OSCILLATION PHYSICS WITH KM3NeT/ORCA

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Neutrino Oscillation Workshop 2022
Ostuni (Italy) - September 6th, 2022

Outline

- Introduction: atmospheric neutrinos in a nutshell

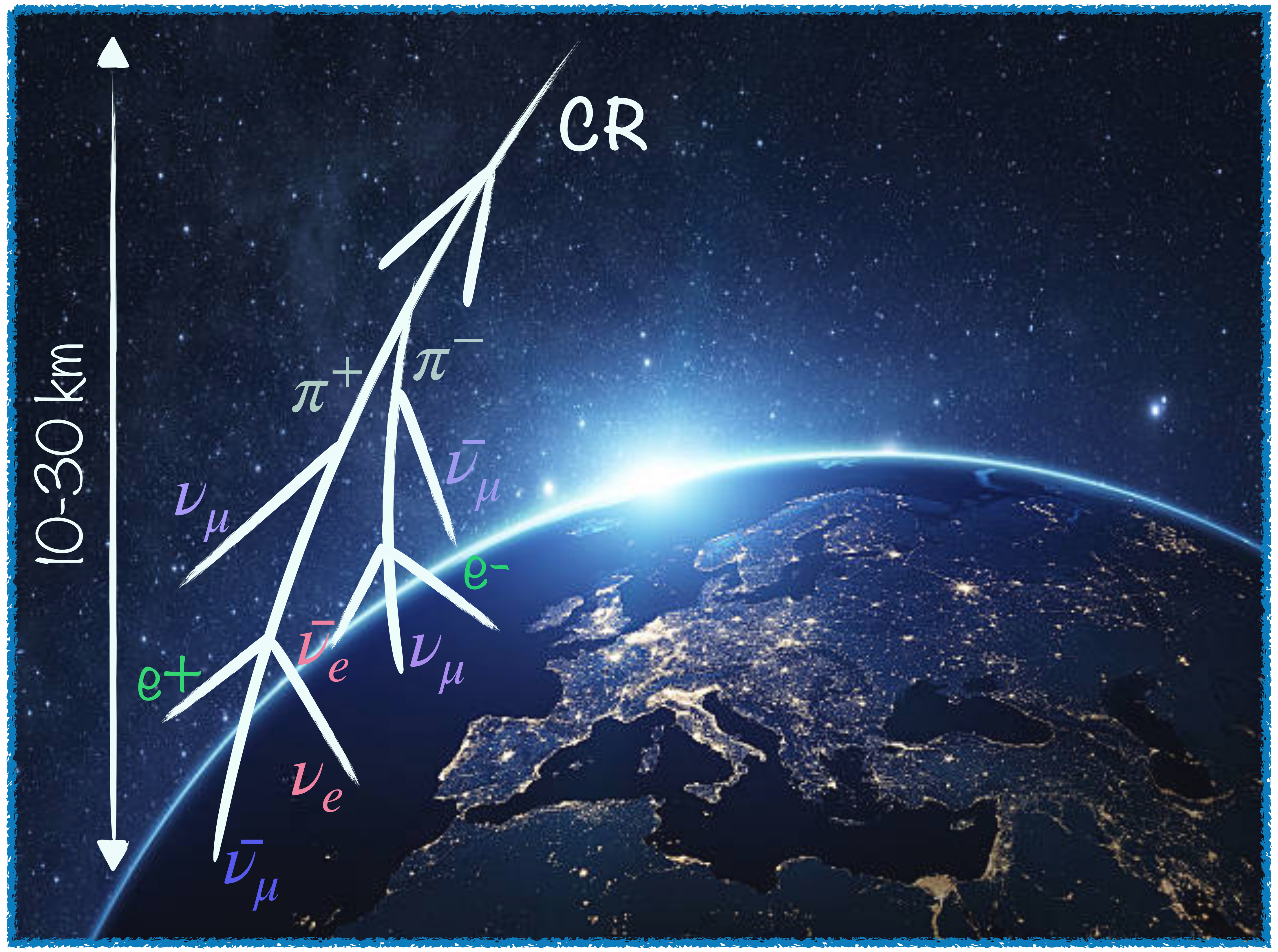
- The KM3NeT experiment: detection principle, technology, and detector geometry

- Neutrino oscillation in KM3NeT/ORCA
  - ❍ sensitivity to main physics studies
  - ❍ other “low-energy” physics searches
  - ❍ current analyses and first results

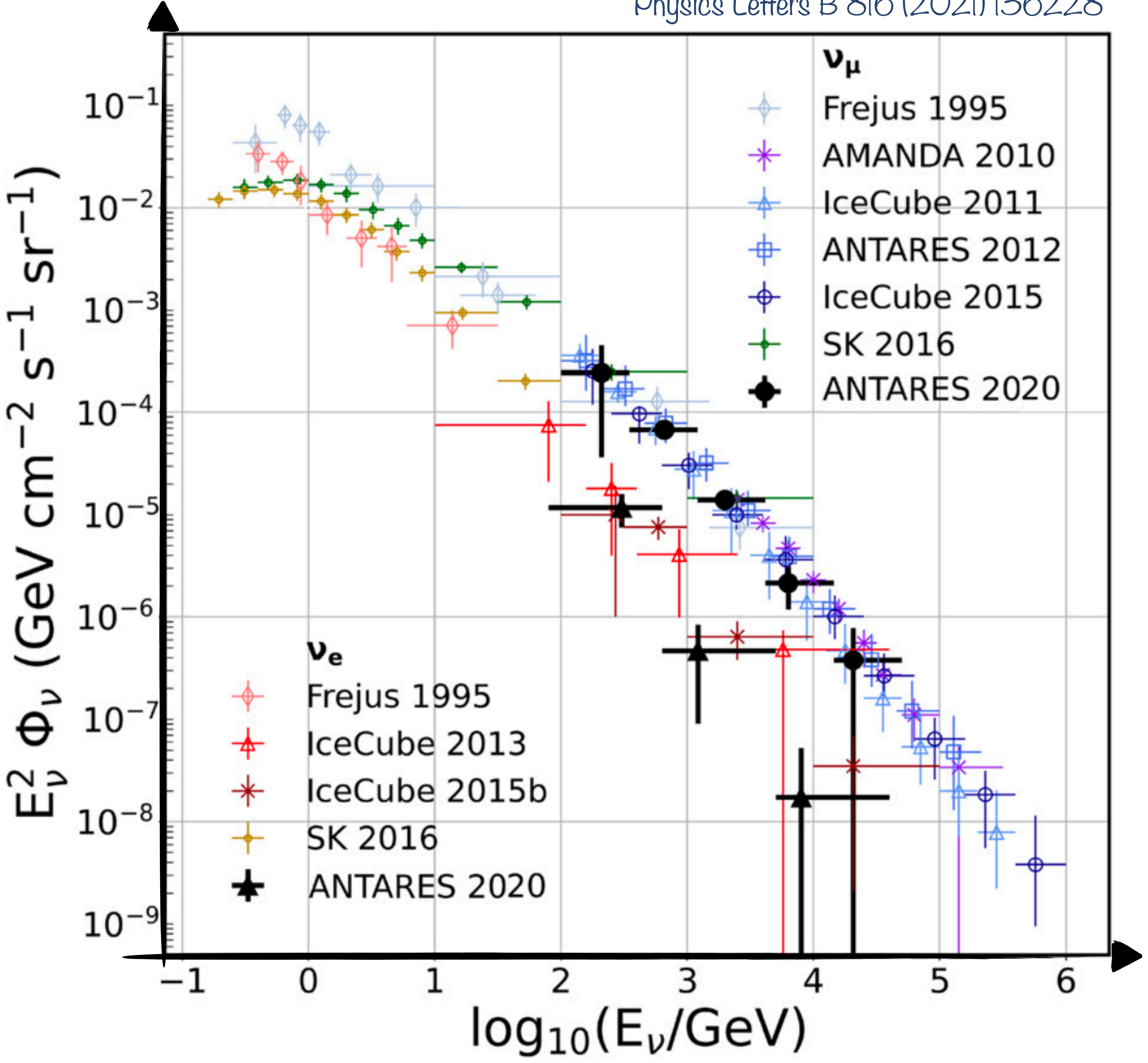
- Summary and outlook

Introduction: atmospheric neutrino flux

- **Secondary particles** produced from the **interaction of Cosmic Rays (CR) with the earth's atmosphere**:
  - energy range spanning between few GeV up to TeV
  - $\nu_\mu/\nu_e \sim 2$ at around 1 GeV, otherwise $\nu_\mu/\nu_e > 2$

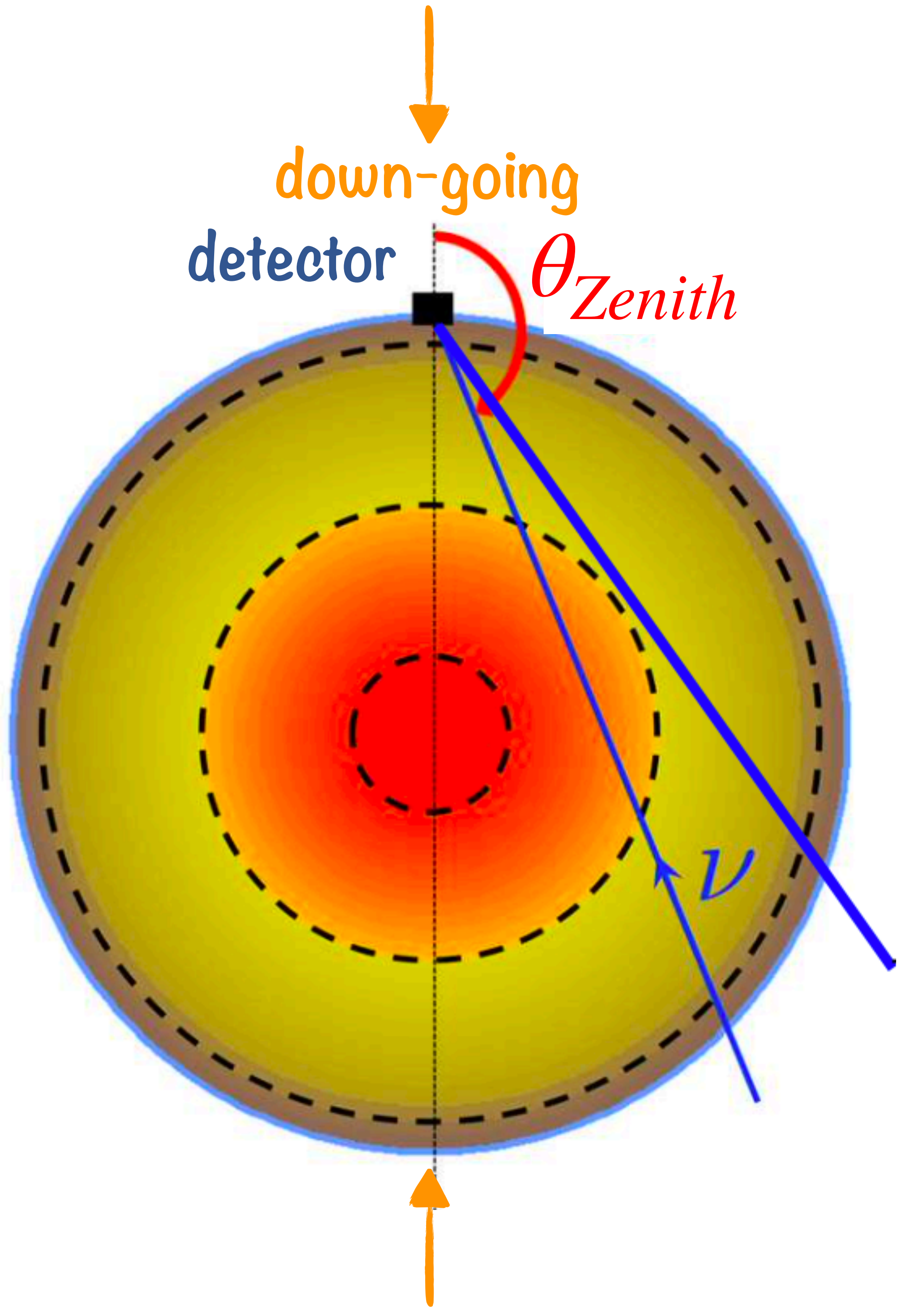


Physics Letters B 816 (2021) 136228

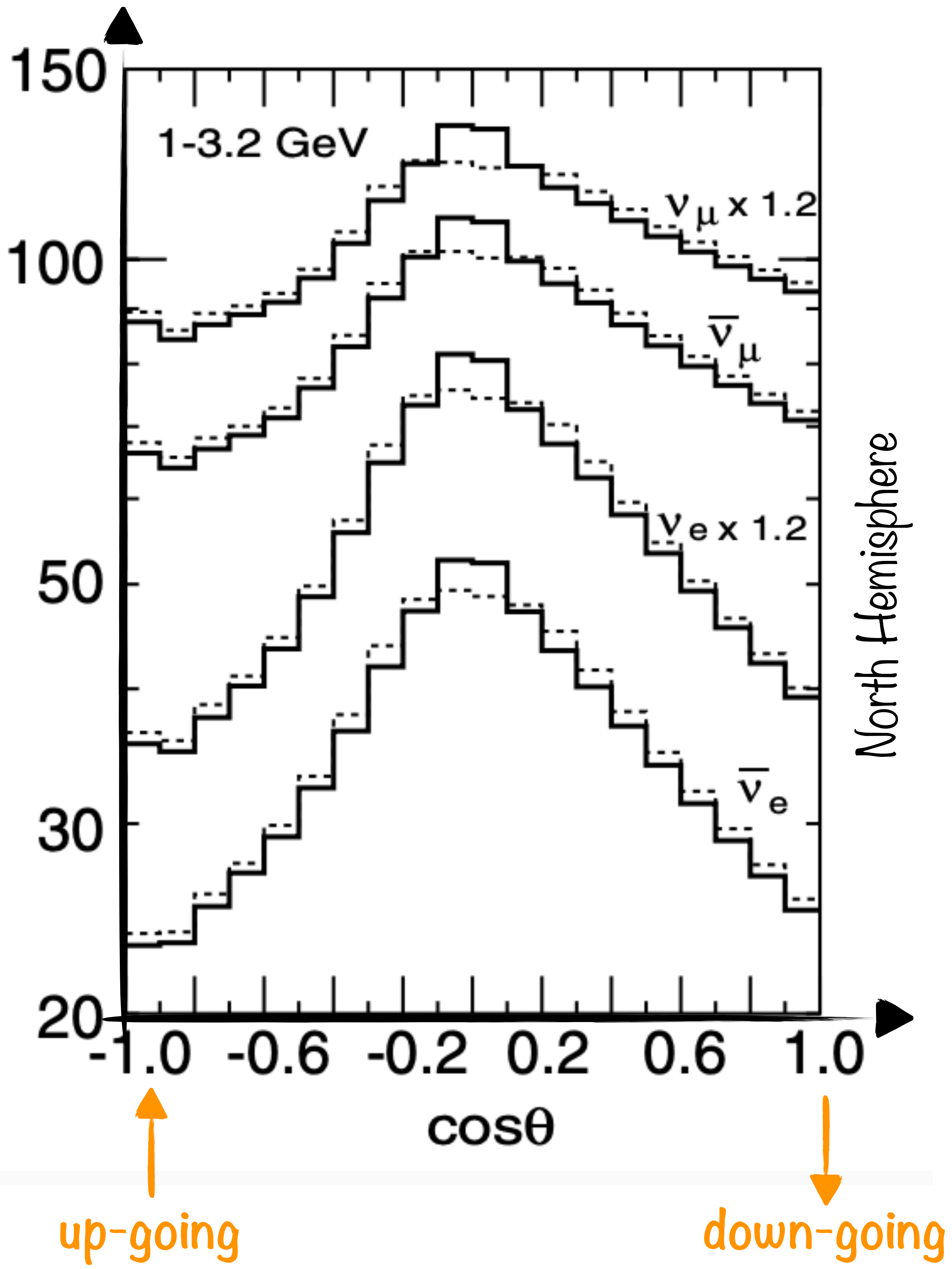


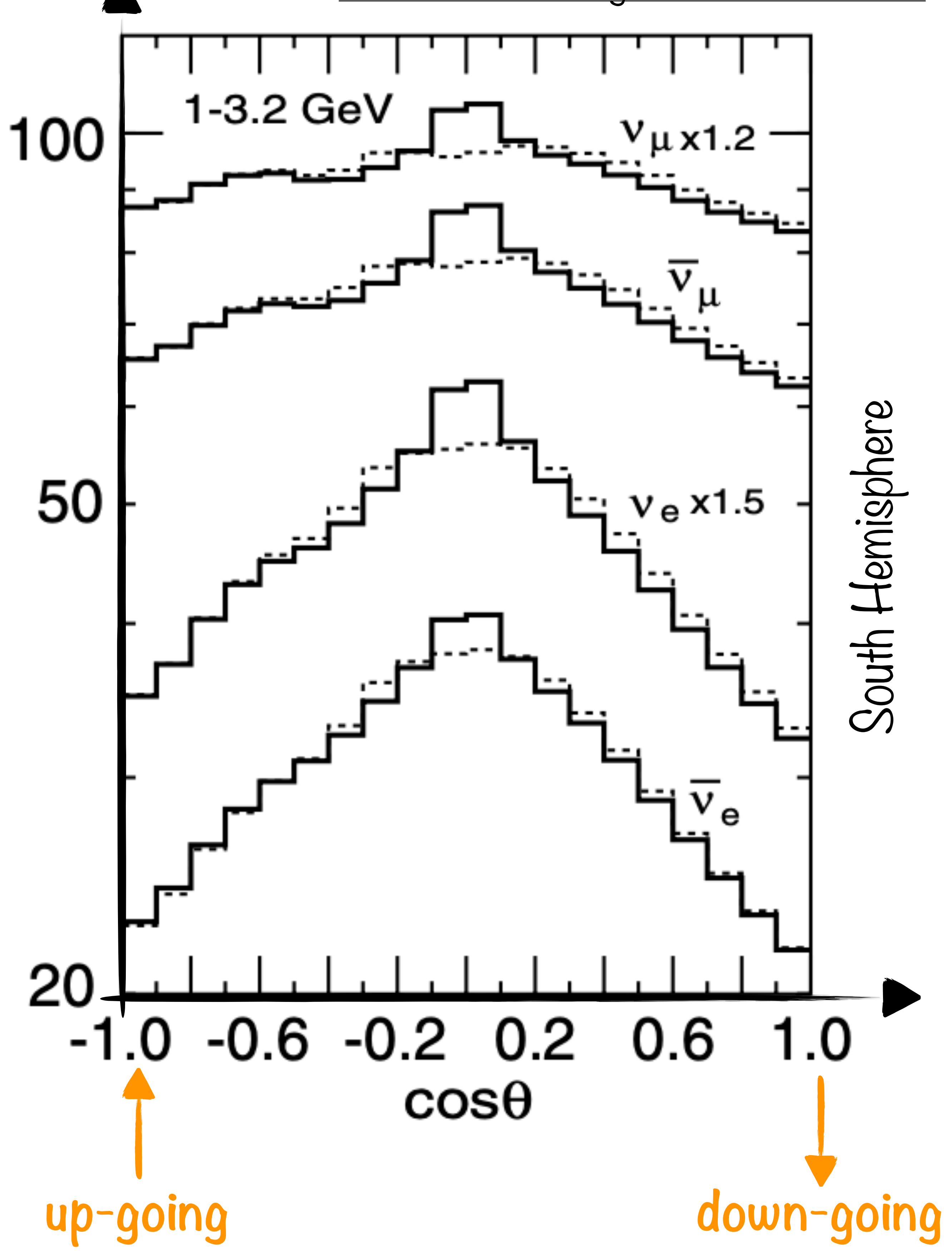
Introduction: atmospheric neutrino oscillation measurement

- Measurement of the **atm. neutrino flux** as a function of the **zenith angle** and **energy**
  - ❍ baseline ~ cosine zenith angle of the incoming neutrino
  - ❍ very wide baseline range, from 10-30 km up to 13000 km (up-going events crossing the earth)

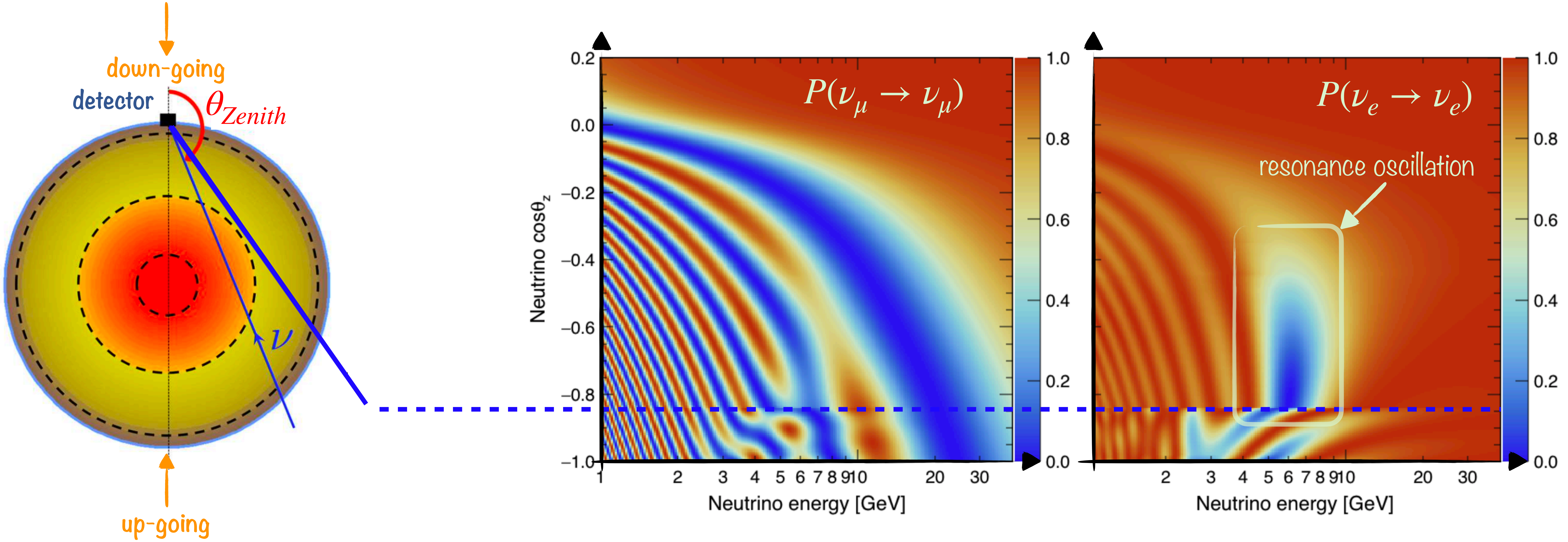


New Journal of Physics 6 (2004) 194



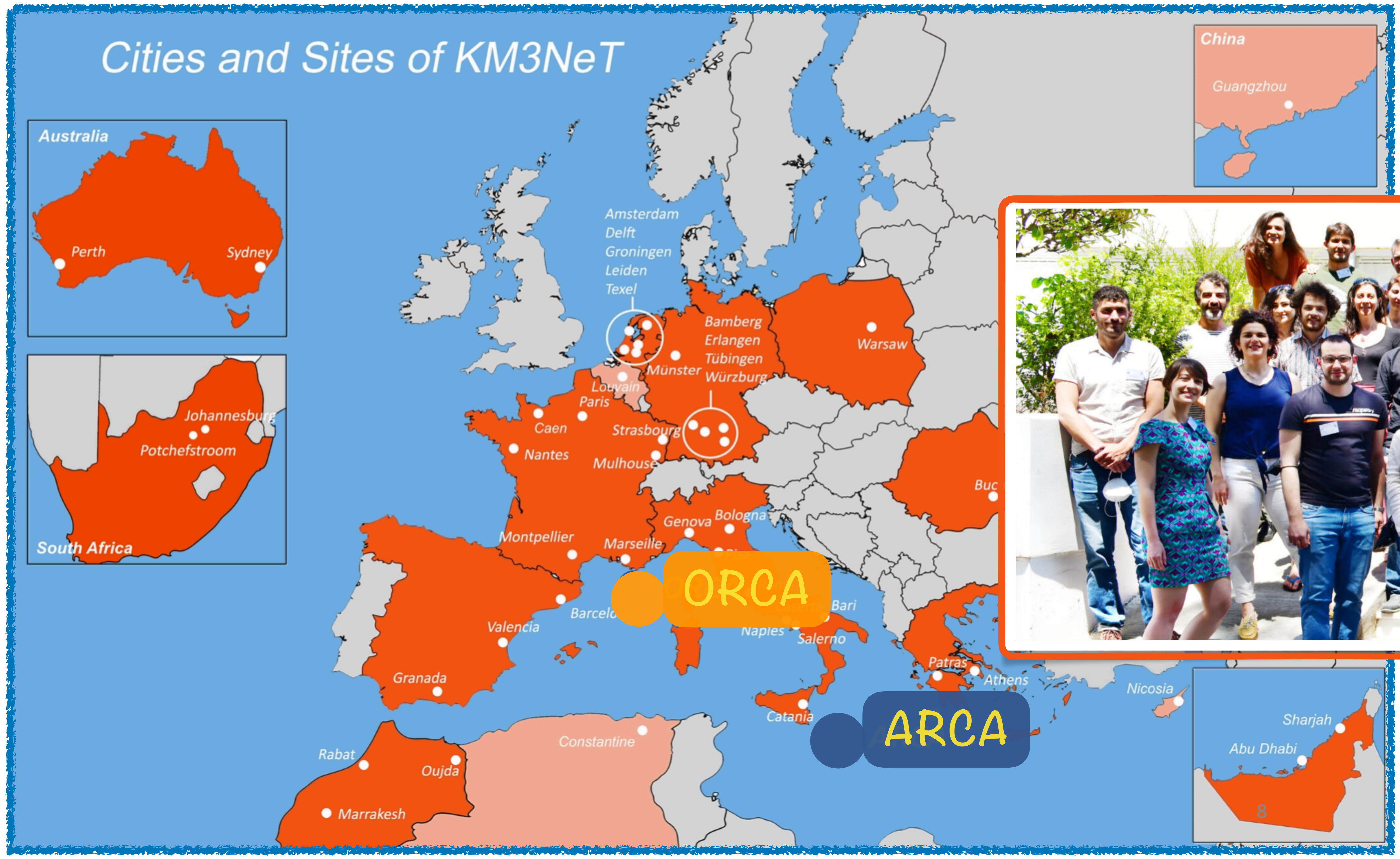


- ν_μ **disappearance** is the dominant effect:
  - measurement of **neutrino oscillation parameters**, θ_{23} and Δm^2_{32}
- ν_e **appearance**, sub-dominant effect:
  - sensitive to the **Neutrino Mass Ordering (NMO)**, resonance oscillation in the earth due to matter effect



KM3NeT: detection principle

- **KM3NeT**, Cubic Kilometre Neutrino Telescope: **Water Cherenkov neutrino telescope** in the **deep Mediterranean Sea**

