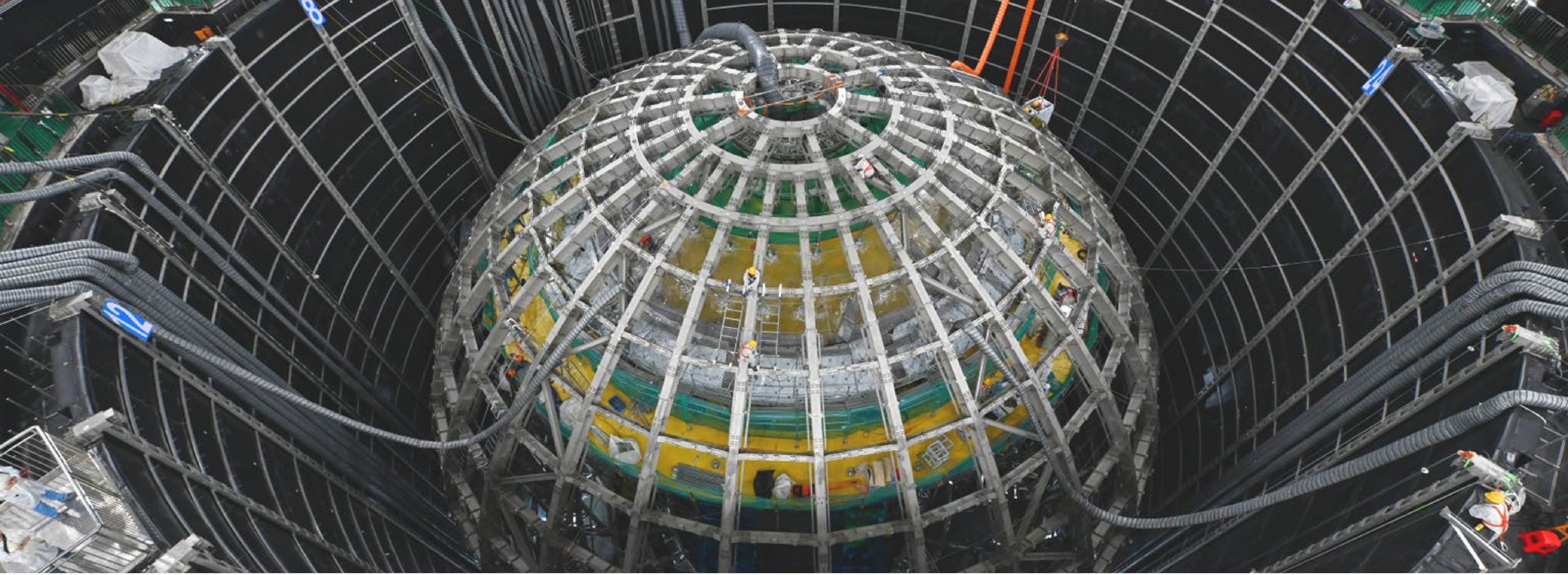


JUNO: Current status and prospects

Beatrice Jelmini, on behalf of the JUNO Collaboration
beatrice.jelmini@pd.infn.it

Lake Louise Winter Institute 2023
Lake Louise, Canada | February 19-24, 2023

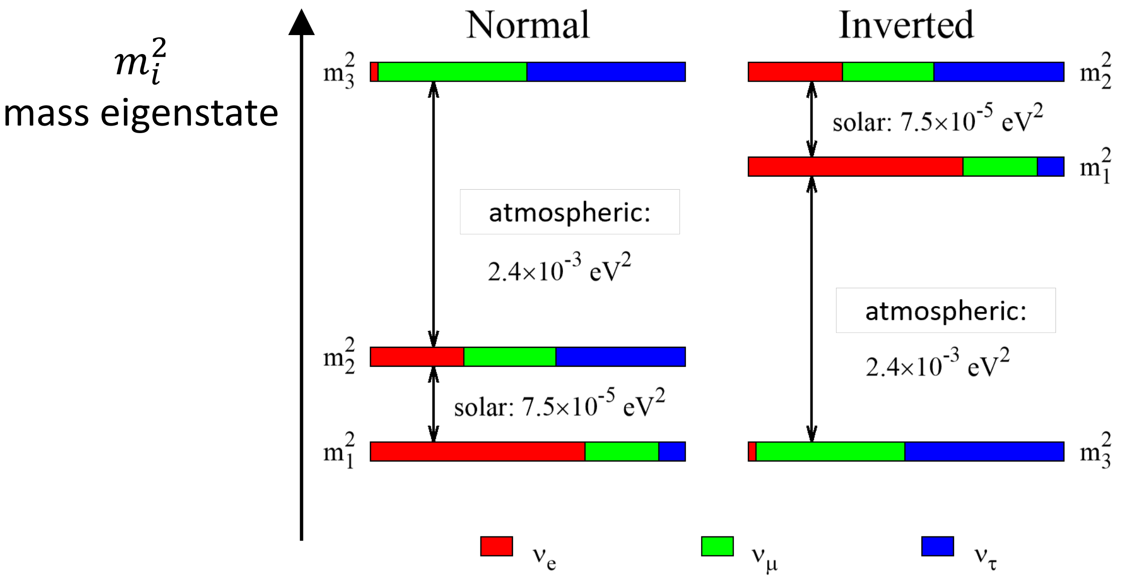
Università degli Studi di Padova
INFN

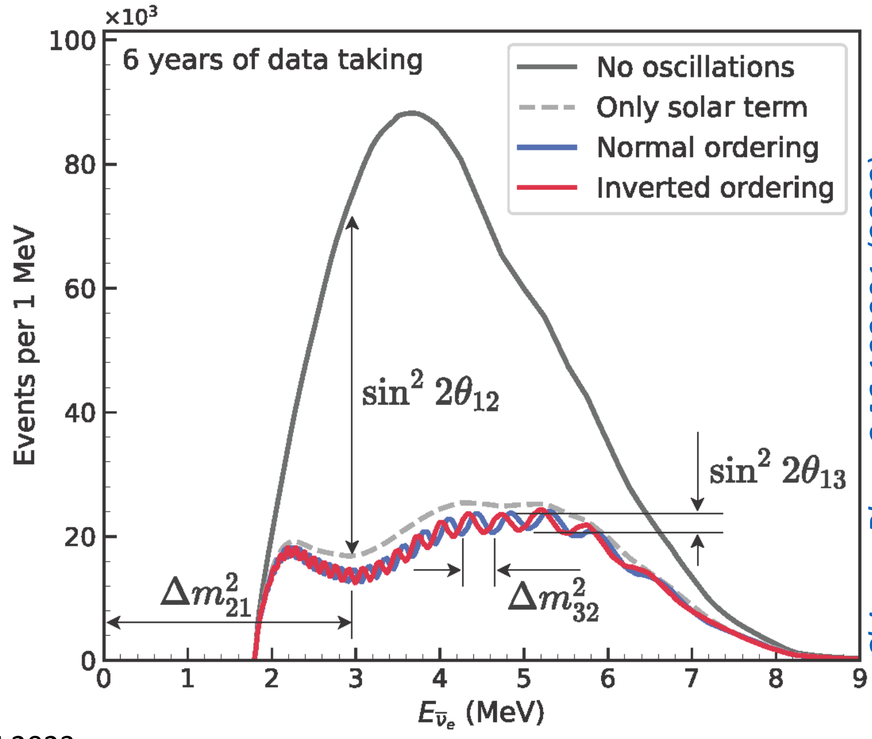
Why JUNO?

- Neutrino oscillations observed
  → neutrinos are massive

- Neutrino mass ordering?
  $\Delta m^2_{32} \gtrless 0$? $\Delta m^2_{ij} = m_i^2 - m_j^2$

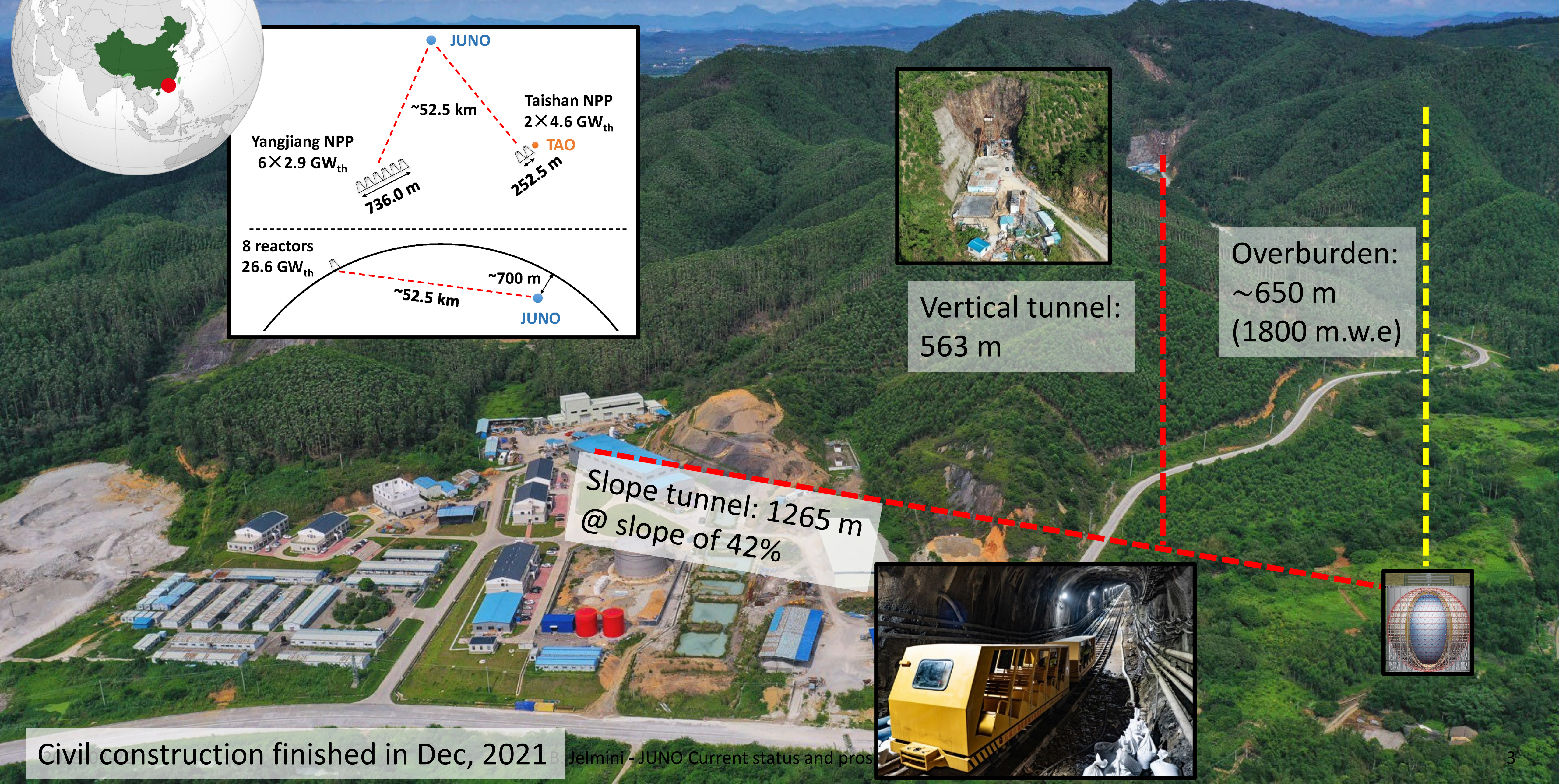
- Could be determined:
  - 2 complementary approaches
  - Matter-enhanced oscillation with accelerator ν @ long-baseline experiments
  - Vacuum oscillation with reactor $\overline{\nu}_e$ independent of θ_{23} and δ_{CP} ➡ JUNO





Chinese Phys. C 46 123001 (2022)

