STATUS OF THE JUNO EXPERIMENT

IRN Neutrino
12-13 June 2025

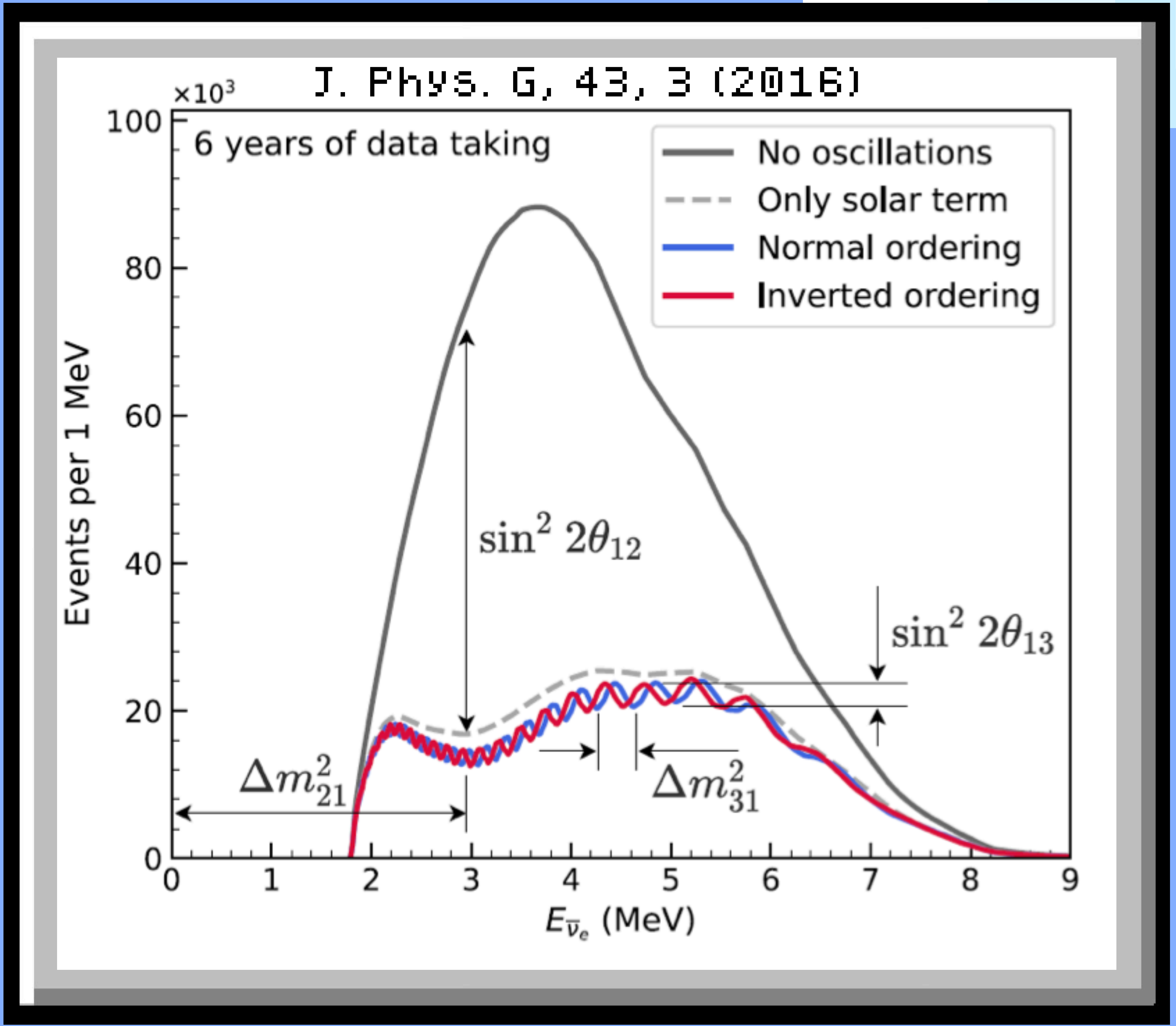
L. Labit
Strasbourg University - IPHC

2 MASS ORDERING

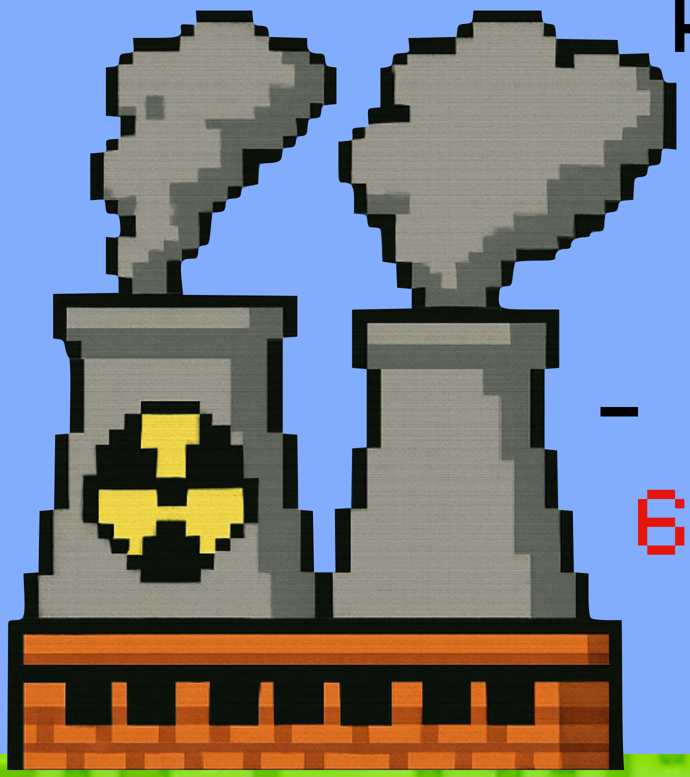
- **Neutrino mass ordering with reactor antineutrino:**

  - Survival probability given by :

$$\mathcal{P}(\overline{\nu}_e \to \overline{\nu}_e) = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\frac{\Delta m^2_{21}\times L}{4E_\nu}\right) - \sin^2 2\theta_{13}\left(\frac{\Delta m^2_{31}\times L}{4E_\nu}\right)$$
$$-\sin^2\theta_{12}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{21}\times L}{4E_\nu}\right)\cos\left(\frac{2|\Delta m^2_{31}|\times L}{4E_\nu}\right)$$
$$\pm\frac{\sin^2\theta_{12}}{2}\sin^2 2\theta_{13}\sin\left(\frac{2\Delta m^2_{21}\times L}{4E_\nu}\right)\sin\left(\frac{2|\Delta m^2_{31}|\times L}{4E_\nu}\right)$$



  - Requires very good energy resolution and precise modeling of the energy response



  - Expected 3σ sensitivity after 6 years of data taking

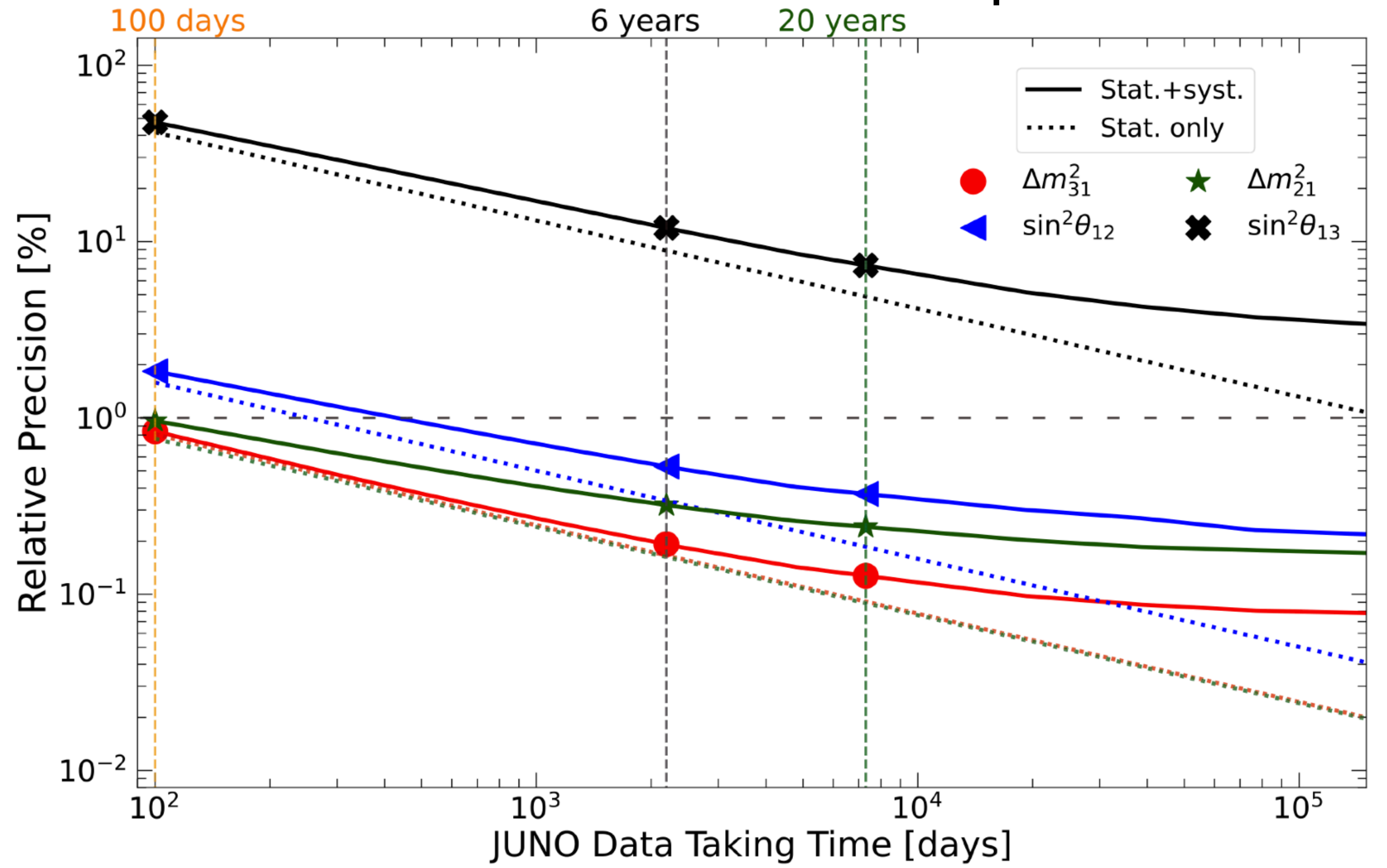
3 OSCILLATION PARAMETERS

- **Precision measurement of oscillation parameters**

- Simultaneous measurement of Δm^2_{12} and Δm^2_{13}

- Subpercent precision on 3 key parameters within 6 years of data taking

Chin.Phys.C 46 (2022) 12, 123001



	Central Value	PDG2020	100 days	6 years
Δm^2_{31} ($\times 10^{-3}$ eV^2)	2.5283	±0.034 (1.3%)	±0.021 (0.8%)	±0.0047 (0.2%)
Δm^2_{21} ($\times 10^{-5}$ eV^2)	7.53	±0.18 (2.4%)	±0.074 (1.0%)	±0.024 (0.3%)
$\sin^2\theta_{12}$	0.307	±0.013 (4.2%)	±0.0058 (1.9%)	±0.0016 (0.5%)
$\sin^2\theta_{13}$	0.0218	±0.0007 (3.2%)	±0.010 (47.9%)	±0.0026 (12.1%)

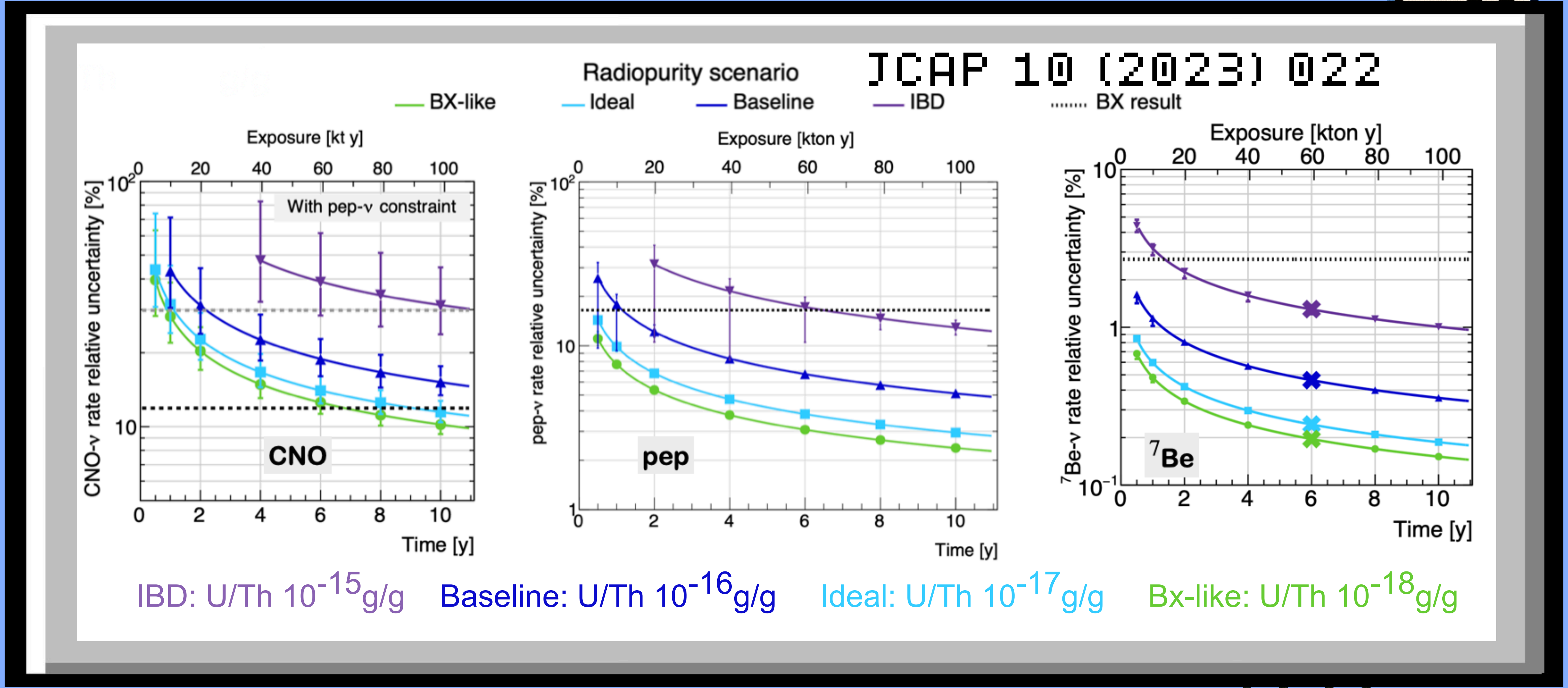
4 SOLAR NEUTRINOS

- **Solar neutrinos:**

-Large statistic from ^{8}B solar neutrinos: ~60 000 events after 10 yr:

constrain Δm^2_{21} and $\sin^2 2\theta_{12}$ from solar neutrinos alone

constrain day-night asymmetry at ~0.9%



-Sensitivity to intermediate solar neutrinos energy for different radiopurity scenarii

GEO, SN NEUTRINOS

- **Geo neutrinos:**

  -Neutrinos from Earth's ^{238}U and ^{232}Th

  ~400 /year ⇒ 2 times more than actual total world sample (KamLAND + Borexino ~200)

- **SuperNovae neutrinos:**

  -Constrain absolute neutrino mass

  -Study of star physics: late-stage stellar evolution, SN hydrodynamic models

- **And other:**

  -Diffuse SN neutrino background, nucleon decay, ...

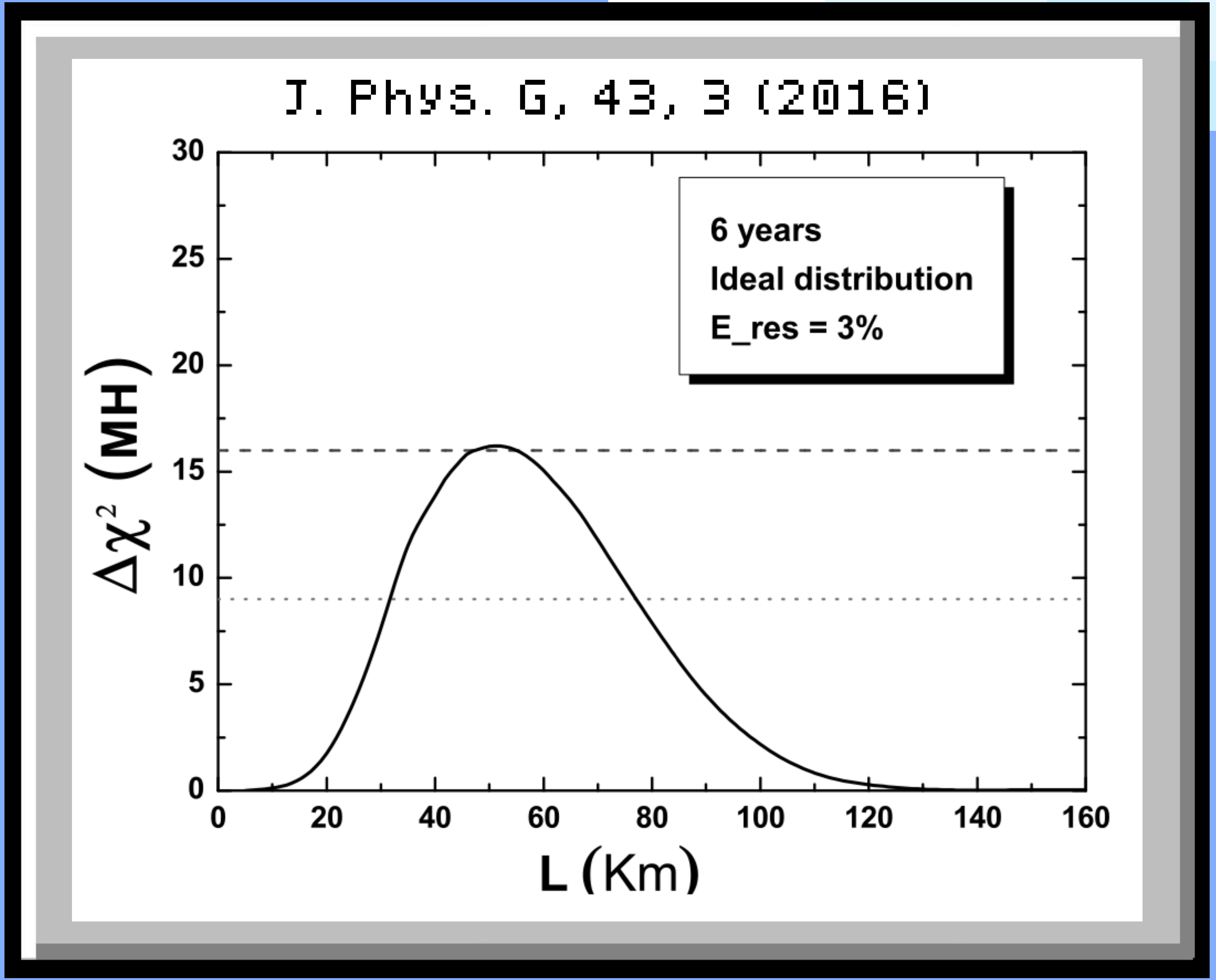
6

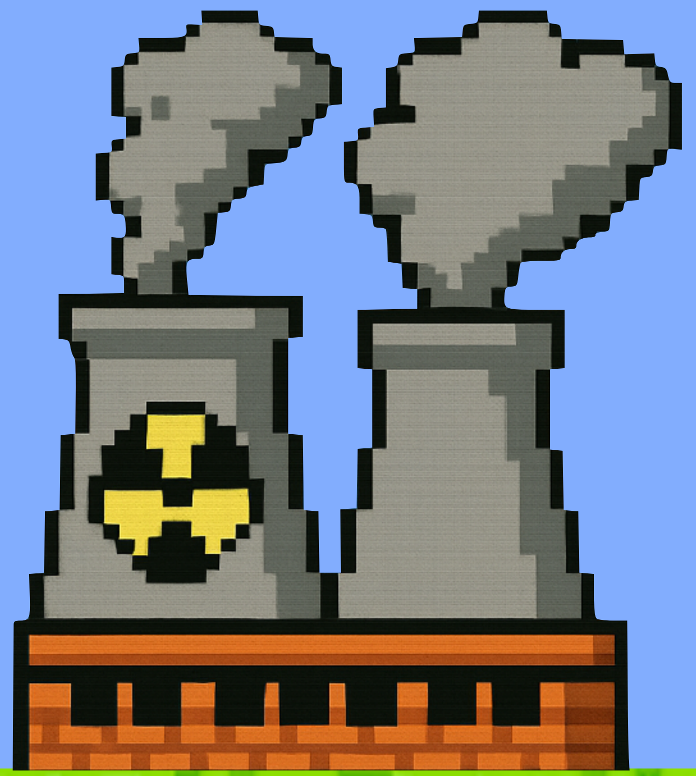
THE JUNO EXPERIMENT

- The Jiangmen Underground Neutrino Observatory:

- Largest liquid scintillator based neutrino detector: 20 kTons target

- Located at ~53 km from Taishan & Yangjiang NPP (26.6 GW_{th}) to optimise neutrino ordering discrimination





- Underground detector: 650m overburden ~2000 m.w.e → ~4muons/s in LS

- Energy resolution of 3% at 1 MeV

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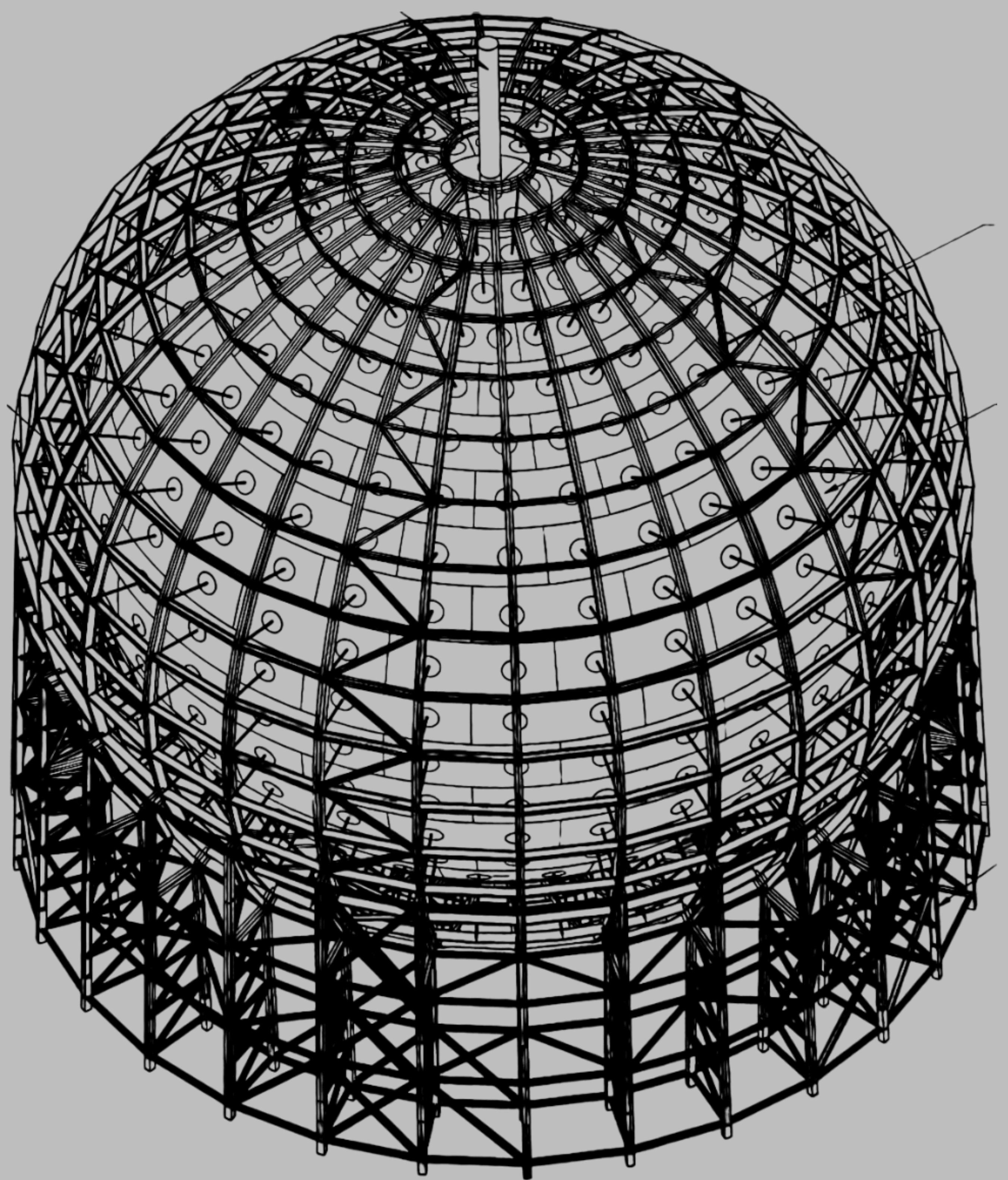
THE JUNO EXPERIMENT

- **Central Detector (CD):**

- 35.4m diameter sphere composed of 260 acrylic panels 12 cm thick
- 20 kilotons of liquid scintillator: LAB + PPO + bis-MSB + BHT
- High photon yield ~10000 ± 10% photons/MeV
- NMO minimal U/Th concentration requirement: $\leq 10^{-15}$g/g

- Very transparent: attenuation length ~25m
- 17612 large 20-inch PMTs (LPMT) & 25600 small 3-inch PMTs (SPMT)
High optical coverage: 75% LPMT and 3% SPMT
- High PMT's quantum efficiency: ~30%



JUNO's Central Detector

THE JUNO EXPERIMENT

- **Water Cherenkov Detector (WP)**

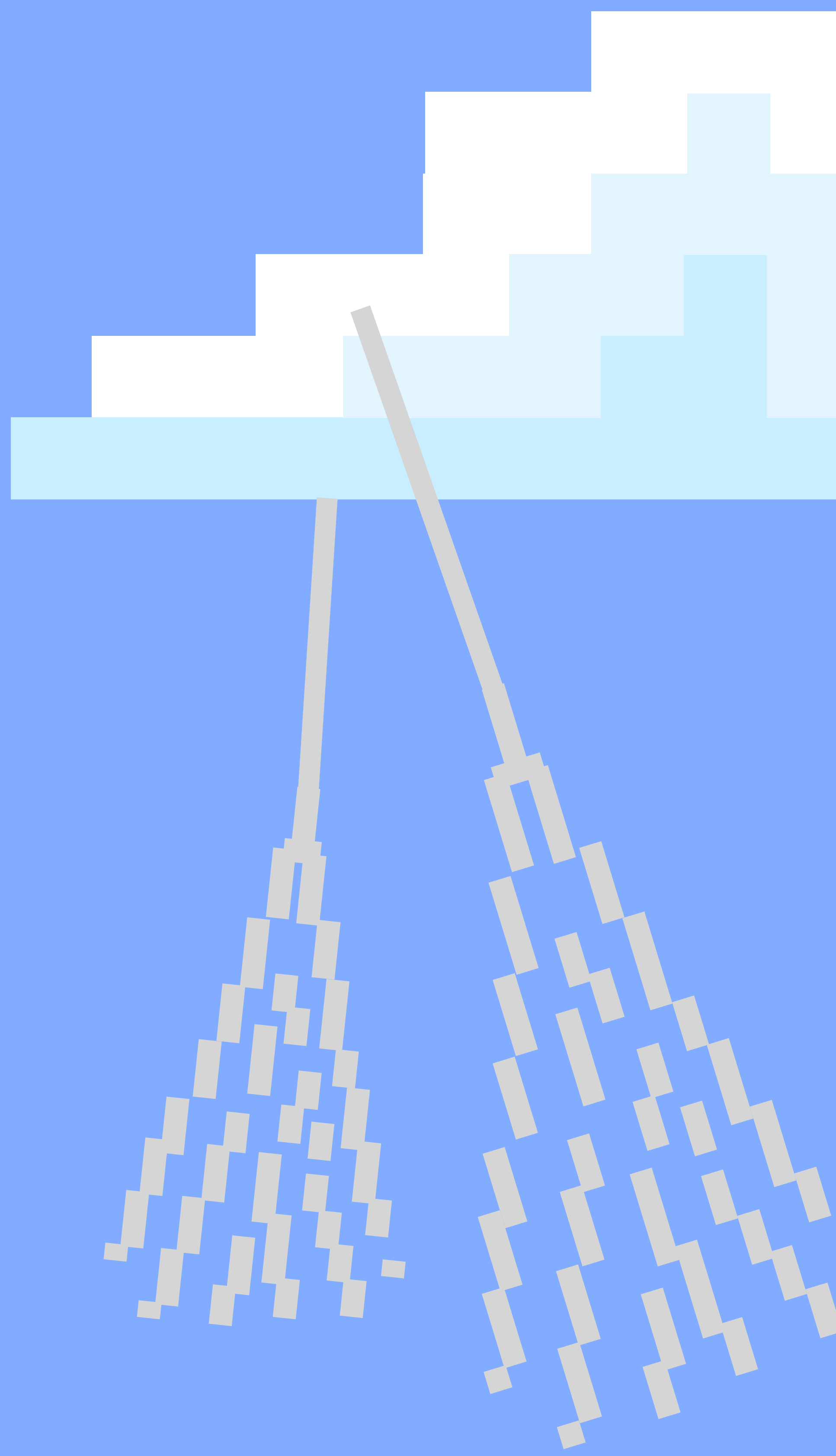
- 43.5×44m cylinder filled with 35 kilotons of ultrapure (degased) water : Radon concentration ~10mBq/m^3

- Seen by 2400 LPMT and 600 8-inch PMTs refurbished from Daya Bay

- Passive shielding against natural radioactivity from surrounding rock and fast neutrons from cosmic muons

