Km Baseline Neutrino Experiments

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on behalf of the JUNO Collaboration

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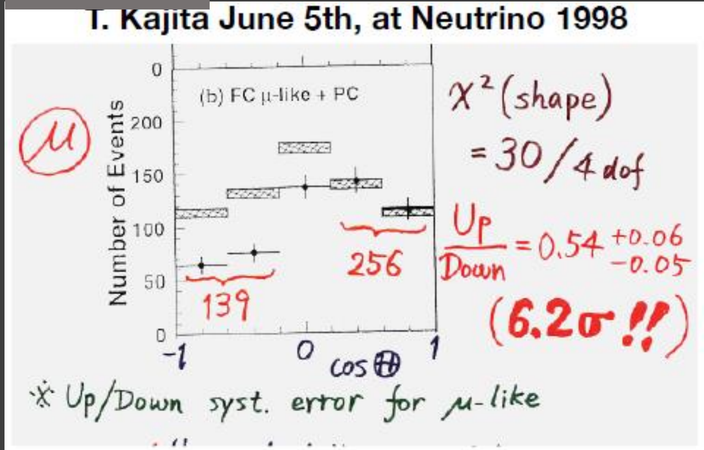
Neutrino oscillation

- Observations from various neutrino sources at different baselines are consistent with the three neutrino oscillation framework

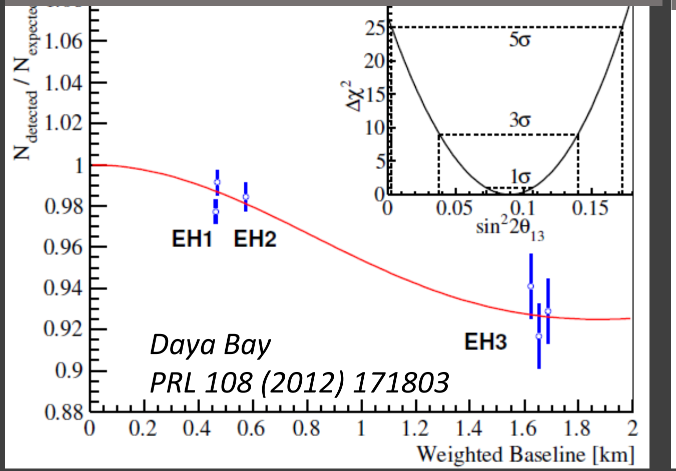
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{-i\delta_1} & 0 & 0 \\ 0 & e^{-i\delta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

θ_{23}~45° by atmospheric neutrinos (1998)	θ_{13}~9° by reactor and accelerator neutrinos (2012)	θ_{12}~34° by solar neutrinos (2001)

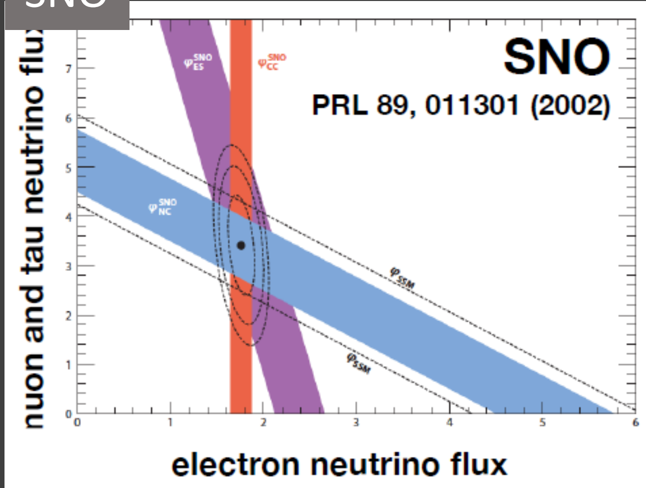
Super- K



Daya Bay/RENO/Double Chooz/T2K

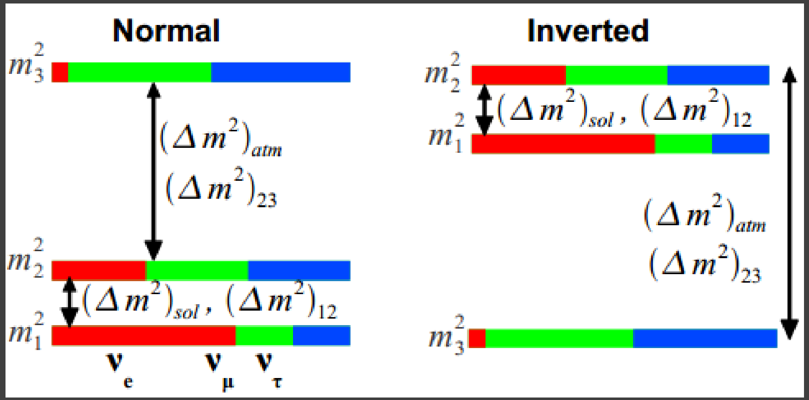


SNO

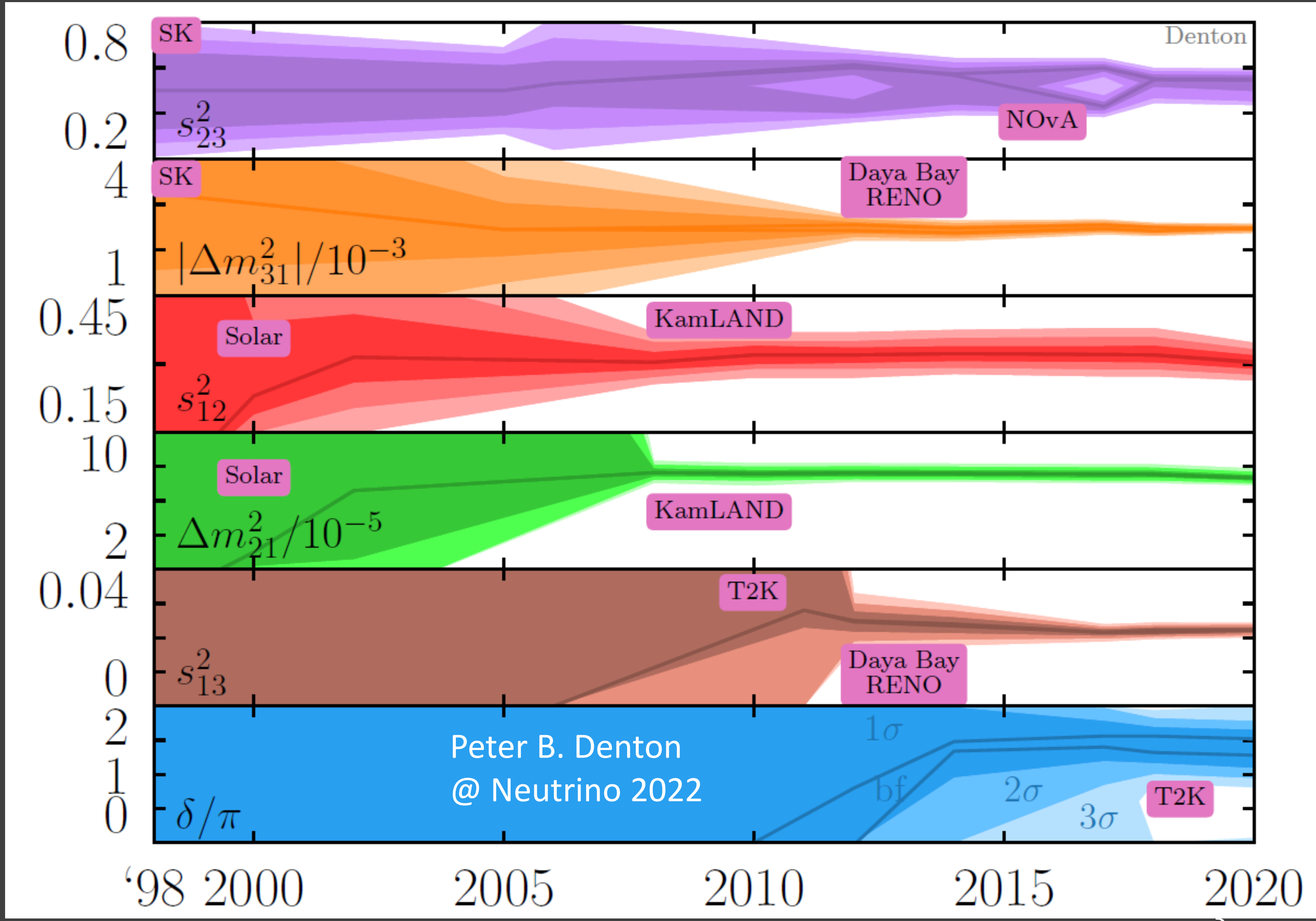


From discovery to precision

- known: θ_{12}, θ_{13}, θ_{23}, Δm^2_{21}, $|\Delta m^2_{32}|$
- Unknowns:
  - mass ordering
  - CP phase
  - θ_{23} octant (< 45° or > 45°)



$m_1 < m_2 < m_3$ $m_3 < m_1 < m_2$



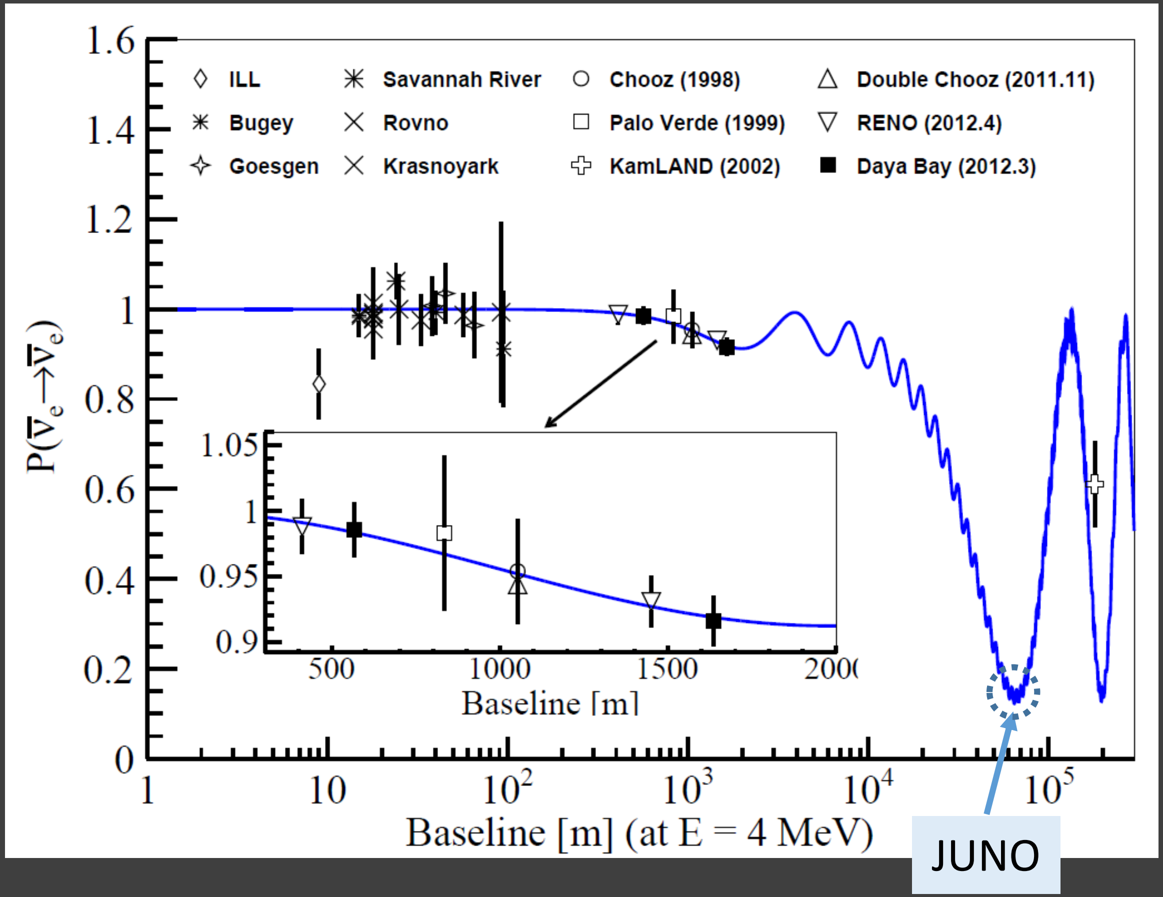
Km Baseline Neutrino Experiments

- A “golden” channel **at km baseline** for oscillation parameters and mass ordering

$$
\begin{aligned}
P_{ee}(L/E) &= 1 - P_{21} - P_{31} - P_{32} \\
P_{21} &= \cos^4(\theta_{13}) \sin^2(2\theta_{12}) \sin^2(\Delta_{21}) \\
P_{31} &= \cos^2(\theta_{12}) \sin^2(2\theta_{13}) \sin^2(\Delta_{31}) \\
P_{32} &= \sin^2(\theta_{12}) \sin^2(2\theta_{13}) \sin^2(\Delta_{32})
\end{aligned}
$$

$$\Delta_{ij} = \frac{\Delta m_{ij}^2 L}{4E}$$

- Independent on CP phase and θ_{23}
- 2-km oscillation: θ_{13} and Δm_{32}^2
- 50-km oscillation: θ_{12} and Δm_{21}^2
- JUNO (52.5 km) can observe both Δm_{32}^2 and Δm_{21}^2 driven oscillations, and is sensitivity to neutrino mass ordering



This talk will focus on JUNO and include a brief overview of θ_{13} measurement by Daya Bay, RENO and Double Chooz

Outline

- Overview of JUNO
- JUNO detector progress
- Updates on JUNO physics sensitivity

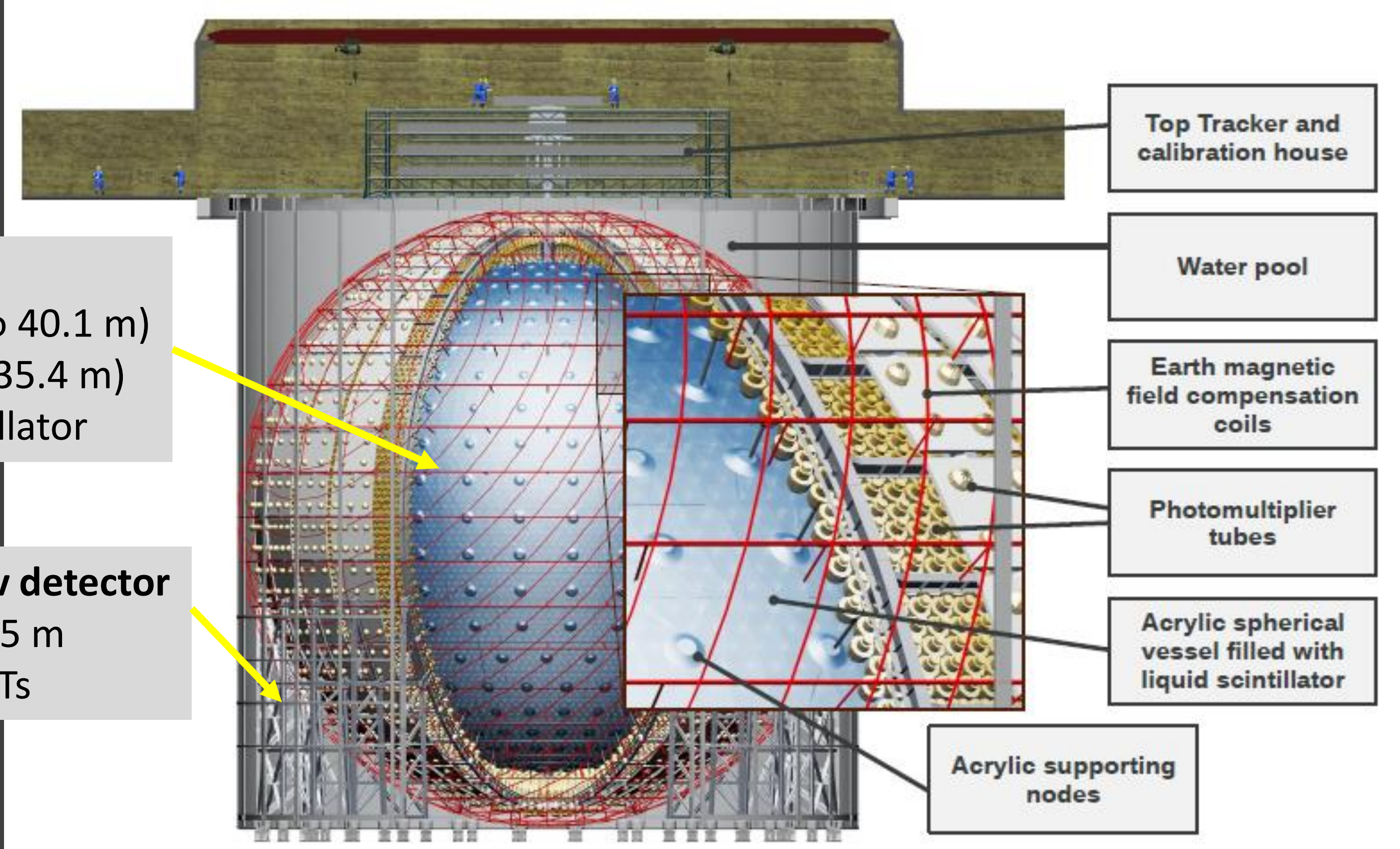
- Overview of Daya Bay, RENO, and Double Chooz

Jiangmen Underground Neutrino Observatory

The JUNO detector

Central detector
Steel structure (ϕ 40.1 m)
Acrylic vessel (ϕ 35.4 m)
20 kt liquid scintillator

