Combined sensitivity of JUNO and KM3NeT/ORCA to the neutrino mass ordering

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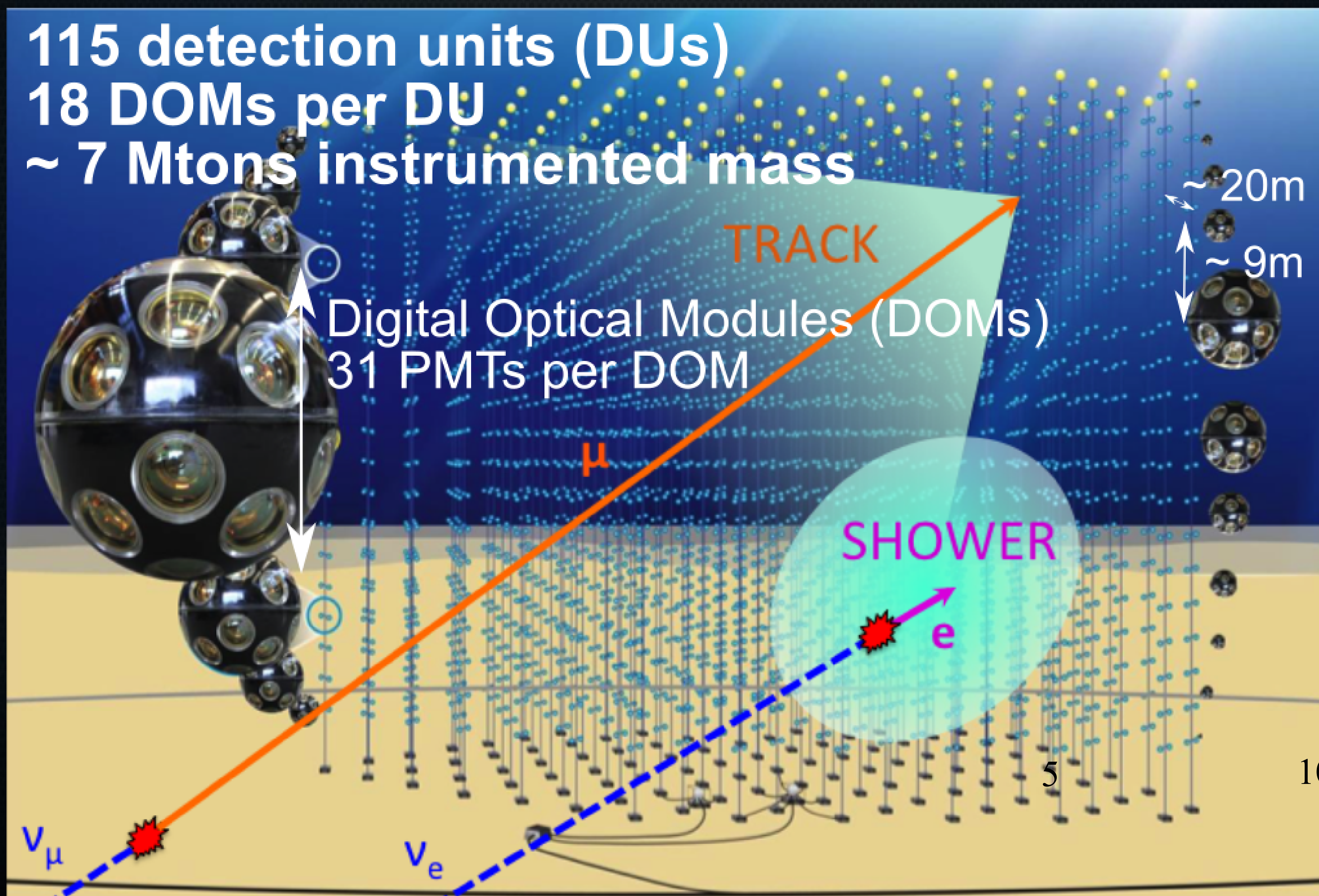
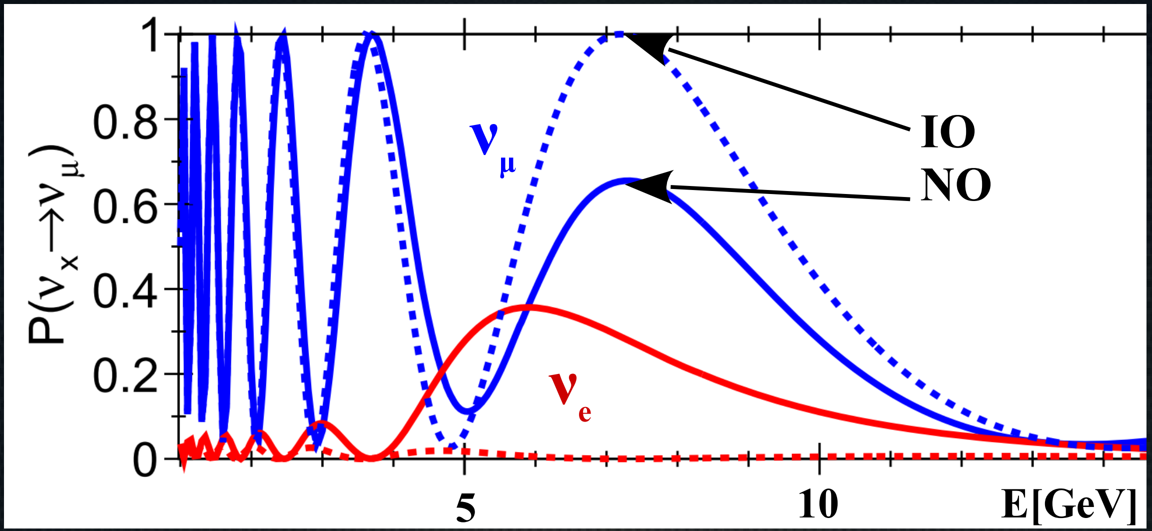
The KM3NeT/ORCA detector

- ORCA: Oscillation Research with Cosmic in the Abyss
- Optimized for atmospheric neutrino measurement above 1 GeV.
- 10 DUs deployed and in operation.



