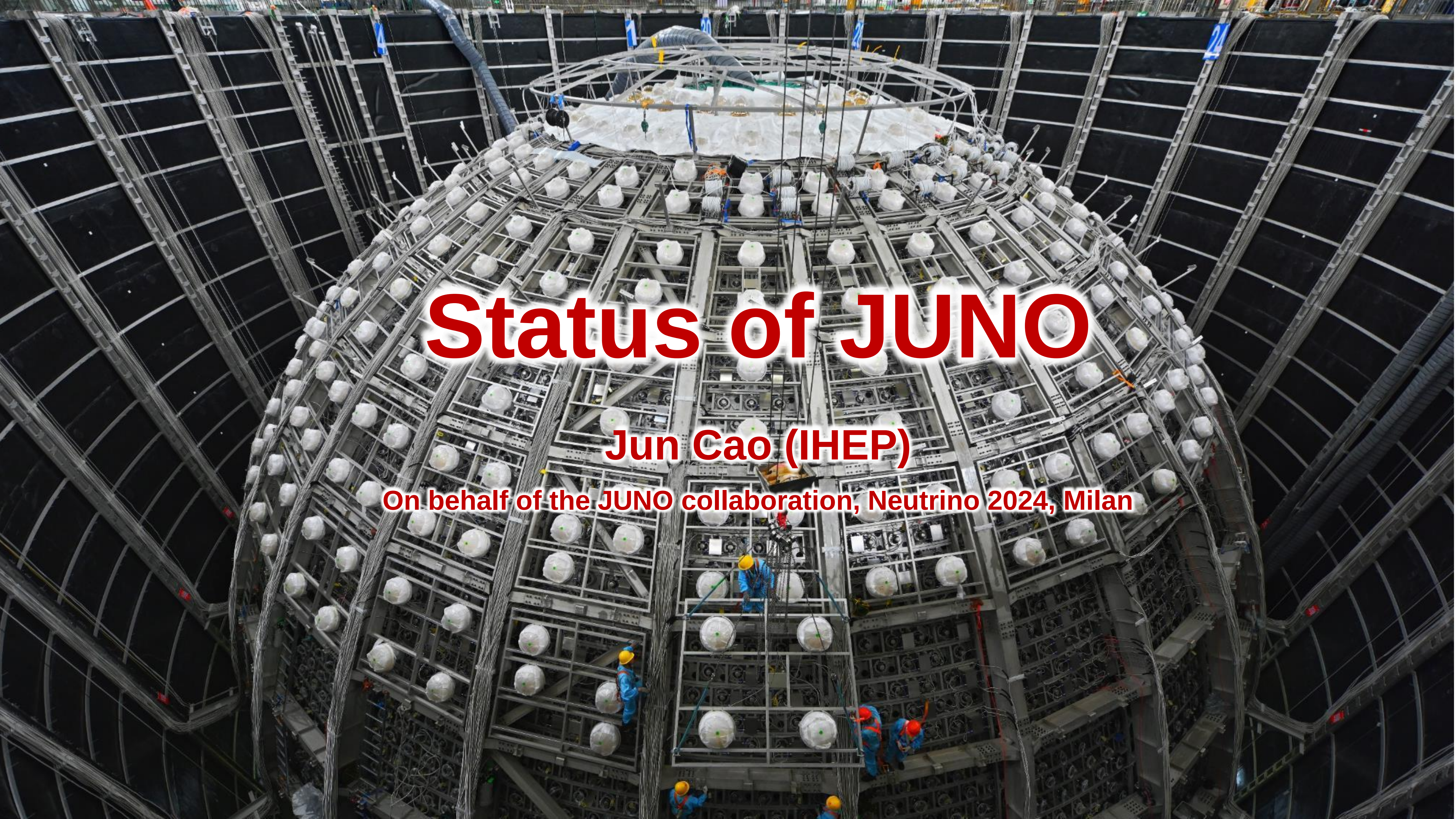


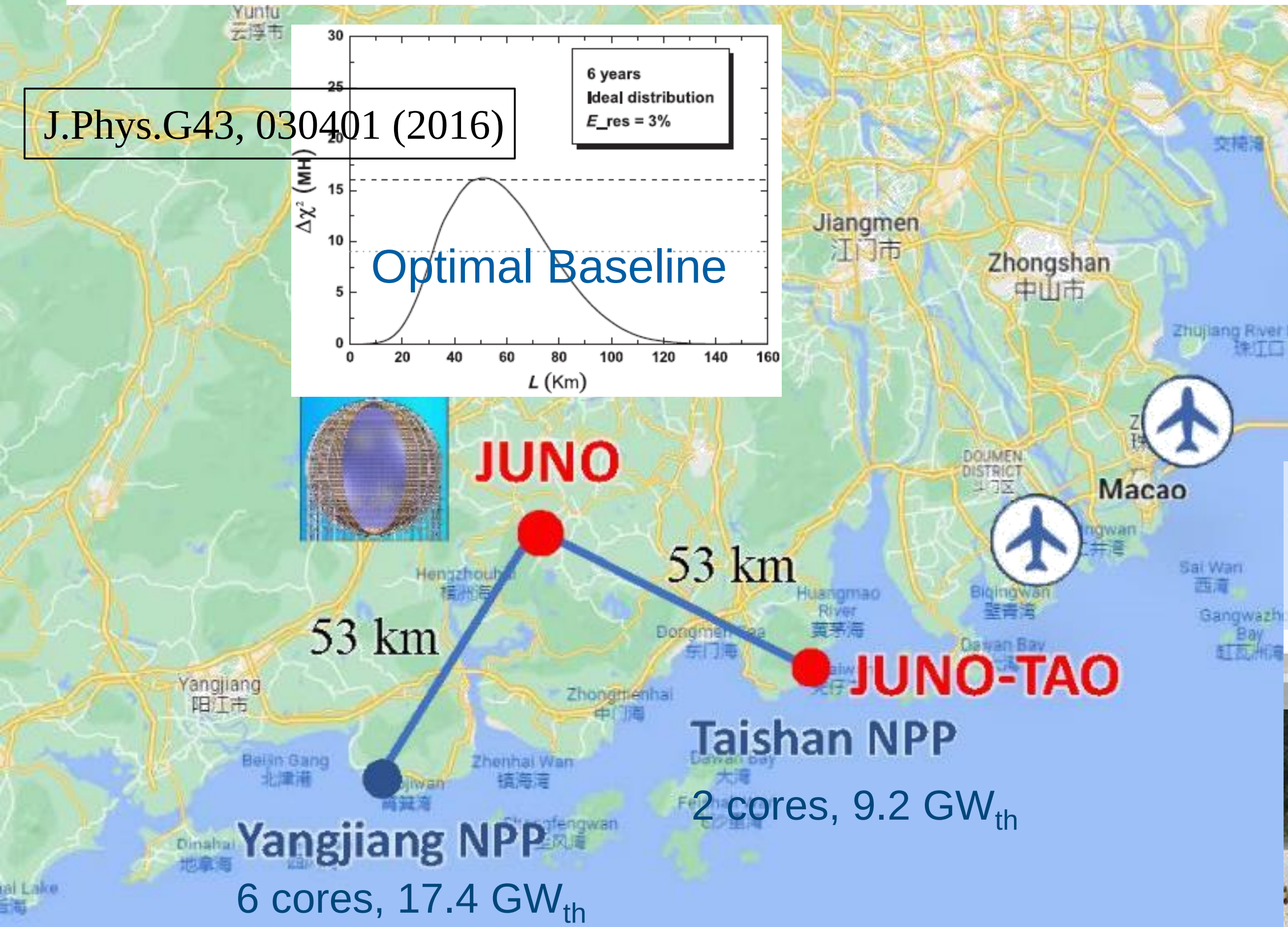
Status of JUNO

Jun Cao (IHEP)

On behalf of the JUNO collaboration, Neutrino 2024, Milan

Jiangmen Underground Neutrino Observatory (JUNO)

- **Proposed as a reactor neutrino experiment for mass ordering in 2008** (PRD78:111103,2008; PRD79:073007,2009)
  - ⇨ **driving the design specifications: location, 20 kton LS, 3% energy resolution, 700 m underground**
- **Rich physics program in solar, supernova, atmospheric, geo-neutrinos, proton decay, exotic searches**
- **Approved in 2013. Construction in 2015-2024**



74 institutions, >700 collaborators

Asia: China (34), Taiwan,China (3) Thailand (3), Pakistan, Armenia
Europe: Italy (8), Germany (7), France (5), Russia (3), Belgium, Czech, Finland, Latvia, Slovakia, UK
America: Brazil (2), Chile (2), USA (2)

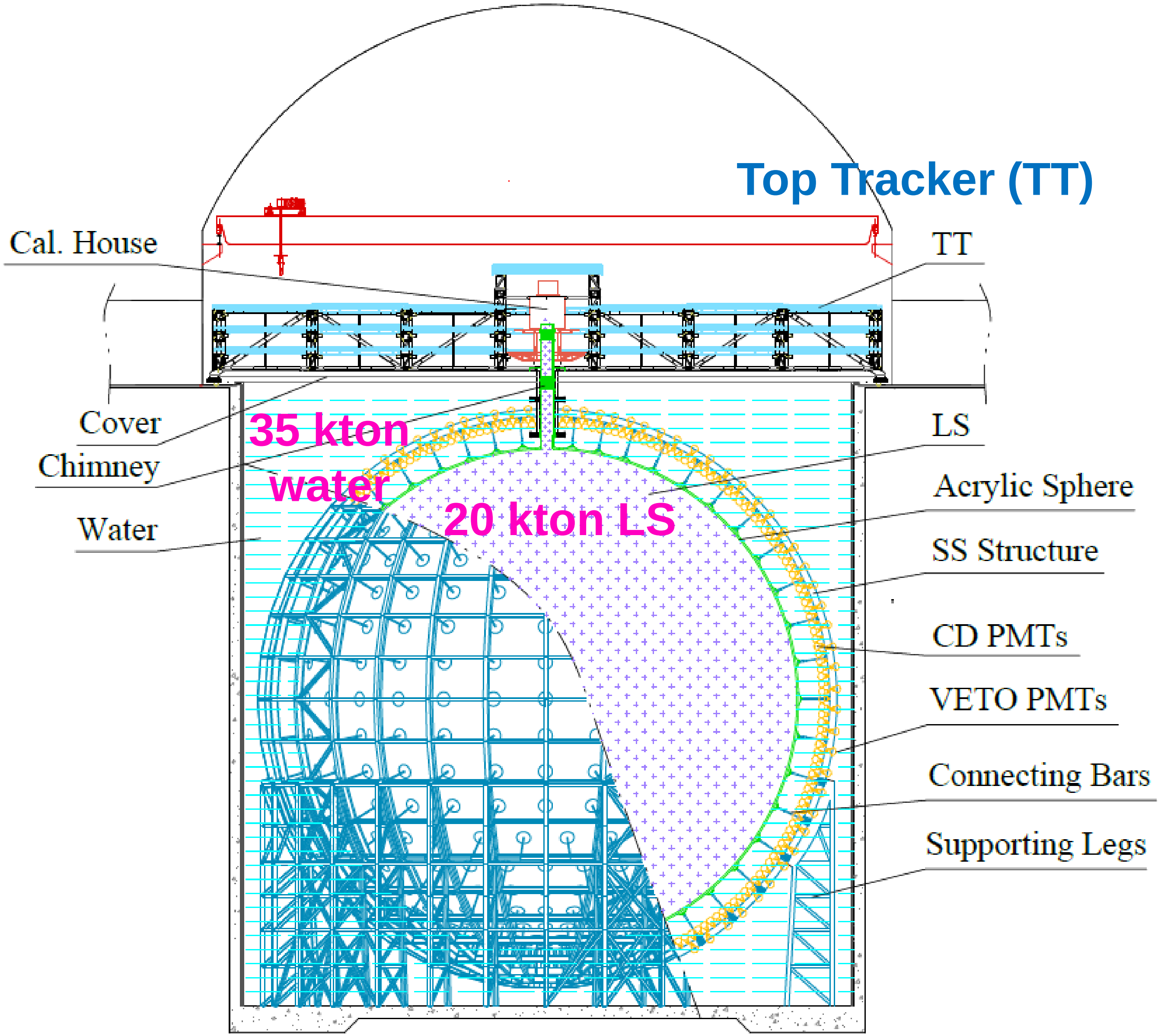
JUNO Site

Surface buildings / campus

- **Office / Dorm**
- Surface Assembly Building
- LAB storage (5 kton)
- Water purification / Nitrogen
- Computing
- Power station
- Cable train

