

# **Jiangmen **U**nderground **N**eutrino **O**bservatory**

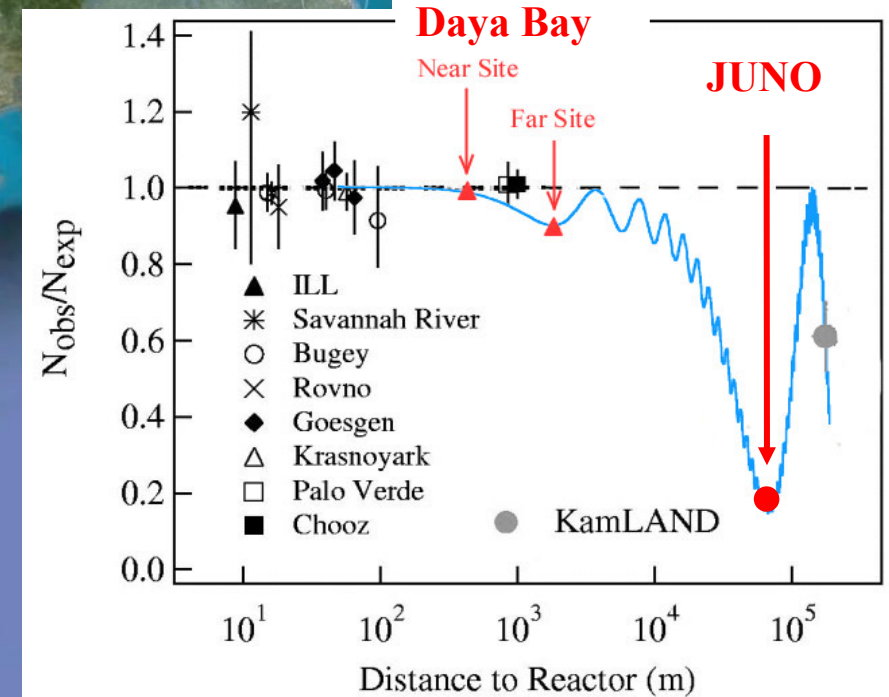
## **Status and Prospects**

**Xiaonan Li**  
**IHEP, CAS, Beijing**  
**On behalf of JUNO Collaboration**

- **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 GW | 17.4 GW | 17.4 GW     | 9.2 GW      |



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



# JUNO Project and Collaboration

- Project initially approved in China in 2013 and later in other countries. Construction started in January 2015
- Collaboration established in 2014, now >700 collaborators from 74 institutions in 16 countries/regions



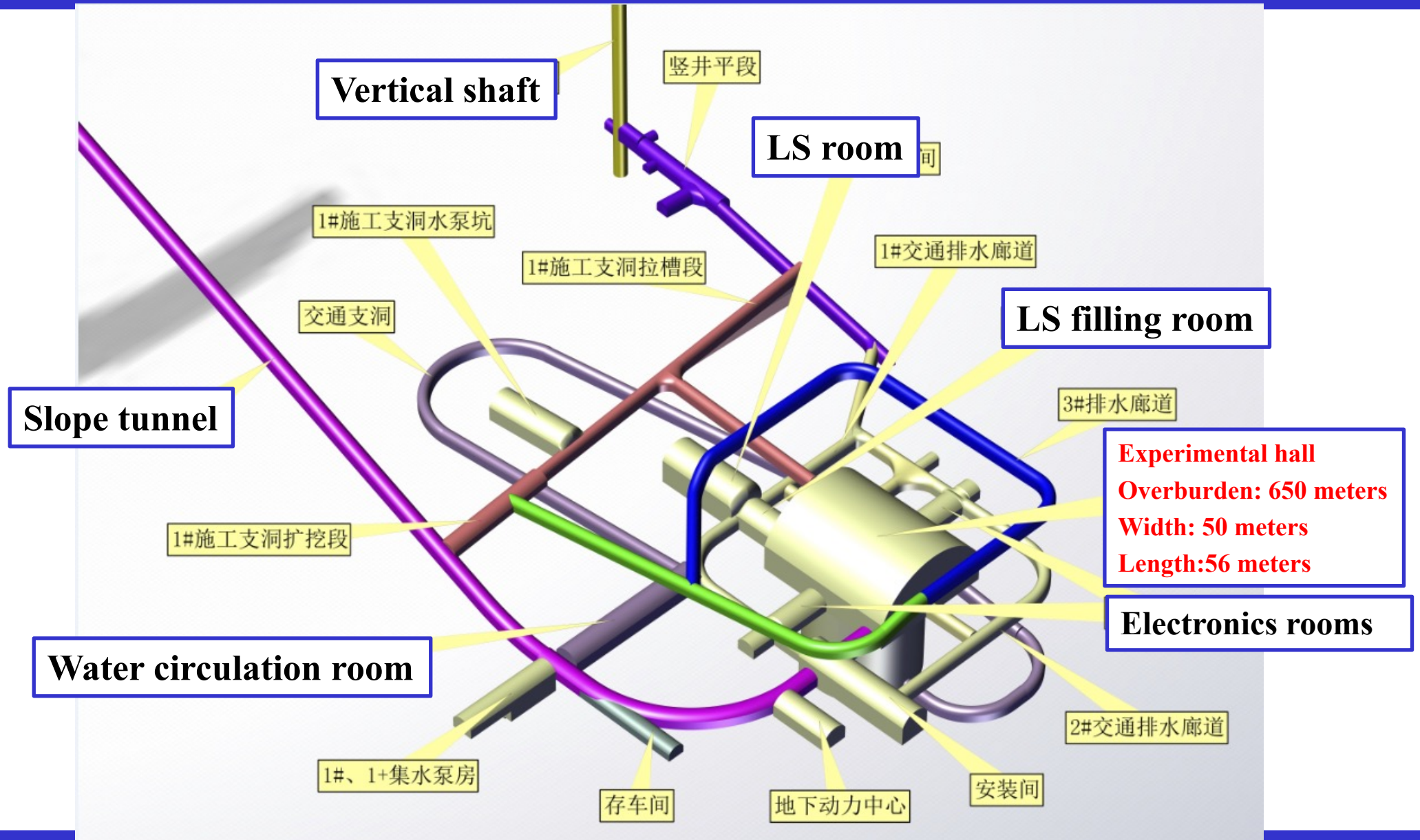


# Facility and Detector











# Bird-eye view of Facility

- Surface assembly building
- LAB storage (5kt)
- LS purification and mixing
- Water purification system
- Chilling water system
- Computing and power station
- Office, dorm and canteen





- ◆ Rock temperature ~ 31 °C, Experimental hall controlled to ~21°C
- ◆ VAC provides fresh air of 40 kM<sup>3</sup>/hour for underground cavern.

- ◆ Cleanliness control

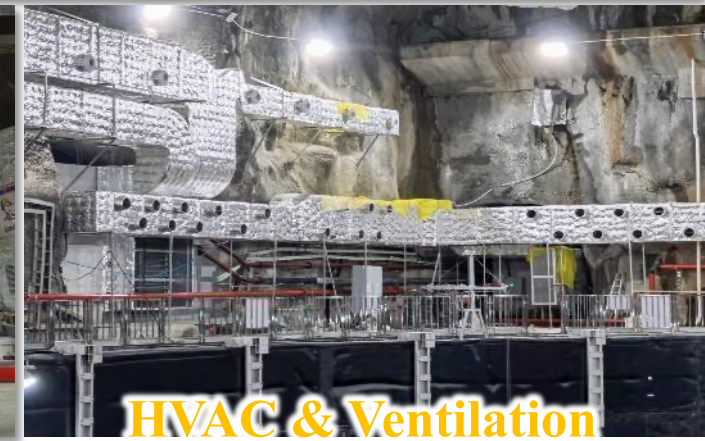
**Experimental hall**



**Assembly hall**



**LS hall**



**HVAC & Ventilation**



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



- Target mass of 20 kt liquid scintillator → × 20 KamLAND, × 40 Borexino
- Energy resolution < 3%@ 1MeV → Greater than 1200 PE/MeV

|                         | 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      |

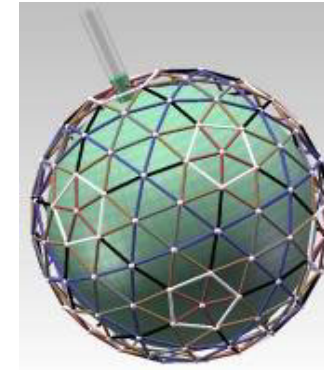
- Lifetime: >30 years

- **Technology R&D since 2009:**

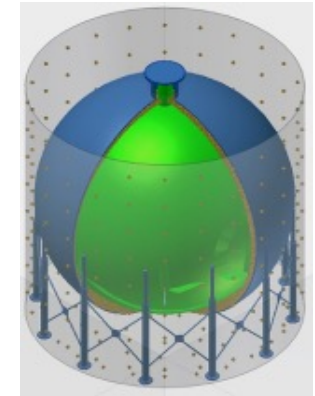
- Transparent & high light yield liquid scintillator
- High detection efficiency 20" PMTs
- Radiopurity U/Th/K <  $10^{-17}$  g/g for 20 kt LS

- **Detector Design:**

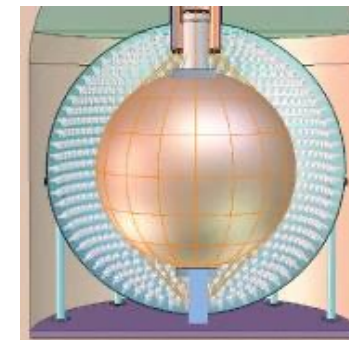
- Central target container: acrylic or balloon ?
- Mechanical structure: steel frame or steel tank ?
- Buffer layer: Water or Mineral oil ?



