JUNO's PERSPECTIVE FOR GEONEUTRINOS

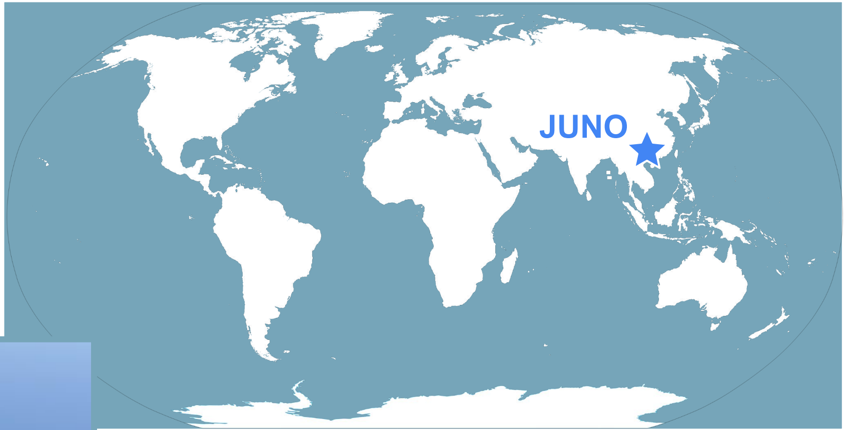
Multi-Messenger Tomography of Earth
July 4-7, 2023

Yury Malyshkin[1,2] on behalf of the JUNO collaboration

1. GSI Helmholtzzentrum für Schwerionenforschung
2. Forschungzentrum Jülich

Jiangmen Underground Neutrino Observatory

- Located near Kaiping, Jiangmen in Guangdong province in Southern China
- Designed to measure reactor neutrinos from two NPP at 52.5 km distance (~700 m deep)

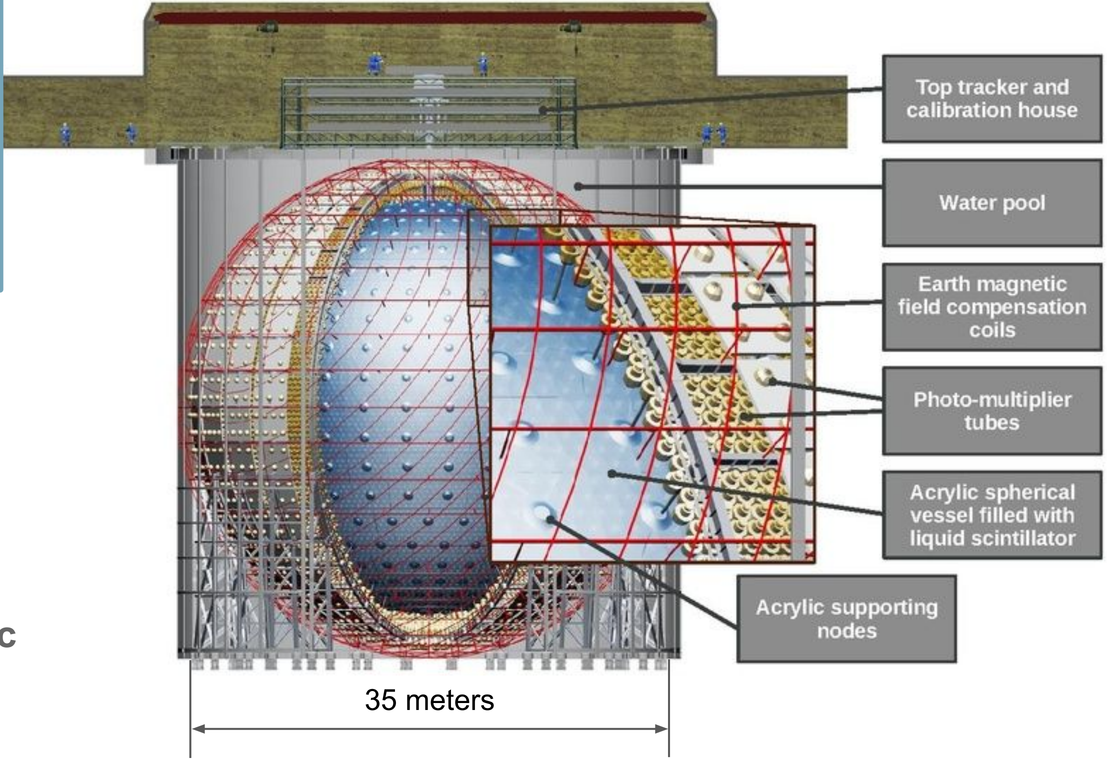


Jiangmen Underground Neutrino Observatory

- Located near Kaiping, Jiangmen in Guangdong province in Southern China
- Designed to measure reactor neutrinos from two NPP at 52.5 km distance (~700 m deep)
- Designed for unprecedented energy resolution (3% at 1 MeV)

