Applied Antineutrino Physics Workshop 2024

28th - 30th October 2024 - Aachen, Germany

The JUNO and TAO detectors and their physics potential

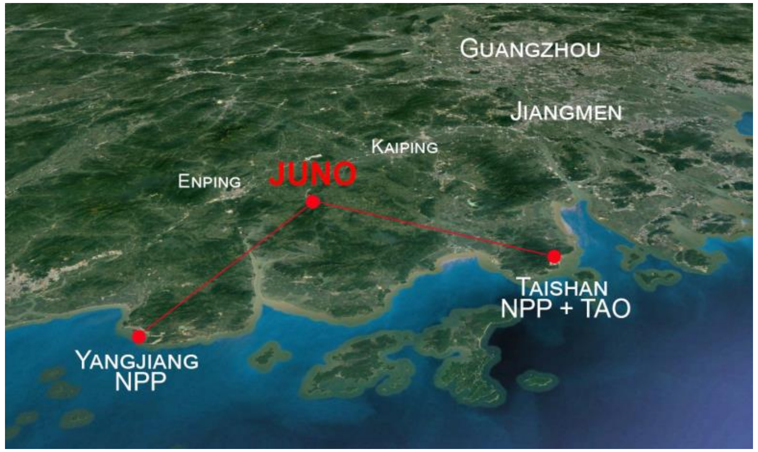
Davide Chiesa on behalf of the JUNO collaboration

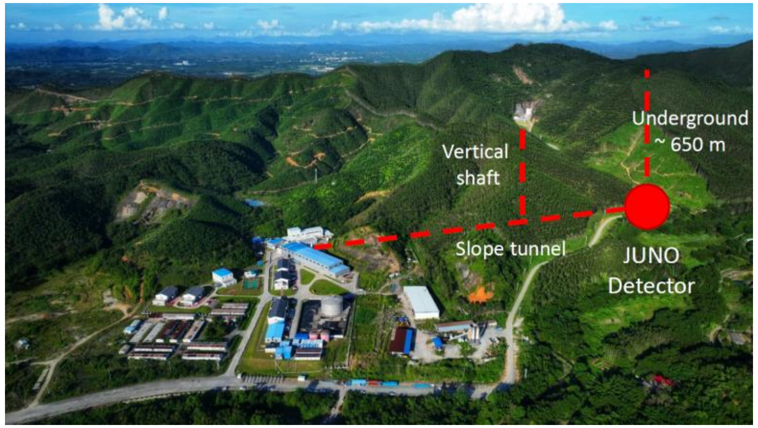
University of Milano-Bicocca, INFN Milano Bicocca

davide.chiesa@mib.infn.it

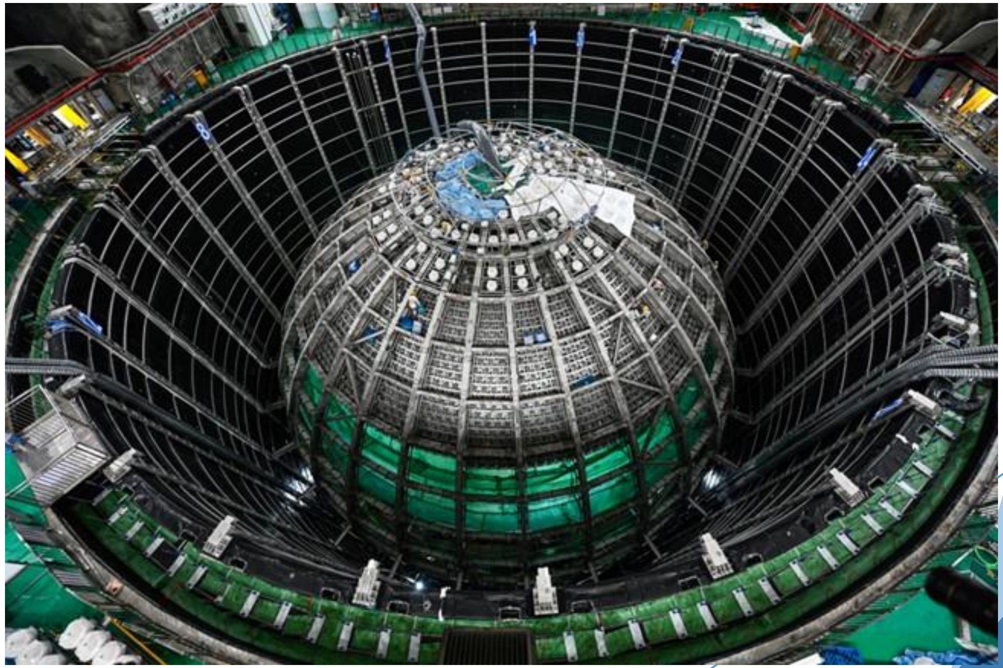
The JUNO experiment

- JUNO (Jiangmen Underground Neutrino Observatory) is a $20\ \mathrm{kton}$ liquid scintillator detector located $\sim 650\ \mathrm{m}$ underground at $\sim 52.5\ \mathrm{km}$ from two Nuclear Power Plants in China.





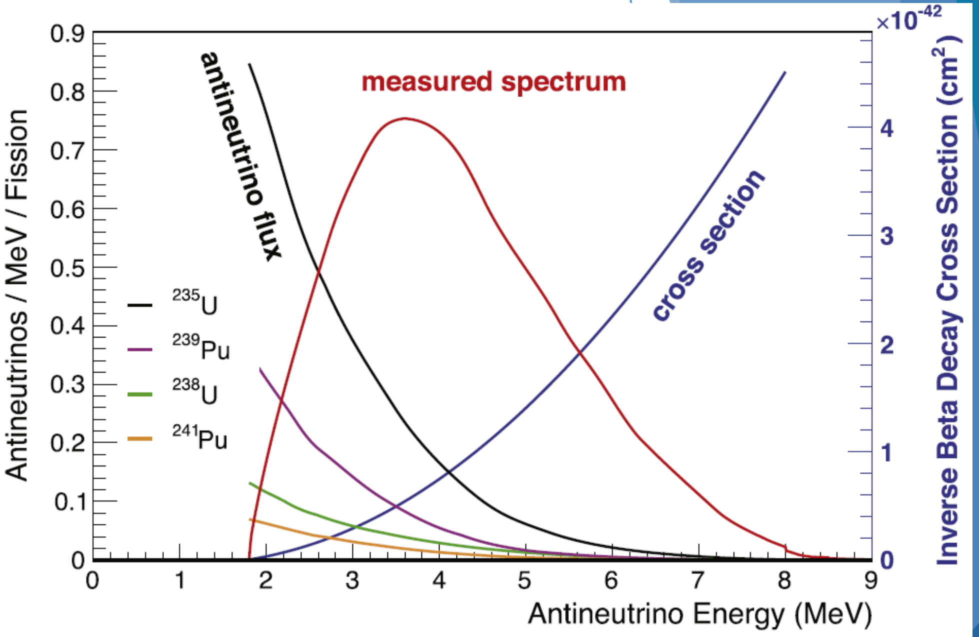
- Construction of the JUNO detector is nearly complete and we expect to start data taking next year.



