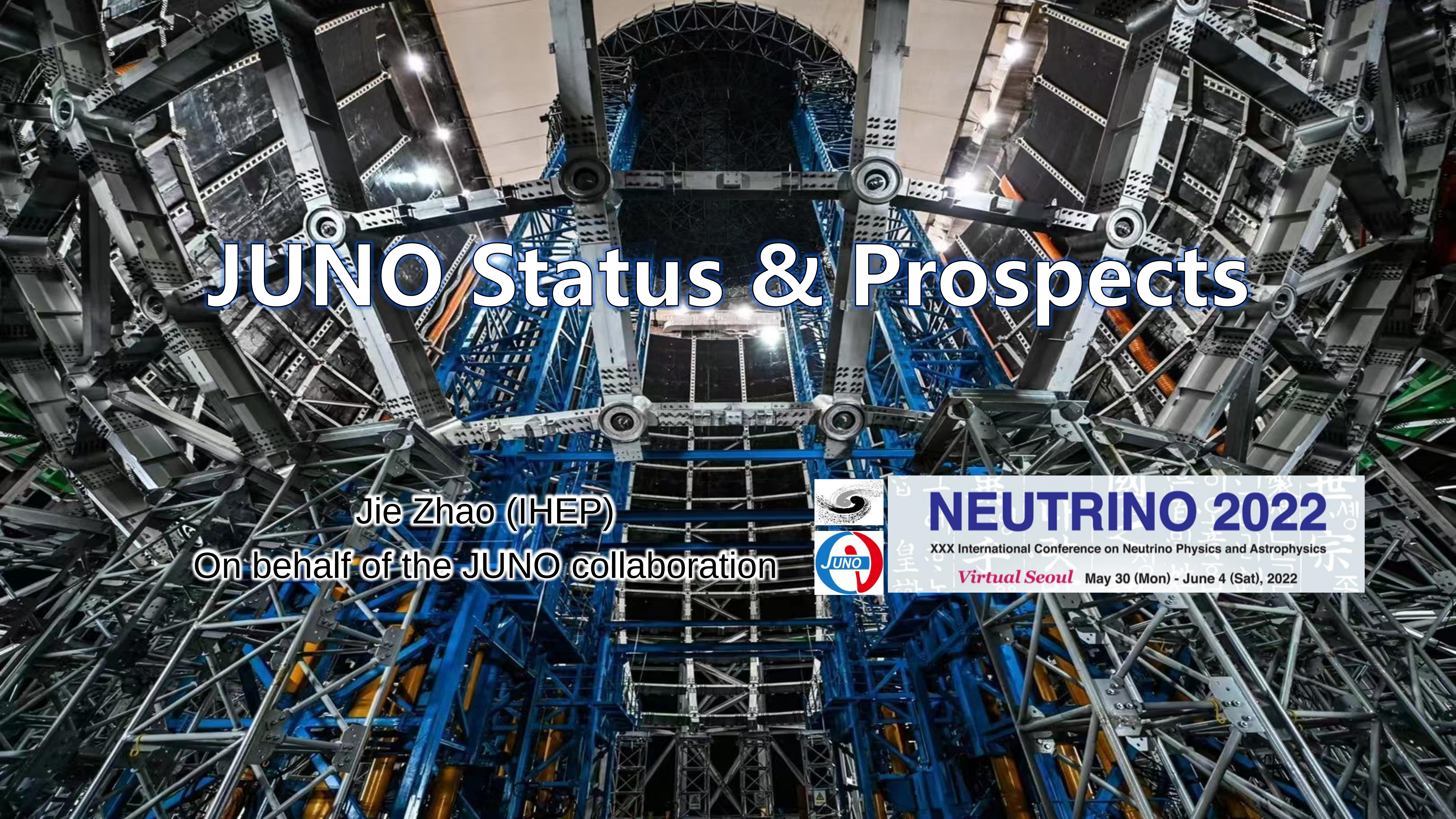


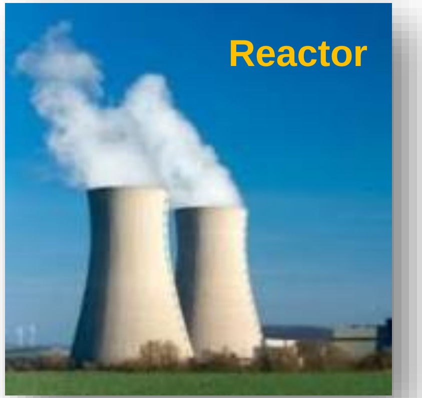
JUNO Status & Prospects

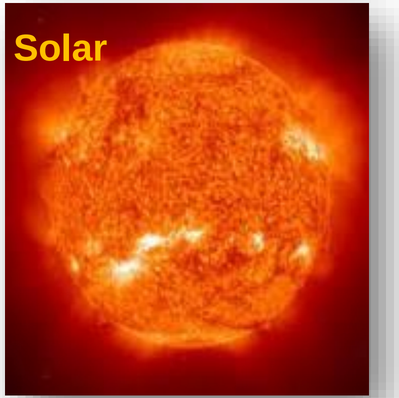
Jie Zhao (IHEP)
On behalf of the JUNO collaboration

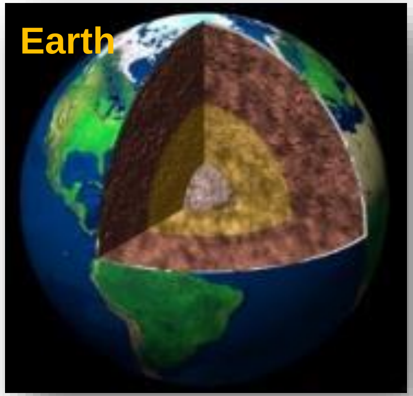
NEUTRINO 2022
XXX International Conference on Neutrino Physics and Astrophysics
Virtual Seoul May 30 (Mon) - June 4 (Sat), 2022

Jiangmen Underground Neutrino Observatory

A multi-purpose observatory







\+ New physics

~60 IBDs per day

Several per day

Hundreds per day

~5000 IBDs for CCSN @10 kpc

Several IBDs per day

Neutrino oscillation & properties

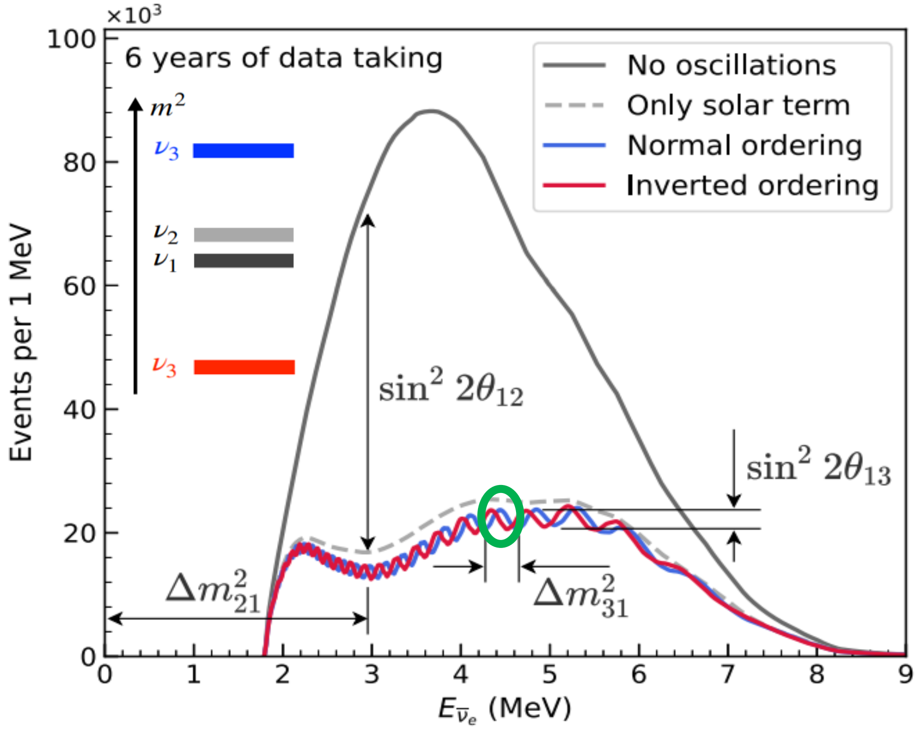
Neutrinos as a probe

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

CCSN: core-collapse supernova

Requirement for rich physics program

Example: Precision Neutrino Oscillation Measurements

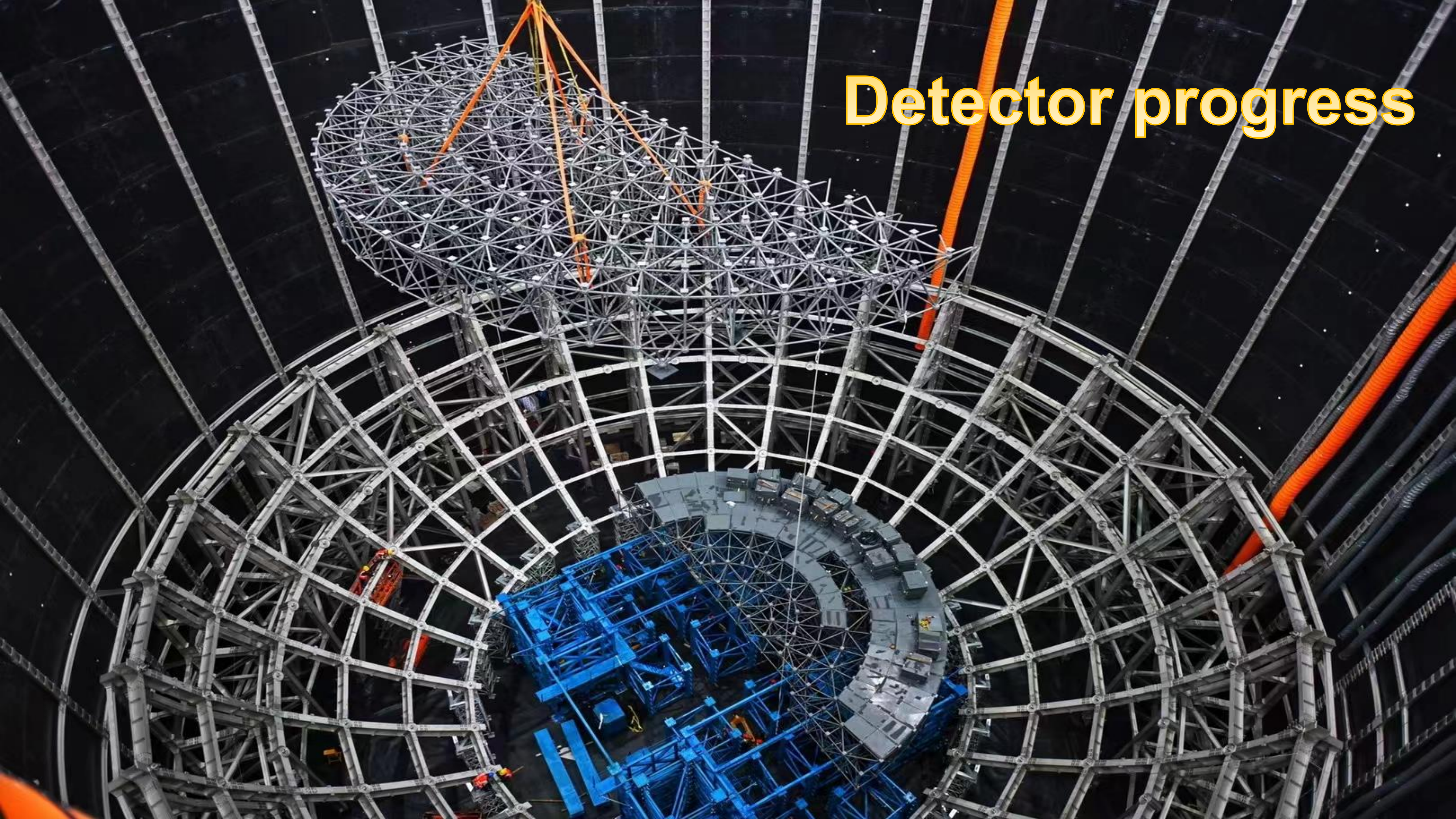


Detector properties

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

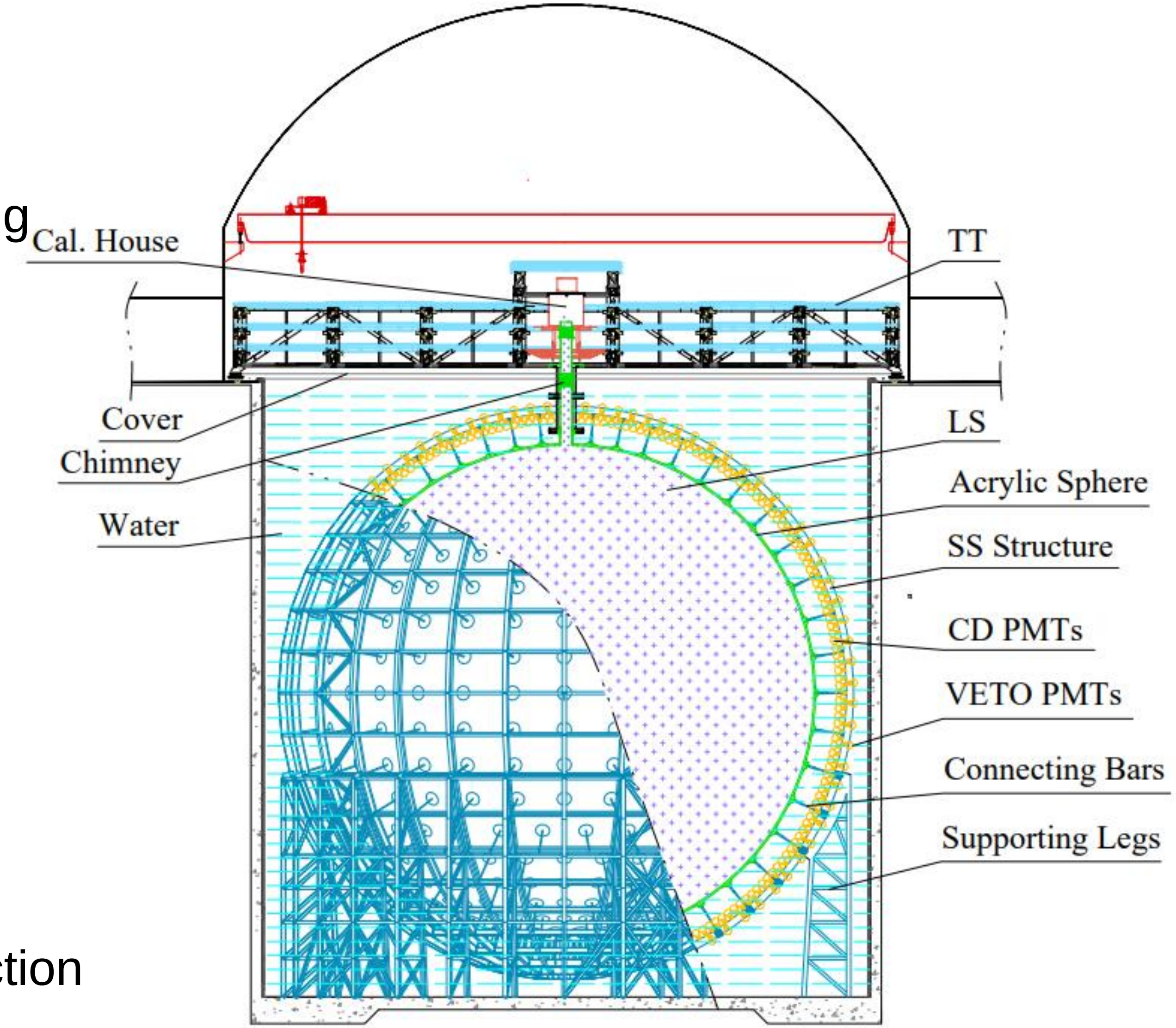
For solar neutrinos: tighter requirements on Liquid Scintillator (LS) radiopurity by 1~2 orders of magnitude.