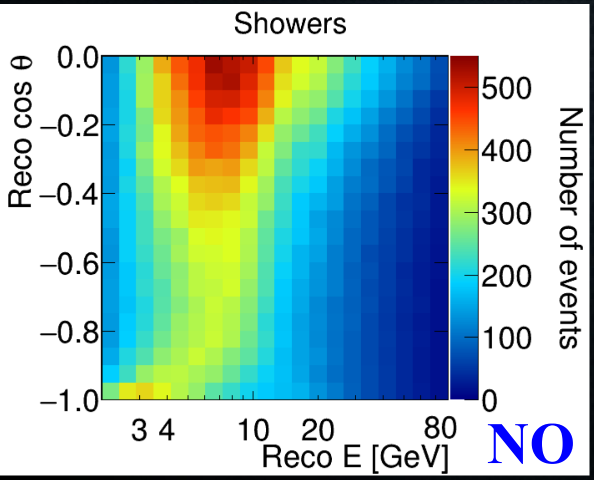
The KM3NeT/ORCA detector

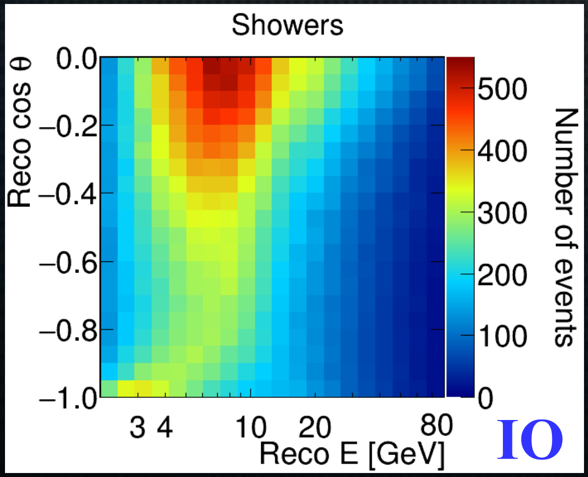
- Neutrino Mass Ordering (NMO) determination thanks to matter effect.
- Relevant oscillation parameters: θ_{23} , Δm^2_{31} , θ_{13} , δ_{CP}.



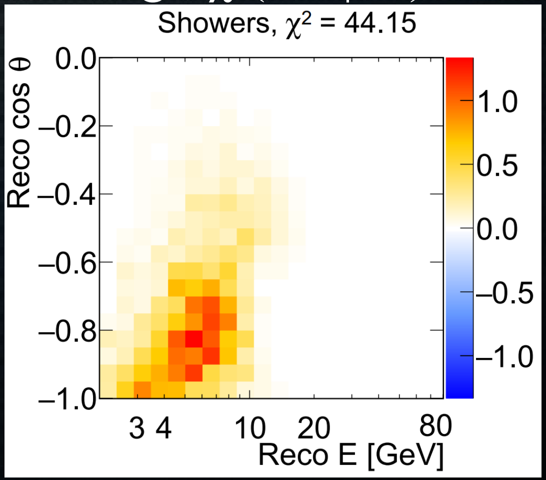
Event distributions in ORCA:

Event distribution – 6 years



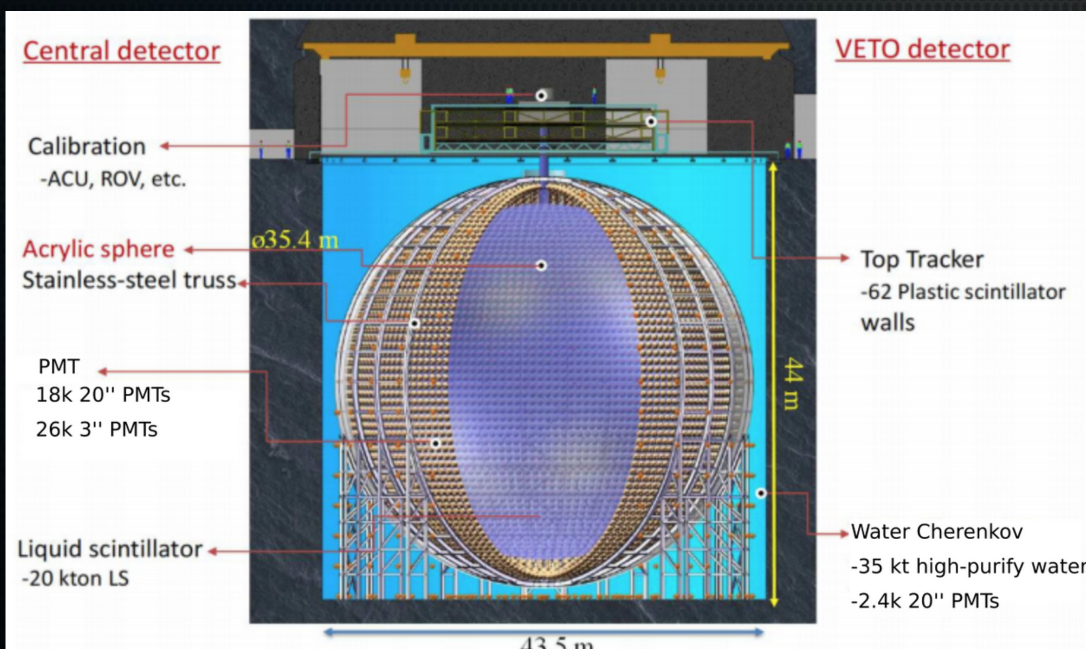


Sign χ^2(NO|IO)