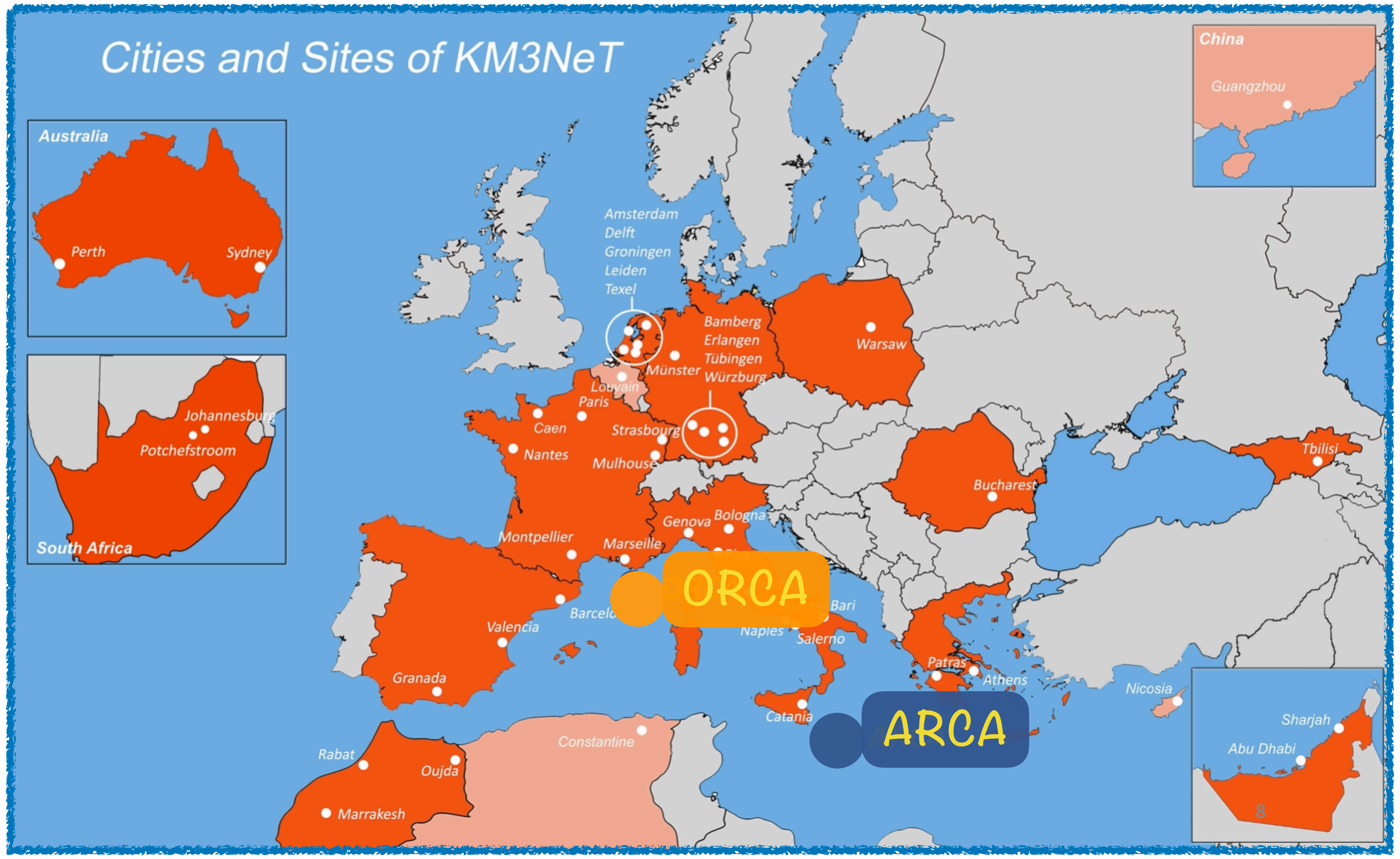


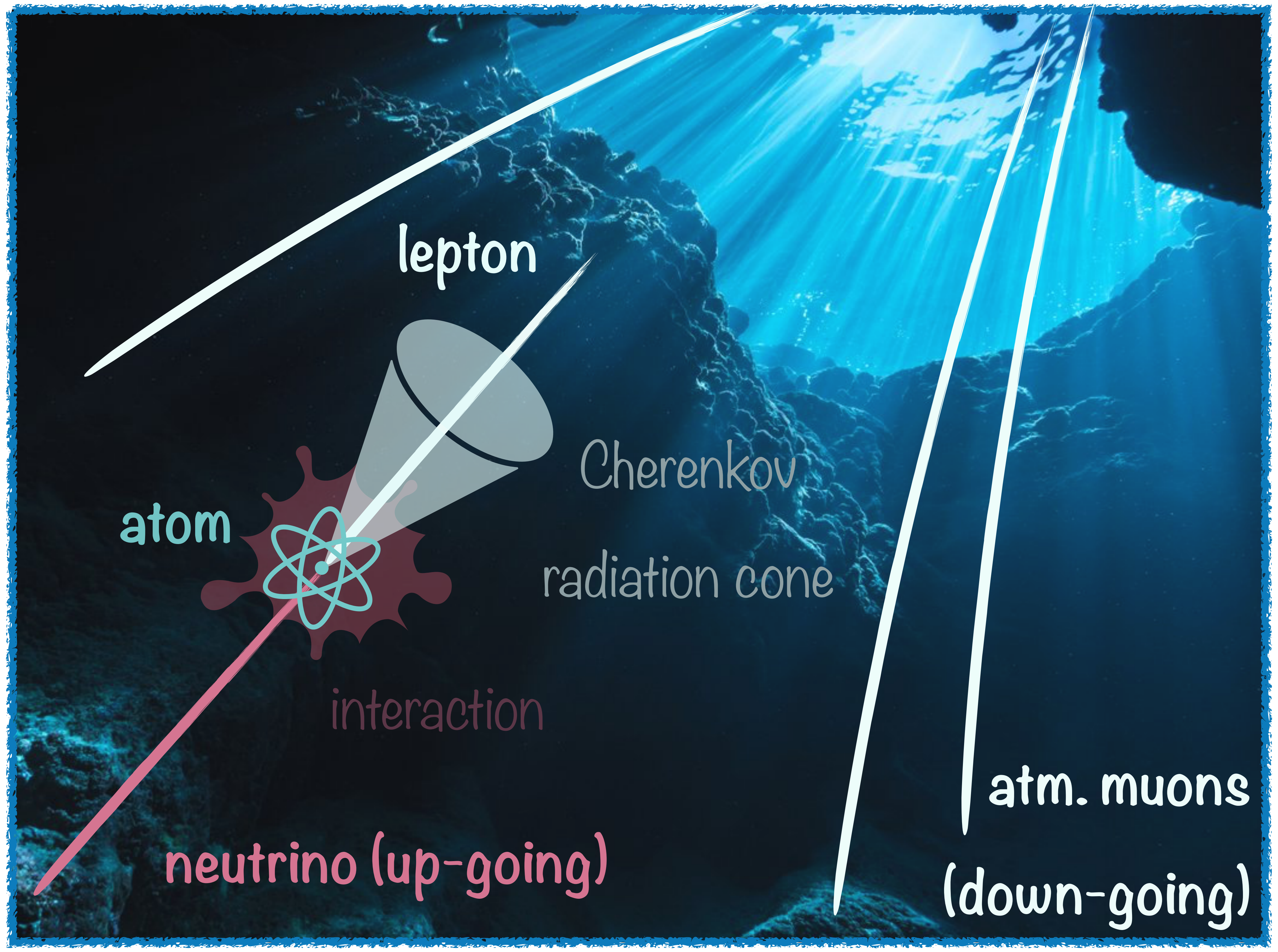
KM3NeT Collaboration meeting (May, 2022)

- 55 groups
- 16 countries
- 4 continents
- 2 detector sites

KM3NeT: detection principle

- **KM3NeT**, Cubic Kilometre Neutrino Telescope: **Water Cherenkov neutrino telescope** in the **deep Mediterranean Sea**
  - ❍ large detection volume which allows for huge statistics
  - ❍ large array of photosensors for detecting the Cherenkov radiation from secondary particles





KM3NeT: technology

Eur. Phys. J. C 80, 99 (2020)
J. Phys. G: Nucl. Part. Phys. 43 084001 (2016)

- Same **modular structure** adaptable for different physics purposes:
  - **high time precision** (~ns)
  - **good spatial resolution** (~10 cm)

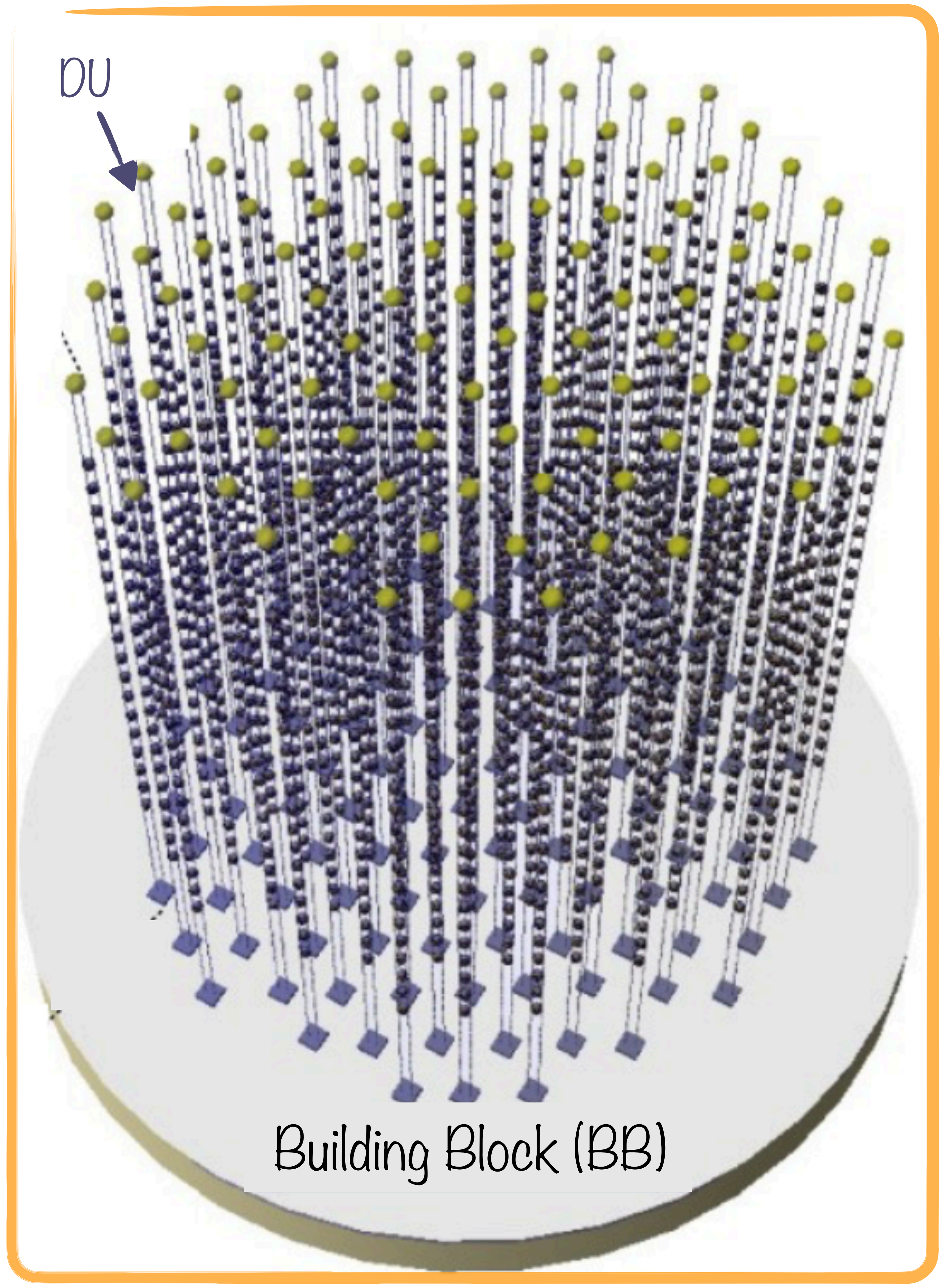
3" PMTs

x 31

Digital Optical Module (DOM)

x 18

x 115

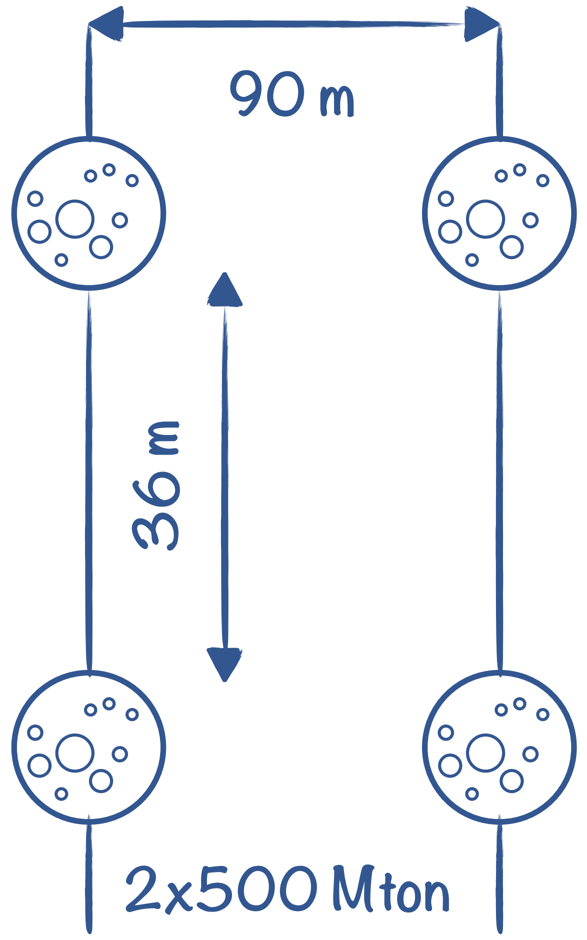


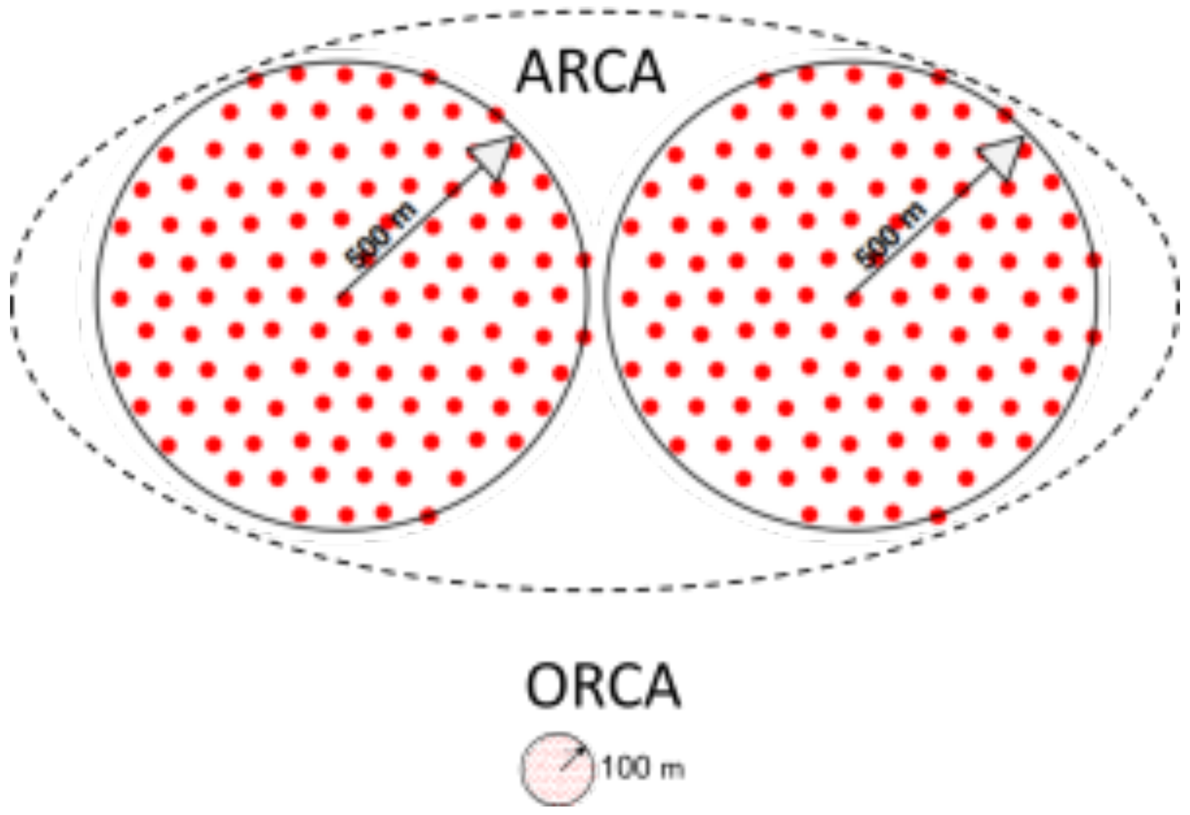
Building Block (BB)

KM3NeT: detector geometry

- Two detection sites (**ARCA** in Italy, and **ORCA** in France) with a wide **physics program: from GeV to PeV**
  - ARCA, Astroparticle Research with Cosmics in the Abyss

- 3560 m depth
  (~100 km off-shore Capo Passero, in Sicily)
- 2 BB (230 DUs, 128340 PMTs)
- Detector configuration optimised for **neutrino astronomy** in the **[1 TeV, 10 PeV]** energy range
- so far, 19/230 lines installed (~8% of nominal vol.)





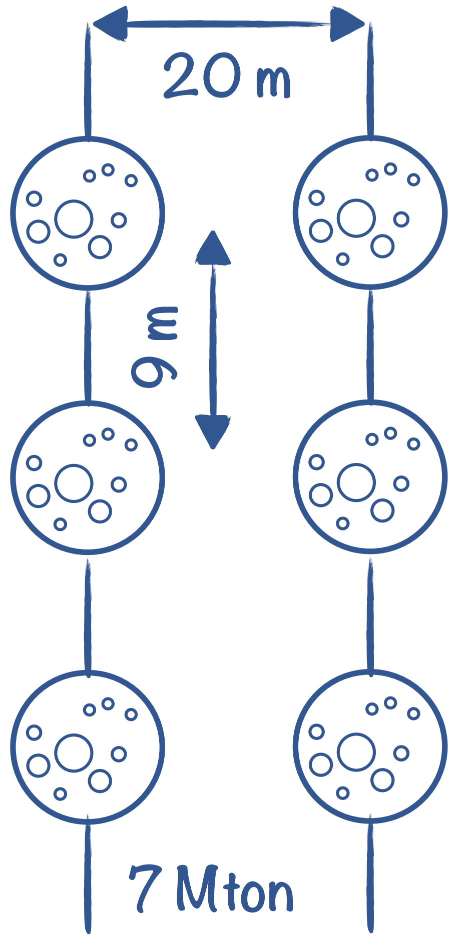
KM3NeT: detector geometry

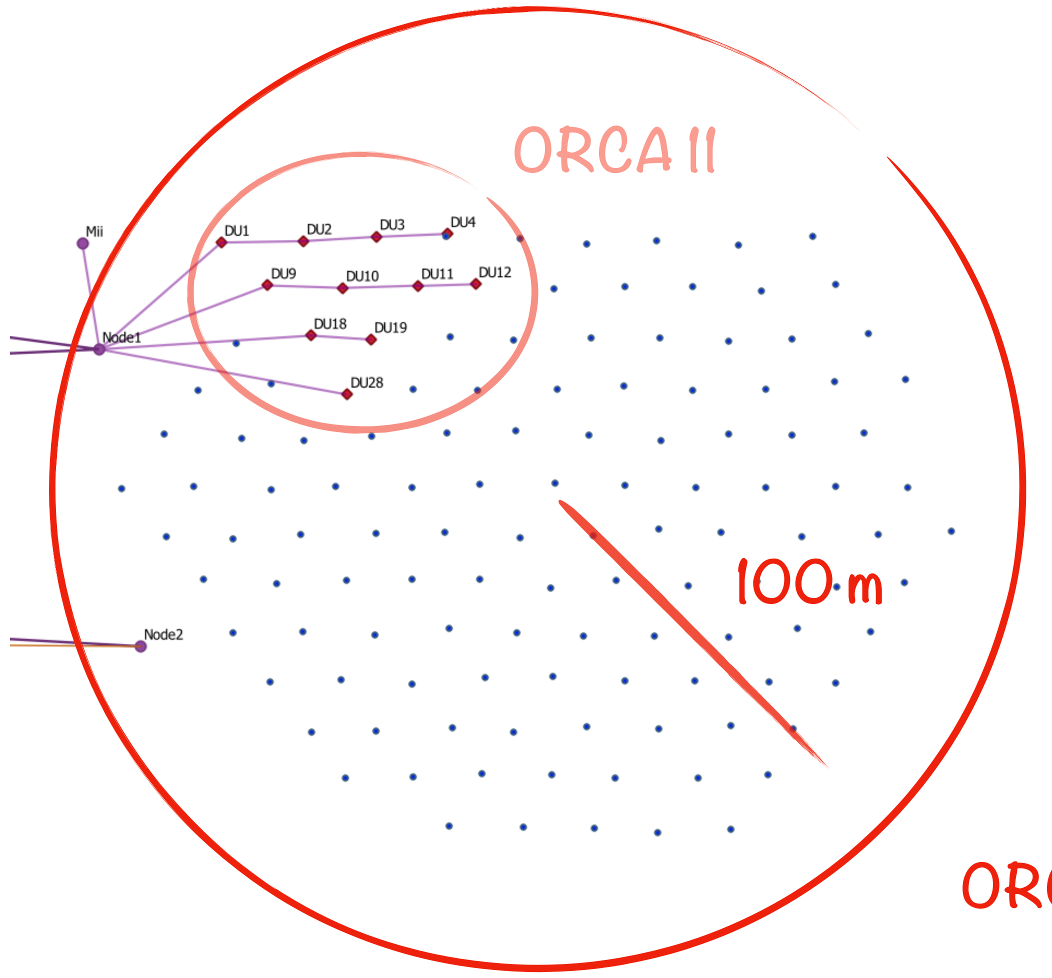
- Two detection sites (**ARCA** in Italy, and **ORCA** in France) with a wide **physics program: from GeV to PeV**
  - ARCA, Astroparticle Research with Cosmics in the Abyss
  - ORCA, Oscillation Research with Cosmics in the Abyss

- 2450 m depth (~40 km off-shore Toulon, in Provence)
- 1 BB (115 DUs, 64170 PMTs)
- Detector configuration optimised for **neutrino oscillation physics** in the **[1 GeV, 100 GeV]** energy range

(this talk)

- so far, 11/115 lines installed (~10% of nominal vol.)

