IRN Neutrino Meeting

KIT Karlsruhe (Germany)

27/11/2023

Recent results from KM3NeT/ORCA

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KM3NeT – Under water Cherenkov detectors

Oscillation Research with Cosmics in the Abyss
ORCA

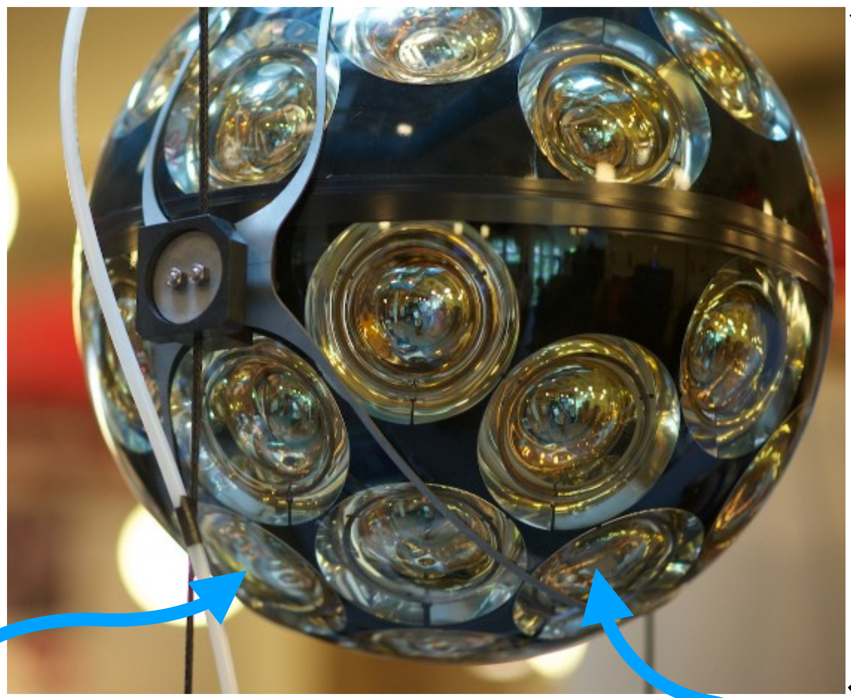
- Main goal -> NMO and oscillation parameters
- Dense instrumentation for few GeV atmospheric neutrinos
- 40km off southern French coast near Toulon
- Sea floor depth of the ORCA site ~2450m
- 18 out of 115 Detection Units deployed

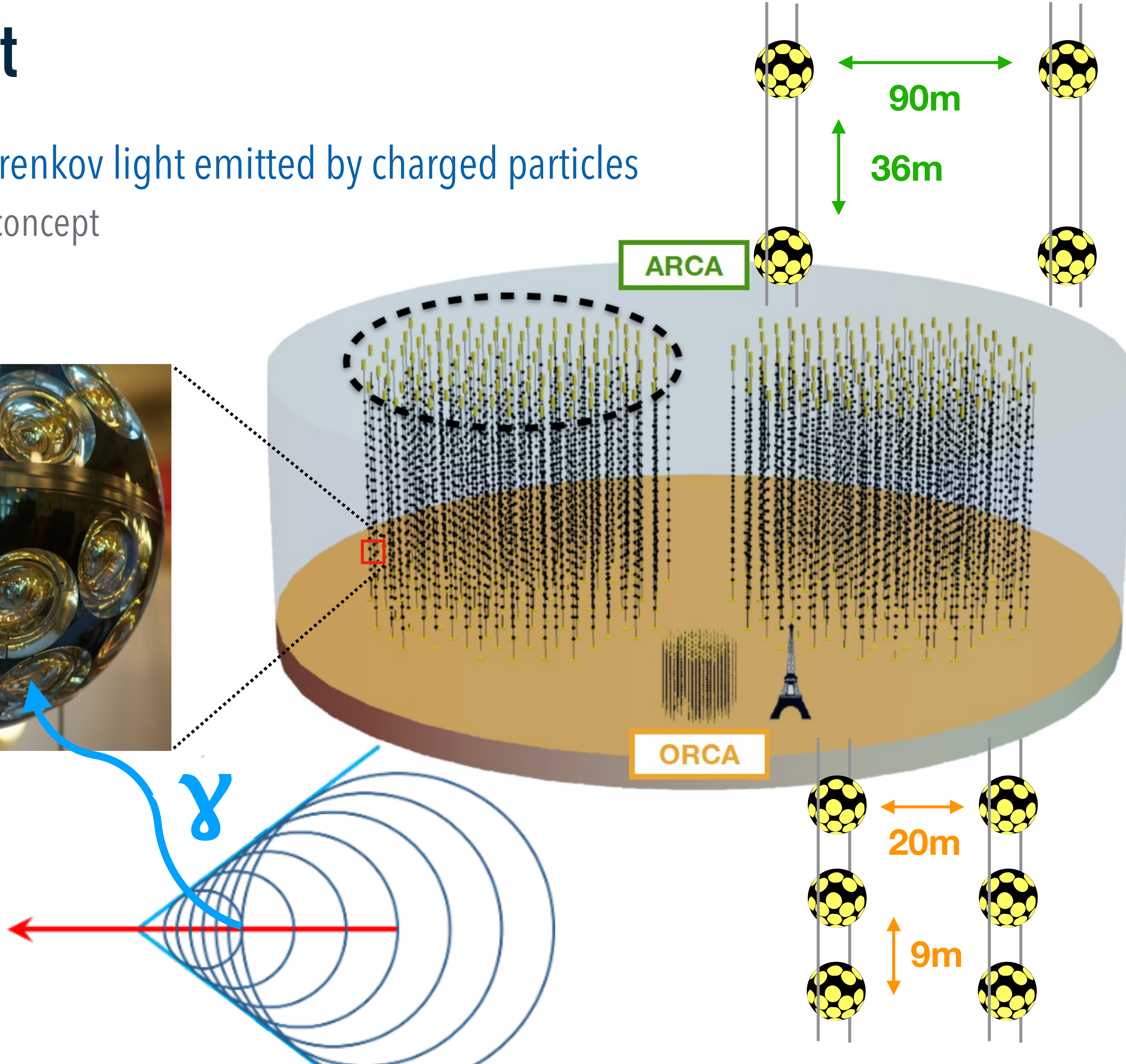
Astroparticle Research with Cosmics in the Abyss
ARCA

- Main goal -> High-energetic astrophysical neutrinos
- Sparse instrumentation covering 1km^3 instrumented volume
- 120 km off Sicily
- Sea floor depth of the ARCA site ~3500m
- 28 out of 2x115 Detection Units deployed

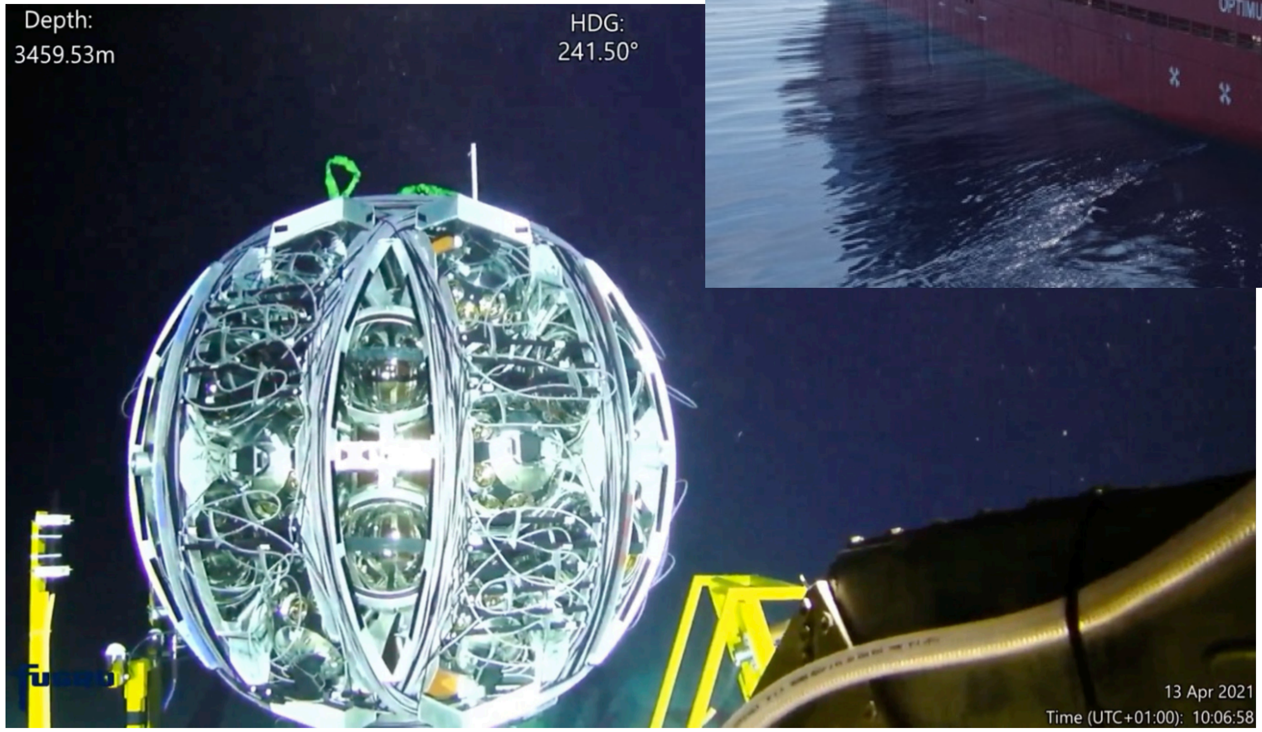
Detector layout

- Sensitive to Cherenkov light emitted by charged particles
  - Multi-PMT concept



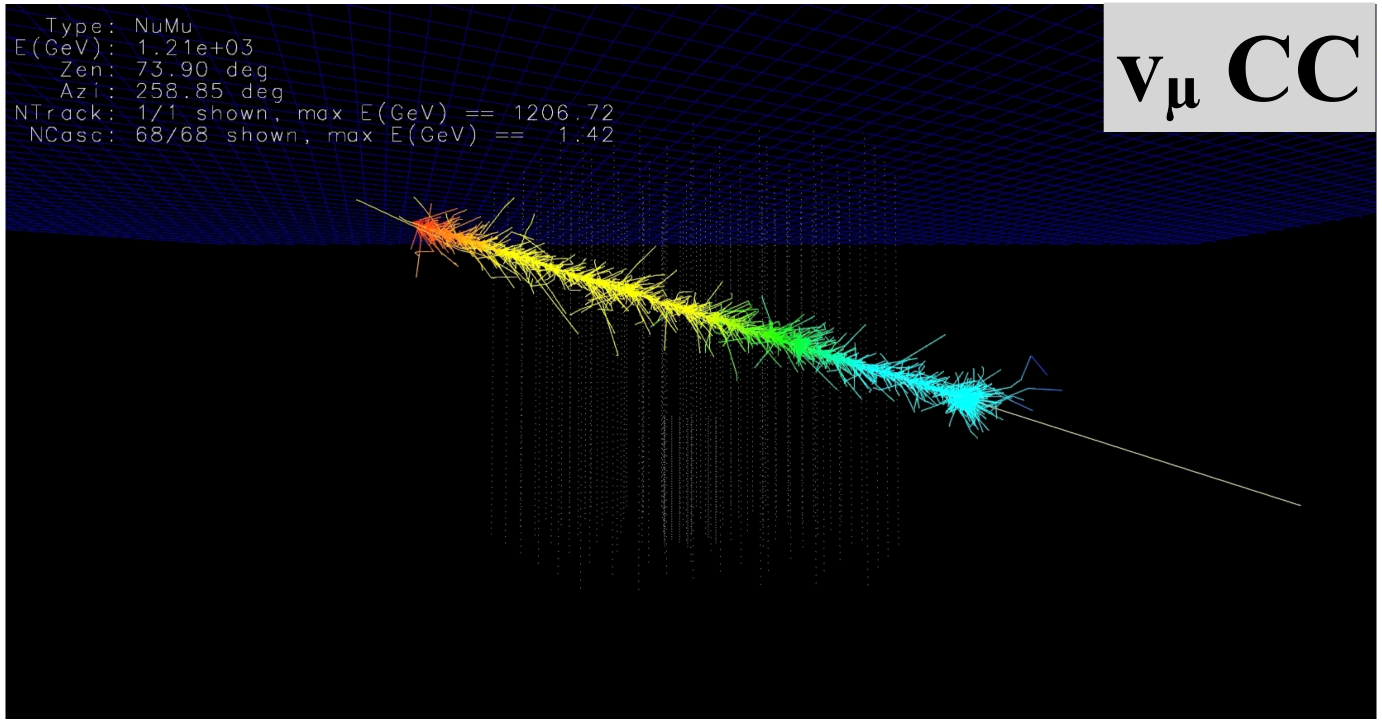


Deployment campaign

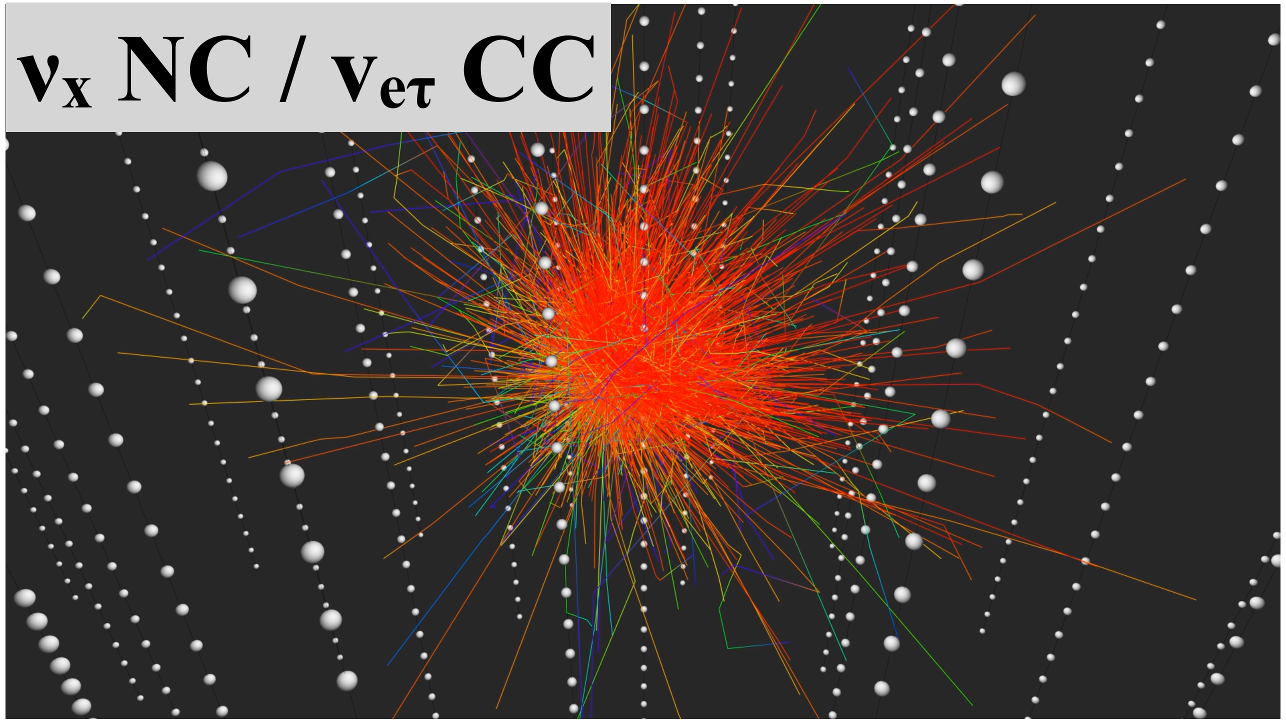


Detection principle

- Flavour identification using morphology of light pattern
  - Tracks → ν_μ CC
  - Showers → ν_x NC / $\nu_{e,\tau}$ CC



