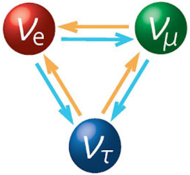
A first look at neutrino oscillations with JUNO

João Pedro Athayde Marcondes de André and Loïc Labit
for the JUNO Collaboration

IPHC/IN2P3/CNRS

Introduction to Neutrino oscillations

3 types of neutrino with different flavor & mass eigenstates:



$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = U_{PMNS}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

$$U_{PMNS} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}, \qquad \begin{aligned}c_{ij} &= \cos\theta_{ij}\\ s_{ij} &= \sin\theta_{ij}\end{aligned}$$

$$P(\nu_\alpha \to \nu_\beta) = \sum_{j,k} U^*_{\alpha j}U_{\alpha k}U_{\beta j}U^*_{\beta k}\ \exp\left(-i\frac{L}{2E}\Delta m^2_{kj}\right), \qquad \Delta m^2_{kj} = m^2_k - m^2_j$$

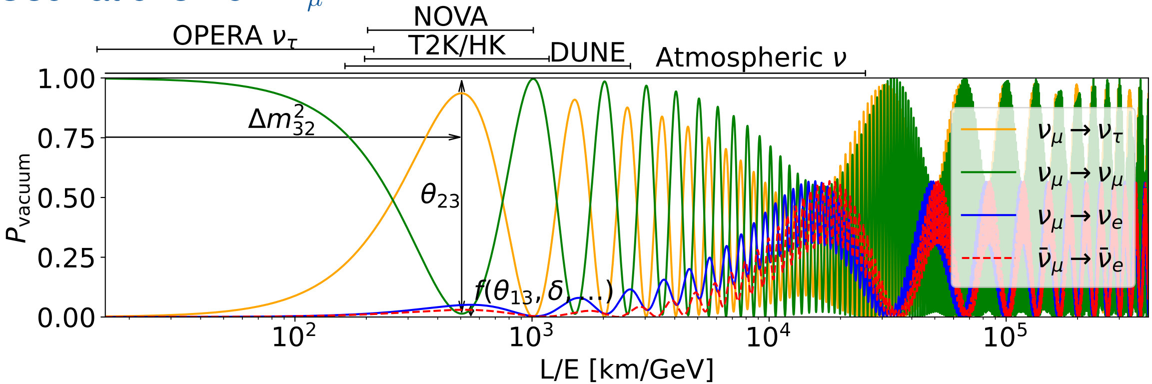
Amplitude: $\theta_{12}, \theta_{13}, \theta_{23}, \delta$

Frequency: $\Delta m^2_{21}, \Delta m^2_{31}$

2-flavors: $$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\ \sin\left(\frac{L}{4E}\Delta m^2\right), \qquad \alpha \neq \beta$$

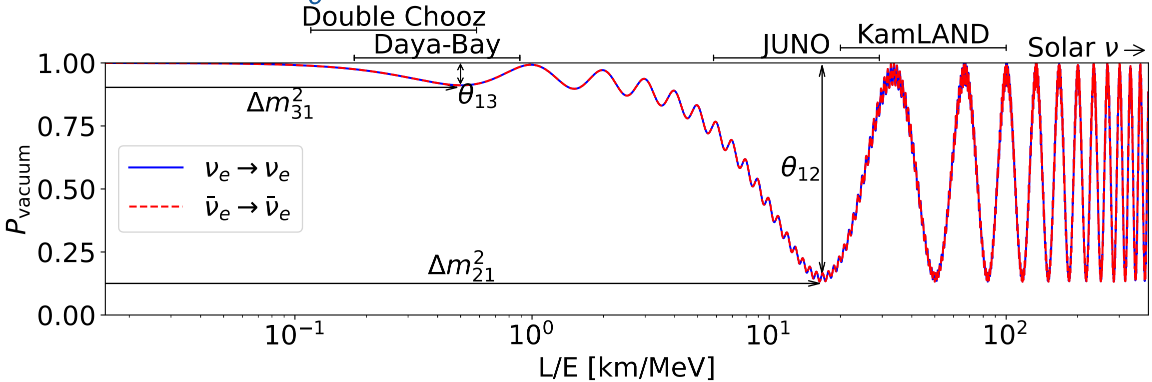
Neutrino oscillations $\Rightarrow$ neutrinos have mass as $\Delta m^2 \neq 0$

Oscillations from ν_μ



- Accelerator experiments mostly see Δm^2_{32} oscillation
  - Mainly sensitive to Δm^2_{32}, θ_{23}, θ_{13}, δ
  - $P(\nu_\mu \to \nu_e)$ depends on many oscillation parameters at same time
- Atmospheric neutrinos cover an even larger range
  - Not enough resolution to see both frequencies together
  - Flux at production contains mix of ν_μ and ν_e (also of ν and $\bar{\nu}$)

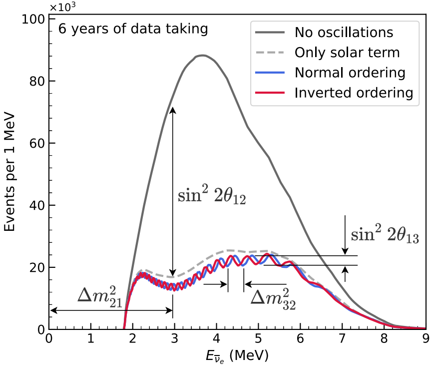
Oscillations from ν_e

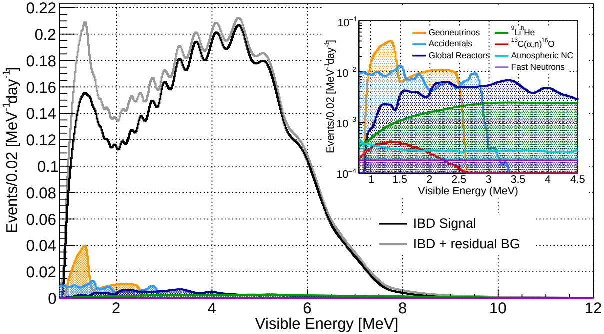


- Reactor anti-neutrino disapperance only sensitive to Δm^2_{31}, θ_{13}, Δm^2_{21}, θ_{12}
  - Select largest oscillation by defining detector distance
  - JUNO: expect to measure both oscillations frequencies together for first time
    - Requires good energy resolution to distinguish fast oscillations in spectra!
- Solar neutrinos see mostly 'averaged' oscillations
  - Sensitivity to Δm^2_{21} thanks to matter effects (but worse precision than w/ reactor $\bar{\nu}_e$)

Expected reactor $\bar{\nu}_e$ spectrum in JUNO

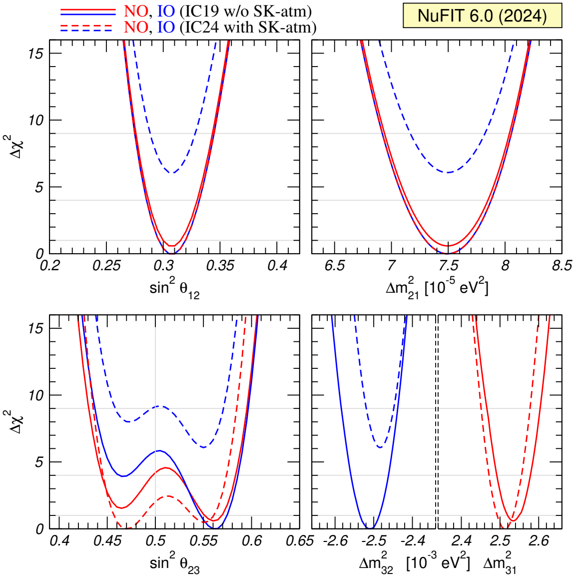
"Sub-percent precision measurement of neutrino oscillation parameters with JUNO," Chin. Phys. C **46** (2022) no.12, 123001



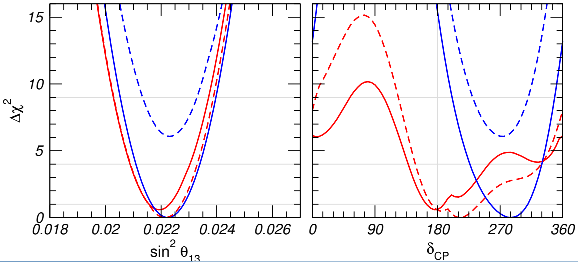


- Energy resolution smears low energy oscillations
  - critical importance of energy resolution

Status of neutrinos oscillation parameters before JUNO started

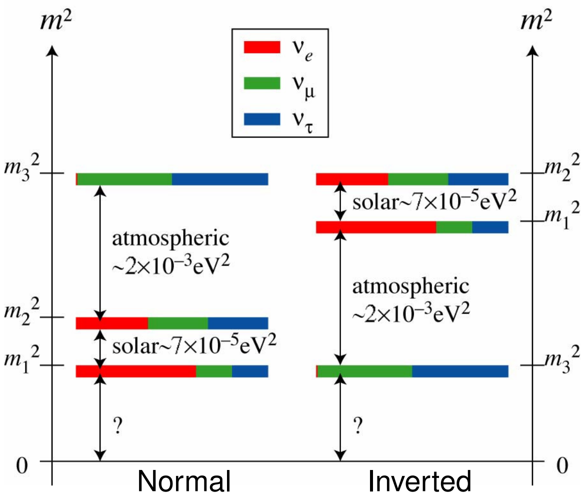


- Relative precisions:
  - Δm^2_{21} : $\sim$ 2.5%
  - $\sin^2\theta_{12}$: $\sim$ 3.9%
  - $|\Delta m^2_{3l}|$: $\sim$ 1%
  - $\sin^2\theta_{23}$: $\sim$ 3%   (30%@3 σ)
  - $\sin^2\theta_{13}$: $\sim$ 2.4%
- Sign of Δm^2_{3l} preference flips between fits
- δ depends strongly on sample & ordering

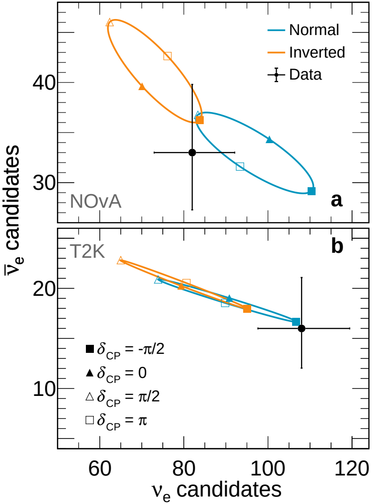


Open questions with regards to neutrino oscillations

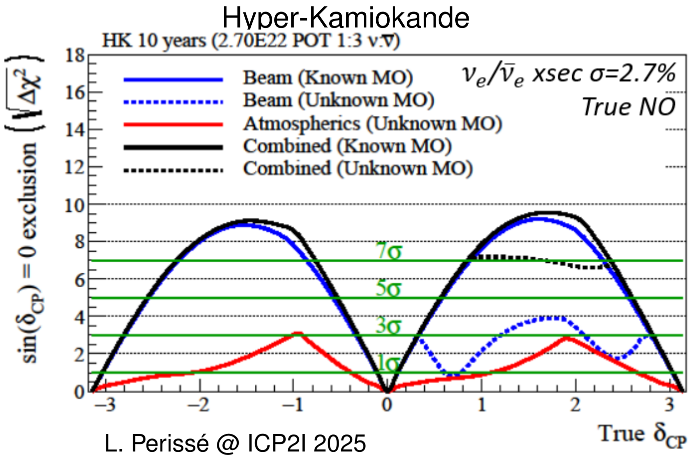
- Neutrino Mass Ordering
  - main goal of JUNO
- Mixing Matrix U is Unitary?
  - Expect direct results from JUNO too
- CP-violation phase in lepton sector
  - $P(\nu_\alpha \to \nu_\beta) \stackrel{?}{=} P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$
- ν Majorana or Dirac Particle
- Absolute Scale of Neutrino Masses



NMO determination: impact on determination of CP-violation phase

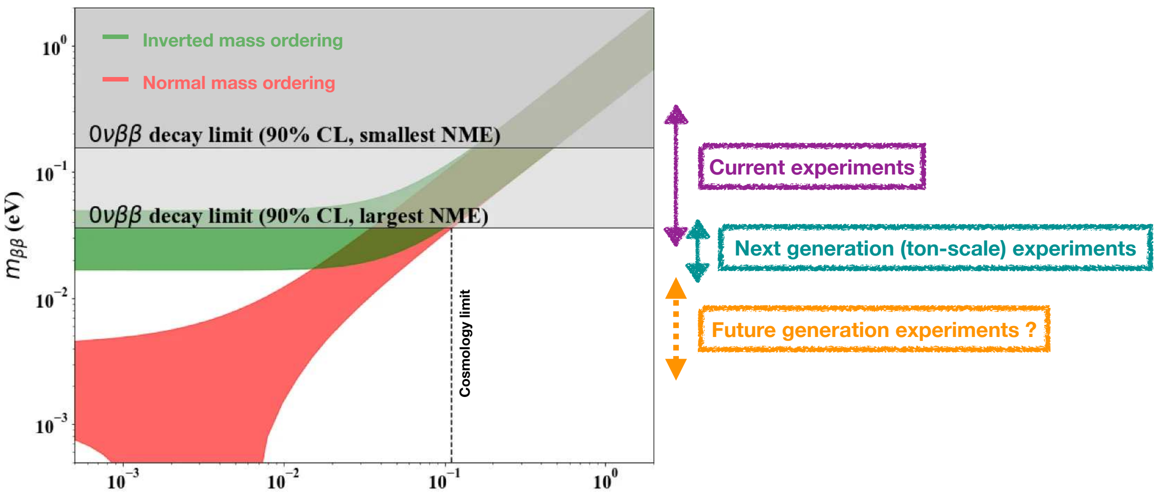


T2K + NOvA, Nature **646** (2025) no.8086, 818-824 [2510.19888]



- δ and NMO both create differences in ν_e and $\bar{\nu}_e$ appearance
- External definition of ordering helps δ measurement in T2K, NOvA & HK

NMO determination: impact on search for Majorana ν



Riv. Nuovo Cim. **46**, 619–692 (2023).

