EXPLOITING KM3NeT/ORCA DATA TO STUDY ν_τ AND TESTING THE NON-UNITARITY MIXING

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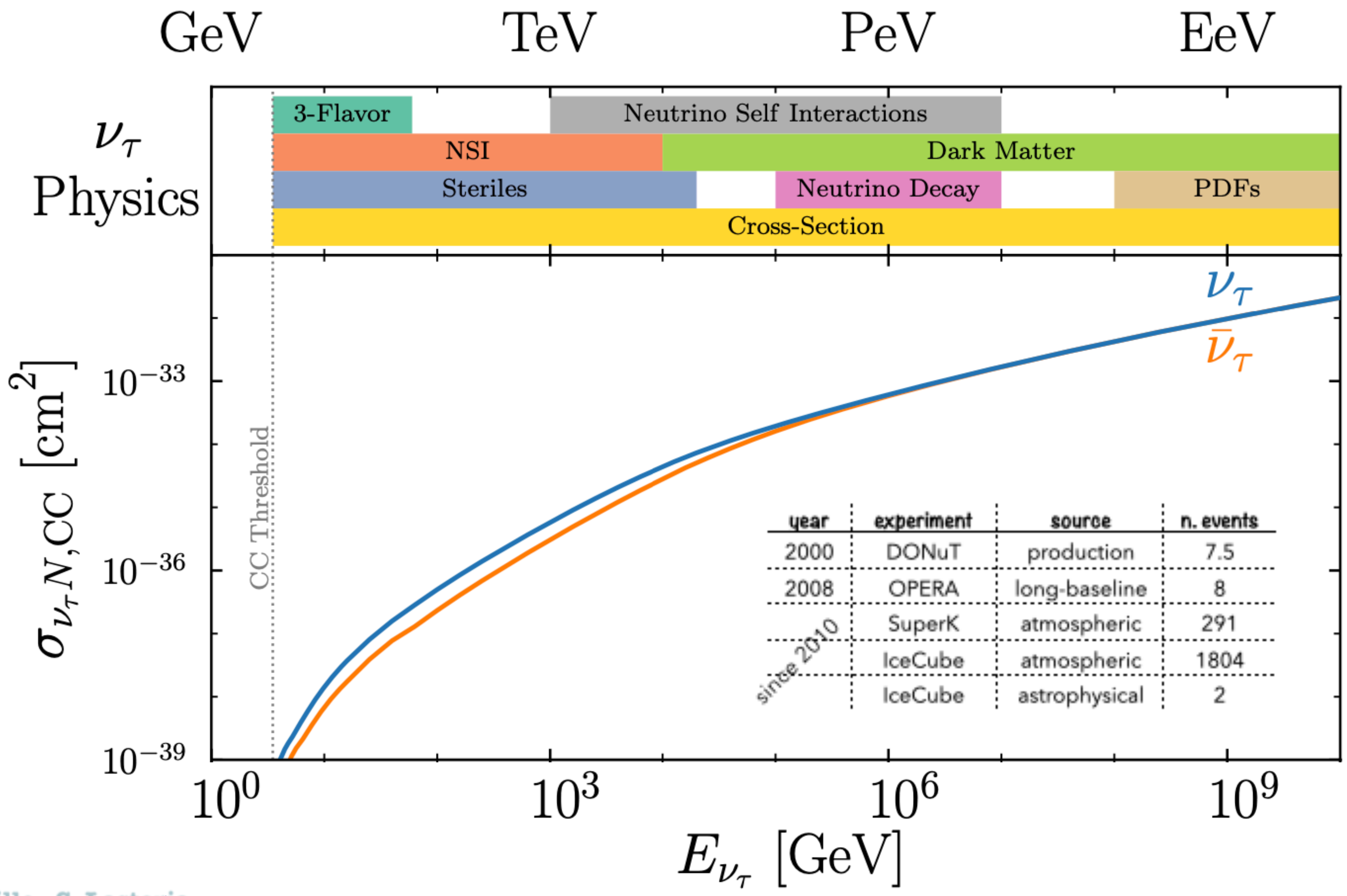
On behalf of the KM3NeT Collaboration

EPS-HEP, Marseille, 08/07/2025

Why studying ν_τ?

- **still one of the less studied Standard Model (SM) particles** (~2100 detected, so far)
  - ❍ relatively high **production threshold**
  - ❍ **low cross-section**



year	experiment	source	n. events
2000	DONuT	production	7.5
2008	OPERA	long-baseline	8
since 2010	SuperK	atmospheric	291
	IceCube	atmospheric	1804
	IceCube	astrophysical	2

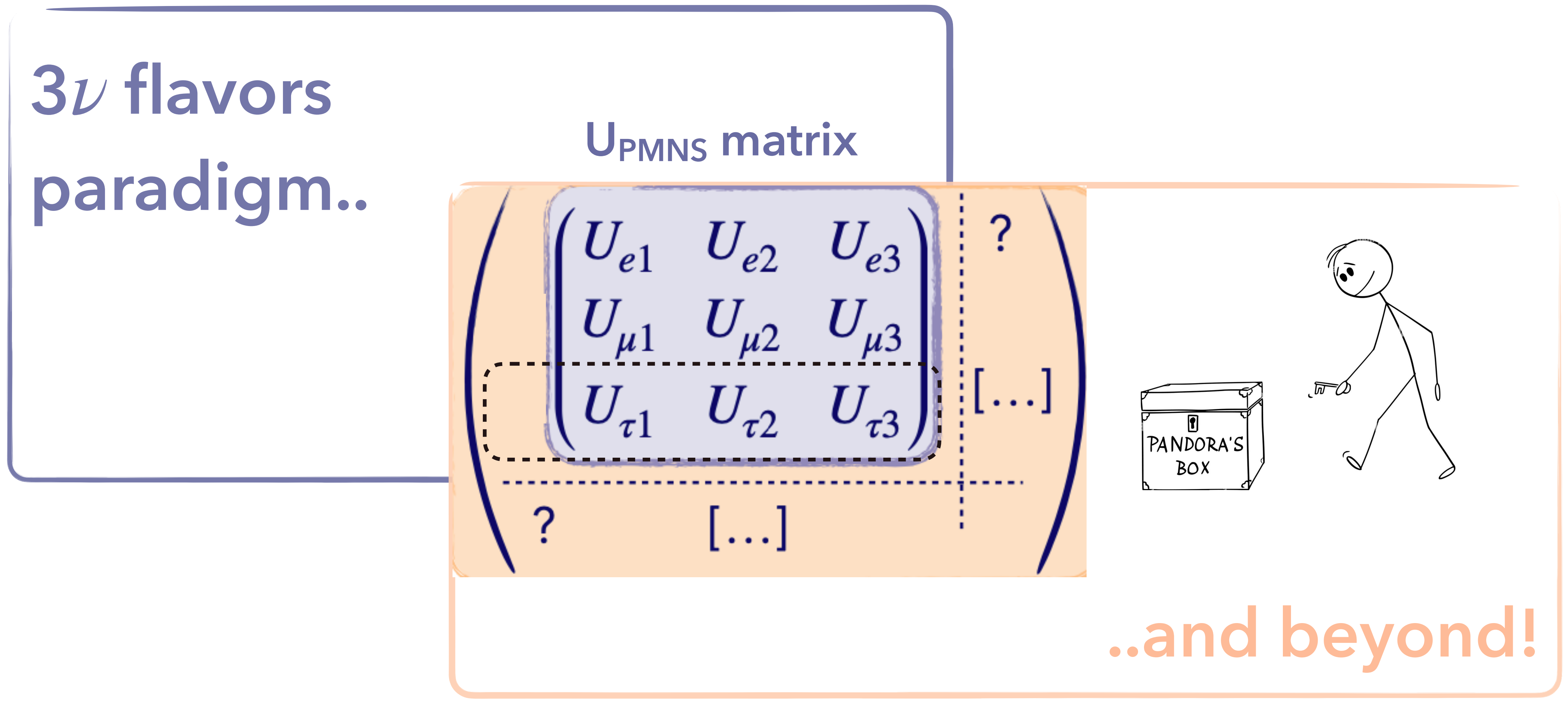
2022 J. Phys. G: Nucl. Part. Phys. 49 110501

Why studying ν_τ?

- next-generation neutrino experiments aims at reaching sub-percent precision in oscillation parameters
  - **constraints on PMNS elements $\leq$ 10%**

    (< 1% in e-row, but ~ 10 % in τ-row)
  - **neutrino mixing non-unitarity** extensions to explore

    Beyond Standard Model (BSM) physics

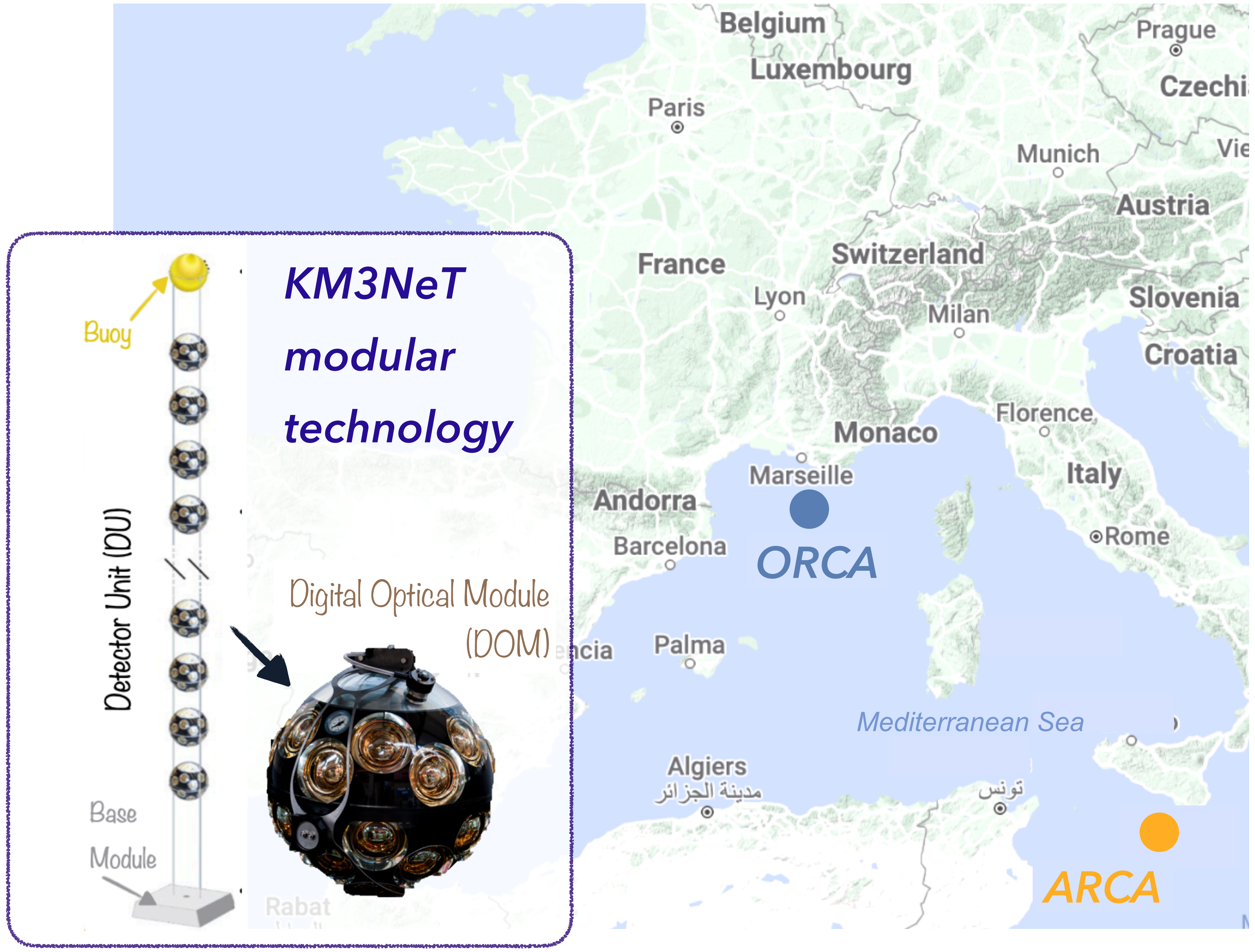


<u>*Complementarity: different energy scale and sensitivity to BSM parameters*</u>

- **long-baseline accelerator neutrino experiments** (e.g.OPERA, DUNE, HK)
  - remarkable event reconstruction
- **atmospheric neutrino experiments** (e.g. SK, IceCube, KM3NeT/ORCA)
  - larger statistics (e.g. ~3000 ν_τ / year, in KM3NeT/ORCA)

The KM3NeT experiment

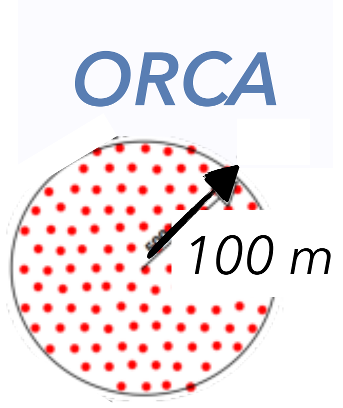
- **Water Cherenkov neutrino telescope**
- two detection sites for a **complementary physics program**