Detector progress



Detector construction status

- **Acrylic panels**
  - 220 of total 265 pieces ready for shipping
- **Stainless Steel structure**
  - Bottom half has been assembled
- **20012 20” PMTs + 25600 3” PMTs**
  - Production and performance test done
  - Waterproof potting finished
- **Liquid scintillator**
  - Purification plants under onsite construction



Central detector (acrylic vessel)

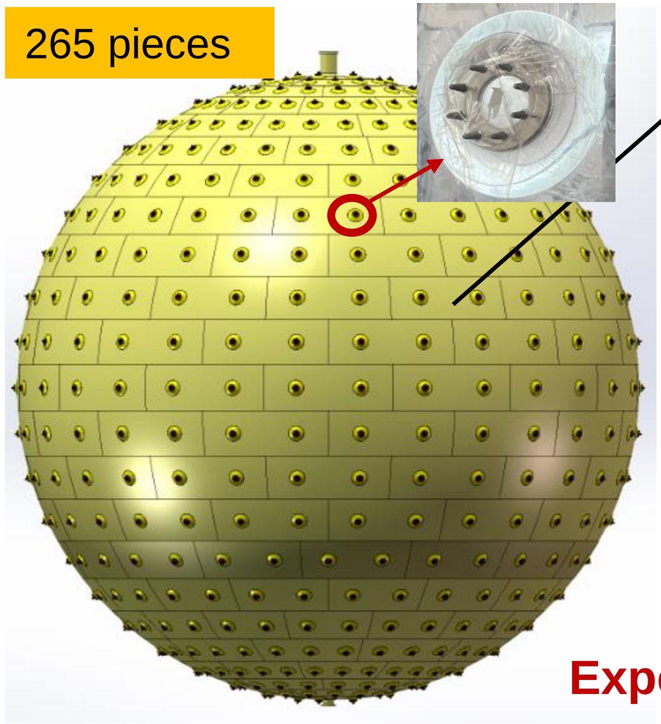
LS container: Poster: #184

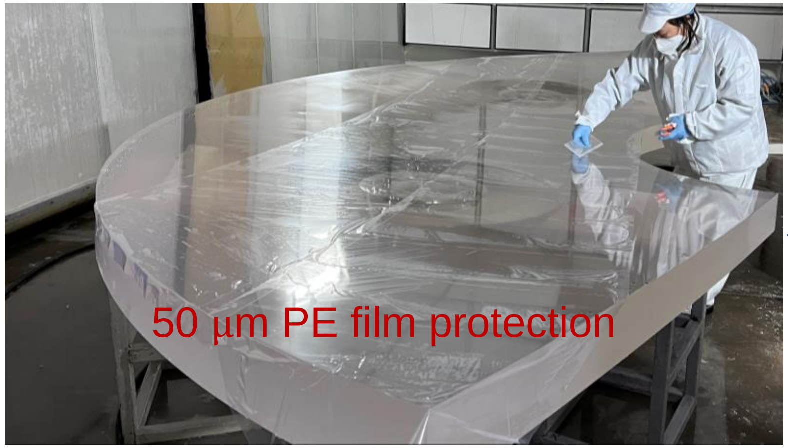
Inner diameter: 35.40±0.04 m

Thickness: 124±4 mm

Light transparency > 96% @ LS

Radiopurity: U/Th/K < 1 ppt



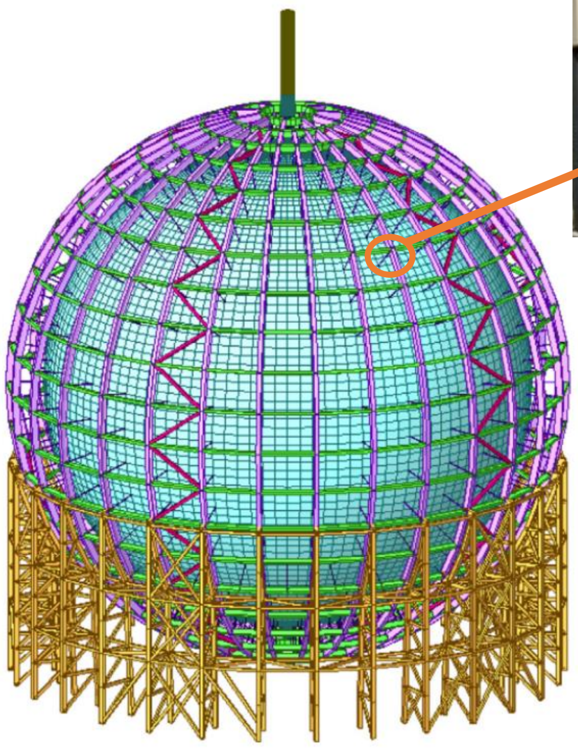


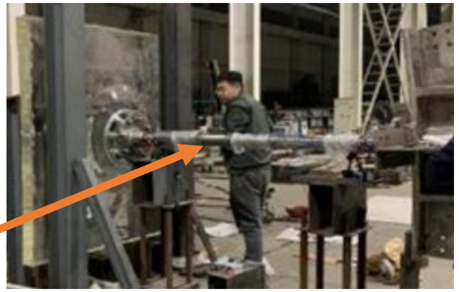
Expect to start onsite installation in late-June.

Central detector (SS structure)

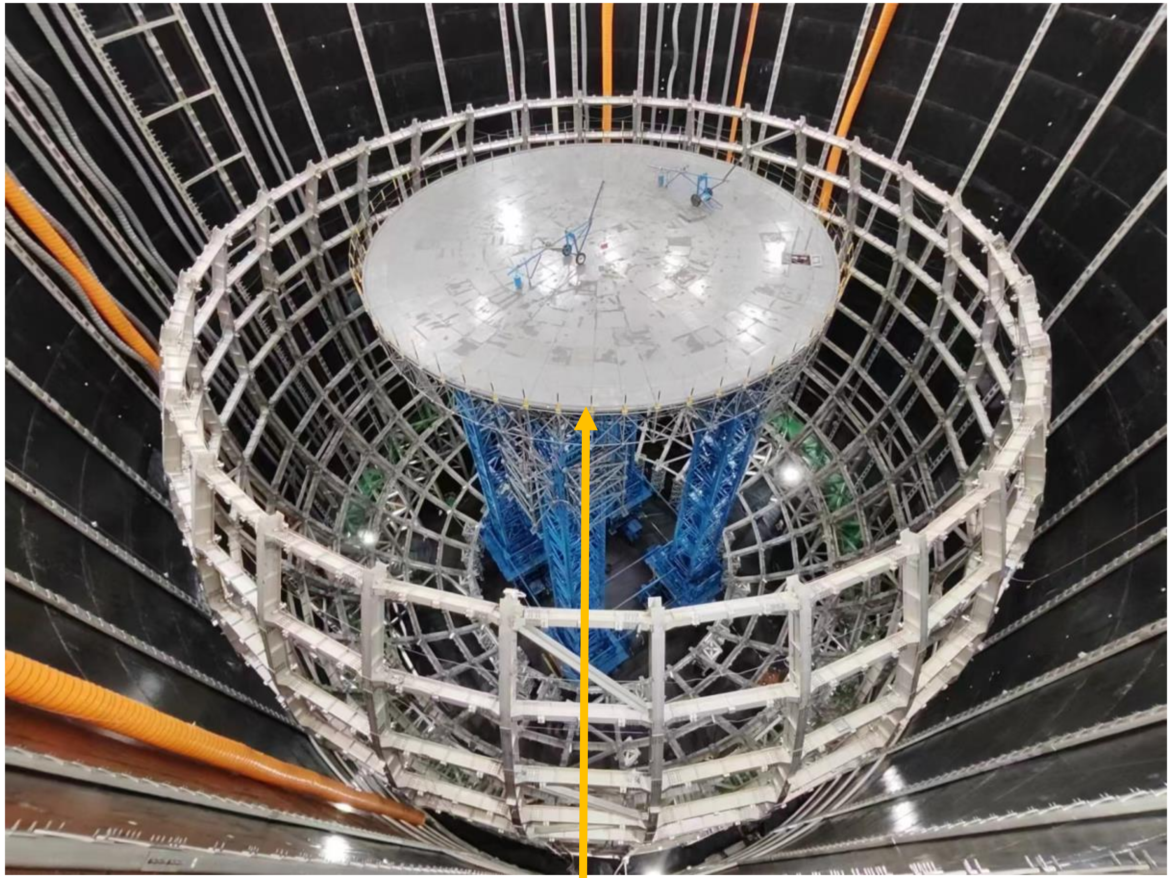
Acrylic vessel is supported by D = 40.1 m stainless steel structure via 590 Connecting Bars

Assembly precision: < 3 mm for each grid





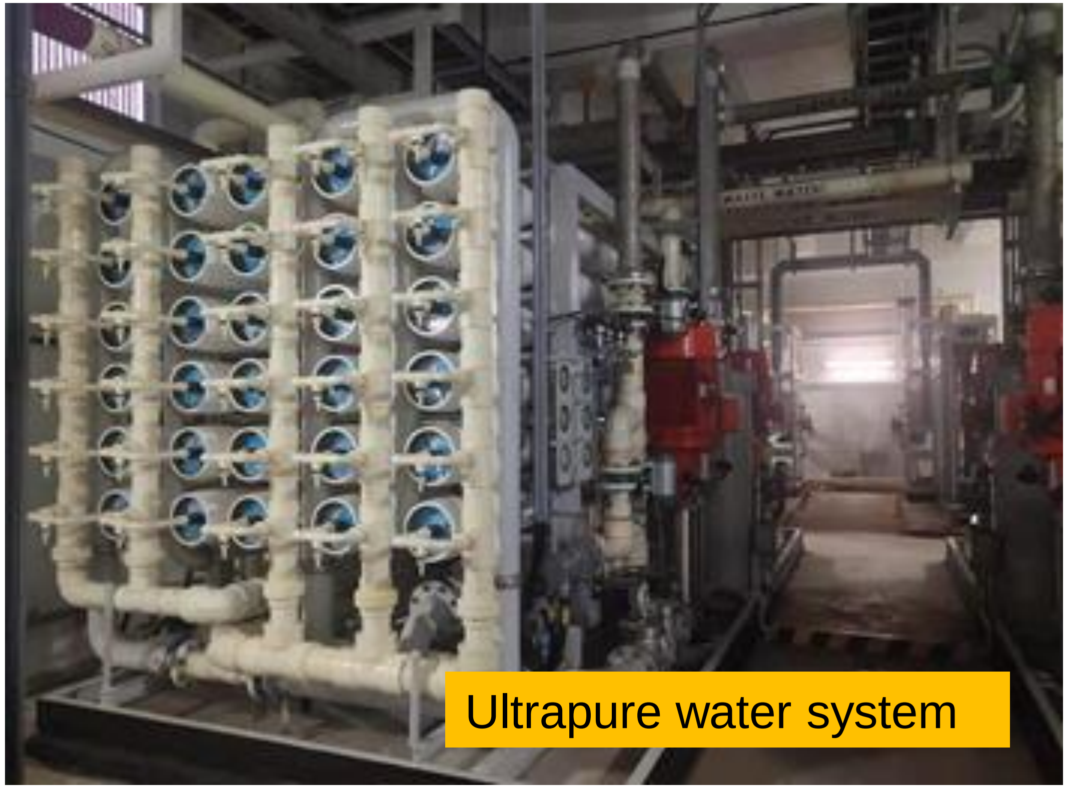
The bottom half of SS structure has been assembled.
Expect to finish this month.



The platform to install the acrylic vessel has been finished.

Veto detector (Water Cherenkov)

Poster: #347 ~650 m rock overburden (1800 m.w.e.) → R_μ = 4 Hz in LS, $< E_\mu >$ = 207 GeV

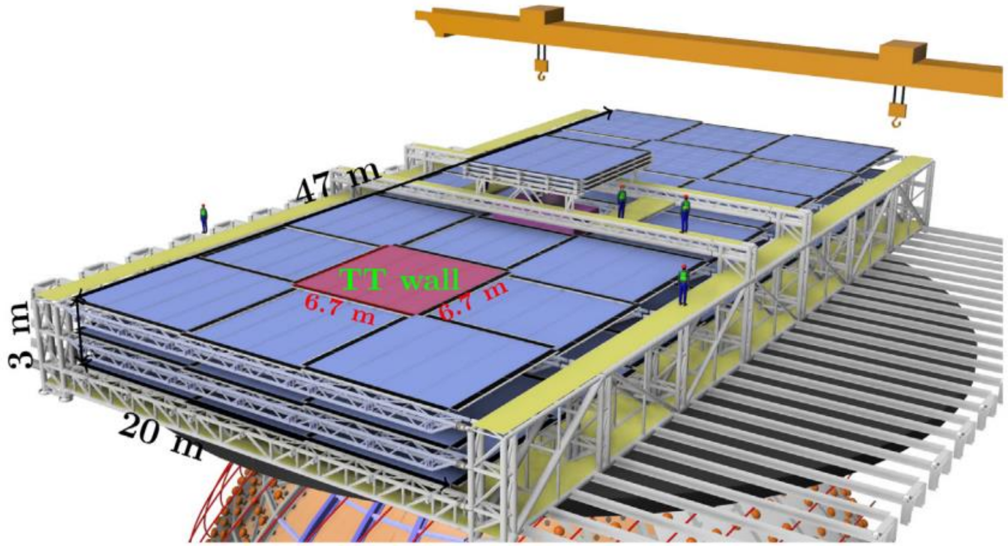


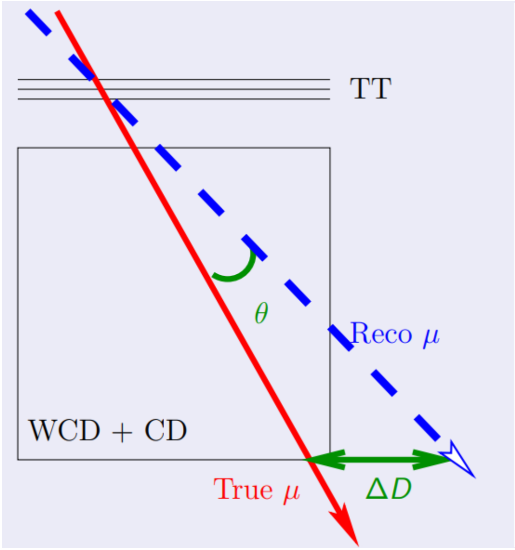
35 kton of ultrapure water serving as passive shield and water Cherenkov detector.

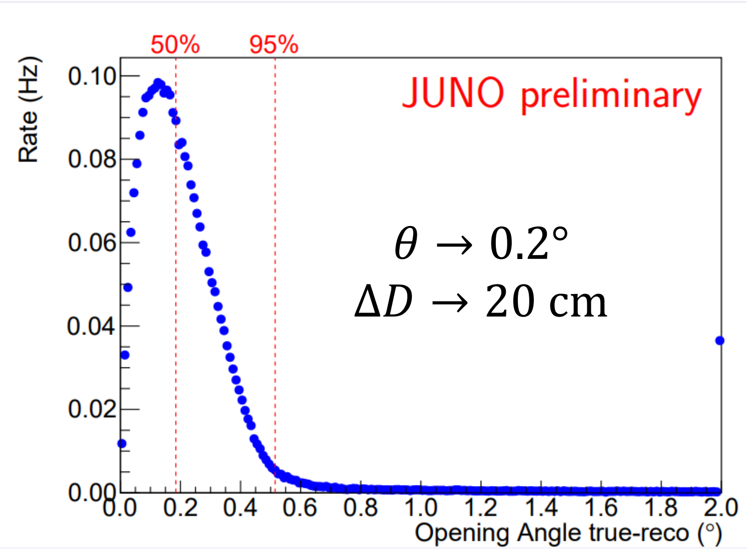
- ✓ 2400 20-inch MCP PMTs, detection efficiency of cosmic muons larger than 99.5%
- ✓ Keep the temperature uniformity 21℃±1℃
- ✓ Quality: ^{222}Rn < 10 mBq/m^3, attenuation length 30~40 m

Veto detector (Top Tracker)

Poster: #365







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

Liquid scintillator (20 kton)

Poster: #265

NIM.A 908 (2021) 164823

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

5000 m³ LAB tank

Al_2O_3 to remove particles

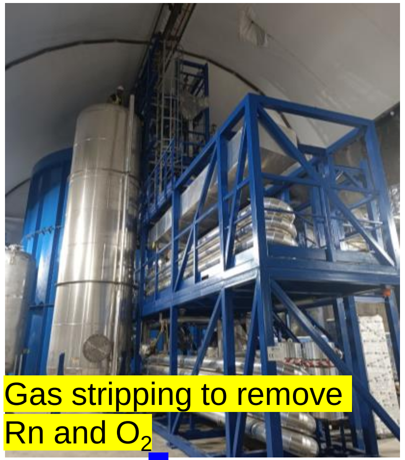
Distillation to remove radioactive impurities

Add 2.5 g/L PPO and 3 mg/L bis-MSB

All the LS related systems will finish assembly in summer.

