Design and progress of the Central Detector of JUNO

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On behalf of JUNO Collaboration
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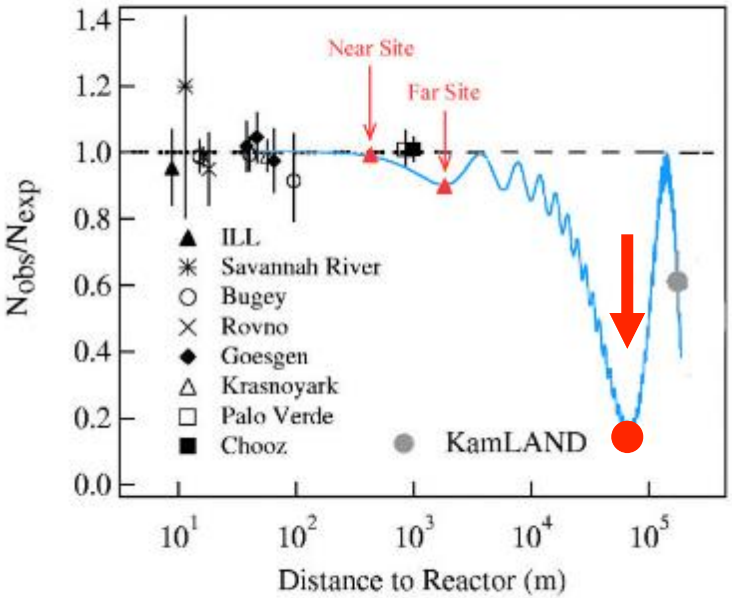
NuFact @ Virginia Tech

Outline

- JUNO physics and requirements on the detectors
- The central detector system
  - Structure design and progress
  - Liquid scintillator
  - PMT of 20’’ and 3’’
  - Electronics readout
  - Calibration system
- Summary

Determine MH with Reactors

Method from Petcov and Piai, Physics Letters B 553, 94-106 (2002)

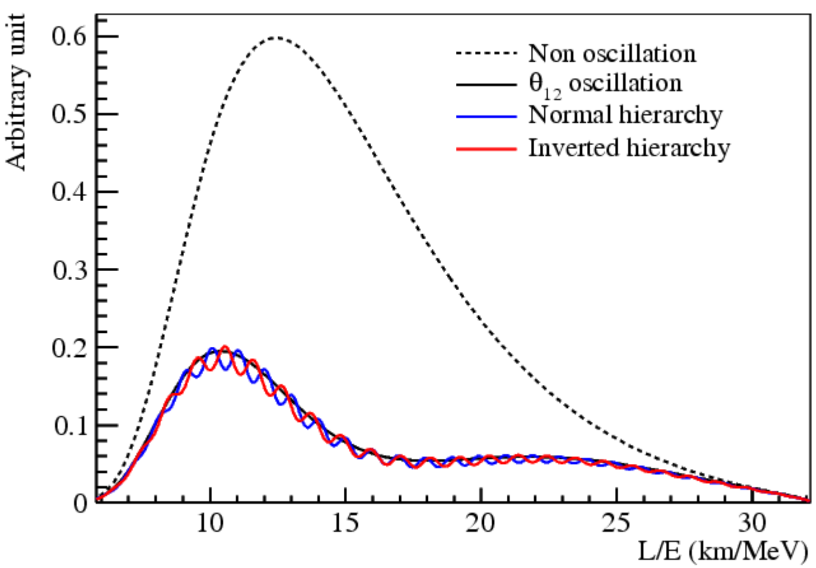


Also refer to arXiv1210.8141

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

$$
\begin{aligned}
P_{ee} = 1 &- \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2(\Delta_{21}) \\
&- \sin^2 2\theta_{13}\sin^2(|\Delta_{31}|) \\
&- \sin^2\theta_{12}\sin^2 2\theta_{13}\sin^2(\Delta_{21})\cos(2|\Delta_{31}|) \\
&\pm \frac{\sin^2\theta_{12}}{2}\sin^2 2\theta_{13}\sin(2\Delta_{21})\sin(2|\Delta_{31}|)
\end{aligned}
$$

+ NH
- IH



- **The big suppression is the "solar" oscillation → Δm^2_{21} , $\sin^2\theta_{12}$**
- **"Large" value of θ_{13} crucial**
- **The NH or IH can be distinguished if we have neutrinos' spectrum with much quantity and with good precision, for example 100k events and 3% resolution at 1 MeV.**

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**

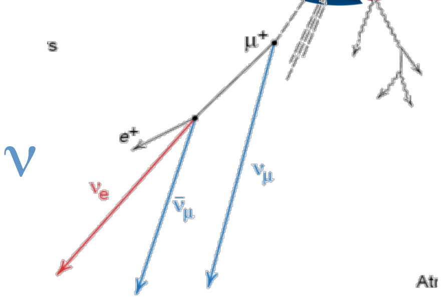
JUNO will be the largest liquid scintillator detector and with the best energy resolution in the world