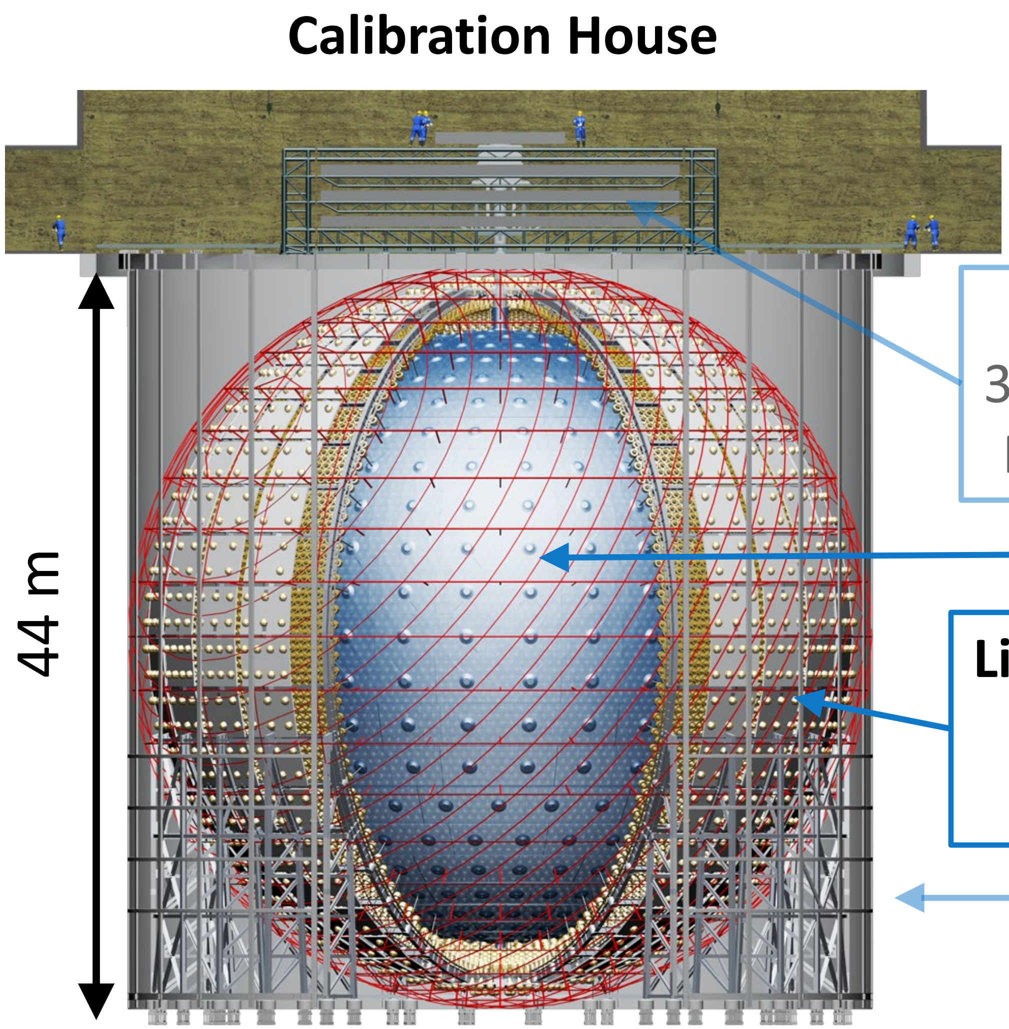
Jiangmen Underground Neutrino Observatory



JUNO in a nutshell

	Target Mass	Coverage	Energy resolution	Light yield [PE/MeV]
Daya Bay	20 ton (x8)	12%	8% @ 1 MeV	160
Borexino	300 ton	34%	5% @ 1 MeV	500
KamLAND	1 kton	34%	6% @ 1 MeV	250
JUNO*	20 kton	78%	3% @ 1 MeV	>1300

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



Top Tracker (TT):
3 plastic scintillator layers
Precision muon tracking

Central Detector (CD):
20 kton Liquid Scintillator (LS)
Acrylic vessel (Ø 35.4 m)
Steel structure (Ø 40.1 m)

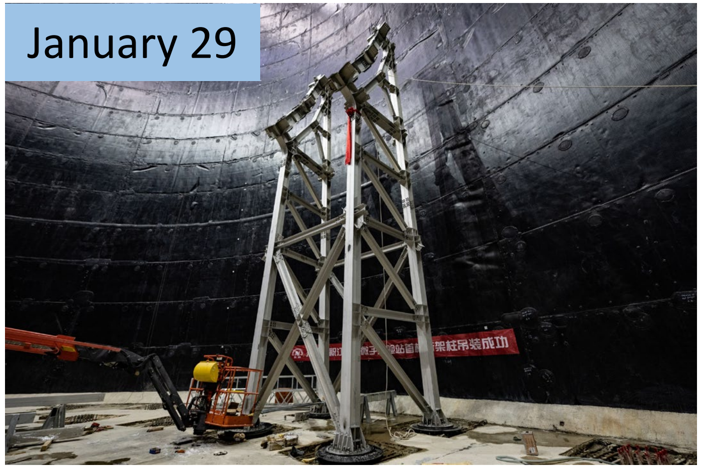
Light detection system:
17612 20-inch PMTs
25600 3-inch PMTs

Water Cherenkov Detector (WCD):
35 kton ultra-pure water
2400 20-inch PMTs

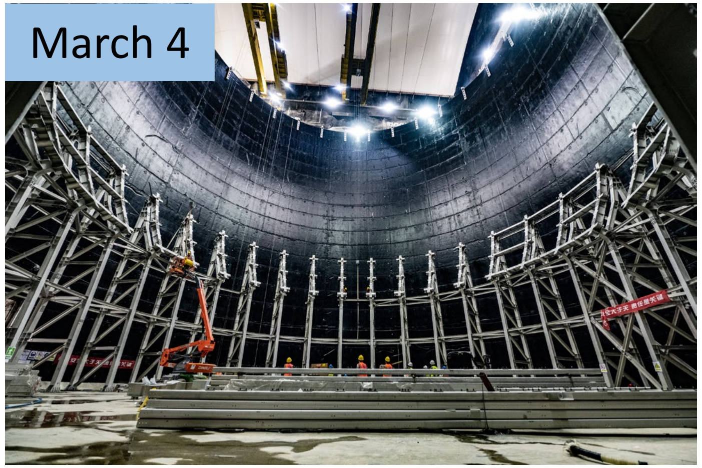
CD: Stainless Steel Structure

Support for acrylic vessel, PMTs, front-end electronics, …

40.1 m diameter
Assembly precision: < 3 mm
Low background material

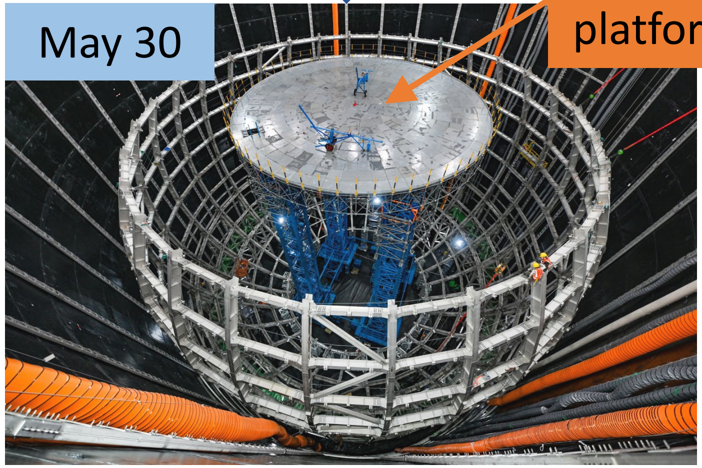


January 29

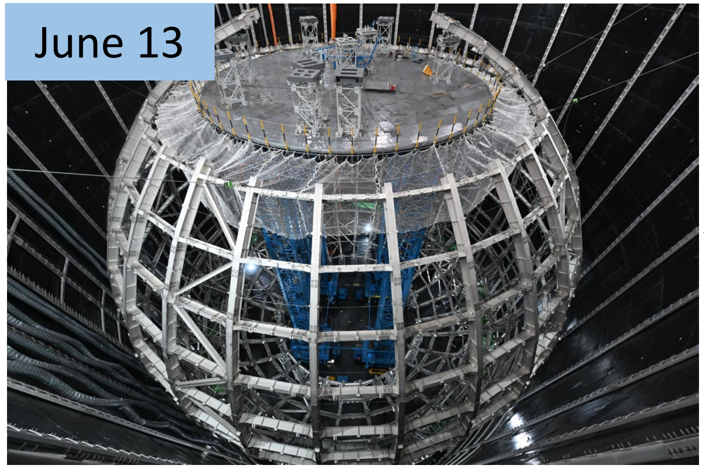


March 4

April 14



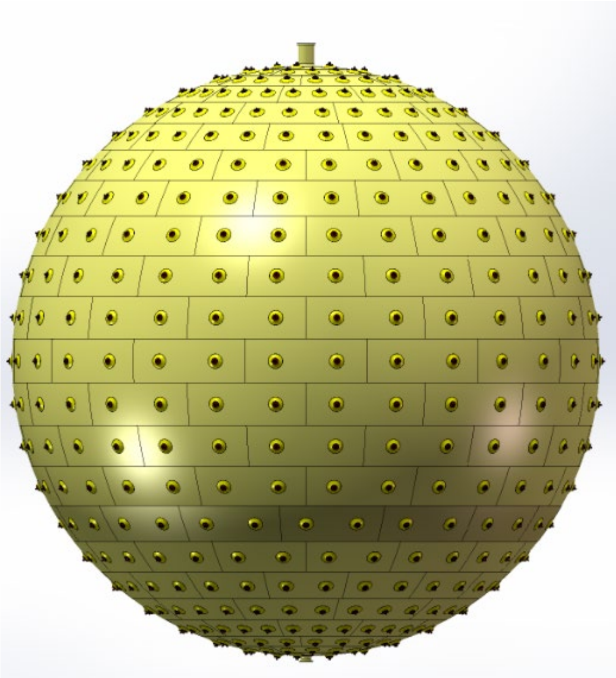
May 30



June 13

June 24 - completed

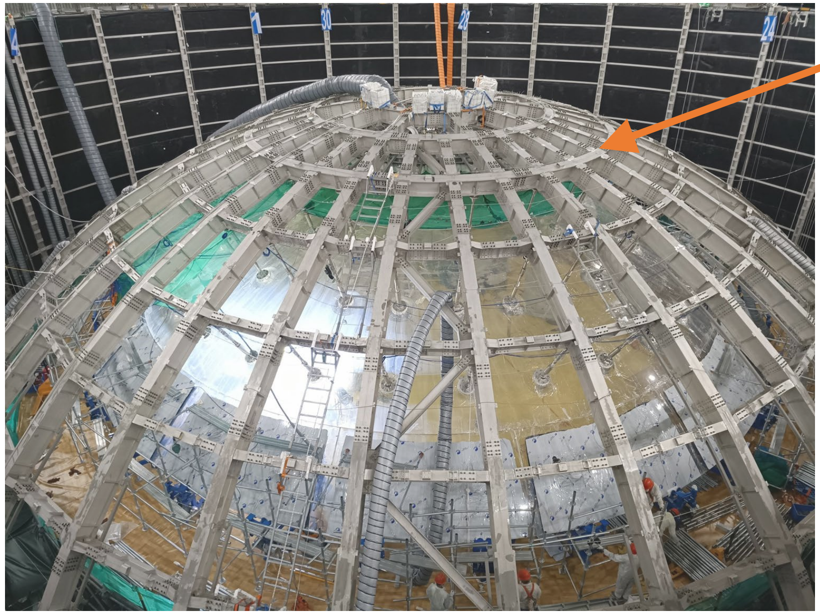
CD: Acrylic Vessel



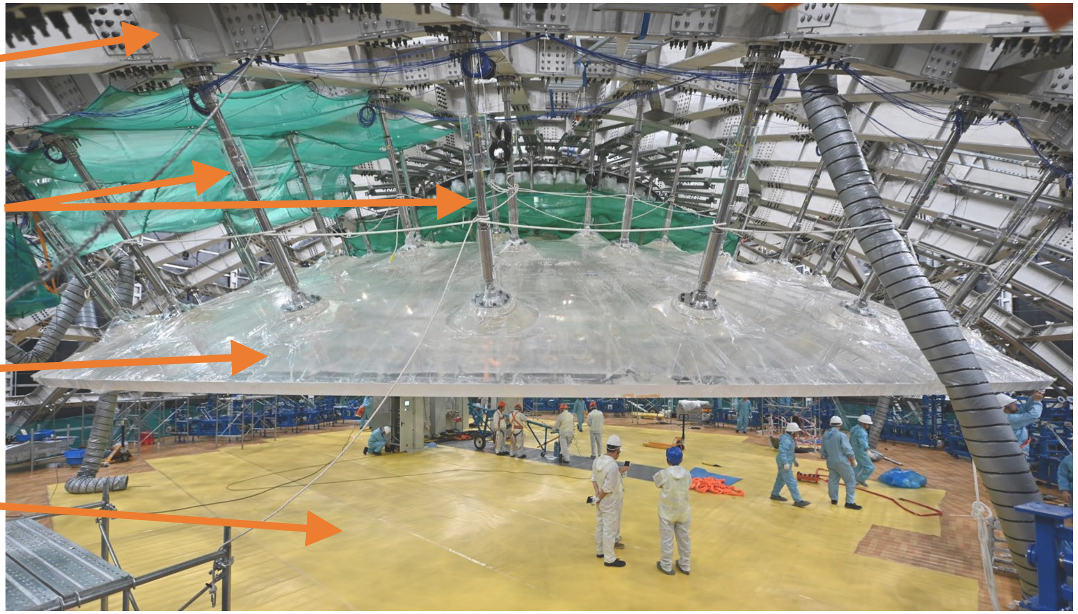
Contains 20 kton of LS
Inner diameter: 35.40 $\pm$ 0.04 m
Thickness: 124 $\pm$ 4 mm

