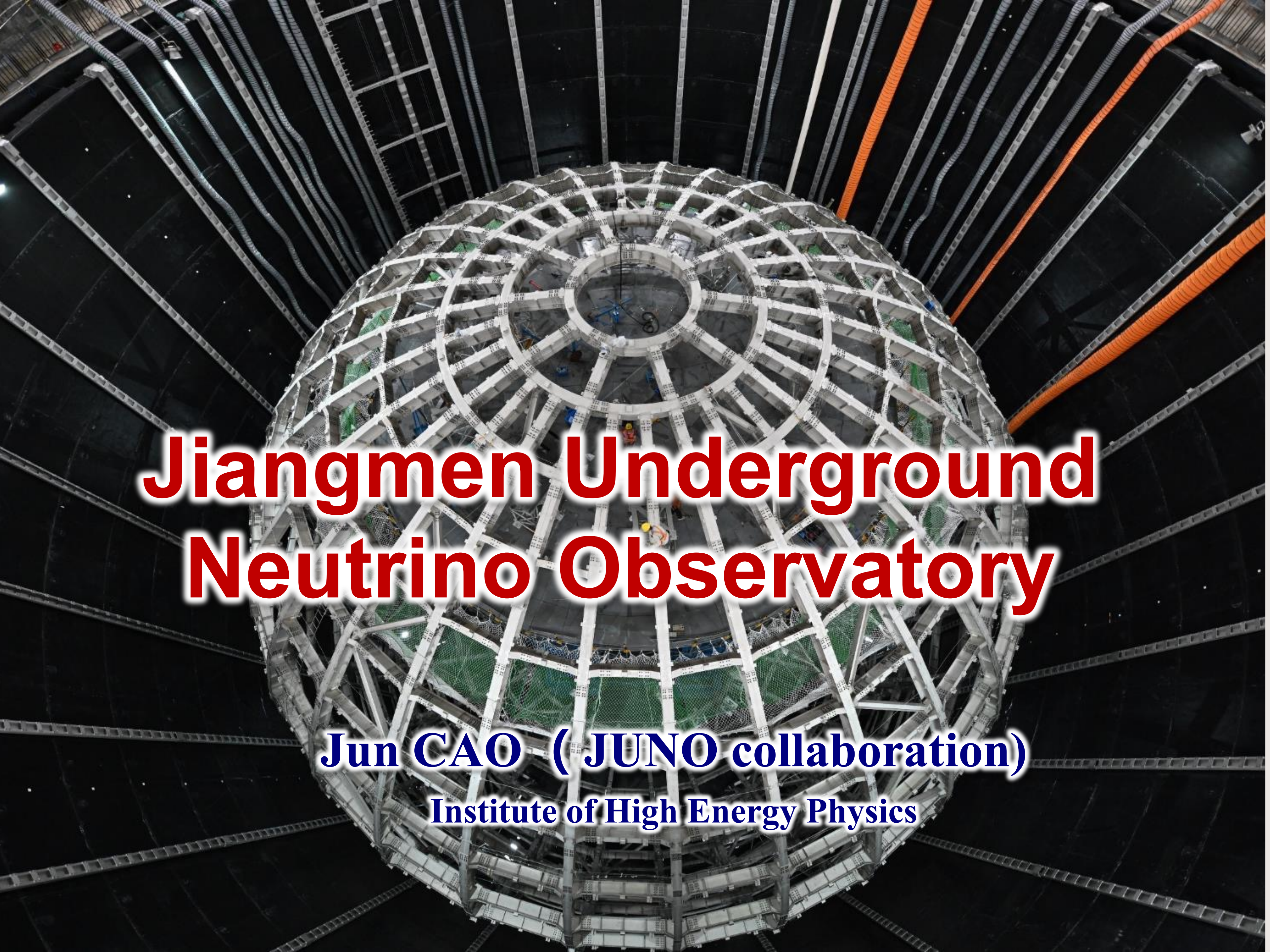
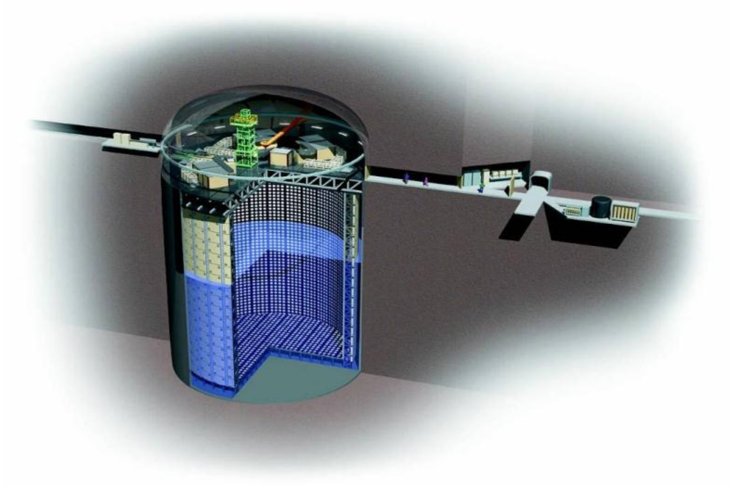


Jiangmen Underground Neutrino Observatory

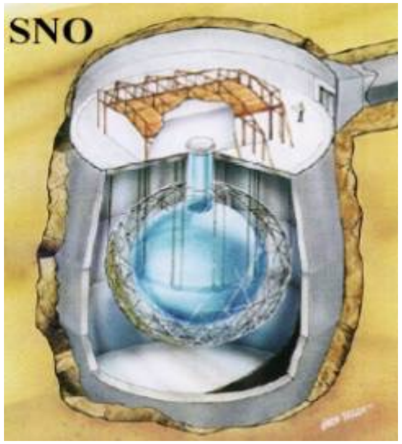
Jun CAO（JUNO collaboration)

Institute of High Energy Physics

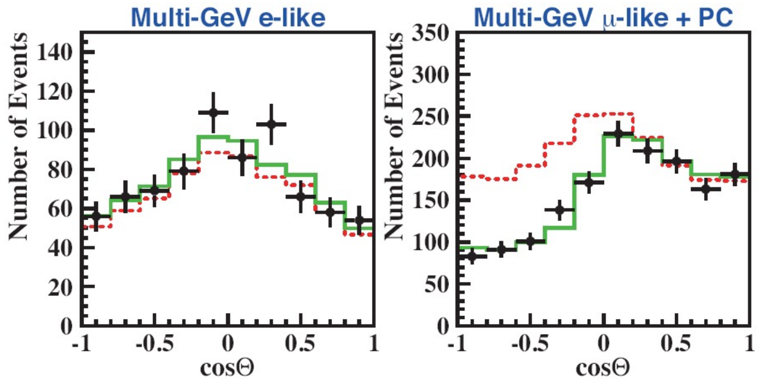
Neutrino Oscillation



1998, Super-K discovered neutrino oscillation via atmospheric ν

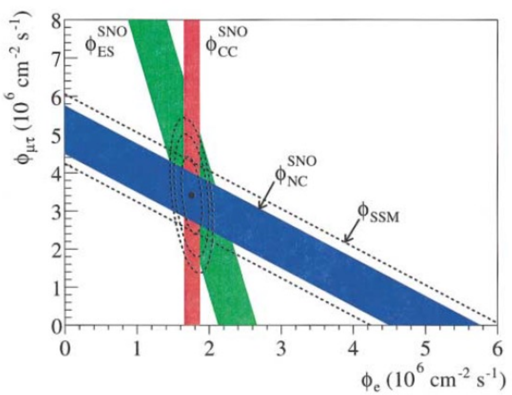


2001, SNO discovered solar neutrino oscillation



$$\sin^2 2\theta_{23} = 1$$

$$\Delta^2 m_{32} = 2.5\times10^{-3} eV^2$$



$$\sin^2 2\theta_{12} = 0.85$$

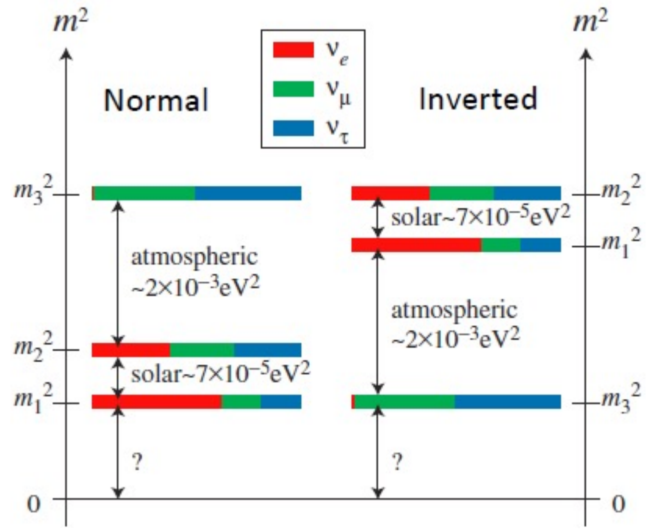
$$\Delta^2 m_{21} = 7.5\times10^{-5} eV^2$$

Neutrino Oscillation

- 2-neutrino oscillation: $(\Delta m^2, \theta)$
- 3-neutrino oscillation:
  → **6 parameters**

θ_{12}	θ_{23}	θ_{13}	δ_{CP}
Δm^2_{21}	$\|\Delta m^2_{32}\|$	Δm^2_{31}	

Mass ordering



$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{-i\alpha_1/2} & 0 & 0 \\ 0 & e^{-i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$c_{ij} \equiv \cos\theta_{ij}$

