



Status and Physics Prospects of the JUNO Experiment

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On behalf of the JUNO collaboration



Current Status of PMNS Matrix

Six independent parameters govern the neutrino oscillation and were measured with precisions at a few percent level

$$|\nu_\alpha\rangle = \sum_{i=1}^3 U_{\alpha i} |\nu_i\rangle$$

Atmospheric, accelerator

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Solar, reactor L~60km

Reactor L~2km, accelerator

Ref. NuFIT group <http://www.nu-fit.org/?q=node/238>

	Best Fit		Global 1 σ
	NO	IO	
Δm_{21}^2 (eV ²)	7.42×10^{-5}		~2.8 %
Δm^2 (eV ²)	2.510×10^{-3}	2.430×10^{-3}	~1.1 %, sign is unknown
$\sin^2 \theta_{12}$	3.04×10^{-1}		~4%
$\sin^2 \theta_{13}$	2.246×10^{-2}	2.241×10^{-2}	~2.8%
$\sin^2 \theta_{23}$	4.50×10^{-1}	5.70×10^{-1}	3~6%
δ_{CP}	223°	278°	9~18%

With SK data

$$\Delta m^2 = |m_3^2 - (m_1^2 - m_2^2)/2|$$



Still Unknowns...

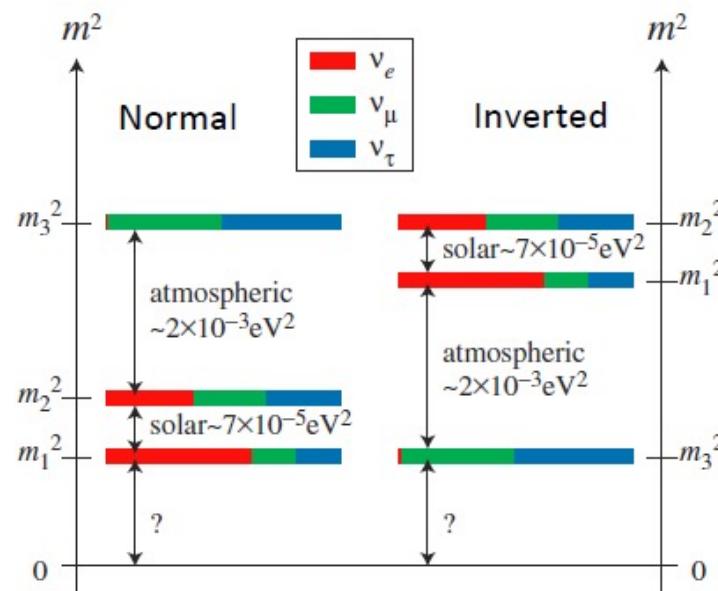
- Neutrino Mass Ordering (NMO)
- Leptonic CP-violating phase δ_{CP} in the PMNS matrix
- Octant of the mixing angle θ_{23}
- Precise values of mixing angles and mass splittings
- Majorana (neutrino identical to anti-neutrino) or Dirac particles?
- Sterile states or only 3 flavors?
- Lorenz Invariance Violation?
- Non-standard interactions?
- ...

JUNO's Main Goal:

Determine neutrino mass hierarchy (MH)

❖ Not dependent on:

CP-violating phase and θ_{23} octant

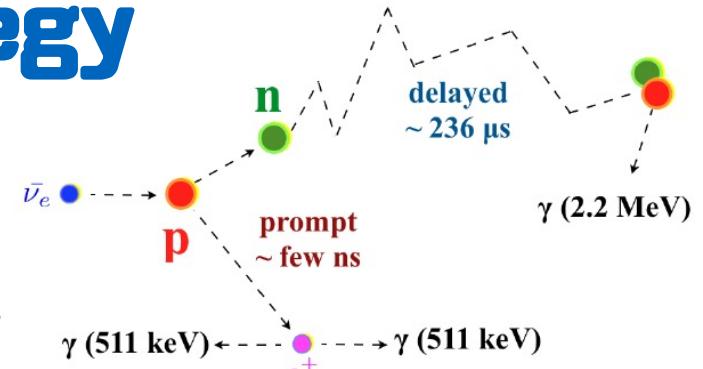




Measurement Strategy



- Prompt signal: annihilation process
- Delayed signal: neutron capture
- Prompt + Delayed coincidence provides distinctive signature



The determination of the mass hierarchy relies on the identification on the positron spectrum of the “imprinting” of the anti- ν_e survival probability

$$P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} = 1 - \sin^2 2\theta_{13} (\cos^2 \theta_{12} \sin^2 \Delta_{31} + \sin^2 \theta_{12} \sin^2 \Delta_{32}) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{21}$$

$$\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$$

$$\Delta m_{21}^2 \approx 7.5 \times 10^{-5} \text{ eV}^2$$

$$|\Delta m_{32}^2| \approx 2.5 \times 10^{-3} \text{ eV}^2$$

$$\text{NH: } |\Delta m_{31}^2| = |\Delta m_{32}^2| + |\Delta m_{21}^2|$$

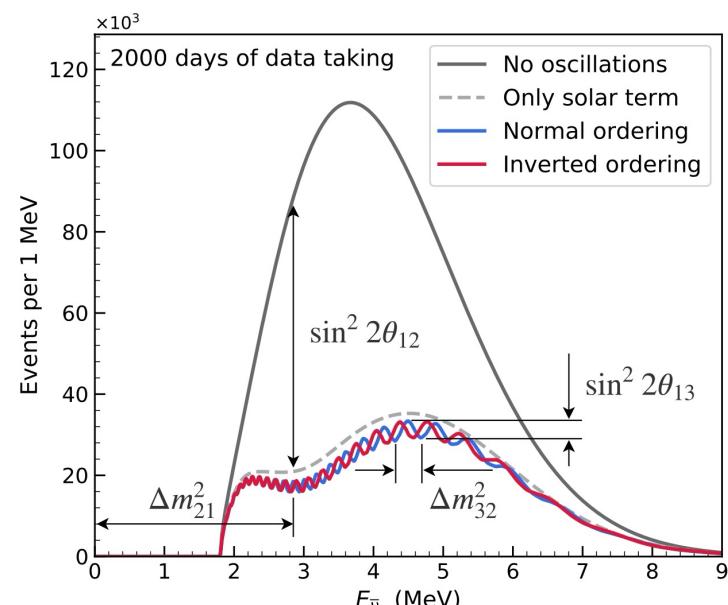
$$\text{IH: } |\Delta m_{31}^2| = |\Delta m_{32}^2| - |\Delta m_{21}^2|$$