20 kton of liquid scintillator
—> high statistics

18k 20” PMTs + 25k 3” PMTs
—> powerful calorimetric measurement of neutrino energy



Jiangmen Underground Neutrino Observatory

- Located near Kaiping, Jiangmen in Guangdong province in Southern China
- Designed to measure reactor neutrinos from two NPP at 52.5 km distance (~700 m deep)
- Designed for unprecedented energy resolution (3% at 1 MeV)

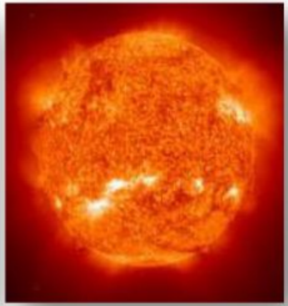
Multi-purpose detector:

- Neutrino Oscillations: mass ordering (3σ in ~6 years)
- Sub-percent precision for 3 out of 6 neutrino oscillation parameters
- **Geoneutrinos**
- Atmospheric neutrinos
- Solar neutrinos
- Supernova collapse neutrinos
- …

Reactor anti-ν

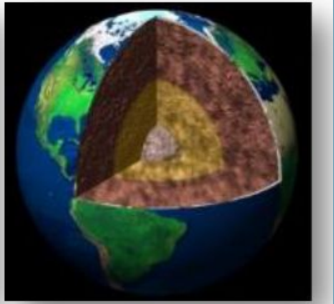
Atmospheric ν

Solar ν



Supernovae (SN) ν

Geoneutrinos



\+ New physics

Signal Prediction at JUNO

1 TNU (Terrestrial Neutrino Unit) = 1 event / 10^{32} target protons (~1kton LS) / year with 100% detection efficiency

Geonu = Lithosphere + Mantle

Lithosphere (crust + CLM) predictions

Lithosphere model	Signal [TNU]	Uncertainty [%]
Global [Prog. in Earth and Planet. Sci. 2, 5, 2015]	$30.9^{+6.5}_{-5.2}$	+21 -17
JULOC [Phys.Earth.Planet.Inter. 299, 2020]	$40.4^{+5.6}_{-5.0}$	+14 -12

Three groups of BSE models for **mantle**:

- Cosmochemical (CC): ~2 TNU
- Geochemical (GC): ~10 TNU
- Geodynamical (GD): ~20 TNU

Accessible via anti-ν_e measurement

$$^{238}_{92}\mathrm{U} \rightarrow {}^{206}_{82}\mathrm{Pb} + 8\alpha + 6e^- + 6\bar{\nu}_e + 51.698\ \mathrm{MeV}$$

$$^{235}_{92}\mathrm{U} \rightarrow {}^{207}_{82}\mathrm{Pb} + 7\alpha + 4e^- + 4\bar{\nu}_e + 46.402\ \mathrm{MeV}$$

$$^{232}_{90}\mathrm{Th} \rightarrow {}^{208}_{82}\mathrm{Pb} + 6\alpha + 4e^- + 4\bar{\nu}_e + 42.652\ \mathrm{MeV}$$

$$^{40}_{19}\mathrm{K} \xrightarrow{89.3\%} {}^{40}_{20}\mathrm{Ca} + e^- + \bar{\nu}_e + 1.311\ \mathrm{MeV}$$

$$^{40}_{19}\mathrm{K} \xrightarrow{10.7\%} {}^{40}_{18}\mathrm{Ar} + \nu_e + 1.505\ \mathrm{MeV}$$