~200 people working onsite now

JUNO Detector



Acrylic Sphere:

Inner Diameter (ID): 35.4 m

Thickness:12 cm

Stainless Steel (SS) Structure:

ID: 40.1 m, Outer Diameter (OD): 41.1 m

17612 20-inch PMTs, 25600 3-inch PMTs

Water pool:

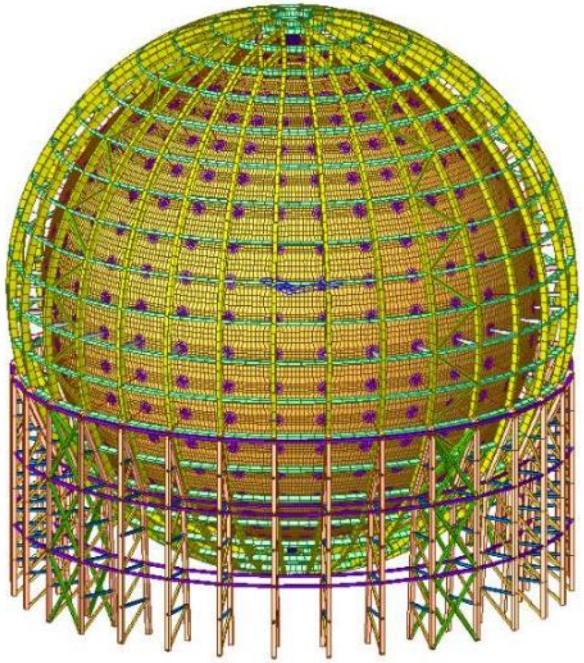
ID: 43.5 m, Height: 44 m, Depth: 43.5 m

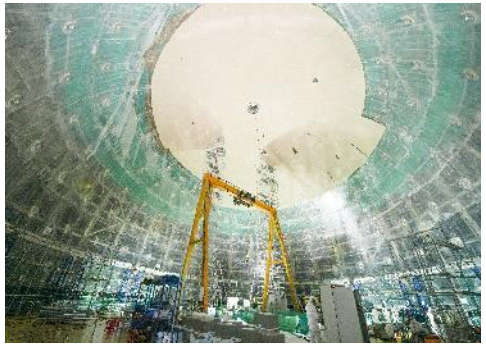
2400 20-inch PMTs

Central Detector

arXiv: 2311.17314 (2023)

- **35.4 m spherical acrylic vessel, containing 20 kton LS, supported by the 41.1 m Stainless Steel structure via 590 supporting bars**
- **SS structure completed except bottom 4 layers**
- **Acrylic panel production completed**
  - ⇨ A special production line for low backgrounds (< 1 ppt U/Th/K)
  - ⇨ Processed while maintaining **high transparency** (>96%) and **low surface background** (<5 ppt U/Th in 50 μm thickness): Shaping, sanding/polishing, cleaning, machining, and protection of panels by PE film
- **Acrylic vessel construction on-going (critical path)**
  - ⇨ SS structure built from bottom to top, then, acrylic built from the top to bottom, layer by layer, **17/23 layers finished**, defects repaired
  - ⇨ SS bars connecting the acrylic and SS, sensors for stress monitoring





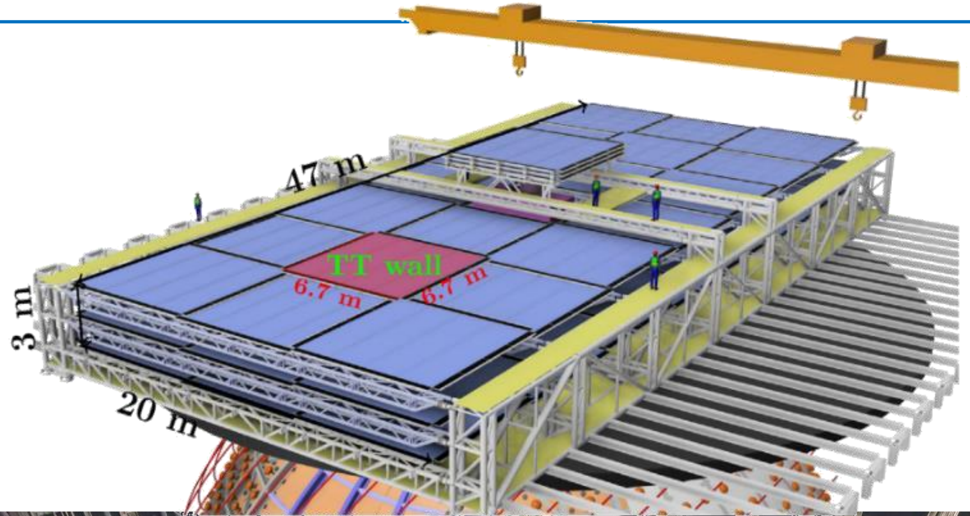
Inside the detector

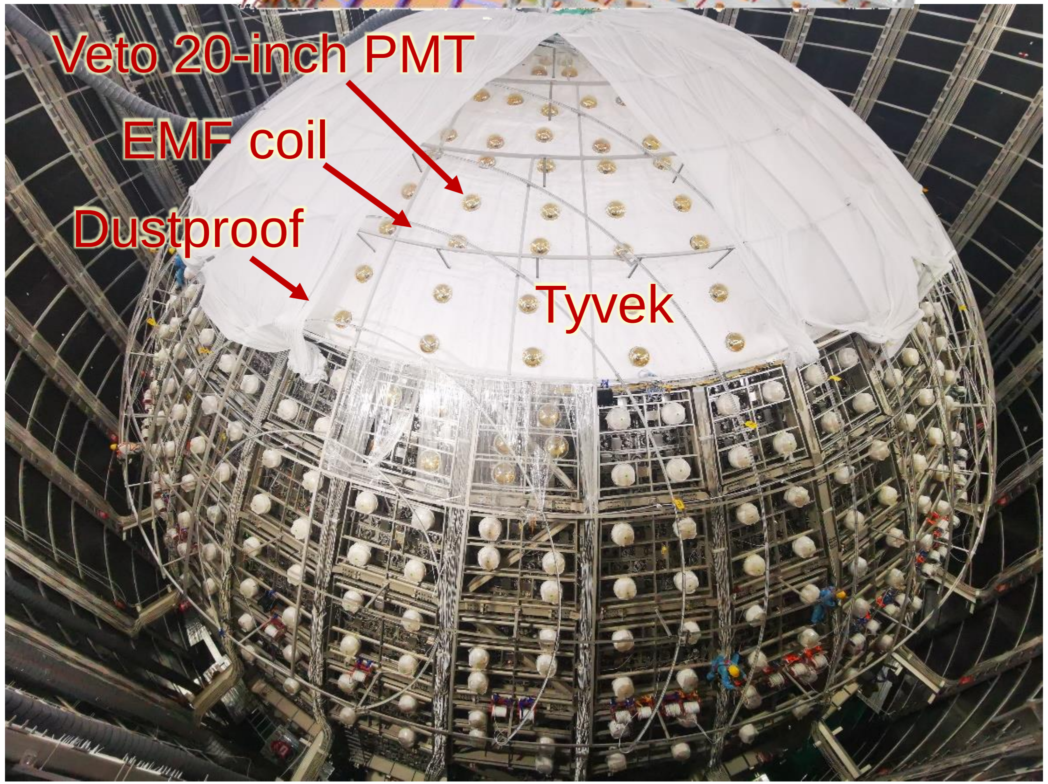
Veto Detectors

- **Water Cherenkov + Top tracker**
- **Water Cherenkov detector**
  - 35 kton water to shield backgrounds from the rock
  - Instrumented w/ 2400 20-inch PMTs on SS structure
  - Water pool lining: 5 mm HDPE (black) to keep the clean water and to stop Rn from the rock, will cover w/ tyvek
  - 100 ton/h pure water system installed. Requirement: U/Th/K<10^{-14} g/g and Rn<10 mBq/m^3, attenuation length>40 m, temperature controlled to (21±1) °C
- **Top tracker (to be installed)**

NIMA 1057 (2023) 168680

  - Refurbished OPERA scintillators
  - 3 layers, ~60% coverage on the top
  - $\Delta\theta \sim 0.2°$, $\Delta D \sim 20$ cm
- **Earth Magnetic Field compensation coil**





PMT

- **20-inch PMT: 15,012 MCP-PMT (NNVT) + 5,000 Dynode PMT(Hamamatsu)**
  3.1-inch PMT: 25,600 Dynode PMT (HZC XP72B22)
  - ⇨ All PMTs delivered and their performance tested OK
- **Water proof potting** done: **failure rate < 0.5%/6 years**
- **Implosion protection: acrylic top & SS bottom** (JINST 18 (2023), P02013)
  - ⇨ Mass production completed

	LPMT (20-in)		SPMT (3-in)
	Hamamatsu	NNVT	HZC
Quantity	5,000	15,012	25,600
Charge Collection	Dynode	MCP	Dynode
Photon Det. Eff.	**28.5%**	**30.1%**	**25%**
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

