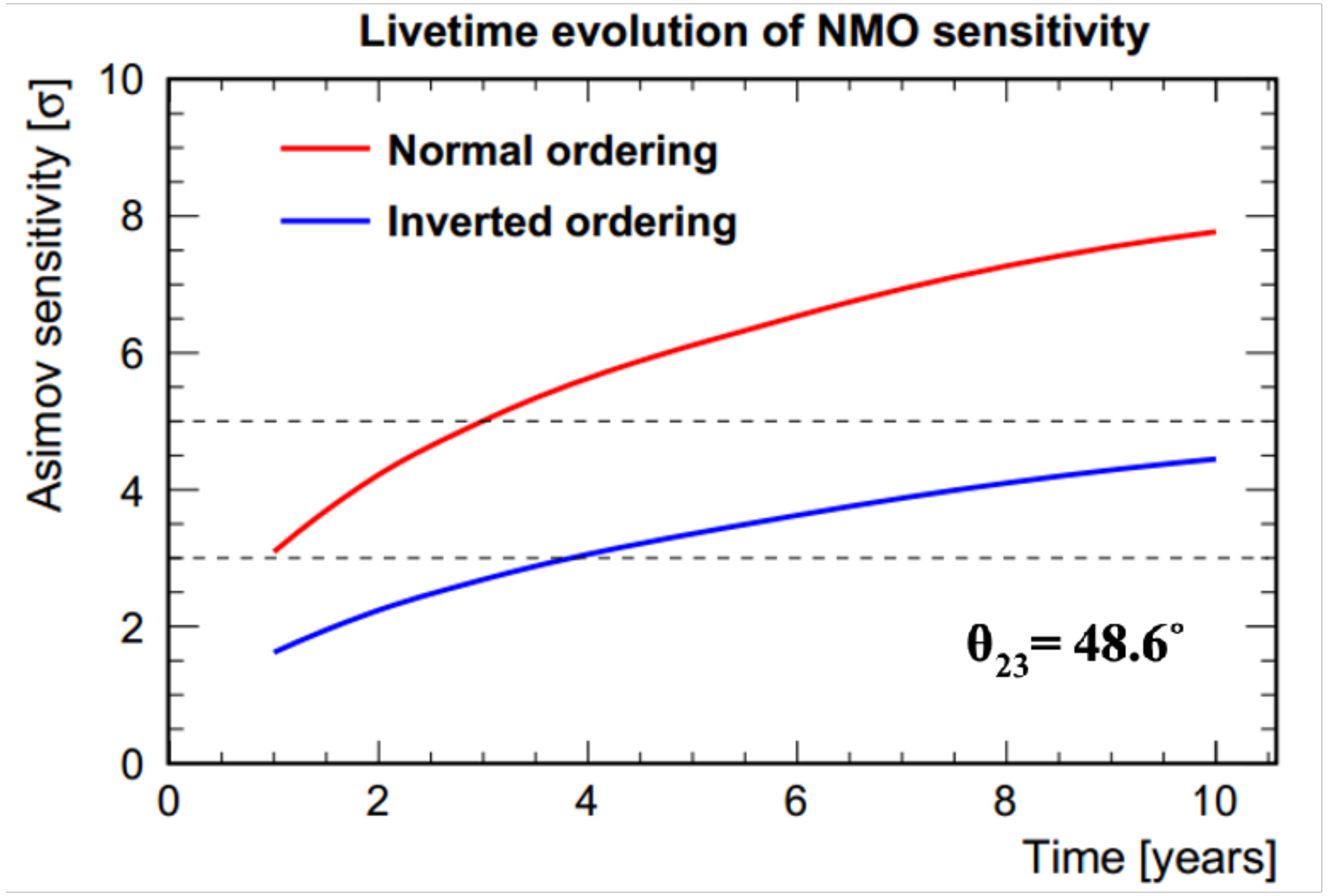
# NMO determination with ORCA

- Evaluation of NMO sensitivity with full ORCA (115 DUs/lines).
- Matter effect allows the determination.
- Data not available yet → pseudo-data from an assumed true scenario.
- Asimov dataset + Wilk's theorem for extracting the median significance (in $\sigma$).

→ How strong we can exclude a wrong ordering with an assumed true one

# NMO determination with ORCA

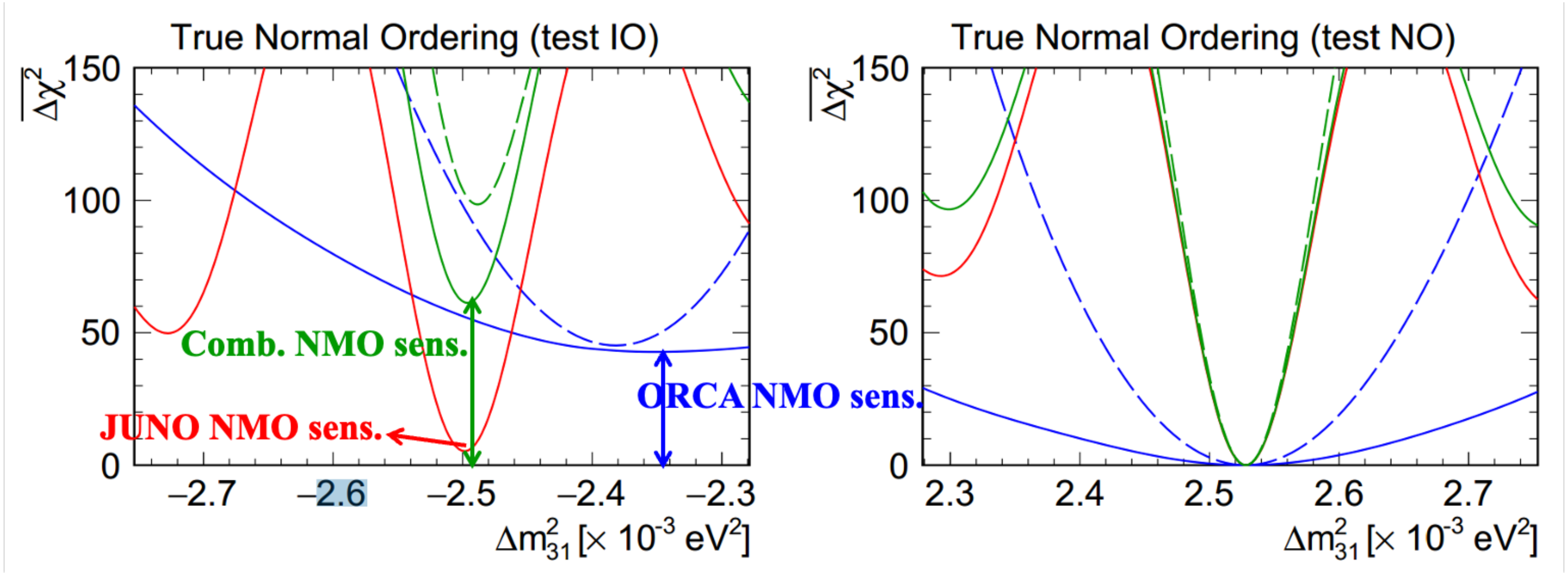



- Depend on the mixing angle $\theta_{23}$ and the true NMO
- 3 (5) $\sigma$ within 1 (3) years in the most optimistic case (NO and upper octant)

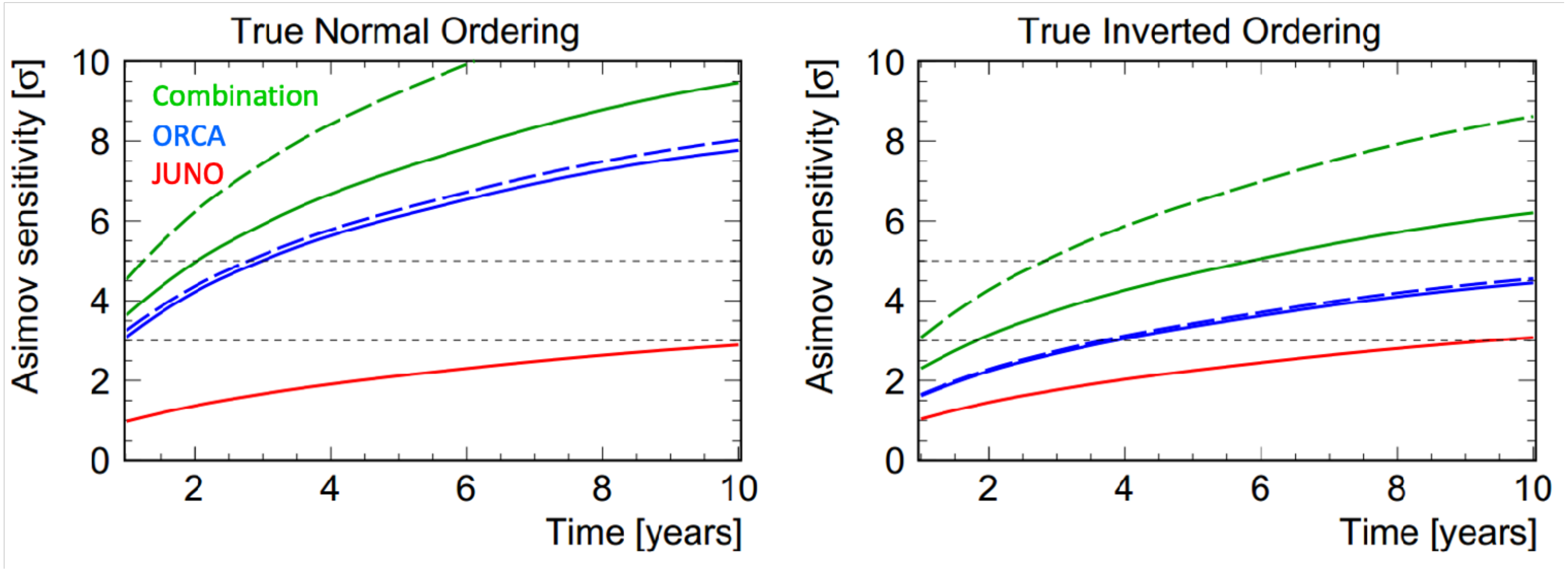
# ORCA and JUNO combination

- A combination of reactor (JUNO) and atmospheric experiments (ORCA) could yield a boost in NMO sensitivity:



