JUNO's Sensitivity to the Neutrino Mass Ordering

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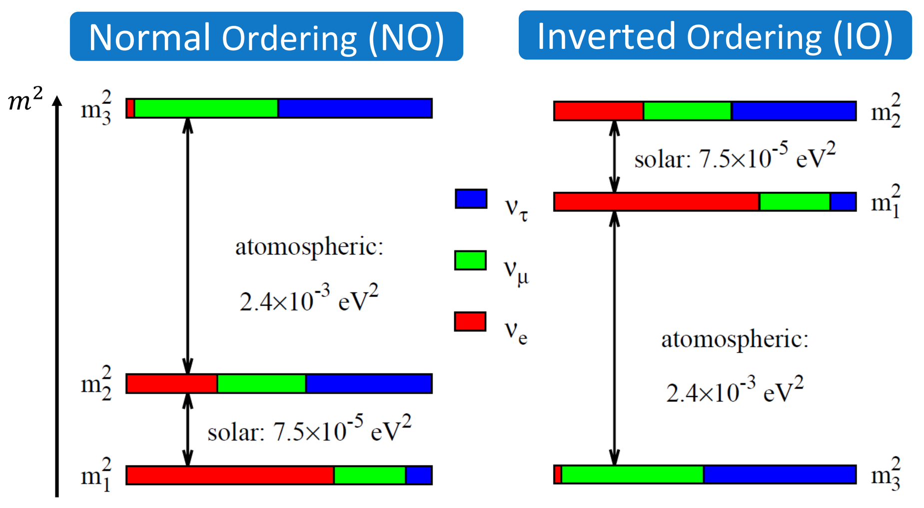
Physics Motivation

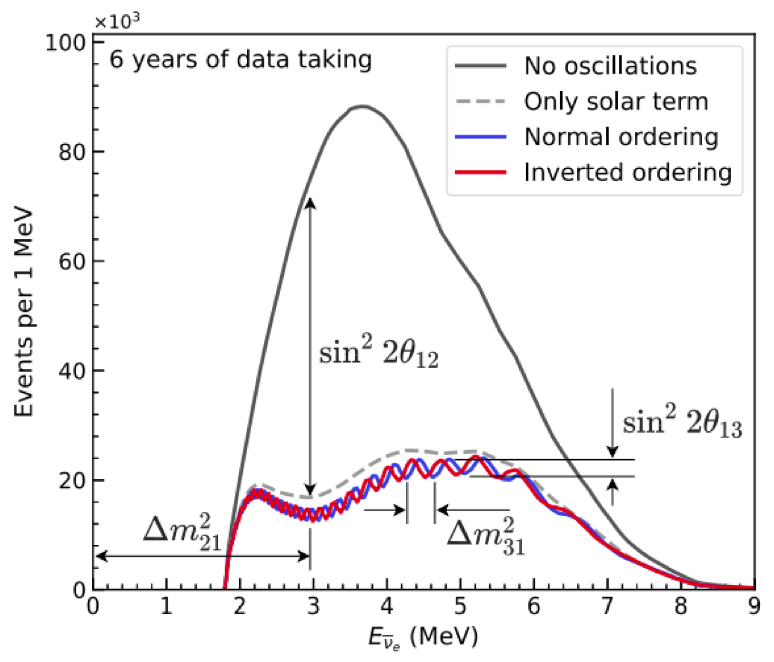
- Neutrino flavour states (e, μ, τ) can be described as a superposition of definite neutrino mass states (1, 2, 3)
- The mass values m_i of the three neutrino mass states are still unknown, however it is possible to measure the mass-squared differences $\Delta m_{ij}^2 = m_i^2 - m_j^2$
- While the sign of Δm_{12}^2 is known, it is not known whether m_3 is the heaviest or lightest state, so the sign of Δm_{31}^2 is also unknown. This leads to two possible mass orderings – "normal" (NO) and "inverted" (IO) ordering



- JUNO is designed to distinguish between both neutrino mass orderings
- The survival probability $P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$ is dependent on the mass ordering:

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{12} \cos^4\theta_{13} \sin^2 \frac{\Delta m_{21}^2 L}{4E} - \sin^2 2\theta_{13}\left[\sin^2\theta_{12}\sin^2\frac{\Delta m_{32}^2 L}{4E} + \cos^2\theta_{12}\sin^2\frac{\Delta m_{31}^2 L}{4E}\right]$$