$$\sin^2(\theta_{12}) = 0.307 \pm 0.013$$

$$\sin^2(\theta_{13}) = (2.18 \pm 0.07) \times 10^{-2}$$

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

- S.T. Petcov et al., PLB533(2002)94
 S.Choubey et al., PRD68(2003)113006
 J. Learned et al., PRD78, 071302 (2008)
 L. Zhan, PRD78:111103, 2008, PRD79:073007, 2009
 J. Learned et al., arXiv:0810.2580
 Y.F Li et al, PRD 88, 013008 (2013)
 ...

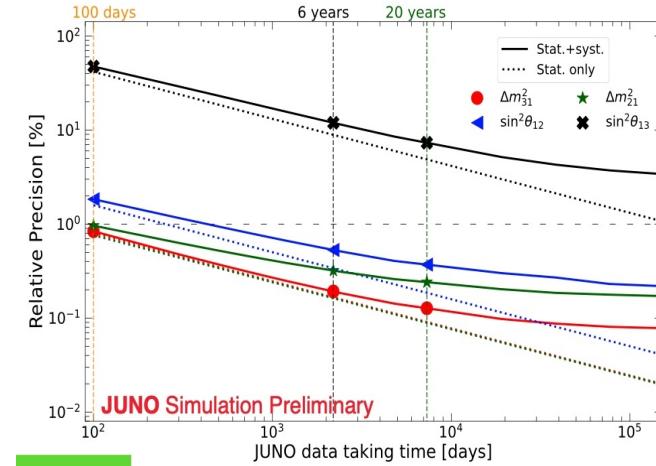




Keys to Precise Measurement

❖ JUNO will determine NMO at 3σ in 6 years of data taking.

	Δm_{31}^2	Δm_{21}^2	$\sin^2 \theta_{12}$
Dominant Exps.	T2K	KamLAND	SNO+SK
Individual 1σ	2.6%	2.4%	4.5%
PDG2020	1.4%	2.4%	4.2%
JUNO 6 years	~0.2%	~0.3%	~0.5%



To achieve:

- Baseline optimization: $53 \pm 0.5 \text{ km}$
- Excellent energy resolution: $3\%/\sqrt{E[\text{MeV}]}$

We should have

- ✓ Powerful source: 2 power plants operate by ($26.6 \text{ GW}_{\text{th}}$ in 2020, later $35.7 \text{ GW}_{\text{th}}$)
- ✓ Ideal baseline: $\sim 52.5 \text{ km}$ (distance between target and reactor core)
- ✓ Shielding: 700 m underground \rightarrow Muon event rate: $\sim 3 \text{ s}^{-1}$
- ✓ Huge target mass:
 - Single 20 kt LS detector $\sim 10^5$ events in 6 years detected via IBD
- ✓ Superb energy resolution: $3\% @ 1 \text{ MeV}$
 - High-yield scintillator: attenuation length $> 20 \text{ m} @ 430 \text{ nm}$
 - $\sim 78\%$ photo coverage for Large PMT
- ✓ Systematics suppression:
 - Unique combination of two sets of PMTs: $17k$ 20-inch PMTs + $25k$ 3-inch PMTs



JUNO Collaboration



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



Location

- ✓ **Powerful source:** 10 nuclear reactors
- ✓ **Ideal baseline:** 52.5 km
- ✓ **Shielding:** 700 m underground → Muon event rate: $\sim 3 \text{ s}^{-1}$



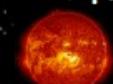
Cores	YJ-1	YJ-2	YJ-3	YJ-4	YJ-5	YJ-6	TS-1	TS-2	DYB	HZ
Power (GW)	2.9	2.9	2.9	2.9	2.9	2.9	4.6	4.6	17.4	17.4
Baseline(km)	52.74	52.82	52.41	52.49	52.11	52.19	52.77	52.64	215	265

Core-collapse supernovae

$\sim 10^4$ IBD/10 s @10 kpc



Atmospheric ν
Several / day



Solar ν
tens of ${}^8\text{B}-\nu$ /day
10 s – 1000 s / day

Cosmic Ray

$\sim 250\text{k}/\text{day}$ 0.003 Hz/m^2 , 215
GeV 10% multiple-muon

DSNB

1-2 evts/year

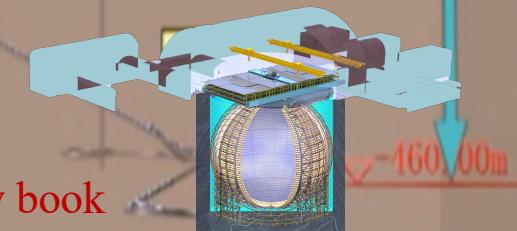
Reactor ν
 ~ 60 / day

26.6 GW, 53 km

Geo- ν
1~2 / day

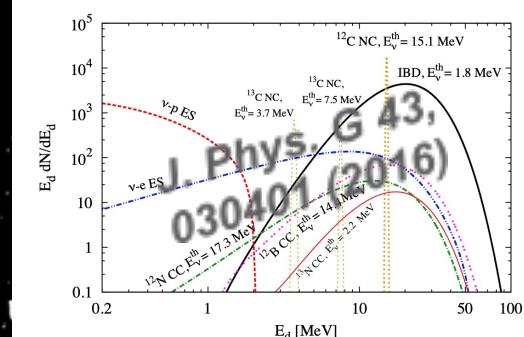
DSNB: Diffuse Supernova Neutrino Background

