Jiangmen Underground Neutrino Observatory

Status and Prospects

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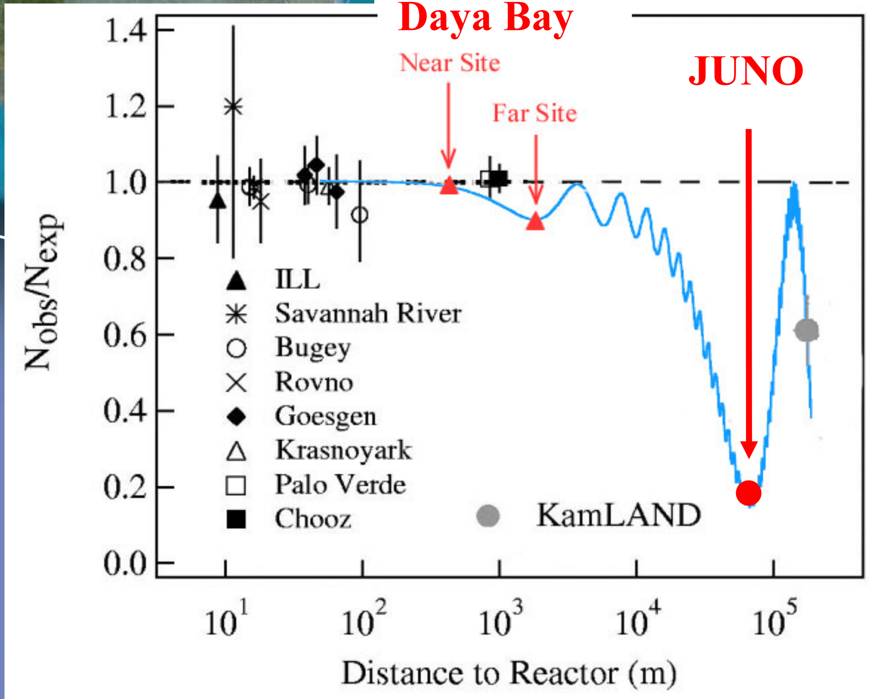
Context

- **Facility and Detector**
- **Installation status**
- **Performance and Physics Prospects**
- **Summary**

The Location of JUNO Facility

NPP	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	Operational	Planned	Planned	Operational	Operational
Power	17.4 GW	17.4	17.4 GW	17.4 GW	18.4 GW/2



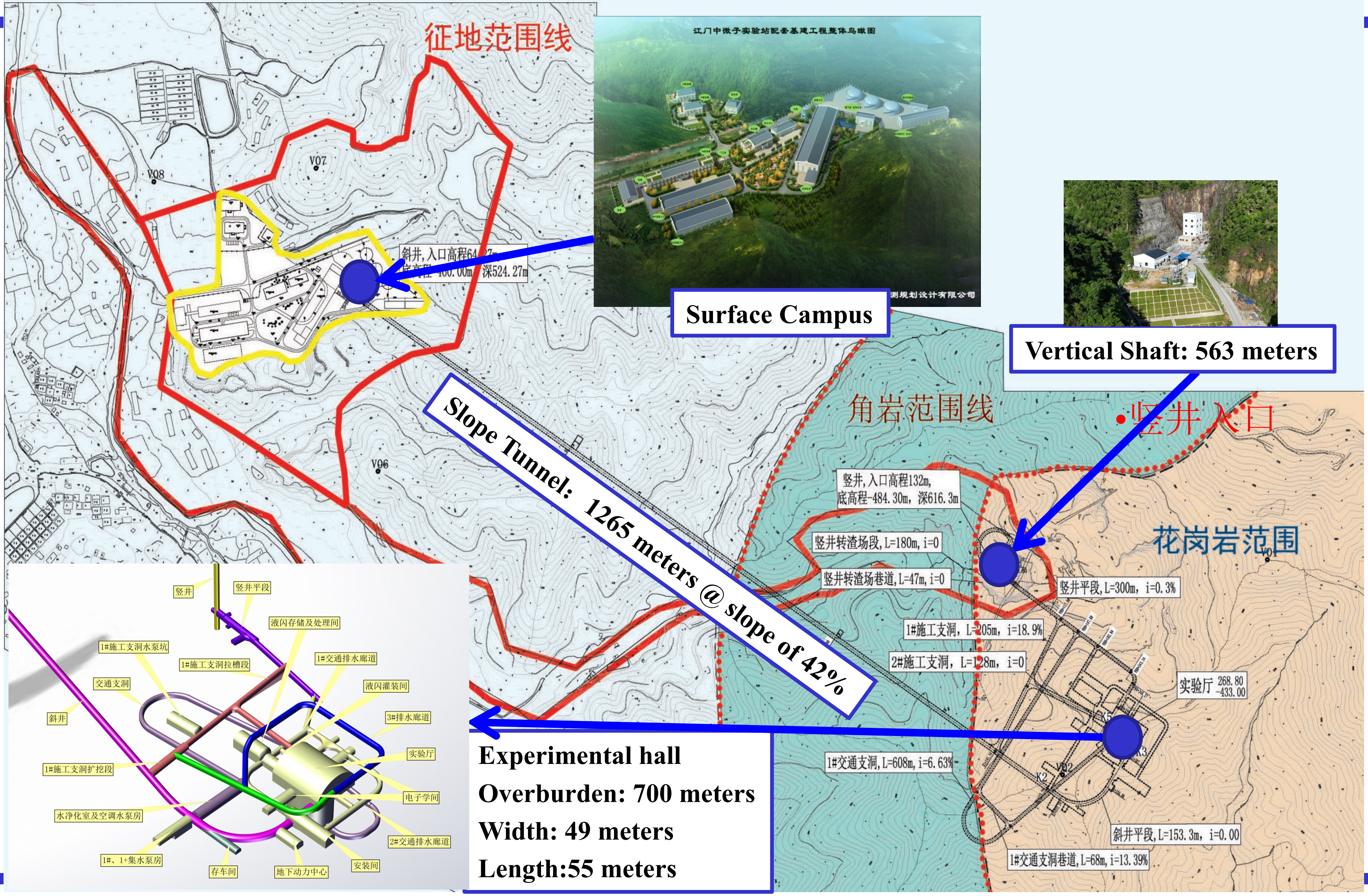
J. Phys. G 43: 030401 (2016) (arXiv:1507.05613)

JUNO Project and Collaboration

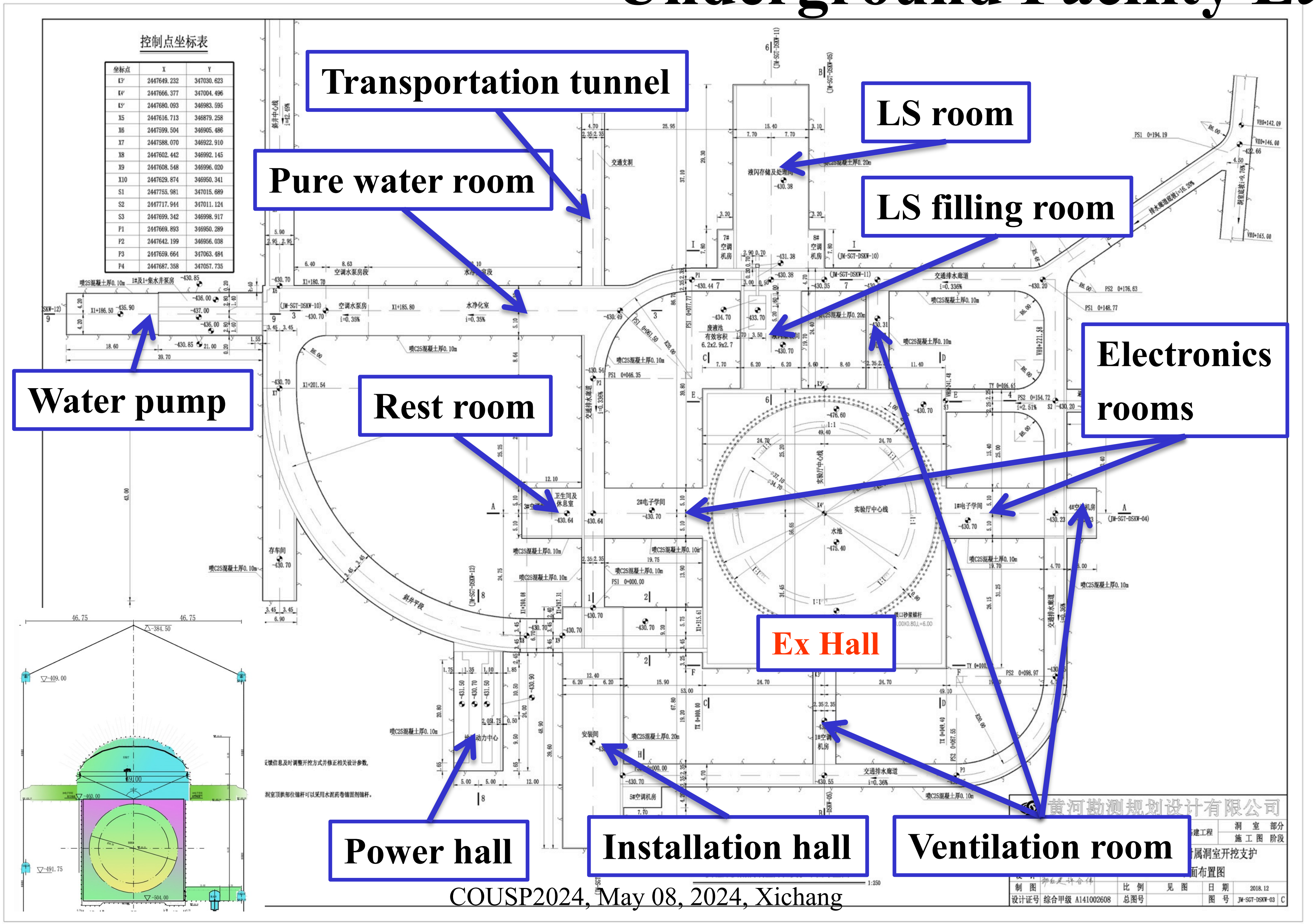
- Project firstly approved in China in 2013 and later in other countries. Construction started in January of 2015
- Collaboration established in 2014, now >700 collaborators from 74 institutions in 17 countries/regions

