Design and Construction of the Central Detector of JUNO

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On behalf of the JUNO collaboration

The 16th PISA Meeting

May, 2024

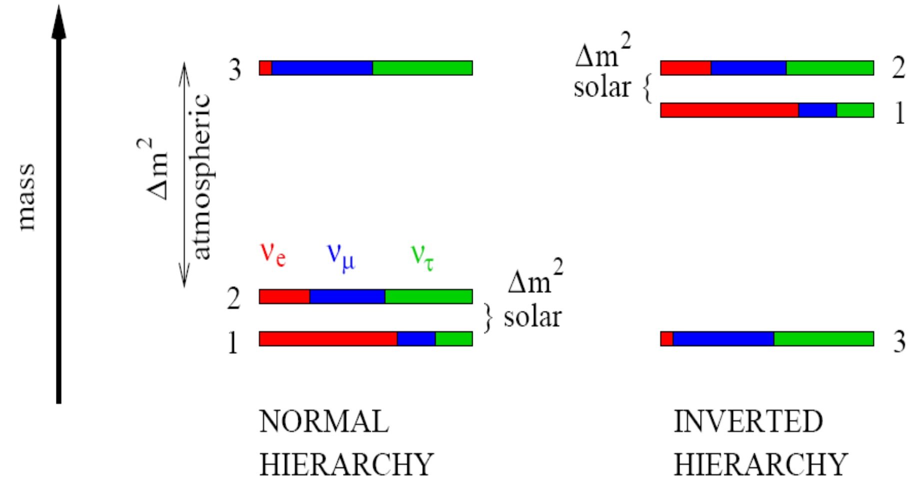
Outline

- **Introduction**
  - Physics motivation
- **Design of CD**
  - Many options
  - Acrylic + steel: optimization
- **Construction**
  - Stainless steel structure
  - Acrylic: special formula and bonding method
  - PMT systems
  - LS purification and filling
- **Summary**

Neutrino Oscillation

- **Mixing matrix(PMNS):**

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} V_{e1} & V_{e2} & V_{e3} \\ V_{\mu 1} & V_{\mu 2} & V_{\mu 3} \\ V_{\tau 1} & V_{\tau 2} & V_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



Atmospheric | reactor & CP phase | Solar | Majorana phase

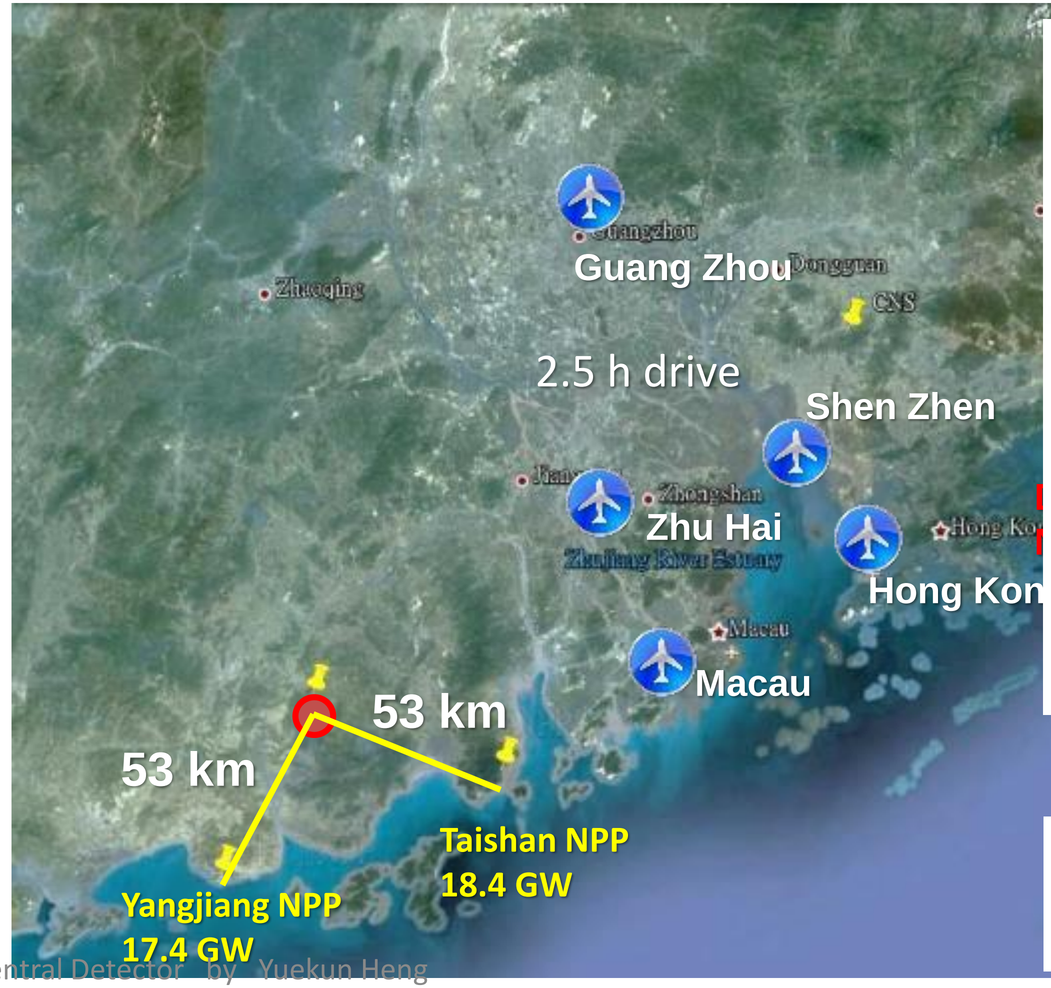
$$V = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & e^{-i\delta} & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\rho} & 0 & 0 \\ 0 & e^{i\sigma} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

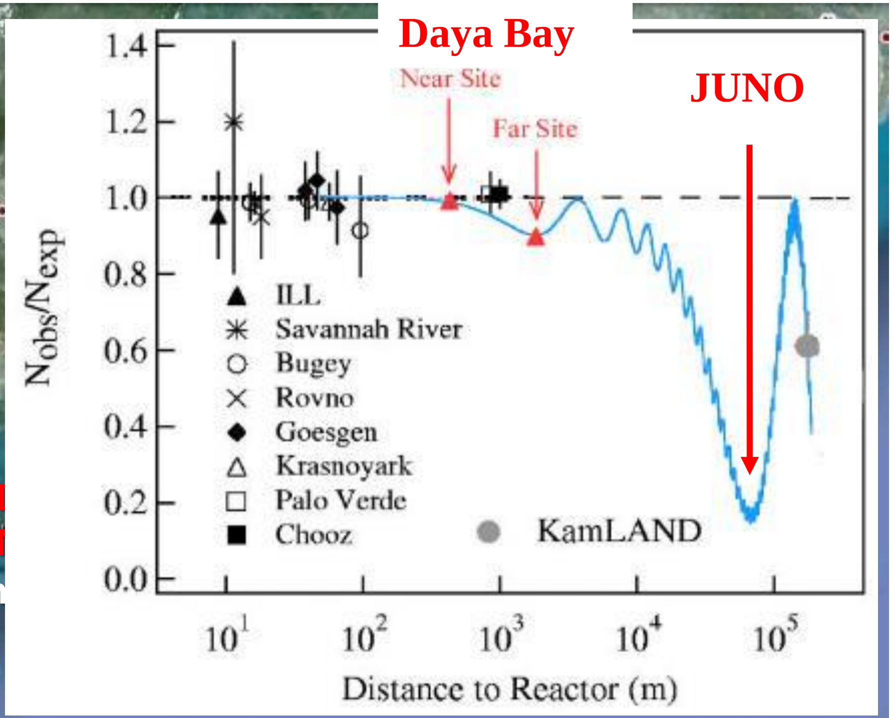
- **Known parameters:** θ_{23}, θ_{12}, θ_{13}, $|\Delta m^2_{32}|$, Δm^2_{21}
- **Unknown parameters: sign of** Δm^2_{32}, **CP phase** δ

1998 Atm. ν osc. θ_{23}, $|\Delta m^2_{32}|$
2002 Solar ν osc. θ_{12}, Δm^2_{21}
2012 reactor ν osc. θ_{13}

Idea of the JUNO Experiment

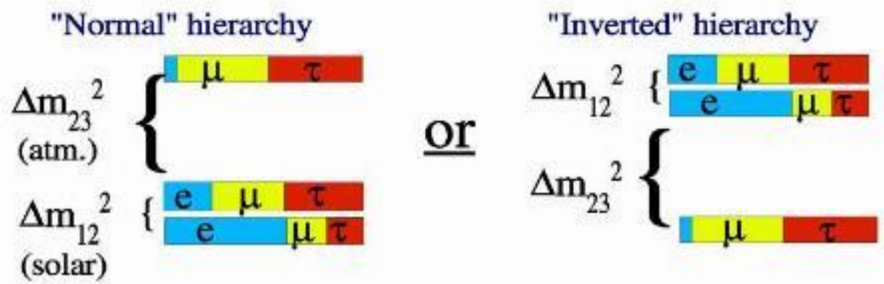
- Next step of the Daya Bay Exp.: continue using reactor neutrinos and liquid scintillator
- To determine the mass ordering (sign of Δm^2_{32}) independent of the CP phase δ
- Equal baseline to two reactor power plants: Yangjiang and Taishan





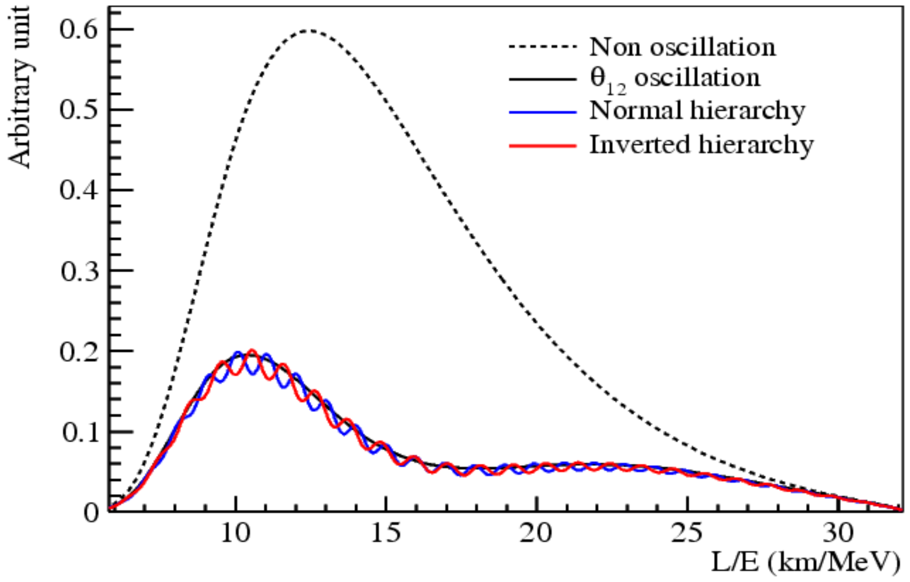
Talk by Y.F. Wang at ICFA seminar 2008, Neutel 2011;
Paper by L. Zhan, Y.F. Wang, J. Cao, L.J. Wen,
PRD78:111103,2008; PRD79:073007,2009

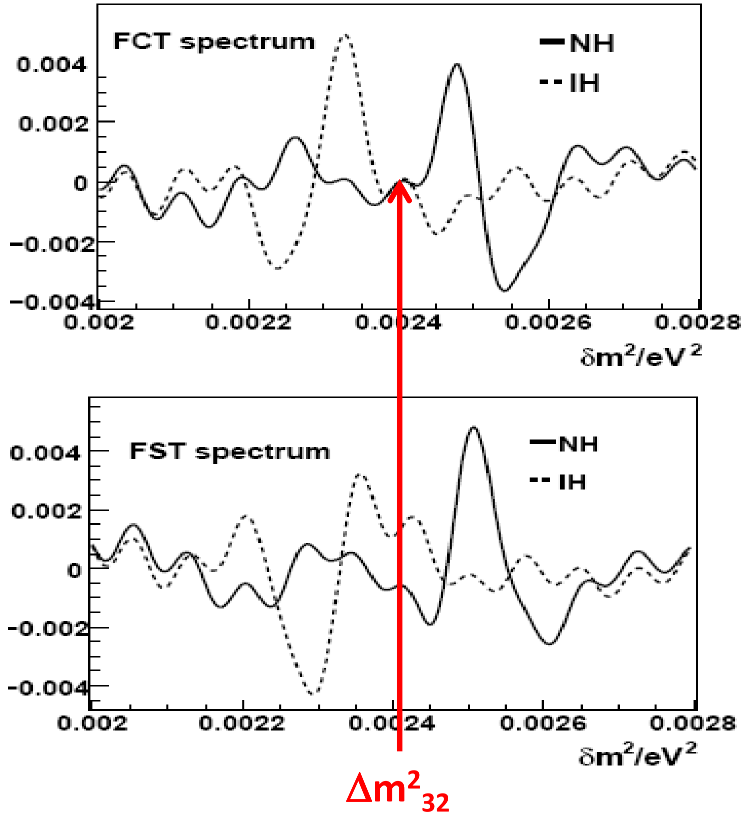
Mass Ordering by Reactor Neutrinos



$$
\begin{aligned}
\Delta m^2_{31} &= \Delta m^2_{32} + \Delta m^2_{21} \\
\text{NH}: \ |\Delta m^2_{31}| &= |\Delta m^2_{32}| + |\Delta m^2_{21}| \\
\text{IH}: \ |\Delta m^2_{31}| &= |\Delta m^2_{32}| - |\Delta m^2_{21}|
\end{aligned}
$$

$$\frac{\Delta m^2_{21}}{|\Delta m^2_{32}|} \sim 3\%$$





$$
\begin{aligned}
P_{ee}(L/E) &= 1 - P_{21} - P_{31} - P_{32} \\
P_{21} &= \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21}) \\
P_{31} &= \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31}) \\
P_{32} &= \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32})
\end{aligned}
$$

S. Petcov and Piai, Phys. Lett. B 553, 94-106(2002)
J. Learned et al., PRD 78(2008)071302
L. Zhan, YFW et al., PRD 78(2008)111103