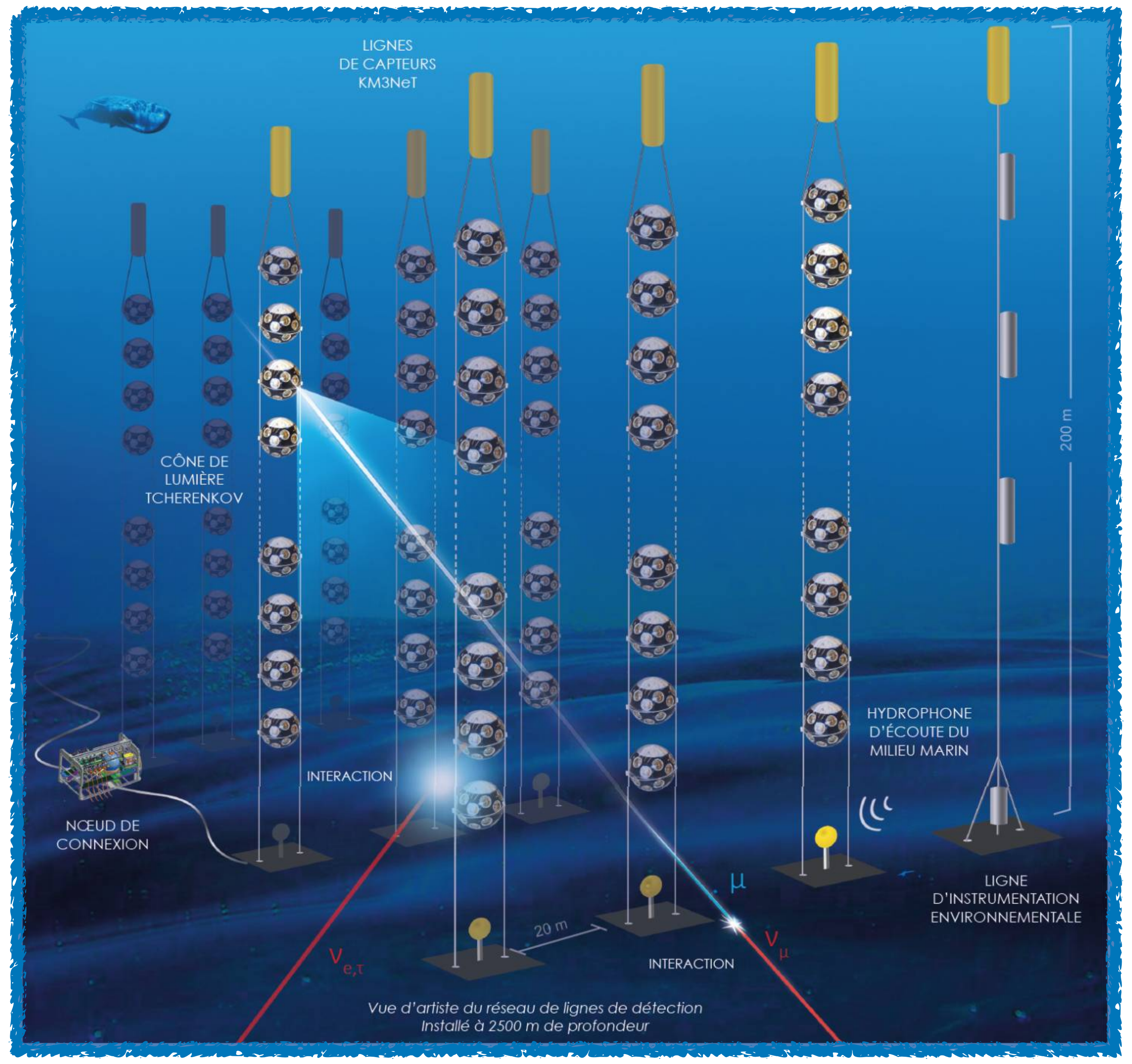


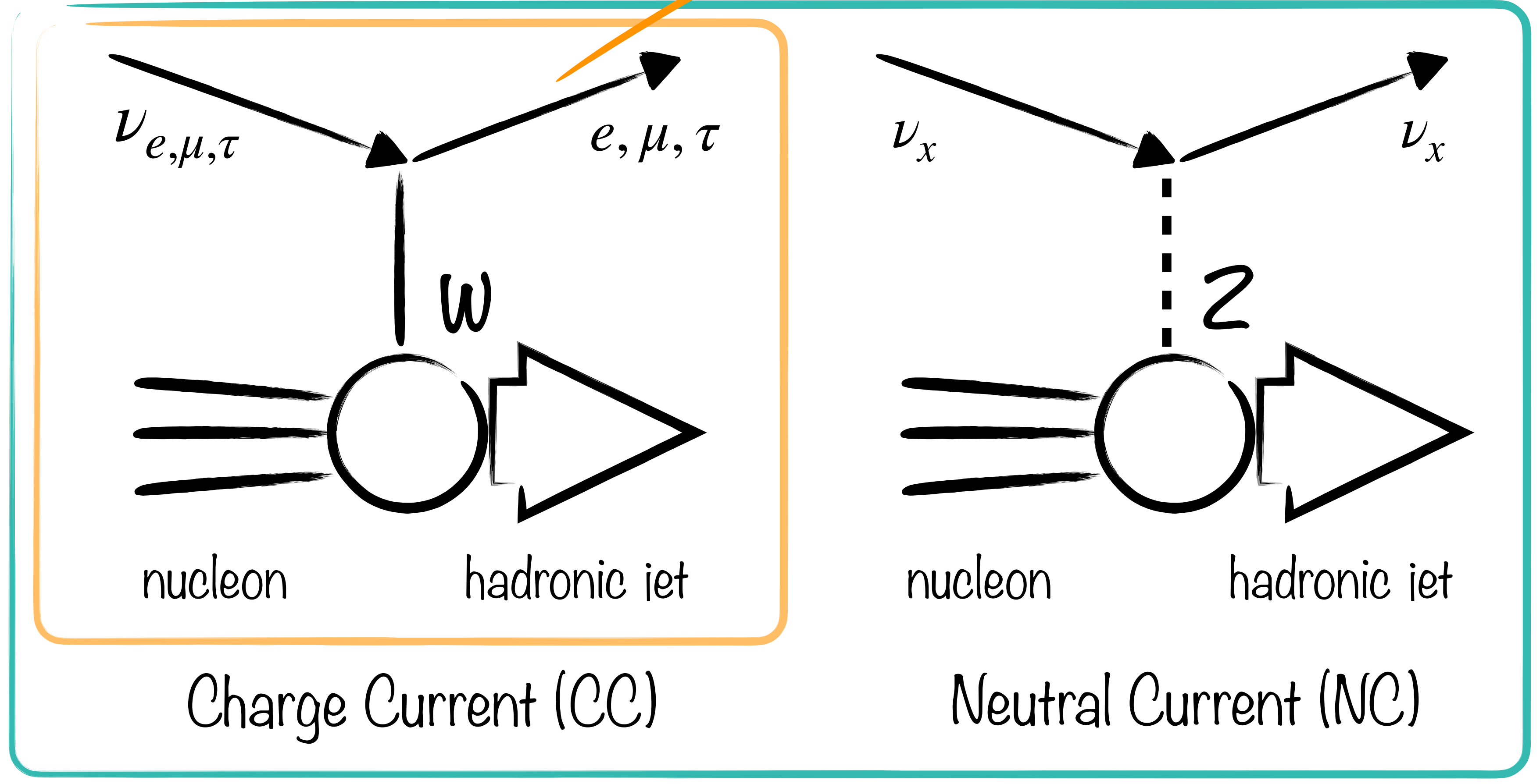


KM3NeT/ORCA: neutrino topologies

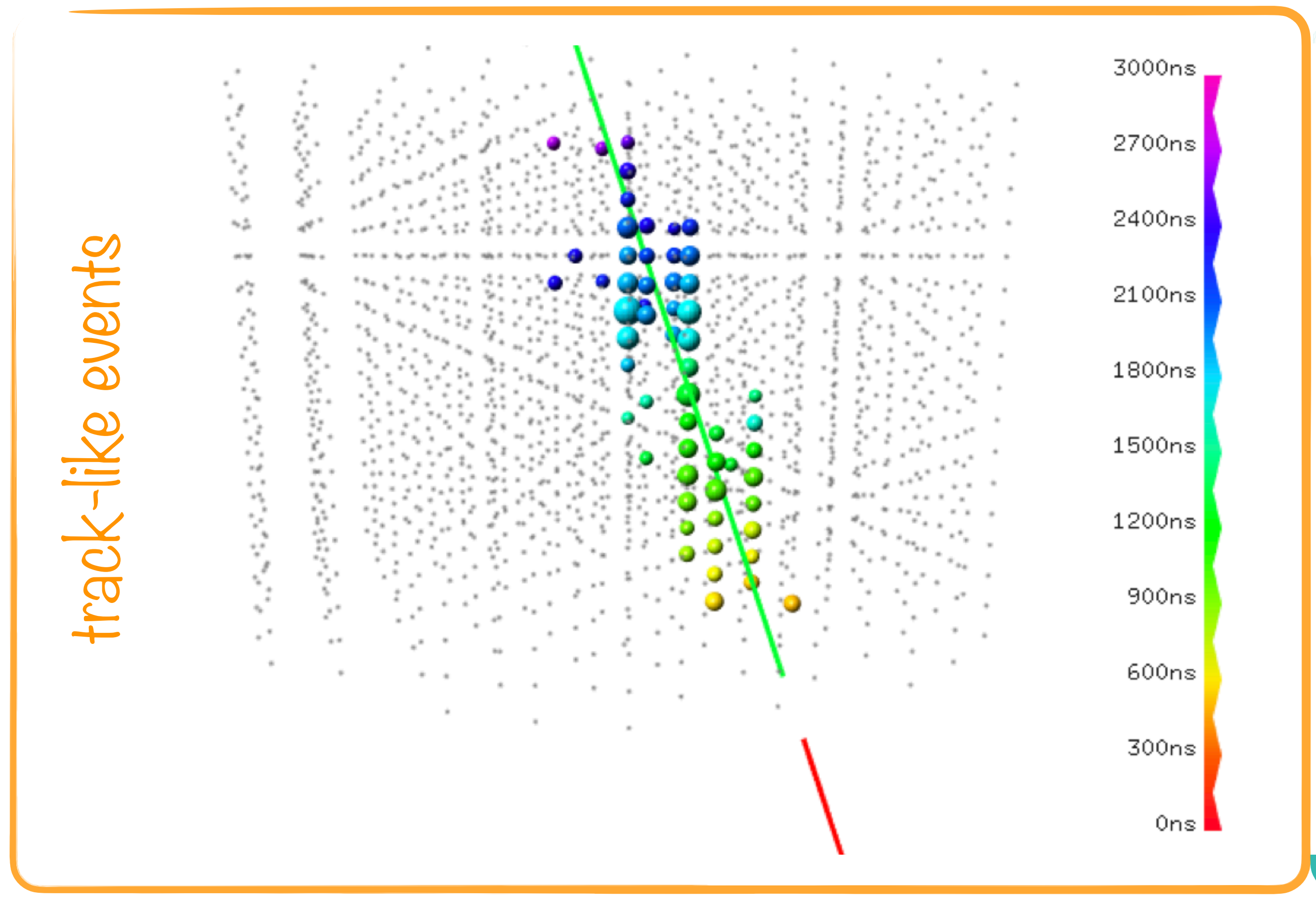
- **Depending on the neutrino flavor and interaction**, two event topologies can be detected:
  - ❍ **track-like** events, very elongated and easier to be reconstructed
  - ❍ **shower-like** events, more spherical

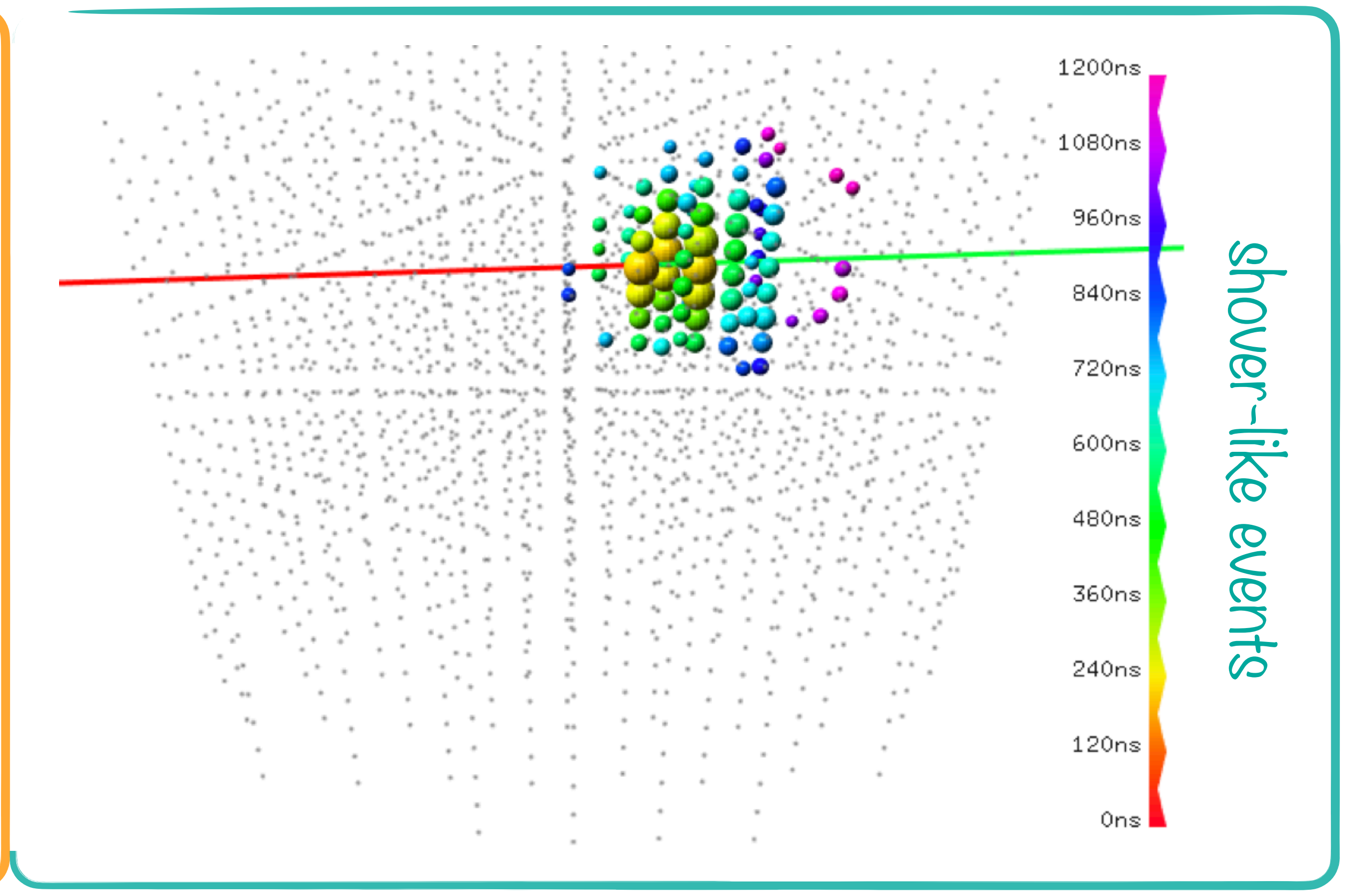
- At very low energy, the two topologies are more difficult to be distinguished





there is a 17% Branching Ratio of ν_τ that can create track-like events

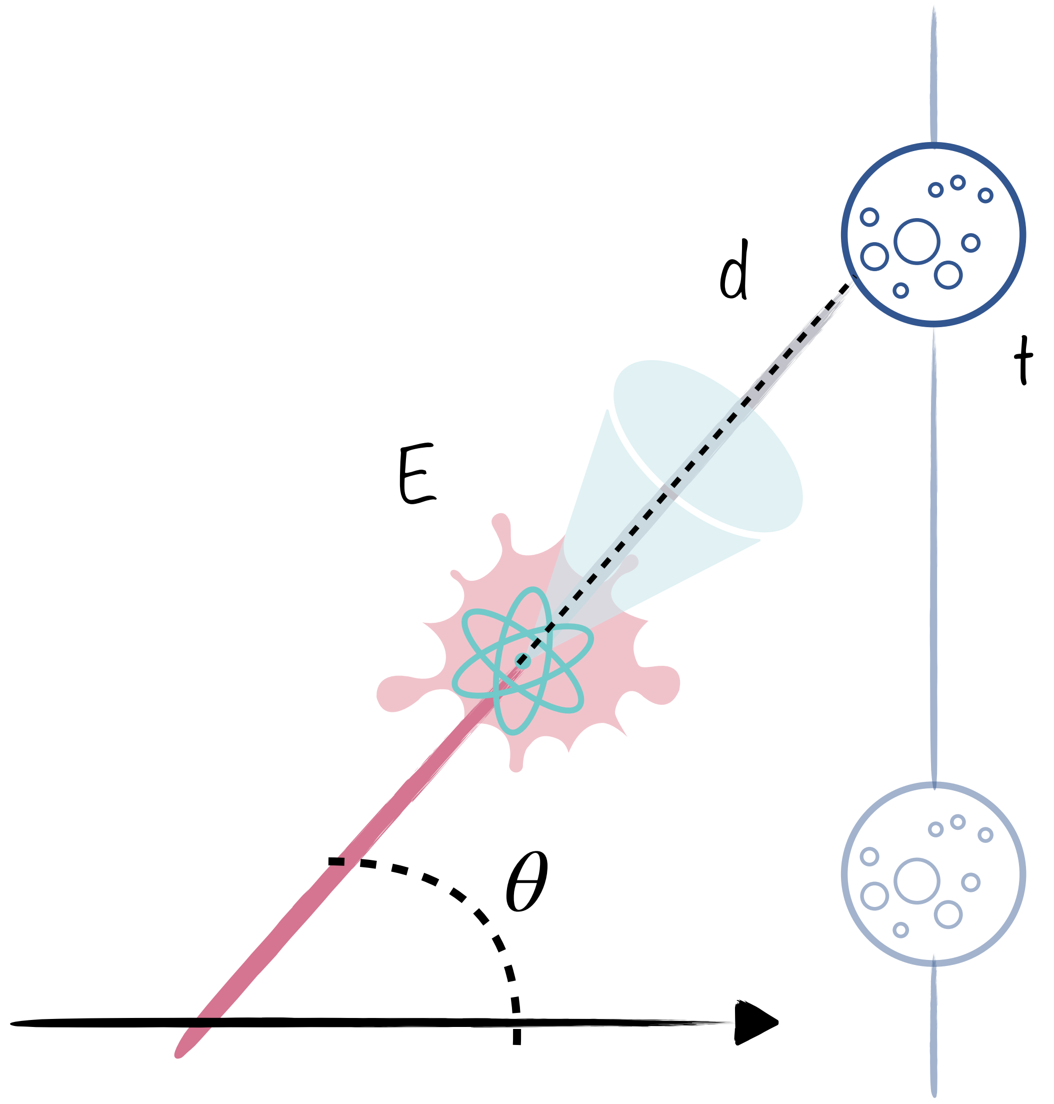




J. Phys. G: Nucl. Part. Phys. 43 084001 (2016)

KM3NeT/ORCA: events reconstruction

- **Event reconstruction:**
  - **maximum likelihood algorithms** optimized for the two topologies
    - direction, energy, time in each PMT, and position of the interaction vertex



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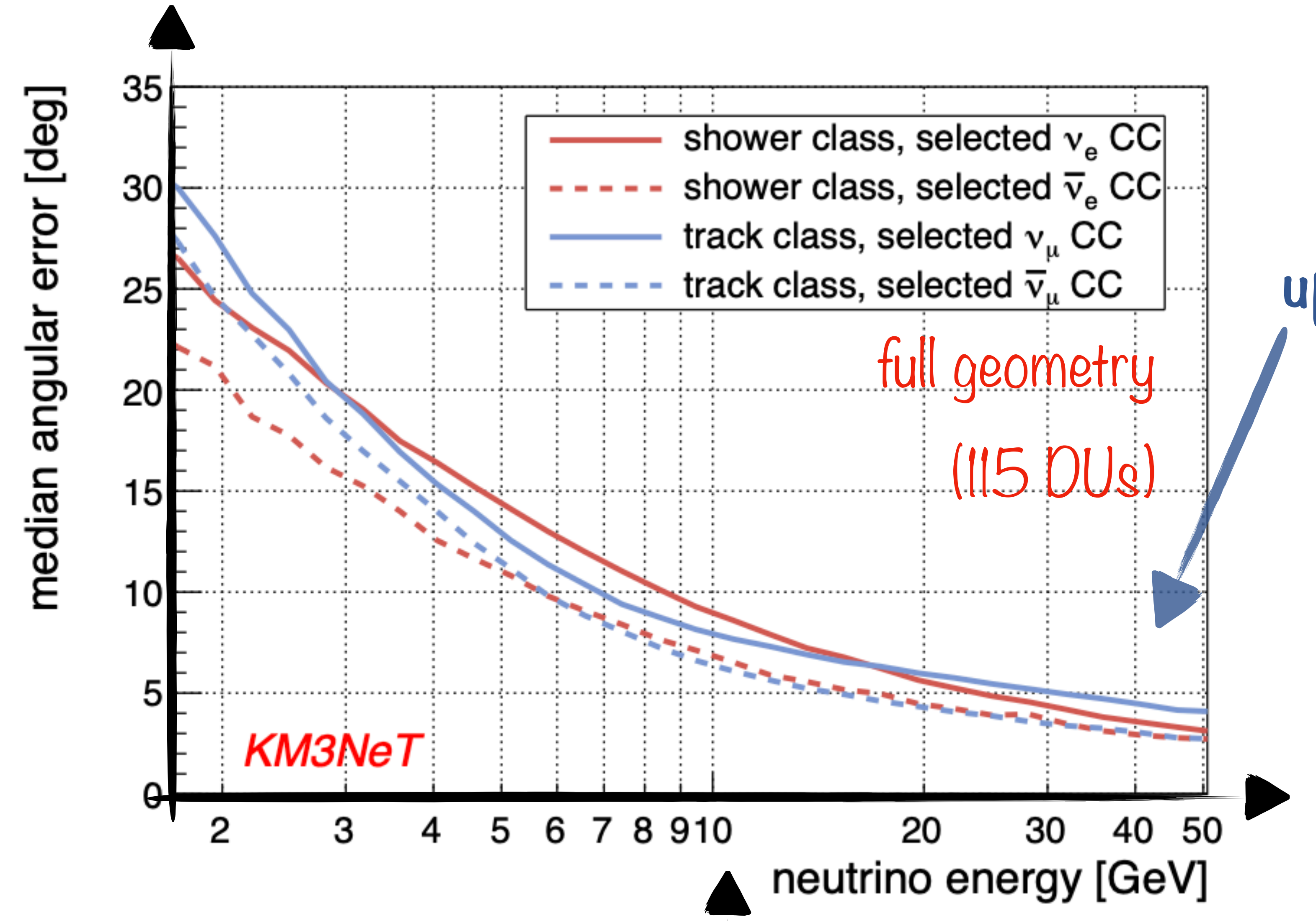
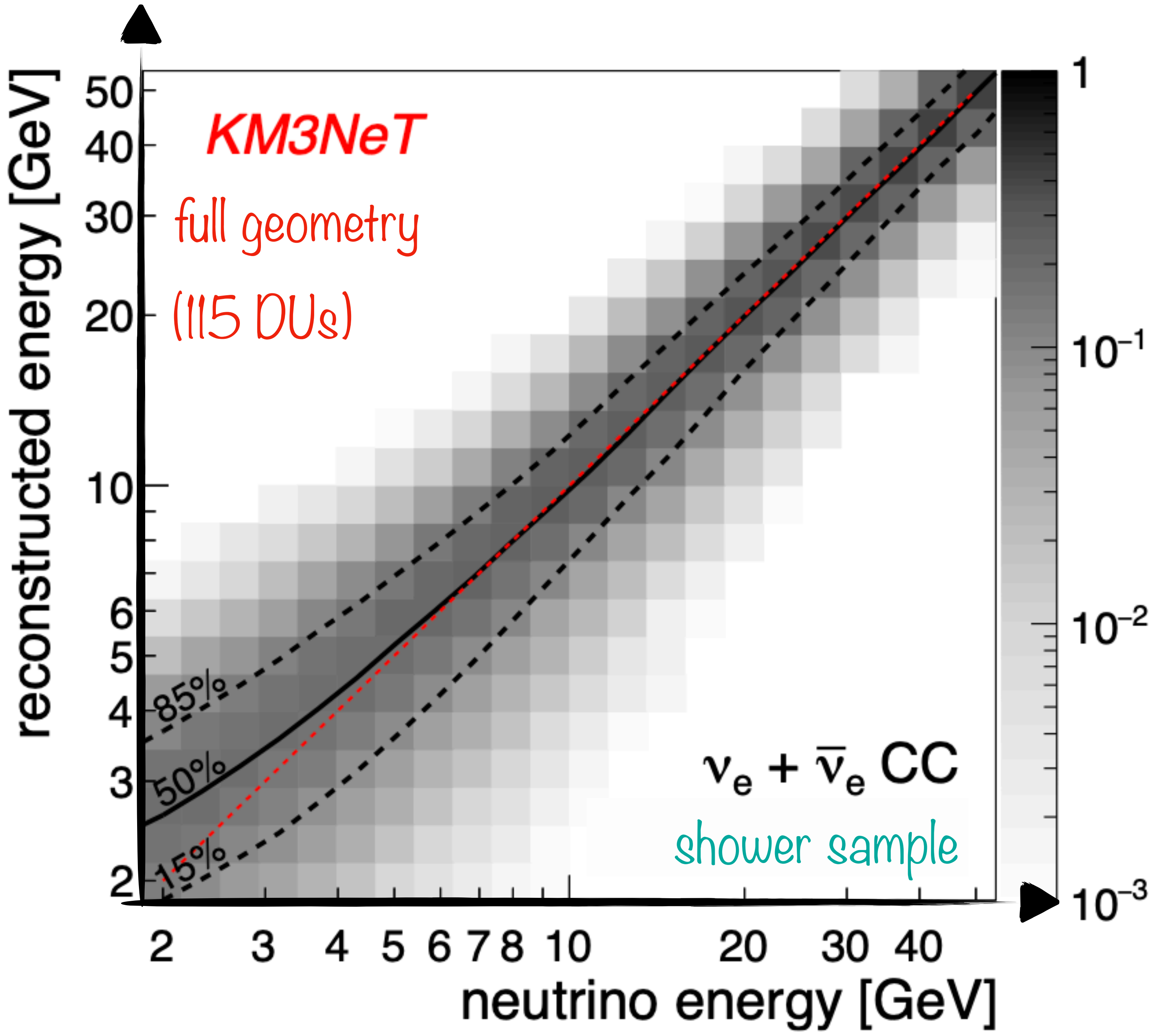
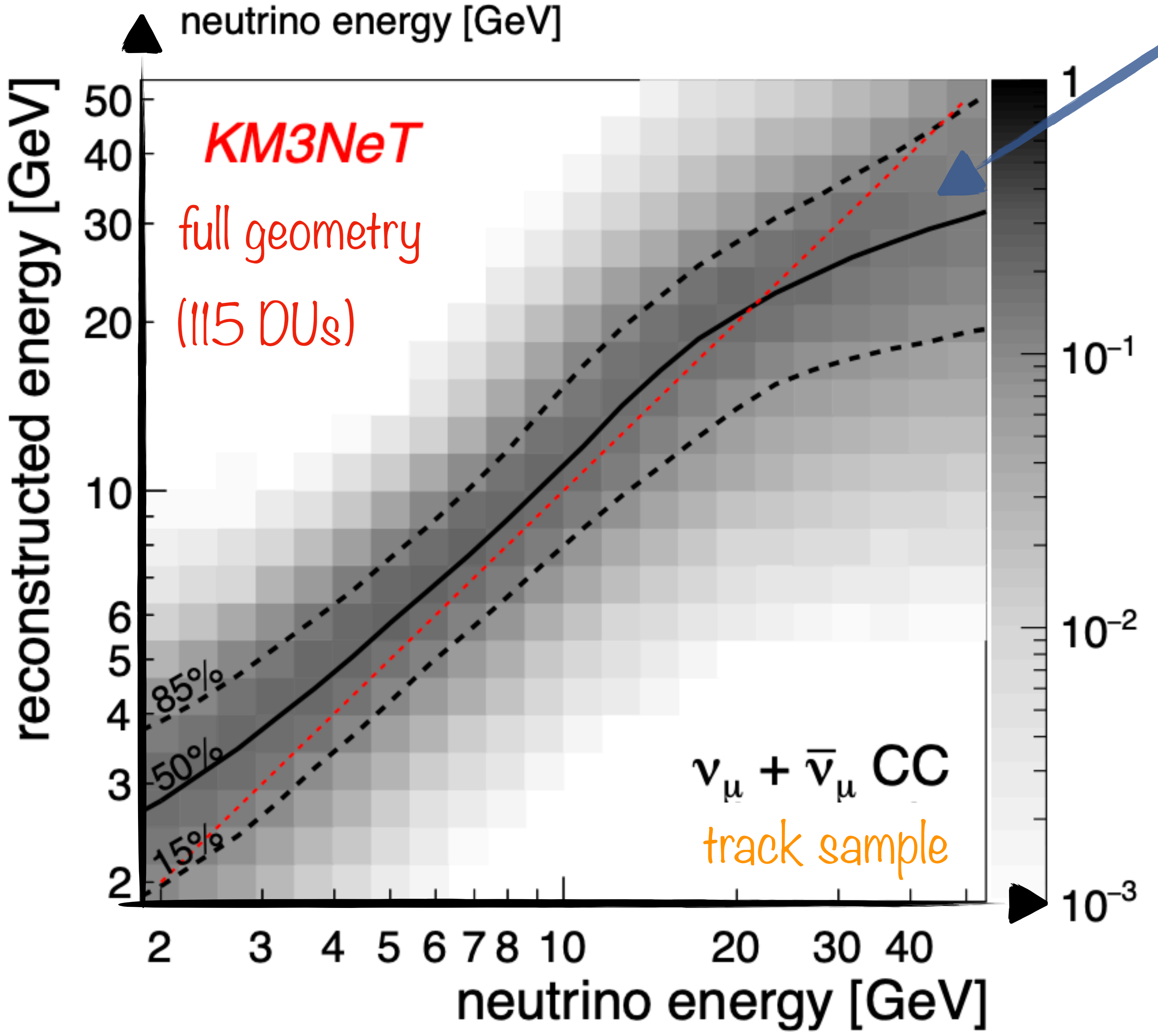


up to 5° resolution!

very elongated events (real int. vertex, outside the instrum. vol.)