Facility and Detector

JUNO Site Facility



Underground Facility Layout



控制点坐标表

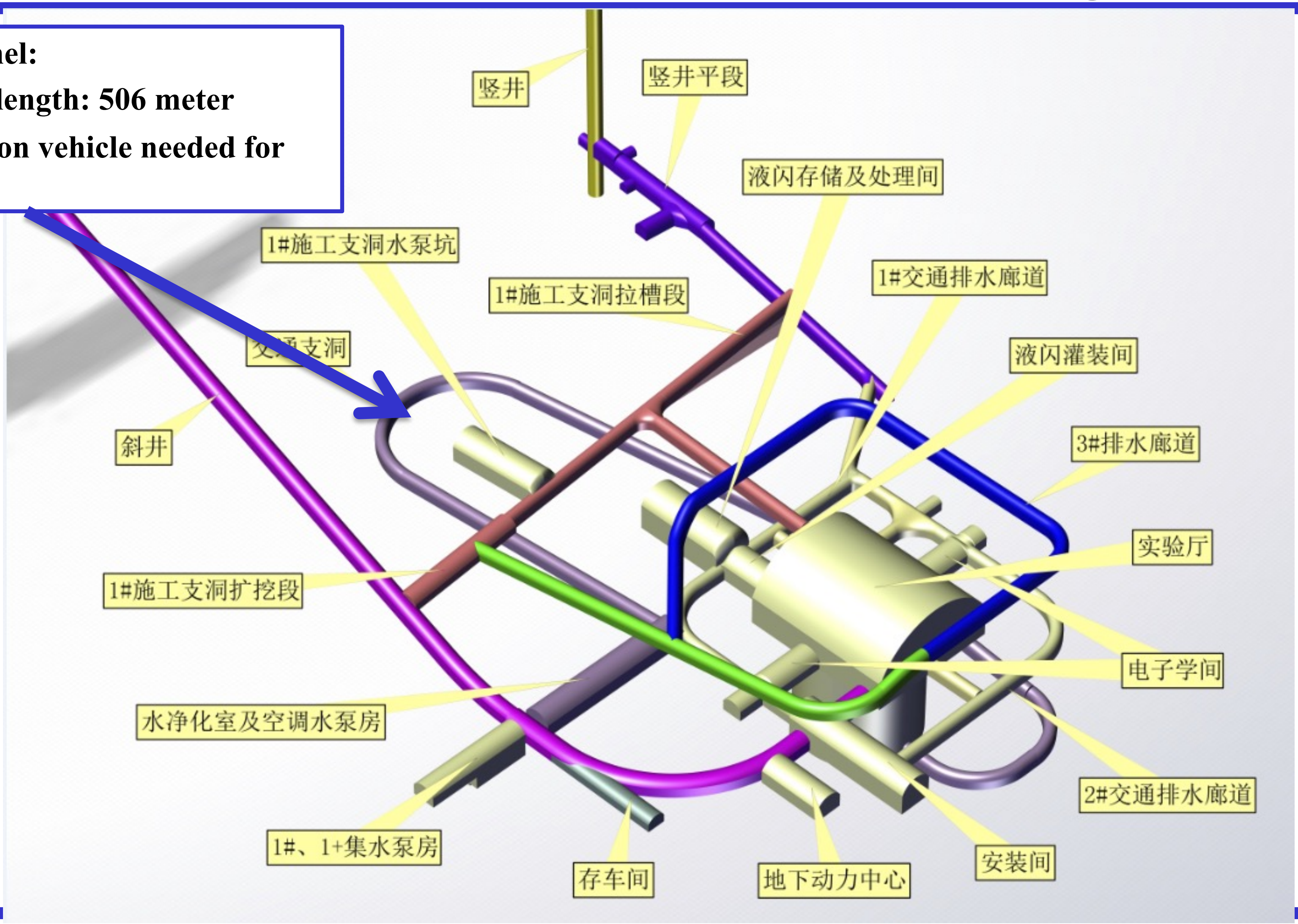
坐标点	X	Y
K3′	2447649.232	347030.623
K4′	2447666.377	347004.496
K5′	2447680.093	346983.595
X5	2447616.713	346879.258
X6	2447599.504	346905.486
X7	2447588.070	346922.910
X8	2447602.442	346992.145
X9	2447608.548	346996.020
X10	2447629.874	346950.341
S1	2447755.981	347015.689
S2	2447717.944	347011.124
S3	2447699.342	346998.917
P1	2447669.893	346950.289
P2	2447642.199	346956.038
P3	2447659.664	347063.484
P4	2447687.358	347057.735

Underground Facility

Transportation tunnel:

Slope: 3% @ 12%; length: 506 meter

Special transportation vehicle needed for installation



Bird-eye view of Facility

Underground Civil Construction

- **Dig down is generally difficult, especially in the presence of water and faults**
  - Largest water flow rate seen ~ 600m^3/h
- **More water than expected:**
  - Geological survey shows that the rock resistivity is low
  - Bore holes found no water, but iron ore with a low grade
  - Water are mostly from cracks and faults, not directly from the surface
- **Mitigations:**
  - Water drainage tunnel over and around exp. Hall
  - Drill holes to inject cement to seal water, and then drill holes for blasting
  - Elevate the hall by 35 m, shift the hall location to avoid cracks
  - Add a tunnel at the top of the hall to release the water pressure
- **Delayed by ~ 4 years**

Underground Transportation

For people, materials and equipment

Underground Halls

- Rock temperature ~ 31 °C, Exp. hall reduced and controlled to ~21°C
- VAC provided fresh air of 40 kM³/hour for underground cavern.
- Cleanness control

Experimental hall


Assembly hall


LS hall

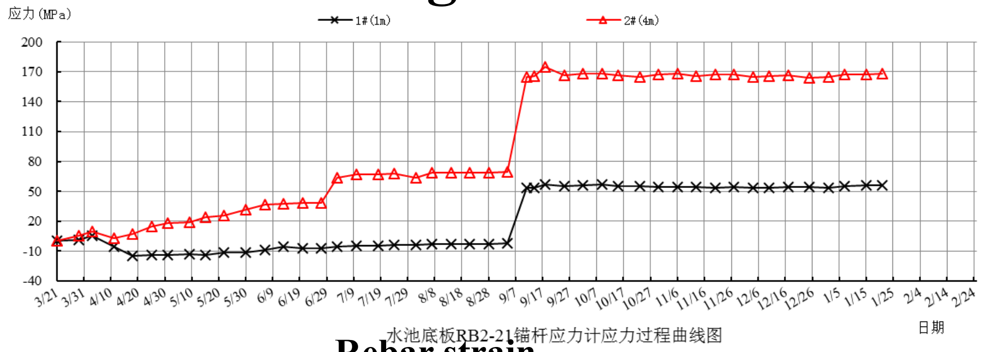

HVAC & Ventilation

Water Pool

- Water pool HDPE(High Density PE) liner, thickness of 5mm

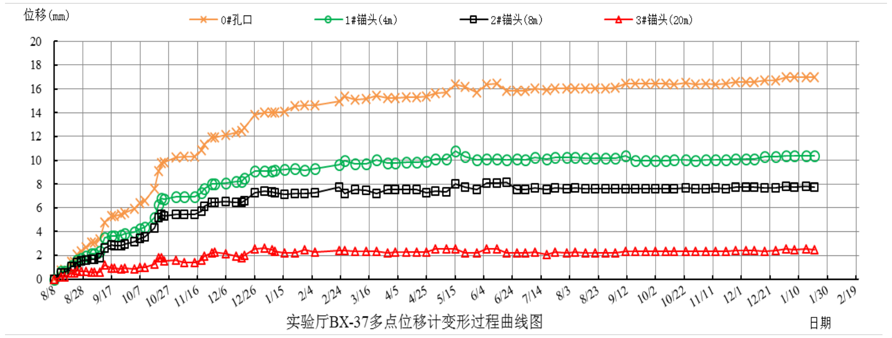
Cavern Status

- **Stability monitoring of cavern structure**
  - Number of cavern stability monitoring sensors: 156
  - Underground water level

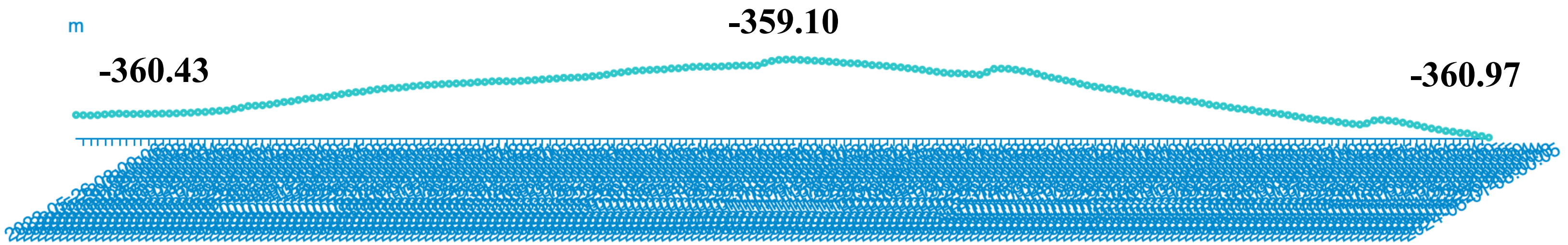


Rebar strain

	Displacement	Rebar strain	Cable strain	Water pressure
Experimental hall	12	23	4	3
Water pool	21	58	8	19
Installation hall	3	3		



Displacement



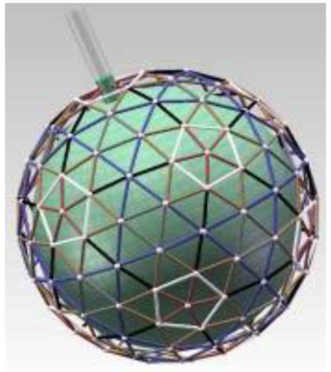
Underground water level (in a year)

Design of JUNO Detector

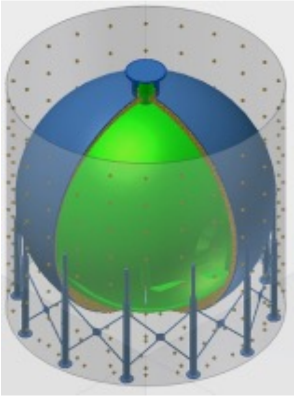
- Target mass of 20 kt liquid scintillator ➔ × 20 KamLAND, × 40 Borexino
- Energy resolution < 3%@ 1MeV ➔ 1200 PE/MeV
- Life time: >30 years

	KamLAND	JUNO	PE Ratio
Photon Statistics	250 p.e./MeV	1200 p.e./MeV	5
PMT coverage	34%	75%	2.2
LS transparency	~12 m	> 20 m	~0.9
Light yield(anthracene)	30%	45%	~1.5
Detection Eff.(QE×CE)	~15%	30%	~ 2

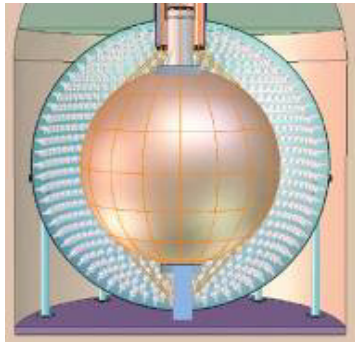
- **Technology R&D since 2009:**
  - Transparent & high light yield liquid scintillator
  - High detection efficiency 20" PMTs
  - Radiopurity U/Th/K < 10^{-17} g/g for 20 kt LS
- **Detector Design：**
  - Central target container: acrylic or balloon ?
  - Mechanical structure: steel frame or steel tank ?
  - Buffer layer: Water or Mineral oil ?