JUNO Neutrino detection capabilities

Supernova ν
5-7k in 10s for 10kpc

Solar ν
(10s-1000s)/day

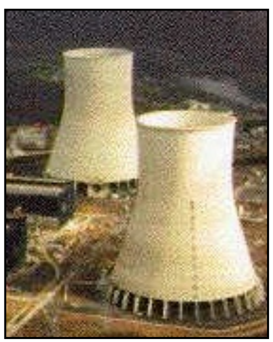
Atmospheric ν
several/day



700 m

Cosmic muons
~ 250k/day

0.003 Hz/m^2
215 GeV
10% muon bundles



36 GW, 53 km

20k ton
LS

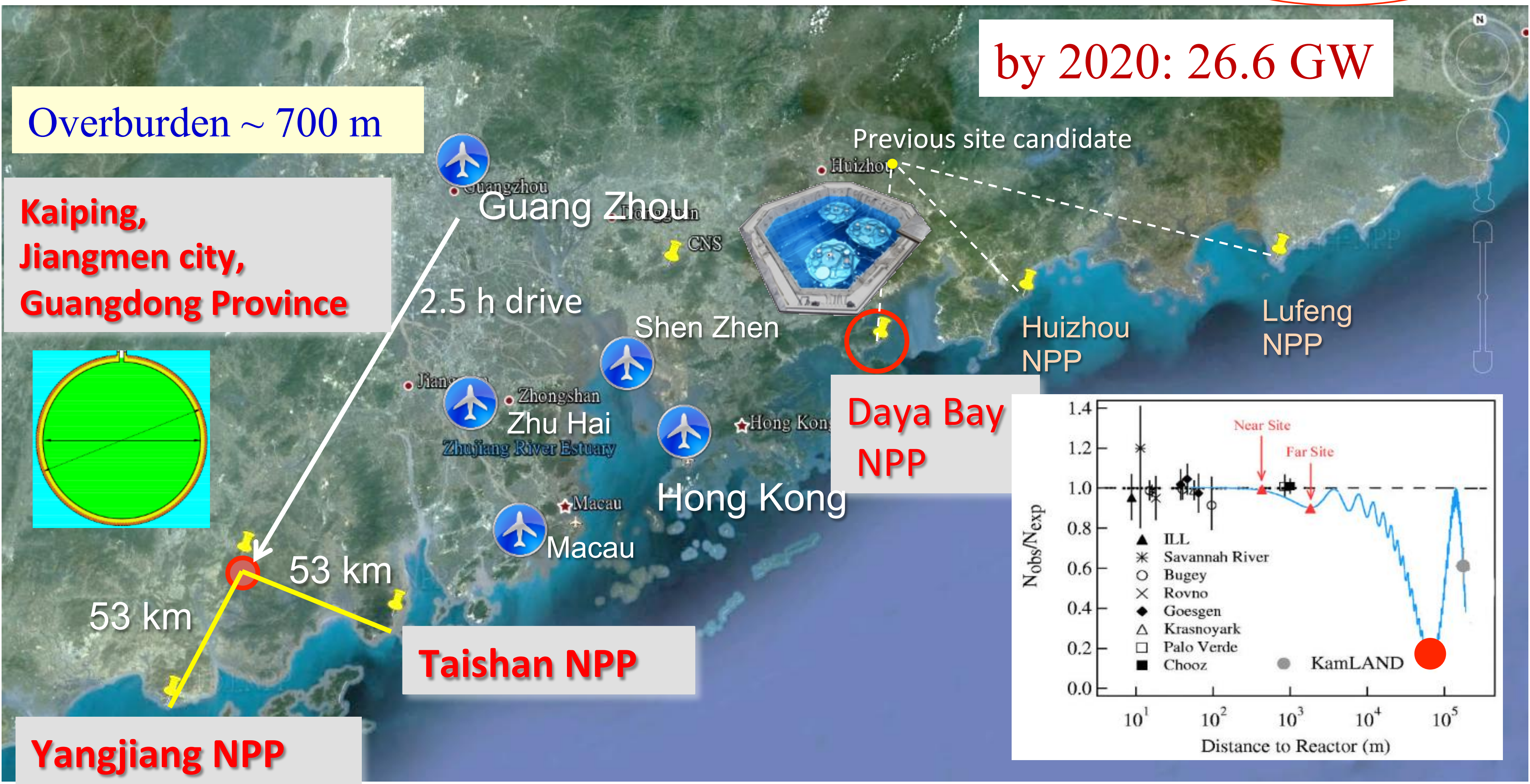
Reactor ν, 60/day
Bkg: 3.8/day

Geo-neutrinos
1.1/day

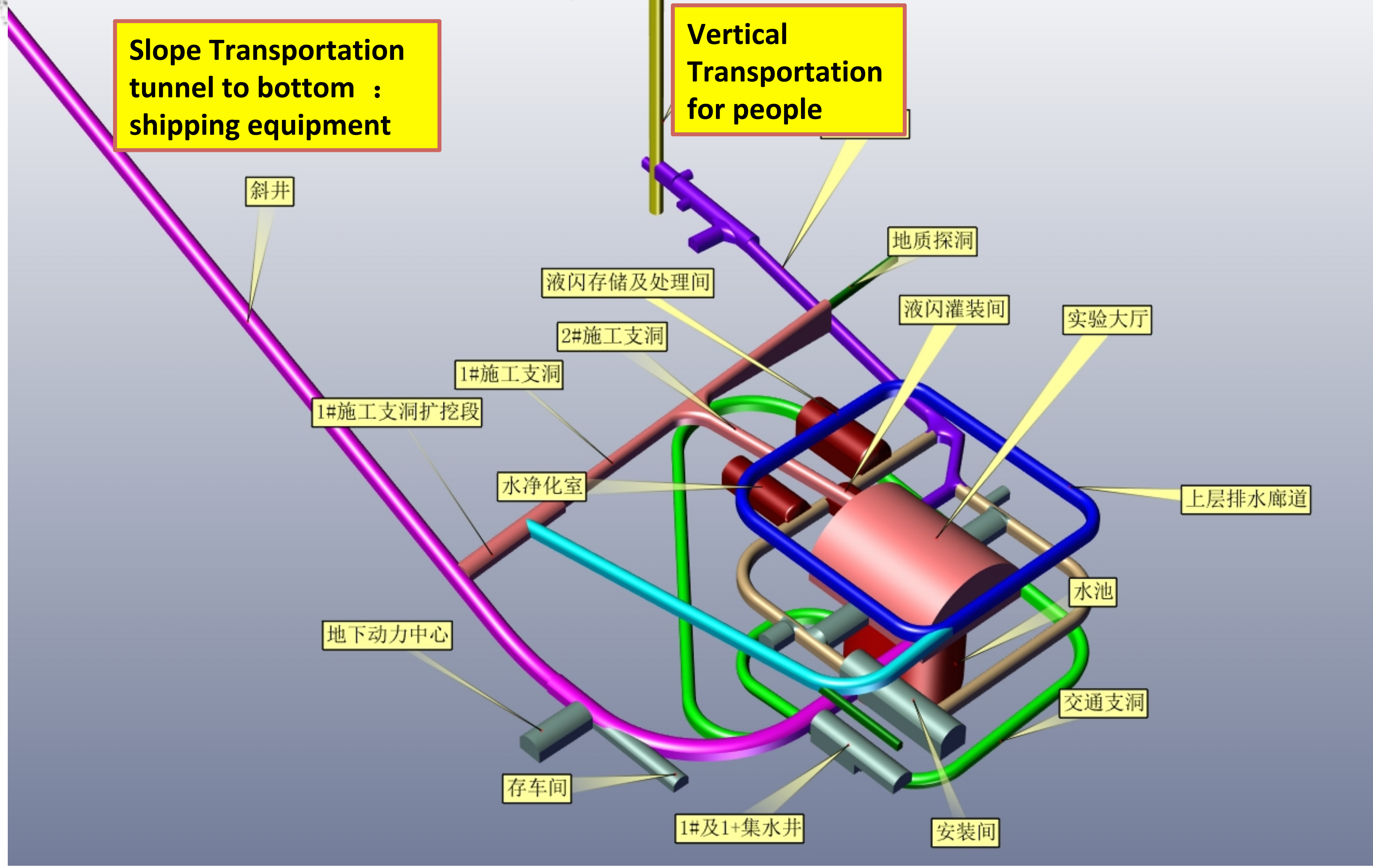
JUNO Site

JUNO has been approved in Feb. 2013. with ~ 300 M$ support by China

NPP	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	Operational	Planned	Planned	Under construction	Under construction
Power	17.4 GW	17.4 GW	17.4 GW	17.4 GW	18.4 GW



Underground Layout



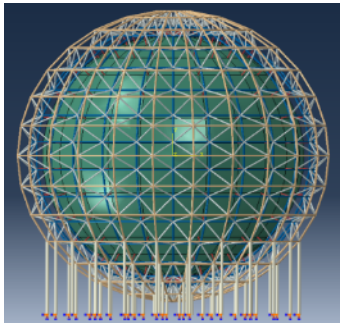
Surface Building

Outline

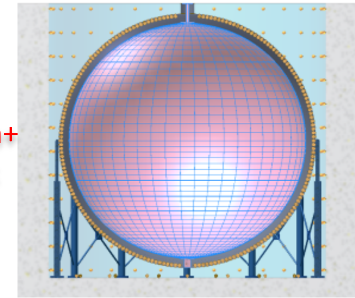
- JUNO physics and requirements on the detectors
- The central detector system
  - Structure design and progress
  - Liquid scintillator
  - PMT of 20'' and 3''
  - Electronics readout
  - Calibration system
  - Shielding and veto
- Summary

