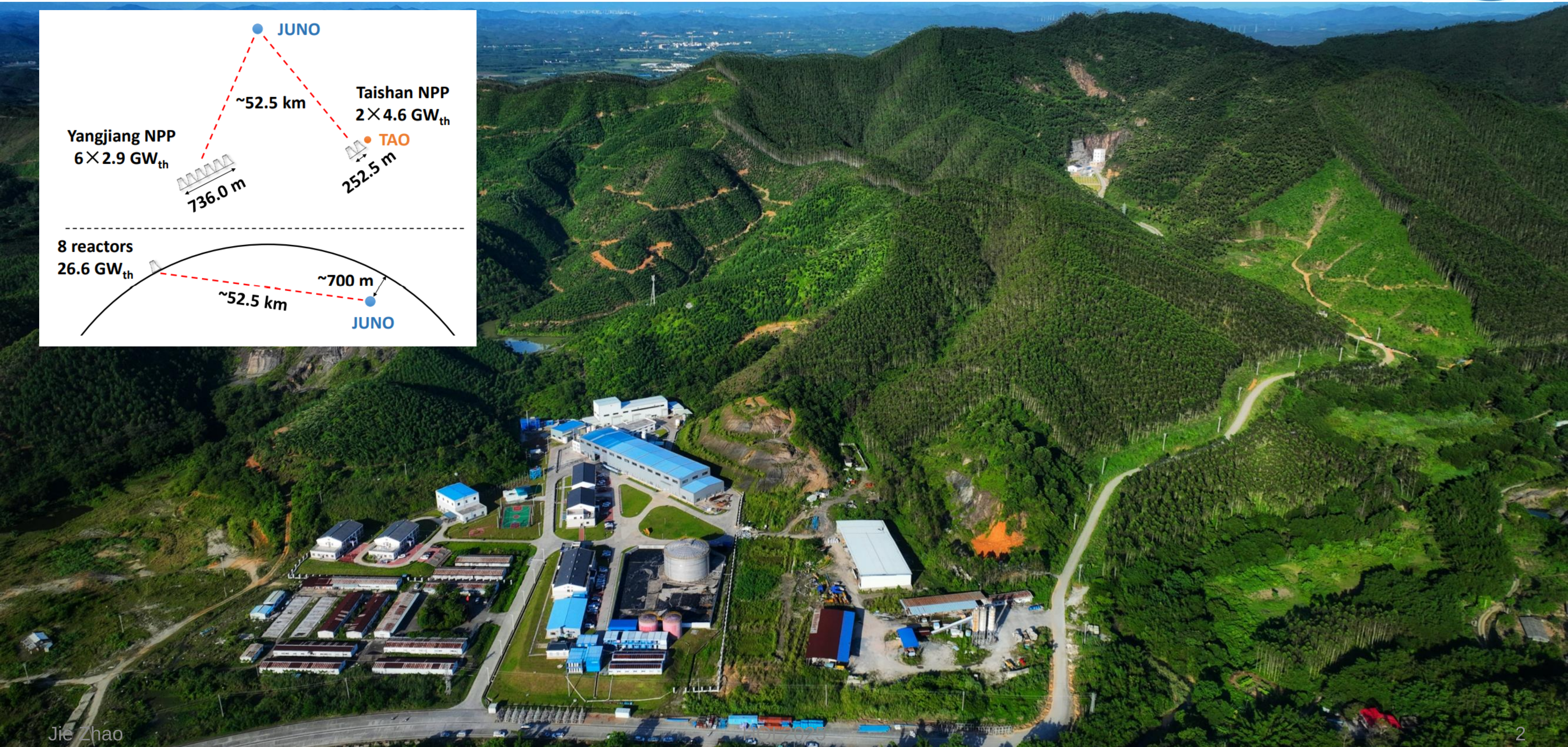
JUNO Status & Prospects

Jie Zhao (IHEP)

On behalf of the JUNO collaboration

HQL2025 THE 17th INTERNATIONAL CONFERENCE ON HEAVY QUARKS AND LEPTONS Sept. 15-19, 2025 · Beijing, China

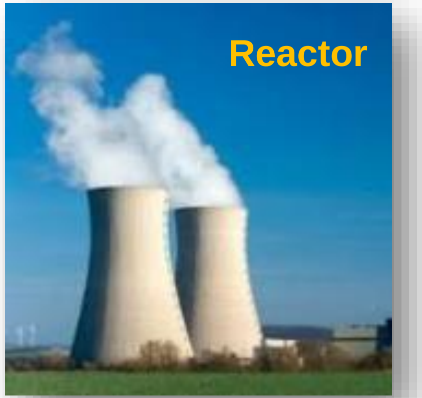
Jiangmen Underground Neutrino Observatory

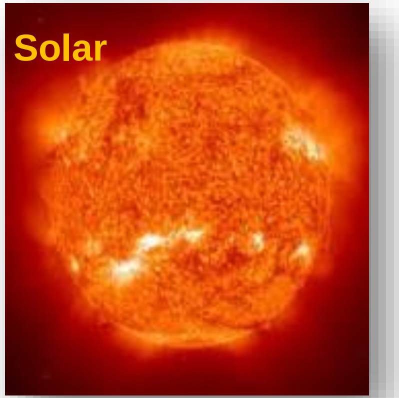


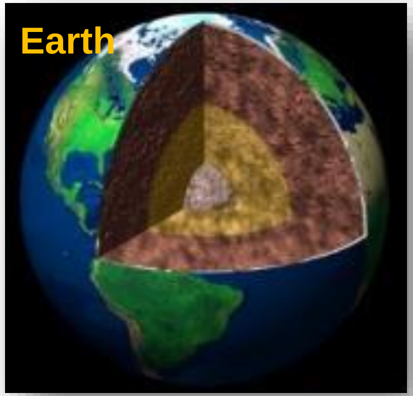
Jiangmen Underground Neutrino Observatory

Civil construction finished in Dec, 2021
Detector construction finished in Dec, 2024

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

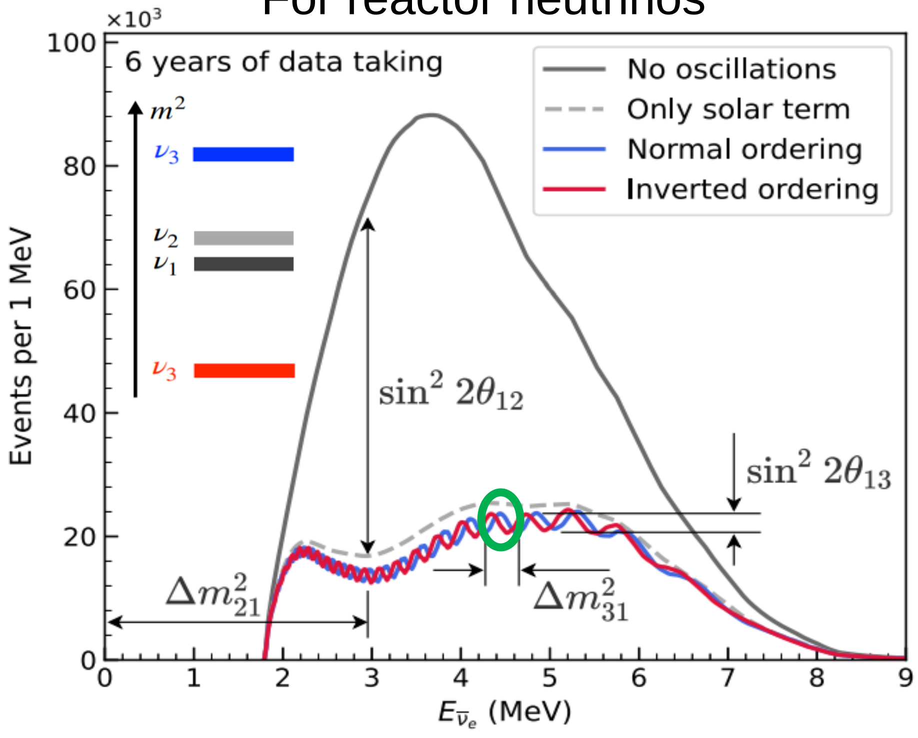
IBD: inverse beta decay $\bar{\nu}_e + p \to e^+ + n$