JUNO:Multiple Purpose Observatory

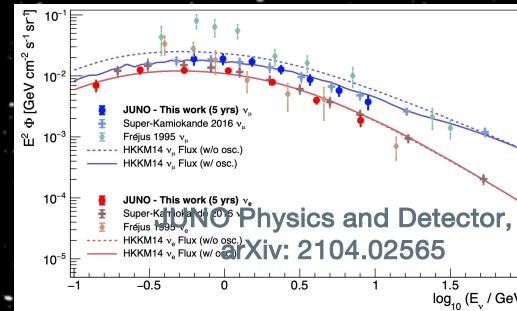


JUNO Yellow book
J. Phys. G 43, 030401 (2016)

Core-collapse supernovae



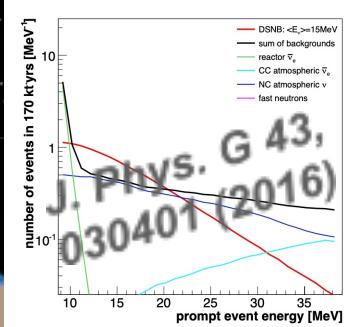
Atmospheric ν



Reactor ν

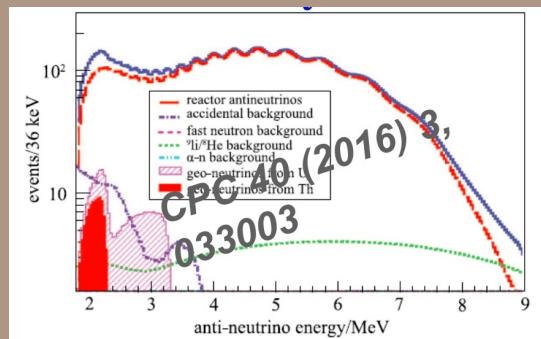


DSNB

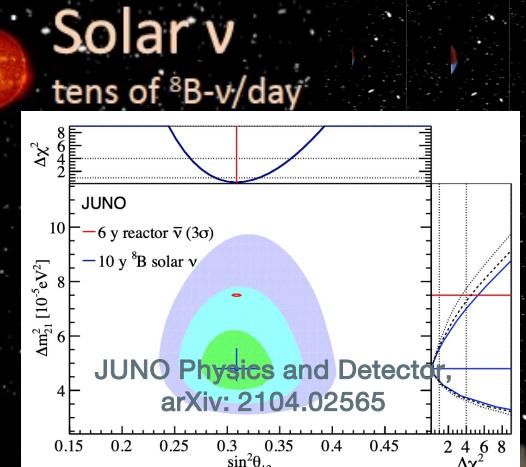


26.6 GW, 53 km

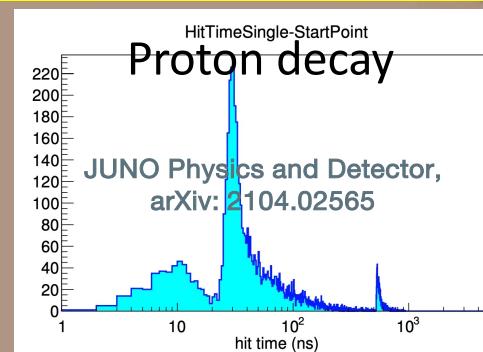
Geo- ν



Solar ν



JUNO:Multiple Purpose Observatory



DSNB: Diffuse Supernova Neutrino Background

JUNO Physics and Detector, arXiv: 2104.02565





VETO System

Top tracker

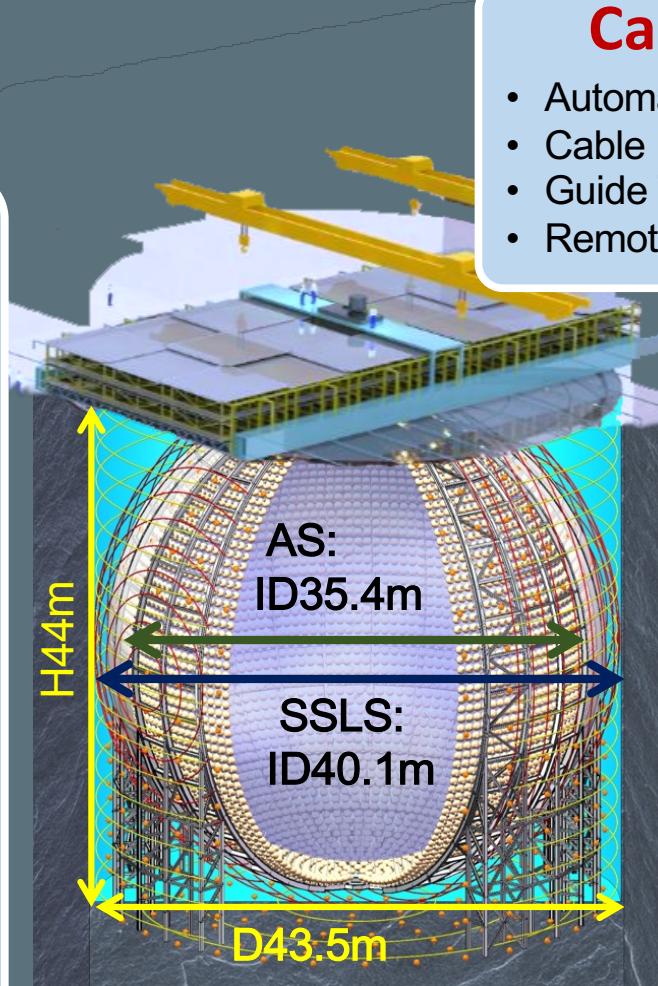
- Precision muon tracking
- 3 plastic scintillator layers
- Covering half of the top of the water pool

Water Cherenkov veto pool

- 2400 20" PMTs
- 35 kton ultra-pure water
- Efficiency >95%
- Radon control → < 0.2 Bq/m³

Compensation coils

- Earth magnetic field <10%
- Necessary for 20" PMTs



Calibration System

- Automatic Calibration Unit ([ACU](#))
- Cable Loop System ([CLS](#))
- Guide Tube Calibration System([GTCS](#))
- Remotely Operated Vehicles ([ROV](#))

Central detector (CD)