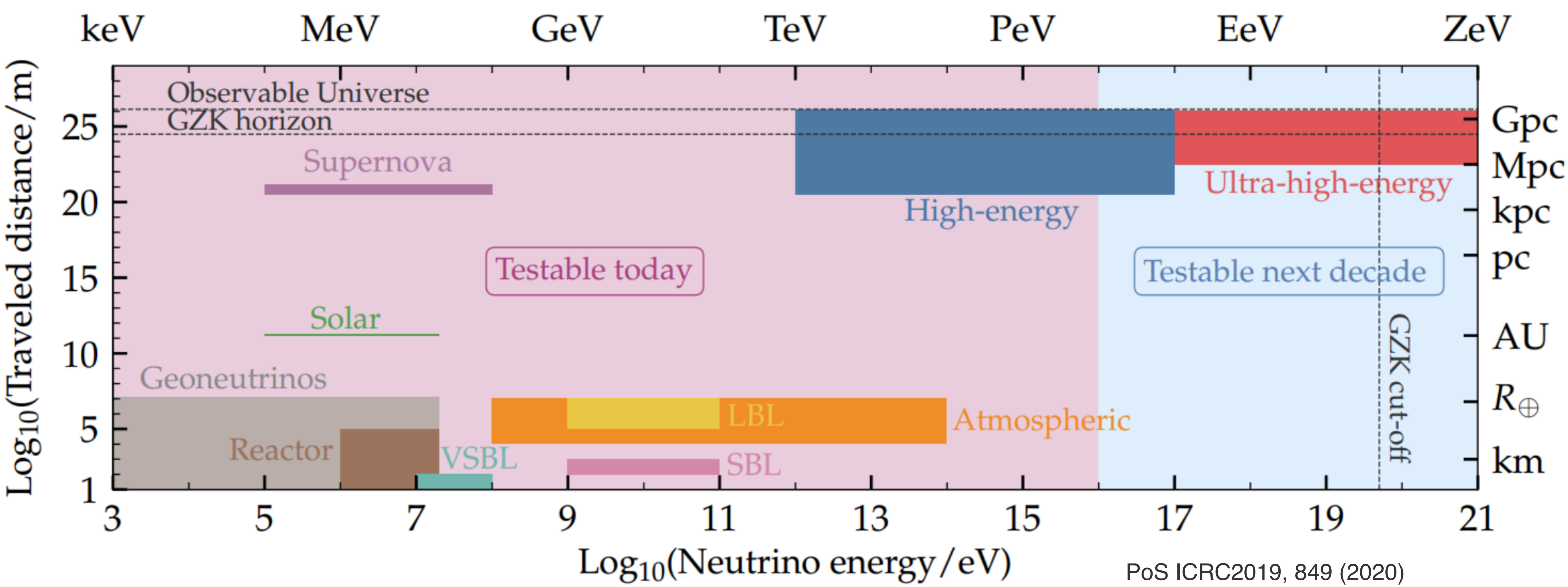
1 TeV



1 TeV

Physics goals

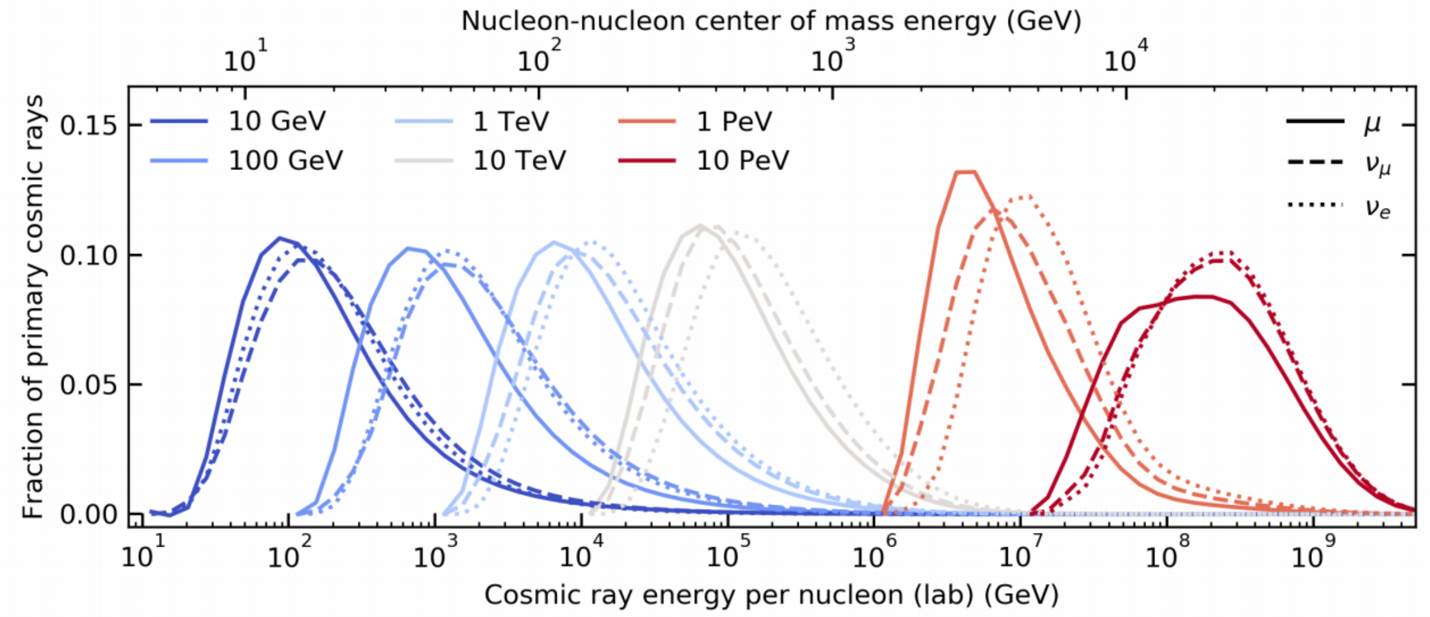
- Study neutrinos in a vast energy range: from MeV to PeV
  - Supernova explosions
  - **Atmospheric neutrino oscillations**
  - Indirect dark matter searches
  - High energy cosmic neutrinos

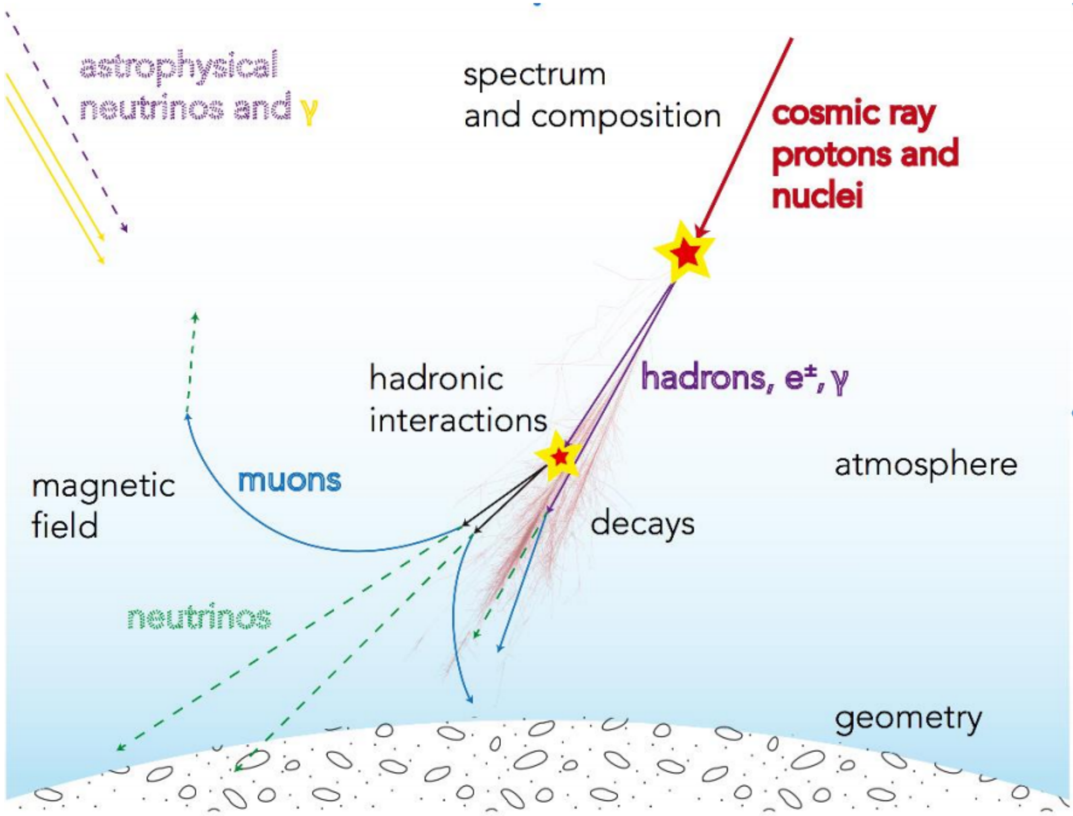


PoS ICRC2019, 849 (2020)

Atmospheric neutrinos

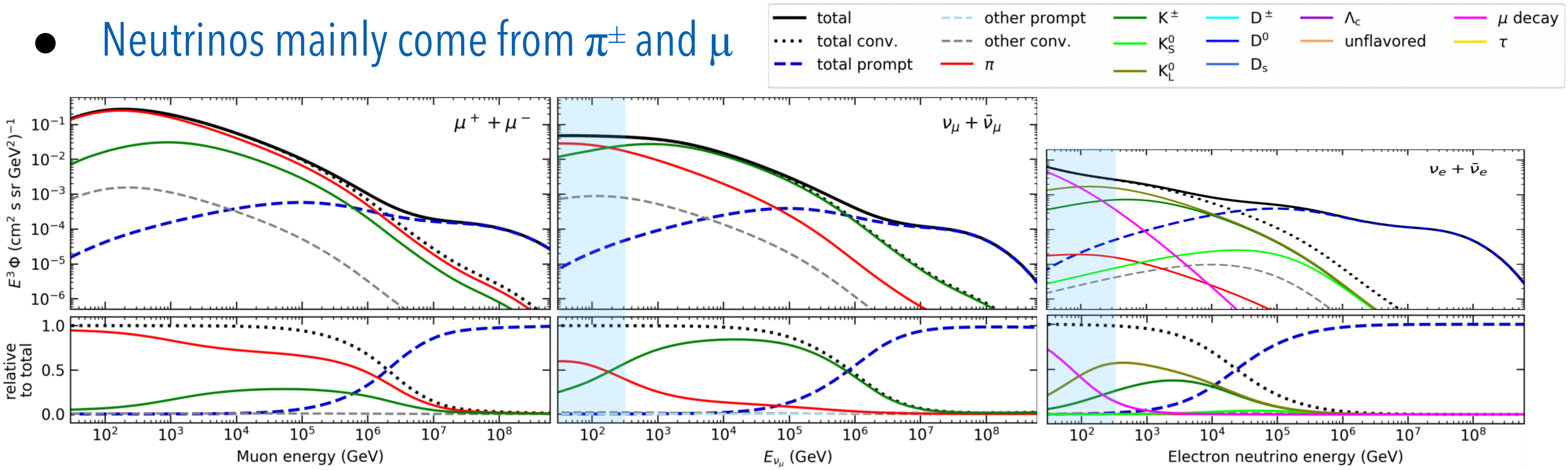
- 1/10th of the energy from the parent cosmic ray





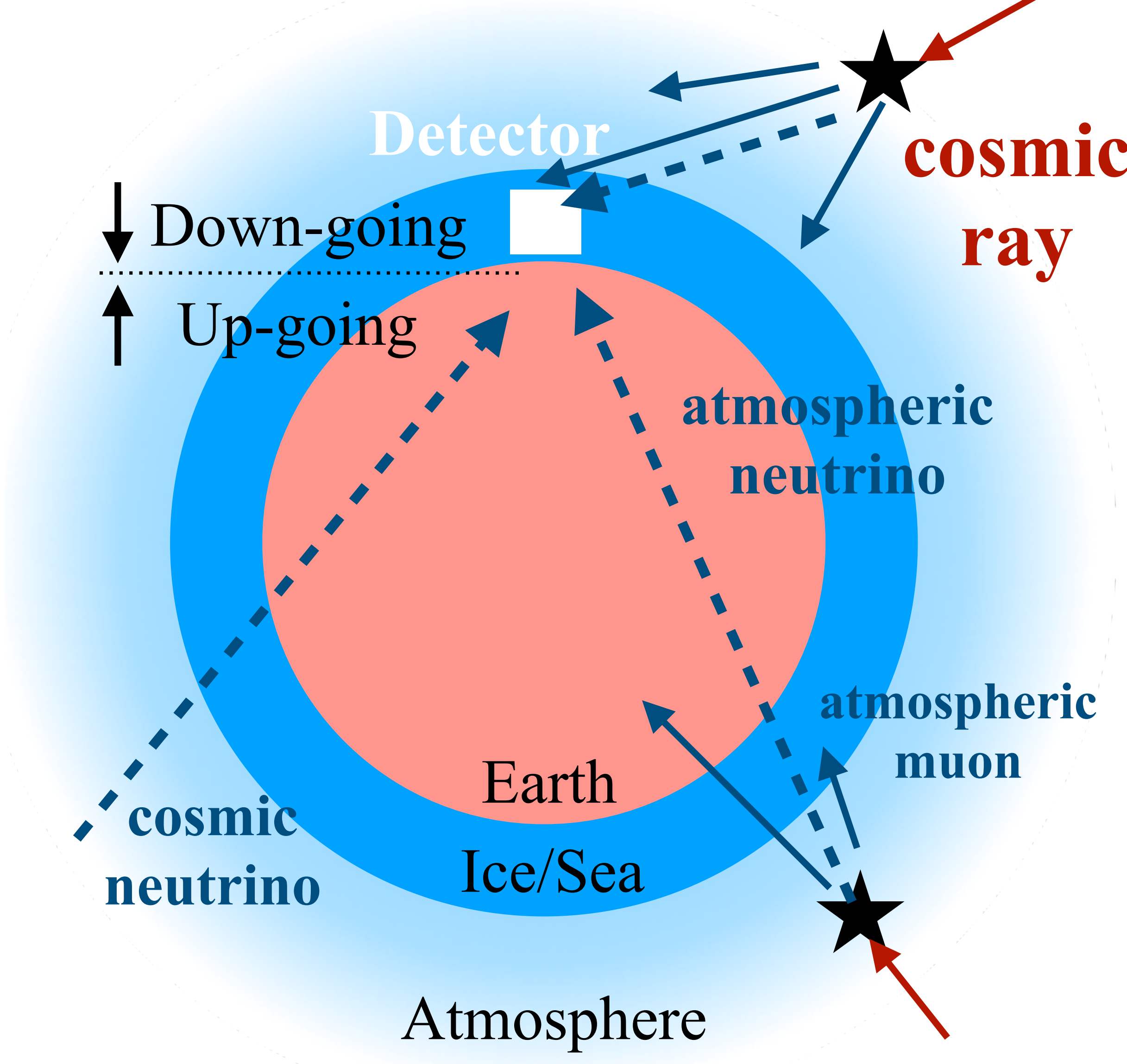
Phys. Rev. D 100, 103018 (2019)

- Neutrinos mainly come from $\pi^{\pm}$ and μ



Oscillations

- Multiple baselines, energies, and flavours
  - Reconstructed topology, energy and zenith
- Downgoing vs upgoing asymmetry
  - Constrains systematics



Vacuum

$$P(\nu_e \to \nu_e) \simeq 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - 4\cos^2\theta_{13}\sin^2\theta_{23}(1-\cos^2\theta_{13}\sin^2\theta_{23})\sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

$$P(\nu_\mu \leftrightarrow \nu_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

$$P(\nu_\mu \leftrightarrow \nu_\tau) \simeq \sin^2 2\theta_{23}\cos^4\theta_{13}\sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

$$P(\nu_e \leftrightarrow \nu_\tau) \simeq \cos^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