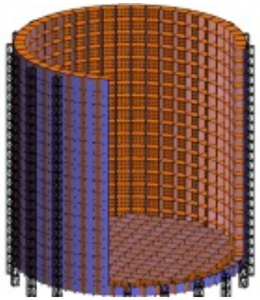
Steel frame+ Acrylic tank



Steel tank+ Acrylic tank



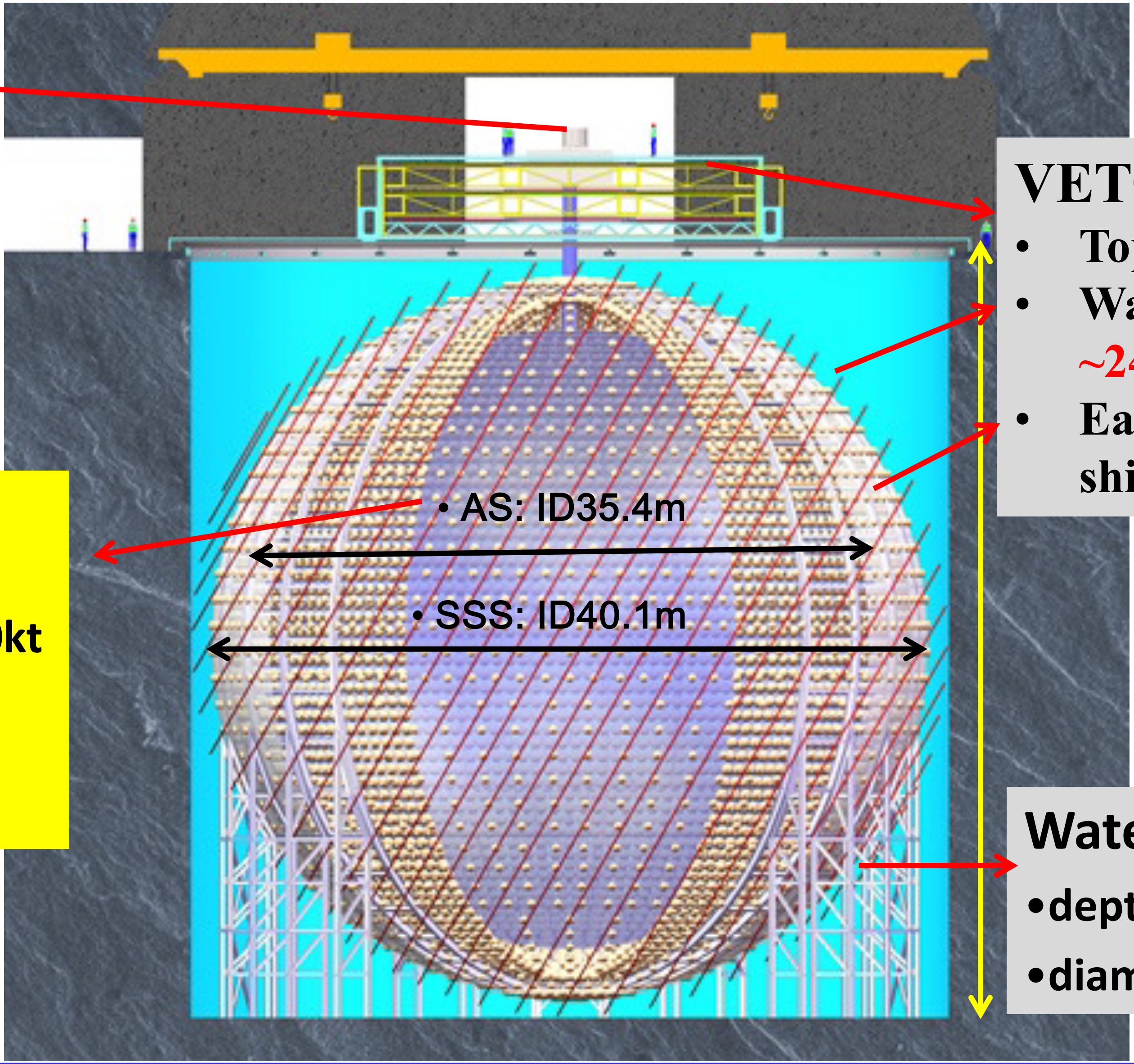
Steel Tank + Balloon



Steel Tank + Acrylic blocks

JUNO Detector Key Parameters

Calibration



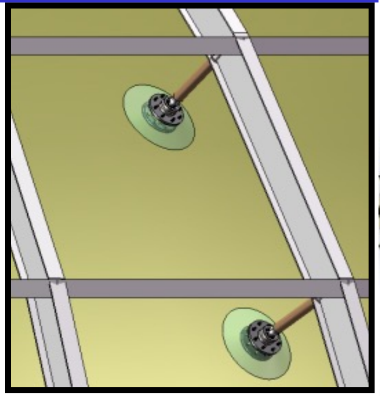
VETO system
- Top Tracker
- Water VETO with ~2400 20” PMT
- Earth Magnetic Field shielding coils

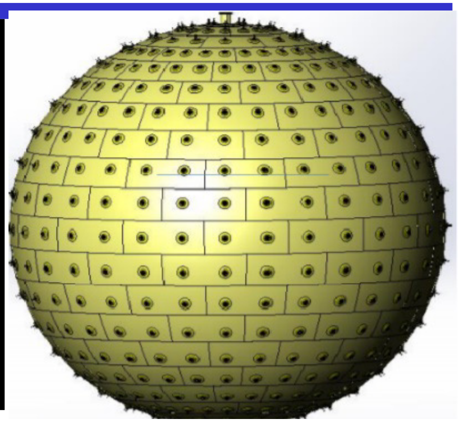
Central detector
- Steel structure (SSS)
- Acrylic sphere(AS) +20kt Liquid scintillator
- ~17612 20” PMT
- ~25600 3” PMT

Water Pool
- depth: 44m
- diameter: 43.5m

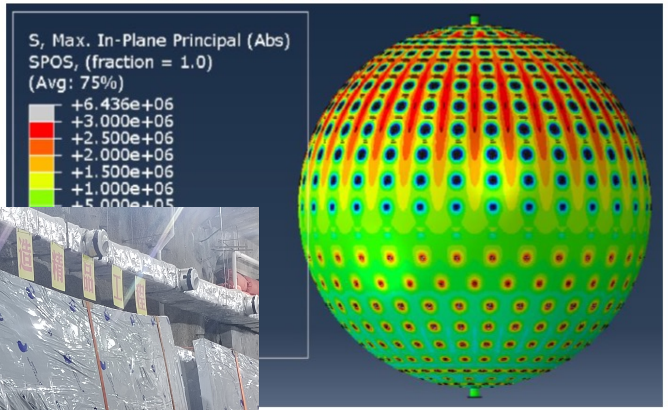
Ccentral Detector

- **Acrylic sphere was chosen over balloon for safety, lower backgrounds and longevity**
- **Structure: SS frame with supporting bars to hold the acrylic sphere and to mount PMTs**
  - 263 Acrylic panels: ~8m × 3m ×12 cm
  - Thermally pressed and machined to the spherical shape
  - Panels are bonded through PMMA polymerization
  - 1.7m long steel anchor bolts welded to the concrete steel structure to hold the SS frame against the buoyancy
- **Main issues:**
  - Mechanical precision for PMT clearance ~3 mm
  - No welding, clearance between screw and hole < 1mm
  - Thermal expansion controlled at 21ºC ± 1ºC
  - Earth quake safety with liquid-solid coupling, level 7
  - Acrylic quality and strength:
    - Effects of aging, creep, crazing, etc. < 20% loss of strength
    - Bonding: fast and good quality, effects < 20% loss of strength
    - Stress of the supporting rod < 3.5 MPa





工况：自重+水压（内4.5m高度）

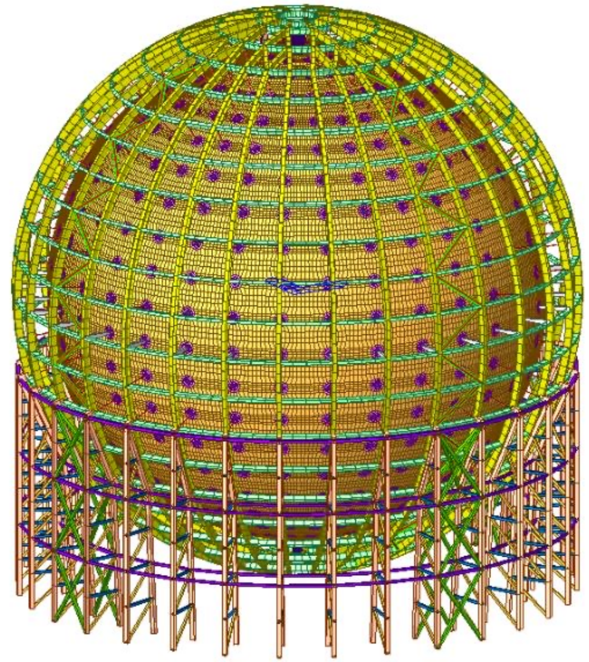


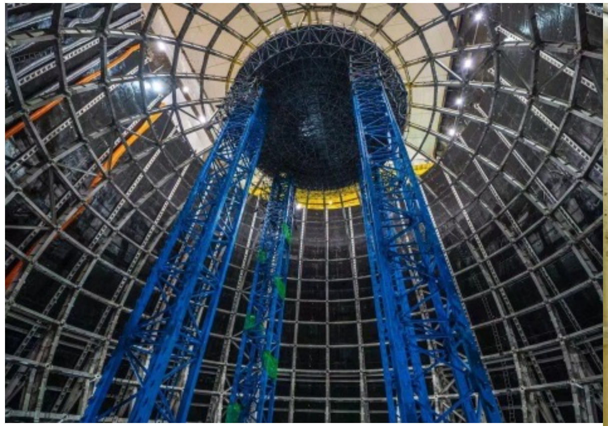
应力情况

arXiv: 2311.17314

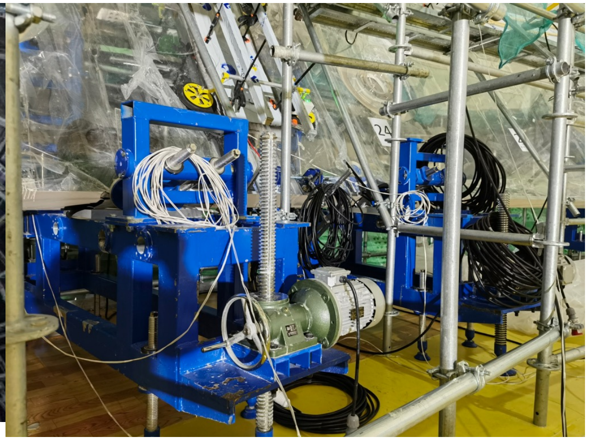
CD: Installation

- **SS structure completed except bottom 4 layers**
- **Acrylic panel production completed**
  - A special production line for low backgrounds (< 1 ppt U/Th/K)
  - Shaping, sanding/polishing, cleaning, machining and protection of
  - panels by 50μm PE, while maintaining high transparency (>96%)
  - and low surface background (< 5 ppt U/Th)
- **Acrylic sphere construction on-going**
  - Lifting platform: frequently change the diameter and height
  - Acrylic sphere built from the top, 16/23 layers finished, defects repaired
  - SS bars connecting the acrylic and SS, sensors for stress monitoring

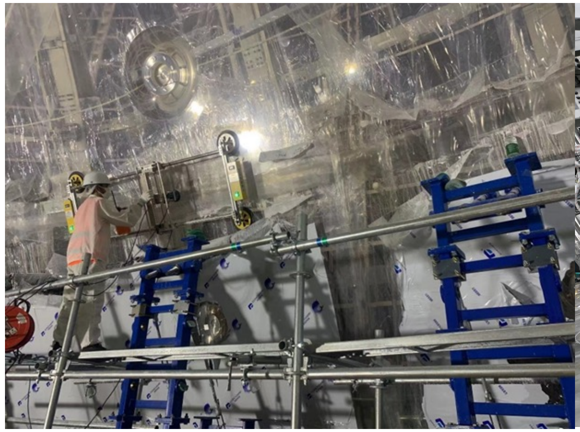




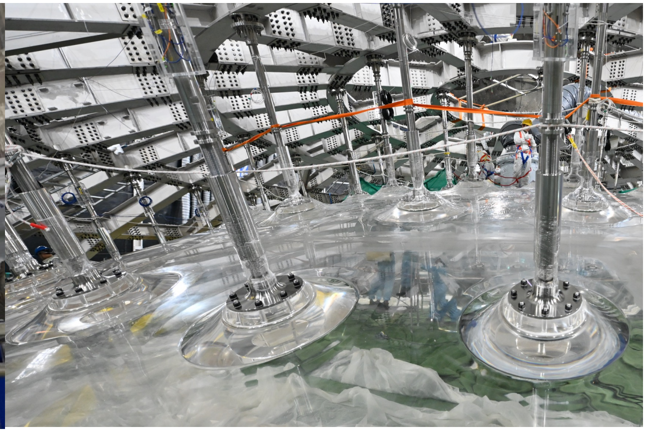
Hydraulic Lifting platform



Annealing



Sanding and polishing



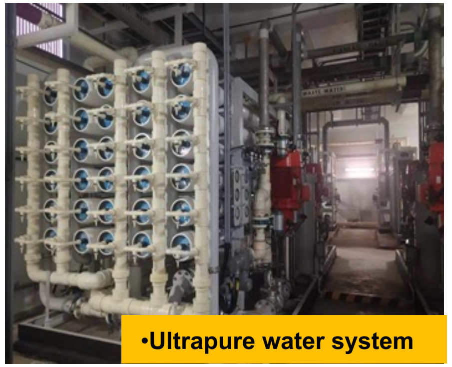
Bars between SS and acrylic

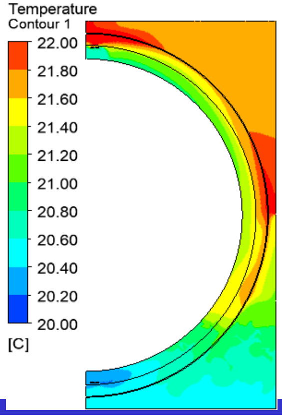
VETO: Water Pool and Top Tracker

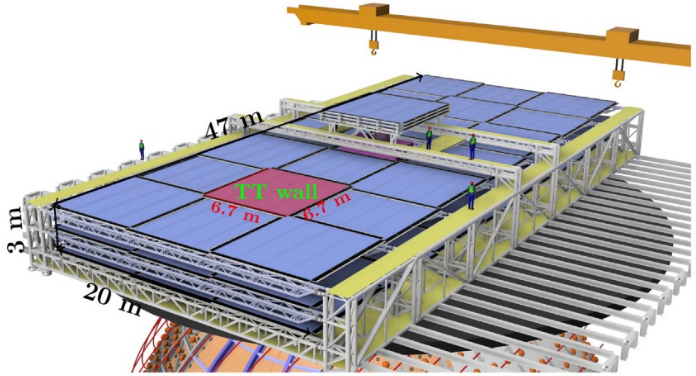
- **Design:**
  - 700m overburden ➔ R_μ=0.004 Hz/m², $<E_\mu>$= 207 GeV
  - 35 kt water to shield backgrounds from the rock
  - 2400 20" PMTs in water to tag & reconstruct cosmic muons
  - Top tracker: refurbished OPERA scintillators
- **Water pool lining: 5mm HDPE to keep the clean water and to stop Rn from the rock**
- **Earth magnetic field compensation coil**