Option selection route

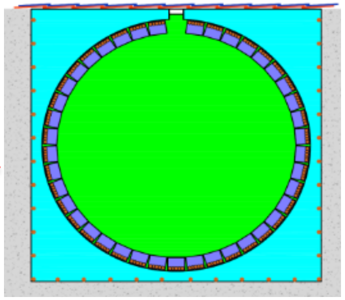
Acrylic sphere+ SS truss



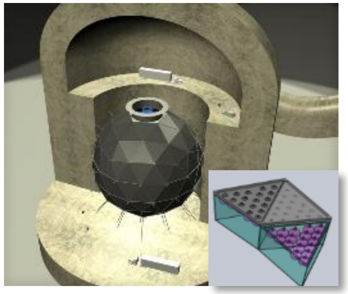
Balloon+ SS tank



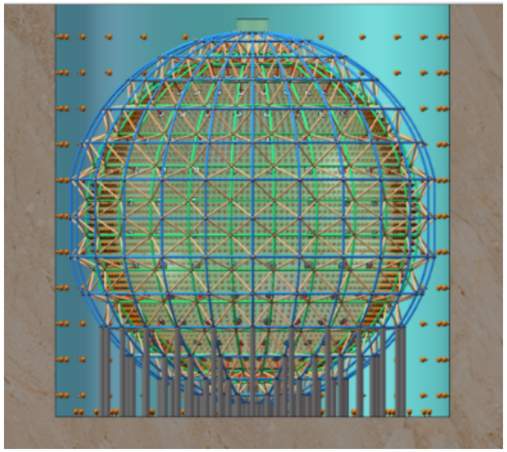
Acrylic module+ SS tank



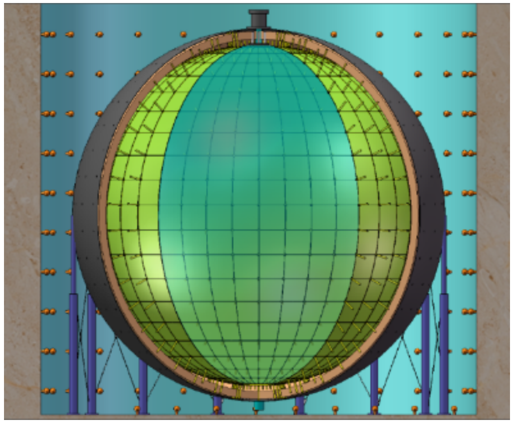
Acrylic sphere+ SS tank



March, 2014

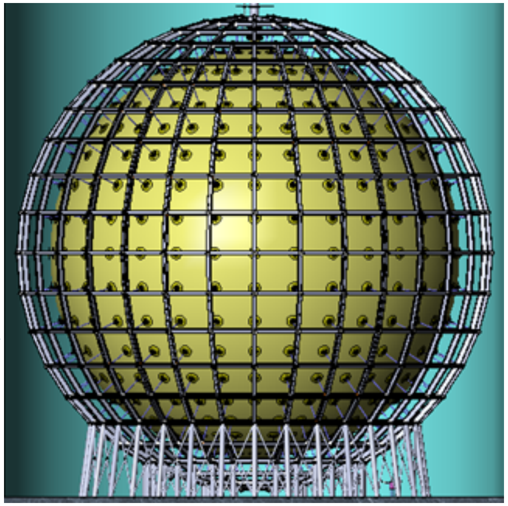


SS truss+ Acrylic sphere



Balloon + Acrylic support+ SS tank

July, 2015



Final decision:
Acrylic sphere + SS structure

JUNO Detectors

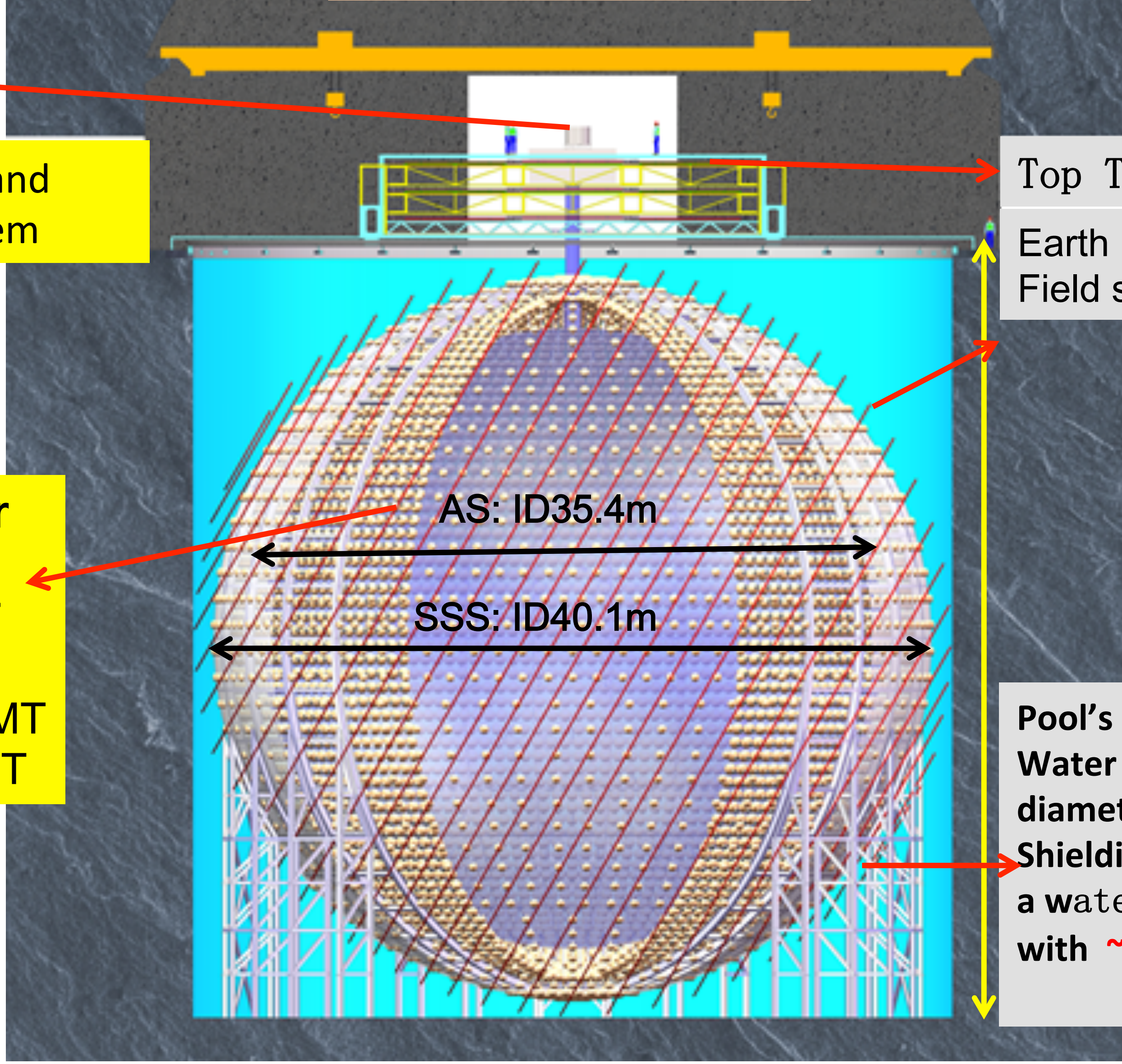
Calibration

Liquid scintillator and
Water Filling system

Top Tracker

Earth Magnetic
Field shielding coils

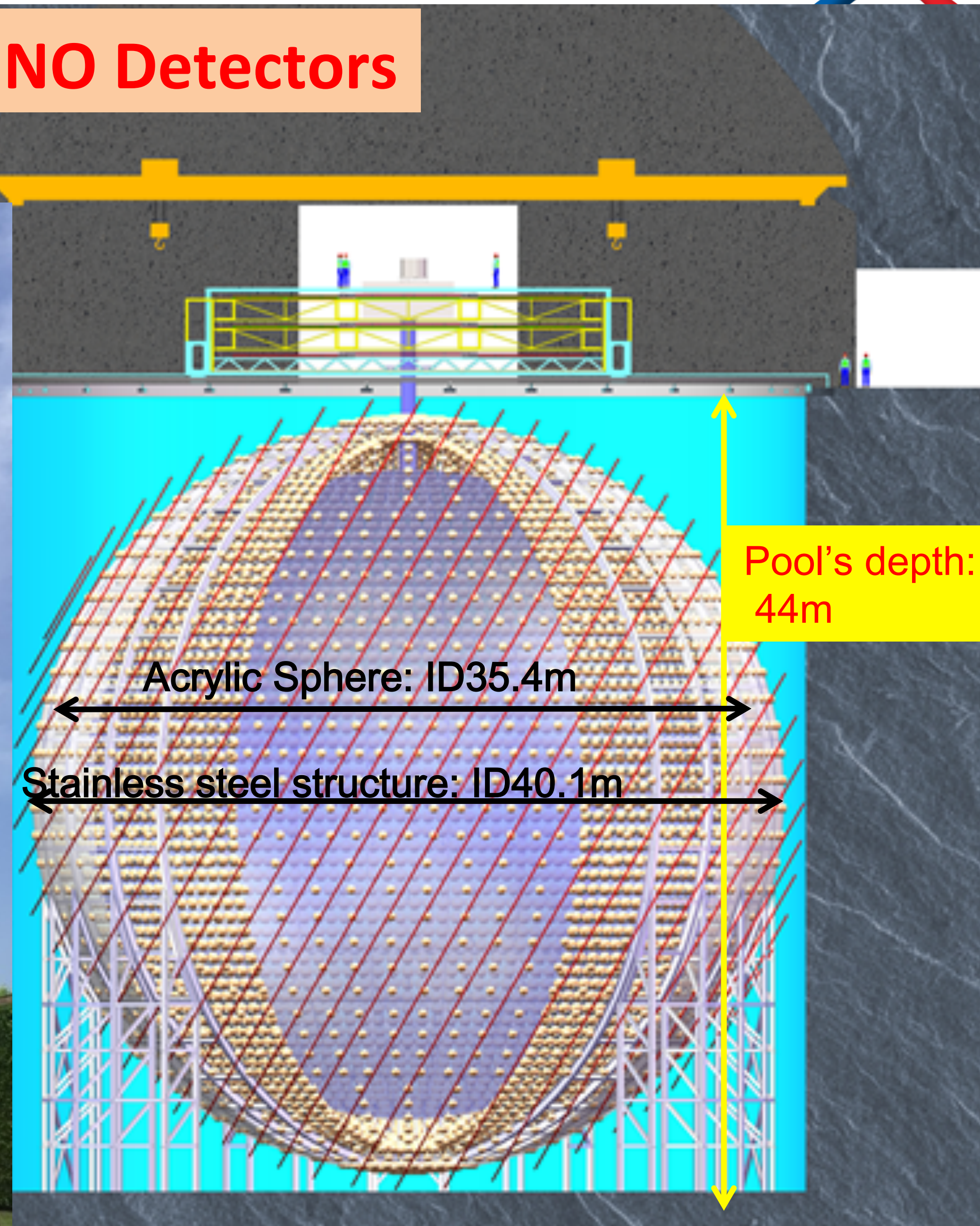
Central detector
- Steel structure
- Acrylic sphere +
- 20kt Liquid Scin
- ~18000 20" PMT
- ~25000 3" PMT



