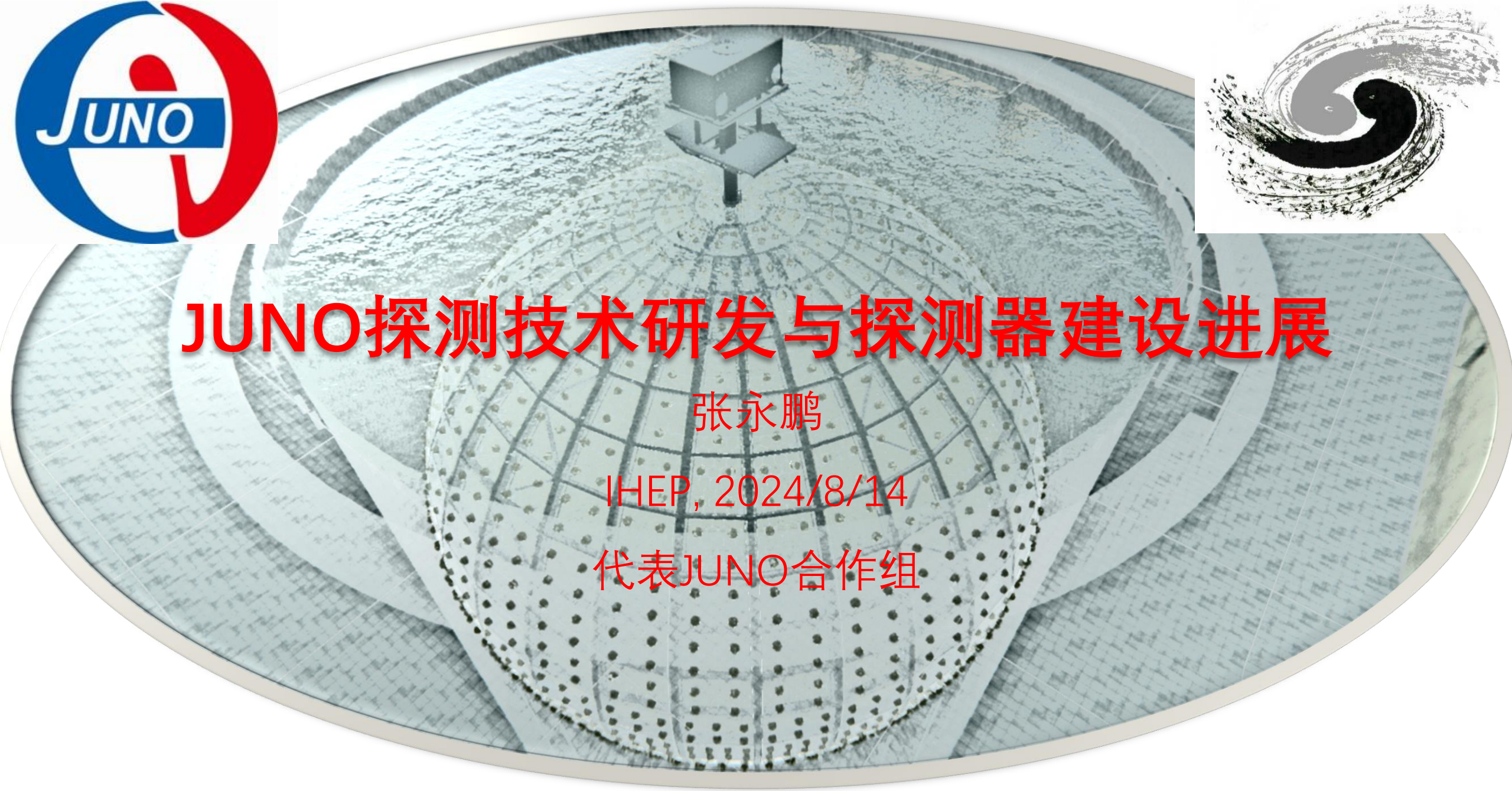


JUNO探测技术研发与探测器建设进展

张永鹏

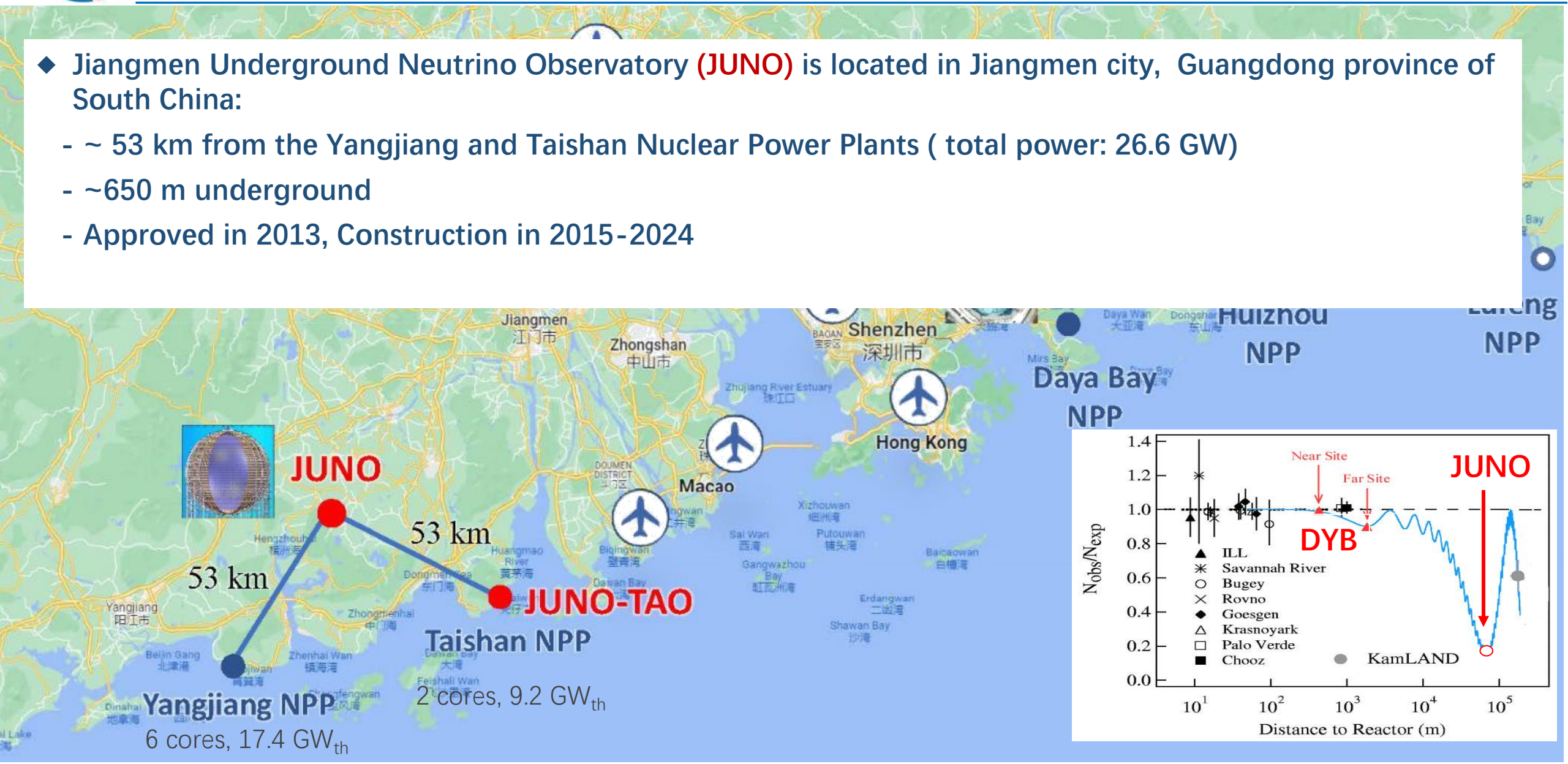
IHEP, 2024/8/14

代表JUNO合作组

中国物理学会高能物理分会第十四届全国粒子物理学术会议, 8/13-8/18, 2024

JUNO experiment

- Jiangmen Underground Neutrino Observatory (JUNO) is located in Jiangmen city, Guangdong province of South China:
  - ~ 53 km from the Yangjiang and Taishan Nuclear Power Plants (total power: 26.6 GW)
  - ~650 m underground
  - Approved in 2013, Construction in 2015-2024



JUNO collaboration

- Collaboration established in 2014
- now more than 700 collaborators from 74 institutions in 17 countries/regions