- Muon detection efficiency of 99.5 %

- Host the underwater box containing PMT's readout electronics



THE JUNO EXPERIMENT

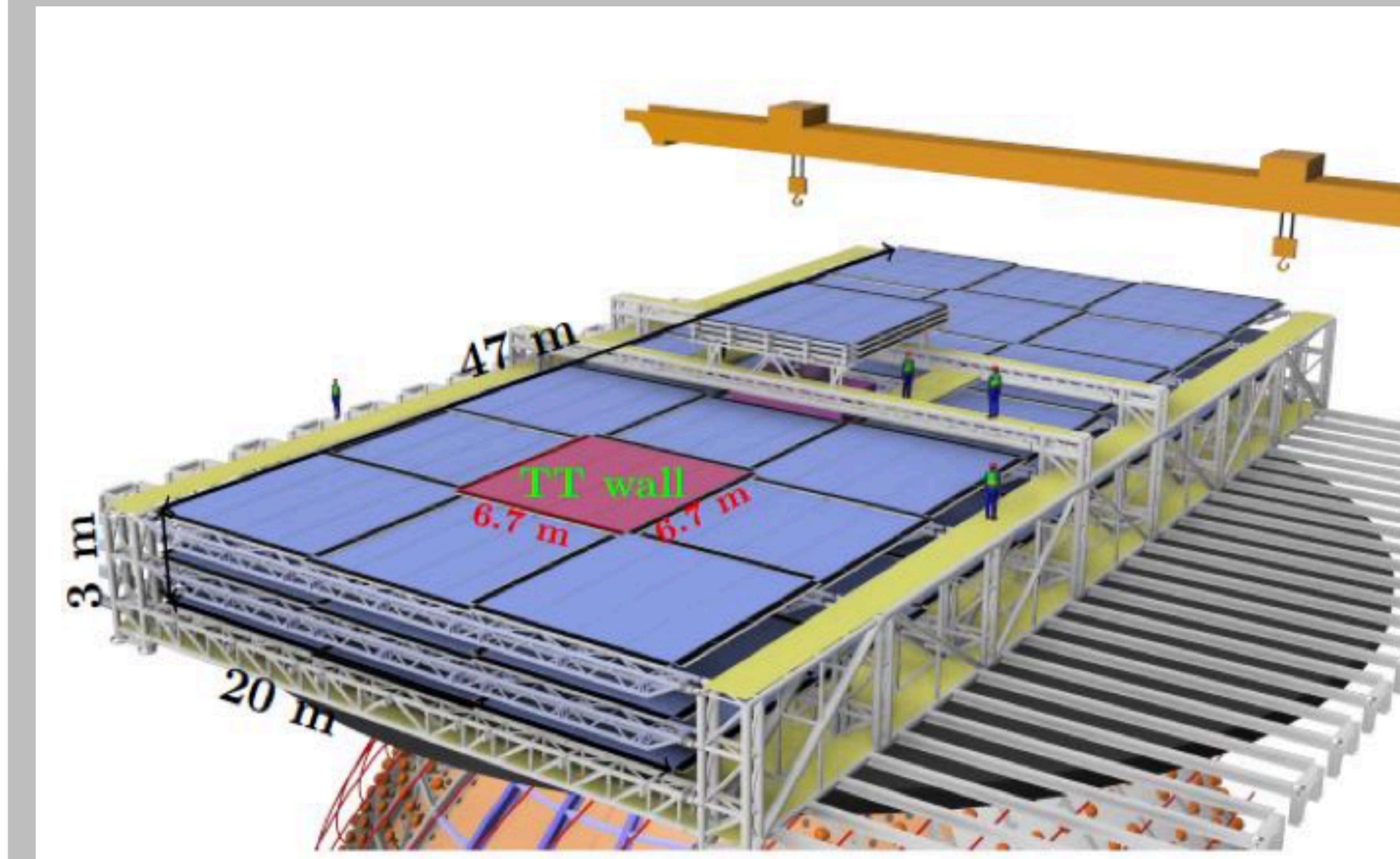
- **Top Tracker (TT)**

- 3 layers of plastic scintillator refurbished from OPERA's Target Tracker

- 50% coverage

- 2.6 x 2.6 cm^2 granularity

- Muon track angular resolution of 0.2°



- Provide a muon control sample to validate track reconstruction and study cosmogenic background

10 THE JUNO EXPERIMENT

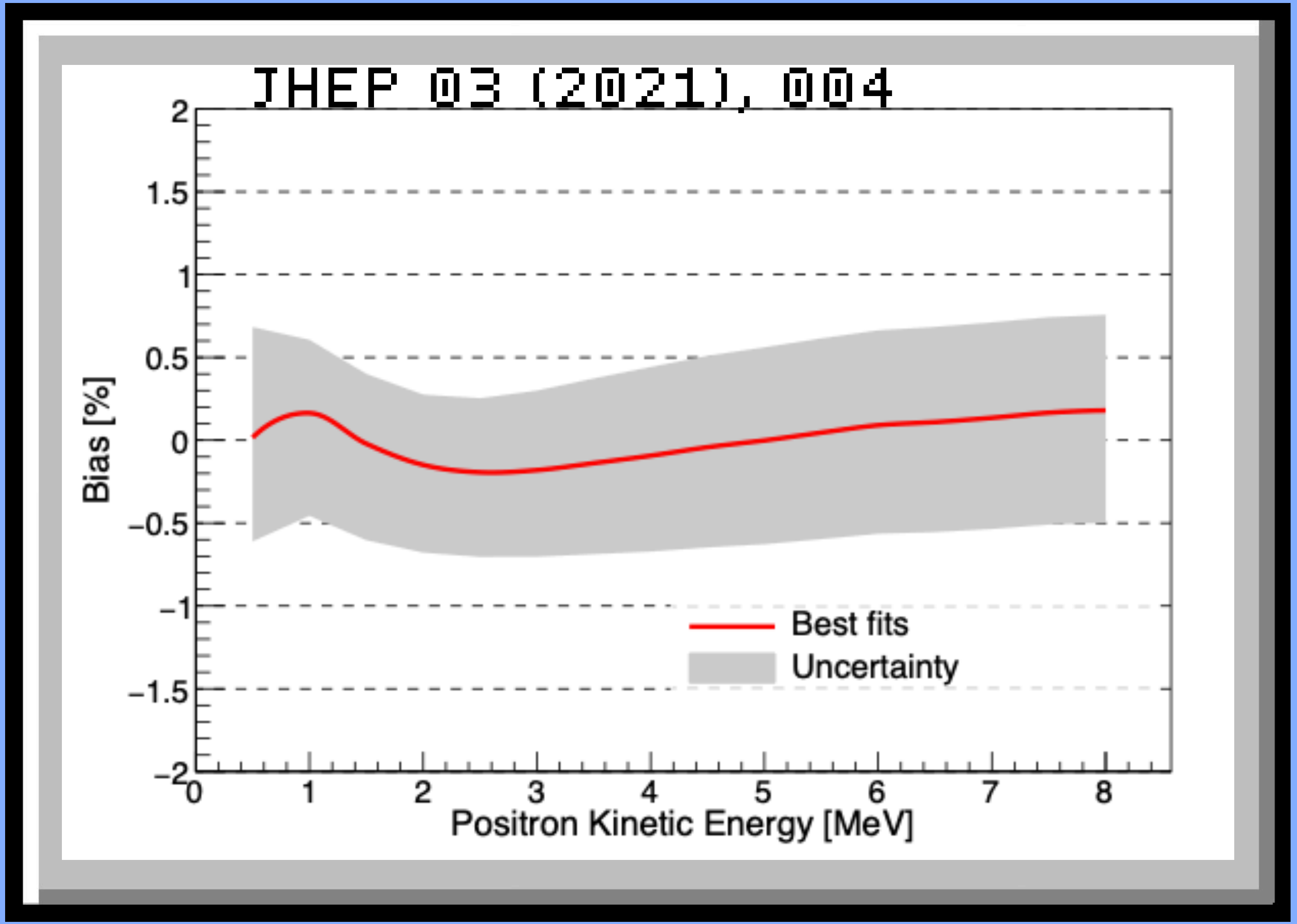
- **Calibration strategy:**

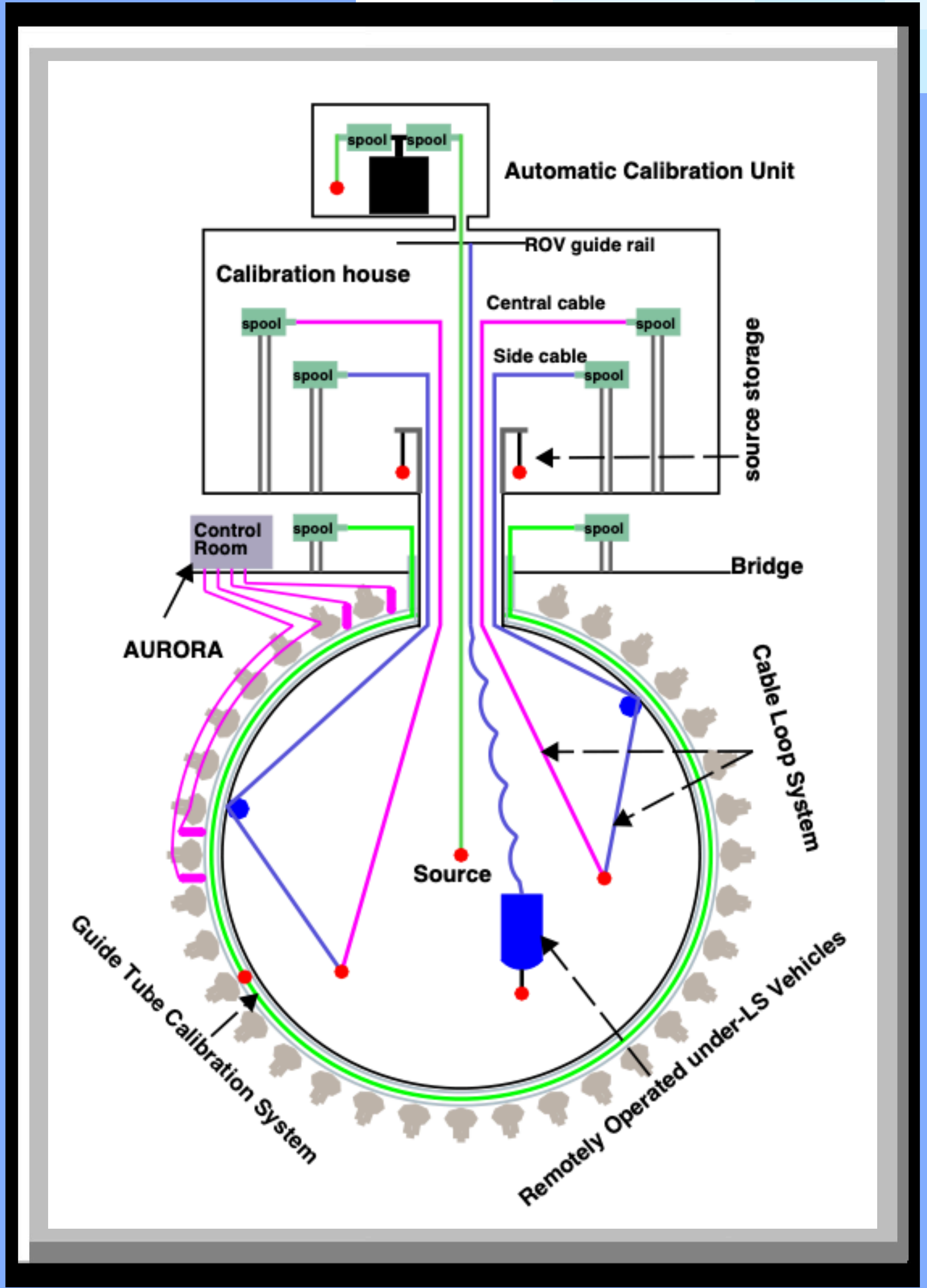
Requires good control of
energy scale,
energy non-linearity,
response non-uniformity

- Many radioactive sources
in [~0.5, ~6] MeV

- 1D, 2D and 3D scan systems

- e^+ energy bias uncertainty < 1%





11 THE JUNO EXPERIMENT

- **Taishan Antineutrino Observatory:**

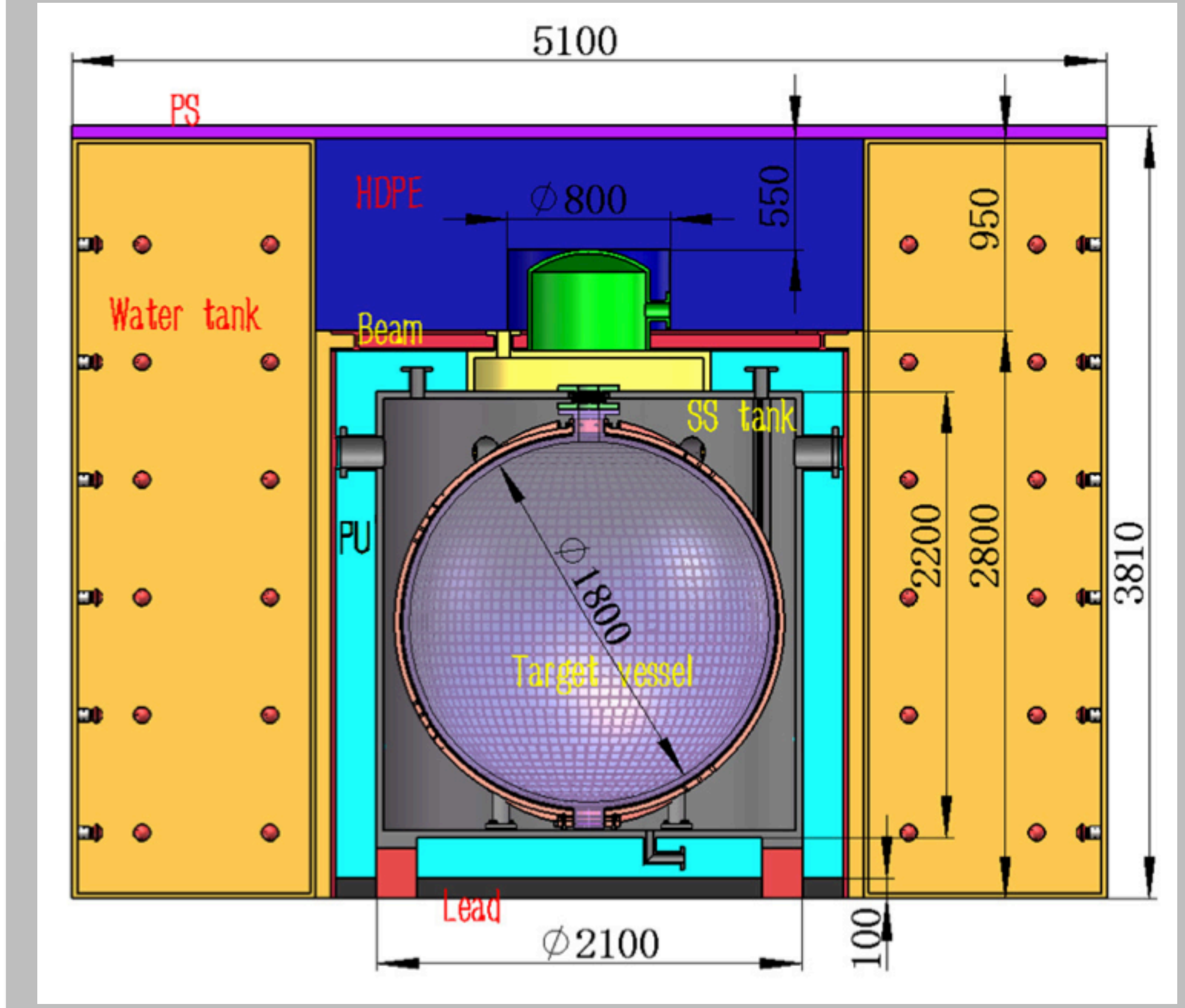
  - 1 ton fiducial volume Gd loaded LS detector

  - 10 m^2 of SiPM operated at -50°C

  - Located at ~30m from one of Taishan's 4.6 GW_{th} core

  - Energy resolution < 2% at 1 MeV

  - Provides a precise reference reactor spectrum for JUNO



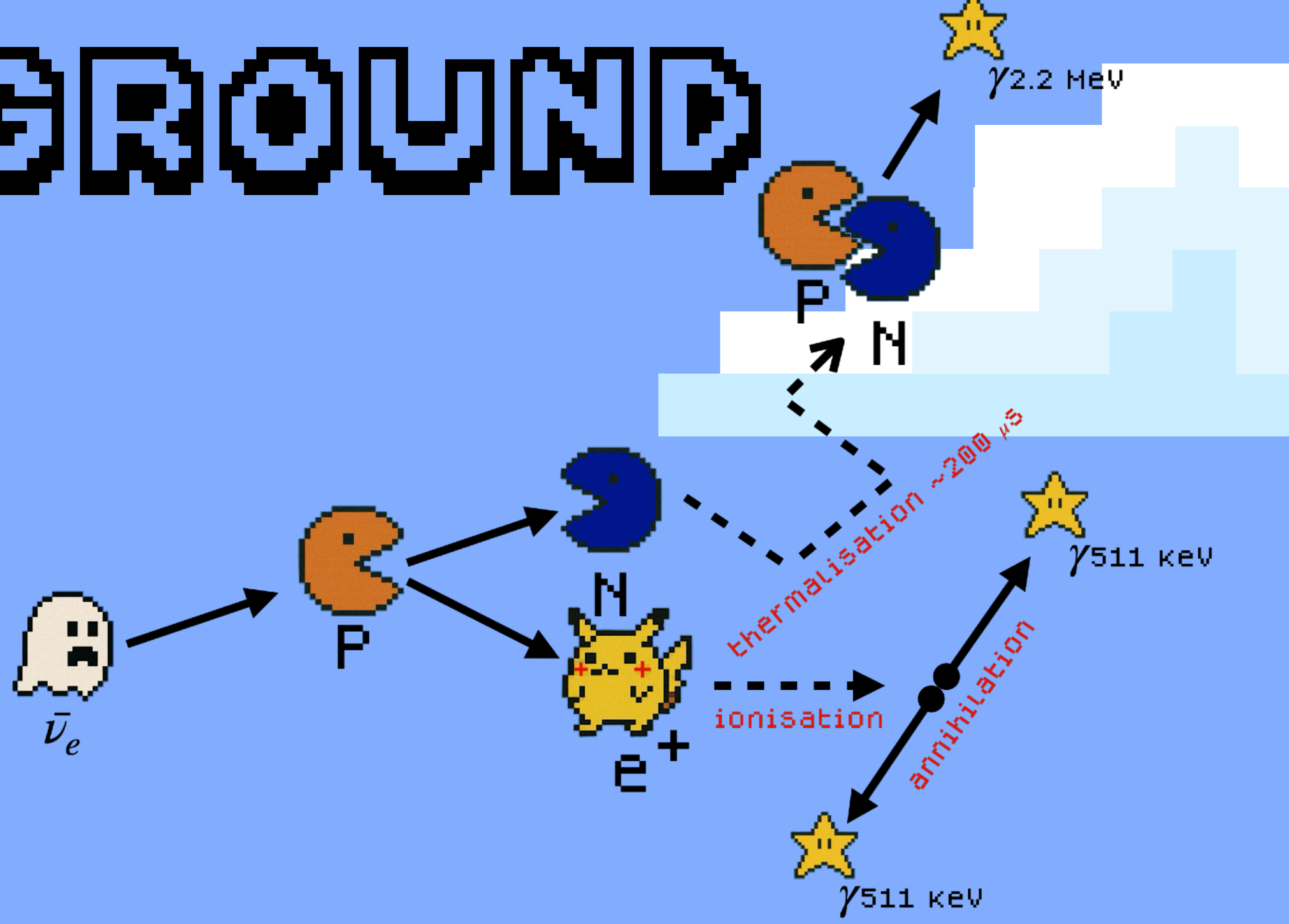
SIGNAL AND BACKGROUND

- **Neutrino detection:**

  -Inverse β decay $\bar{\nu}_e + p \rightarrow n + e^+$

  $E_{vis}(e^+) \simeq E(\bar{\nu}_e) - 0.8$ MeV

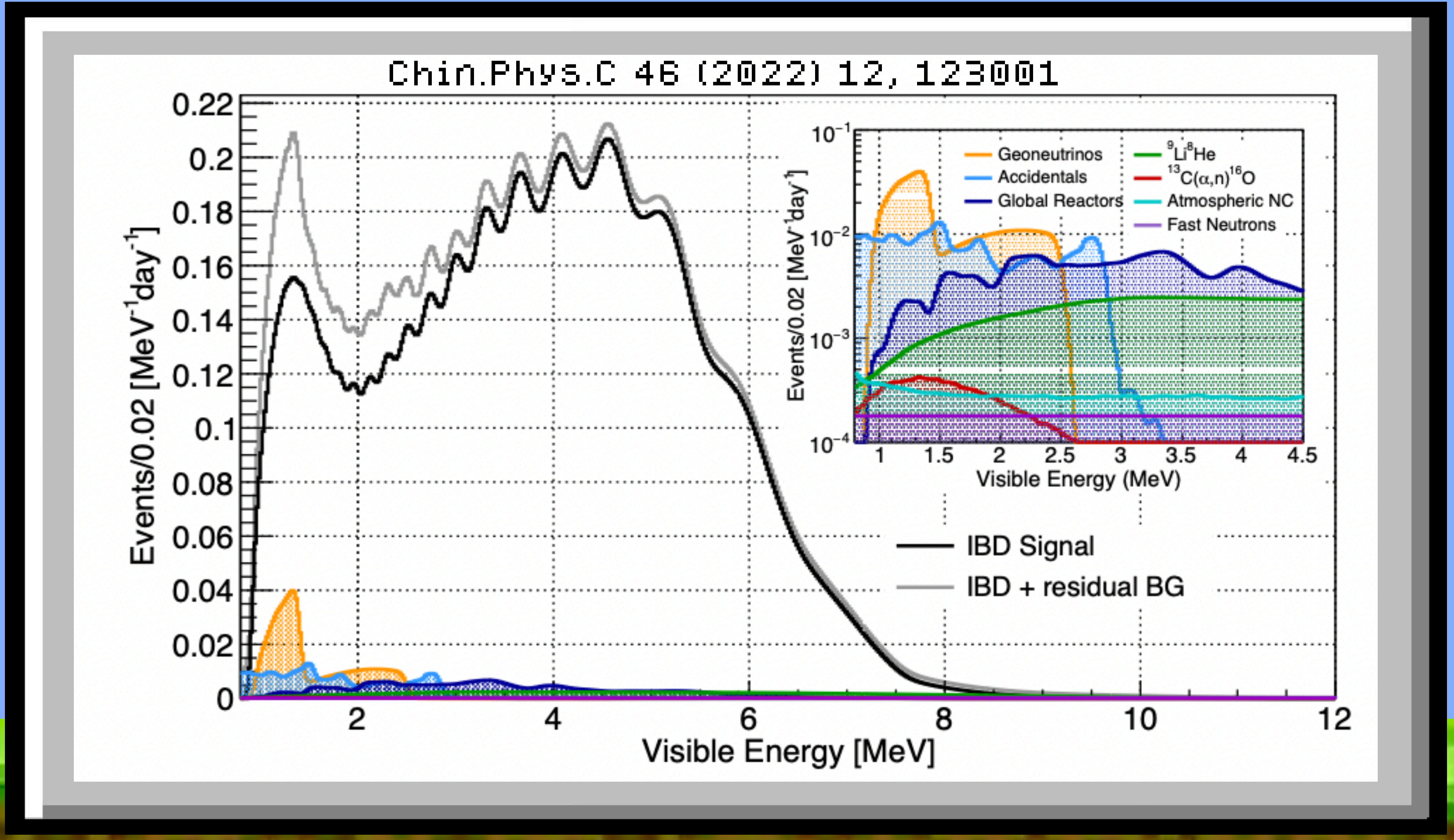
  -Prompt-delay signature ensures large background suppression



- **Background:**

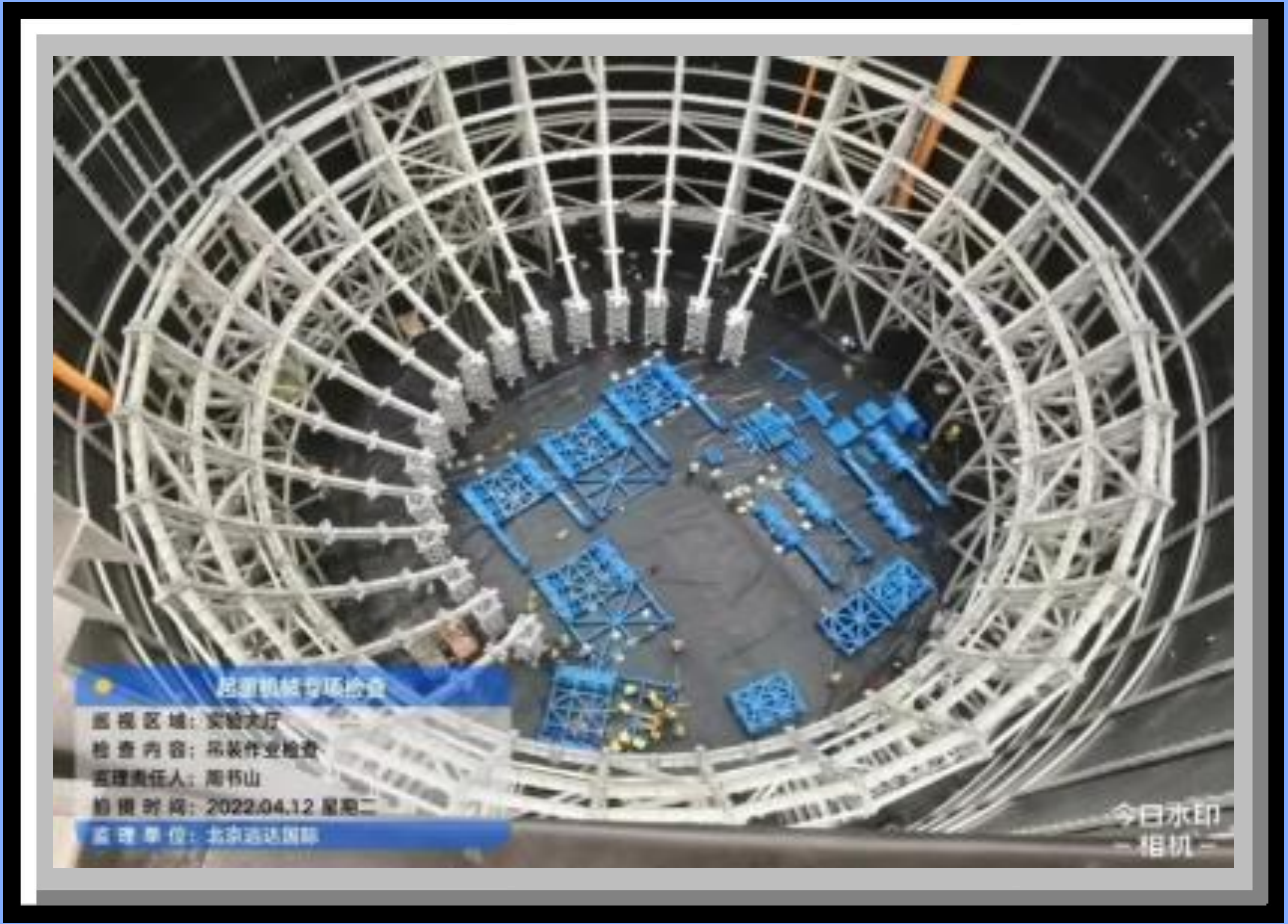
  -Selection cut on time & space correlation between prompt and delay signal, energy threshold and muon veto strategy

  - After selection cuts:
  ~47 signal events/day
  ~4 background events/day

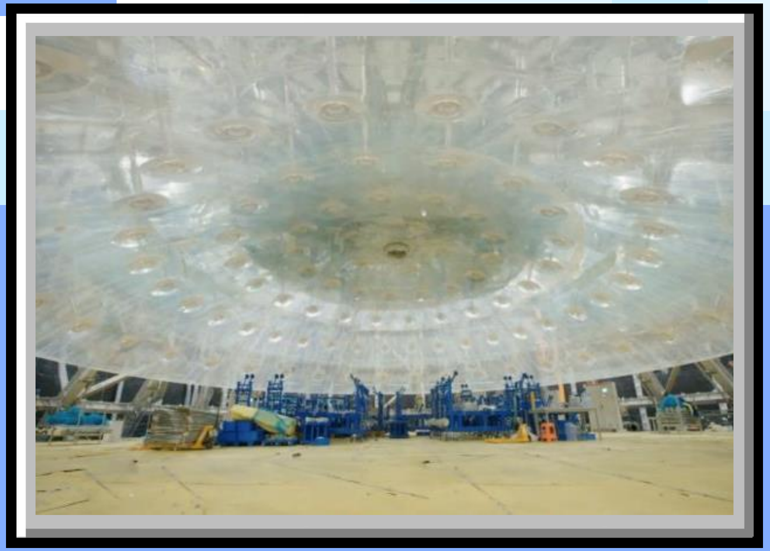


CD CONSTRUCTION

Bottom structure Jan. 2022



5 Acrylic layers



Acrylic assembly platform

20 Acrylic layers

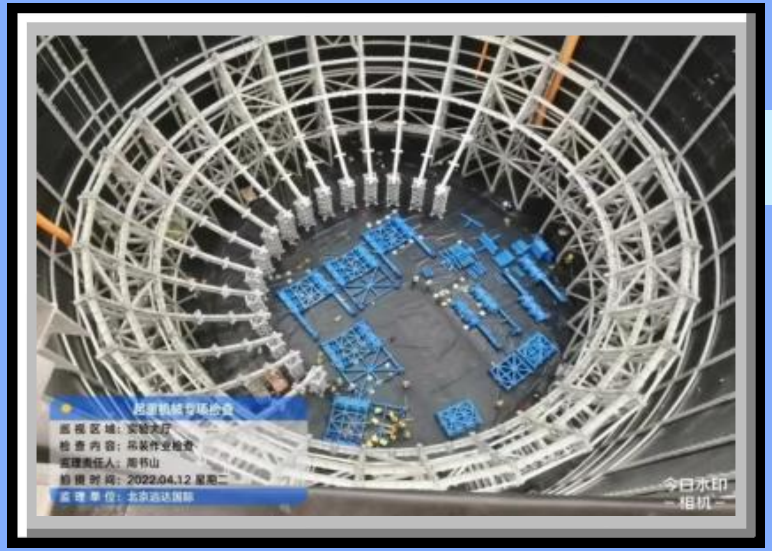
Top structure

23 Acrylic layers

13 CD CONSTRUCTION

Acrylic assembly platform

Bottom structure



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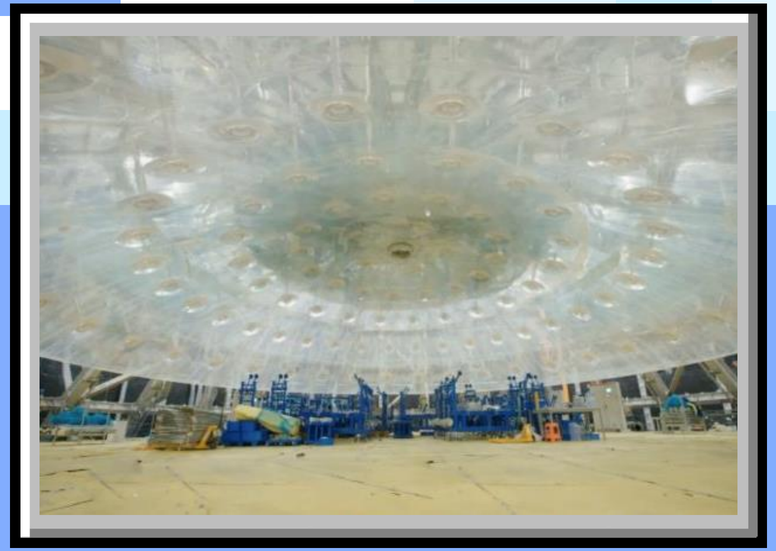

