Probing neutrino oscillations with reactor antineutrinos in JUNO

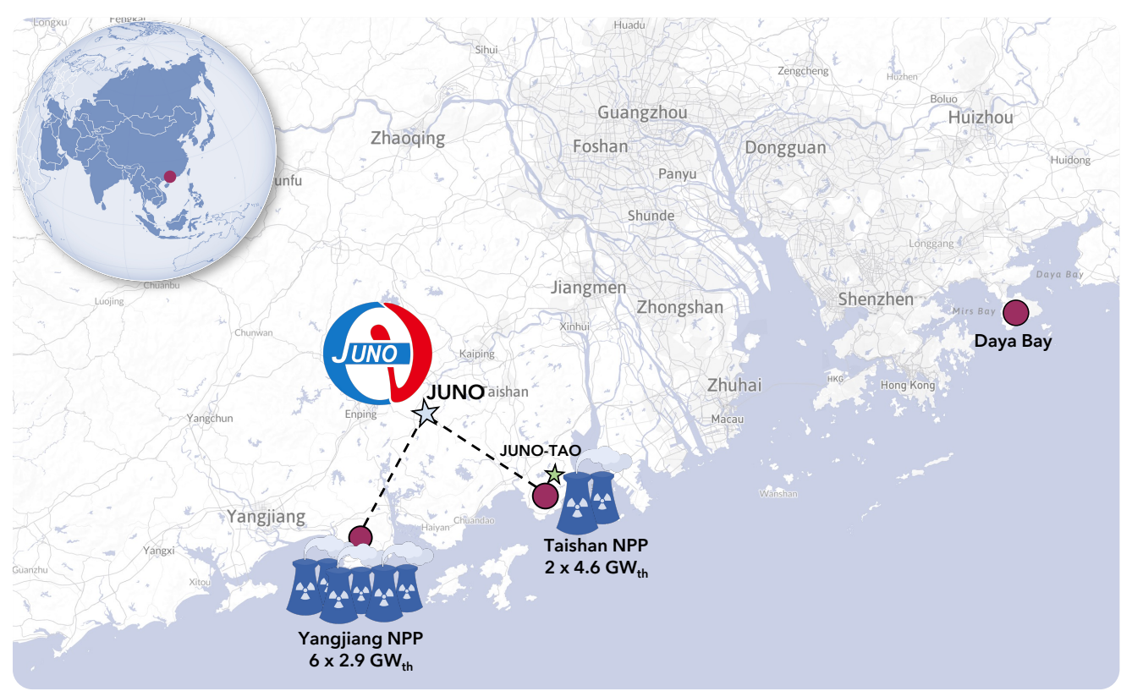
Vanessa Cerrone[1,2,a], on behalf of the JUNO collaboration
[1]University of Padova, Department of Physics G. Galilei, Italy , [2]INFN - Sezione di Padova, Italy
[a]vanessa.cerrone@pd.infn.it