Water Cherenkov detector
H = 44 m, D = 43.5 m
2400 20-inch PMTs



Top tracker
3 plastic scintillator layer

Water pool dimension
height: 44 m
diameter: 43.5 m

Light collection
17612 20-inch PMTs
25600 3-inch PMTs

The largest liquid scintillator detector
Unprecedented energy resolution

Experiment	Daya Bay	BOREXINO	KamLAND	JUNO
LS mass	20 ton	~ 300 ton	~ 1 kton	20 kton
Coverage	~ 12%	~ 34%	~ 34%	~ 78%
Energy resolution	~ 8% /√E	~ 5% /√E	~ 6% /√E	~ 3% /√E
Light yield	~ 160 p.e. /MeV	~ 500 p.e. /MeV	~ 250 p.e. /MeV	> 1345 p.e. /MeV

The JUNO collaboration

- 75 institutions, ~650 members

Country	Institute	Country	Institute	Country	Institute
Armenia	Yerevan Physics Institute	China	SYSU	Germany	U. Mainz
Belgium	Universite libre de Bruxelles	China	Tsinghua U.	Germany	U. Tuebingen
Brazil	PUC	China	UCAS	Italy	INFN Catania
Brazil	UEL	China	USTC	Italy	INFN di Frascati
Chile	PCUC	China	U. of South China	Italy	INFN-Ferrara
Chile	SAPHIR	China	Wu Yi U.	Italy	INFN-Milano
Chile	UNAB	China	Wuhan U.	Italy	INFN-Milano Bicocca
China	BISEE	China	Xi'an JT U.	Italy	INFN-Padova
China	Beijing Normal U.	China	Xiamen University	Italy	INFN-Perugia
China	CAGS	China	Zhengzhou U.	Italy	INFN-Roma 3
China	ChongQing University	China	NUDT	Latvia	IECS
China	CIAE	China	CUG-Beijing	Pakistan	PINSTECH (PAEC)
China	DGUT	China	ECUT-Nanchang City	Russia	INR Moscow
China	Guangxi U.	China	CDUT-Chengdu	Russia	JINR
China	Harbin Institute of Technology	Czech	Charles U.	Russia	MSU
China	IHEP	Finland	University of Jyvaskyla	Slovakia	FMPICU
China	Jilin U.	France	IJCLab Orsay	Taiwan-China	National Chiao-Tung U.
China	Jinan U.	France	LP2i Bordeaux	Taiwan-China	National Taiwan U.
China	Nanjing U.	France	CPPM Marseille	Taiwan-China	National United U.
China	Nankai U.	France	IPHC Strasbourg	Thailand	NARIT
China	NCEPU	France	Subatech Nantes	Thailand	PPRLCU
China	Pekin U.	Germany	RWTH Aachen U.	Thailand	SUT
China	Shandong U.	Germany	TUM	U.K.	U. Warwick
China	Shanghai JT U.	Germany	U. Hamburg	USA	UMD-G
China	IGG-Beijing	Germany	FZJ-IKP	USA	UC Irvine

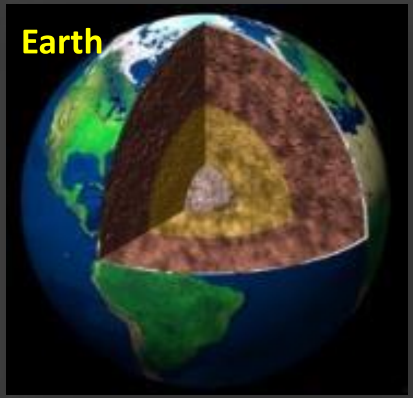
A multi-purpose observatory

~60 IBDs per day

Several per day

Hundreds per day

~5000 IBDs for CCSN @10 kpc



Several IBDs per day

\+ New physics

Neutrino oscillation & properties

Neutrinos as a probe

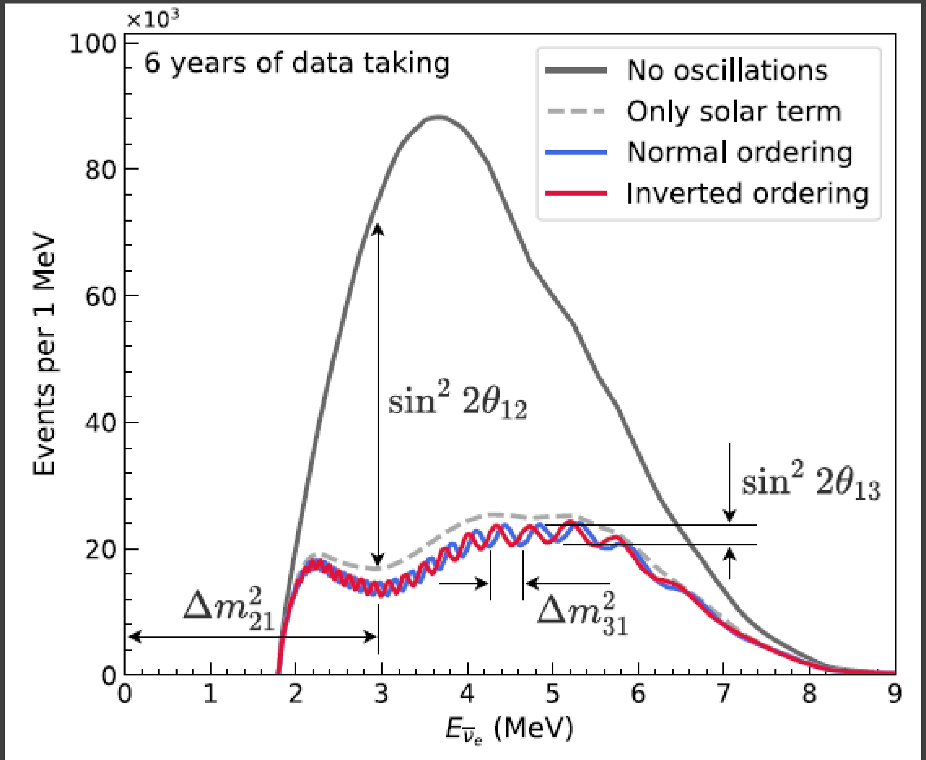
IBD: inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$

CCSN: core-collapse supernova

PPNP 123 (2022) 103927
JPG 43 (2016) 030401

Requirement for rich physics program

Primary goal: measurements of neutrino mass ordering and oscillation parameters using reactor antineutrinos at 52.5 km baseline



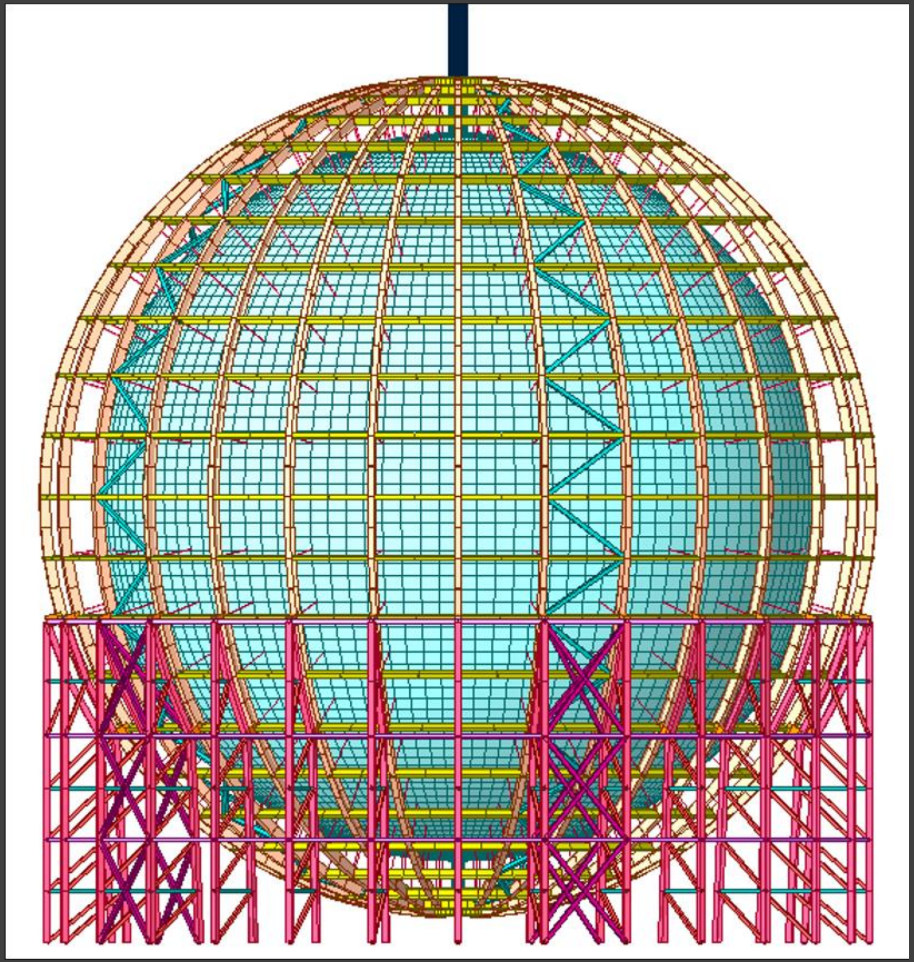
Detector properties

- Statistics
  - Large target mass (20 kton LS)
  - Powerful nuclear reactors (26.6 GW_{th})
- Energy resolution
  - Very high PMT coverage (78%)
  - Highly transparent LS
  - High efficiency PMTs (PDE~30%)
- Shape/energy scale
  - Satellite detector (TAO)
  - Redundant calibration system
- Background
  - Good overburden (~650 m)
  - Highly-efficient veto system (>99.5%)
  - Material screening
  - Clean installation

JUNO Detector Progresses

Central Detector

- **Acrylic vessel**
  - 265 pieces of panels in total
  - More than half panels have been installed (from top to equator)
- **Stainless steel structure**
  - Completely assembled (except bottom layers to grant access)
- **Liquid scintillator**
  - Purification plants are constructed onsite under initial flushing/testing
- **17612 20’’ PMTs + 25600 3’’ PMTs**
  - 5300 20’’ PMTs and 5500 3’’ PMTs installed (July, 2023)



Details in the talk by Xiaohui Qian “Key technologies in the design and construction of the JUNO central detector”

Acrylic vessel

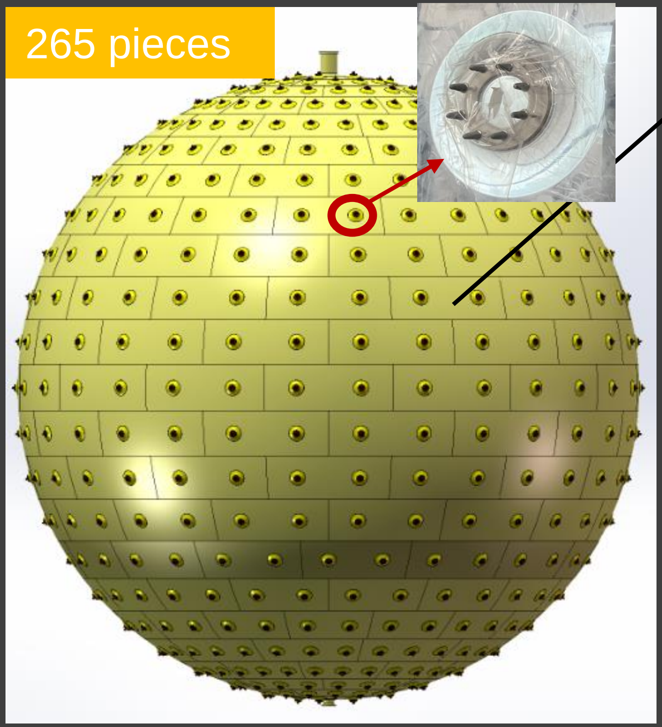
High requirements on the cleanness and transparency

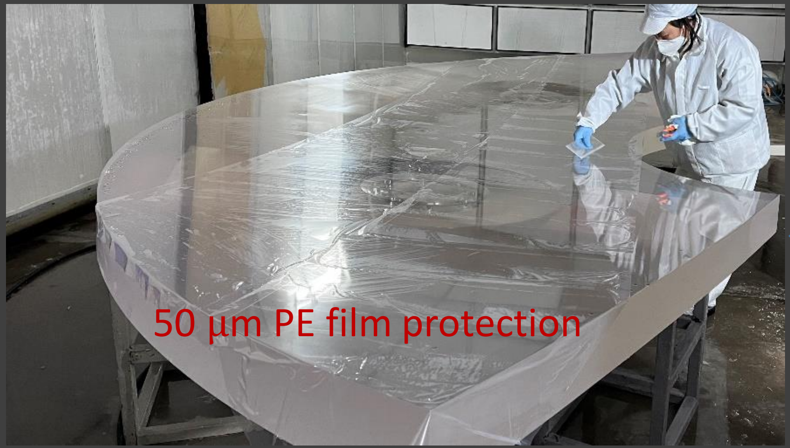
Inner diameter: 35.40±0.04 m

Thickness: 124±4 mm

Light transparency > 96% @ LS

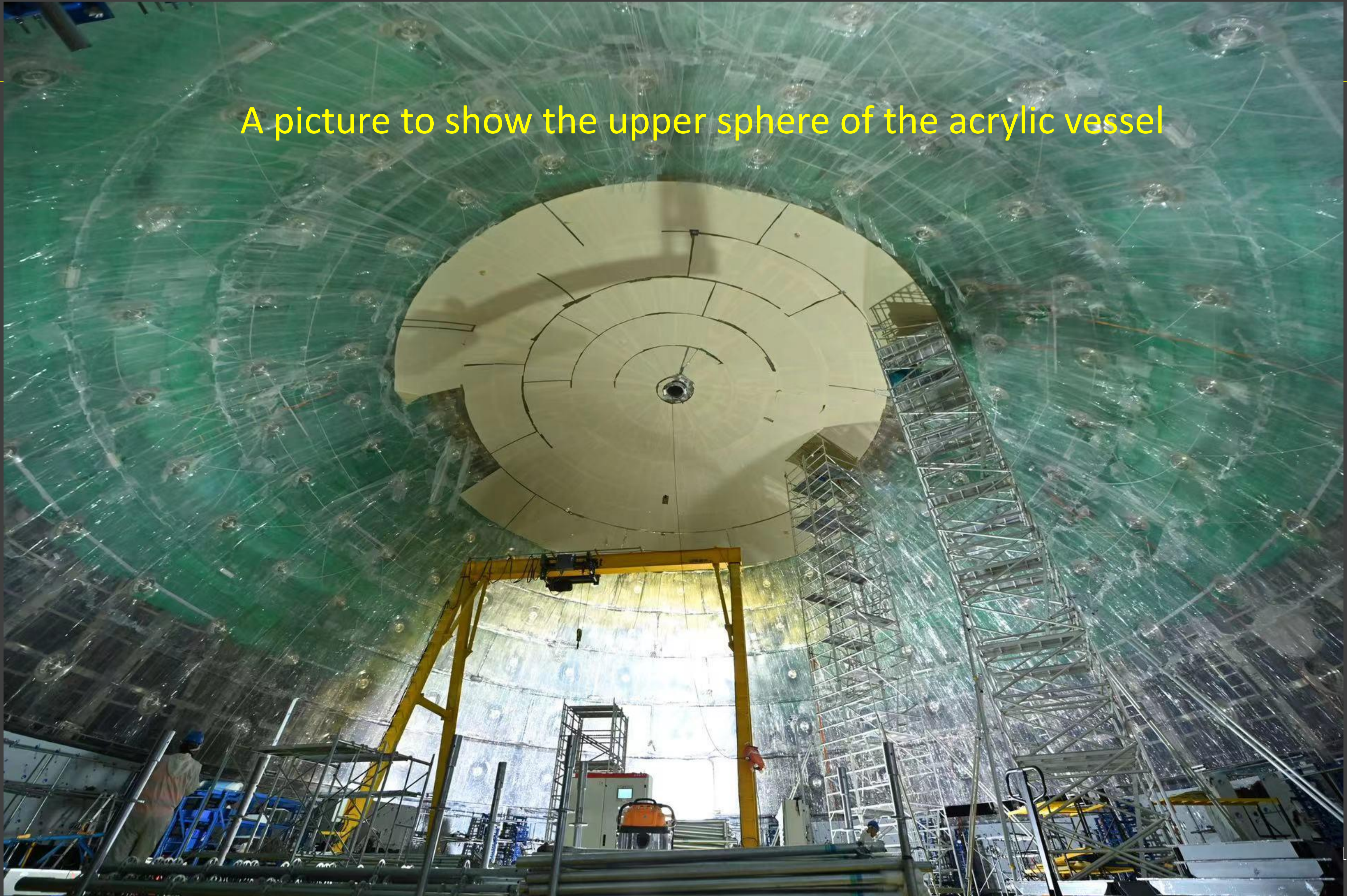
Radiopurity: U/Th/K < 1 ppt





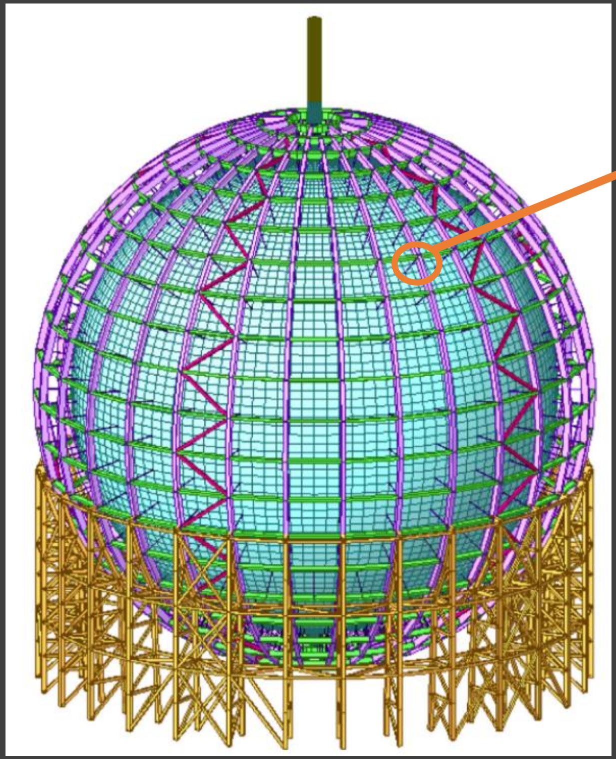
Installed from top to bottom, pieces at equator have been installed

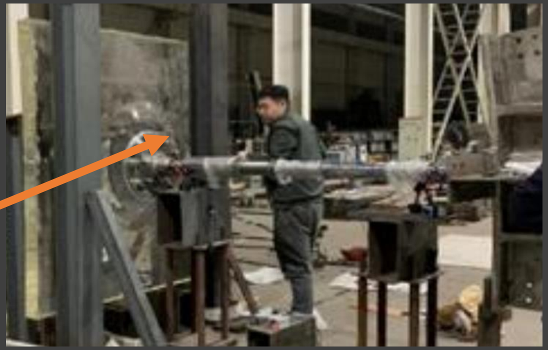
A picture to show the upper sphere of the acrylic vessel



Stainless steel structure

- Supports the load of acrylic vessel, liquid scintillator, PMTs, front-end electronics, light separation plate, EM coils, etc.
- Acrylic vessel is supported via 590 connecting bars
- Made of low background SS304
- Assembly precision: < 3 mm to minimize clearance and to maximize PMTs





Completely assembled (except bottom layers to grant access), June, 2022

Lift platform for acrylic vessel installation

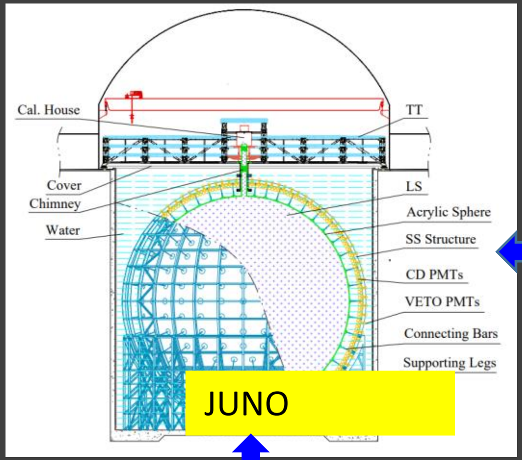
Liquid scintillator (20 kt)

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

All the LS related systems will finish assembly in summer.