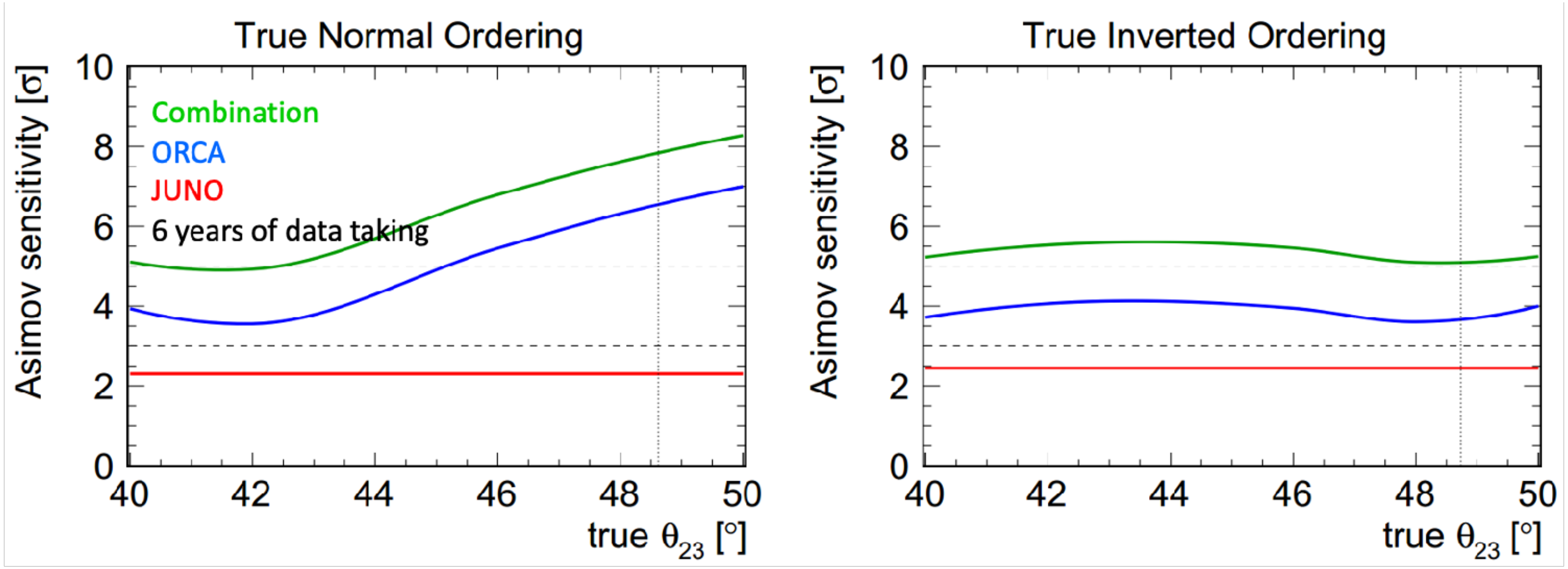

- Tension in $\Delta m^2_{31}$ best-fit arises due to each experiments observes oscillations starting from different neutrino flavours ($\bar{\nu}_e$ for JUNO, $\nu_\mu + \bar{\nu}_\mu$ for ORCA)

# ORCA and JUNO combination



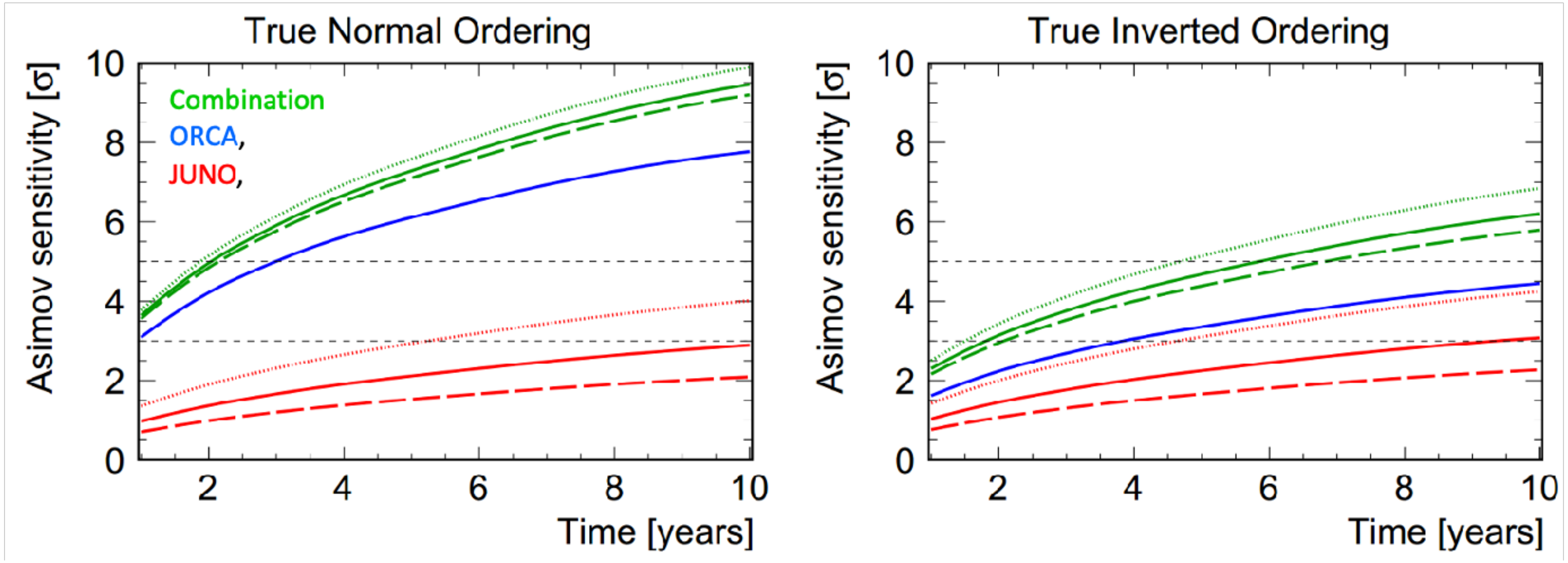

- Time required for $5\sigma$ reduced by at least one year compared to ORCA alone.
- $5\sigma$ significance within 2/6 years in case of true NO/IO respectively.

# ORCA and JUNO combination




- $\theta_{23}$ dependence driven by ORCA sensitivity.
- Combination ensures $5\sigma$ after 6 years regardless true NMO or values of $\theta_{23}$

