Design and status of the JUNO detector

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On behalf of the JUNO collaboration

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NuFact 2024

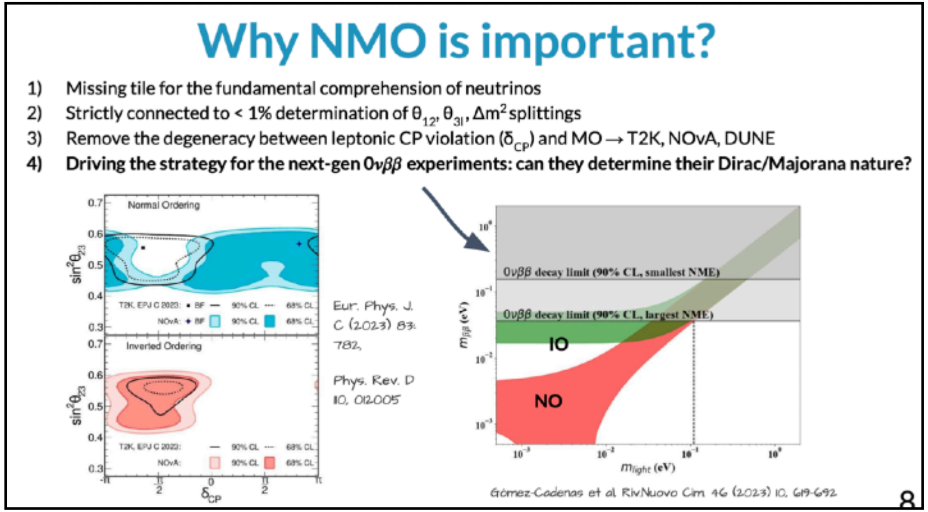
The Jiangmen Underground Neutrino Observatory

JUNO is a **20 kton** multi-purpose underground **liquid scintillator** detector.

Baseline of about **32.6 miles** from **two nuclear plants** in the Guangdong Province of South China.

Why a reactor experiment at an accelerator devoted conference?

Neutrino physics



Slide from Davide Basilico’s plenary talk

Why a reactor experiment at an accelerator devoted conference?

Neutrino physics

Slide from Iwan's parallel talk

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1. Gigantic detector → engineering challenges
2. Strict requirements on energy resolution for NMO determination
3. Strict requirements on internal radiopurity especially for solar neutrino analysis

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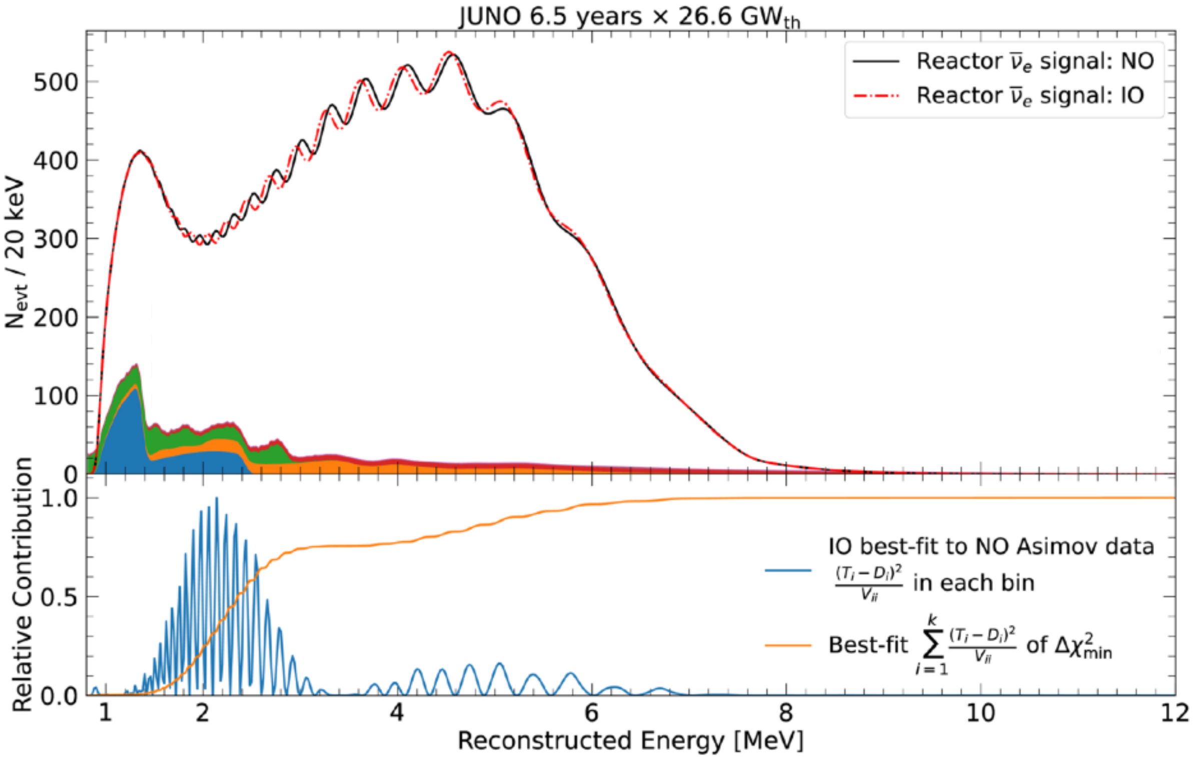
The aim of this talk is describing how we will meet the physics requirements

What do we need to measure the NMO?

From: [2405.18008] Potential to Identify the Neutrino Mass Ordering with Reactor Antineutrinos in JUNO (arxiv.org)

1) Energy resolution



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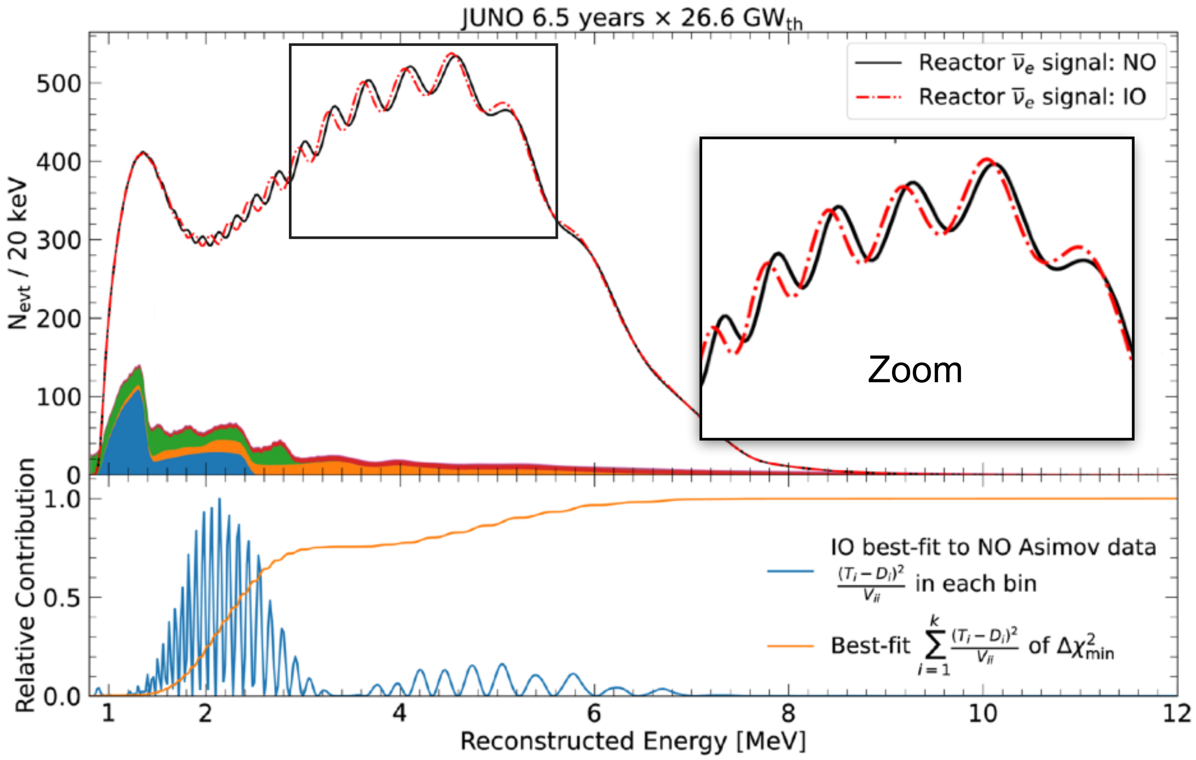

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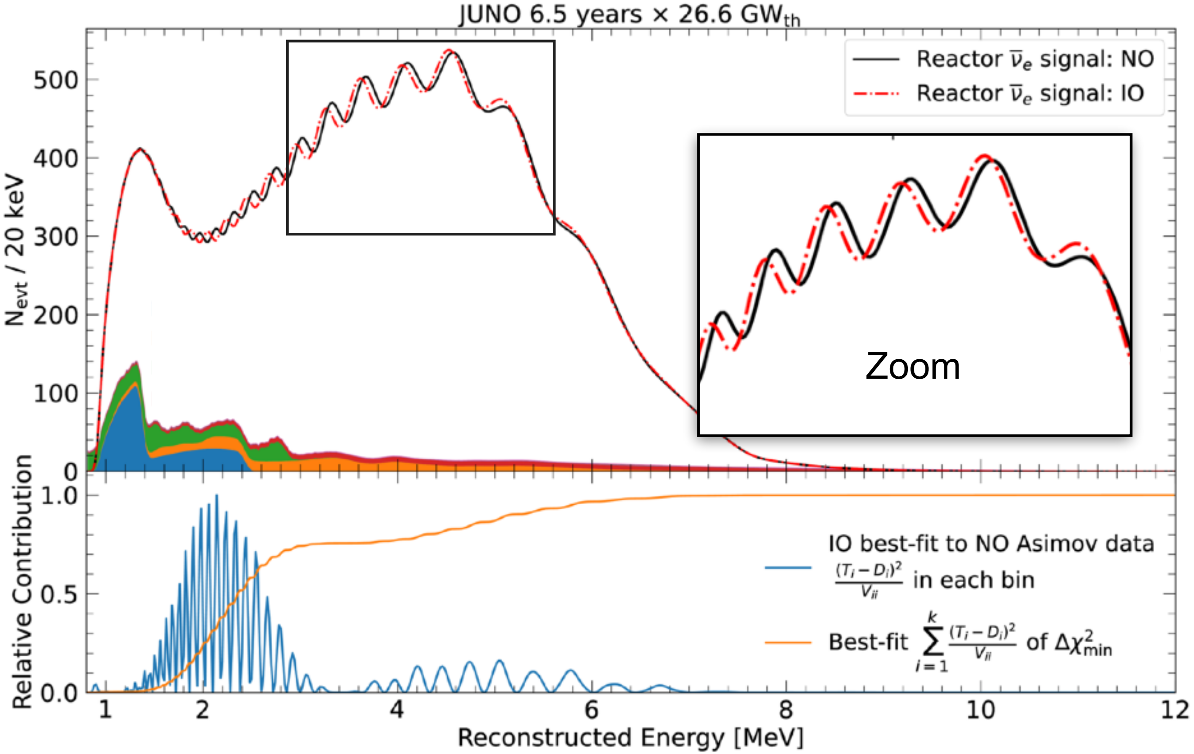