SS pipes to underground

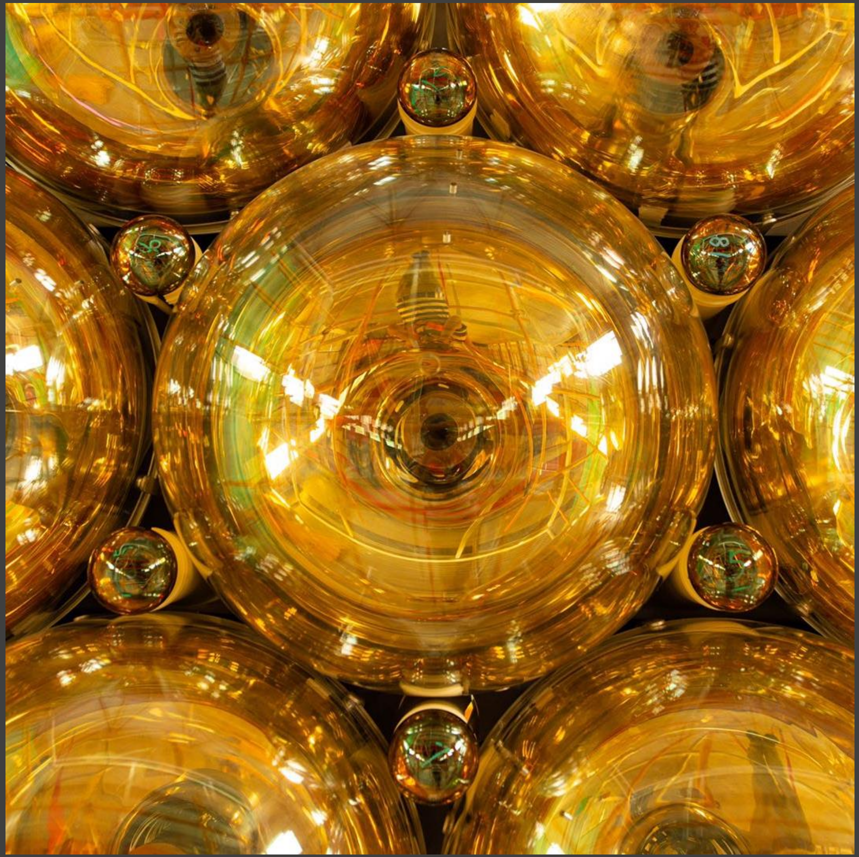
15%

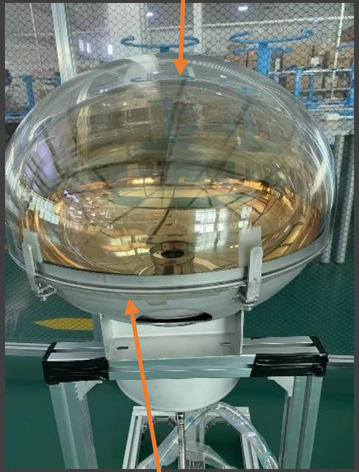


85%

Photomultiplier Tubes (PMT)

Synergetic 20-inch and 3-inch PMT systems to ensure energy resolution and charge linearity





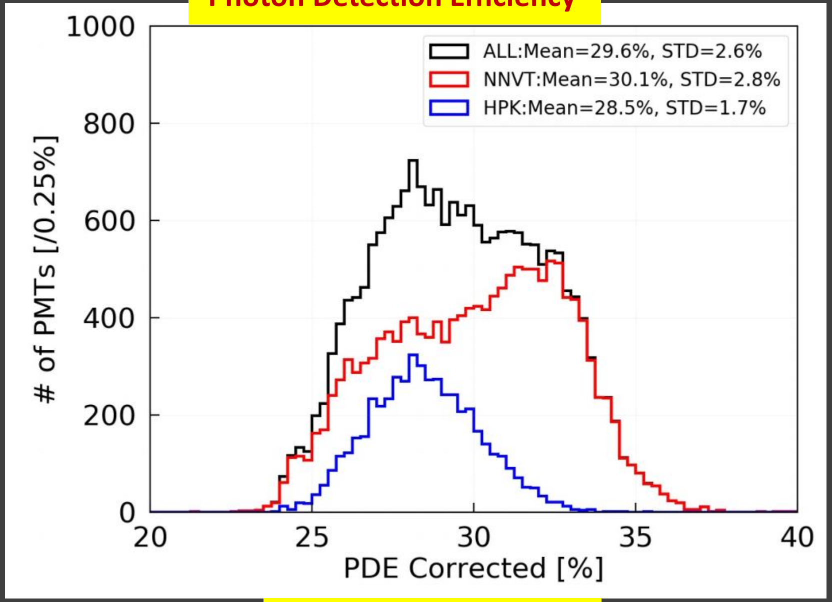
Clearance between PMTs: 3 mm → **Assembly precision: < 1 mm**

Coverage: 75% for 20-inch PMTs and 3% for 3-inch PMTs

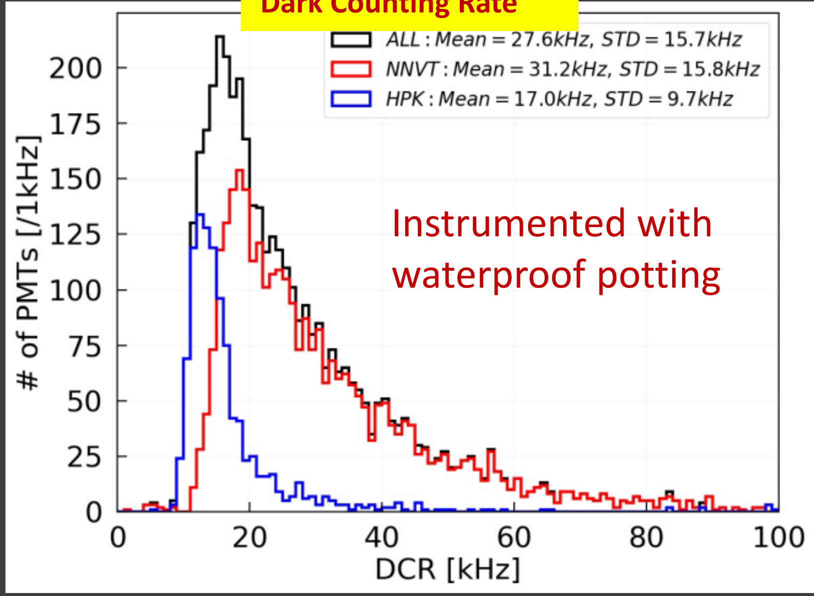
Bei-zhen Hu's Poster: **The Double Calorimetry System in JUNO**

PMT performance

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		Eur.Phys.J.C 82 (2022) 12, 1168		NIM.A 1005 (2021) 165347

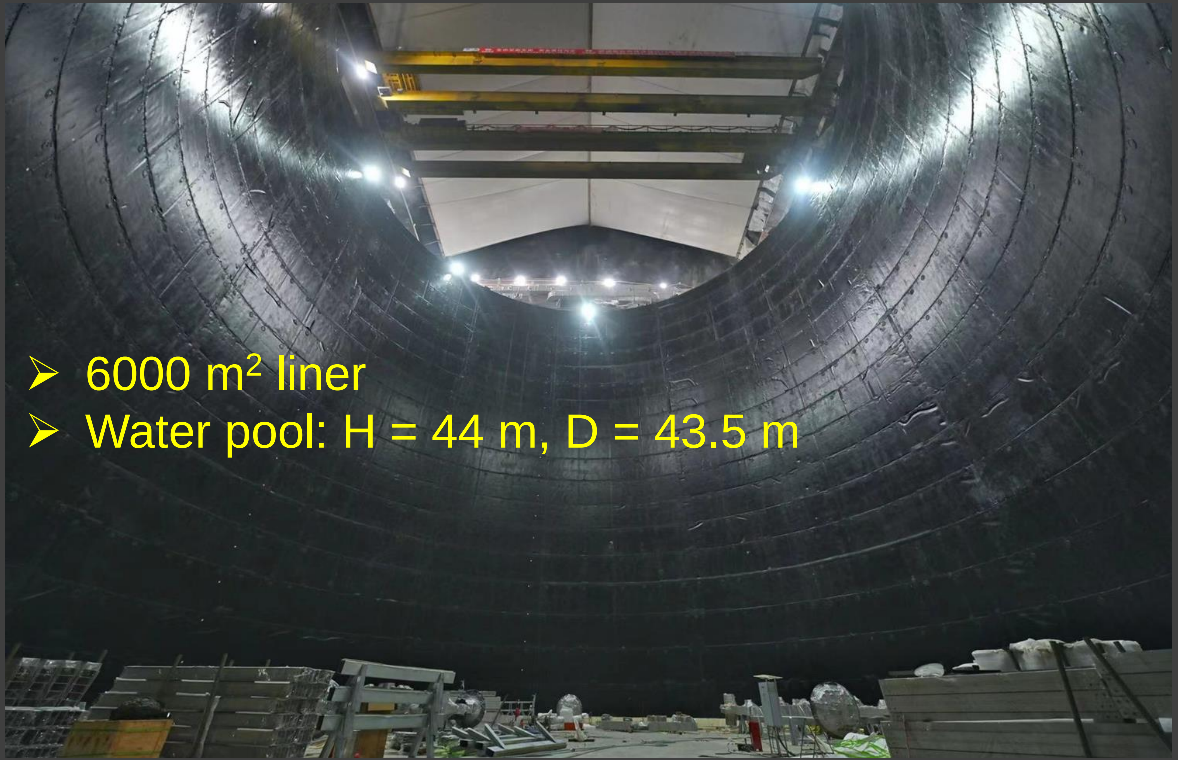
PDE > 27% (original requirement in the design)

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


5300 20’’ PMTs and 5500 3’’ PMTs are installed (July, 2023)

Veto detector (Water Cherenkov)

~650 m rock overburden (1800 m.w.e.) → R_μ = 4 Hz in LS, $< E_\mu >$ = 207 GeV

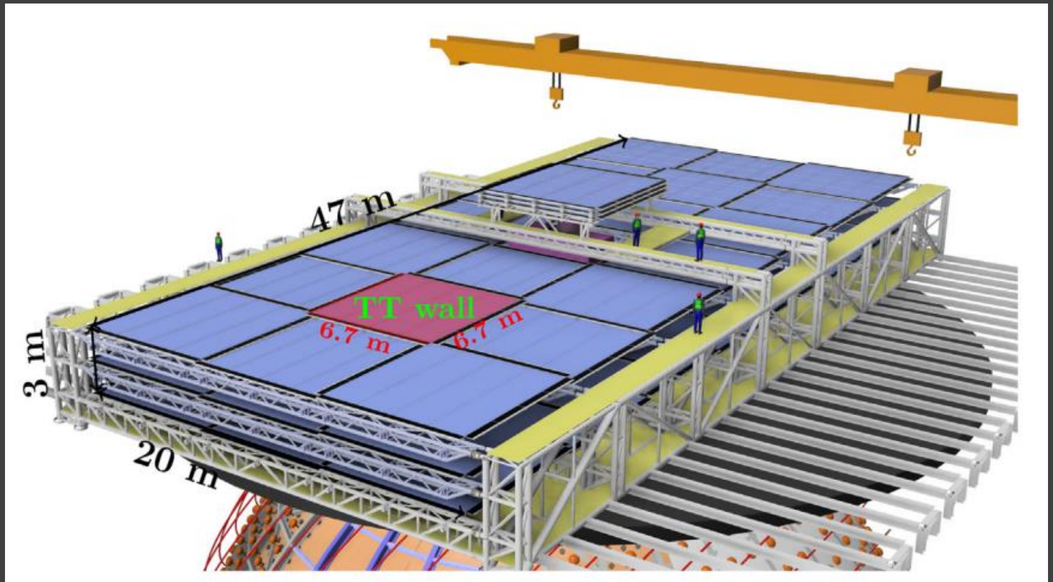


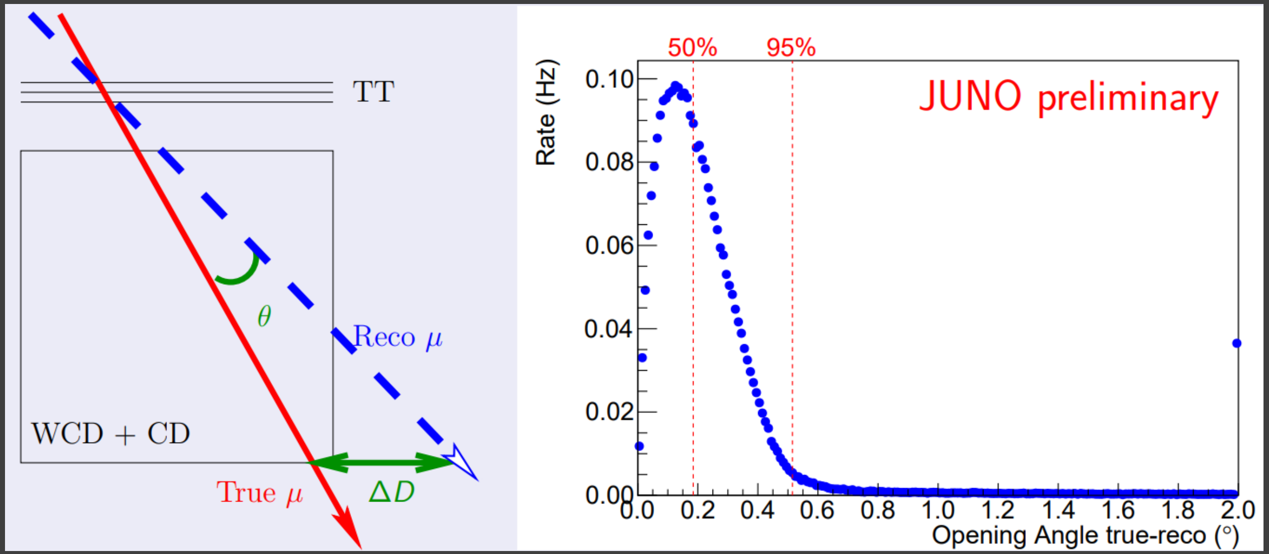
35 kt of ultrapure water serving as passive shield and water Cherenkov detector.