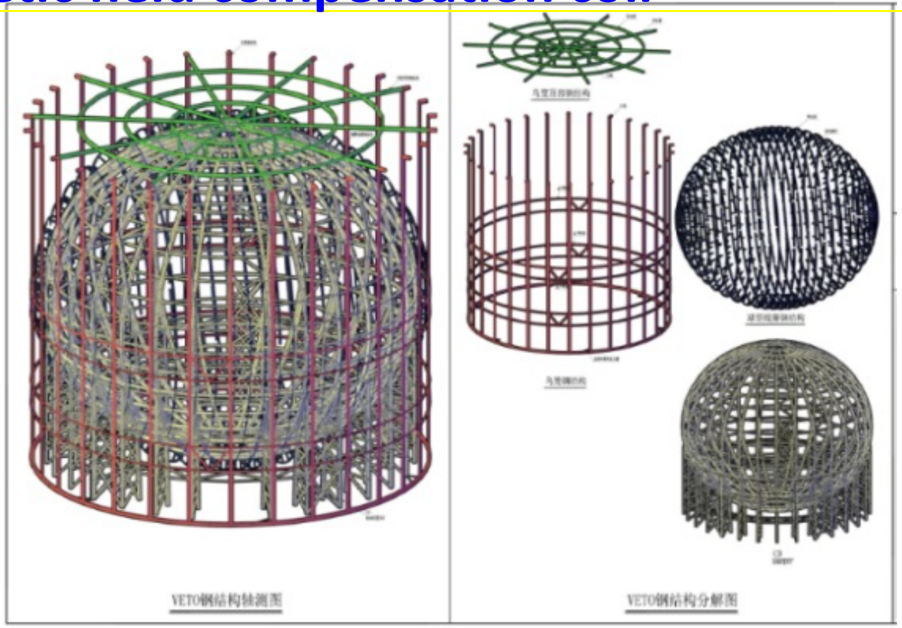
100t/h pure water production for U/Th/K<10^{-14} g/g and Rn<10 mBq/m³, attenuation length>40m, temperature controlled to (21±1) °C

报告：郭聪，江门中微子实验低氡超纯水研制







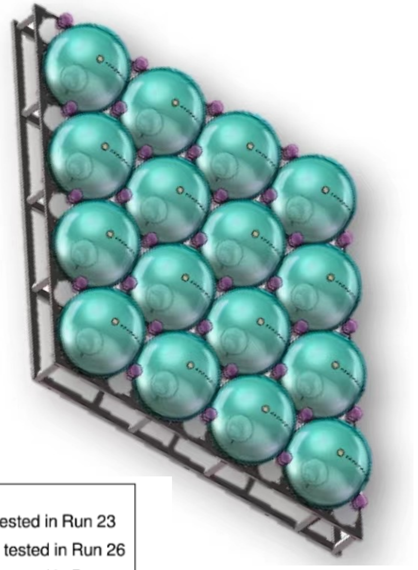


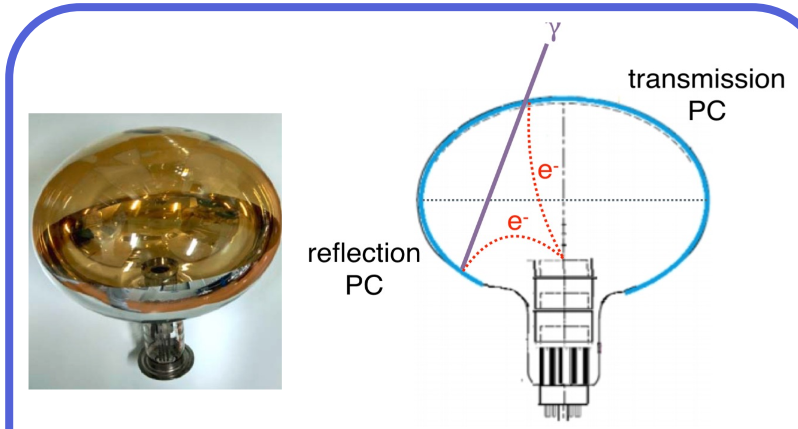
Large PMT

- **uses large 20-inch PMTs as its main light-detection device:**
  - **MCP-PMT(NNVT): 15000**
  - **Dynode PMT(Hamamatsu): 5000**

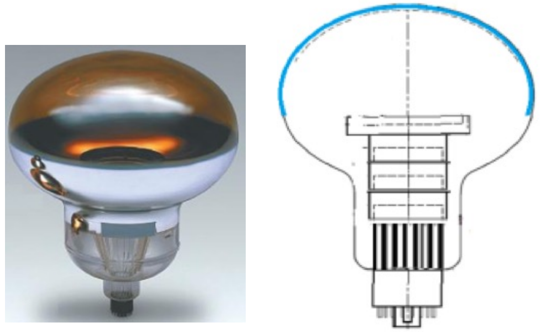
clearance of 3 mm

Coverage: 75%

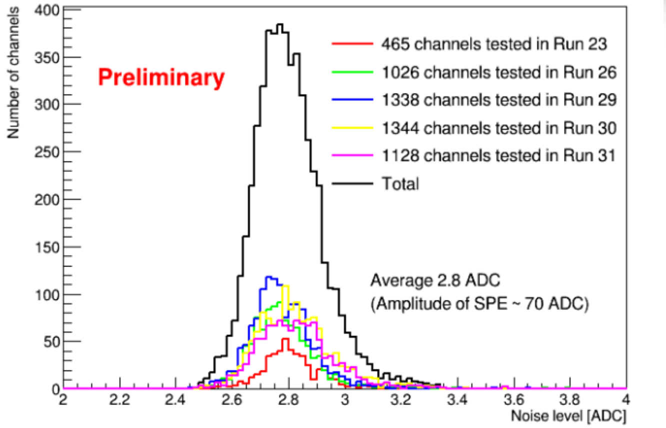




Microchannel plate (MCP)-PMTs



Dynode-PMTs



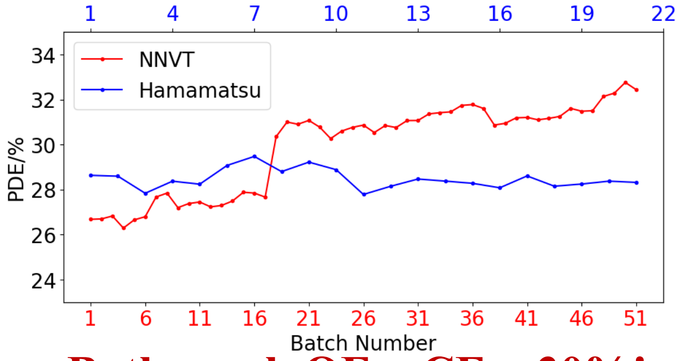
Higher collection efficiency

High efficiency photocathode, low backgrounds glass, …

High production yield, automatic mass production

Noise level is ~ 0.05 PE: good grounding and shielding

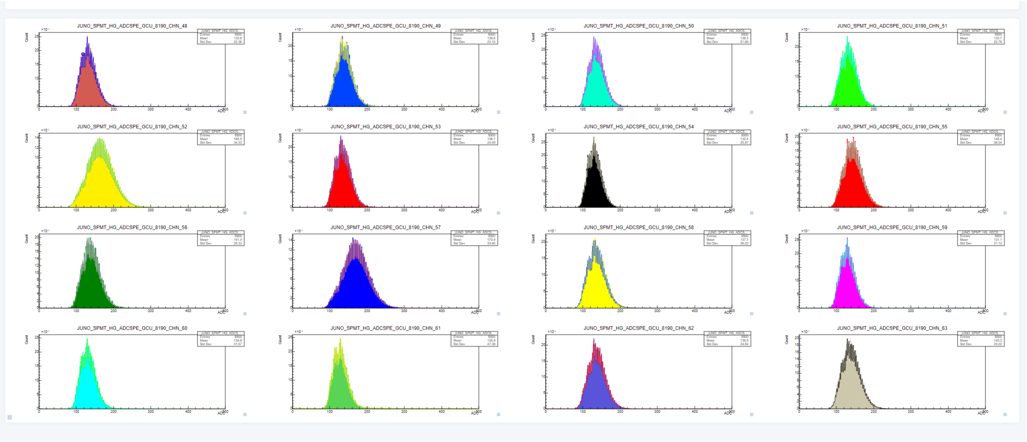
New type of SBA



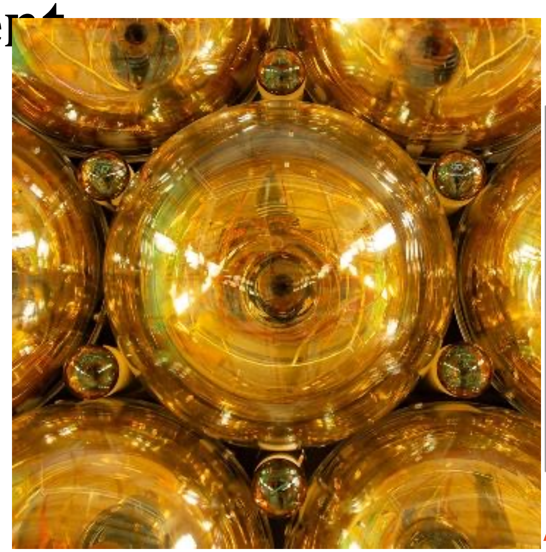
Both reach QE x CE ~ 30%!

Small PMT System

- **Mass production and waterproofing of 26,000 3-inch PMTs (XP72B22) from HZC Photonics**
- **Goal: 3% more light, higher dynamic range for muons, uniformity and linearity calibration for large PMTs, …**
- **Two eye system look at same event with different systematics**
  - **Aid to position reconstruction and muon track reconstruction**
  - **Aid to supernova neutrino measurement**



First commissioning data: SPE spectra of a group of 16 PMTs

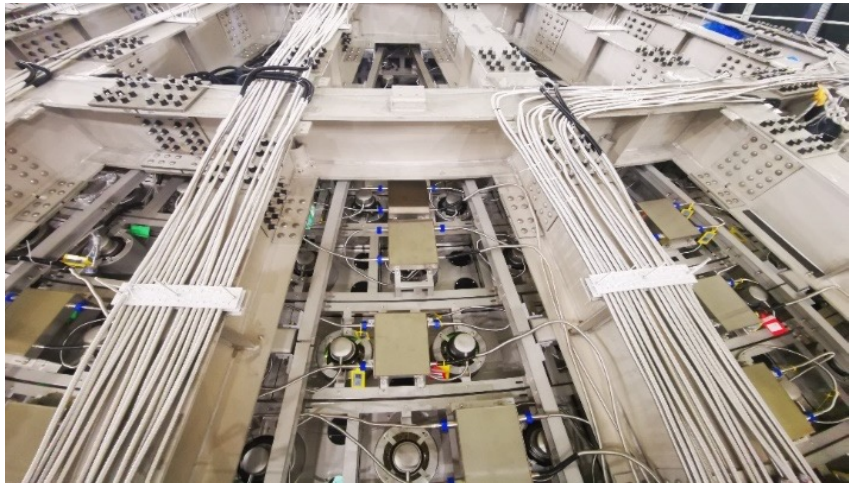


NIM A 1005 (2021) 165347

XP72B22

A custom design for JUNO!