Pool's depth: 44m
Water depth and diameter: 43.5m
Shielding and making a water Cherenkov with ~2400 20" PMT

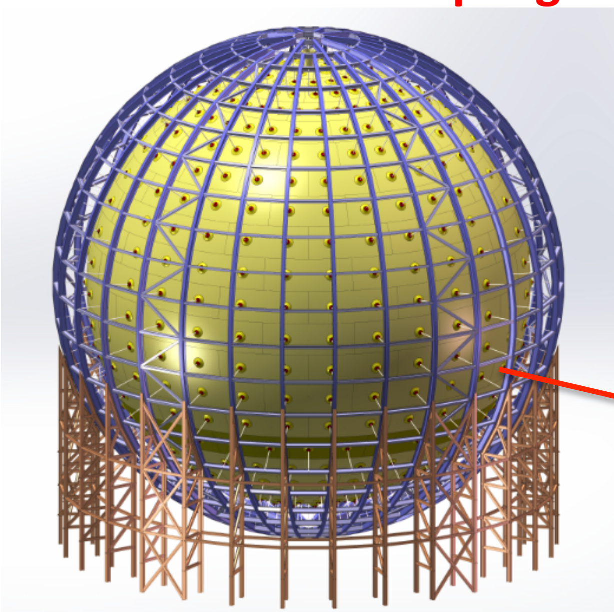
AS: Acrylic Sphere; SSS: Stainless Steel Structure

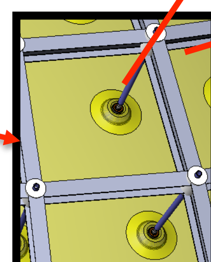
JUNO Detectors

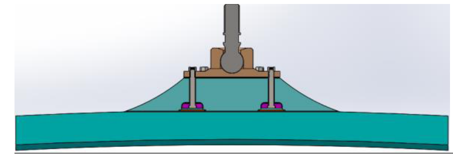


Structure Design & Optimization

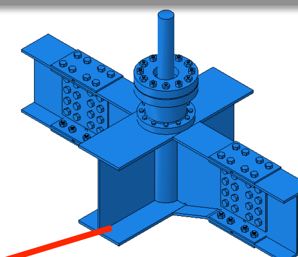
- **Optimization:**
  - **Reduce the max stress on the acrylic node**
  - **Simplify the structure, reduce the weight**
  - **Evaluate the influence from earthquake and fluid solid coupling**



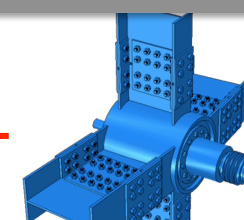




590 acrylic nodes to hold the acrylic sphere with pushing and pulling load



370 Steel joints with locking bearing



220 Steel joints with spring disk

- **In the LS-Water filled configuration, total net buoyancy: ~3000 tons, counteracted by the connecting bars**
- **Forces in the connecting bars: Pulling < 9 tons (< 3.5 Mpa) / Pushing < 15 tons (< 3.0 Mpa)**

R&D about acrylic

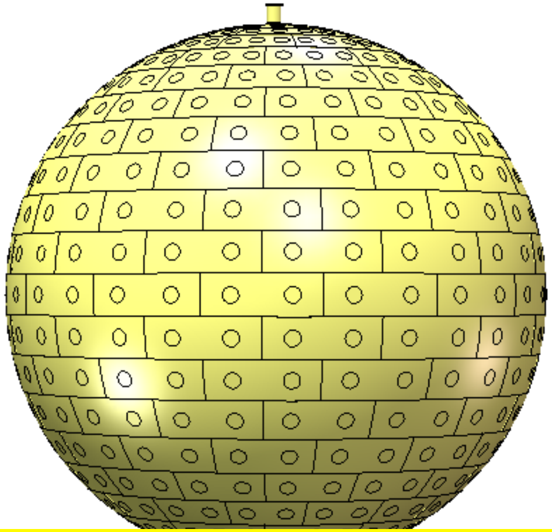
- **How about the life time of acrylic?**
  - Strength reduce to ~70% for 20 years @ 5.5 Mpa
  - Creep: over 100 years
- **Can the spherical panel be made?**
  - 3 companies made samples
  - 2017.2 Donchamp won the bid.
- **How about the max stress control on acrylic?**
  - ≤ 3.5 Mpa, less than 5 Mpa in Daya Bay
- **How strong the acrylic node need to be?**
  - Max pulling load: ~ 8 tons
  - Break at load: ~100 tons
- **How to control the radiation back-ground and the quality of acrylic?**
- **How to make the bulk-polymerization on site？**

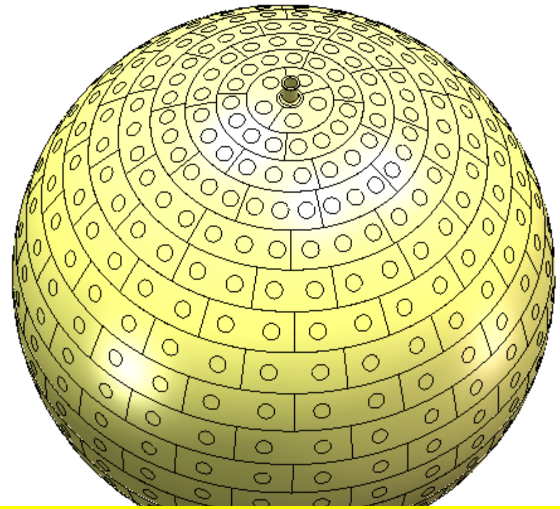
Thermoforming the spherical panel:
3m x 8m x 120mm

Test for bulk-polymerization

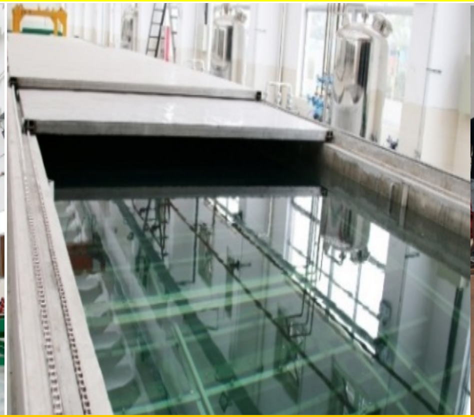
Load test of node: break at 100 tons

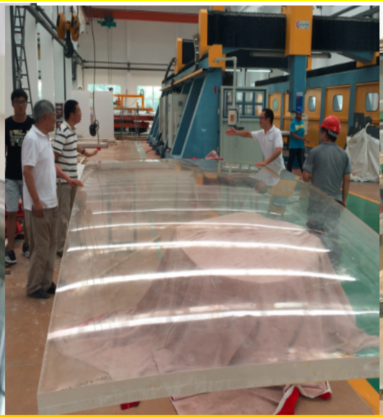
Acrylic panels and production line

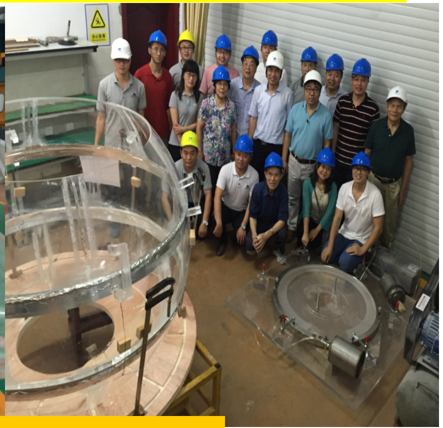




Be composed of 265 spherical panels, Net Weight: ~600 tons







- A new production lines special for JUNO are finished
- A constant temperature workshop is being made for acrylic panels machining and pre-assembly