SS pipes to underground

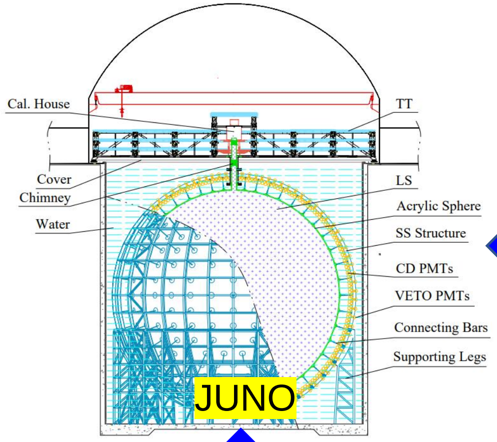
Water extraction to remove radioactive impurities



Gas stripping to remove Rn and O_2

15%

OSIRIS for LS qualification



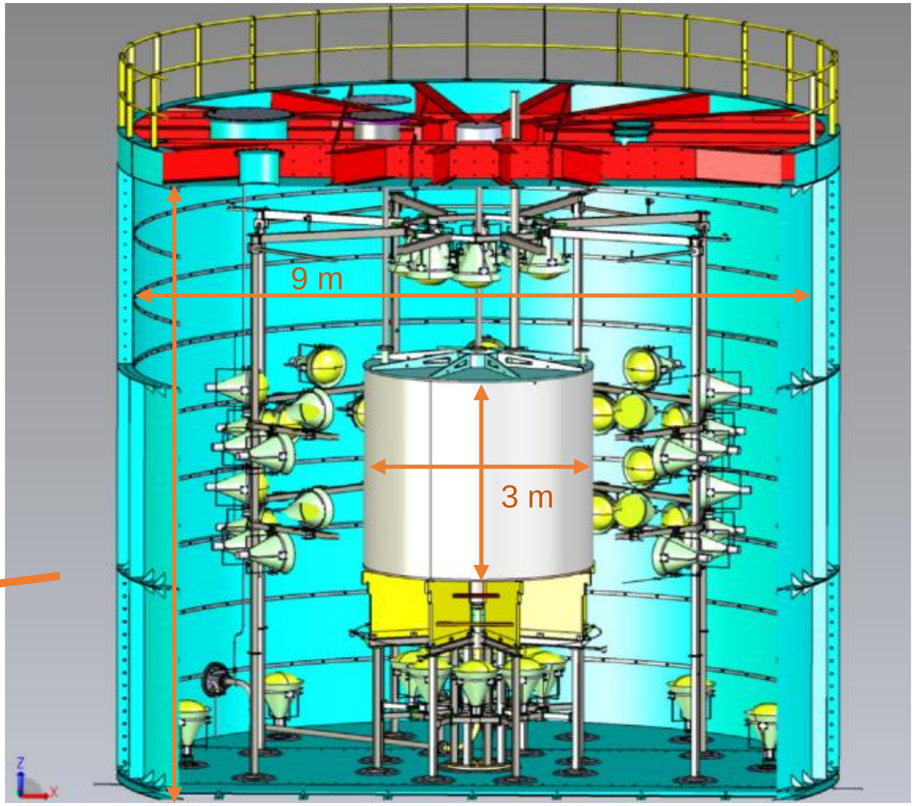
JUNO

85%

Online Scintillator Internal Radioactivity Investigation System (OSIRIS)

Poster: #195

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



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

Expect to start commissioning in July.

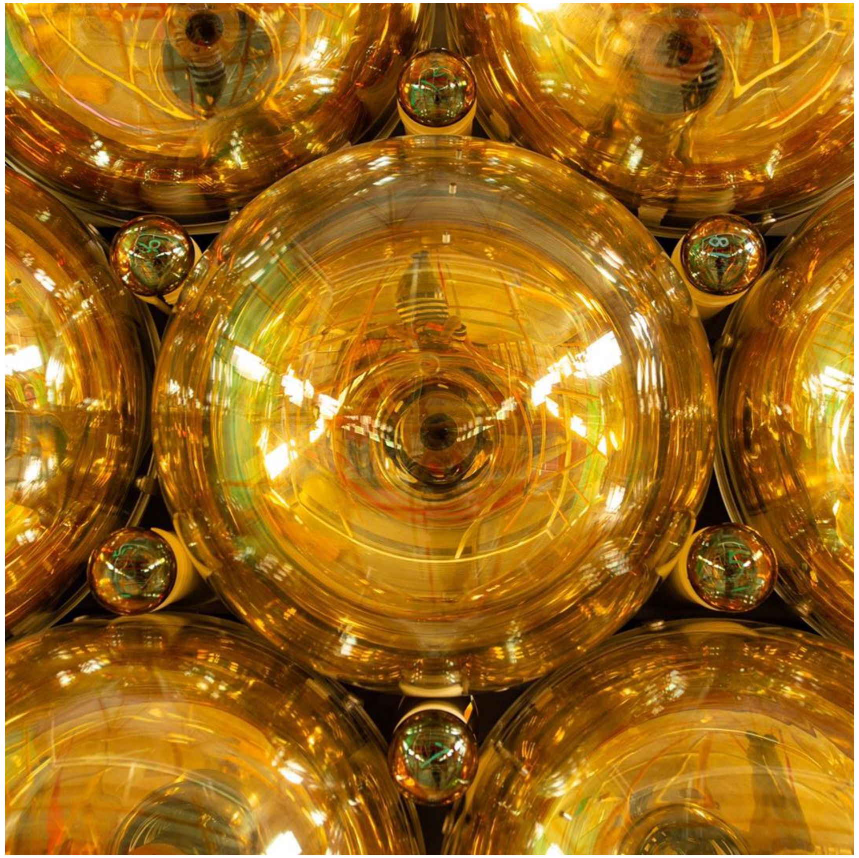
Possible upgrade to Serappis (SEarch for RAre PP-neutrinos In Scintillator): *arXiv: 2109.10782*

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

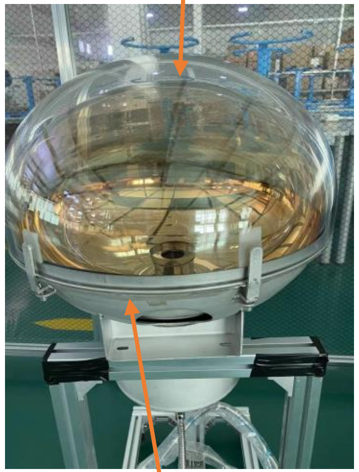
Photomultiplier Tubes

Poster: #360

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



Acrylic cover

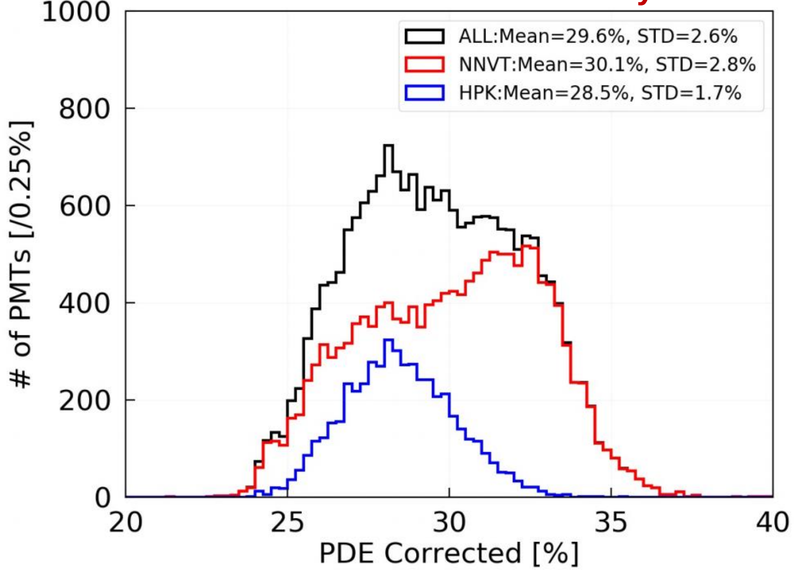


Stainless Steel cover

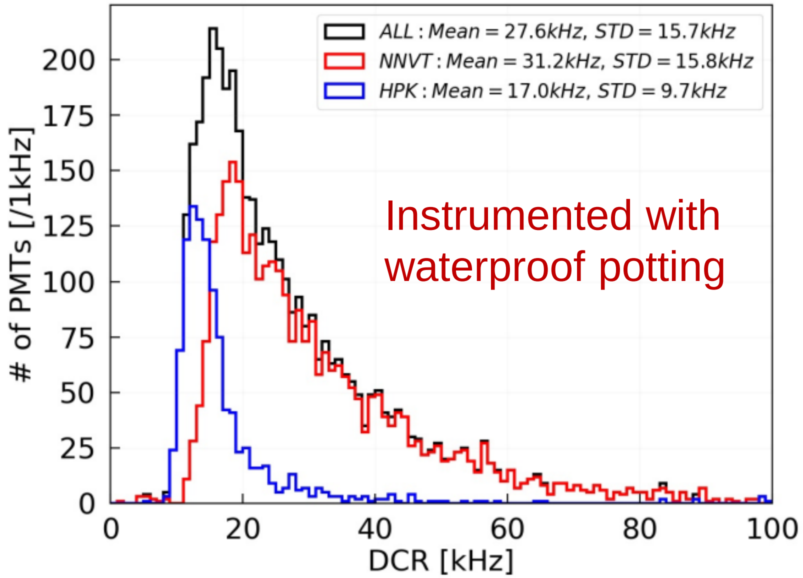
Clearance between PMTs: 3 mm → **Assembly precision: < 1 mm**

Photomultiplier Tubes

Photon Detection Efficiency



Dark Counting Rate



All PMTs produced, tested, and instrumented with waterproof potting

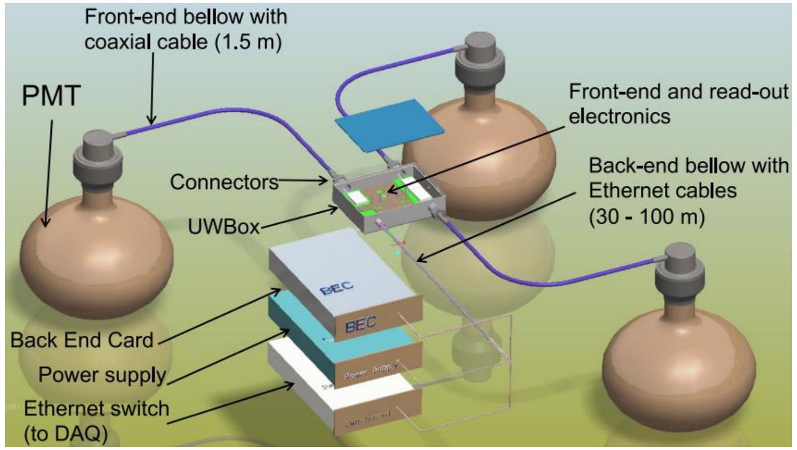
		LPMT (20-inch)		SPMT (3-inch)
		Hamamatsu	NNVT	HZC
Quantity		5000	15012	25600
Charge Collection		Dynode	MCP	Dynode
Photon Detection Efficiency		**28.5%**	**30.1%**	25%
Mean Dark Count Rate [kHz]	Bare	15.3	49.3	0.5
	Potted	**17.0**	**31.2**	
Transit Time Spread (σ) [ns]		1.3	7.0	1.6
Dynamic range for [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.

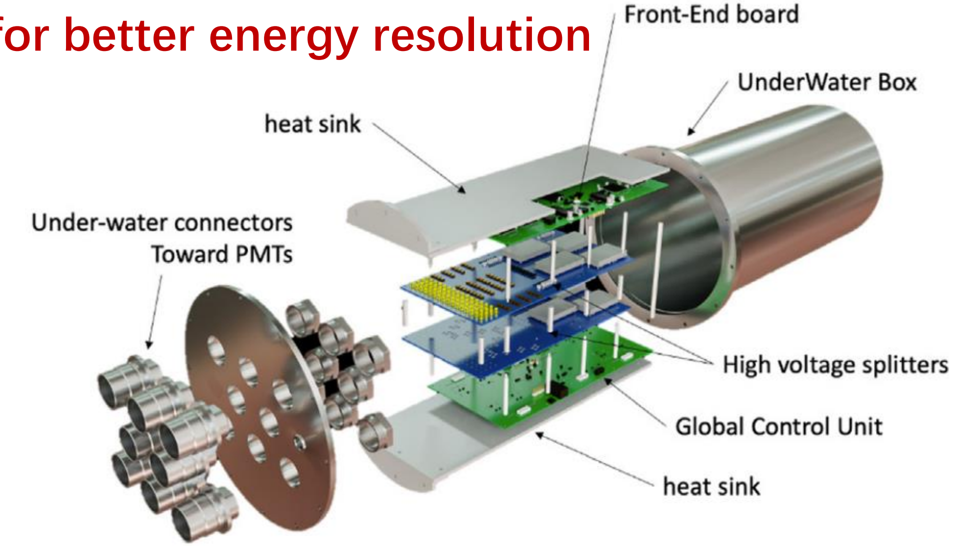
Electronics

Posters: #216, # 218, #270

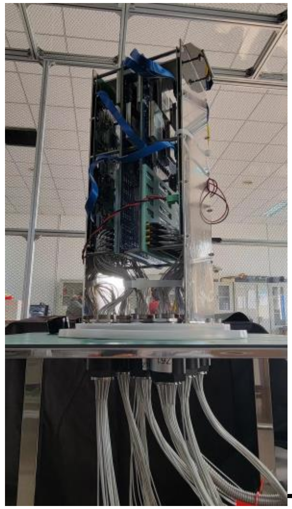
Underwater electronics to improve signal-to-noise ratio for better energy resolution



