JUNO Neutrino Experiment

Yifang Wang
Institute of High Energy Physics
CERN, March 20, 2024

12 years anniversary, What a coincidence !

Observation of Electron Anti-neutrino Disappearance at Daya Bay

Yifang Wang
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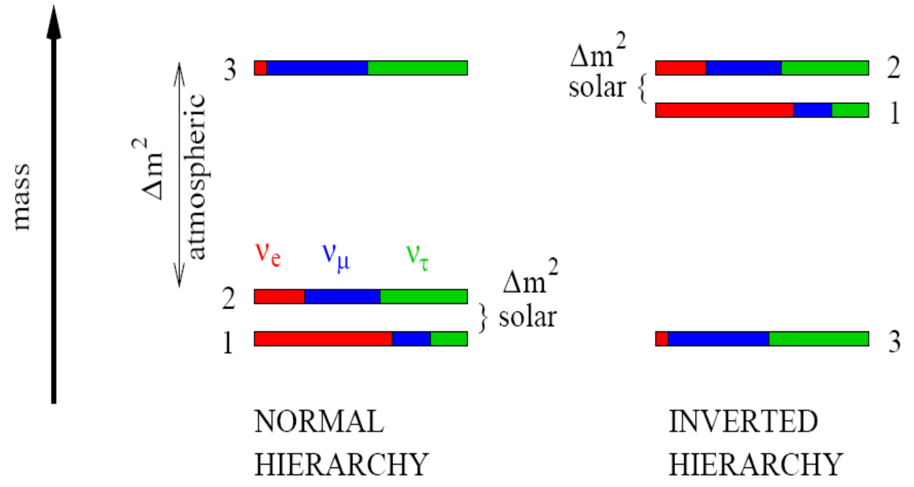
CERN，March 20, 2012

Neutrino Oscillation

- **Mixing matrix(PMNS):**

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix} V_{e1} & V_{e2} & V_{e3}\\ V_{\mu 1} & V_{\mu 2} & V_{\mu 3}\\ V_{\tau 1} & V_{\tau 2} & V_{\tau 3}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$



Atmospheric **reactor & CP phase** **Solar** **Majorana phase**

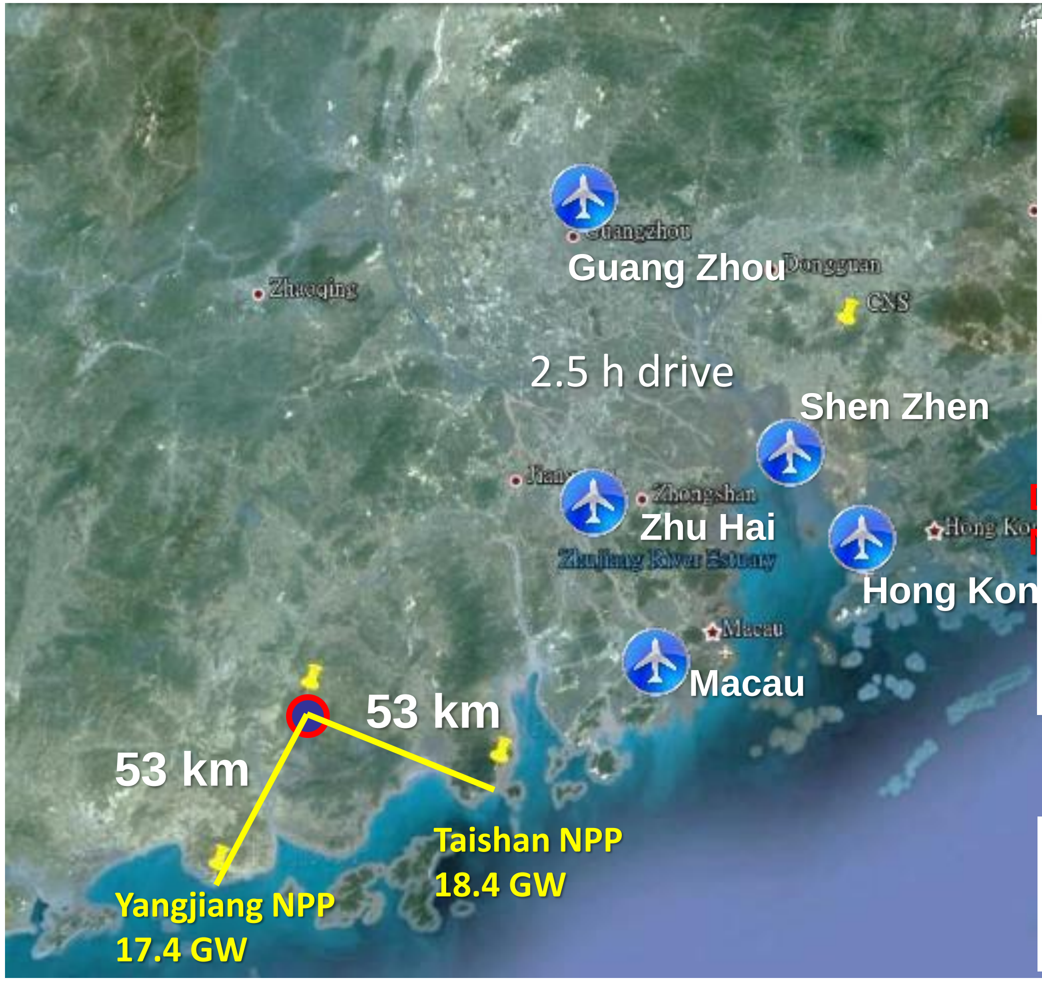
$$V = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}\\ 0 & e^{-i\delta} & 0\\ -s_{13} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}e^{i\rho} & 0 & 0\\ 0 &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

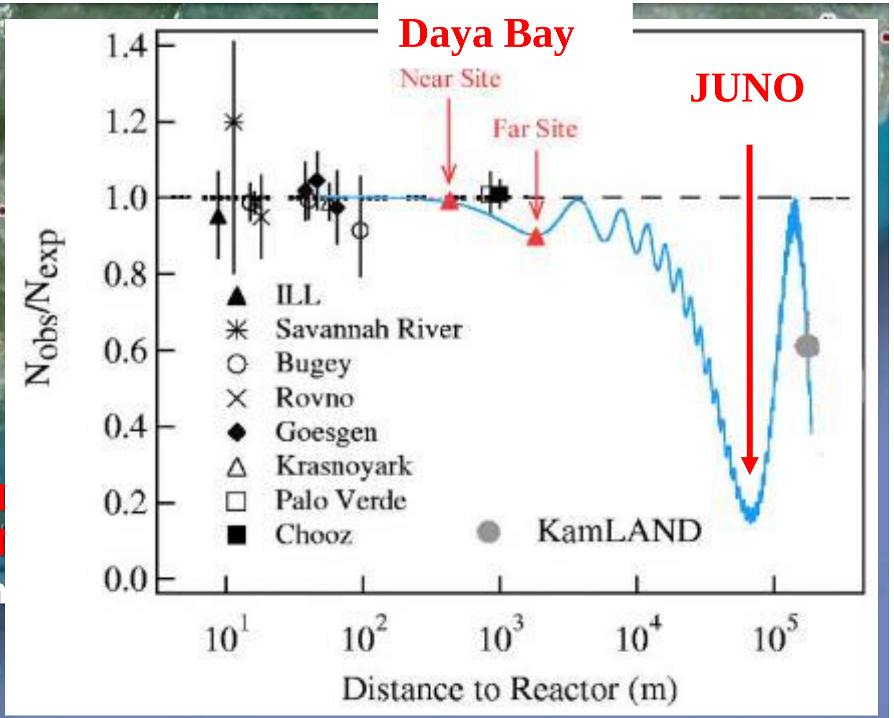
- **Known parameters:** $\theta_{23}, \theta_{12}, \theta_{13}, |\Delta m^2_{32}|, \Delta m^2_{21}$
- **Unknown parameters: sign of Δm^2_{32}, CP phase δ**

1998 Atm. ν osc. $\theta_{23}, |\Delta m^2_{32}|$
2002 Solar ν osc. $\theta_{12}, \Delta m^2_{21}$
2012 reactor ν osc. θ_{13}

Idea of the JUNO Experiment

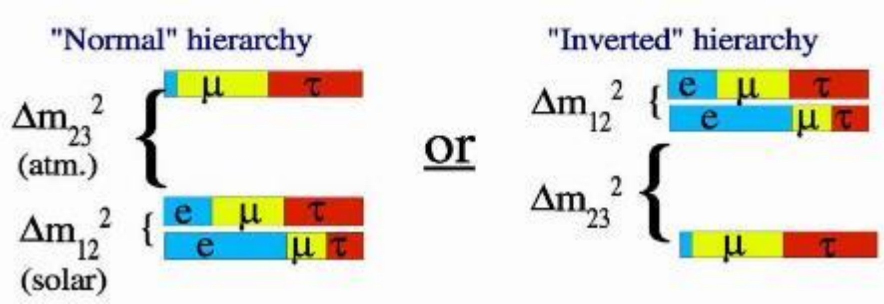
- Next step of the Daya Bay Exp.: continue using reactor neutrinos and liquid scintillator
- To determine the mass ordering (sign of Δm^2_{32}) independent of the CP phase δ
- Equal baseline to two reactor power plants: Yangjiang and Taishan





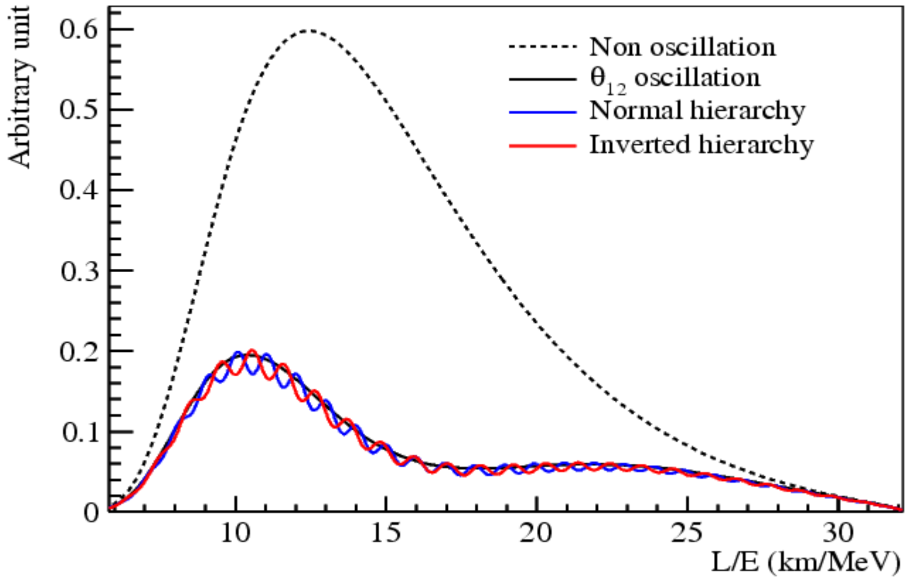
Talk by Y.F. Wang at ICFA seminar 2008, Neutel 2011;
Paper by L. Zhan, Y.F. Wang, J. Cao, L.J. Wen, PRD78:111103,2008; PRD79:073007,2009

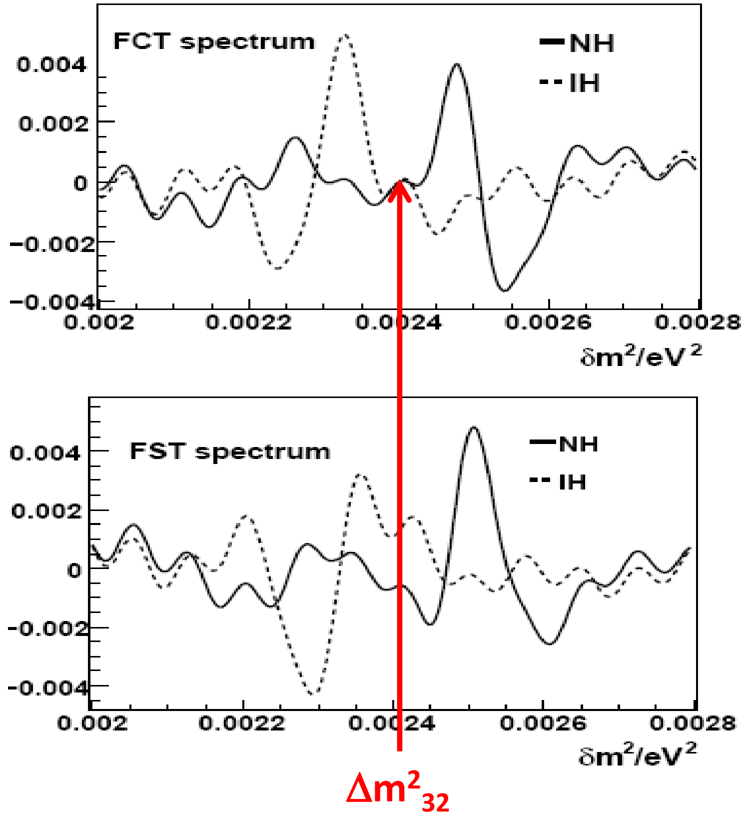
Mass Ordering by Reactor Neutrinos



$$
\begin{aligned}
\Delta m^2_{31} &= \Delta m^2_{32} + \Delta m^2_{21} \\
\mathrm{NH}: \ |\Delta m^2_{31}| &= |\Delta m^2_{32}| + |\Delta m^2_{21}| \\
\mathrm{IH}: \ |\Delta m^2_{31}| &= |\Delta m^2_{32}| - |\Delta m^2_{21}|
\end{aligned}
$$

$$\boxed{\frac{\Delta m^2_{21}}{|\Delta m^2_{32}|} \sim 3\%}$$



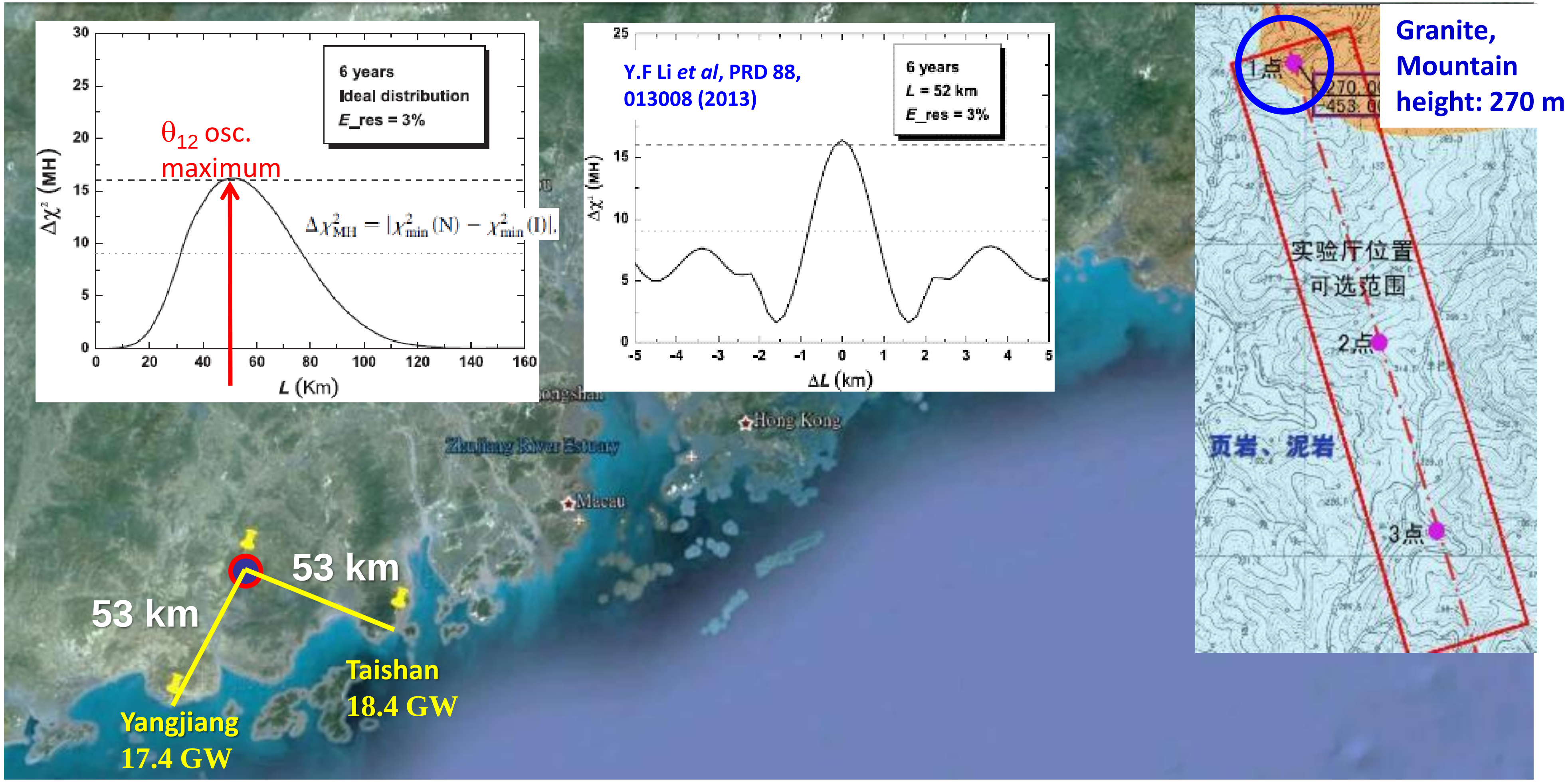


$$
\begin{aligned}
P_{ee}(L/E) &= 1 - P_{21} - P_{31} - P_{32} \\
P_{21} &= \cos^4(\theta_{13}) \sin^2(2\theta_{12}) \sin^2(\Delta_{21}) \\
P_{31} &= \cos^2(\theta_{12}) \sin^2(2\theta_{13}) \sin^2(\Delta_{31}) \\
P_{32} &= \sin^2(\theta_{12}) \sin^2(2\theta_{13}) \sin^2(\Delta_{32})
\end{aligned}
$$