Reactor antineutrinos in a nutshell

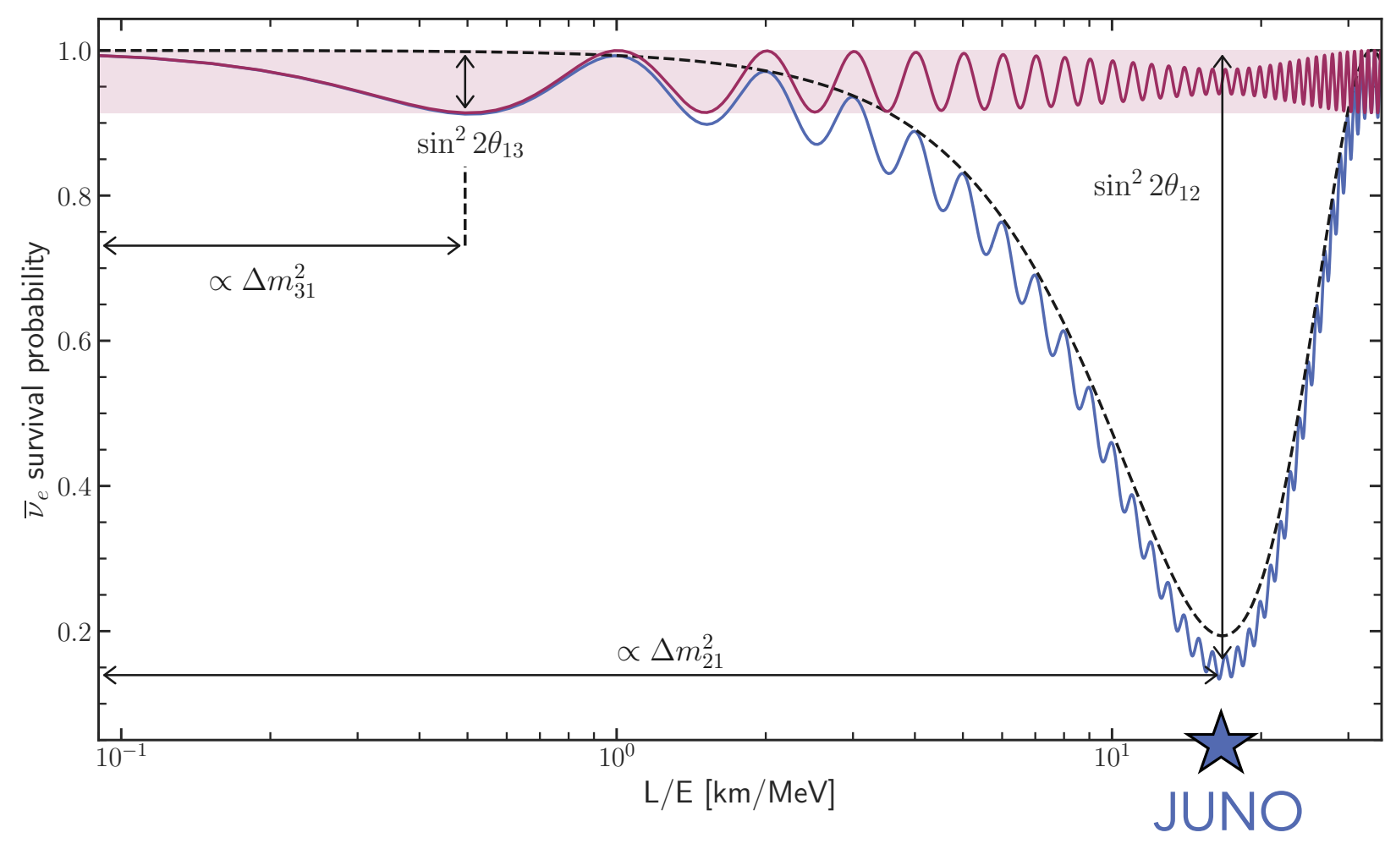
Why reactor antineutrinos?

- Pure and intense source of electron-flavor antineutrinos
- Energy: MeV scale rather than GeV (as in beams from accelerators)
- Synergetic efforts with accelerator experiments

JUNO [1] will detect $\bar{\nu}_e$'s emitted by the nearby Taishan and Yangjiang Nuclear Power Plants (NPPs), at an average distance of 52.5 km from the experimental site → strategic baseline at the first solar oscillation maximum.



Energy scale ≈ 1-10 MeV: possibility to measure only electron flavor neutrinos
Experimental observable: deficit in number of $\bar{\nu}_e$ interactions → $\bar{\nu}_e$ survival probability



Why JUNO?

- Unique capability to simultaneously probe the effects of oscillations on both solar (Δm^2_{21}) and atmospheric (Δm^2_{31}) scales
- Optimized baseline for the determination of the Neutrino Mass Ordering (NMO)

$$\boxed{\mathcal{P}(\bar{\nu}_e \to \bar{\nu}_e)}^{*} = 1 - \boxed{\sin^2 2\theta_{12}\, c^4_{13}\, \sin^2\Delta_{21}} - \boxed{\sin^2 2\theta_{13}\left(c^2_{12}\sin^2\Delta_{31} + s^2_{12}\sin^2\Delta_{32}\right)}$$

*Matter effects with effective oscillation parameters, *Physics Letters B 803, 135354 (2020)*

$c_{ij} \equiv \cos\theta_{ij},\ s_{ij} \equiv \sin\theta_{ij},\ \Delta_{ij} = \Delta m^2_{ij} L/4E$