Matter

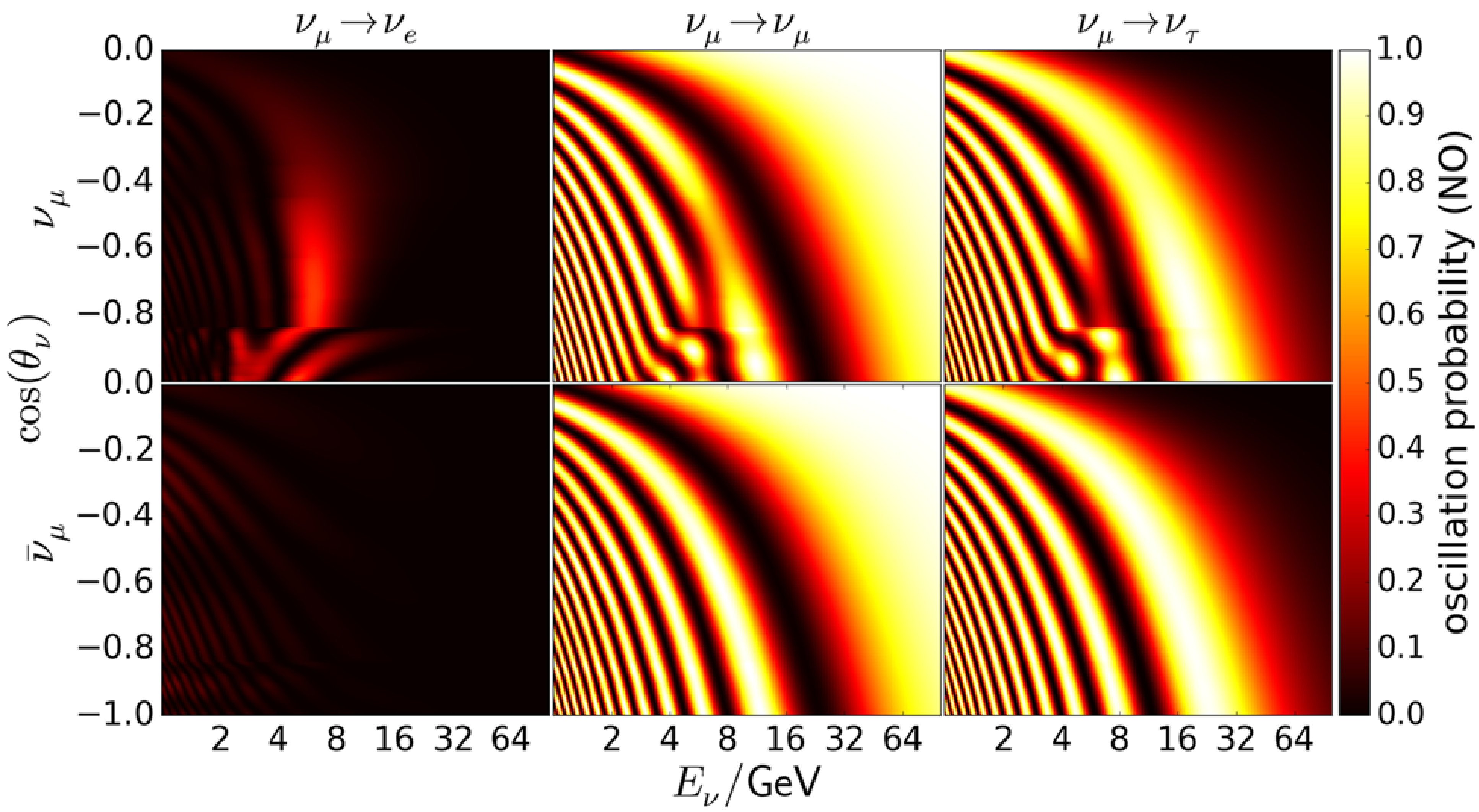
$$V_e = \pm\sqrt{2}G_F N_e$$

$$\Delta m^2_{31,M} = \Delta m^2_{31}\sqrt{\sin^2 2\theta_{13} + (2EV_e/\Delta m^2_{31} - \cos 2\theta_{13})^2}$$

$$\sin^2 2\theta_{13,M} = \frac{\sin^2 2\theta_{13}}{\sin^2 2\theta_{13} + (2EV_e/\Delta m^2_{31} - \cos 2\theta_{13})^2}$$

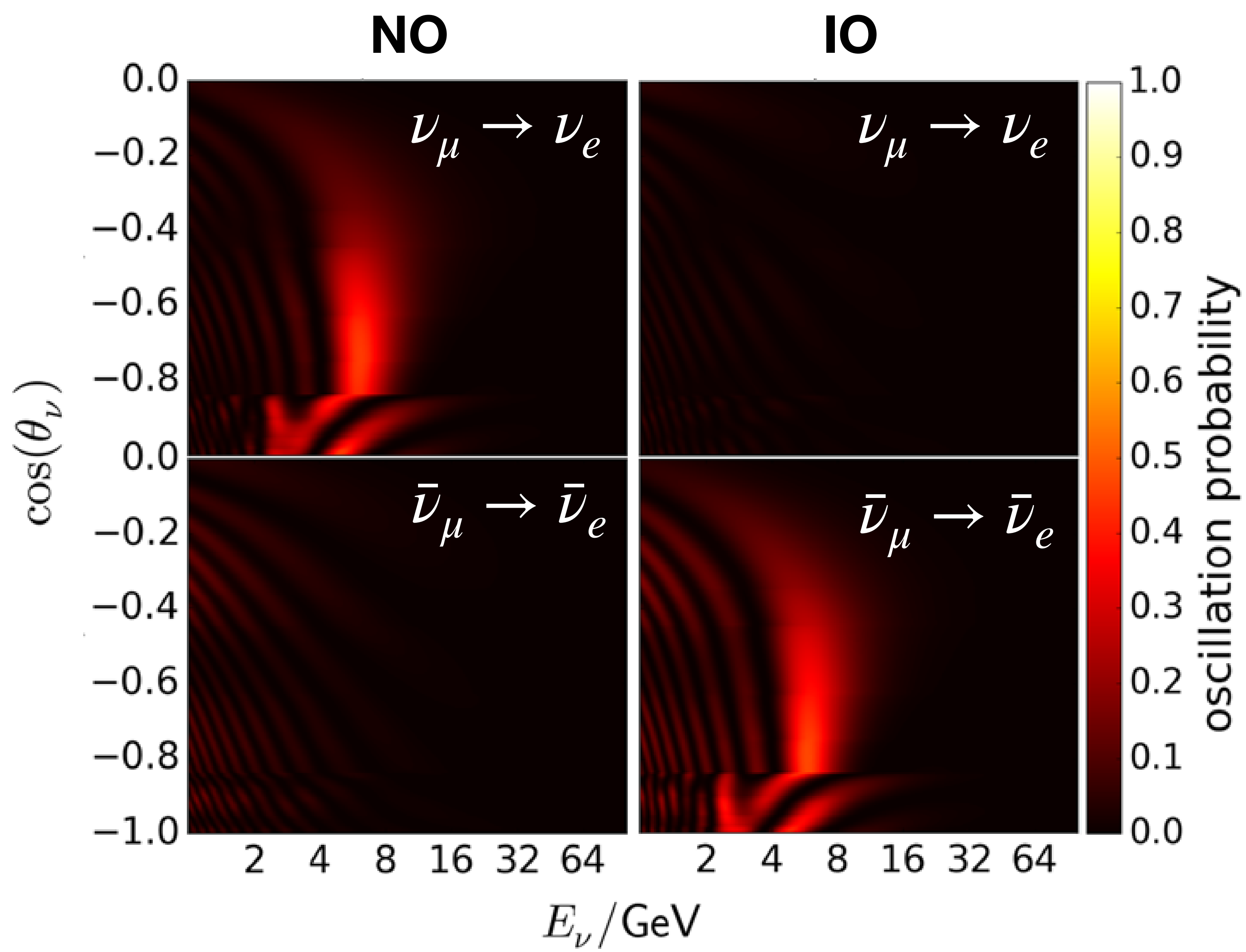
Oscillations

- Neutrino energy > 100 GeV
  - Too high energies to observe oscillations ⟶ interesting for BSM
- Multi-GeV
  - First oscillation $\nu_\mu \longrightarrow \nu_\tau$ very sensitive to θ_{23} and $\Delta m_{31}{}^2$

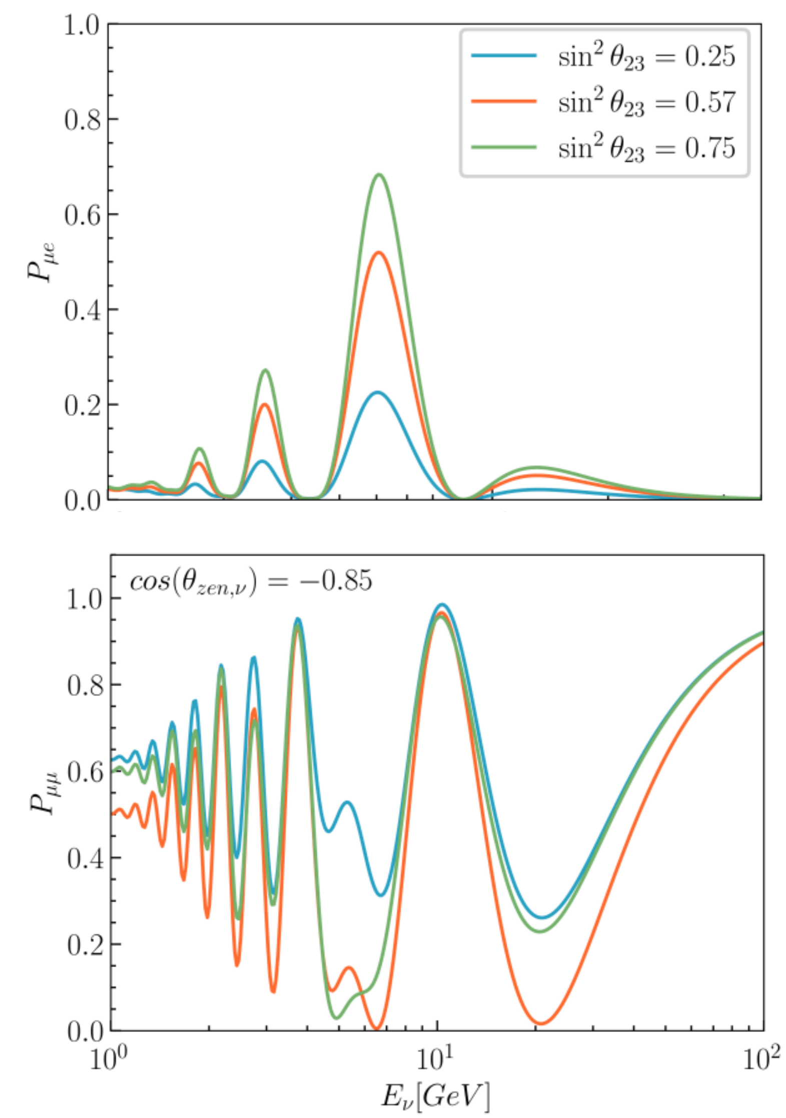


Oscillations

- Few-GeV
  - Mass ordering → matter effects difference between $\nu_\mu \longrightarrow \nu_e$ and $\bar{\nu}_\mu \longrightarrow \bar{\nu}_e$
  - Octant θ_{23} can also be extracted

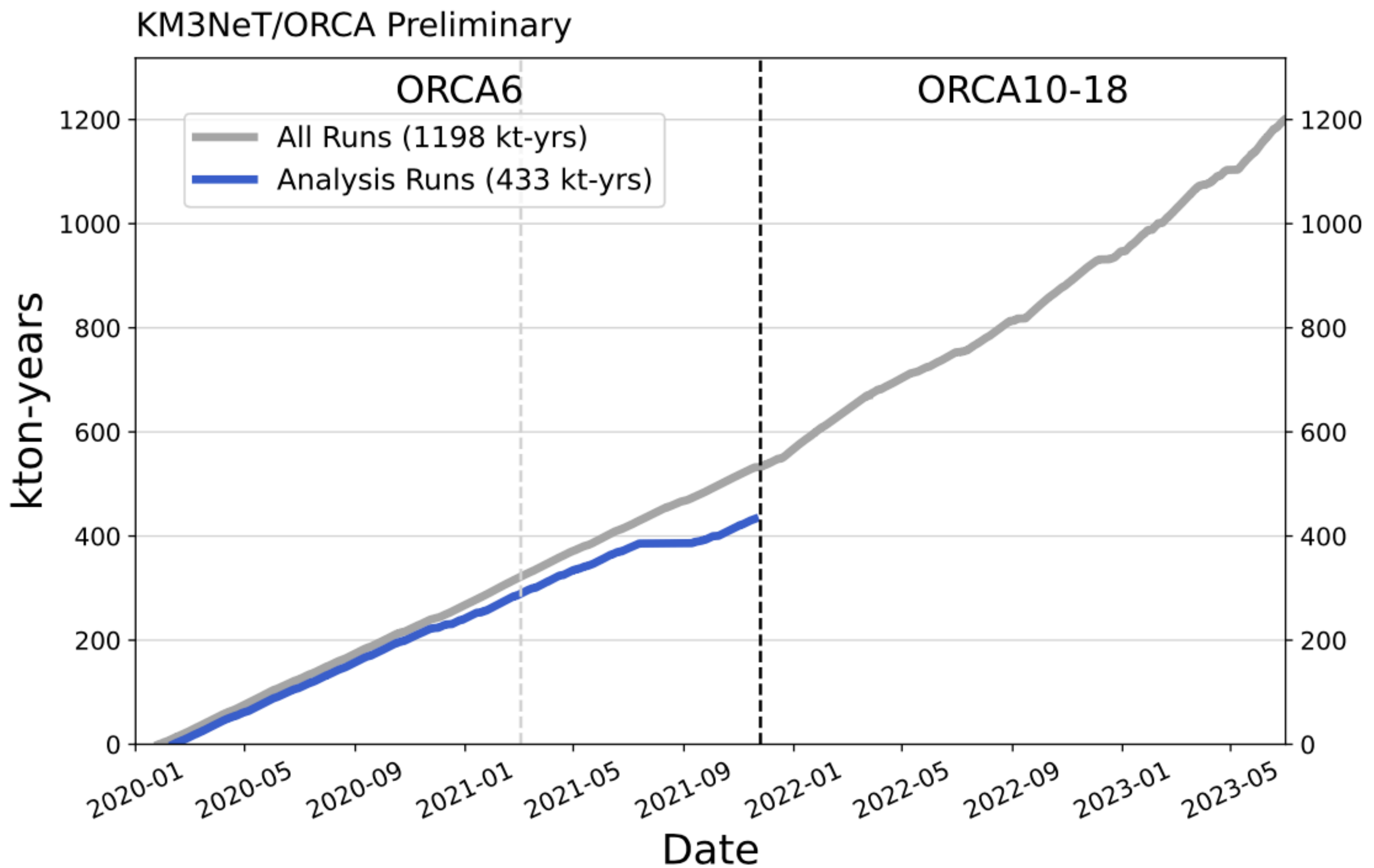


arXiv:2211.02666



ORCA 6 results

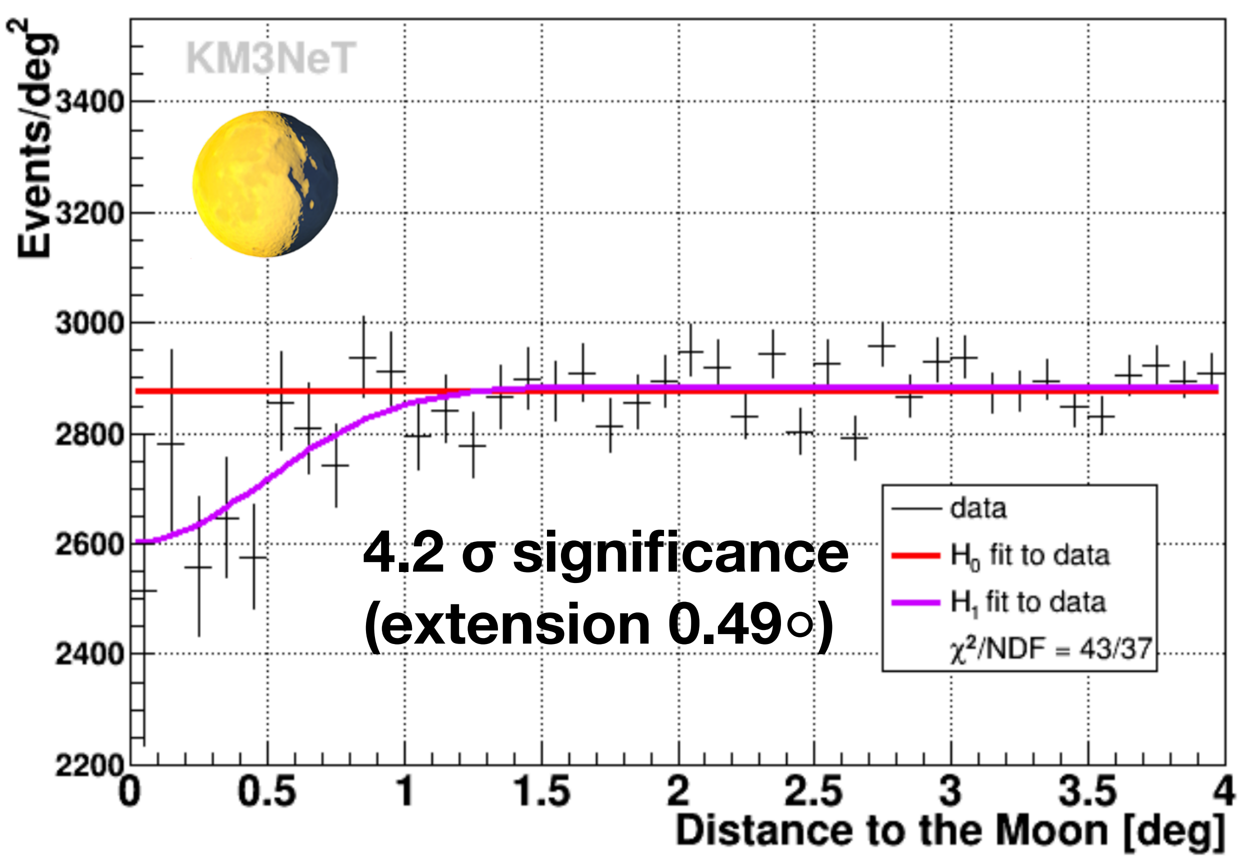
- Configuration with 6 Detection Units
- Analysed almost two years of data
  - Selecting good quality runs (i.e. stable sea conditions) ⟶ 510 days of data-taking time
  - Factor 1.5 more kton-years than previous analysis

