KM3NeT, A BRIDGE BETWEEN MULTI-MESSENGER ASTRONOMY AND PARTICLE PHYSICS

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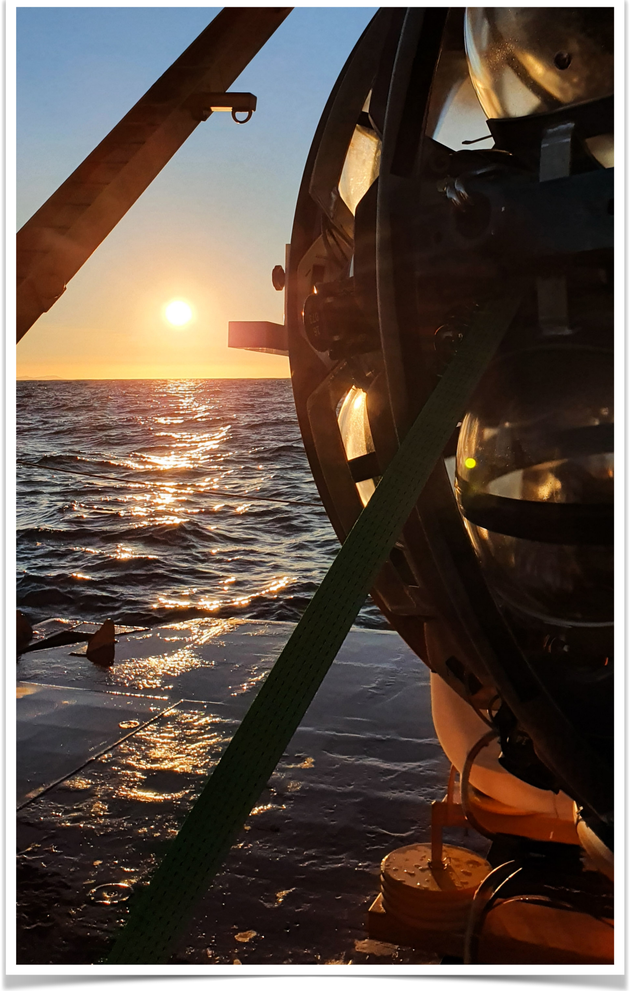
Queen Mary University of London - Feb 4th, 2026

KM3NeT LPC CAEN UNICAEN UNIVERSITÉ CAEN NORMANDIE

Outline



- **The role of neutrinos in astrophysics and particle physics**
  - ❍ neutrino telescopes in multi-messenger astronomy
  - ❍ open questions in neutrino oscillation physics
- **The KM3NeT experiment**
  - ❍ detection principle and technology
  - ❍ from installation to physics data
- **First study of tau neutrinos in KM3NeT/ORCA data**
  - ❍ selection of the ν sample
  - ❍ ν_τ appearance analysis
  - ❍ neutrino mixing non-unitarity test
- **Summary and prospects**

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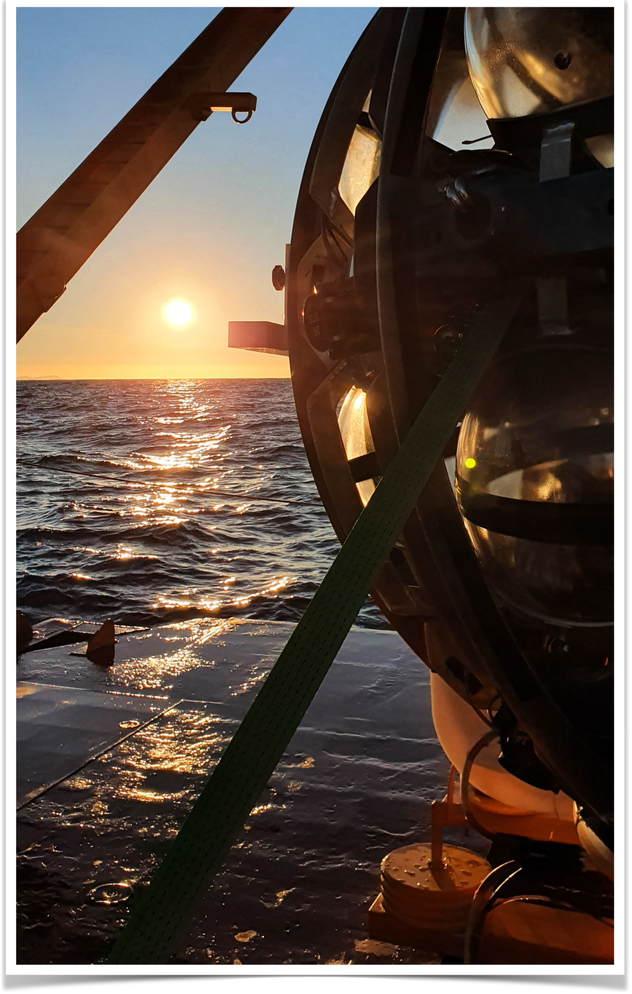

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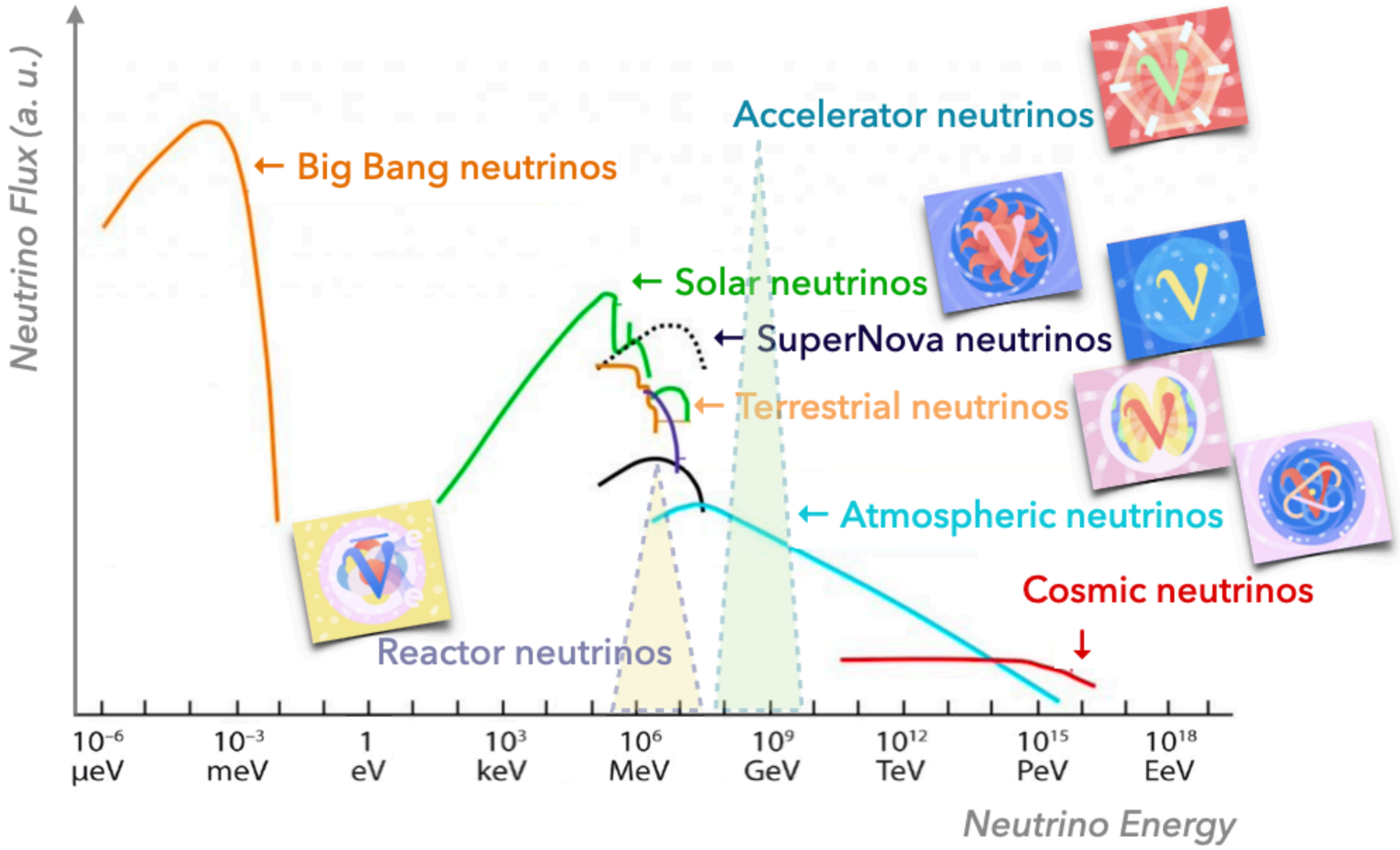
Neutrino physics in a nutshell

- Neutrinos are among the most **abundant** and **elusive** particles in the Universe
  - ❍ in the Standard Model (SM): **neutral leptons, massless, weak interactions**



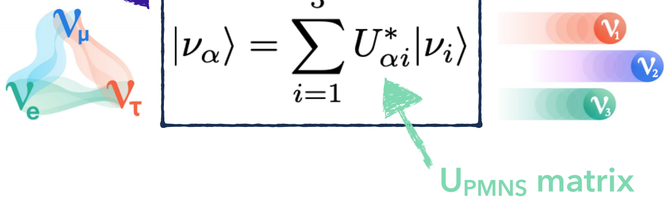
- **Neutrinos are unique *messenger***
  - ❍ astroparticle physics
  - ❍ SM validation and gateway toward its extension

Neutrino physics in a nutshell

- **neutrino oscillation mechanism:** first evidence of **beyond the SM (BSM) physics**

flavour eigenstates,
$\alpha = (e, \mu, \tau)$

mass eigenstates,
$i = (1, 2, 3)$



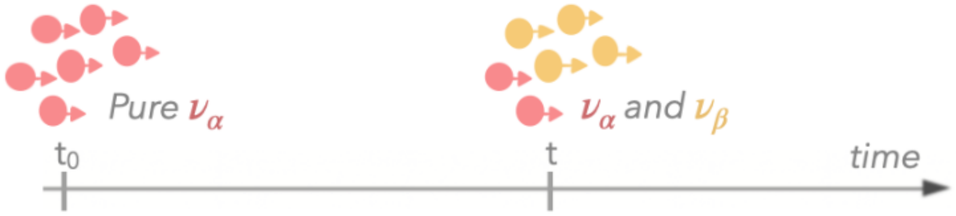
U_{PMNS} (3x3, unitary)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{Atmospheric}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}}_{\text{Reactor/Accelerator}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

* $s_{ij} = \sin\theta_{ij}$, $c_{ij} = \cos\theta_{ij}$

Oscillation probability: $P(\nu_\alpha \to \nu_\beta) \simeq \sin^2(2\theta) \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$

θ = mixing angle, $\Delta m^2 = m_1^2 - m_2^2$,
L = baseline, E = energy

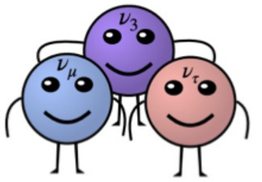


Open questions in neutrino oscillation

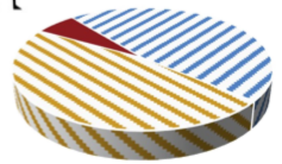
- is ν_3 mostly ν_μ or ν_τ? θ_{23} **octant**
- which neutrino is the lightest? **Neutrino Mass Ordering**
- is the charge-parity (CP) violated in the leptonic sector? δ_{CP} **phase**

Taken from NuFit 6.0

parameter	measurement	uncertainty
Δm^2_{21}	$(7.49 \pm 0.19) \times 10^{-5}$ eV^2	3 %
$\lvert\Delta m^2_{3l}\rvert$	$(2.52 \pm 0.03) \times 10^{-3}$ eV^2	1 %
$\sin^2\theta_{12}$	$(0.307\ ^{+0.012}_{-0.011})$	4 %
$\sin^2\theta_{13}$	$(0.02195\ ^{+0.00054}_{-0.00058})$	3 %
$\sin^2\theta_{23}$	$(0.561\ ^{+0.012}_{-0.015})$	5 %
sign Δm^2_{31}	unknown	
δ_{CP}	unknown	

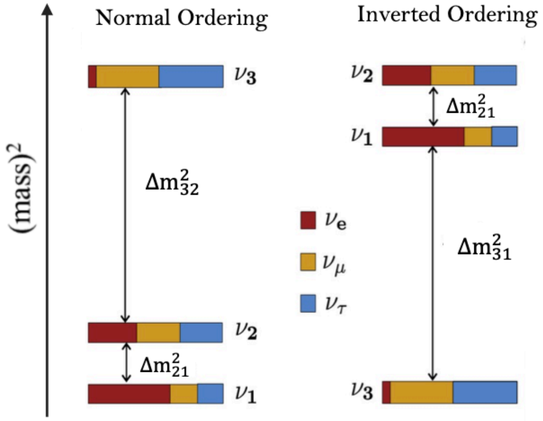


ν_3



5% precision on $\sin\theta_{23}$

if θ_{23}=45°, $|U_{\mu 3}| = |U_{\tau 3}|$



we know that:

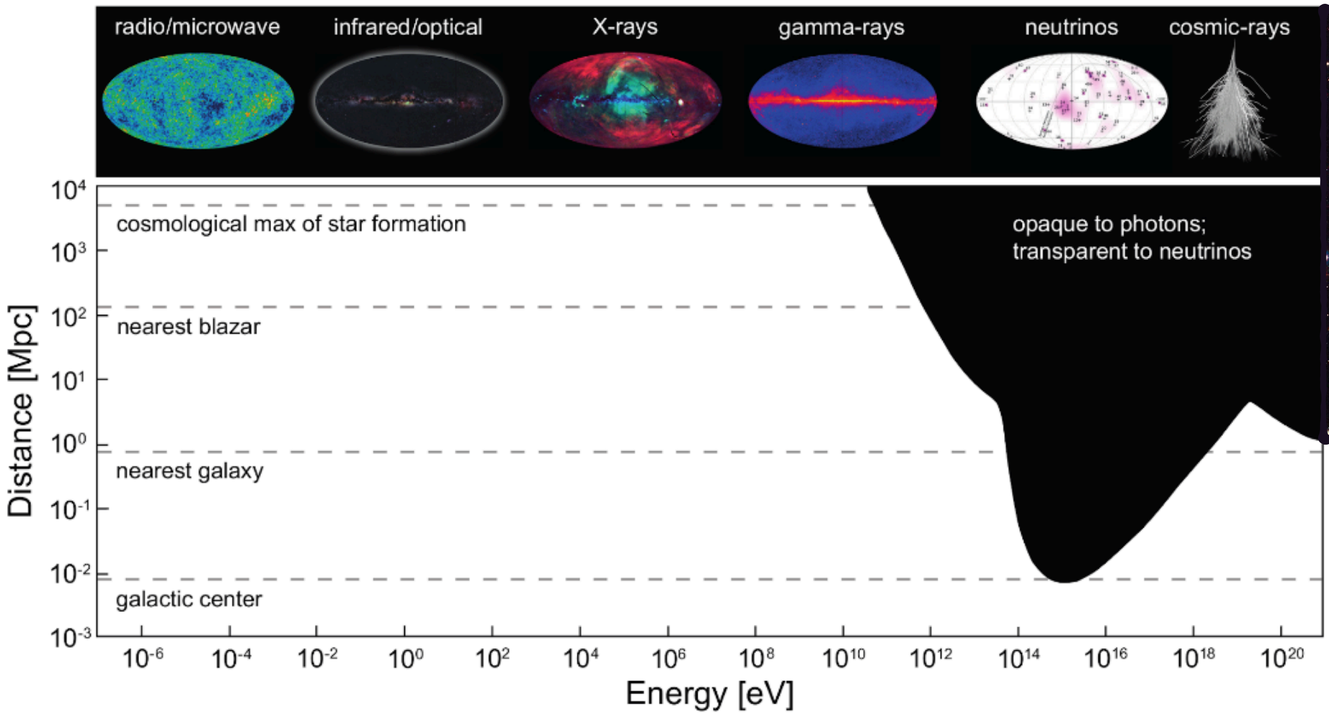
- $m_1^2 < m_2^2$
- $m_2^2 - m_1^2 << |m_3^2 - m_{1,2}^2|$

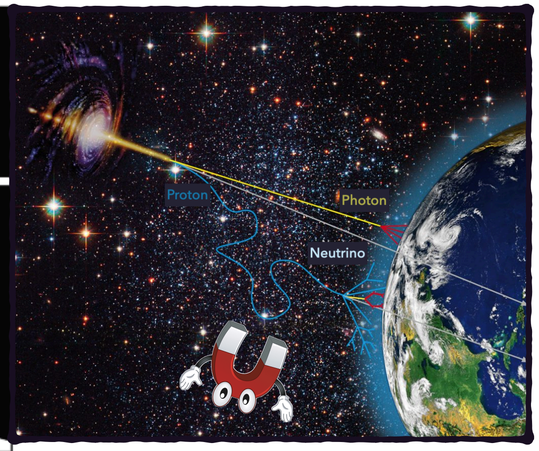
what about signΔm^2_{31}?

Do neutrinos and anti-neutrinos oscillate differently?

Multi-messenger astronomy with neutrino telescopes

- Due to weak interactions, **neutrinos travel undisturbed** over huge distances

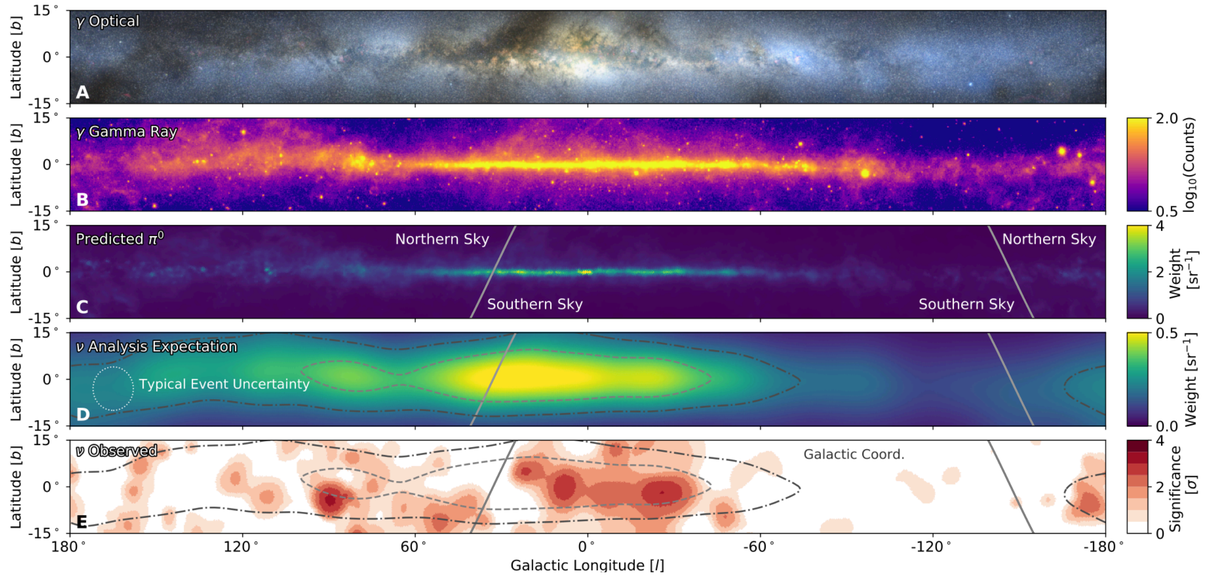




❍ **protons**' direction is deviated by galactic magnetic fields

❍ **photons** can be absorbed

IceCube Coll., Science, 380 (2023) 1338

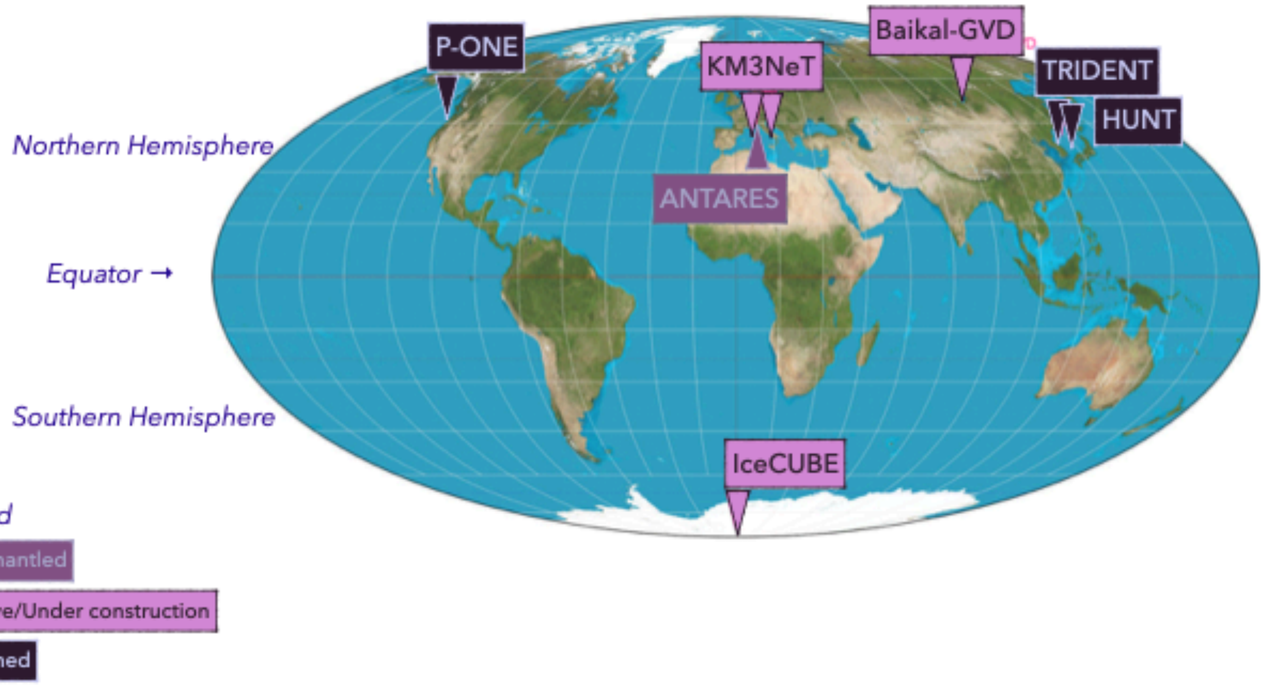


- **Pointing** to the source
- Reveal the **production mechanism**

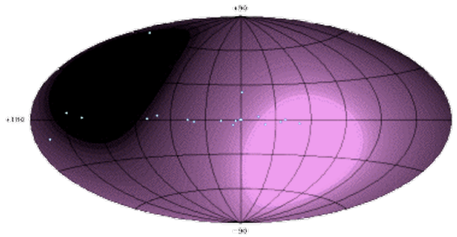
  (e.g. Sun, SuperNovae, other astronomical sources as Active Galactic Nuclei, black holes, etc…)

Neutrino telescopes overview

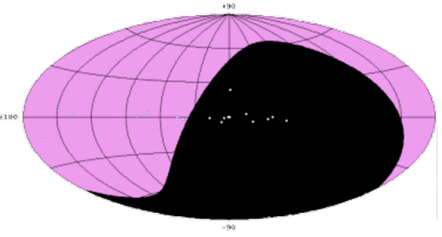
- Strong complementarity
  - ❍ **location**: accessible visible sky
  - ❍ **technology**: diverse neutrino astronomy targets



Visible sky

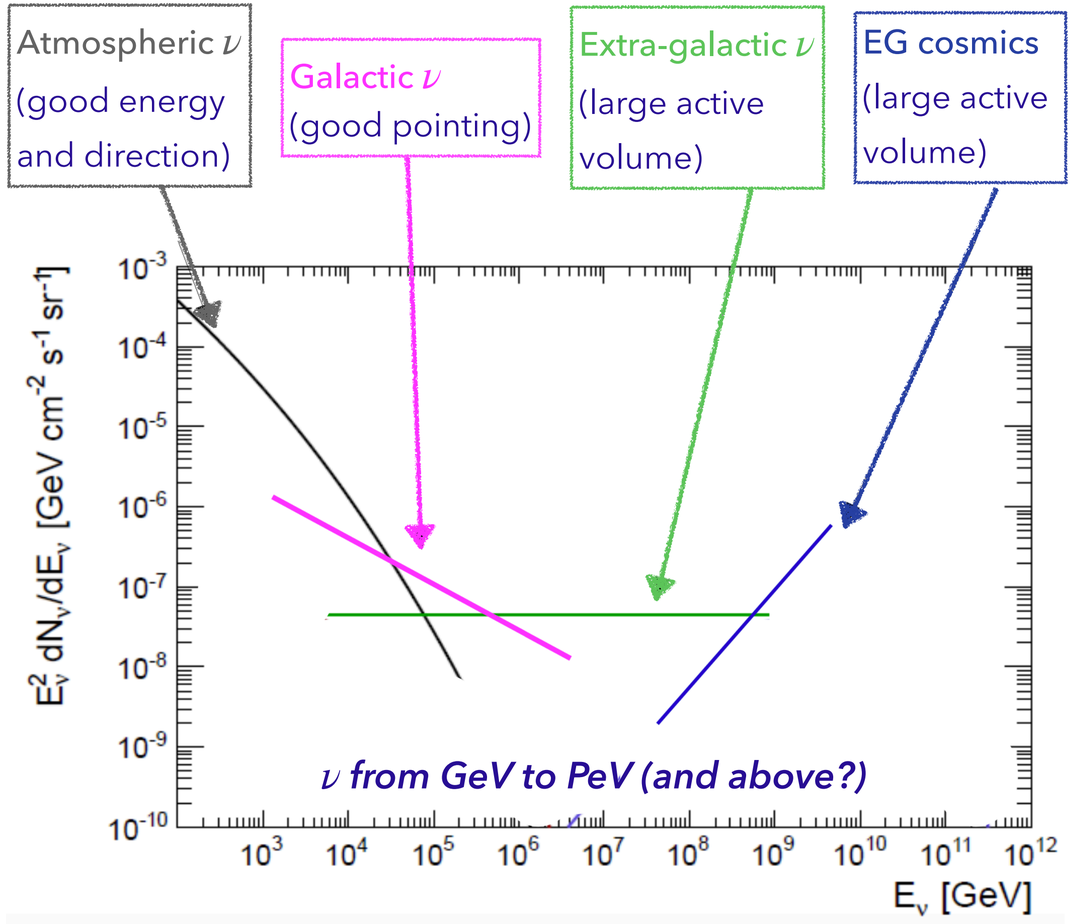


Mediterranean



South Pole

Astronomy targets



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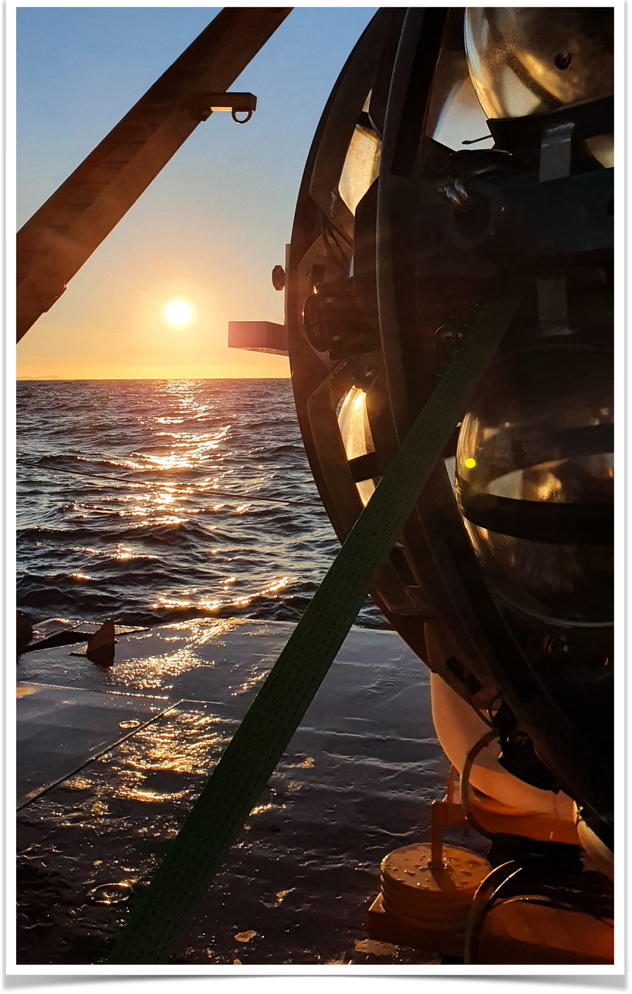

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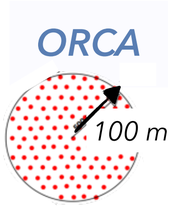
The KM3NeT experiment

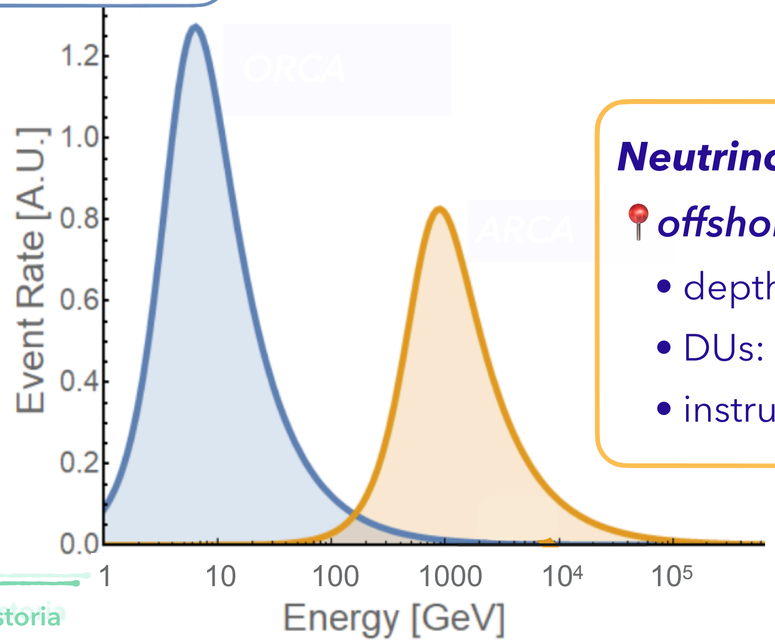
- **Water Cherenkov neutrino telescope** under construction in the **deep Mediterranean Sea**
- two detection sites for a **complementary physics program**