# ORCA and JUNO combination

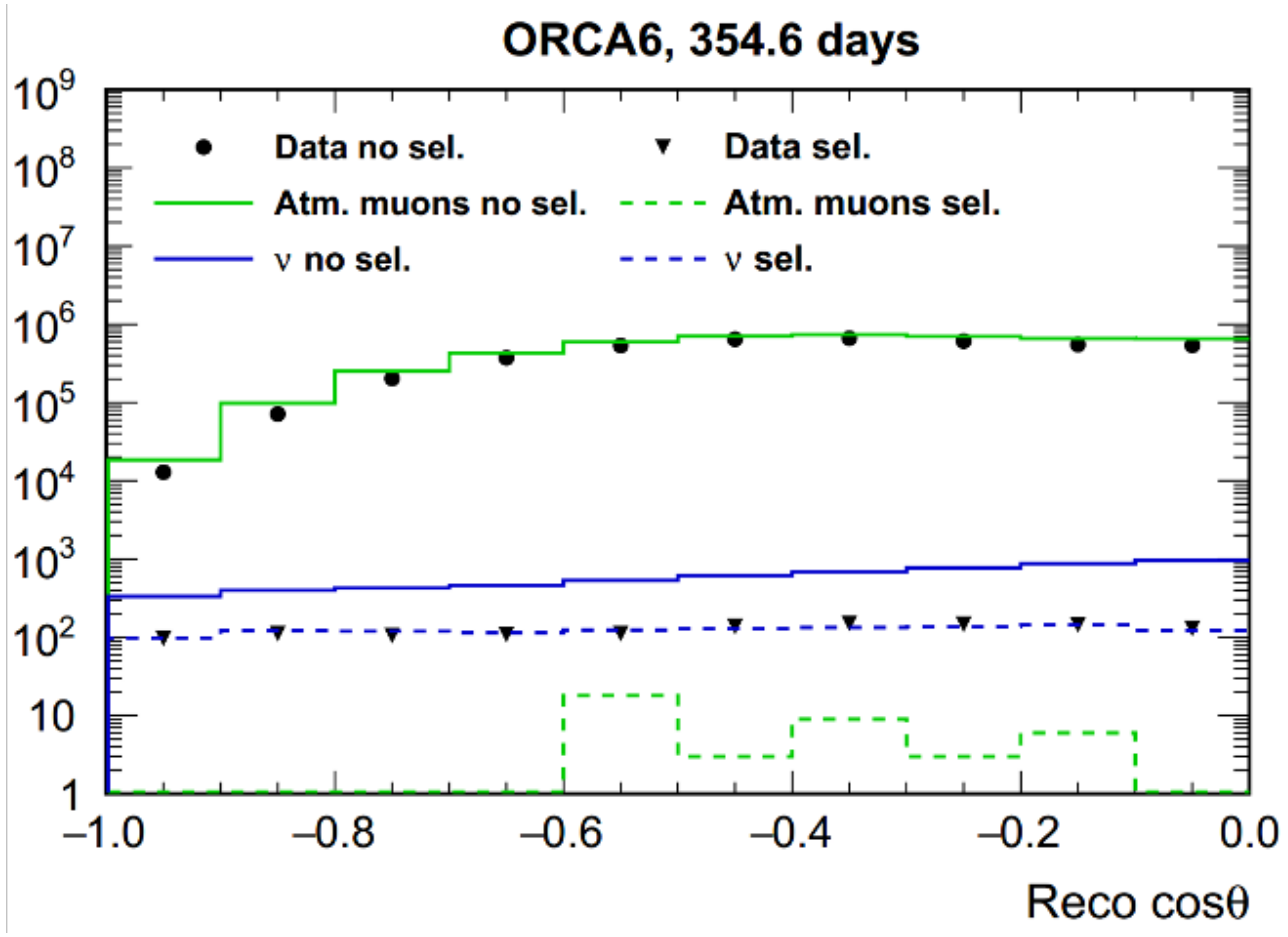


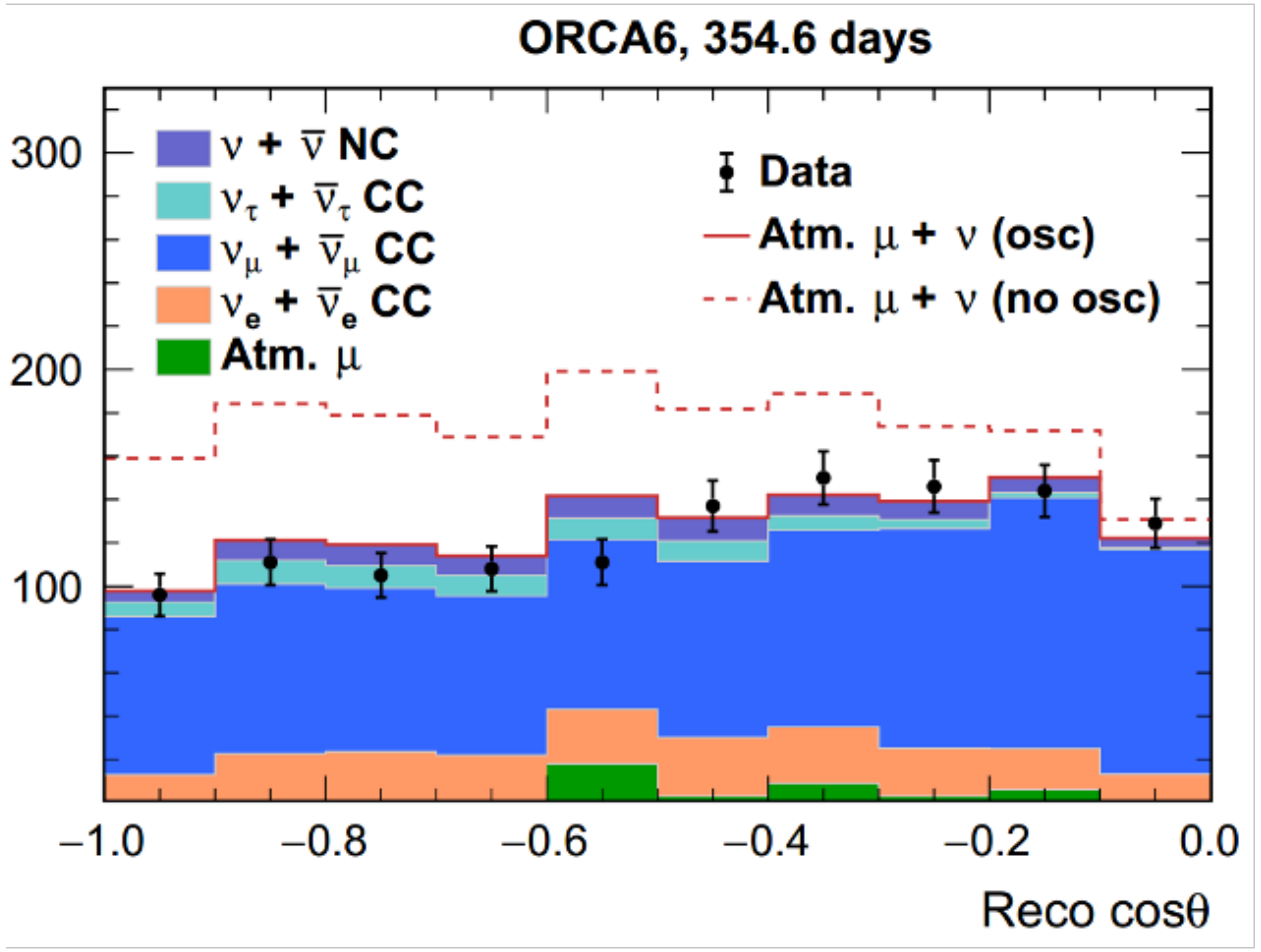

- 3 considered resolution for JUNO: nominal - $3.0\,\%\sqrt{E/MeV}$ (solid), $2.5\,\%\sqrt{E/MeV}$ (dotted), $3.5\,\%\sqrt{E/MeV}$ (dashed).
- Energy resolution of JUNO has the small impact on the combination.
- The boost relies on the $\Delta m^2_{31}$ tension rather than NMO sensitivity of each experiment.

# First oscillation measurement with ORCA6

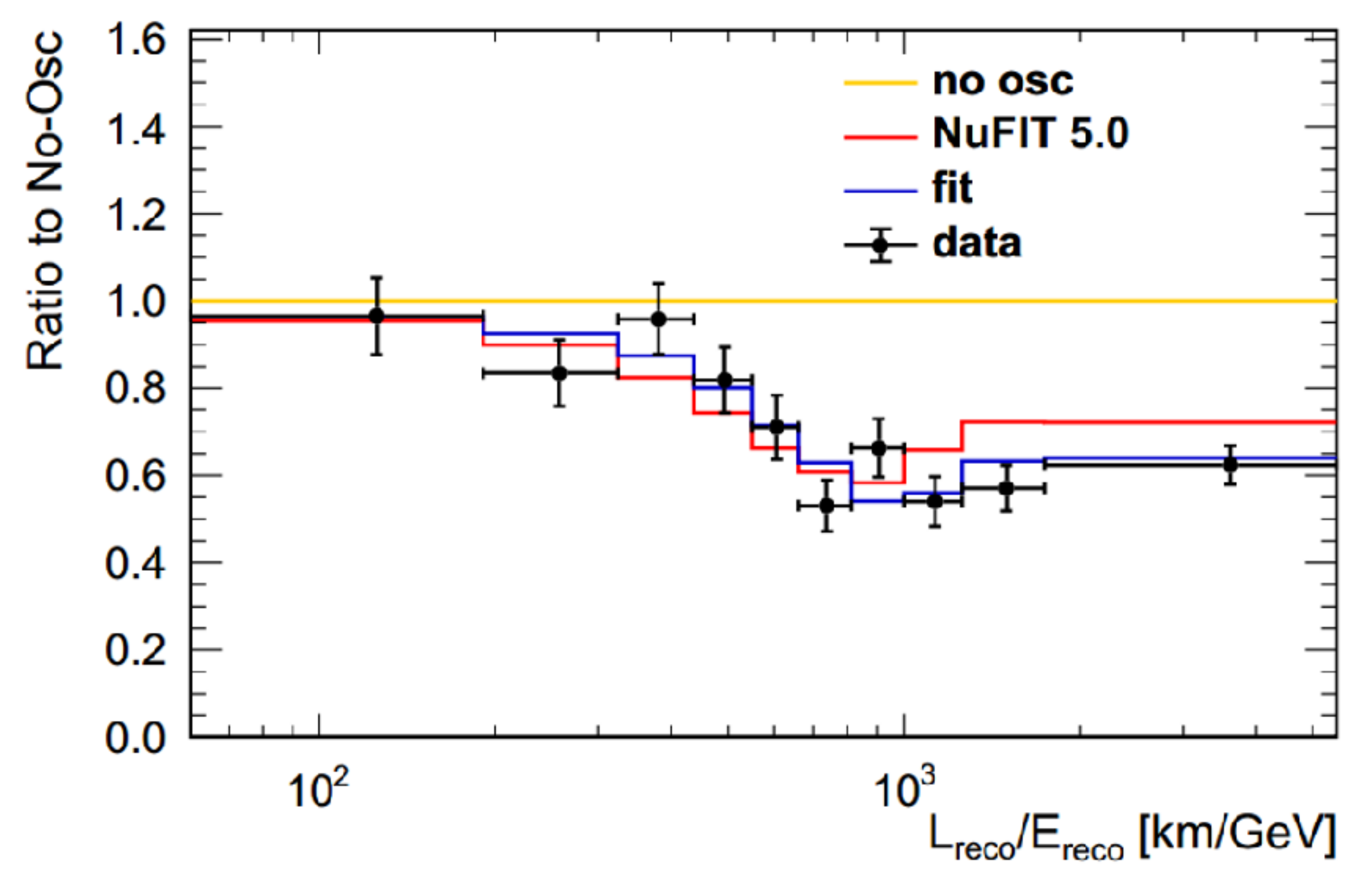
# Data sample

- Data set of 354.6 days with 6 active DUs (ORCA6): ~2020-2021
- Event selection applied to obtain high neutrino purity and good reconstructed data sample (no PID yet).
- Good data and MC agreement.



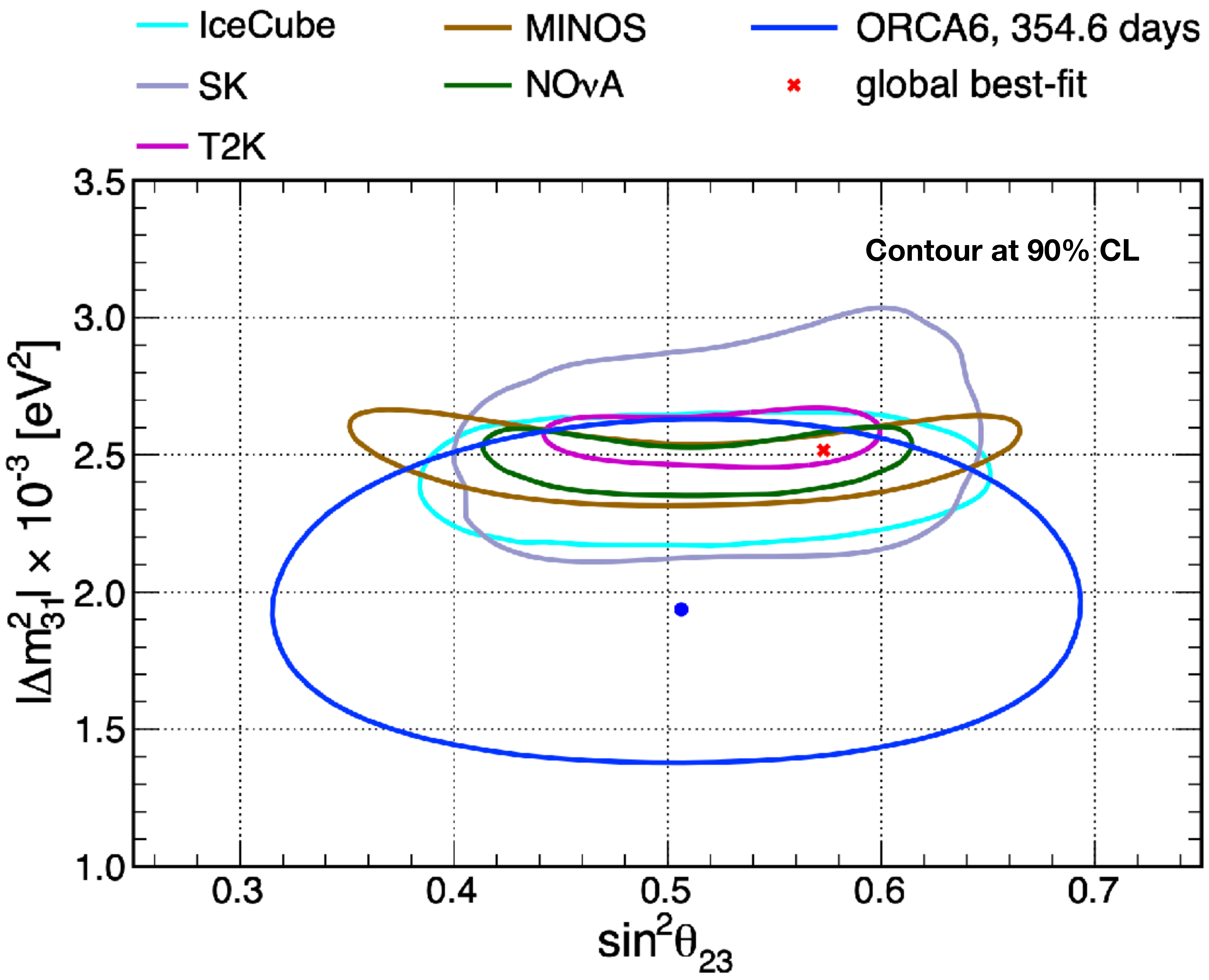



# First oscillation measurement with ORCA6




- Exclude no oscillation with more than $5\sigma$.
- Agree within ~$1.9\sigma$ compare to the global fit (NuFIT5.0).
- First oscillation maximum at higher value of L/E compared to NuFIT →prefer lower $\Delta m^2_{31}$.