3 mm clearance

Electronics

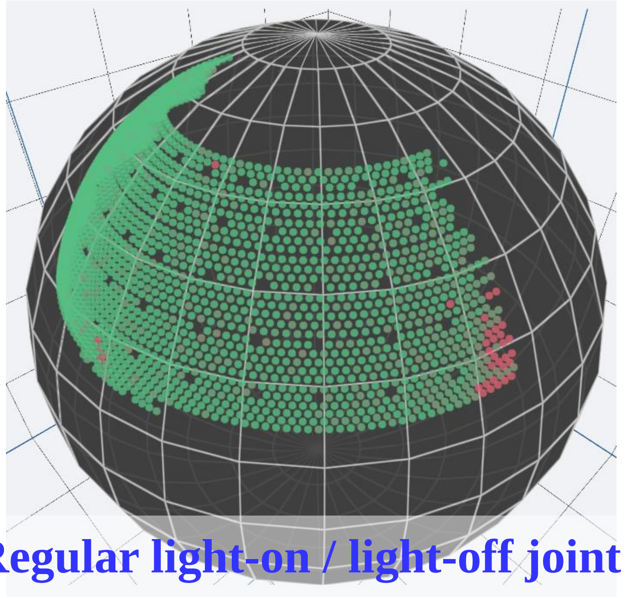
Poster ID#499, SPMT Performance

Poster ID#349, Q recon on FPGA

- **LPMT electronics: 20012 channels**
  - ⇨ Dynamic range: 1- 4000 PE, Noise: <10% @1 PE, Resolution: <10%@1 PE, <1%@100 PE
- **1 GHz FADC in an underwater box (3 ch./box),** connected to PMTs by water proof connectors
- **Failure rate: < 0.5% / 6 years**

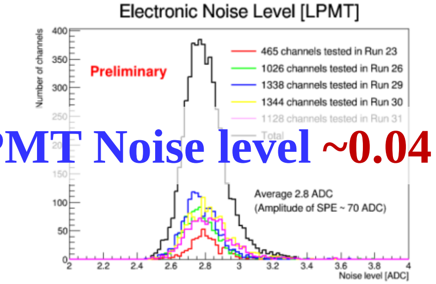
- **SPMT electronics: 25600 channels**
- **200 underwater boxes, each for 128 PMTs read by ASIC Battery Cards (ABC), each with 8 CatiROC chips**
- **Joint test**

- **Joint test with PMT-electronics-DAQ-software: all installed PMTs and related systems work well!**

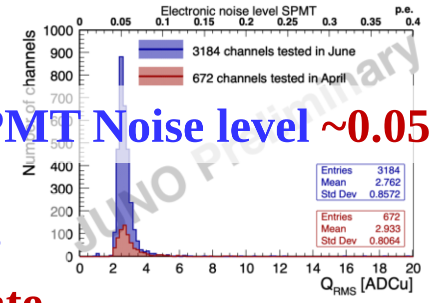


Regular light-on / light-off joint tests

Online display of PMT Dark Count Rate

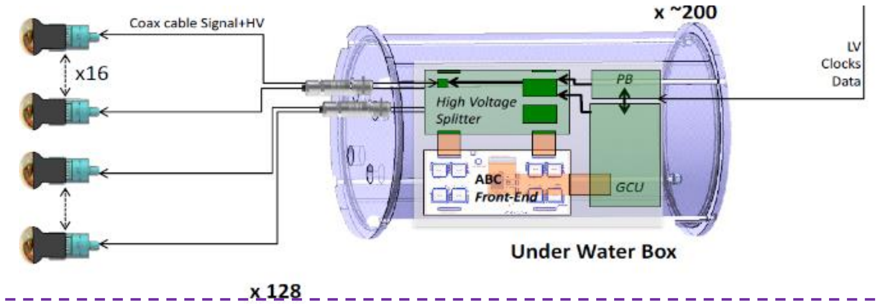


LPMT Noise level ~0.04 PE



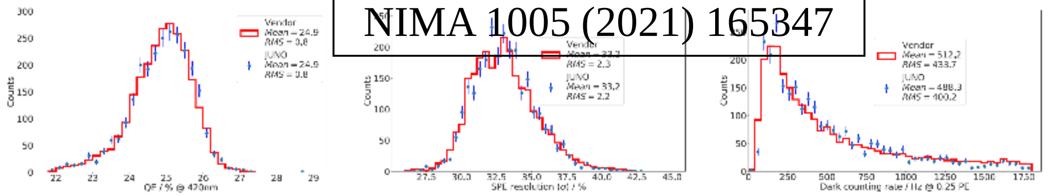
SPMT Noise level ~0.05 PE

System overview: 200 boxes × 128 PMTs



Performances highlight of all 25,600 PMTs

NIMA 1005 (2021) 165347



$\overline{QE} = 24.9\%$ $\overline{\sigma_{SPE}} = 33.2\%$ $\overline{DCR} \approx 500$ Hz

Liquid Scintillator

ID#235, LS Purification	ID# 238, Optical charactr
ID#472, OSIRIS	ID#618, OSIRIS hardware

- **LAB + 2.5 g/L PPO + 3 mg/L bis-MSB**
  - ⇨ Attenuation length: LAB > 24m, LS > 20 m
  - ⇨ Minimum U/Th requirement (for NMO) < 1e-15 g/g, aiming at 1e-17 g/g for solar and future 0νββ
- **All 60 ton PPO delivered, U/Th < 0.1 ppt**
- **Bis-MSB complete production soon (< 5 ppt)**
- **Plants commissioned individually and jointly**
- **20 kton LAB to be delivered, U/Th ~ 1 ppq**

5000 m³ LAB storage tank

1) Al_2O_3 for optical transparency

2) Distillation for radiopurity

2.4%

Mixing LAB with PPO and bis-MSB

97.6%

Mixing

1800 m SS pipes to underground

3) Water extraction to remove radioactive impurities

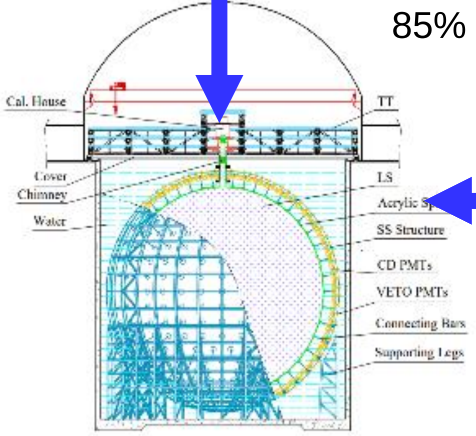
4) Gas stripping to remove Rn and O_2

15%

Commissioning

Monitoring pre-detector (OSIRIS)

85%



Liquid Scintillator

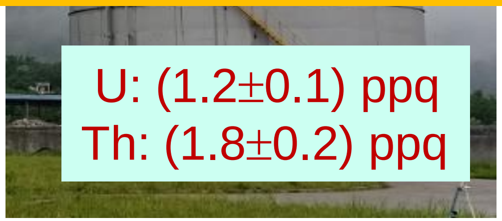
ID#235, LS Purification | ID# 238, Optical charactr
ID#472, OSIRIS | ID#618, OSIRIS hardware

- **LAB + 2.5 g/L PPO + 3 mg/L bis-MSB**
  - ⇨ Attenuation length: LAB > 24m, LS > 20 m
  - ⇨ Minimum U/Th requirement (for NMO) < 1e-15 g/g, aiming at 1e-17 g/g for solar and future 0νββ

- **All 60 ton PPO delivered, U/Th < 0.1 ppt**
- **Bis-MSB complete production soon (< 5 ppt)**
- **20 kton LAB to be delivered, U/Th ~ 1 ppq**
- **Plants commissioned individually and jointly**

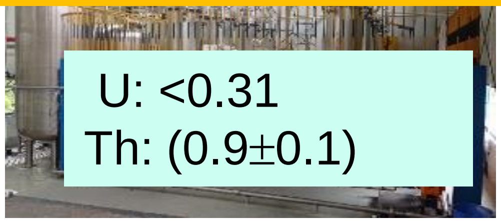
ICP-MS & neutron activation analysis developed sensitivity ~ ppq level (10^{-15} g/g)

ID#500, NAA



U: (1.2±0.1) ppq
Th: (1.8±0.2) ppq

5000 m³ LAB storage tank



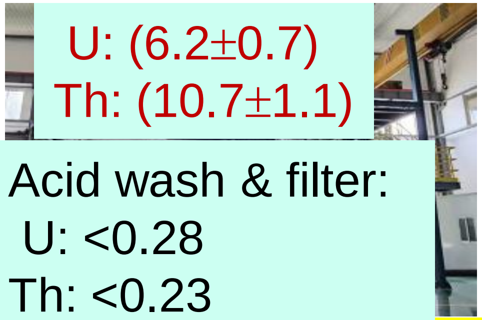
U: <0.31
Th: (0.9±0.1)

1) Al_2O_3 for optical transparency

U: <0.28
Th: <0.22

2) Distillation for radiopurity

2.4%



U: (6.2±0.7)
Th: (10.7±1.1)

Acid wash & filter:
U: <0.28
Th: <0.23

Mixing LAB with PPO and bis-MSB

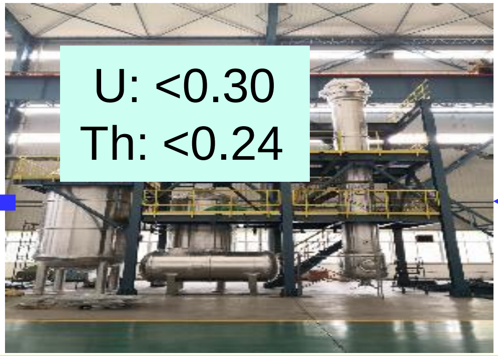
97.6%

Mixing

U: <0.30
Th: <0.24

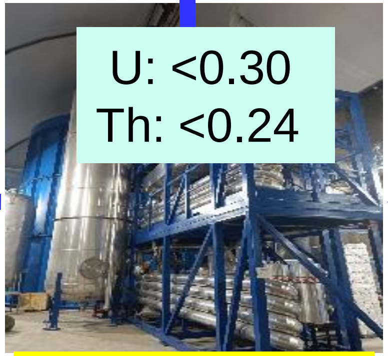
pipes to underground

U: (0.34±0.06)
Th: (0.85±0.09)



U: <0.30
Th: <0.24

3) Water extraction to remove radioactive impurities



U: <0.30
Th: <0.24

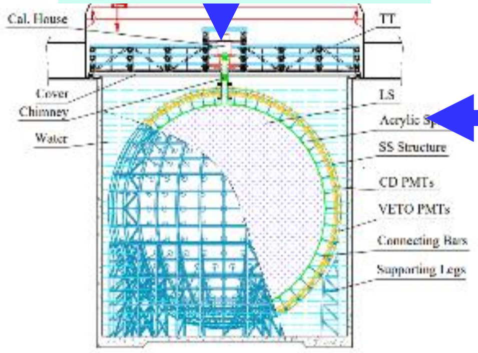
4) Gas stripping to remove Rn and O_2

15%

Commissioning

Monitoring pre-detector (OSIRIS)