JUNO

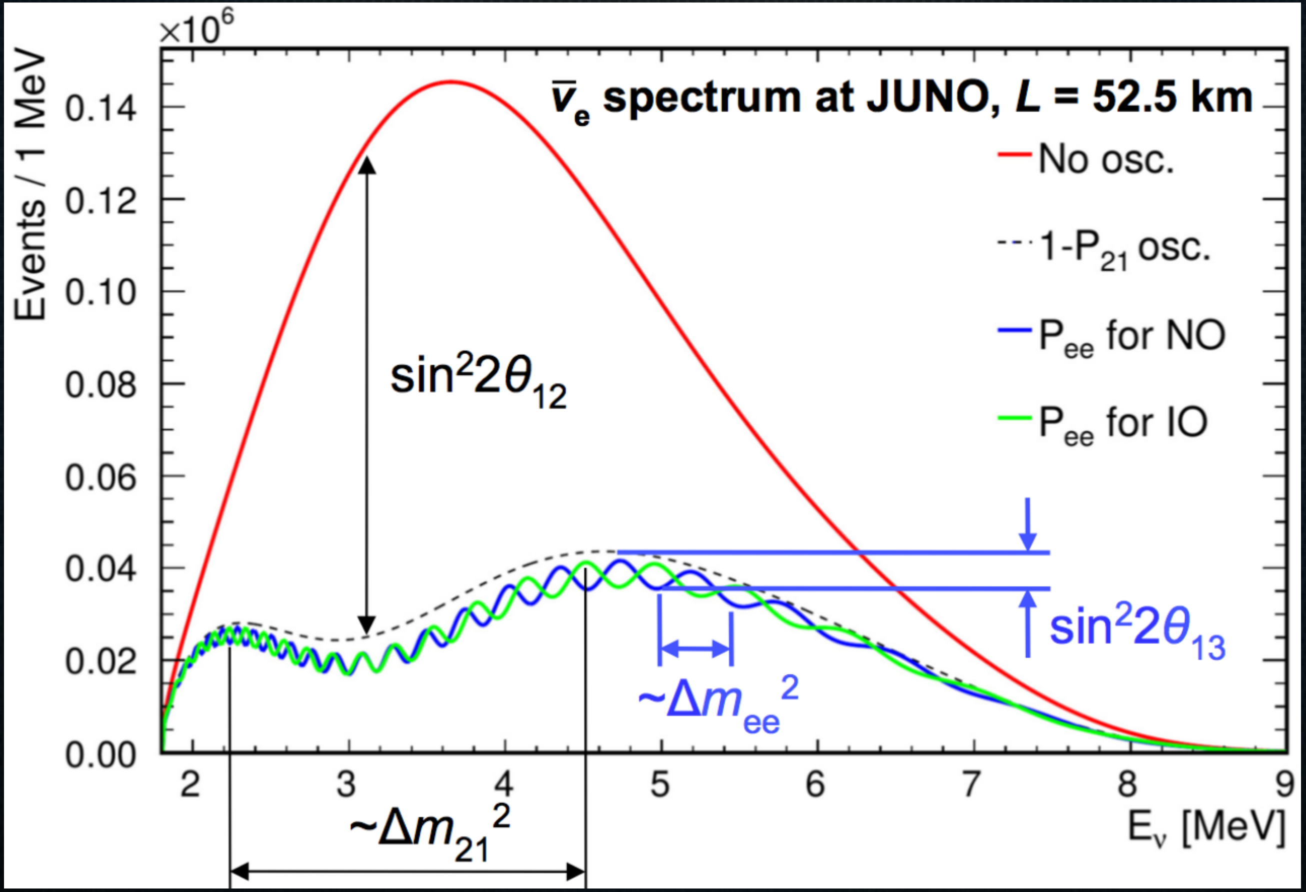
- JUNO: The Jiangmen Underground Neutrino Observatory.
- Reactor neutrinos at medium baseline (~53 km).
- The Yangjiang NPP is already fully operational with 6 reactors and Taishan NPP has already 2 reactors in operation.



JUNO

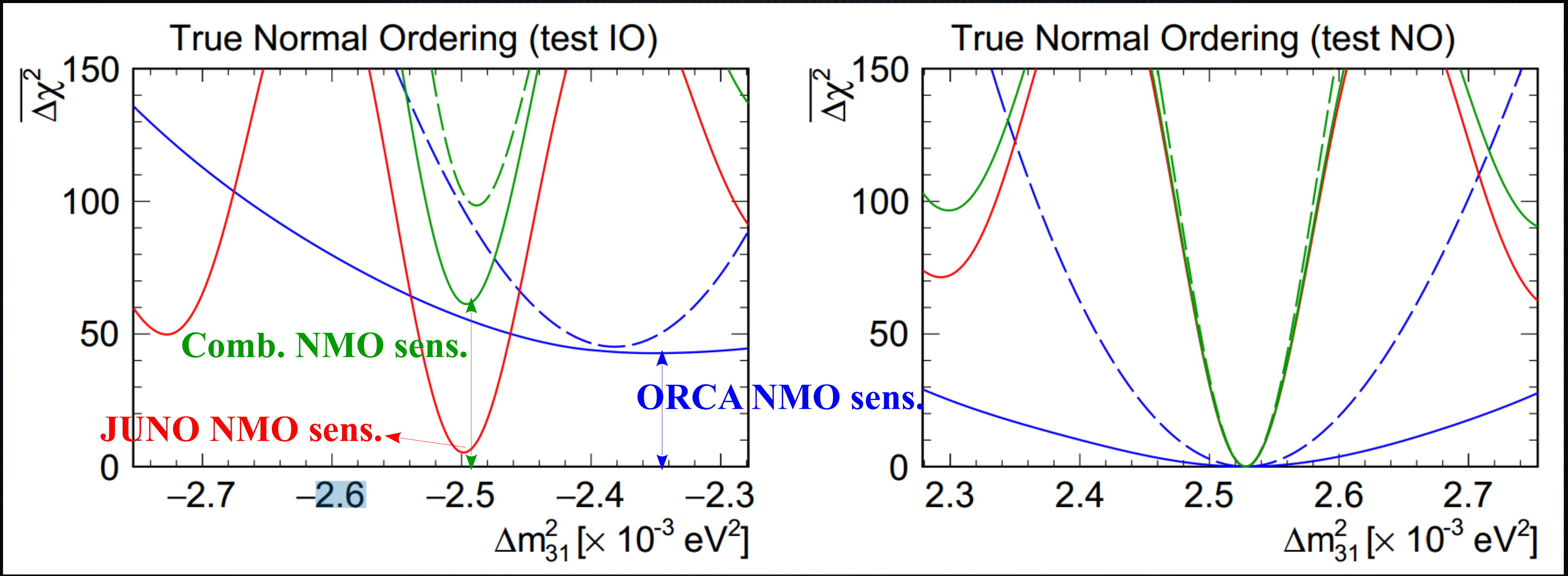
- NMO determination thanks to the interplay between fast oscillations driven by Δm^2_{31} and Δm^2_{32}