Country	Institute	Country	Institute	Country	Institute
Armenia	Yerevan Physics Institute	China	Tsinghua U.	Germany	U. Tuebingen
Belgium	Universite libre de Bruxelles	China	UCAS	Italy	INFN Catania
Brazil	PUC	China	USTC	Italy	INFN di Frascati
Brazil	UEL	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	Pakistan	PINSTECH (PAEC)
China	CIAE	China	CUG-Beijing	Russia	INR Moscow
China	DGUT	China	ECUT-Nanchang City	Russia	JINR
China	Guangxi U.	China	CDUT-Chengdu	Russia	MSU
China	Harbin Institute of Technology	Czech	Charles U.	Slovakia	FMPICU
China	IHEP	Finland	University of Jyvaskyla	Taiwan-China	National Chiao-Tung U.
China	Jilin U.	France	IJCLab Orsay	Taiwan-China	National Taiwan U.
China	Jinan U.	France	LP2i Bordeaux	Taiwan-China	National United U.
China	Nanjing U.	France	CPPM Marseille	Thailand	NARIT
China	Nankai U.	France	IPHC Strasbourg	Thailand	PPRLCU
China	NCEPU	France	Subatech Nantes	Thailand	SUT
China	Pekin U.	Germany	RWTH Aachen U.	U.K.	U. Liverpool
China	Shandong U.	Germany	TUM	U.K.	U. Warwick
China	Shanghai JT U.	Germany	U. Hamburg	USA	UMD-G
China	IGG-Beijing	Germany	GSI	USA	UC Irvine
China	SYSU	Germany	U. Mainz		

The 24th JUNO collaboration meeting

JUNO: A multi-purpose observatory

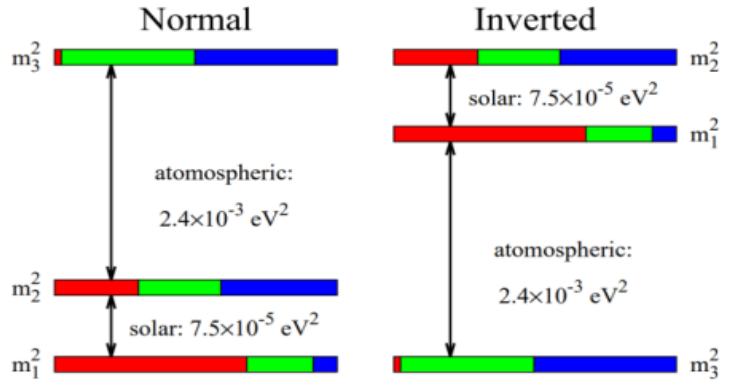
- **Neutrino Mass Ordering (NMO)measurement**
  - -Reactor: JUNO will determine NMO with 3σ significance in 6 years exposure
  - -Atmospheric neutrino: Combined analysis with reactor further improve the NMO sensitivitv

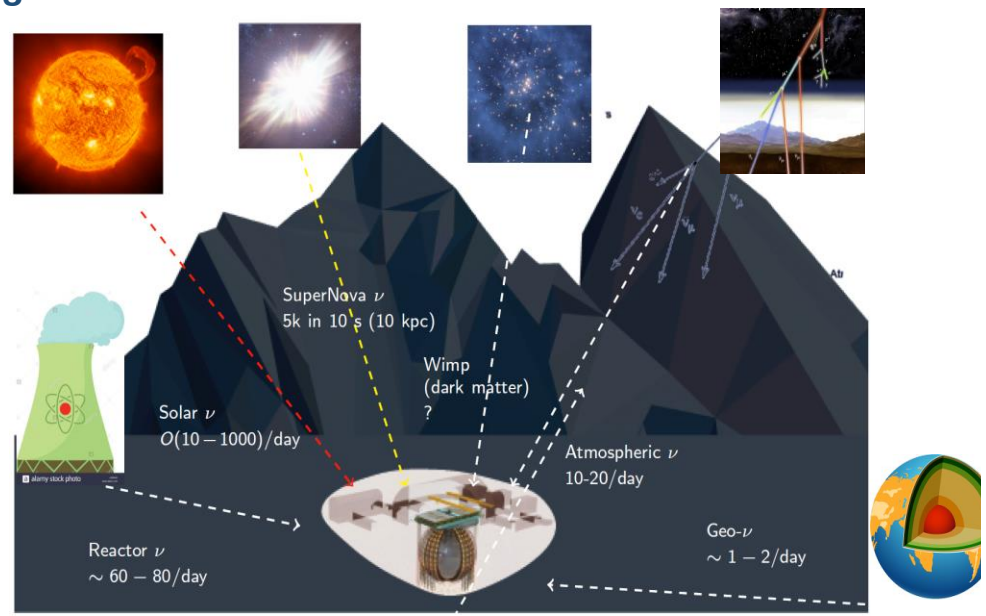
arXiv:2405.18008 (2024)

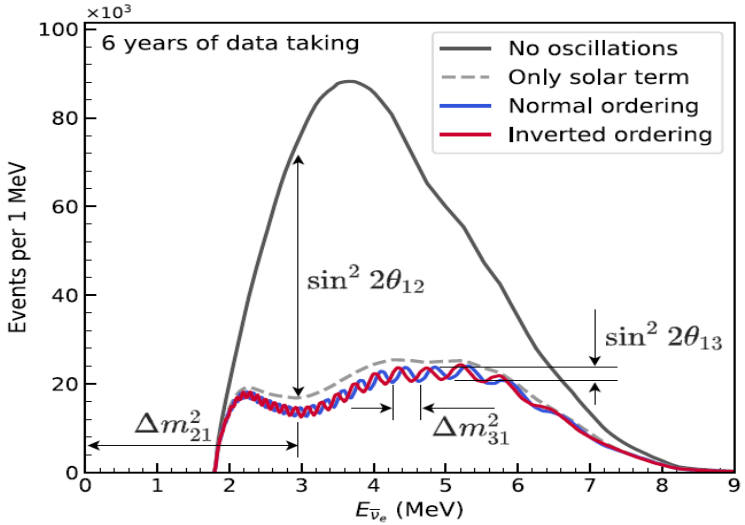
- **Precision measurement of oscillation parameters**
  - for $\sin^2 2\theta_{12}$, Δm^2_{21}, $|\Delta m^2_{32}|$, world-leading precision in 100 days, and precision <0.5% in 6 years

Chin. Phys. C46 (2022) 12, 123001

- **Many other physics programs**
  - Solar neutrinos
  - Geo-neutrinos
  - Supernova burst neutrinos
  - Supernova relic neutrinos
  - Exotic neutrinos
  - Nucleon decay







Details in Runze Zhao's and Yibing Zhang's talks

"Neutrino Physics with JUNO," J. Phys. G **43** (2016) no.3, 030401

"JUNO Physics and Detector," Prog. Part. Nucl. Phys. **123** (2022), 103927

JUNO Site

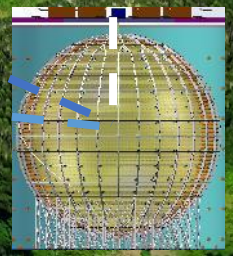
Surface buildings / campus

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

Vertical Shaft, 564 m
put into use in 2023

Slope tunnel, 1266 m

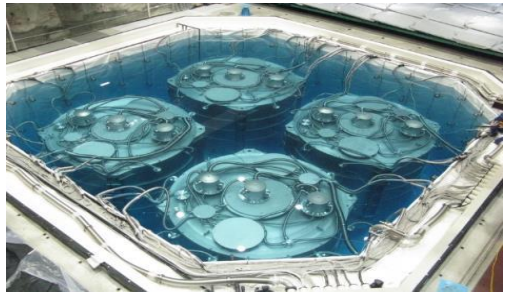
~ 650 m
R_μ ~ 0.004 Hz/m^2
$\langle E_\mu \rangle$ ~ 207 GeV



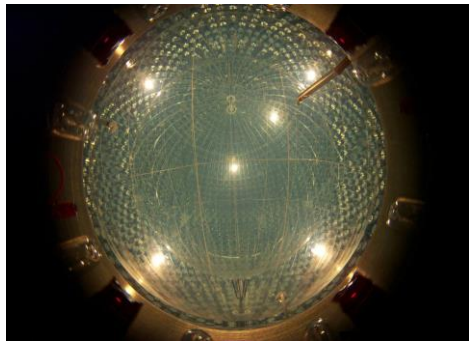
JUNO detector requirement

- **Main requirement: Target mass of 20 kton liquid scintillator, Energy resolution 3%@ 1MeV**
- **Unprecedented liquid scintillator neutrino experiment**