1:12 scaling CD prototype

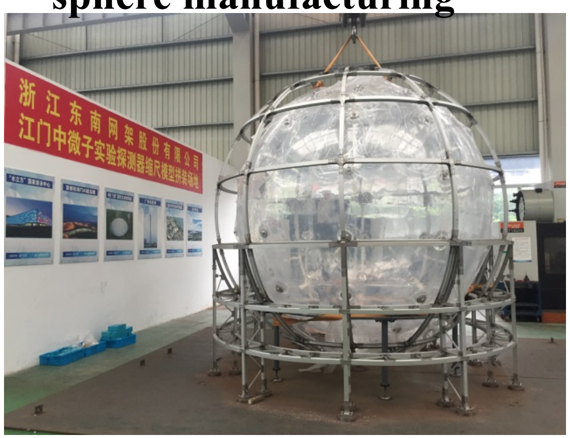
Manufacturing and assembly and test

Small prototype of acrylic sphere manufacturing

Tests to be done

- Verify the FEM calculation
- Check the spring effects
- Check the temperature load
- Test the monitor system
- Test the filling/overflow system

Adjusting steel structure



Pre-assembly

Lifting test

Small prototype and steel cylinder for testing

Low radiation BG for acrylic and steel

- Low radiation background requirements:

Parts	Mass (t)	^{238}U	^{232}Th	^{40}K	^{60}Co	Singles (Hz)
Acrylic	**600**	**1 ppt**	**1 ppt**	**1 ppt**		**0.39**
Node stainless steel	23.6	0.1 ppb	2 ppb	0.05 ppb	2 mBq/kg	1.9
Shell stainless steel	583.79	1 ppb	5 ppb	0.2 ppb	20mBq/kg	0.02
Connection bar	67.18	0.1 ppb	2 ppb	0.05 ppb	2 mBq/kg	0.28

- Process control for low radiation background
  - **Filter in MMA material**
  - **Special reaction kettle/pipe**
  - **Moulding: pure water/clean room**
  - **Thermoforming: film or placket to shield the dust and radon**
  - **Bonding: filled with clean air or N_2**
  - **Shield Rn: plastic film on the surface of the acrylic**
  - **Clean the inner surfaces of the acrylic sphere: air cushion to support**
  - **Filling: first to fill pure water then replace with LS / LS tank covered with pure N_2**

In the clean room class 10000 with the radon < 100 Bq/m^3 , totally exposed time: less than 10 days

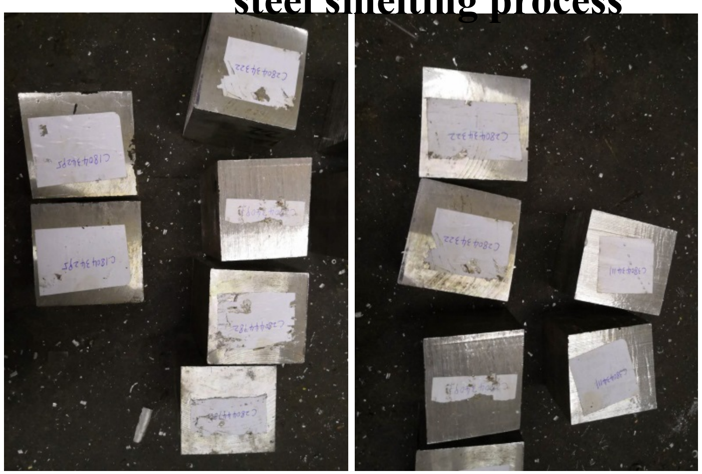
The samples for acrylic has met the 1 ppt requirements for U/Th/K.

First batch of stainless steel with low background

- **the first batch of raw materials for the CD steel structure: ~330 ton, smelting and low radioactive background testing were completed, and the test results met the technical requirements;**

All iron water converter stainless steel smelting process

Hot rolling steel slab

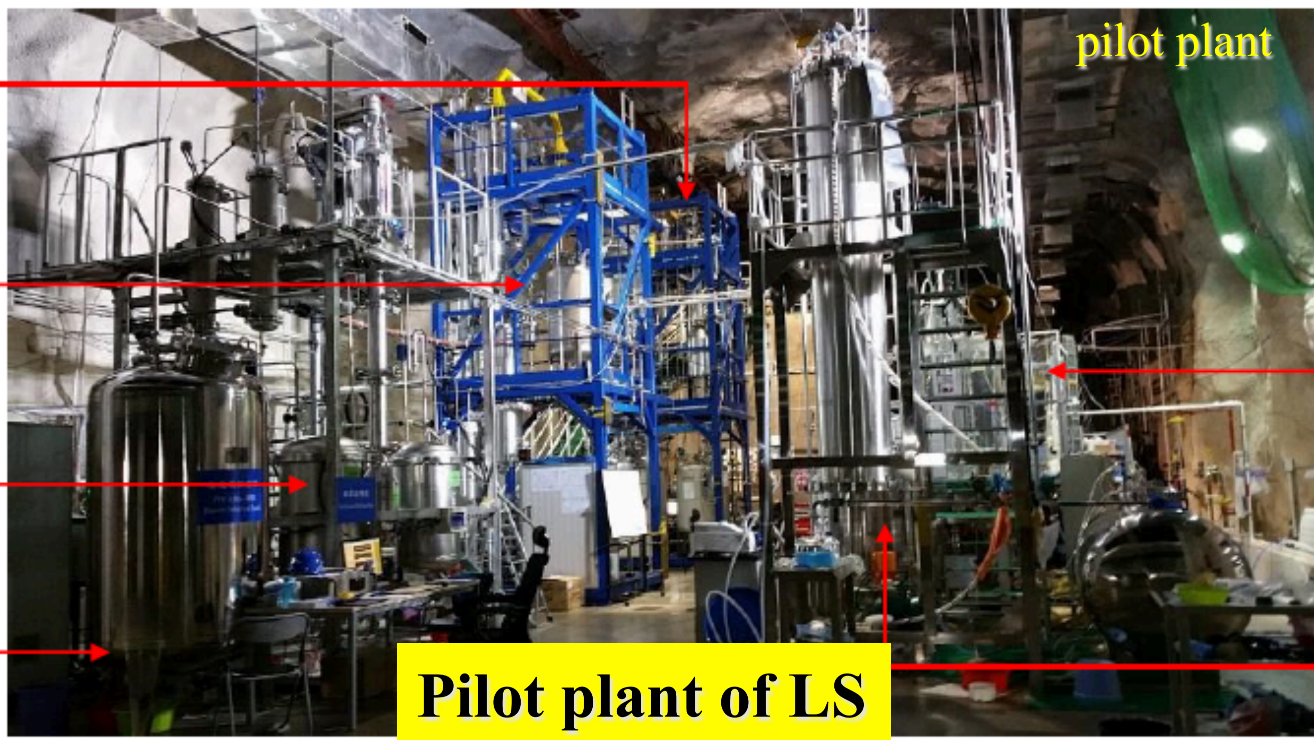


Stainless steel sample for background testing

	Radioactive background requirements for steel structure	Sample1 A2802246	Sample2 A2802245
^{238}U	1 ppb (12.4mBq) /kg	6.14±1.69 mBq/kg	< 8.3 mBq/kg
^{232}Th	5 ppb (20mBq) /kg	< 2.68 mBq/kg	< 8 mBq/kg
^{40}K	0.2 ppb (51.36mBq) /kg	< 16.10 mBq/kg	< 20 mBq/kg
^{60}Co	20 mBq/kg	< 0.83 mBq/kg	< 1.1 mBq/kg