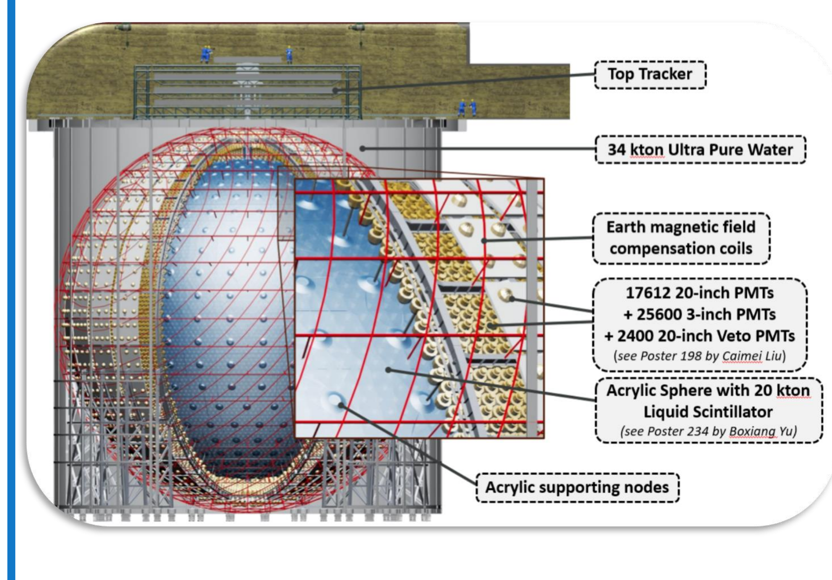
with $|\Delta m_{31}^2| > |\Delta m_{32}^2|$ for NO, $|\Delta m_{31}^2| < |\Delta m_{32}^2|$ for IO



Detector Design

Jiangmen Underground Neutrino Observatory

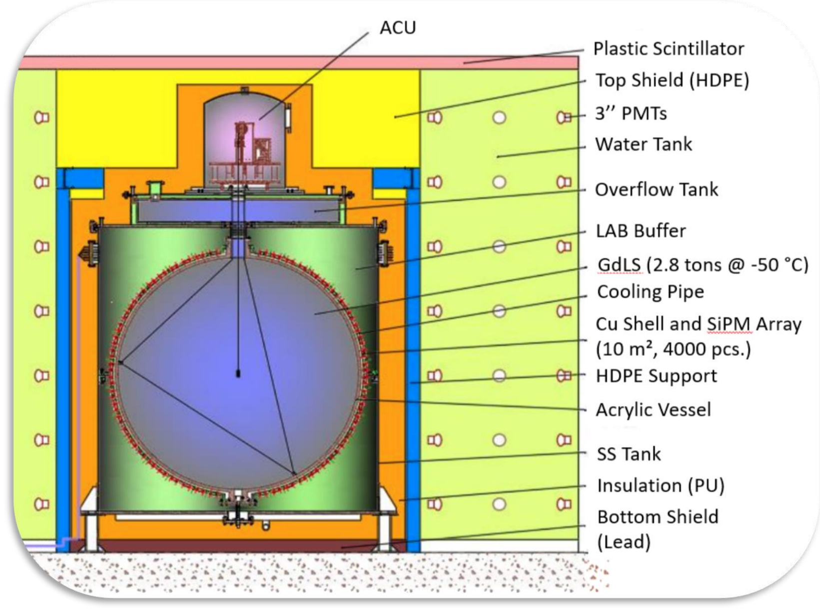
Located in the southeast of China at a distance of 53 km from the Taishan and Yangjiang nuclear power plants with a total of 8 reactor cores and a combined thermal power of 26.6 GW



See also JUNO COLLABORATION, et al. JUNO physics and detector. *Progress in Particle and Nuclear Physics*, 2022, 123. Jg., S. 103927.