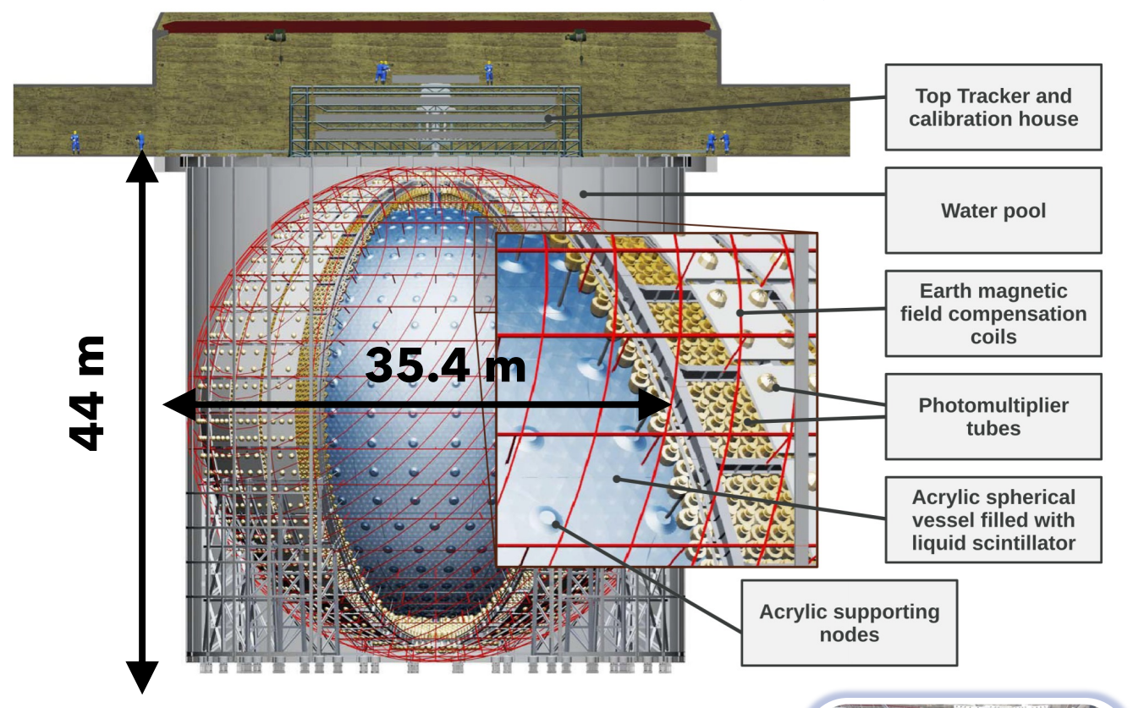
Oscillation physics in JUNO

The Jiangmen Underground Neutrino Observatory (**JUNO**) [1] is a multi-purpose neutrino experiment currently under construction in South China.

Experimental challenges

- Large antineutrino statistics
  - 20 kton Liquid Scintillator (LS) target
- Energy resolution ≈ 2.95 % @ 1 MeV
  - Total photocoverage ≈ 78%
  - Light yield ≈ 1660 PE/MeV
- Energy scale uncertainty < 1%
  - Comprehensive **calibration** program [2]

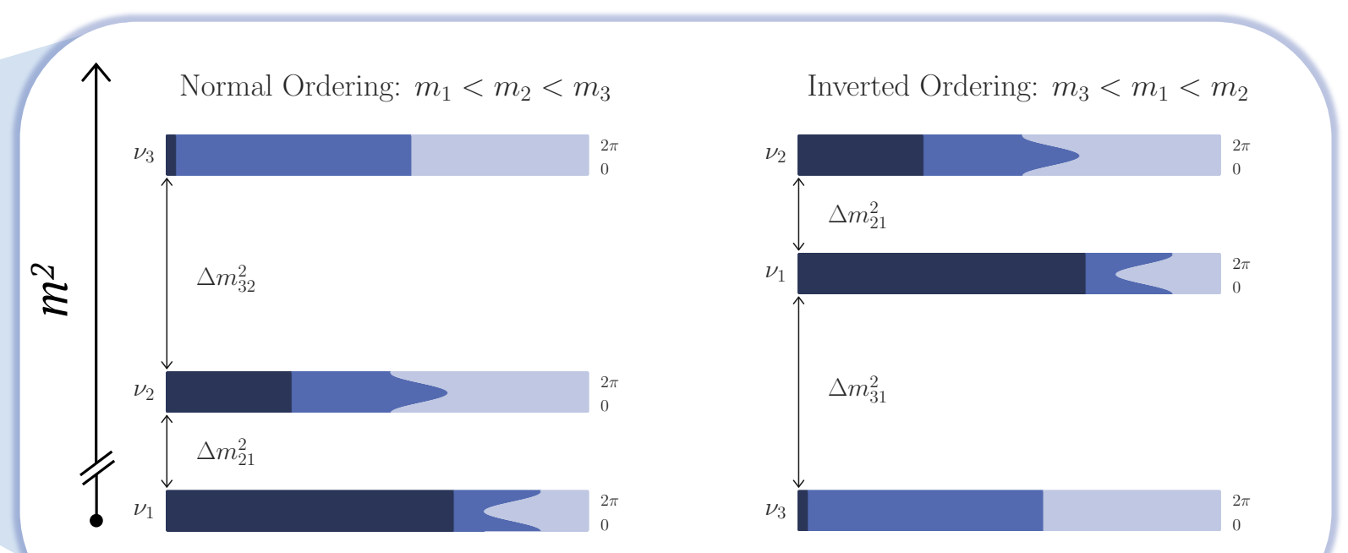
20 kton Central Detector (CD)