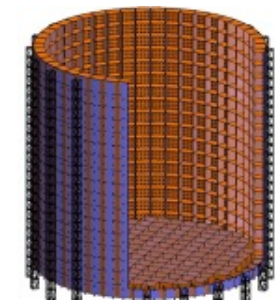
Steel frame+ Acrylic tank



Steel tank+ Acrylic tank



Steel Tank + Balloon



Steel Tank + Acrylic blocks



# JUNO Detector Key Parameters

## Calibration

## Central detector

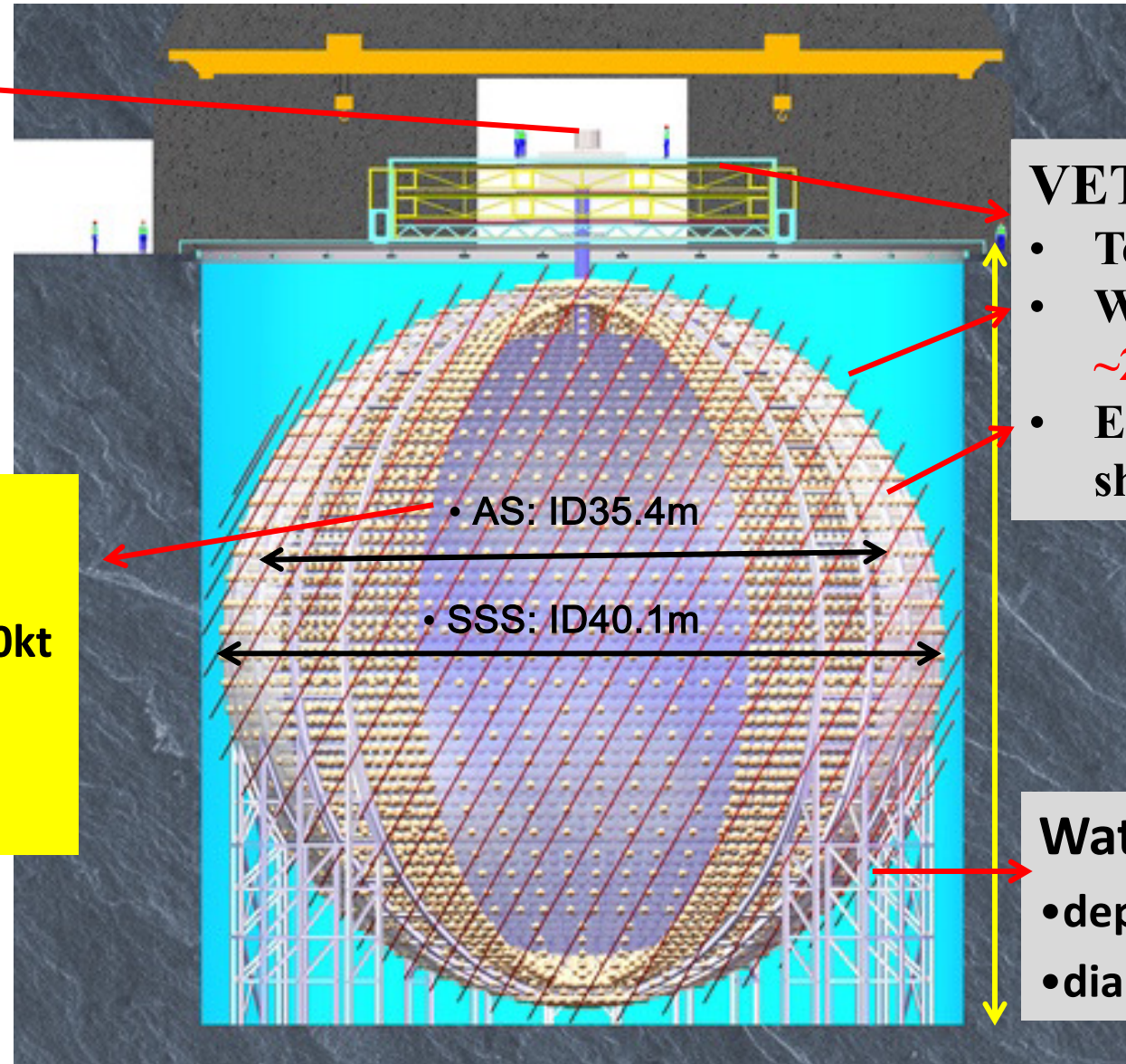
- Steel structure (SSS)
- Acrylic sphere (AS) +20kt Liquid scintillator
- ~17612 20" PMT
- ~25600 3" PMT

## VETO system

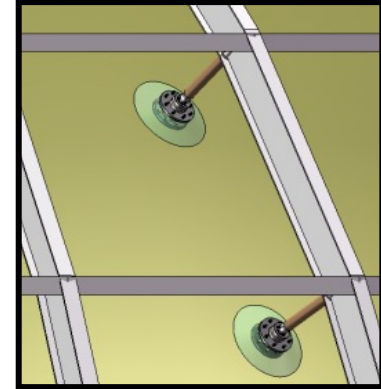
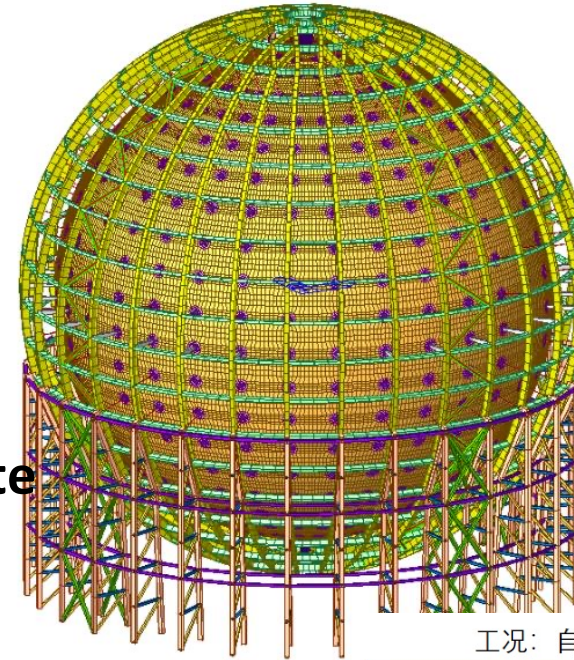
- Top Tracker
- Water VETO with ~2400 20" PMT
- Earth Magnetic Field shielding coils

## Water Pool

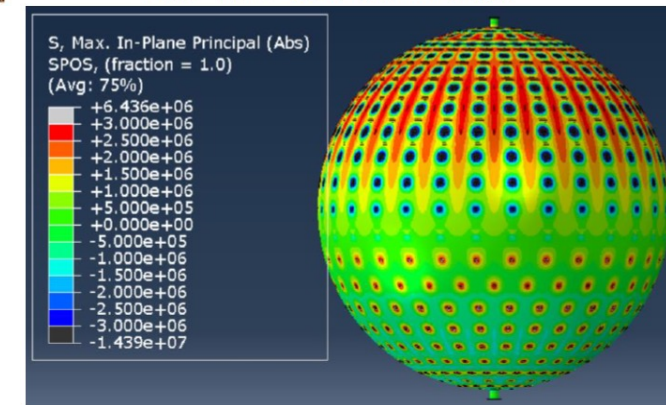
- depth: 44m
- diameter: 43.5m



- 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:  $\sim 8\text{m} \times 3\text{m} \times 12\text{ cm}$
  - 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  $\sim 3\text{ mm}$
  - No welding, clearance between screw and hole  $< 1\text{mm}$
  - Thermal expansion controlled at  $21^\circ\text{C} \pm 1^\circ\text{C}$
  - Earthquake 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  $< 3.5\text{ MPa}$



工况：自重+水压（内4.5m高度）



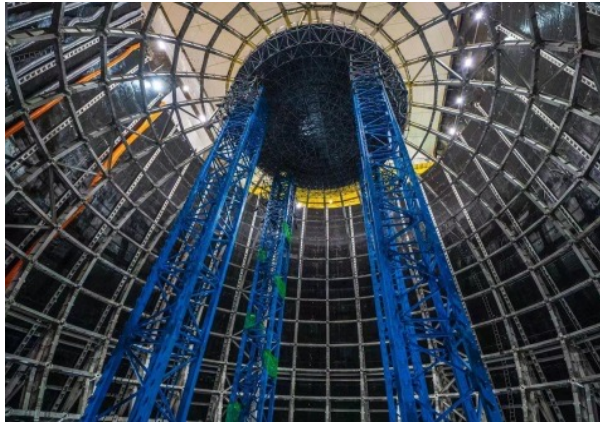
外表面应力情况

arXiv: 2311.17314



# CD: Production and Construction Completed

- **SS structure**
  - ~900 tons
  - Radioactive bkg control:  $^{238}\text{U}$ : 1 ppb=12.4 mBq/kg;  $^{232}\text{Th}$ : 3 ppb=12.21 mBq/kg;  $^{40}\text{K}$ : 0.2 ppb=53 mBq/kg
- **Acrylic panel production**
  - A special production line for low backgrounds ( $< 1$  ppt U/Th/K)
  - Shaping, sanding/polishing, cleaning, machining and protection of panels by  $50\mu\text{m}$  PE, while maintaining high transparency ( $>96\%$ ) and low surface background ( $< 5$  ppt U/Th)
- **Acrylic sphere construction**
  - Lifting platform: frequently change the diameter and height
  - Acrylic sphere built from the top, defects repaired
  - SS bars connecting the acrylic and SS, sensors for stress monitoring



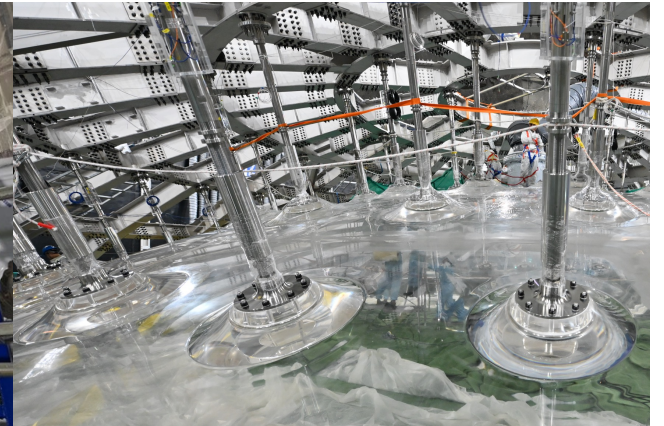
Hydraulic Lifting platform



Annealing



Sanding and polishing



Bars between SS and acrylic

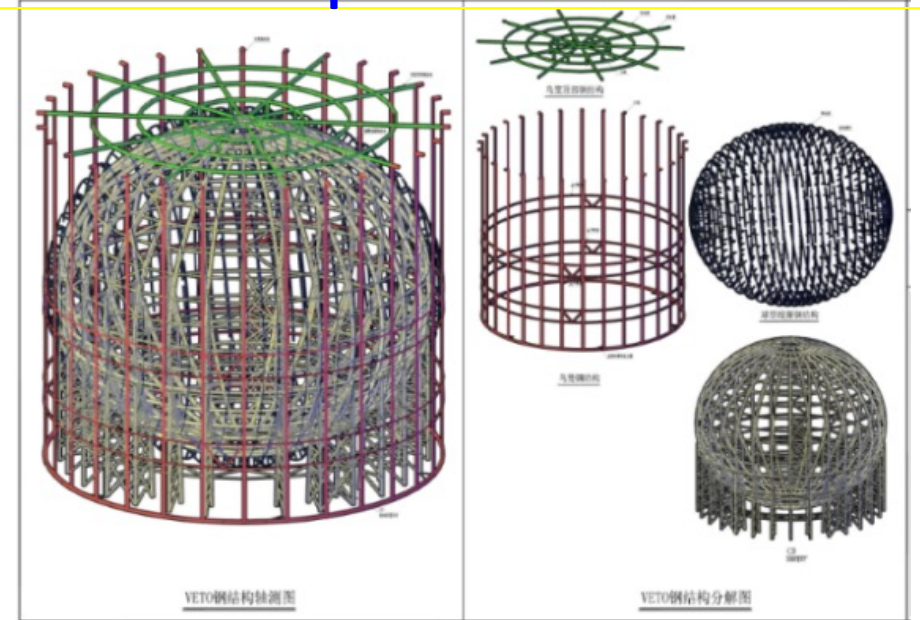
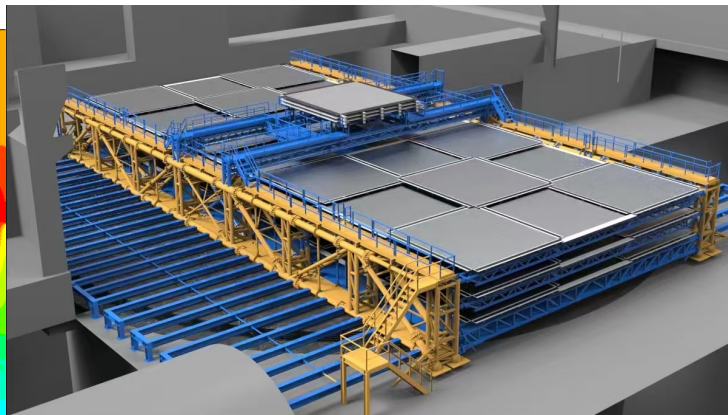
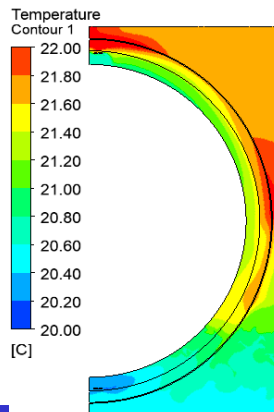
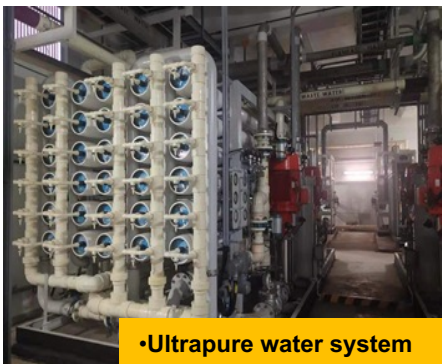