Light transparency: > 96% @ LS
Radiopurity: U/Th/K < 1 ppt
265 panels + 2 chimneys

Installation started in July 2022, from the top
6/23 layers completed

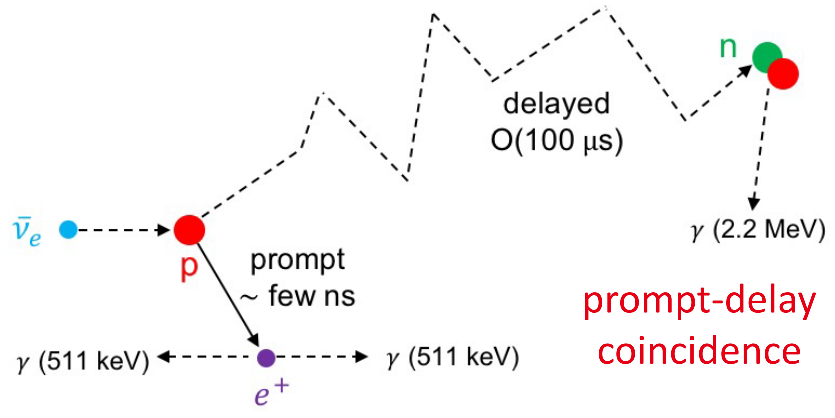


Steel structure
Connecting rods (590 in total)
Acrylic vessel
Lift platform

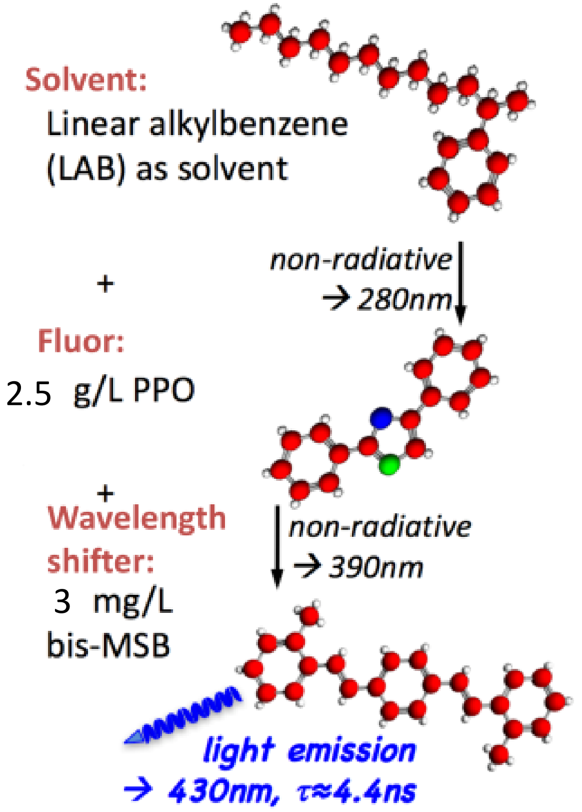


CD: Liquid scintillator

Reactor ν: inverse beta decay (IBD)

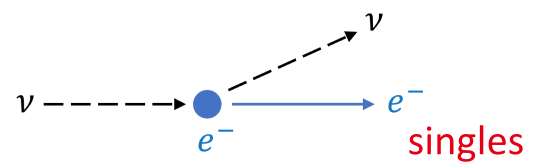


NIM A 988(2021)164823



Attenuation length at 430 nm: 20 m

Solar ν: elastic scattering



Radiopurity target:

	^{238}U / ^{232}Th	^{40}K	^{210}Pb
IBD (reactor) ν	$< 10^{-15}$ g/g	$< 10^{-16}$ g/g	$< 10^{-22}$ g/g
Solar ν	$< 10^{-17}$ g/g	$< 10^{-18}$ g/g	$< 10^{-24}$ g/g

Purification process

- Alumina filtration: improvement of optical properties
- Distillation: remove of heavy metals, improvement of transparency
- Water extraction: removal of heavy elements U/Th/K
- Gas stripping: removal of volatile impurities Ar/Kr/Rn

} Underground after LS mixing

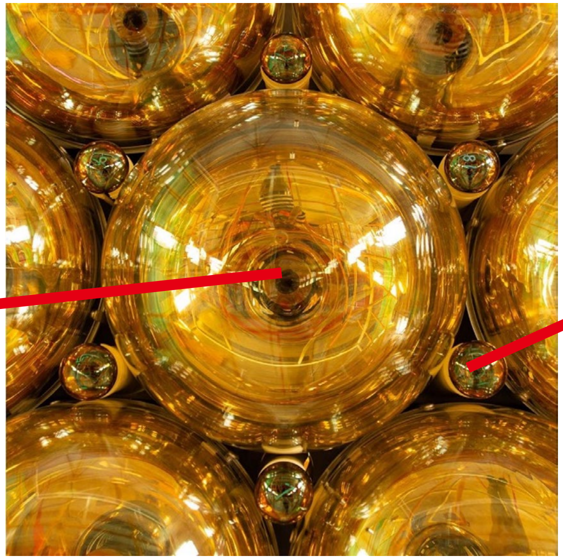
LS checked by OSIRIS

Online Scintillator Internal Radioactivity Investigation System

Photomultiplier Tubes

Total photocathode coverage: 77.9%

17612 (CD) + 2400 (veto) 20-inch PMTs
Dynamic range: 0 - 100 PE

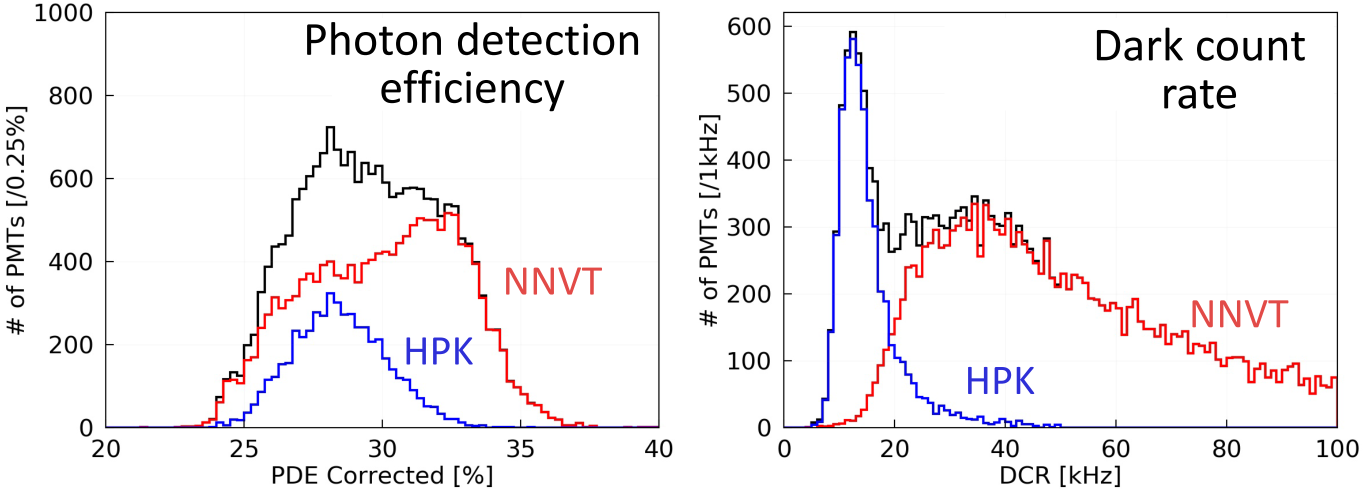


25600 3-inch PMTs
Dynamic range: 0 - 2 PE
Linear reference for 20” PMTs

15012 Micro-channel Plate PTMs from Northern Night Vision Technology (NNVT)

5000 dynode PMTs from Hamamatsu Photonics K. K. (HPK)

Eur. Phys. J. C **82**, 1168 (2022)



20-inch PMTs:

- All potted and tested
- Protection cover under production

3-inch PMTs:

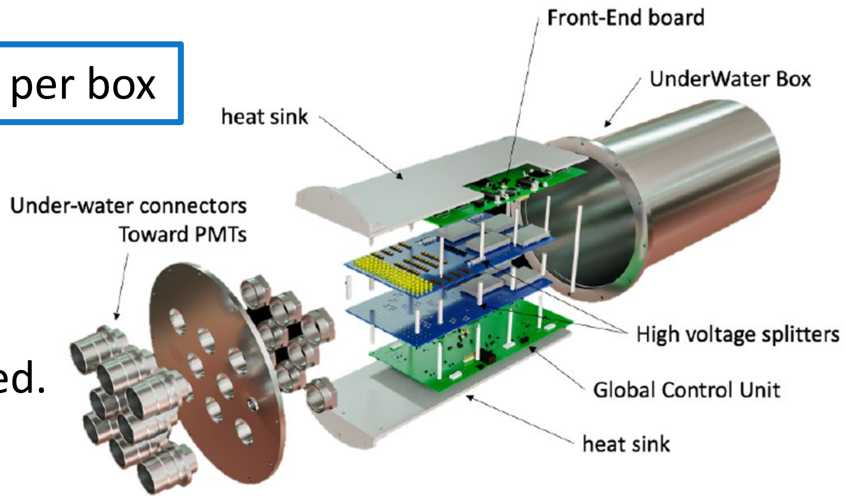
- All potted and tested

First PMTs installed!

Electronics installation

128 3-inch PMTs per box

Box integration still ongoing.
First boxes installed.



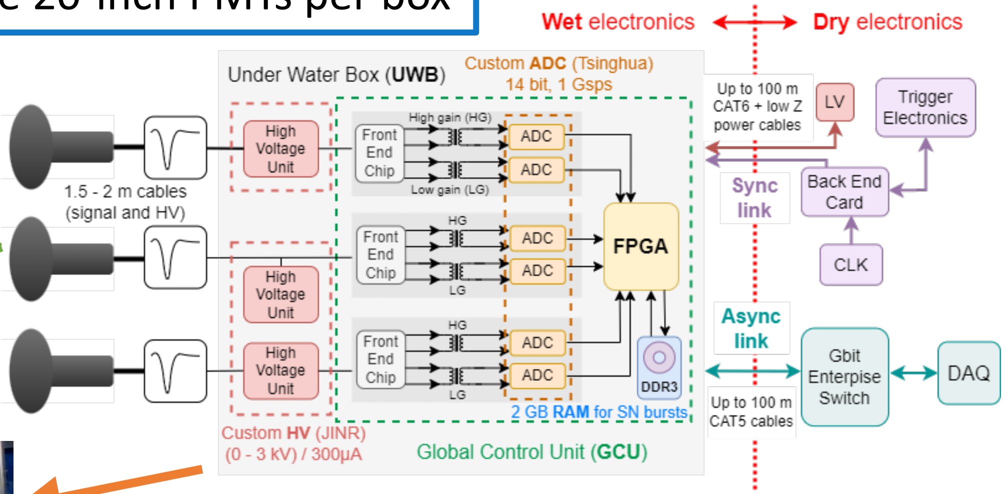
20-inch PMT under-water electronics:

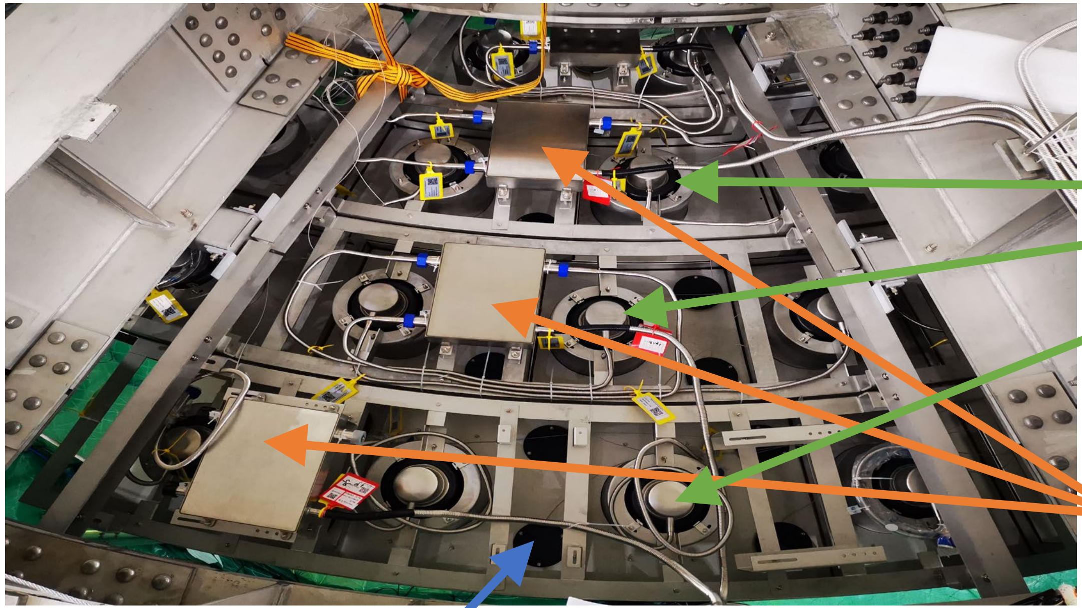
- 1 GHz sampling
- Dynamic range: 1- 1000 PE
- Noise: < 10% @ 1 PE
- Failure rate: < 0.5% over 6 years

Installation started after production and mass testing.

three 20-inch PMTs per box

20-inch PMTs





Open box

3-inch PMTs

Successful first light-off test done in December 2022!