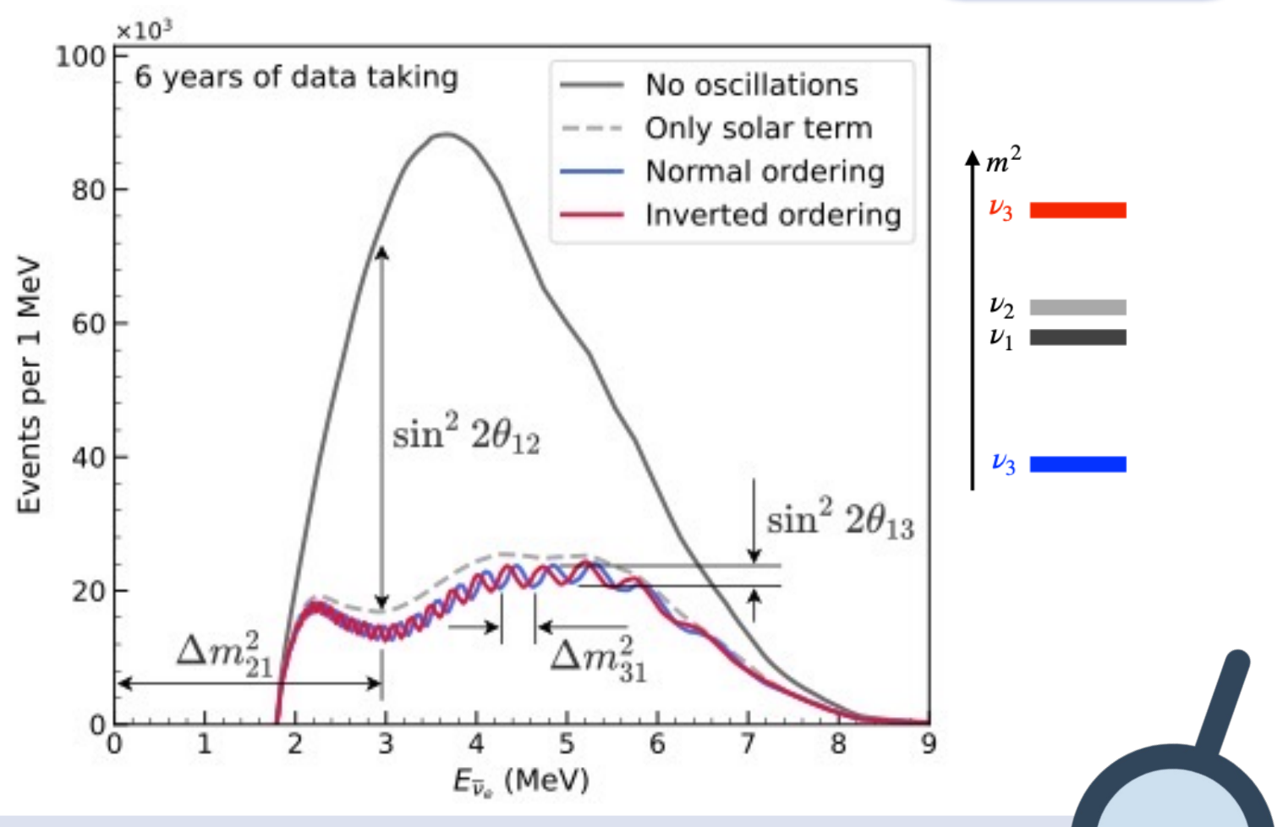


CD PMT system:
17612 20-inch (Large-)PMTs
25600 3-inch (Small-)PMTs

JUNO oscillation physics goals [1]

- Independent determination of 4 oscillation parameters: Δm^2_{21}, $\sin^2\theta_{12}$, Δm^2_{31}, $\sin^2\theta_{13}$.
- Determination of NMO





- First experiment to address NMO question through vacuum oscillations
- Complementary to long baseline experiments
- Independent of δ_{CP} and θ_{23}

Antineutrino detection

Reactor antineutrinos are detected in JUNO through the **Inverse Beta Decay (IBD)** reaction.

$$\bar{\nu}_e + p \to e^+ + n$$

Detector response effects [2] on the spectrum are considered in spectrum calculation: non-linearity (NL) and resolution (Res).