# First oscillation measurement with ORCA6




$$\Delta m^2_{31} = 1.94^{+0.30}_{-0.28}[10^{-3}\mathbf{eV}^2]$$
$$\sin^2\theta_{23} = 0.51^{+0.10}_{-0.10}$$

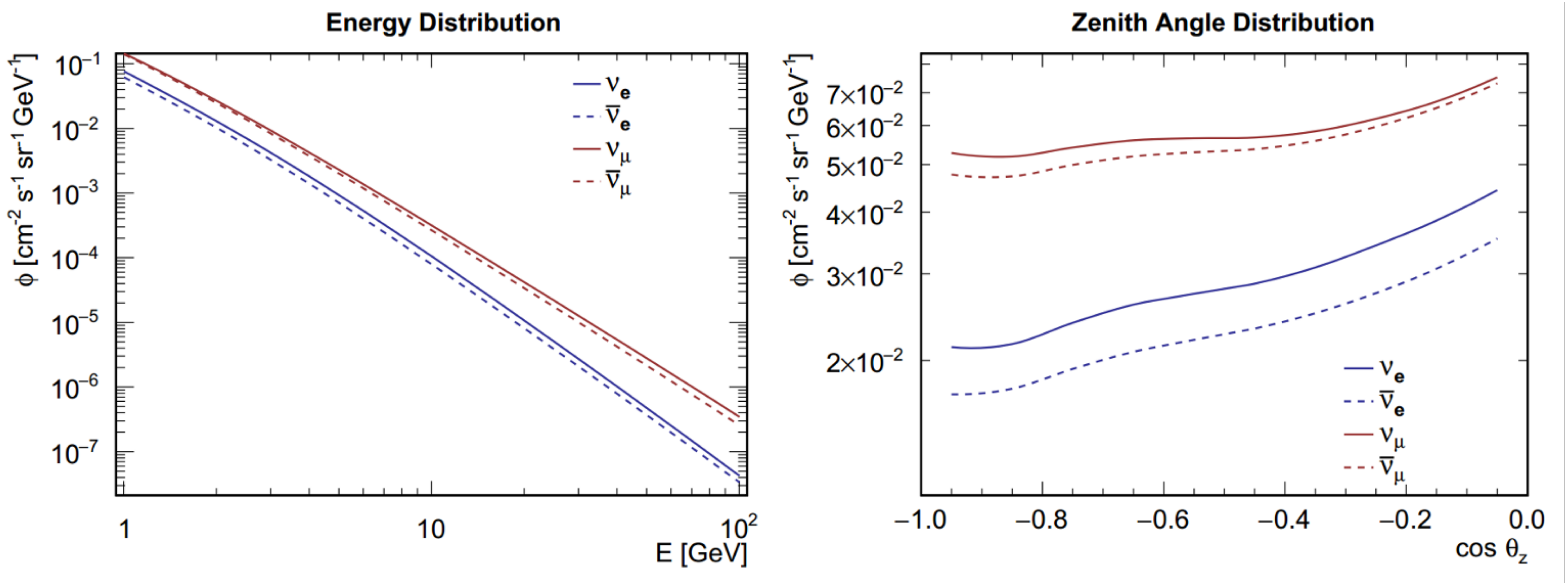
# Conclusions

- KM3NeT/ORCA is expected to unravel the NMO.
- ORCA and JUNO combination can enhance the NMO sensitivity.
- Very first oscillation measurement with only 6 DUs in ~1 years give comparable results to current experiments.
- Will soon contribute more to the global picture of neutrino oscillations since the detector is growing and more data is taking!

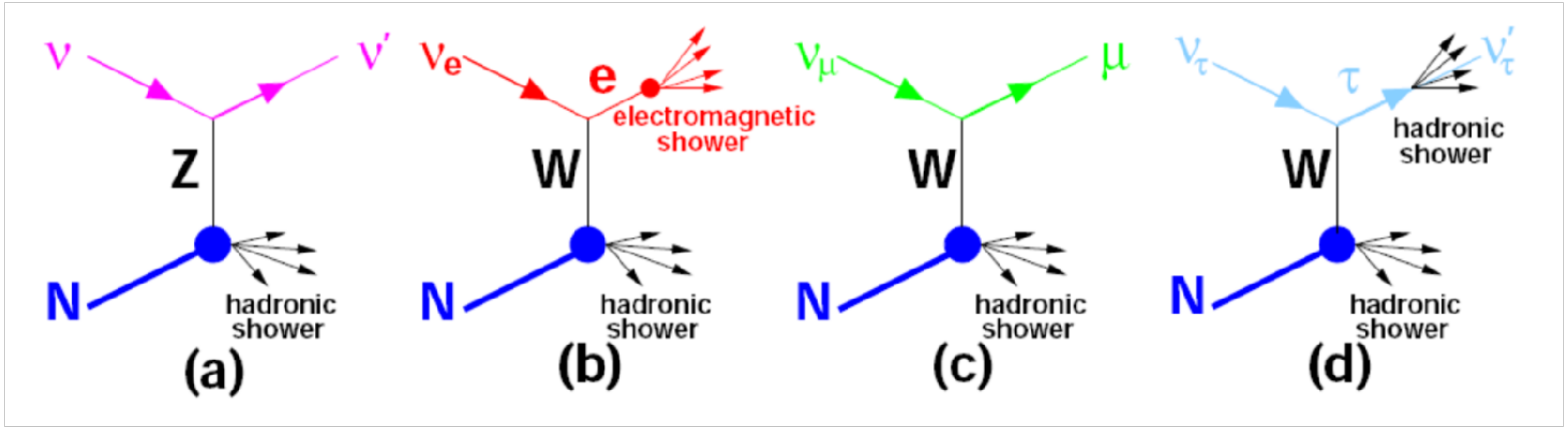
# Thank you for your attention!

# Back up

# Atmospheric fluxes



# Neutrino interactions in ORCA




Shower-like

Track-like

Mainly shower-like
17% produced muon→ track-like

# Background in the deep-sea

- Radio activity

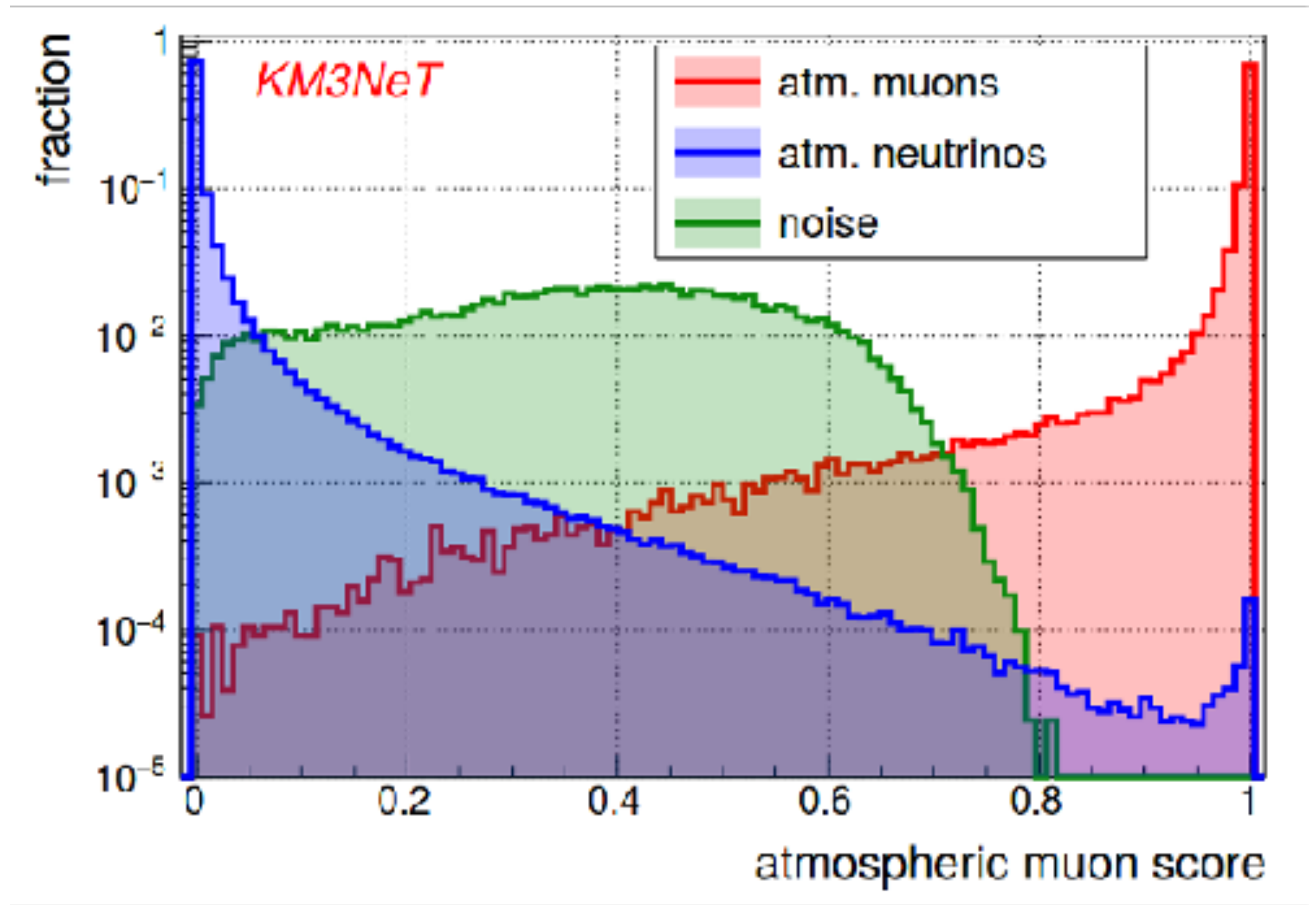
$$^{40}\mathrm{K} \rightarrow {}^{40}\mathrm{Ca} + \bar{\nu}_e + e^-$$