R. Guenette @ Neutrino 2024

The JUNO Collaboration

Country	Institute	Country	Institute	Country	Institute
Armenia	YerPhI	China	SDU	Italy	INFN-CT
Belgium	ULB	China	SJTU	Italy	INFN-FE
Chile	SAPHIR	China	SUSTech	Italy	INFN-LNF
Chile	UNAB	China	SYSU	Italy	INFN-MI
China	BISEE	China	THU	Italy	INFN-MIB
China	CDUT	China	UCAS	Italy	INFN-PD
China	CNPRI	China	WHU	Italy	INFN-PG
China	CUGB	China	WuYiU	Italy	INFN-Roma3
China	DGUT	China	XJTU	Pakistan	PINSTECH (PAEC)
China	ECUT	China	XMU	Russia	JINR
China	GXU	China	ZZU	Slovakia	FMFI-UK
China	HIT	Czech	Charles U.	Taiwan-China	NCTU
China	HunanU	Finland	JyU	Taiwan-China	NKNU
China	IGGCAS	France	CPPM	Taiwan-China	NTU
China	IHEG-CAGS	France	IJCLab	Taiwan-China	NTUT
China	IHEP	France	IPHC	Thailand	CHULA
China	IMP	France	LP2iB	Thailand	NARIT
China	JNU	France	Subatech	Thailand	SUT
China	JXNU	Germany	EKUT	U.K.	U. Liverpool
China	KNRC	Germany	GSI	U.K.	U. Warwick
China	Nankai U.	Germany	U. Hamburg	USA	UCI
China	NCEPU	Germany	JGUMainz	USA	UMD-G
China	NJU	Germany	RWTH-AC		
China	RNCG	Germany	TUM		

70 institutes, $\sim$700 collaborators

JUNO physics

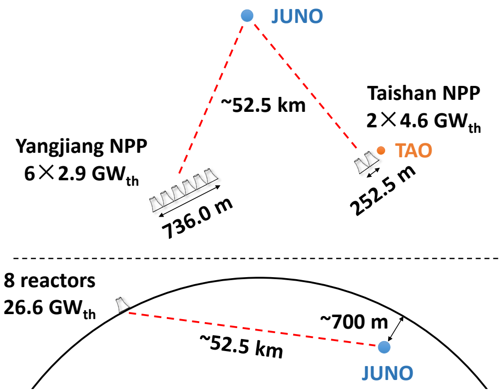
"Neutrino Physics with JUNO," J. Phys. G **43** (2016) no.3, 030401
"JUNO Physics and Detector," Prog. Part. Nucl. Phys. **123** (2022), 103927

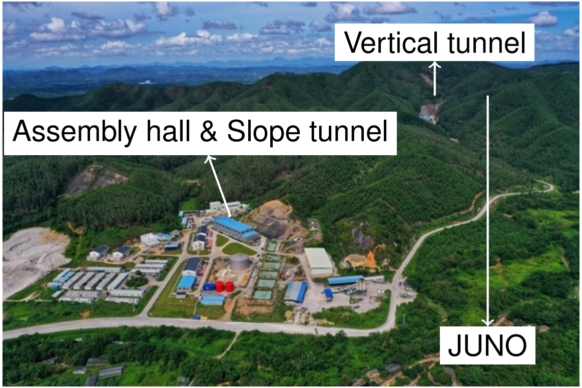
- Neutrino Mass Ordering (NMO)
- Precision measurement of oscillation parameters
- Atmospheric neutrinos
- Geoneutrinos
- Supernova (SN) neutrinos
- Diffuse SN neutrino background
- Solar neutrinos
- Nucleon decay & Exotic searches

Research	Expected signal	Energy region	Major backgrounds
Reactor antineutrino	60 IBDs/day	0–12 MeV	Radioactivity, cosmic muon
Supernova burst	5000 IBDs at 10 kpc	0–80 MeV	Negligible
	2300 elastic scattering		
DSNB (w/o PSD)	2–4 IBDs/year	10–40 MeV	Atmospheric ν
Solar neutrino	hundreds* per year for ^{8}B	0–16 MeV	Radioactivity
Atmospheric neutrino	hundreds per year	0.1–100 GeV	Negligible
Geoneutrino	$\sim$ 400 per year	0–3 MeV	Reactor ν

* in fact, 6k νES signals from ^{8}B per year expected after cuts with U/Th @ 10^{-17} level [JUNO, CPC 45 (2021) 023004]

JUNO site





- $\sim$700 m rock overburden (1800 m.w.e.) to suppress atmo. μ

The JUNO detector

Top Tracker:

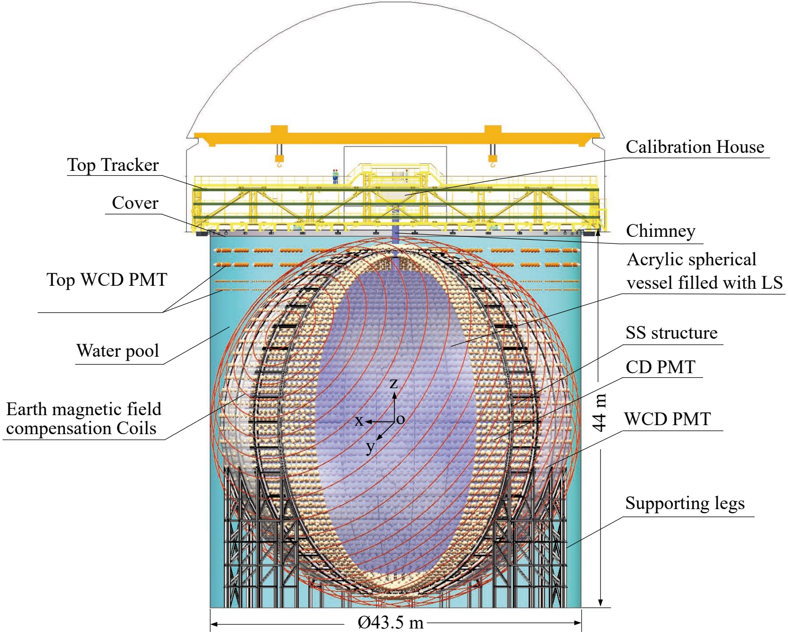
- 3 layers plastic scintillator
- 60% coverage of WCD

Water Pool:

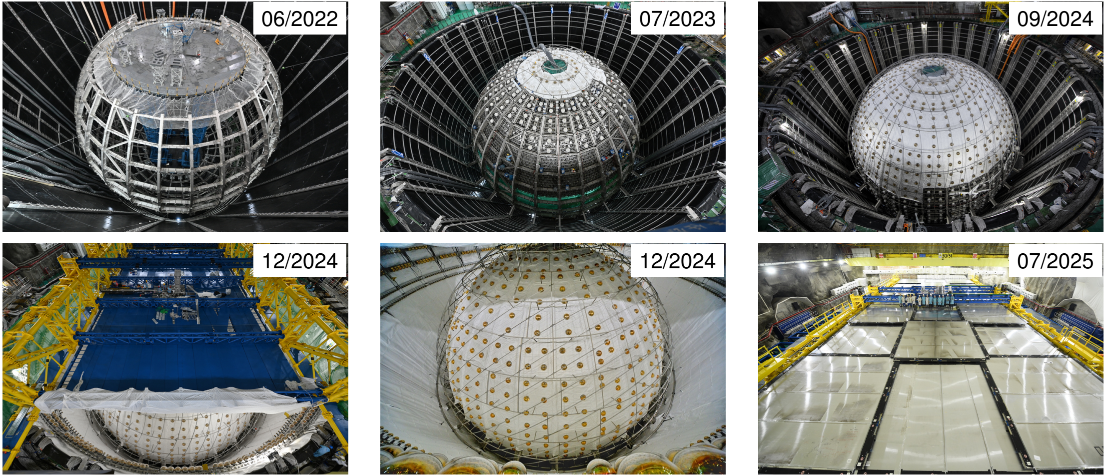
- High-purity water
- 35 kt in WCD
- PM in SS: 2.4k 20”
- Top PM: 384 20” + 600 8”

Central Detector (CD):

- Acrylic vessel ⌀=35.4 m
- 20 kt of liquid scintillator
- PM: 17.6k 20” + 25.6k 3”

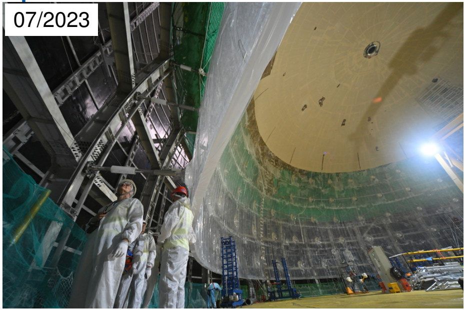


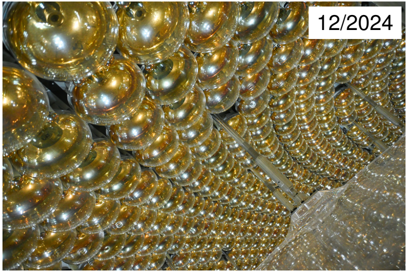
JUNO construction

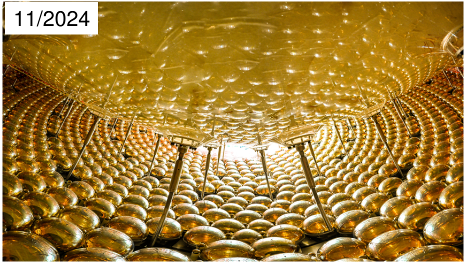


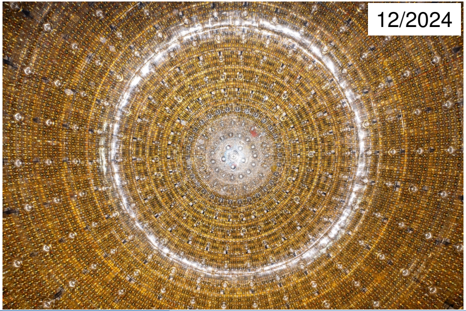
- CD and WCD finished end 2024
- TT started installation in Jan 2025, completed by Jun 2025

A few photos from inside

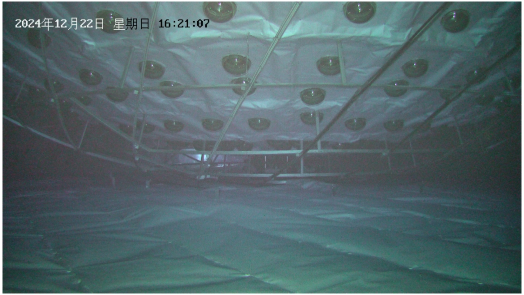








Filling the detector



2024-12-18 Start of water filling

2025-02-01 End of water filling

- Water phase

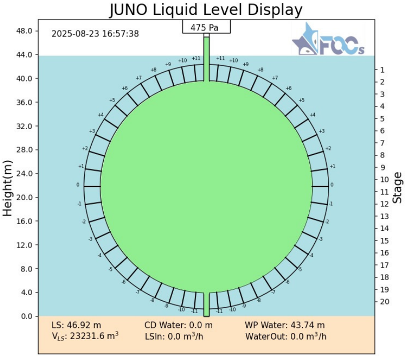
2025-02-08 Start of LS filling

- Mixed Water/LS phase

2025-08-22 End of LS filling

- Calibrations with full LS

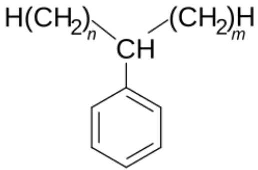
2025-08-26 Start of data taking

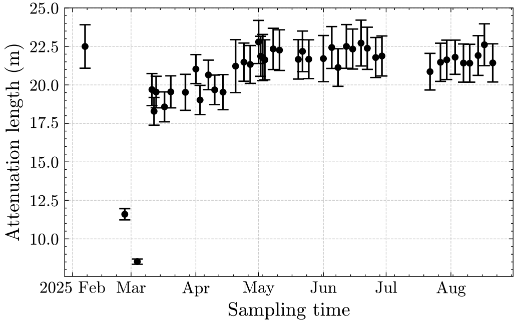


Liquid scintillator

- Recipe:
  - Linear AlkylBenzene (LAB, solvent)
  - 2.5 g/l PPO (fluor)
  - 3 mg/l Bis-MSB (shifter)
- $\sim 10^4$ photons emitted per MeV deposited
- High transparency
  - requirement > 20 m @ 430 nm
  - achieved 20.6 m @ 430 nm at end of filling
- Radiopure LS $\rightarrow$ see next slide
- LS purification plants on-site to reach goals
  - LS samples taken during filling to control quality

