

JUNO experiment first results on neutrino oscillations

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Neutrino oscillations in a nutshell

Neutrino flavor oscillation induced by **quantum mechanics**.

Neutrino flavor tag in production and detection through CC weak interaction (ν_e, ν_μ, ν_τ), but vacuum propagation as combination of mass eigenstates (ν_1, ν_2, ν_3).

The mixing matrix is called Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix.

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\begin{matrix} \mathbf{c} = \mathbf{cos} \vartheta \\ \mathbf{s} = \mathbf{sin} \vartheta \end{matrix}$$

Majorana phases omitted because unobservable in neutrino oscillations.

Inside the matrix, three mixing angles, θ_{12}, θ_{13} and θ_{23} , and one phase δ (**CP violation**).

Oscillation probability in vacuum:

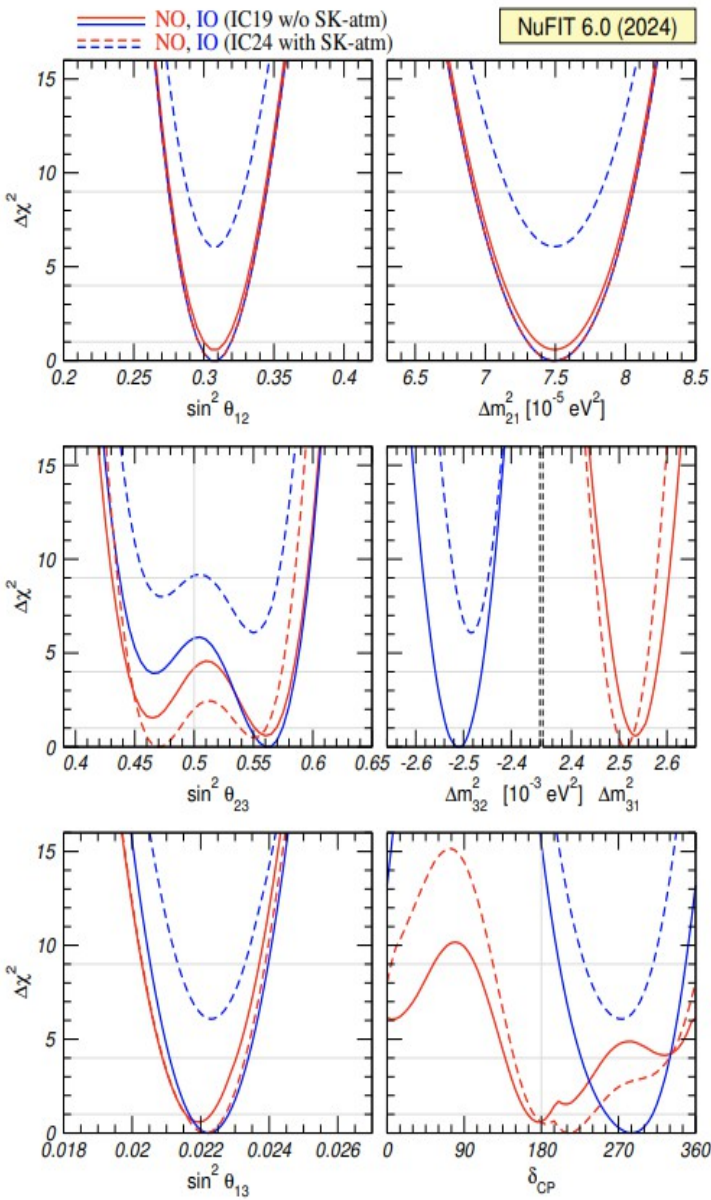
$$P_{\alpha \rightarrow \beta} = \delta_{\alpha\beta} - 4 \sum_{i>j} \text{Re}(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin^2 \left(\frac{\Delta m_{ij}^2 L}{4E} \right) + 2 \sum_{i>j} \text{Im}(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*) \sin \left(\frac{\Delta m_{ij}^2 L}{2E} \right)$$

Detection of ν -oscillation:

- **Neutrinos have mass**
- **ν mass not degenerate**
- 2 independent $\Delta m^2 \Rightarrow 3 \nu$

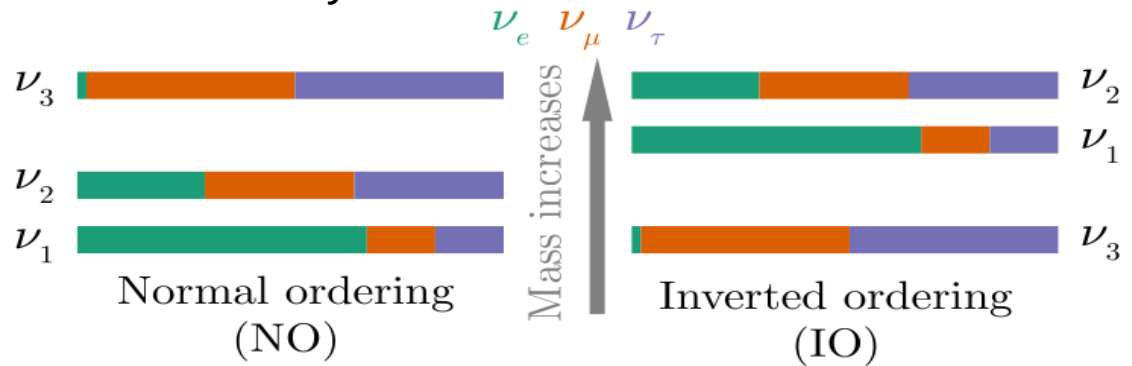
Neutrino knowledge: present status

So far many experiments detected neutrino oscillations, using natural (solar, atmospheric neutrinos) as well as artificial sources (neutrino beams, from decays on flight of mesons, or nuclear reactors).



Mixing parameters measured at few % level by global fits:
 Gonzalez-Garzia et al. JHEP 12(2025) 216
 Capozzi et al. ArXiv 2503.07752
 De Salas et al. ArXiv 2006.11237

Not known:
 Mass hierarchy



θ_{23} octant

CP violation phase ?

neutrino absolute mass ?

Neutrinos a la Dirac (4 states) or a la Majorana (2 states).

Nuclear Reactors as antineutrino source



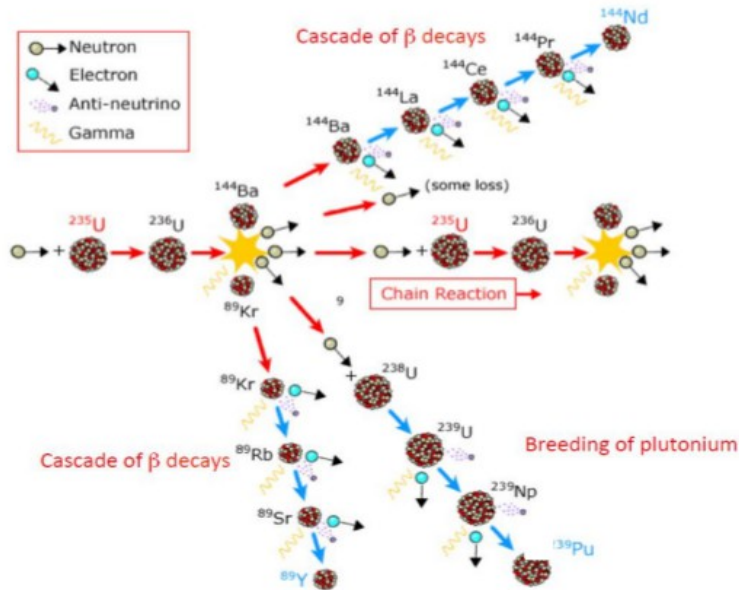
Nuclear reactors are a pure anti- ν_e source from β -decay of fission daughters.

Low energy: $E < 10$ MeV.

Flux: ≈ 6 anti- ν_e per fission. $2 \cdot 10^{20}$ anti- ν_e per Gw_{th} .

Commercial reactors are powered by a fuel mixture (^{235}U , ^{239}Pu , ^{238}U , ^{241}Pu) with Low Enriched Uranium content.

A precise estimation of anti- ν_e flux on the experimental site requires knowledge of fuel composition evolution in time.



Detected anti- ν_e spectrum:

$$S(E, L, t) \sim \sum_j f_j(E, t) * S_j(E) * P_{ee}(E, L) * \sigma(E) * \varepsilon(E)$$

$f_j(E, t)$ = isotope j fission fraction

$S_j(E)$ = isotope j fission neutrino spectrum

$P_{ee}(E, L)$ = oscillation survival probability

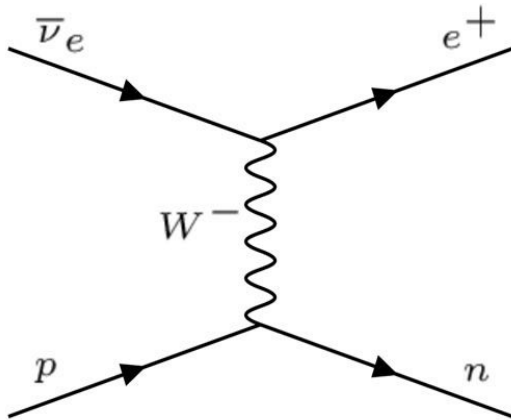
$\sigma(E)$ = Inverse Beta Decay cross section

$\varepsilon(E)$ = selection efficiency

E =neutrino energy, t =time, L =baseline

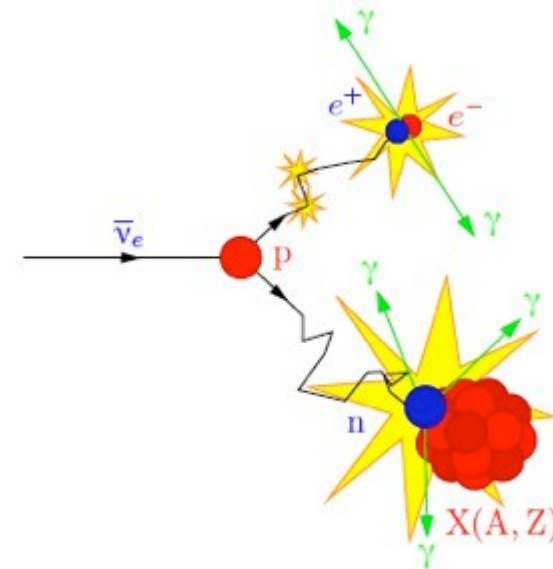
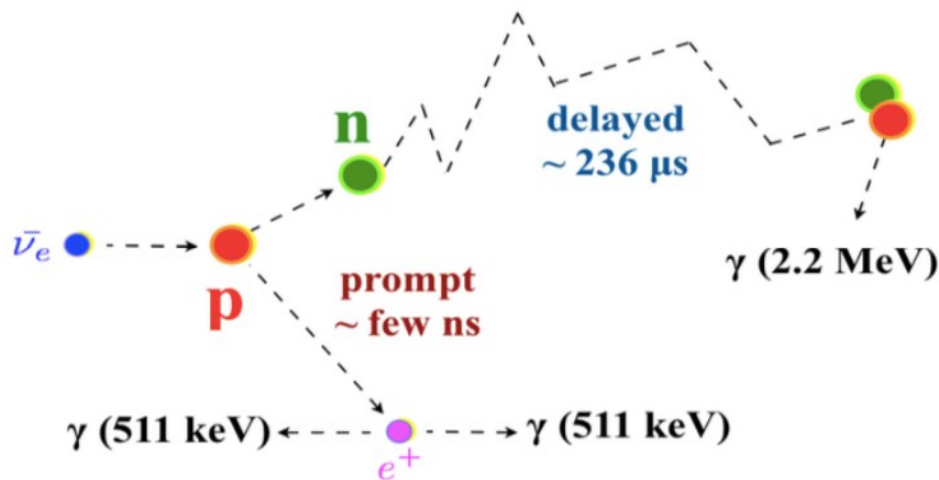
Inverse Beta Decay (IBD)

Antineutrino detection through Inverse Beta Decay (IBD).



- 1.8 MeV threshold on neutrino energy
- Relatively large cross section
- Background rejection using coincidence between positron (prompt) and neutron (delayed) signals
- $E_{\text{prompt}} = E_{\nu} - 0.8 \text{ MeV}$ (neglecting n recoil kinetic energy)

Most experiments use liquid scintillator as target and detector: $n+p \rightarrow \gamma$ (2.2 MeV).

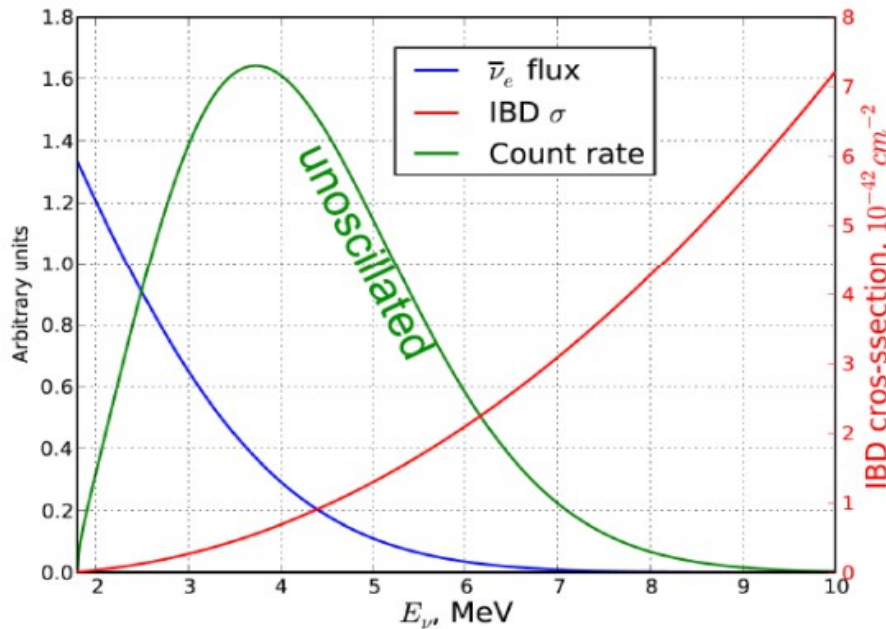


Gadolinium doping for faster neutron capture (tens of μs): $n+\text{Gd} \rightarrow \gamma\text{-rays}$ (8 MeV).

