Université de Genève
(Switzerland)

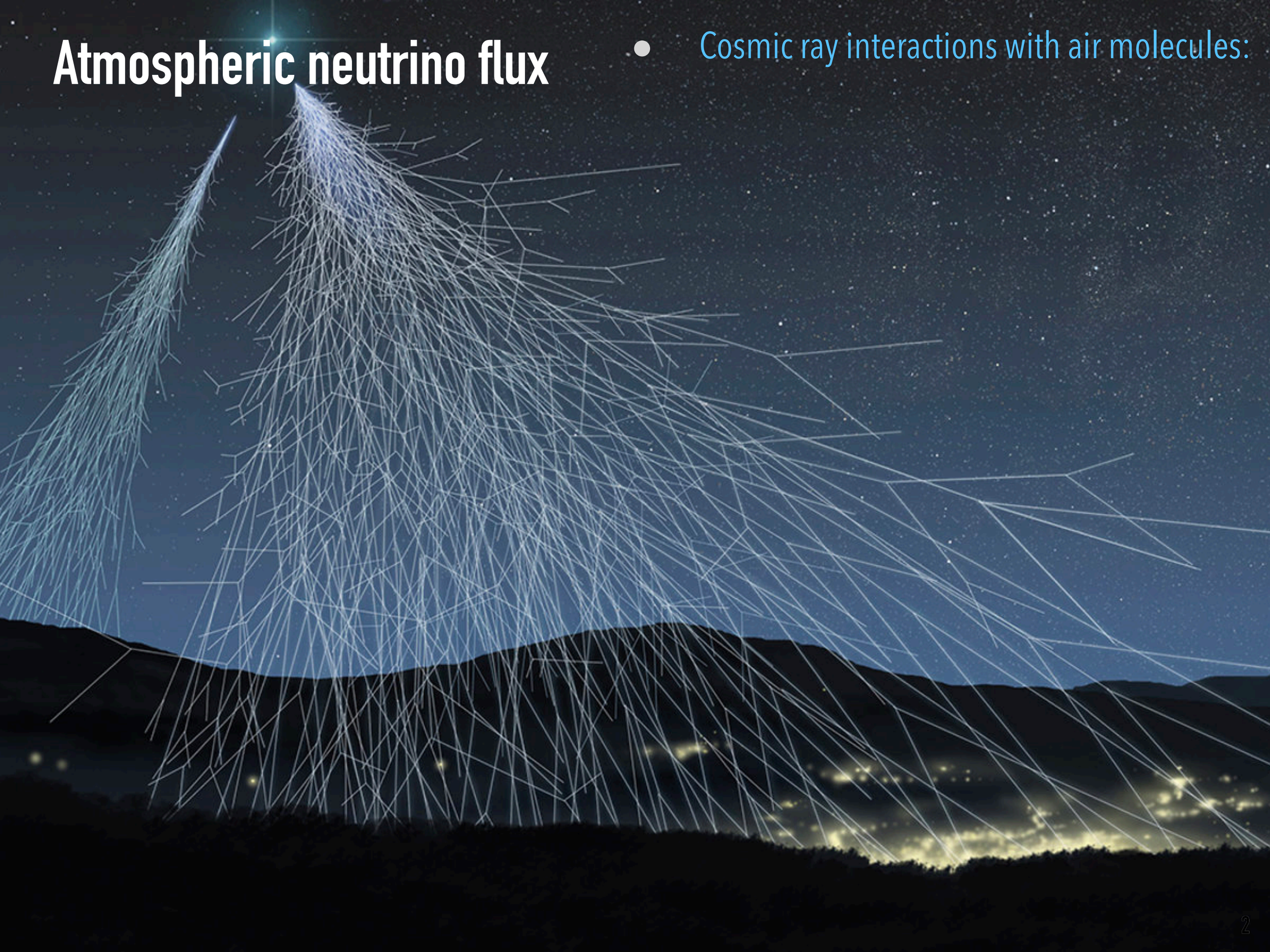
Toward Precision Oscillation Measurements with Atmospheric Neutrinos

Alfonso Garcia

alfonso.garcia@ific.uv.es

Atmospheric neutrino flux

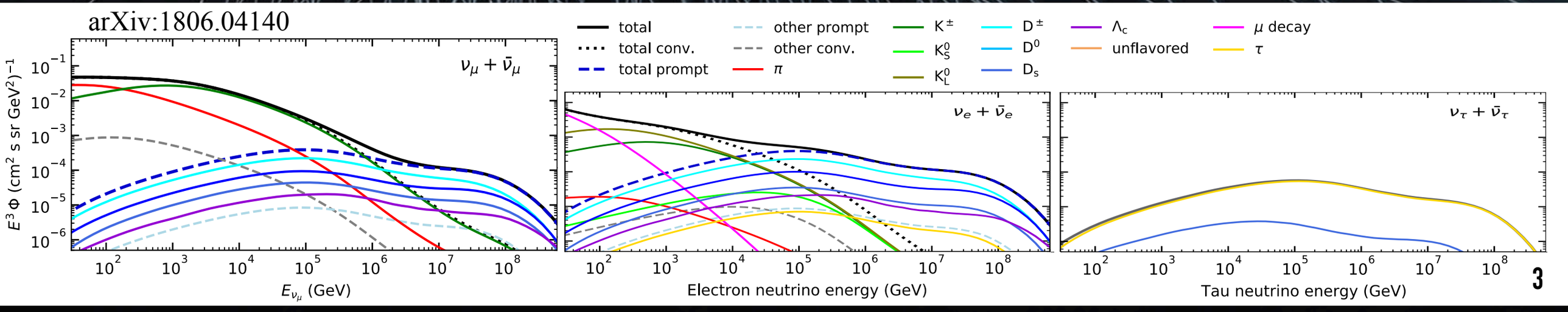
- Cosmic ray interactions with air molecules:



Atmospheric neutrino flux

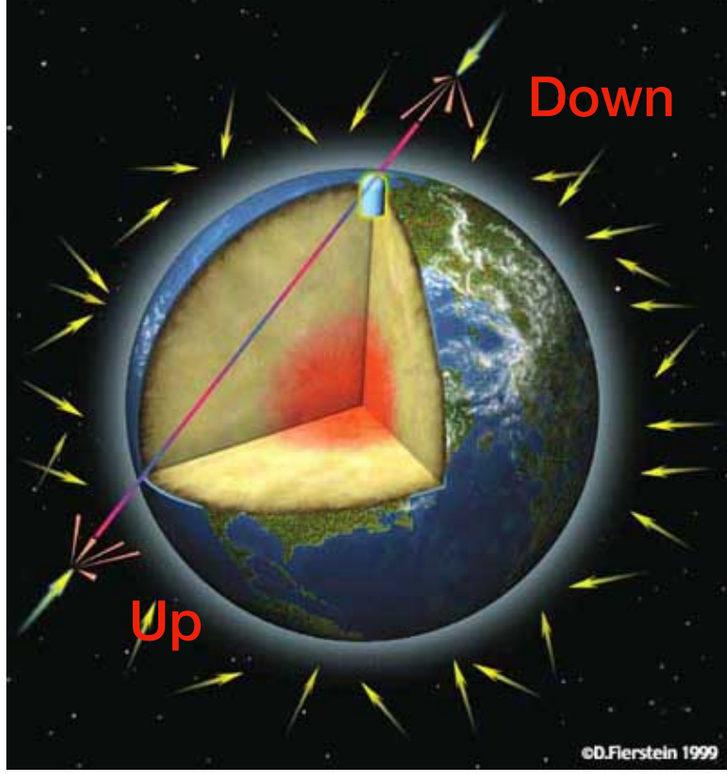
- Cosmic ray interactions with air molecules:
  - Muon neutrinos leading contribution
  - Electron neutrinos from muon decay
  - "No" tau neutrino

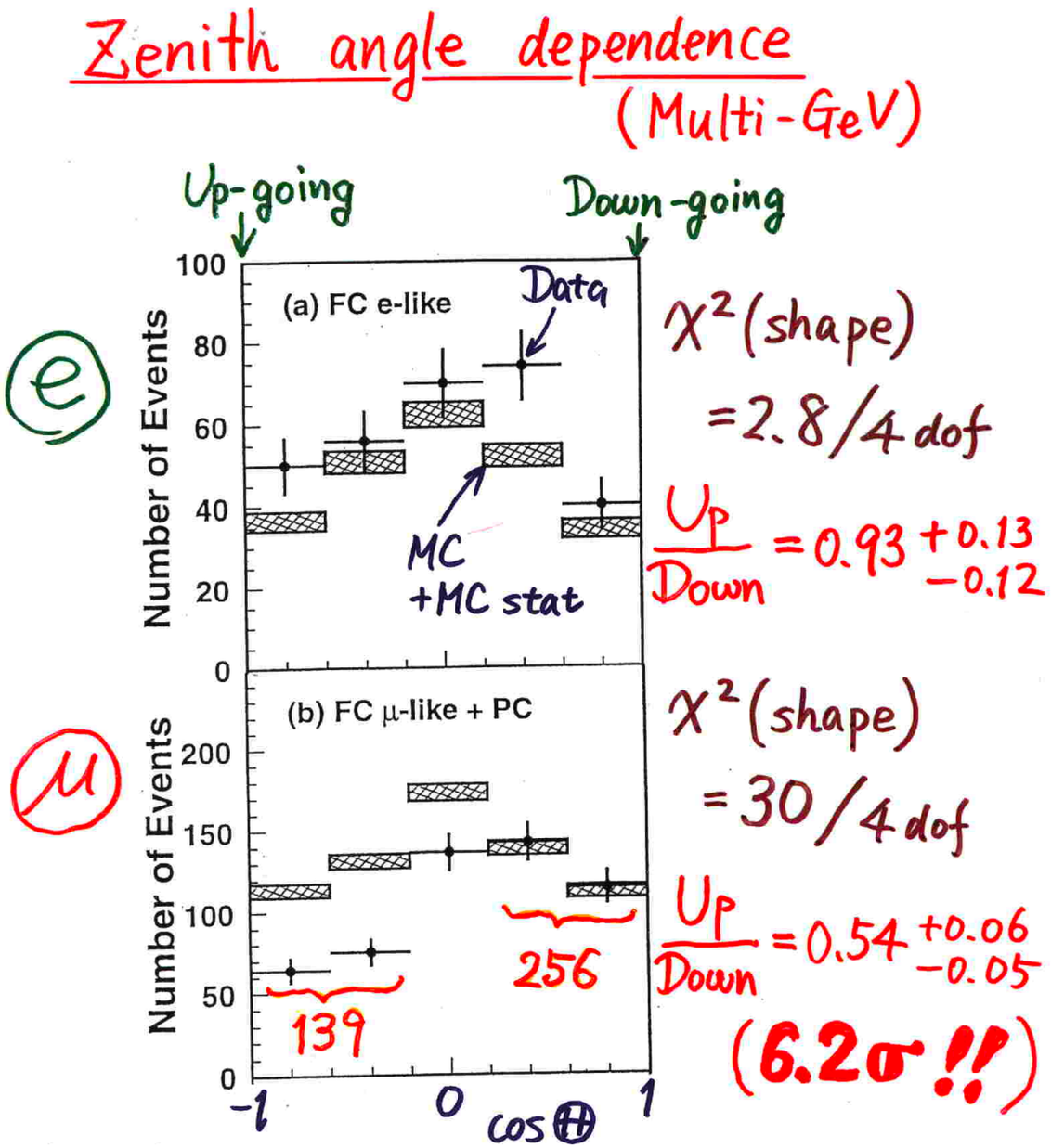
arXiv:1806.04140



Recap

- Atmospheric neutrinos -> first strong evidence of oscillations

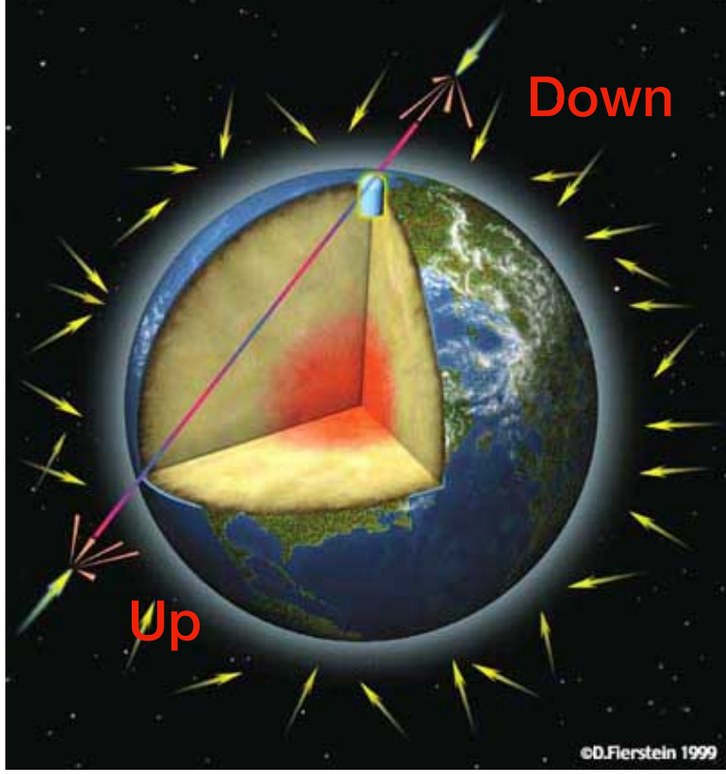


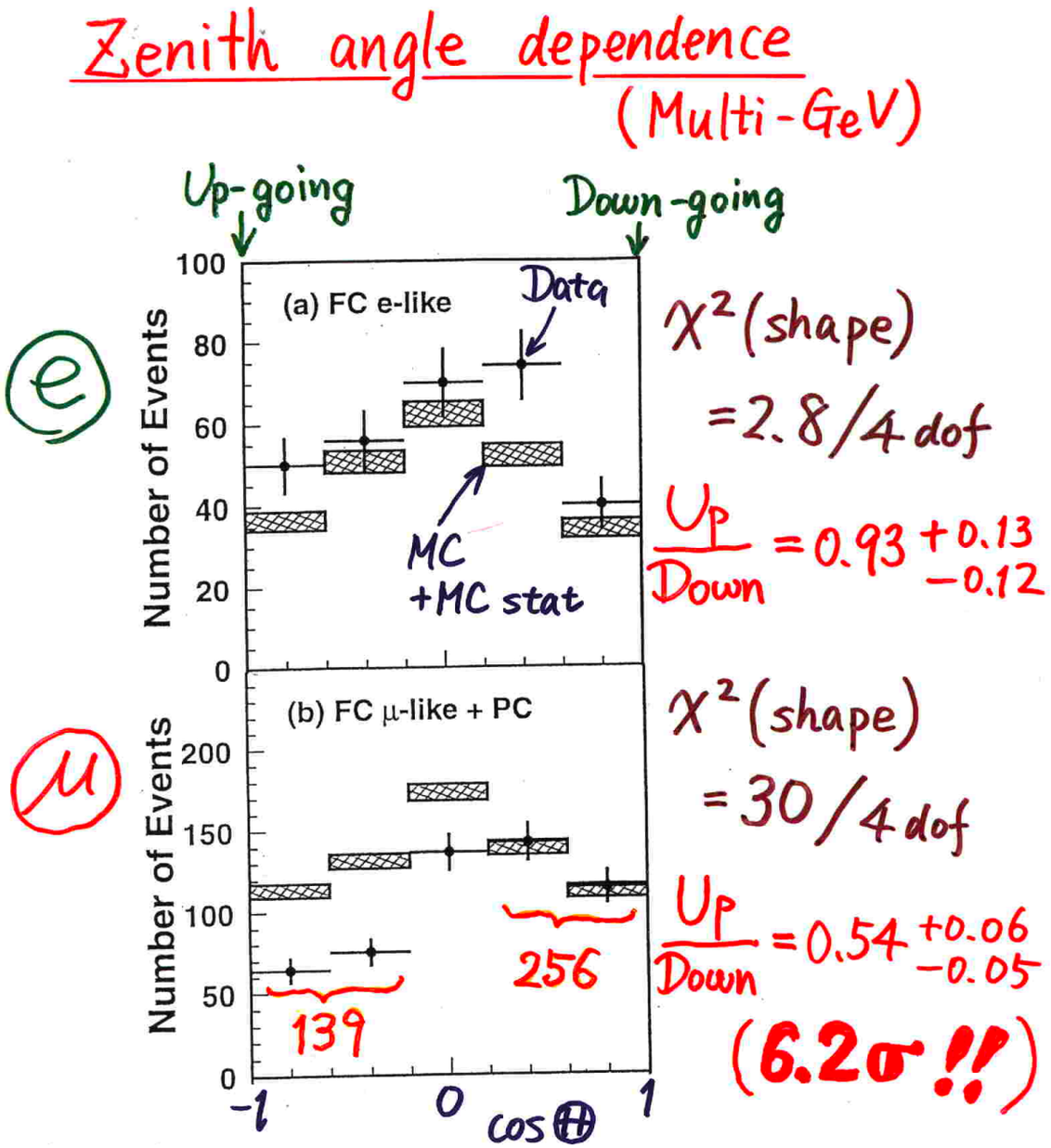


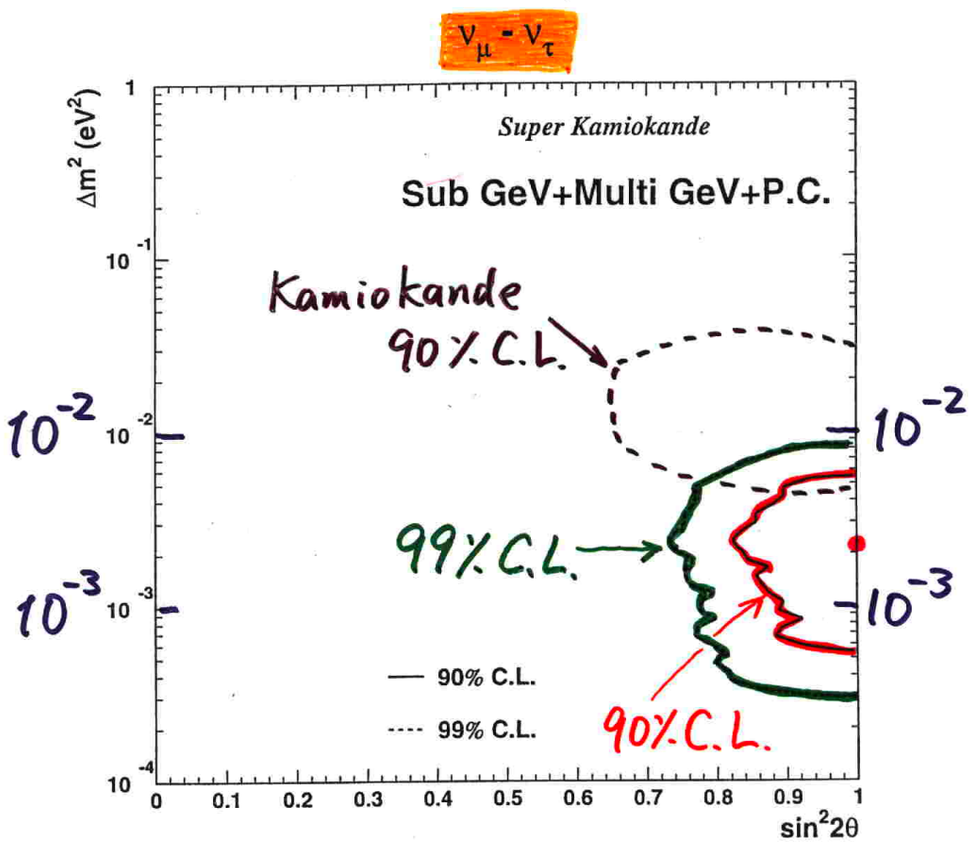
T.Kajita (Neutrino 98)

Recap

- Atmospheric neutrinos -> first strong evidence of oscillations



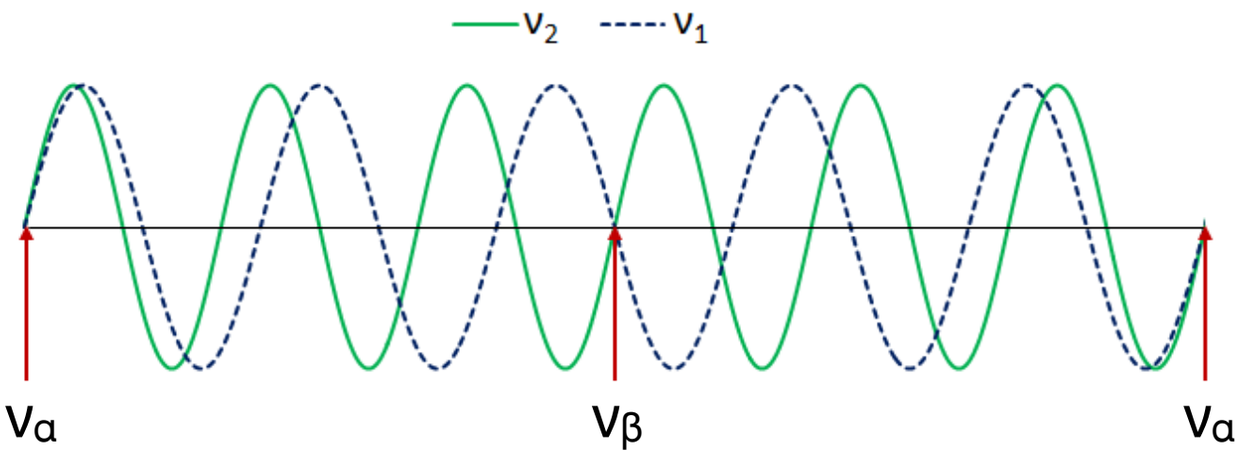




T.Kajita (Neutrino 98)

Neutrino oscillations

- Flavor states -> superposition of mass states (i.e, massless particles don't work)
  - Quantum interference observable at macroscopic distances



$$P(\nu_\alpha \to \nu_\beta) = sin^2(2\theta) sin^2(1.27\Delta m^2 \frac{L}{E_\nu})$$

Two-flavor oscillation

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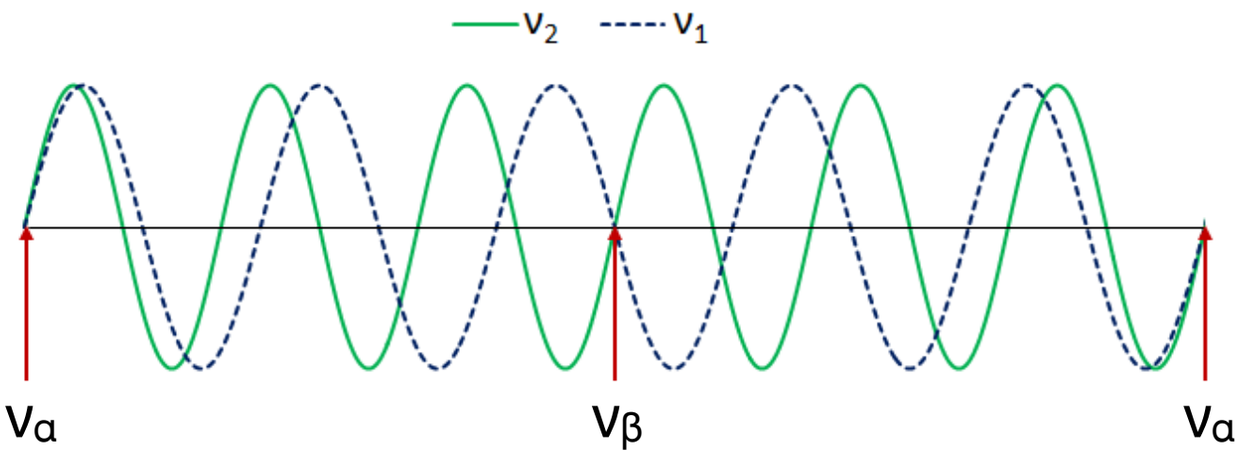
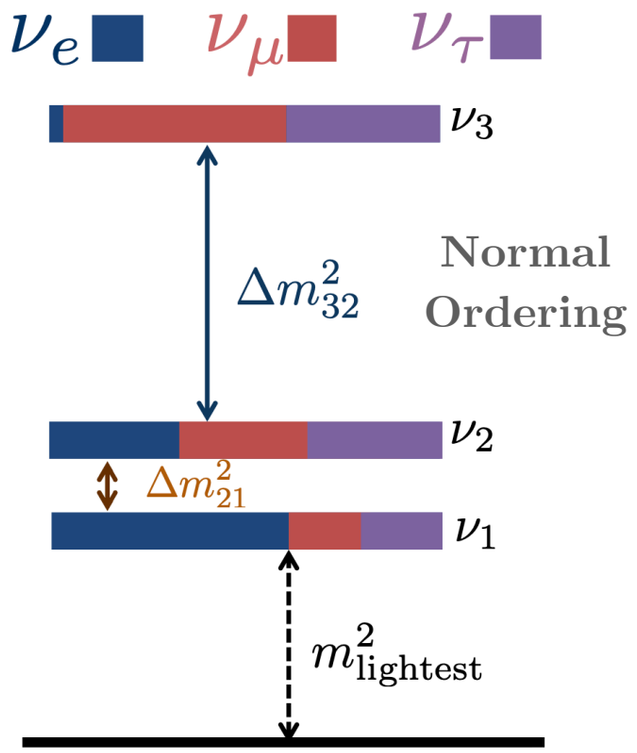


$$P(\nu_\alpha \to \nu_\beta) = sin^2(2\theta) sin^2(1.27\Delta m^2 \frac{L}{E_\nu})$$

Two-flavor oscillation

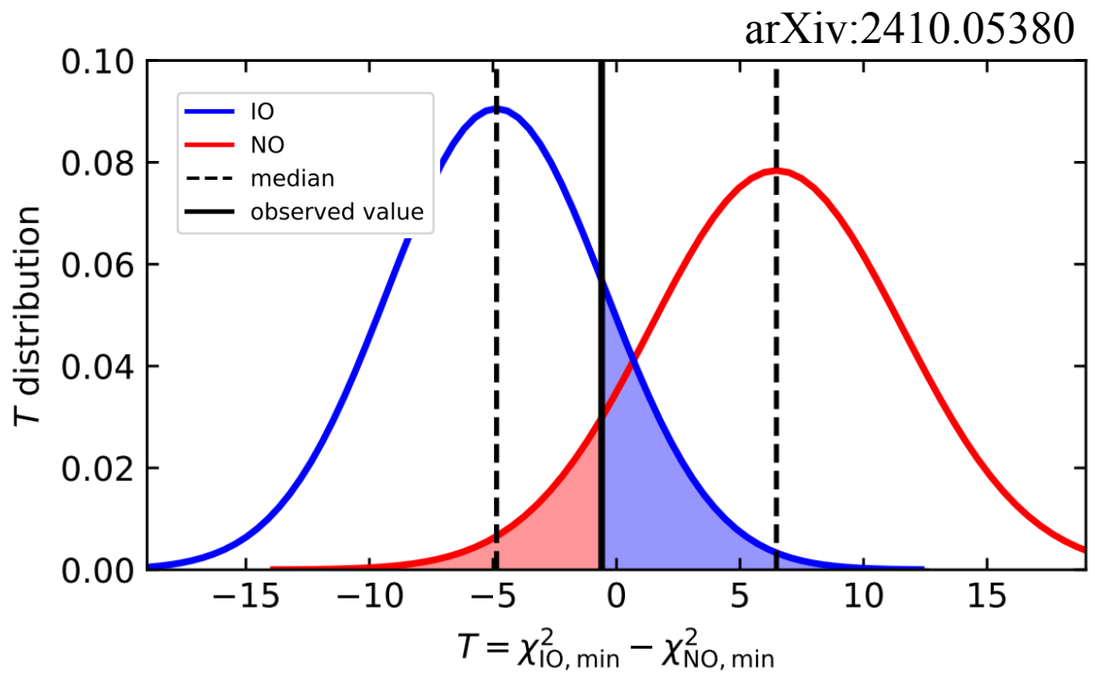
- PMNS (unitary mixing matrix) -> combination of states
  - Measured most of the free parameters at percent level

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{Atmospherics / Accelerators}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix}}_{\text{Reactors / accelerator}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar / reactors}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