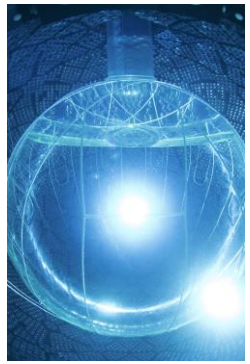
	Daya Bay	BOREXINO	SNO+	KamLAND	**JUNO**
Target Mass	8* 20 ton	300 ton	780 ton	1 kton	**20 kton**
Number of PMTs	8 *192 8-in.	2212 8-in.	~10000 8-in.	1325 20-in. + 554 17-in.	**20012 20-in.+ 25600 3-in.**
Photoelectron Yield (p.e./MeV)	160	450	520	250	**>1300**
Photocathode Coverage	12%	30%	50%	34%	**78%**
Energy Resolution@1MeV	7.5%	5%	6%	6%	**3%**
Energy calibration	<1%	1%	⩽ 1%	2%	**≤ 1%**



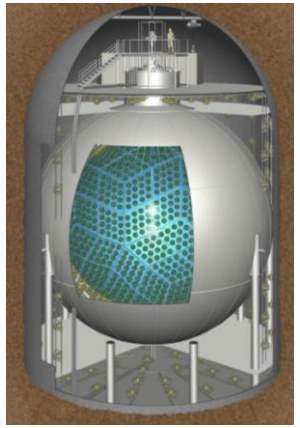
Daya Bay (20x8t)



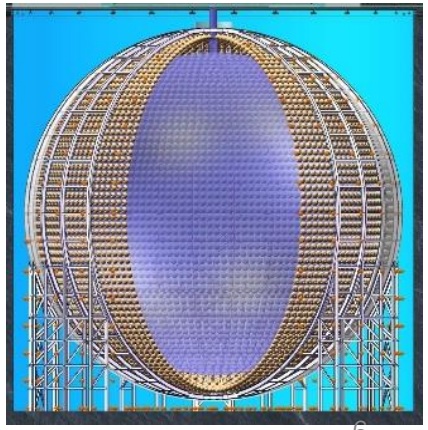
Borexino(300t)



SNO+ (780t)

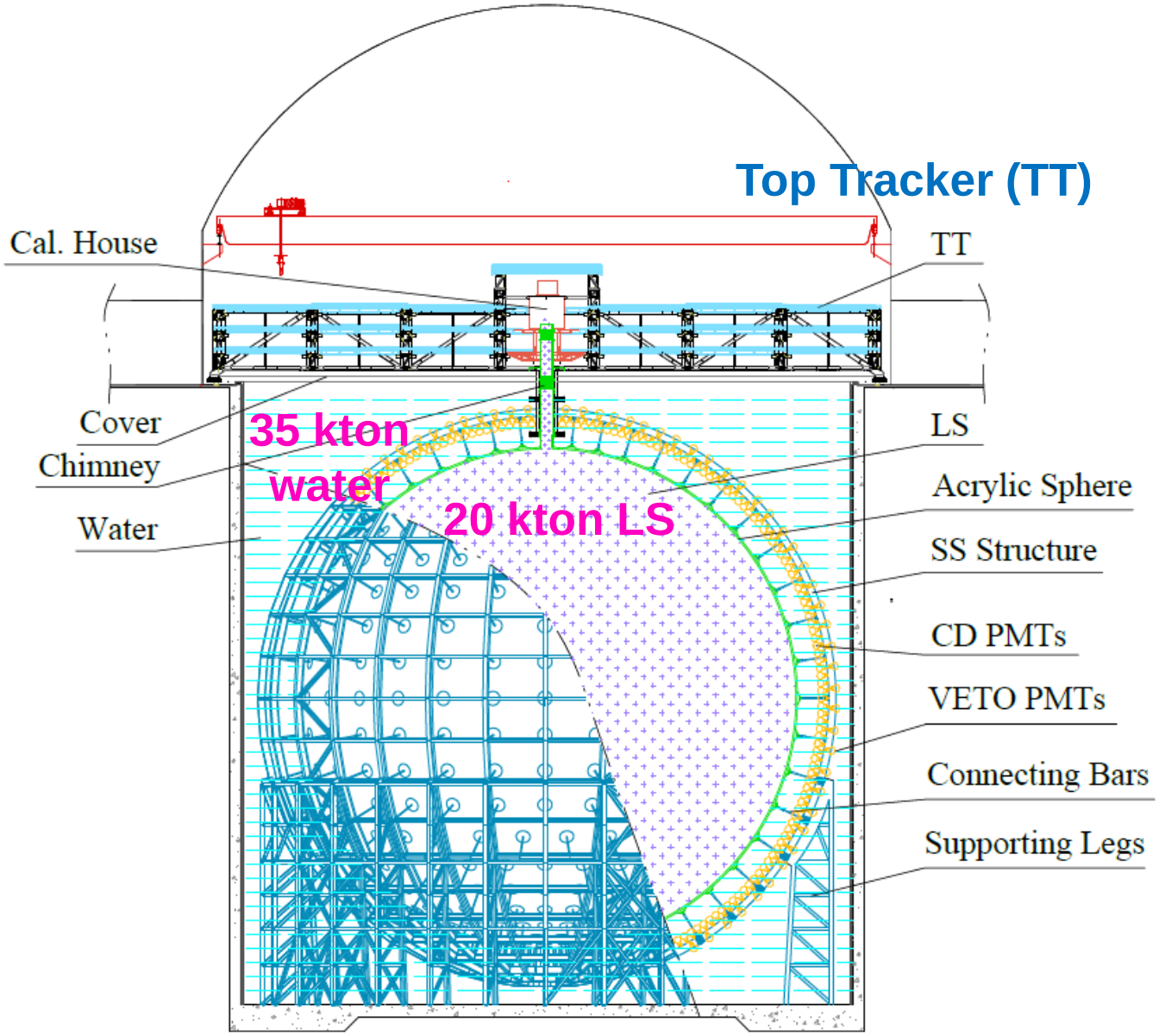


KamLand(1000t)



JUNO (20 kt)

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

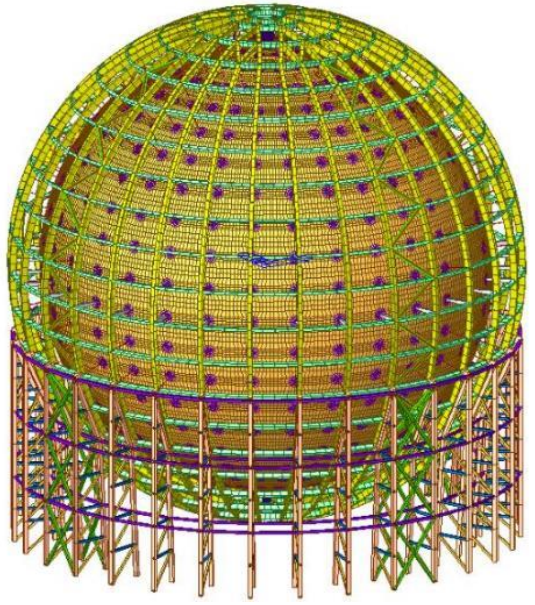
Water pool:

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

2400 20-inch PMTs

Central detector

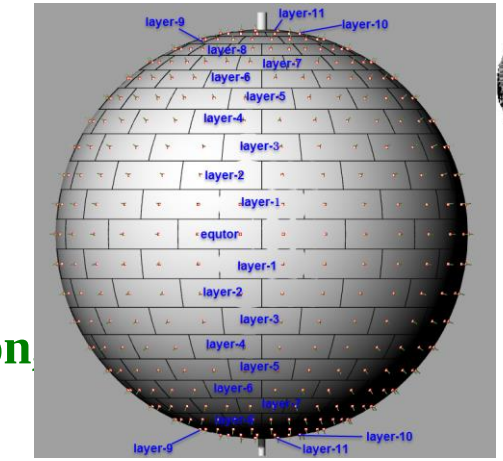
ϕ 35.4 m acrylic sphere supported by ϕ 41.1 m SS structure via 590 supporting bars

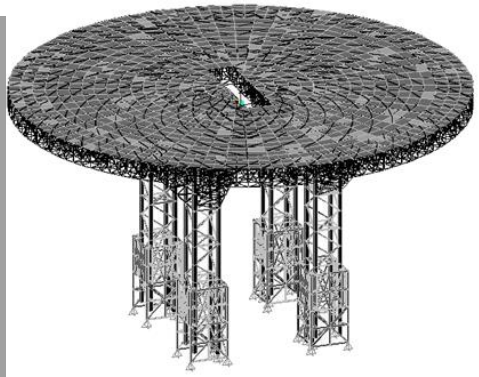


- Acrylic sphere
  - made by 263 acrylic panels, 23 layers
  - good transparency(>96% in water), and low background (< 1 ppt for U/Th)
- Stainless-steel structure (SS structure)
  - latticed shell made by latitude and longitude beams
  - 30 supporting legs fixed on the water pool base
  - 800 tons low-radioactivity stainless-steel (type 304, radio-impurity <1ppb)
  - small deviation in radius after survey
    - ✓ design: 20550 mm; survey: 20530 mm; deviation: <20mm (1‰)

arXiv: 2311.17314 (2023)