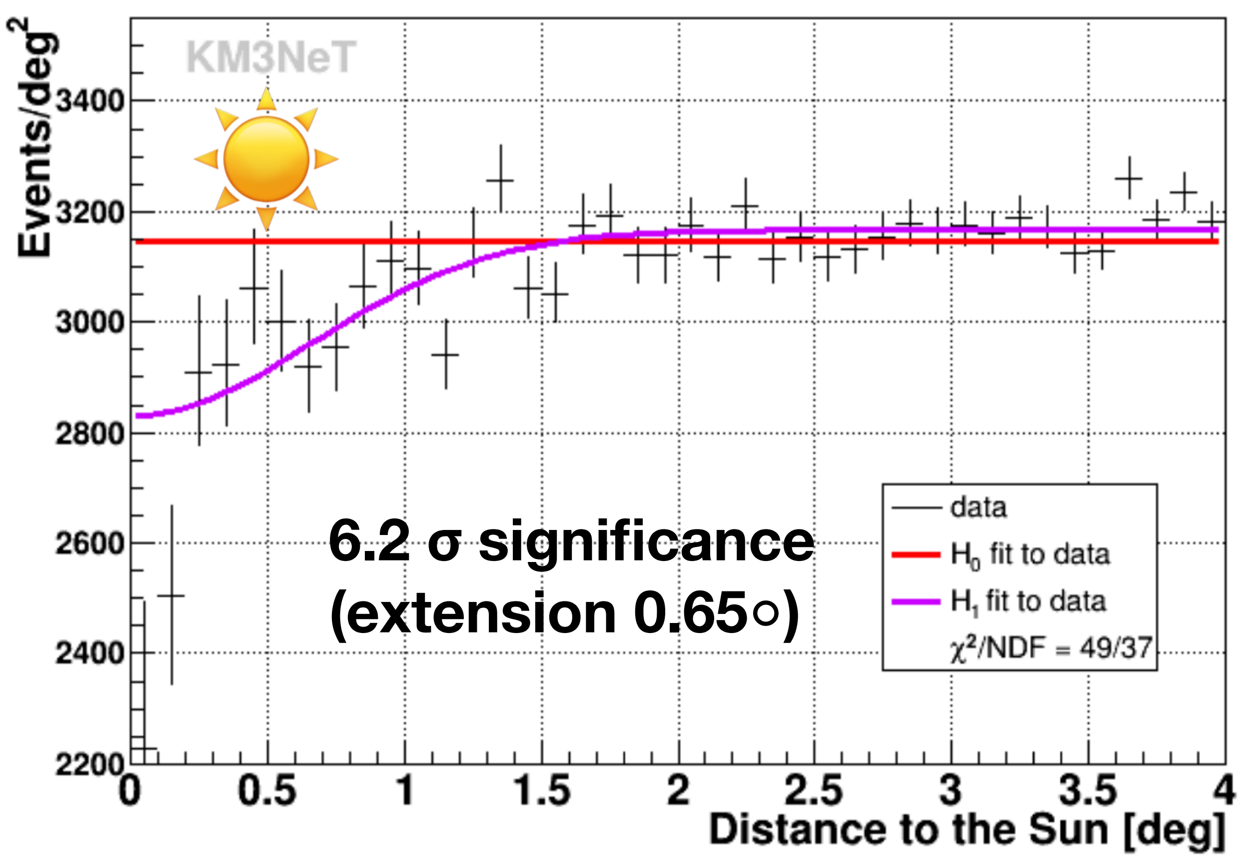


Calibration

- Multiple calibration stages (K40 measurements, optical beacons, acoustic data, atmospheric muons, etc.)
- Run-by-run MC to account for changes in detector configuration (bioluminescence, position, active PMTs, etc.)
- Moon/Sun shadow → Data driven estimation of absolute positioning and angular resolution agrees with our expectation

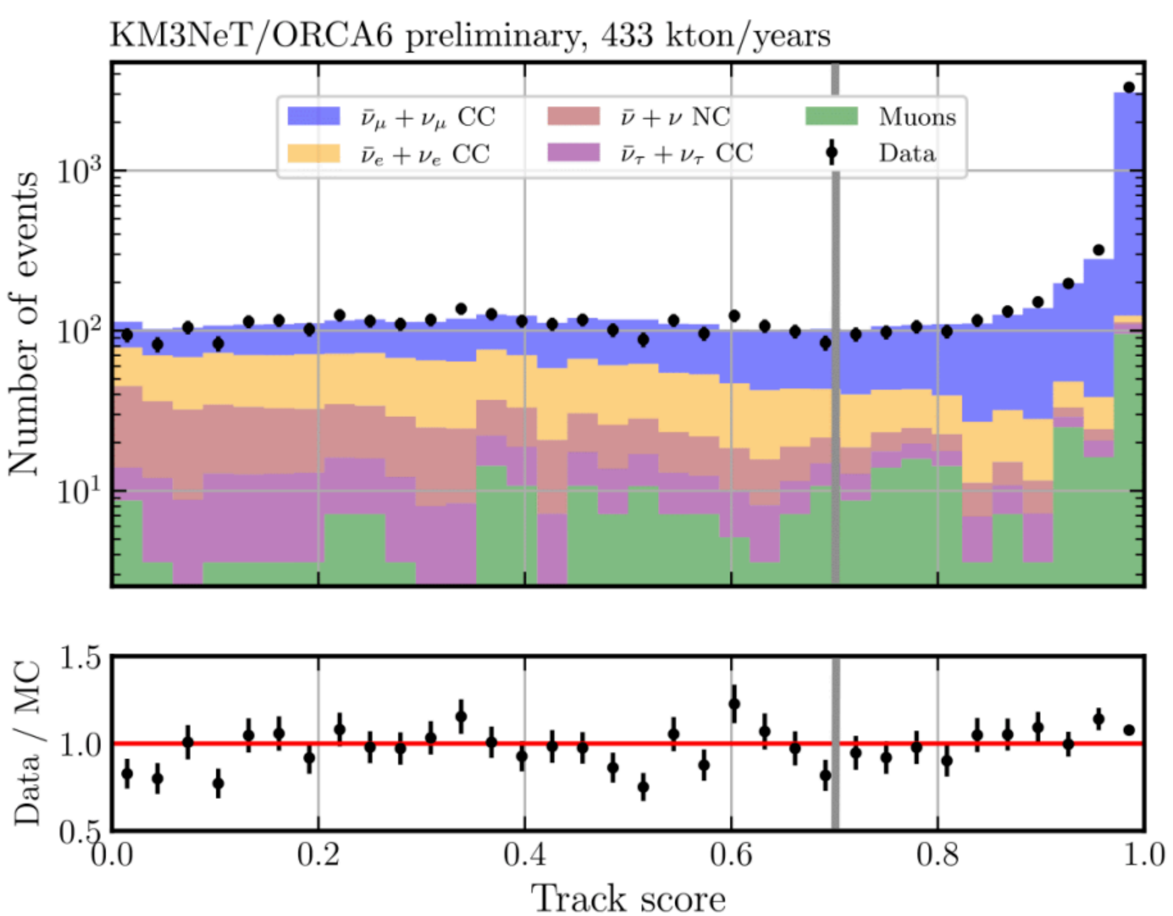
L. Cerisy, Eur. Phys. J. C 83, 344 (2023)

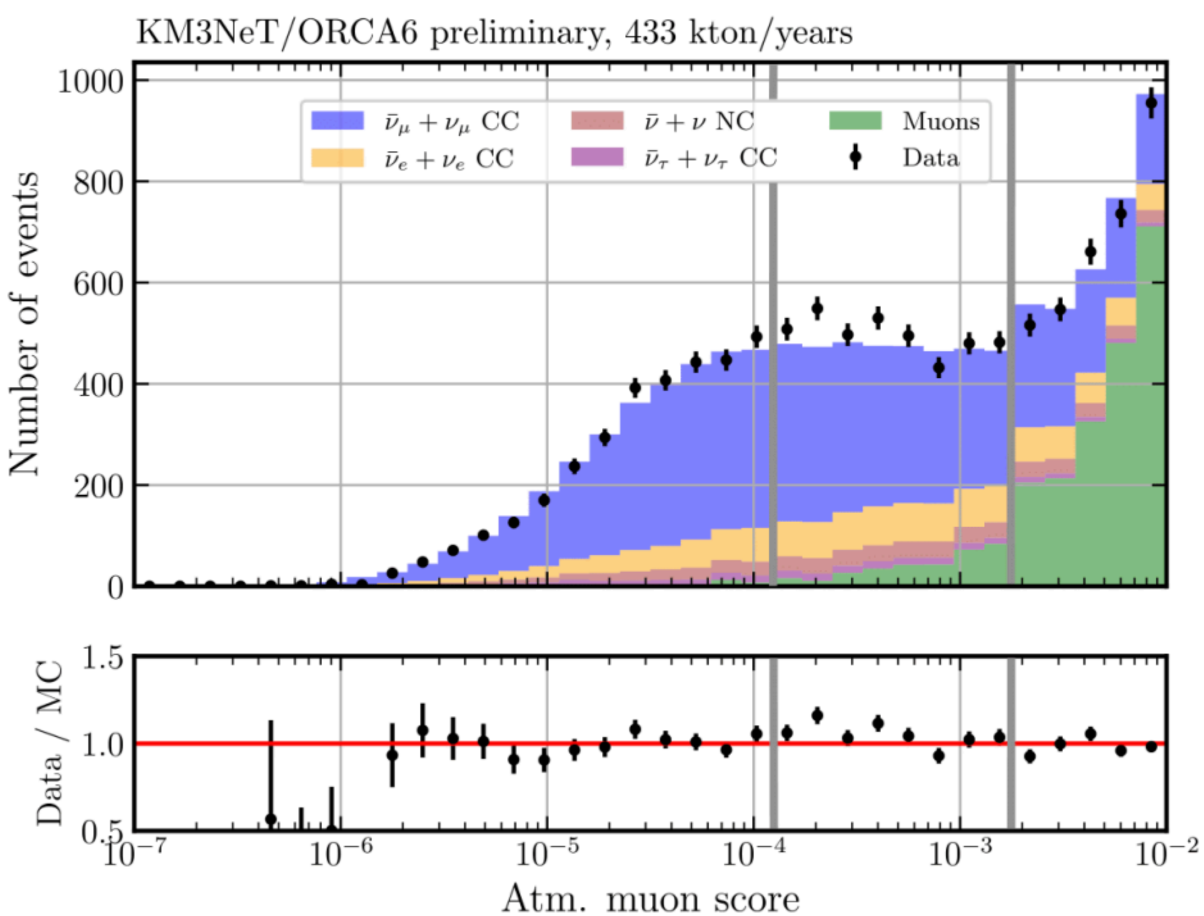




Event selection

- Two BDTs have been developed
  - Reduce atmospheric muon background
  - Distinguish between shower and tracks
- Good data/MC agreement
  - **5828 events** observed after applying cuts

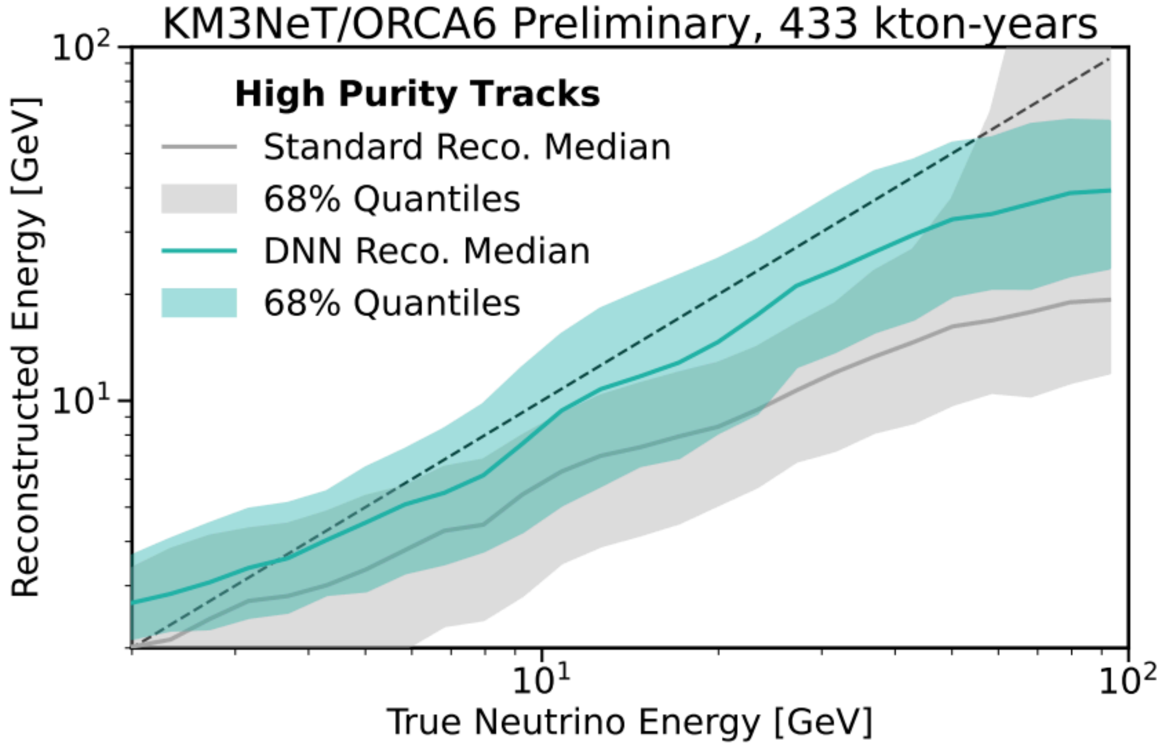




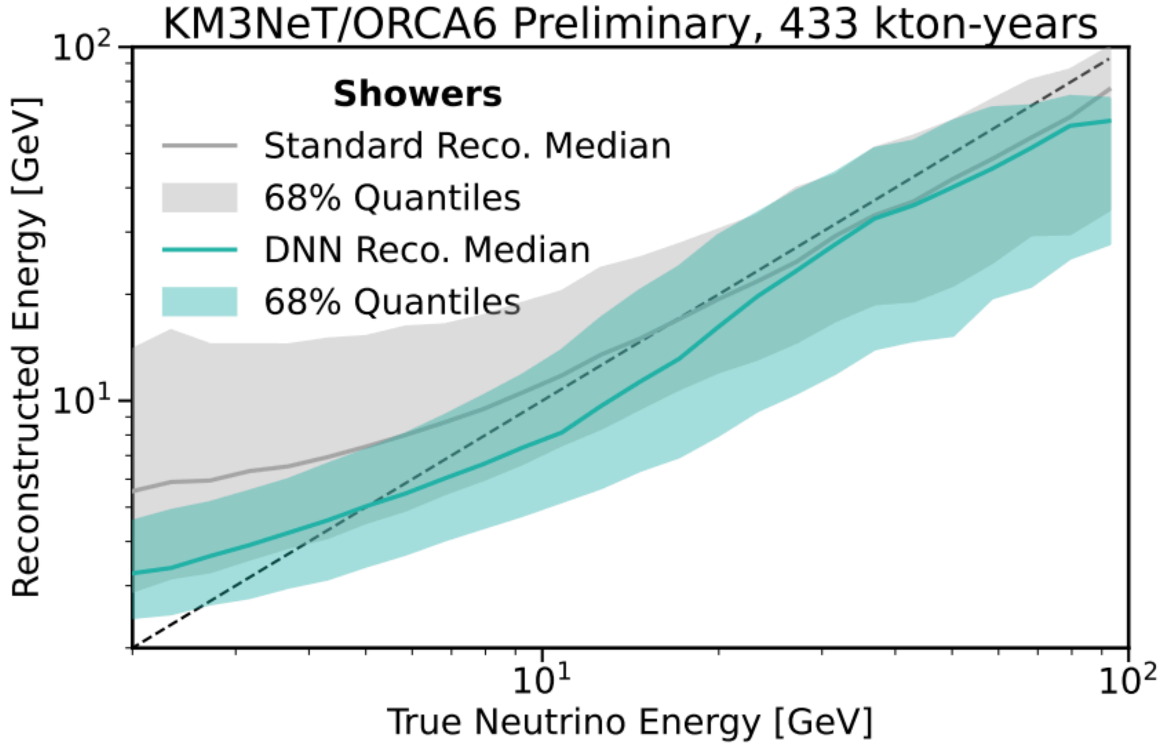
Reconstruction

- Two main variables
  - Energy (muon → length vs showers → light).
  - Direction (direct photons).
- Current approach is likelihood-based but promising performance with DNNs