$s_{ij} \equiv \sin\theta_{ij}$

Atmospheric: $\theta_{23} \approx 45°$

"CP" sector: $\theta_{13} = 9°$

Solar: $\theta_{12} \approx 34°$

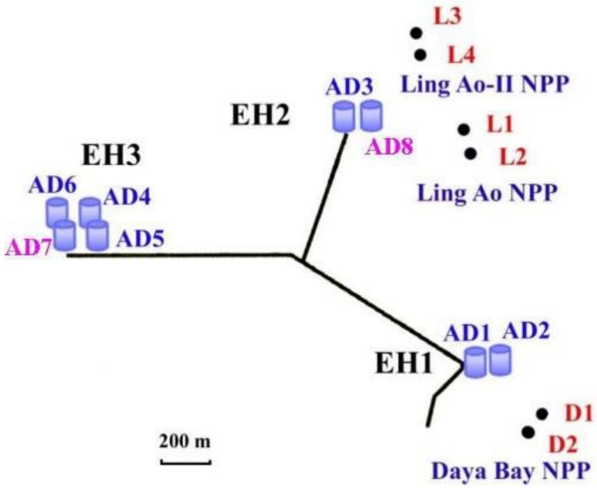
Majorana

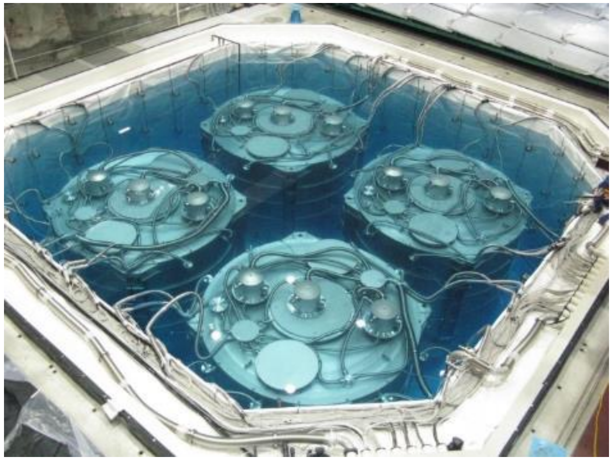
$|\Delta m^2_{32}| \approx |\Delta m^2_{31}| \approx 2.4 \times 10^{-3}\ \mathrm{eV}^2$

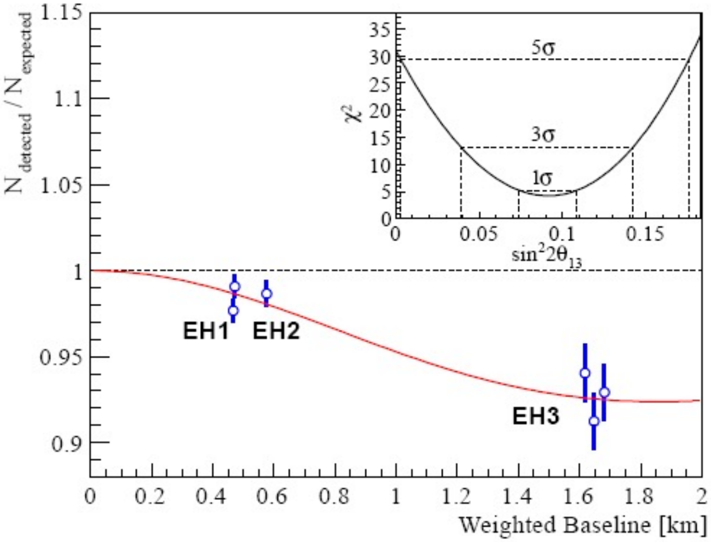
$\Delta m^2_{21} \approx 7.6 \times 10^{-5}\ \mathrm{eV}^2$

Daya Bay

- Daya Bay proposed in 2003
- Approved in 2006
- Civil construction 2007.10
  - ⇨ Idea for JUNO in 2008
- First detector operation 2011.8.15
- All three sites w/ 6 detectors 2011.12.24
- Discovered the 3rd oscillation 2012.3.8
- Completed all 8 detectors 2012.10.19
- Shutdown 2020.12.12, completed decommission 2021.7



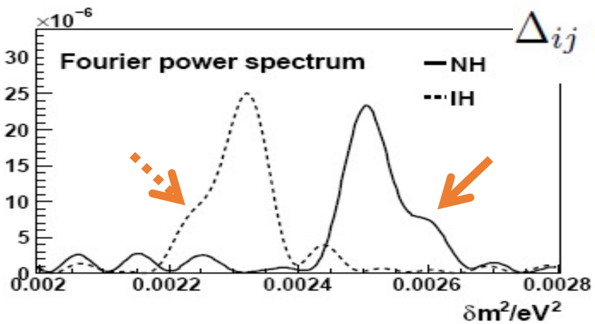


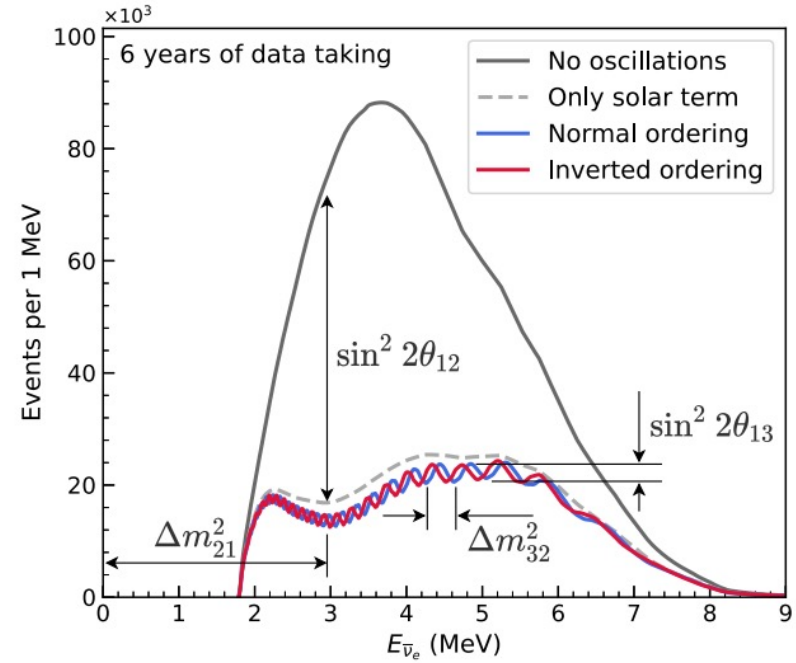


Mass Ordering with Reactor

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

$$\Delta_{ij} = \frac{\Delta m^2_{ij} L}{4E}$$





Petcov et al., PLB533(2002) 94,
J. Learned et al., PRD78, 071302 (2008),
L. Zhan, Y. Wang, J. Cao, L. Wen, PRD78:111103, 2008, PRD79:073007, 2009

- Relative measurement
- Not rely on δ_{CP} and θ_{23}
- JUNO energy resolution: $3\%/\sqrt{E}$

Δm^2_{31} **and** Δm^2_{32} **Interplay**	Δm^2_{ee} **and** $\Delta m^2_{\mu\mu}$ **difference**	**Matter Effect**

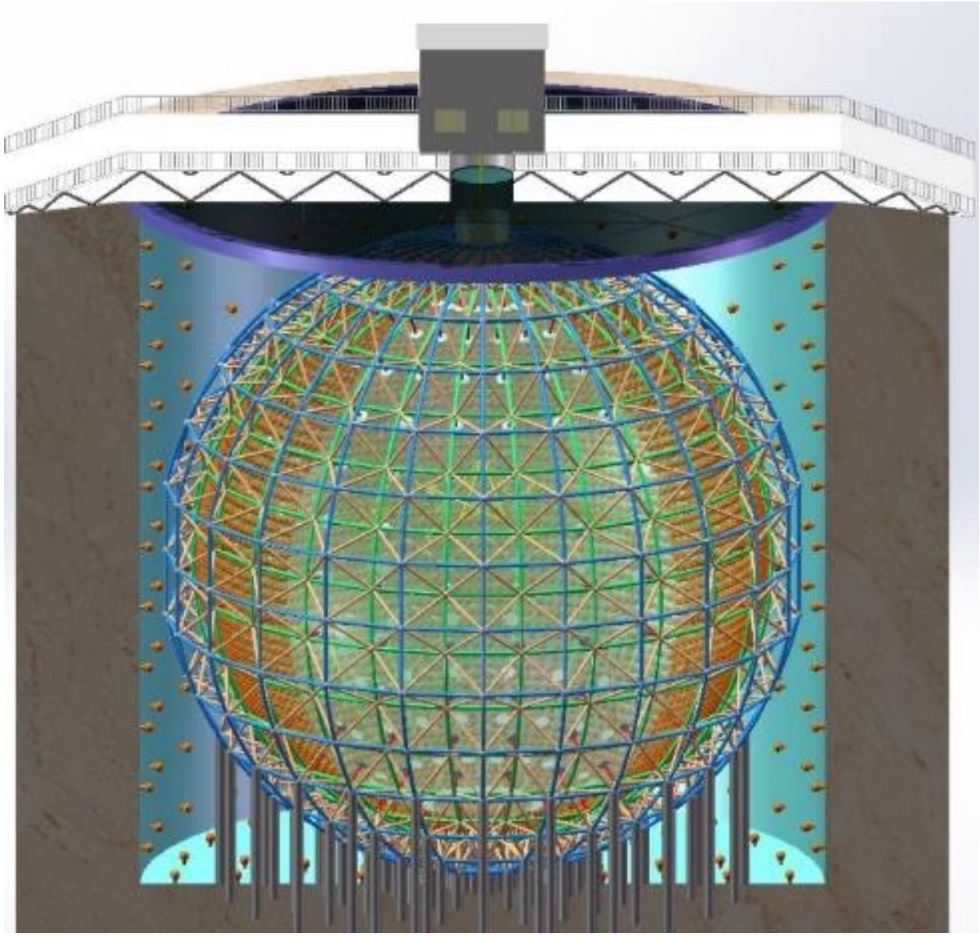
Reactor

Atmospheric

Accelerator

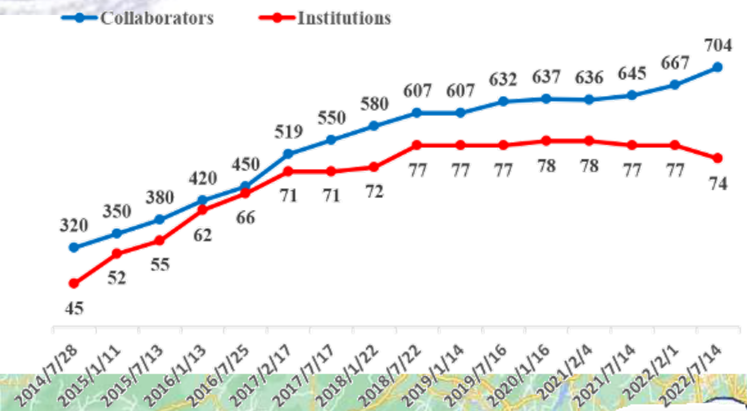
The JUNO Experiment

- Jiangmen Underground Neutrino Observatory (JUNO), a multiple-purpose neutrino experiment. Approved in Feb. 2013. ~ 300 M$. Ground-breaking in 2015. Construction to be completed in 2023.