Reactors and neutrino physics

First neutrino detection by Reines e Cowan (1956) using reactor anti-neutrinos. $\text{H}_2\text{O} + \text{CdCl}_2$ as target, 2 liquid scintillator tanks as target.

More recently neutrino oscillations parameters measurement.



Given the energies, $\nu_{\mu,\tau}$ cannot produce μ,τ in CC interactions.....

Oscillation (disappearance) probability

$$P_{ee}(L/E) = 1 - P_{21} - P_{31} - P_{32}$$

$$P_{21} = \cos^4(\theta_{13}) \sin^2(2\theta_{12}) \sin^2(\Delta_{21})$$

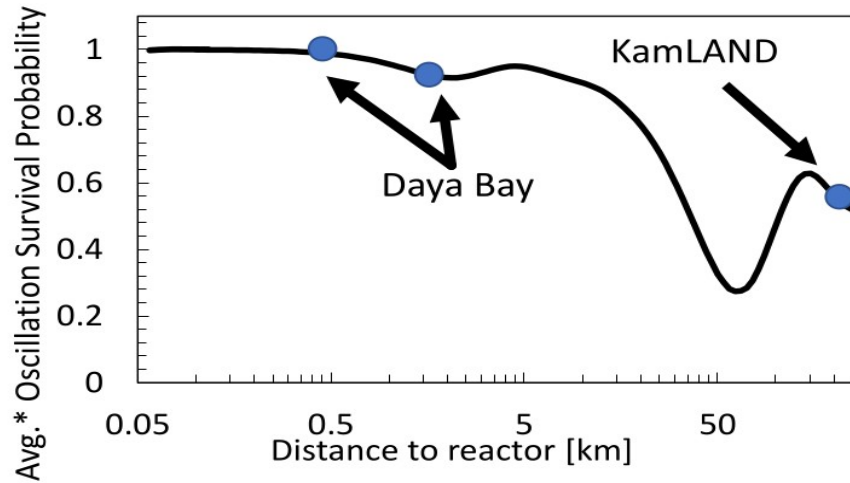
$$P_{31} = \cos^2(\theta_{12}) \sin^2(2\theta_{13}) \sin^2(\Delta_{31})$$

$$P_{32} = \sin^2(\theta_{12}) \sin^2(2\theta_{13}) \sin^2(\Delta_{32})$$

Independent from θ_{23}
and CP violation phase !!

$$\Delta_{ij} = \Delta m_{ij}^2 L / (4E)$$

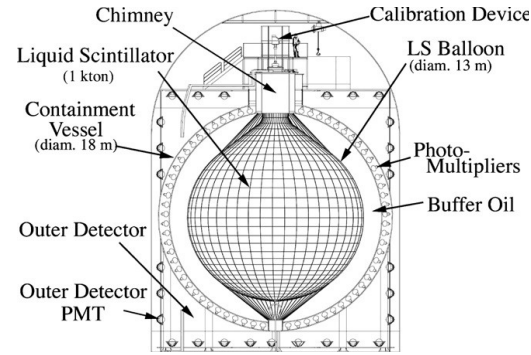
Neutrino oscillations and reactors



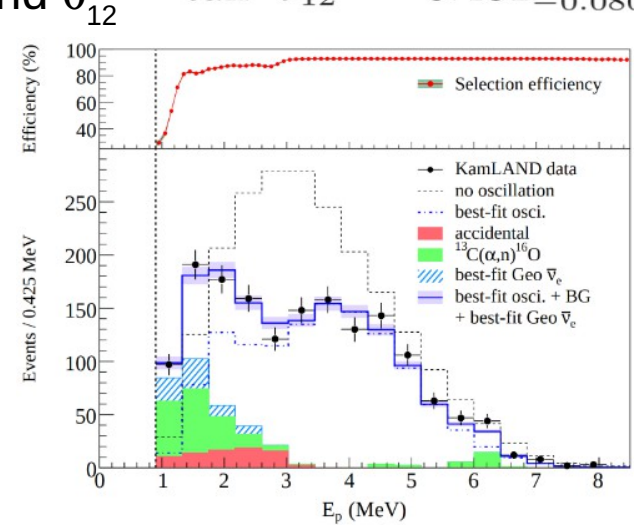
KamLAND @180 km baseline
Measurement of Δm_{21}^2 and θ_{12}

$$\Delta m_{21}^2 = 7.54_{-0.18}^{+0.19} \times 10^{-5} \text{ eV}^2$$

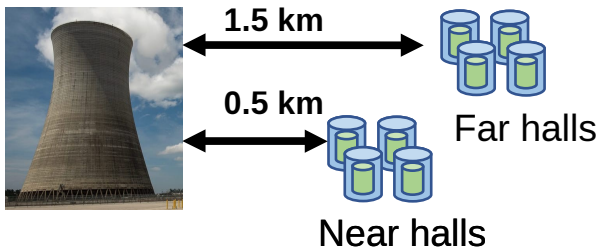
$$\tan^2 \theta_{12} = 0.481_{-0.080}^{+0.092}$$



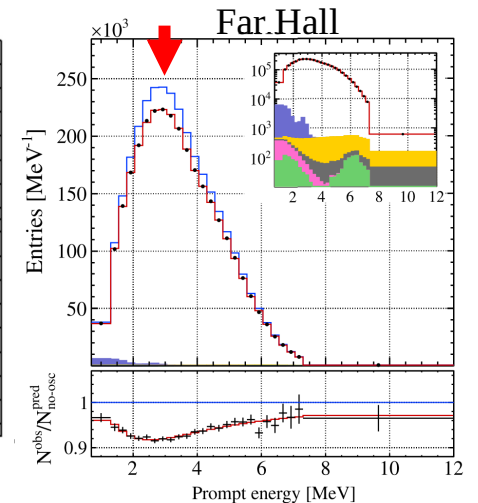
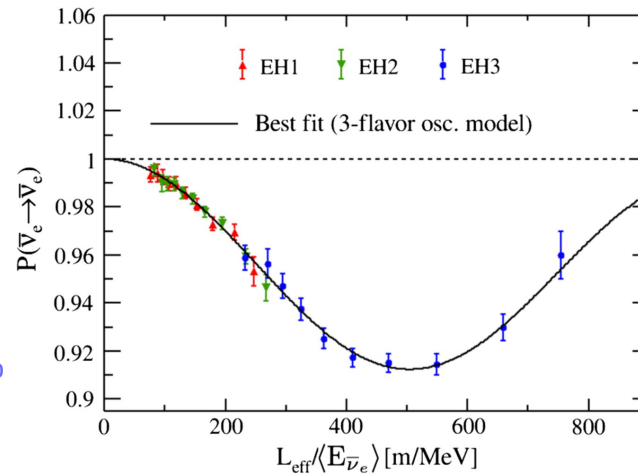
1 kton LS detector



Daya Bay (and Double CHOOZ, Reno)
Measurement of Δm_{31}^2 and θ_{13}



$$\theta_{13} \sim 9^\circ$$



Neutrino mass hierarchy measurement

Can be measured also with reactor neutrino experiments, exploiting Δm_{31}^2 oscillation amplitude interference with Δm_{21}^2 amplitude @L=50 km.

Physics Letters B 533 (2002) 94 (Petcov, Piai)

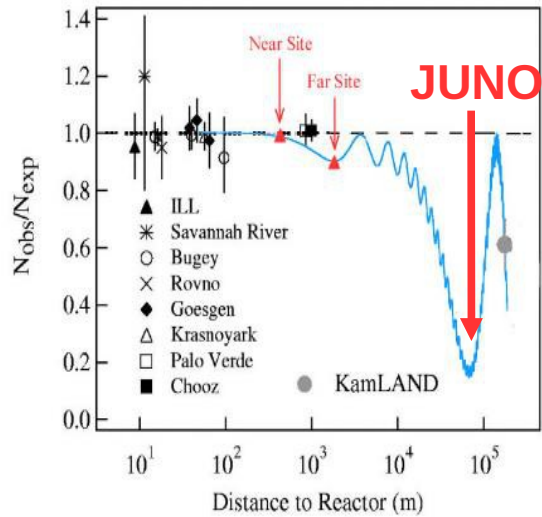
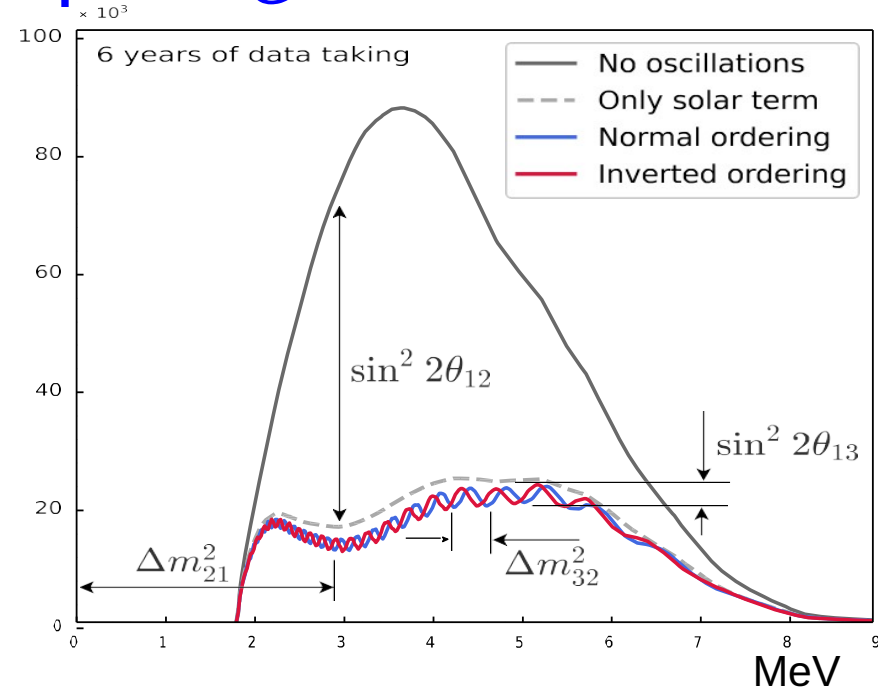
$$P_{ee}(L/E) = 1 - \boxed{P_{21}} - \boxed{P_{31}} - \boxed{P_{32}}$$

$$P_{21} = \cos^4(\theta_{13}) \sin^2(2\theta_{12}) \sin^2(\Delta_{21})$$

$$P_{31} = \cos^2(\theta_{12}) \sin^2(2\theta_{13}) \sin^2(\Delta_{31})$$

$$P_{32} = \sin^2(\theta_{12}) \sin^2(2\theta_{13}) \sin^2(\Delta_{32})$$

P_{ee} independent from θ_{23} and CP violation phase....



JUNO detector concept:

Equal distance L from 2 reactor power plants
 Total power 26.6 GWth
 L=52.5 km (maximum of Δm_{21}^2 induced oscil)

Large mass (20 kt) of Liquid scintillator (LS)
 Energy resolution: 3% @1 MeV

- High LS light yields and transparency ($\lambda_{att} > 20m$)
- 30% PMT qe and large coverage