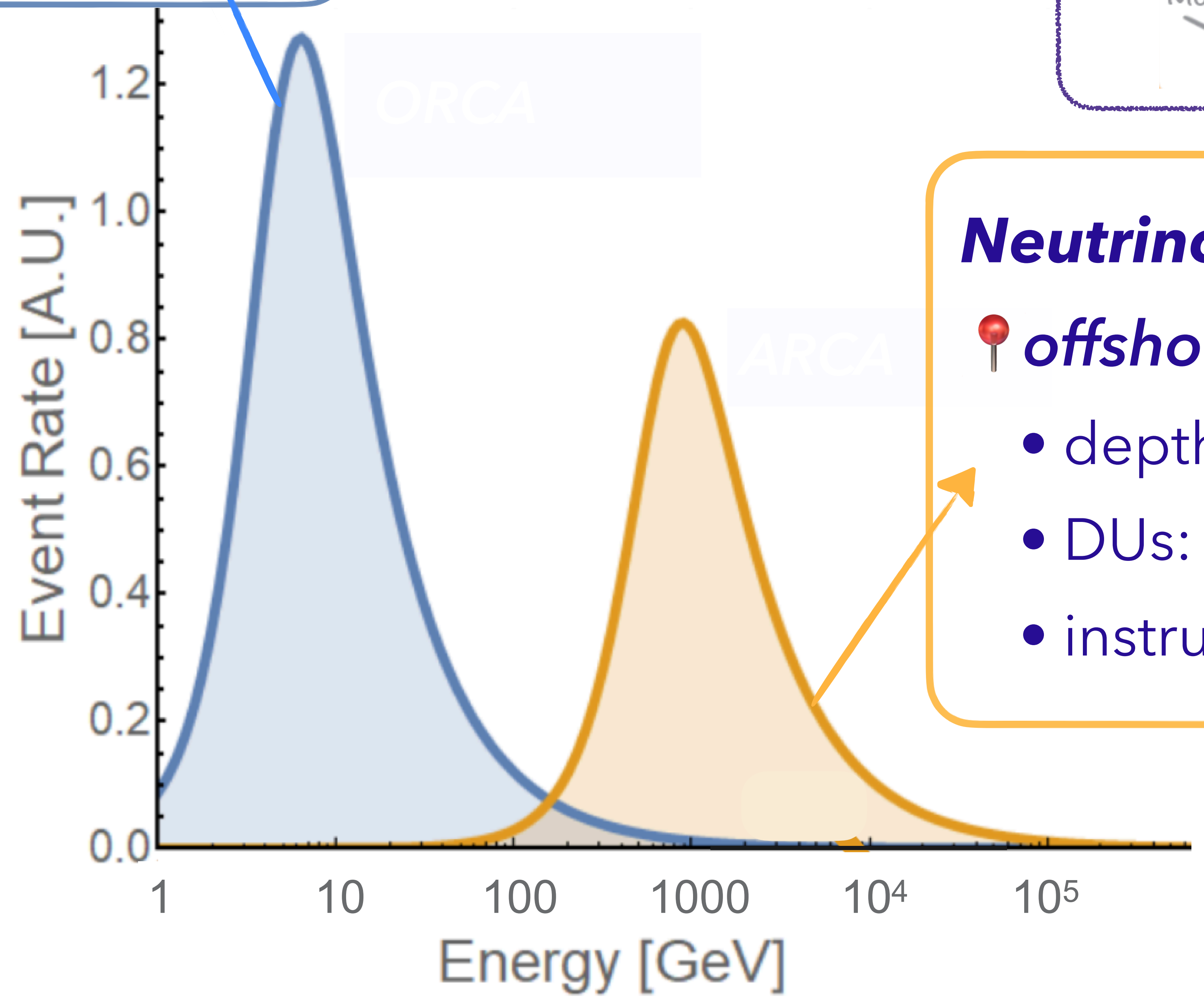
Neutrino oscillations in ORCA

📍 ***offshore Toulon (France)***

- depth: 2450 m
- Detection Units (DUs): 115
- instrumented vol. ~ 24%



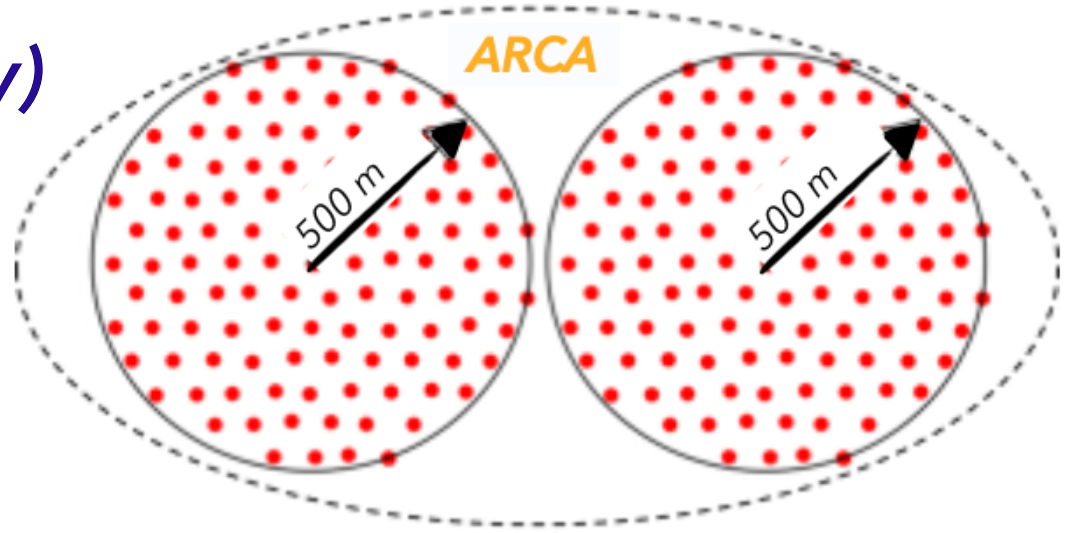
- **atmospheric neutrinos**:
  - ❍ wide energy range (1-100 GeV)
  - ❍ different baselines (L), from ~10 to ~13000 km



Neutrino astronomy in ARCA

📍 ***offshore CapoPassero (Italy)***

- depth: 3560 m
- DUs: 230
- instrumented vol. ~ 12%

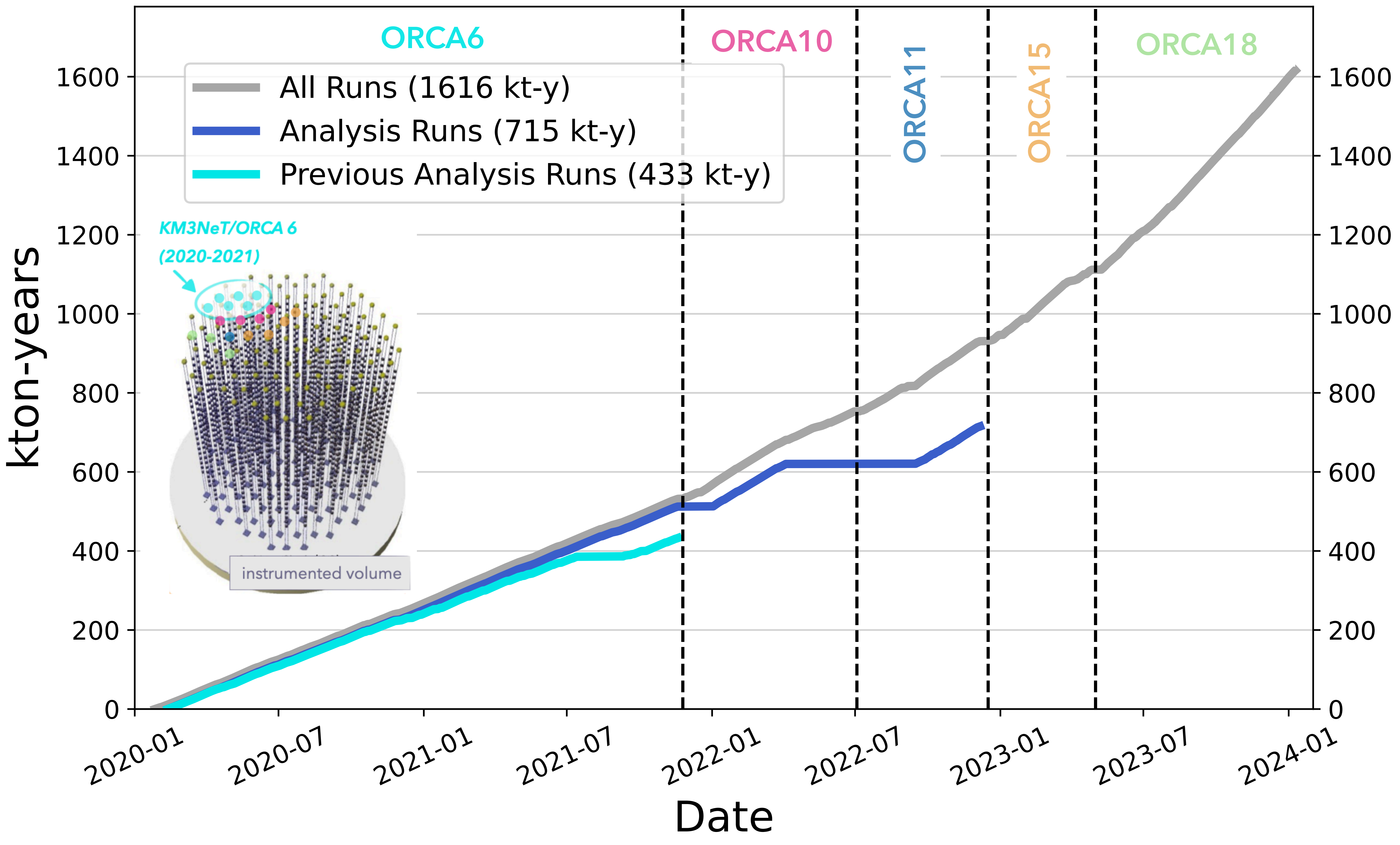


A growing detector

- Flexible and robust **data quality criteria** for each detector configuration
  - ❍ stable detector operation, low-bioluminescence conditions, high-timing accuracy
  - ❍ ~3 years of *high-quality* data (ARCA and ORCA, 11 configurations, 1161 days, ~**95% overall efficiency**)

- Two main topologies: **tracks** and **showers**

- **KM3NeT/ORCA 6**: many exploited novelties
  - ❍ reconstruction of both **tracks** & **showers** (first time!)
  - ❍ event selection using **machine learning** algorithms (e.g. BDT, RGS)
  - ❍ **opening to new oscillation analyses** exploiting the shower topology



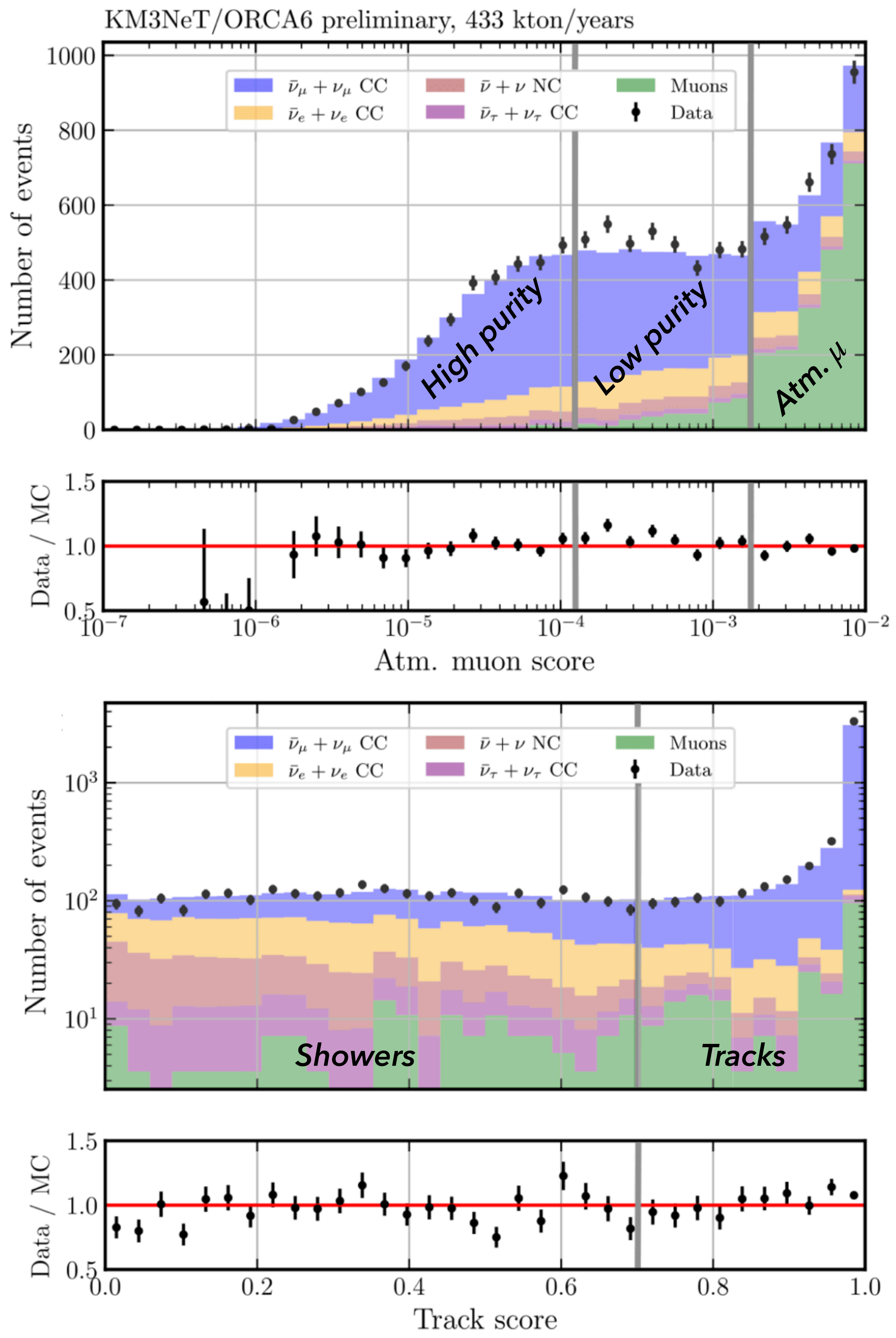
Event selection

- **BDT algorithm** for background rejection and track-shower separation
  - trained on MC (maximum likelihood variables)
  - **challenging classification** at low E (70% track-purity, ~30GeV)
  - **three classes**: high/low purity track, and showers

	all events	showers*	tracks (HP)	tracks (LP)
MC	5831	1959	1870	2002
Data	5828	1958	1868	2002

(*expected $\nu_\tau = 185 \pm 1$ in the 3ν-paradigm)

- **remarkable statistics**: ν_τ identified as an **excess in the shower class**



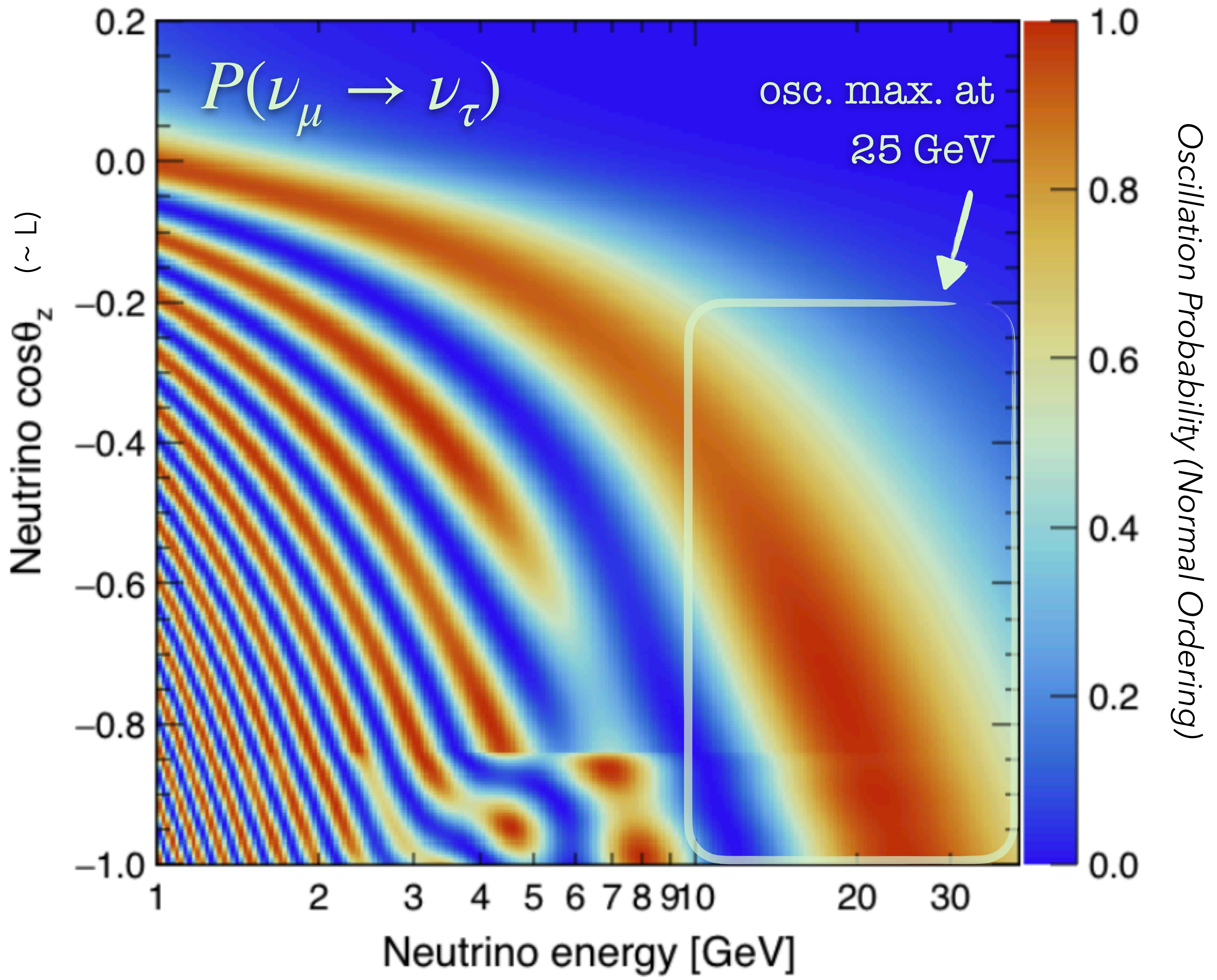
L. Cerisy, C. Lastoria et al., PoS ICRC2023 (2023) 1191

ν_τ normalisation fit in KM3NeT/ORCA 6

- 2D bin log-likelihood minimization of $\mathbf{E_{reco}}$ and $\mathbf{\cos\theta_{reco}}$ distributions
- **oscillation hp $\otimes$ flux model $\otimes$ cross-section $\otimes$ detector response**
  - assuming both normal and inverted ordering
  - Δm^2_{31} and θ_{23} free
  - **ν_τ-normalization**

$$\frac{\text{n. of observed } \nu_\tau}{\text{n. of expected } \nu_\tau |_{\text{tested osc. model}}}$$