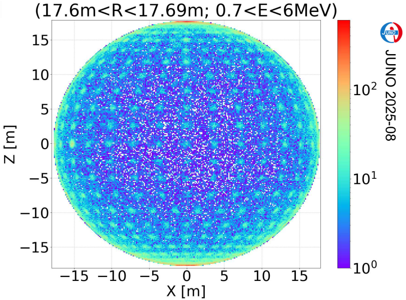
Linear AlkylBenzene (LAB)





Cleanliness of JUNO

- Radiopurity control of raw materials (JHEP 11 (2021) 102)
  - Careful screening of materials
  - 15% better than specifications!
- Radiopurity control during installation/filling
  - Leak check of all joints for ^{222}Rn and ^{85}Kr
  - Cleaning/washing of all pipes & vessels
  - Clean room environment during installation
  - Acrylic surface treatment & protection
  - LS filling after water washing & replacing water



Veto Water

- U/Th $< 0.4 \cdot 10^{-15}$ g/g
- ^{222}Rn < 10 mBq/m^3
- ^{226}Rn < 1 mBq/m^3
- Single (R < 17.2 m & E > 0.7 MeV) rates < 7 Hz (design 7.2 Hz)

LS: very close to other solar ν exp

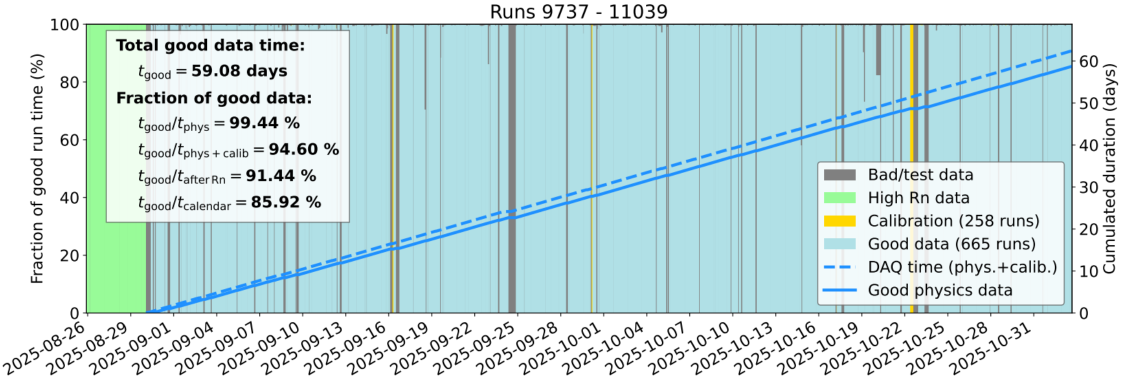
	JUNO	Borexino*
^{238}U	$< 3 \cdot 10^{-17}$ g/g (small FV) $< 1 \cdot 10^{-16}$ g/g (from Rn fit)	$(1.6 \pm 0.1)10^{-17}$ g/g
^{232}Th	$< 1 \cdot 10^{-16}$ g/g (R<13 m)	$(6.8 \pm 1.5)10^{-18}$ g/g
^{210}Po	$< 1 \cdot 10^{5}$ cpd/kt	$8 \cdot 10^{4}$ cpd/kt

- Likely impossible to recirculate LS

* Borexino: PRL 101 (2008) 091302

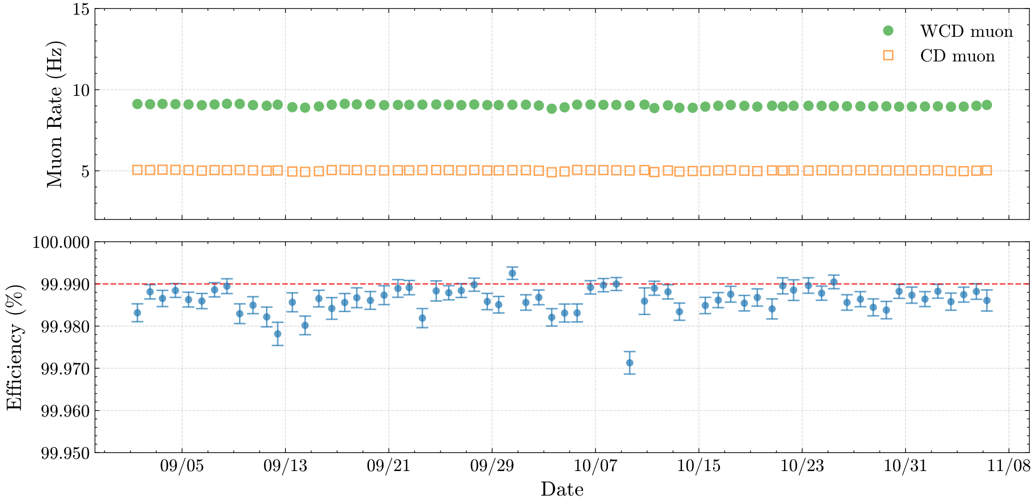
Stable Detector Operation

- Detector taking data with little downtime over two months
- Initial part of data removed to avoid impact from higher Rn contamination, but could be used in other analyses



Muon detection performance

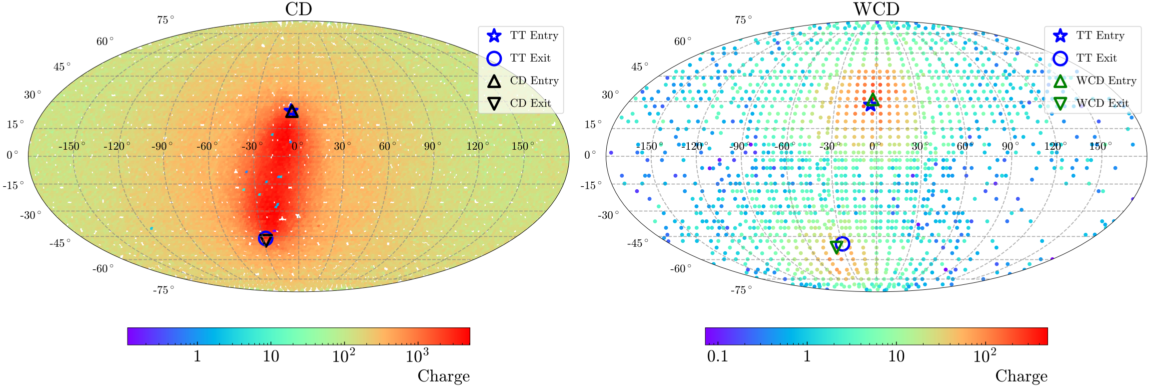
JUNO, "Initial performance results of the JUNO detector," [arXiv:2511.14590]



- Constant μ detection rate & efficiency around 99.98% during physics data taking

Atmospheric muons in JUNO

JUNO, "Initial performance results of the JUNO detector," [arXiv:2511.14590]



- Muons can be tracked crossing all sub-components of JUNO: TT, WCD, CD
- Atmospheric μ angular distributions in good agreement with expectation

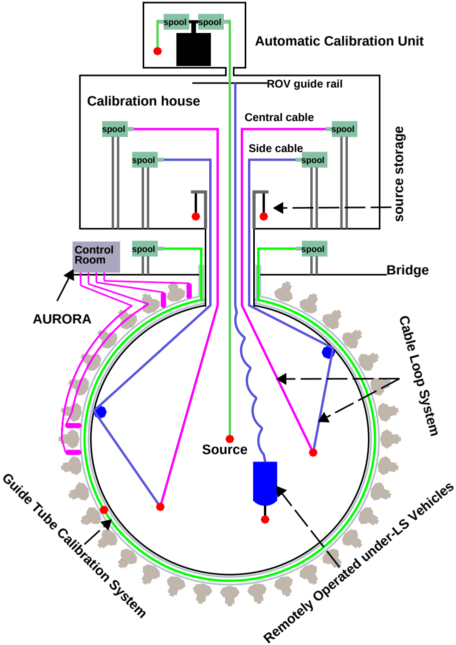
Detector calibration

- 1D, 2D and 3D scan systems
  - See JHEP **03** (2021), 004 for details
  - ACU: along z-axis
  - CLS: 2D plane
  - GT: along acrylic vessel
- For now, most sources along z-axis

Source	Energy	System	Activity
Gamma Sources			
^{68}Ge	0.511 × 2 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}Am–^{13}C	neutron + 6.13 MeV (^{16}O*) (n,γ)p 2.223 MeV (n,γ)^{12}C 4.94 MeV (n,γ)^{56}Fe 7.63 MeV, etc.	ACU CLS	130 Bq 100 Bq
^{241}Am–^{9}Be	neutron + 4.43 MeV (^{12}C*) (n,γ)p 2.22 MeV	GT	30 Bq
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.

(see arXiv:2511.14590)



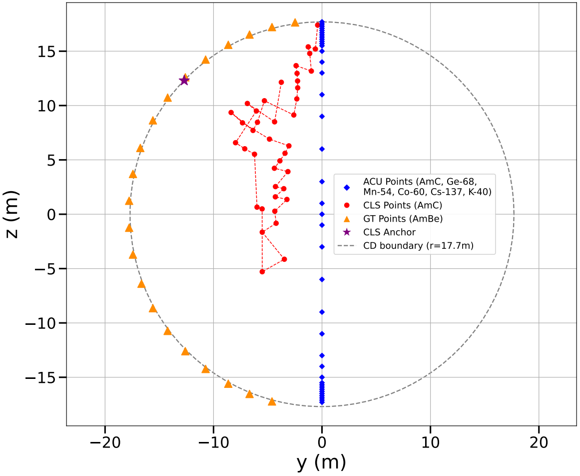
Detector calibration

- 1D, 2D and 3D scan systems
  - See JHEP **03** (2021), 004 for details
  - ACU: along z-axis
  - CLS: 2D plane
  - GT: along acrylic vessel
- For now, most sources along z-axis

Source	Energy	System	Activity
Gamma Sources			
^{68}Ge	0.511 × 2 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}Am–^{13}C	neutron + 6.13 MeV (^{16}O*) (n,γ)p 2.223 MeV (n,γ)^{12}C 4.94 MeV (n,γ)^{56}Fe 7.63 MeV, etc.	ACU CLS	130 Bq 100 Bq
^{241}Am–^{9}Be	neutron + 4.43 MeV (^{12}C*) (n,γ)p 2.22 MeV	GT	30 Bq
Optical Calibration			
Laser	Optical pulses (420 nm and 266 nm)	ACU	50 Hz

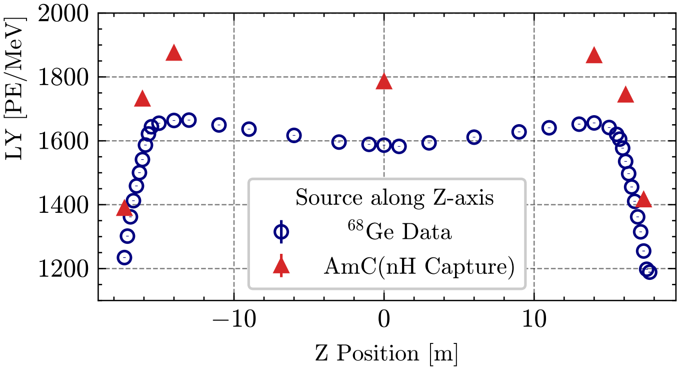
[a] Reference activity measured on 6/21/2023.
[b] Reference activity measured on 4/6/2021.

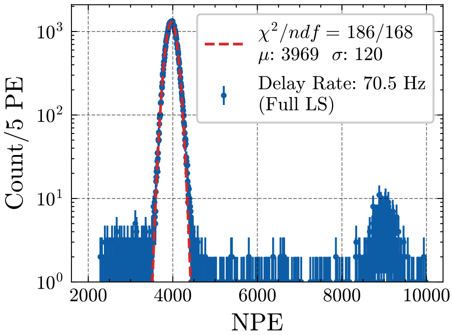
(see arXiv:2511.14590)



Light yield

JUNO, "Initial performance results of the JUNO detector," [arXiv:2511.14590]

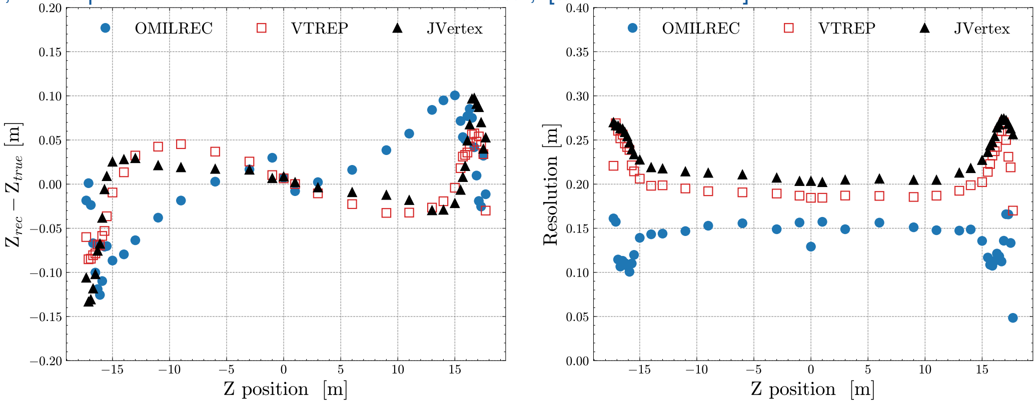




- Light yield from n-H capture in center of detector:
  - Our last expectation (Chin.Phys.C 49 (2025) 1, 013003): 1665 PE/MeV
    - This was used for our last NMO paper
  - Measurement using JUNO data: 1785 PE/MeV
    - About 10% larger than expected!

