Status of the JUNO detector

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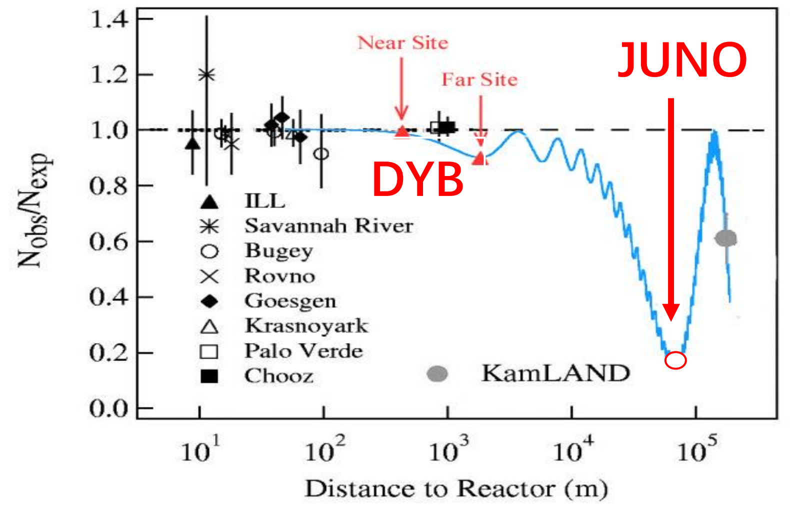
On behalf of the JUNO collaboration

ICHEP 2024， Prague

ICHEP 2024 | PRAGUE

JUNO experiment

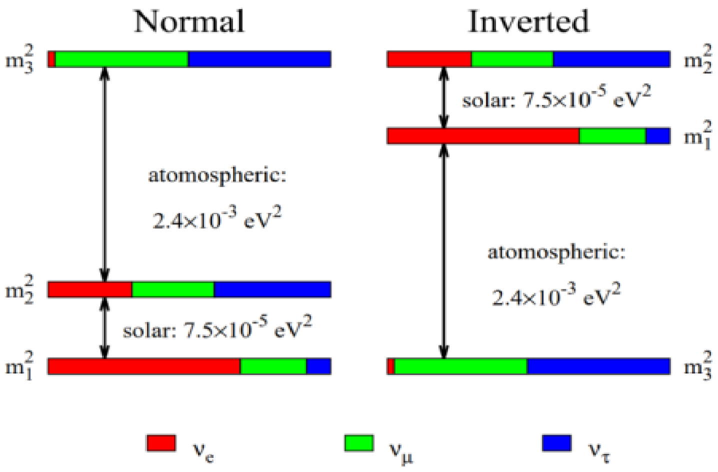
- Jiangmen Underground Neutrino Observatory **(JUNO)** is located in Jiangmen city, Guangdong province of South China:
  - ~ 53 km from the Yangjiang and Taishan Nuclear Power Plants (total power: 26.6 GW)
  - ~700 m underground (1800 m.w.e)
  - a successor of the Daya Bay neutrino experiment (DYB)
  - approved in 2013, construction started in 2015



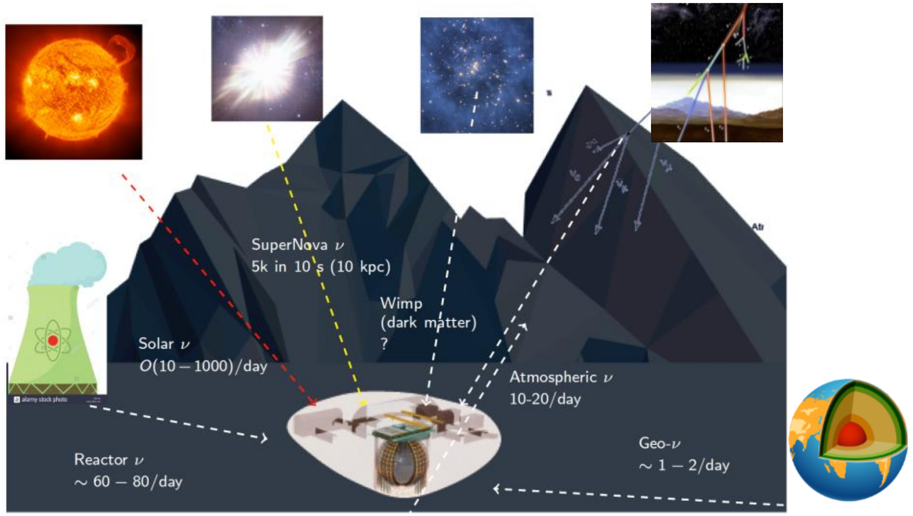
Physics motivations of JUNO

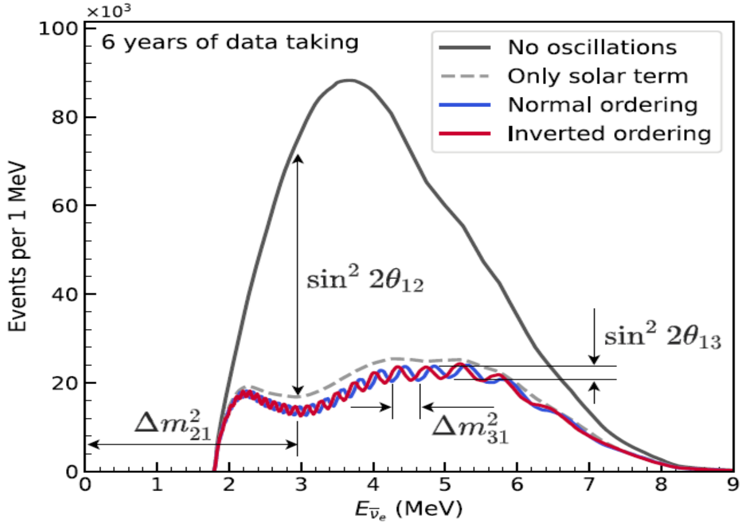
- **Neutrino Mass Ordering (NMO)measurement**
  - -Normal mass ordering： $m_1<m_2<m_3$
  - -Inverted mass ordering: $m_3<m_1<m_2$
  - -JUNO will determine NMO with 3σ significance in 6 years

arXiv:1507.05613



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





JUNO collaboration

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

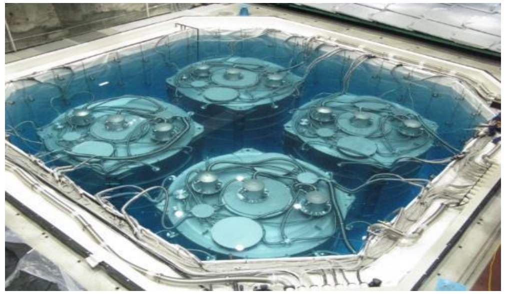
Country	Institute	Country	Institute	Country	Institute
Armenia	Yerevan Physics Institute	China	Tsinghua U.	Germany	U. Tuebingen
Belgium	Universite libre de Bruxelles	China	UCAS	Italy	INFN Catania
Brazil	PUC	China	USTC	Italy	INFN di Frascati
Brazil	UEL	China	U. of South China	Italy	INFN-Ferrara
Chile	SAPHIR	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		

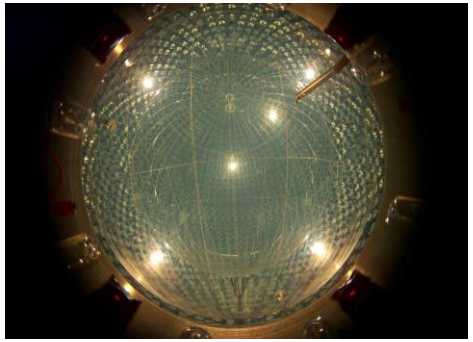
the 24th JUNO collaboration meeting + physics analysis workshop, June 29- July 5, 2024
~240 participants

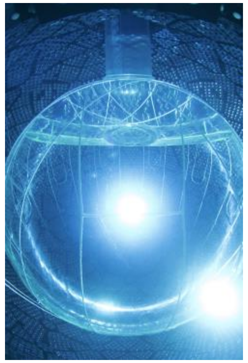
JUNO detector requirement

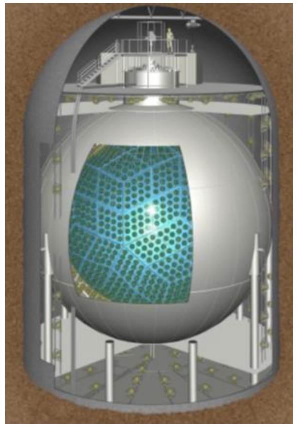
- Main requirement: Target mass of 20 kton liquid scintillator, Energy resolution 3%@ 1MeV
- Unprecedented liquid scintillator neutrino experiment

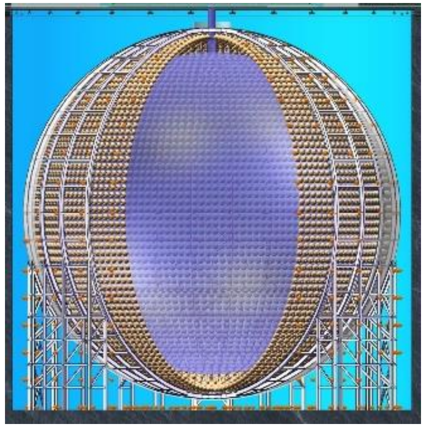
	Daya Bay	BOREXINO	SNO+	KamLAND	JUNO
Target Mass	8* 20 ton	300 ton	780 ton	1 kton	**20 kton**
Number of PMTs	8 *192 8-in.	2212 8-in.	~10000 8-in.	1325 20-in. + 554 17-in.	**20012 20-in.+ 25600 3-in.**
Photoelectron Yield (p.e./MeV)	160	450	520	250	**>1300**
Photocathode Coverage	12%	30%	50%	34%	**78%**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


Daya Bay (20x8t)