  - two tested hypotheses, assuming or not the PMNS matrix unitarity



ν_τ normalisation within the 3ν paradigm

a) S_τ : **PMNS unitarity hypothesis**

- ❍ ν_τ-norm. $\neq 1$, due to neutrino interaction modelization
- ❍ **variation in ν_τ-CC rate**
- ❍ **ν_τ charge-current cross-section**

Main sources of **systematics**

		Parameter	*Constraint*
atmospheric neutrino flux	flux shape	δ_γ	0.3
		δ_θ	2%
	neutrino composition	$s_{\mu\bar{\mu}}$	5%
		$s_{e\bar{e}}$	7%
		$s_{\mu e}$	2%
neutrino interactions		f_{NC}	20%
detector response	light propag.	E_s	9%
		f_{HE}	50%
	overall norms	f_{all}	unconstrained
		f_{HPT}	unconstrained
		f_{S}	unconstrained
		f_{μ}	unconstrained
ν_τ cross-section		S_τ	Depending on analysis

ν_τ normalisation within the 3ν paradigm

a) S_τ : PMNS unitarity hypothesis

- ❍ ν_τ-norm. ≠ 1, due to neutrino interaction modelization
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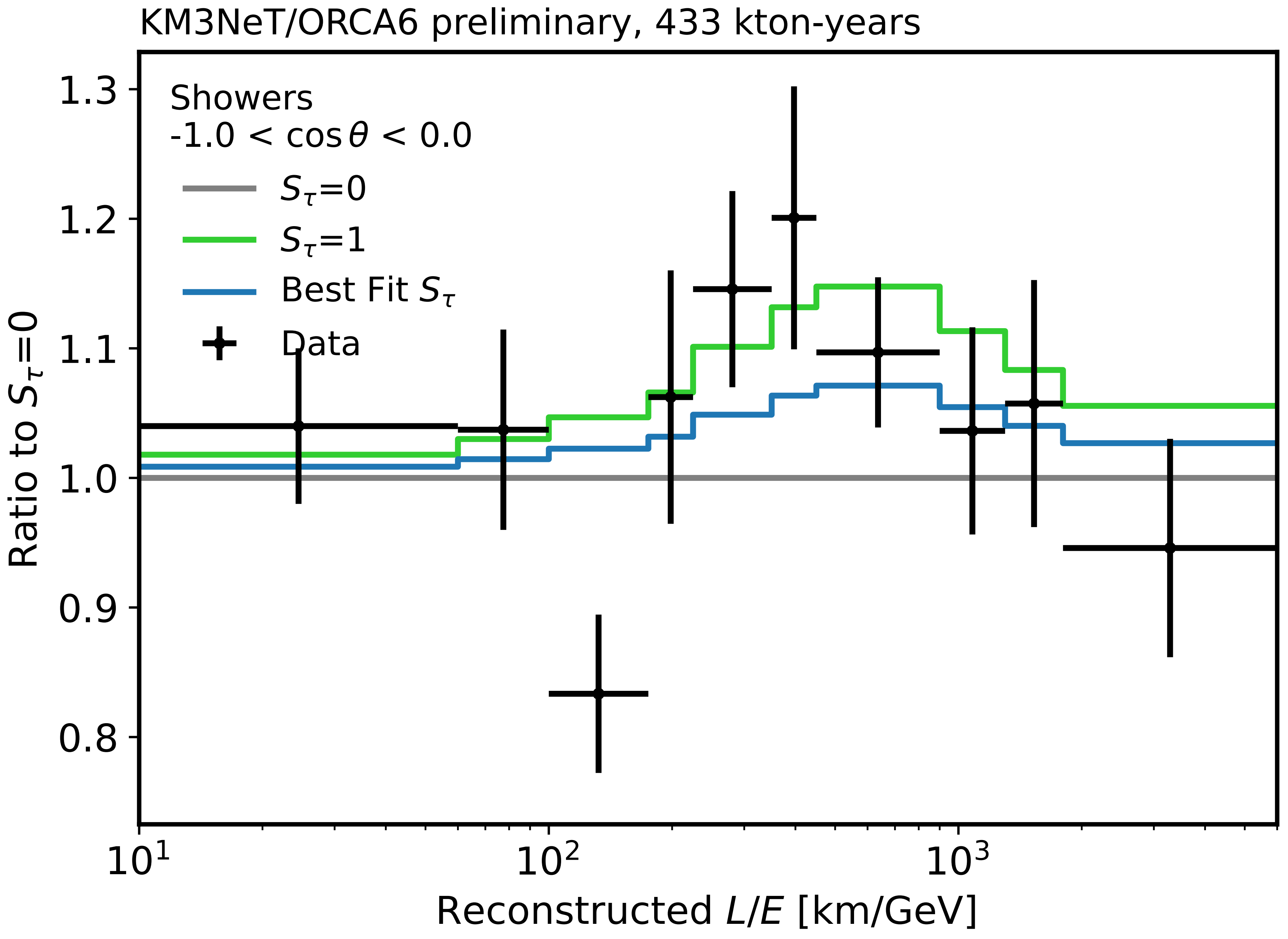
L. Cerisy, N. Geißelbrecht, C. Lastoria, arXiv:2502.01443, accepted on JHEP



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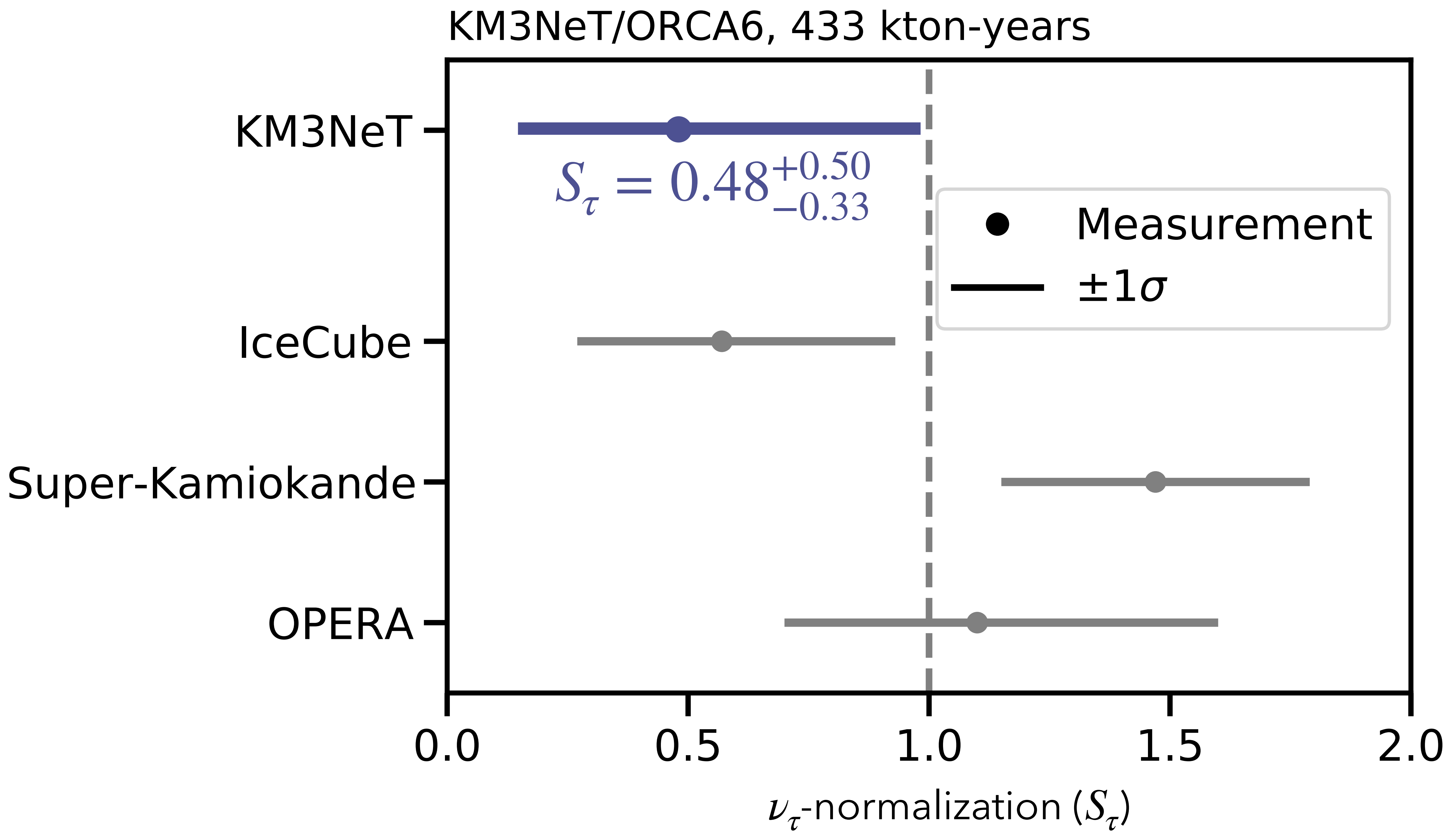
		f_μ	unconstrained
ν_τ cross-section		S_τ	Depending on analysis

ν_τ normalisation measurement

- **strong complementarity among the different experiments**
  - ❍ neutrino energy, source, and identification techniques
  - ❍ fit method and sensitivity to other oscillation parameters

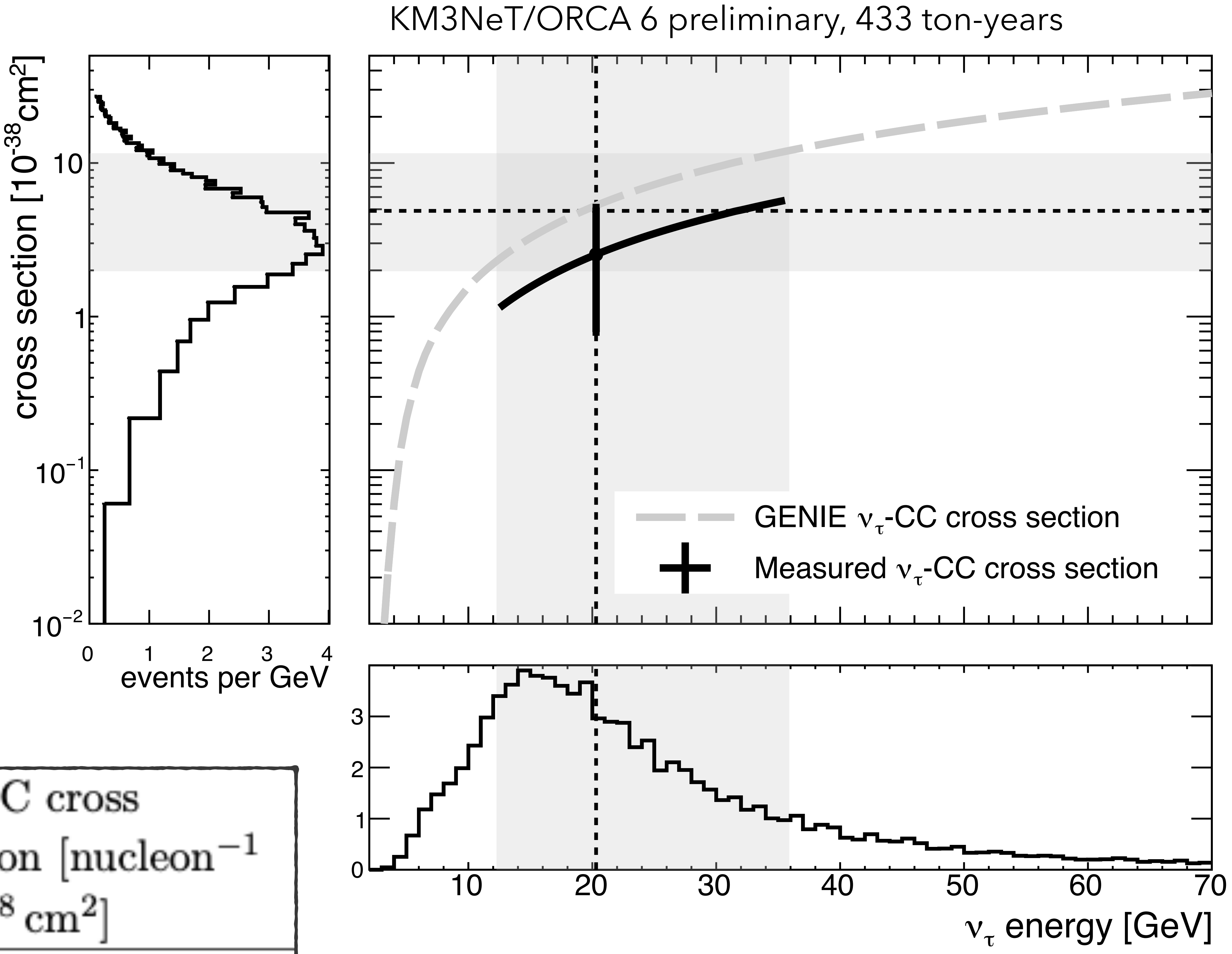


no robust rejection of the 3ν-flavor paradigm

L. Cerisy, N. Geißelbrecht, C. Lastoria, arXiv:2502.01443, accepted on JHEP

ν_τ-CC cross-section measurement

- ν_τ**-normalization** behaves as **scaling factor** for the measured ν_τ**-CC cross-section**: $\sigma_{meas} = S_\tau \times \langle\sigma_{theory}\rangle$
- additional inputs to **constrain cross-section** (sensitivity to different energy ranges and interaction media)



L. Cerisy, N. Geißelbrecht, C. Lastoria, arXiv:2502.01443, accepted on JHEP

[OPERA] Phys. Rev. Let. 115 (2015)
[SuperKamiokande] Phys. Rev. D 98, 052006 (2018)

Experiment	Interaction medium	Energy [Gev]	N. of observed ν_τ	ν_τ CC cross section [nucleon^{-1} 10^{-38} cm^2]
OPERA	lead	$\leq$20	10	$2.46^{+1.15}_{-0.98}$
Super-Kamiokande	water	$\sim$25	338.1$\pm$72.7	0.94 ± 0.20
ORCA6 (this work)	water	$20.3^{-8.0}_{+15.6}$	92^{+90}_{-63}	$2.5^{+2.6}_{-1.8}$

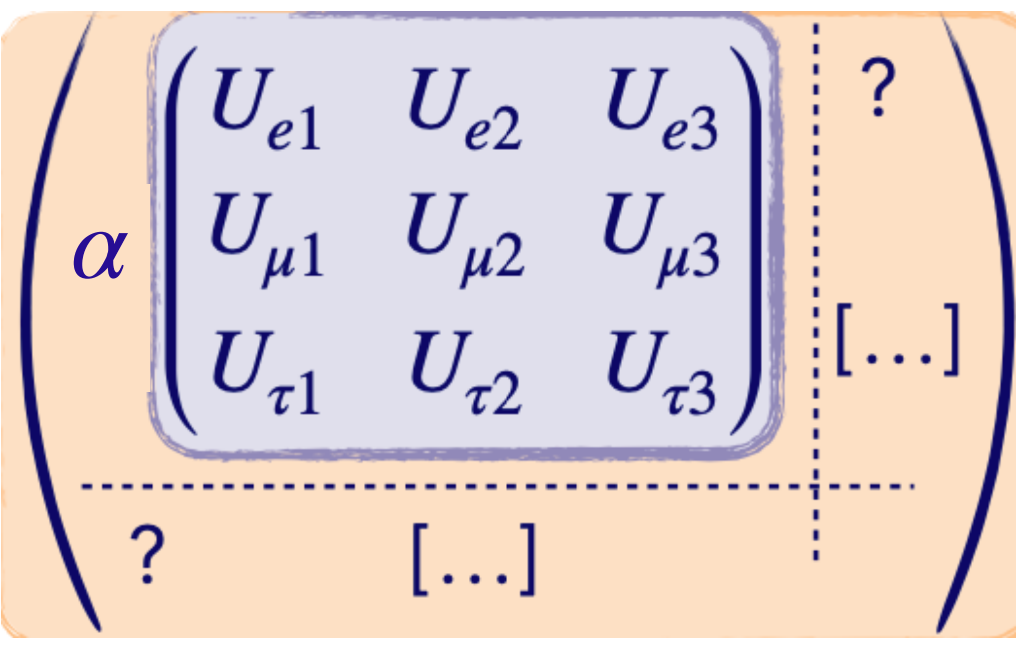
Non-Unitarity Neutrino Mixing (NUNM)

b) **α_{33} : nxn unitarity matrix**

- ❍ **Heavy Neutral Leptons** (*seesaw* mechanism for neutrino masses generation)
- ❍ oscillation probabilities impacted by α_{33}