3 20-inch PMTs connected to one underwater box



128 3-inch PMTs connected to one underwater box



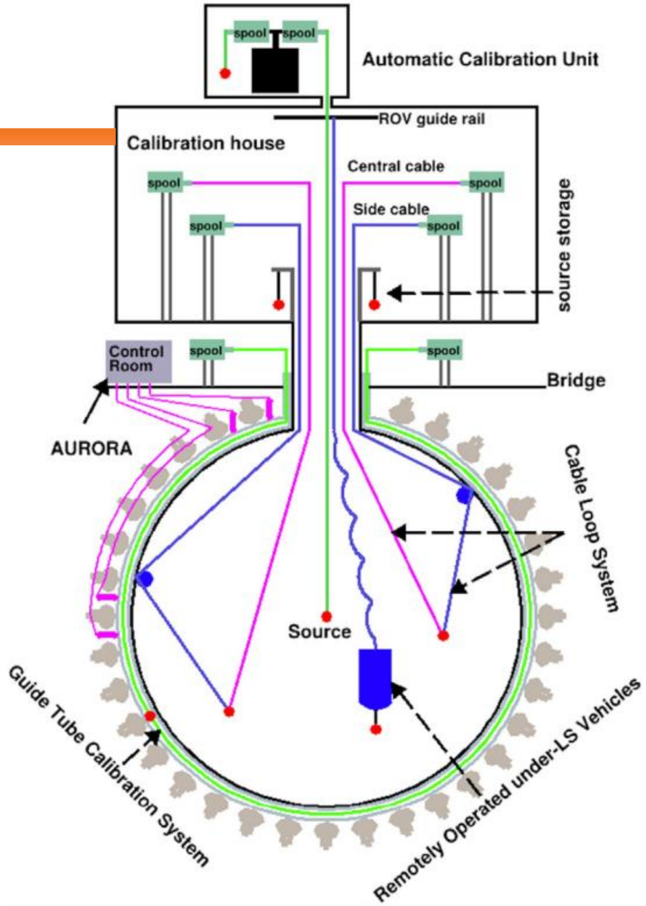
Electronics assembly ongoing

Calibration

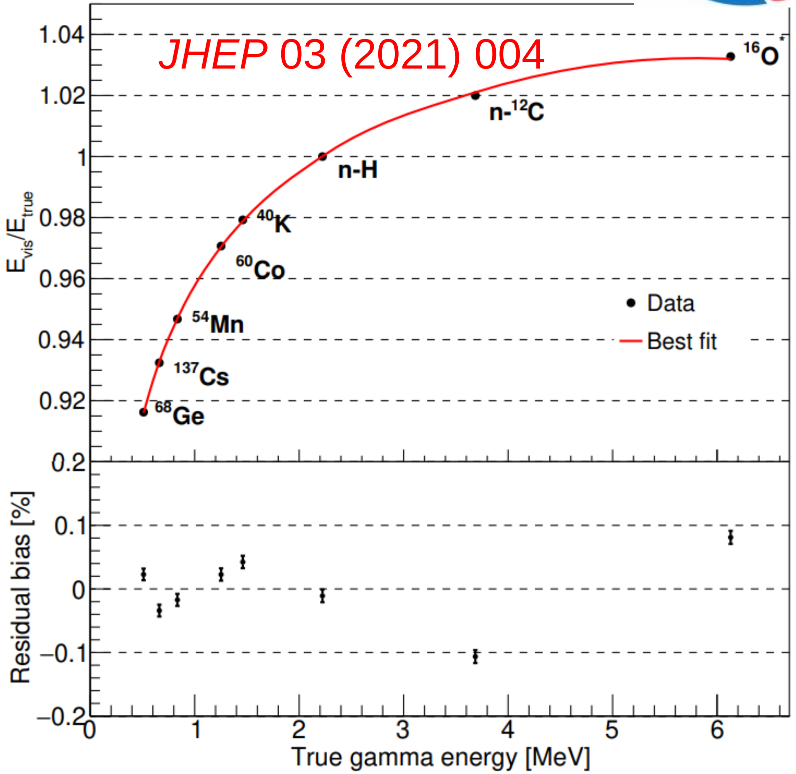
Poster: #293

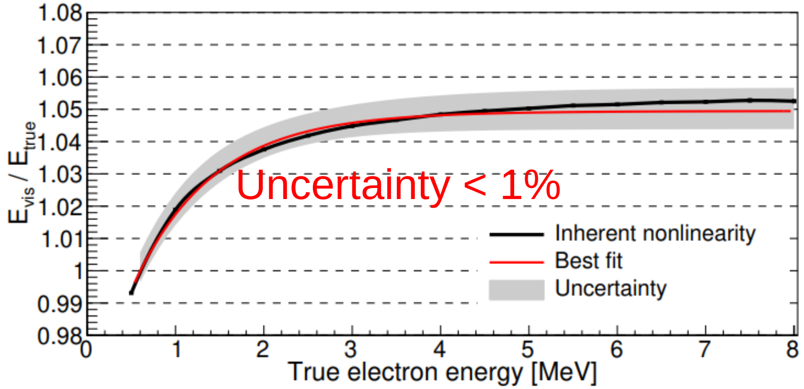
1D,2D,3D scan systems with multiple calibration sources to control the energy scale, detector response non-uniformity, and < 1% energy non-linearity

Cable system finished prototype test



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





Radiopurity control

Reduced by 15% compared to the design. Ref: *JHEP* 11 (2021) 102

Singles (R < 17.2 m, E > 0.7 MeV)	Design [Hz]	Change [Hz]	Comment
LS	2.20	0	
Acrylic	3.61	**-3.2**	10 ppt -> 1 ppt
Metal in node	0.087	**+1.0**	Copper -> SS
PMT glass	0.33	**+2.47**	Schott -> NNVT/Ham
Rock	0.98	**-0.85**	3.2 m -> 4 m
Radon in water	1.31	**-1.25**	200 mBq/m^3 -> 10 mBq/m^3
Other	0	**+0.52**	Add PMT readout, calibration sys
Total	8.5	**-1.3**	

Radiopurity control on raw material:

- ✓ Careful material screening
- ✓ Meticulous Monte Carlo Simulation
- ✓ Accurate detector production handling

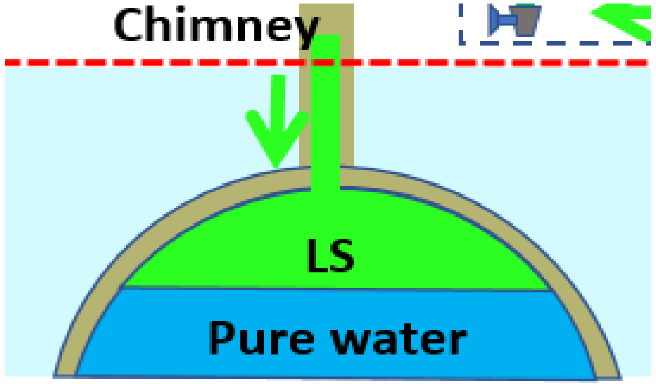
Liquid Scintillator Filling

✓ Recirculation is impossible at JUNO due to its large size

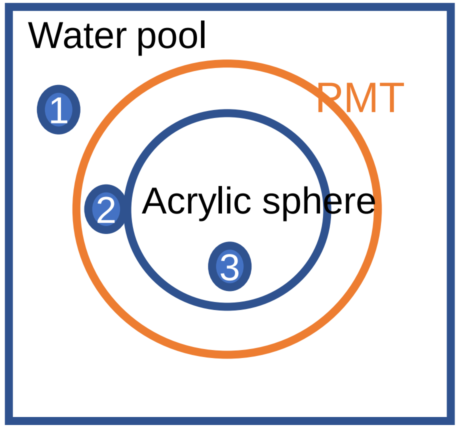
→ Target radiopurity need to be obtained from the beginning

✓ **Strategies:**

1. **Leakage** (single component < 10^{-6} mbar·L/s)
2. **Cleaning vessel** before filling
3. **Clean environment**
4. **Water/LS filling**

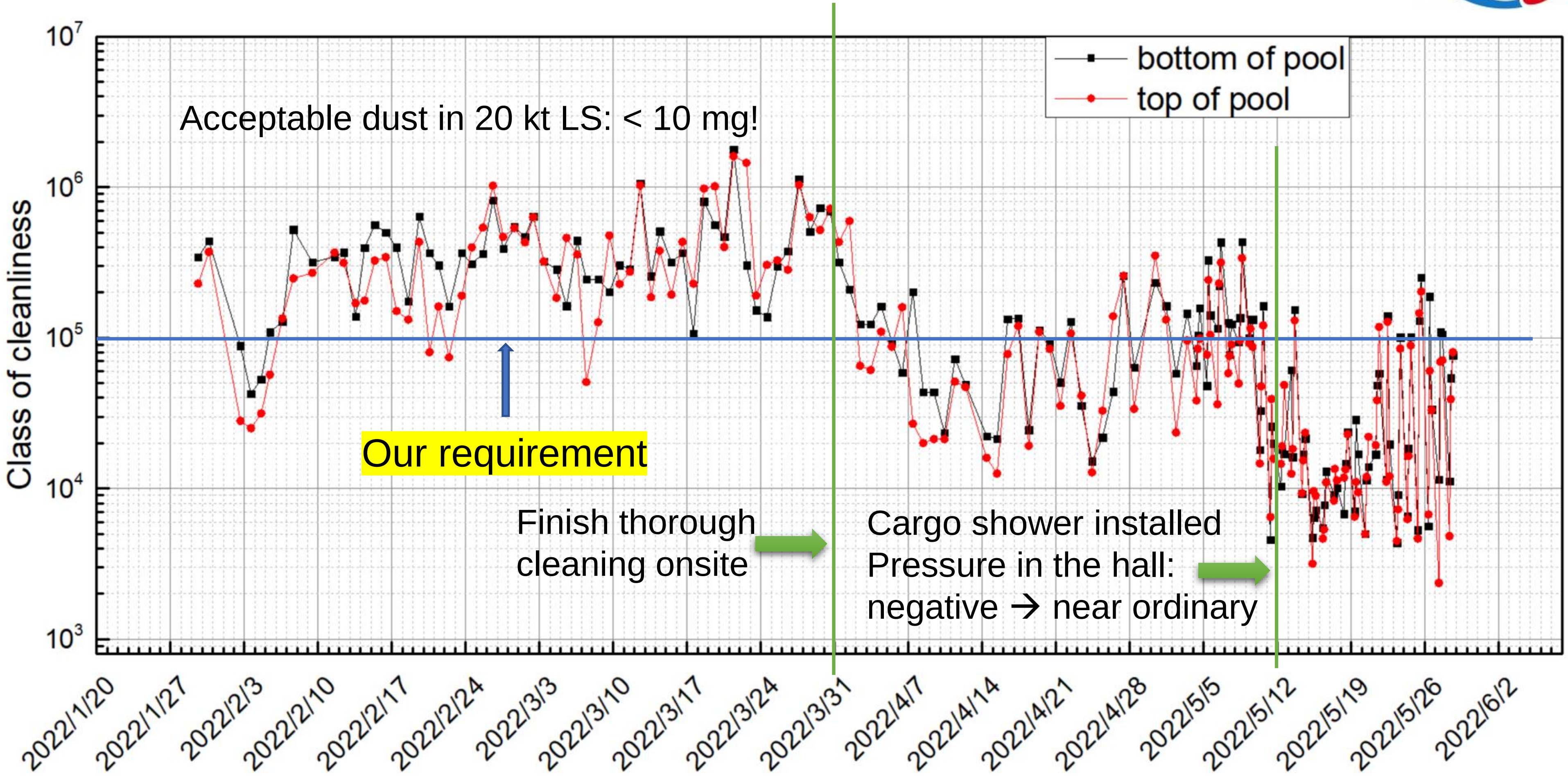


Radiopurity control: environment cleanliness



Region	Level
1	Class 100,000
2	Class 10,000
3	Class 1000

Temperature: 21℃±1℃



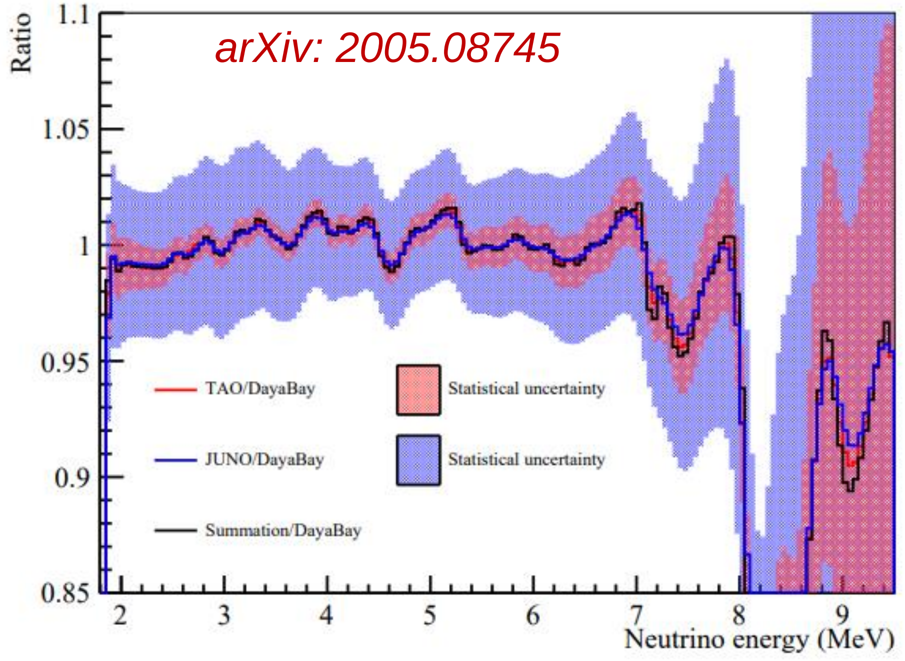
With great efforts on onsite cleanliness control, the cleanliness in the hall reaches better than Class 100,000.

Taishan Antineutrino Observatory (TAO)

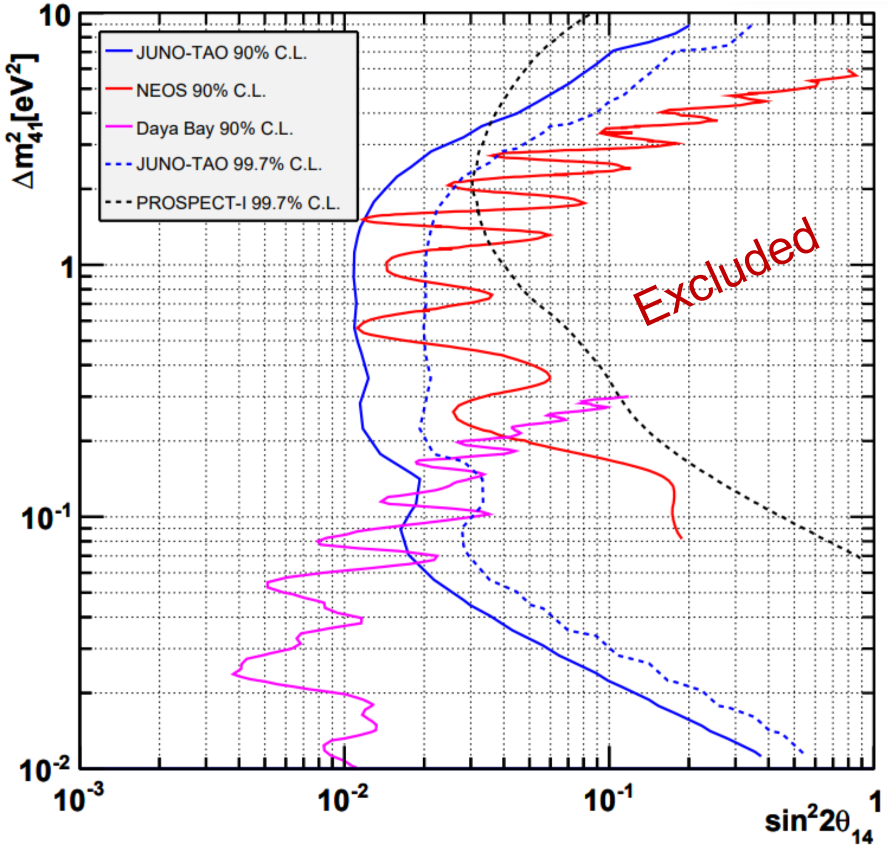
Posters: #673, #817

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



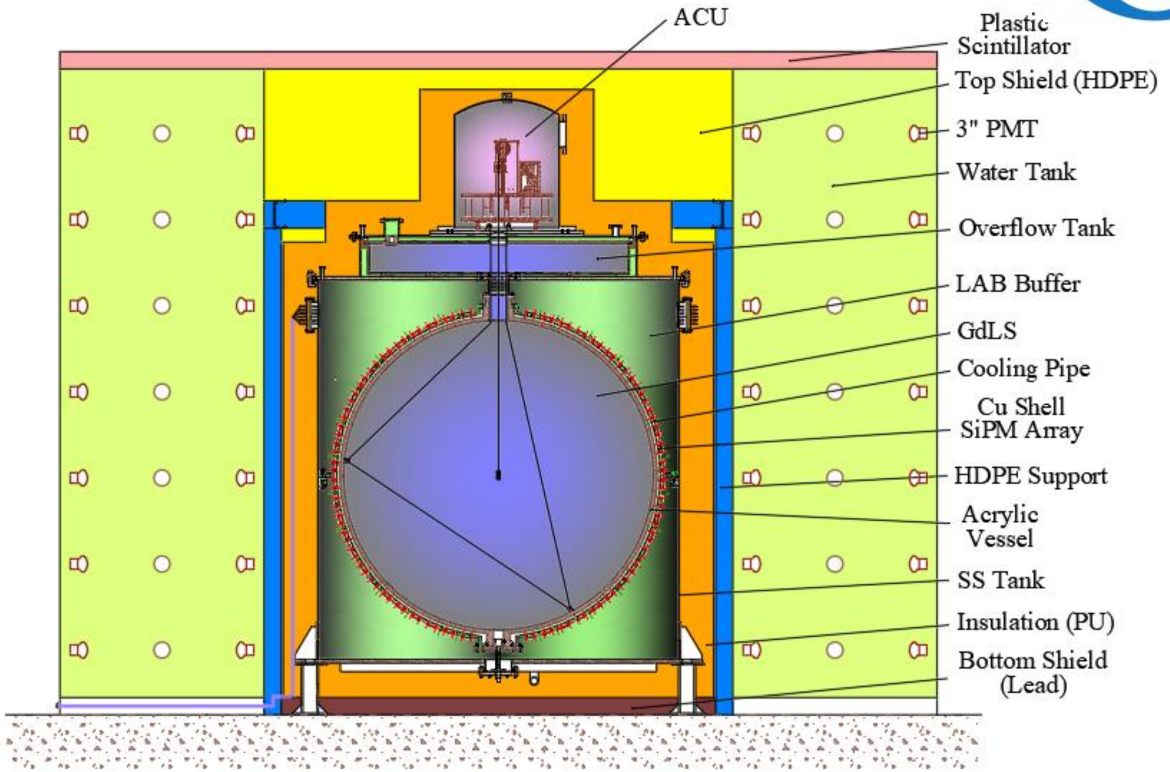
Constrain the fine structure in [2.5,6] MeV to < 1%