- Optical separation: Acrylic sphere
- Stainless Steel Latticed Shell
- 20 kton Liquid Scintillator
- PMTs: 17k 20" PMTs + 25k 3" PMTs
- Ultra-pure water buffer (2 m)



Central Detector (CD)

[JUNO collaboration, NIM-A 988, 2021]

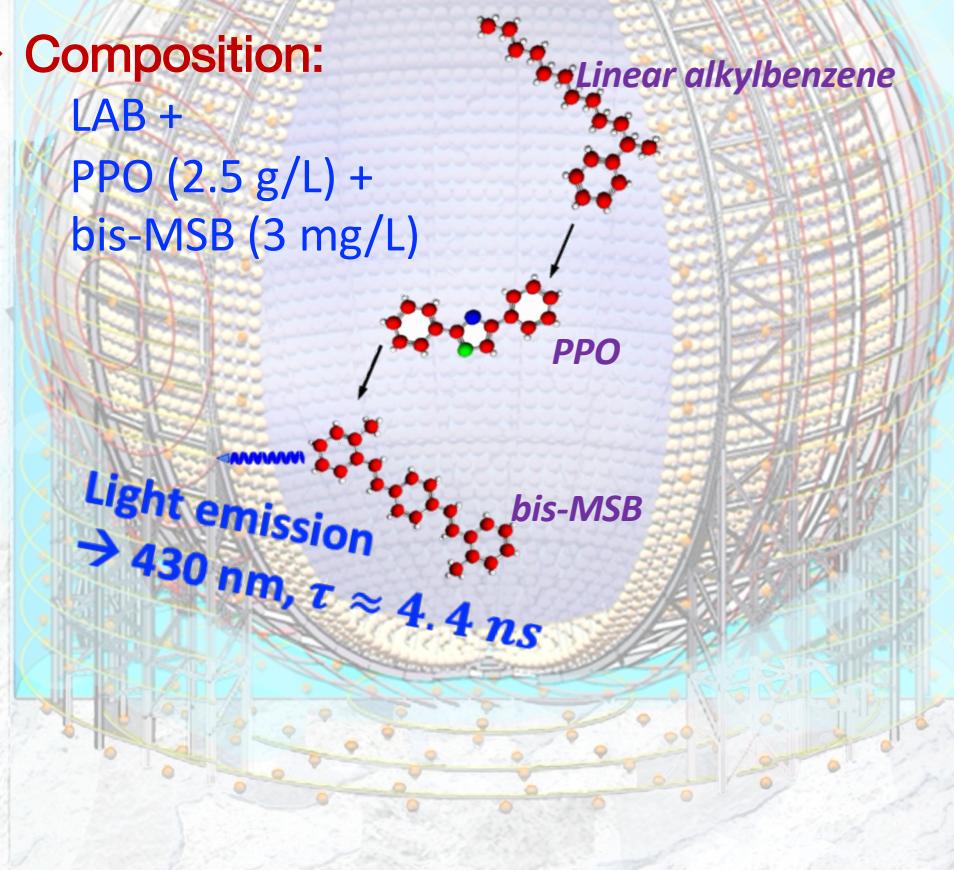
➤ Liquid Scintillator

■ Requirements for JUNO LS

- Lower background for reactor antineutrino physics: $^{238}\text{U} < 10^{-15} \text{ g/g}$, $^{232}\text{Th} < 10^{-15} \text{ g/g}$, $^{40}\text{K} < 10^{-17} \text{ g/g}$
- High light yield: 10^4 PE/MeV
concentration of flour need to be optimized
- Long attenuation length: $> 20 \text{ m@430 nm}$

❖ Composition:

LAB +
PPO (2.5 g/L) +
bis-MSB (3 mg/L)

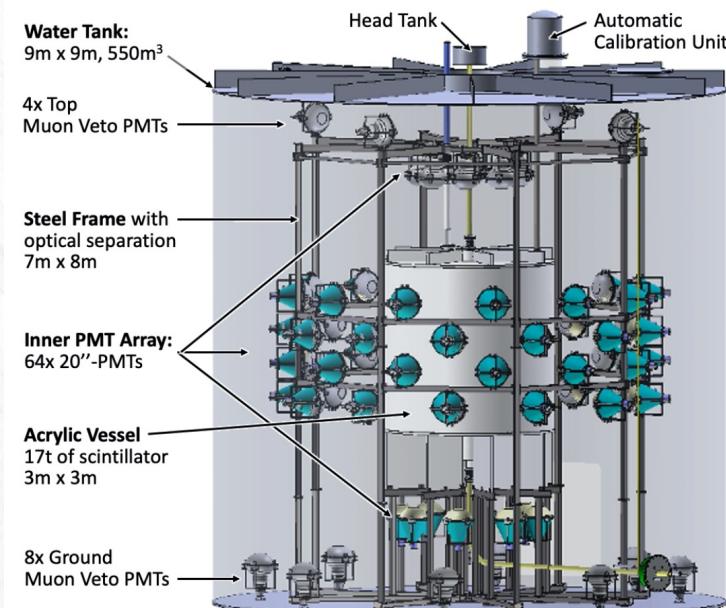


❖ Strategy for improving LAB purification:

1. **Al₂O₃ filtration column**
→ optical properties improvement
2. **Distillation**
→ heavy elements removal/transparency improvement
3. **Water extraction**
→ U/Th/K radioisotopes removal
4. **Steam/Nitrogenstripping**
→ Gaseous impurities- Ar,Kr,Rn-removal