CCSN: core-collapse supernova

Requirement for rich physics program

Example: Precision Neutrino Oscillation Measurements

For reactor neutrinos



Detector properties

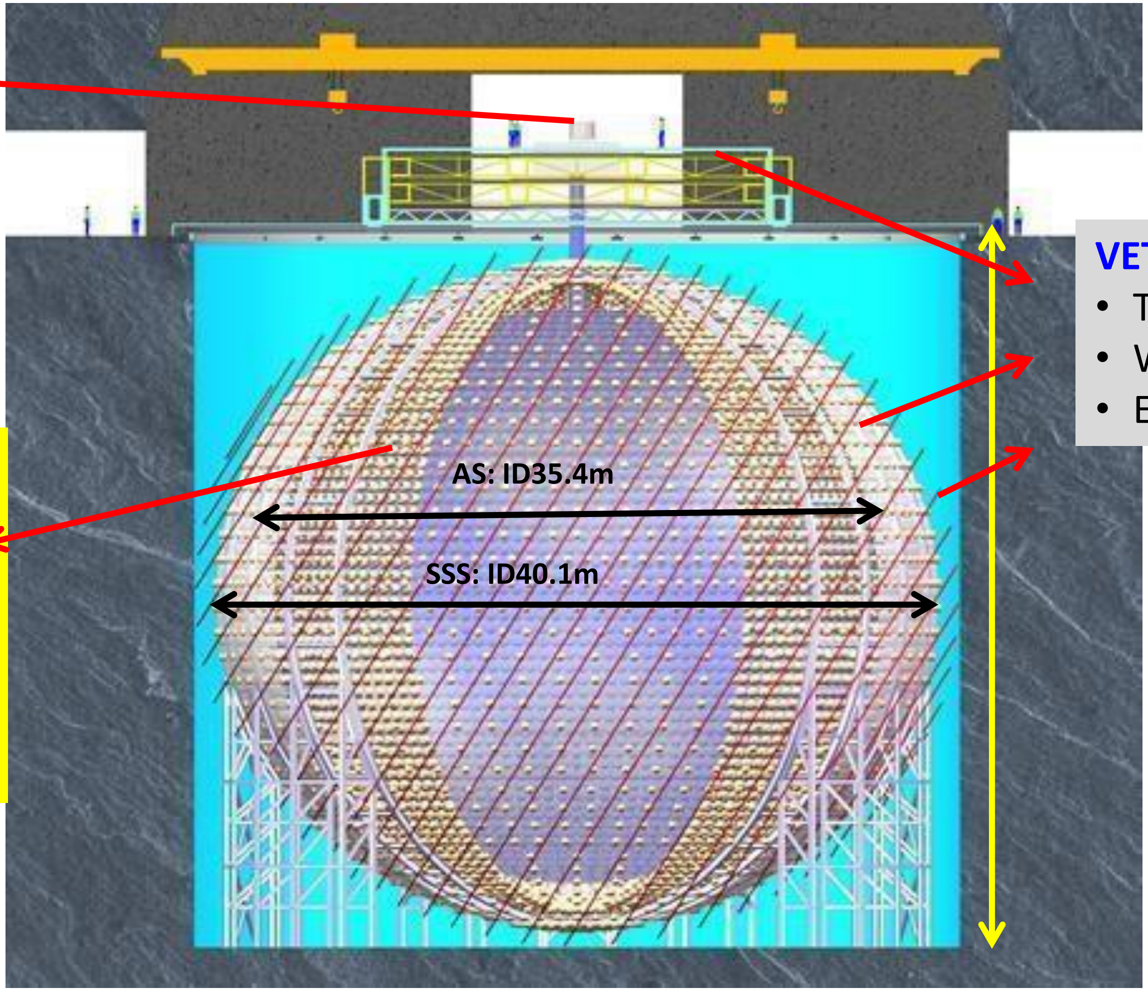
- **Statistics (10^5 in 6y)**
  - Large target mass (20 kton LS)
  - Powerful nuclear reactors (26.6 GW_{th})
- **Energy resolution ($3\%/\sqrt{E}$)**
  - Very high PMT coverage (78%)
  - Highly transparent LS
  - Highly efficient PMTs (PDE~30%)
- **Shape uncertainty (1%)**
  - Satellite detector (TAO)
- **Background (3%)**
  - Good overburden (~650 m)
  - Highly-efficient veto system (>99.5%)
  - Material screening
  - Clean installation

For solar neutrinos: tighter requirements on Liquid Scintillator radiopurity (U/Th ~ 10^{-15} g/g) by 1~2 orders of magnitude.

JUNO detector design

- **Two-layers structure for simplicity and cost: stainless steel frame + Acrylic tank**
- **Water as VETO and Buffer(instead of oil) → radiopurity control of water**

Calibration



Central detector
- Steel structure
- Acrylic sphere + 20kt Liquid scintillator
- 17612 20” PMT
- 25600 3’’ PMT

VETO system (for cosmic muon detection)
- Top Tracker: plastic scintillator
- Water + 2400 20’’ PMT
- Earth Magnetic Field shielding coils

Central detector (SS structure)

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

Assembly precision: < 3 mm for each grid. The final radius deviation -13 mm (0.06%)

Connected by 120,000 sets of special rivet bolts: high strength, high consistency, no welding.

2022.1~2022.6, pillar and shell most finished. 2024.11, bottom 4 layers of SS shell finished.

Central detector (acrylic tank)

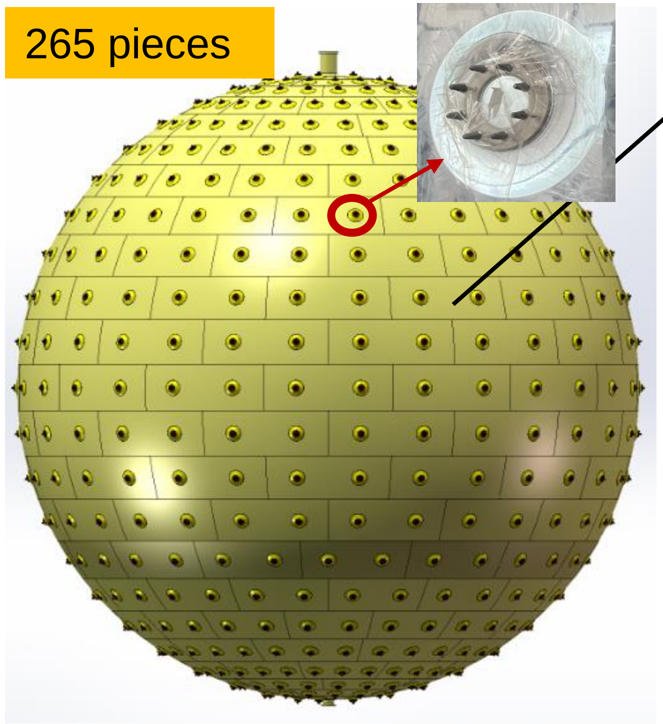
LS container:

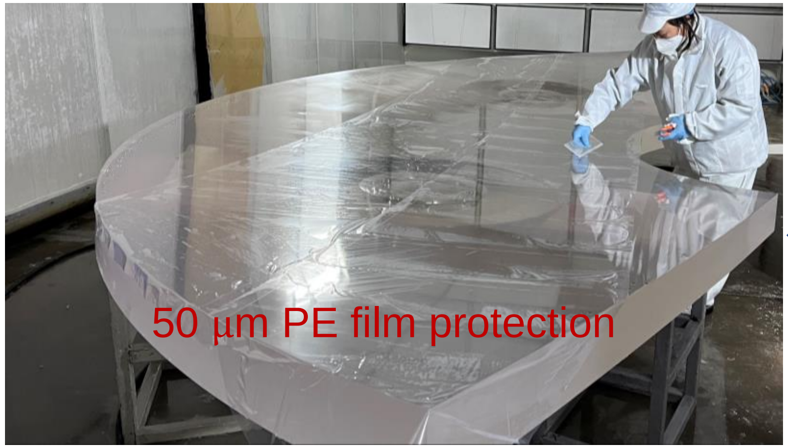
Inner diameter: 35.40±0.04 m

Thickness: 124±4 mm

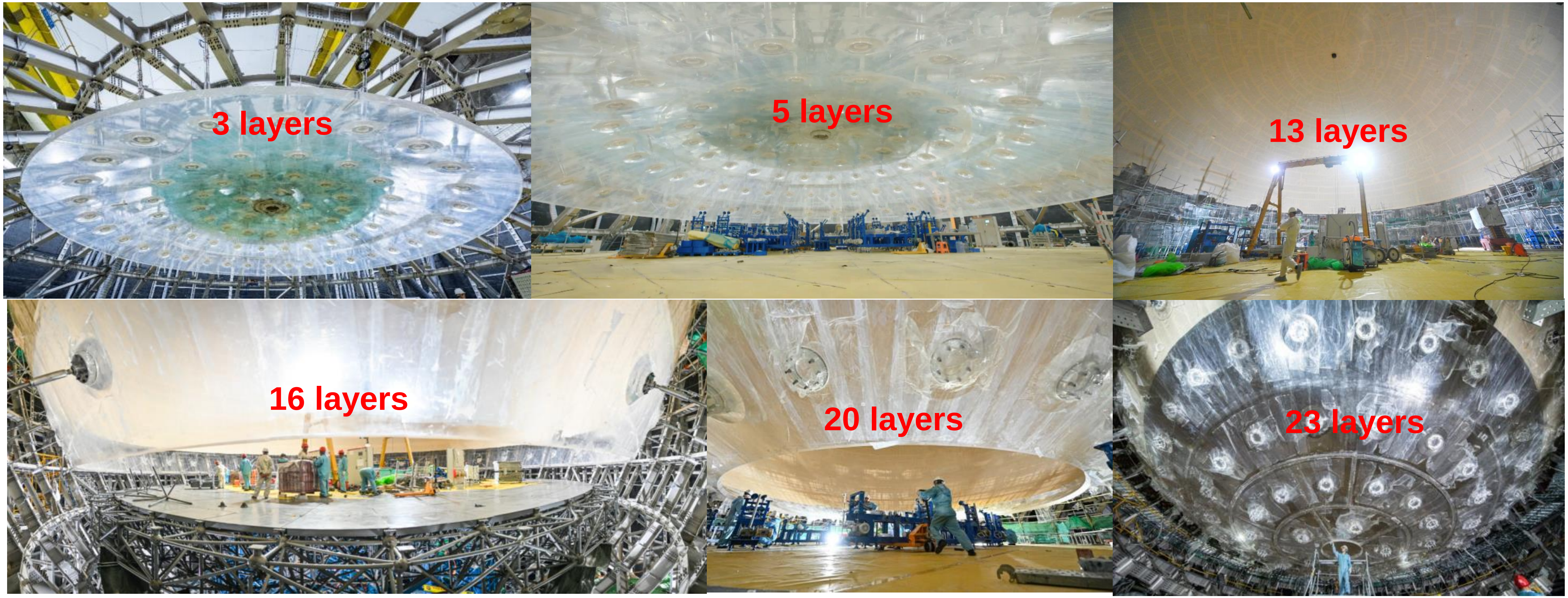
Light transparency > 96% @ LS

Radiopurity: U/Th/K < 1 ppt





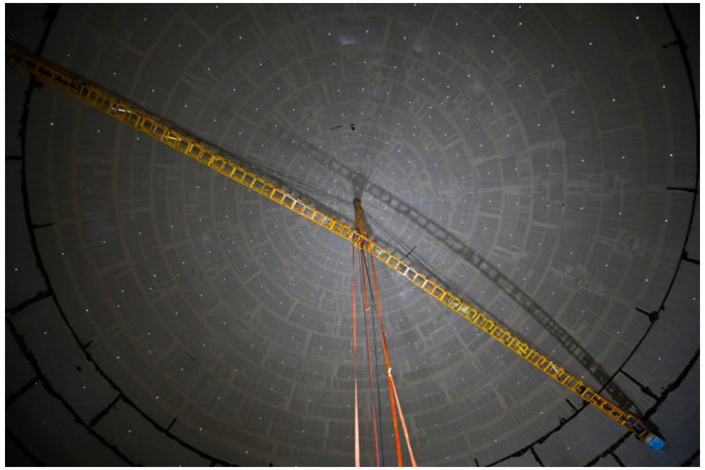
Central detector (acrylic tank)



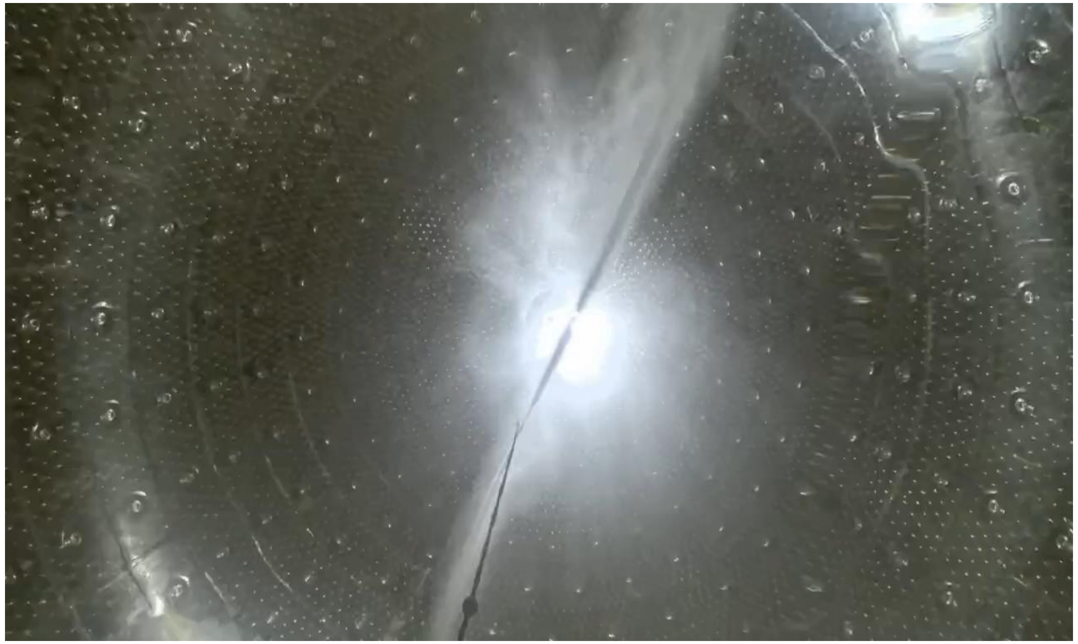
23 layers/263 spherical panels + top and bottom chimneys were bonded onsite (finished in Oct. 2024).

- ✓ A total of 21 cyclic operations for the construction, each lasting 20-30 days, with a total bonding length reaching 2 km.
- ✓ Developed large-volume injection, polymerization and annealing technology. The final fitting result of the diameter deviation: -23mm (0.06%)

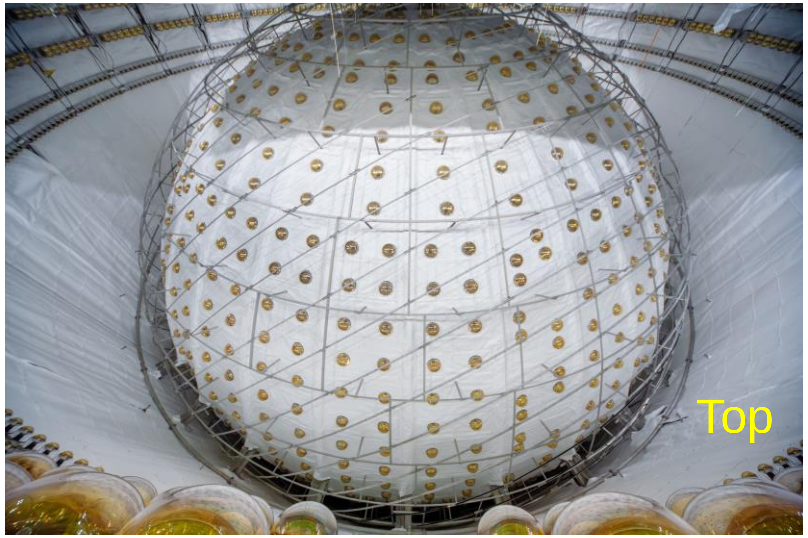
Central detector (acrylic tank)

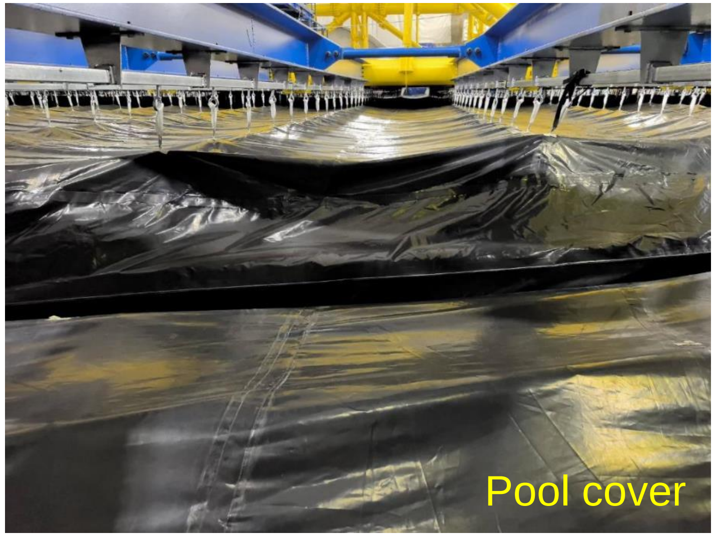


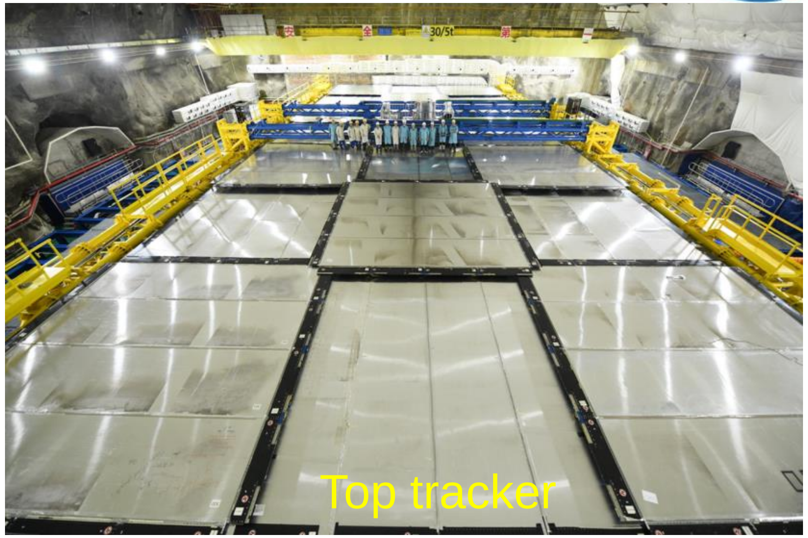
- Final checks of the acrylic tank inside and outside.
- **Moisture spray over two days** reduced dust levels inside CD air **from ~10,000 to ~100**.
- **Two weeks high pressure water jet** to **remove the protection film and clean the inner acrylic surface** by 3D rotating nozzle. Check water cleanness until satisfactory.