S. Petcov and Piai, Phys. Lett. B 553, 94-106(2002)
J. Learned et al., PRD 78(2008)071302
L. Zhan, YFW et al., PRD 78(2008)111103

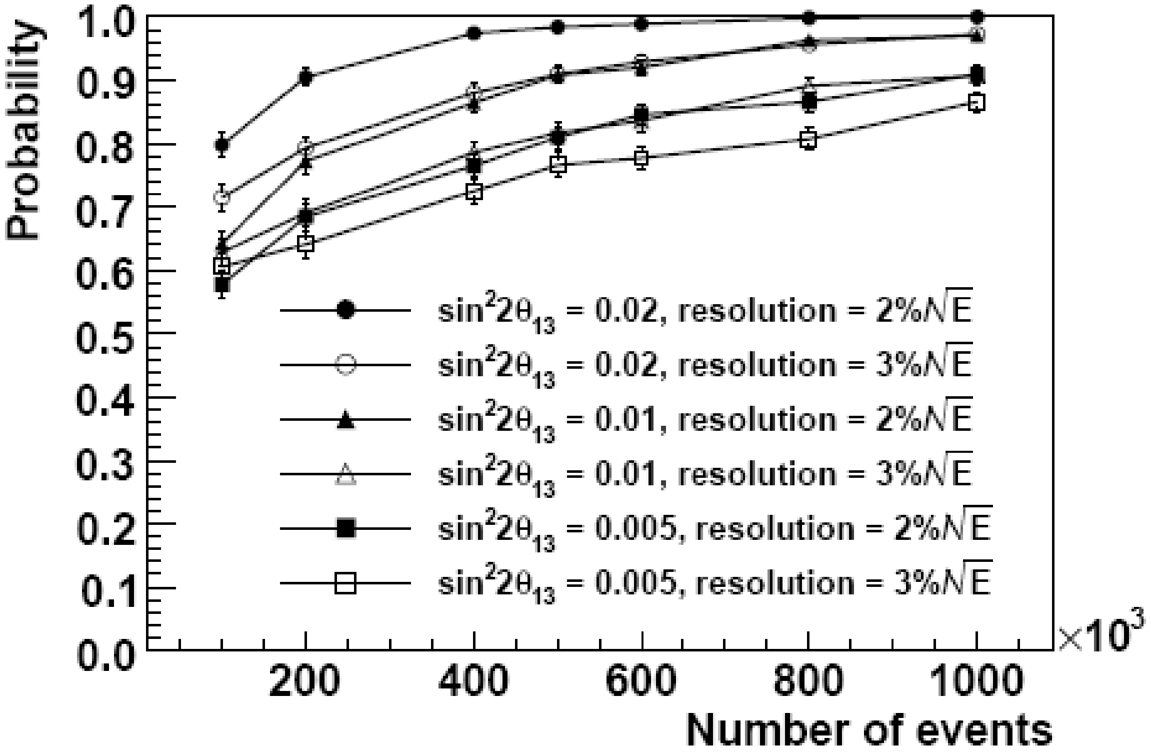
Optimum Baseline and Site Selection

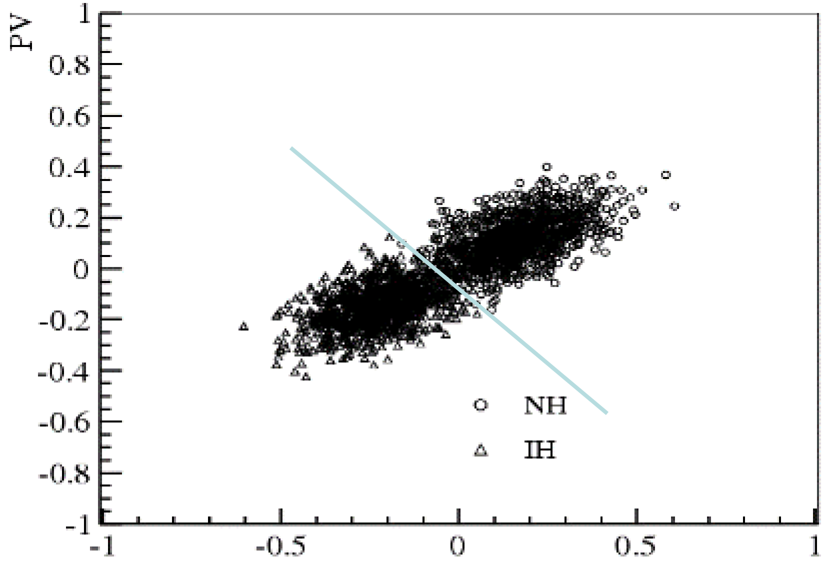
- Optimum sensitivity at the oscillation maximum of θ_{12}
- Multiple baseline reactors may wash out the oscillation structure
  - Baseline difference should be < 500 m

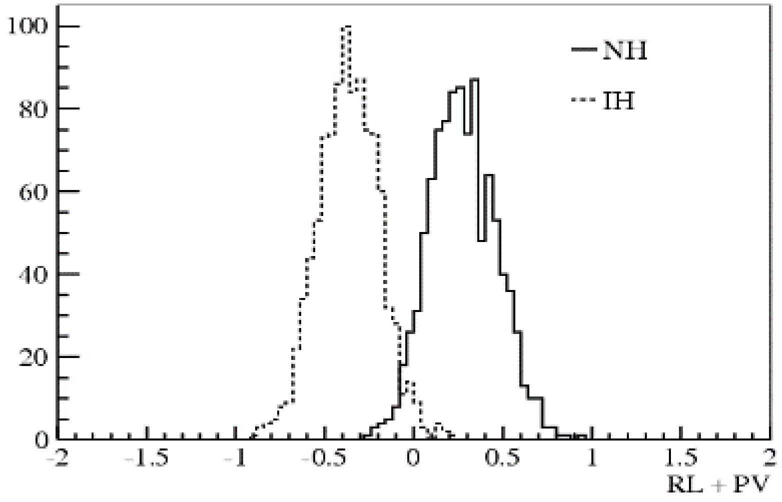


First Experimental Proposal

- Key parameters:
  - Detector size: 20kt
  - Energy resolution: 3%/√E
  - Thermal power: 36 GW
  - Baseline: ~58 km



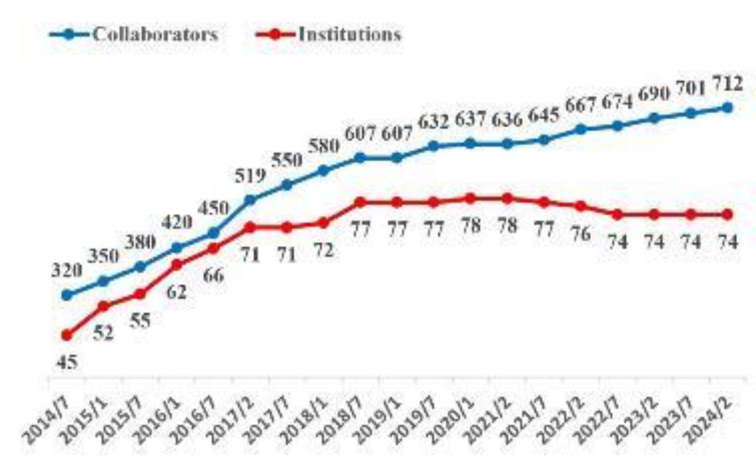




L. Zhan, YFW et.al, PRD79:073007, 2009

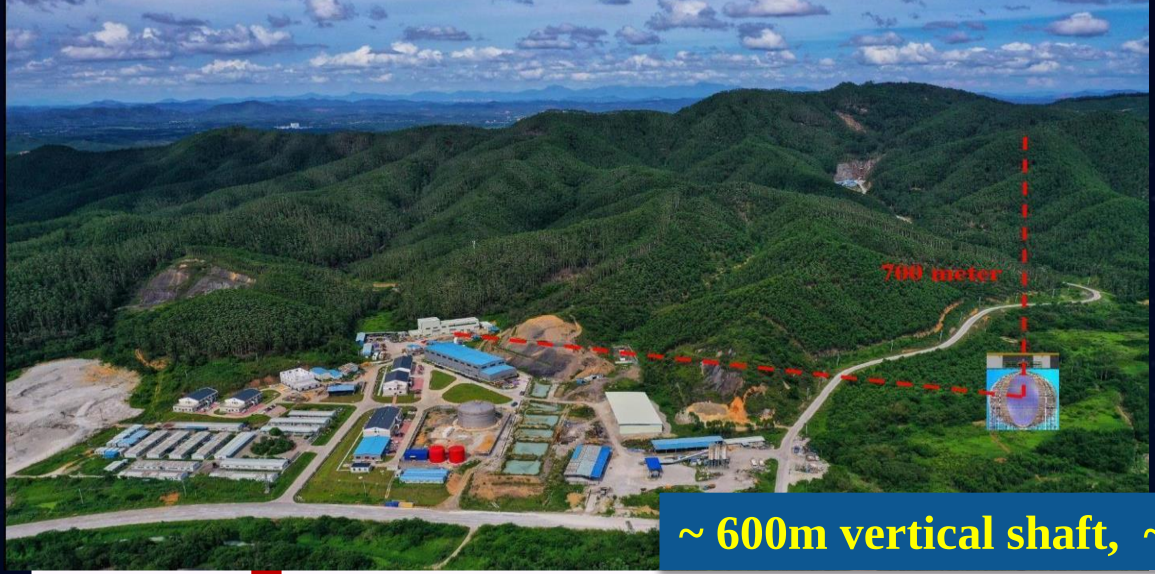
JUNO Project and the collaboration

- Project firstly approved in China in 2013 and later in other countries. Construction started in 2015
- Collaboration established in 2014, now >700 collaborators from 74 institutions in 17 countries/regions

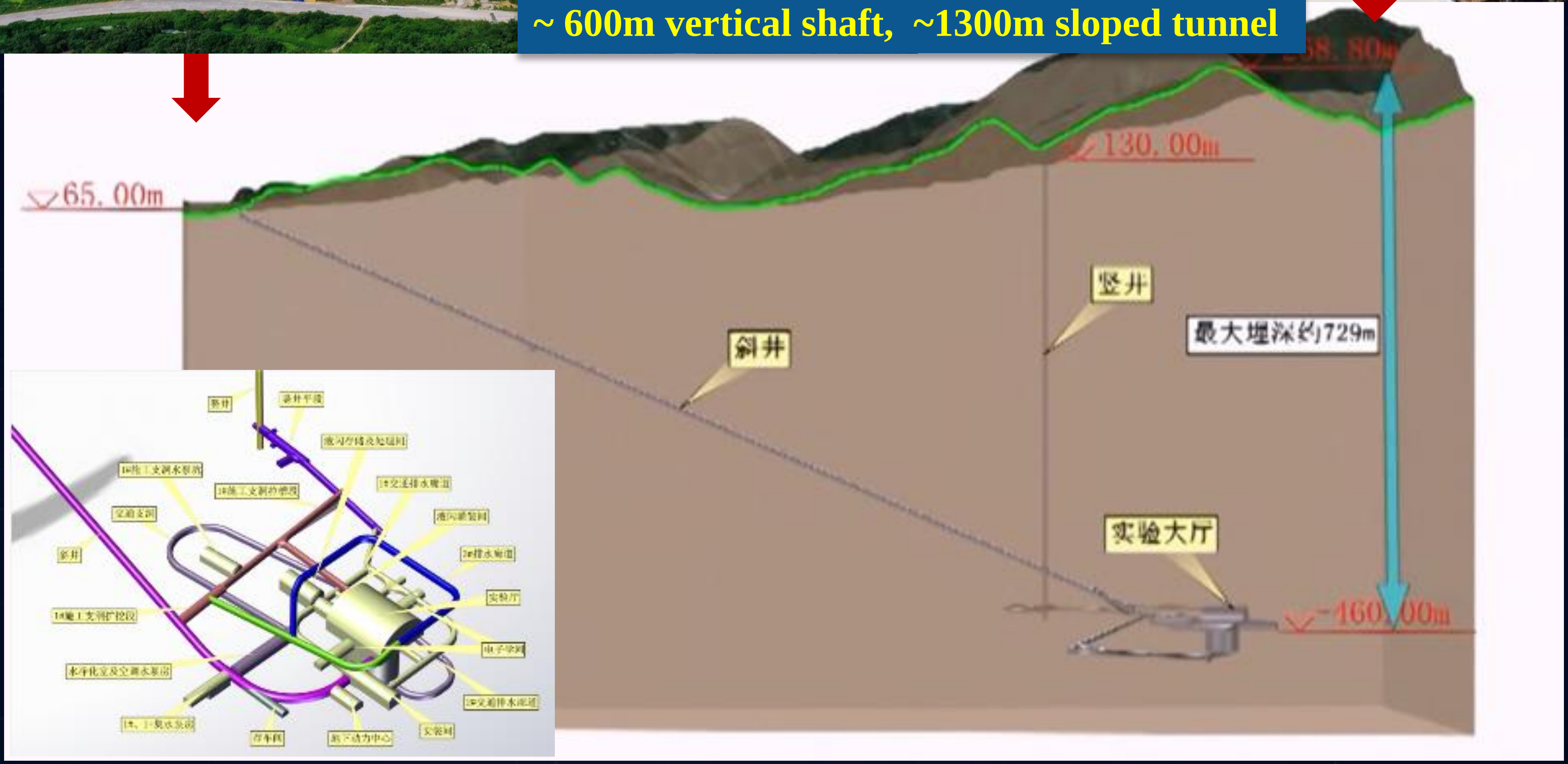


China	ChongQing University	China	NUDT	Pakistan	PINSTECH (PAEC)
China	CIAE	China	CUG-Beijing	Russia	INR Moscow
China	DGUT	China	ECUT-Nanchang City	Russia	JINR
China	Guangxi U.	China	CDUT-Chengdu	Russia	MSU
China	Harbin Institute of Technology	Czech	Charles U.	Slovakia	FMPICU
China	IHEP	Finland	University of Jyvaskyla	Taiwan-China	National Chiao-Tung U.
China	Jilin U.	France	IJCLab Orsay	Taiwan-China	National Taiwan U.
China	Jinan U.	France	LP2i Bordeaux	Taiwan-China	National United U.
China	Nanjing U.	France	CPPM Marseille	Thailand	NARIT
China	Nankai U.	France	IPHC Strasbourg	Thailand	PPRLCU
China	NCEPU	France	Subatech Nantes	Thailand	SUT
China	Pekin U.	Germany	RWTH Aachen U.	U.K.	U. Warwick
China	Shandong U.	Germany	TUM	USA	UMD-G
China	Shanghai JT U.	Germany	U. Hamburg	USA	UC Irvine
China	IGG-Beijing	Germany	FZJ-IKP		