Neutrino mass ordering

- Connection across very different experiments:
  - Neutrino oscillations



Neutrino mass ordering

- Connection across very different experiments:
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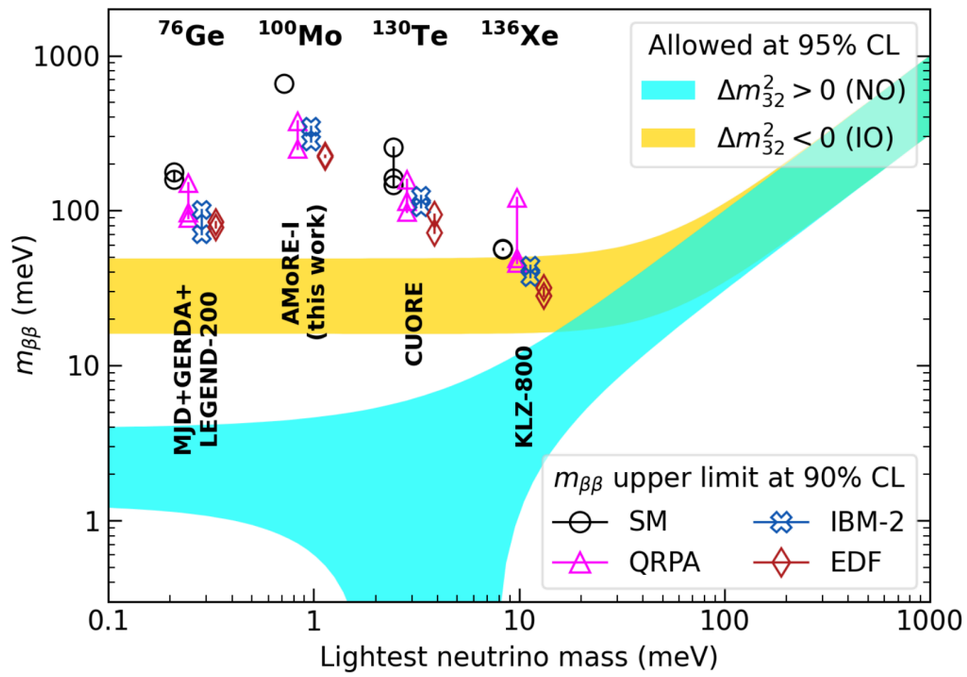
  - Neutrinoless double beta decay

arXiv:2407.05618



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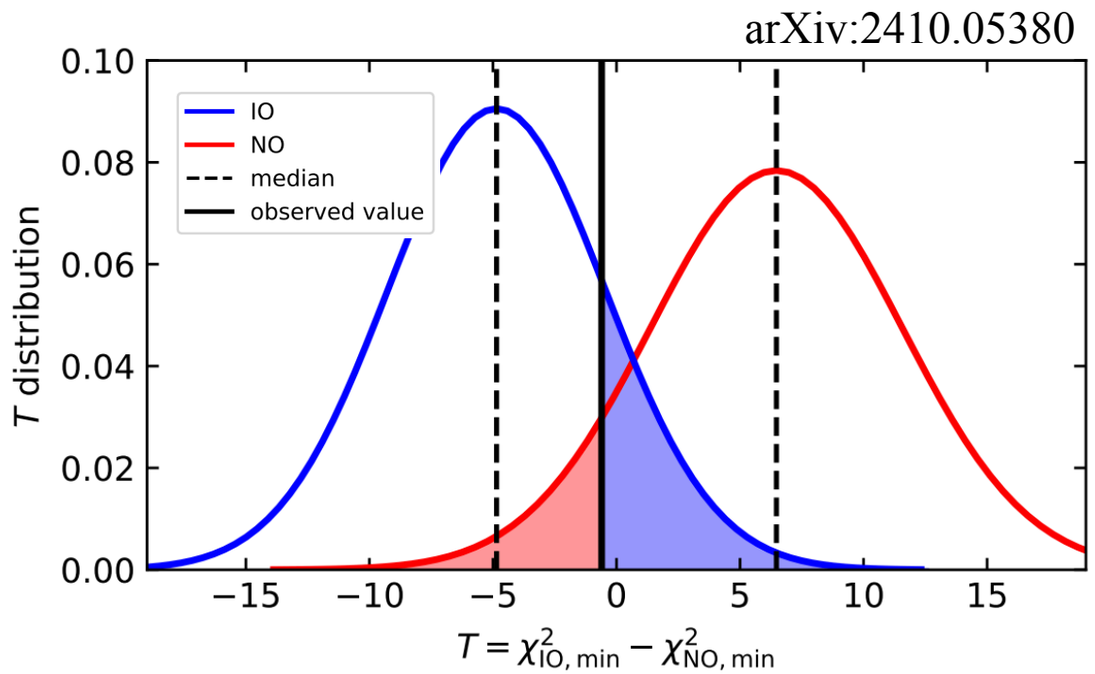
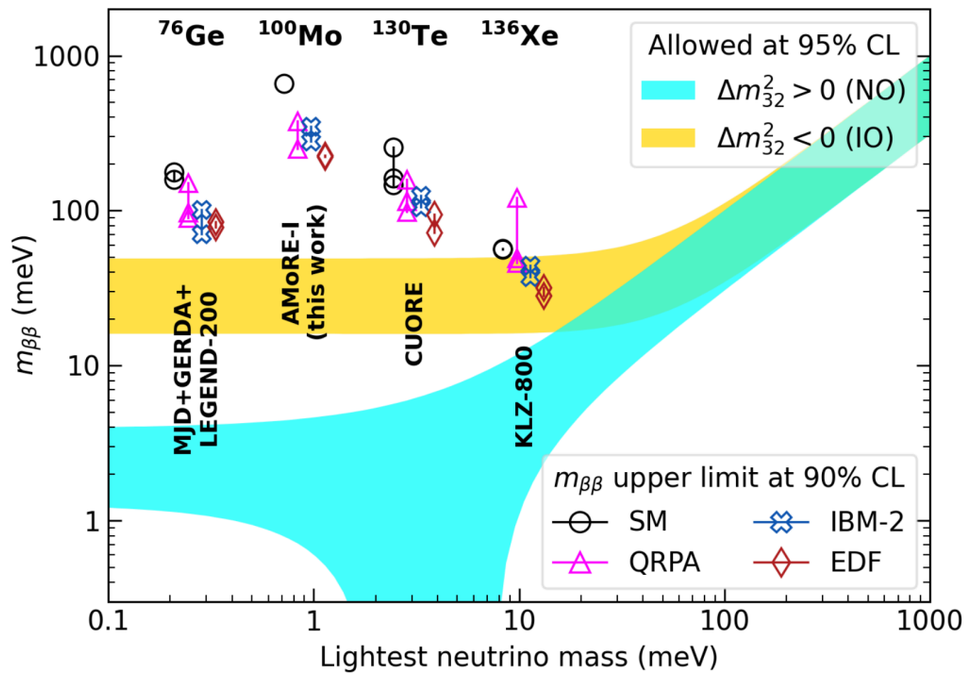


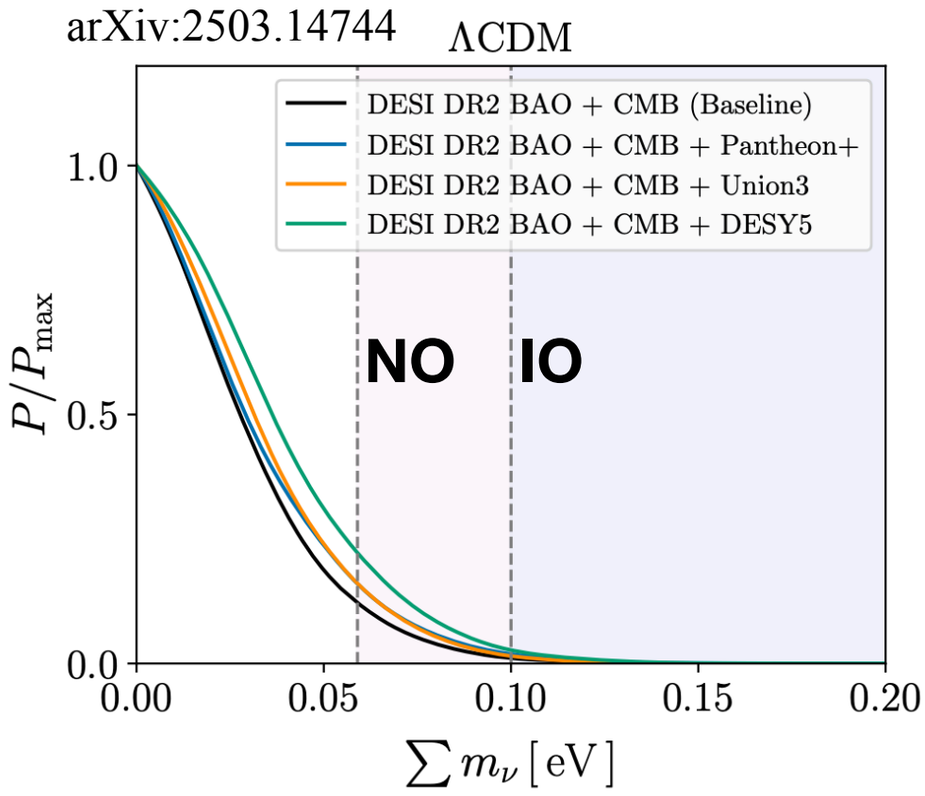
Neutrino mass ordering

- Connection across very different experiments:
  - Neutrino oscillations
  - Neutrinoless double beta decay
  - Cosmology

arXiv:2407.05618



arXiv:2503.14744



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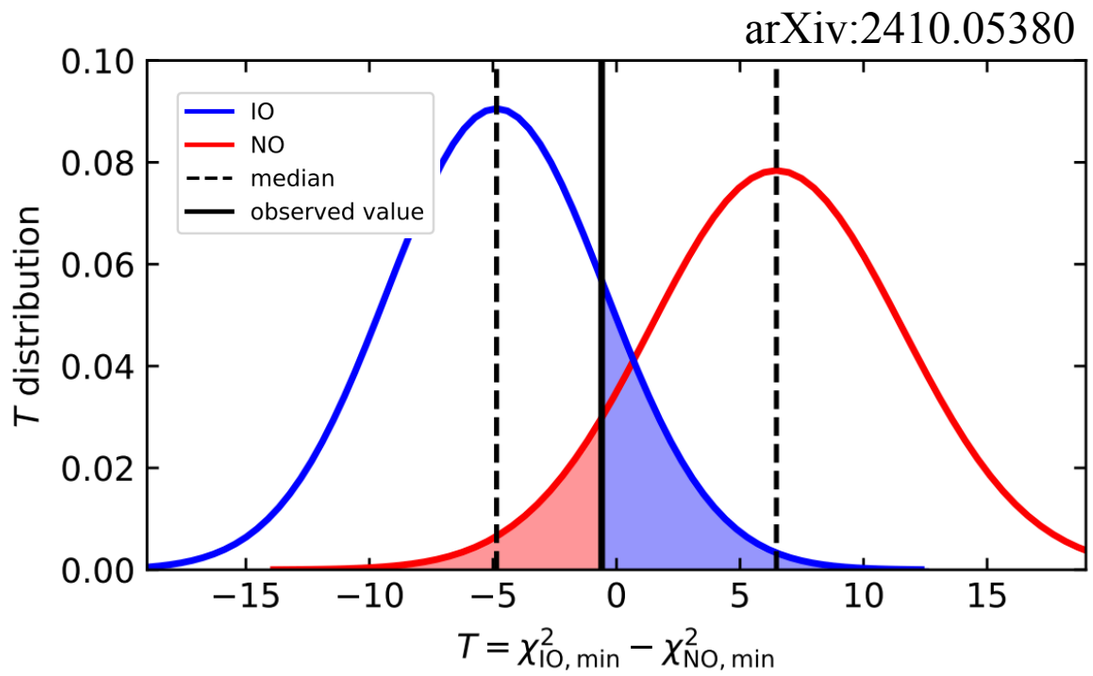
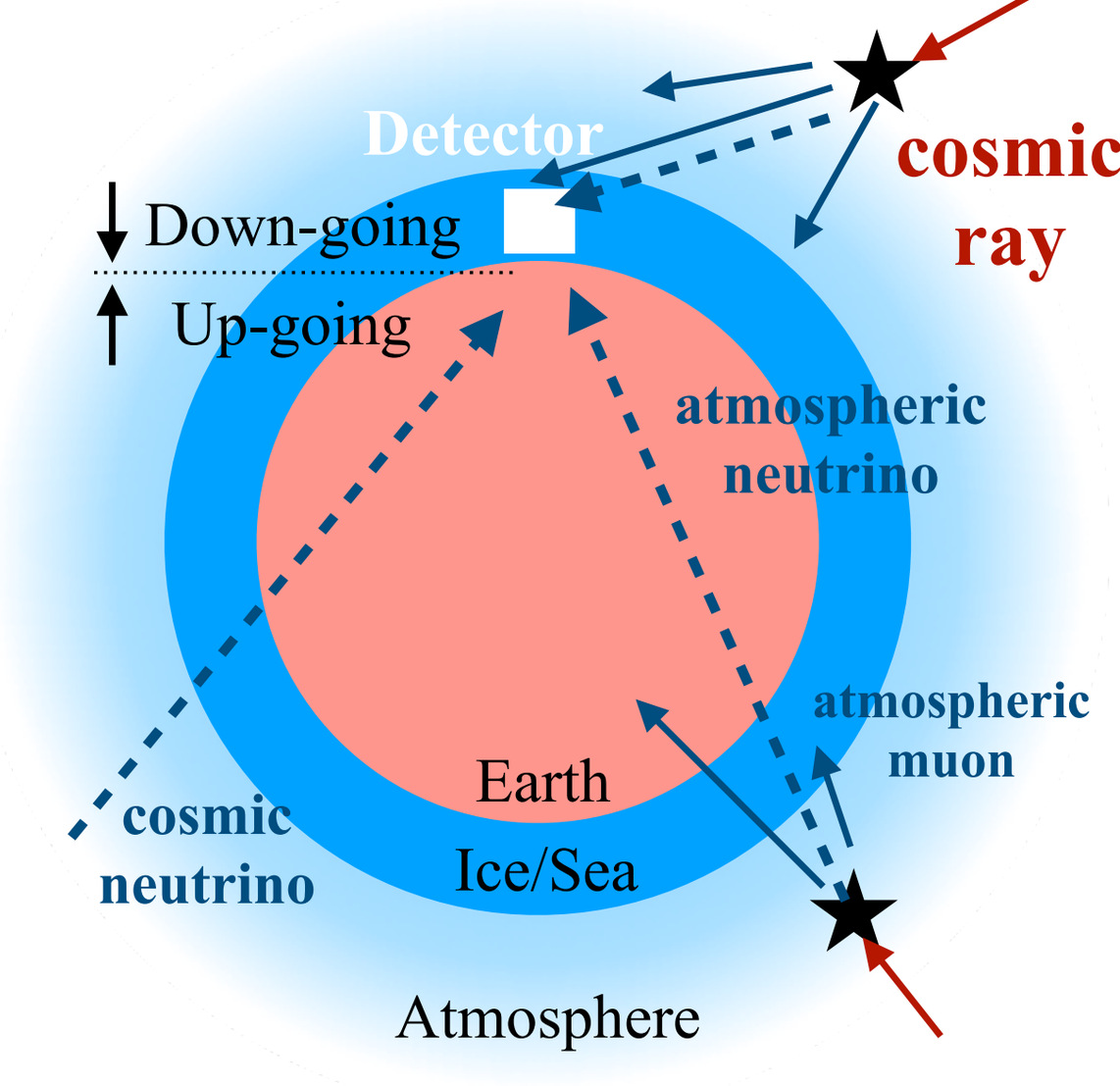


Oscillations

- Multiple baselines and flavors:
  - Reconstructed topology, energy and zenith
- Down-going vs up-going asymmetry:
  - Constrain systematics



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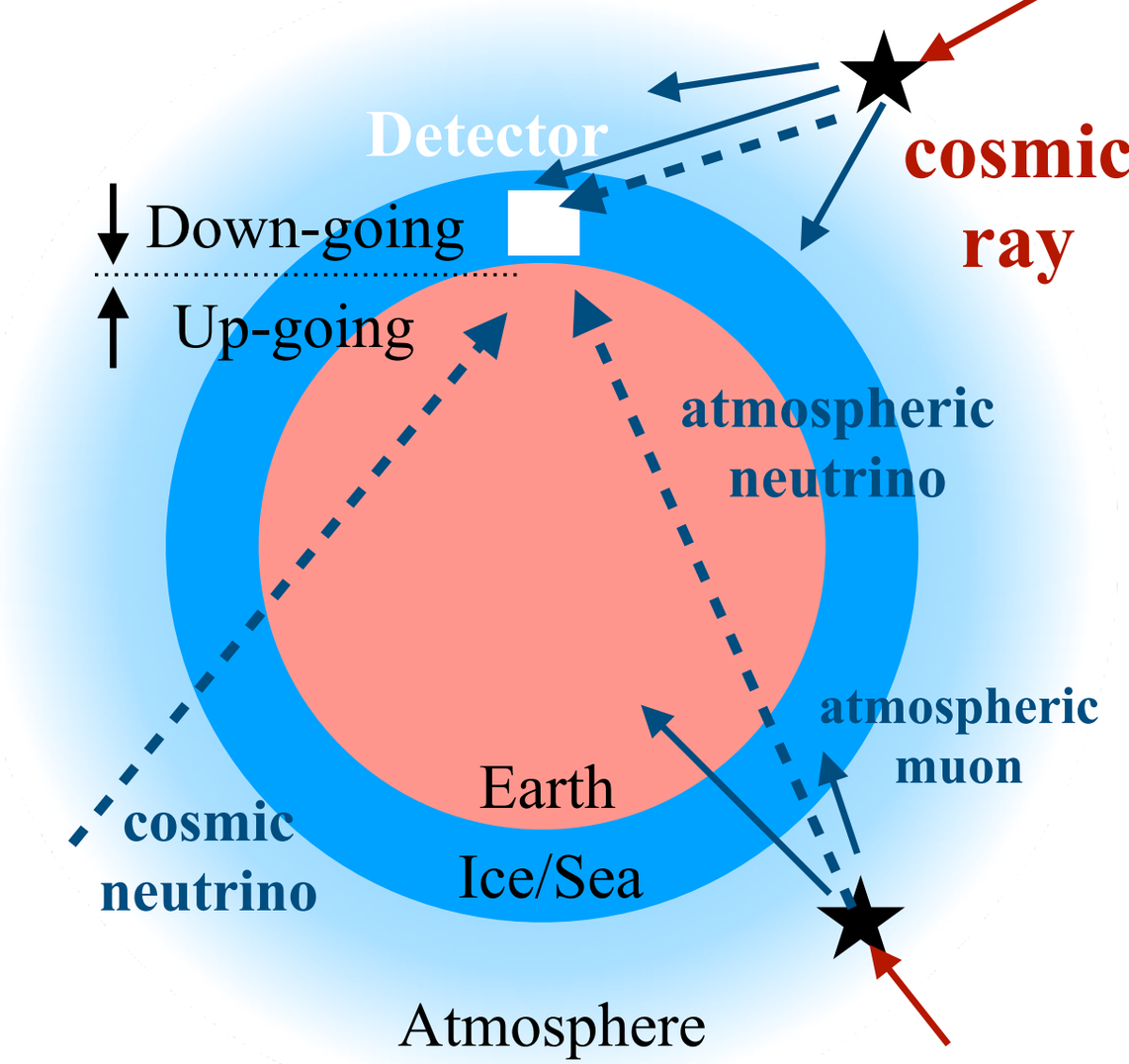


Vacuum

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

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

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

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

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

Matter

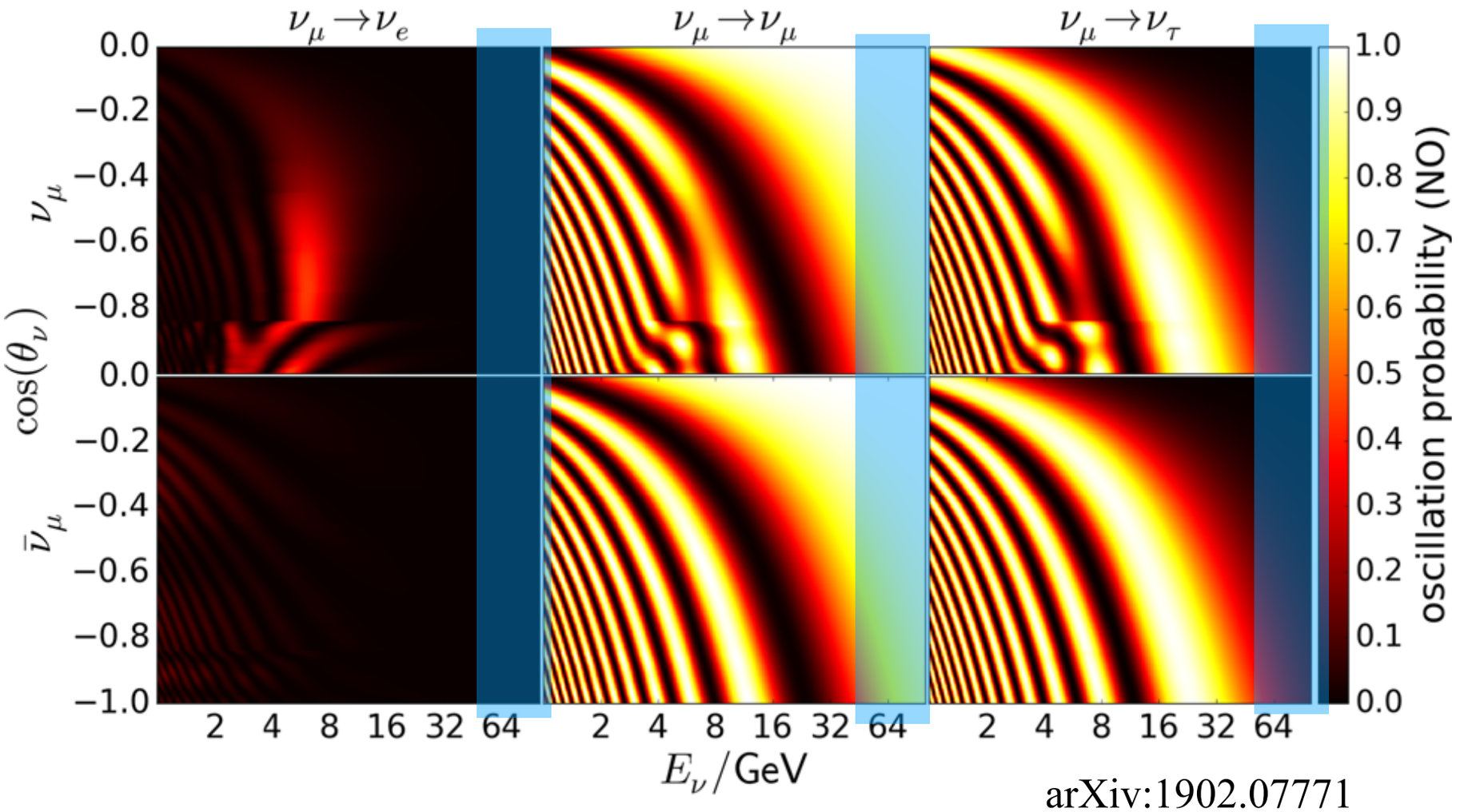
$$V_e = \pm\sqrt{2} G_F N_e$$

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

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

Oscillations

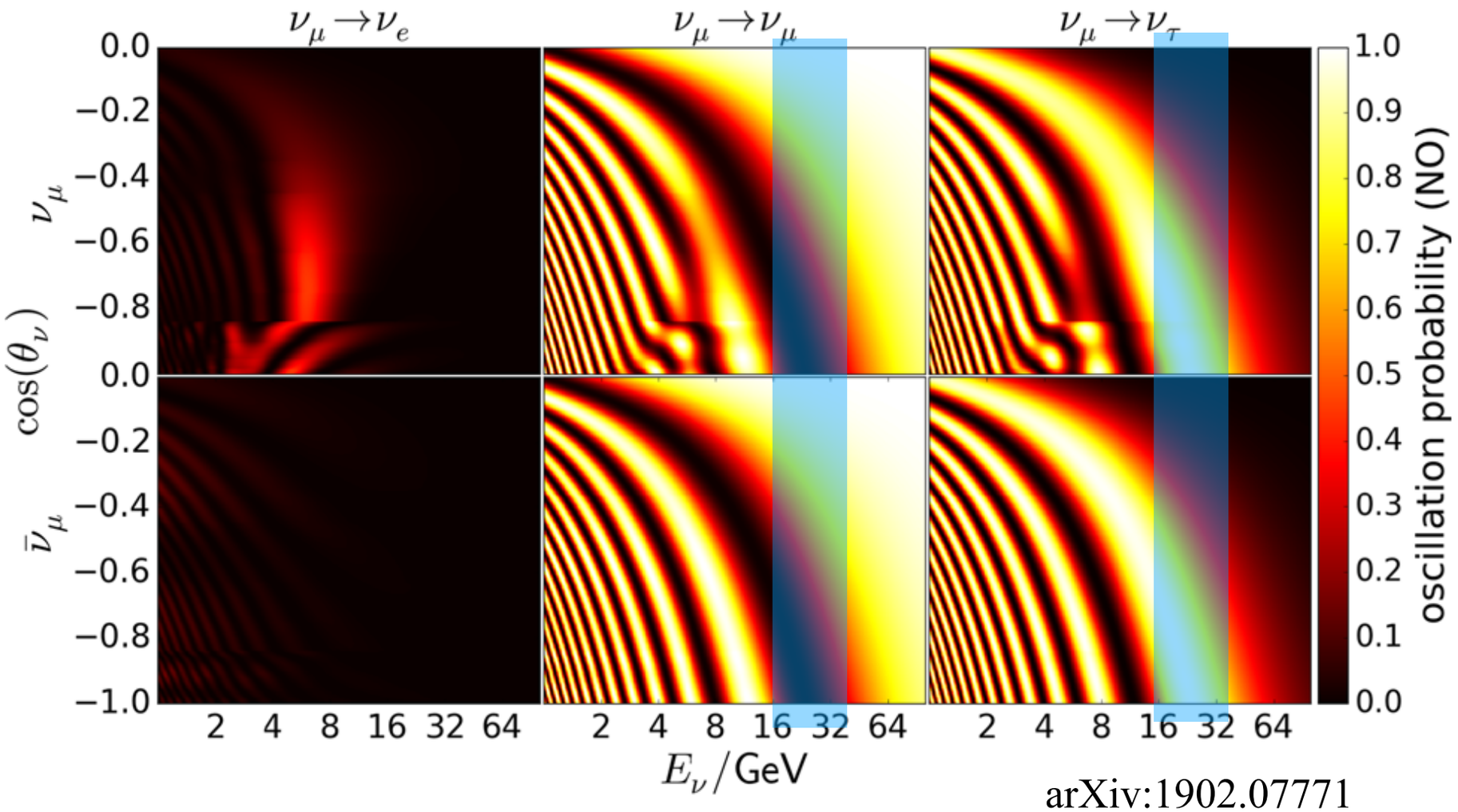
- E>100 GeV:
  - Too high energies to observe oscillations



arXiv:1902.07771

Oscillations

- E>100 GeV:
  - Too high energies to observe oscillations
- Multi-GeV:
  - First oscillation $\nu_\mu \longrightarrow \nu_\tau$ very sensitive to θ_{23} and Δm_{31}



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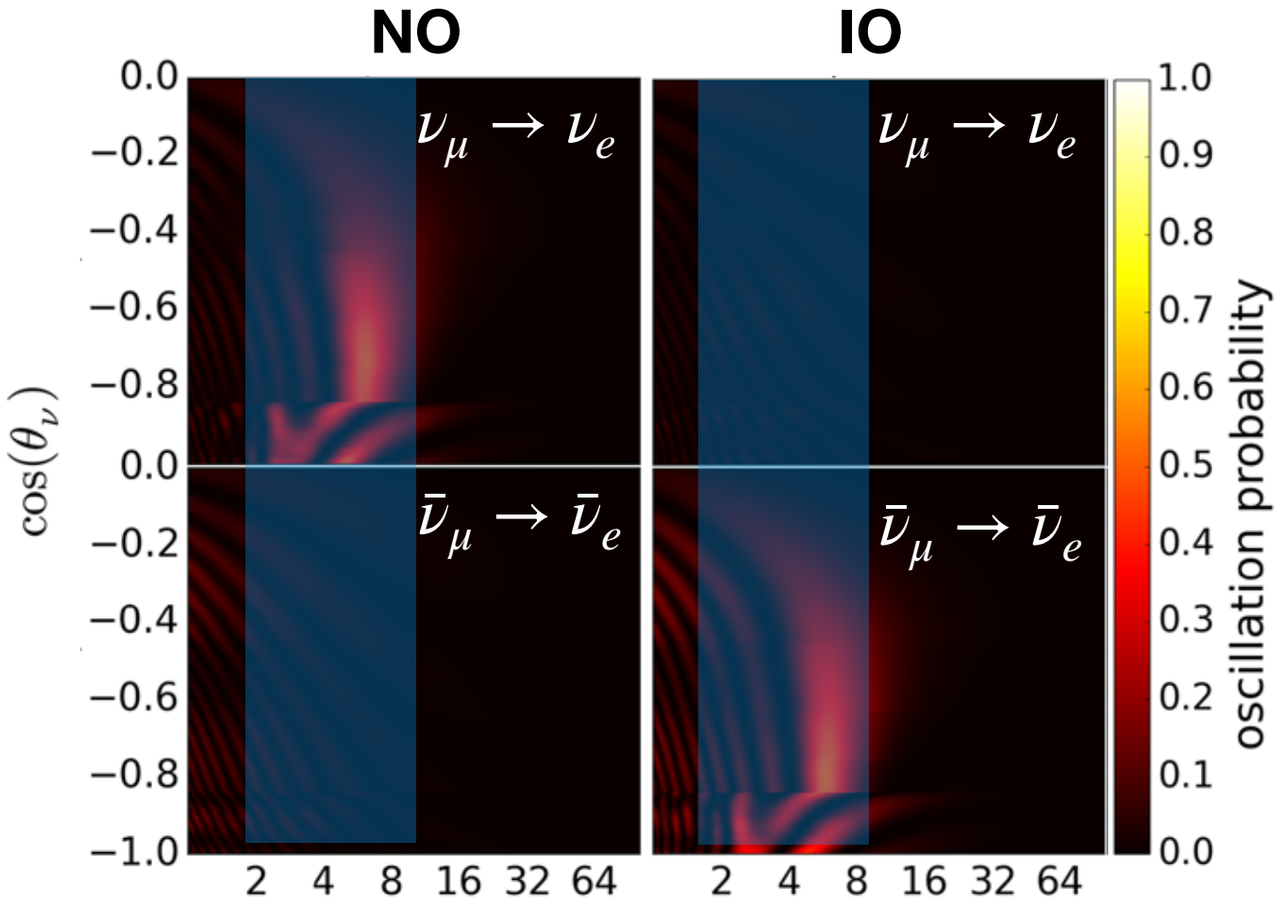
Oscillations

- Few-GeV:
  - Mass ordering -> matter effects difference between $\nu_\mu \longrightarrow \nu_e$ and $\bar{\nu}_\mu \longrightarrow \bar{\nu}_e$