Reactor neutrino detection

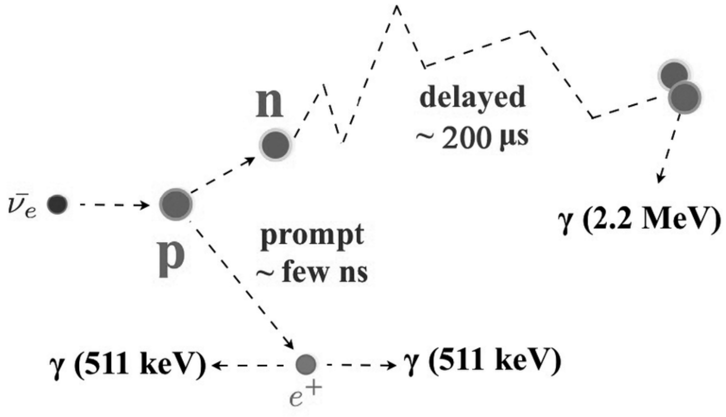
In nuclear reactors, $\bar{\nu}_e$ are emitted from β-decays of fission fragments:

- typical flux $\sim 2 \times 10^{20}\ \bar{\nu}_e/\mathrm{s}/\mathrm{GW_{th}}$
- most reactor $\bar{\nu}_e$ have energy $\mathrm{E}\ <\ 10\ \mathrm{MeV}$
- $>\ 99\%$ of reactor $\bar{\nu}_e$ emissions come from fissions of four main isotopes: ^{235}U, ^{239}Pu, ^{241}Pu, ^{238}U.



$\bar{\nu}_e$ can be detected via the Inverse Beta Decay (IBD) reaction:

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



- Energy threshold: $1.806\ \mathrm{MeV}$
- Prompt visible energy:

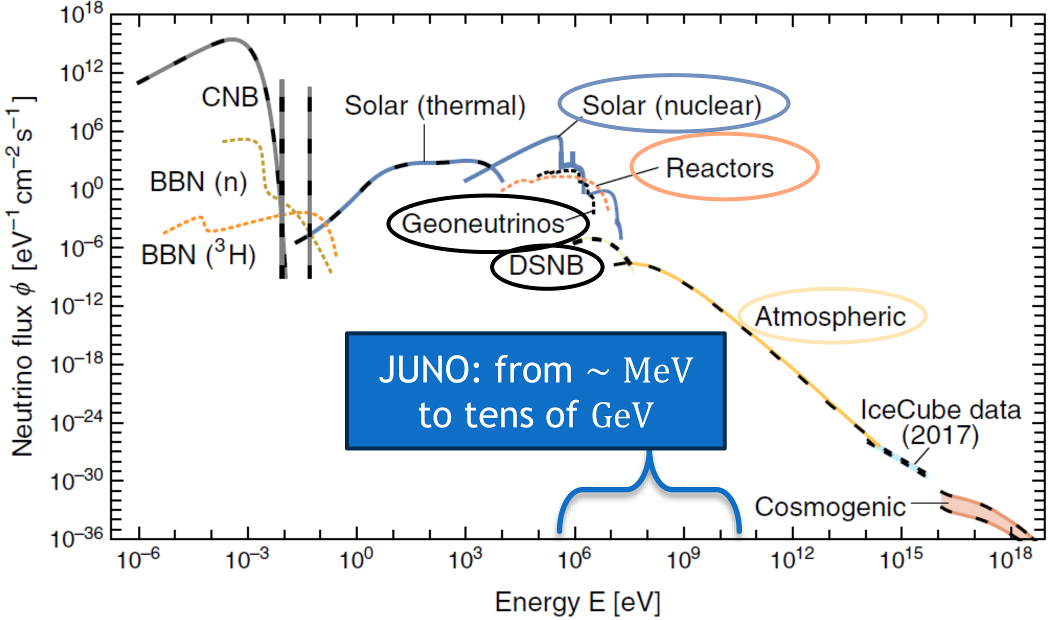
$$E_{vis} = E_{\nu} - 0.784\ \mathrm{MeV}$$

- Time and space coincidence between prompt and delayed signal allows to reject uncorrelated background

JUNO: a multipurpose experiment

- The JUNO detector will measure neutrinos from different sources in the energy range from ~MeV to tens of GeV
- JUNO will offer exciting opportunities for addressing many important topics in neutrino and astro-particle physics

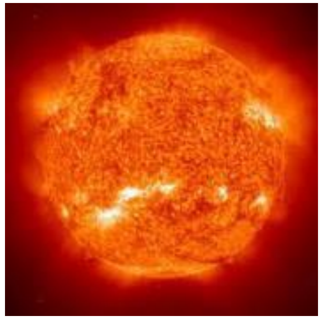
Grand unified neutrino spectrum at Earth
Rev. Mod. Phys. 92, 045006 (2020)



JUNO: from $\sim$ MeV to tens of GeV

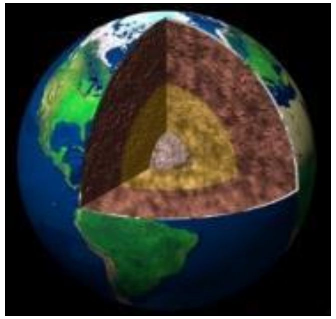
JUNO collaboration, Prog.Part.Nucl.Phys. 123 (2022) 103927