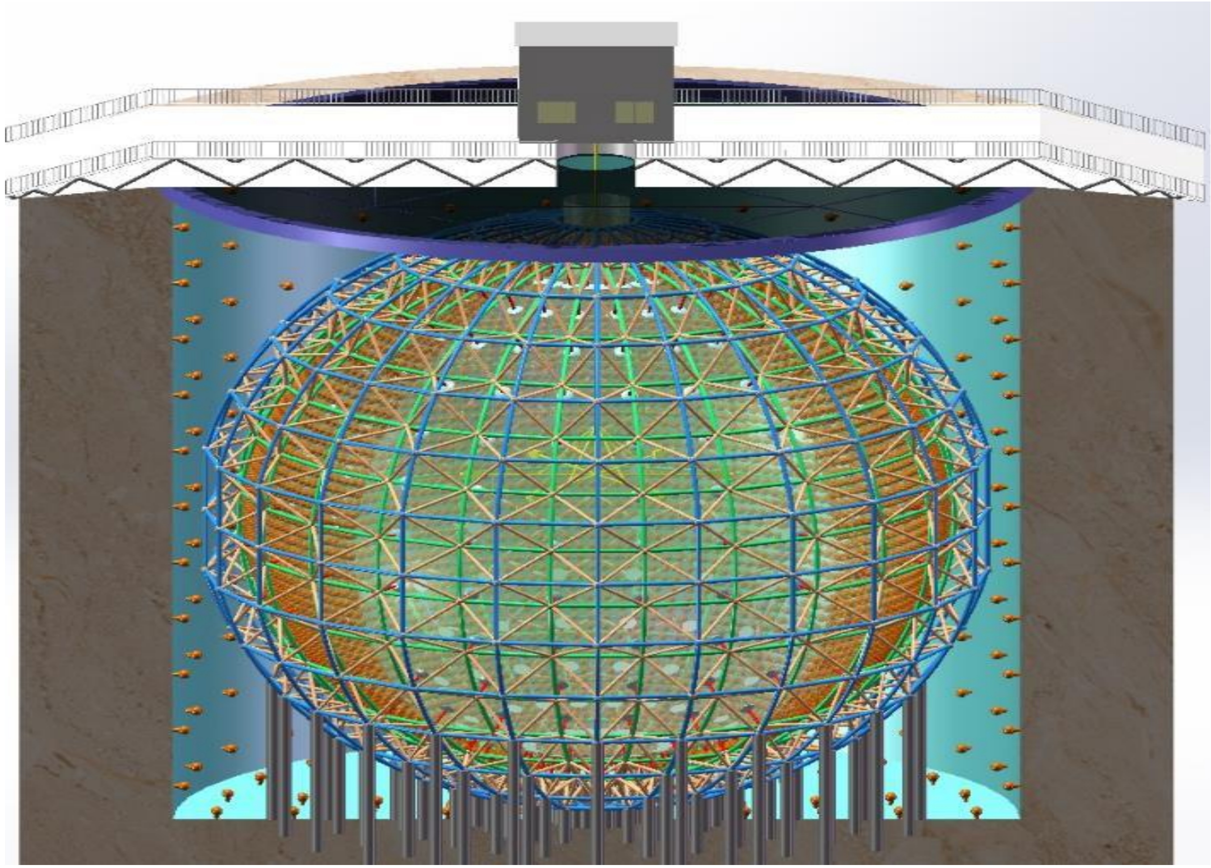
JUNO Project and the collaboration

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

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. Warwick
China	Shandong U.	Germany	TUM	USA	UMD-G
China	Shanghai JT U.	Germany	U. Hamburg	USA	UC Irvine
China	IGG-Beijing	Germany	FZJ-IKP		

A CERN Recognised Experiment (RE34)

Rich Physics Program
with Huge and precise LS Detector



- **20 kton LS detector**
- **3% energy resolution**
- **700 m underground**
- **Rich physics possibilities**
  - **Reactor neutrino for Mass hierarchy**
  - **Precision measurement of oscillation parameters**
  - **Supernovae neutrino**
  - **Geoneutrino**
  - **Solar neutrino**
  - **Atmospheric neutrino**
  - **Exotic searches** including proton decay, dark matter

Neutrino physics with JUNO, J. Phys. G 43, 030401 (2016)
JUNO physics and detector, Progress in Particle and Nuclear Physics, V 123, 103927 (2022)

Physics Requirements on Central Detector

- Statistical error-->Target Mass: 20 ktons, biggest LS Detector
- Energy Resolution for LS Detector: 3%/√E
  - PMT coverage: > 75%
  - Photon Detection Efficiency: > 27%, Quantum Efficiency and Collection Efficiency of PMT
  - Transparent LS
- Energy and Vertex reconstruction and correction:
  - spherical shape, also better for structure
- Energy range and linearity:
  - PMT response and electronics
- Background Radiation Rate, fiducial volume cut
  - Material, Clean consideration
- Life time: ~ 20-30 years
  - Aging and stable, Creep effects, Earthquake

Central detector: 20 ktons LS with 3% energy resolution @1 MeV

	KamLAND	BOREXINO	Daya Bay	JUNO
Target Mass	1 kt	300 t	20 t x 8	20 kt
PE Collection (PE/MeV)	250	500	160	1200
Photocathode Coverage	34%	34%	12%	75%
Energy Resolution	6%/√E	5%/√E	7.5%/√E	3%/√E
Energy Calibration	2%	1%	1.5%	<1%

- **Increasing statistics of photoelectrons:**
  - **Photocathode coverage: > 75%,**
  - **PMT photon detection eff.: > 27%**
  - **LS attenuation length: >20 m**
    ➔ **abs. 60 m + Rayl. scatt. 30m**
- **Reduce the systematic error: good calibration**

4 Basic Questions for Design

- Physics performances
- Engineering feasibility and reliability
  - Mechanics Analysis, Proving the Reliability
  - Long term stability
  - Earthquake: 0.1g (seismic intensity： 7 level)
  - Temperature Changing： (21±1° C)
  - Low radiation background
  - Compatible with Liquids
  - FOC(Filling/Overflow/Circulation)
  - System interfaces: LS/PMT/Calibration/VETO/Civil
- Time for construction
- Price

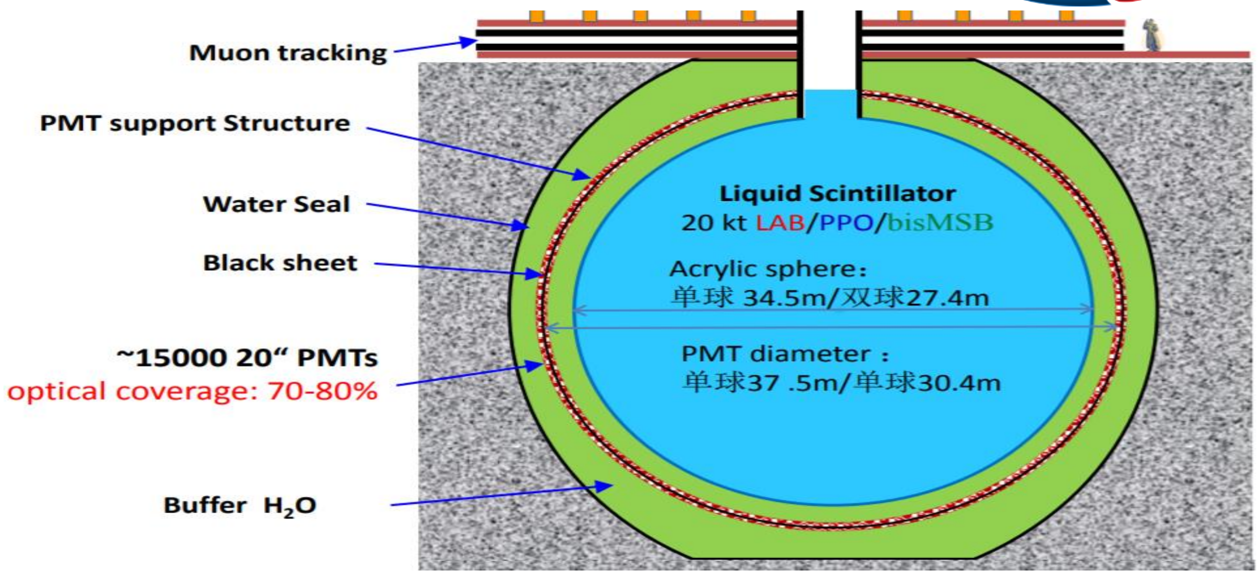
Acrylic stress < 3.5 Mpa

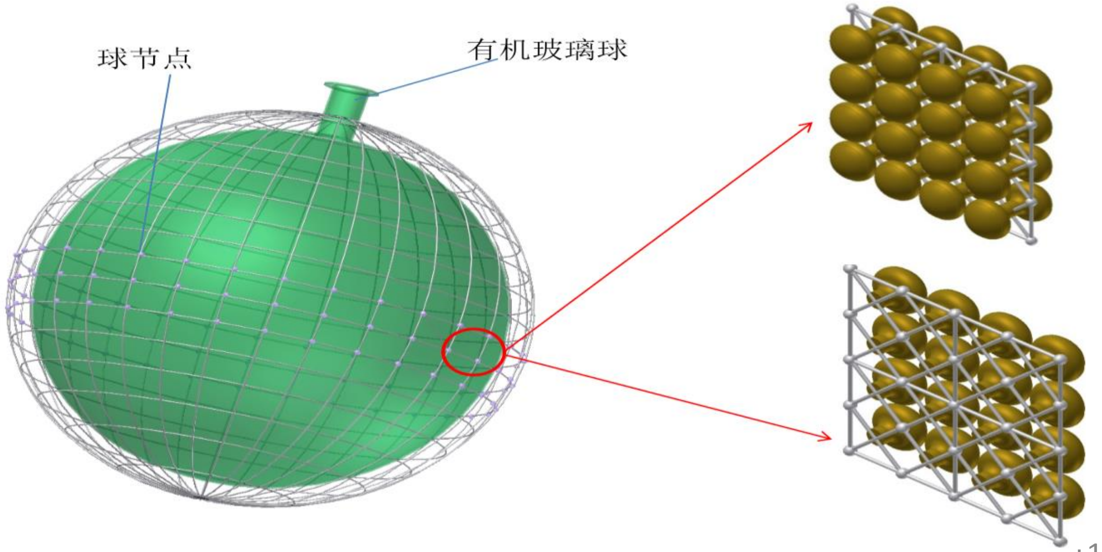
1. How good in physics?
2. Can it be made and can it work stably and reliably in long term? Risks under control?
3. How long to make it?
4. Cost?

Option 1: Acrylic sphere + Steel structure

- No more interference
- "Easy" for PMT holding
- Water buffer ➔ cheap
- PMT: place on steel with inner and outer direction for CD/Veto respectively
- Difficulties:
  - Total buoyancy ~ 3000 tons
  - Larger pressure difference:

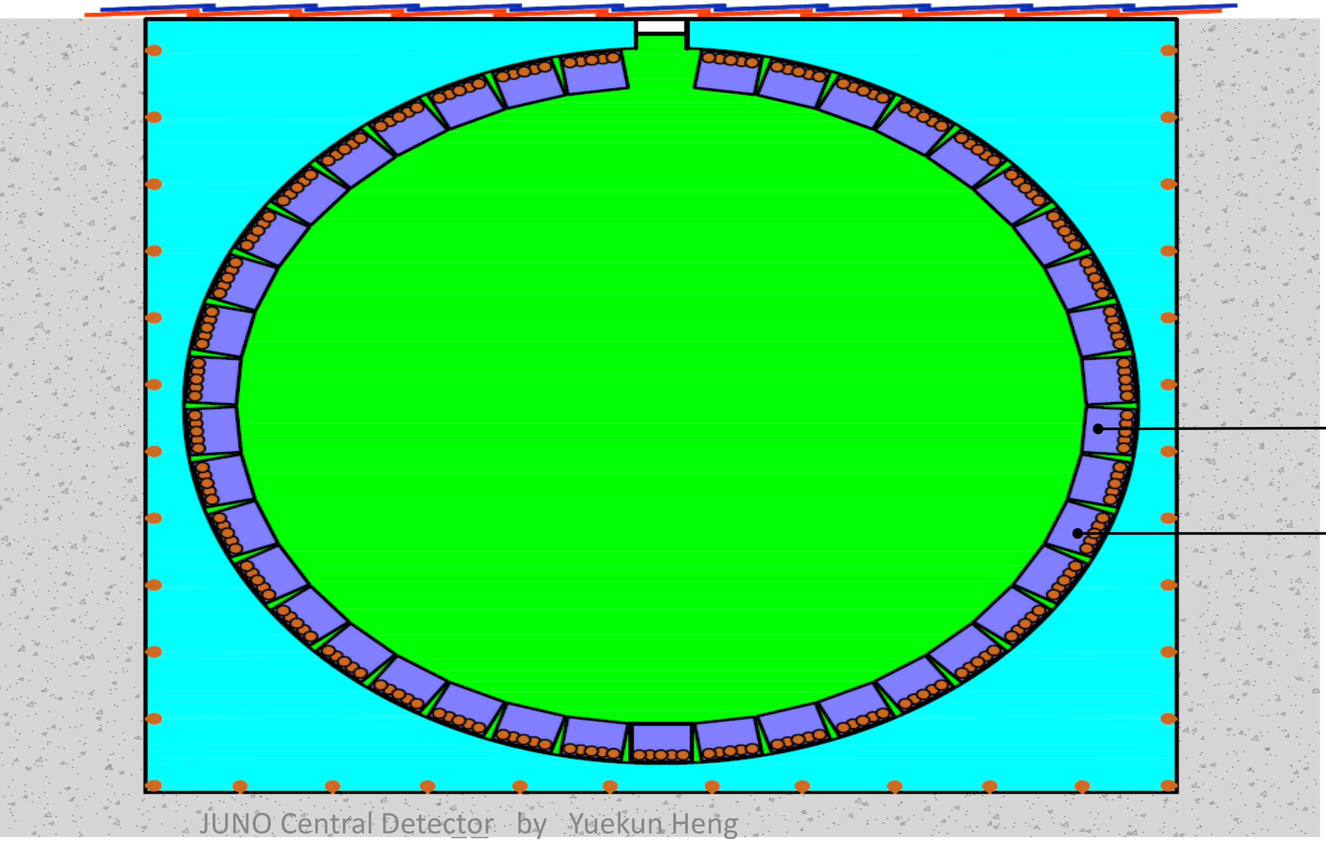
15% density difference leads to a maximum pressure of ~6m in air ➔
A normal aquarium ➔
Not a major problem

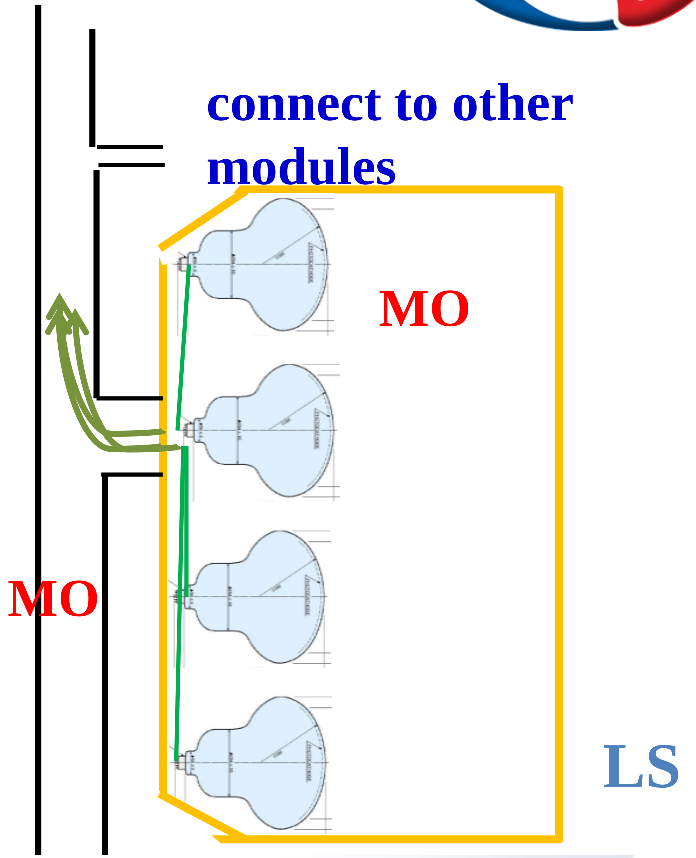


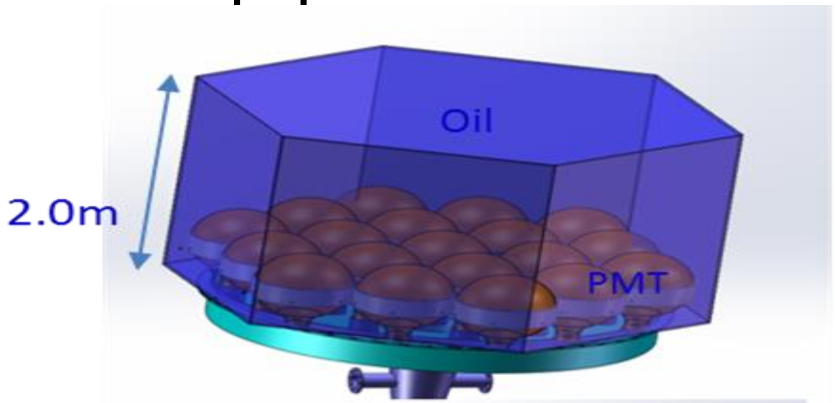


Option 2: Acrylic box + steel tank

- Mineral Oil in the optical modules.
- Pipe for filling MO and cabling
- Concerns
  - LS in gaps btw boxes may produce background scintillation light
  - Leakage through cables