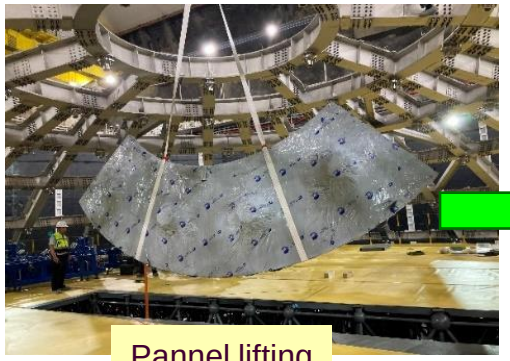
- **Acrylic vessel construction on-going (critical path, Jul. 2022 – now)**
  - currently 19/23 finished
  - a lifting platform used, height and diameter changeable
  - Panels bonded by the bulk-polymerization technique
  - **Many problems solved during construction: explosive polymerization, defects repairing, stress monitoring measurement, etc**



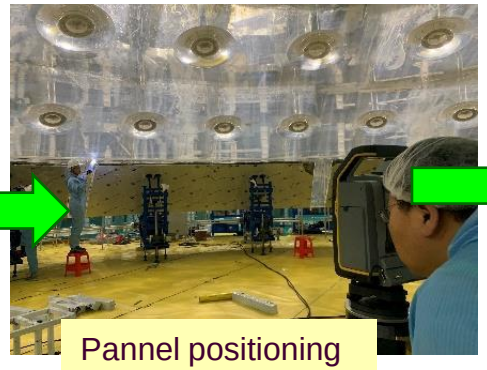


lifting Platform

Construction of acrylic sphere

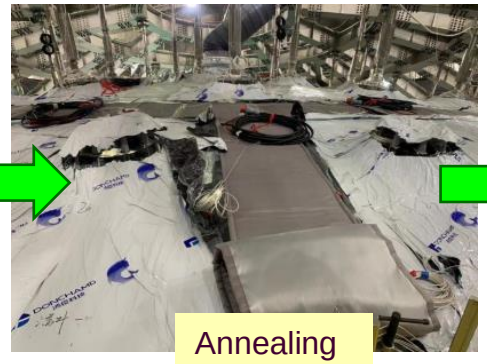


Pannel lifting



Pannel positioning

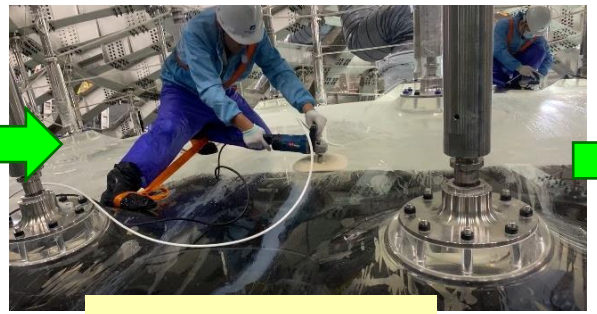
Polymerization



Annealing

Sensor installation

Supporting bar installation



Bonding line sanding

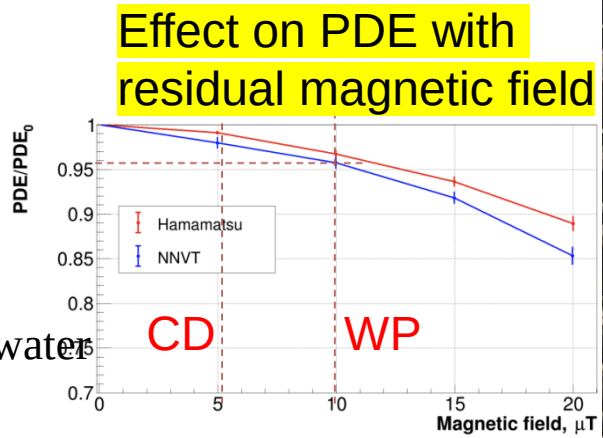
Cleaning

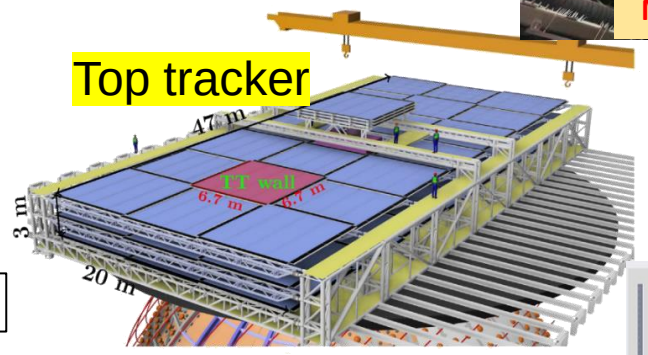
Filming

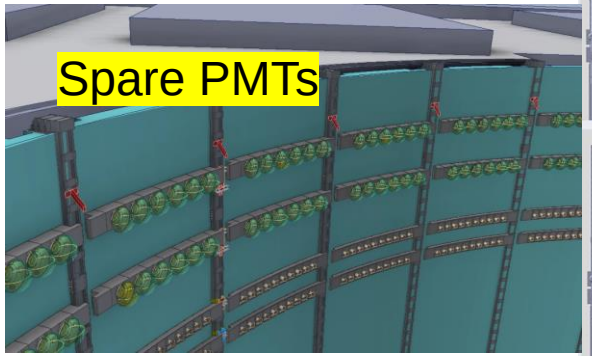
Inside the detector

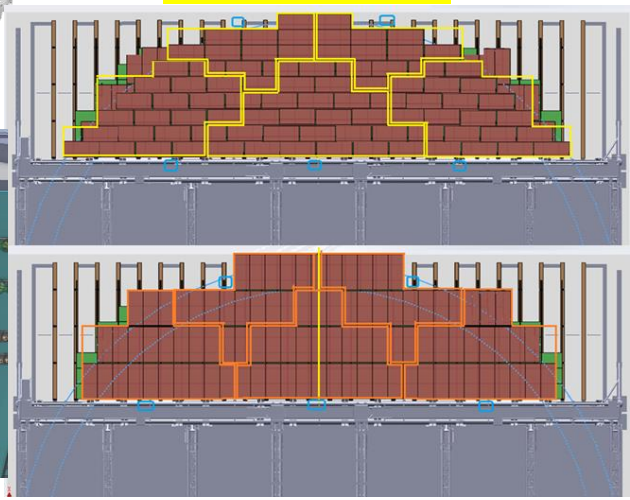
Veto detector

- **Earth Magnetic Field (EMF) compensation coil**
  - ⇨ Big effect on the 20 inch PMT performance and detection efficiency losing up to 60% w/ EMF
- **Water Cherenkov detector**
  - ⇨ 35 kton water to shield backgrounds from the rock
  - ⇨ Instrumented w/ 2400 20-inch PMTs
  - ⇨ Water pool lining: 5 mm HDPE (black) to keep the clean water and to stop Rn from the rock
  - ⇨ Sealed cover and filling nitrogen gas over the water surface
  - ⇨ 100 ton/h high-purity 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**
  - ⇨ Refurbished OPERA plastic scintillators NIMA 1057 (2023) 168680
  - ⇨ 3 layers, 63 walls of 6.7 m * 6.7 m
  - ⇨ ~60% coverage on the top
  - ⇨ Angular resolution: Δθ ~ 0.2° (median value)
- **Plan to install all spare PMTs on top wall of the water pool and reuse RPC from ARGO-YBJ to improve performance of atmospheric neutrino analysis**