Neutrino oscillations in ORCA

📍 *offshore Toulon (France)*

- depth: 2450 m
- Detection Units (DUs): 115
- instrumented vol. ~ 28%

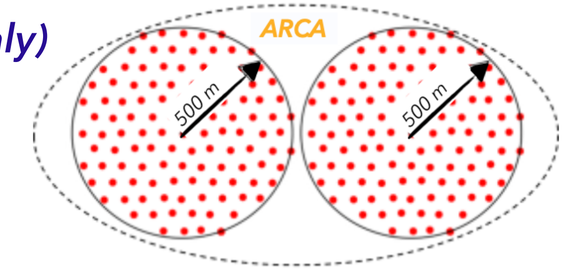




Neutrino astronomy in ARCA

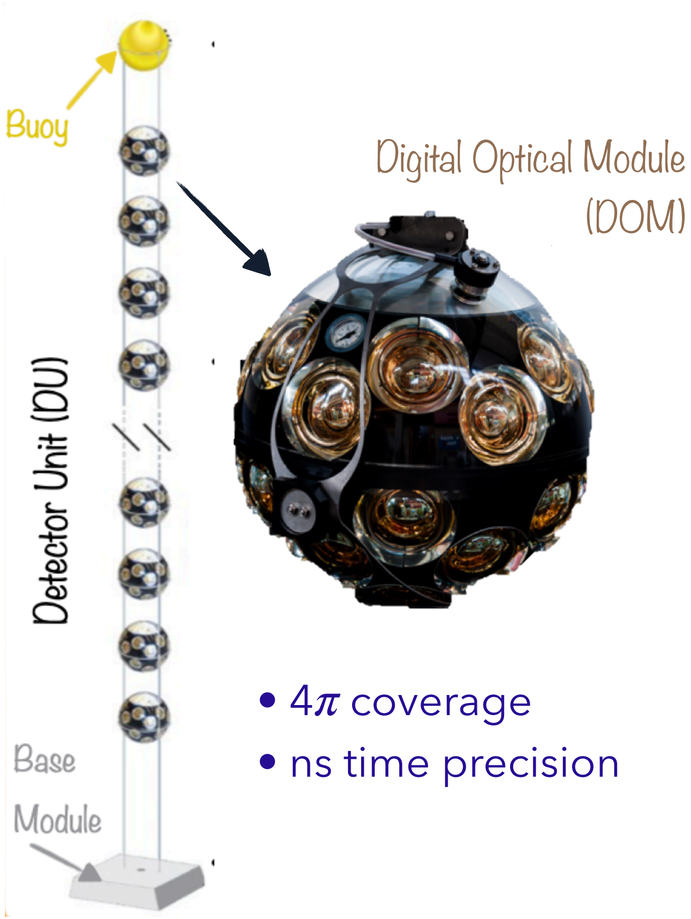
📍 *offshore CapoPassero (Italy)*

- depth: 3560 m
- DUs: 230
- instrumented vol. ~ 22%



The KM3NeT experiment

- same **modular structure** to detect Cherenkov radiation of secondary particle from ν interactions
  - ❍ 31 three-inches PMTs in each DOM, 18 DOM in each DU
  - ❍ accessible energy depending on interDOM/interDU distance



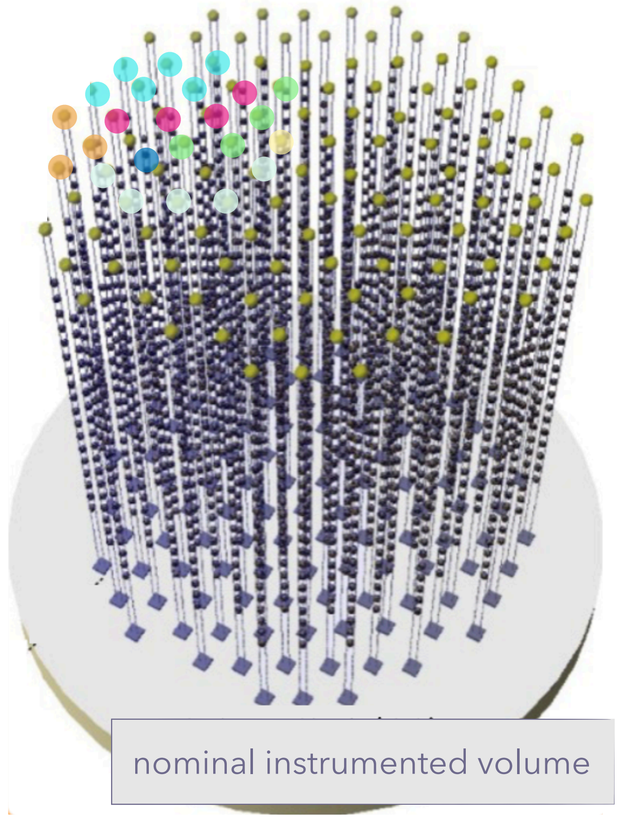
- 4π coverage
- ns time precision

ADVANTAGES

- well-known detection principle
- perform **physics studies from the installation phase**

CHALLENGES

- **several detector configurations**
- data taking optimization

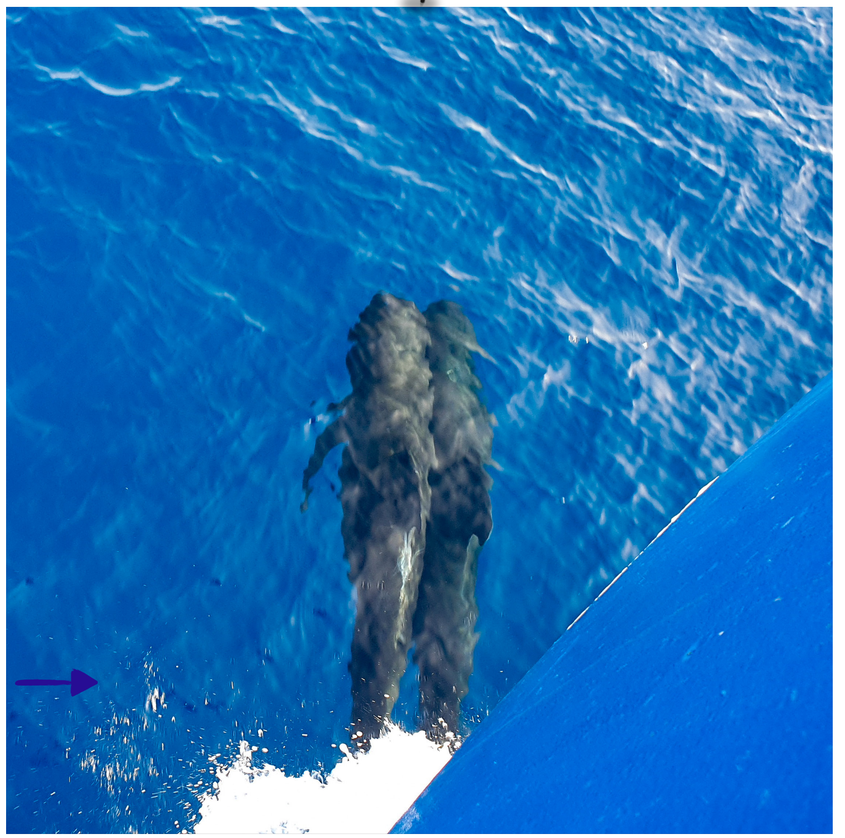


nominal instrumented volume

KM3NeT/ORCA: detector installation

- DU assembly in several labs in Europe (LPC Caen, Nantes, Strasburg, Nikhef)
- DU integration and pre-installation calibration in Marseille (CPPM)

..navigating with the dolphins!



KM3NeT/ORCA: detector installation

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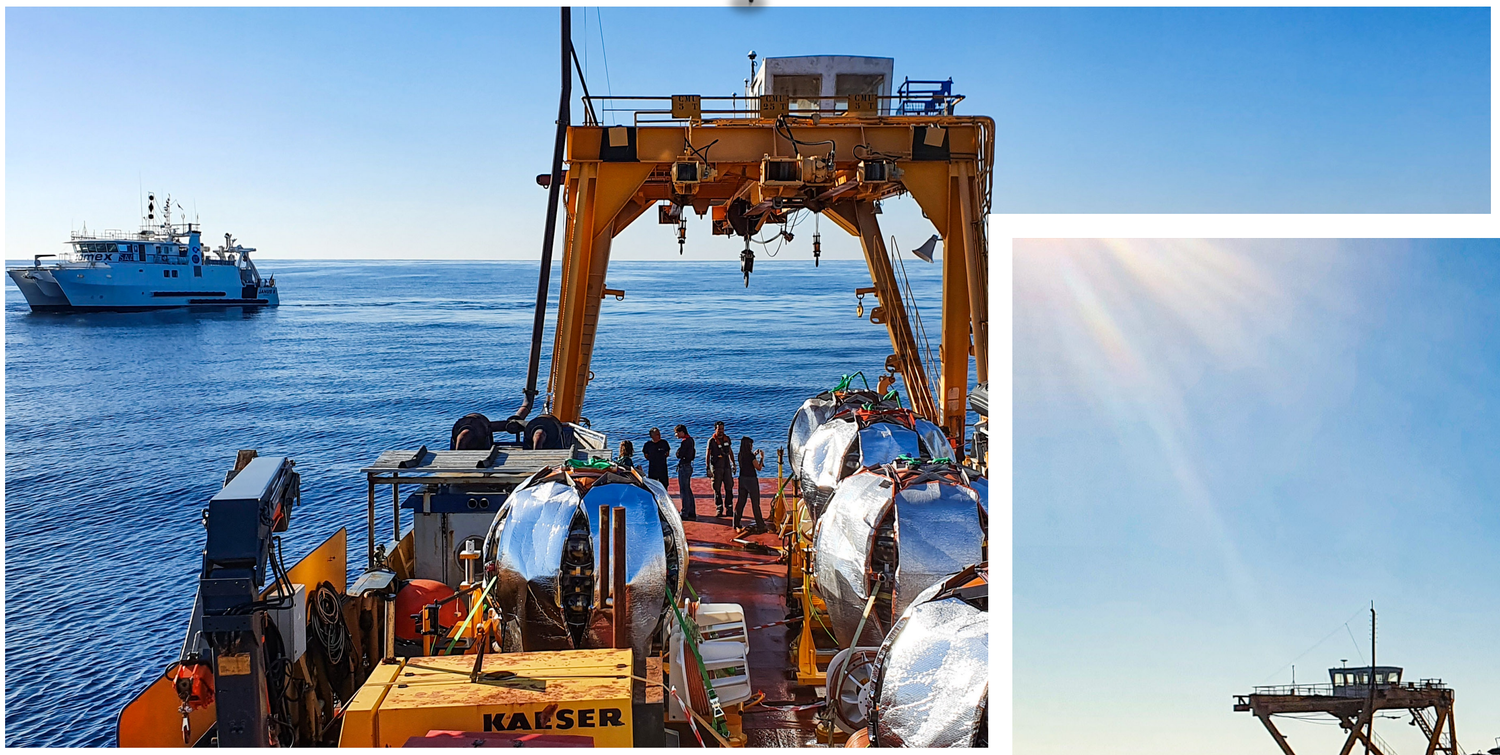

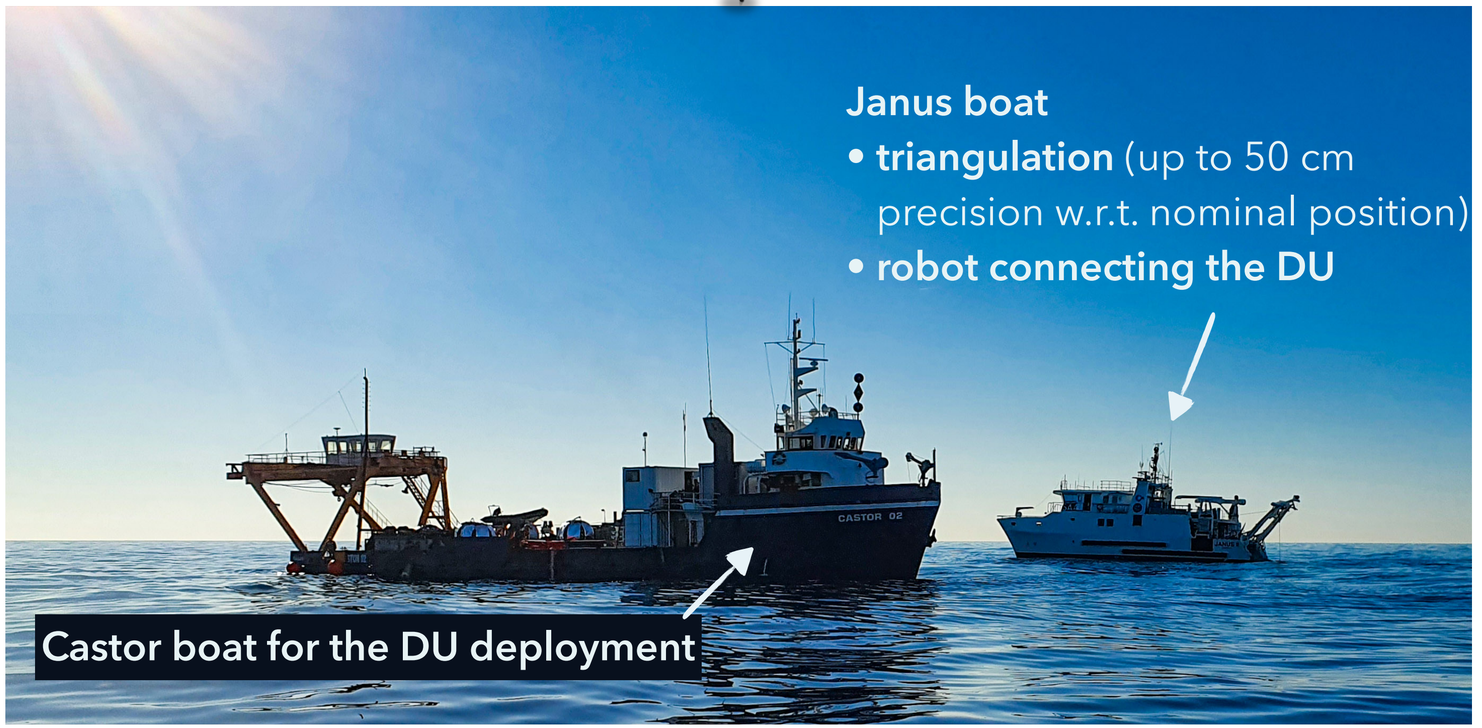

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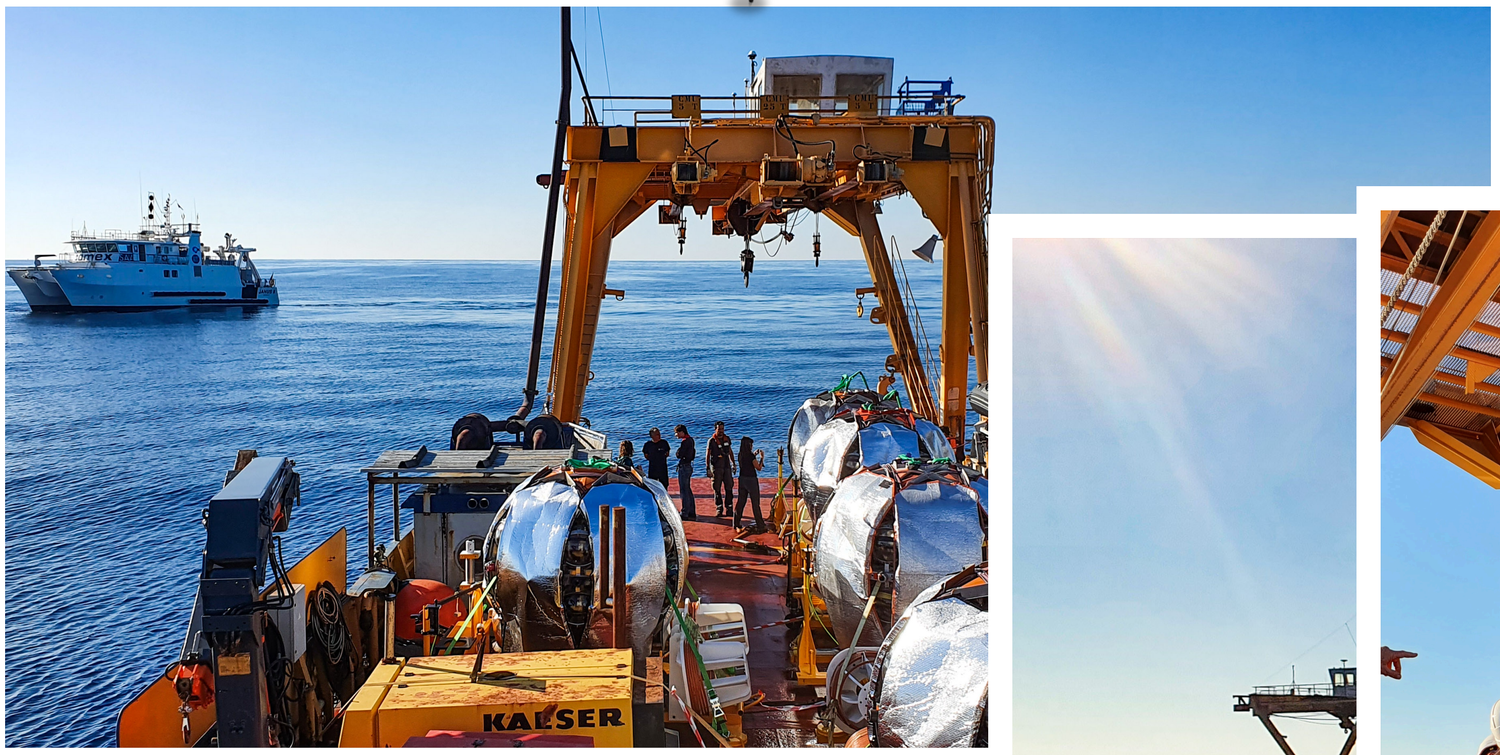
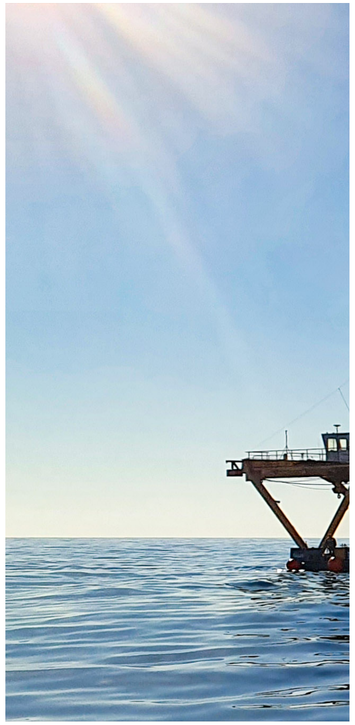
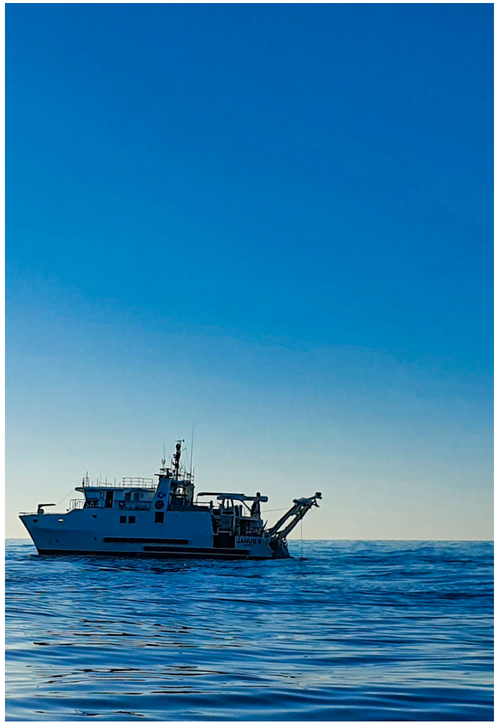
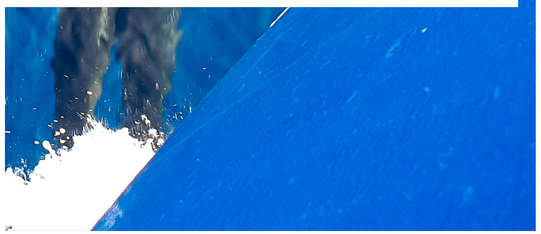


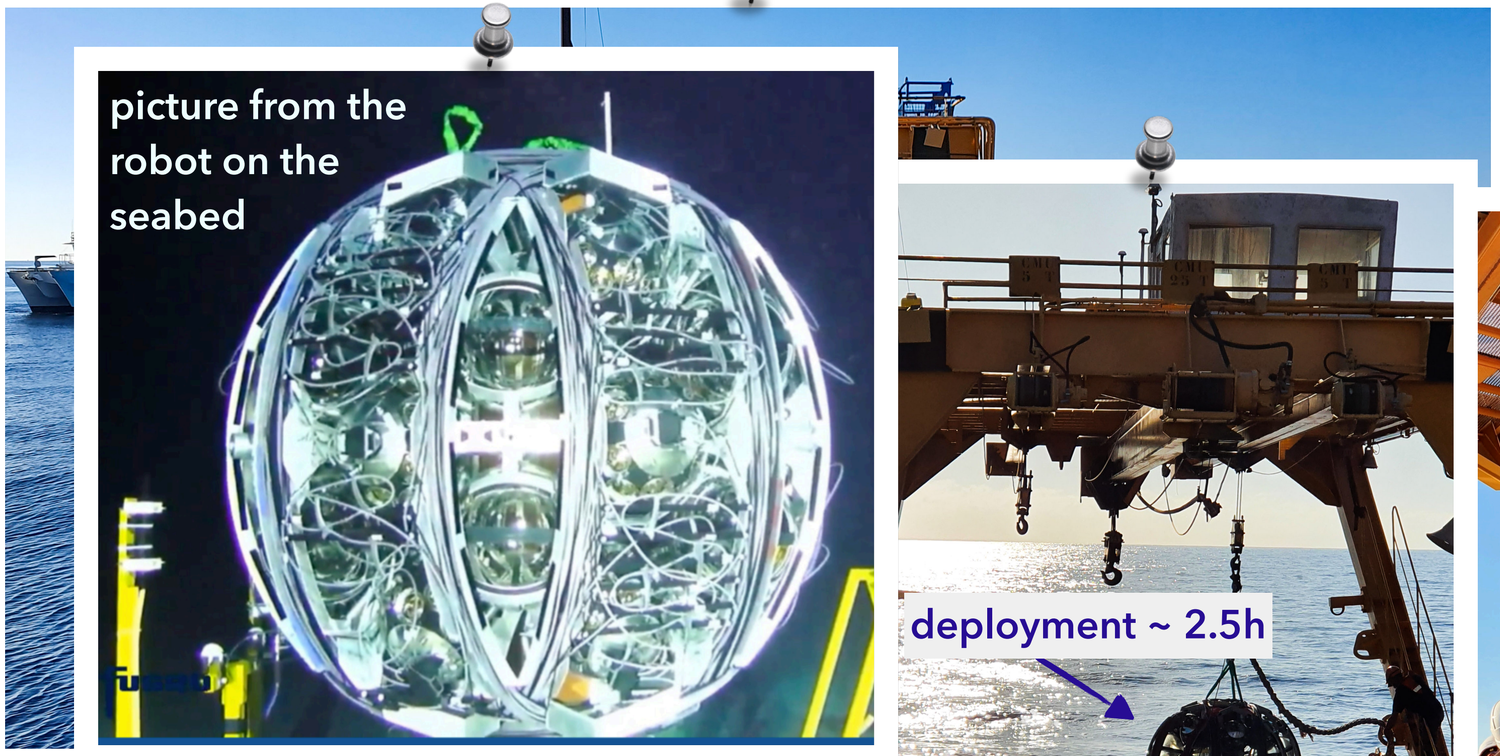


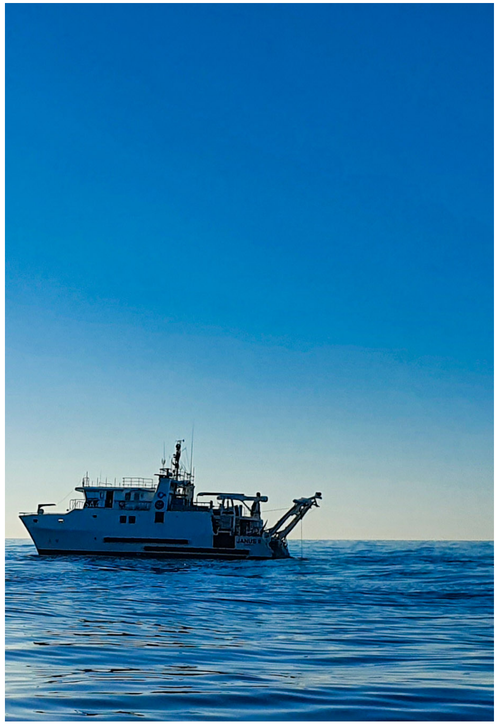




▷ check of the **proper position** of all DU components (cables, DOMs orientation, etc..)

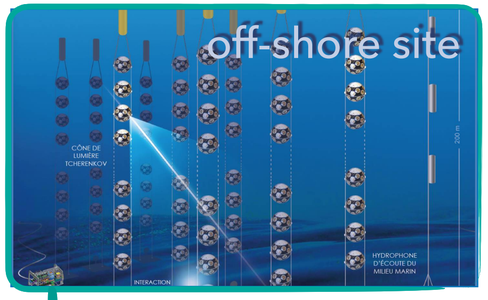
KM3NeT/ORCA: detector installation





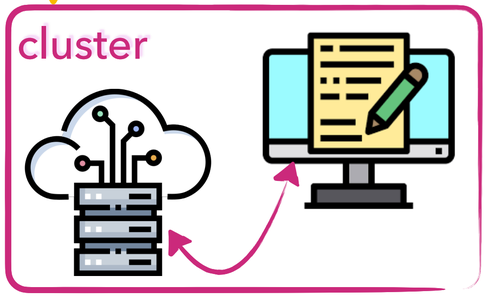
▷ on-shore, tests of **DU response after connection and unfurling** (HV, optics, humidity, etc..)