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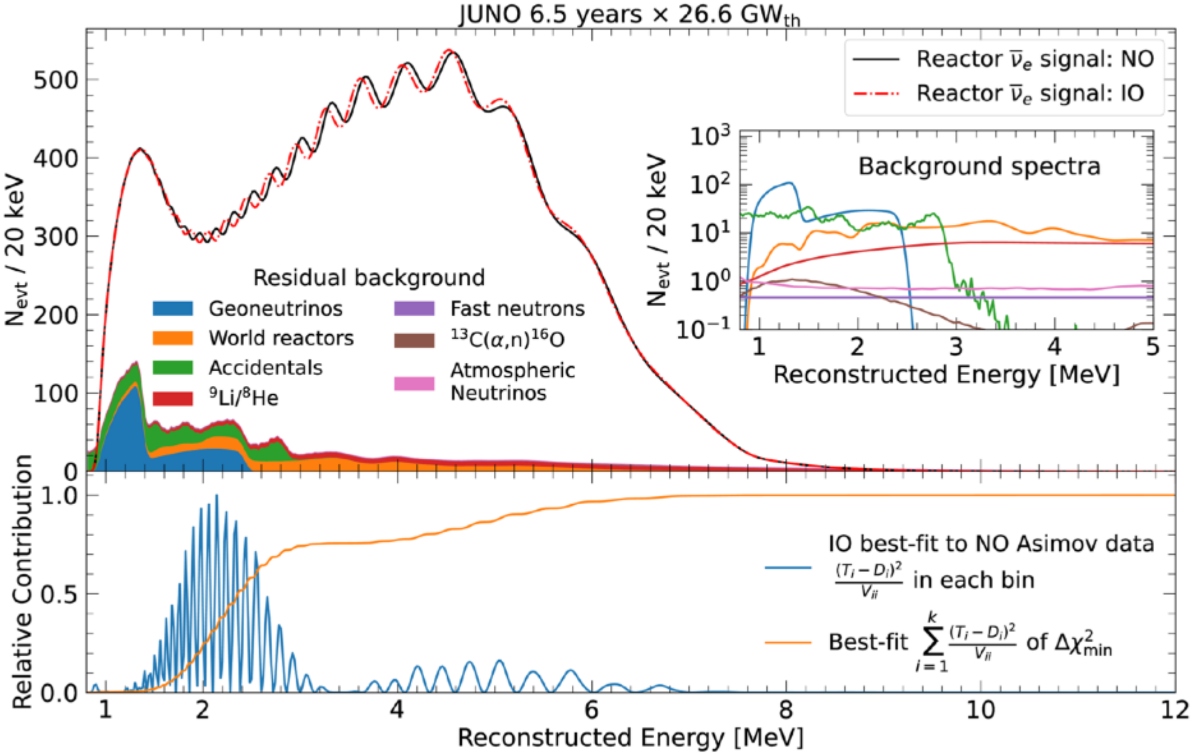

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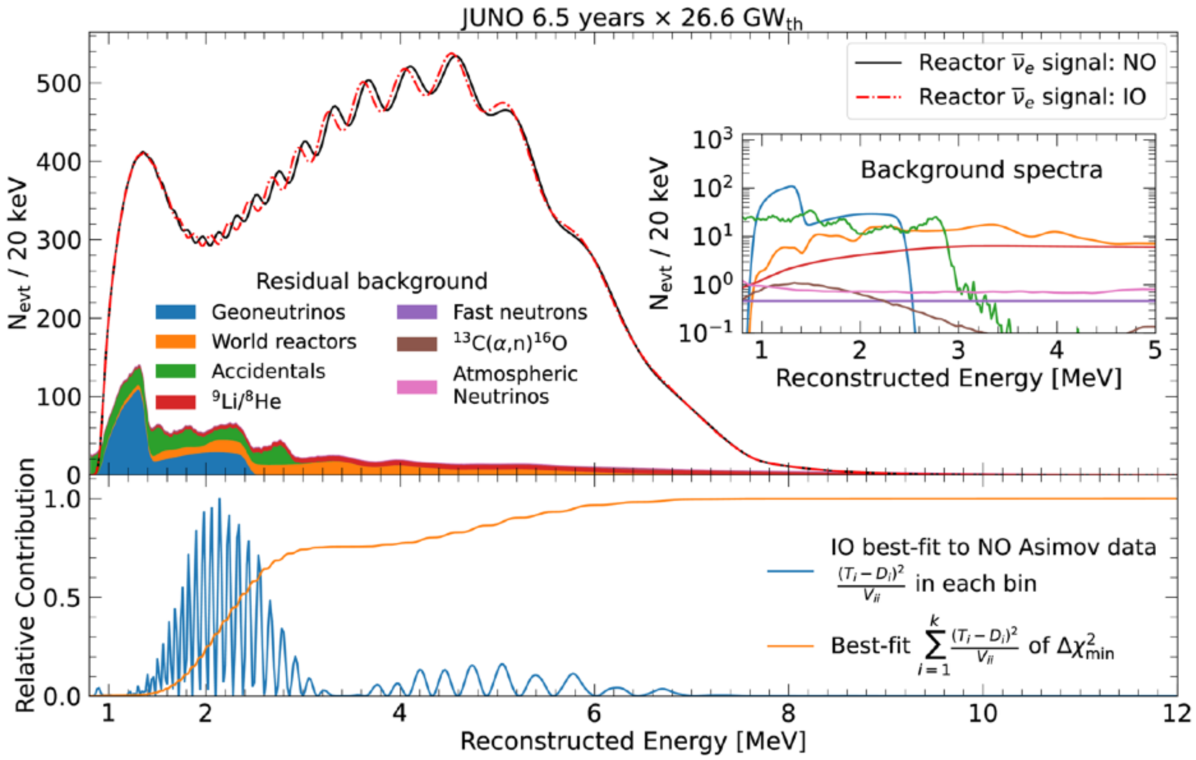
→ Low backgrounds

→ Huge mass



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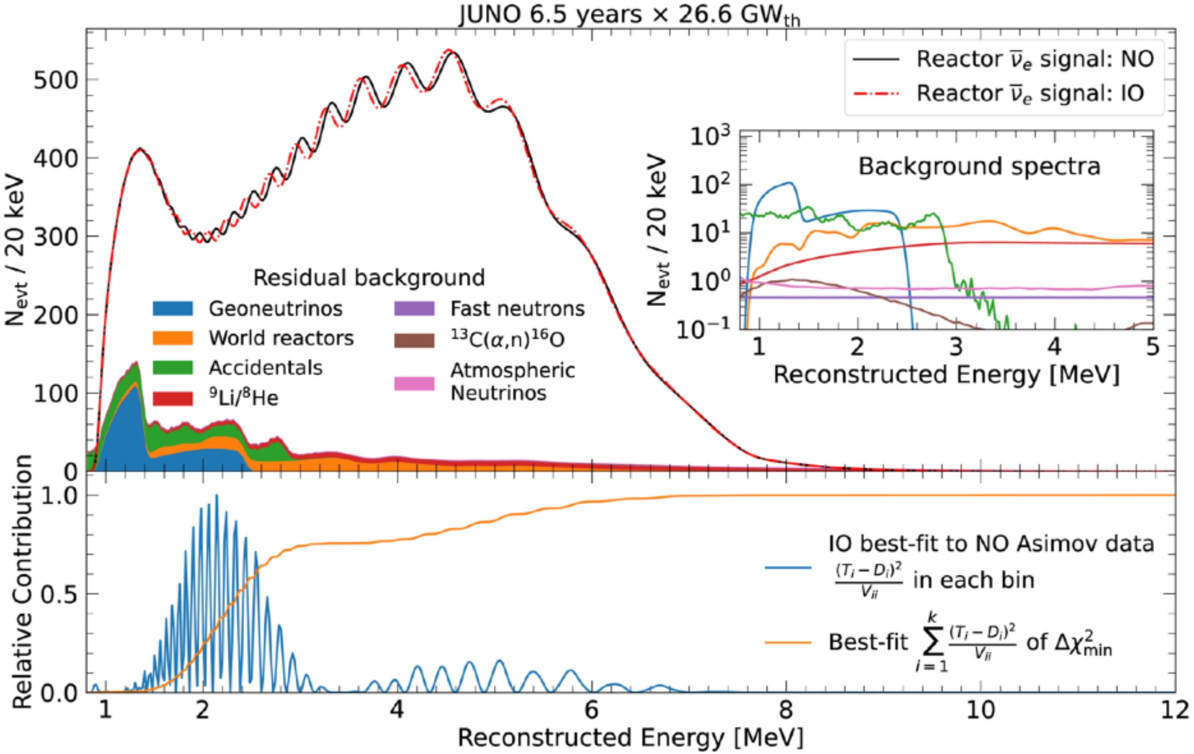

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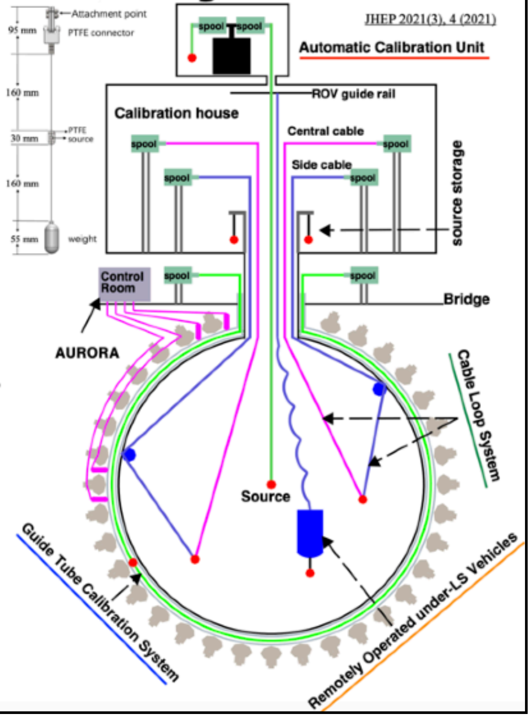
→ Multi calibration campaign

JUNO Calibration System

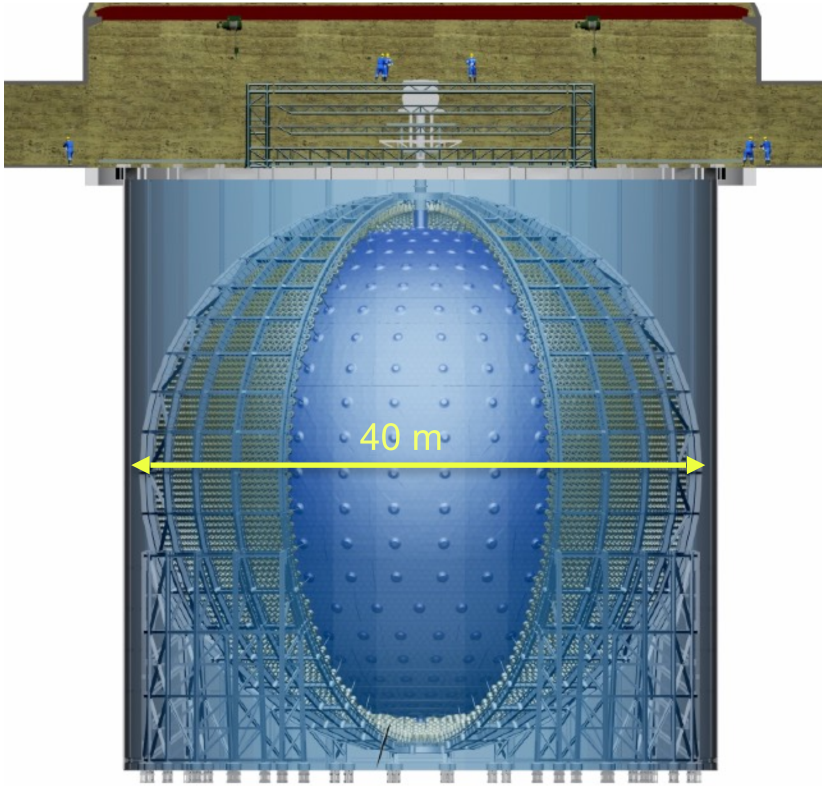
- Multiple calibration source deployment devices will be installed, placing a calibration source at different positions:
  - Automatic Calibration Unit (ACU) will cover the central axis.
  - Cable Loop System (CLS) can cover the off-axis region in a two-dimensional plane.
  - Guide Tube Calibration System (GTCS) will deploy the source on the outer surface of the acrylic sphere.
  - Remotely Operated Vehicle (ROV) can access any position inside the LS volume.