  Require very good energy resolution $(3\%/\sqrt{E/\text{MeV}})$
  Relevant oscillation parameters θ_{12}, Δm^2_{21}, θ_{13}, Δm^2_{31}



JUNO and ORCA Combination

- A combination of reactor (JUNO) and atmospheric experiments (ORCA) could yield a boost in NMO sensitivity when assuming wrong ordering:



- Collaborative work between APC (ORCA) and IPHC (JUNO) → recently submitted paper[1]

[1] arXiv:2108.06293 - Combined sensitivity of JUNO and KM3NeT/ORCA to the neutrino mass ordering

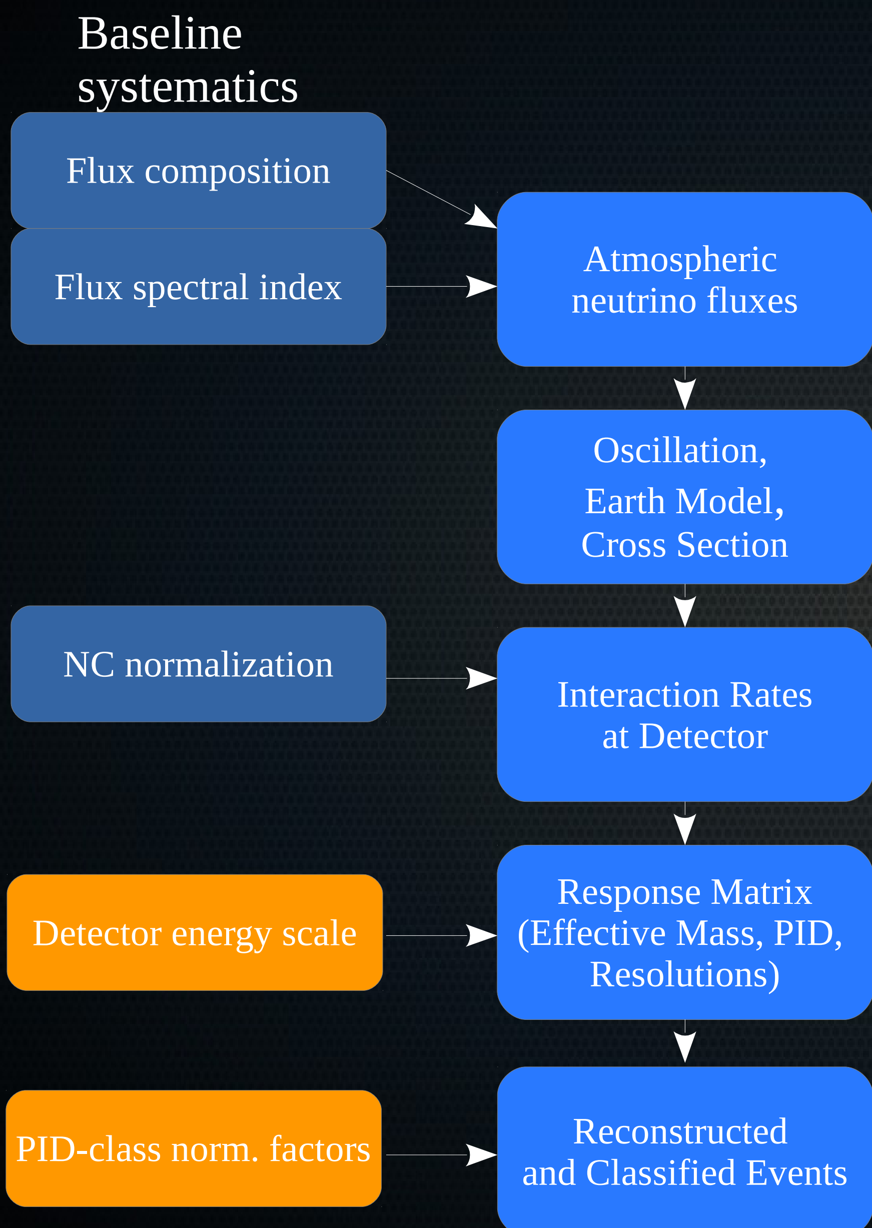
Combination Strategy

- χ^2 minimization of Asimov dataset.
- True parameter from global fit NuFIT4.1.
- Combination on Δm^2_{31} and θ_{13} using a scanned grid:

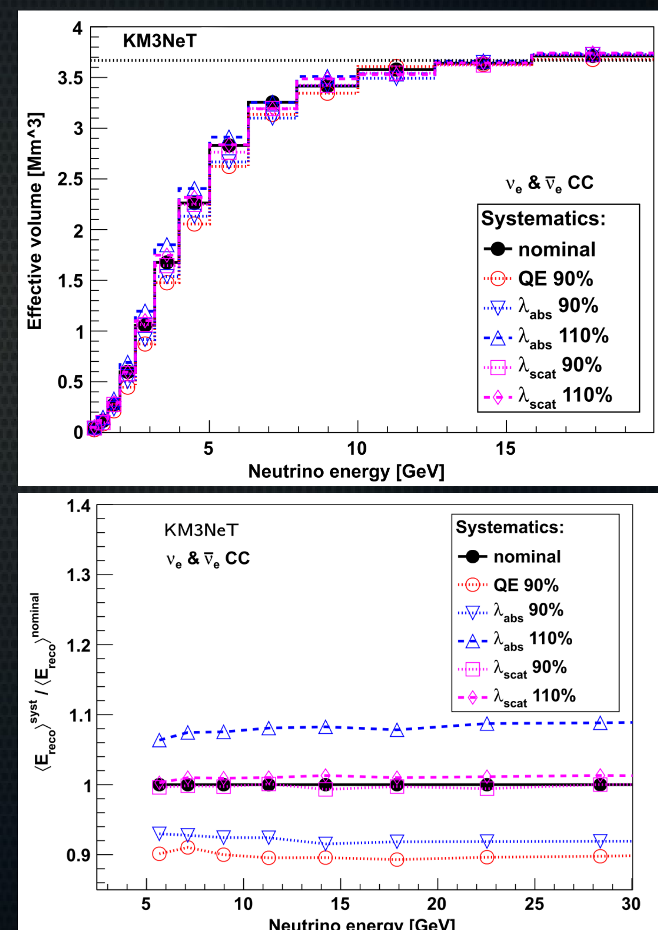
$$\chi^2(\Delta m^2_{31}, \theta_{13}) = \chi^2_{\text{JUNO}}(\Delta m^2_{31}, \theta_{13}) + \chi^2_{\text{ORCA}}(\Delta m^2_{31}, \theta_{13}) + \underbrace{\frac{(\sin^2\theta_{13} - \sin^2\theta_{13}^{GF})^2}{\sigma^2_{\sin^2\theta_{13}^{GF}}}}_{\text{Constrains from current global fit}}$$

