Future* detectors for atmospheric neutrinos

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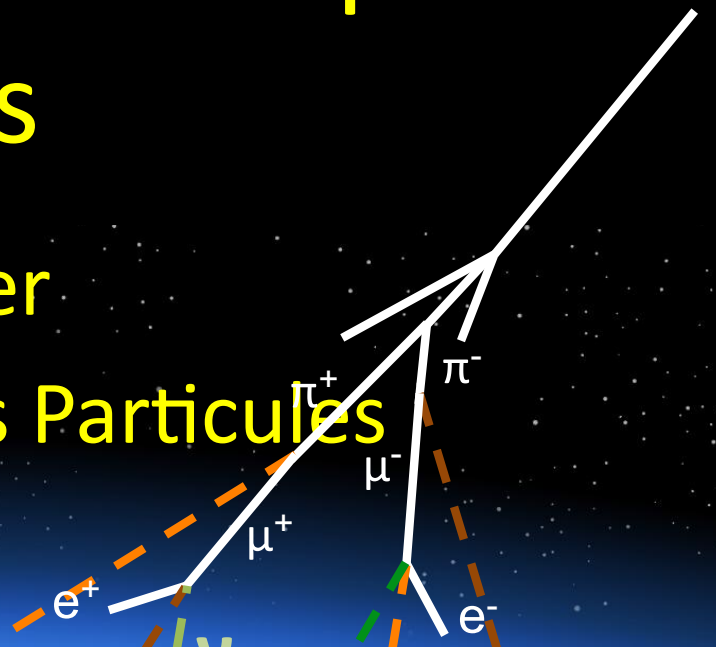
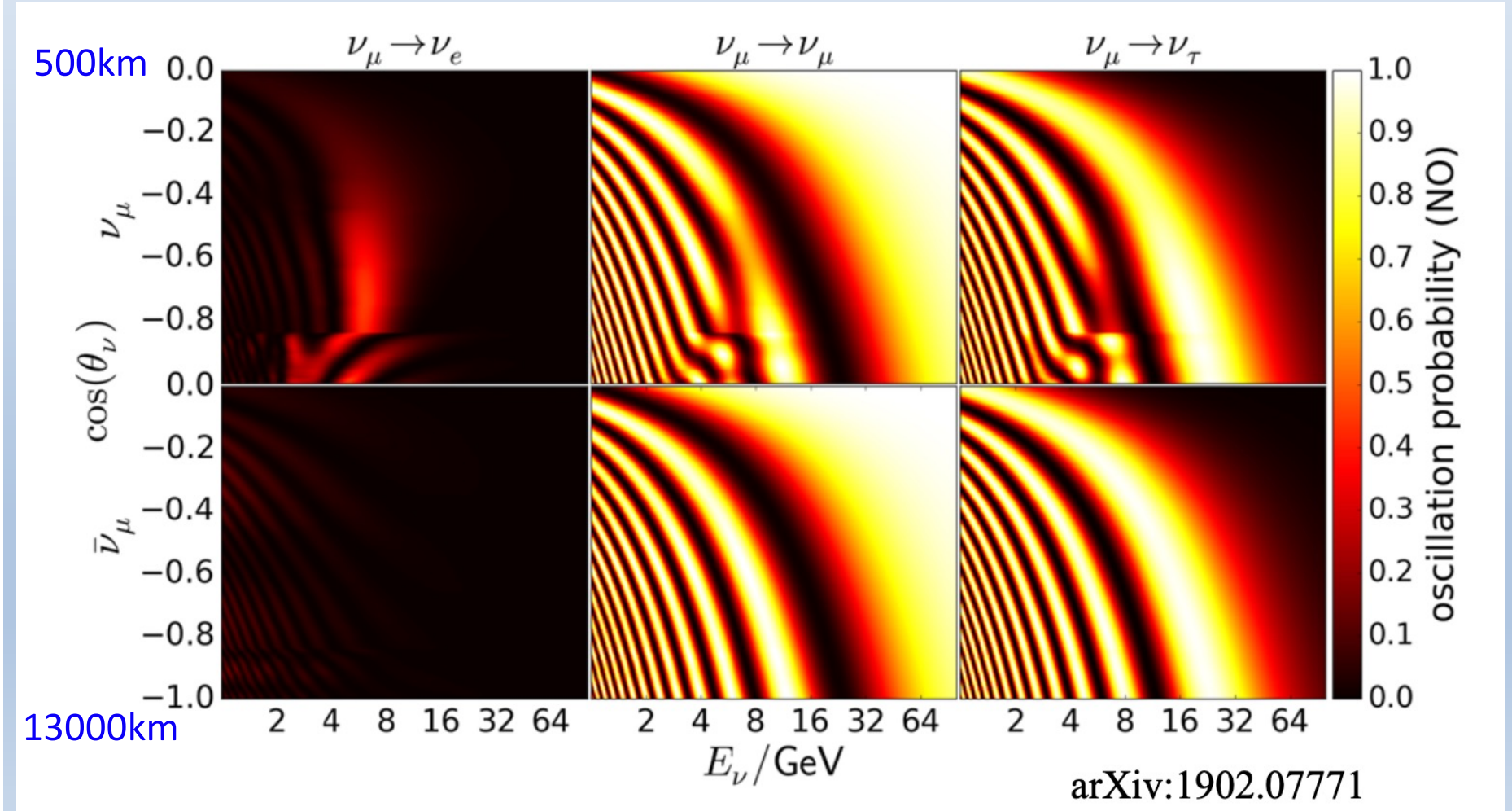


* This decade

XXXI International Conference on Neutrino Physics and Astrophysics
June 16-22, 2024 Milan, Italy

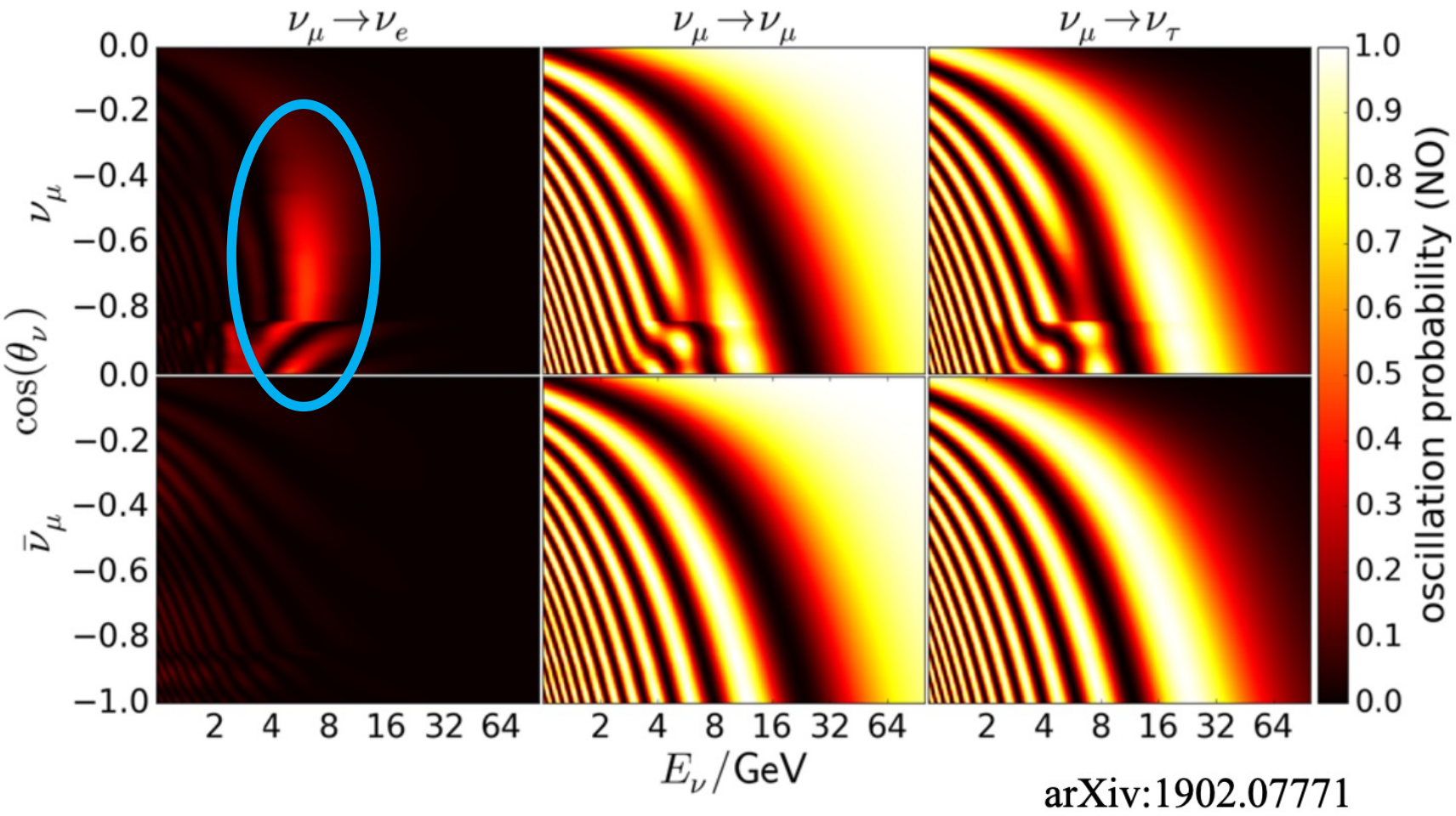
Neutrino oscillations

- Rich phenomenology in the 1-100 GeV energy range
- Baselines between 500 km and 13000 km