Veto detector







Water Cherenkov:

- ✓ 40 kt pure water for backgrounds shielding & tagging + 2400 20” PMTs + Tyvek for light reflection
- ✓ 100 t/h pure water production system
- ✓ Pool lining: 5 mm HDPE for clean water and Rn prevention
- ✓ Pool cover by using 0.6 mm vulcanized fabric

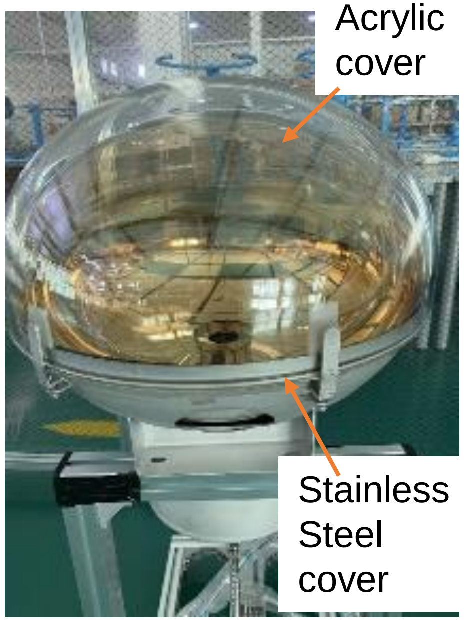
Top tracker: refurbished OPERA plastic scintillators

Earth magnetic field compensation coil

PMT testing

All PMTs were produced, tested, and instrumented with waterproof

Water proof potted PMT

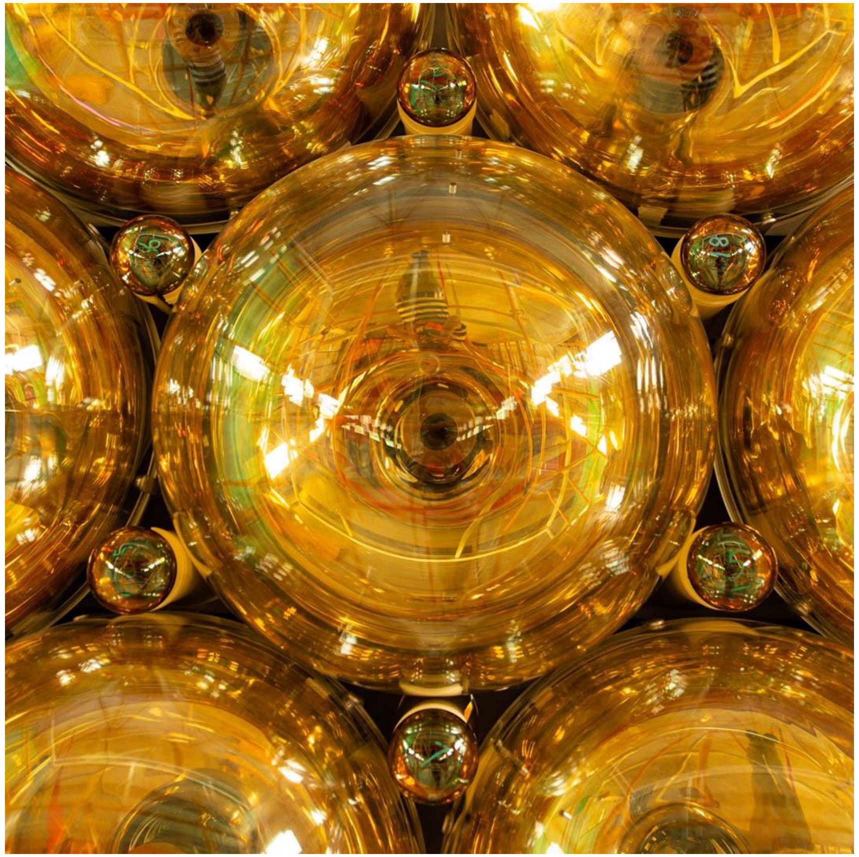


potting		LPMT (20-inch)		SPMT (3-inch)
		Hamamatsu	NNVT	HZC
Quantity		5000	15012	25600
Charge Collection		Dynode	MCP	Dynode
Photon Detection Efficiency		**28.5%**	**30.1%**	25%
Mean Dark Count Rate [kHz]	Bare	15.3	49.3	0.5
	Potted	**17.0**	**31.2**	
Transit Time Spread (σ) [ns]		1.3	7.0	1.6
Dynamic range for [0-10] MeV		[0, 100] PEs		[0, 2] PEs
Coverage		75%		3%
Reference		EPJC 82 (2022) 12, 1168		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.

PMT installation

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

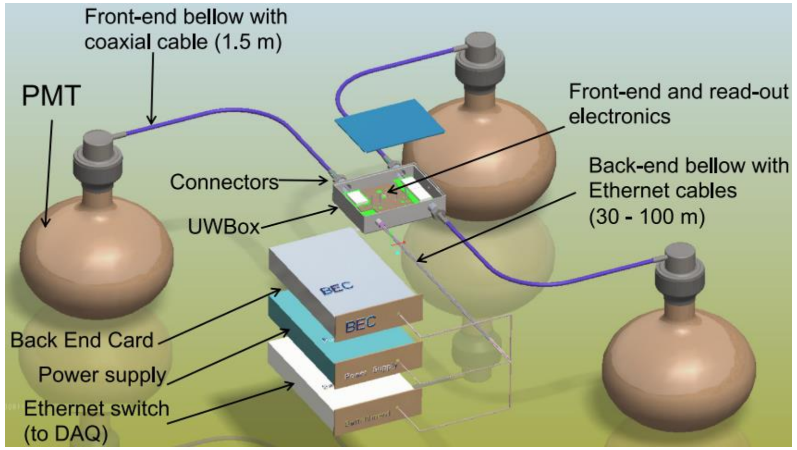


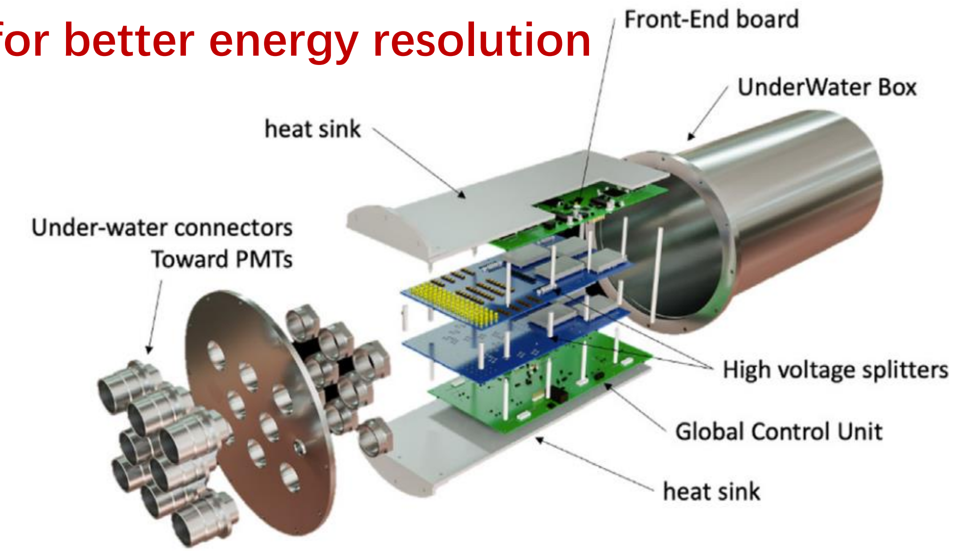
Clearance between PMTs: 3 mm → **Assembly precision: < 1 mm**

17612-16 LPMTs installed for CD, 2400-1 LPMTs installed for VETO, 25600-13 sPMT installed for CD

Electronics

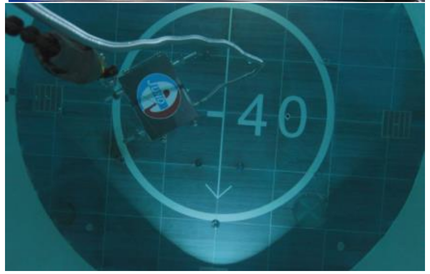
Underwater electronics to improve signal-to-noise ratio for better energy resolution