- 20 kton LS detector
- 3% energy resolution
- 700 m underground
- Rich physics possibilities
  - ⇨ Reactor neutrino for Mass Ordering and precision measurement of oscillation parameters
  - ⇨ Supernovae neutrino
  - ⇨ Geoneutrino
  - ⇨ Solar neutrino
  - ⇨ Atmospheric neutrino
  - ⇨ Proton decay
  - ⇨ Exotic searches

Location, Collaboration



75 institutions, 700 collaborators

Asia: China (31), Taiwan,China (3) Thailand (3), Pakistan, Armenia

Europe: Italy (8), Germany (7), France (5), Russia (3), Belgium, Czech, Finland, Latvia, Slovakia, Croatia

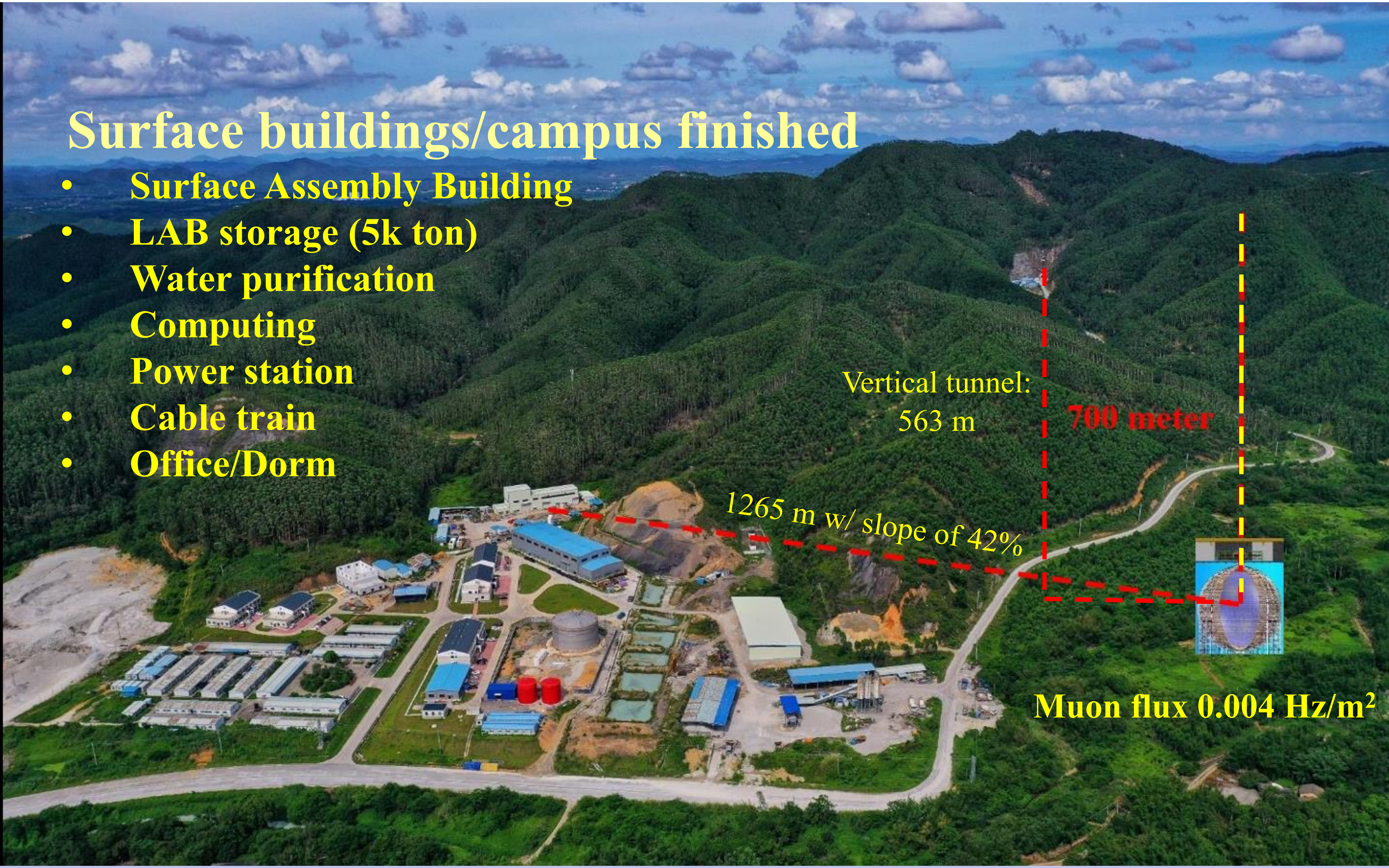
America: Brazil (2), Chile (2), USA (2)

Yangjiang	Taishan
2.9GW × 6	4.6GW × 2

JUNO Site

Surface buildings/campus finished

- Surface Assembly Building
- LAB storage (5k ton)
- Water purification
- Computing
- Power station
- Cable train
- Office/Dorm

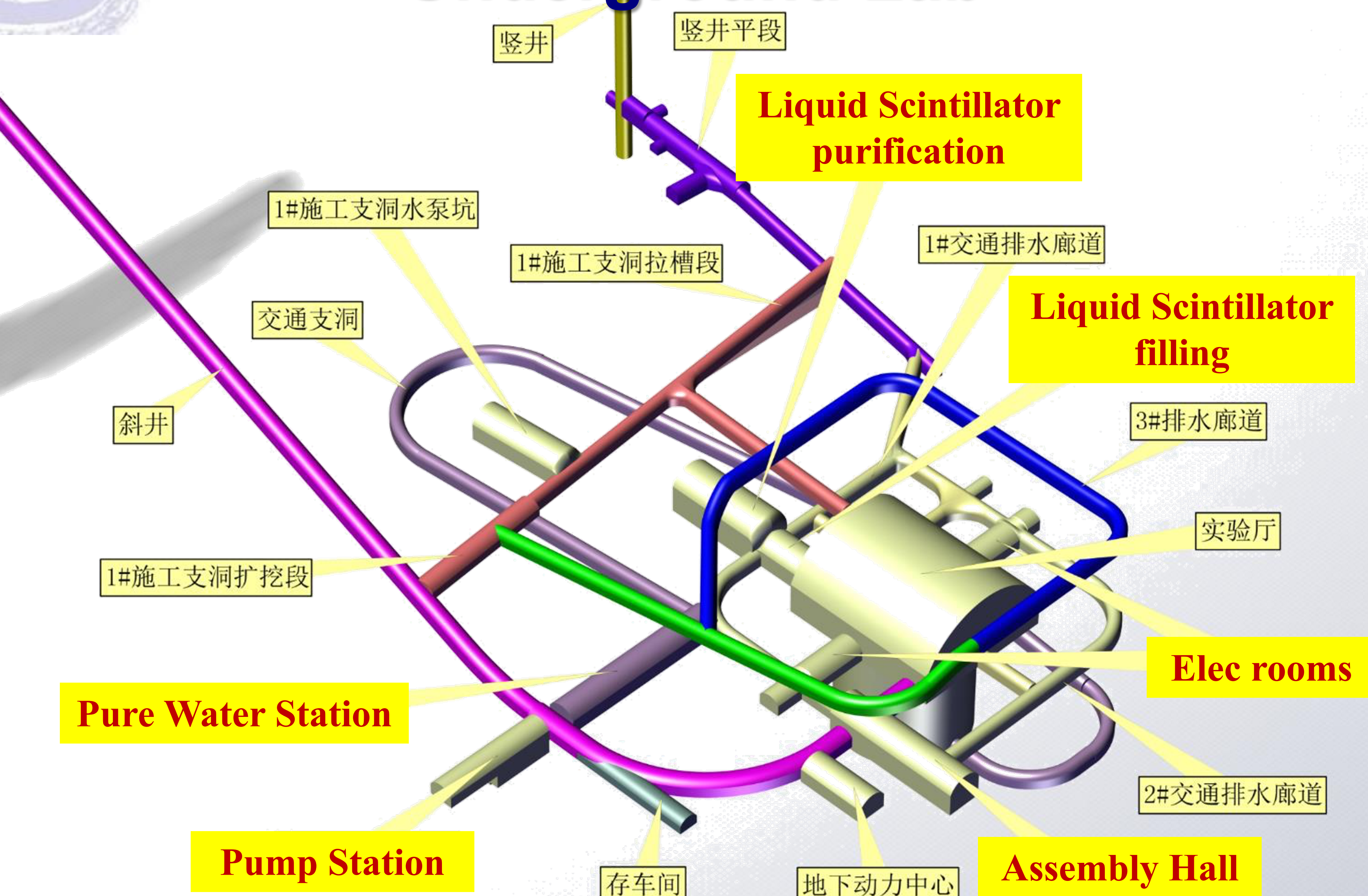


Transportation

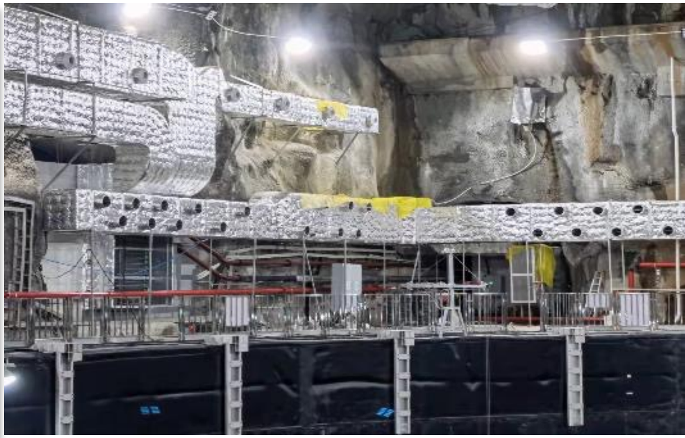
Cable train for cargo and people now.