- ✓ 2400 20-inch NNVT PMTs, detection efficiency of cosmic muons larger than 99.5%
- ✓ Keep the temperature uniformity 21℃±1℃
- ✓ Quality: ^{222}Rn < 10 mBq/m^3, attenuation length 30~40 m

Cong Guo's Poster: **The status and the radioactive background control of JUNO's Water Cherenkov Detector**

Veto detector (Top Tracker)



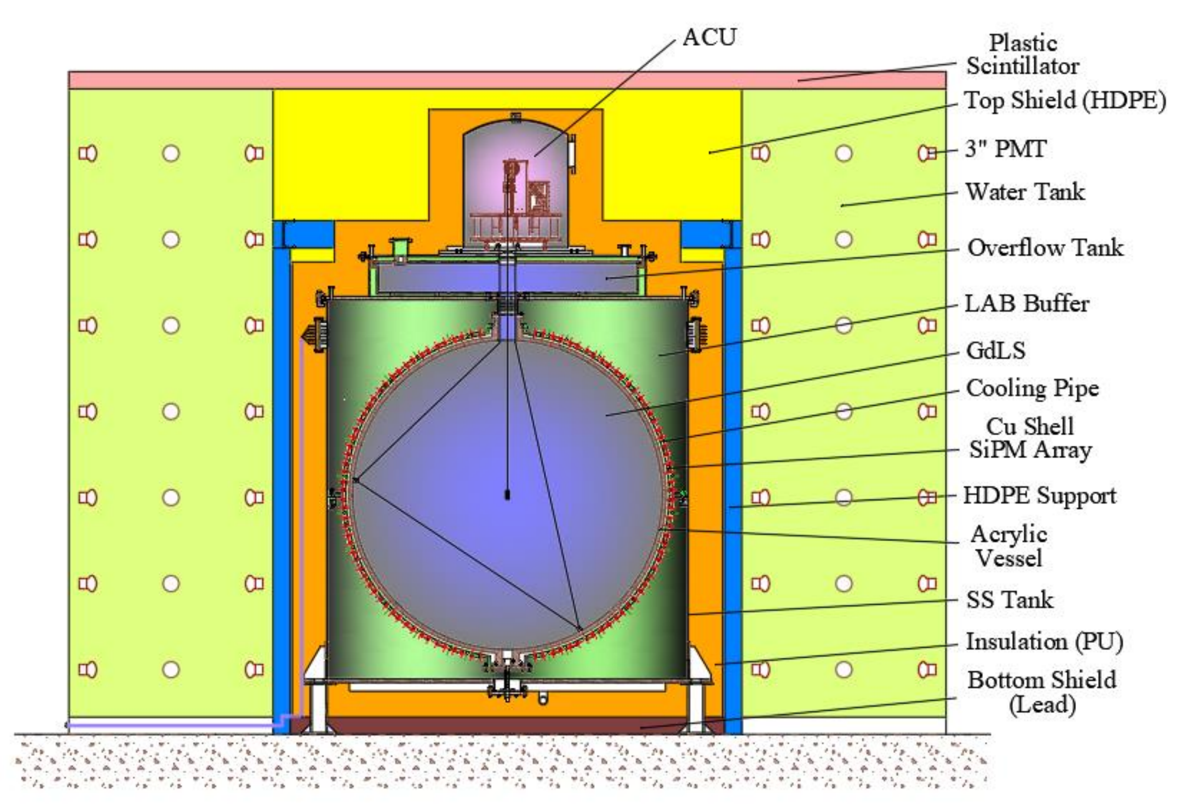


Plastic scintillator from the OPERA experiment

- ✓ About 50% coverage on the top, three layers to reduce accidental coincidence
- ✓ All scintillator panels arrived on site in 2019
- ✓ Provide control muon samples to validate the track reconstruction and study cosmogenic backgrounds

Taishan Antineutrino Observatory (TAO)

2.8 ton GdLS detector	*arXiv: 2005.08745*
Baseline	~30 m
Reactor Thermal Power	4.6 GW
Light Collection	SiPM
Photon Detection Efficiency	>50%
Working Temperature	-50 ℃
Dark Count Rate [Hz/mm^2]	~100
Coverage	~94%
Detected Light yield [PE/MeV]	4500
Energy resolution	< 2% @ 1 MeV

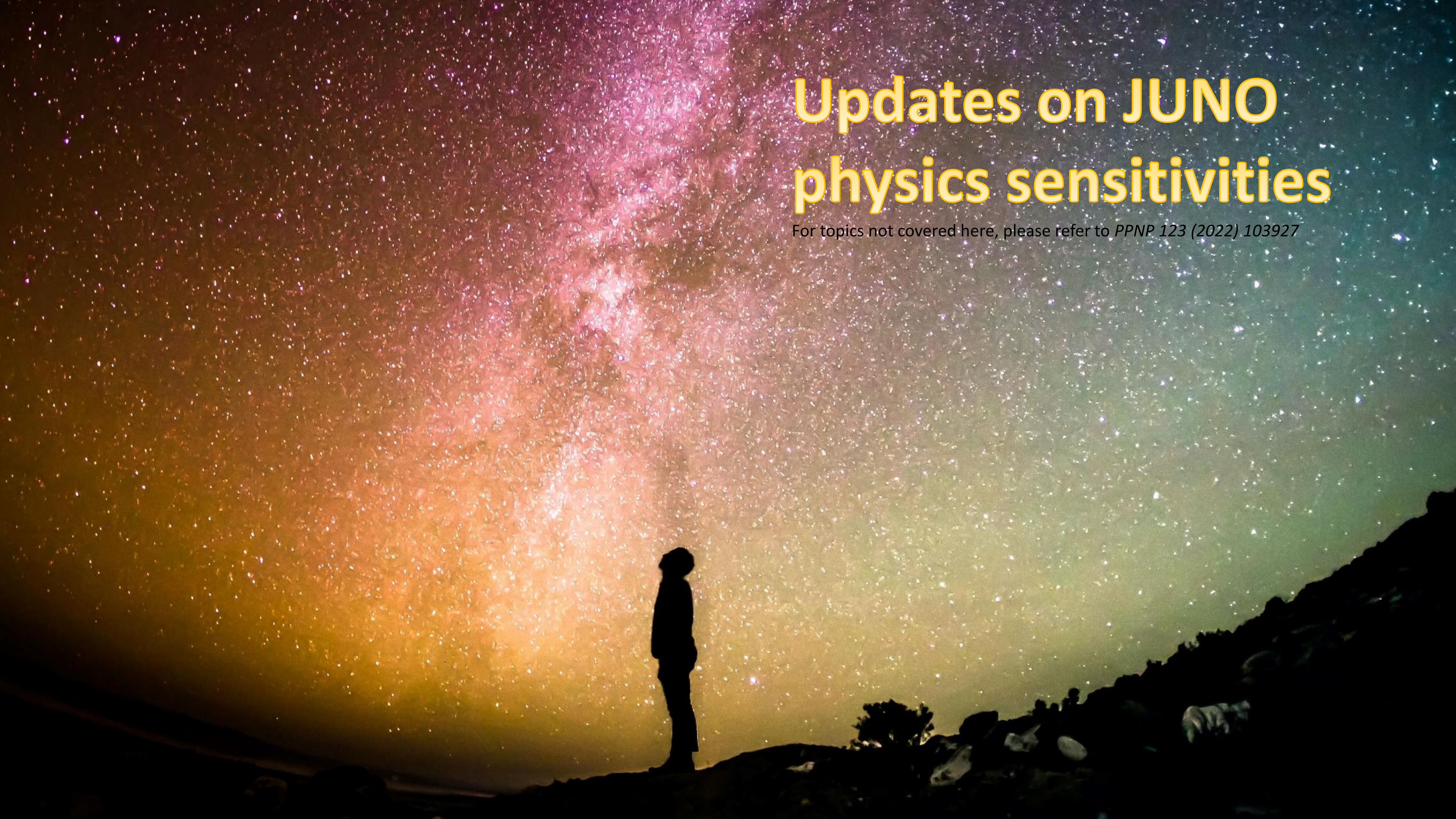


- ✓ SiPM is used to achieve high light yield with ~94% coverage
  → 4500 PEs/MeV & energy resolution < 2% @ 1 MeV
- ✓ Gd-LS works at -50℃ to lower the dark noise of SiPM

1:1 Prototype is being built at IHEP

Updates on JUNO physics sensitivities

For topics not covered here, please refer to *PPNP 123 (2022) 103927*



Reactor Antineutrino Oscillation

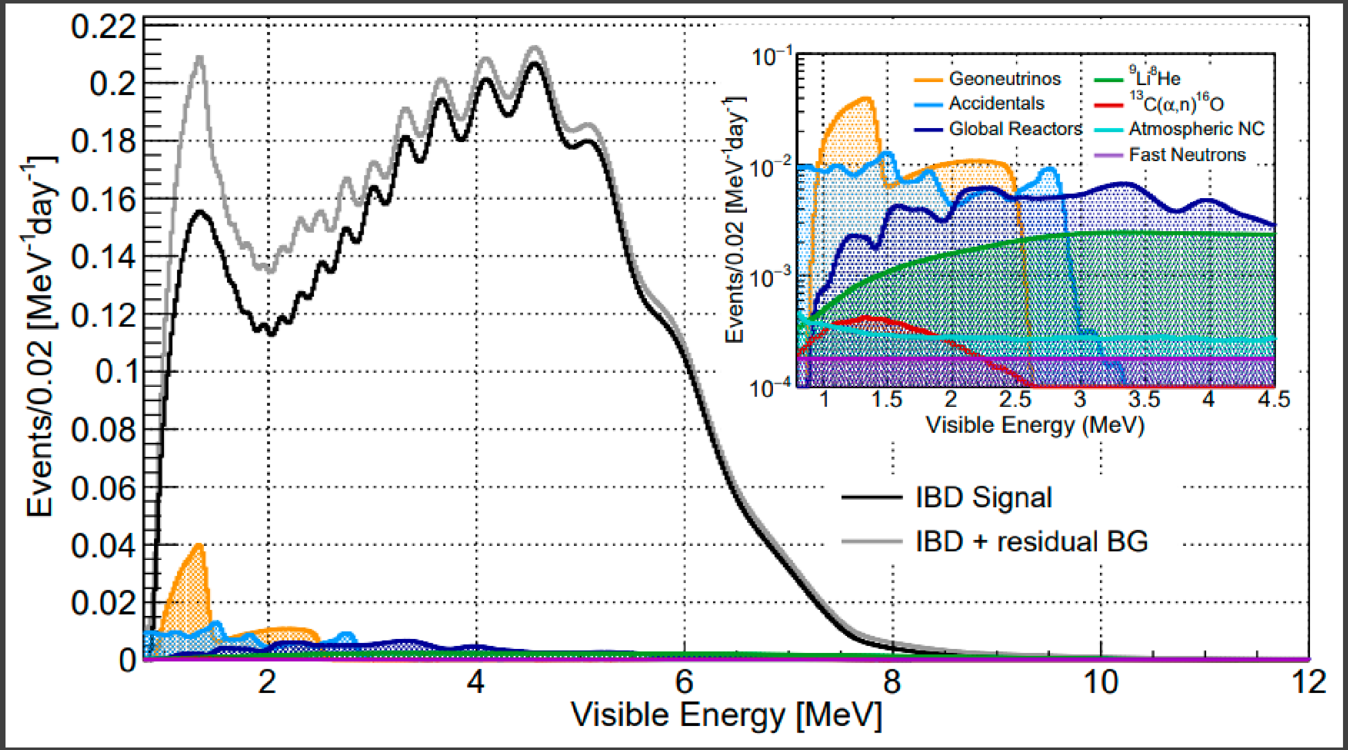
$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$

Inverse beta decay reaction $\bar{\nu}_e + p \to e^+ + n$

Reactor cores: 10 → 8 (only two Taishan cores)

Update background estimations

New backgrounds included



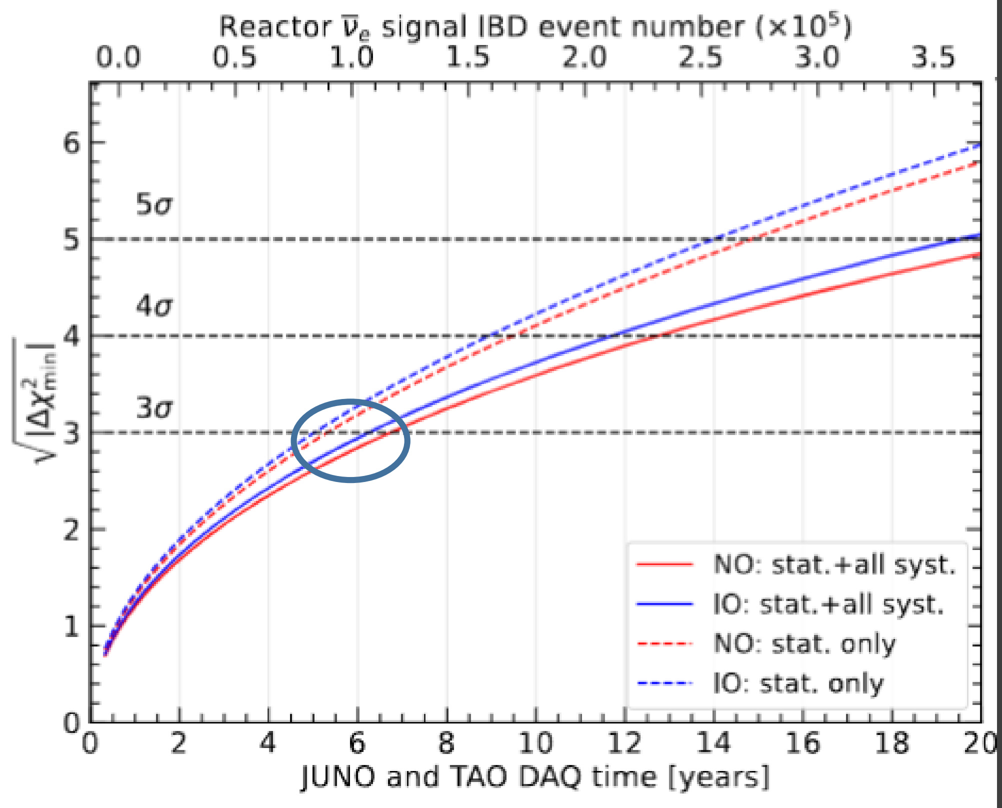
Event type	Rate [/day]	Relative rate uncertainty	Shape uncertainty
Reactor IBD signal	60 → **47**	-	-
Geo-ν's	1.1 → **1.2**	30%	5%
Accidental signals	0.9 → **0.8**	1%	negligible
Fast-n	0.1	100%	20%
^{9}Li/ ^{8}He	1.6 → **0.8**	20%	10%
^{13}C(α, n) ^{16}O	0.05	50%	50%
Global reactors	0 → **1.0**	**2%**	**5%**
Atmospheric ν's	0 → **0.16**	**50%**	**50%**

Design in Physics book
J. Phys. G 43:030401 (2016)

Precision of oscillation parameters:
Chin.Phys.C 46 (2022) 12, 123001

Neutrino mass ordering sensitivity:
paper under preparation

Neutrino Mass Ordering



	Design (J. Phys. G 43:030401 (2016))	Now (2022)
Thermal Power	36 GW_{th}	**26.6 GW_{th} (26%↓)**
Overburden	~700 m	~650 m
Muon flux in LS	3 Hz	**4 Hz (33%↑)**
Muon veto efficiency	83%	**93% (12%↑)**
Signal rate	60 /day	**47.1 /day (22%↓)**
Backgrounds	3.75 /day	**4.11 /day (10%↑)**
Energy resolution	3% @ 1 MeV	**2.9% @ 1 MeV (3%↑)**
Shape uncertainty	1%	**JUNO+TAO**
3σ NMO sensitivity exposure	< 6 yrs × 35.8 GW_{th}	~ 6 yrs × 26.6 GW_{th}

JUNO sensitivity on NMO: **3σ (reactors only) @ ~6 yrs * 26.6 GW_{th} exposure**

Estimation of NMO sensitivity with combined reactor + atmospheric neutrino analysis under preparation

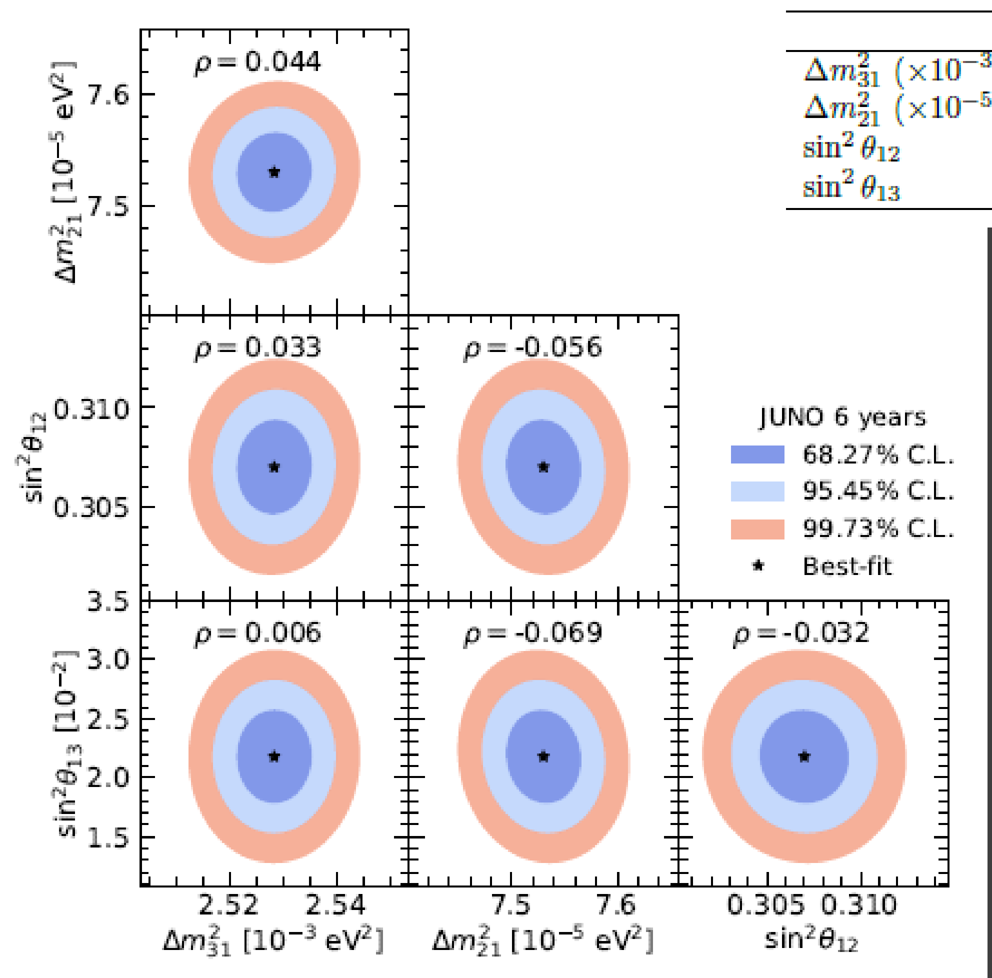
Wuming Luo's talk: atmospheric neutrino oscillations at JUNO