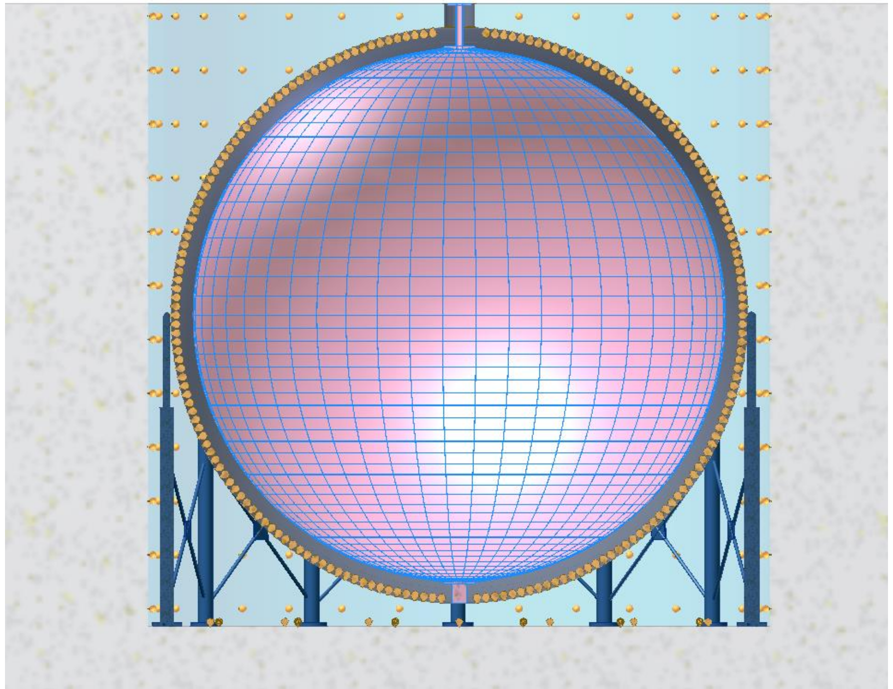






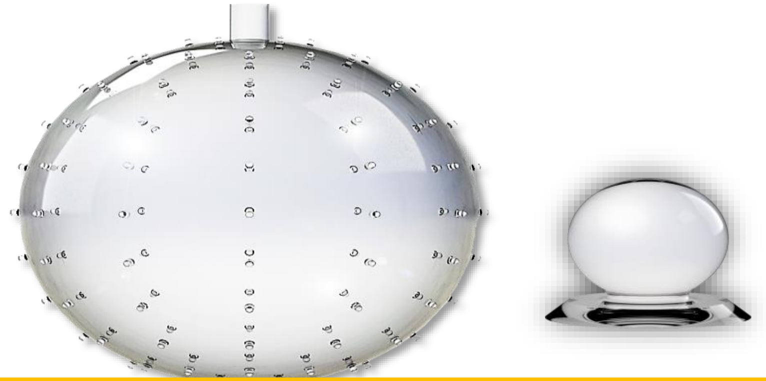
Option 3： Balloon + steel tank

- “Easy” for construction & quick for installation
- Experience from Borexino (0.5kt) & KamLAND (1kt)
- Concerns: cleanness, leak checking, deployment, backup plan if fails ……



Option 4: Acrylic tank + steel tank

- Main idea: Two tanks
  - Acrylic load is small
  - Mineral oil or LAB as shielding material
- Concerns
  - How to assembly the second tank after any first tank is made.
  - Cost much