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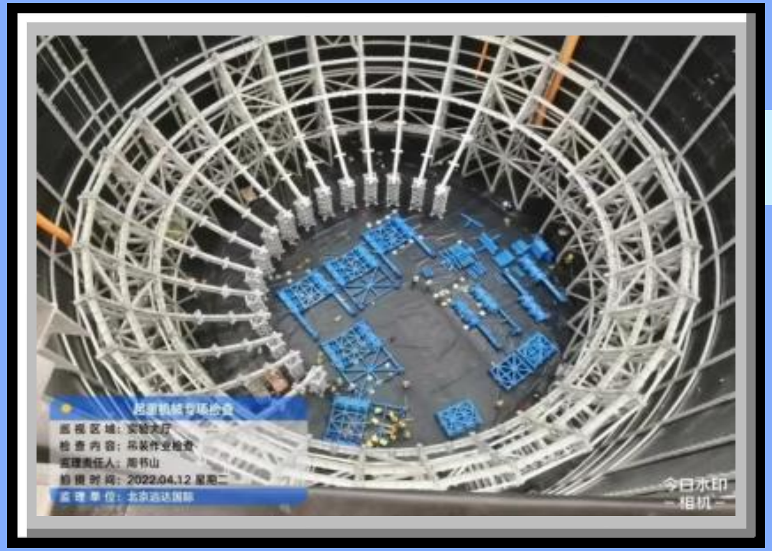

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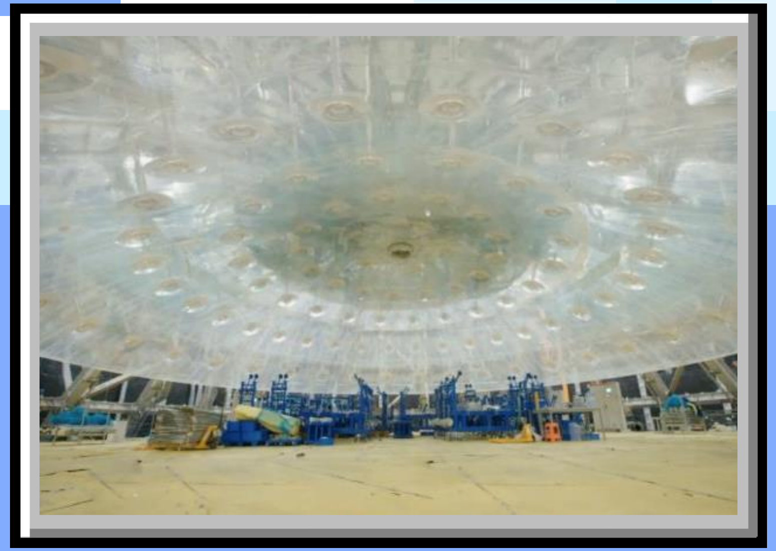

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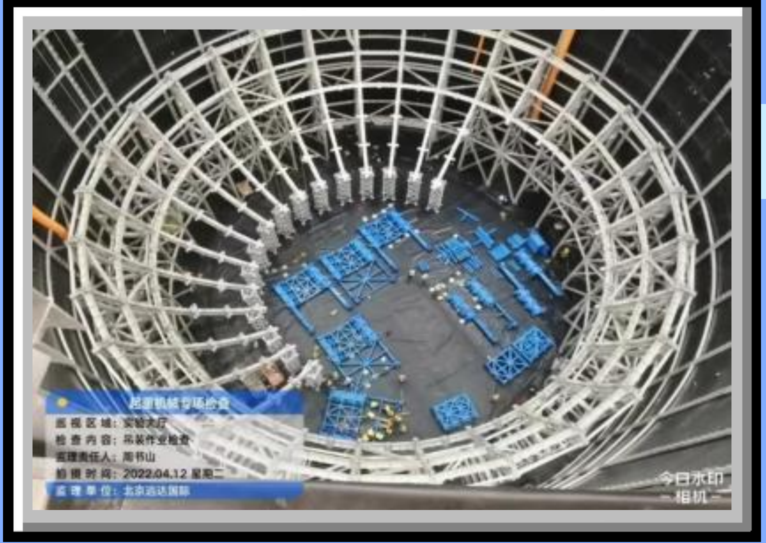

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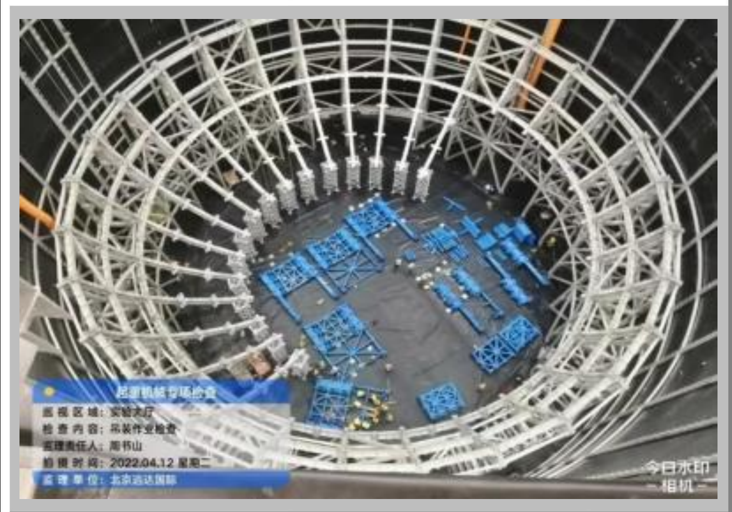

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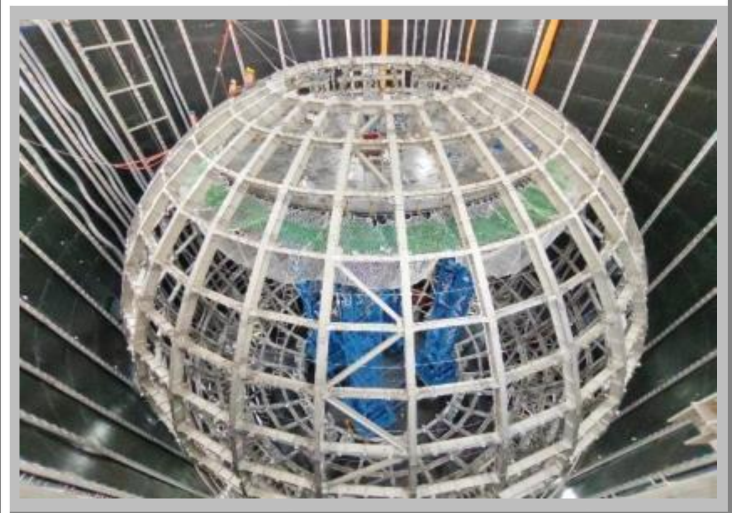

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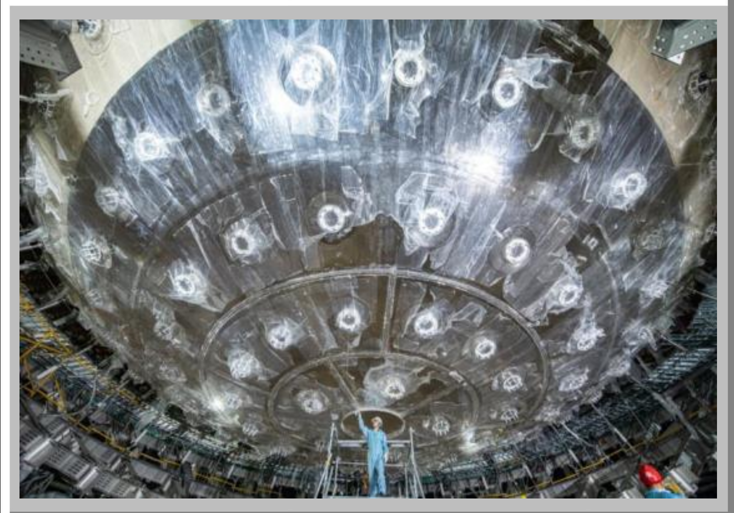

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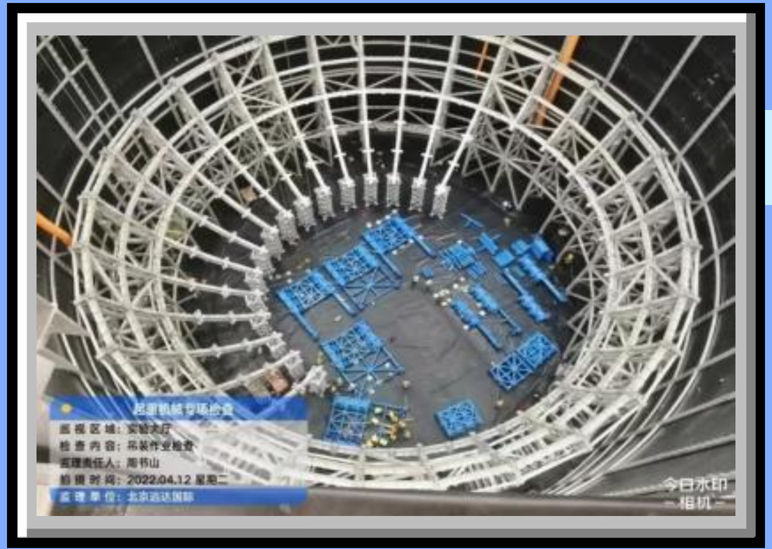

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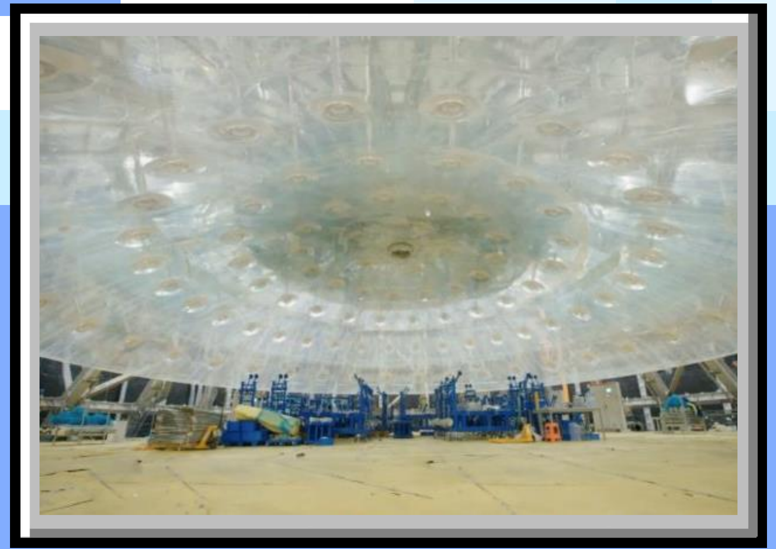

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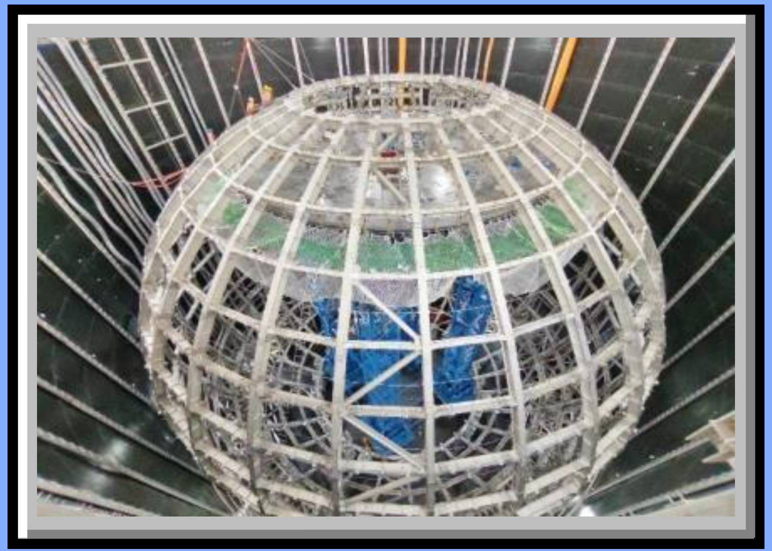
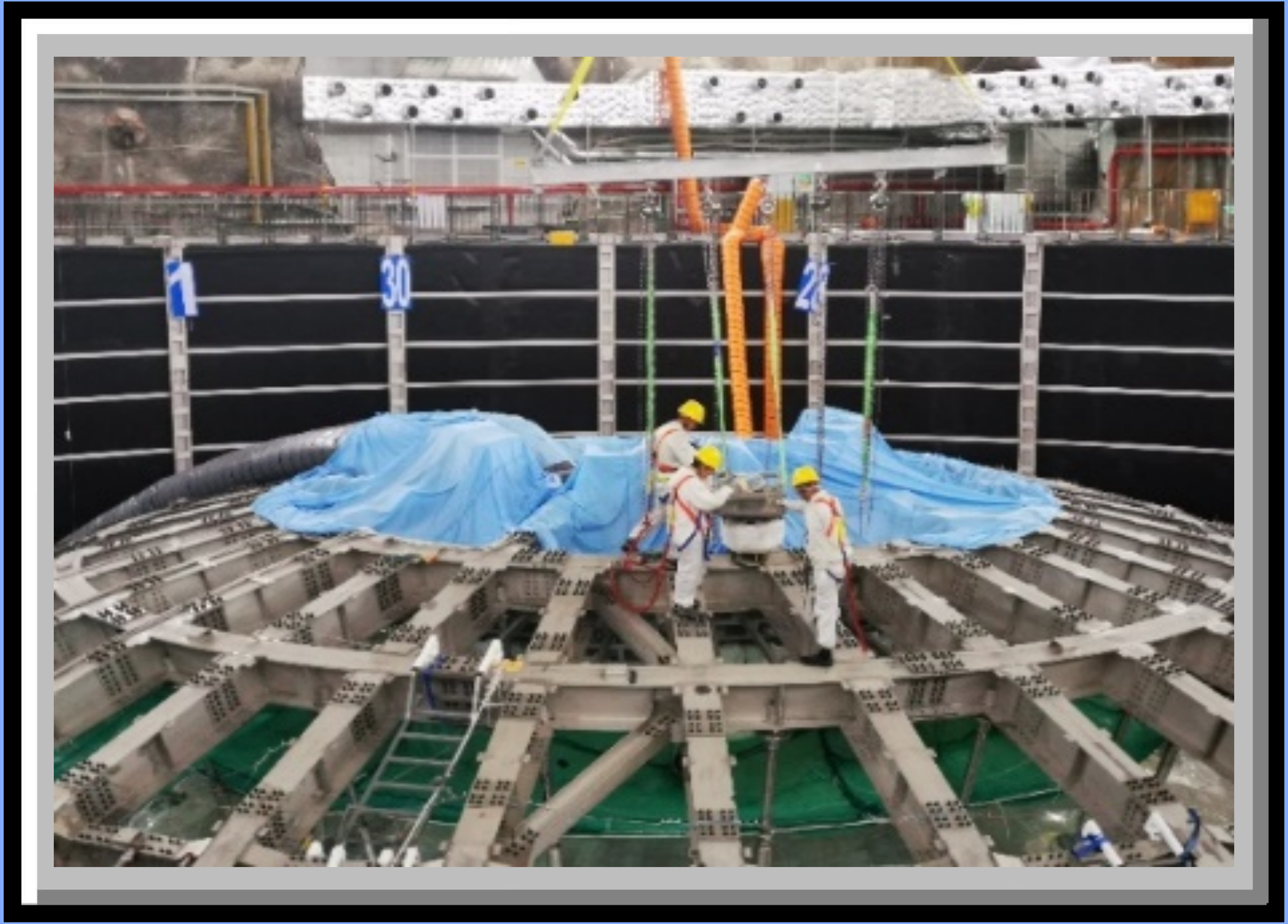


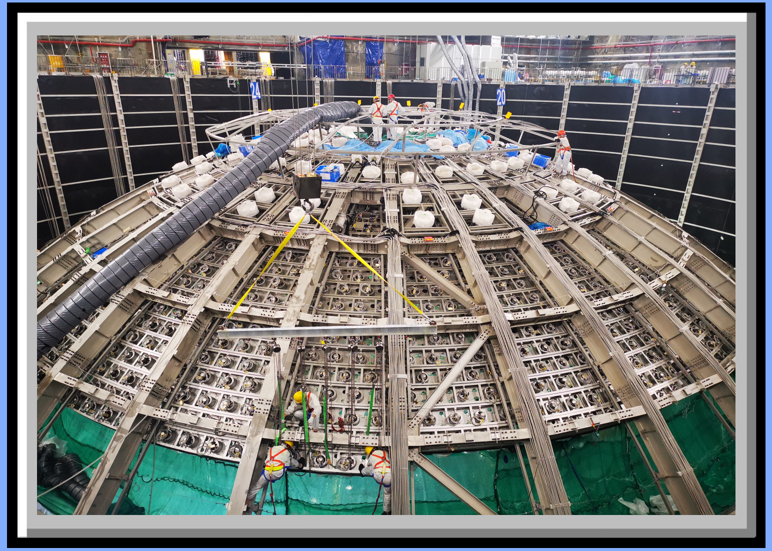
1 4 PMT INSTALLATION

1 PMT layer Oct. 2022

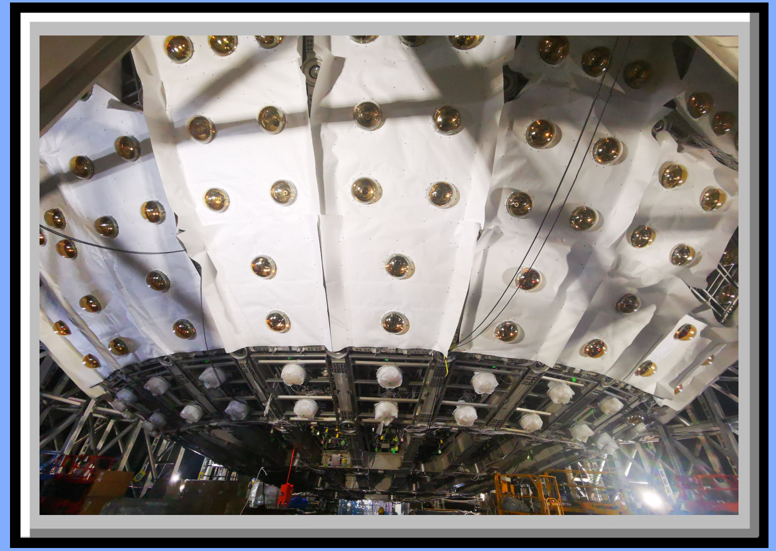


Inside view

4 PMT layers

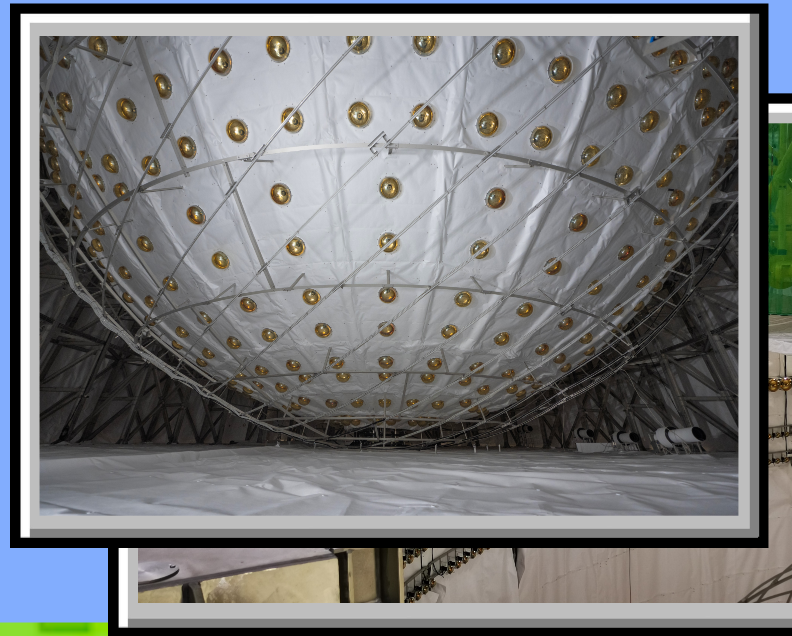


22 PMT layers



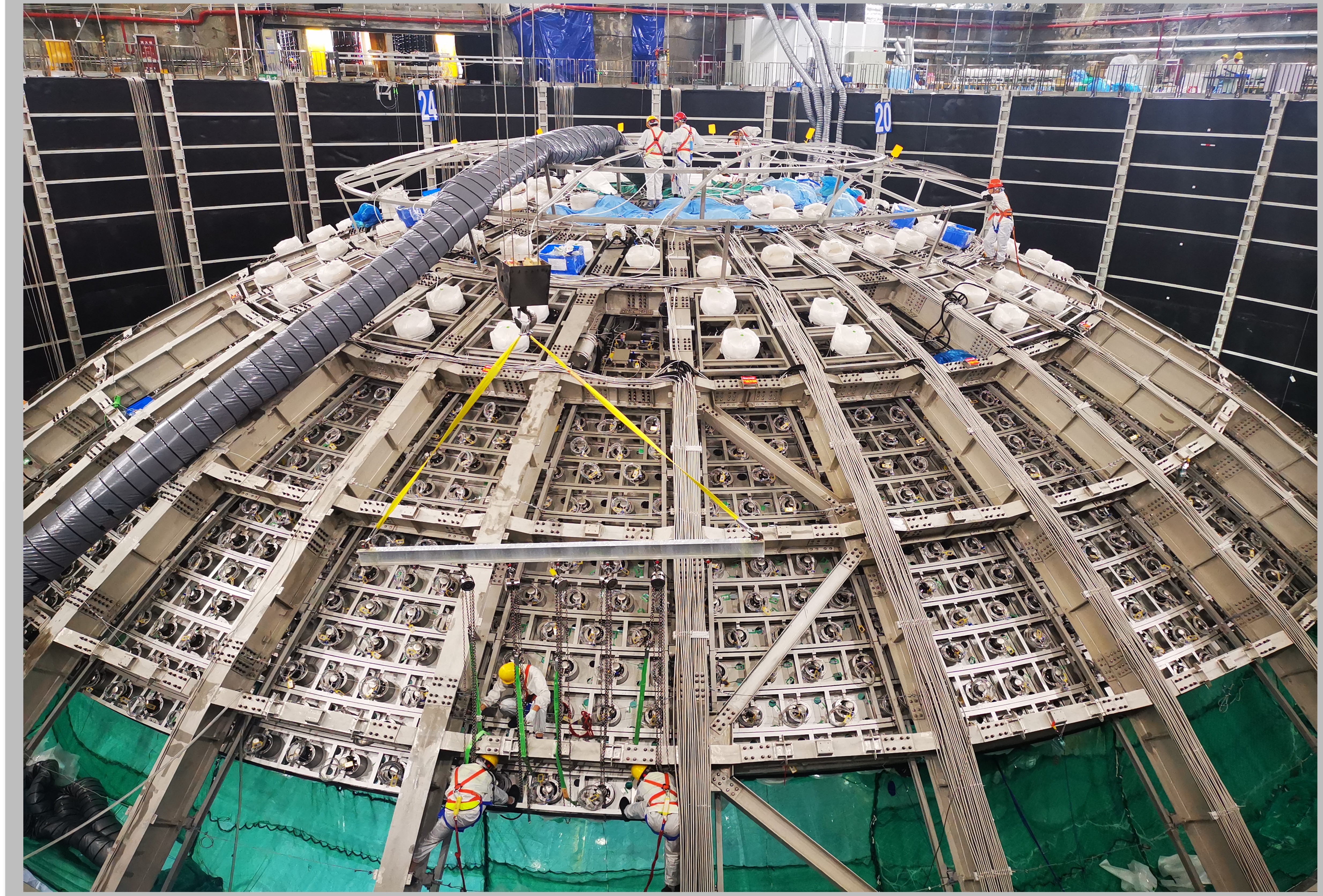
9 PMT layers

CD completion

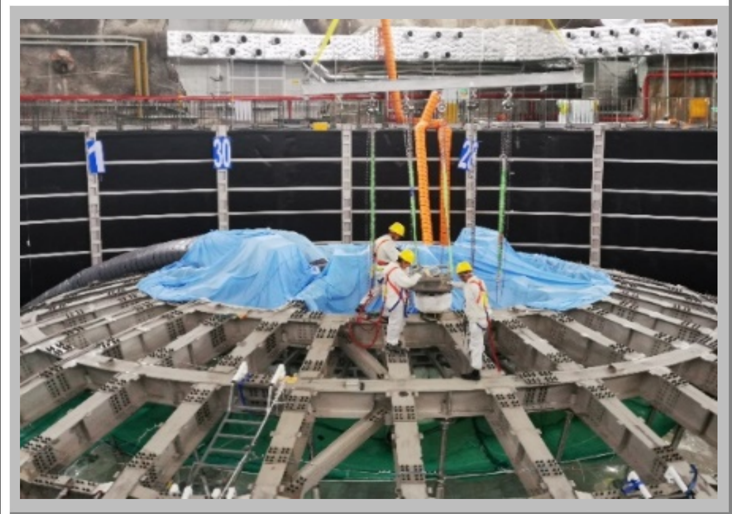


1 4 PMT INSTALLATION

PMT 4 layers

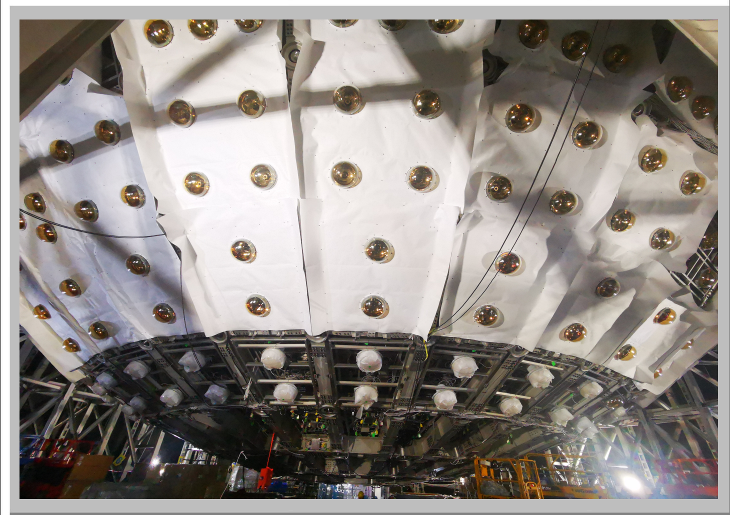


PMT 1 layer



Inside view

22 PMT layers



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CD completion

14 PMT INSTALLATION

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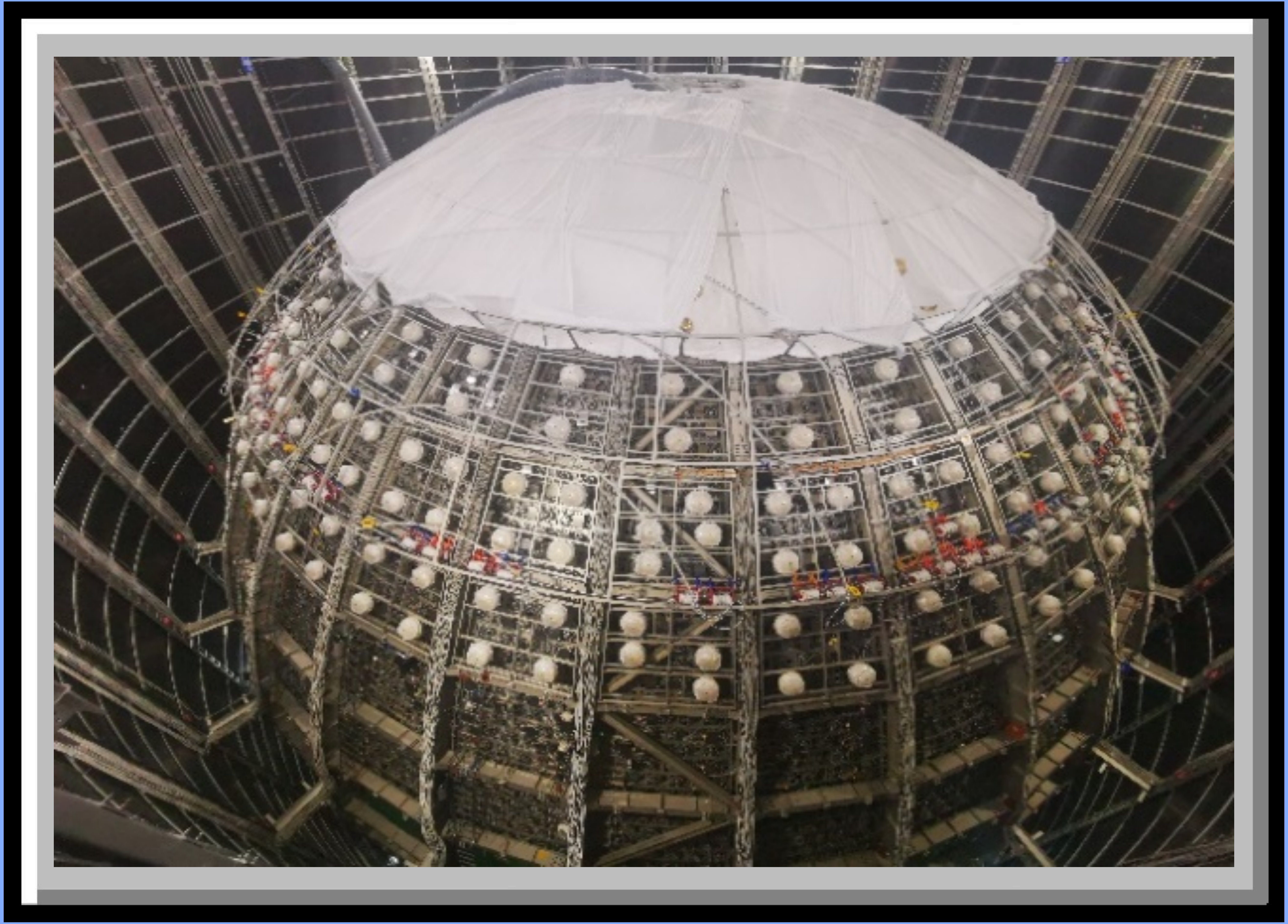