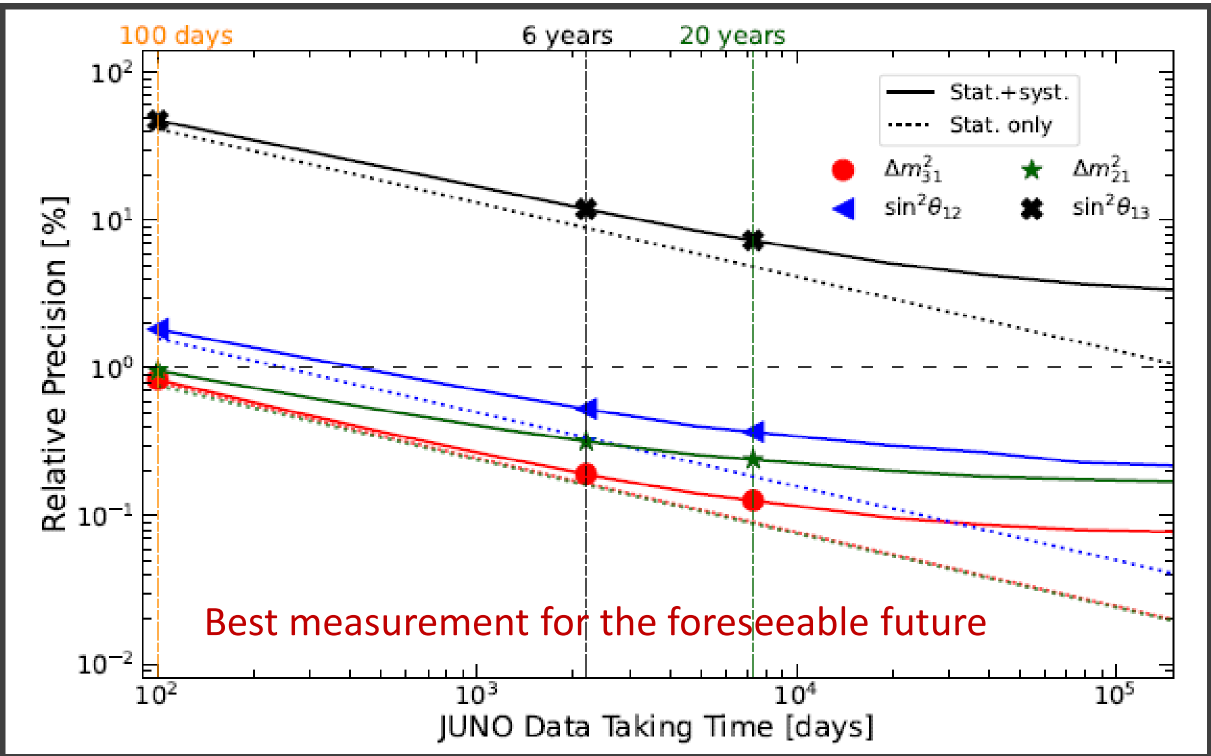
Neutrino oscillation parameters

Chin.Phys.C 46 (2022) 12, 123001

Precision of $\sin^2 2\theta_{12}$, Δm^2_{21}, $|\Delta m^2_{32}|$ < 0.5% in 6 yrs

	Central Value	PDG2020	100 days	6 years	20 years
Δm^2_{31} ($\times 10^{-3}$ eV^2)	2.5283	±0.034 (1.3%)	±0.021 (0.8%)	±0.0047 (0.2%)	±0.0029 (0.1%)
Δm^2_{21} ($\times 10^{-5}$ eV^2)	7.53	±0.18 (2.4%)	±0.074 (1.0%)	±0.024 (0.3%)	±0.017 (0.2%)
$\sin^2\theta_{12}$	0.307	±0.013 (4.2%)	±0.0058 (1.9%)	±0.0016 (0.5%)	±0.0010 (0.3%)
$\sin^2\theta_{13}$	0.0218	±0.0007 (3.2%)	±0.010 (47.9%)	±0.0026 (12.1%)	±0.0016 (7.3%)



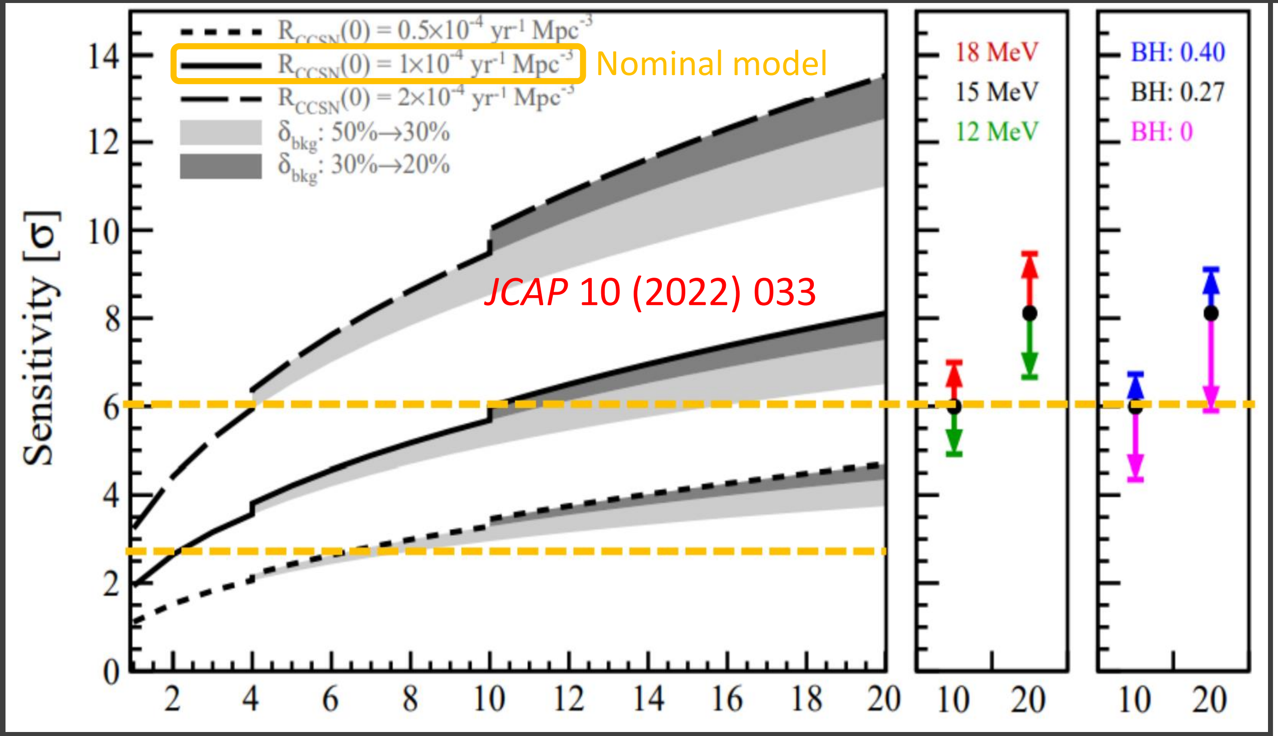


The improvement in precision over existing constraints will be about one order of magnitude except for θ_{13}

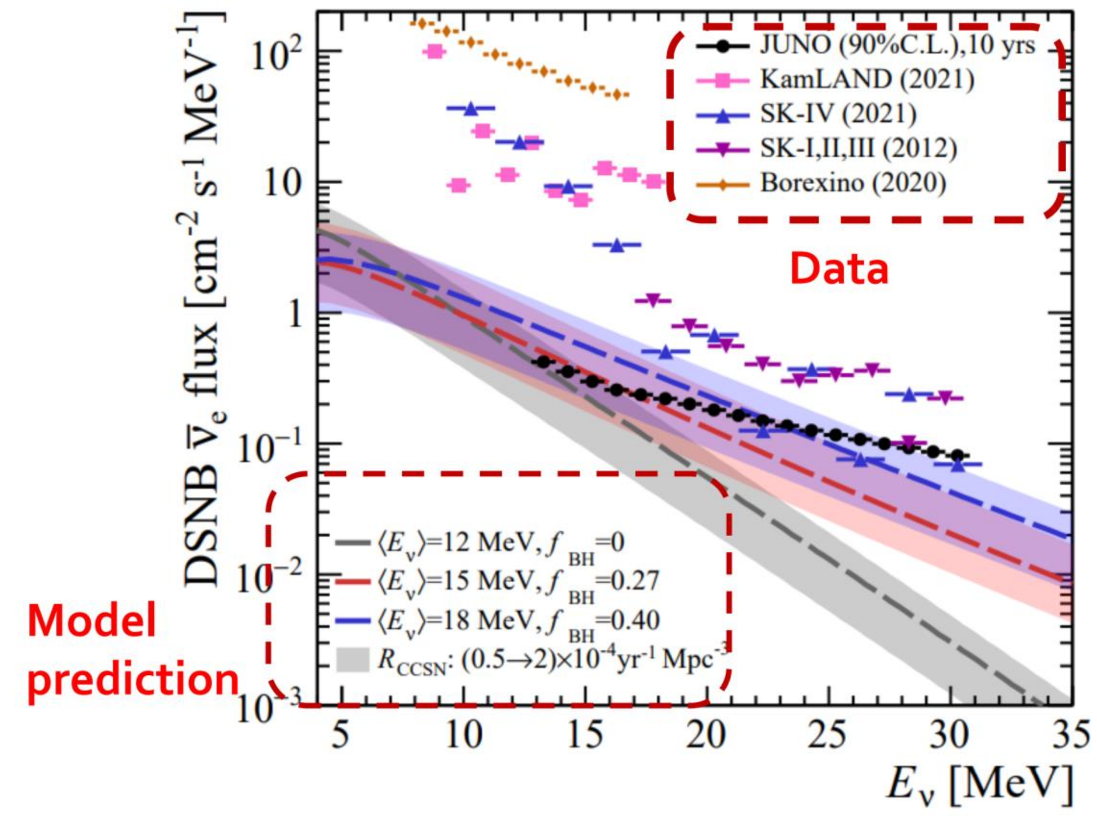
Diffuse Supernova Neutrino Background

Improvements: background evaluation (0.7 per year → 0.54 per year),
pulse shape discrimination (signal efficiency 50%→80%),
better DSNB signal model (non-zero fraction of failed Supernova)

S/B improved from 2 to 3.5



DSNB discovery potential: 3σ in 3 yrs with nominal model



Neutrinos from Sun (E_{vis}>2MeV)

arXiv: 2210.08437

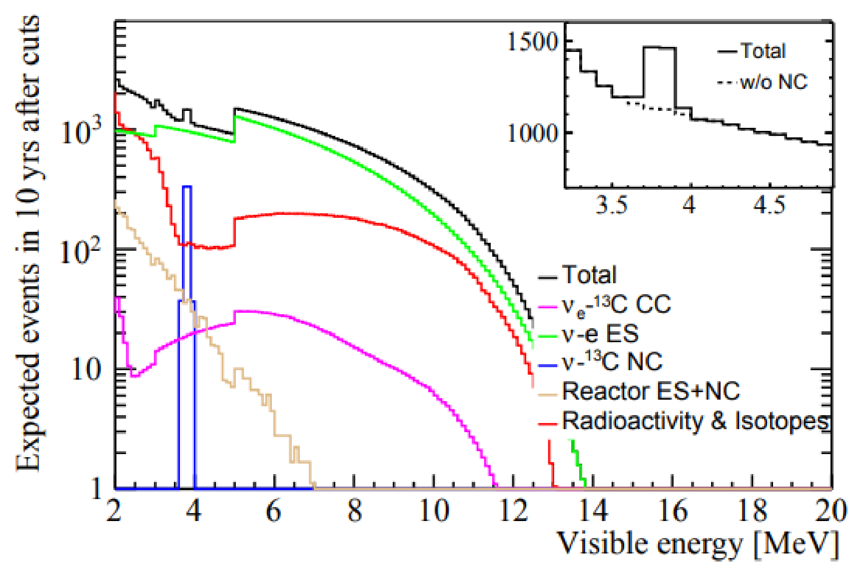
200 ton ^{13}C in JUNO LS → enable observation of **B8 solar neutrino** CC and NC interactions on ^{13}C

	Channels	Threshold [MeV]	Signal	Event numbers [200 kt×yrs]	Event numbers after cuts
CC	$\nu_e + ^{13}C \rightarrow e^- + ^{13}N\,(\frac{1}{2}^-;\text{gnd})$	2.2 MeV	$e^- + ^{13}N$ decay	3929	647
NC	$\nu_x + ^{13}C \rightarrow \nu_x + ^{13}C\,(\frac{3}{2}^-;3.685\,\text{MeV})$	3.685 MeV	γ	3032	738
ES	$\nu_x + e \rightarrow \nu_x + e$	0	e^-	3.0×10^5	6.0×10^4

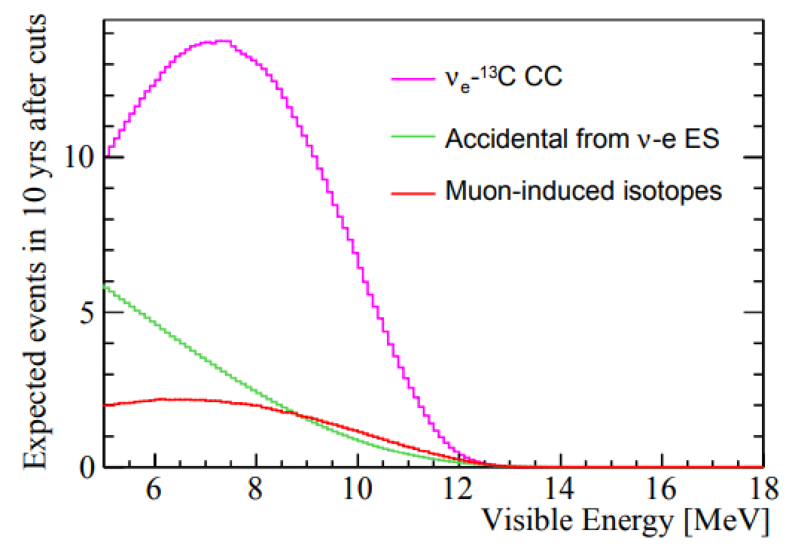
Correlated events (CC)

Singles event (NC, ES)

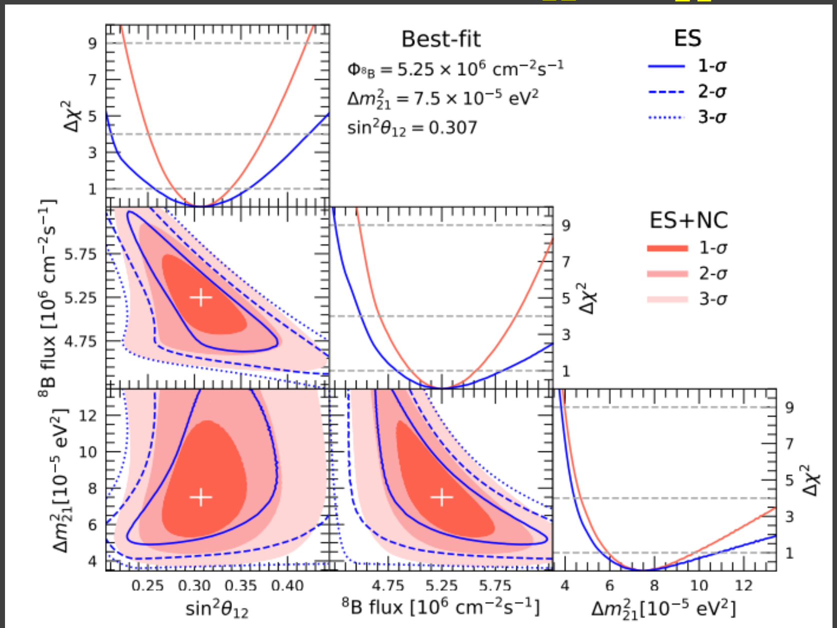
Measurement of ^8B solar neutrino flux (~5%) and oscillation parameters $\sin^2\theta_{12}$, Δm^2_{21}



Single visible signal channel

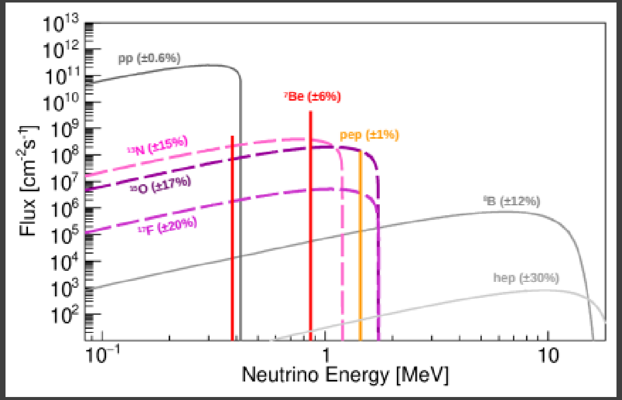


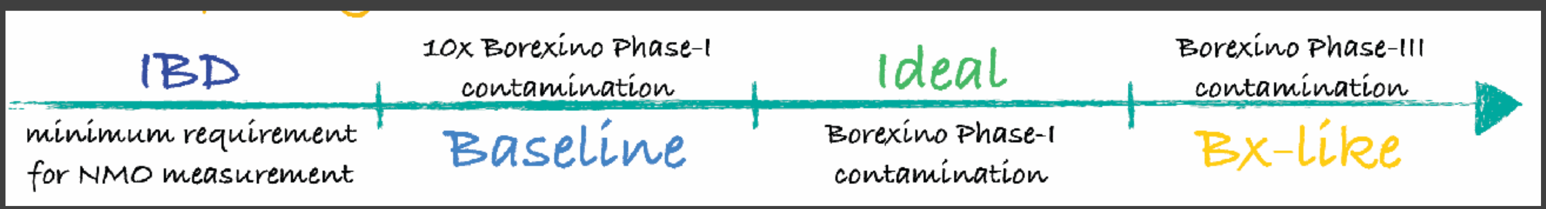
Prompt signal of the prompt-delayed pair signal channel