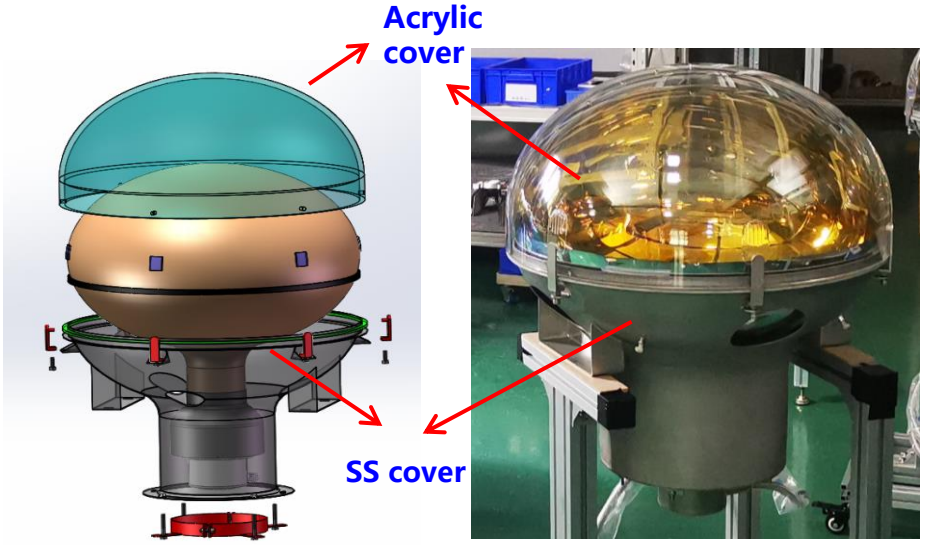


JUNO PMT

- **20-inch PMT: 15,012 MCP-PMT (NNVT) + 5,000 Dynode PMT(Hamamatsu)**
  3-inch PMT: 25,600 Dynode PMT (HZC XP72B22)
  - ⇨ All PMTs delivered and their performance (HV, SPE, PDE, DCR, TTS, P/V) 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%	24.9%
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
Coverage		75%		3%
Reference		Eur.Phys.J.C 82 (2022) 12, 1168		NIM.A 1005 (2021) 165347

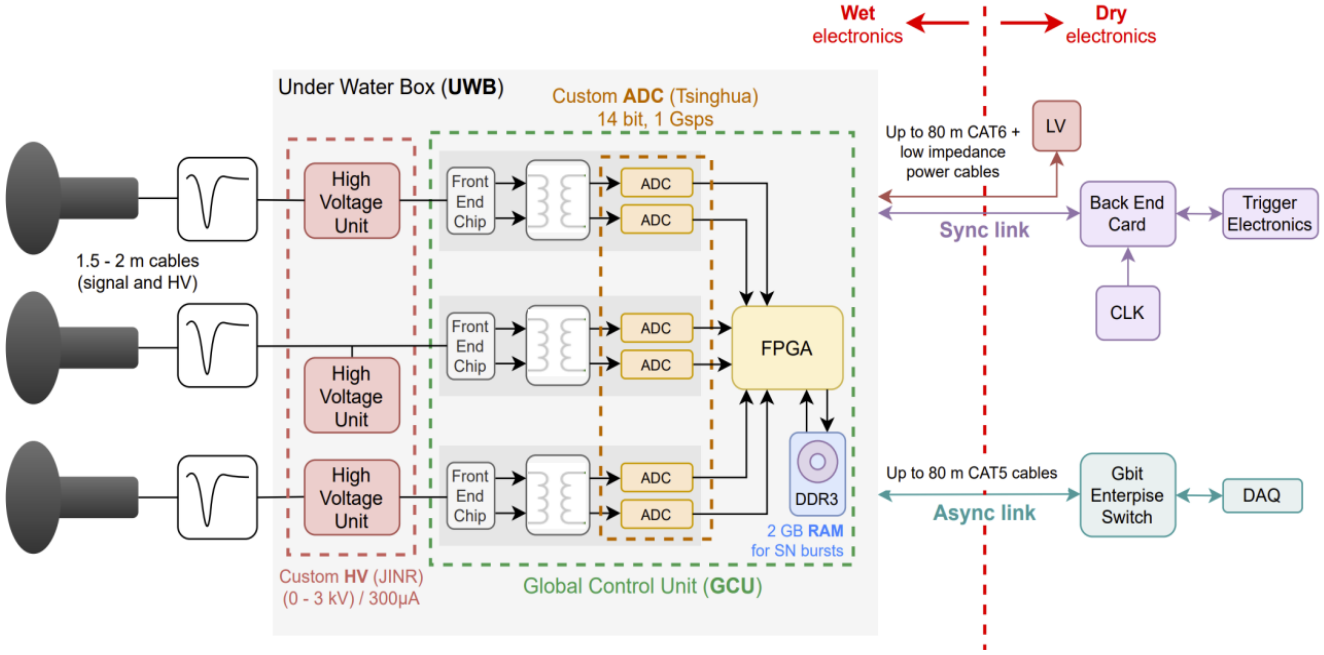
Synergetic 20-inch and 3-inch PMT systems to ensure energy resolution and charge linearity



Inner view of PMTs

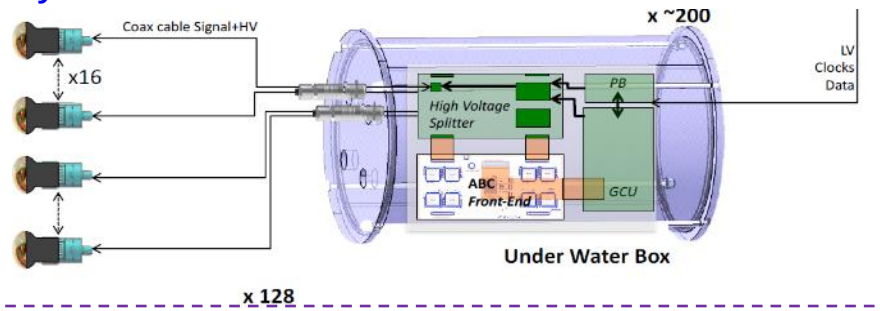
Electronics

- **LPMT electronics: 20012 channels**
  - ⇨ Dynamic range: 1- 4000 PE, Noise: <10% @1 PE, Resolution: <10%@1 PE, <1%@100 PE
- 1 GHz FADC (14 bit) in an underwater box (3 ch./box), connected to PMTs by water proof connectors
- Failure rate: < 0.5% / 6 years



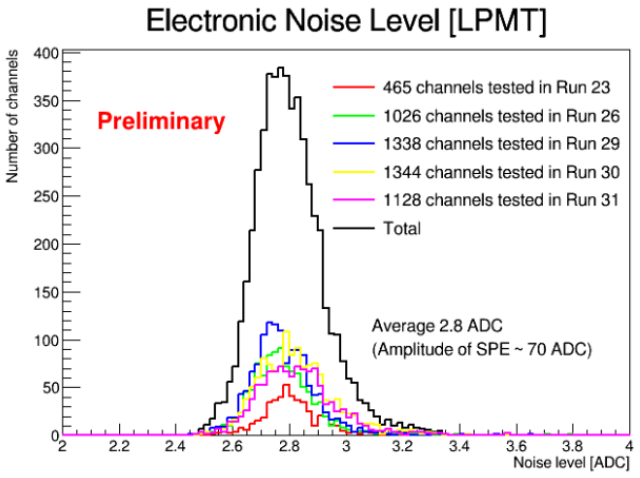
- **SPMT electronics: 25600 channels**
- 200 underwater boxes, each for 128 PMTs read by ASIC Battery Cards (ABC), each with 8 CatiROC chips
- Only time/charge readout