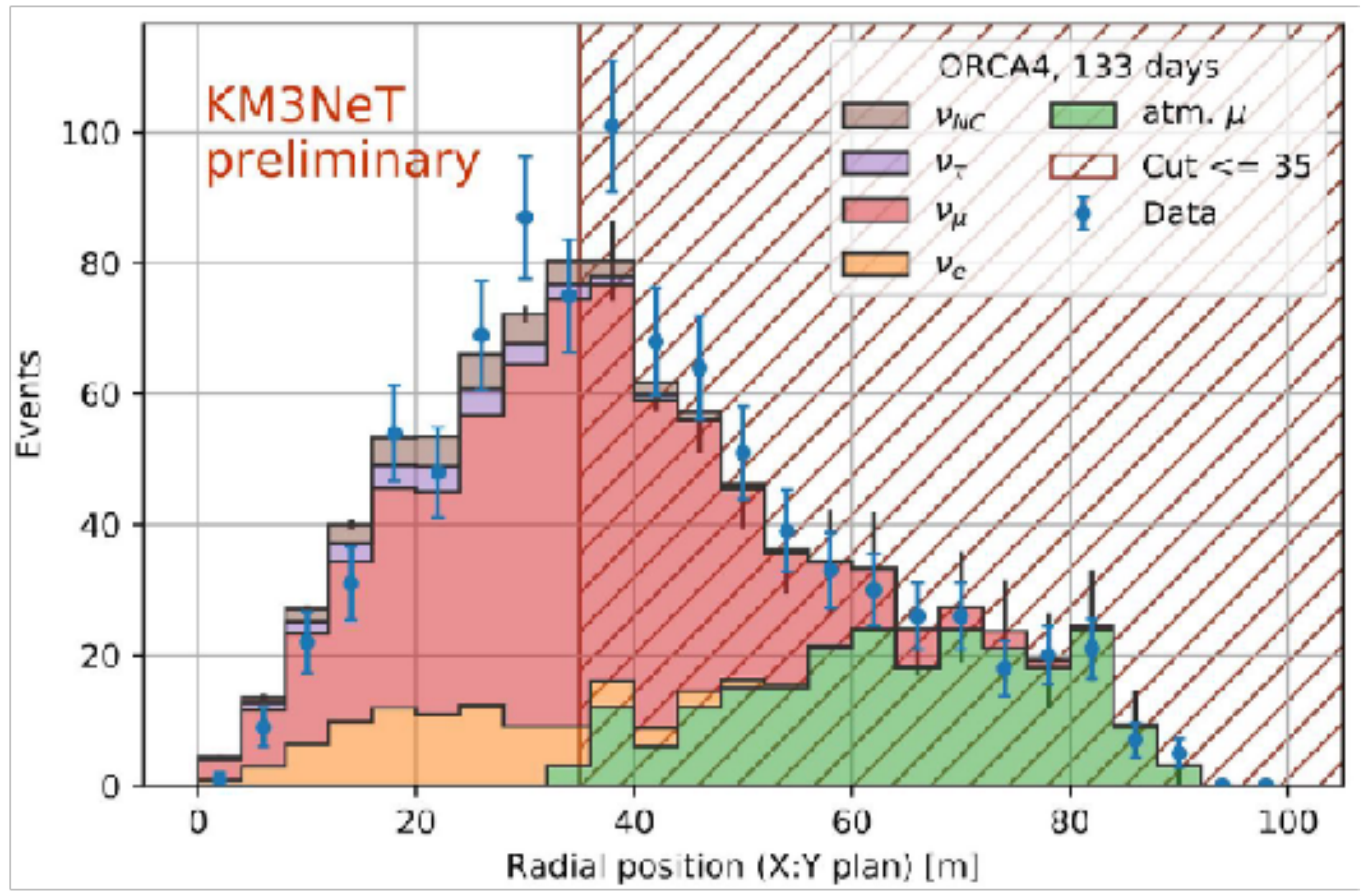
$$^{40}\mathrm{K} + e^- \rightarrow {}^{40}\mathrm{Ar}^* + \bar{\nu}_e \rightarrow {}^{40}\mathrm{Ar} + \bar{\nu}_e + \gamma$$

Uncorrelated in time and space
Rejected thanks to trigger with suitable causality condition

- Bioluminescence

- Atmospheric muons: directional cuts (up-going) + reco quality + ML based classifier