From detector installation to high-quality data



raw-data rate
(0.1-1 Tb/s)

triggering, quasi-online
calibration and reco
(10-100 Mb/s)



off-line calibration, simulation, and reconstruction

- ***all-data-to-shore***

  digitisation of all analog signal (>0.3 P.E.) for real-time processing

- **trigger**
  - ❍ online calibration (L0)
  - ❍ time and geometrical constraints (L1/L2)
  - ❍ SuperNova: hits multiplicity

- **offline calibration** (crucial for pointing and timing)
  - ❍ intraDOM synchronisation
  - ❍ interDOM orientation and position

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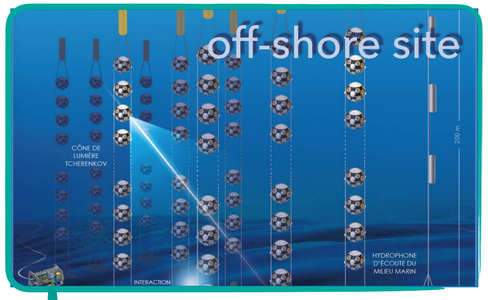

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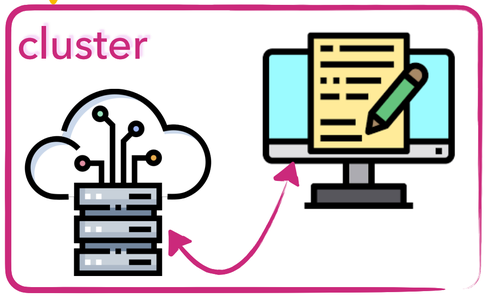

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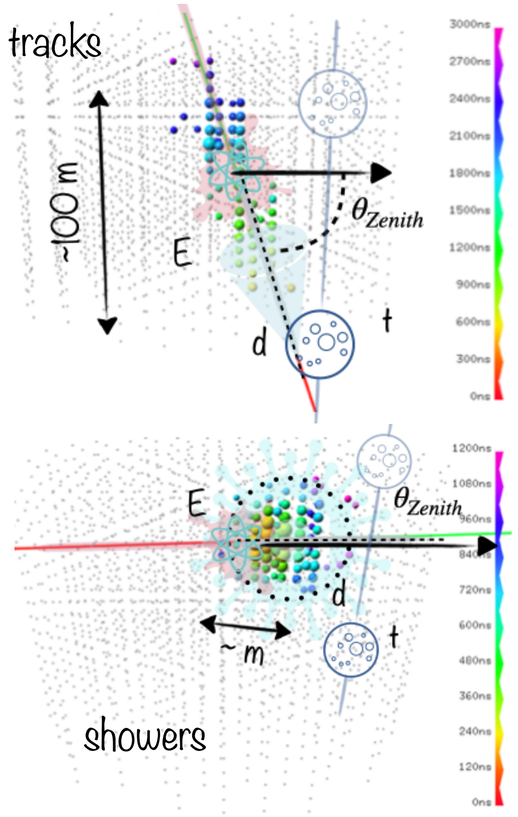
- **reconstruction (maximum likelihood algorithms)**
  - ❍ causality between triggered hits
  - ❍ PMT time and time-over-threshold within 10μs
  - ❍ interaction vertex position and direction (~1° angular error)
  - ❍ energy estimation



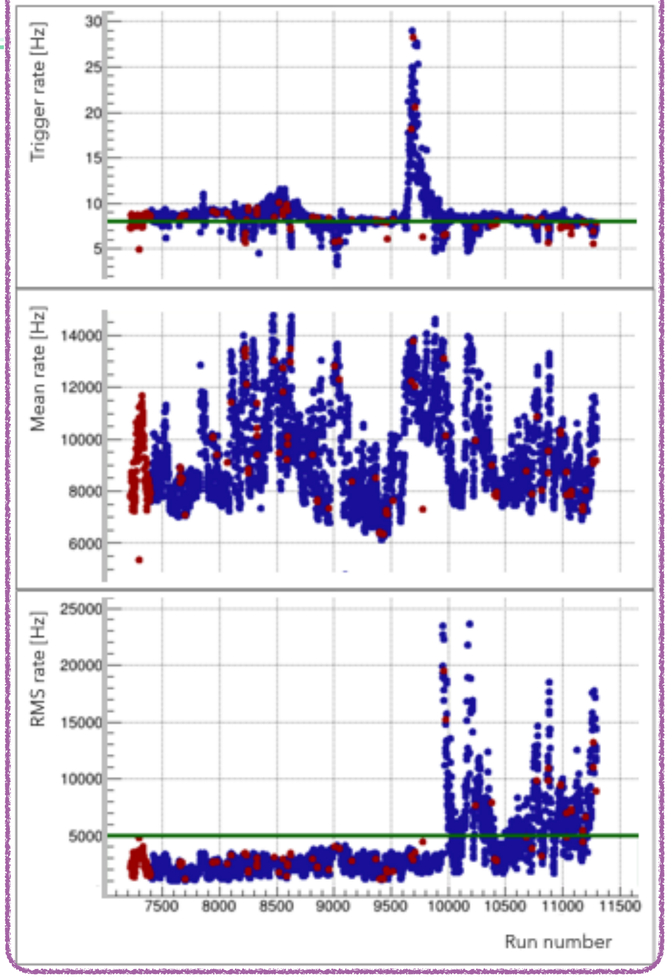
Schematics for maximum likelihood algorithm's reconstruction of track-like (top) and shower-like (bottom) events

KM3NeT Coll., J. Phys. G: Nucl. Part. Phys. 43 084001

From data acquisition to simulation

- **Run-by-run monitoring, processing, and quality benchmarking**
  - ❍ time-dependent data-taking conditions (sea-current, bioluminescence, etc…)
  - ❍ **data-driven Monte Carlo optimisation** (trigger rate, PMT mean and RMS rates, etc..)
  - ❍ data-quality monitoring (1-3h delay after run acquisition)

example of data quality monitoring



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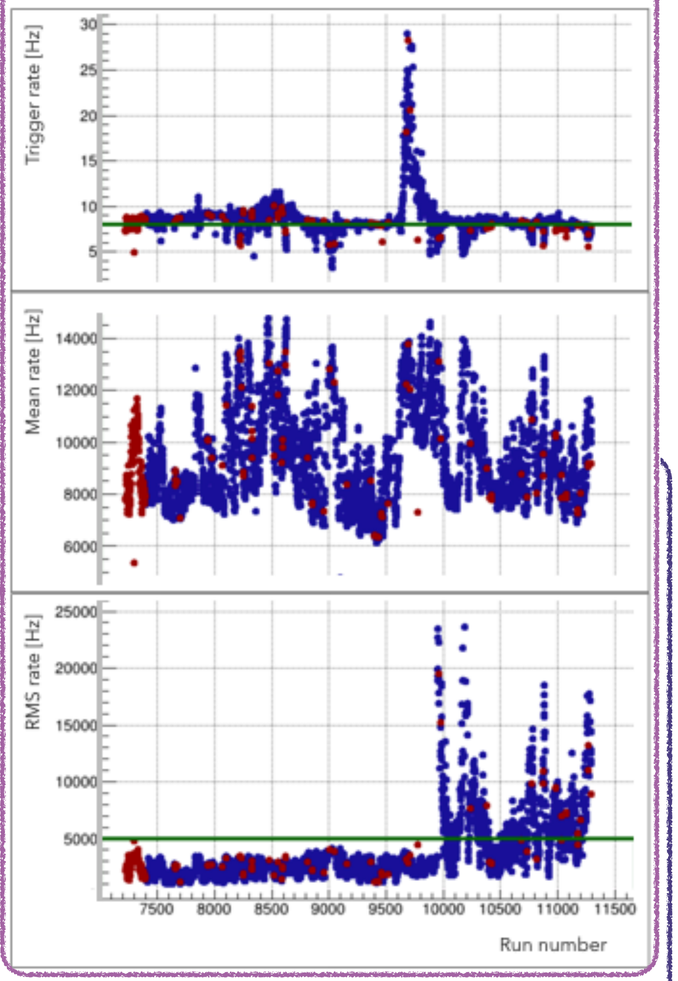


Monte Carlo (MC) simulations

- signal: **atmospheric and cosmic neutrinos** in the GeV-TeV energy scale
  (all flavours, charge-current (CC) and neutral-current (NC) interactions)
- backgrounds:
  - ❍ **atmospheric muons**
  - ❍ **optical noise** (^{40}K decay, PMT dark counts, bioluminescence)

event generation
- cosmic muons (MUPAGE)
- neutrinos (gSeaGen), HONDA flux and others

light propagation
full tracking and look-up tables
- absorption/scattering length
- PMT QE

trigger
- PMT electronic response
- data-driven optical bkg

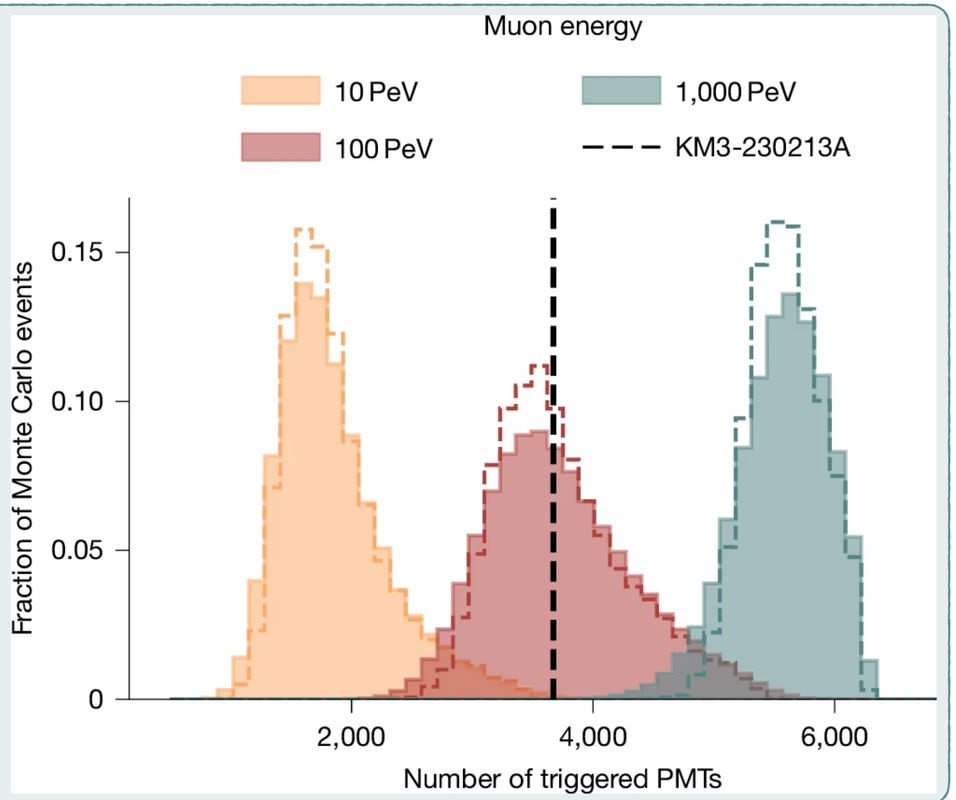
reconstruction
- maximum likelihood algorithms
- track-like and shower-like event hypothesis

The KM3-230213A: direction and energy reconstruction

- an horizontal muon (*..too horizontal to be cosmic muons!*)
- muon energy reconstructed from collected amount of light
- neutrino energy estimation assuming a E^{-2} source spectrum

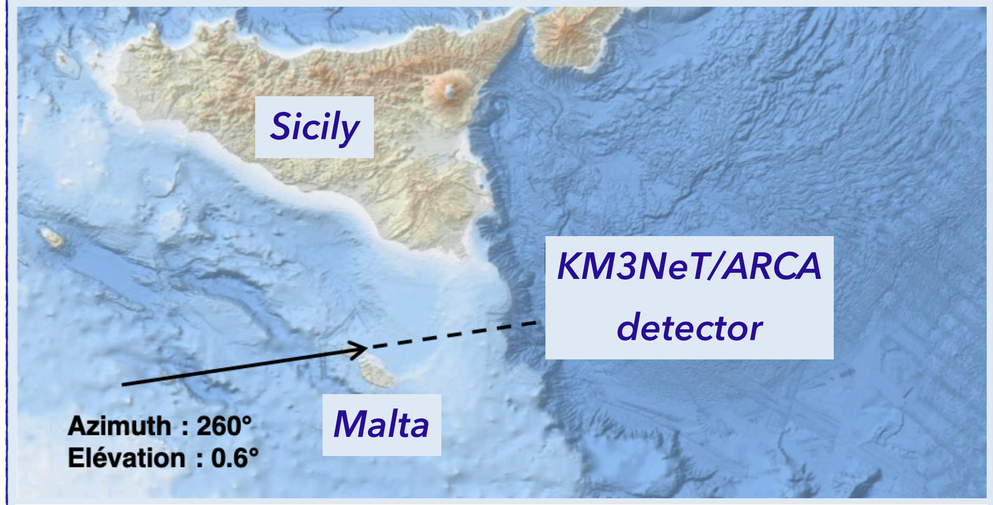
Energy

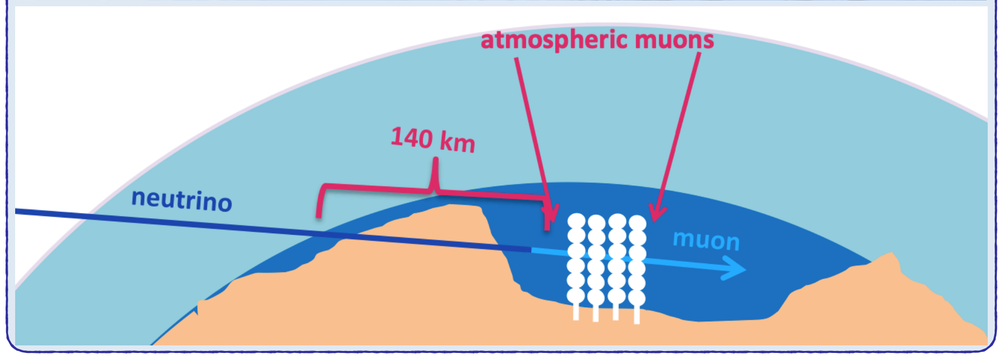
- $E_\mu = 120^{+110}_{-60}$ PeV
- $E_\nu = 220^{+570}_{-100}$ PeV



KM3NeT Coll, Nature 638, 376-382 (2025)

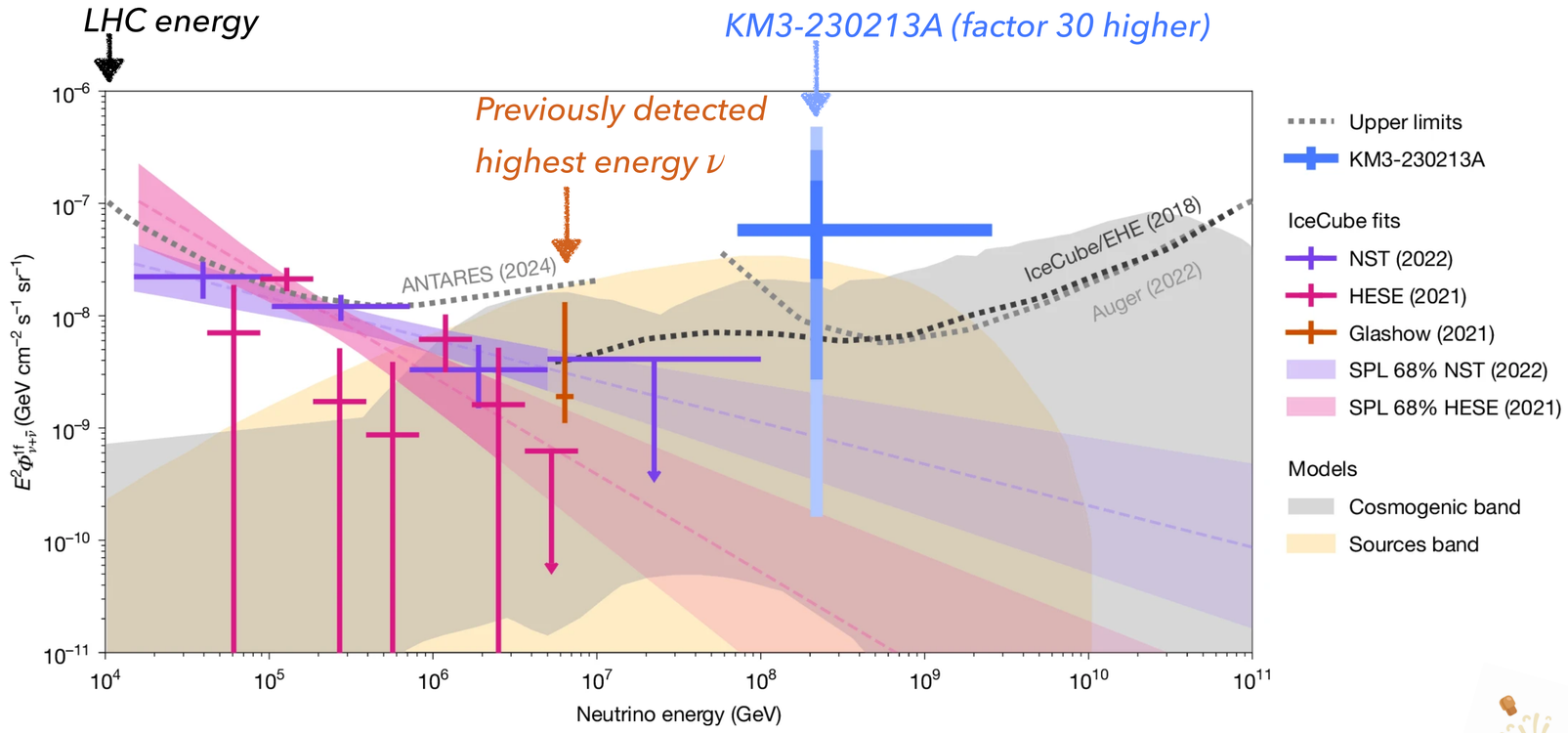
Direction





The KM3-230213A: interpretation

- **the Very High Energetic neutrino event (hypotheses to be confirmed)**
  - ❍ produced in cosmic higher-energy accelerator such as Active Galactic Nuclei, associated with massive black hole
  - ❍ cosmogenic neutrino (if so, it would be the first ever detected)



KM3NeT Coll, Nature 638, 376-382 (2025)

Article

Observation of an ultra-high-energy cosmic neutrino with KM3NeT

https://doi.org/10.1038/s41586-024-08543-1
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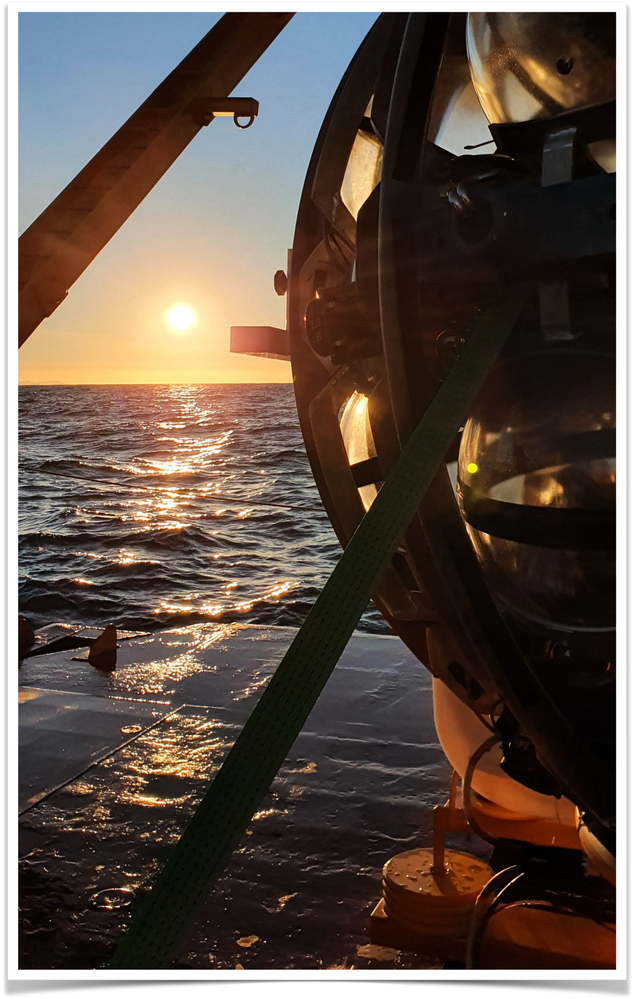
Check for updates

The KM3NeT Collaboration[58]

The detection of cosmic neutrinos with energies above a teraelectronvolt (TeV) offers a unique exploration into astrophysical phenomena[1–3]. Electrically neutral and interacting only by means of the weak interaction, neutrinos are not deflected by magnetic fields and are rarely absorbed by interstellar matter: their direction indicates that their cosmic origin might be from the farthest reaches of the Universe. High-energy neutrinos can be produced when ultra-relativistic cosmic-ray protons or nuclei interact with other matter or photons, and their observation could be a signature of these processes. Here we report an exceptionally high-energy event observed by KM3NeT, the deep-sea neutrino telescope in the Mediterranean Sea[4], which we associate with a cosmic neutrino detection. We detect a muon with an estimated energy of 120^{+110}_{-60} petaelectronvolts (PeV). In light of its enormous energy and near-horizontal direction, the muon most probably originated from the interaction of a neutrino of even higher energy in the vicinity of the detector. The cosmic neutrino energy spectrum measured up to now[1–3] falls steeply with energy. However, the energy of this event is much larger than that of any neutrino detected so far. This suggests that the neutrino may have originated in a different cosmic accelerator than the lower-energy neutrinos, or this may be the first detection of a cosmogenic neutrino[5], resulting from the interactions of ultra-high-energy cosmic rays with background photons in the Universe.

no firm conclusion can be drawn from a single event detection

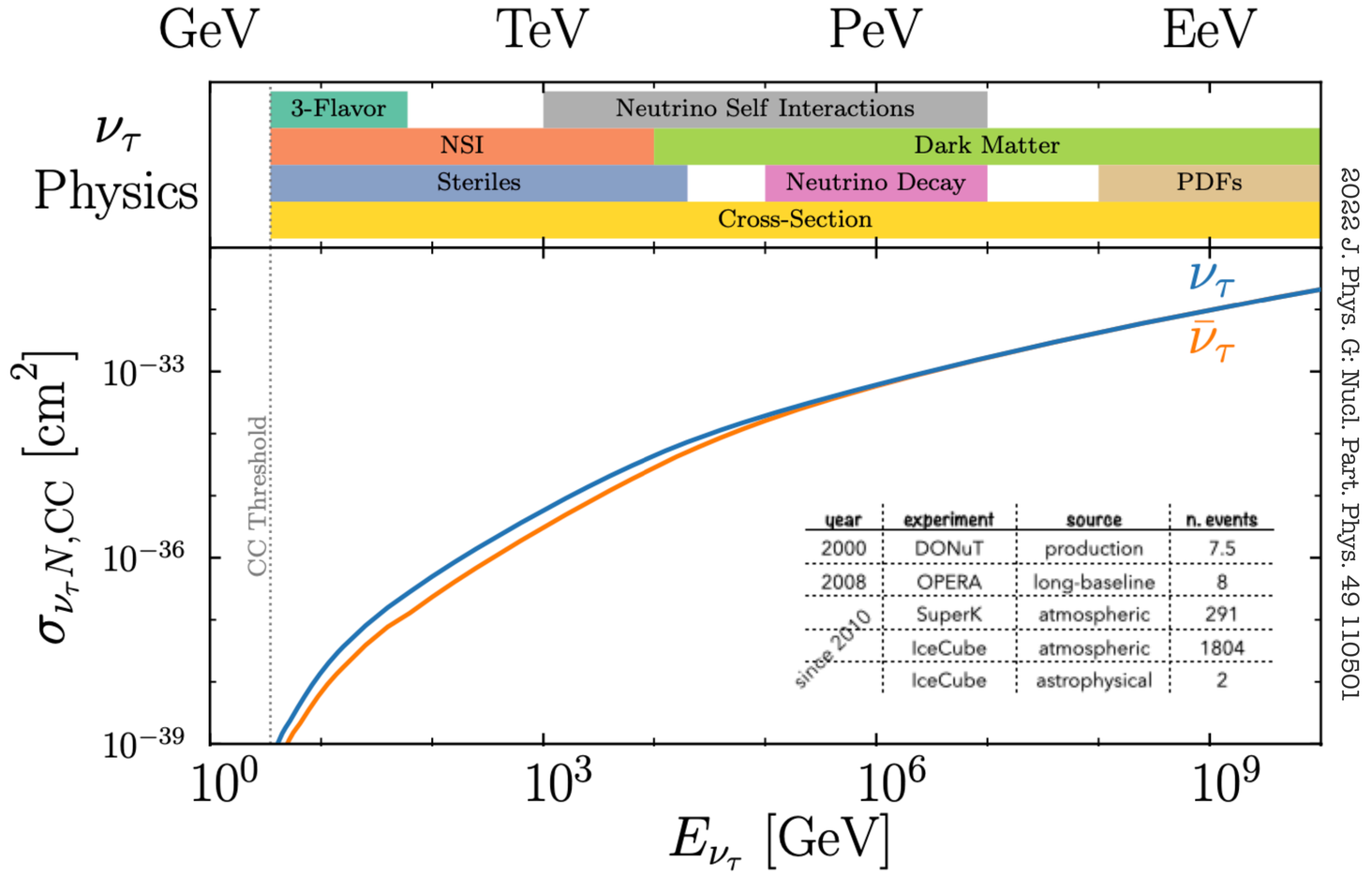
Outline



- The role of neutrinos in astrophysics and particle physics
  - ❍ neutrino telescopes in multi-messenger astronomy
  - ❍ open questions in neutrino oscillation physics
- The KM3NeT experiment
  - ❍ detection principle and technology
  - ❍ from installation to physics data
- **First study of tau neutrinos in KM3NeT/ORCA data**
  - ❍ selection of the ν sample
  - ❍ ν_τ appearance analysis
  - ❍ neutrino mixing non-unitarity test
- Summary and prospects

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**

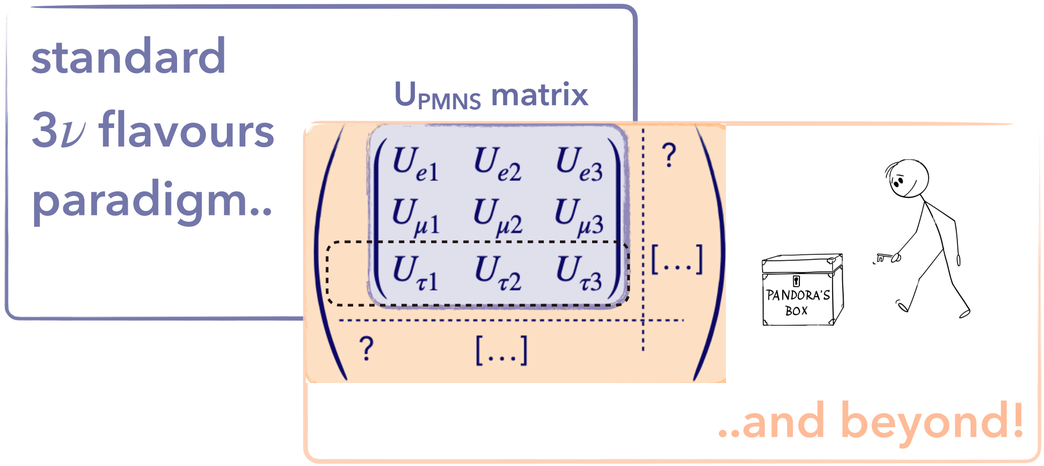


Why studying ν_τ?

- next-generation neutrino experiments aims at reaching sub-percent precision in oscillation parameters
  - ❍ **constraints on PMNS elements**

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

    Beyond Standard Model (BSM) physics

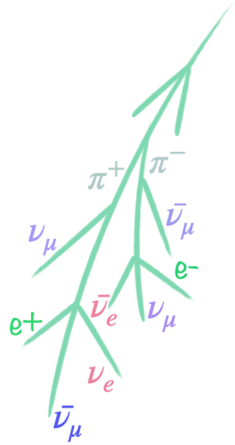


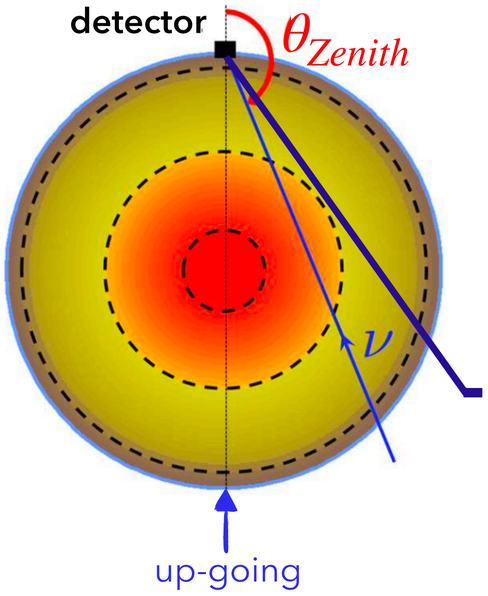
Exploiting complementarity: different energy scale and sensitivity to oscillation parameters

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

KM3NeT/ORCA physics goals

- **atmospheric neutrinos**: secondary particle from cosmic ray interaction with Earth's atmosphere

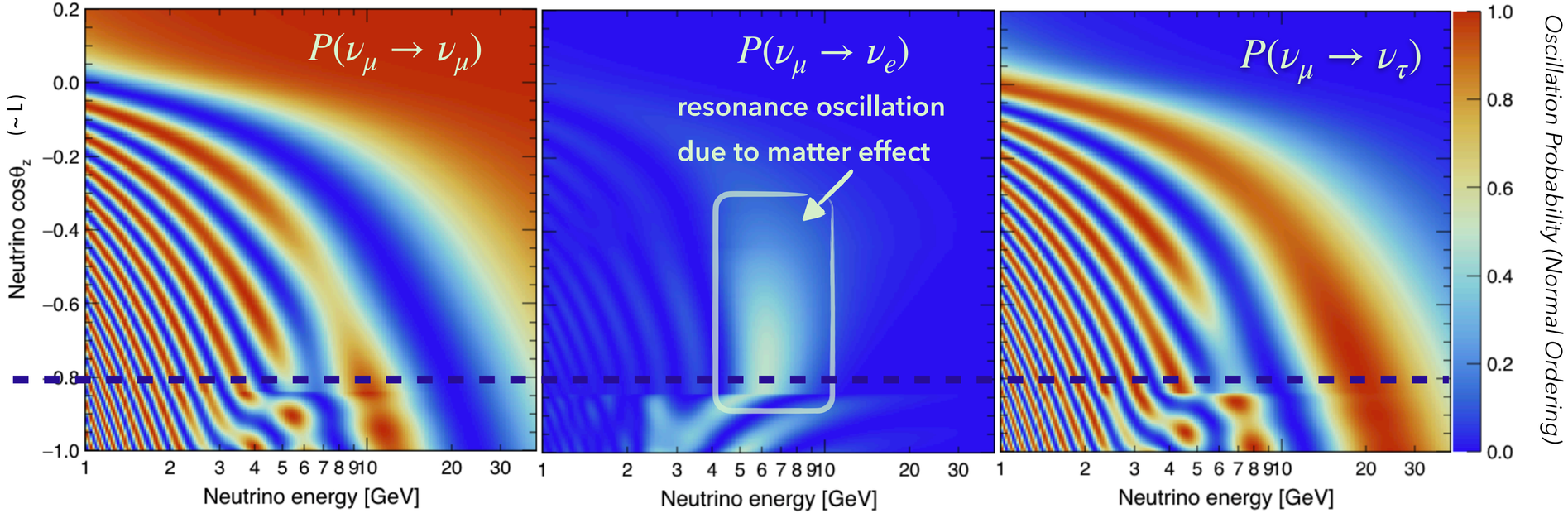




❍ ν_μ **disappearance (dominant effect)**: neutrino oscillation parameters θ_{23}, Δm^2_{32}

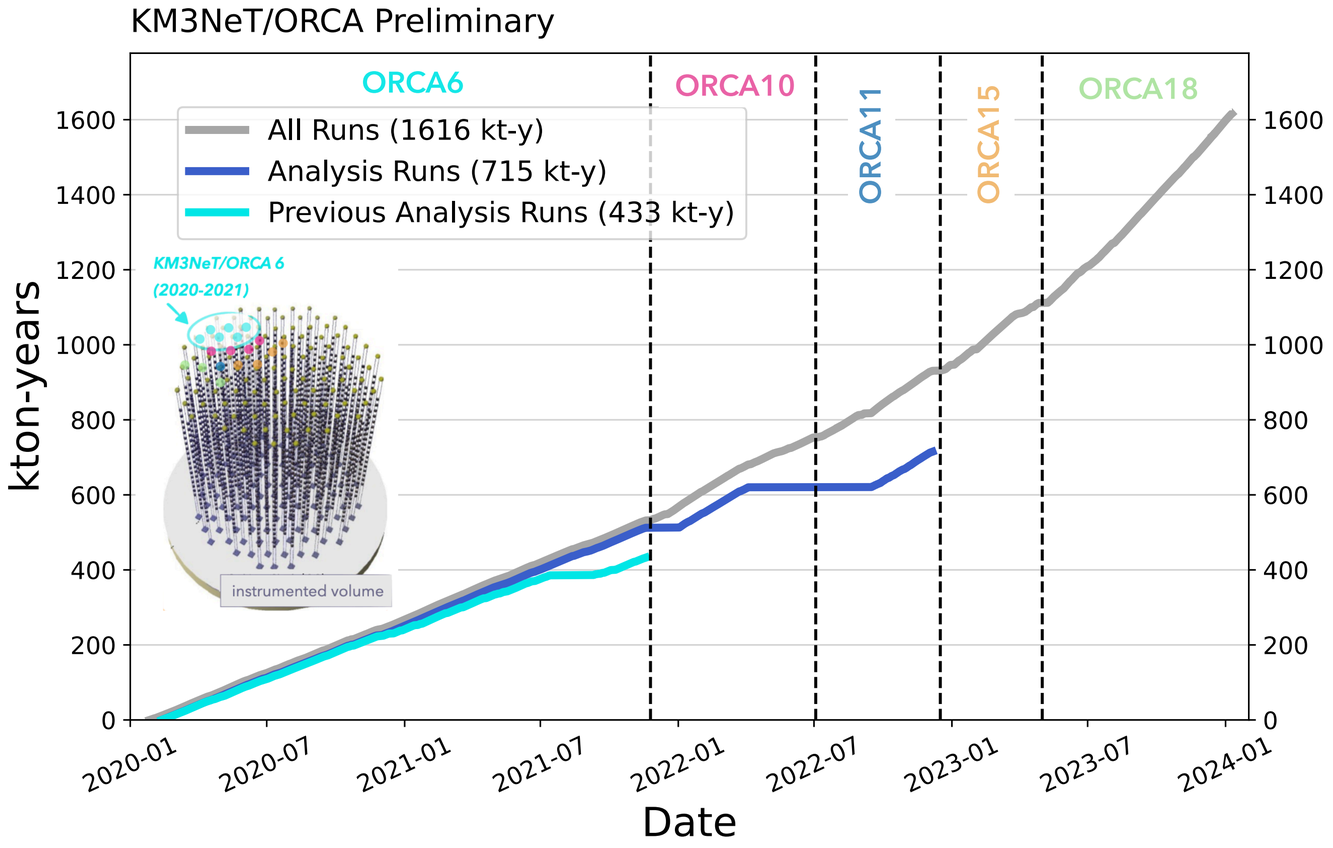
❍ ν_e **appearance (sub-dominant effect)**: sensitive to the **Neutrino Mass Ordering (NMO)**