1. IBD reaction and cross section, e^+ deposited energy

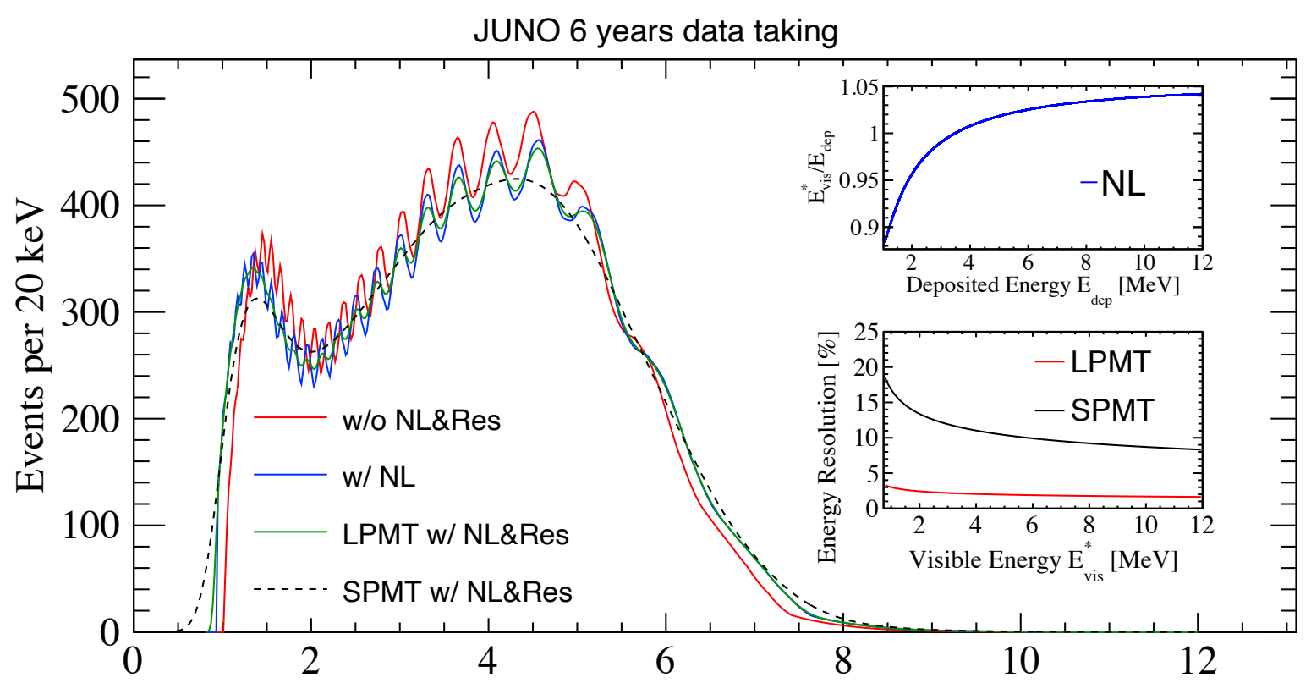
$$E_{\rm dep} \simeq E_{\bar{\nu}_e} - 0.782\,{\rm MeV}$$

2. Liquid scintillator non-linearity (LSNL), visible energy ∝ detected PEs

$$E_{\rm vis} = f_{\rm LSNL}(E_{\rm dep}) \cdot E_{\rm dep}$$

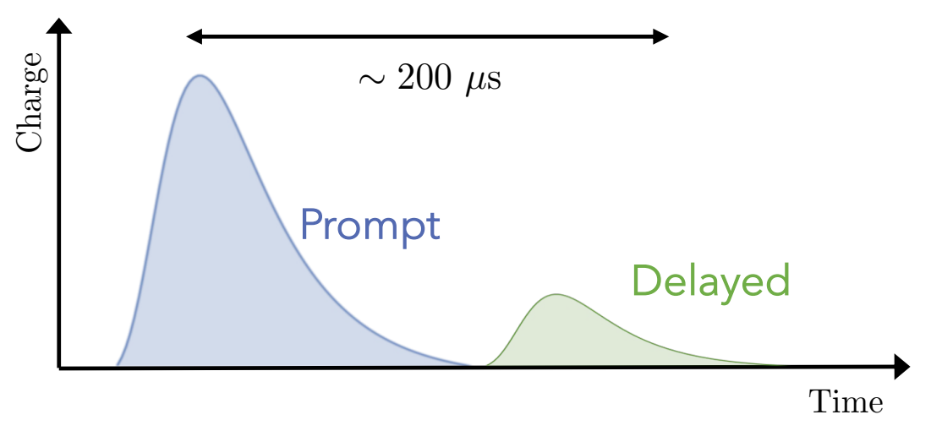
3. Energy resolution

$$\frac{\sigma_{E_{\rm rec}}}{E_{\rm vis}} = \sqrt{\left(\frac{a}{\sqrt{E_{\rm vis}}}\right)^2 + b^2 + \left(\frac{c}{E_{\rm vis}}\right)^2}$$



Event selection and backgrounds

Reactor IBD signal (≈ 57.4 events/day) is rare with respect to the dominant background (mainly due to natural radioactivity).