Slide from Akira's parallel talk

Huge active mass

The Central Detector of the JUNO experiment is a gigantic sphere of 40 m of diameter which support all the parts of the detector:



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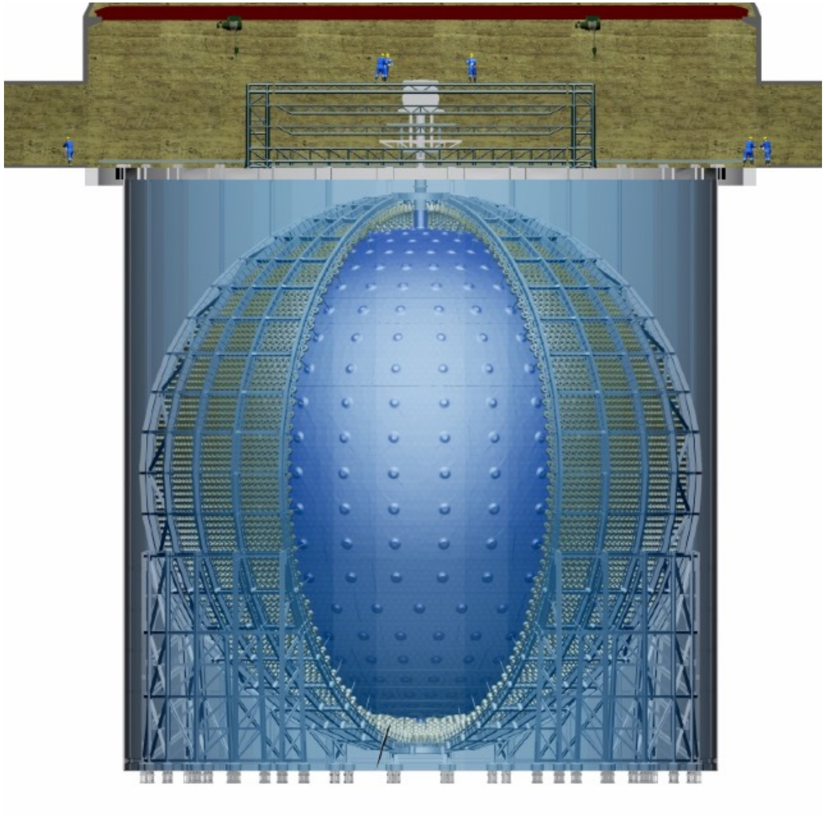
The Central Detector of the JUNO experiment is a gigantic sphere of 40 m of diameter which support all the parts of the detector:

_ More then **42000 Photo-Multiplier Tubes** with all the electronic boxes

_ An **acrylic sphere of 35.5 m of diameter** needed to contain the liquid scintillator

_ **20 000 tons** of an organic liquid scintillator:
LAB + 2.5 g/l PPO + 3 mg/l bis-MSB

All submerged in ultra-pure water



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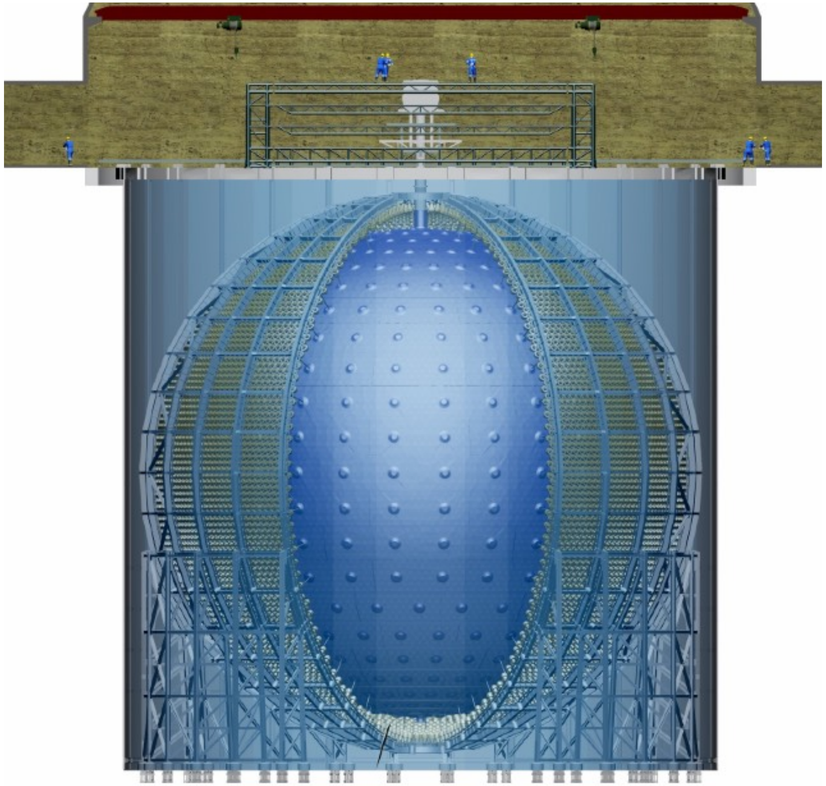


→ **Detecting ~60 IBDs per days**

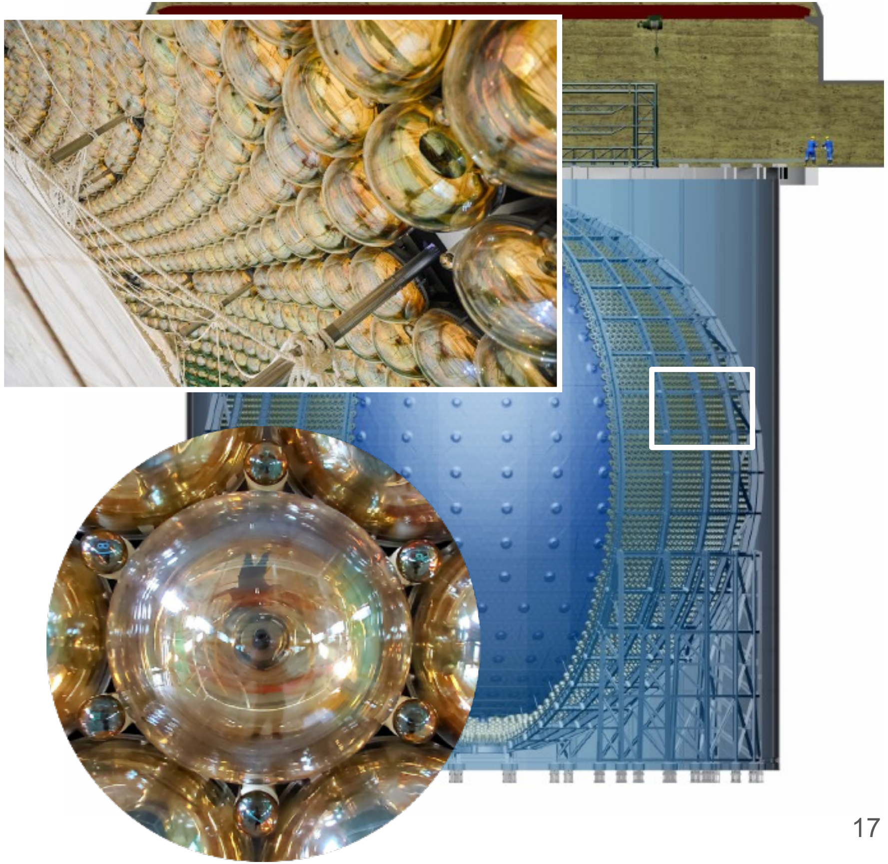
High Energy Resolution

The energy resolution is related to the total number of photon detected. For these reason several strategies were adopted to increase this number as much as possible:

1. Exceptional optical coverage: 78 %

This is possible thanks to an enormous number of PMTs (42 000) divided in two system, small and large to fill the gaps between different PMTs

20” PMTs called Large PMTs
3” PMTs called Small PMTs



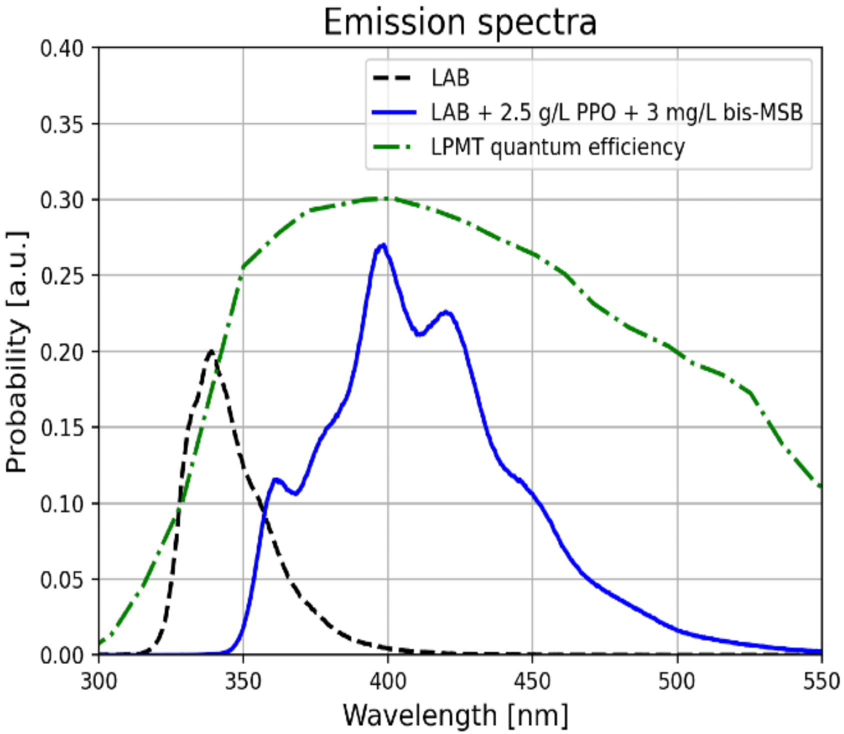
High Energy Resolution

The energy resolution is related to the total number of photon detected. For these reason several strategies were implied to increase this number as much as possible:

2. Good matching of the photon spectral emission with the PMTs detection efficiency

The JUNO liquid scintillator receipt: the addition of two elements (PPO and bis-MSB) move the emission of LAB in the optimal spectral region for Large PMTs

LAB + 2.5 g/l PPO + 3 mg/l bis-MSB



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3. High transparency in the 400-420 nm region

Given the large JUNO dimensions, the scintillator absorption length must be larger than 20 m

A plant dedicated to the optical purification of the liquid scintillator is present, the Alumina Filtration Plant (AFP)

Low backgrounds

Reducing the backgrounds inside the JUNO detector is crucial not only for the purpose of measure the NMO but also for detecting geoneutrinos or solar neutrinos

Backgrounds could be divided in external or internal

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The main source of external backgrounds are muons and the material around the acrylic vessel

To reduce muons JUNO is build in an underground laboratory with **650 m of rock above**

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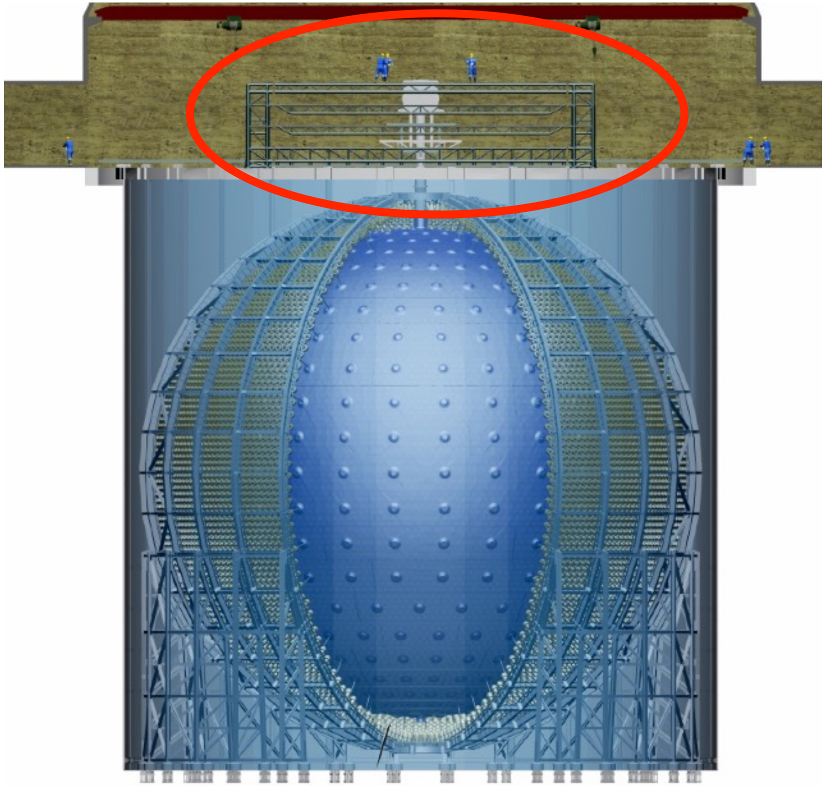
To reduce muons JUNO is build in an underground laboratory with **650 m of rock above**

A **top tracker** will be placed over the acrylic vessel to tag about 30 % of the muons

The water pool will be instrumented with more then **2400 LPMTs to tag the Cherenkov light**

→ **Reaching the identification of 99.5 % of muons**

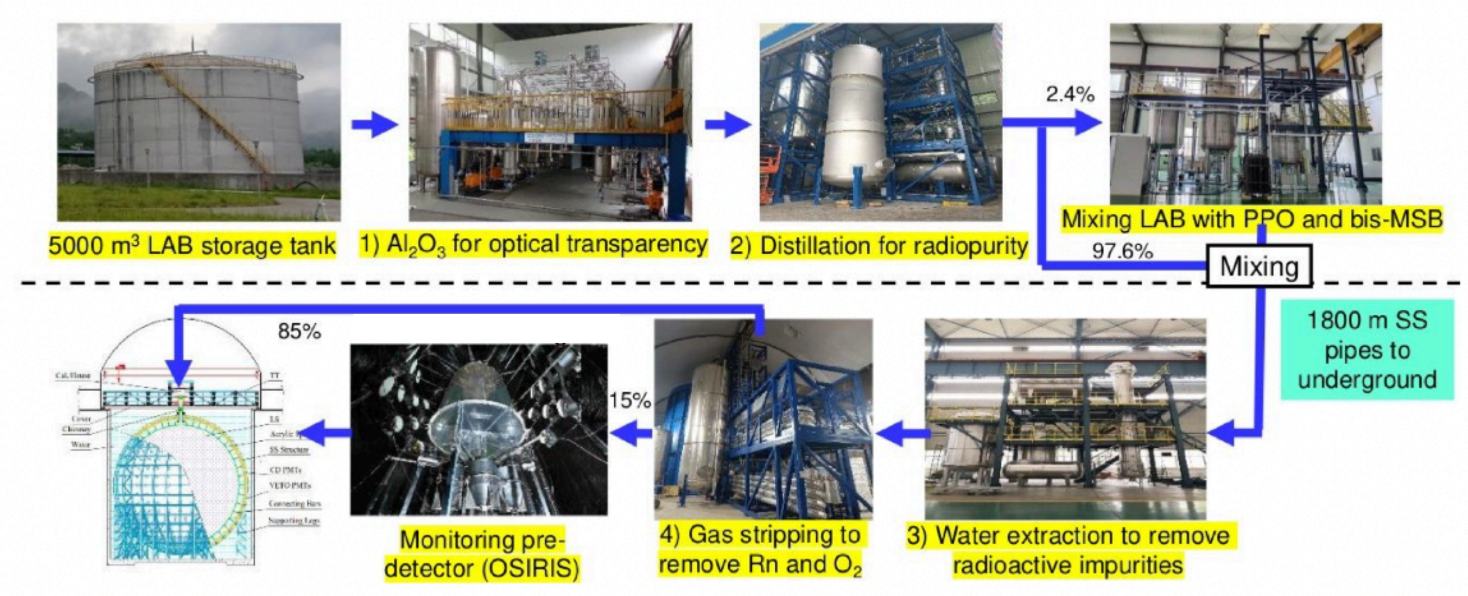


Low backgrounds: internal

To measure the **NMO** a limit of 10^{-15} g/g on the concentration of ^{238}U and ^{232}Th was set in the design phase

In addition a level of 10^{-16} - 10^{-17} g/g is aimed for the Solar neutrino campaign

→ An online purification chain is mandatory during the filling to reach those levels.