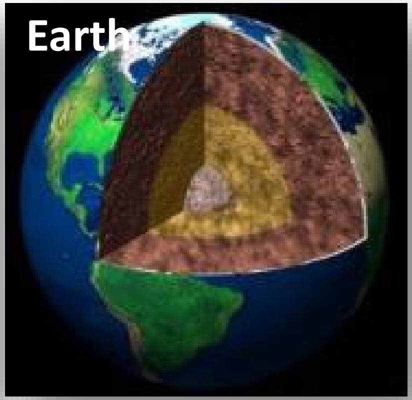
JUNO: a Neutrino Observatory

$\sim$60 $\overline{\nu}_e$ / day

Several / day

^{8}B: $\sim$50 / day
CNO: $\sim$1000 / day
^{7}Be: $\sim$10000 / day

Core Collapse SN:
$\sim$7300 at 10 kpc in few sec
DSNB: 2-4 $\overline{\nu}_e$ per year



$\sim$400 / year

\+

New physics

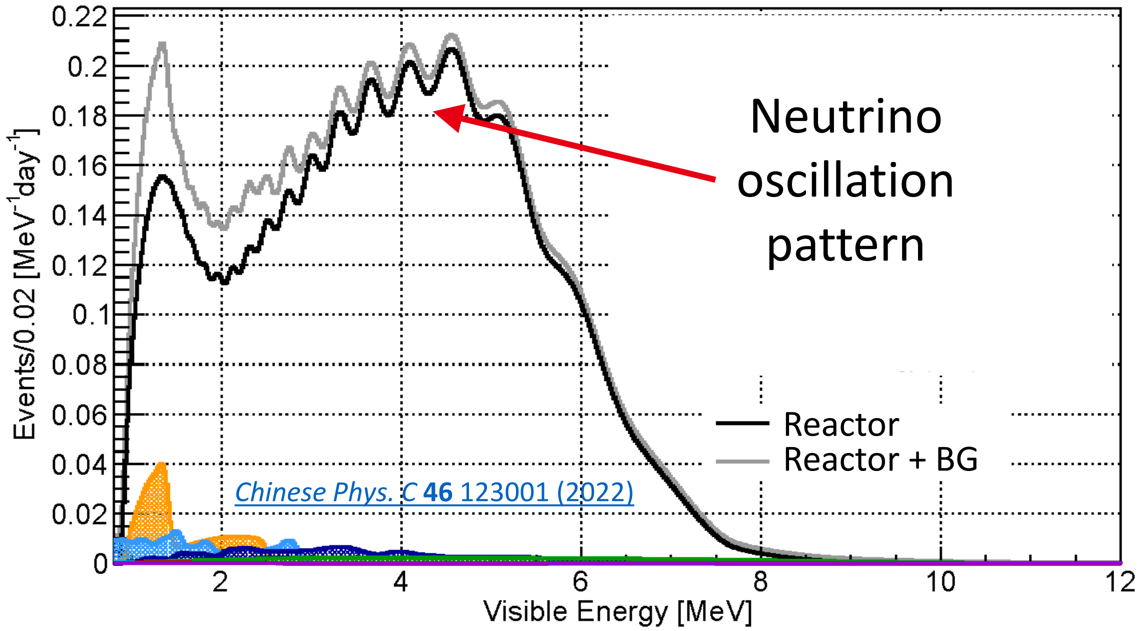
- Proton decay
- ν magnetic moment
- Sterile Neutrinos
- Non-standard interactions
- Lorentz invariance
- …

Neutrino oscillation & properties

Neutrinos as probes

Original sensitivities studies: Neutrino Physics with JUNO, 2016 *J. Phys. G: Nucl. Part. Phys.* **43** 030401
Updated studies: JUNO Physics and Detectors, Prog. Part. Nucl. Phys. 123 (2022) 103927

Reactor $\bar{\nu}_e$ analysis



Signal source: 26.6 GW_{th} from 2 reactor plants

Detection via inverse beta decay:

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

Prompt signal: positron

Delayed signal: n-H (2.22 MeV, $\tau \sim 200 \mu s$)

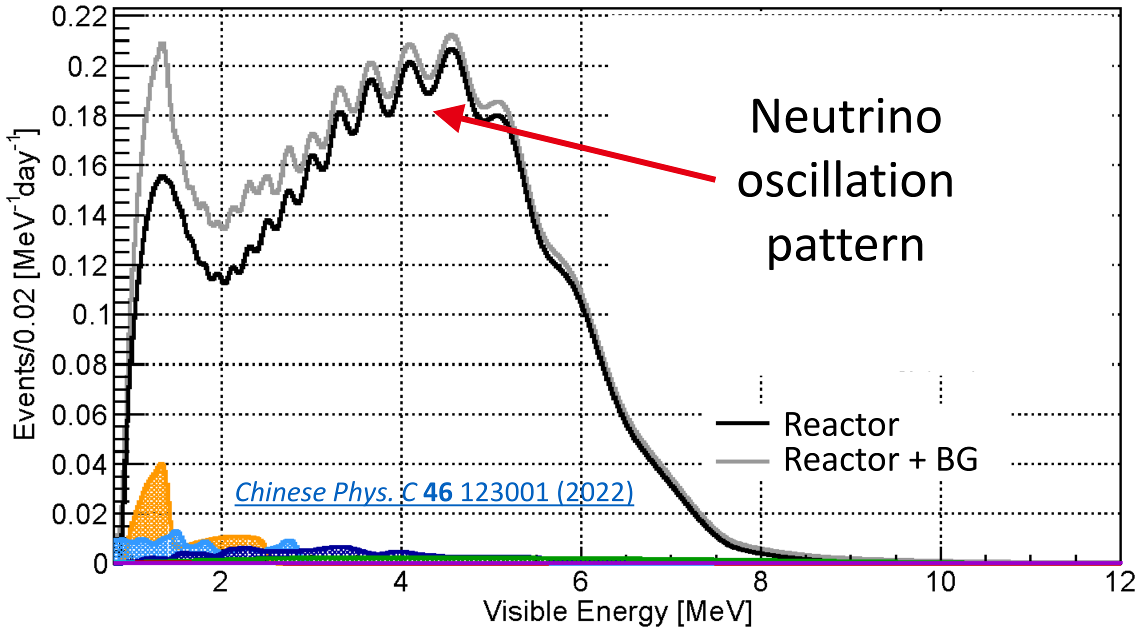
Prompt-delayed coincidence to suppress background

Expected signal rate: 47.1 IBD/day

Expected background rate: 4.11 /day

after selection cuts

Reactor $\overline{\nu}_e$ analysis: neutrino mass ordering



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Prompt signal: positron

Delayed signal: n-H (2.22 MeV, $\tau \sim 200 \mu s$)

Prompt-delayed coincidence to suppress background

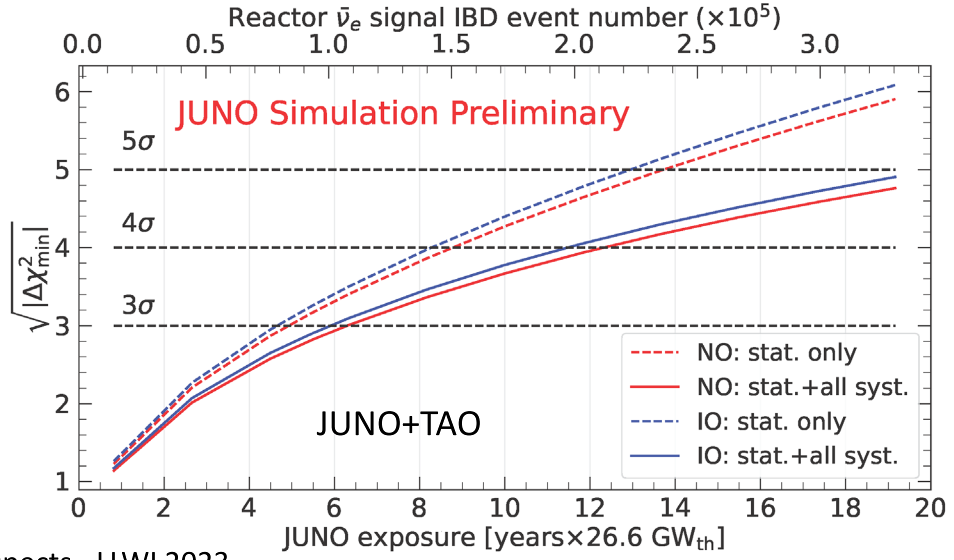
Expected signal rate: 47.1 IBD/day

Expected background rate: 4.11 /day

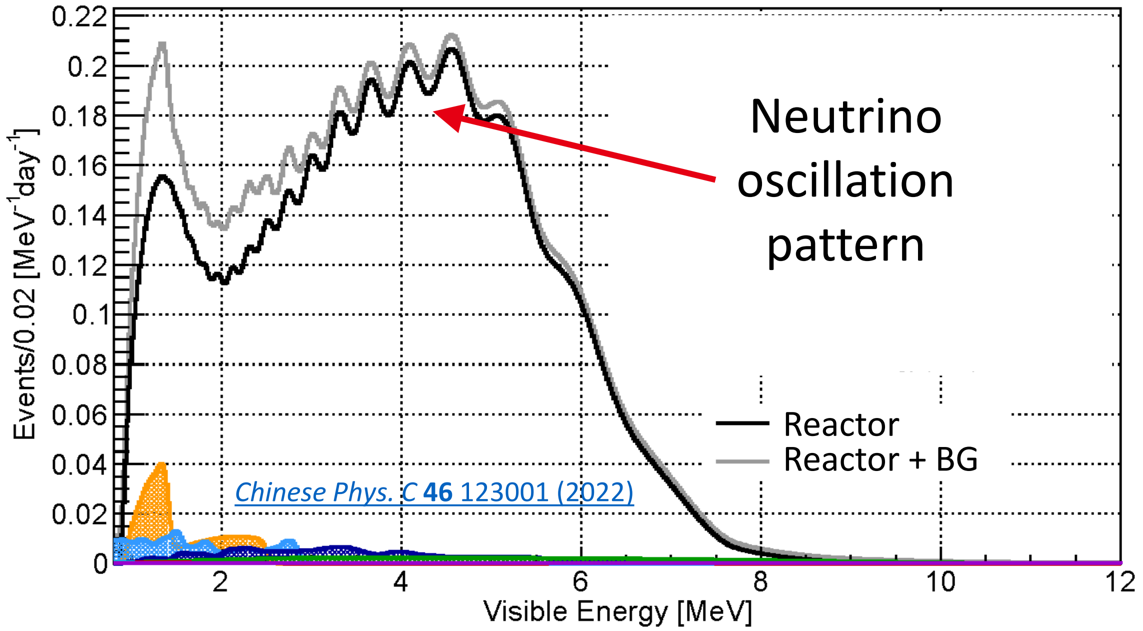
after selection cuts

JUNO expected sensitivity on neutrino mass ordering:
3σ in ~6 years with 26.6 GW_{th}

a paper is under preparation
zenodo.6775075 @ Neutrino 2022



Reactor $\bar{\nu}_e$ analysis: oscillation parameters



Signal source: 26.6 GW_{th} from 2 reactor plants

Detection via inverse beta decay:

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

Prompt signal: positron

Delayed signal: n-H (2.22 MeV, $\tau \sim 200 \mu s$)

Prompt-delayed coincidence to suppress background

Expected signal rate: 47.1 IBD/day

Expected background rate: 4.11 /day

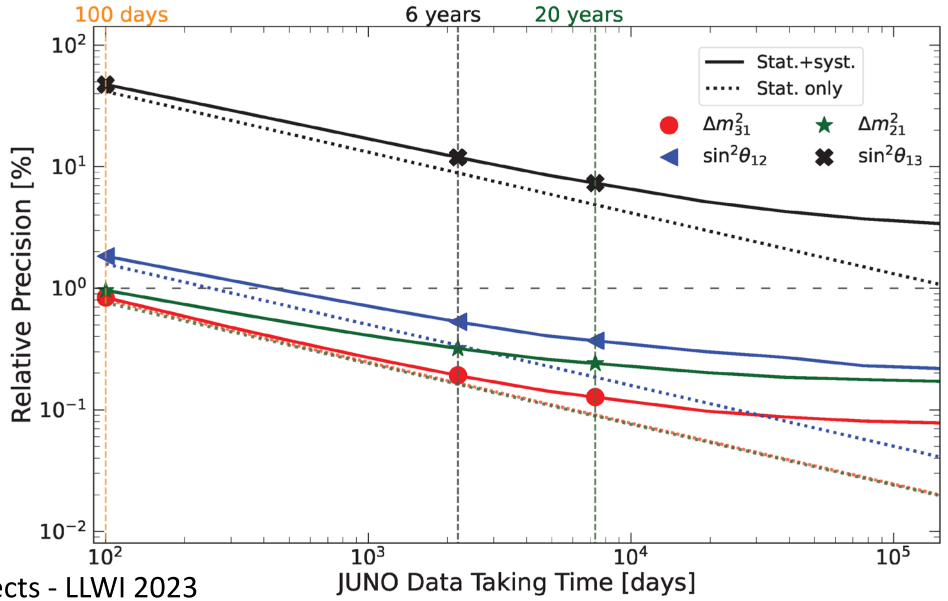
after selection cuts

Sub-percent precision on Δm^2_{31} and Δm^2_{21} within 100 days

Sub-percent precision on $\sin^2\theta_{12}$ within 1 year

	Δm^2_{31}	Δm^2_{21}	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$
PDG 2020	1.4%	2.4%	4.2%	3.2%
JUNO 6 years	~0.2%	~0.3%	~0.5%	~12%

Chinese Phys. C **46** 123001 (2022)



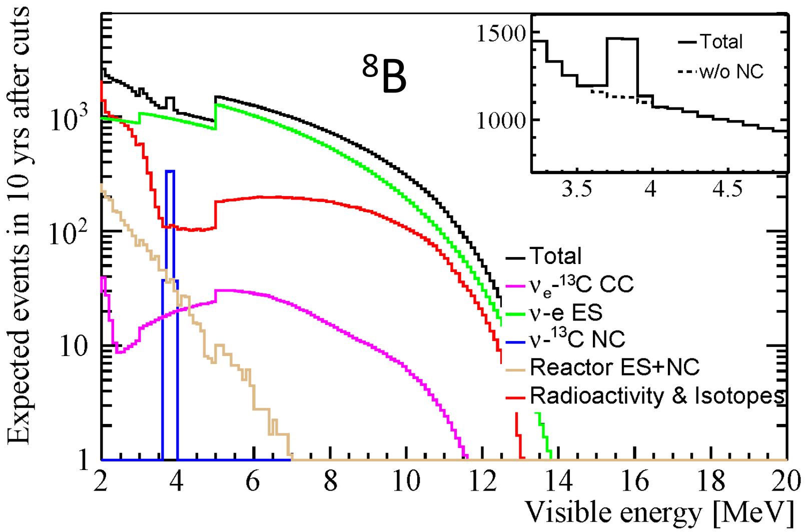
Solar neutrinos

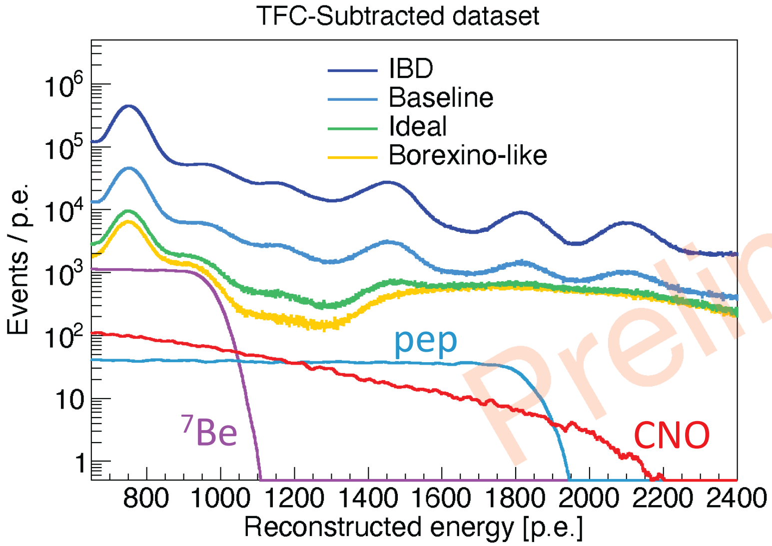
Detection through elastic scattering on e^-

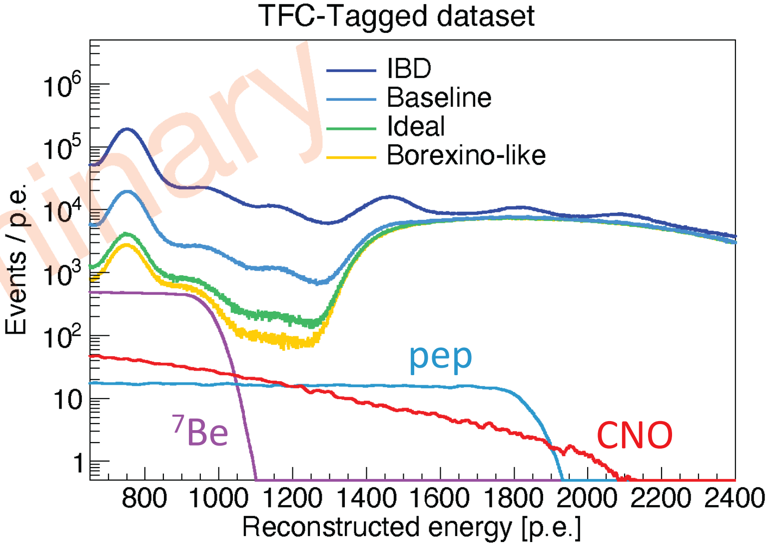
Intermediate-energy ν: ^{7}Be, pep, CNO
- Different radiopurity scenarios
- Improve Borexino results:
  ^{7}Be and pep in 1-2 years
  CNO in 2-4 years
- New paper soon on arXiv

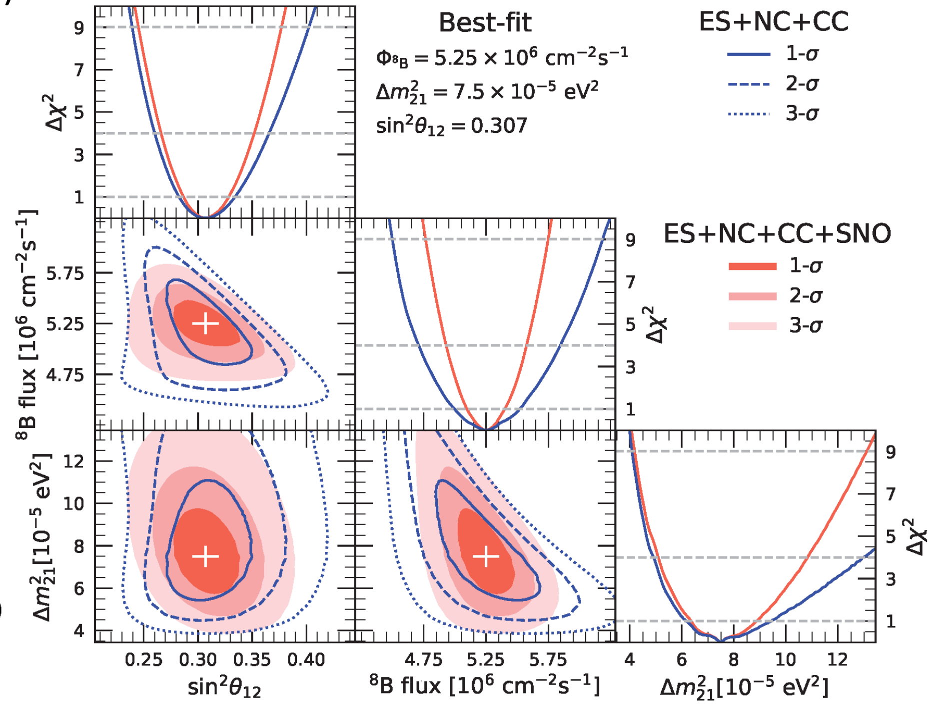
High-energy ν: ^{8}B
expected precision in 10 years:
- ^{8}B flux: 5%
- $\sin^2\theta_{12}$: +9% / -8%
- Δm^2_{21}: +25% / -17%

arXiv:2210.08437 (submitted to APJ)

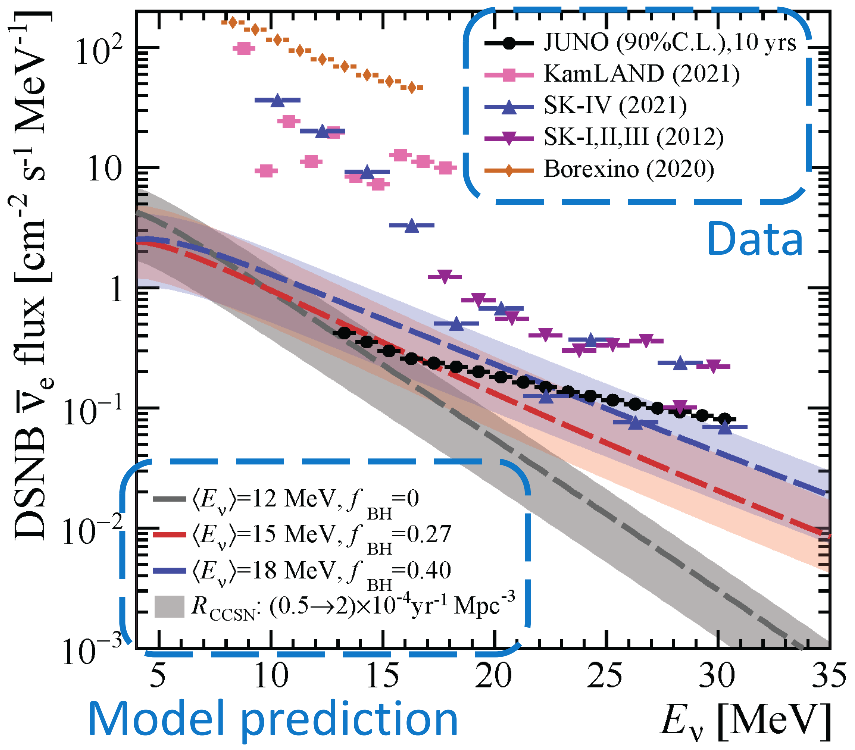








Diffuse Supernova Neutrino Background (DSNB)