Elevator (for people) under installation, ready in this year

Underground Lab



Underground Facility Ready

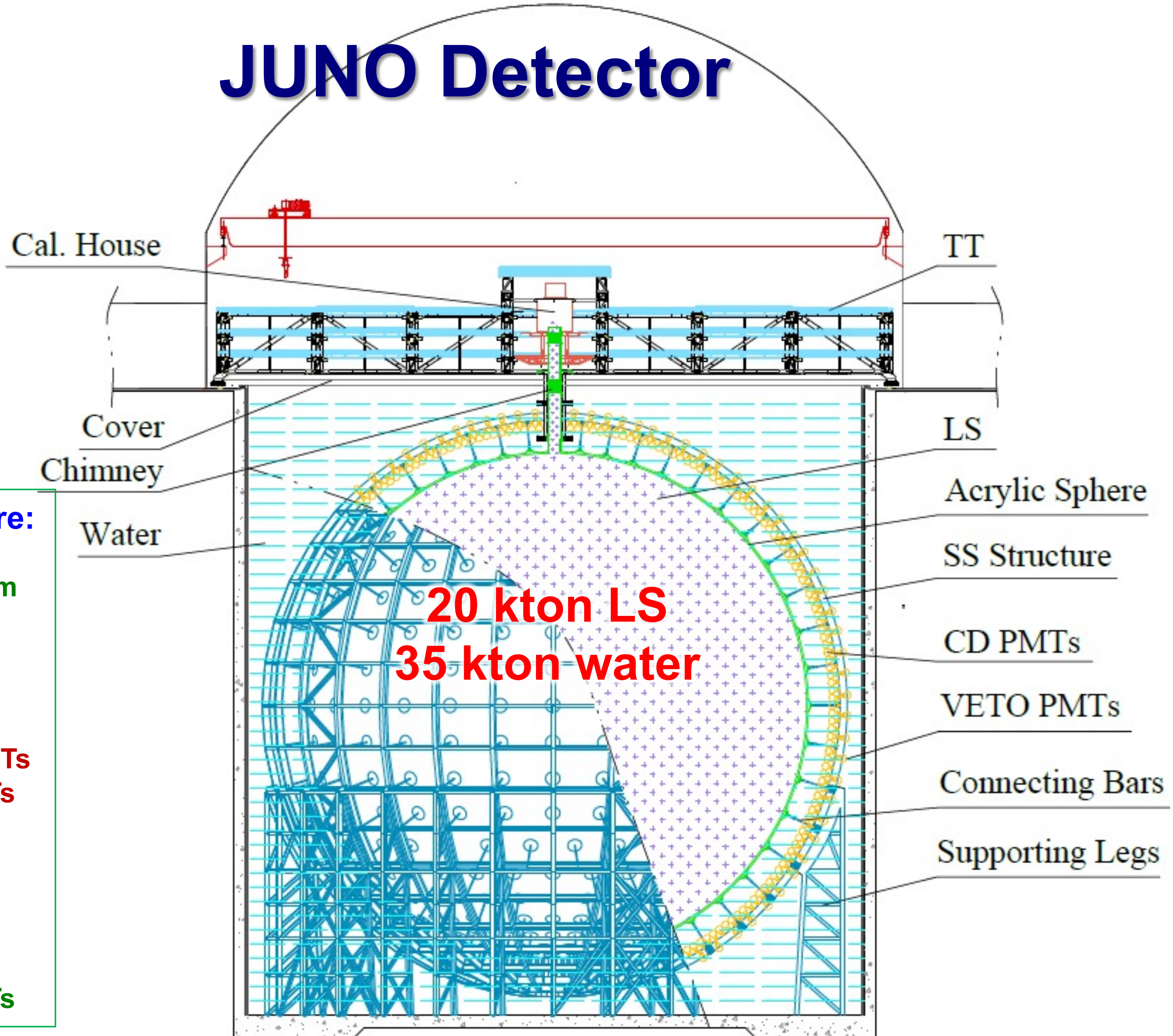


Assembly Hall

LS Hall

VAC System

JUNO Detector



Acrylic Sphere:
ID: 35.4m
Thickness:12cm

SS Lattice:
ID: 40.1m
OD: 41.1m
17716 20-in PMTs
25600 3-in PMTs

Water pool:
ID: 43.5m
Height: 44m
Depth: 43.5m
2400 20-in PMTs

State-of-Art LS Detector

Mass Ordering measurement drives the detector specification:

- Unprecedented energy resolution (3%)
  - ⇨ PMT Coverage 78%
  - ⇨ PMT Detection Eff. > 27%
  - ⇨ LS attenuation length > 20 m
- Low background (e.g. 1 ppt for acrylic, 10^{-15} g/g/ for LS)
- 20 times larger than any existing LS det., mechanical challenges

	Daya Bay	BOREXINO	KamLAND	**JUNO**
Target Mass	~20 t	~300 t	~1 kt	**~20 kt**
Photoelectron Yield (PE/MeV)	~160	~500	~250	**~1200**
Photocathode Coverage	~12%	~34%	~34%	**~78%**
Energy Resolution	~8%/√E	~5%/√E	~6%/√E	**3%/√E**

Multi-purpose detector requirements:

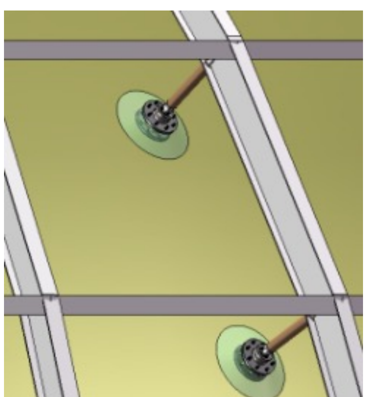
- Solar neutrino (and future $0\nu\beta\beta$) → low bkg 10^{-17} g/g for LS
- Supernova neutrino → Electronics, Trigger, DAQ, Onsite computing

→ Refresh many studies by an order

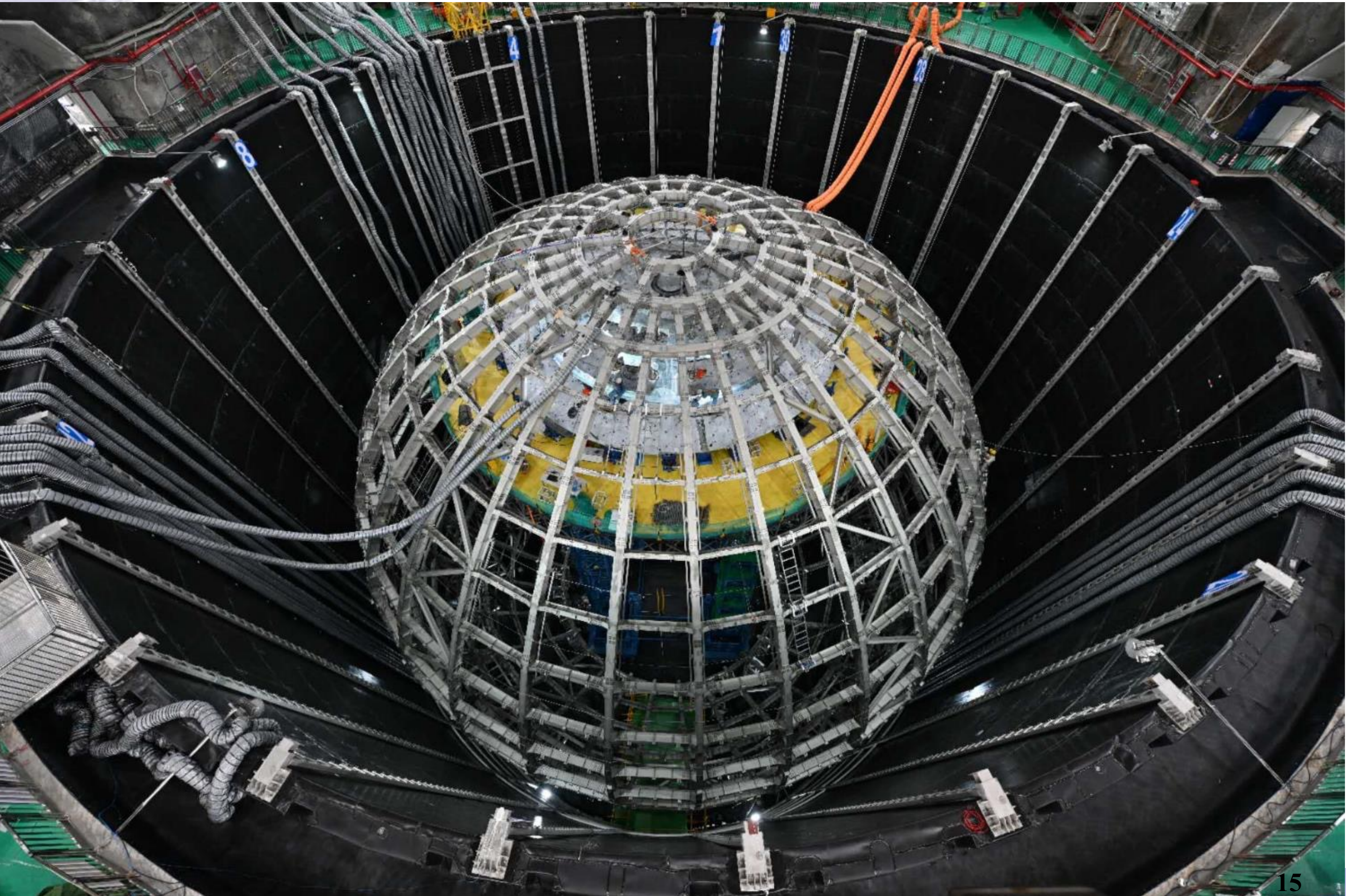
Central Detector

- **Acrylic Vessel + Stainless Steel Truss support**
  - Acrylic Sphere ID 35.4 m, thickness 120 mm
  - SS truss ID 40.1 m, OD 41.1 m
  - Buoyancy ~ 3000 ton. 590 supporting bars to hold the acrylic. Stress of acrylic <3.5 MPa
- **Main difficulties**
  - Acrylic transparency >96%, U/Th/K <1 ppt
  - Fast bonding of 265 acrylic panels
  - Mechanical precision for 3 mm PMT clearance
  - Thermal expansion matching: $21^{o}C \pm 1^{o}C$
  - Earth quake and liquid-solid coupling