❖ Monitored during filling by OSIRIS

Online Scintillator Internal Radioactivity Investigation System



[arXiv:2103.16900 (2021)]^{±1}



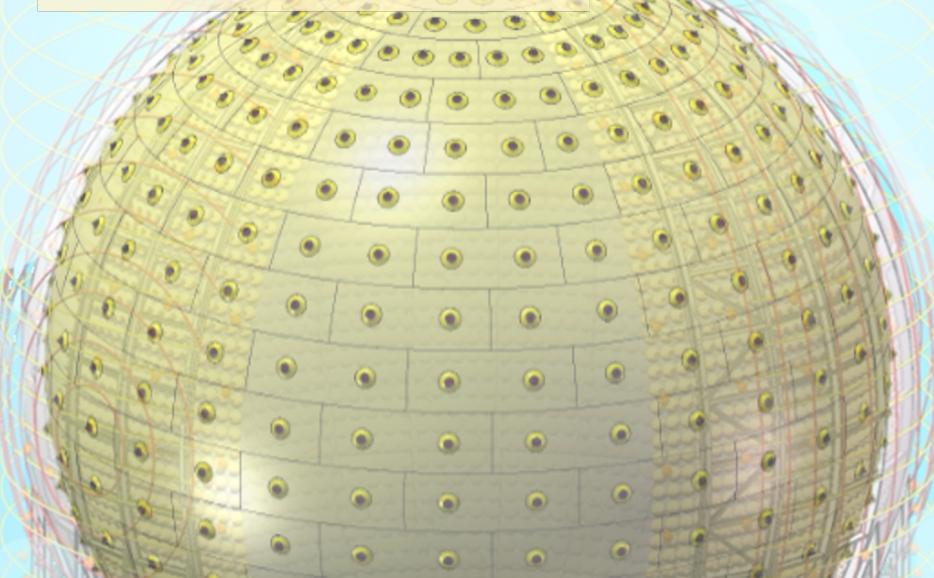
Central Detector (CD)

➤ Acrylic Sphere:

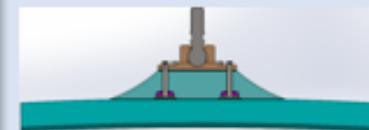
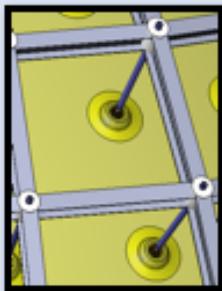
35.4 m diameter, 120 mm thickness, 600 tons

▪ Requirements:

- Transmittance >96%
- Radiopurity ($U/Th/K < 1\text{ ppt}$)



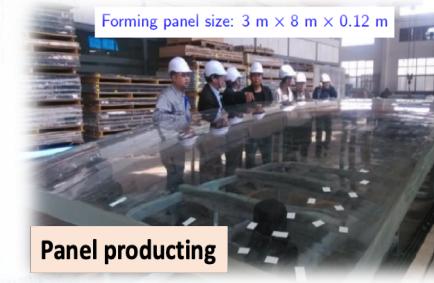
Connection bars



Acrylic node

Current status:

- ✓ Pannels producing and nodes bonding
- ✓ Pre-Assembly of the installation platform



Panel producing



Panel machining & node bonding



Acrylic panel and lift structure



The top of acrylic sphere



Pre-assembly of the Installation platform



Central Detector (CD)

➤ Stainless Steel Shell

SS structure to hold a acrylic sphere and to mount PMTs

- ✓ Supporting bar to hold the Acrylic tank
- ✓ Stress of acrylic <3.5 MPa everywhere

- 40.1 m diameter
- 590 tons
- 590 connecting bars
- Support all Photomultipliers

Current status:

- ✓ SS shells are producing
- ✓ Anchors are embedded in WP



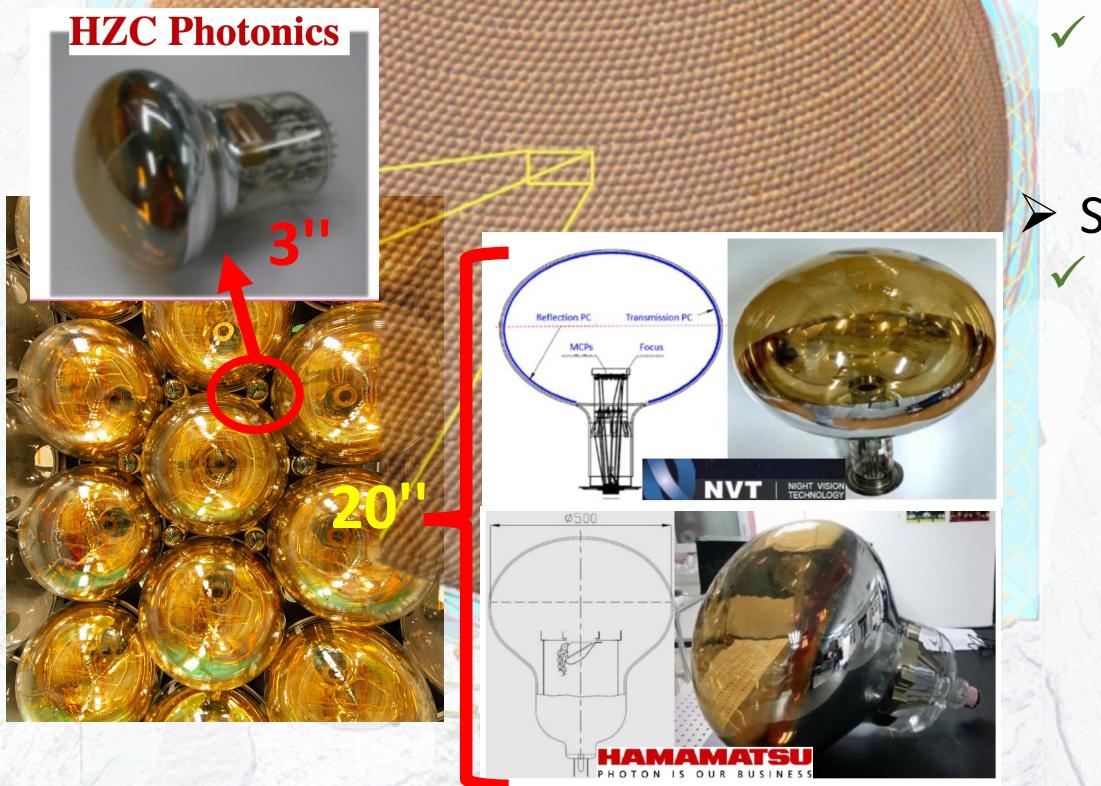
Embedded anchors in WP



Central Detector (CD)