FOC: U: <0.28
Th: <0.23

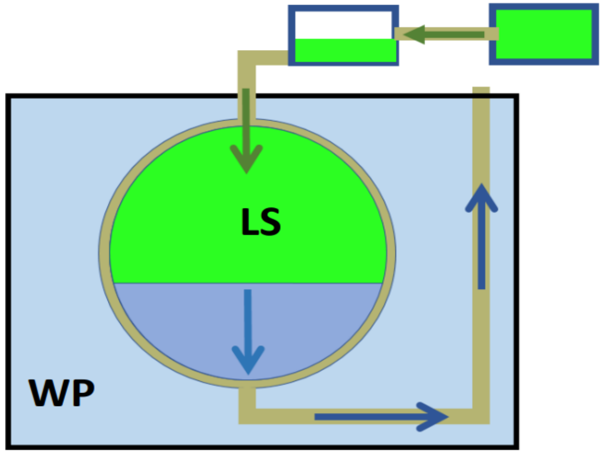


Detector Final Cleaning Plan and LS Filling

Reduce dust to class 1000 and Radon by an order of magnitude

- Complete CD construction → 1-2 weeks settlement with proper moisture → Remove the protective film on the acrylic and wash the surface by the high pressure water spray
- → Fill CD and VETO by high purity water → replacing water in CD by LS

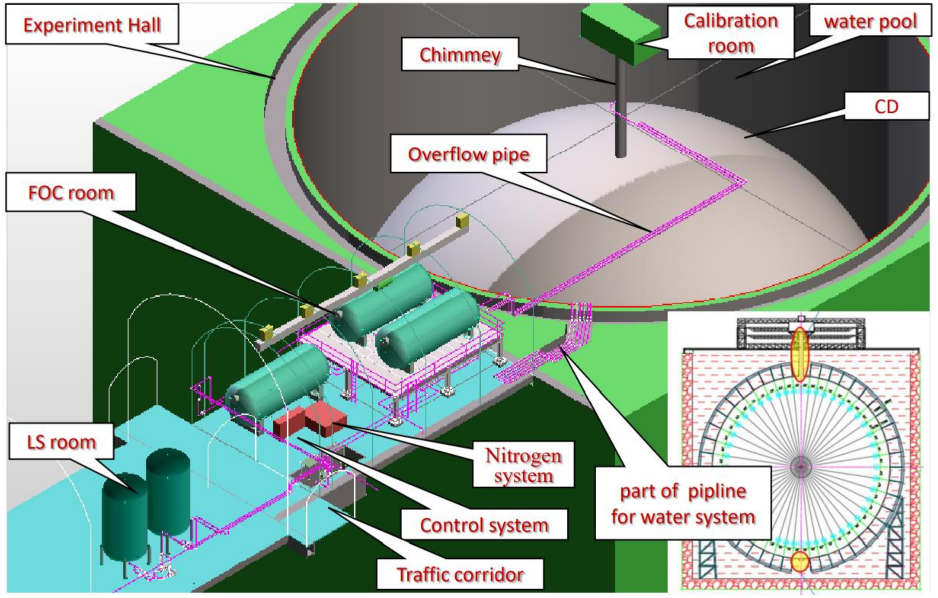
LS production and filling (7 m^3/hour)



Drain water (7 m^3/hour)

Water for CD: U/Th<10^{-15} g/g, ^{226}Ra<0.1 mBq/m^3

Water for VETO: U/Th<10^{-14} g/g



Prototype test for water spray cleaning

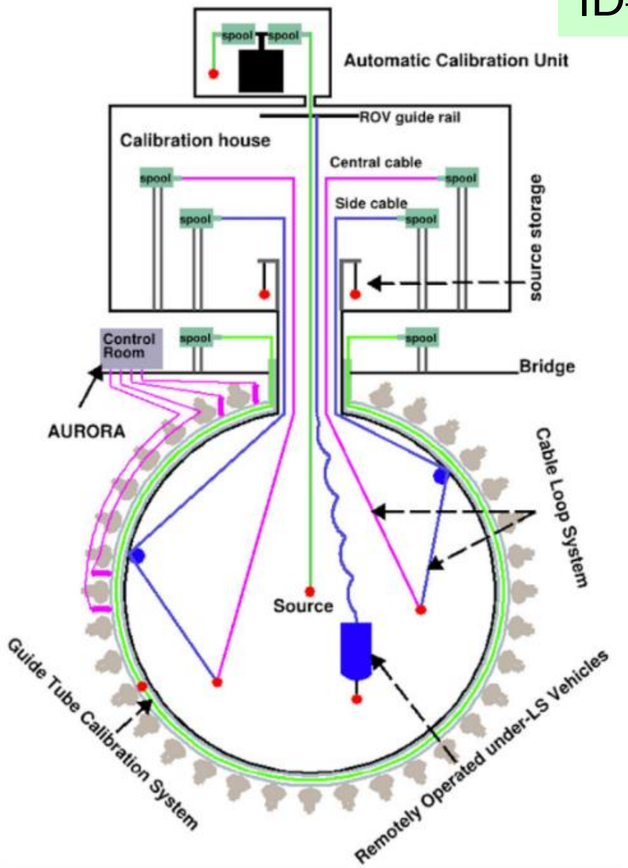
Calibration and Expected Energy Resolution

- **Four systems** for 1D, 2D, 3D scan with multiple sources
- **Energy scale** and **non-linearity** will be calibrated to **<1%** using γ peaks and cosmogenic ^{12}B beta spectrum

JHEP 03 (2021) 004

ID#320, Calibration strategy

ID#283, Natural radioactivity



Calibration house

All systems ready for installation

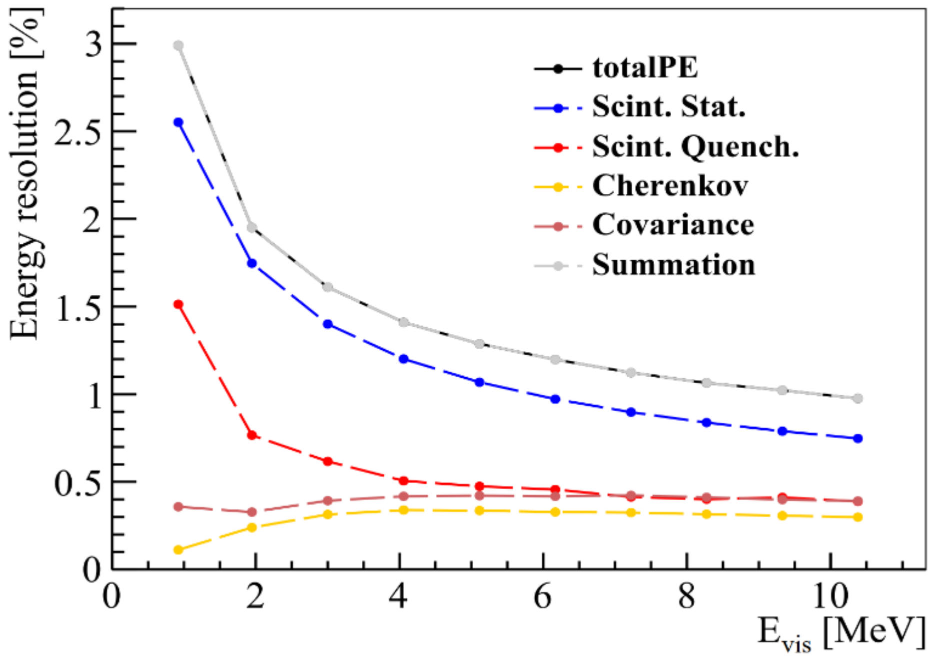
arXiv:2405.17860 (2024)

For positron

$$\frac{\sigma}{E_{vis}} = \sqrt{\left(\frac{2.61\%}{\sqrt{E_{vis}}}\right)^2 + (0.64\%)^2 + \left(\frac{1.20\%}{E_{vis}}\right)^2}$$

- Photon statistics
- Constant term
- Dark noise, Annihilation-induced γs

Expected energy resolution: **2.95% @1MeV**



JUNO-TAO

ID#308, JUNO-TAO overview

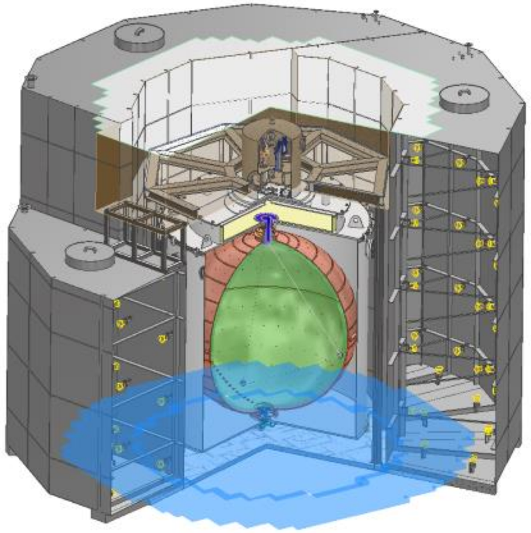
ID#369, Spectrum evolution

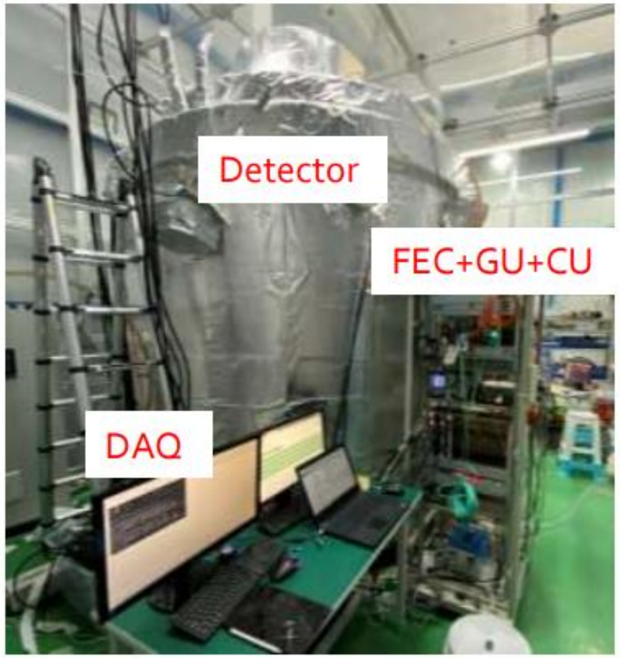
ID#279, SiPM mass testing

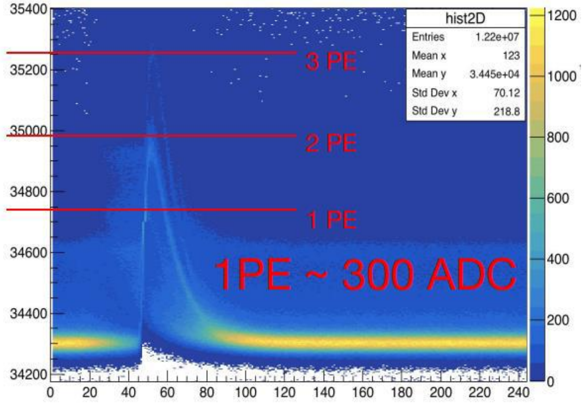
ID#319, TAO Reconstruction

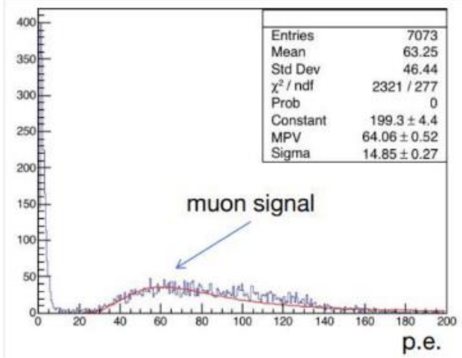
- **Main goal: Measure the reactor neutrino spectrum (as a reference to JUNO)**
  - ⇨ better resolution to reduce fine structure effects and spectrum uncertainties
  - ⇨ Improve nuclear database
- **10 m^2 SiPM + 2.8 ton Gd-loaded LS @-50°C**
  - ⇨ 700k/year@44m from the core (4.6 GW), ~10% bkg
  - ⇨ **Energy resolution: <2%/√E, 4500 p.e./MeV**
  - ⇨ SiPM (>94% coverage) w/ PDE > 50%
  - ⇨ Operating at -50°C, dark rate 100k→100 Hz/mm^2
  - ⇨ 2.8 ton (1-ton FV) new type of Gd-LS for -50°C
- **Detector assembled at IHEP with ~100 SiPM tiles/readout (out of 4100 in total)**
  - ⇨ Temperature uniformity and stability OK!
  - ⇨ Single PE readout
- **Disassembling, to be re-installed in the Taishan Nuclear Power Plant in 2024**