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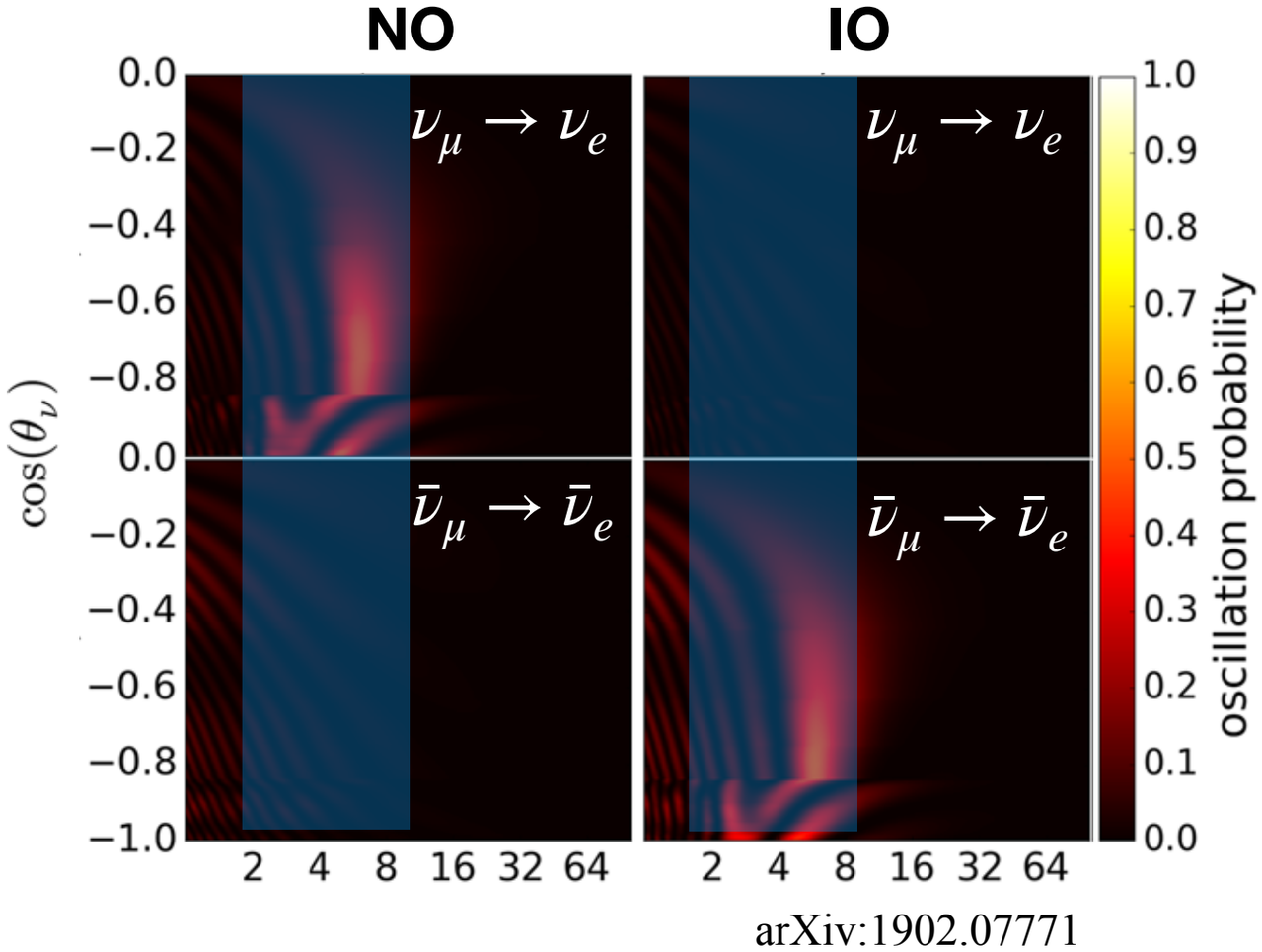
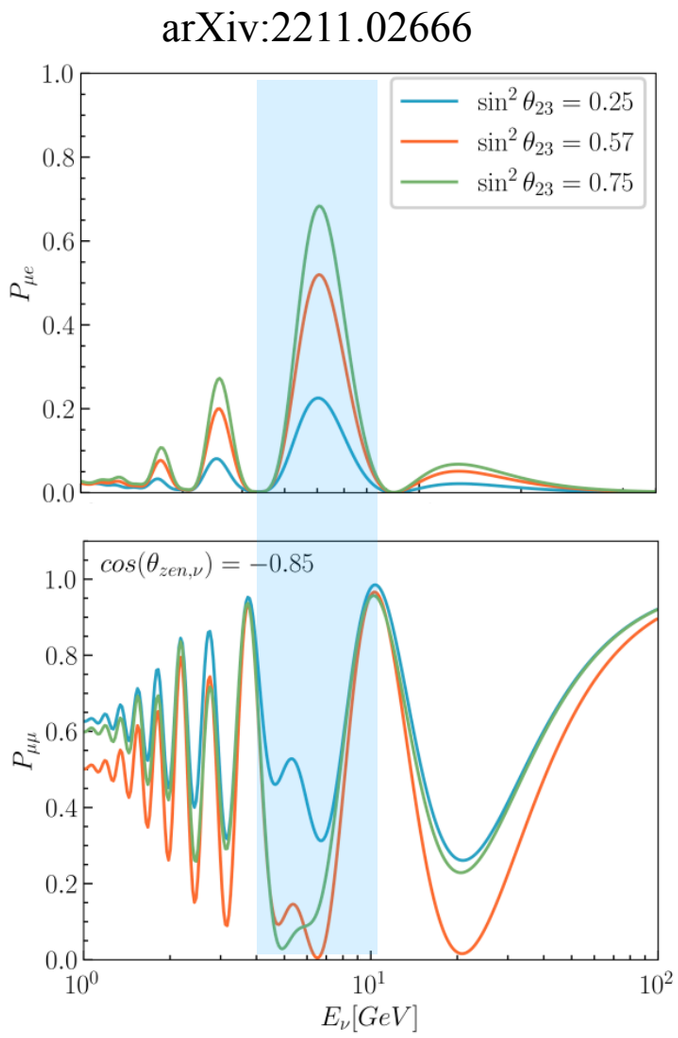
Oscillations

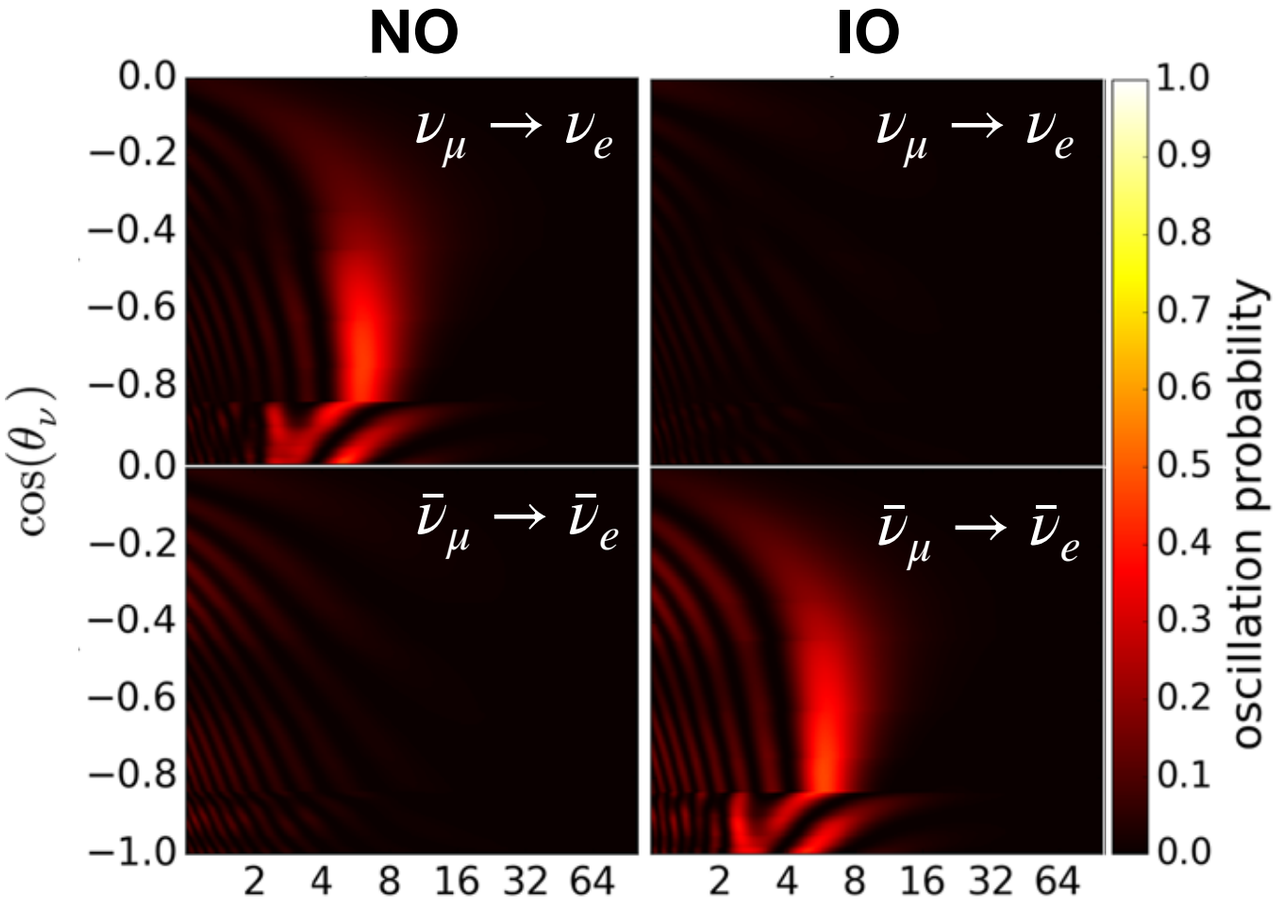
- Few-GeV:
  - Mass ordering -> matter effects difference between $\nu_\mu \longrightarrow \nu_e$ and $\bar{\nu}_\mu \longrightarrow \bar{\nu}_e$
  - Octant θ_{23} can also be extracted





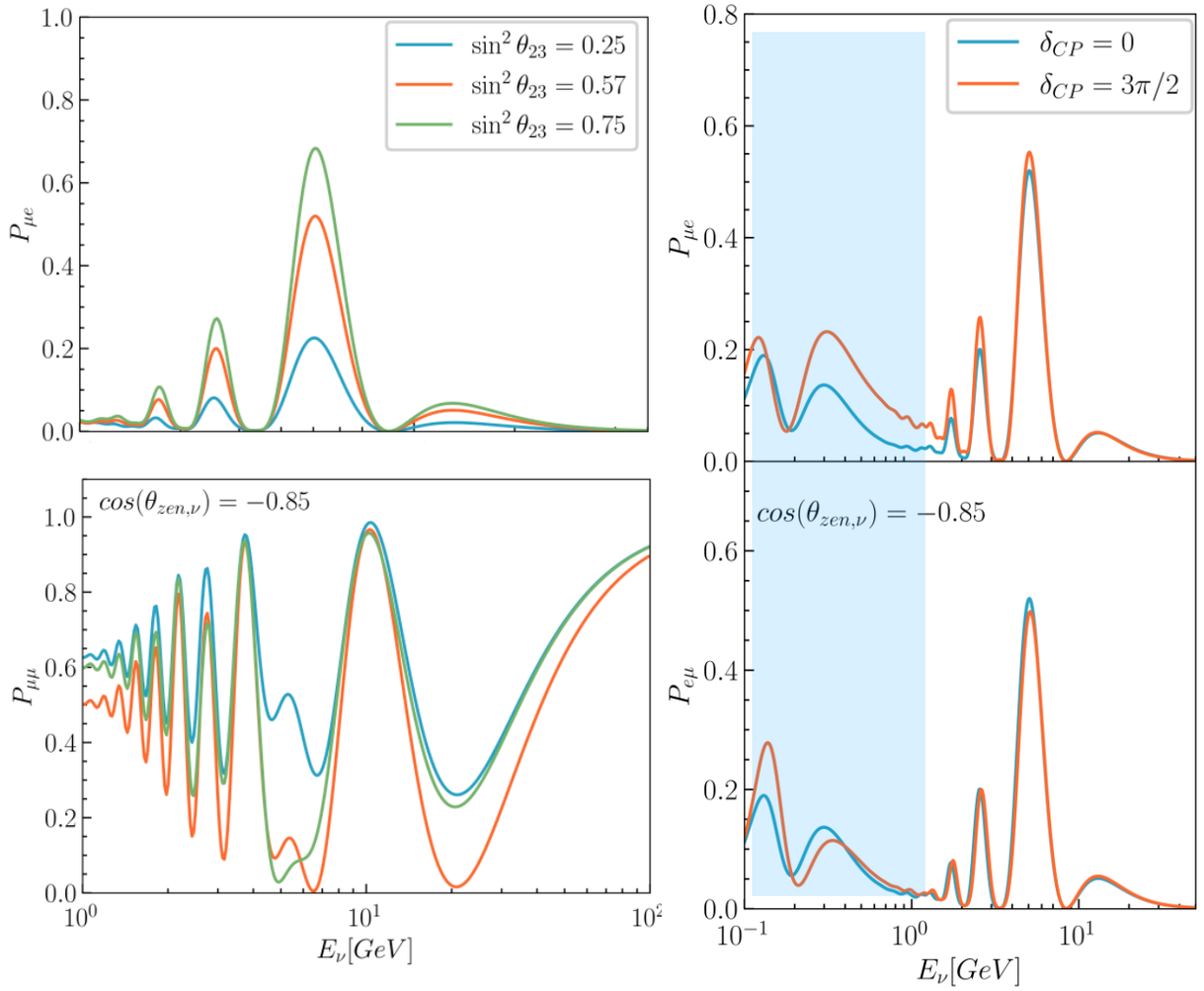
Oscillations

- 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
- Sub-GeV:
  - ν_e appearance sensitive to CP term



arXiv:1902.07771

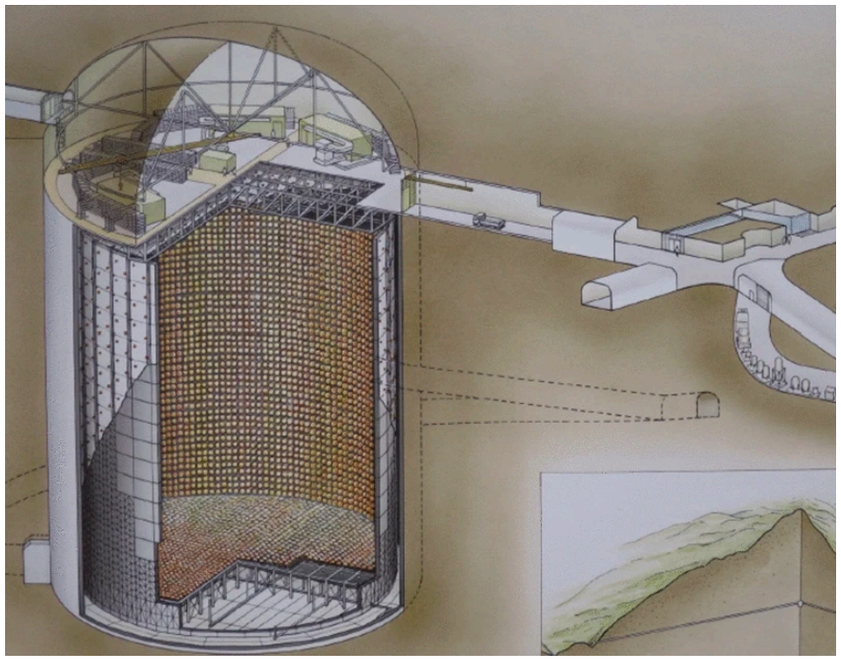
arXiv:2211.02666

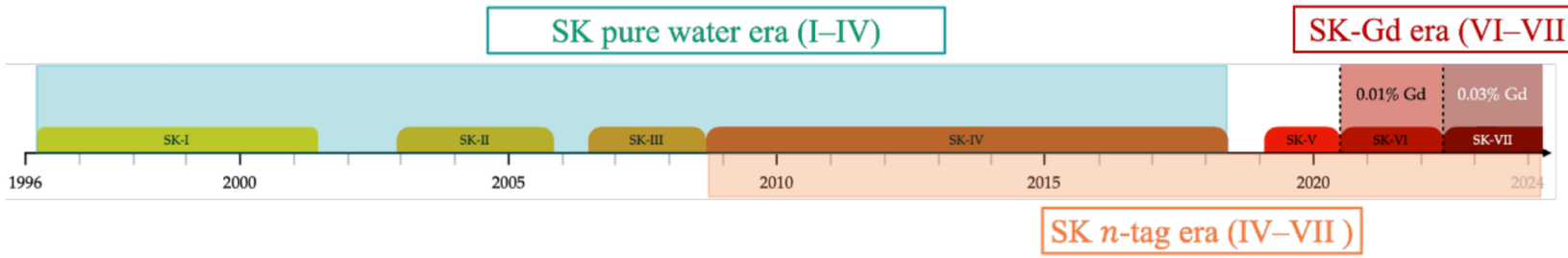


Running detectors

- Three detectors are currently operational:

SuperK





1k under rock
50 kton
11k PMTS
>25y data

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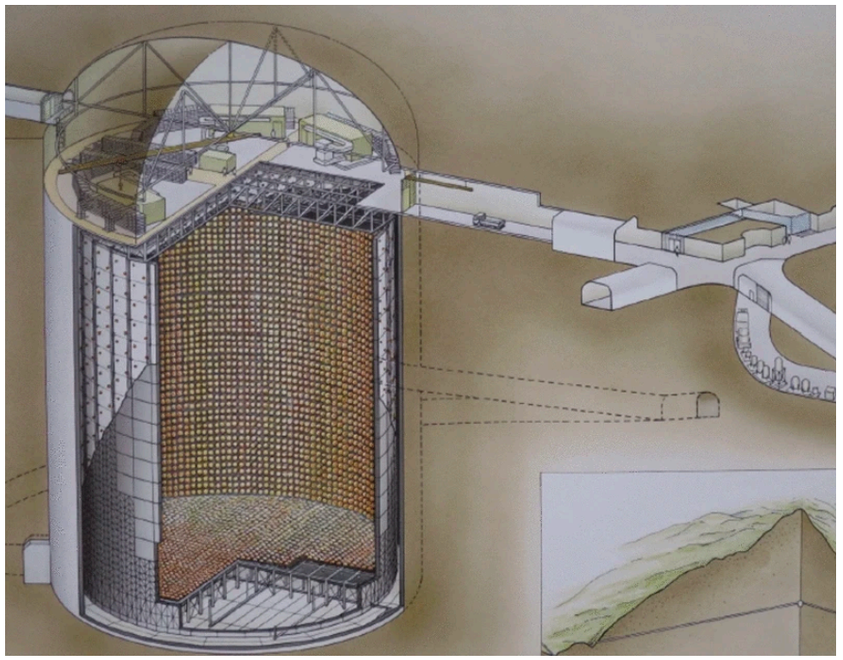

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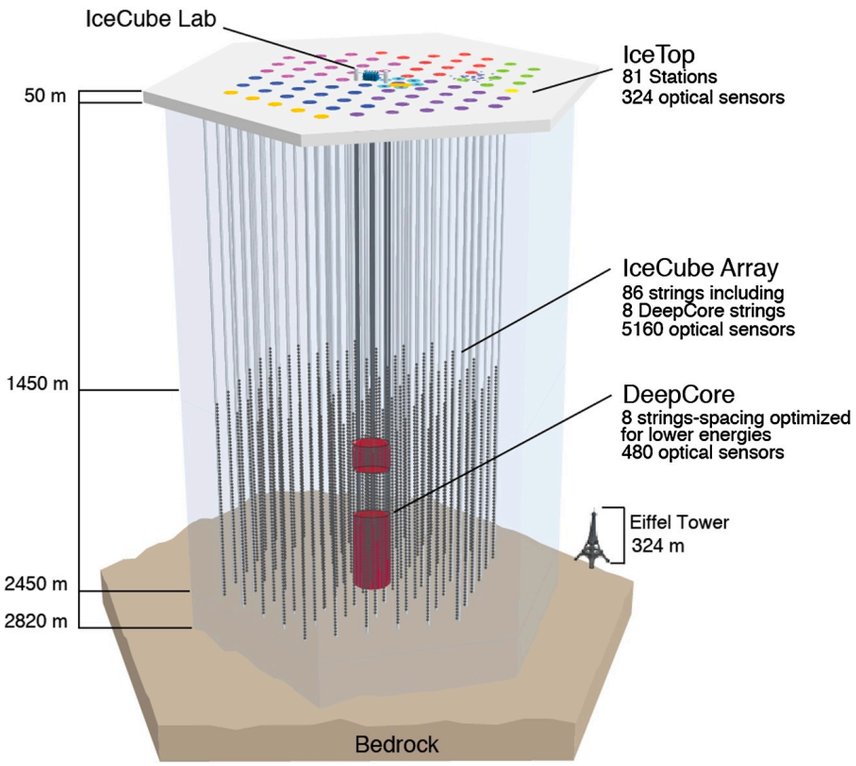
IceCube-DeepCore

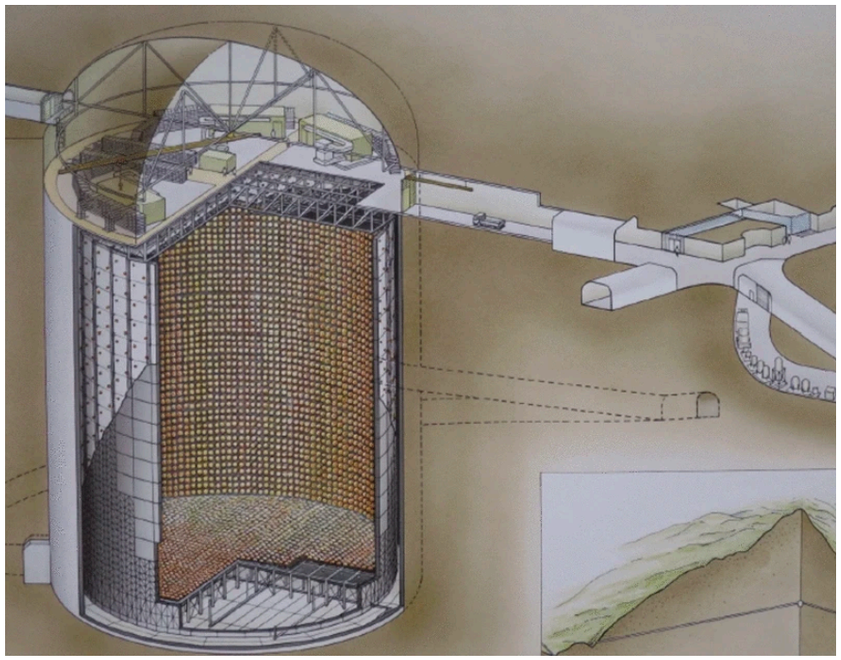


2.5 km under ice
10 Mton
>500 OMs
~50m horizontal
~7m vertical
>9y data

Running detectors

- Three detectors are currently operational:

SuperK



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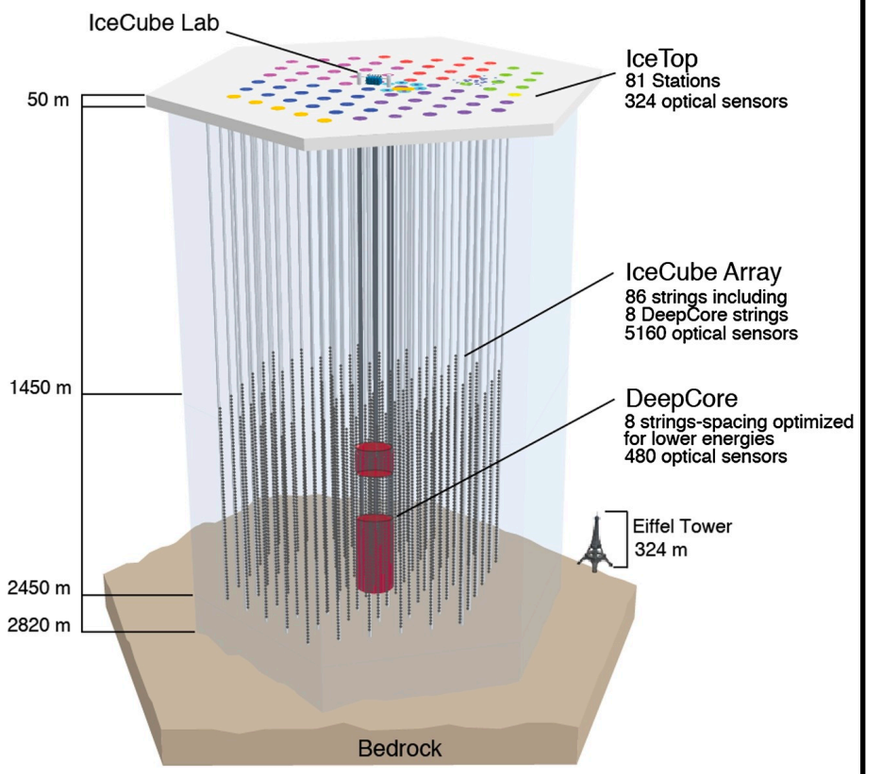

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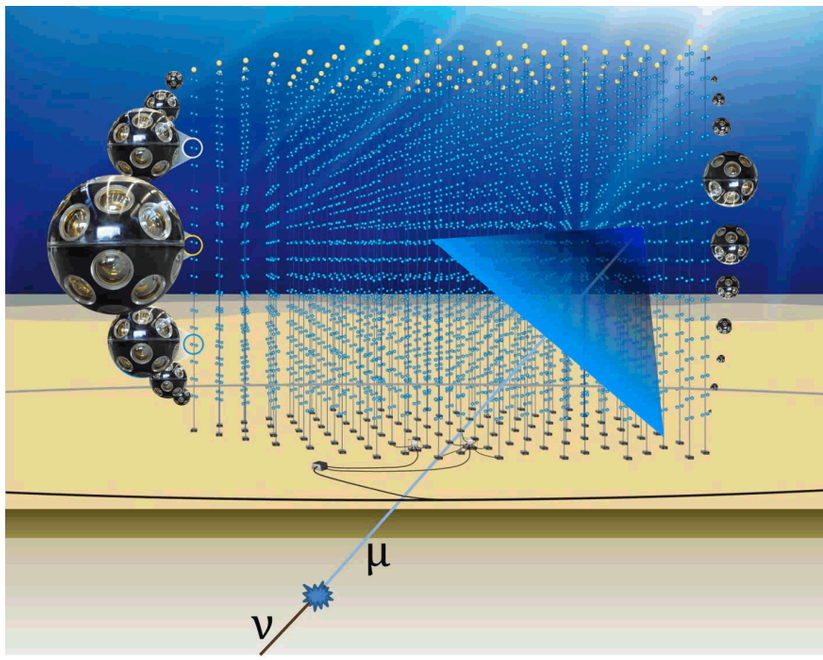
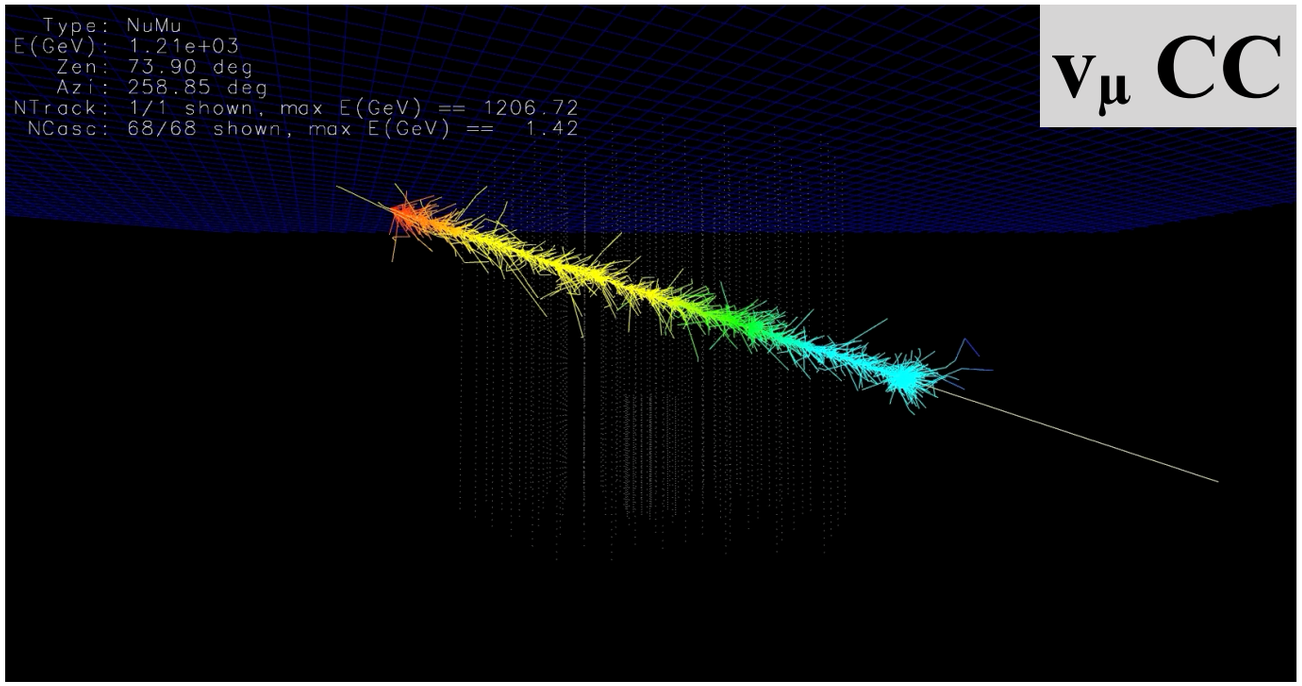
KM3NeT-ORCA

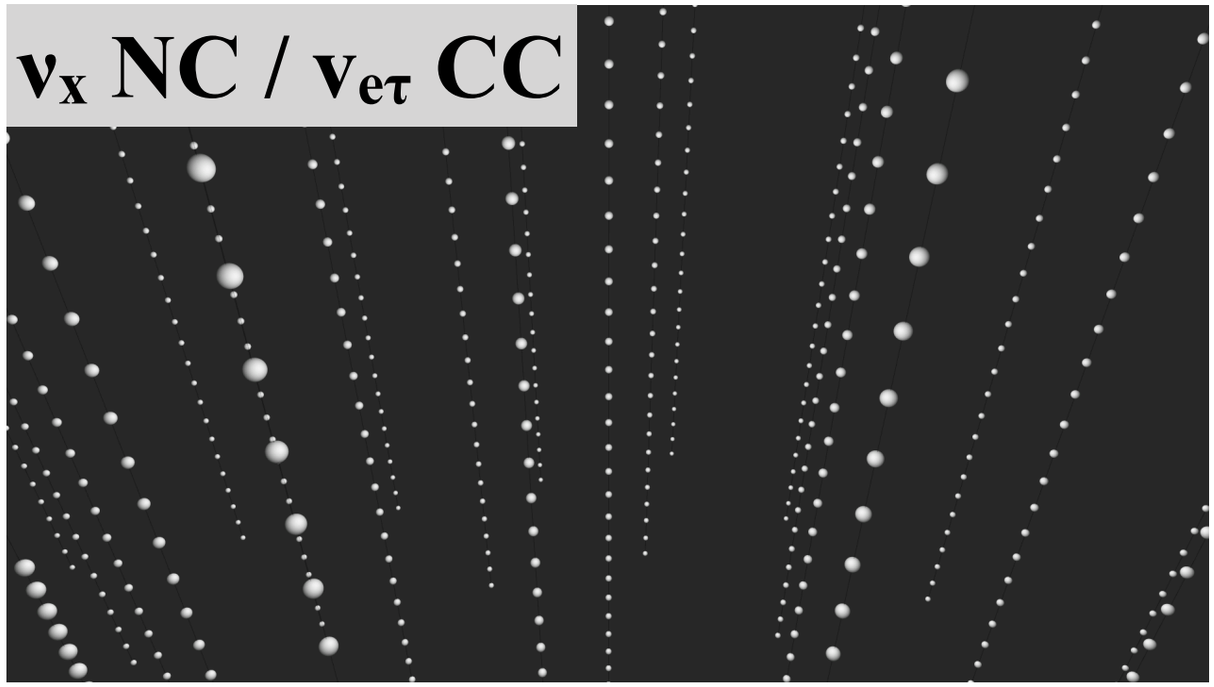


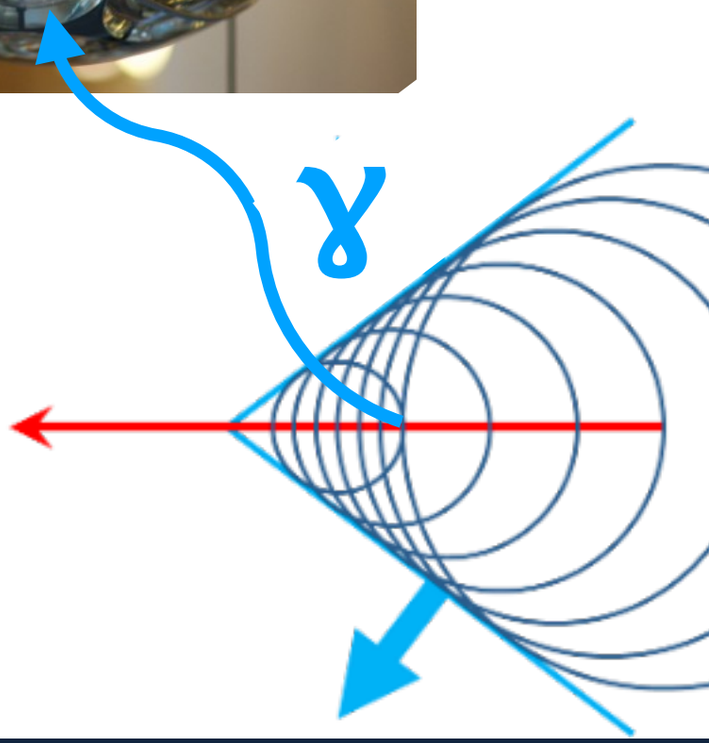
2.5 km under water
7 Mton
64k PMTs (2000 OMs)
~20m horizontal
~9m vertical
Under construction (25%)
(>5y partial)

