Results and Prospects from atmospheric neutrinos

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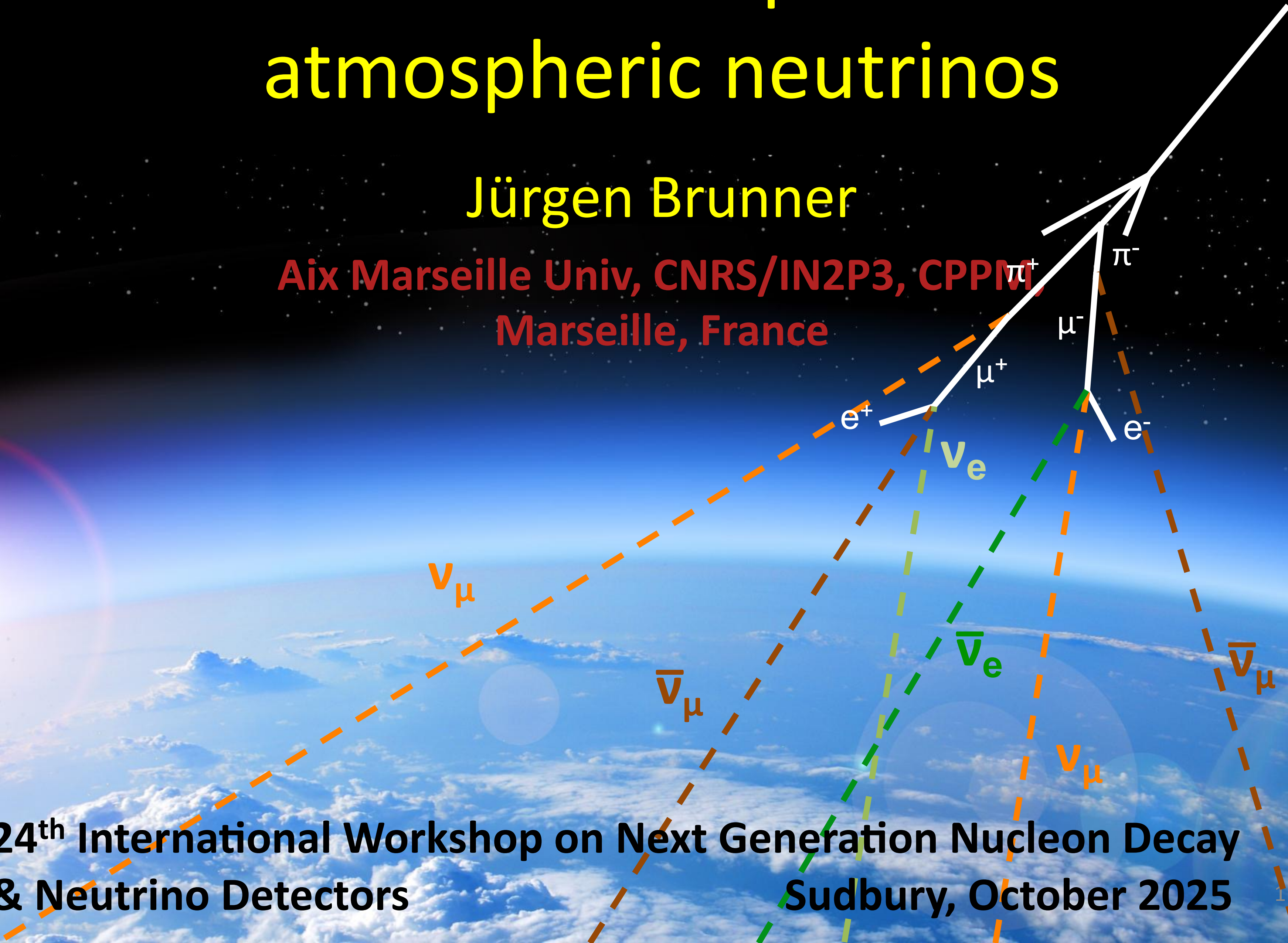
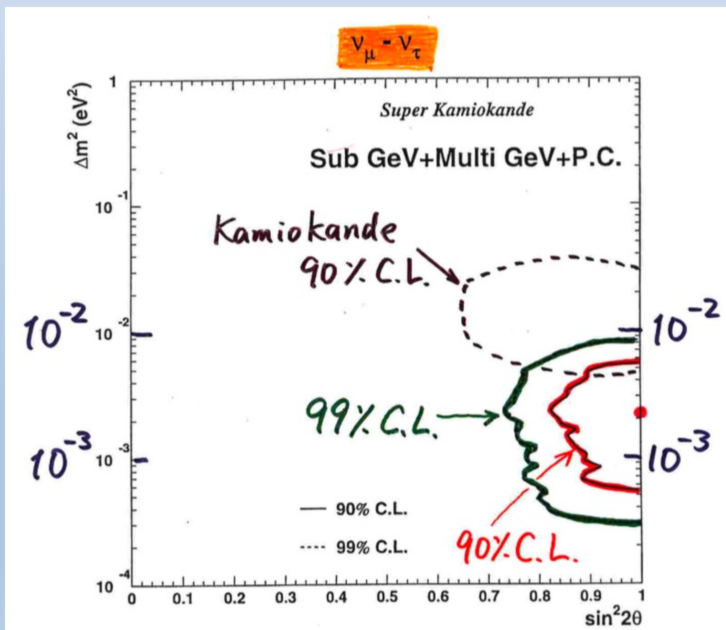


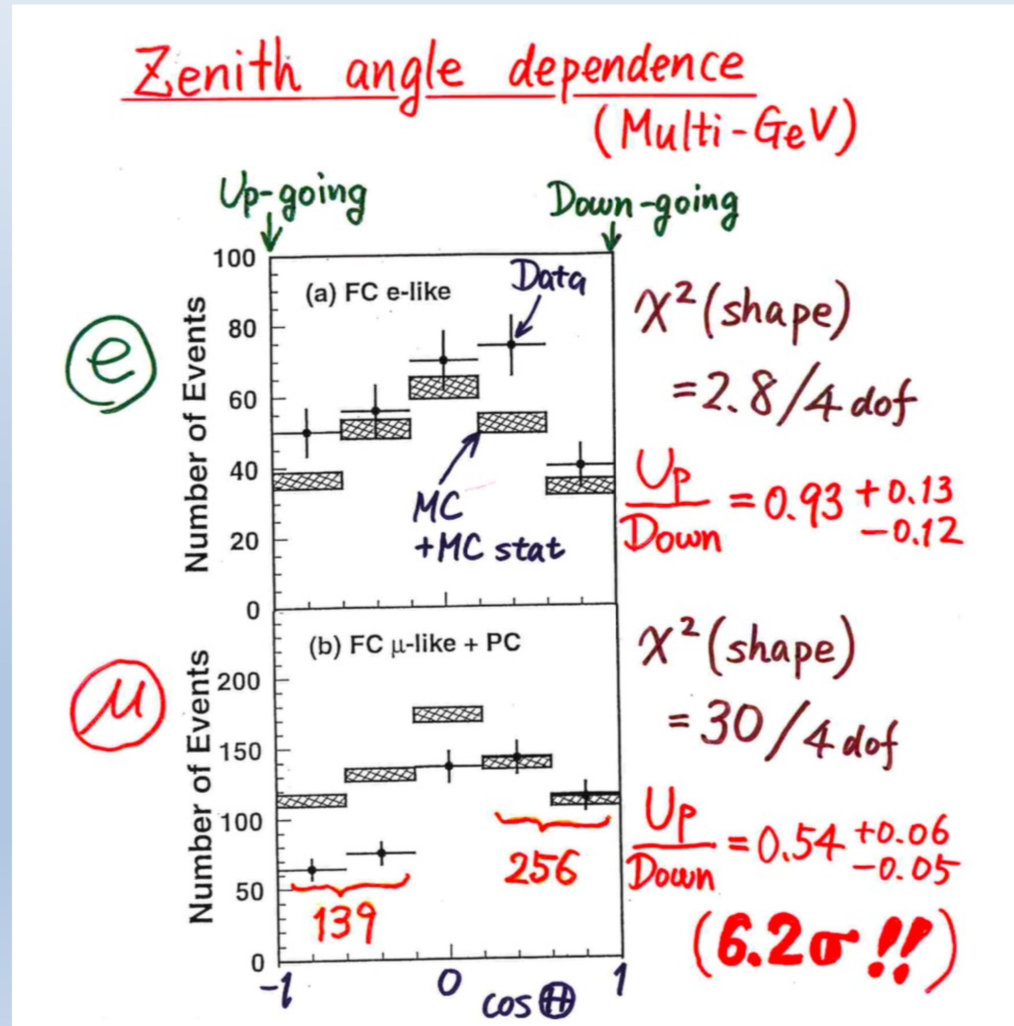
24th International Workshop on Next Generation Nucleon Decay & Neutrino Detectors

Sudbury, October 2025

History – 27 years ago

- First strong evidence for neutrino oscillations
- $\nu_\mu \rightarrow \nu_\tau$

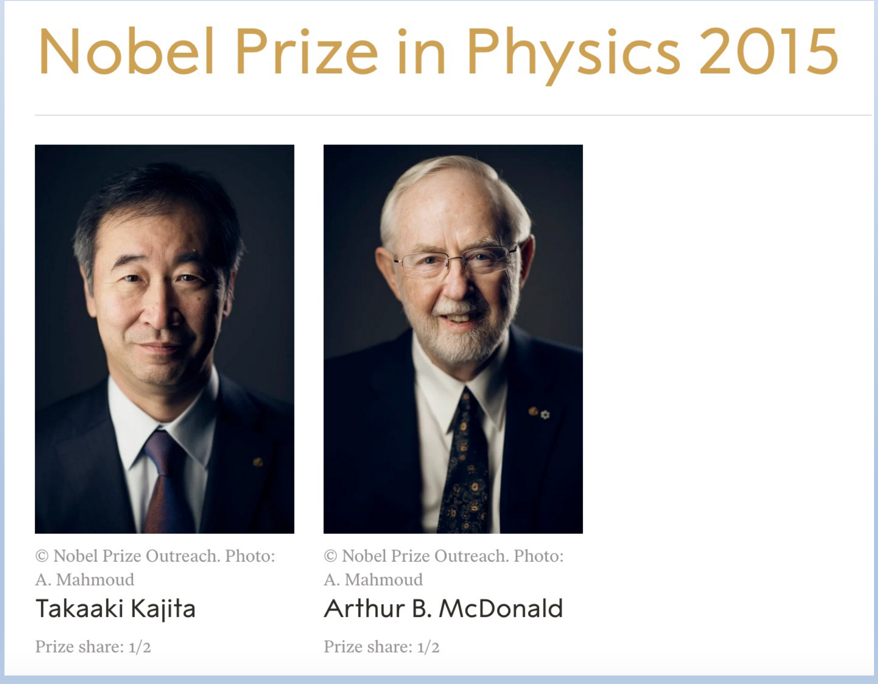


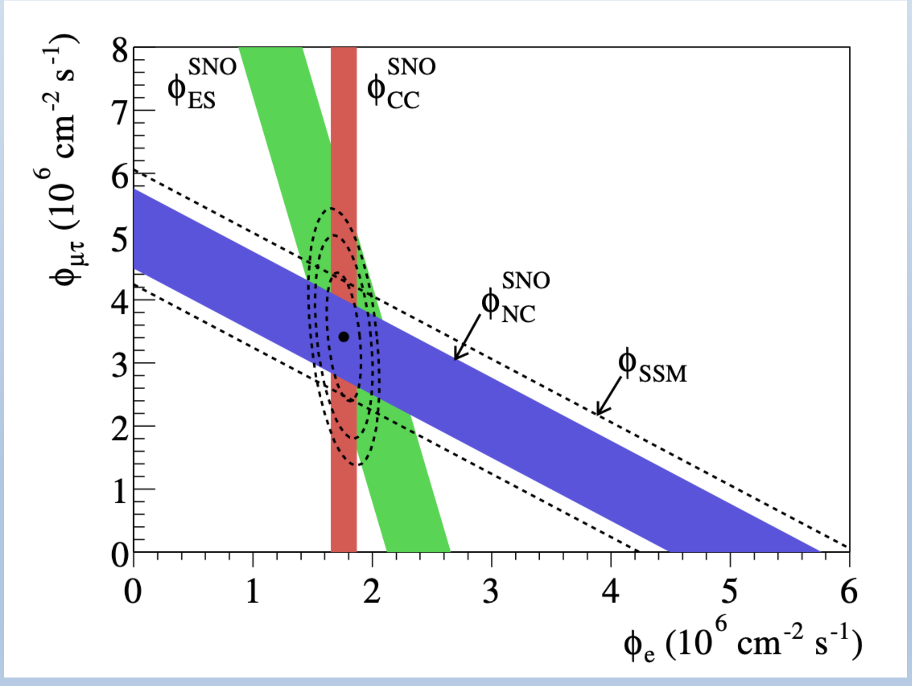


T. Kajita, Neutrino 1998

History – 10 years ago

- Nobel prize for discovery of neutrino oscillations
- based on atmospheric and solar neutrinos

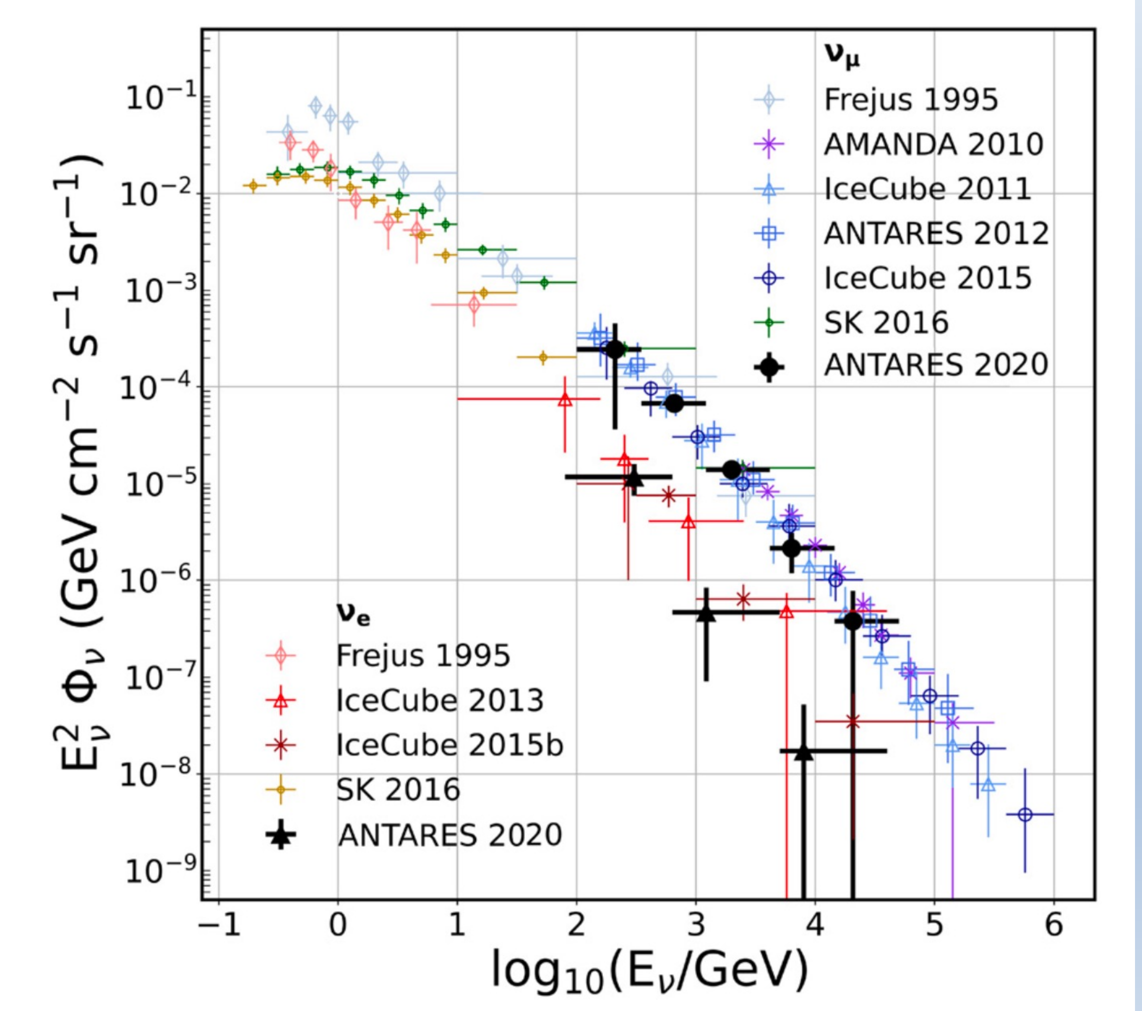




SNO, 2004

Atmospheric Neutrino Spectrum

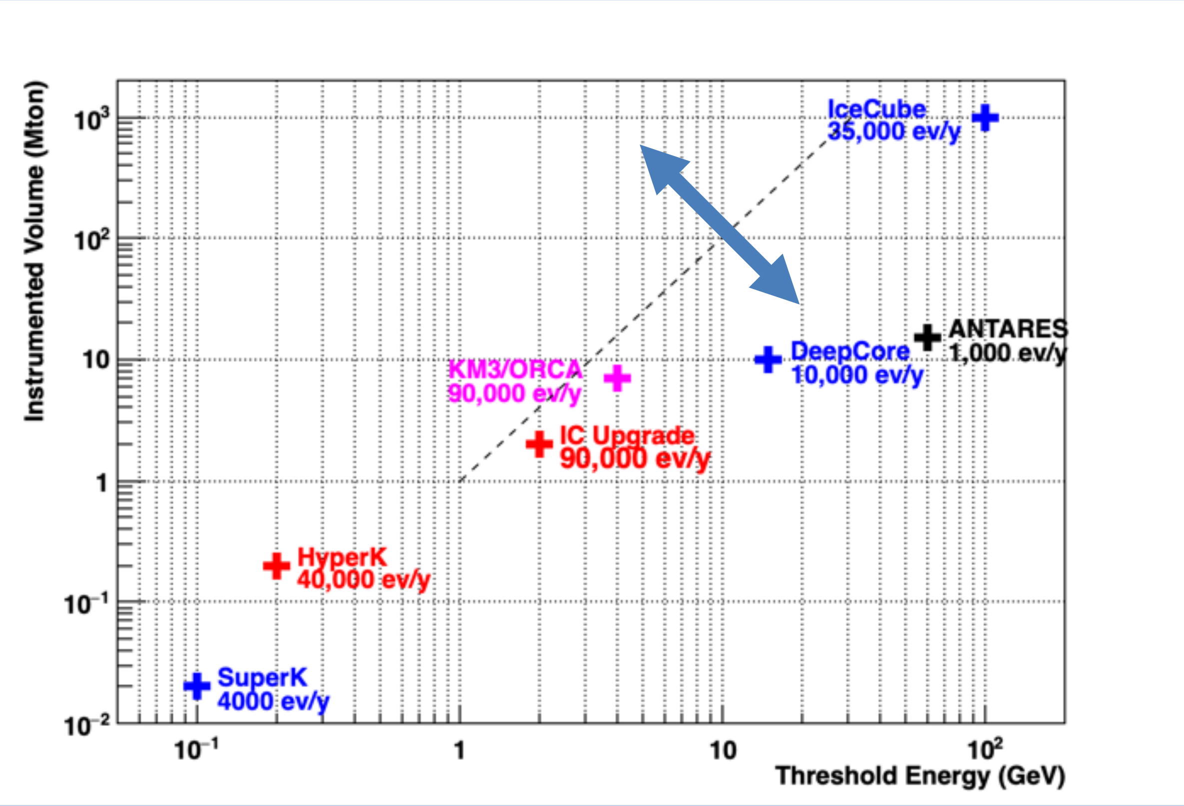
- 30 years of measurements
- 7 orders of magnitude
- ν_μ & ν_e