A CERN Recognised Experiment (RE34)



~ 600m vertical shaft, ~1300m sloped tunnel



Civil Construction

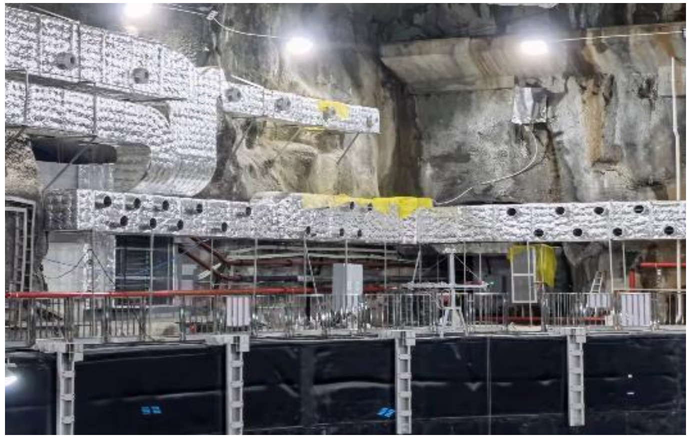
- **Dig down is generally difficult, especially in the presence of water**
  - Largest water flow rate seen ~ 600m^3/h
- **More water than expected:**
  - Geological survey shows that the rock resistivity is low
  - Bore holes found no water, but iron ore with a low grade
  - Water are mostly from cracks and faults, not directly from the surface
- **Mitigations:**
  - Drill holes to inject cement to seal water, and then drill holes for blasting
  - Elevate the hall by 35 m, shift the hall location to avoid cracks
  - Add a tunnel at the top of the hall to release the water pressure
- **Delayed by ~ 4 years**

Civil Construction Completed

- Rock ceiling (ϕ=50m) is stable, rock temperature ~ 31 °C,
- Temperature of the hall is controlled at ~21±1 °C

Sloped tunnel

LS hall



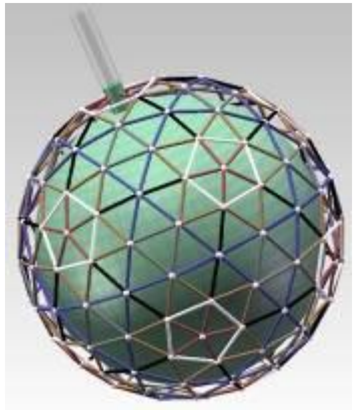
HVAC & Ventilation

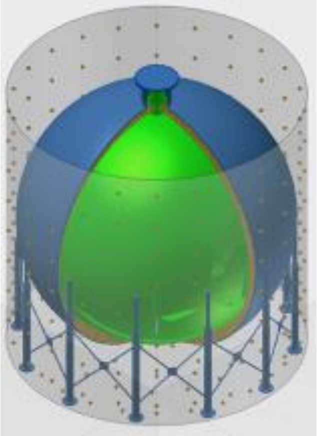
JUNO Detector

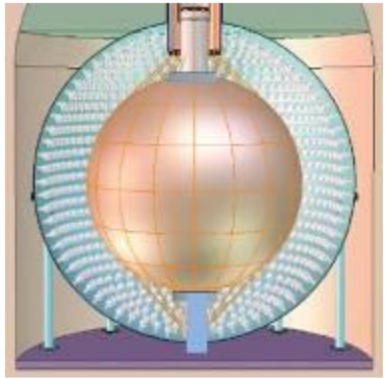
- Target mass of 20 kt liquid scintillator ➔ × 20 KamLAND, × 40 Borexino
- Energy resolution < 3%@ 1MeV ➔ 1200 PE/MeV

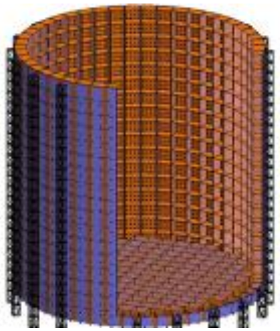
	KamLAND	JUNO	PE Ratio
Photon Statistics	**250 p.e./MeV**	**1200 p.e./MeV**	**5**
PMT coverage	**34%**	**75%**	**2.2**
LS transparency	**~12 m**	**> 20 m**	**~0.9**
Light yield(anthracene)	**30%**	**45%**	**~1.5**
Detection Eff.(QE×CE)	**~15%**	**30%**	**~ 2**

- Technology R&D since 2009:
  - Transparent & high light yield liquid scintillator
  - High detection efficiency 20” PMTs
  - Radiopurity U/Th/K < 10^{-17} g/g for 20 kt LS
- Detector Design(tens options)：
  - Central target container: acrylic or balloon ?
  - Mechanical structure: steel frame or steel tank ?
  - Buffer layer: Water or Mineral oil ?


Steel frame+ Acrylic tank

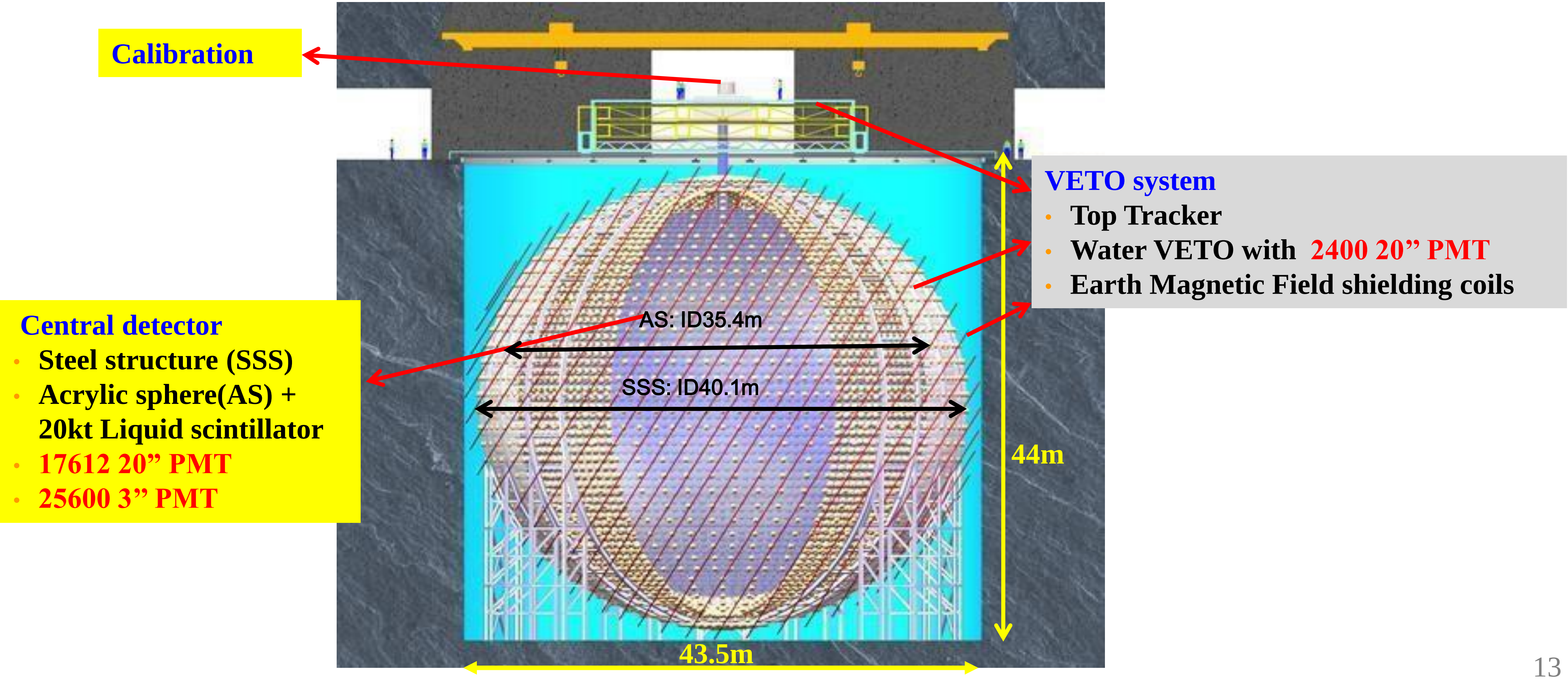

Steel tank+ Acrylic tank


Steel Tank + Balloon


Steel Tank + Acrylic blocks

Concept of JUNO for Mass Ordering

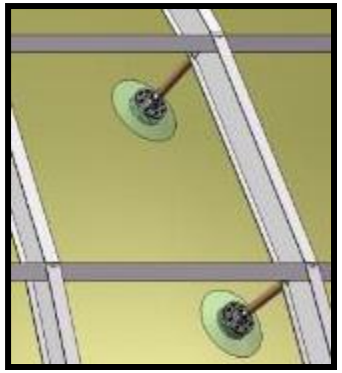
- Two-layer structure for simplicity and cost: stainless steel frame + Acrylic tank
- Water as VETO and Buffer ➔ radiopurity control of water

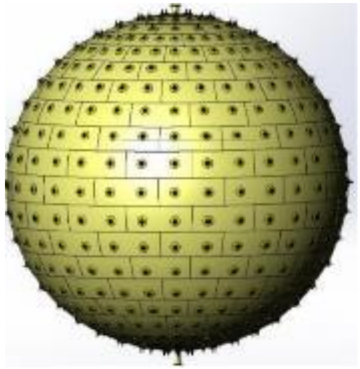


Central Detector

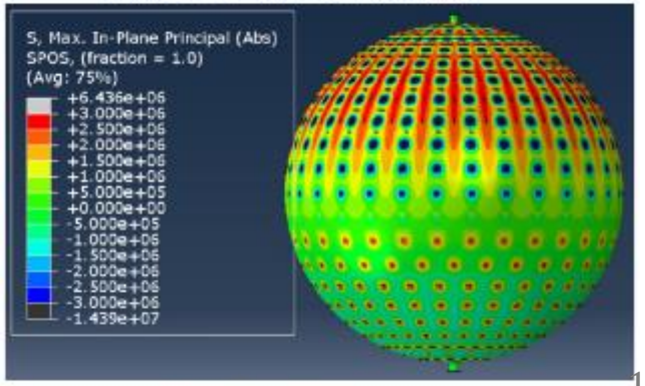
- **Acrylic sphere was chosen over balloon for safety, lower backgrounds and longevity**
- **Structure: SS frame with supporting bars to hold the acrylic sphere and to mount PMTs**
    - 263 Acrylic panels: ~8m × 3m ×12 cm
    - Thermally pressed and machined to the spherical shape
    - Panels are bonded through PMMA polymerization
    - 1.7m long steel anchor bolts welded to the concrete steel structure to hold the SS frame against the buoyancy
- **Main issues:**
    - Mechanical precision for PMT clearance ~3 mm
    - No welding, clearance between screw and hole < 1mm
    - Thermal expansion controlled at 21°C ± 1°C
    - Earth quake safety with liquid-solid coupling
    - Acrylic quality and strength:
        - Effects of aging, creep, crazing, etc. < 20% loss of strength
        - Bonding: fast and good quality, effects < 20% loss of strength
        - Stress of the supporting node < 3.5 MPa

Balloon test





工况：自重+水压（内4.5m高度）

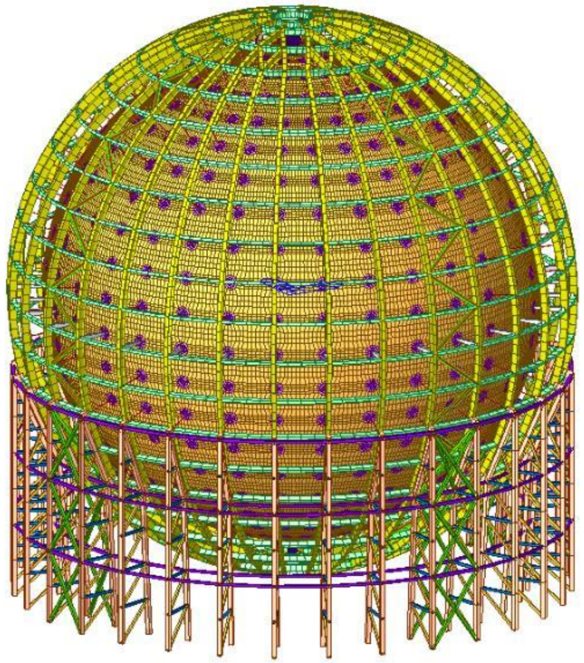


外表面应力情况

arXiv: 2311.17314

Central Detector Construction

- **SS structure completed except bottom 4 layers**
- **Acrylic panel production completed**
  - ✓ A special production line for low backgrounds (< 1 ppt U/Th/K)
  - ✓ Shaping, sanding/polishing, cleaning, machining and protection of panels by 50μm PE, while maintaining high transparency (>96%) and low surface background (< 5 ppt U/Th)
- **Acrylic sphere construction on-going**
  - ✓ Lifting platform: frequently change the diameter and height
  - ✓ Acrylic sphere built from the top, 15/23 layers finished, defects repaired
  - ✓ SS bars connecting the acrylic and SS, sensors for stress monitoring



Hydraulic Lifting platform

The first five layers of Acrylic

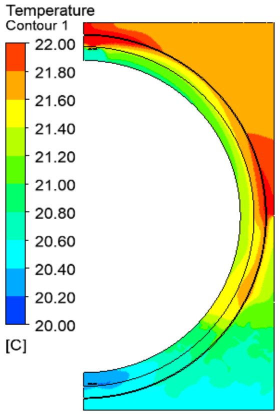
Sanding and polishing

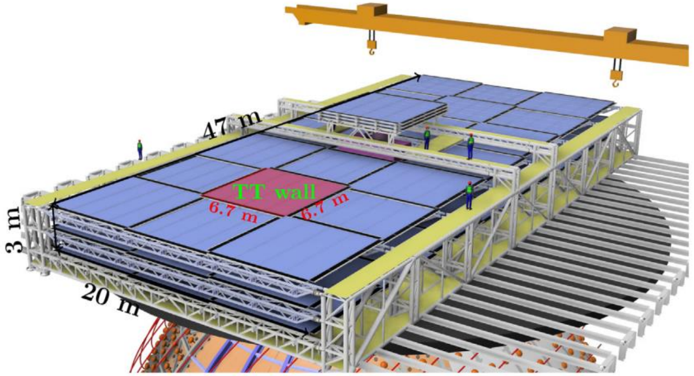
Bars between SS and acrylic

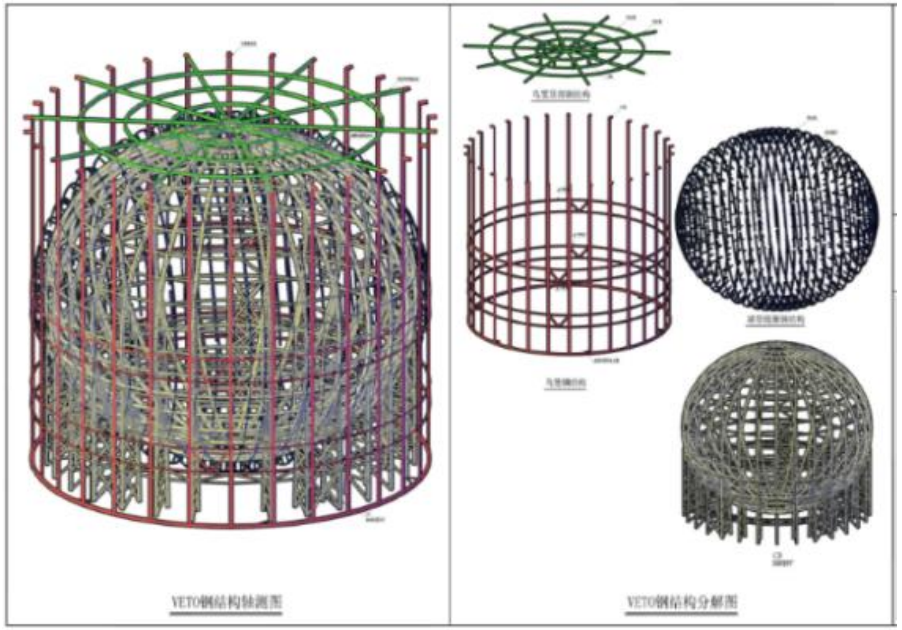
VETO

- **Design:**
  - 700m overburden ➔ R_{μ}=0.004 Hz/m^2, $< E_{\mu} >$= 207 GeV
  - 35 kt water to shield backgrounds from the rock
  - 2400 20” PMTs in water to tag & reconstruct cosmic muons
  - Top tracker: refurbished OPERA scintillators
- Water pool lining: 5mm HDPE to keep the clean water and to stop Rn from the rock
- Earth magnetic field compensation coil