# VETO: Water Pool and Top Tracker



- ◆ **Design:**
  - ⇒ 650m overburden →  $R_\mu = 0.004 \text{ Hz/m}^2$ ,  $\langle E_\mu \rangle = 207 \text{ GeV}$
  - ⇒ 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  $U/Th/K < 10^{-14} \text{ g/g}$  and  $Rn < 10 \text{ mBq/m}^3$ , attenuation length  $> 40\text{m}$ , temperature controlled to  $(21 \pm 1)^\circ\text{C}$

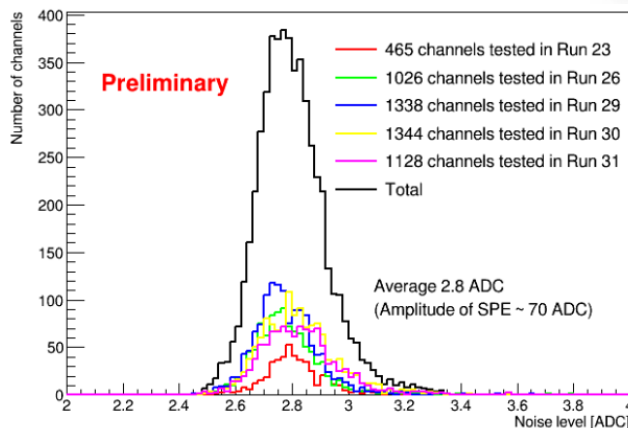
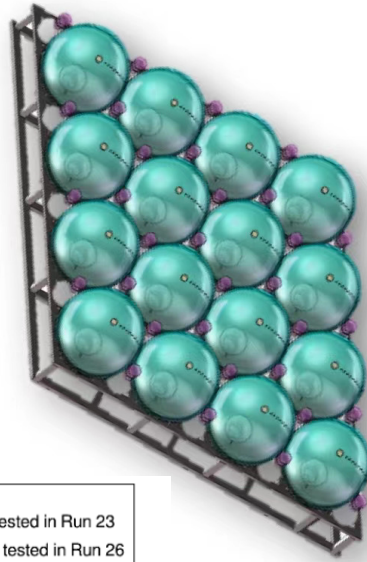




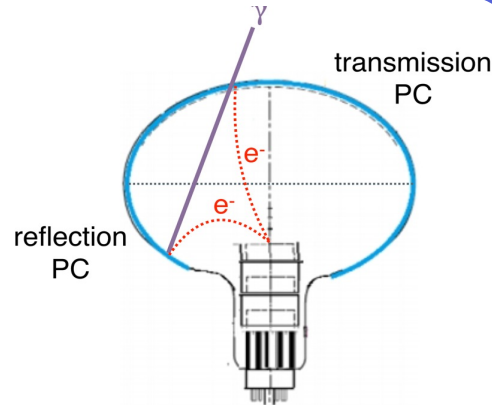
- **20-inch PMTs are the main light-detection device in JUNO**

- MCP-PMT(NNVT): 15000
- Dynode PMT(Hamamatsu): 5000

clearance of 3 mm  
Coverage: 75%

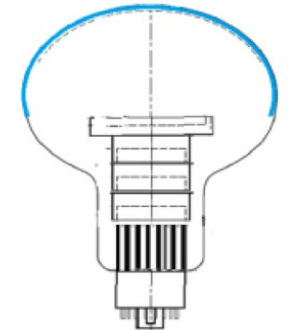


Noise level is ~ 0.05 PE  
Good grounding and shielding

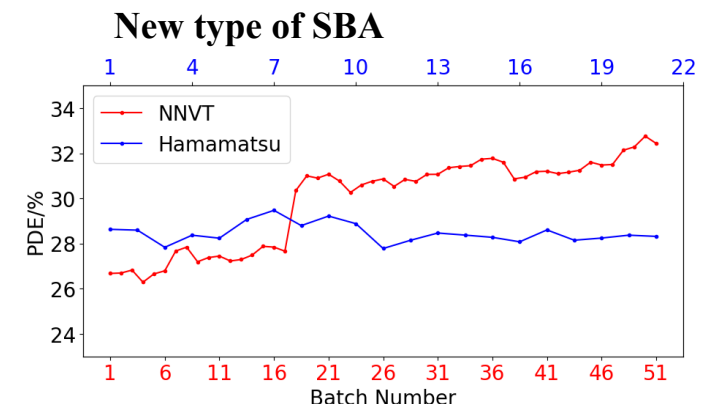


**Microchannel plate (MCP)-PMTs**

Higher collection efficiency  
High efficiency photocathode, low backgrounds glass, ...  
High production yield, automatic mass production

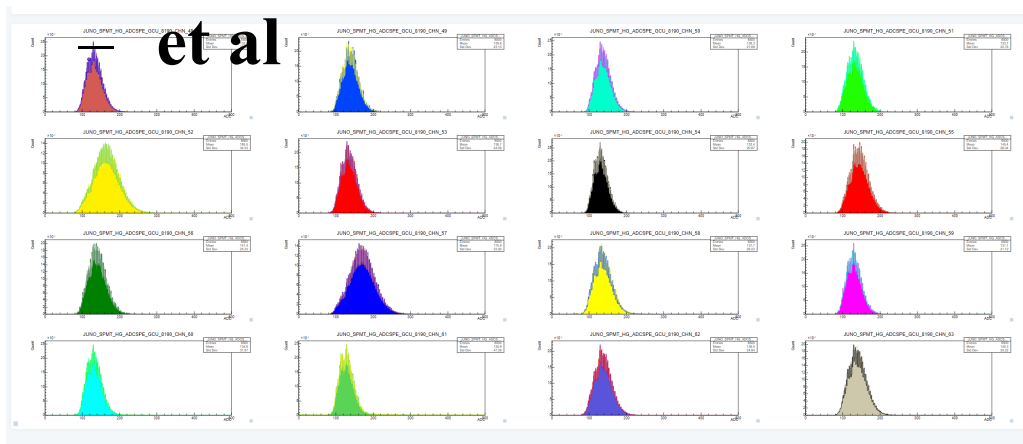


**Dynode-PMTs**

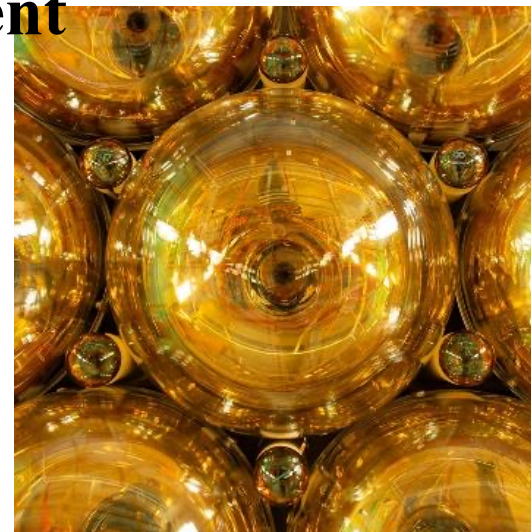


**Both reach QE x CE ~ 30%!**

- 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, ...
- Look at the same events using systems 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

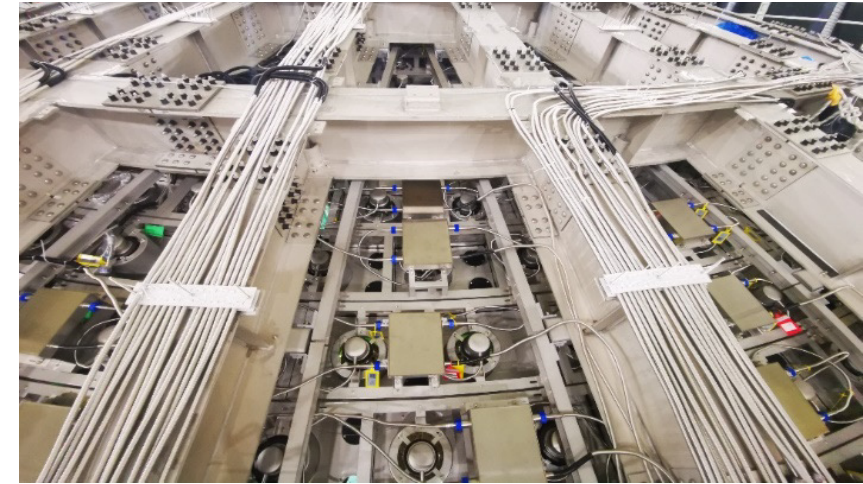
**XP72B22**



**A custom design  
for JUNO!**

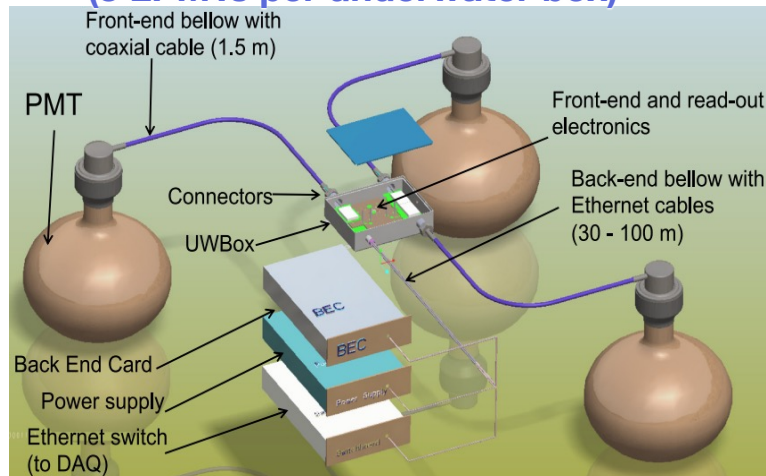


- **LPMT and sPMT frontend electronics are housed in SS underwater boxes**
  - Power the PMTs, decouple signal from HV, process the analog signals and send the information to surface via digital CAT5 cables
- **Cables are in the stainless steel bellows**



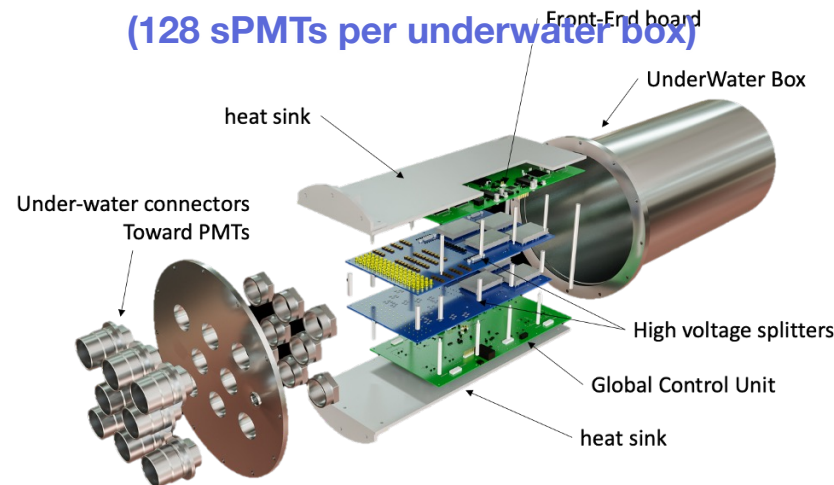
## LPMT System

(3 LPMTs per underwater box)