➤ Double Calorimetry System

- >75% photo coverage
- LPMT: energy resolution 3% @ 1MeV
 - 17612 20" MCP PMTs for CD (~75%)
 - 2400 20" dynode PMTs for Veto;
- sPMT: control of systematics
 - 25600 3" PMTs (~2.7%);



Current status:

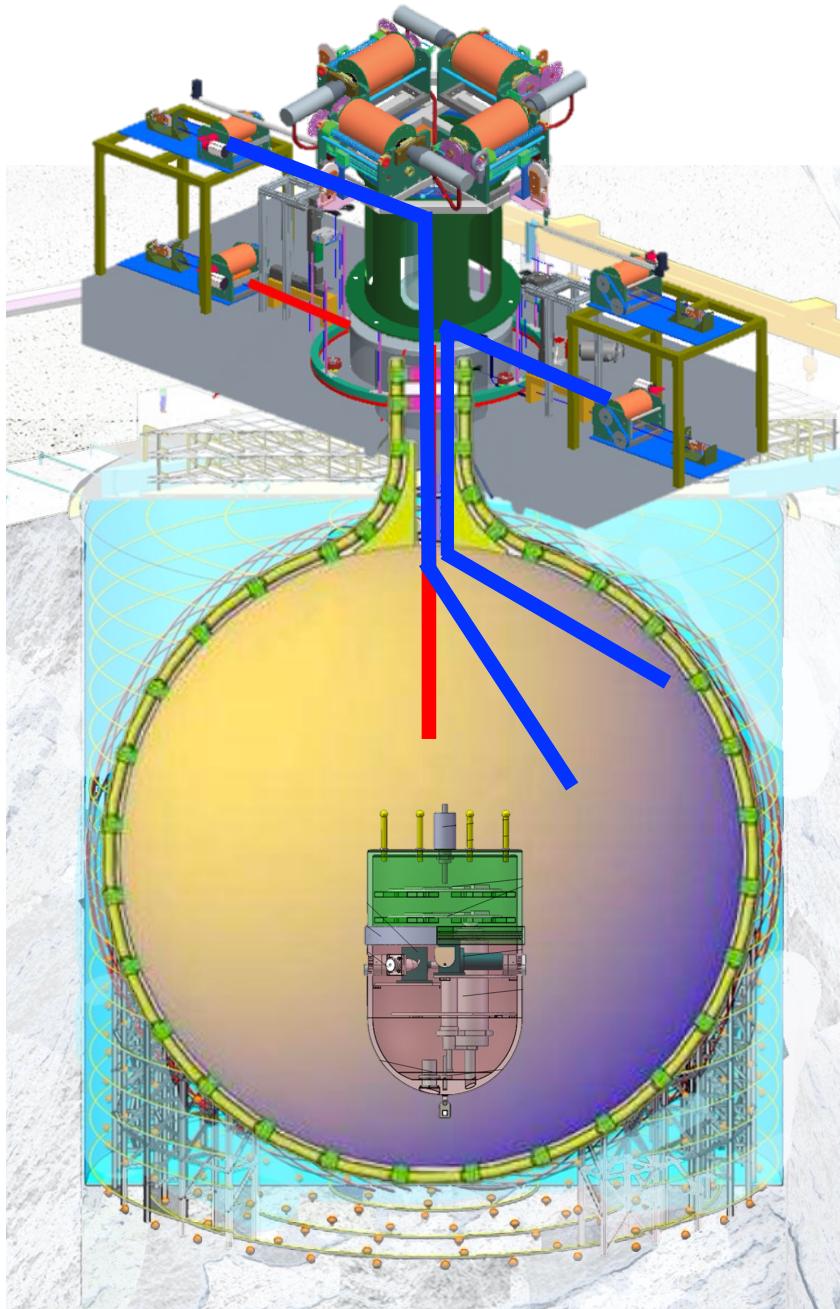
- LPMT:
 - ✓ Production:
 - 5000 HPK dynode PMTs + 15000 NNVT MCP PMTs
 - ✓ All delivered and qualified now:
 - average PDE ~29% for CD (required/aimed ~27%)
 - ✓ Waterproof potting
 - ✓ Implosion protection:
Production/assembly/installation are going on
- SPMT:
 - ✓ Production(~65%)/Waterproof potting/Acceptance testing are goin on

MCP: micro-channel plate ¹⁴



Calibration System

JUNO Calibration, *JHEP* 03
(2021) 004, arXiv:2011.06405



■ The challenge:

- overall energy resolution: $\leq 3\%/\sqrt{E[\text{MeV}]}$
- energy scale uncertainty: <1%

■ Calibration systems

- **1D: Automatic Calibration Unit (ACU)**
→ central axis scan
- **2D: Cable Loop System (CLS)**
→ scan vertical planes
Guide Tube Calibration System (GTCS)
→ CD outer surface scan
- **3D: Remotely Operated under-LS Vehicle (ROV)**
→ whole detector scan
- **Auxiliary systems:** Calibration house, Ultrasonic Sensor System (USS), CCD and A Unit for Researching Online the LSc tRAnsparency (AURORA)

JHEP 03, 004 (2021)