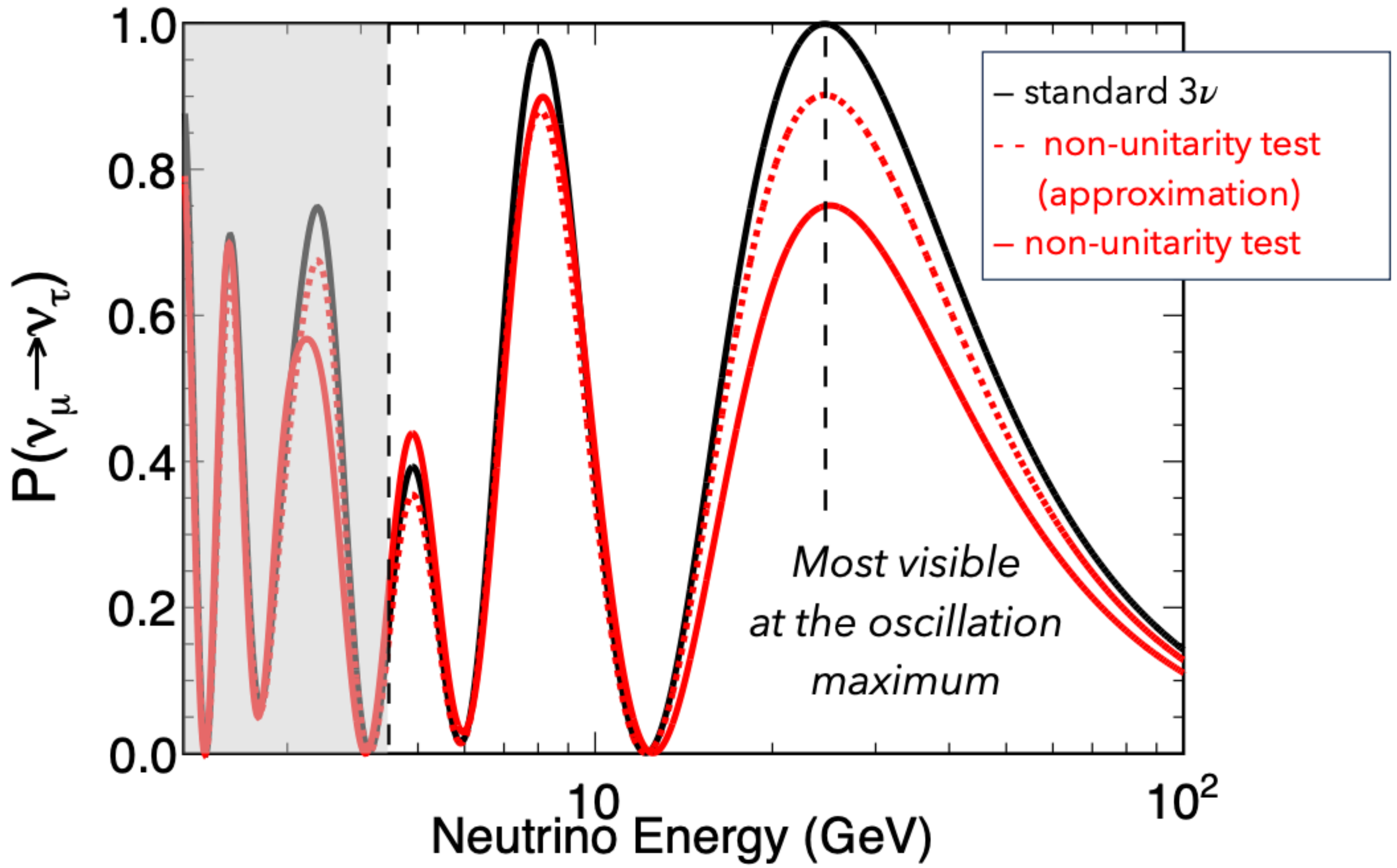
$$P_\beta^\alpha = P_{\beta e} + P_{\beta\mu} + \alpha_{33}^2 P_{\beta\tau}$$

U_{PMNS} matrix



- ❍ **NC affected** due to neutrons in the Earth (V_{NC} potential non-negligible)

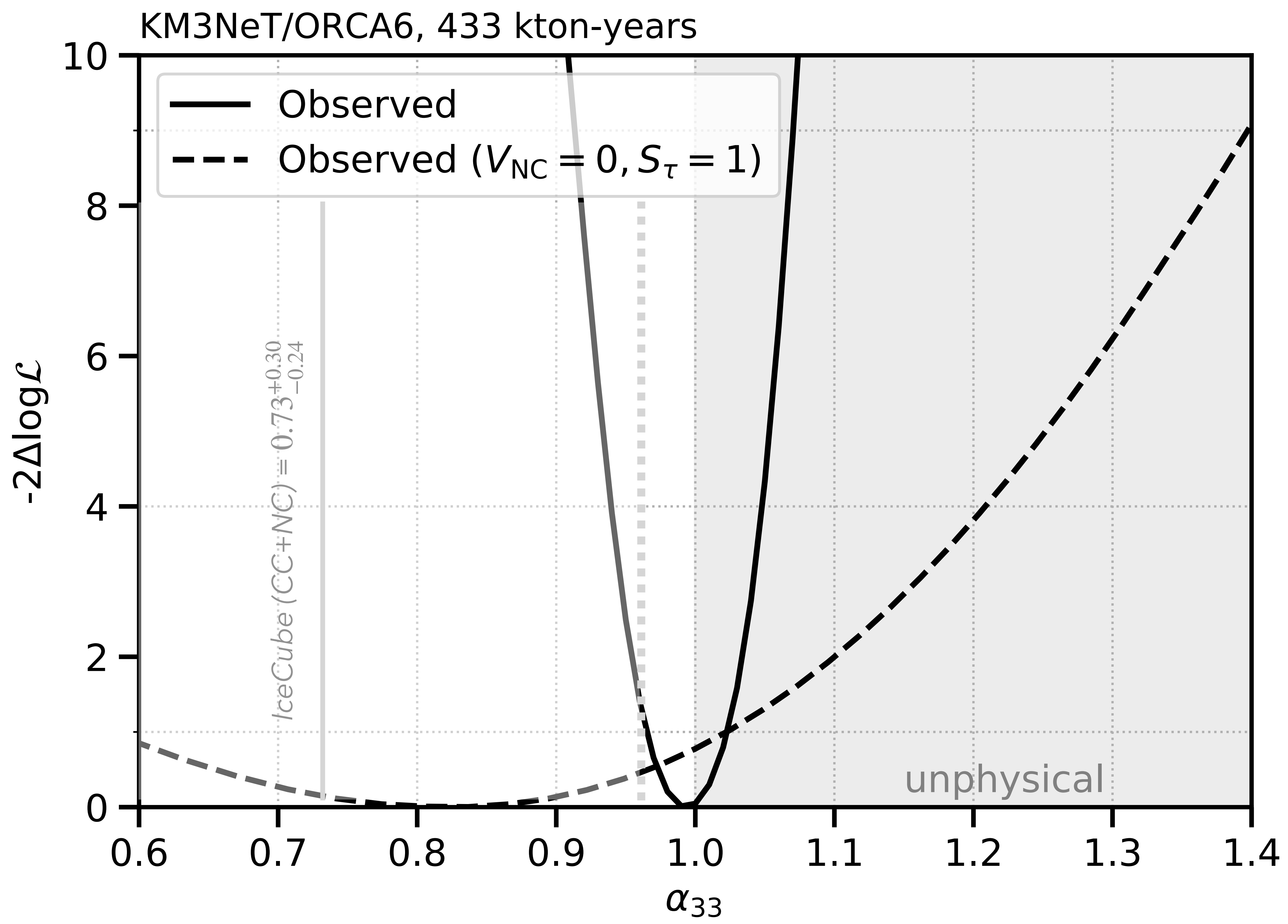
- **first test on atmospheric neutrino data**



Non-Unitarity Neutrino Mixing (NUNM)

- impact on both CC and NC rates
- at the best fit,
  - $\alpha_{33} = 0.83^{+0.20}_{-0.25}$ (if V_{NC} =0, $S_\tau = 1$)
  - $\alpha_{33} = 0.993^{+0.026}_{-0.025}$ (otherwise)

	(V_{NC}!=0, S_τ free)	(V_{NC}=0, S_τ=1)
n. of ν_τ-CC	170^{+5}_{-9}	132^{+60}_{-61}
n. of NC	325^{+1}_{-4}	313^{+11}_{-13}



current best limit on α_{33}: [0.95, 1.04] at 95% CL

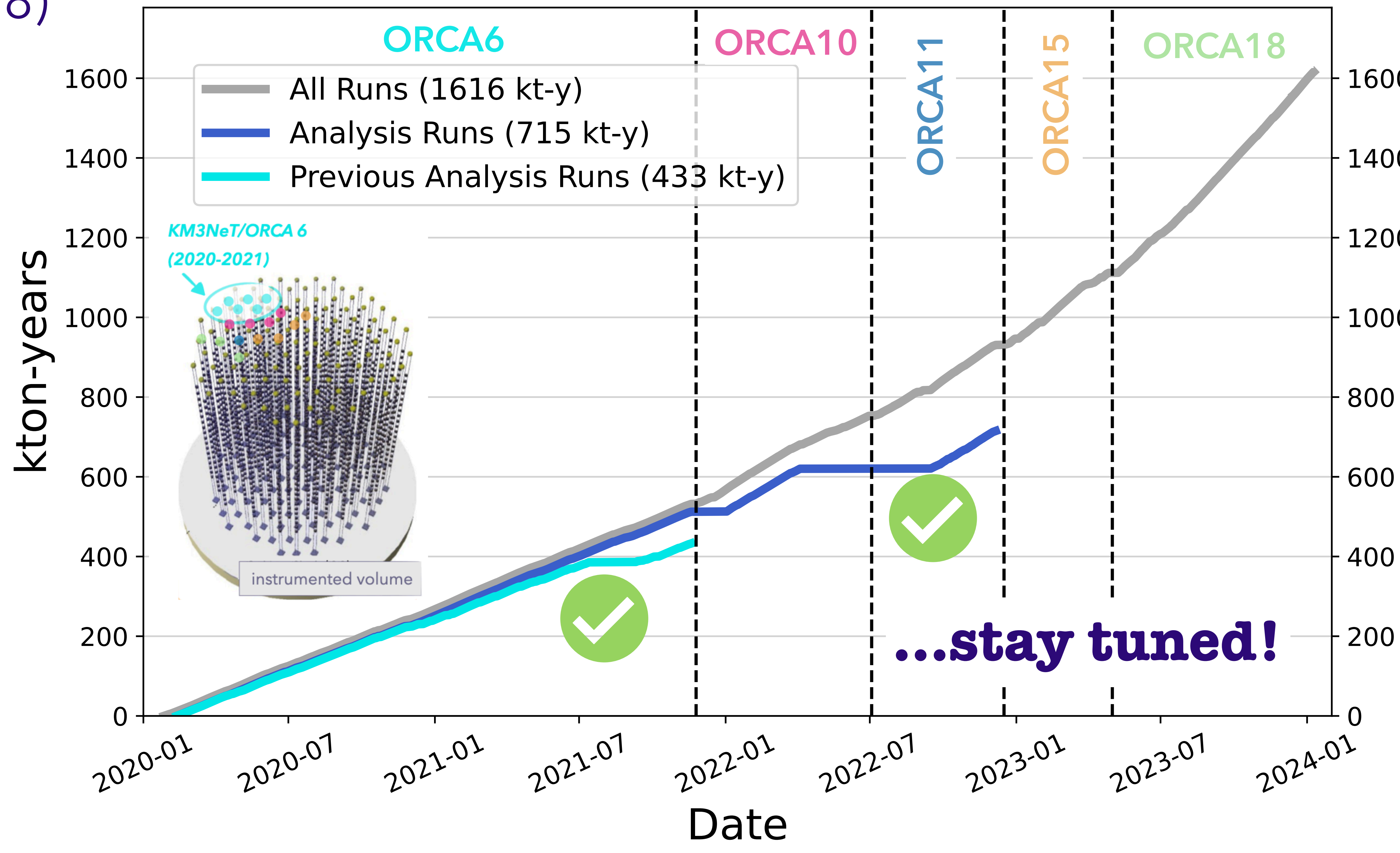
L. Cerisy, N. Geißelbrecht, C. Lastoria, arXiv:2502.01443, accepted on JHEP

Limitations and prospects

- Precise measurement of ν_τ **appearance** is a key study to deepen the understanding of neutrino properties
  - ❍ test the **3ν flavor paradigm**
  - ❍ BSM **non-unitarity** extensions

What's next in KM3NeT?

- **analyses of larger configurations** are in the pipeline!
  - ❍ expected $\nu_\tau \sim 420$/year (CC) in 16% active volume (e.g. ORCA18)
  - ❍ toward 3000 ν_τ /year (CC) in full ORCA
- alternative **Deep Learning techniques** are under study (e.g. transformers, GNN)
- **extend current set of systematics** and **fit** methods (e.g. Bayesian approach)
  - ❍ better understanding of the detector response
  - ❍ achieve enhanced purity of the shower class