Phys. Lett. B 816 (2021) 136228

Atmospheric ν event count

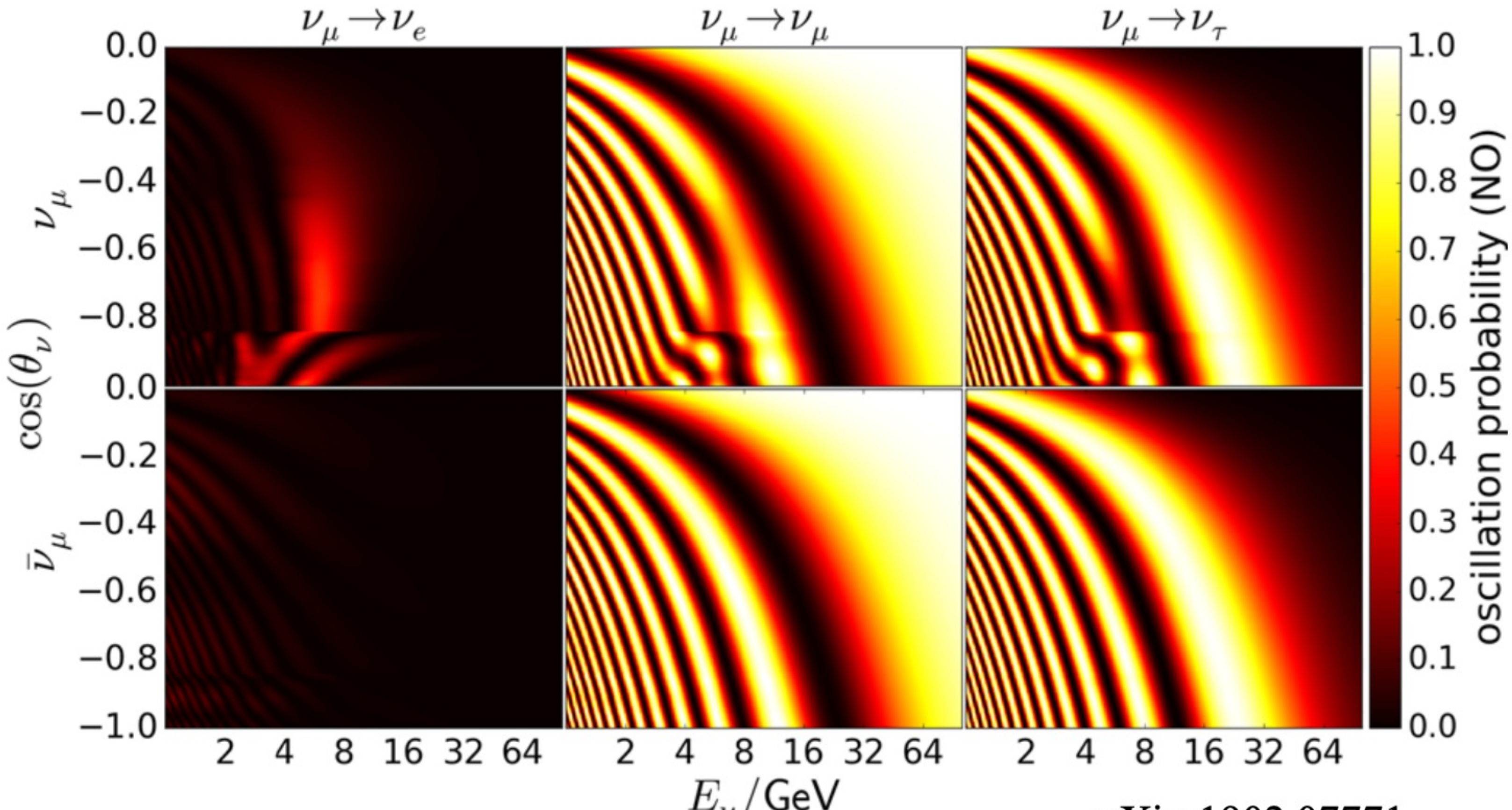
- Largest existing neutrino sample for E > 0.1 GeV
- radical increase in the near future
- covers crucial 1-100 GeV energy region



IC : arXiv:2502.17890
ANT: JHEP 2019, 113 *(2019)*
DC : PRL 134, 091801 (2025)
ORCA: JHEP 2024, 206 (2024)
IC-Up: arXiv:2307.15295
SK/HK: Phys. Rev. D 109, 072014 (2024)

Neutrino oscillations

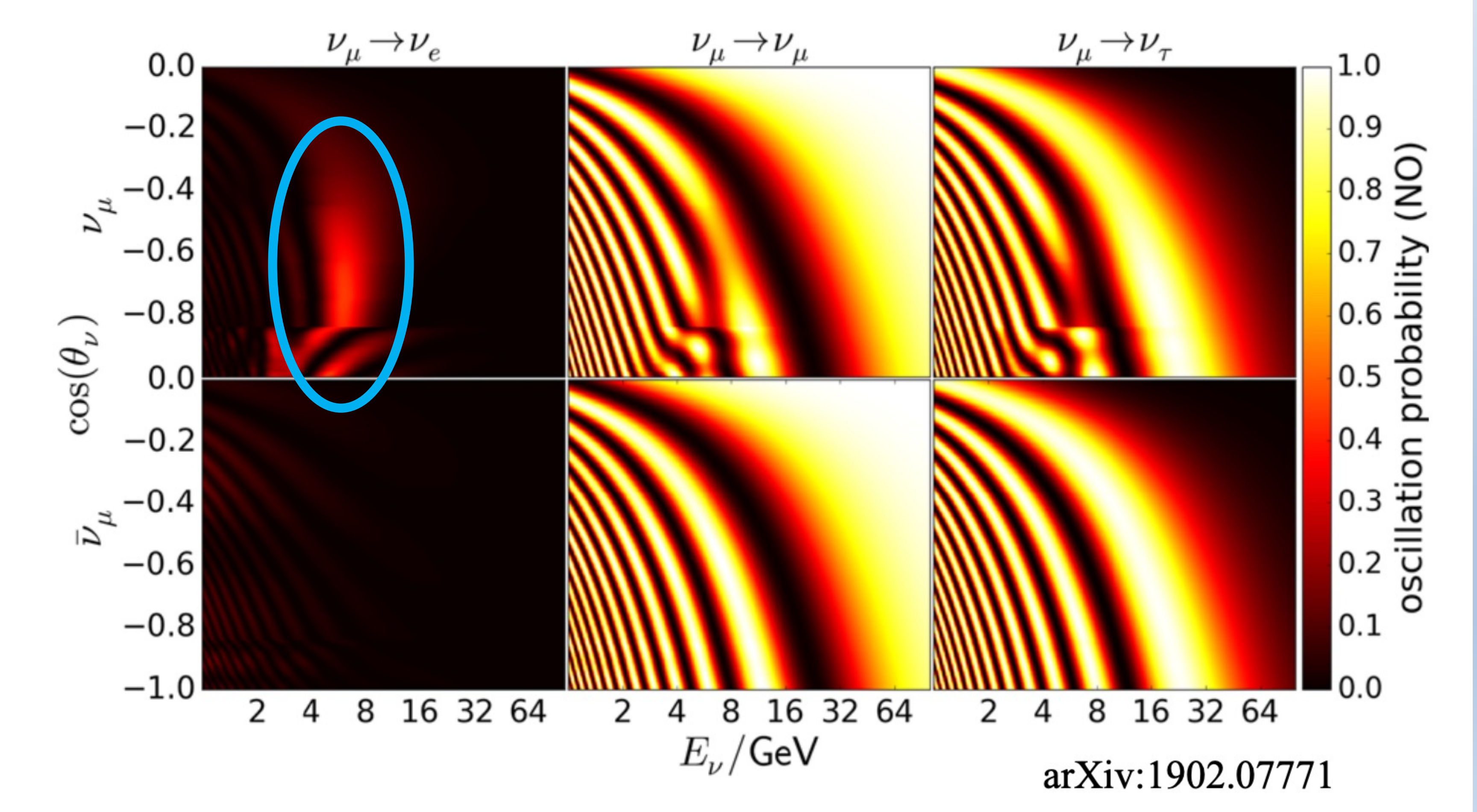
- Rich phenomenology in the 1-100 GeV energy range



arXiv:1902.07771

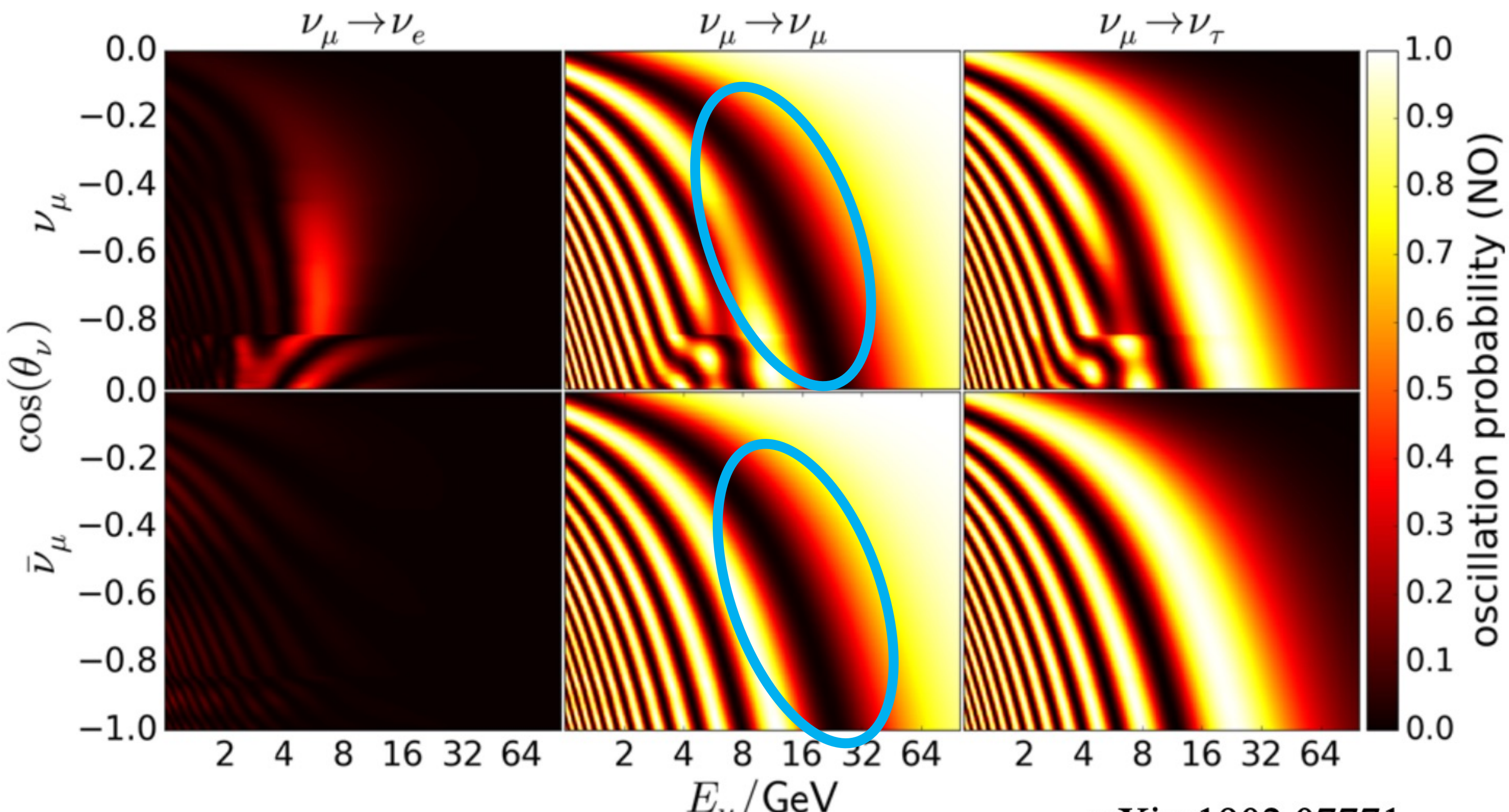
Neutrino oscillations

- Matter resonance 4-10 GeV
  → neutrino mass ordering



Neutrino oscillations

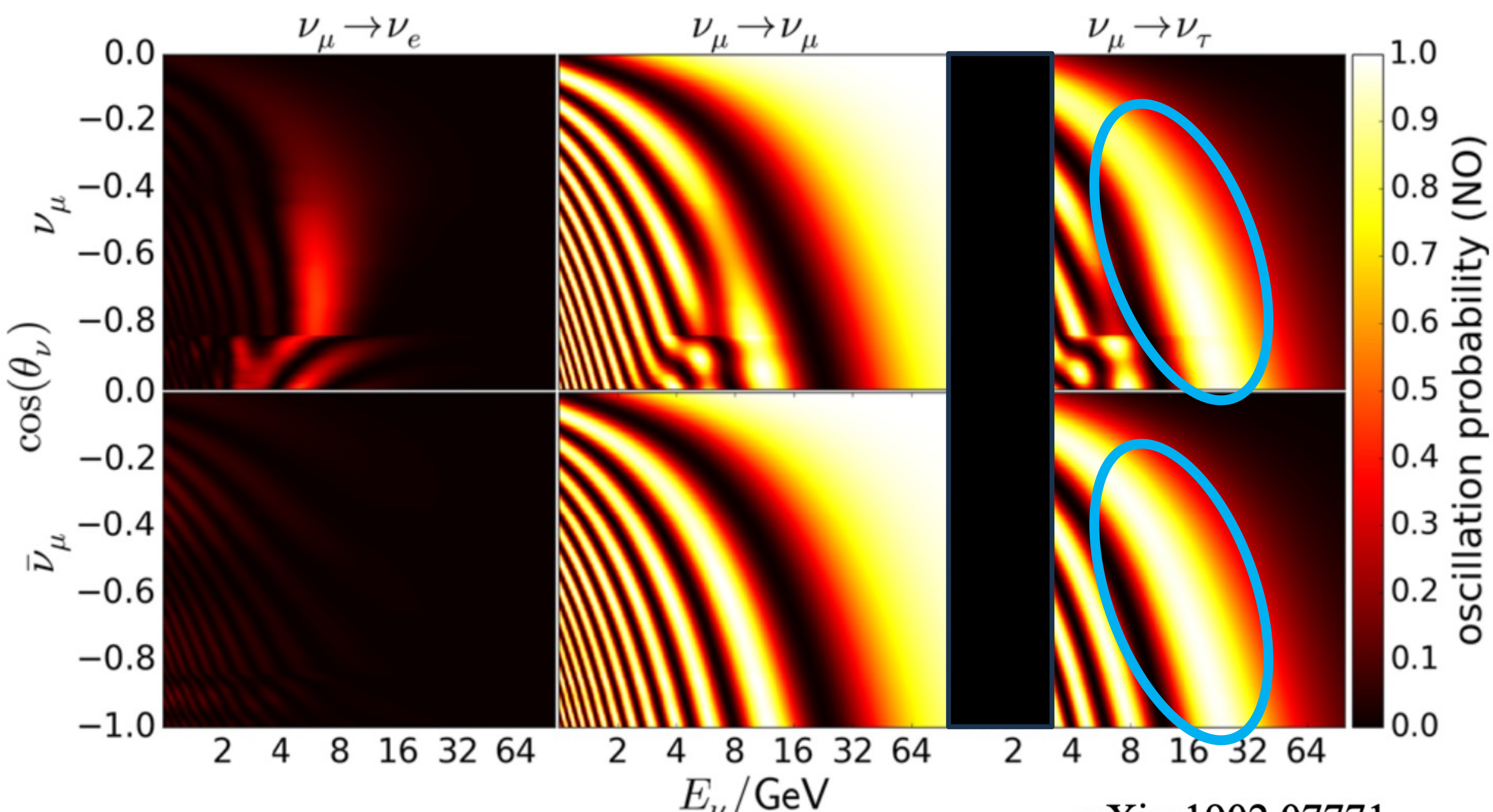
- ν_μ disappearance 10-40 GeV
  → precision measurements Δm^2_{31} , θ_{23}