arXiv:2005.08745







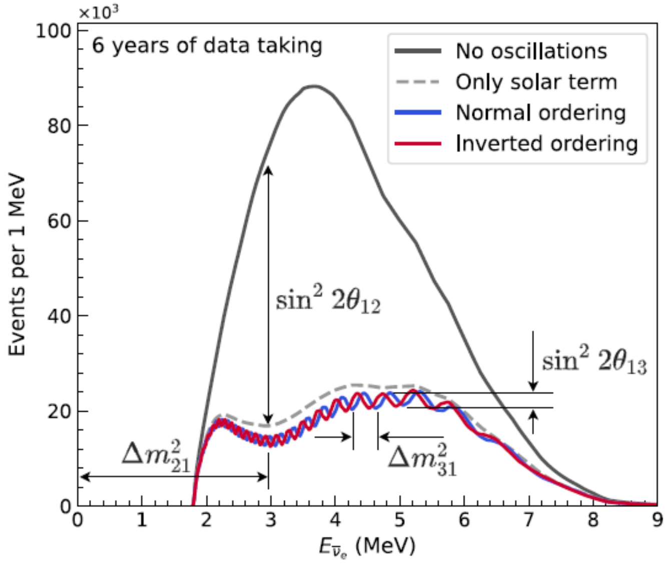


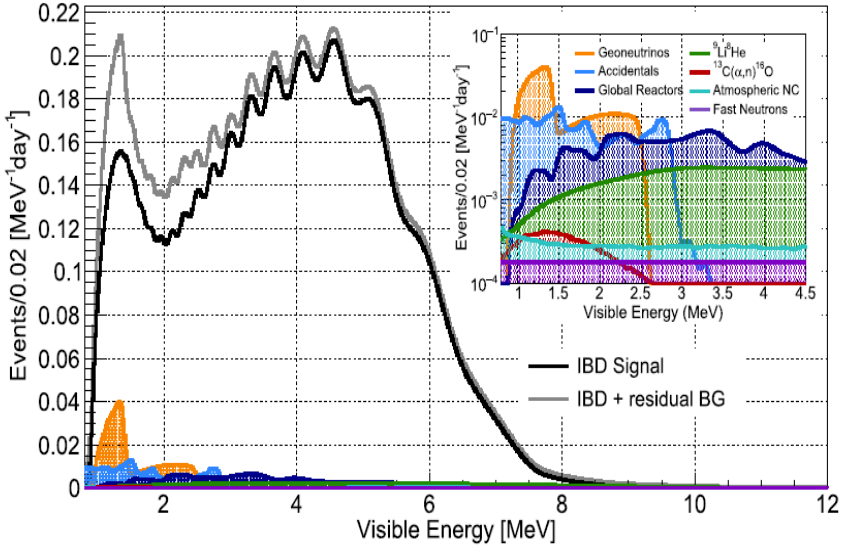
Precision Measurement of oscillation parameters

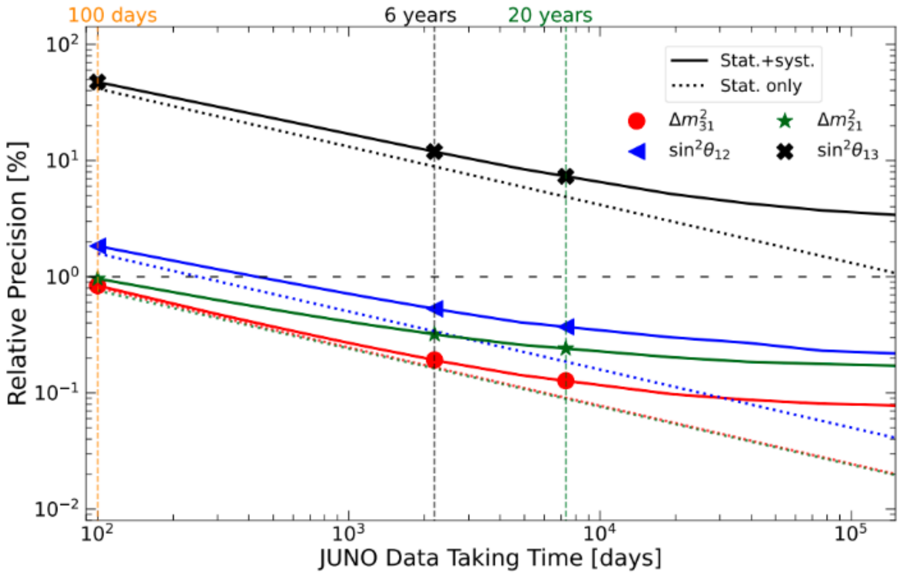
$$\mathcal{P}(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$

ID#223, Precision Measurement

Chin. Phys. C46 (2022) 12, 123001







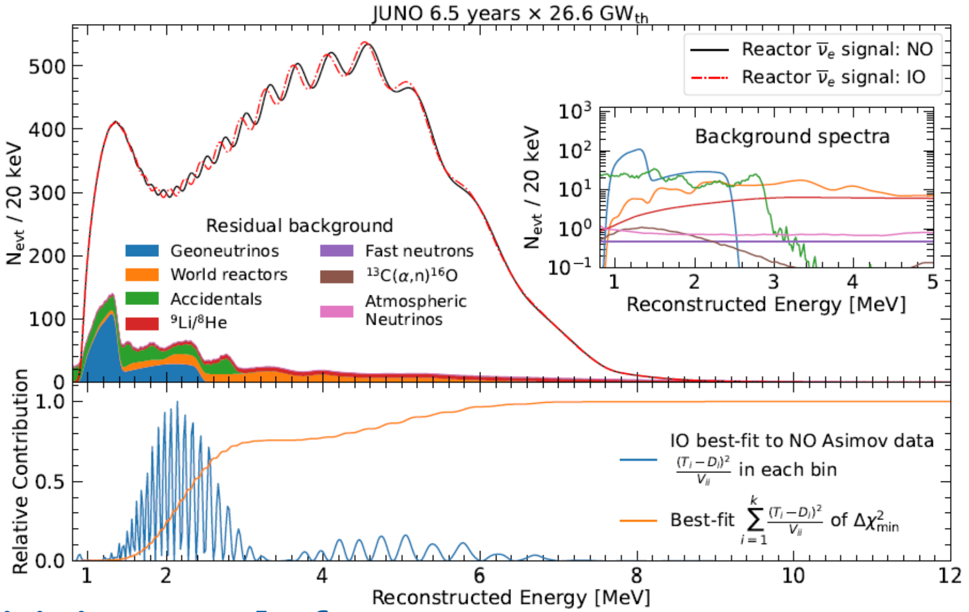
	Central Value	PDG2020	100 days	6 years	20 years
Δm^2_{31} ($\times10^{-3}$ eV^2)	2.5283	±0.034 (1.3%)	±0.021 (0.8%)	±0.0047 (0.2%)	±0.0029 (0.1%)
Δm^2_{21} ($\times10^{-5}$ eV^2)	7.53	±0.18 (2.4%)	±0.074 (1.0%)	±0.024 (0.3%)	±0.017 (0.2%)
$\sin^2\theta_{12}$	0.307	±0.013 (4.2%)	±0.0058 (1.9%)	±0.0016 (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%)

$\sin^2 2\theta_{12}$, Δm^2_{21}, $|\Delta m^2_{32}|$, leading measurements in 100 days; precision <0.5% in 6 years

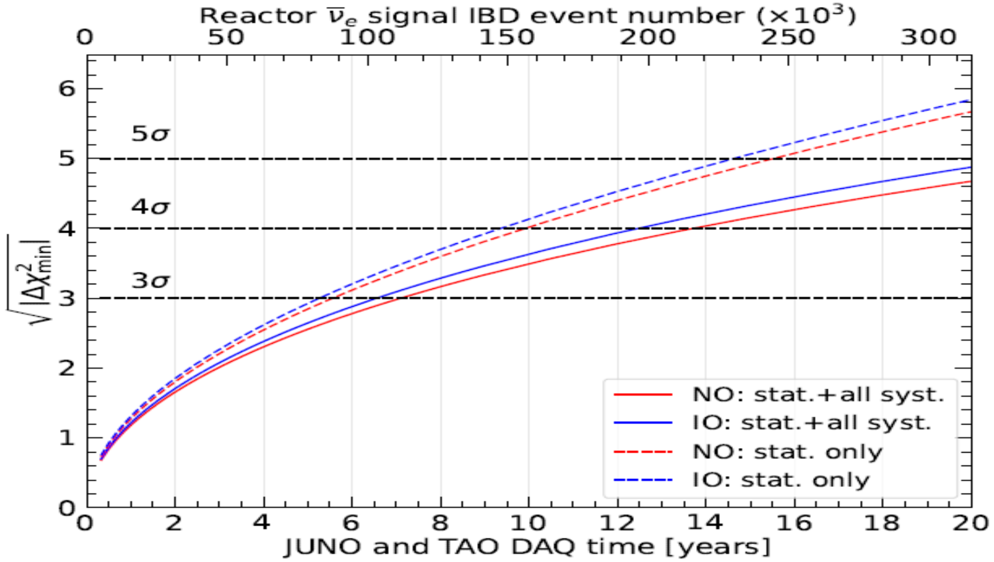
Neutrino Mass Ordering

ID#506, NMO sensitivity

ID#335, IBD selection



Sensitivity mostly from 1.5-3 MeV



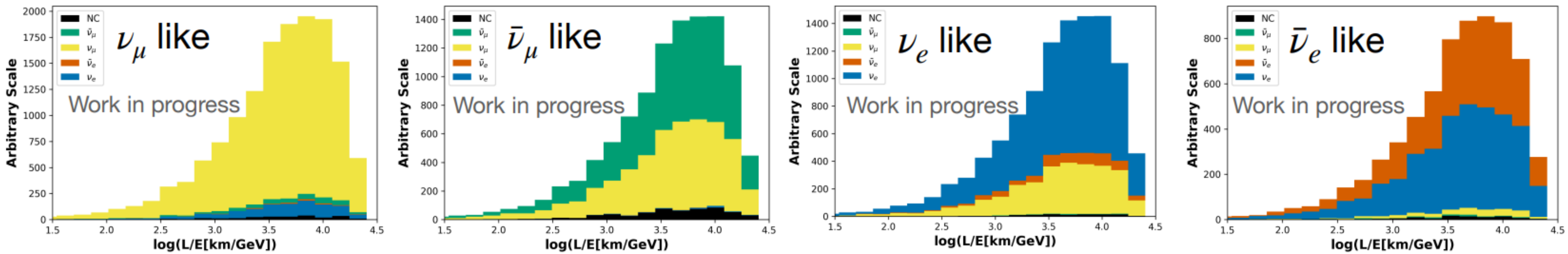
arXiv:2405.18008 (2024)