## sPMT System

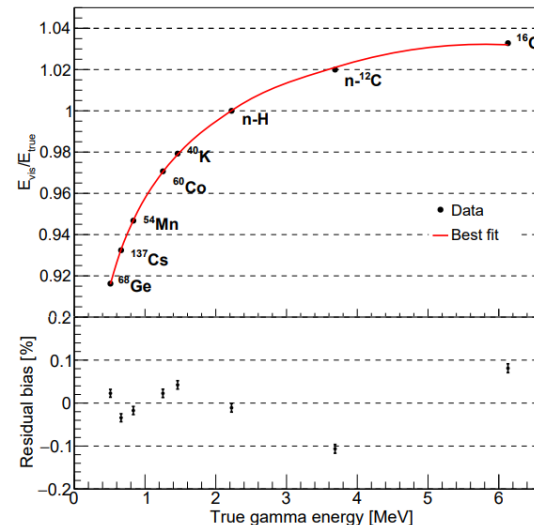
(128 sPMTs per underwater box)



## Power Modules, BEC and others

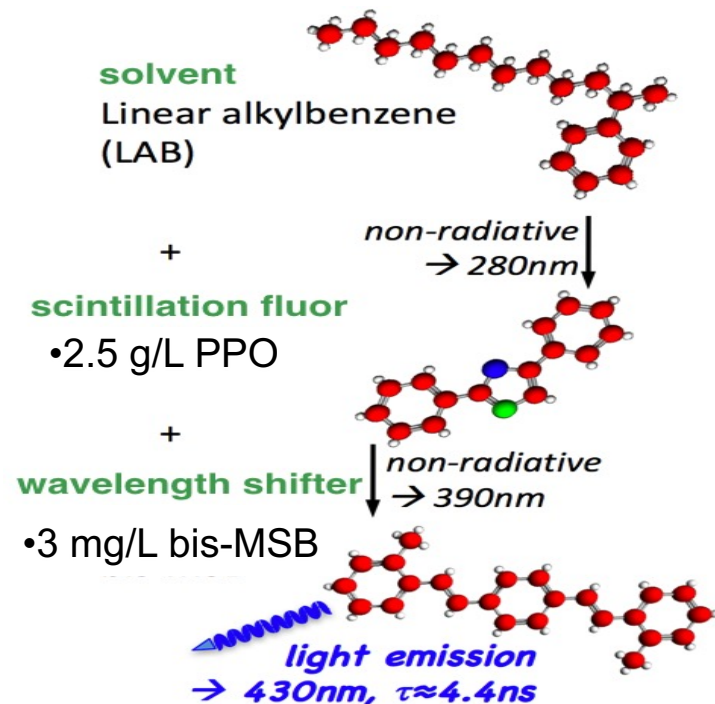


- JHEP 2021, 04 (2021)

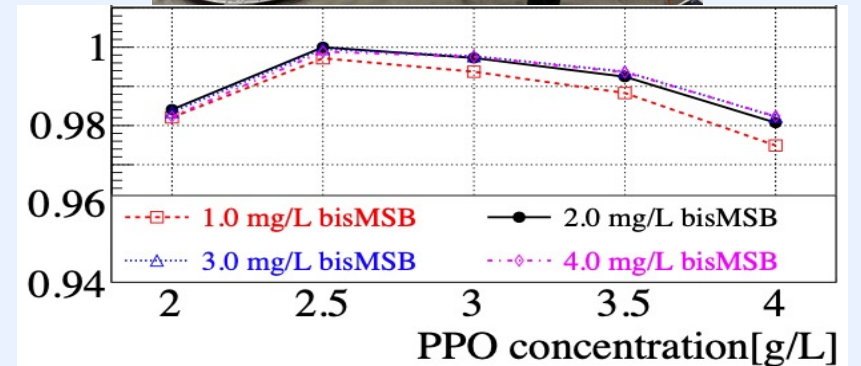
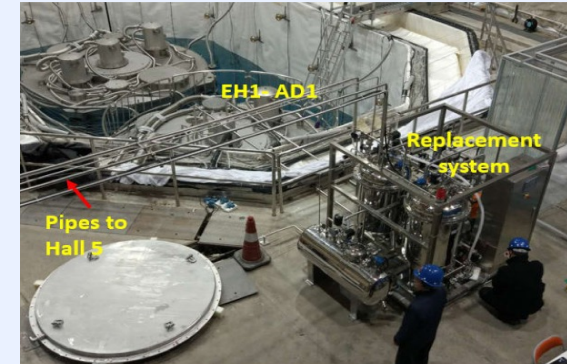




- Main requirements: high light yield, high transparency and high radiopurity
- Recipe: Based on Daya Bay experience with dedicated optimization for higher light yield.
  - LAB + 2.5g/L PPO + 3 mg/L bis-MSB
- No doping with gadolinium



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



• 5000 m<sup>3</sup> LAB storage tank



• 1)  $Al_2O_3$  for optical transparency

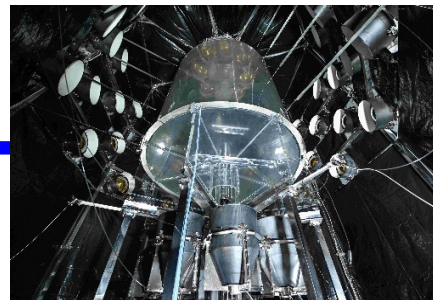
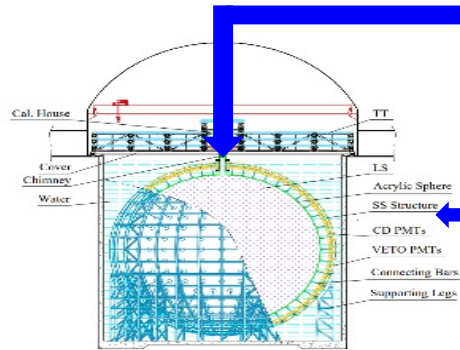


• 2) Distillation for radiopurity



• Mixing LAB with PPO and bis-MSB

Aboveground



• OSIRIS to monitor the LS quality



• 4) Gas stripping to remove Rn and  $O_2$



• 3) Water extraction to remove radioactive impurities



• 1800 m SS pipes to underground

Underground

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



# Radiopurity and Cleanliness Control

- Radiopurity control of raw material:**

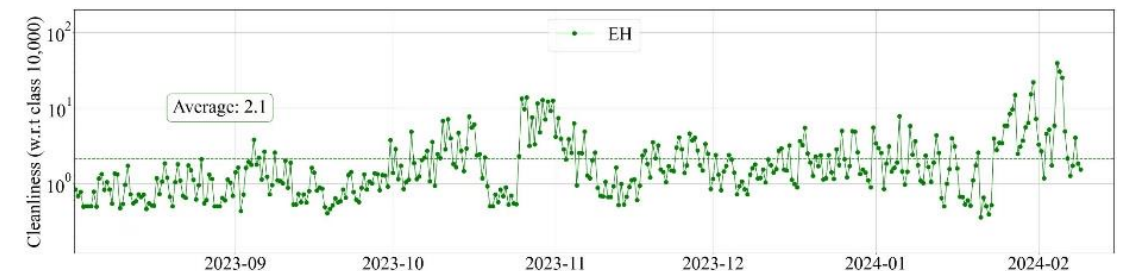
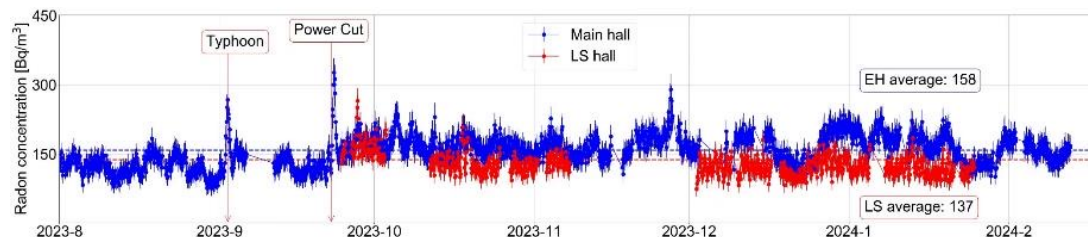
- ✓ Careful material screening
- ✓ Meticulous Monte Carlo Simulation
- ✓ Accurate detector production handling

- Radon and cleanliness control of hall environment :**

- High efficient VAC and component/personnel access control into experimental hall
- Radon concentration: **~160 Bq/m<sup>3</sup>** in the Exp. Hall, **~140 Bq/m<sup>3</sup>** in the LS hall
- Cleanliness: class **20,000**

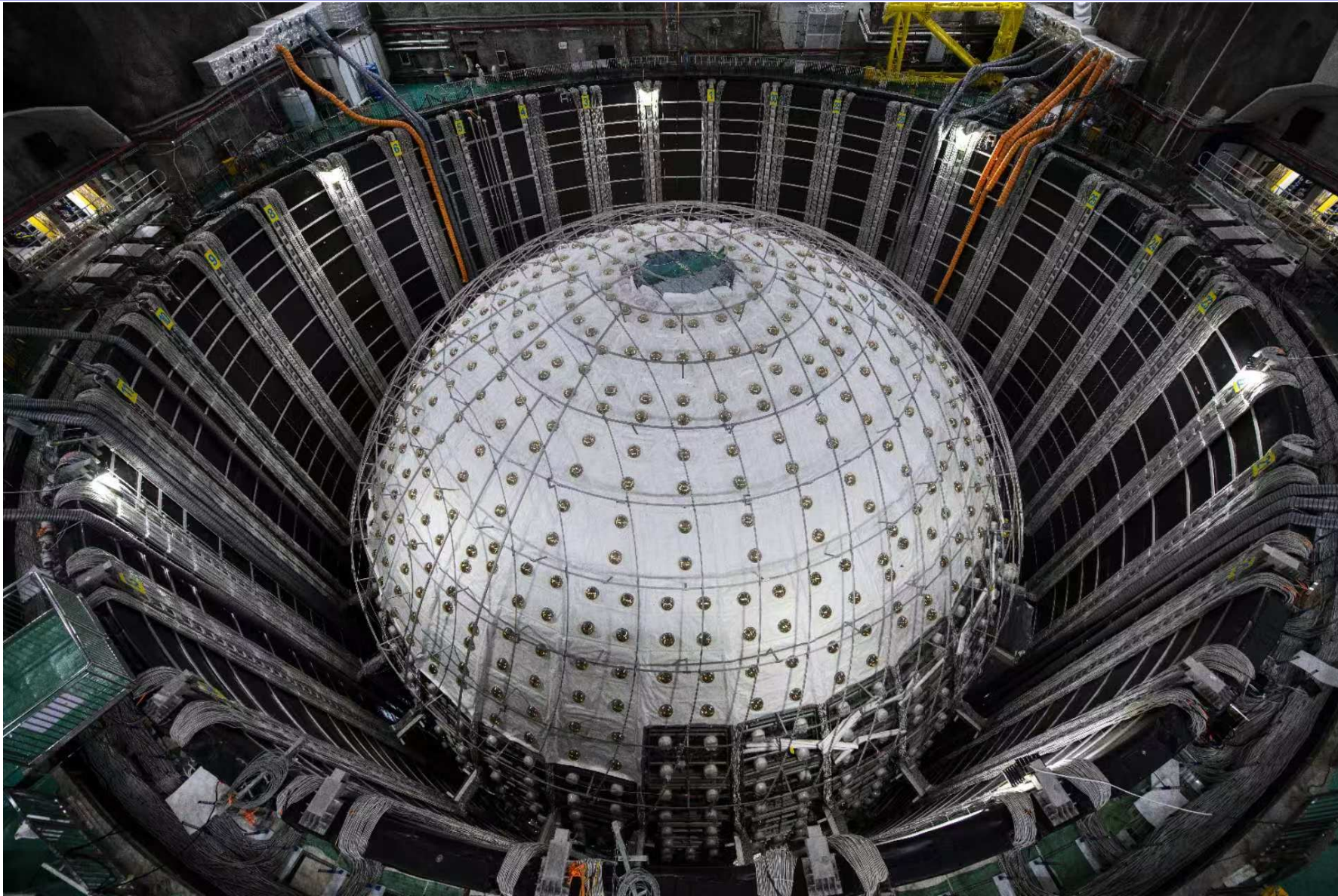
• [JHEP 2021, 102 \(2021\)](#)

| 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 <sup>3</sup> -> 10 mBq/m <sup>3</sup> |
| Other                             | 0           | +0.52       | Add PMT readout, calibration sys                |
| Total                             | 8.5         | -1.3        | Better than spec. by 15%                        |