arXiv:1902.07771

Neutrino oscillations

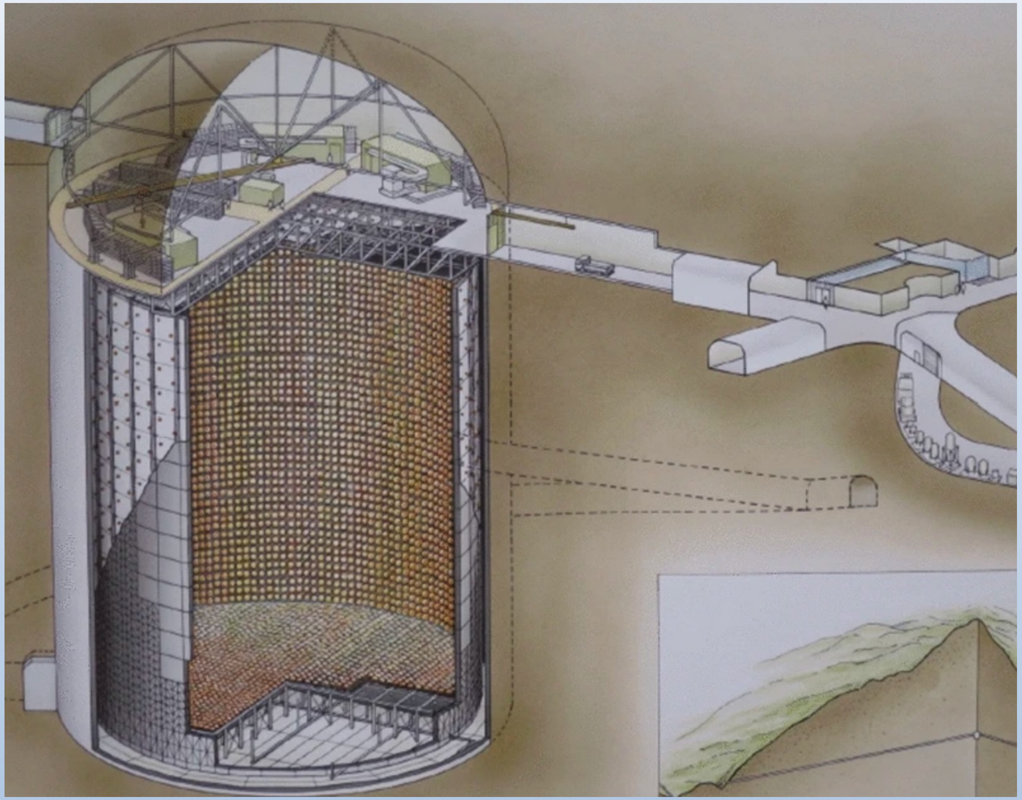
- ν_τ appearance 10-40 GeV
  -→ ν_τ cross section, ν_τ sector BSM tests

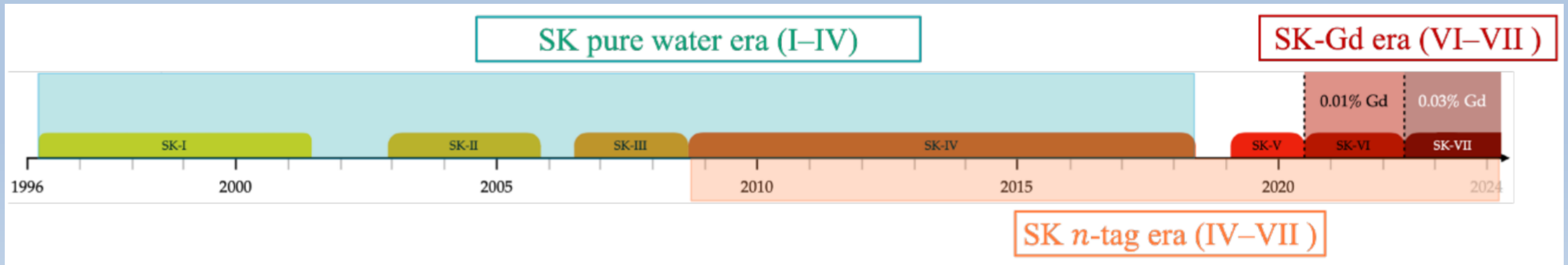


arXiv:1902.07771

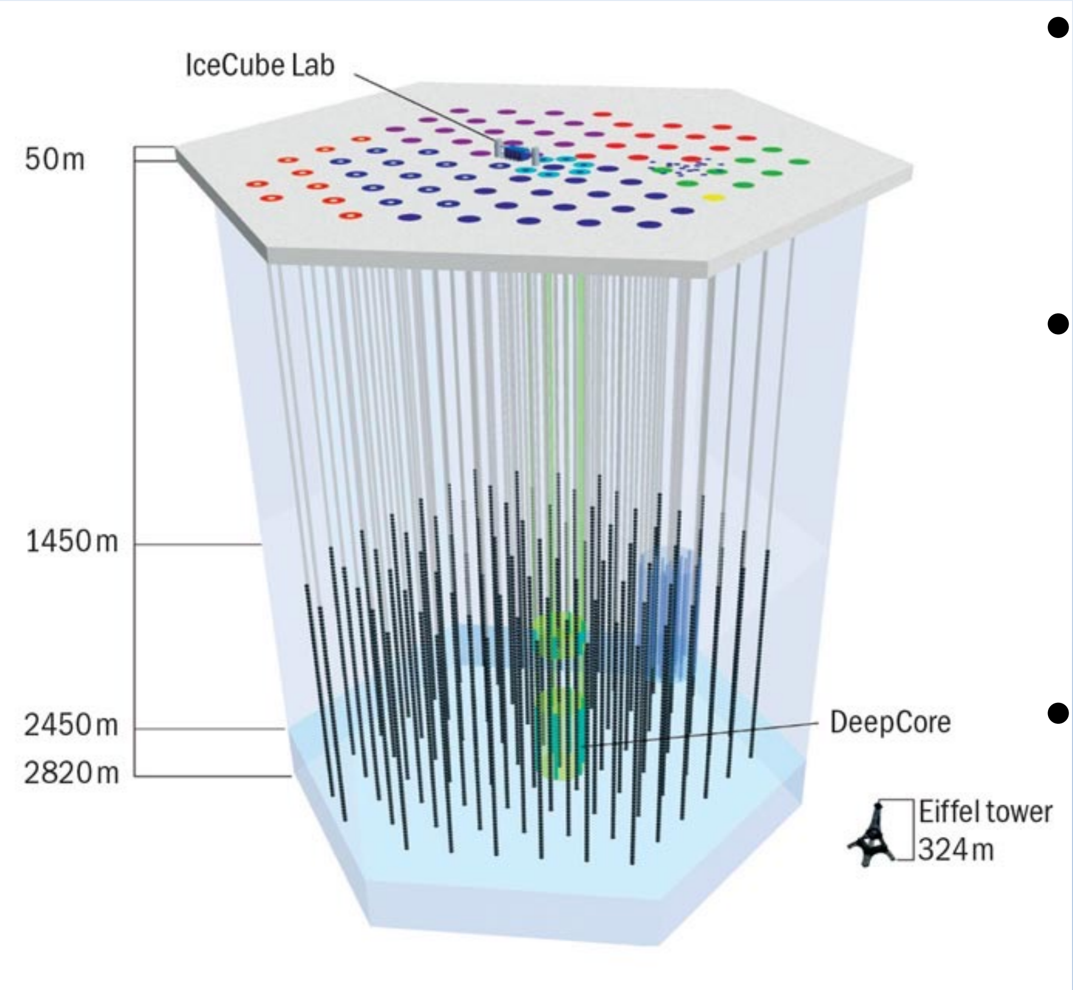
Detectors - Superkamiokande

- 22 kt fiducial volume
- 11,000 PMTs,
- 25 years of data



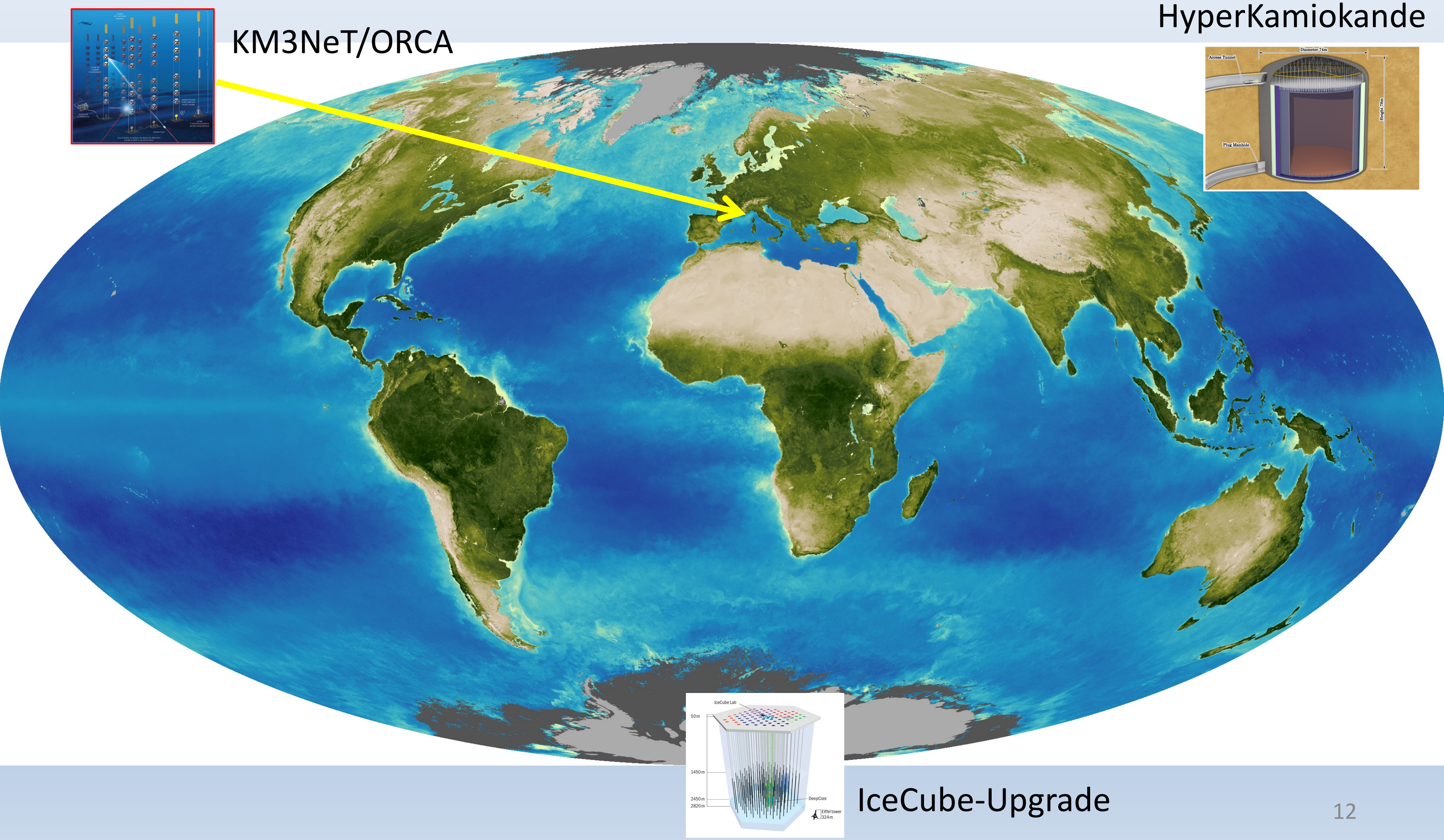


Detectors - IceCube / DeepCore



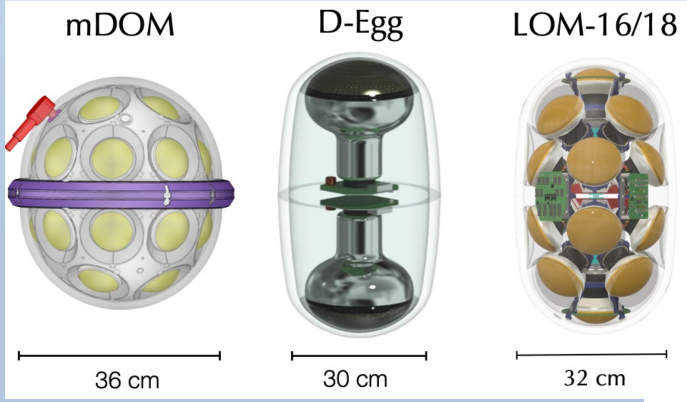
- 86 strings with 60 DOMs instrumenting $1km^3$
- Deep Core : dense core for atmospheric neutrino physics at 10-100 GeV
- Operational since 2011

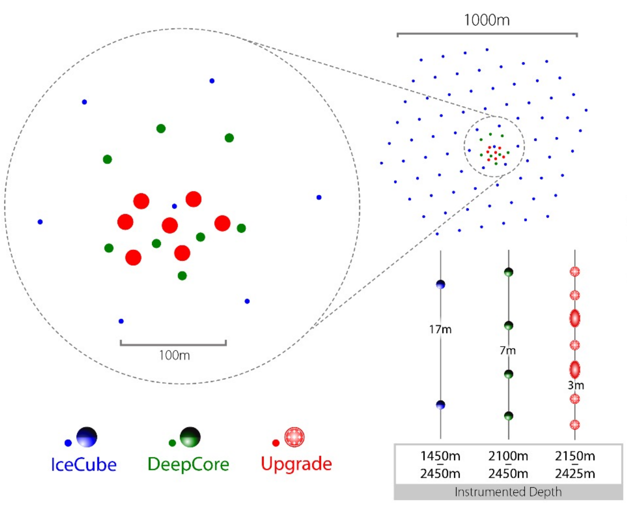
Next generation detectors

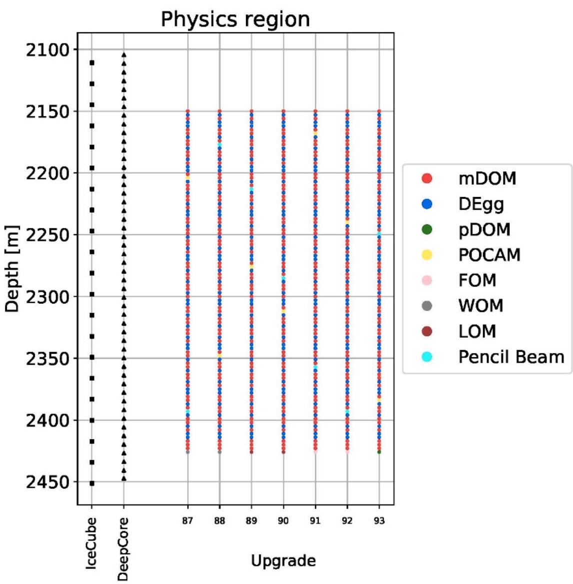


Detectors - IceCube upgrade

- 7 new strings inside DeepCore region
- 20m string spacing, 3m module spacing
- Energy threshold lowered from ~15 GeV to ~2 GeV
- 2 Mtons instrumented volume
- Installation during 2025/2026 campaign