Largest Panel: 3m x 8m x 0.12m

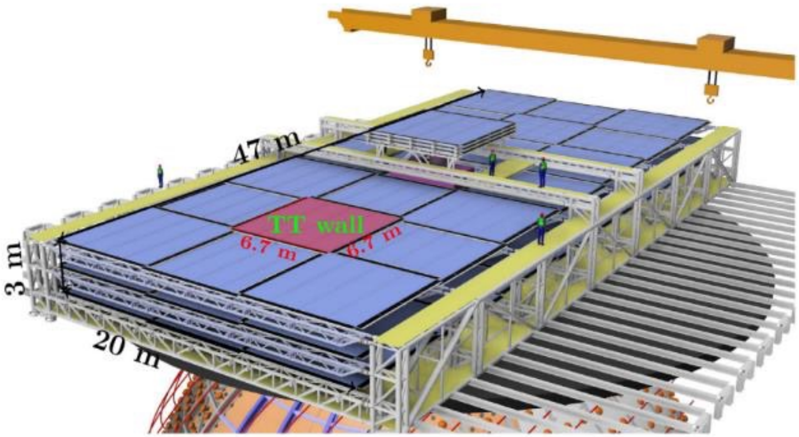


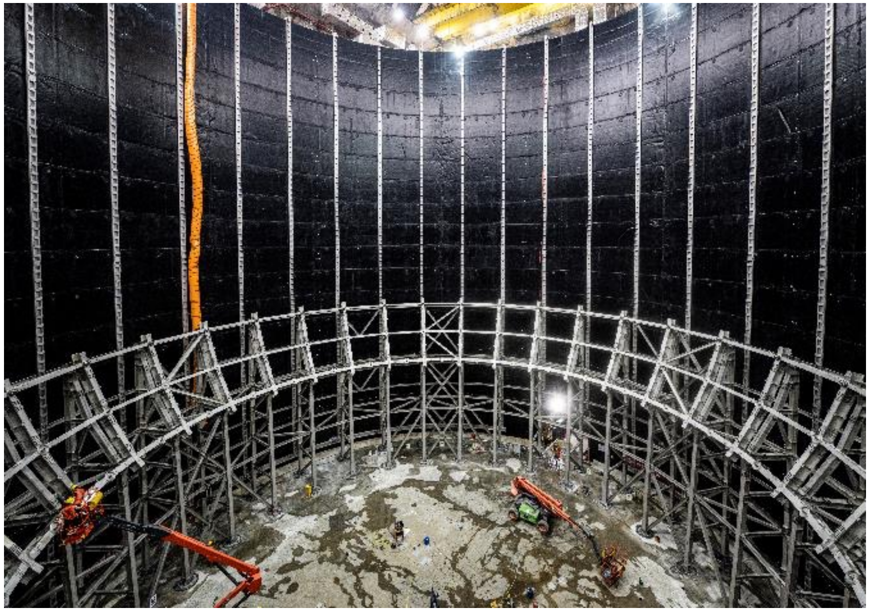
Central Detector under Construction



Veto

- **Tasks**
  - Shield rock-related backgrounds
  - Tag & reconstruct cosmic-rays tracks w/ **Top Tracker** and **Water Č det.**
- **Top tracker: OPERA scintillators**
  - 3 layers, ~50% coverage on the top
  - $\theta \to 0.2°,\ \Delta D \to 20$ cm
- **Water Cerenkov detector**
  - 35 kton water, 2400 20-inch PMTs, detection efficiency >99.5%
  - Keep uniform temp 21°C±1°C
  - ^{222}Rn < 10 mBq/m^3 (w/ micro-bubble system)
- **Pool lining: HDPE**
- **Earth magnetic field compensation coil**





Liquid scintillator

- **Four purification plants to achieve target radio-purity 10^{-17} g/g U/Th and 20 m attenuation length at 430 nm. 7 ton/hour.**

5000 m^3 LAB tank

1) Al_2O_3 for optical

2) Distillation for radiopurity

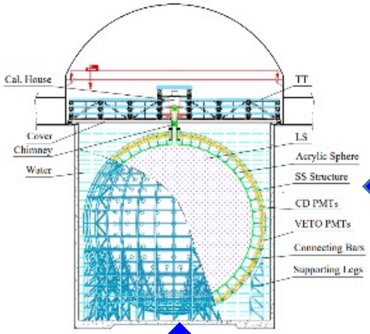
Mixing PPO and bis-MSB

SS pipes to underground

3) Water extraction to remove radioactive impurities

4) Gas stripping to remove Rn and O_2

OSIRIS to monitor the LS quality

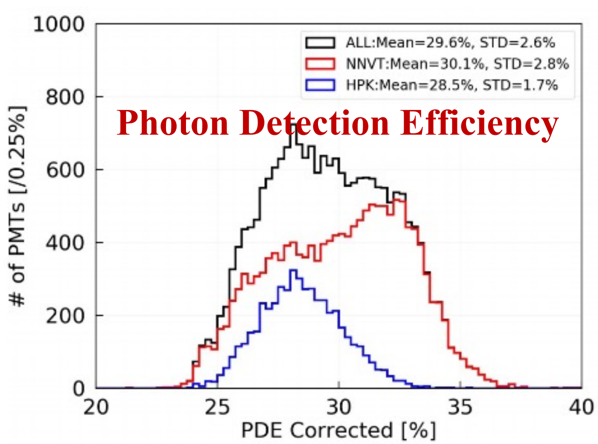


U/Th in PPO (production) ~ 0.1 ppt, in water ~10^{-16} g/g

Photomultiplier Tubes

- **20,012 20-inch PMTs: 15,012 MCP (2,400 for veto) and 5,000 dynode**
- **25,600 3-inch PMTs (all for CD)**
- **All has been produced, tested, and potted.**
  PDE 30.1% (higher than designed 27%)

arXiv:2205.08629



		LPMT (20-inch)		SPMT (3-inch)
		Hamamatsu	NNVT	HZC
Quantity		5000	15012	25600
Charge Collection		Dynode	MCP	Dynode
Photon Detection Efficiency		28.5%	30.1%	25%
Mean Dark Count Rate [kHz]	Bare	15.3	49.3	0.5
	Potted	17.0	31.2	
Transit Time Spread (σ) [ns]		1.3	7.0	1.6
Dynamic range for [0-10] MeV		[0, 100] PEs		[0, 2] PEs
Coverage		75%		3%
Reference		arXiv: 2205.08629		NIM.A 1005 (2021) 165347

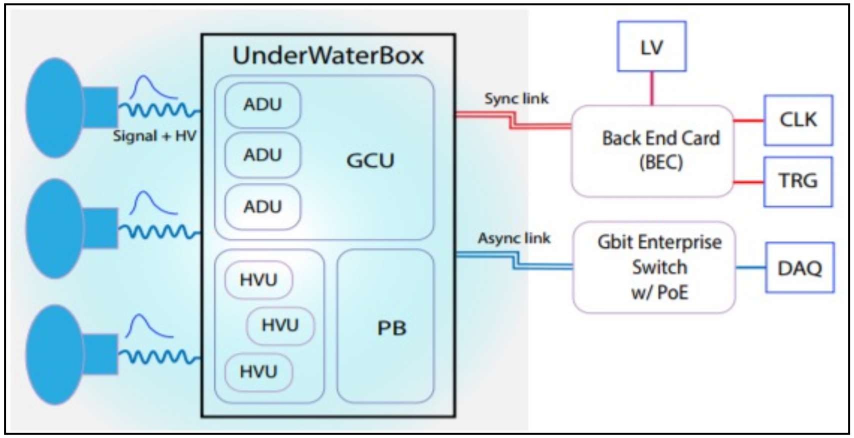
Electronics

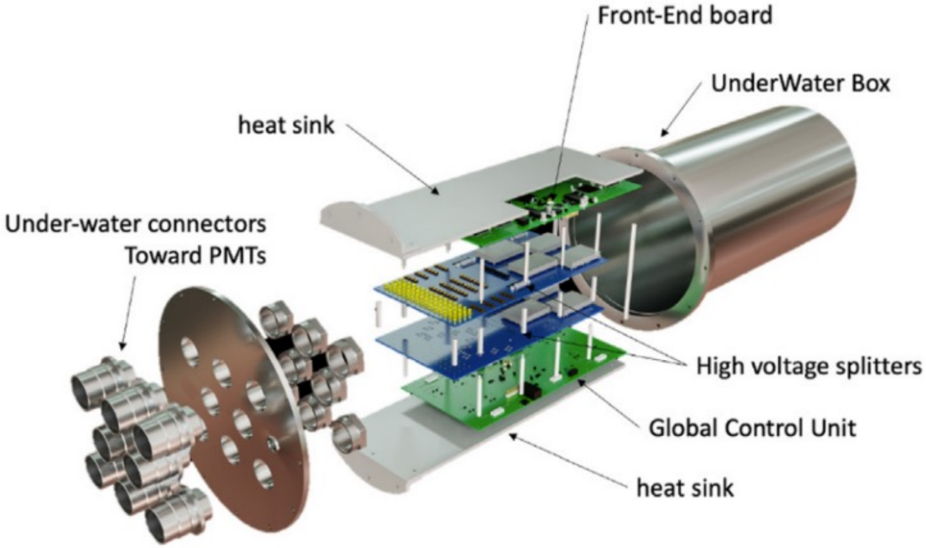
Underwater electronics for good signal-to-noise ratio.