Liquid Scintillator

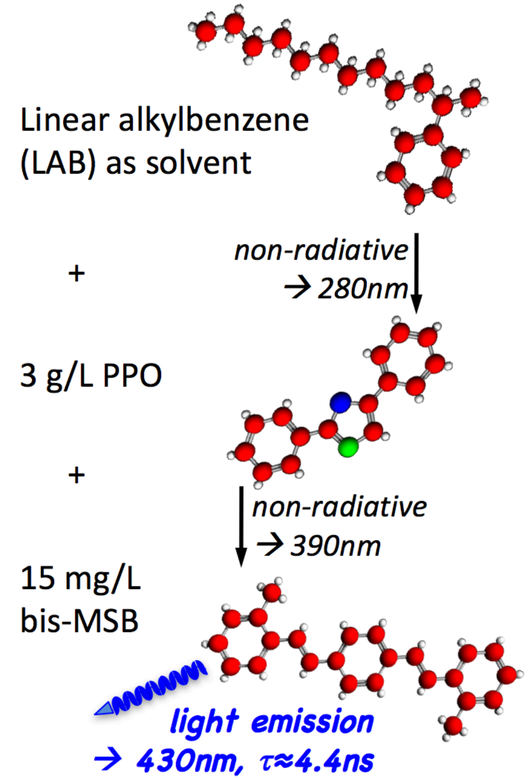
- Use one of Daya Bay detectors through replacing the target LS of 20 tons by the produced LS from the pilot plant to test and check:
  - Optimize the recipe
  - Reduce radioactive background
  - Increase the transparency



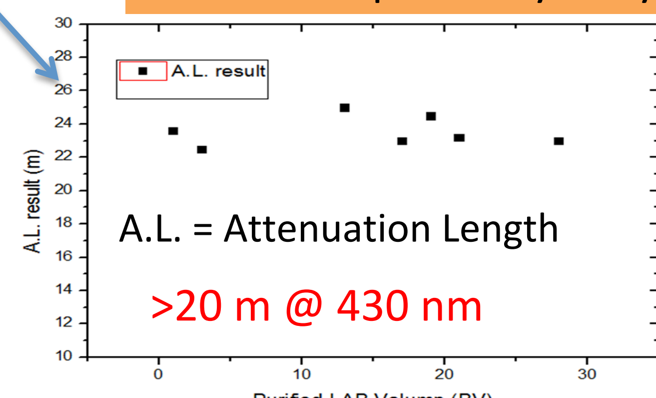
Liquid Scintillator

- **Using a recipe inspired from Daya Bay's experience**
- **Tested and changed to be more suitable for JUNO**
  - **High light-yield VS transparency:**
    - **2.5g/L PPO**
    - **1-4mg/L bis-MSB**
- **Requirements and methods:**
  - **Attenuation length: > 20 m @430 nm with Al_2O_3 purification**
  - **Good radio purity:**
    - **< 10^{-15} g/g in U/Th**
    - **< 10^{-16} g/g in K**

3 methods to reduce the radio BG
- **Distillation**
- **Water extraction**
- **Steam stripping: Rn/Kr**

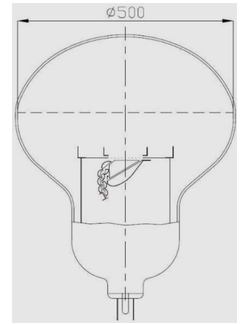
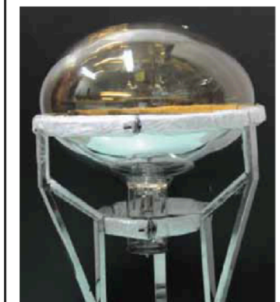
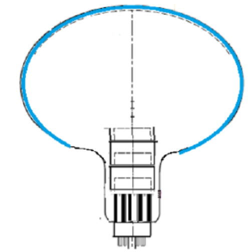


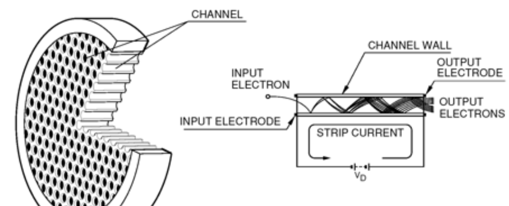
The old recipe in Daya Bay



20000 20" PMT

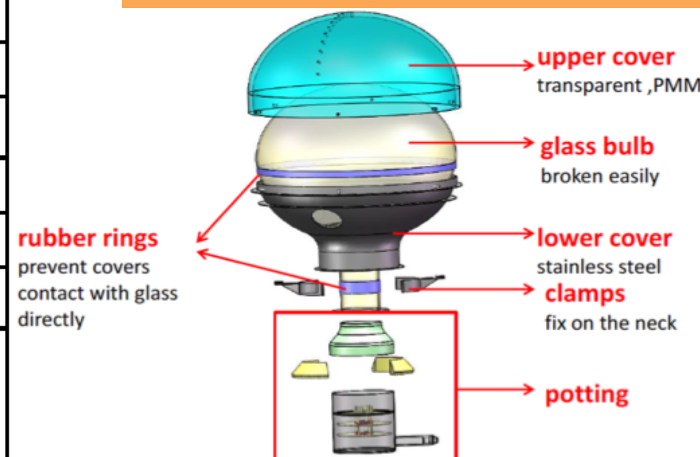
- Contracts were signed in 2015
- **15000 MCP-PMT (75%) from NNVT**
- **5000 Dynode (25%) from Hamamatsu**

20-inch Hamamatus PMT-Dynode Ellipsoidal Glass	20-inch IHEP-MCP-PMT-Ellipsoidal Glass
 	 



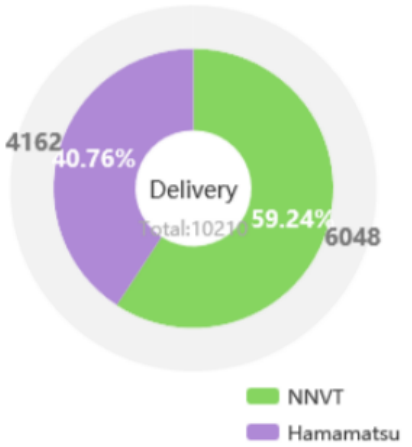
2 MCPs to replace Dynodes

Characteristics	unit	MCP-PMT (NNVT)	R12860 (Hamamatsu)
Detection Efficiency (QE*CE*area)	%	27%, > 24%	27%, > 24%
P/V of SPE		3.5, > 2.8	3, > 2.5
TTS on the top point	ns	~12, < 15	2.7, < 3.5
Rise time/ Fall time	ns	R~2, F~12	R~5, F~9
Anode Dark Count	Hz	20K, < 30K	10K, < 50K
After Pulse Rate	%	1, <2	10, < 15
Radioactivity of glass	ppb	238U:50 232Th:50 40K: 20	238U:400 232Th:400 40K: 40