Contribution to Earth's heat

Refer to talk given by Virginia Stratti

JUNO Timeline

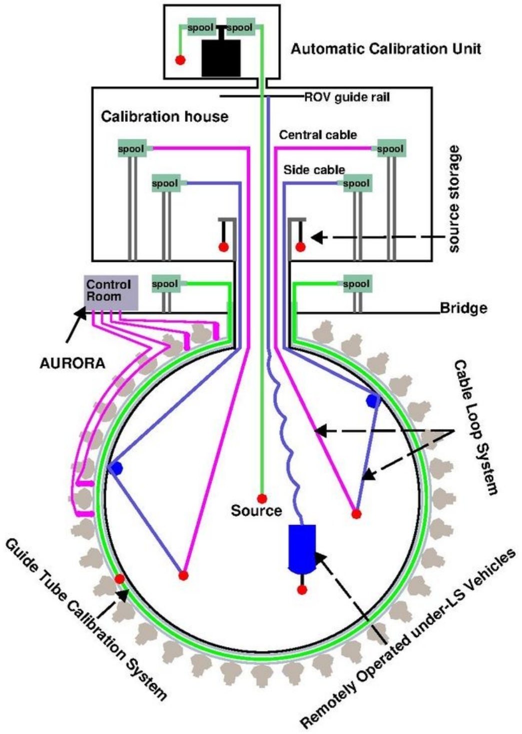
2022-2023 Installation

2023 Completion of the construction

2024 Filling and commissioning

Refer to talk given by Mariam Rifai

Energy Scale Calibration

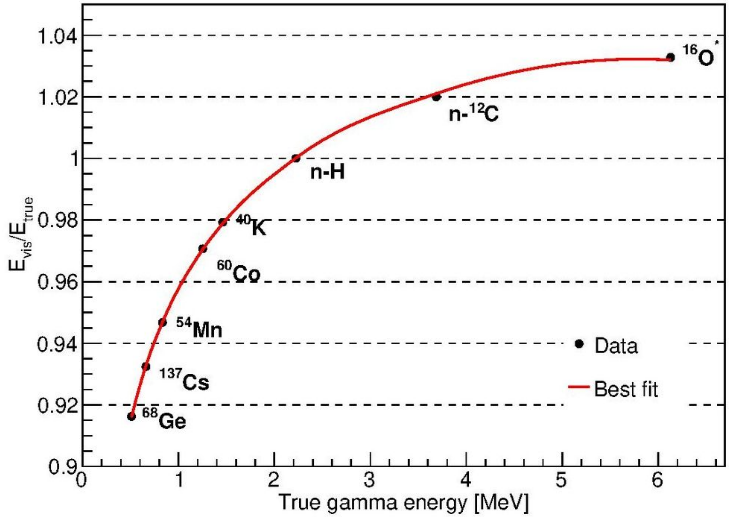


[JUNO collaboration, JHEP 2021, 4 (2021)]

Calibration sources will be regularly inserted into detector

- Understanding of the detector response
- Testing of the reconstruction algorithms
- Calibration of the intrinsically non-linear energy scale

Non-linearity calibration curve



< 1% energy scale uncertainty

Event Selection (same for geo- and reactor neutrinos)

Inverse Beta-Decay (IBD):

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

(reaction threshold: 1.8 MeV)

Prompt signal
handle for neutrino energy:

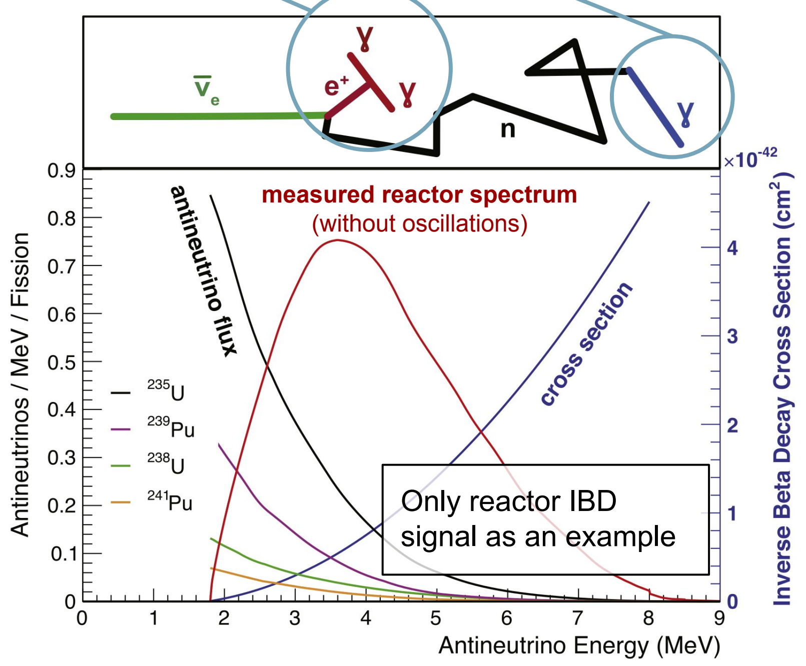
$$E_\nu \simeq E_{e^+} + \Delta m_{n-p} + T_n$$