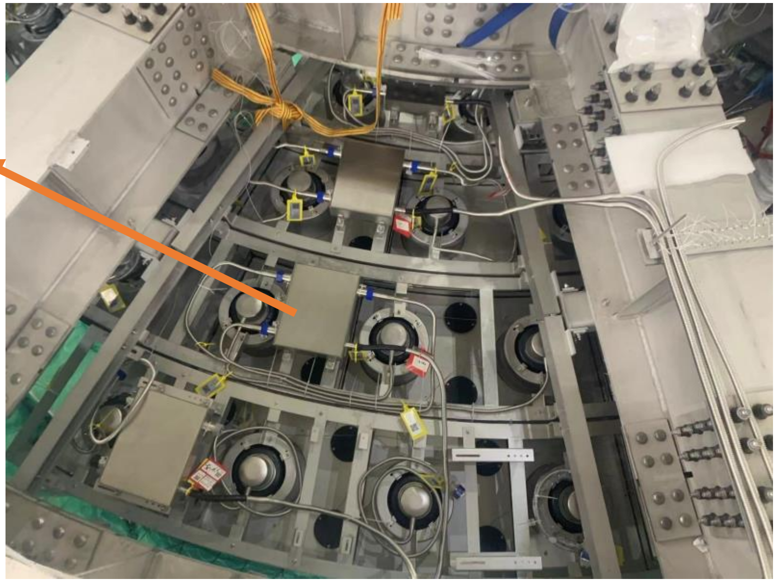


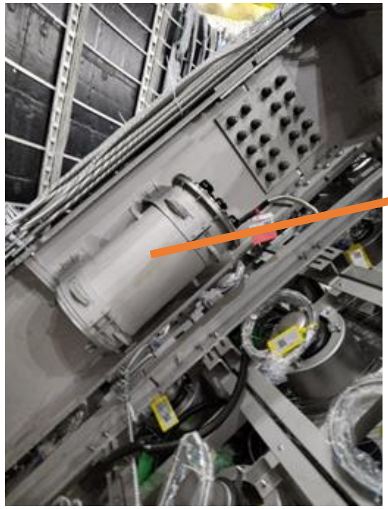


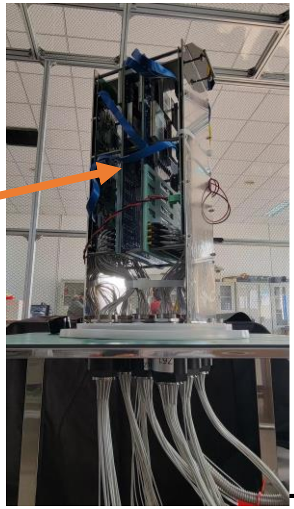
3 20-inch PMTs connected to one underwater box

128 3-inch PMTs connected to one underwater box







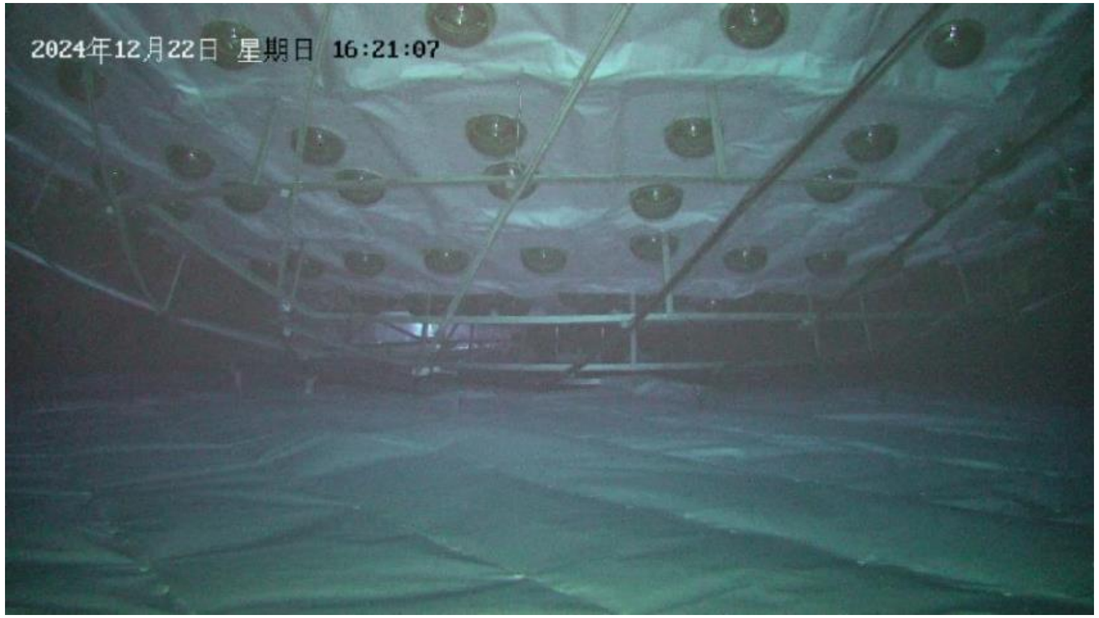


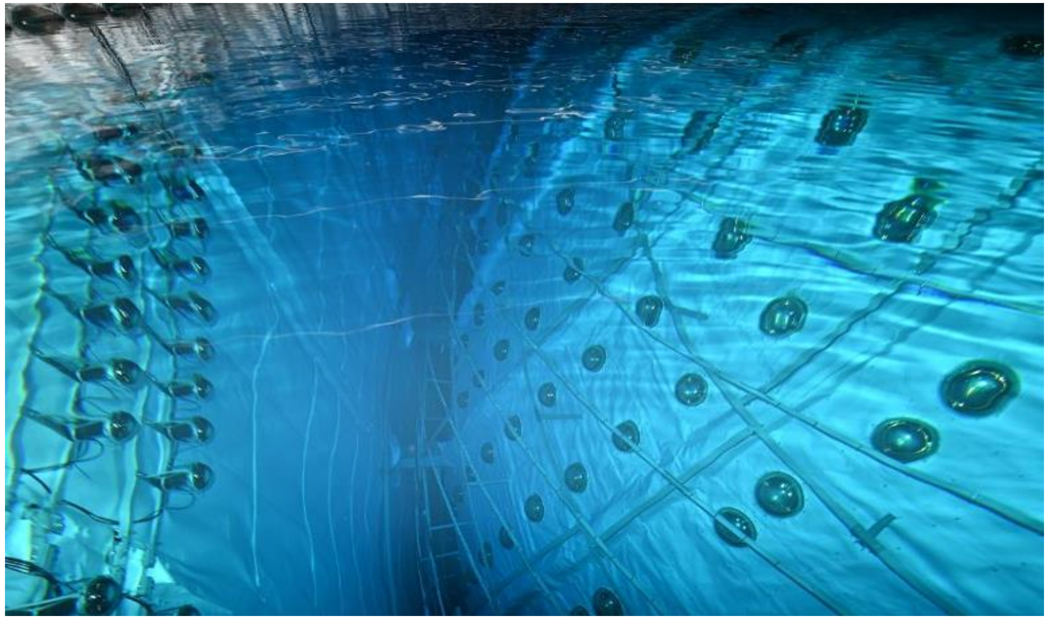
External perspective

Internal perspective

Filling the detector with water

Simultaneous filling of ultrapure water inside and outside the sphere → totally filled 60 kt





- ✓ **Filling started on Dec. 18, 2024, and finished in 45 days. No light and gas leak.** Keep the temperature uniformity **21.1℃±0.5℃**
- ✓ Liquid and air pressure were kept the same between the inside and outside of the acrylic tank. Water pipes and acrylic tank “breath” with N_2
- ✓ Stress of the detector structure closely monitored, in good agreement with expectations

	Muon rate [Hz]	Efficiency [%]	Attenuation length [m]	U/Th [10^{-15} g/g]	^{222}Rn [mBq/m^3]	^{226}Ra [mBq/m^3]
Design	~4	99.5	30-40	10	<10	<1
Reached	5	99.99	>60	<0.4	<5	<0.01

Liquid scintillator (20 kton)

Four purification plants + LS Mixing + QA/QC + high purity N_2 and water production plant to guarantee radio-purity and transparency