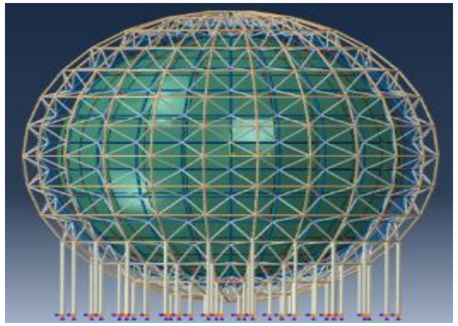
Acrylic sphere and node

Stainless steel tank

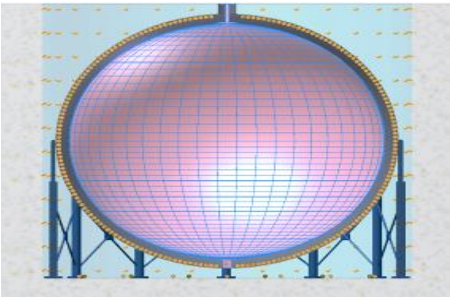
Option selection route

Acrylic sphere+ SS truss

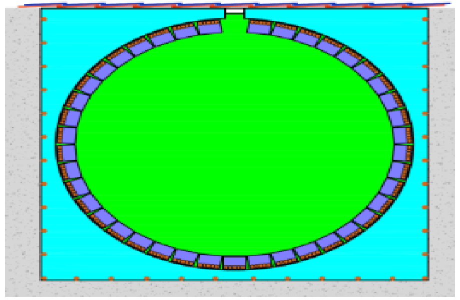
Began in 2012



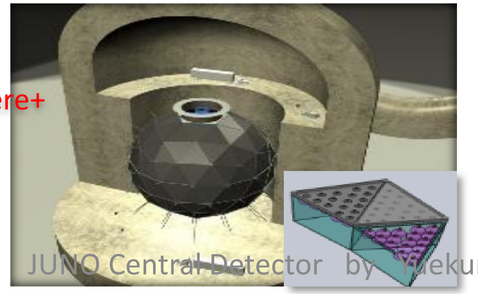
Balloon+ SS tank



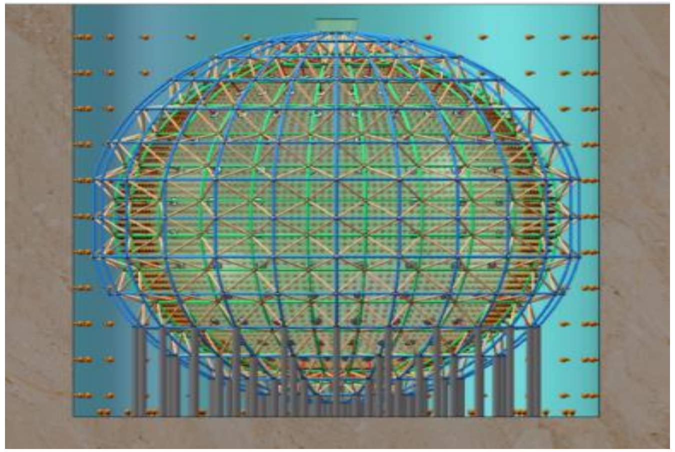
Acrylic module+ SS tank



Acrylic sphere+ SS tank

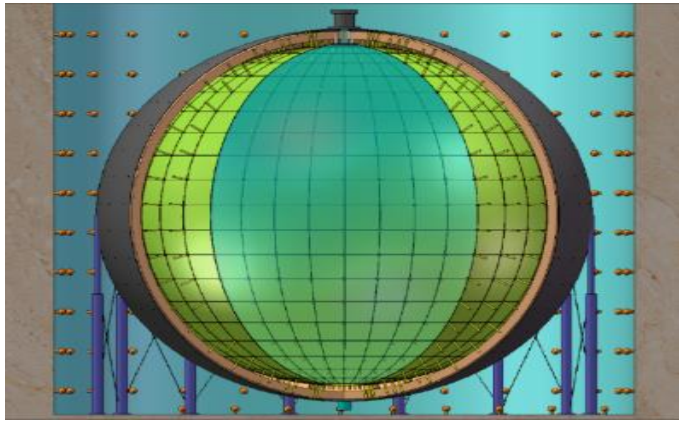


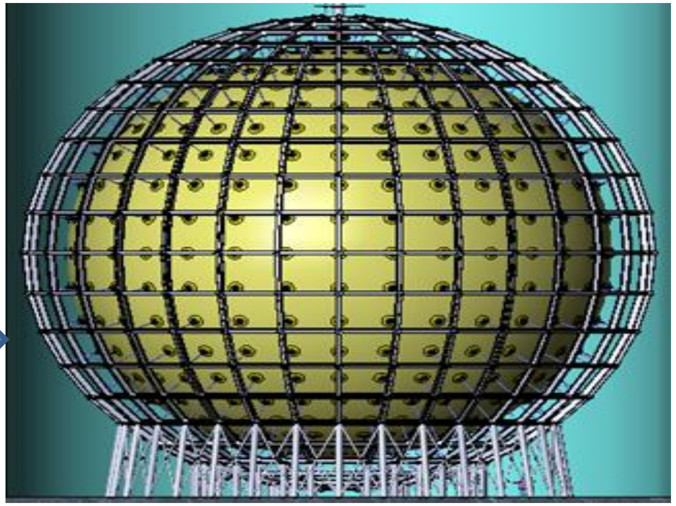
March, 2014



SS truss + Water shielding + Acrylic sphere

SS tank + LAB or MO shielding + Balloon

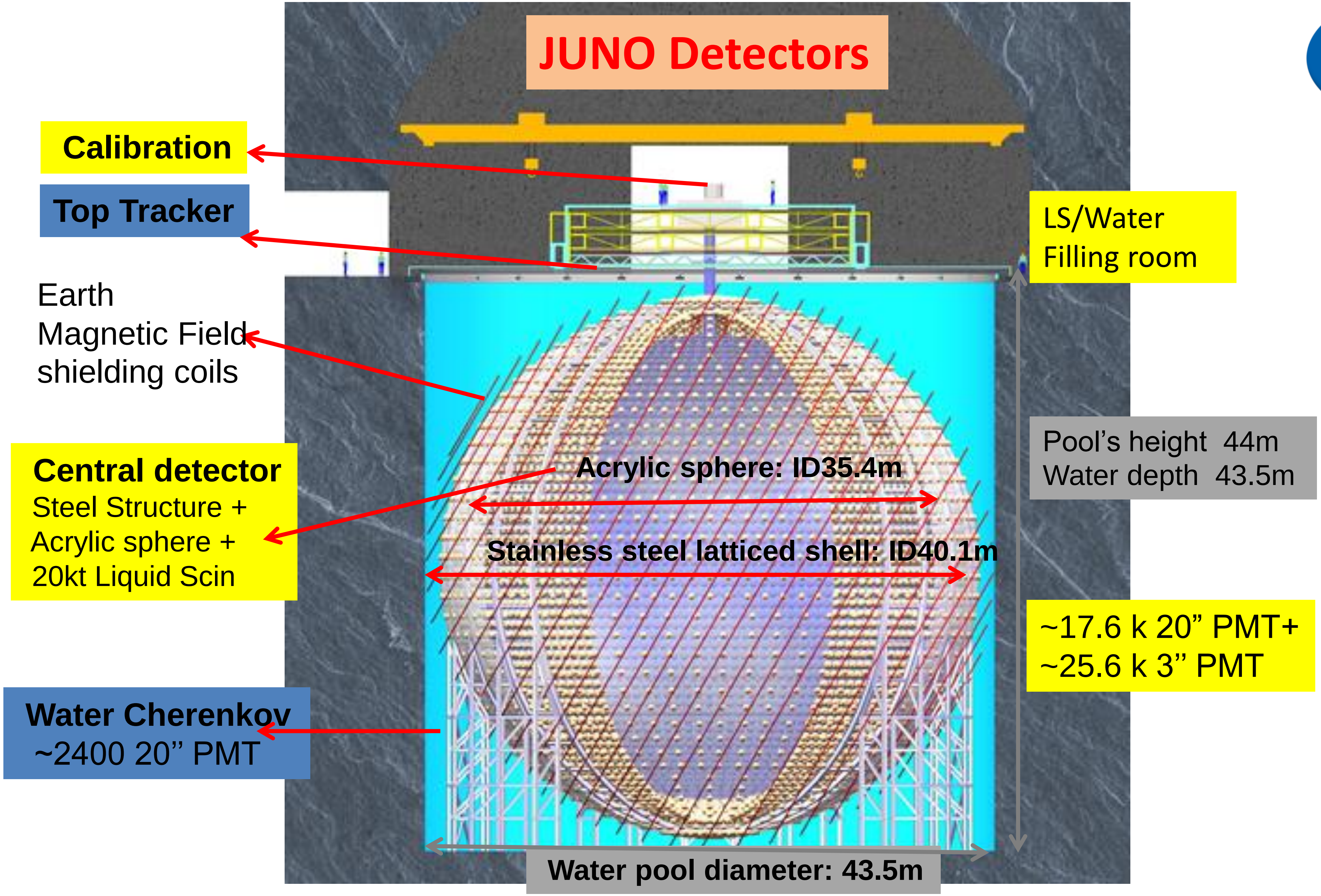




Final decision:
Acrylic sphere + SS structure

July, 2015

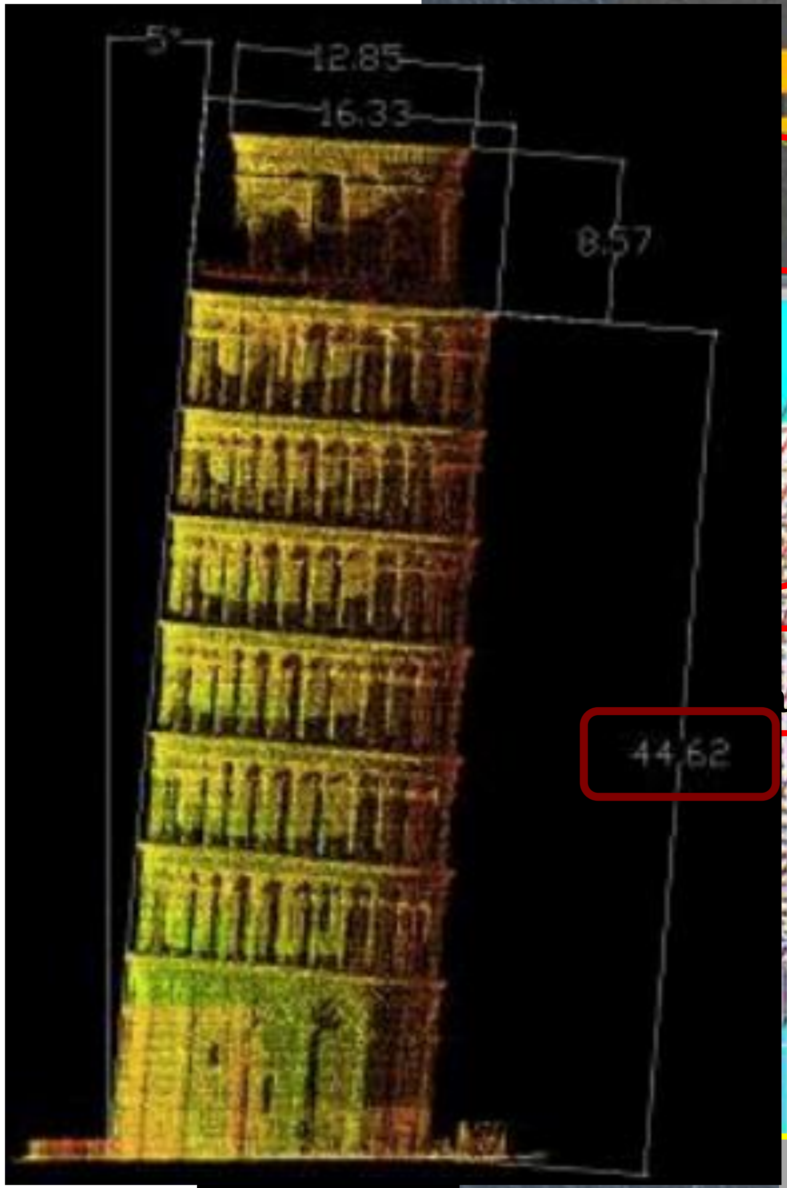
JUNO Detectors



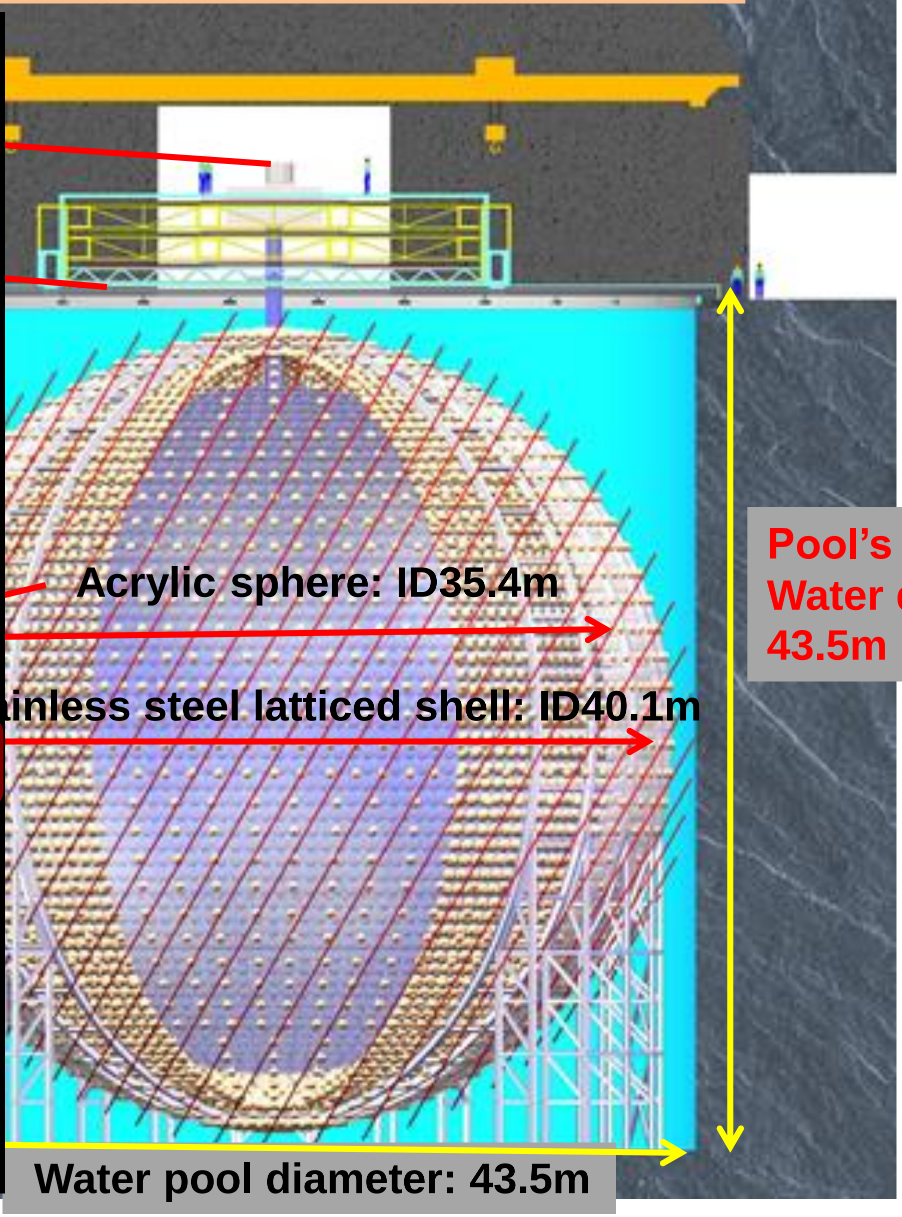
Yellow: CD

Blue: Veto

JUNO Detectors & Pisa Tower

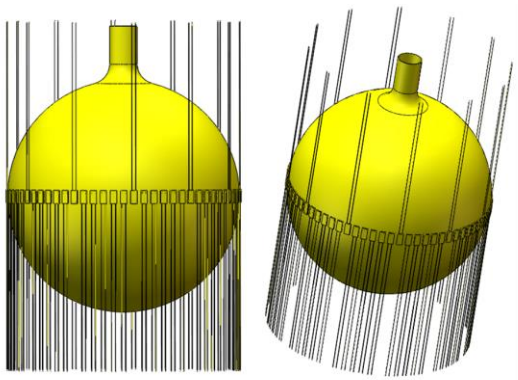


PISA Tower

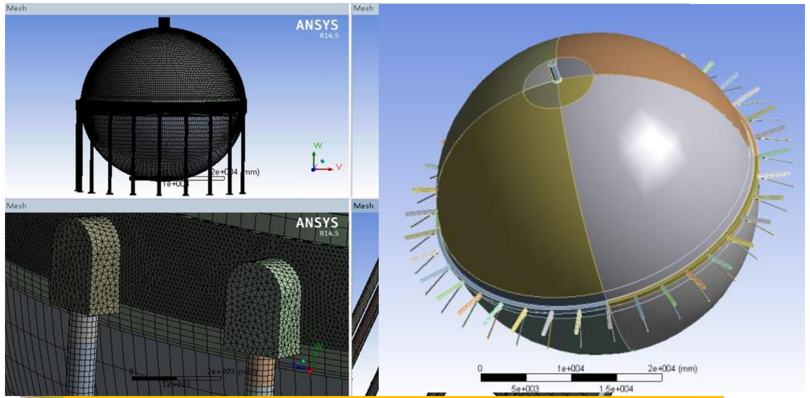


Pool’s height 44m
Water depth
43.5m

Researches on Acrylic sphere + steel structure

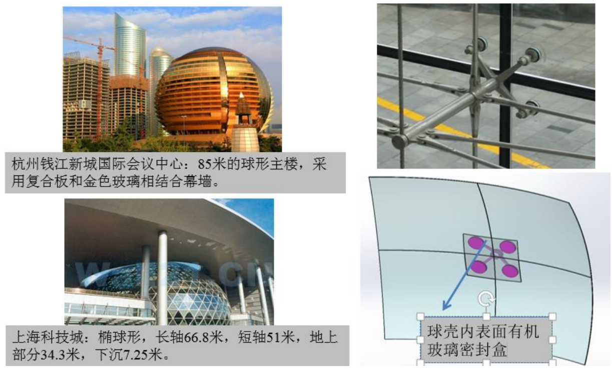


Rope

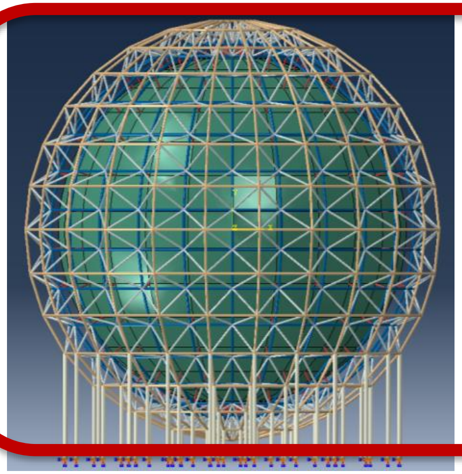


Equator support – Zhejiang U

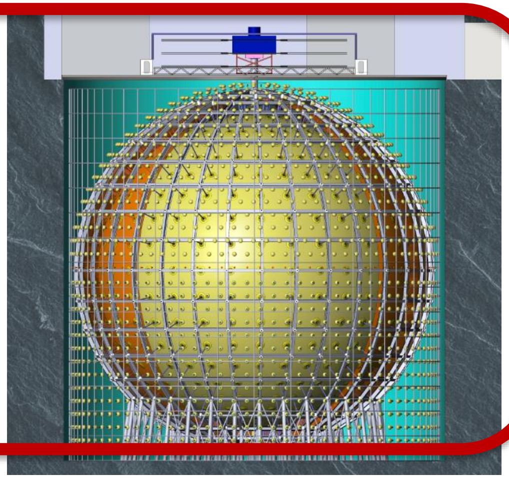
Equator + leg – Argonne



Glass-curtain-wall like



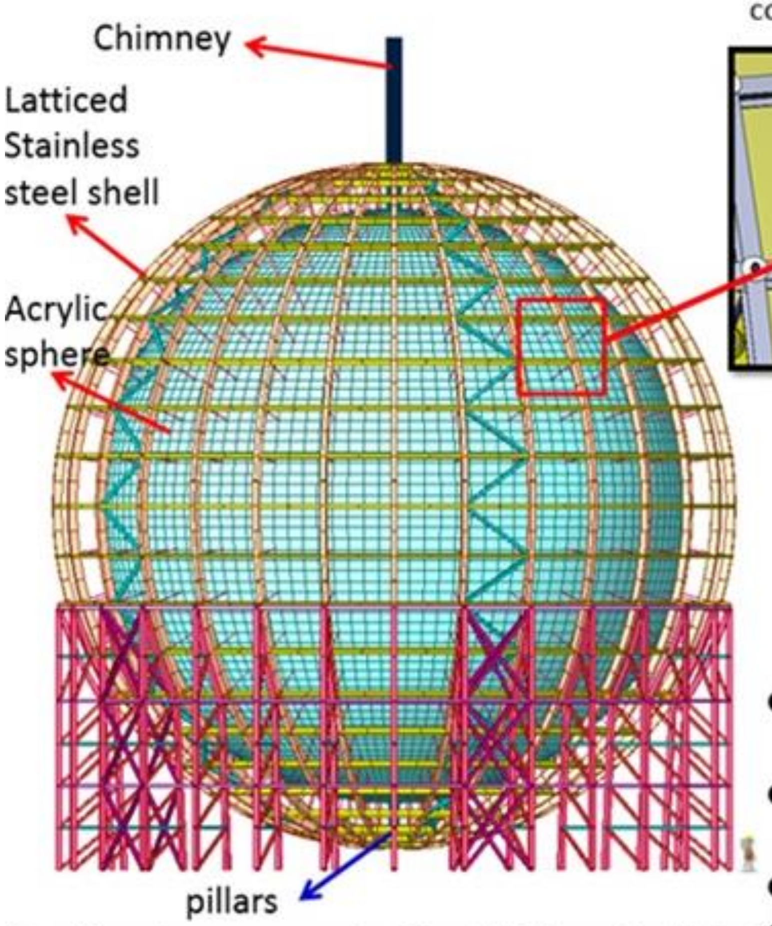
Space Grid – Tsinghua U



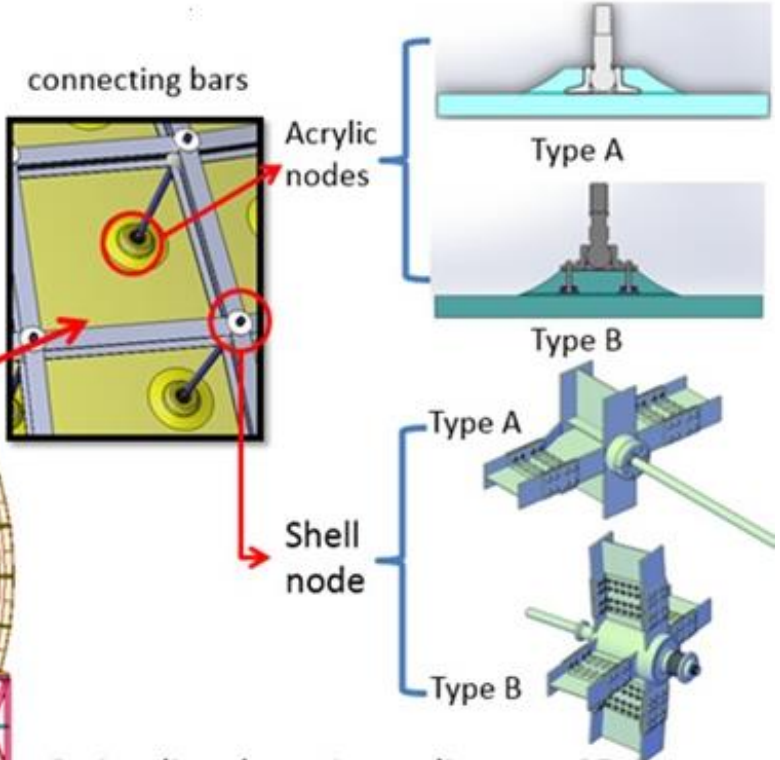
Steel shell – CAAS/BIADR

CD final structure design

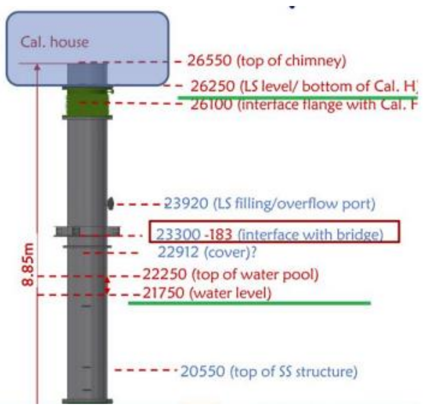
Finished In 2017

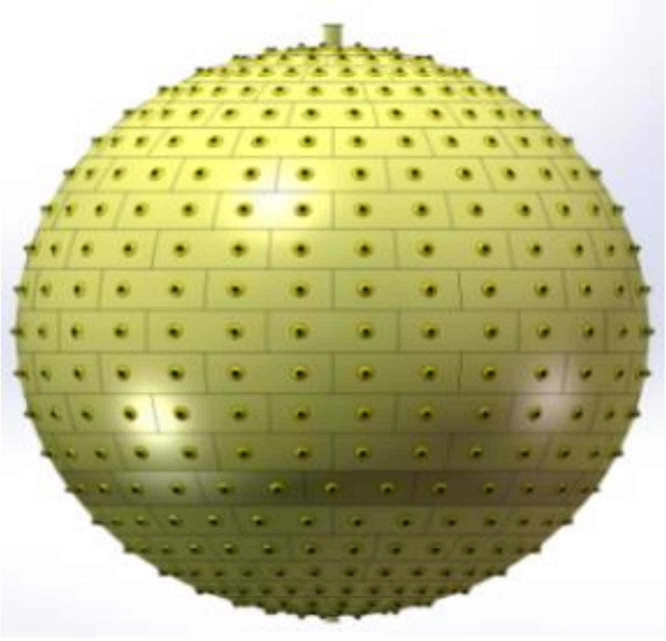


Acrylic sphere supported by stainless steel shell

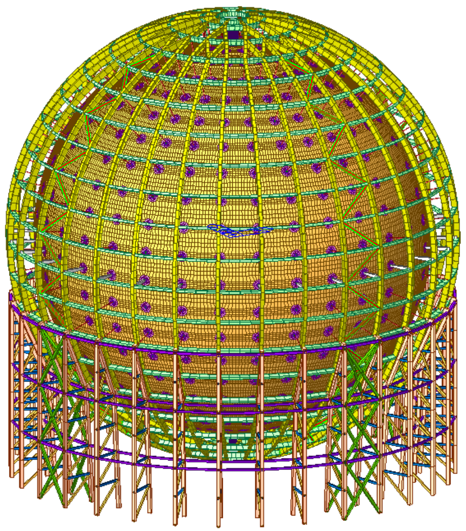


- Acrylic sphere: Inner diameter 35.4m. thickness: 120mm.
- Stainless shell: Inner diameter 40.1m. Divided into 30 longitudes and 23 layers.
- Weight of acrylic sphere: ~600t.
- Weight of shell: ~590 t.
- No. of connecting bars: 590