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

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 Level [PE/MeV]	4500
Energy resolution	< 2% @ 1 MeV



Surface not treated yet

- ✓ 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 will be built in summer at IHEP

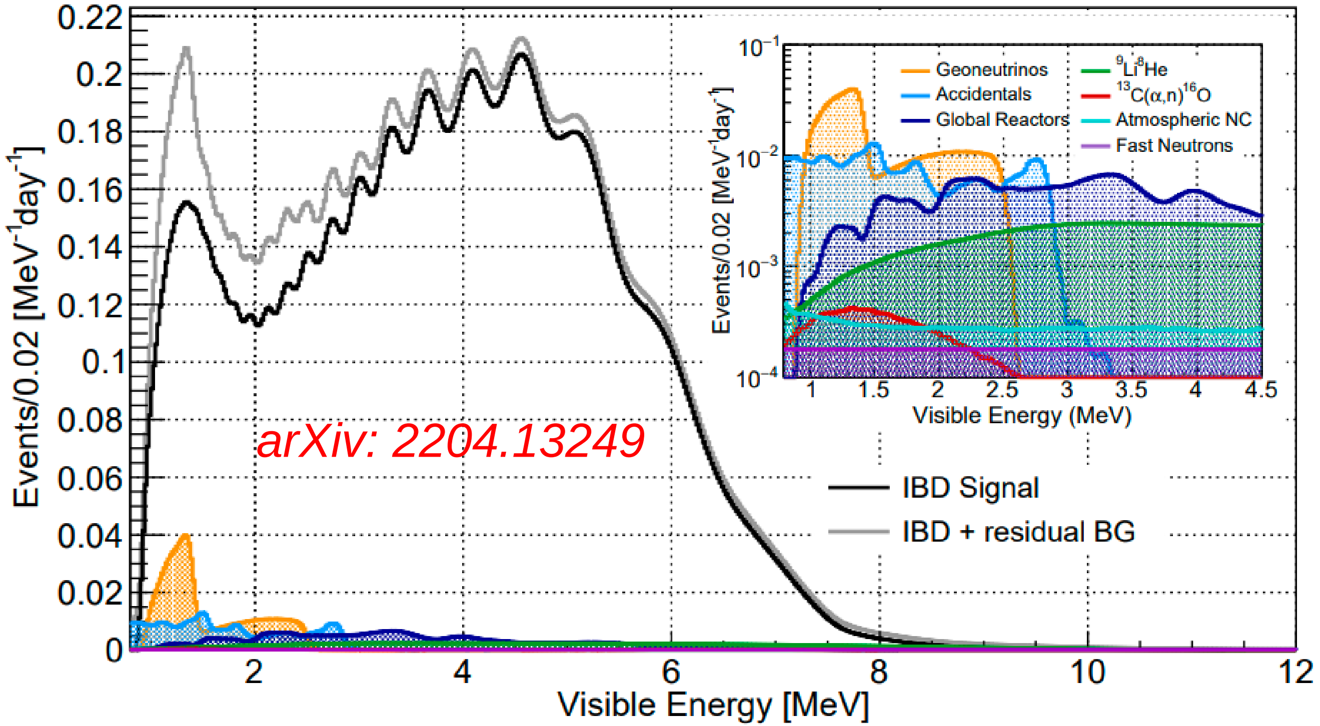
Updates on physics sensitivities

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

Reactor Antineutrino Oscillation & Detection

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

(matter effect contributes maximal ~4% correction at around 3 MeV, *arXiv:1605.00900, arXiv:1910.12900*)



Inverse beta decay reaction

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

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 → **this update**

J. Phys. G 43:030401 (2016)

Update of energy resolution

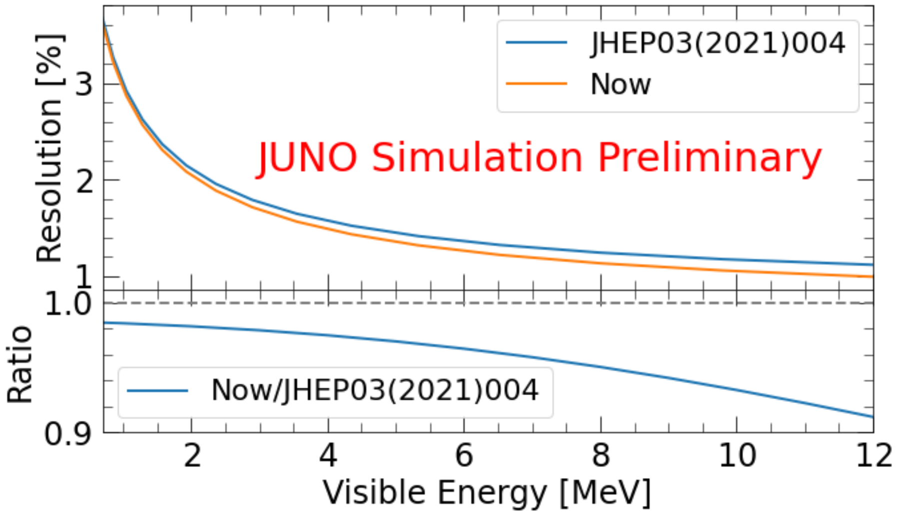
Change	Light yield in detector center [PEs/MeV]	Energy resolution	Reference
Previous estimation	1345	3.0% @1MeV	*JHEP03(2021)004*
Photon Detection Efficiency (27%→30%)	+11%↑	**2.9% @ 1MeV** (Poster #519)	arXiv: 2205.08629
New Central Detector Geometries	+3%↑		Poster #184
New PMT Optical Model	+8%↑		*EPJC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

Positron energy resolution is understood:

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

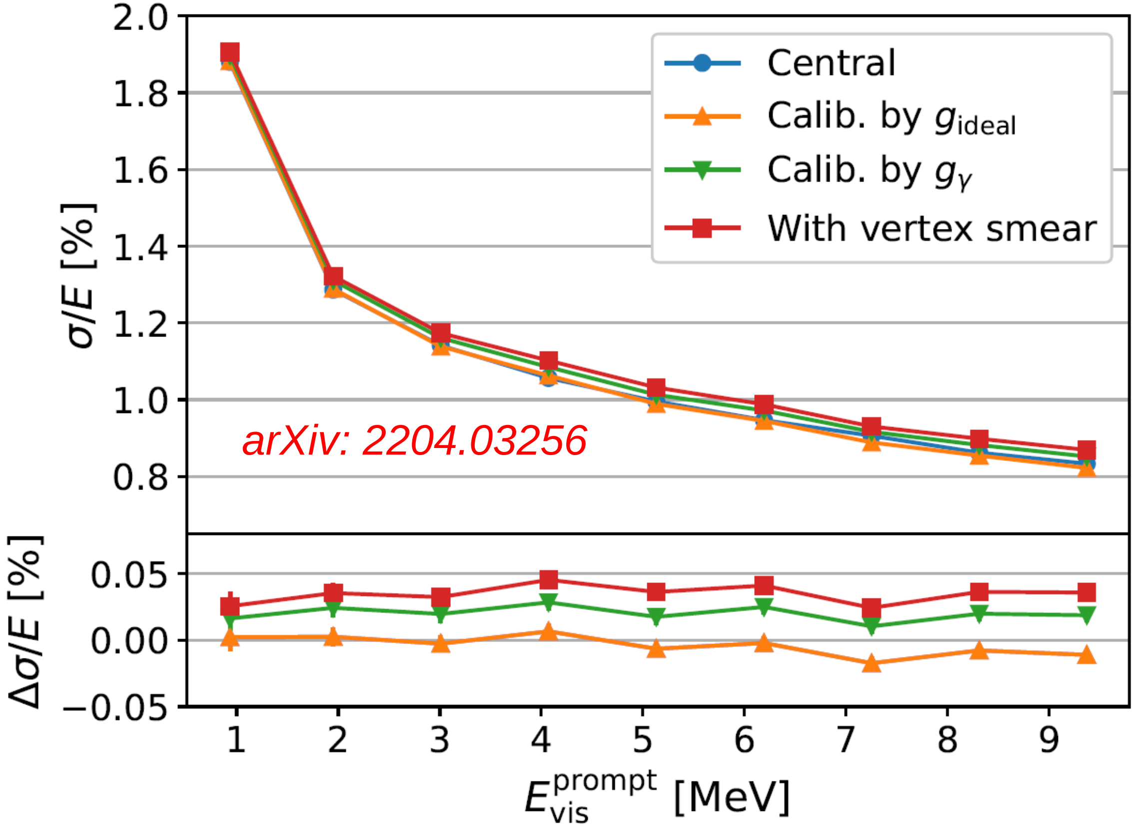
- **Photon statistics**
- **Scintillation quenching effect**
  - LS Birks constant from table-top measurements
- **Cherenkov radiation**
  - Cherenkov yield factor (refractive index & re-emission probability) is re-constrained with Daya Bay LS non-linearity
- **Detector uniformity and reconstruction**

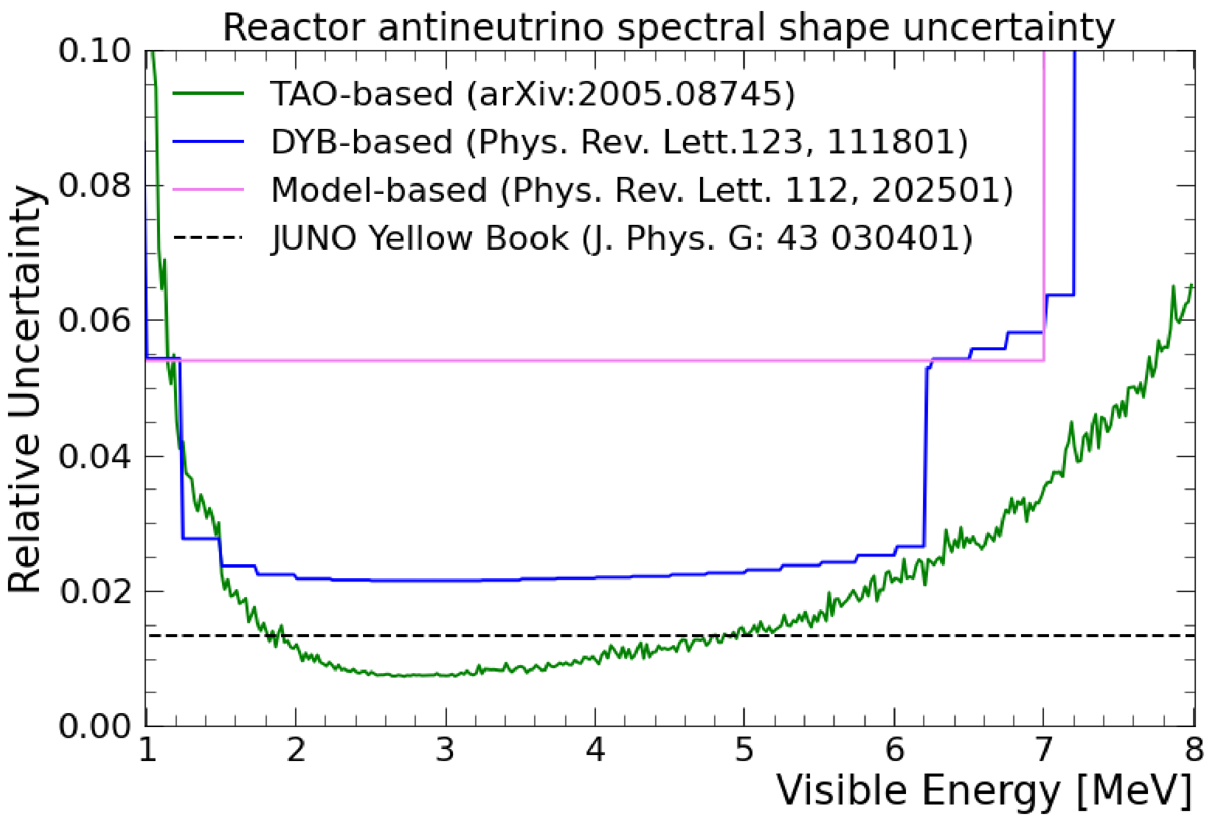
- **Annihilation-induced γs**
- **Dark noise**



Reactor Antineutrino Spectrum from TAO

Poster: #185



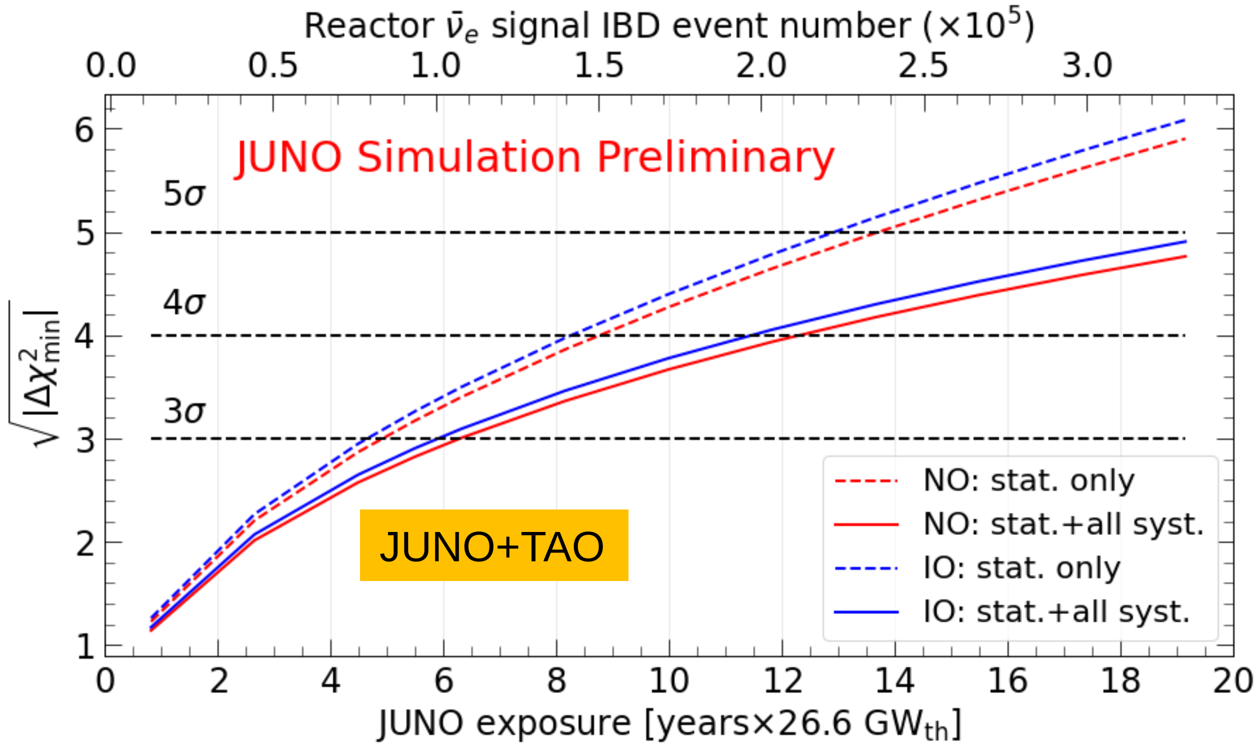


1. ~94% coverage of SiPM with ~50% PDE
2. Inner diameter of target: 1.8 m, absorption of scintillation very small
3. Gd-LS works at -50℃, increase the photon yield