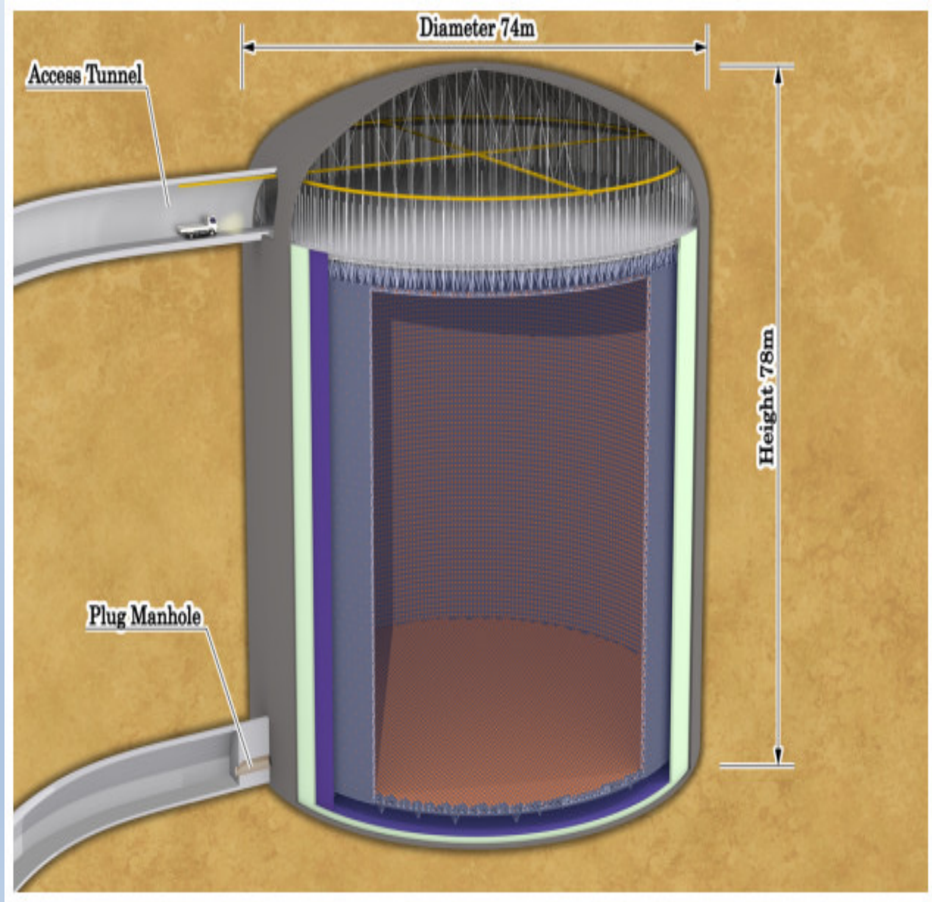




arXiv:1908.09441

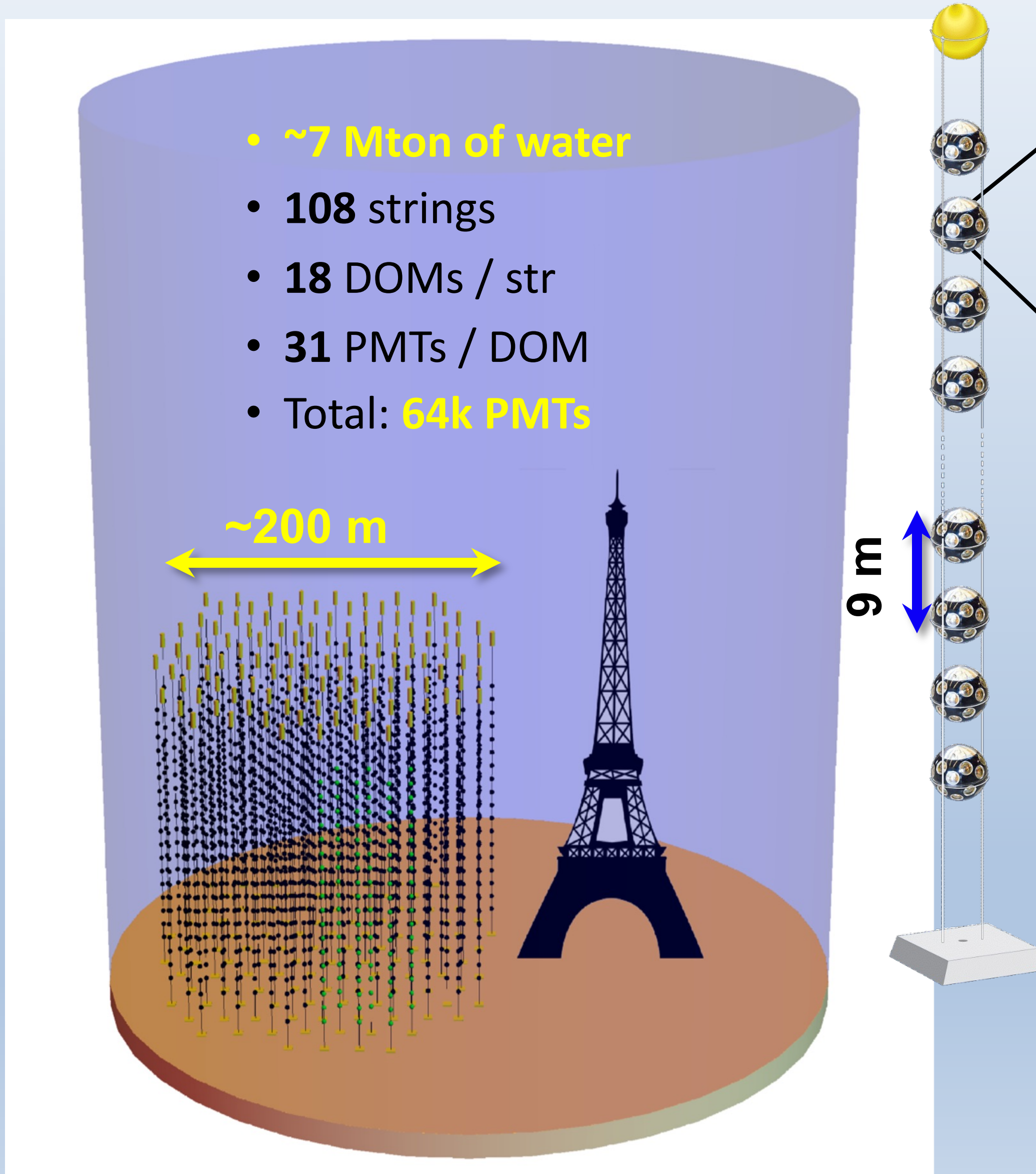
Detectors - HyperKamiokande

- 258 kton of water
- Fiducial volume ~0.2 Mton
- 20,000 50cm PMTs
- Data taking start planned for 2028



Detectors - KM3NeT/ORCA

- ~7 Mton of water
- **108** strings
- **18** DOMs / str
- **31** PMTs / DOM
- Total: 64k PMTs



- 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 for in all next-generation detectors
- Photon counting, nsec coincidences, directionality
- Better calibrations

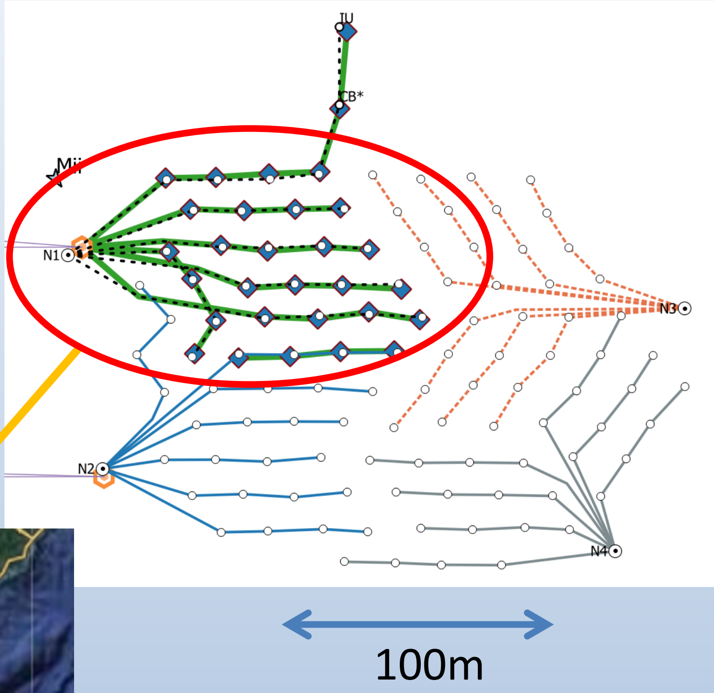
KM3NeT

IC upgrade

Hyperkamiokande

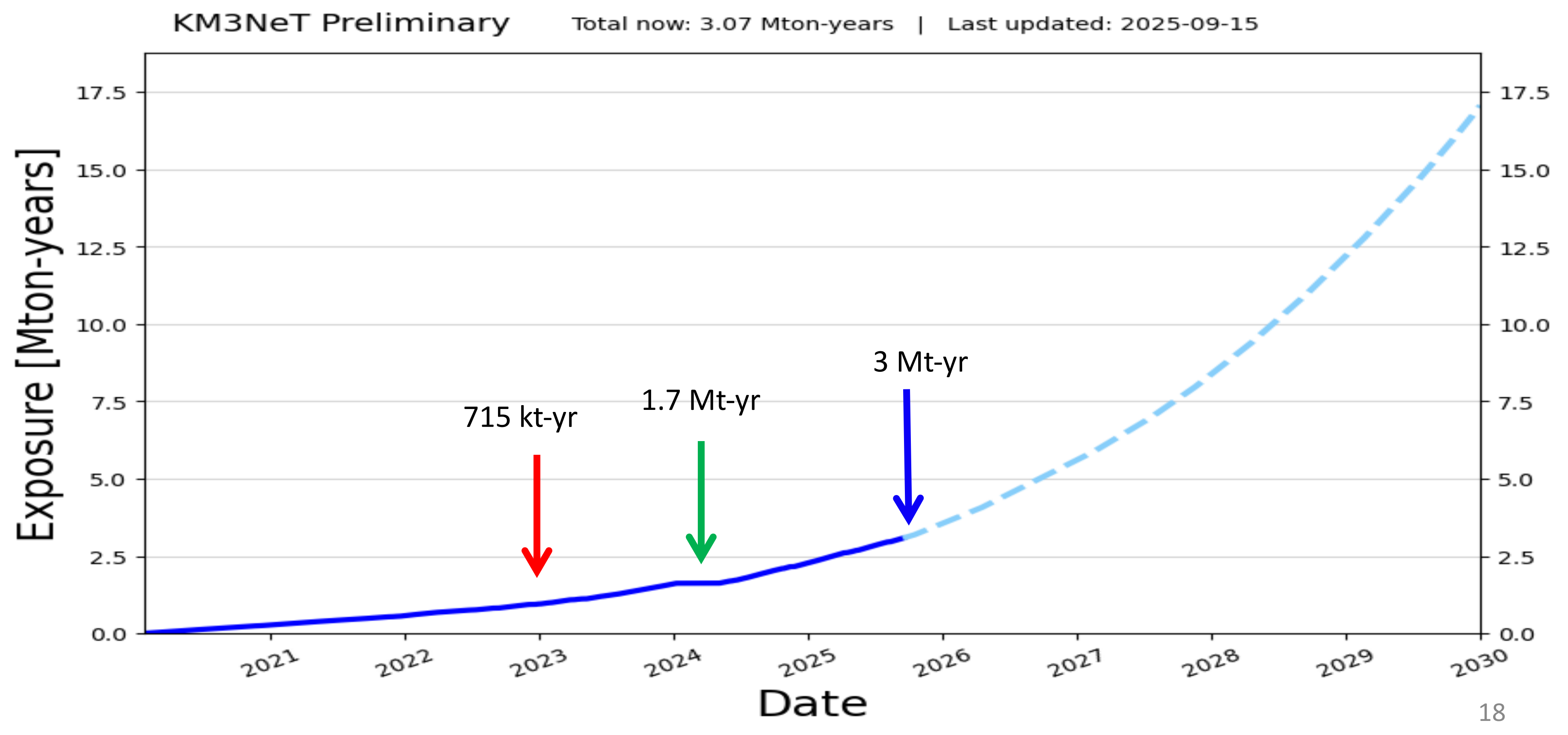
Detectors - Status of KM3NeT/ORCA

- 28 DUs and 2 junction boxes installed on sea floor
- Data taking currently with 24 DUs, 20% of final detector



Detectors - KM3NeT/ORCA

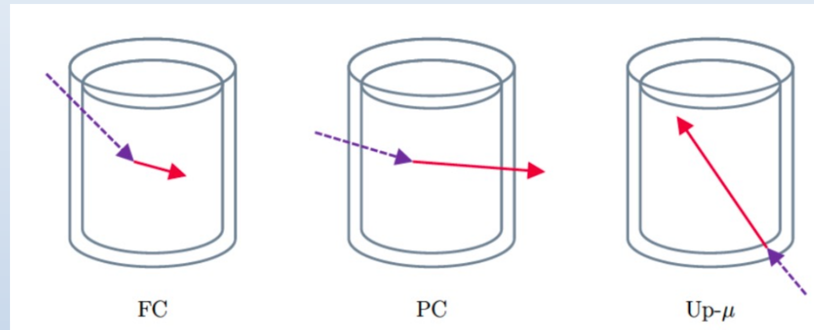
- 715 kt-yr : results published → see later
- 1.7 Mt-yr being analysed , 3 Mt-yr on tape , 20 Mt-yr by 2031

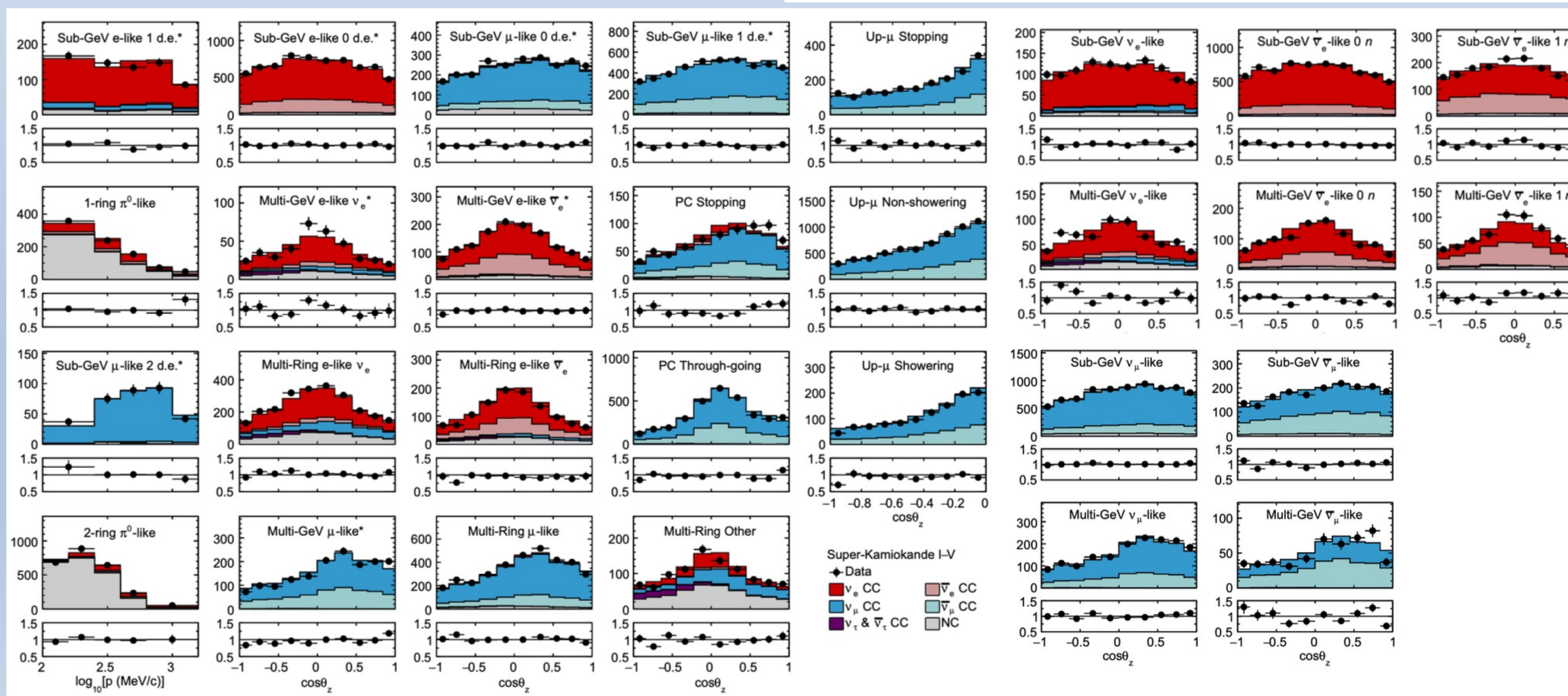


Analysis strategy - SuperKamiokande

- 29 samples binned in energy and zenith angle
- 190 systematics
- 80,000 events over 18y

Phys. Rev. D **109**, 072014 (2024)



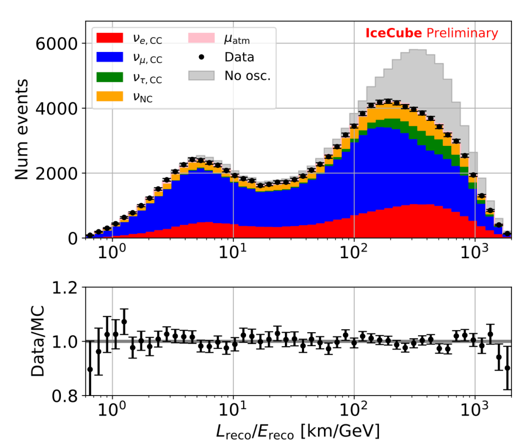


Analysis strategy – IC/DeepCore

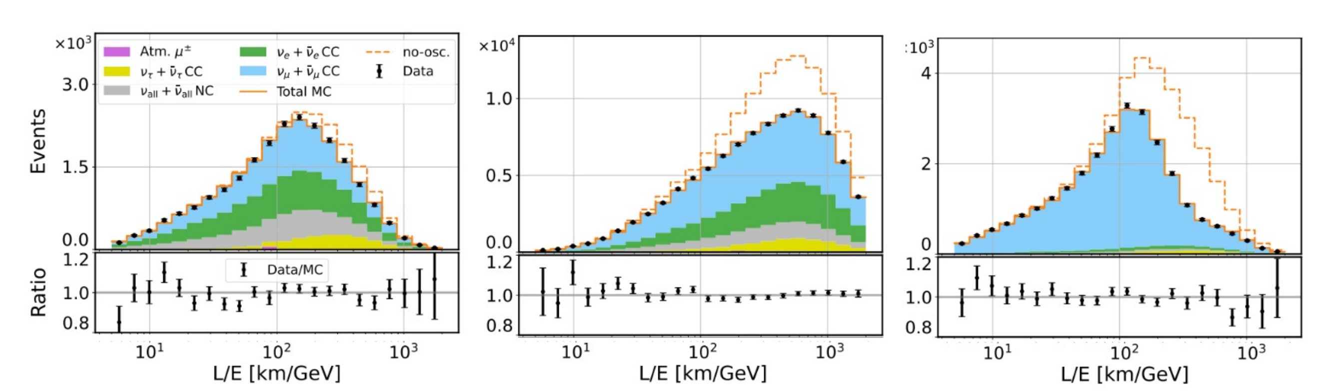
- 3 samples binned in energy and zenith angle

• CNN	• GNN
• 17 systematics	• 18 systematics
• 150,000 events	• 109,000 events
• 9.3 yrs	• 11.1 yrs