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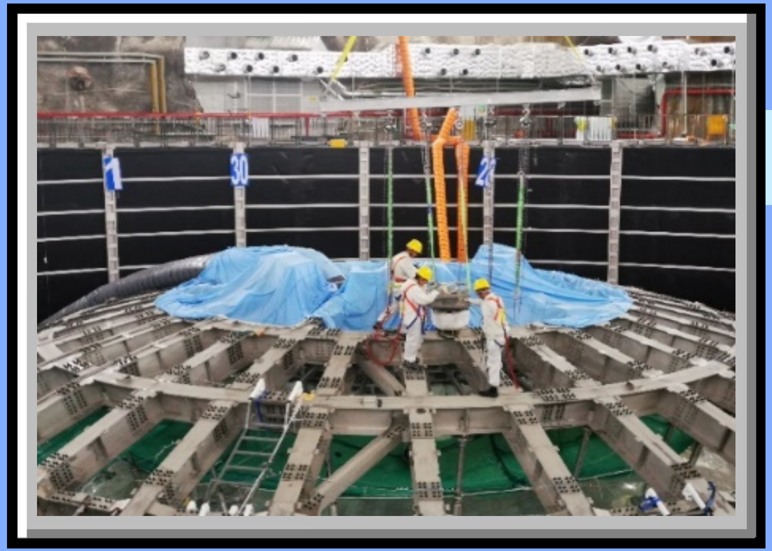
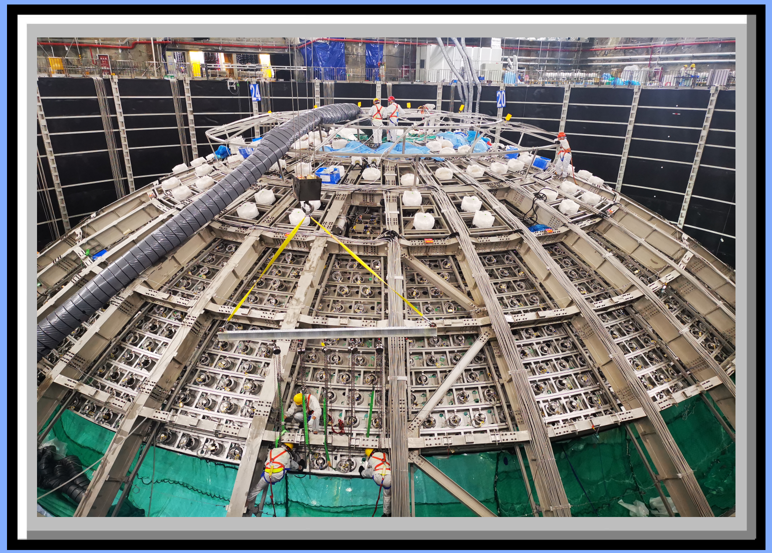


Inside view

PMT 4 layers



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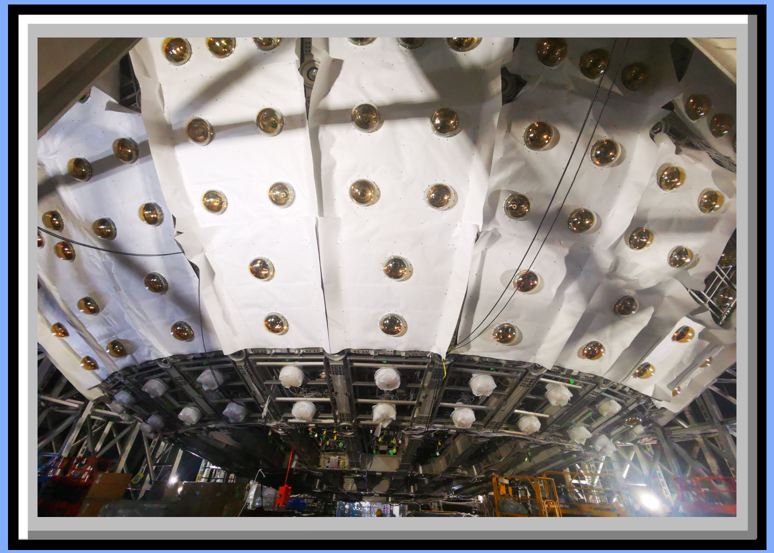

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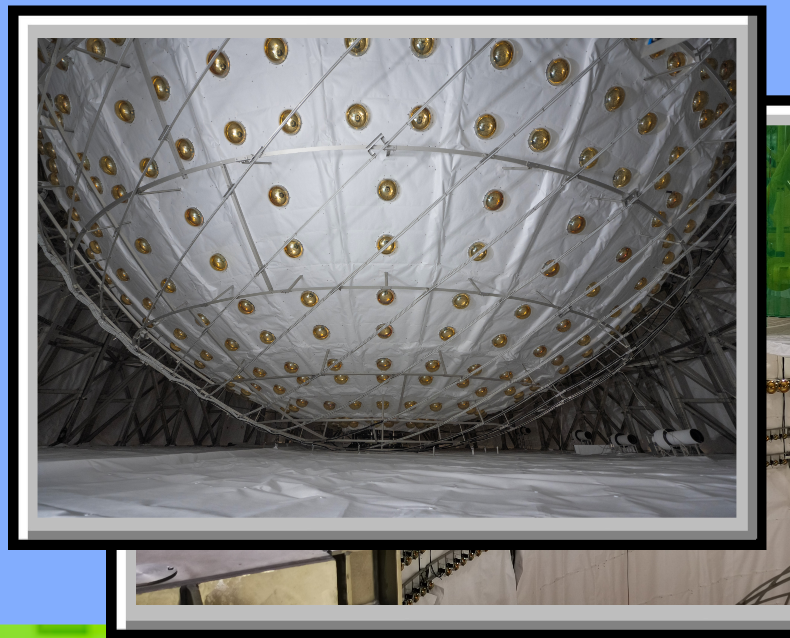
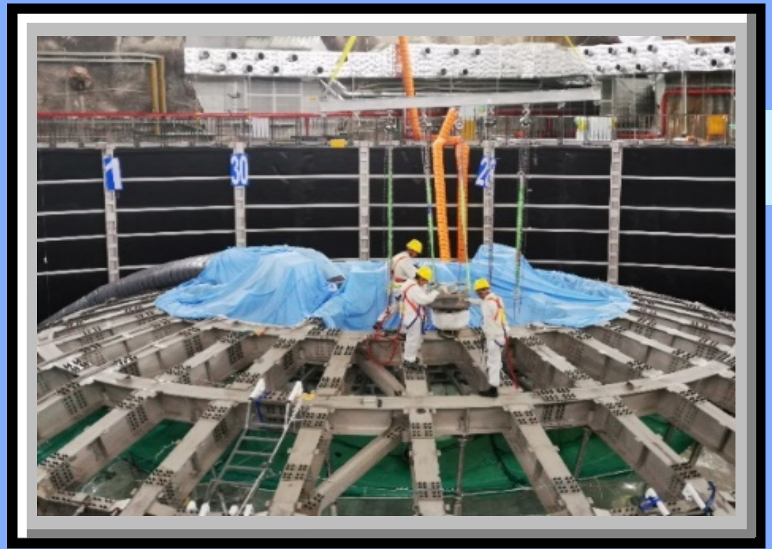


14 PMT INSTALLATION

Inside view

PMT 1 layer



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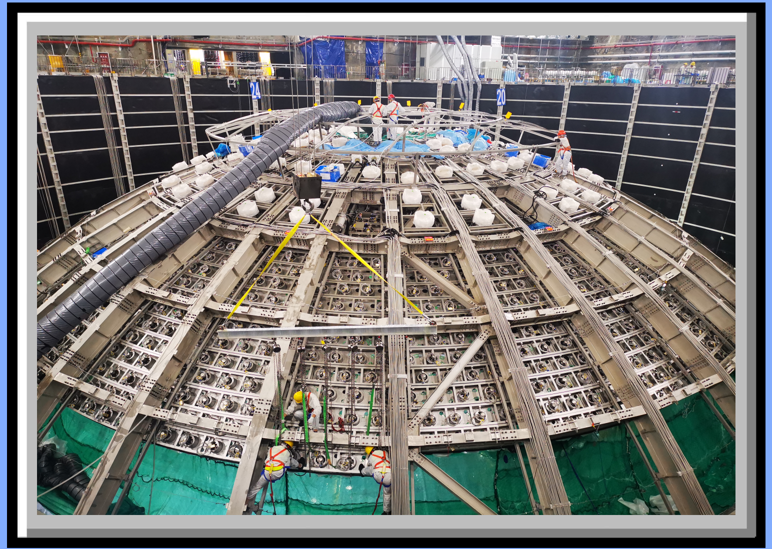

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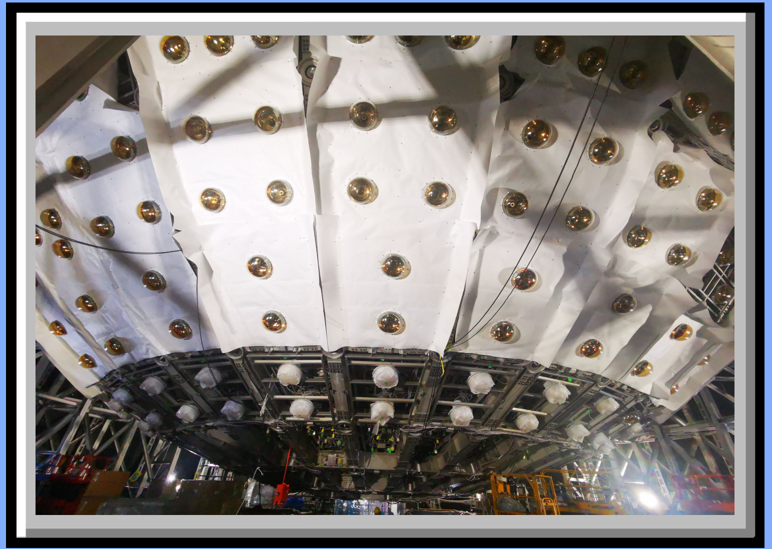

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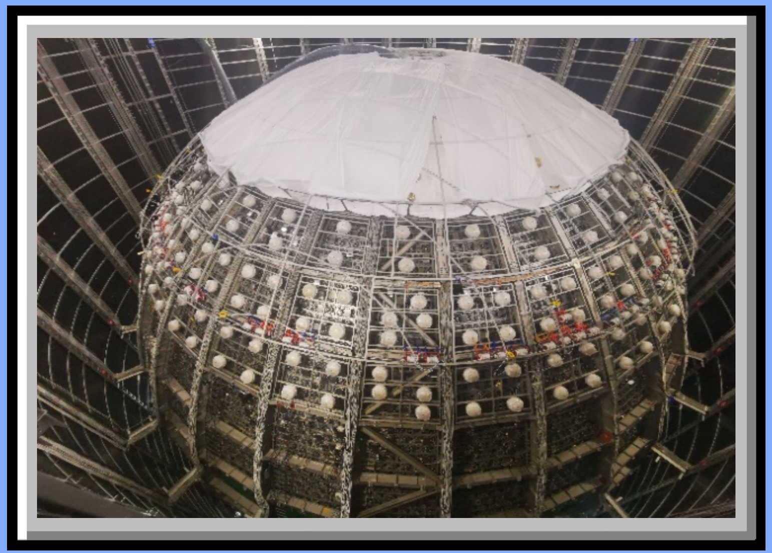

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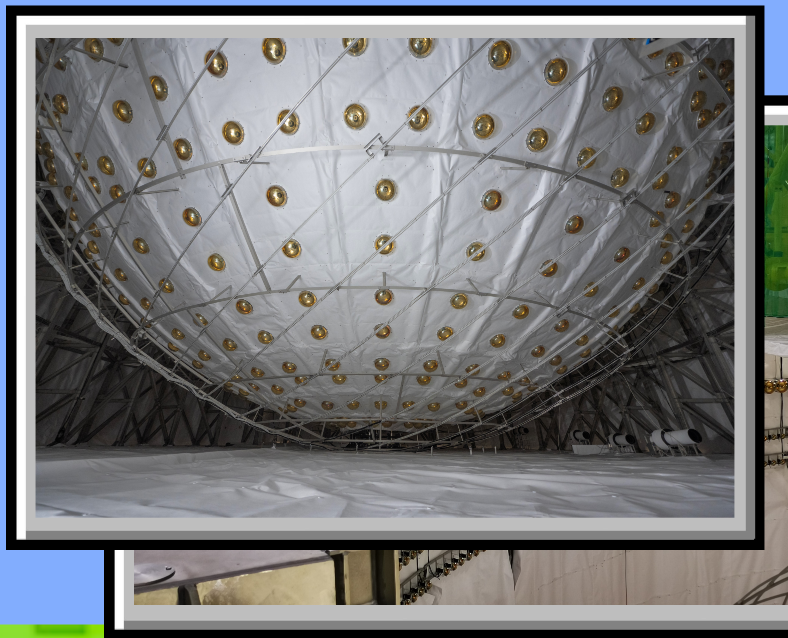

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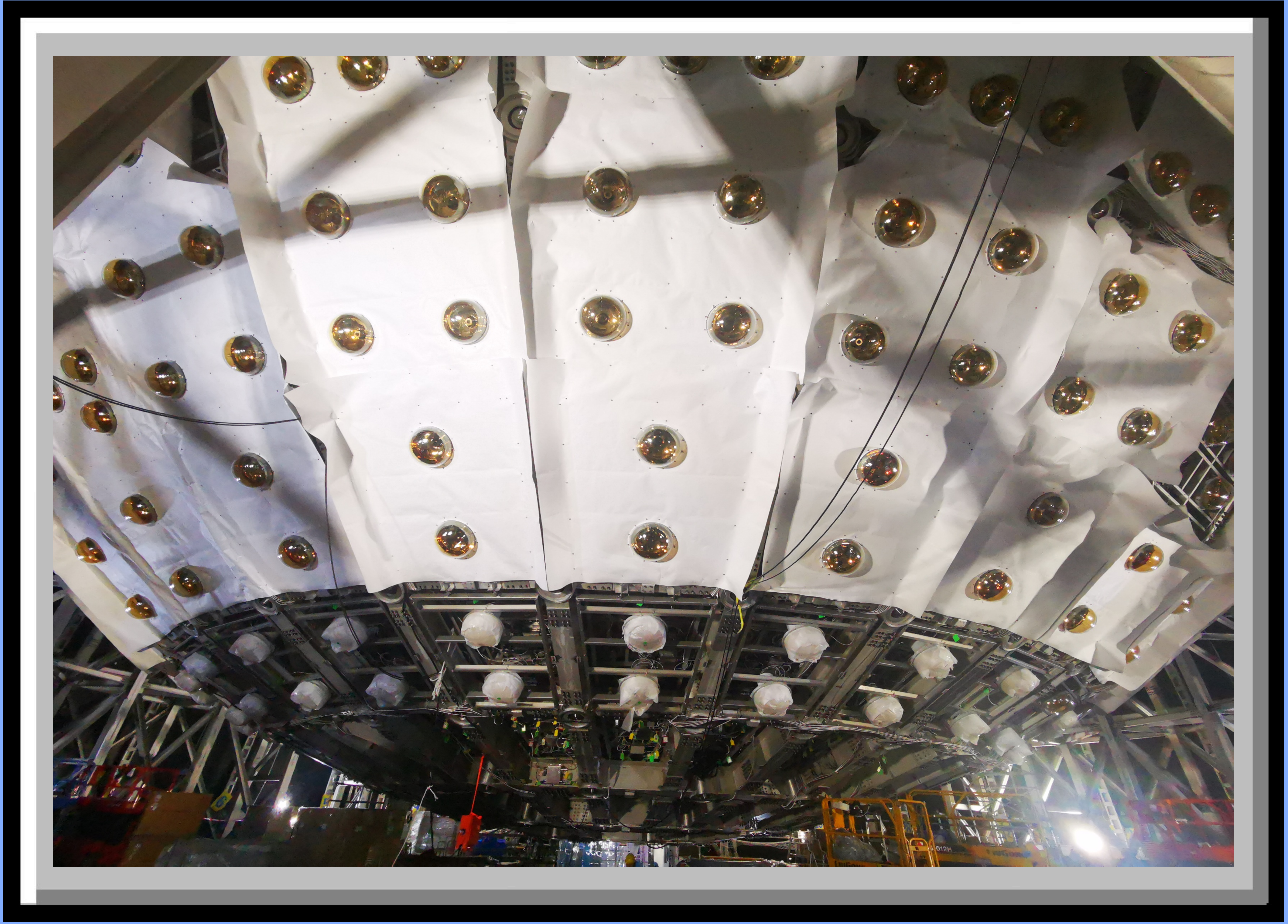

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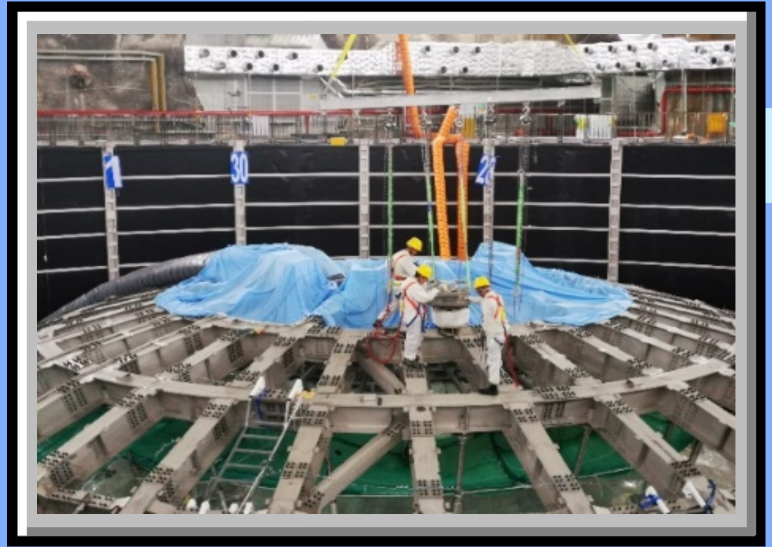
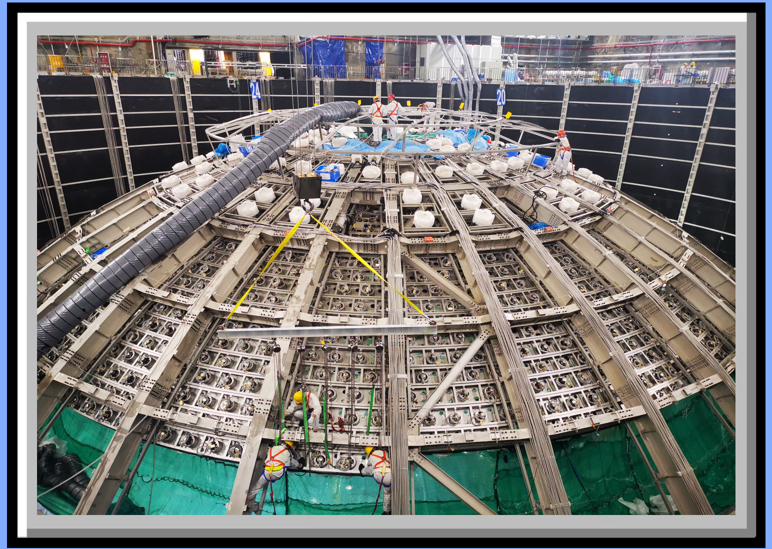


Inside view

PMT 4 layers



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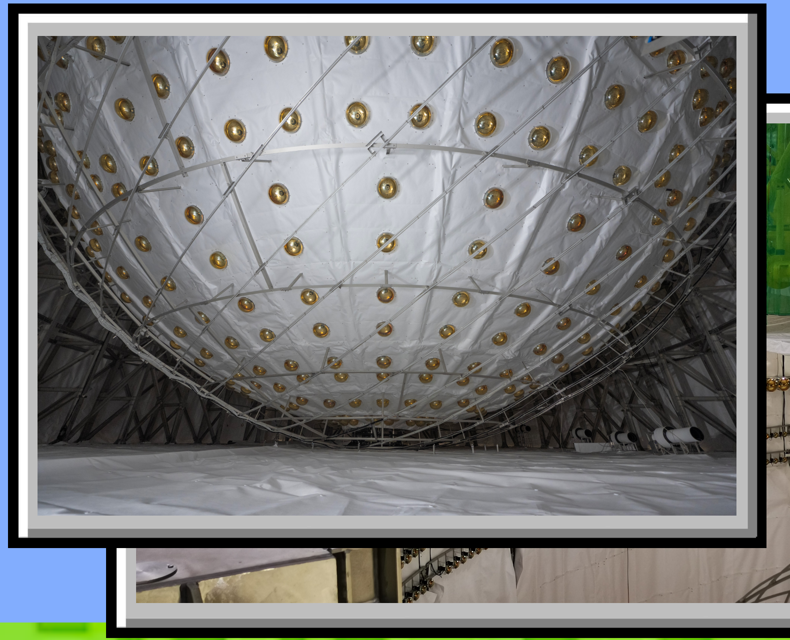
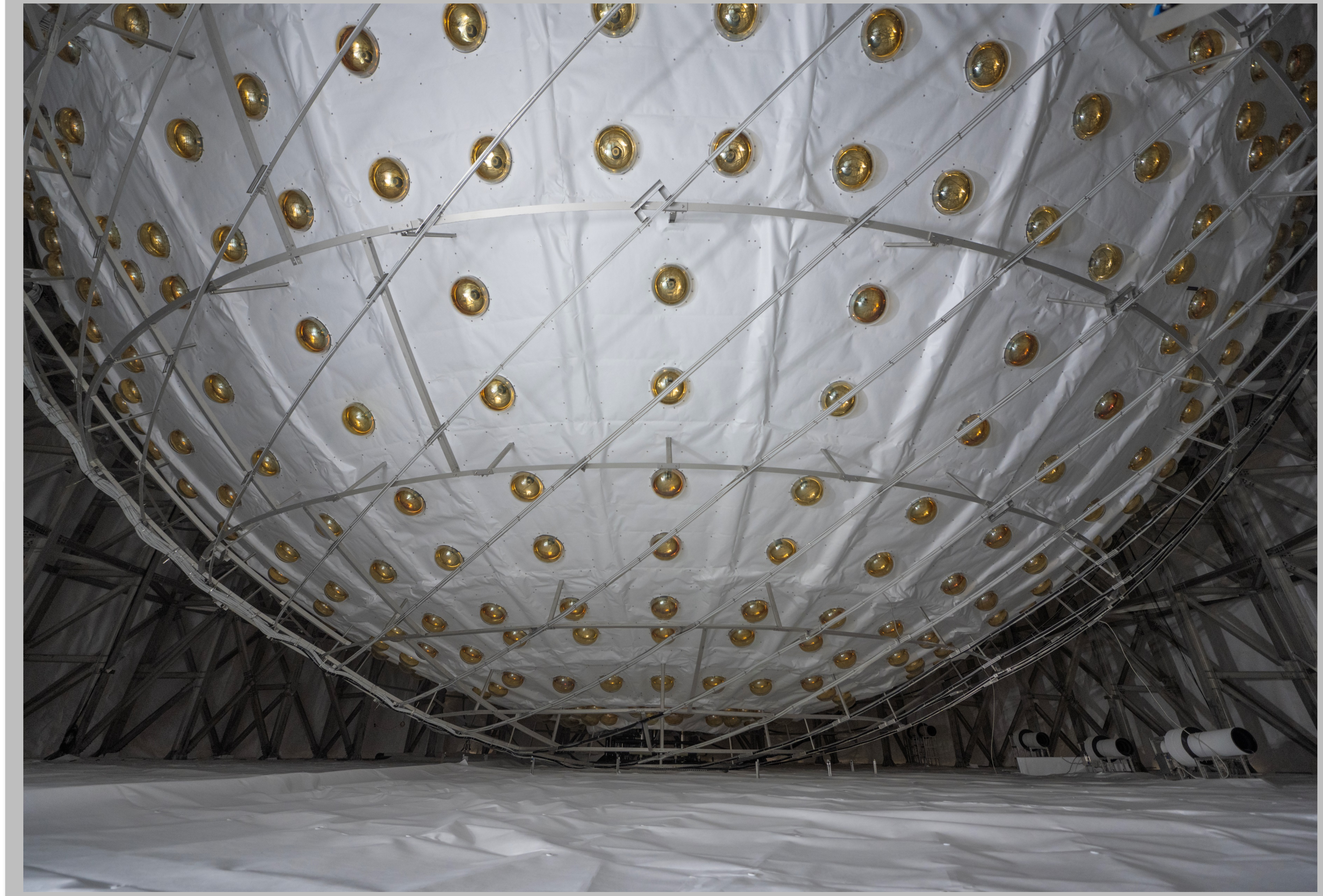


14 PMT INSTALLATION

CD completion Dec. 2024



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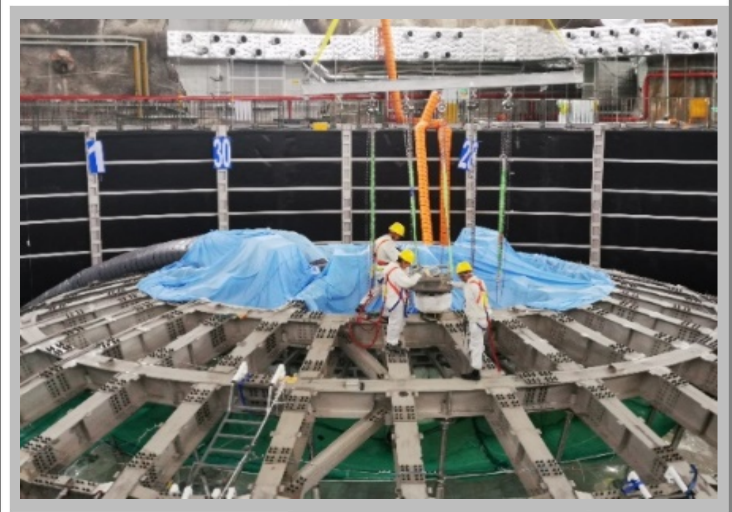
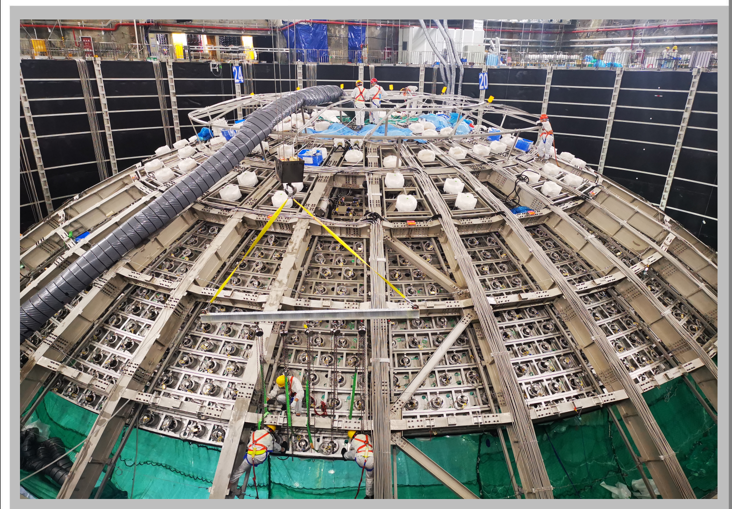