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

Neutrino Mass Ordering

Poster: #185



	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**

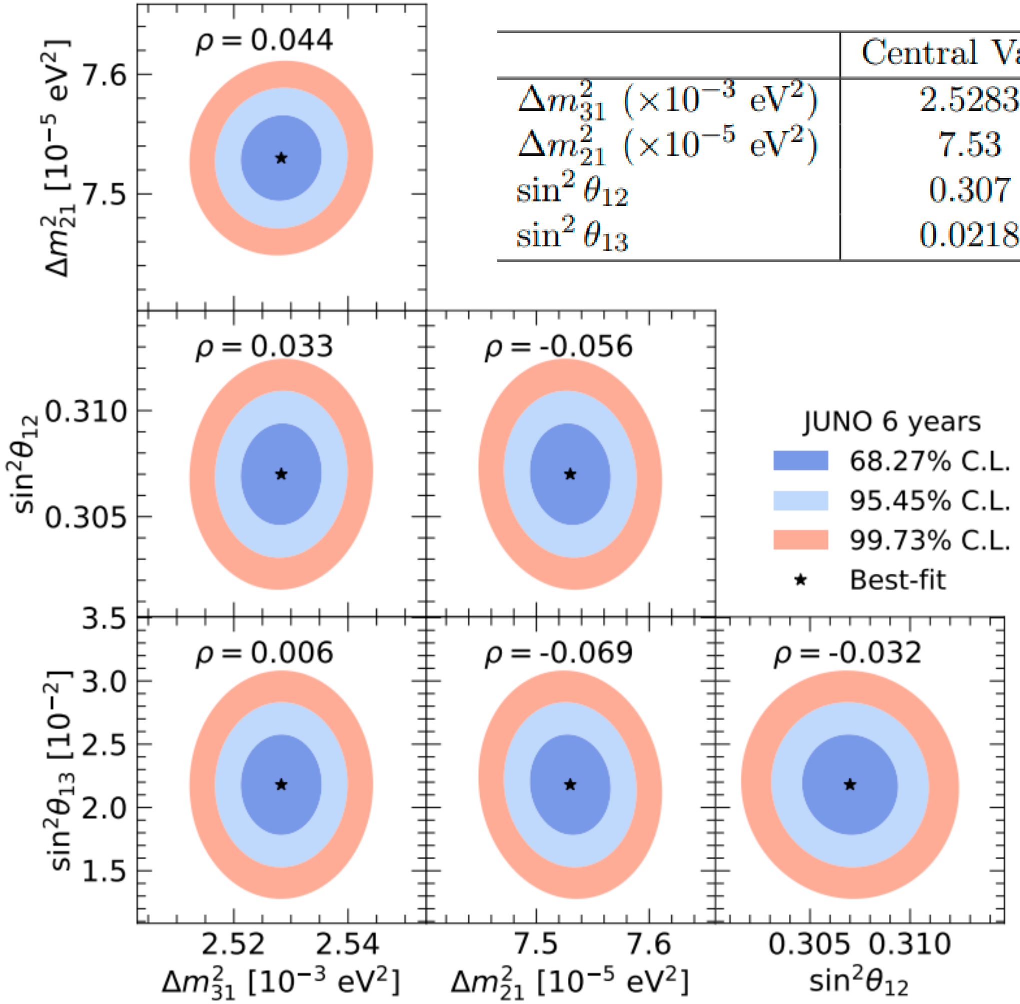
Estimation of NMO sensitivity with combined reactor + atmospheric neutrino analysis under preparation

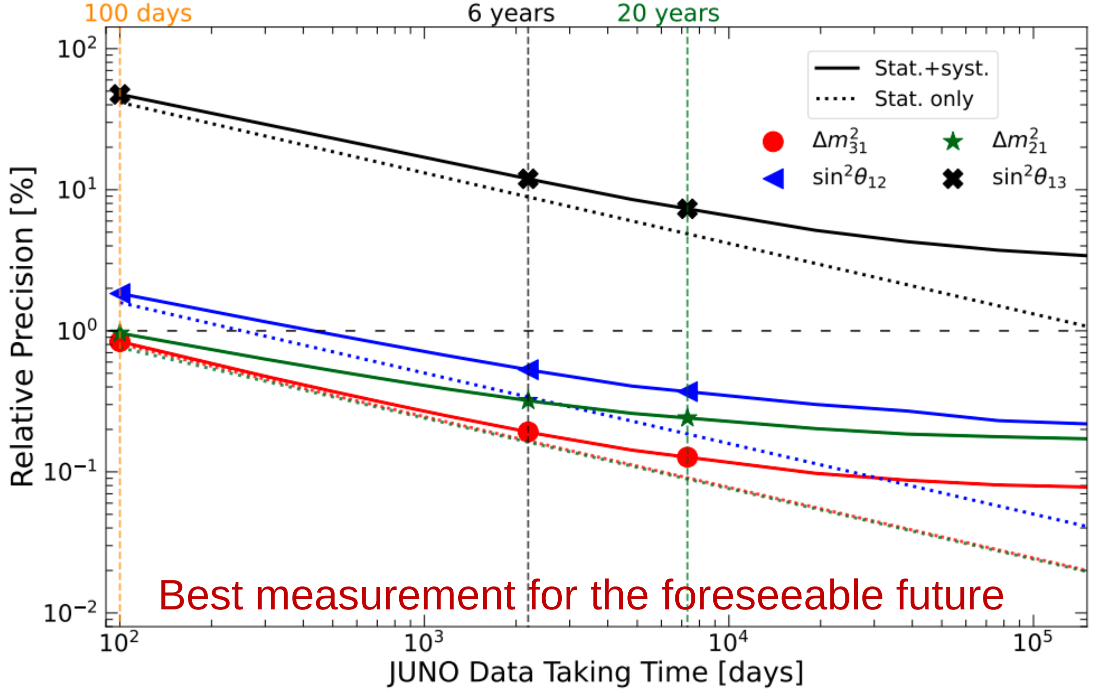
Neutrino oscillation parameters

arXiv: 2204.13249

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





Best measurement for the foreseeable future

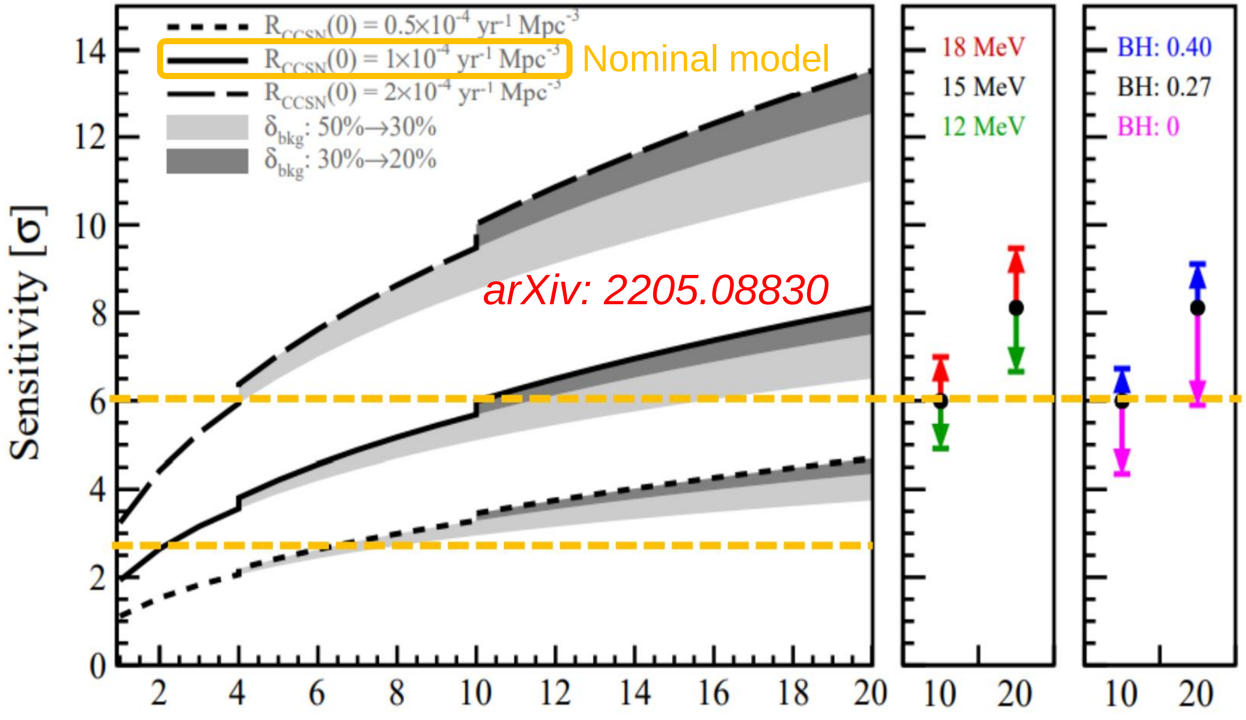
The improvement in precision over existing constraints will be about one order of magnitude

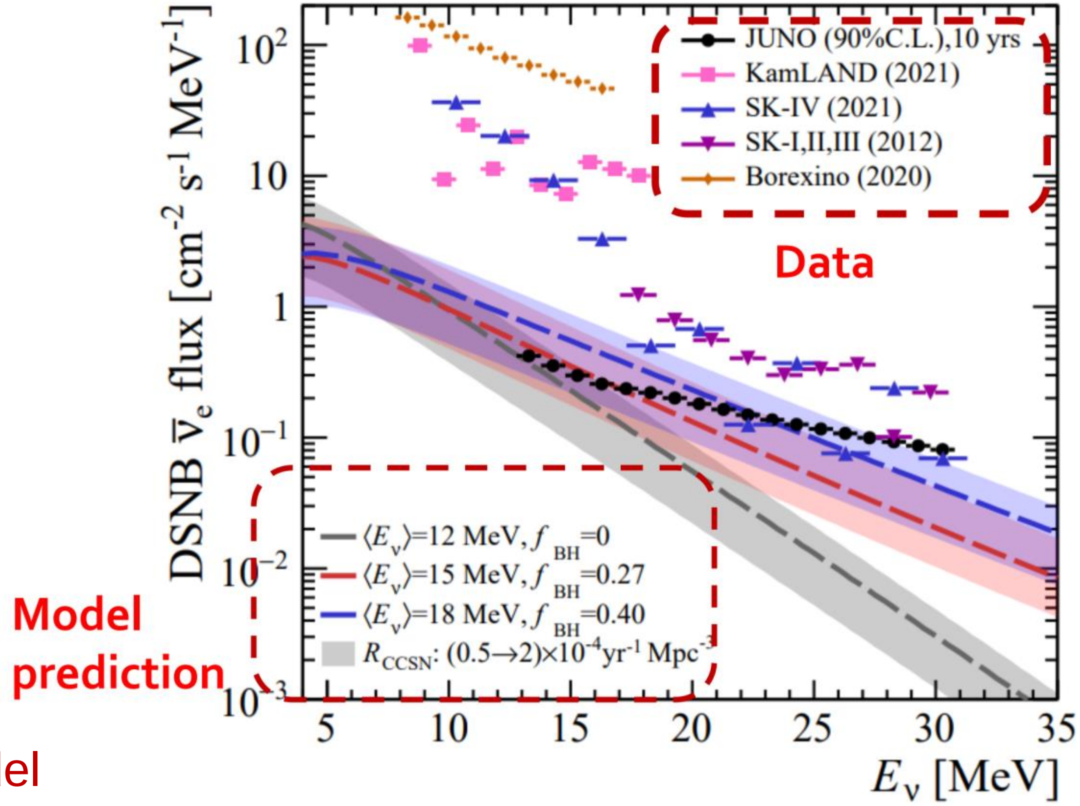
Diffuse Supernova Neutrino Background

Poster: #400

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





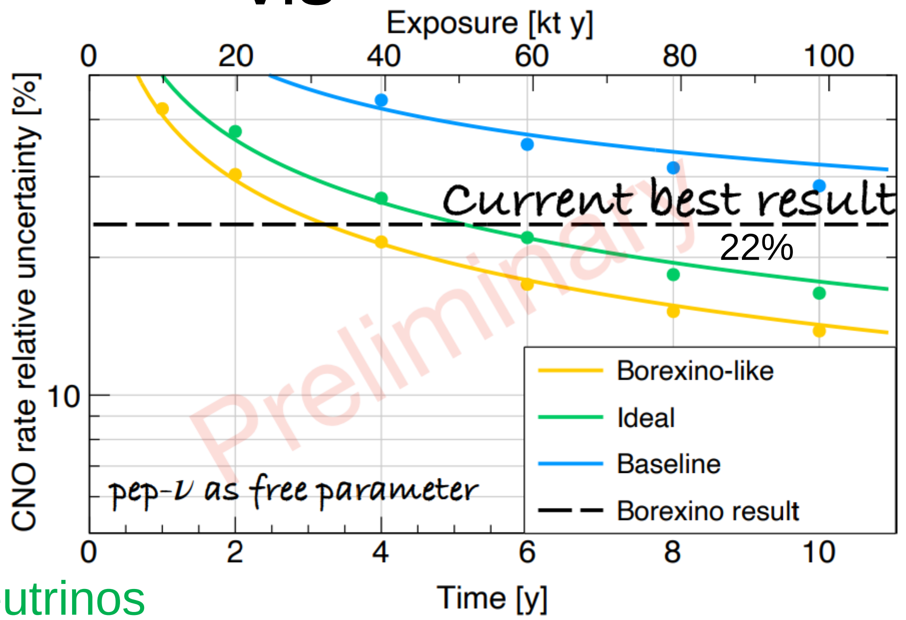
DSNB discovery potential: 3σ in 3 yrs with nominal model

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

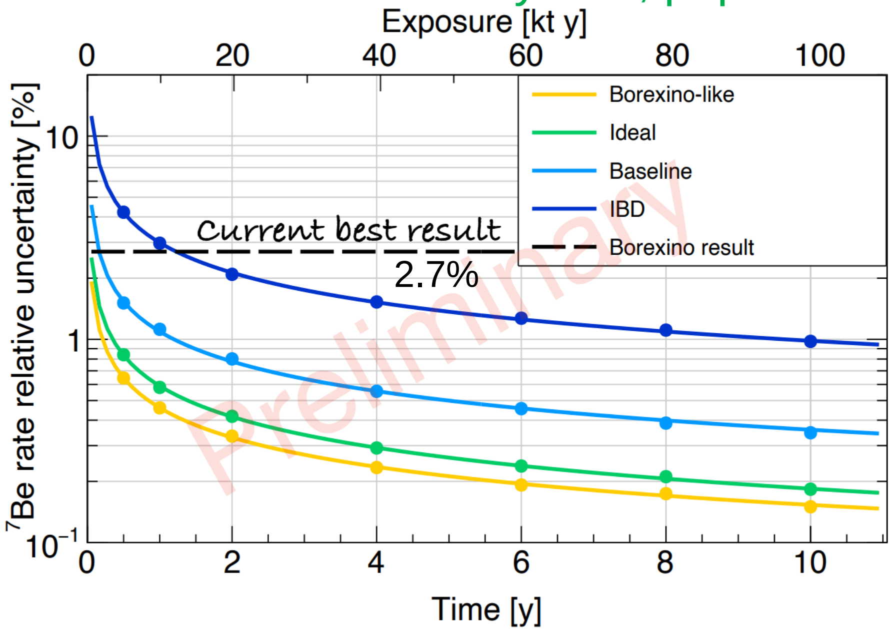
Poster: #327

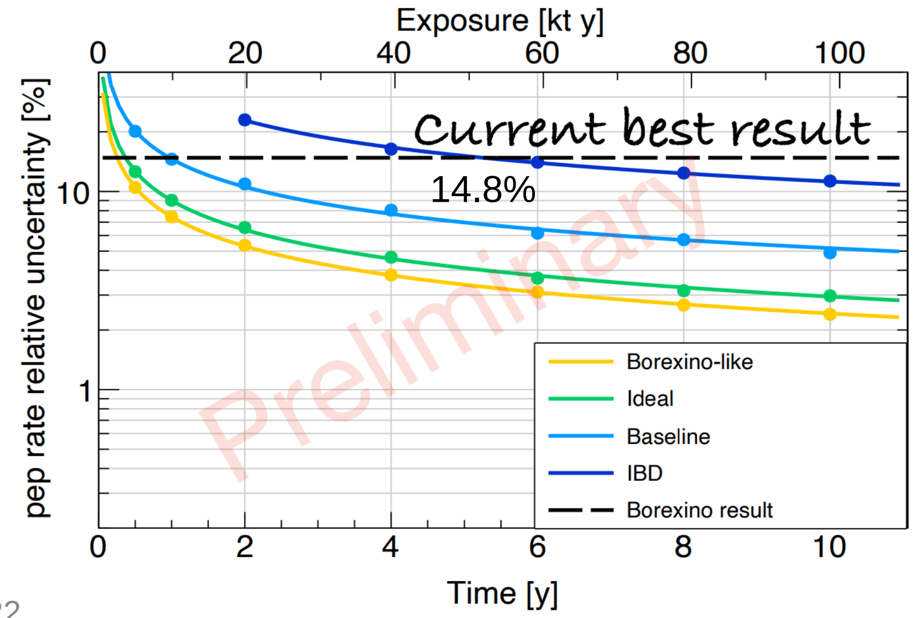
Radio-purity Scenario		^{40}K	^{85}Kr	^{232}Th-chain	^{238}U-chain	^{210}Pb/ ^{210}Bi	^{210}Po
IBD	c [g/g]	1×10^{-16}	-	1×10^{-15}	1×10^{-15}	5×10^{-23}	-
	R [cpd/kt]	2289	5000	3508	15047	12031	12211
Baseline	c [g/g]	1×10^{-17}	-	1×10^{-16}	1×10^{-16}	5×10^{-24}	-
	R [cpd/kt]	229	500	351	1505	1203	1221
Ideal	c [g/g]	1×10^{-18}	-	1×10^{-17}	1×10^{-17}	1×10^{-24}	-
	R [cpd/kt]	23	100	35	150	241	244
Borexino	c [g/g]	-	-	$<5.7 \times 10^{-19}$	$<9.4 \times 10^{-20}$	-	-
	R [cpd/kt]	4.2	100	1.4	2	115	446.9