Recipe: LAB + 2.5g/L PPO + 3 mg/L bis-MSB

NIM.A 908 (2021) 164823


5000 m^3 LAB tank


Al_2O_3 to remove particles

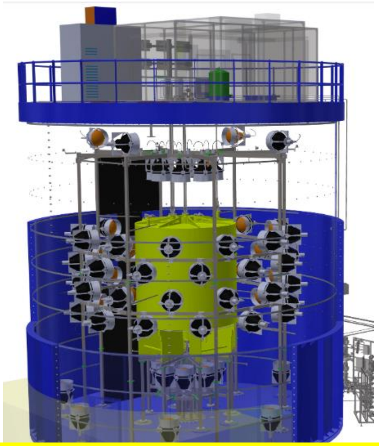

Distillation to remove radioactive impurities

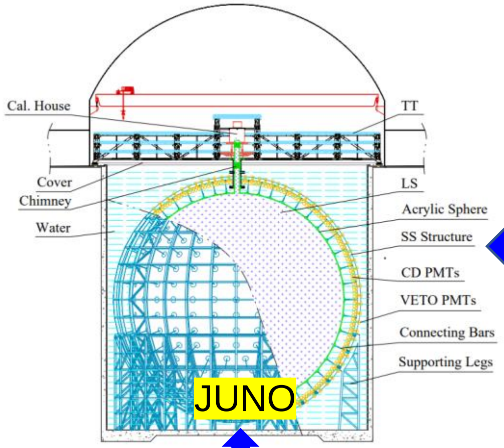

Add 2.5 g/L PPO and 3 mg/L bis-MSB

SS pipes to underground


Water extraction to remove radioactive impurities


Gas stripping to remove Rn and O_2


OSIRIS for LS qualification



JUNO

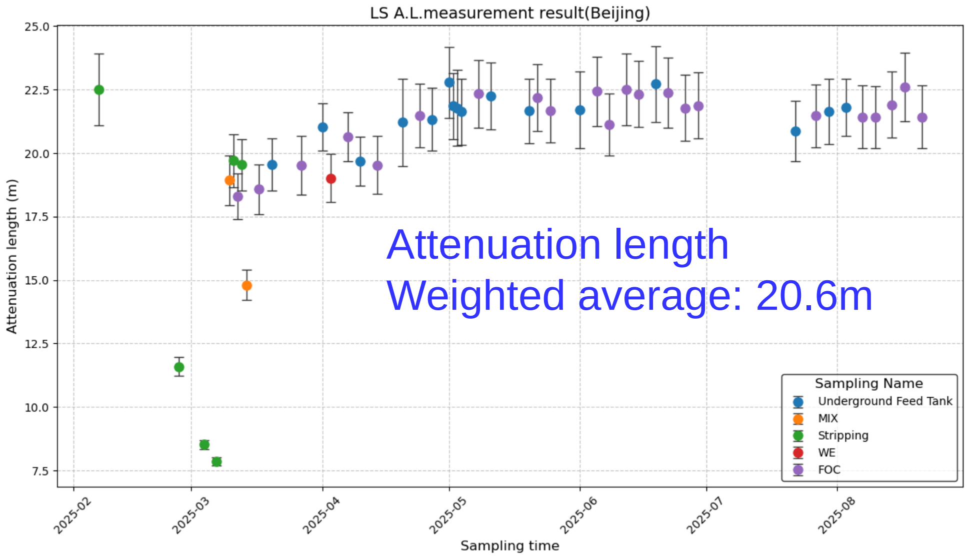
Samples tested by ICP-MS every week for radiopurity, verified by NAA and other methods

Liquid scintillator filling

Simultaneous water extraction and LS filling

Comprehensive QC/QA program for LS production, measured for batches:

- ✓ Radiopurity by ICP-MS every week: U/Th < 1×10^{-16} g/g
- ✓ ^{222}Rn in fresh LS, monitored by CD: <1 mBq/m^3
- ✓ ^{222}Rn leak < 0.5 mBq/h
- ✓ Frequent radiopurity monitoring for N_2 and water
- ✓ Weighted average attenuation length > 20m



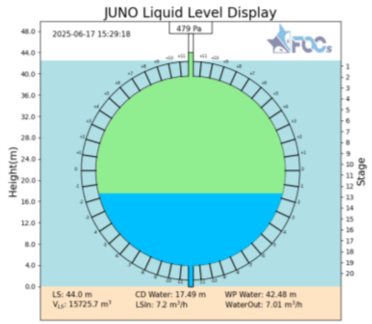
2024, Dec 18 — Start of Water Filling

2025, Feb 1 — End of Water Filling

Water Phase

2025, Feb 8 — Start of LS Filling

Mixed Phase



2025, Aug 22 — End of LS Filling

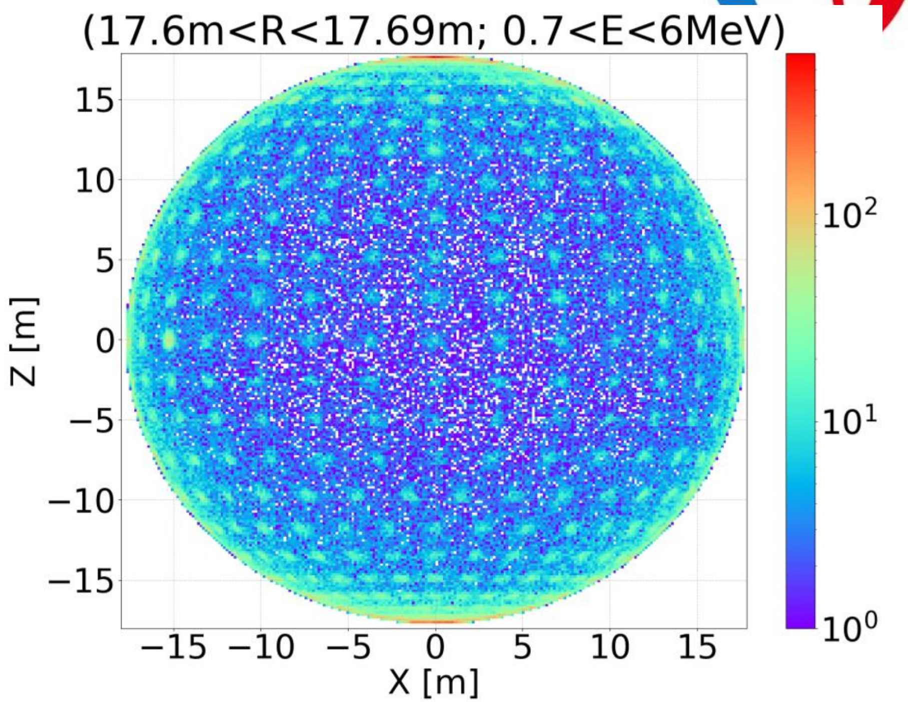
2025, Aug 23 — Replace 100 t old LS

Full detector calibration

2025, Aug 26 08:00 — Start of Data Taking

A clean detector

- **VETO Water:**
  - U/Th<0.4×10^{-15} g/g, ^{222}Rn<10 mBq/m^3, ^{226}Ra<1 mBq/m^3
- **Acrylic, water, PMTs, steel and LS are clean and water shielding works :**
  - Single rate <7 Hz for R<17.2m & E>0.7MeV (design 7.2Hz)
  - Good enough for reactor neutrinos
- **LS cleanness is very close to other solar neutrino experiments**
  - ^{238}U < 3×10^{-17} g/g (low radon area in a small fiducial volume)
    < 1×10^{-16} g/g (fitted plateau from full detector radon decay)
  - ^{232}Th < 1×10^{-16} g/g (R<13m)
  - ^{210}Po < 1×10^{5} [cpd/kt]



Radiopurity control of raw material:

- ✓ Meticulous Monte Carlo Simulation for proper distribution of radioactivity budget
- ✓ Careful material screening
- ✓ Accurate detector production handling

Better than spec. by 15% !

JHEP 11 (2021) 102

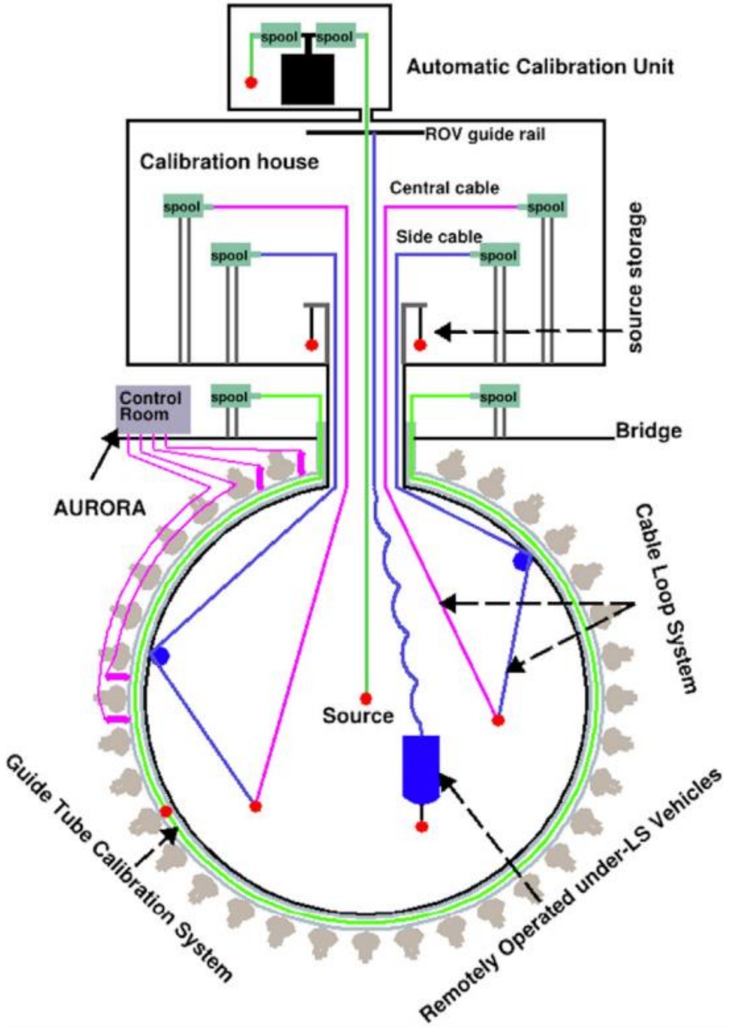
Radiopurity control during installation :