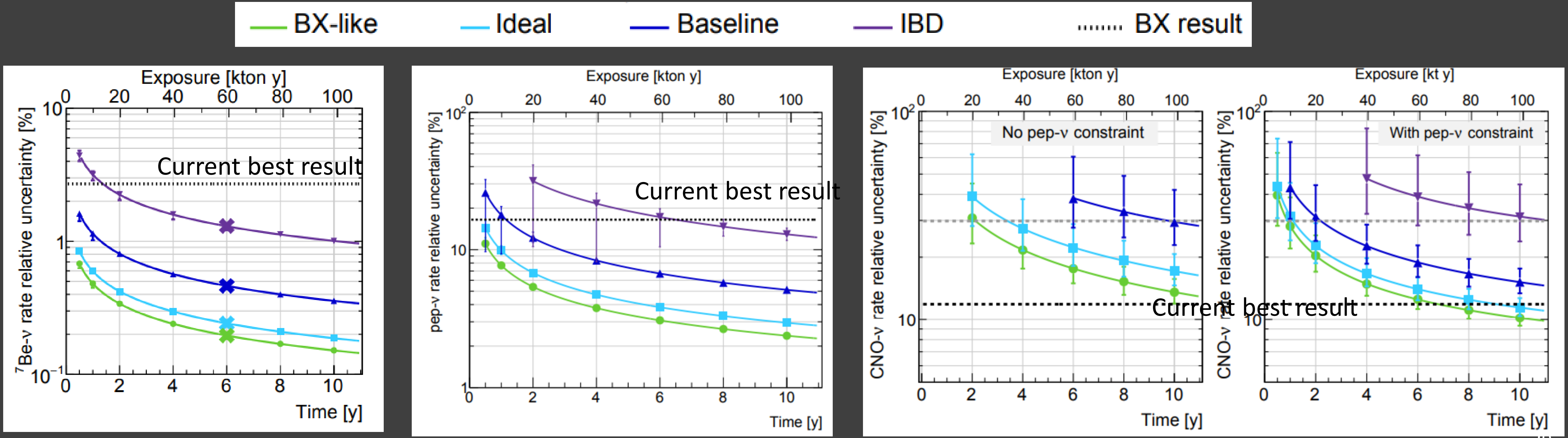


Neutrinos from Sun (E_{vis}<2MeV)

Sensitivity to ^{7}Be, *pep*, and CNO solar neutrinos (arXiv: 2303.03910) with different radiopurity scenarios considered







Outlook of JUNO

2013

Approved

2015

Civil construction

2022

Detector construction

now

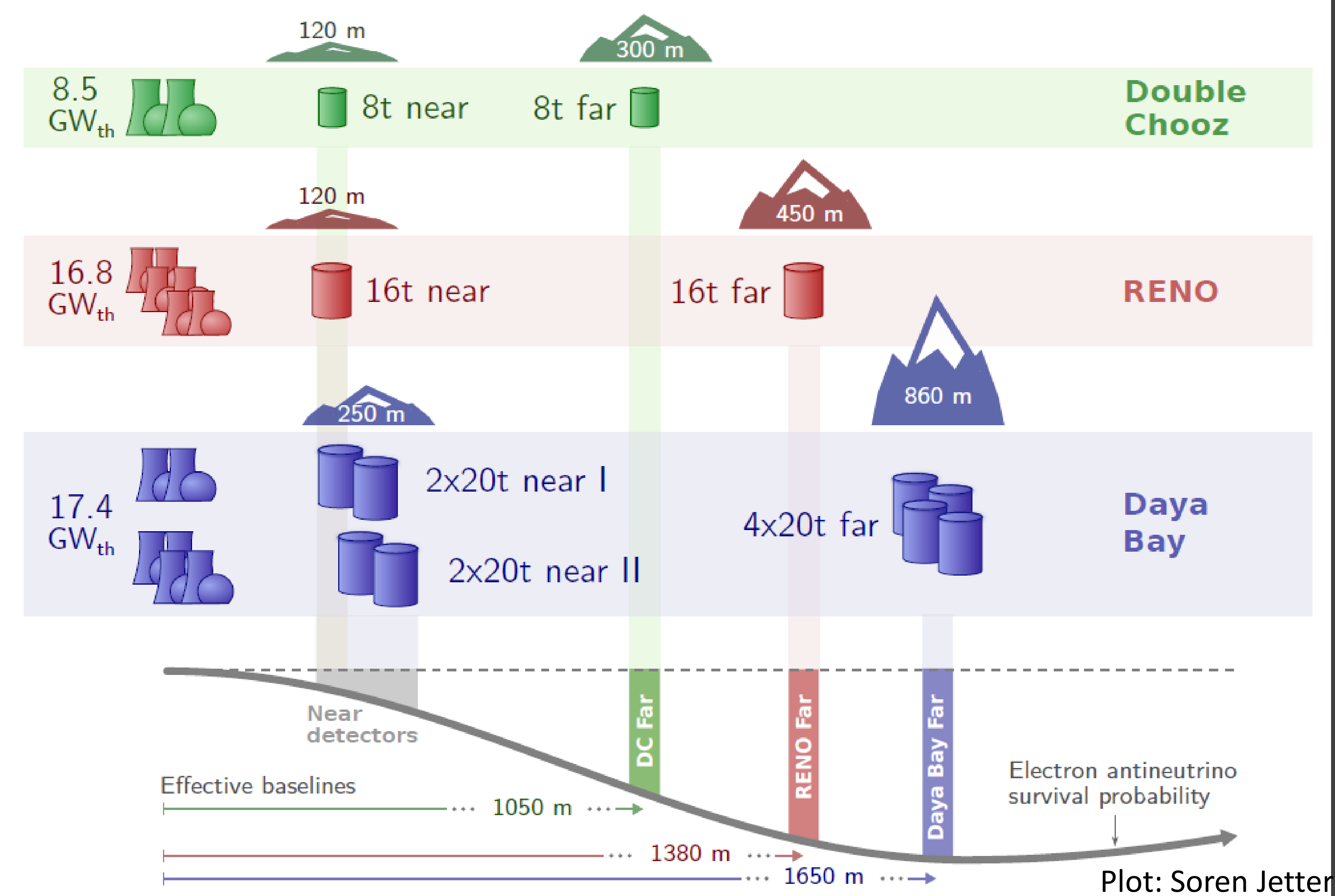
2023-2024

Detector completed

Overview of Daya Bay, RENO, and Double Chooz

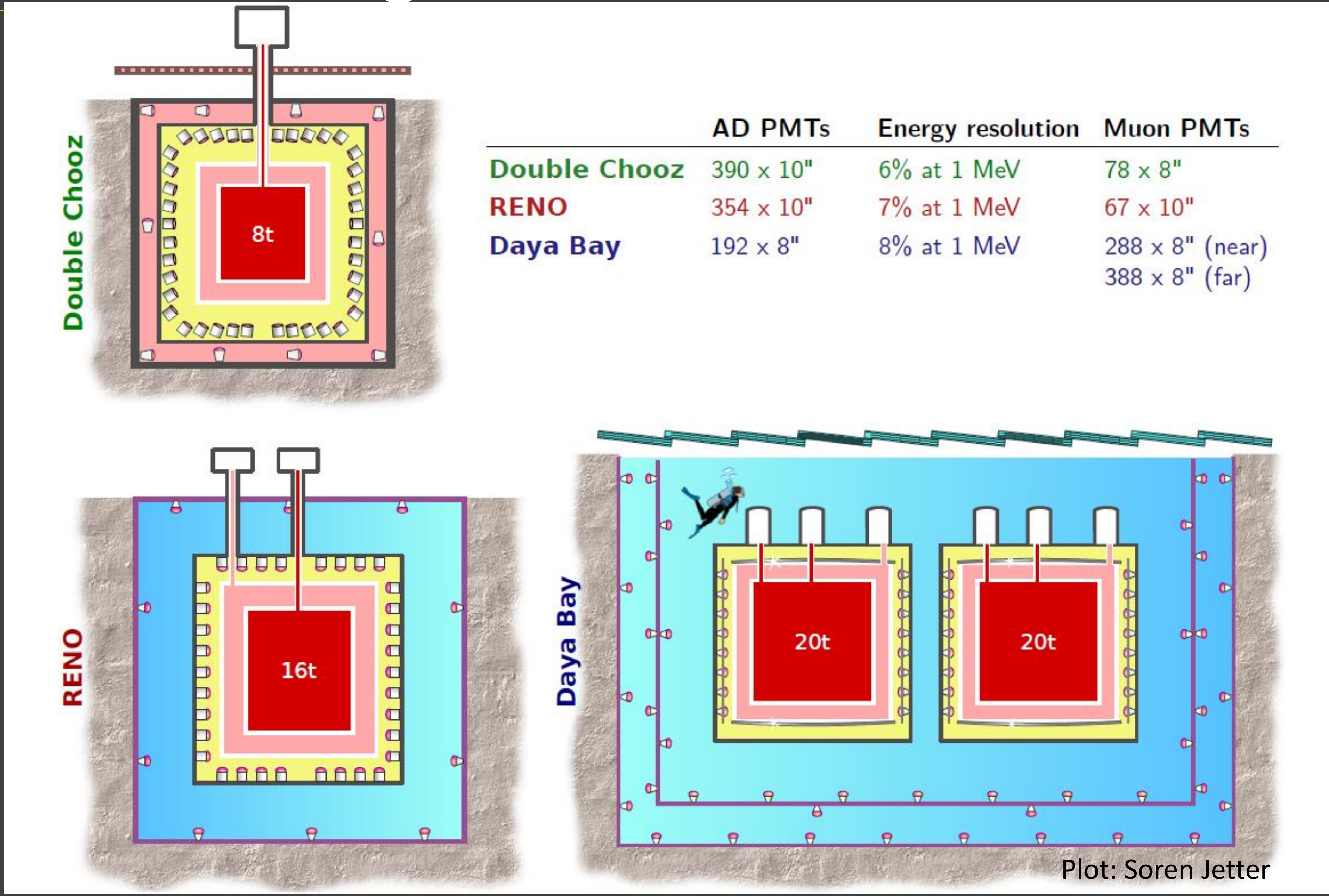
Experiment layout

Common feature: near/far relative measurement



Plot: Soren Jetter

Detector design



	AD PMTs	Energy resolution	Muon PMTs
Double Chooz	390 x 10"	6% at 1 MeV	78 x 8"
RENO	354 x 10"	7% at 1 MeV	67 x 10"
Daya Bay	192 x 8"	8% at 1 MeV	288 x 8" (near) 388 x 8" (far)

Plot: Soren Jetter

Latest result from Daya Bay

Phys. Rev. Lett. 130, 161802 (2023)

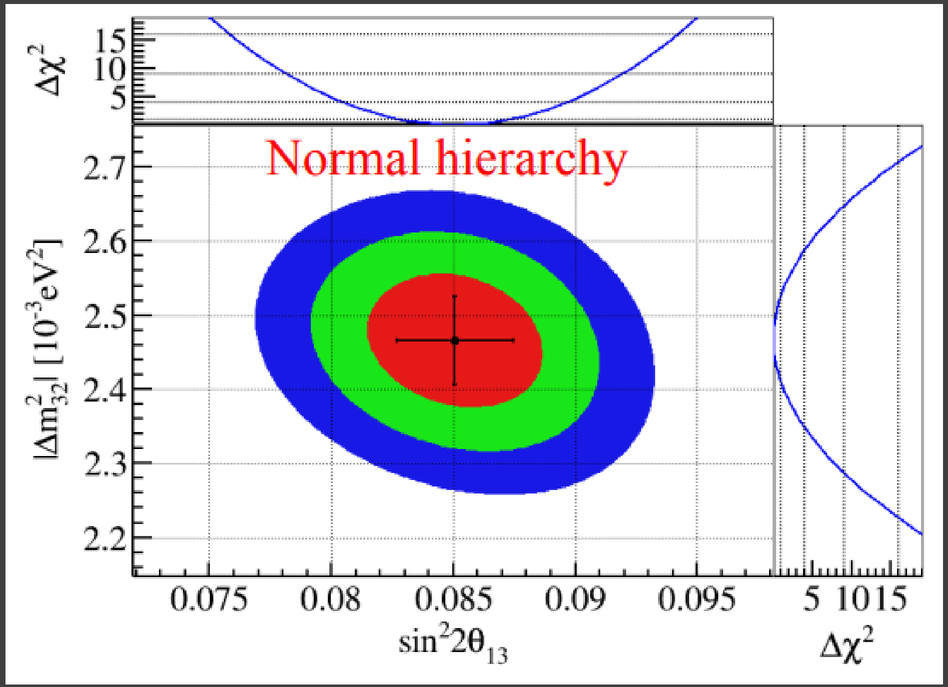
- Data-taking life: Dec 2011 - Dec 2020
- Current best results on $\sin^2 2\theta_{13}$ with full data-set IBD selection from neutron capture on gadolinium

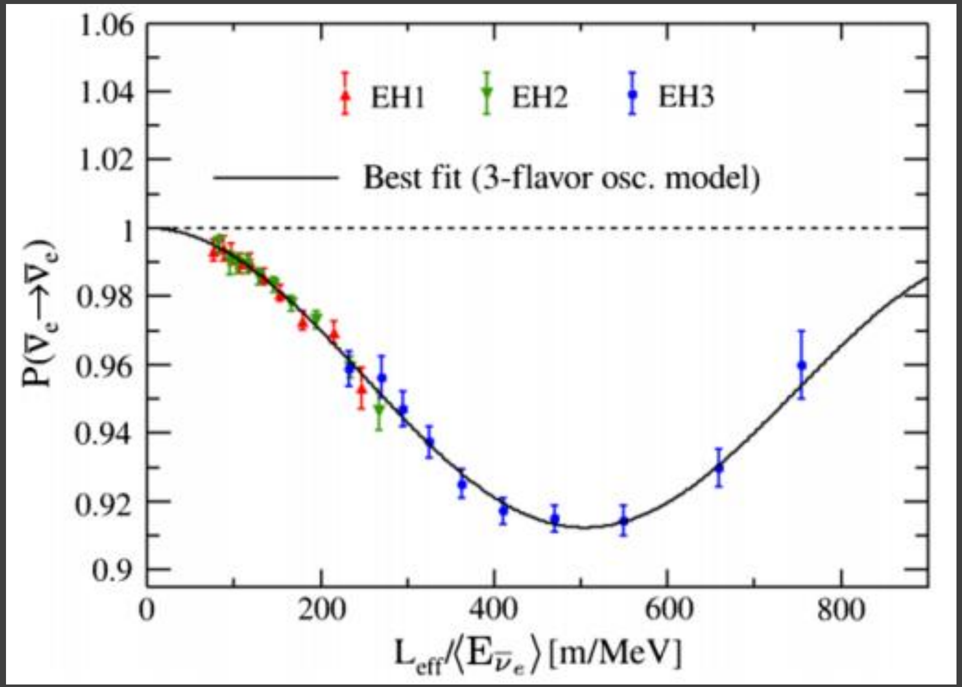
Best-fit results: $\chi^2/\text{ndf} = 559/518$

$\sin^2 2\theta_{13} = 0.0851^{+0.0024}_{-0.0024}$ (2.8% precision)

Normal hierarchy: $\Delta m^2_{32} = +(2.466^{+0.060}_{-0.060}) \times 10^{-3}\text{eV}^2$ (2.4% precision)

Inverted hierarchy: $\Delta m^2_{32} = -(2.571^{+0.060}_{-0.060}) \times 10^{-3}\text{eV}^2$ (2.3% precision)

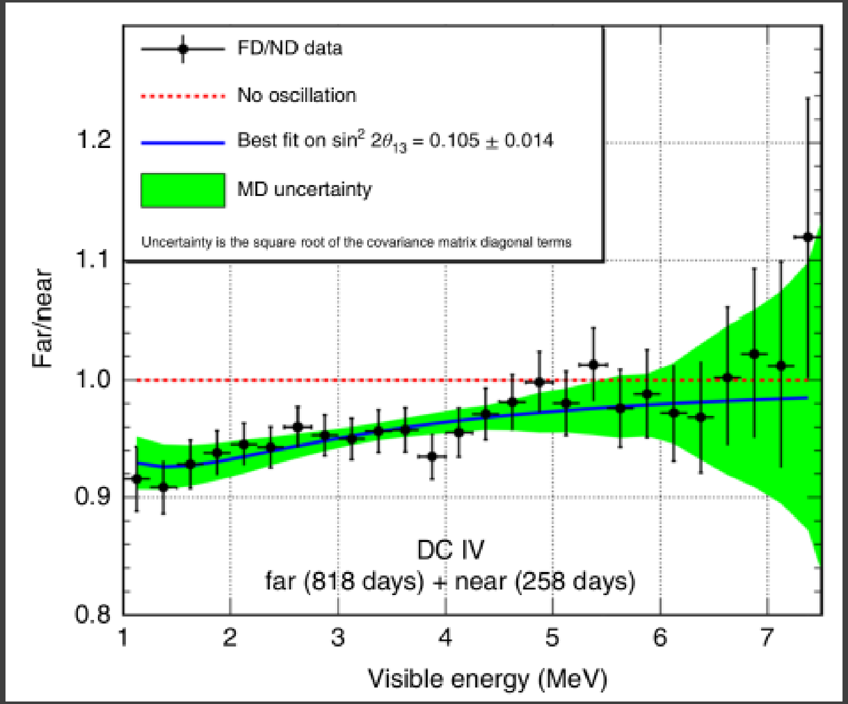




Latest results of Double Chooz and RENO

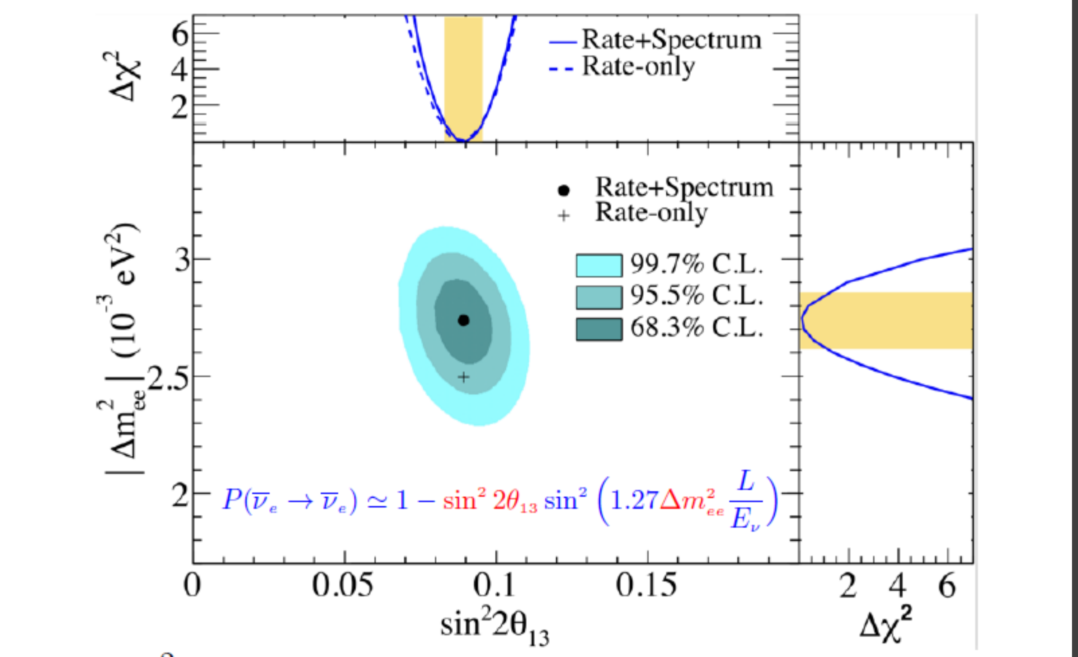
- Double Chooz: 2011-2017

$$\sin^2(2\theta_{13}) = 0.102 \pm 0.011\ (\text{syst.}) + 0.04\ (\text{stat.})$$