# Construction Status



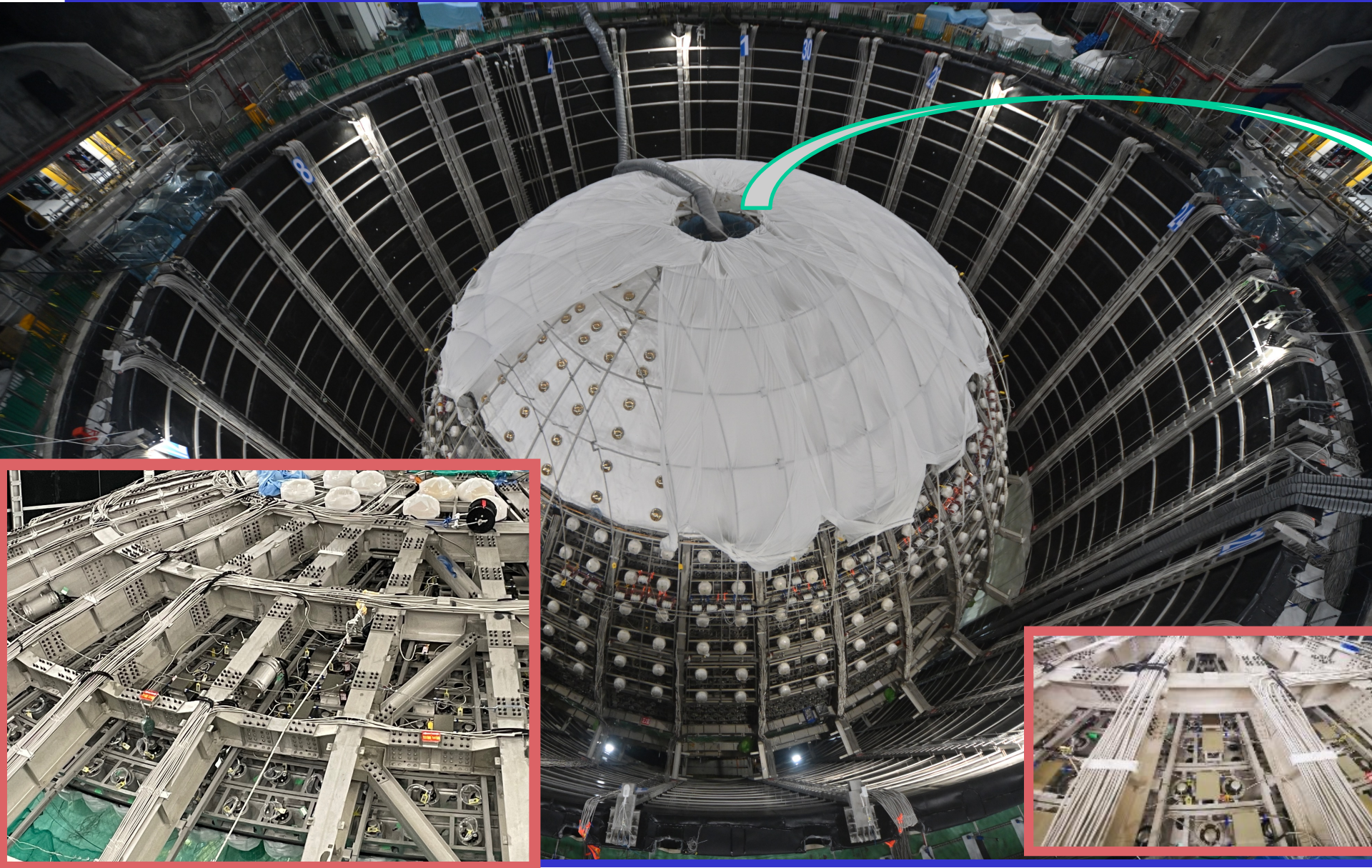








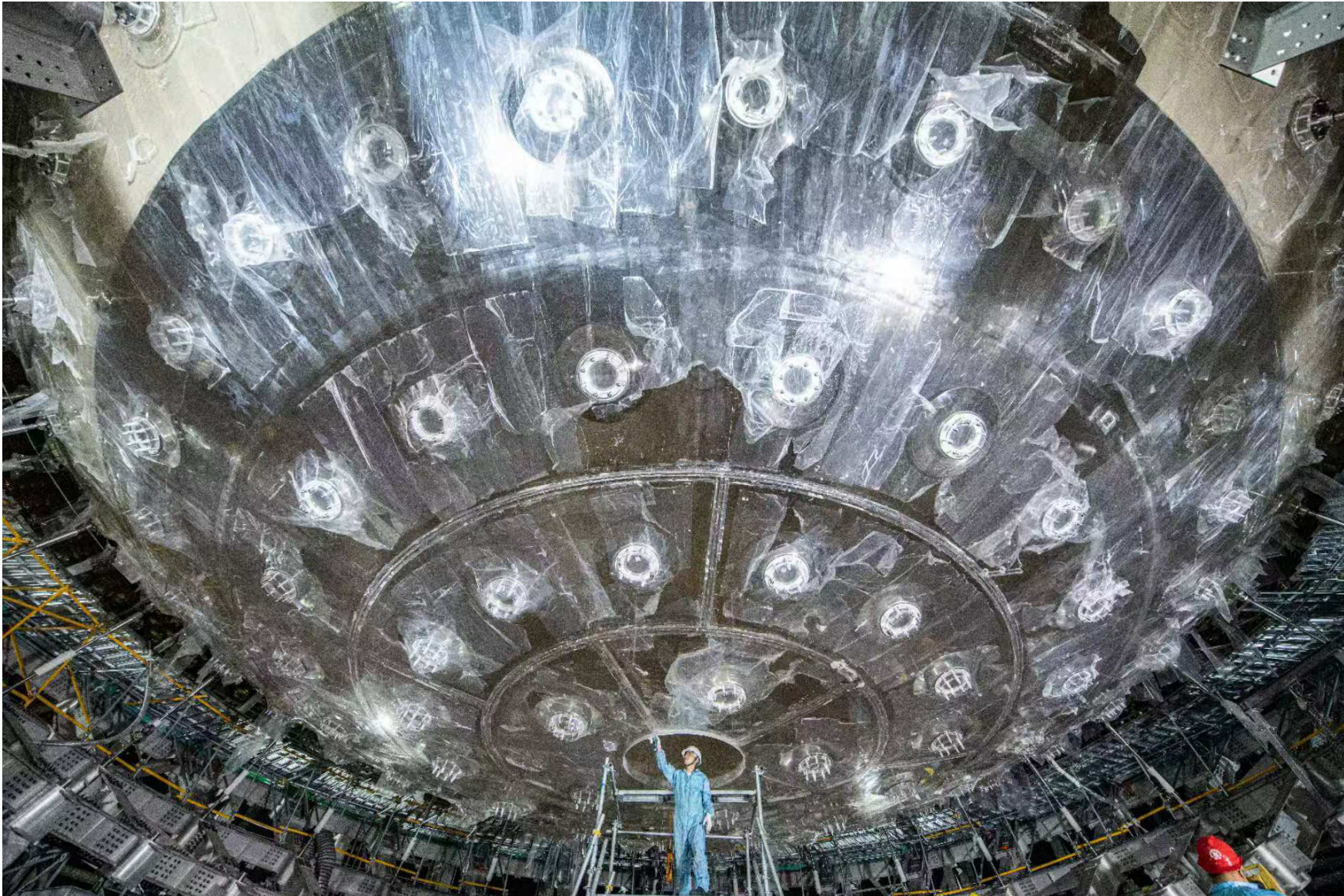
# The details on the SS



**Chimney: 8.85 meter high**





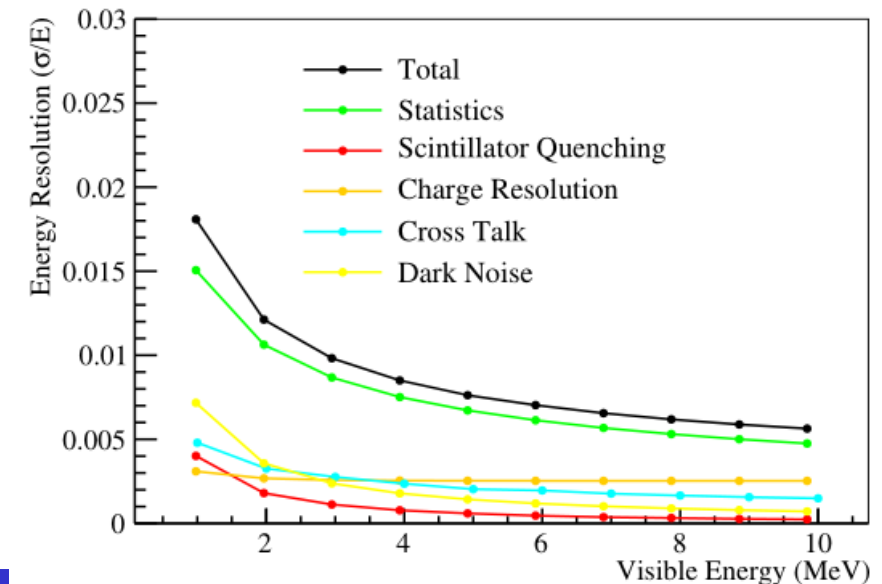
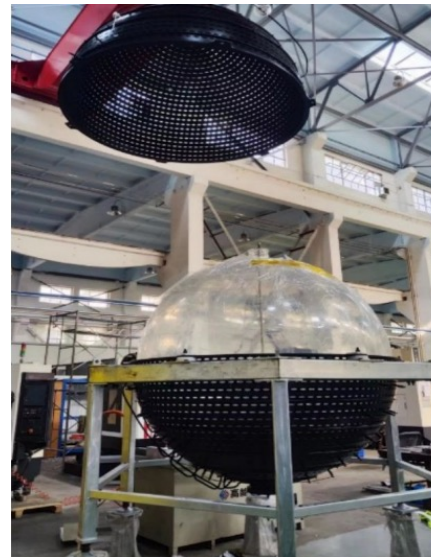
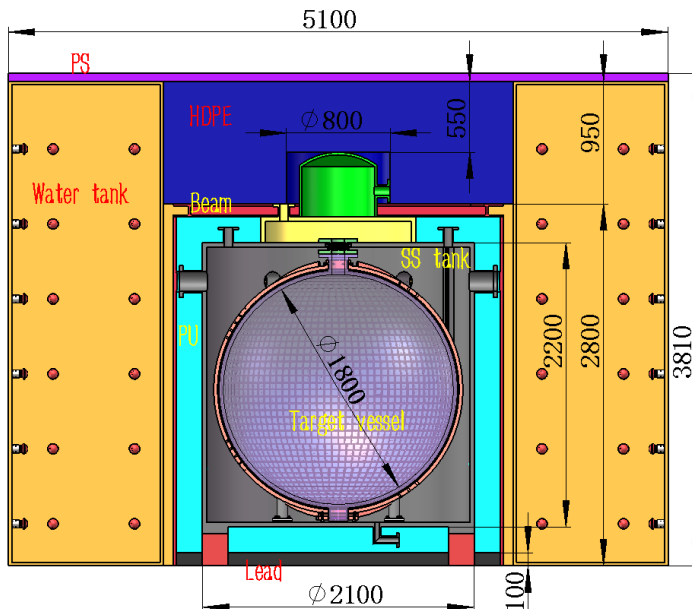
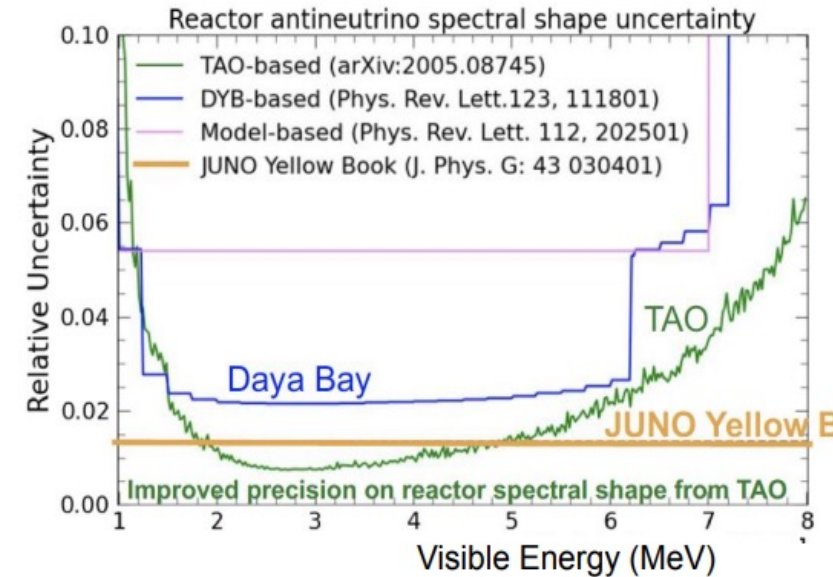








- To measure the reactor neutrino spectrum as a reference to JUNO
  - better resolution to measure fine structure effects and reduce spectrum uncertainties
  - Improve nuclear database, search for sterile neutrinos
- **Baseline: Gd-loaded LS @-50°C + SiPM**