J. Koskinen, NuFact 2025



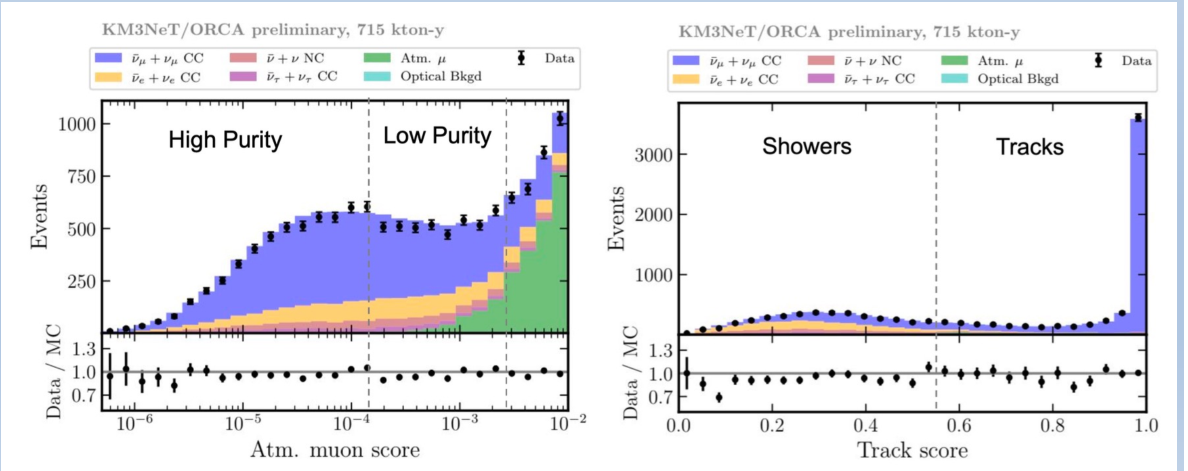
Phys. Rev. Lett. **134**, 091801 (2025)

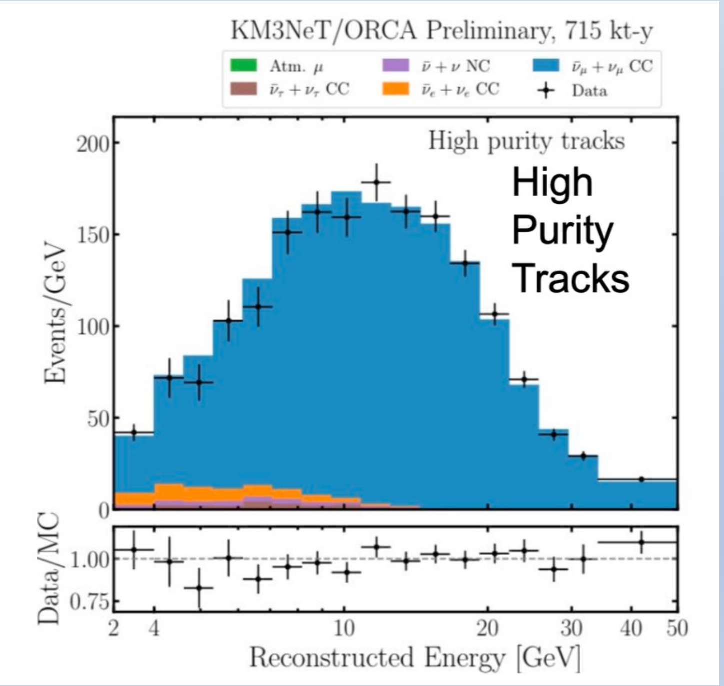


Analysis strategy – KM3NeT/ORCA

- 3 samples binned in energy and zenith angle (BDT)
- 13 systematics
- 10,000 events over 715 kt-yr

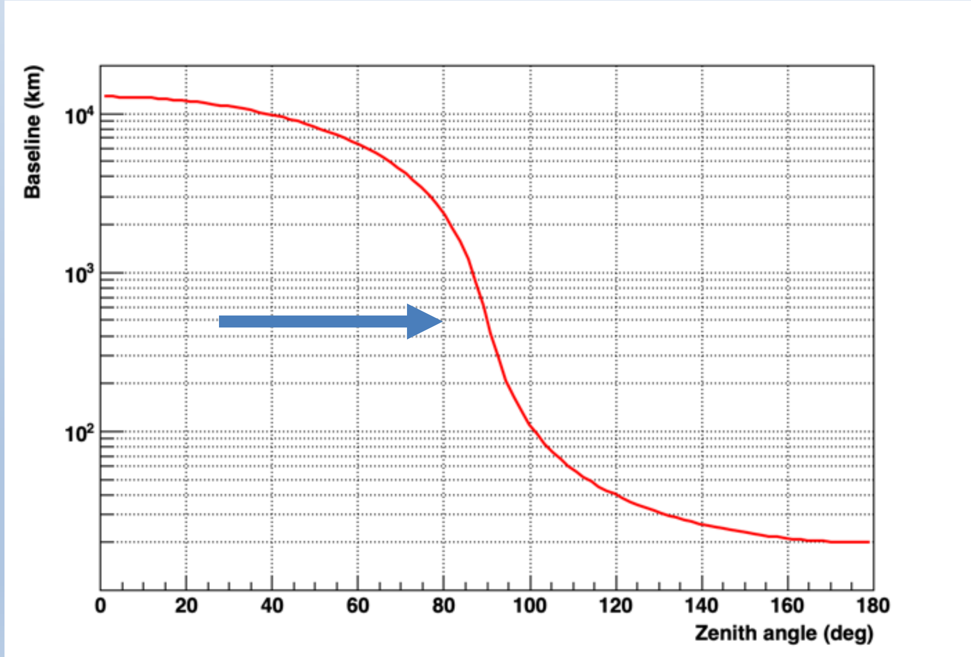
DOI 10.5281/zenodo.13234816 (2024)

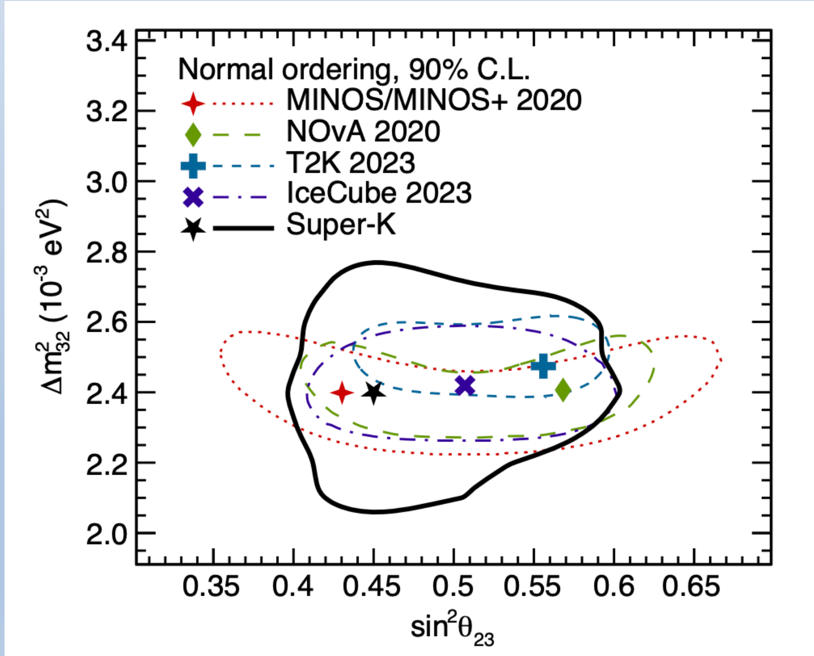




SuperKamiokande - Δm^2_{31} , θ_{23}

- Sensitivity in Δm^2_{31} limited by position of first oscillation maximum : L/E = 500 km/GeV → close to horizontal

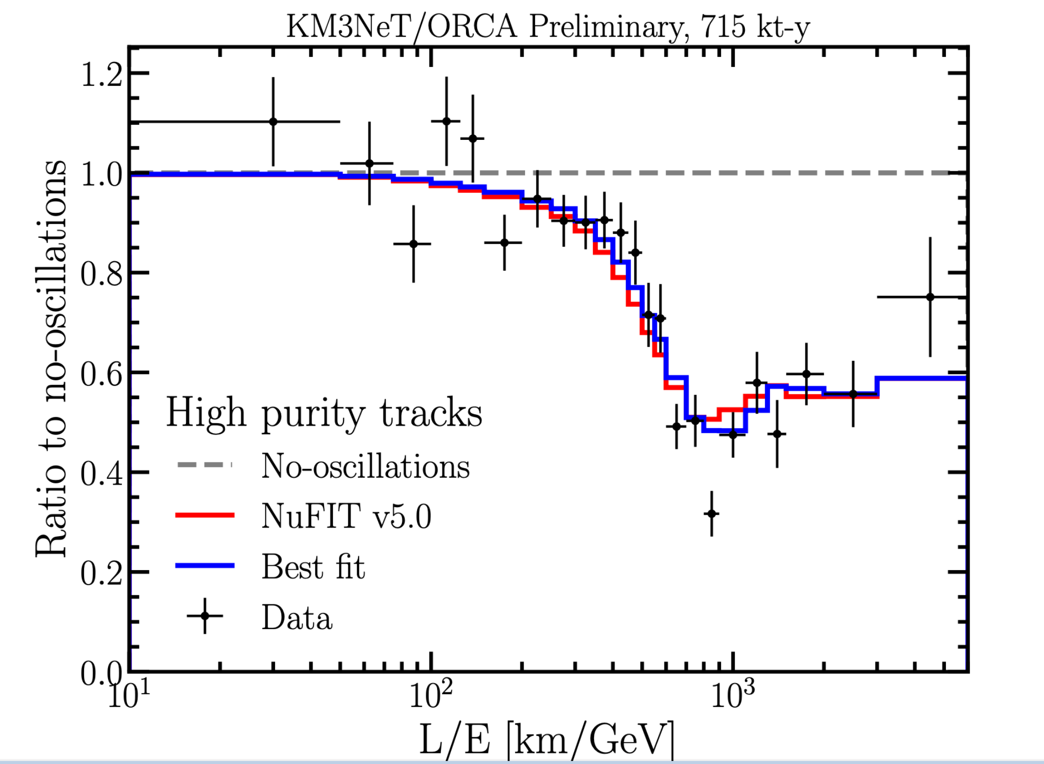


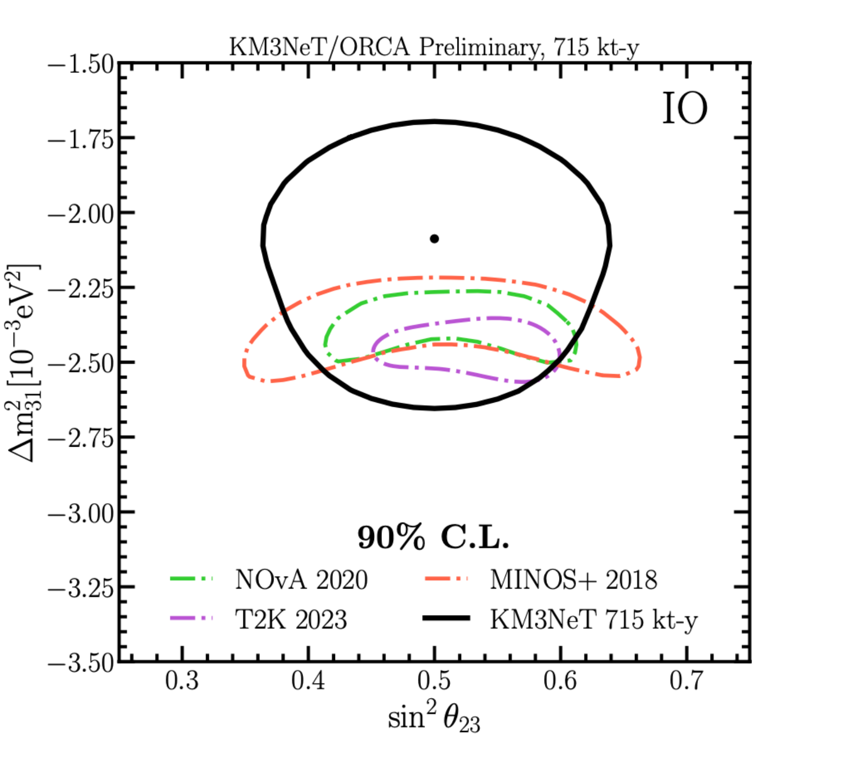


Phys. Rev. D **109**, 072014 (2024)

KM3NeT/ORCA - Δm^2_{31}, θ_{23}

- High statistics right at the first oscillation peak
- slight preference for IO, but not significant



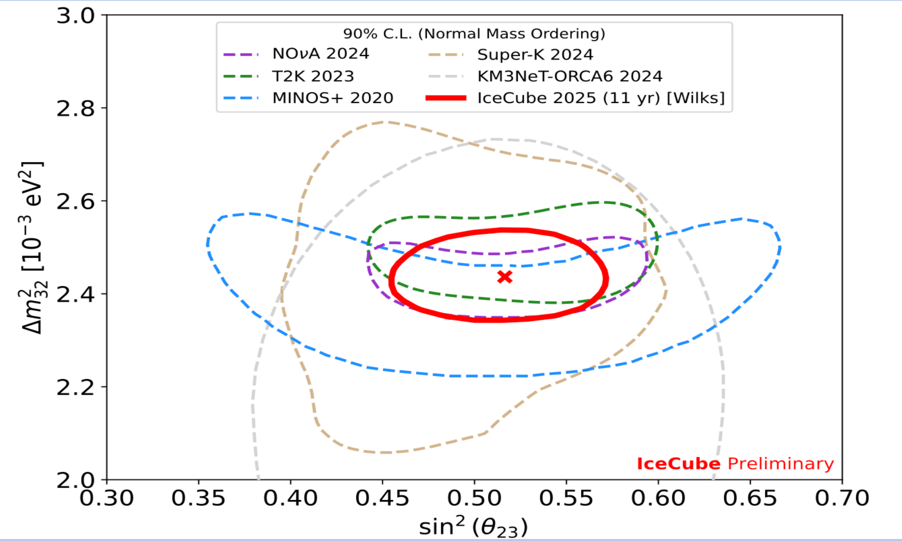


DOI 10.5281/zenodo.13234816 (2024)

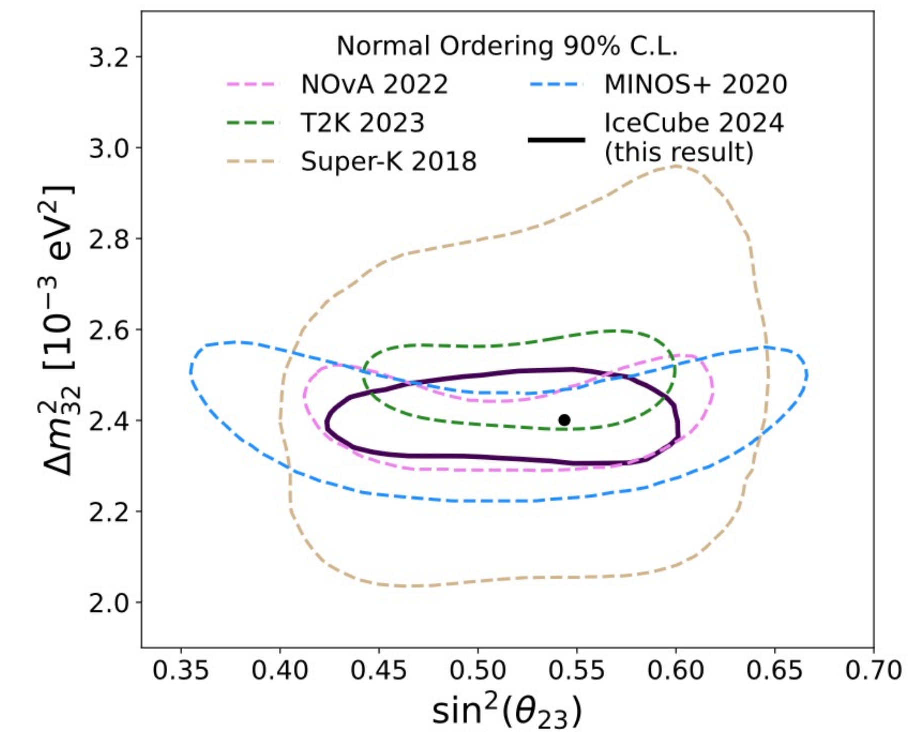
IC/DeepCore - Δm^2_{31}, θ_{23}

- Excellent performance already now
- Δm^2_{31} with ~2.0%, $\sin^2\theta_{23}$ ~8%

11.1 yr DeepCore



9.3 yr DeepCore



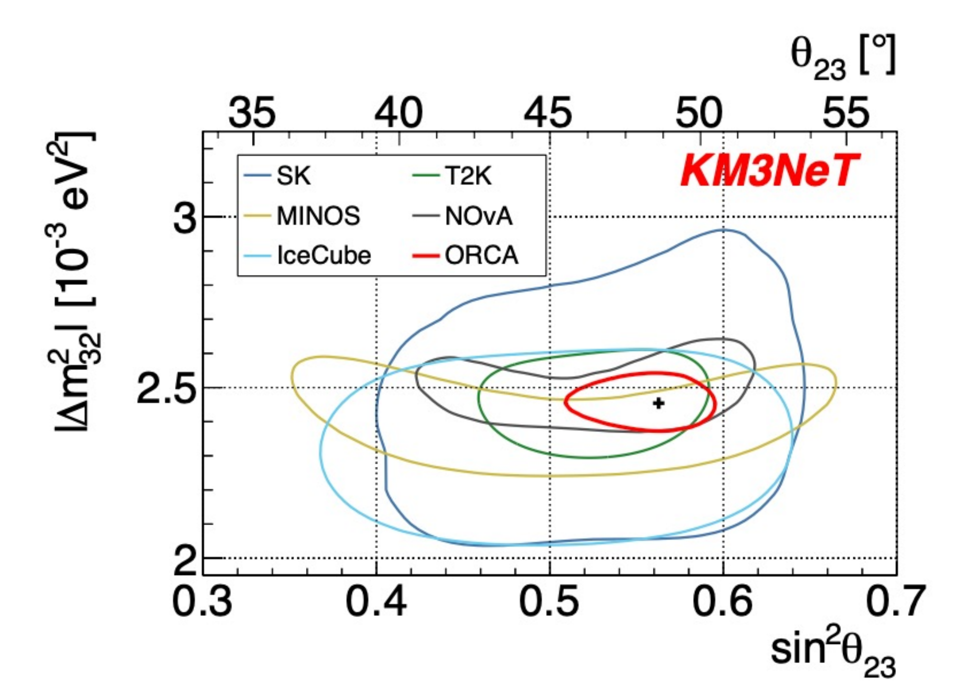
J. Koskinen, NuFact 2025

Phys. Rev. Lett. **134**, 091801 (2025)