JUNO Collaboration

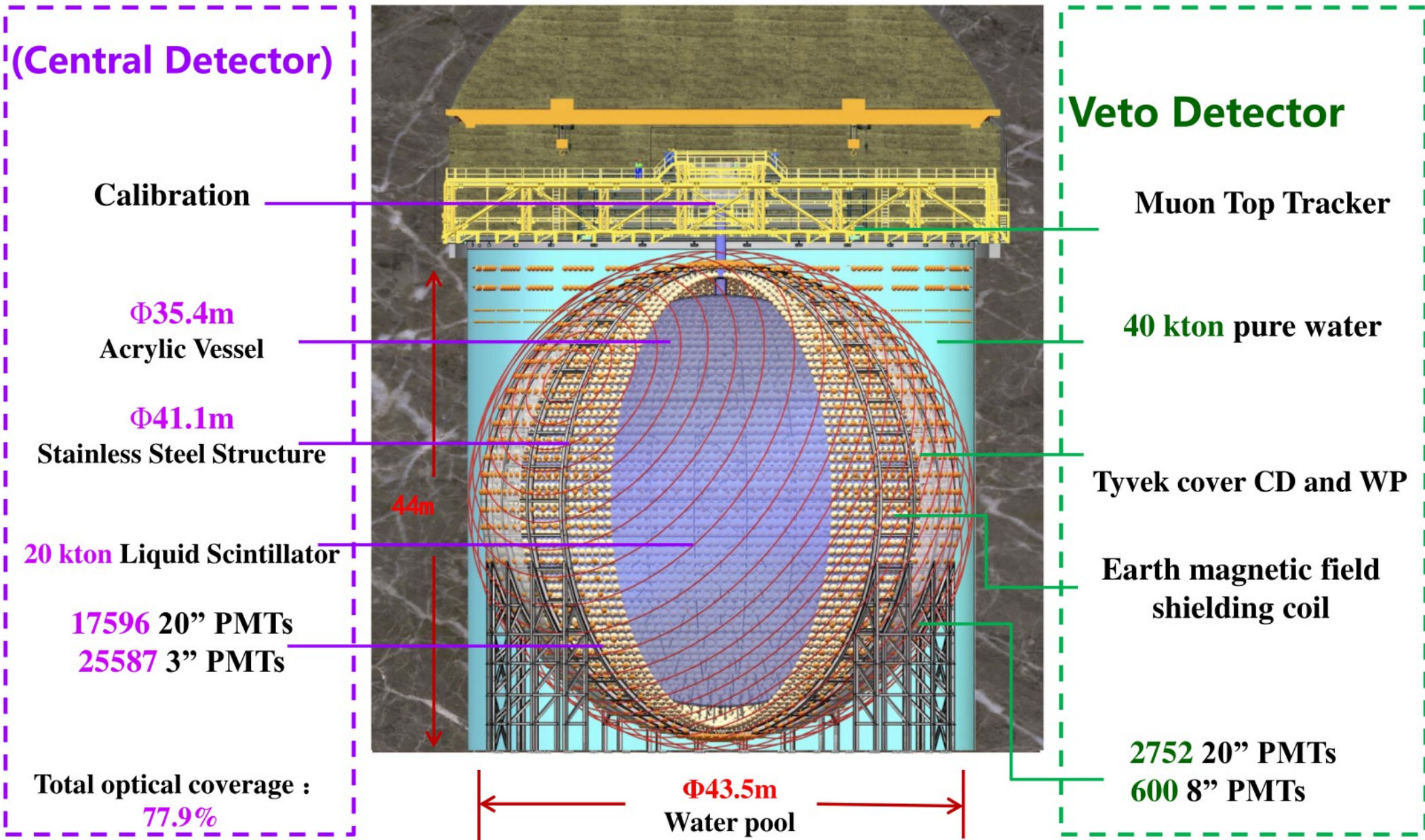
Country	Institute	Country	Institute	Country	Institute
Armenia	Yerevan Physics Institute	China	Wuhan U.	Italy	INFN Catania
Belgium	Universite Libre de Bruxelles	China	Xi'an JT U.	Italy	INFN di Frascati
Chile	SAPHIR	China	Xiamen University	Italy	INFN-Ferrara
Chile	UNAB	China	Zhengzhou U.	Italy	INFN-Milano
China	BISEE	China	JXNU	Italy	INFN-Milano Bicocca
China	CAGS	China	CUG-Beijing	Italy	INFN-Padova
China	CNPRI	China	ECUT-Nanchang City	Italy	INFN-Perugia
China	DGUT	China	CDUT-Chengdu	Italy	INFN-Roma 3
China	Guangxi U.	China	SUSTech-Shenzhen	Pakistan	PINSTECH (PAEC)
China	Harbin Institute of Technology	China	Hunan U.	Russia	JINR
China	IHEP	Czech	Charles U.	Slovakia	FMPICU
China	Jinan U.	Finland	University of Jyvaskyla	Taiwan-China	National Chiao-Tung U.
China	Nanjing U.	France	IJCLab Orsay	Taiwan-China	National Taiwan U.
China	Nankai U.	France	LP2i Bordeaux	Taiwan-China	
China	NCEPU	France	CPPM Marseille	Taiwan-China	NKNU
China	Shandong U.	France	IPHC Strasbourg	Taiwan-China	NTUT
China	Shanghai JT U.	France	Subatech Nantes	Thailand	NARIT
China	IGG-Beijing	Germany	RWTH Aachen U.	Thailand	PPRLCU
China	SYSU	Germany	TUM	Thailand	SUT
China	Tsinghua U.	Germany	U. Hamburg	U.K.	U. Liverpool
China	UCAS	Germany	GSI	U.K.	U. Warwick
China	U. of South China	Germany	U. Mainz	USA	UMD-G
China	Wu Yi U.	Germany	U. Tuebingen	USA	UC Irvine

+Observers: USTC, Pekin Uni., Jilin Uni., Beijing Normal Uni., CIAE (China), PUC, UEL (Brazil)

Collaboration established in 2014.

At present 69 institutions, more than 600 collaborators.

JUNO detector

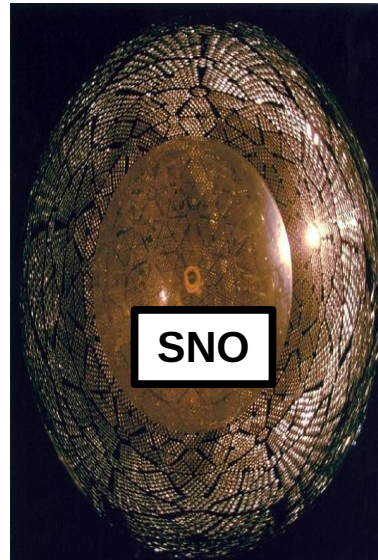
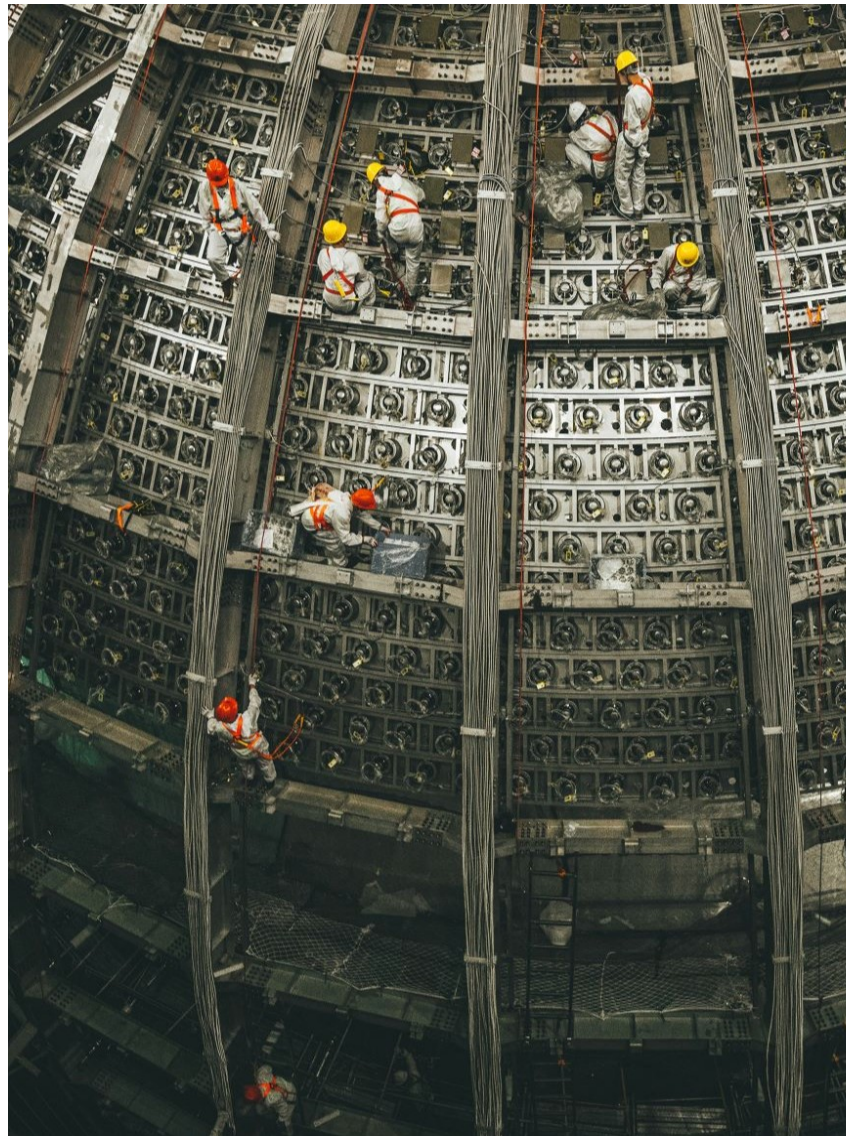


JUNO CDR: arXiv:1508.07166 (2015)
Update in arXiv:2104.02565

	KL	BX	SNO+	JUNO
# PMTs	1900	2200	10000	17596 LPMTs 25600 SPMTs
Coverage	~34%	~30%	~50%	78%
Npe/MeV	~250	~450	~520	>1600

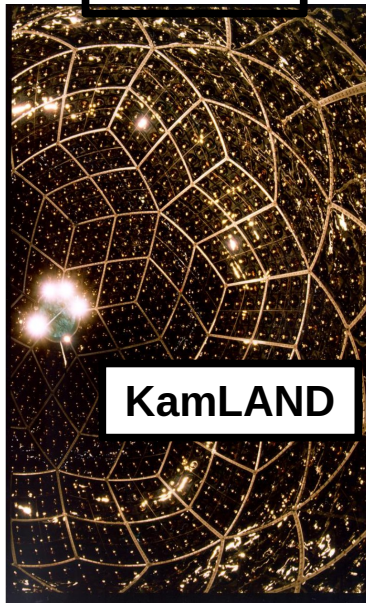
JUNO detector

**JUNO
20000 ton**



SNO

1000 ton

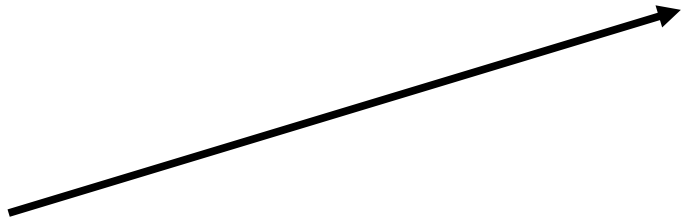


KamLAND

**Borexino
300 ton**



**Daya Bay
8*20 ton**



JUNO liquid scintillator

JUNO LS composition: LAB + 2.5g/L PPO + 3 mg/L bis-MSB

Four purification plants + LS Mixing + QA/QC + high purity N2 and water production plant to guarantee radio-purity and transparency



5000 m3 LAB storage tank



1) Al₂O₃ for optical transparency



2) Distillation for radiopurity



Mixing LAB with PPO and bis-MSB

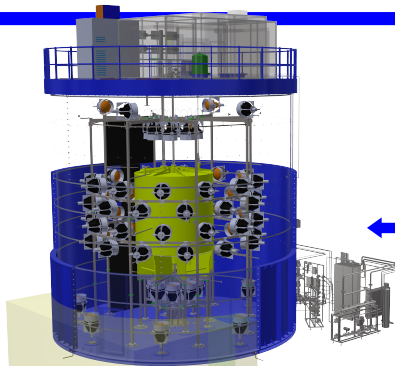


3) Water extraction to remove radioactive impurities

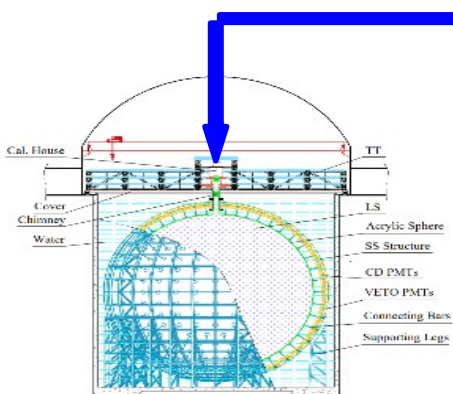
1800 m SS pipes to underground



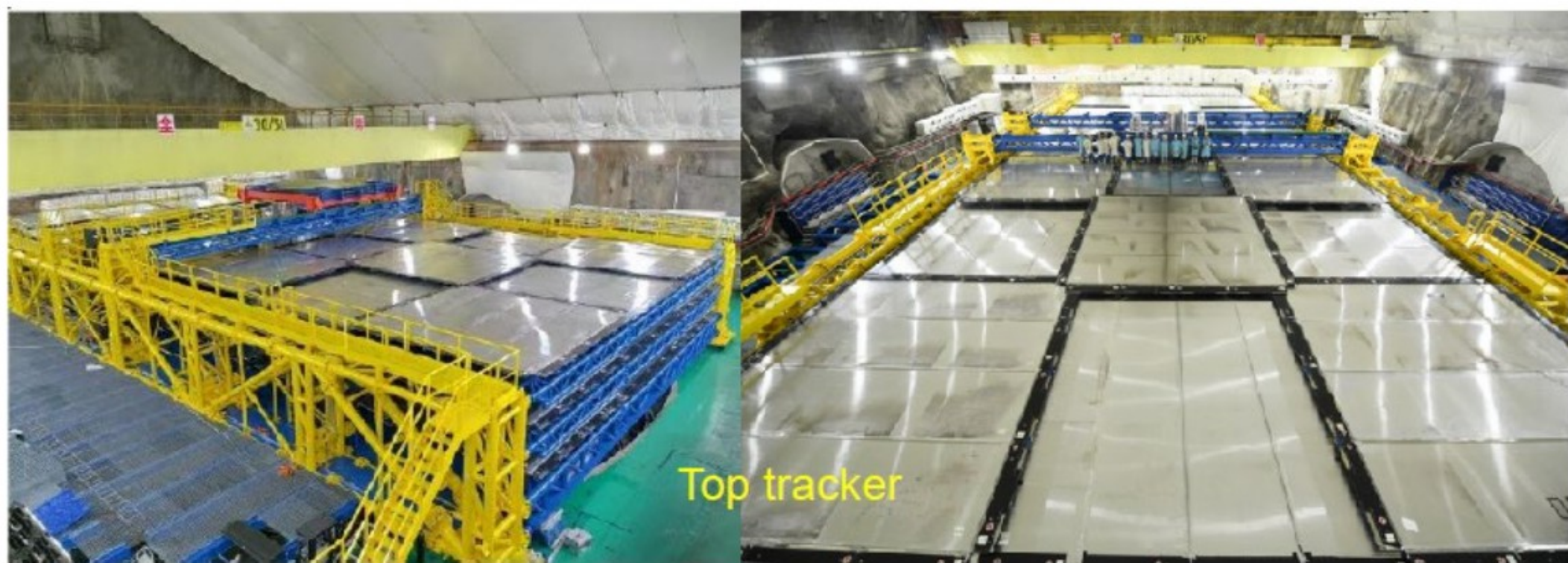
4) Gas stripping to remove Rn and O₂



OSIRIS to monitor Rn and other backgrounds



JUNO Top Tracker



Three layers of x-y plastic scintillator strips (6.7 m long) read-out by 64 ch maPMTs. Recovered from OPERA with electronics refurbished (based on MAROC3 chip). 60% coverage of the top (but only 30% of muons crossing the CD). VETO cosmic muons and monitoring of tagging/tracking performances of WC and CD.