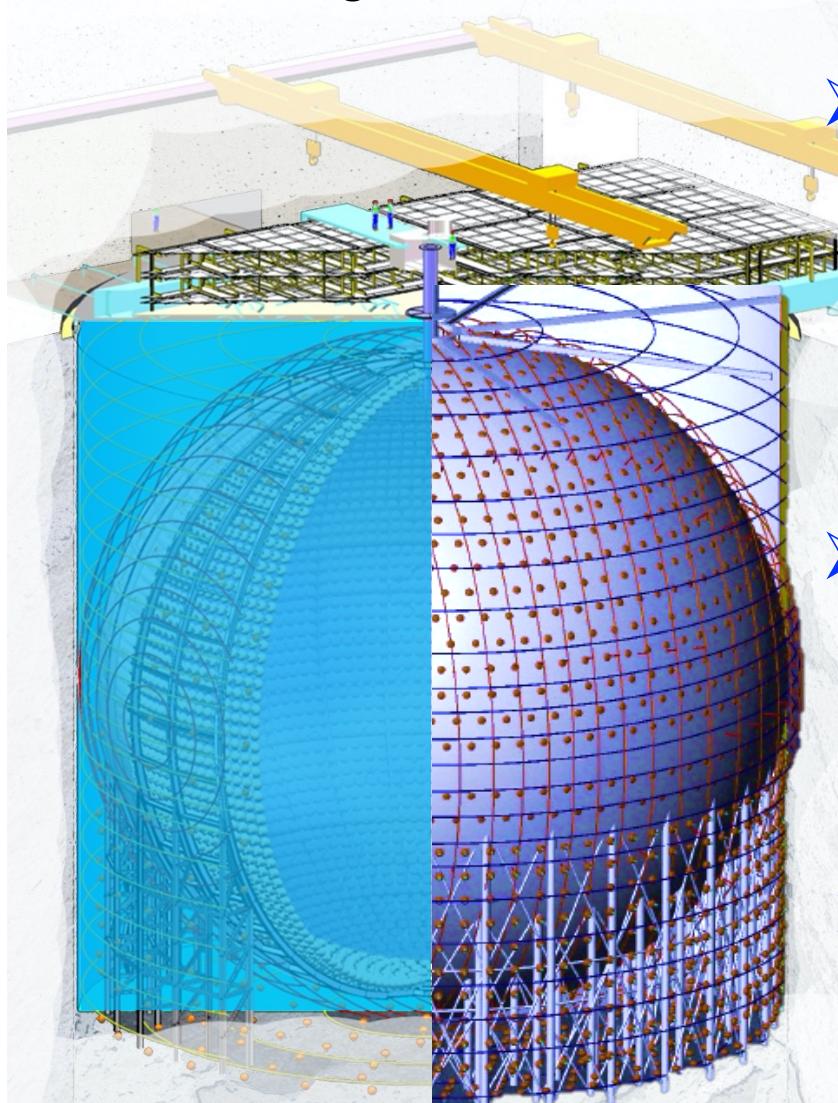
Sources/Processes	Type	Radiation
^{137}Cs	γ	0.662 MeV
^{54}Mn	γ	0.835 MeV
^{60}Co	γ	$1.173 + 1.333$ MeV
^{40}K	γ	1.461 MeV
^{68}Ge	e^+	annihilation $0.511 + 0.511$ MeV
$^{241}\text{Am-Be}$	n, γ	neutron + 4.43 MeV ($^{12}\text{C}^*$)
$^{241}\text{Am-}^{13}\text{C}$	n, γ	neutron + 6.13 MeV ($^{16}\text{O}^*$)
$(n, \gamma)p$	γ	2.22 MeV
$(n, \gamma)^{12}\text{C}$	γ	4.94 MeV or $3.68 + 1.26$ MeV



Veto System

➤ Goals of veto

- Shield rock-related backgrounds
- Tag & reconstruct cosmic-rays tracks



➤ Top tracker

- Precise muon tracking
- Only partial coverage
- Re-using the **OPERA's** Target Tracker
(3-layers of plastic scintillator, $49\text{ m}^2/\text{module}$)
- New electronics cards designed to account for 100 x higher radioactivity from rocks at JUNO site

➤ Water Cherenkov detector

- ~ 2400 20" MCP-PMTs
- 35 kton ultrapure water with a circulation system
- Efficiency $> 99\%$
- Radon control \rightarrow less than 0.2 Bq/m^3

➤ Earth magnetic field (EMF) shielding system



A satellite detector of JUNO — TAO Taishan Antineutrino Observatory

Planned to be online in 2022

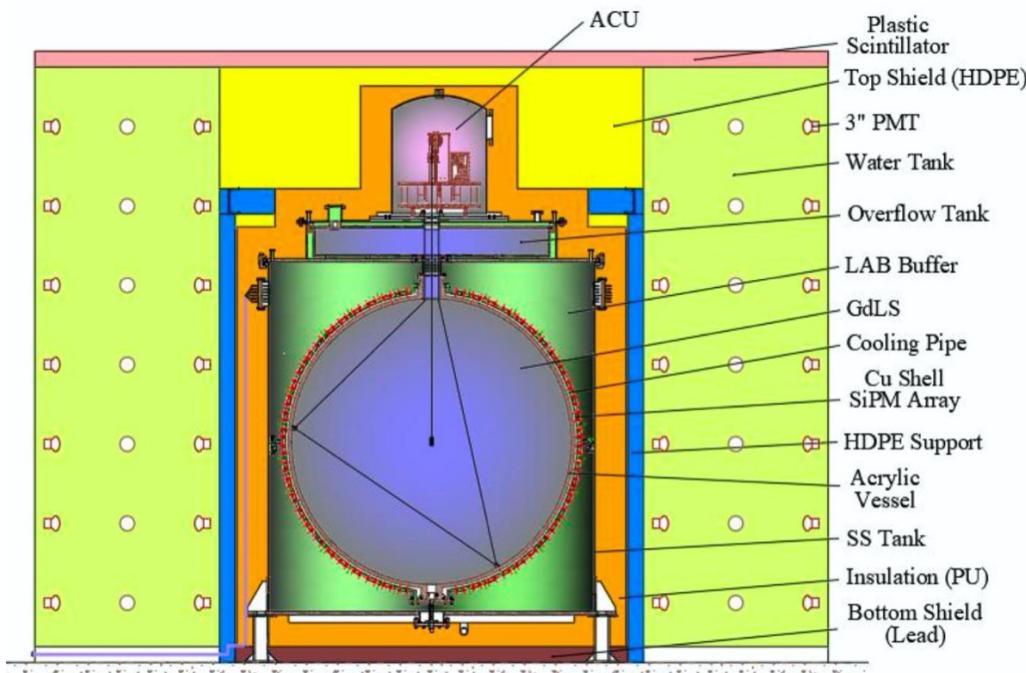
TAO CDR, arXiv:2005.08745

Physics goals:

1. Provide reference spectrum for JUNO
2. Provide a benchmark to examine nuclear database
3. Measure isotopic neutrino spectrum
4. Reactor monitoring
5. Sterile neutrino