Inside view

PMT 4 layers



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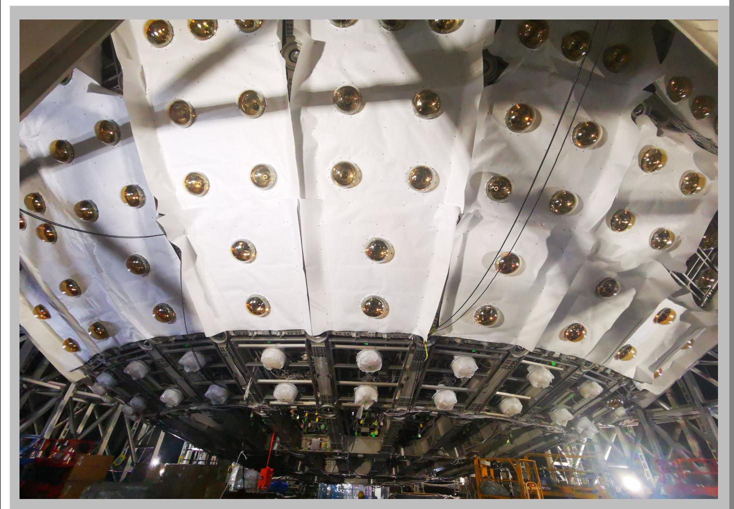
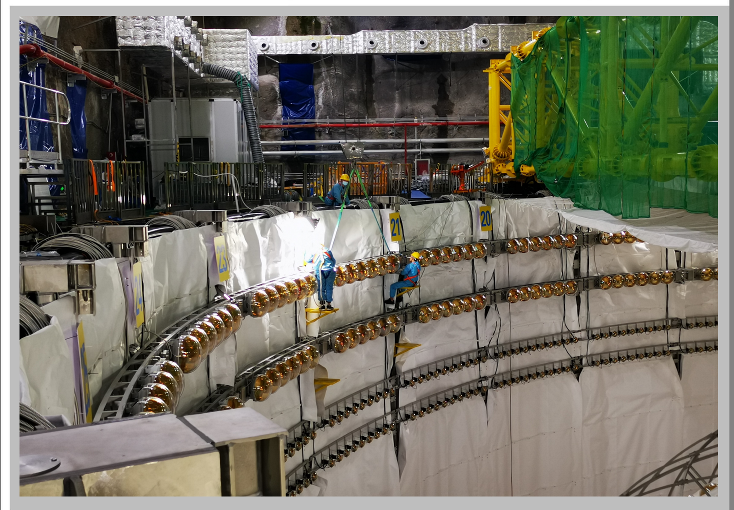


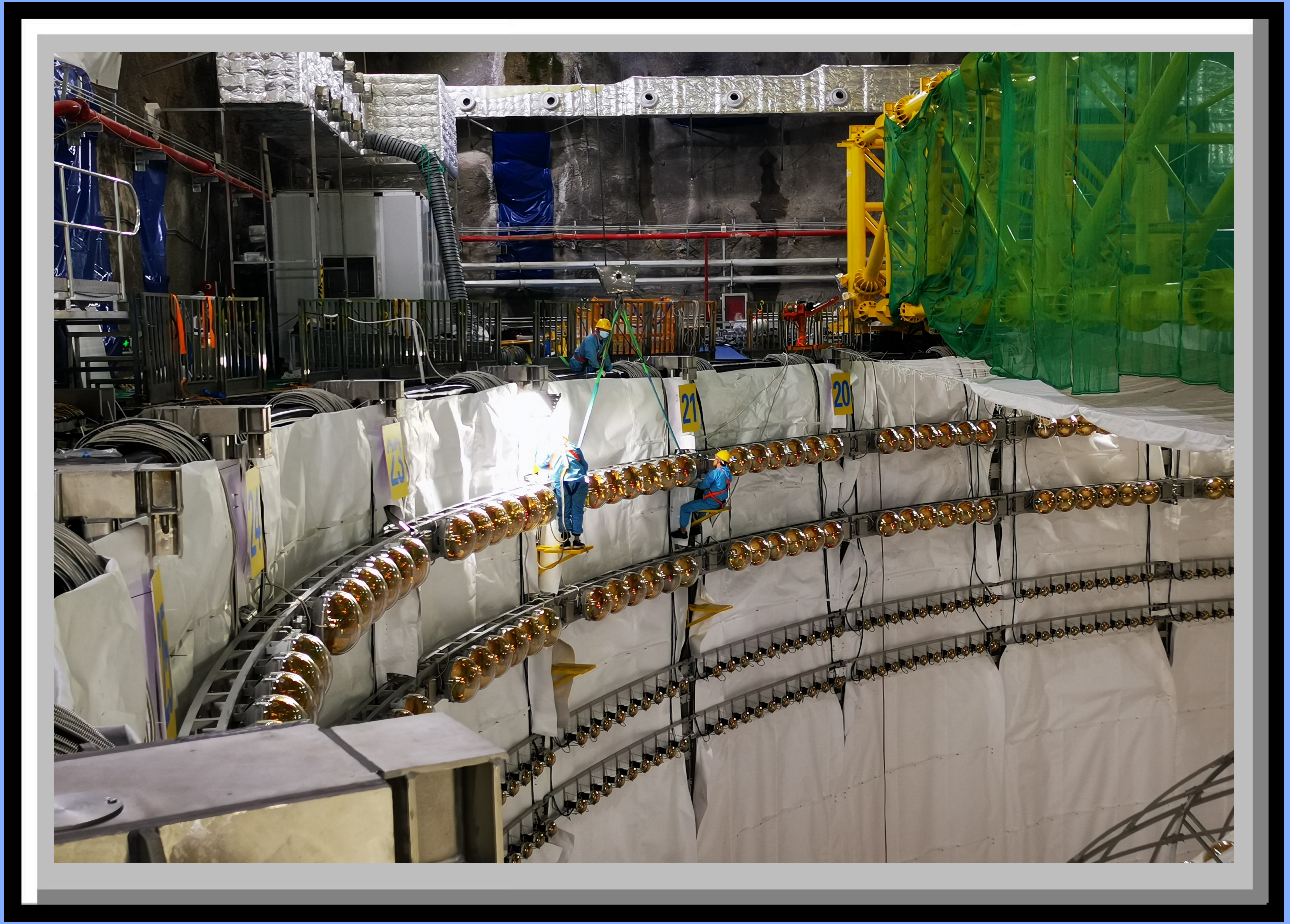
9 PMT layers

Water Pool extra PMTs



14 PMT INSTALLATION

Water Pool extra PMTs Dec. 2024



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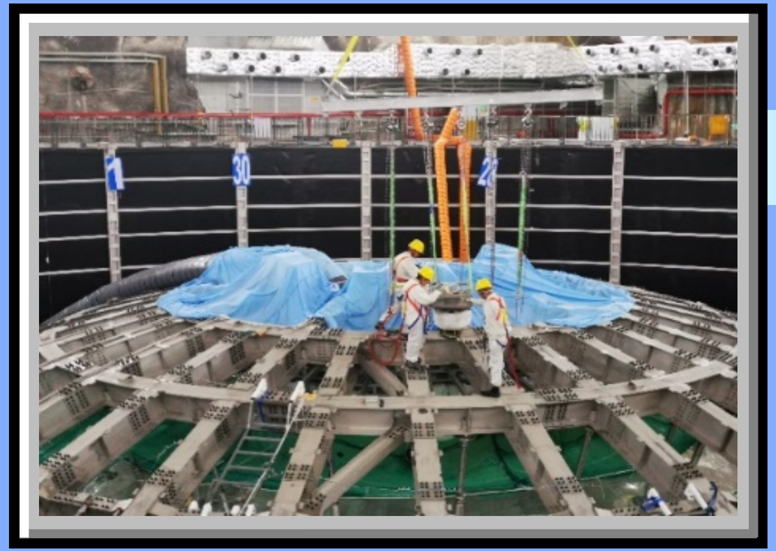

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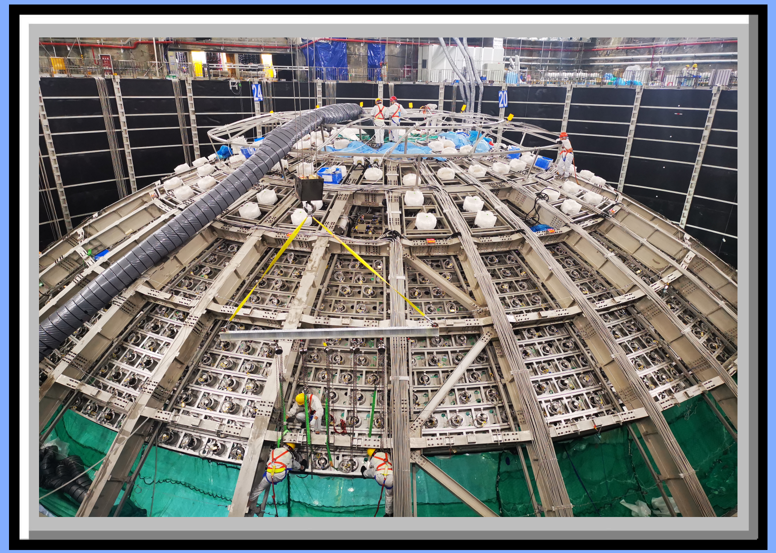
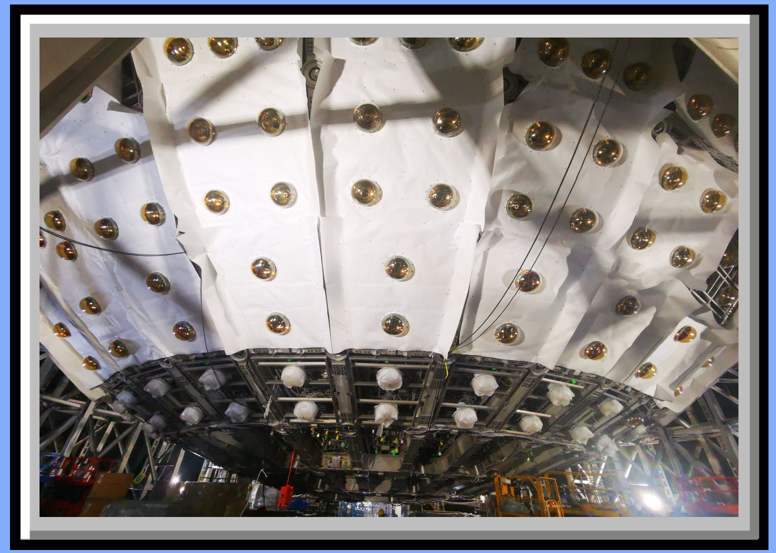
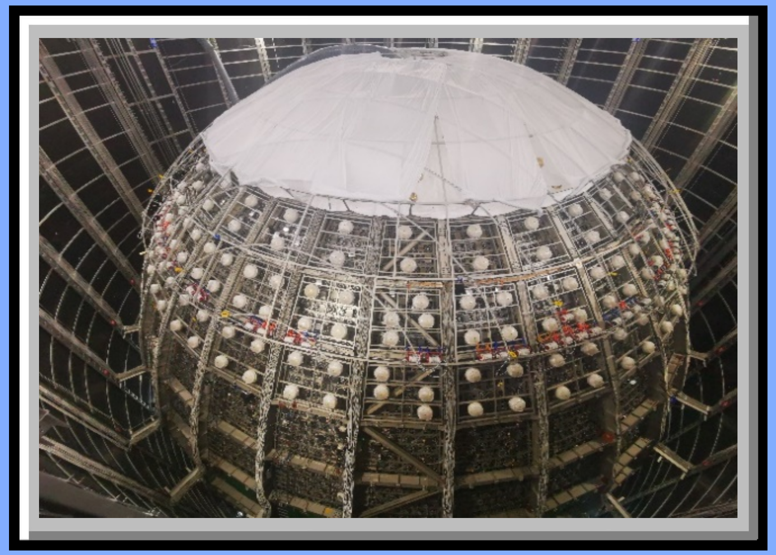