NOTE: Contribution from pileup and reactor neutrinos found negligible in the ROI



Measure simultaneously Be7, pep and CNO solar neutrinos





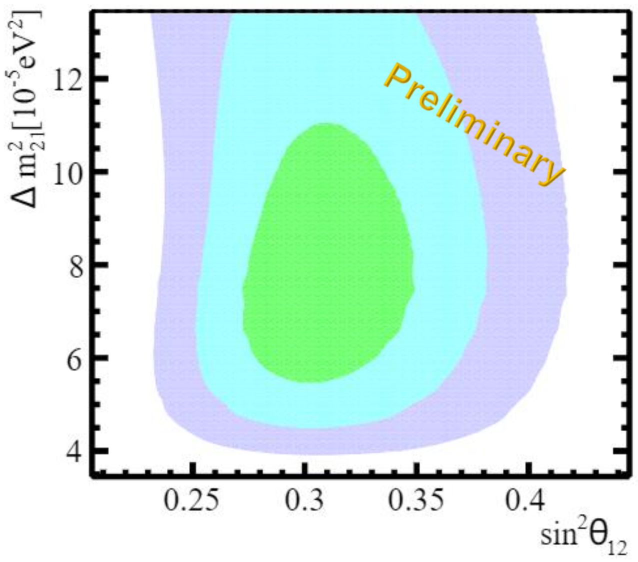
Neutrinos from Sun (E_{vis}>2MeV)

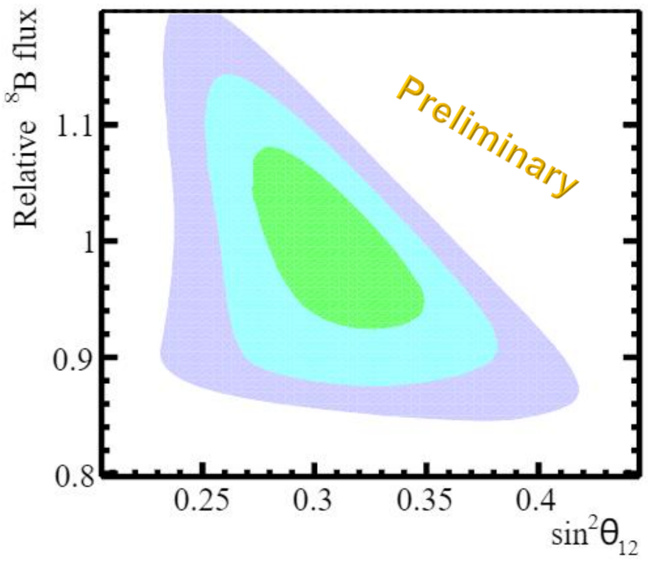
Poster: #290

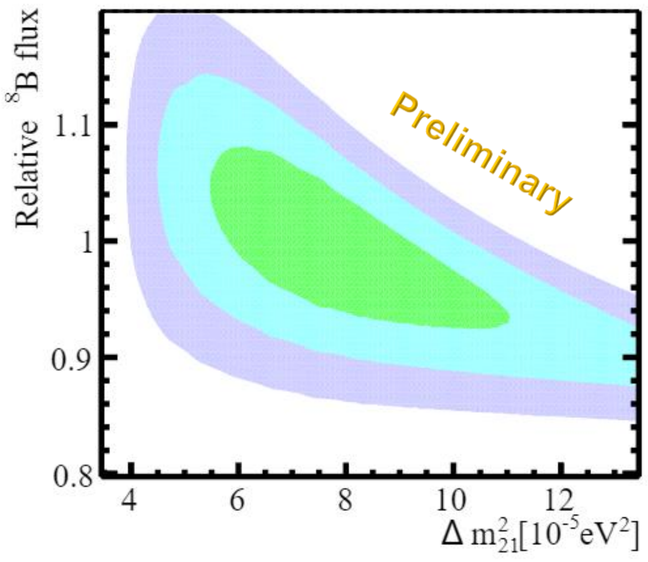
~0.2 kt ^{13}C in JUNO LS → enable observation of **B8 solar neutrino** CC and NC interactions on ^{13}C

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

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







Poster list

Veto

134. Radon background control of JUNO’s Veto Detector
365. Progress of the Top Tracker of the JUNO Experiment
347. The Water Cherenkov detector of the JUNO veto system

PMT

136. Instrumentation and acceptance test of 3-inch PMTs for JUNO
270. Design and performances of the front-end board for the 25,600 3-inch PMT array in the JUNO experiment”
218. Large-PMT electronics performance tests for the JUNO experiment
216. Mass testing of Large-PMT electronics at Kunshan for the JUNO experiment
575. [Neutrino 2022 Poster] Performance analysis of JUNO 20-inch potted PMTs with 1F3 electronics prototype
815. A New Optical Model for the 20-inch PMTs of JUNO

LS and OSIRIS

233. The Calibration of the OSIRIS Subdetector of JUNO
195. OSIRIS: The Online Scintillator Internal Radioactivity Investigation System of JUNO
265. Status of the JUNO liquid scintillator purification system

TAO

817. Status of JUNO Taishan Antineutrino Observatory
673. Search for Sterile Neutrinos with JUNO-TAO
363. WLS+SiPM Plastic Scintillators for JUNO-TAO Muon Veto System
226. Multipurpose UV LED Calibration System for the JUNO-TAO Detector

Calibration

293. Detector calibration in the JUNO experiment
360. Dual Calorimetry in the JUNO experiment

Central detector

184. The Central Detector of JUNO

Poster list

Supernova neutrinos

400. Prospects for Detecting the Diffuse Supernova Neutrino Background in JUNO

814. Pulse Shape Discrimination for Diffuse Supernova Neutrino Background Search at JUNO

288. CCSN detection and spectra reconstruction with the large PMTs of JUNO

631. Core-collapse supernova physics with neutrino time dependent studies using the multi-messenger trigger in JUNO

Solar neutrinos

327. Solar neutrino physics with JUNO: analysis strategy and sensitivity studies for Be7, pep, and CNO neutrinos

290. Model independent measurement of 8B solar neutrino flux in JUNO

Atmospheric neutrinos

379. Atmospheric neutrino neutral current background at JUNO from reactor neutrinos to diffuse supernova neutrino background

305. Atmospheric neutrino physics in JUNO: reconstruction of GeV interaction

356. Particle identification of atmospheric neutrinos in JUNO

Proton decay

124. Simulation Study of Searching for Proton Decay in JUNO

Oscillation physics

167. Possible Implications of the Fine structure in the Reactor Neutrino Spectrum on JUNO's Neutrino Mass Ordering Sensitivity

545. Precision Measurement of Neutrino Oscillation Parameters in JUNO

185. JUNO Neutrino Mass Ordering Sensitivity

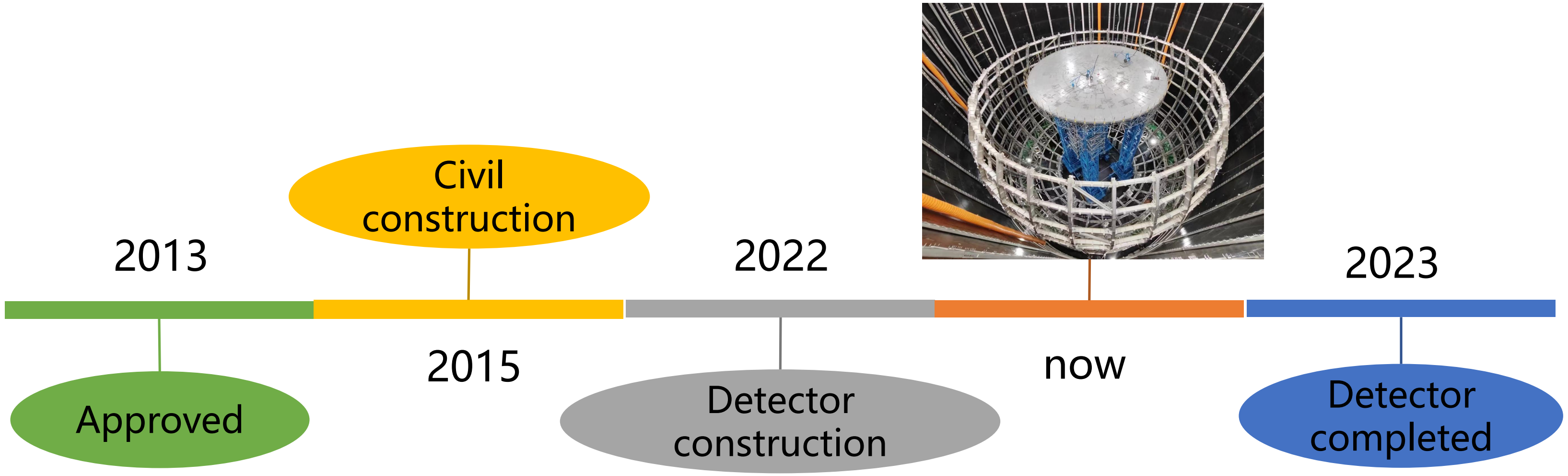
Miscellaneous

818. Radioactivity background and its impact on the neutrino physics in JUNO

303. Maximizing the Astrophysical Potentials of JUNO with the Multi-messenger Trigger System

Outlook

Physics	Sensitivity
Neutrino Mass Ordering	3σ (~1σ) in 6 yrs by reactor (atmospheric) $\bar{\nu}_e$
Neutrino Oscillation Parameters	Precision of $\sin^2\theta_{12}$, Δm^2_{21}, $\lvert\Delta m^2_{32}\rvert$ < 0.5% in 6 yrs
Supernova Burst (10 kpc)	~5000 IBD, ~300 eES and ~2000 pES of all-flavor neutrinos
DSNB	3σ in 3 yrs
Solar neutrino	Measure Be7, pep, CNO simultaneously, measure B8 flux independently
Nucleon decays ($p \to \bar{\nu}K^+$)	8.3×10^{33} years (90% C.L.) in 10 yrs
Geo-neutrino	~400 per year, 5% measurement in 10 yrs

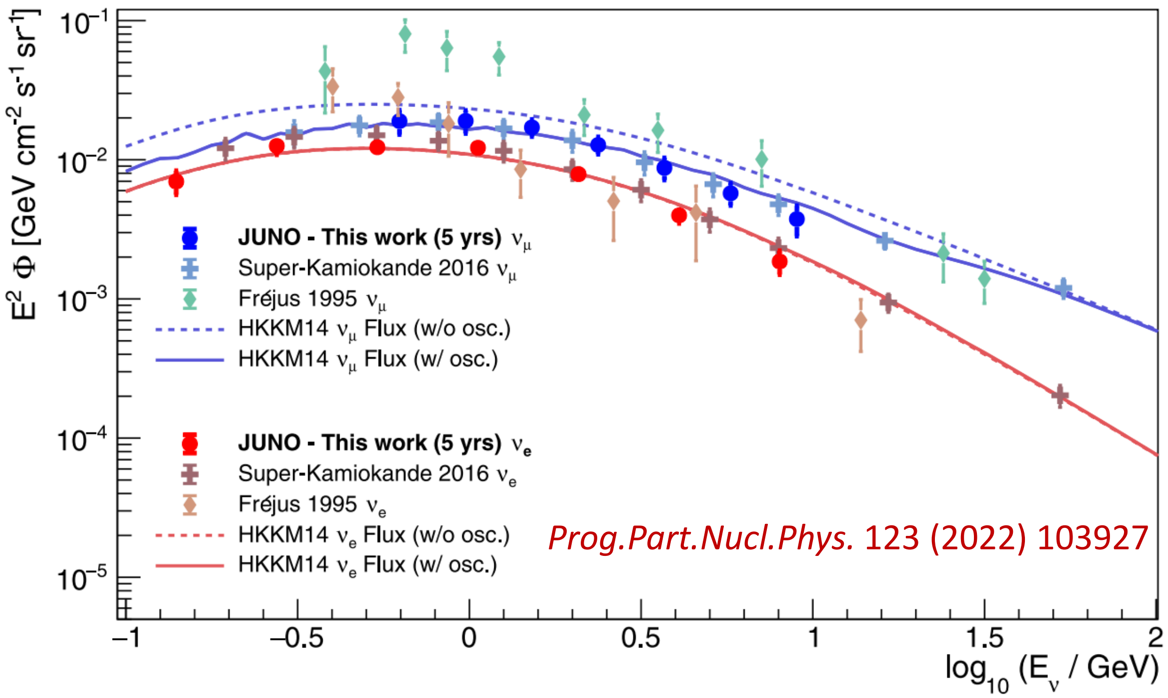


Back up

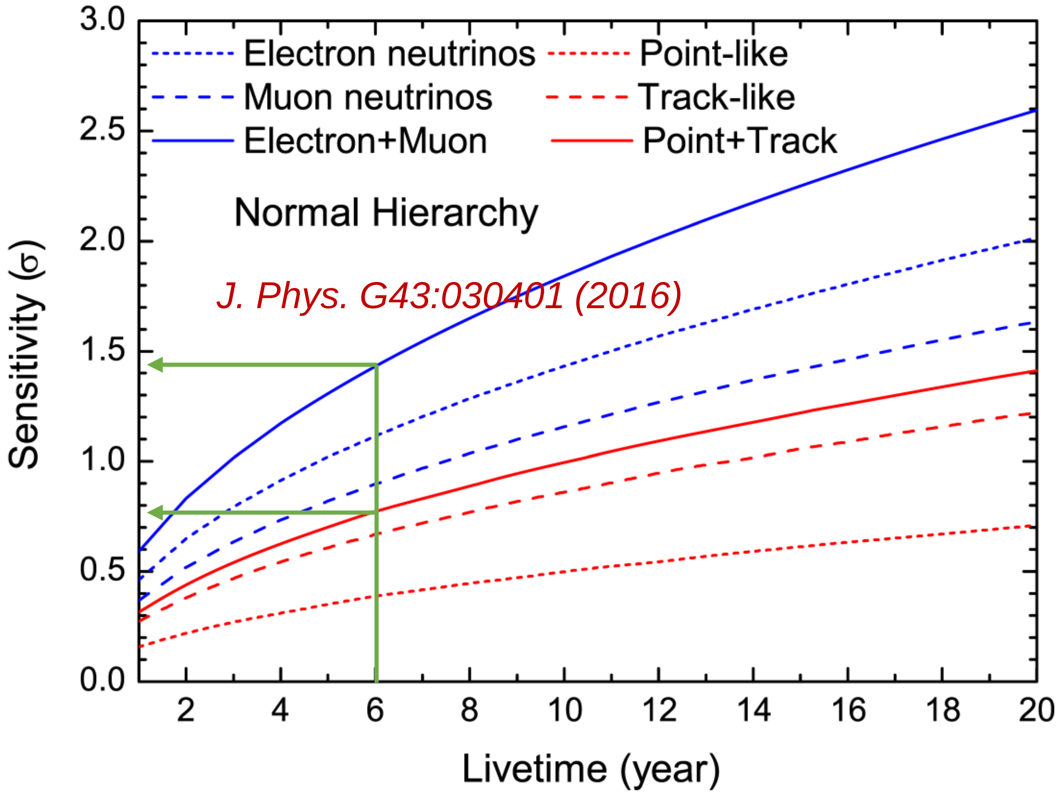
Atmospheric neutrino

MSW effect → Neutrino Mass Ordering (NMO) → Independent measurement from reactor antineutrino