Future - Δm^2_{31}, θ_{23}

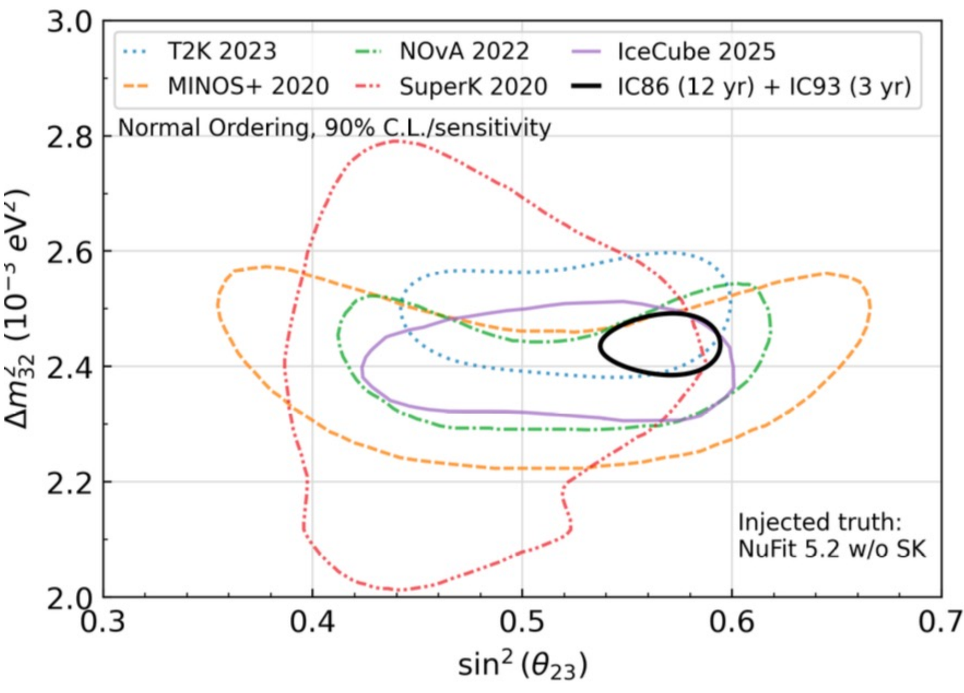
- Competitive measurement expected at 2029/2030
- Δm^2_{31} with ~1.5%, θ_{23} very dependent from true value

21 Mt-yr



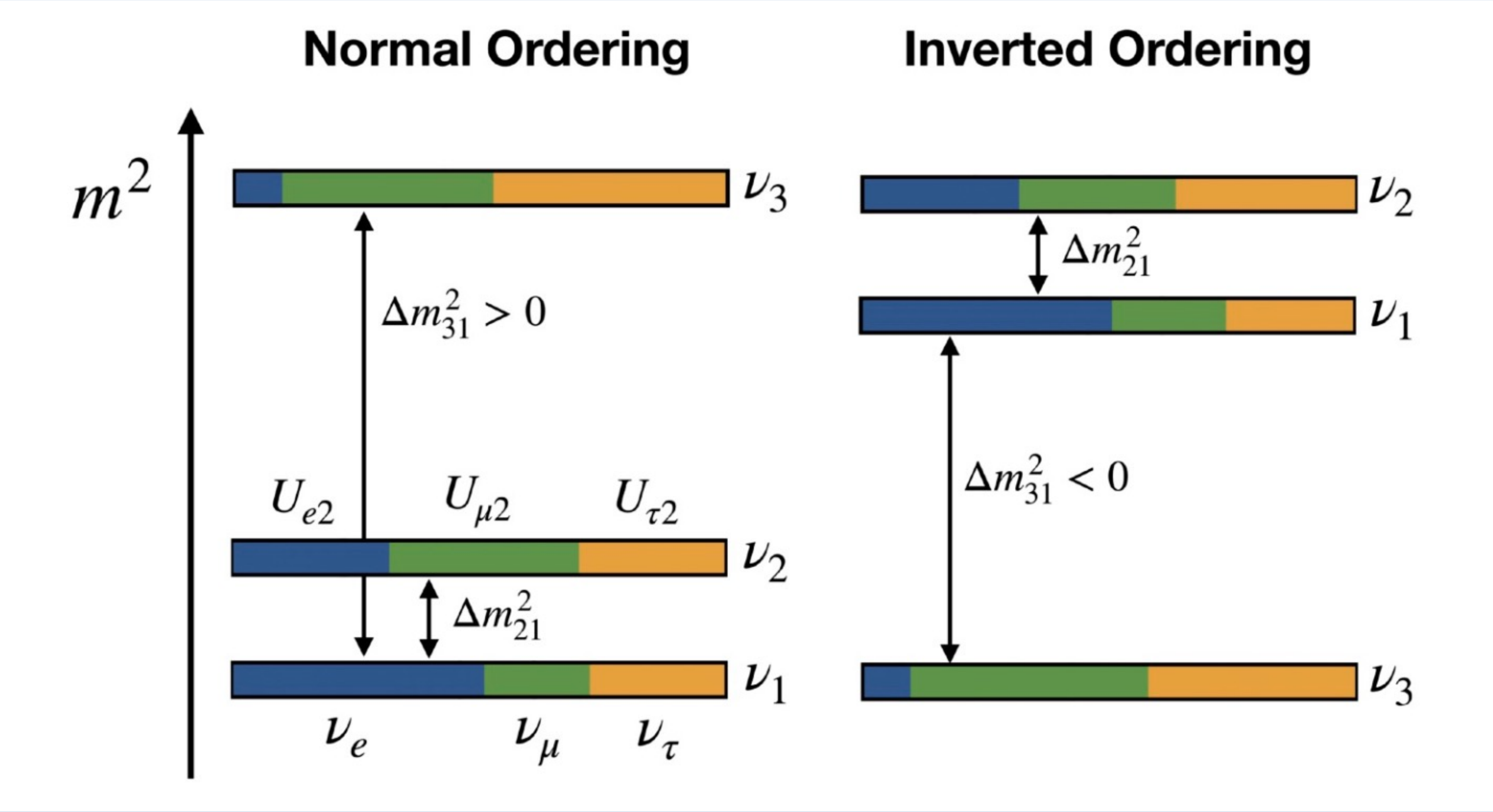
Eur. Phys. J. C 82, 26 (2022)

3yr IC-Upgrade



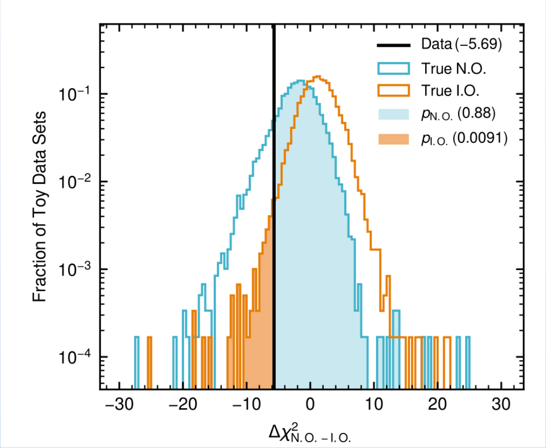
arXiv:2509.13066

Neutrino Mass Ordering

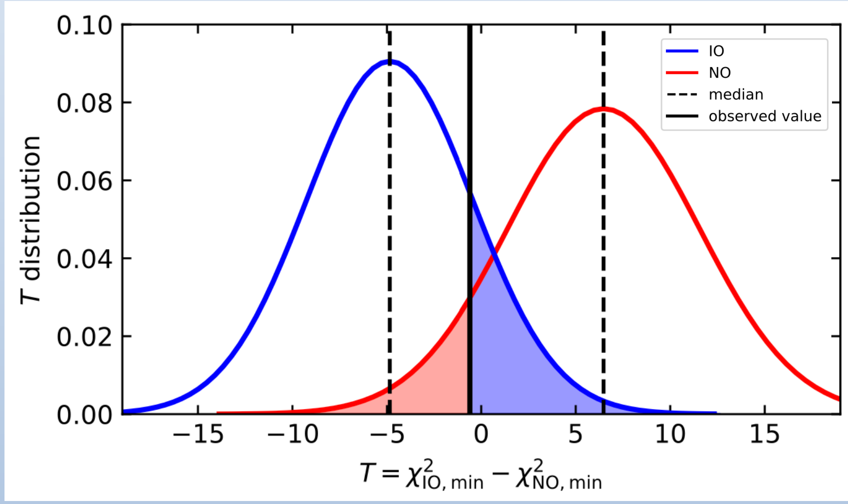


Current situation
Neutrino Mass Ordering

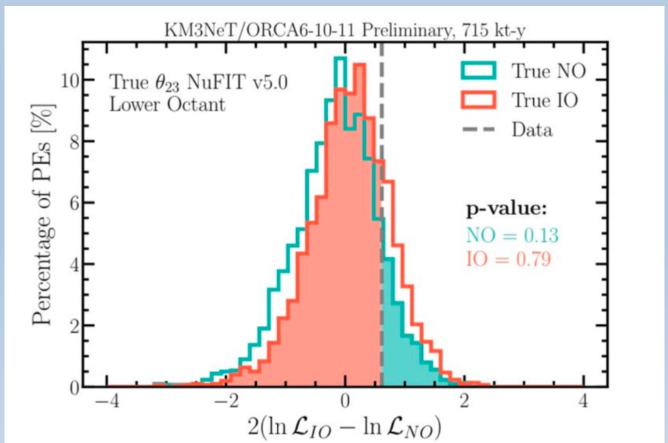
- NMO basically unknown to date



SuperK : IO rejected 82% CLs
Phys. Rev. D **109**, 072014 (2024)



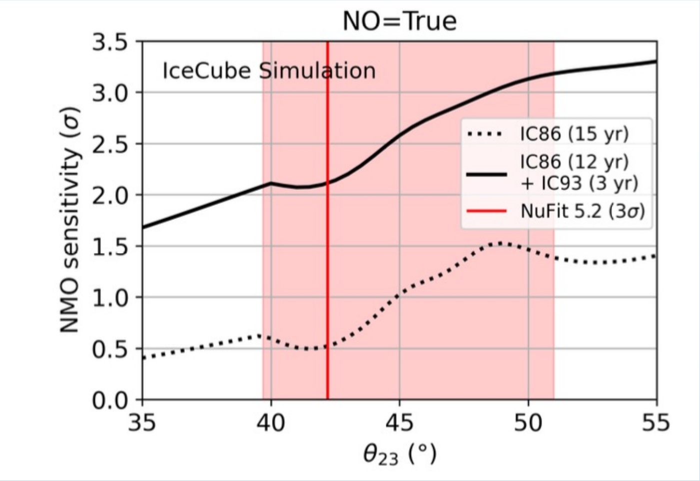
NuFit 6.0 w/o SuperK
JHEP **2024**, 216 (2024)

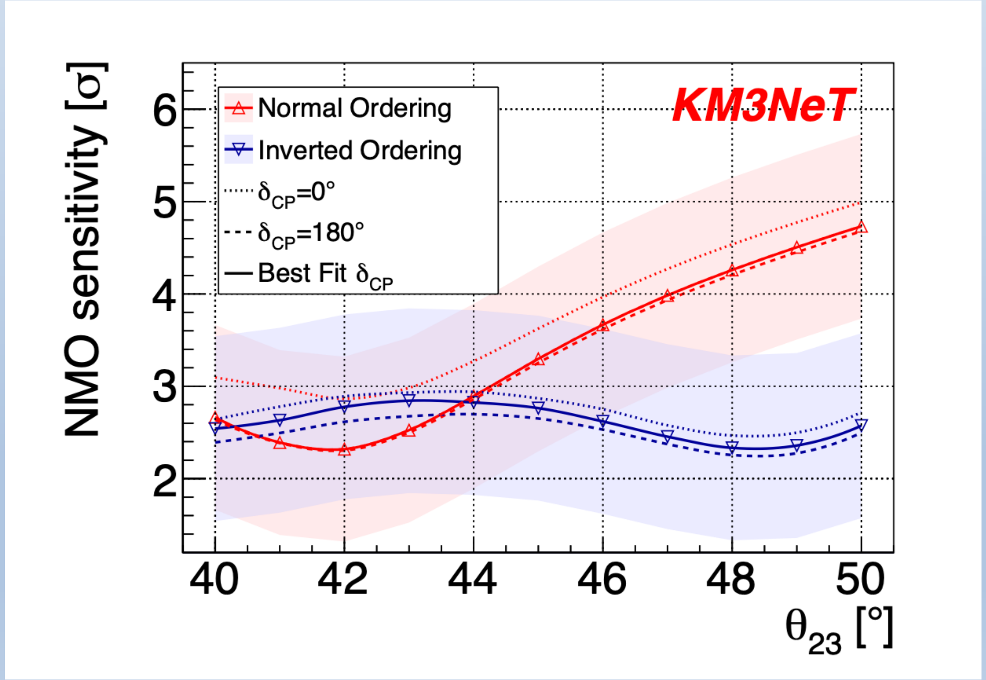


KM3NeT/ORCA 715 kt-yr
DOI 10.5281/zenodo.13234816 (2024)

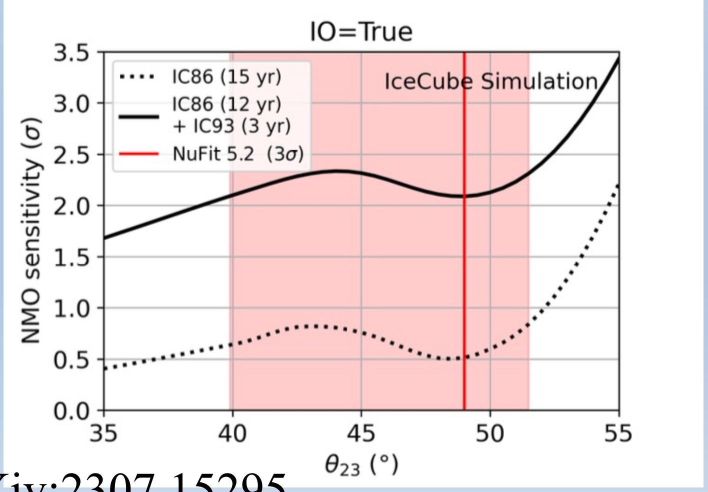
Future
Neutrino Mass Ordering

- KM3NeT/ORCA
- 21 Mt-yrs between 2.5 and 4.5σ





- After 3 years between 1.5 and 3.0σ
- Upgrade crucial for performance

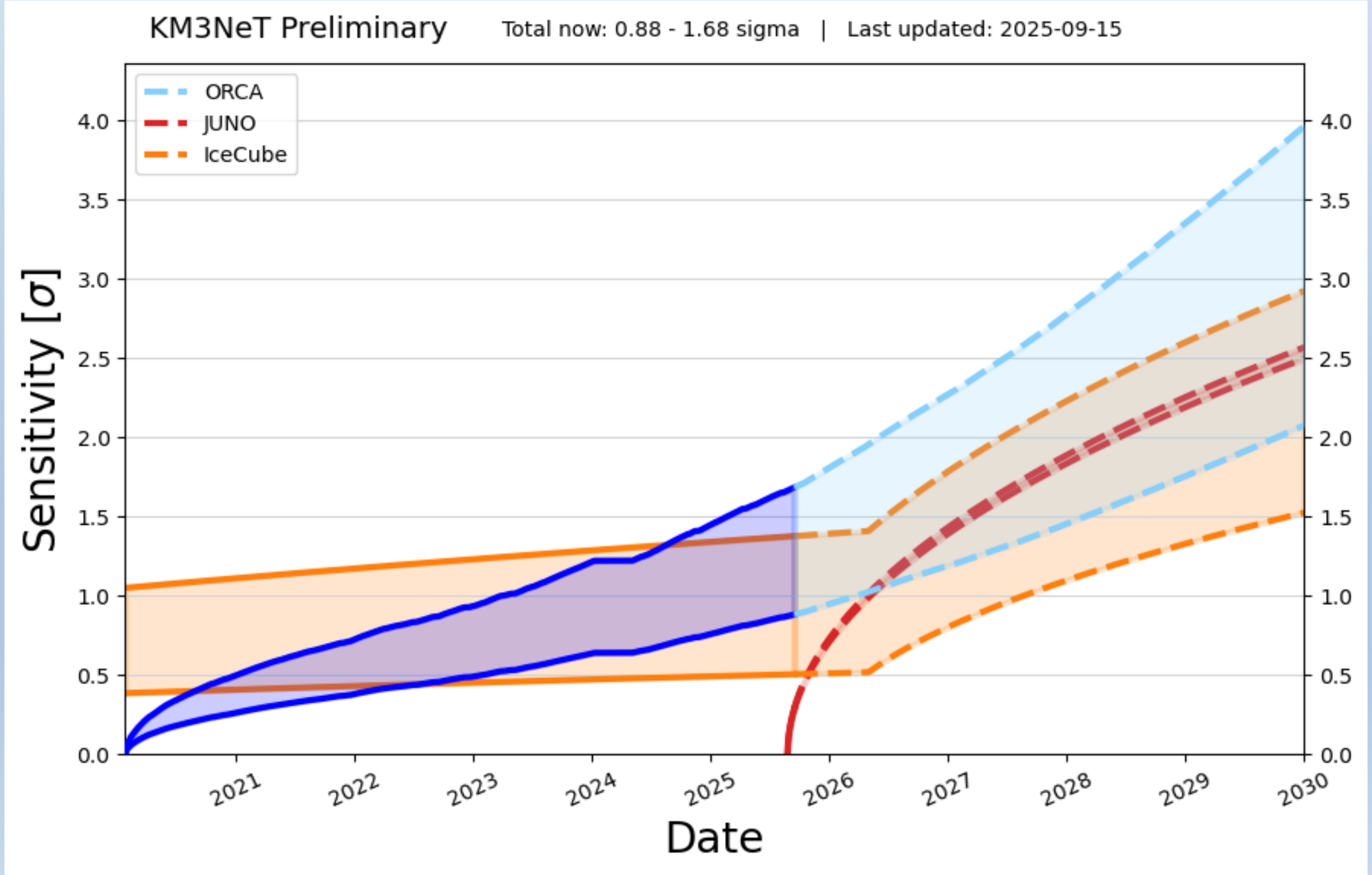


Eur. Phys. J. C 82, 26 (2022)

arXiv:2307.15295

Future
Neutrino Mass Ordering

- Before 2030 unambiguous measurement possible based on atmospheric neutrinos !

