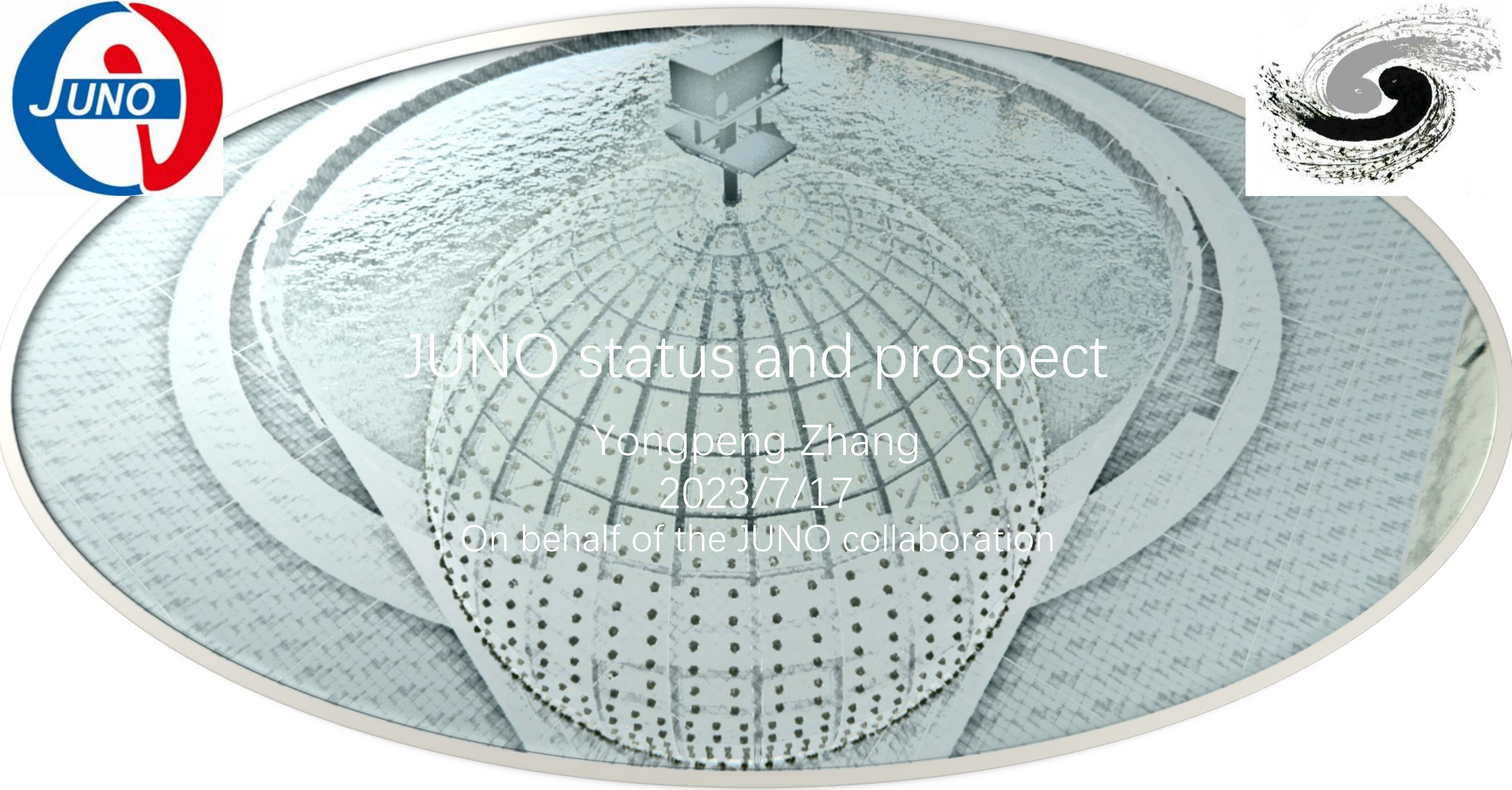


JUNO status and prospect

Yongpeng Zhang

2023/7/17

On behalf of the JUNO collaboration

19th Rencontres du Vietnam, Neutrino Workshop at IFIRSE, July 16th - July 19th, 2023

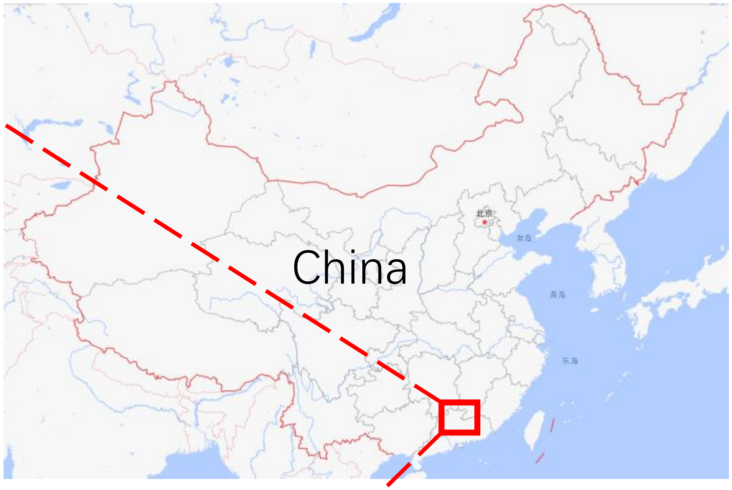
JUNO Collaboration

75 institutes and more than 700 collaborators

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		

JUNO site


JUNO
~52.5 km
Taishan NPP
2×4.6 GW_{th}
Yangjiang NPP
6×2.9 GW_{th}
TAO
736.0 m
252.5 m
8 reactors
26.6 GW_{th}
~700 m
~52.5 km
JUNO
Vertical tunnel:
563 m
Overburden
~650 m
(1800 m.w.e.)
Slope tunnel: 1265 m
@ slope of 42%


China

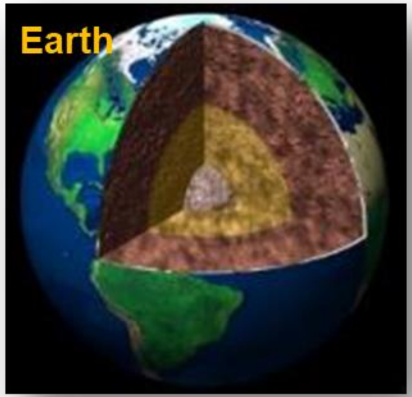
JUNO: A multi-purpose observatory

~60 IBDs per day

Several per day

Hundreds per day

~5000 IBDs for CCSN @10 kpc



Several IBDs per day

\+ New physics

Neutrino oscillation & properties

Neutrinos as a probe

IBD: inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$

CCSN: core-collapse supernova

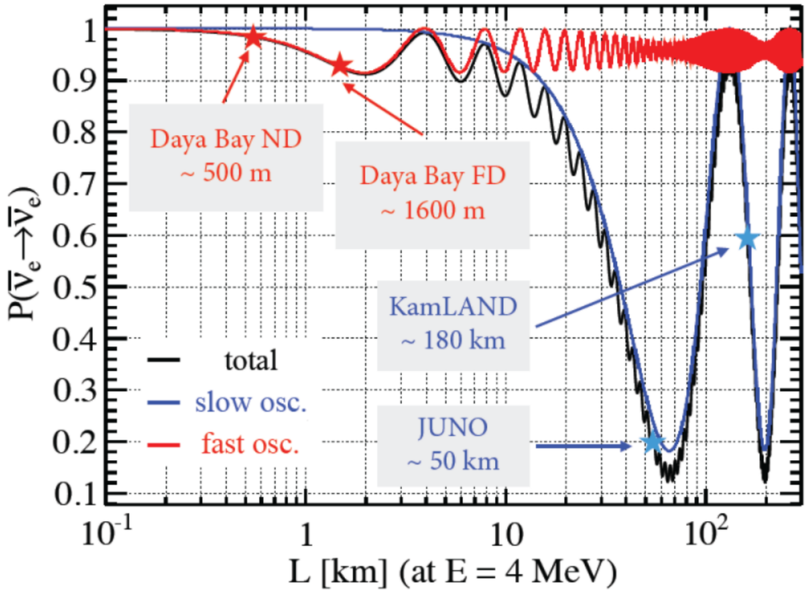
“Neutrino Physics with JUNO,” J. Phys. G **43** (2016) no.3, 030401
“JUNO Physics and Detector,” Prog. Part. Nucl. Phys. **123** (2022), 103927

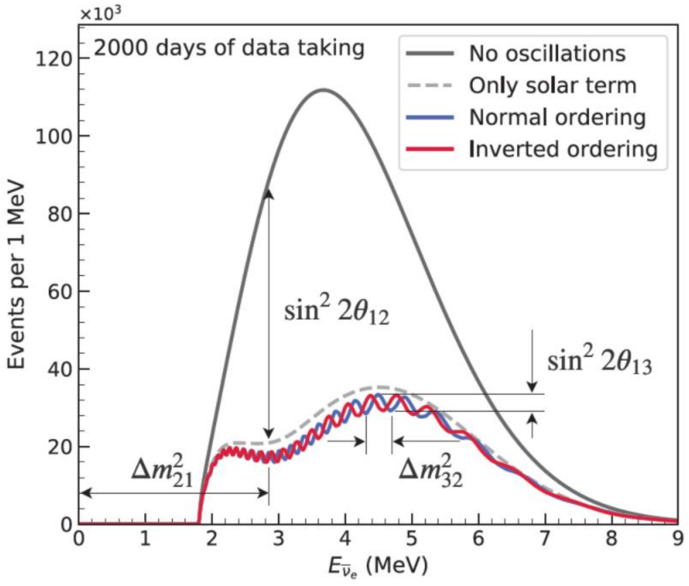
Reactor neutrino oscillation

$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \sin^2 2\theta_{13}\left(\cos^2\theta_{12}\sin^2\frac{\Delta m^2_{31}L}{4E} + \sin^2\theta_{12}\sin^2\frac{\Delta m^2_{32}L}{4E}\right) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\frac{\Delta m^2_{21}L}{4E}$$

(In vacuum)