Position uniformity & resolution

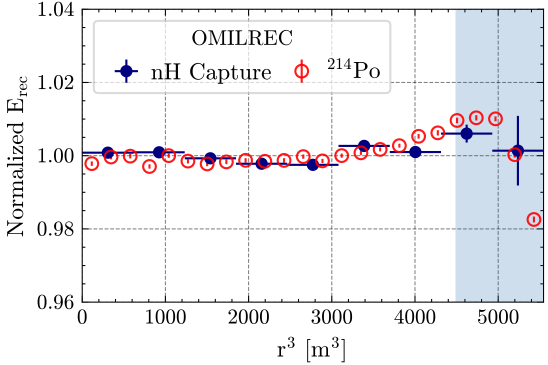
JUNO, “Initial performance results of the JUNO detector,” [arXiv:2511.14590]

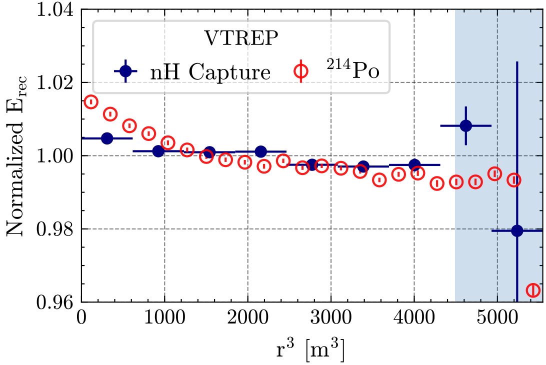


- 3 different vertex reconstructions tested using ^{68}Ge calibration
- Biases within 10 cm is most of detector
- Resolution typically from 15 cm to 20 cm depending on algorithm

Energy spatial uniformity

JUNO, “Initial performance results of the JUNO detector,” [arXiv:2511.14590]

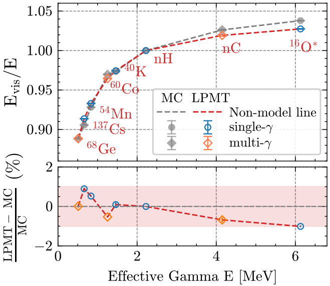


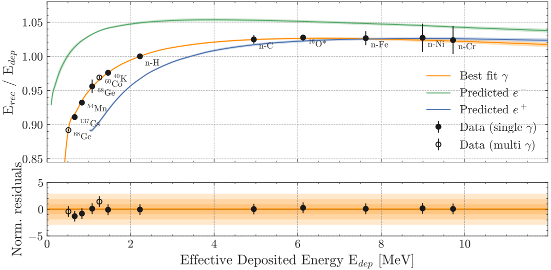


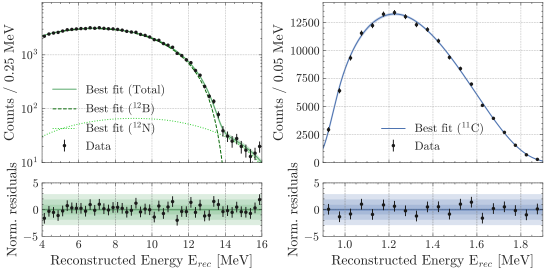
- 2 different energy reconstruction algorithms
- Uniformity better than $\pm 1\%$ within R < 16.5 m (FV)

Residual energy non linearity

JUNO, “Initial performance results of the JUNO detector,” [arXiv:2511.14590]



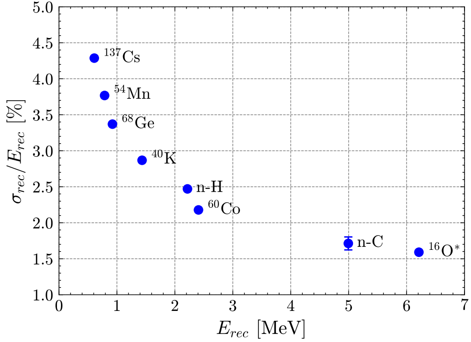


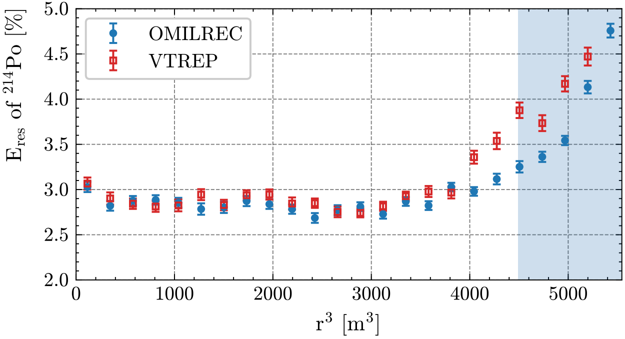


- $< \pm 1\%$ agreement with simulation for γ
- Residual non-linearity adjusted using:
  - γ calibration sources at center
  - cosmogenic ^{12}B β^- decays in FV
  - cosmogenic ^{11}C β^+ decays in FV
- Good agreement between data and energy response model

Energy resolution

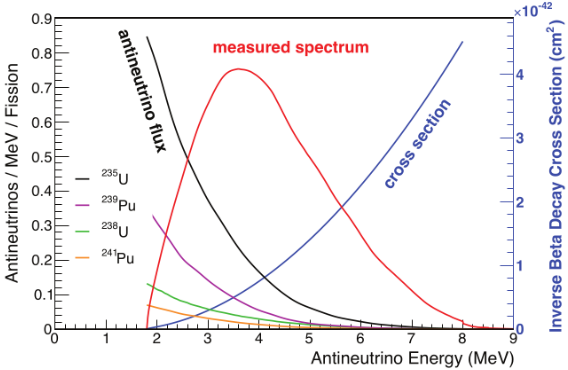
JUNO, "Initial performance results of the JUNO detector." [arXiv:2511.14590]



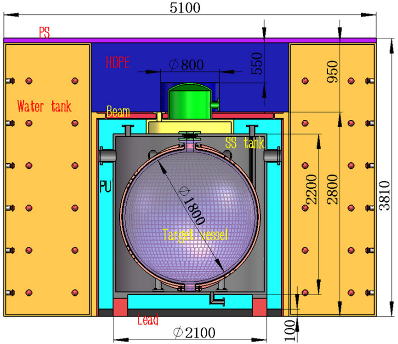


- $\sim$ 3.4% energy resolution from ^{68}Ge (2 $\times$ 511 keV γ) @ CD center
  - A bit worse than expected from MC (3.1%)
  - Work ongoing to improve energy resolution
- Energy resolution of α from ^{214}Po (from ^{238}U decays) roughly constant in FV
  - Small degradation near boundary

Measuring Reactor Antineutrinos: flux & cross-section



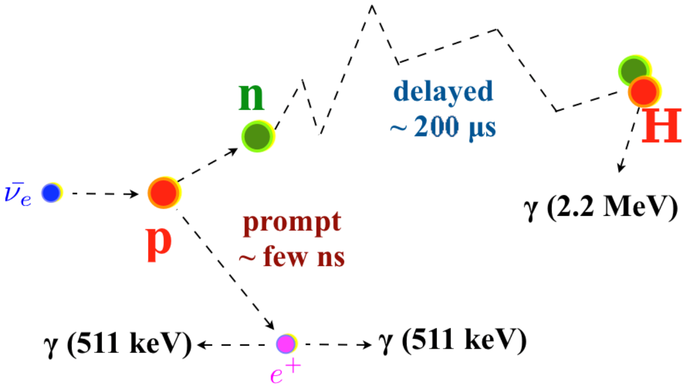
JUNO-TAO



- $\bar{\nu}_e$ flux from commercial nuclear power plants
  - Currently using flux reference from Daya-Bay near detectors
  - In future: use flux measured by JUNO-TAO as reference
    - JUNO-TAO started data taking on Feb 12, 2026!
- Neutrinos detected using Inverse Beta Decay: very well known cross-section
- Detected $\bar{\nu}_e$ energy 2–8 MeV $\Rightarrow$ Only sensitive to $\bar{\nu}_e \to \bar{\nu}_e$

Measuring reactor $\bar{\nu}_e$: Inverse Beta Decay (IBD)

- Detected via IBD: $\bar{\nu}_e + p \rightarrow n + e^+$
  - IBD used since discovery of $\bar{\nu}$
  - Prompt+delayed signal $\Rightarrow$ large background suppression

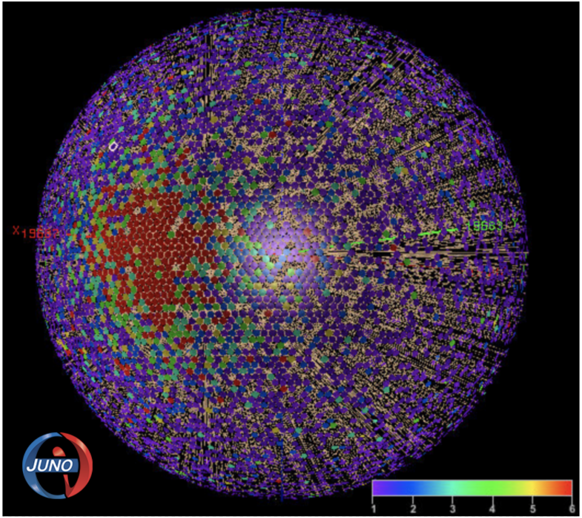


- $E_{vis}(e^+) \simeq E(\bar{\nu}) - 0.8$ MeV $\leftarrow$ used to as proxy for antineutrino energy

An IBD event @ JUNO

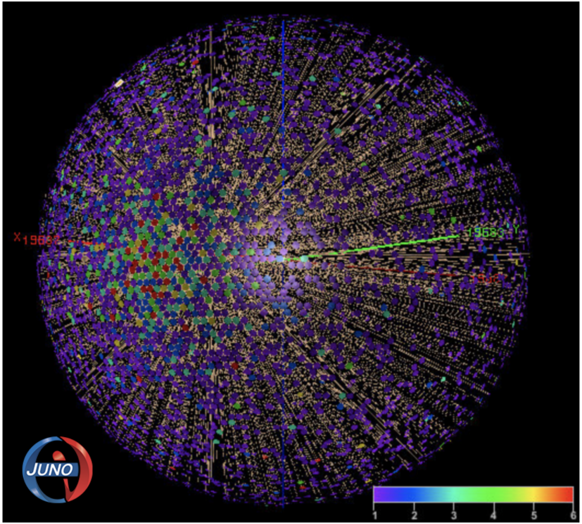
Prompt e^+ signal

Mon, 25 Aug 2025 22:50:45
RecEnergy = 6.3 MeV
RecVertex (-9458, -9707, 3820) mm



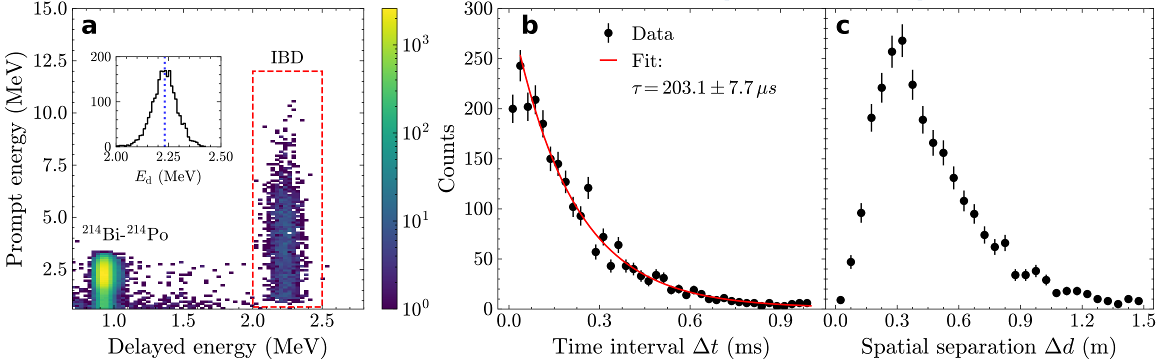
Delayed n signal

Mon, 25 Aug 2025 22:50:45
RecEnergy = 2.4 MeV
RecVertex (-10393, -9794, 4333) mm



Selecting IBD events

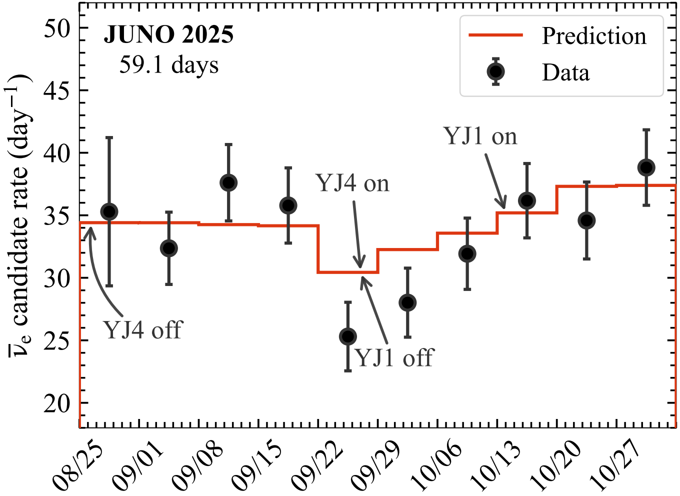
JUNO, “First measurement of reactor neutrino oscillations at JUNO,” [arXiv:2511.14593]