- Leak check of all joints (each < 10^{-8} mbar·L/s) for ^{222}Rn and ^{85}Kr √
- Cleaning and washing of all pipes & vessels to remove dust (by check water/LAB cleanness) √
- Clean room environment during installation √
- Acrylic Surface treatment and protection(Rn daughters) √
- LS filling scheme: water replacement and water washing √

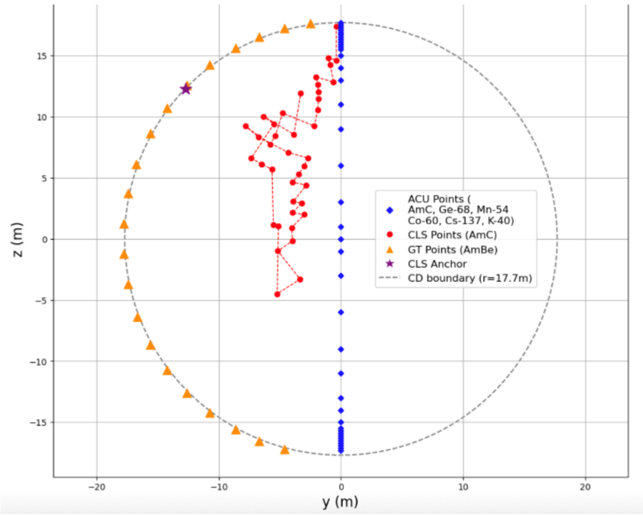
Recirculation probably impossible, unlike Borexino, KamLAND, SNO+,…

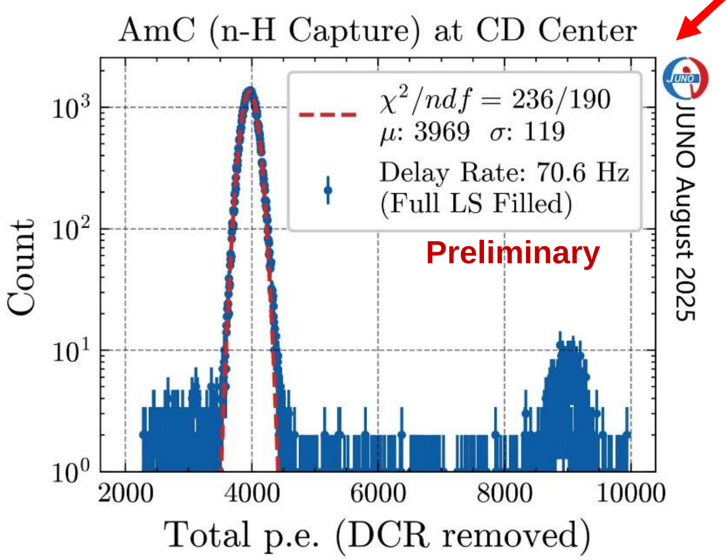
Calibration

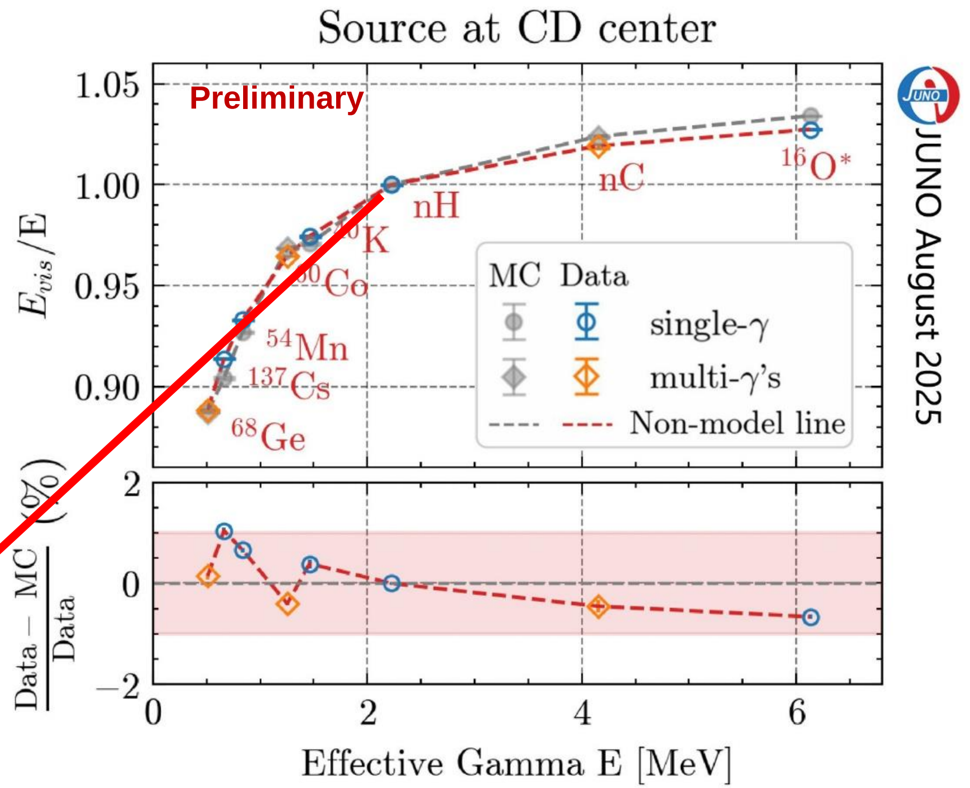
1D, 2D, 3D scan systems using laser/e^+/γ/n sources + n/α background events