Calibration system

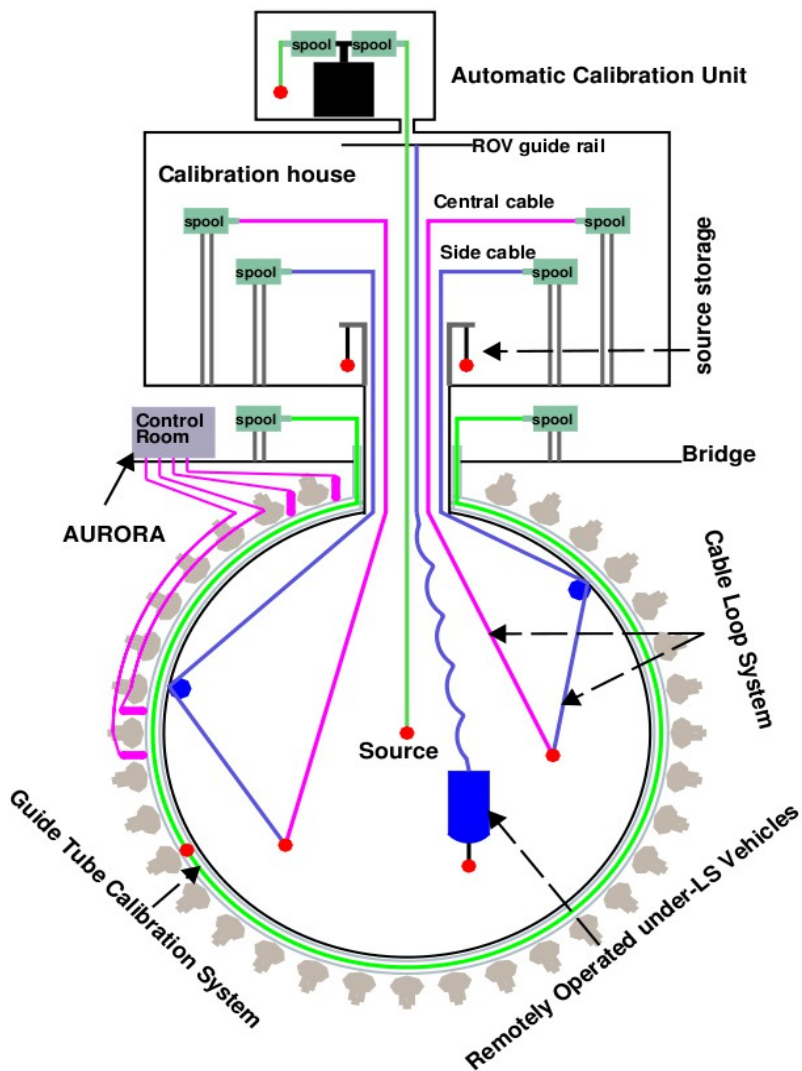
To keep energy scale uncertainty below 1%, **four calibration systems**:

Automatic Calibration Unit (ACU): 1D along z-axis.

Cable Loop System (CLS): 2D plane inside vessel.

Guide Tube (GT): 2D plane inside vessel.

Remotely Operated Vehicle (ROV): 3D anywhere inside vessel.



Source list

Sources/Processes	Type	Radiation
^{137}Cs	γ	0.662 MeV
^{54}Mn	γ	0.835 MeV
^{60}Co	γ	1.173 + 1.333 MeV
^{40}K	γ	1.461 MeV
^{68}Ge	e^+	annihilation 0.511 + 0.511 MeV
$^{241}\text{Am-Be}$	n, γ	neutron + 4.43 MeV ($^{12}\text{C}^*$)
$^{241}\text{Am-}^{13}\text{C}$	n, γ	neutron + 6.13 MeV ($^{16}\text{O}^*$)
$(n, \gamma)\text{p}$	γ	2.22 MeV
$(n, \gamma)^{12}\text{C}$	γ	4.94 MeV or 3.68 + 1.26 MeV

System strategy:

Different sources (LS non-linearity)

Tunable light source: electronics non-linearity

Many locations (detector non-uniformity)

More details in JHEP 03, 004 (2021)

JUNO PMT systems

- JUNO will use 20" Photomultipliers as its main photodetection system.
- Water-proof potting (voltage divider) and implosion protection.
- Also ~25600 3" PMTs: improve the control of systematics and increase dynamic range in photon-counting mode.
- Extensively tested before installation.

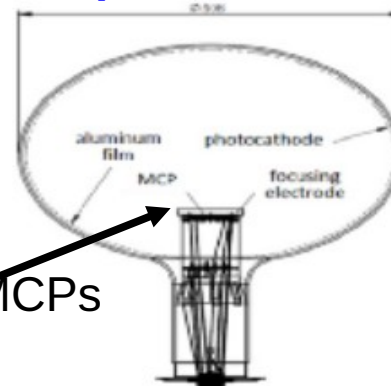
Tight arrangement with photocatode coverage > 75%
(78% including Small PMTs).

Large PMT

Small PMT

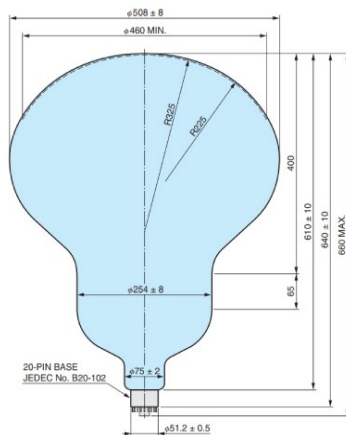
2 Horizontal MCPs

MCP-PMT



NIMA 971 (2020) 164021

Dynode PMT



Two complementary LPMT technologies:

- ~15000 MCP-PMTs from NNVT (Microchannel plates) with larger PhotoDetection Efficiency (energy measurement)
- ~5000 dynode PMTs from Hamamatsu with better Transit Time Spread (vertex reconstruction and tracking in Central Detector)

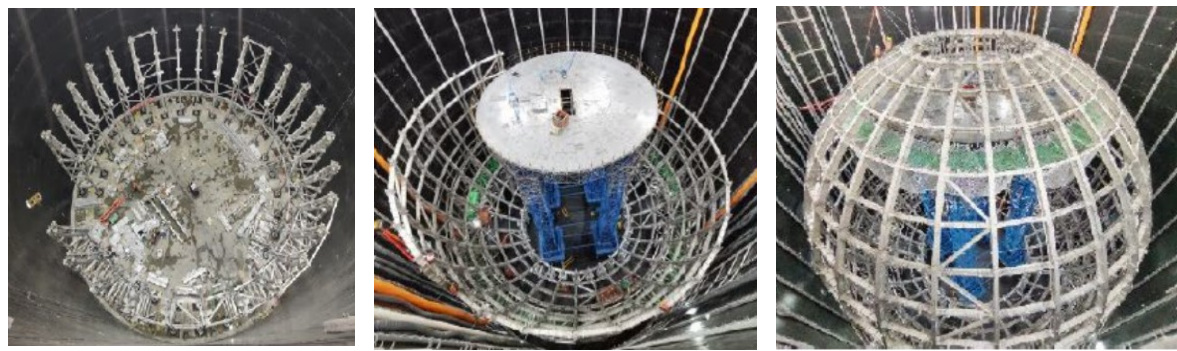
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From Hamamatsu R12860 datasheet

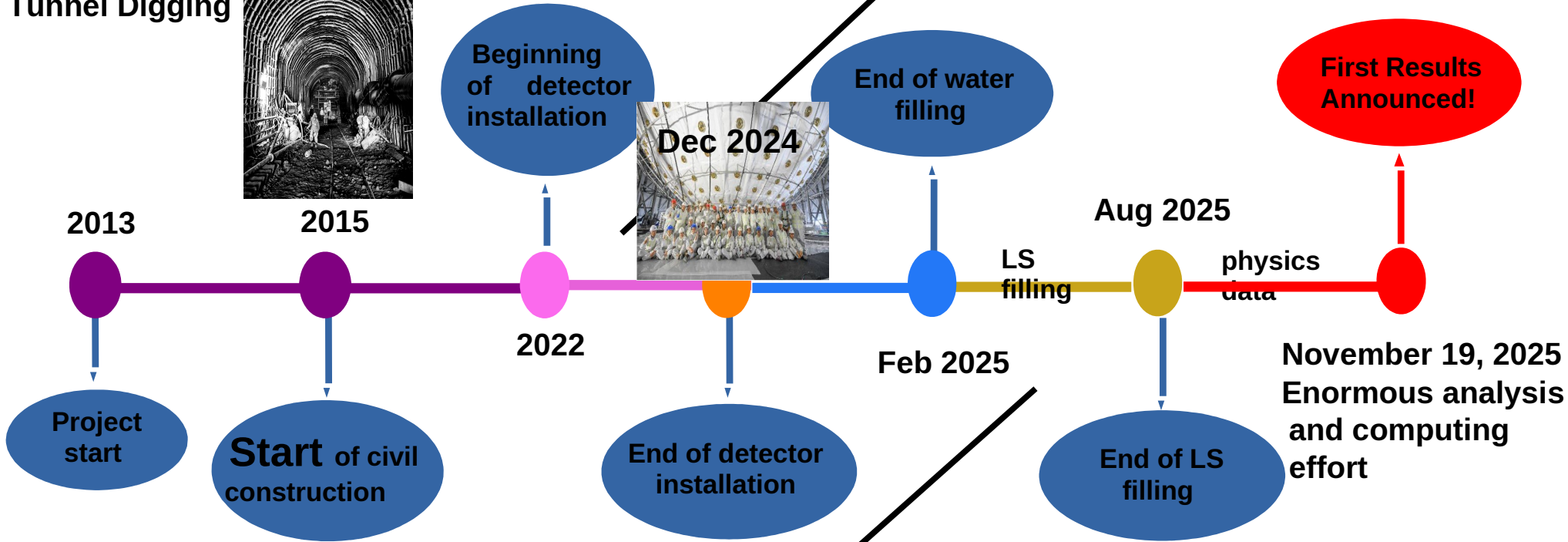
JUNO in pictures



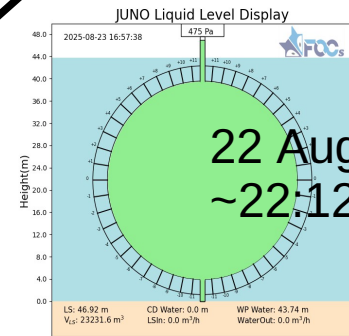
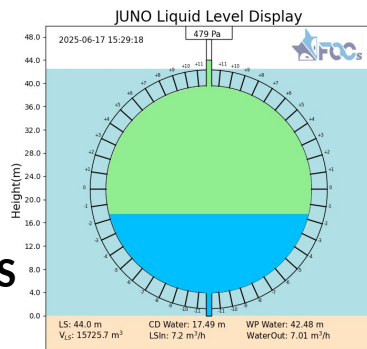
A long journey...