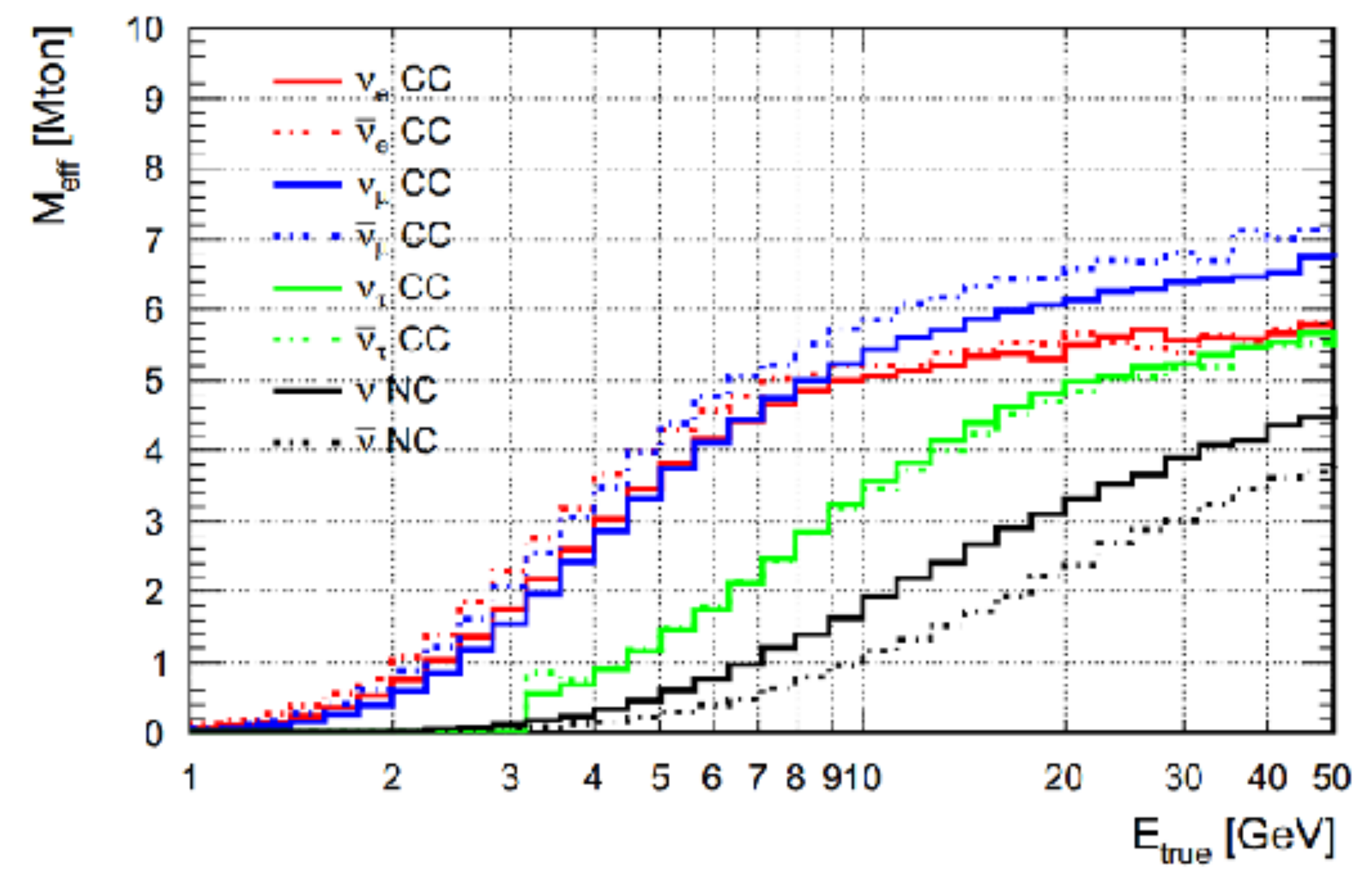


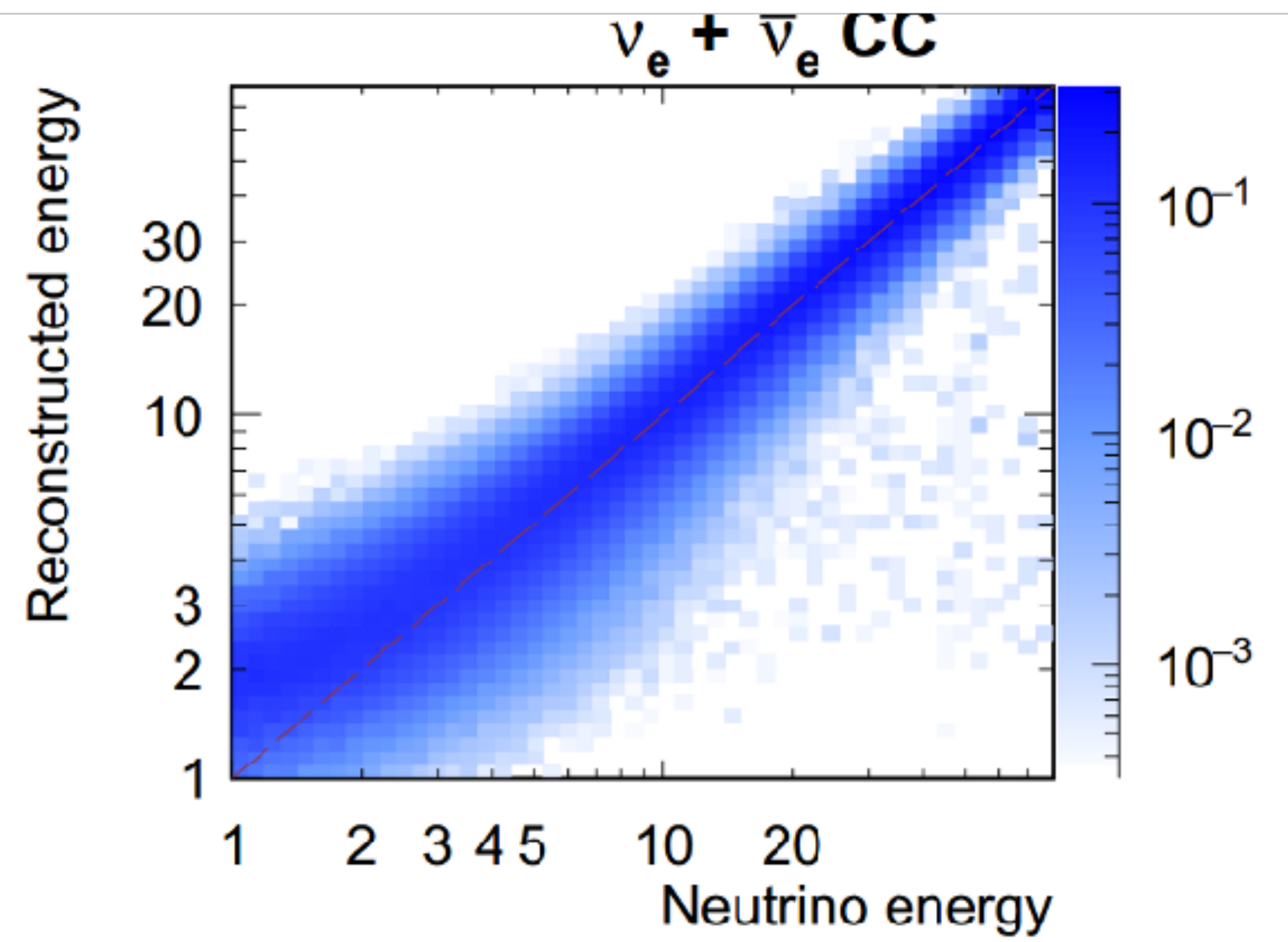
# Detector Response

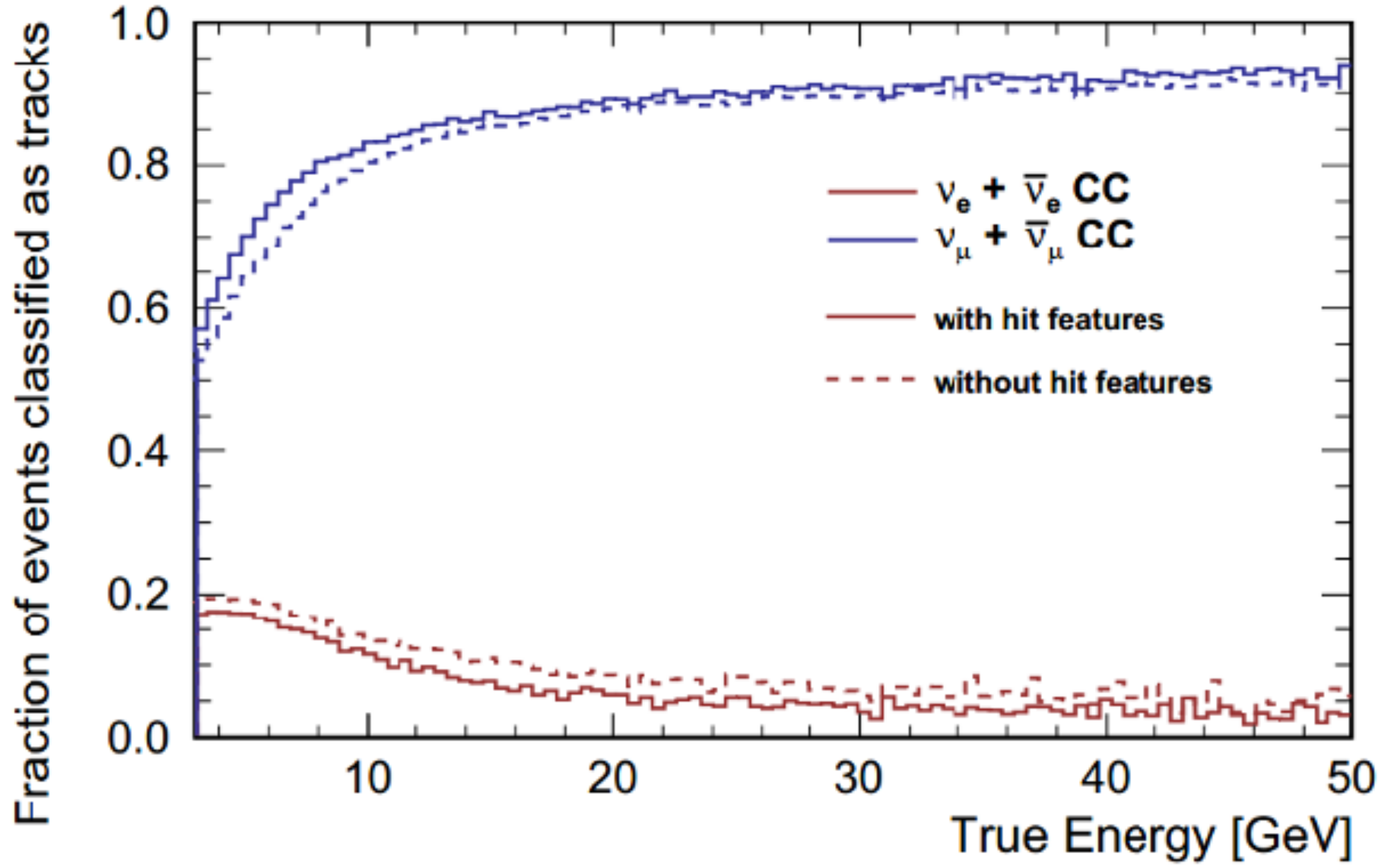
$$R^{[\nu_x\to i]}(E,\theta,y;E',\theta',y') = p_{reco}^{\nu_x\to i}(E,\theta,y,E',\theta',y') \cdot P_{PID}^{\nu_x\to i}(E,\theta,y) \cdot \frac{M_{eff}^{\nu_x}(E,\theta,y)}{M_{ref}}$$

$$M_{eff}^{\nu_x}(E,\theta,y) = M_{ref}\frac{\sum_{i,E',\theta',y'} N_{sel}^{[\nu_x\to i]}(E,\theta,y;E',\theta',y')}{N_{gen}(E,\theta,y)}$$



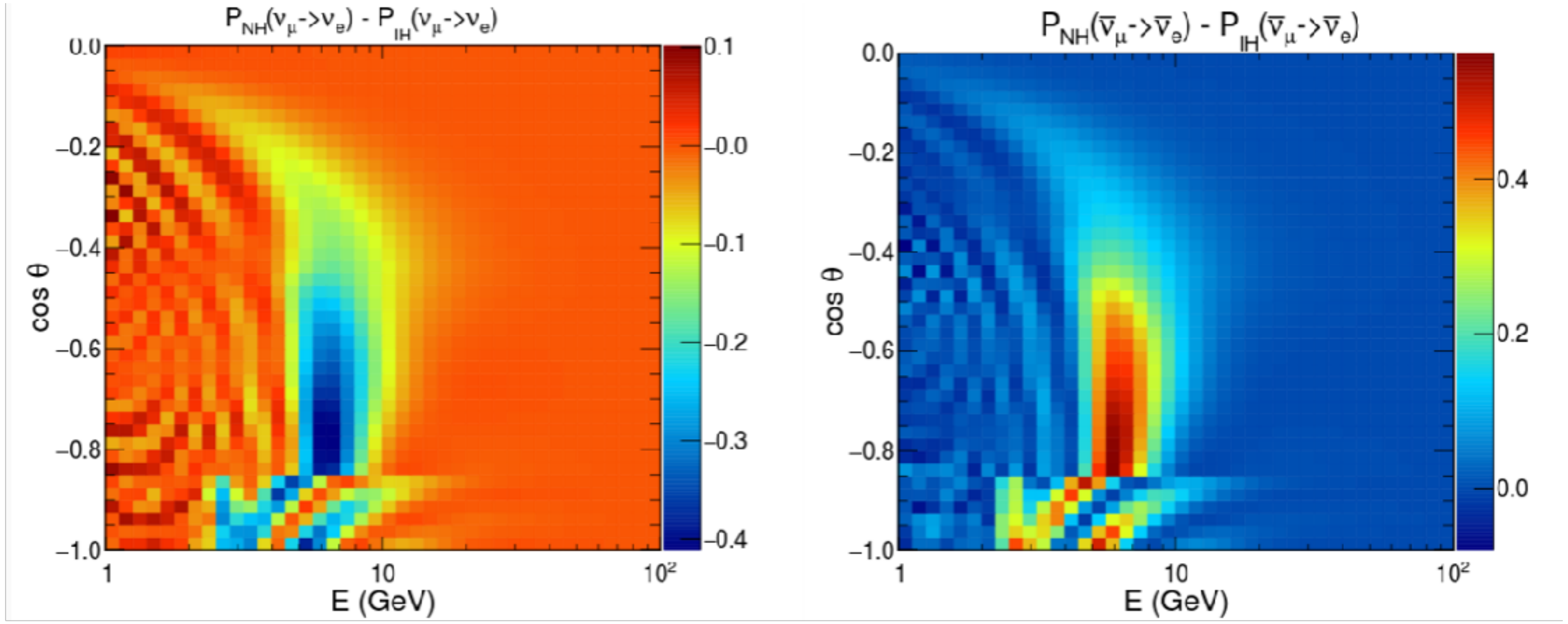

$$p_{reco}^{\nu_x\to i}(E,\theta,y;E',\theta',y') = \frac{N_{sel}^{[\nu_x\to i]}(E,\theta,y;E',\theta',y')}{\sum_{E',\theta',y'} N_{sel}^{\nu_x\to i}(E,\theta,y;E',\theta',y')}$$