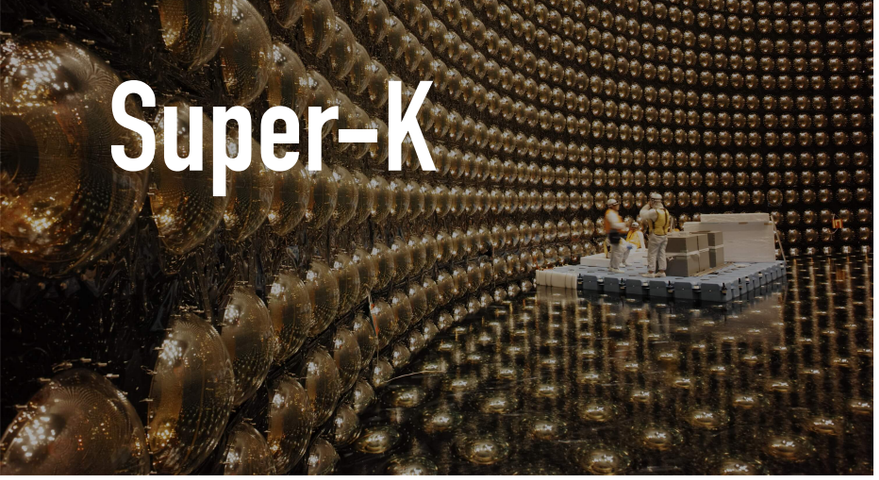
Detection principle

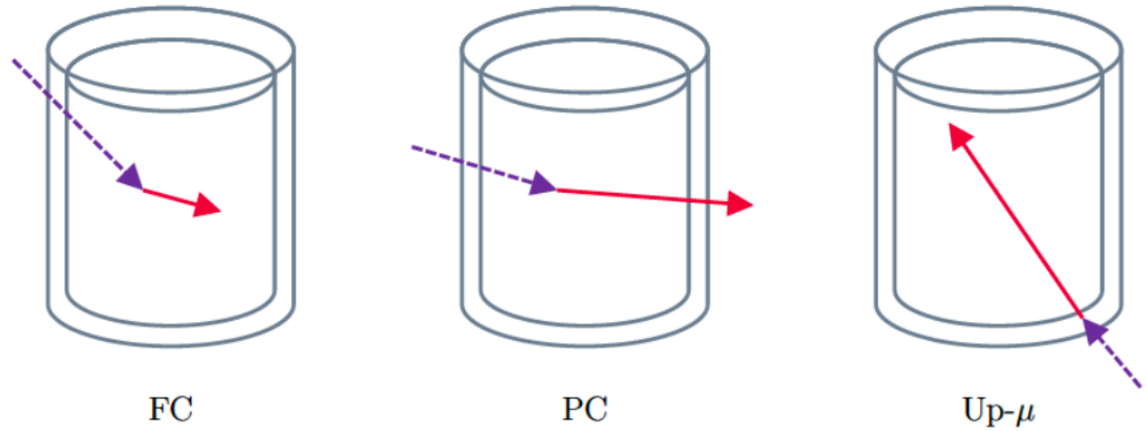
- Cherenkov light:





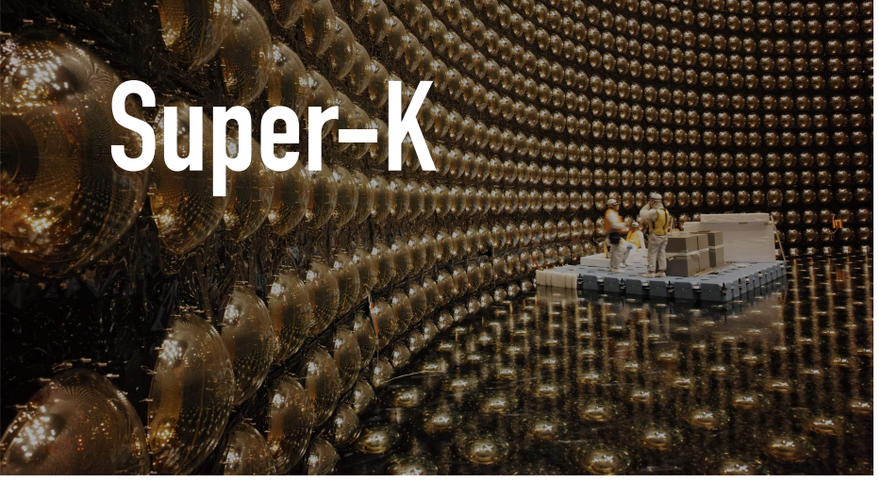


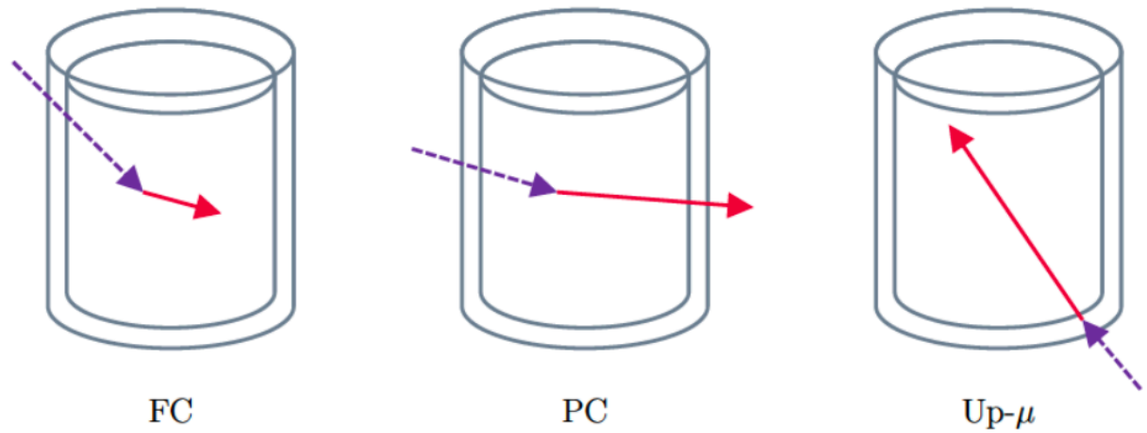




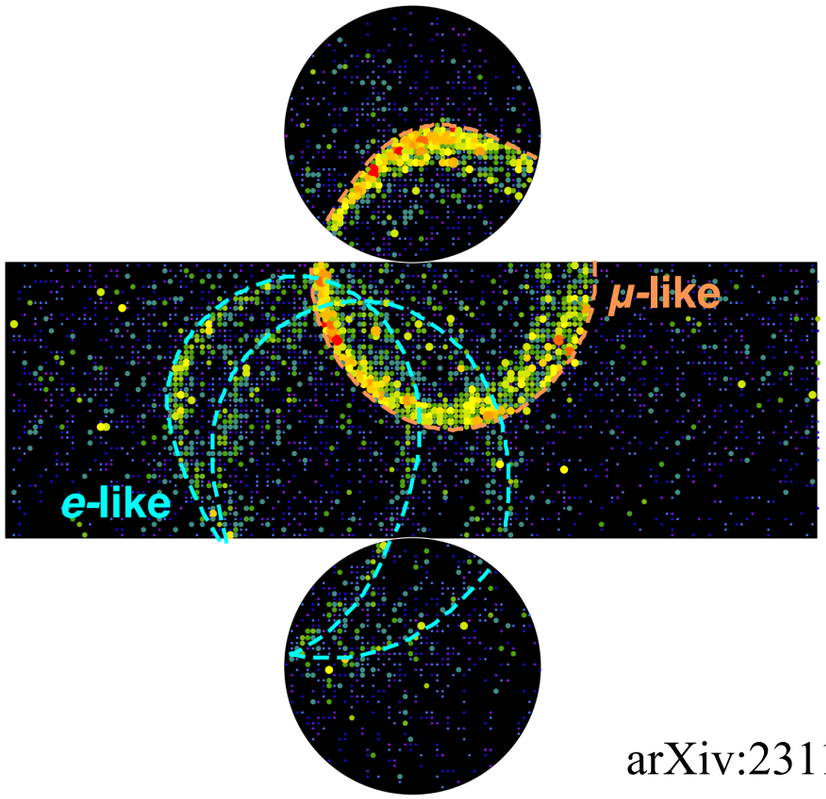
- Three event topologies:
  - Veto from outer detector plays crucial role (latest analysis increased FV by 20%)
  - FC -> best energy estimator

Super-K

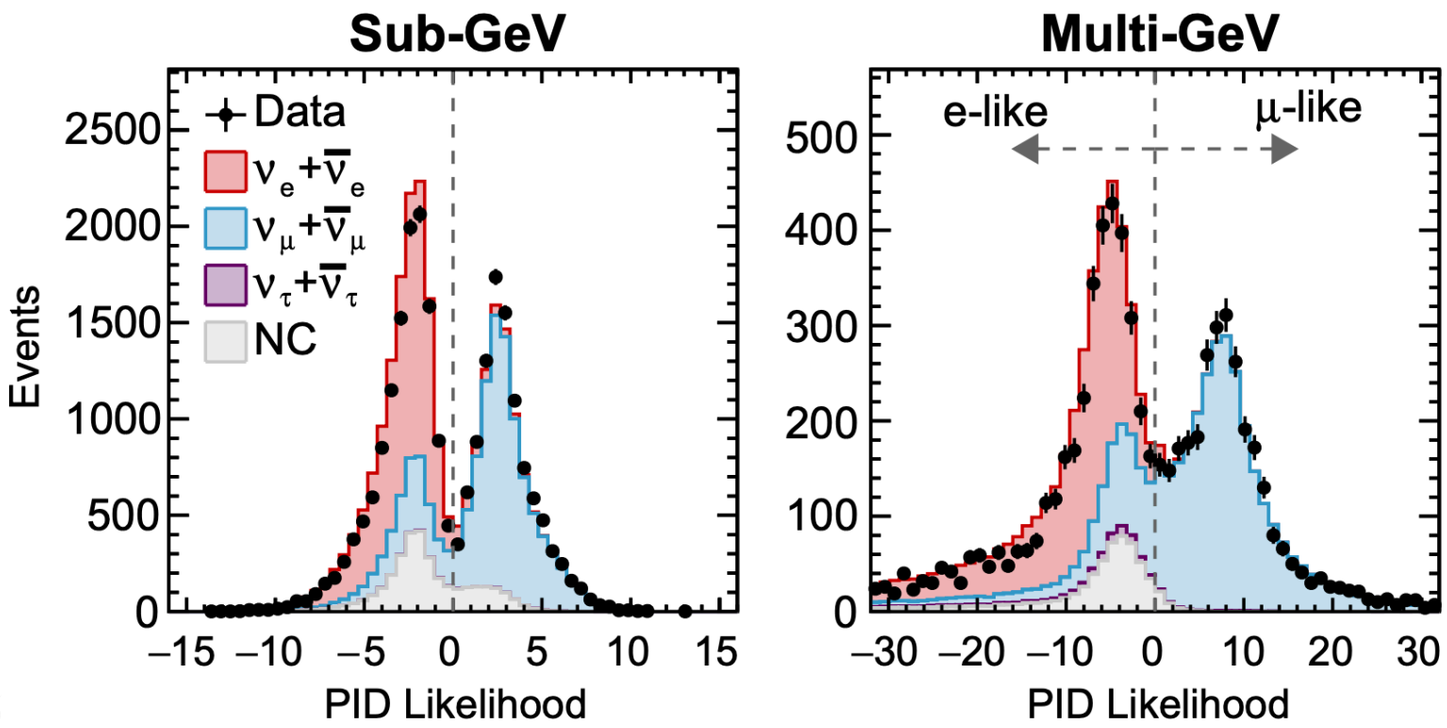




- Three event topologies:
  - Veto from outer detector plays crucial role (latest analysis increased FV by 20%)
  - FC -> best energy estimator
- Features of Cherenkov rings allow to distinguish electron/muon neutrinos
  - Latest analysis also include samples with neutron tagging ($\nu/\bar{\nu}$ separation)



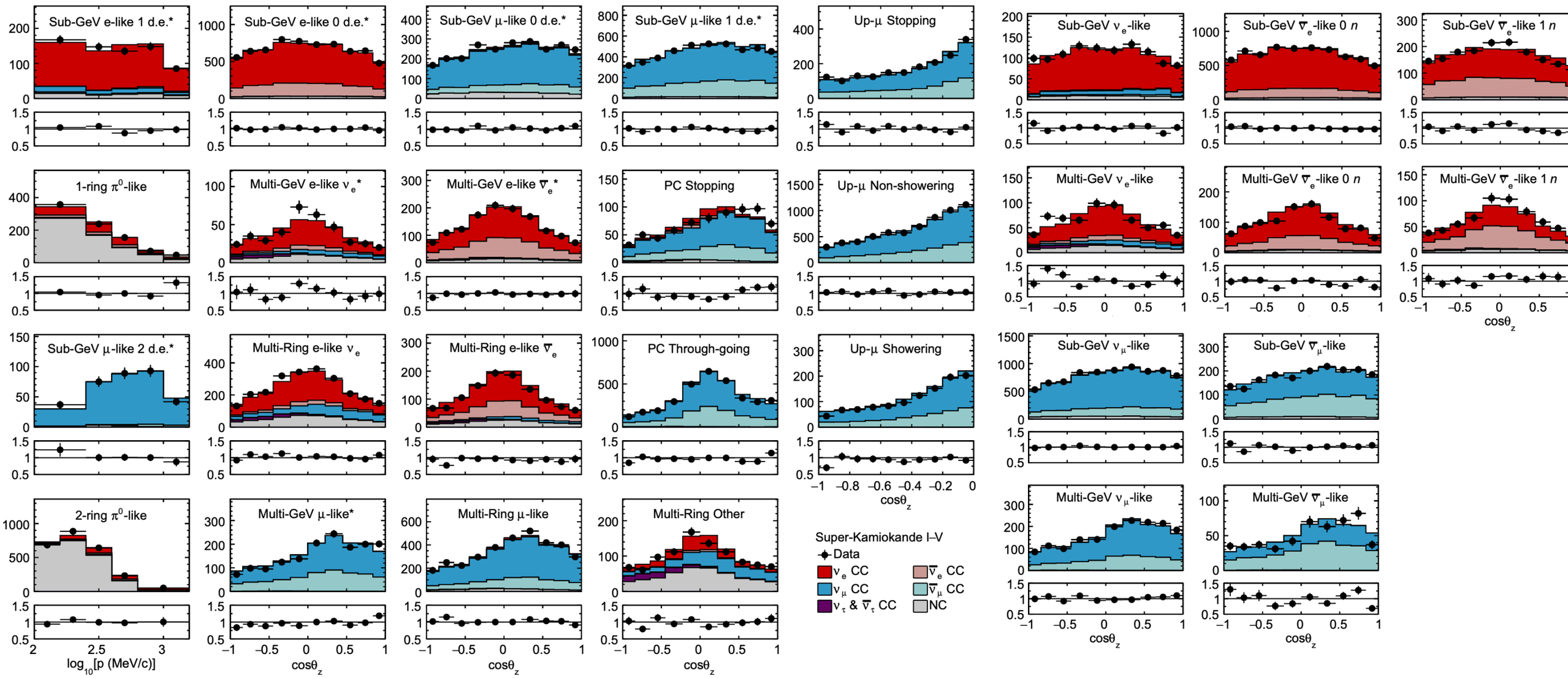
arXiv:2311.05105



Super-K

- Analysis strategy:
  - 29 samples binned in zenith, energy with >190 systematics
  - Grid scan in θ_{13}, θ_{23}, $\Delta m^2_{31/32}$, δ_{CP}
  - Also analysis combining with T2K

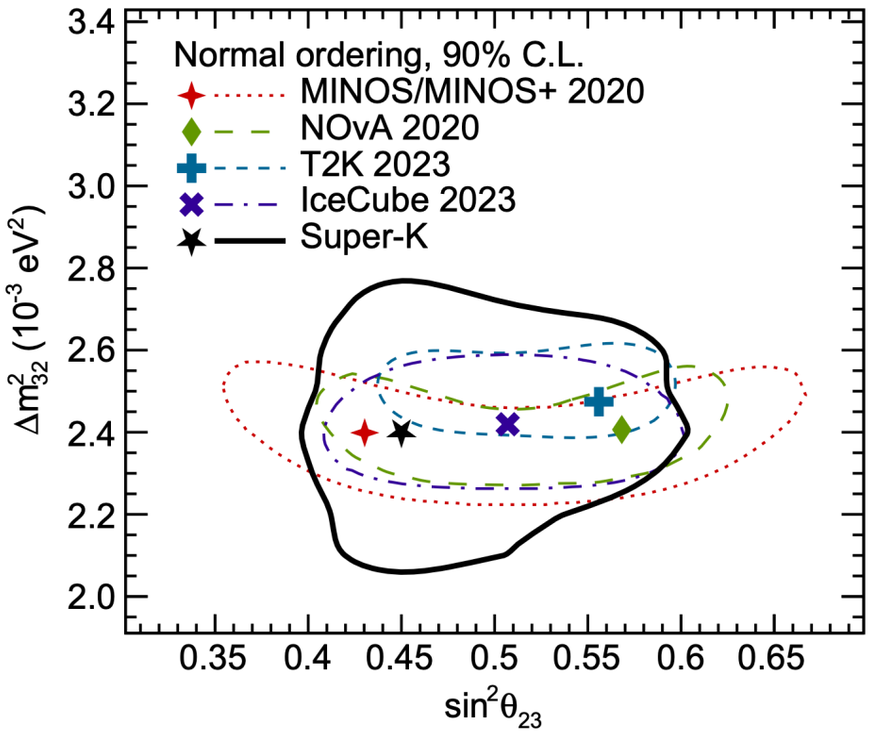
arXiv:2311.05105



Super-K

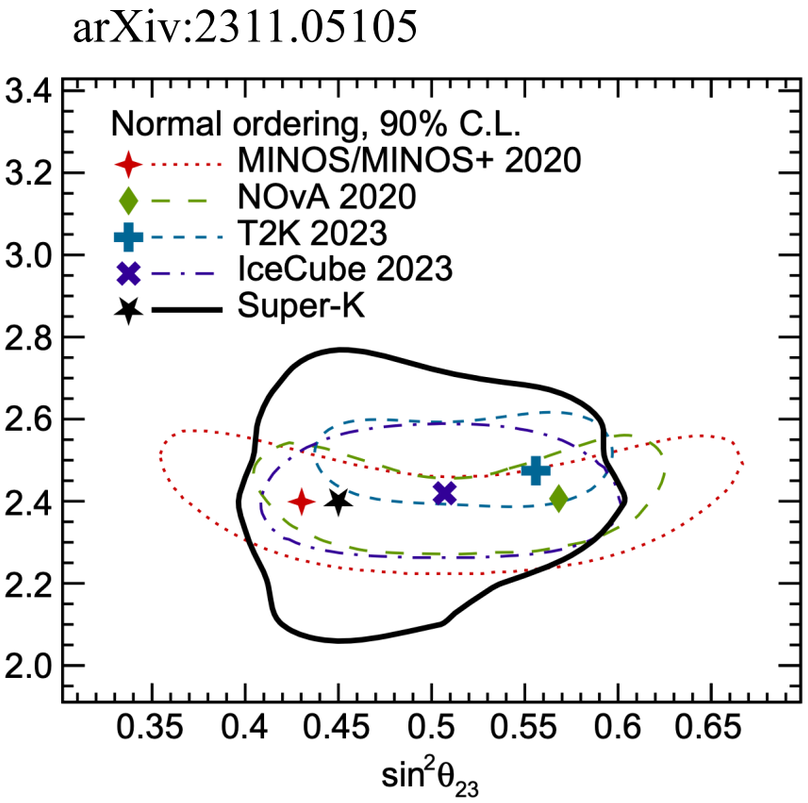
- Competitive results on atmospheric mixing parameter

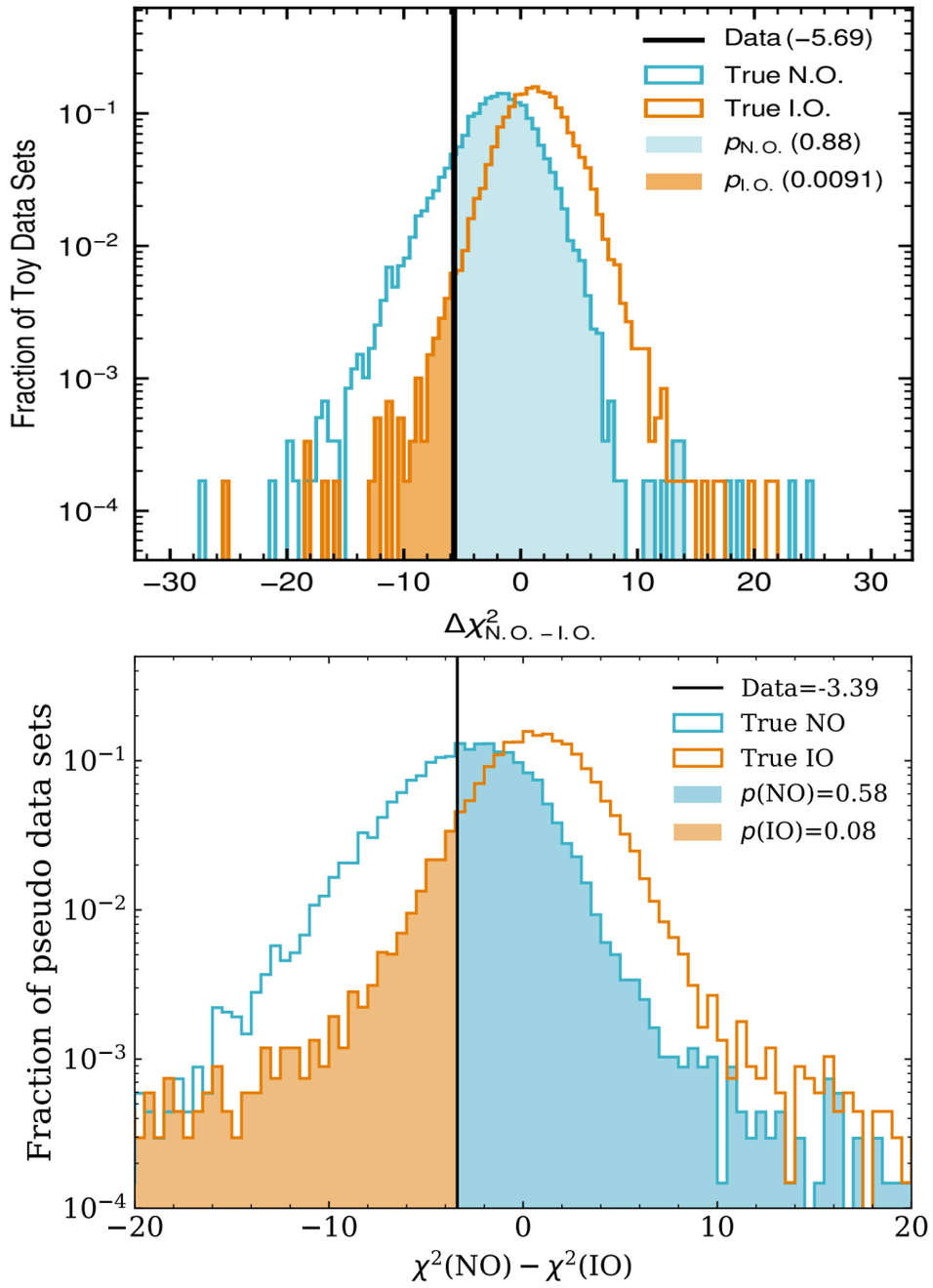
arXiv:2311.05105



Super-K

- Competitive results on atmospheric mixing parameter and NMO





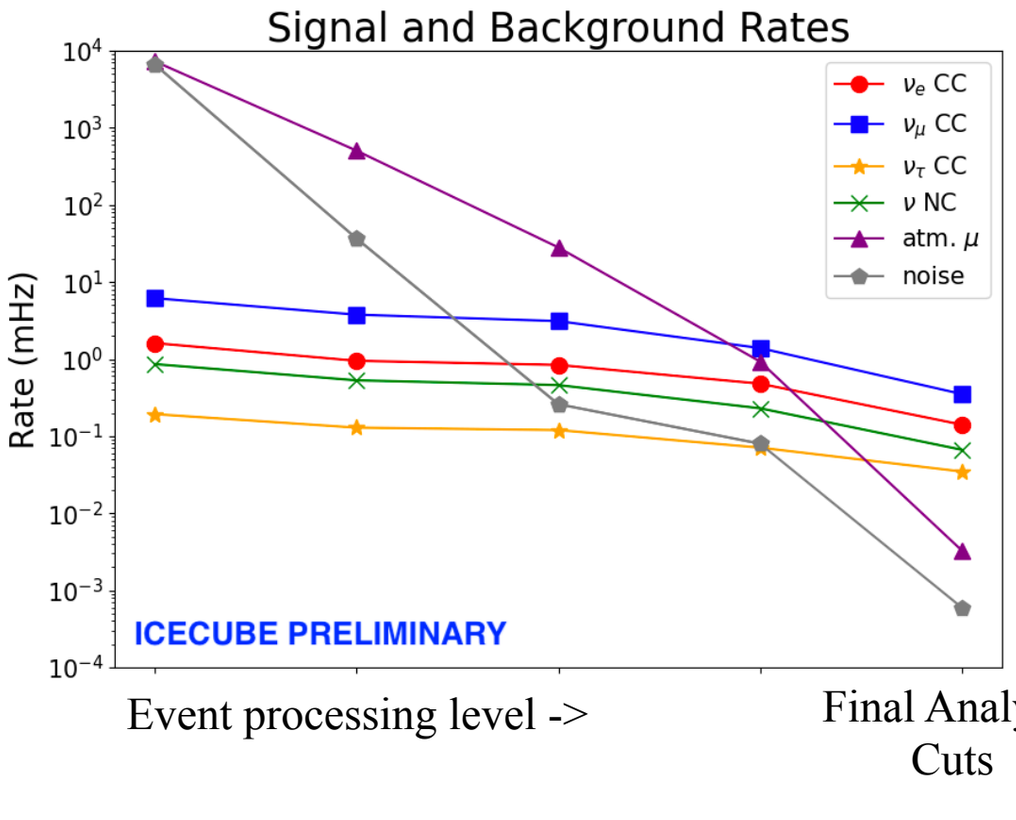
<u>SK only</u>*
IO rejected
at **92% C.L.**
(arXiv:2311.05105)

<u>SK+T2K</u>*
IO rejected
at **82% C.L.**
(arXiv:2405.12488)