Tunnel Digging



Water extraction and LS filling simultaneously

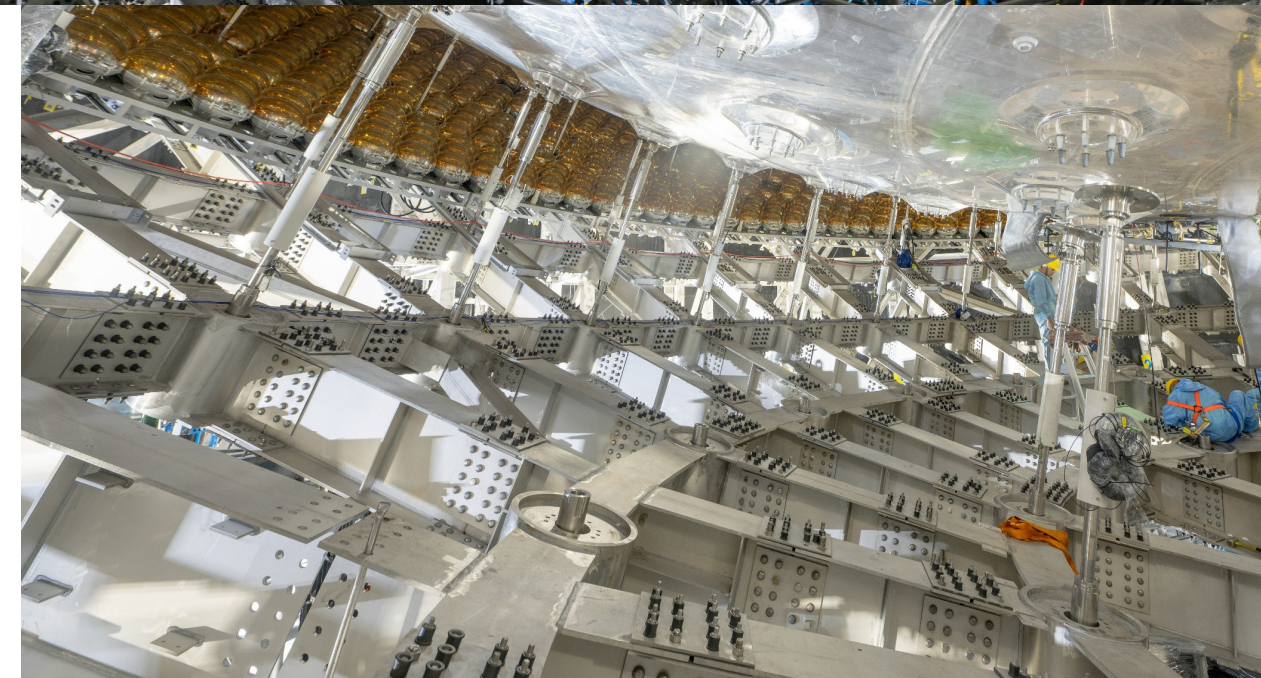
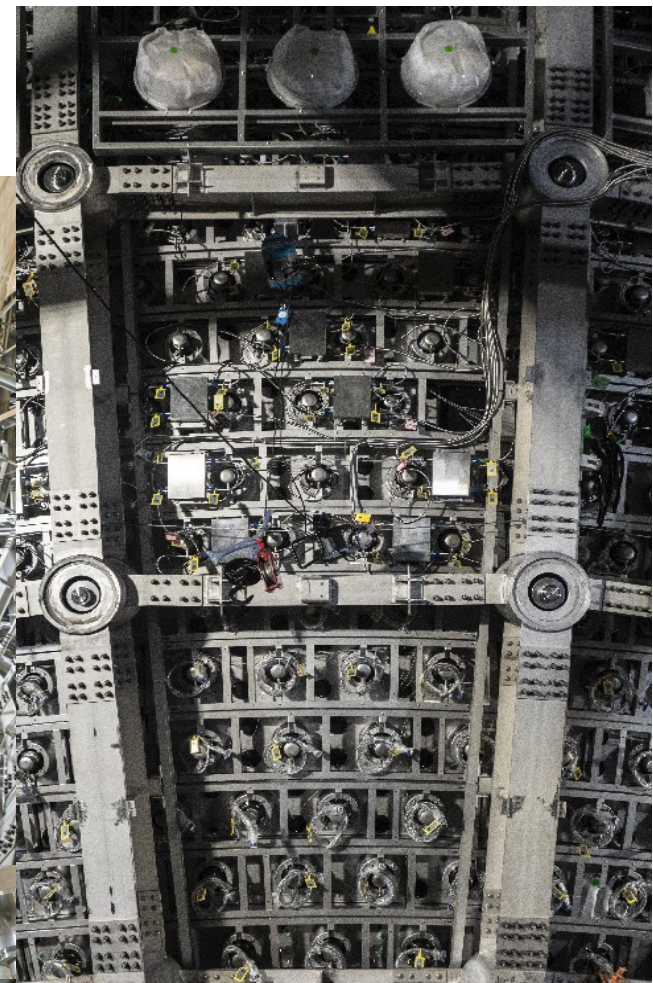
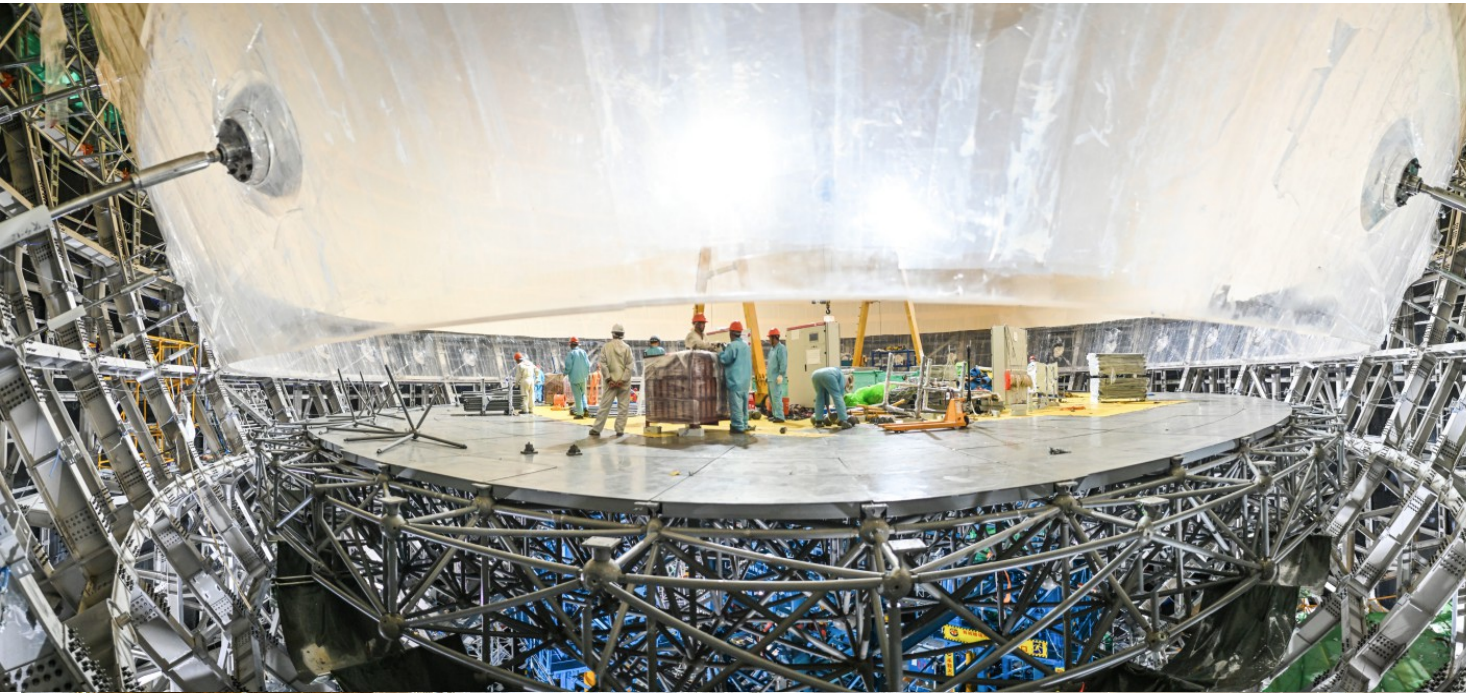


22 August
~22:12

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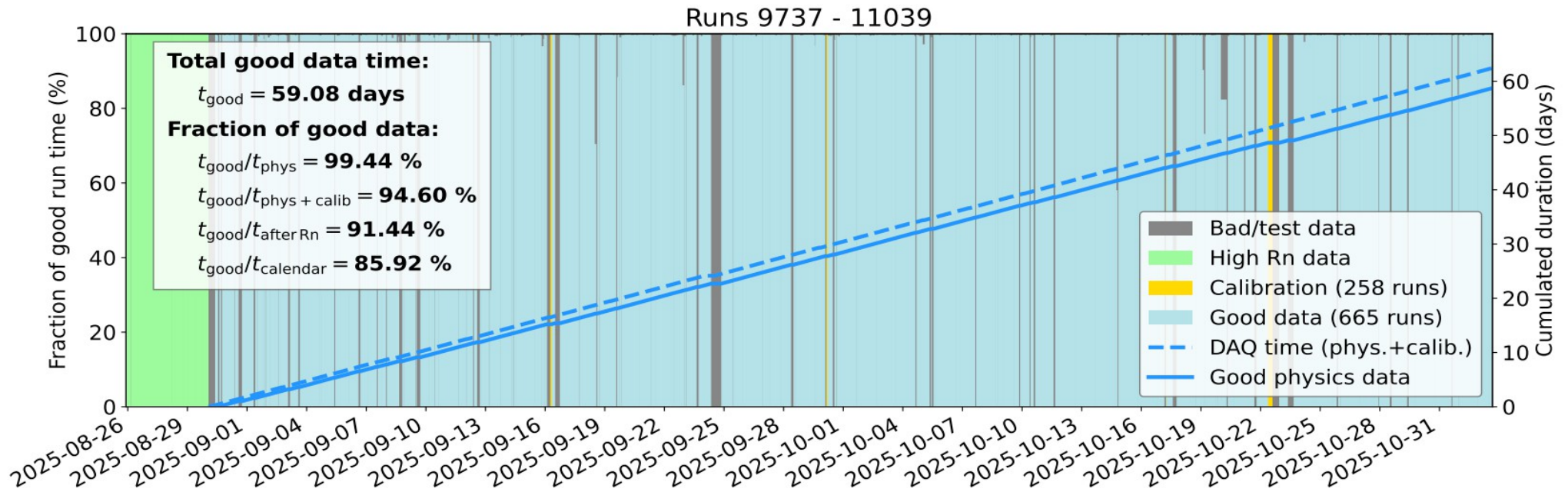


JUNO selected pictures



And finally data taking...

Detector live for 97.8% of time from 30th August to 2nd November 2025.
First release of results after about 2 months of data taking.



arXiv > hep-ex > arXiv:2511.14590

High Energy Physics - Experiment

[Submitted on 18 Nov 2025]

Initial performance results of the JUNO detector

arXiv > hep-ex > arXiv:2511.14593

High Energy Physics - Experiment

[Submitted on 18 Nov 2025]

First measurement of reactor neutrino oscillations at JUNO

Initial detector performances

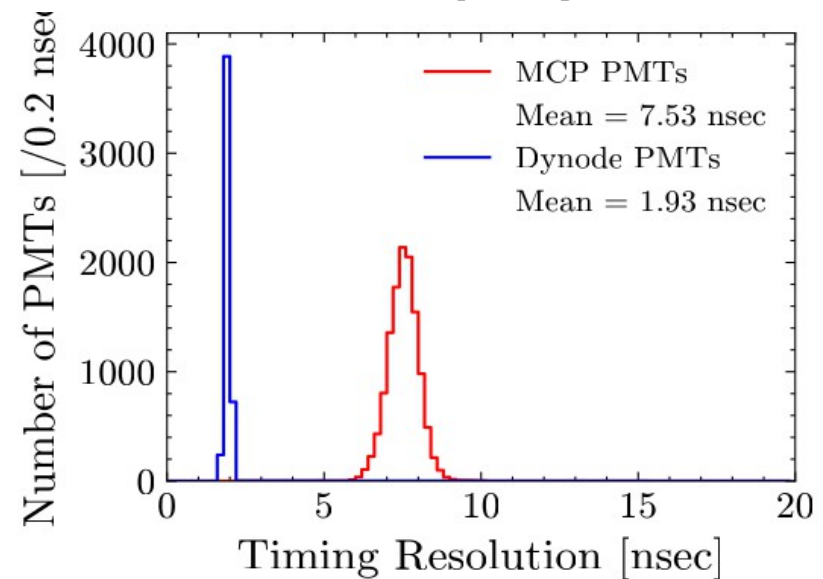
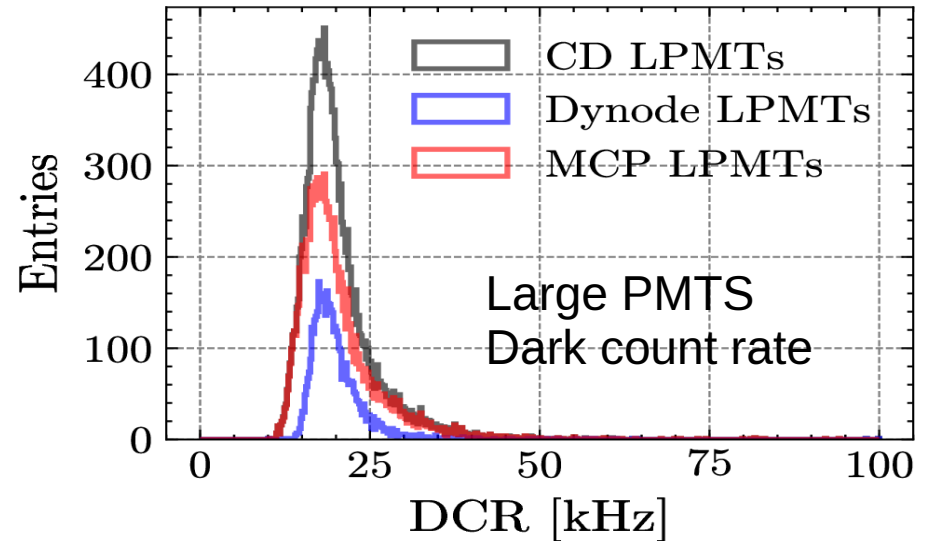
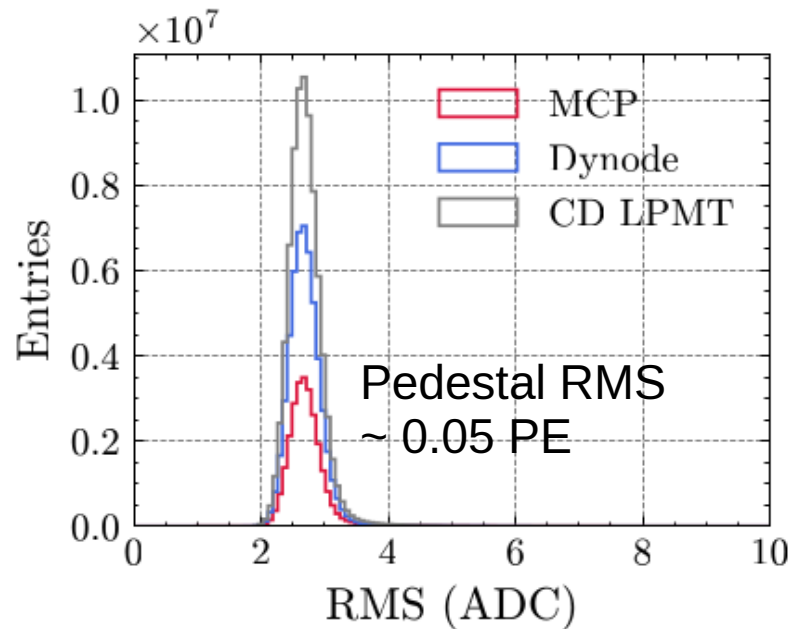
arXiv > hep-ex > arXiv:2511.14590

High Energy Physics - Experiment

[Submitted on 18 Nov 2025]

Initial performance results of the JUNO detector

PMTs performances



LS purity assessed by Bi-Po β - α coincidences. Main contaminations:

^{238}U $(7.5 \pm 0.9) \times 10^{-17}$ g/g, ^{232}Th $(8.2 \pm 0.7) \times 10^{-17}$ g/g

One order of magnitude better than design requirement for NMO measurement.