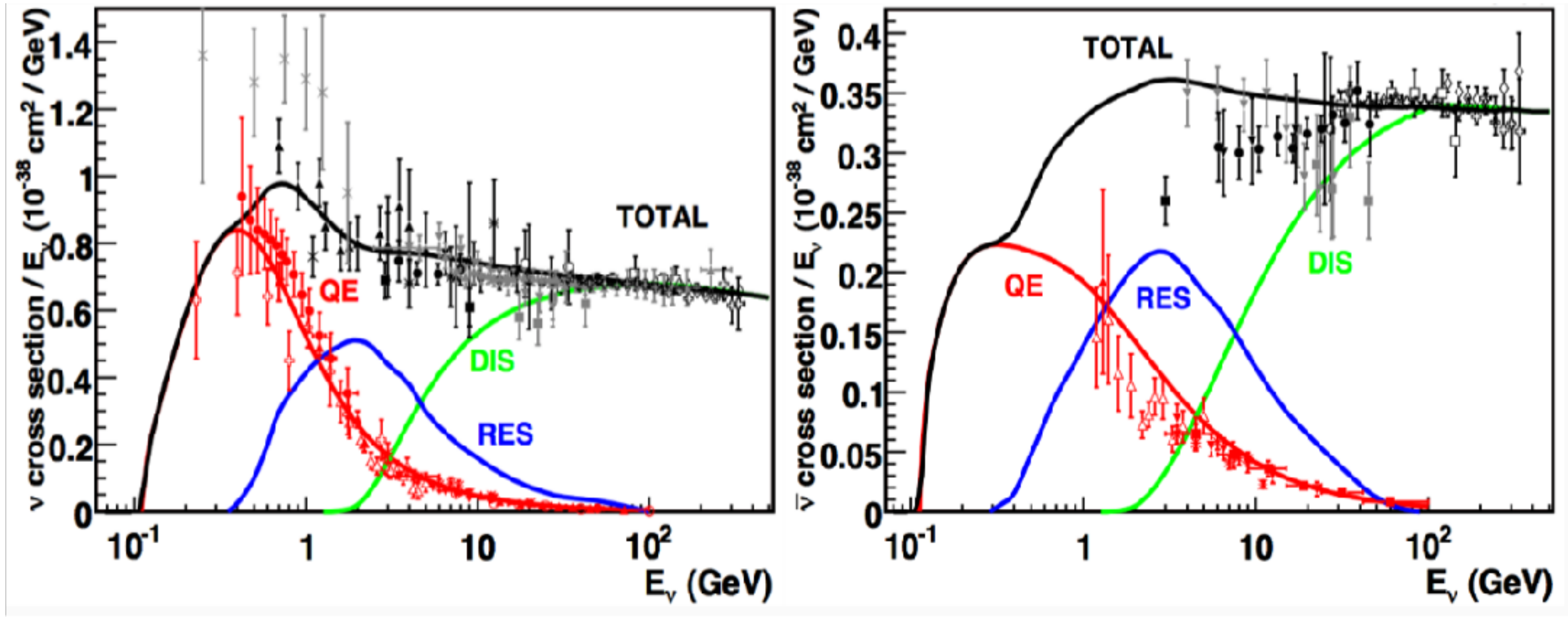



$$P_{PID}^{\nu_x\to i}(E,\theta,y) = \frac{\sum_{E',\theta',y'} N_{sel}^{[\nu_x\to i]}(E,\theta,y;E',\theta',y')}{\sum_{i,E',\theta',y'} N_{sel}^{[\nu_x\to i]}(E,\theta,y;E',\theta',y')}$$

# NMO sensitivity in ORCA




NMO sensitivity preserved thanks to the different in cross-section between neutrinos and antineutrinos

# Parameter treatment

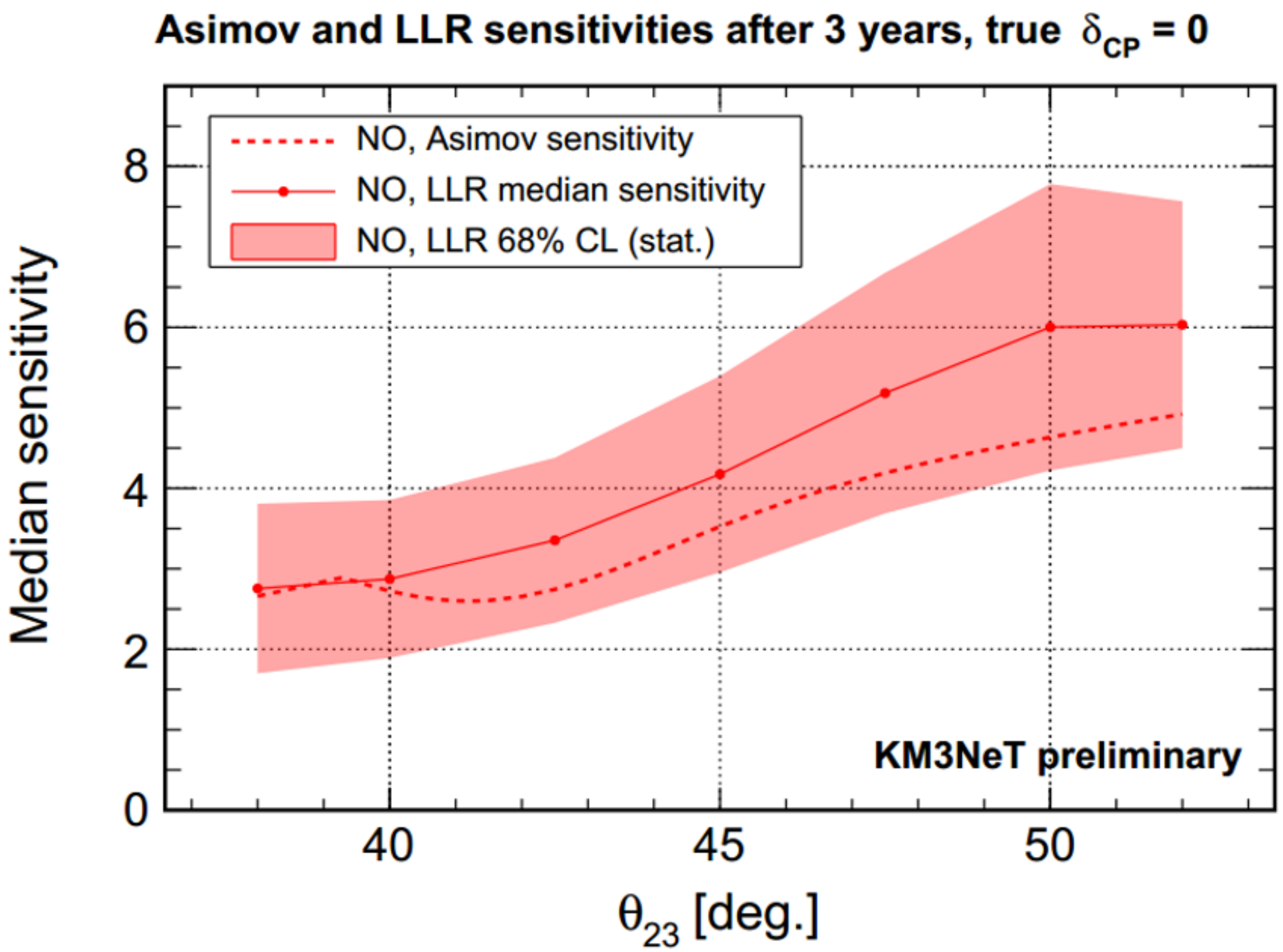
| Parameter | True value | Treatment | Prior |
|---|---|---|---|
| $\theta_{23}(\mathrm{deg})$ | 48.6 (NO)<br>48.8 (IO) | *Fitted* | $\times$ |
| $\theta_{13}(\mathrm{deg})$ | 8.60 (NO)<br>8.64 (IO) | *Fitted* | $\mu = 8.60, \sigma = 0.13$ |
| $\theta_{12}(\mathrm{deg})$ | 33.82 | Fixed | $\times$ |
| $\Delta m^2_{31}(10^{-3}\mathrm{eV}^2)$ | 2.528 (NO)<br>-2.510 (IO) | *Fitted* | $\times$ |
| $\Delta m^2_{21}(10^{-5}\mathrm{eV}^2)$ | 7.39 | Fixed | $\times$ |
| $\delta_{CP}(\mathrm{deg})$ | 221 (NO)<br>282 (IO) | *Fitted* | $\times$ |
| Flux $\nu_e/\bar{\nu}_e$ skew | 0 | *Fitted* | $\mu = 0, \sigma = 0.07$ |
| Flux $\nu_\mu/\bar{\nu}_\mu$ skew | 0 | *Fitted* | $\mu = 0, \sigma = 0.05$ |
| Flux $\nu_e/\bar{\nu}_\mu$ skew | 0 | *Fitted* | $\mu = 0, \sigma = 0.02$ |
| Flux spectral index | 0 | *Fitted* | $\times$ |
| Flux zenith slope | 0 | *Fitted* | $\mu = 0, \sigma = 0.05$ |
| NC normalization | 1 | *Fitted* | $\mu = 1, \sigma = 0.1$ |
| Energy scale | 1 | *Fitted* | $\mu = 1, \sigma = 0.05$ |
| PID class norm. | 1 | *Fitted* | $\times$ |

# NMO sensitivity - The Asimov approach

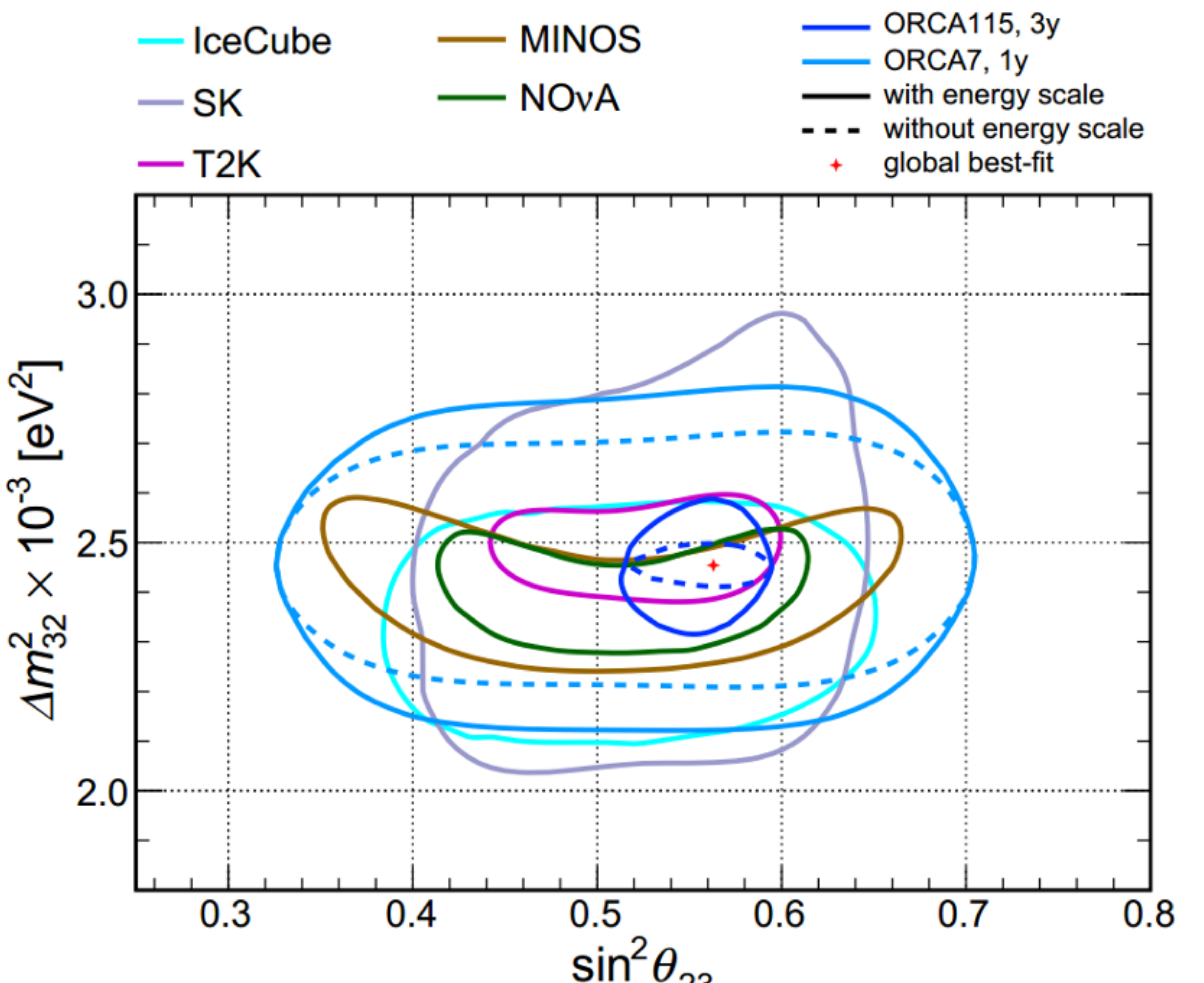
$$S_{NO(IO)} = \sqrt{2}\mathrm{erfc}^{-1}\left[\mathrm{erfc}\left(\frac{\overline{\Delta\chi^2}_{IO} + \overline{\Delta\chi^2}_{NO}}{\sqrt{8\overline{\Delta\chi^2}_{IO(NO)}}}\right)\right]$$