Osc. parameter	JUNO	ORCA
θ_{13}	grid scan	
Δm^2_{31}	grid scan	
θ_{23}	x	fitted
Δm^2_{21}	fitted	*fixed*
θ_{12}	*fixed*	*fixed*
δ_{CP}	x	fitted

Systematics for ORCA



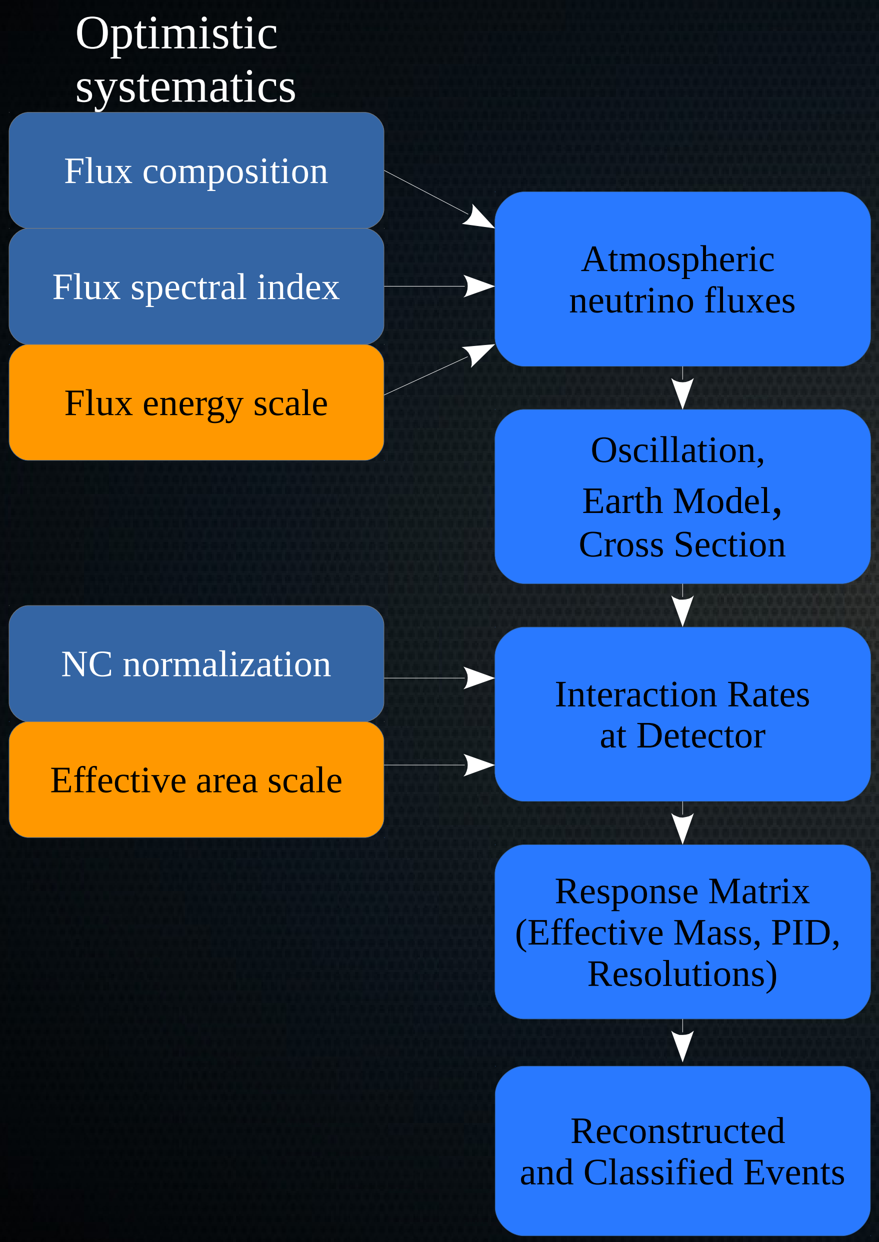
- Baseline approach:
  with detector energy scale systematics to capture the uncertainty of light collection efficiency to the detector response.



*Figures from Ref[4]