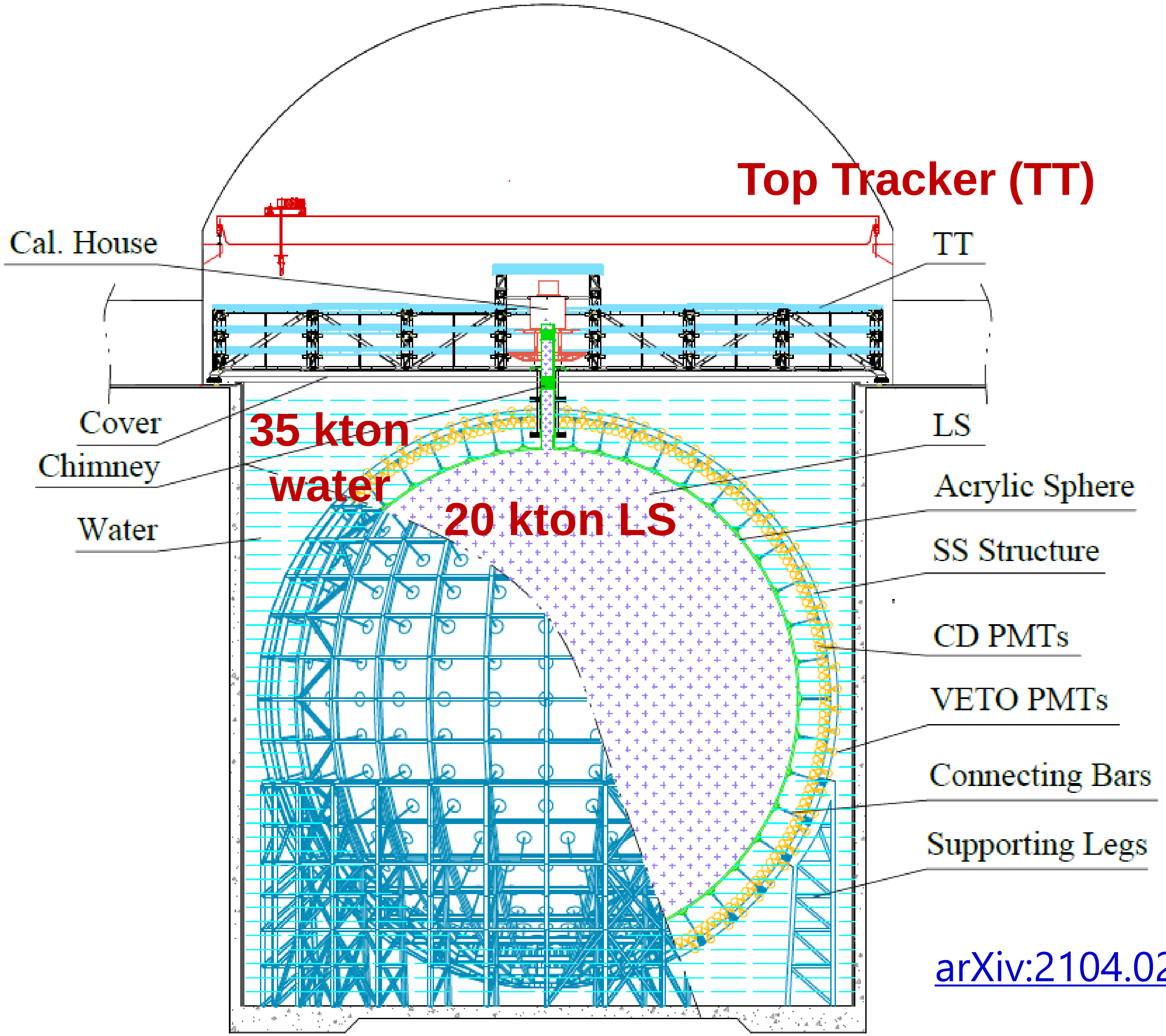

Borexino(300t)


SNO+ (780t)


KamLand(1000t)

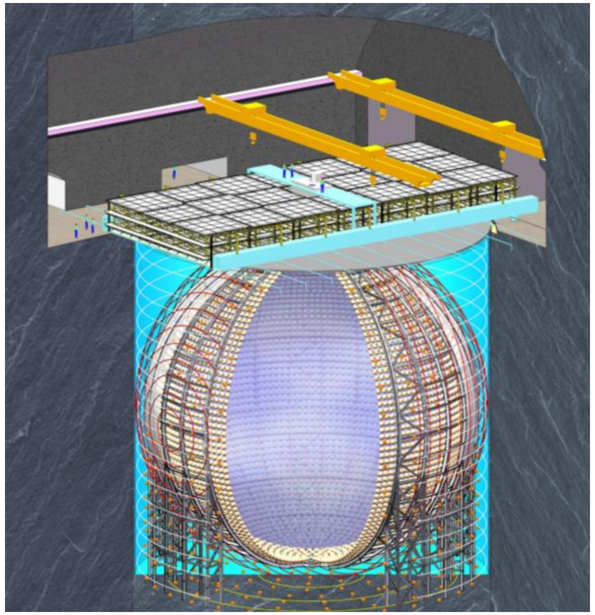

JUNO (20 kt)

JUNO detector design



- **Acrylic Sphere: containing 20 kton LS**
  Inner Diameter (ID): 35.4 m
  Thickness:12 cm
- **Stainless Steel (SS) Structure: supporting acrylic sphere and PMTs**
  ID: 40.1 m, Outer Diameter (OD): 41.1 m
  17612 20-inch PMTs, 25600 3-inch PMTs
- **Water pool: 35 kton water + 2400 20" PMTs**
  ID: 43.5 m, Height: 44 m, Depth: 43.5 m

arXiv:2104.02565v2



Tunnel digging& Cavern excavation finished

Getting to 700 m underground was really difficult, 7 years spent:

- Tunnel digging started in 2015, finished in 2017

  -1265 m slope tunnel

  - 563 m vertical shaft

  -1300 m others tunnels for transportation and connection

- Experimental cavern excavation finished in 2020, water pool finished in 2021

  - 49 m * 55 m * 71 m (incl. water pool)

- Much more underground water than expected

  - max. 600 tons/h, pumping out to surface

Slope tunnel and vertical shaft digging

Cavern and water pool excavating

Underground halls/rooms excavated

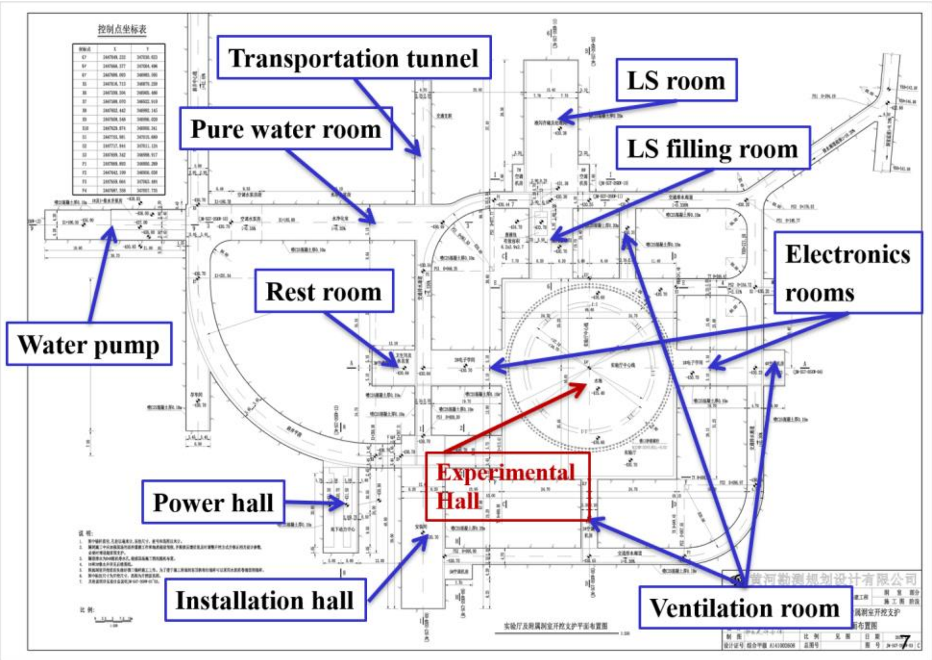

Main experimental hall

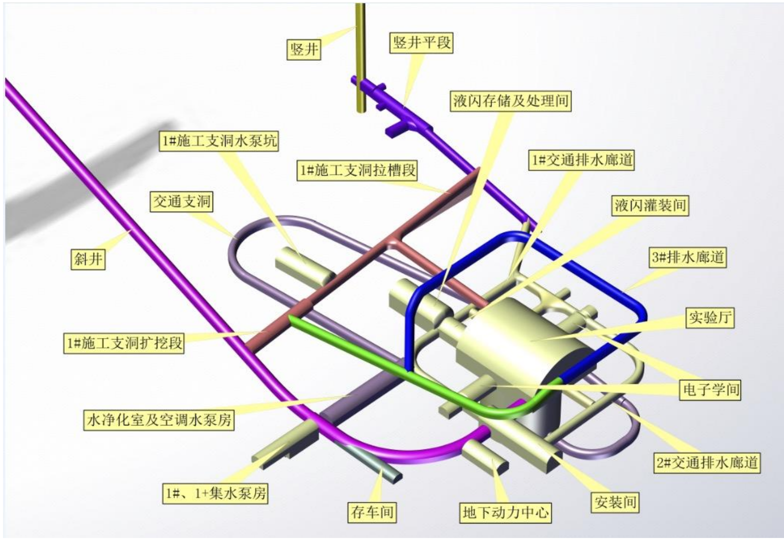

LS purification hall


LS filling hall

- **More than 10 halls/rooms,** total excavated volume: ~300k m^3, and total length of tunnels: ~3 km