- Prompt energy: $E_p \in [0.7, 12.0]$ MeV
- Delayed energy: $E_d \in [2.0, 2.5]$ MeV
- Time interval: $\Delta t \in [5\ \mu s, 1\ ms]$
- Spatial separation: $\Delta d < 1.5$ m

IBD rate per week

JUNO, “First measurement of reactor neutrino oscillations at JUNO,” [arXiv:2511.14593]



- Pre unblinding checks done using nominal expected power output
- Power plants not operational continously
  - Drop around Sept 24 due to Typhoon Ragasa
- $\bar{\nu}_e$ candidate rate tracks expected rate based on power plant activity

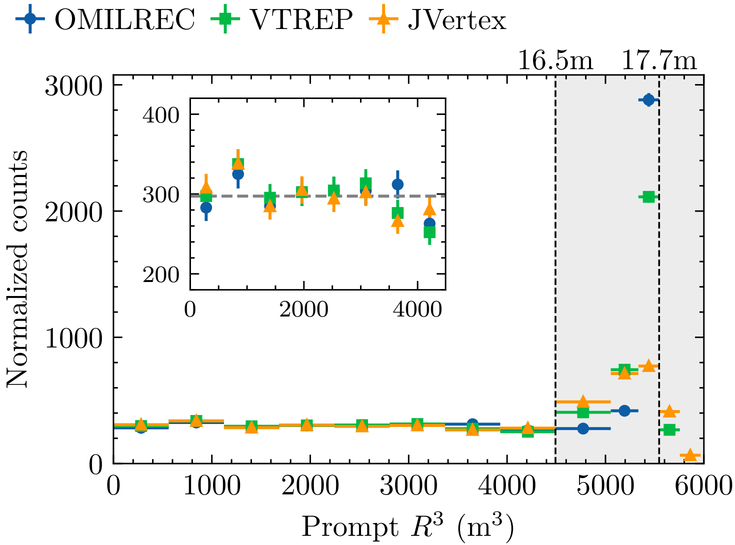
Event selection used in first analysis

JUNO, “First measurement of reactor neutrino oscillations at JUNO,” [arXiv:2511.14593]

- FV cut: prompt candidate vertices with $R < 16.5$ m and $|z| < 15.5$ m
  - Slight differences between analysis I, II, and III
  - Each analysis used different vertex reconstruction algorithm
- Flasher rejection based on std-dev of PMT hit multiplicity & timing distributions
- μ veto
  - μ: CD triggers with $Q > 3 \cdot 10^4$ PE or WP triggers with $Q > 700$ PE
    - ★ Reject events within 5 ms following a μ
    - ★ One analysis also tested cylindrical cut around μ but not chosen as baseline for now
  - Spallation neutron: $\Delta t_\mu \in [40\ \mu\text{s}, 2\ \text{ms}]$ and $E \in [1.5, 20]$ MeV
    - ★ Reject events within 4 m of a spallation neutron up to 1.2 s after the neutron
- Multiplicity: reject events with extra energy deposits close to delayed signal
- Prompt-delayed coincidence (ie, IBD-like)
  - Prompt energy: $E_p \in [0.7, 12.0]$ MeV
  - Delayed energy: $E_d \in [2.0, 2.5]$ MeV
  - Time interval: $\Delta t \in [5\ \mu\text{s}, 1\ \text{ms}]$
  - Spatial separation: $\Delta d < 1.5$ m

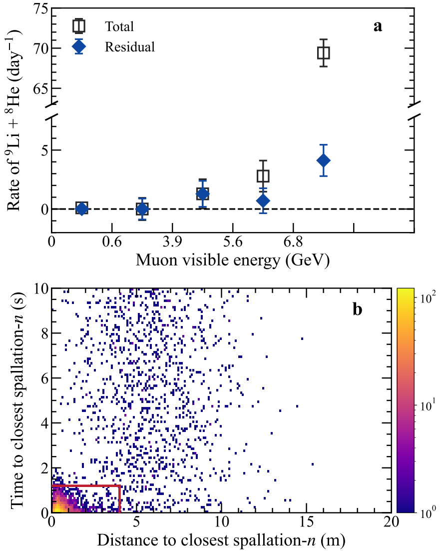
IBD uniformity within FV

JUNO, "Initial performance results of the JUNO detector," [arXiv:2511.14590]



Cosmogenic background rejection

JUNO, “First measurement of reactor neutrino oscillations at JUNO,” [arXiv:2511.14593]

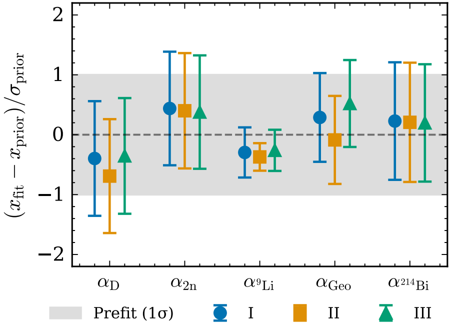


- Rejection IBD-like events close to identified spallation neutron:
  - distance < 4 m
  - up to 1.2 s after neutron
- Cosmogenic ^{9}Li/^{8}He rate reduced by > 90%
- Even with such rejection this is still largest background
  - For first result we preferred to only use ‘simple’ selection (small impact given limited livetime)
  - Still room to improve ^{9}Li/^{8}He rejection

IBD selection and rate & remaining backgrounds

JUNO, "First measurement of reactor neutrino oscillations at JUNO," [arXiv:2511.14593]

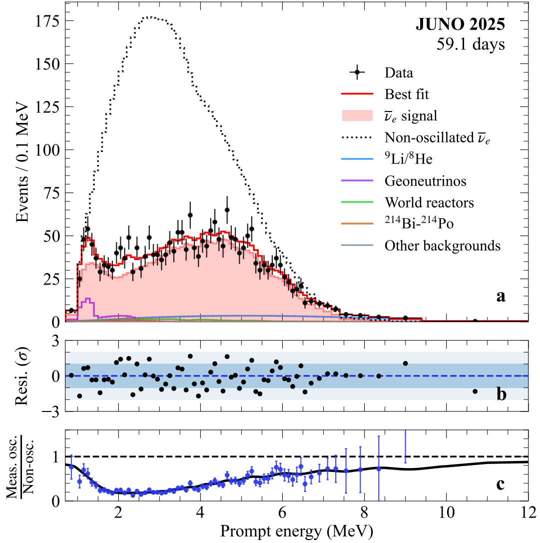
Antineutrinos ($\overline{\nu}_e$) Candidates Summary		
DAQ live time (days)	59.1	
$\overline{\nu}_e$ candidates	2379	
Selection Efficiencies (%)	ε	σ_{rel}
Fiducial volume	80.6	1.6
PMT flasher rejection	>99.9	negligible
μ veto	93.6	negligible
Multiplicity	97.4	negligible
Prompt-delayed coinc.	95.1	0.13
Total efficiency (ε_{tot})	69.9	1.6
$\overline{\nu}_e$ signal (cpd[1])		
w/o ε_{tot} corrected	33.5 ± 1.7	
w/ ε_{tot} corrected	47.9 ± 2.6	
Non-oscillated $\overline{\nu}_e$	150.9 ± 2.7	
Backgrounds (cpd)	Pre-fit	Best-fit
$^{9}Li/^{8}He$	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}Bi-^{214}Po	0.18 ± 0.10	0.20 ± 0.10
$^{13}C(\alpha, n)^{16}O$	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



- 33.5 $\bar{\nu}_e$ observed in average
  - For now, smaller FV than in sensitivity studies
- Consistent results from 3 independent analyses groups

Measured reactor $\bar{\nu}_e$ spectra

JUNO, "First measurement of reactor neutrino oscillations at JUNO," [arXiv:2511.14593]

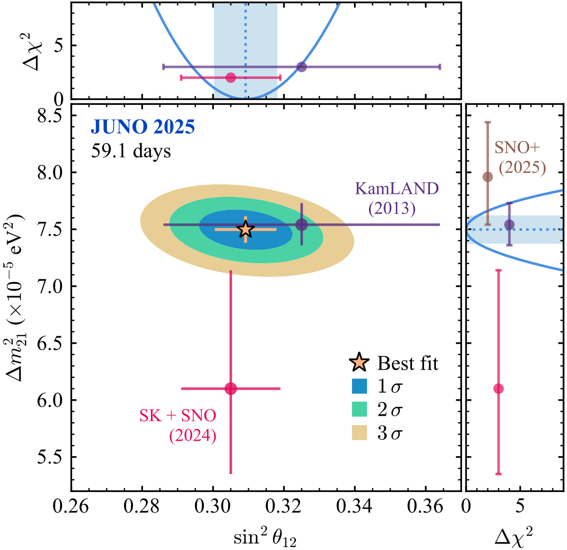


- Clear effect from $\bar{\nu}_e$ disappearance driven by $(\theta_{12}, \Delta m^2_{21})$ observed
- Statistics still too low for proper measurement of Δm^2_{31} driven oscillations
- Additionally, in future TAO will help constrain the non-oscillated $\bar{\nu}_e$ flux with good energy resolution
  - Currently using Daya-Bay spectrum as reference

First JUNO results on θ_{12} and Δm^2_{21}

JUNO, "First measurement of reactor neutrino oscillations at JUNO." [arXiv:2511.14593]

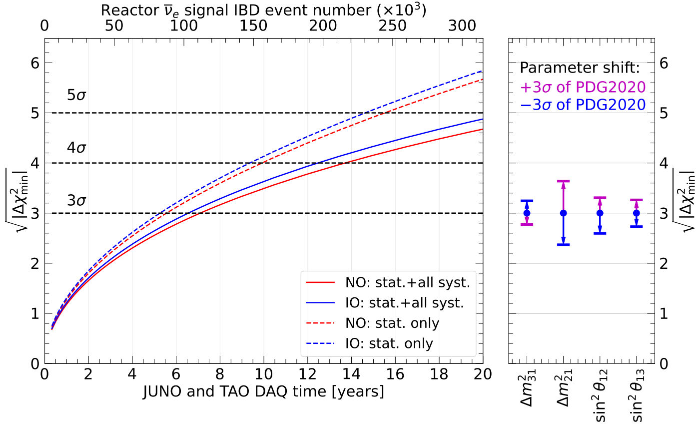
- Similar results from 3 independent analysis
- $\sin^2\theta_{12} = 0.3092 \pm 0.0087$
- $\Delta m^2_{21} = (7.50 \pm 0.12) \times 10^{-5}\ \text{eV}^2$
- Results in good agreement with previous world averages
- 1.6× improvement in precision in each parameter with respect to KamLAND and Solar-ν

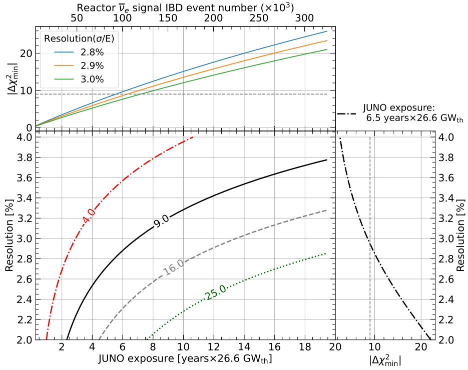


Looking beyond 59 days of data. . .

Neutrino Mass Ordering using Reactor Neutrinos

"Potential to identify neutrino mass ordering with reactor antineutrinos at JUNO," Chin. Phys. C **49** (2025) no.3, 033104

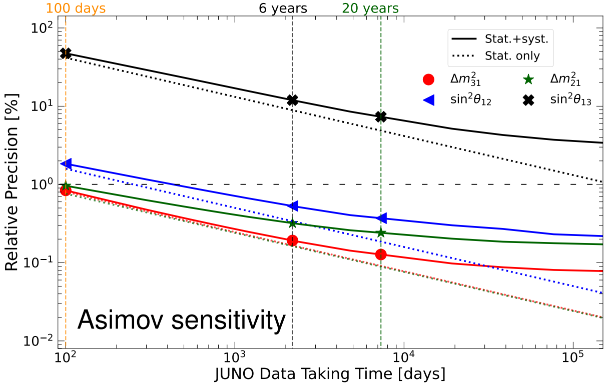




- 3σ in $\sim$7 years $\times$ 26.6 GW_{th} exposure
- Complementary to other experiments!