No θ_{23}
No δ_{CP}



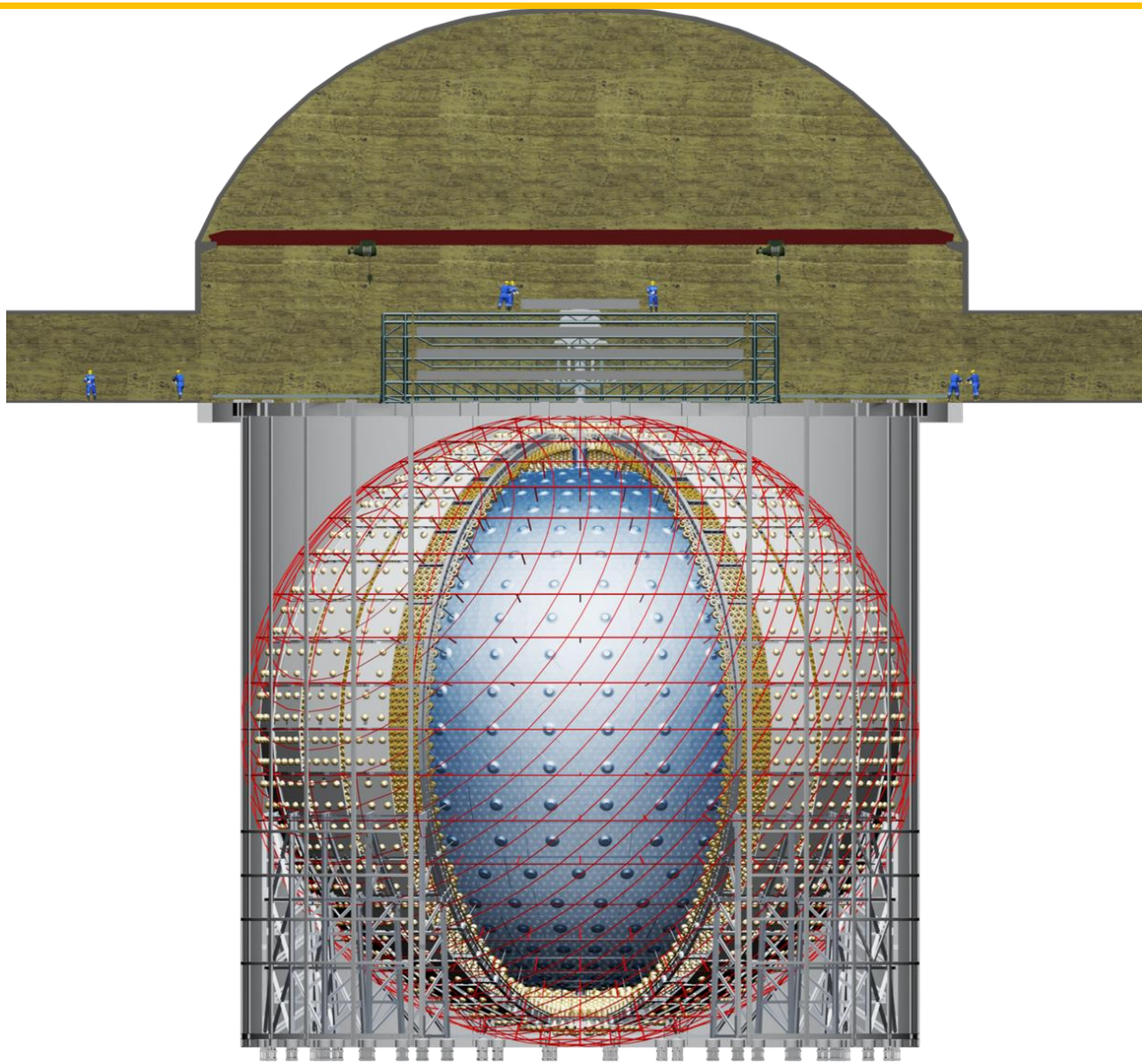


J. Phys. G43:030401 (2016)

- Keys to precise measurement
  - ✓ Powerful source
  - ✓ Optimized distance
  - ✓ Excellent ***E*** resolution(3%@1 MeV)
  - ✓ Low Background

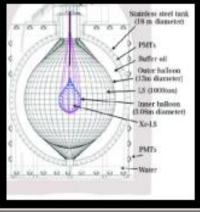
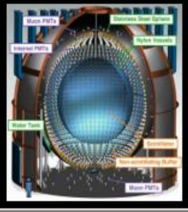
How to achieve incredible energy resolution

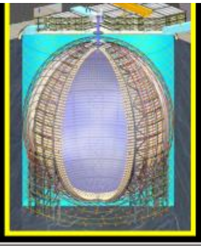
- ✓ JUNO is largest liquid scintillator target with 20 kt LS
- ✓ High-yield scintillator and attenuation length > 20 m @ 430 nm
- ✓ Double calorimetry with ~78% photo coverage for 20” PMTs + 3” PMTs
- ✓ Highly efficient PMTs (PDE~30%)
- ✓ Complementary calibration systems to reduce energy scale uncertainty to <1%



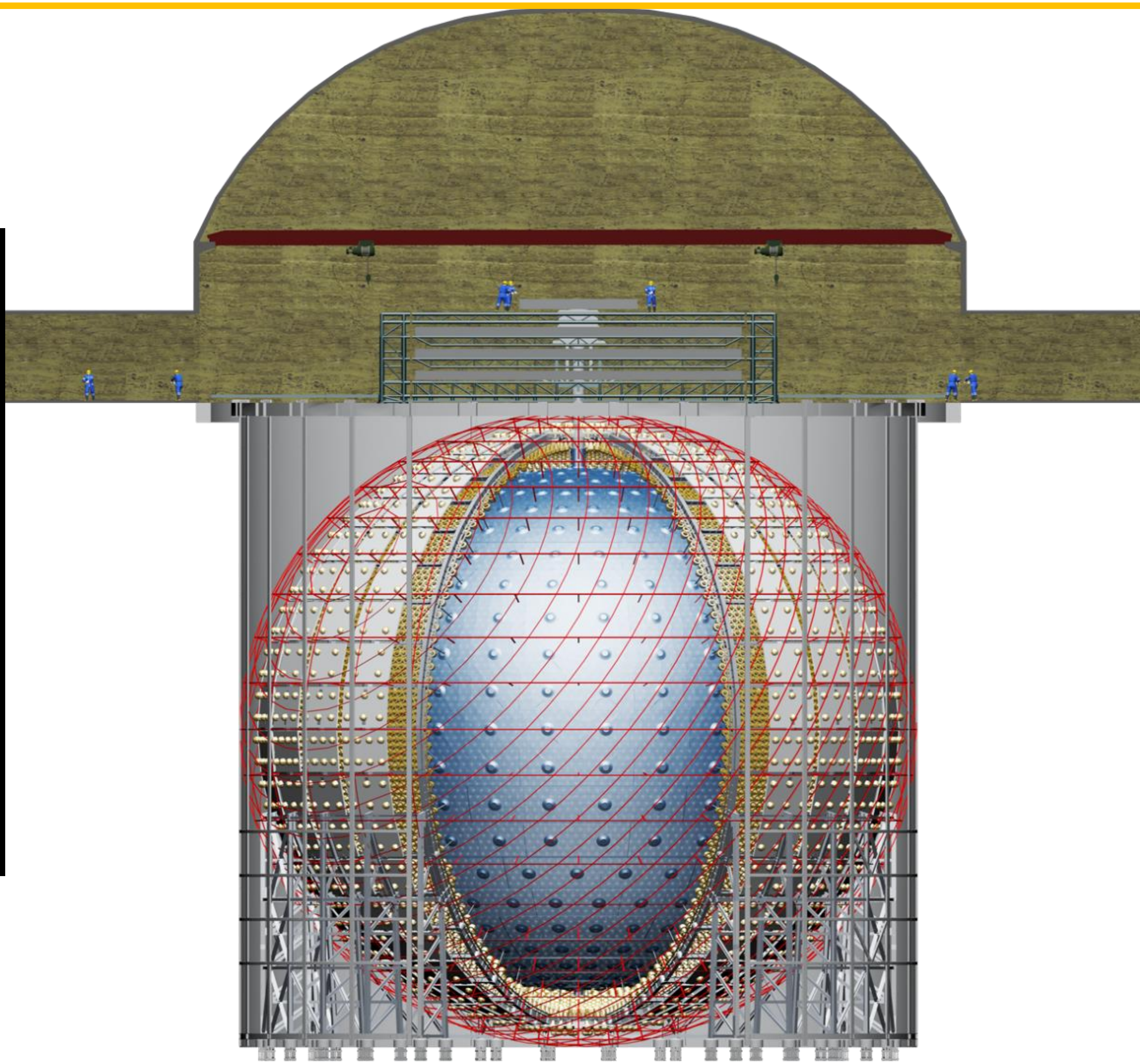
How to achieve incredible energy resolution

JUNO:
Energy Resolution
3% @ 1MeV

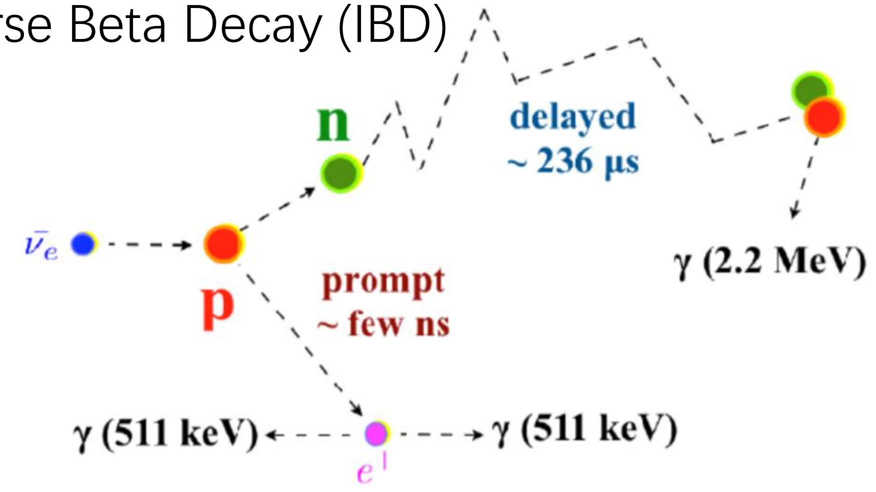


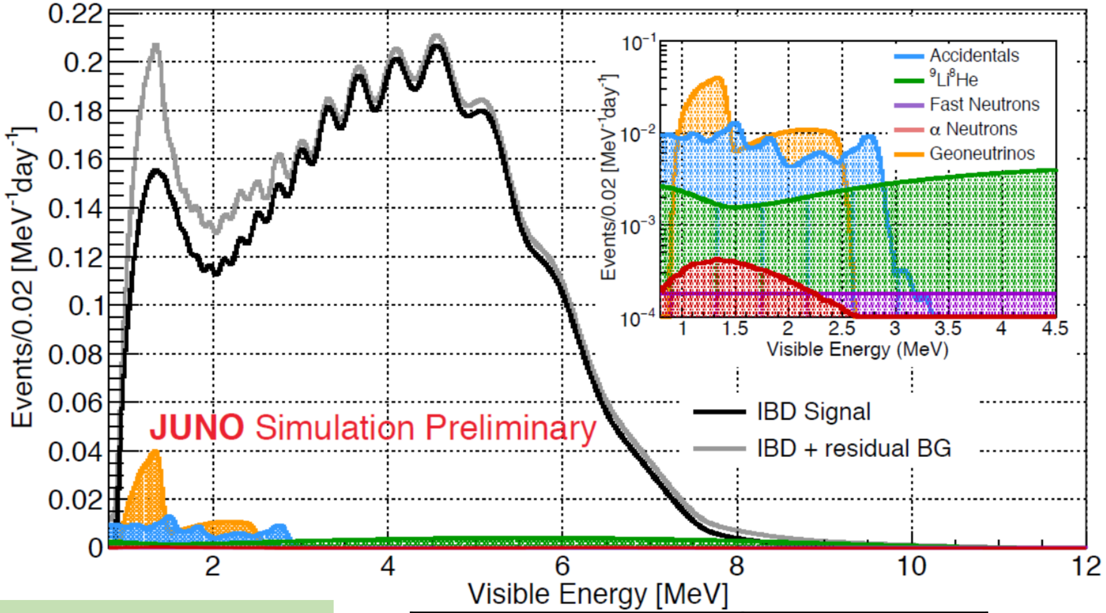
	KamLAND [2]	Borexino [3]	SNO+ [4]	JUNO
Target Mass [kilotons]	1	0.3	0.78	20
Number of PMTs	1900	2200	10,000	18,000 + 26,000
PMT Coverage	~34%	~30%	~50%	~80%
Light Collection [photoelectrons/MeV]	~250	~450	~520	>1300



IBD signal and backgrounds

- Golden channel for neutrino detection
  Inverse Beta Decay (IBD)





Background reduction strategy:

- Careful material screening
- Meticulous Monte Carlo simulations
- Accurate detector production handling
- Clean environment

Main selection cuts:

- Fiducial volume: R_{LS} < 17.2 m
- Energy threshold: E_{vis} > 0.7 MeV
- Time correlation: $\Delta T_{p\text{-}d}$ < 1 ms
- Spatial correlation: $\Delta R_{p\text{-}d}$ < 1.5 m
- Muon veto (Temporal⊕Spatial)