***w/ priors on θ_{13} from reactor experiments**

IC-DeepCore

- >150k events in 9 years:
  - background contamination <1%



S. Yu and J. Micallef (ICRC 23)

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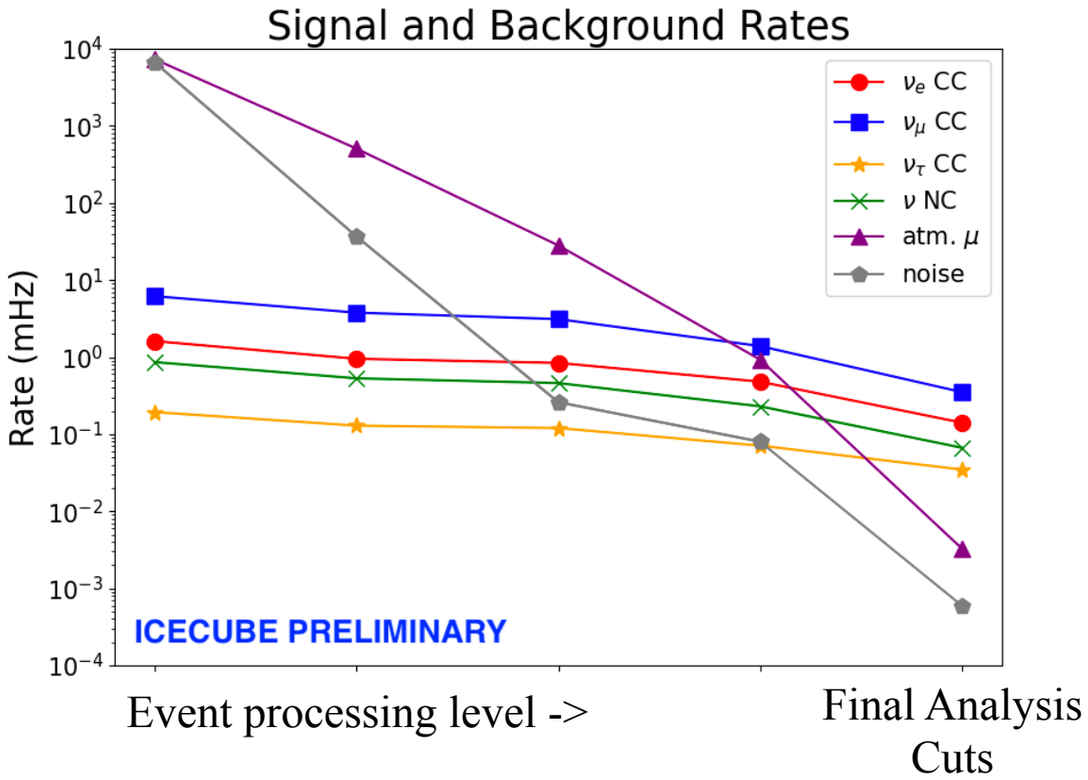
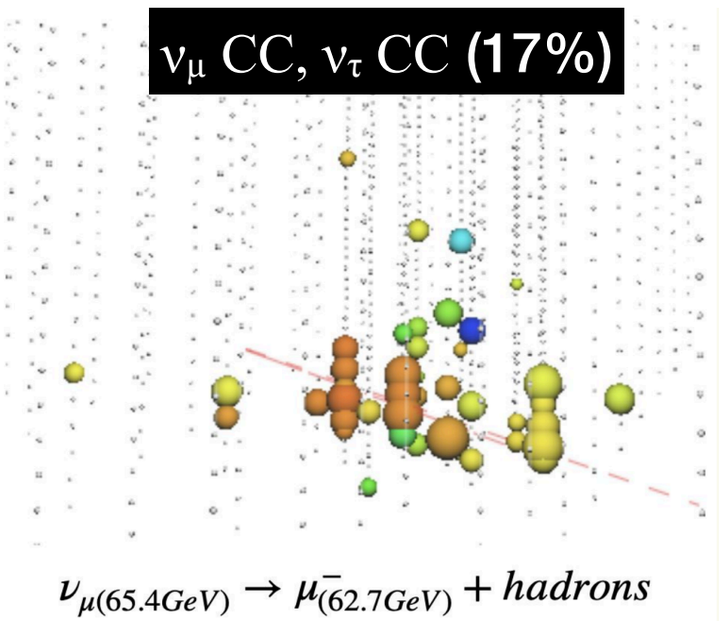
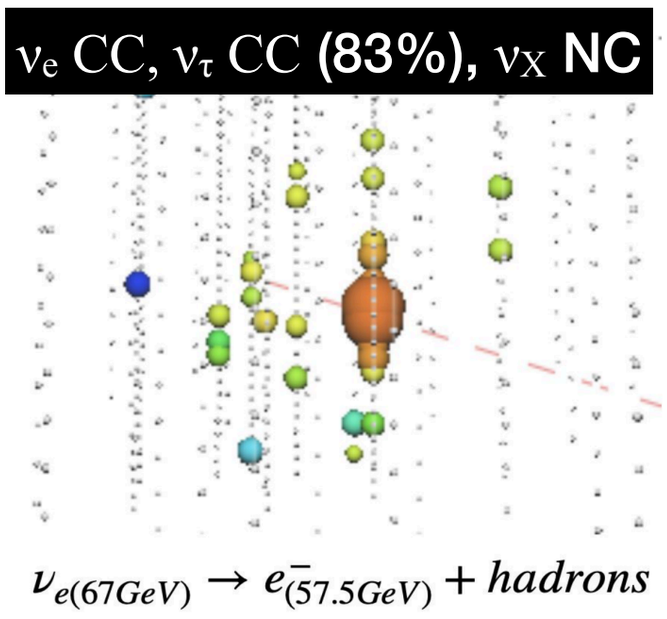
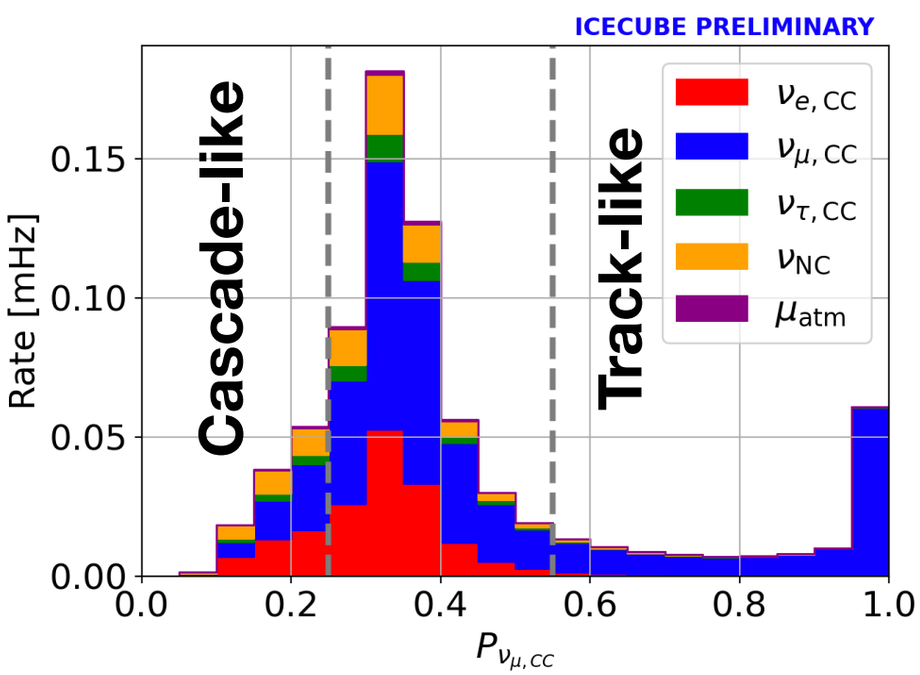


- Two main topologies: track and cascades

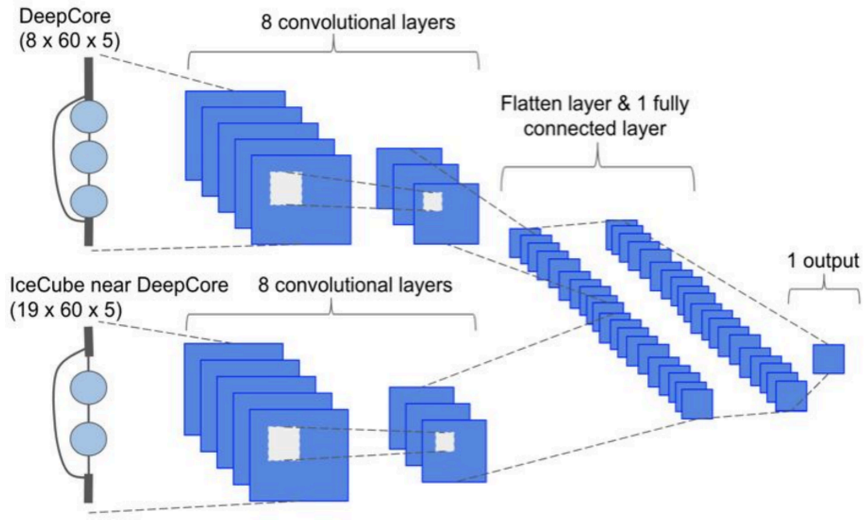
S. Yu and J. Micallef (ICRC 23)





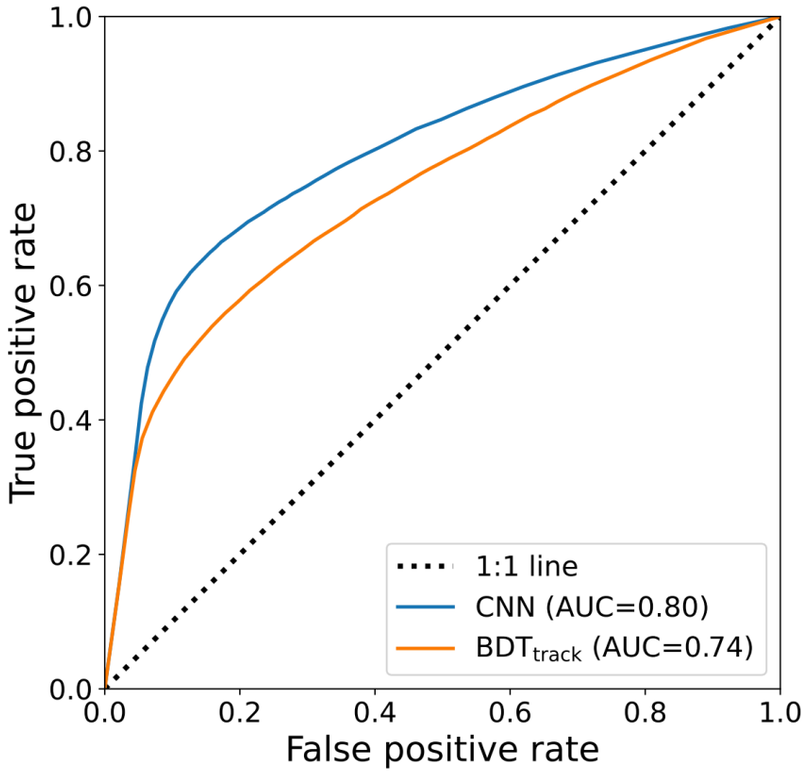


IC-DeepCore



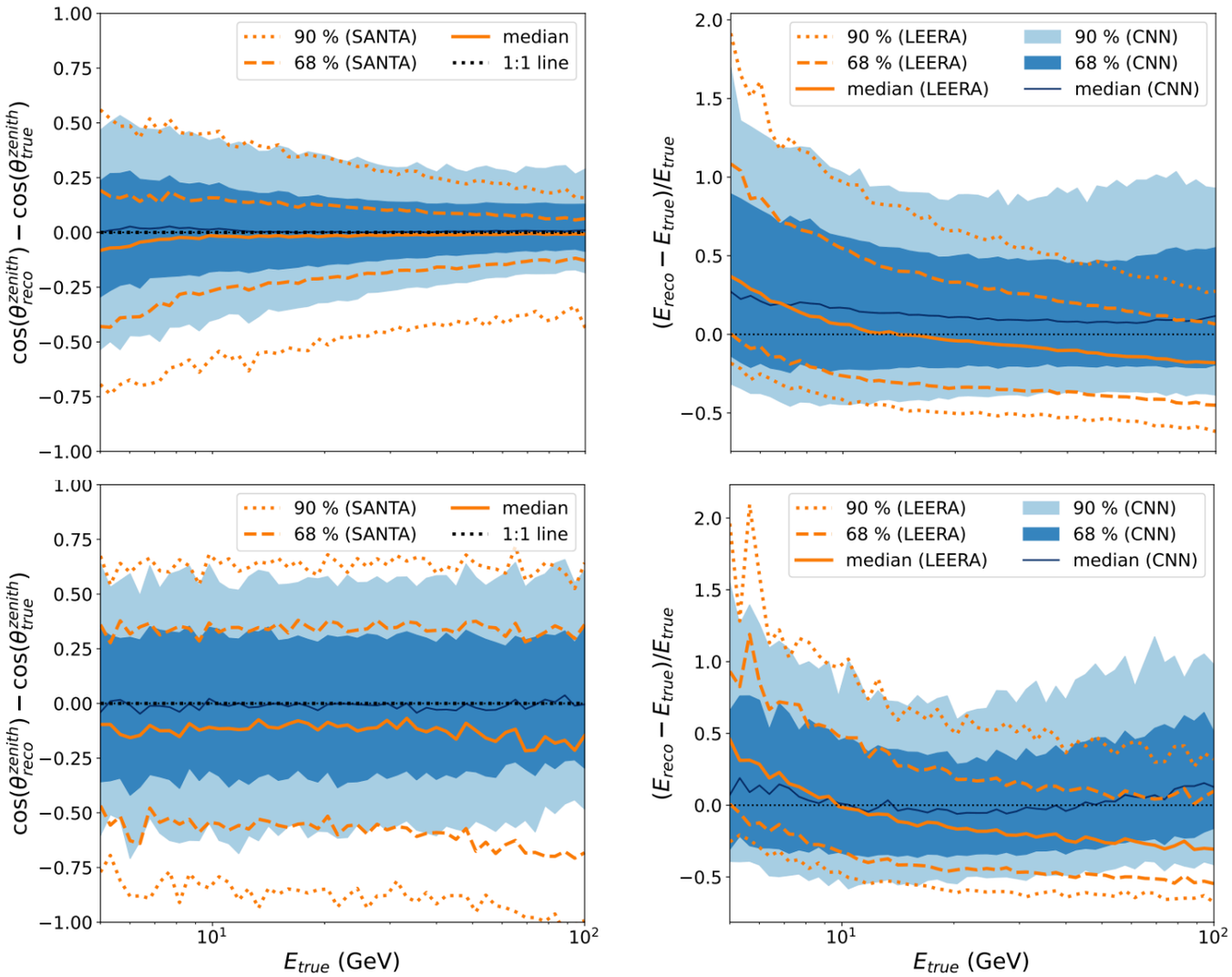
- Profit from machine-learning techniques
  - Energy, direction, and classifiers extracted from CNN

ν_μ CC tagger



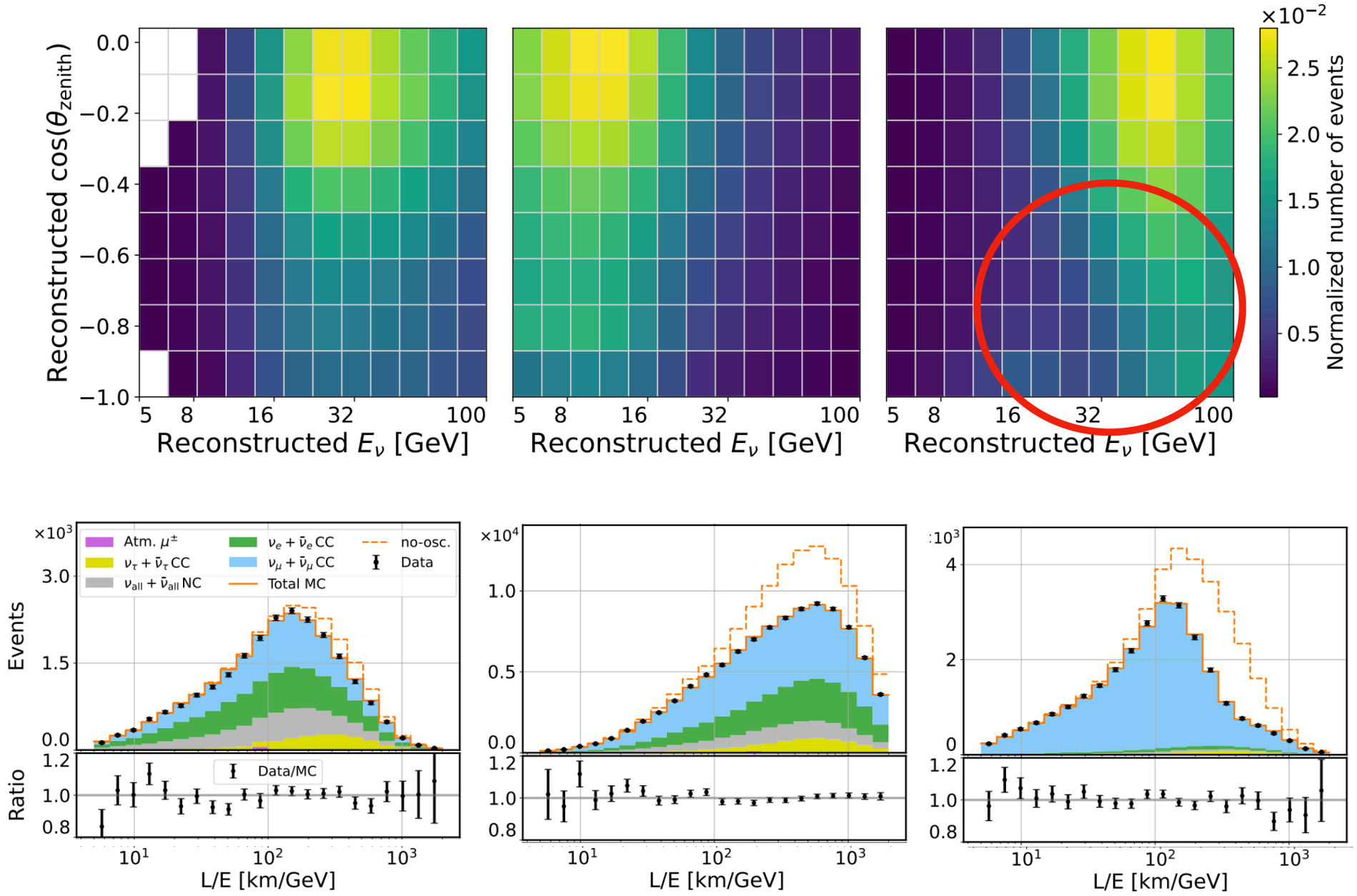
arXiv:2505.16777

Top=ν_μ CC // Bottom=ν_e CC



IC-DeepCore

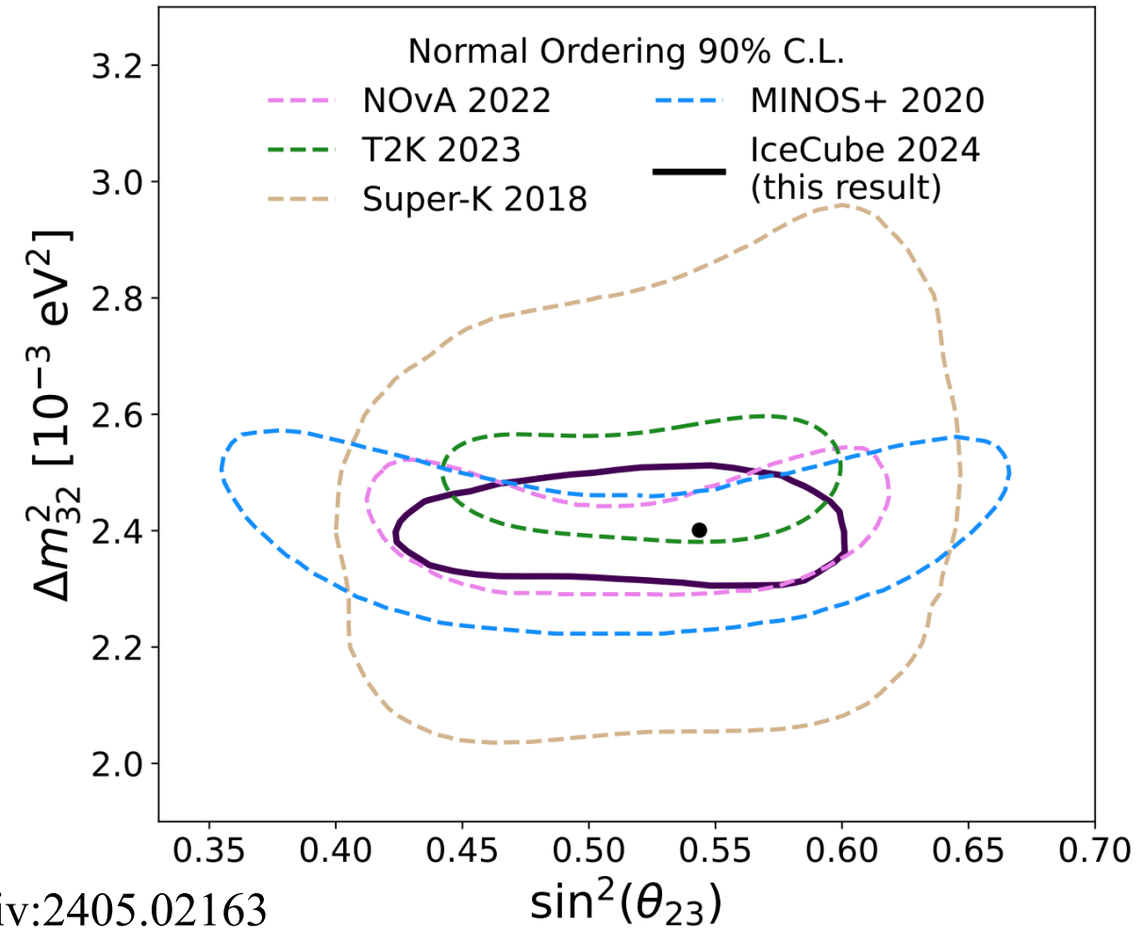
- Analysis strategy:
  - 3 samples binned in zenith, energy with 17 systematics



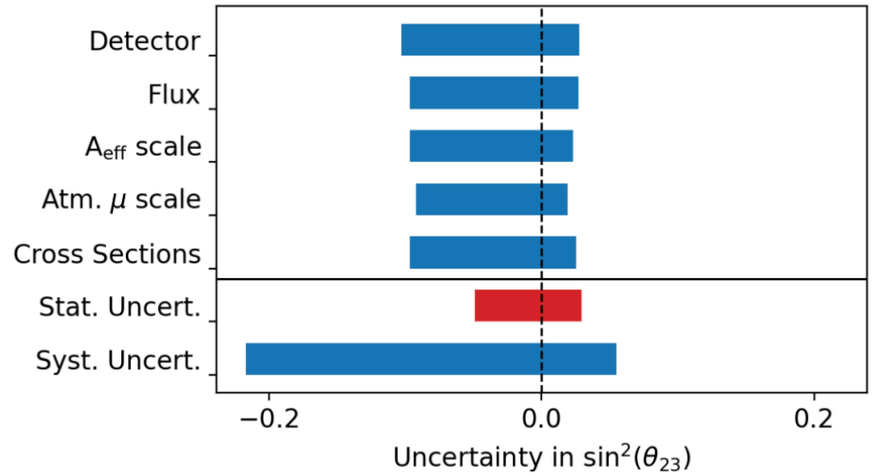
arXiv:2405.02163

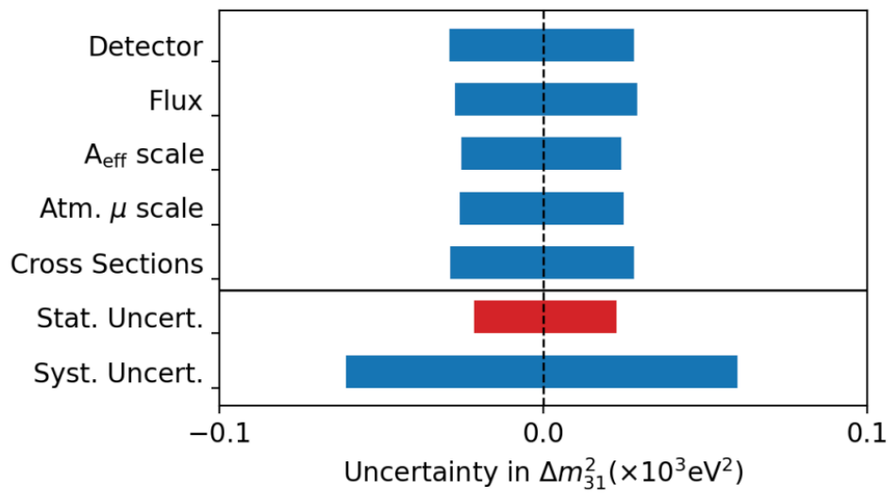
IC-DeepCore

- Results:
  - Compatible with the existing measurement -> very competitive mass splitting!
  - Complementarity with long baseline: different energy range and systematics
  - Mixing and mass splitting error dominated by systematics
  - Mass ordering results coming soon



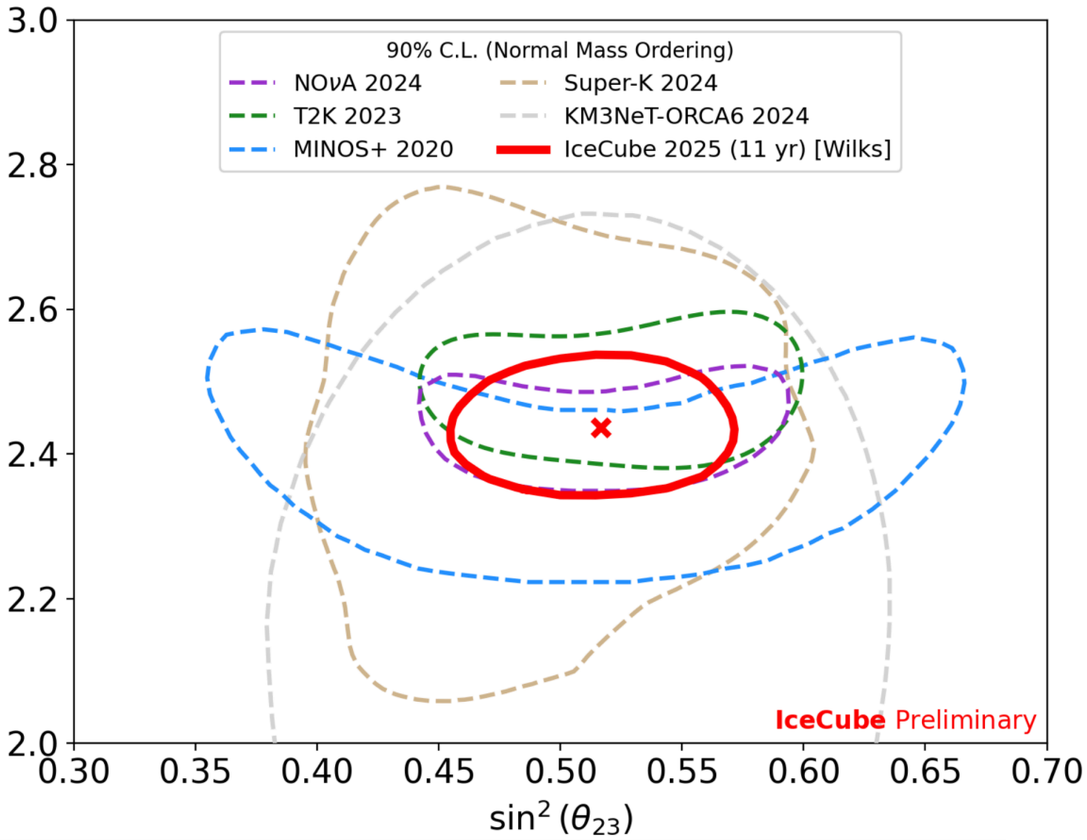
arXiv:2405.02163





IC-DeepCore (lastest result)

- New results presented from few weeks ago:
  - New reconstruction algorithm (GNN), and PMT noise filtering and modeling of systematic uncertainties.
  - World-leading measurement of the mixing



108,784 ± 129 events (total)
0.7% atm. μ contamination

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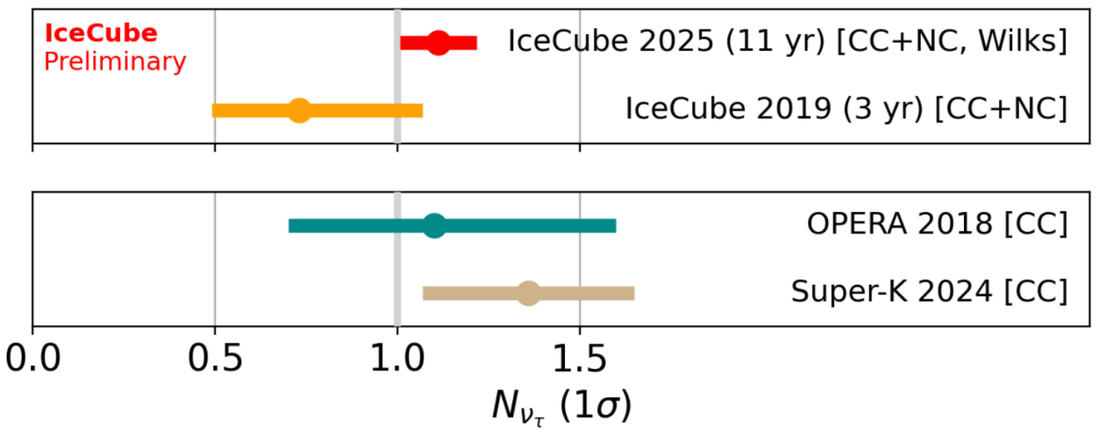
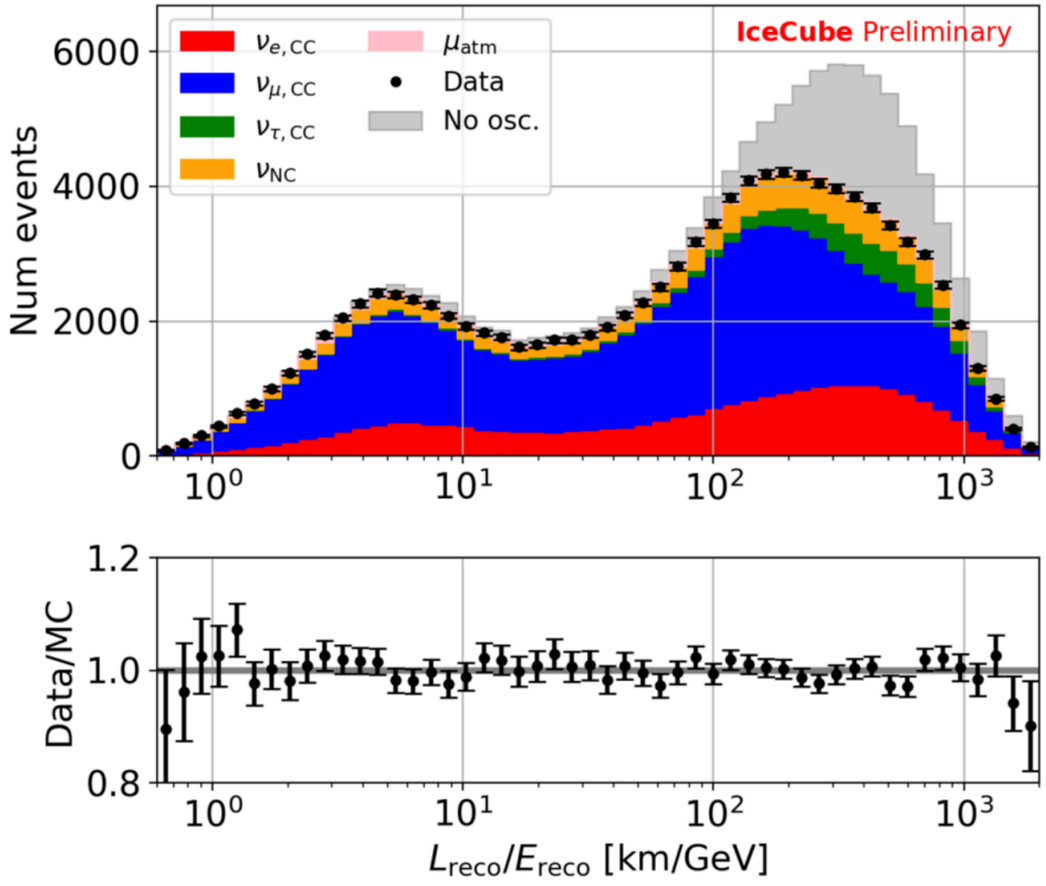
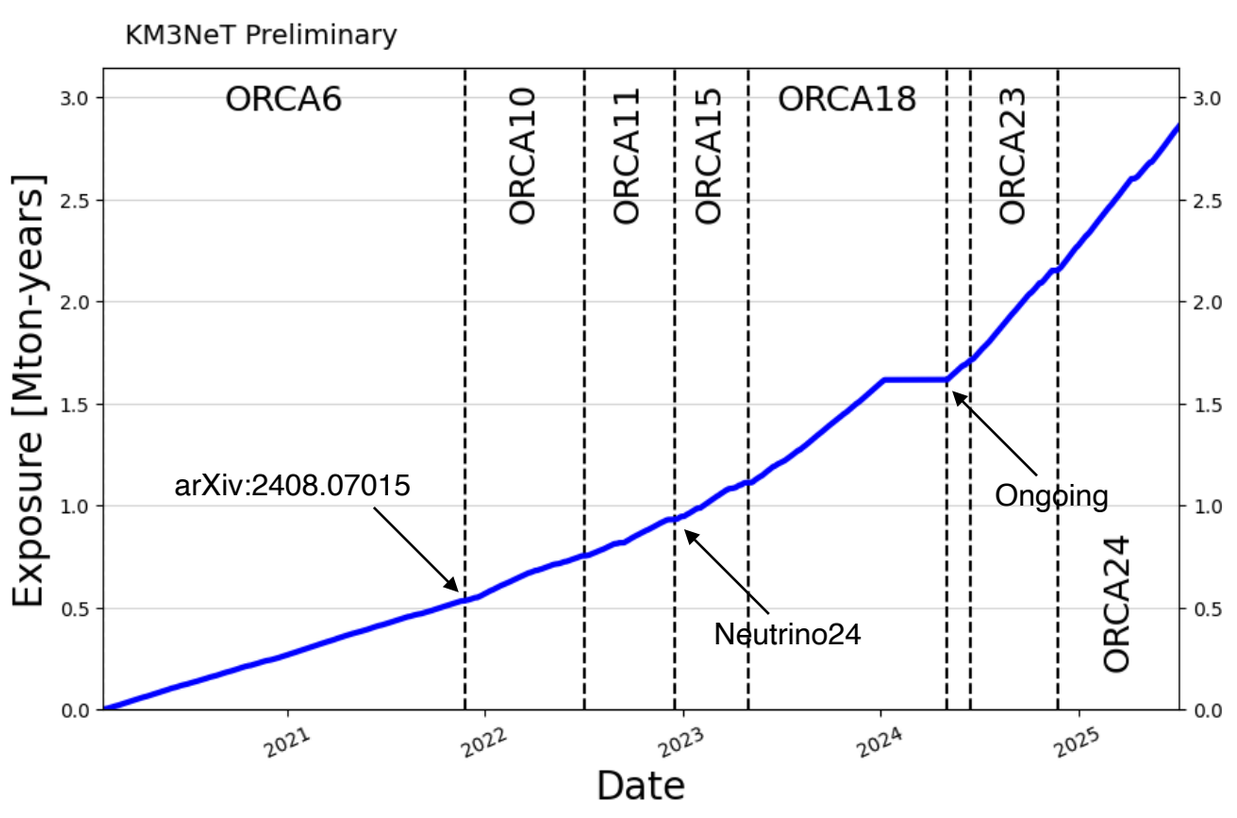