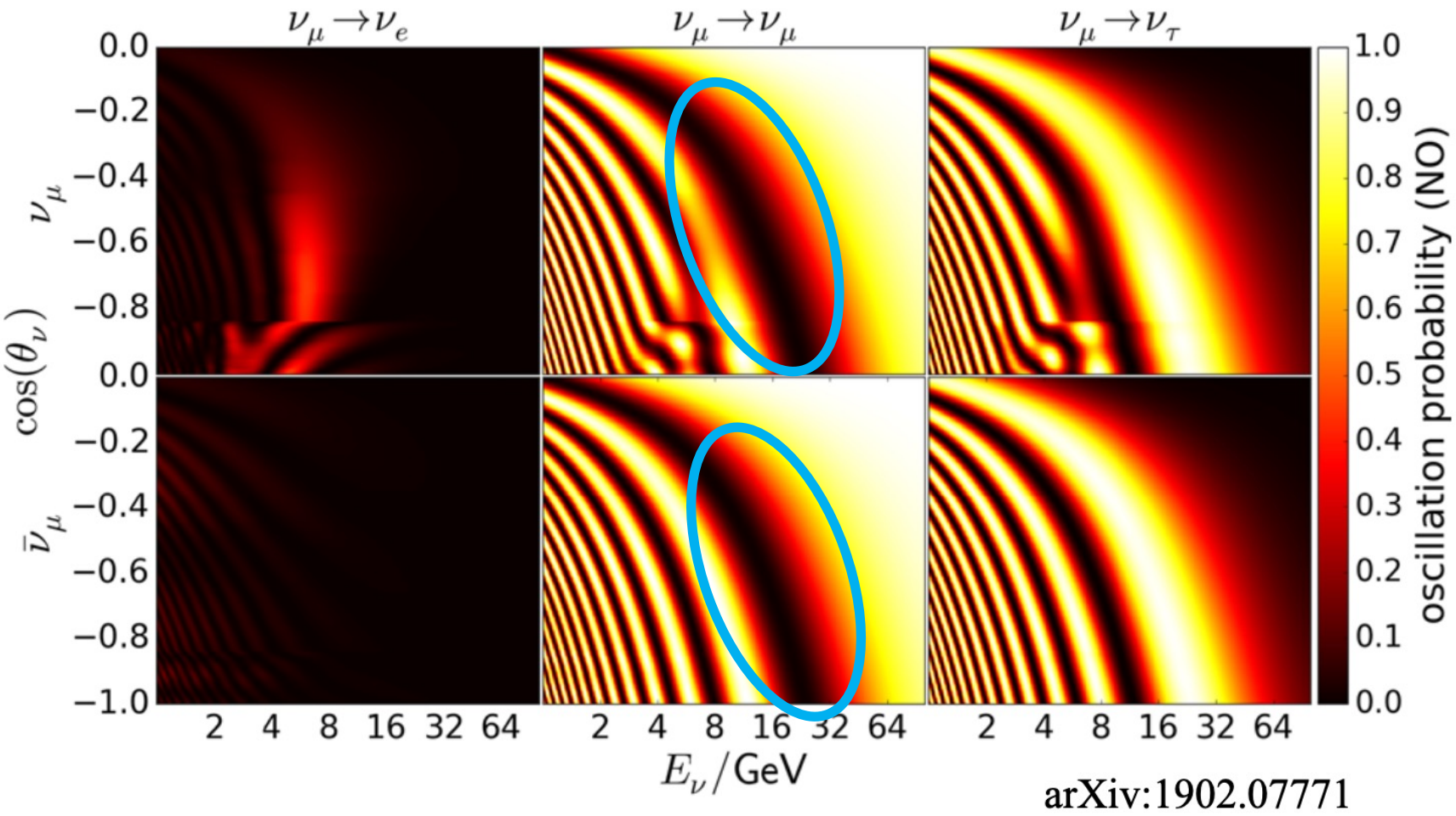
Neutrino oscillations

- Matter resonance 4-10 GeV
  → neutrino mass ordering



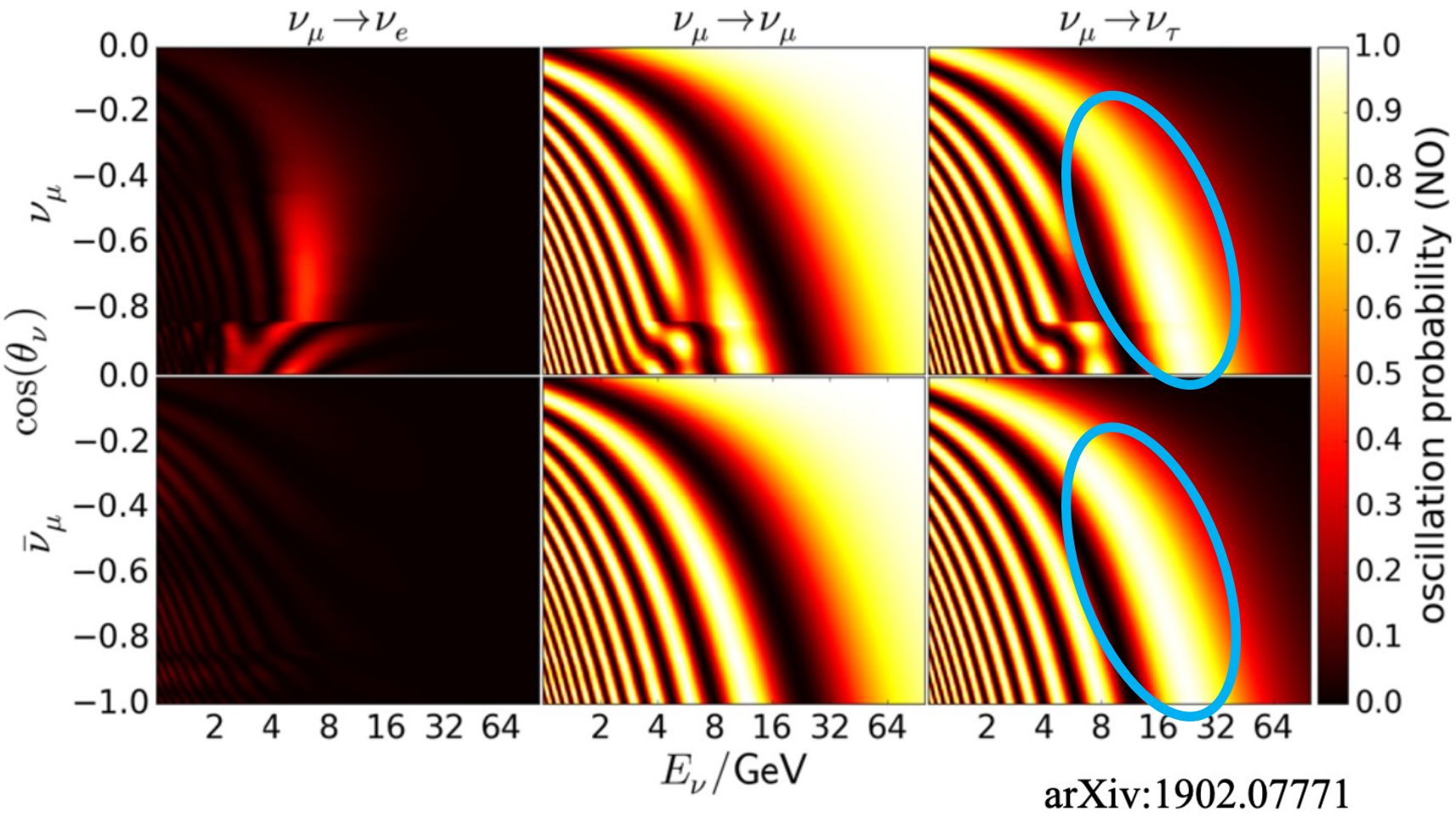
Neutrino oscillations

- ν_μ disappearance 10-40 GeV
  → precision measurements Δm^2_{31} , θ_{23}

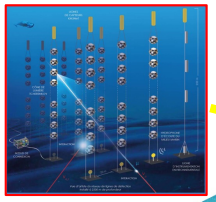


Neutrino oscillations

- ν_τ appearance 10-40 GeV
  → ν_τ cross section, ν_τ sector BSM tests

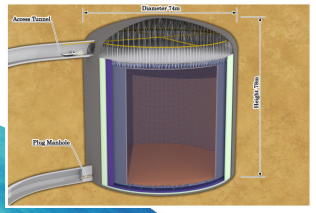


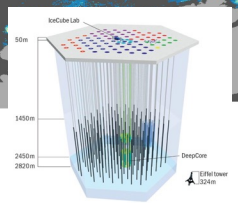
Next generation detectors



KM3NeT/ORCA

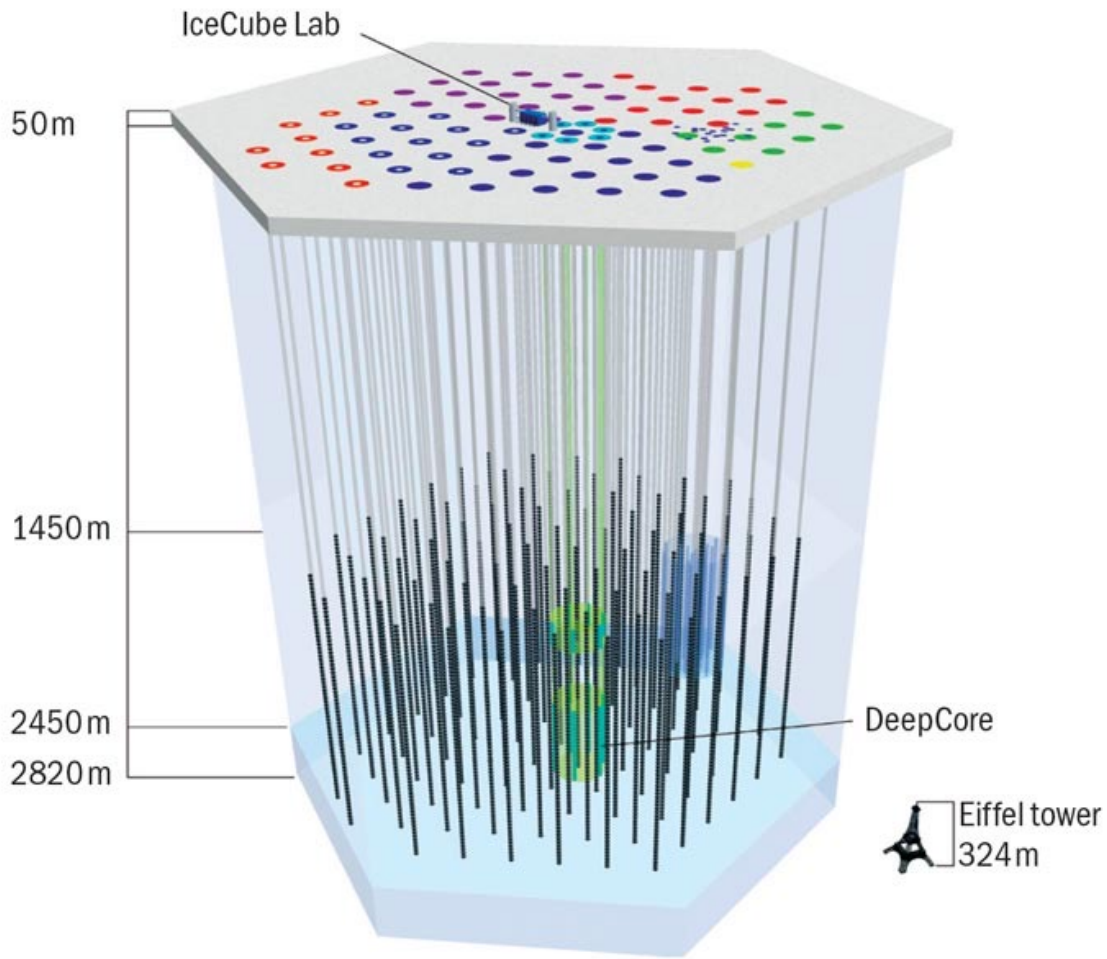
HyperKamiokande





IceCube-Upgrade

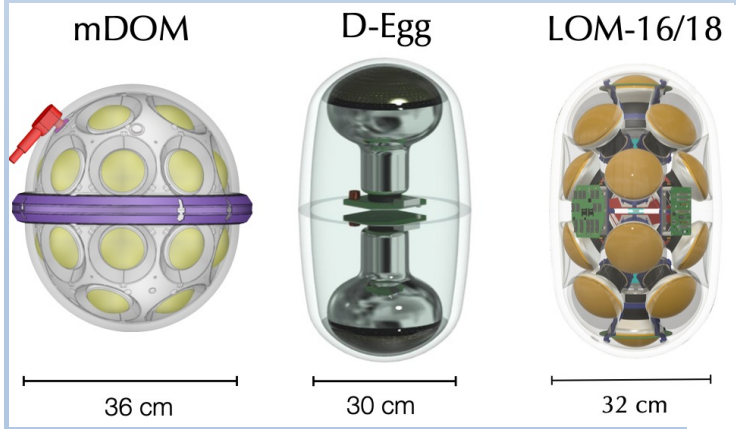
Detectors - IceCube / DeepCore

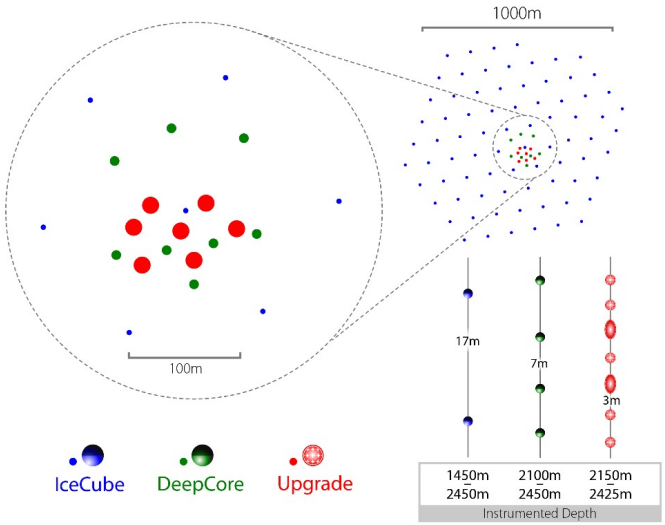


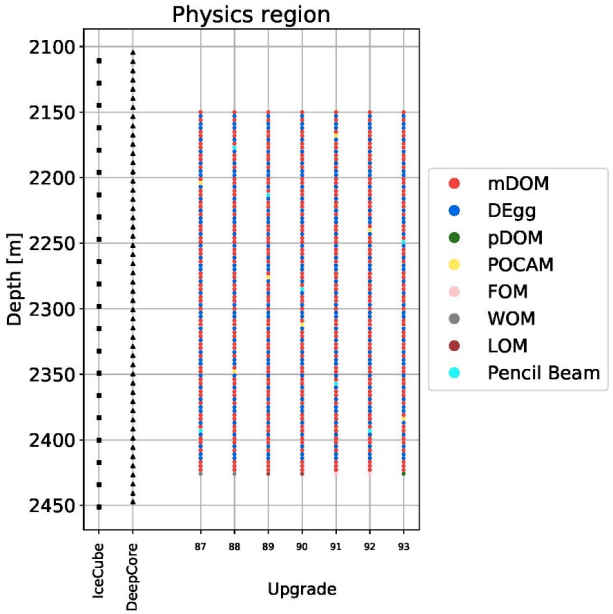
- 86 strings with 60 DOMs instrumenting $1km^3$
- Deep Core : dense core for atmospheric neutrino physics at 10-100 GeV
- Operational since 2011

Detectors - IceCube upgrade

- 7 new strings inside DeepCore region
- 20m string spacing, 3m module spacing
- Energy threshold lowered from ~10 GeV to ~2 GeV
- Several Mtons instrumented volume
- Installation during 2025/2026 campaign



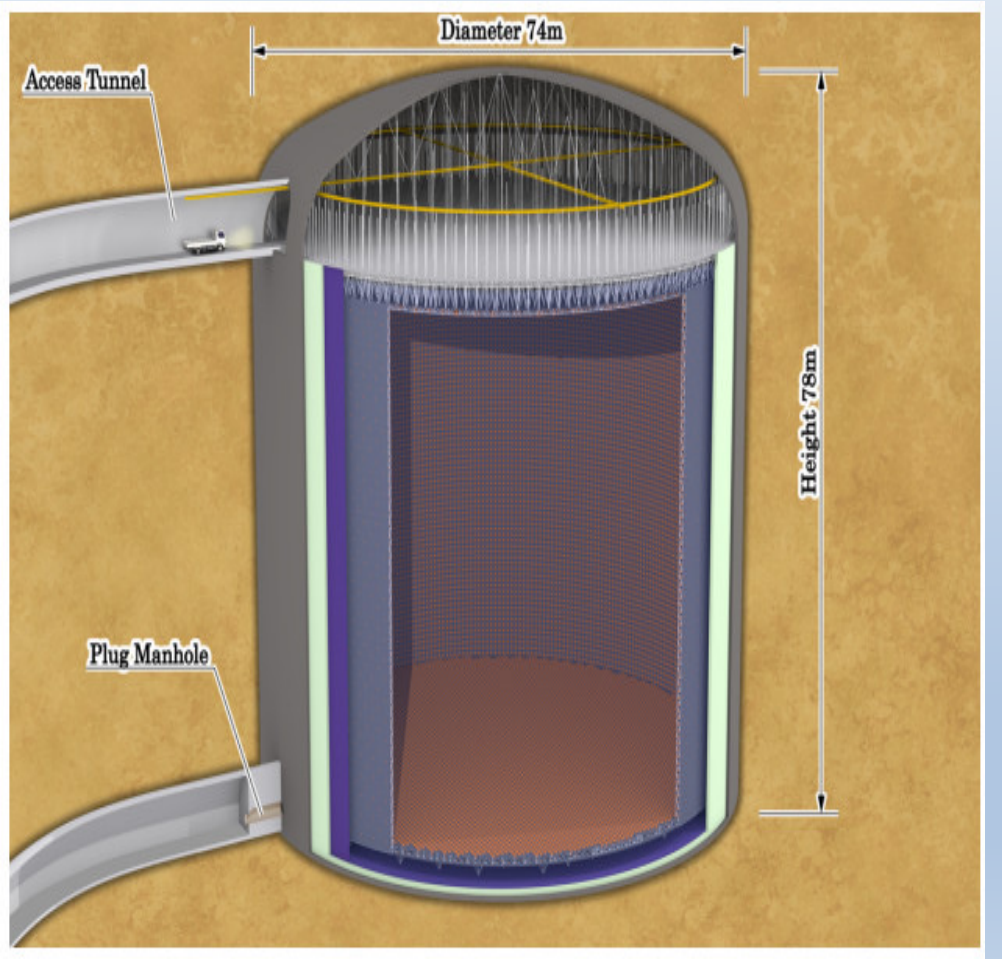




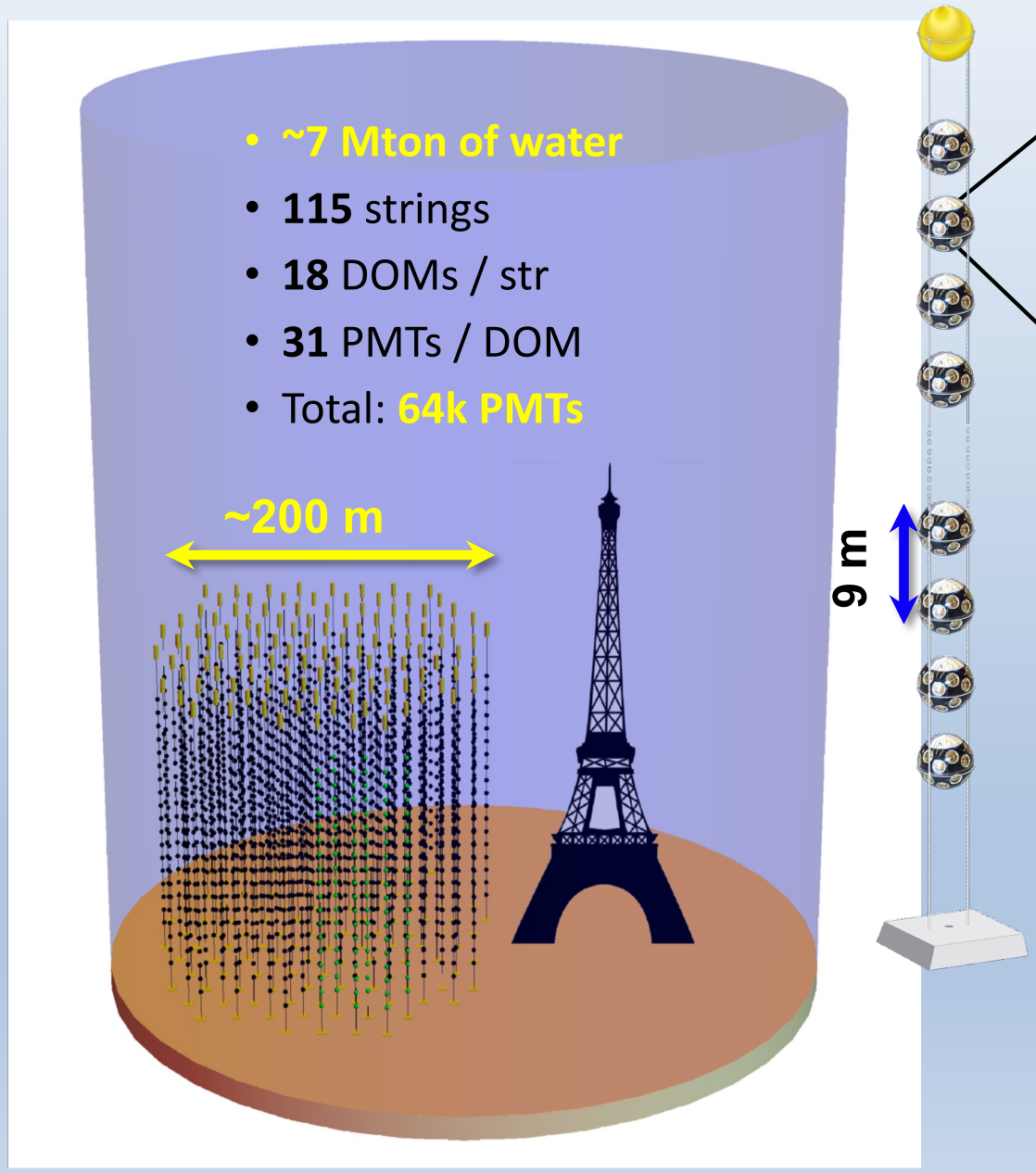
arXiv:1908.09441

Detectors - HyperKamiokande

- 258 kton of water
- Fiducial volume ~0.2 Mton
- 20,000 50cm PMTs
- Data taking start planned for 2027