	Design	Now
Thermal Power	36 GW$_{th}$	26.6 GW$_{th}$ (26%↓)
Signal rate	60 /day	47.1 /day (22%↓)
Overburden	~700 m	~ 650 m
Muon flux in LS	3 Hz	4 Hz (33%↑)
Muon veto efficiency	83%	91.6% (11%↑)
Backgrounds	3.75 /day	4.11 /day (10%↑)
Energy resolution	3.0% @ 1 MeV	2.95% @ 1 MeV (2%↑)
Shape uncertainty	1%	JUNO+TAO
3σ NMO sens. Exposure	<6 yrs × 35.8 GW$_{th}$	~6 yrs × 26.6 GW$_{th}$

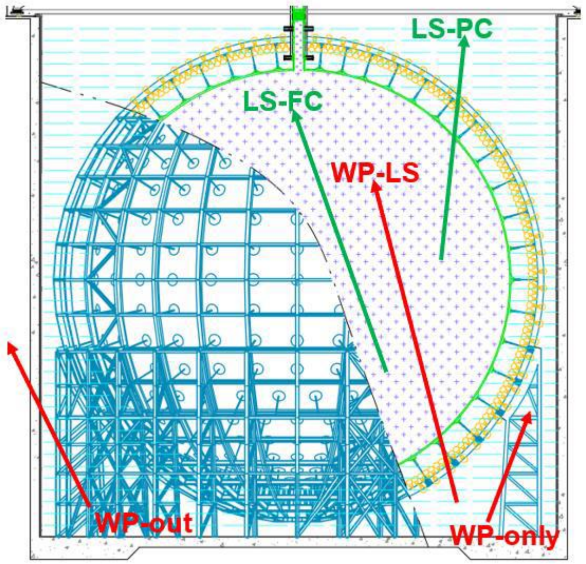
- **JUNO NMO median sensitivity:**
  3σ (reactors only) @ ~6 yrs * 26.6 GW$_{th}$ exposure
- **Combined reactor and atmospheric neutrino analysis in progress: further improve the NMO sensitivity (see next page→)**

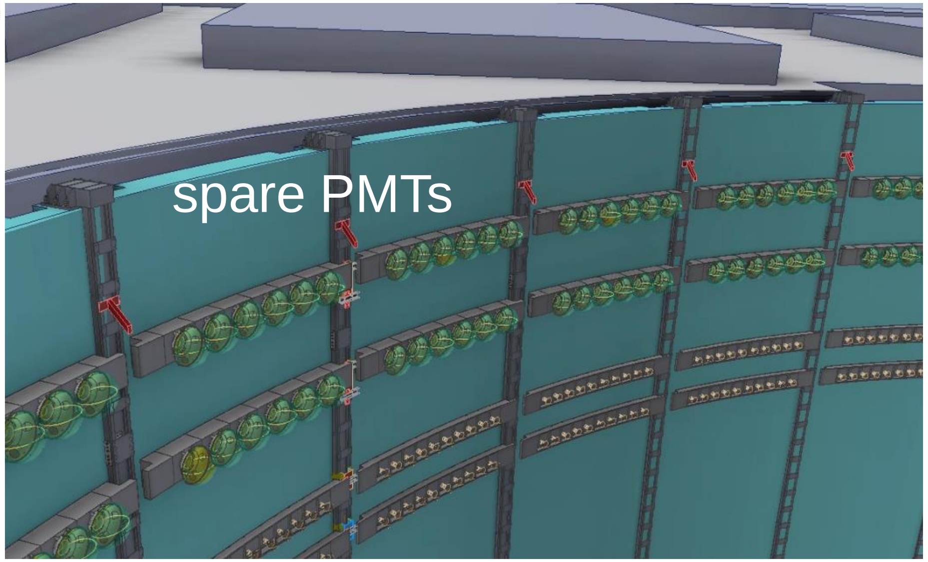
Atmospheric Neutrino

- **JUNO will be the first to study atmospheric neutrino oscillation with liquid scintillator: e/μ separation, $\nu/\bar{\nu}$ separation, ν energy (instead of lepton energy), track direction in LS**

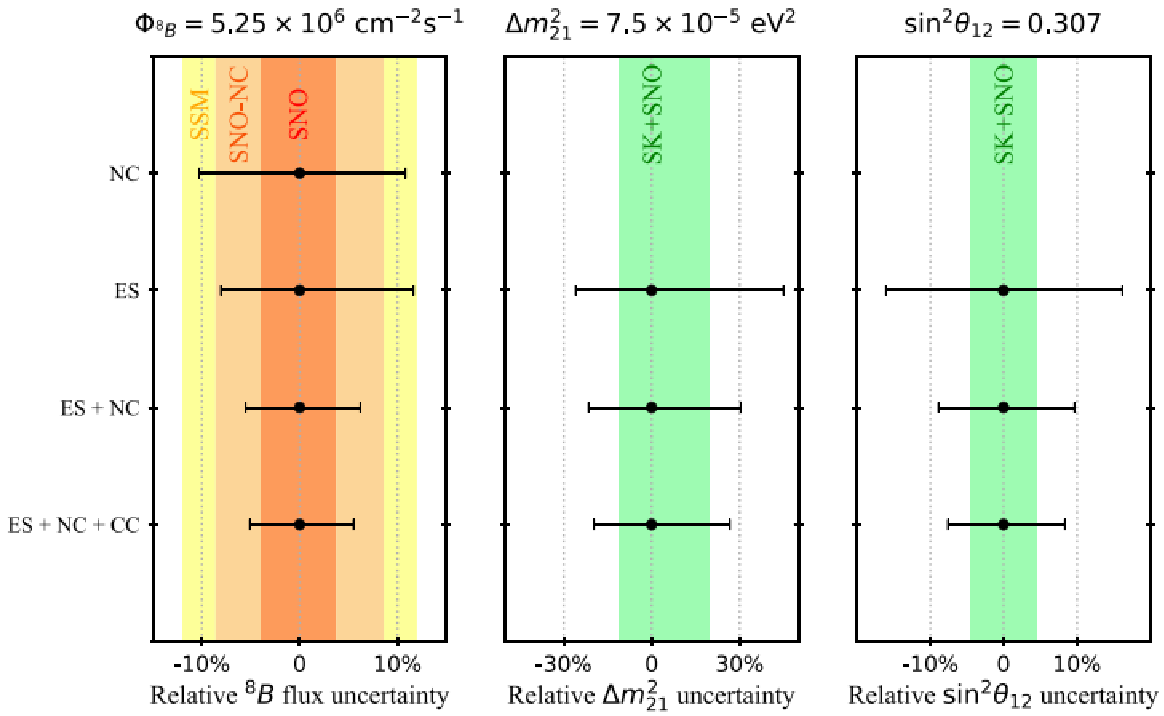


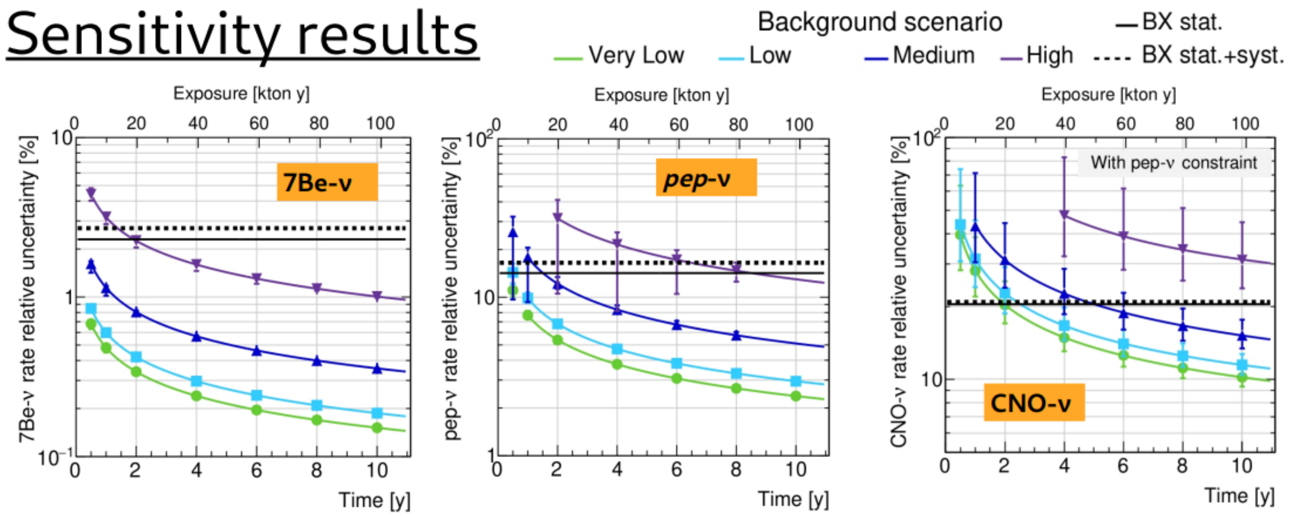
- **Improving the reconstruction and PID algorithm, as well as sensitivity**
- **Plan to install all spare PMTs on top wall of the water pool to improve PID and direction reconstruction**





Solar Neutrino





- **60,000 ES and 600 NC/CC on ^{13}C**
- **The largest ^{13}C ES+NC+CC sample, ^8B flux can be model-independently measured to 5% in 10 years (SNO 3%)**

ID#286, ^8B on ^{13}C

Astrophys. J 965, 122 (2024)

- **For most background scenarios, JUNO will reduce the Borexino uncertainty on ^7Be, pep, CNO flux measurement**