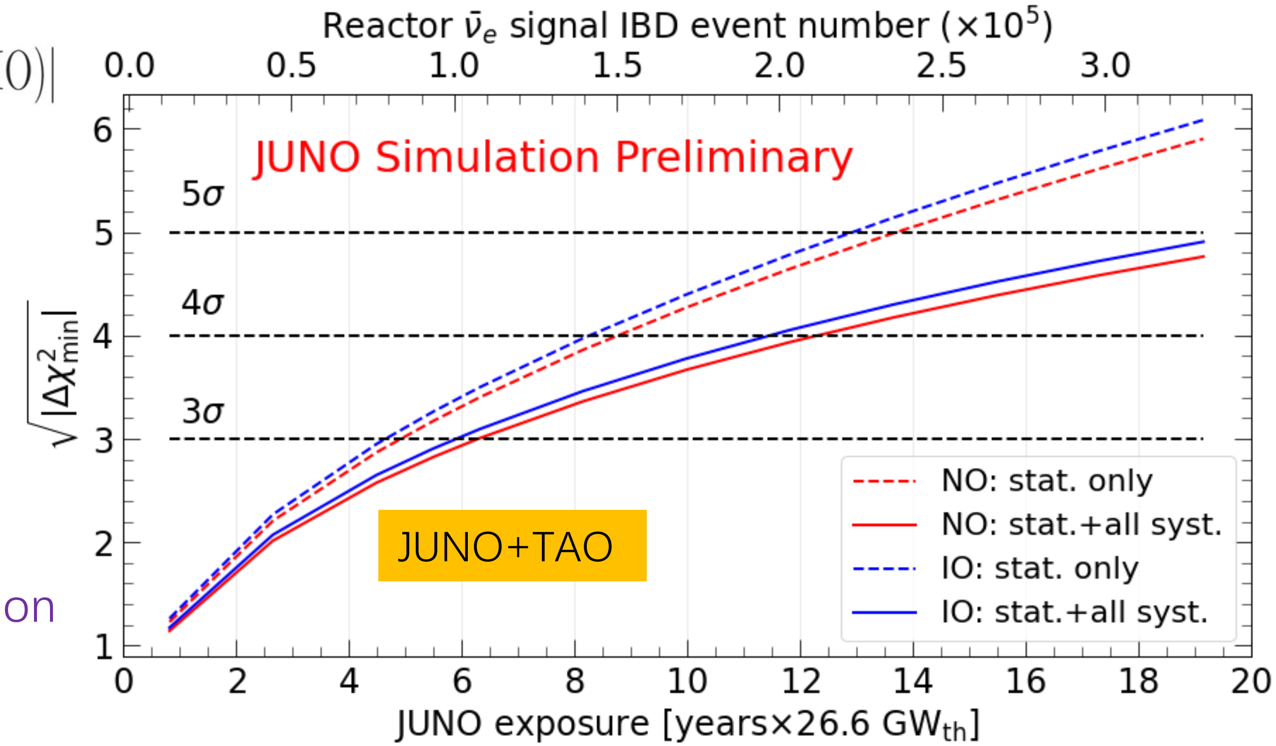
Event type	Rate [/day]
Reactor IBD signal	47.1
Geo-ν's	1.2
Accidental signals	0.8
Fast-n	0.1
$^{9}Li/^{8}He$	0.8
$^{13}C(\alpha,n)^{16}O$	0.05
Global reactors	1.0
Atmospheric ν's	0.16

Sensitivities of NMO

✓ Fit the spectrum assuming the normal ordering or inverted ordering with the χ^2 method and take the difference of the minima as a measure of the median NMO sensitivity

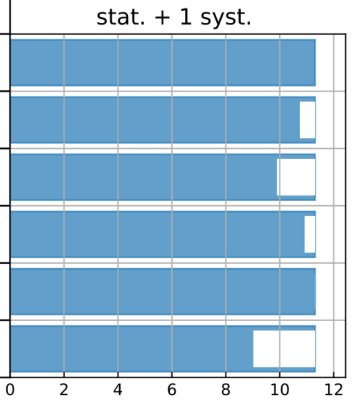
$$\Delta\chi^2_{MO} = |\chi^2_{min}(NO) - \chi^2_{min}(IO)|$$

NMO paper in preparation



Impact of systematics

	$\Delta\chi^2_{min}$
Statistics	11.3
Stat.+Flux error	-0.6
Stat.+Backgrounds	-1.4
Stat.+Nonlinearity	-0.4
Stat.+Others	< -0.05
Total	9.0



JUNO Simulation Preliminary

JUNO sensitivity on NMO: **3σ (reactors only) @ ~6 yrs * 26.6 GW_{th} exposure**

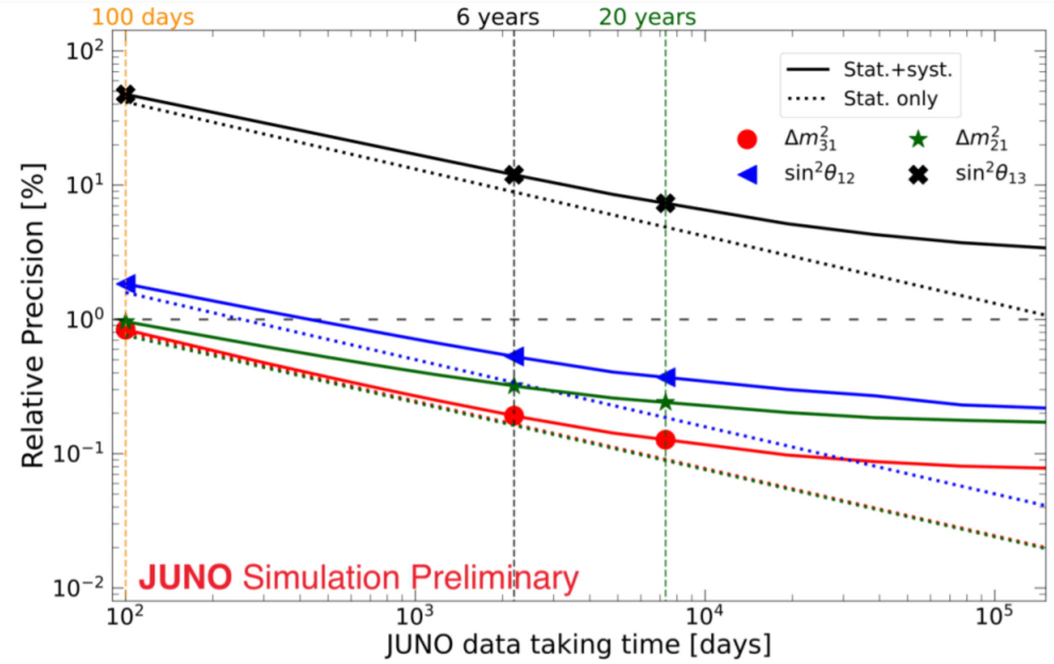
Estimation of NMO sensitivity with combined reactor + atmospheric neutrino analysis under preparation

Precision measurement of oscillation parameters

- ✓ JUNO will be the first to simultaneously observe an oscillation pattern containing two independent frequencies
- ✓ Measure neutrino mixing parameters at sub-percentage level: Δm^2_{31}, Δm^2_{21}, $sin^2\theta_{12}$

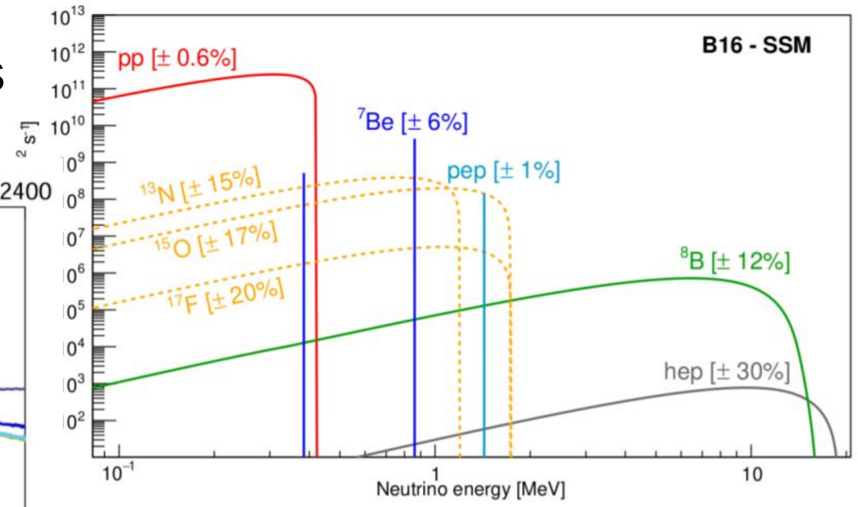
	Δm^2_{31}	Δm^2_{21}	$\sin^2\theta_{12}$
Dominant Exps.	T2K	KamLAND	SNO+SK
Individual 1σ	2.6%	2.4%	4.5%
PDG2020	1.4%	2.4%	4.2%
JUNO 6 years	~0.2%	~0.3%	~0.5%

J. Phys. G43:030401 (2016)



Solar neutrinos

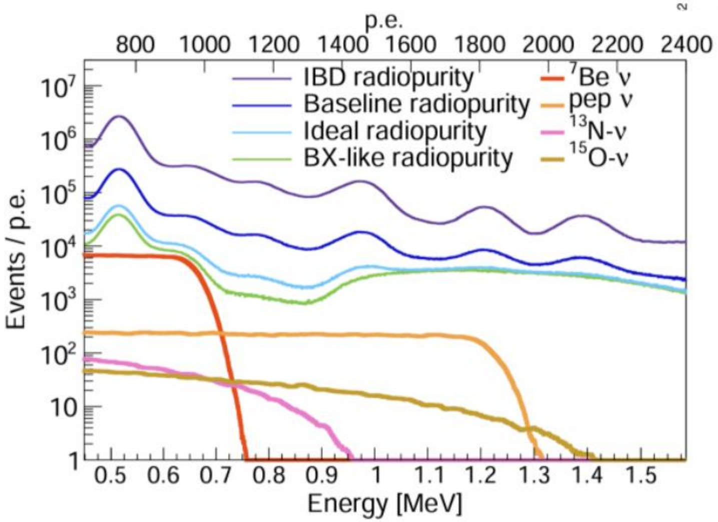
- JUNO sensitive to both high and intermediate energy solar neutrinos



- Intermediate energy solar neutrinos

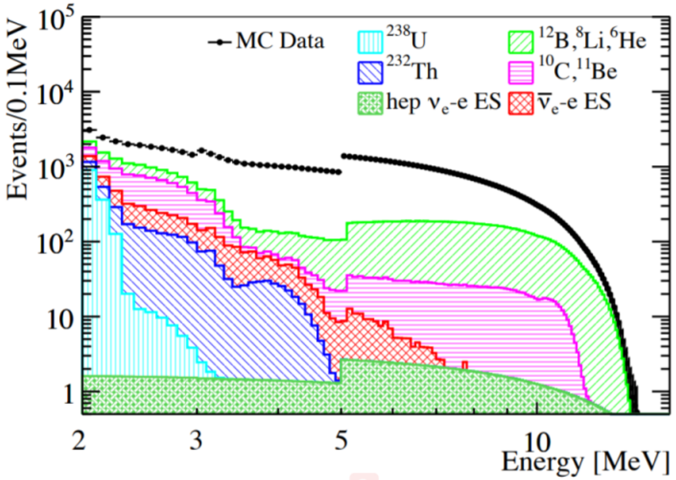
More radiopurity efforts (U/Th ~ 1×10^{-17} g/g)

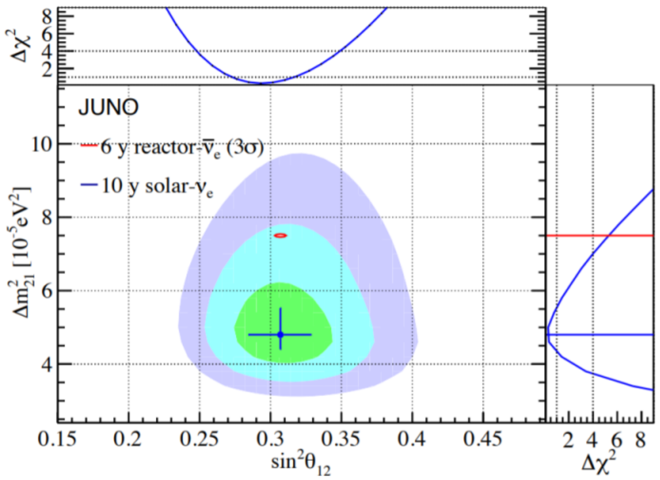
JUNO sensitivity to 7Be, pep, and CNO solar neutrinos
arXiv:2303.03910