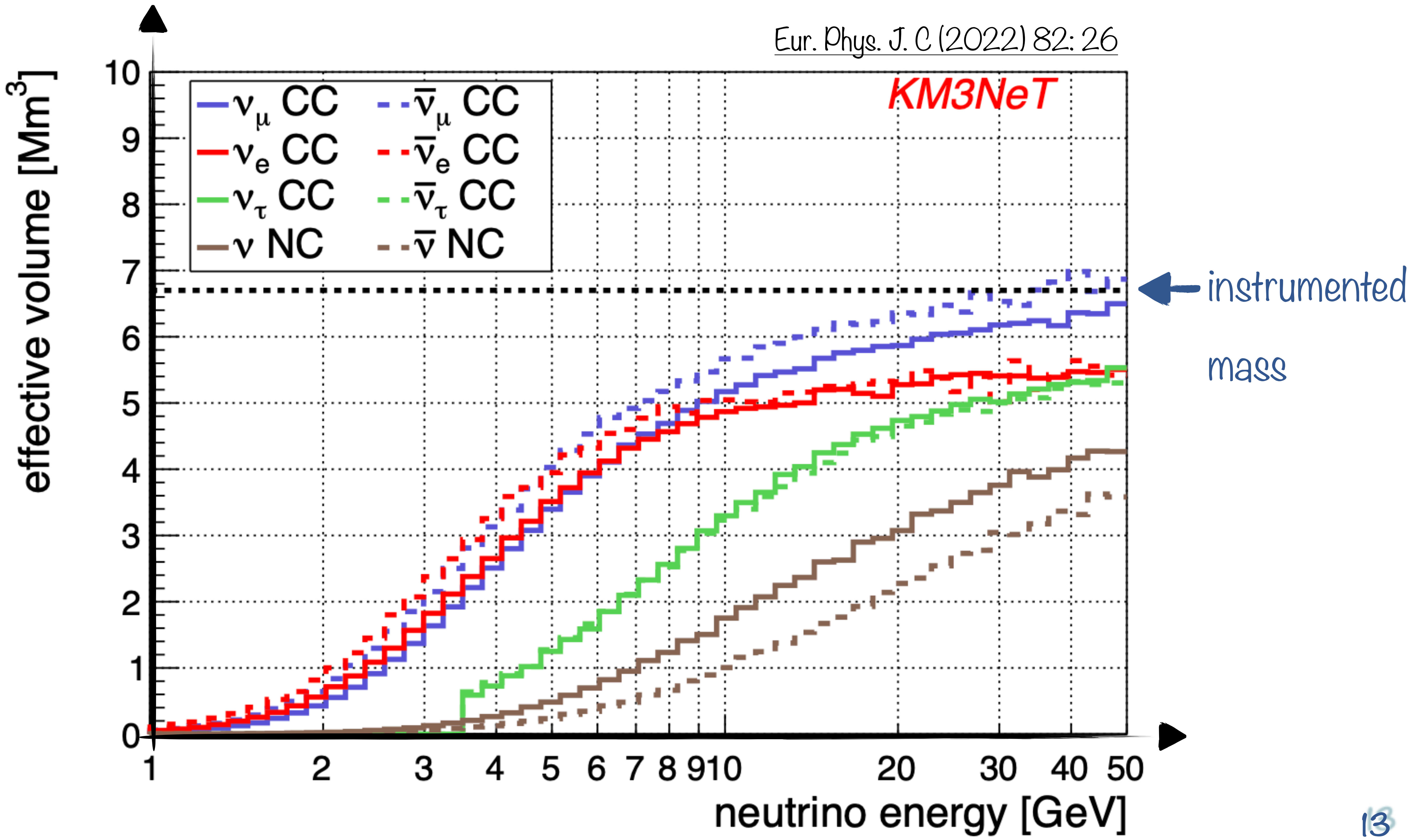


KM3NeT/ORCA: events reconstruction

- **Event reconstruction**:
  - ❍ **maximum likelihood algorithms** optimized for the two topologies
    - ⦿ direction, energy, time in each PMT, and position of the interaction vertex

- Event (pre-)**selection**:
  - ❍ **up-going** events (rejection of atm. muons)
  - ❍ **containment** of the interaction vertex
  - ❍ **noise** rejection

- Main sources of **backgrounds**:
  - ❍ down-going **atmospheric muons**
  - ❍ **optical noise** (^{40}K decays, PMT dark counts, bioluminescence)



KM3NeT/ORCA: neutrinos classification

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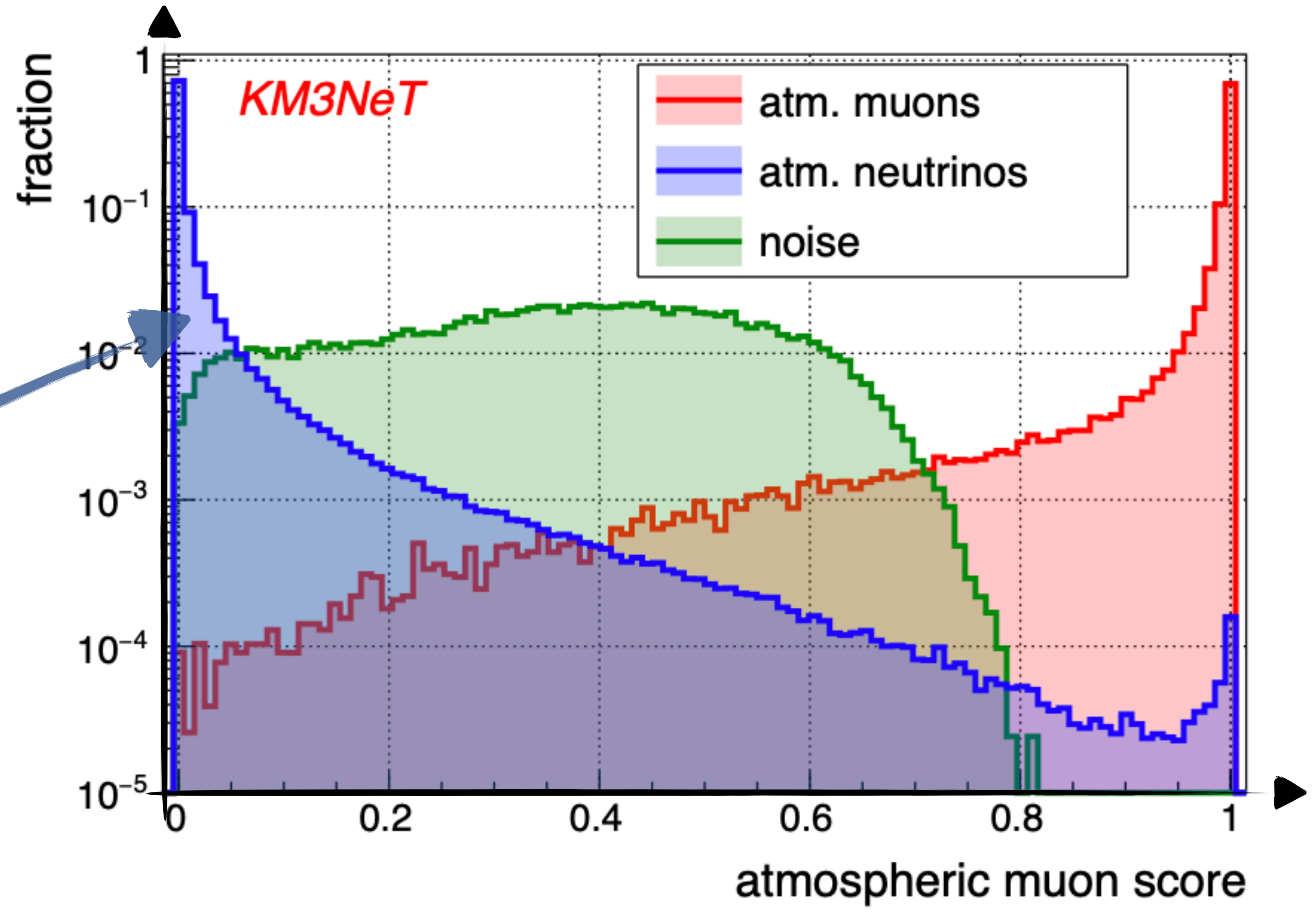
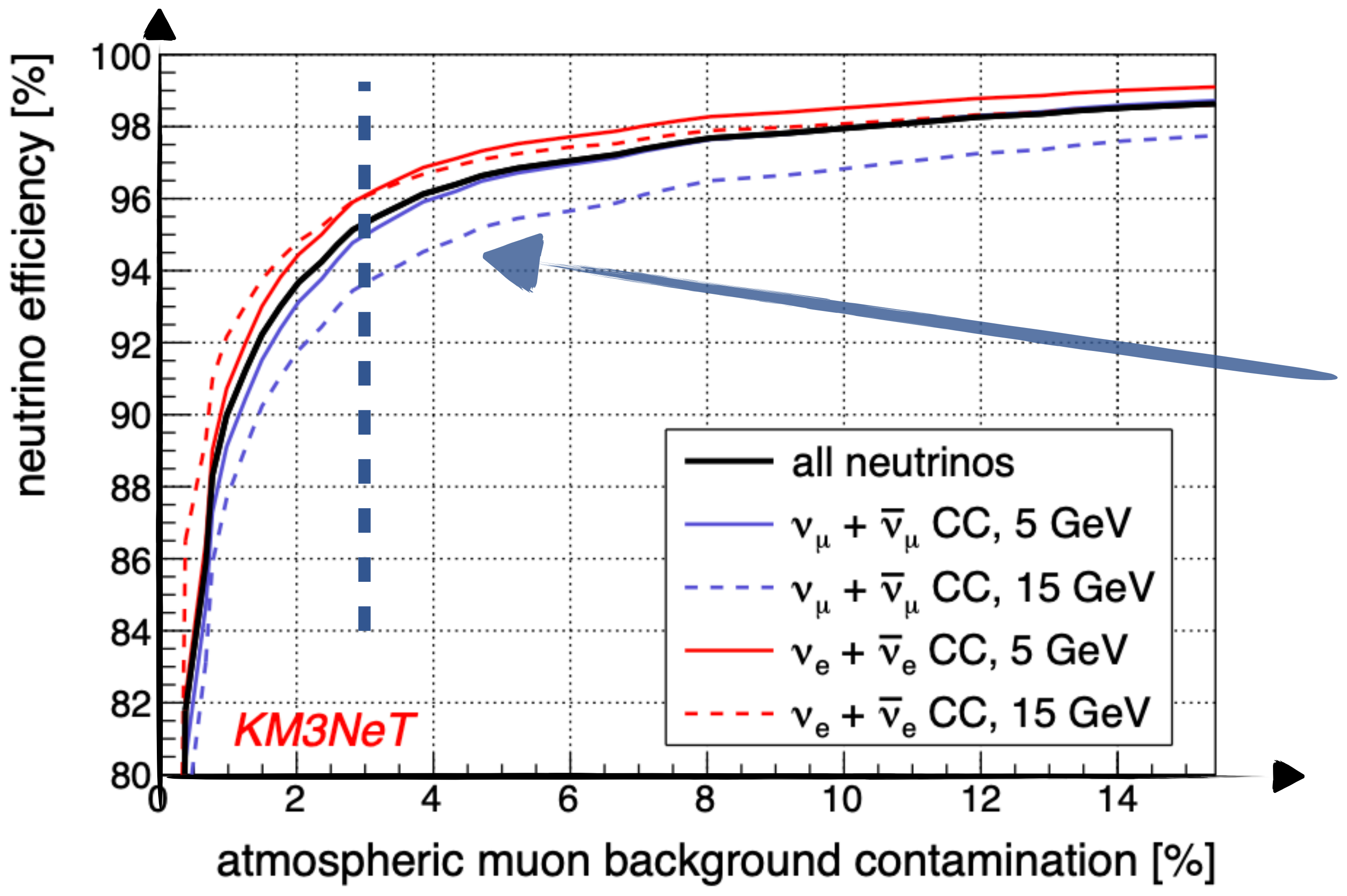
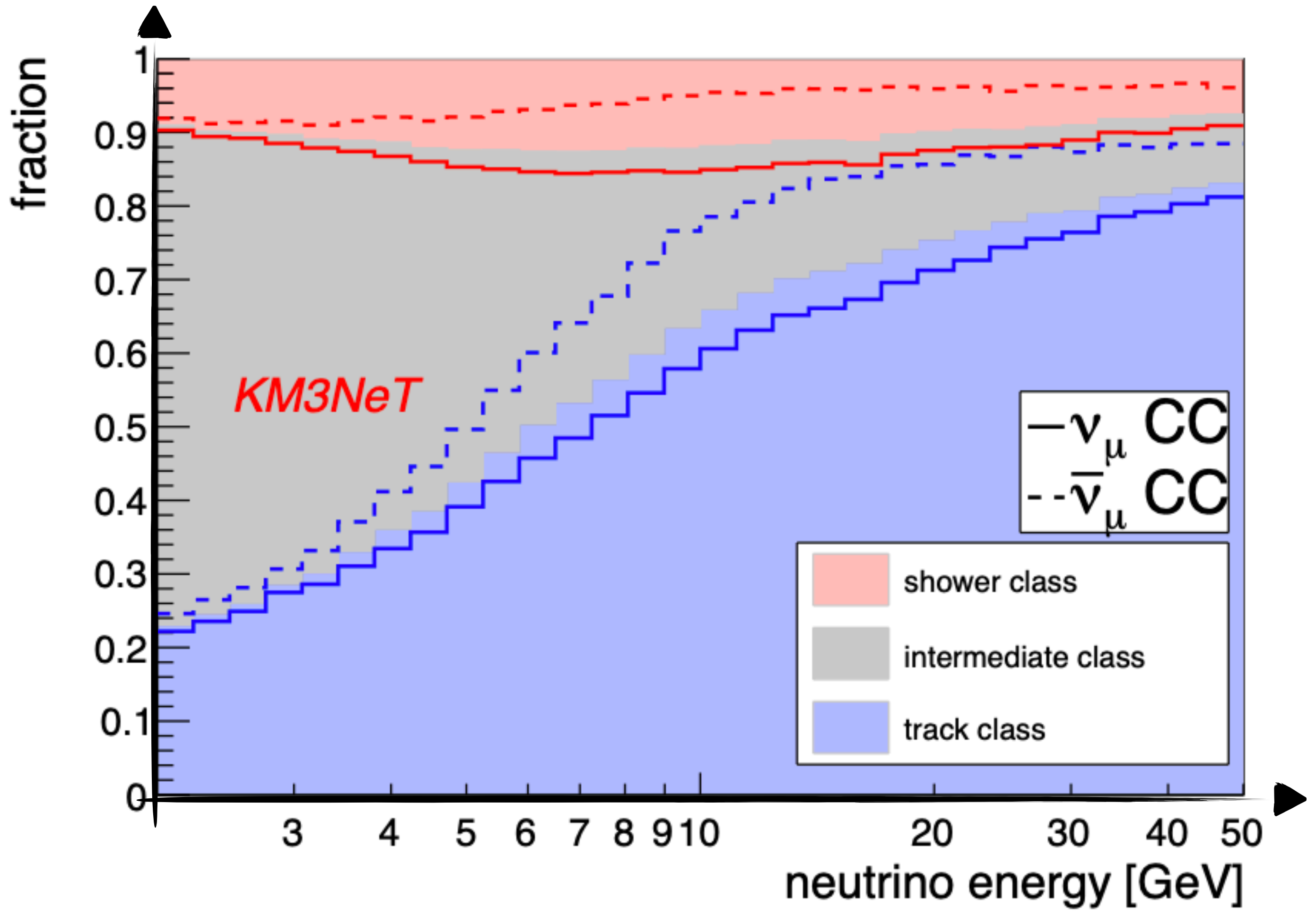
- **Event classification**:
  - **multivariate analyses** and **Neural Network** techniques (RDF, BDT, GNN, and other NN methods)

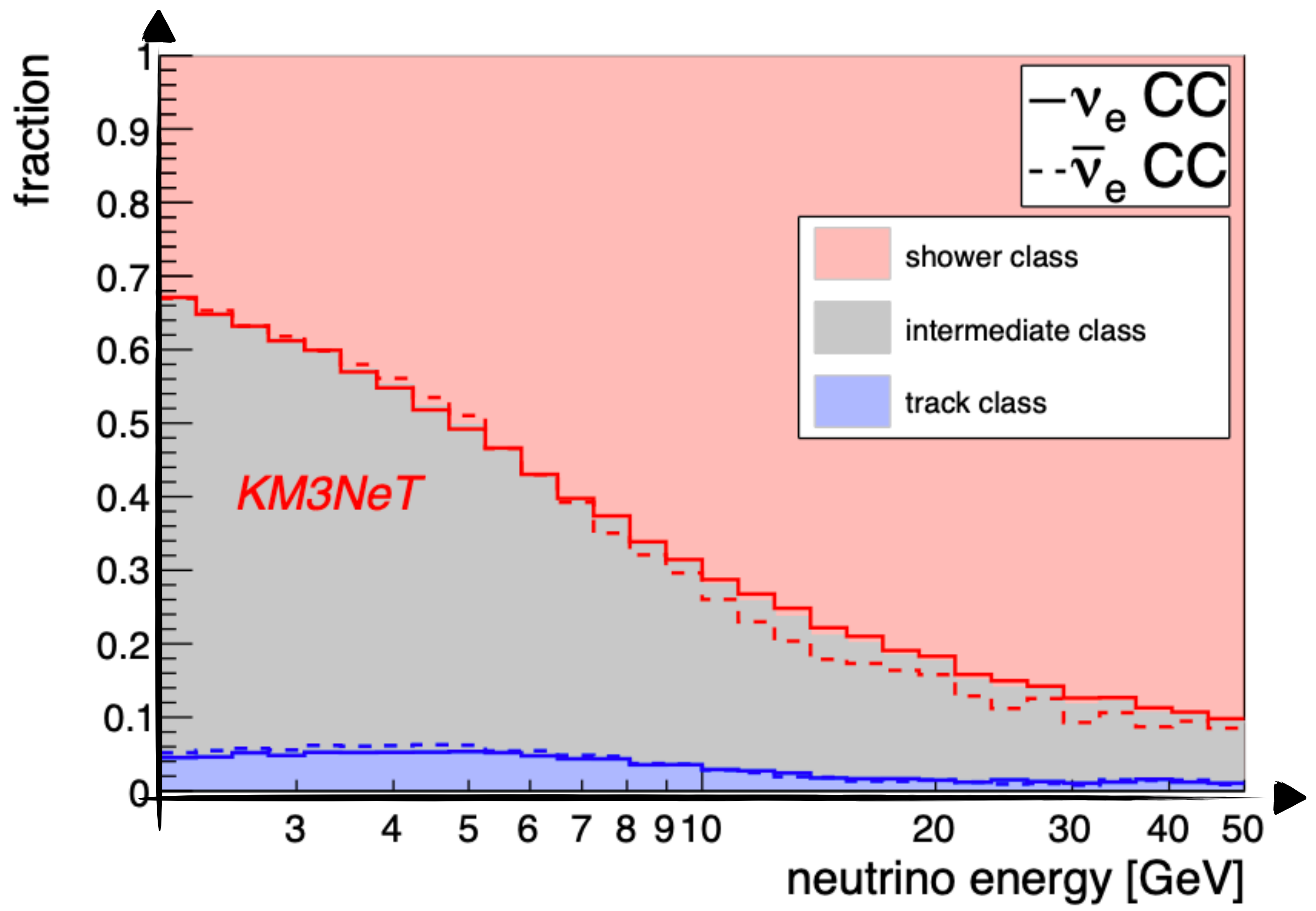


Good classification of the signal against the main bkgs!



quickly reached a high neutrino classification efficiency (> 95%) with very low atm. muons contamination (~4%) !





Based on the track score, the final neutrino sample is classified into three classes:

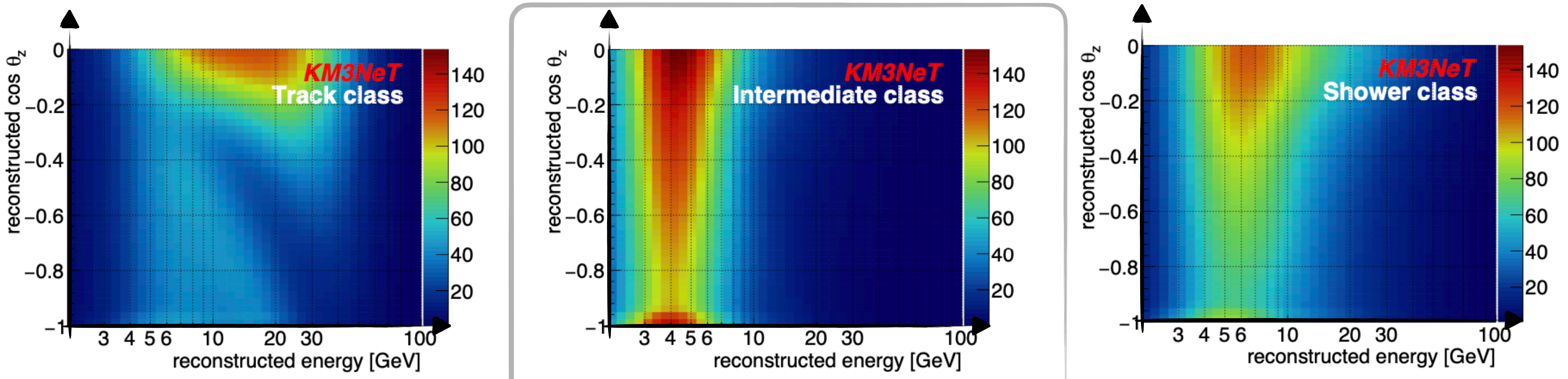
- track class
- shower class
- intermediate class

high purity samples

used as inputs for the neutrino oscillation fit

KM3NeT/ORCA: sensitivity to main physics searches

- **Fit methodology**:
  - ❍ **2D binned log-likelihood maximization energy and cosine zenith distributions** for the three classes
  - ❍ Asimov dataset to derive the median sensitivity to either the oscillation parameters or mass ordering



Less pure but important for constraining systematics

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- **Main Systematics**:
  - ❍ **neutrino flux** (spectral index, relative n. of $\nu_{e,\mu}$ and anti-$\nu_{e,\mu}$, their direction)
  - ❍ **cross-section** (n. of NC and ν_τ and anti-ν_τ CC events)
  - ❍ **detector response** (PMT efficiency, light yield in the hadronic showers, n. of events in the three classes)

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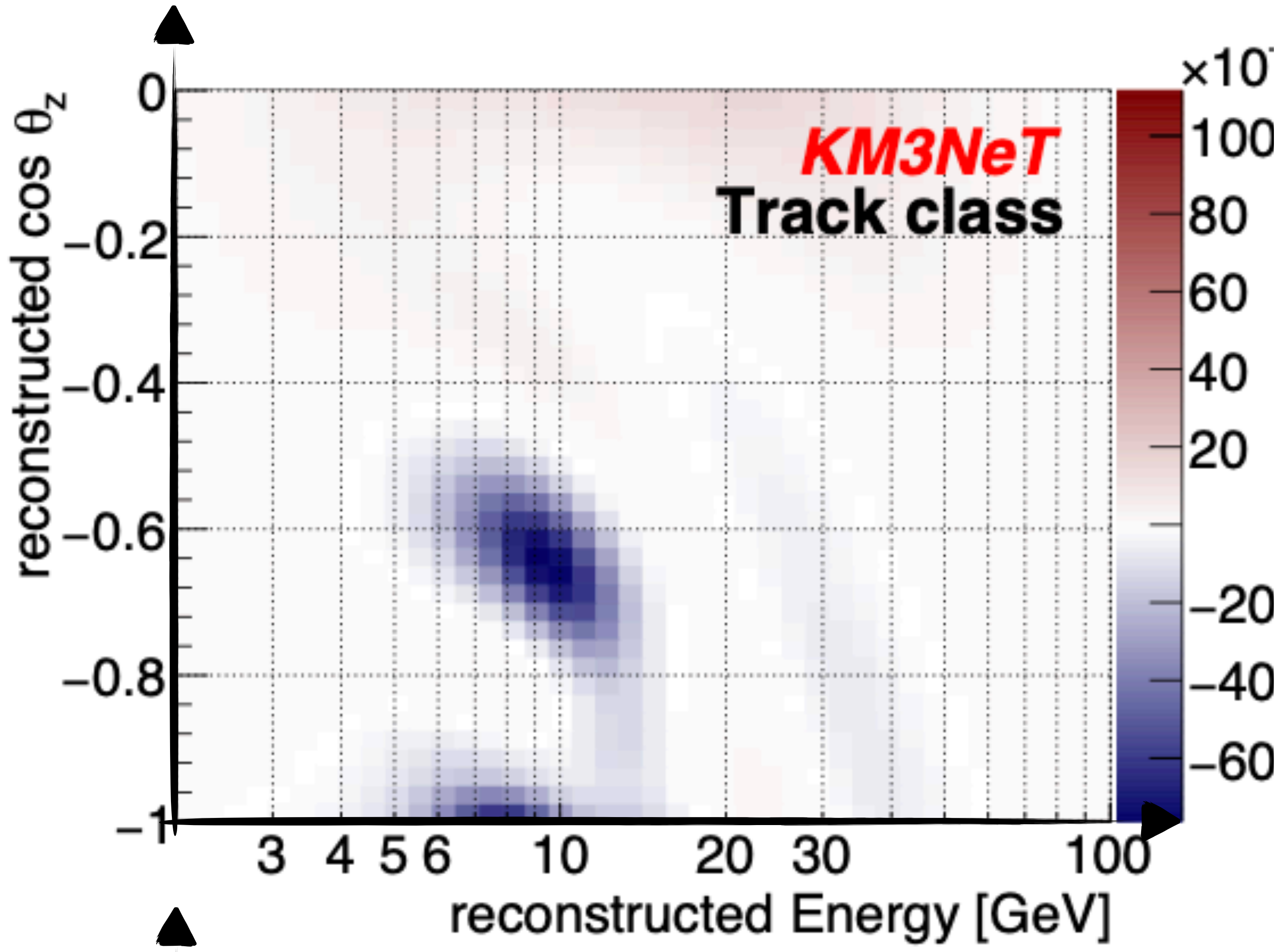
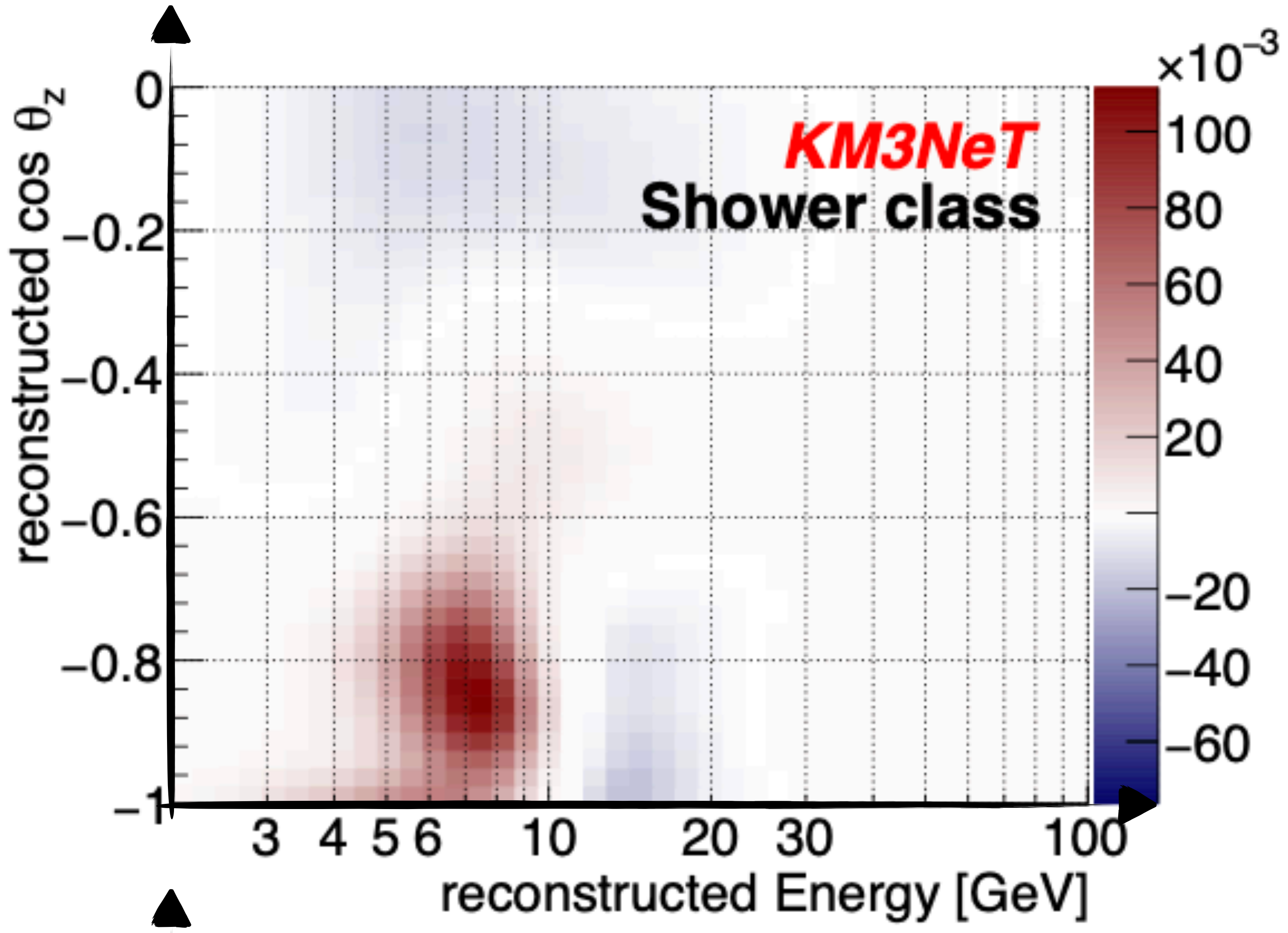
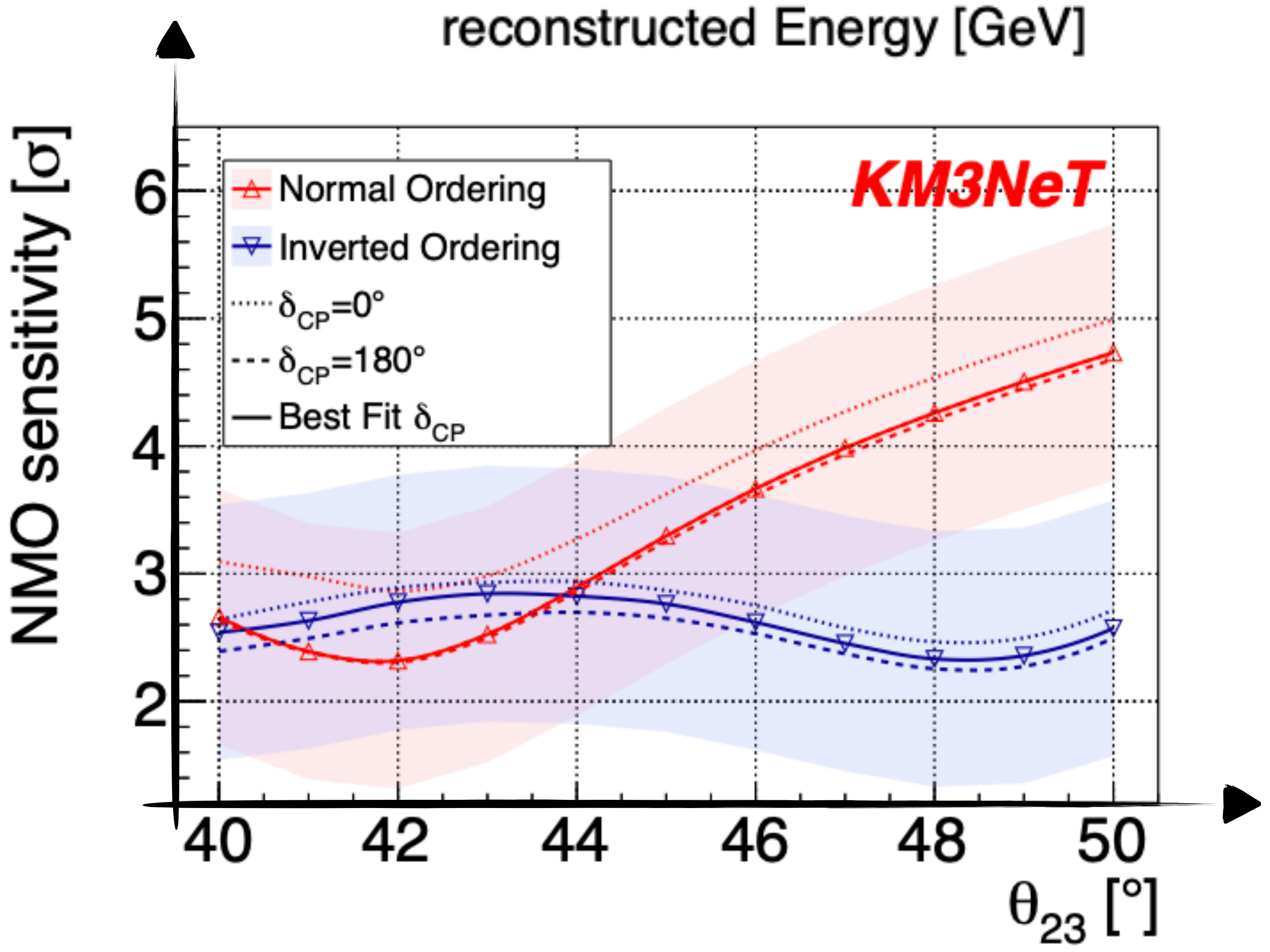
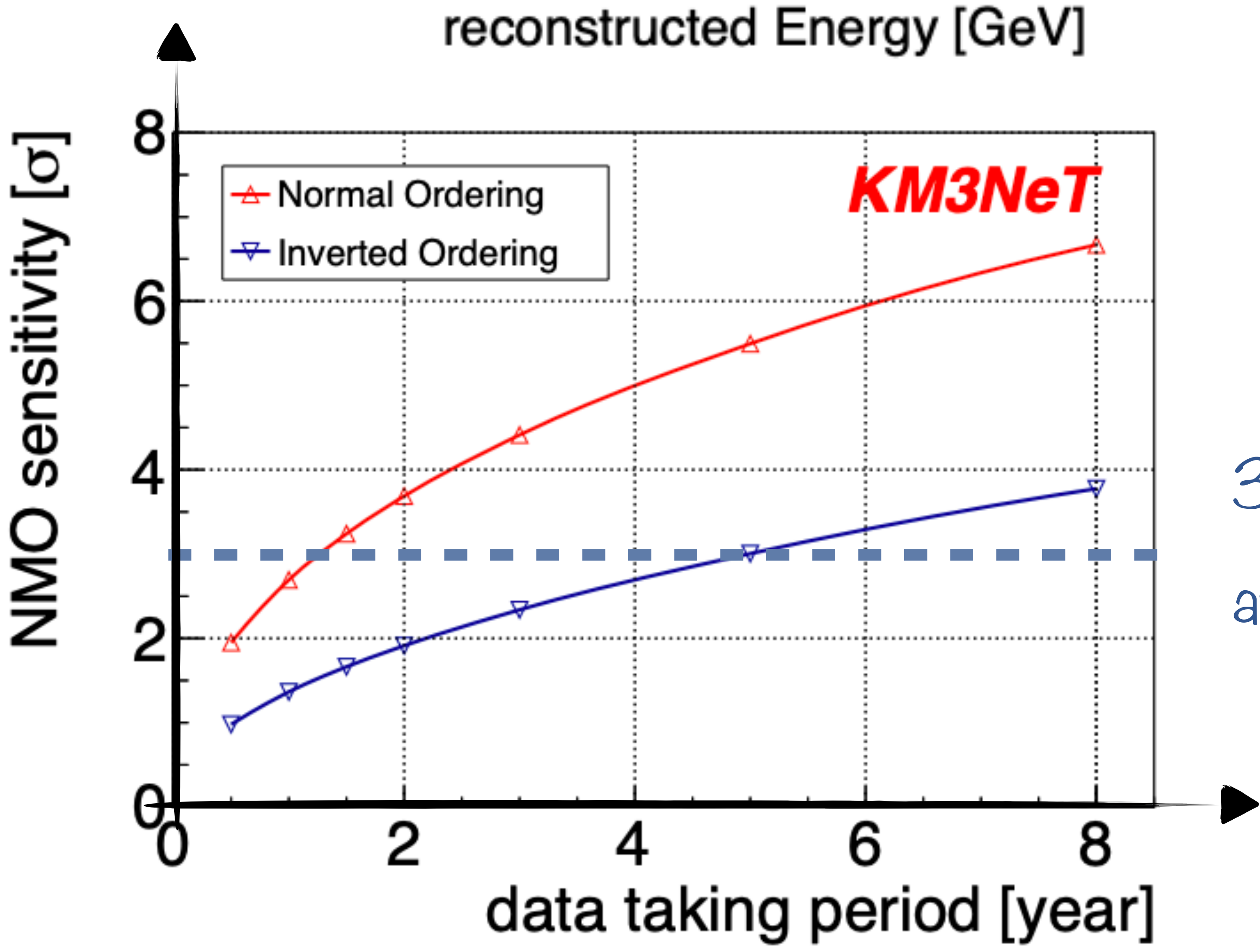
- **Neutrino Mass Ordering (NMO):**
  - ❍ Asimov approach, with Inverted Ordering (IO) as the *alternate hypothesis* to the Normal Ordering