Critical techniques: energy and angular resolutions, flavor identifications



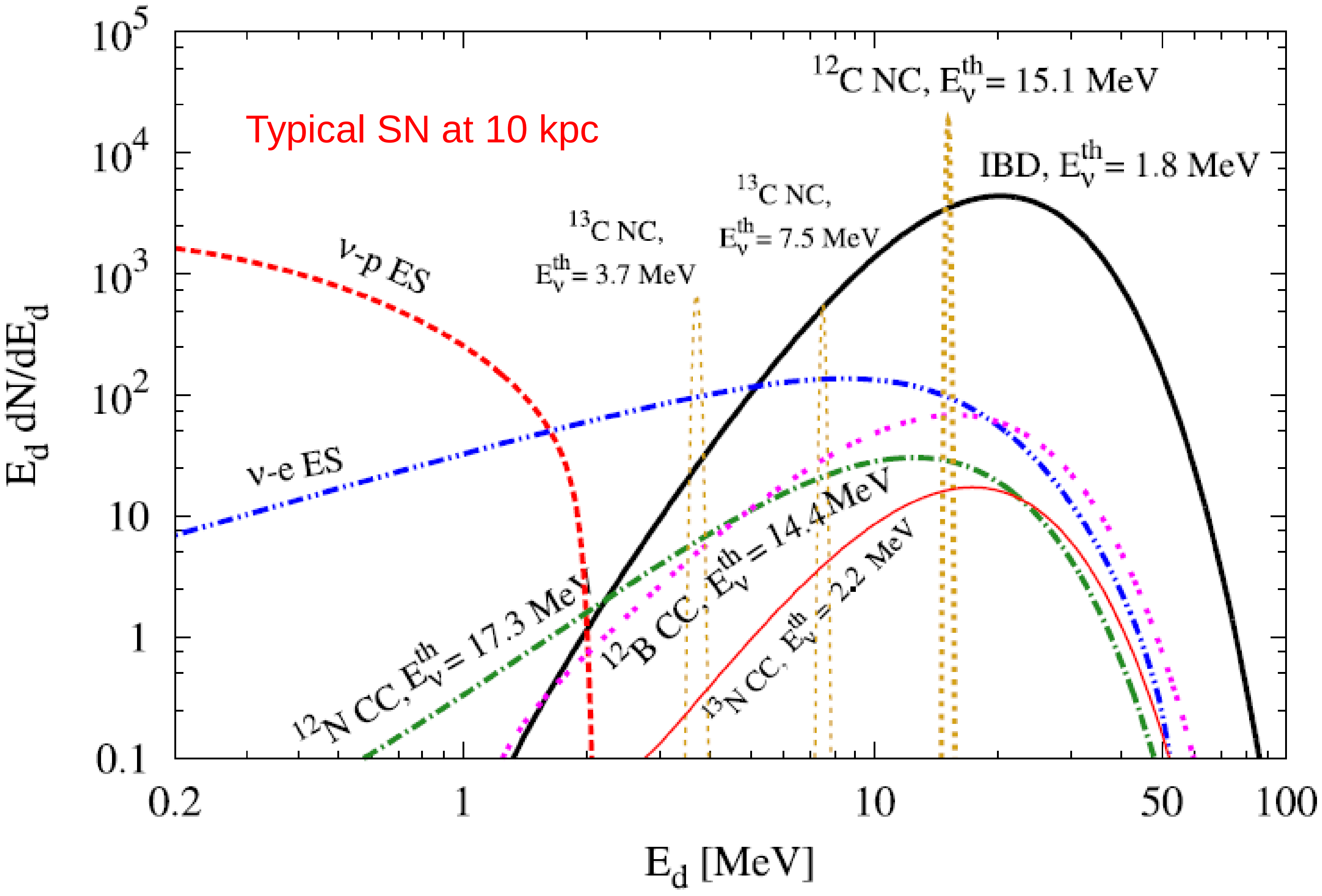
ν_e/ν_μ discrimination thanks to PMT hit pattern



JUNO sensitivity on NMO: **0.7~1.4 σ (atmospheric only) @ ~6 yrs exposure**

Combined analysis of reactor antineutrino and atmospheric neutrinos on NMO are in progress.

Neutrinos from Supernova

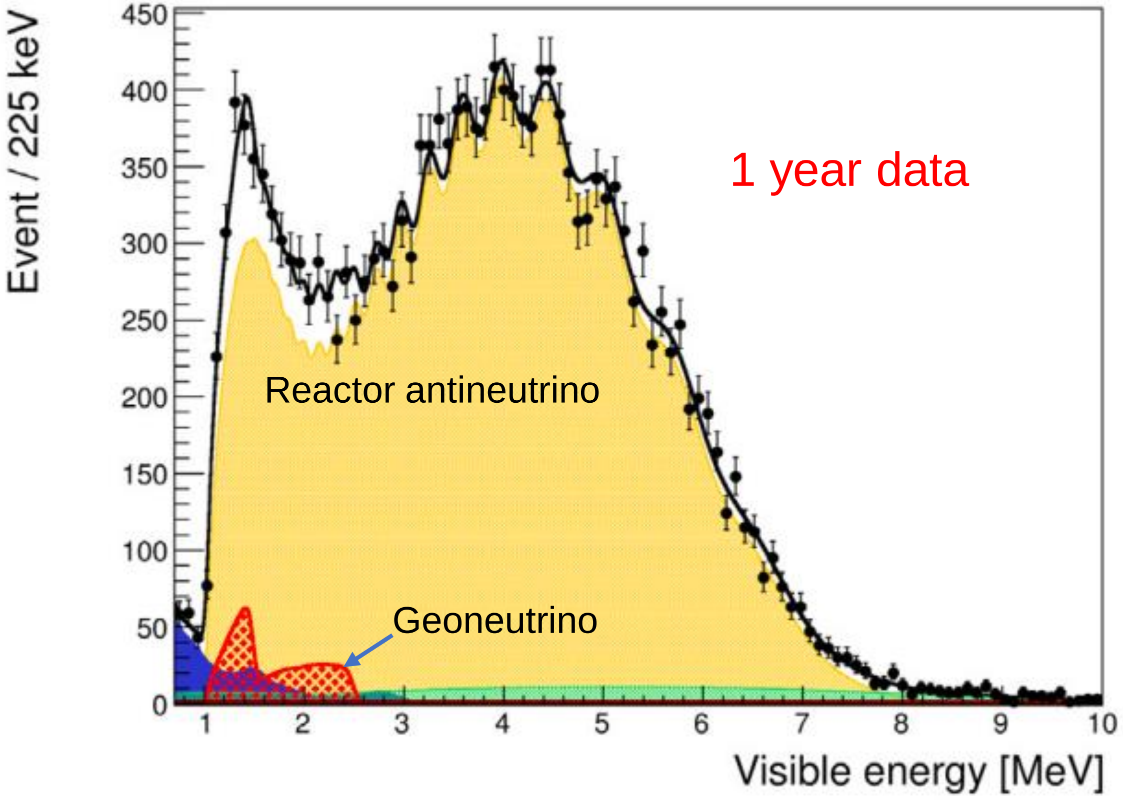


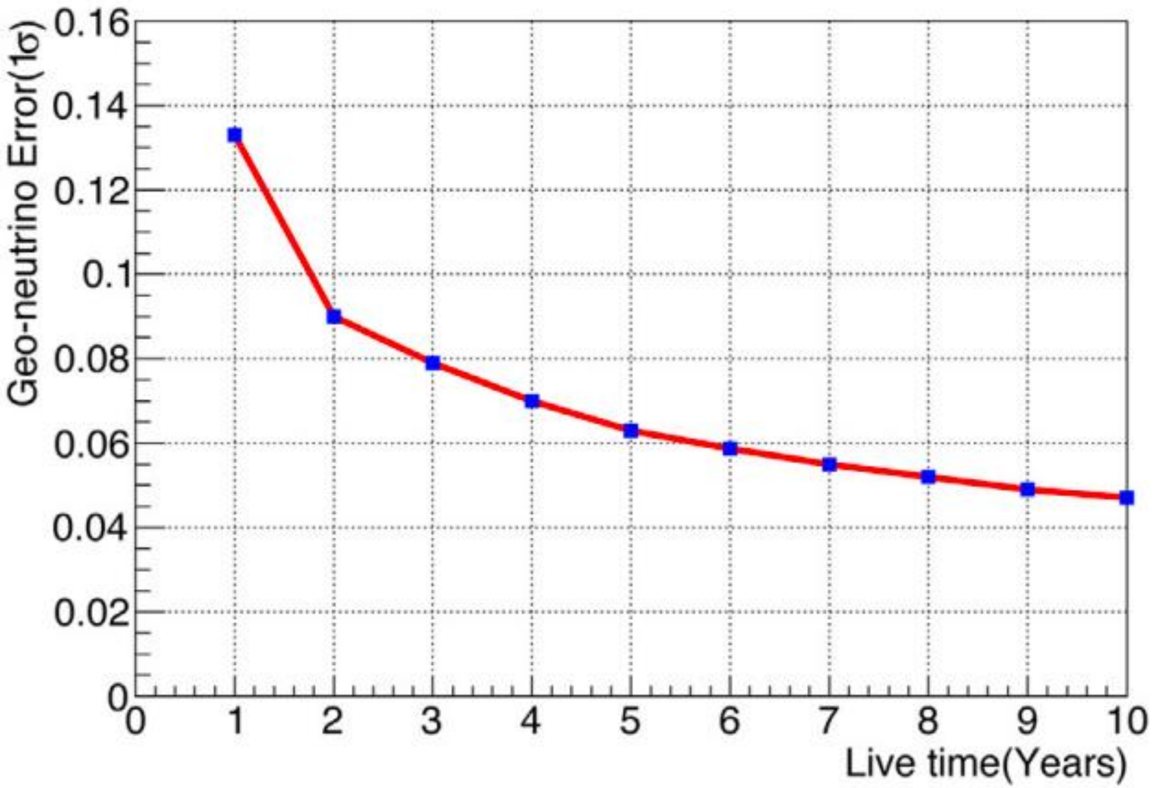
Detect all flavors of the $\mathcal{O}$(10 MeV):

~5000 IBD, ~300 eES, ~2000 pES, ~200 ^{12}C CC, ~300 ^{12}C NC

Neutrinos from earth

$\bar{\nu}_e$ from ^{238}U and ^{232}Th decay chains in earth





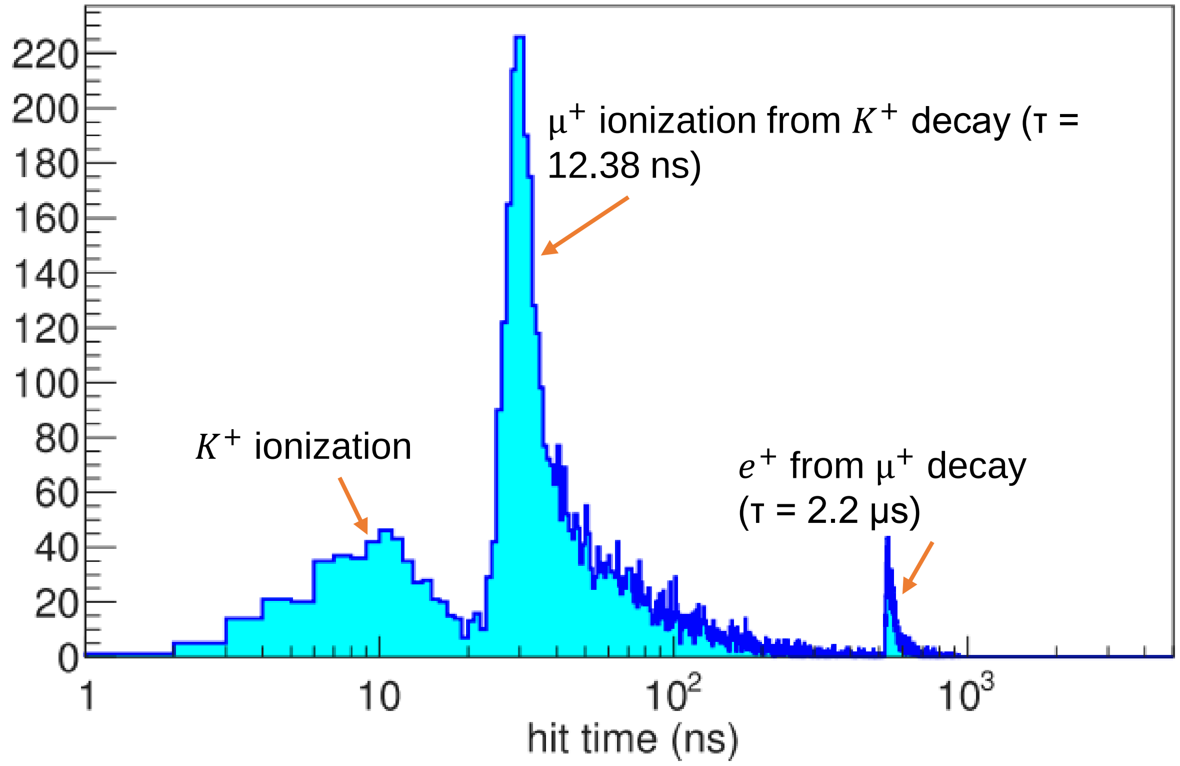
Signal in JUNO: 39.7 +6.5 −5.2 TNU (~400 geoneutrinos per year), 5% measurement in 10 years.

JUNO can observe as much geo-ν as Borexino and KamLAND for the whole time combined in 1 yr.

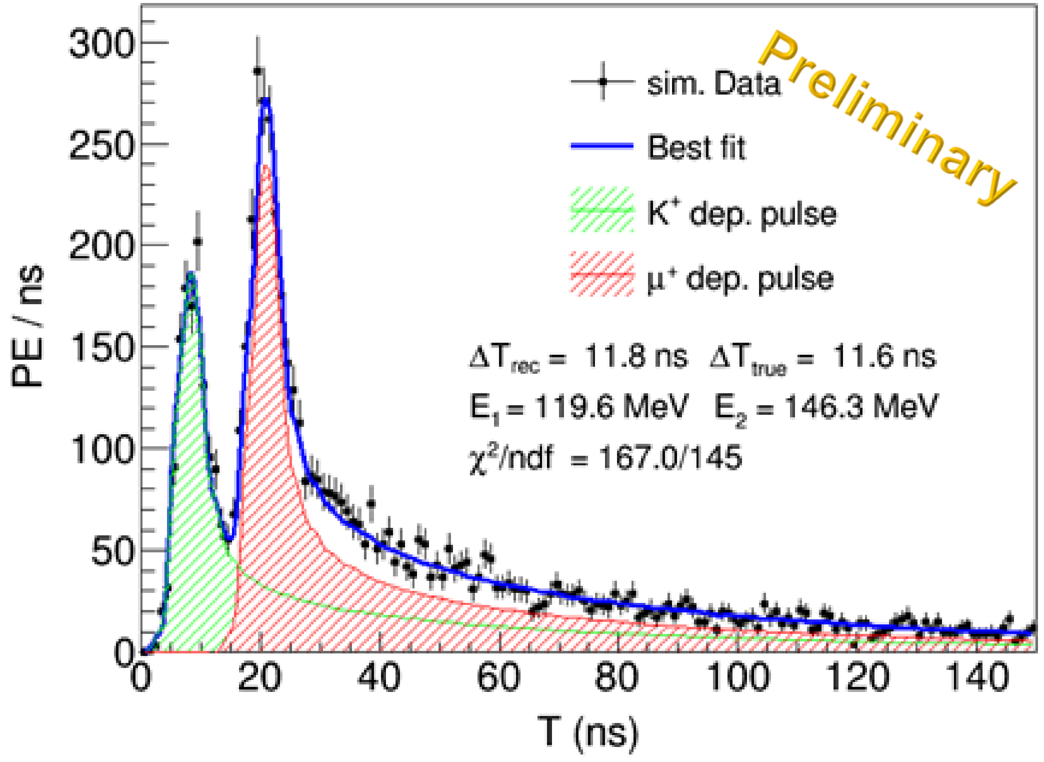
Nucleon decays

$p \to \bar{\nu} K^+$ Signature: three-fold time coincidence

Time-of-flight-corrected Hit time



Disentangle pile-up of signals with 3-inch PMTs



Expect sensitivity: 8.3×10^{33} years (90% C.L.) for 10 years