- High energy solar neutrinos (^{8}B)

- Model independent measurement of ^{8}B solar neutrino flux (~5%) and oscillation parameters $\sin^2\theta_{12}$, Δm^2_{21}



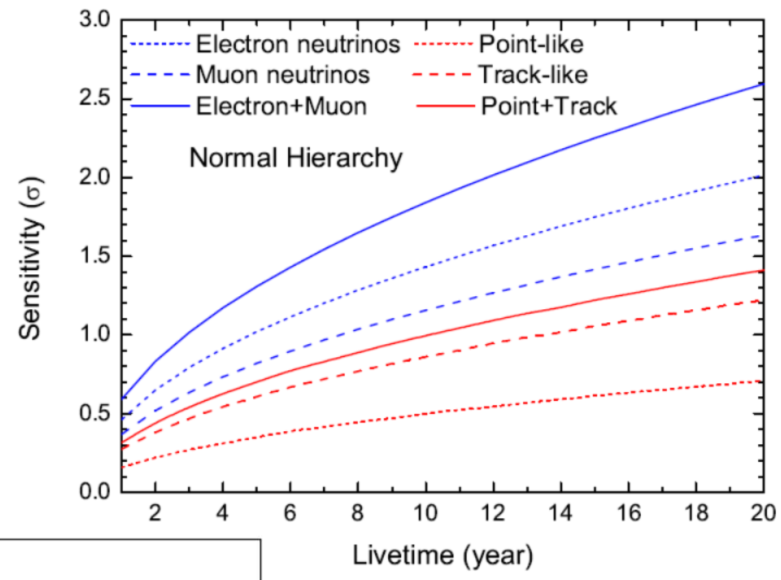


Chin. Phys. C 45 (2021) 2, 023004

Atmospheric neutrino

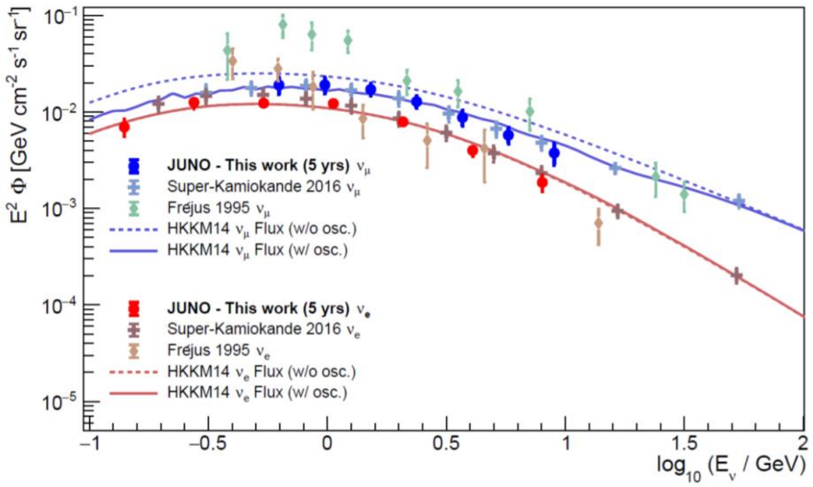
- JUNO NMO sensitivity from atmospheric neutrinos is complementary to that from the reactor neutrino results.
- Exploit matter effects for neutrinos crossing the Earth.
- Contributions to the sensitivity of NMO, $\theta_{23}$and δ_{CP}.

J. Phys. G: Nucl. Part. Phys. 43 030401 (2016)



- Promising potential towards the low energy range.
  - ✓ Atmospheric ν spectrum measurement.

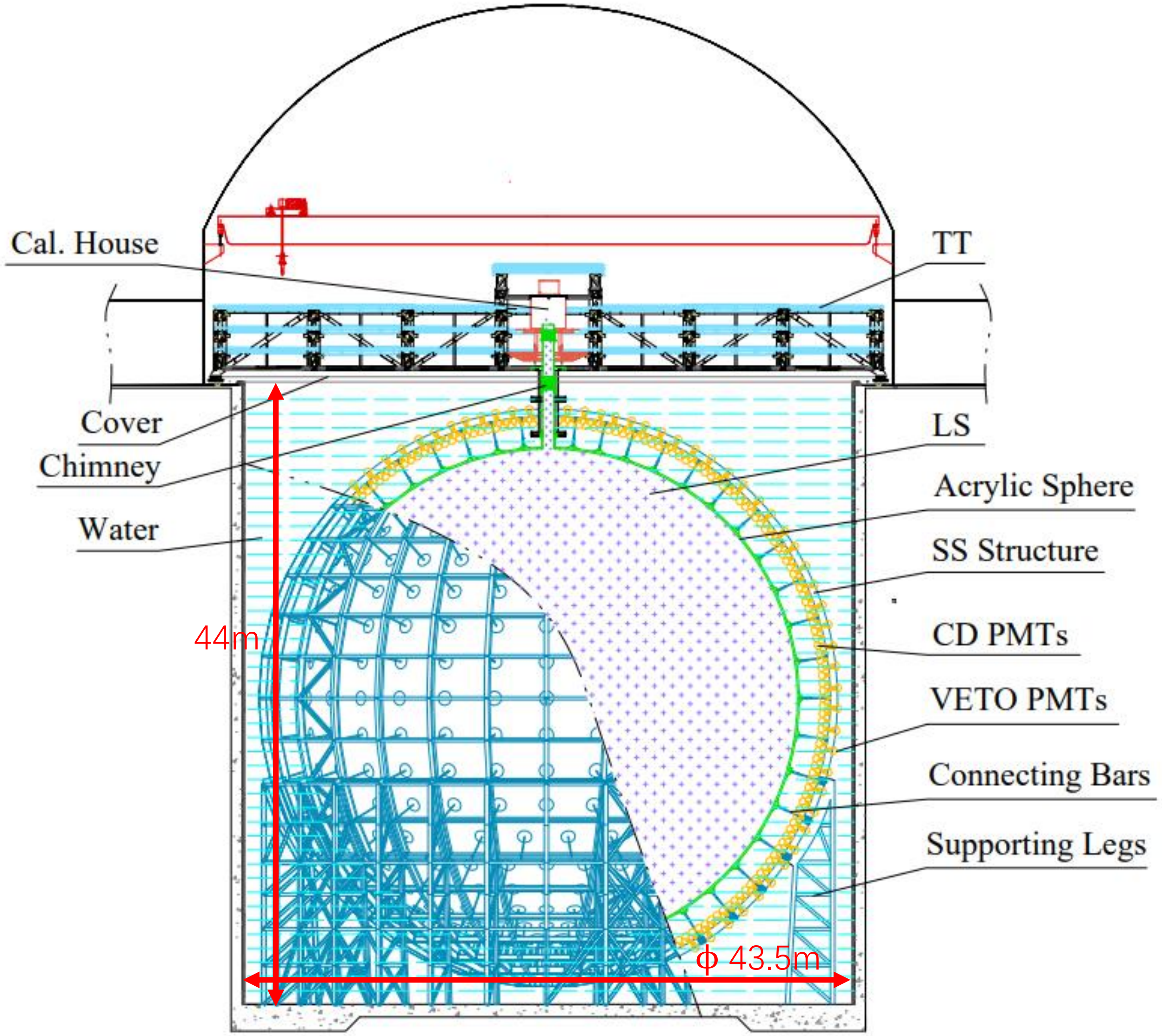
Eur. Phys. J. C (2021) 81:887



Detector progress

JUNO detector

- **Acrylic panels**
  - Half of total 265 pieces installed
- **Stainless Steel structure**
  - Assembly finished
- **20012 20'' PMTs + 25600 3'' PMTs**
  - Production and performance test done
  - Waterproof potting finished
  - Under installation
- **Liquid scintillator**
  - Purification plants under onsite construction



Central detector (acrylic vessel)

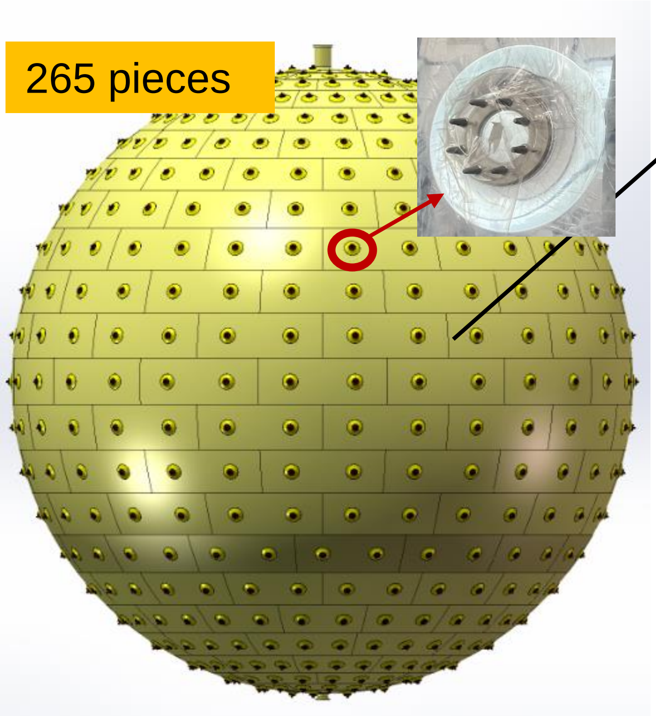
LS container:

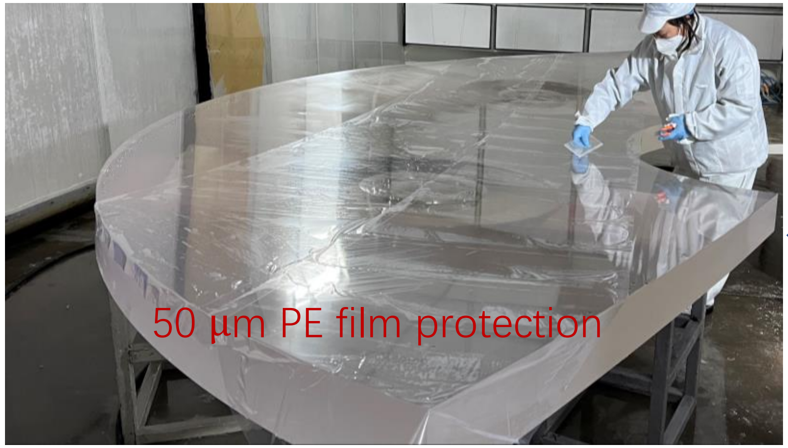
Inner diameter: 35.40±0.04 m

Thickness: 124±4 mm

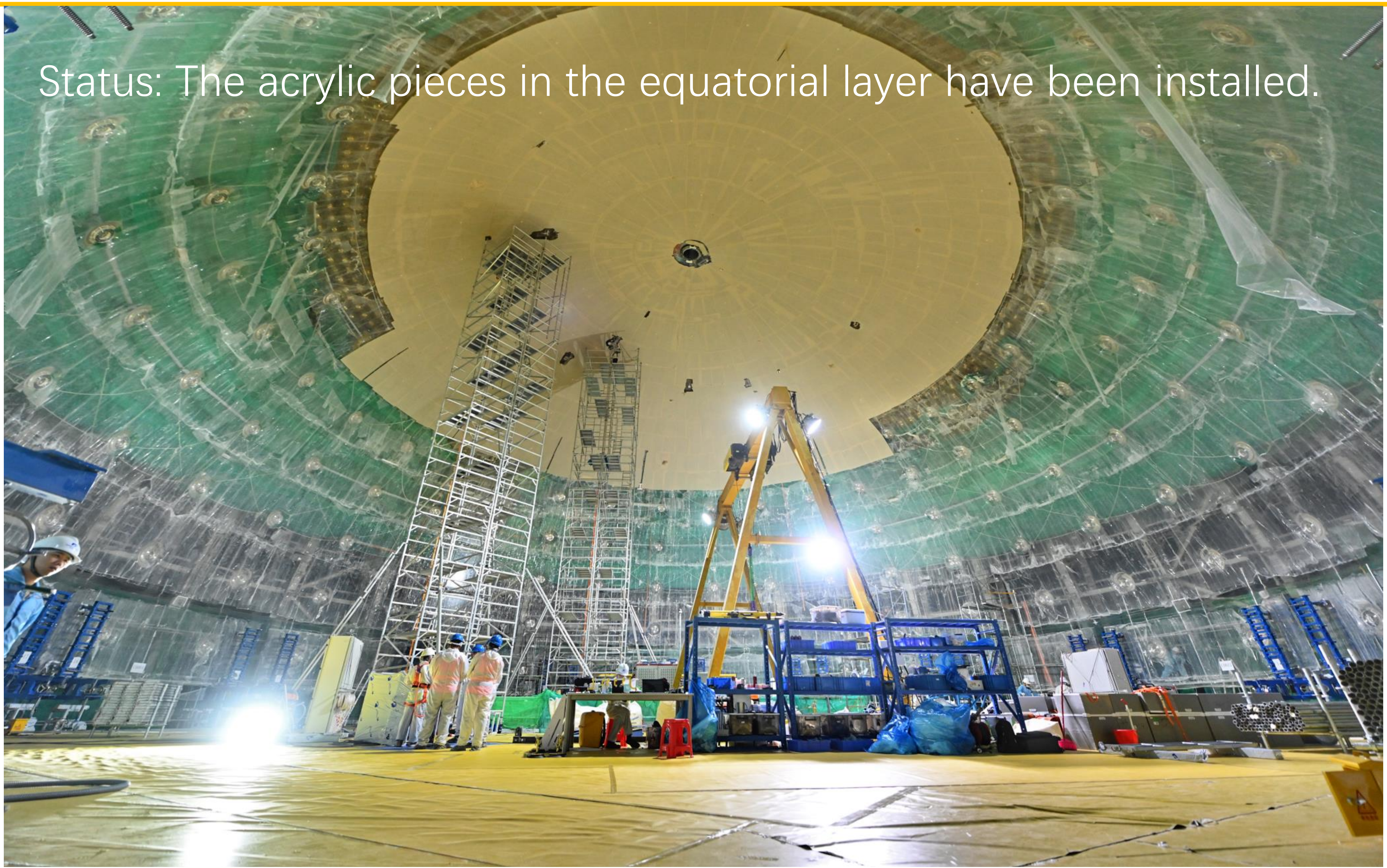
Light transparency > 96% @ LS

Radiopurity: U/Th/K < 1 ppt





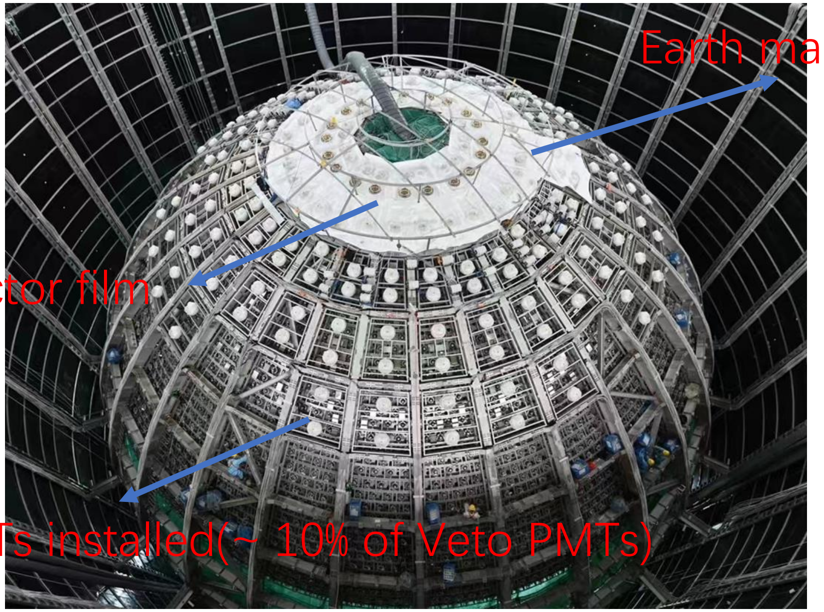
Central detector (acrylic vessel)



Veto detector (Water Cherenkov)

~650 m rock overburden (1800 m.w.e.) → R_μ = 4 Hz in LS, $<E_\mu>$ = 207 GeV

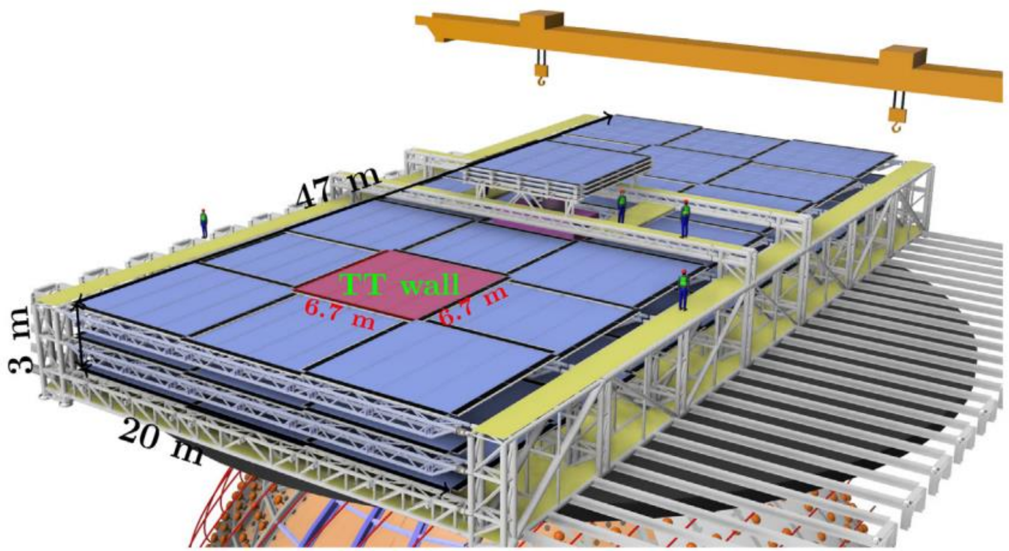
- ✓ In LS, about 127 ^{9}Li and 40 ^{8}He isotopes, but 57 $\overline{\nu_e}/\mathrm{day}$
- ✓ Effective veto strategy keeps 47.1 $\overline{\nu_e}/\mathrm{day}$ but only 0.8 residual Li/He background

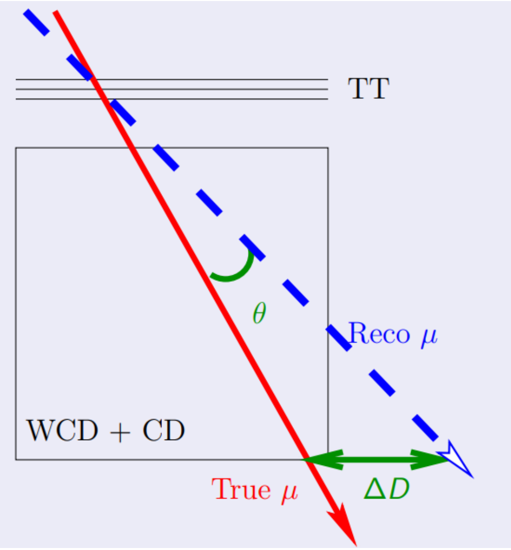


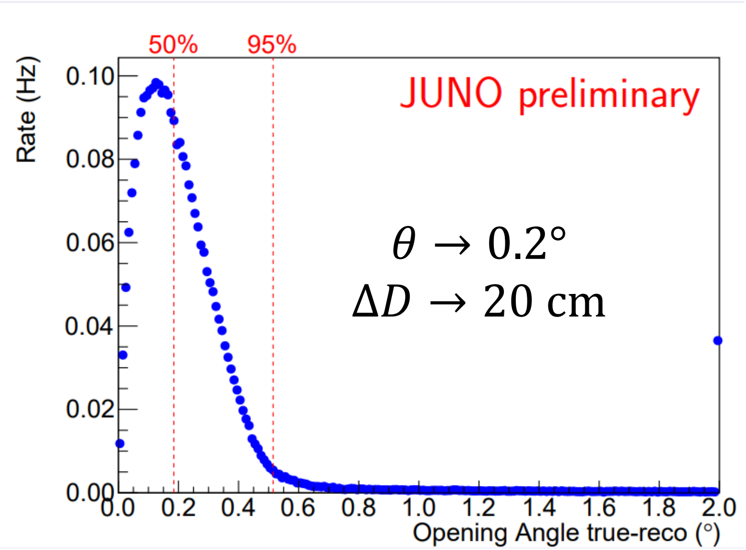
35 kton of ultrapure water serving as passive shield and water Cherenkov detector.

- ✓ 2400 20-inch MCP PMTs, detection efficiency of cosmic muons larger than 99.5%
- ✓ Keep the temperature uniformity 21℃±1℃
- ✓ Quality: ^{222}Rn < 10 mBq/m^3, attenuation length 30~40 m

Veto detector (Top Tracker)







Plastic scintillator from the OPERA experiment

- ✓ About 50% coverage on the top, three layers to reduce accidental coincidence
- ✓ All scintillator panels arrived on site in 2019
- ✓ Provide control muon samples to validate the track reconstruction and study cosmogenic backgrounds
- ✓ The Top Tracker support bridge is ready for production.

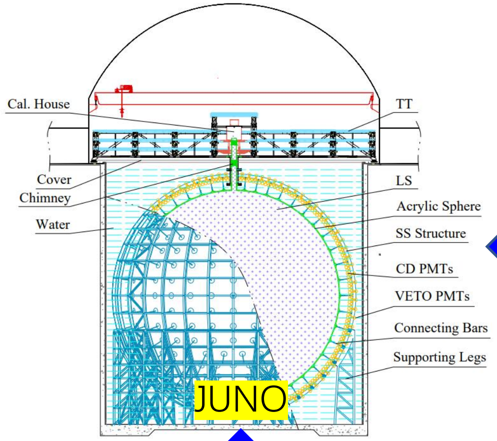
Liquid scintillator (20 kton)

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

SS pipes to underground

15%

85%



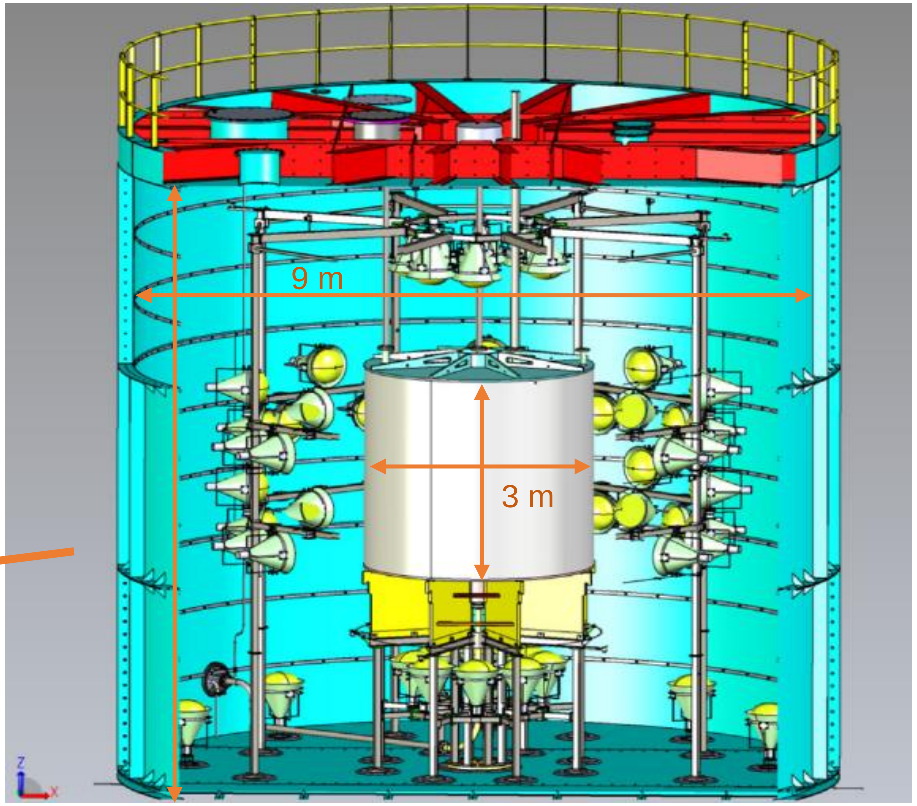
NIM.A 908 (2021) 164823

Online Scintillator Internal Radioactivity Investigation System (OSIRIS)