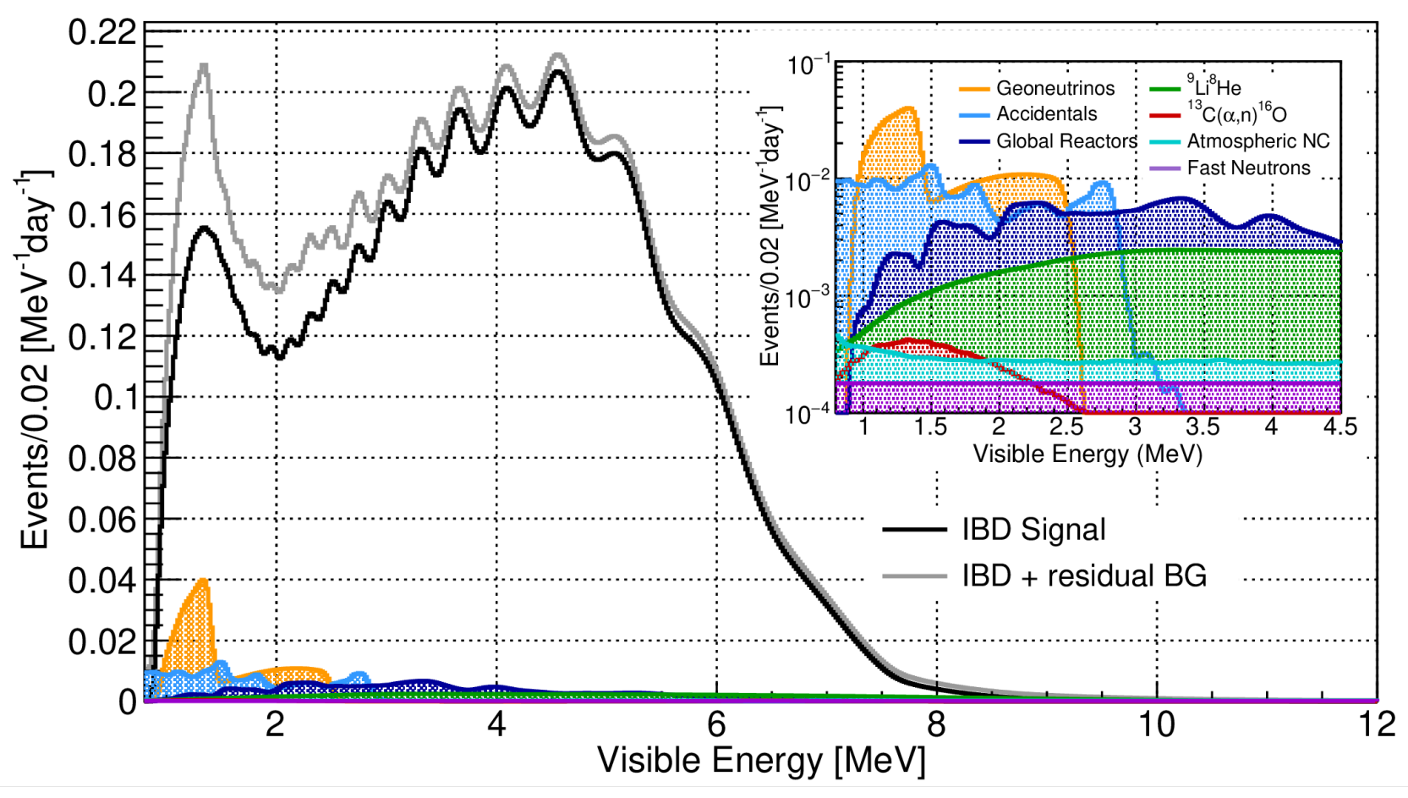


Prompt signal: energy deposited by positron in LS
Delayed signal: neutron capture on H (or ^{12}C): 2.22 MeV (4.95 MeV) gamma emission, $\tau \sim 200\ \mu s$.

Neutrino interaction in JUNO: detection of a pair of **time-correlated** events. Selection is based on **prompt-delayed coincidence signature.**

~82% efficiency for reactor IBD events → 47.1 events/day [3]