Detectors - KM3NeT/ORCA



- Signals digitized inside module
  - Time stamp
  - time over threshold
- Compass for orientation
- Piezo for acoustic positioning

Detectors - Multi-PMTs

- Design developed by KM3NeT
- Applied now in all next-generation detectors
- Photon counting, nsec coincidences, directionality
- Better calibrations

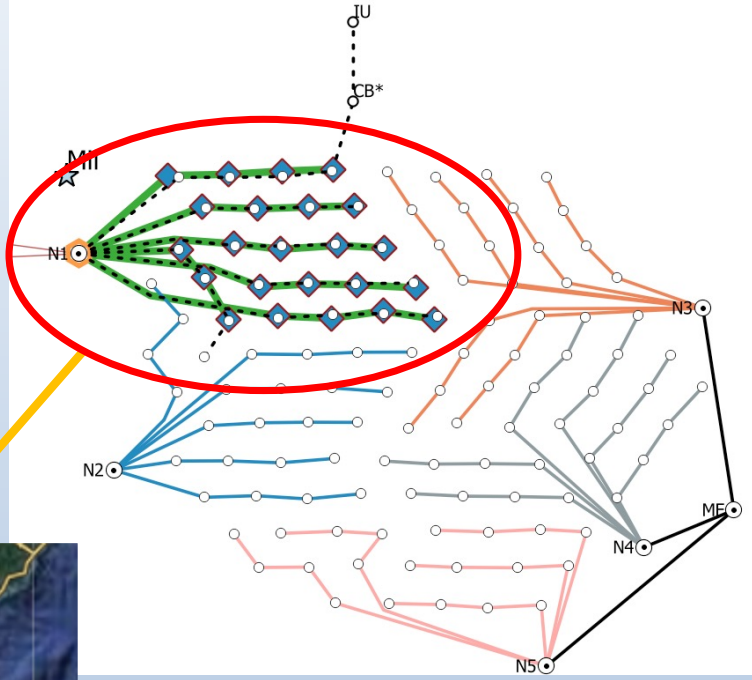
KM3NeT

IC upgrade

Hyperkamiokande

Detectors - Status of KM3NeT/ORCA

- 23 DUs installed on sea floor
- 20% of final detector

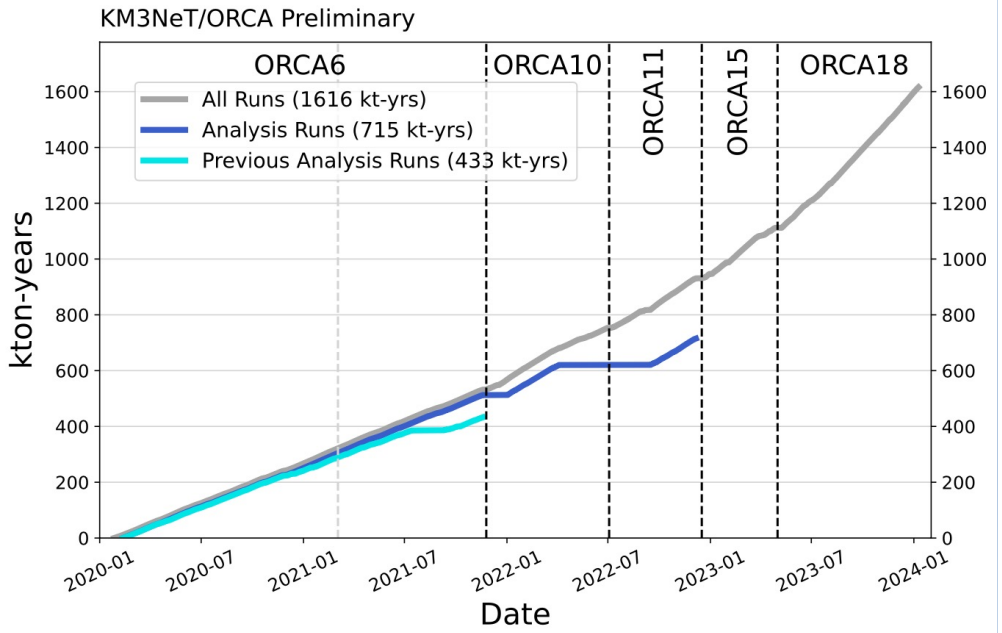


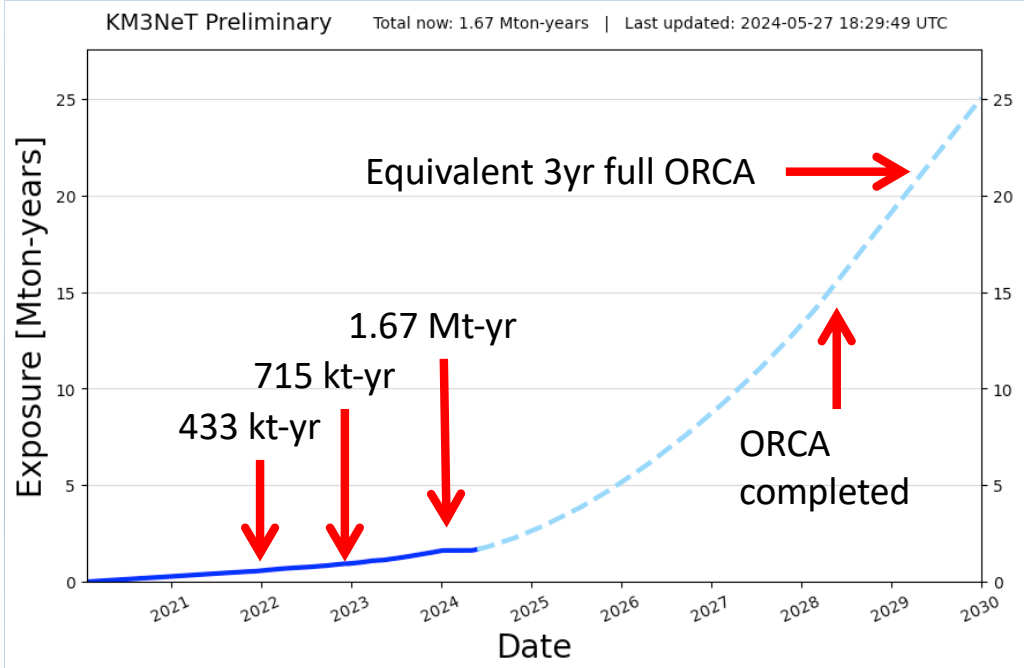
100m

Detectors - KM3NeT/ORCA construction

- Data taking and current analyses
- 433 and 715 kt-yr results
- 1.6 Mt-yr on tape

- Construction schedule
- Data sample equivalent of 3 years full ORCA before end of decade