- **Electronics for 20-inch:**
  - 3 PMTs connect to one underwater box
  - Noise: < 10% @ 1 PE
  - Resolution: 10%@1PE
  - 1 GHz sampling
  - Failure rate: < 0.5%/6 years

- **Electronics for 3-inch:**
  - 128 PMTs connect to one underwater box
  - CATIROC ASICs
  - Timing 200 ps
  - Dynamic range 1-hundreds p.e.

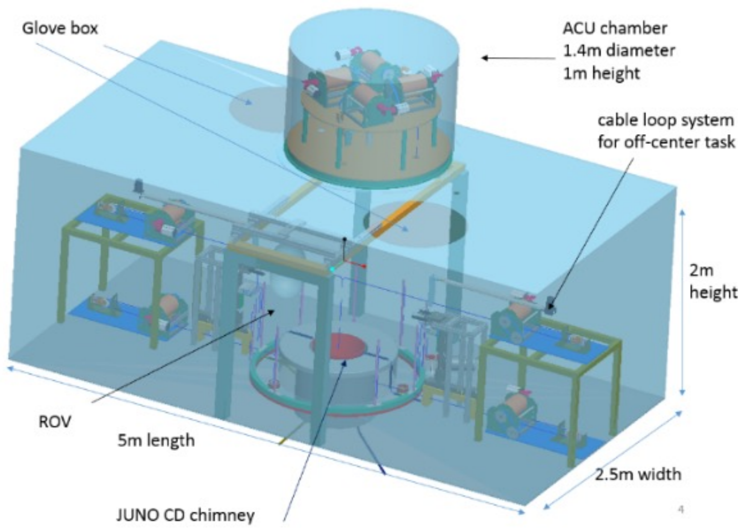
NIMA 1043 (2022) 167499

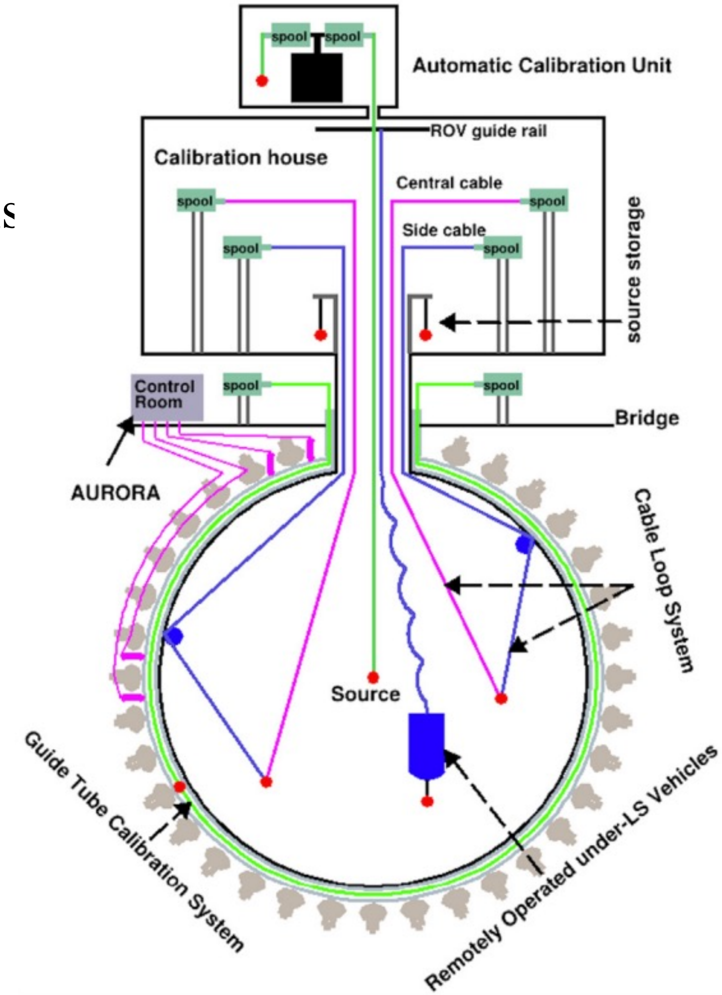




Calibration

- **4 calibration facilities**
  - ⇨ Routinely Source into LS by
    - Automatic Calibration Unit: at central axis
    - Rope Loop System : a plane
  - ⇨ Source into Guided Tube adhere to acrylic outer wall
  - ⇨ ROV: "sub-marine" anywhere in the LS
- Ready for installation





JHEP 03 (2021) 004

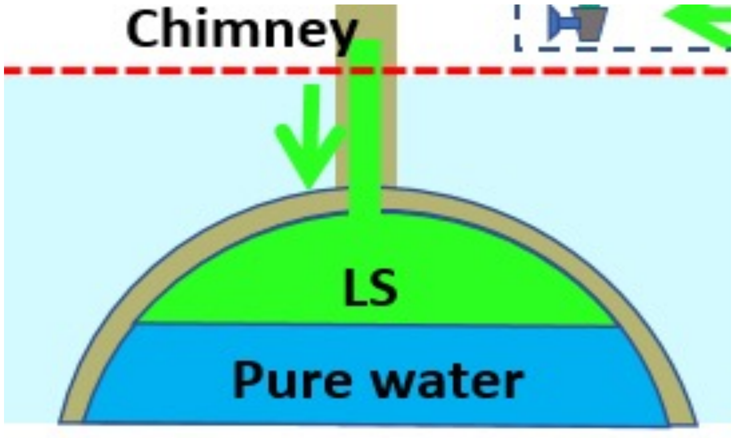
Radiopurity control

- **Required <10 Hz singles in fiducial volume**
- **Radiopurity control on raw material:**
  - ⇨ Material screening
  - ⇨ Detector production handling

Singles (R < 17.2 m, E > 0.7 MeV)	Design [Hz]	Change [Hz]	Comment
LS	2.20	?	To be produced
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 → 4 m
Radon in water	1.31	-1.25	200 → 10 mBq/m³
Other	0	+0.52	Missing parts
Total	**8.5**	-1.3	

Compared to the design (JHEP 11 (2021) 102)

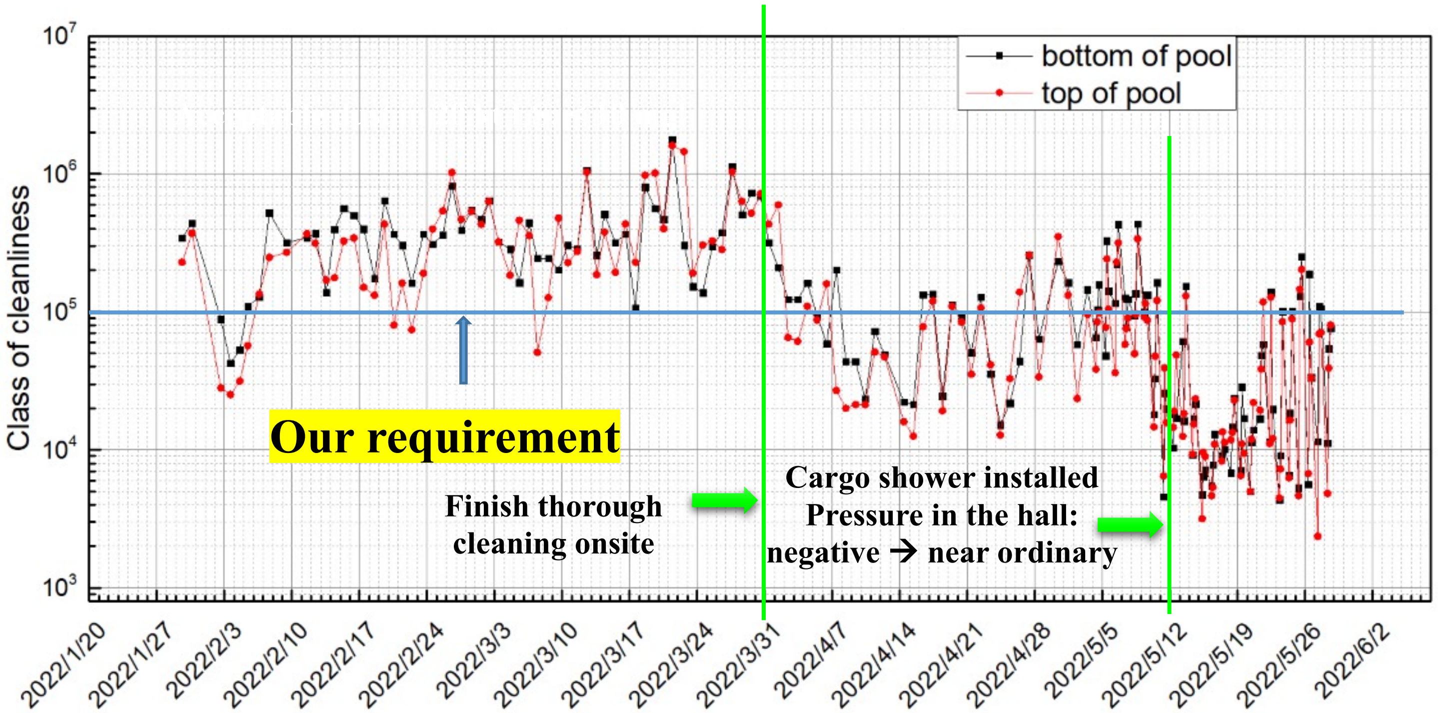
- **Liquid Scintillator Filling**
  - ⇨ Recirculation is difficult at JUNO. Radiopurity need to be obtained from the beginning
- **Strategies:**
  - ⇨ Leakage (single component < 10^{-6} mbar·L/s)
  - ⇨ Cleaning vessel before filling
  - ⇨ Clean environment
  - ⇨ Water/LS filling