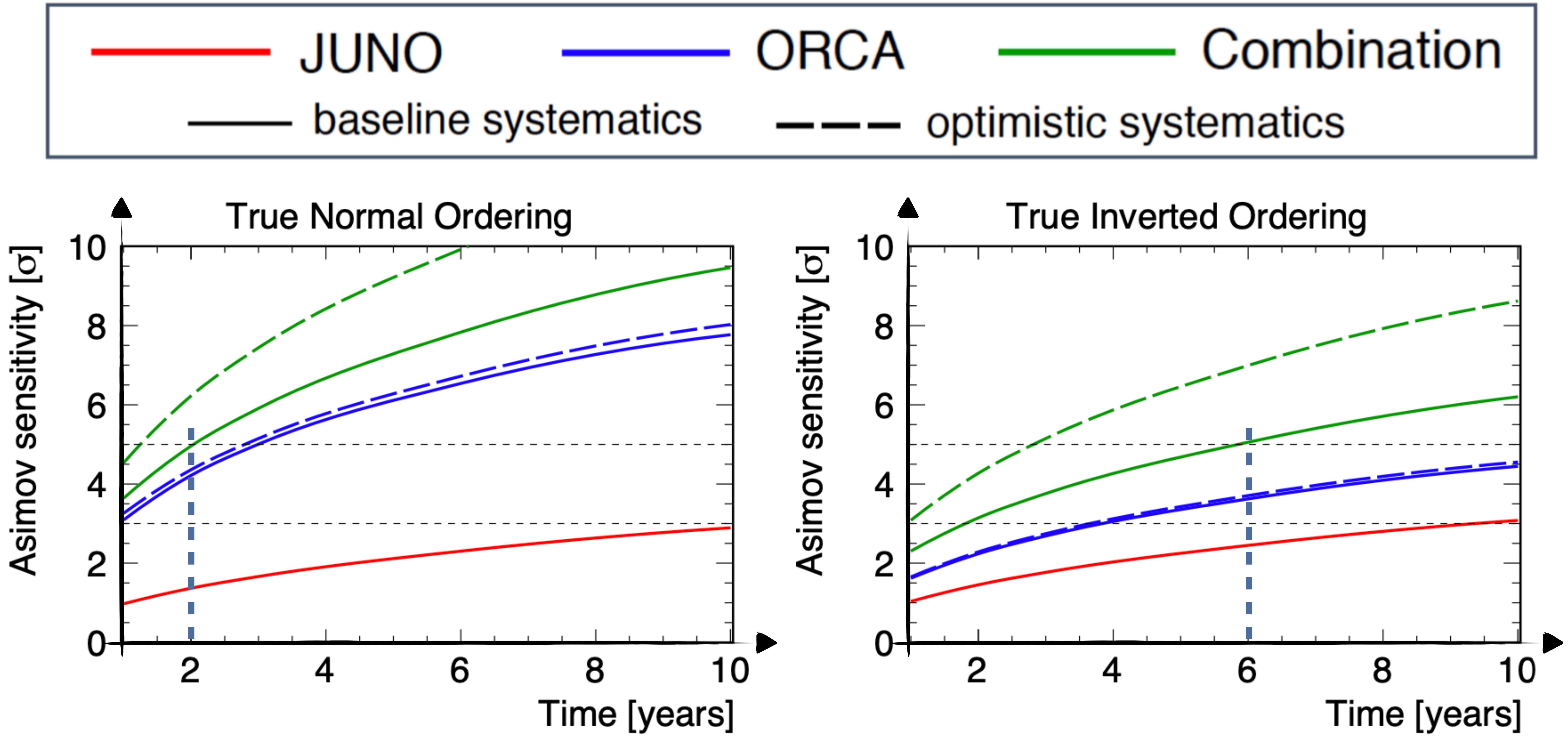
NMO sensitivity vs true θ_{23} value, after 3 years of data taking





3σ sensitivity to IO, after 5 years of data taking

- Neutrino Mass Ordering (NMO), combined analysis with JUNO:
  - ❍ advantage: tension in the Δm^2_{31} best fits from both experiments when assuming the wrong hypothesis
  - ❍ 5σ measurement of NMO within 6 years!
    - ⦿ reachable within 2 years in the favorable scenario of NO and θ_{23} in the positive octant!!



J. High Energ. Phys. 2022, 55

KM3NeT/ORCA: sensitivity to main physics searches

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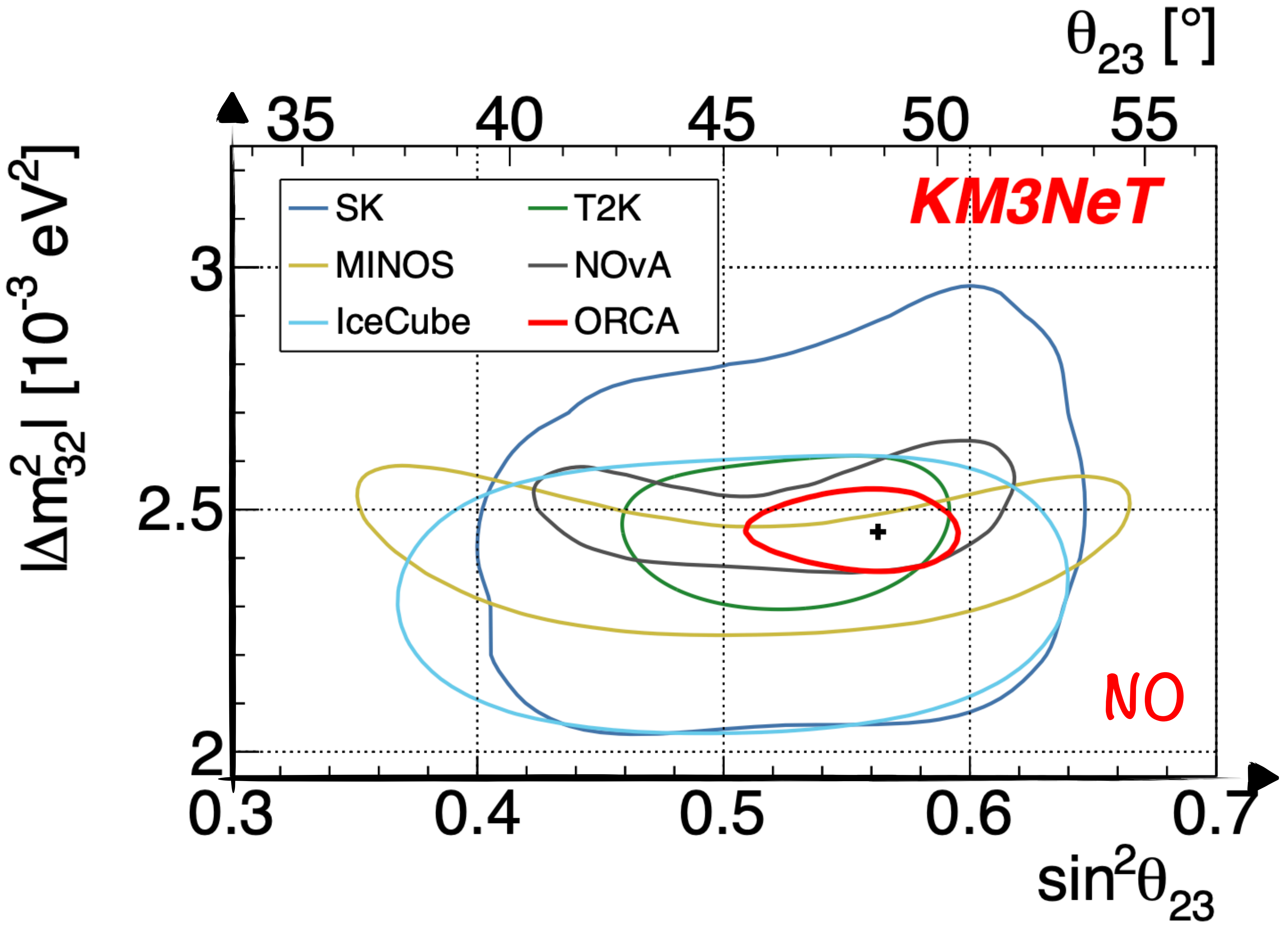
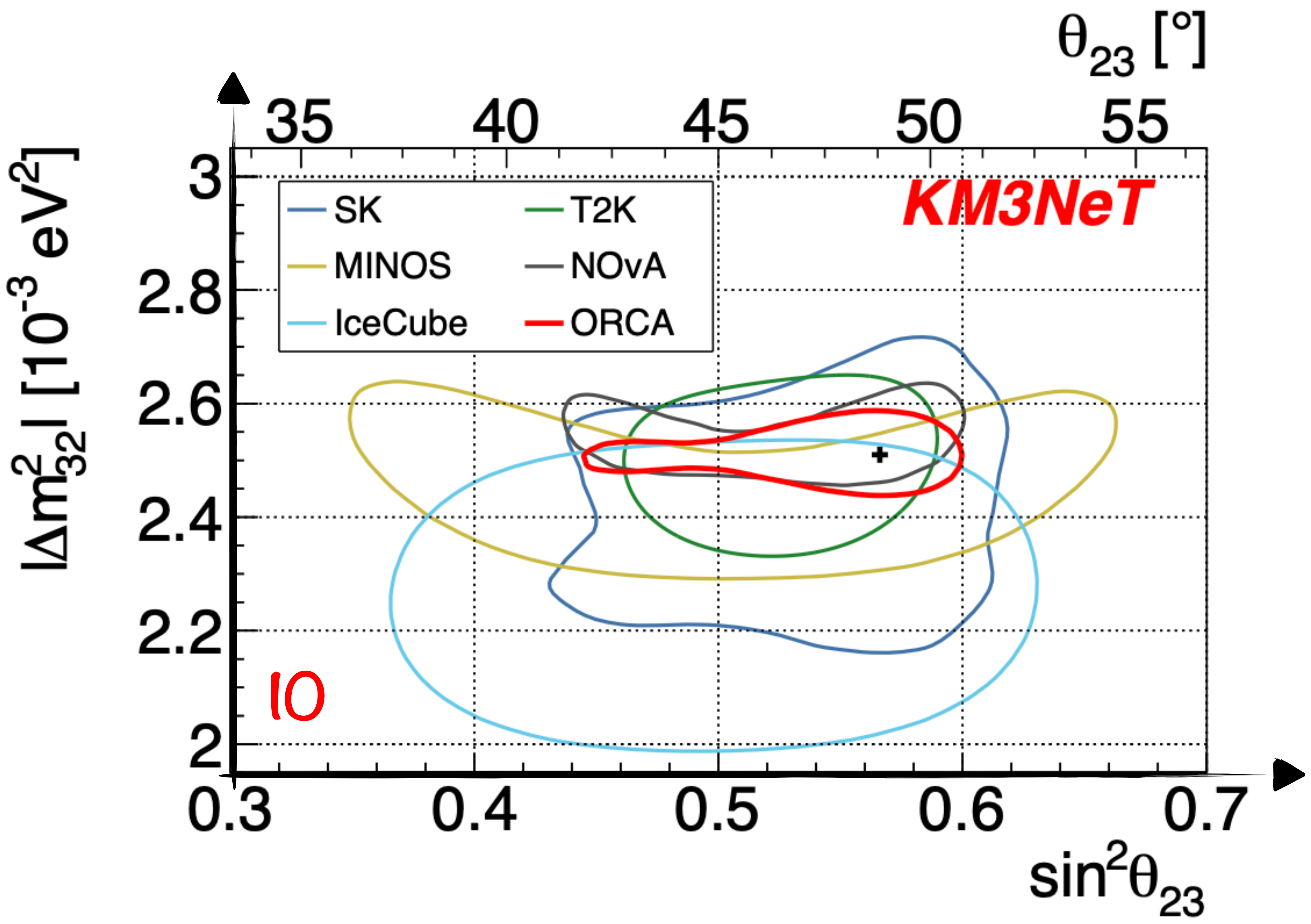
- **Neutrino oscillation parameters**: θ_{23} and Δm^2_{32}
  - Normal Ordering (NO) hypothesis on the left and Inverted Ordering (IO) hypothesis on the right





Expected KM3NeT/ORCA precision after 3 years of data taking at 90% of C.L.

KM3NeT/ORCA: sensitivity to other low-energy searches

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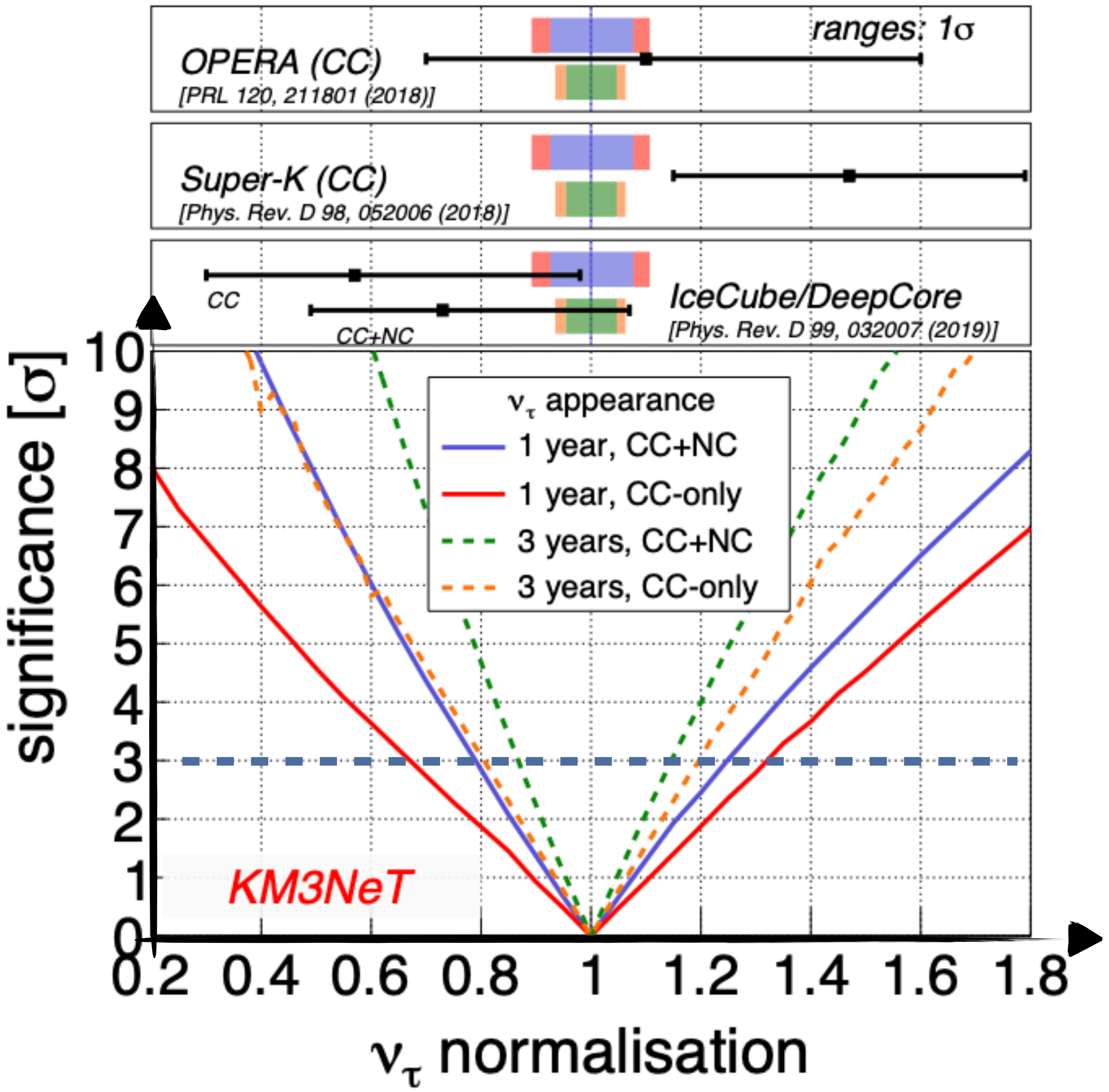
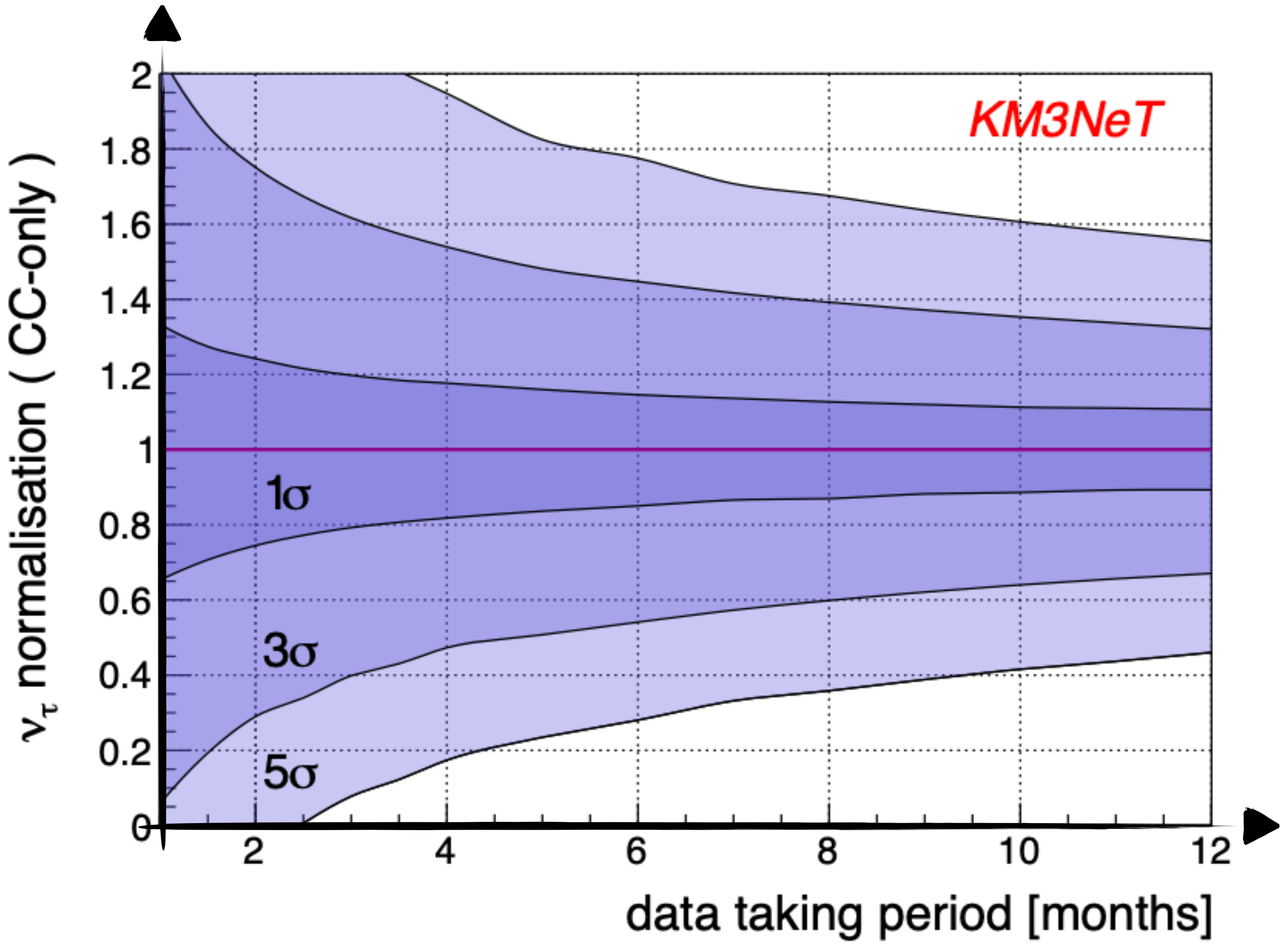
- ν_τ **appearance search** as independent test for **new physics**:
  - ❍ a good **reconstruction of shower-like** events is **crucial**!
  - ❍ measured from the ν_τ **normalization factor**, n. of (anti-)ν_τ events in the NO hyp.
  - ❍ Asimov approach:
    - ⦿ *null hyp* if ν_τ norm = 1
    - ⦿ 2 options for *alt. hyp:* *(anti-)*ν_τ CC varying and NC fixed to 1, or *(anti-)*ν_τ CC+NC scale free in the fit