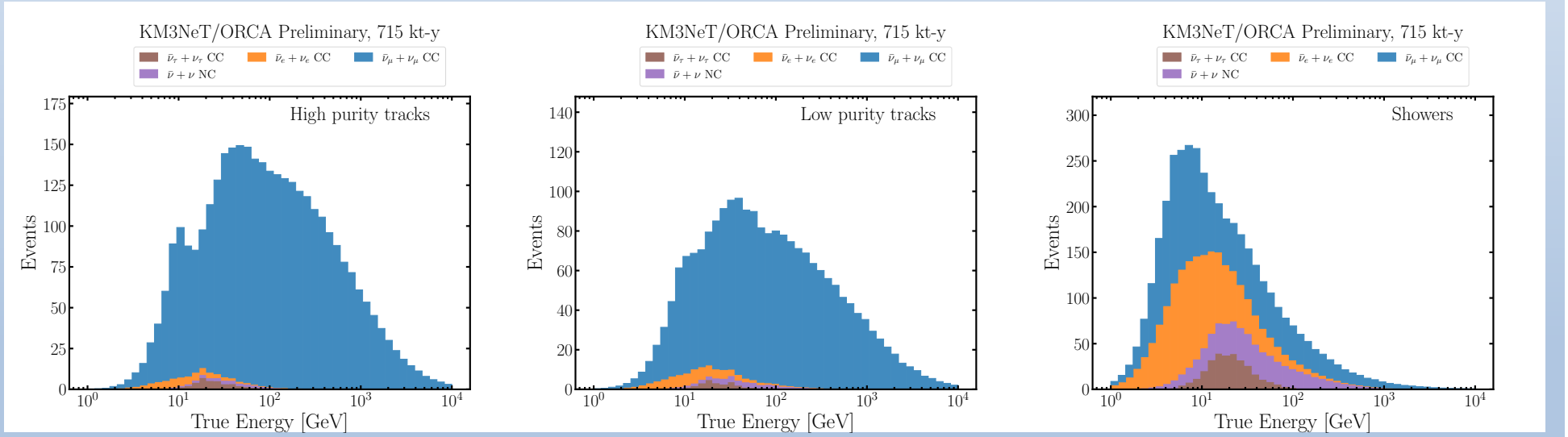
Event sample - KM3NeT/ORCA

- Extrapolation from current analysis 0.7 Mt-yr
- 3 particle ID classes

High-purity tracks
3400 events

low-purity tracks
2000 events

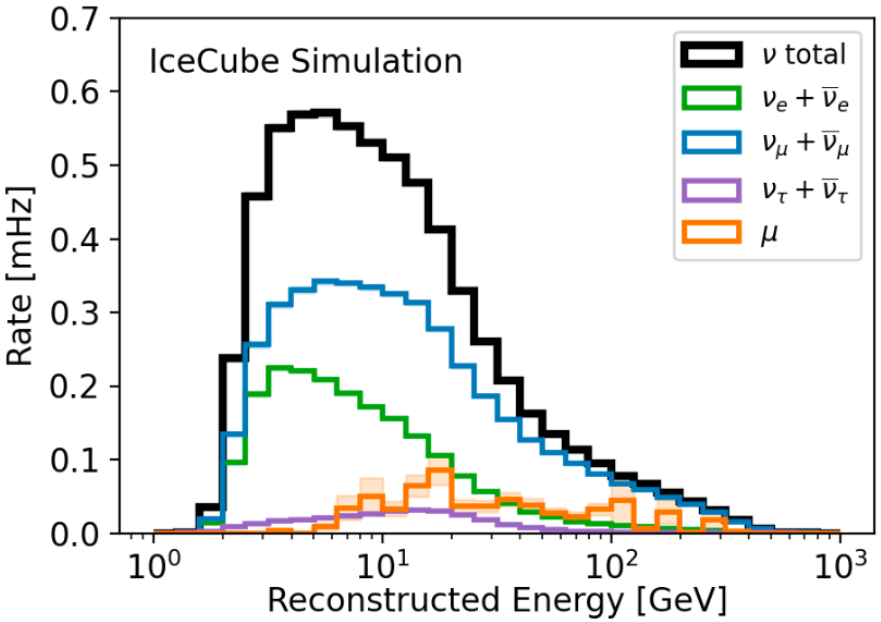
showers
3800 events

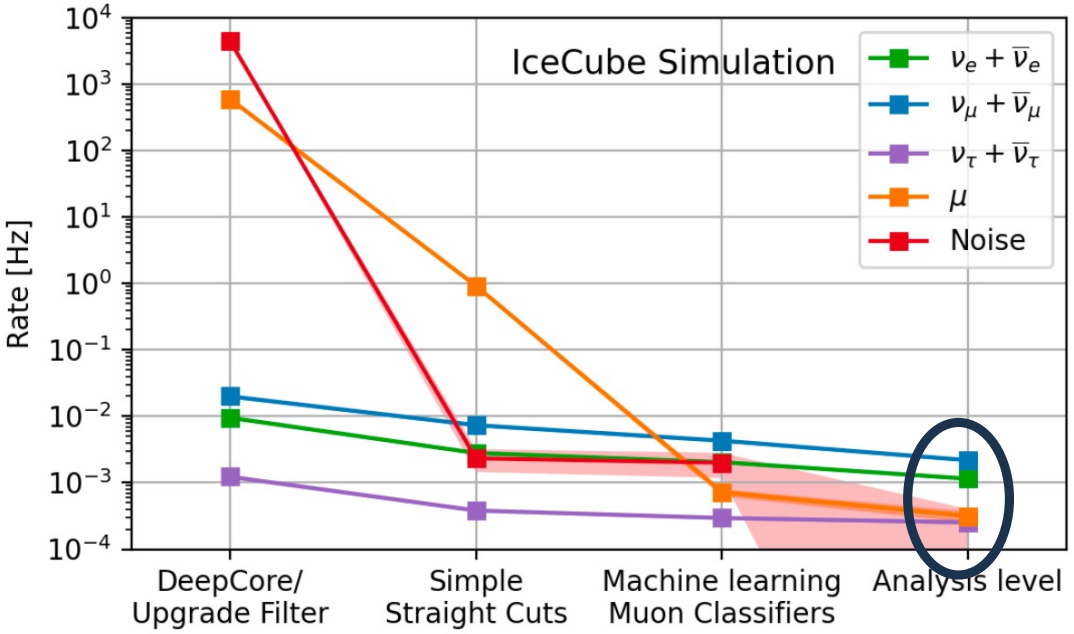


- full ORCA (7 Mt-yr) : 90,000 neutrinos per year
- 2 GeV – few TeV

Event sample - IC upgrade

- 3mHz → 90,000 neutrinos per year
- 2-100 GeV

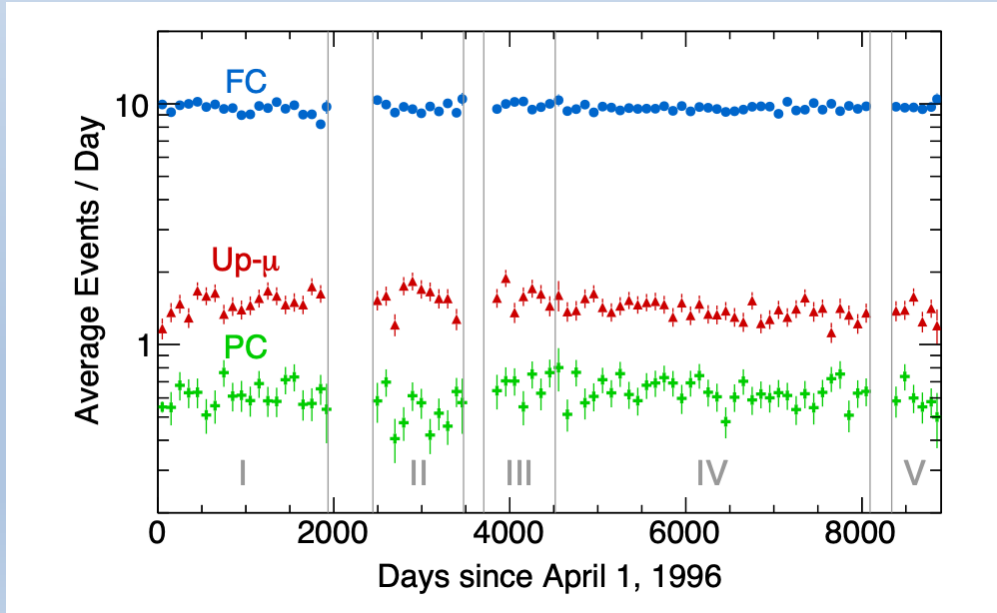


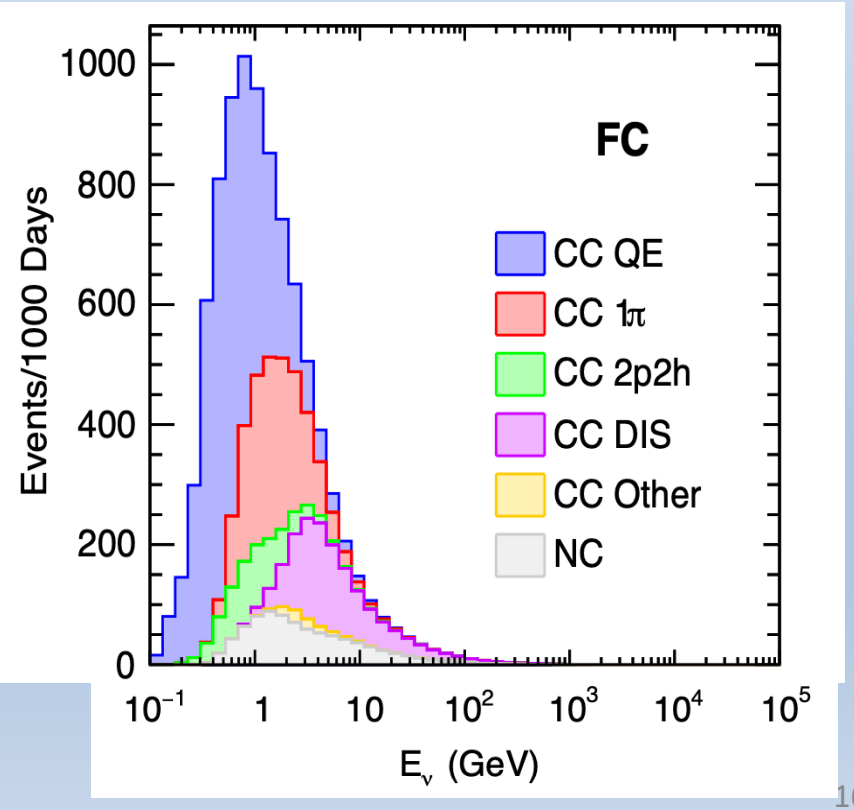


arXiv:2307.15295

Event sample - Hyperkamiokande

- Extrapolation from Superkamiokande
- 80 events per days → 30,000 neutrinos per year
- Dominantly fully contained (FC) events 0.2-20 GeV



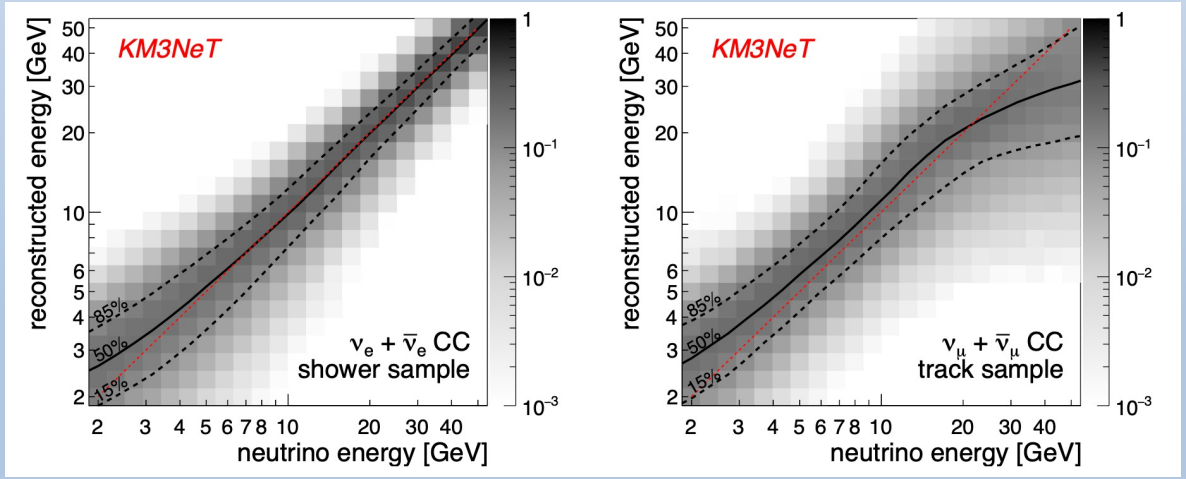


Phys. Rev. D 109, 072014 (2024)

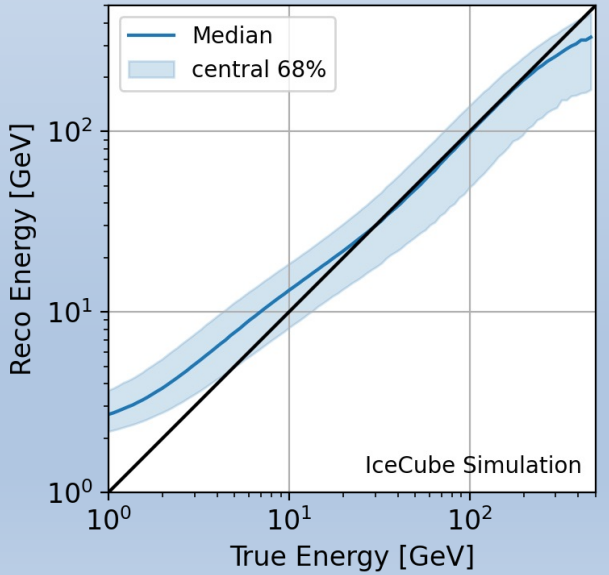
Detector response - energy resolution

- KM3NeT/ORCA
- At 10 GeV 25% for ν_e and 35% for ν_μ

- IC upgrade
- Similar performance



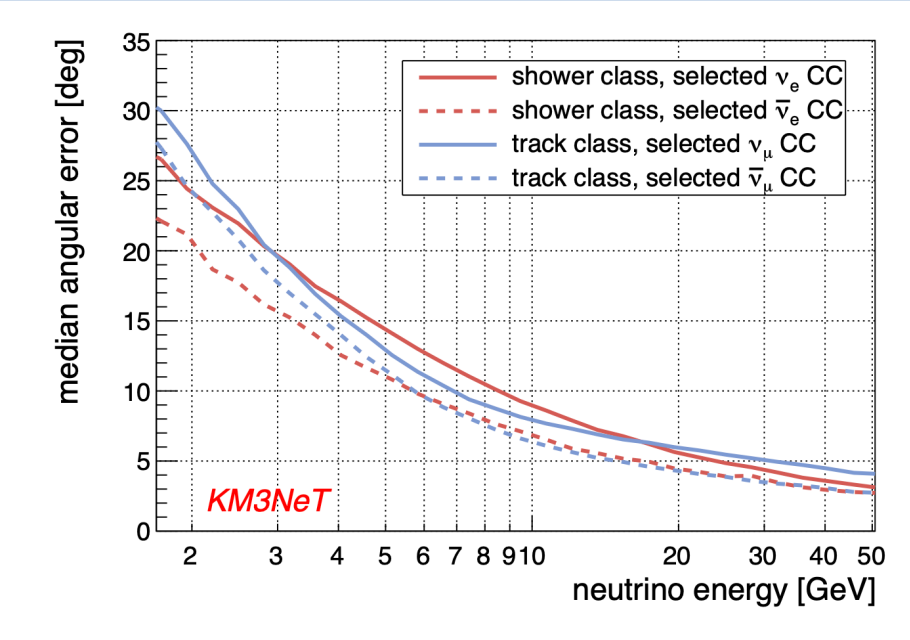
Poster → K. Dutta



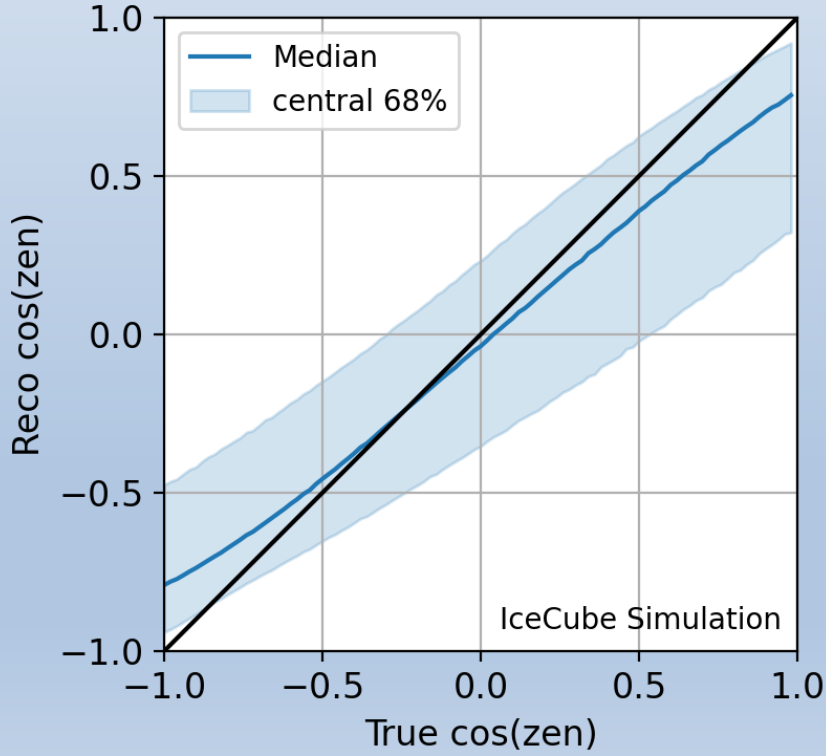
Eur. Phys. J. C 82, 26 (2022)

Detector response - angular resolution

- KM3NeT/ORCA
- Between 5º and 10º at 10 GeV
- Kinematics dominated



- IC upgrade



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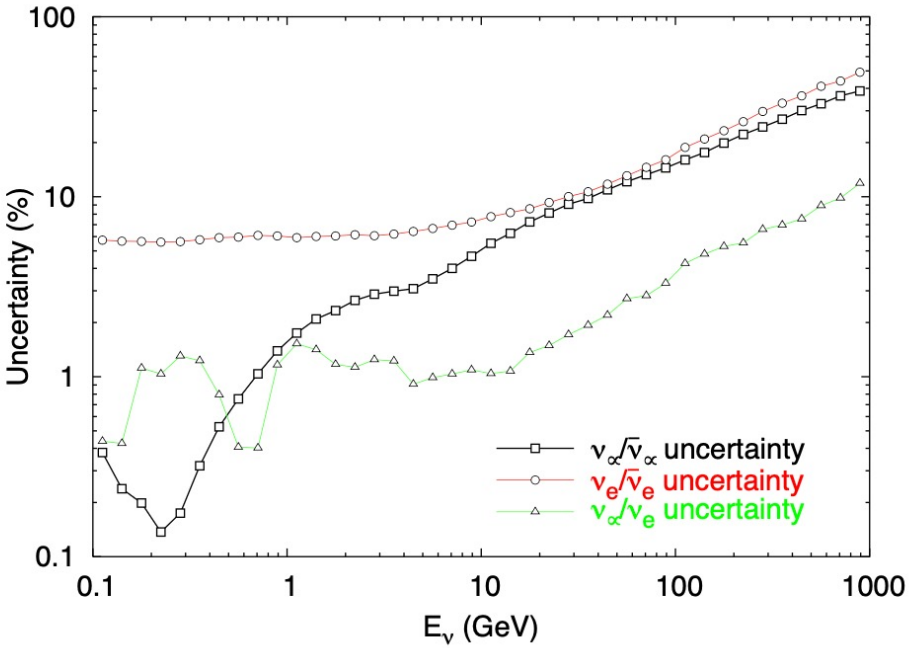
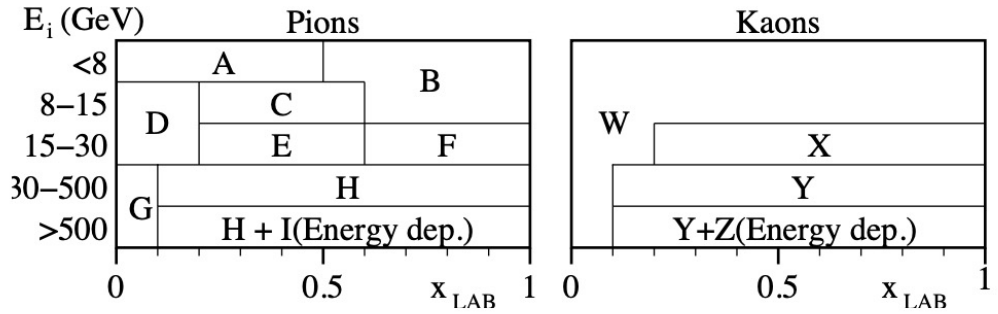
Systematics – neutrino flux