100t/h pure water production for U/Th/K<10^{-14} g/g and Rn<10 mBq/m^3, attenuation length>40m, temperature controlled to (21$\pm$1) °C

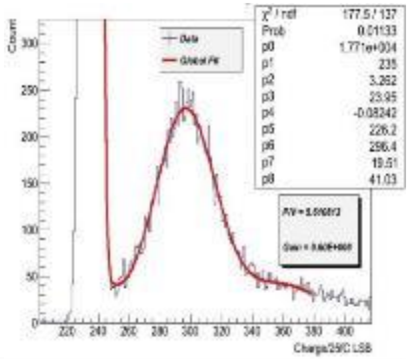


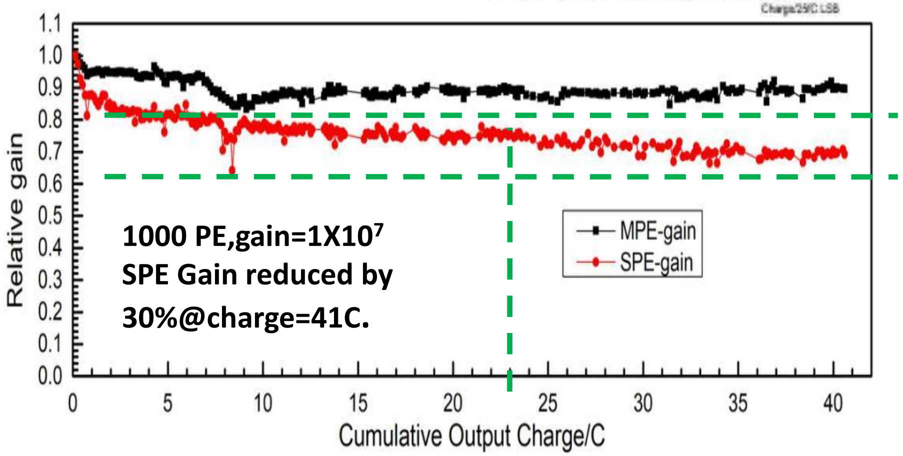


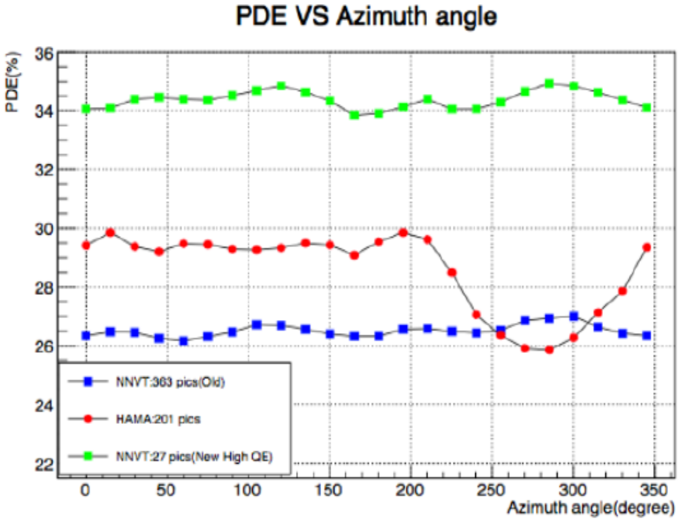


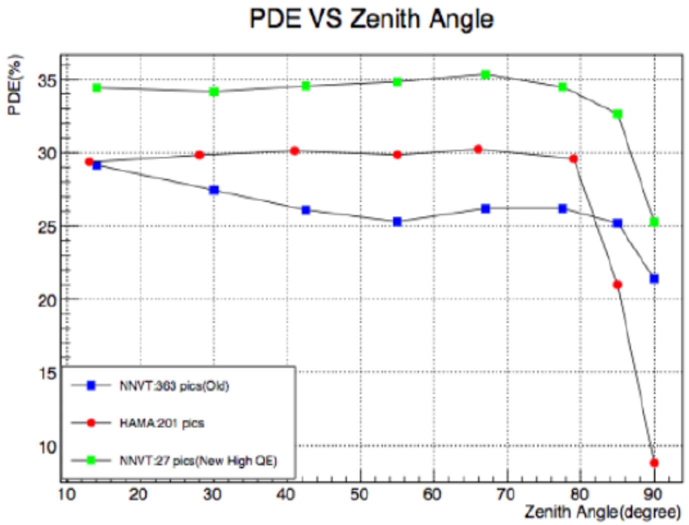
High QE PMT R&D

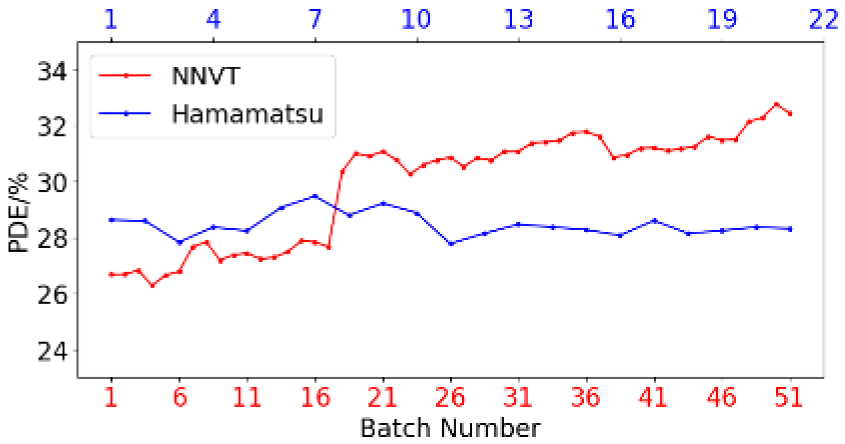
- **Use Micro-Channel Plates (MCPs) instead of dynode for better collection efficiency (CE)**
- **IHEP & NNVT jointly developed technologies & prototypes**
  - Higher collection efficiency
  - High efficiency photocathode, low backgrounds glass, …
  - High production yield, automatic mass production
- **Hamamatsu developed 20” SBA PMTs**
- **Purchase optimized considering performance, cost, risk, etc.**
  - MCP-PMT: 15000
  - Dynode PMT(Hamamatsu): 5000











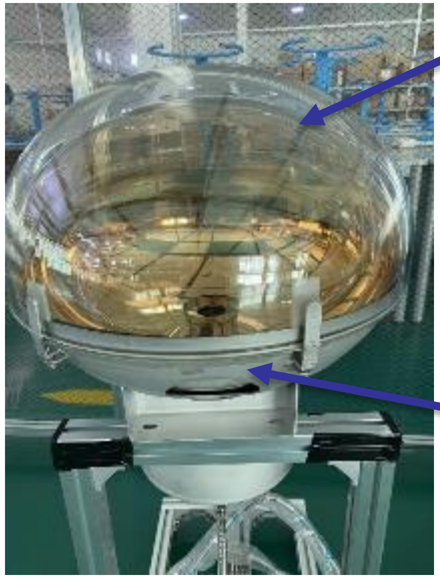
PMT Instrumentation

Potted PMT

PMTs after potting

Implosion test of PMTs on the module structure

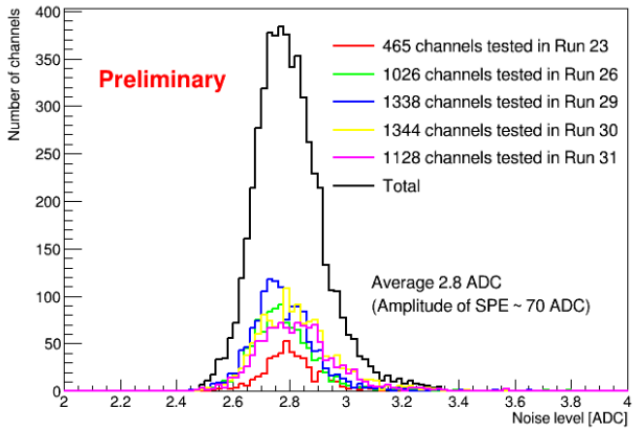
- All PMTs delivered and their performance tested OK
- Water proof potting
  - Required failure rate<0.5%/6 years
  - Technology invented, aging and pressurized tests are satisfactory
- Implosion protection JINST 18 (2023), P02013
  - Acrylic top & SS bottom
  - Final test: no chain reactions
- Mass production successfully completed



LPMT Electronics

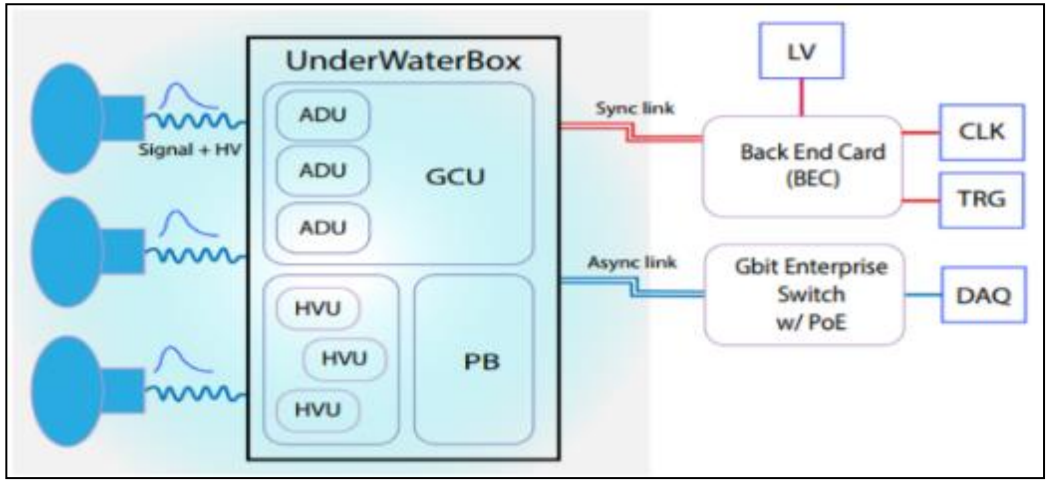
- ~20000 ch., each with 100 m long cable
- Dynamic range: 1- 4000 PE
- Noise: < 10% @ 1 PE
- Resolution: <10%@1PE, <1%@100 PE
- Failure rate: < 0.5%/6 years

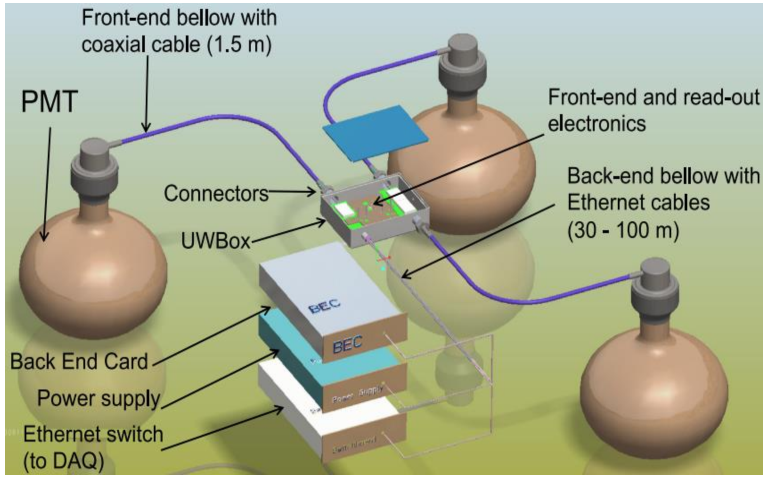
- Joint PMT-electronics-DAQ-software test shows that all installed PMTs and related systems work well
- Noise level is ~ 0.05 PE: good grounding and shielding

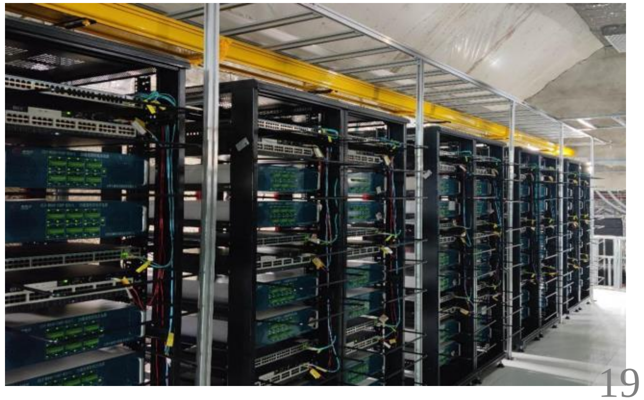


Solution:

- **1 GHz FADC in an underwater box (3 ch./box), connected to PMTs by water proof connectors and <2m long cables**
- **All cables in corrugated SS pipes for water proof**

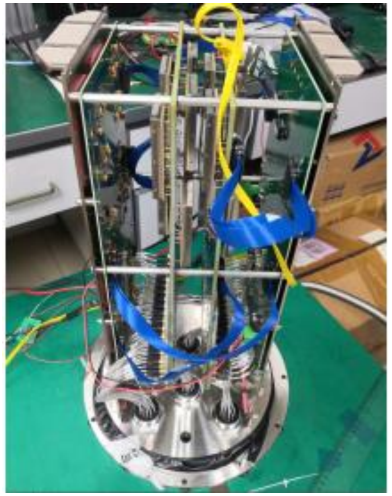






Small PMT system

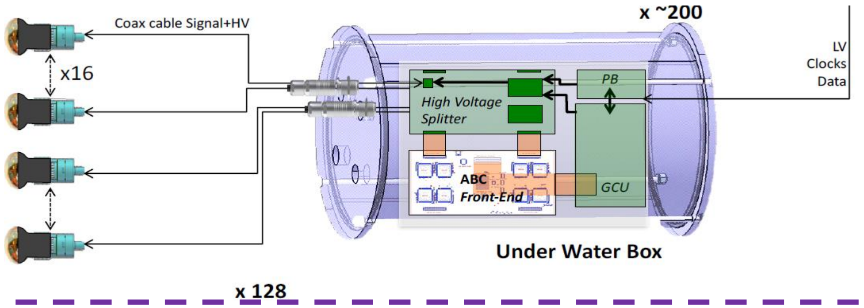
- Goal: 3% more light, higher dynamic range for muons, uniformity and linearity calibration for large PMTs, …
- Mass production and waterproofing of 26,000 3.1” PMTs (XP72B22) from HZC Photonics completed, and tested OK
- Electronics: 200 underwater boxes, each for 128 PMTs read by ASIC Battery Cards (ABC), each with 8 CatiROC chips
- Installation and commissioning under way