Simple squared root for median significance only a good approximation
When: $\Delta\chi^2_{NO} \approx \Delta\chi^2_{IO}$

- ~1.5 sigma underestimation



# Oscillation parameter measurement

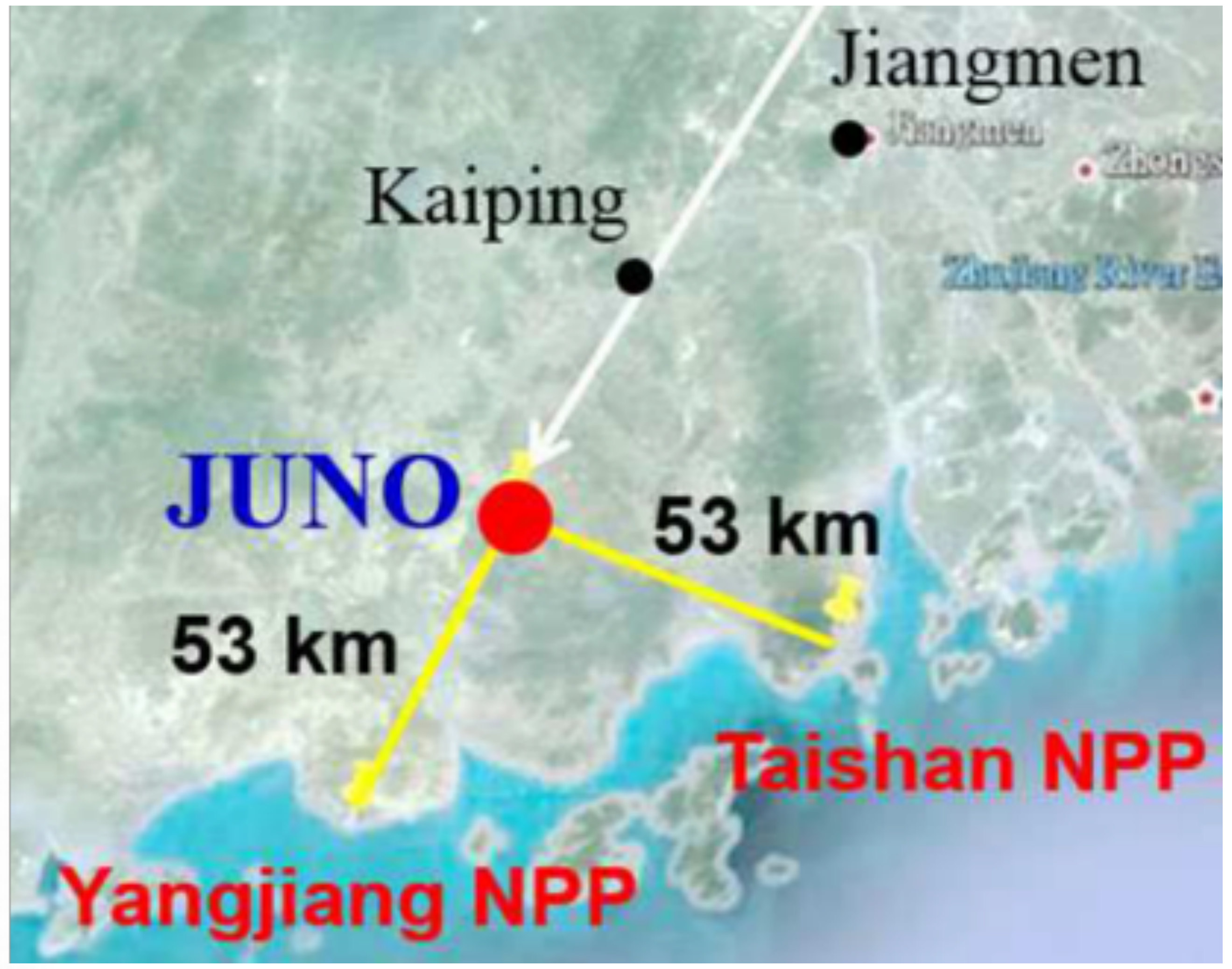


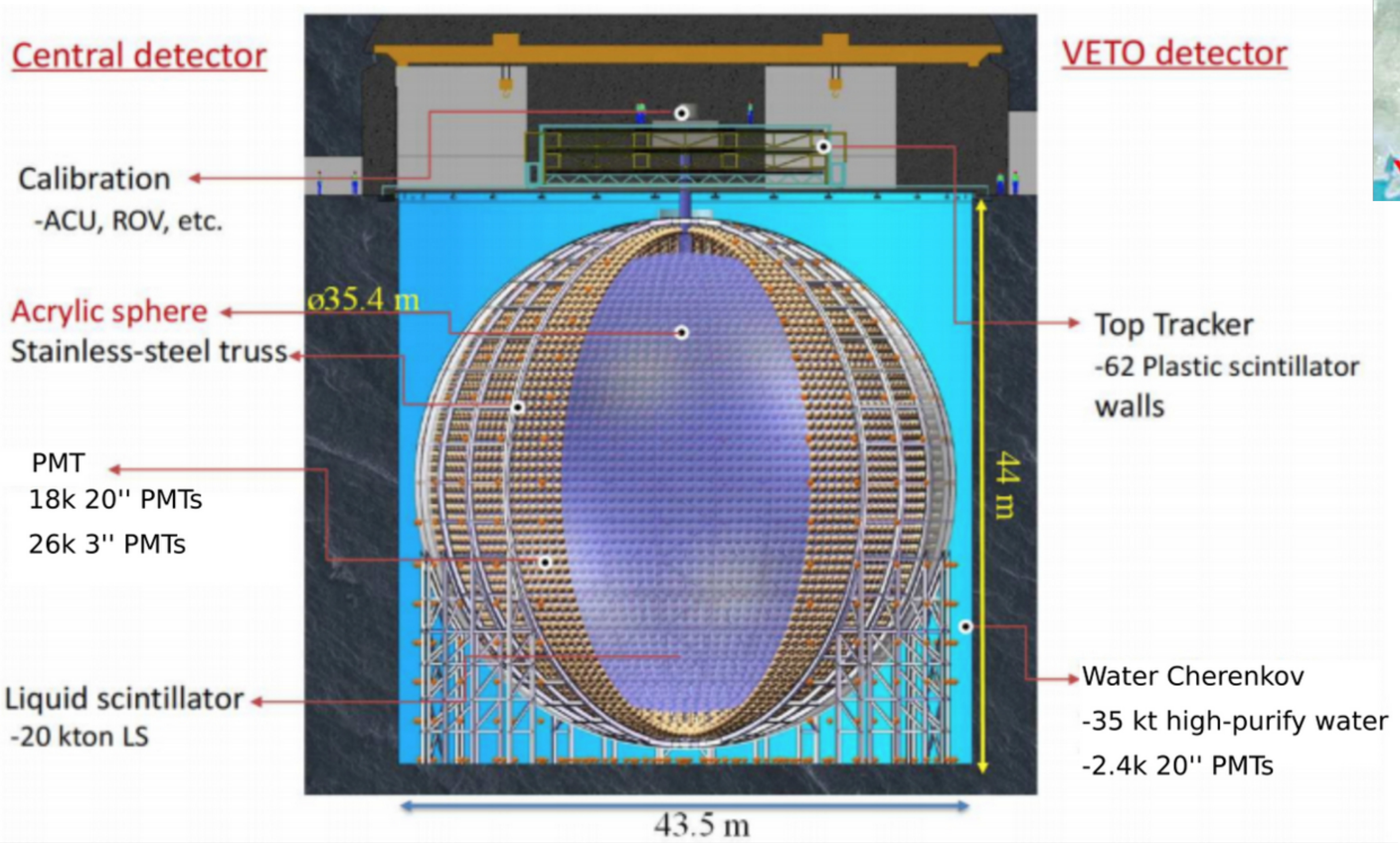
# ORCA and JUNO Combination

$$\chi^2(\Delta m^2_{31}, \theta_{13}) = \chi^2_{\text{JUNO}}(\Delta m^2_{31}, \theta_{13}) + \chi^2_{\text{ORCA}}(\Delta m^2_{31}, \theta_{13}) + \frac{\left(\sin^2\theta_{13} - \sin^2\theta_{13}^{GF}\right)^2}{\sigma^2_{\sin^2\theta_{13}^{GF}}}$$

| Osc. parameter | JUNO | ORCA |
|---|---|---|
| $\theta 13$ | grid scan | |
| $\Delta m^2{}_{31}$ | grid scan | |
| $\theta 23$ | x | fitted |
| $\Delta m^2{}_{21}$ | fitted | *fixed* |
| $\theta 12$ | *fixed* | *fixed* |
| $\delta$CP | x | fitted |

# JUNO detector



# Early phase of ORCA + JUNO