- parametric approach
  - Spectral index
  - Normalisation, skews



- Hadronic production uncertainties
- MCEq

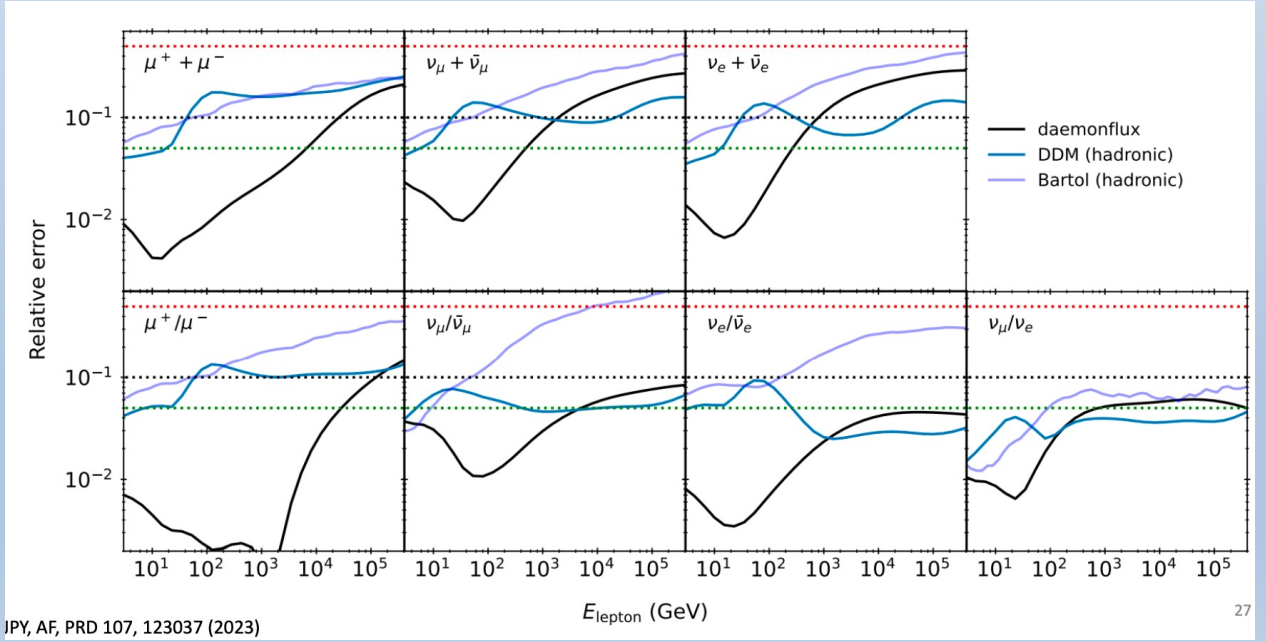
arXiv:1503.00544
Matrix Cascade Equations



Phys.Rev.D74:094009 (2006)

Systematics – neutrino flux

- Most recent development : daemonflux
- Combine Cosmic Ray composition, hadronic interaction model, adjust to muon spectrometer data
- Substantial improvements in relevant energy range possible
- Work in progress



JPY, AF, PRD 107, 123037 (2023)

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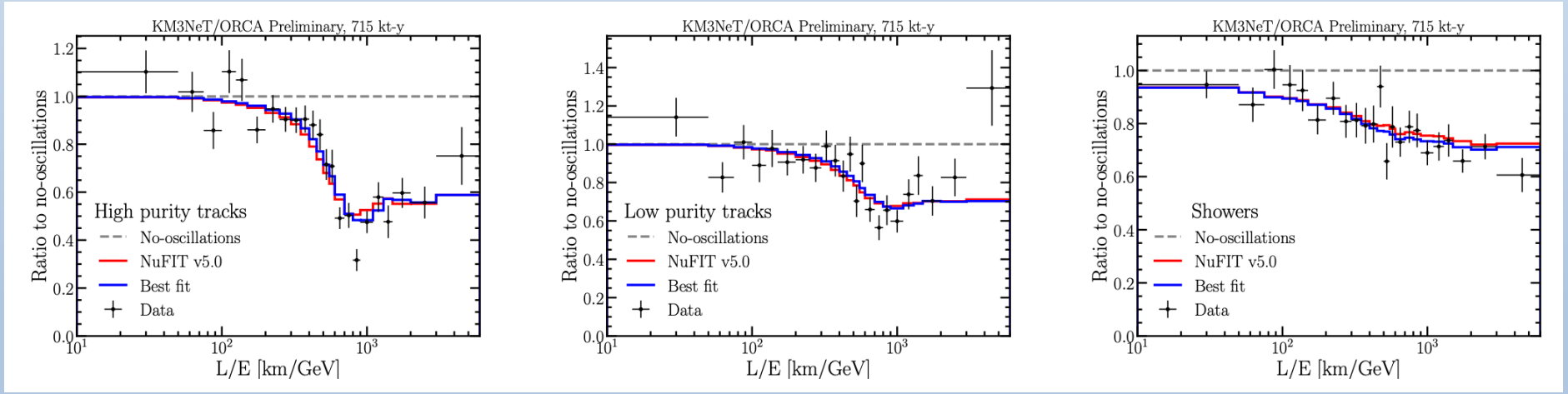
Data Driven Hadronic interaction model (DDM)
A. Fedynitch, M. Huber PRD 106 (2022)

Calibration of DDM+GSF with muon spectrometer data
J. P. Yañez, A. Fedynitch, PRD 107, 123037 (2023)

Performance - Δm^2_{31} , θ_{23}

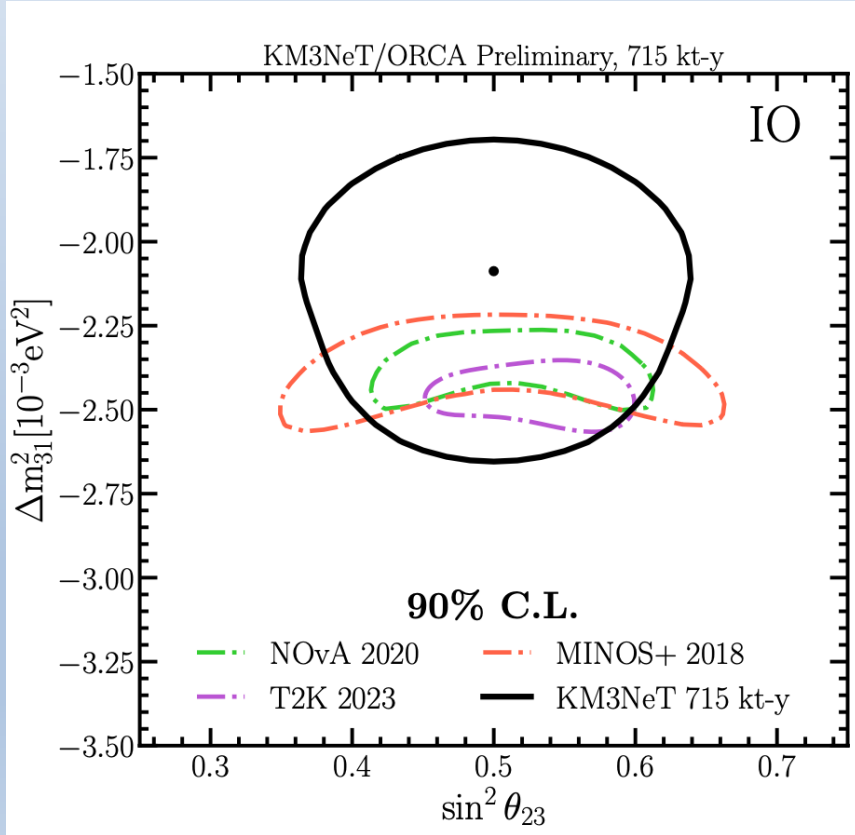
- High statistics right at the first oscillation peak
- Actual fit done in multi-dimensional phase pace
- Example from KM3NeT/ORCA 715 kt-yr



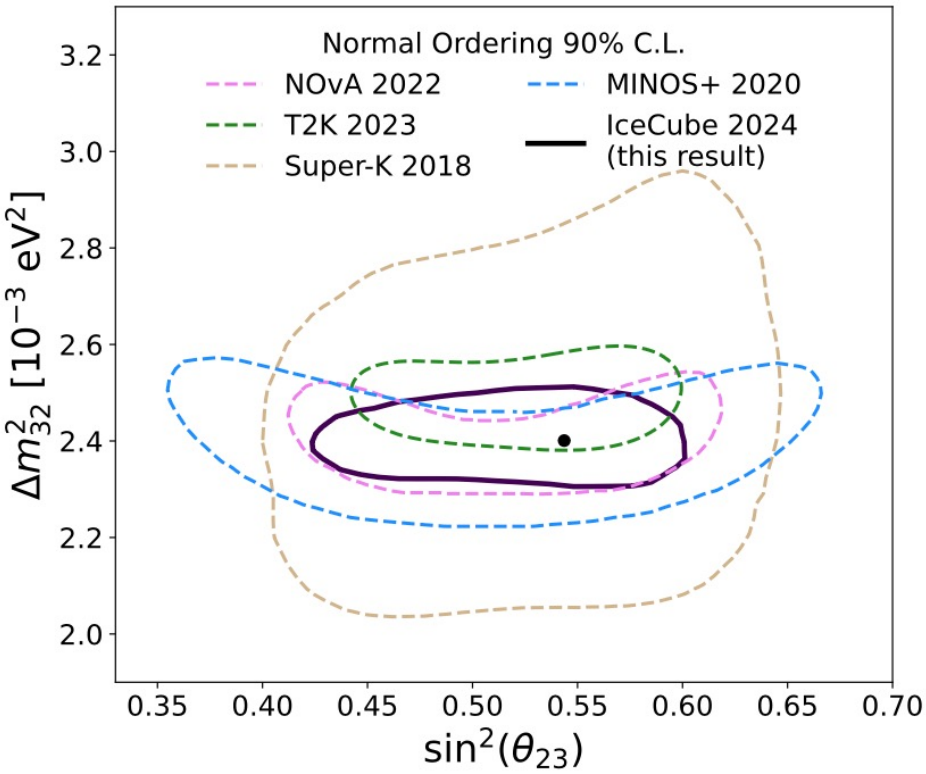
J.Coelho, 715 kt-yr

Performance - Δm^2_{31}, θ_{23}

- Excellent performance already now
- Δm^2_{31} with ~2.0%, θ_{23} ~8%



9.3 yr DeepCore



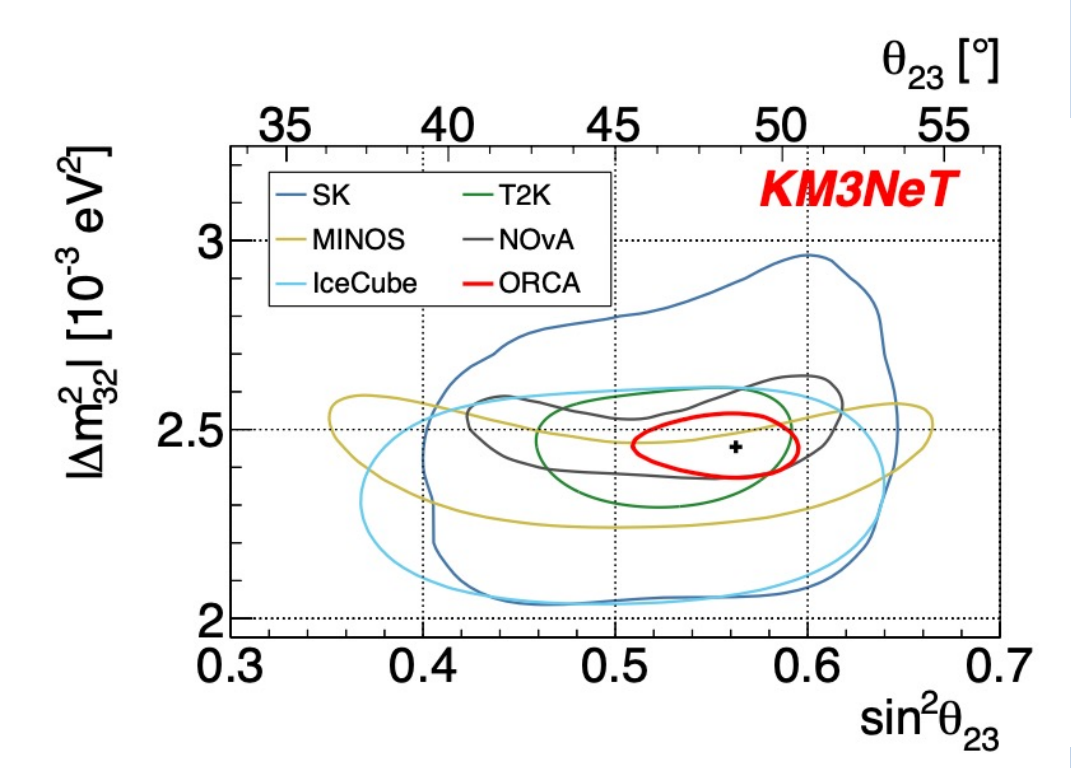
J.Coelho, Poster → S. Peña-Martienz

J.P. Yanez, arXiv:2405.01263

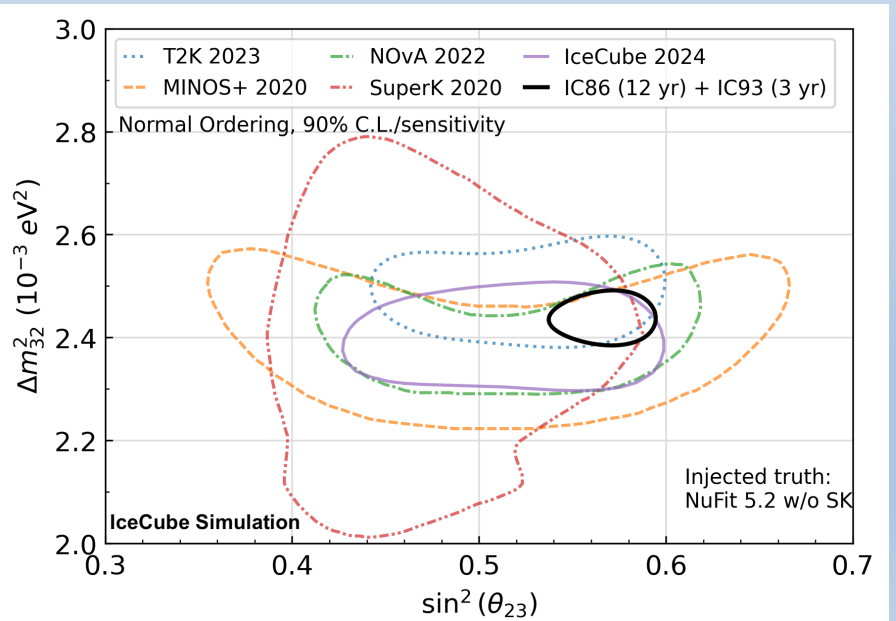
Performance - Δm^2_{31}, θ_{23}

- Competitive measurement after 3 years
- Δm^2_{31} with ~1.5%, θ_{23} few % dependent from true value