Delayed signal:
IBD tag: 2.2 and 4.9 MeV within ~200 μs

Selection of IBD candidates:

- Muon veto
- Selection cuts (~10^4 suppression of IBD-like events):
  - Prompt energy: [0.7, 12.0] MeV
  - Delayed energy: [1.9, 2.5] ∪ [4.4, 5.5] MeV
  - Time difference: 1 ms
  - Distance: 1.5 m

Neutrino selection efficiency: **82.2%**

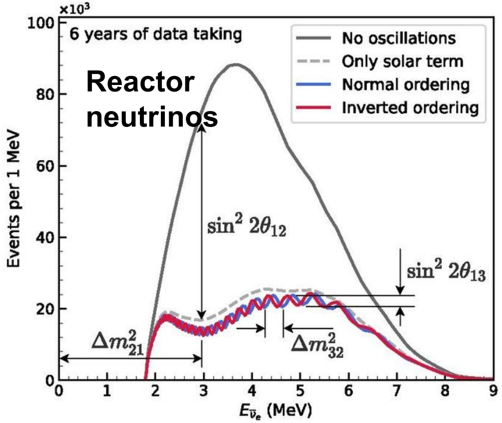


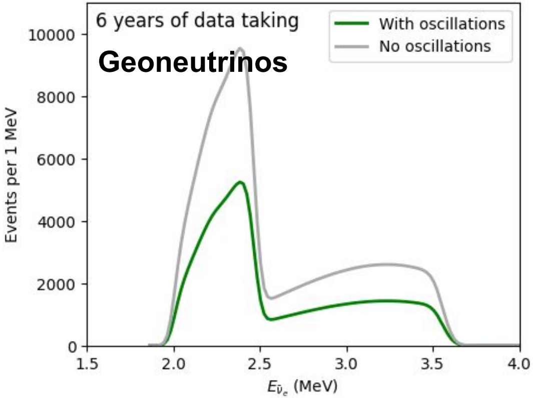
Neutrino Oscillations

- Neutrinos “change” their flavour on the way to the detector.
  (more precisely, the probability to be detected in the same flavour eigenstate as created depends on energy and travel distance)

- Only electron antineutrinos are visible in JUNO
  (via inverse beta-decay)

- Both geo- and reactor antineutrinos oscillate, but the oscillation pattern is different:
  - **Reactor neutrino**: fixed baseline (52.5 km) – very clear oscillation pattern
  - **Geoneutrino**: different baselines (distributed in the Earth) – averaged probability is a working approximation, but an accurate calculation is important when considered together with reactor.





Oscillation parameters must be taken into account. JUNO will measure some of them – important help for geoneutrino measurement!

Geoneutrino Signal and Backgrounds

Signal – geoneutrino

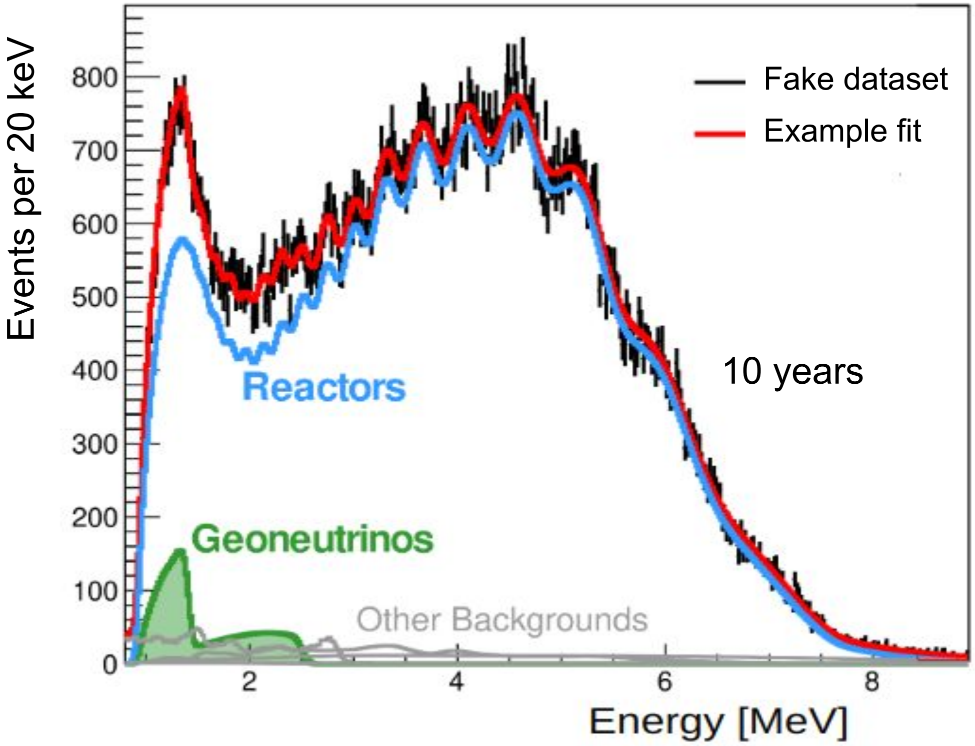
- about 1 event per day
- contributed by ^{232}Th and ^{238}U decays