❍ other searches: ν_τ **appearance** , **sterile** and other **BSM searches,** etc…



First look at KM3NeT/ORCA 6 data

- **Six operational lines** (ORCA6) and **433 ton-years exposure** (510 days): many exploited novelties
  - ❍ reconstruction of **both tracks** & **showers** (first time!)
  - ❍ **opening to new oscillation analyses** by exploiting the shower topology
  - ❍ event selection using **machine learning** algorithms (e.g. Boosted Decision Trees - BDT, Random Grid Searches - RGS)



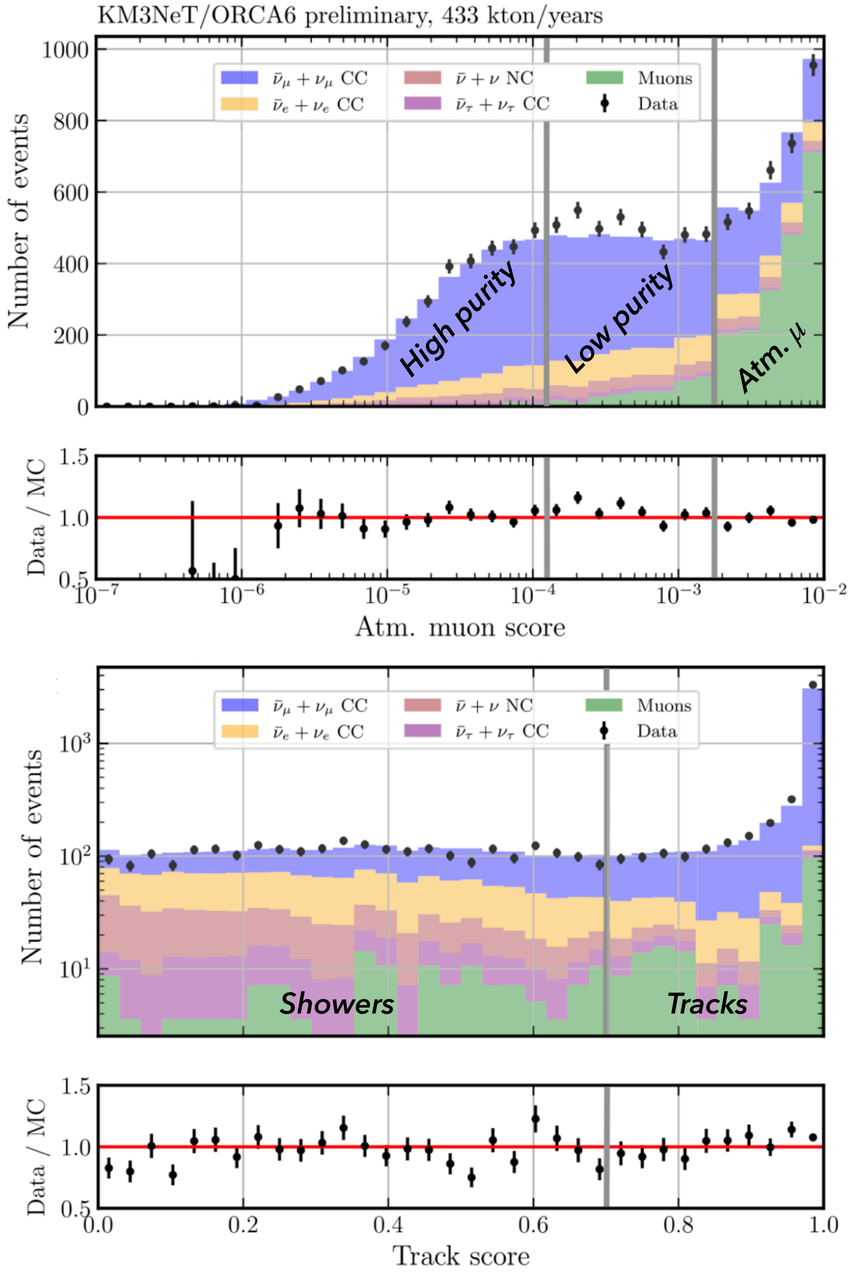
Event selection and data sample

- **BDT algorithm** for background rejection and track-shower separation
  - ❍ trained on MC (maximum likelihood algorithm's variables)
  - ❍ **challenging classification at low E**: 70% track-purity below 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 standard 3ν-paradigm)*

- **remarkable statistics**: ν_τ mostly reconstructed **in the shower class**



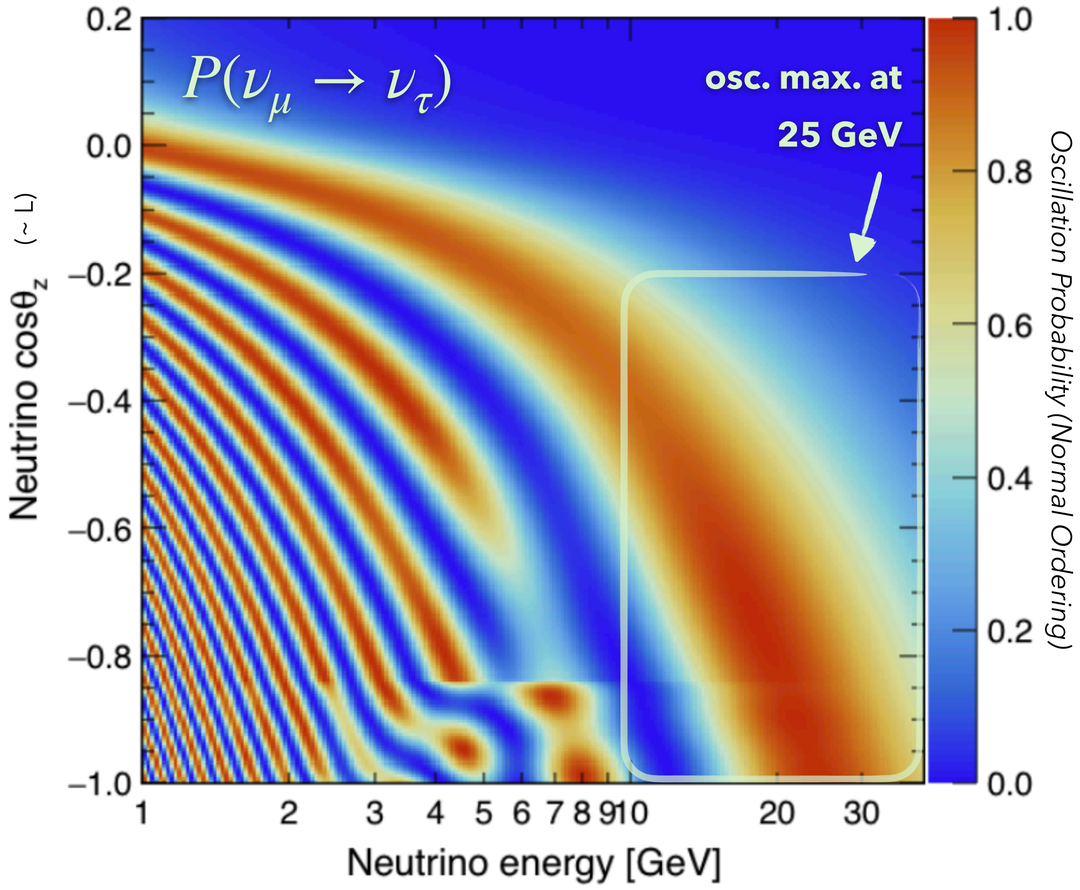
L. Cerisy, C. Lastoria et al., PoS ICRC2023 (2023) 1191

Analysis method

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

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

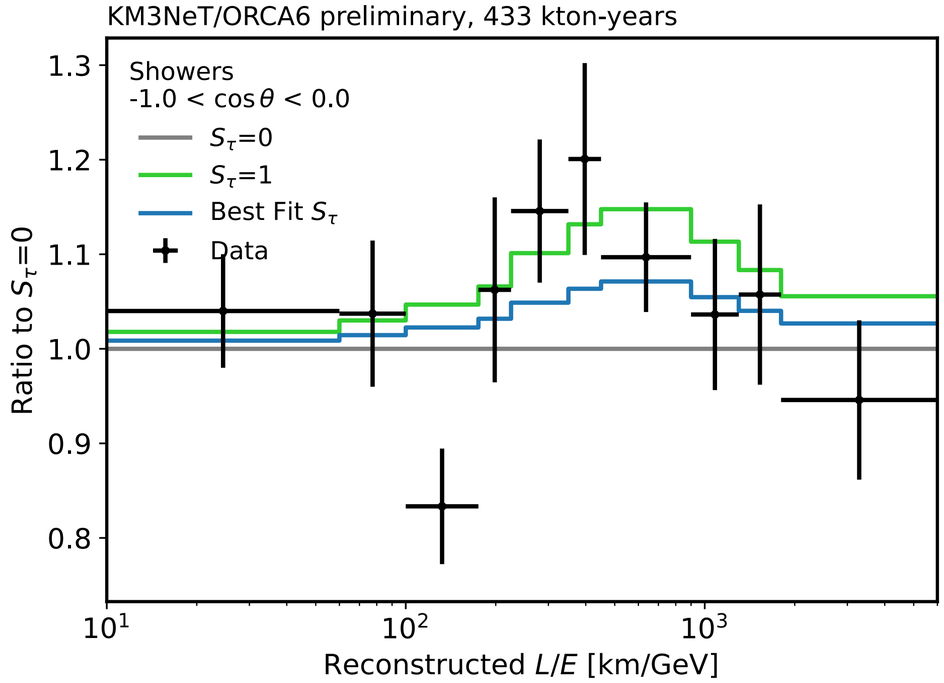
  - ❍ two tested hypotheses, assuming or not the PMNS matrix unitarity



ν_τ normalisation within the 3ν flavour paradigm

a) S_τ : PMNS unitarity hypothesis

- ν_τ-norm. $\neq$ 1, due to ν_τ **charge-current cross-section** modelization
- **impact on ν_τ-CC rate**



Excess in the shower class under the two extreme hypotheses on ν_τ-normalisation (equal to 0 or 1)

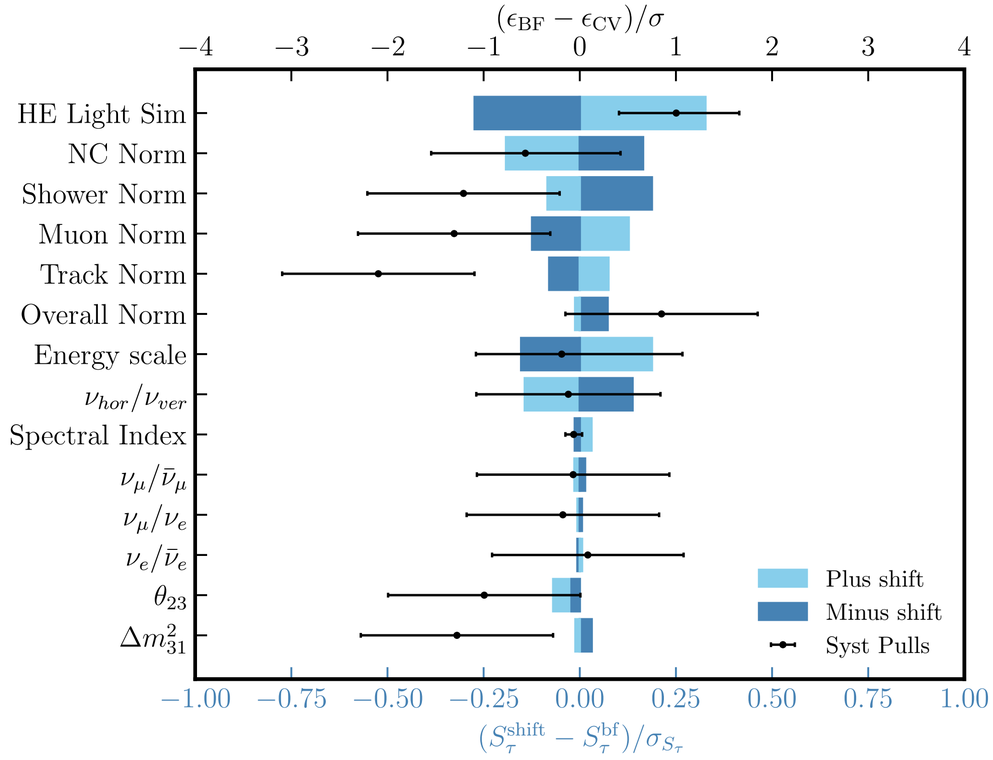
L. Cerisy, N. Geißelbrecht, C. Lastoria, JHEP 07 (2025) 213, e-print: 2502.01443

ν_τ normalisation within the 3ν flavour paradigm

a) S_τ : PMNS unitarity hypothesis

- ν_τ-norm. $\neq 1$, due to ν_τ **charge-current cross-section** modelization
- **impact on ν_τ-CC rate**

		Parameter	Constraint
atmospheric neutrino flux	flux	δ_γ	0.3
	shape	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

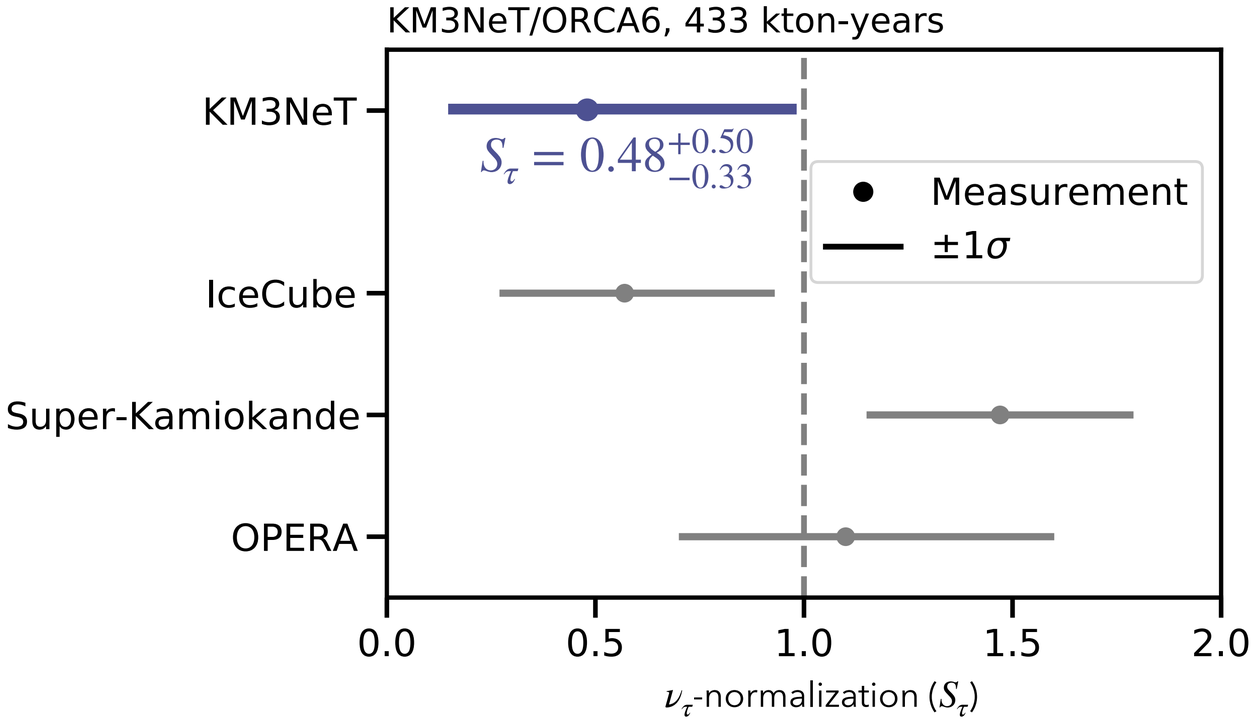


Main sources of **systematics** and their impact on the fit

L. Cerisy, N. Geißelbrecht, C. Lastoria, JHEP 07 (2025) 213, e-print: 2502.01443

ν_τ normalisation measurement

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

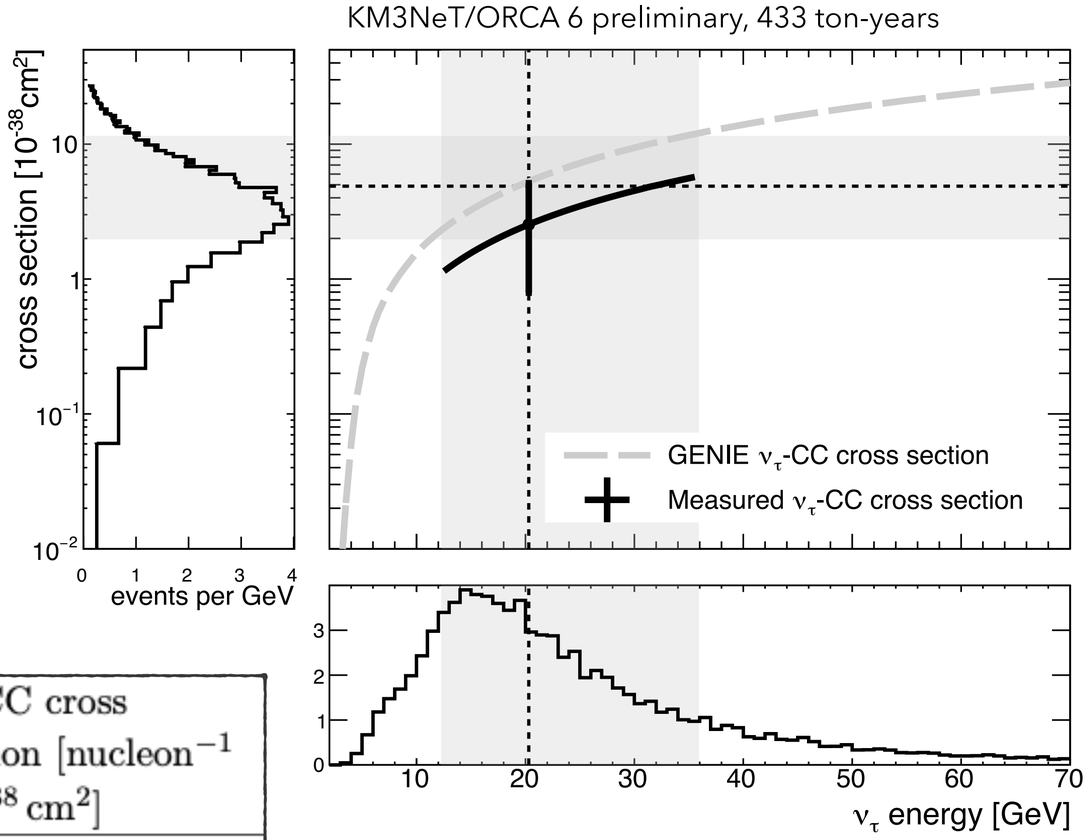


no statistically robust rejection of the 3ν-flavor paradigm

L. Cerisy, N. Geißelbrecht, C. Lastoria, JHEP 07 (2025) 213, e-print: 2502.01443

ν_τ-CC cross-section constraint

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



[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 $\pm$ 0.20
ORCA6 (this work)	water	$20.3^{-8.0}_{+15.6}$	92^{+90}_{-63}	$2.5^{+2.6}_{-1.8}$

L. Cerisy, N. Geißelbrecht, C. Lastoria, JHEP 07 (2025) 213, e-print: 2502.01443

Non-Unitary Neutrino Mixing (NUNM)

b) α_{33} : nxn unitarity matrix

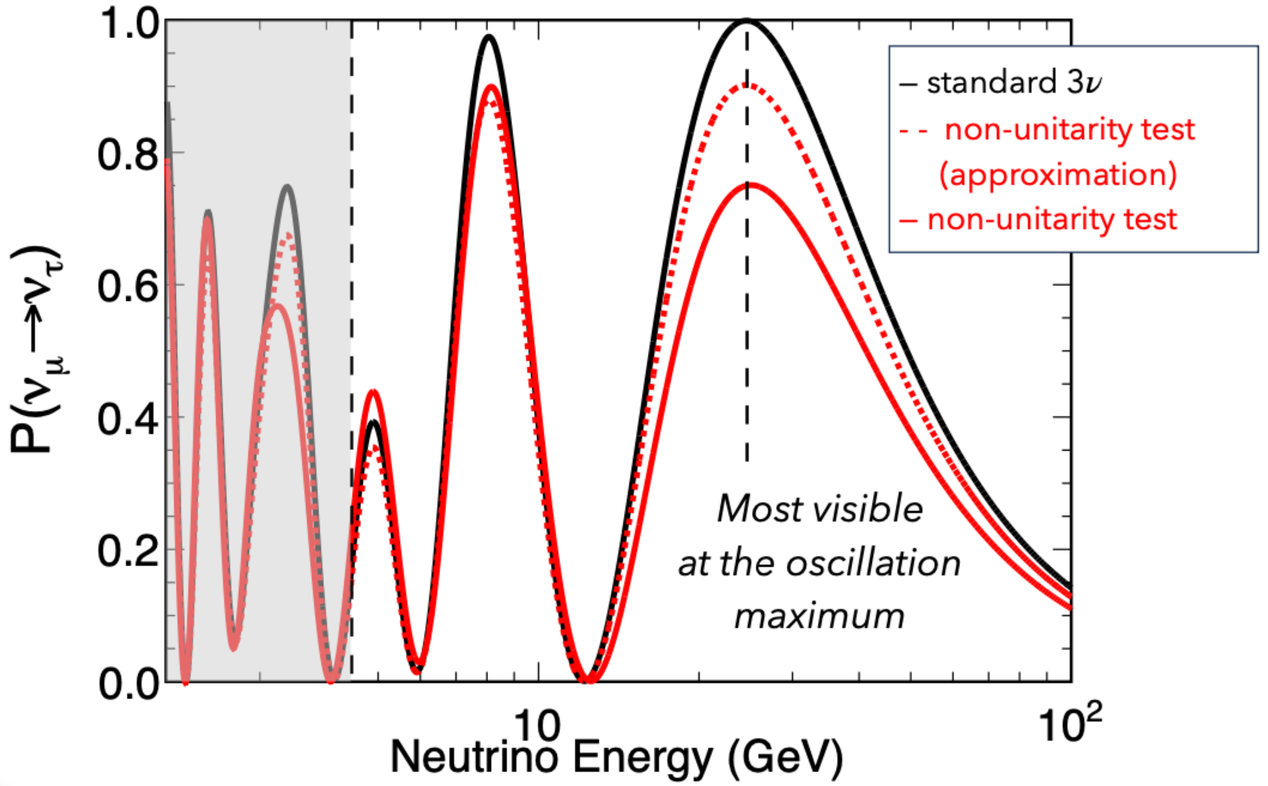
- **Heavy Neutral Leptons** (*seesaw* mechanism for neutrino masses generation)
- oscillation probabilities impacted by α_{33}

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

U_{PMNS} matrix

$$\begin{pmatrix} \alpha \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} & \begin{matrix} ? \\ [\ldots] \end{matrix} \\ \begin{matrix} ? & [\ldots] \end{matrix} & \end{pmatrix}$$

- **interaction also with neutrons in the Earth**
  (non-negligible V_{NC} potential)



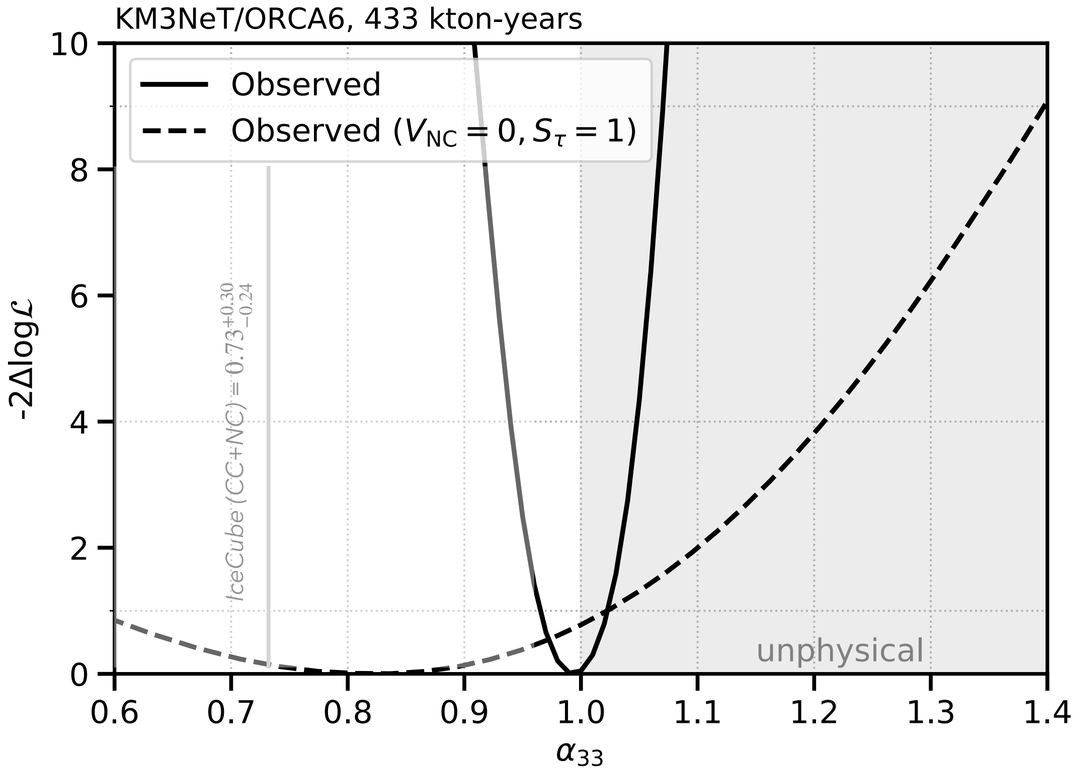
First test on atmospheric neutrinos data

L. Cerisy, N. Geißelbrecht, C. Lastoria, JHEP 07 (2025) 213, e-print: 2502.01443

Non-Unitary 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 =1)
n. of ν_τ-CC	132^{+60}_{-61}
n. of NC	313^{+11}_{-13}



L. Cerisy, N. Geißelbrecht, C. Lastoria, JHEP 07 (2025) 213, e-print: 2502.01443

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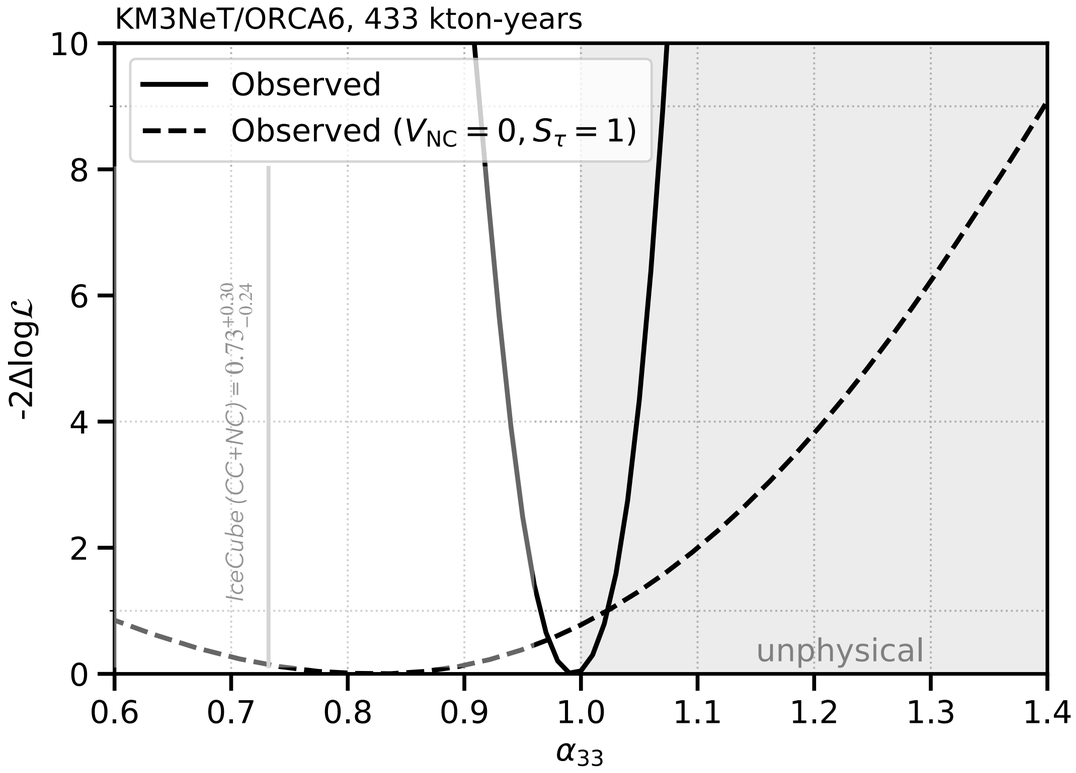
  - ❍ $\alpha_{33} = 0.993^{+0.026}_{-0.025}$ (otherwise)