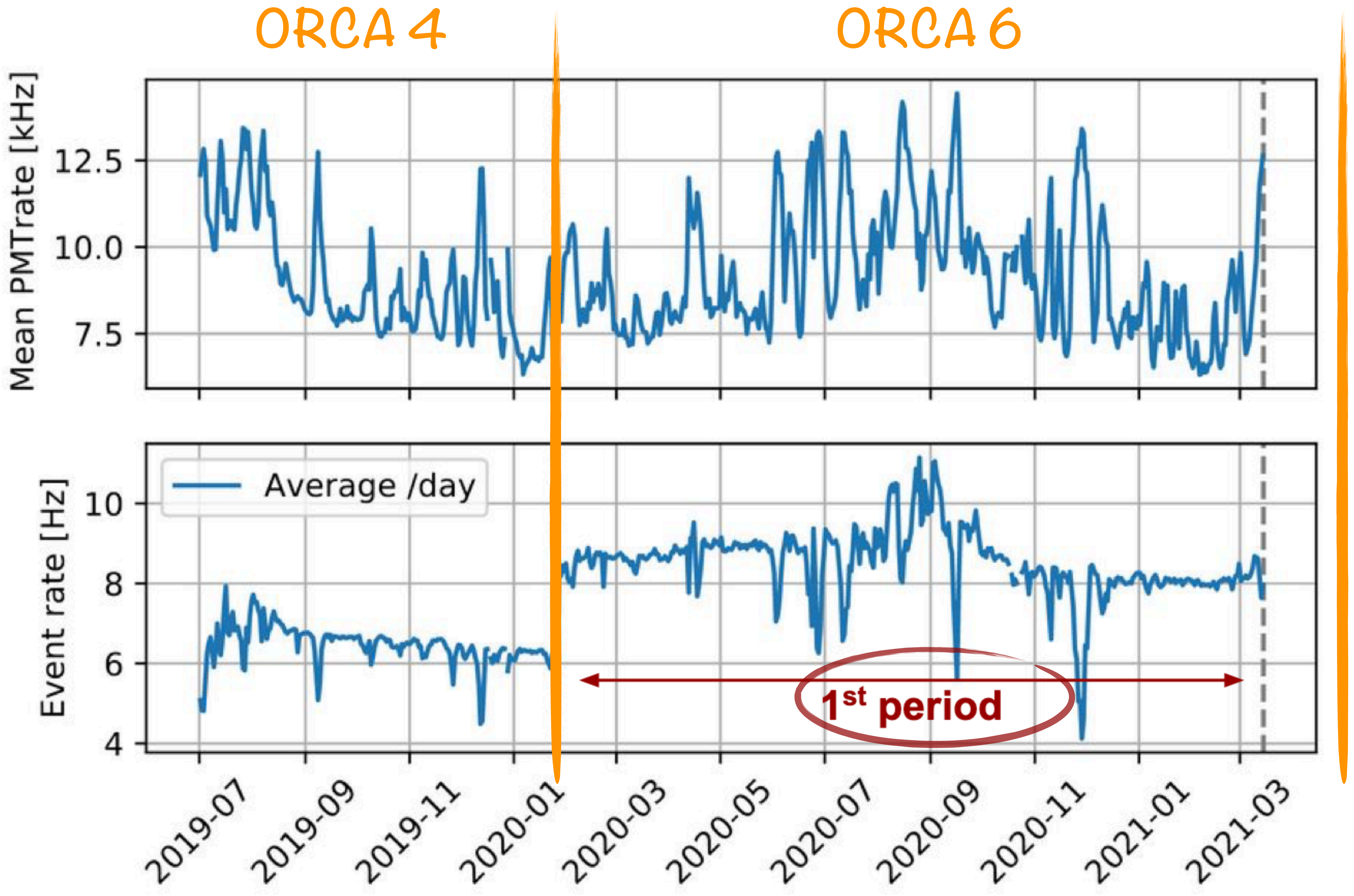


- and other studies: **sterile neutrino**, **neutrino earth tomography**, **low-energy astrophysics**, etc. …

KM3NeT/ORCA: current detector geometry

KM3NeT Coll. at ICHEP 2022

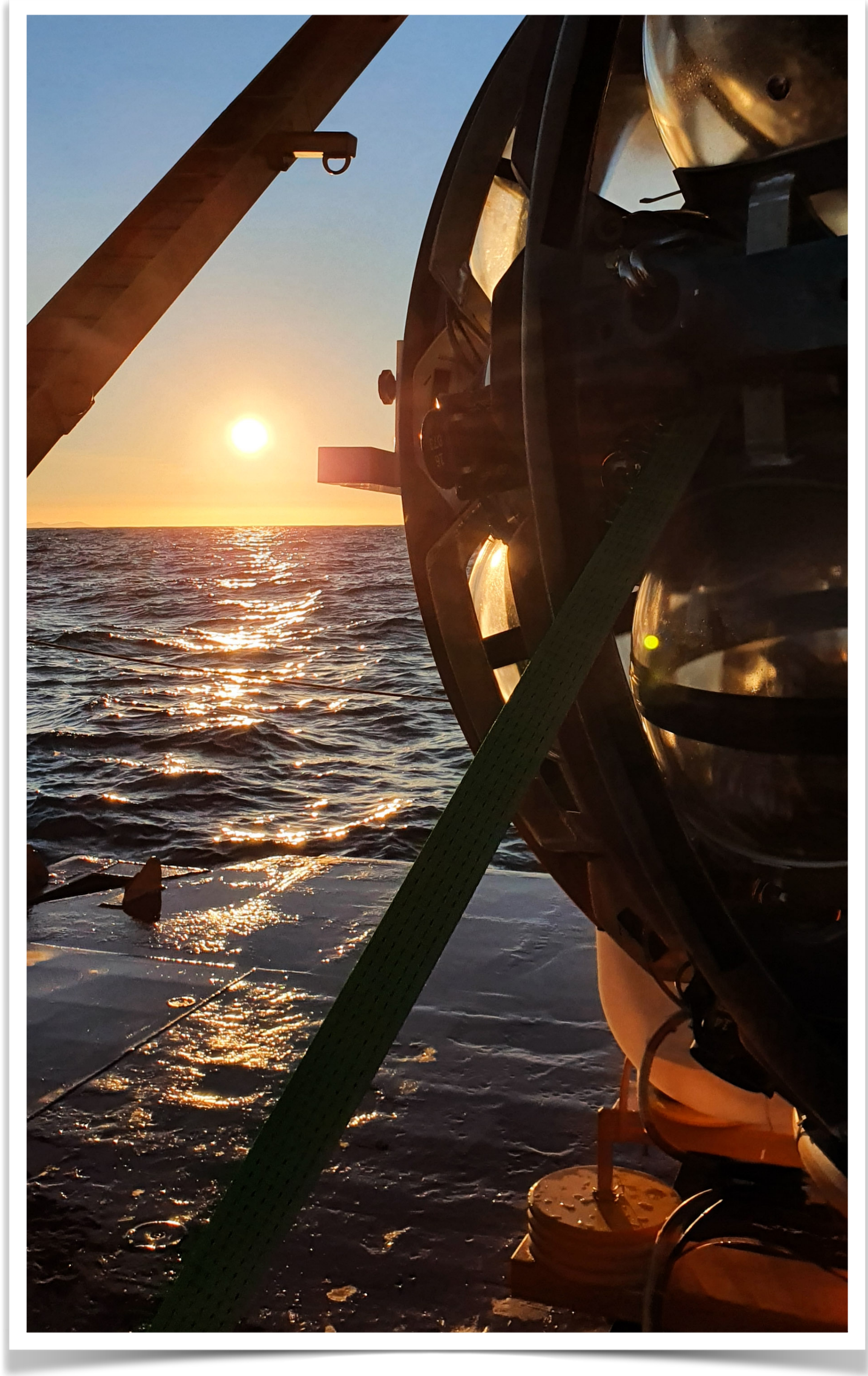
- **KM3NeT** allows for **physics studies since the commissioning phase**:
  - ❍ stable data taking, efficiency: from 91%, in 2019, to 98%, in 2022
  - ❍ efficient trigger algorithms (based on PMT and DOMs coincidences)
  - ❍ good event rate stability (~3% fluctuations)



ORCA 11

4 new lines in June & currently, a sea operation is ongoing!

..expected +4 DUs! 🤞



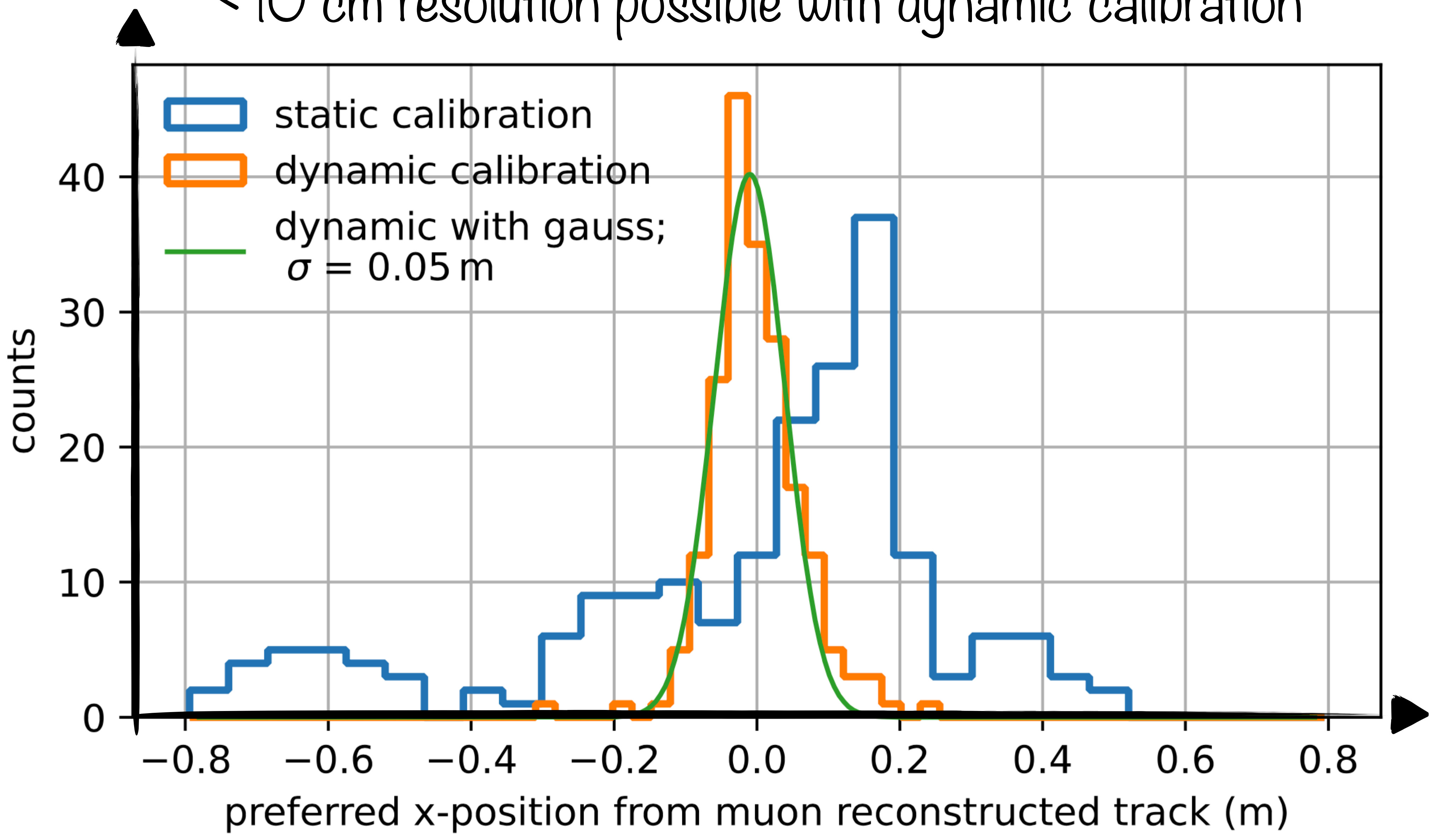
+ 50% dataset, until June '22, improved analyses are ongoing!

KM3NeT/ORCA 6: detector performance

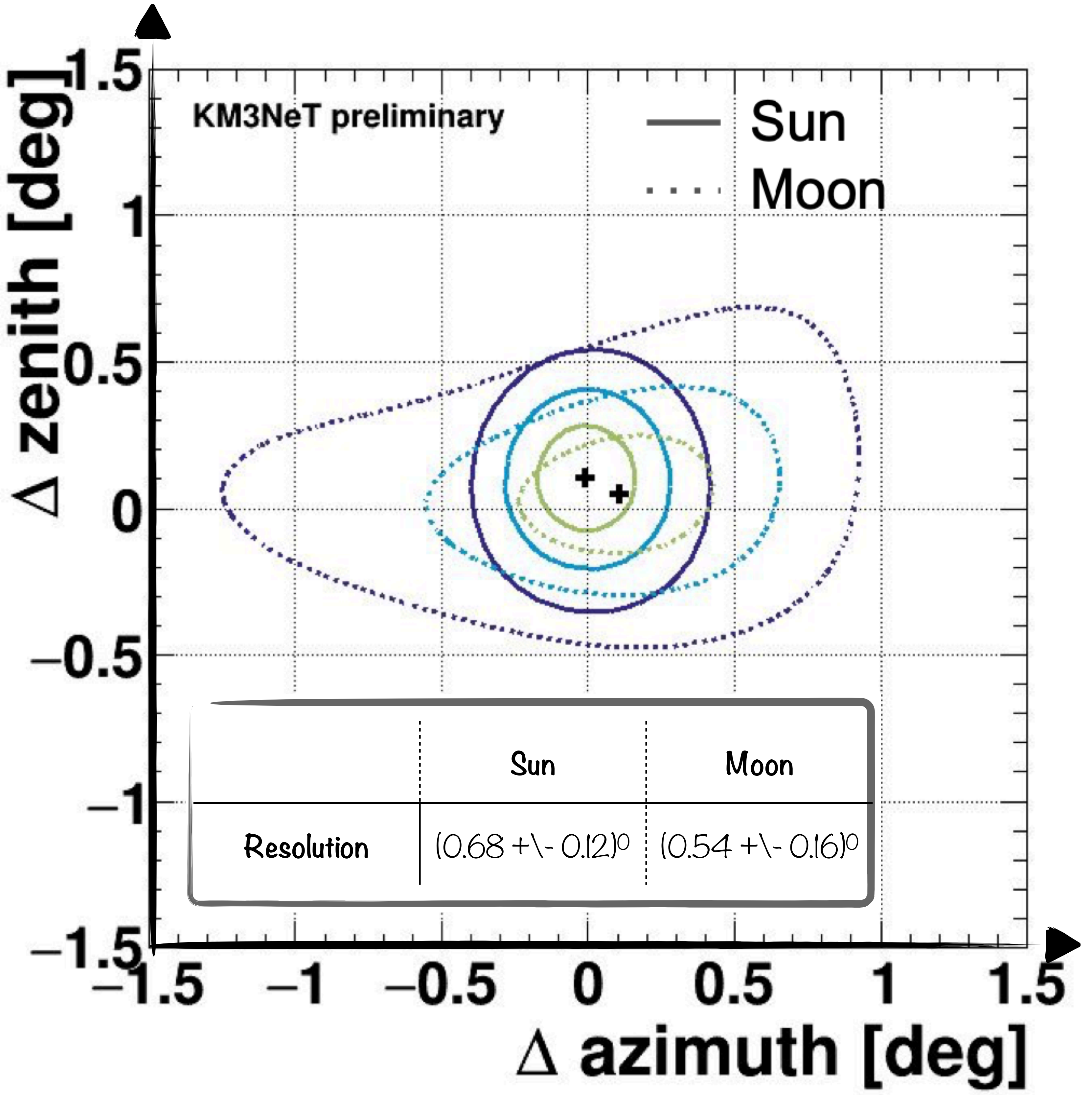
KM3NeT Coll. at Neutrino 2022

- KM3NeT allows for **physics studies since the commissioning phase**:
  - **DU calibration** (before and after the installation) allows for **precise alignment measurement**
  - detector **resolution in track reconstruction < 1 degree**

< 10 cm resolution possible with dynamic calibration



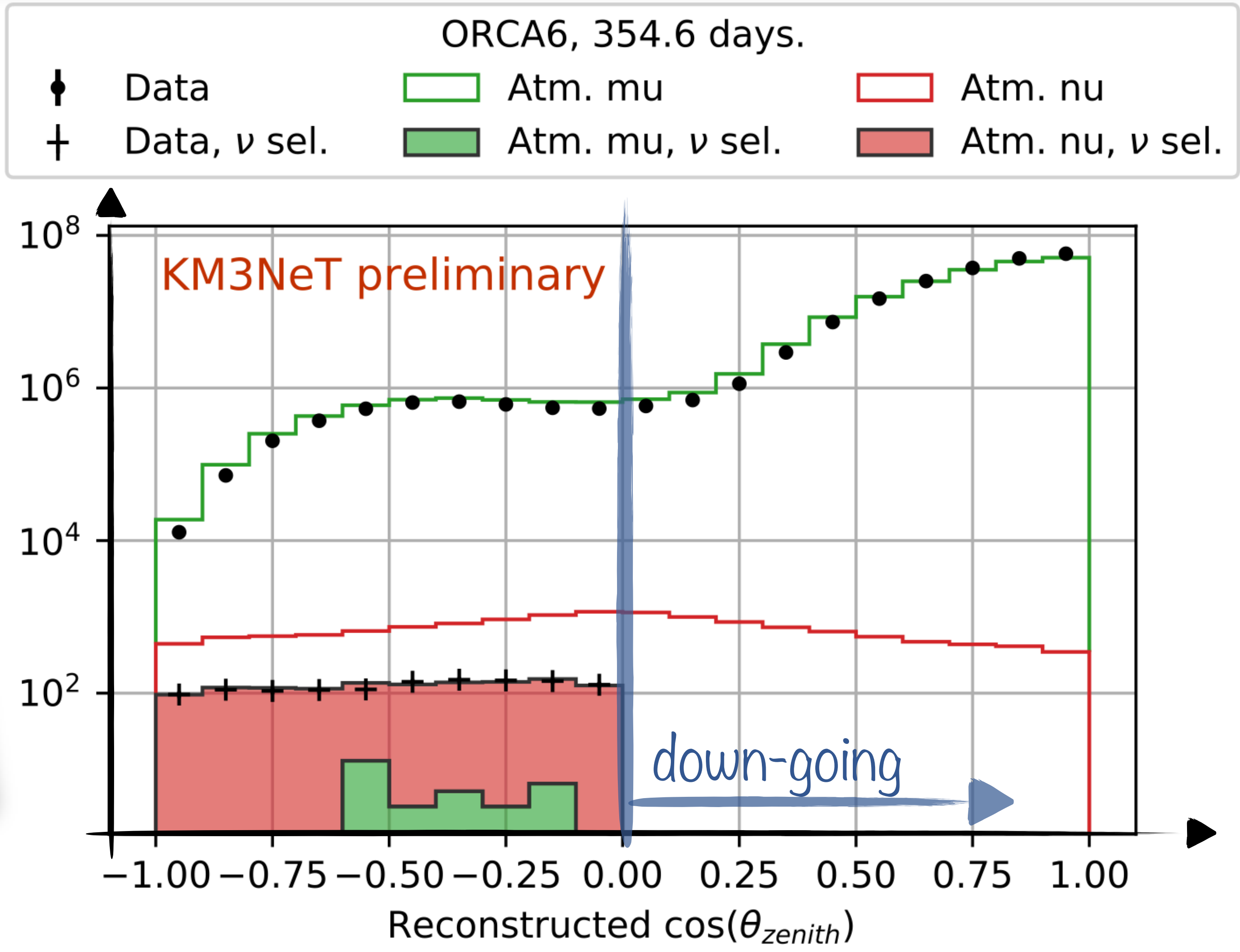
← DU in the darkroom ready for calibration

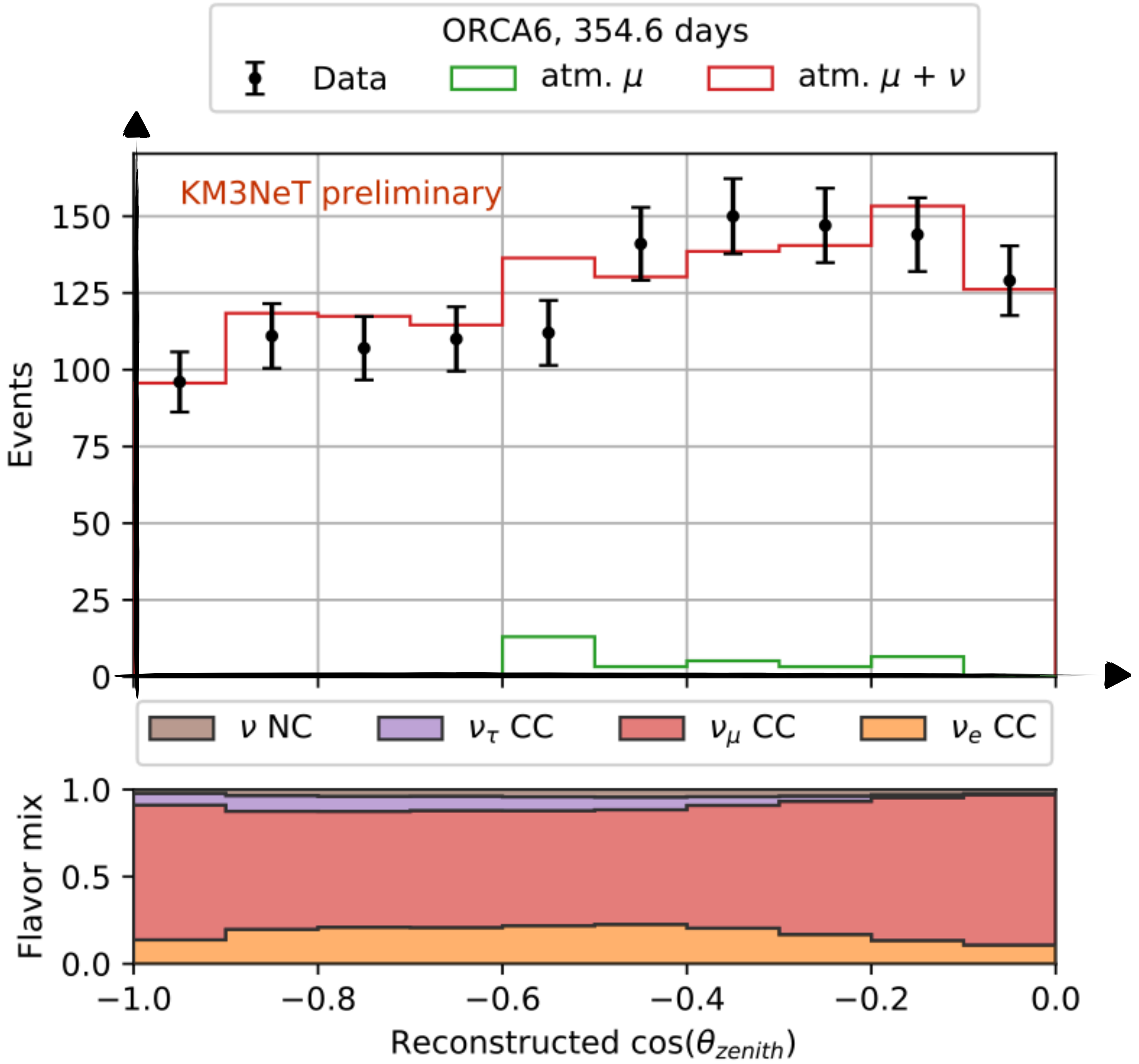


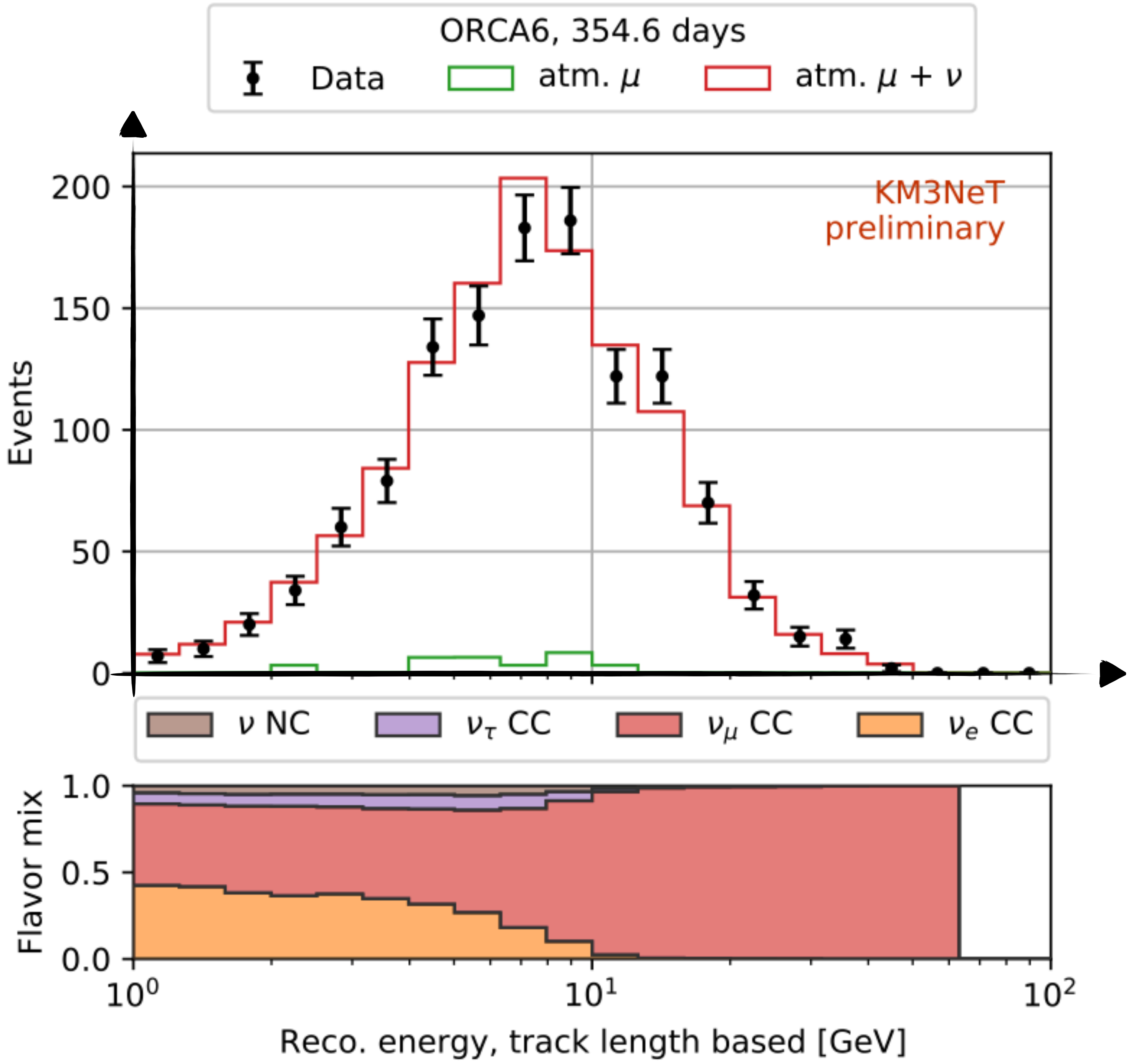
- first **KM3NeT/ORCA 6 neutrino oscillation analysis** included only the track class
  - ❍ **atmospheric muons** as the main rejected bkg
  - ❍ **neutrino selection** includes only:
    - ⦿ up-going events
    - ⦿ well-reconstructed tracks (from max. likelihood reco variables)
    - ⦿ containment in ~1.5 Mton instr. mass (start point in r=60 m)

Simulation:
- MUPAGE for atm. muons (including full CR- shower simulation, HEMAS)
- gSeaGen for neutrinos (GENIE-based code for KM3NeT & NuFit 5.0 parameters, with NO. hypothesis)

- 1237 neutrino candidates in 354.6 days
- S/B ~ 40!