JINST 16 (2021), P05010

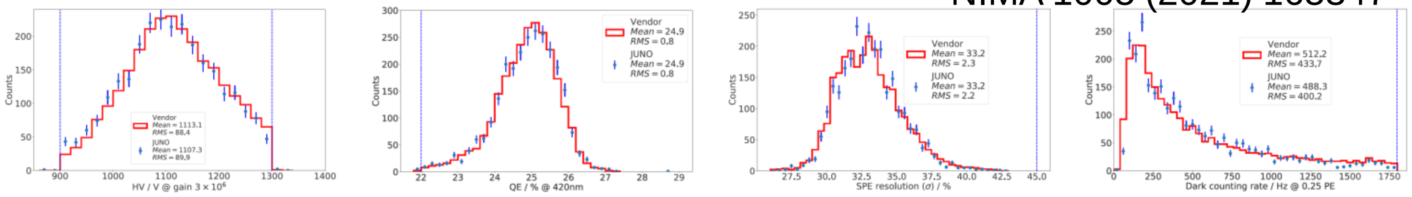
PMTs and electronics

System overview: 200 boxes × 128 PMTs



Performances highlight of all 26,000 PMTs

NIMA 1005 (2021) 165347

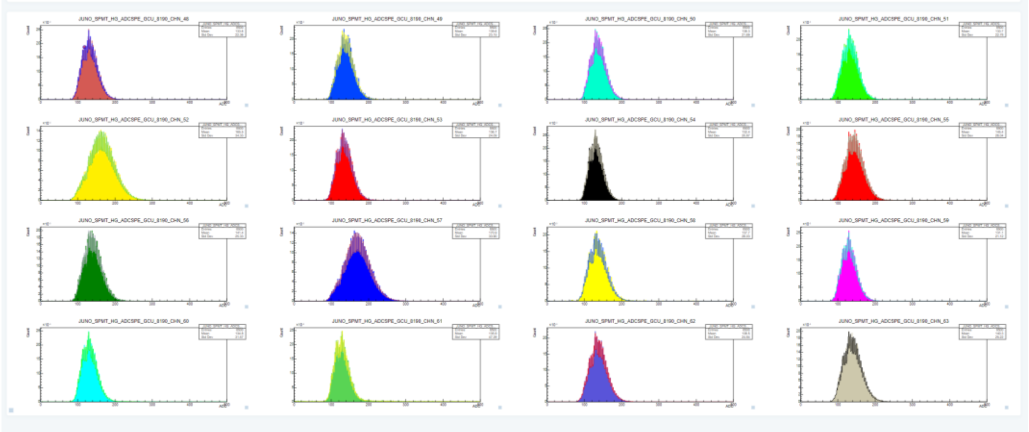


HV: 900-1325V

$\overline{\mathrm{QE}} = 24.9\%$

$\overline{\sigma_{\mathrm{SPE}}} = 33.2\%$

$\overline{\mathrm{DCR}} \approx 500$ Hz



First commissioning data:
SPE spectra of a group of 16 PMTs

PMT Statistics and the Installation

	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%
Dynamic range for [0-10] MeV	[0, 100] PEs		[0, 2] PEs
Coverage	75%		3%
Reference	Eur.Phys.J.C 82 (2022) 12, 1168		NIM.A 1005 (2021) 165347

7,225 LPMTs and 9,293 SPMTs (~1/3) installed and tested OK

Radiopurity Control

Radiopurity of raw materials

JHEP 11 (2021) 102

Singles (R < 17.2 m, E > 0.7 MeV)	Design [Hz]	Change [Hz]	Comment
LS	2.20	0	
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 m -> 4 m
Radon in water	1.31	-1.25	200 mBq/m^3 -> 10 mBq/m^3
Other	0	+0.52	Add PMT readout, calibration sys
Total	8.5	-1.3	

Radiopurity control of raw material:

- ✓ Careful material screening
- ✓ Meticulous Monte Carlo Simulation
- ✓ Accurate detector production handling

Better than spec. by 15%

Good enough for reactor ν's

LS for solar neutrinos:

U/Th<10^{-17} g/g, ^{40}K<10^{-18} g/g, ^{85}Kr<50 μBq/m^3,
^{226}Ra<5×10^{-24} g/g (0.1 μBq/m^3), ^{210}Pb<10^{-24} g/g (^{222}Rn<5 mBq/m^3)

Recirculation seems impossible for JUNO, not like Borexino, KamLAND, SNO+,…

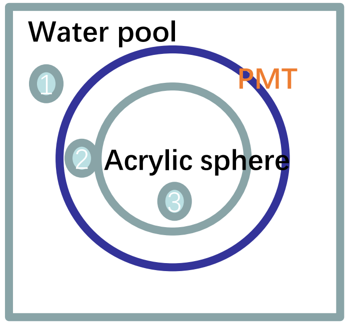
Radiopurity control of LS:

- Leak check (single component < 10^{-8} mbar·L/s) of all joints to reduce ^{222}Rn and ^{85}Kr √
- Cleaning and wash of all pipes, vessels to remove dust (check water cleanness) √
- Clean room environment during installation √
- Surface treatment of the acrylic vessel (Rn daughters) √
- LS filling strategy √

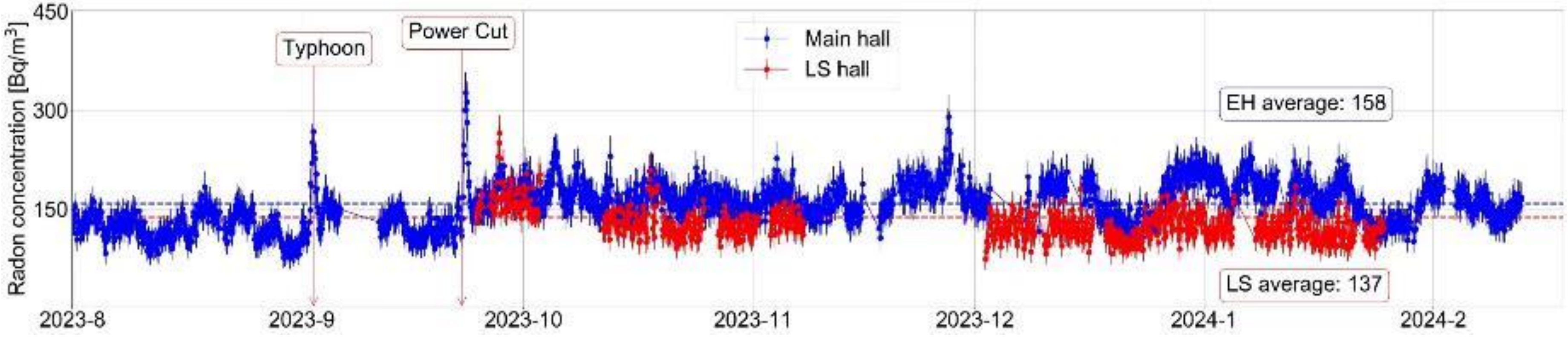
Cleanness of Environment

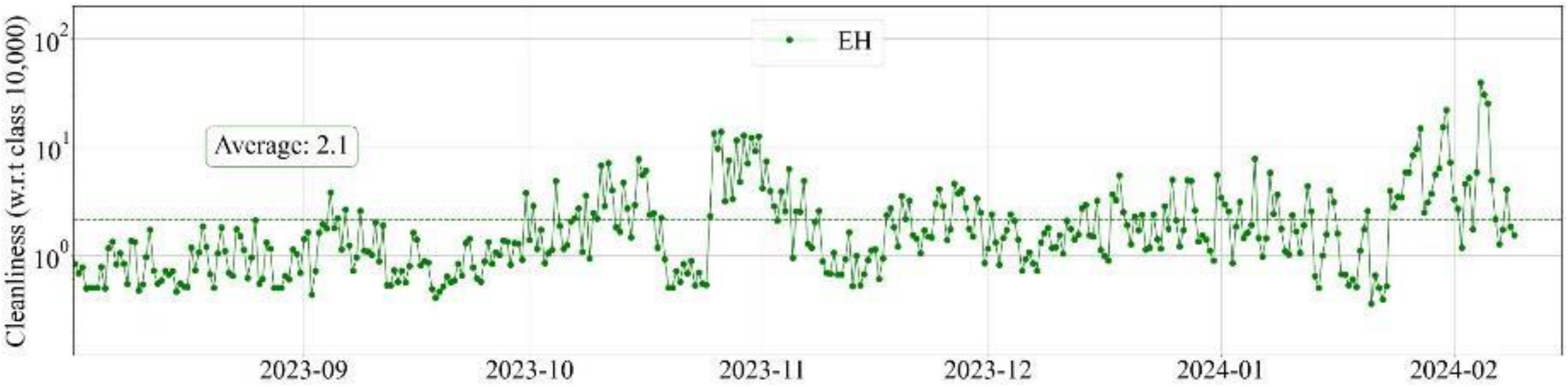
- **Average radon and cleanliness:**
  - Radon concentration: ~160 Bq/m^3 in the EH, ~140 Bq/m^3 in the LS hall
  - Cleanliness: class 20,000

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



Radon concentration in air: < 200 Bq/m^3

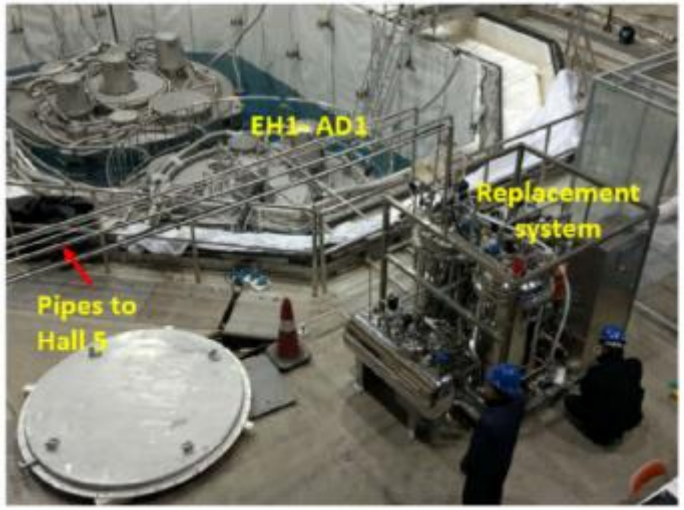


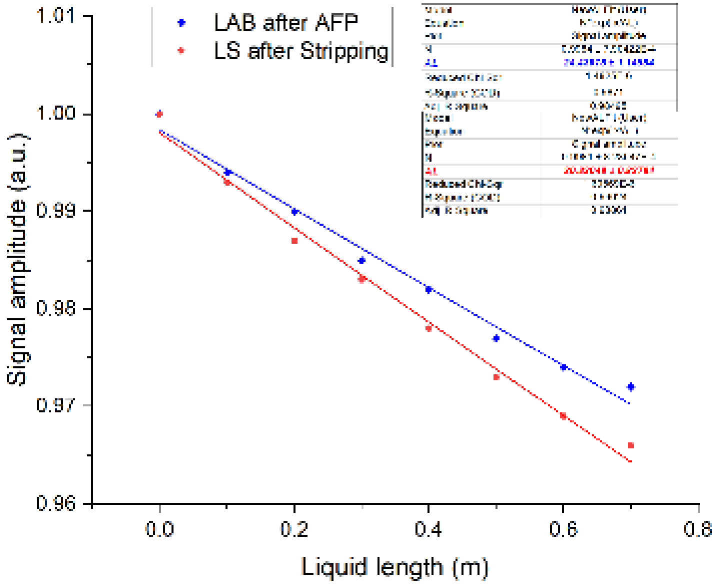


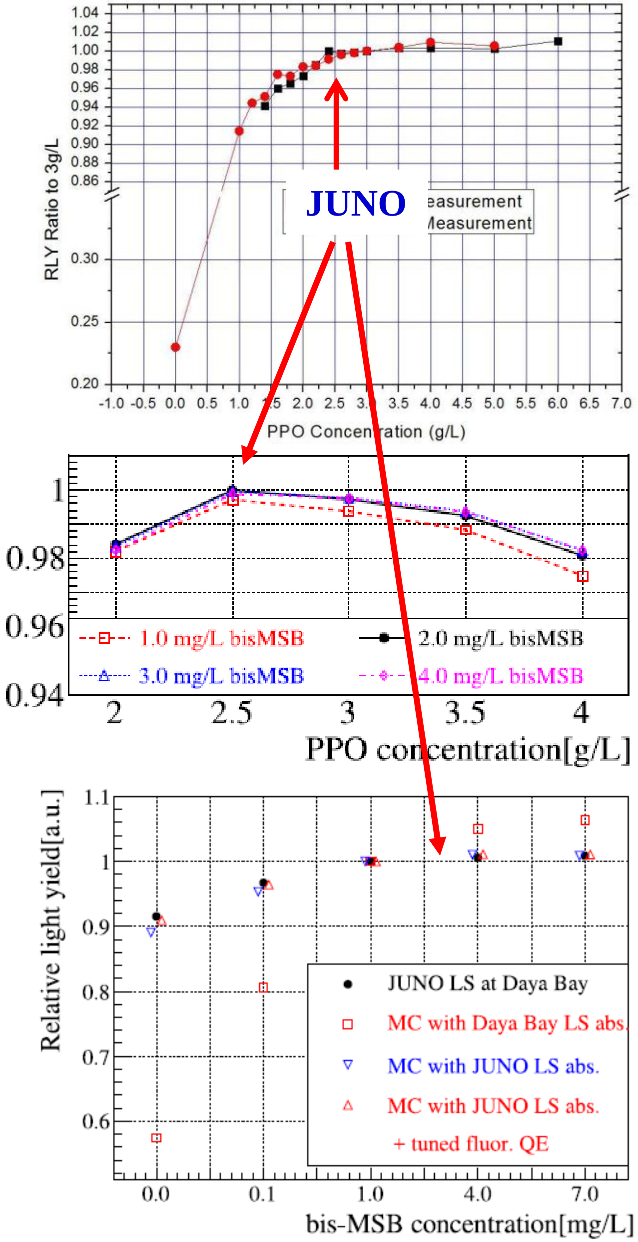
Liquid Scintillator

- **Recipe：** Based on Daya Bay experience
  - ⇨ LAB for transparency and safety
  - ⇨ R&D for highest light yield:
    - ✓ A Daya Bay module for test (*NIMA 988 (2021) 164823)*
    - ✓ extrapolation to the JUNO size using a new LS optical model (*NIMA 967 (2020) 163860)*
  - ⇨ Final result: LAB + 2.5g/L PPO + 3 mg/L bis-MSB
- **Production:**
  - ⇨ ~50t PPO delivered, U/Th < 0.1 ppt; 20kt LAB to be delivered, U/Th ~ 1 ppq
  - ⇨ LAB attenuation length > 24m, LS attenuation length > 20m

Experimental Hall 1







Liquid Scintillator Production and Purification

Four purification plants + LS Mixing + QA/QC + high purity N_2 and water production plant to guarantee radio-purity and transparency

5000 m^3 LAB storage tank

1) Al_2O_3 for optical transparency

2) Distillation for radiopurity

Mixing LAB with PPO and bis-MSB

1800 m SS pipes to underground

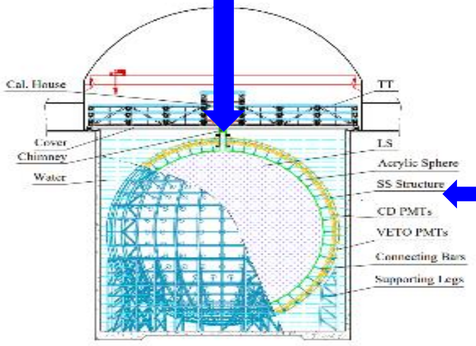
3) Water extraction to remove radioactive impurities