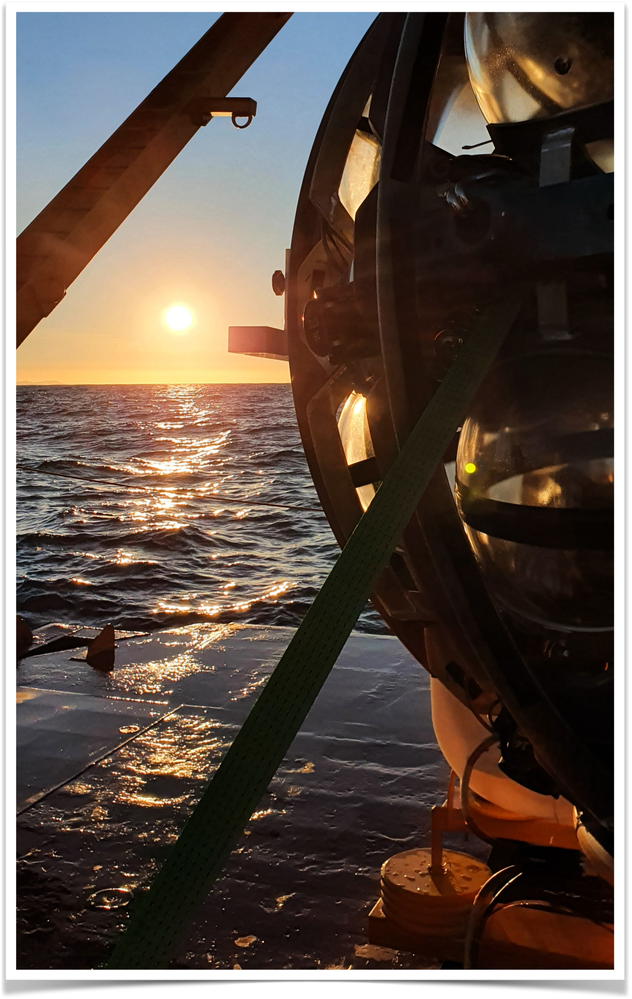
	(V_{NC}=0, S_τ =1)	(V_{NC}!=0, S_τ free)
n. of ν_τ-CC	132^{+60}_{-61}	170^{+5}_{-9}
n. of NC	313^{+11}_{-13}	325^{+1}_{-4}



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

L. Cerisy, N. Geißelbrecht, C. Lastoria, JHEP 07 (2025) 213, e-print: 2502.01443

Outline

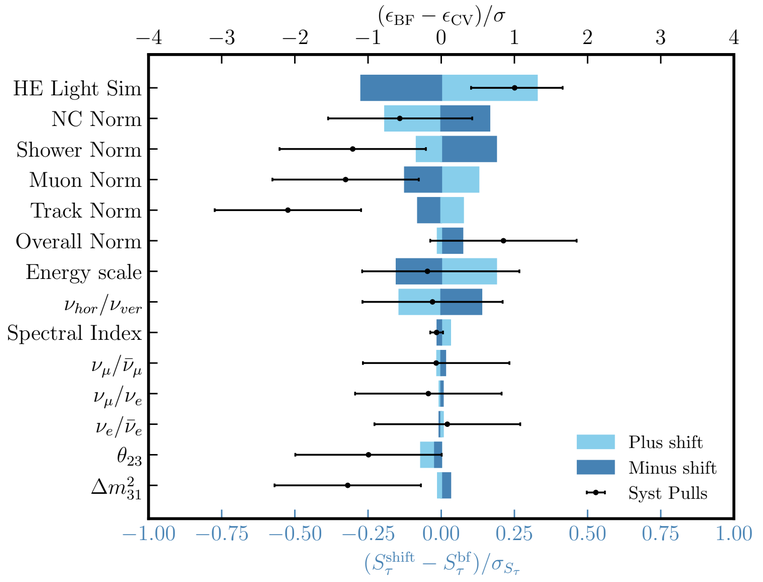


- **The role of neutrinos in astrophysics and particle physics**
  - ❍ neutrino telescopes in multi-messenger astronomy
  - ❍ open questions in neutrino oscillation physics
- **The KM3NeT experiment**
  - ❍ detection principle and technology
  - ❍ from installation to physics data
- **An unexpected *surprise*: the ultra-high energetic (UHE) neutrino**
- **First look at atmospheric neutrino oscillations in KM3NeT/ORCA data**
  - ❍ selection of the ν sample
  - ❍ ν_τ appearance analysis
  - ❍ neutrino mixing non-unitarity test
- **Summary and prospects**

Impact, limitations and prospects

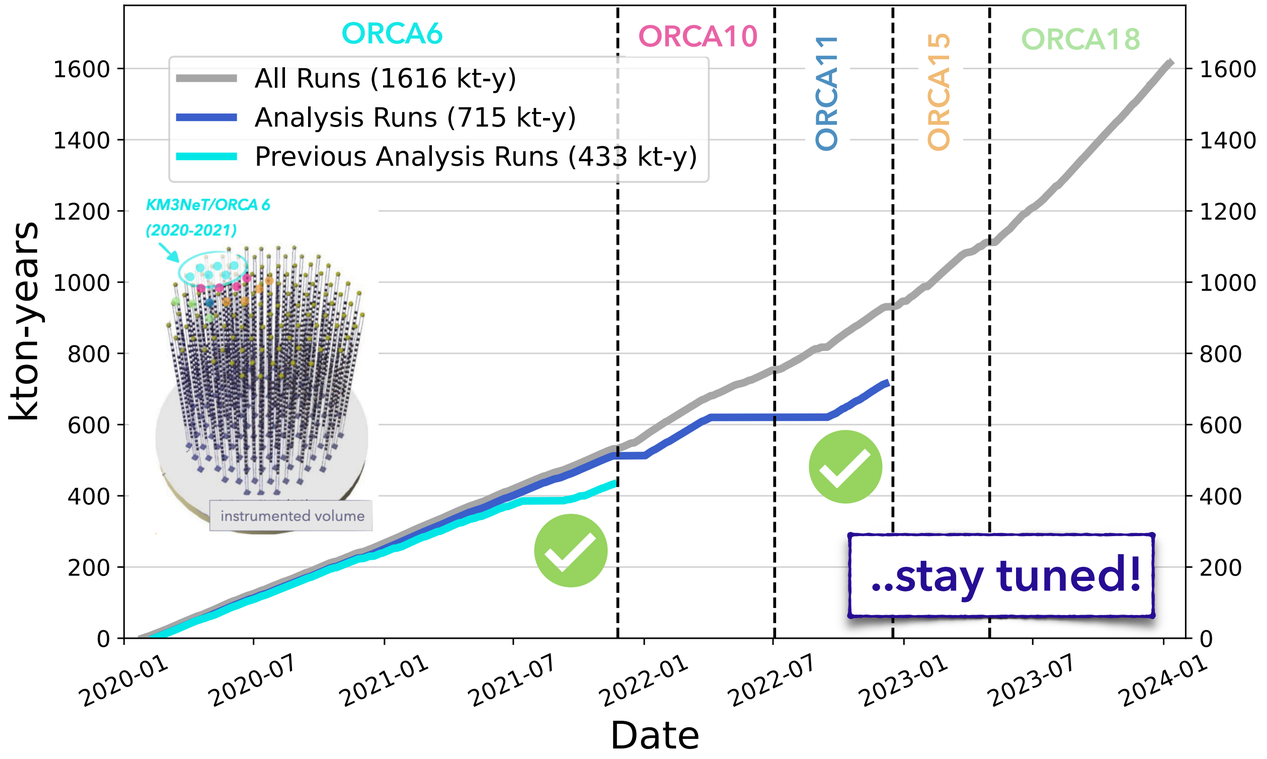
- Precise measurement of ν_τ **appearance** is a key study to deepen the understanding of neutrino properties
  - ❍ test the **3ν flavor paradigm**
  - ❍ **BSM non-unitarity extensions** and alternative seesaw mechanisms - Nucl.Phys.B 1013 (2025) 116853

- **Exploration of KM3NeT/ORCA 6 data demonstrated the experiment potential in the field**
  - ❍ comparable performance with other experiments in the standard 3ν flavor paradigm
  - ❍ **non-unitarity mixing matrix parameters in the atmospheric sector**
    - is a key measurement to evaluate the **impact of non-unitarity on oscillation probabilities** - Nucl.Phys.B 1017 (2025) 116944
    - KM3NeT measurement is leading the **current world-wide best limit on α_{33}**
  - ❍ ORCA6 pointed out some **limitations in the set of systematics used both in standard and NUNM analyses**



Impact, limitations and prospects

- **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 and ν_τ tagging)
- **extend current set of systematics** and **fit methods** (e.g. Bayesian approach)
  - ❍ better understanding of the detector response
  - ❍ enhanced purity of the shower class



Wrapping up and outlook

- **Neutrinos are unique *messengers* able to bridge astroparticle and particle physics**
  - ❍ neutrino telescopes allows for exploring our Universe over very large distances
  - ❍ focusing on atmospheric neutrinos, these telescopes allows to answer crucial questions in oscillation physics

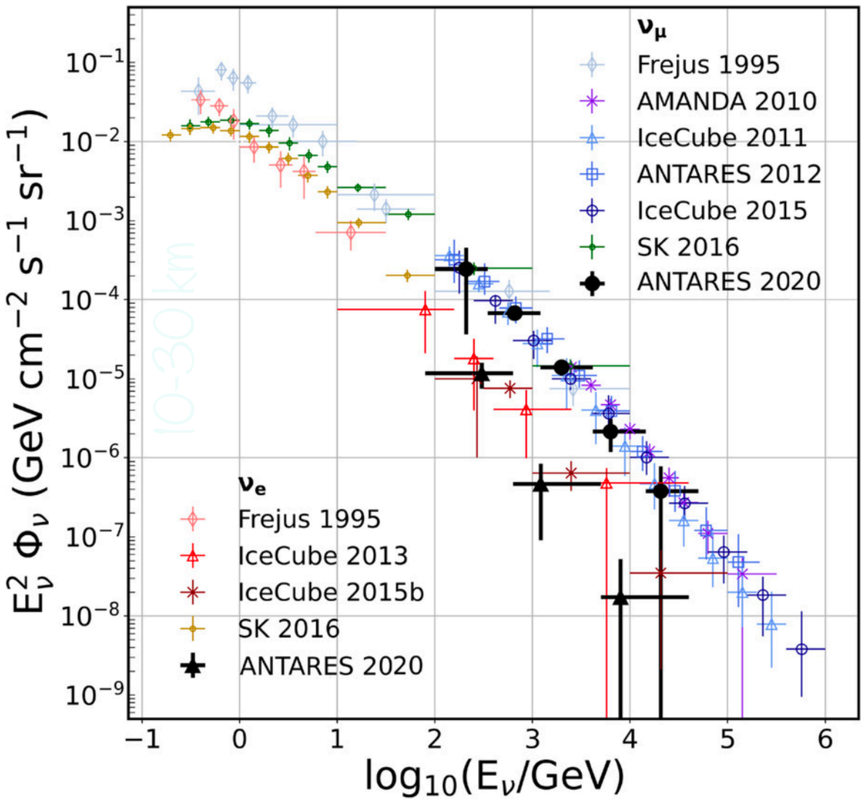
- Thanks to its active volume, **KM3NeT will exploit an unprecedented statistics**
  - ❍ data collected in other configurations are being analysed
  - ❍ **ARCA** has shown its enormous potential to cover a central player in **multi-messenger astronomy**
  - ❍ **ORCA** is ready to aim at measuring the **neutrino mass ordering**

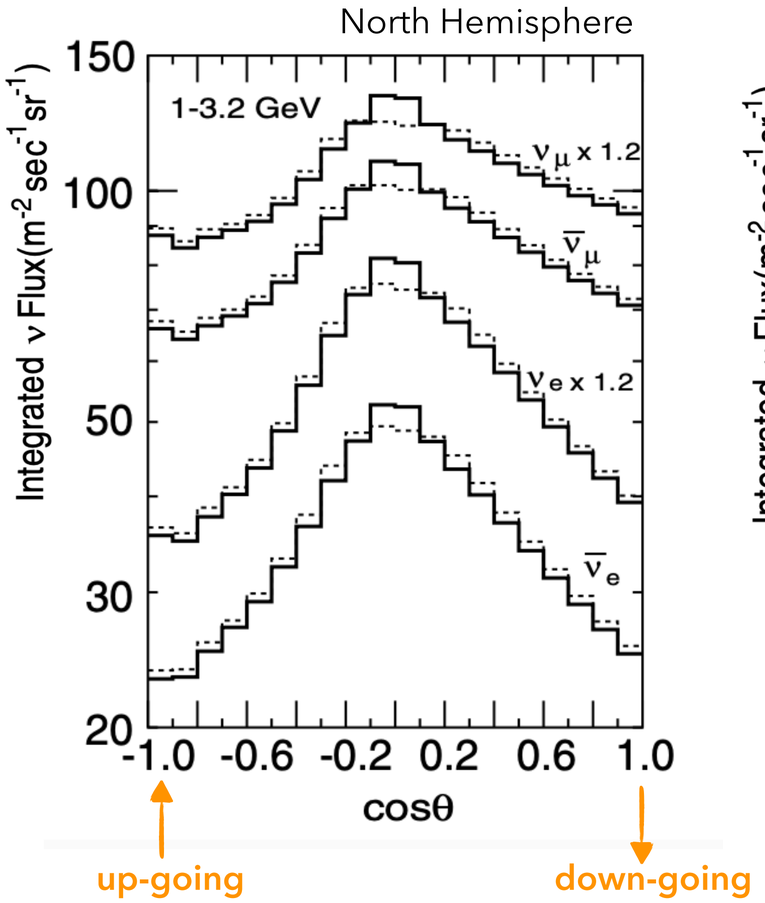
...thanks a lot for your attention !

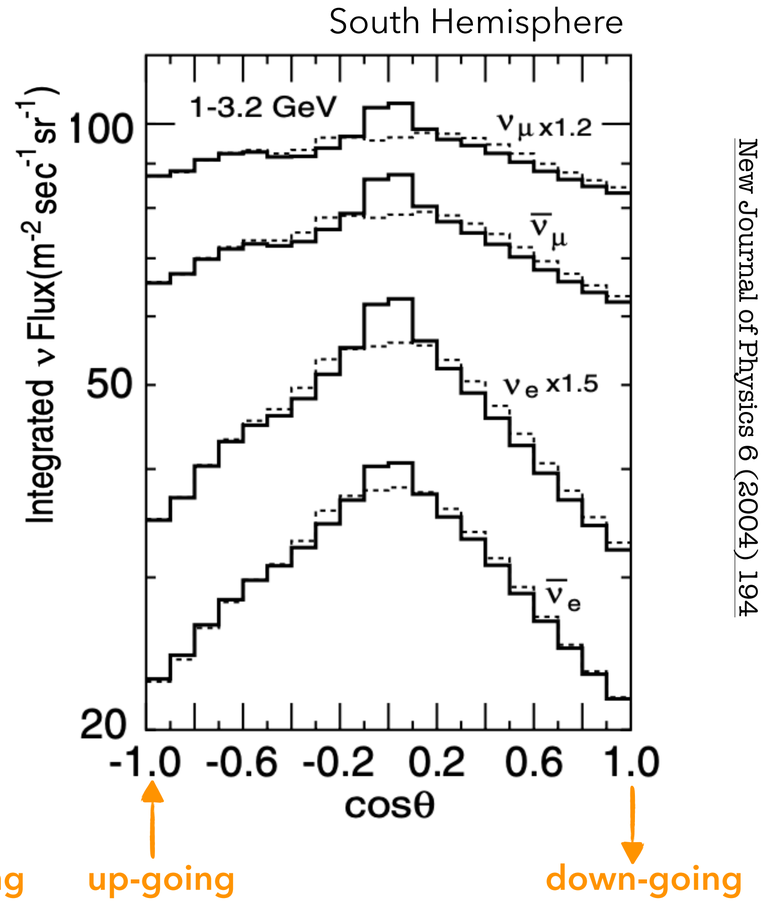
BONUS SLIDES

Atmospheric neutrino flux

Physics Letters B 816 (2021) 136228



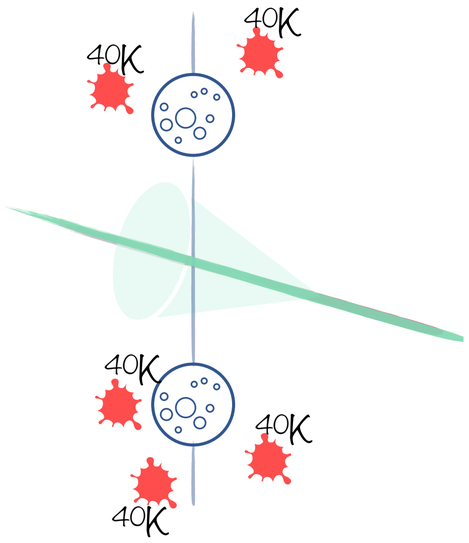


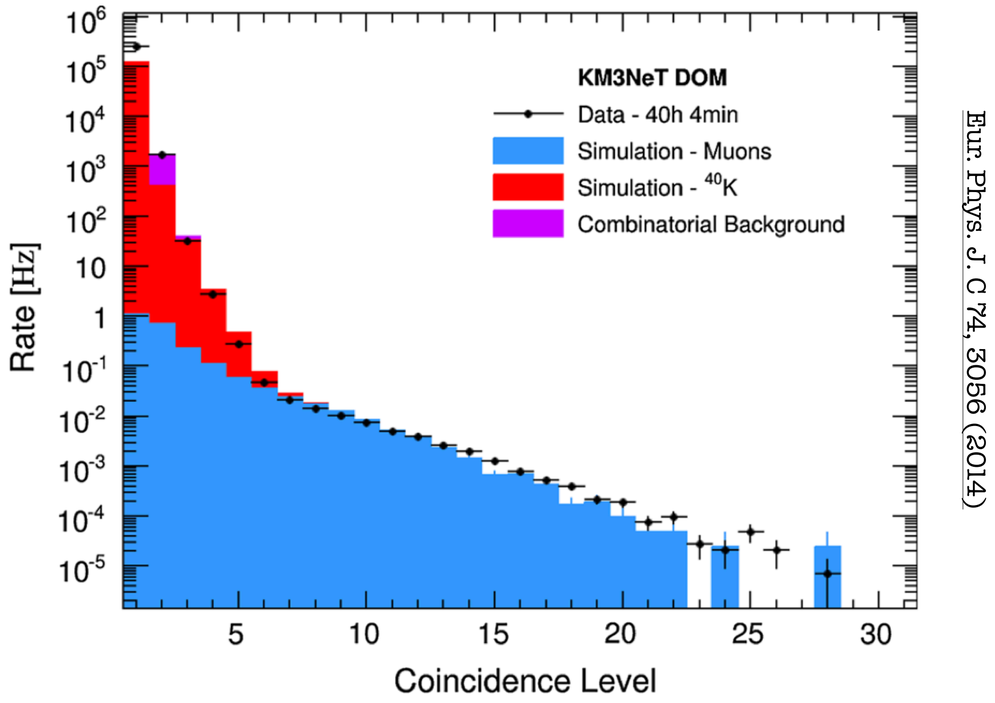


New Journal of Physics 6 (2004) 194

Optical noise background

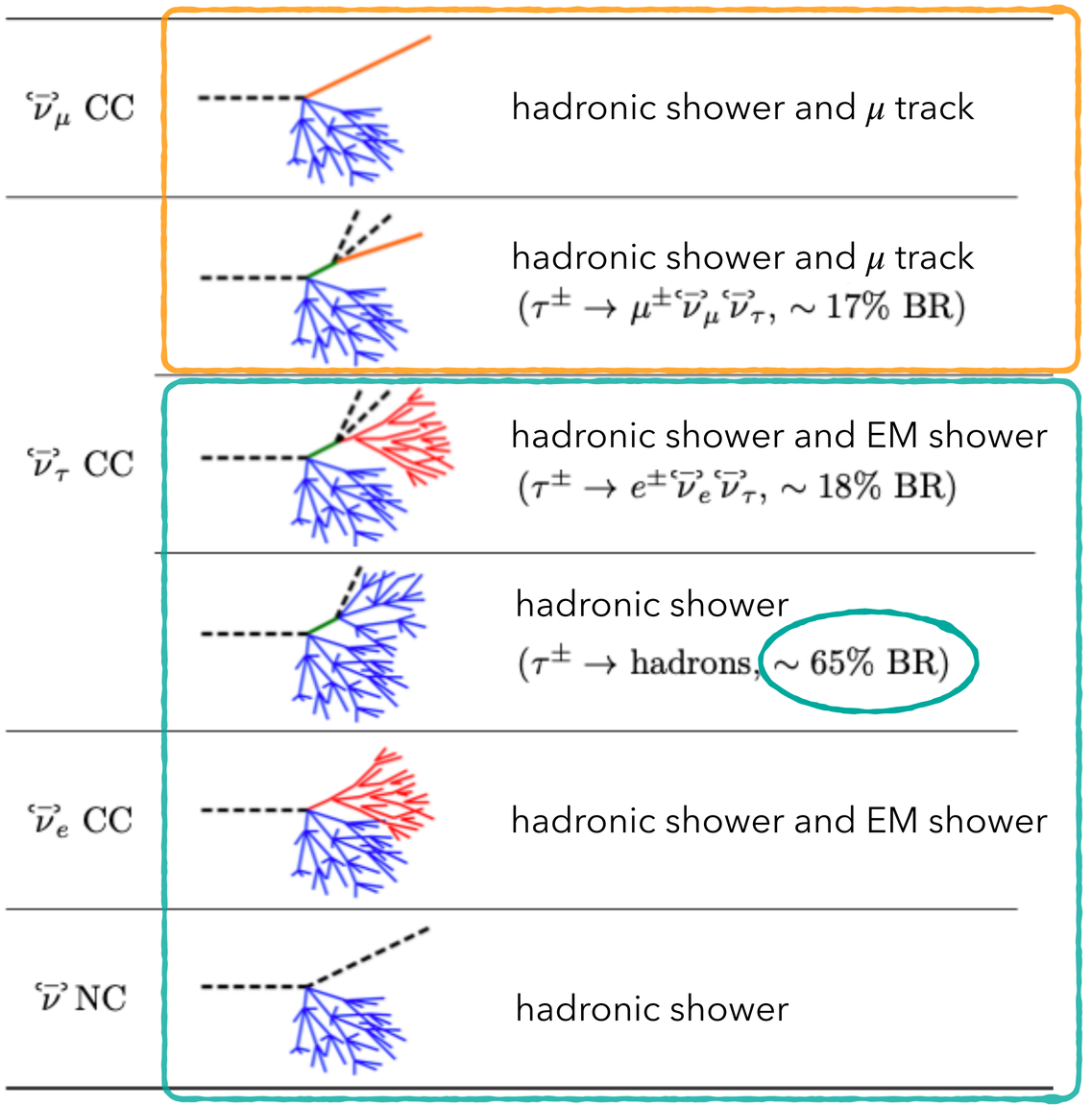
- count rate dominated by ^{40}K decays, PMT dark counts, bioluminescence:
  ~8kHz uncorrelated single-hits, 340 Hz two-hits coincidence/PMT, ~a few Hz including hit causality





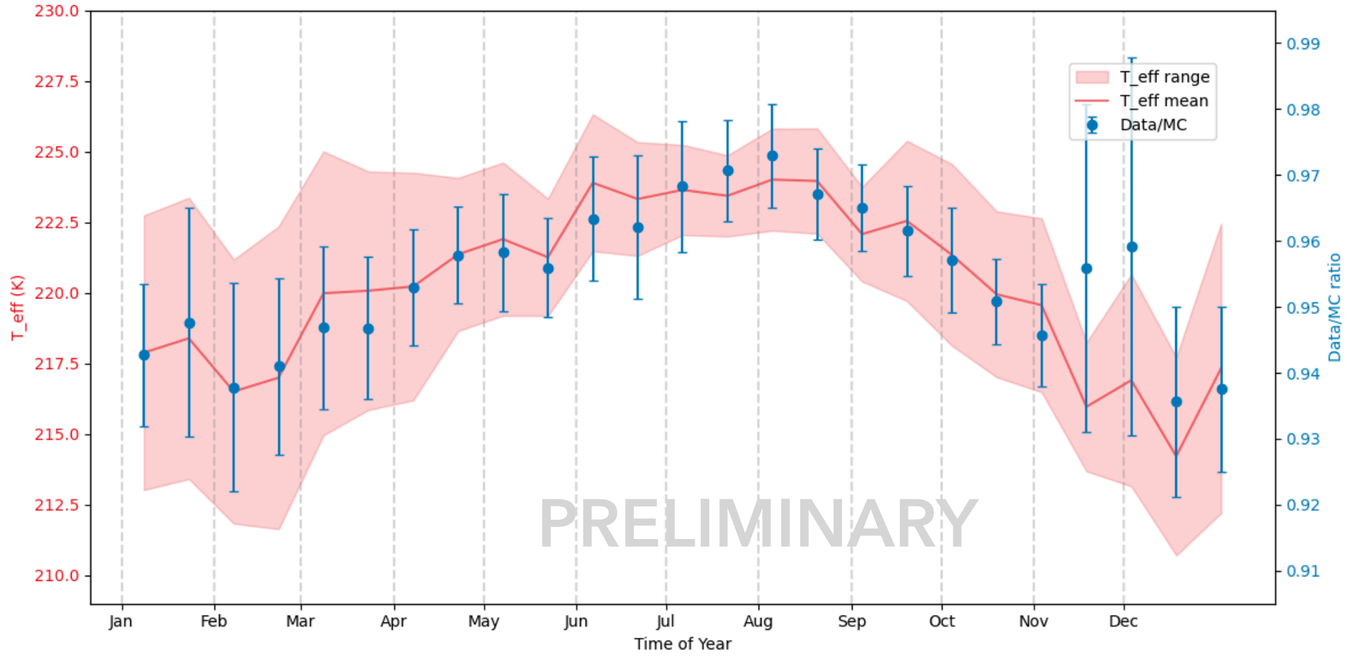
Eur. Phys. J. C 74, 3056 (2014)

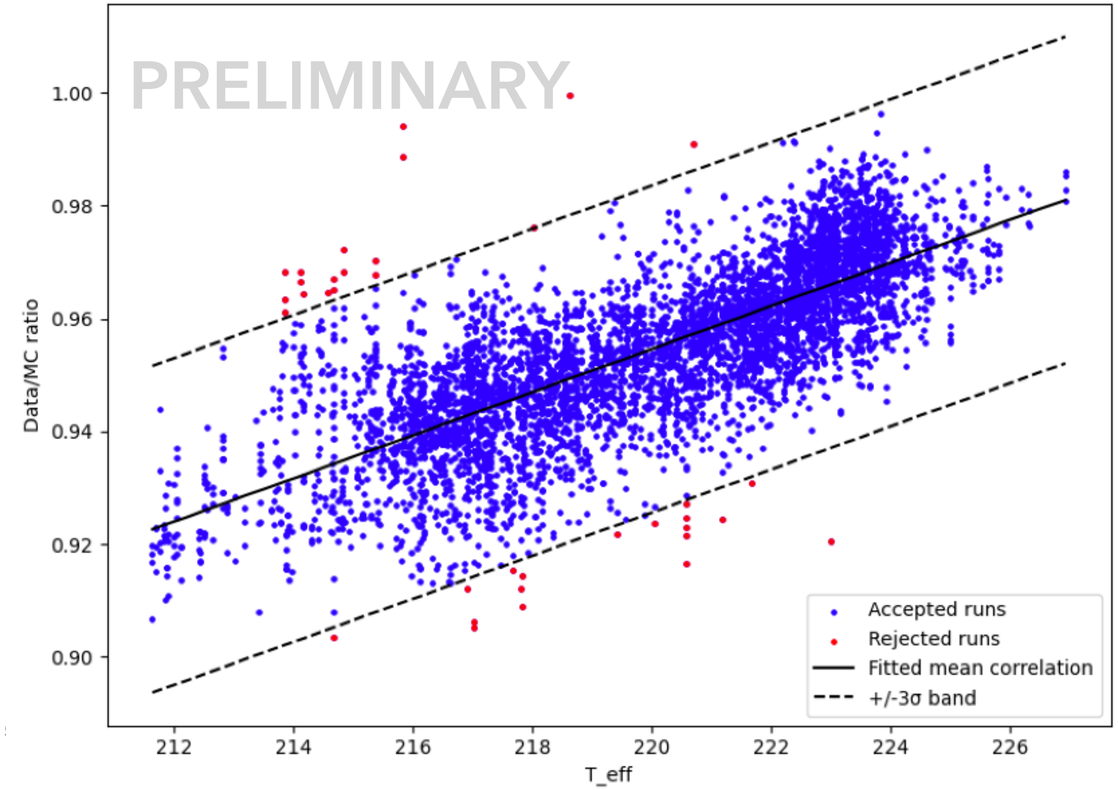
Reconstructed topologies



Data Quality workflow

~ 4 years of data taking in ORCA configurations: 6 to 18 DUs

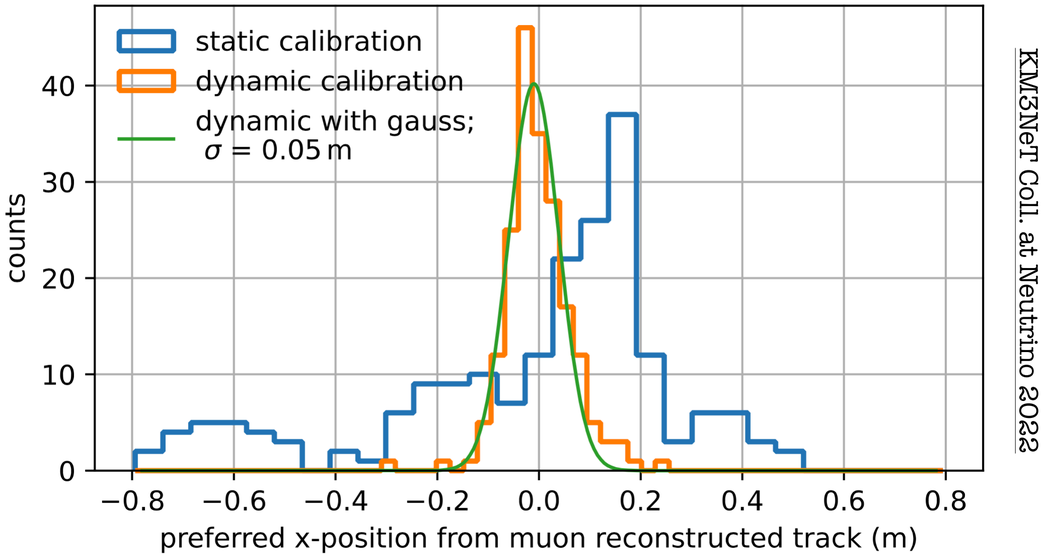




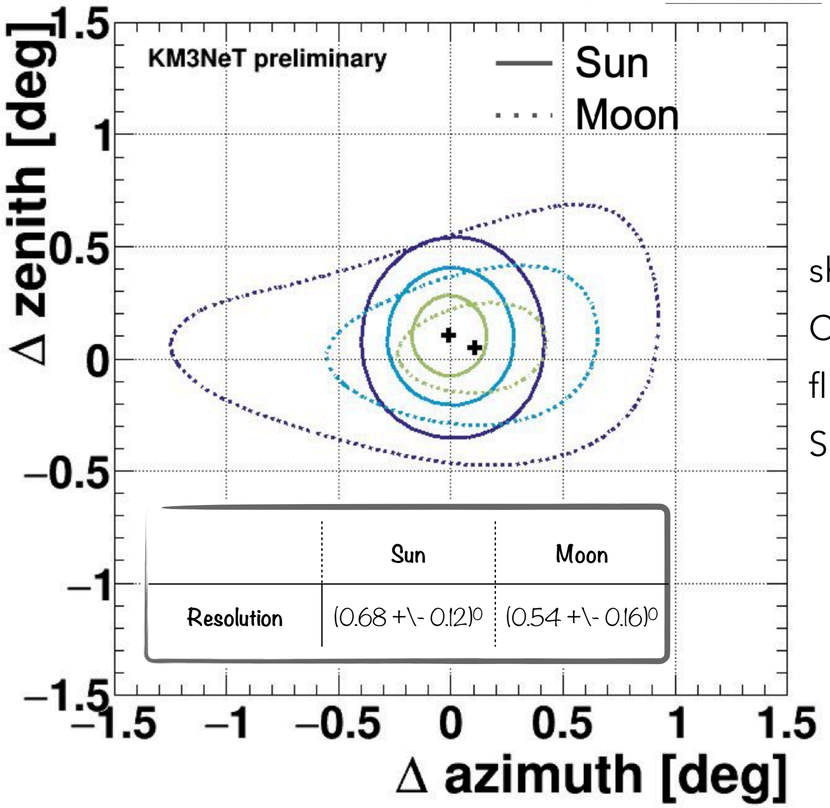
Event reconstruction in KM3NeT/ORCA 6

- **DU calibration** allows for **precise alignment measurement**
- detector **resolution in track reconstruction < 1 degree** (important for pointing)