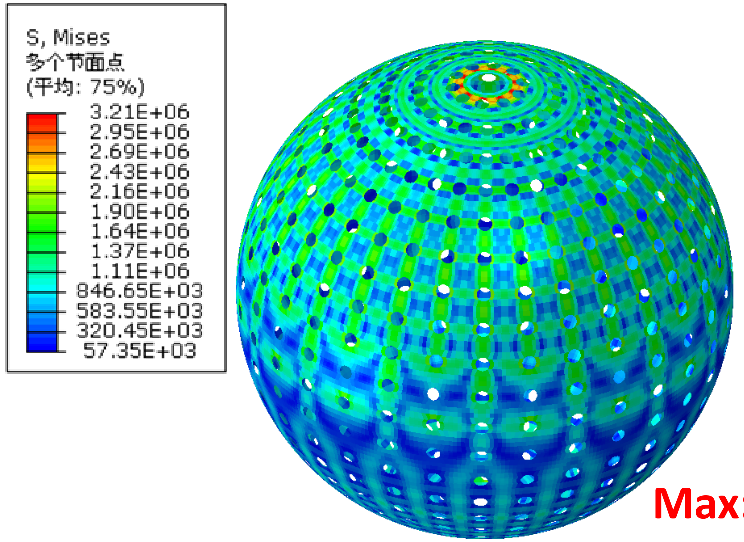




Acrylic sphere's stress contour

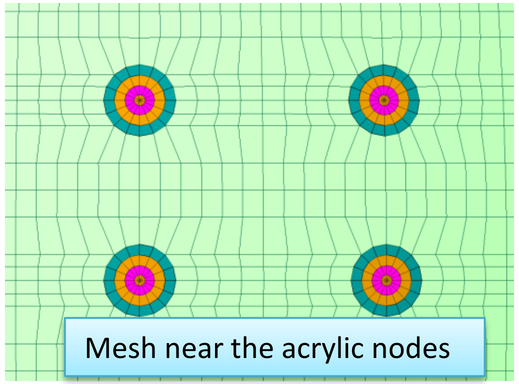


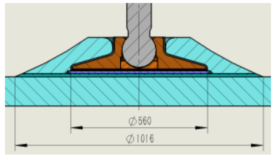
Modified analysis model



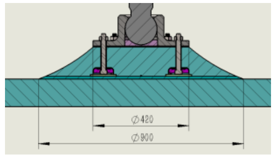
Max:3.21MPa

Contours of Acrylic ball's stress(without node panels)

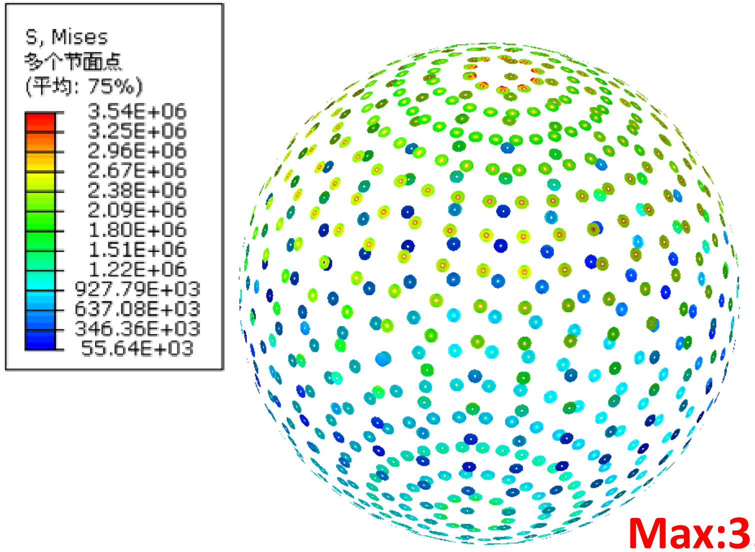




Type A



Type B



Max:3.54MPa

Contours of Acrylic ball's stress(only node panels)

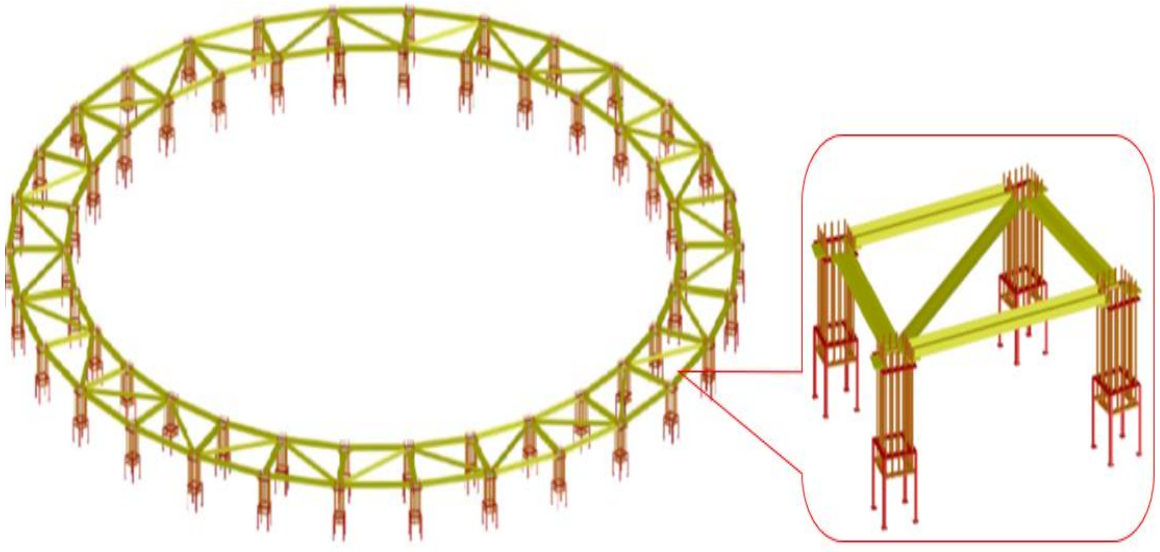
Acrylic node's max stress is about 3.5MPa

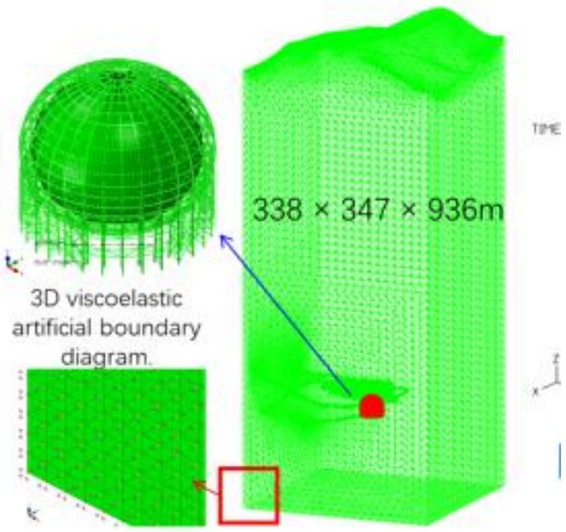
Outline

- Introduction
  - Physics motivation
- Design of CD
  - Many options
  - Acrylic + steel: optimization
- Construction
  - Stainless steel structure
  - Acrylic: special formula and bonding method
  - PMT systems
  - LS purification and filling
- Summary

SS structure: foundation

- **60 sets of embedded anchor under WP bottom**
  - Installed in the end, 2021
  - Second pouring of cement: March, 2022
- **Precision: 2 mm VS 40 m, 0.005%**
  - By a whole fixing structure
- **Loads：**
  - Weights: ss structure 10 MN + supporting 12 MN
  - Buoyancy: 30 MN
- **Strength for earthquake:**
  - Seismic analysis: Near-field seismic response / fluid-solid coupling / earthquake wave
  - Reaction force: 1.66 MN / set, totally 100 MN





Near-field seismic response analysis model

	Exceeding probability in the future 50 years	recurrence interval (year)	Peak acceleration (cm/s²)	Result (kN)	Result*0.77 (kN)	Result*0.85 (kN)
Frequent earthquake	63.20%	50	25	1221	940	1040
	32.5%	127	39.3	1718	1323	1464
	24.8%	175	46.5	1948	1500	1659
	17.5%	259	53.6	2160	1663	1841
Moderate earthquake	10%	474	68	2551	1964	2173
Rare earthquake	2%	2474	115	3439	2648	2930

SS structure: installation

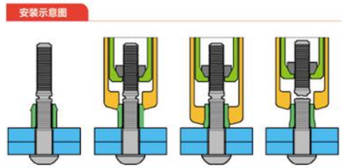
Assembled by 120 k high strength bolts with precision of mm in 40 m range

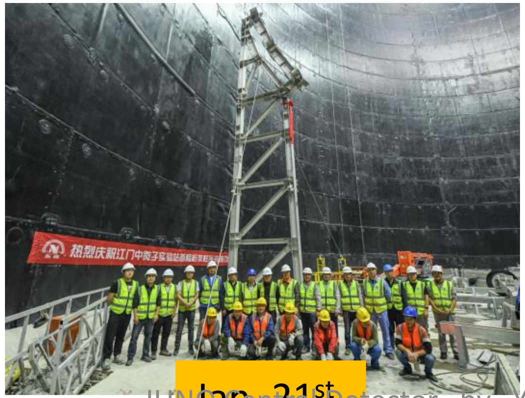
Support columns+bt2-bt4 layer members installation 62 days (1.21-3.23)	→	Support structure cleaning + Back grouting for each supporting column 10 days (3.24-4.2)	→	Bt4-bt7, bt1-up11 layers steel structure members installation 88 days (4.3-6.28)

CD SS structure installation: 150 days (2022.1.21-2022.6.28)

- Jan. 21st , first leg was erected
- March 8th , all 30 legs and 3 circular rings were installed
- June 28th , finished
- Several rounds of cleaning were done
- Bottom four-layer structure will be installed after acrylic vessel is finished.

Installation tool   Removal tool




Jan. 21st


Mar. 8th

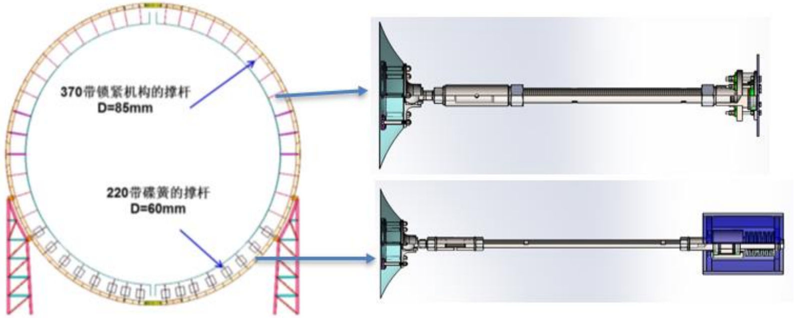

April 28th


May 27th

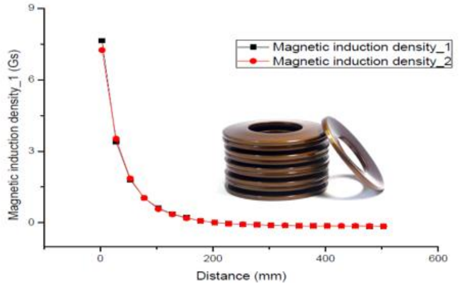

July 1st

SS structure: connection with acrylic

- **Acrylic node:** ss plate embedded, 1000 kN, strict bg requ.
- **S.S. node**
  - Angle adjusting: ±5 °
  - 370 half fixing nodes
  - 220 disc-spring nodes: to adjust the axial stiffness and control the internal force
    - Reduce the max pulling stress in the acrylic
    - Strong spring: Small displacement (1~2mm) VS Big load (8 tons)
- **Connection bars**
  - Two kinds: D 85 mm and D 60 mm
  - Length adjusting: -60 ~ 100 mm
- **Force monitor in connection bar**
  - 4 fiber grating (FBG) sensors and 1 temperature in each bar
  - FBG precision: ~ 5 pm/ µξ, 1.2 kN for D 85, 0.6 kN for D 60
- **Force analysis**
  - Initial loading by adjusting the length according to design
  - Max axial forces:
    - 40 kN during Installation
    - 90 kN pulling and 140 kN pushing during operation

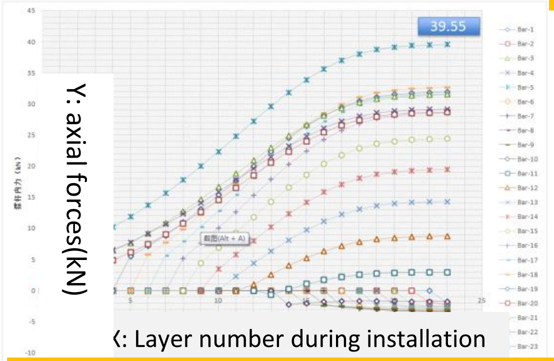


Connecting structure btw acrylic and ss structure

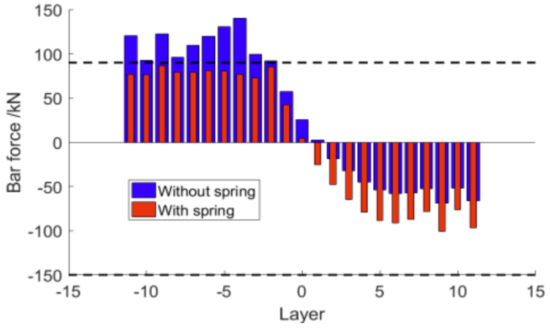


Disk spring and residue magnetic induction

Connection process: sensor installation and test → connected with SS→ with acrylic→ pre-loading→ unloading the fixtures, transfer acrylic weight to the bars → monitoring load



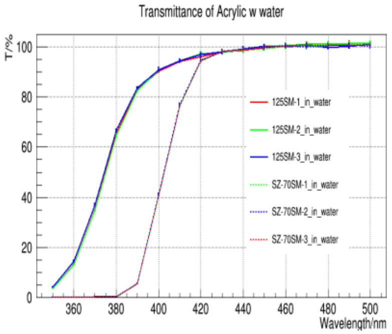
Bar force during installation



Bar force during operation

Acrylic: trans. and long term performance

- **Transmittance: >96% @420nm, 120 mm thickness**
  - No anti-UV and No plasticizer
  - Thermoforming for spherical panels： easy to be yellow → find a suitable curve
- **Long term performance**
  - Creep w/o plasticizer is better, but crisper
  - Creep test： at stress of 30~12 Mpa soaking in water and LS with 20 ℃ → Result of creaking time: 104 years at 3.5 MPa stress
  - Aging test: at 5.5 MPa soaking in water and LS with temperature: 30~50℃ → Result: 50 years for tensile strength decreasing 30%



Trans. VS anti-UV

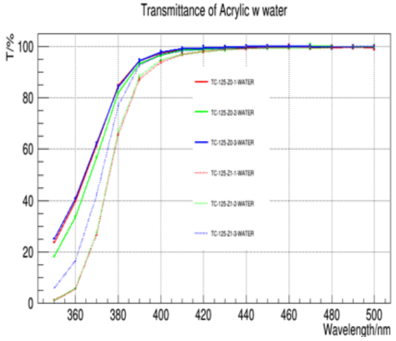


Fig. Trans. VS plasticizer

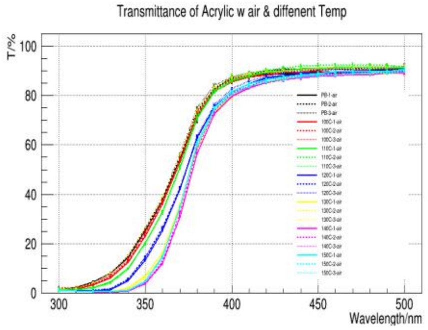


Fig. Trans VS temp.