Location:

Laboratory in a basement at -10 m,
~30 m from Taishan core (4.6 GW)



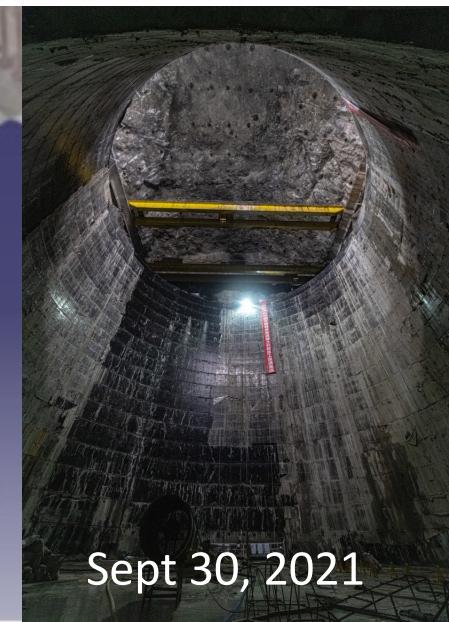
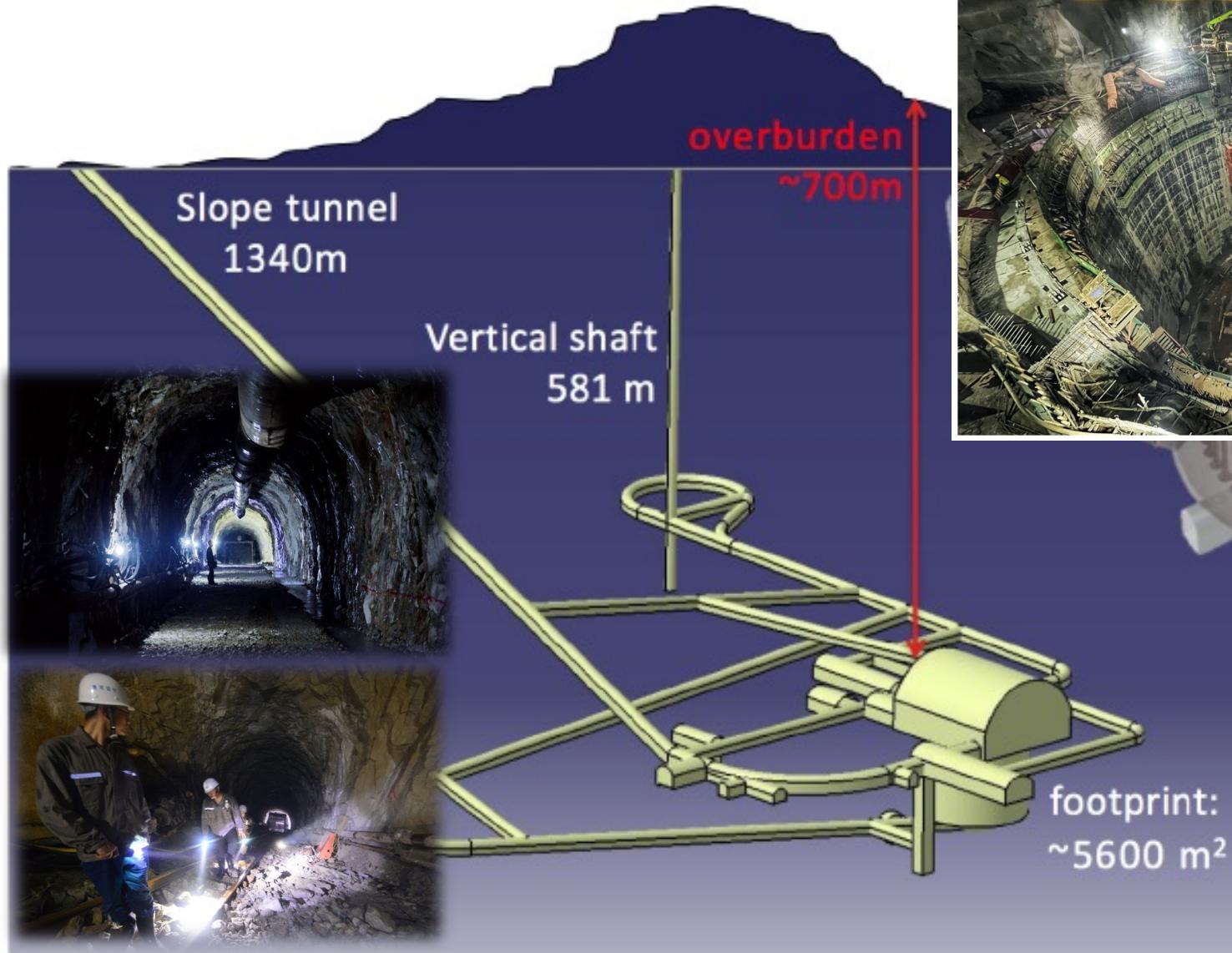
Design:

- **Target: 2.6 ton Gd-LS in total**
(**1 ton** fiducial target, **4000 v's/day**)
- **10 m² SiPM**, with PDE> 50%, Coverage: >95%
- **Effective Light yield: ~ 4500 p.e. / MeV**
- **Energy Resolution: ~ 1.8% @ 1 MeV**



Civil Construction

➤ Civil construction for underground site started 2015





Summary

Progress is well underway, and expect to complete the construction of the detector by 2022

➤ **JUNO will be**

- ✓ multipurpose experiment
- ✓ first experiment to measure two neutrino oscillation modes simultaneously
- ✓ able to measure MH by using reactor neutrino oscillations on medium baseline

➤ **Status of JUNO experiment**

Civil construction: water pool civil construction completed, surface laboratory active

Central detector: Production of acrylic panels and stainless steel is in progress.

PMT system: PMTs production are going to finish before May, 2022

Liquid scintillator: LS Monitor system (OSIRIS) is going to survey the LS filling

➤ **New short-baseline experiment TAO, High energy solution measurement of reactor neutrino spectrum**