< 10 cm resolution possible with dynamic calibration



arXiv: 2211.08977



shadow in the CR flux due to the Sun and Moon

Full KM3NeT/ORCA reconstruction performance

- Sensitivity to event **reconstruction performance**
  - ❍ **up to 5° resolution** for both topologies
  - ❍ **linear energy estimation** in the full energy range

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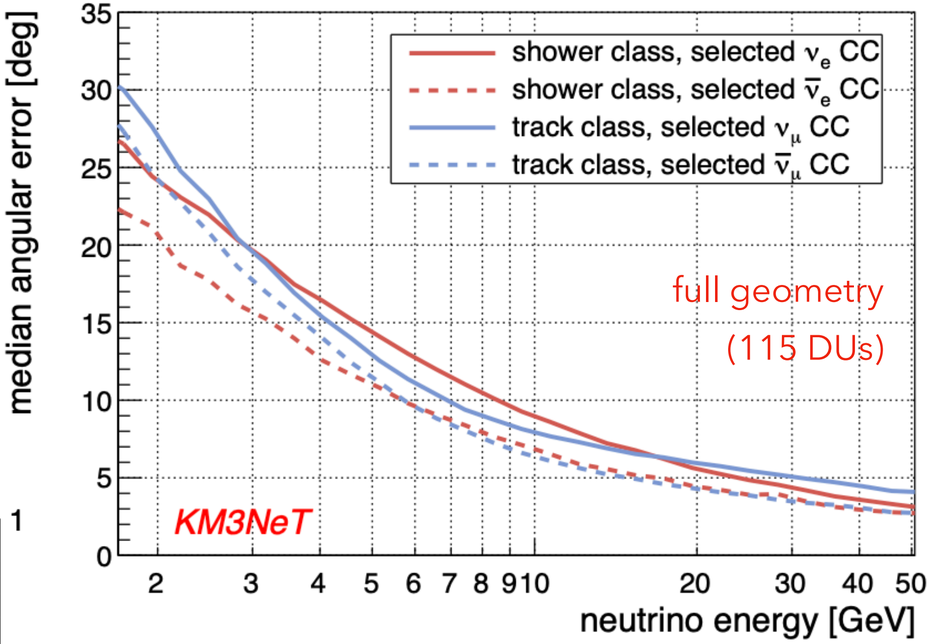
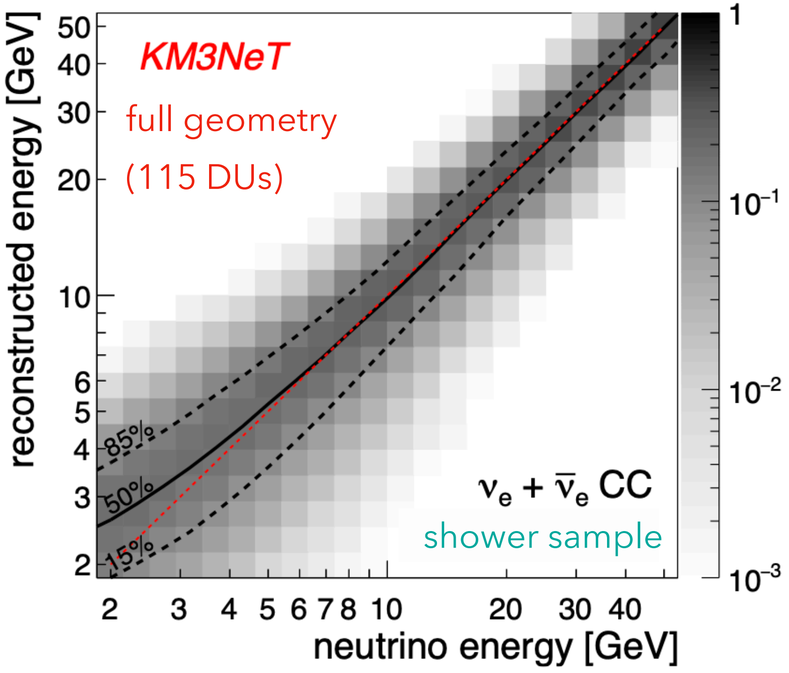
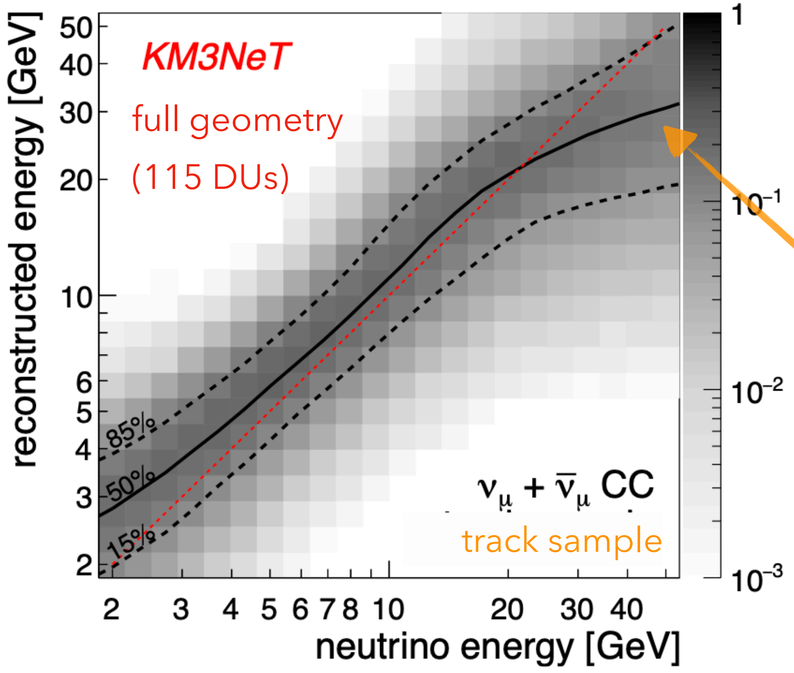


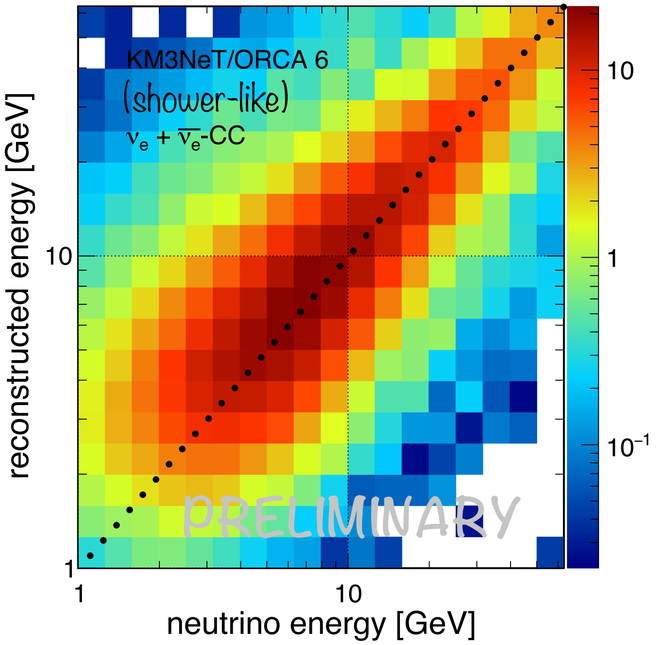


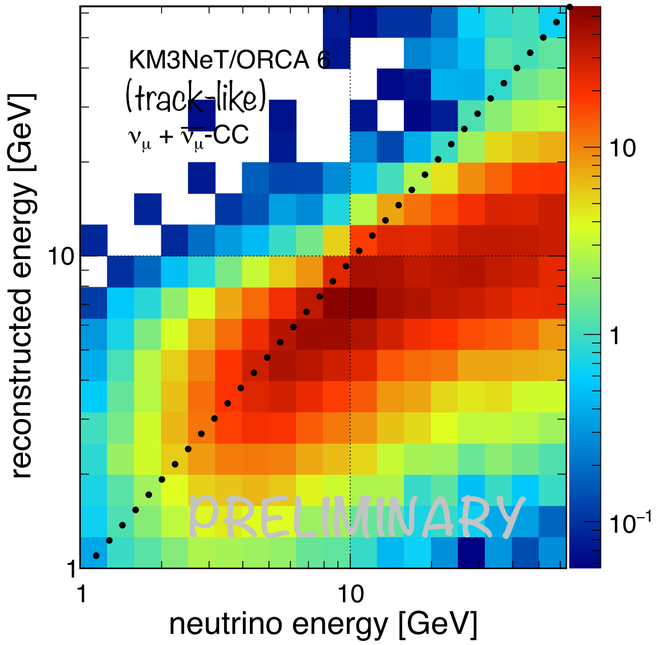


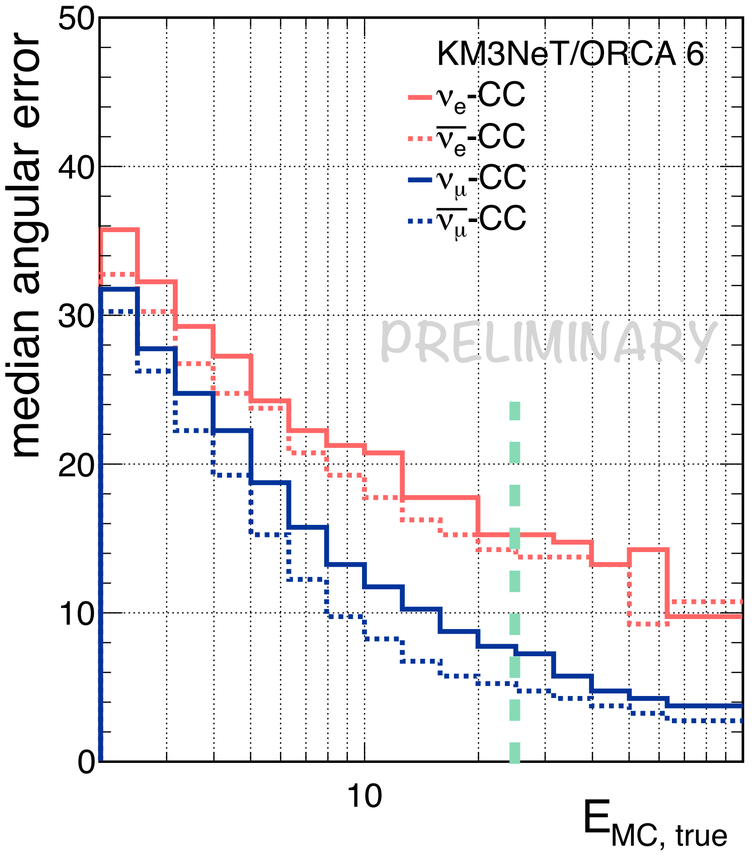
very elongated events (real int. vertex, outside the instrum. vol.)

The shower topology reconstruction

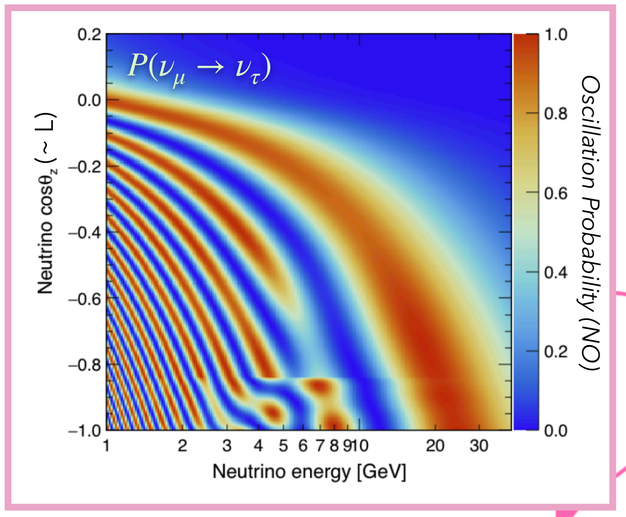
- new shower reconstruction algorithm using **single-PMT information** (instead of single-DOM)
  - ❍ intrinsic limitation in angular shower resolution in small geometries
  - ❍ overall linear energy estimation for both topologies
  - ❍ overall good data/MC comparison for both algorithms

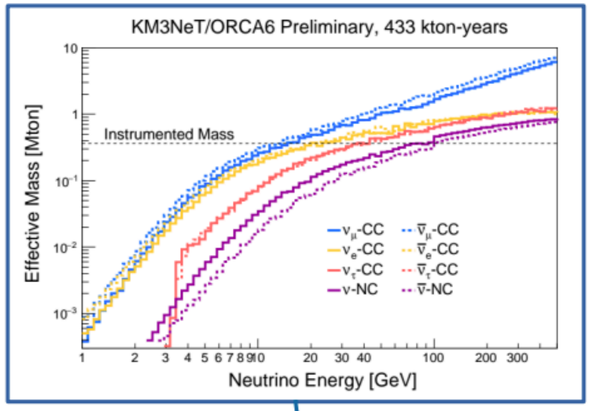






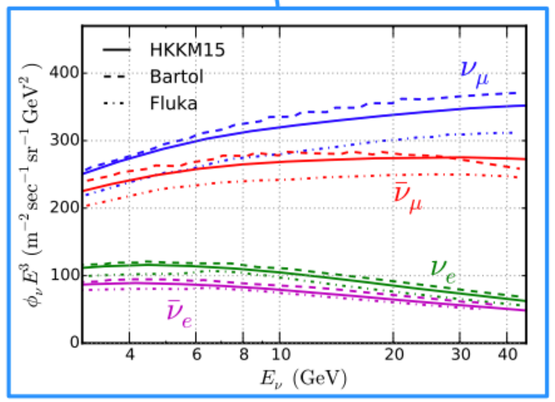
Analysis method



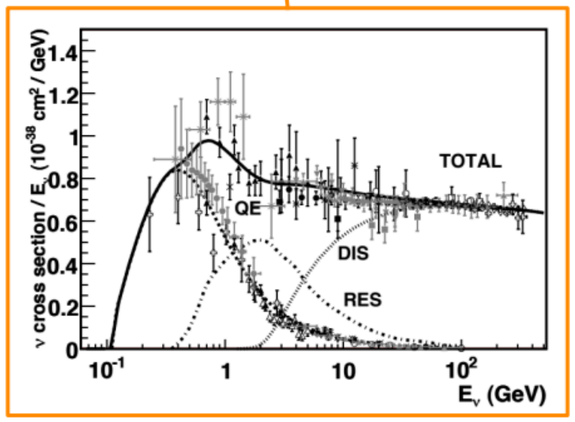


$$-2\log\mathcal{L} = \sum_i 2\left[\left(\beta_i N_i^{\mathrm{mod}} - N_i^{\mathrm{dat}}\right) + N_i^{\mathrm{dat}} \ln\left(\frac{N_i^{\mathrm{dat}}}{\beta_i N_i^{\mathrm{mod}}}\right)\right] + \frac{(\beta_i - 1)^2}{\sigma_{\beta_i}^2} + \sum_k \left(\frac{\epsilon_k - \langle\epsilon_k\rangle}{\sigma_{\epsilon_k}}\right)^2$$

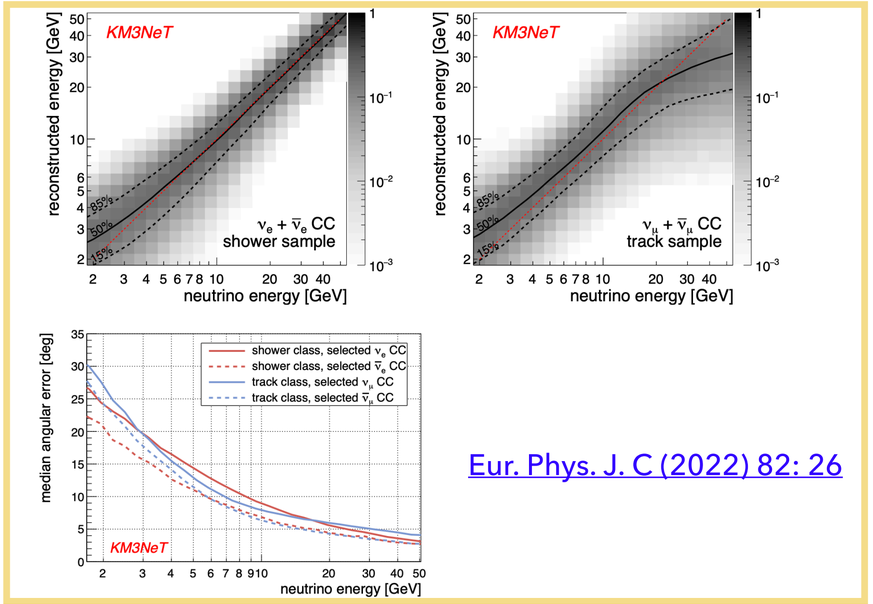
$$\phi_{atm}^{\nu_y}(E_t, \theta_t) \times P_{\nu_y \to \nu_x}(E_t, \theta_t) \times \sigma_{\nu_x}(E_t) \times M_{eff}^{\nu_x}(E_t) \times R_i(E_t, \theta_t, \nu_x, E_r, \theta_r)$$



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



Rev. Mod. Phys. 84, 1307



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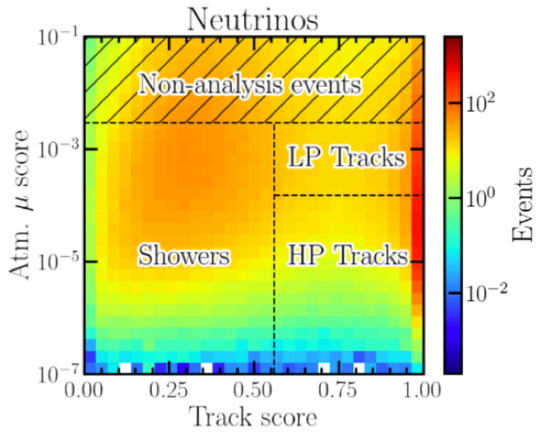
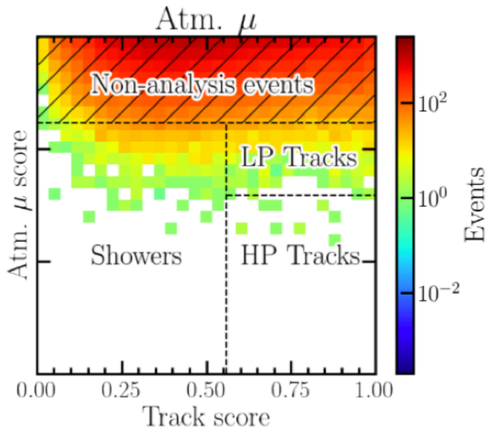
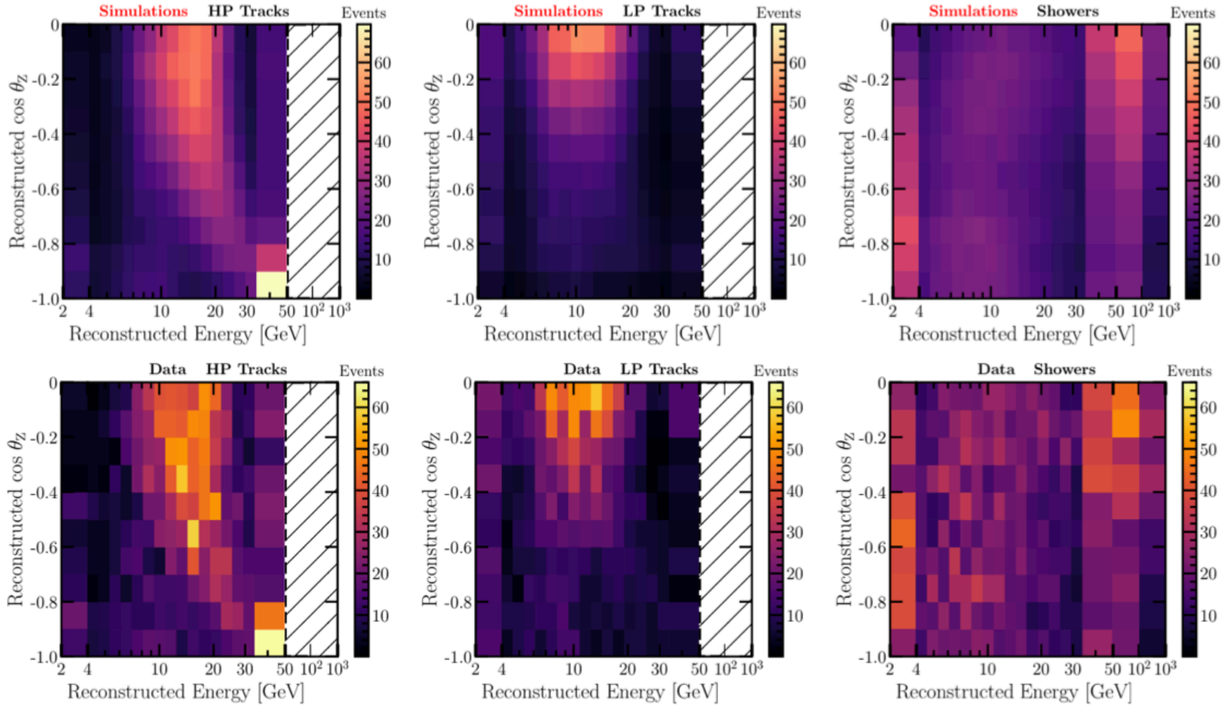
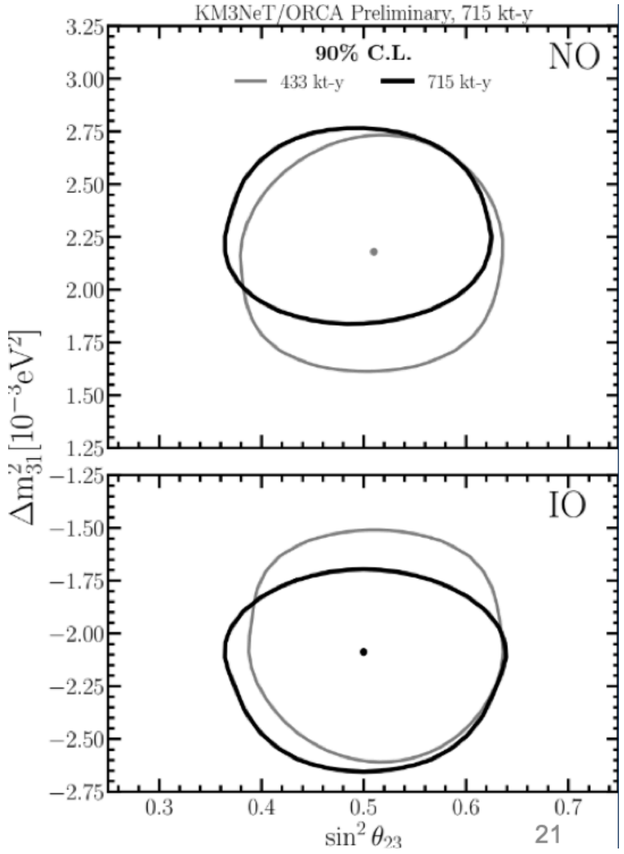
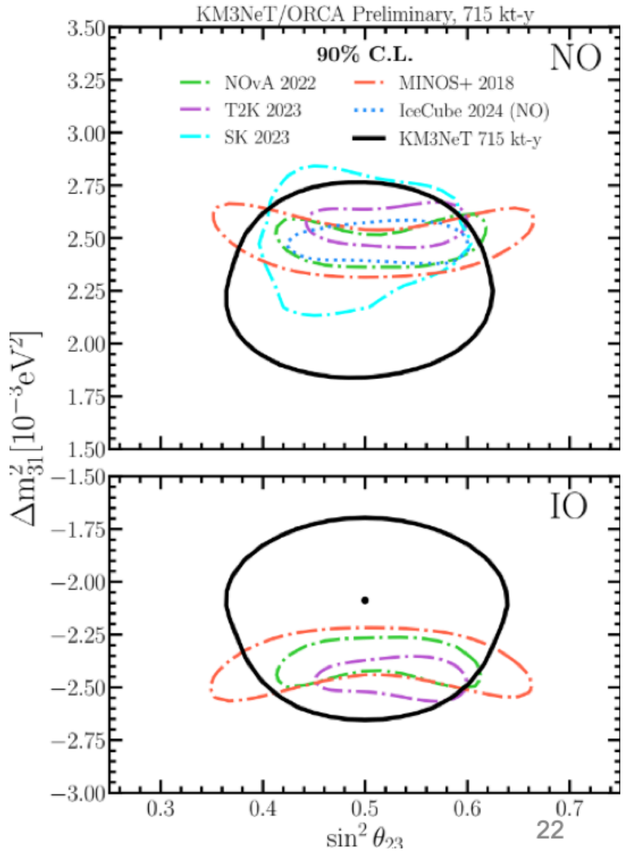
Neutrino oscillation parameters in KM3NeT/ORCA 715 kton-years