Nature Phys. 16 (2020) 5, 558-564

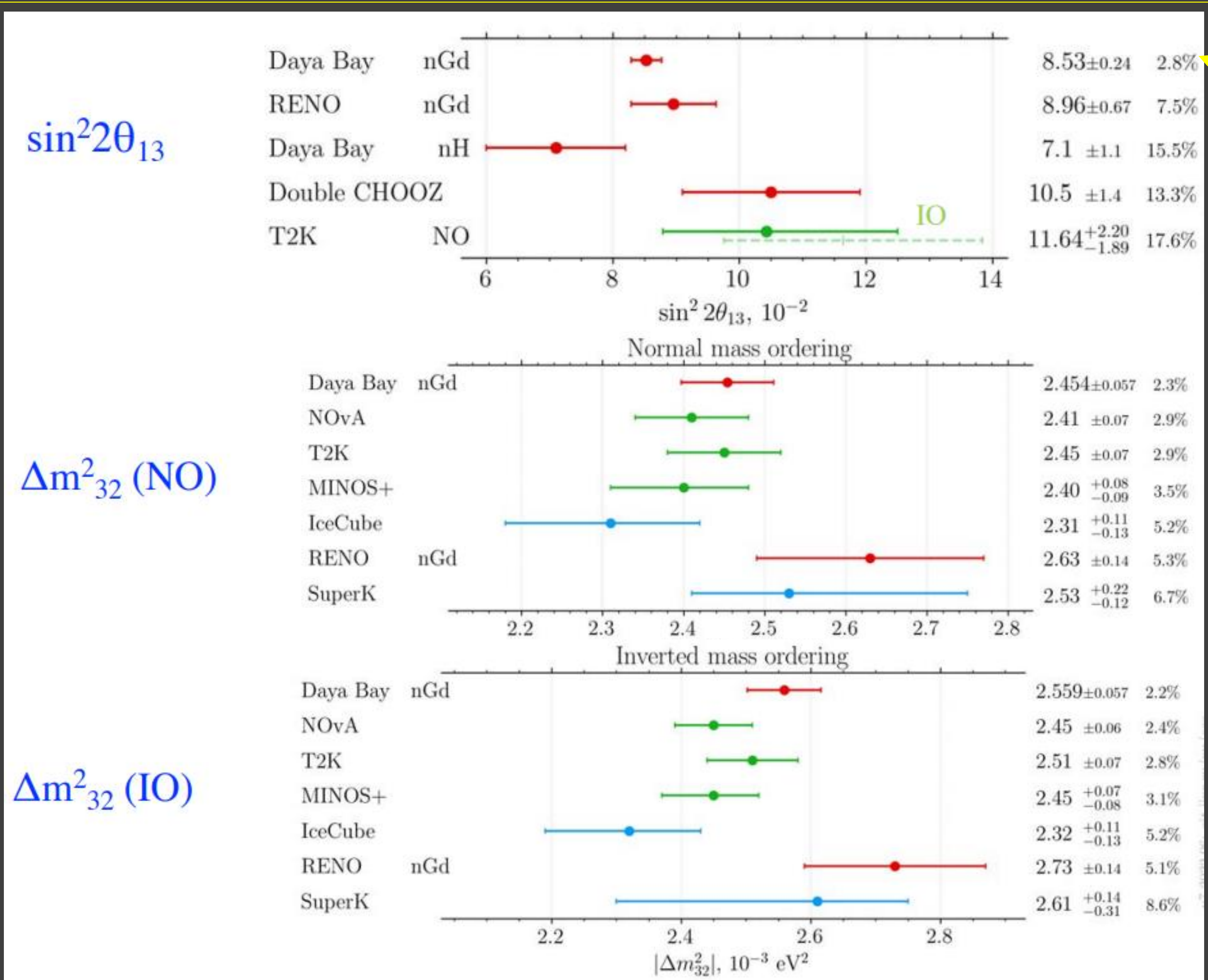
- RENO: running since 2011



$\sin^2 2\theta_{13} = 0.0892 \pm 0.0044(stat.) \pm 0.0045(sys.)$ **± 7.0%**

$|\Delta m^2_{ee}| = 2.74 \pm 0.10(stat.) \pm 0.06(sys.)(\times 10^{-3}\text{eV}^2)$ **± 4.4%**

Present Global Landscape



Daya Bay provides the best measurement in the foreseeable future

Km baseline reactor neutrino experiment provide consistent Δm^2_{32} results with accelerator and atmospheric experiments

Summary

- Great success from reactor neutrino experiments at 2 km
- Daya Bay, RENO, Double Chooz obtained the best $\sin^2 2\theta_{13}$ precision, which is a key input for future neutrino experiments
- Bright future of JUNO is expected
  - Rich physics potentials
  - Neutrino mass ordering: 3 sigma with 6 years
  - Oscillation parameters: best precision for $\sin^2\theta_{12}$, Δm^2_{32}, Δm^2_{21}

Backup slides

Neutrino mixing

- 2015 Nobel Prize: Neutrinos oscillate and thus have masses.
- The flavor eigenstates are mixing of mass eigenstates.

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

- Generation and detection via flavor eigenstates
  - Solar: ν_e
  - Reactor: $\overline{\nu}_e$
  - Atmospheric: ν_e, ν_μ, ν_τ
  - Accelerator: ν_e, ν_μ, ν_τ
  - Cosmic, supernova, …

- Mixing matrix measured by neutrino oscillation
  - Mixing angle: θ_{12}, θ_{13}, θ_{23}
  - CP violation phase: δ_{cp}
  - Majorana phases: δ_1, δ_2 (invisible)
- Oscillation probability also relies on relative masses and mass ordering
  - Δm_{21}^2, Δm_{32}^2, Δm_{31}^2
  - $m_1 < m_2 < m_3$ or $m_3 < m_2 < m_1$

- Tiny but (at least two) non-zero masses
  - β decay

    $$m_\beta \equiv \sqrt{|U_{e1}|^2 m_1^2 + |U_{e2}|^2 m_2^2 + |U_{e3}|^2 m_3^2}$$

  - Double β decay

    $$m_{\beta\beta} \equiv \left|U_{e1}^2 m_1 + U_{e2}^2 m_2 + U_{e3}^2 m_3\right|$$

  - Cosmology

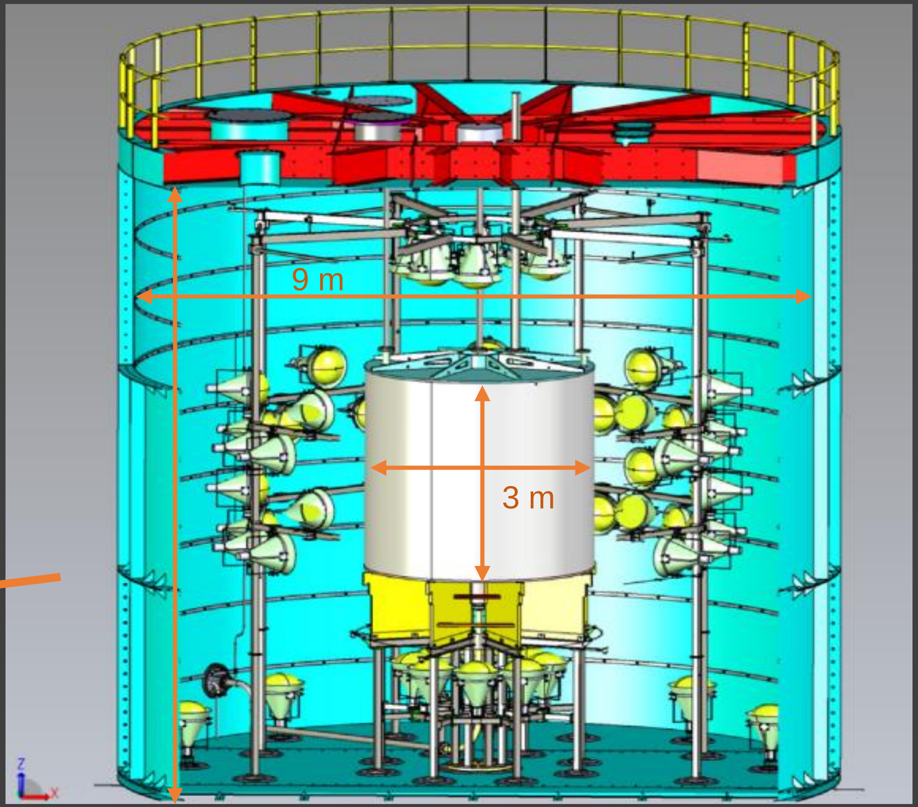
    $$\sum m_\nu = m_1 + m_2 + m_3$$

Online Scintillator Internal Radioactivity Investigation System (OSIRIS)

A 20-t detector to monitor radiopurity of LS before and during filling to the central detector

- ✓ Few days: U/Th (Bi-Po) ~ 1×10^{-15} g/g (reactor baseline case)
- ✓ 2~3 weeks: U/Th (Bi-Po) ~ 1×10^{-17} g/g (solar ideal case)
- ✓ Other radiopurity can also be measured: ^{14}C, ^{210}Po and ^{85}Kr

Eur.Phys.J.C 81 (2021) 11, 973

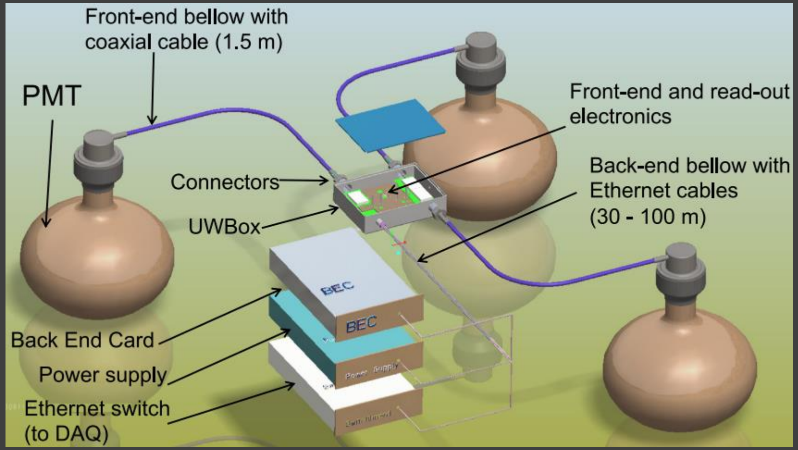


Possible upgrade to Serappis (SEarch for RAre PP-neutrinos In Scintillator): *EPJC* 82 (2022) 9, 779

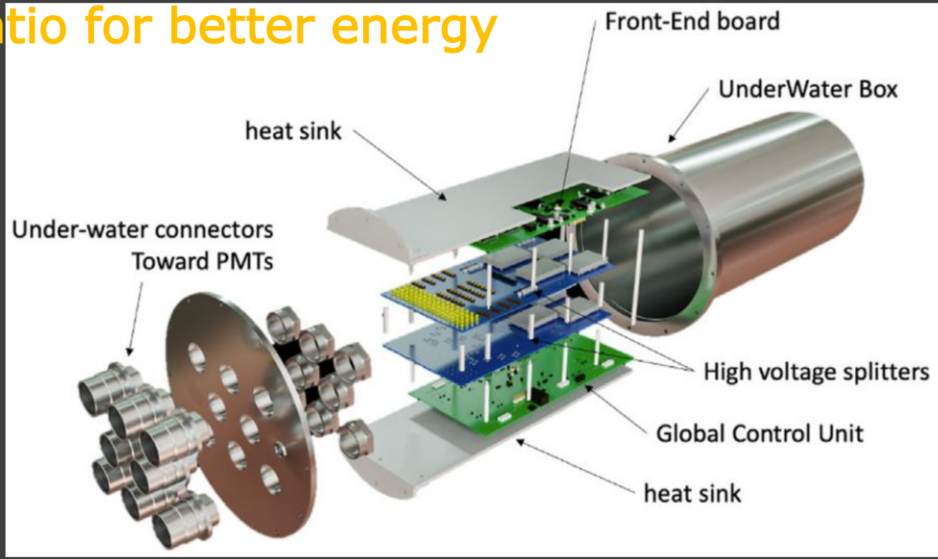
- ✓ A precision measurement of the flux of solar *pp* neutrinos on the few-percent level