[4] J.Phys.G 43 (2016) 8, 084001 - Letter of intent for KM3NeT 2.0

Systematics for ORCA

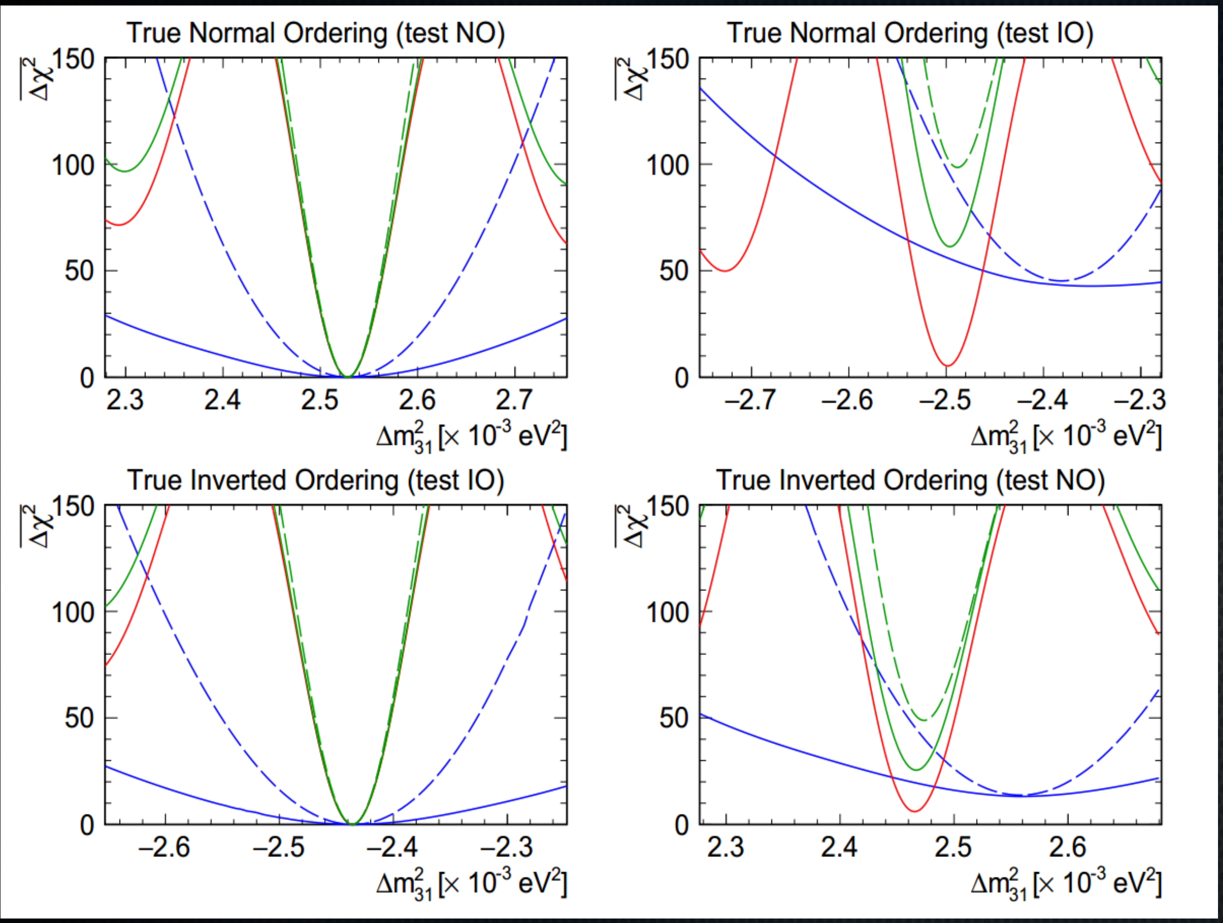


- **Optimistic approach:** with similar set of systematics as in the previous work of JUNO/PINGU/IceCube Upgrade combination [3]

[3] 10.1103/PhysRevD.101.032006 - Combined sensitivity to the neutrino mass ordering with JUNO, the IceCube Upgrade, and PINGU

Synergy effect – 6 years of data taking

ORCA (blue), JUNO (red), Combination (green)



- 2 systematic approaches for ORCA:

  Dashed – Optimistic systematics

  Solid – Baseline systematics

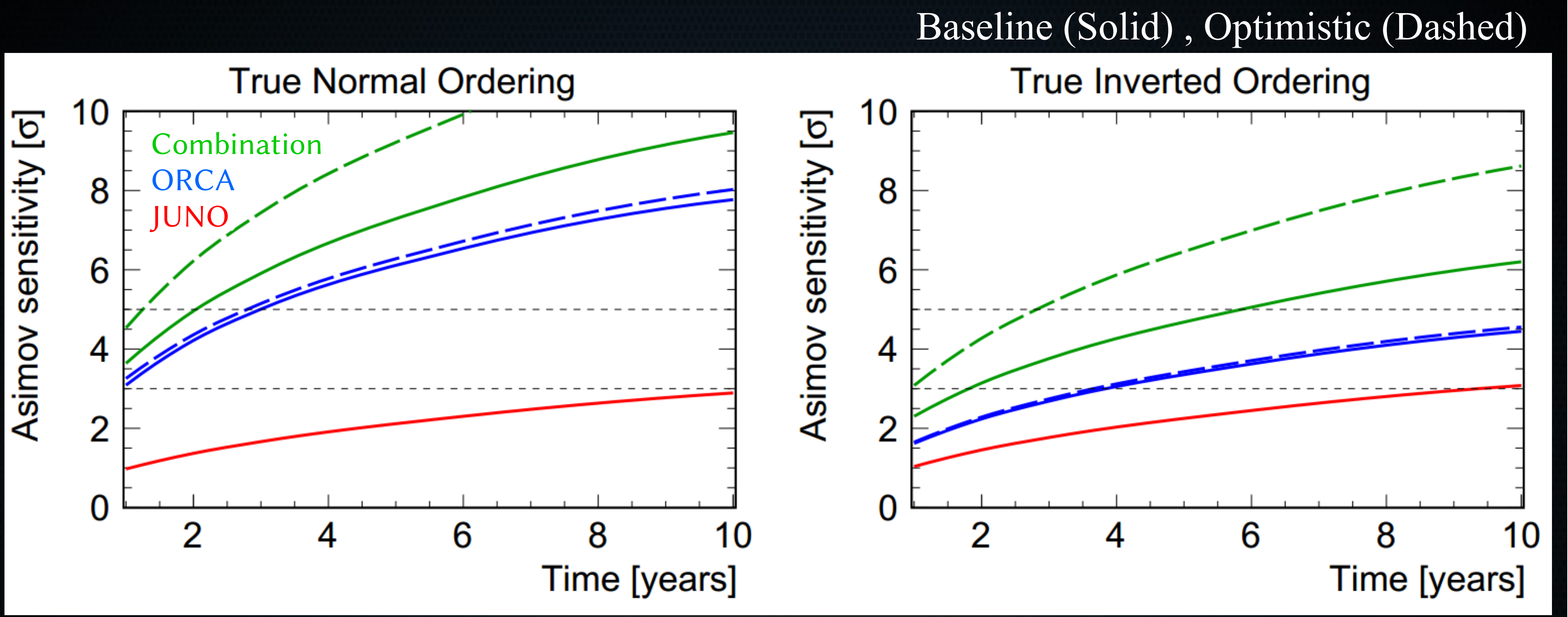
- Detector energy scale systematics leading to worse precision on Δm^2_{31}.