  - 2.8 ton (1t fiducial volume) new type of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





# Physics and Prospects

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

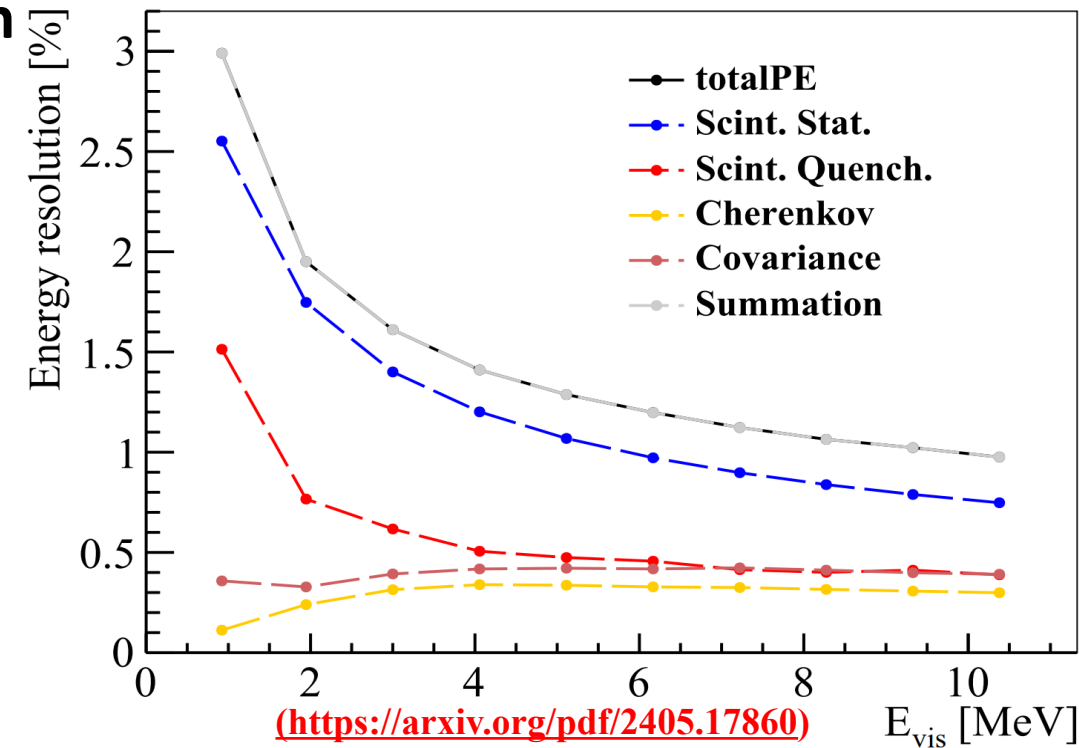
$$\frac{\sigma}{E_{vis}} = \sqrt{\left(\frac{2.614\%}{\sqrt{E_{vis}}}\right)^2 + 0.64\%^2 + \left(\frac{1.205\%}{E_{vis}}\right)^2}$$

↓  
Photon statistics
↓  
Constant term
↓  
Annihilation-induced  $\gamma$ s Dark noise

## •Main changes vs design (*JHEP03(2021)004*):

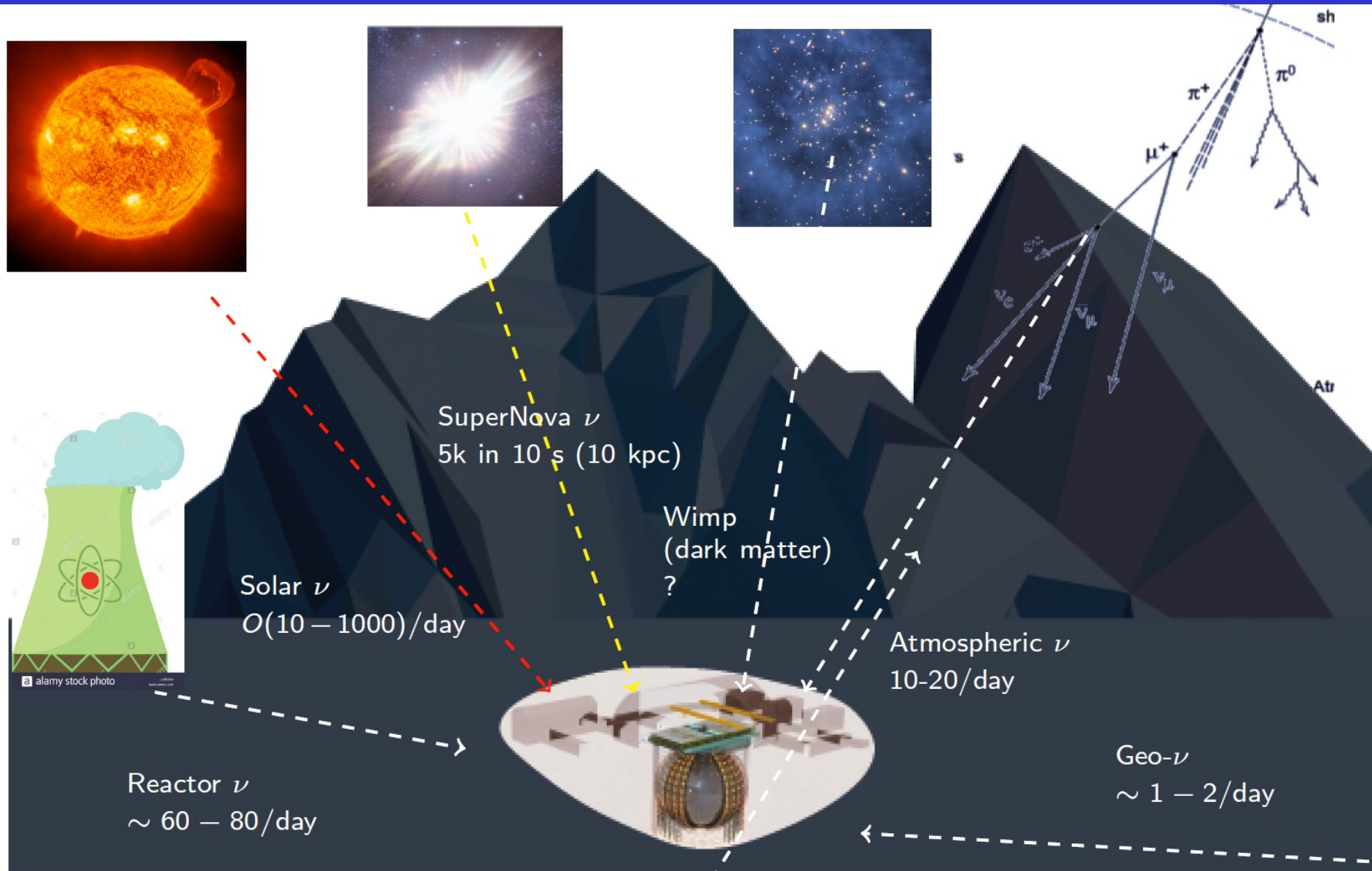
- Photon detection eff.: 27% → 30%
- (*EPJC 82 (2022) 12, 1168*)
- New PMT optical model: +8%
- (*EPJC 82 329 (2022)*)
- New central detector geometry and LS: 3%