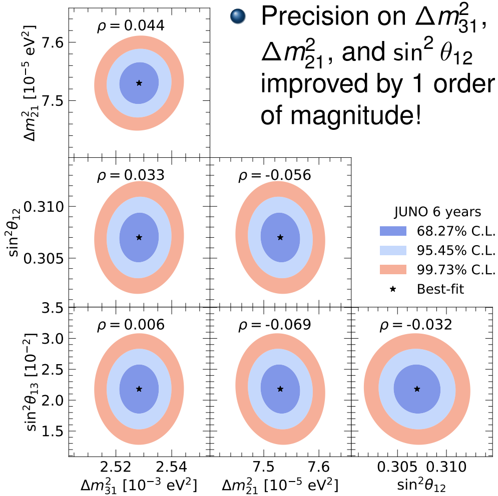
Precision Measurement of Neutrino Oscillation Parameters

"Sub-percent precision measurement of neutrino oscillation parameters with JUNO," Chin. Phys. C **46** (2022) no.12, 123001



	Δm^2_{31}	Δm^2_{21}	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$
JUNO 6 years	~0.2%	~0.3%	~0.5%	~12%
PDG2020	1.4%	2.4%	4.2%	3.2%

- Precision on Δm^2_{31}, Δm^2_{21}, and $\sin^2\theta_{12}$ improved by 1 order of magnitude!



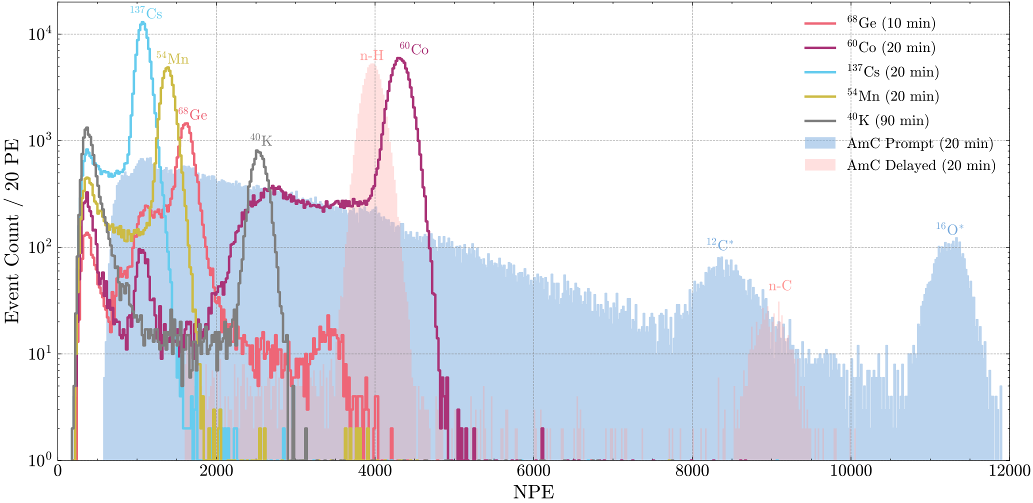
Conclusions

- JUNO has been completed & data taking started mid-2025
  - Very good detector performance from the start
  - Detector globally meets or exceeds design specifications
- First results with first 2 months of data taking
  - 1.6$\times$ improvement on precision on θ_{12} and Δm^2_{21}!
  - Still need a bit more statistics to measure Δm^2_{31}, no show stopper identified
  - JUNO-TAO started taking data $\rightarrow$ $\bar{\nu}_e$ spectra w/ better energy resolution than JUNO
- Very good prospects for continuing data taking!
- Keep in mind JUNO only just started taking data
  - Working on better understanding of detector to further improve performance
- Rich physics & astrophysics program beyond reactor-$\bar{\nu}_e$ analysis

Backup

Calibration sources spectra

JUNO, “Initial performance results of the JUNO detector,” [arXiv:2511.14590]



Measuring NMO with reactor neutrinos

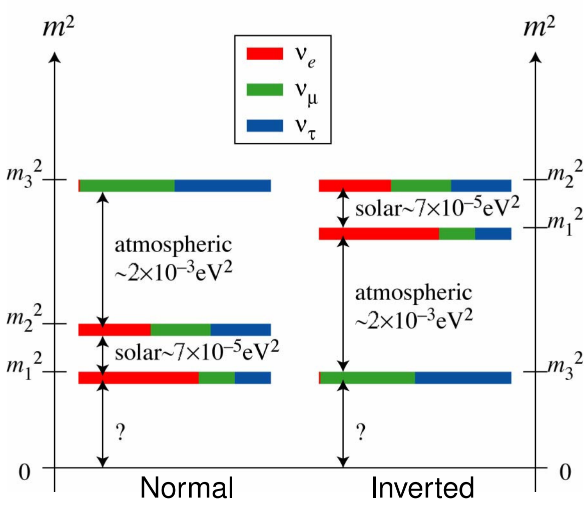
method: S. T. Petcov, M. Piai, Phys. Lett. B **533** (2002) 94; formulas: S. F. Ge, *et al*, JHEP **1305** (2013) 131

$$P_{ee} = \left| \sum_{i=1}^{3} U_{ei} \exp\left(-i\frac{m_i^2}{2E_i}\right) U_{ei}^* \right|^2$$
$$= 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2(\Delta_{21})$$
$$- \cos^2\theta_{12}\sin^2 2\theta_{13}\sin^2(\Delta_{31})$$
$$- \sin^2\theta_{12}\sin^2 2\theta_{13}\sin^2(\Delta_{32}),$$

$$P_{ee} = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2(\Delta_{21})$$
$$- \sin^2 2\theta_{13}\sin^2(|\Delta_{31}|)$$
$$- \sin^2\theta_{12}\sin^2 2\theta_{13}\sin^2(\Delta_{21})\cos(2|\Delta_{31}|)$$
$$\pm \frac{\sin^2\theta_{12}}{2}\sin^2 2\theta_{13}\sin(2\Delta_{21})\sin(2|\Delta_{31}|),$$

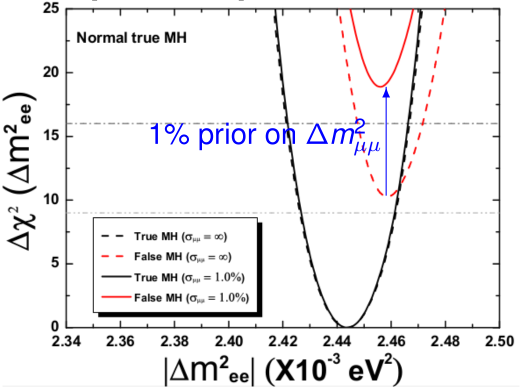
$$\Delta_{ij} \equiv \frac{\Delta m_{ij}^2 L}{4E_\nu}, \quad (\Delta m_{ij}^2 \equiv m_i^2 - m_j^2)$$

- Orderings: Normal $\rightarrow +$; Inverted $\rightarrow -$

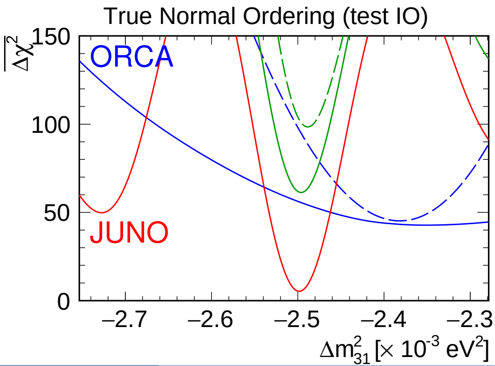


NMO via combined fits of JUNO and other experiments

- Intrinsic differences between $\nu_e \to \nu_e$ and $\nu_\mu \to \nu_\mu$, precise measurements of Δm^2 obtain different best-fit values for Δm^2_{31} when wrong ordering assumed
  - JUNO independent of δ_{CP}, θ_{23}, and doesn't rely on matter effects
- Dedicated studies performed with external priors and with other experiments
  - IceCube [1306.3988] & [1911.06745], accelerators [2008.11280], KM3NeT/ORCA [2108.06293]



Combined JUNO+ORCA



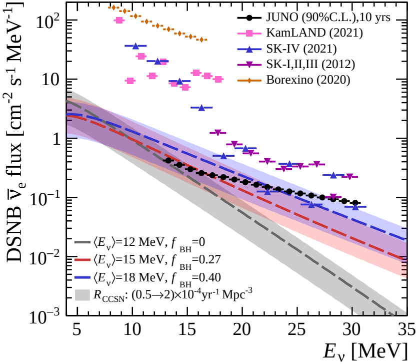
Precision Measurement of Neutrino Oscillation Parameters: σ

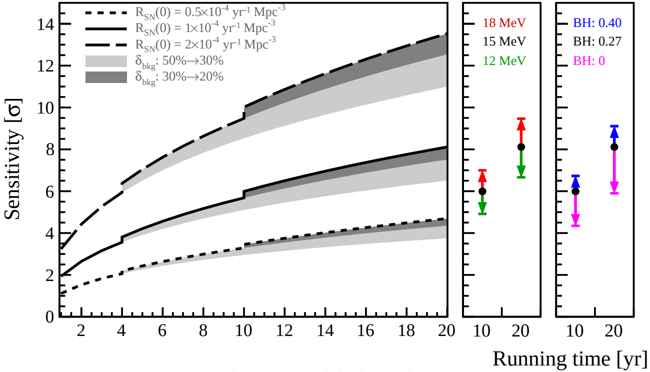
"Sub-percent precision measurement of neutrino oscillation parameters with JUNO," Chin. Phys. C **46** (2022) no.12, 123001

1σ (%)	$\sin^2\theta_{12}$	Δm^2_{21}	Δm^2_{31}	$\sin^2\theta_{13}$
Statistics	0.34	0.16	0.17	8.94
Reactor:				
- Uncorrelated	0.10	0.01	< 0.01	2.53
- Correlated	0.27	0.03	0.01	6.83
- Reference spectrum	0.09	0.07	0.05	3.48
- Spent Nuclear Fuel	0.05	0.07	< 0.01	1.55
- Non-equilibrium	0.10	0.14	< 0.01	2.65
Detection:				
- Efficiency	0.23	0.02	0.01	5.81
- Energy resolution	0.01	0.01	< 0.01	0.39
- Nonlinearity	0.09	0.05	0.04	2.09
- Backgrounds	0.20	0.18	0.04	4.89
Matter density	0.07	0.01	0.01	0.98
All systematics	0.40	0.27	0.08	8.16
Total	0.52	0.32	0.19	12.11

Diffuse Supernova Neutrino Background

"Prospects for Detecting the Diffuse Supernova Neutrino Background with JUNO," JCAP **10** (2022), 033



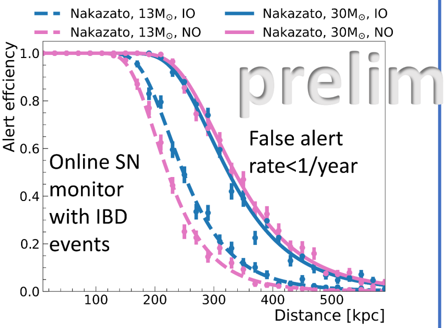


- For reference model:
  - @ 3 years $\rightarrow$ 3 σ sensitivity
  - @ 10 years $\rightarrow$ 5 σ sensitivity

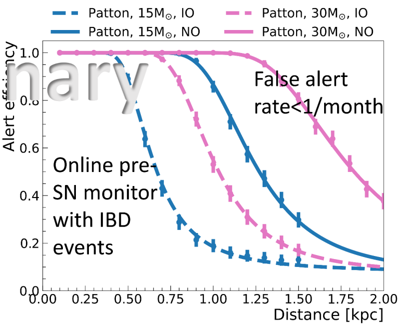
- Improvements in sensitivity due to:
  - Reduced expected background
  - Increase signal efficiency (50% $\rightarrow$ 80%) w/ PSD
  - Better DSNB model

Core Collapse Supernova Neutrinos

See poster 10.5281/zenodo.6785184 from Neutrino 2022, paper in preparation



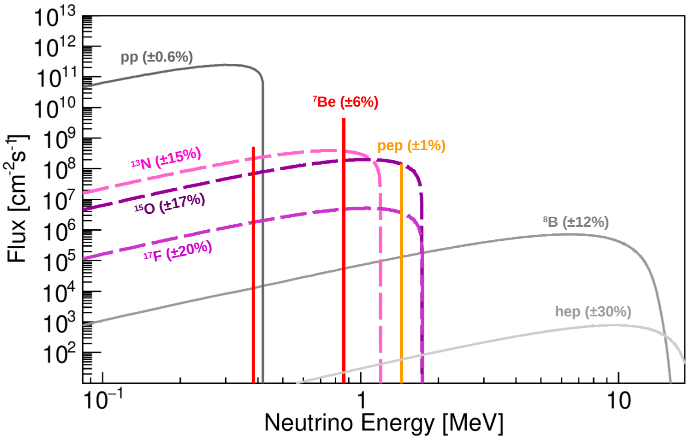
Alert efficiency for SN of online monitor. False alert rate is set to be smaller than 1/year.