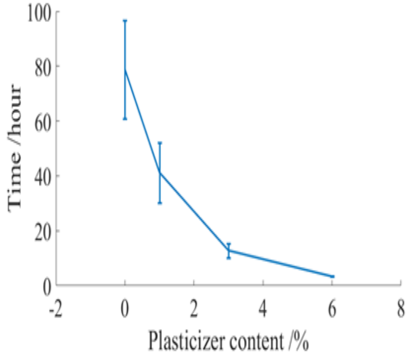
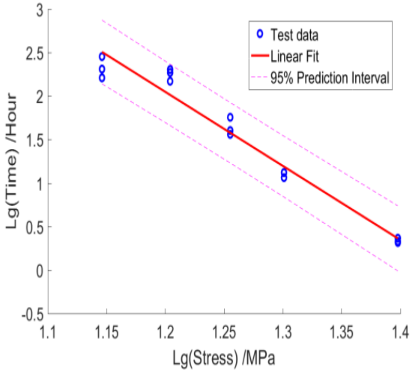
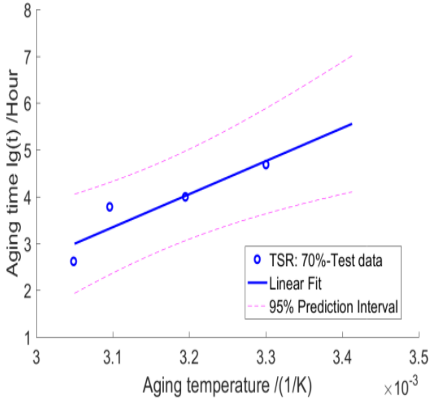


Fig. Influence of plasticizer on creep

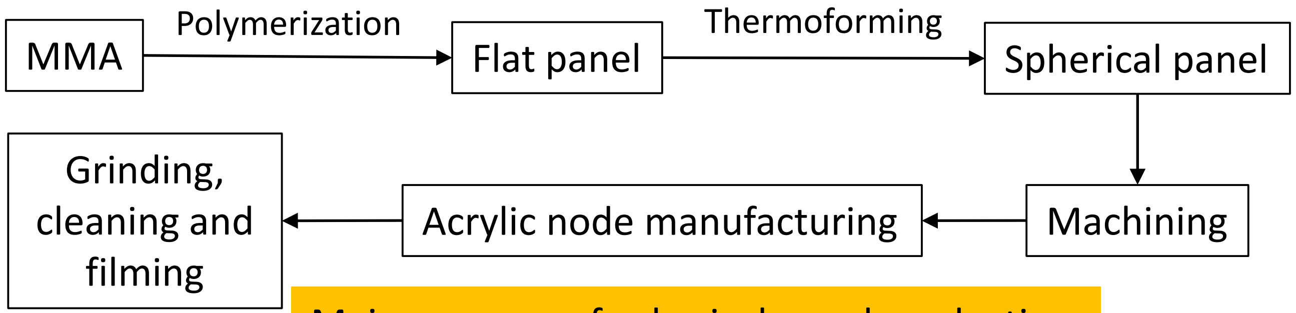




Creeping and aging performance with bonding line

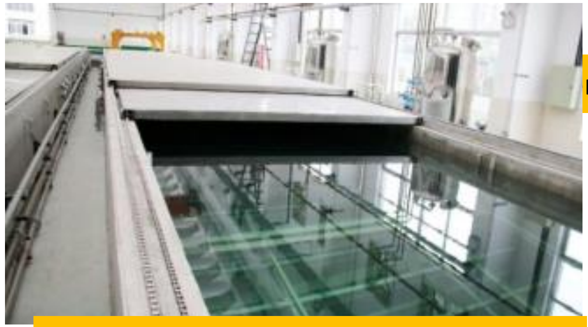
Acrylic: production

- **Why special production line ?**
  - **Formula no anti-UV and plasticizer**
  - **Spherical panels**
  - **Low radioactive bg.**
    - **U238: < 0.3 ppt**
    - **Th232: 0.4±0.02 ppt**
- **Progress**
  - **All spherical panels and nodes' manufactures are finished**



Main progress of spherical panel production

Special pipeline for MMA



Pool for panel polymerization

Filming

Thermoforming

Machining

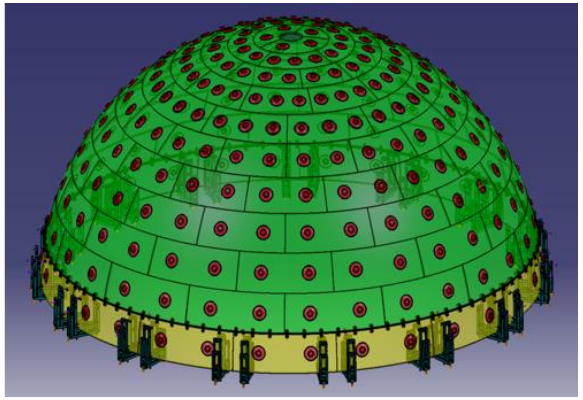
Grinding and polishing

Cleaning

Filming

Acrylic: polymerization

- Special polymerization
  - One time polymerization for the vertical and circular lines while no spacing adjusting as usually
  - Easy and more precise positioning, fewer times of glue injection, shorter construction time
  - E.g., the equator bonding lines' length , for one time: 110 m + 2.8 m X 15 = 152 m (total bonding length: 2 km)
- Challenges and technologies:
  - Glue volume decreases during polymerization →glue shortage in the bonding line → make a dam that can hold more MMA
  - Avoid cracking during annealing → change the annealing method



Locate and fix the whole circle panels and polymerize for vertical and circular lines at the same time.

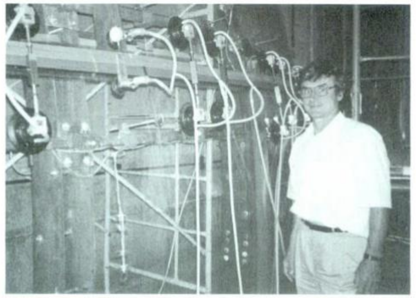
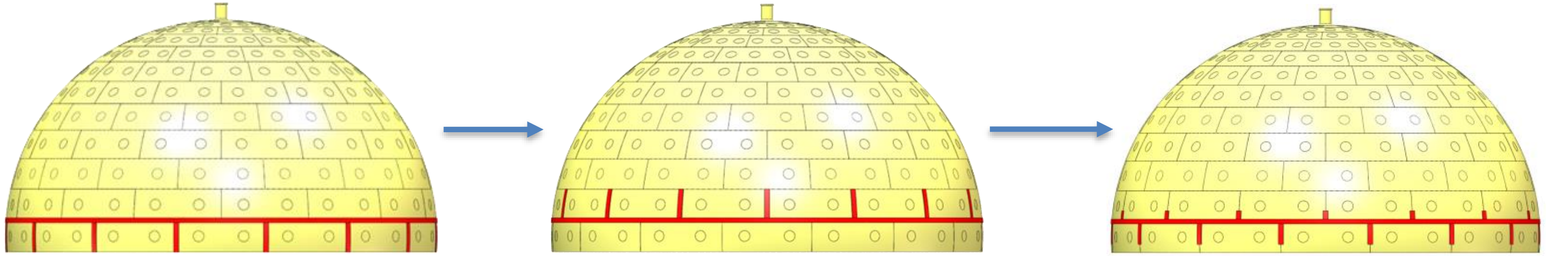


Figure 16.11
The joint spacing between vertical acrylic panels during bonding procedure is maintained by standoffs consisting of threaded steel turnbuckles fastened at both ends to vacuum actuated suction cups. During polymerization of the cement, the spacing is adjusted to accommodate shrinkage of the bond. Dr. Davis Earle of Sudbury Neutrino Observatory monitors here the progress of cement polymerization.

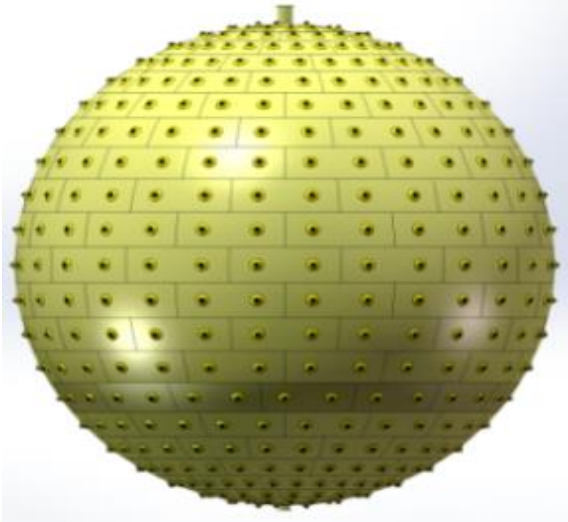
Picture from "Handbook of Acrylics" by Stachiw
Panels are needed moving nearer during polymerization due to the shrinkage in most other projects.



Annealing scheme improving.
- **Avoid the edge bonding area be heated and reduce the heating stress**
- **Work height is compromise.**

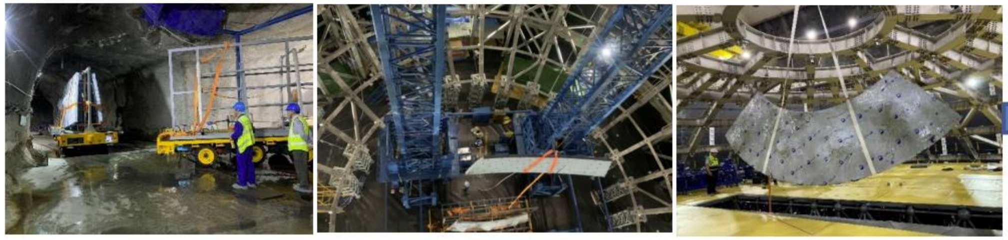
Bonding experiment of horizontal and vertical bonding line

Acrylic: installation steps

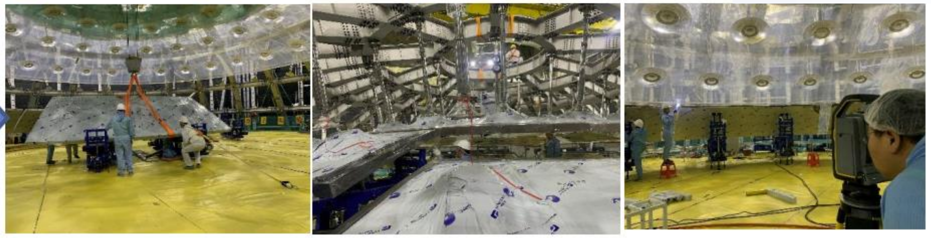


- **23 layer, 263 panels + 2 chimneys**
  - **Totally 21 times cyclic operations, each time needs about 20 to 30 days.**
  - **We have installed about 80% since July 2022**
  - **It will be finished in the second half year 2024.**

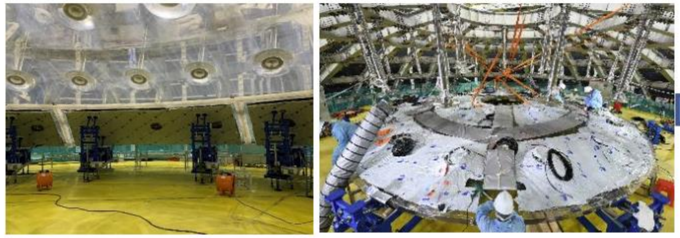
① Transporting, lifting



② Locating, positioning



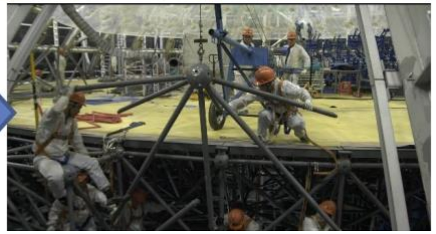
③ Bonding, annealing



④ Installing connecting bars

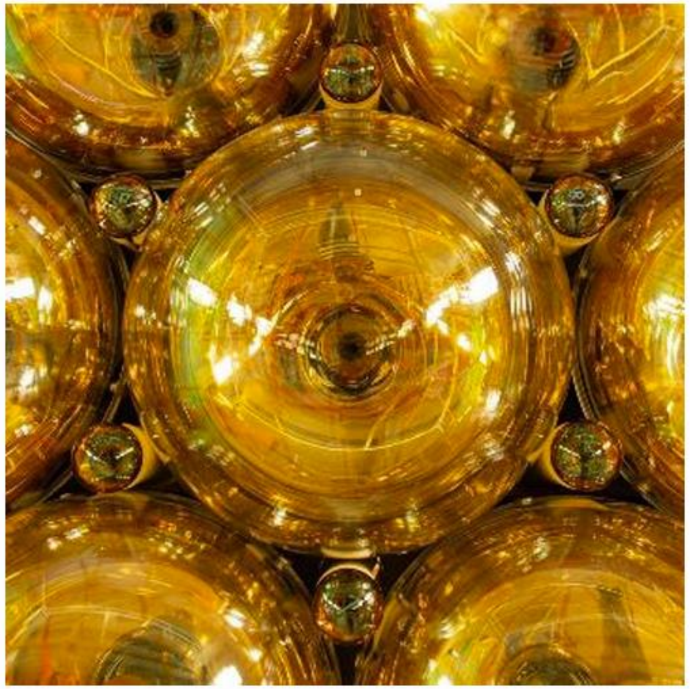
⑤ unloading, sanding, polishing, cleaning, filming