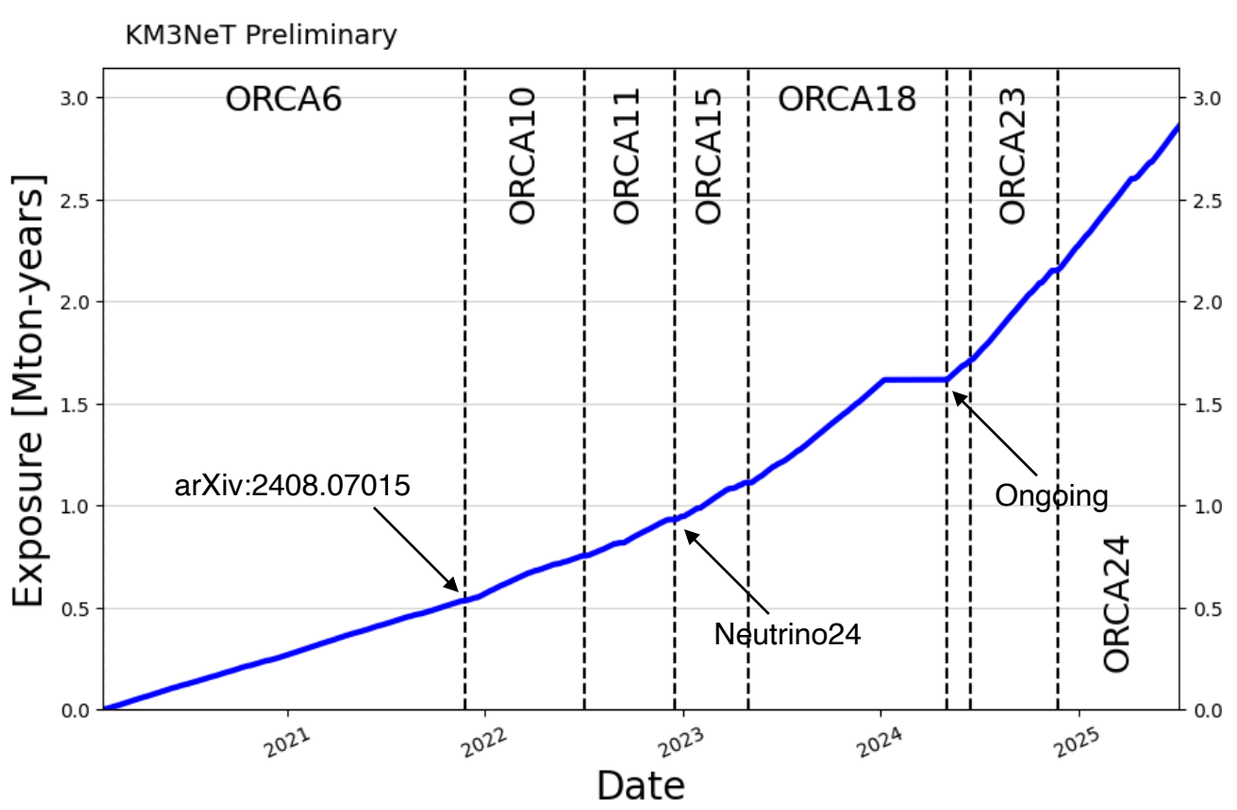
KM3NeT-ORCA



- ~10k events in 3 years with 6-11 DUs:
  - ORCA24 already online (3x more data)!

V. Carretero (EPS-HEP 25)

KM3NeT-ORCA



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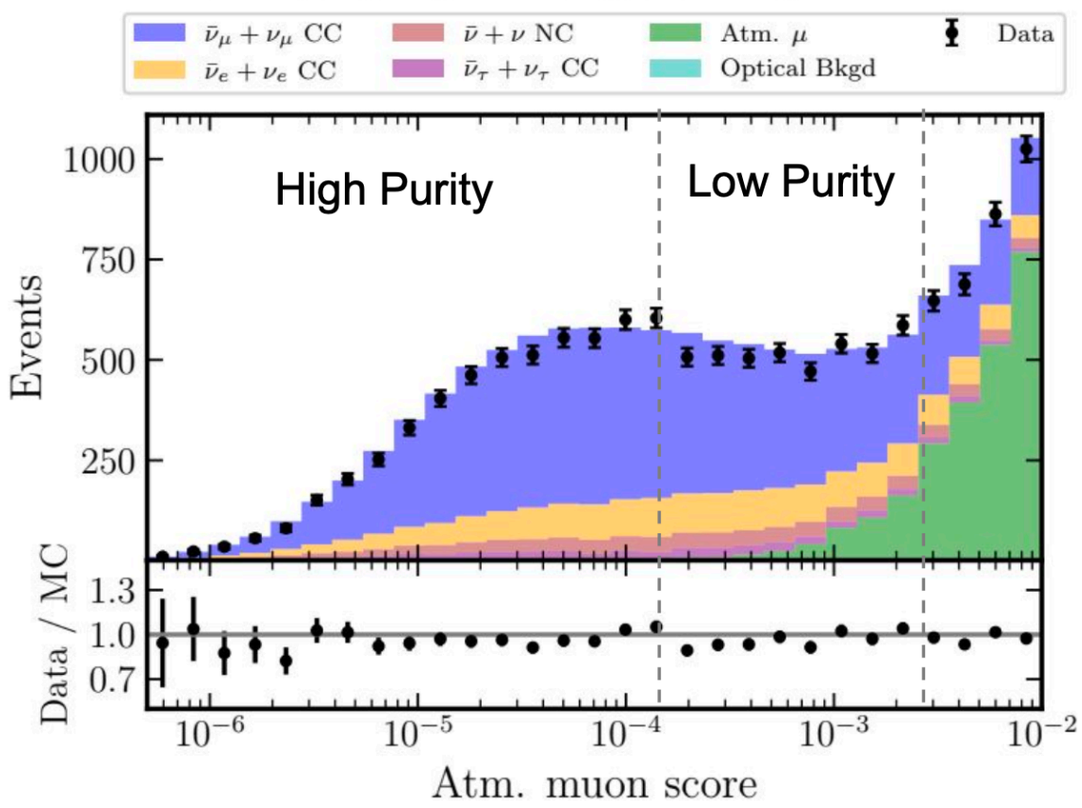
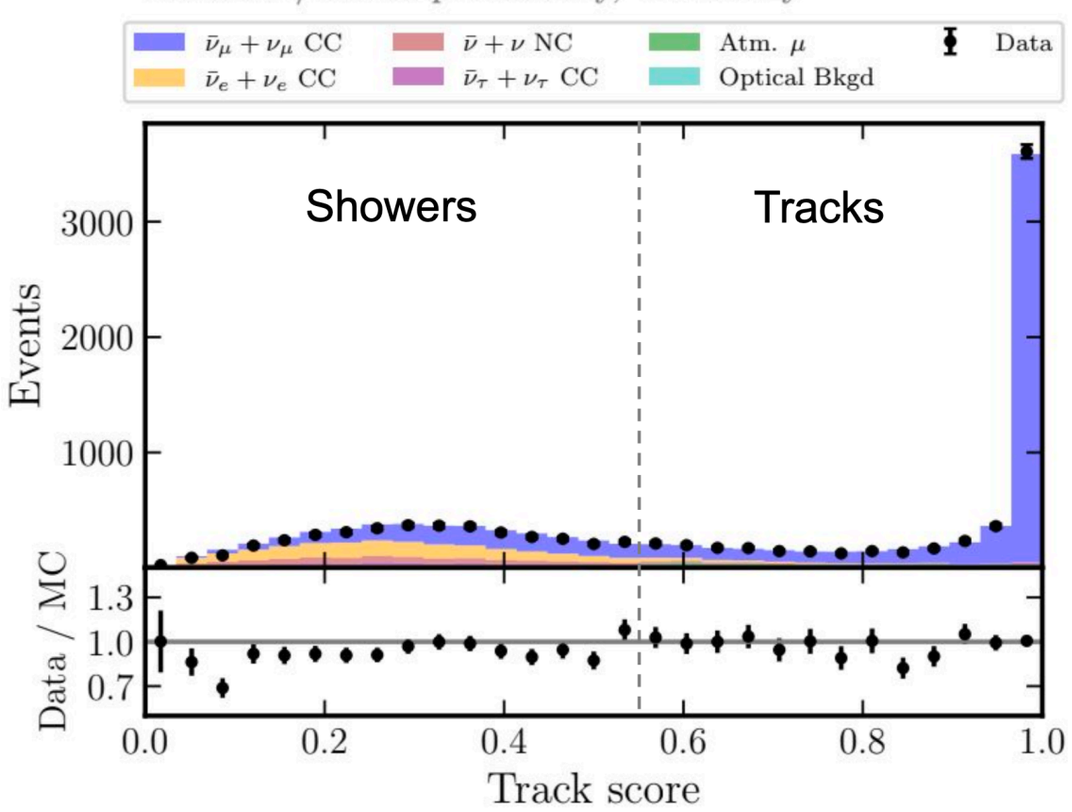
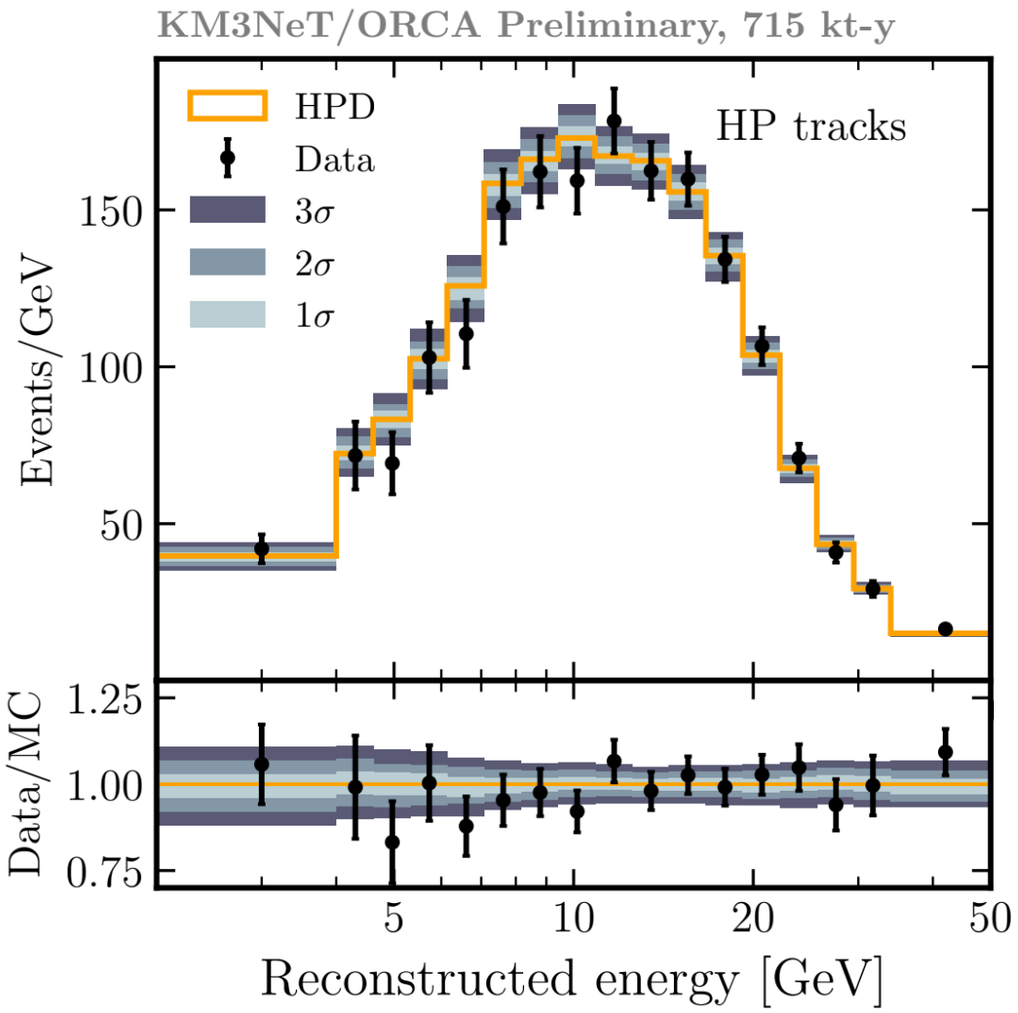
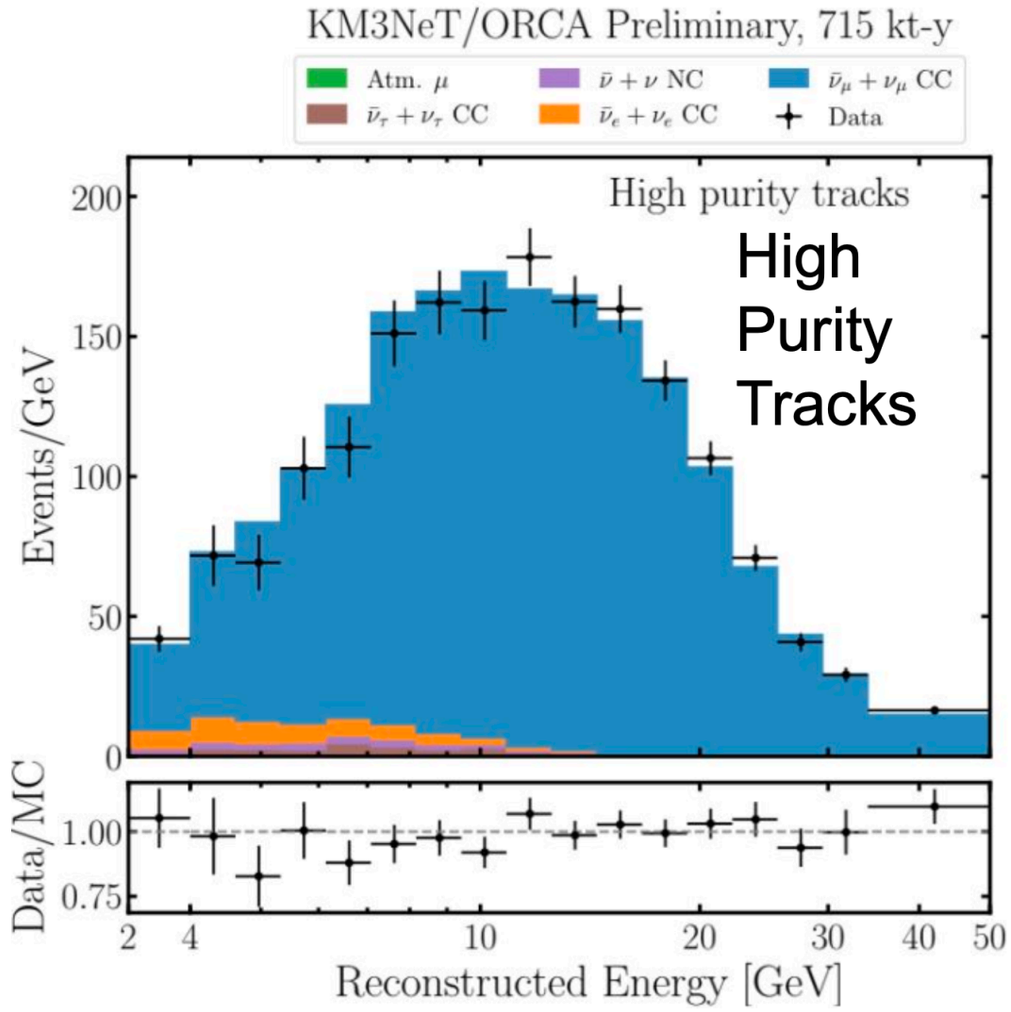




KM3NeT-ORCA

- Analysis strategy:
  - 3 samples binned in zenith, energy with 13 systematics
  - Both frequentist and Bayesian analyses!
  - Goodness-of-fit (& posterior predictive p-value) shows a very good performance

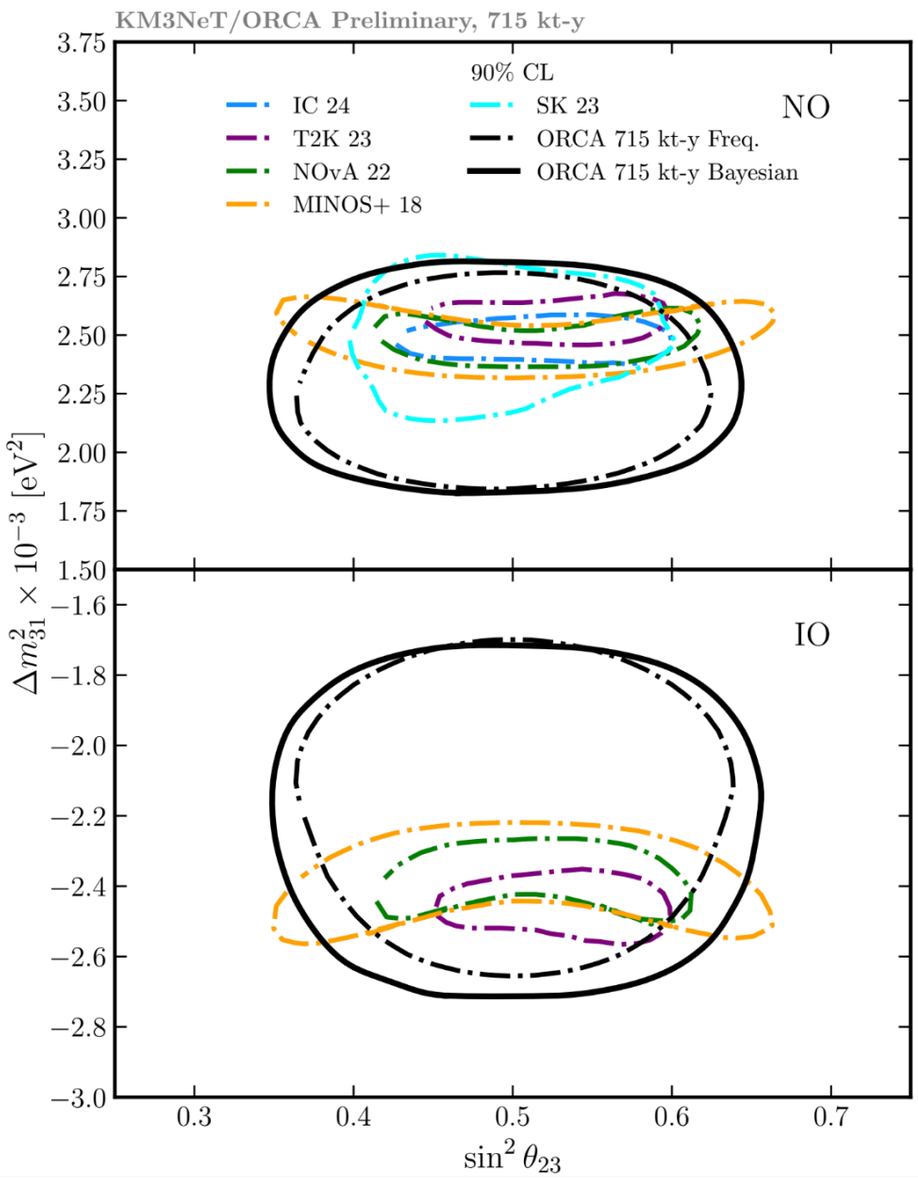




V. Carretero (EPS-HEP 25)

KM3NeT-ORCA

- Results:
  - Compatible with the existing measurement
  - Bayesian and freq. methods show good agreement



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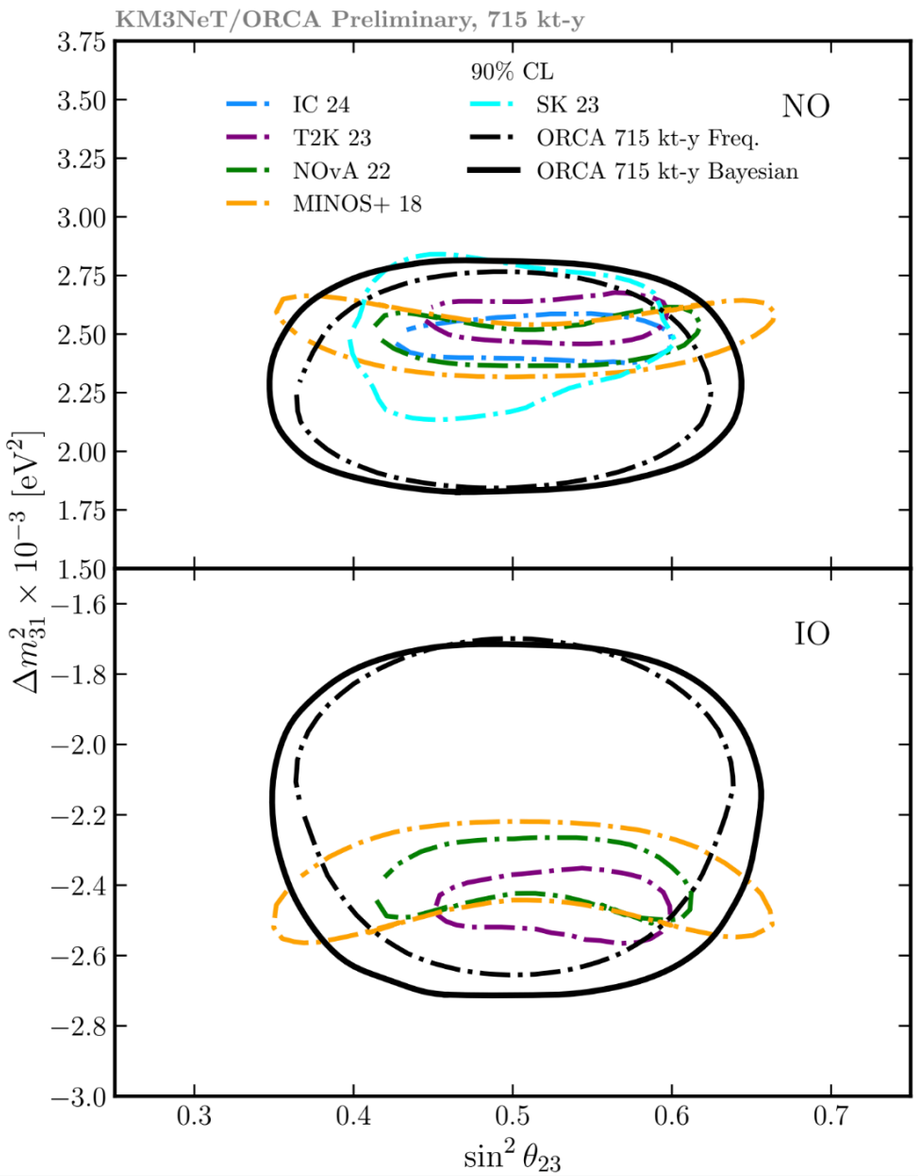
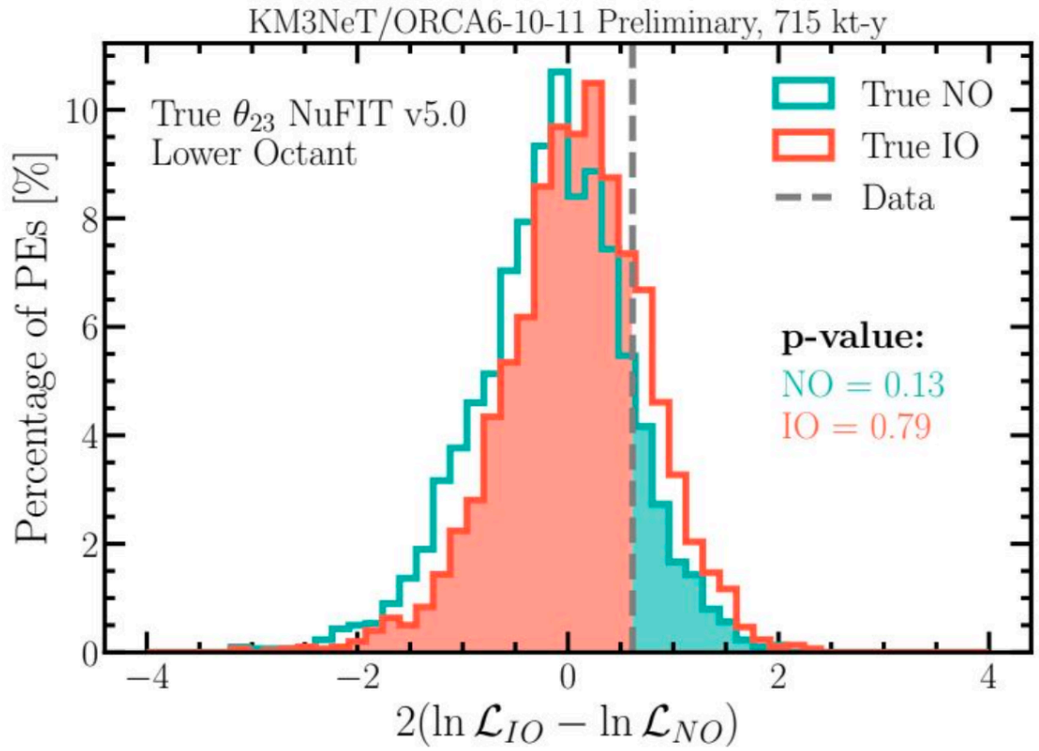
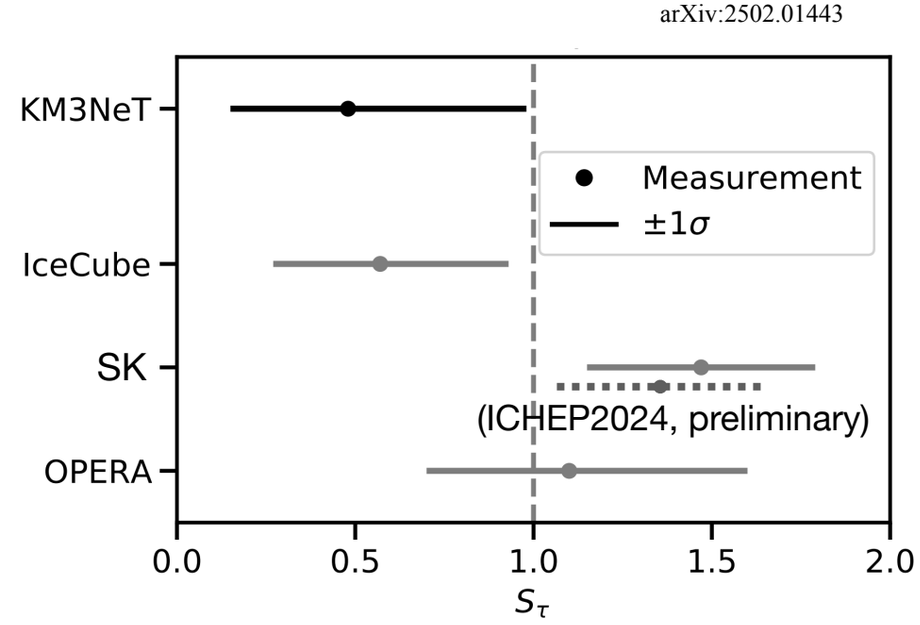




NO rejected at 87(IO)/92(UO)% C.L.