Reactor ν
$\sim$ 50 IBD/day

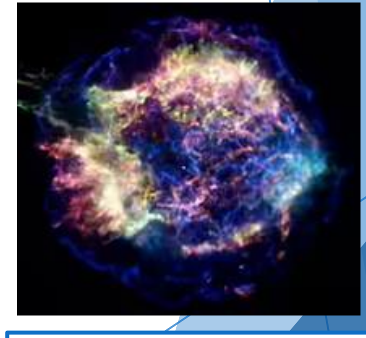


Solar ν
hundreds/day

Atmospheric ν
several/day



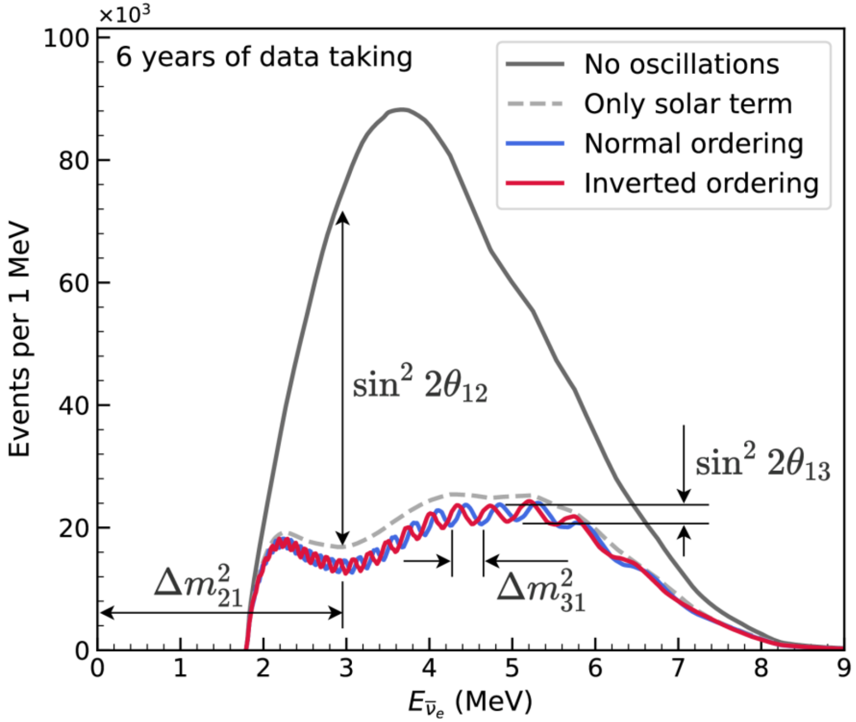
Geoneutrinos
$\sim$ 400 IBD/yr



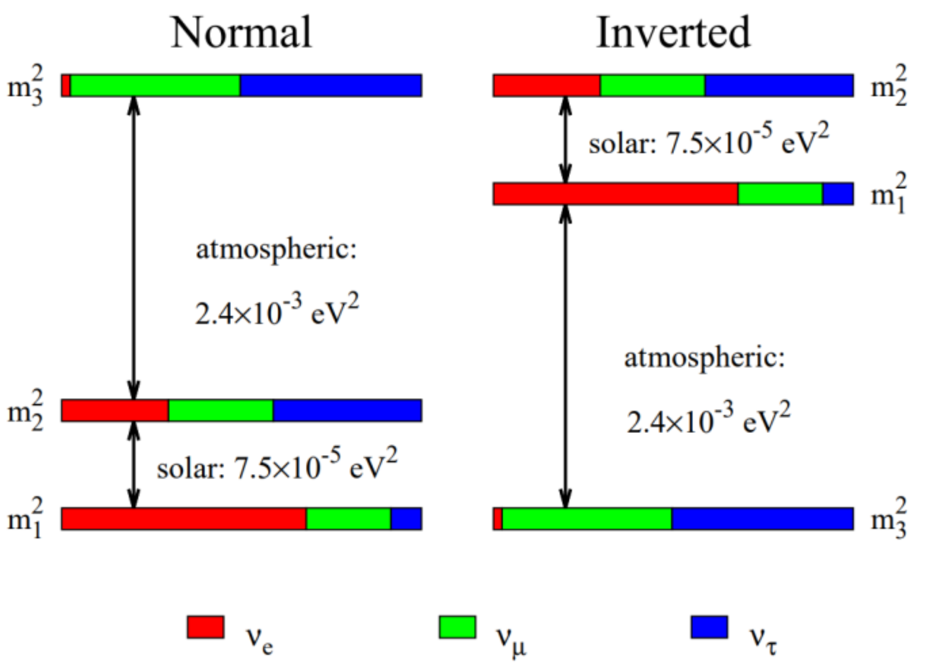
Supernova ν
$\sim$ 5000 IBD in 10 s
for CCSN at 10 kpc

The JUNO primary physics goals

- Determine the Neutrino Mass Ordering (NMO)
- Measure three oscillation parameters ($\sin^2\theta_{12}$, Δm^2_{21}, Δm^2_{31}) with sub-percent precision



JUNO collaboration, CPC 46, 123001 (2022)



JUNO will be the first experiment to observe both fast ($\sin^2\theta_{13}$, Δm^2_{31}) and slow ($\sin^2\theta_{12}$, Δm^2_{21}) oscillations in vacuum

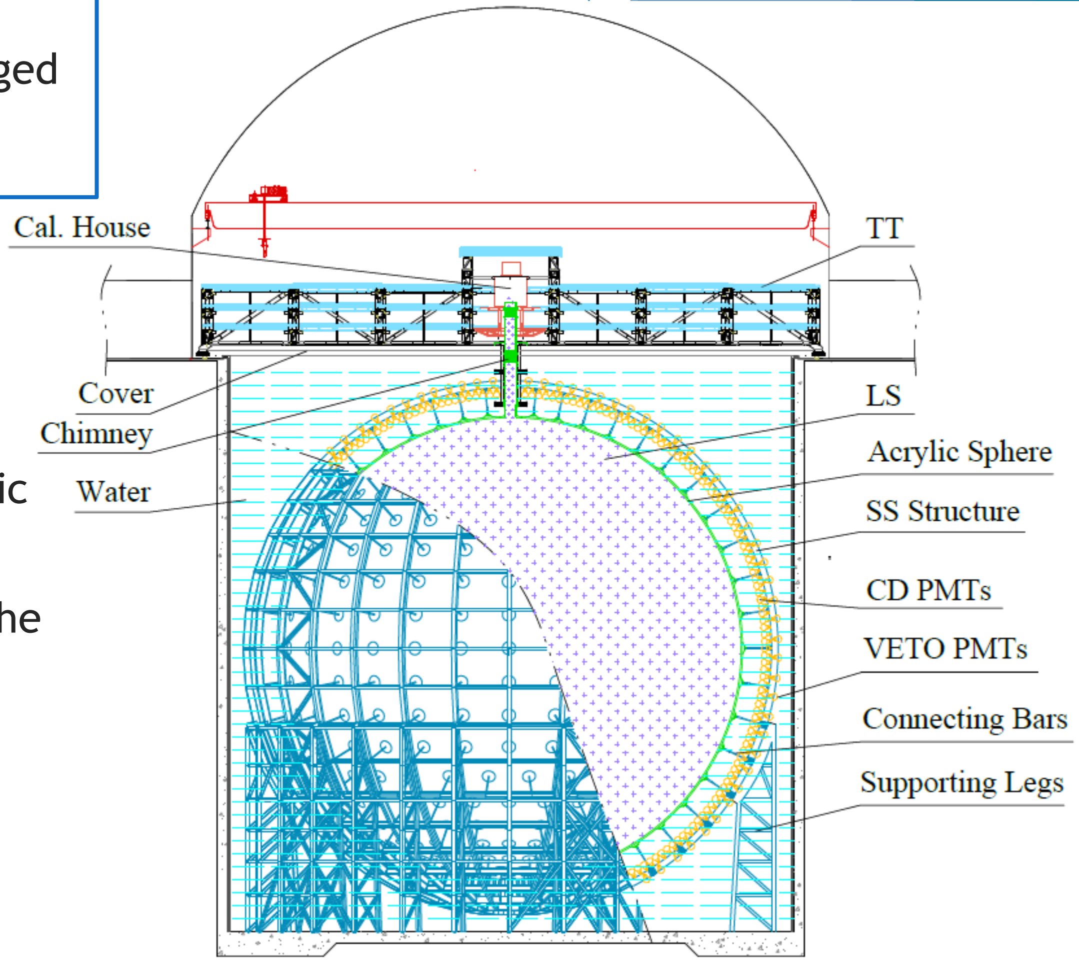
↓

The interference pattern depends on NMO

The JUNO detector

- ❑ 20 kton liquid scintillator (LS) detector
- ❑ Water Cherenkov detector in which the LS detector is submerged
- ❑ Plastic scintillator array on top (Top Tracker)