A 20-t detector to monitor radiopurity of LS before and during filling to the central detector

- ✓ Few days: U/Th (Bi-Po) ~ 1×10^{-15} g/g (reactor baseline case)
- ✓ 2~3 weeks: U/Th (Bi-Po) ~ 1×10^{-17} g/g (solar ideal case)
- ✓ Other radiopurity can also be measured: ^{14}C, ^{210}Po and ^{85}Kr

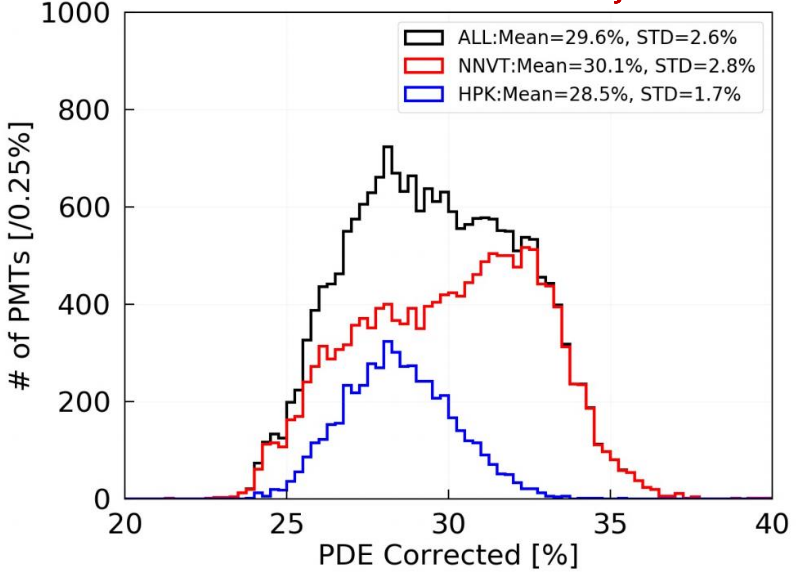
Eur.Phys.J.C 81 (2021) 11, 973



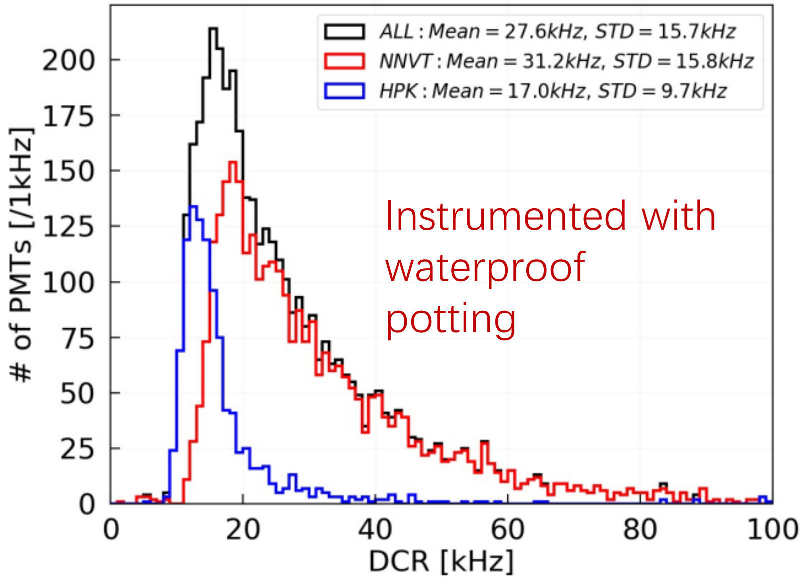
Under commissioning now.

Photomultiplier Tubes

Photon Detection Efficiency



Dark Counting Rate

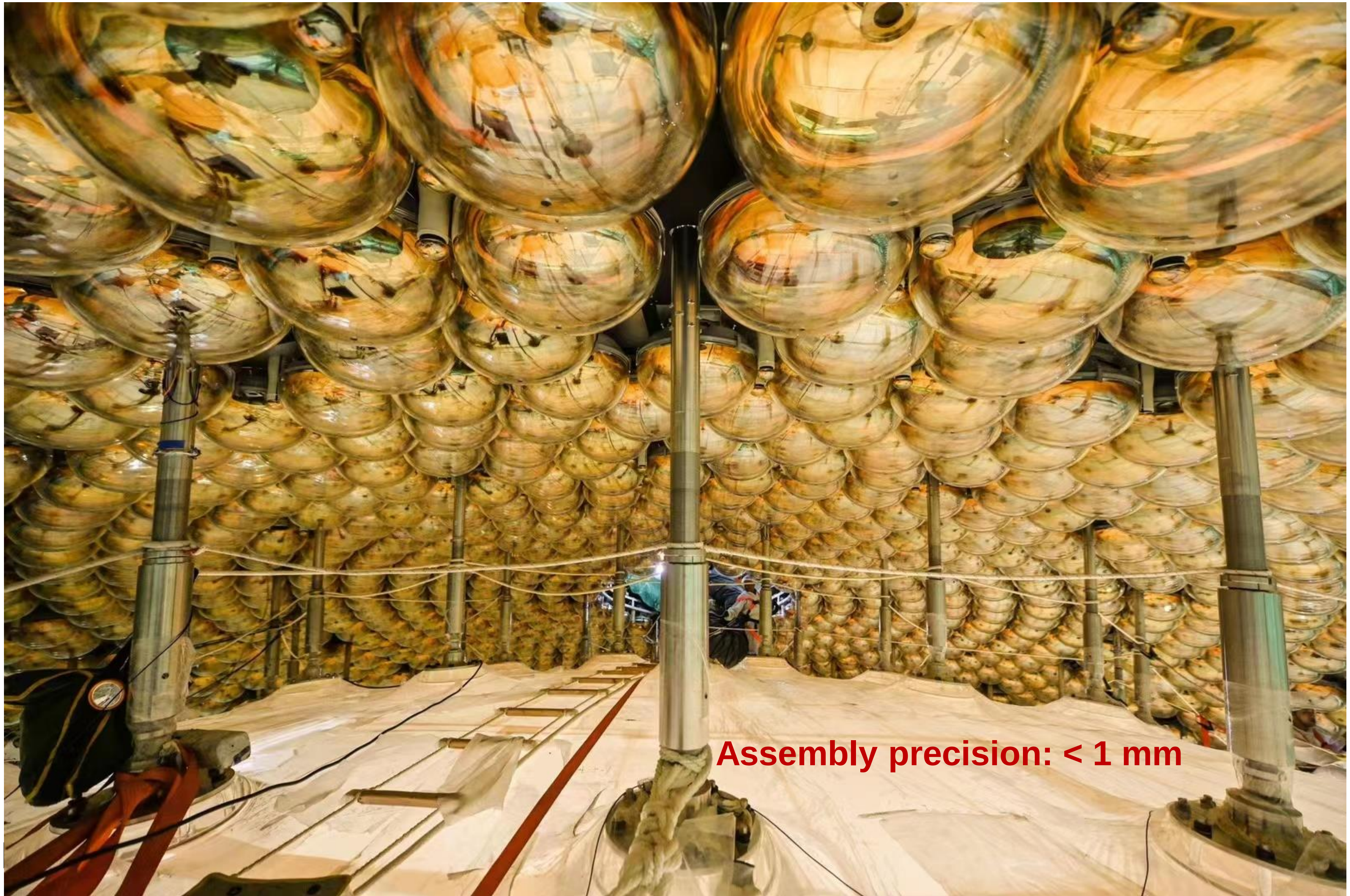


All PMTs produced, tested, and instrumented with waterproof potting

		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

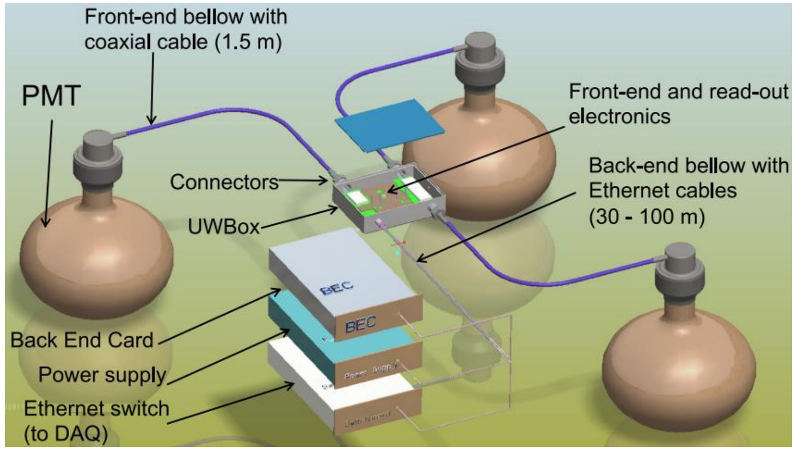
- ✓ 12.6k NNVT PMTs with highest PDE are selected for light collection from LS and the rest are used in the Water Cherenkov detector.
- ✓ Synergetic 20-inch and 3-inch PMT systems to ensure energy resolution and charge linearity

Photomultiplier Tubes

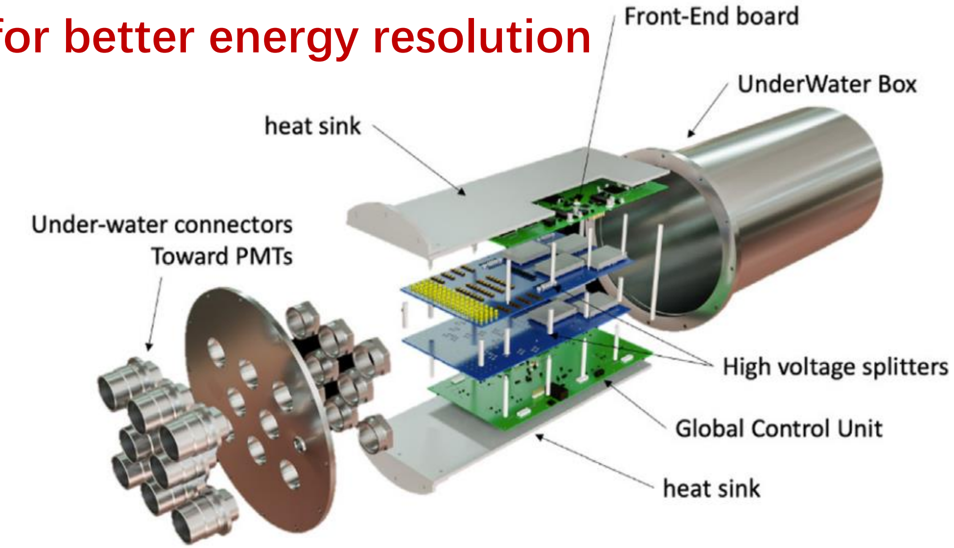


Electronics

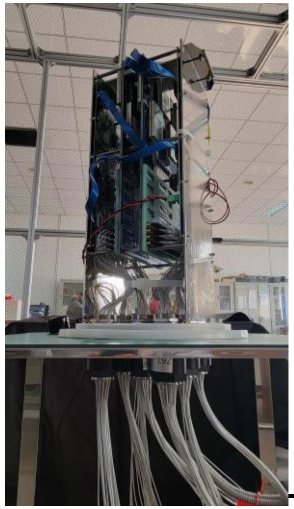
Underwater electronics to improve signal-to-noise ratio for better energy resolution