  → Decrease the combination

- More than 5σ for both ordering even with Baseline systematics.

True NMO	JUNO (8 reactor cores)	ORCA	Simple sum	Combination
NO	2.3 σ ($\Delta\chi^2$=5.3)	6.5 σ ($\Delta\chi^2$=42.3)	6.8 σ ($\Delta\chi^2$=47.6)	7.8 σ ($\Delta\chi^2$=60.8)
IO	2.4 σ ($\Delta\chi^2$=5.8)	3.6 σ ($\Delta\chi^2$=13.0)	4.3 σ ($\Delta\chi^2$=18.8)	5.1 σ ($\Delta\chi^2$=26.0)

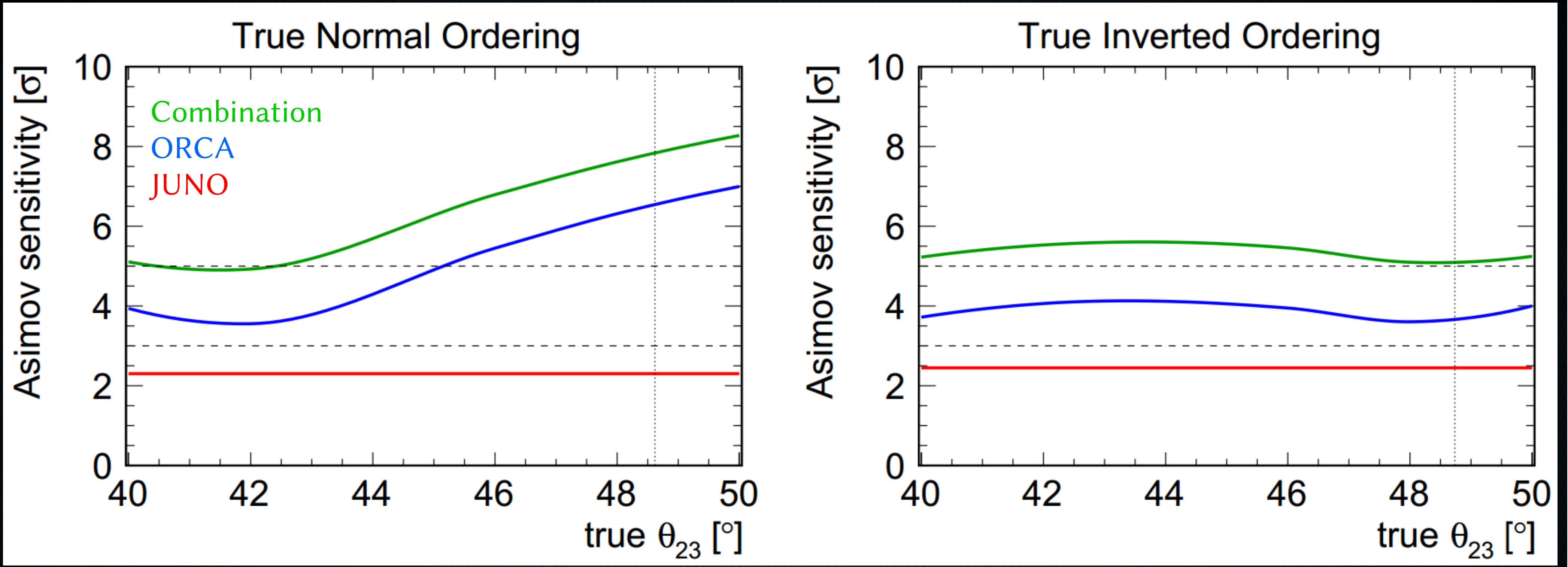
Livetime evolution of the sensitivity



With the combined analysis

- Time required for 5σ is reduced by at least one year compared to ORCA alone.
- 5σ significance within 2/6 years in case of true NO/IO respectively.

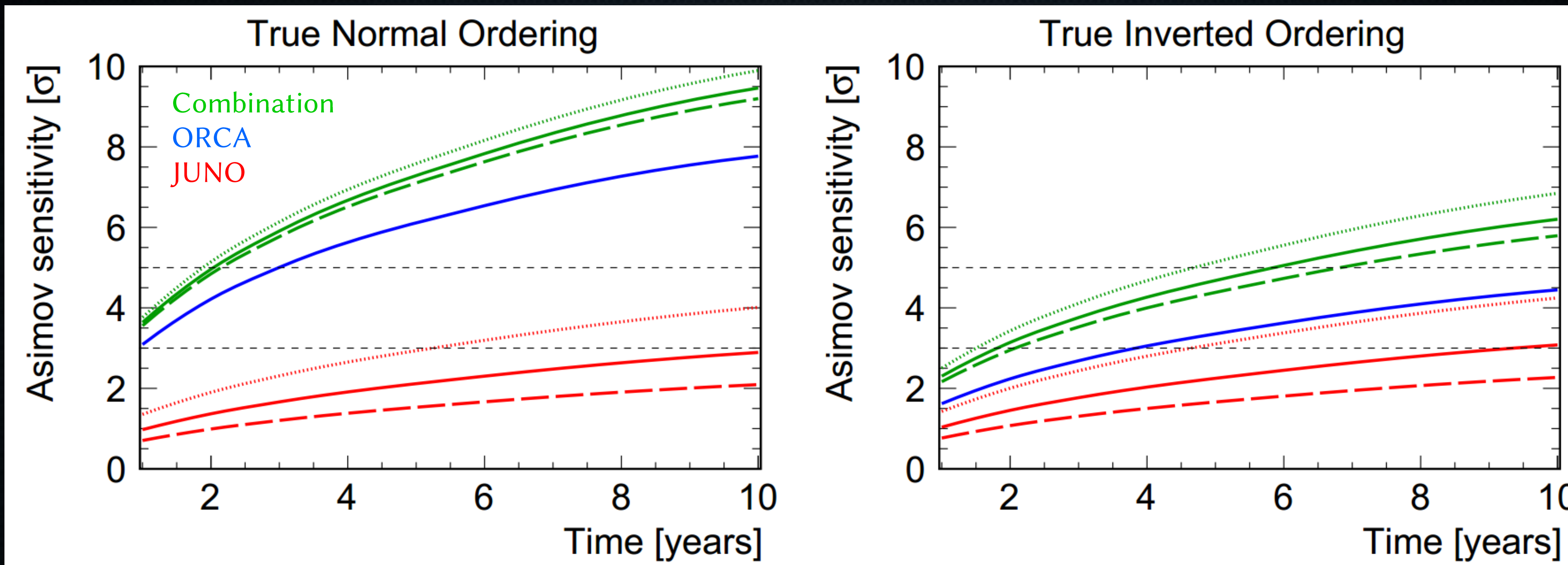
θ_{23} dependence, 6 years of data taking