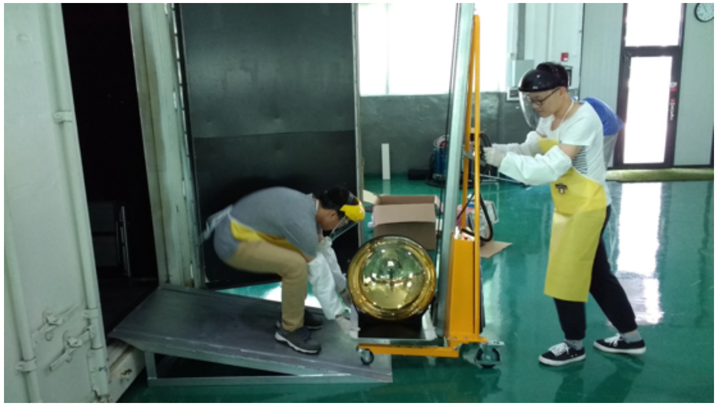
PMT assembly

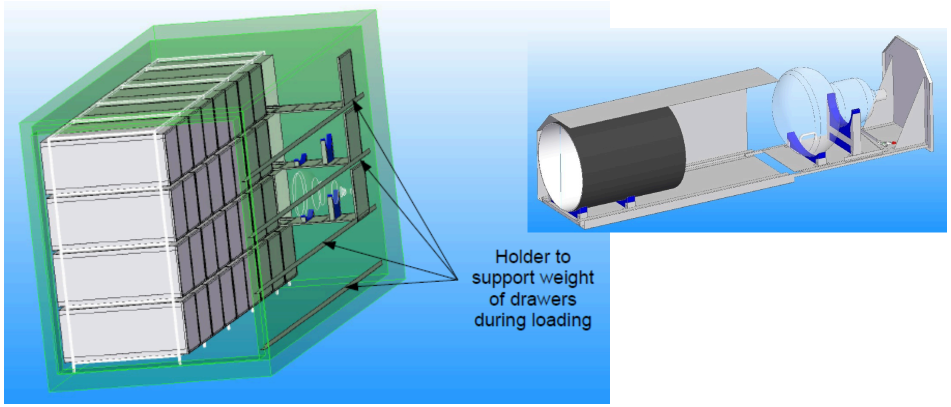
Batch test of 20" PMT



20" PMT Arrived ~10000

20" PMT inspection

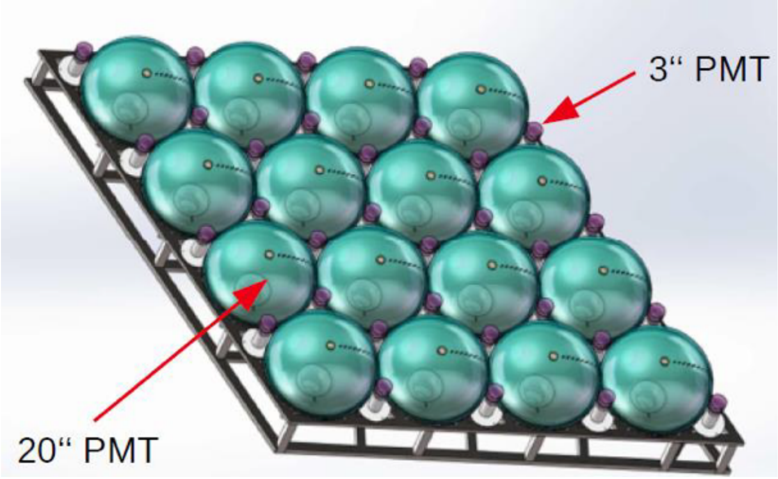




Container: ~ 30 PMTs to be tested simultaneously

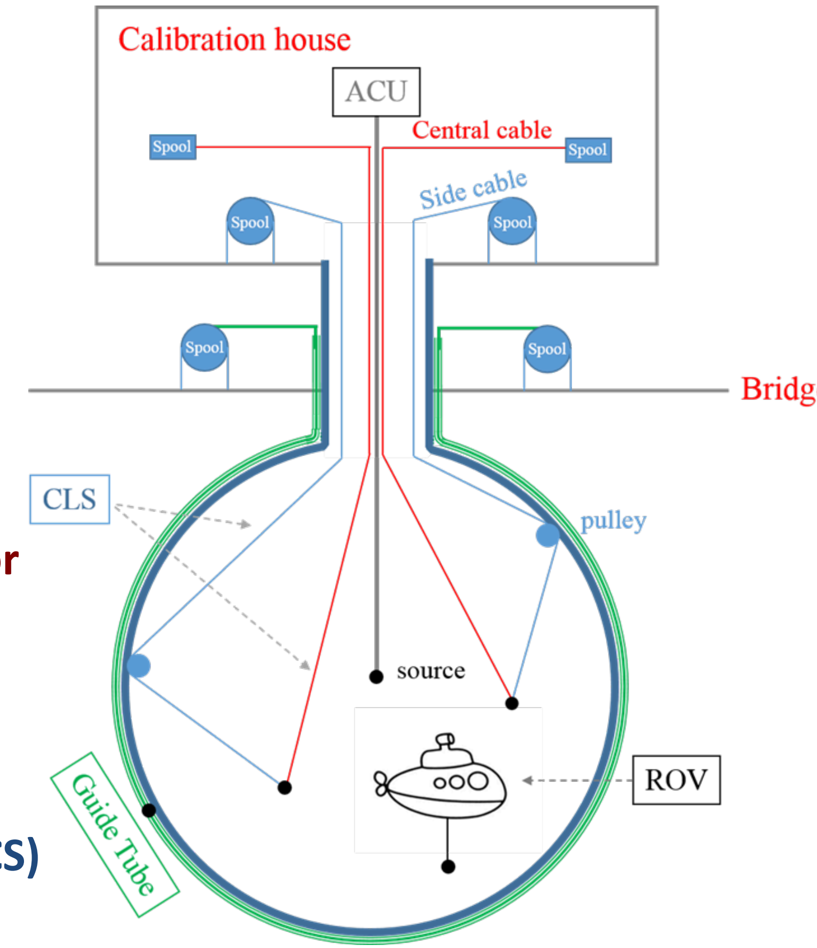
25000 3" PMT

- Work together with the 20-in PMT to provide a double calorimeter system
  - Energy measurement via "photon counting", better control of systematics
  - Muon tracking, supernova detection …
  - Increase the dynamic range.
  - Increase photon statistics by ~2.5%
- 25000 3-inch PMTs, contracted to HZC (China)，which has produced ~6000 3-inch PMTs



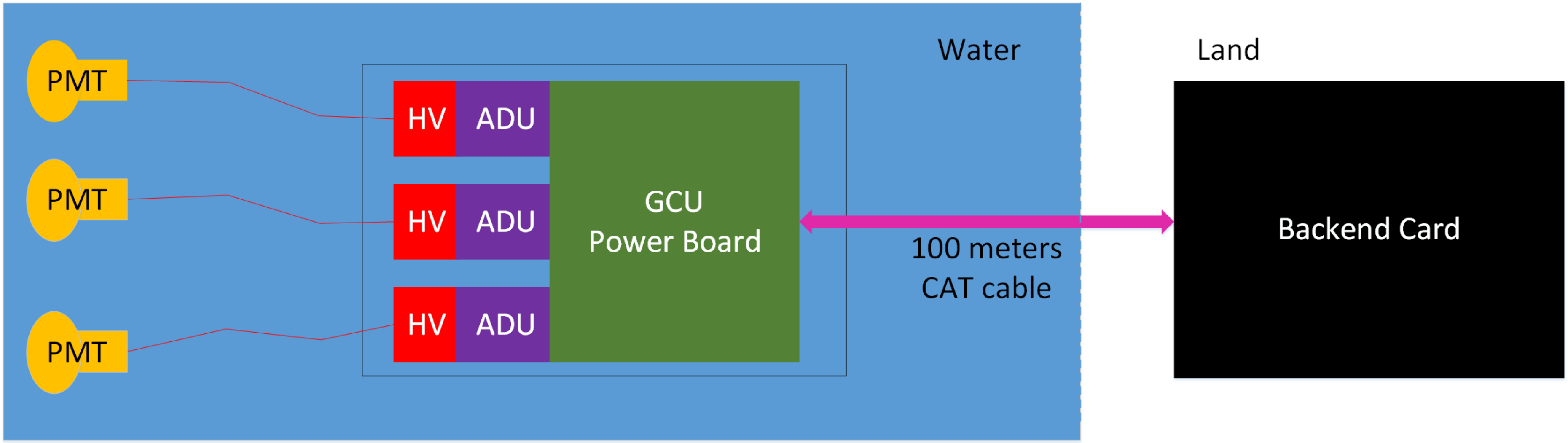
Calibration system

- **The goal:**
  - Overall energy resolution: ≤ 3%/√E
  - Energy scale uncertainty: <1%
- **Radioactive sources:**
  - γ： ^{40}K, ^{54}Mn, ^{60}Co, ^{137}Cs
  - e+： ^{22}Na, ^{68}Ge
  - n： ^{241}Am-Be, ^{241}Am- ^{13}C or ^{241}Pu- ^{13}C, ^{252}Cf
- **Four complementary calibration systems**
  - 1-D: Automatic Calibration Unit (ACU) → for central axis scan,
  - 2-D:
    - Cable Loop System (CLS) → scan vertical planes,
    - Guide Tube Calibration System (GTCS) → CD outer surface scan,
  - 3-D: Remotely Operated under-LS Vehicle (ROV) → full detector scan