4) Gas stripping to remove Rn and O_2

85%

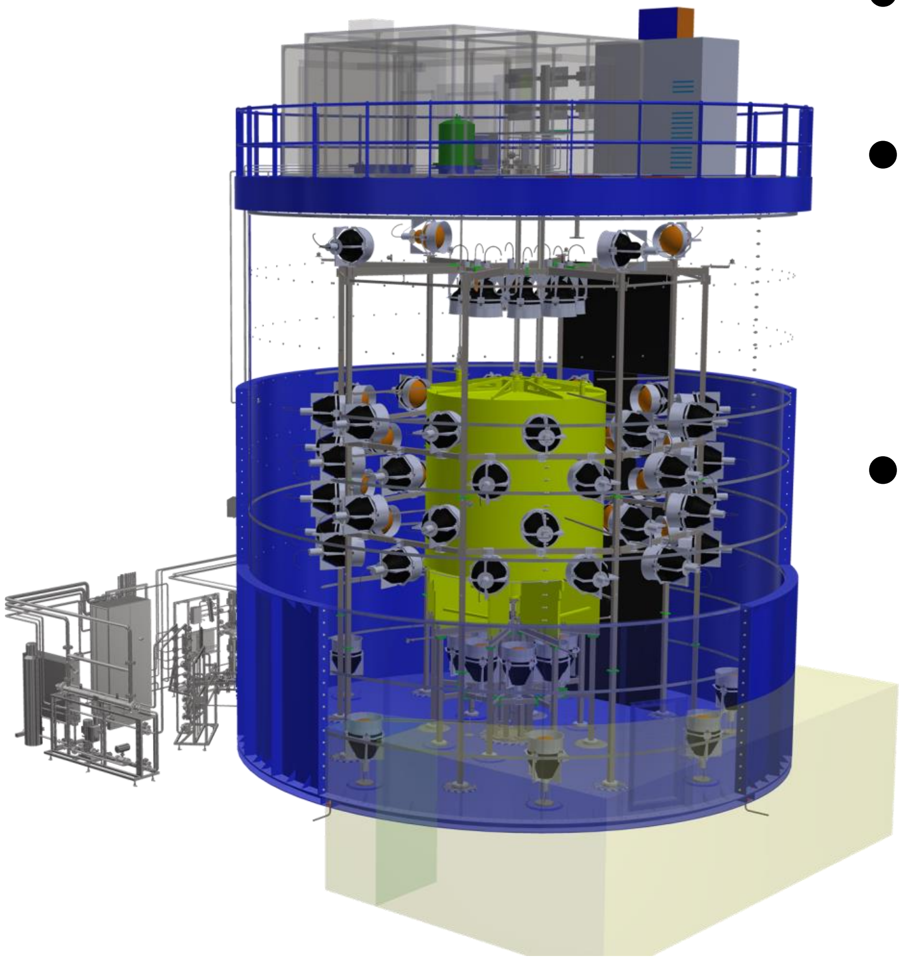
15%

OSIRIS to monitor the LS quality



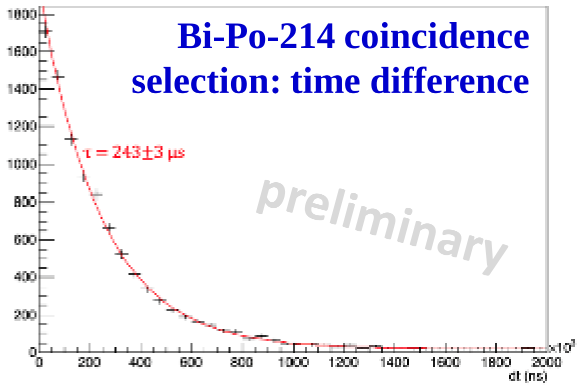
All plants are individually tested, and all requirements are satisfied

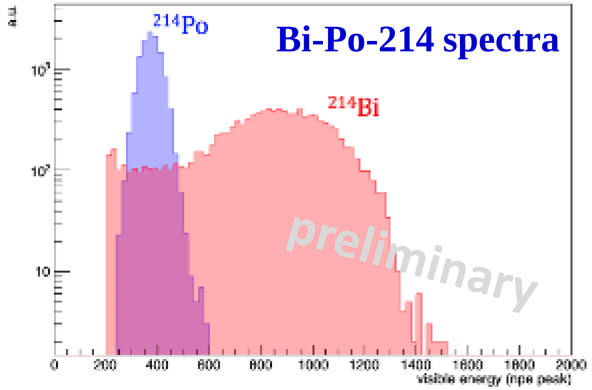
OSIRIS: LS Radiopurity Verification before Filling

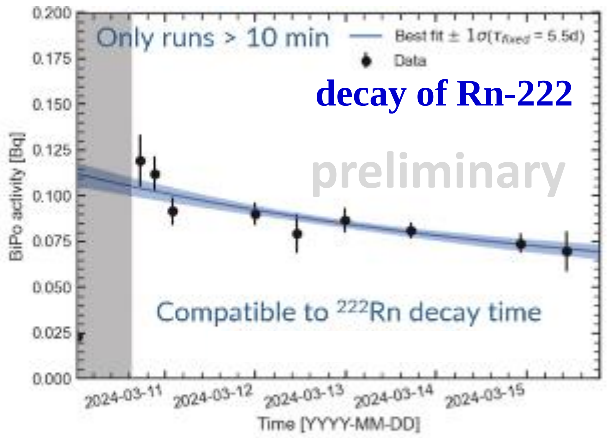


EPJ C 81 (2021) 11, 973

- A dedicated pre-detector to verify the radioactivity levels of LS
- 20 tons of LS in 3m-by-3m acrylic vessel, 76 MCP-PMTs, 3m of water shielding → first test run successful
- First batch of JUNO LS filled into the detector on March 11
  - U/Th tagging by Bi-Po-214 coincidence, which is now still dominated by ^{222}Rn → have to wait several ^{222}Rn lifetimes (τ=5.5 days) to reach U/Th <10^{-15} g/g
  - Analysis for ^{14}C, ^{210}Po, … in progress

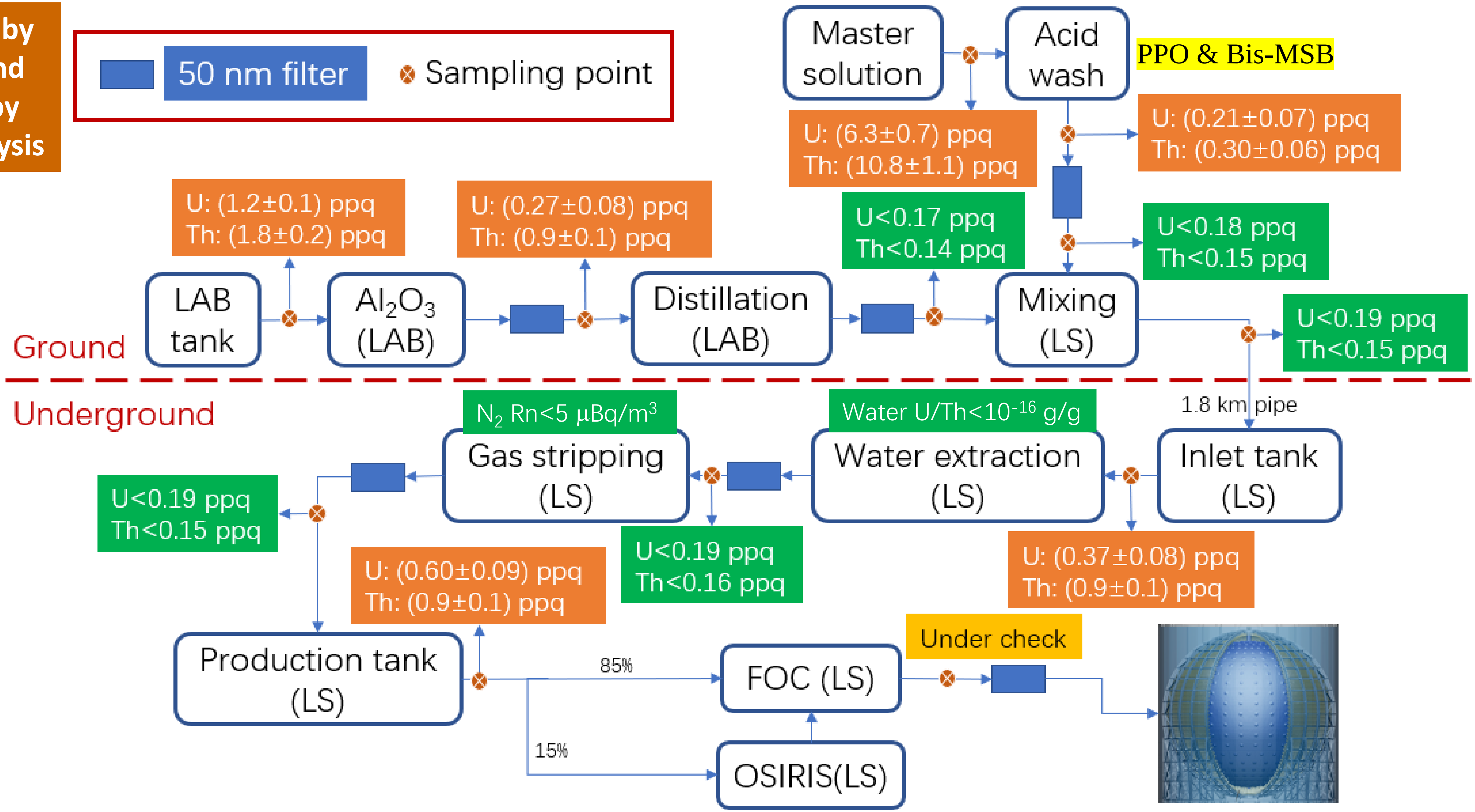






Commissioning of the Liquid Scintillator system

Screened by ICP-MS and checked by NAA analysis

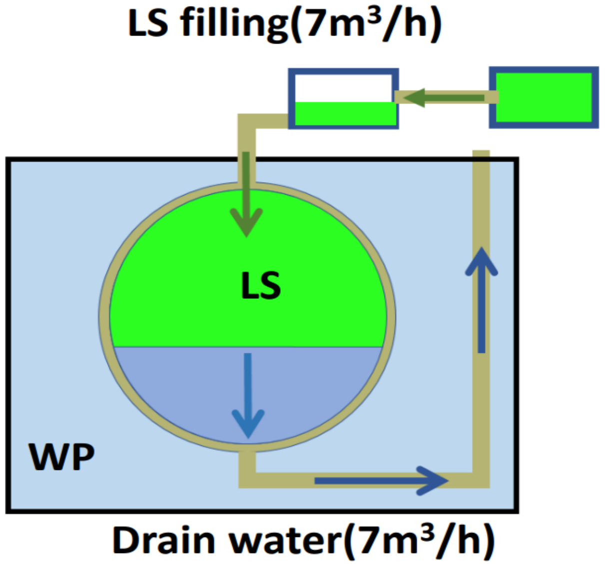


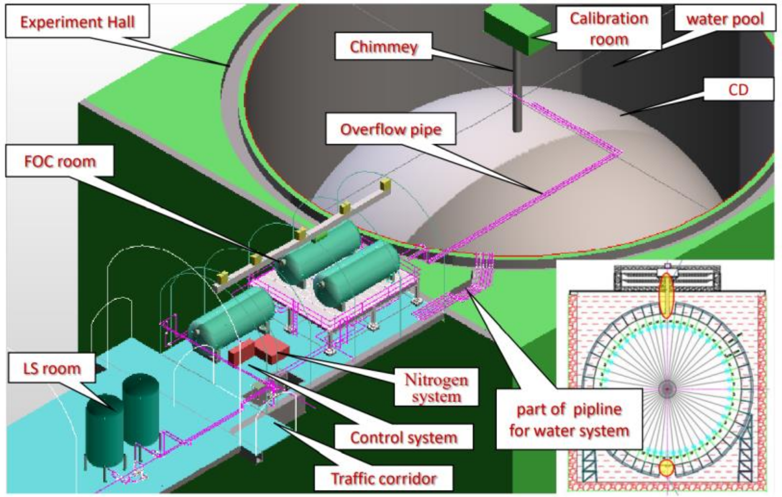
Final Cleaning Plan and Liquid Scintillator Filling Scheme

Reduce dust to class 1000, Rn by ÷10

Complete CD construction → 1-2 weeks settlement with proper moisture → Remove the protective film and wash the acrylic surface by the high pressure water spray → Fill CD and VETO by high purity water → replacing water in CD by LS

Water for CD: U/Th$<10^{-15}$ g/g, ^{226}Ra<0.1 mBq/m^3
Water for VETO: U/Th$<10^{-14}$ g/g

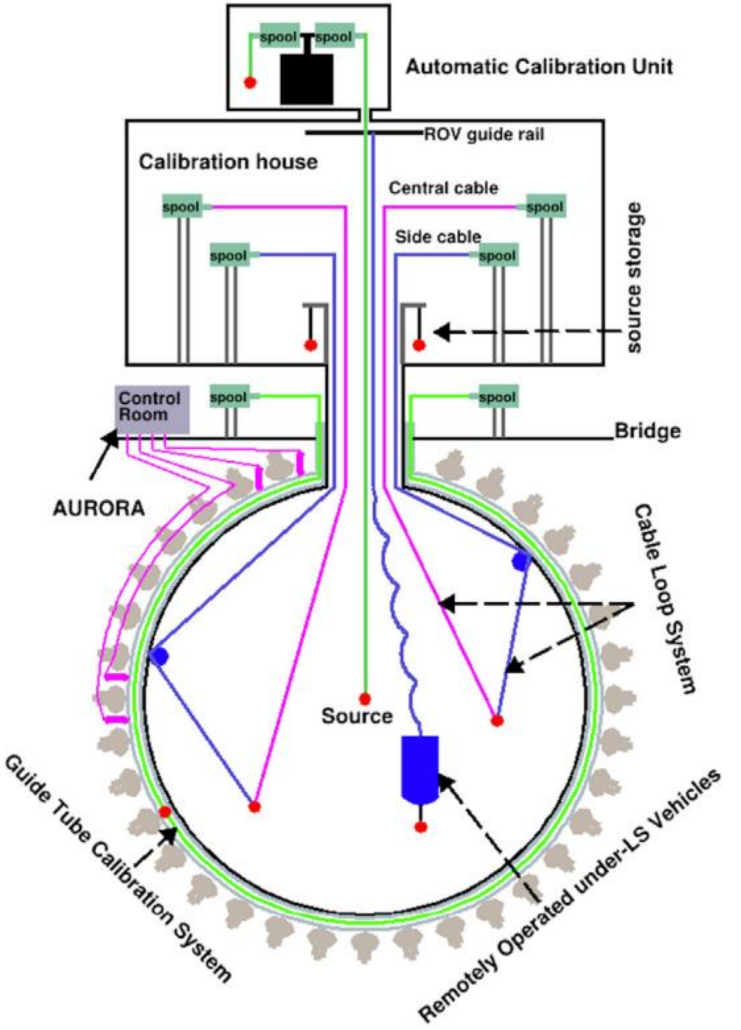




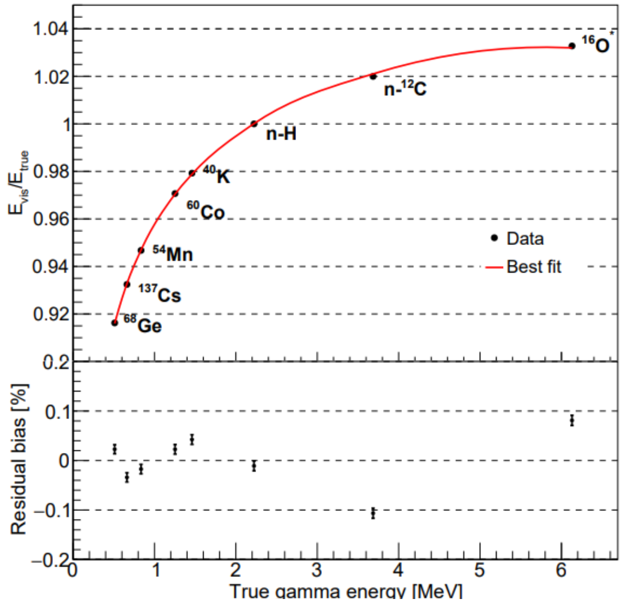
Calibration

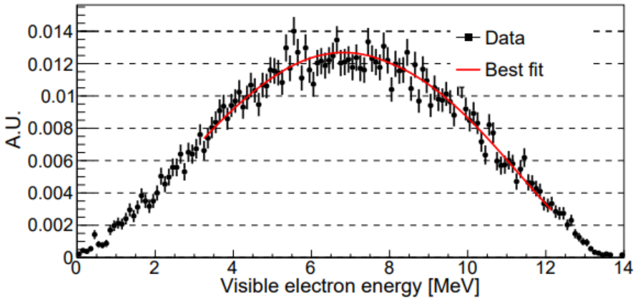
1D, 2D, 3D scan systems with multiple calibration sources