..thanks for your attention!
SAAS
JANUS II

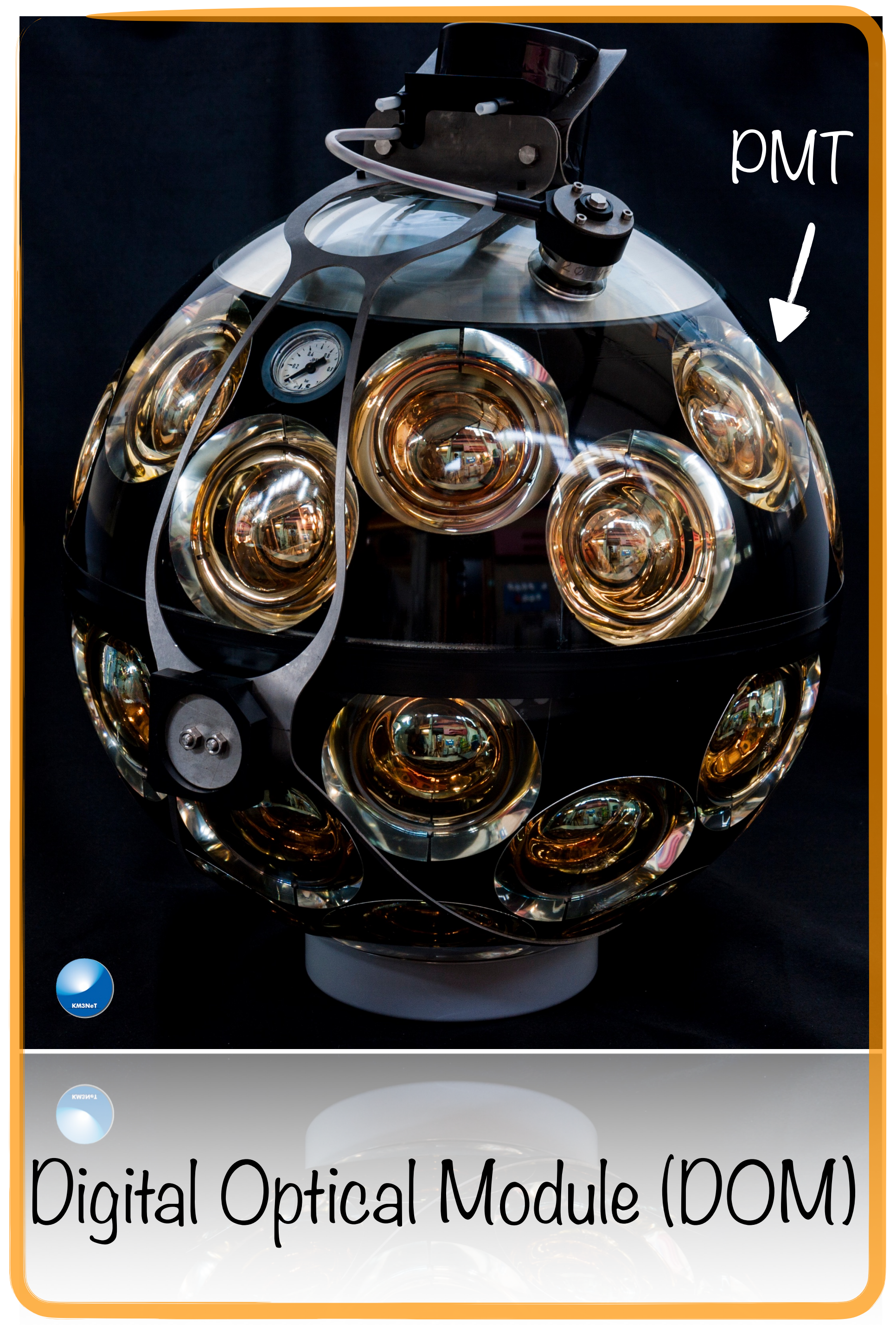
Extra slides

KM3NeT: technology

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

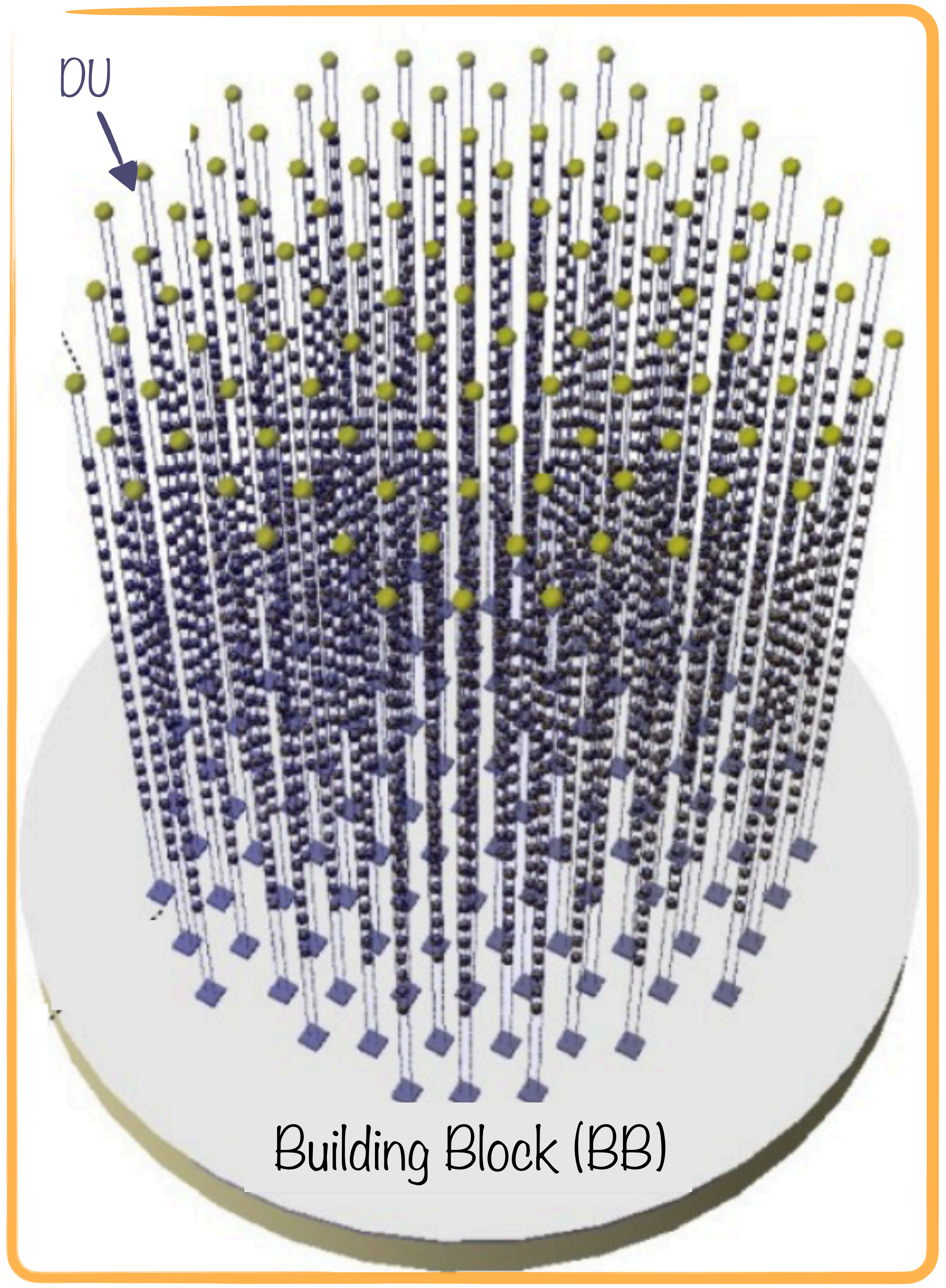
- 3″ Hamamatsu PMTs assembled into a spherical structure for a 4π coverage:
  - ❍ high time precision (~ns)
  - ❍ good spatial resolution (~10 cm)

x 31



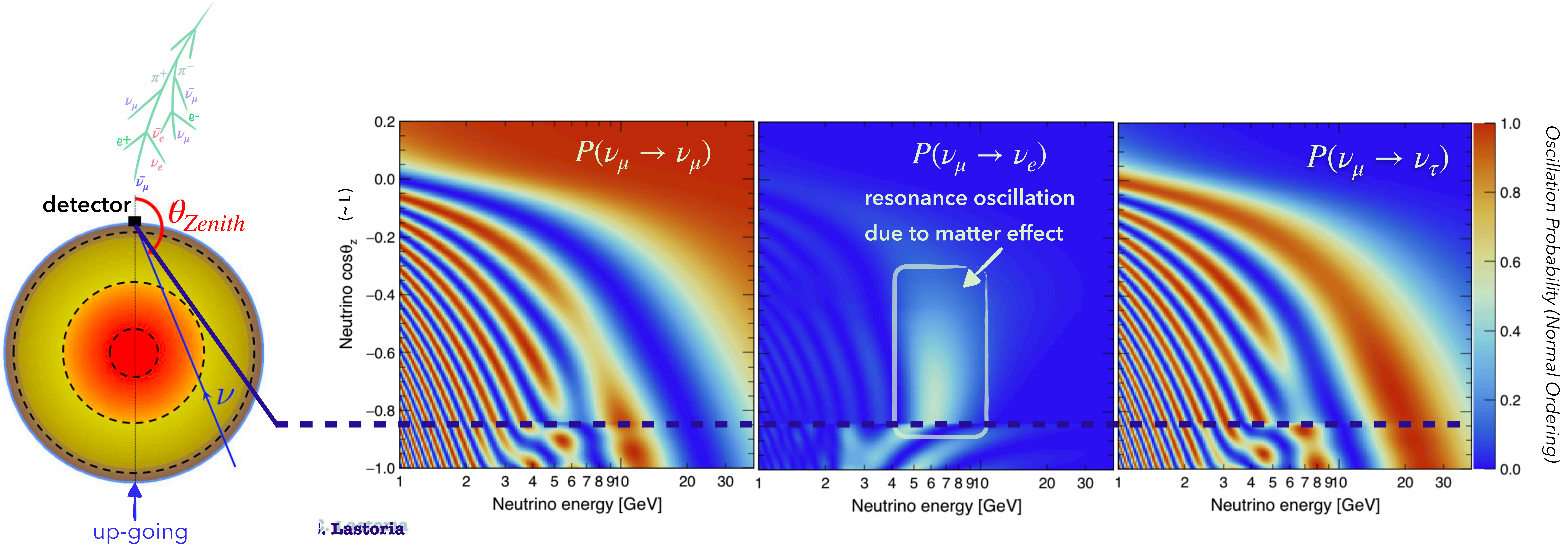
x 18

x 115



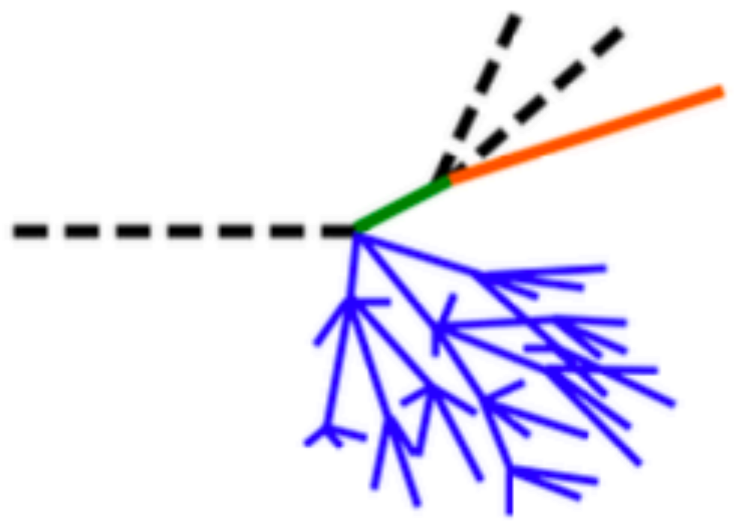
KM3NeT/ORCA physics goals

- **atmospheric neutrinos**: secondary particle of cosmic ray interaction with Earth's atmosphere
  - ❍ wide energy range (1-100 GeV) and baseline (L, from ~10 to ~13000 km)
  - ❍ ν_μ **disappearance (dominant effect)**: neutrino oscillation parameters θ_{23}, Δm^2_{32}
  - ❍ ν_e **appearance (sub-dominant effect)**: sensitive to the **Neutrino Mass Ordering (NMO)**
  - ❍ other searches: ν_τ **appearance**, **sterile** and other **BSM searches,** etc…



ν_τ topologies

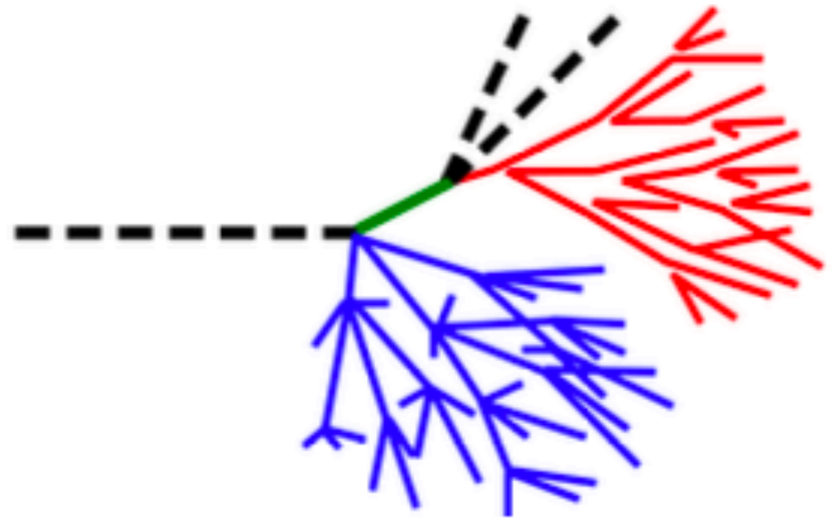
$\overset{(-)}{\nu}_\tau$ CC



hadronic shower and μ track

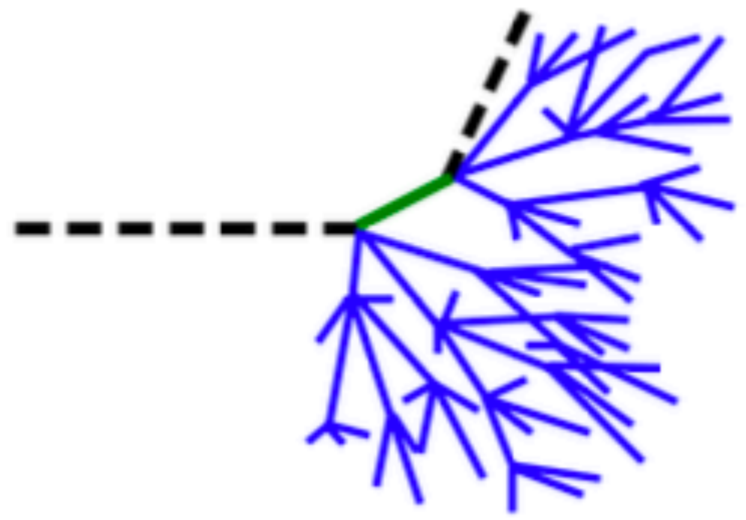
$(\tau^\pm \to \mu^\pm \overset{(-)}{\nu}_\mu \overset{(-)}{\nu}_\tau, \sim 17\%\ \mathrm{BR})$

track-like events



hadronic shower and EM shower

$(\tau^\pm \to e^\pm \overset{(-)}{\nu}_e \overset{(-)}{\nu}_\tau, \sim 18\%\ \mathrm{BR})$