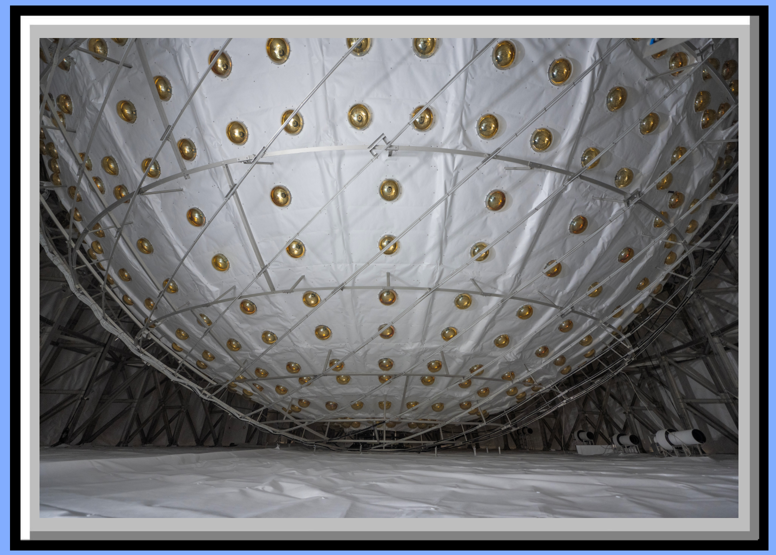
22 PMT layers



9 PMT layers



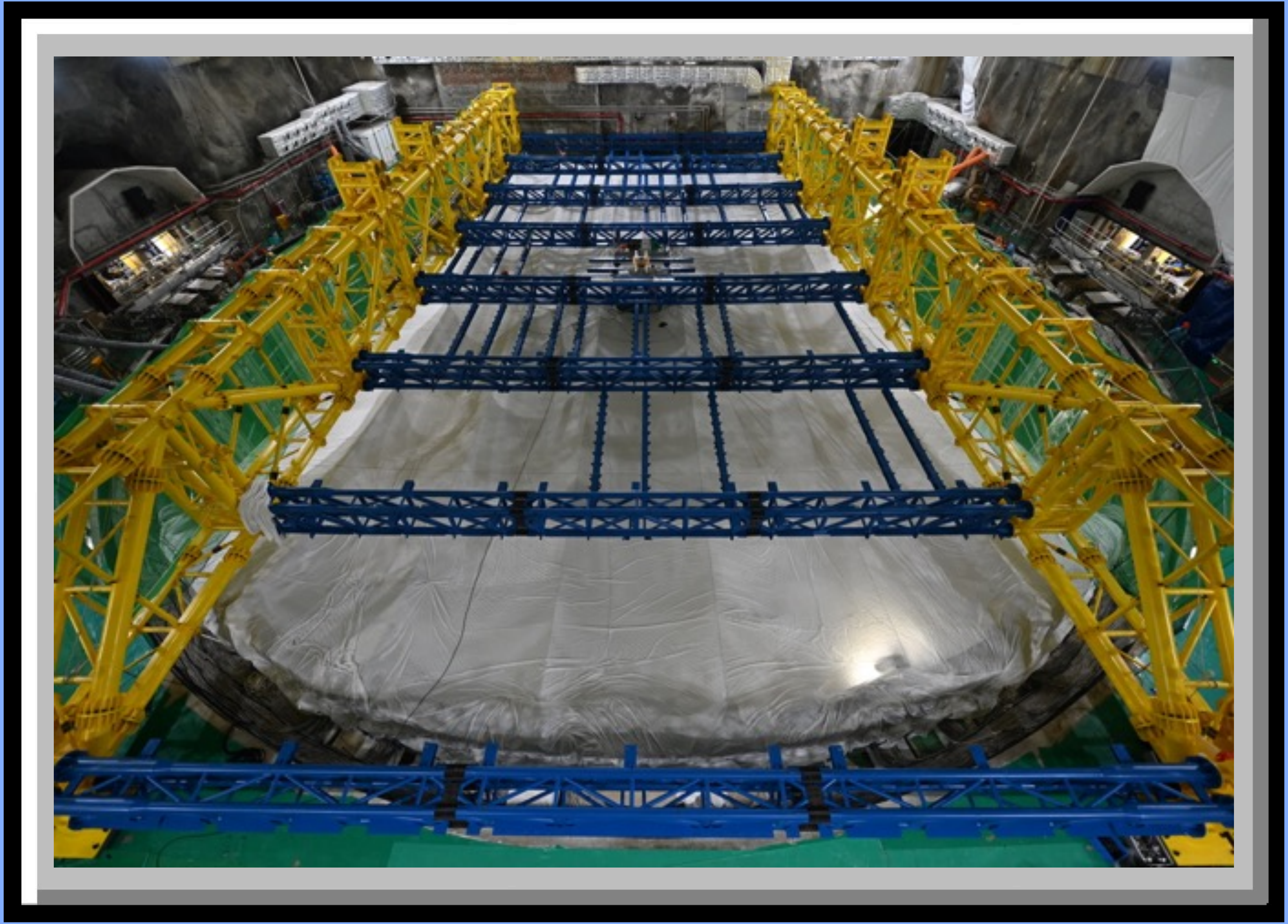
CD completion



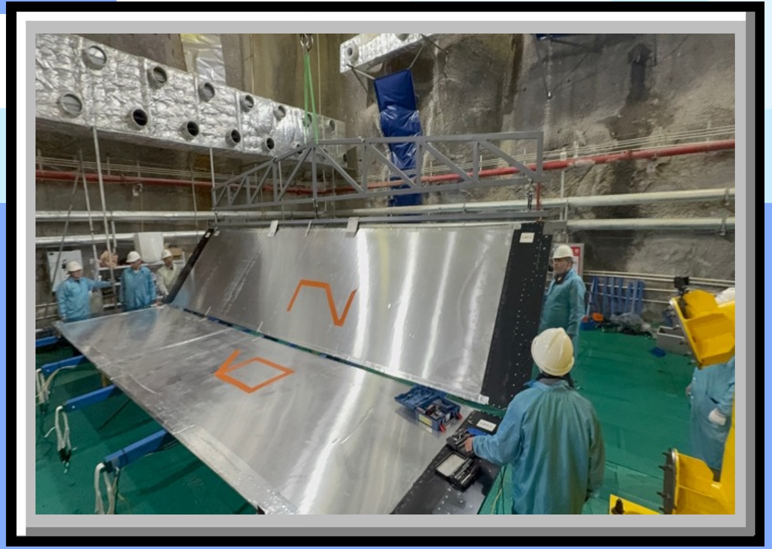
15

TT INSTALLATION

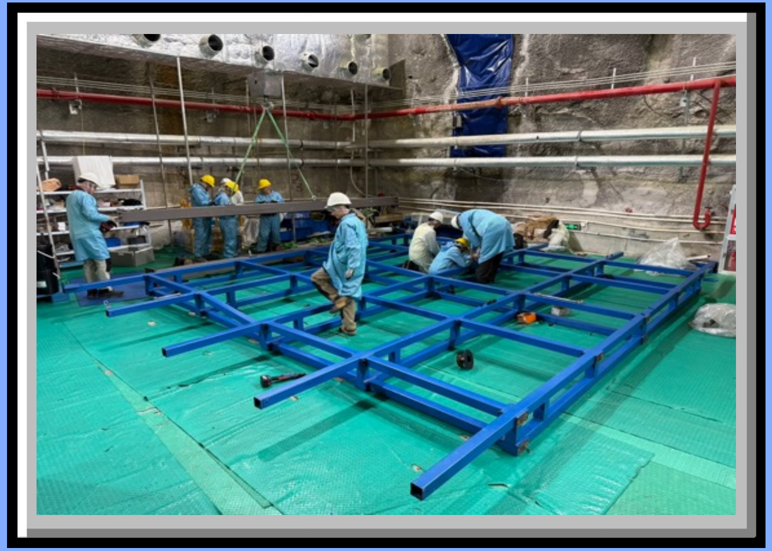
Top Tracker Bridge Jan. 2025



Modules positioning



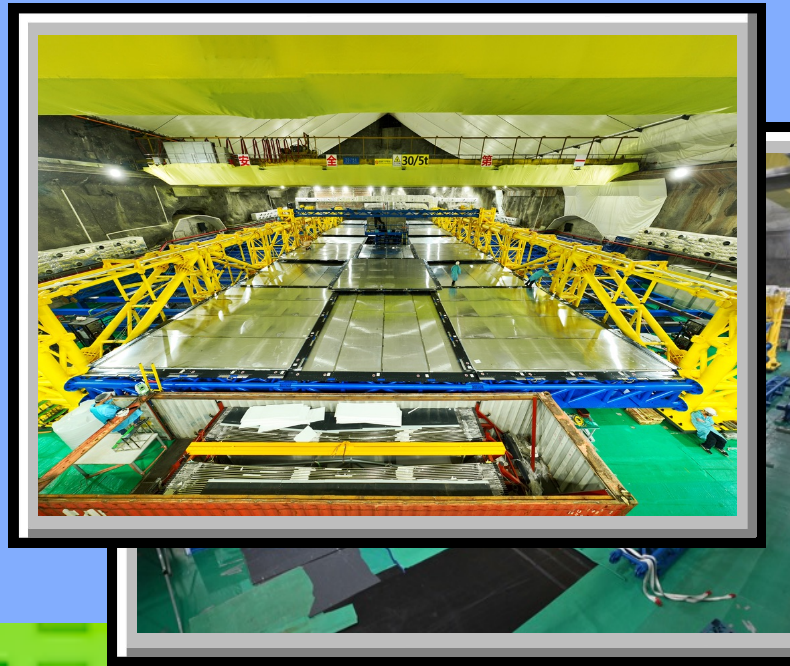
Support Table assembly



Wall positioning

Module testing & validation

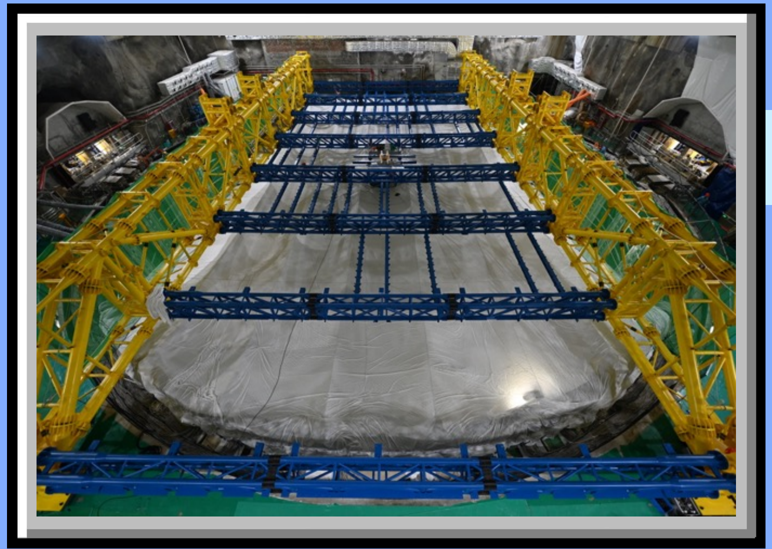
1st Top Tracker layer



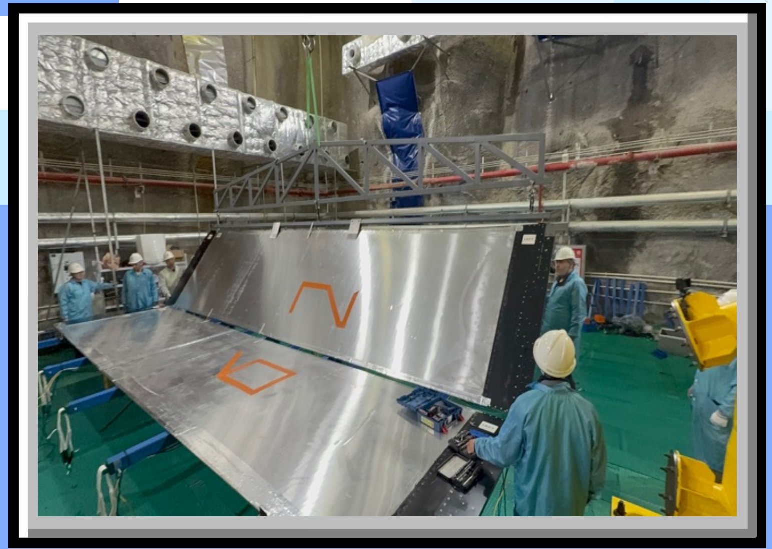
15 TT INSTALLATION

Support Table assembly

Top Tracker Bridge



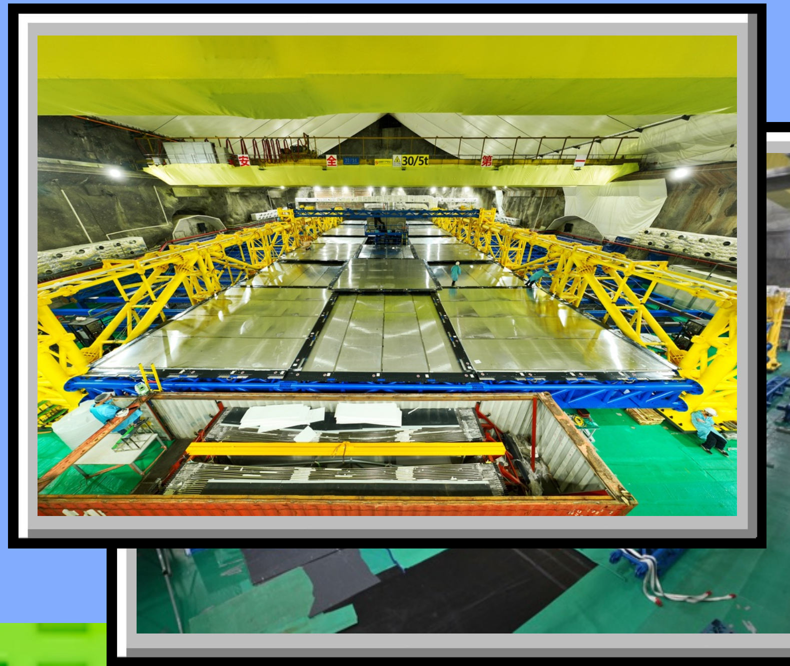
Modules positioning



Wall positioning

Module testing & validation

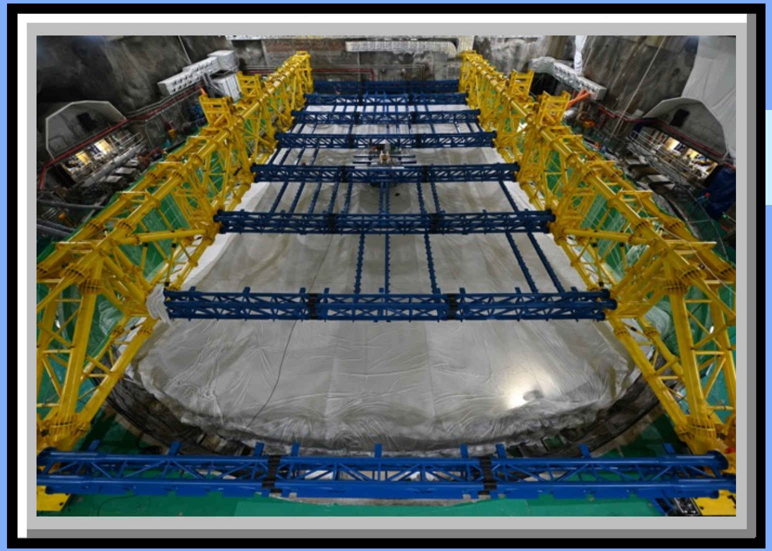
1st Top Tracker layer



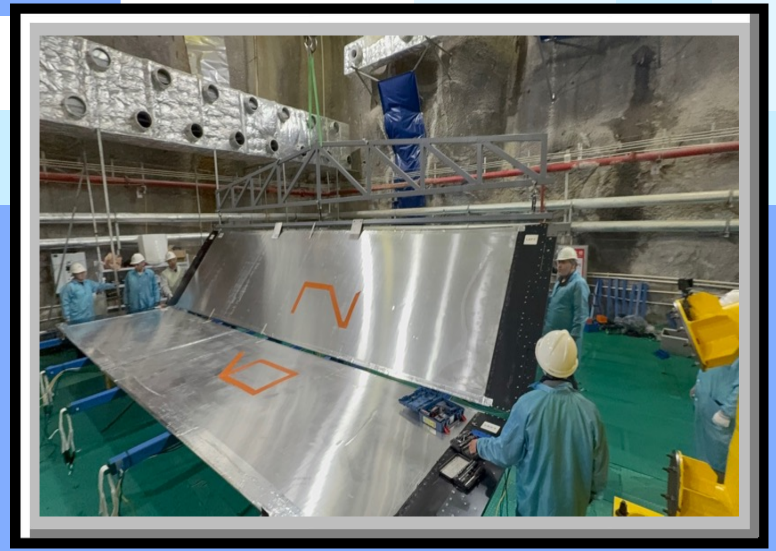
TT INSTALLATION

Module testing & validation

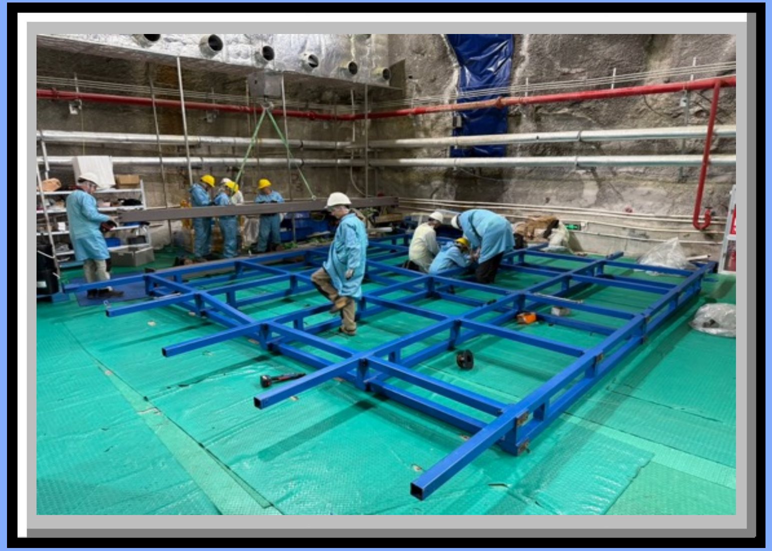
Top Tracker Bridge



Modules positioning

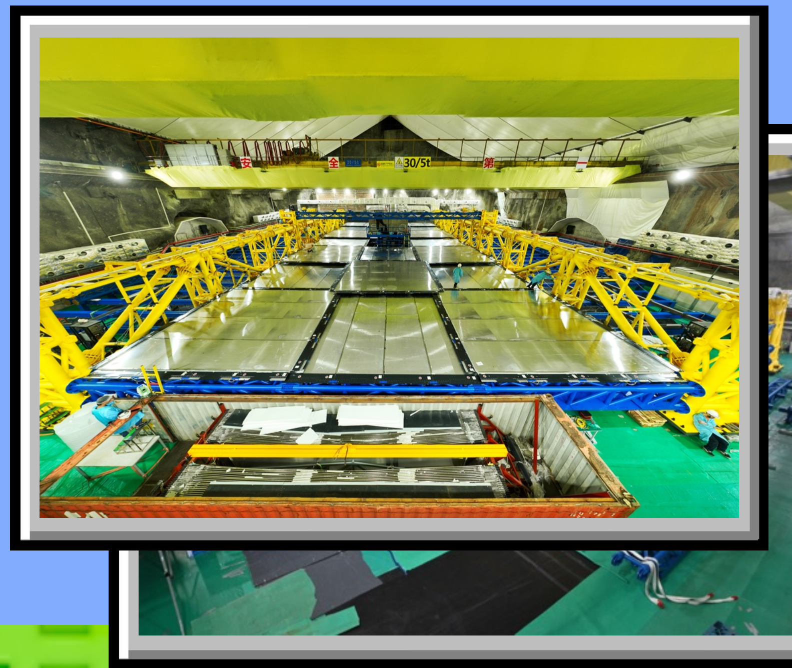


Support Table assembly



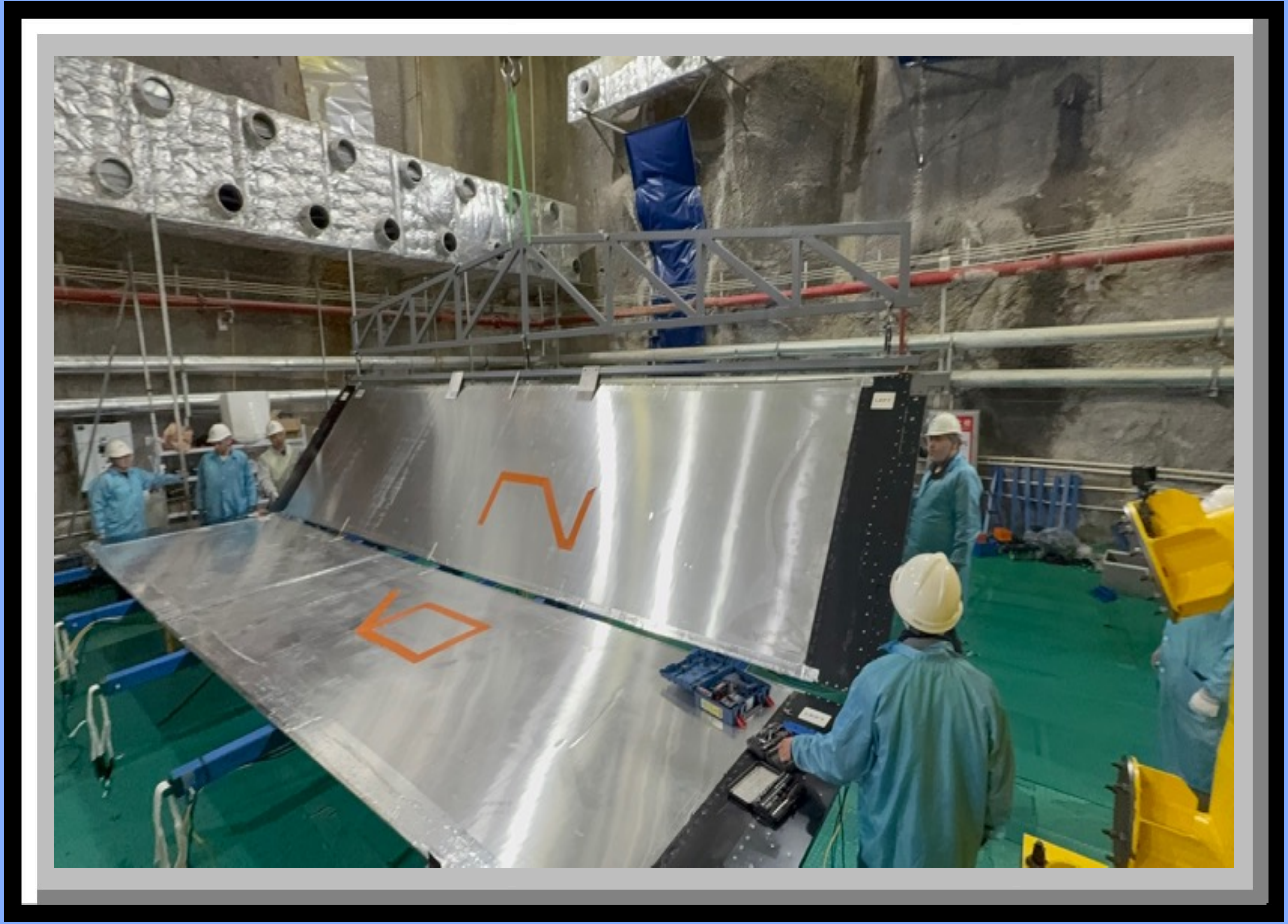
Wall positioning

1st Top Tracker layer



TT INSTALLATION

Modules positionning



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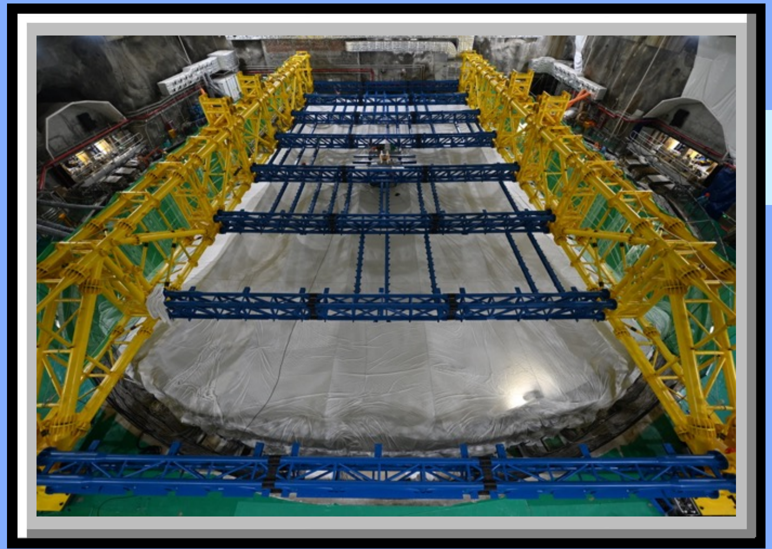
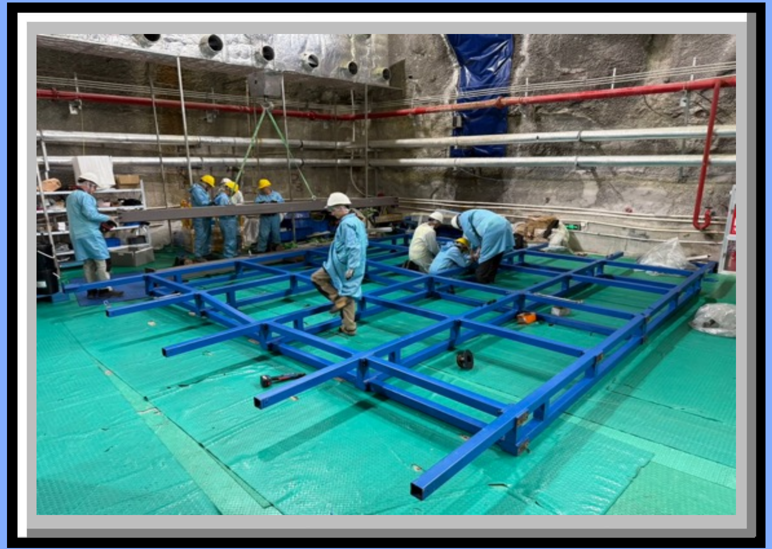