Alert efficiency for pre-SN of online monitor. False alert rate is smaller than 1/month.

- Capability to detect pre-SN neutrinos from close SN-candidates
- >50% efficiency to detect CCSN up to 250–300 kpc
  - For reference: Milky Way diameter ∼30 kpc; Andromeda galaxy distance ∼ 780 kpc

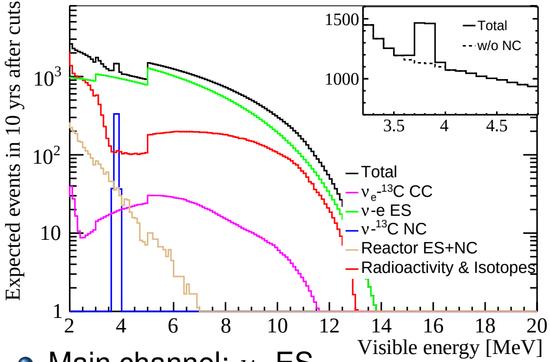
Solar Neutrinos



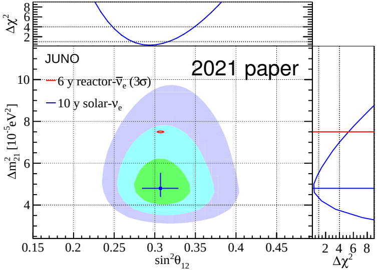
- Nuclear fusion in Sun $\Rightarrow \nu_e$
  - ν energy depends on specific reaction
  - Probe Sun composition
- JUNO expected to be able to measure ^{8}B, ^{7}Be, pep, CNO
  - Main limitation from radioactive backgrounds

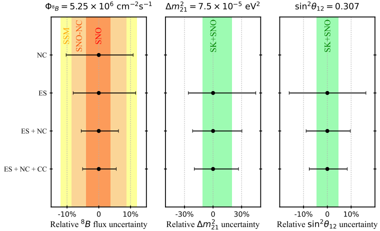
Solar Neutrinos: ^{8}B @ JUNO

"Feasibility and physics potential of detecting ^{8}B solar neutrinos at JUNO," Chin. Phys. C **45** (2021) no.2, 023004 and "Model Independent Approach of the JUNO ^{8}B Solar Neutrino Program," arXiv:2210.08437



- Main channel: ν_e ES
- Also visible:
  - $\nu_x + ^{13}$C NC: 3.7 MeV γ
  - $\nu_e + ^{13}$C CC: 2.2 MeV β^+



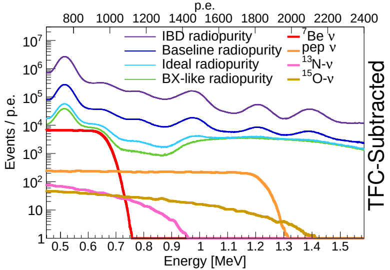


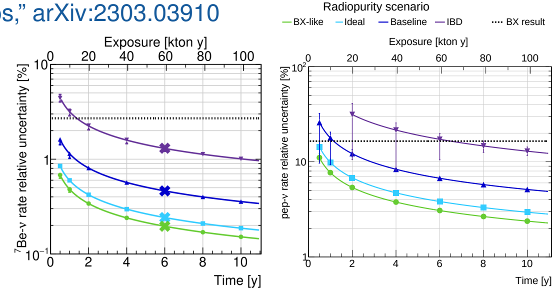
2022 paper

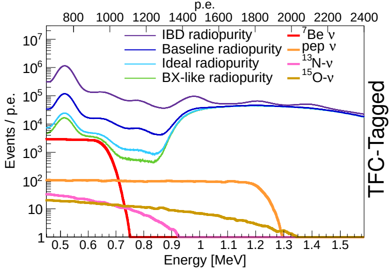
Solar Neutrinos: ^{7}Be, pep, CNO @ JUNO

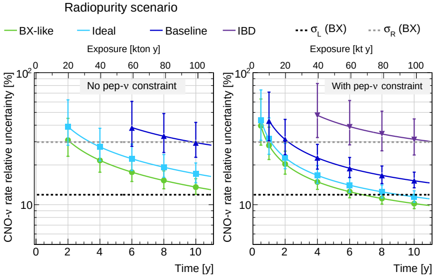
*BX: Borexino

"JUNO sensitivity to ^{7}Be, *pep*, and CNO solar neutrinos," arXiv:2303.03910



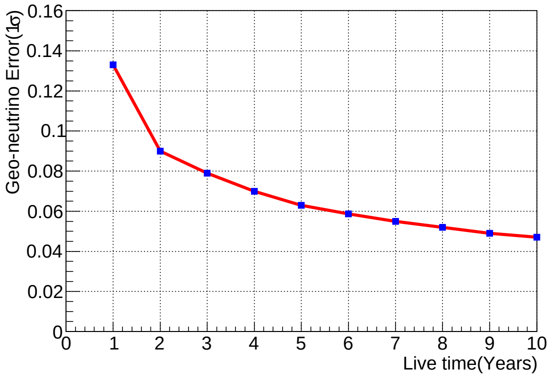






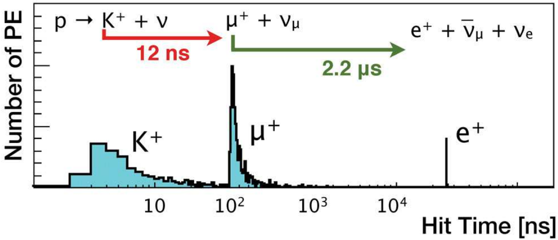
Other topics in JUNO

Geo $\bar{\nu}$



- Also potential to constrain Th/U ratio

Nucleon decay



- Triple coincidence signature from p $\rightarrow \bar{\nu} + K^{+}$
- Other nucleon decay modes also being investigated

Among other topics discussed in J. Phys. G **43** (2016) no.3, 030401 and Prog. Part. Nucl. Phys. **123** (2022), 103927

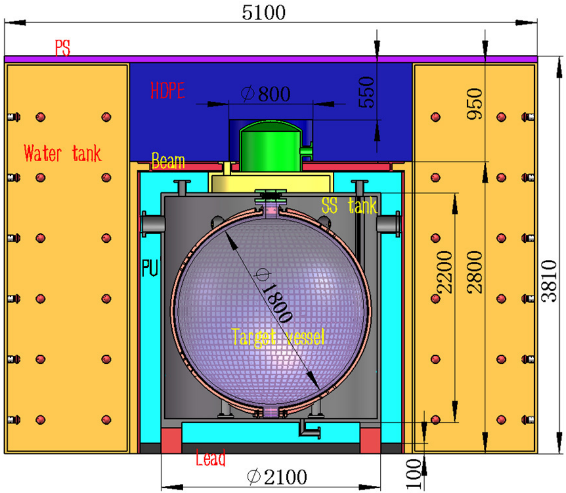
JUNO-TAO

"TAO Conceptual Design Report: A Precision Measurement of the Reactor Antineutrino Spectrum with Sub-percent Energy Resolution," arXiv:2005.08745

- JUNO-TAO provides reference for reactor spectrum
- Better energy resolution than JUNO (4500 PE/MeV)

JUNO-TAO detector:

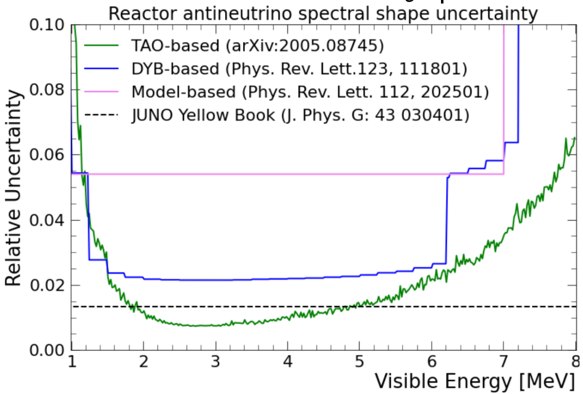
- 1 ton fiducial volume Gd-LS detector
  - 30 m from one of Taishan's 4.6 GW_{th} reactor core
  - $30\times$ JUNO event rate
- 10 m^2 SiPM of 50% photon detection efficiency (PDE) operated at $-50°C$
  - >95% photo-coverage



JUNO-TAO – Physics potential

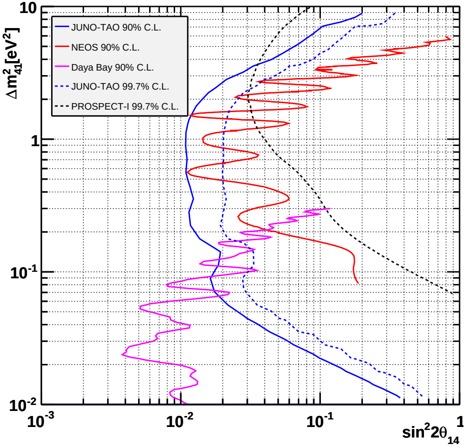
"TAO Conceptual Design Report: A Precision Measurement of the Reactor Antineutrino Spectrum with Sub-percent Energy Resolution," arXiv:2005.08745

Precise measurement of $\bar{\nu}_e$ spectra

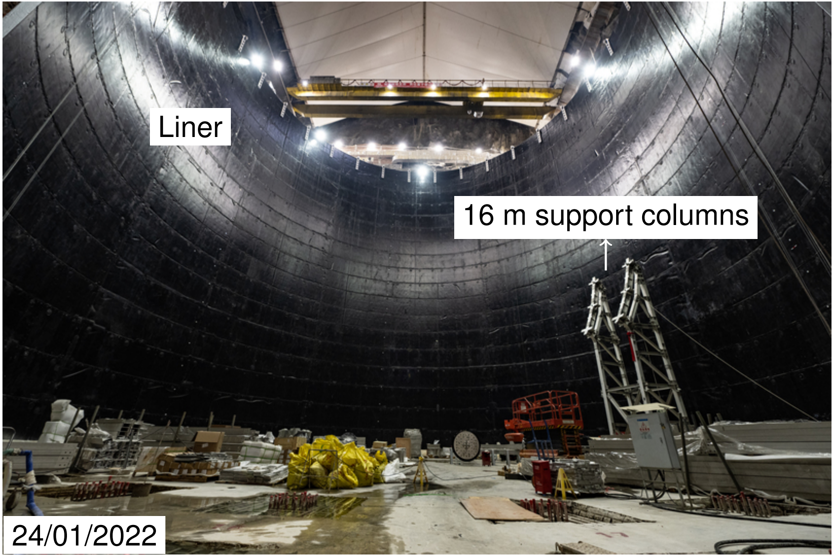


- TAO energy resolution <2% @ 1 MeV

Sterile Neutrino searches

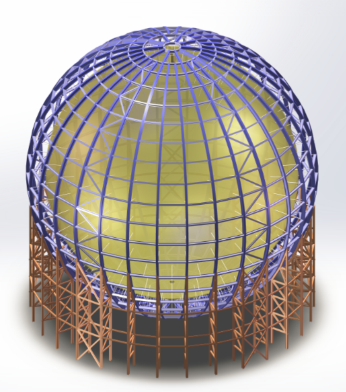


The JUNO detector – inside Water Cherenkov Detector



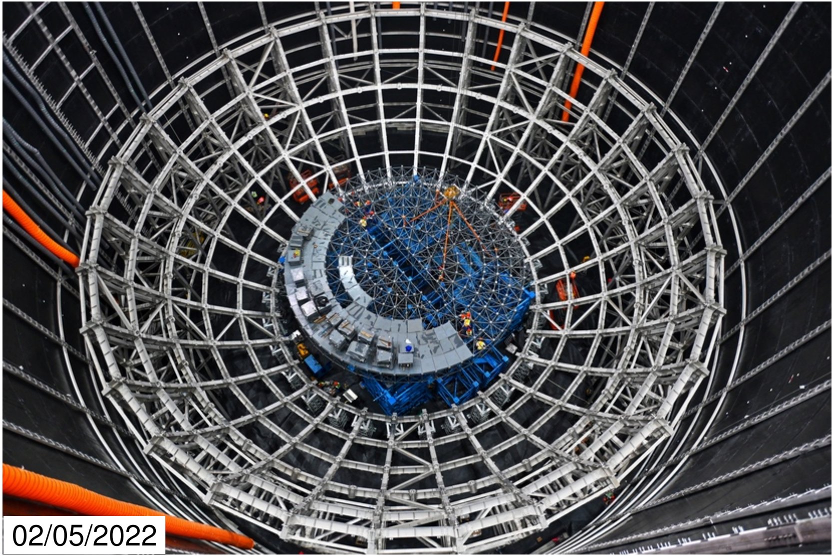
- 35 kt ultrapure water
- 2400 20" MCP PMTs
- μ det. eff. > 99.5%
- passive shield for radioactivity
- ^{222}Rn < 10 mBq/m^3
- Keep temperature @ $(21 \pm 1)^{\circ}$C

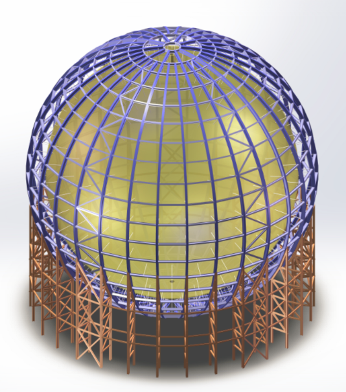
The JUNO detector – CD Support Structure



- Acrylic Sphere supported by 590 connecting bars

The JUNO detector – CD Support Structure and Lift Platform





- Acrylic Sphere supported by 590 connecting bars

The JUNO detector – CD Support Structure and Lift Platform

- Assembly of SS finished now
- Starting to install acrylic sphere

The JUNO detector – Acrylic Sphere

Assembly test in factory

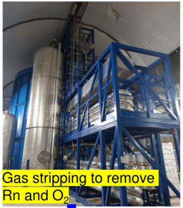
- 265 acrylic plates
- thickness: 124$\pm$4 mm
- radiopurity: U/Th/K < 1 ppt
- Each plate:
  - polished
  - cleaned
  - PE protective film added
- PE film to be removed after installation

The JUNO detector – Liquid Scintillator

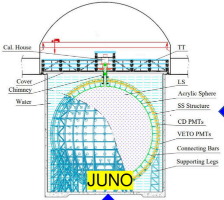
Four purification plants to achieve target radio-purity 10^{-17} g/g U/Th and 20 m attenuation length at 430 nm.