Other analyses

- Multiple analyses that can be done with <100GeV atmospheric neutrinos
  - Mostly looking for distortions in the oscillations patterns
- List a few: tau appearance,



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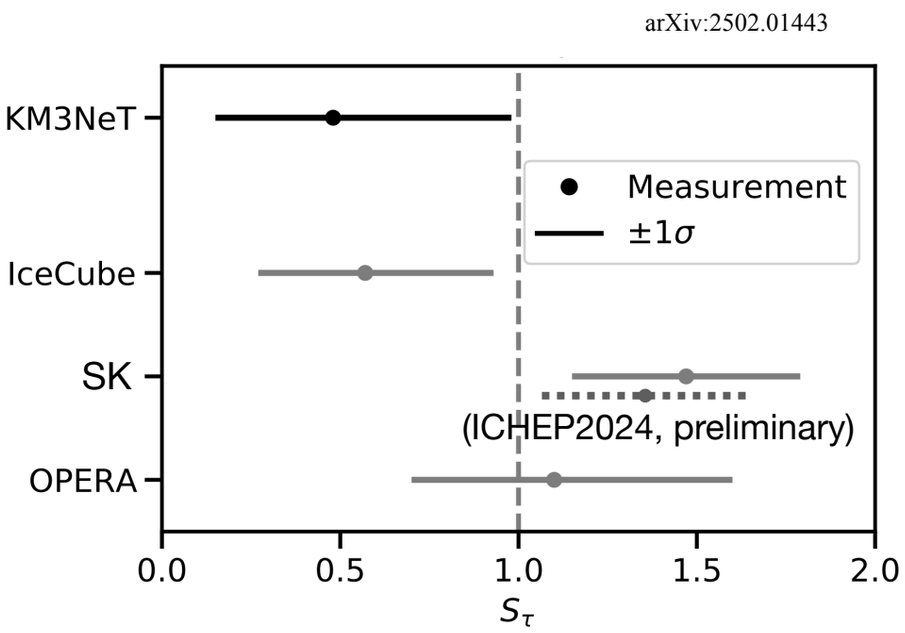

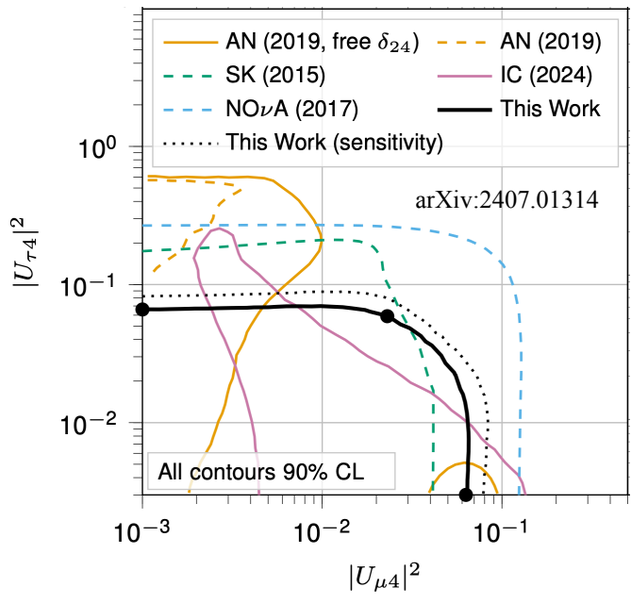

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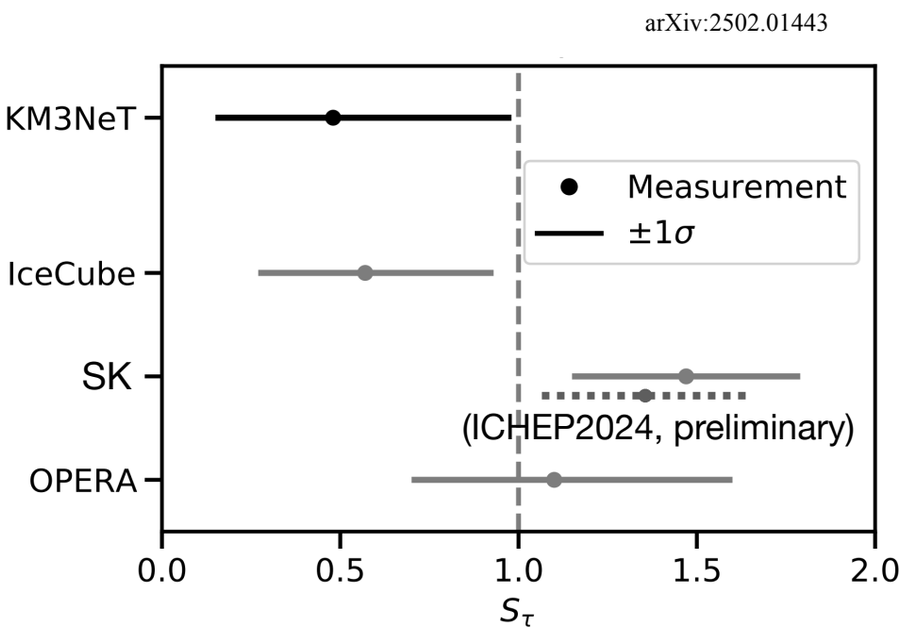

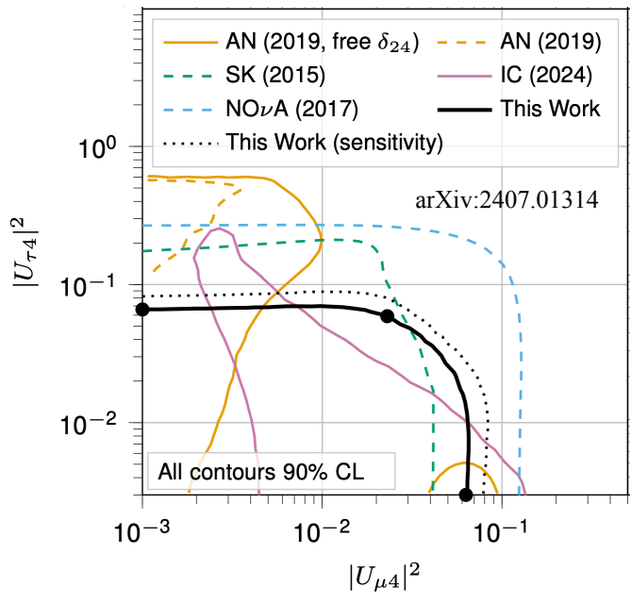

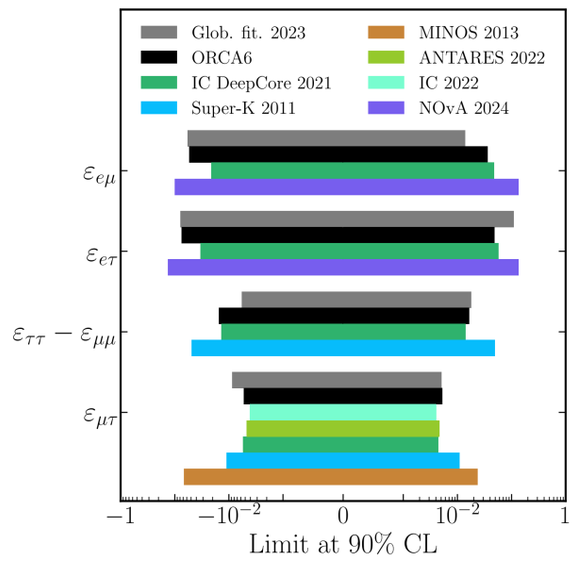

arXiv:2411.19078

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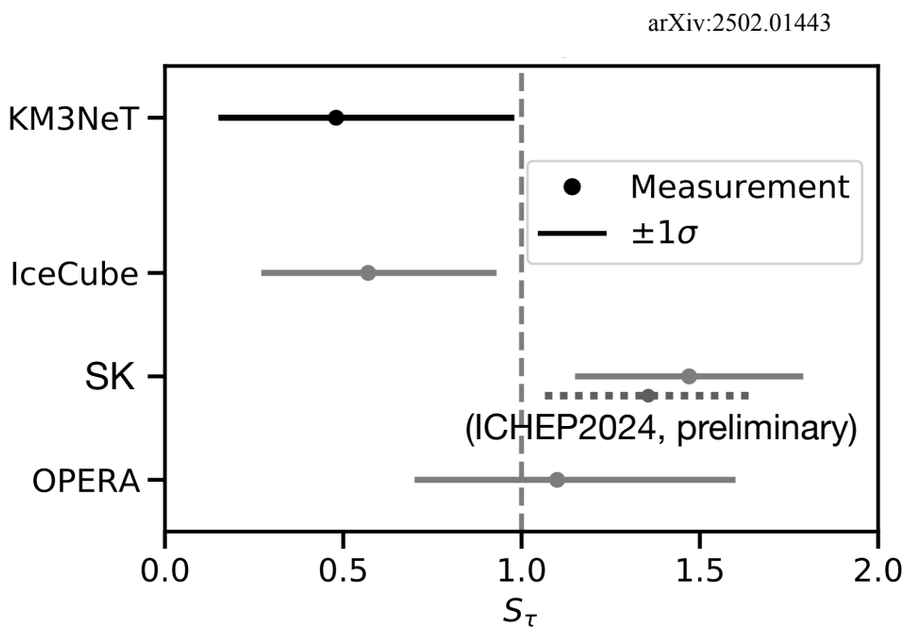

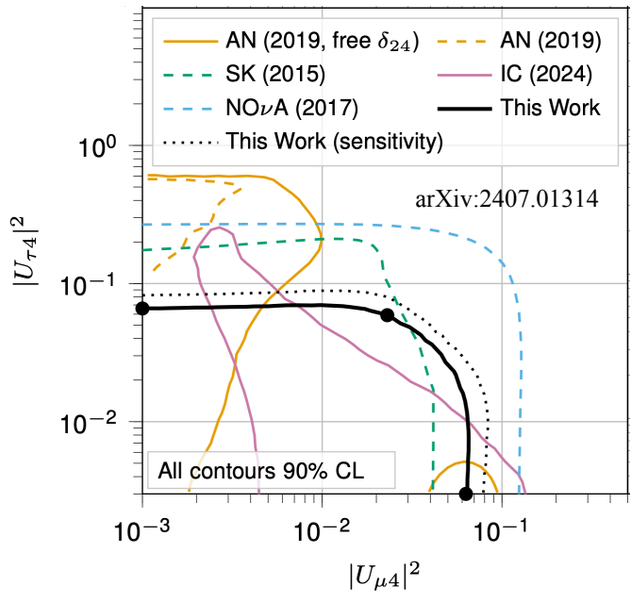

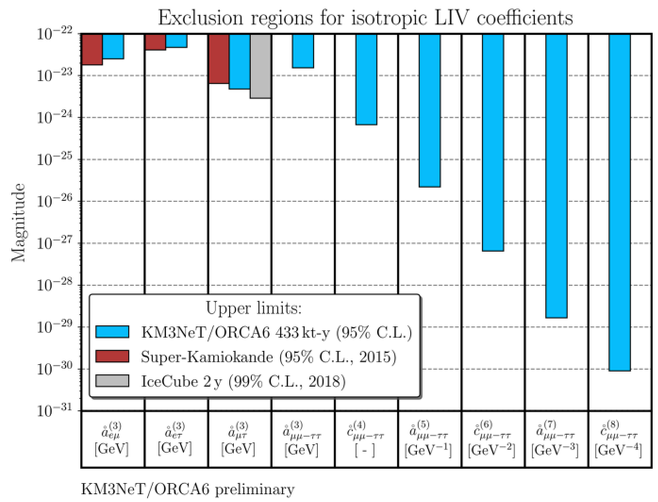

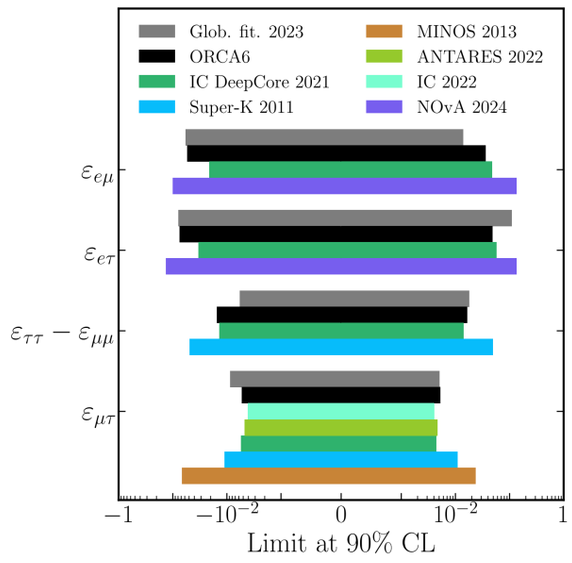

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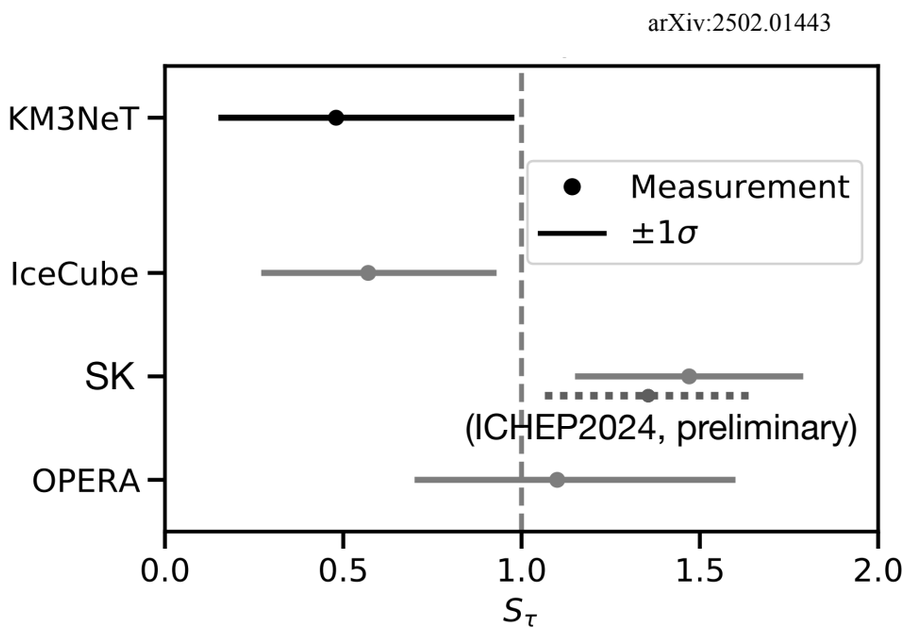
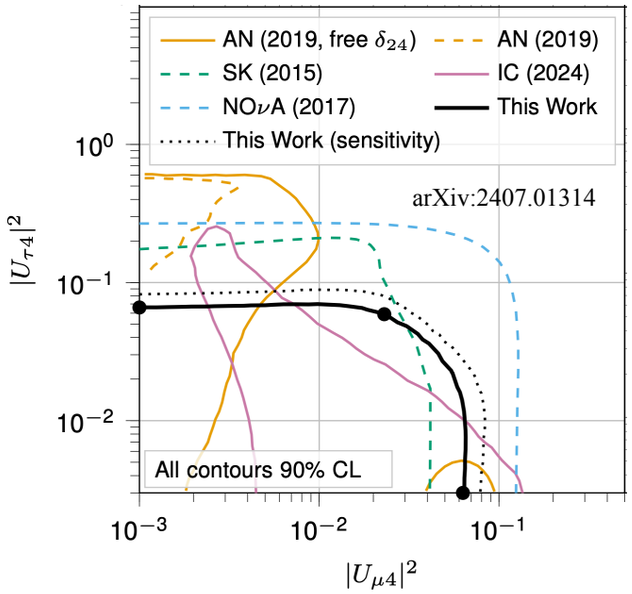
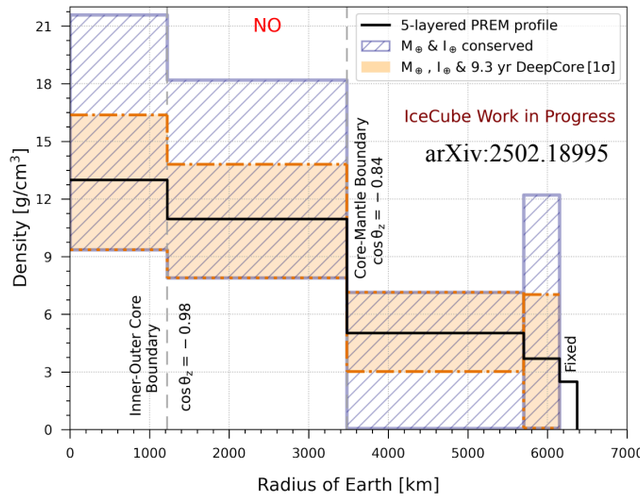
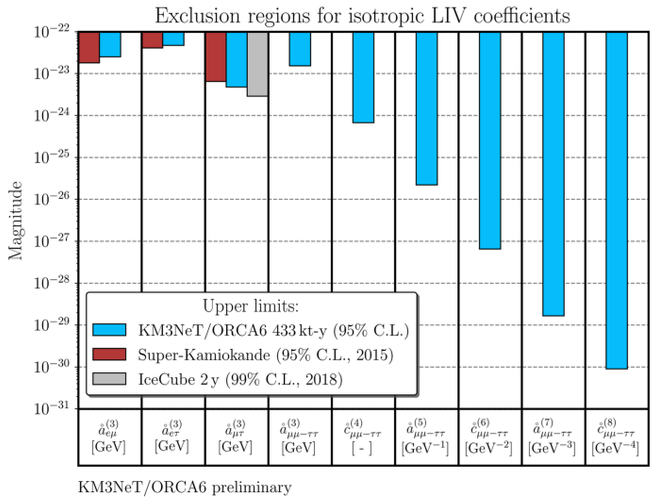
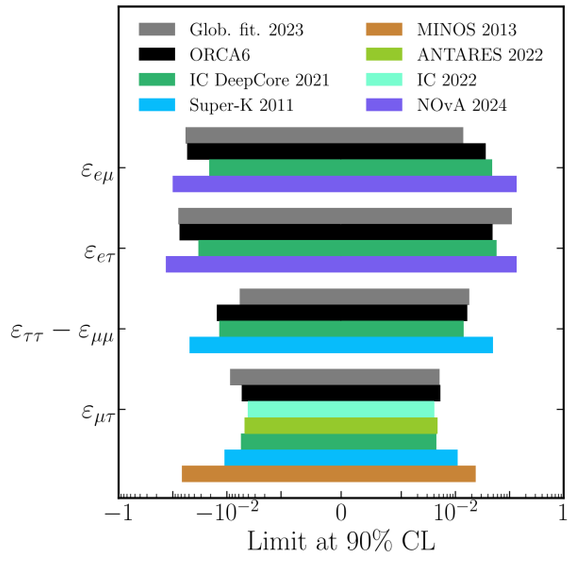






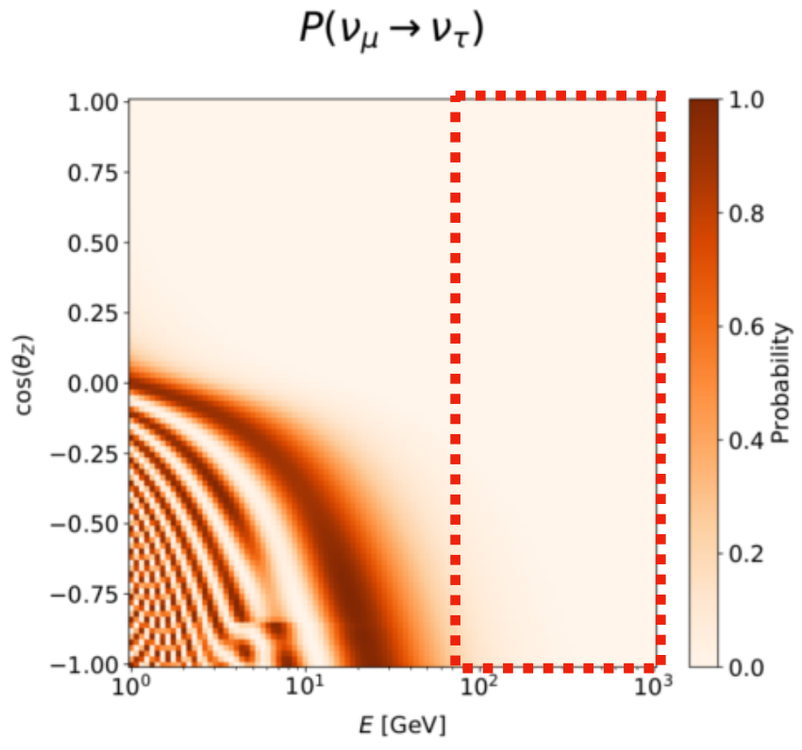




arXiv:2411.19078

Going to higher energies

- For energies ≳100GeV no oscillations are expected for atmospheric neutrinos
  - No degeneracies with standard oscillation parameters
  - Higher energies -> lower fluxes -> larger volumes (IC, KM3NeT/ARCA, etc)



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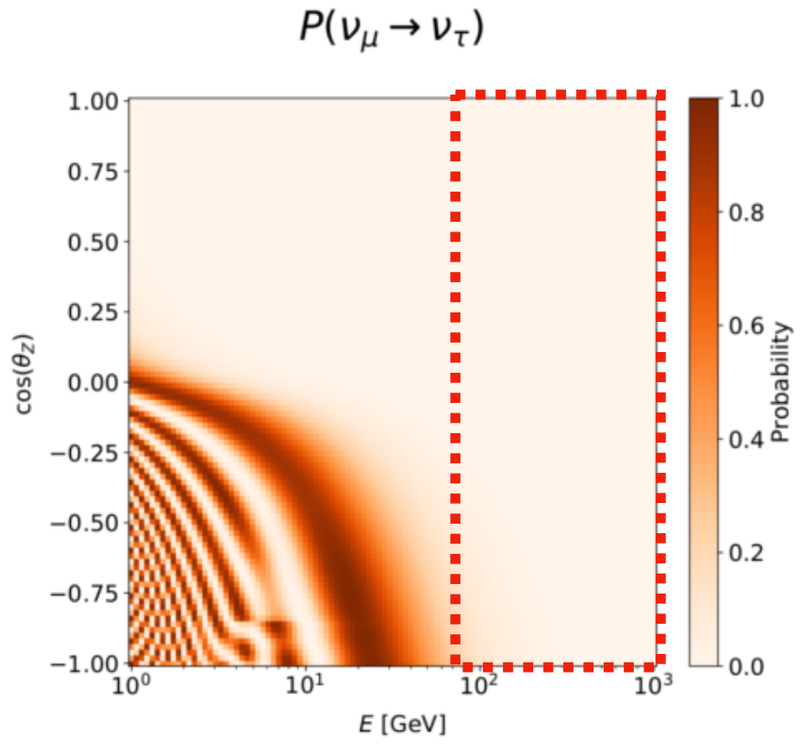
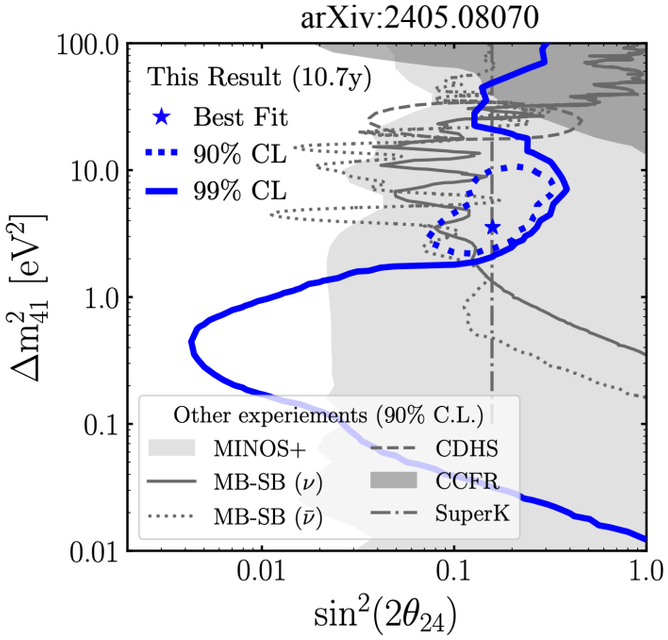
- IC has released world-leading BSM constraints



arXiv:2405.08070



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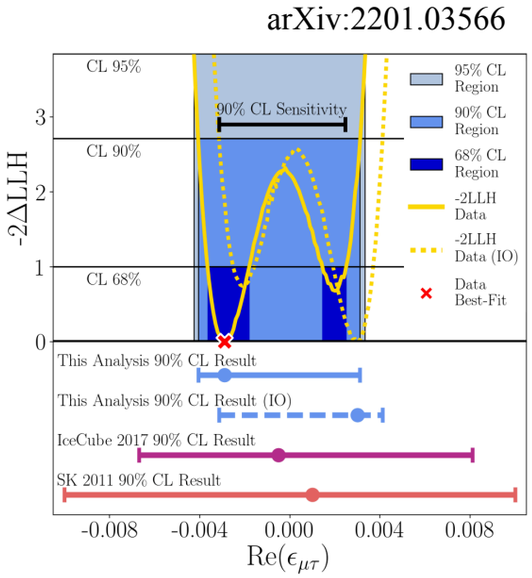

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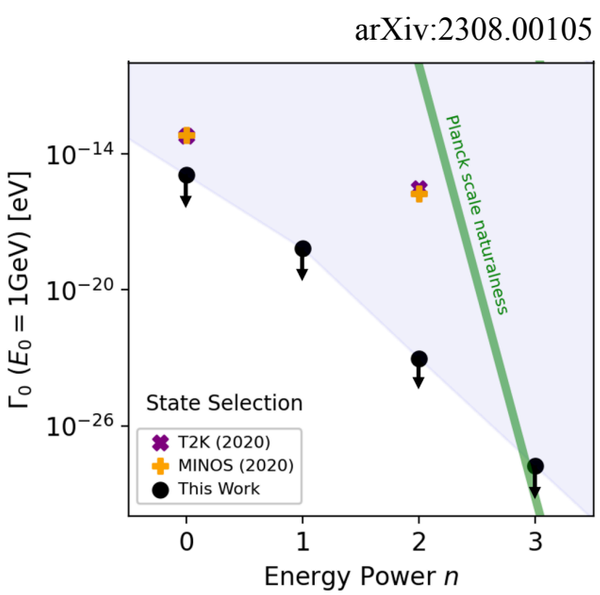
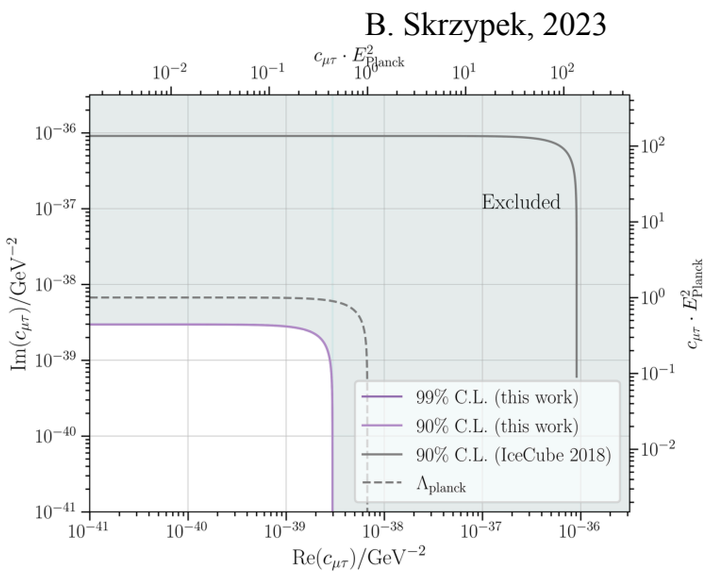
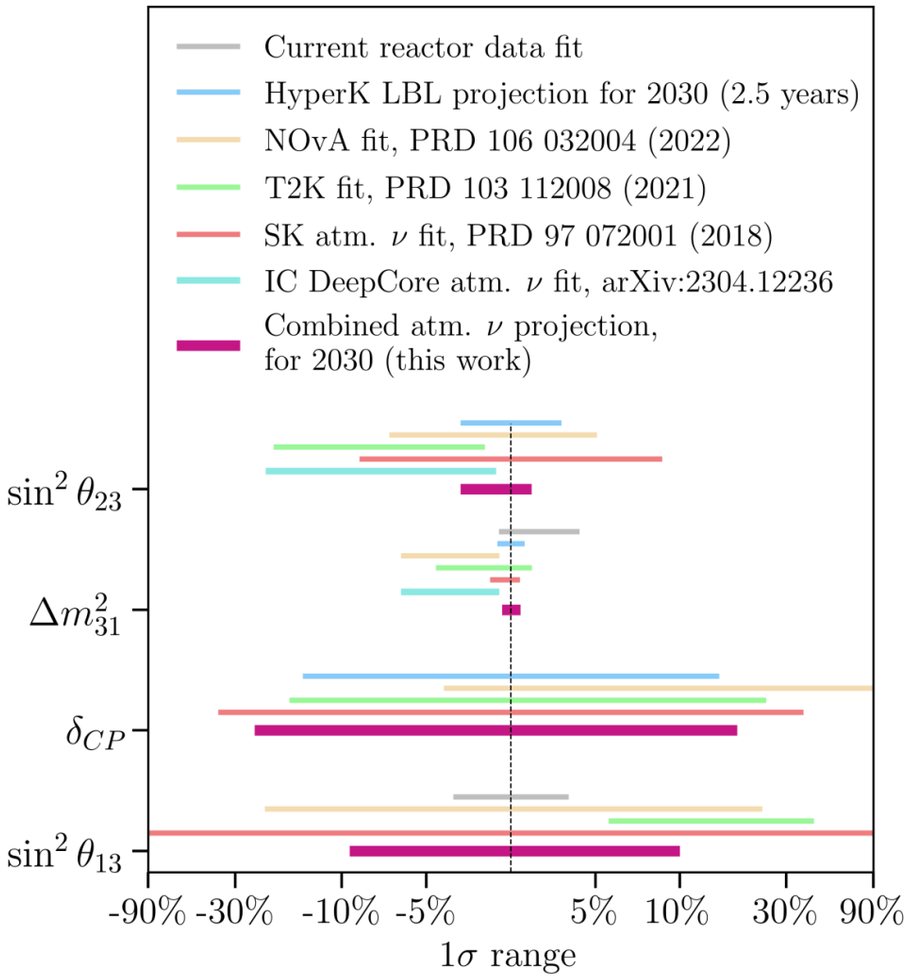