- Water still under pumping out: ~400 ton/h






Water pool


Electronics room

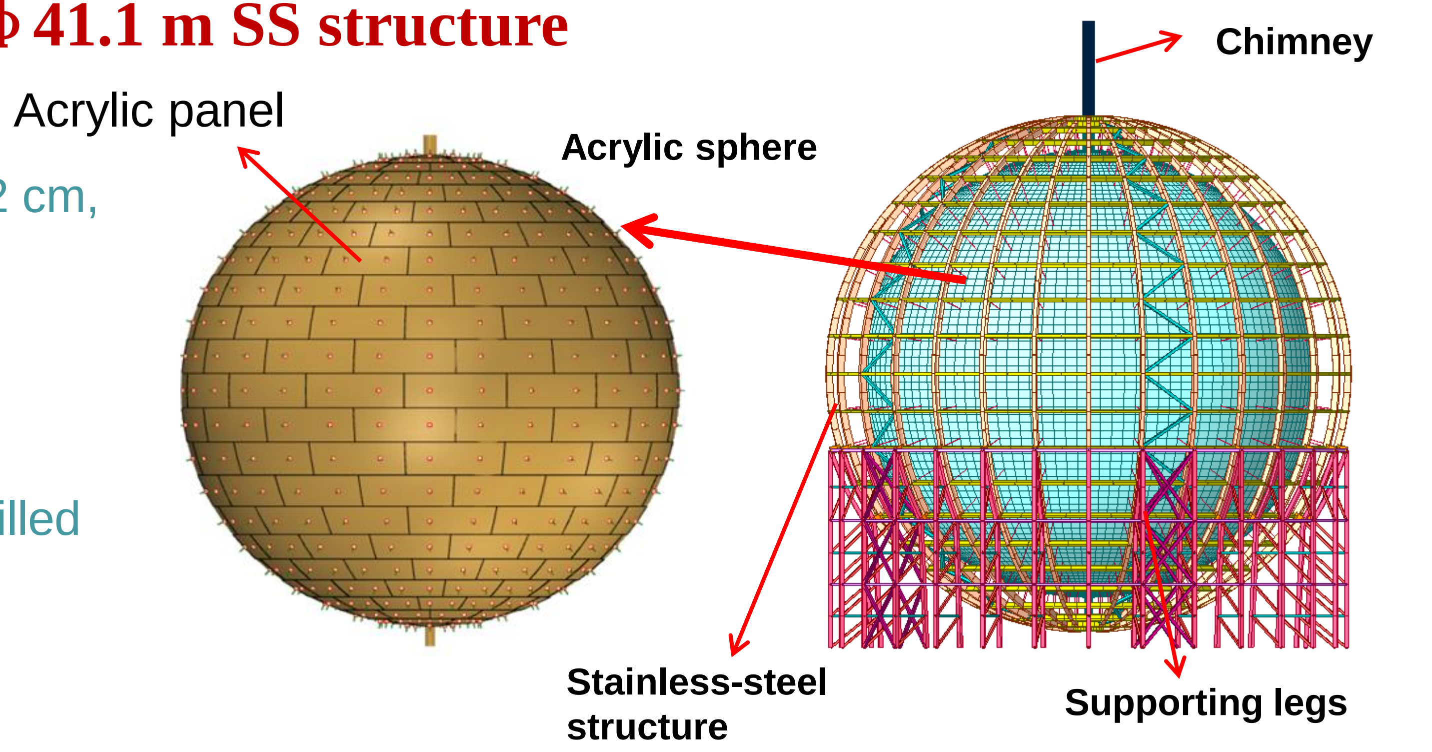

Assembly hall

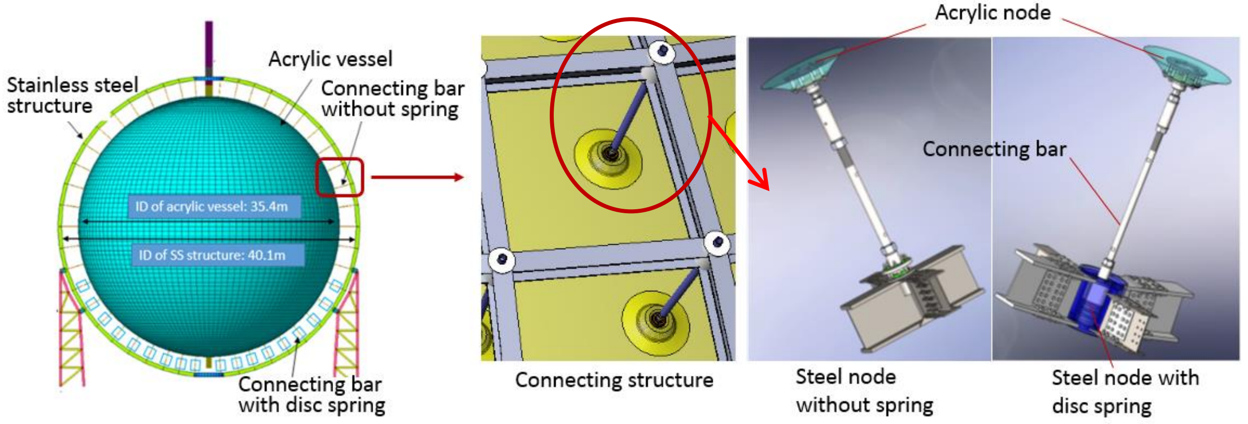
Central detector design

ϕ 35.4 m acrylic sphere supported by ϕ 41.1 m SS structure

- **Acrylic sphere**
  - made by 263 acrylic panels: ~3 m × 8 m ×12 cm, 23 layers
  - total weight ~600 tons
  - good transparency(>96% in water), and low background (< 1 ppt for U/Th)
  - low mechanical stress(< 3.5 MPa) after LS filled
- **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)
- **Special nodes designed for connecting acrylic sphere to SS structure**
  - in total 590 nodes

arXiv: 2311.17314 (2023)





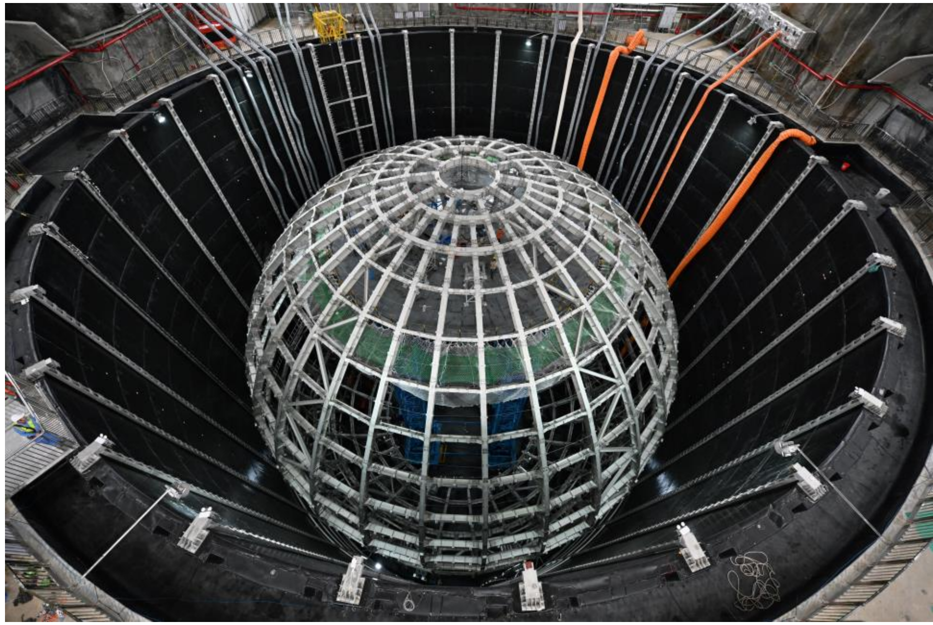
Construction of SS structure finished

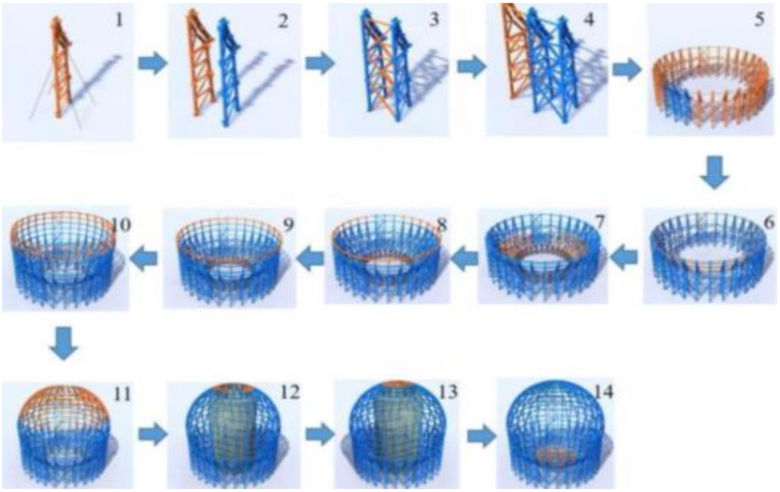
- **Installation sequence**: supporting legs firstly (step 1-5), then downwards (step 6-7), finally upwards (step 8-4)
- **Beams connected by bolts instead of welding**

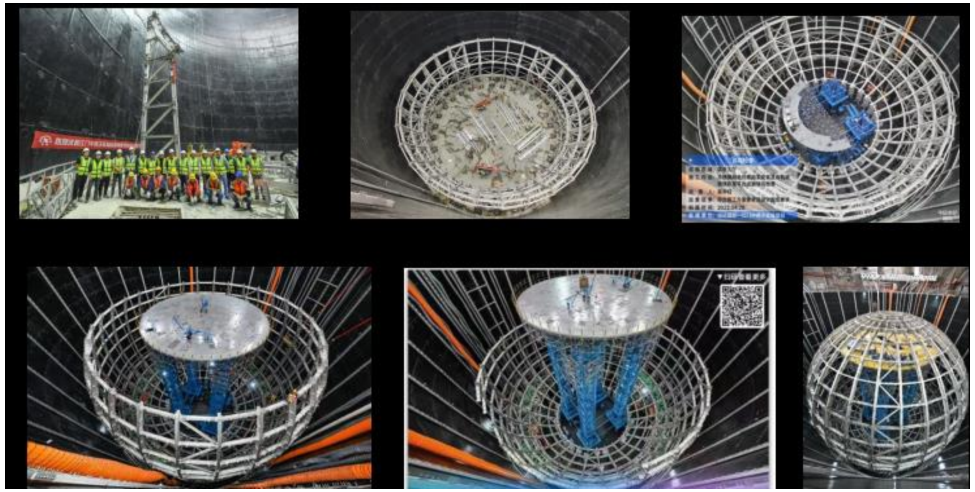
  - 120000 sets of high friction bolts, final friction coefficient up to 0.5 by SS surface coarsening

  - high strength bolts, with special riveting device for fast installing, preventing loosen, reliable, avoiding seizing on nut
- **Spent only 5 months for construction, small deviation in radius after survey**

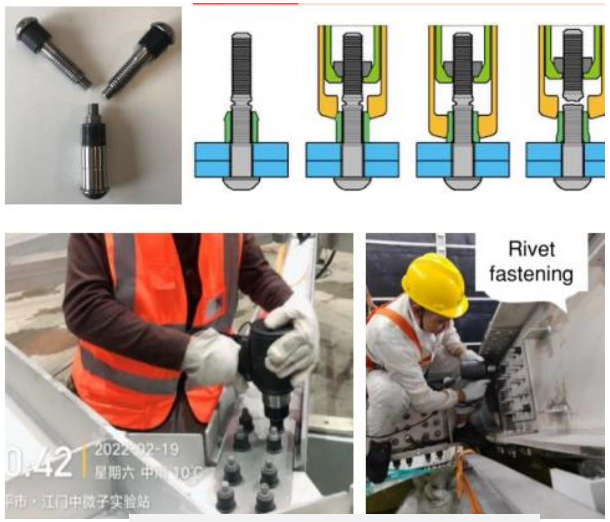
  - design: 20550 mm; survey: 20530 mm; deviation: <20mm (1‰)







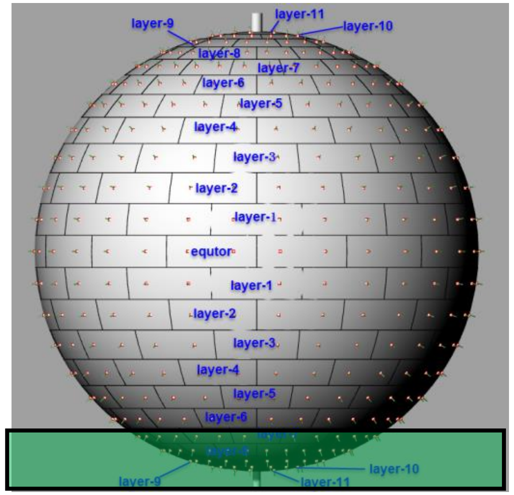
Installation sequence

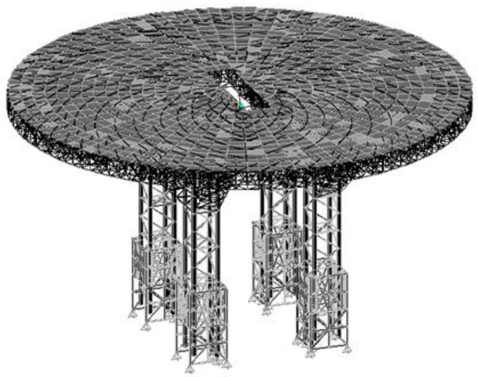


Bolts and riveting

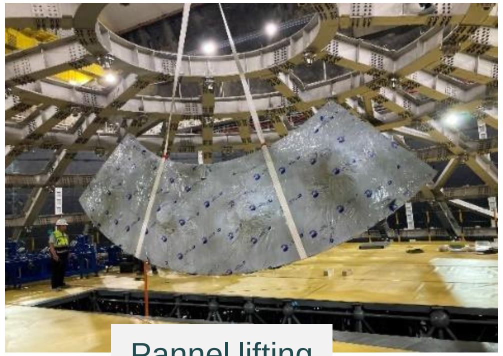
Construction of acrylic sphere ongoing

- **Build the sphere layer by layer from top to bottom, currently 18/23 finished, 2 years spent (Jul. 2022 – now)**
  - a lifting platform used, height and diameter changeable
- **Panels bonded by the bulk-polymerization technique (MMA->PMMA)**
  - circle lines and vertical lines bonded simultaneously
- **Many problems solved during construction**: explosive polymerization, defects repairing, stress measurement, etc.