3 20-inch PMTs connected to one underwater box



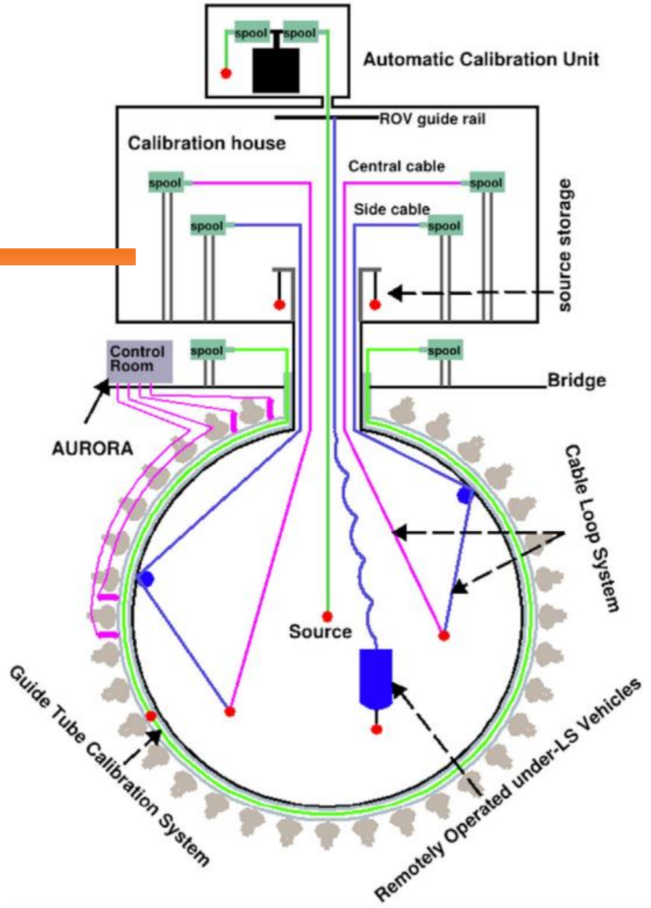
128 3-inch PMTs connected to one underwater box

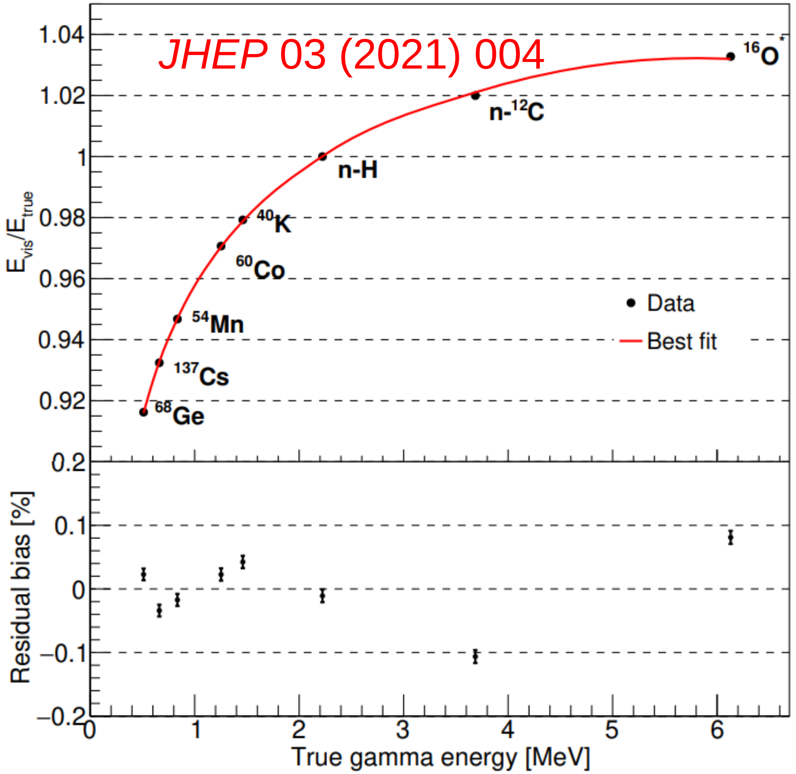


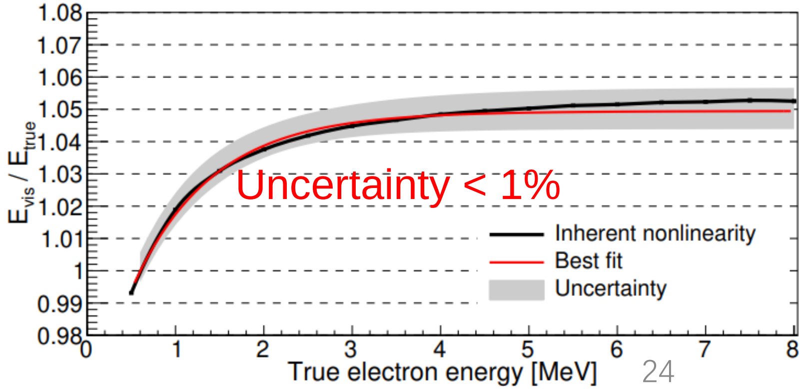
Electronics assembly ongoing

Calibration

1D,2D,3D scan systems with multiple calibration sources to control the energy scale, detector response non-uniformity, and < 1% energy non-linearity







✓ Shadowing effect uncertainty from Teflon capsule of radioactive sources: < 0.15%

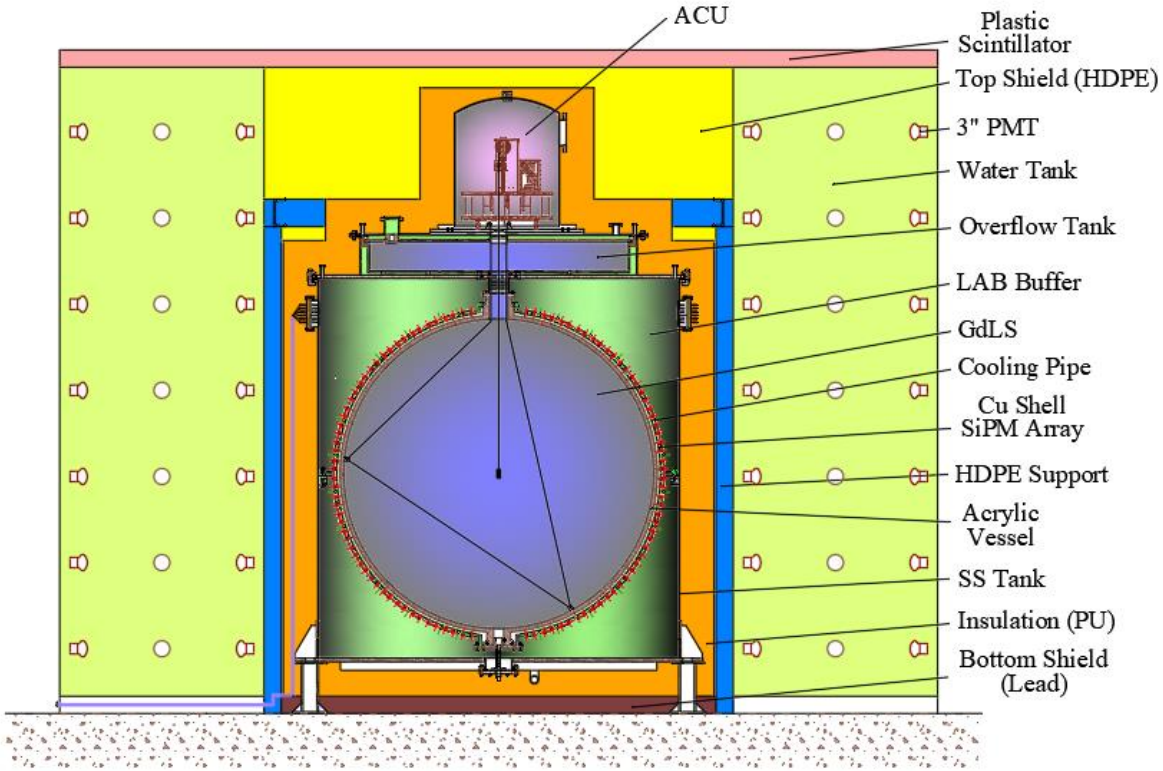
Taishan Antineutrino Observatory (TAO)

Physics potential

- ✓ Precise measurement of antineutrino spectra
- ✓ Sterile neutrino searches
- ✓ Provide a reference spectrum for JUNO, nuclear databa
- ✓ etc.

arXiv: 2005.08745

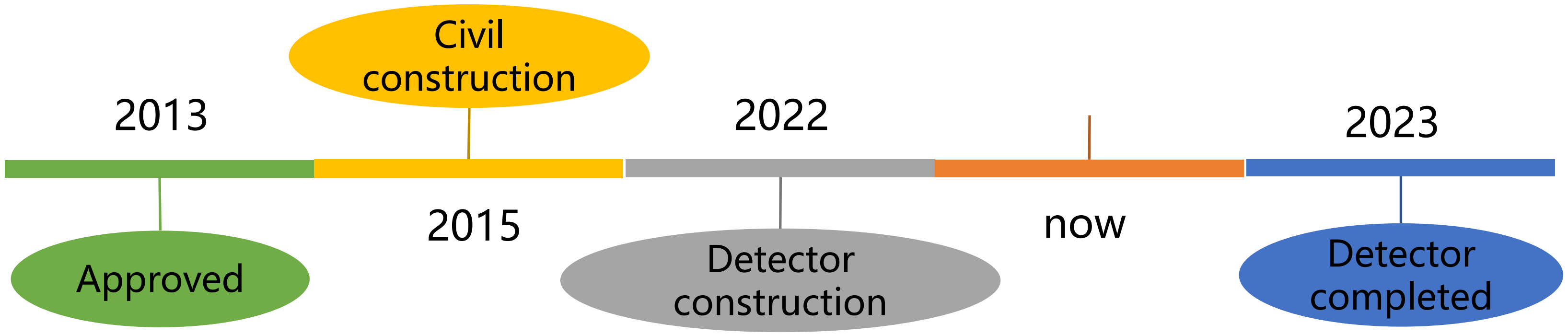
2.8 ton GdLS detector	
Baseline	~30 m
Reactor Thermal Power	4.6 GW
Light Collection	SiPM
Photon Detection Efficiency	>50%
Working Temperature	-50 ℃
Dark Count Rate [Hz/mm^2]	~100
Coverage	~94%
Detected Light Level [PE/MeV]	4500
Energy resolution	< 2% @ 1 MeV



- ✓ 10 m^2 SiPM is used to achieve high light yield with ~94% coverage
  → 4500 PEs/MeV & energy resolution < 2% @ 1 MeV
- ✓ Gd-LS works at -50℃ to lower the dark noise of SiPM

Summary

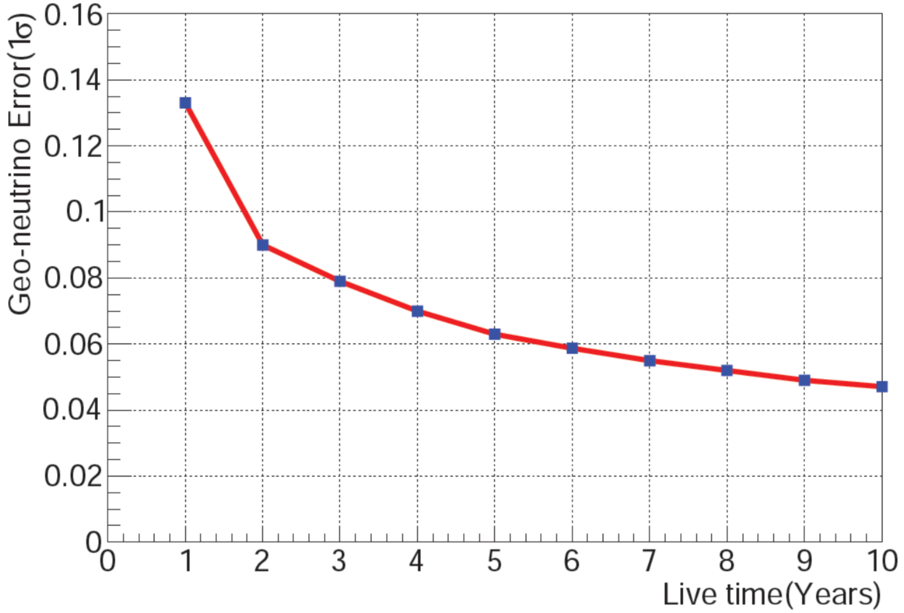
- JUNO detector with huge target mass and extremely high energy resolution will make incredible contributions to the field of neutrinos.
- JUNO will measure mass order (3σ with 6 years data taking based on only reactor ν) and precision oscillation parameters to sub-percentage level.
- JUNO have rich physics potential beyond reactor neutrinos analysis.