Irreducible background — reactor neutrinos

- No way to distinguish (in the energy window of geoneutrinos)
- Much higher rate (x35)
- Affected by neutrino oscillations, which JUNO will also measure

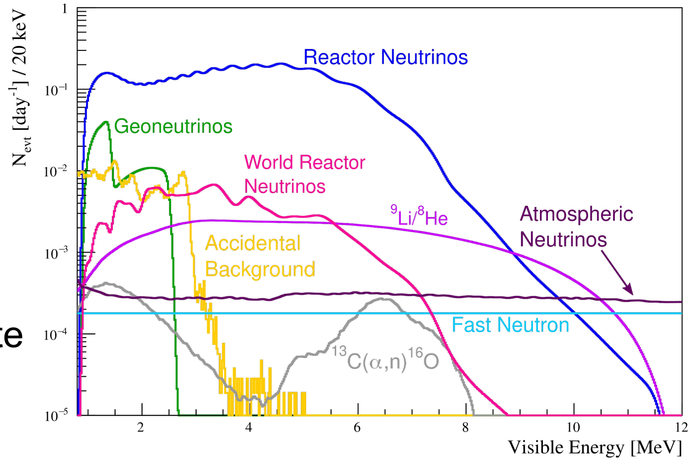
Other backgrounds

- Highly suppressed by selection cuts
- May still impact geoneutrino measurement



What is New Since 2016*

- Inclusion of the oscillation parameters in the fit - the main effect
- Updated detector response modeling
- Updated set of backgrounds
- Updated reactor flux (less cores will be built)
- Use of reactor antineutrino spectral shape constraint from Daya Bay experiment until we can get a constraint from the TAO satellite detector
- Increased exposure (83.0% -> 91.6%) thanks to improved muon veto strategy
- New and complementary analyses:
  - Asimov datasets (without statistical fluctuations) – two working groups
  - Toy Monte Carlo datasets with all fluctuations – one working group



	Rate [counts per day]	Rate uncertainty	Shape uncertainty
Geoneutrinos	1.2	-	5%
Reactor Neutrinos	43.175	-	Daya Bay
Accidentals	0.8	1%	-
$^{9}Li/^{8}He$	0.8	10%	10%
$^{13}C(\alpha,n)^{16}O$	0.05	50%	50%
Fast Neutron	0.1	100%	20%
World Reactor Neutrinos	1	5%	5%
Atmospheric Neutrinos	0.16	50%	5%

[Yellow Book (2015)]

* **Previous publications:** Yellow Book (2015), R. Han et al. (2016)

Sensitivity to the Total Geoneutrino Flux (Th/U fixed)

Fit configuration:

- Th/U abundance fixed to the chondritic ratio (3.9)
- Geo- and reactor neutrino rates are free
- Other background rates are constrained
- Shape uncertainty
- Energy scale uncertainty (negligible impact)
- Oscillation parameters free

Expected geoneutrino precision*
(assuming Th/U mass ratio fixed to 3.9)

PRELIMINARY

1 year	**~22%**
6 years	**~10%**
10 years	**~8%**

* These and further sensitivity numbers are shown for the first time. Paper under preparation.