Tracks



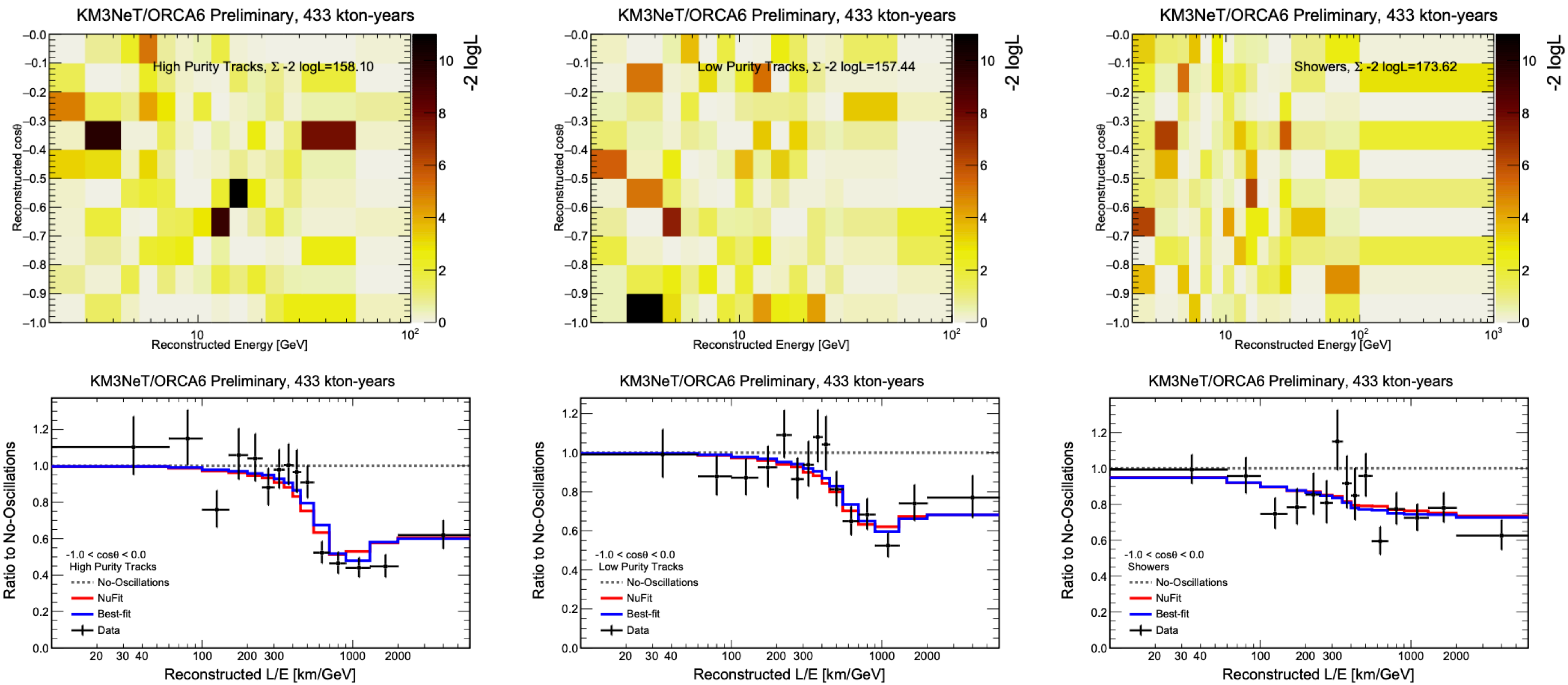
Showers



S. Peña, PoS(ICRC2023)1035.

Atmospheric oscillations

- Analysis strategy
  - Bins zenith, energy, and event types

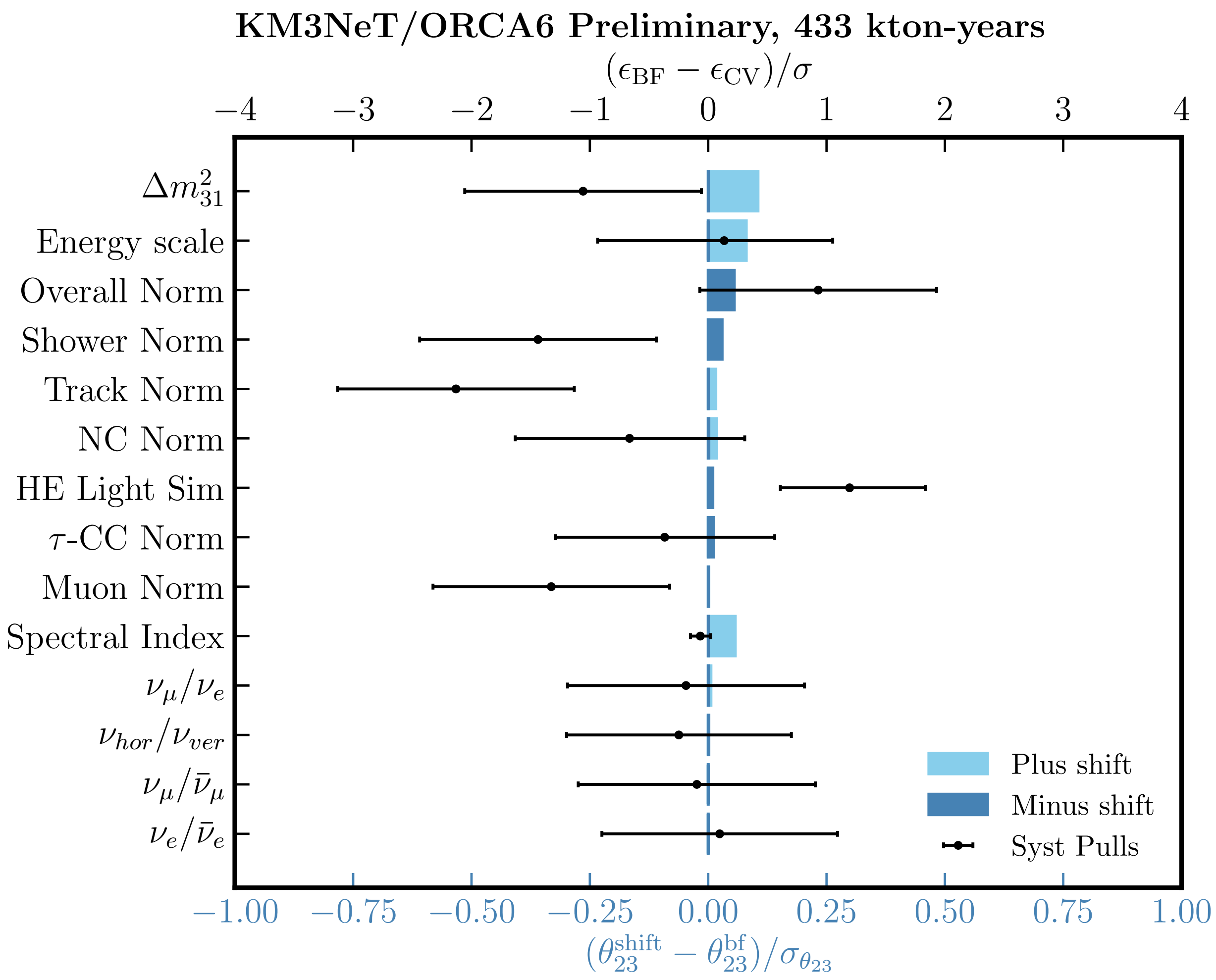


High Purity Tracks | Low Purity Tracks | Showers

Systematics

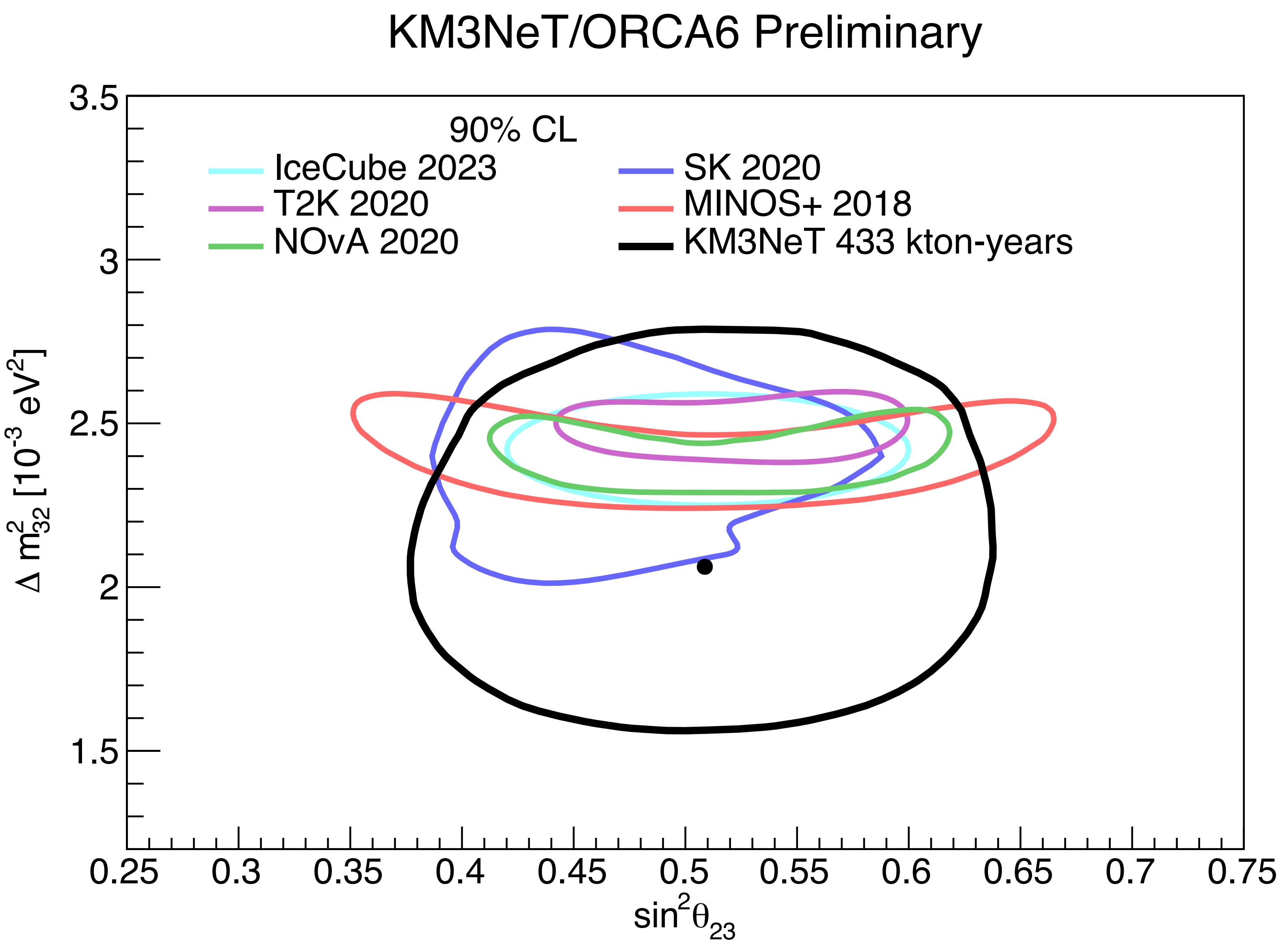
- 13 nuisance parameters to model flux, cross section and detector uncertainties
  - Gaussian penalty terms (priors) introduced for some of them
  - Values fitted within boundaries

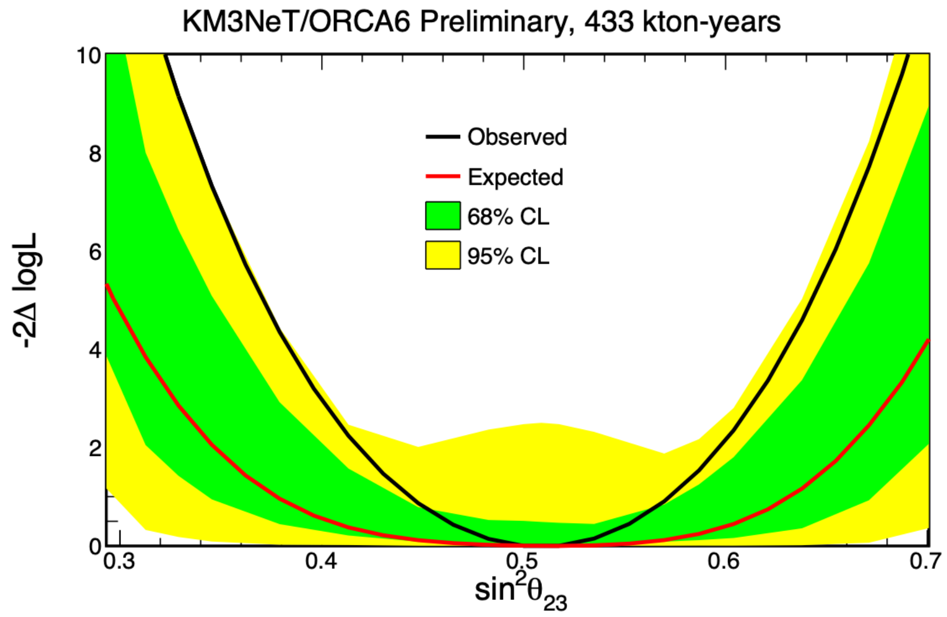
Systematic	Expectation, $\langle \epsilon_k \rangle$	Std deviation, σ_k
Overall normalisation	1	No prior
Track normalisation	1	No prior
Shower normalisation	1	No prior
NC normalisation	1	20%
τ-CC normalisation	1	20%
High Energy Light Sim.	1	50%
Atm. muon normalisation	1	No prior
$\nu_\mu/\bar{\nu}_\mu$ skew	0	5%
$\nu_e/\bar{\nu}_e$ skew	0	7%
ν_μ/ν_e skew	0	2%
ν_{hor}/ν_{ver} skew	0	2%
Spectral index	0	0.3
Energy scale	1	9%

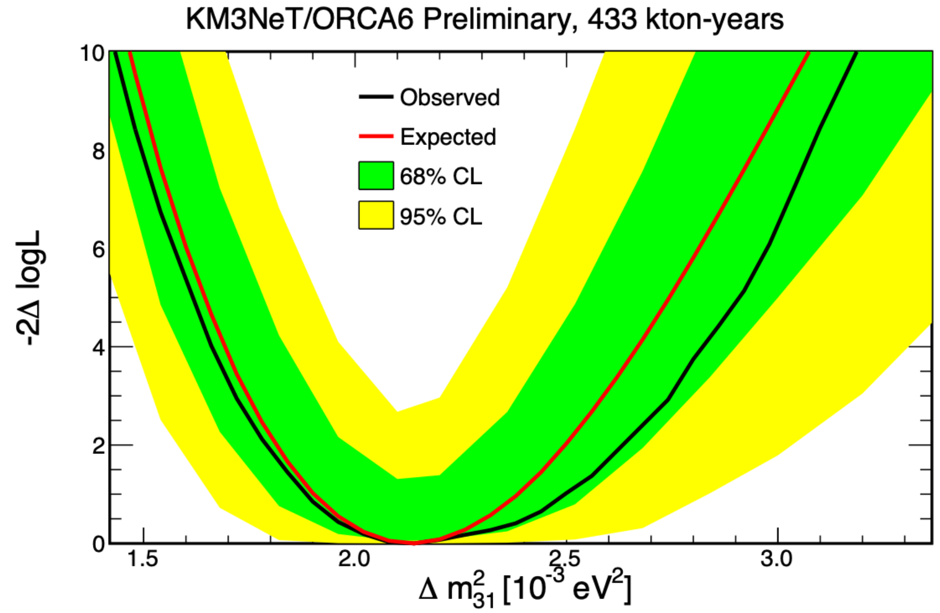


Atmospheric oscillations

- Results compatible with the existing measurements
- Dedicated talk on tau appearance → Spoiler alert: Very competitive!