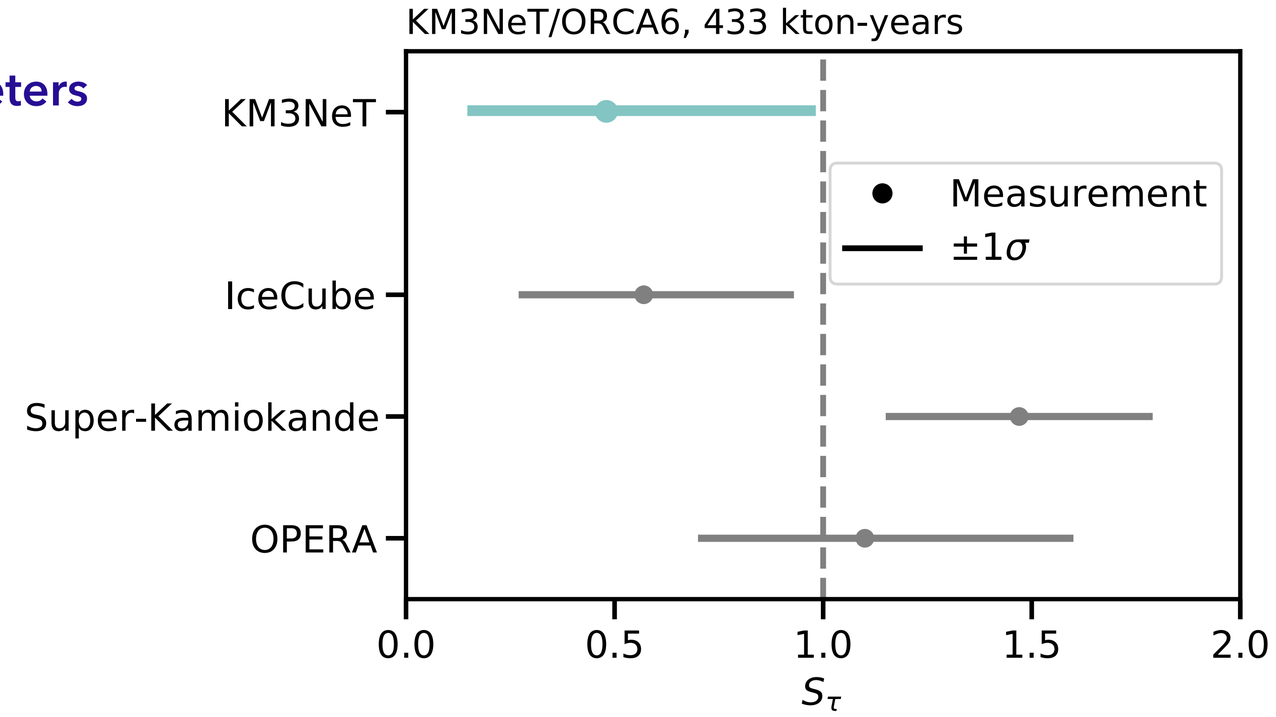


$$\Delta m^2_{31} = \begin{cases} -2.09^{+0.17}_{-0.21} \times 10^{-3}\text{eV}^2, & \text{IO} \\ [2.10, 2.37] \times 10^{-3}\text{eV}^2, & \text{NO} \end{cases}$$

$$\sin^2\theta_{23} = 0.50 \pm 0.07$$

Complementarity among experiments

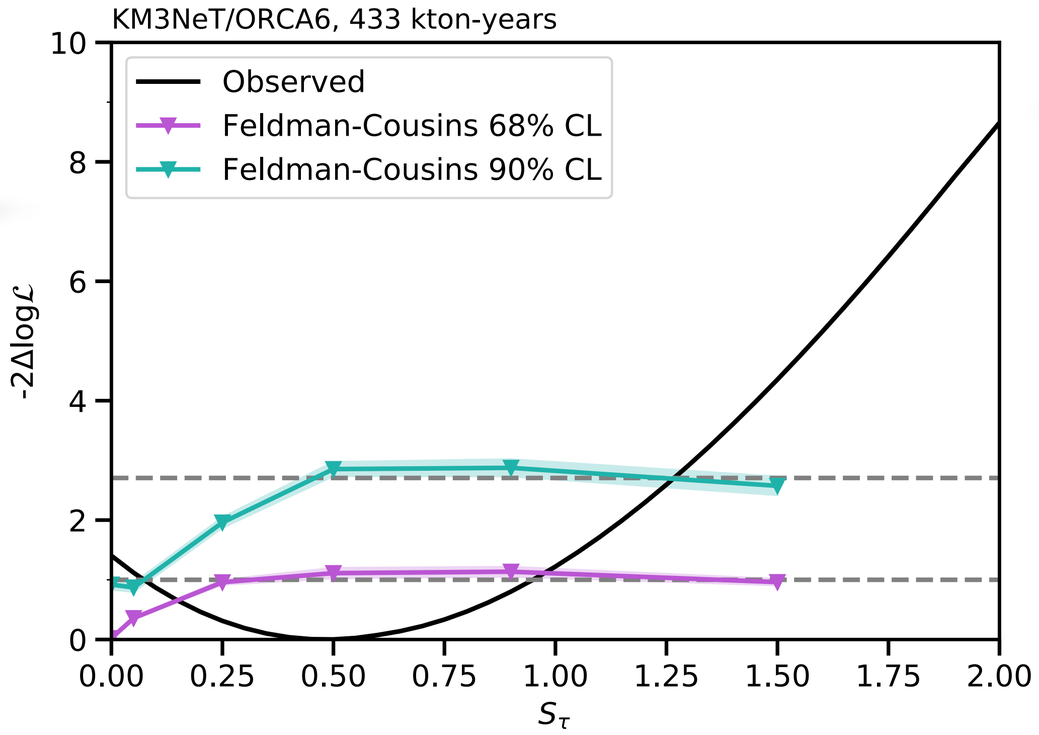
- **neutrino energy and source**
  - ❍ SuperKamiokande, IceCube, KM3NeT/ORCA: atmospheric neutrinos at ~25 GeV
  - ❍ OPERA: beam neutrinos <20 GeV
- **identification techniques**
  - ❍ IceCube, KM3NeT/ORCA: no direct ν_τ identification
  - ❍ SuperKamionaknde: ML techniques for $\nu_\tau/\bar{\nu}_\tau$ classification in the show sample
  - ❍ OPERA: direct tagging and $\nu_\tau/\bar{\nu}_\tau$ separation
- **fit method and sensitivity to other oscillation parameters**



ν_τ-normalization fit in the 3ν-flavor paradigm

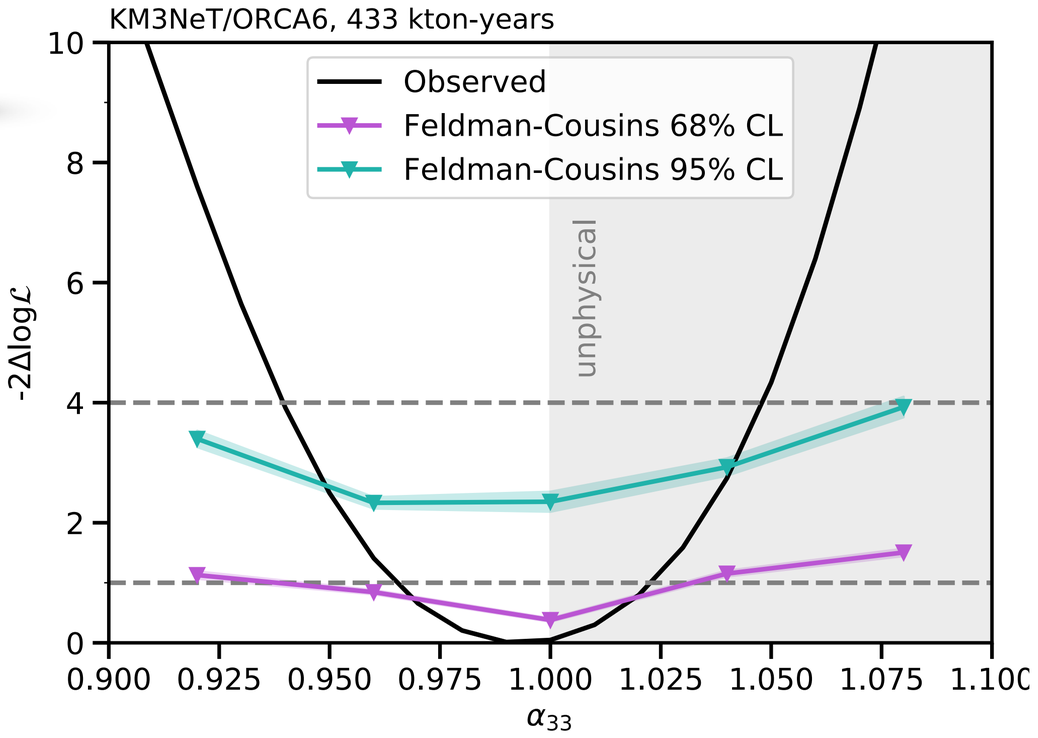
S_τ : PMNS unitarity hypothesis

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



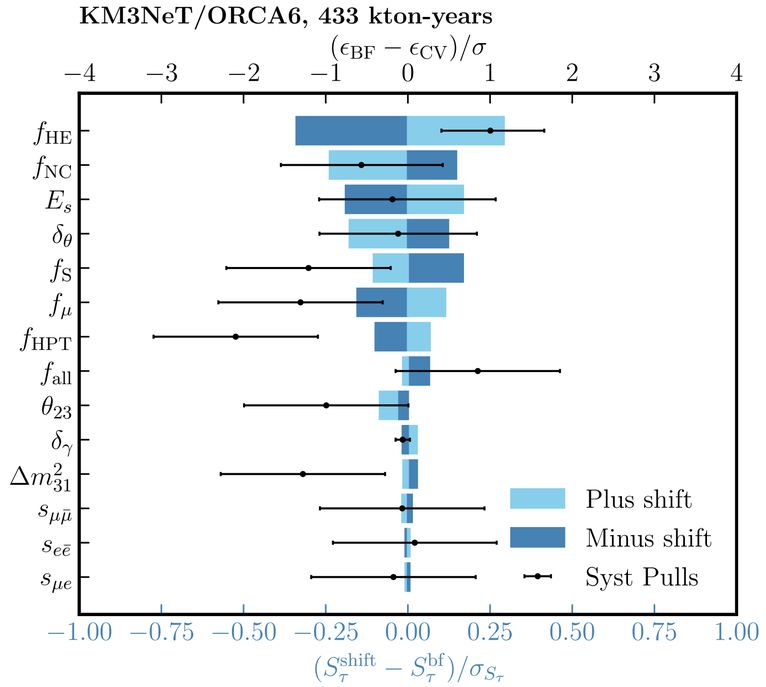
α_{33} : non-unitarity mixing

- 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

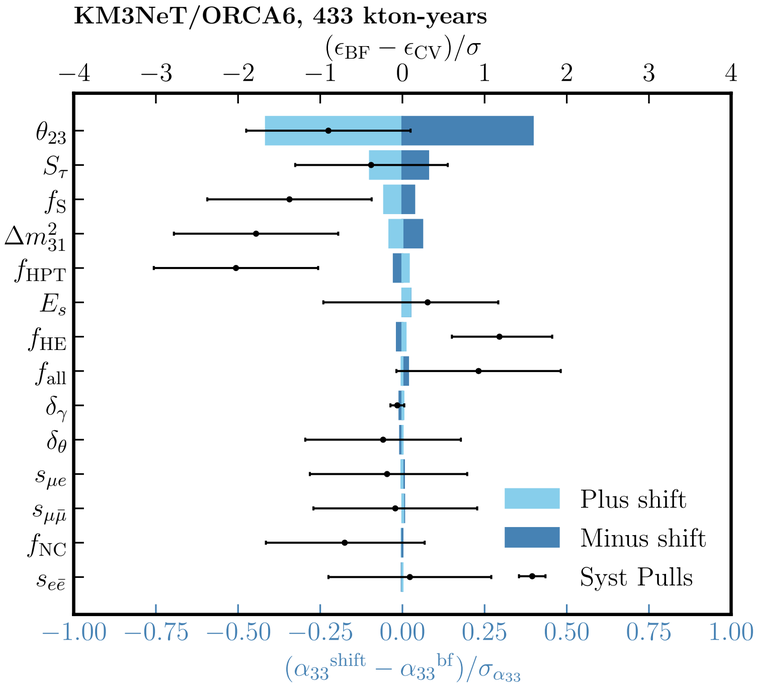


L. Cerisy, N. Geißelbrecht, C. Lastoria, arXiv:2502.01443

ν_τ-normalization and systematic uncertainties



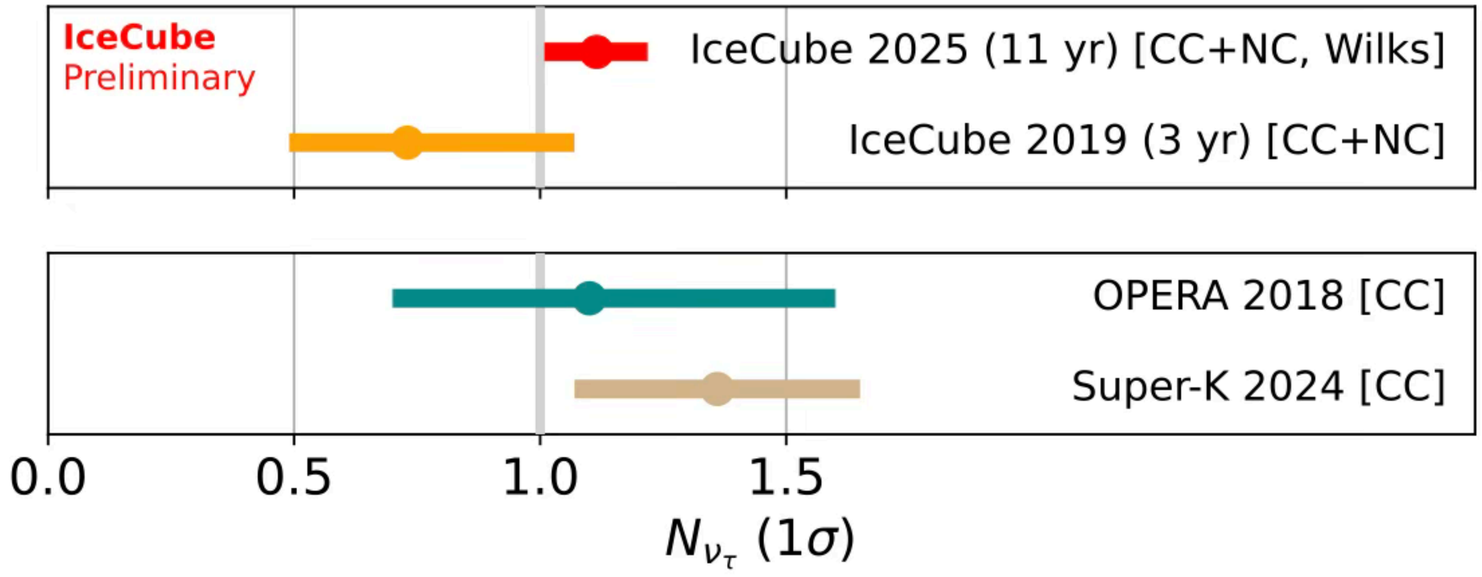
Systematic uncertainty	S_τ $\epsilon \pm 1\sigma$	α_{33} $\epsilon \pm 1\sigma$
θ_{23}	46^{+4}_{-4}	46^{+4}_{-4}
Δm^2_{31} $[10^{-3}\,\mathrm{GeV}^2]$	$2.15^{+0.29}_{-0.28}$	$2.18^{+0.19}_{-0.35}$
δ_γ	$-0.019^{+0.027}_{-0.026}$	$-0.019^{+0.02}_{-0.02}$
δ_θ	$-0.002^{+0.019}_{-0.019}$	$-0.005^{+0.01}_{-0.01}$
$s_{\mu\bar{\mu}}$	$0.00^{+0.05}_{-0.05}$	$0.00^{+0.05}_{-0.05}$
$s_{e\bar{e}}$	$0.01^{+0.07}_{-0.07}$	$0.01^{+0.07}_{-0.07}$
$s_{\mu e}$	$-0.004^{+0.020}_{-0.020}$	$-0.004^{+0.02}_{-0.01}$
f_{NC}	$0.89^{+0.20}_{-0.20}$	$0.86^{+0.19}_{-0.19}$
E_s	$0.98^{+0.11}_{-0.08}$	$1.03^{+0.08}_{-0.11}$
f_{HE}	$1.50^{+0.33}_{-0.30}$	$1.59^{+0.32}_{-0.29}$
f_{all}	$1.09^{+0.17}_{-0.11}$	$1.11^{+0.11}_{-0.12}$
f_{HPT}	$0.91^{+0.04}_{-0.04}$	$0.92^{+0.04}_{-0.04}$
f_S	$0.92^{+0.06}_{-0.06}$	$0.92^{+0.06}_{-0.06}$
f_μ	$0.5^{+0.44}_{-0.4}$	$0.51^{+0.4}_{-0.35}$
S_τ	PoI	$0.92^{+0.19}_{-0.18}$



ν_τ-normalization, latest result from IceCube

- increased statistics: 11 years of data (~4 times the previous analysis)
- improved event selection and classification (deep learning techniques)
- enhanced understanding and treatment of ν_τ simulation and cross-section

NuFact 2025, D. Koskinen

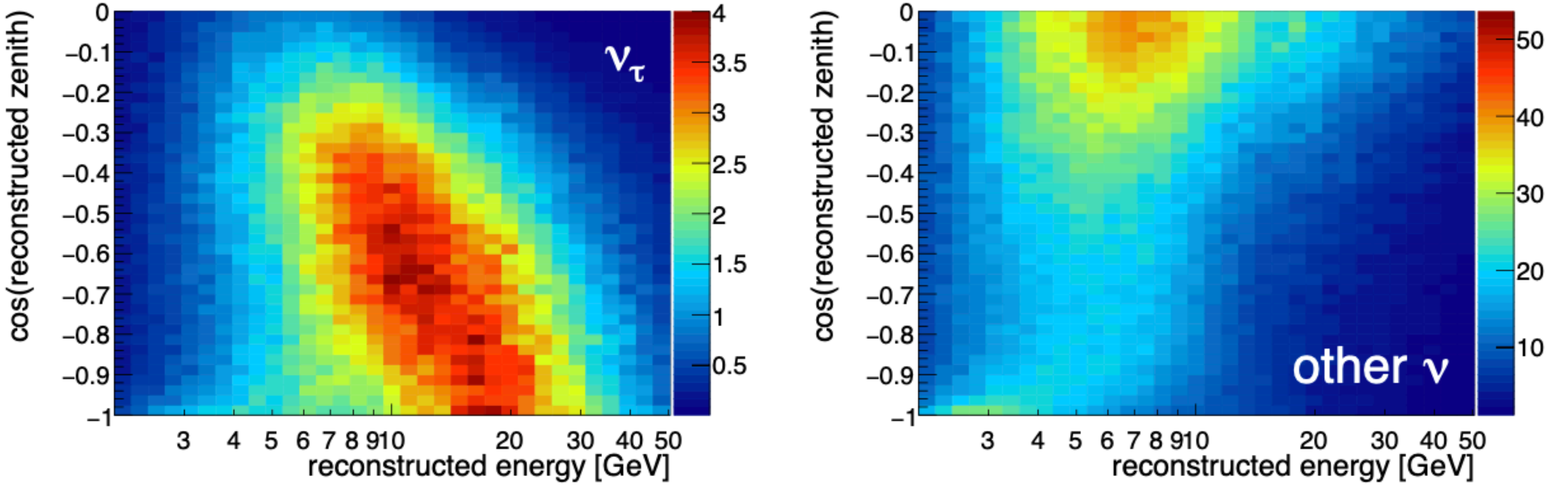


Sensitivity to ν_τ-appearance in full KM3NeT/ORCA

- 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)



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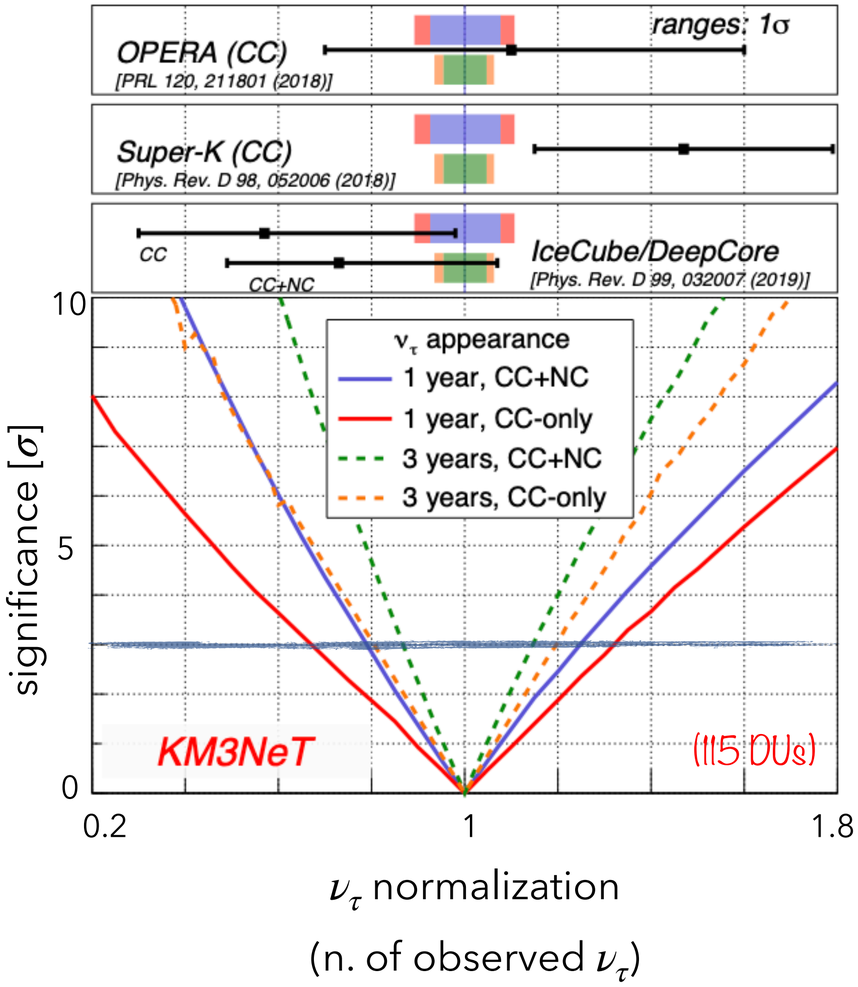
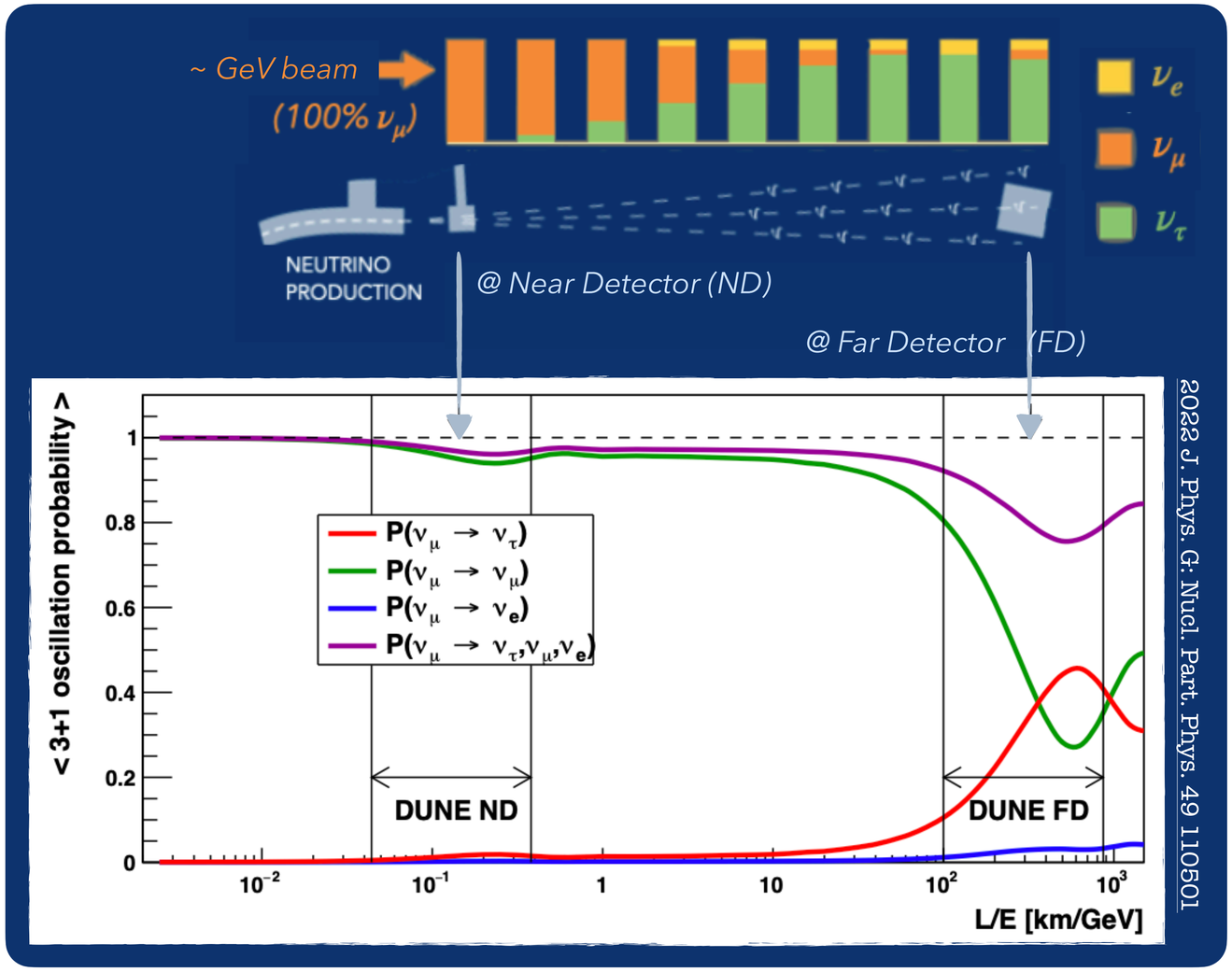


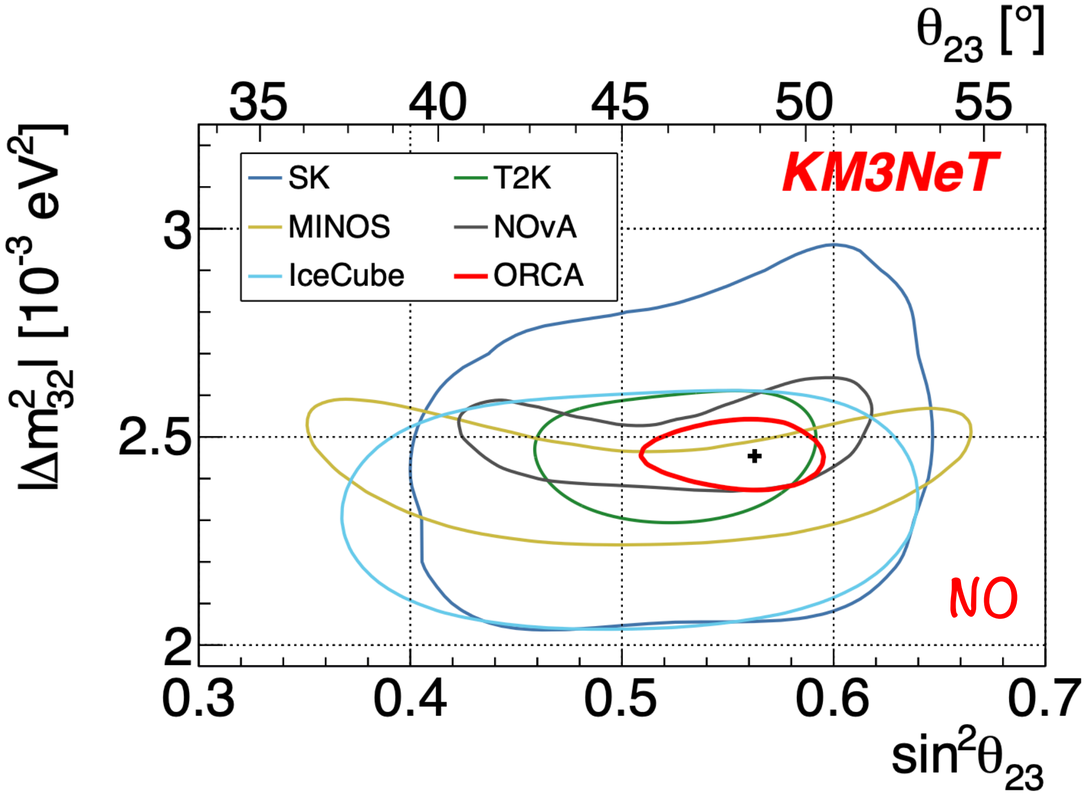
The ν_τ-appearance channel

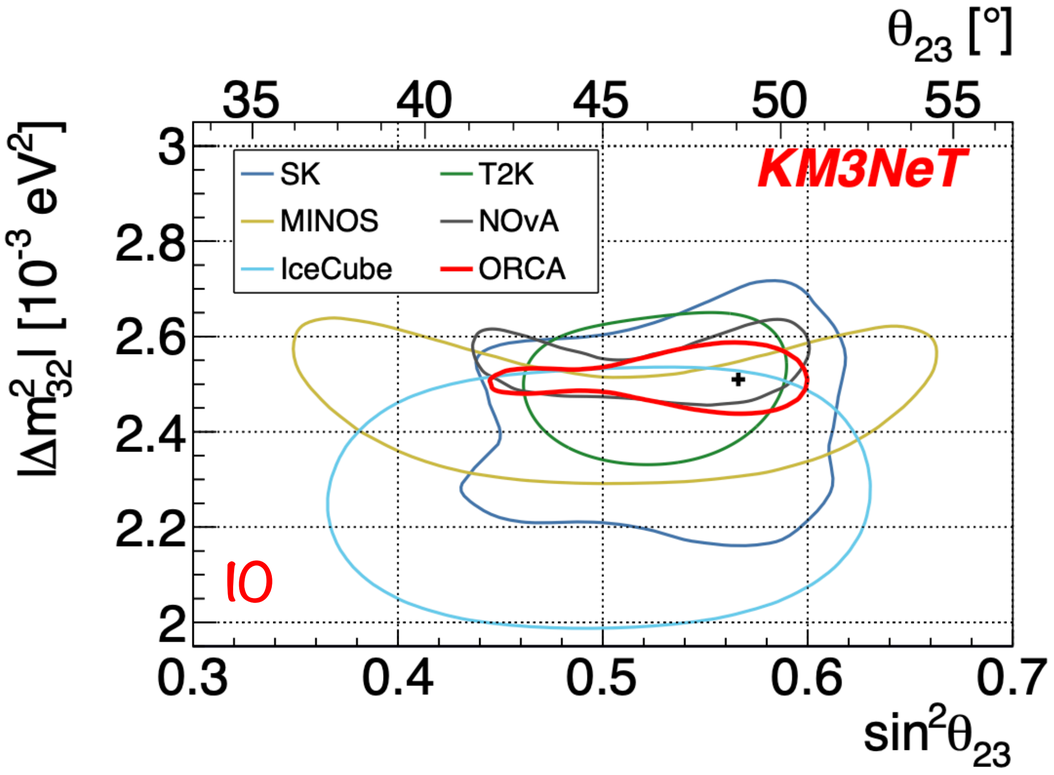
- **long-baseline accelerator neutrino experiments** such as DUNE
  - ❍ **remarkable event reconstruction and powerful neutrino beam**
  - ❍ possible both at near and at far detector



Sensitivity in full KM3NeT/ORCA

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





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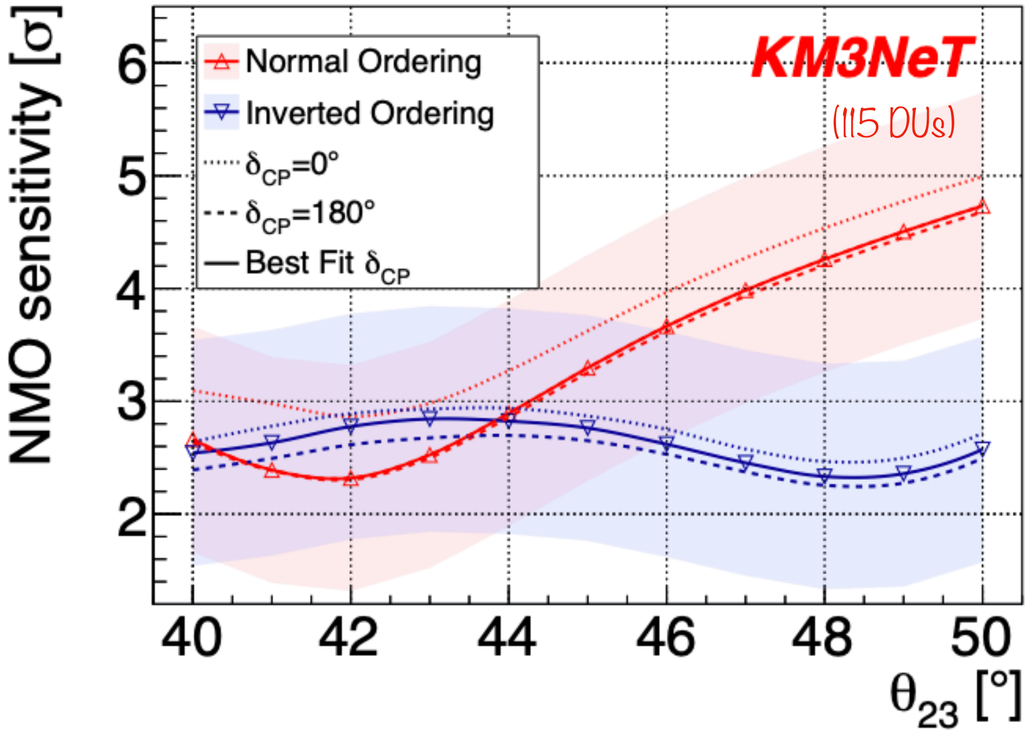
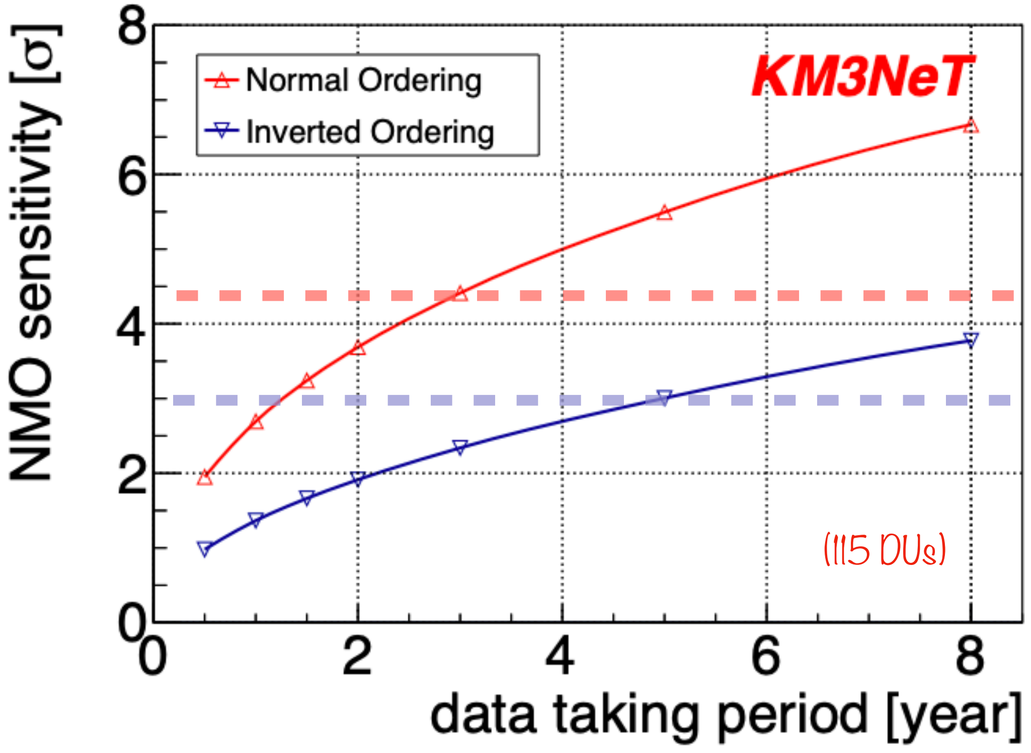
Expected KM3NeT/ORCA precision after 3 years of data taking at 90% of C.L.