Existing measurements:

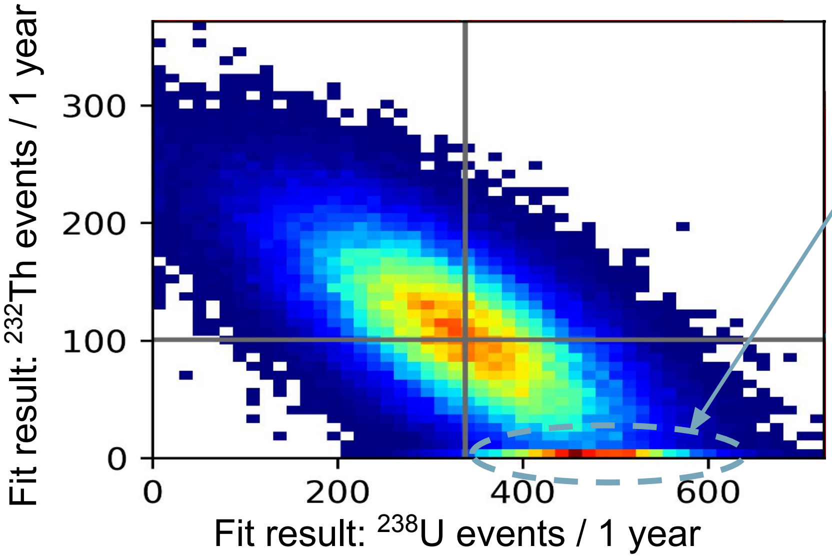
2020 Borexino 17% with 8.9 years [M.Agostini et al., Phys. Rev. D 101, 2020]

2022 KamLAND 15% with 14.3 years [S.Abe et al., Geophys. Res. Lett. 49 (16), 2022]

Refer to talk given by Livia Ludhova

Sensitivity to the Total Geoneutrino Flux (Th/U free)

Distribution of possible fit results with fixed oscillation parameters



- **High statistics is crucial:** after 1 year there is a large chance to get Th railed to 0 even with fixed oscillation parameters
- **Th and U are strongly anticorrelated:** JUNO can disentangle the Th and U contributions and make a very good measurement of their sum

Expected precision

	6 years	10 years
^{232}Th:	**~40%**	**~35%**
^{238}U:	**~35%**	**~30%**
^{232}Th+^{238}U:	**~18%**	**~15%**
^{232}Th/^{238}U ratio:	**~70%**	**~55%**

PRELIMINARY

Sensitivity to Mantle Contribution:

Assuming no difference in spectral shapes for lithosphere and mantle:

Mantle = Total Geonu Measurement – Lithosphere Prediction

Existing lithospheric prediction:

Global: $30.9^{+6.5}_{-5.2}$ TNU
[Prog. in Earth and Planet. Sci. 2, 5, 2015]
JULOC: $40.4^{+5.6}_{-5.0}$ TNU
[Phys.Earth.Planet.Inter. 299, 2020]

Existing measurements:

2020 Borexino: $20.8^{+9.4}_{-9.2}$ TNU
[M.Agostini et al., Phys. Rev. D 101, 2020]
2022 KamLAND: $4.8^{+5.6}_{-5.9}$ TNU
[S.Abe et al., Geophys. Res. Lett. 49 (16), 2022]

Refer to talks of Livia Ludhova and Virginia Stratti

- Ongoing effort on **making a better prediction for the lithospheric signal near JUNO** with local geo-model: better precision for mantle measurement
- Estimation of discovery potential (strongly depending on the chosen BSE model) is ongoing

Summary

- **Highest geoneutrino statistics** — the main advantage w.r.t. other experiments JUNO will collect more geoneutrino events than all the other experiments in 1 year.

- **The main challenge is disentangling the geoneutrino signal from the dominant reactor neutrino signal:** JUNO is designed to measure it!

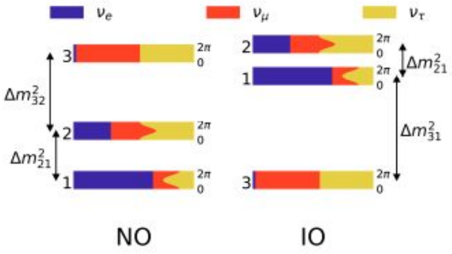
- **Precise measurement of total geoneutrino flux:**
  - JUNO will reach the level of Borexino and KamLAND (~15%) within few years, assuming fixed chondritic Th/U, and improve it to ~10% in 6 years
  - Making no assumption on Th/U ratio JUNO will reach ~15% in 10 years

- **Potential to observe signal from mantle:** JUNO is expected to provide the most statistically significant measurement, complementary to KamLAND and Borexino. Ongoing effort on the local geological model will improve the result.