Status of the JUNO detector

From what we started …

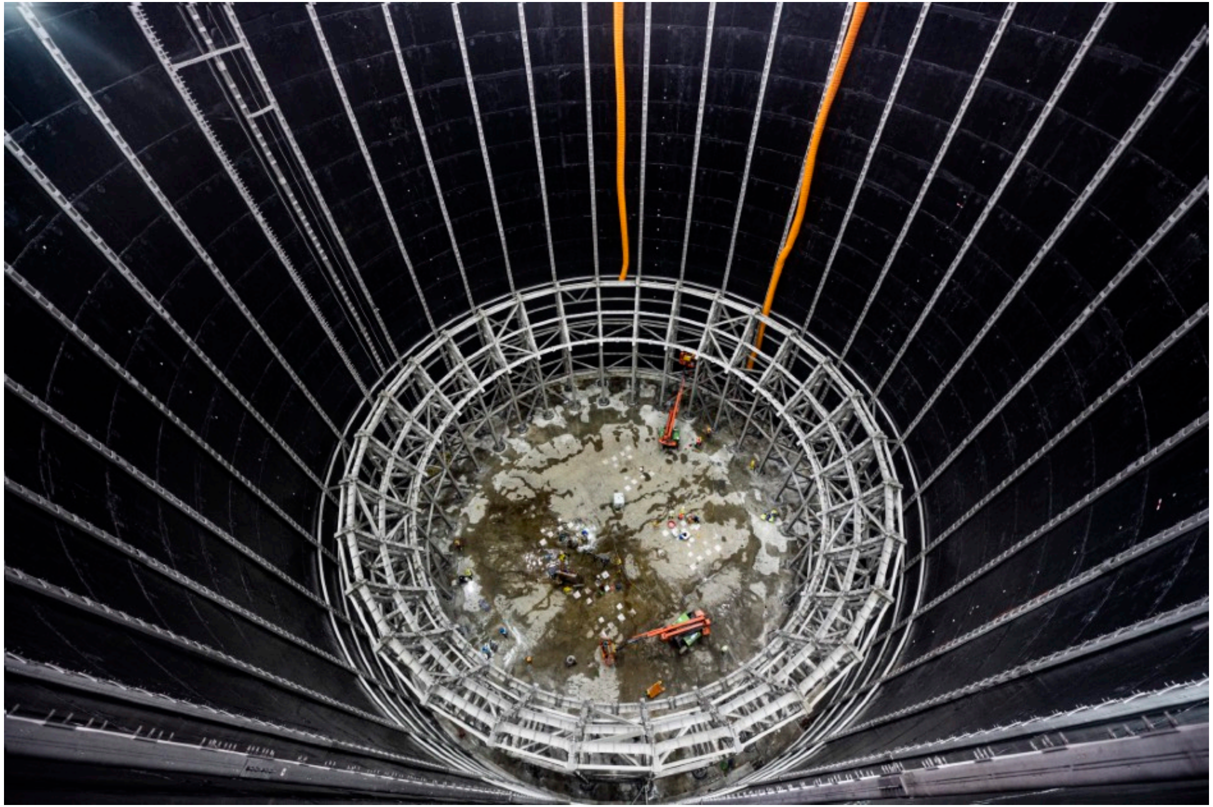
Experimental hall

… digging hole …

Experimental hall

Excavation of the pool

… we started to build the detector …



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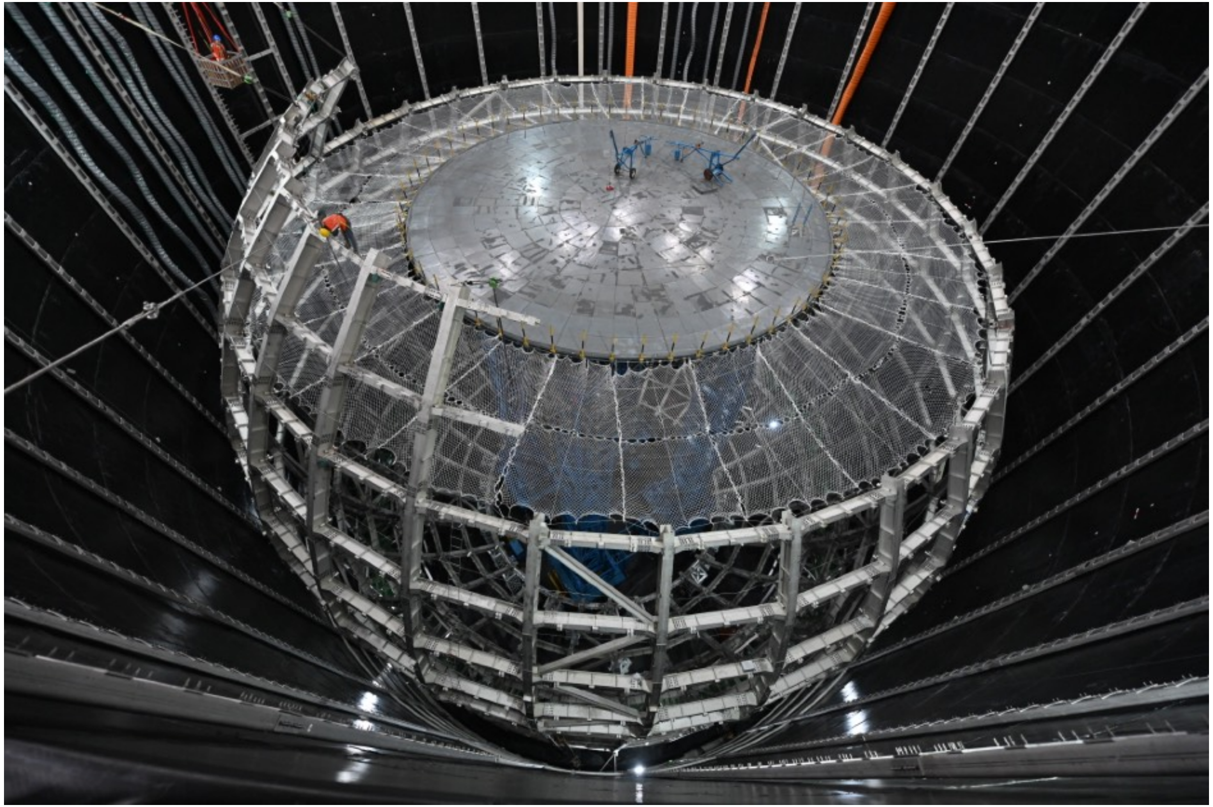

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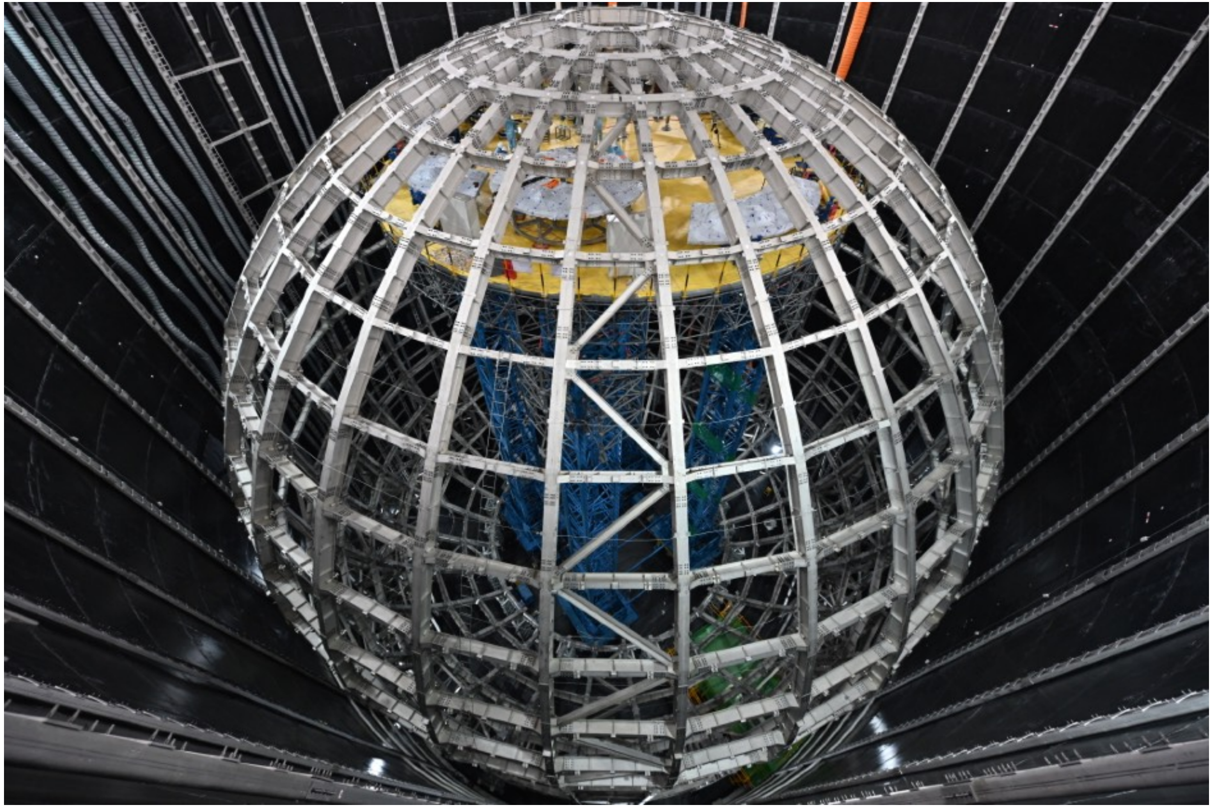

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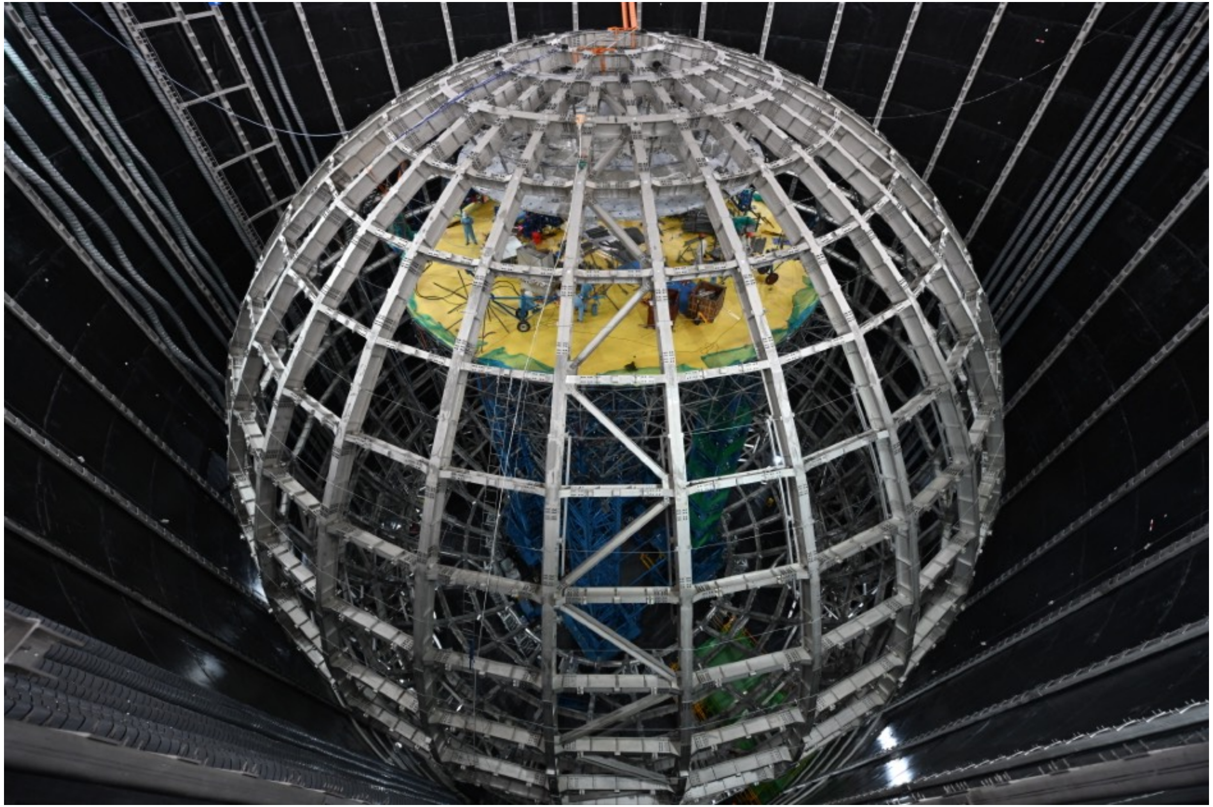

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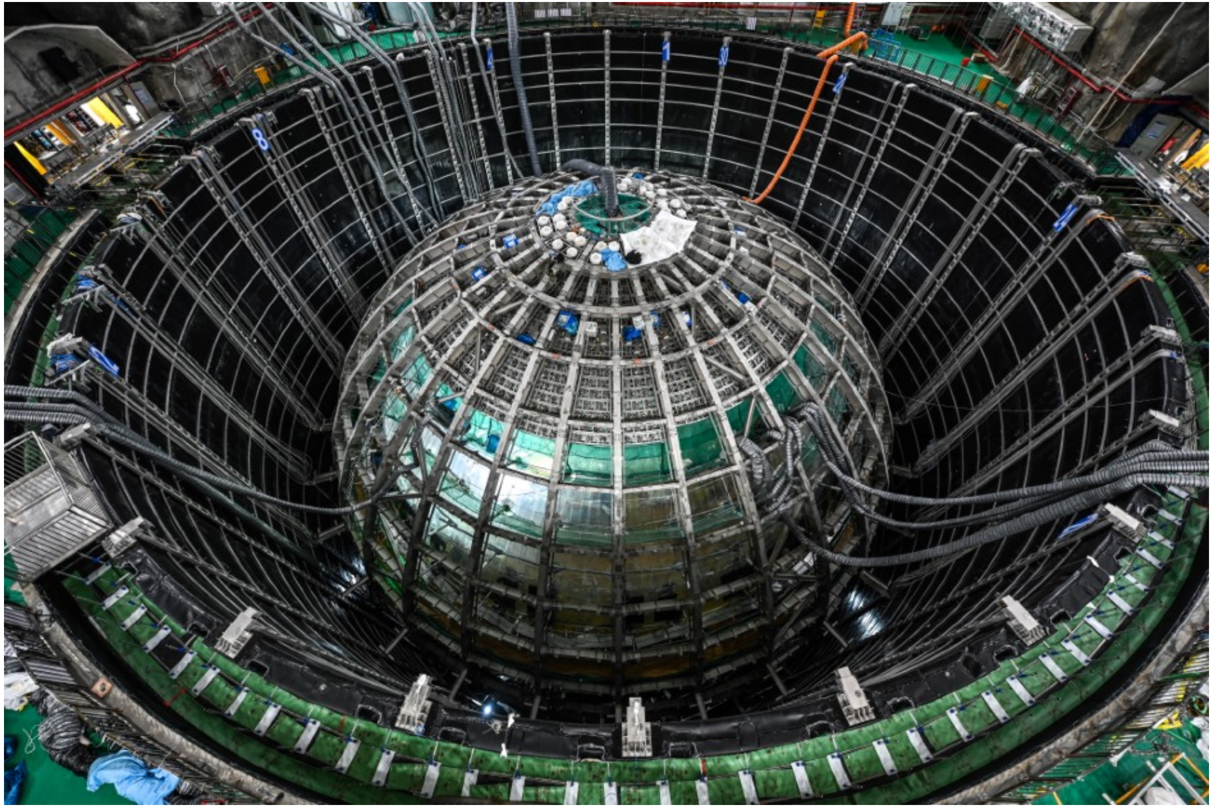