21 Mt-yr



3yr IC-Upgrade



Poster → K. Leonard deHolton

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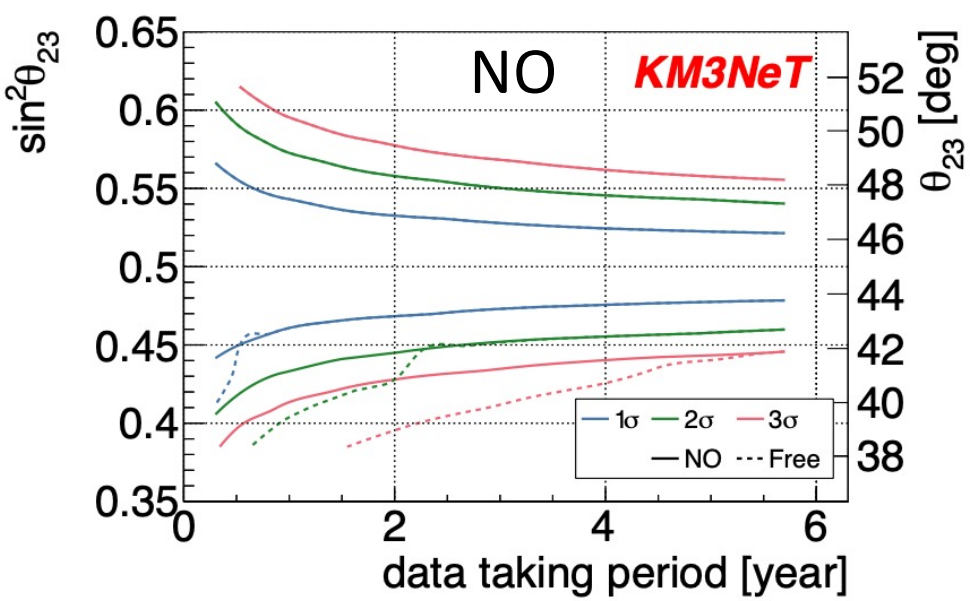
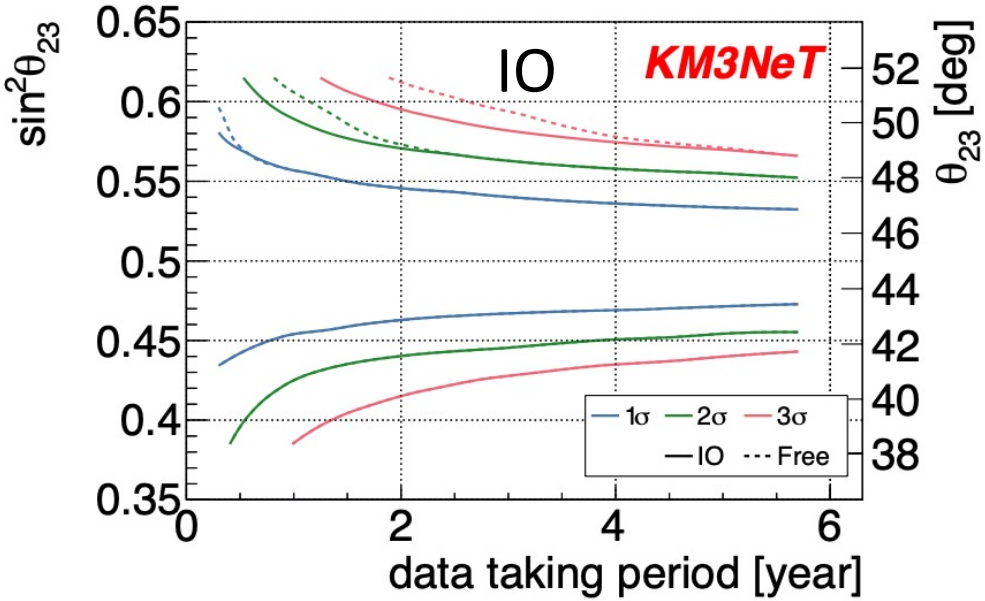
Performance - Δm^2_{31}, θ_{23}

- Octant of θ_{23} can be deterimed if not too close to maximal mixing





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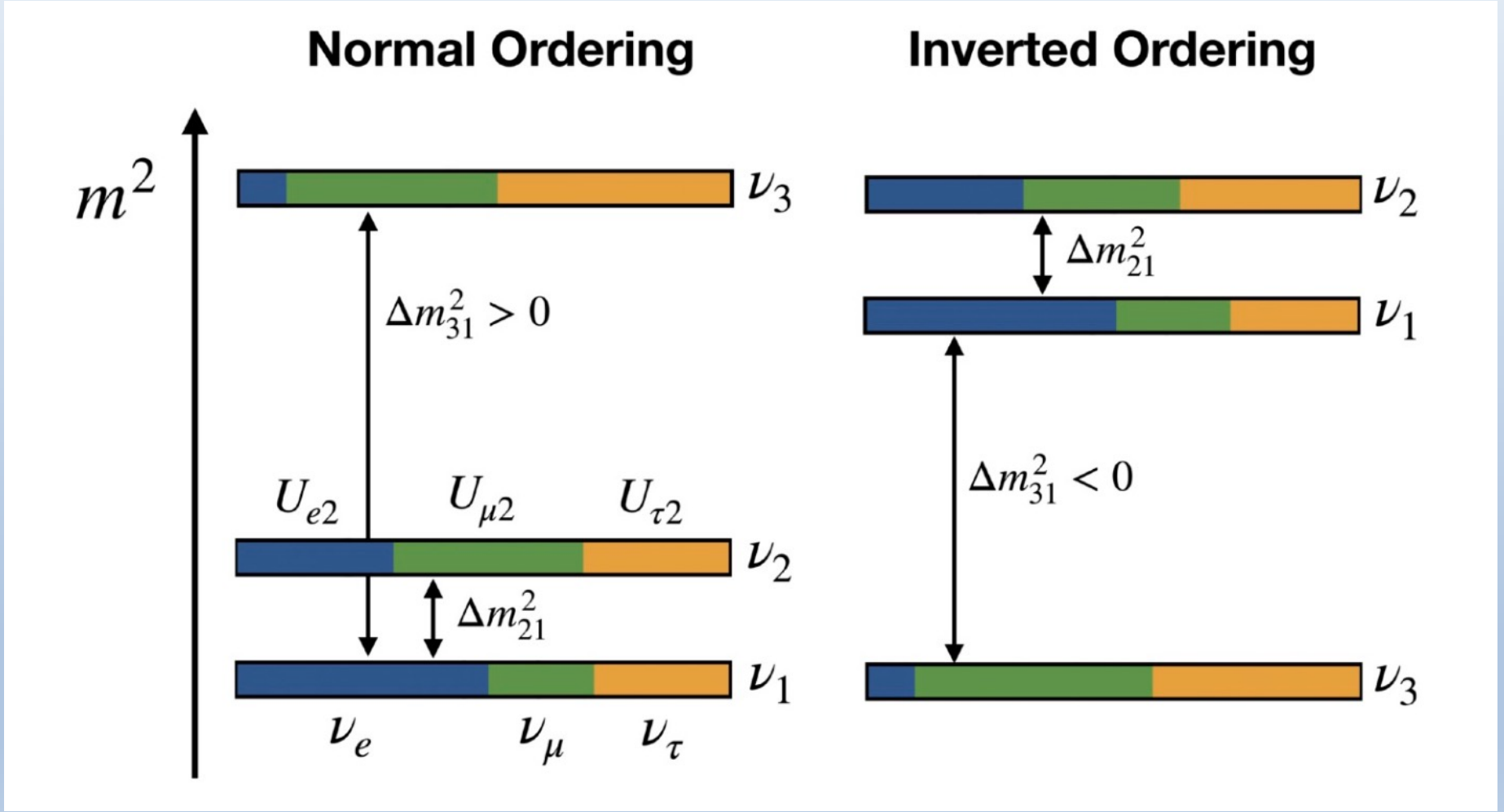
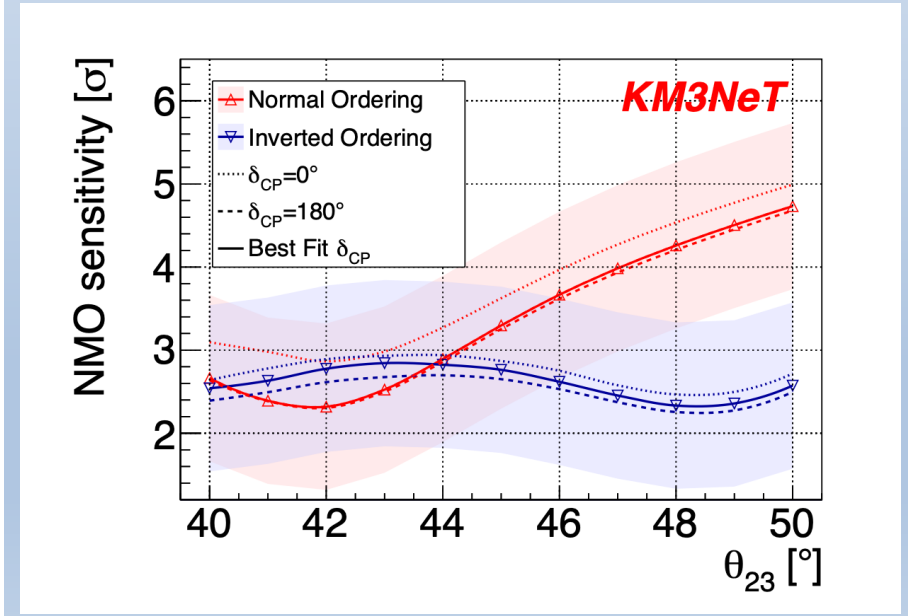
Performance
Neutrino Mass Ordering



Performance
Neutrino Mass Ordering

- KM3NeT/ORCA 21 Mt-yr
- 2029 : 2.5 - 4.5σ
- IC 2030 : 1.6 – 3.2σ
- Upgrade crucial for performance



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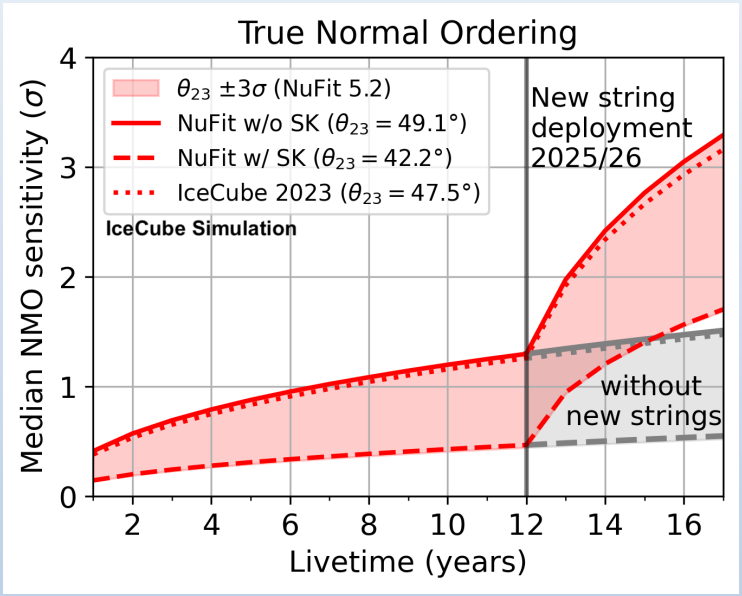
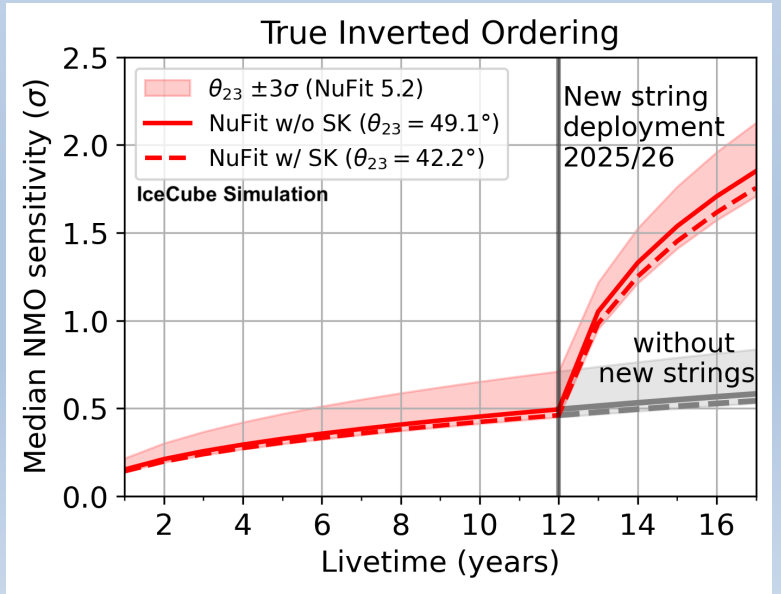




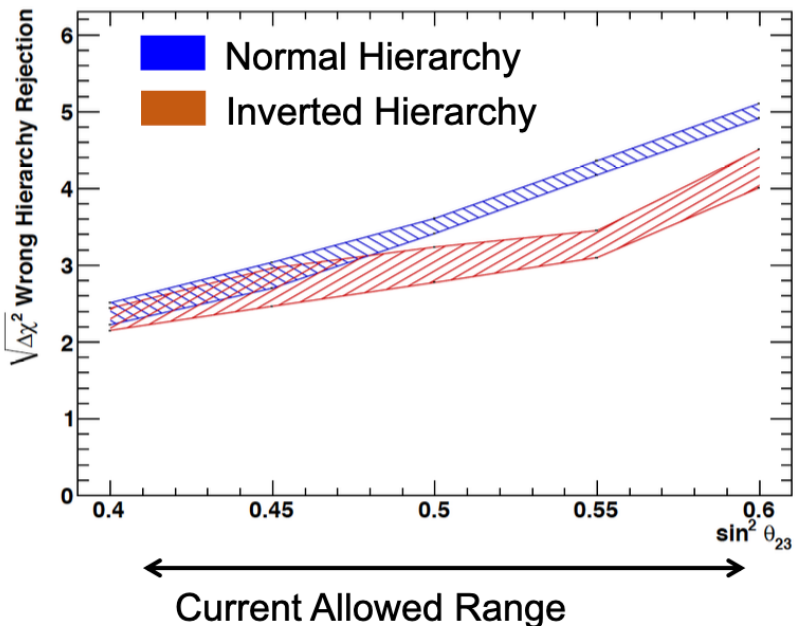
IC Nu-2024

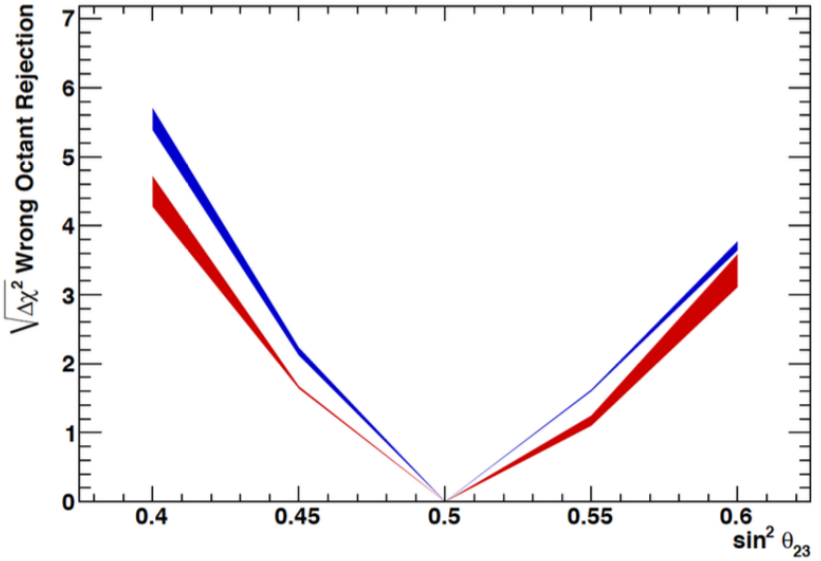
Performance
Neutrino Mass Ordering

Mass Hierarchy Sensitivity After 10 Years (186 kton)