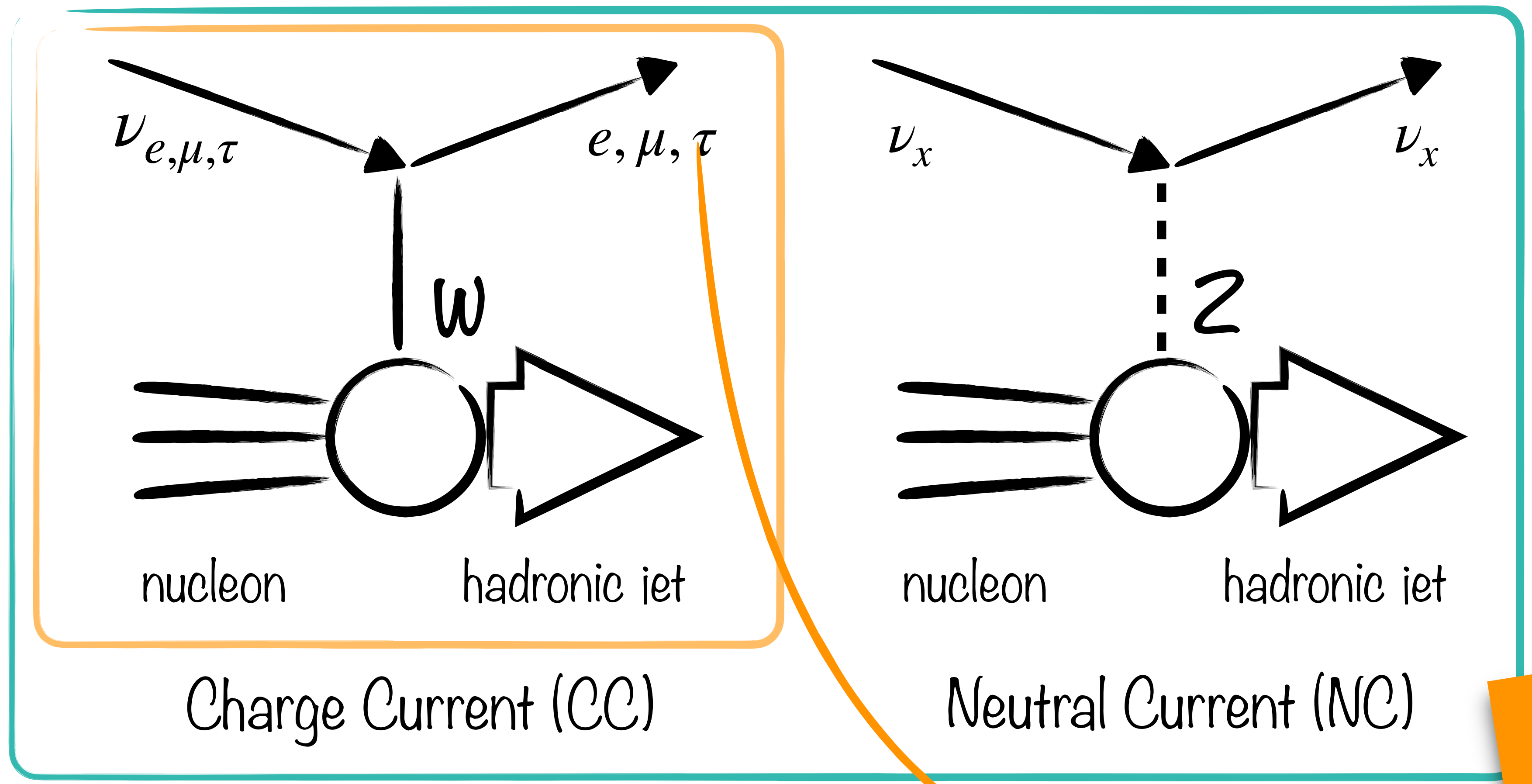
hadronic shower

$(\tau^\pm \to \mathrm{hadrons}, \sim 65\%\ \mathrm{BR})$

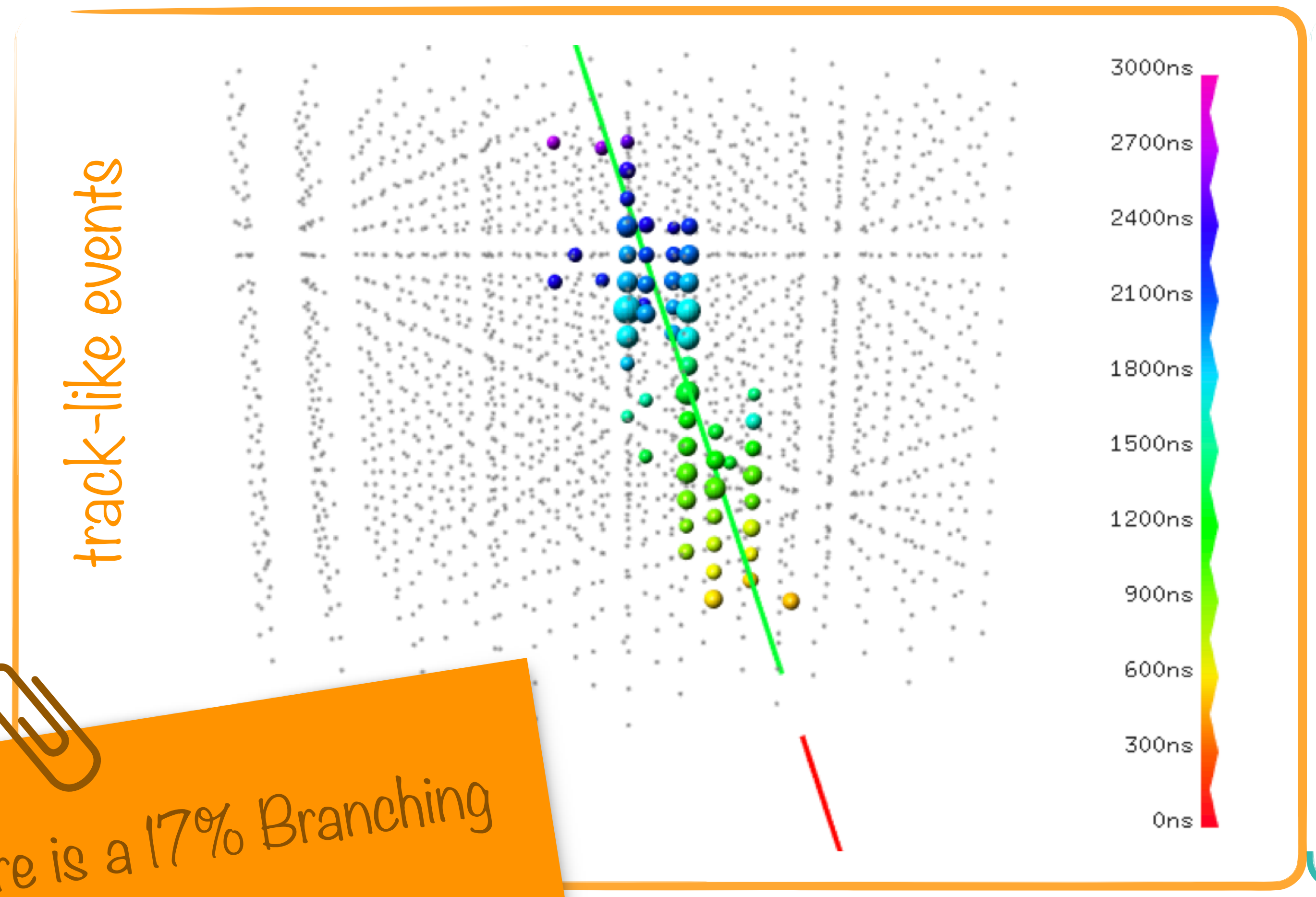
shower-like events

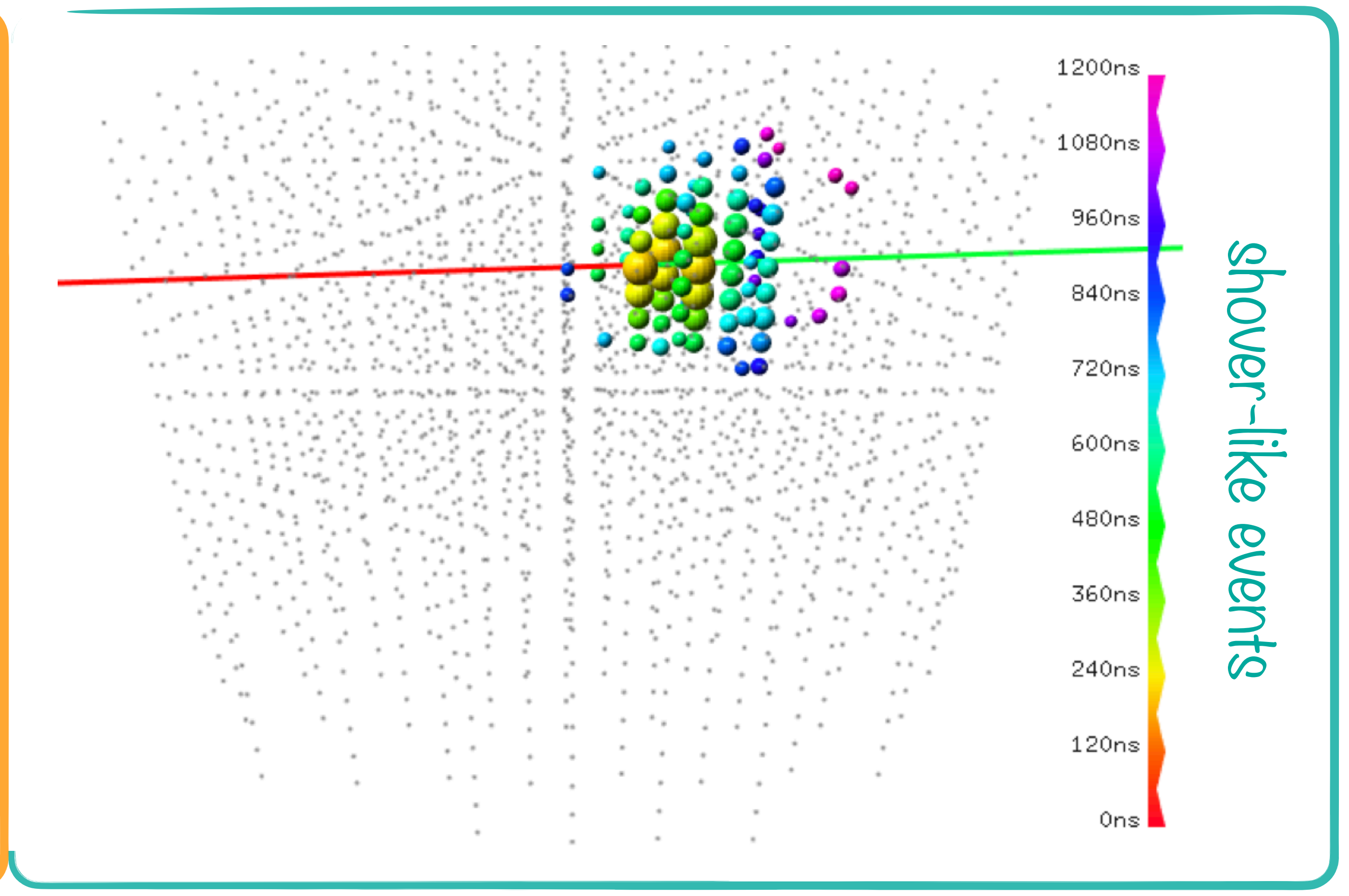
KM3NeT/ORCA: neutrino topologies

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



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

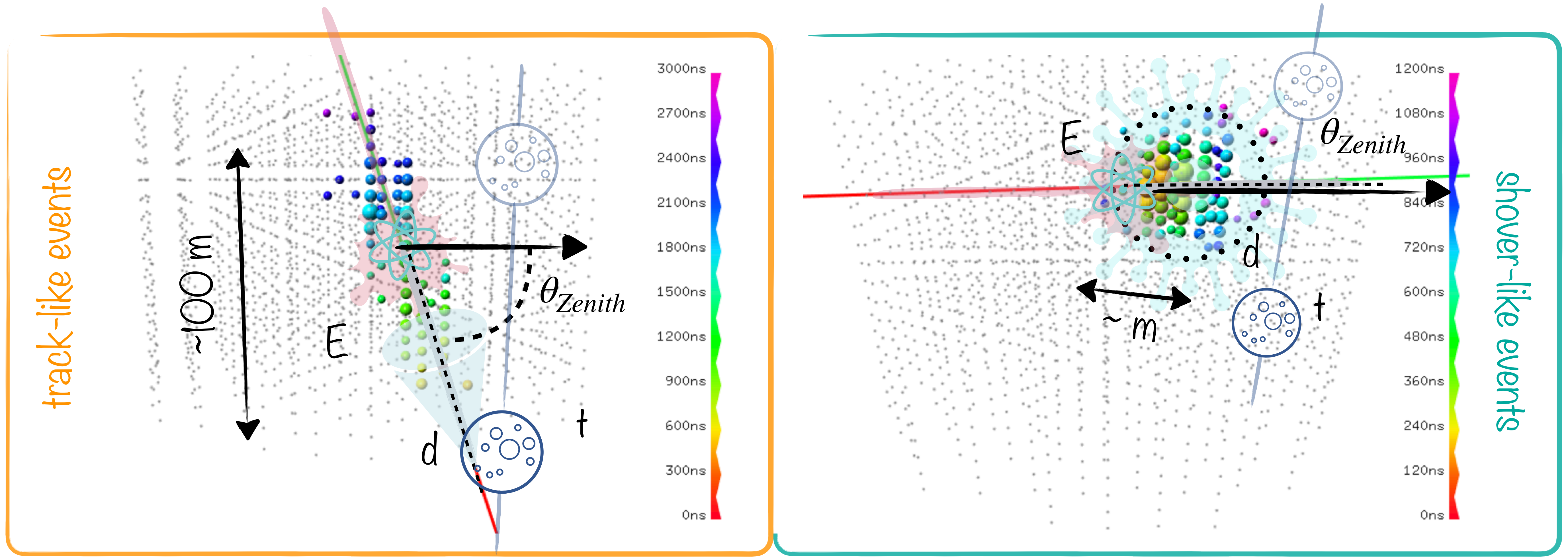




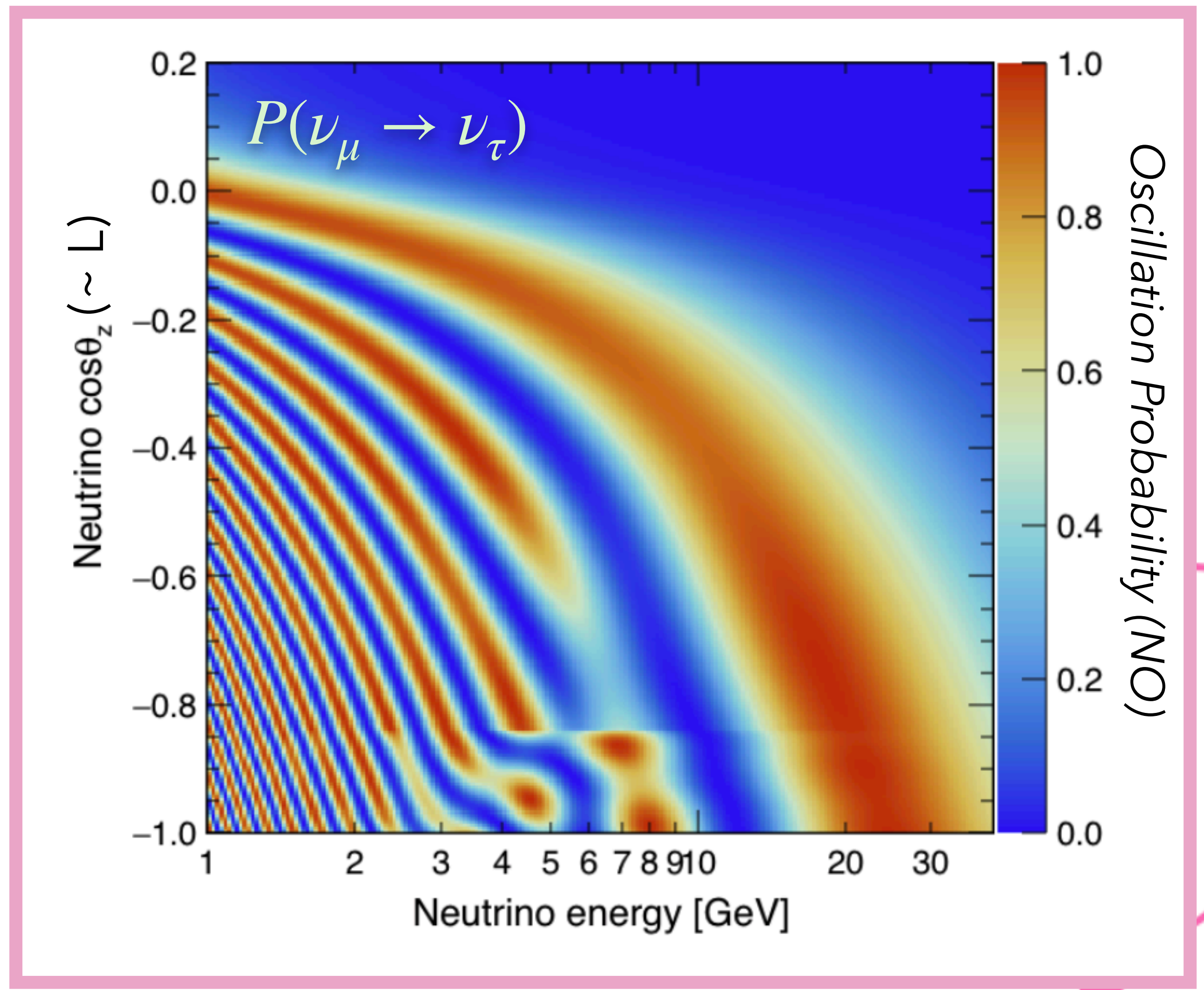
J. Phys. G: Nucl. Part. Phys. 43 084001 (2016)