Keep digging new physics !

Geo Neutrinos

- Unique neutrino source to probe the inner structure of Earth, from ^{238}U and ^{232}Th decays in Earth's mantle and crust
- Measurement of the thorium to uranium ratio can provide valuable insight to the Earth's origin and evolution.
- Provide an exciting opportunity to obtain a high statistics measurement of geo-neutrinos.
- Detection channel: IBD
- ~400 events/year are expected
- Main background is reactor neutrinos

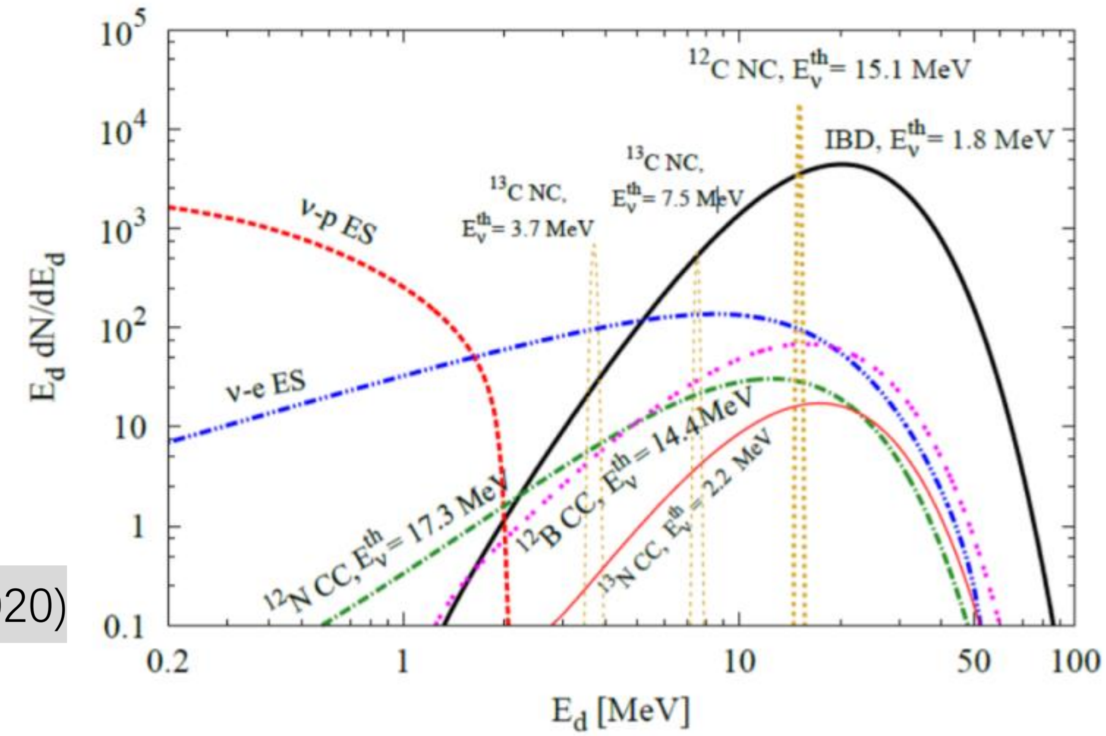


Chin. Phys. C 40 (2016) 3, 033003

Supernova neutrinos(SN)

- A high-statistics detection of neutrinos from a galactic SN will provide us with precious information about the explosion mechanism and intrinsic properties of neutrinos themselves.
- JUNO has excellent capability of detecting all flavors of the O(10 MeV) postshock neutrinos.
- Determination of the time evolution, energy spectra and flavor contents of SN neutrinos
- Main detection channel: IBD, ν-p ES, andν-e ES
- Real-time detection of ~5000 IBD, ~1000 ν-p ES and ~4000 ν-e ES events for a SN @10kpc, assuming 0.2 MeV threshold and with special triggers design

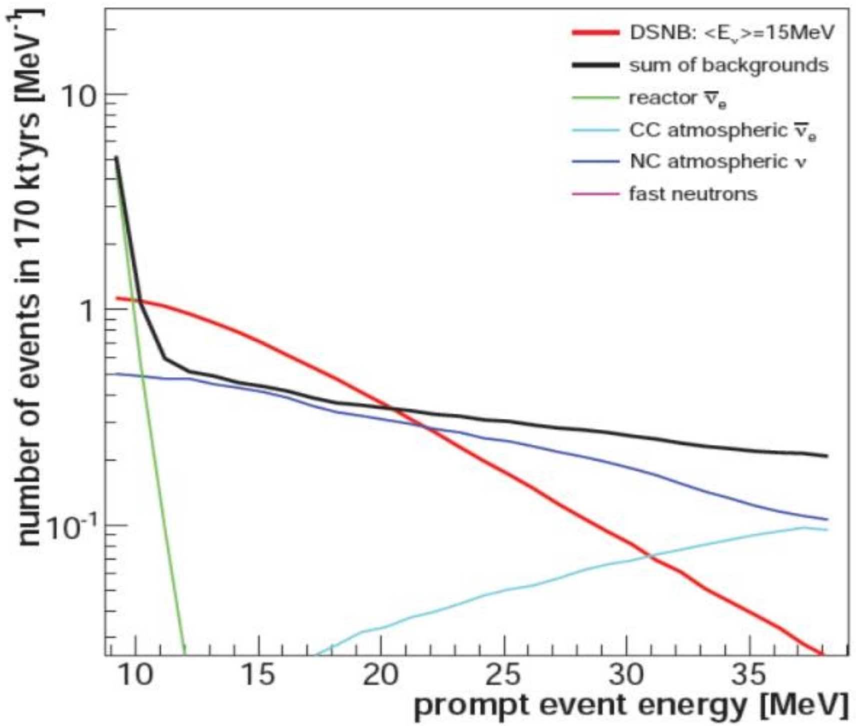
JCAP 05 049 (2020)



Diffuse Supernova Neutrino Background (DSNB)

- The integrated neutrino flux from all past core-collapse events in the visible universe forms the diffuse supernova neutrino background (DSNB)
- Provide information: the red-shift dependent supernova rate, average SN neutrino energy spectrum and the fraction of black hole formation in core-collapse SNe

J. Phys. G43:030401 (2016)



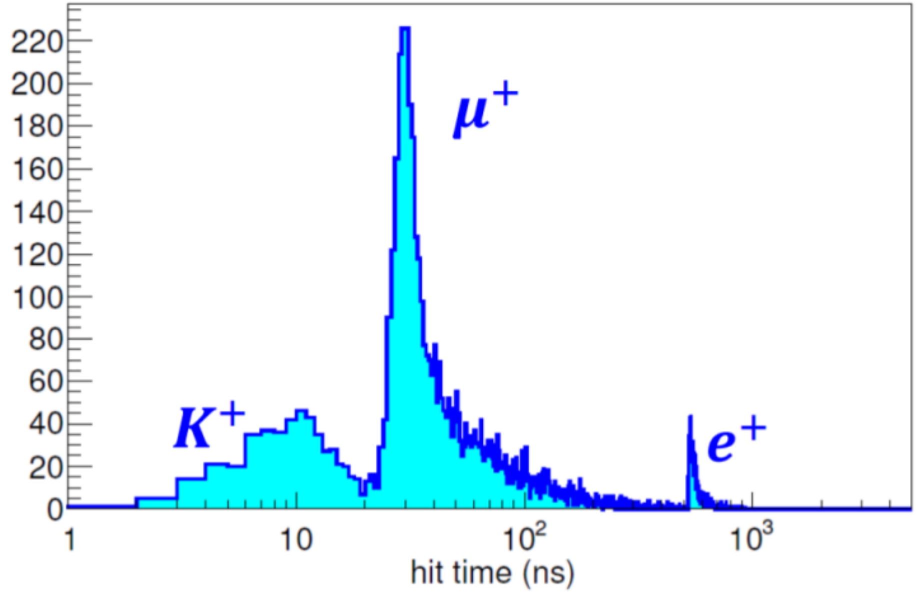
- Detection channel: IBD
- Background
  - ✓ $\bar{\nu}_e$ from reactor and atmospheric neutrino
    - → Visible energy range (10 , 30) MeV
  - ✓ atmospheric neutrino NC
    - → PSD helps to suppress
  - ✓ cosmogenic isotopes/fast neutron
    - → Muon veto
- For $\langle E_\nu \rangle \geq 15$ MeV, 3σ evidence after 10 years.

Exotic process

Proton decay

- Main search channel: $p \to \bar{\nu} K^+$
- Clear signature from 3–fold coincidence in JUNO

K^+ ionization → μ^+ ionization from K^+ decay → e^+ from μ^+ decay



- Background:
  - Muon → muon veto
  - Atmospheric neutrino → energy , Michel electron, neutron, time character
- Expected sensitivity: 8.34 x 10^{33} years (90% CL) in 10 years data-taking

J. Phys. G43:030401 (2016)
JCAP01 039 (2016)
Chinese Phys. C 40 033003 (2016)

Other new physics

- ✓ Indirect dark matter search
- ✓ Light sterile neutrino searches
- ✓ Lorentz Invariance Violation
- ✓ Majorana neutrinos (Phase 2, upgraded JUNO)
- ✓

Multi-messager astrophysics

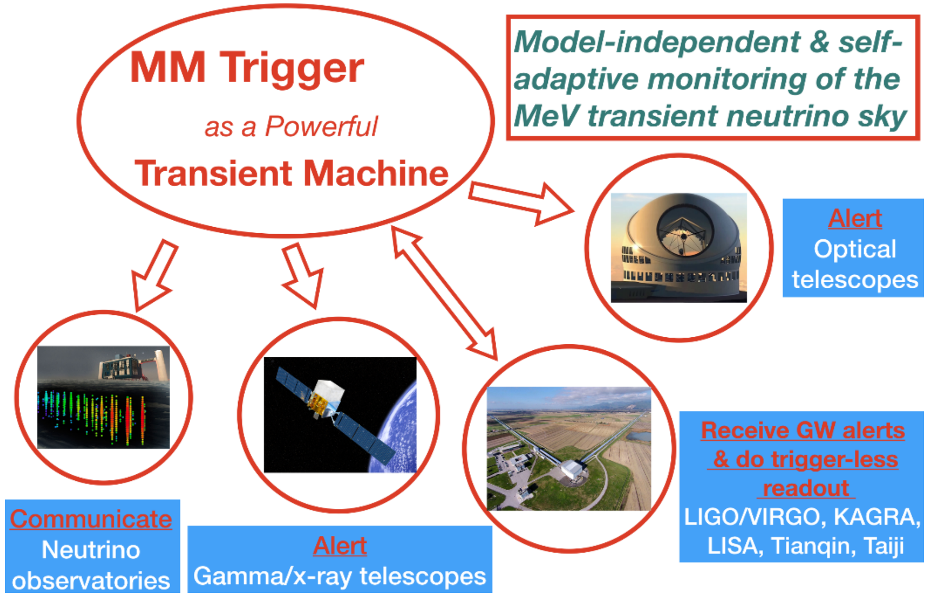
- Real-time monitoring of the MeV transient neutrino sky

- Two major trigger systems in JUNO:
  - Global trigger (threshold ~ 200 keV)
  - **Multi –messenger (MM) trigger threshold: ~O(10) keV**

- MM trigger
  - Fast filtering algorithms on FPGA to reject >99.9% dark noise

- Improve physics potential in the unprecedentedly low-threshold
  - Low energy solar neutrinos
  - Neutrino magnetic moment
  - …

- Major role in the next-generation Supernova Early Warning System (SNEWS2.0) for MM astronomy



arXiv:2011.0035