- The **20 kton LS** is contained in an **Acrylic Sphere**
  - Inner Diameter (ID): 35.4 m
  - Thickness: 12 cm
- A Stainless Steel **(SS) Structure** (40.1 m ID) supports the acrylic sphere via 590 connecting bars
- The light emitted by the LS is detected by **PMTs** installed on the inner surface of the SS structure
  - 17612 20-inch PMTs (75.2% photocathode coverage)
  - 25600 3-inch PMTs (2.7% photocathode coverage)
- The **Water pool** is filled with 35 kton of ultrapure water
  - ID: 43.5 m, Height: 44 m
  - 2400 20-inch PMTs installed on the outer surface of the SS structure

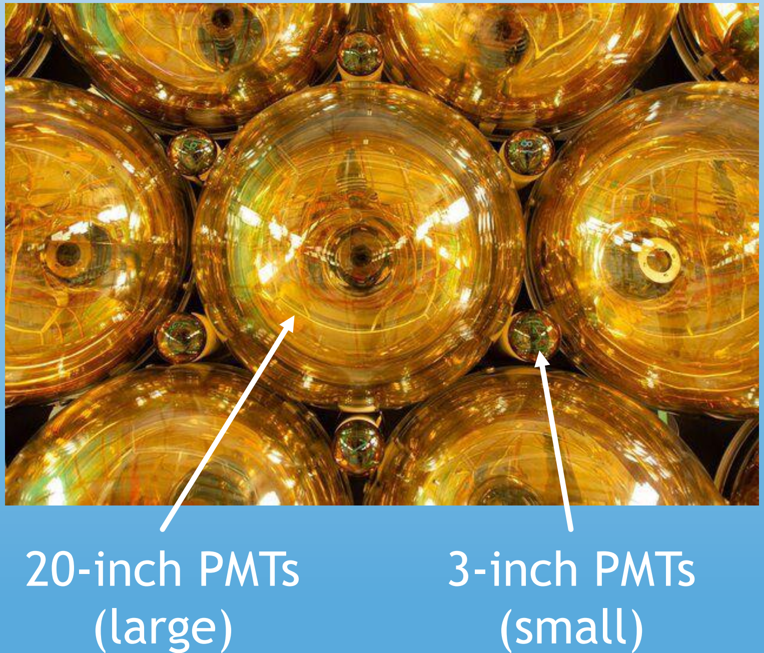


The JUNO detector construction

- SS structure built from bottom to top

- Then, acrylic sphere built from top to bottom, layer by layer

Production and testing done for all PMTs, installation close to completion



The JUNO key challenges

1. Large statistics
   - huge scintillator mass ($\sim 1.5 \times 10^{33}$ target protons)
   - nuclear reactor power: $26.6\ \mathrm{GW_{th}}$ (6 reactors 2.9 $\mathrm{GW_{th}}$ each at Yangjiang + 2 reactors 4.6 $\mathrm{GW_{th}}$ each at Taishan)
2. Energy resolution: 2.95% @ 1MeV arXiv:2405.17860

   Uncertainty on the intrinsically non-linear energy scale: $\leq 1\%$
3. Low background:
   - underground laboratory
   - scintillator purification system
   - material screening to meet the requirements for Th/U/K contaminations:

     $< 10^{-15}\mathrm{g/g}$ in LS and $< 10^{-12}\ \mathrm{g/g}$ in acrylic
   - veto systems (Top Tracker, Water Cherenkov detector)
4. Knowledge of unoscillated reactor spectra

Taishan Antineutrino Observatory (TAO)

Expected $\overline{\nu_e}$ spectrum at JUNO

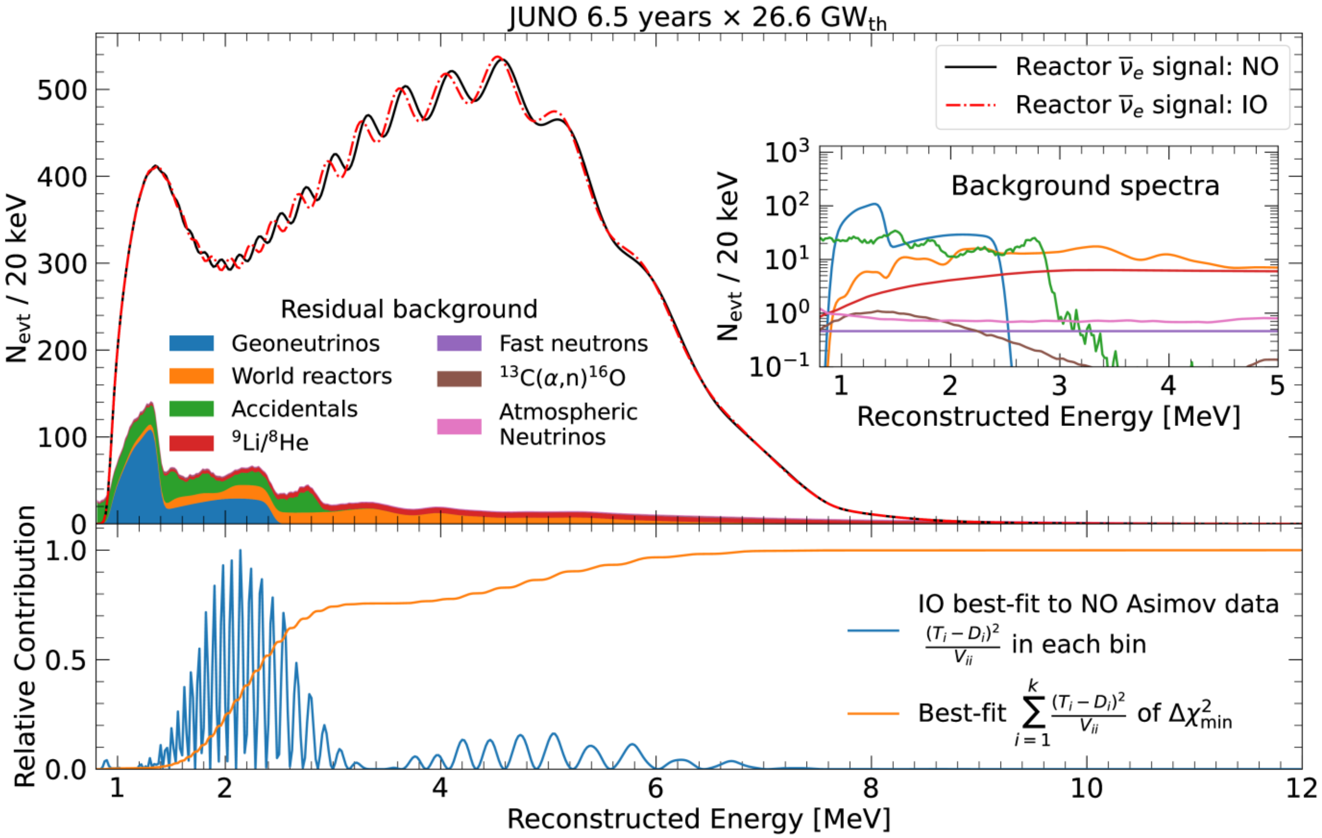
Top panel:

- Energy spectra in both the NO and IO scenarios without any statistical or systematic fluctuations
- The background spectra in the main figure are stacked on top of each other

Bottom panel:

- Relative contribution to the $\Delta\chi^2$ obtained when fitting the IO spectrum with the NO hypothesis.