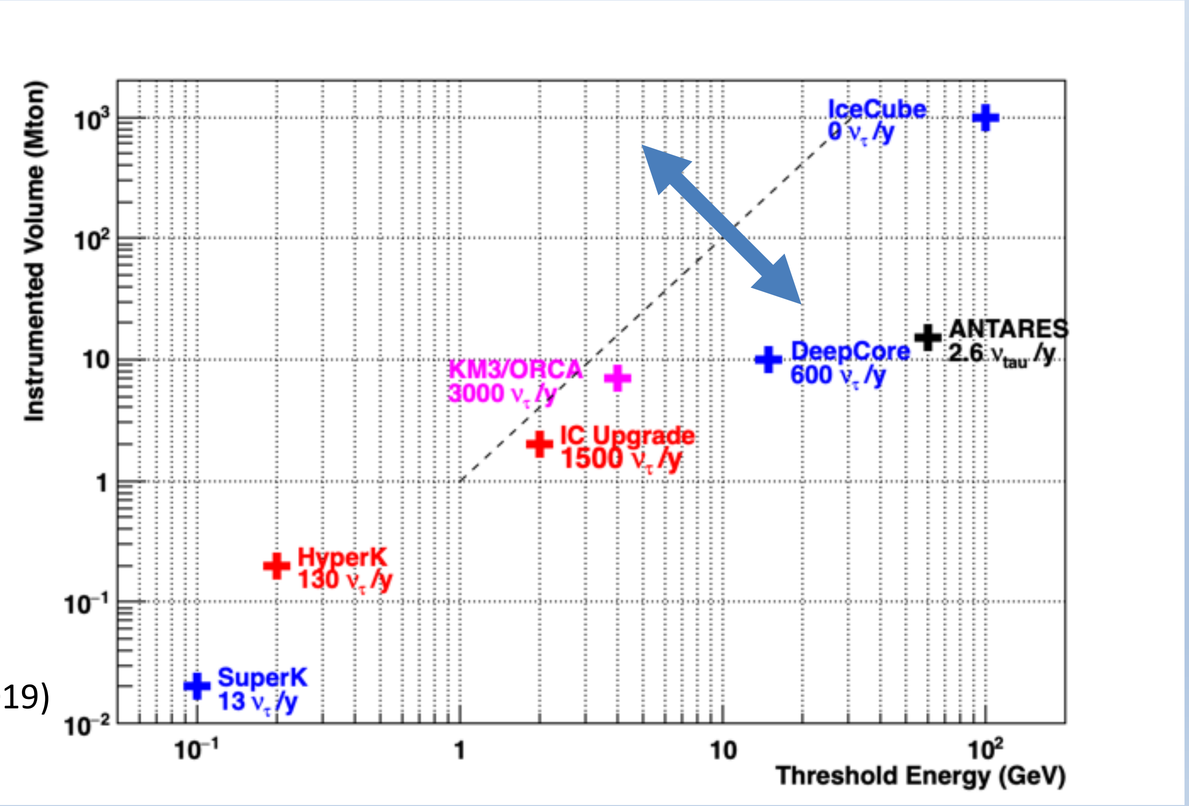


Chinese Phys. C **49** (2025) 033104.

arXiv:2307.15295

Atmospheric ν_τ–CC event count

- Largest existing ν_τ neutrino sample
- radical increase in the near future
- only produced via neutrino oscillations

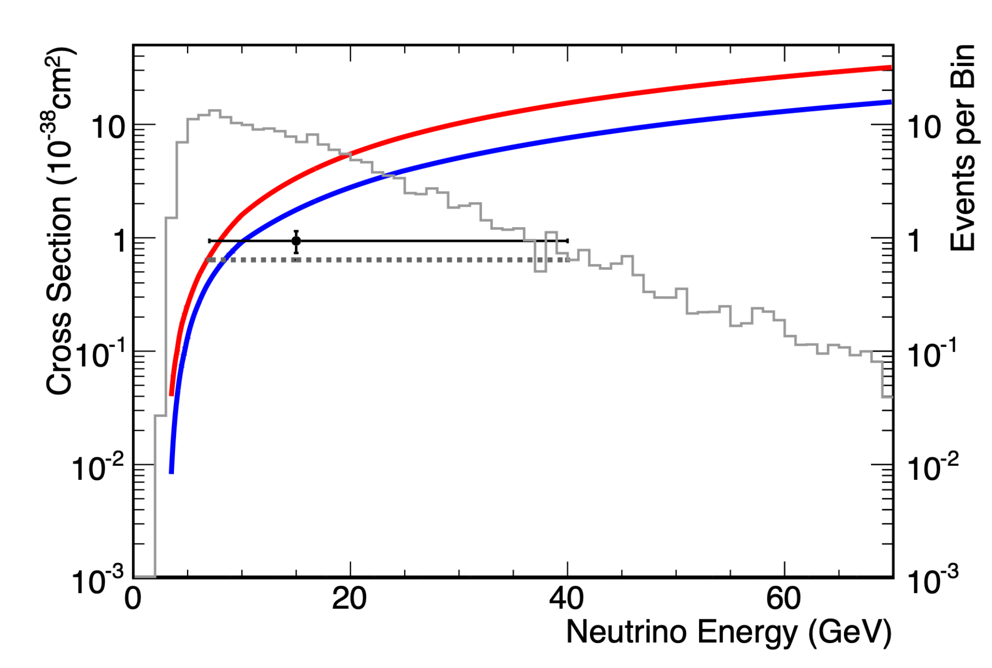


ANT: JHEP 2019, 113 *(2019)*
DC : Phys. Rev. D **99**, 032007 (2019)
ORCA: JHEP **2025**, 213 (2025)
IC-Up: arXiv:1908.09441
SK/HK: Phys. Rev. D 98, 052006 (2018)

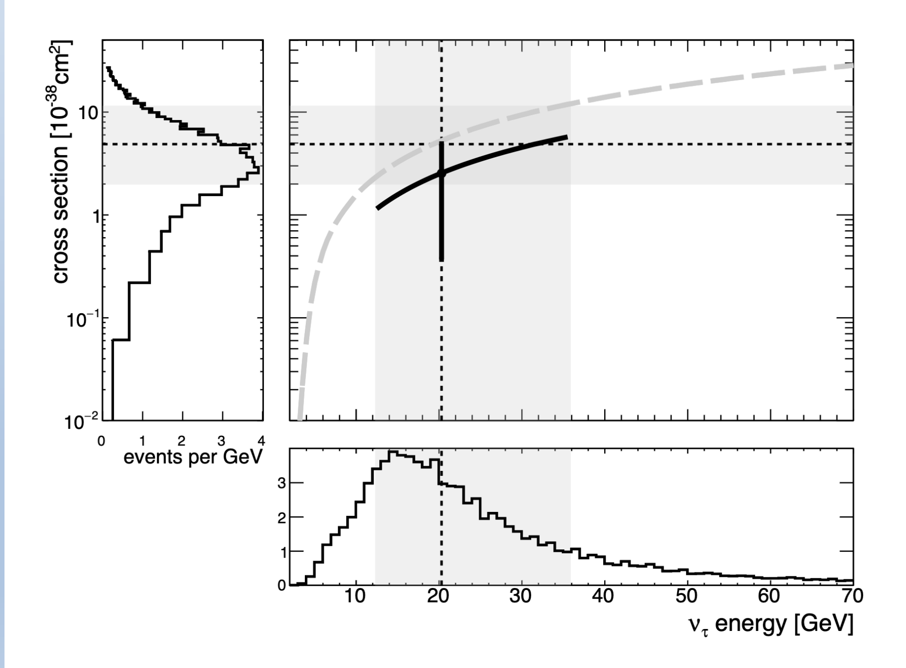
Current situation ν_τ cross-section

- Measurements from SuperKamiokande and KM3NeT/ORCA
- Close to kinematical threshold

SuperKamiokande, 14 years
Phys. Rev. D 98, 052006 (2018)



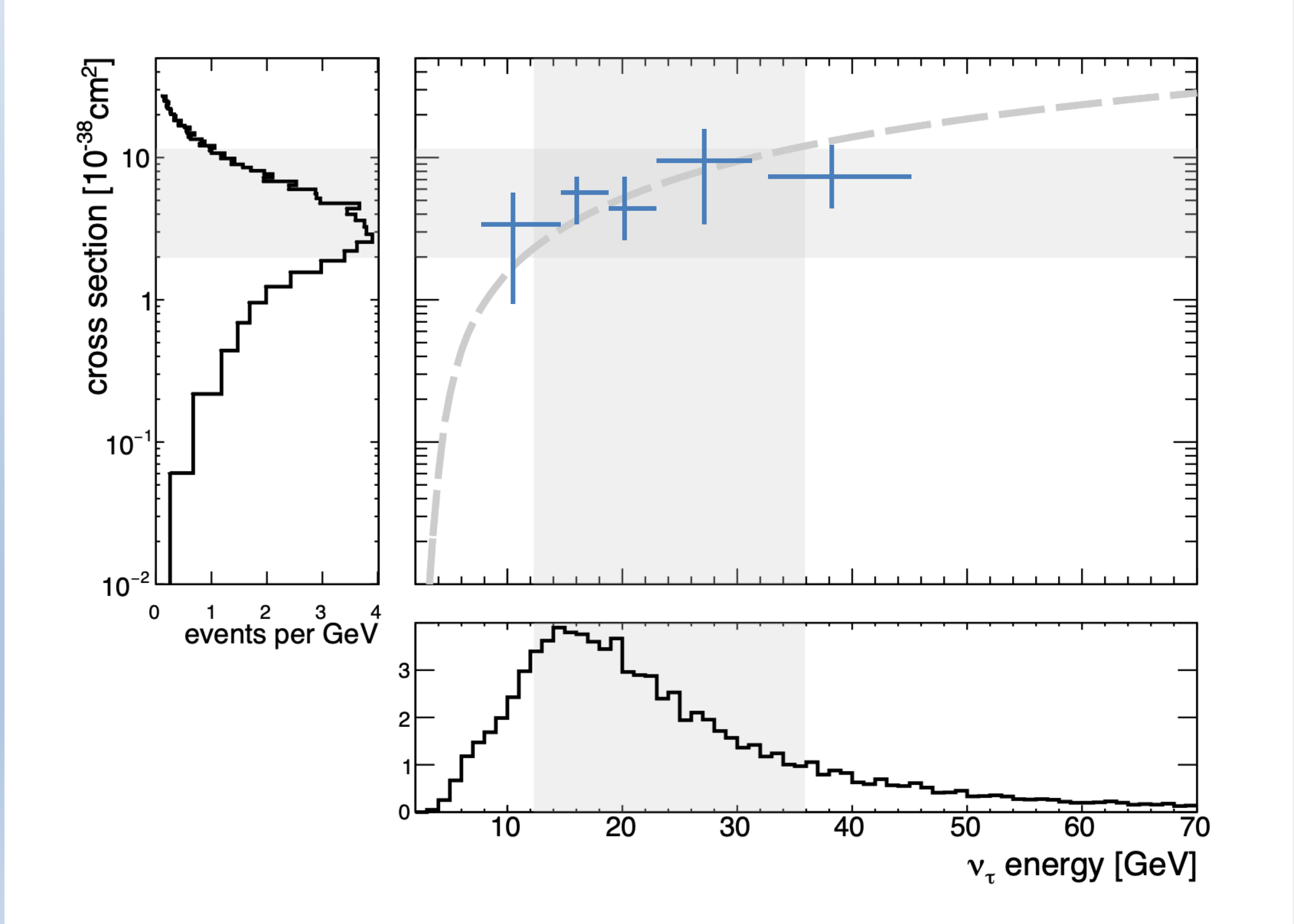
KM3NeT/ORCA 433 kt-yr
JHEP **2025**, 213 (2025)



Both measurements based on 185 ν_τ events, each

Future ν_τ cross-section

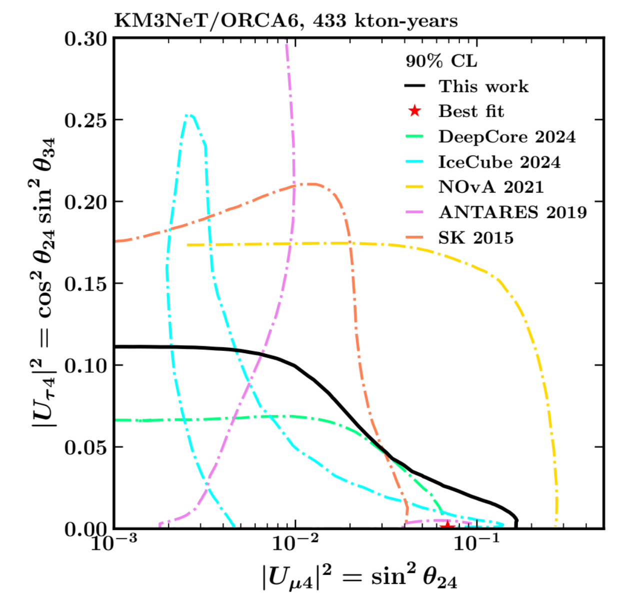
- Probes different structure function components and new physics
- Possible situation 2030



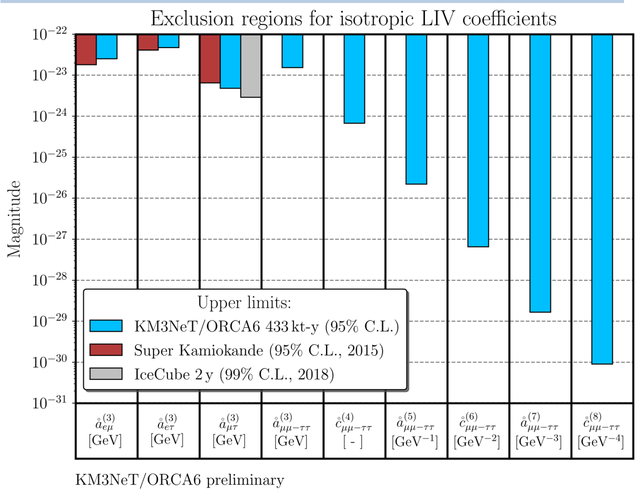
Potential for new physics

- rich phenomenology can be probed
- in particular relating to third lepton family

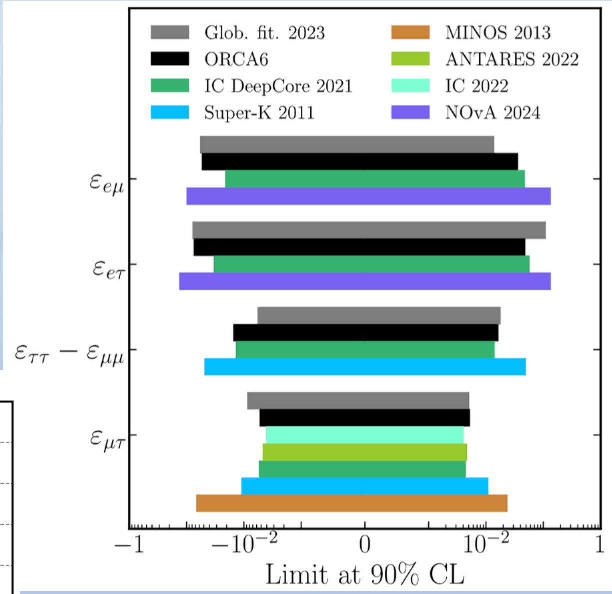
sterile neutrinos



Lorentz Invariance Violation



Non-Standard Interactions
JCAP 02 (2025) 073



Conclusion

- Rich physics from atmospheric neutrino analyses
- Next generation detectors soon online
- several 100,000 neutrino events within a few years
- Unambigouos determination of NMO before 2030