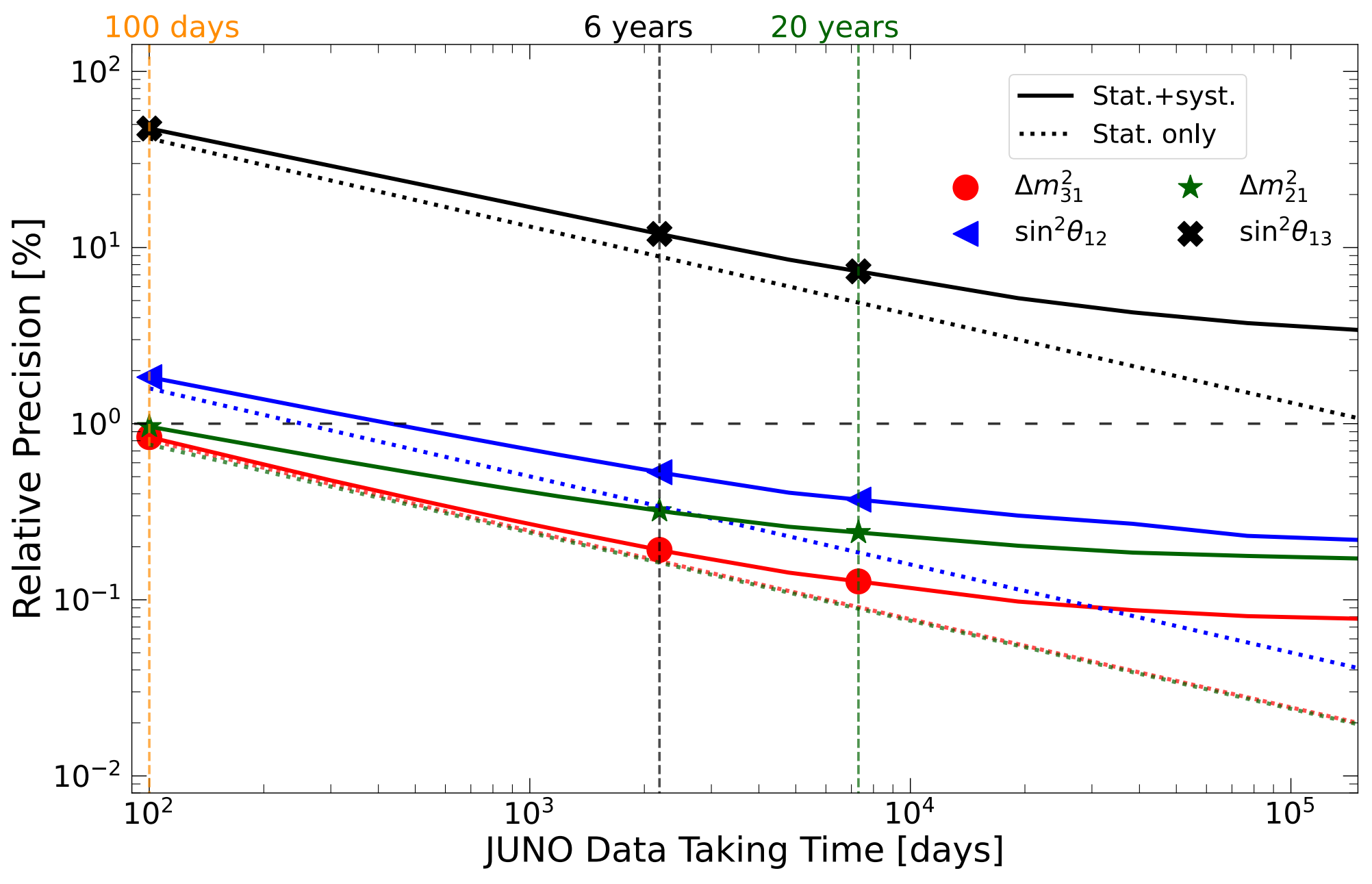
Background	Rate (day^{-1})
Geoneutrinos	1.2
World reactors	1.0
Accidentals	0.8
^{9}Li/^{8}He	0.8
Atmospheric neutrinos	0.16
Fast neutrons	0.1
^{13}C(α,n)^{16}O	0.05



Reactor antineutrino sensitivity analysis and results

Precision measurement of oscillation parameters [3]

- Sensitivity to the two mixing angles dominated by rate systematic uncertainties.
- Sensitivity to the two mass splittings dominated by systematic uncertainties distorting the spectral shape → reference spectrum** and detector non-linearity.



Precision levels for the oscillation parameters: current knowledge (PDG2020) compared with 100 days, 6 years, and 20 years of JUNO data taking.

	Δm^2_{31}	Δm^2_{21}	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$
PDG 2020	1.3%	2.4%	4.2%	3.2%
JUNO 100 days	~0.8%	~1.0%	~1.9%	~47.9%
JUNO 6 years	~0.2%	~0.3%	~0.5%	~12%
JUNO 20 years	~0.1%	~0.2%	~0.3%	~7.3%

Improve current precision of almost one order of magnitude in 6 years for Δm^2_{21}, $\sin^2\theta_{12}$, and Δm^2_{31}, surpassing global precision on these parameters within the initial 100 days of data acquisition.