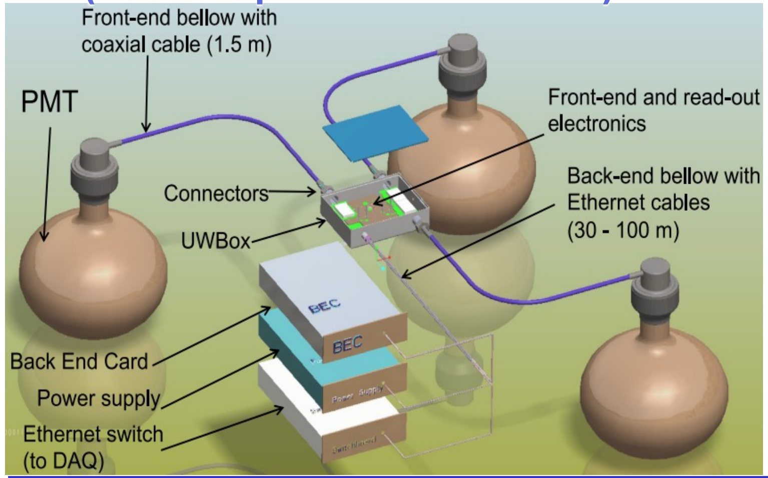
- **LPMT and sPMT frontend electronics are housed in SS underwater boxes**
  - **Power the PMTs, decouple signal from HV, process the analog signals and send the information to surface via digital CAT5 cables**
- **Cables are in the SS corrugated pipes**



胡俊：Design and production of readout electronics for the 20-inch PMT

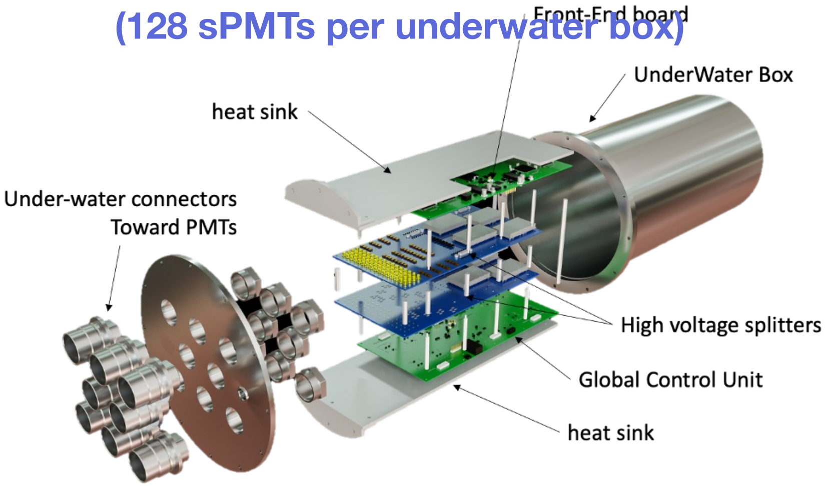
LPMT System

(3 LPMTs per underwater box)



sPMT System

(128 sPMTs per underwater box)



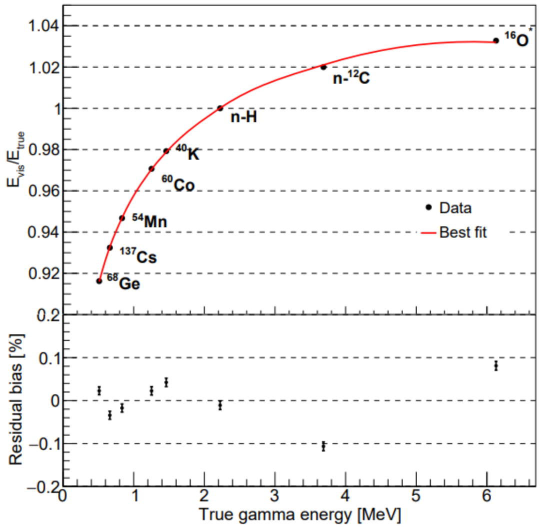
Power Modules, BEC and others

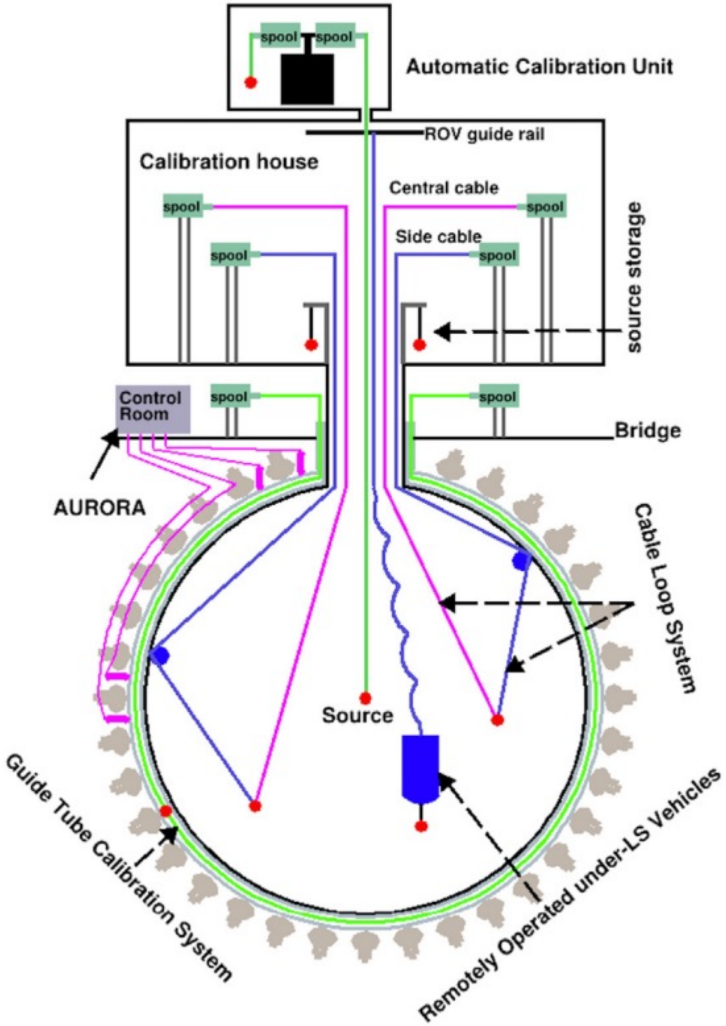
Calibration System

- Have an comprehensive calibration program:
  - 1D: Automated Calibration Unit (ACU) deploys radioactive and laser (1ns, keV-TeV range) sources along the central axis
  - 2D: Cable Loop System (CLS) to scan vertical planes
  - 2D: Guide Tube to scan the outer surface of the central detector (where the CLS cannot reach)
  - 3D: Remotely Operated Vehicle (ROV) operating inside the LS to scan the full volume

JHEP 2021, 04 (2021)

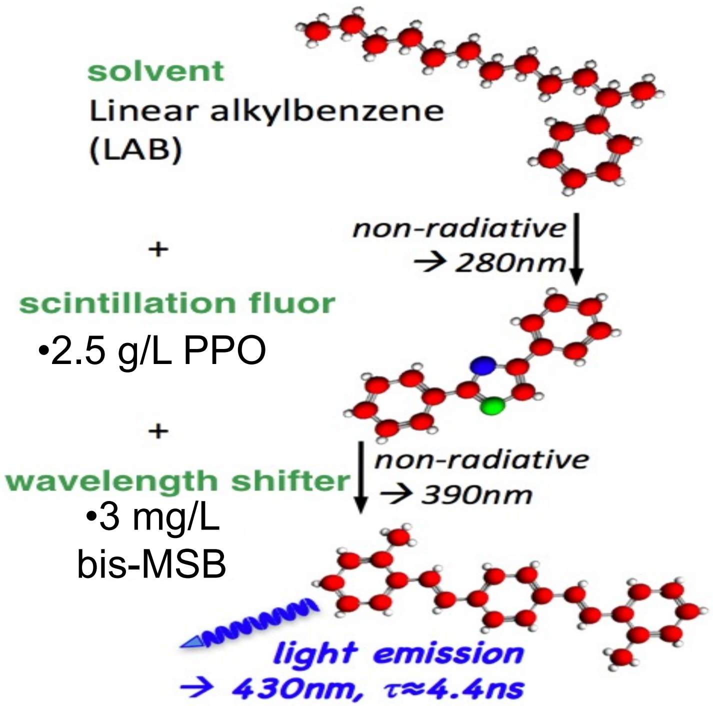
Calibrate energy scale and non-linearity to better than 1% using γ peaks and cosmogenic ^{12}B beta spectrum



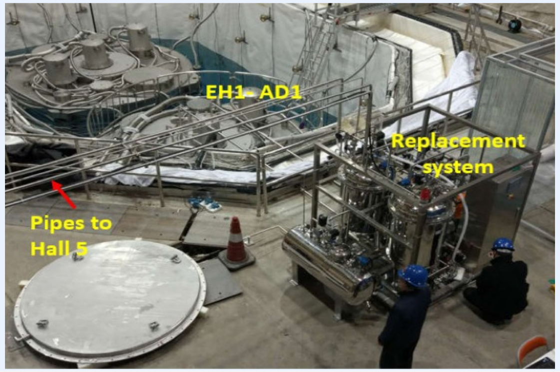


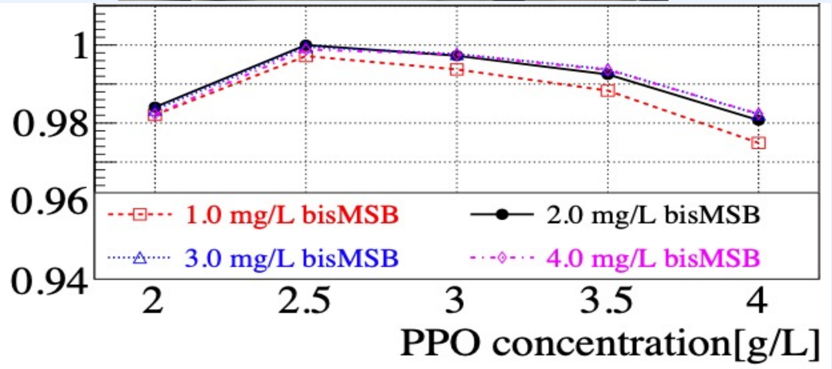
Liquid Scintillator

- Main requirements: high light yield, high transparency and high radiopurity
- **Recipe： Based on Daya Bay experience with dedicated optimization for higher light yield.**
  - LAB + 2.5g/L PPO + 3 mg/L bis-MSB
- No dope



Recipe optimized with a decommissioned Daya Bay detector whose results were extrapolated to JUNO size using a new optical model





• NIMA 998, 164823 (2021)

Recent measurements: LAB attenuation length > 24 m, LS attenuation length > 20 m

LS Production and Purification

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

俞伯祥：High pure nitrogen plant of JUNO

孙希磊，江门中微子实验的超纯液闪

Aboveground

- 5000 m^3 LAB storage tank

- 1) Al_2O_3 for optical transparency

- 2) Distillation for radiopurity

- Mixing LAB with PPO and bis-MSB

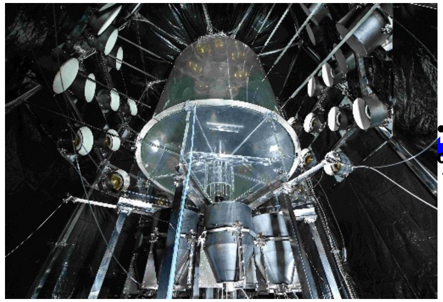
- 1800 m SS pipes to underground

Underground

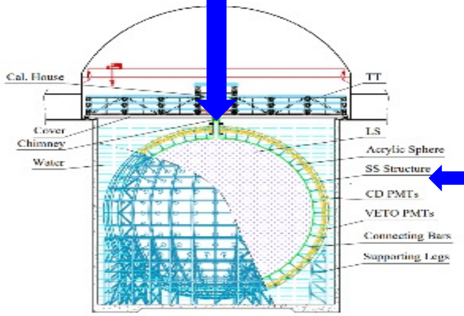
- 3) Water extraction to remove radioactive impurities