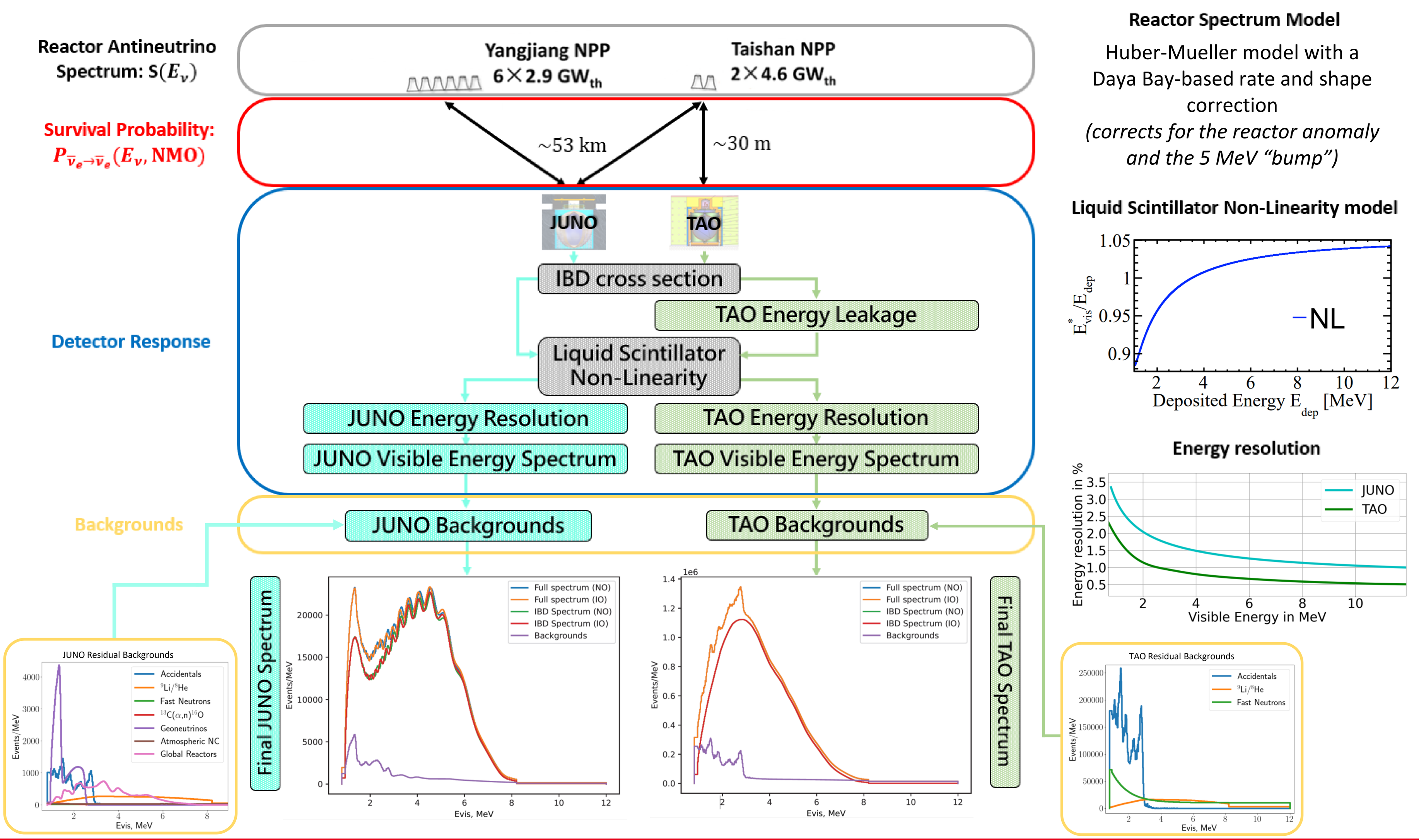
Taishan Antineutrino Observatory

As JUNO's satellite detector it is designed to provide a reference measurement of the unoscillated reactor antineutrino spectrum at a distance of 30 m and 225 m resp. from the Taishan reactor cores



See also ABUSLEME, Angel, et al. TAO conceptual design report: a precision measurement of the reactor antineutrino spectrum with sub-percent energy resolution. *arXiv preprint arXiv:2005.08745*, 2020

IBD Spectrum Prediction



Analysis Method

The analysis was done by three independent analysis groups. Exemplarily, one analysis method is described in the following:

- For each neutrino mass ordering (NMO) an Asimov dataset x of the expected measured spectrum is generated
- The χ^2 function, which is being minimized, is defined as