Radiopurity control: environment cleanliness

- Daily monitor the dust and Radon level, and improve the cleanliness of the experimental hall

Region	Level
1	Class 100,000
2	Class 10,000
3	Class 1000

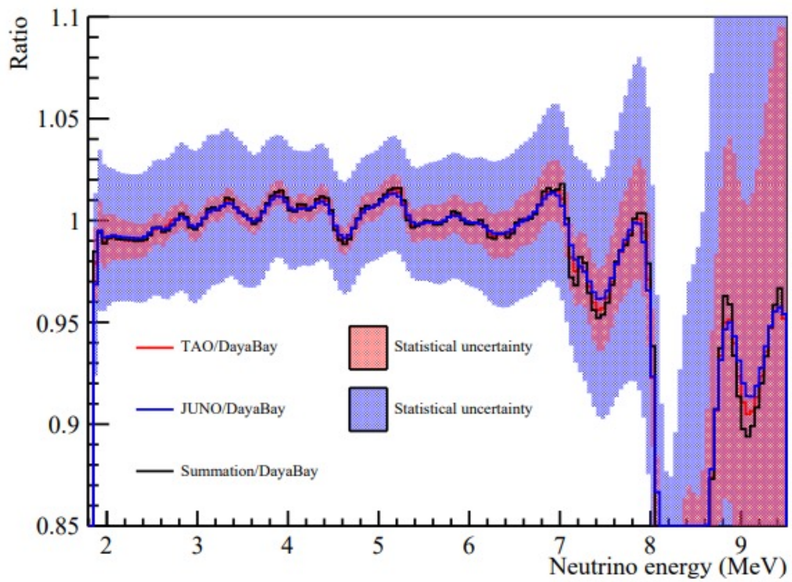


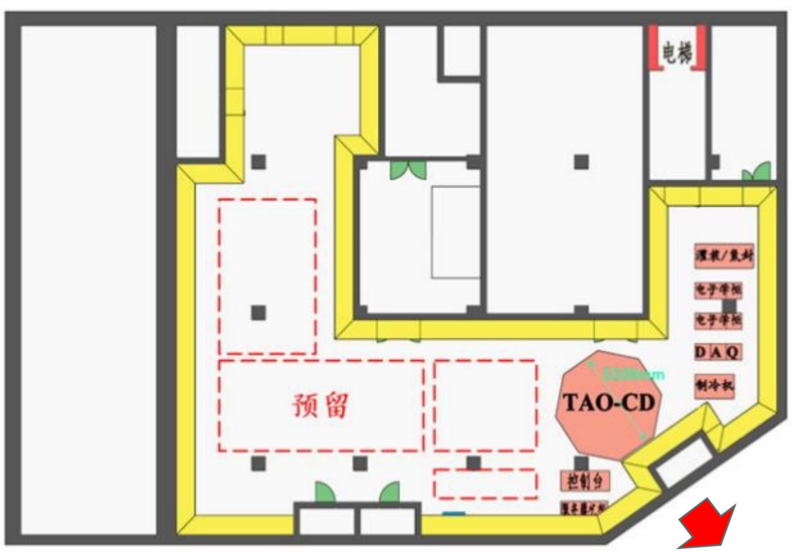
With great efforts on onsite cleanliness control, the cleanliness in the hall reaches better than Class 100,000, and the radon is 50~100 Bq/m^3

JUNO-TAO

- Taishan Antineutrino Observatory (TAO), a ton-level, high energy resolution LS detector at 30 m from the core, a satellite detector of JUNO.
- Measure reactor neutrino spectrum w/ sub-percent E resolution.
  - ⇨ model-independent reference spectrum for JUNO
  - ⇨ a benchmark for investigation of the nuclear database
- Taishan Nuclear Power Plant, 30 m from a 4.6 GW core, in a hall at -10 m underground.

TAO CDR: arXiv: 2005.08745

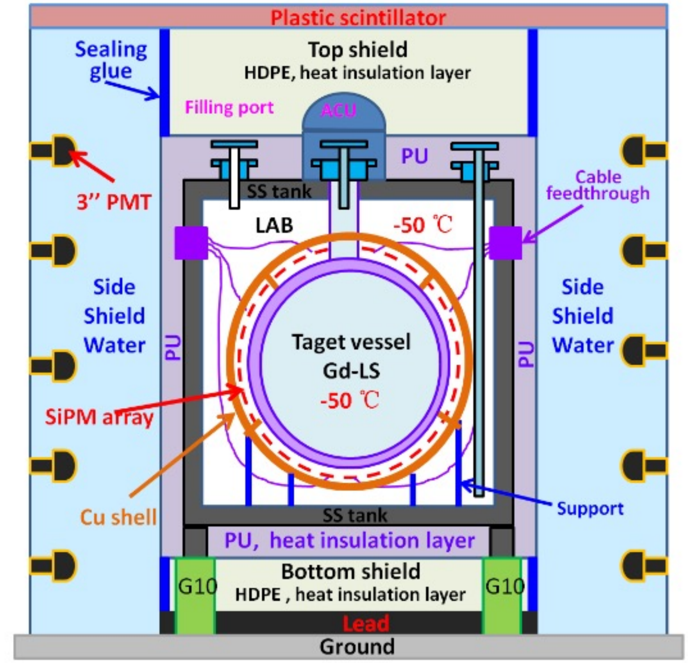




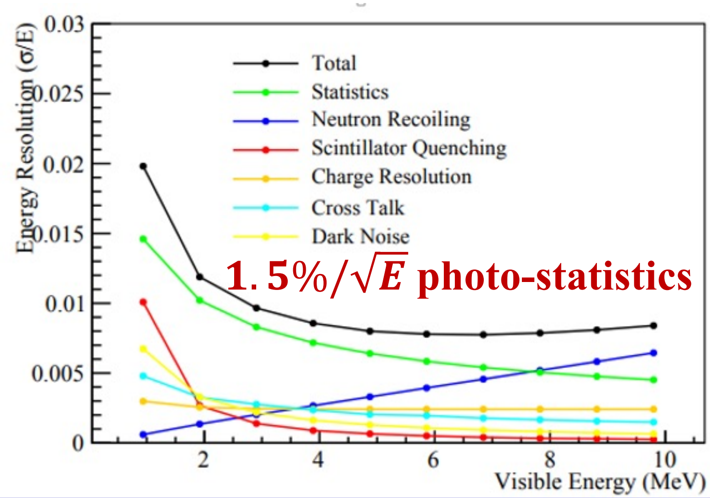
Constrain the fine structure in [2.5,6] MeV to < 1%

JUNO-TAO

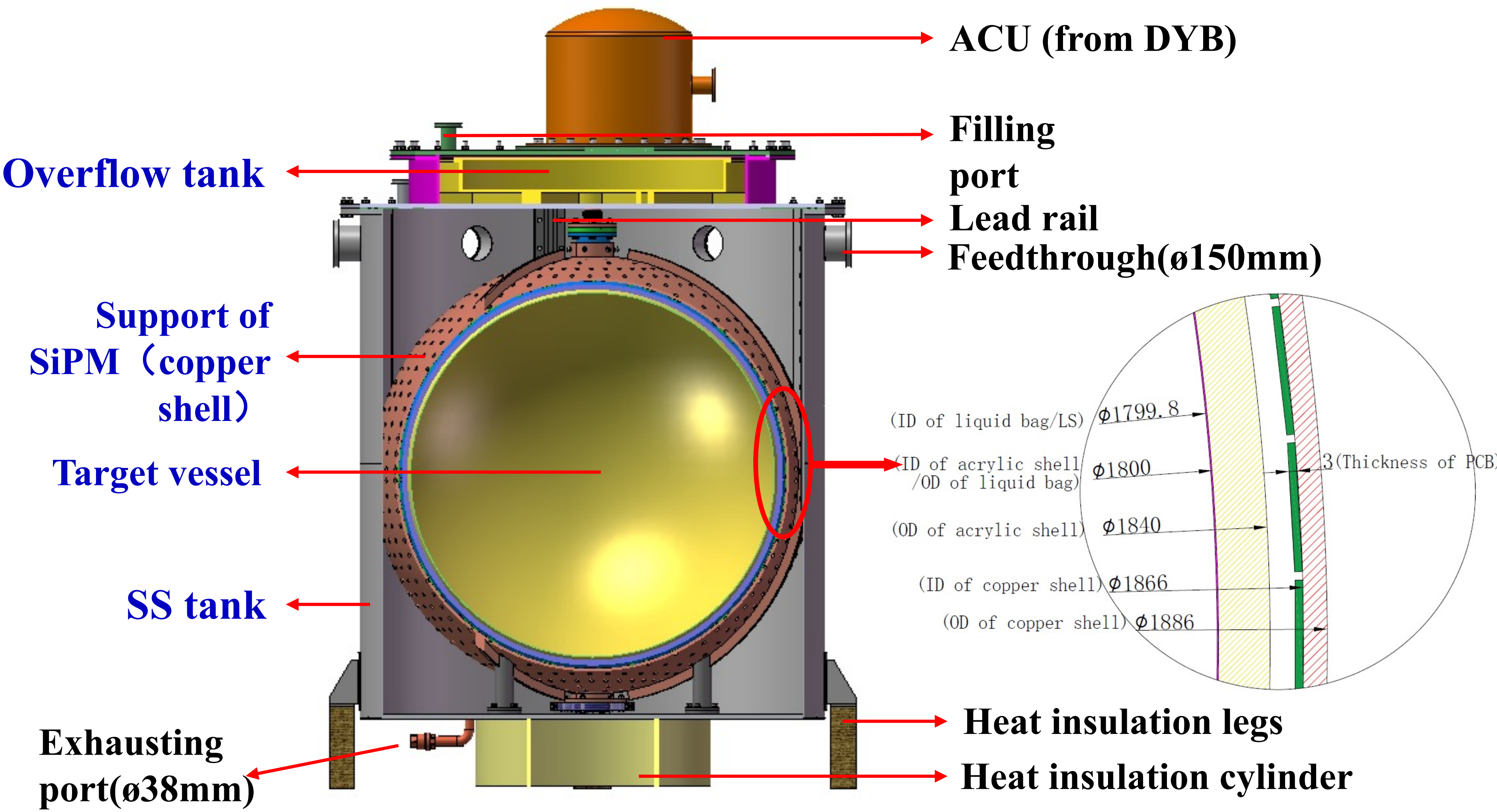
- 2.8 ton Gd-LS (1 ton fiducial mass), produced
- 94% coverage of SiPM w/ PDE > 50%, 1st batch received, under testing
- 1.8-m ID acrylic vessel, Copper Shell, SS tank, and GdLS are ready
- Electronics, in production
- Operate at -50 °C (SiPM dark noise)
- To be tested at IHEP, w/ SiPM samples.
- 4500 p.e./MeV → < 2% resolution
- Neutron back-to-signal ratio ~2%
  (*JINST* 17 (2022) 09, P09024)