- 4) Gas stripping to remove Rn and O_2

- 85 %
- 15 %



- OSIRIS to monitor the LS quality



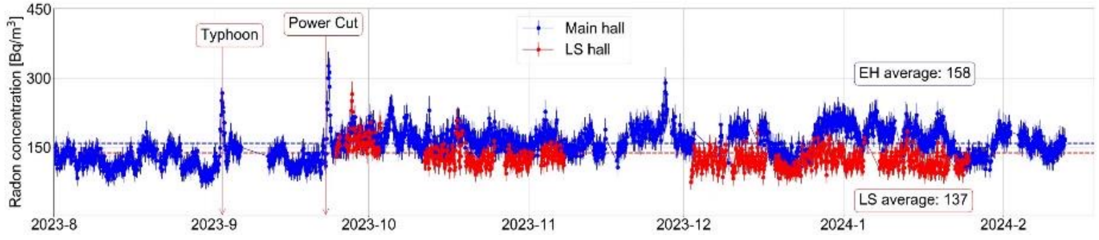
- **Full chain of equipment were successfully commissioning and ready for final filling**

Radiopurity and Cleanness Control

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

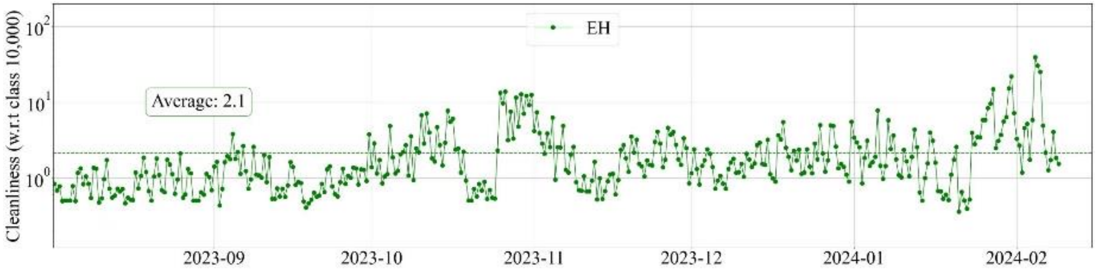
- **Radon and cleanness control of hall environment :**
  - High efficient VAC and component/personnel access control into exp. hall
  - Radon concentration: ~160 Bq/m^3 in the EH, ~140 Bq/m^3 in the LS hall
  - Cleanliness: class 20,000

崔晨阳：Study on dust fallout during installation



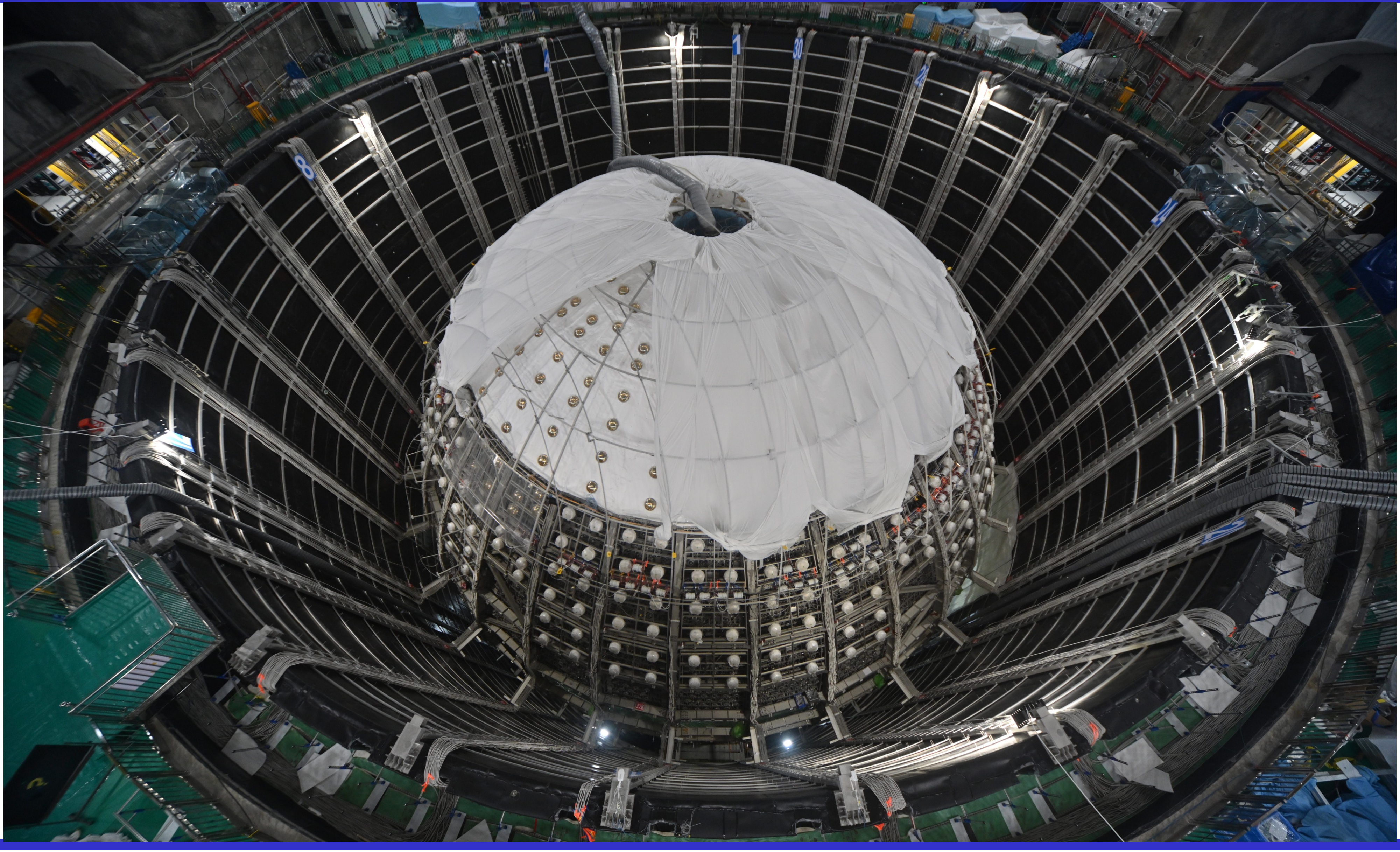
•JHEP 2021, 102 (2021)

Singles (R < 17.2 m, E > 0.7 MeV)	Design [Hz]	Change [Hz]	Comment
LS	2.20	0	
Acrylic	3.61	-3.2	10 ppt -> 1 ppt
Metal in node	0.087	+1.0	Copper -> SS
PMT glass	0.33	+2.47	Schott -> NNVT/Ham
Rock	0.98	-0.85	3.2 m -> 4 m
Radon in water	1.31	-1.25	200 mBq/m^3 -> 10 mBq/m^3
Other	0	+0.52	Add PMT readout, calibration sys
Total	8.5	-1.3	Better than spec. by 15%