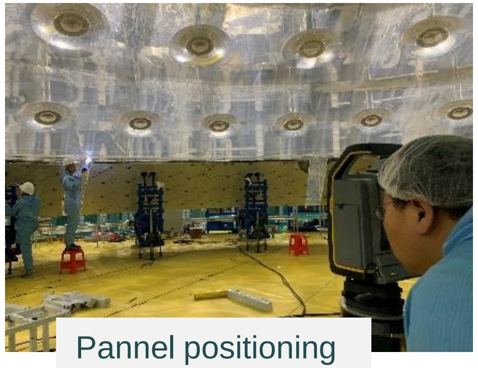




lifting Platform

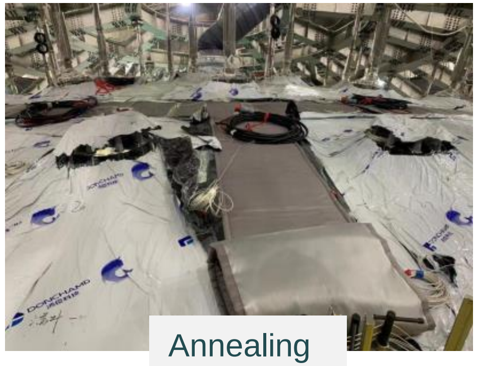


Pannel lifting



Pannel positioning

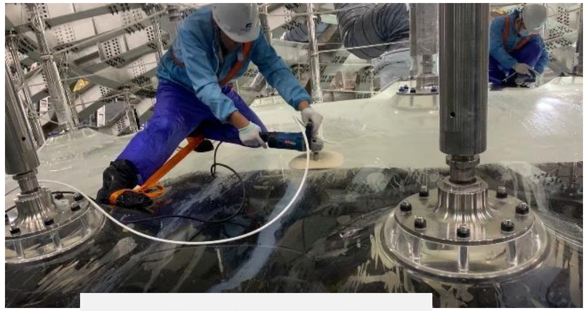
Polymerization



Annealing

Sensor installation

Supporting bar installation

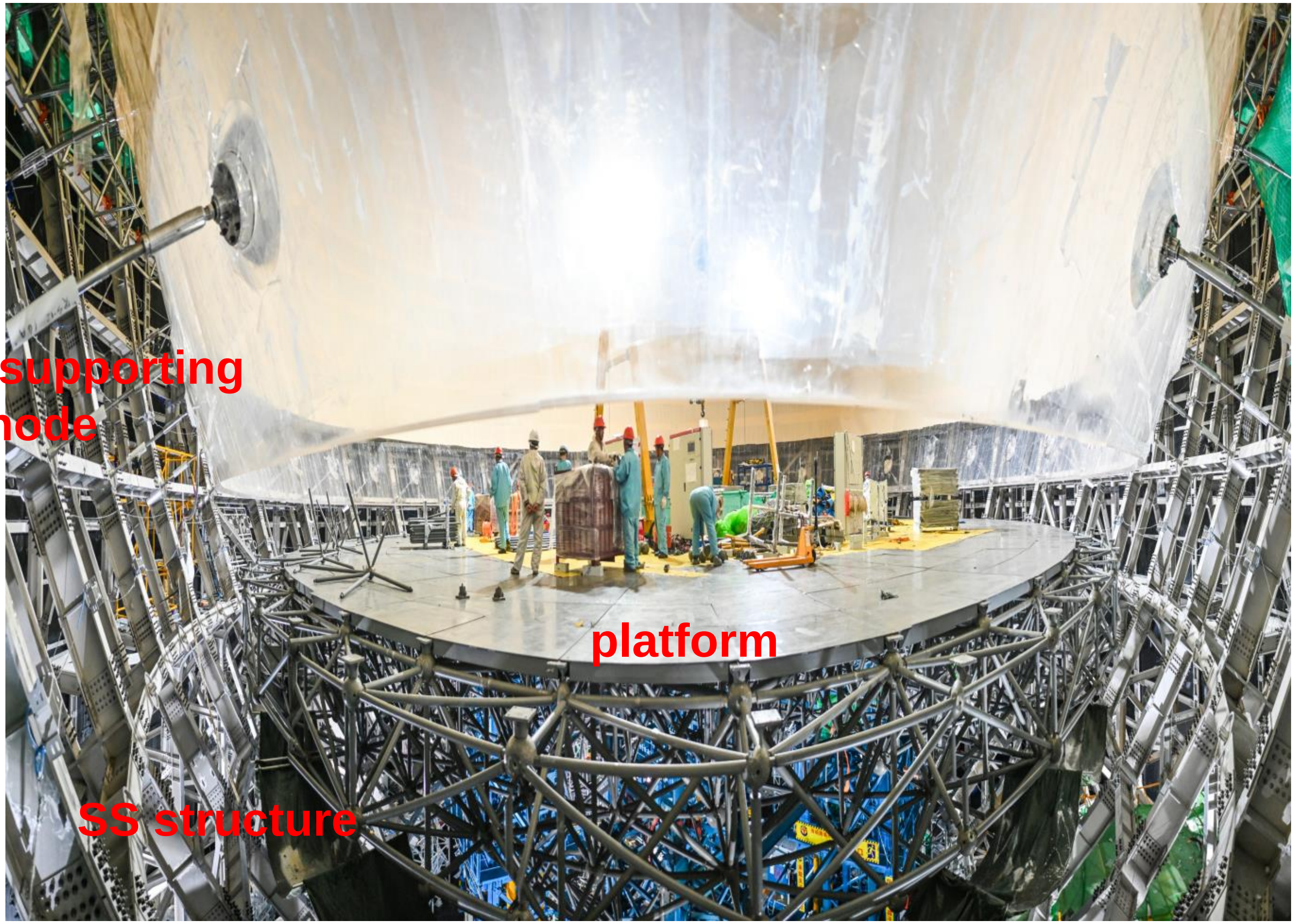


Bonding line sanding

Cleaning

Filming

the acrylic sphere (18 /23 finished now)



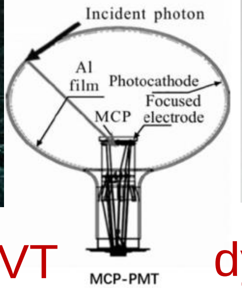
Inside view of the sphere (upper semi-sphere)

Outside view of the sphere (lower semi-sphere)

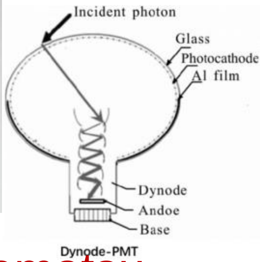
JUNO 20-inch PMT

- **In total 20012 20" PMT for JUNO**:
  - 15,012 MCP-PMT (NNVT) + 5,000 Dynode PMT(Hamamatsu)
  - an optical coverage of 75%
- **All PMTs delivered and performance tested**
  - HV, SPE, PDE, DCR, TTS, P/V …

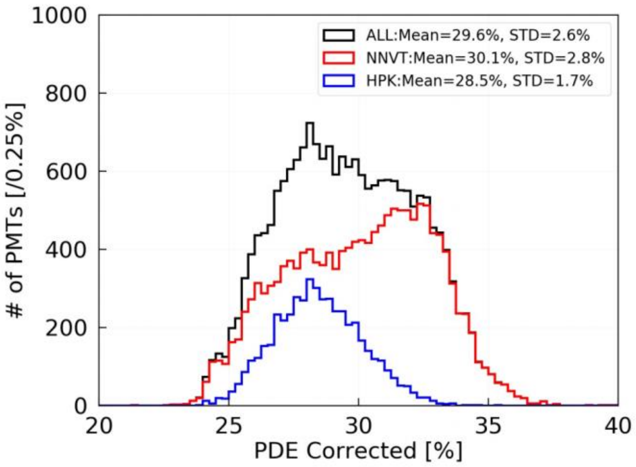
Parameters		LPMT (20-inch)	
		Hamamatsu (Dynode)	NNVT (MCP)
High Voltage (V) at 10^7 of Gain		1863	1748
SPE amplitude (mV)		6.5	7.5
Photon Detection Efficiency		28.5%	30.1%
Dark Count Rate [kHz]	Bare	15.3	49.3
	Potted	17.0	31.2
Transit Time Spread (σ) [ns]		1.3	7.0
P/V		3.8	3.9
Rise time (ns)		6.9	4.9
For more information		Eur.Phys.J.C 82 (2022) 12, 1168	

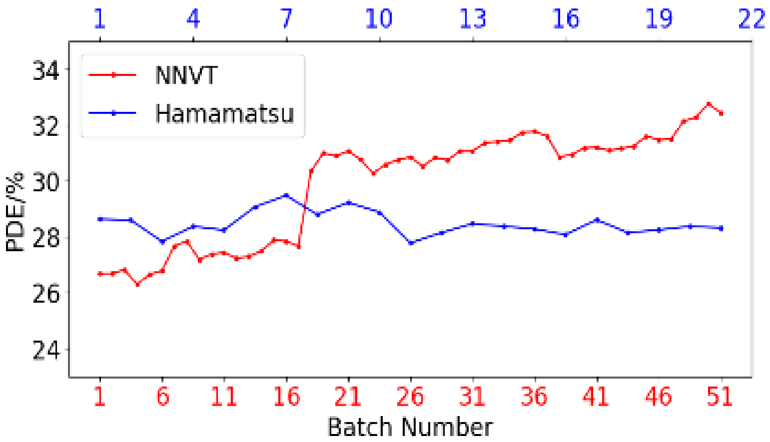


MCP PMT from NNVT (15,012)



dynode PMT from Hamamatsu (5000)





Photon detection efficiency (PDE)

PMT waterproof potting and protection finished

- **Water proof potting**
  - Required failure rate <0.5%/6 years
  - Technology invented for both MCP and dynode PMT, patented
  - all 20012 PMTs being potted in 2 years
  - leakage test found no failure (SF_6 tested for every PMT, 1% sampling test in pressurized water tank)