System overview: 200 boxes × 128 PMTs

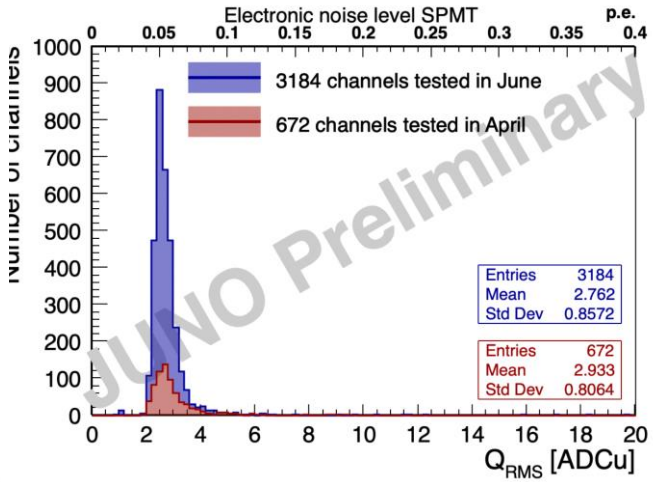


Commissioning during installation

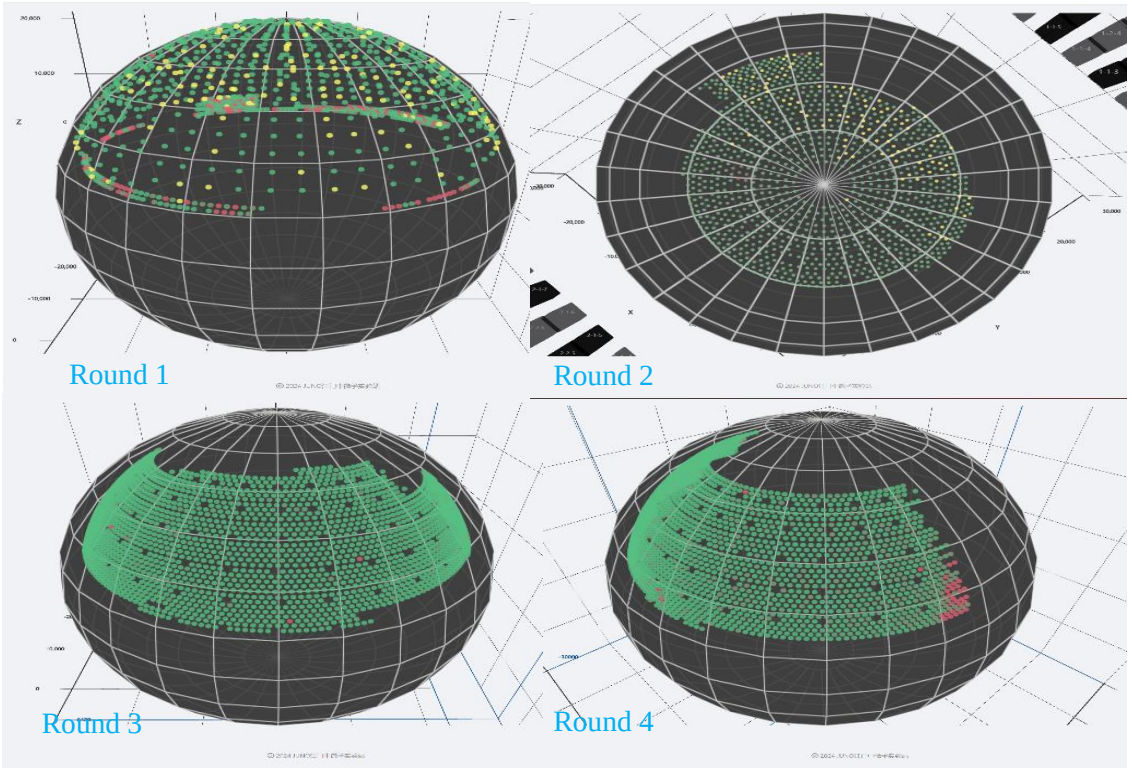
- Regular commissioning/joint test of PMTs, Elec., DAQ/DCS, during installation:
  - light-on test: Elec. /trigger/DAQ/DCS joint test w/o PMTs
  - Light-off test: PMT dark rate data taking and full chain test
- PMTs are working well, electronics shows very low noise (<5% of SPE), and good shielding and grounding;



LPMT Noise level ~0.04 PE



SPMT Noise level ~0.05 PE



Online display of PMT Dark Count Rate

Liquid Scintillator

- **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 m^3 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

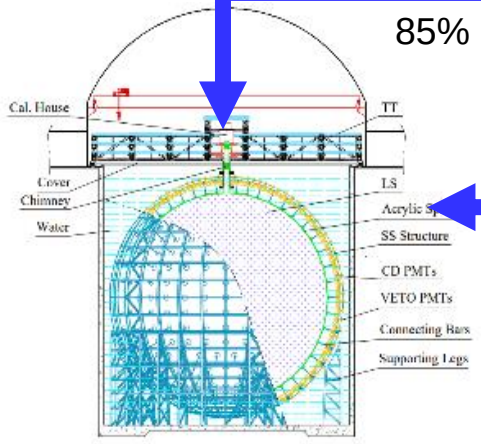
4) Gas stripping to remove Rn and O_2

15%

Monitoring pre-detector (OSIRIS)

Commissioning

85%



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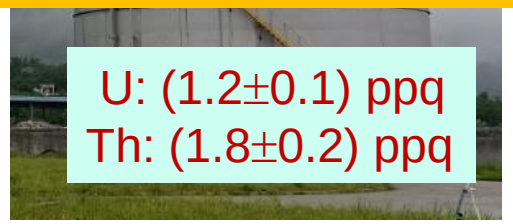
ICP-MS & neutron activation analysis developed sensitivity ~ ppq level (10^{-15} g/g)



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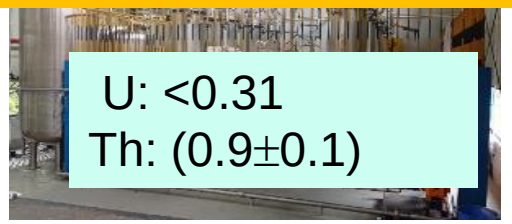
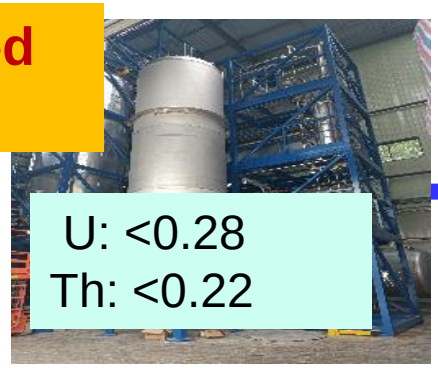
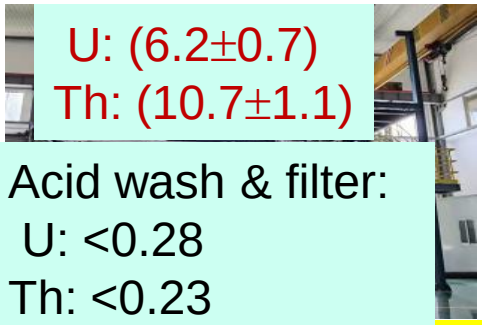


1) Al_2O_3 for optical transparency



2) Distillation for radiopurity

2.4%



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

Mixing LAB with PPO and bis-MSB

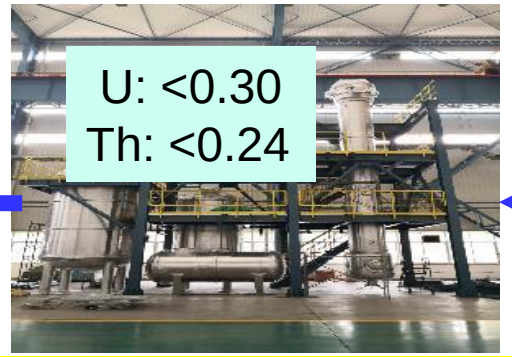
97.6%

Mixing

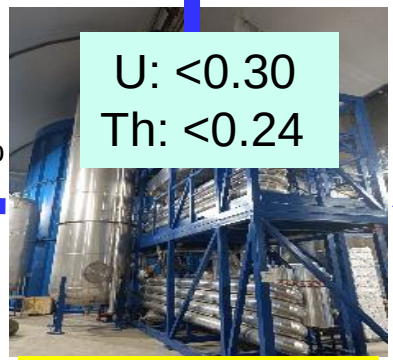
U: <0.30
Th: <0.24

pipes to underground

U: (0.34±0.06)
Th: (0.85±0.09)



3) Water extraction to remove radioactive impurities



4) Gas stripping to remove Rn and O_2

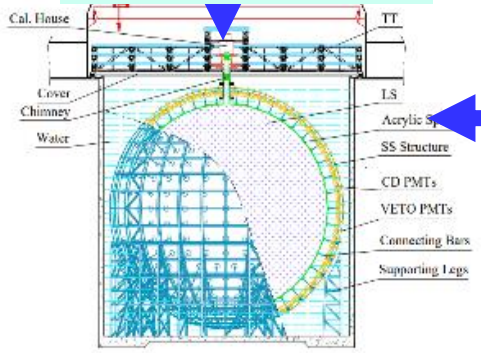
15%

Monitoring pre-detector (OSIRIS)