The most sensitive region for JUNO's NMO determination is in the visible energy range from 1.5 to 3 MeV



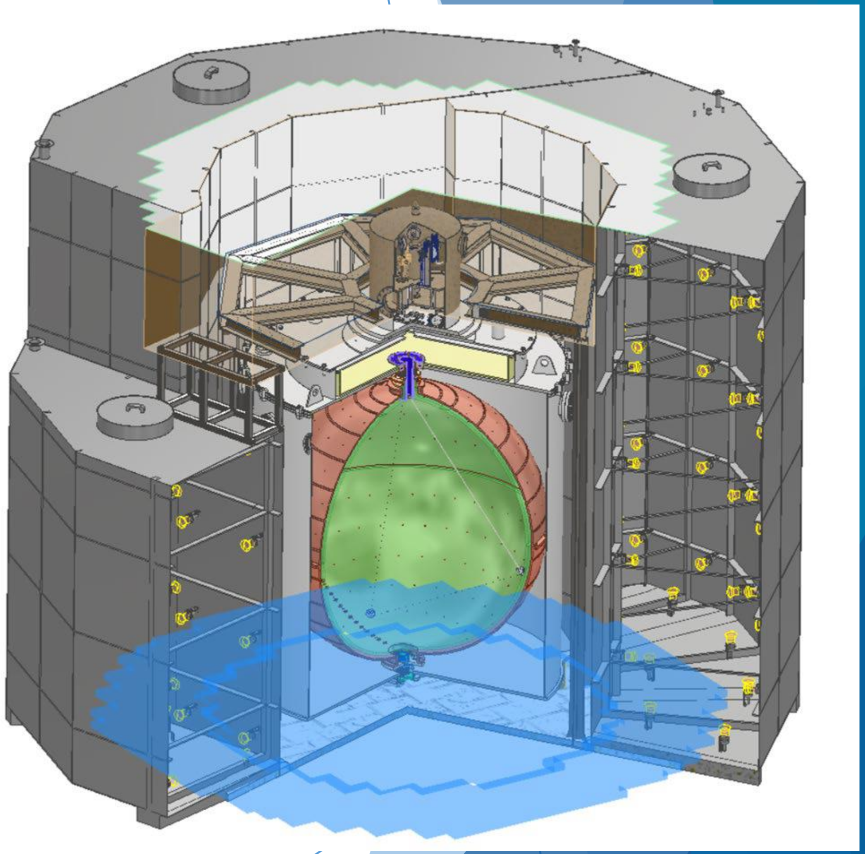
A 3σ median sensitivity to reject the wrong mass ordering hypothesis can be reached with an exposure of about 6.5 years × 26.6 GW thermal power

arxiv:2405.18008

The TAO experiment

TAO (Taishan Antineutrino Observatory) is a satellite experiment of JUNO consisting of a ton-level liquid scintillator detector:

- positioned at **44 m** from the core of the Taishan-1 reactor and at 217 m from Taishan-2;
- will measure the $\bar{\nu}_e$ spectrum with unprecedented **energy resolution** (better than **2% at 1 MeV**);
- will observe **$\sim$1000 IBDs/day** in the fiducial volume.



The main goals and physics potential of TAO are:

- provide a **reference spectrum** for JUNO;
- **benchmark for** future reactor neutrino **experiments** and **nuclear databases** (fine structures observation);
- measurement of isotopic IBD yields with larger sampled range of fission fractions;
- light sterile neutrino searches;
- increase the reliability and verify the technology for reactor monitoring.

TAO at the Taishan NPP

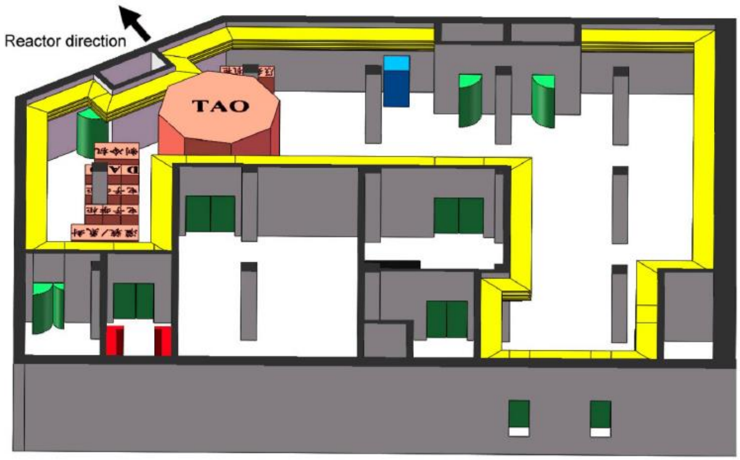
- Taishan Nuclear Power Plant has two cores currently in operation (other two cores might be built later)
- Both reactors are European Pressurised Reactor (EPR) with 4.6 GW_{th} thermal power
- Taishan-1 reached first criticality and was connected to the grid in June 2018

  → the first running EPR in the world!

- The TAO detector will be installed in a basement at 9.6 m underground, outside of the concrete containment shell of the reactor core
  - >99.99% signal from Taishan-1+Taishan-2
  - 4% signal from Taishan-2
- Muon rate and cosmogenic neutron rate are measured to be 1/3 of those on the ground


Taishan Nuclear Power Plant (NPP), Guangdong, China

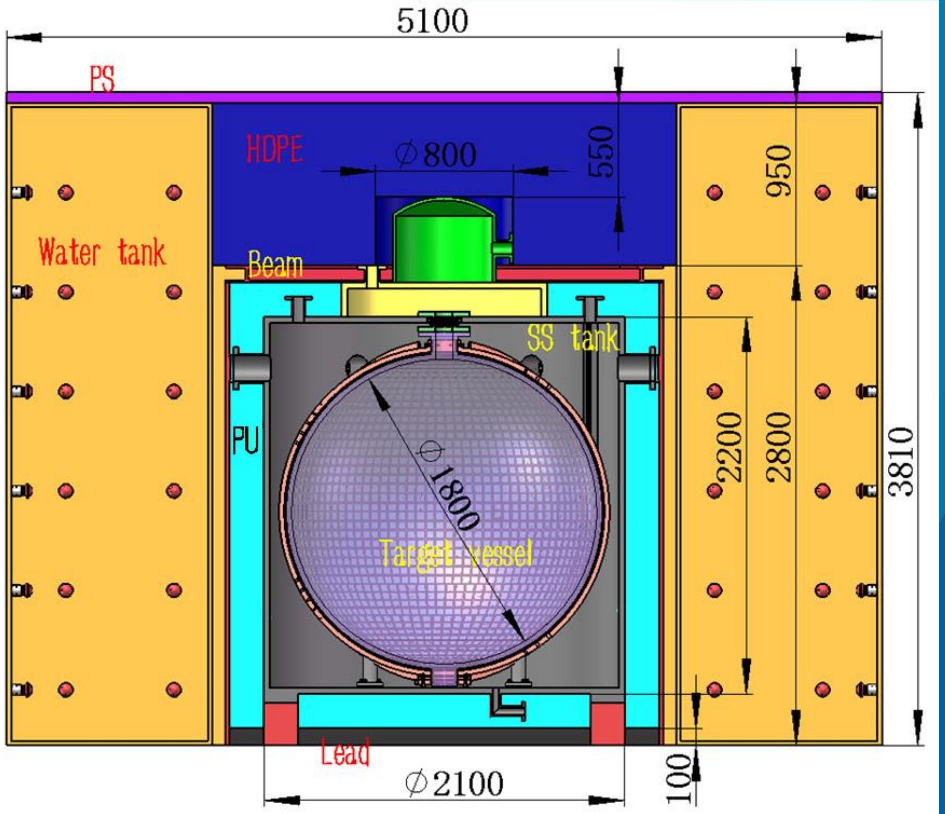
EDF Energy, Attribution, via Wikimedia Commons