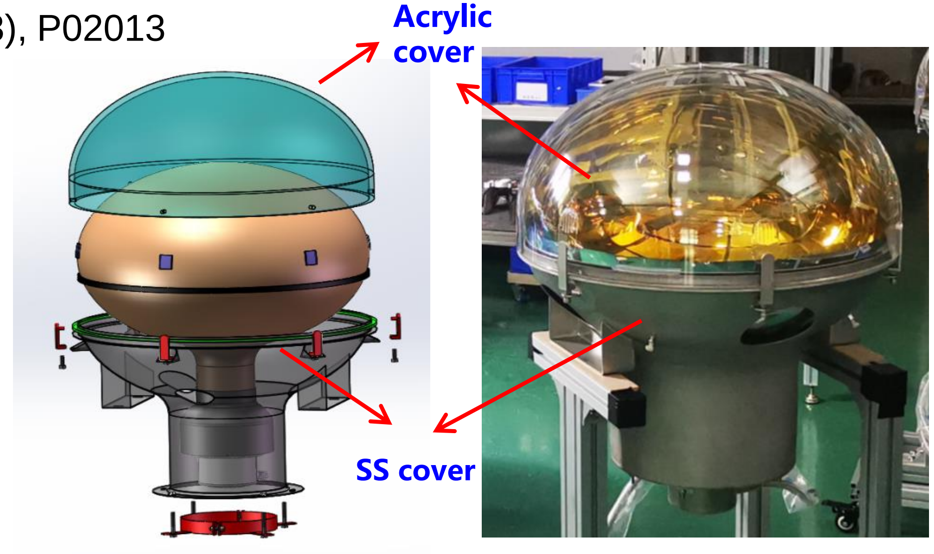
A potted PMT

PMT potting station

Leakage test after potting

- **Implosion protection**
  - avoid the accident happened like in Super-K
  - protection method developed
    Acrylic cover at top + Stainless-steel cover at bottom
  - validation test in water tank: no chain reaction
  - all covers produced, assembly ongoing

JINST 18 (2023), P02013



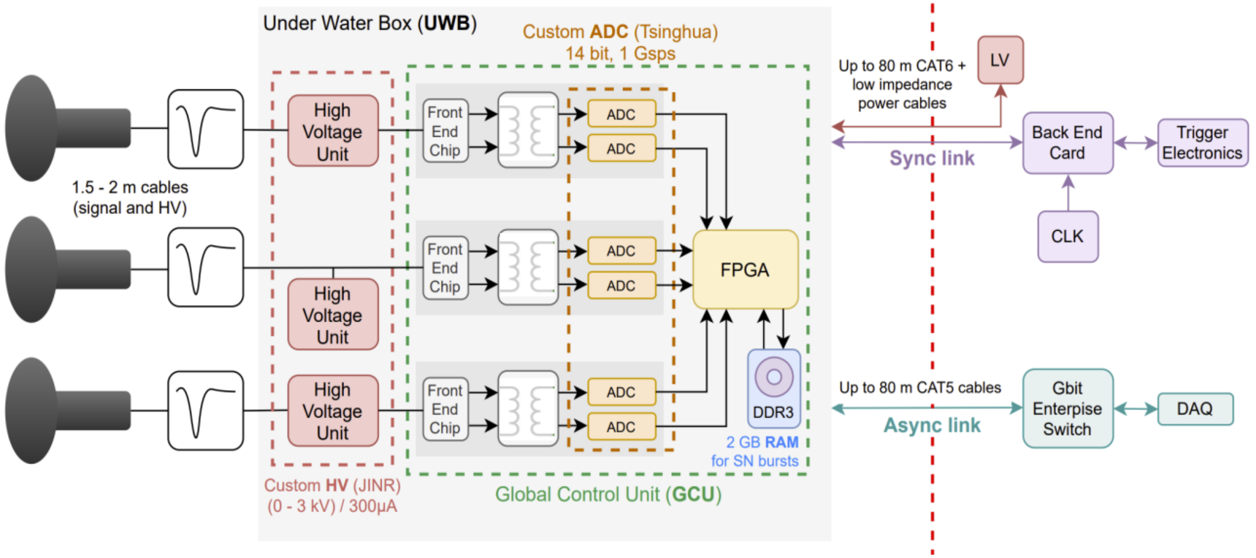
PMT protection design

Implosion test

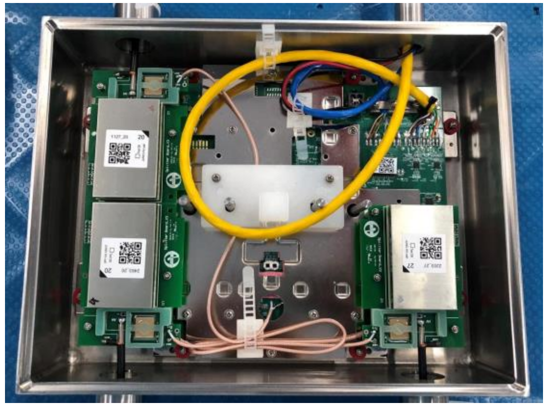
20" PMT readout electronics

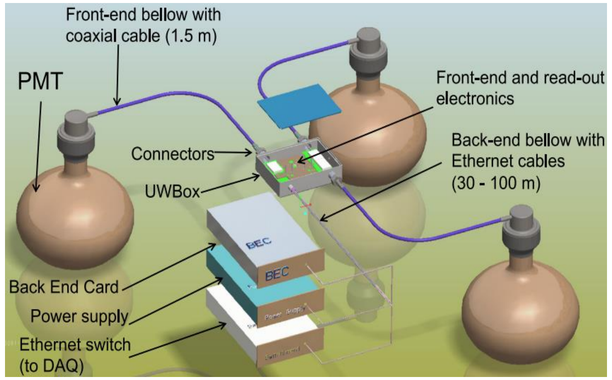
- **JUNO requirement:**
  - Dynamic range: 1- 4000 PE
  - Noise: < 10% @ 1 PE
  - Resolution: 10%@1PE, 1%@>100 PE
  - Failure rate: < 0.5%/6 years
- **Solution:**
  - 1 GHz FADC (14 bit) + GCU in an waterproofed box for PMT waveform measurement
  - cables in the corrugated pipe (bellow)
  - Back-end card and low power supply in electronics room
- **All electronics produced and tested**

Readout electronics design

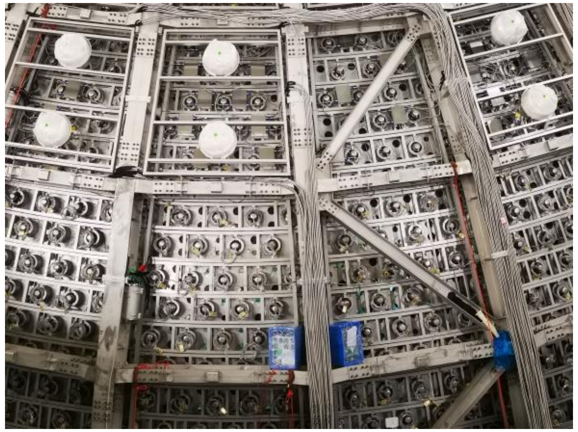


NIM A 1052 (2023) 168255

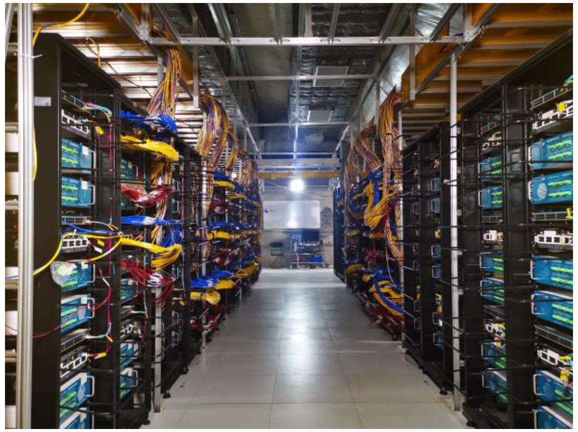




Under-water(waterproofed) box and the scheme



Cable routing on truss (~70 m long)



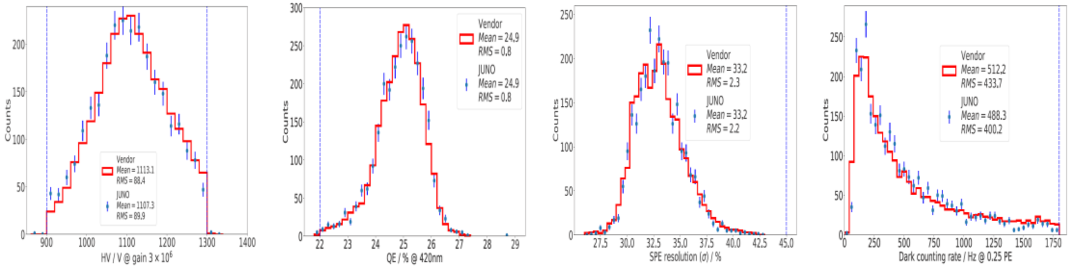
Electronics room

3” PMT system

25600 3” PMT (XP72B22 from HZC photonics)

- **Goal:** 3% more light, higher dynamic range for muons, calibration for 20” PMTs’ non-linearity.
- **Mass production, potting and performance test of all 3” PMTs completed**

Performances highlight of all 26,000 PMTs



HV: 900-1325V $\overline{QE} = 24.9\%$ $\overline{\sigma_{SPE}} = 33.2\%$ $\overline{DCR} \approx 500$ Hz

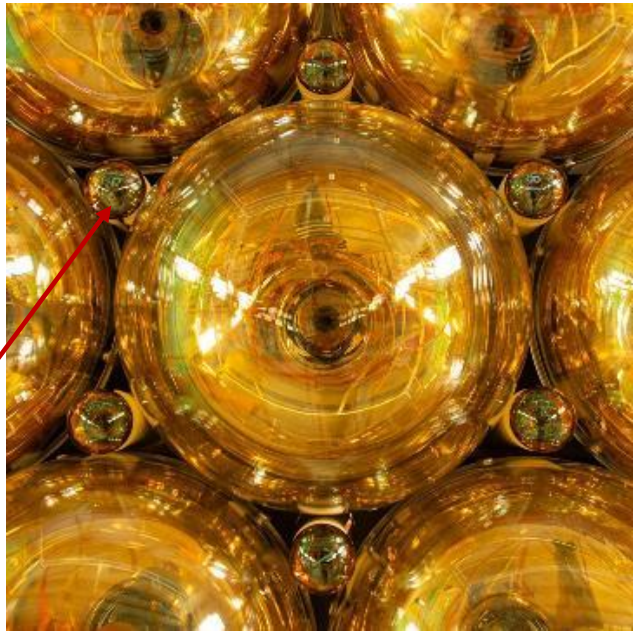
NIMA 1005 (2021) 165347

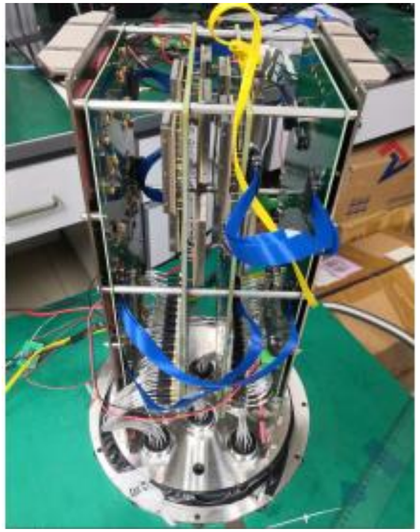
- **Readout electronics:**

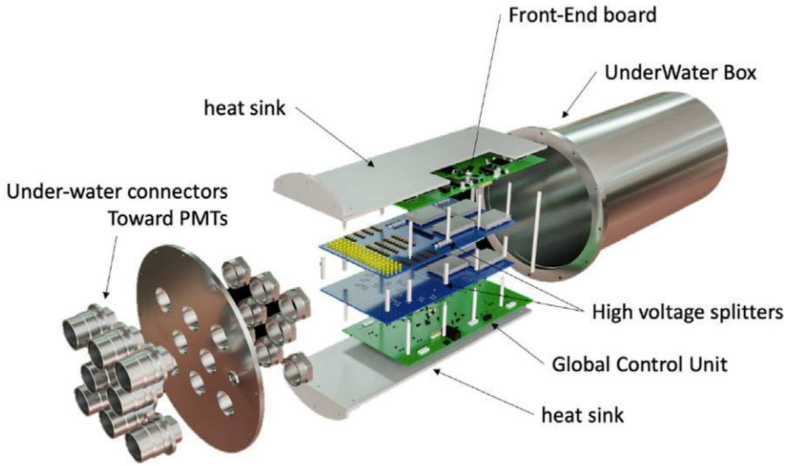
-200 underwater boxes, each for 128 PMTs read by ASIC Battery Cards (ABC), each with 8 CatiROC chips, only charge readout