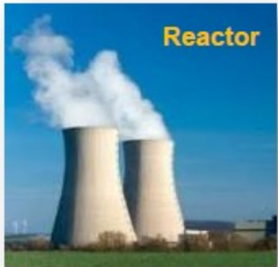
arXiv: 2204.03256



TAO Central Detector

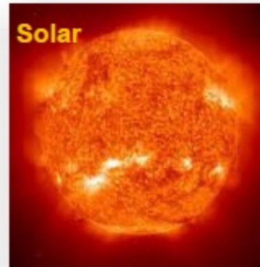


JUNO Physics (reactor)



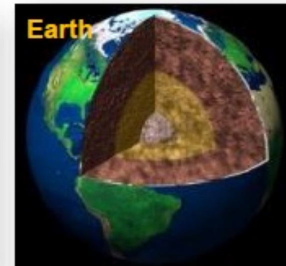
~60 IBDs per day

Several per day



Hundreds per day

~5000 IBDs for CCSN @10 kpc



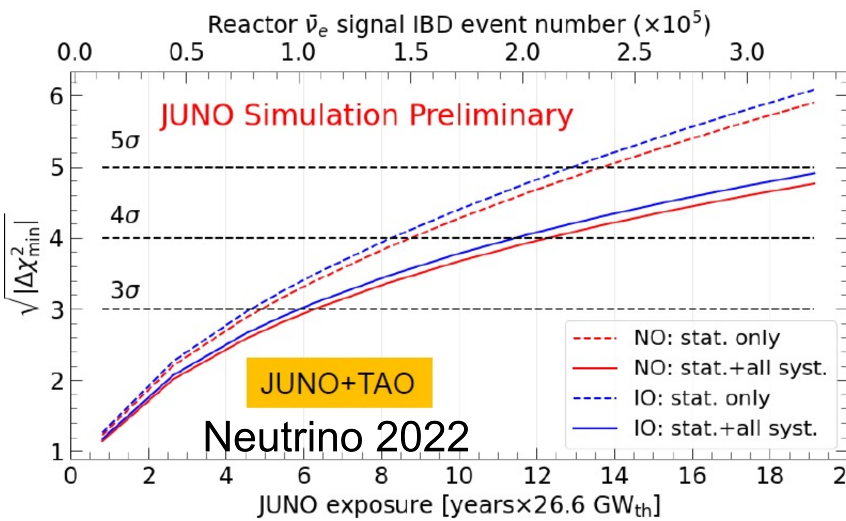
Several IBDs per day

+ New physics

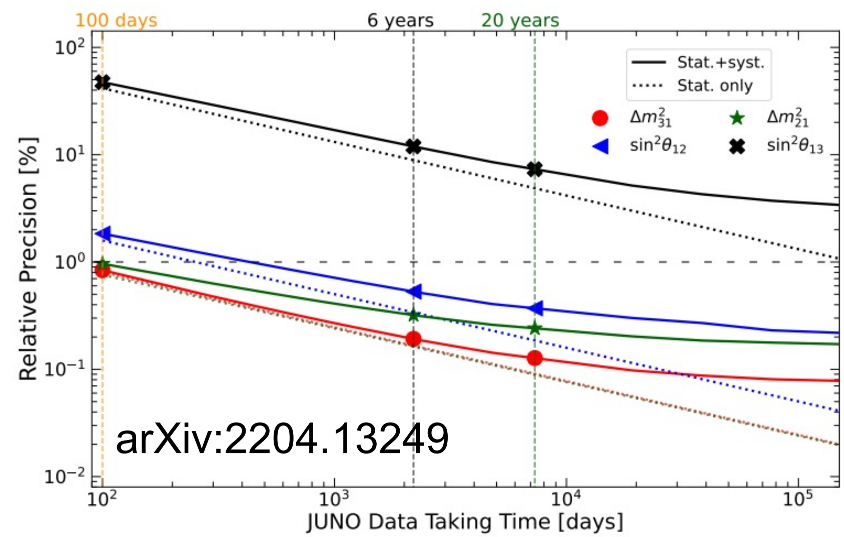
Prog. Part. Nucl. Phys. 123, 103927 (2022)

Neutrino oscillation & properties

Neutrinos as a probe



Neutrino 2022



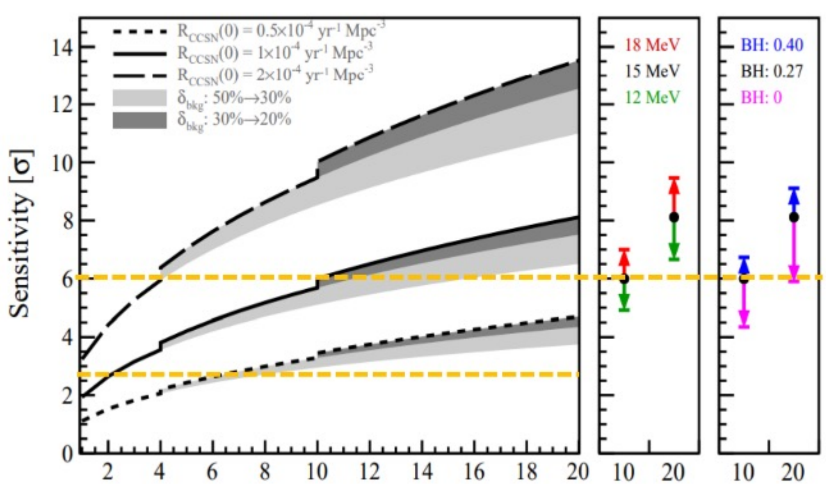
arXiv:2204.13249

Energy resolution 2.9% w/ full simulation
MO: 3σ (reactors only) @ ~6 yrs

Precision of $\sin^2 2\theta_{12}$, Δm^2_{21}, $|\Delta m^2_{32}|$ < 0.5% in 6 yrs

JUNO Physics (e.g.)

Physics	Sensitivity
Supernova Burst (10 kpc)	~5000 IBD, ~300 eES and ~2000 pES of all-flavor
DSNB	3σ in 3 yrs
Solar neutrino	Measure Be7, pep, CNO simultaneously, B8 flux
Atmospheric neutrino	0.7-1.4σ for NMO in 6 yrs. Boost the reactor result
Nucleon decays ($p \rightarrow \bar{\nu} K^{+}$)	8.3×10^{33} years (90% C.L.) in 10 yrs
Geo-neutrino	~400 per year, 5% measurement in 10 yrs



DSNB discovery potential: 3σ in 3 yrs with nominal model

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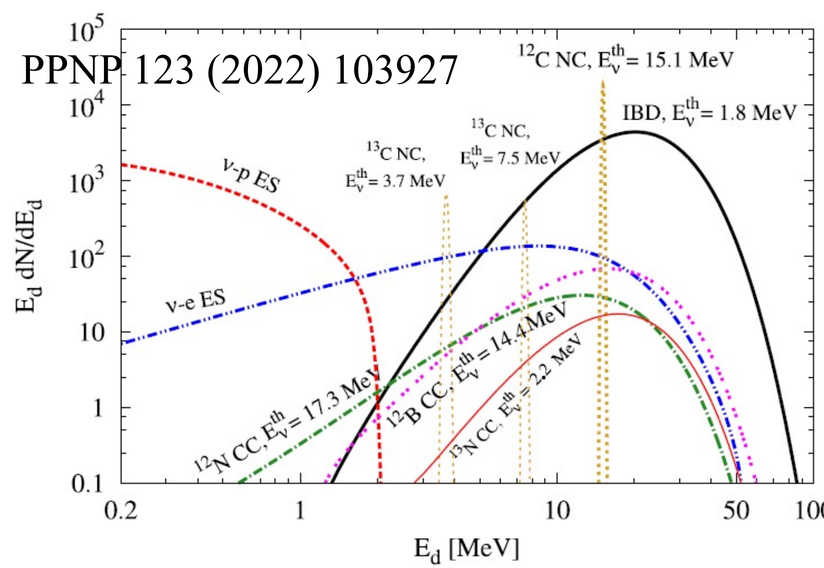

10kpc Supernova: ~5000 IBD, ~300 eES, ~2000 pES， ~200 ^{12}C CC, ~300 ^{12}C NC

Summary

- JUNO is motivated to measure the Neutrino Mass Ordering
  - ⇨ 20 kton liquid scintillator
  - ⇨ 3%/sqrt(E) energy resolution
  - ⇨ Advance detector technology
- Rich physics program. World-leading studies on
  - ⇨ Precision measurement of oscillation parameters, Supernova ν, DSNB, Geo-ν, solar ν, proton decay, …
  - ⇨ Future JUNO-0νββ
- Construction going on well since the detector installation, to be completed in 2023.
- Short-baseline experiment TAO, High energy solution measurement of reactor neutrino spectrum
  - ⇨ JUNO reference spectrum and benchmark for nuclear database