HyperKamiokande

Atmospheric ν Only





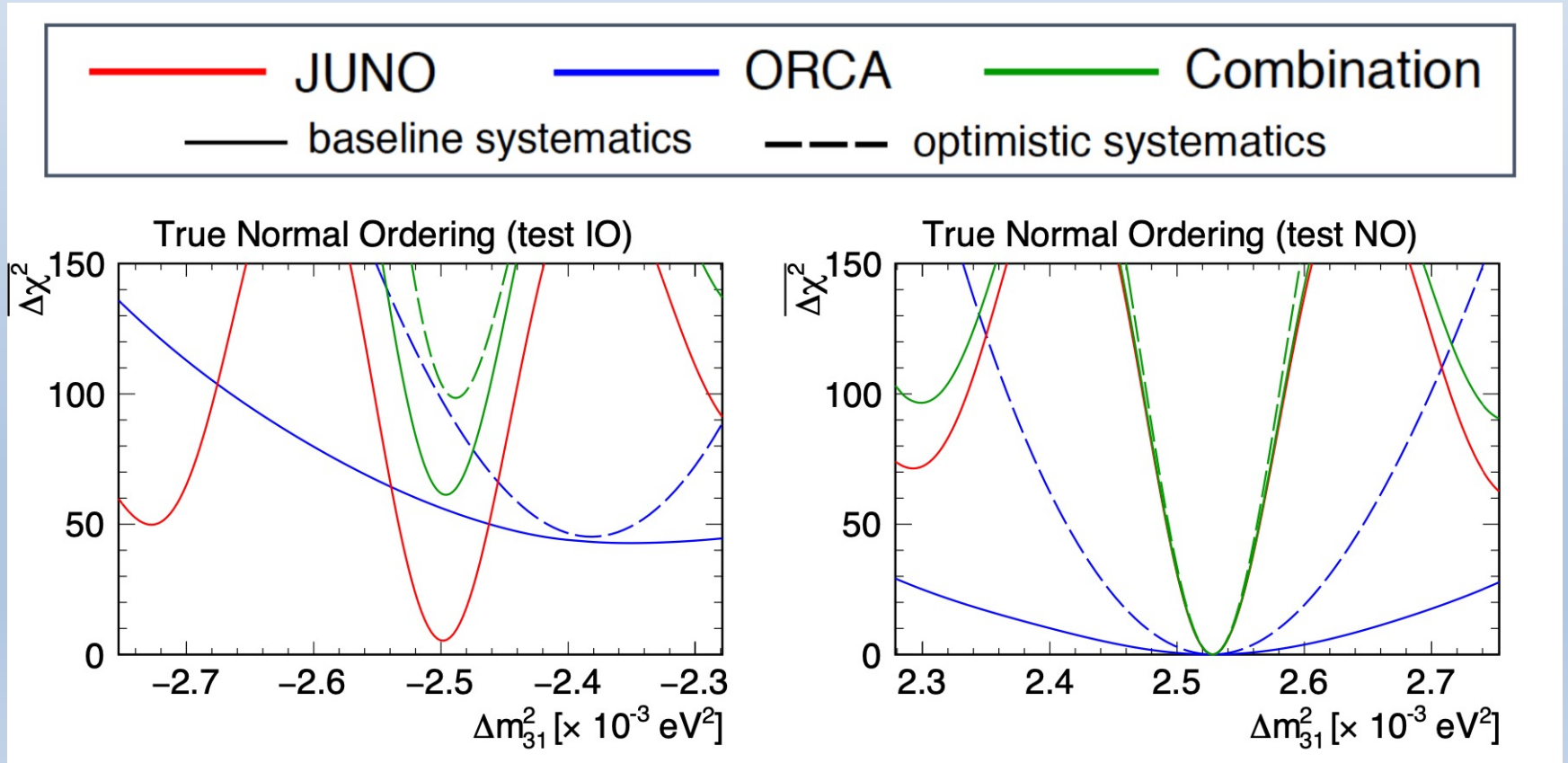
	$\sin^2\theta_{23}$	Atmospheric neutrino	Atm + Beam
Mass ordering	0.40	2.2 σ	→ 3.8 σ
	0.60	4.9 σ	→ 6.2 σ
θ_{23} octant	0.45	2.2 σ	→ 6.2 σ
	0.55	1.6 σ	→ 3.6 σ

10 years with 1.3MW, normal mass ordering is assumed

R. Wendell, 2019/04

Performance NMO
Adding constraints from JUNO

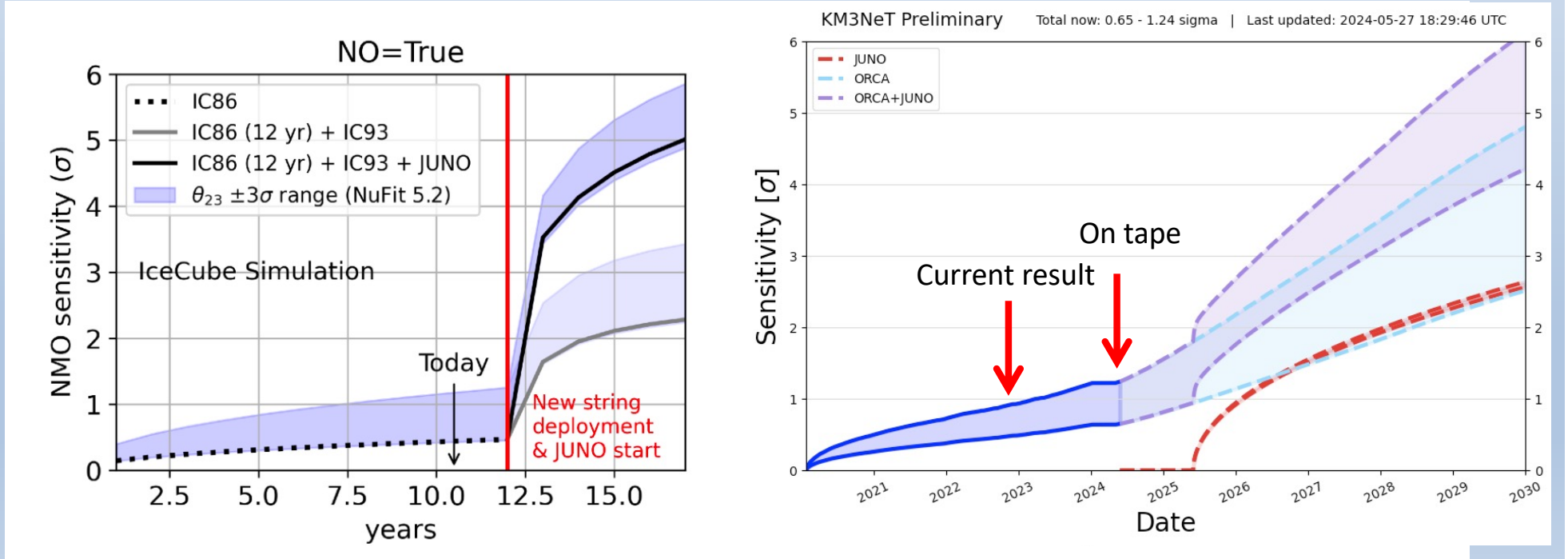
- Using Δm^2_{31} tension between JUNO and IC/ORCA when assuming wrong NMO significantly increases the rejection power for wrong NMO



J. High Energ. Phys. **2022**, 55 (2022).

Performance
Neutrino Mass Ordering

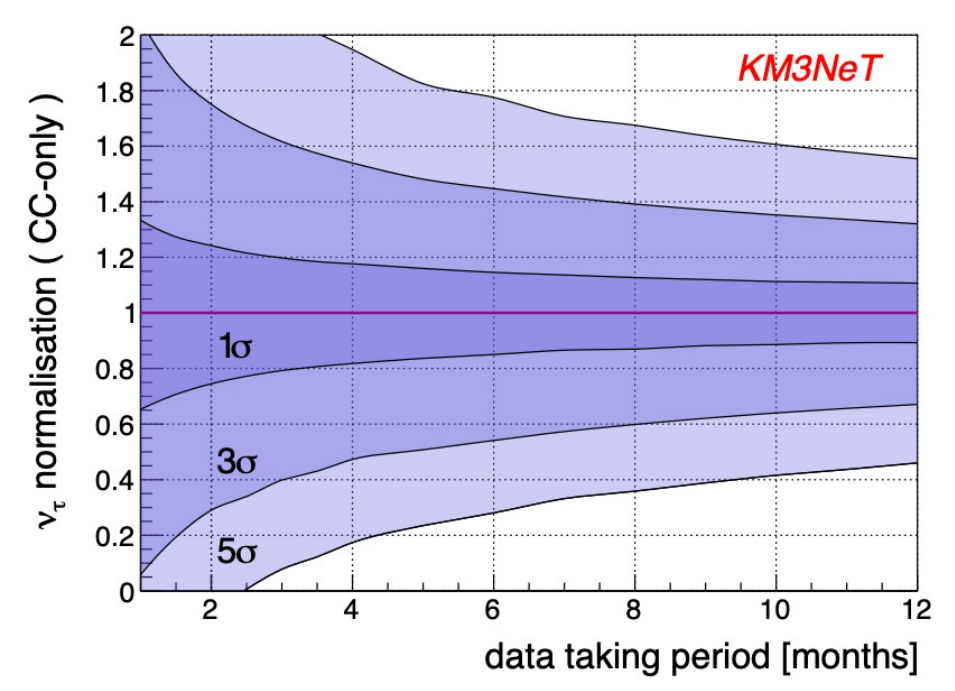
- KM3NeT/ORCA & IC-upgrade combination with JUNO
- 2σ gain in sensitivity
- Overall combination : 5σ NMO determination by 2030

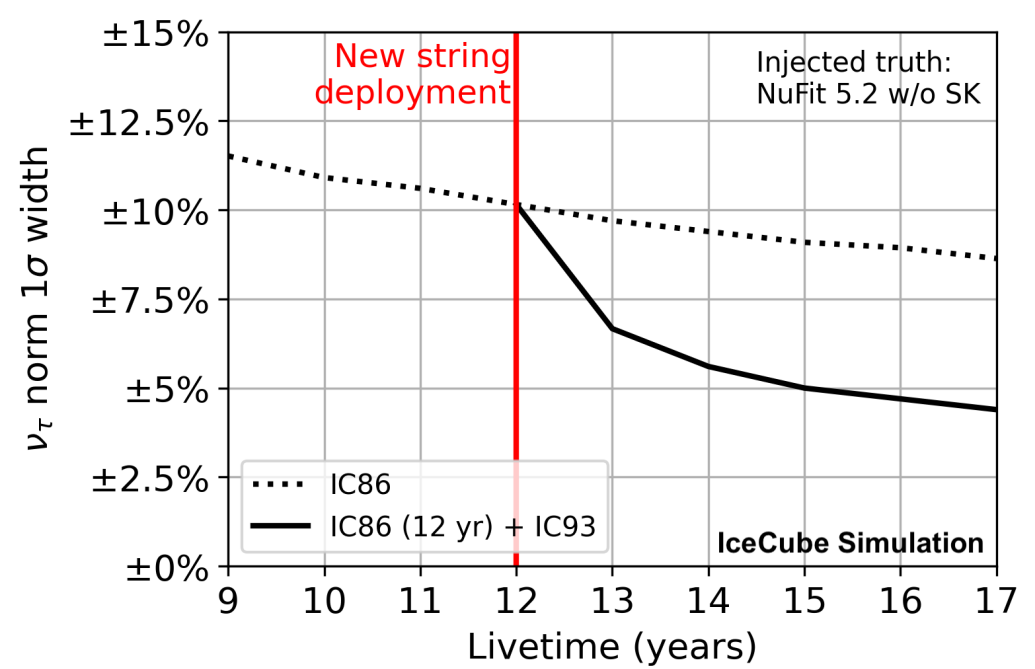


M. Prado Rodriguez, NuFact 2023

Performance ν_τ cross-section

- Several 1000 ν_τ CC events in KM3NeT/ORCA and IceCube per year
- ν_τ normalization measured to better than 5% after 3 years