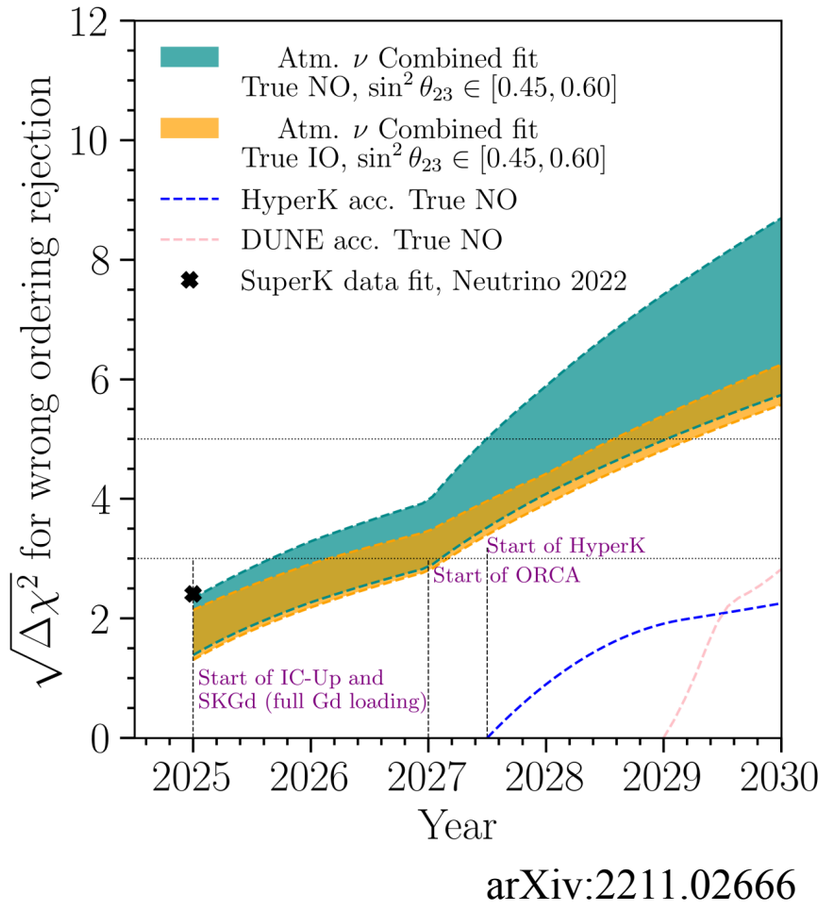
B. Skrzypek, 2023



More data

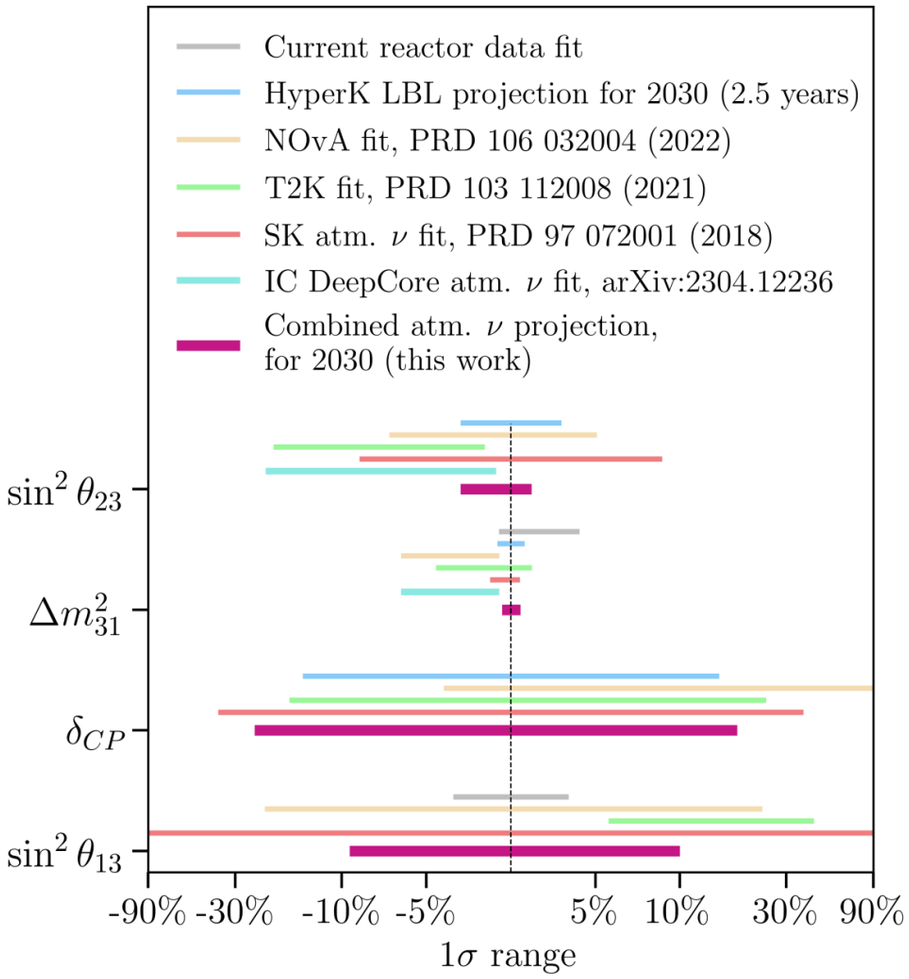
- Prospects in the next years:
  - More detectors: SuperK-Gd, IC-Upgrade (deploy in 25/26), and KM3NeT-ORCA115

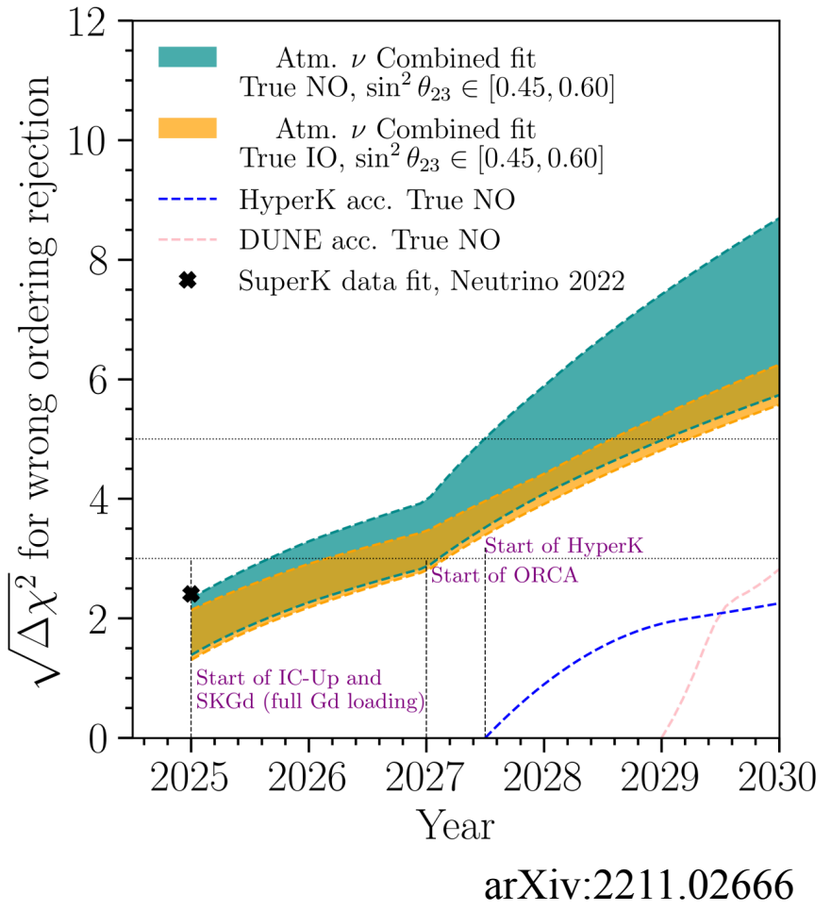


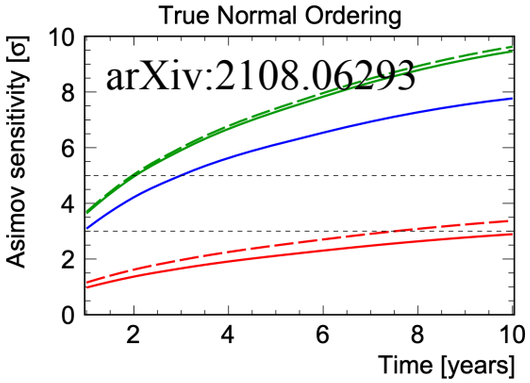


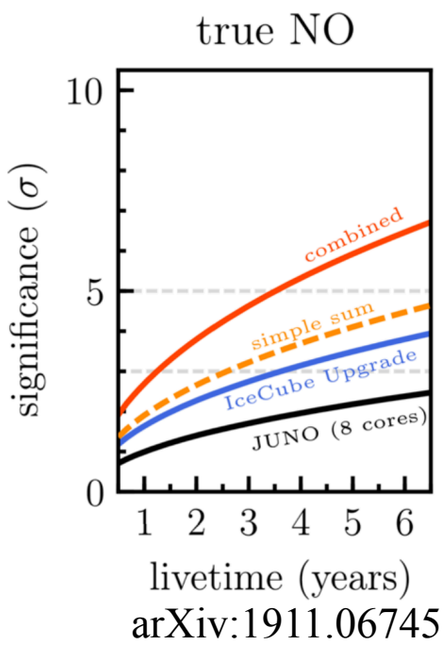
More data

- Prospects in the next years:
  - More detectors: SuperK-Gd, IC-Upgrade (deploy in 25/26), and KM3NeT-ORCA115
  - Combination with JUNO enhances NMO sensitivity (synergy in Δm^2_{31})









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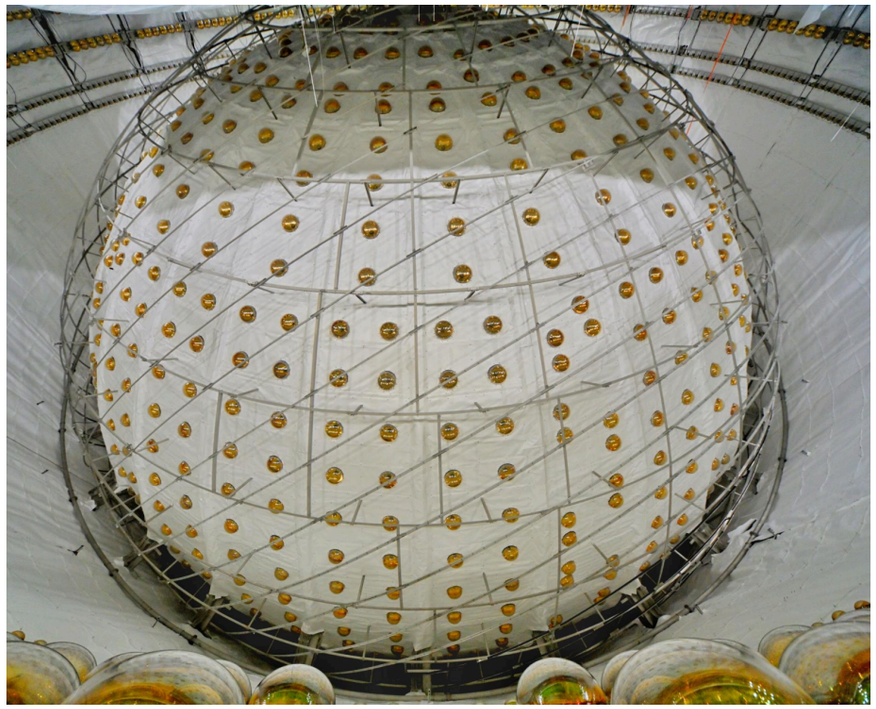

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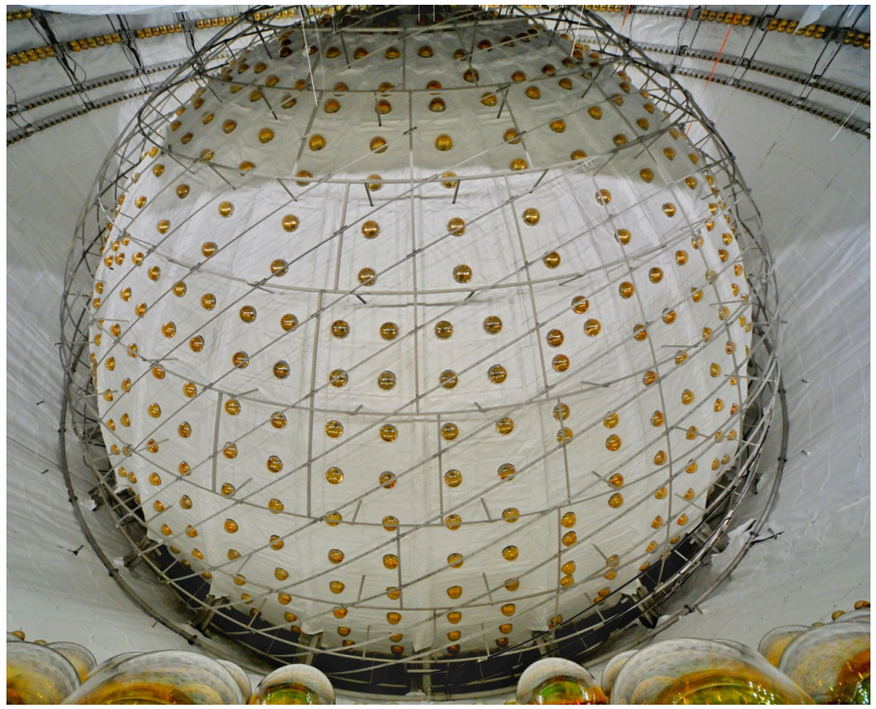

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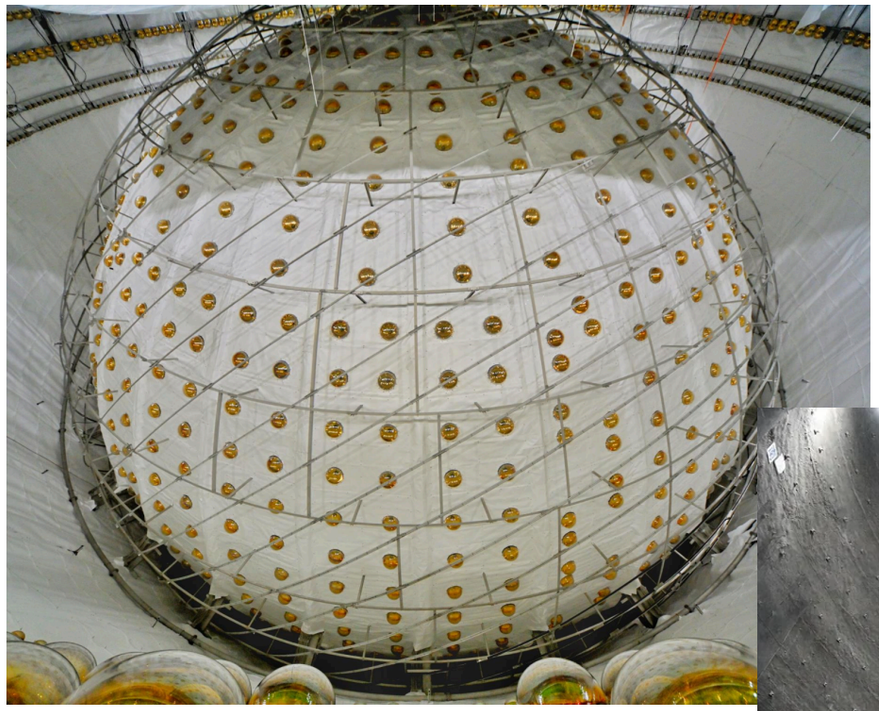
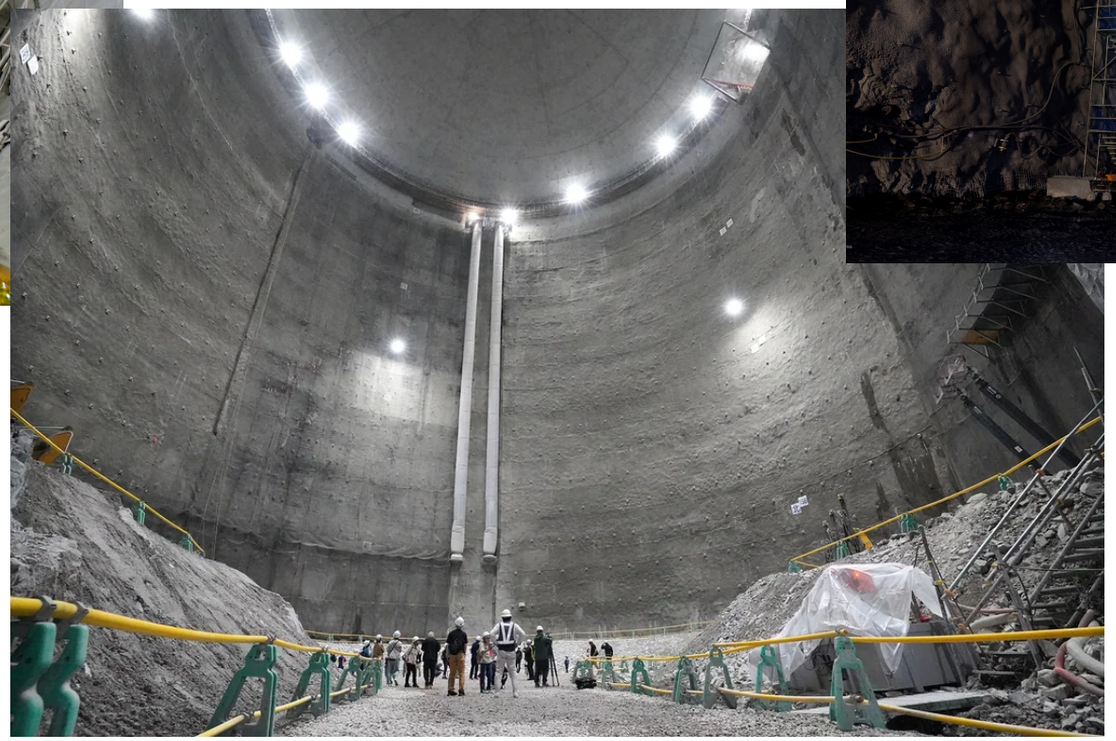
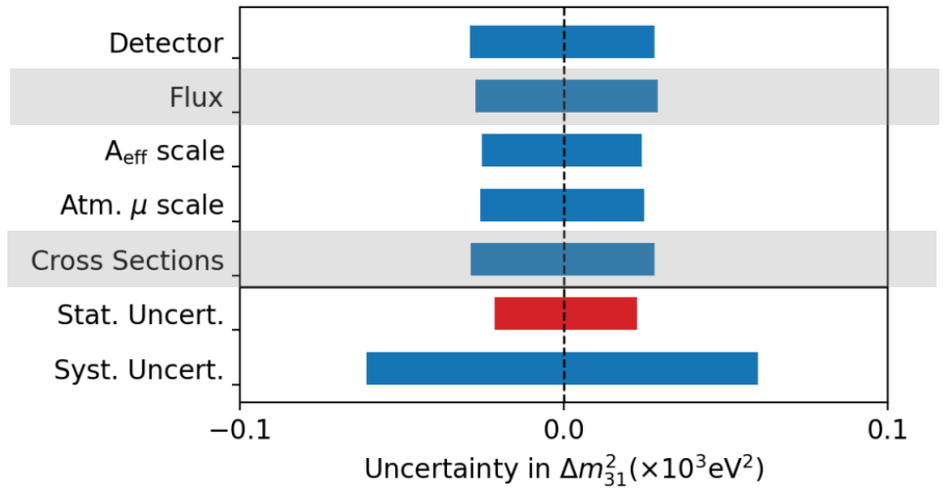
  - Hyper-K: Water Cherenkov tank (cavern completed, data end 2027)



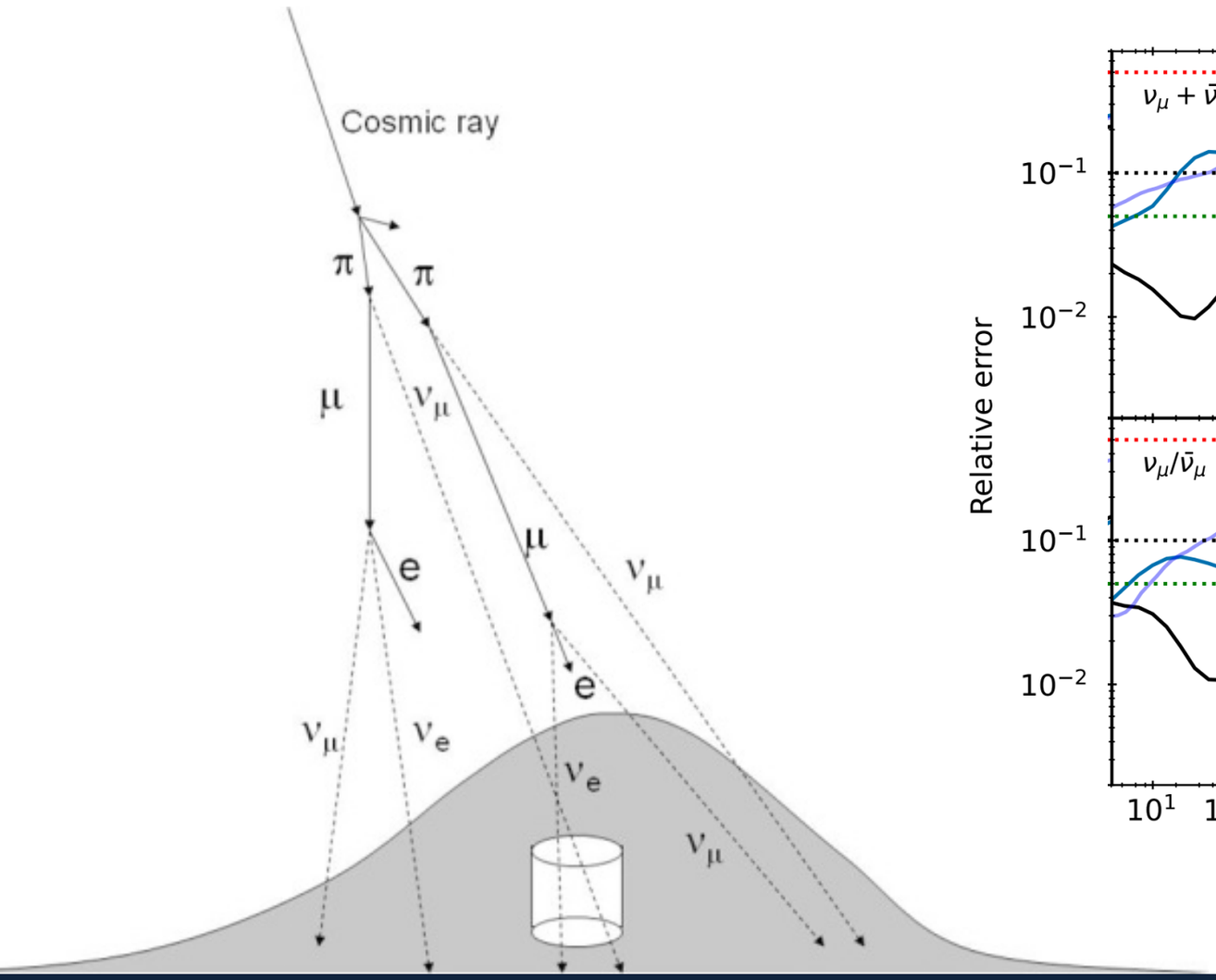


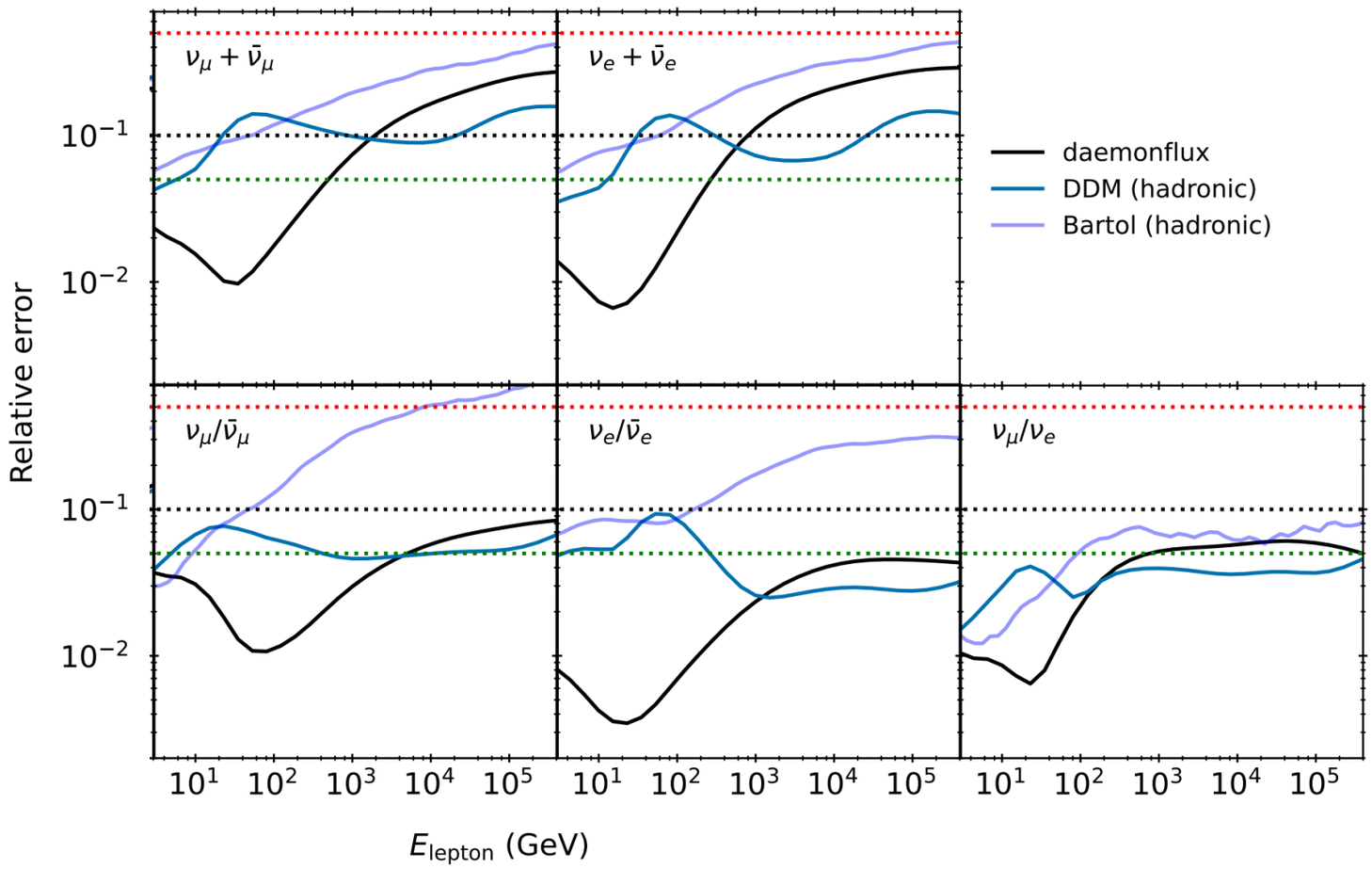
New ideas

- Dominant systematics in oscillation analysis:



- An idea to constrain the flux systematic:





New ideas

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  - Inject a small amount of gas few hundreds meters away from ATLAS/CMS

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arXiv:2510.11816

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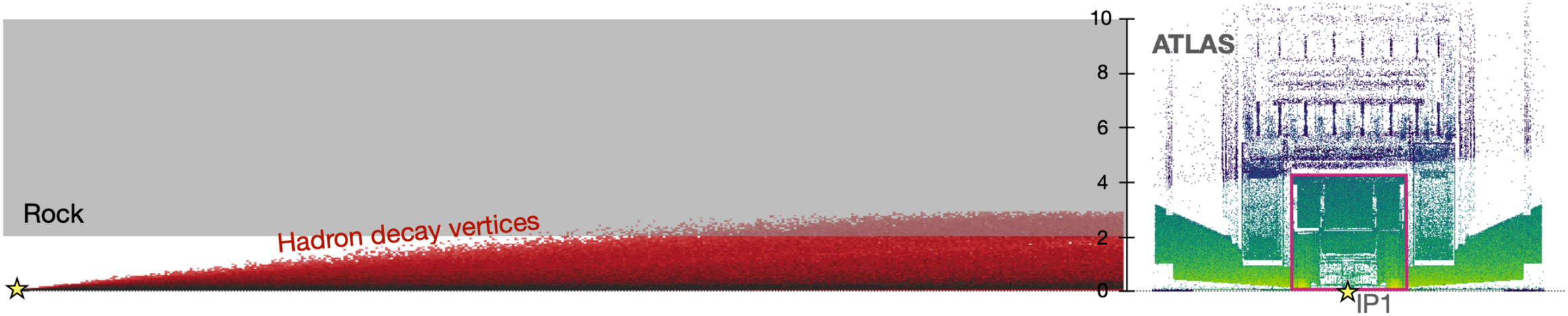

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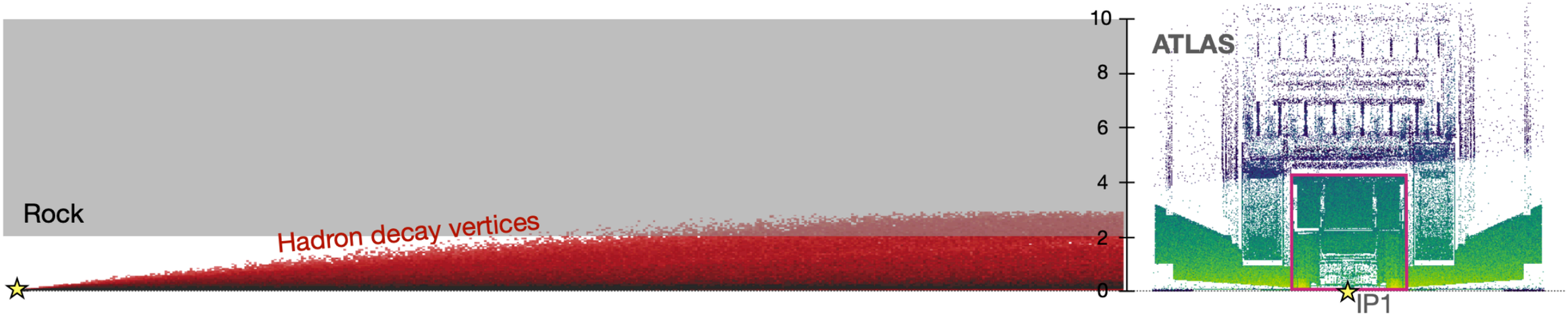
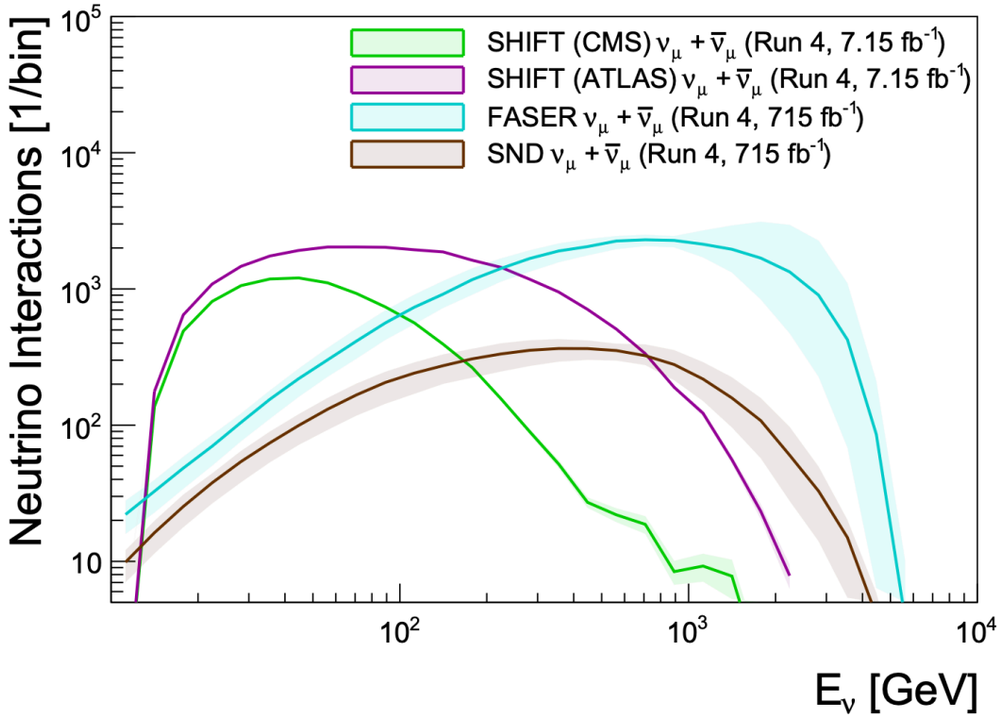


  - Sizable amount of neutrino interactions in the calorimeters
  - Energy regime relevant for atmospheric neutrinos



Conclusions

- Atmospheric neutrinos very valuable to understand neutrino properties
  - Competitive measurements of standard neutrino oscillations.
  - World-leading constraints on BSM scenarios.

- Samples with large statistics -> systematics are primary challenge
  - Rich program to improve the modeling of atmospheric neutrino fluxes.
  - Detector and cross section uncertainties are also being targeted.

- New technologies are coming online!