ID#240, ^7Be, pep, CNO

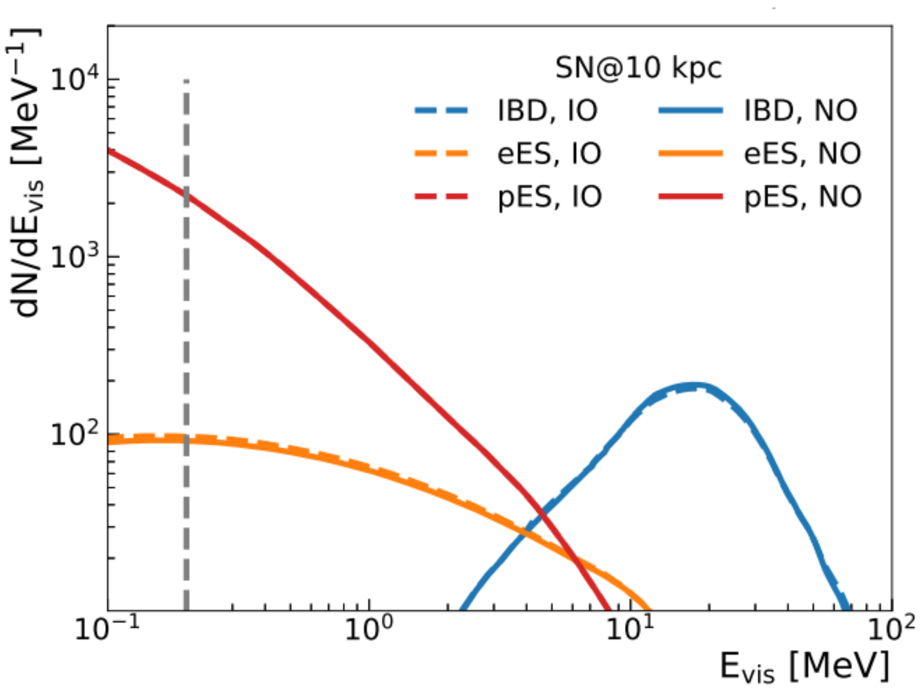
JCAP 10, 022 (2023)

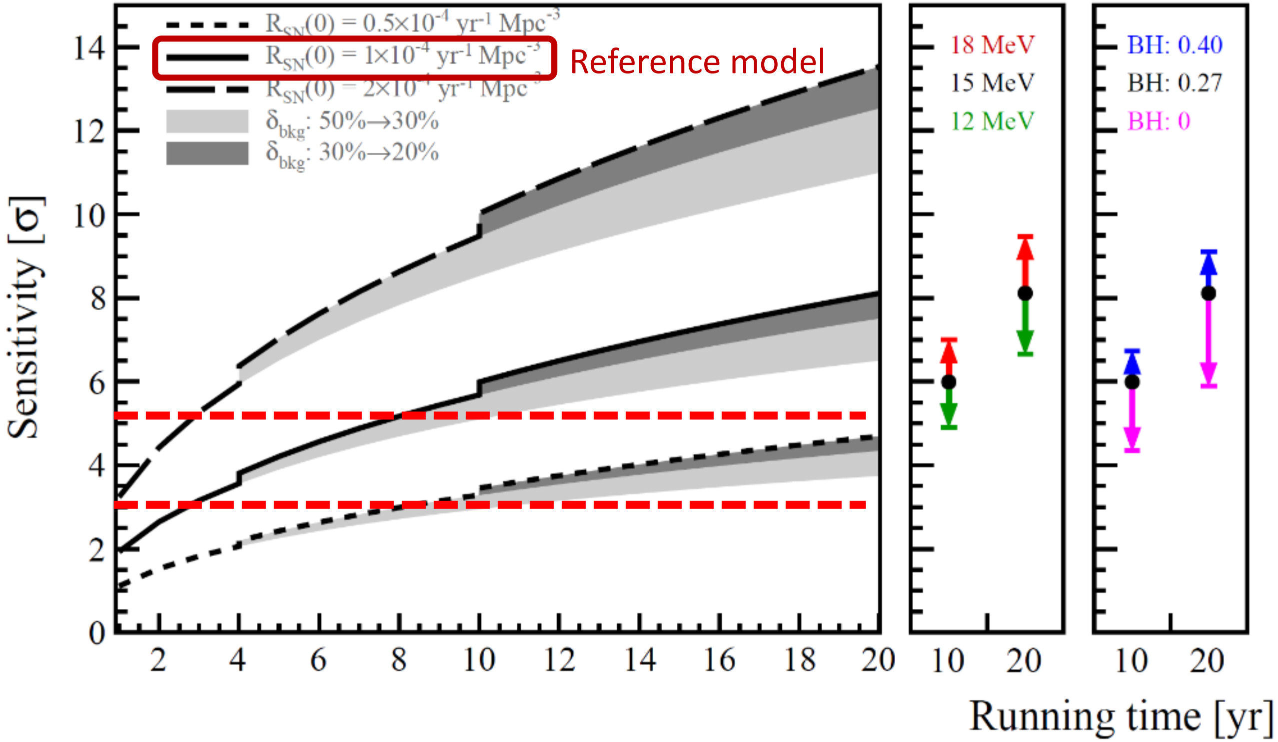
ID#330, ^7Be and CNO directional

Supernova Neutrino

ID#300, supernova w/ LPMT

ID#392, supernova w/ SPMT





- **3 detection channels sensitive to all flavors**
- **Excellent capability for early warning**
  - ➪ 220~400 kpc with 50% probability
  - ➪ **pre-SN** 1.6 (0.9) kpc
  - ➪ 10~30 ms for typical 10 kpc

JCAP01 (2024) 057

ID#392, Monitoring

- **Diffuse Supernova Neutrino Background**
  S/B ratio improved from 2 to 3.5 with Pulse Shape Discrimination
- **Using the reference model:**
  3σ in 3 years and >5σ in 10 years

JCAP 10 (2022) 033

ID#477, DSNB

Summary

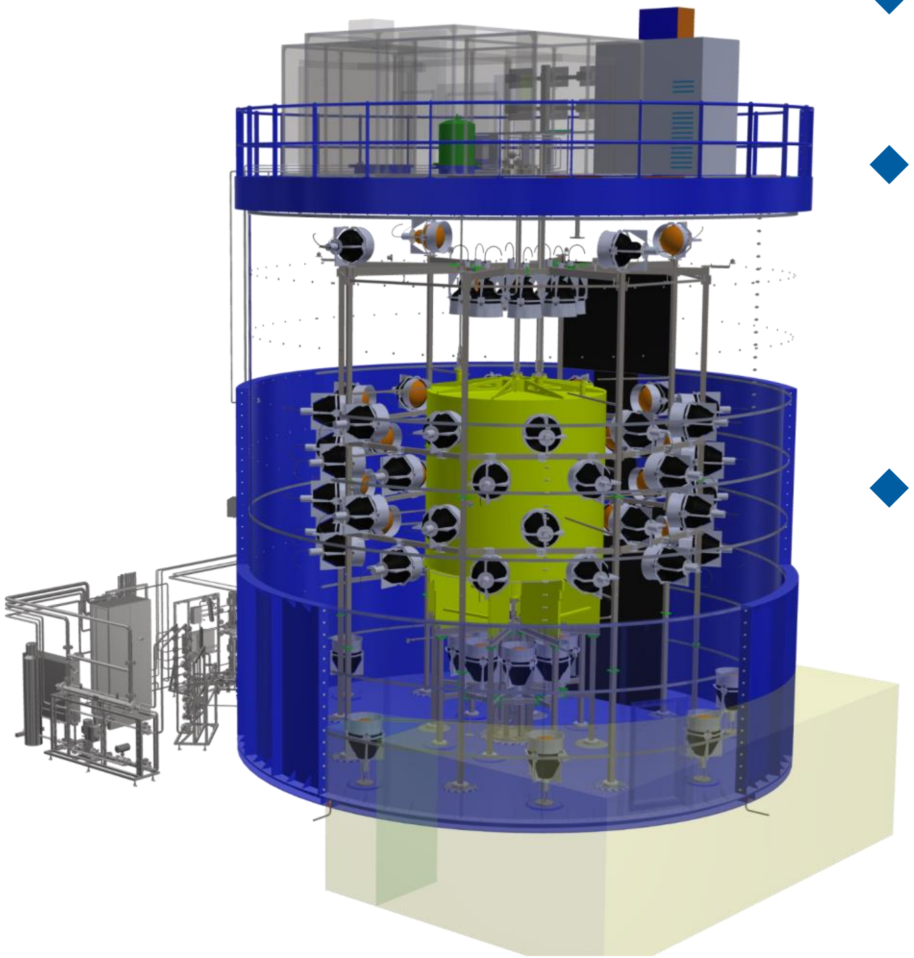
- **After overcoming many challenges, JUNO construction is nearing completion. We anticipate finishing the construction in 2024 and start the detector filling**
- **High quality components will lead to high performance**
- **Well-prepared for data taking and physics**

Not covered topics, c.f. JUNO posters

- Neutron source based reconstruction, ID#285
- Cosmogenic background in Te-LS, ID#299
- PMT Optical Model, ID#304
- Dual Calorimeter, ID#311
- On waveform Recon., ID#313
- (alpha,n) background, ID#322
- Sensitivity to invisible modes of neutron decay, ID#324
- Sensitivity to Geoneutrinos, ID#333 (also Livia's review talk)
- Tagging Correlated Events in a Small-Scale LS Detector, ID#347
- Unbinned Likelihood with GPU, ID#395