## •Total photon statistics: ~1660/MeV



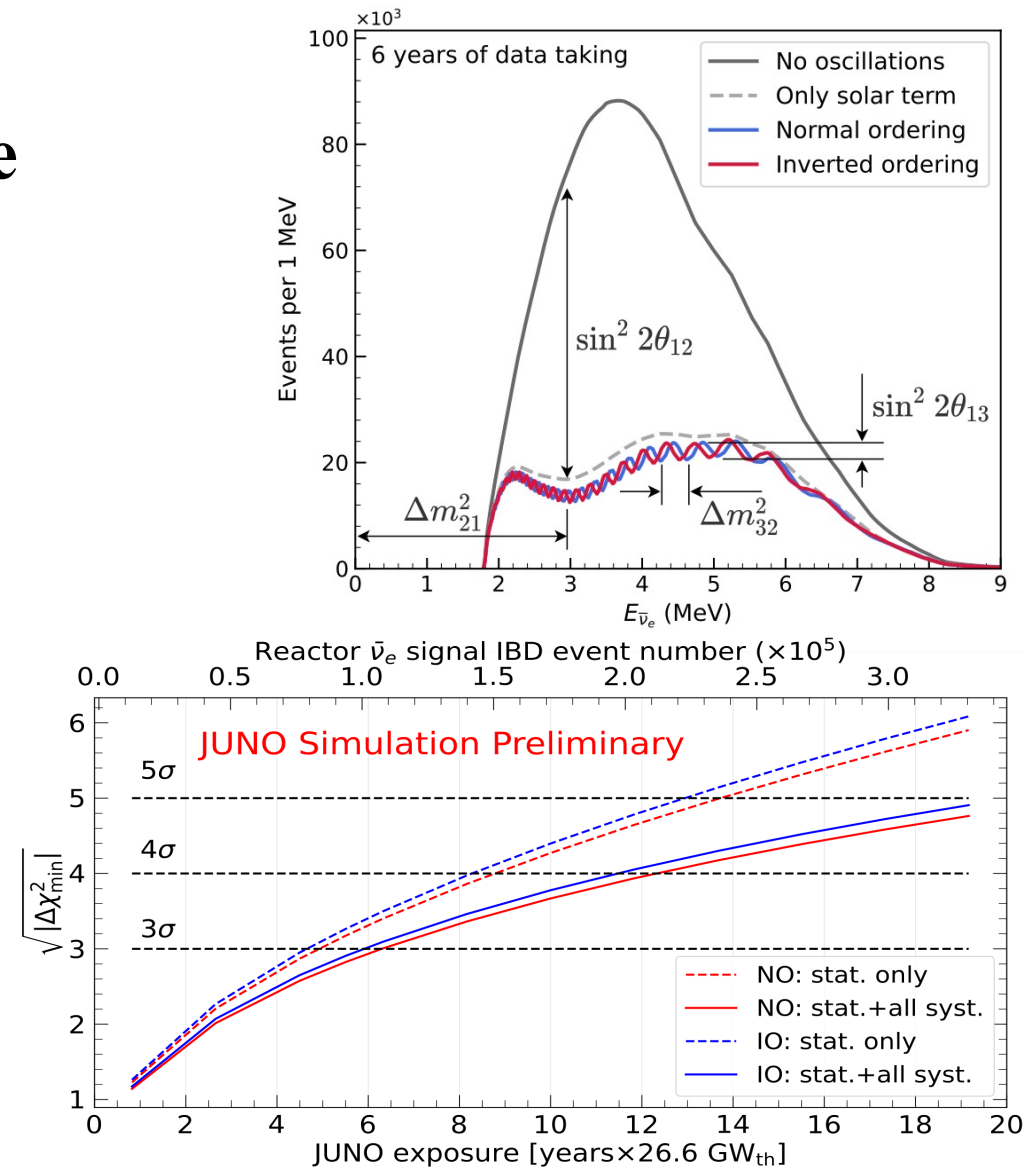


# A Multi-Purpose Neutrino Observatory



- Determine mass ordering
  - Exploit interference effects in the fine structure of the oscillated spectrum
  - $3\sigma$  sensitivity within  $\sim 6$  years
  - Independent of  $\theta_{23}$  and  $\delta_{CP}$
- Additional sensitivity from atmospheric neutrinos under study

(<https://arxiv.org/abs/2405.18008>)

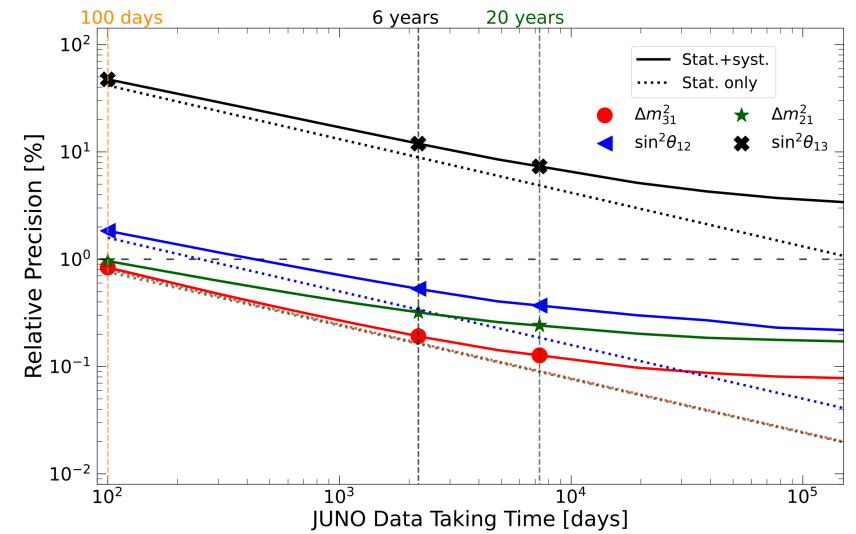




# Reactor Neutrino Oscillation Physics

- Measure  $\sin^2 \theta_{12}$ ,  $\Delta m_{21}^2$  and  $\Delta m_{31}^2$  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<sub>PMNS</sub> unitarity tests )
  - Narrow down parameter space for  $0\nu\beta\beta$  searches

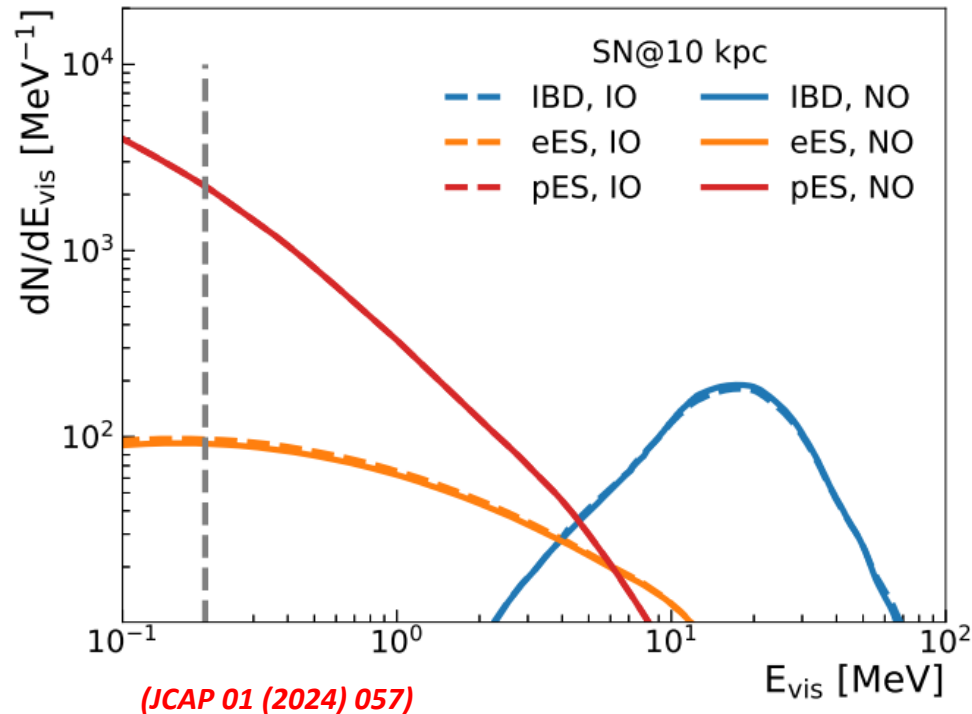
(Chinese Phys. C 46 123001 (2022))



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

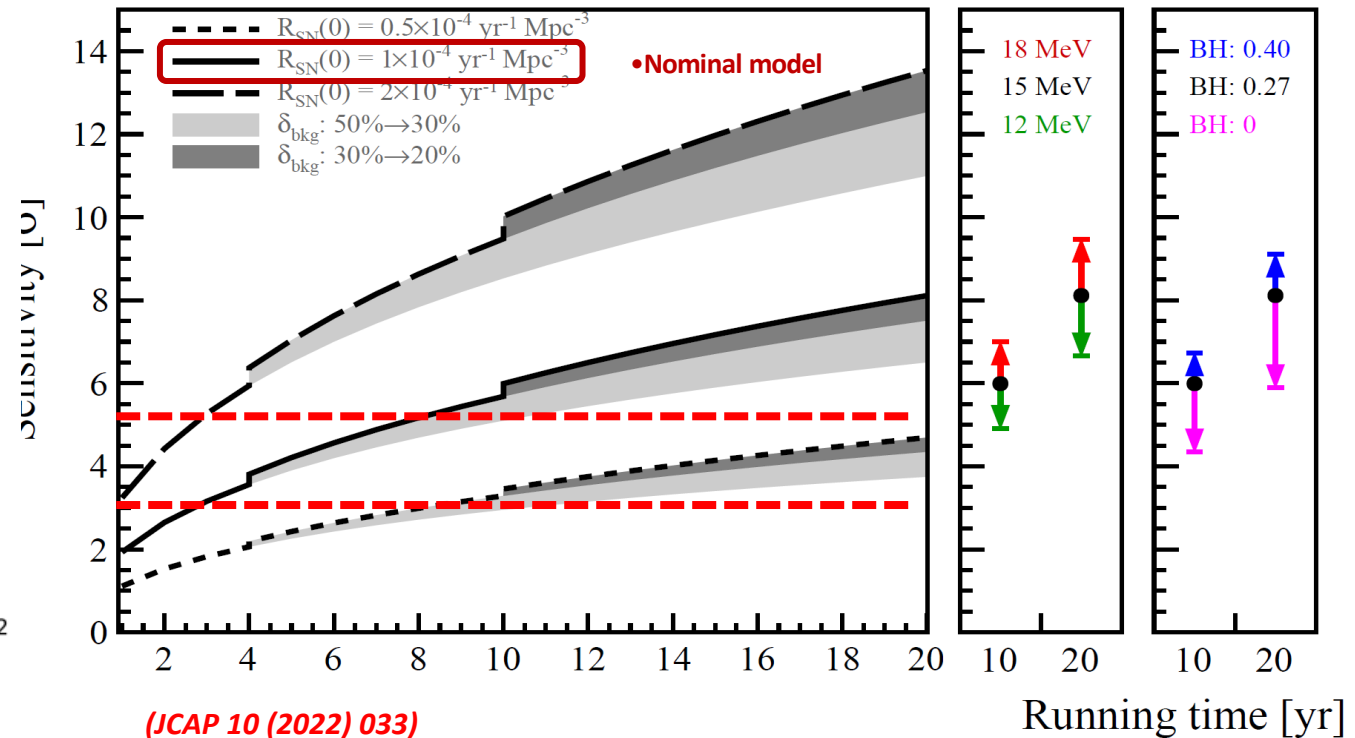
| Parameter          | $\sin^2 \theta_{12}$ | $\Delta m_{21}^2$ | $\Delta m_{31}^2$ | $\sin^2 \theta_{13}$ |
|--------------------|----------------------|-------------------|-------------------|----------------------|
| Current Precision* | 4.2%                 | 2.4%              | 1.5%            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