- **Full release of updated sensitivities soon**

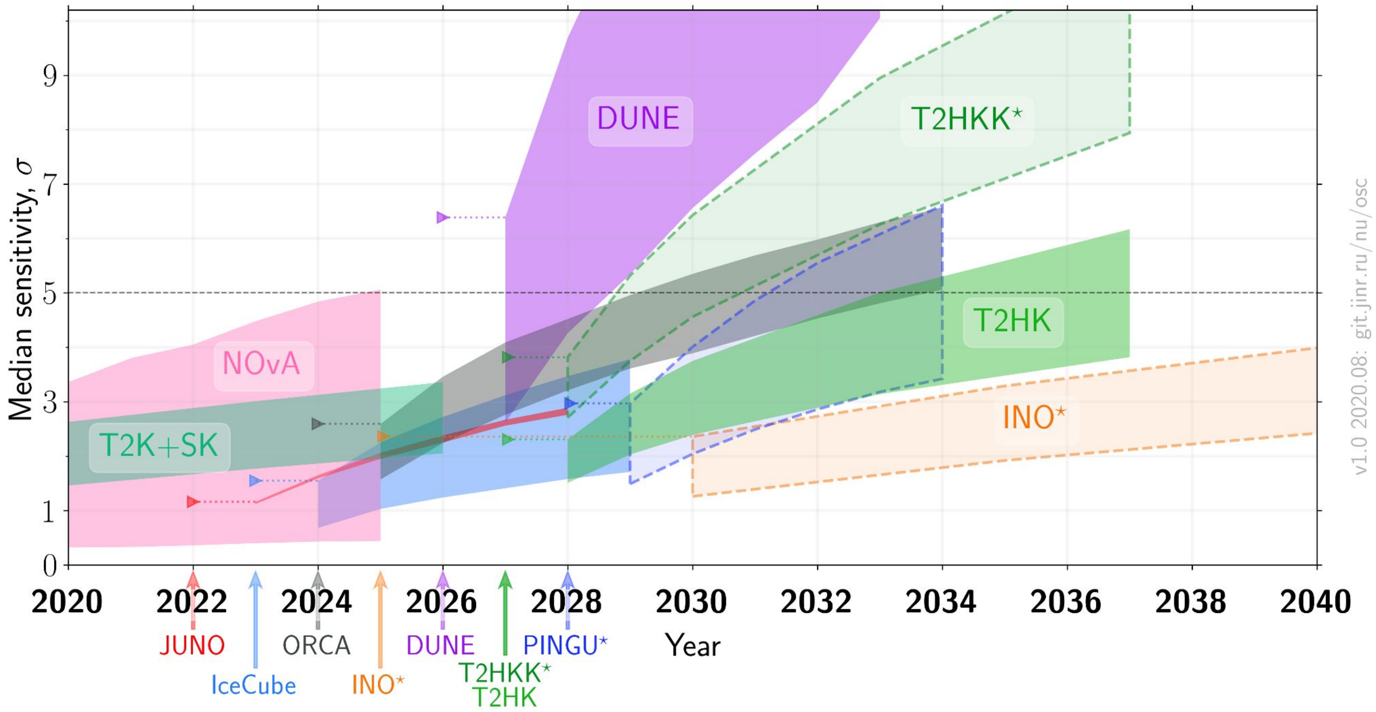
Backup Slides

Neutrino Mass Ordering

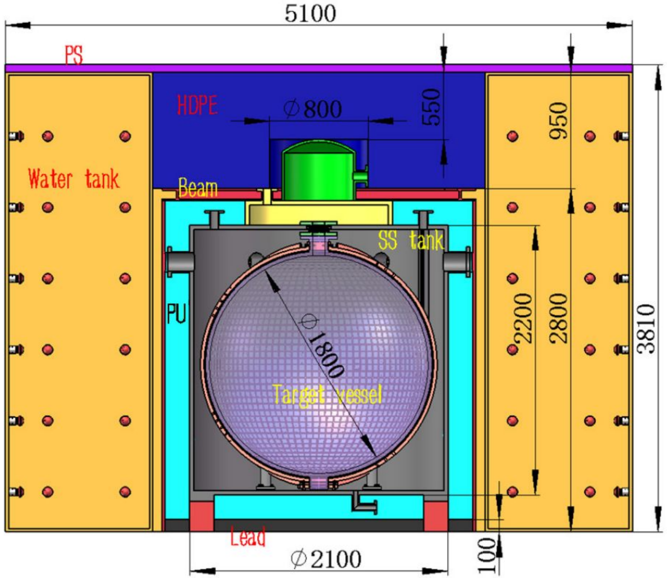


Probability of finding the α neutrino flavor in the i-th neutrino mass eigenstate. The CP-violating phase is varied (0→2π).