⑥ Lowering and enlarging platform



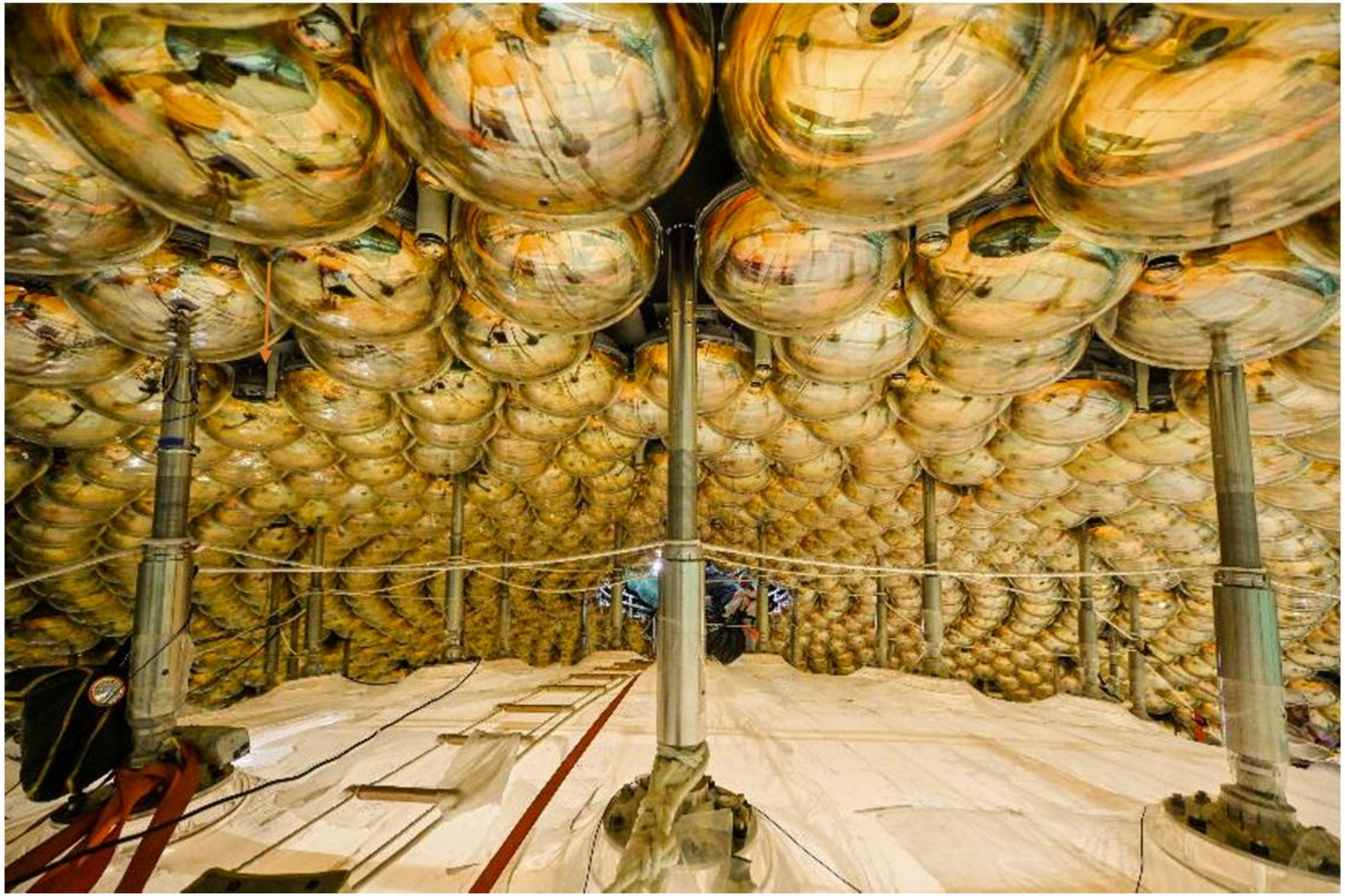
Installation of Large PMT and small PMT

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



Clearance between PMTs: 3 mm →

Assembly precision: < 1 mm



w/ protection cover (JINST18(2023) 02, P02013

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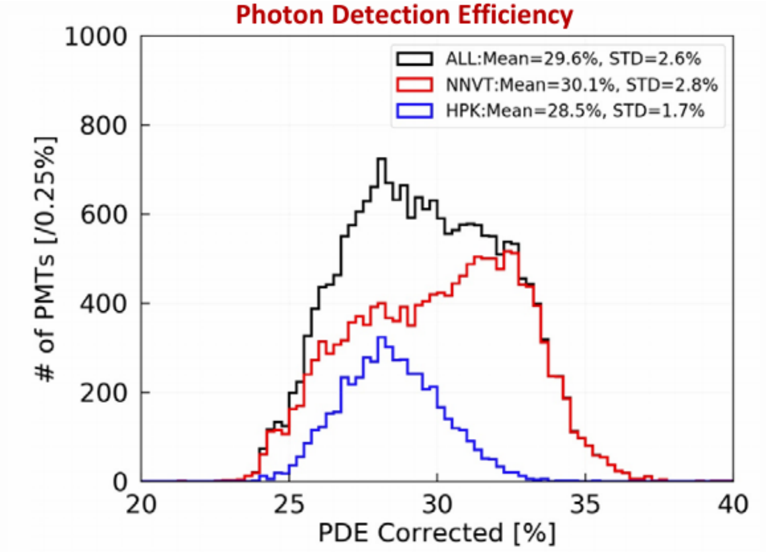
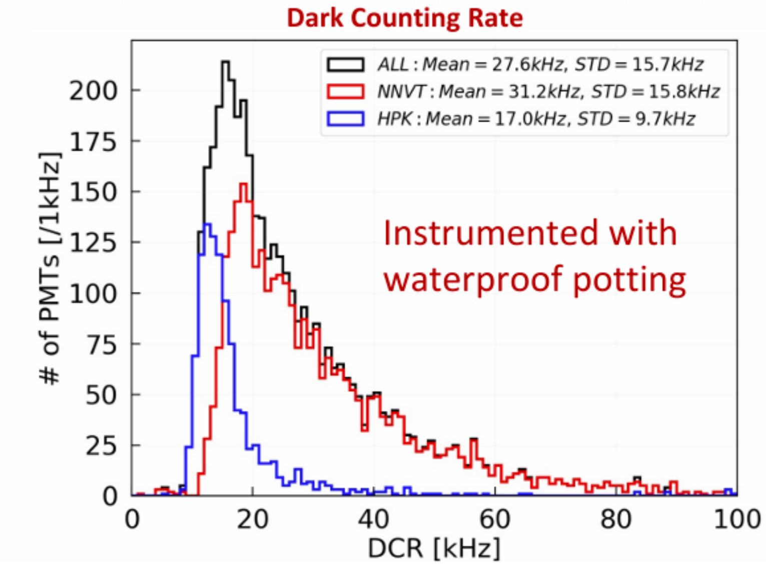
PMT Statistics





All PMTs produced, tested, and instrumented with waterproof potting

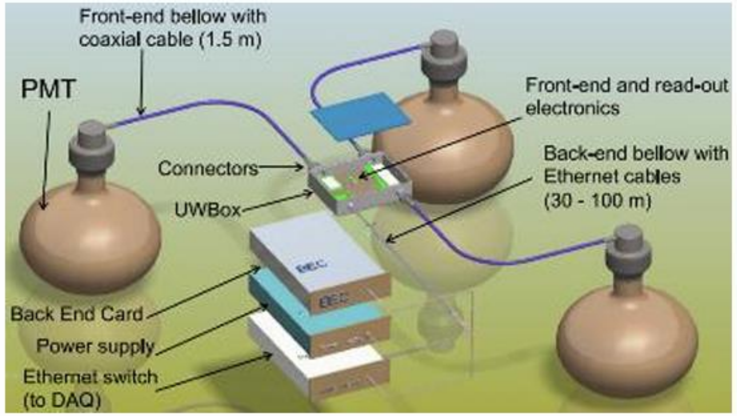
12.6k NNVT PMTs with highest PDE are selected for light collection from LS and the rest are used in the Water Cherenkov detector.

		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		arXiv: 2205.08629		NIM.A 1005 (2021) 165347

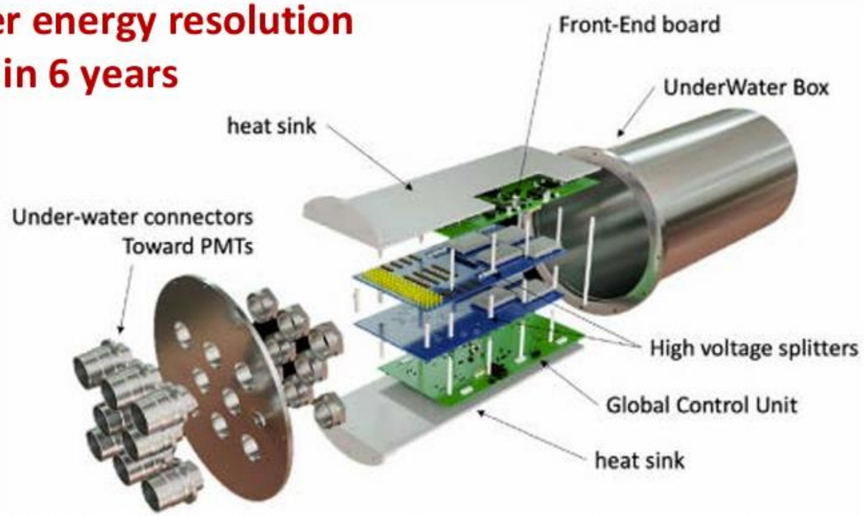
Failure rate requirement: <0.5% in 6 yrs, while same for underwater Elec.

Electronics

Underwater electronics to improve signal-to-noise ratio for better energy resolution
1 GHz waveform digitization, expected loss rate < 0.5% in 6 years

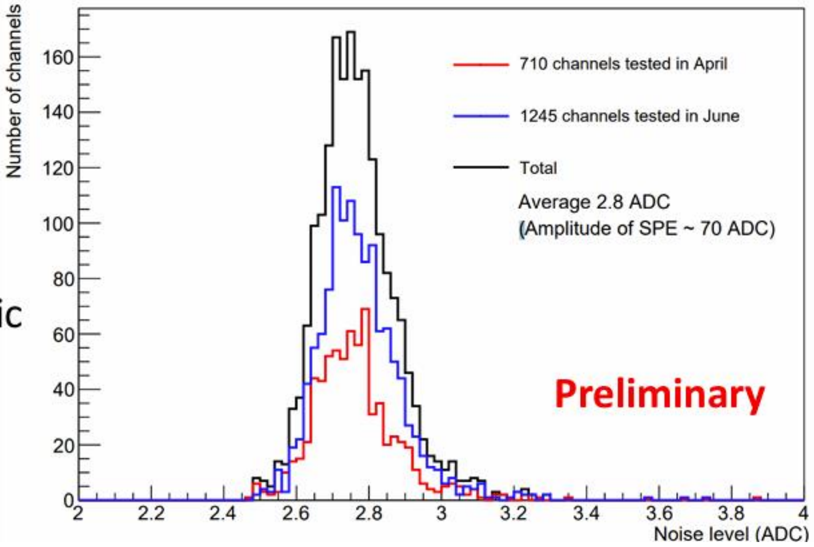


3 20-inch PMTs connected to one underwater box



128 3-inch PMTs connected to one underwater box

Electronic Noise Level [LPMT]



- 6862 boards produced and tested before installation
- Ongoing test campaign during installation
- Careful design & excellent grounding: noise level: 4% at 1 photoelectron better than specs: 10% at 1 p.e.

1

Liquid Scintillator

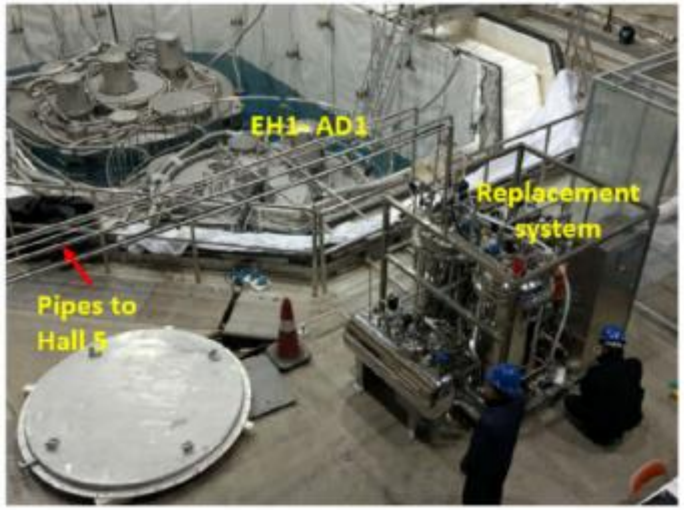
Recipe: Based on Daya Bay experience

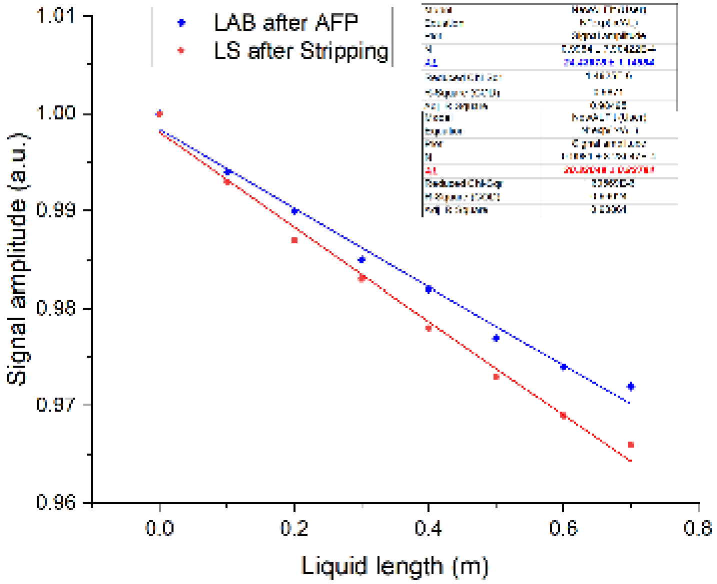
- ⇨ LAB for transparency and safety
- ⇨ R&D for highest light yield:
  - ✓ A Daya Bay module for test (*NIMA 988 (2021) 164823)*
  - ✓ extrapolation to the JUNO size using a new LS optical model (*NIMA 967 (2020) 163860)*
- ⇨ Final result: LAB + 2.5g/L PPO + 3 mg/L bis-MSB

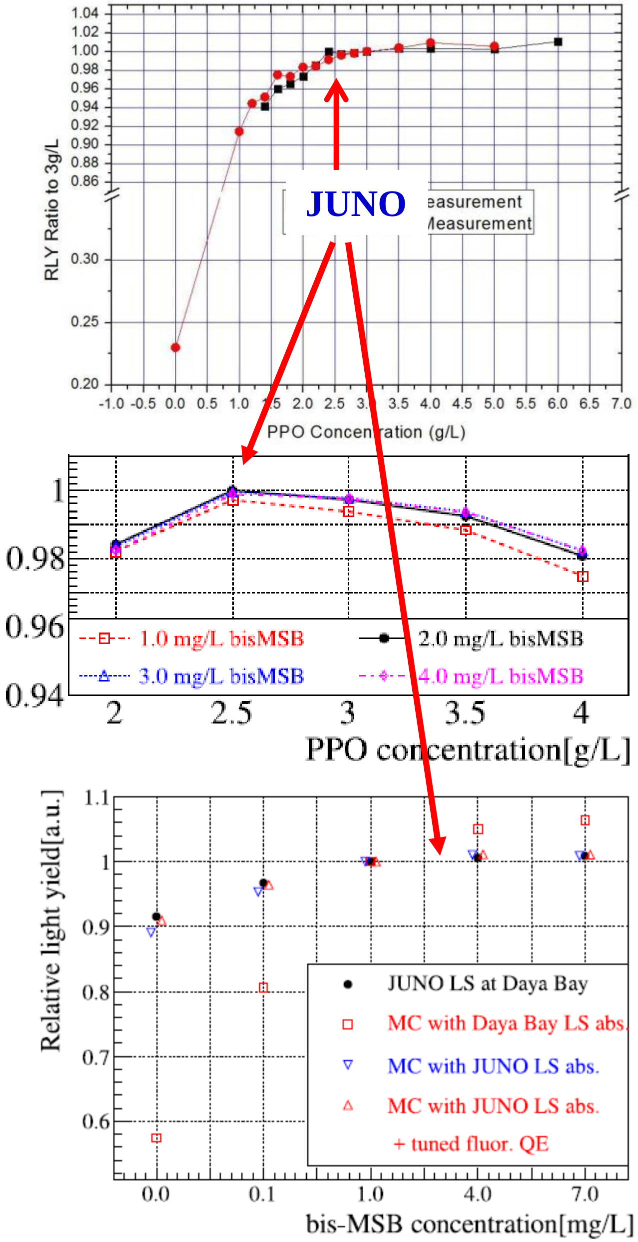
Production:

- ⇨ ~50t PPO delivered, U/Th < 0.1 ppt; 20kt LAB to be delivered, U/Th ~ 1 ppq
- ⇨ LAB attenuation length > 24m, LS attenuation length > 20m

Experimental Hall 1







Liquid Scintillator Production and Purification

Four purification plants + LS Mixing + QA/QC + high purity N_2 and water production plant

to guarantee radio-purity and transparency

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

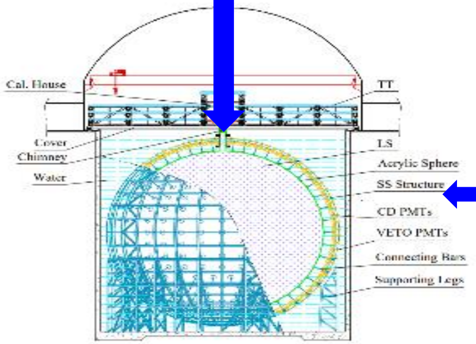
3) Water extraction to remove radioactive impurities

4) Gas stripping to remove Rn and O_2

85%

15%

OSIRIS to monitor the LS quality



All plants are individually tested, and all requirements are satisfied

Final Cleaning Plan and Liquid Scintillator Filling Scheme

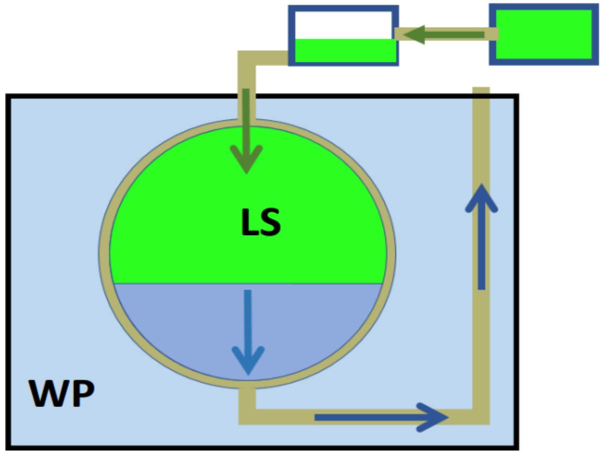
Reduce dust to class 1000, reduce Rn one order

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

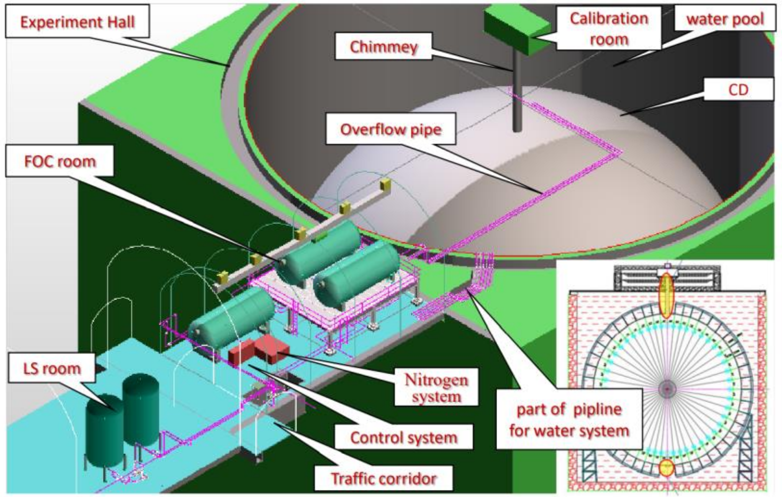
Water for CD**: U/Th<10^{-15} g/g, ^{226}Ra<0.1 mBq/m^3**

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

LS filling(7m^3/h)



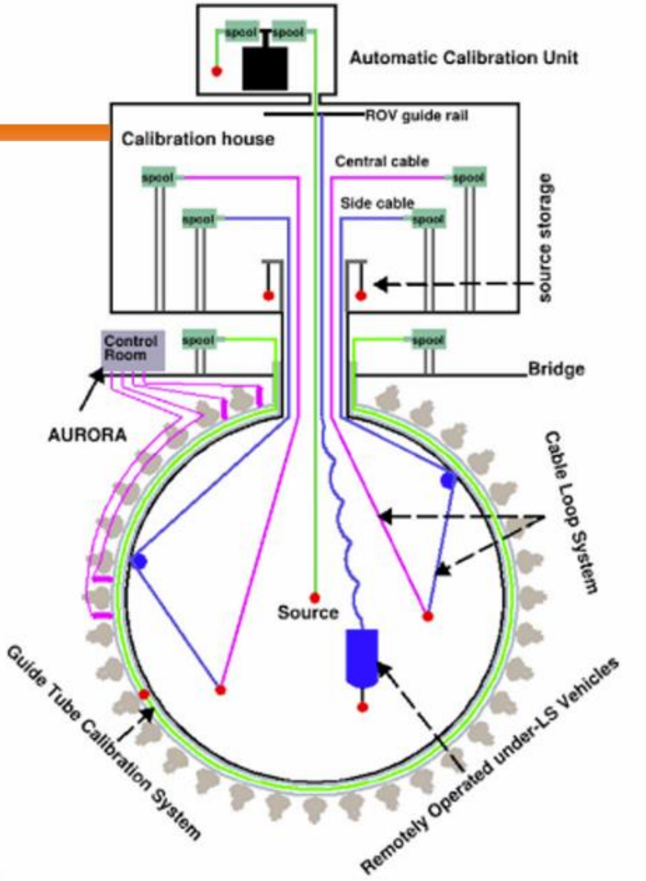
Drain water(7m^3/h)



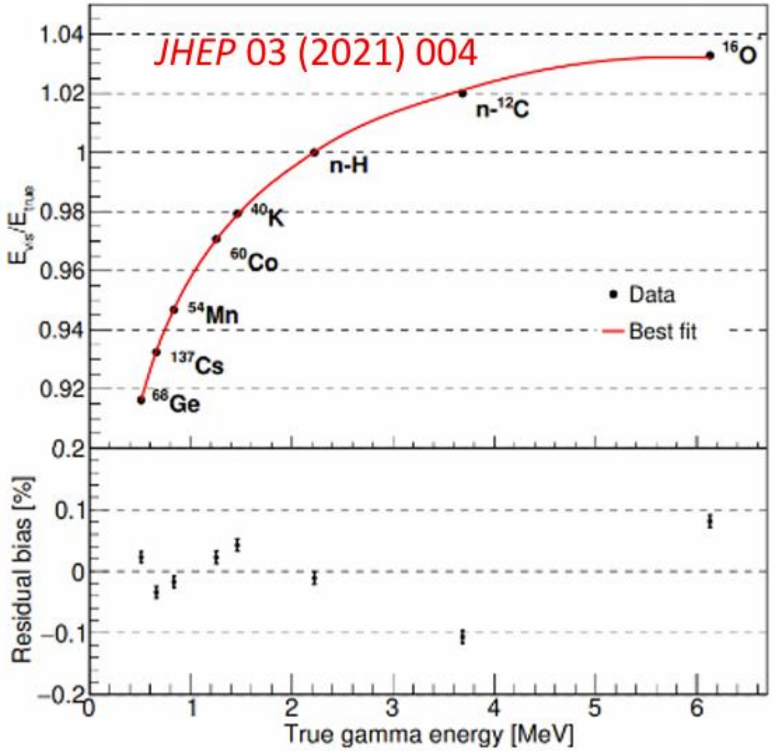
Calibration

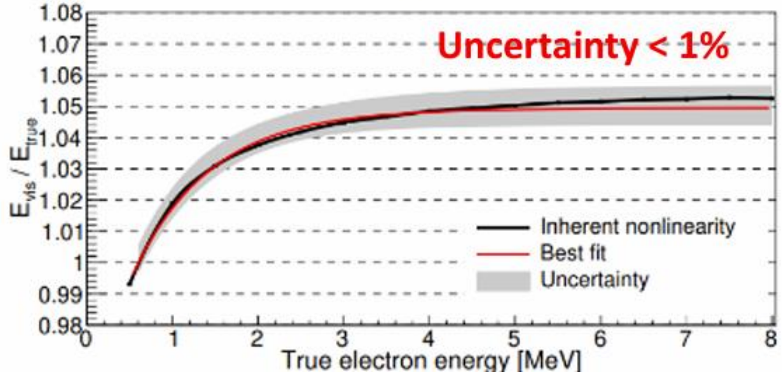
1D,2D,3D scan systems with multiple calibration sources to control the energy scale, detector response non-uniformity, and < 1% energy non-linearity

Cable system prototype



Shadowing effect uncertainty from Teflon capsule of radioactive sources: < 0.15%





Summary

- **Design**
  - Two-layer structure for simplicity and cost: stainless steel frame + Acrylic tank
  - Water as VETO and Buffer, radiopurity control of water
  - PMT： more coverage with higher photon detection efficiency
  - LS： higher transparency and radiopurity
- **Construction:**
  - SS structure with 120 k screws
  - Huge acrylic spherical vessel ~ installation spending about 2 years
  - PMT Installation
  - LS purification and filling

Civil construction finished in Dec, 2021

Challenges…

50 m x 70 m
Exp. Hall

35.4 m
acrylic sphere,
vs. 13 m@ SNO

20 kton
Liquid scintillator,
Borexino X40,
KamLAND X20
λ>20 m,
U/Th<10^{-17} g/g

20,000
20-in PMT, ε~30%

Best Light yield
Borexino X2,
KamLAND X5

Thanks!

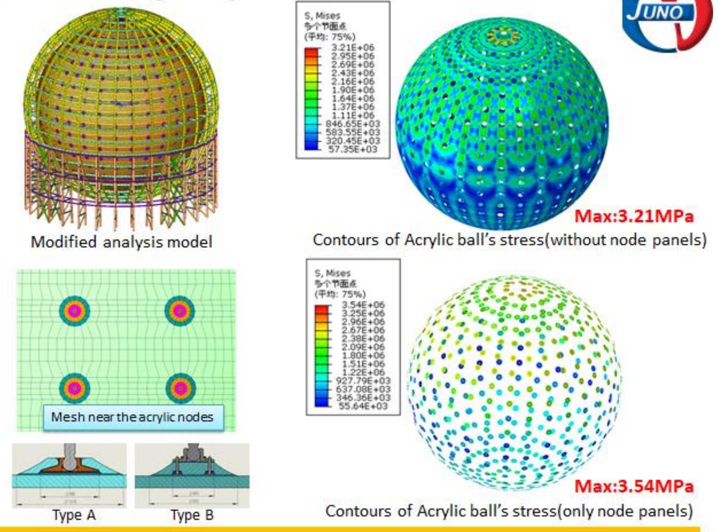
Backups

Milestones of CD

- **2008,** Physics idea paper published.
- **2012,** The concept of the acrylic spherical vessel + water + ss structure was proposed.
- **2015,** The collaboration determined the design.
- **2017,** The detailed engineering design was finished.
- **2018/19,** The manufacturers of acrylic, ss structure and FOC through bidding was determined.
- **2021. end,** Foundation of ss structure was finished and began detector installation.
- **2022. middle,** The ss shell was almost finished and acrylic vessel began to assembly.
- **2024. end,** Acrylic vessel to be finished and liquid to be filled

Key points of the safety

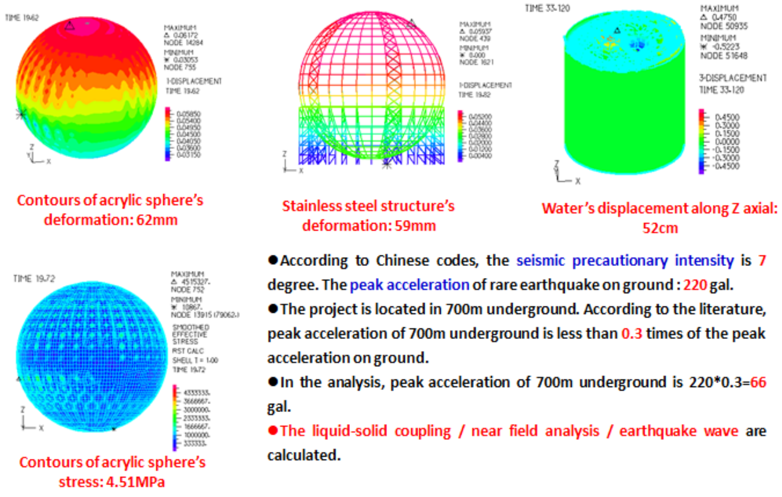
Acrylic sphere's stress contour



Acrylic node's stress is a little bigger than 3.5MPa

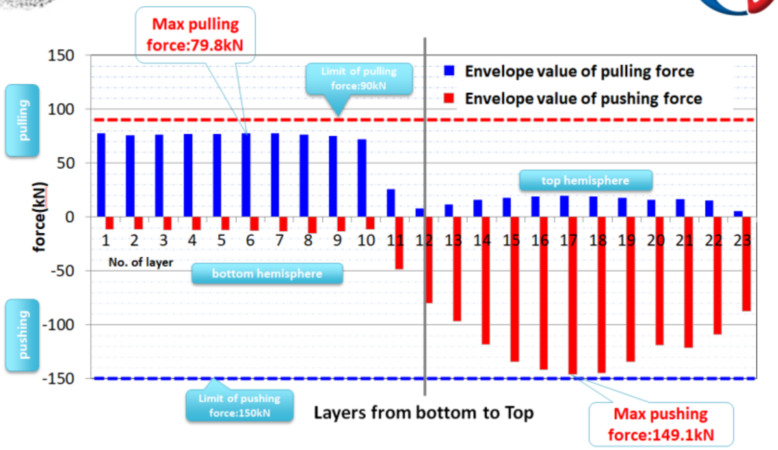
Central Detector by Yuekun Heng

Seismic analysis



- According to Chinese codes, the seismic precautionary intensity is 7 degree. The peak acceleration of rare earthquake on ground : 220 gal.
- The project is located in 700m underground. According to the literature, peak acceleration of 700m underground is less than 0.3 times of the peak acceleration on ground.
- In the analysis, peak acceleration of 700m underground is 220*0.3=66 gal.
- The liquid-solid coupling / near field analysis / earthquake wave are calculated.

Summary of FEA result of Bar force

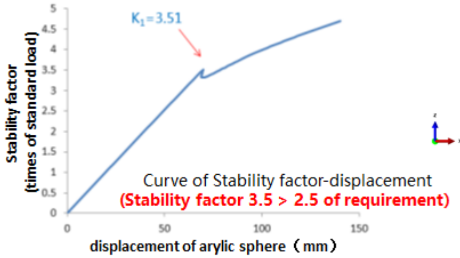


Envelope of Bar force of 4 Load Conditions

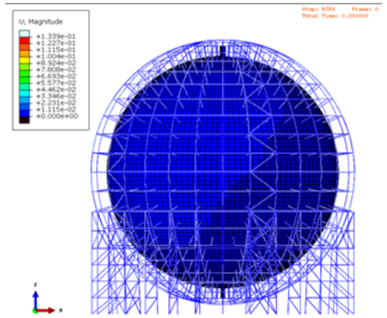
Meeting the requirements of Pulling force less than 90kN, pushing force less than 150kN

Stability analysis

- Analysis Software: Abaqus 6.09, Analysis Module: Abaqus-Riks
- Considering geometric nonlinearity
- Considering the nonlinearity of stainless steel material.
- Acrylic material considered as elastic.
- Load: 1.0 weight + 1.0 buoyancy



Curve of Stability factor-displacement
(Stability factor 3.5 > 2.5 of requirement)



The deformation process of Stability analysis