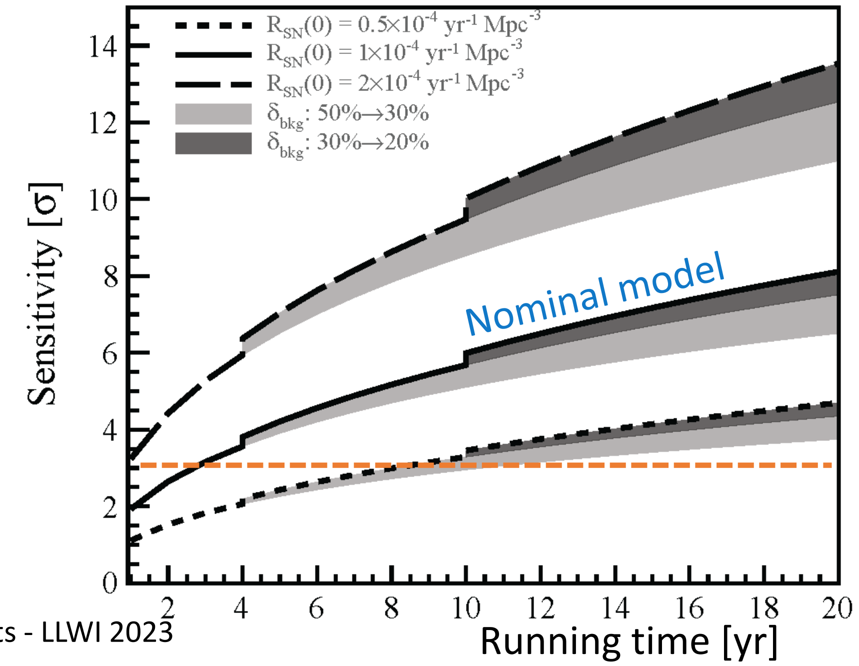


Integrated flux of all past Supernovae (SN) explosions in the visible Universe

- Not yet observed
- Expected signal: few IBD per year
- Main backgrounds:
  - IBD from reactor ν (E > 10 MeV)
  - NC interactions from atmospheric ν on ^{12}C (pulse shape discrimination – efficiency 50% → 80%)

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

JCAP10(2022)033



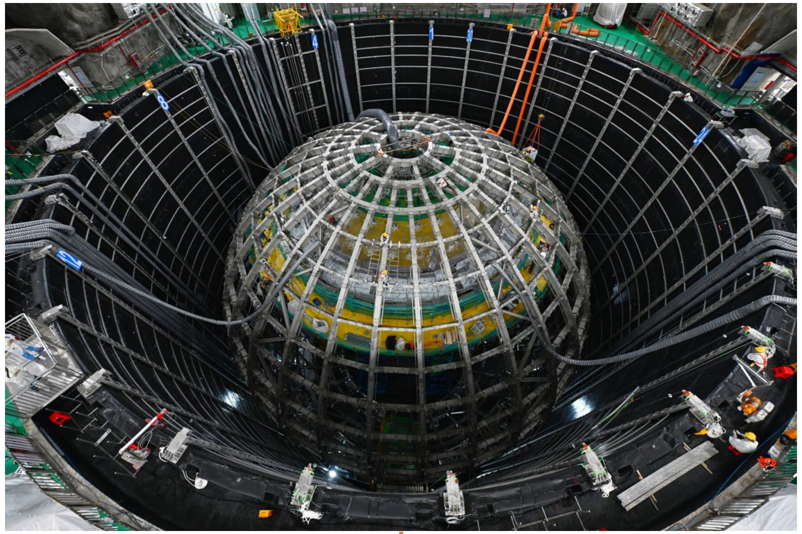
The JUNO Collaboration

International collaboration
75 Institutes from 18 countries
> 650 collaborators

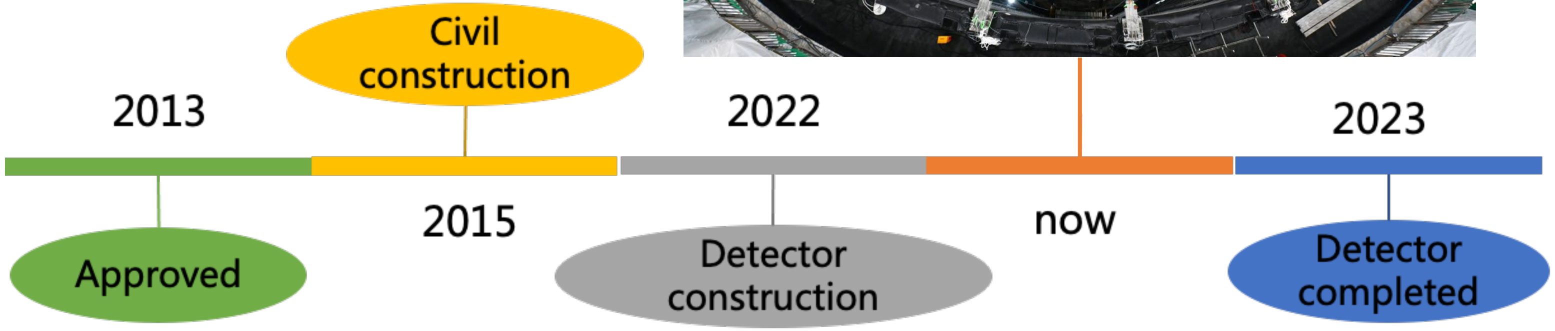
21st JUNO collaboration meeting, Feb. 6-10, 2023, Kaiping

Country	Institute	Country	Institute	Country	Institute
Armenia	Yerevan Physics Institute	China	SYSU	Germany	U. Mainz
Belgium	Universite libre de Bruxelles	China	Tsinghua U.	Germany	U. Tuebingen
Brazil	PUC	China	UCAS	Italy	INFN Catania
Brazil	UEL	China	USTC	Italy	INFN di Frascati
Chile	PCUC	China	U. of South China	Italy	INFN-Ferrara
Chile	SAPHIR	China	Wu Yi U.	Italy	INFN-Milano
Chile	UNAB	China	Wuhan U.	Italy	INFN-Milano Bicocca
China	BISEE	China	Xi'an JT U.	Italy	INFN-Padova
China	Beijing Normal U.	China	Xiamen University	Italy	INFN-Perugia
China	CAGS	China	Zhengzhou U.	Italy	INFN-Roma 3
China	ChongQing University	China	NUDT	Latvia	IECS
China	CIAE	China	CUG-Beijing	Pakistan	PINSTECH (PAEC)
China	DGUT	China	ECUT-Nanchang City	Russia	INR Moscow
China	Guangxi U.	China	CDUT-Chengdu	Russia	JINR
China	Harbin Institute of Technology	Czech	Charles U.	Russia	MSU
China	IHEP	Finland	University of Jyvaskyla	Slovakia	FMPICU
China	Jilin U.	France	IJCLab Orsay	Taiwan-China	National Chiao-Tung U.
China	Jinan U.	France	LP2i Bordeaux	Taiwan-China	National Taiwan U.
China	Nanjing U.	France	CPPM Marseille	Taiwan-China	National United U.
China	Nankai U.	France	IPHC Strasbourg	Thailand	NARIT
China	NCEPU	France	Subatech Nantes	Thailand	PPRLCU
China	Pekin U.	Germany	RWTH Aachen U.	Thailand	SUT
China	Shandong U.	Germany	TUM	U.K.	U. Warwick
China	Shanghai JT U.	Germany	U. Hamburg	USA	UMD-G
China	IGG-Beijing	Germany	FZJ-IKP	USA	UC Irvine

Summary



- JUNO is a multi-purpose large LS detector
- Construction is ongoing



- Broad physics reach
  neutrino mass ordering: 3σ in 6 years
  Δm^2_{31}, Δm^2_{21}, $\sin^2\theta_{12}$ precision < 1% in 1 year
  solar: ^{7}Be, pep, CNO, ^{8}B
  DSNB: 3σ in 3 years
  …

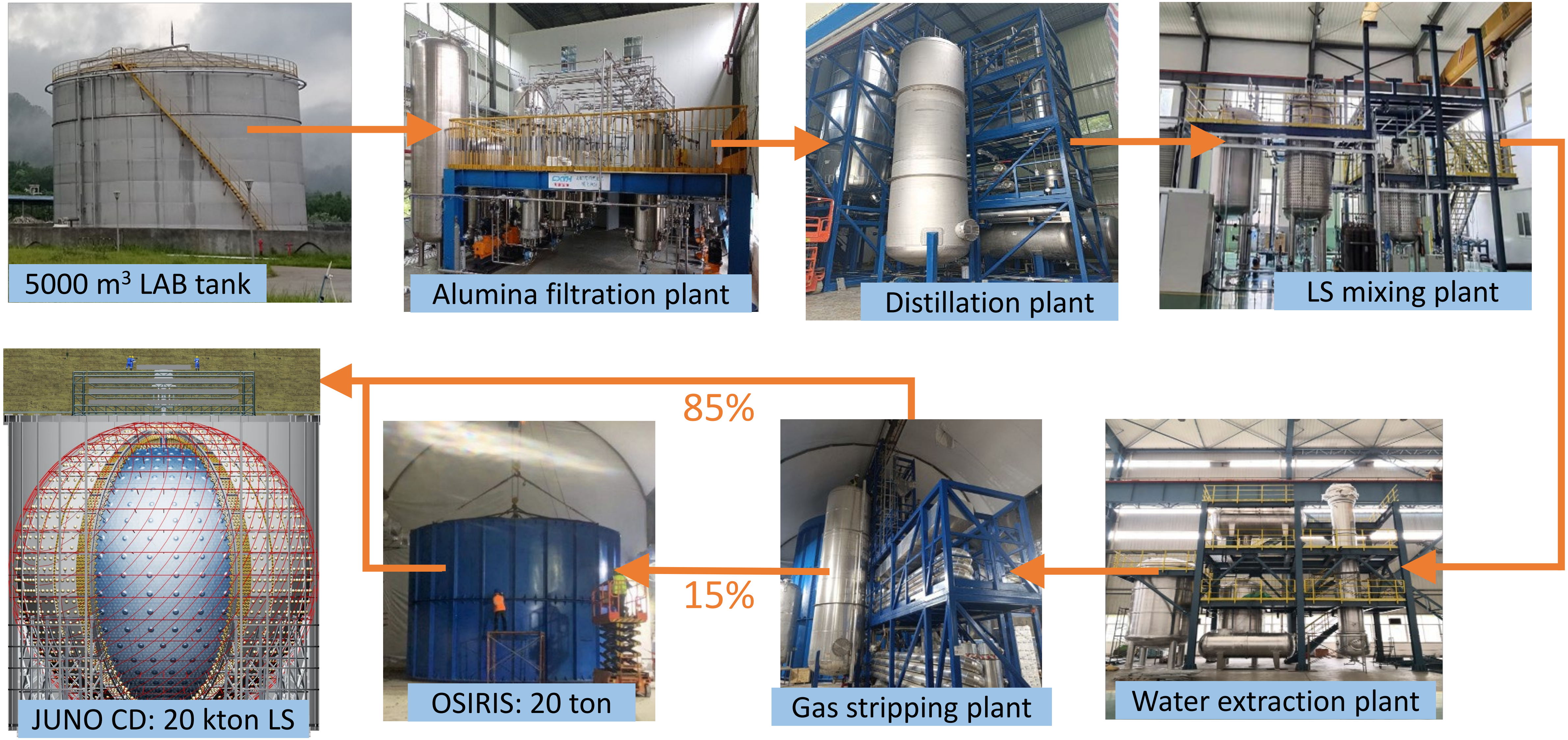
Stay tuned!

Thank you for listening!