[P.F. de Salas et al, arXiv:1806.11051]



JUNO TAO (Taishan Antineutrino Observatory)



An innovative apparatus:

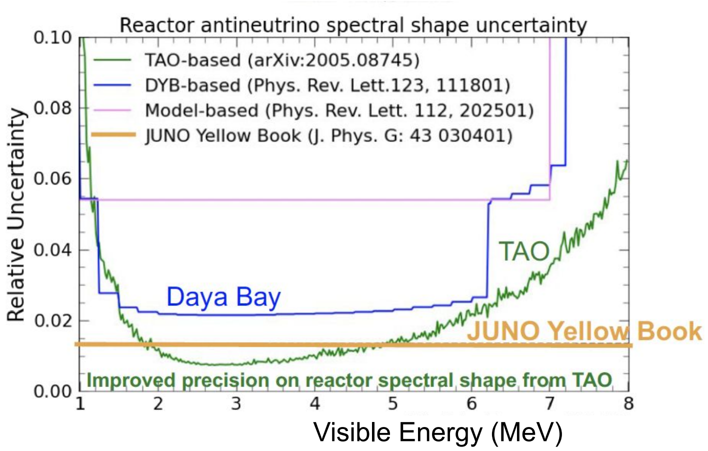
- 1 ton fiducial volume / 2.6 tons of Gd-LS
- Almost full coverage with SiPM (~50% PDE @ -50°C)

~2% at 1 MeV energy resolution
(Gaussian sigma)

30 x JUNO statistics

Measurement of reactor ν_e spectrum at 30 m distance from a Taishan NPP core (no oscillations):

- Will be sensitive to fine structure with better precision
- Provide model-independent reference spectrum for JUNO
- Improvement of nuclear databases



Liquid Scintillator of JUNO

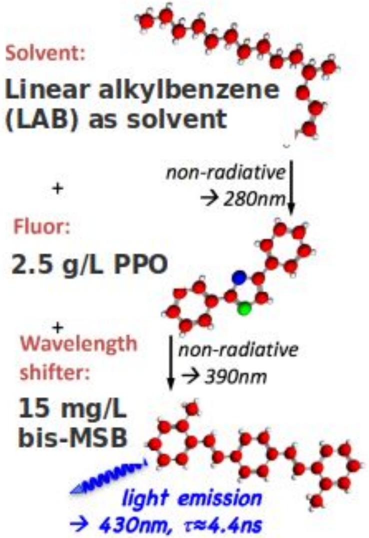
Composition:

LAB +

PPO (2.5 g/L) + bis-MSB (3 mg/L)

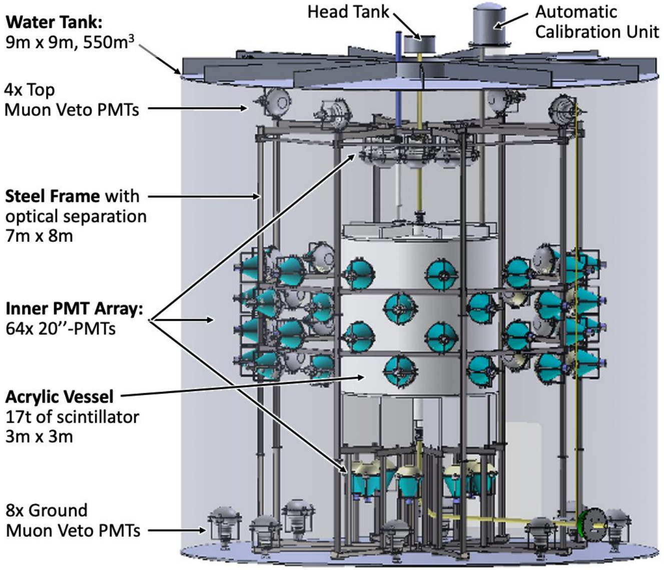
LAB purification:

1. Al_2O_3 filtration column (optical properties improvement)
2. Distillation (heavy elements removal/
3. transparency improvement)
4. Water extraction (U/Th/K radioisotopes removal)
5. Steam/nitrogen stripping (removal of Ar, Kr, Rn gaseous impurities)



[JUNO collaboration, NIM-A 988, 2021]

Monitored during filling by OSIRIS (Online Scintillator Internal Radioactivity Investigation System)



[arXiv:2103.16900 (2021)]

Uncertainty Estimation with Toy MC