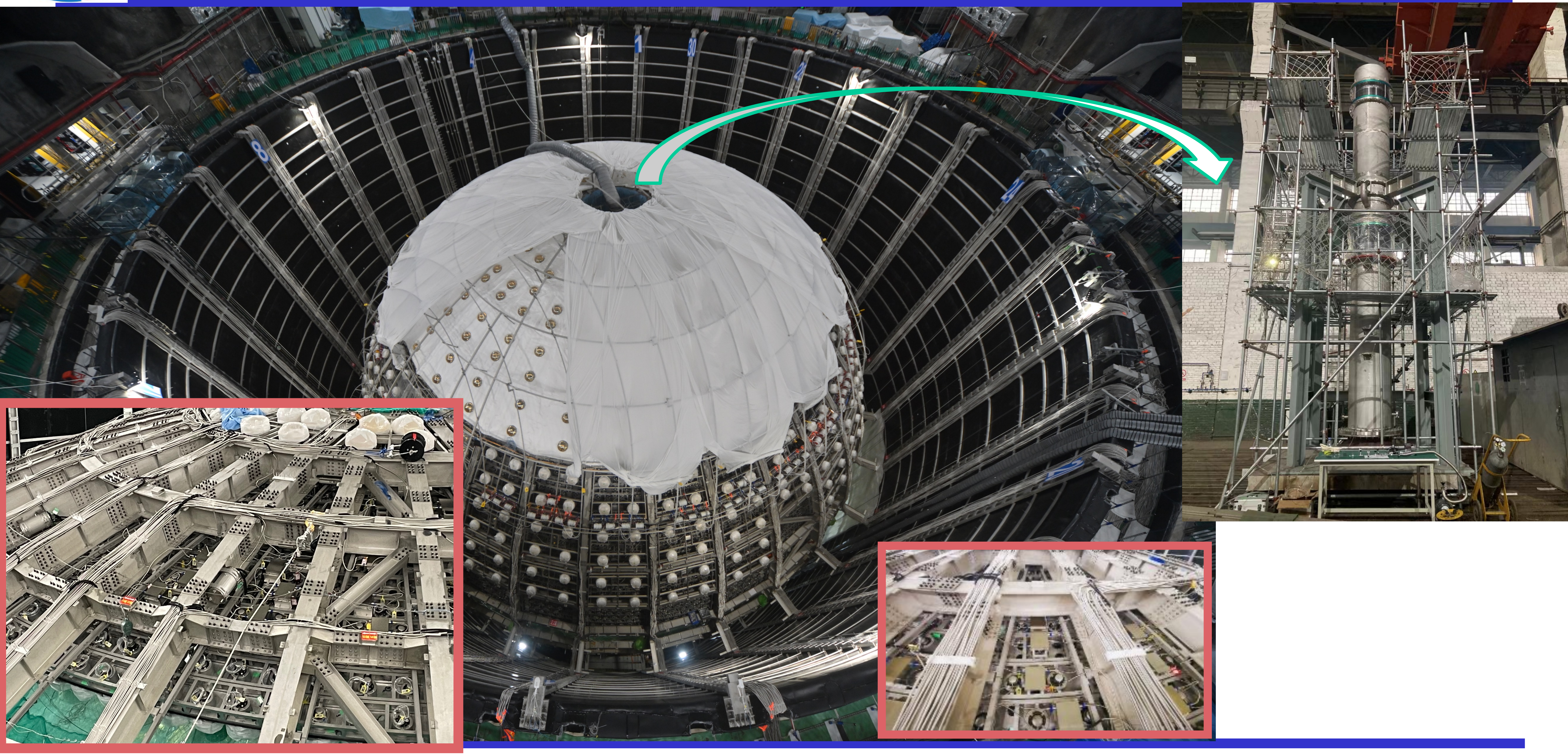
Construction Status

Inside Water Pool



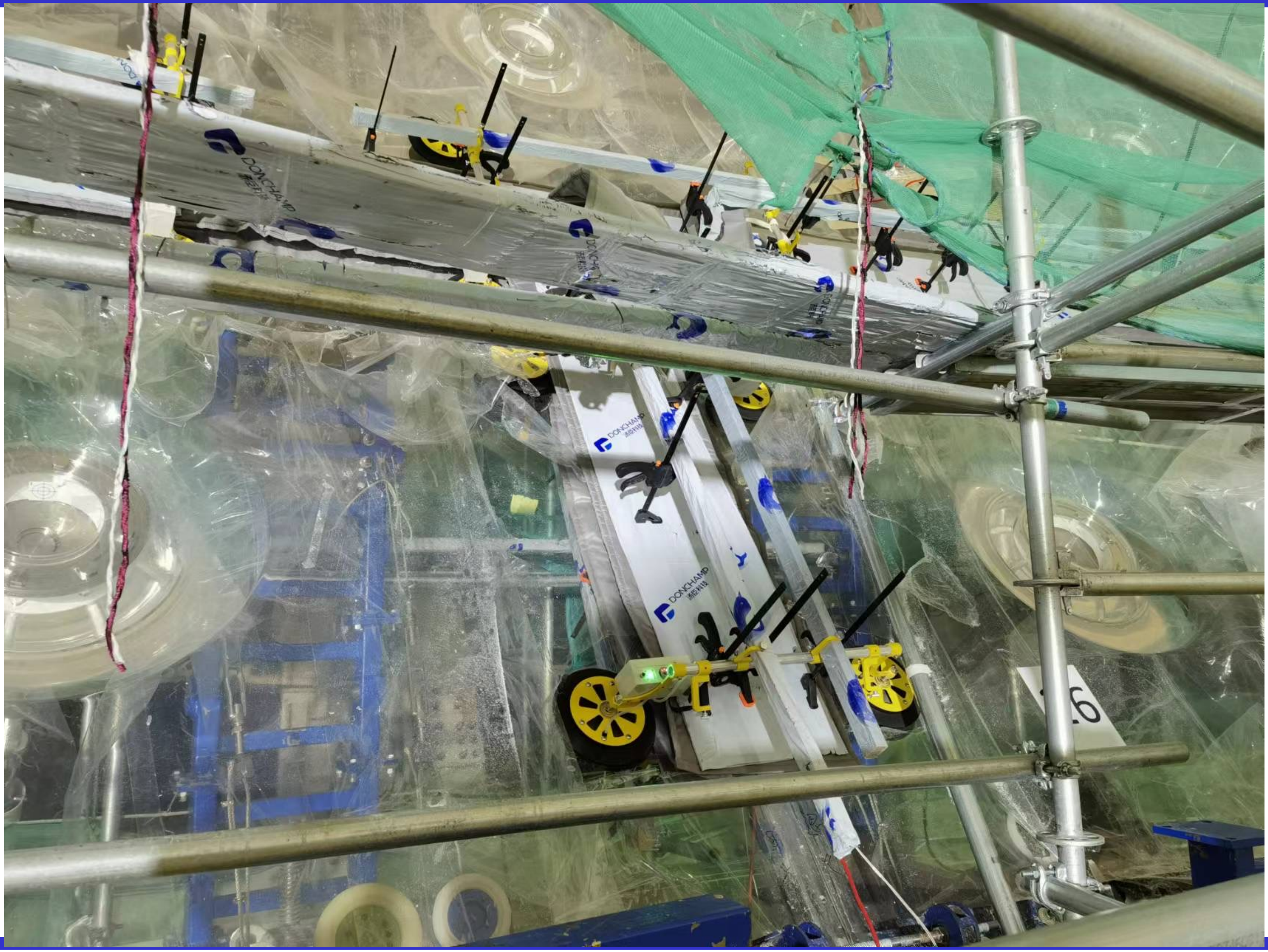
LPMT Installation

The details on the SS

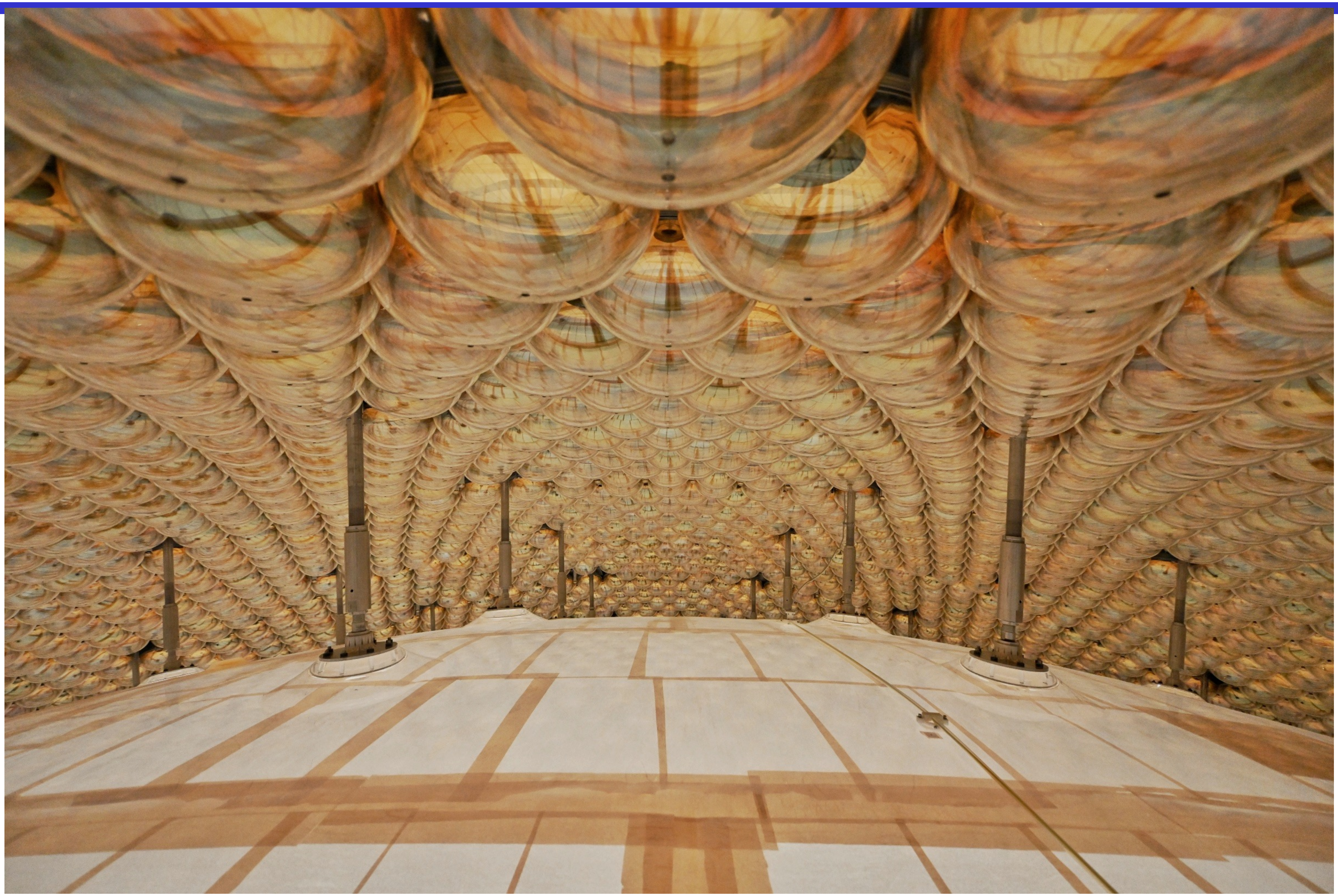


Art View

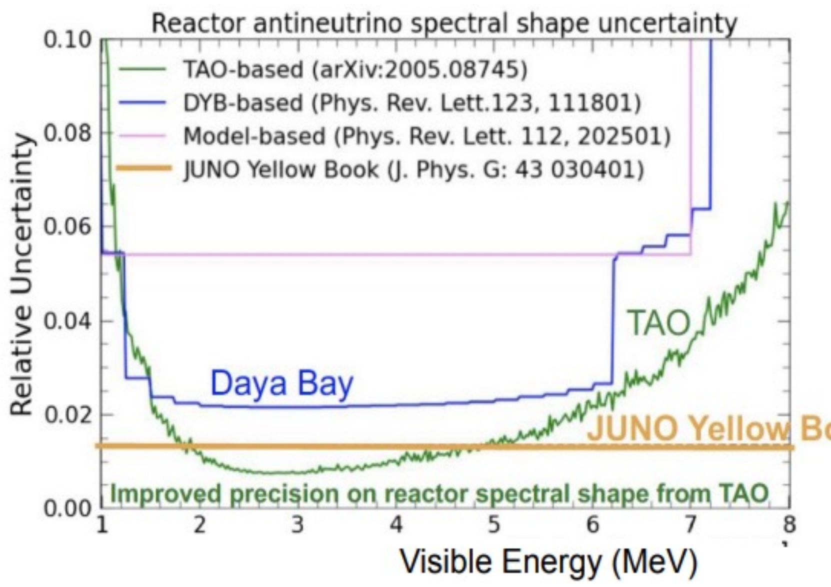
Acrylic Annealing

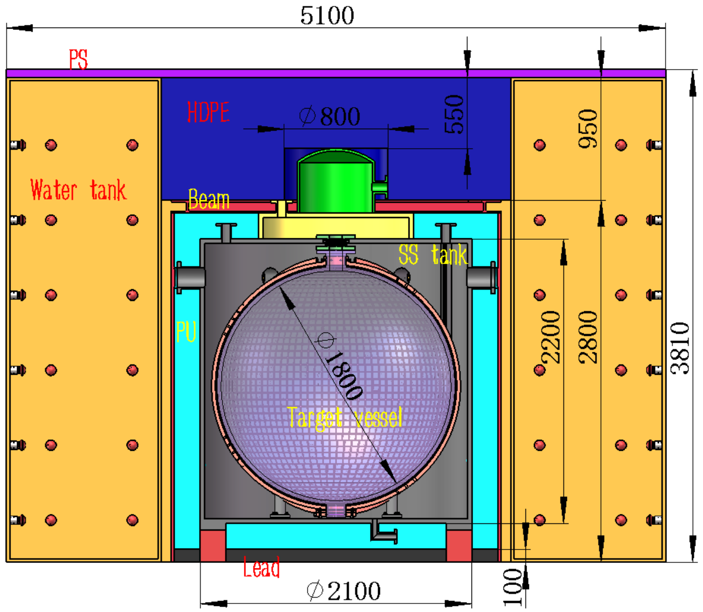


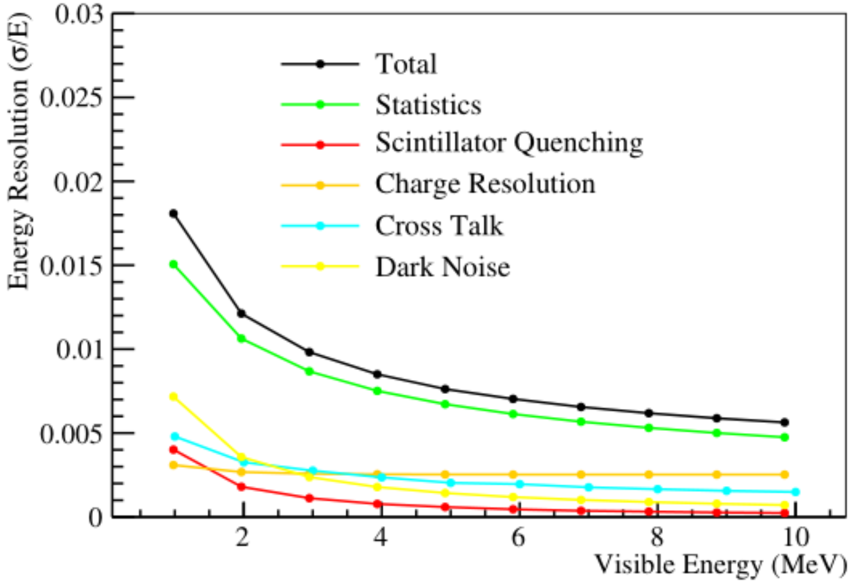
Outside Acrylic



- **To measure the reactor neutrino spectrum as a reference to JUNO**
  - better resolution to reduce fine structure effects and spectrum uncertainties
  - Improve nuclear database, search for sterile neutrinos
- **Idea: Gd-loaded LS @-50ºC + SiPM**
  - 700k neutrinos/year@44m from the core(4.6 GW), with ~10% bkg.
  - Energy resolution: ~1.5%/√E, 4500 p.e./MeV
  - 10 m^2 SiPM (>94% coverage) w/ PDE > 50%
  - Operating at -50 ºC to reduce the SiPM dark rate by 10^3 to 100 Hz/mm^2
  - 2.8 ton(1t fiducial volume) new type of Gd-LS for -50 ºC
- **Component production mostly completed**