Sensitivity in full KM3NeT/ORCA

- **Neutrino Mass Ordering (NMO)**:
  - ❍ after 3 years of data taking, 4.4σ if NO with the current best-fit oscillation parameters
  - ❍ 3σ sensitivity to IO, after 5 years of data taking





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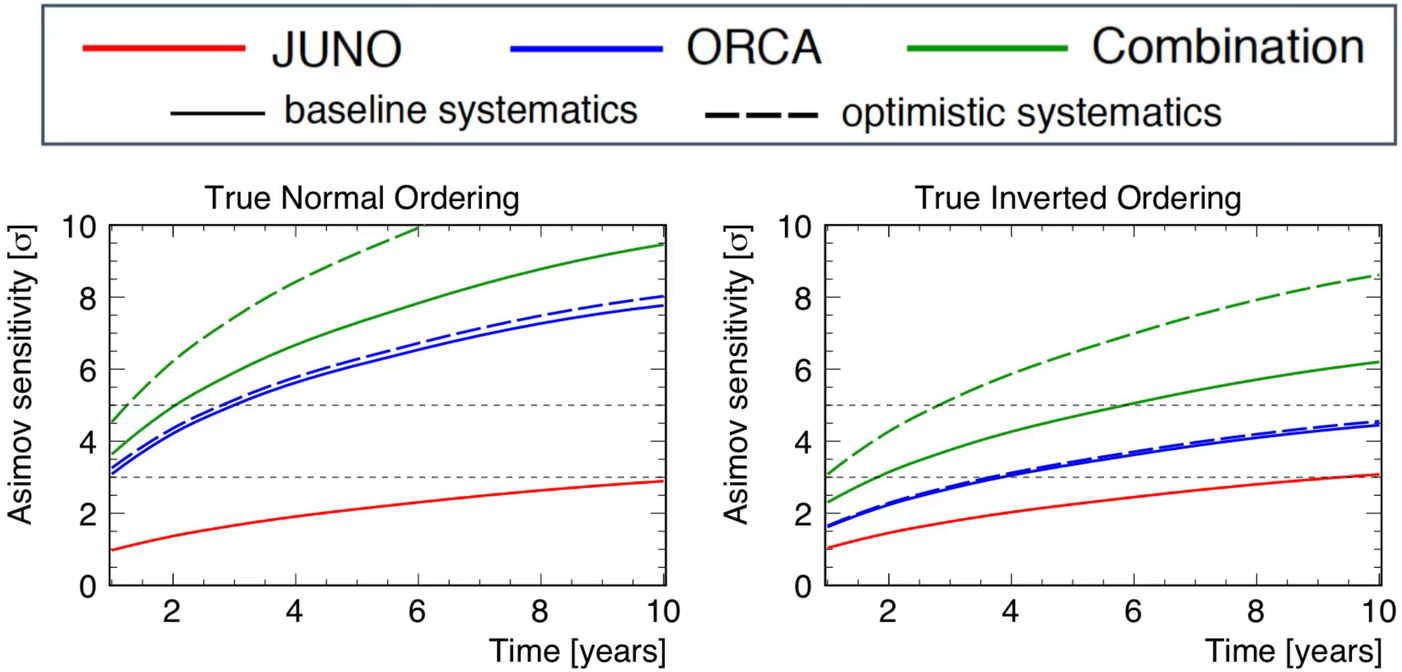
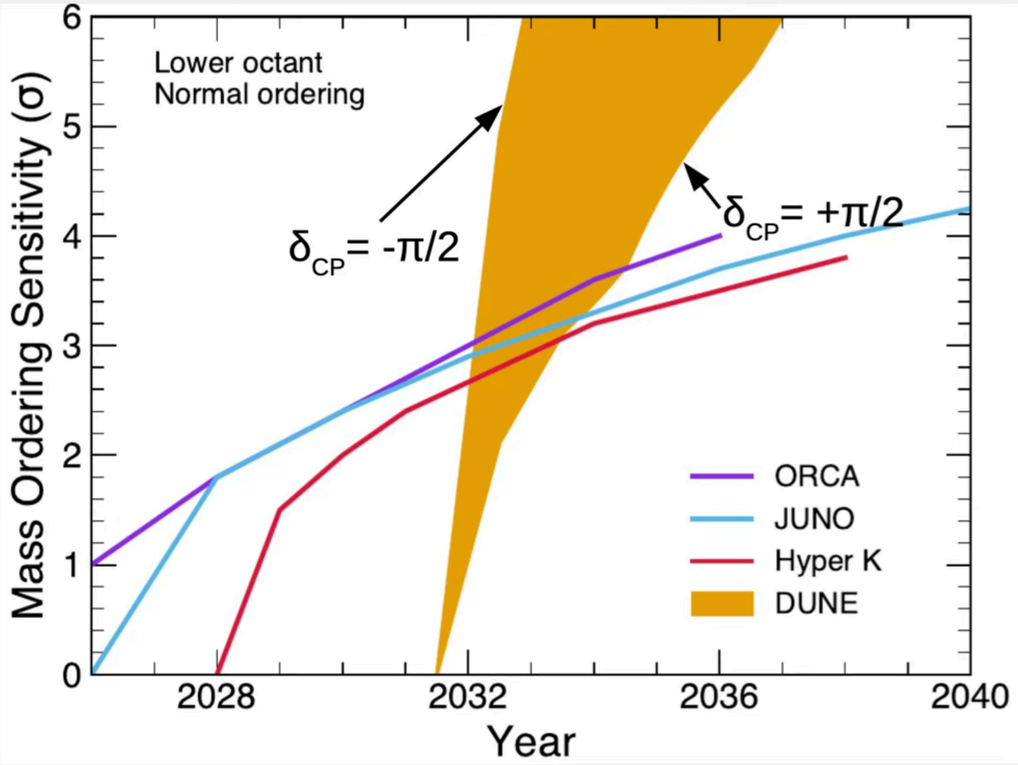
NMO sensitivity in/with other experiments

KM3NeT Collab., JHEP 2022 55 (2022)



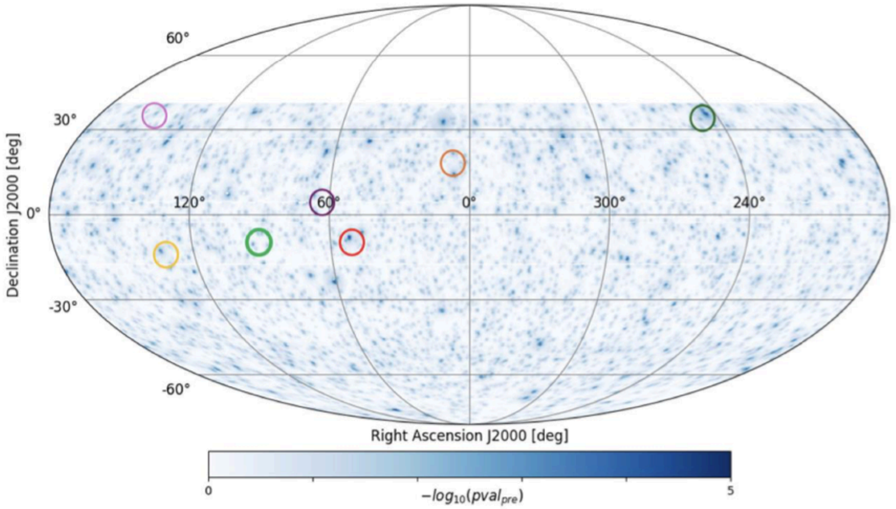
CERN Seminar on DUNE experiment - I. Gil-Botella



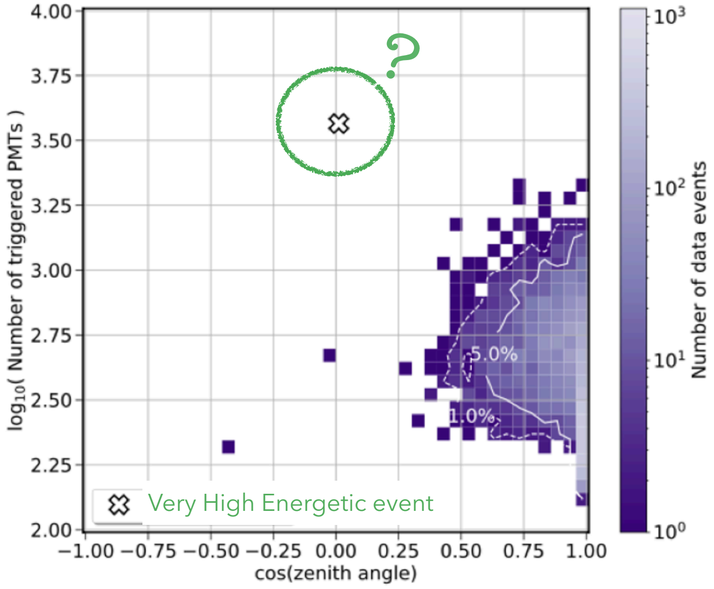
Main physics results in ARCA21

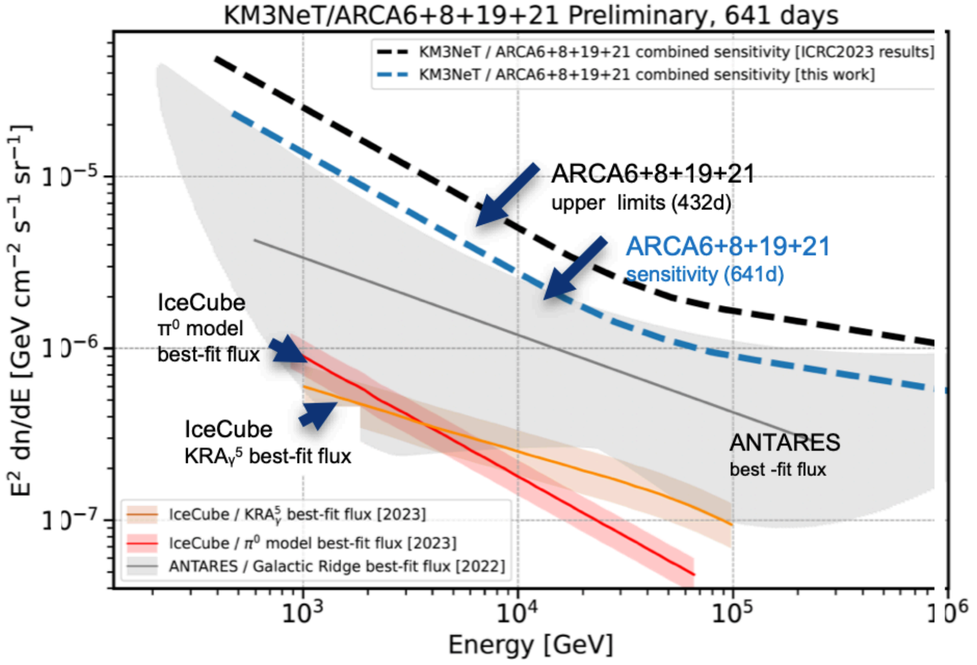
- Combined geometry analyses: ARCA 6+8+19+21
  - ❍ **point source searches**
  - ❍ **diffuse astronomical neutrino flux** (E_ν > 1TeV)

"and, here, I have this event in data that I can't cut away..!" 🤷🏻



Detected sources
- CGCG 420-015
- J0854+2006
- J1613+3412
- Mkn_421
- J1337-1257
- Very High Energetic event

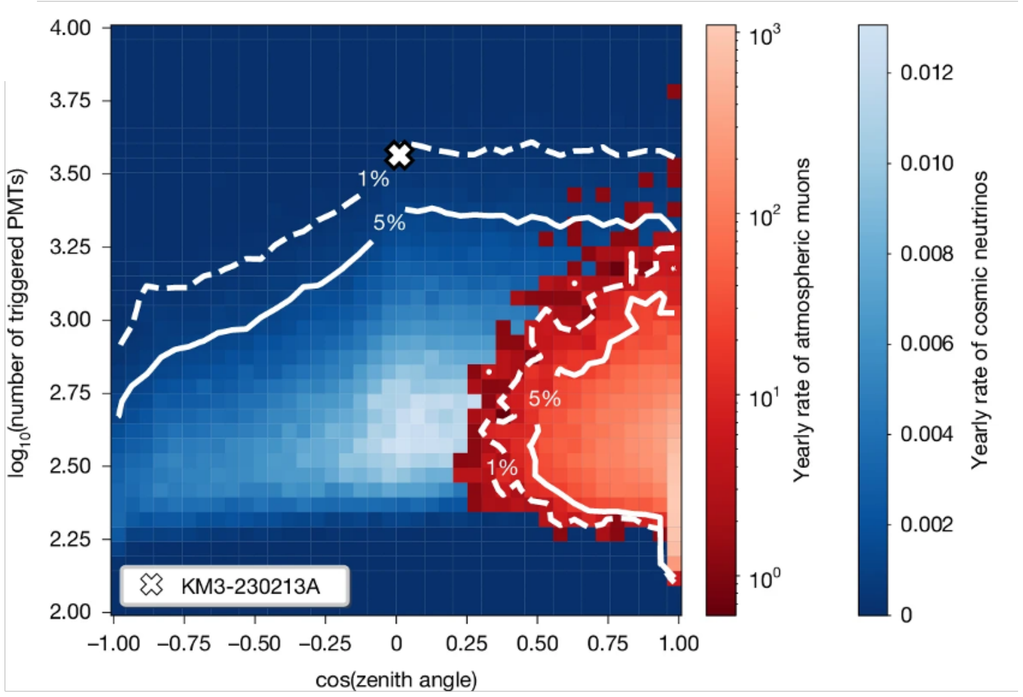


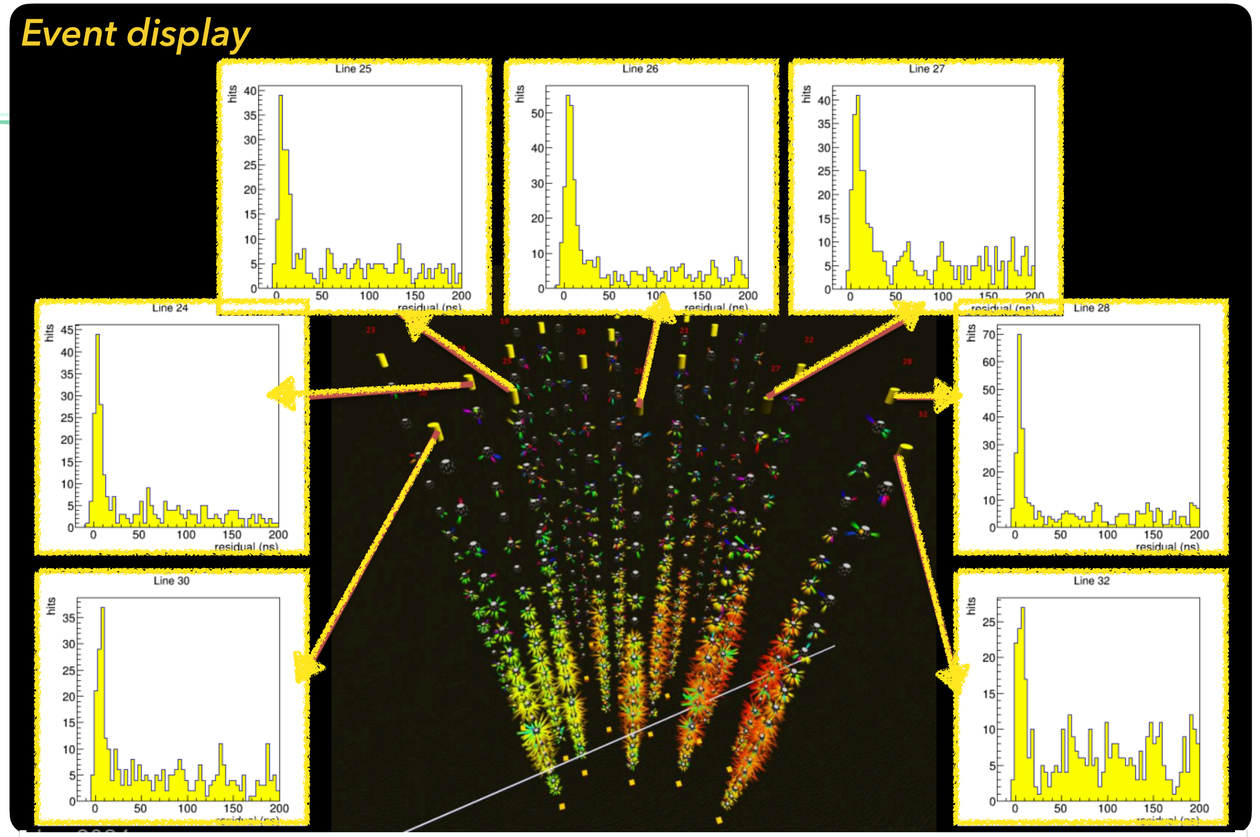


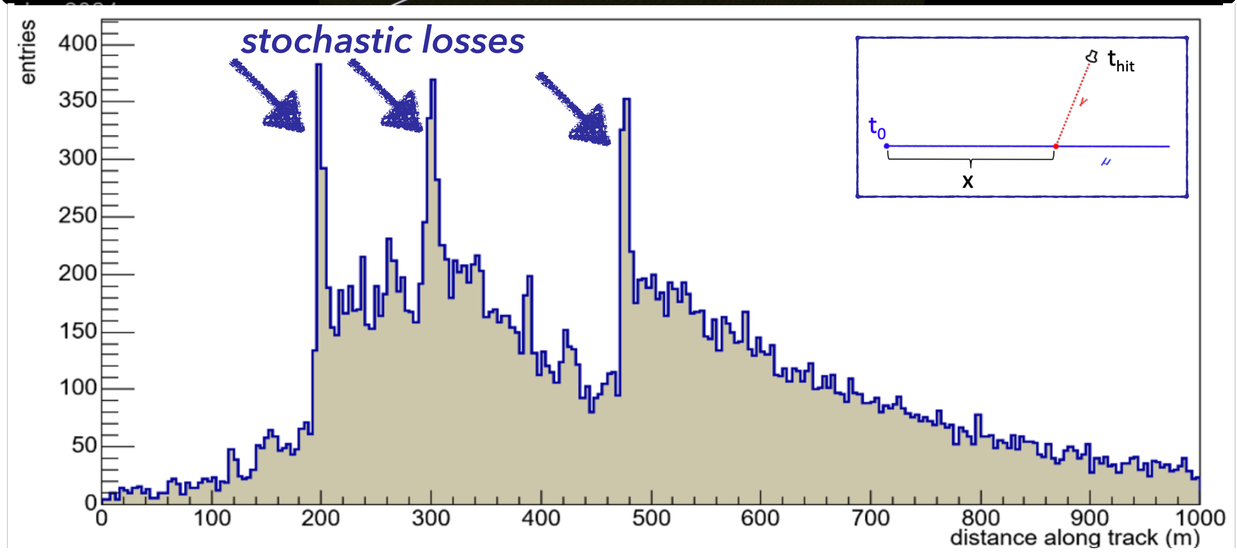
e.g. check out KM3NeT contributions at Neutrino 2024

The VHE event: KM3-230213A

- very well reconstructed Very-High Energetic (VHE) muon crossing ARCA21 detector
- consistent light profile in each DU
- three clear stochastic losses, typical of VHE muon
- **..outside the known signal-background phase space**



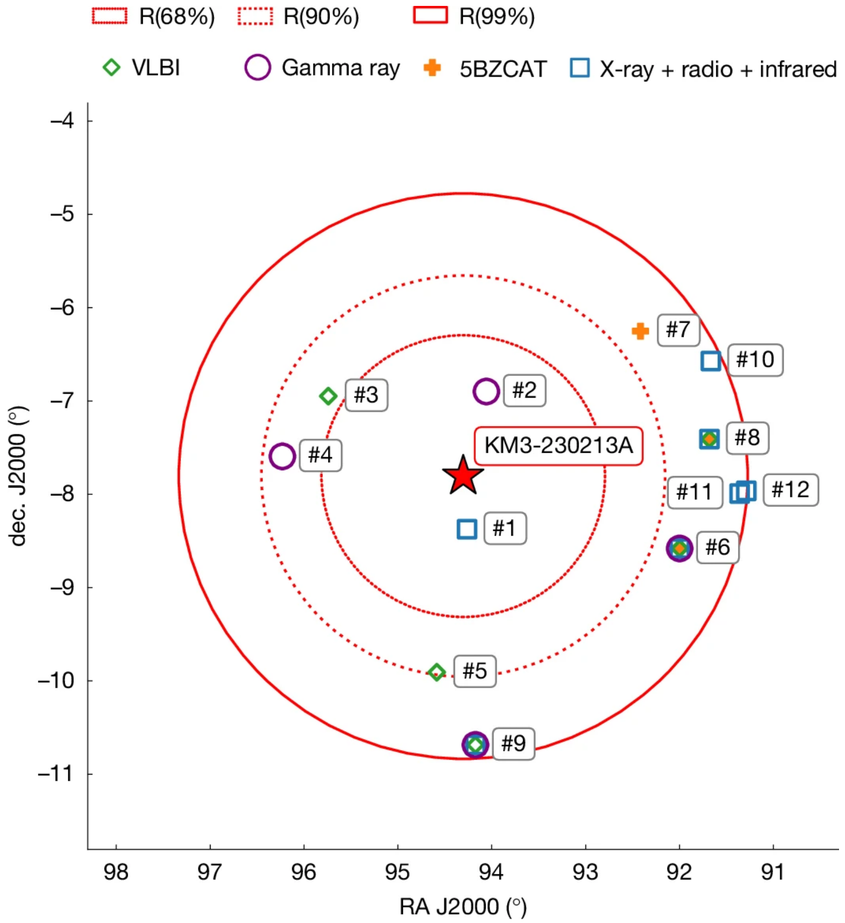




KM3NeT Coll, Nature 638, 376-382 (2025)

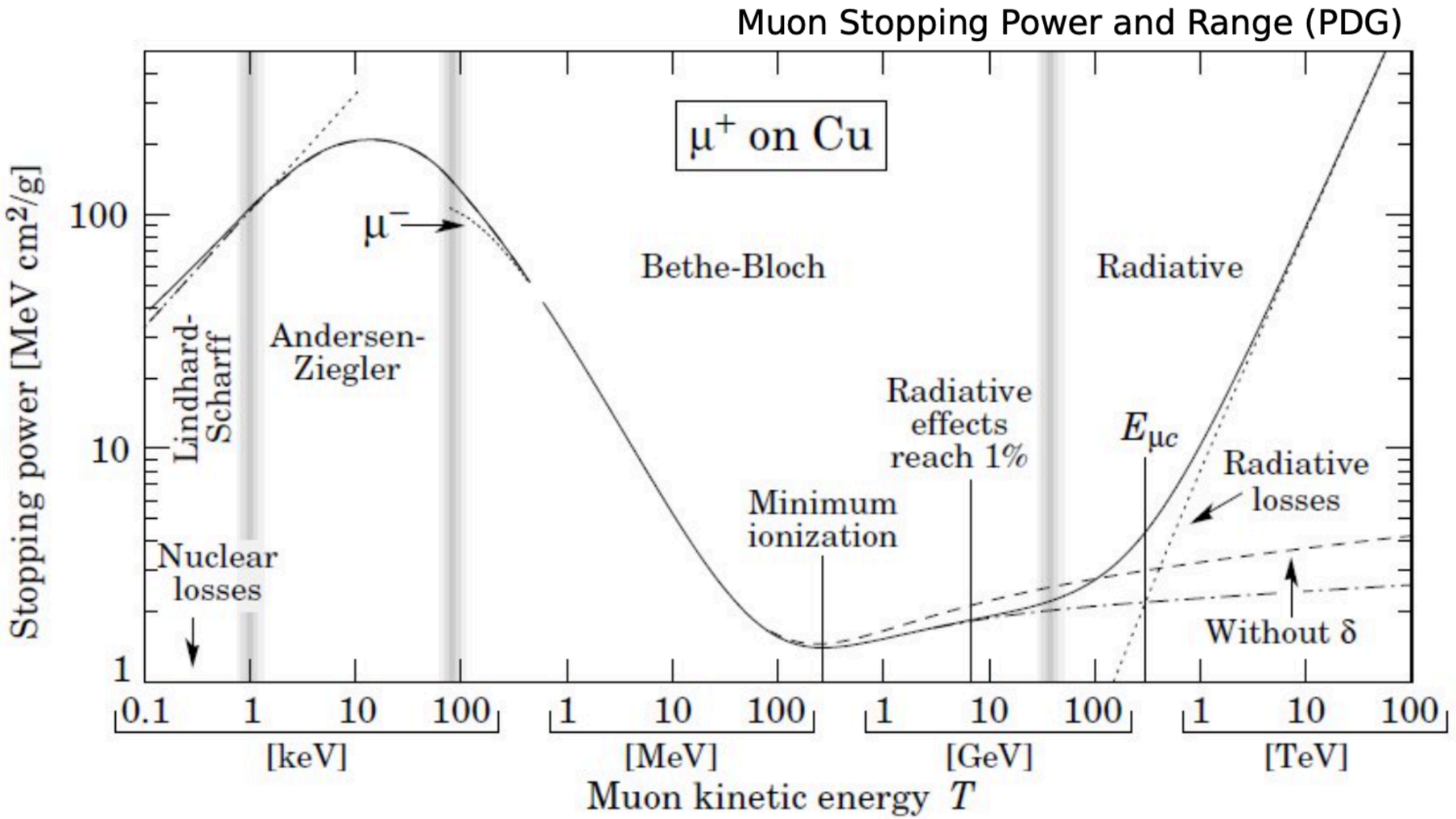
The VHE event: KM3-230213A

- Sky map in the direction on the KM3-230213A



- **considered hypotheses (to be confirmed)**
  - ❍ produced in cosmic higher-energy accelerator
    (Active Galactic Nuclei, associated with massive black hole)
  - ❍ first cosmogenic neutrino ever detected

- **discarded hypotheses (most probably)**
  - ❍ produced in the galactic plane (no matching compelling sources)
  - ❍ flaring blazers (not conclusive yet)

- **Ongoing studies**
  - ❍ improvement in the pointing calibration in ARCA detector
  - ❍ (re-)analyse ARCA21 data

Bethe-Block reminder