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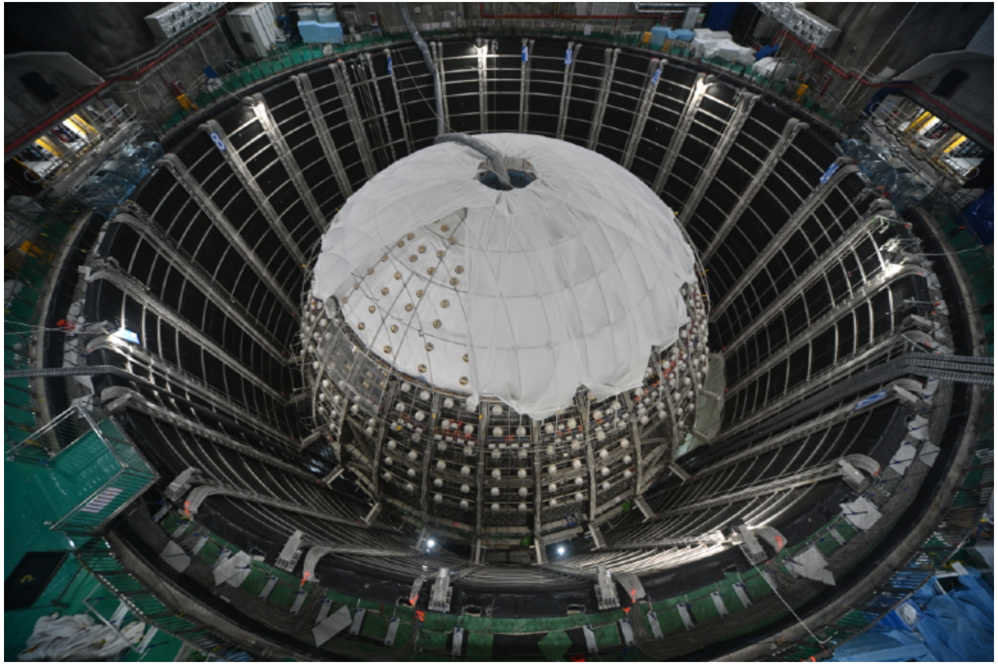
… to where we are now



Stainless **steel structure completed**
(Except 4 layers waiting for the acrylic)

17/23 acrylic layers completed:
_ production completed (<1 ppt U/Th/K contamination)
_ high transparency reached (>96%)

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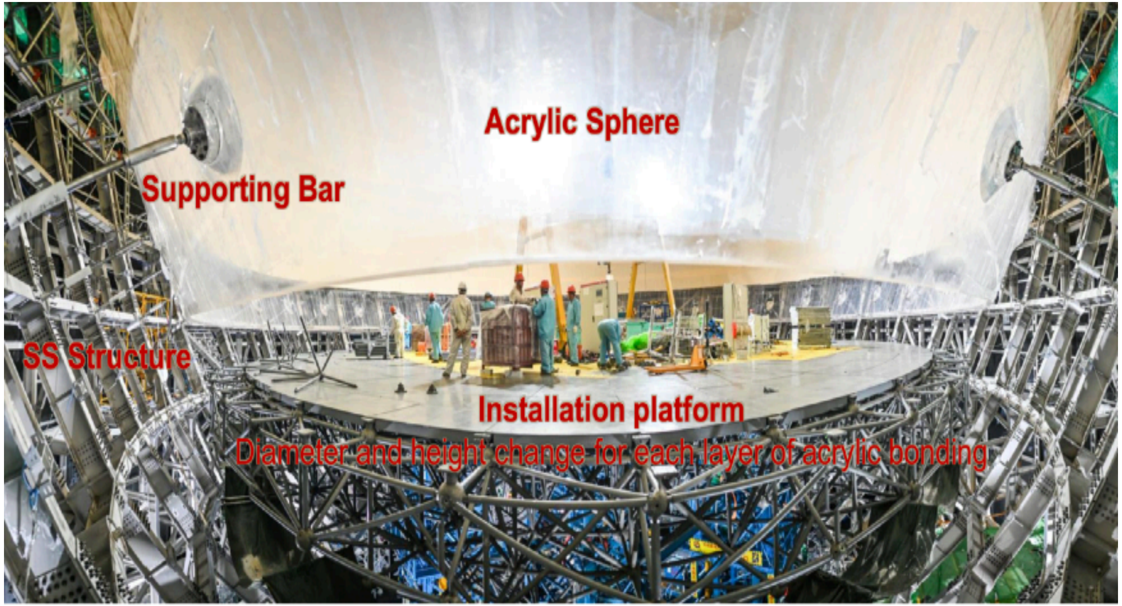

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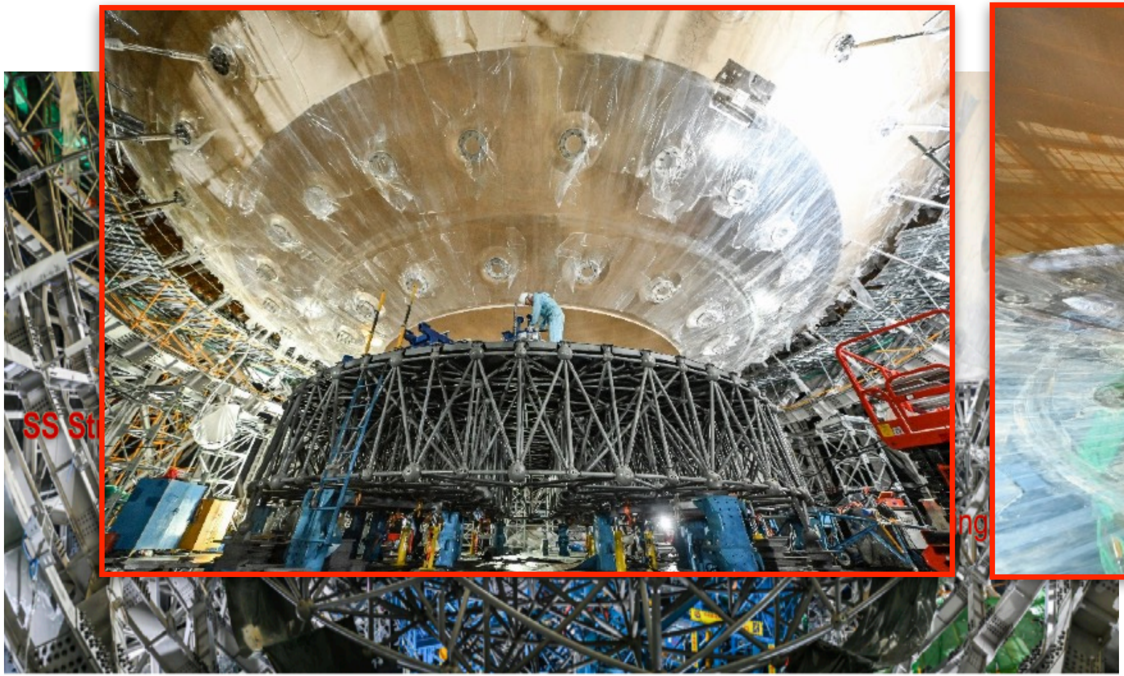

Last week update

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All **PMTs tested** and **characterized**

Dimension	Type	Number	Phot. Det. Eff.	Dark Noise	Transit time spread (1σ)
20” L-PMT	MCP-PMT (NNVT)	15,012	**30.1%**	31.2 kHz	7.0 ns
	Dynode PMT(Hamamatsu)	5,000	**28.5%**	17.0 kHz	1.3 ns
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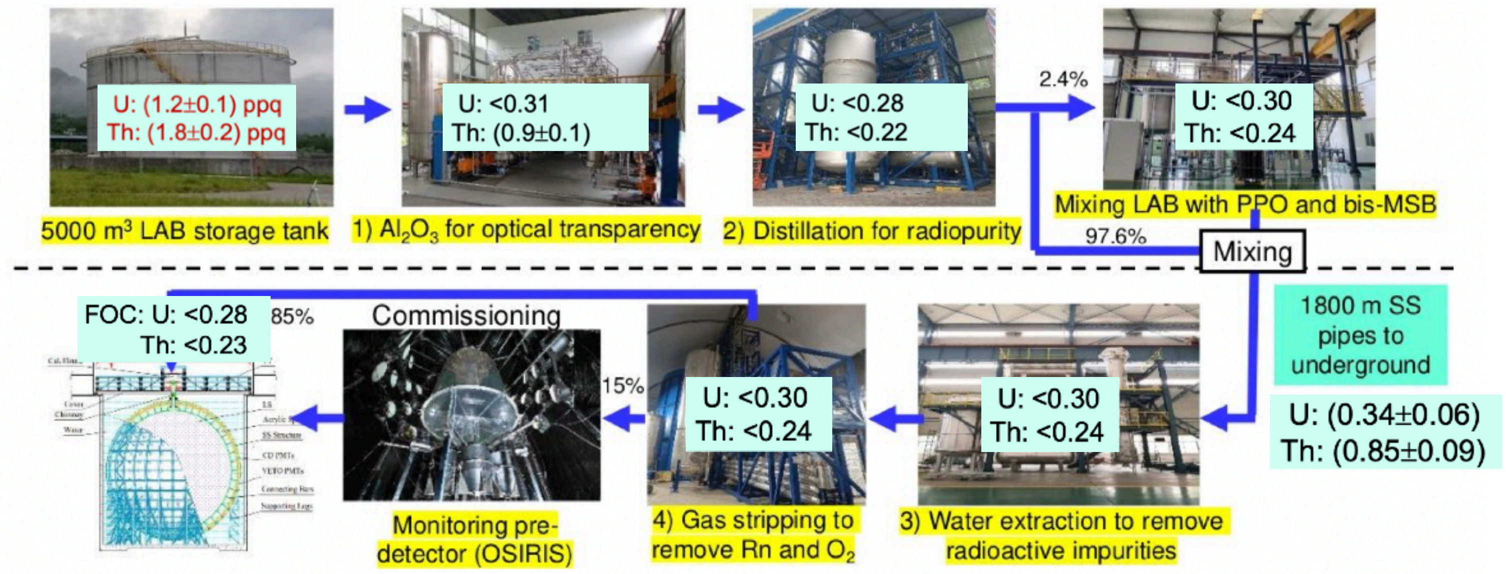
Purification of the liquid scintillator

All the plants have been fully installed and commissioned.

4 campaigns of joint commissioning have been done testing the purification efficiency and the filling speed of 7 m^3/h (six moth to fill JUNO).