谢宇广报告：TAO
张杰：MicroTCA' Application in TAO

Physics and Prospects

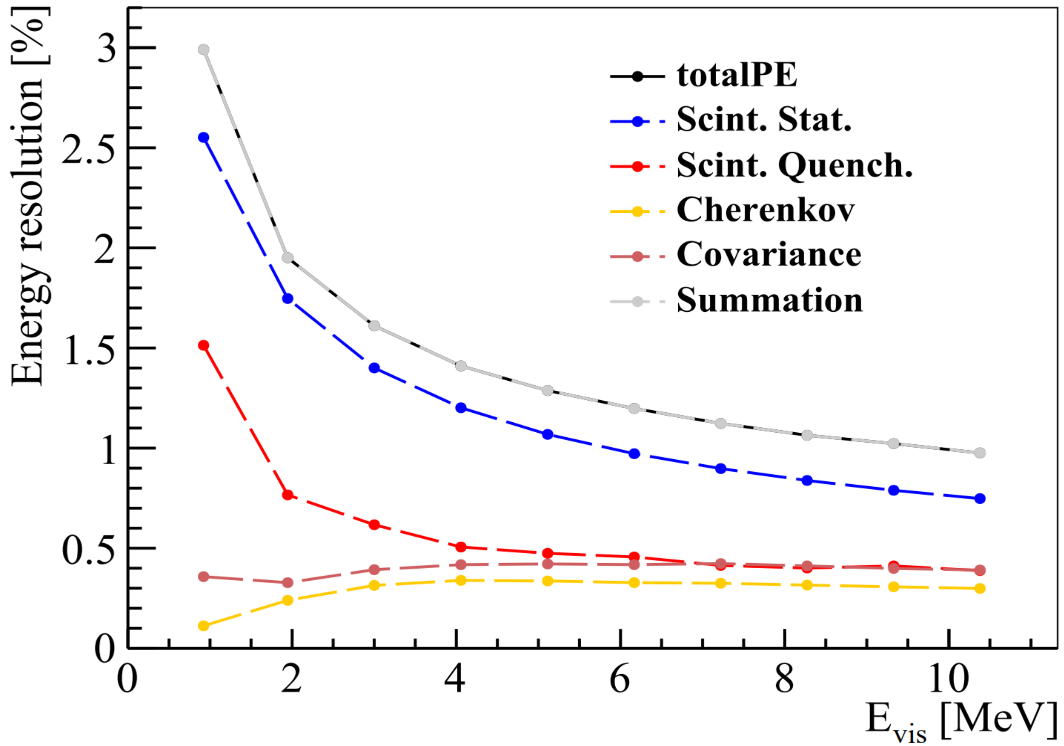
Expected Performance

- Bkg. in LS can reach U/Th/K < 10^{-15} g/g for MH
- 10^{-17} g/g is feasible for solar ν and 0νββ decays
- From measured PMT, LS and acrylic properties, the energy resolution will be < 3%@1MeV, based on full simulation, calibration and reconstruction

$$\frac{\sigma}{E_{vis}} = \sqrt{\left(\frac{2.614\%}{\sqrt{E_{vis}}}\right)^2 + 0.64\%^2 + \left(\frac{1.205\%}{E_{vis}}\right)^2}$$

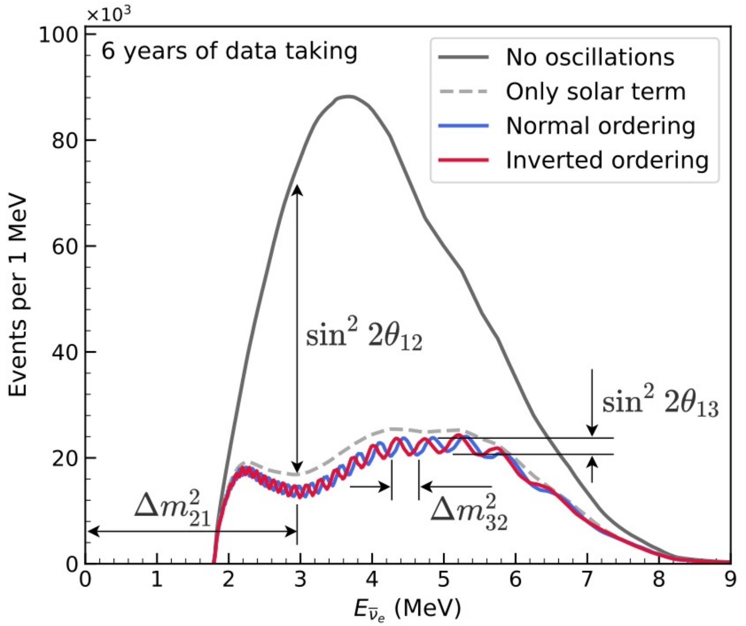
Photon statistics; Constant term; Annihilation -induced γs Dark noise

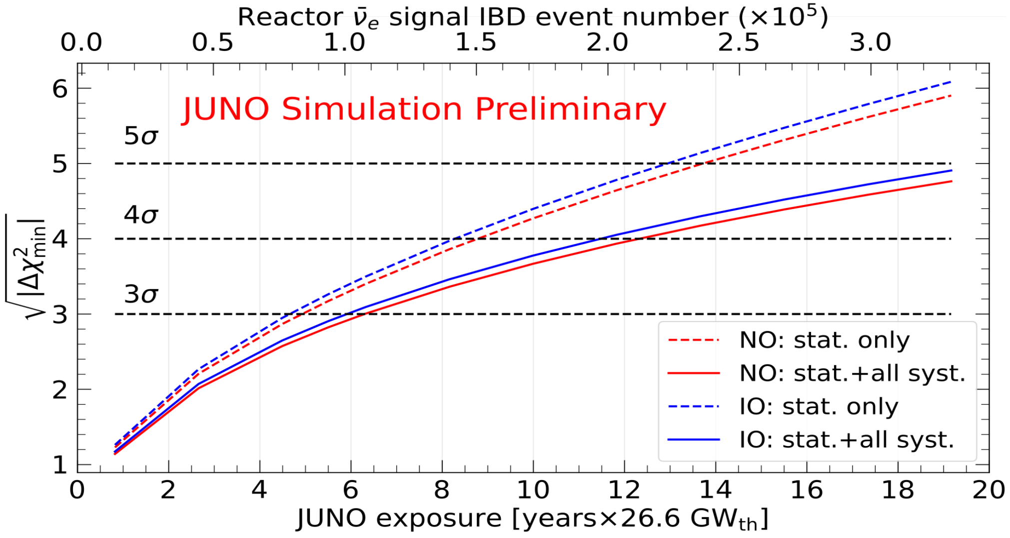
- **Main changes vs design** *(JHEP03(2021)004)*:
  - Photon detection eff.: 27% → 30%
  - (EPJC 82 (2022) 12, 1168)
  - New PMT optical model: +8%
  - (EPJC 82 329 (2022))
  - *New central detector geometry and LS: 3%*
- **Total photon statistics: ~1660/MeV**



Mass Ordering Determination

- **Determine mass ordering**
  - Exploit interference effects in the fine structure of the oscillated spectrum
  - 3σ sensitivity within ~ 6 years
  - Independent of θ_{23} and δ_{CP}
- **Atmospheric neutrino is under consideration**

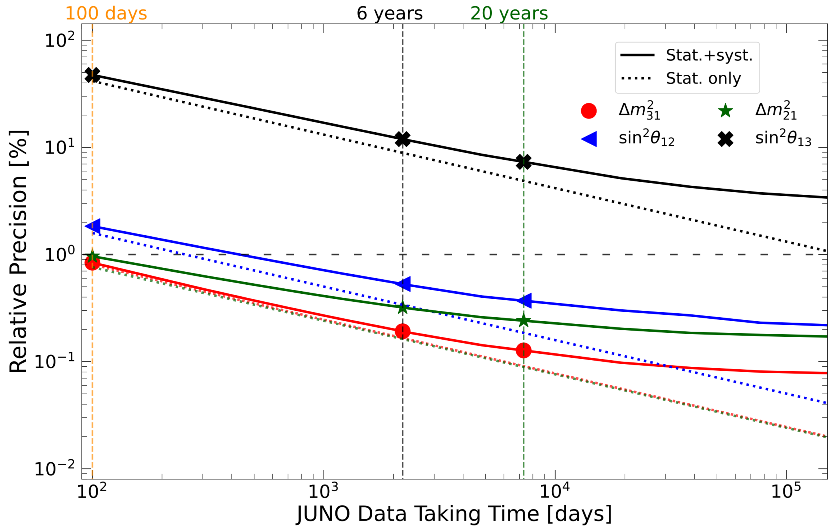




程婕，Oscillation Physics Potential with Reactor Neutrino at JUNO

Reactor Neutrino Oscillation Physics

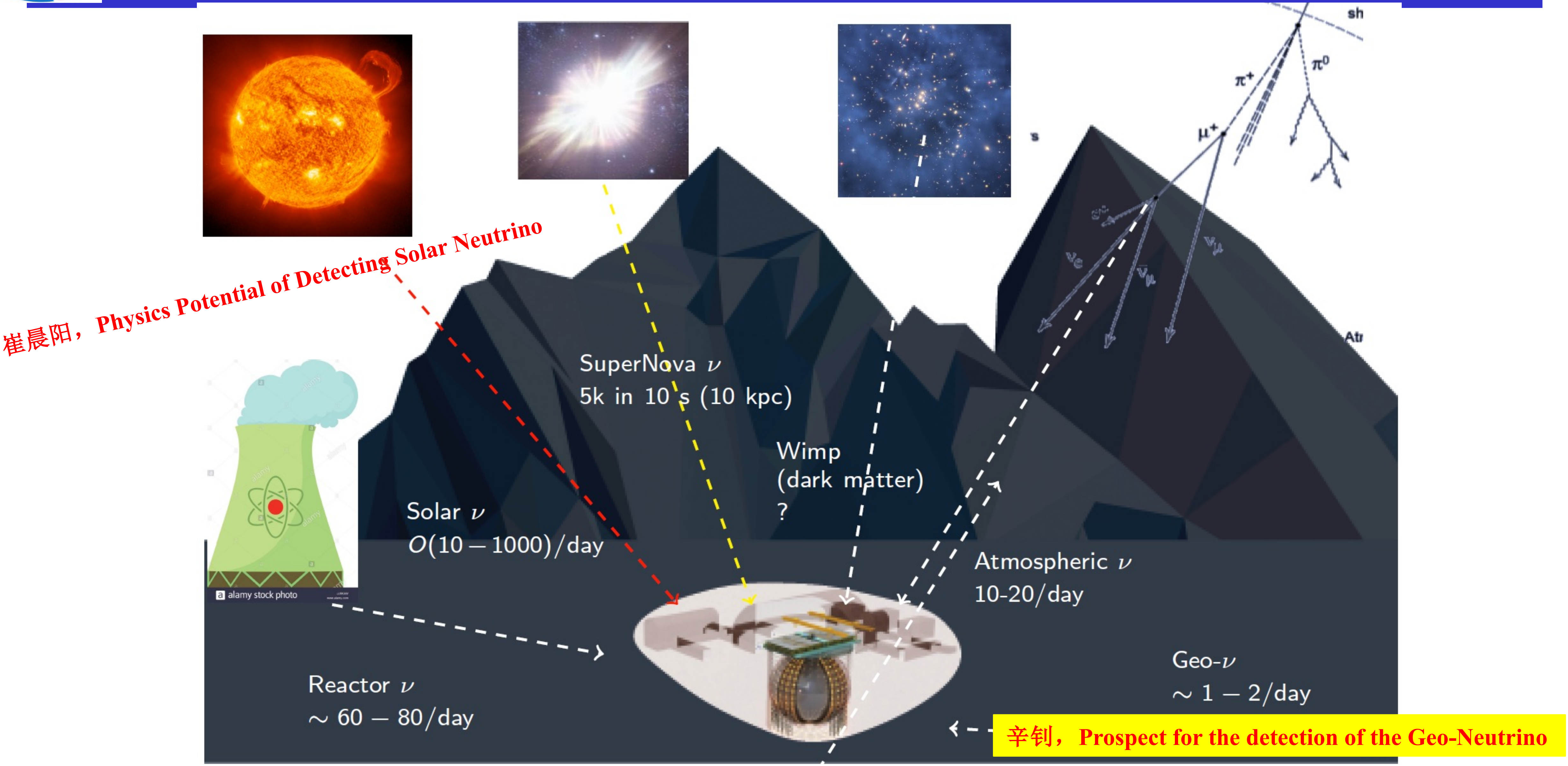
- **Measure $sin^2\theta_{12}$, Δm^2_{21} and Δm^2_{31} to better than 0.5% in 6 years**
  - **New era of precision for neutrino mass & mixing models**
  - **Model independent tests of the three-neutrino oscillation framework (U_{PMNS} unitarity tests)**
  - **Narrow down parameter space for $0\nu\beta\beta$ searches**



Roughly one order of magnitude improvement over existing precision for 3 parameters!

Parameter	$\sin^2\theta_{12}$	Δm^2_{21}	Δm^2_{31}	$\sin^2\theta_{13}$
Current Precision*	4.2%	2.4%	1.5%	3.2%
JUNO 6 years	0.5%	0.3%	0.2%	12.1%

A Multi-Purpose Neutrino Observatory



Summary

- **Although the project delayed, overcome a lot of challenges, the installation is under progress**
- **Commissioning shows that the performance of (part of) components/detector is better than the requirement**
- **Expect to beginning filling this year**
- **Mass ordering expected to determine in the decade**
- **Anticipating more exciting physics results**

十年磨一剑

THANKS