## SN neutrinos of 30 $M_{\odot}$ Nakazato model



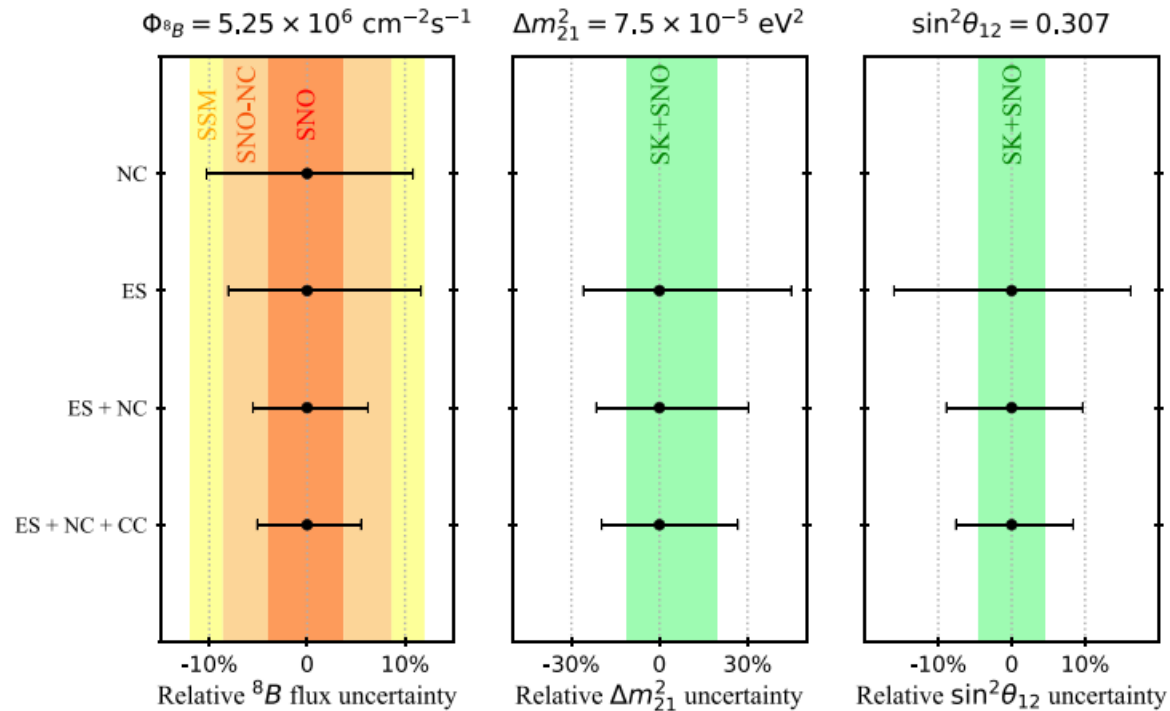
- Three detection channels sensitive to all flavors
- Excellent capability for **early warning**
  - 220~400 kpc with 50% probability
  - pre-SN 1.6 (0.9) kpc
  - Alert time is 10~30 ms for typical 10 kpc

## Diffuse supernova neutrino background



- Expected detection significance of  $3\sigma$  in ~3 years and  $>5\sigma$  in 10 years using reference model
- S/B ratio improved from 2 to 3.5 w/ **Pulse Shape Discrimination**

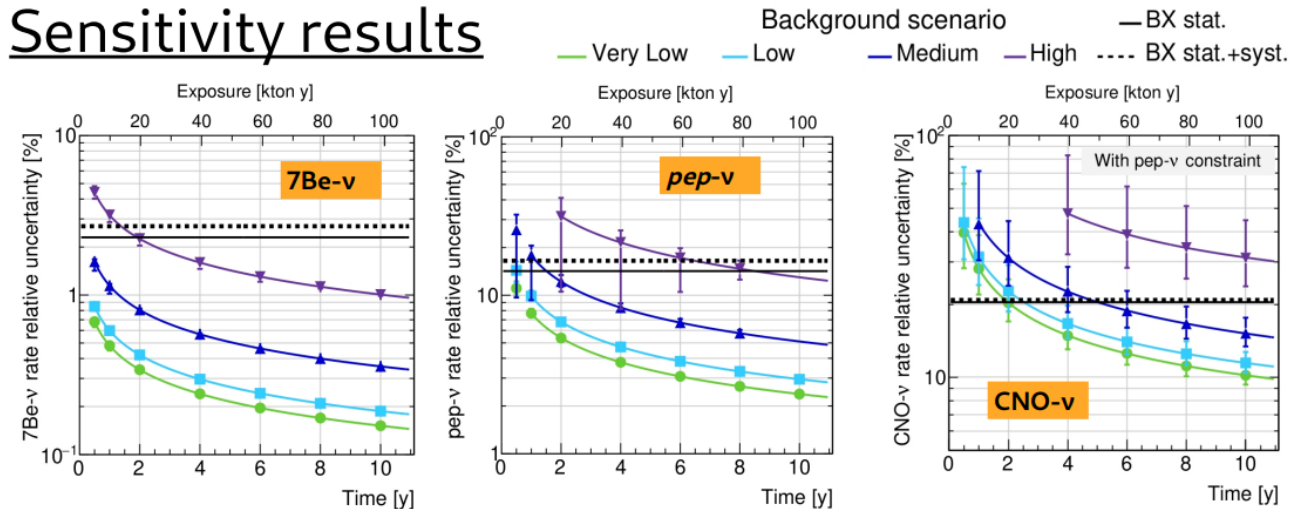




(Astrophys. J 965, 122 (2024))

(JCAP 10, 022 (2023))

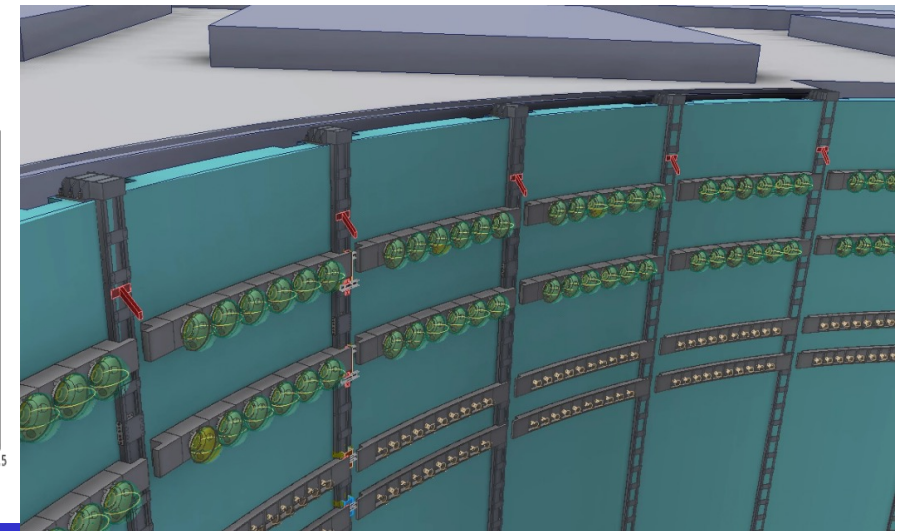
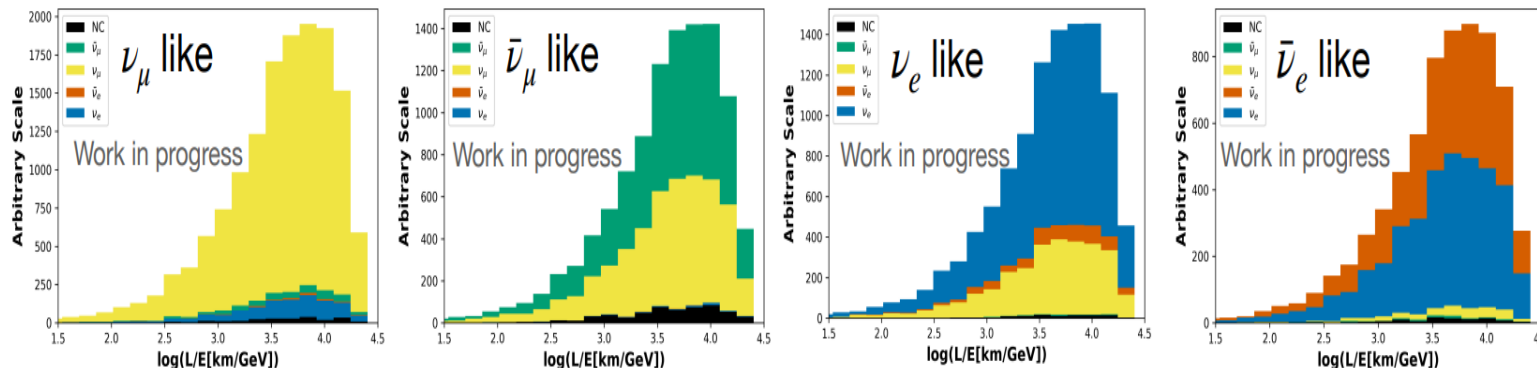
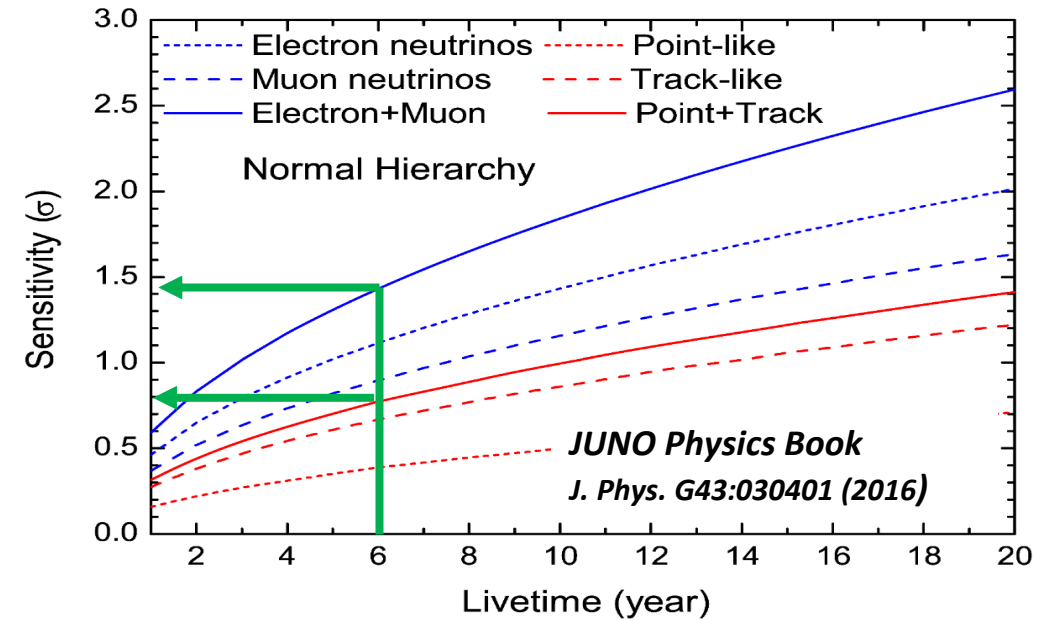
## Sensitivity results



- 60,000 ES and 600 NC/CC on  $^{13}\text{C}$
- The largest  $^{13}\text{C}$  ES+NC+CC sample,  $^8\text{B}$  flux can be model-independently measured to 5% in 10 years (SNO 3%)

- For most background scenarios, JUNO will reduce the Borexino uncertainty on  $^7\text{Be}$ , pep, CNO flux measurement

- NMO sensitivity:  $0.8 \sim 1.4\sigma$  @ 6 years with atm  $\nu$  only
- Significant progress on event reconstruction and selection methods
- Reevaluation of sensitivity combined with reactor neutrinos in progress
- Plan to install spare PMTs on top wall of the water pool to improve PID and direction reconstruction





- Although the project delayed, many challenges were overcome and the installation is nearing its end
- Commissioning shows that the performance of (part of ) components/detector is better than the requirement
- Expect to start filling phase in December of this year
- Mass ordering expected to determine in the next decade
- Anticipating more exciting physics results

十年磨一剑

*Ten Years to Make a Sword*

***THANKS***