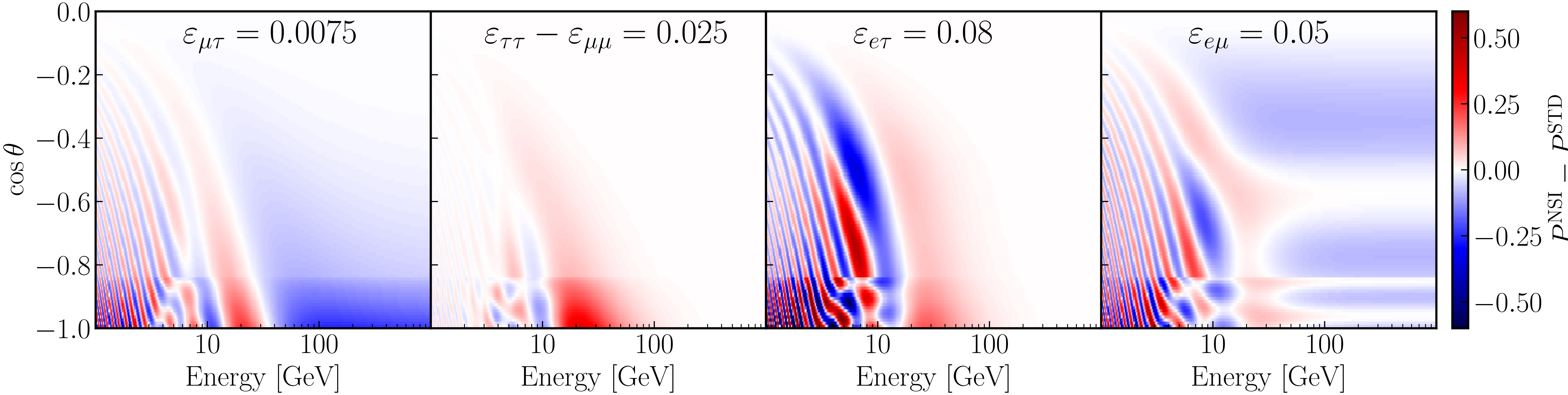


V. Carretero, PoS(ICRC2023)996

Non Standard Interactions

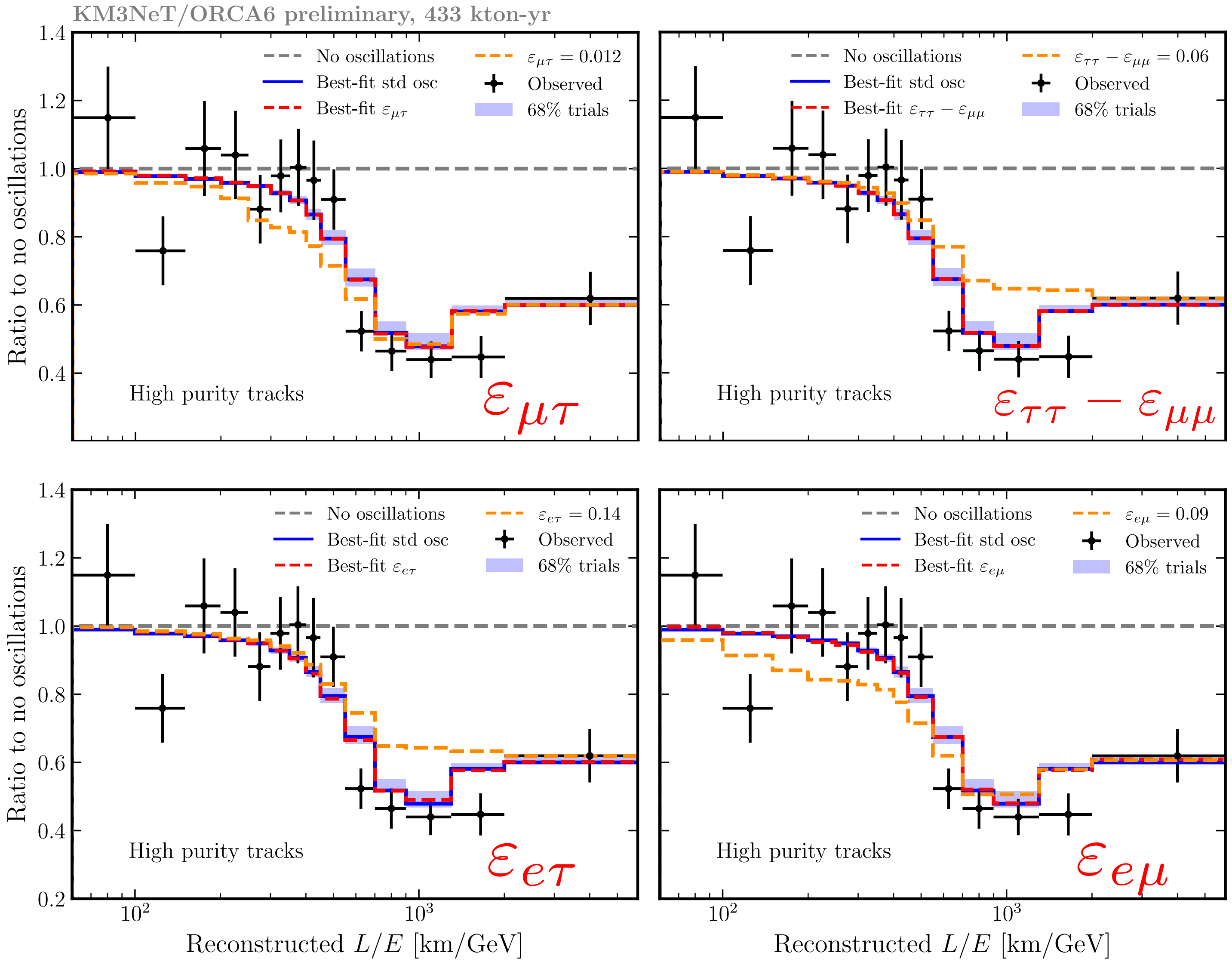
- NC NSIs may alter neutrino oscillations in matter
  - Very sensitive to $\varepsilon_{\mu\tau}$ and $\varepsilon_{\tau\tau}$-$\varepsilon_{\mu\mu}$

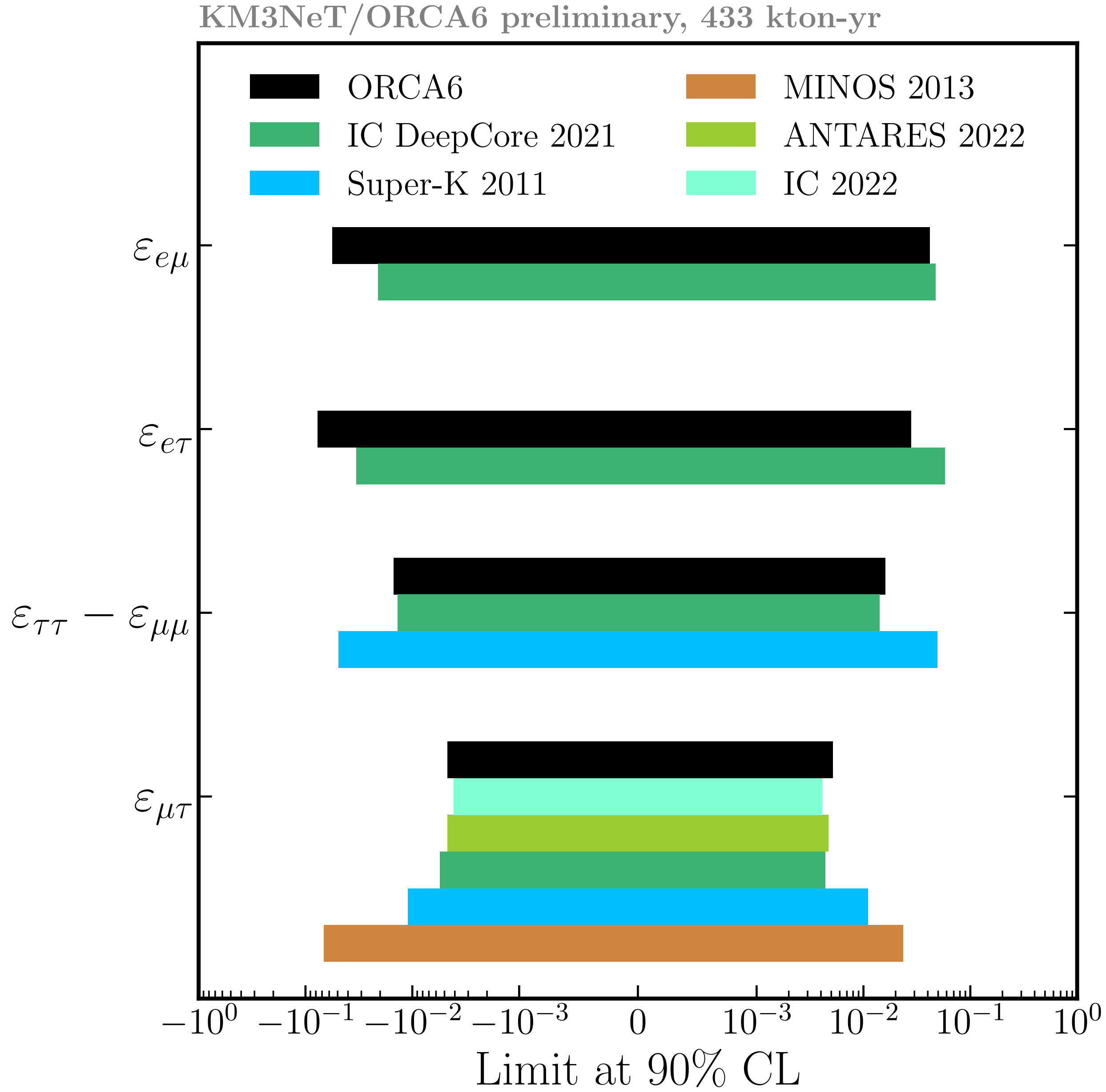
$$\mathcal{H}_{\text{eff}} = \frac{1}{2\text{E}}\mathcal{U}_{PMNS}\begin{bmatrix} 0 & 0 & 0 \\ 0 & \Delta \text{m}^2_{21} & 0 \\ 0 & 0 & \Delta \text{m}^2_{31} \end{bmatrix}\mathcal{U}^{+}_{PMNS} + \text{A}(x)\begin{bmatrix} 1+\varepsilon_{\text{ee}} & \varepsilon_{\text{e}\mu} & \varepsilon_{\text{e}\tau} \\ \varepsilon^*_{\text{e}\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon^*_{\text{e}\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau} \end{bmatrix}, \quad \text{A}(x) = \sqrt{2}G_F n_{\text{e}}(x)$$



Non Standard Interactions

- Competitive constraints for multiple parameters

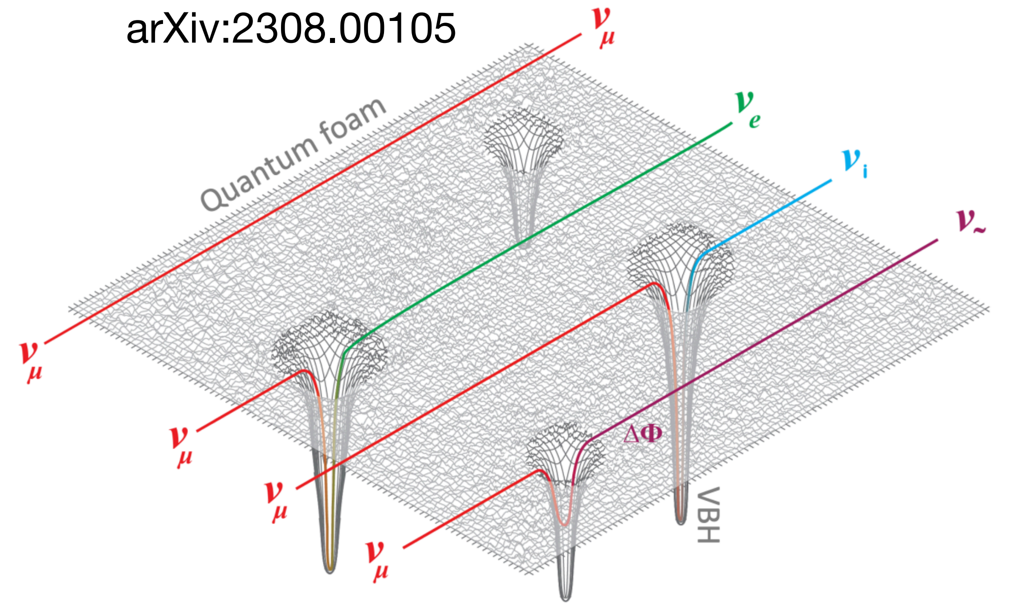




A. Lazo, PoS(ICRC2023)998

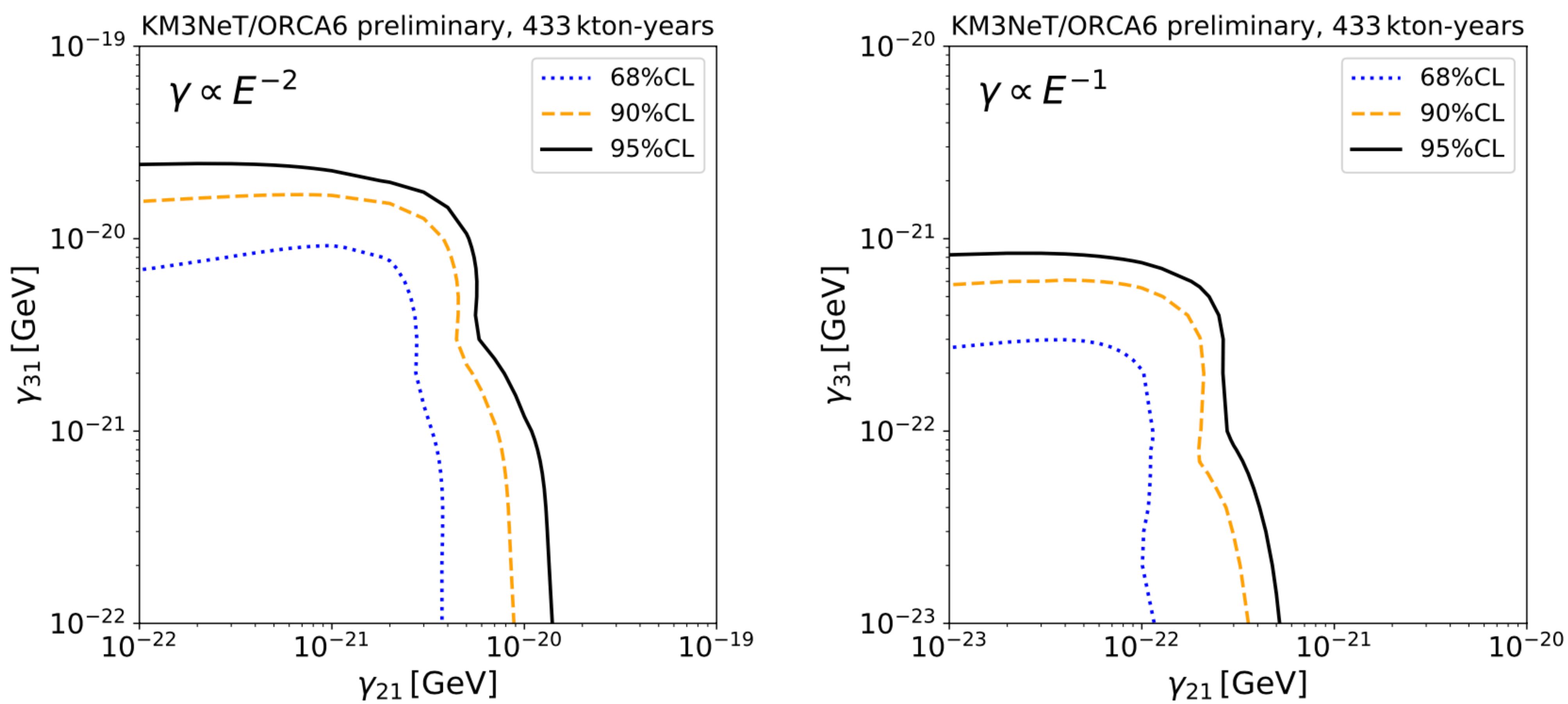
Quantum decoherence

arXiv:2308.00105



- Neutrinos may interact with fluctuating spacetime
  - Decoherence of neutrino oscillations