Measured also ^{210}Po concentration $(4.3 \pm 0.3) \times 10^4$ cpd/kton

Initial detector performances

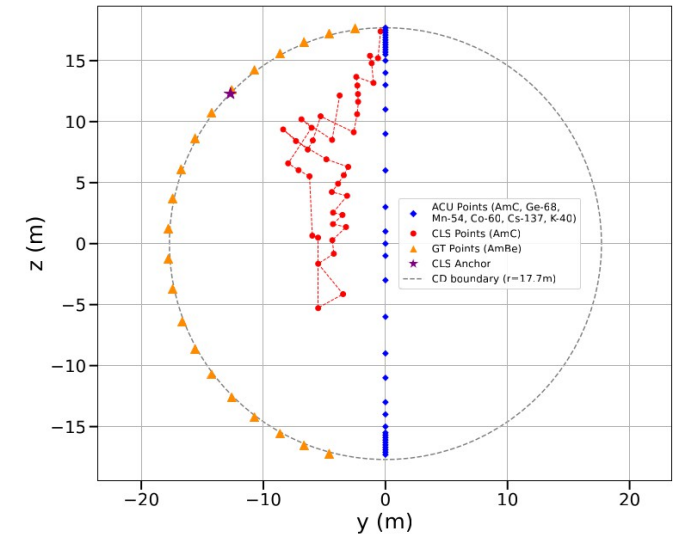
Calibration summary

List of sources

Source	Energy	System	Activity
Gamma Sources			
^{68}Ge	$0.511 \times 2 \text{ MeV}$	ACU	595 Bq ^a
^{137}Cs	0.662 MeV	ACU	140 Bq ^b
^{54}Mn	0.835 MeV	ACU	521 Bq ^a
^{40}K	1.460 MeV	ACU	13 Bq
^{60}Co	1.173+1.333 MeV	ACU	165 Bq ^b
Neutron Sources			
$^{241}\text{Am}-^{13}\text{C}$	neutron + 6.13 MeV ($^{16}\text{O}^*$)	ACU	130 Bq
	(n, γ)p 2.223 MeV	CLS	
	(n, γ) ^{12}C 4.94 MeV		
$^{241}\text{Am}-^9\text{Be}$	(n, γ) ^{56}Fe 7.63 MeV, etc.		30 Bq
	neutron + 4.43 MeV ($^{12}\text{C}^*$)	GT	
$^{241}\text{Am}-^9\text{Be}$	(n, γ)p 2.22 MeV		
Optical Calibration			
Laser	Optical pulses (420 nm and 266 nm)	ACU	50 Hz

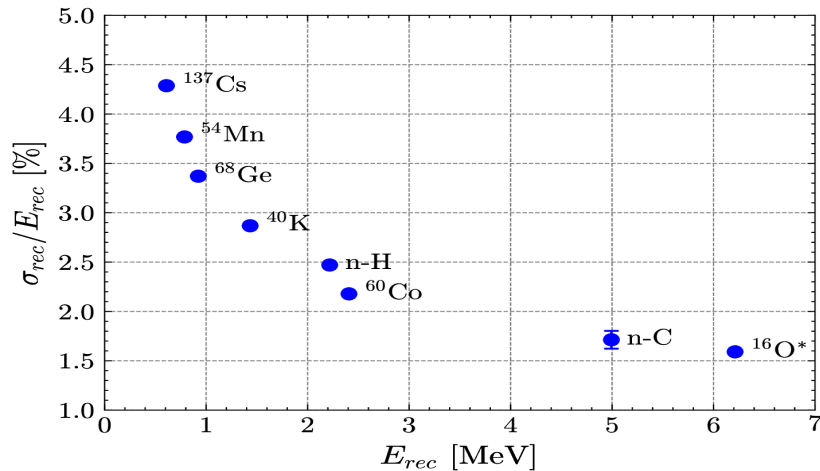
^a Reference activity measured on 6/21/2023.

^b Reference activity measured on 4/6/2021.

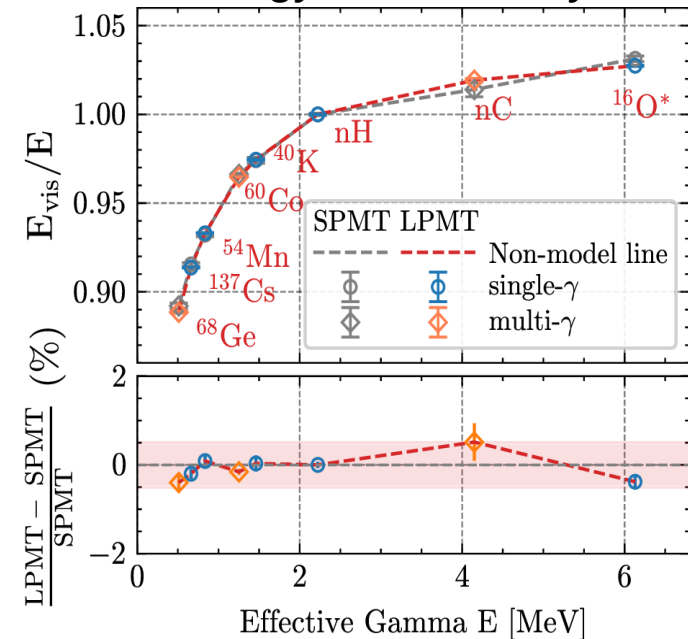


Used also natural contaminants of LS for calibration

Energy resolution



Energy non-linearity

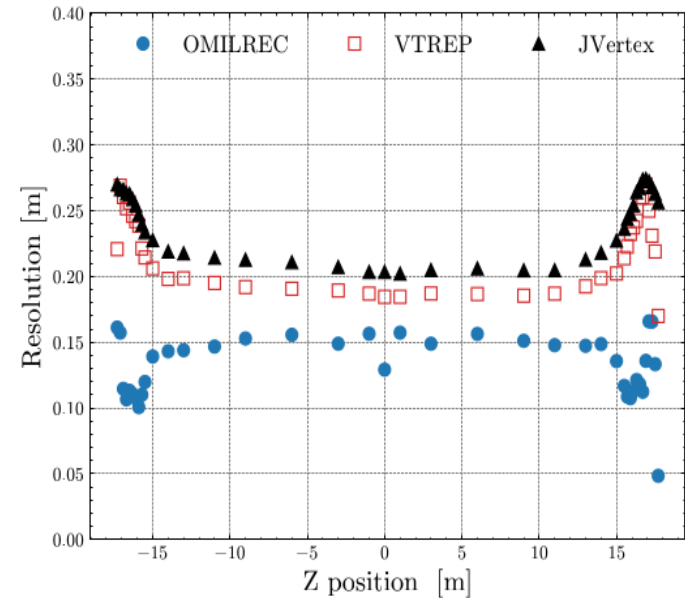


Initial detector performances

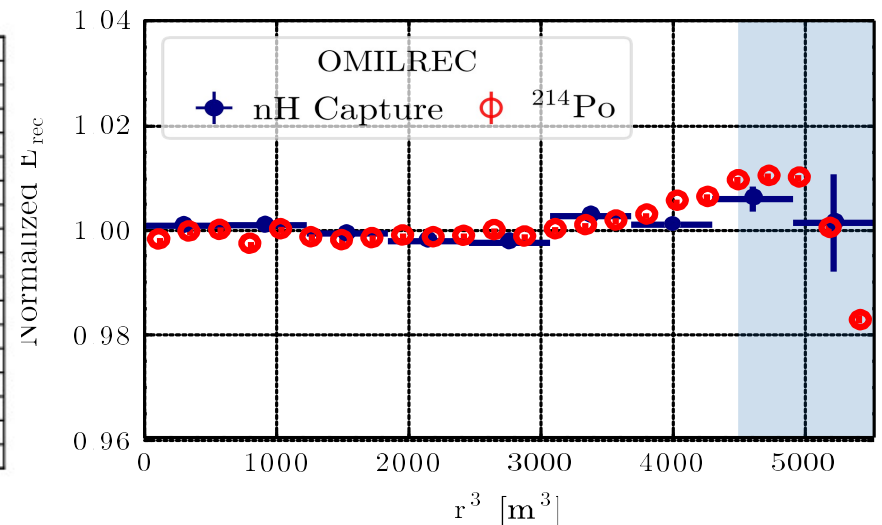
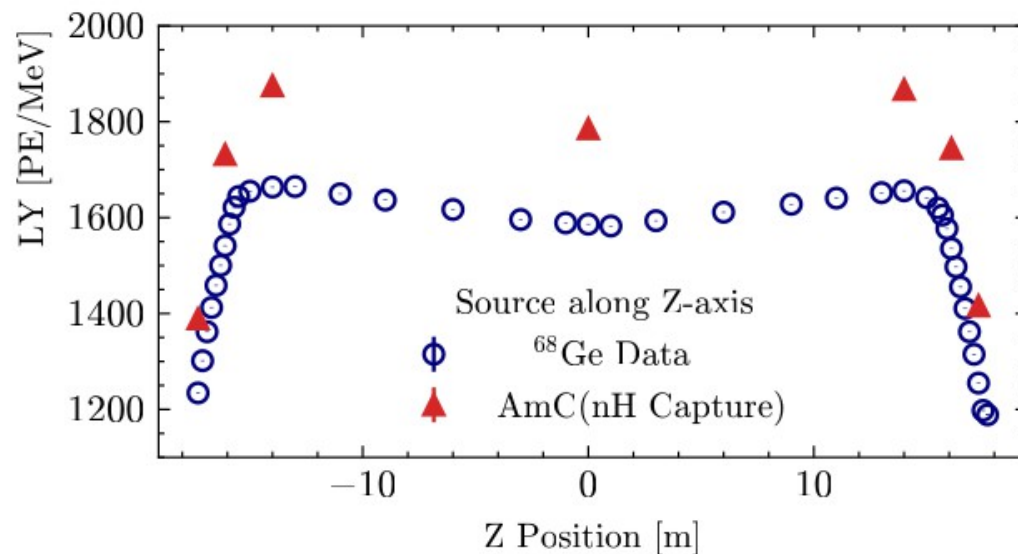
Energy and vertex reconstruction, based on time/charge pattern of PMTs, performed by three different algorithms...

Room for improvement of energy and space resolutions, near specifications, but not yet optimal.