Radiopurity of samples have been tested with NAA and ICMPs, with a sensibility of ~10^{-15} g/g level



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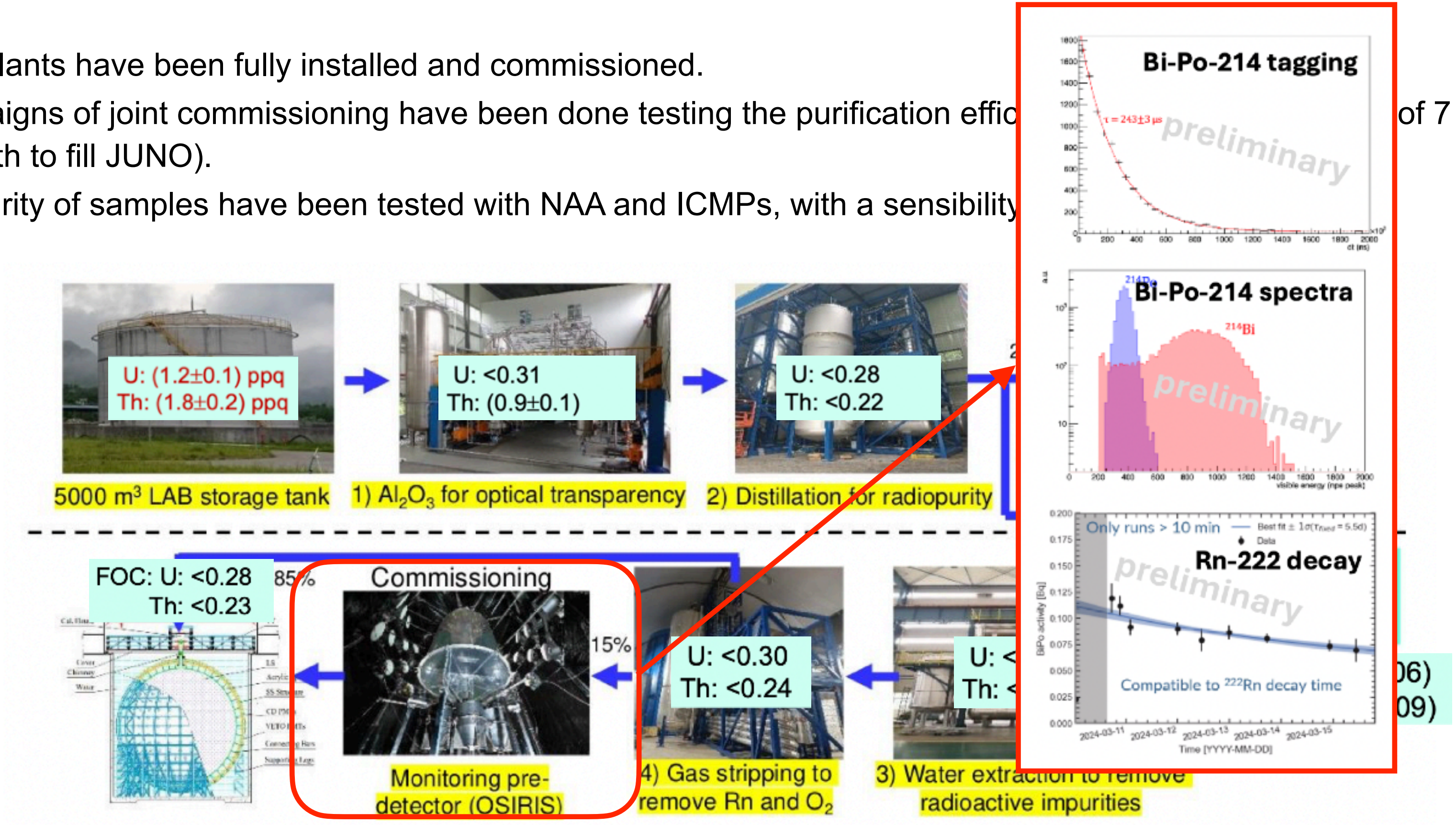


Conclusion

JUNO is a colossal work of engineering

The construction is going to be completed in Fall 2024

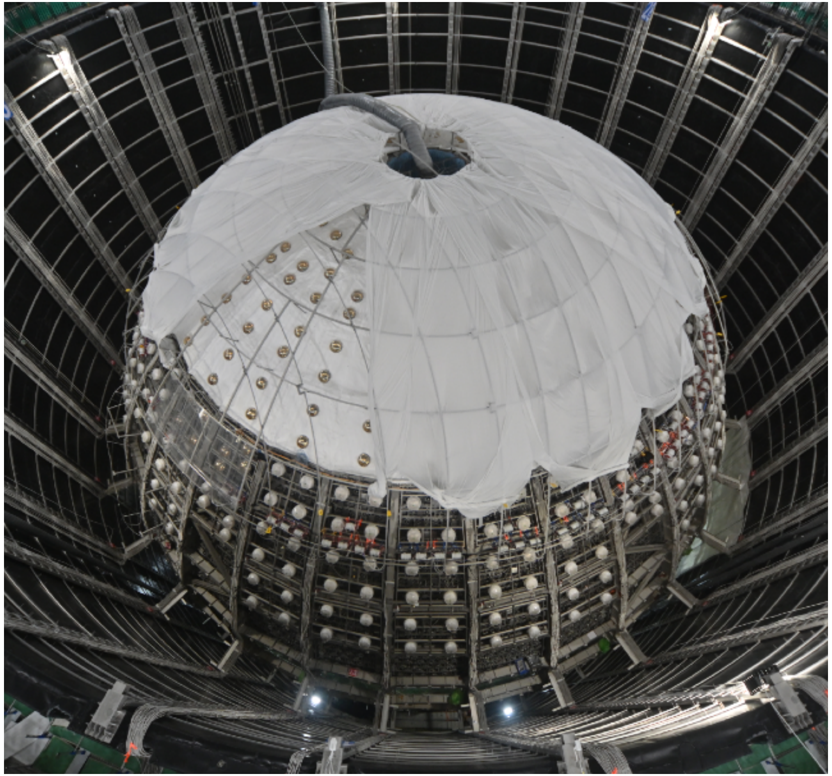
Filling with water will start before the end of 2024

Filling with liquid scintillator will start in late Winter/ start of Spring 2025

The data-taking will start in 2025

JUNO will be the biggest liquid scintillator

Stay tuned!

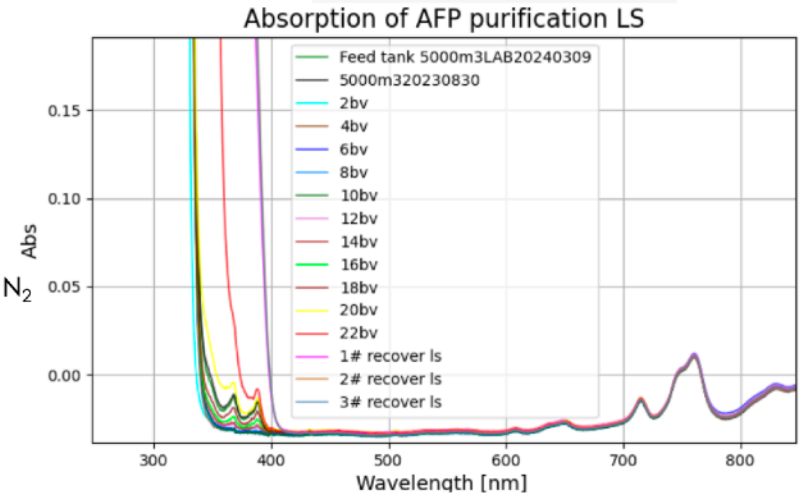


Thank you

Since 2014, >700 collaborators from 74 institutions in 17 countries/regions

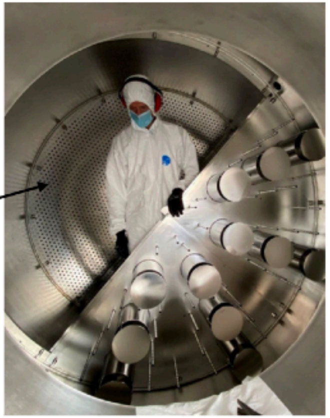
Backup: Alumina

- **Main design parameters:**
- Flow rate: 7 m^3/h (2 BV/h/column, 8 total column with one always in maintenance)
- Al_2O_3 powder first batch purchased from Hunan company (first 20 tons of 500 tons required)
  - Particle size: between 30 and 300 μm
  - Unit surface area: >150 m^2/g
  - Powder purity: = 99.5%
  - Average pore width: 5 nm ~ 6 nm
  - Active powder volume: 0.5 m^3/column
  - Low powder radioactivity: < 0.3 Bq/kg in ^{238}U and ^{232}Th
  - Transportation and storage in double aluminum bags under N_2
- Wasted alumina recycled by vendor
- LAB pumping pressure: 15 bar
- Column Diameter: 600 mm
- Column H:D ratio = 3:1
- Two stage Filters: 220 nm + 50 nm (Pall / Cobetter)
- Radon contribution from Al2O3 purification system: < 10 mBq/m^3.

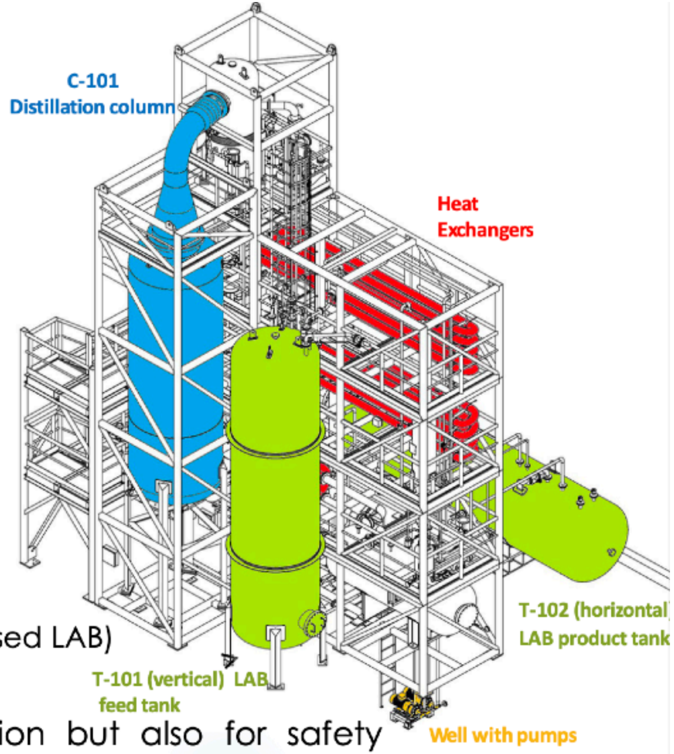


Backup: Distillation

- **Main design parameters**:
- Flow rate: 7 m^3/h
- Column height: 7 m
- Column diameter: 2 m
- Number of trays: 6 Sieve trays
- Pressure on column top: 5 mbar
- Temperature at the reboiler = 220 °C
- Internal reflux: ~30%
- Bottom discharge: 1 – 2 %
- Number of theoretical stages: 4 - 5
- Heating Thermal Power(Hot Oil): 100 kW_{th}
- Water cooling tower: 1000 kW_{th}
- Heat exchanger energy recovery: 400 kW_{th} (feed / condensed LAB)
- Filters: 50 nm (Pall / Cobetter)
- Nitrogen blanket either to avoid oxidation/contamination but also for safety reason (LAB temperature > flash point only inside the distillation column)