- Calibrate energy scale and non-linearity to better than 1% using γ peaks and cosmogenic ^{12}B beta spectrum
- Successful at Daya Bay and other exp.s



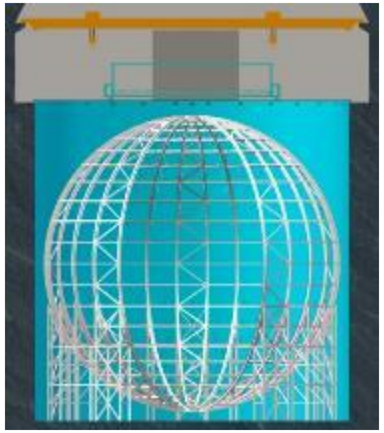
All systems ready for installation



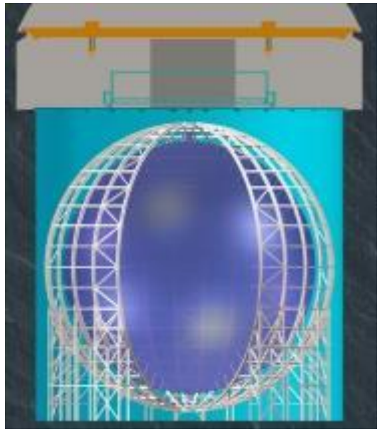


JHEP 03 (2021) 004

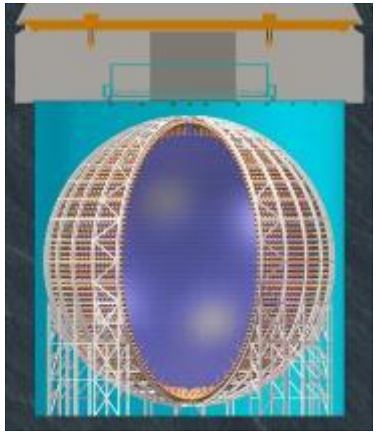
Installation



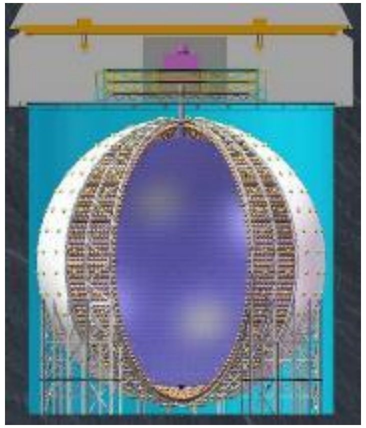
SS MAIN STRUCTURE



+ACRYLIC SPHERE



+PMT



+VETO/CALIBRATION

SS Main Structure

Acrylic sphere Installation

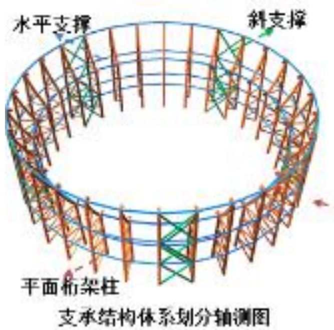
PMT Module

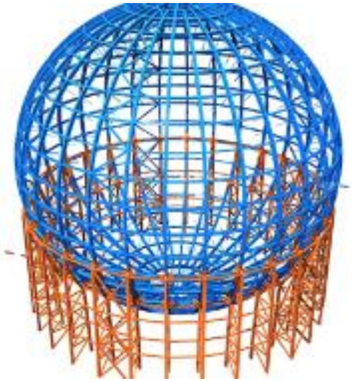
Pool lining、 Earth magnetic field shielding coils、 Tyvek etc.

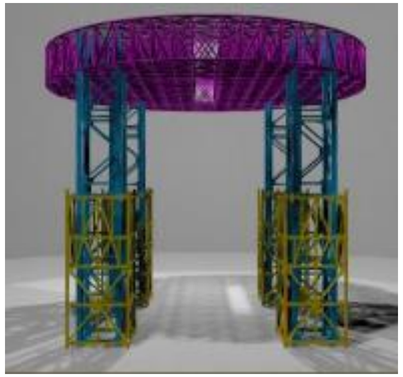
Clean

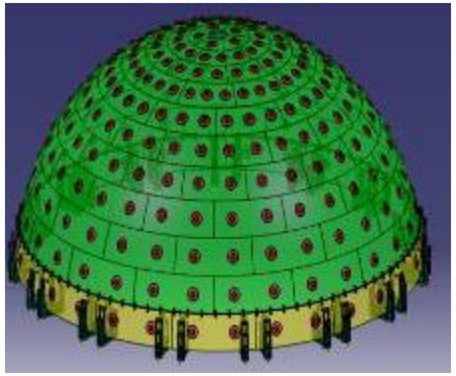
Bridge, cover, Cali., TT in parallel

Water and LS Filling









Expected Performance

- Bkg. in LS can reach U/Th/K < 10^{-15} g/g for MH
- 10^{-17} g/g is feasible for solar ν and 0νββ decays
- From measured PMT, LS and acrylic properties, the energy resolution will be < 3%@1MeV, based on full simulation, calibration and reconstruction

$$\frac{\sigma}{E_{vis}} = \sqrt{\left(\frac{2.614\%}{\sqrt{E_{vis}}}\right)^2 + 0.64\%^2 + \left(\frac{1.205\%}{E_{vis}}\right)^2}$$

Photon statistics

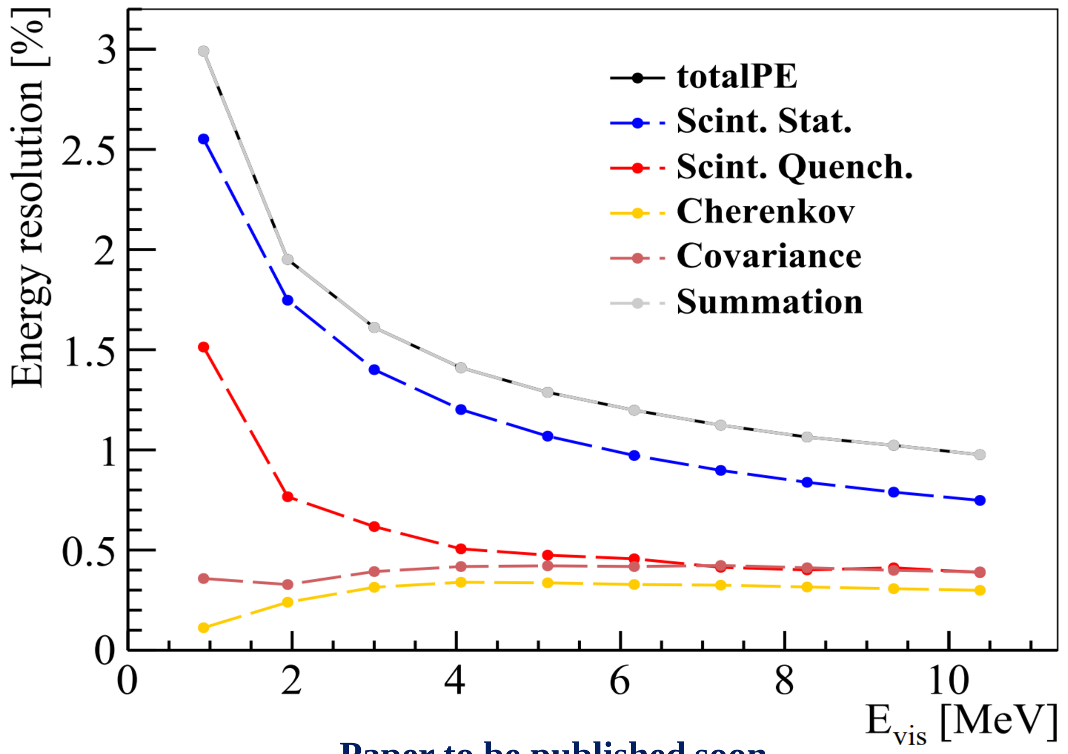
Constant term

Annihilation -induced γs Dark noise

Main changes vs design *(JHEP03(2021)004)*:

- Photon detection eff.: 27% ➔ 30%
  (EPJC 82 (2022) 12, 1168)
- New PMT optical model: +8%
  (EPJC 82 329 (2022))
- *New central detector geometry and LS: 3%*

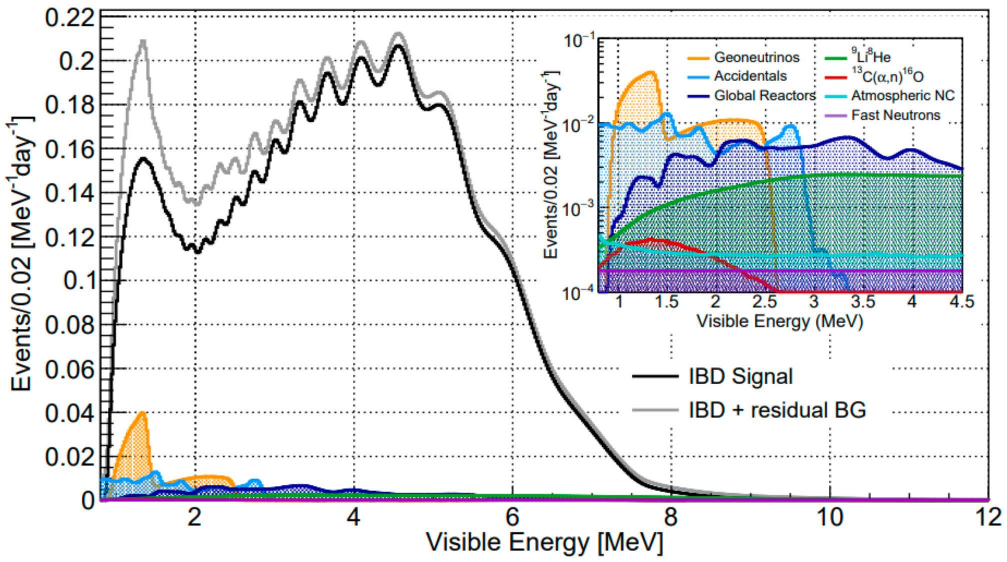
Total photon statistics: ~1660/MeV



Paper to be published soon

Reactor Antineutrino Spectrum

CPC 46 (2022) 12, 123001



Event type	Rate [/day]	Relative rate uncertainty	Shape uncertainty
Reactor IBD signal	60 → 47	-	-
Geo-ν's	1.1 → 1.2	30%	5%
Accidental signals	0.9 → 0.8	1%	negligible
Fast-n	0.1	100%	20%
^{9}Li/ ^{8}He	1.6 → 0.8	20%	10%
^{13}C (α, n) ^{16}O	0.05	50%	50%
Global reactors	0 → 1.0	2%	5%
Atmospheric ν's	0 → 0.16	50%	50%

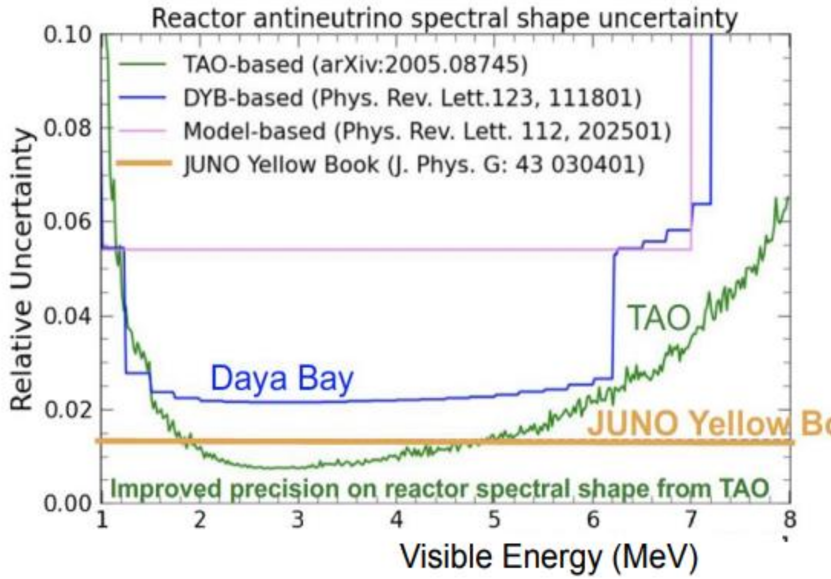
JUNO physics book *(J. Phys. G43:030401(2016))* → **updated analysis**

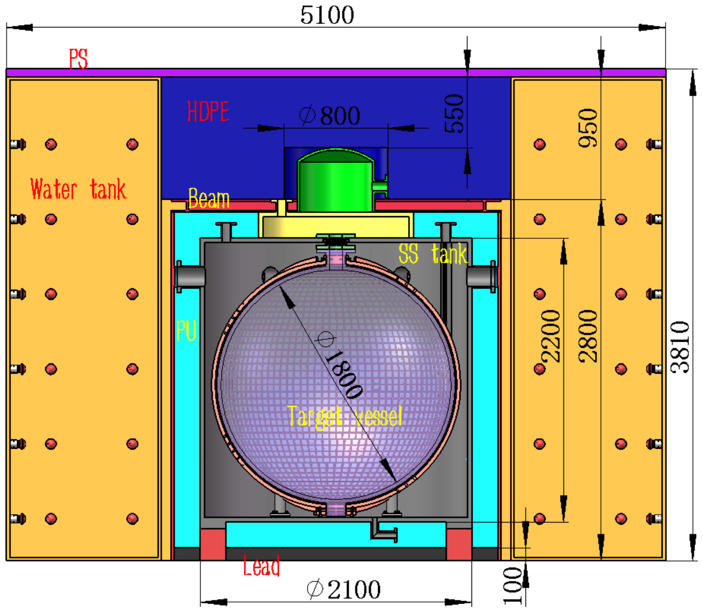
Updates for the spectra and rates since JUNO (2016)

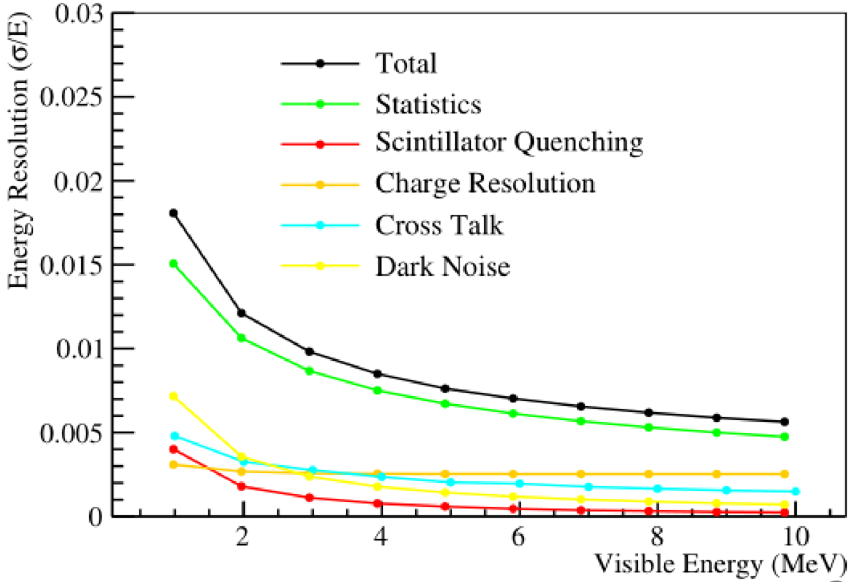
- ☹ 2 reactor cores missing in Taishan
- 😆 Better muon veto strategy
- 😆 Improved energy resolution:
  3.0% @1MeV → 2.9% @1MeV
- 😆 More realistic estimate on signals and backgrounds
- ☹ Slightly less overburden
- 😆 Lower radioactivity background based on latest measurements