The TAO detector

- 2.8 ton Gadolinium-doped Liquid Scintillator (**Gd-LS**) filled in a spherical **acrylic vessel** of 1.8 m in inner diameter (ID).
- Scintillation and Cherenkov light is detected by **4024** Silicon Photomultipliers (**SiPM**) $5.08\ \mathrm{cm} \times 5.08\ \mathrm{cm}$ each, covering $\sim 10\ \mathrm{m}^2$ with 50% photon detection efficiency.
- SiPM tiles on the inner surface of a spherical **copper shell** $(ID = 1.882\ \mathrm{m})$
- Cylindric **stainless steel tank** $(OD = 2.1\ \mathrm{m}\ ,\ H = 2.2\ \mathrm{m})$ filled with Linear Alkylbenzene (LAB) as buffer liquid to shield the radioactivity, stabilize the temperature, and optically couple acrylic and SiPMs.
- SS tank is insulated with 20 cm thick Polyurethane (PU) to operate at $-50^\circ\mathrm{C}$ → reduce the dark noise of SiPMs to $\sim 100\ \mathrm{Hz/mm^2}$.
- The central detector is surrounded by:
  - 1.2 m thick water tanks on the sides
  - 1 m High Density Polyethylene (HDPE) on the top
  - 10 cm lead at the bottom

to shield the ambient radioactivity and cosmogenic neutrons.



- Muon veto system: water tank instrumented with PMTs + plastic scintillator array on top

IBD detection and event selection in TAO

Inverse beta decay (IBD) in LS with 0.1% Gd-loading:

- 87% neutron captures by Gd (and 13% by hydrogen)
- Average capture time by Gd is about 30 μs

Event selection:

- Fiducial volume cut: 25 cm from the LS boundary to reduce energy leakage and mitigate backgrounds → 1 ton fiducial mass
- Delayed energy cut: $7\ \mathrm{MeV} < E_d < 9\ \mathrm{MeV}$ to reduce background rate by one order of magnitude
- Prompt energy cut: $E_p > 0.9\ \mathrm{MeV}$
- Prompt-delayed time coincidence cut: $1\ \mu s < \Delta t < 100\ \mu s$

	Efficiency
Captures by Gd	87%
Delayed energy cut	59%
Prompt energy cut	99.8%
Time coincidence cut	97%

Overall detection efficiency ~ 50%

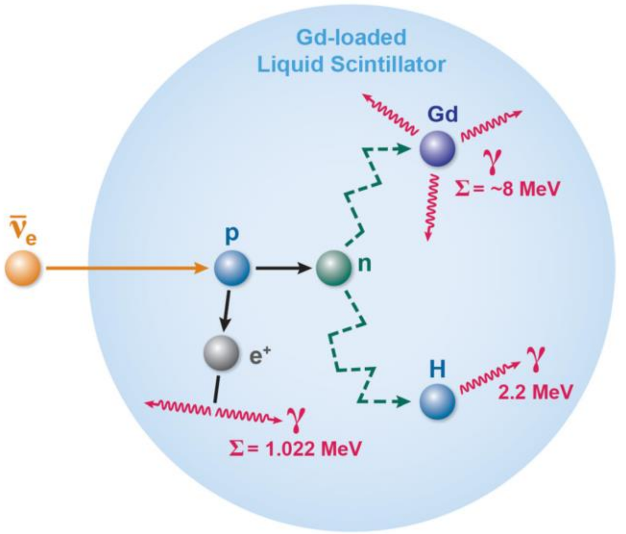
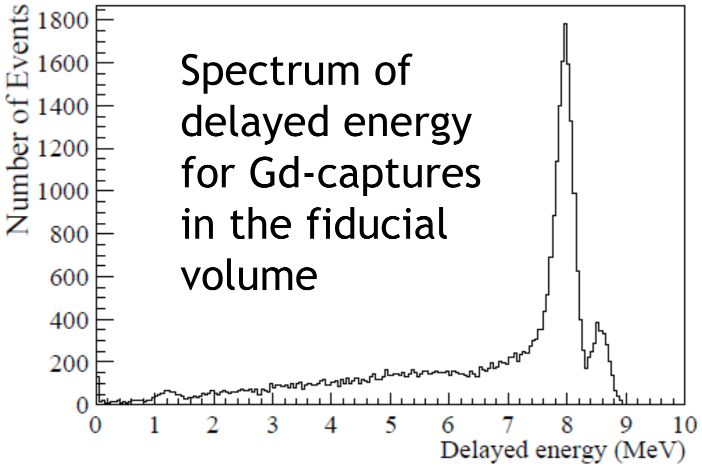


Image Credit:
Rep. Prog. Phys. 82, 036201 (2019)