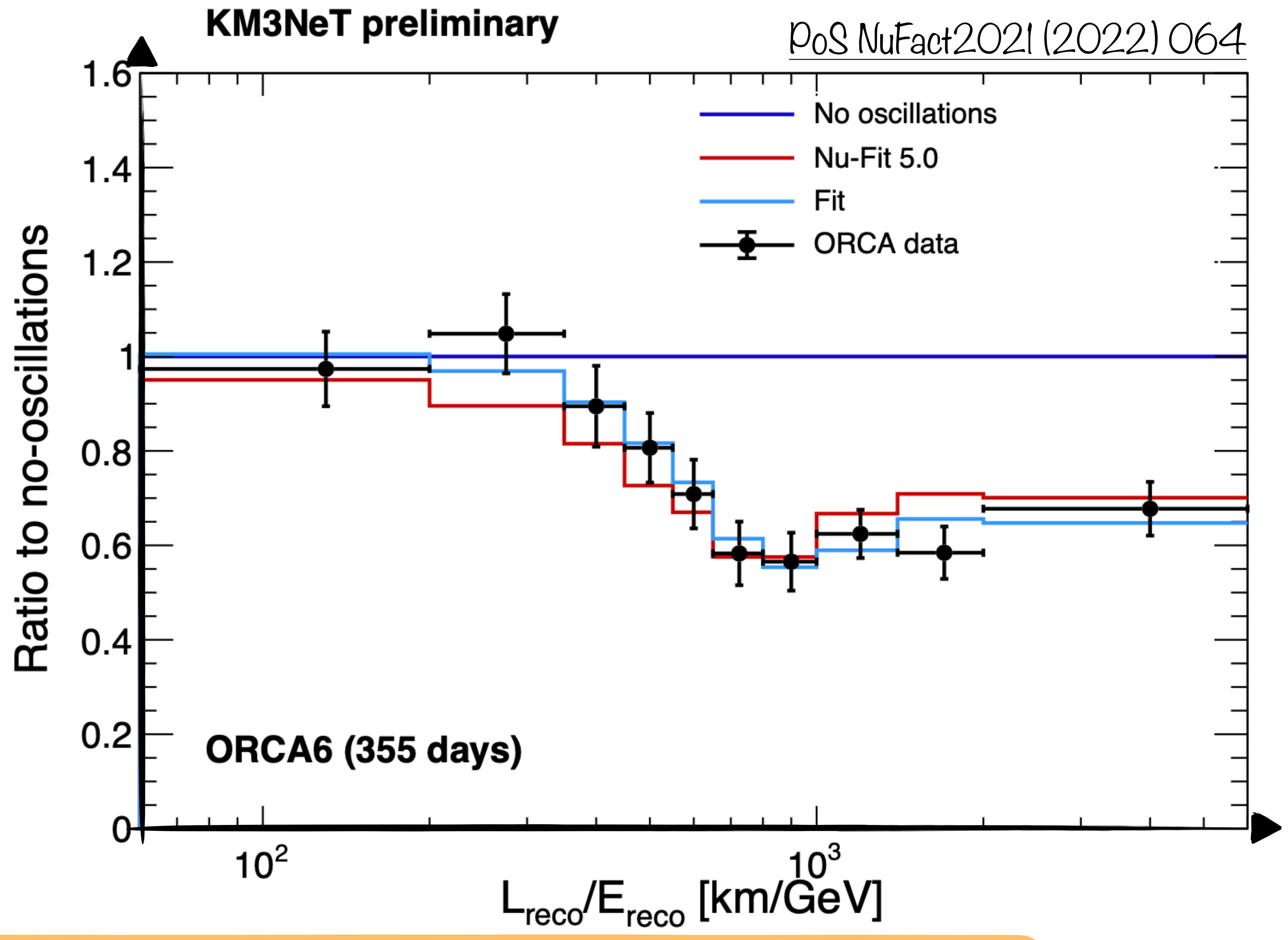




PoS NuFact2021 (2022) 064

KM3NeT/ORCA 6: current analysis

- first **KM3NeT/ORCA 6 neutrino oscillation analysis** included only the track class
  - ❍ **max. binned-likelihood** in **2D energy** and **cosine zenith** distributions
  - ❍ **NuFit 5.0**, **assuming NO**, as the null hypothesis
  - ❍ improved source of **systematics** compared to full ORCA sensitivity studies:
    - ⦿ atm. neutrino flux
    - ⦿ cross-section
    - ⦿ **overall normalization**
    - ⦿ detector response



❍ **clear oscillation pattern** (..only track class, 6 DUs, and ~1 year of collected data!!)

KM3NeT/ORCA 6: current analysis

- first **KM3NeT/ORCA 6 neutrino oscillation analysis** included only the track class
  - ❍ **max. binned-likelihood** in **2D energy** and **cosine zenith** distributions
  - ❍ **NuFit 5.0**, **assuming NO**, as the null hypothesis
  - ❍ **already in the game with the other experiments** (..only track class, 6 DUs, and ~1 year of collected data!!)

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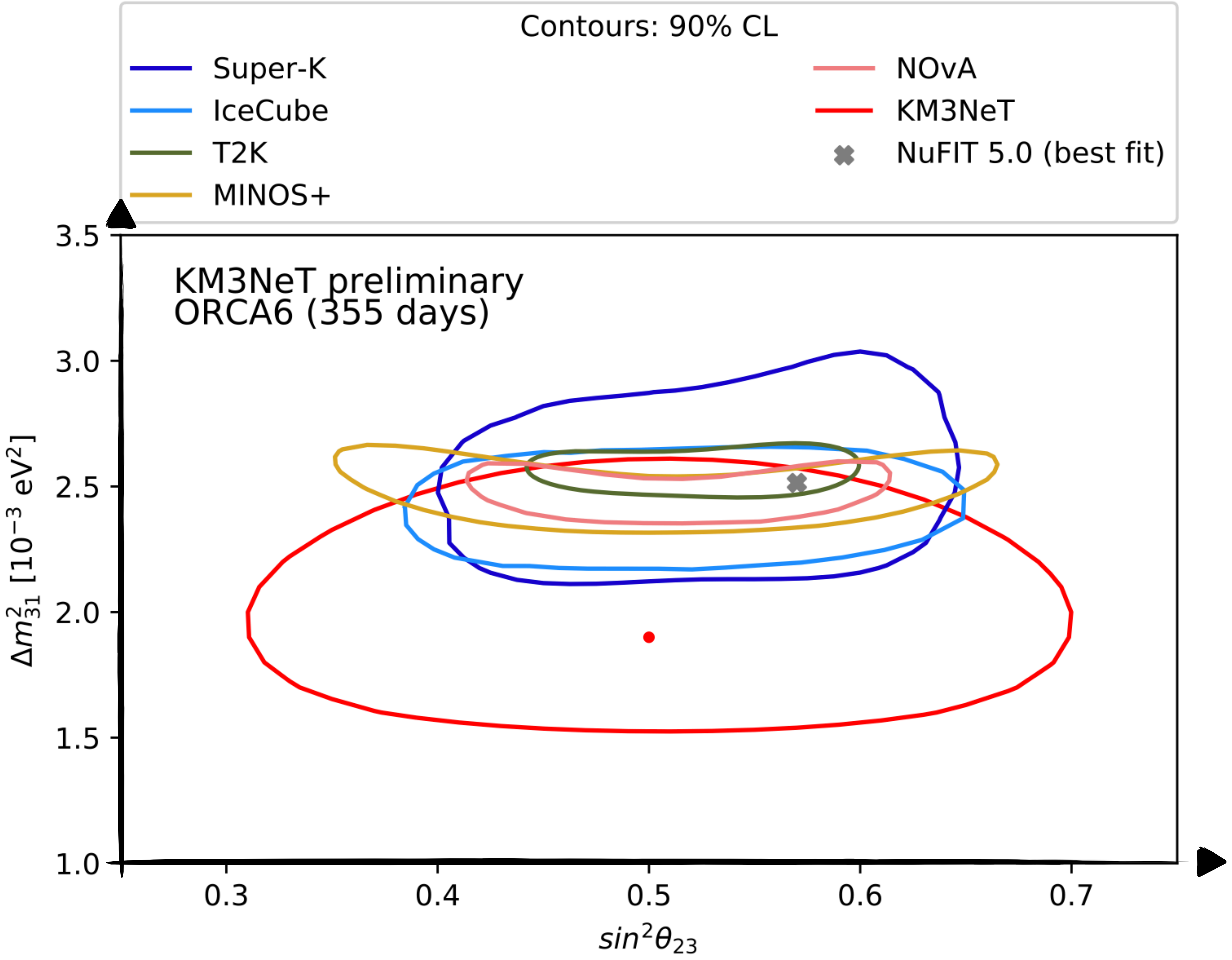
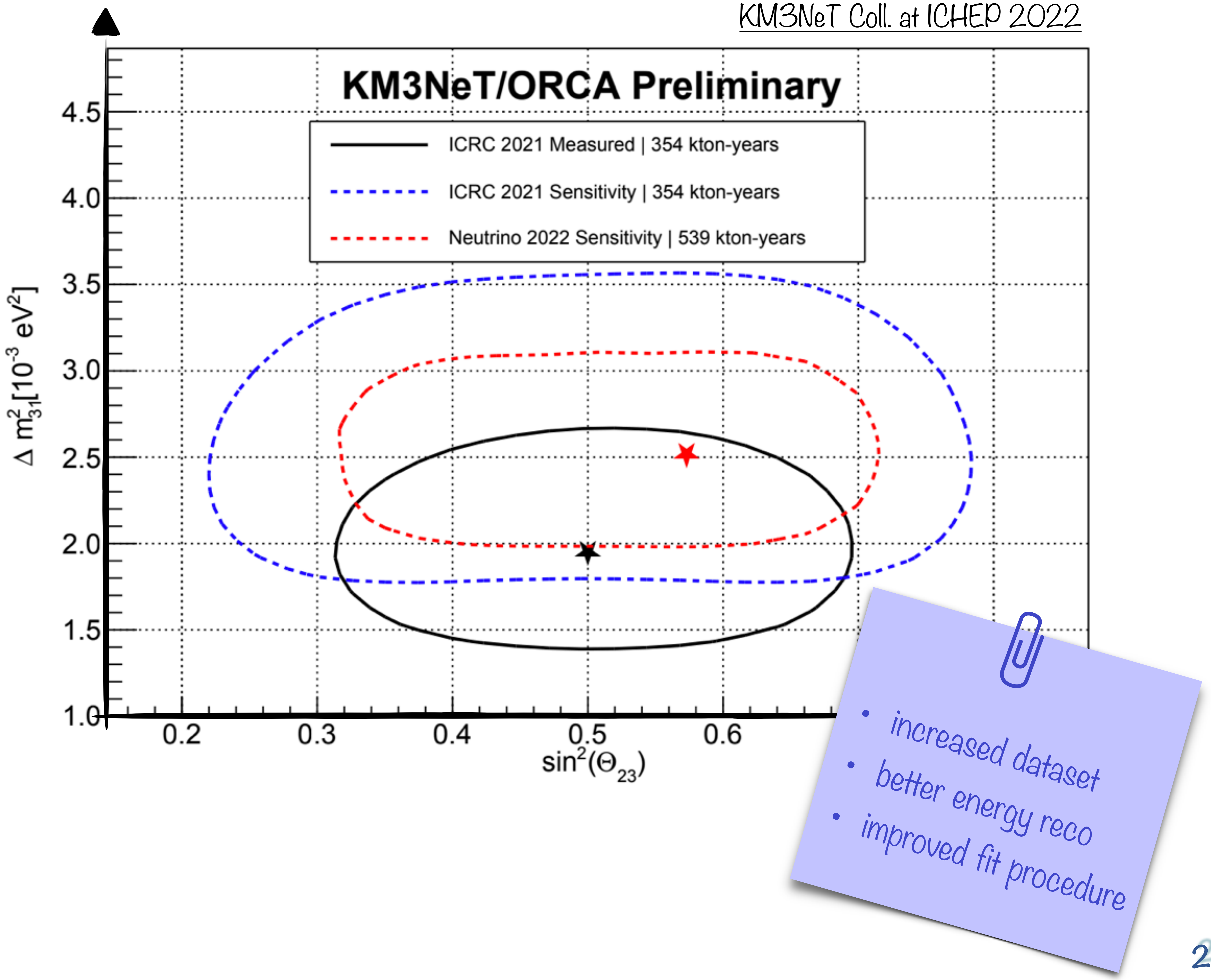


KM3NeT/ORCA 6: current analysis & ongoing improvements

- first **KM3NeT/ORCA 6 neutrino oscillation analysis** included only the track class
  - ❍ **max. binned-likelihood** in **2D energy** and **cosine zenith** distributions
  - ❍ **NuFit 5.0**, **assuming NO**, as the null hypothesis
  - ❍ **already in the game with the other experiments** (..only track class, 6 DUs, and ~1 year of collected data!!)

- **Short-term improvements for the final ORCA 6 analysis:**
  - ❍ **increased data set** (539 days of collected data)
  - ❍ track-vs-shower classification (BDT, GNN, others)
  - ❍ reconstruction and selection of shower-like events
  - ❍ inclusion of shower class in the fit procedure
  - ❍ improved study on systematics

KM3NeT Coll. at ICHEP 2022



- first **KM3NeT/ORCA 6 neutrino oscillation analysis** included only the track class
  - **max. binned-likelihood** in **2D energy** and **cosine zenith** distributions
  - **NuFit 5.0 assuming NO** as the null hypothesis
  - **already competitive with other experiments** (..only track class, 6 DUs, and ~1 year of collected data!!)

- **Short-term improvements for the final ORCA 6 analysis:**
  - **increased data set** (539 days of collected data)
  - **track-vs-shower classification** (BDT, GNN, others)
  - reconstruction and selection of shower-like events
  - inclusion of shower class in the fit procedure
  - improved study on systematics

Getting ready for ν_τ appearance analysis:

- study of the shower reconstruction algorithm performance in ORCA 6
- traditional and NN techniques for selection (shower vs tracks, ν_τ vs showers)
- dedicated study of the systematics for the fit of the ν_τ normalization factor

Summary and outlook

- **KM3NeT/ORCA** will contribute to the **NMO measurement (3σ after 5 years)** and **neutrino oscillation parameters**
- **KM3NeT/ORCA 6** data ready for neutrino oscillation physics!
  - only 9% of instrumented volume, only 1 year of data, only track class included
  - **clear oscillation pattern favoured at 5.9 σ**
  - **first measurement of θ_{23} and Δm^2_{32} parameters**

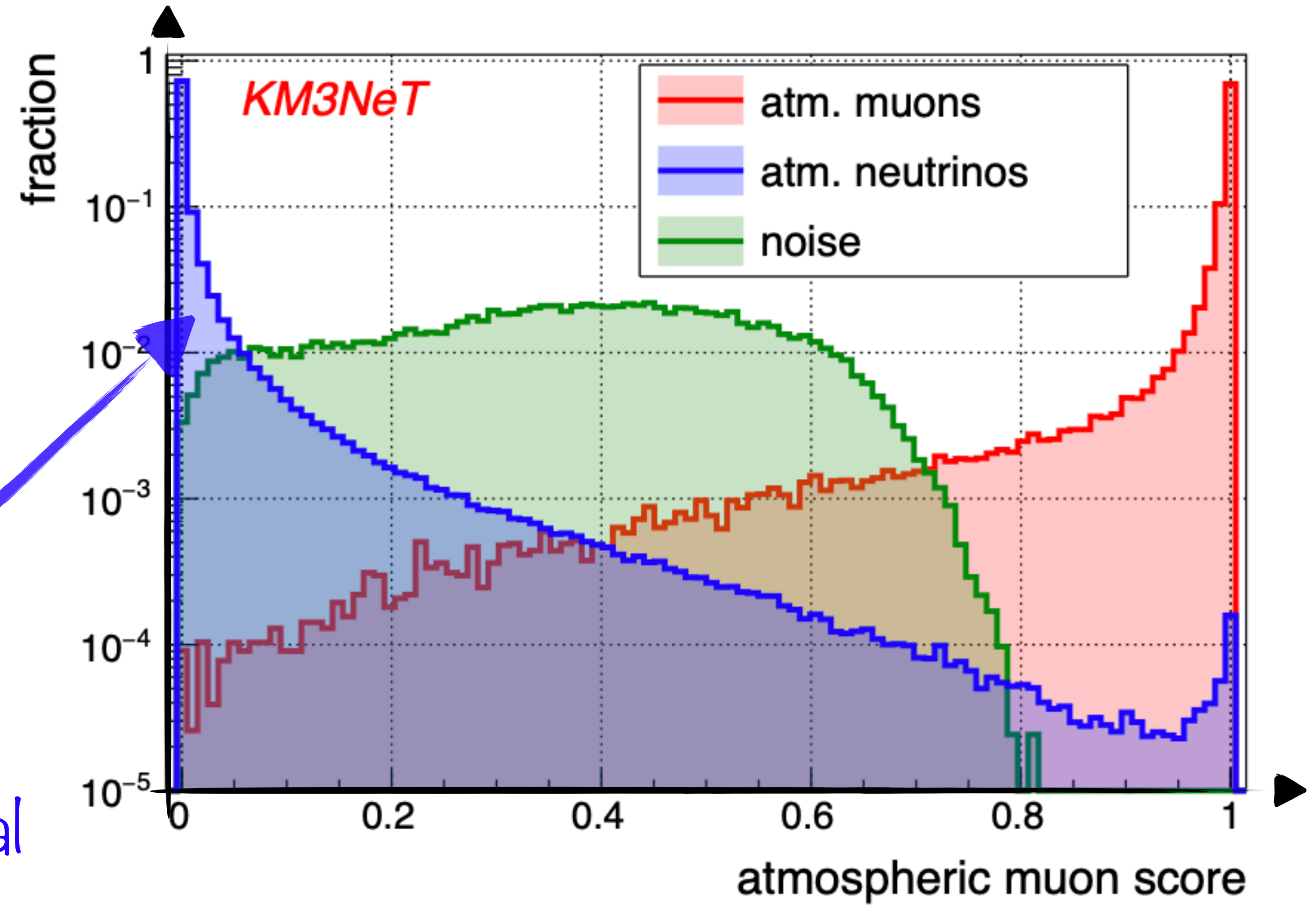
A new KM3NeT/ORCA 6 mass production is underway:

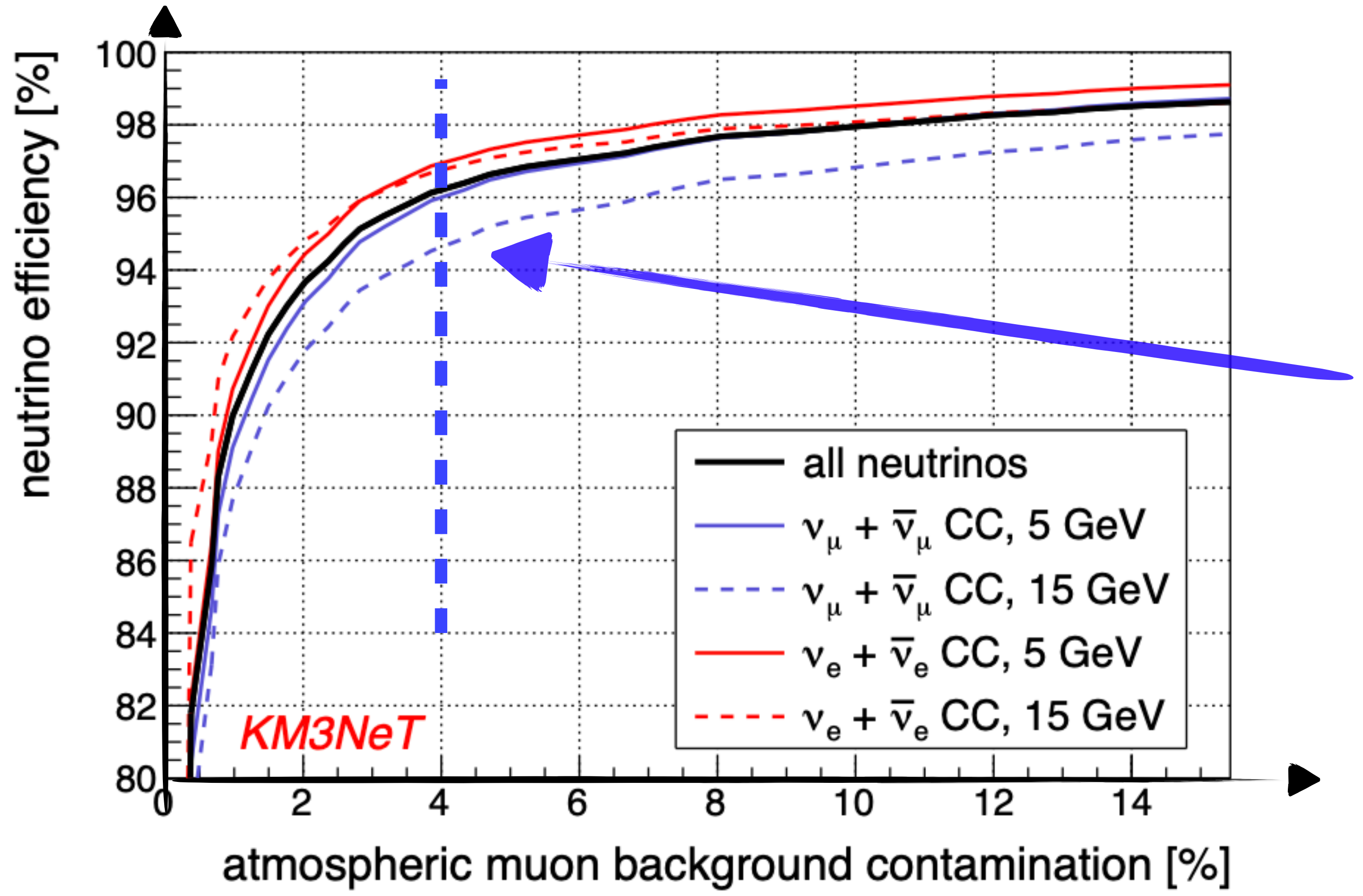
- **improving statistics** (+50% of the current dataset) and **detector size** (soon ORCA13!)
- **inclusion of track-vs-shower classification** (BDT, GNN, other techniques)
- **shower-like** events reconstruction, selection, and inclusion in the fit
- **improvement of the fit procedure** (event classes and systematics)
- ν_τ **appearance** studies started


..thanks for your attention!
SAAS CO
JANUS II

Extra Slides

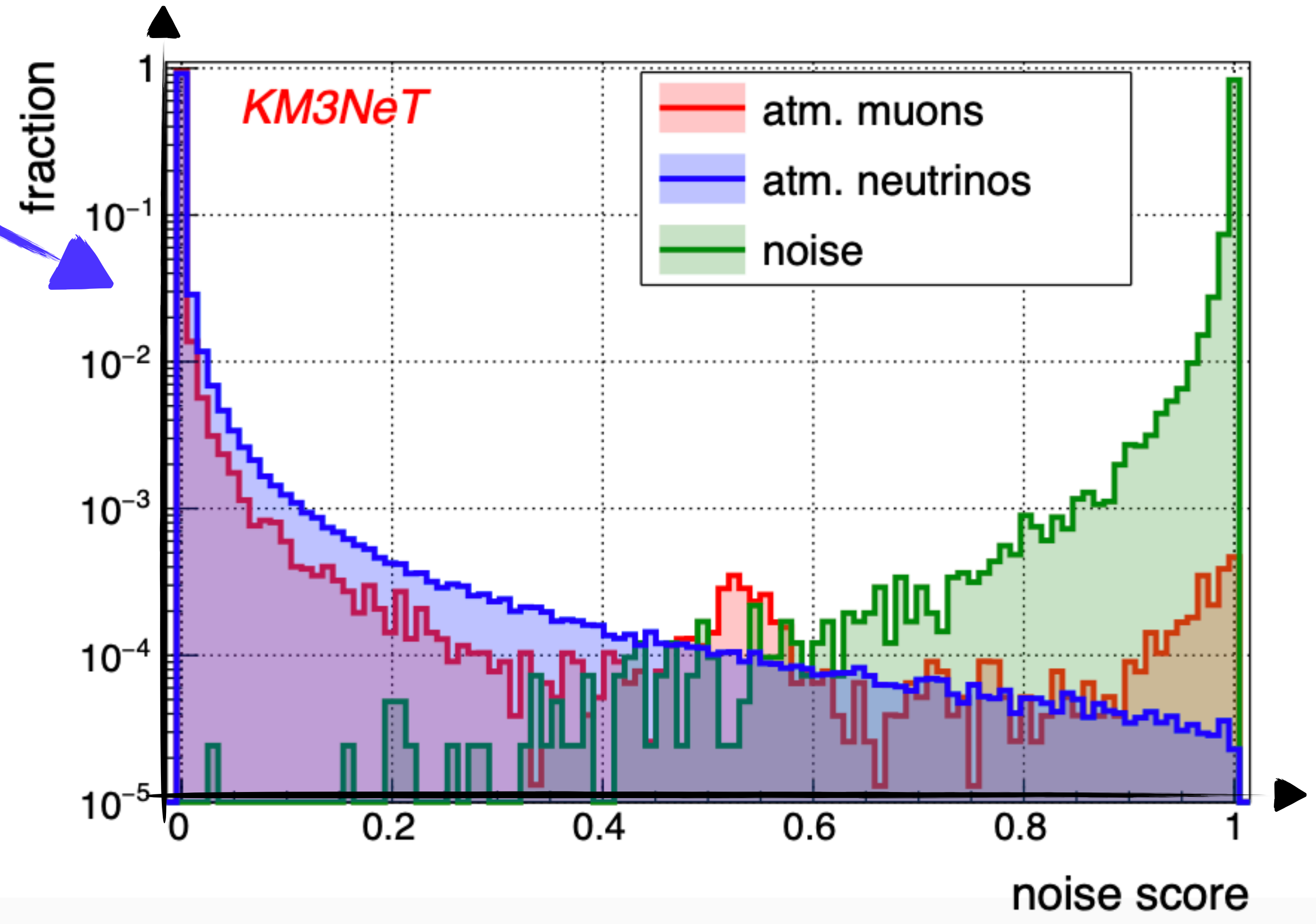
- **Event classification:**
  - ❍ **multivariate** and **neural network** topology algorithms (RDF, BDT, GNN, and other NN techniques)

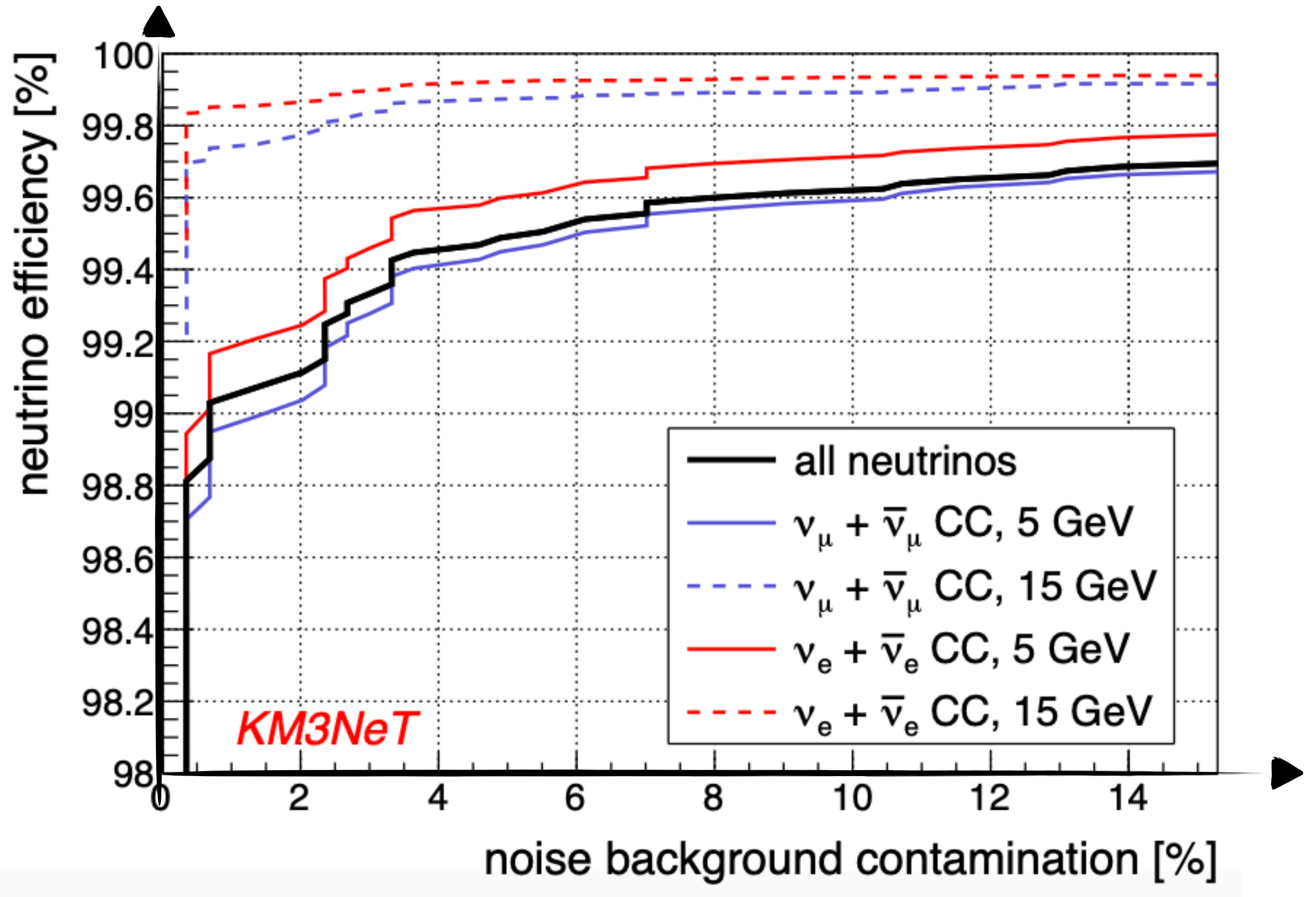




quickly reached a high neutrino classification efficiency (> 95%) with very low atm. muons contamination (~4%) !