Calibration position performed





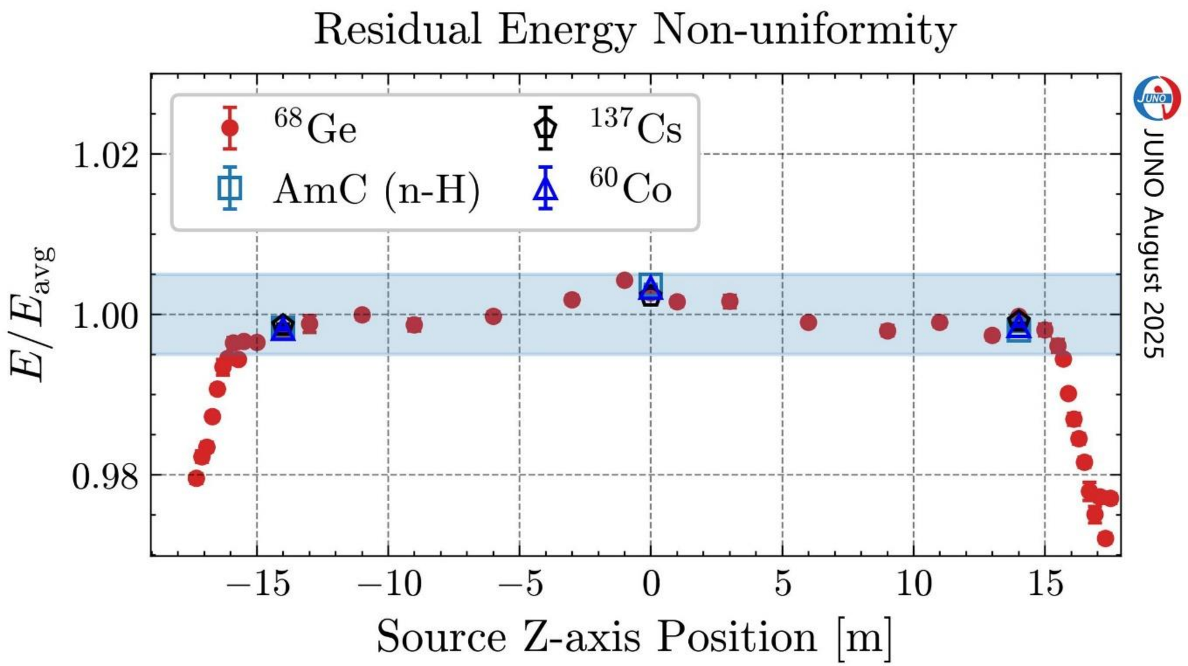


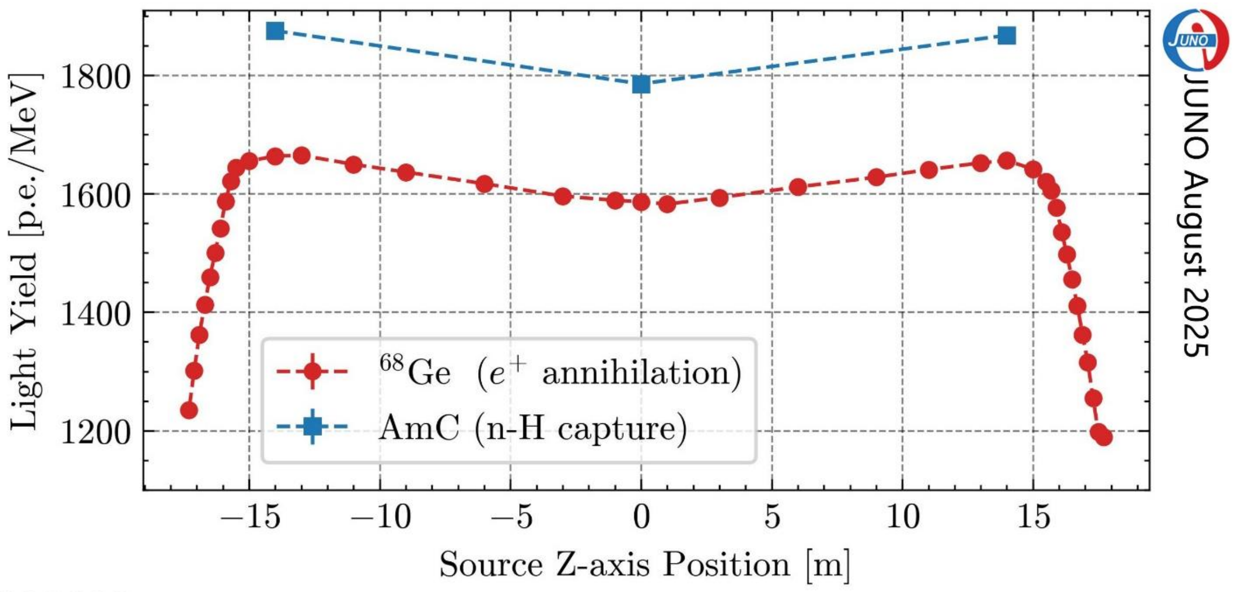
(E_{vis}: scaled from total charge)

Energy Non-linearity is known to < 1% !

Uniformity and light yield

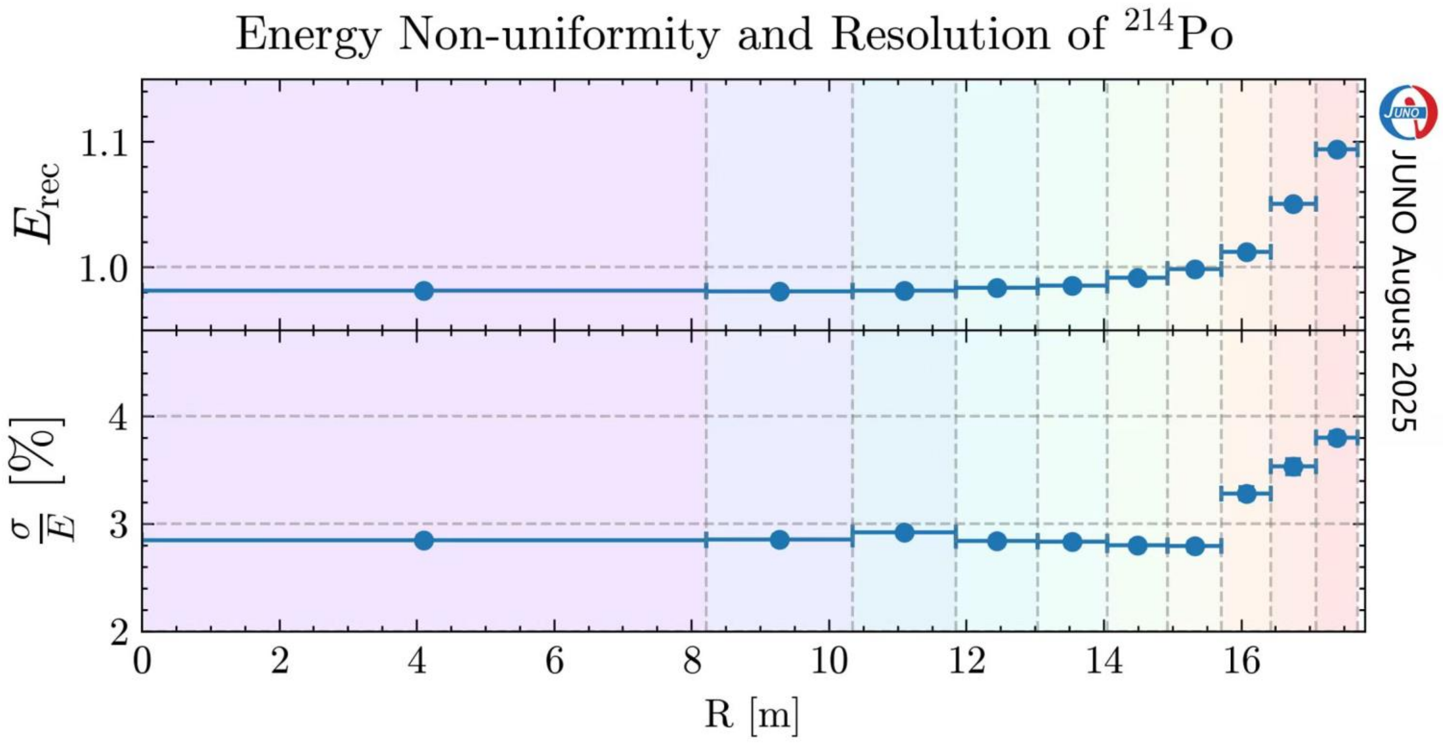
- For R<16m, residual energy non-uniformity scanned along the Z-axis is <0.5%
- Light yield is >1600 PE/MeV for ^{68}Ge, >1800 PE/MeV for neutron, better than expectations (difference due to non-linearity, *Chinese Phys. C 49 (2025) 013003*)
- Edge effects still exist, more calibration data and software work needed

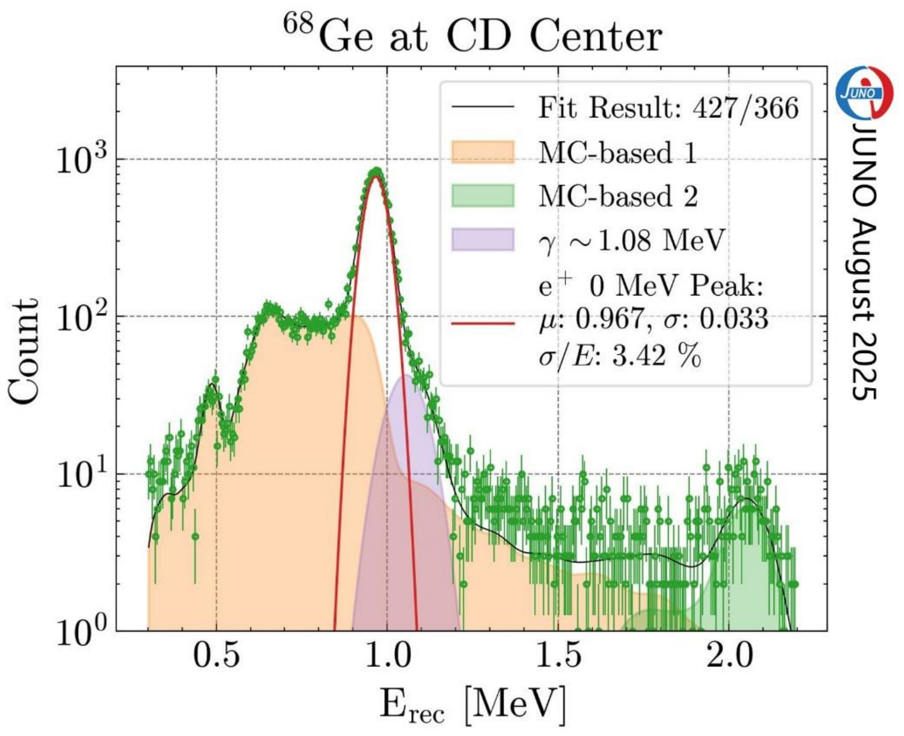




Energy Resolution

- Energy resolution for alpha from ^{214}Po is ~3% @0.92MeV
- Energy resolution for ^{68}Ge is ~3.4% @ 2× 0.511 MeV, already close to but slightly worse than the expectation of 3.1%
- Further improvement are coming: more calibration data, noise/flasher removal, reconstruction and fit, …





Summary and outlook

- After 17 years efforts, from idea to construction, JUNO detector is fully completed, despite numerous challenges
- Initial testing and performance studies show that key specifications have been mostly met
- We are excited to have started the physics data taking:
    - Results from reactor and astrophysical neutrinos will come soon

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
Diffuse Supernova Neutrino Background	3σ in 3 yrs
Solar neutrino	Measure Be7, pep, CNO simultaneously, measure B8 flux independently
Nucleon decays ($p \rightarrow \bar{\nu} K^+$)	9.6×10^{33} years (90% C.L.) in 10 yrs
Geo-neutrino	~400 per year, 8% measurement in 10 yrs