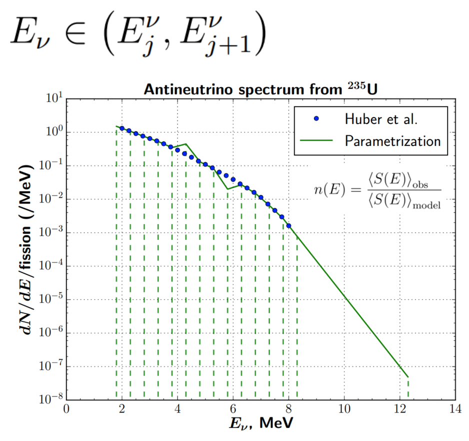
$$\chi^2 = [\boldsymbol{x} - \boldsymbol{\mu}(\boldsymbol{\theta}, \boldsymbol{\eta})]^T V^{-1} [\boldsymbol{x} - \boldsymbol{\mu}(\boldsymbol{\theta}, \boldsymbol{\eta})] + (\boldsymbol{\eta} - \boldsymbol{\eta}^0)^T V_\eta^{-1} (\boldsymbol{\eta} - \boldsymbol{\eta}^0)$$

where V is the covariance matrix (containing statistical errors and bin-to-bin uncertainties) and $\mu(\theta, \eta)$ the fit model for the expected signal with the three free oscillation parameters θ (Δm_{31}^2, Δm_{21}^2, $\sin^2 2\theta_{12}$) and 73 constrained nuisance parameters η

- The reactor antineutrino spectrum for the isotope i is parametrized as a piecewise exponential in every energy segment j:

$$S_{ij}\left(E^\nu\right) = n_j k_{ij} e^{-b_{ij}\left(E^\nu - E_j^\nu\right)} \quad \text{with} \quad E_\nu \in \left(E_j^\nu, E_{j+1}^\nu\right)$$

  - k_{ij} are defined by the antineutrino yield of the input model
  - b_{ij} are chosen that the whole function is continuous
  - n_j are the weights for all energy segments j that describe the deviation of the observed spectrum from the input model (*149 segments in this analysis*)



Example definition of the weights for 15 segments

- The spectral weights n_j are added as free parameters to the χ^2 function and therefore estimated by the fit
- Since the parametrization appears in the JUNO and TAO model as they observe the same individual isotope spectra emitted by the reactors, possible deviations of the observed spectrum from the input spectrum model are corrected
- The median sensitivity to determine the NMO is given by the difference between the two minimum χ^2 values for IO and NO hypothesis fit to the Asimov dataset x with specific NMO

$$|\Delta\chi^2_{\min}| = |\chi^2_{\min}(\text{IO}) - \chi^2_{\min}(\text{NO})|$$

IBD Event Selection and Background

Selection Criteria

Type	Value
Prompt Energy	$E_p \in [0.7, 12.0]$ MeV
Delayed Energy	$E_d \in [1.9, 2.5]$ MeV ∪ [4.4, 5.5] MeV
Fiducial Volume	$R < 17.2$ m
Time difference between prompt and delayed signal	$\Delta T_{p-d} < 1$ ms
Distance between prompt and delayed signal	$\Delta R_{p-d} < 1.5$ m

Selection Criterion	Efficiency (%)	IBD Rate (day^{-1})
All IBDs	100.0	57.4
Fiducial Volume	91.5	52.5
IBD Selection	98.1	51.5
Energy Range	99.8	-
Time Correlation (ΔT_{p-d})	99.0	-
Spatial Correlation (ΔR_{p-d})	99.2	-
Muon Veto (Temporal⊕Spatial)	91.6	47.1
Combined Selection	82.2	47.1

Residual Backgrounds

JUNO

Background	Rate (1/day)
Geoneutrinos	1.2
World Reactors (L > 300 km)	1.0
Accidentals	0.8
^{9}Li/ ^{8}He	0.8
Atmospheric neutrinos	0.16
Fast neutrons	0.1
^{13}C$(\alpha, n)^{16}$O	0.05