$$P(\nu_\alpha \to \nu_\beta) = \sum_{i,j} \tilde{U}_{\alpha i}\tilde{U}^*_{\beta i}\tilde{U}^*_{\alpha j}\tilde{U}_{\beta j} e^{-i\Delta\tilde{E}_{ij}t - \gamma_{ij}t} \qquad \gamma_{ij} = \gamma^0_{ij}\left(\frac{E}{\mathrm{GeV}}\right)^n$$

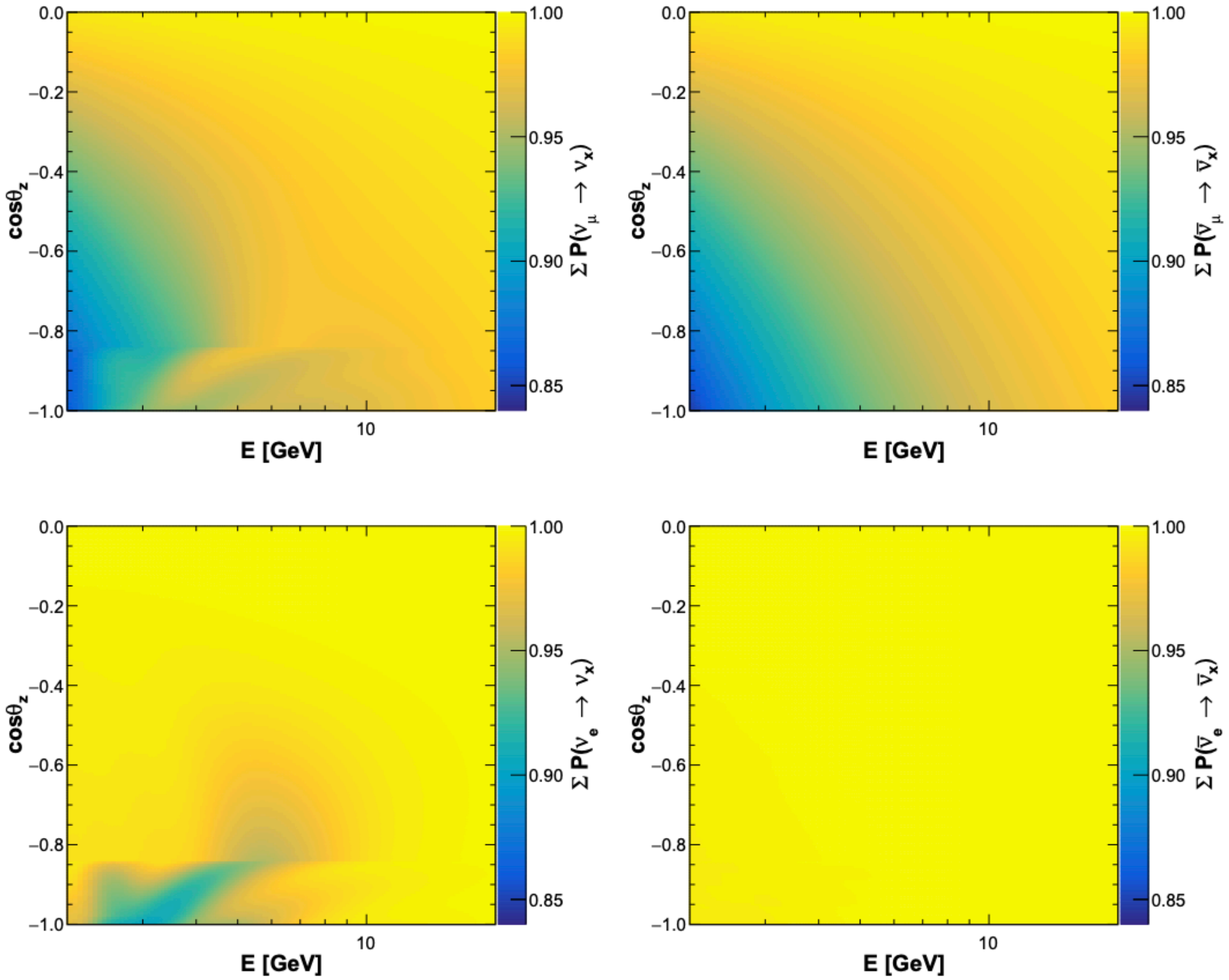


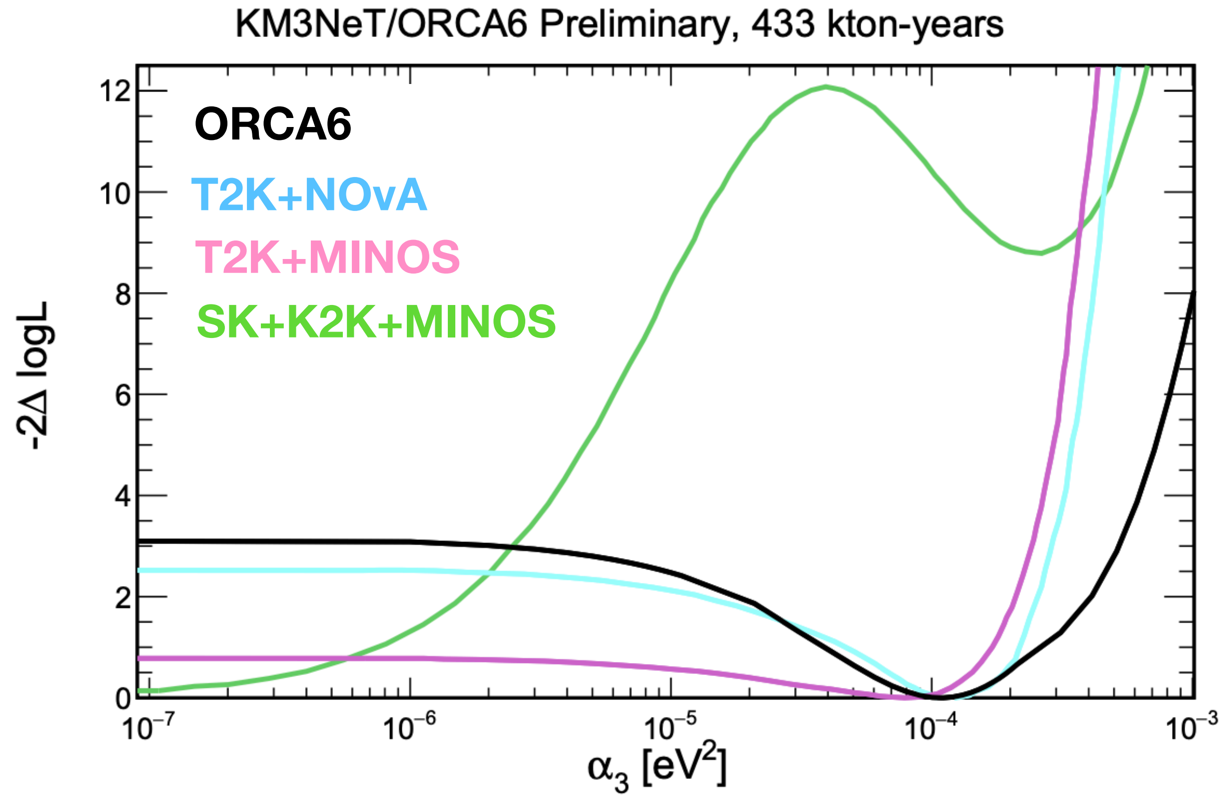
N. Lessing, PoS(ICRC2023)1025

Invisible Decay

- Damping term in the third mass state → Non-unitarity
  - Latest analysis shows a 1.8 σ for preference decay scenario

$$H_{\text{Total}} = \frac{1}{2E}\left[U\begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m_{21}^2 & 0 \\ 0 & 0 & \Delta m_{31}^2 \end{pmatrix}U^\dagger + U\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -i\alpha_3 \end{pmatrix}U^\dagger\right] + \begin{pmatrix} V & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

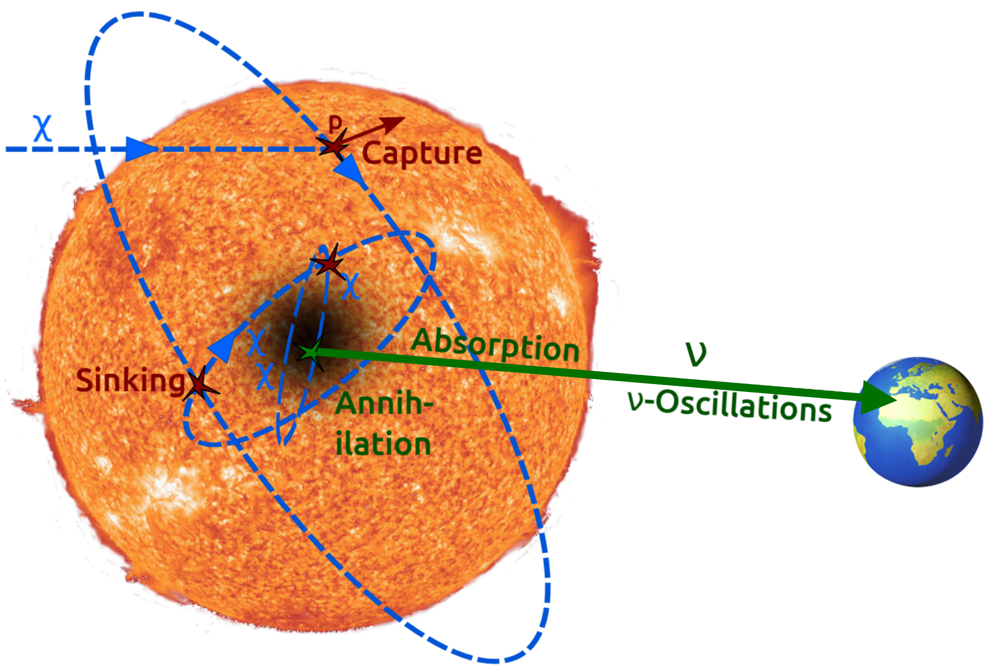




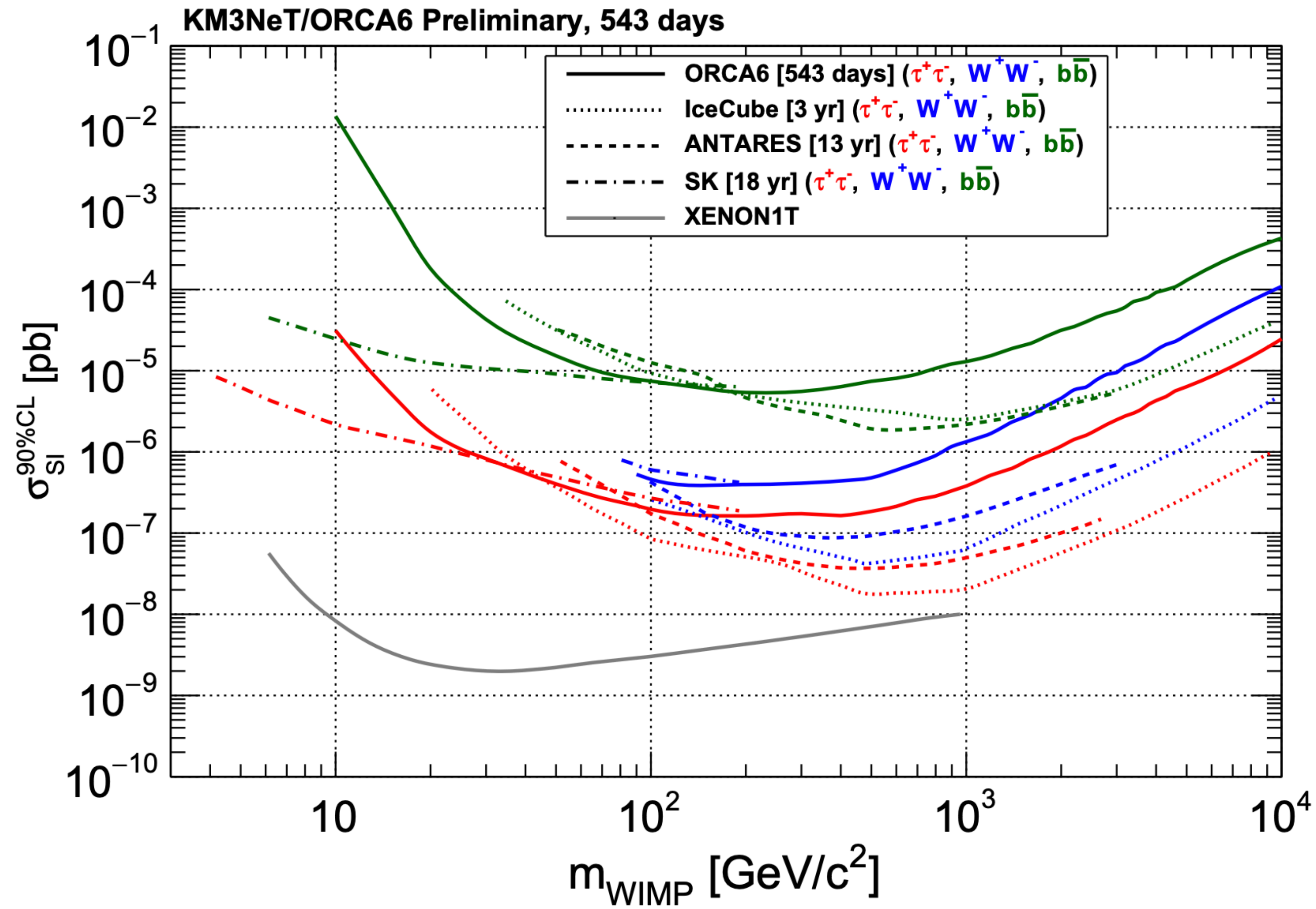
V. Carretero, PoS(ICRC2023)997

Dark matter

- Annihilation of dark matter particles in the Sun
  - Expect an excess of neutrinos in that direction (annihilation channels → different energy spectrums)