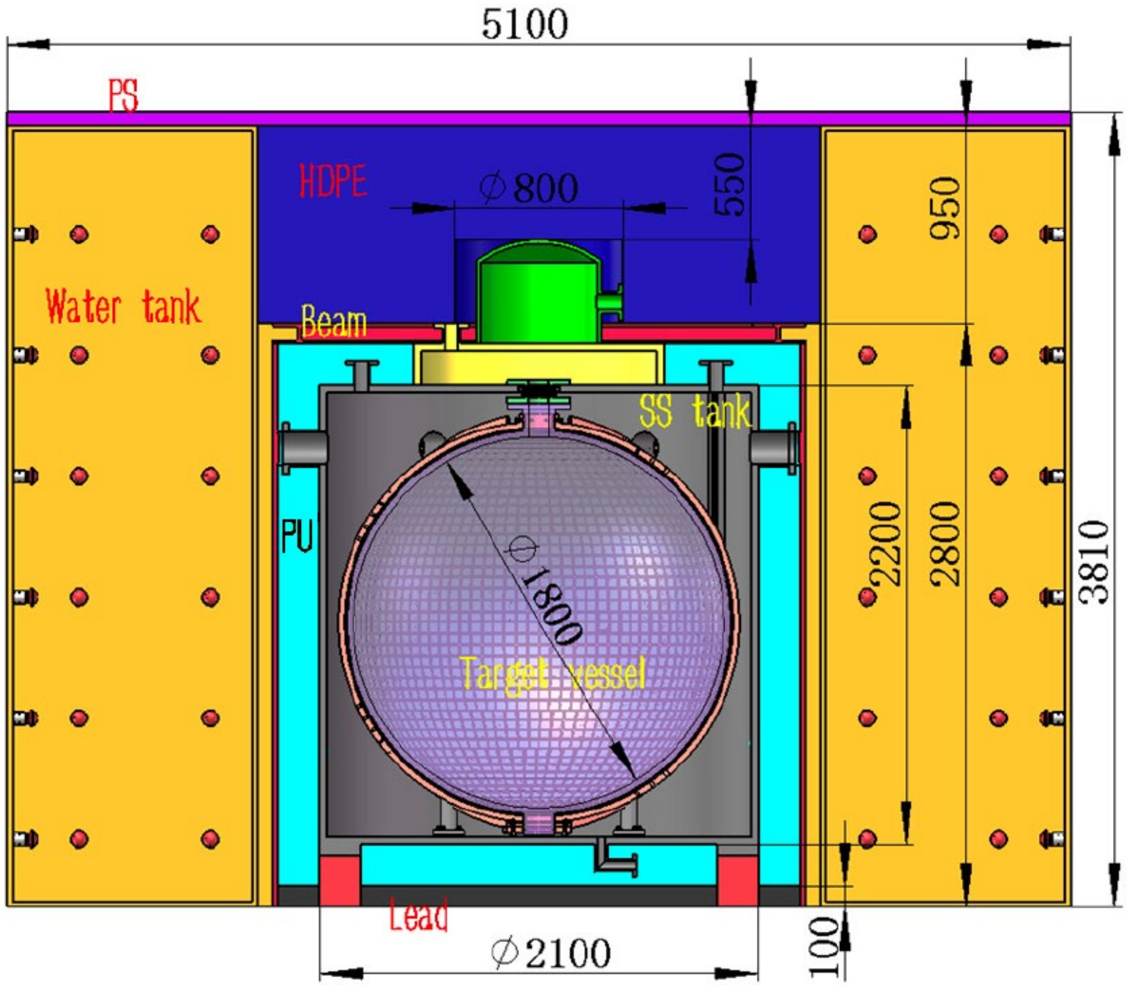
Backup

LS: Radiopurity control strategy

Most installation done
Commissioning will start soon



Taishan Antineutrino Observatory - TAO



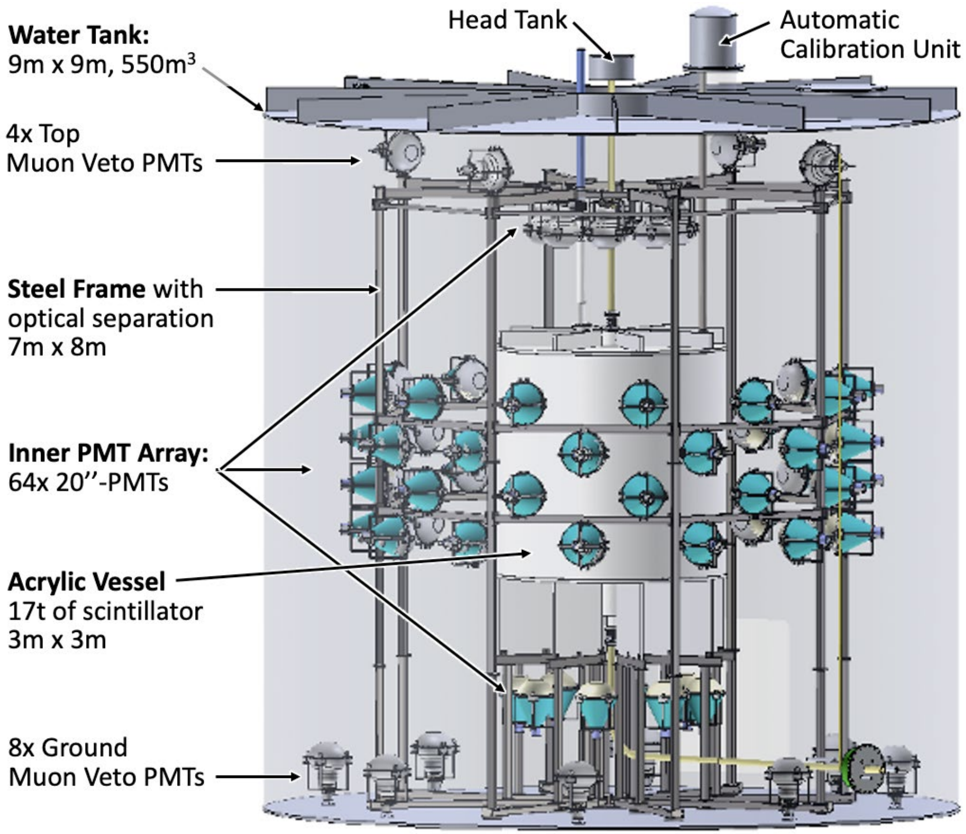
arXiv: 2005.08745

- 2.8 ton Gd-LS in acrylic vessel
- 10 m^2 SiPM → ~94% coverage
- 50% PDE for light detection
- Operated @ -50°C
- 4500 PE/MeV
- Energy resolution < 2% @ 1 MeV
- 30 m from Taishan core

Main goals:

- Reference spectrum for JUNO
- Benchmark for nuclear databases
- Isotopic yields and spectra
- Search for sterile neutrinos

Online Scintillator Internal Radioactivity Investigation System - OSIRIS



EPJC 81 (2021) 973

A 20 ton detector to monitor LS radiopurity before and during JUNO detector filling

280 PE/MeV
Energy resolution: 6% @ 1 MeV

64 x 20-inch PMTs for LS – 9% coverage
12 x 20-inch PMTs for muon veto

Expected sensitivity:
- $\sim 10^{-15}$ g/g for U/Th in a few days (reactor)
- $\sim 10^{-17}$ g/g for U/Th in 2-3 weeks (solar)

Other measurable isotopes: ^{14}C, ^{210}Po, ^{85}Kr

Possible upgrade to Serappis *Eur. Phys. J. C* **82**, 779 (2022)
(SEarch for RAre PP-neutrinos In Scintillator)

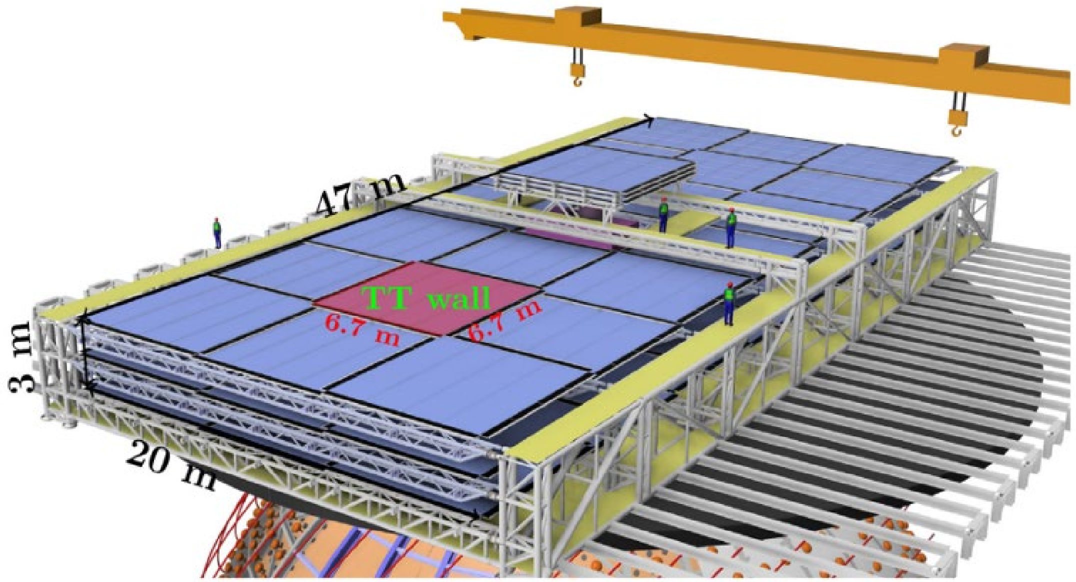
Veto Water Cherenkov detector

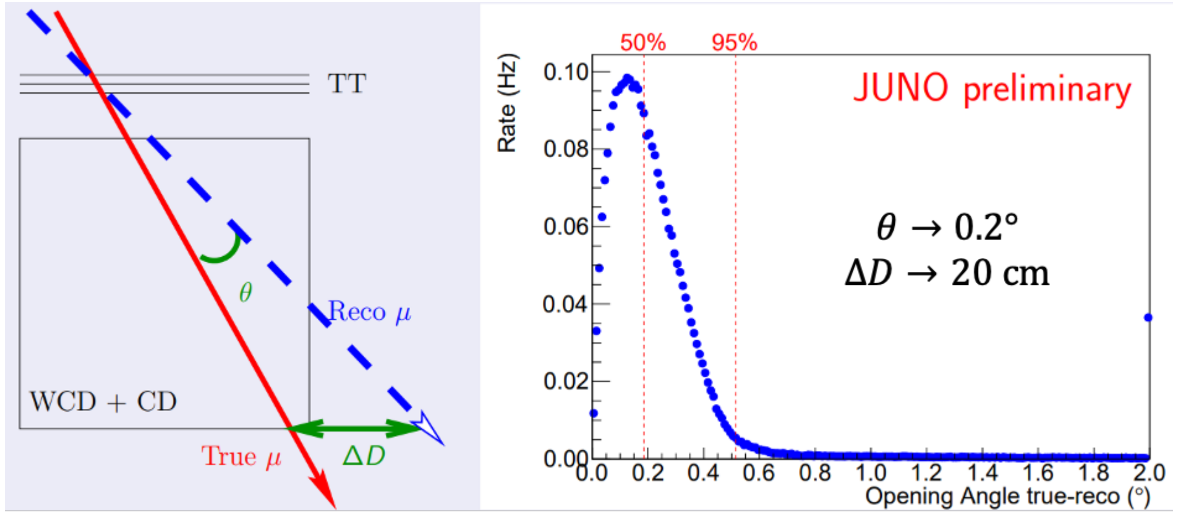
~650 m rock overburden (1800 m.w.e.) → muon rate: 4 Hz, mean muon energy: 207 GeV

35 kton of ultra-pure water serving as passive shield and Water Cherenkov detector

- 2400 20-inch MCP PMTs, detection efficiency of cosmic muons larger than 99.5%
- Keep the temperature uniform and stable at (21±1)°C
- Quality: ^{222}Rn < 10 mBq/m3, attenuation length 30~40 m

Veto detector: Top Tracker

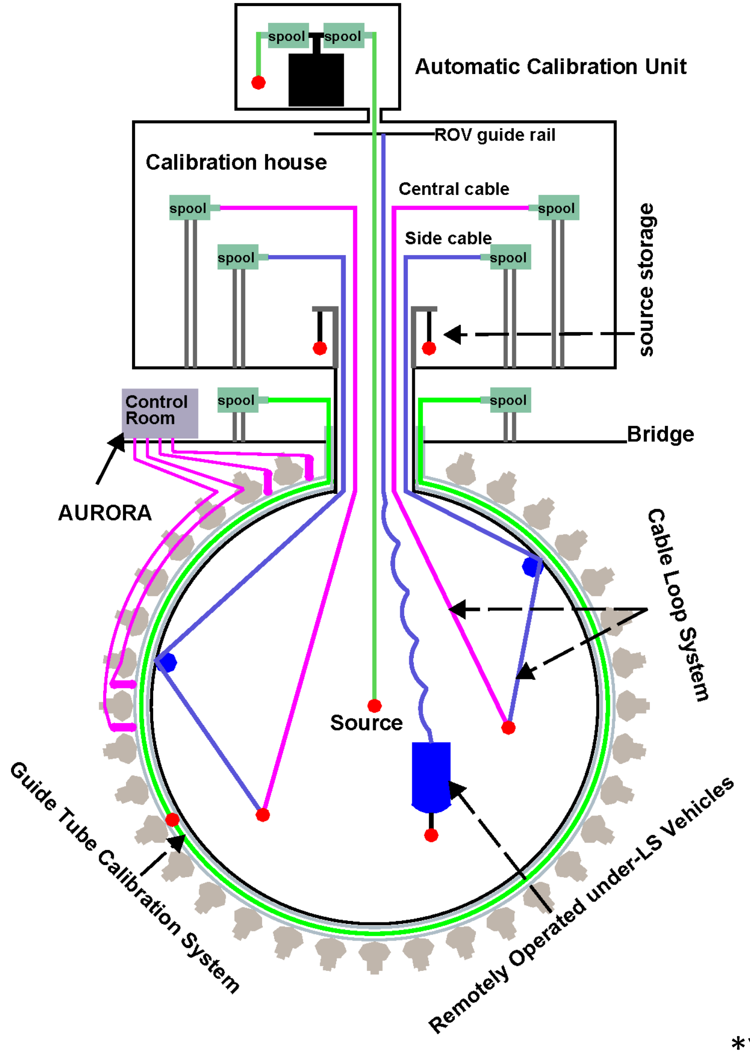




3 layers of plastic scintillators refurbished from the OPERA experiment:

- Covering about 50% of the top of the water pool
- Three scintillator layers to reduce accidental coincidences
- All scintillator panels arrived on site in 2019
- Precision muon tracking
- Study of cosmogenic background

Calibration system



4 sub-systems JHEP 03(2021)004

Liquid scintillator non-linearity:

- 5 gamma sources
- 2 neutron sources
- Continuous ^{12}B spectrum

Instrumental non-linearity:

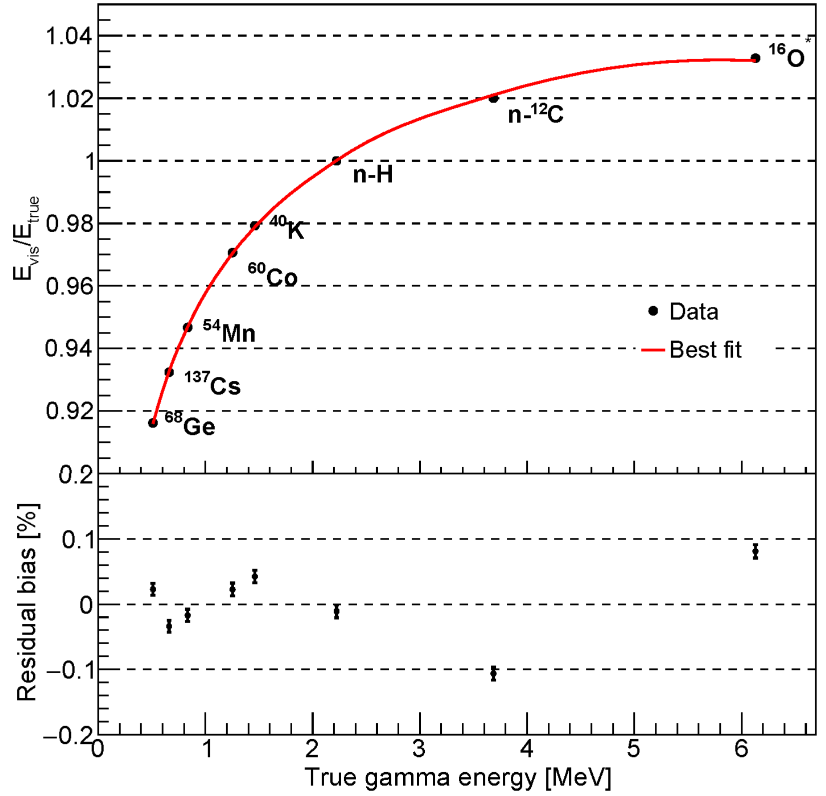
- Tunable UV laser
- Gamma source

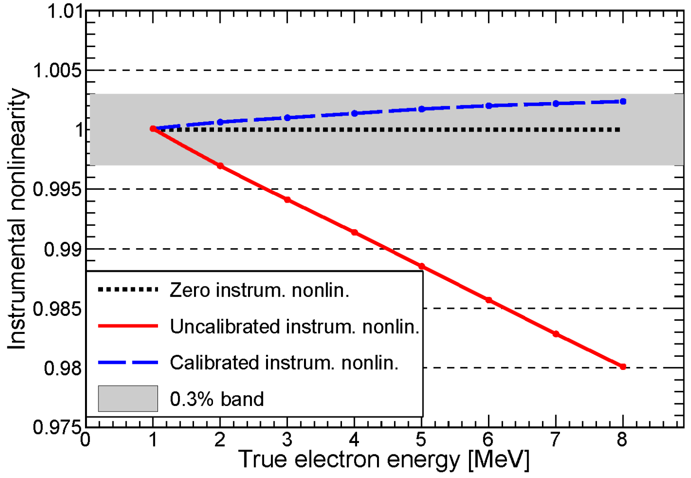
Dual Calorimetry Calibration*

- Use 3-inch PMTs as linear reference
- Correct 20-inch PMT channel-wise non-linearity

→ Residual NL < 0.3%

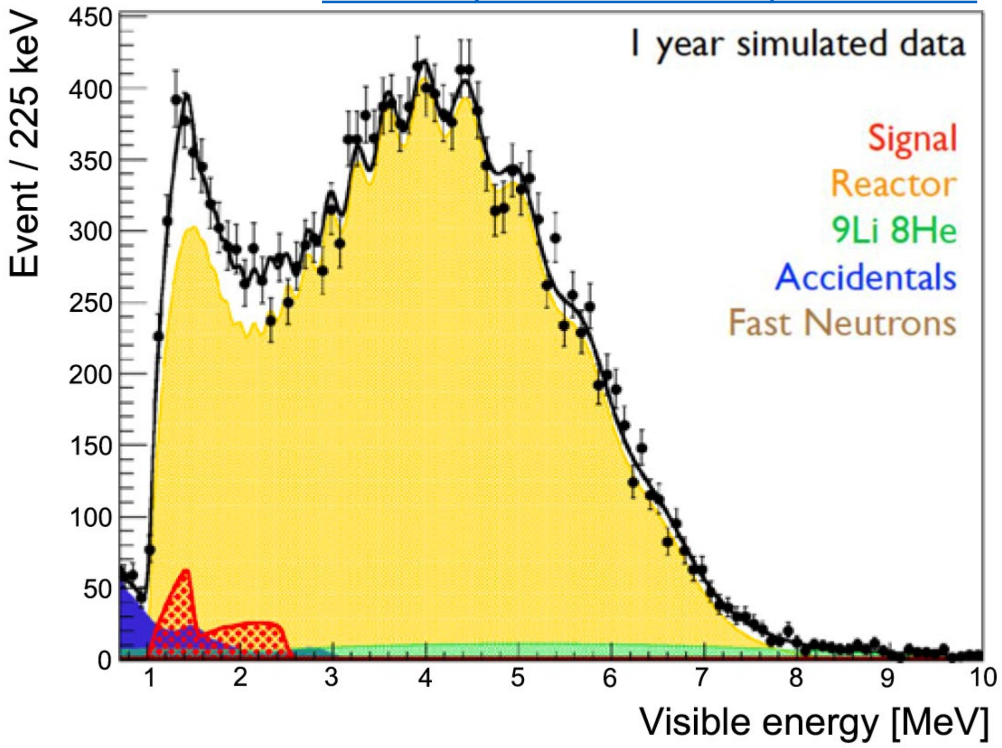
*Yang Han, https://hal.archives-ouvertes.fr/tel-03295420v1





Geoneutrinos

[2016 *J. Phys. G: Nucl. Part. Phys.* **43** 030401]



$$^{238}\mathrm{U} \rightarrow {}^{206}\mathrm{Pb} + 8\alpha + 6\beta^- + 6\bar{\nu}_e$$
$$^{232}\mathrm{Th} \rightarrow {}^{208}\mathrm{Pb} + 6\alpha + 4\beta^- + 4\bar{\nu}_e$$
$$^{40}\mathrm{K} \rightarrow {}^{40}\mathrm{Ca} + \beta^- + \bar{\nu}_e$$

Motivation:

- Earth radiogenic heat, especially from the mantle
- U/Th ratio → insight about the Earth formation

- Expected ~400 IBD per year
- Challenge: reactor-ν background, ~40 times larger
- Flux precision: 13% in 1 year → 5% in 10 years (current precision ~16-18%)
- Sensitive to Th/U ratio at percent level
- Interdisciplinary team of physicists and geologists at work to develop a local refined crust model (required to get information on the mantle)

Atmospheric neutrinos

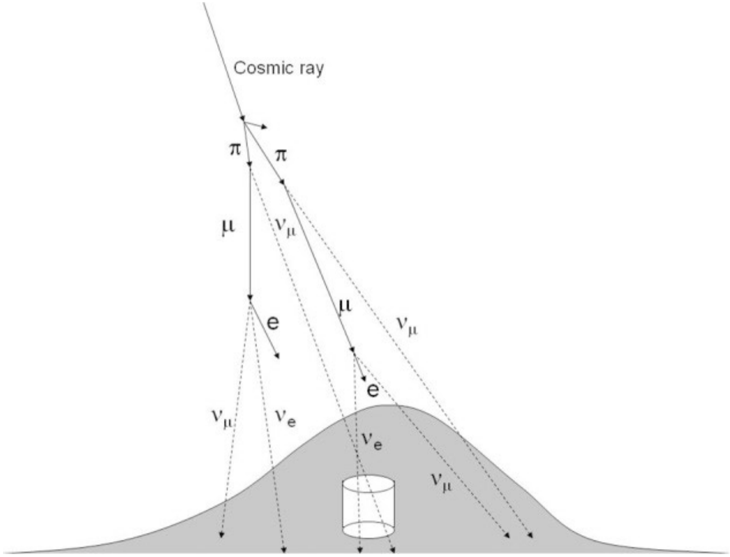
First measurement with LS: can give important inputs in the 100 MeV - 10 GeV energy range

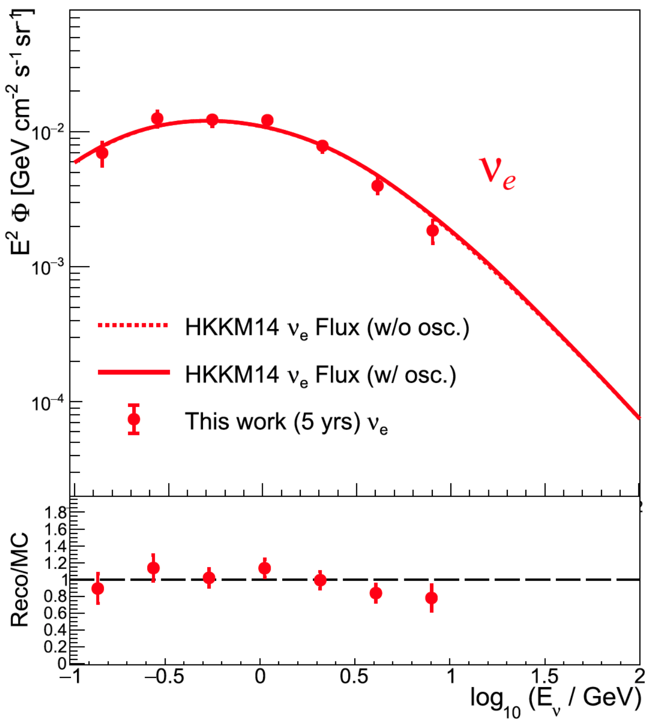
Detection through CC and NC interactions – CC-only analysis

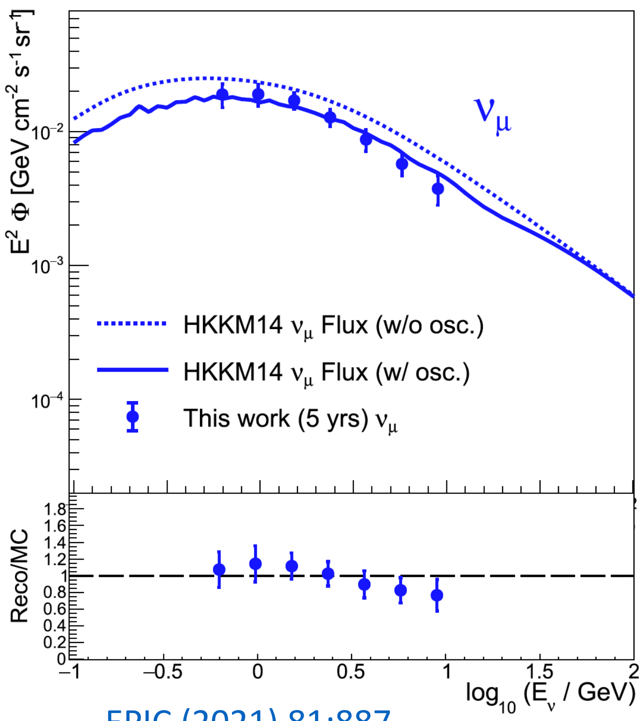
Muon/electron flavour discrimination: ν_e and ν_μ spectra with precision of 10% to 25% in 5 years

NMO determination through matter effects – complementary to reactor neutrinos
→ Combined analysis under study

Measurement of θ_{23}







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Supernova (SN) neutrinos

Galactic core-collapse SN (CCSN) rate:
~3 per century

CCSN emits 99% of energy in form of neutrinos

Supernova Burst @ 10 kpc:
~5000 IBD
~300 eES
~2000 pES (all flavours)

Dedicated electronics to handle high rate of events within few seconds.

Determination of flavour content,
energy spectrum,
time evolution of the signal

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