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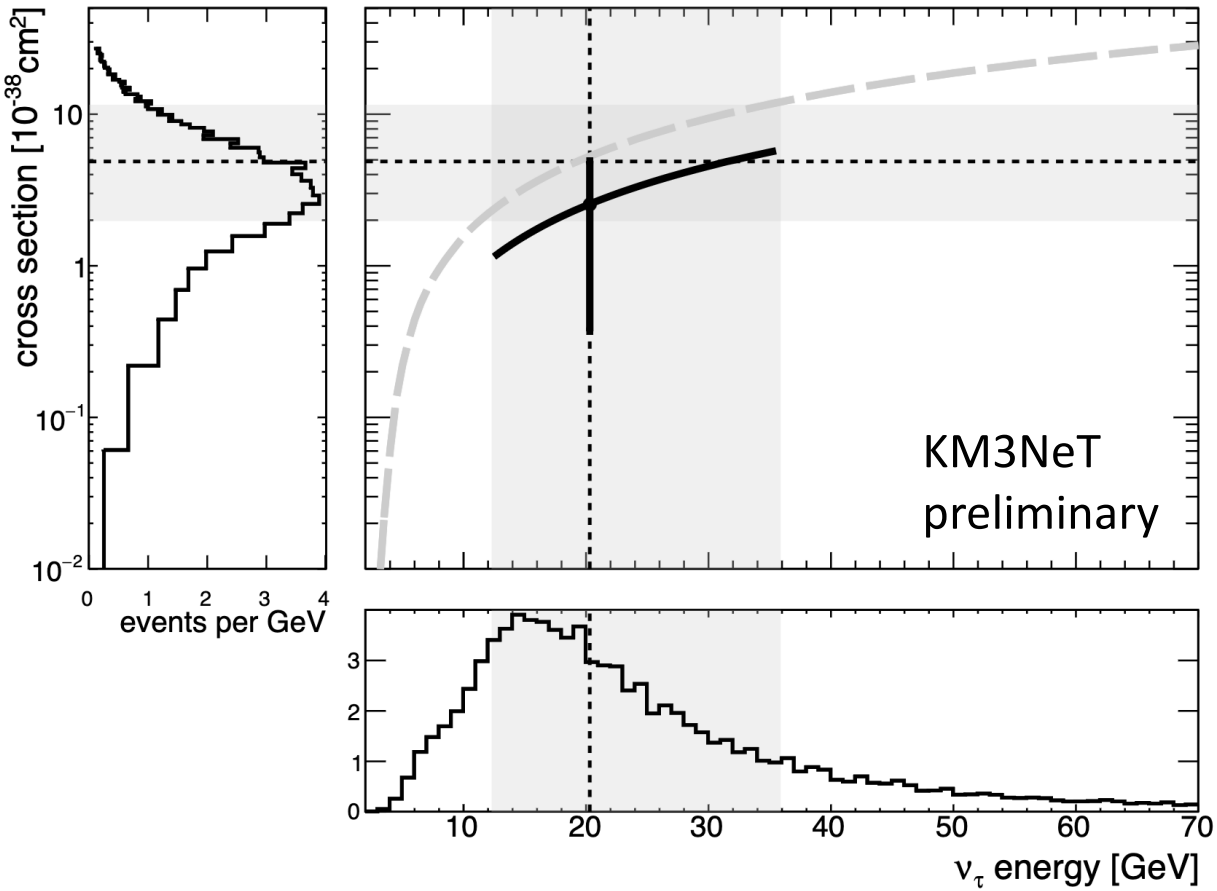
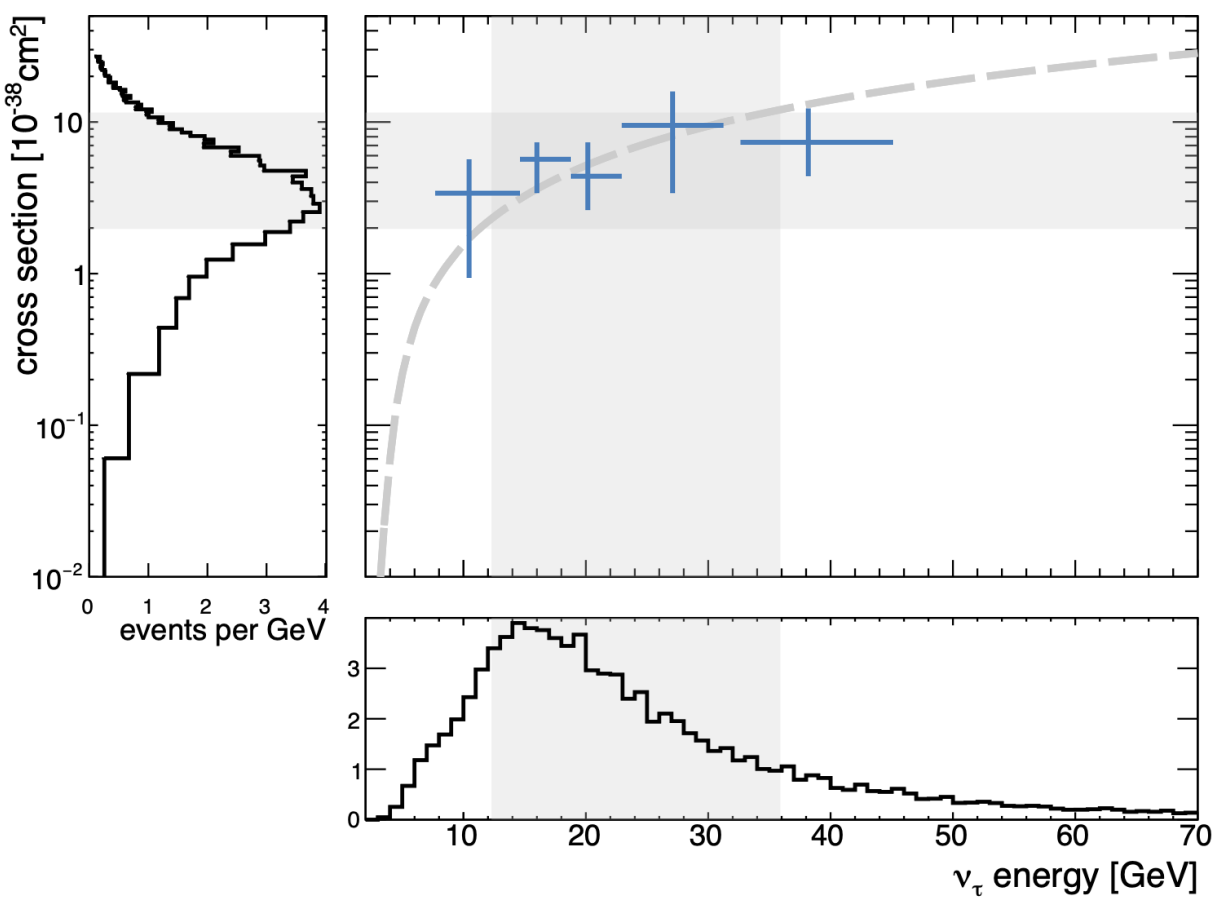
Performance ν_τ cross-section

- Measurement from KM3NeT/ORCA (433 kt-yr)
- Close to kinematical threshold



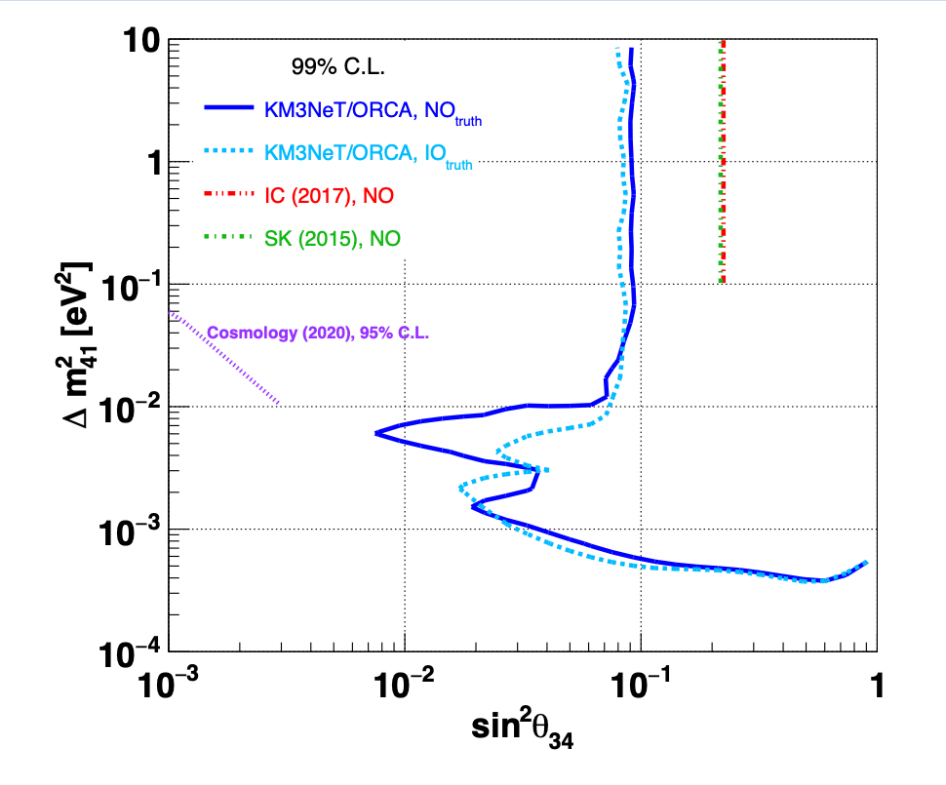
Performance ν_τ cross-section

- Probes different structure function components and new physics
- Possible situation 2030

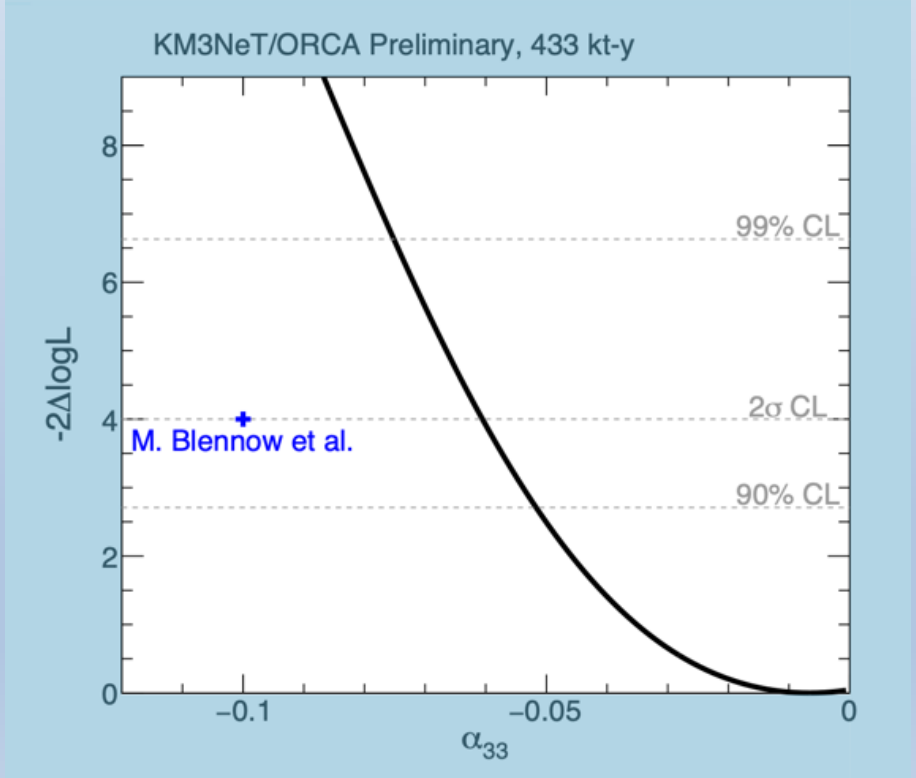


Performance ν_τ new physics

- New coupling to 3rd family not strongly constrained so far
- Probe mixing of additional sterile neutrinos or non-unitarity of PMNS
- Examples : θ_{34} 3 years KM3NeT/ORCA , α_{33} 433 kt-yr KM3NeT/ORCA
- Competitive measurement/limit can be derived



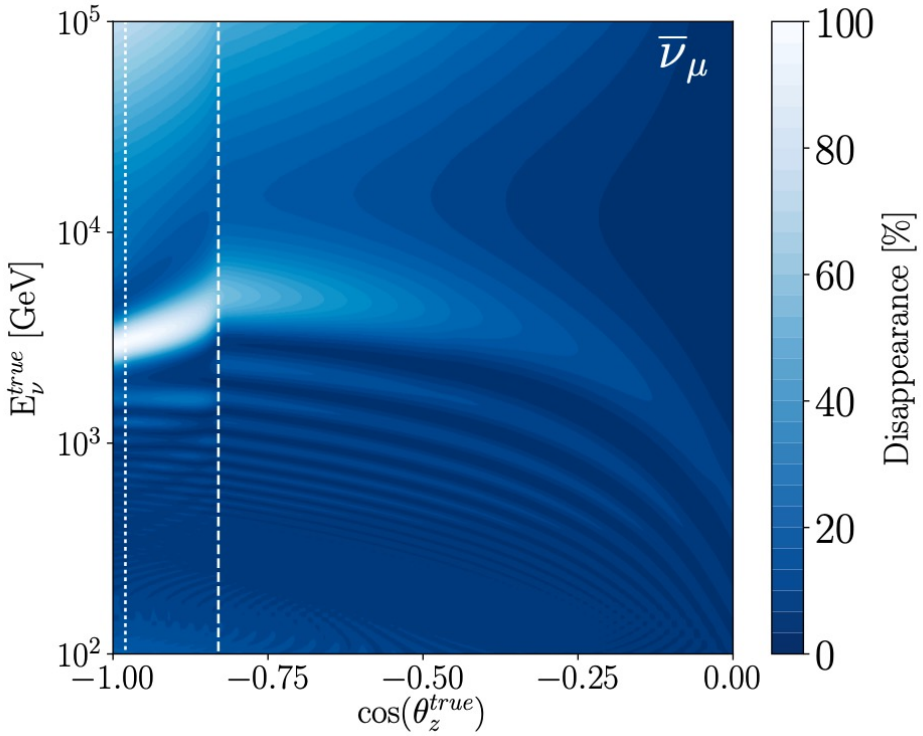
Poster → L. Bailly-Salins



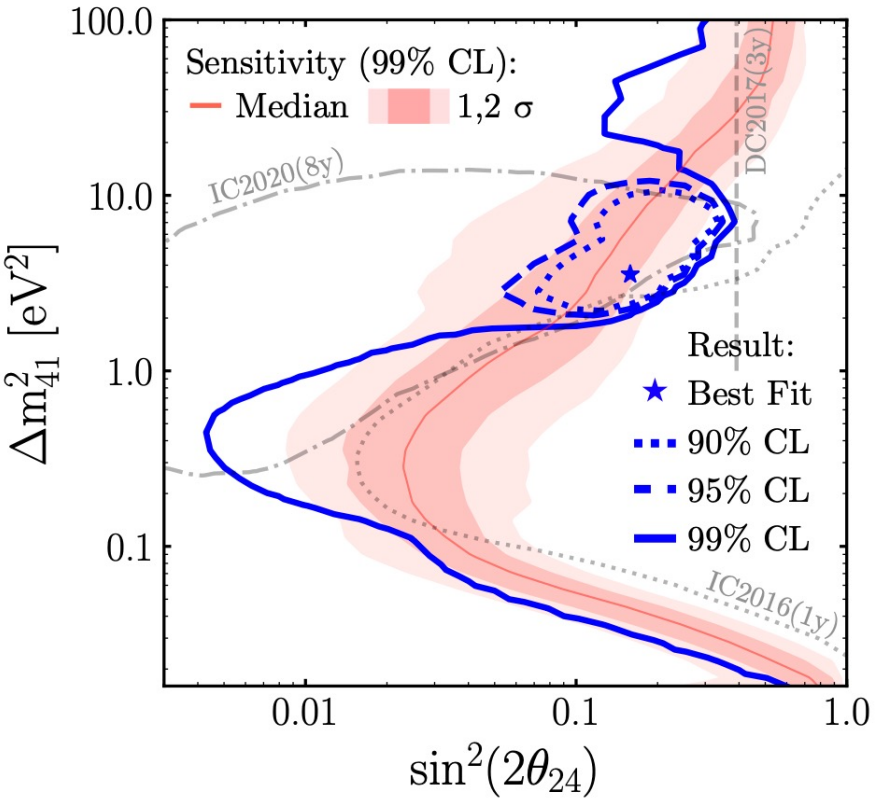
Poster → L. Cerisy

Performance High energies

- Matter resonance from heavy mass states in TeV energies
- High sensitivity to sterile neutrinos in HE atmospheric neutrinos



$(\Delta m^2_{41} = 1.3\ \mathrm{eV}^2,\ \sin^2(2\theta_{24}) = 0.07,\ \sin^2(2\theta_{34}) = 0.0).$



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arXiv:2405.08070

Conclusion

- Next generation of atmospheric neutrino detectors becomes reality
- several 100,000 neutrino events within a few years
- Unambiguous determination of NMO before 2030

- **Precision measurement of Δm^2_{31}, θ_{23}**
- **World largest sample of many 1000 ν_τ**


Backup