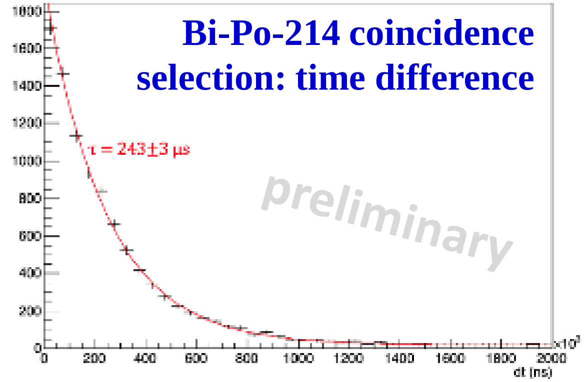
Backup

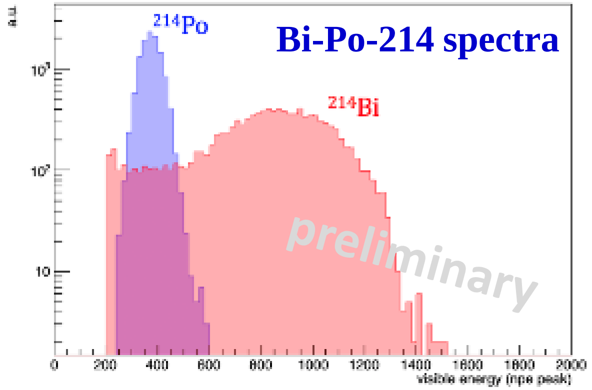
Backup: OSIRIS

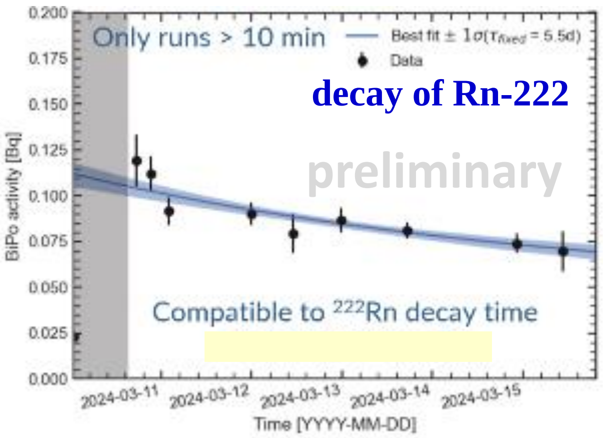


EPJ C 81 (2021) 11, 973

- A dedicated pre-detector to verify the radioactivity levels of LS
- 20 tons of LS in 3m-by-3m acrylic vessel, 76 MCP-PMTs, 3m of water shielding → first test run successful
- First batch of JUNO LS filled into the detector
  - U/Th tagging by Bi-Po-214 coincidence, which is now still dominated by ^{222}Rn → have to wait several ^{222}Rn lifetimes (τ=5.5 days) to reach U/Th <10^{-15} g/g
  - Analysis for ^{14}C, ^{210}Po, … in progress



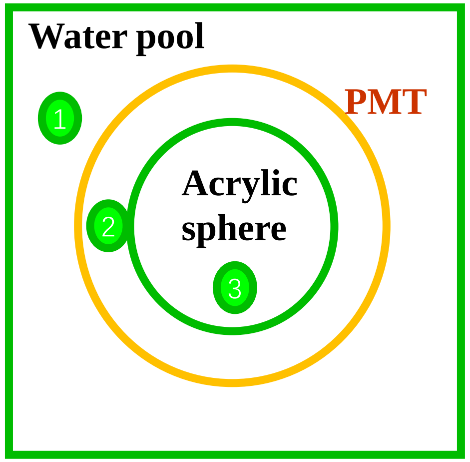




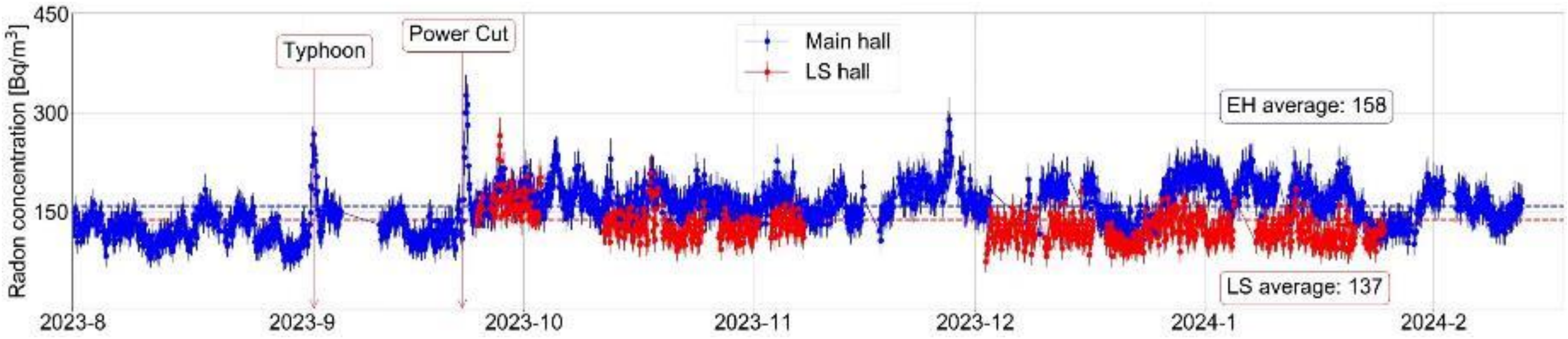
Backup: Cleanness of Environment

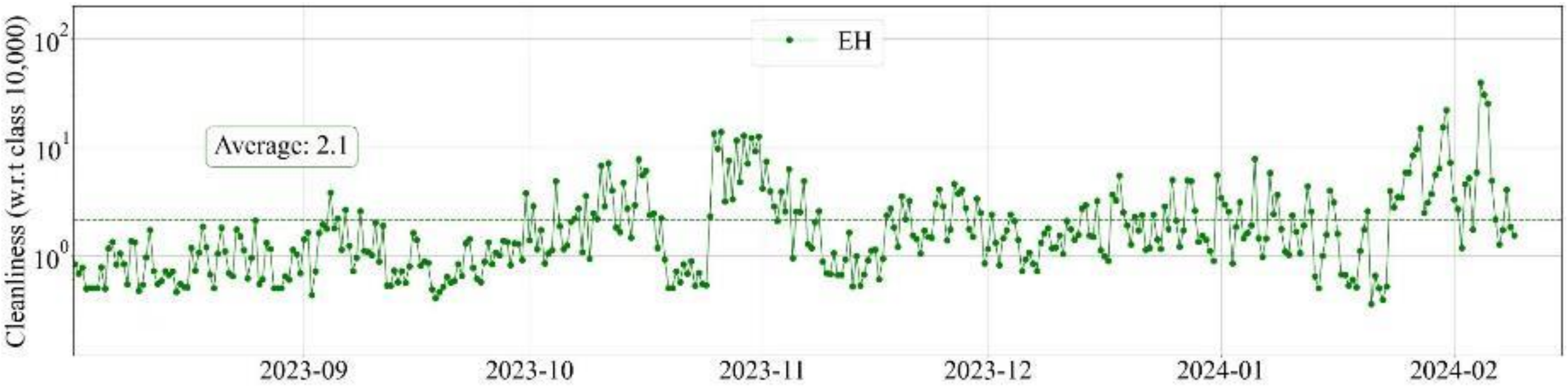
- **Average radon and cleanliness:**
  - Radon concentration: ~160 Bq/m³ in the EH, ~140 Bq/m³ in the LS hall
  - Cleanliness: class 20,000

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



Radon concentration in air: < 200 Bq/m³

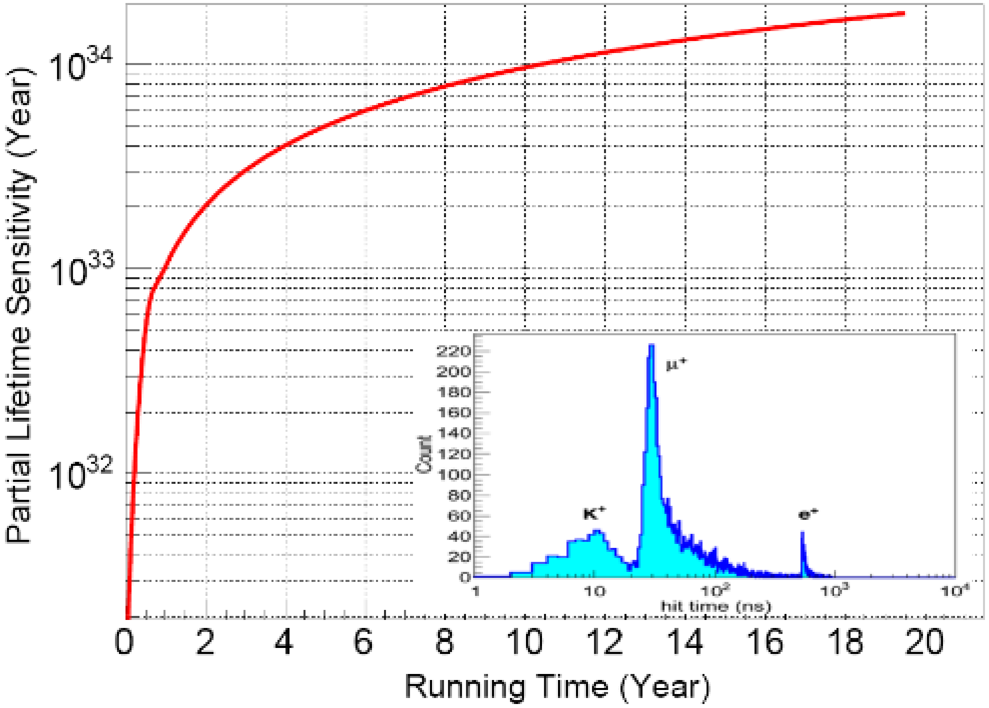




Backup: Nucleon Decays

Target mass: 20 kton LS → 1.45×10^{33} free protons, 5.30×10^{33} bound protons/neutrons

$p \to \bar{\nu} K^+$ triple coincidence



$\tau/B(p \to \bar{\nu} K^+) > 9.6 \times 10^{33}$ yrs / 10 yrs

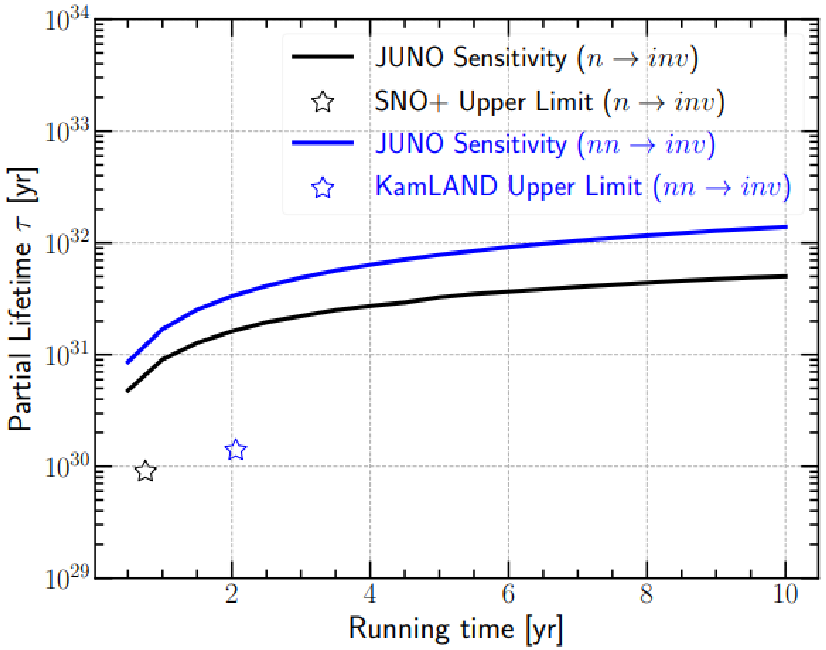
Best limit: 5.9×10^{33} yrs from Super-K

CPC 47, 113002 (2023)

Neutron invisible decays

$n \to inv \ (^{12}C \to {}^{11}C^*)$

$nn \to inv \ (^{12}C \to {}^{10}C^*)$



An order of magnitude improvement to the current best limits in 2 years data taking

arXiv: 2405.17792