Electronics

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

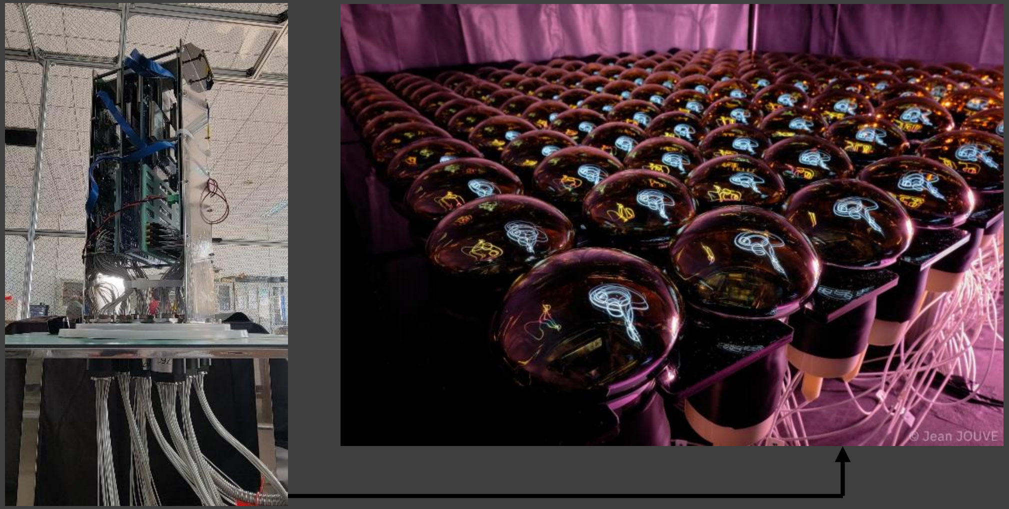


3 20-inch PMTs connected to one underwater box



128 3-inch PMTs connected to one underwater box

1 GHz waveform digitization, expected loss rate < 0.5% in 6 years

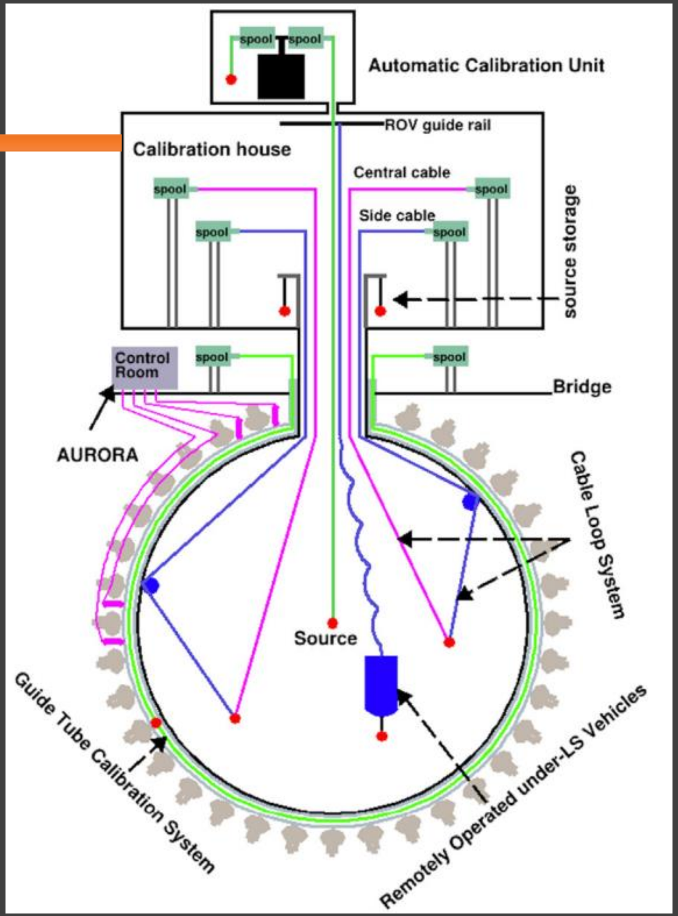


Electronics assembly ongoing

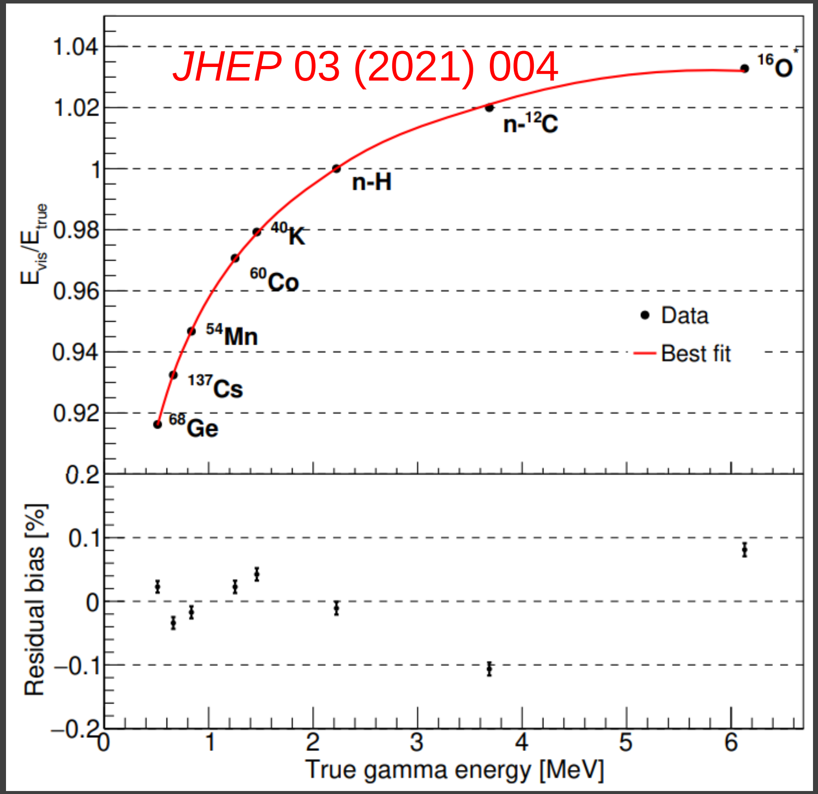
Calibration

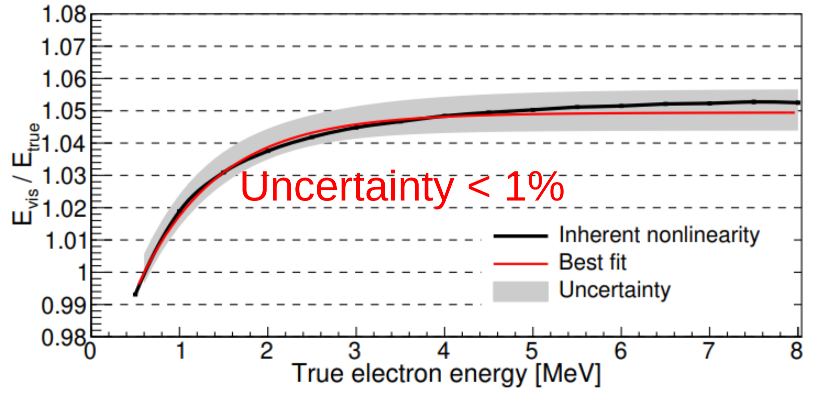
1D,2D,3D scan systems with multiple calibration sources to control the energy scale, detector response non-uniformity, and < 1% energy non-linearity

Cable system finished prototype test



Shadowing effect uncertainty from Teflon capsule of radioactive sources: < 0.15%

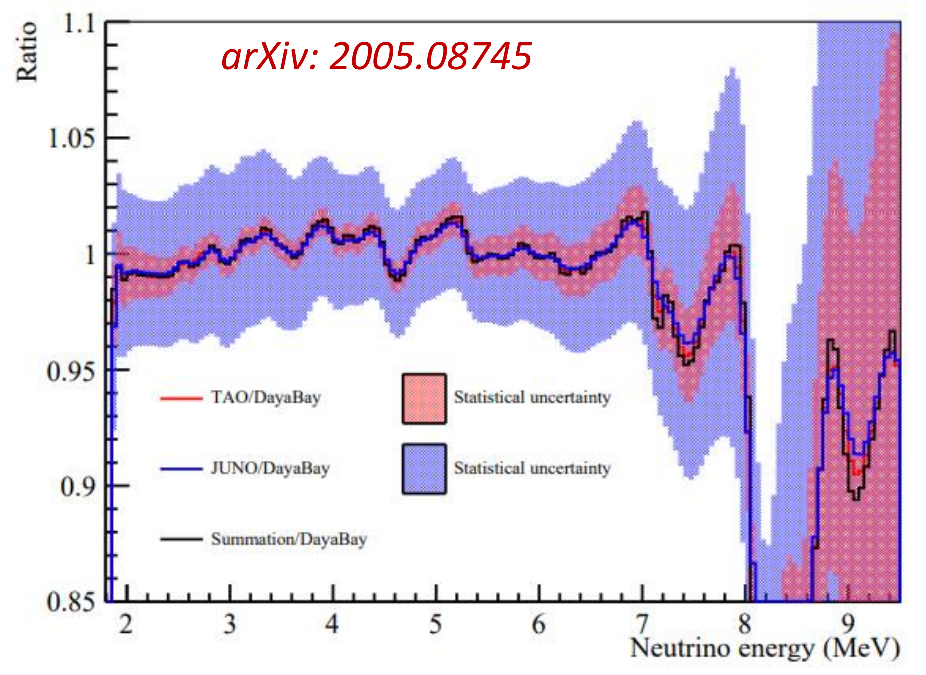




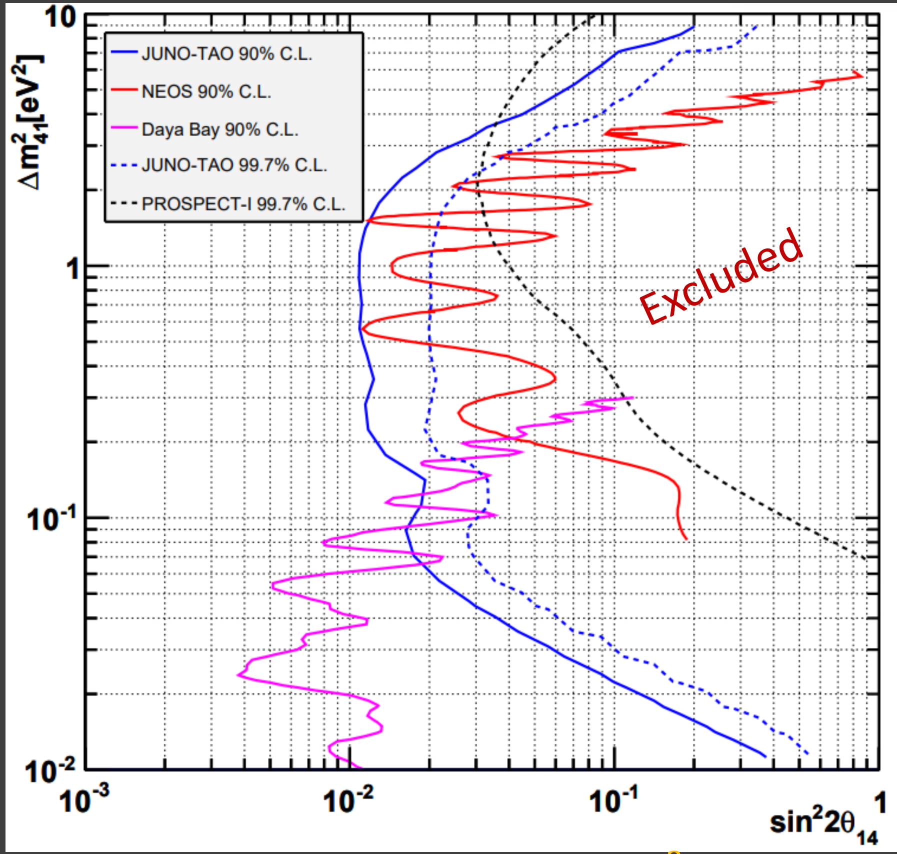
Taishan Antineutrino Observatory (TAO)

Goals:

1. Measure the reactor antineutrino spectrum with unprecedented energy resolution and see its fine structure for the first time.
2. Provide a reference spectrum for JUNO, other experiments, and nuclear databases
3. Search for light sterile neutrinos
4. Make improved measurements of isotopic yields & spectra



Constrain the fine structure in [2.5,6] MeV to < 1%



TAO sensitive in region 10^{-2} eV^2 < Δm^2_{41} < 10eV^2

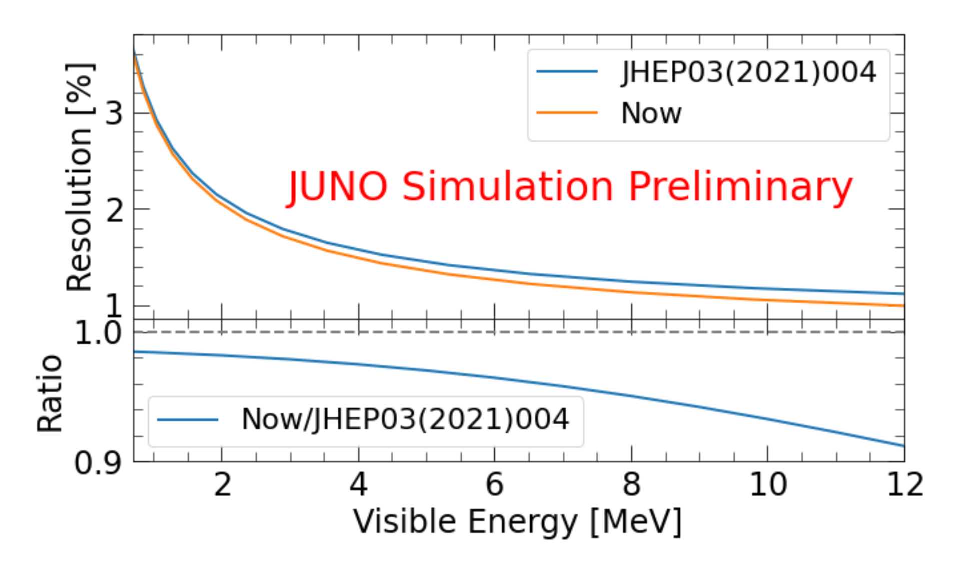
Update of energy resolution

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**	arXiv: 2205.08629
New PMT Optical Model	+8%↑		*EPJC 82 329 (2022)*

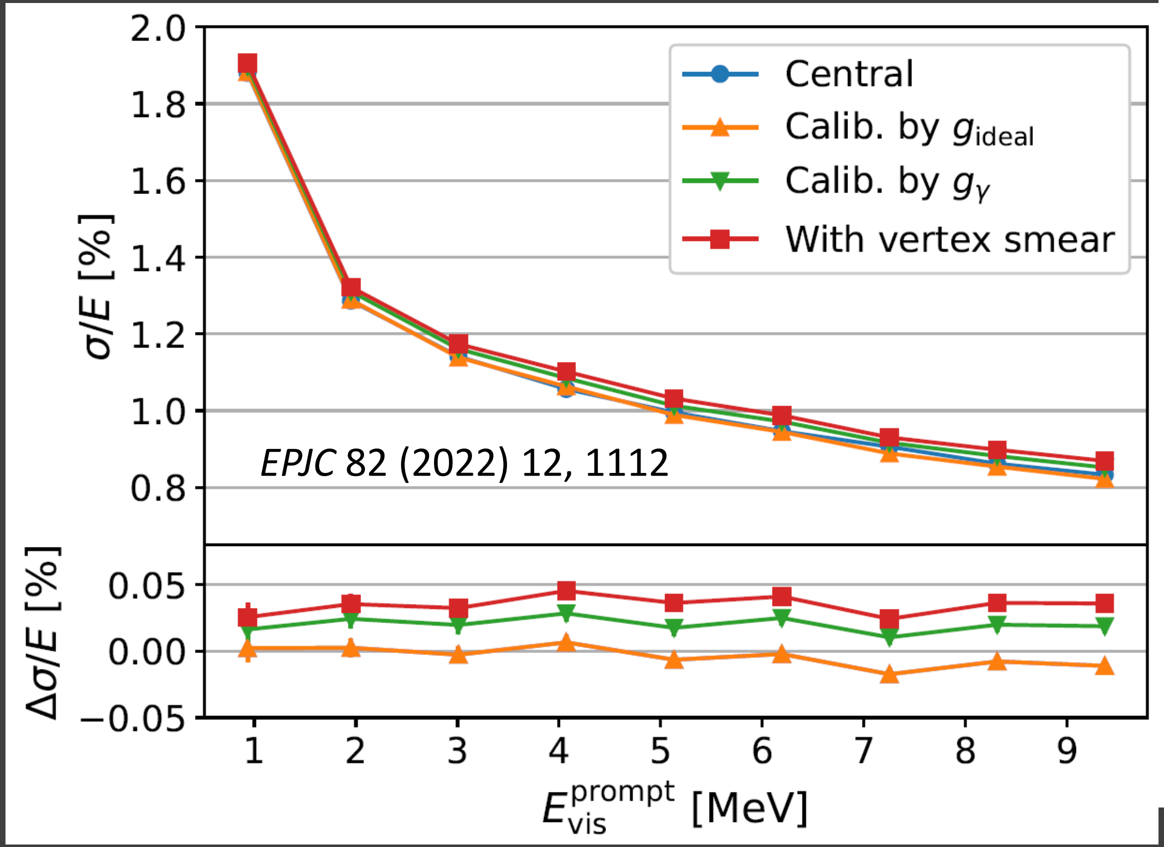
Positron energy resolution is understood:

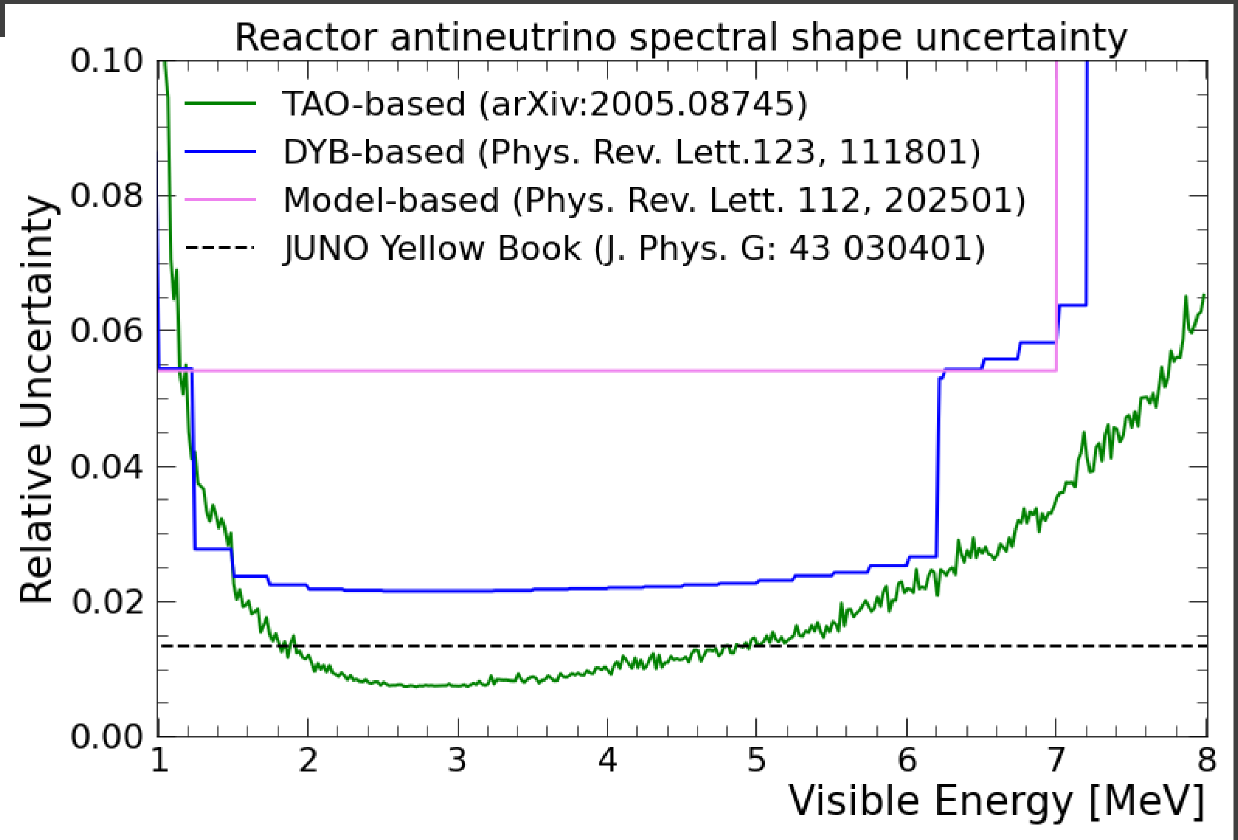
$$\frac{\sigma}{E_{\rm vis}} = \sqrt{\left(\frac{a}{\sqrt{E_{\rm vis}}}\right)^2 + b^2 + \left(\frac{c}{E_{\rm vis}}\right)^2}$$

- **Photon statistics** (from a)
- **Annihilation-induced γs** (from c)
- **Dark noise** (from c)
- **Scintillation quenching effect** (from b, also linked to c)
  - 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**



Reactor Antineutrino Spectrum from TAO





1. ~94% coverage of SiPM with ~50% PDE
2. Inner diameter of target: 1.8 m, absorption of scintillation very small
3. Gd-LS works at -50℃, increase the photon yield

- ✓ Unprecedented energy resolution < 2% @ 1 MeV
- ✓ Shape uncertainty close to the assumption in the JUNO Physics Book (*J. Phys. G43:030401 (2016)*)