3” PMT

(25600)



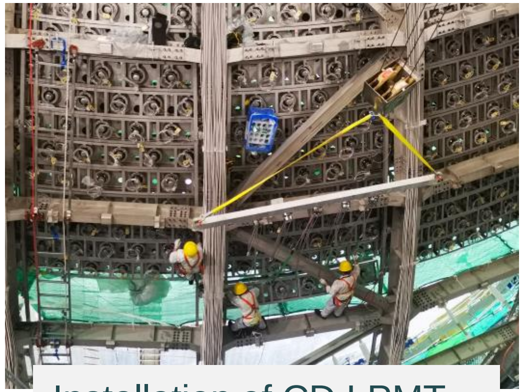




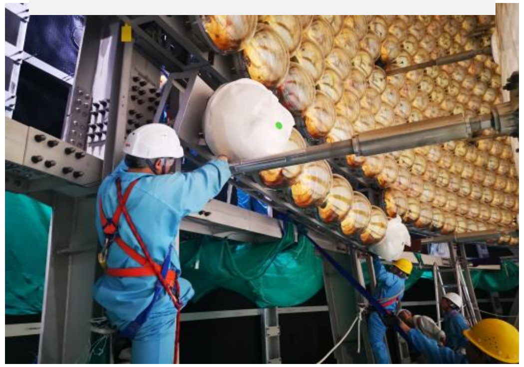
Installation of PMTs/Electronics ongoing

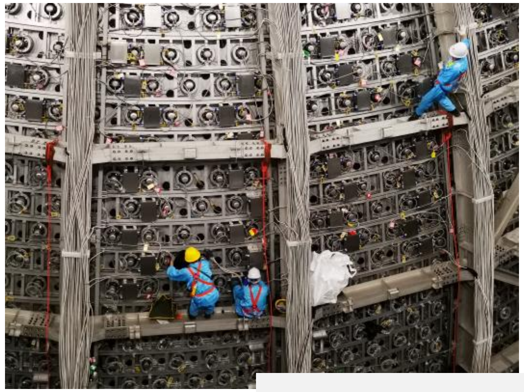
Total number installed now:

- CD 20” PMT(LPMT)
  - layer# +11 to -3 finished
  - 12565 PMTs (71% of 17612)
- CD 3” PMT(sPMT)
  - layer# +11 to -1 finished
  - 15740/25600 PMTs (61%)
- 20” PMT electronics
  - layer# +11 to + 1 finished
  - 3228 UWBs (48% of 6681)
- VETO module
  - layer# +11 ~+2 finished
  - 850 PMTs (35% of 2400)
- VETO EMF shielding coils
  - layer# +11~+4 finished
- Tyvek film reflector:
  - layer# +11 to +5 finished



Installation of CD LPMT





Installation of LPMT electronics

Installation of sPMT and electronics

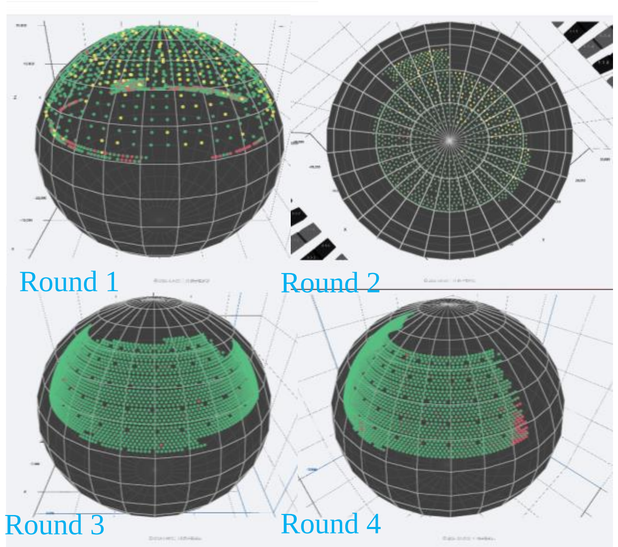
Inner view of PMTs

PMTs/Electronics commissioning during installation

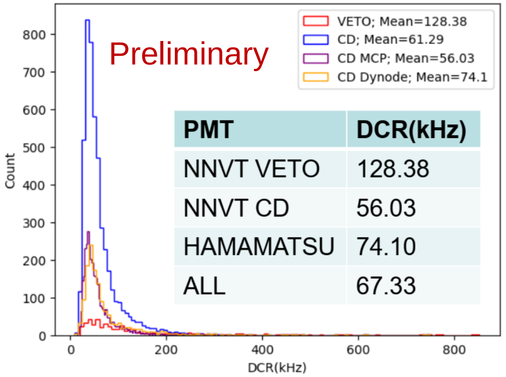
- Regular commissioning/joint test of PMTs, Elec., DAQ/DCS, during installation:
  - light-on test: Elec. /trigger/DAQ/DCS joint test w/o PMTs
  - Light-off test: PMT dark rate data taking and full chain test

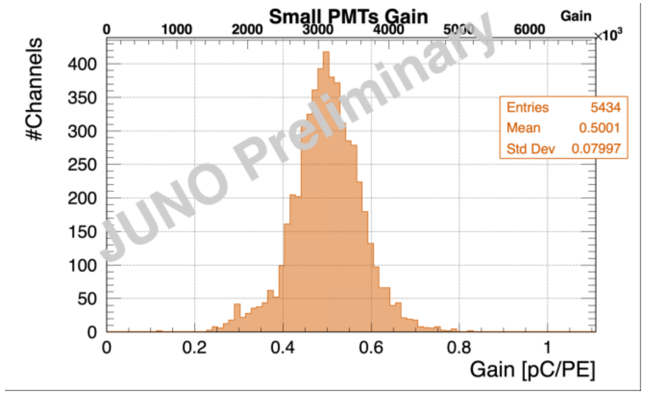
- PMTs are working well, all tested PMTs (~7000 20" + 11000 3") powered to operating voltage; electronics shows very low noise (<5% of SPE), and good shielding and grounding;

Light-off test



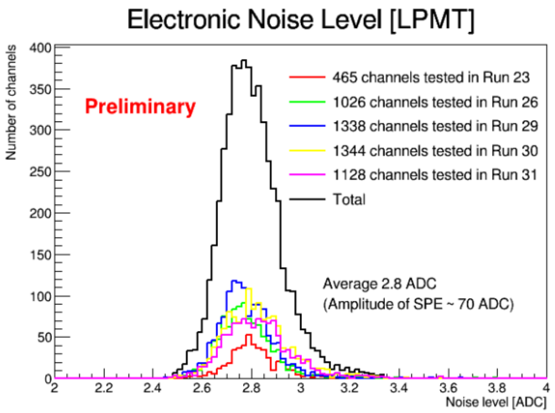
DAQ 3D display of DCR

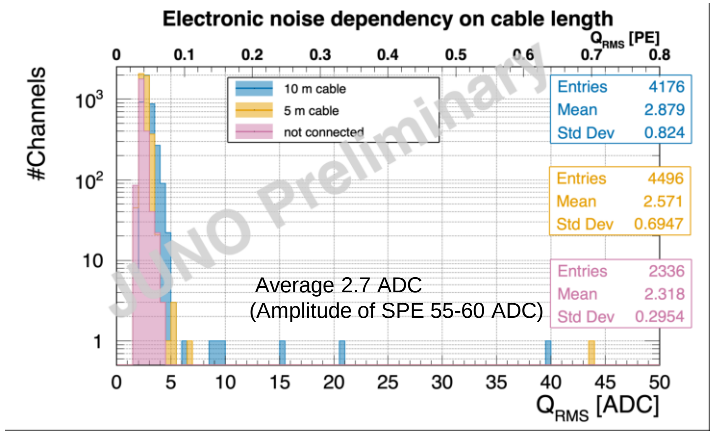




20'' PMT average DCR: 67 KHz (not sufficient cooling-down time)

3'' PMTs: gain consistent with nominal value 3 x 10^6





Electronics noise for both 20'' and 3'' PMTs:

only 2.7-2.8 ADCs, corresponding to ~4-5% of SPE

Liquid Scintillator

See also poster ID#859

- **JUNO recipe: LAB + 2.5 g/L PPO + 3 mg/L bis-MSB**
  - ⇨ High light yield: 12000 photons/MeV @420 nm
  - ⇨ High attenuation length: LAB > 24m, LS > 20 m
  - ⇨ Low radioactivity: U/Th for NMO< 1e-15 g/g, for solar and future $0\nu\beta\beta$ <1e-17 g/g

- **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**
- **All purification plants built and commissioned**

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

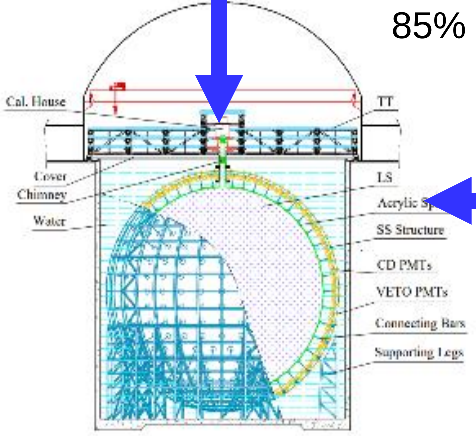
4) Gas stripping to remove Rn and O_2

15%

Commissioning

Monitoring pre-detector (OSIRIS)

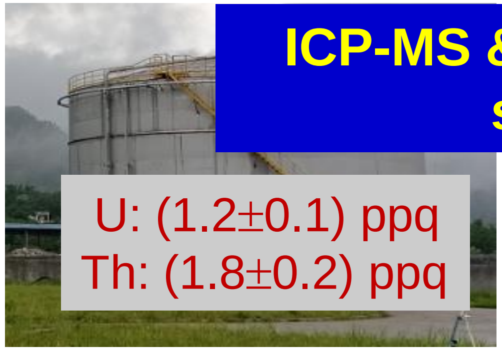
85%



Liquid Scintillator

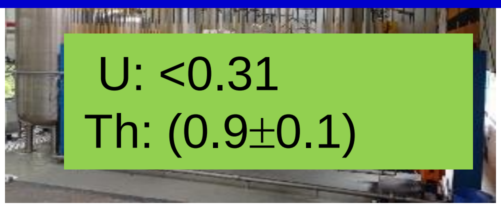
- **JUNO recipe: LAB + 2.5 g/L PPO + 3 mg/L bis-MSB**
  - Light yield: 12000 photons/MeV @420 nm
  - Attenuation length: LAB > 24m, LS > 20 m
  - Minimum U/Th requirement (for NMO) < 1e-15 g/g, aiming at 1e-17 g/g for solar and future $0\nu\beta\beta$
- **All 60 ton PPO delivered, U/Th < 0.1 ppt**
- **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)