Commissioning

5%

FOC: U: <0.28
Th: <0.23



Detector final cleaning plan and LS filling

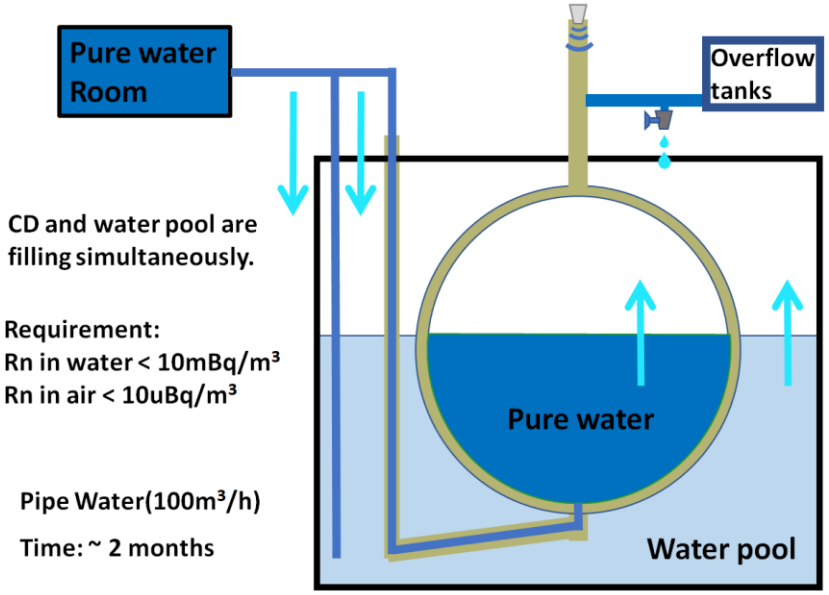
Reduce dust to class 1000 and Radon by an order of magnitude

Complete CD construction → **1-2 weeks settlement with proper moisture** → **Remove the protective film and wash the acrylic surface by the high pressure water spray**

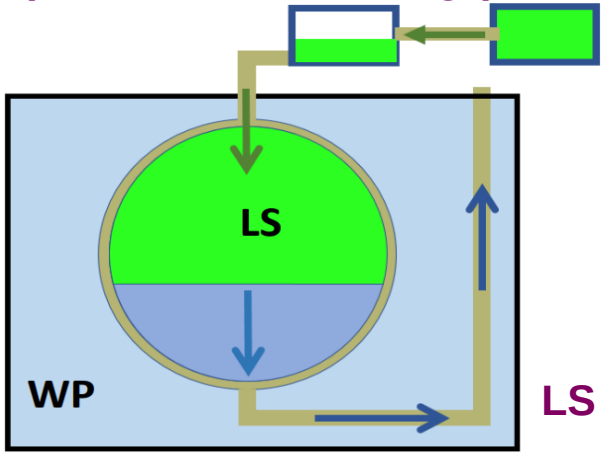
Fill CD and VETO by high purity water ← **replacing water in CD by LS**

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



LS production and filling (7 m³/hour)

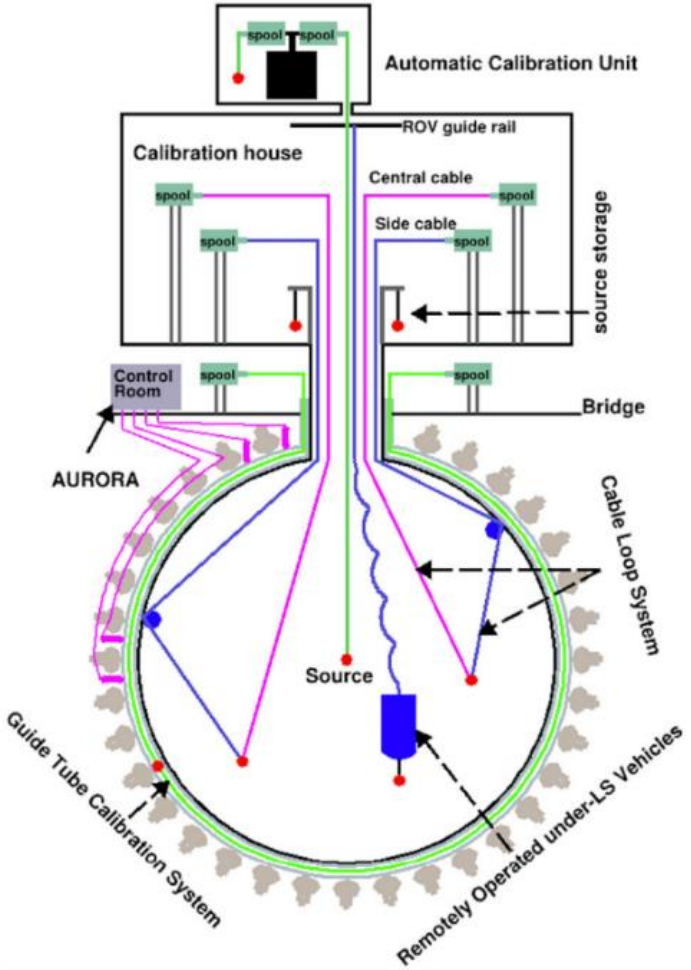


LS filling time ~ 6 months

Drain water (7 m^3/hour)

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**



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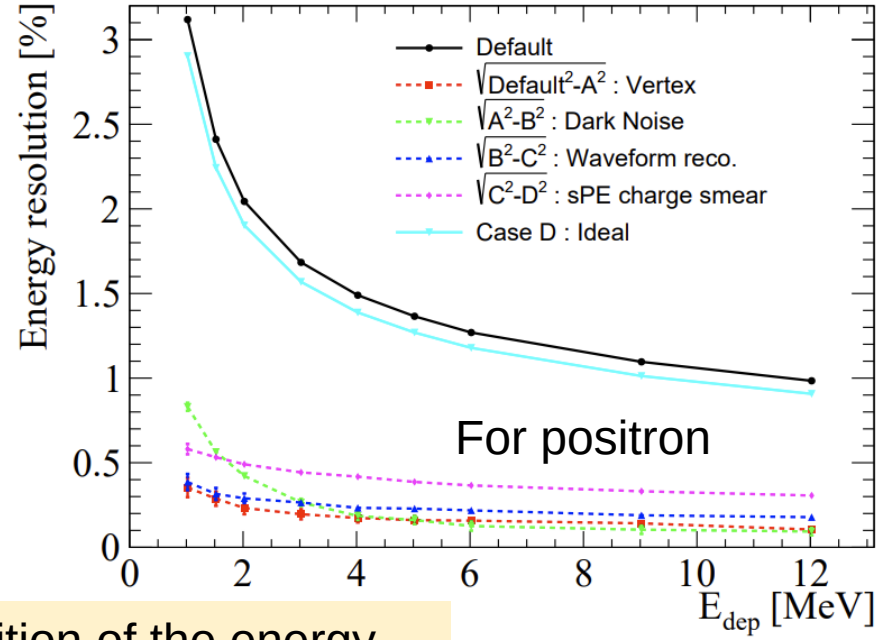
All systems ready for installation

arXiv:2405.17860 (2024)

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

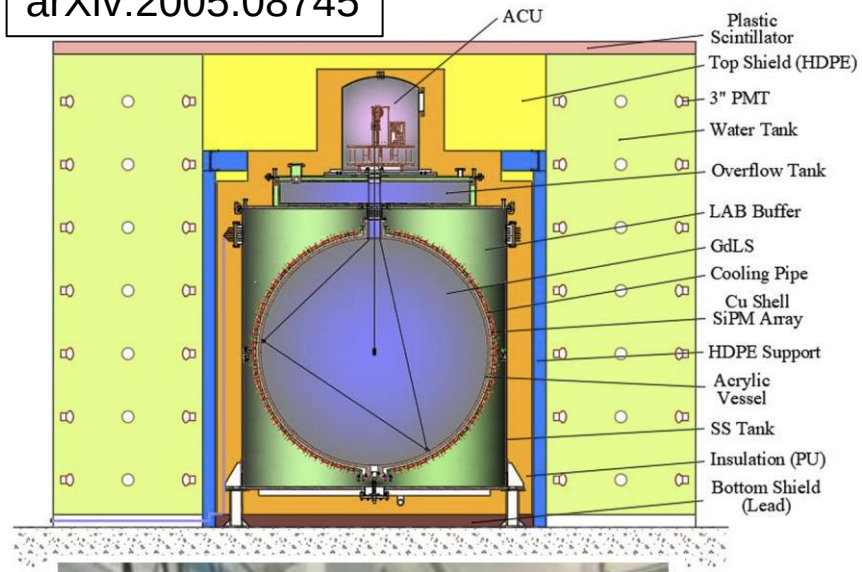


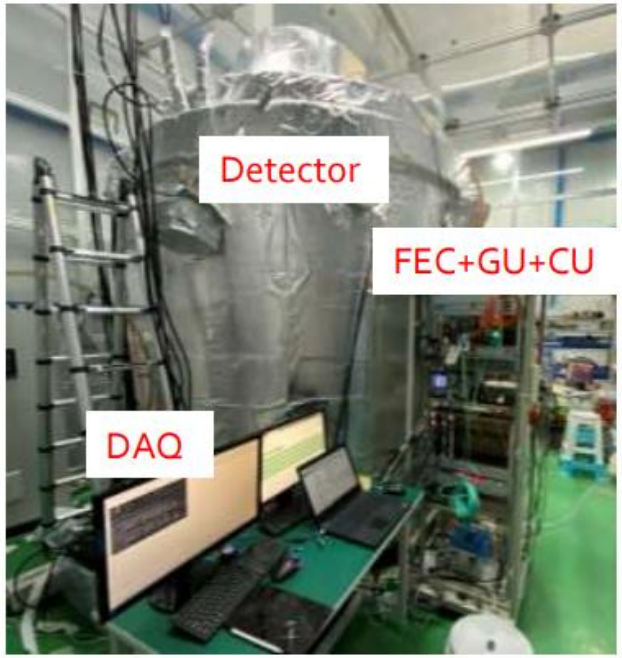
Decomposition of the energy resolution in the reconstruction