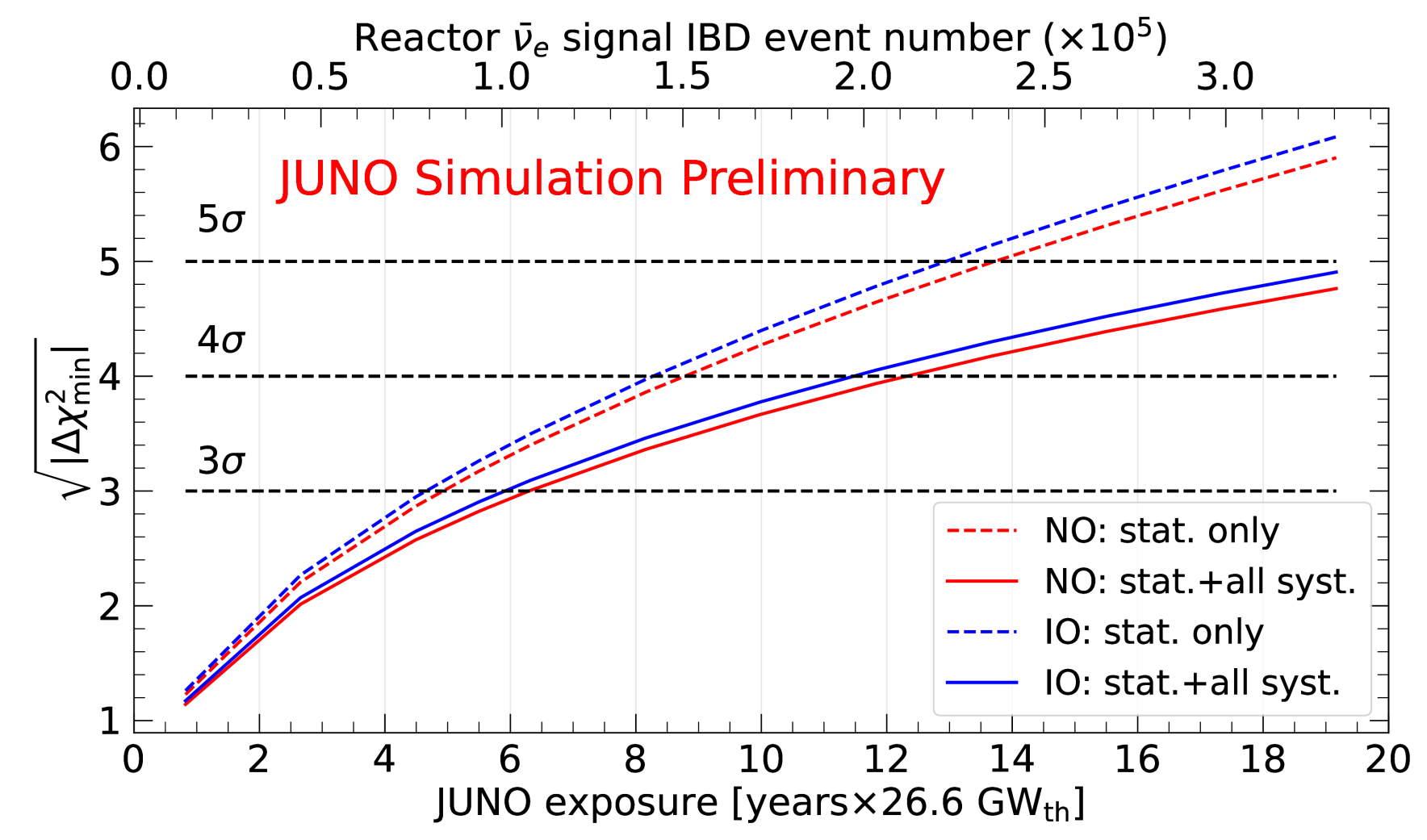
**Good knowledge of the unoscillated spectrum is needed.

The satellite detector **Taishan Antineutrino Observatory (TAO)** will be located at ≈ 40 m from one reactor core, and it will provide a model independent reference antineutrino spectrum for JUNO's analysis.

Mass Ordering sensitivity

Median sensitivity discriminator by fitting normal ordering (NO) and inverted ordering (IO) Asimov data under both NO and IO hypotheses:

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



- 3σ median sensitivity in ~ 6.7 years DAQ time via only reactor $\bar{\nu}_e$
- Sensitivity boost via atmospheric $\nu_\mu/\bar{\nu}_\mu$ in JUNO
- Potential in combining atmospheric and accelerator neutrino experiments measurements
- Dedicated publication coming soon

By-product of sub-percent precision on oscillation parameters [1]

- Rigorous tests of the neutrino sector of the Standard Model (e.g., unitarity of the PMNS matrix)
- Precise searches for physics beyond the Standard Model
- Discriminator of neutrino masses and mixing models

References

[1] PPNP 123 (2022) 103927
[2] JHEP 03 (2021) 004
[3] CPC 46 (2022) 123001