- θ_{23} dependence driven by ORCA sensitivity
- The combination ensures 5σ after 6 years regardless of the true value of θ_{23} and the true NMO

Energy resolution in JUNO

Nominal: $3.0\%/\sqrt{E/\mathrm{MeV}}$(solid) $2.5\%/\sqrt{E/\mathrm{MeV}}$(dotted) $3.5\%/\sqrt{E/\mathrm{MeV}}$(dashed)



Small impact of JUNO energy resolution on the combined analysis.

The boost relies on the tension of Δm^2_{31} rather than NMO sensitivity of each experiment.

Conclusions

- The tension in the best fit values of Δm^2_{31} boosts the NMO sensitivity in a joint fit between JUNO and KM3NeT/ORCA.

- 5σ can be reached after 6 years of combination of JUNO and ORCA regardless of the NMO and octant scenarios.

- Detector energy scale is an important systematic for neutrino telescopes, with potentially large effects on the combined sensitivity.

Back up

JUNO systematics

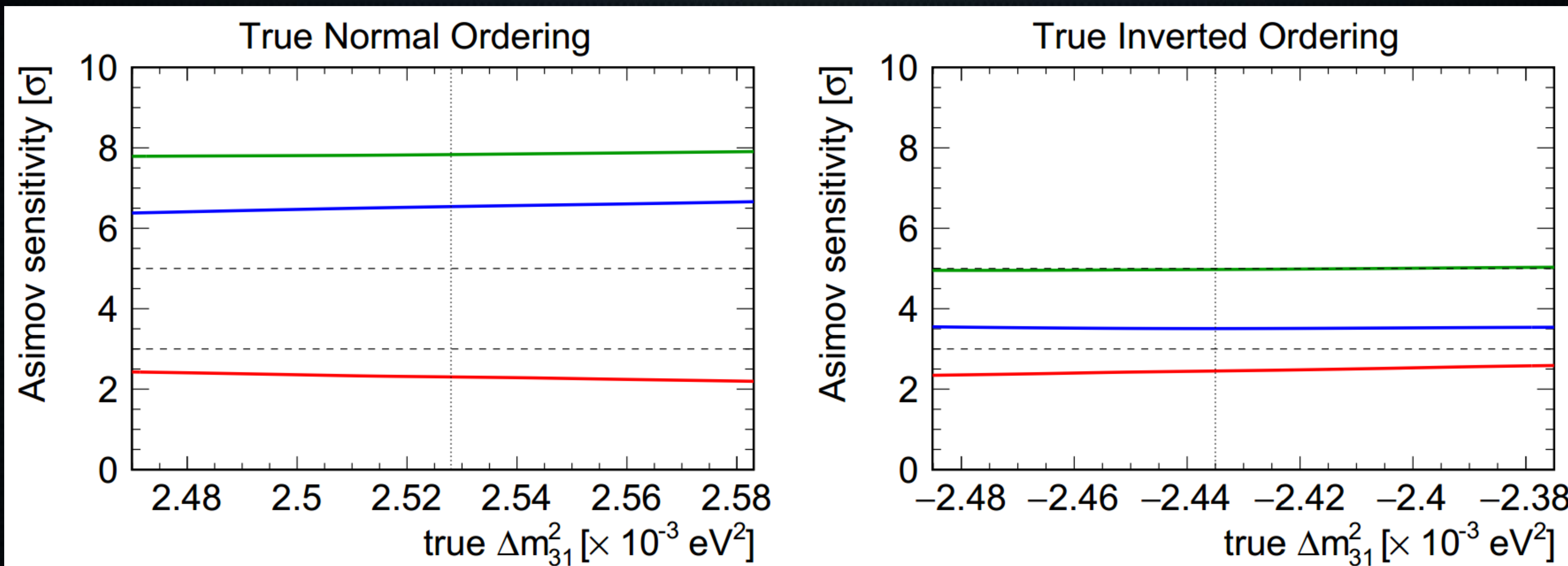
Parameter	Uncertainty
Correlated reactor error	2.0%
Uncorrelated reactor error	0.8%
Reactor spectrum	1.0%
Detector response	1.0%

Background	Rate (/day)	Uncertainty on rate	Uncertainty on shape
Cosmogenic	1.6	20%	10%
Geo-neutrino	1.1	30%	5%
Accidental	0.9	1%	0%
Fast neutrons	0.1	100%	20%
$^{13}C(\alpha, n)^{16}O$	0.05	50%	50%

ORCA Systematics

Parameter	Baseline scenario	Optimistic scenario
PID-class norm. factors	free	×
Effective area scale	×	10% prior
Detector energy scale	5% prior	×
Flux energy scale	×	10% prior
Flux $\nu_e/\bar{\nu}_e$ skew	7% prior	
Flux $\nu_\mu/\bar{\nu}_\mu$ skew	5% prior	
Flux $\nu_e/\bar{\nu}_\mu$ skew	2% prior	
Flux spectral index	free	
NC normalization	10% prior	

• Δm^2_{31} dependence, 6 years data taking



10-core scenario in JUNO

JUNO 8 cores (solid), JUNO 10 cores (dashed)