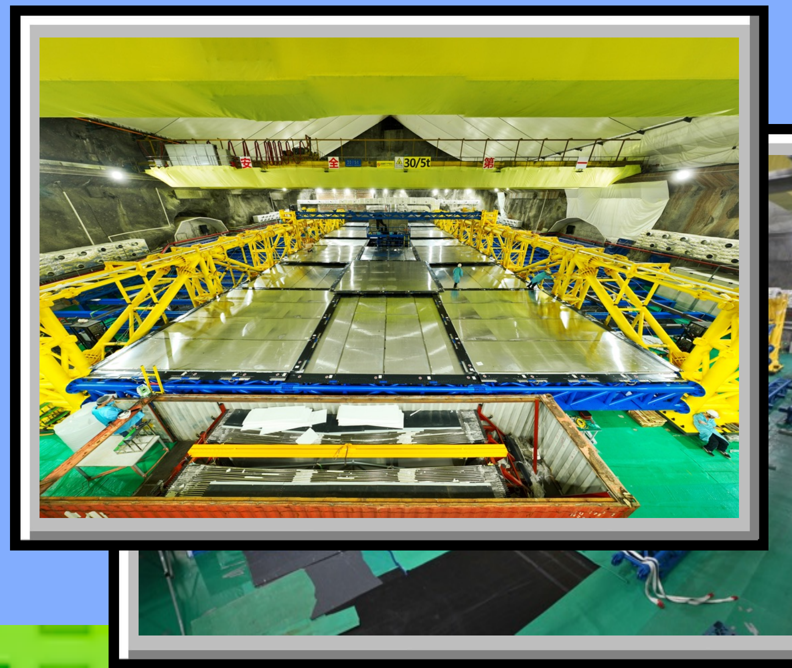
Support Table assembly



Wall positioning

Module testing & validation

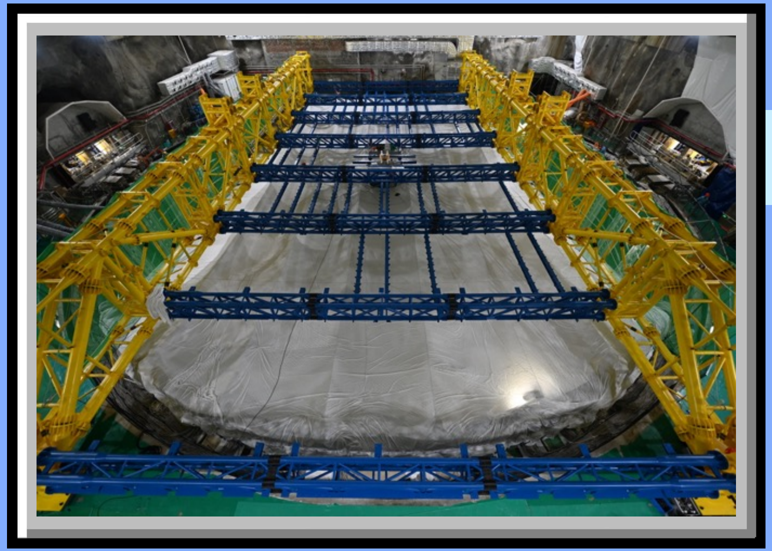
1st Top Tracker layer



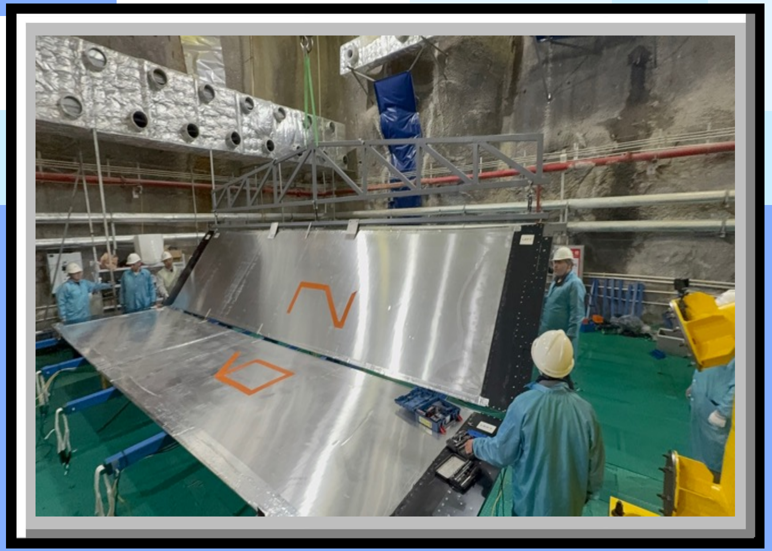
15 TT INSTALLATION

Wall positioning

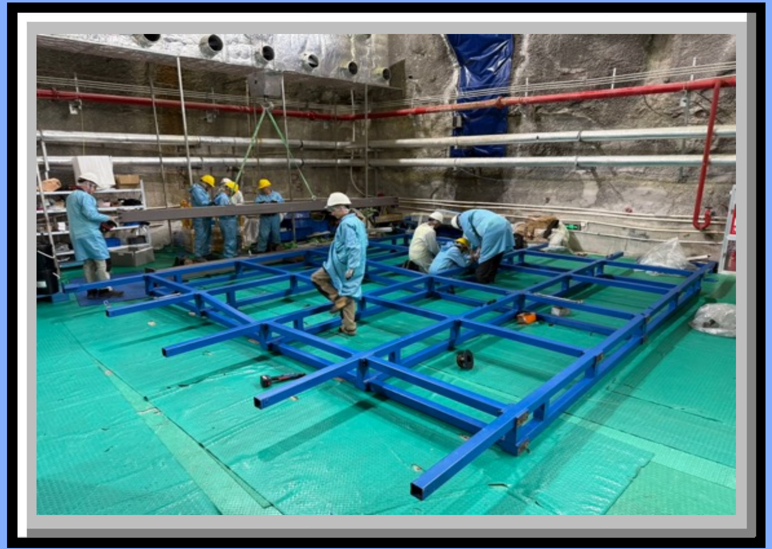
Top Tracker Bridge



Modules positioning

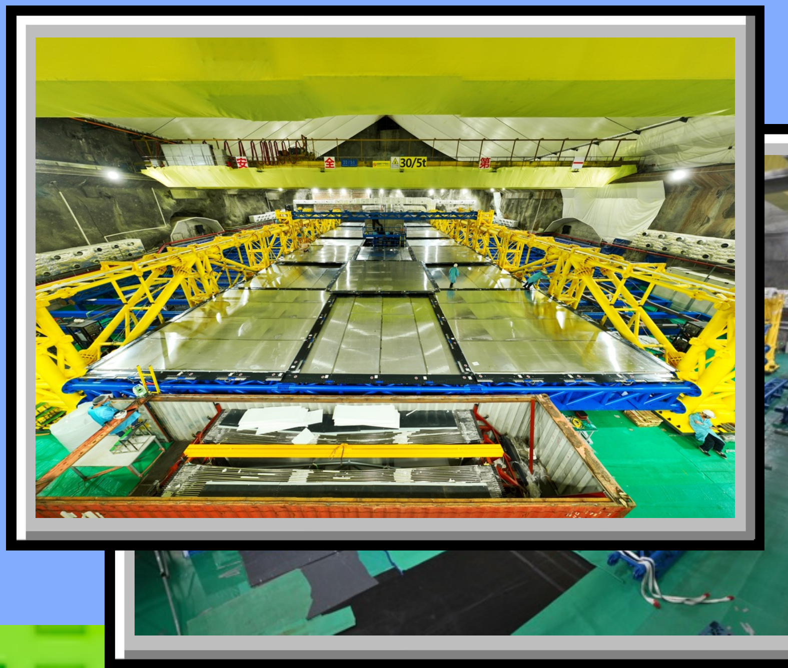


Support Table assembly



Module testing & validation

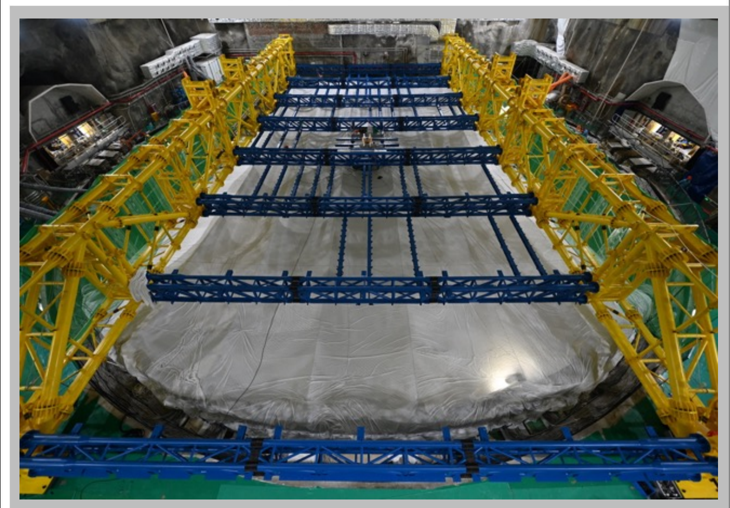
1st Top Tracker layer



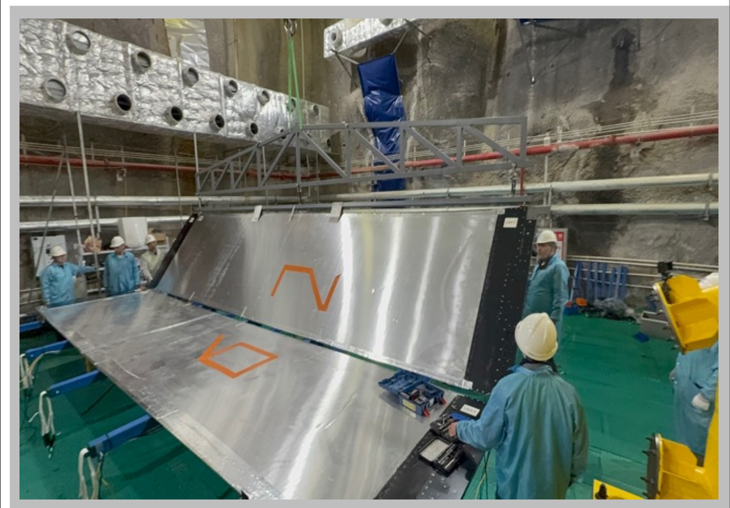
TT INSTALLATION

1st Top Tracker Layer Mar. 2025

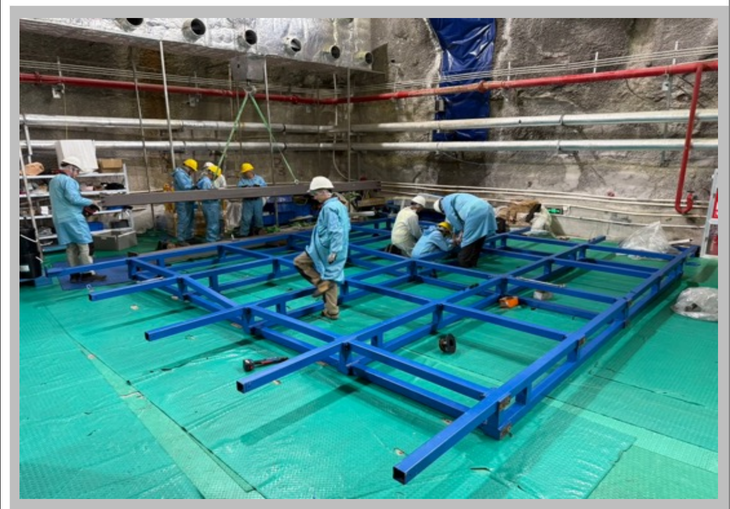
Top Tracker Bridge



Modules positioning

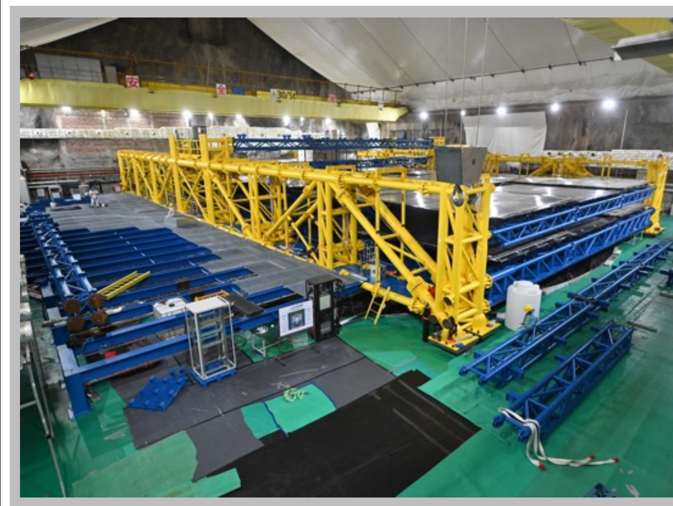


Support Table assembly



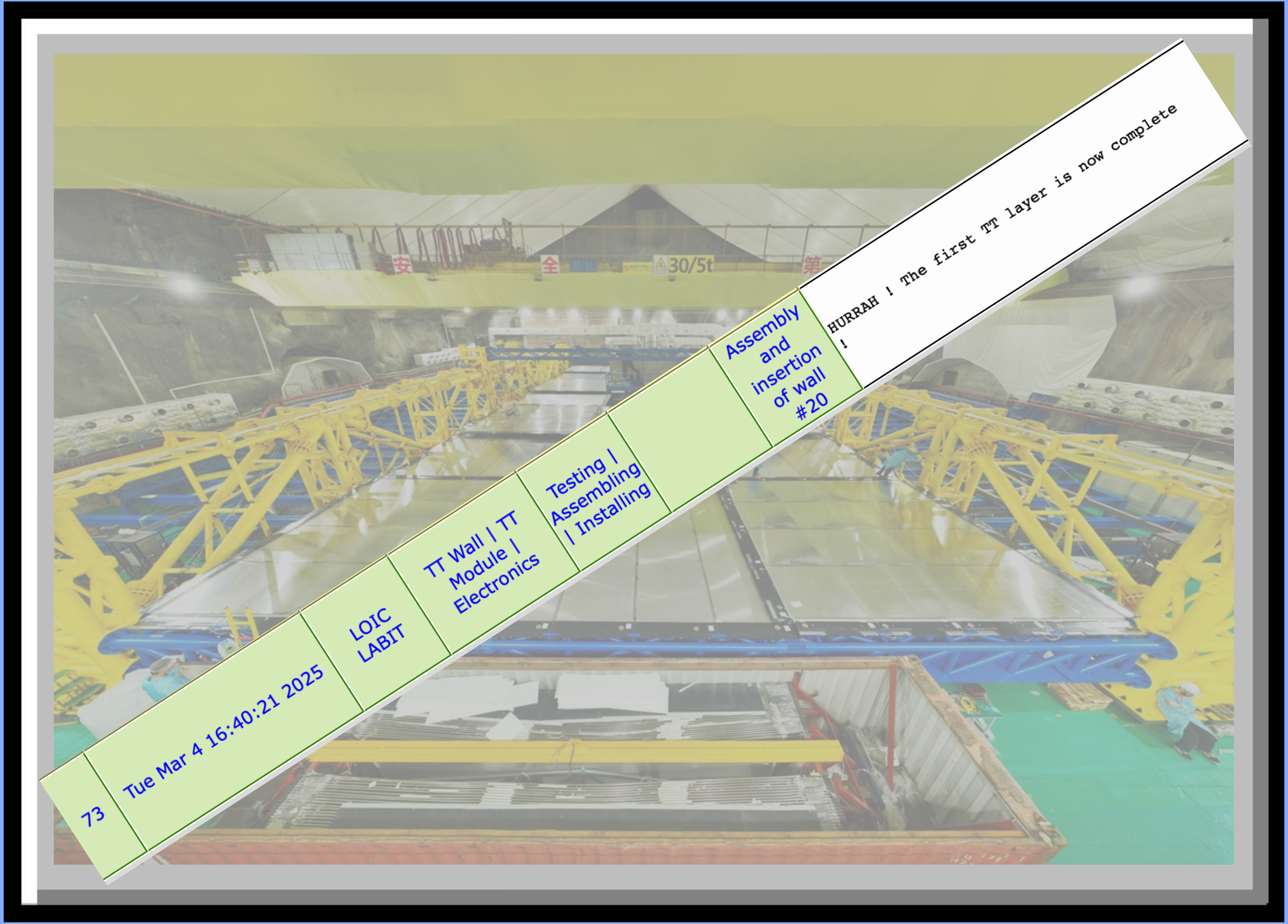
Wall positioning

Module testing & validation

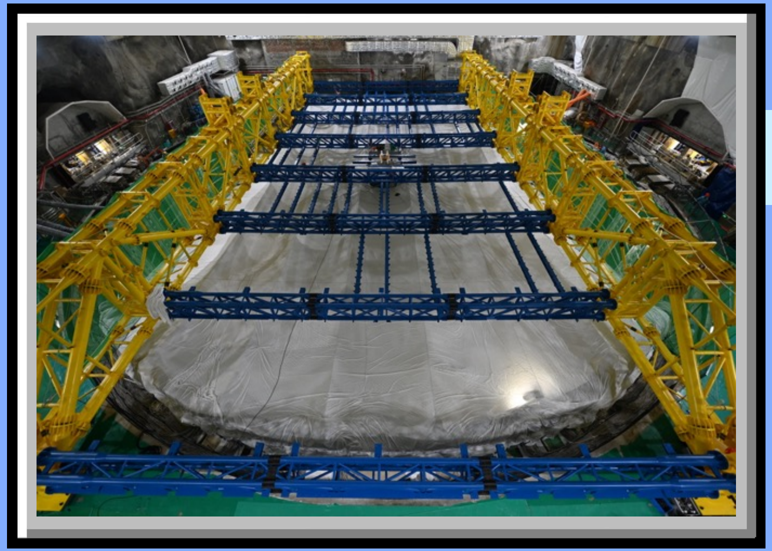


15 TT INSTALLATION

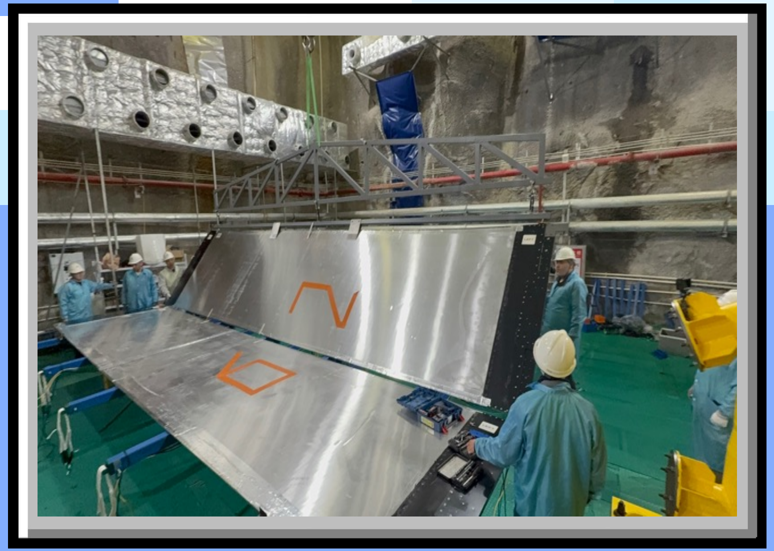
1st Top Tracker layer Mar. 2025



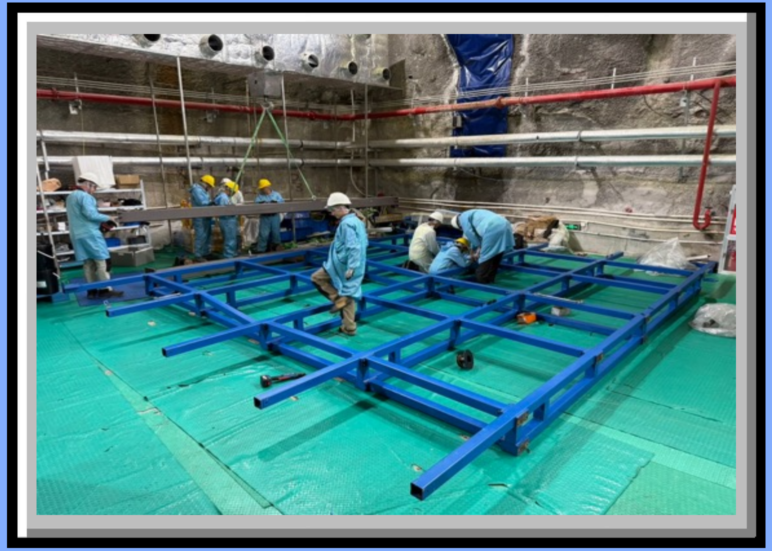
Top Tracker Bridge



Modules positioning



Support Table assembly



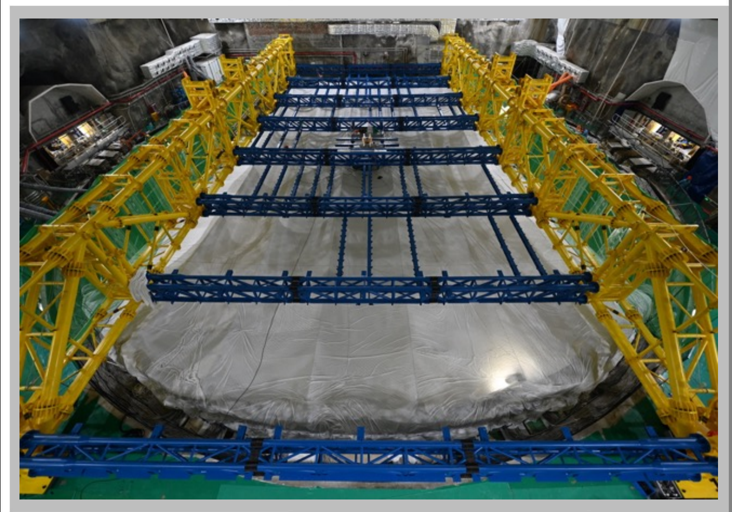
Wall positioning

Module testing & validation

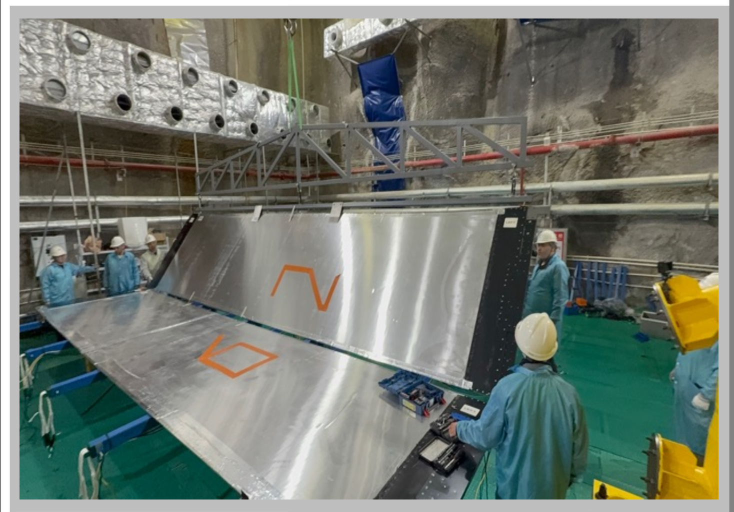
TT INSTALLATION

2nd Top Tracker layer Apr. 2025

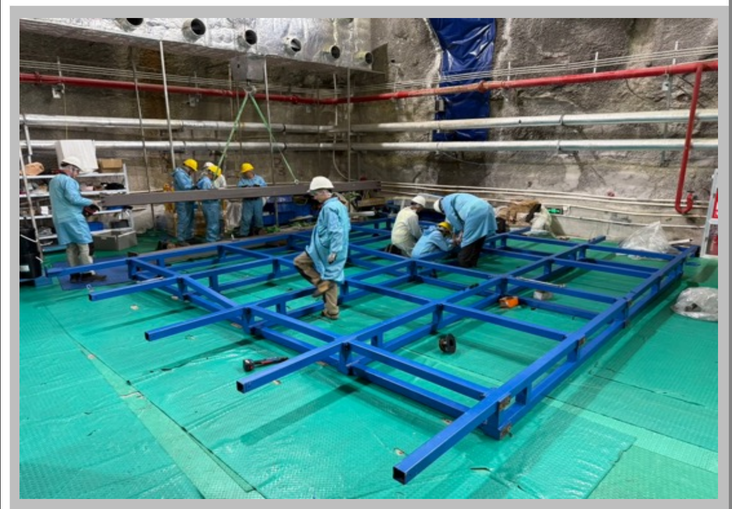
Top Tracker Bridge



Modules positioning



Support Table assembly



Wall positioning

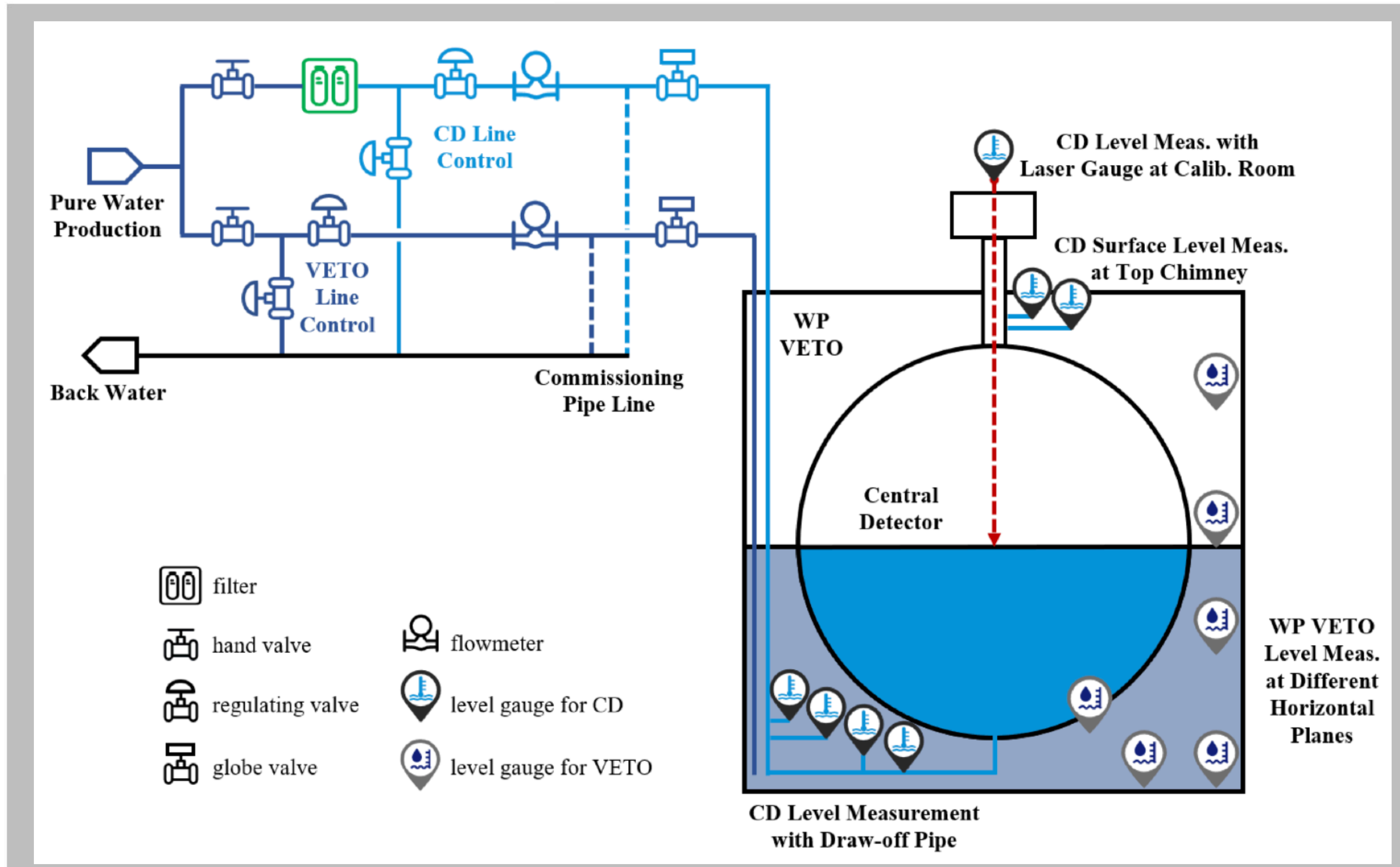
Module testing & validation

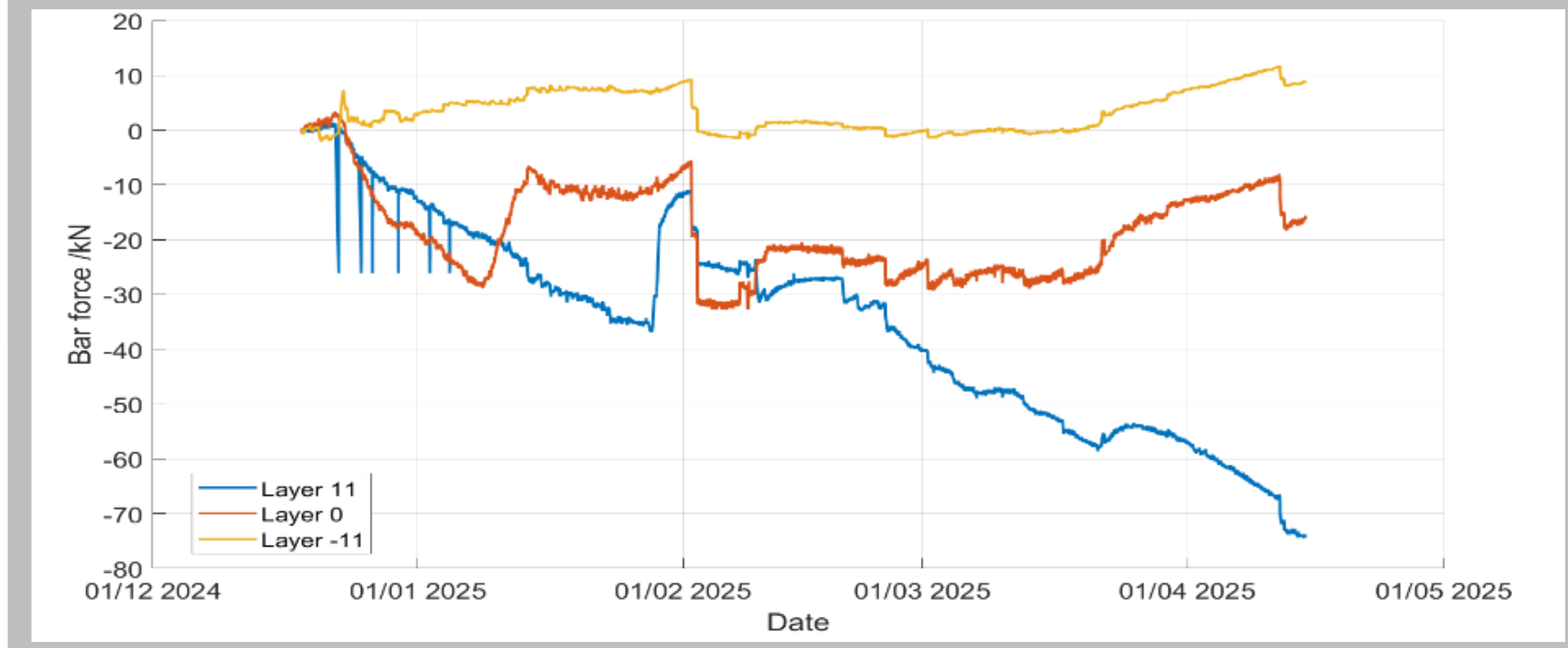
1st Top Tracker layer

16 WATER FILLING

- Synchronised CD & WP filling:
  - Started on Dec. 18th 2024 and ended early Feb. 2025
  - Pure water production ~90 m^3/h
  - Mechanical stress closely monitored during filling

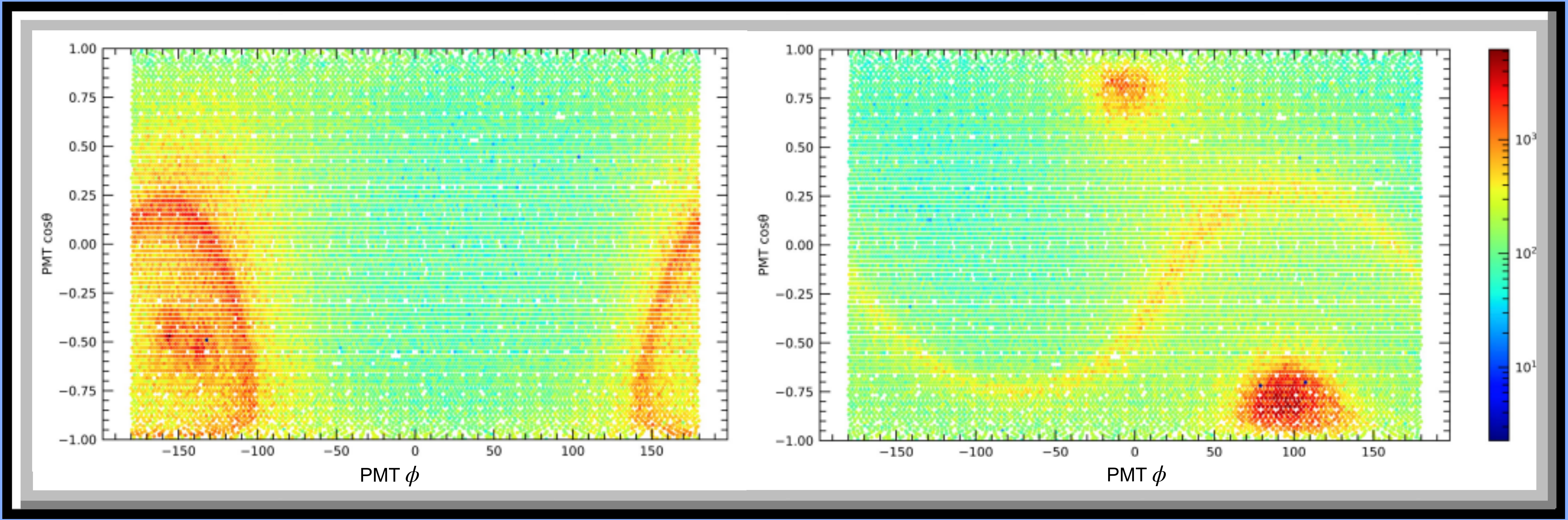
- Water quality meets requirements:
  - Attenuation length > 60m
  - U/Th concentration < 10^{-15} g/g
  - Rn concentration < 10 mBq/m^3





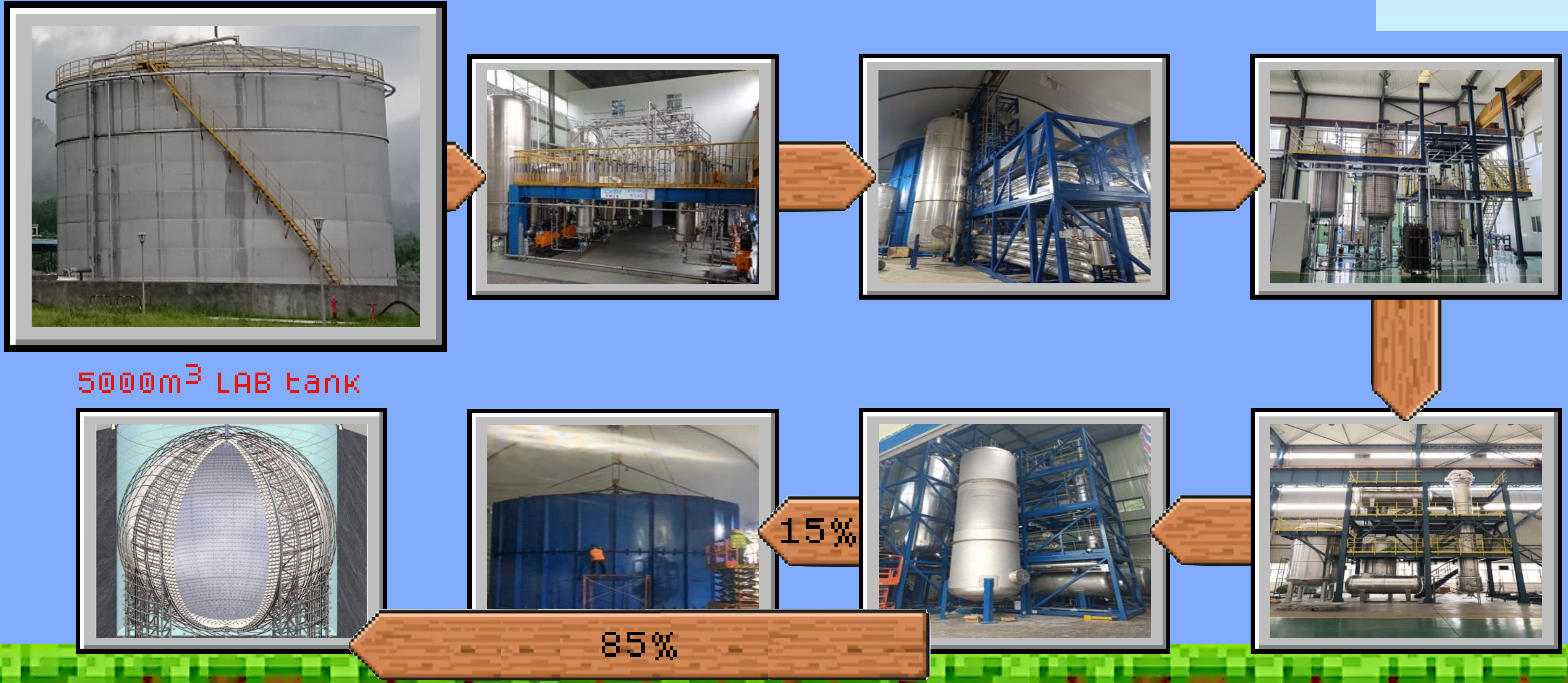
FIRST MUON EVENTS

- First muon events in the Water Pool, early 2025



LS PRODUCTION

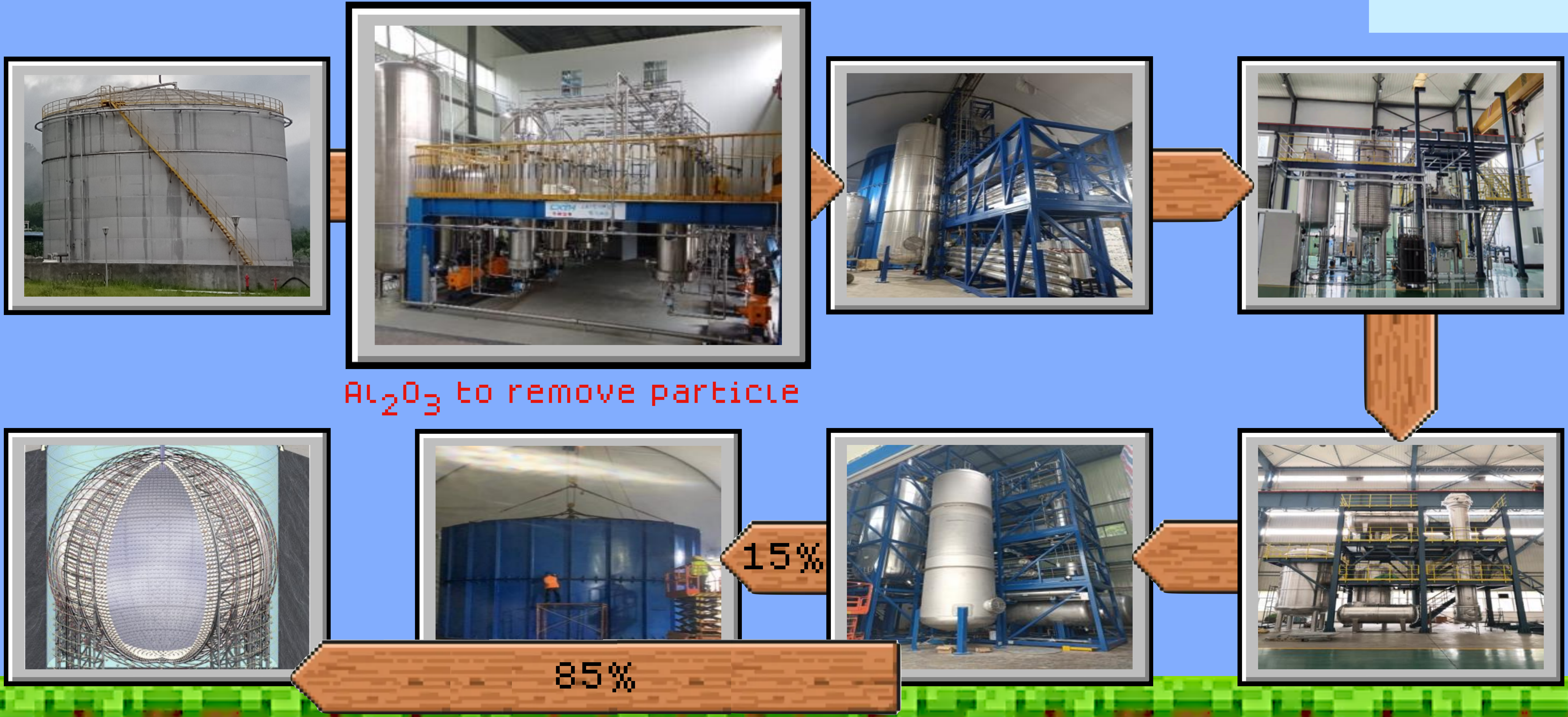
- Four purification plants for optimal radio-purity and attenuation length



18

LS PRODUCTION

- Four purification plants for optimal radio-purity and attenuation length



LS PRODUCTION

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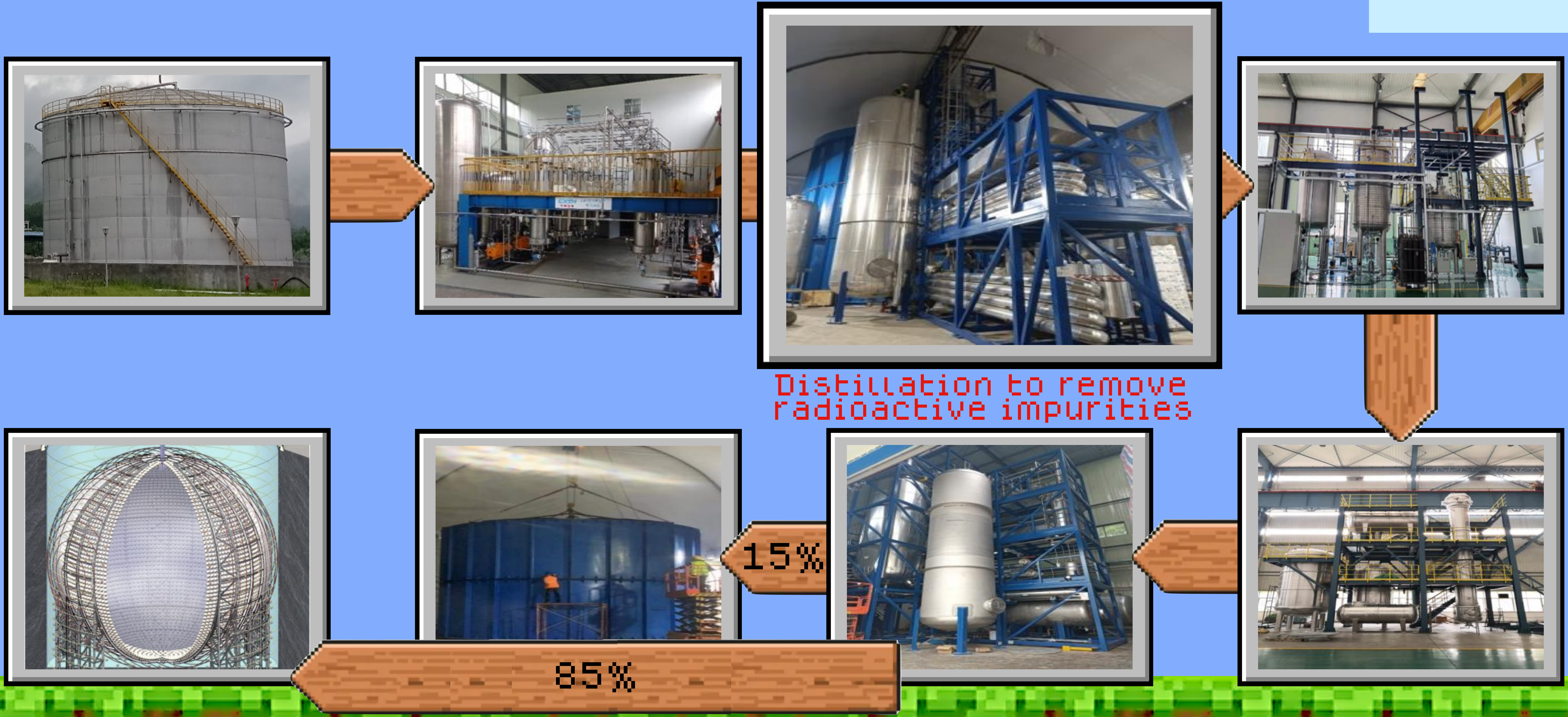

LS PRODUCTION

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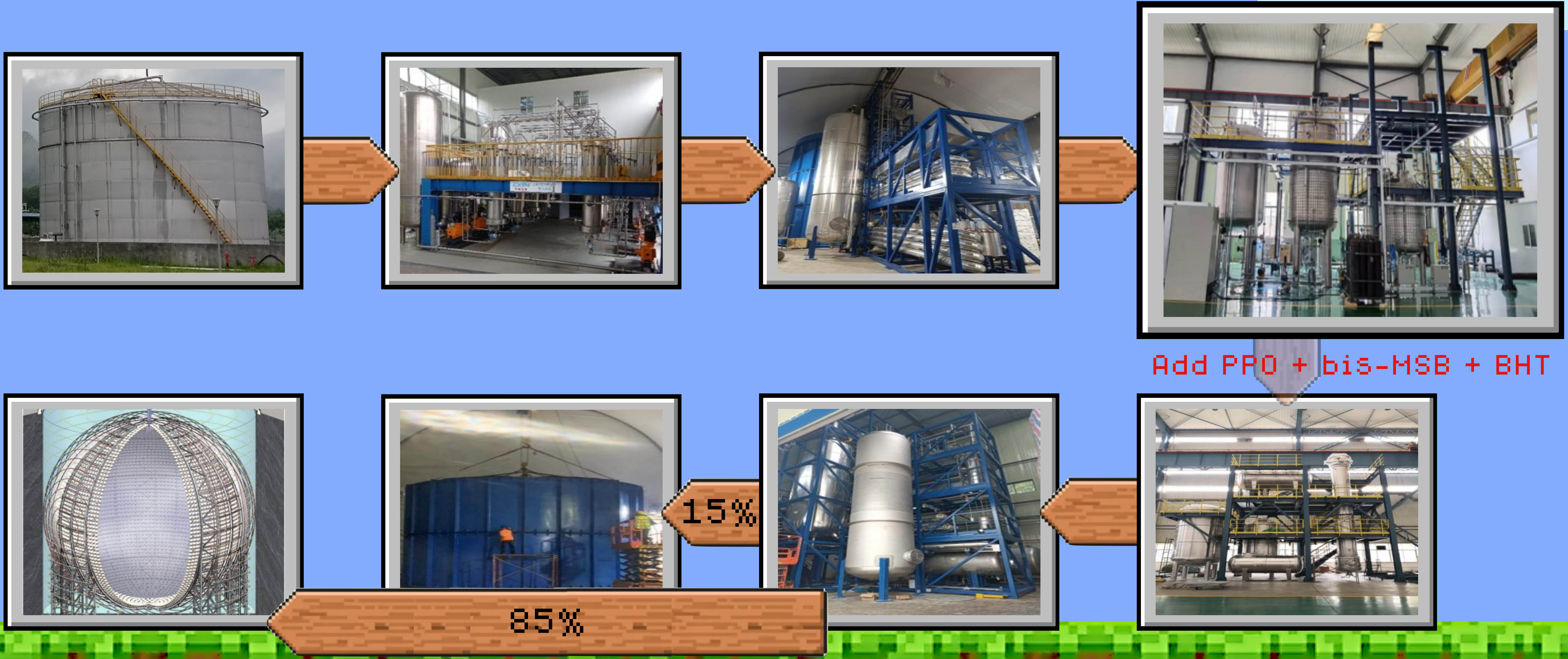

LS PRODUCTION

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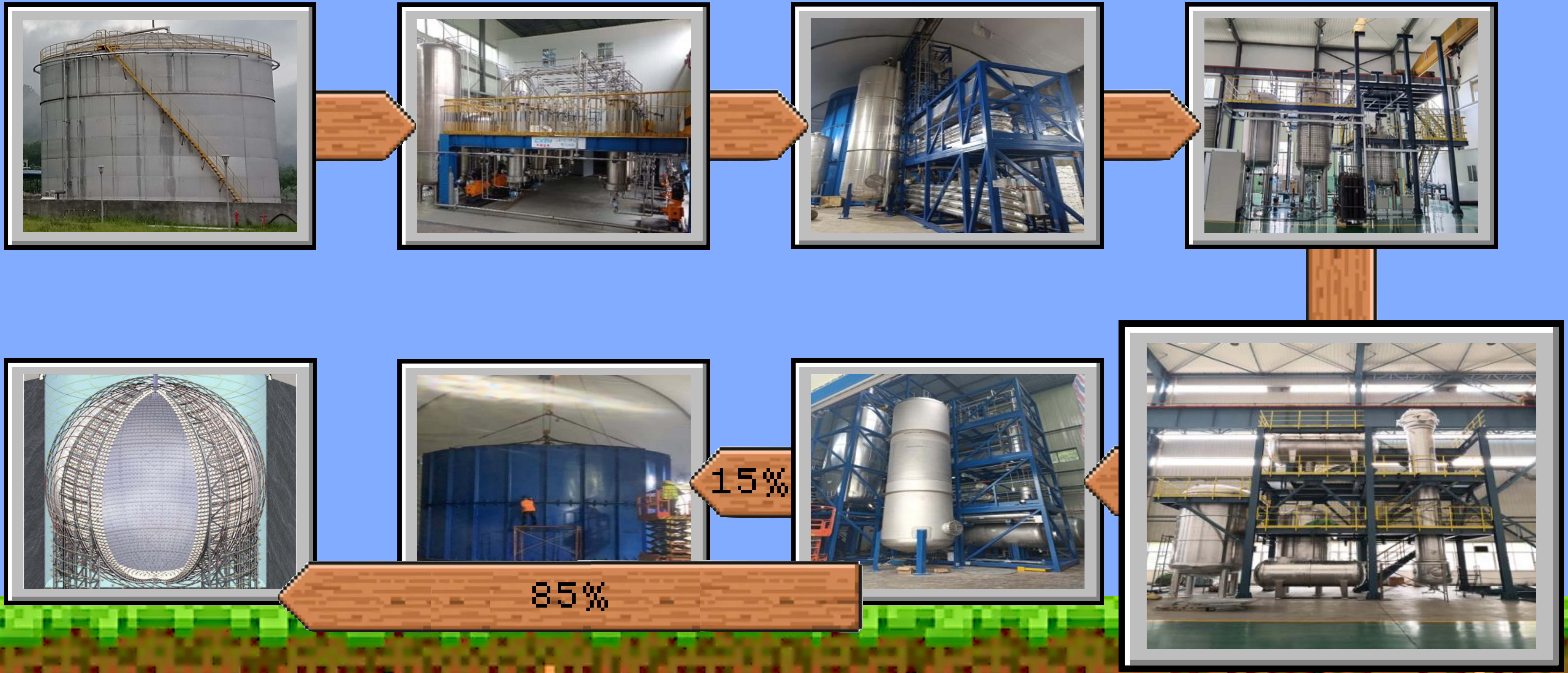