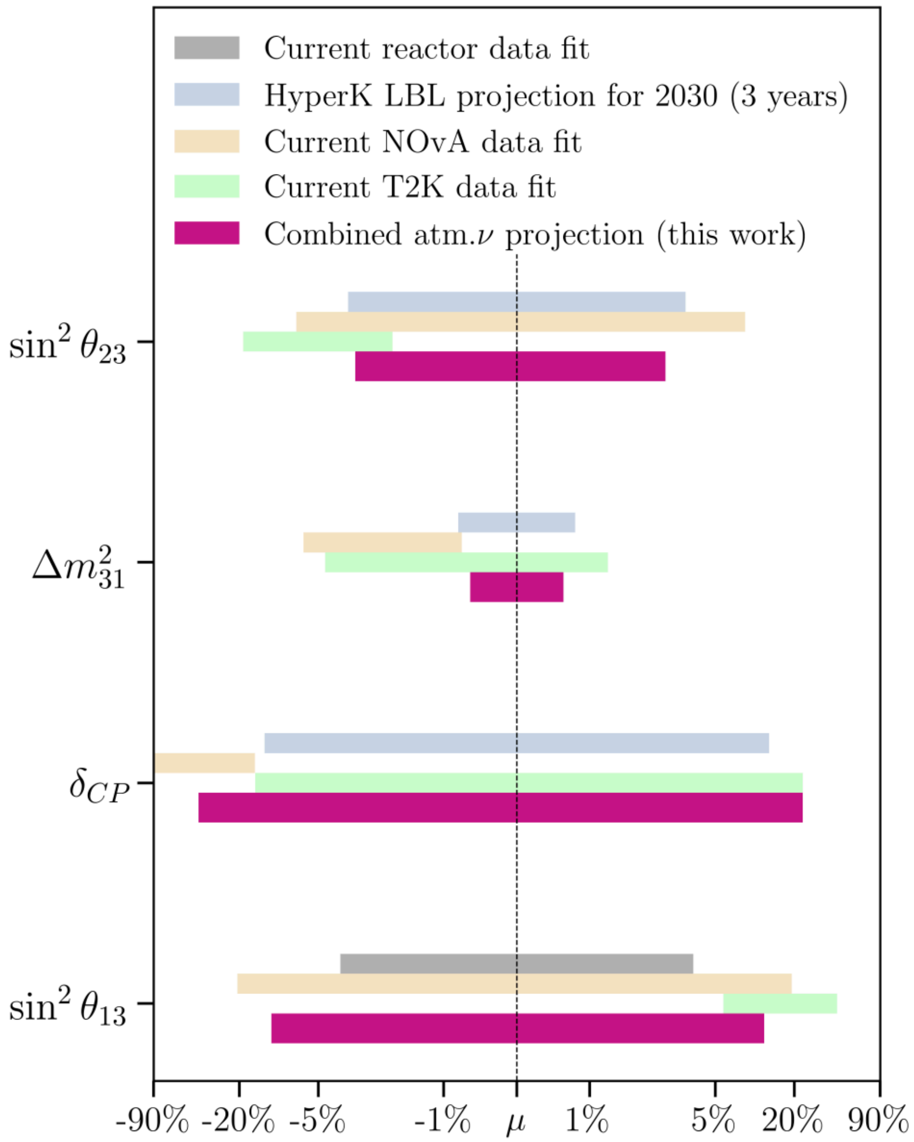
M. C. R. Zoll (Thesis, 2016)

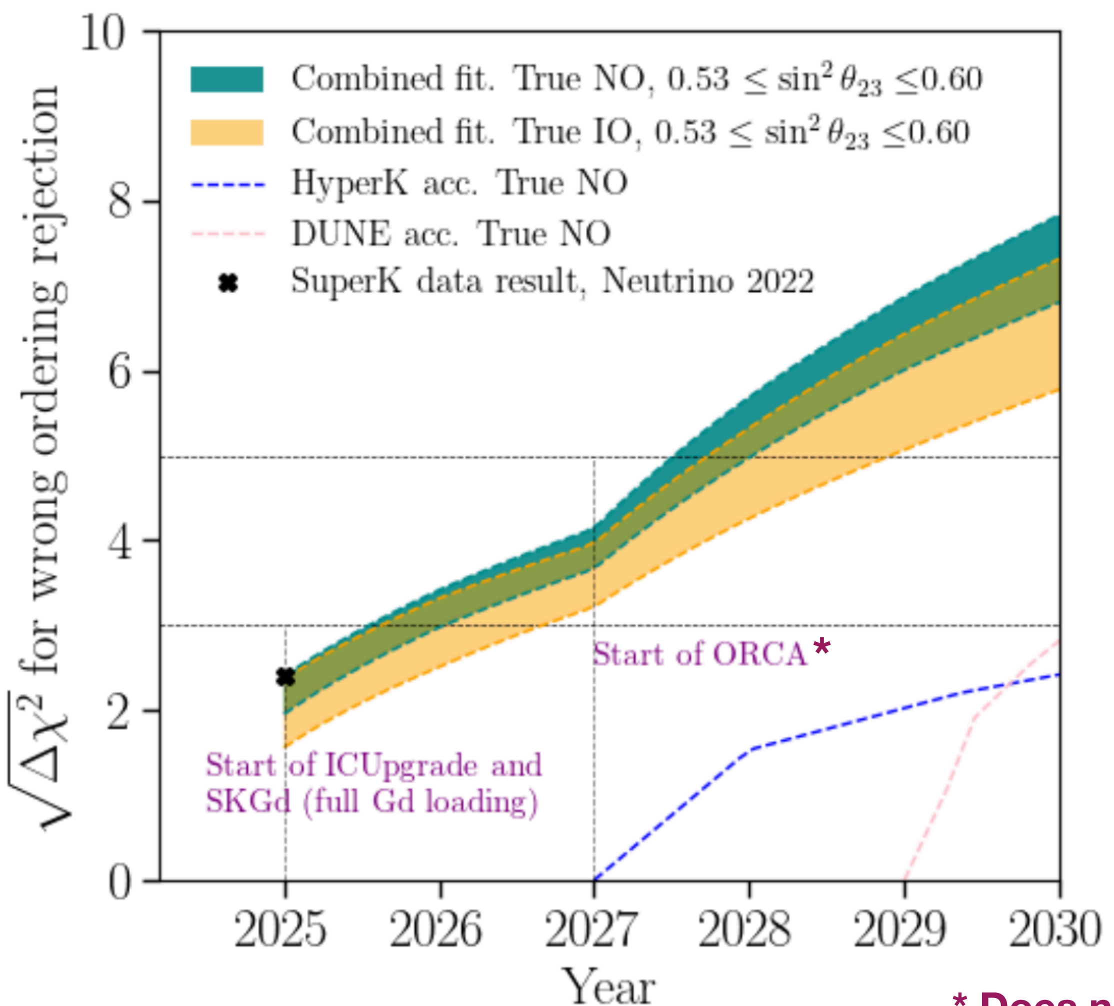


M. Gutierrez, PoS(ICRC2023)1406

Prospects – Standard oscillation

- Before the end of the decade
  - More detectors: SuperK-Gd, IC-Upgrade, KM3NeT-ORCA115, HyperK.
  - Combination with JUNO enhances NMO sensitivity





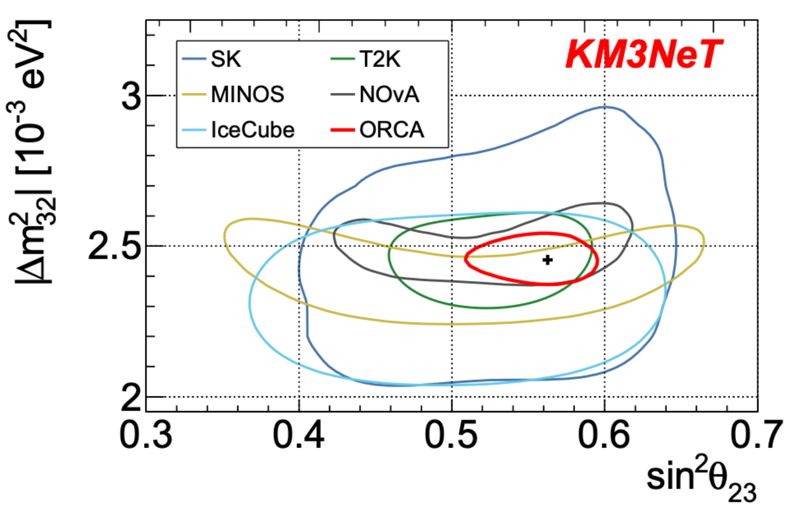
arXiv:2211.02666

*** Does not account for ORCA data with smaller configurations**

Conclusions

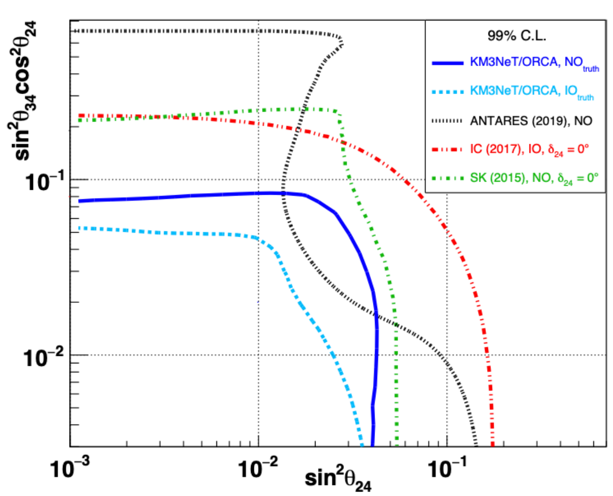
- Take home message from new results of ORCA
  - Calibration and data/MC → better understanding of the detector
  - Competitive results using 5% of the final configuration!
- Prospects:
  - Already collected over 1200 kton-year of data -> ready to analyse
  - Final configuration will play an important role in measuring neutrino oscillations, searching for new physics, and GeV neutrino astronomy.

Standard oscillations



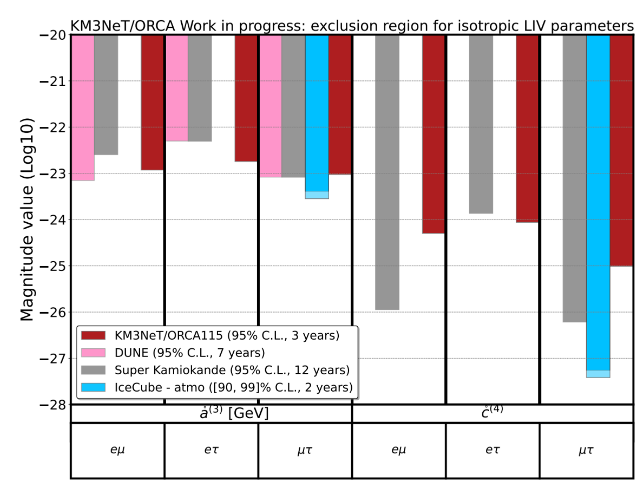
Eur. Phys. J. C 82, 26 (2022)

Sterile Neutrinos



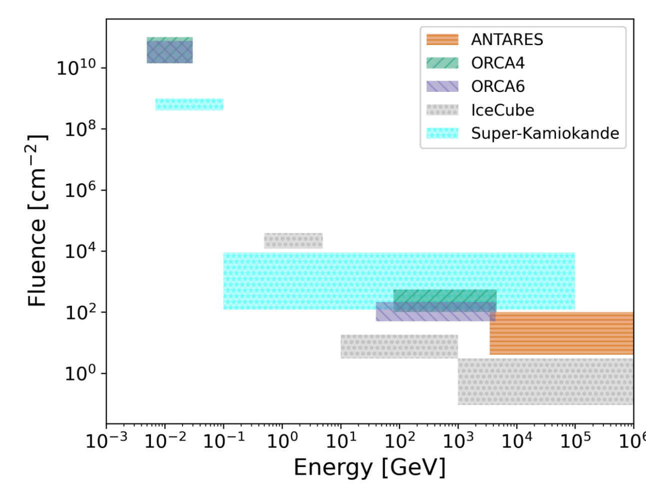
JHEP 10, 180 (2021)

Lorentz Violation

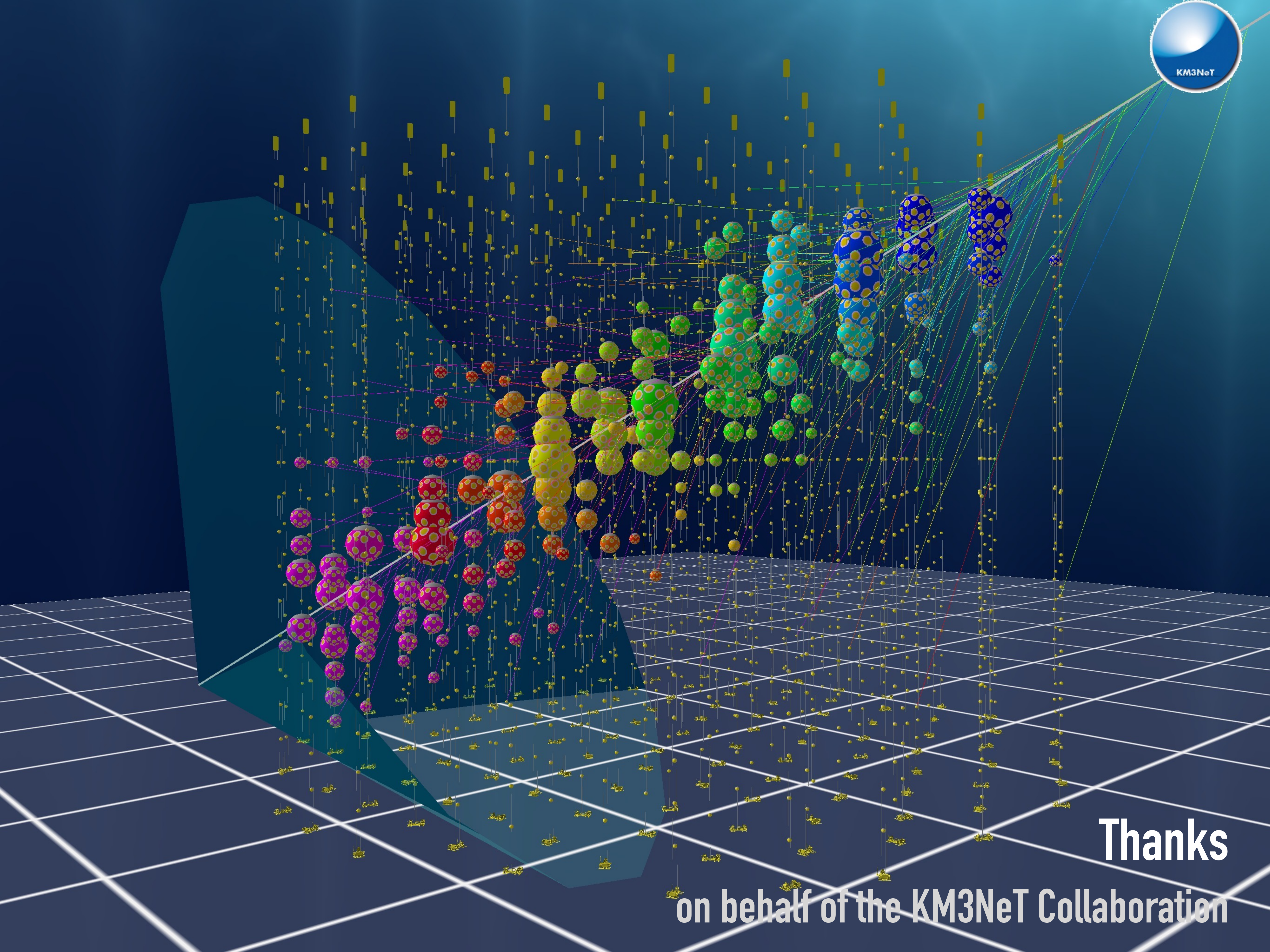


A. Domi, PoS(ICRC2023)1086

GW counterparts



arXiv:2311.03804



Thanks

on behalf of the KM3NeT Collaboration

Acknowledgement:

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