Space resolution



Light yield

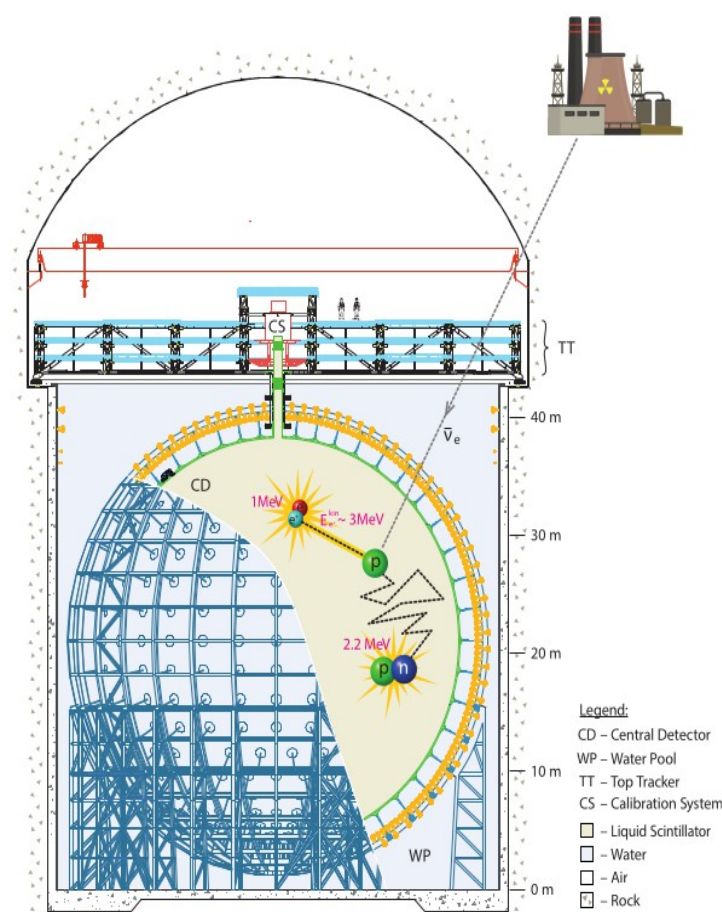


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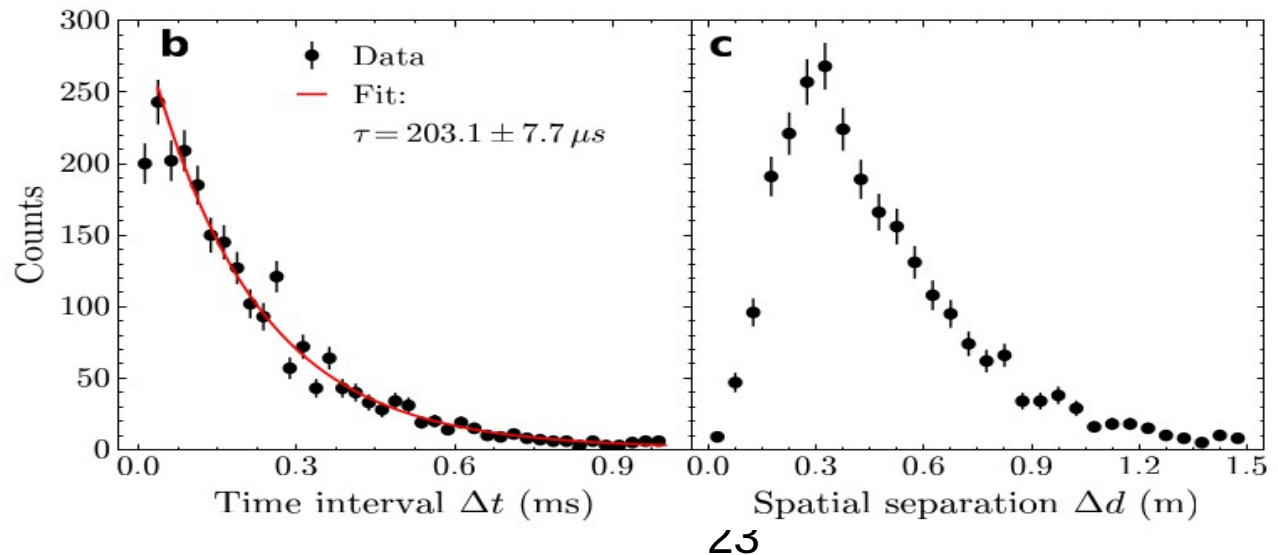
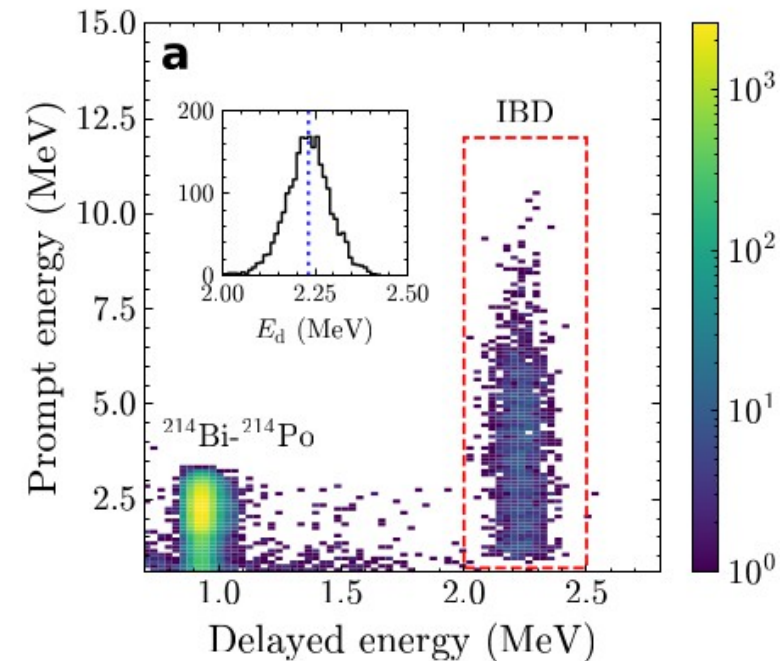
Energy reco
non-uniformity

IBD data selection

- 1) Fiducial volume cut $R < 16.5$ m (remove external bkg and regions with worse detector performance)
- 2) IBD selection (based on values of prompt e^+ and delayed n signals, and on space-time correlation)
- 3) Removal of muon-related backgrounds (external veto, events vetoed for 5 ms after passage of muons)
- 4) Removal of cosmogenic long lived spallation events, ^9Li , ^9Be veto events with $R < 2$ m and $\Delta t < 1.2$ s around spallation n

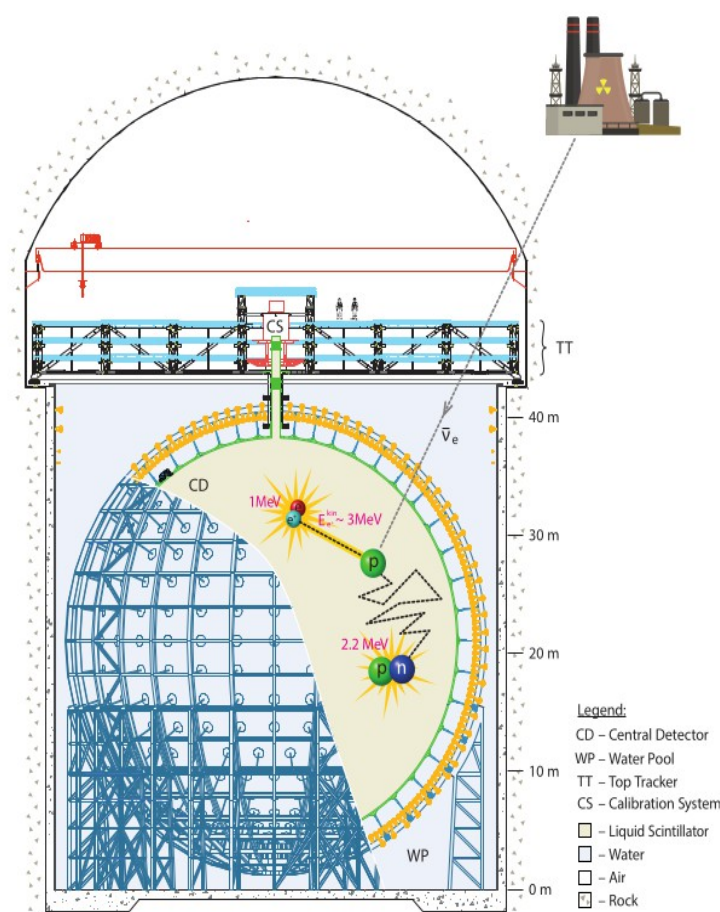


Number of ν candidates = 2379



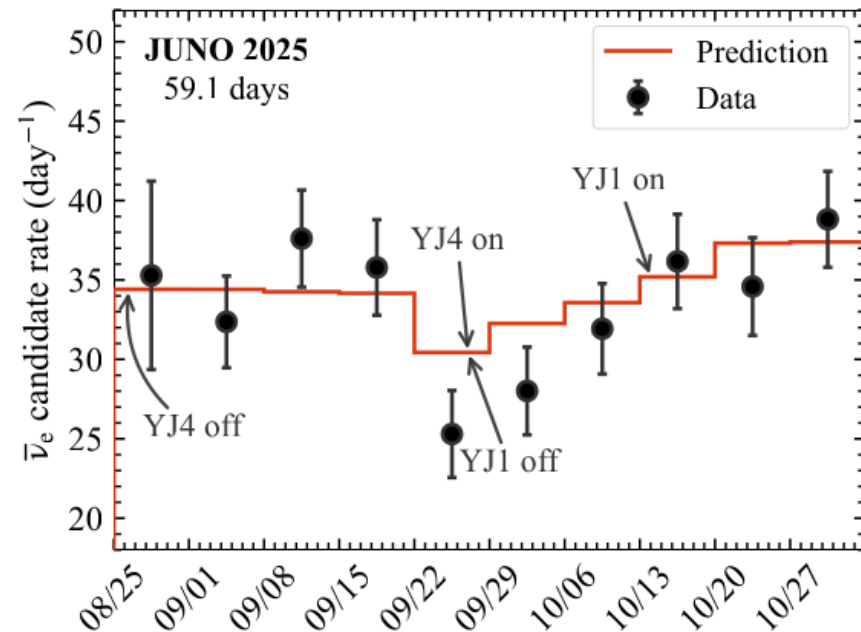
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$N_{\bar{\nu}_e} \sim 34$ ev/day (70% efficiency)

Backgrounds (cpd)	Pre-fit	Best-fit
$^9\text{Li}/^8\text{He}$	4.3 ± 1.4	3.9 ± 0.6
Geoneutrinos	1.2 ± 0.5	1.4 ± 0.4
World reactors	0.88 ± 0.09	0.88 ± 0.09
$^{214}\text{Bi}-^{214}\text{Po}$	0.18 ± 0.10	0.20 ± 0.10
$^{13}\text{C}(\alpha, n)^{16}\text{O}$	0.04 ± 0.02	0.04 ± 0.02
Fast neutrons	0.02 ± 0.02	0.02 ± 0.02
Double neutrons	0.05 ± 0.05	0.07 ± 0.05
Atmospheric neutrinos	0.08 ± 0.04	0.07 ± 0.04
Accidentals ($\times 10^{-2}$)	4.9 ± 0.3	4.9 ± 0.3



Analysis

- Unoscillated spectrum constrained by joint fit with Daya Bay data.
- Frequentist analysis with binned χ^2 with output Δm_{21}^2 , θ_{12} (as well as signal and bkg rates).
- Consistent results among three different analyses with threshold 0.7 MeV.

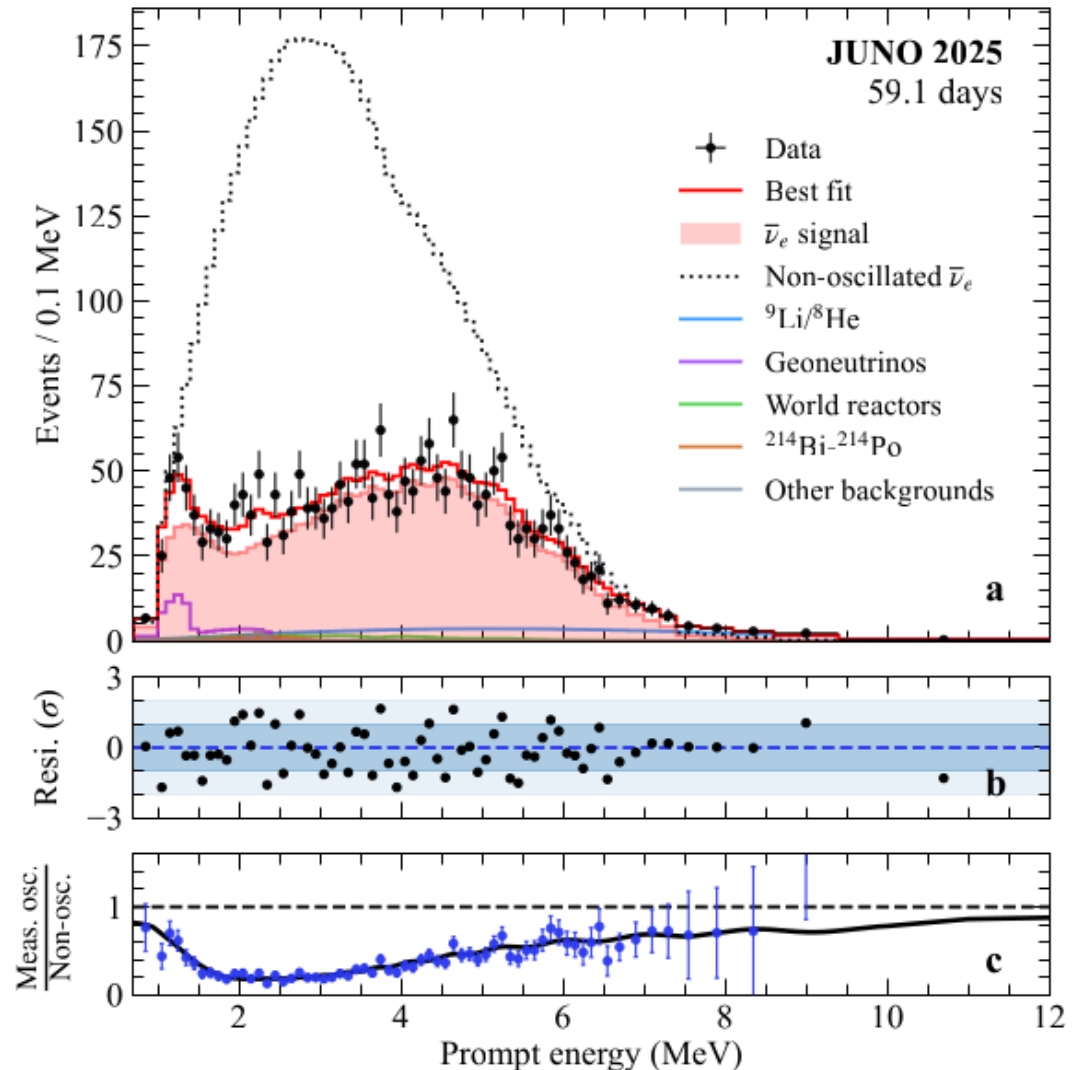
$$\chi^2(\vec{p}, \vec{\eta}, \vec{\alpha}) = (\mu - D)^T V^{-1} (\mu - D) + \lambda_{\text{nuis}}^2(\vec{\eta}) + \lambda_{\text{shape}}^2(\vec{\alpha}) + \chi_{\text{osc}}^2(\sin^2 \theta_{13}, \Delta m_{31}^2)$$

JUNO data (points to $(\mu - D)^T V^{-1} (\mu - D)$)
 Nuisance parameters (detector response, bkg, flux normalization) (points to $\lambda_{\text{nuis}}^2(\vec{\eta})$)
 Reactor flux constraint (Daya Bay) (points to $\lambda_{\text{shape}}^2(\vec{\alpha})$)
 Daya Bay results (points to $\chi_{\text{osc}}^2(\sin^2 \theta_{13}, \Delta m_{31}^2)$)