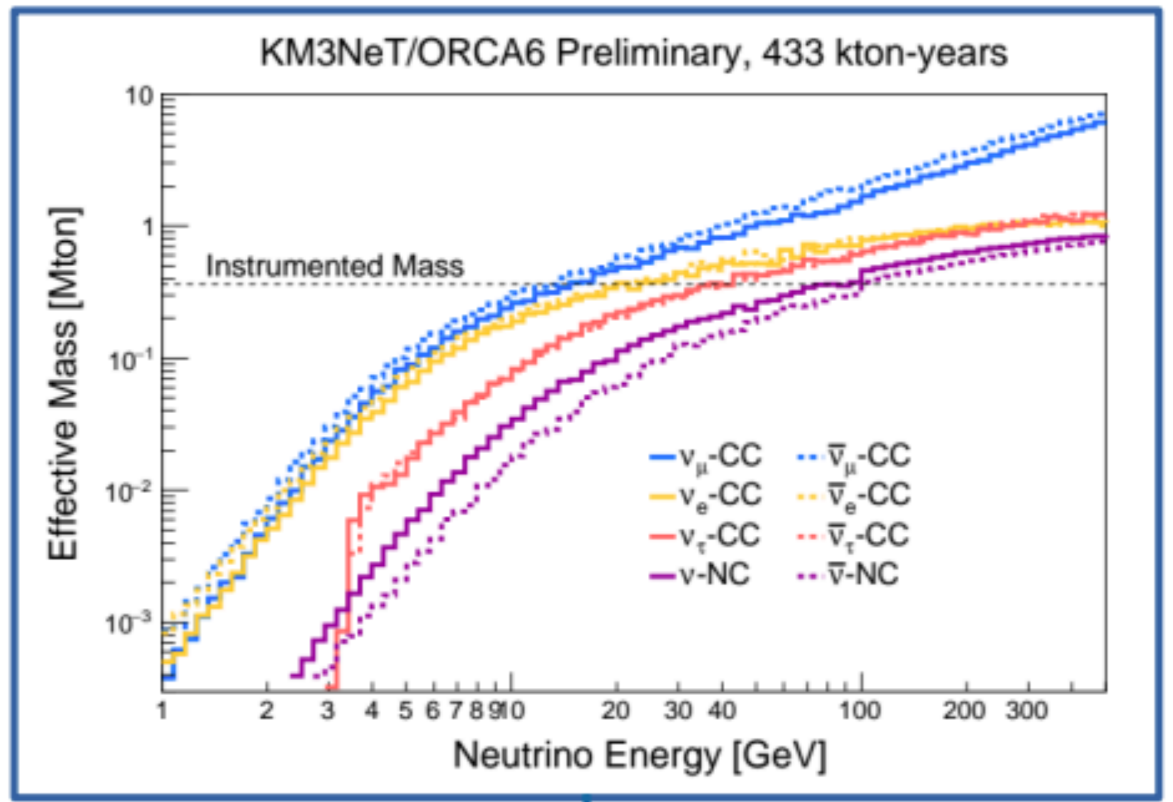
KM3NeT/ORCA: neutrino topologies

- **Maximum likelihood algorithms** optimized for the two topologies:
  - ❍ based on **track and shower hypotheses** per event
  - ❍ **causality** for hit selection
  - ❍ **time** in each PMT
  - ❍ **vertex** and **direction** determination matching the topology hypothesis
  - ❍ **energy estimation**
- since KM3NeT/ORCA 6, **new reconstruction algorithm for showers** using **single-PMT information** (instead of single-DOM)



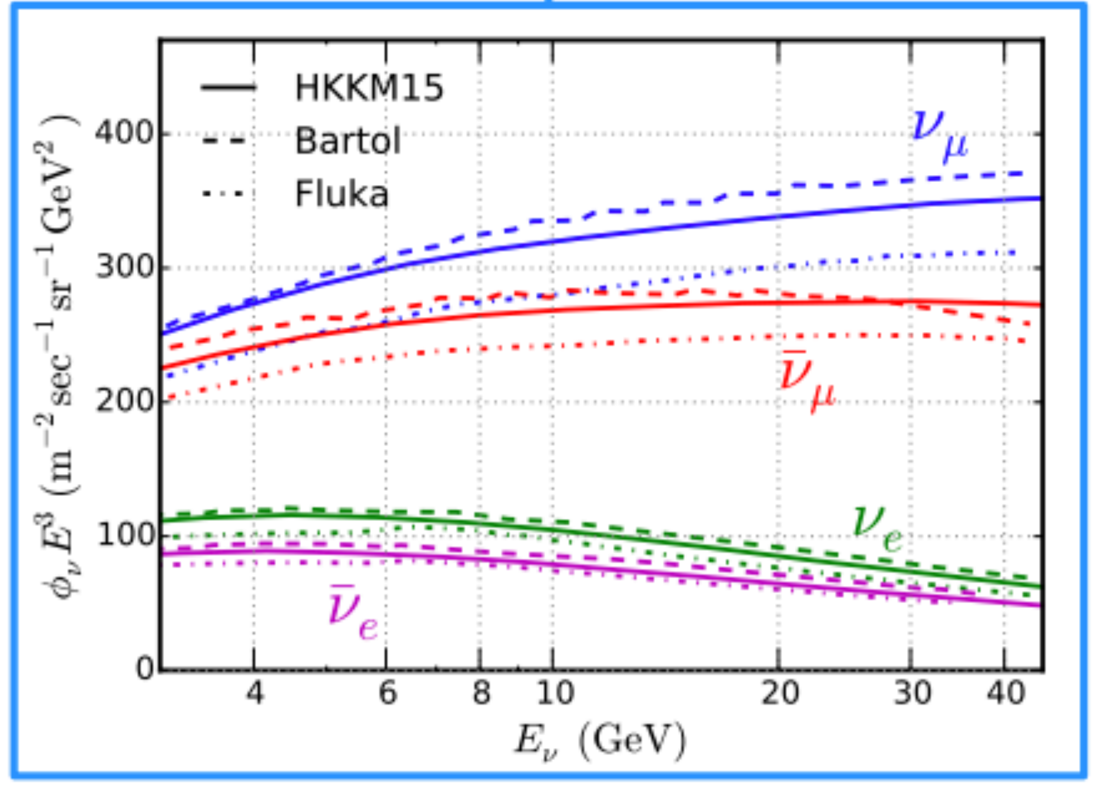
Oscillation fit in KM3NeT/ORCA



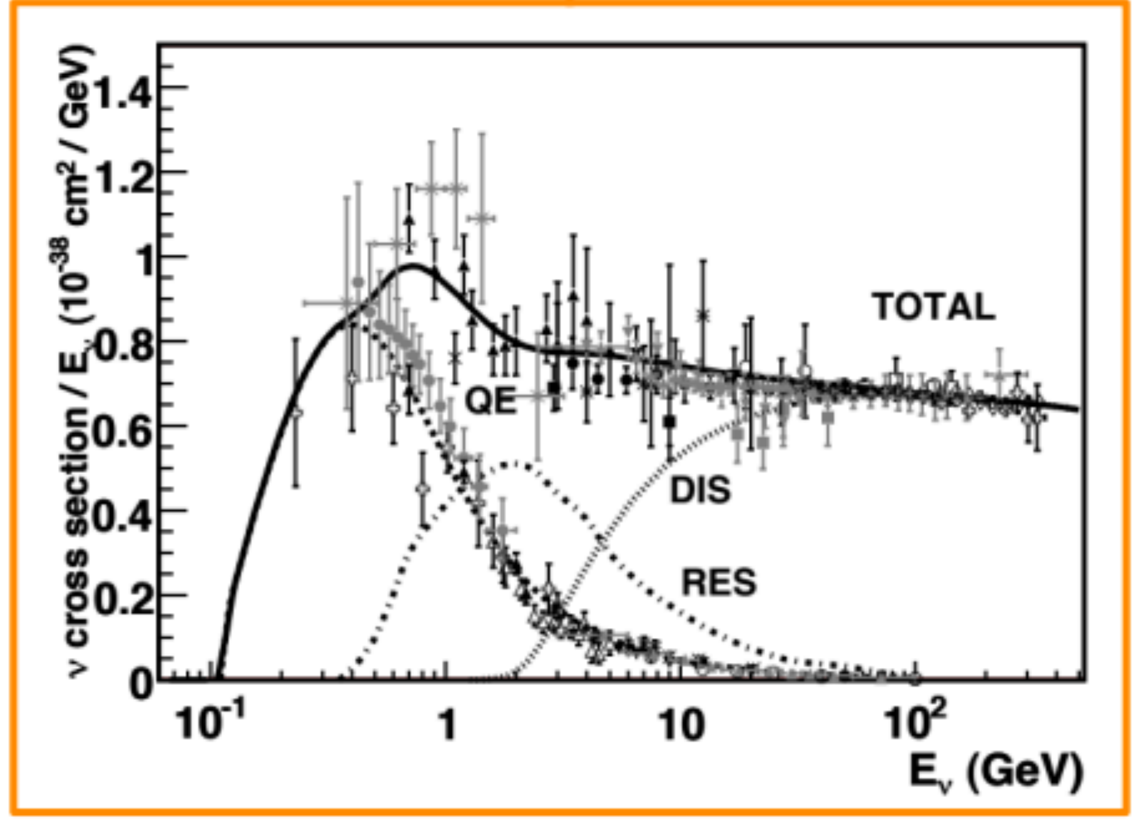


Slide adapted from L. Bailly-Salins

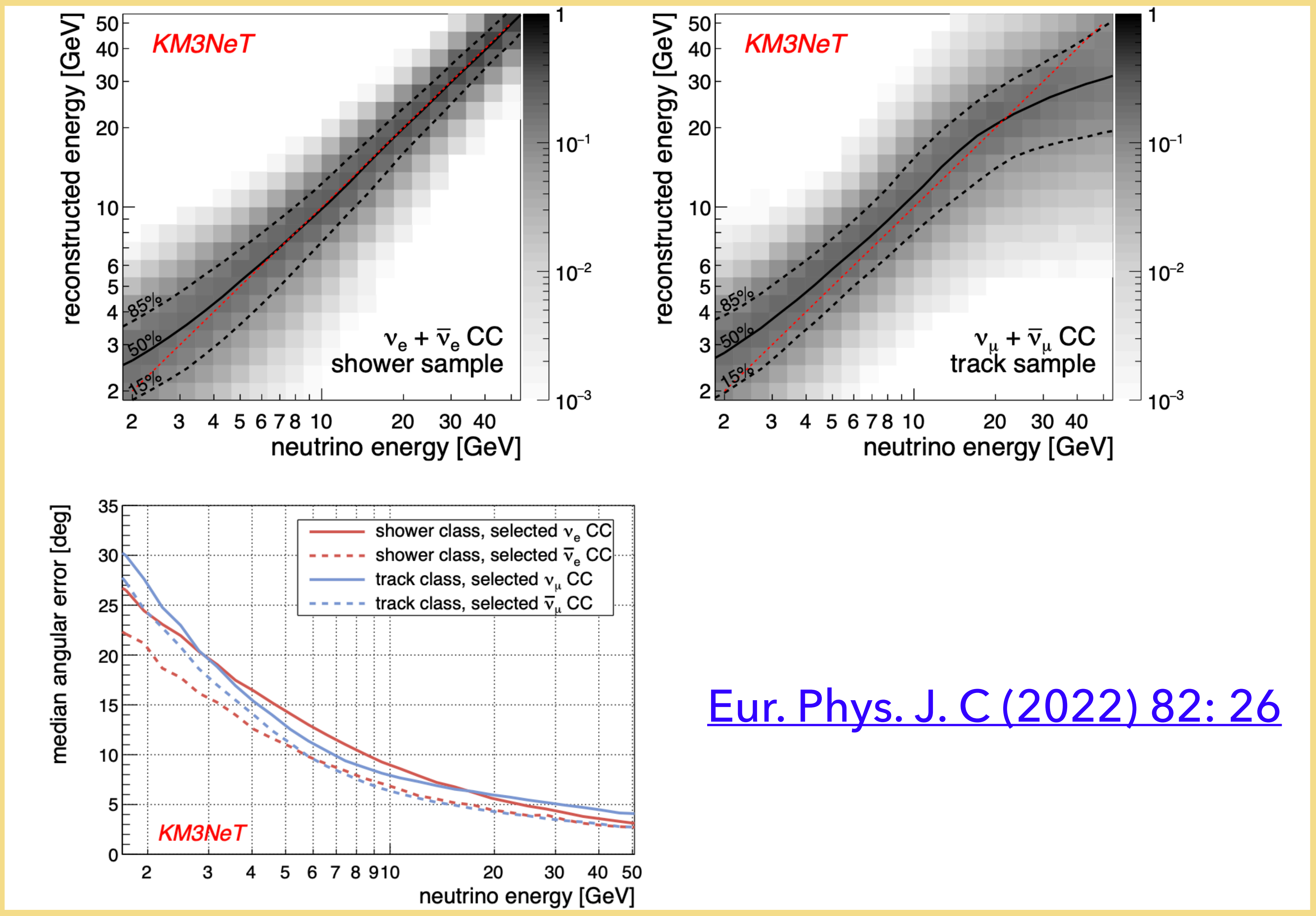
$$\phi_{atm}^{\nu_y}(E_t,\theta_t) \times P_{\nu_y \to \nu_x}(E_t,\theta_t) \times \sigma_{\nu_x}(E_t) \times M_{eff}^{\nu_x}(E_t) \times R_i(E_t,\theta_t,\nu_x,E_r,\theta_r)$$



J. Phys. G: Nucl. Part. Phys. 43 084001



Rev. Mod. Phys. 84, 1307



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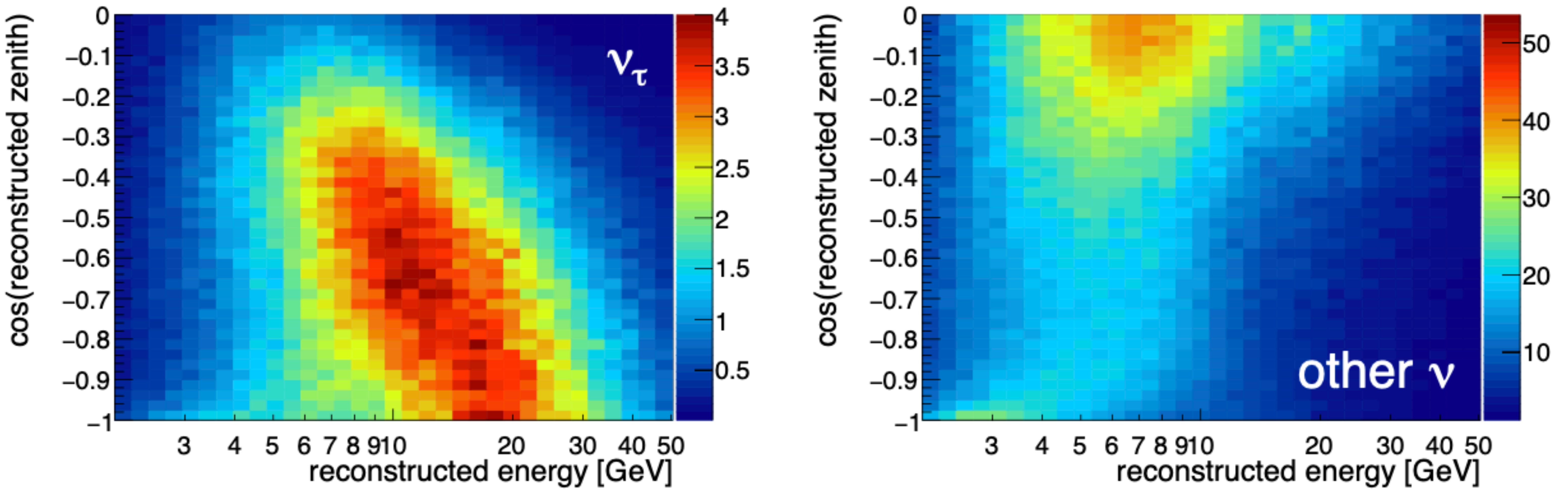
KM3NeT/ORCA: how to study ν_τ appearance?