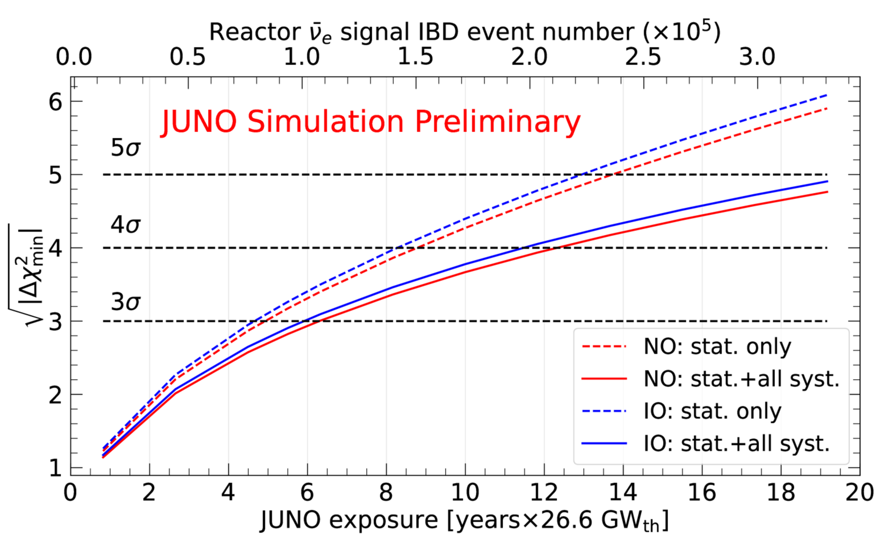
TAO

Background	Rate (1/day)
Accidentals	155
Fast neutrons	92
^{9}Li/ ^{8}He	54

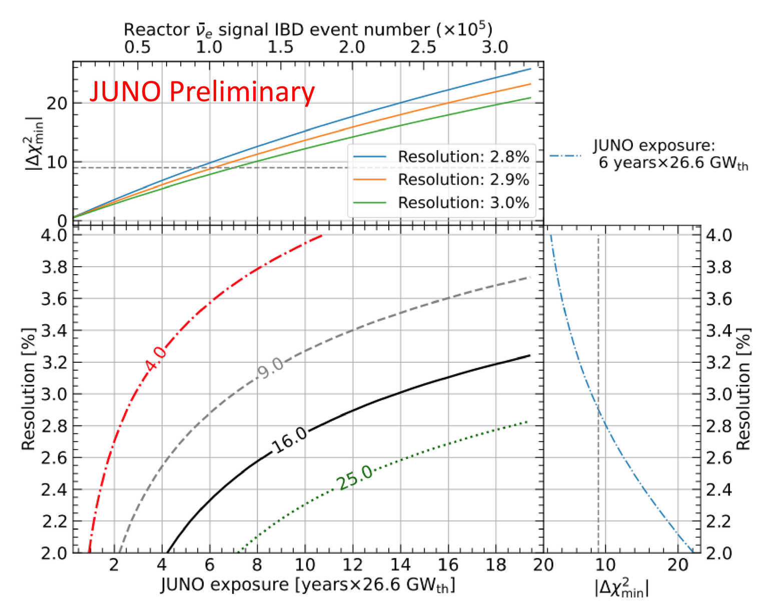
See also ABUSLEME, Angel, et al. Sub-percent precision measurement of neutrino oscillation parameters with JUNO. *Chinese Physics C*, 2022, 46. Jg., Nr. 12, S. 123001.

Results for Median NMO Sensitivity

Analysis by three independent groups:
Considering reactor $\bar{\nu}_e$ only, JUNO's median sensitivity to the NMO will be **3 sigma** for about 6 years x 26.6 GW$_{\text{th}}$ exposure and 2.9% @ 1 MeV energy resolution



NMO sensitivity as a function of the exposure for true NO and IO. The dashed line shows the expected sensitivity for statistics only and the solid line if all systematics are taken into account.



$|\Delta\chi^2_{\min}|$ *for true NO in dependence of energy resolution and exposure.*

Systematics Breakdown (for NO case)

Uncertainty	Statistics only	+ LS Non-Linearity	+ Backgrounds	+ Flux uncertainty	+ Other	Total
$\Delta\chi^2_{\min}$	11.3	10.9	9.7	9.1	9.0	9.0
$\Delta\chi^2_{\min}$ change (w.r.t. statistics only-case)	0	-0.4	-1.2	-0.6	-0.05	-2.3

Summary and Outlook

- Taking into account all systematics in a combined JUNO+TAO analysis, JUNO's median sensitivity to the NMO will be 3 sigma for about 6 years x 26.6 GW$_{\text{th}}$ exposure
- This result was obtained by three independent analysis groups. A collaboration paper on these results will be published soon

- Ongoing studies on atmospheric neutrino oscillation in JUNO (*see Poster 376 by Xinhai He*)
- Potential for boost of NMO sensitivity from joint measurement