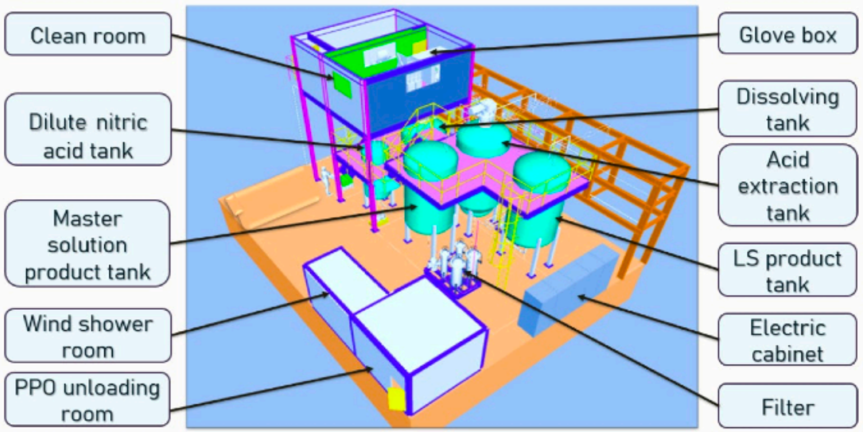


3500 holes (diameter 12 mm)



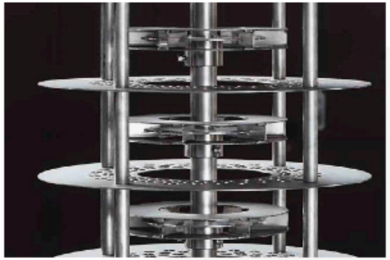
Backup: Mixing

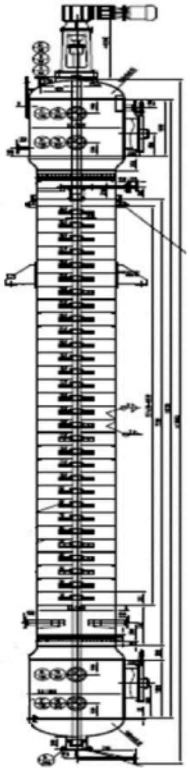
- **Main design parameters:**
  - Master Solution concentration: 105 g/L PPO 126 mg/L bis-MSB
  - Dissolving temperature: 40 °C
  - Method: batch mode with internal stirrer
  - Acid washing:
    - 1 time with 1:2 (2 m^3 acid solution)
    - 40 °C with 5% HNO_3
  - Numbers of water washing= 2 times, 1:1
  - bis-MSB transported and store in double aluminum bags under vacuum
  - PPO transported and store in drums with plastic bags under vacuum



Backup: Water extraction

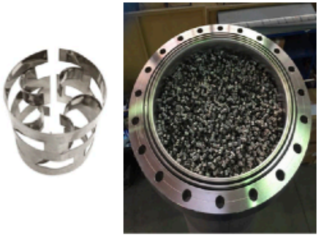
- **Main design parameters:**
  - Flow rate: 7 m^3/h
  - Column height: 13 m
  - Column diameter: 1 m
  - Column design: optimized Kühni turbine extraction tower with 30 stages of turbines connected in series on the shaft, separated into 30 chambers by 31 stages of porous trays.
  - Ultra purity Water flow rate: 2.3 m^3/h
  - LS-water ratio: 3:1
  - Extraction efficiency ≥ 5 theoretical equilibrium stages
  - Rotation speed: 40 – 60 rpm
  - LS temperature at the column = 40 °C
  - HPN blanket either to avoid oxidation and Rn pollution
  - Filters: 200 nm + 50 nm (Pall / Cobetter)

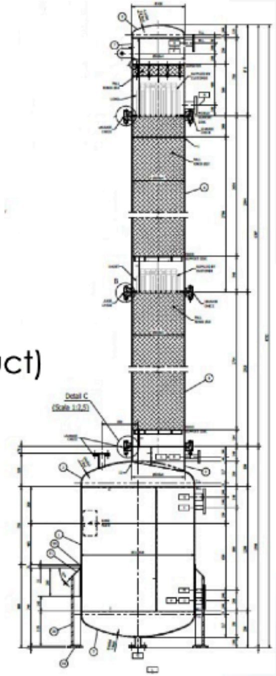


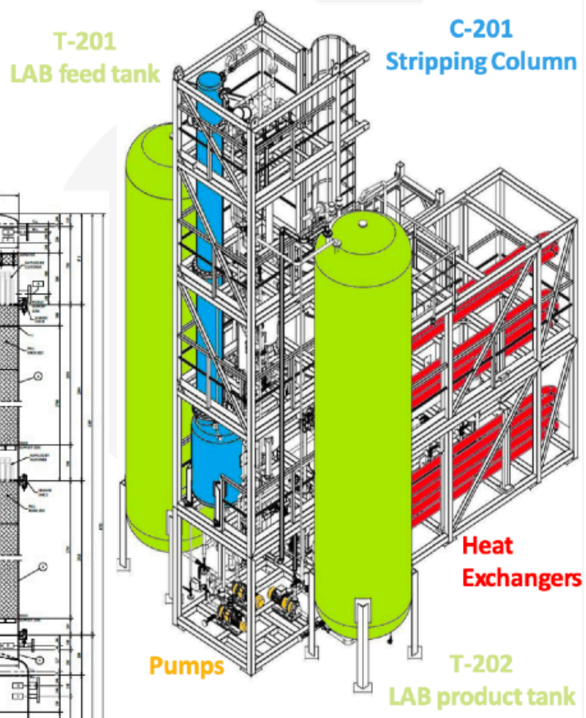


Backup: Stripping

- **Main design parameters:**
  - Flow rate: 7 m^3/h
  - Column active height: 5.6 m
  - Column diameter: 500 mm
  - Unstructured packing: 13 mm stainless steel Pall rings
  - Specific Interface Area: 430 m^2/m^3
  - Number of theoretical stages: 3 - 4
  - Pressure on column: 250 mbar
  - LS Temperature at the column = 70 °C
  - Heat exchanger energy recovery: 160 kW_{th} (feed / product)
  - Heating Thermal Power (Hot Oil): 100 kW_{th}
  - Chiller for cooling water: 200 kW_{th}
  - Filters: 50 nm (Pall / Cobetter)
  - HPN blanket either to avoid oxidation and Rn pollution

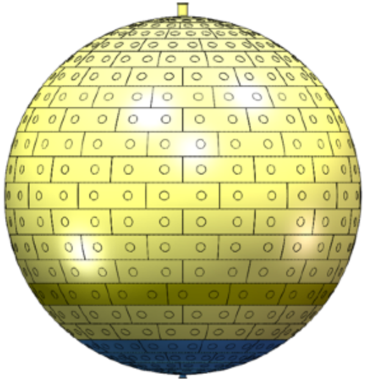


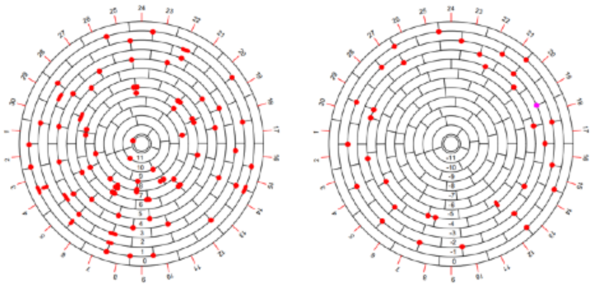




Backup: Acrylic

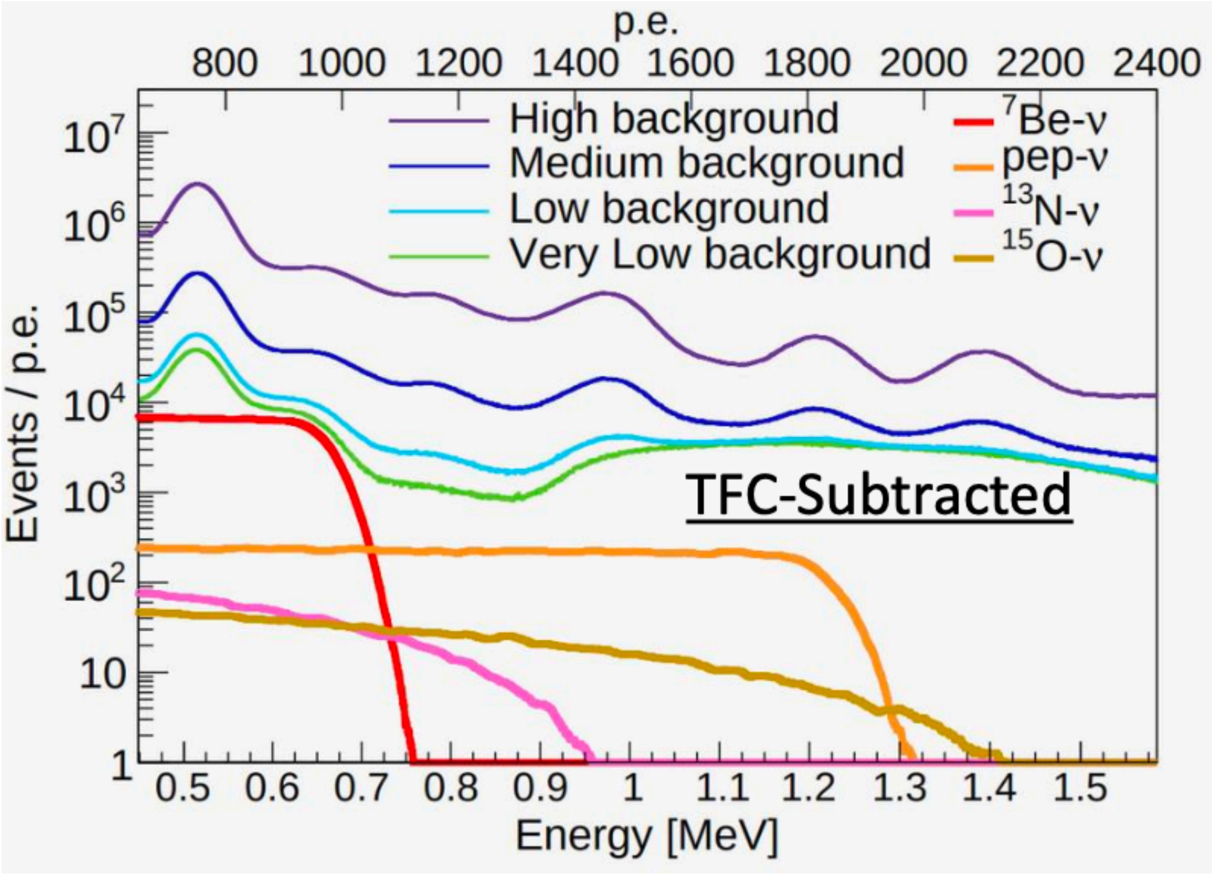
- **Production:**
  - Complete production of all panels in the factory: 263 panels + 2 chimneys;
  - 256/263 panels transported onsite: layer -9# panels are ready onsite
- **Construction:**
  - Completed the construction of layer -5# acrylic ring.
  - Layer -6# is under bonding
  - **Repairing works**: ~74 defects at the upper hemisphere, ~37 defects at the lower hemisphere. Now, only 1 defect is under repaired at the layer -5#
  - The top layers of bonding have been thoroughly inspected, and regular inspections are planned.





Distribution of defects

Backup: Solar neutrino backgrounds



Backup: Energy resolution

arXiv:2405.17860