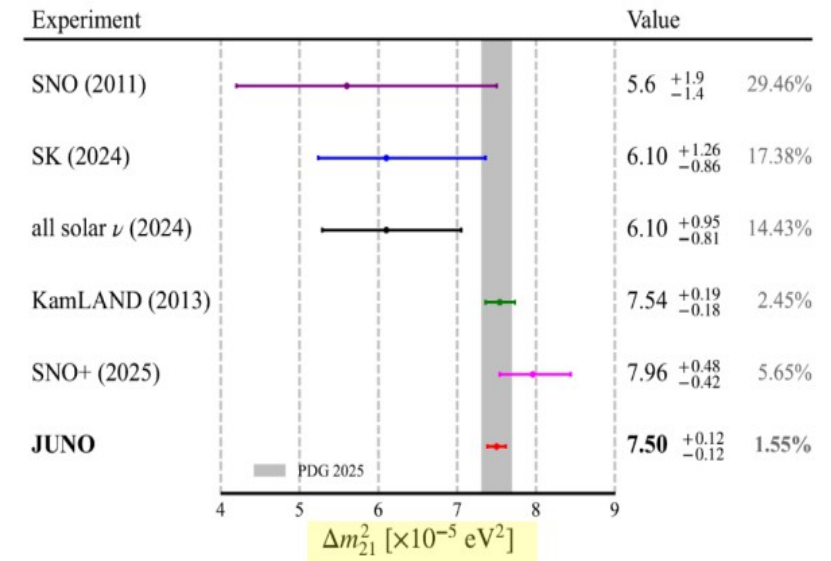
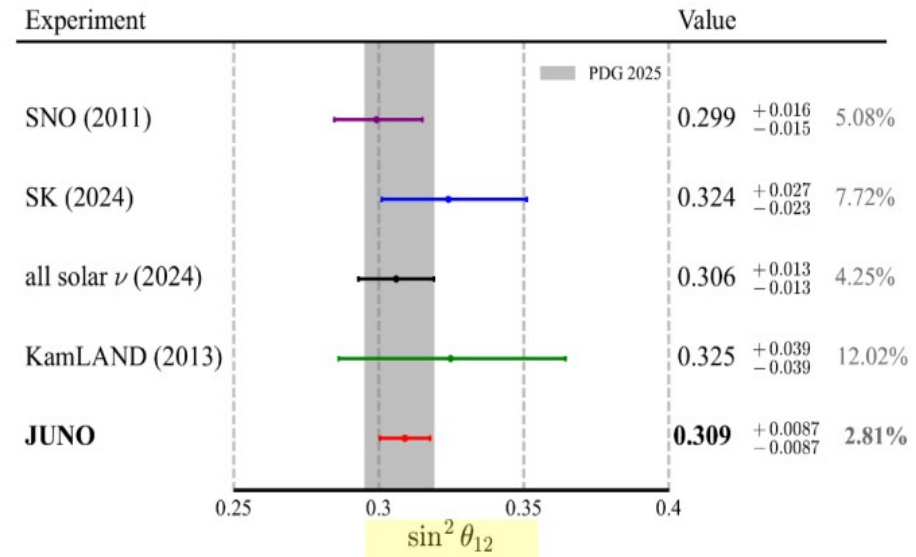
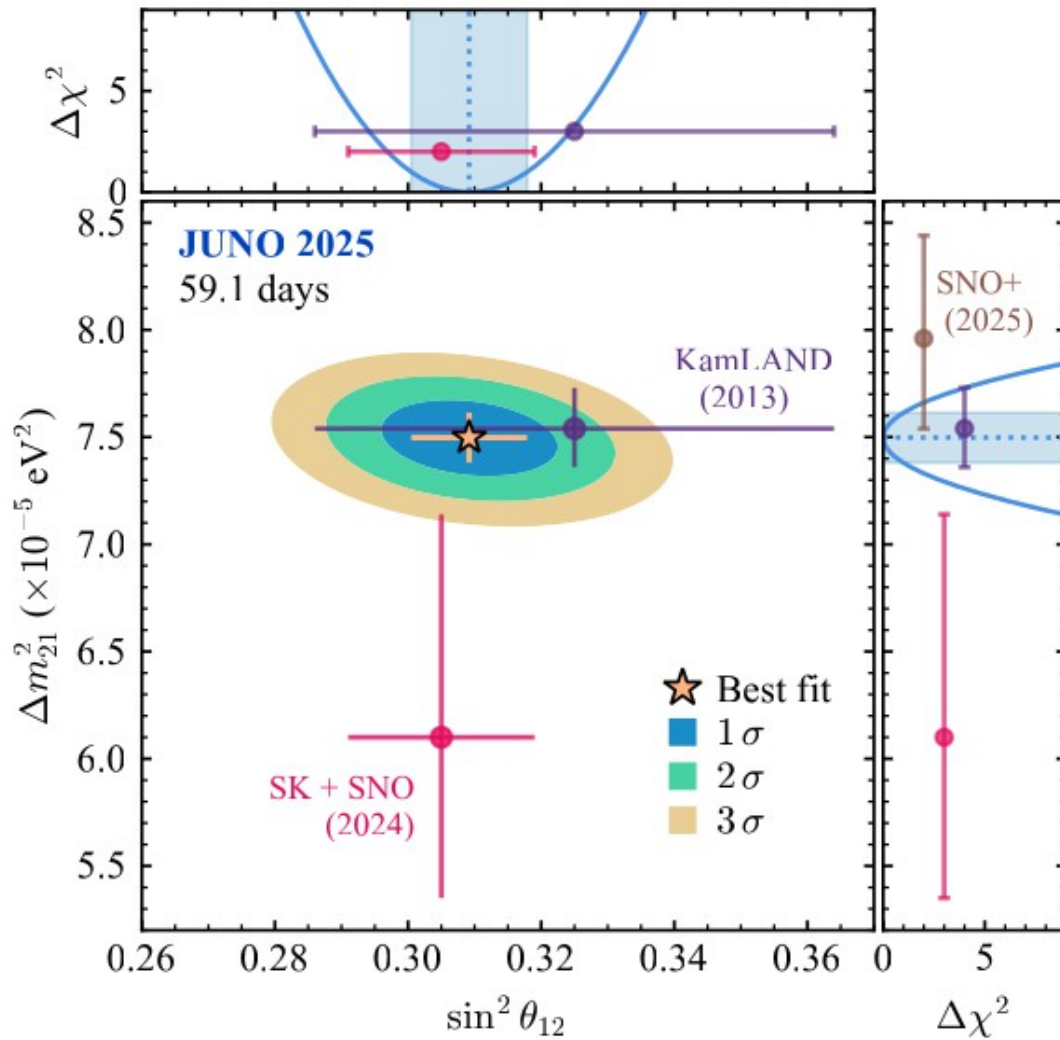
Oscillation parameters fit result

$$\sin^2 \theta_{12} = 0.3092 \pm 0.0087,$$

$$\Delta m_{21}^2 = (7.50 \pm 0.12) \times 10^{-5} \text{ eV}^2$$

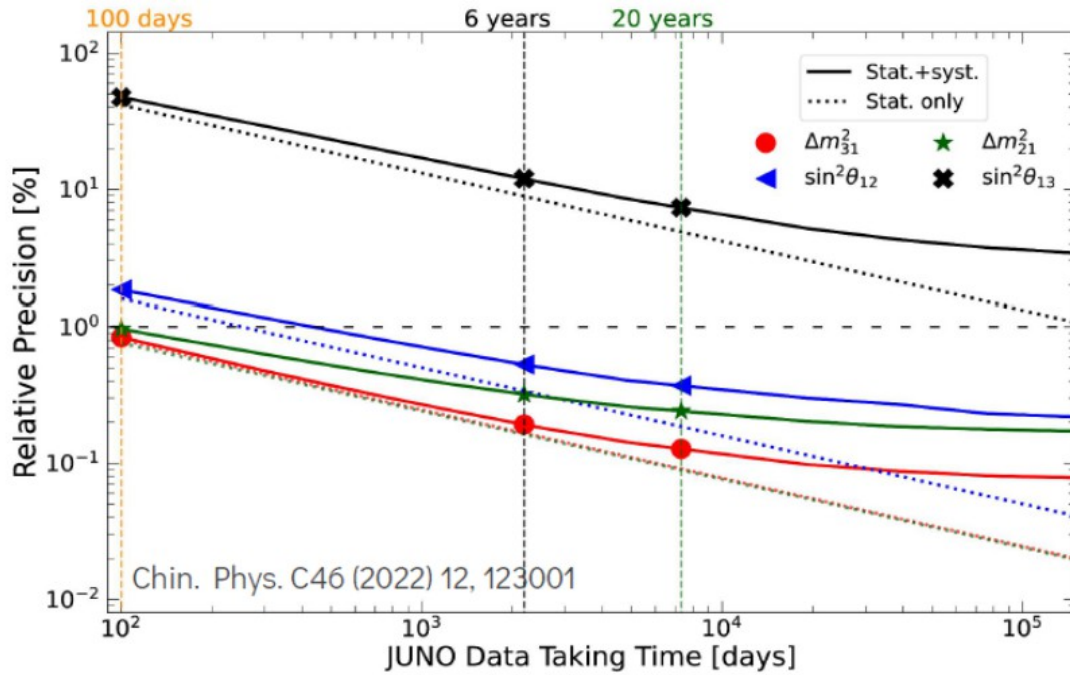


Analysis



World's best precision in 59 days....

Next steps

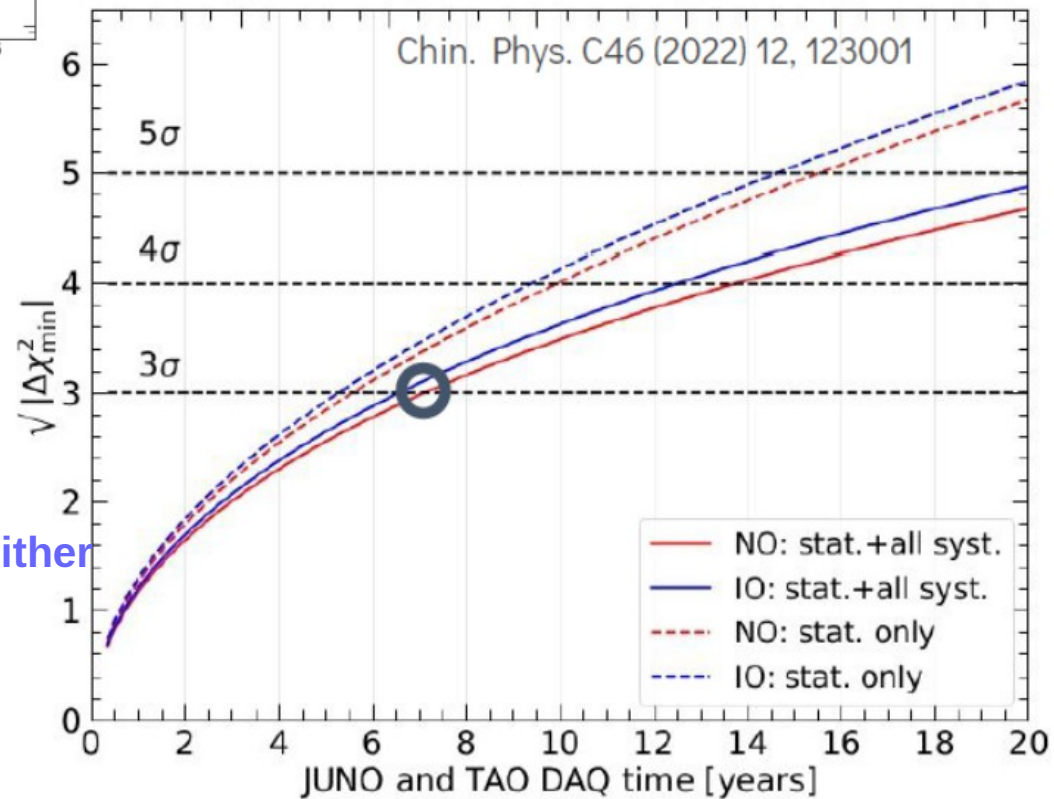


Precise determination of oscillation parameters:
 Improve precision on θ_{12} and Δm^2_{21}
 Perform also Δm^2_{31} measurement at % level

Neutrino mass ordering (NMO):
 NMO determination at 3σ in 7 years using
 JUNO data alone

More sensitivity comparing/combining with
 ν_μ disappearance data.

Δm^2_{31} measurement is one key, but right now we neither
 have enough statistics nor TAO (see next slide).

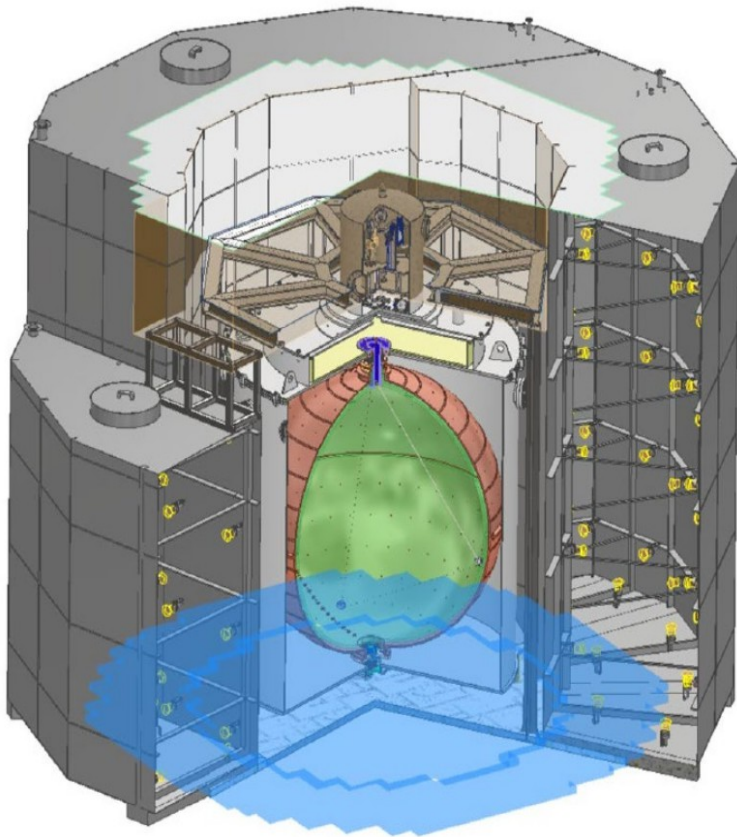


TAO (Taishan Anti-neutrino Observatory)

Measure anti-neutrino spectrum at % level to provide:
a model-independent reference spectrum for JUNO
a benchmark for investigation of the nuclear database

2.8 ton (1 ton FV) Gd-doped LS detector at ~40 m from a Taishan reactor core (4.6 GW)
Full coverage (94%) SiPM read-out (50% PDE)
Liquid Scintillator and SiPM operated at -50 °C
Expected energy resolution $<2\%/\sqrt{E}$ (MeV)
~1000 IBD/day

TAO CDR: arXiv:2005.08745



Under commissioning
Data taking soon...



Summary and Conclusions

JUNO is the largest reactor anti-neutrino detector ever built (20 kton of liquid scintillator) with an unprecedented energy resolution (3% @ $E=1$ MeV).

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