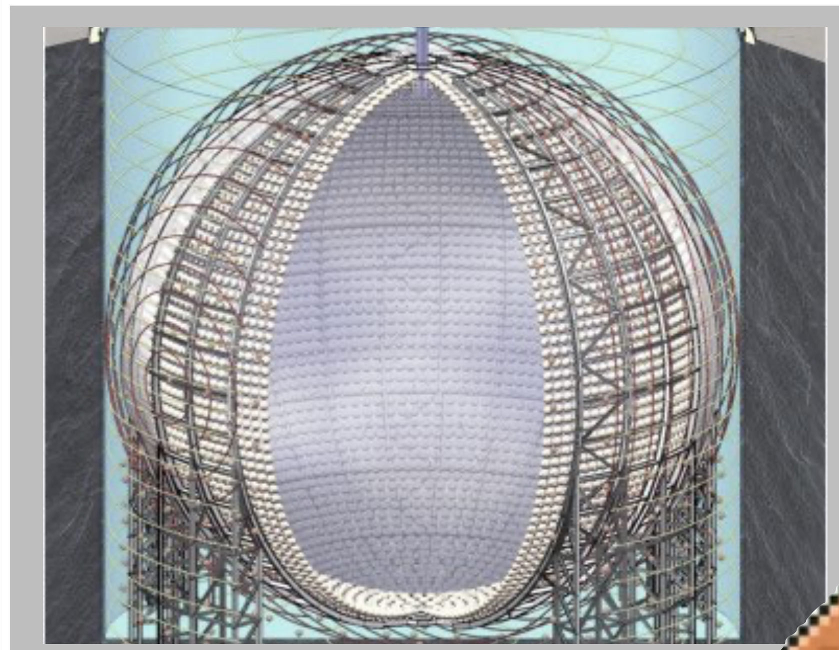
Water extraction to remove radioactive impurities

LS PRODUCTION

- Four purification plants for optimal radio-purity and attenuation length

Gas stripping to remove Rn and O_2

85%



LS PRODUCTION

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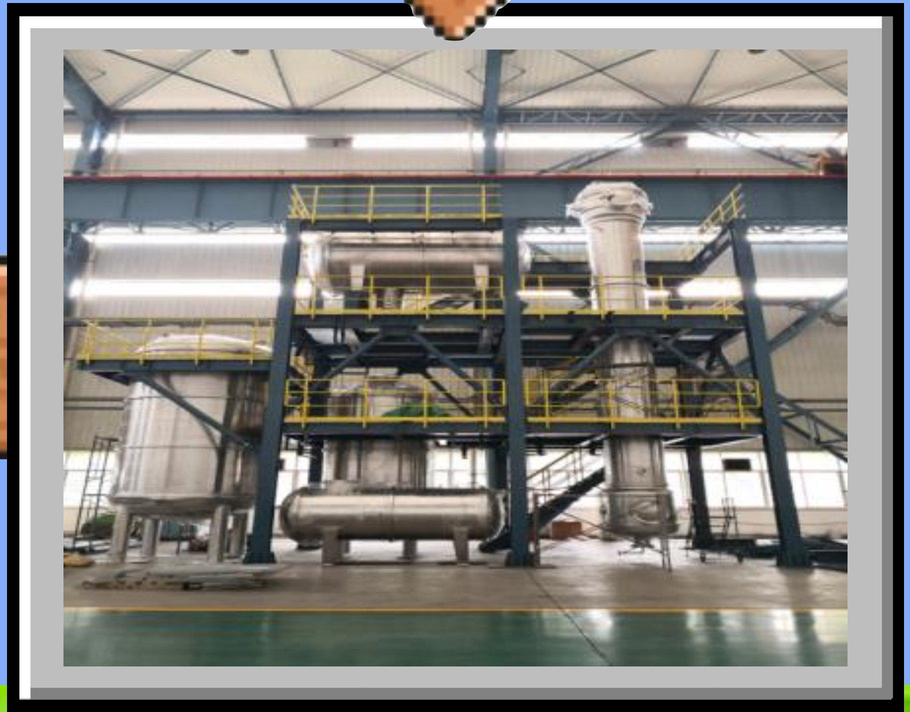
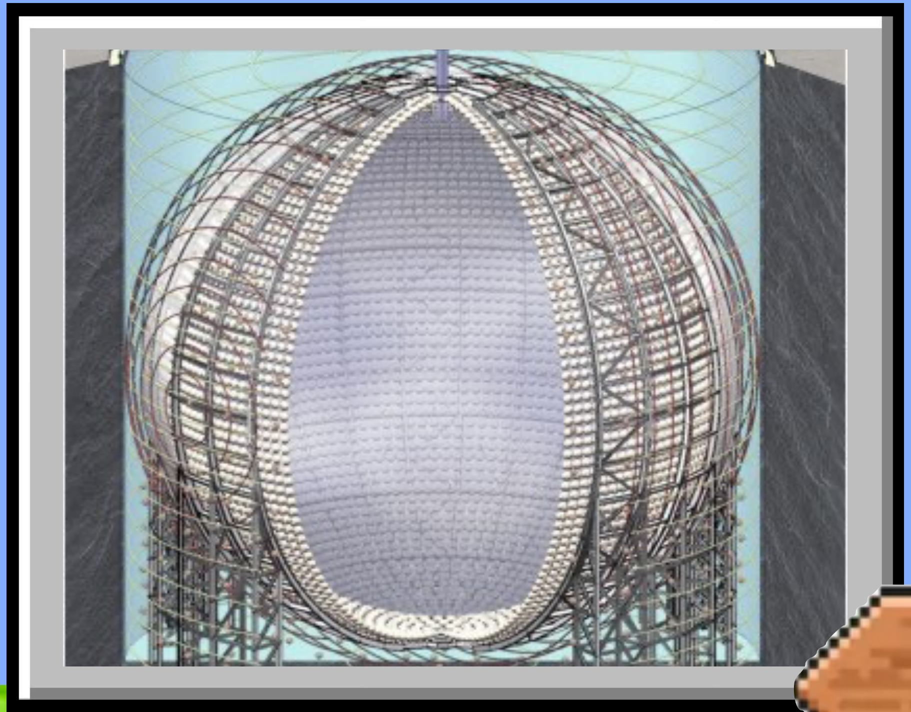
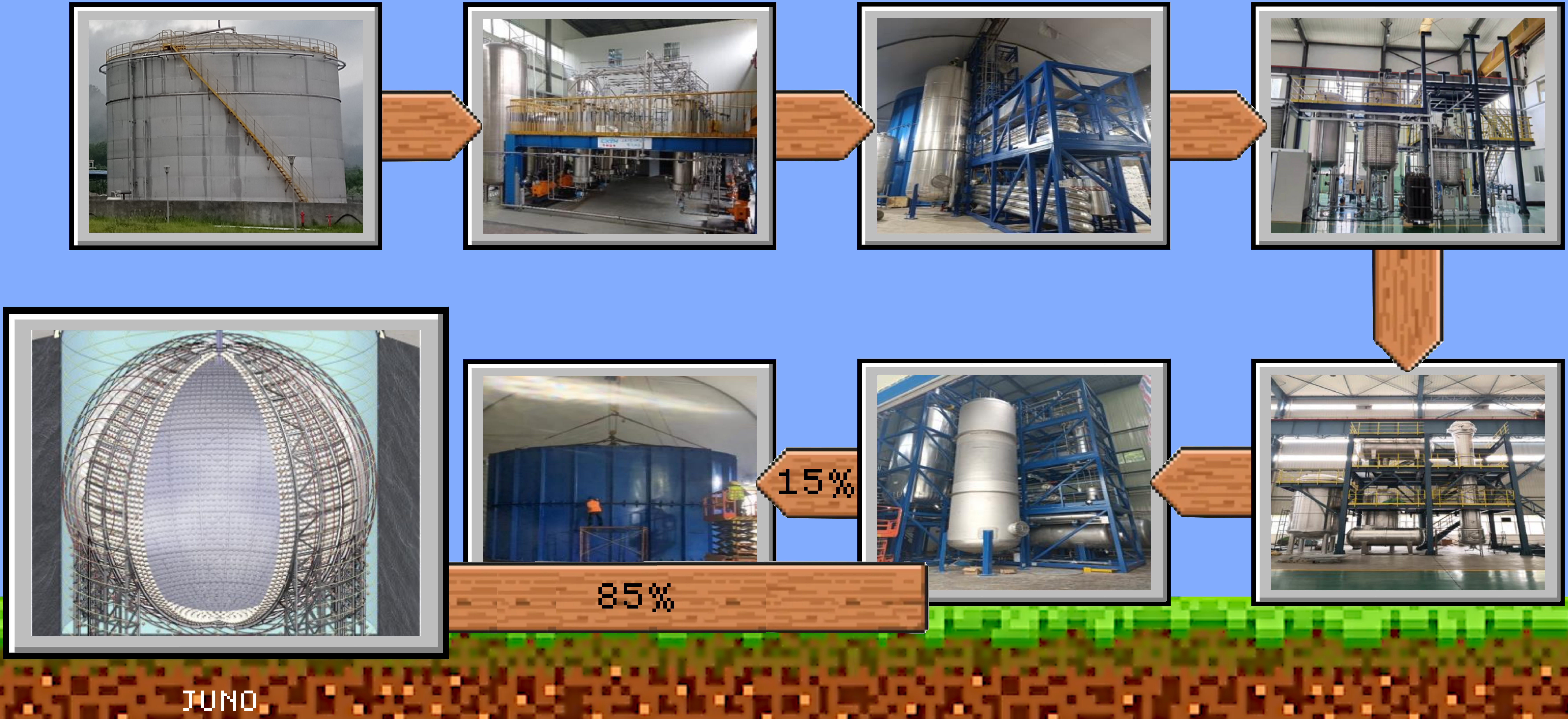




OSIRIS for LS qualification

LS PRODUCTION

- Four purification plants for optimal radio-purity and attenuation length



19 WATER-LS EXCHANGE

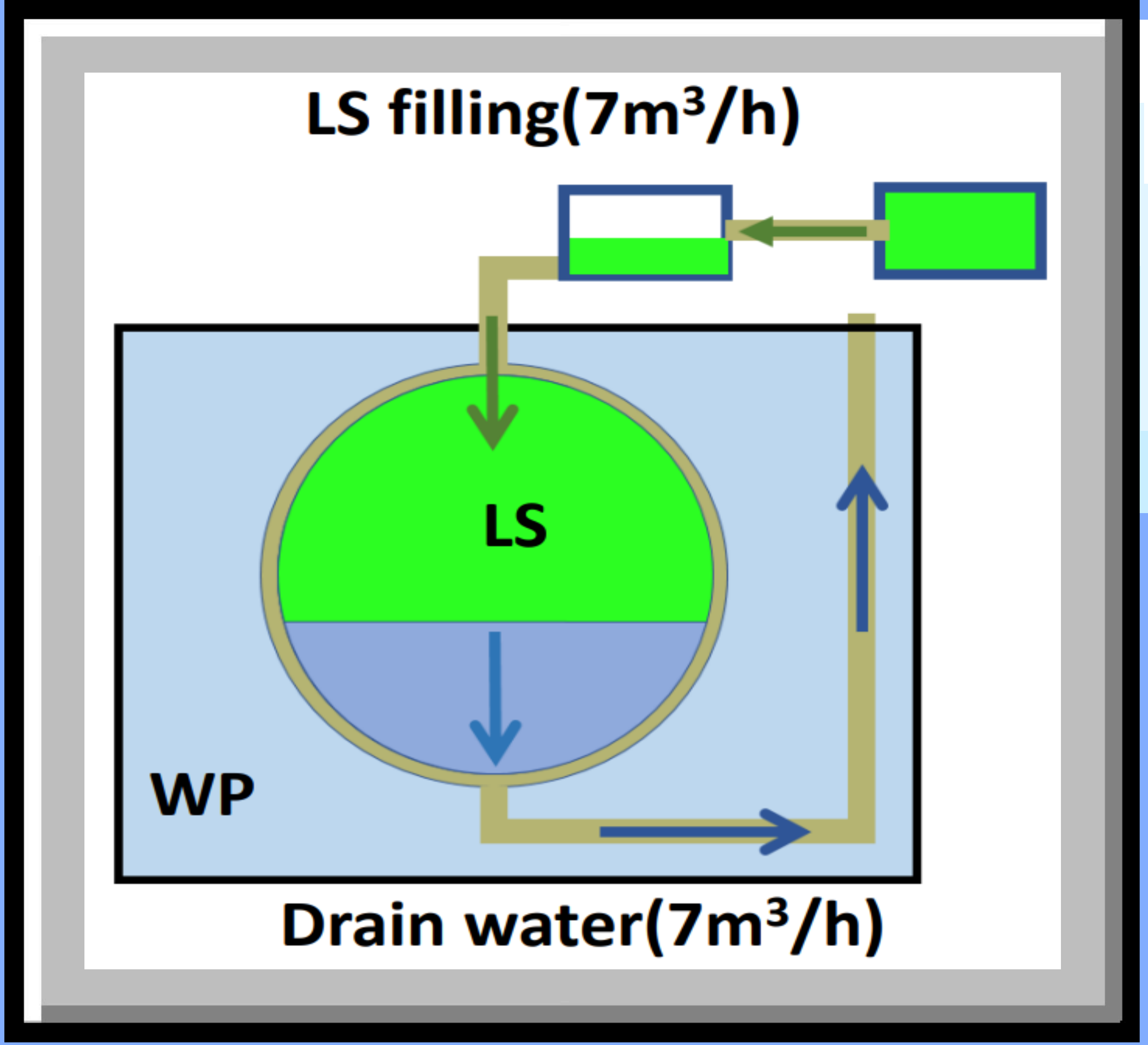
- Water - liquid scintillator exchange:
  - Started on Feb. 2nd 2025

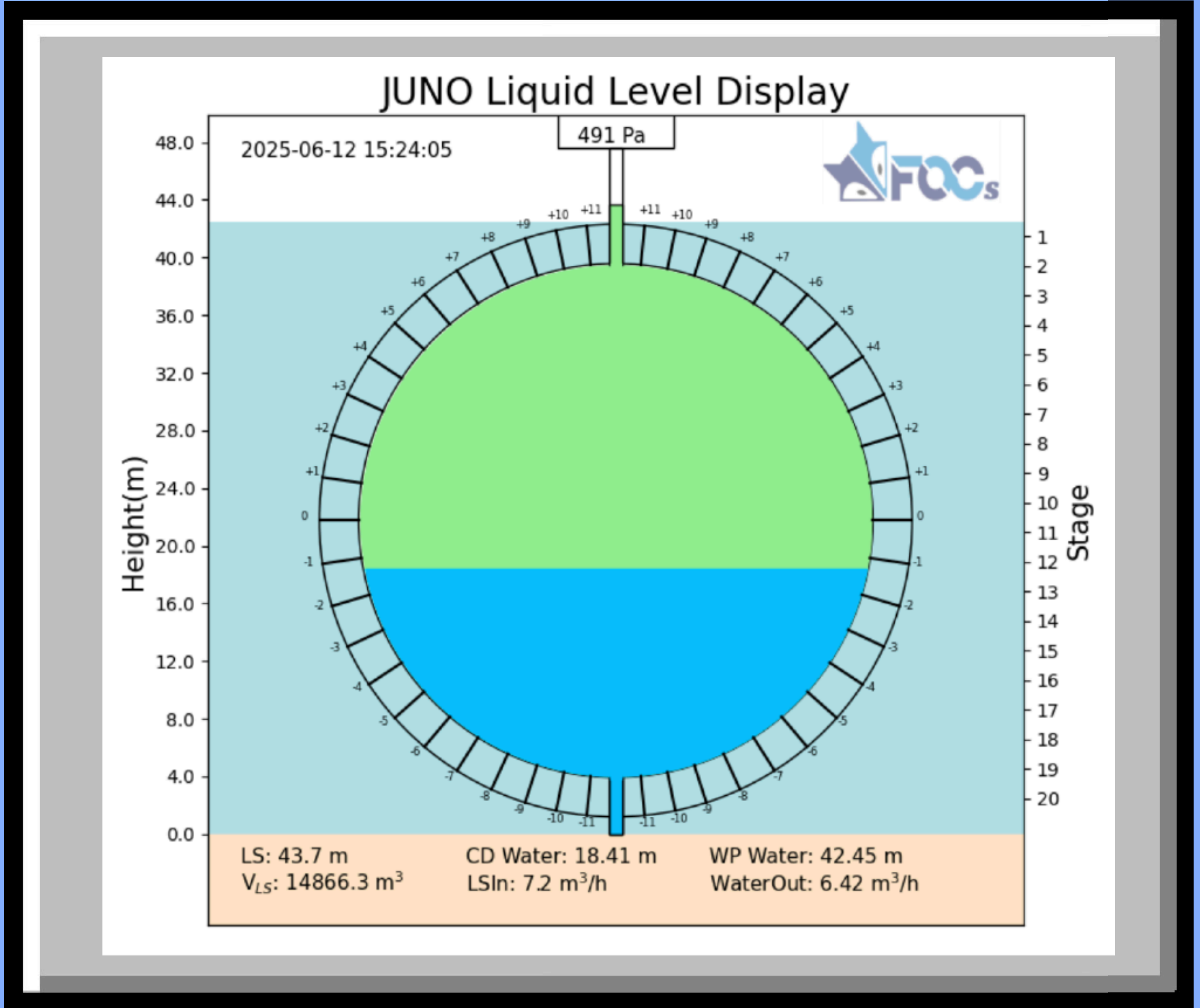
- LS quality monitored :
  - Attenuation length for sampled batch ~20m
  - Radiopurity by ICP-MS every week:

    U/Th concentration $< 10^{-15}$ g/g

    Rn concentration ~0.5 mBq/m^3

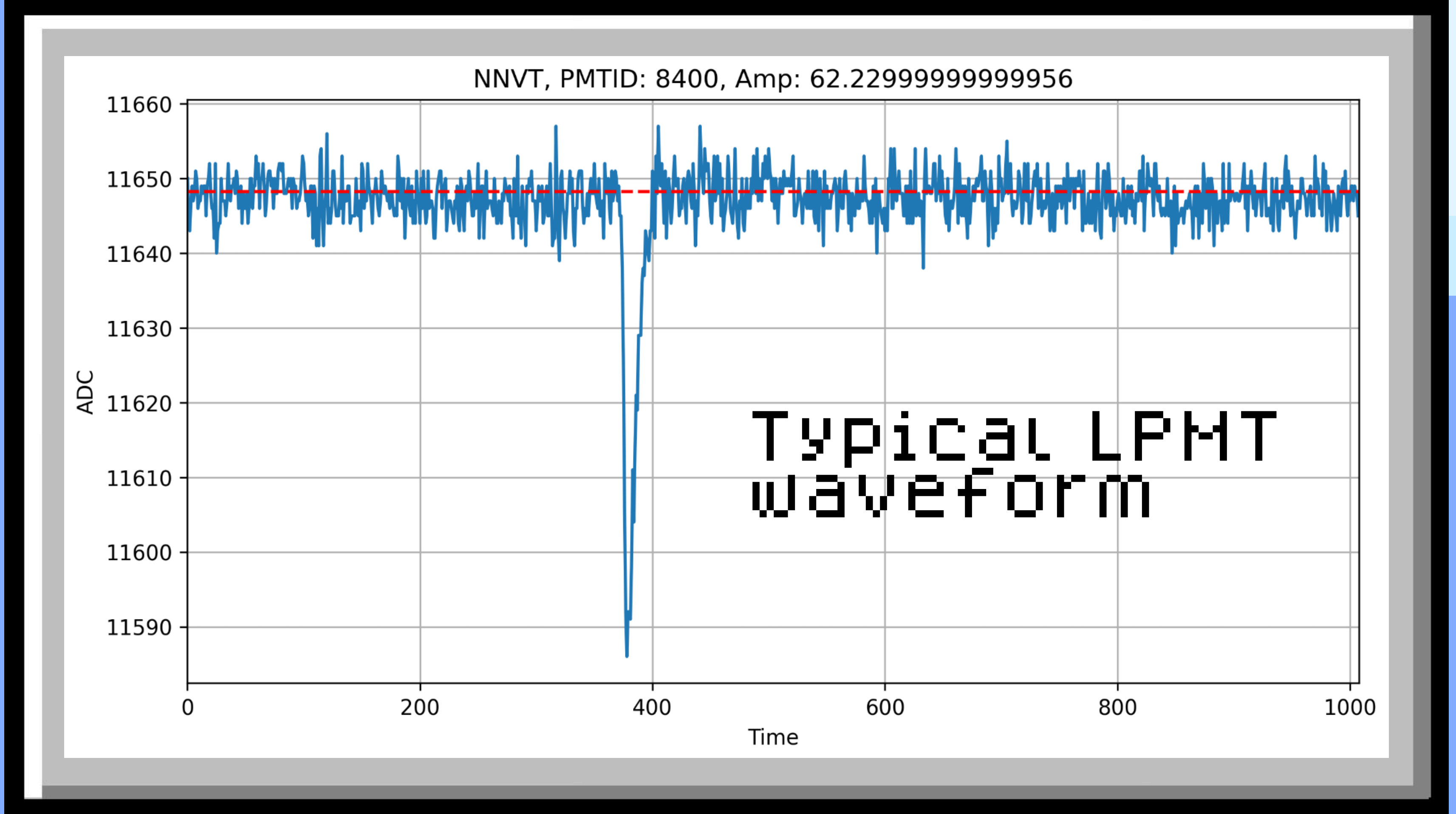
- End of liquid scintillator filling expected August 2025

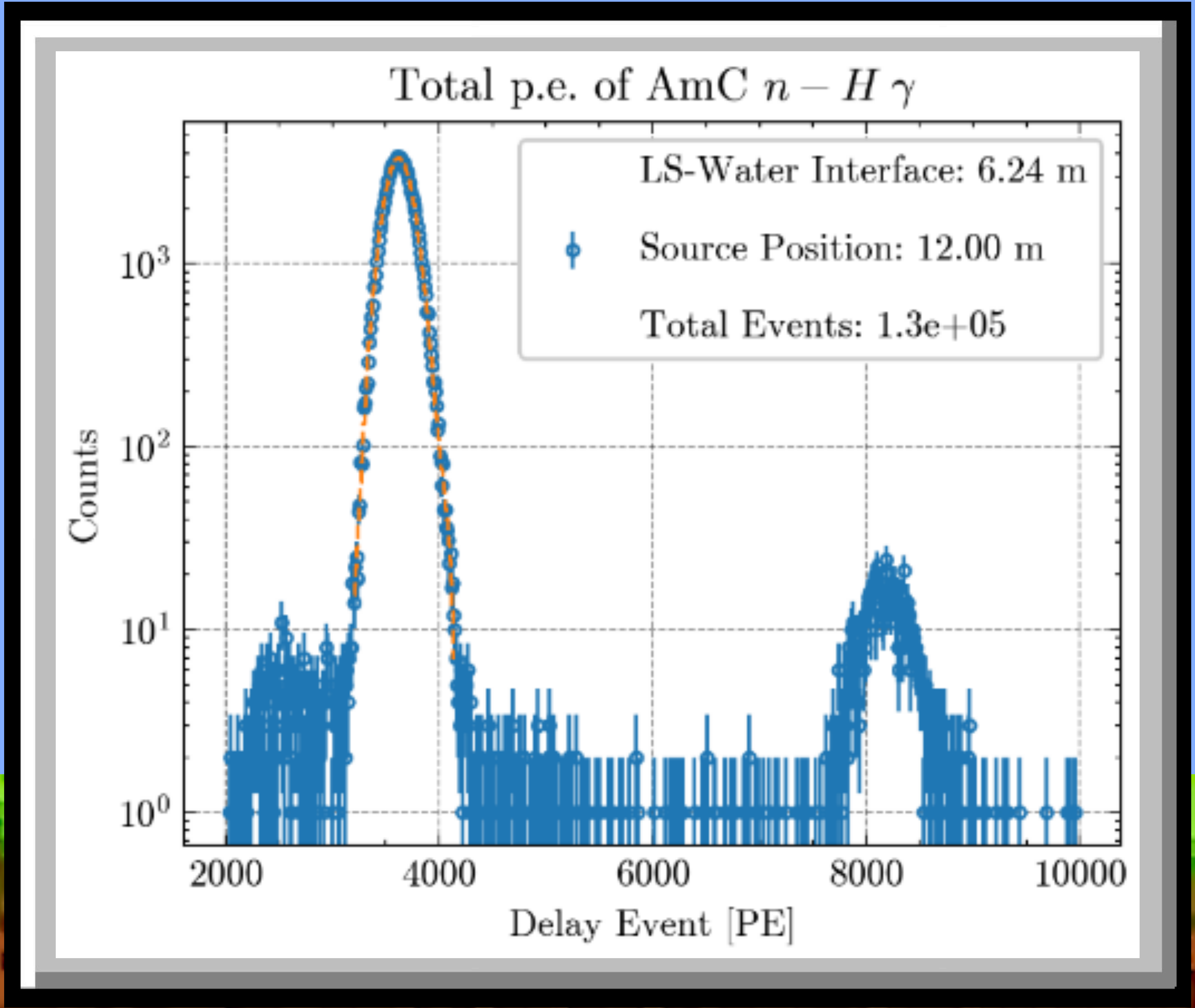




20 DETECTOR PERFORMANCE

- **LPMT status:**
  - 16/17612 LPMTs not installed because of space conflict
  - 8 dead LPMTs
  - ~130 with fluctuating dark rate
  - Gain stable at 1% level
  - Low electronic noise : RMS ~0.055 PE (threshold : 0.2 PE)
  - Low trigger threshold ~150keV (300 PMTs/225 ns)
- **SPMT status:**
  - 13/25600 channels lost during installation
  - ~100 channels with high dark rate or abnormal SPE spectra
  - average gain 3.8×10^6
  - average dark rate ~530 cps
  - Low electronic noise: RMS ~0.04 PE (threshold: 0.3 PE)
- **AmBe calibration:**
  - Attenuation length ~20m
  - Light yield > 1600 photons/MeV





JUNO COLLABORATION

COUNTRY	INSTITUTE
ARMENIA	YEREVAN PHYSICS INSTITUTE
BELGIUM	UNIVERSITE LIBRE DE BRUXELLES
BRAZIL	PUC
BRAZIL	UEL
CHILE	SAPHIR
CHILE	UNAB
CHINA	BISEE
CHINA	CAGS
CHINA	CHONGQING UNIVERSITY
CHINA	DGUT
CHINA	GUANGXI U.
CHINA	HARBIN INSTITUE OF TECHNOLOGY
CHINA	IHEP
CHINA	JINAN U.
CHINA	NANJING U.
CHINA	NANKAI U.
CHINA	NCEPU
CHINA	SHANDONG
CHINA	SHANGAI JT U.
CHINA	IGG-BEIJING
CHINA	SYSU
CHINA	TSINGHUA U.
CHINA	UCAS
CHINA	U. OF SOUTH CHINA
CHINA	WU YI U.
CHINA	WUHAN U.
CHINA	XIA 'N JTU.
CHINA	XIAMEN U.
CHINA	ZHENGZHOU U.
CHINA	NUDT
CHINA	CUG-BEIJING
CHINA	ECUT-NANCHANG CITY
CHINA	CDUT-CHENGDU
CHINA	SUSTECH-SHENZHEN
CZECH	CHARLES U.
FINLAND	U. OF JYVASKYLA
FRANCE	IJCLAB ORSAY
FRANCE	LP2I BORDEAUX
FRANCE	CPPM MARSEILLE
FRANCE	IPHC STRASBOURG
FRANCE	SUBATECH NANTES
GERMANY	RWTH AACHEN U.
GERMANY	TUM
GERMANY	U. HAMBOURG
GERMANY	GSI
GERMANY	U. MAINZ
GERMANY	U. TUEBINGEN
ITALY	INFN CATANIA
ITALY	INFN DI FRASCATI
ITALY	INFN-FERRARA
ITALY	INFN-MILANO
ITALY	INFN-MILANO BICOCCA
ITALY	INFN-PADOVA
ITALY	INFN-PERUGIA
ITALY	INFN-ROMA 3
PAKISTAN	PINSTECH (PAEC)
RUSSIA	INR MORSCOW
RUSSIA	JINR
RUSSIA	MSU
SLOVAKIA	FMPICU
TAIWAN-CHINA	NATIONAL CHIAO-TUNG U.
TAIWAN-CHINA	NATIONAL TAIWAN U.
TAIWAN-CHINA	NATIONAL UNITED U.
TAIWAN-CHINA	NKNU
TAIWAN-CHINA	NTUT
THAILAND	NARIT
THAILAND	PPRLCU
THAILAND	SUT
UK	U. LIVERPOOL
UK	U. WARWICK
USA	UMD-G
USA	UC IRVINE

~750 Collaborators across 72 institutes in 20 + countries

22 CONCLUSION

- **JUNO's rich and ambitious physics program includes:**
  - Determination of neutrino mass ordering at 3σ in 6 years
  - Sub-percent precision on θ_{12}, Δm^2_{21}, Δm^2_{32}
  - Sensitivity to solar, geo- and supernovae neutrinos

- **This is enabled by JUNO's unique features:**
  - 20 kiloton liquid scintillator target
  - Excellent energy resolution ($3\%/\sqrt{E}$)
  - Stringent radiopurity requirements
  - Precise reactor spectrum reference provided by the TAO near detector

- **The experiment is transitioning from construction to commissioning :**
  - Water cherenkov detector filled and operating with good performance since Feb. 2025
  - Liquid scintillator filling of the central detector is underway, completion expected by Aug. 2025
  - Top Tracker installation expected to complete by end of June

- **JUNO is on track to become a flagship neutrino experiment, with physics data-taking approaching soon**