U: (1.2±0.1) ppq
Th: (1.8±0.2) ppq

5000 m^3 LAB storage tank



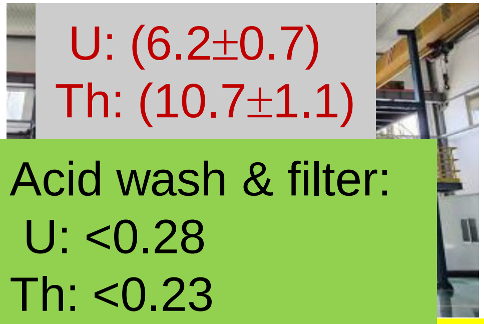
U: <0.31
Th: (0.9±0.1)

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

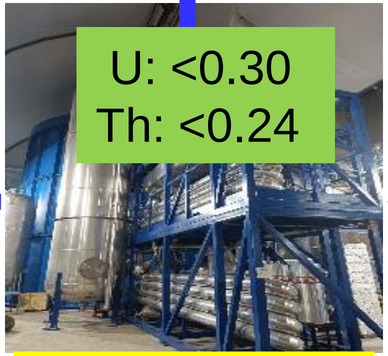
U: <0.30
Th: <0.24

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

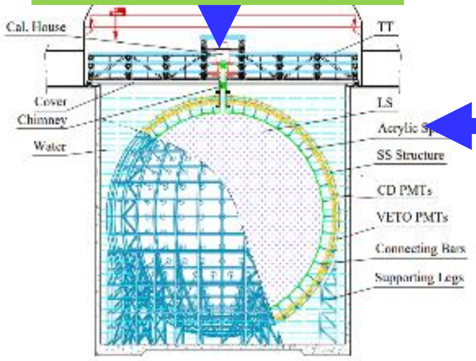
85%

15%

Commissioning

Monitoring pre-detector (OSIRIS)

FOC: U: <0.28
Th: <0.23



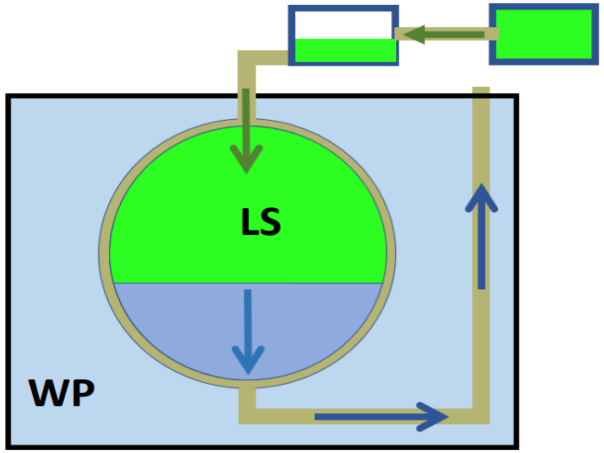
Detector final cleaning plan and LS filling

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

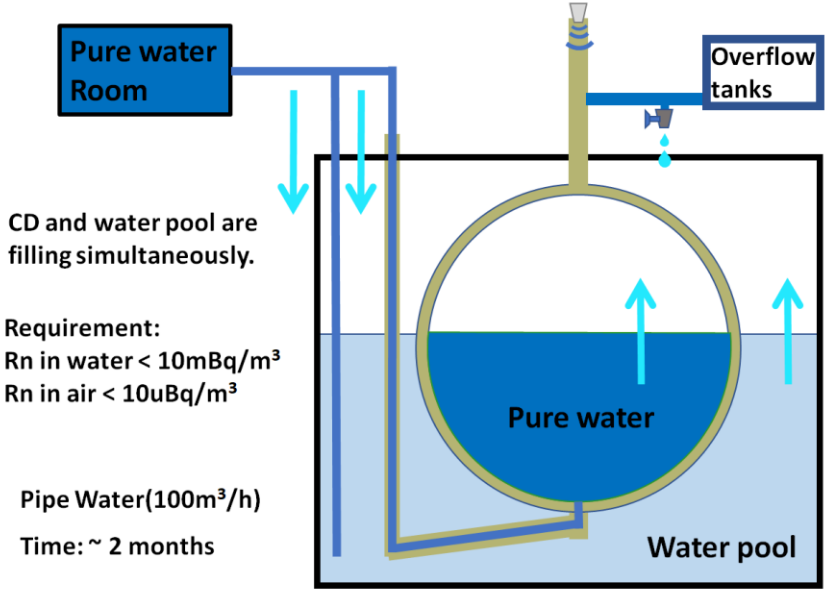
Complete CD construction → 1-2 weeks settlement with proper moisture → Remove the protective film and wash the acrylic surface by the high pressure water spray → Fill CD and VETO by high purity water → replacing water in CD by LS

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

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



Drain water (7 m^3/hour)



Prototype test for water spray cleaning

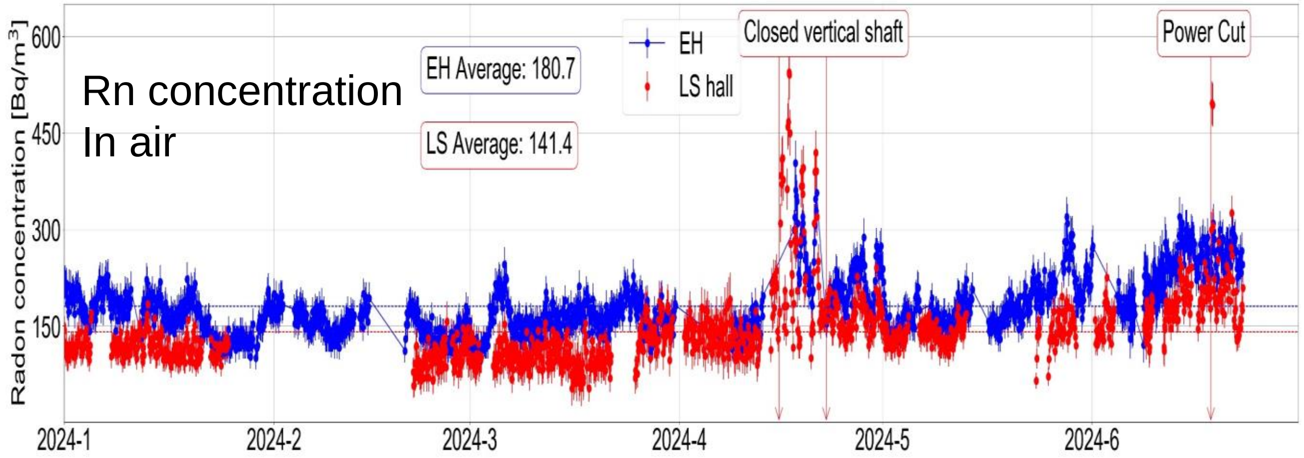
LS filling Control room

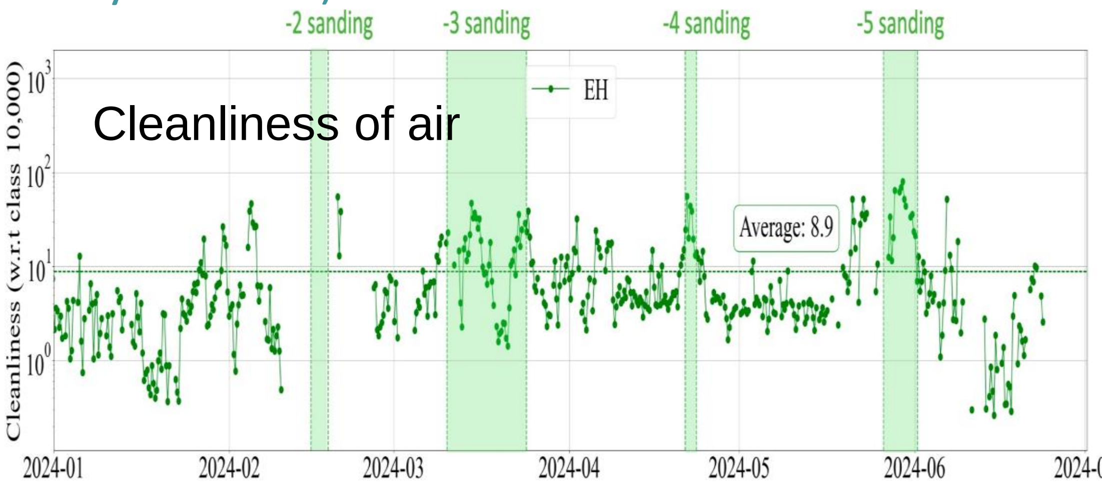
Detector radiopurity control

- **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

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/m³ -> 10 mBq/m³
Other	0	+0.52	Add PMT readout, calibration sys
Total	8.5	-1.3	*JHEP* 11 (2021) 102

- **Environmental control during detector installation:**
  - Radon concentration: 180 Bq/m³ in EH, 140 Bq/m³ in LS hall, sensitive to the fresh air from vertical shaft
  - Cleanliness: class 89,000 (66,000 w/o large scale sanding of acrylic vessel)



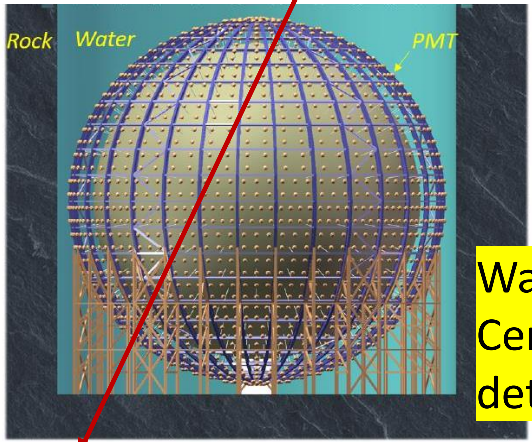


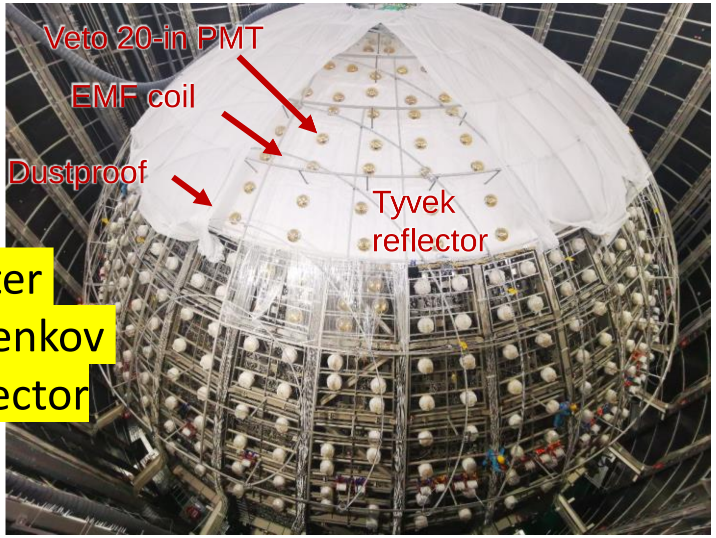
VETO Detector

- **700 m overburden ➔ Muon rate R_{μ}= 4 Hz in LS, $< E_{\mu} >$= 207 GeV**
  - Induced background event ($^{9}Li/^{8}He$) : 127/day (IBD signal: 47/day)
  - Need to reduce the background
    Fast neutrons background: 0.1/day
    $^{9}Li/^{8}He$: 0.8/day
- **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
  - ➪ 100 ton/h high-purity water system installed
- **Top tracker** (to be installed)
  - ➪ Refurbished OPERA plastic scintillators
  - ➪ 3 layers, 63 walls of 6.7 m * 6.7 m,
  - ➪ ~60% coverage on the top
  - ➪ angular resolution: Δθ ~ 0.2° (median value)
  - ➪ spatial resolution at the bottom: ΔD ~ 20 cm