Spectrum of delayed energy for Gd-captures in the fiducial volume

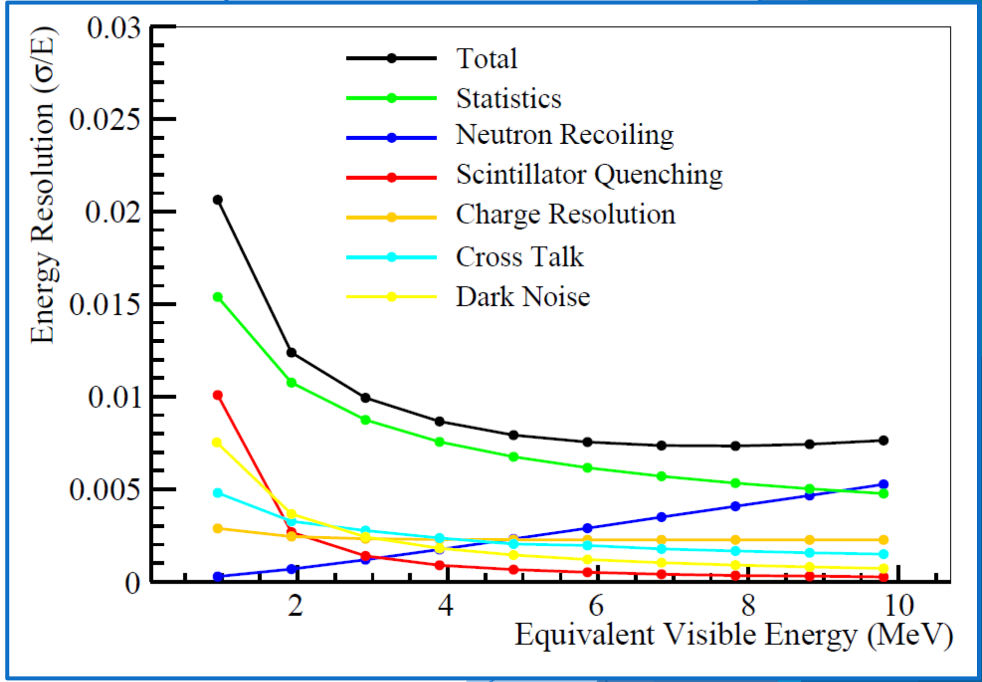
TAO energy resolution

	JUNO	TAO
Coverage	$\sim 75\%$	$\sim 94\%$
Photon detection efficiency	$\sim 30\%$	$> 50\%$
Attenuation length	$> 20\ \mathrm{m}\ \ (R = 17.2\ \mathrm{m})$	$> 20\ \mathrm{m}\ \ (R = 0.9\ \mathrm{m})$
Photoelectron yield	$\sim 1665\ \mathrm{PE/MeV}$	$\sim 4500\ \mathrm{PE/MeV}$
Energy resolution	$2.95\%\ @\ 1\ \mathrm{MeV}$	$\sim 2\%\ @\ 1\ \mathrm{MeV}$

Non-stochastic effects affecting energy resolution in TAO:

- at low energies, the contribution from the LS quenching effect might be quite large;
- at high energies, the smearing from neutron recoil of IBD becomes dominant.

In most of the energy region of interest, the energy resolution of TAO will be sub-percent!