SS pipes to underground

All the LS related systems will finish assembly in summer.



15%



85%

Jie Zhao Neutrino2022

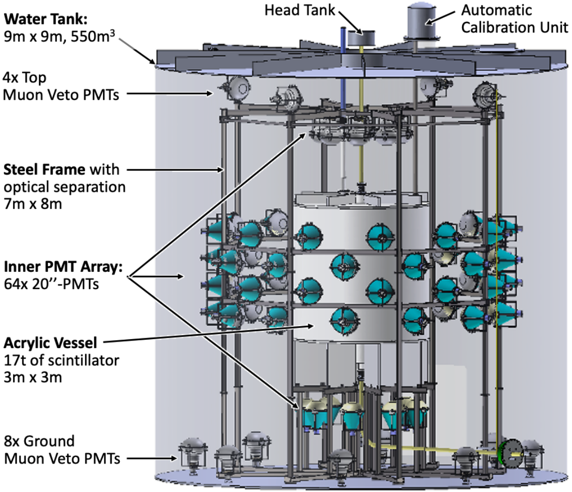
NIM.A 908 (2021) 164823

Eur. Phys. J. C **81** (2021) no.11, 973

The JUNO detector – OSIRIS

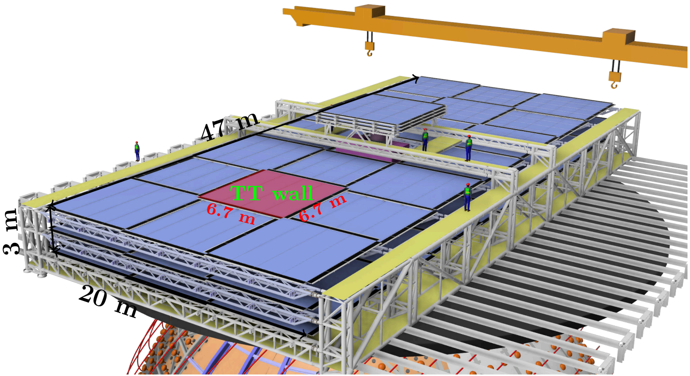
"The design and sensitivity of JUNO's scintillator radiopurity pre-detector OSIRIS", Eur. Phys. J. C **81** (2021) no.11, 973

- Monitor LS radiopurity during before/during filling
- Few days: U/Th $\sim 10^{-15}$ g/g (IBD requirement)
- 2–3 weeks: U/Th $\sim 10^{-17}$ g/g (solar "ideal" case)
- Can also measure ^{14}C, ^{210}Po, ^{85}Kr

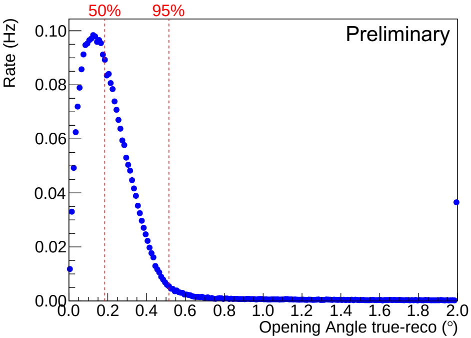


The JUNO detector – Top Tracker

"The JUNO experiment Top Tracker," Nucl. Instrum. Meth. A **1057** (2023). 168680



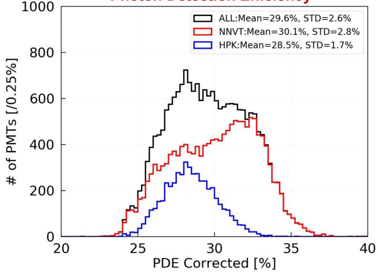
- Refurbished from OPERA experiment



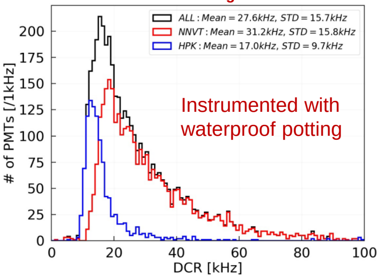
- Very precise μ tracking
  - 2.6×2.6 cm^2 XY granularity
  - 0.2° median angular resolution
- Provide well reconstructed μ sample for other systems

Photomultiplier Tubes

Photon Detection Efficiency



Dark Counting Rate



All PMTs produced, tested, and instrumented with waterproof potting

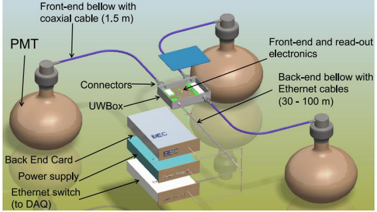
		LPMT (20-inch)		SPMT (3-inch)
		Hamamatsu	NNVT	HZC
Quantity		5000	15012	25600
Charge Collection		Dynode	MCP	Dynode
Photon Detection Efficiency		**28.5%**	**30.1%**	25%
Mean Dark Count Rate [kHz]	Bare	15.3	49.3	0.5
	Potted	**17.0**	**31.2**	
Transit Time Spread (σ) [ns]		1.3	7.0	1.6
Dynamic range for [0-10] MeV		[0, 100] PEs		[0, 2] PEs
Coverage		75%		3%
Reference		arXiv: 2205.08629		NIM.A 1005 (2021) 165347

12.6k NNVT PMTs with highest PDE are selected for light collection from LS and the rest are used in the Water Cherenkov detector.

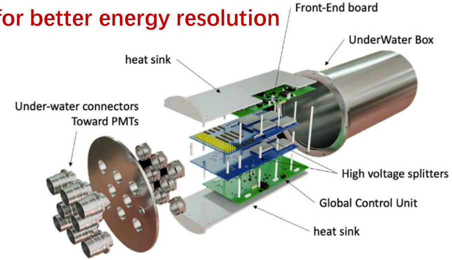
Electronics

Posters: #216, # 218, #270

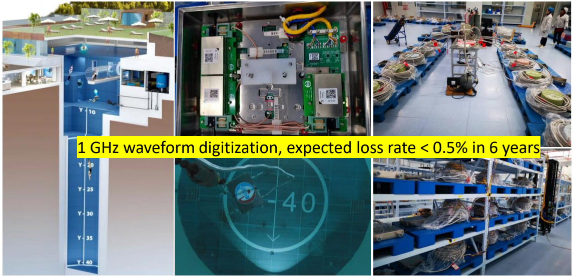
Underwater electronics to improve signal-to-noise ratio for better energy resolution

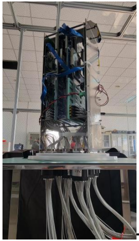


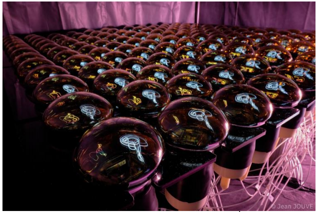
3 20-inch PMTs connected to one underwater box



128 3-inch PMTs connected to one underwater box







Electronics assembly ongoing

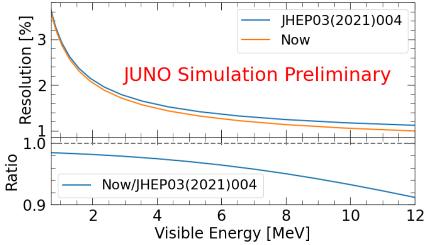
Update of energy resolution

Change	Light yield in detector center [PEs/MeV]	Energy resolution	Reference
Previous estimation	1345	3.0% @1MeV	*JHEP03(2021)004*
Photon Detection Efficiency (27%→30%)	+11%↑	**2.9% @ 1MeV** (Poster #519)	arXiv: 2205.08629
New Central Detector Geometries	+3%↑		Poster #184
New PMT Optical Model	+8%↑		*EPJC 82 329 (2022)* Poster #815

Positron energy resolution is understood:

$$\frac{\sigma}{E_{\text{vis}}} = \sqrt{\left(\frac{a}{\sqrt{E_{\text{vis}}}}\right)^2 + b^2 + \left(\frac{c}{E_{\text{vis}}}\right)^2}$$

- **Photon statistics**
- **Annihilation-induced γs**
- **Dark noise**
- **Scintillation quenching effect**
  - LS Birks constant from table-top measurements
- **Cherenkov radiation**
  - Cherenkov yield factor (refractive index & re-emission probability) is re-constrained with Daya Bay LS non-linearity
- **Detector uniformity and reconstruction**



Positron energy resolution

$$\frac{\sigma}{E} = \sqrt{\left(\frac{a}{\sqrt{E}}\right)^2 + b^2 + \left(\frac{c}{E}\right)^2}$$

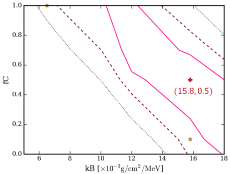
Photon statistics

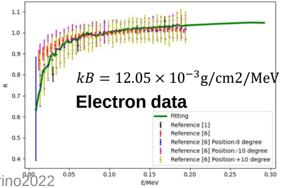
- **Annihilation-induced γs**
- **Dark noise**

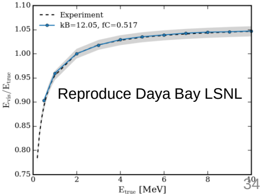
- **Scintillation quenching effect**
  - LS Birks constant **(kB)**
- **Cherenkov radiation**
  - LS refractive index
  - LS re-emission probability
  - Cherenkov yield scale factor **(fC)**
- **Detector uniformity and reconstruction**

- **kB** & **fC** are key parameters to predict energy resolution

- **Firstly attempt to constrain kB & fC with Daya Bay LS non-linearity**
  - Strong correlation between kB and fC
- **Solved by combining a series of table-top measurements on scintillation quenching effect**
  - kB of LS is determined to be $12.05 \times 10^{-3} \mathrm{g/cm2/MeV}$
- **Re-constrain fC with Daya Bay LS non-linearity**
  - fC is determined to be 0.517



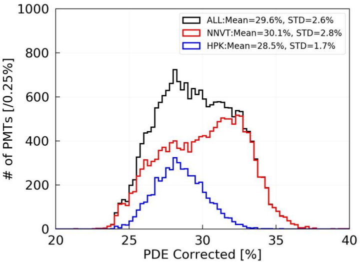




Light yield evolution

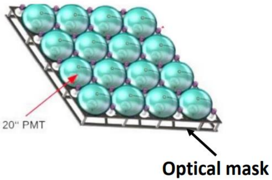
PMT PDE

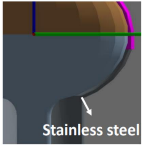
- Averaged PDE:27.0%→30.1%
- 27.0% is based on the original requirement of **QE~30%, CE~90%**
- 30.1% is the selected mean PDE, from **PMT mass testing system**

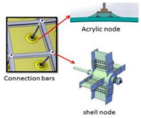


arXiv:2205.08629

New Geometries





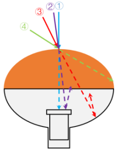


- **Reflections** on them are taken into consideration
- Yield 2.7% more photons

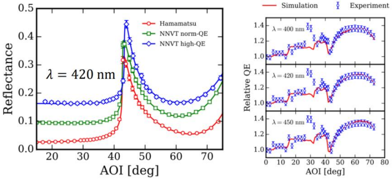
New PMT Optical Model

Optical Processes in PMT

- Reflection on photocathode
- PDE angular response
- Multiple reflections inside PMT



- ◆ Multilayer thin film theory
- ◆ Experimental tests
- ◆ GEANT4 simulation



Poster #815