Muon event tagging efficiency > 99.5%

See also poster ID#733



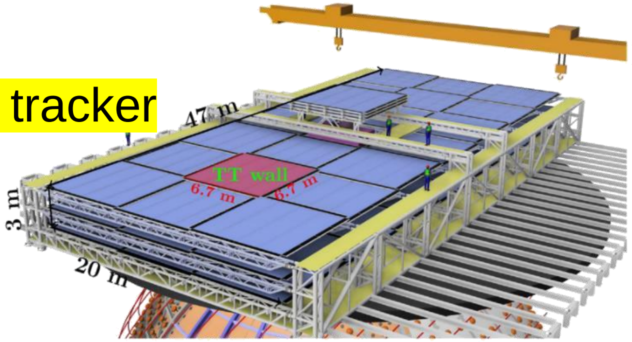


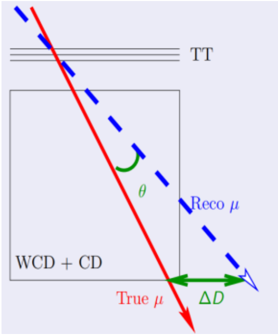
Water Cerenkov detector

100 ton/h water purification system

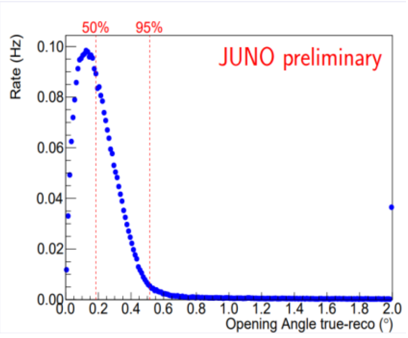
NIMA 1057 (2023) 168680

Top tracker





spatial resolution

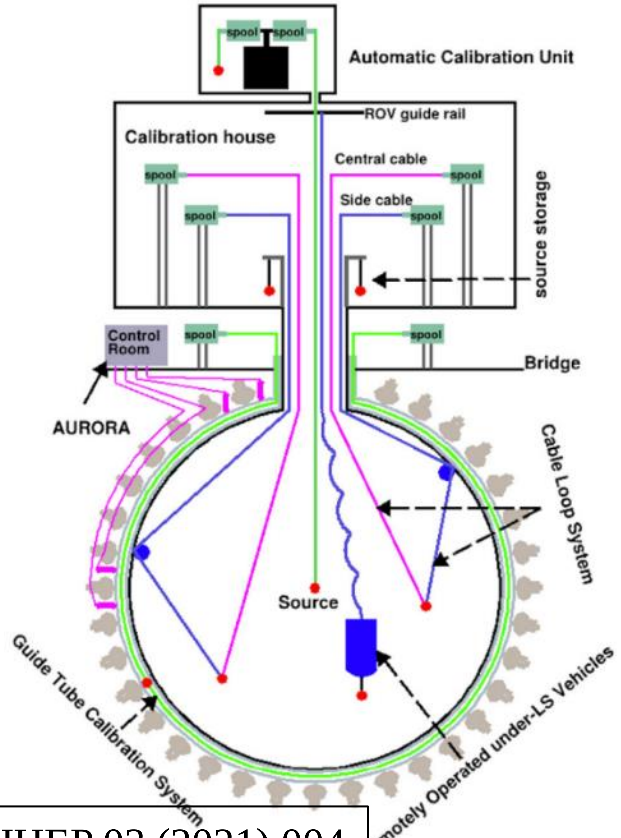


angular resolution

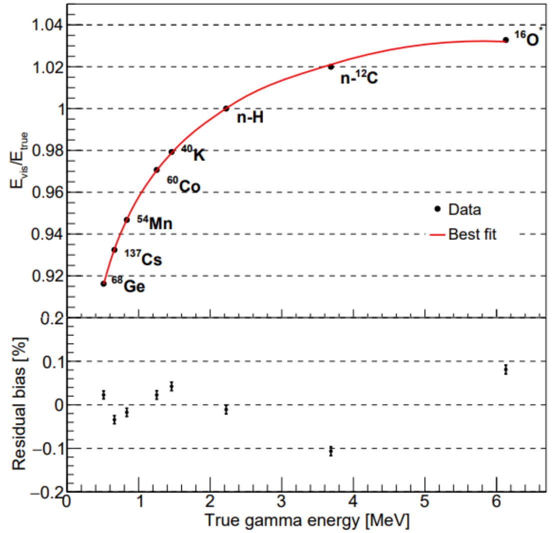
Calibration and Expected Energy Resolution

- Four systems for 1D, 2D, 3D scan with multiple sources - - all systems ready to installation
- Calibrate energy scale uncertainty to < 1% using γ peaks and cosmogenic ^{12}B beta spectrum

See also talk ID#963



JHEP 03 (2021) 004



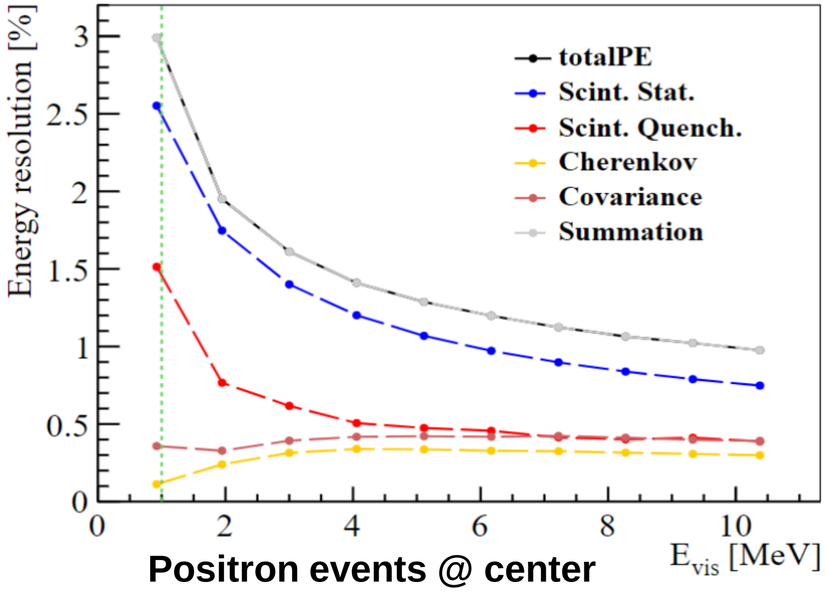
arXiv:2405.17860 (2024)

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

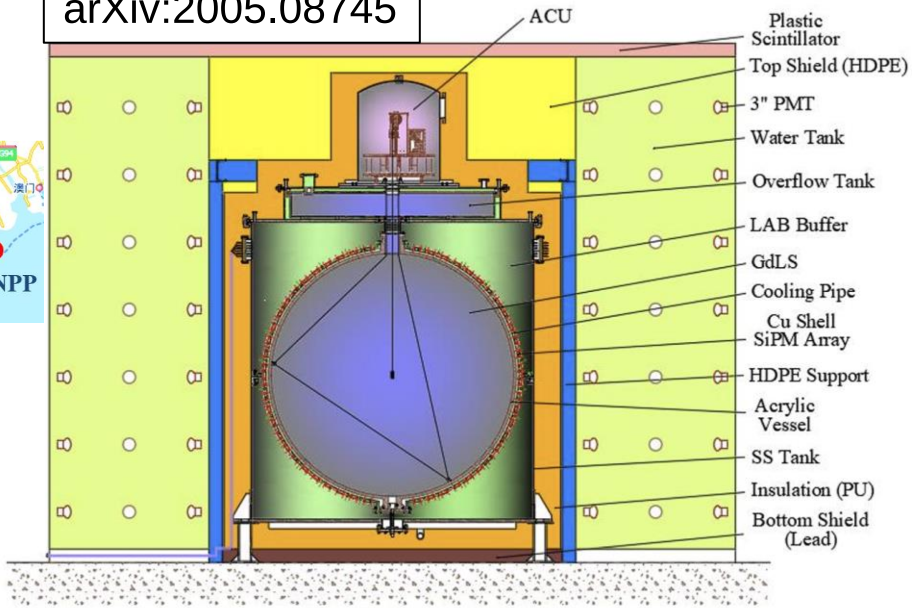
Expected energy resolution: **2.95% @1MeV**



JUNO-TAO(Taishan Antineutrino Observatory)

- **Physics motivation: measure the reactor neutrino spectrum (as a reference to JUNO)**
  - ⇨ better resolution to reduce fine structure effects and spectrum uncertainties, also improve nuclear database
- **Detector features**
  - ⇨ 10 m^2 SiPM + 2.8 ton Gd-loaded LS @-50°C
  - ⇨ 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°C, dark rate 100k→100 Hz/mm^2
- **Detector status**
  - ⇨ Production of major mechanical structures finished
  - ⇨ All 4100 SiPM tiles delivered and under testing
  - ⇨ 1:1 TAO prototype assembled and tested at IHEP
  - ⇨ Will start installation at Taishan in a few months, data taking in 2025.

arXiv:2005.08745

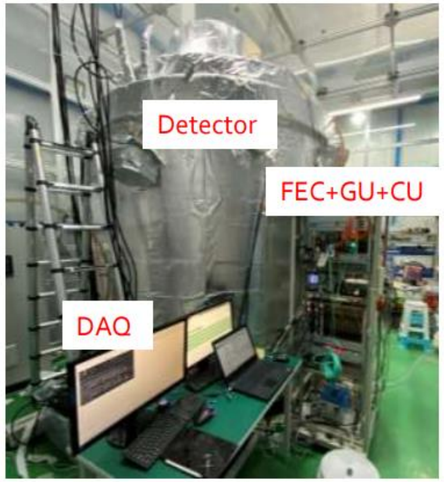


See also talk ID#1061



SS Tank & acrylic vessel & Copper shell

SiPM under testing



1:1 prototype

JUNO Site

Surface buildings / campus

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

~240 people working onsite now

Summary

- JUNO construction is near completion, overcoming a lot of challenges
- Detector will be finished in the end of 2024, then start filling, and data taking in 2025

Thank you for your attention!