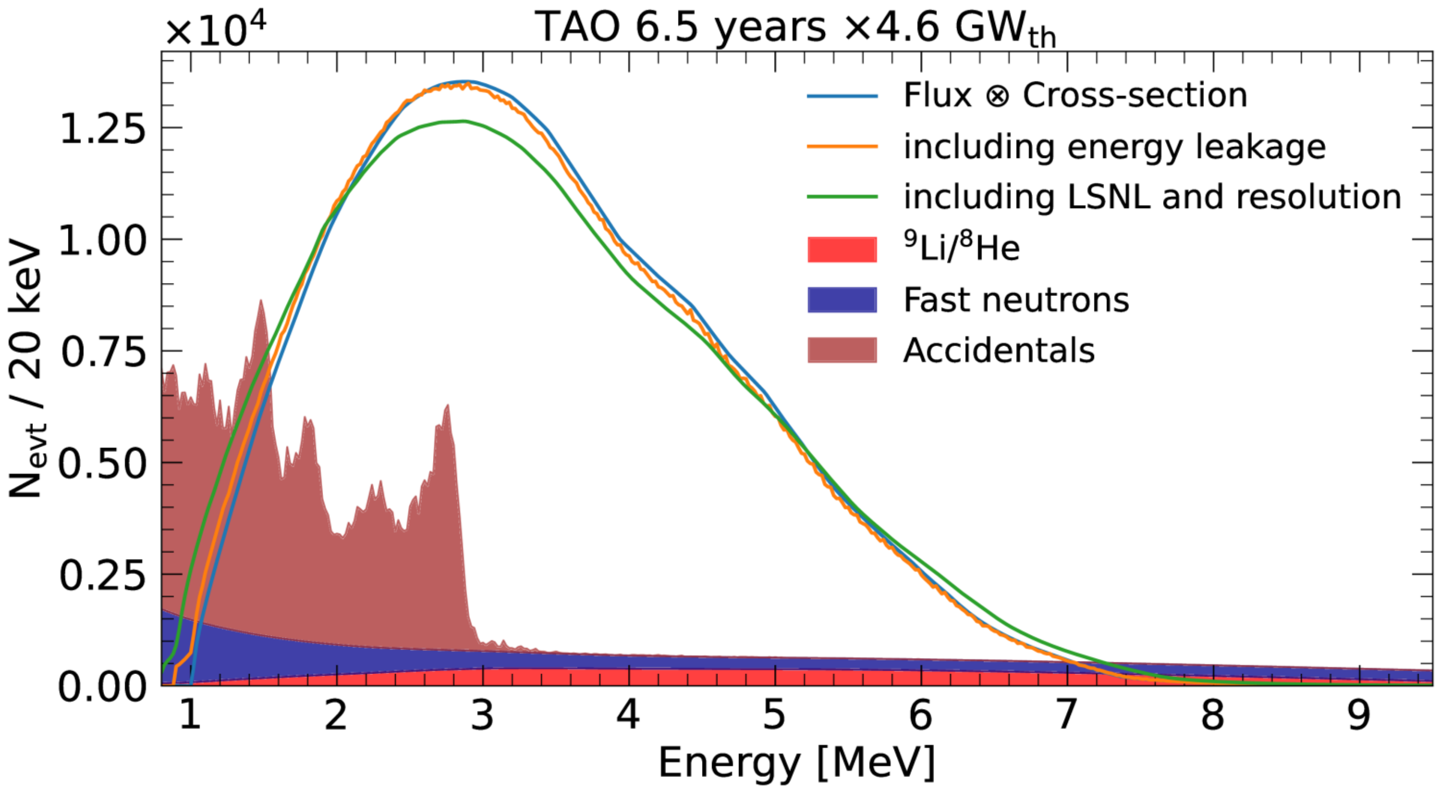


TAO energy resolution

TAO expected signal and background

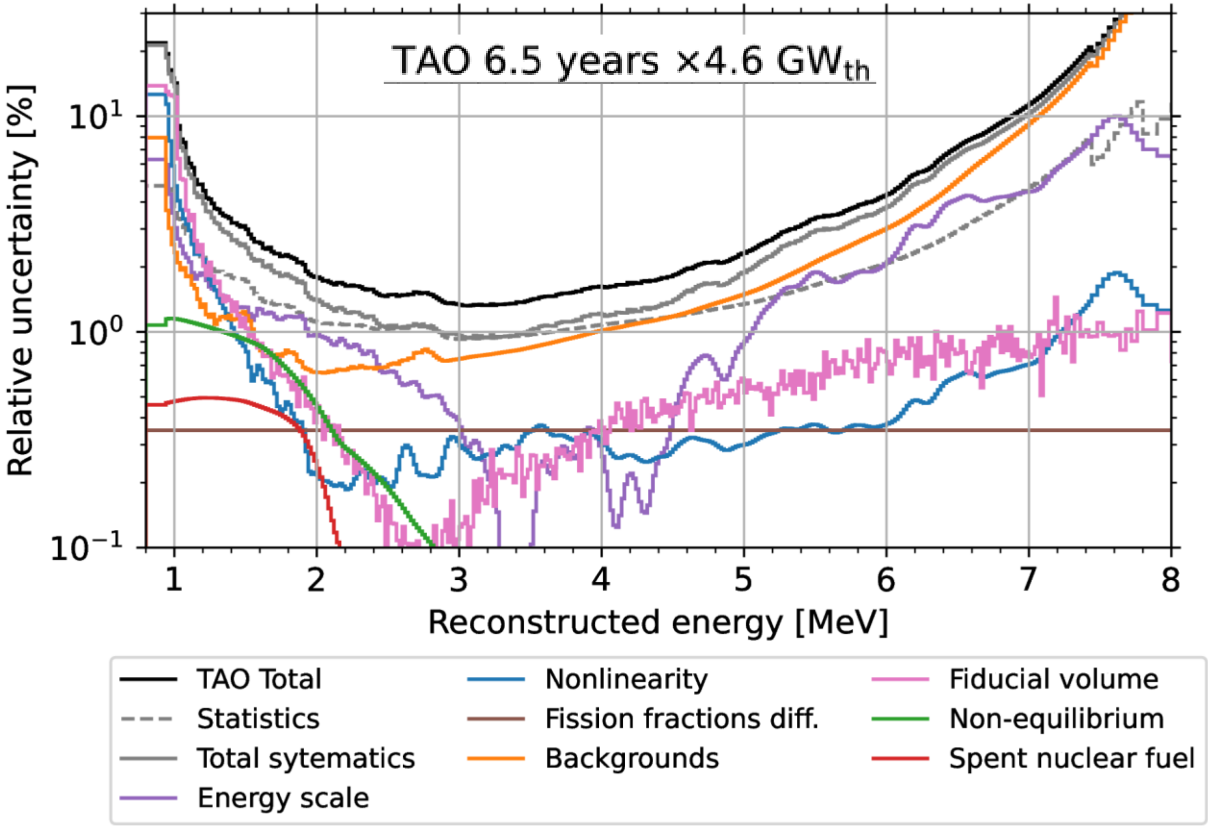
- Signal spectrum: $S(E_\nu) = \frac{N_p \epsilon \sigma(E_\nu)}{4\pi L^2}\phi(E_\nu)$
- The signal spectrum is shown w/ and w/o applying energy leakage, liquid scintillator non-linearity (LSNL), and energy resolution effects.
- TAO backgrounds will be directly measured exploiting the reactor-off data (about one month per year)

Type	Rate [day^{-1}]
Signal	1000
Fast neutron	86
^{9}Li/^{8}He	54
Accidental	190



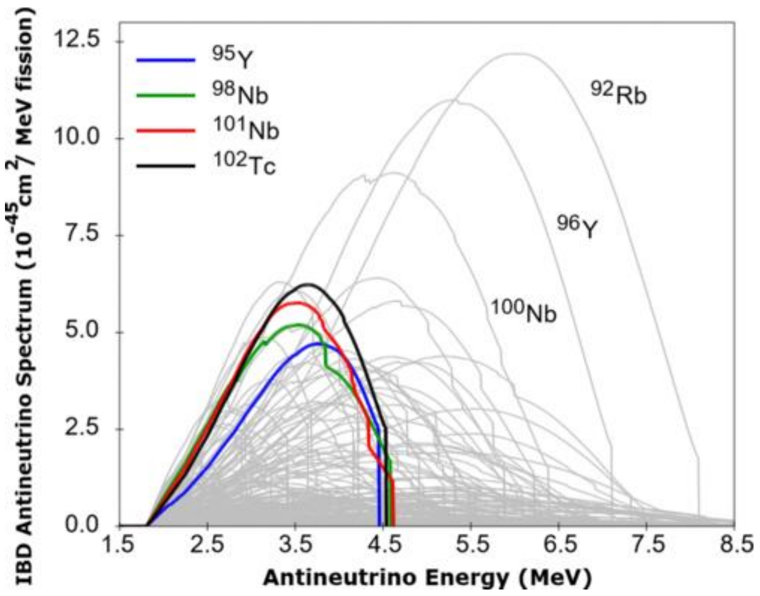
Shape uncertainty of TAO spectrum

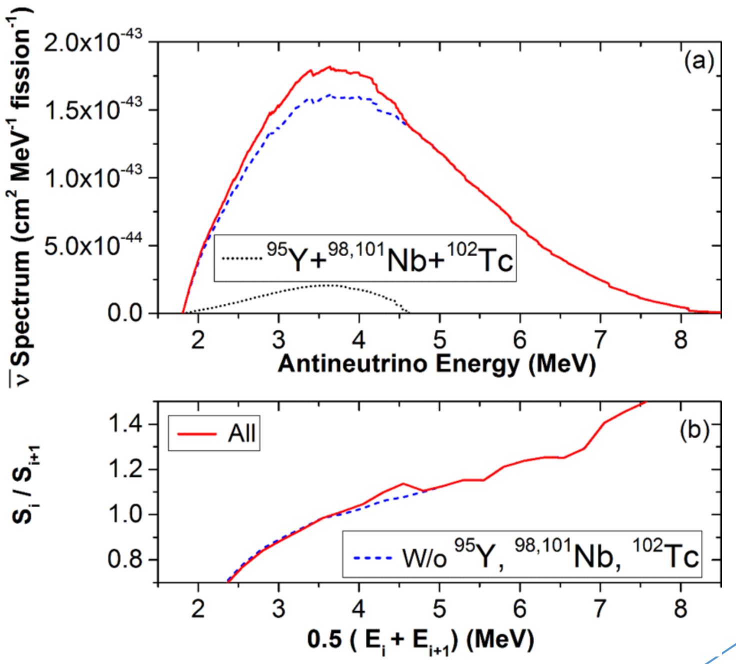
- Statistical uncertainty: $\sim 1\%$ in the energy range $2 - 5\ \mathrm{MeV}$ (20 keV bin width)
- Systematic uncertainties are not negligible at low/high energies, but are $\sim 1\%$ in the central energy range $2 - 5\ \mathrm{MeV}$



Fine structure measurement

- The reactor $\bar{\nu}_e$ spectrum is composed of spectra from thousands of beta decay branches.
- The end point of each $\bar{\nu}_e$ spectrum has a sharp edge (Coulomb correction), which produces a percent-level fine structure.
- Thanks to its excellent energy resolution, TAO will uncover the fine structures of reactor $\bar{\nu}_e$ spectrum for the first time.
- The TAO measurement will provide a benchmark to test nuclear databases, comparing the experimental data with the predictions of the summation method.





Plot taken from A. A. Sonzogni, M. Nino, and E. A. McCutchan, Phys. Rev. C 98, 014323 (2018)

Conclusions

- JUNO detector is in an advanced construction status and is expected to start data taking next year.
- JUNO has a rich physics program in particle and astroparticle physics.
- Main goal: identification of NMO and precise measurement of oscillation parameters thanks to its unprecedented energy resolution.
- TAO 1:1 prototype has been successfully tested at IHEP and, after disassembling and re-installation in Taishan, will start data taking next year.
- TAO will provide a high-resolution reference reactor spectrum for JUNO NMO analysis, but also precious experimental data to be used as benchmark for the modelling of reactor antineutrino spectrum.