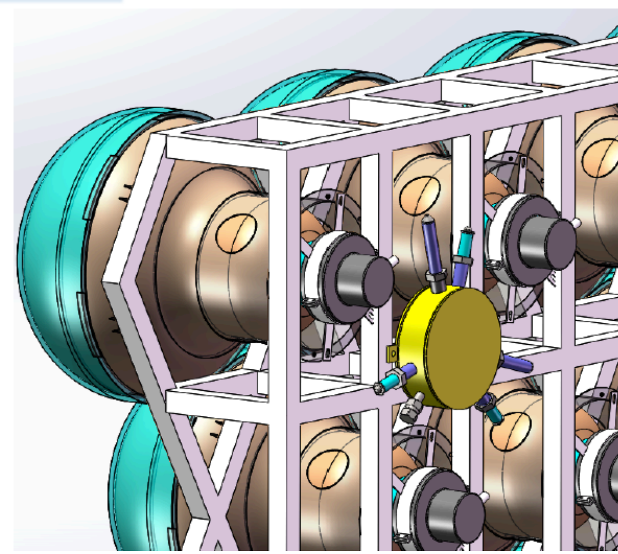
Readout Electronics

1F3 scheme



- PMT: photomultiplier tubes
- HV: High Voltage units
- ADU: Analog to Digital Unit
- GCU: Global Control Unit
- CAT cable: Category 5e cable
- High reliability needed
- Severe constraints by power consumption

PMT signals' waveform are read out by FADC, which is near PMT and guarantee the quality of the analog signals.



Veto Detectors

- **Cosmic muon flux**
  - Overburden：~700 m
  - Muon rate：$0.003 Hz/m^2$
  - Average energy：214 GeV
- **Water Cherenkov Detector**
  - ~4 m water shielding, Radon: <0.2 Bq/m^3
  - ~2000 20”PMTs
  - 40 kton pure water, HDPE lining on pool
  - Similar technology as Daya Bay (99.8% efficiency)
- **Compensation Coil for EMF shield**
- **Top muon tracker**
  - Decommissioned OPERA plastic scintillator

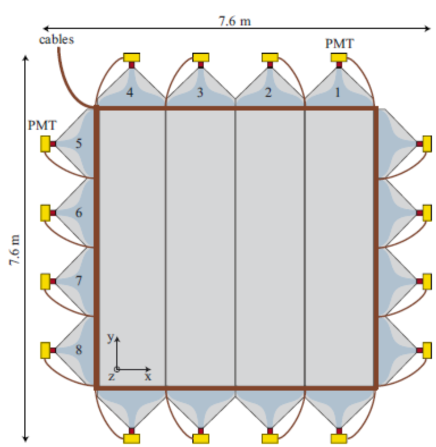
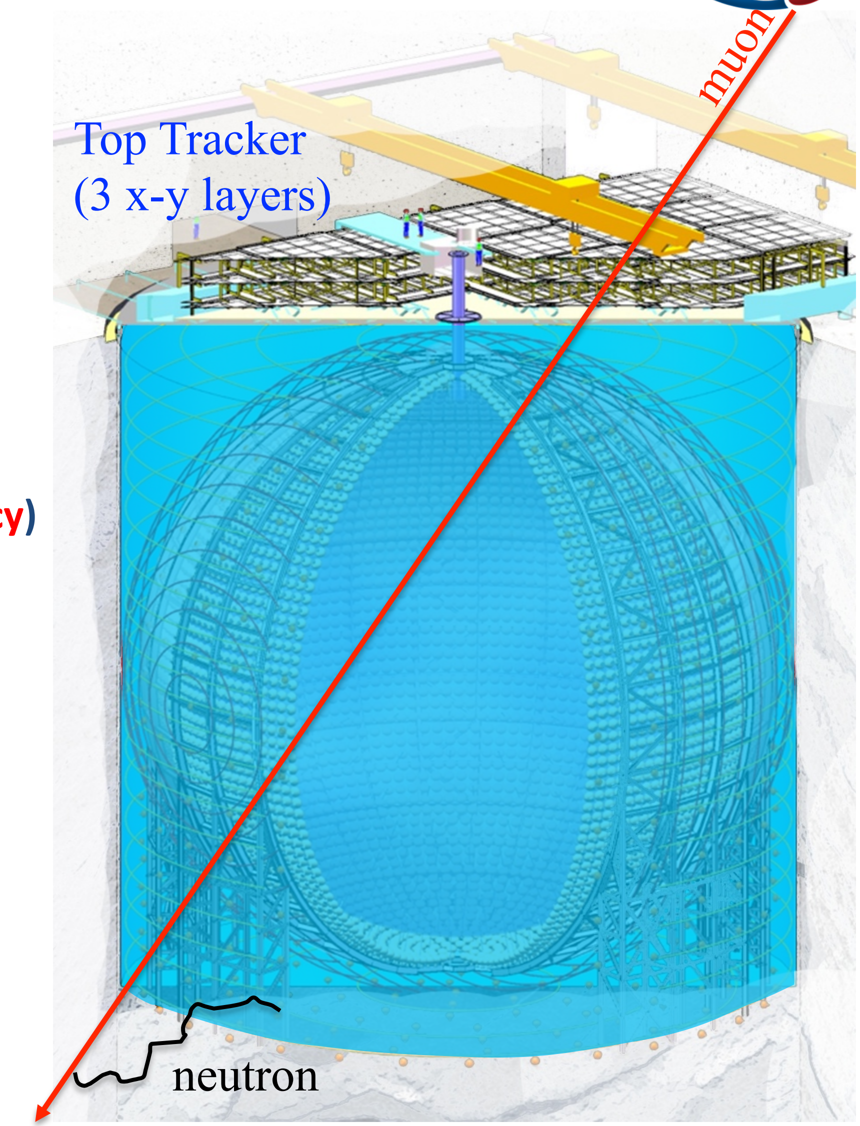


Fig. 3. Schematic view of a plastic scintillator strip wall.



Summary

- **JUNO: Rich neutrino physics prospects**
- **The central detector: a massive LS detector with the precise energy resolution, breaking new ground in LS detection technology**
  - **The largest acrylic sphere ever constructed**
  - **20 kton of highly transparent LS**
  - **18000 20'' PMT and 25000 3'' PMT**
  - **4 calibration subsystems**

Thank you for your attention!

Updated list of JUNO members

Country	Institute	Country	Institute	Country	Institute
Armenia	Yerevan Physics Institute	China	IMP-CAS	Germany	U. Mainz
Belgium	Universite libre de Bruxelles	China	SYSU	Germany	U. Tuebingen
Brazil	PUC	China	Tsinghua U.	Italy	INFN Catania
Brazil	UEL	China	UCAS	Italy	INFN di Frascati
Chile	PCUC	China	USTC	Italy	INFN-Ferrara
Chile	UTFSM	China	U. of South China	Italy	INFN-Milano
China	BISEE	China	Wu Yi U.	Italy	INFN-Milano Bicocca
China	Beijing Normal U.	China	Wuhan U.	Italy	INFN-Padova
China	CAGS	China	Xi'an JT U.	Italy	INFN-Perugia
China	ChongQing University	China	Xiamen University	Italy	INFN-Roma 3
China	CIAE	China	Zhengzhou U.	Latvia	IECS
China	DGUT	China	NUDT	Pakistan	PINSTECH (PAEC)
China	ECUST	China	CUG-Beijing	Russia	INR Moscow
China	Guangxi U.	China	ECUT-Nanchang City	Russia	JINR
China	Harbin Institute of Technology	Czech	Charles U.	Russia	MSU
China	IHEP	Finland	University of Jyvaskyla	Slovakia	FMPICU
China	Jilin U.	France	APC Paris	Taiwan-China	National Chiao-Tung U.
China	Jinan U.	France	CENBG	Taiwan-China	National Taiwan U.
China	Nanjing U.	France	CPPM Marseille	Taiwan-China	National United U.
China	Nankai U.	France	IPHC Strasbourg	Thailand	NARIT
China	NCEPU	France	Subatech Nantes	Thailand	PPRLCU
China	Pekin U.	Germany	FZJ-ZEA	Thailand	SUT
China	Shandong U.	Germany	RWTH Aachen U.	USA	UMD1
China	Shanghai JT U.	Germany	TUM	USA	UMD2
China	IGG-Beijing	Germany	U. Hamburg	USA	UC Irvine
China	IGG-Wuhan	Germany	FZJ-IKP		

Members: 77

Observers: 3, University of Malaya
University of Zagreb (Croatia)
Yale University (USA)