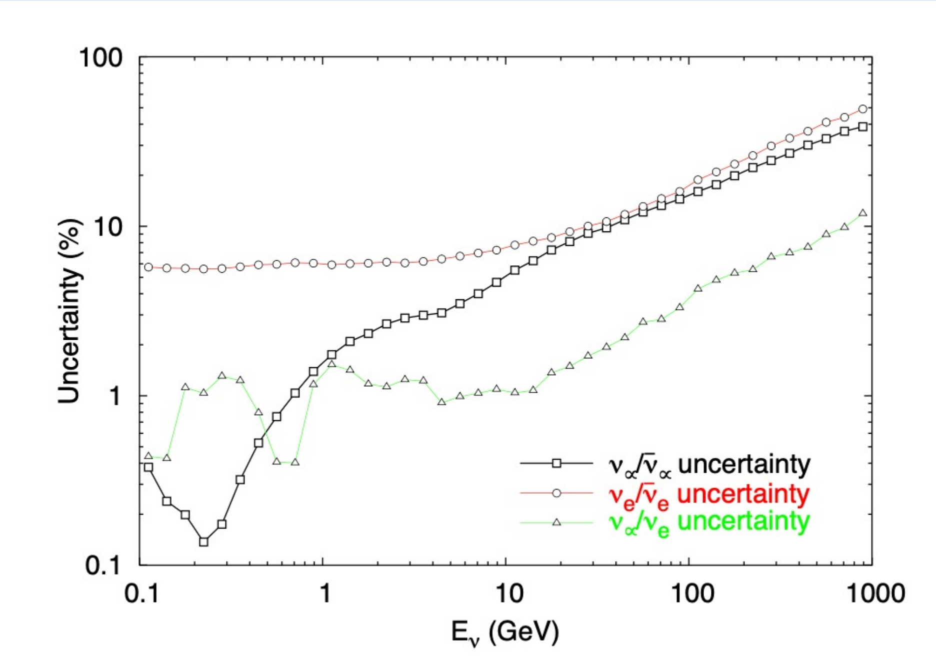
- **Precision measurement of Δm^2_{31}, θ_{23}**
- **World largest sample of many 1000 ν_τ**
- **Rich BSM program**

π^+ π^- μ^- μ^+

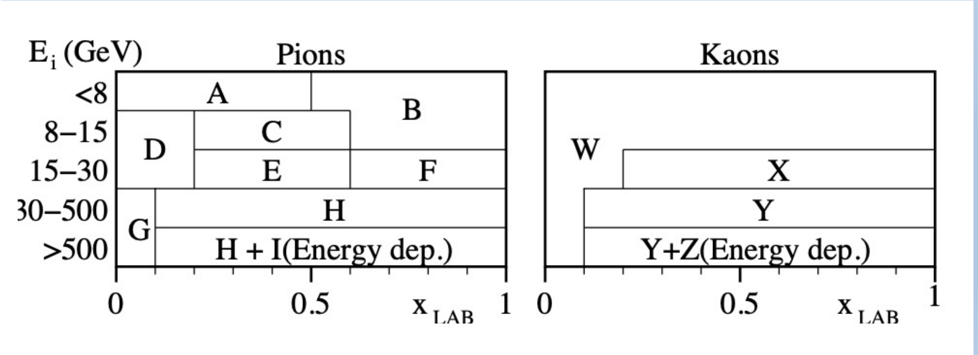
backup

Systematics – neutrino flux

- parametric approach
  - Spectral index
  - Normalisation, skews



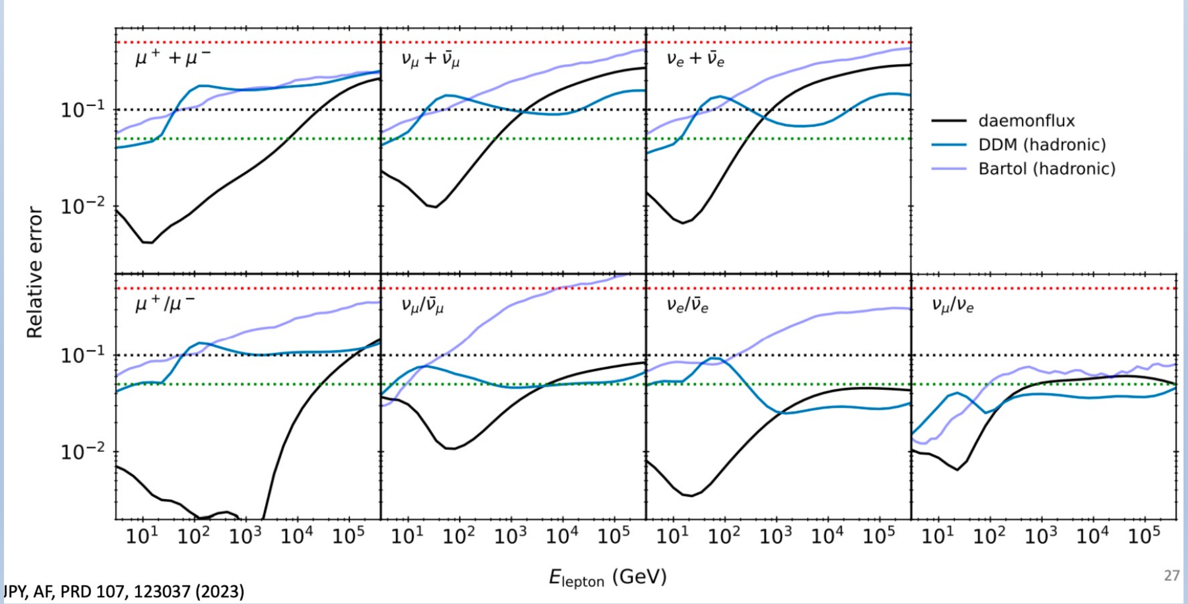
- Hadronic production uncertainties
- MCEq arXiv:1503.00544



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



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 systematics

- IC/Upgrade

KM3NeT/ORCA6

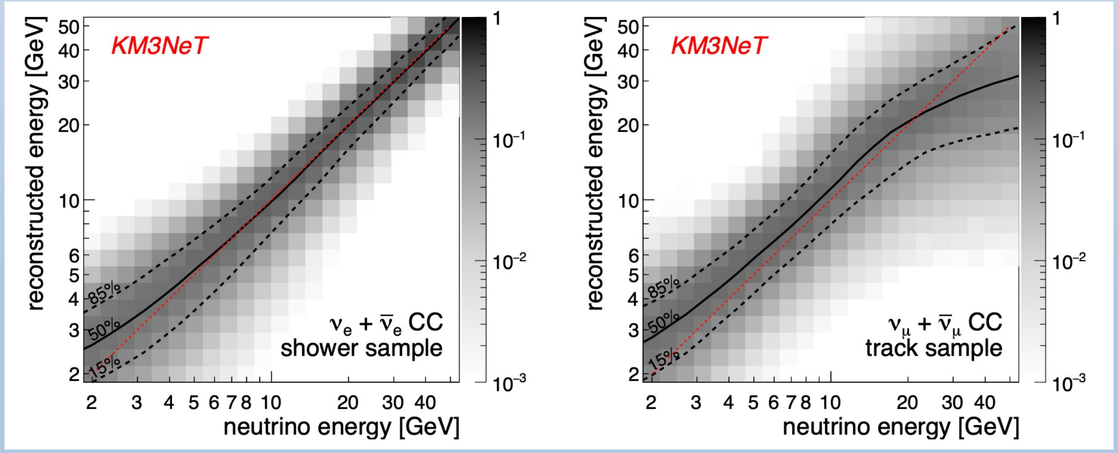
Parameter	Nominal	Prior	$\theta_{23}, \Delta m^2_{32}$	ν_τ	NMO
Detector:					
DOM eff. IC86	1.0	±0.1	✓	✓	✓
DOM eff. ICU	1.0	±0.05	✓	✓	✓
Ice absorption	1.0	±0.05	✓	✓	✓
Ice scattering	1.0	±0.1	✓	✓	✓
Relative eff. p_0	0.10	[-0.6, 0.5]	✓	✓	✓
Relative eff. p_1	-0.05	[-0.15, 0.05]	✓	✓	✓
Flux:					
$\Delta\gamma_\nu$	0.0	±0.1	✓	✓	✓
$\Delta\pi^\pm$ yields D	0.0	±0.3	x	x	✓
$\Delta\pi^\pm$ yields G	0.0	±0.3	✓	✓	✓
$\Delta\pi^\pm$ yields H	0.0	±0.15	✓	✓	✓
$\Delta\pi^\pm$ yields I	0.0	±0.61	✓	✓	✓
ΔK^+ yields W	0.0	±0.4	✓	✓	✓
ΔK^+ yields Y	0.0	±0.3	✓	✓	x
ΔK^+ yields Z	0.0	±0.122	x	x	✓
Cross-section:					
M_A^{CCQE} (in σ)	0.0	±1.0	✓	✓	✓
M_A^{CCRES} (in σ)	0.0	±1.0	✓	✓	✓
M_A^{NCRES} (in σ)	0.0	±1.0	✓	✓	✓
M_A^{coh} (in σ)	0.0	±1.0	x	x	✓
DIS CSMS	0.0	±1.0	✓	✓	x
ν_τ x-sec scale	0.0	[-1.0, +1.0]	x	x	✓
Normalization:					
$A_{\rm eff}$ scale	1.0	[0.1, 2.0]	✓	✓	✓
Atm. muons:					
Atm. μ scale	1.0	[0.1, 3.]	✓	✓	✓

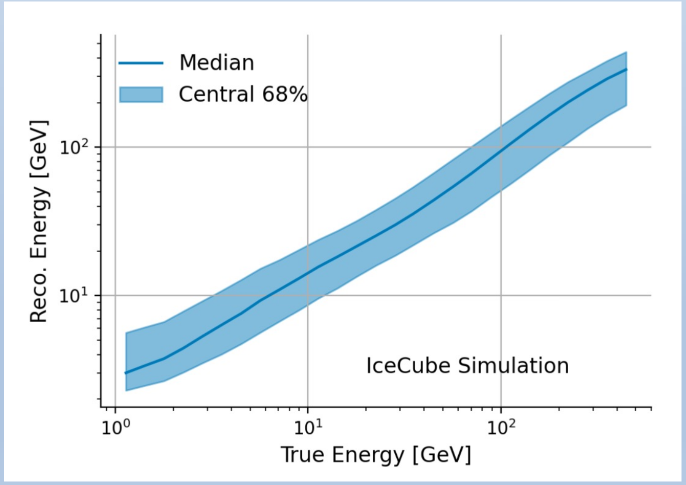
Parameter	Central value $\pm$ uncertainty	Best Fit	Post-fit uncertainty
$f_{\rm all}$	1.00	1.11	$-0.14/+0.13$
$f_{\rm HPT}$	1.00	0.92	$-0.04/+0.04$
$f_{\rm S}$	1.00	0.92	$-0.06/+0.06$
$f_{\rm HE}$	1.00 ± 0.50	1.59	$-0.29/+0.32$
f_μ	1.00	0.51	$-0.35/+0.4$
$f_{\tau{\rm CC}}$	1.00 ± 0.20	0.92	$-0.19/+0.19$
$f_{\rm NC}$	1.00 ± 0.20	0.86	$-0.19/+0.20$
$s_{\mu\bar{\mu}}$	0.00 ± 0.05	0.00	$-0.05/+0.05$
$s_{e\bar{e}}$	0.00 ± 0.07	0.01	$-0.07/+0.07$
$s_{\mu e}$	0.000 ± 0.020	-0.004	$-0.020/+0.020$
δ_γ	0.0 ± 0.3	-0.019	$-0.025/+0.026$
δ_θ	0.000 ± 0.020	-0.005	$-0.019/+0.019$
E_s	1.00 ± 0.09	1.03	$-0.11/+0.08$

Detector response - energy resolution

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

- IC upgrade
- Similar performance





arXiv:2307.15295

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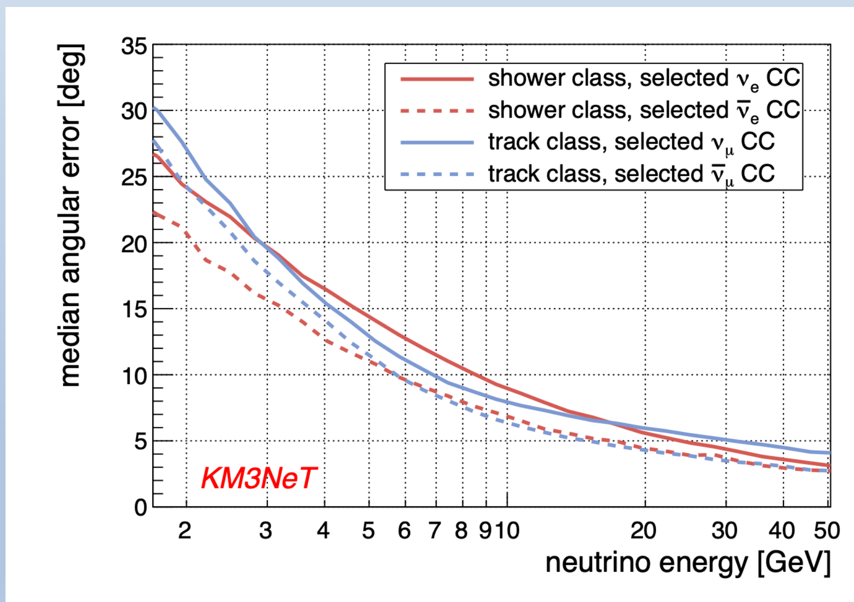
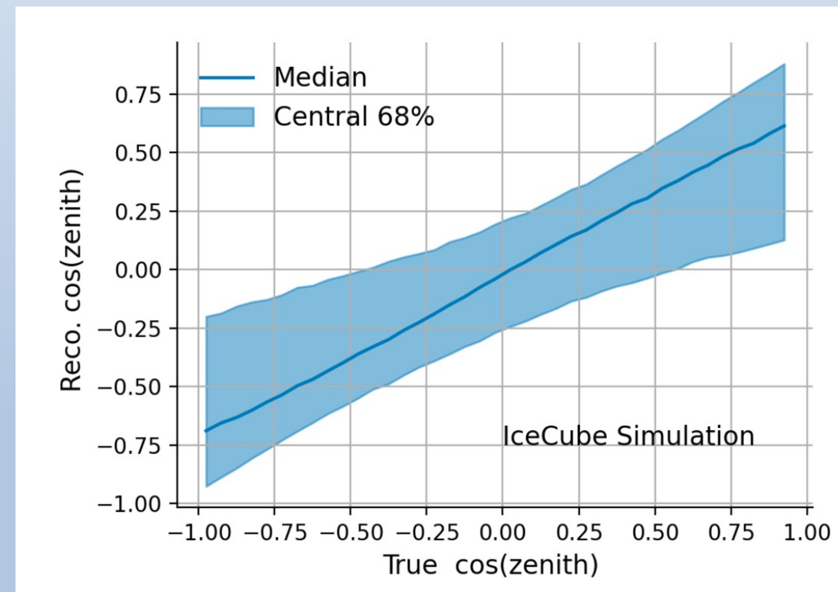
Detector response - angular resolution

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



- IC upgrade



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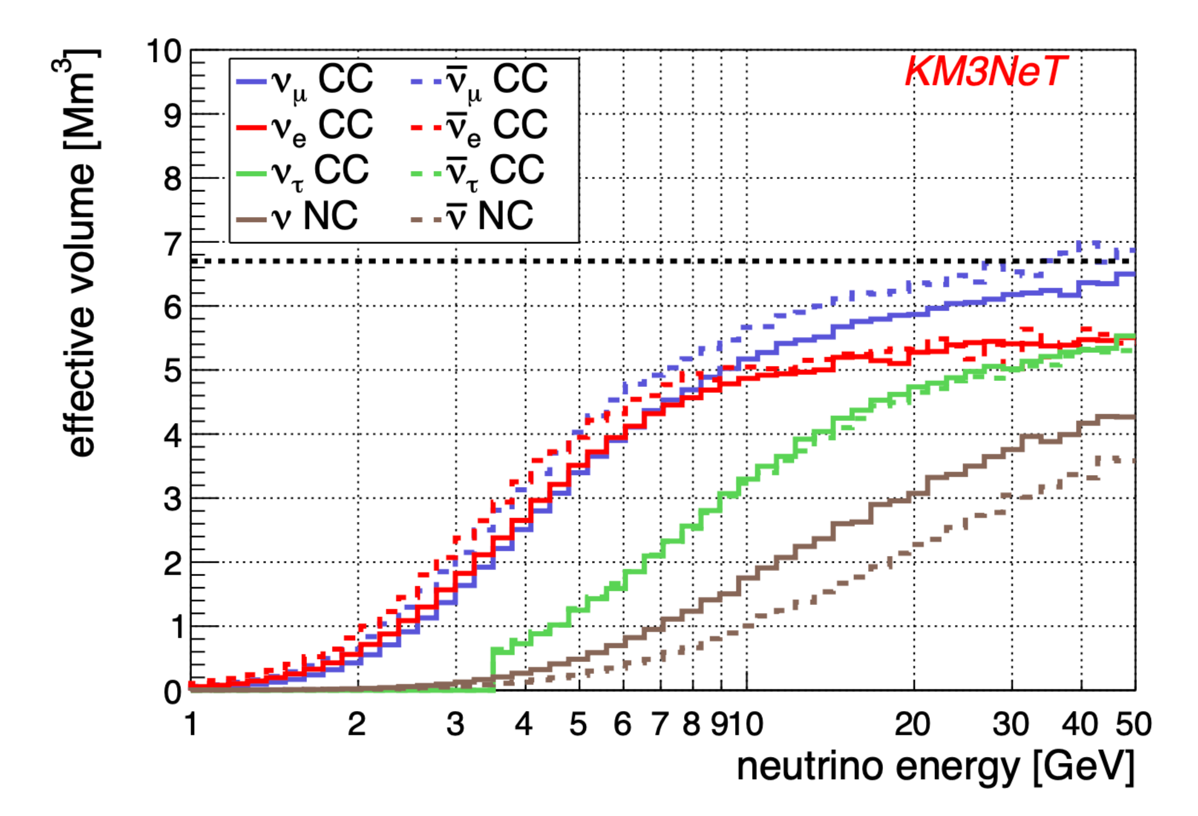
Intrumented versus effective mass

- Example KM3NeT/ORCA
- Instrumented mass of 7 Mtons
- Effective mass approaches effective mass at ~20 GeV
- Effective energy threshold ~2 GeV



arXiv:2103.09885