Good classification of the signal against the main bkgs!

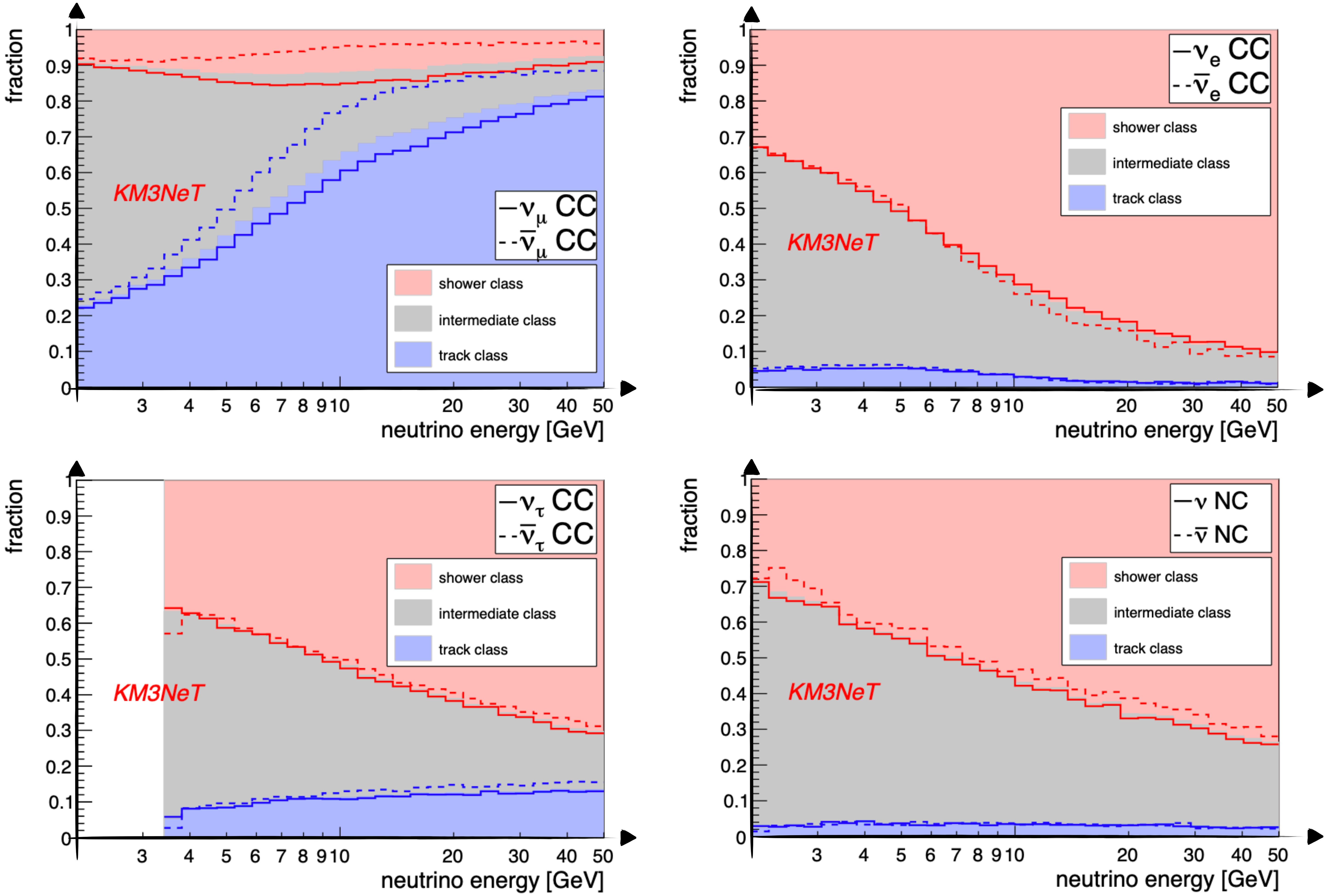




initial neutrino classification efficiency against noise contamination >98% !

KM3NeT/ORCA: neutrinos classification

- **Event classification:**
  - **multivariate** and **neural network** topology algorithms (RDF, BDT, GNN, and other NN techniques)



Based on the track score, the final neutrino sample is classified into three classes:

- track class
- shower class
- intermediate class

The three classes are the inputs for the neutrino oscillation fit

KM3NeT/ORCA: sensitivity to main physics searches

- **Fit methodology**:
  - 2D binned log-likelihood maximization energy and cosine zenith distributions for the three classes
  - Asimov approach:

$$LL_0 = \Sigma_{i\in[E_{rec},cos\theta_{rec}]}\, LL_{0,i} = \Sigma_{i\in[E_{rec},cos\theta_{rec}]} - 2.0\,(n_i^{null}, n_i^{alt} - n_i^{null} ln \frac{n_i^{null}}{n_i^{alt}})$$

    - *null hypothesis* = MC pseudo-data using NuFit parameters
    - *alternate hypothesis* = unblinded data
    - *i*th, each bin in energy and cosine zenith

- **Main Systematics**:
  - neutrino flux (spectral index, relative n. of $\nu_{e,\mu}$ and anti-$\nu_{e,\mu}$, their direction)
  - cross-section (n. of NC and ν_τ and anti-ν_τ CC events)
  - detector response (PMT efficiency, light yield in the hadronic showers, n. of events in the three classes)

KM3NeT/ORCA: main systematics

- Systematics for sensitivity studies

Parameter	Null hypothesis	Dataset Value	Value at Min.	Prior
Δm^2_{32} [eV^2]	NO IO	$2.528 \cdot 10^{-3}$ $2.436 \cdot 10^{-3}$	$(2.51^{+0.11}_{-0.11}) \times 10^{-3}$ $(2.43^{+0.10}_{-0.08}) \times 10^{-3}$	free
Δm^2_{21} [eV^2]	NO IO	$7.39 \cdot 10^{-5}$	$7.39 \cdot 10^{-5}$	fixed
δ_{CP} [°]	NO IO	221.0 282.0	162 ± 180 190 ± 180	free
θ_{13} [°]	NO IO	8.60 8.64	8.63 ± 0.40 8.62 ± 0.29	0.13
θ_{12} [°]	NO IO	33.82	33.82	fixed
θ_{23} [°]	NO IO	48.6 48.8	$49.4^{+2.3}_{-3.9}$ $41.5^{+3.8}_{-1.9}$	free
Spectral index	NO IO	1.0	1.00 ± 0.02 1.01 ± 0.02	free
$n_{\overleftrightarrow{\nu}_{up}}/n_{\overleftrightarrow{\nu}_{horiz}}$	NO IO	1.0	1.01 ± 0.01 1.00 ± 0.01	0.02
$n_{\overleftrightarrow{\nu}_e}/n_{\overleftrightarrow{\nu}_\mu}$	NO IO	1.0	1.02 ± 0.06 $1.00^{+0.05}_{-0.04}$	0.02
$n_{\nu_e}/n_{\bar{\nu}_e}$	NO IO	1.0	$1.02^{+0.22}_{-0.21}$ 1.00 ± 0.16	0.07
$n_{\nu_\mu}/n_{\bar{\nu}_\mu}$	NO IO	1.0	$0.98^{+0.15}_{-0.14}$ $1.00^{+0.12}_{-0.11}$	0.05
Energy scale	NO IO	1.0	1.02 ± 0.05 0.99 ± 0.04	0.06
Had. energy scale	NO IO	1.0	$0.96^{+0.13}_{-0.10}$ $1.00^{+0.11}_{-0.08}$	0.05
n_{NC}	NO IO	1.0	$1.02^{+0.42}_{-0.37}$ $0.89^{+0.32}_{-0.28}$	free
n_τ^{CC}	NO IO	1.0	$1.05^{+0.19}_{-0.20}$ $1.03^{+0.13}_{-0.14}$	free
$n_{Intermediate}$	NO IO	1.0	$1.00^{+0.05}_{-0.06}$ 1.02 ± 0.04	free
n_{Tracks}	NO IO	1.0	0.98 ± 0.04 1.00 ± 0.03	free
$n_{Showers}$	NO IO	1.0	$1.01^{+0.09}_{-0.08}$ $1.03^{+0.07}_{-0.06}$	free

neutrino flux

x-sec

detector response

- Systematics for the current oscillation analysis

Type	Parameter	Treatment
Oscillations	Δm^2_{31} [10^{-3} eV^2]	Free
	θ_{23} [deg]	Free
Model	Normalisation	Free
Flux shape	Spectral index	$\mathcal{N}(0, 0.3)$
	$n_{\nu_{up}}/n_{\nu_{down}}$	$\mathcal{N}(0, 0.07)$
Flux composition	$n_{\nu_\mu}/n_{\bar{\nu}_\mu}$	$\mathcal{N}(0, 0.1)$
	$n_{\nu_e}/n_{\bar{\nu}_e}$	$\mathcal{N}(0, 0.1)$
	n_{ν_μ}/n_{ν_e}	$\mathcal{N}(0, 0.03)$
Cross section	n^{NC}	$\mathcal{N}(1, 0.1)$
	n_τ^{CC}	$\mathcal{N}(1, 0.2)$
Detector	Energy scale	$\mathcal{N}(0, 0.1)$

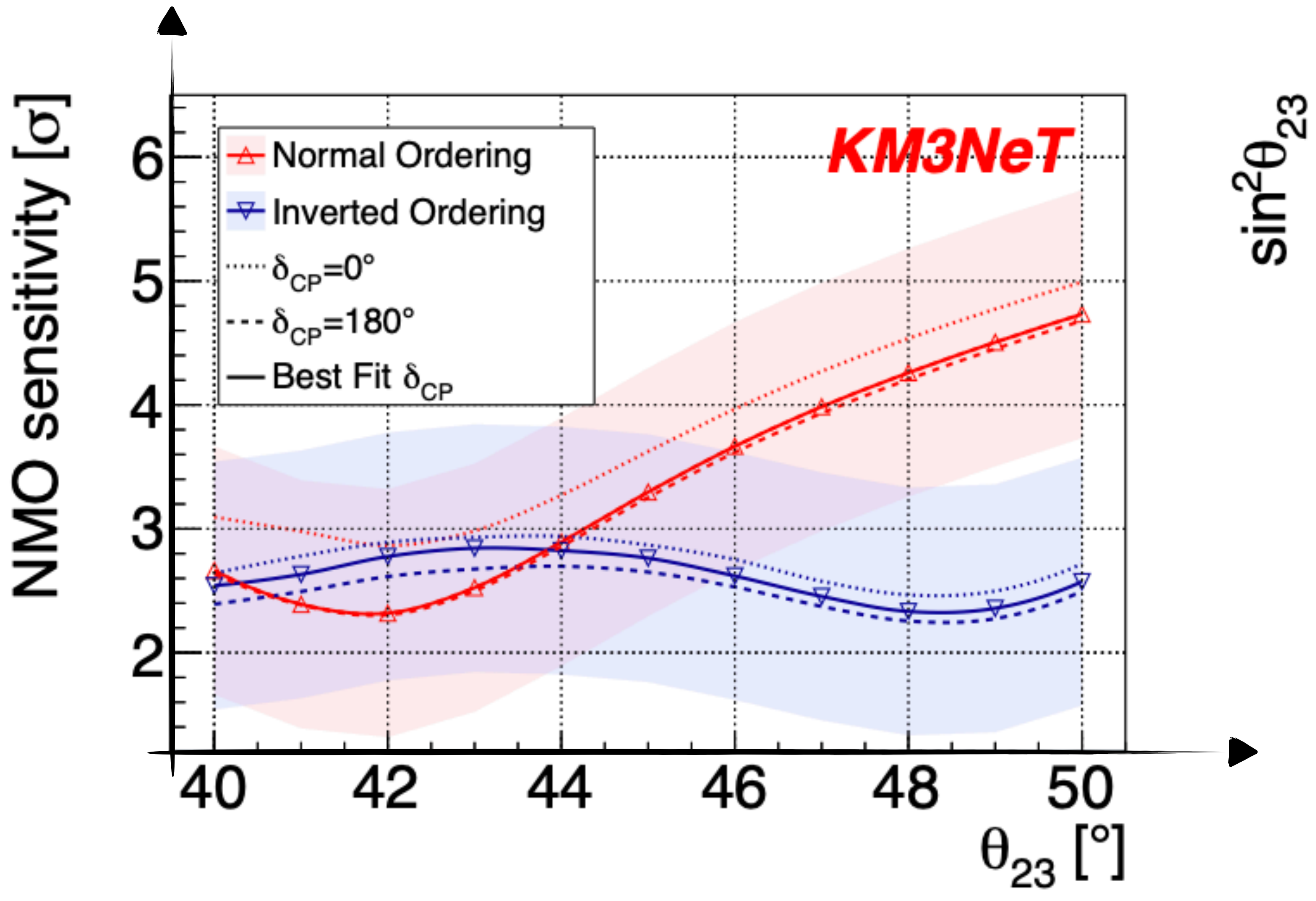
neutrino flux

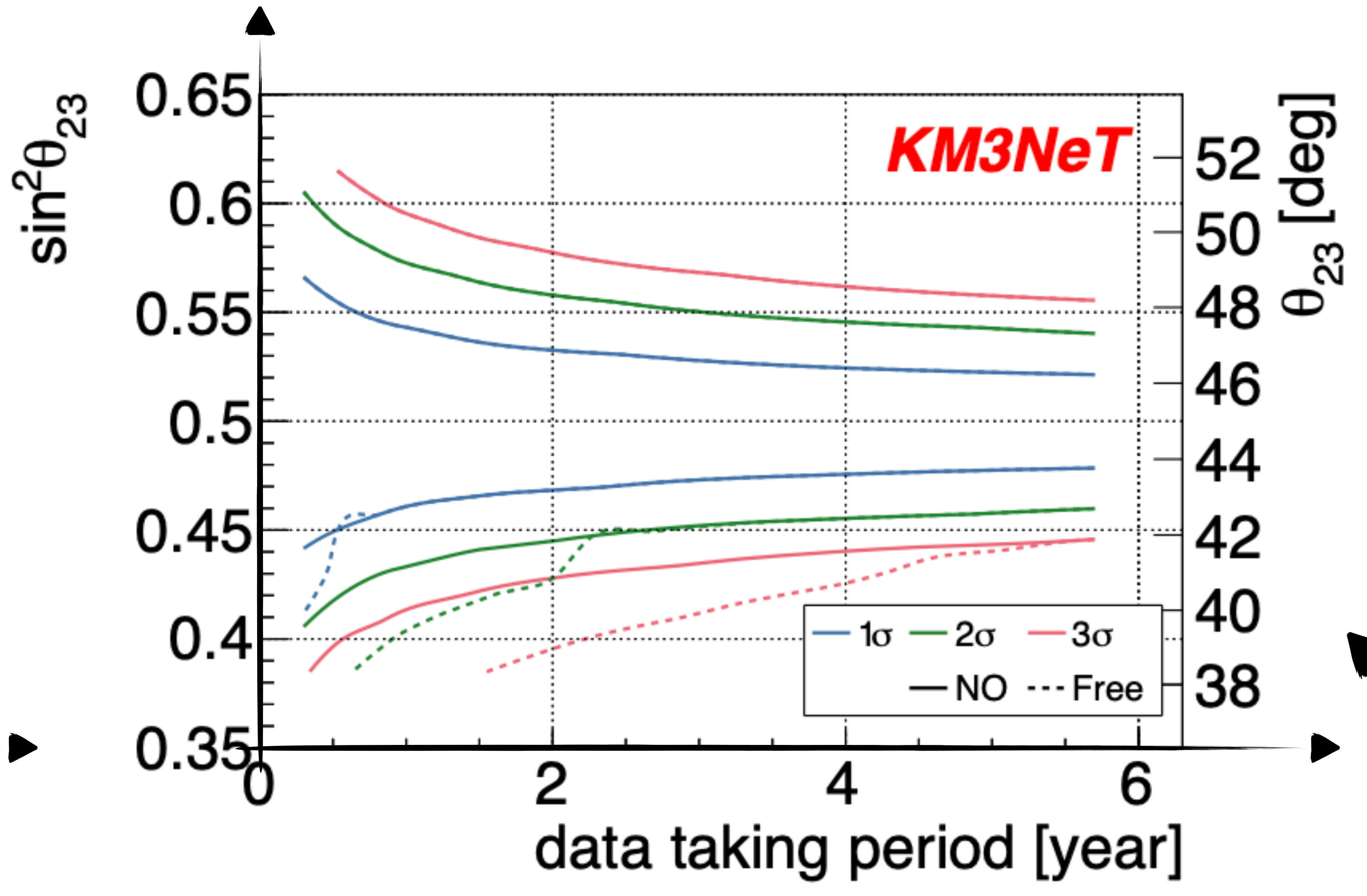
x-sec

detector response

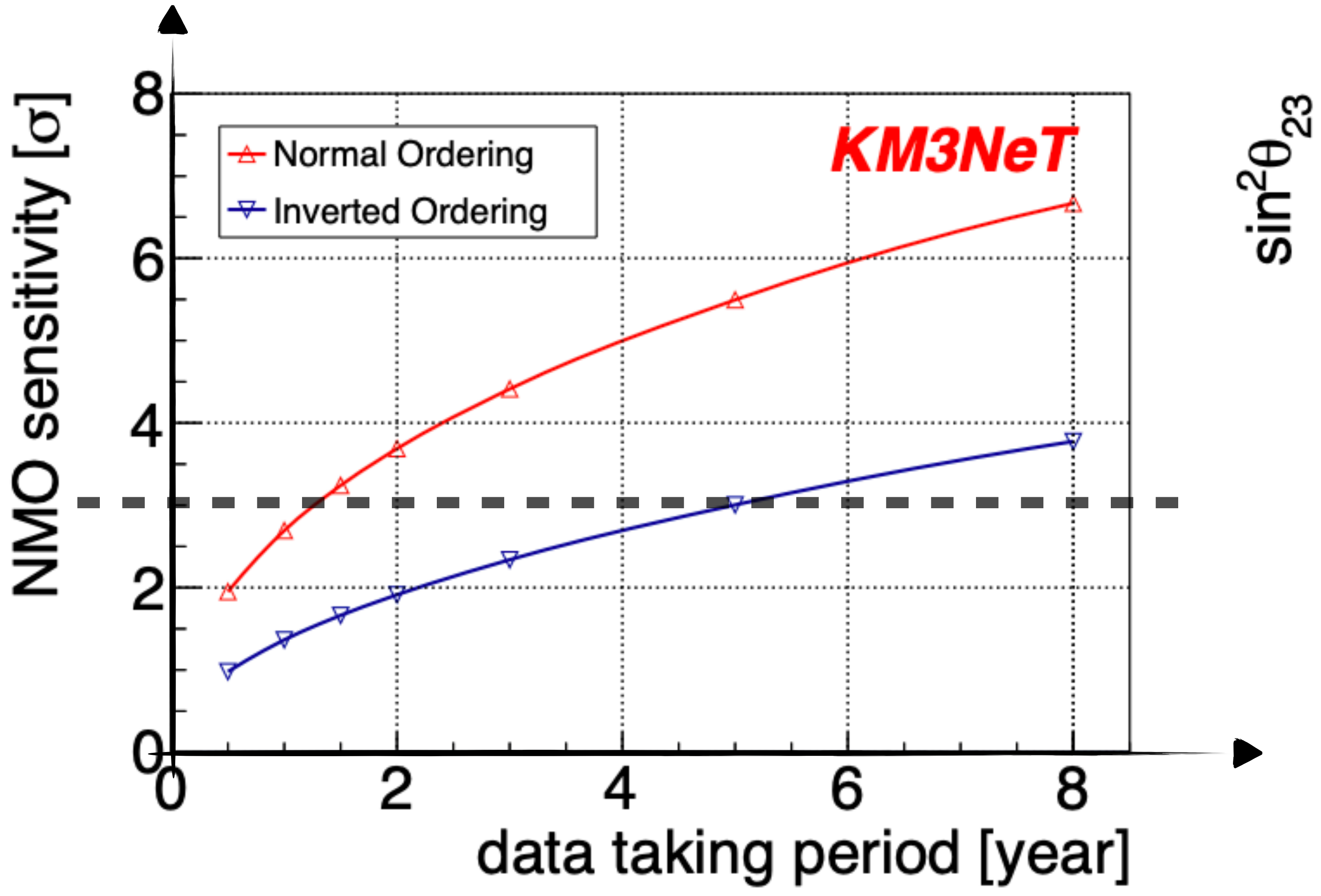
- **Neutrino Mass Ordering (NMO):**
  - Asimov approach, with Inverted Ordering (IO) as the *alternate hypothesis*

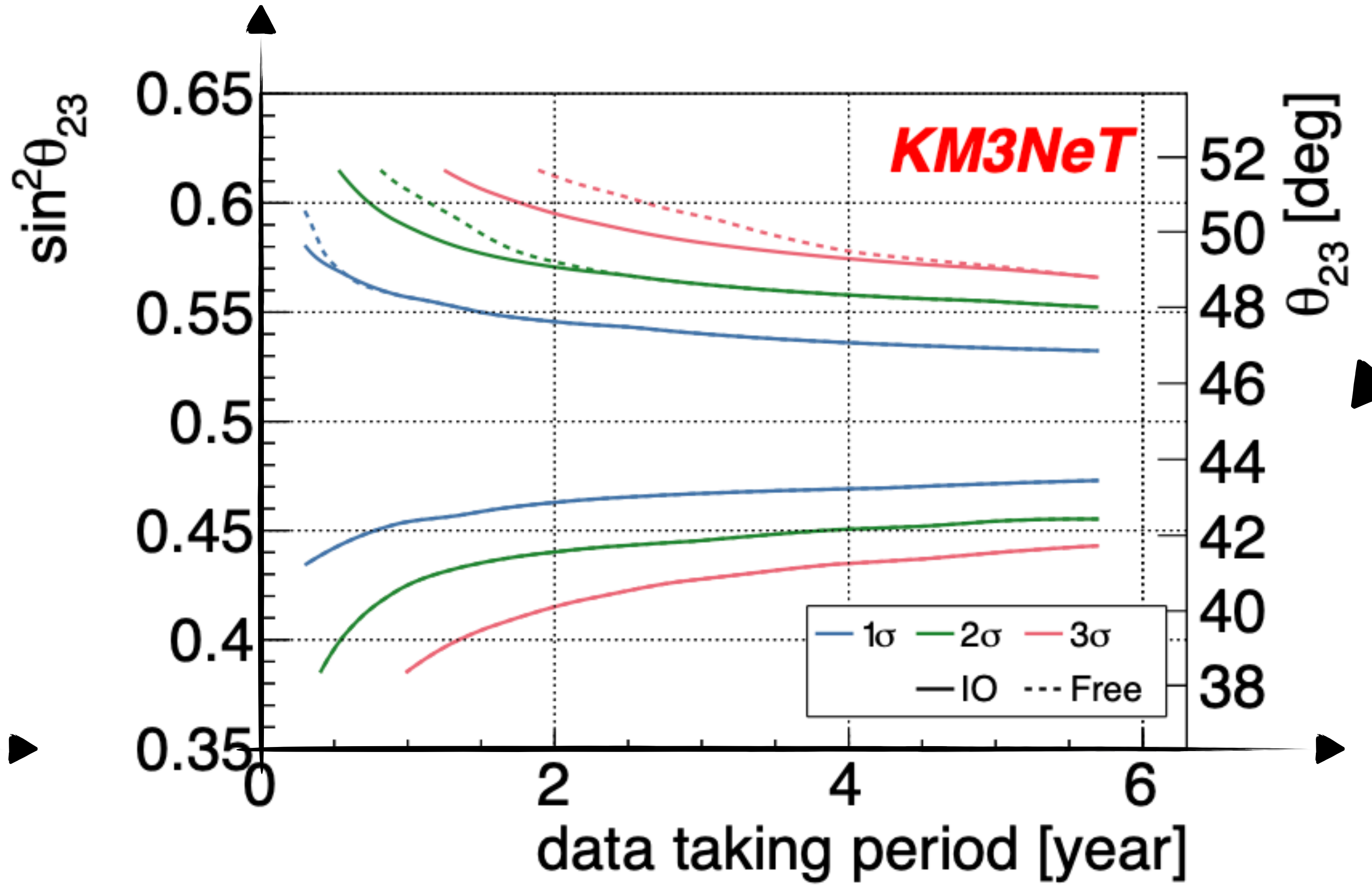
NMO sensitivity vs true θ_{23} value, after 3 years of data taking





3σ sensitivity to IO, after 5 years of data taking





$\sin\theta_{23}$ sensitivity for NO (top) and IO (bottom)

- **Neutrino Mass Ordering (NMO), combined analysis with JUNO:**
  - ❍ advantage: tension in the Δm^2_{31} best fits from both experiments when assuming the wrong hypothesis