- the main **advantage** of KM3NeT/ORCA is the **high statistics**:
  - ❍ using unitarity (hypothesis of ν_τ norm = 1)
  - ❍ 3000 ν_τ events/year in full ORCA
  - ❍ search for an **excess in the shower sample** (a good shower reconstruction is critical!)

shower class (ORCA 115, after 1 year of data taking)



plots from S. Hallmann, PhD thesis

Sensitivity to ν_τ appearance in KM3NeT/ORCA

- **unprecedented ν_τ statistics**: 3000 ν_τ events/year in full geometry
  - ❍ using unitarity (hypothesis of ν_τ norm = 1)
  - ❍ analysis performed on a statistical basis: **excess in shower sample**

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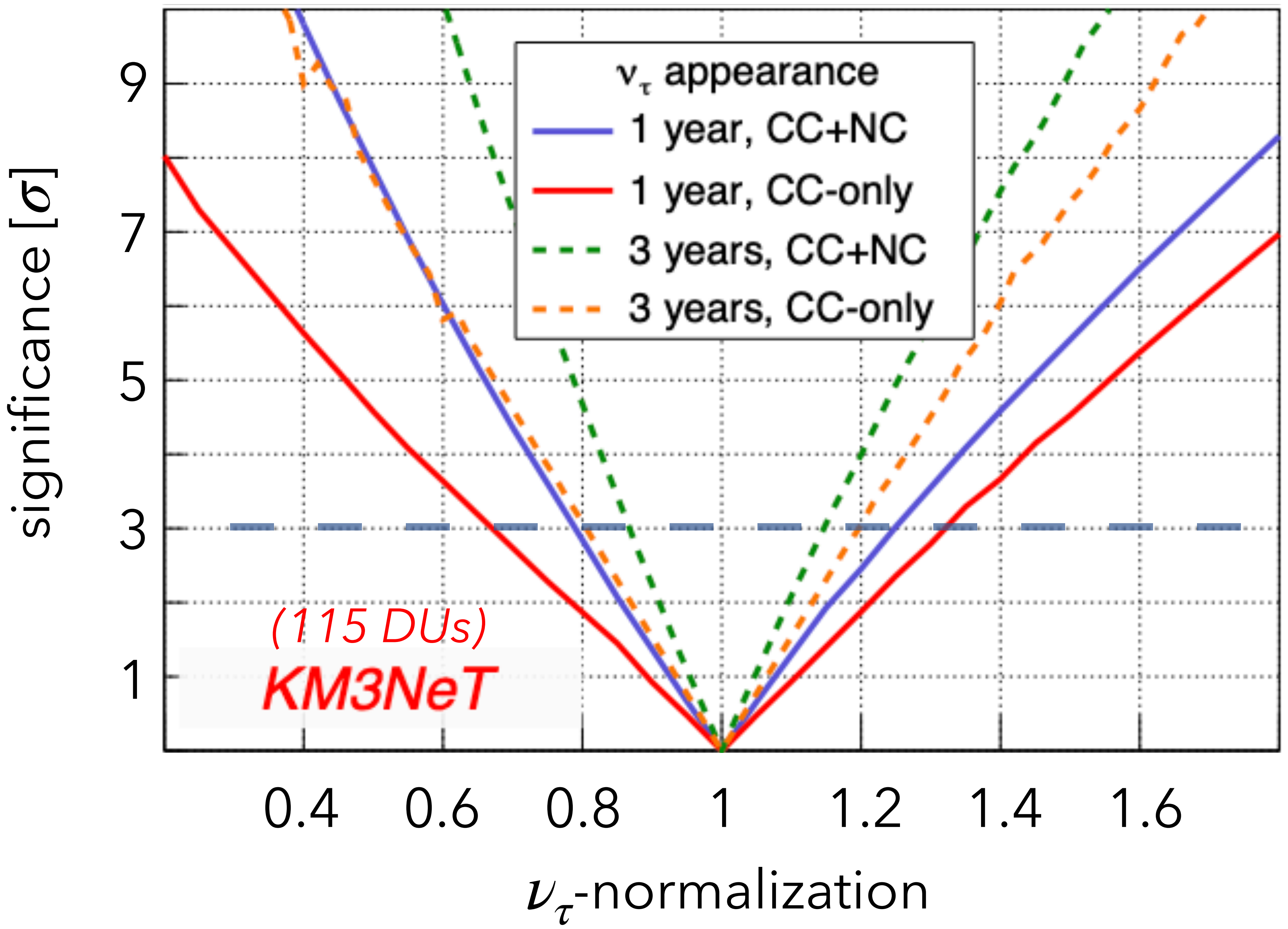
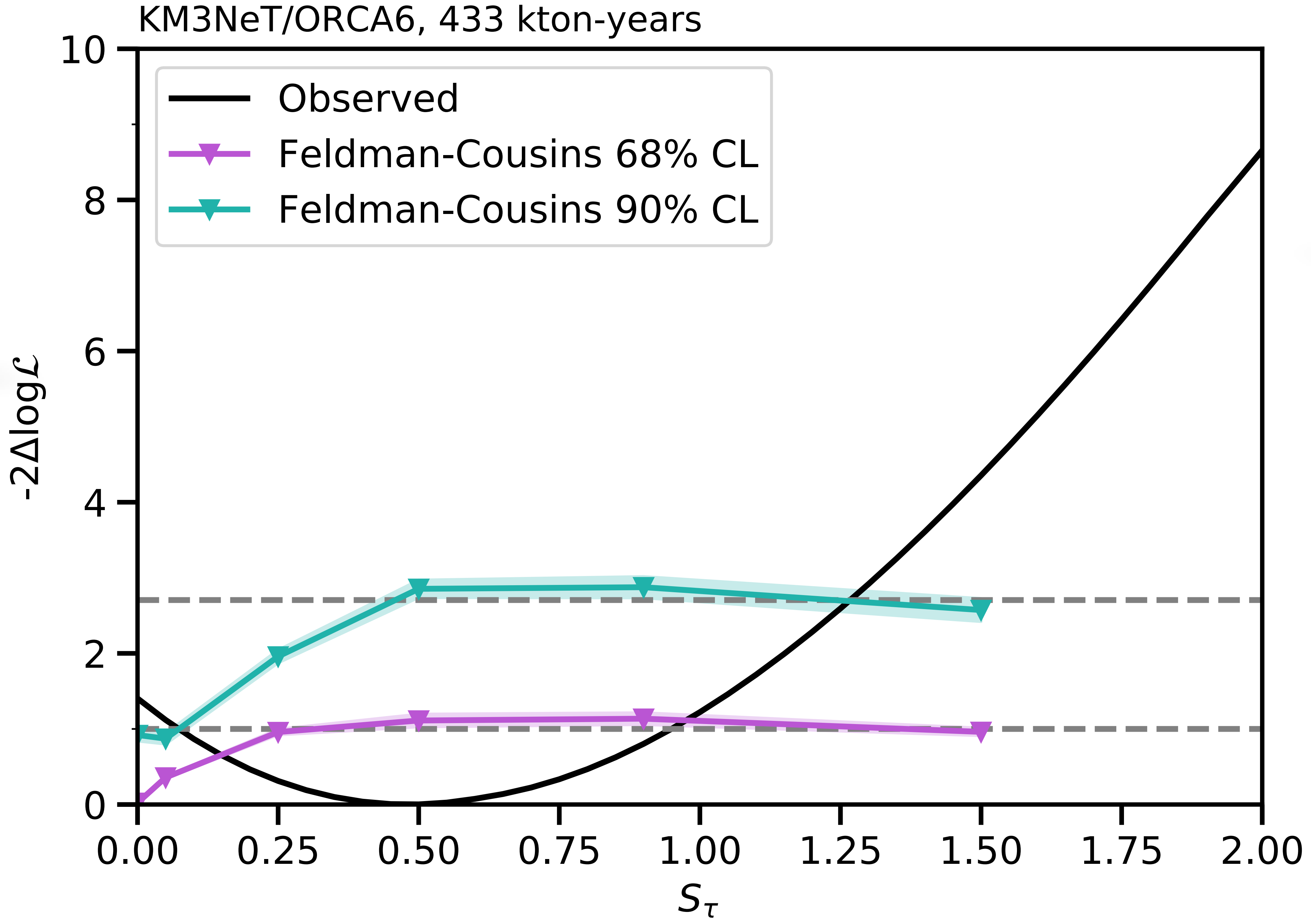


ν_τ normalisation fit in KM3NeT/ORCA 6

- Feldman-Cousins method to evaluate the 68% and 90% confidence level (CL)

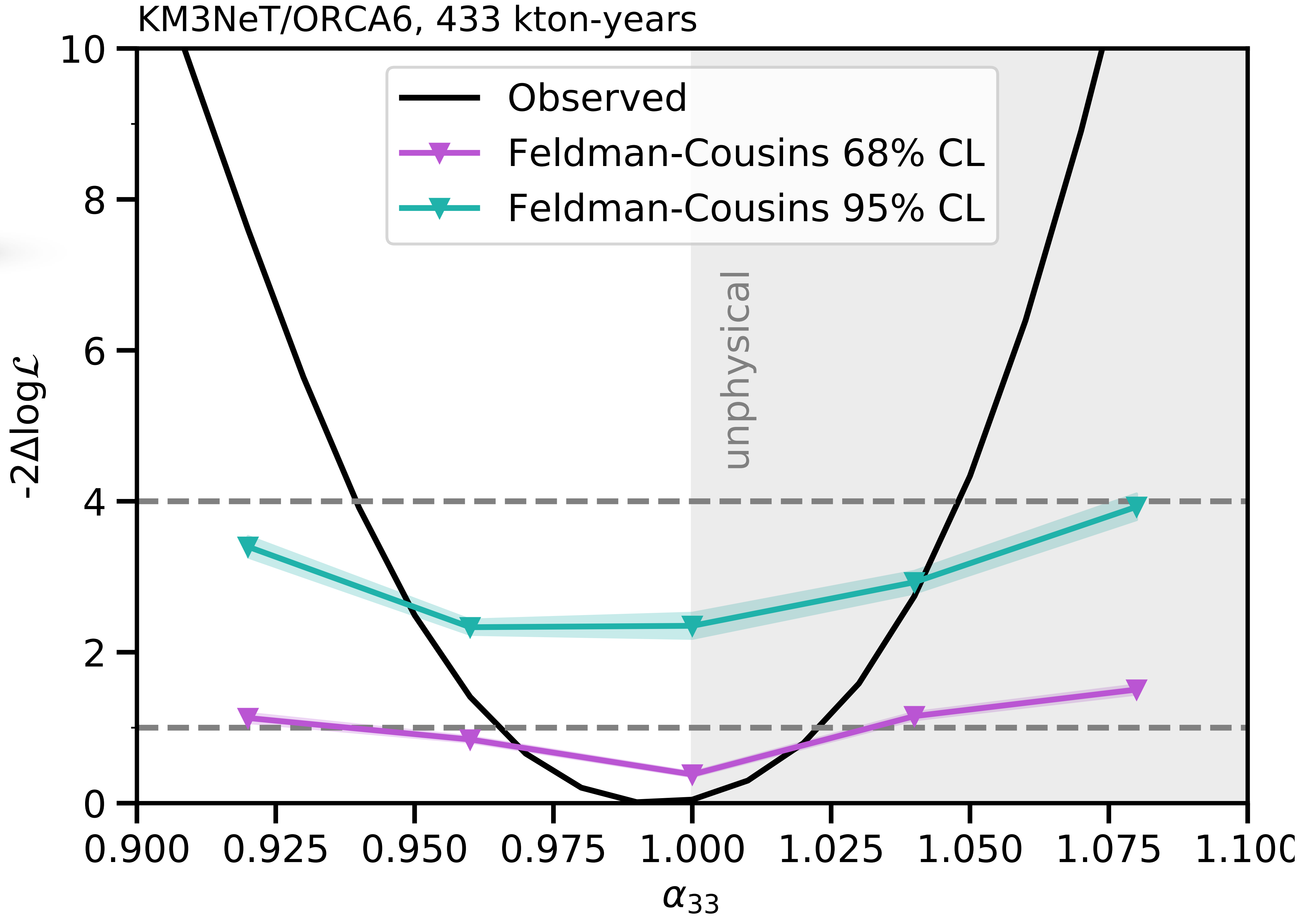
S_τ : PMNS unitarity hypothesis

- at the best fit, $S_\tau = 0.48^{+0.50}_{-0.33}$
  - **n. of observed ν_τ-CC** = 92^{+90}_{-63} events

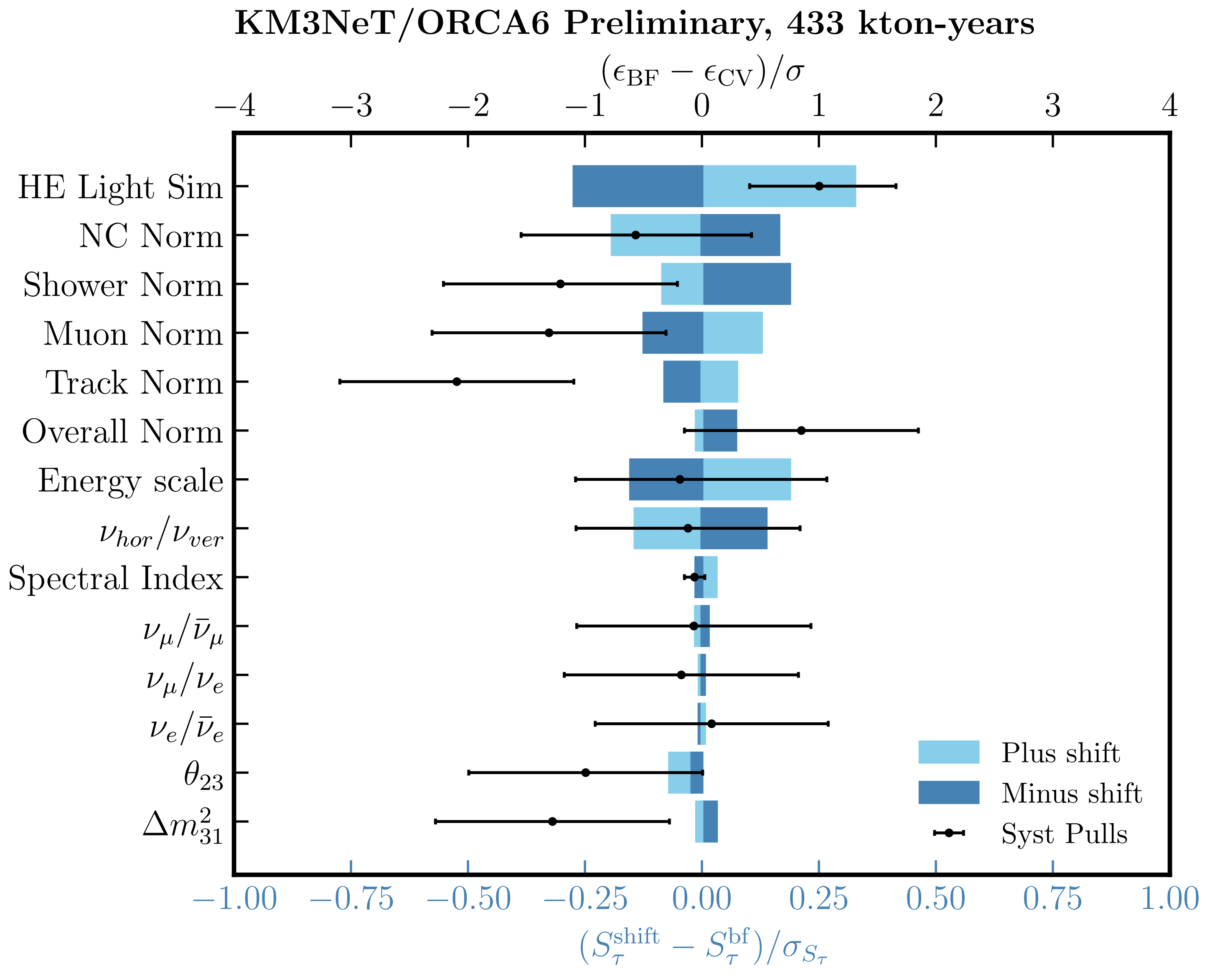


α_{33} : non-unitarity mixing

- at the best fit, $\alpha_{33} = 0.993^{+0.026}_{-0.025}$
  - **n. of observed ν_τ-CC** = 170^{+5}_{-9} events
  - **n. of NC** = 325^{+1}_{-4} events



ν_τ normalisation fit in KM3NeT/ORCA 6



Parameter	Central value ± prior
θ_{23} [°]	49.2 (49.3)
$\Delta m^2_{31} \times 10^{-3}\,\mathrm{GeV}^2$	2.517 (-2.424)
Spectral Index	0.00 ± 0.3
$\nu_{\mathrm{hor}}/\nu_{\mathrm{ver}}$	$0.00 \pm 2\%$
$\nu_\mu/\bar{\nu}_\mu$	$0.00 \pm 5\%$
$\nu_e/\bar{\nu}_e$	$0.00 \pm 7\%$
ν_μ/ν_e	$0.00 \pm 2\%$
S_{NC}	$1.00 \pm 20\%$
Energy scale	$1.00 \pm 9\%$
High-energy Light Simulation	$1.00 \pm 50\%$
Overall Normalisation	1.00
Track Normalisation	1.00
Shower Normalisation	1.00
Muon Normalisation	1.00