JUNO-TAO(Taishan Antineutrino Observatory)

- **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
- **Detector features**
  - ⇨ 10 m^2 SiPM + 2.8 ton new type of Gd-loaded LS @-50℃
  - ⇨ ~2000 IBDs/day@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℃, dark rate 100k→100 Hz/mm^2
- **Detector assembled at IHEP with ~100 SiPM tiles/readout (out of 4100 in total)**
  - ⇨ Temperature uniformity and stability OK!
- **Disassembling, to be re-installed in the Taishan Nuclear Power Plant in 2024**

arXiv:2005.08745



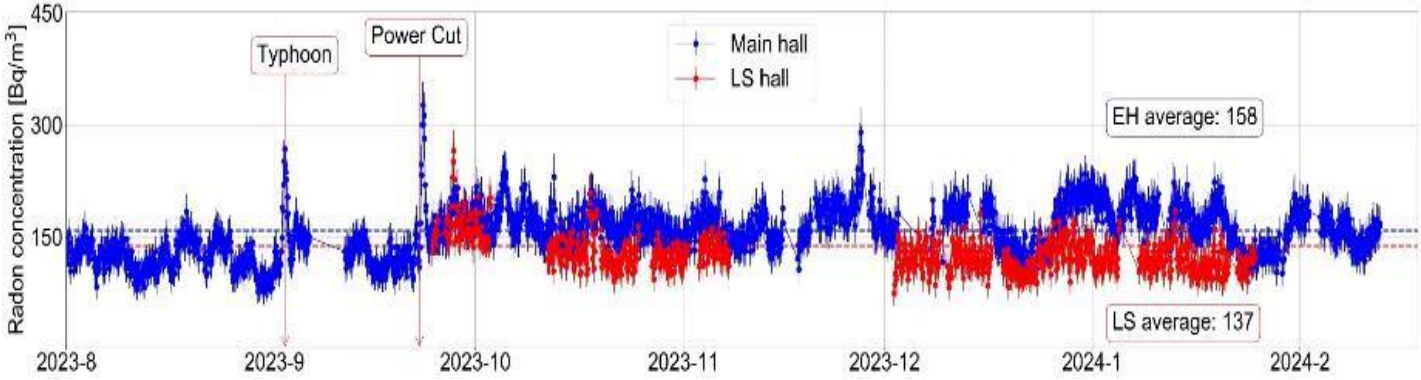


Detector radiopurity control

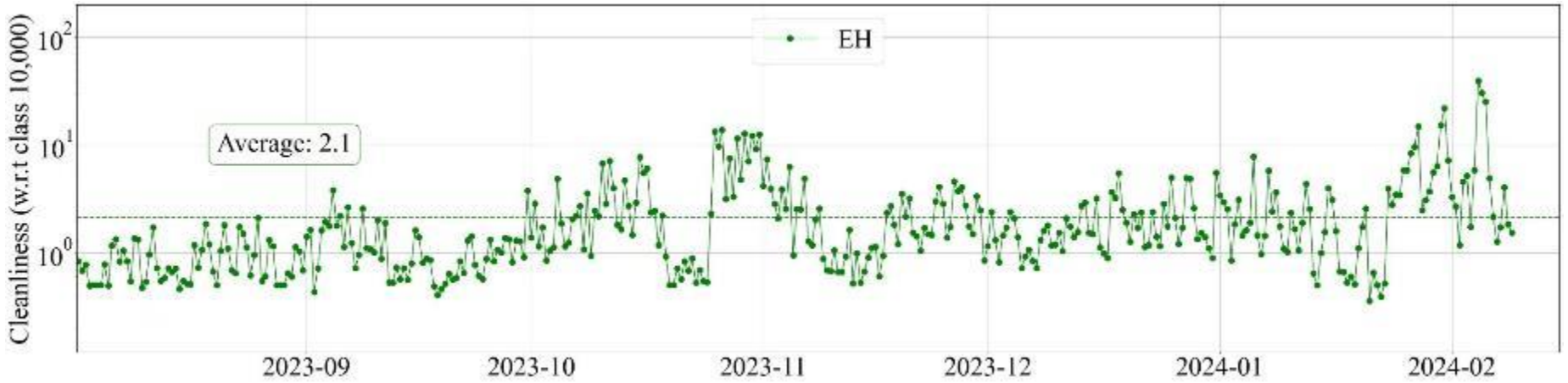
- **Radiopurity control of detector materials:**
  - ✓ Careful material screening
  - ✓ Meticulous Monte Carlo Simulation
  - ✓ Accurate detector production handling

    Better than spec. by 15%

    Good enough for reactor neutrinos



- **Average radon and cleanliness:**
  - Radon concentration: ~160 Bq/m^3 in the EH, ~140 Bq/m^3 in the LS hall
  - Cleanliness: class 20,000

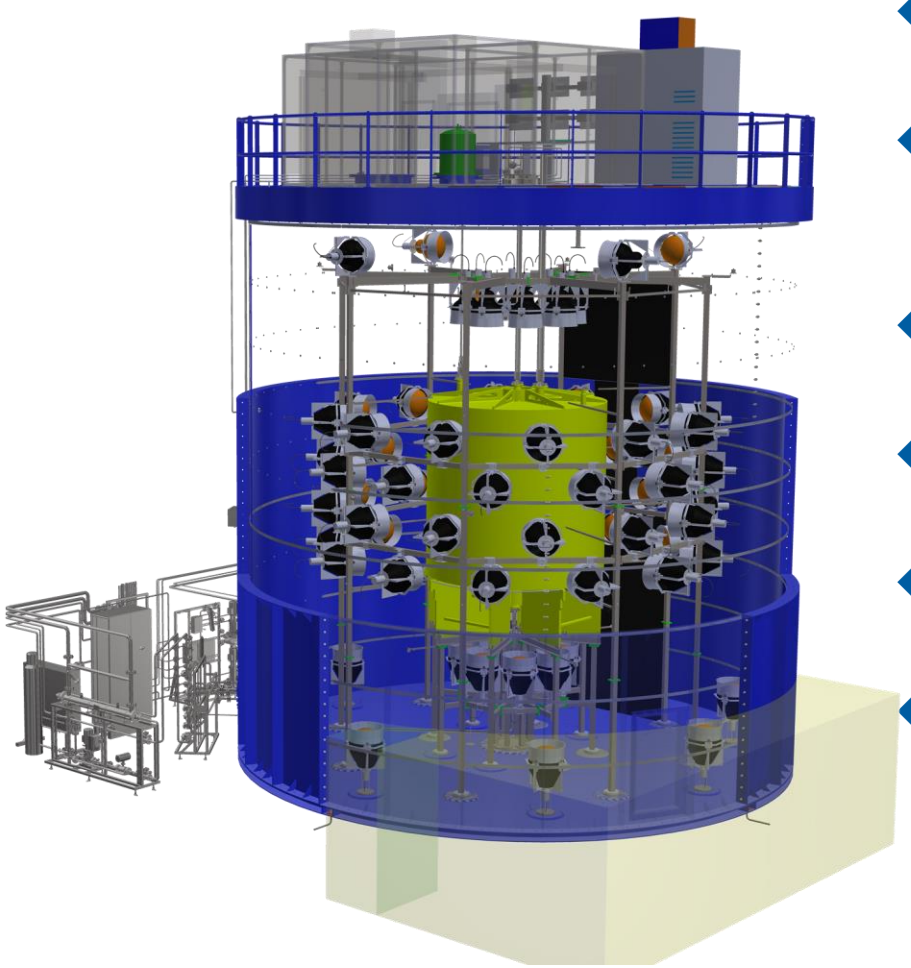


Summary

- **JUNO construction is nearing completion after overcoming a lot of challenges**
- **The construction will be finished in end of 2024 and start the detector filling**
- **Looking forward to the data taking for the largest liquid scintillator detector**


Keep digging new physics !

OSIRIS



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- 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
- 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: 14C, 210Po and 85Kr
- 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