JUNO-Tao

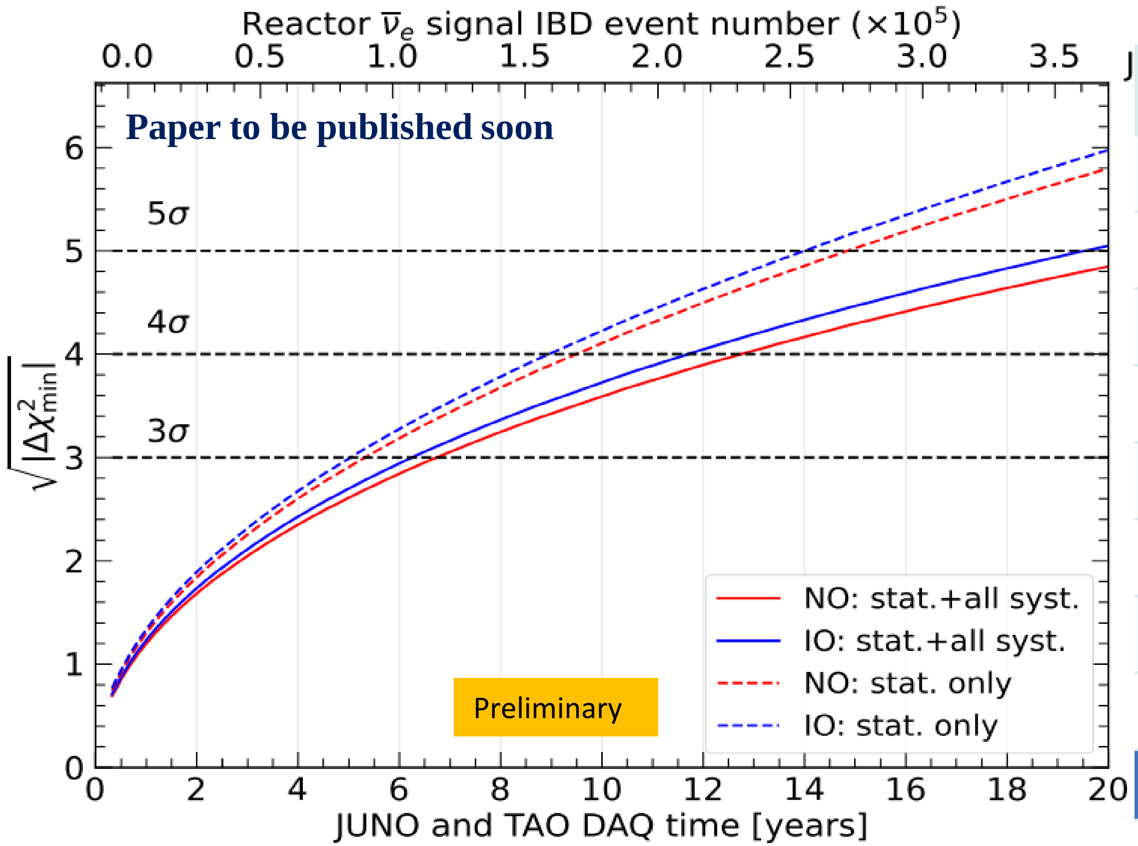
- To measure the reactor neutrino spectrum as a reference to JUNO
  - ⇨ better resolution to reduce fine structure effects and spectrum uncertainties
  - ⇨ Improve nuclear database, search for sterile neutrinos
- Idea: Gd-loaded LS @-50^{o}C + SiPM
  - ⇨ 700k/year@44m from the core(4.6 GW), with ~10% bkg.
  - ⇨ Energy resolution: ~1.5%/√E, 4500 p.e./MeV
  - ⇨ 10 m^2 SiPM (>94% coverage) w/ PDE > 50%
  - ⇨ Operating at -50 ^{o}C to reduce the SiPM dark rate by 10^3 to 100 Hz/mm^2
  - ⇨ 2.8 ton(1t fiducial volume) new type of Gd-LS for -50 ^{o}C
- Component production mostly completed







Neutrino Mass Ordering



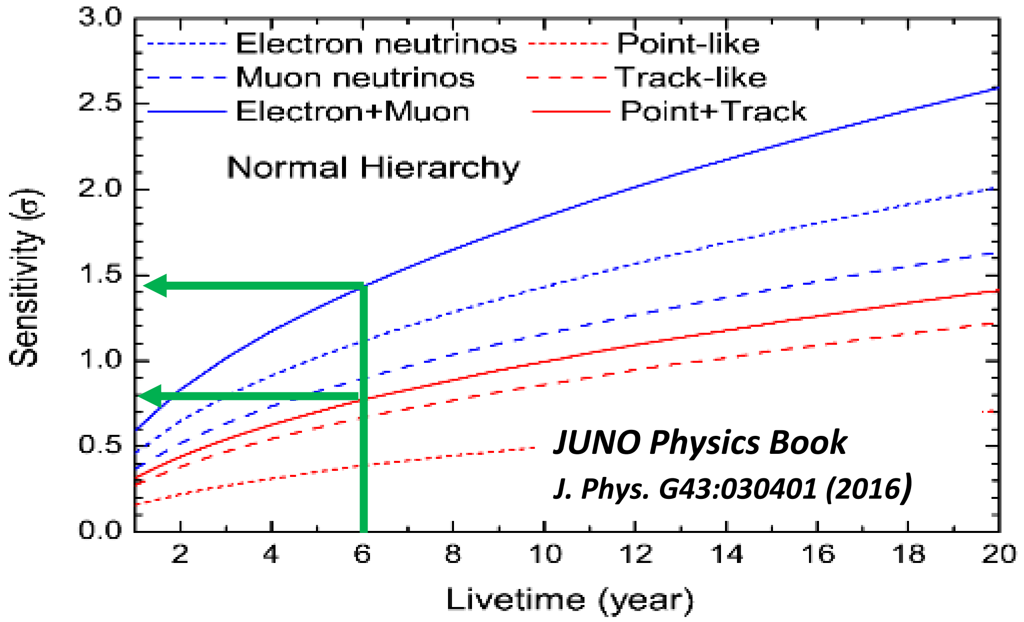
	Design *	Now
Thermal Power	36 GW_{th}	26.6 GW_{th} (**26%↓**)
Signal rate	60 /day	47.1 /day (**22%↓**)
Overburden	~700 m	~ 650 m
Muon flux in LS	3 Hz	4 Hz (**33%↑**)
Muon veto efficiency	83%	91.6% (**11%↑**)
Backgrounds	3.75 /day	4.11 /day (**10%↑**)
Energy resolution	3.0% @ 1 MeV	2.95% @ 1 MeV (**2%↑**)
Shape uncertainty	1%	**JUNO+TAO**
3σ NMO sens. Exposure	**< 6 yrs × 35.8 GW_{th}**	**~ 6 yrs × 26.6 GW_{th}**

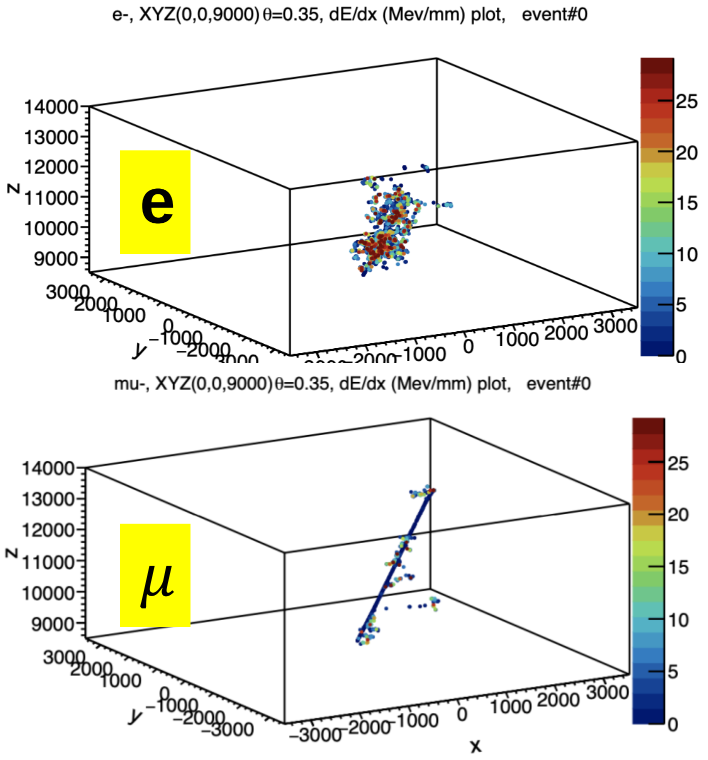
* J. Phys. G 43:030401 (2016)

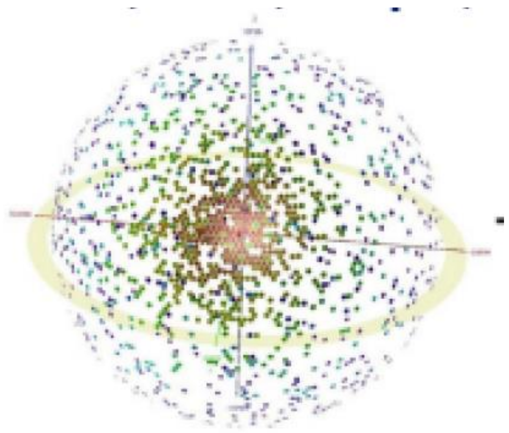
JUNO NMO median sensitivity: **3σ (reactors only) @ ~6 yrs * 26.6 GW_{th} exposure**

Combined reactor+atmospheric neutrino analysis in progress: further improve the NMO sensitivity

Atmospheric Neutrinos



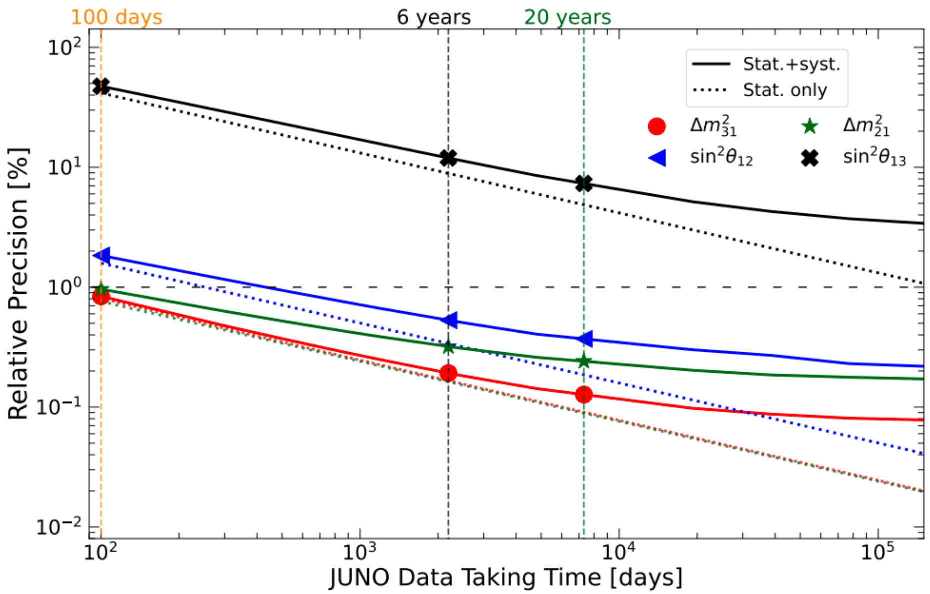


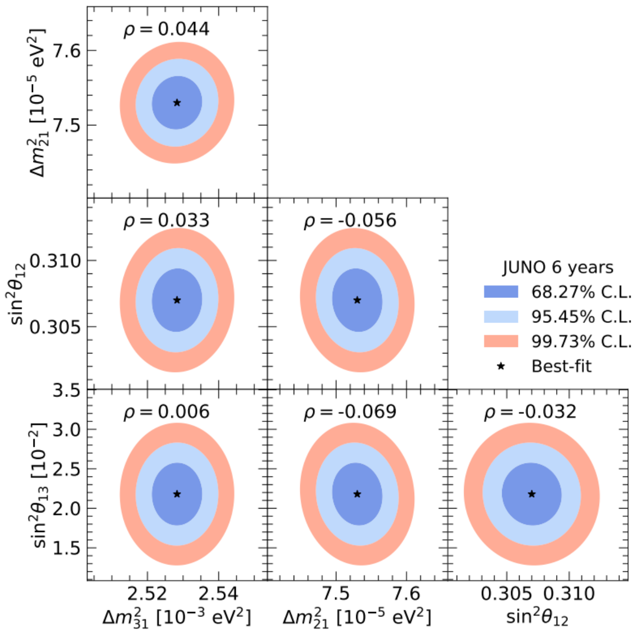


- **NMO sensitivity: 0.8~1.4σ @ 6 years with atm ν only**
- **Significant progress on event reconstruction and selection methods**
- **Full chain atmospheric analysis is ongoing and combination with reactor antineutrinos is expected**

Precision Oscillation Measurement

About <u>one order of magnitude</u> improvements in precision





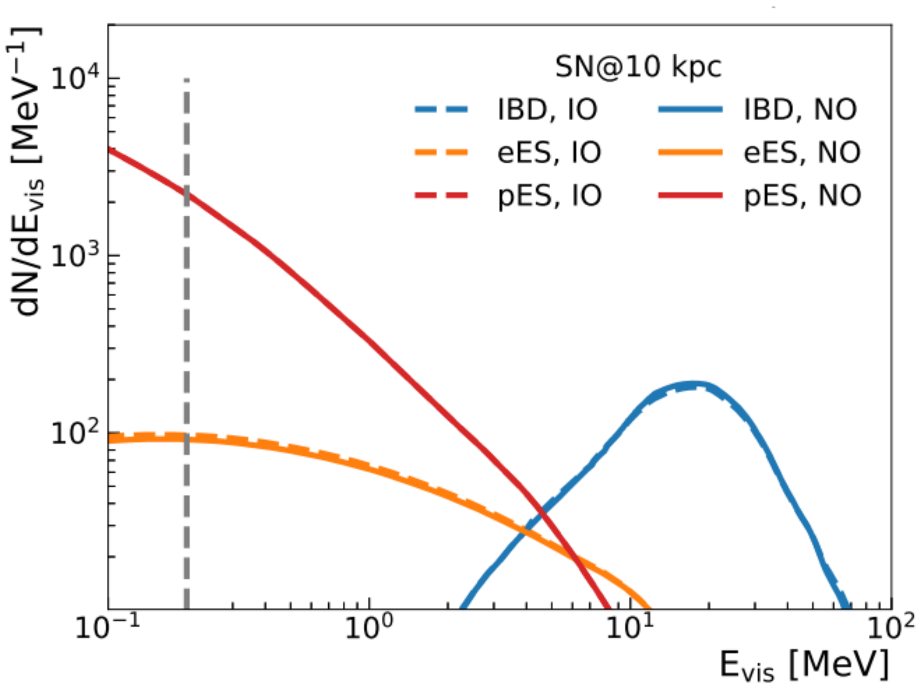
Much better than that of the quark sector even through we had (b,c,s) factories

	Central Value	PDG2020	100 days	6 years	20 years
Δm^2_{31} ($\times 10^{-3}$ eV^2)	2.5283	± 0.034 (1.3%)	± 0.021 (0.8%)	± 0.0047 (0.2%)	± 0.0029 (0.1%)
Δm^2_{21} ($\times 10^{-5}$ eV^2)	7.53	± 0.18 (2.4%)	± 0.074 (1.0%)	± 0.024 (0.3%)	± 0.017 (0.2%)
$\sin^2\theta_{12}$	0.307	± 0.013 (4.2%)	± 0.0058 (1.9%)	± 0.0016 (0.5%)	± 0.0010 (0.3%)
$\sin^2\theta_{13}$	0.0218	± 0.0007 (3.2%)	± 0.010 (47.9%)	± 0.0026 (12.1%)	± 0.0016 (7.3%)

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

Supernovae neutrinos

SN neutrinos of 30 $M_\odot$ Nakazato model



JCAP 01 (2024) 057

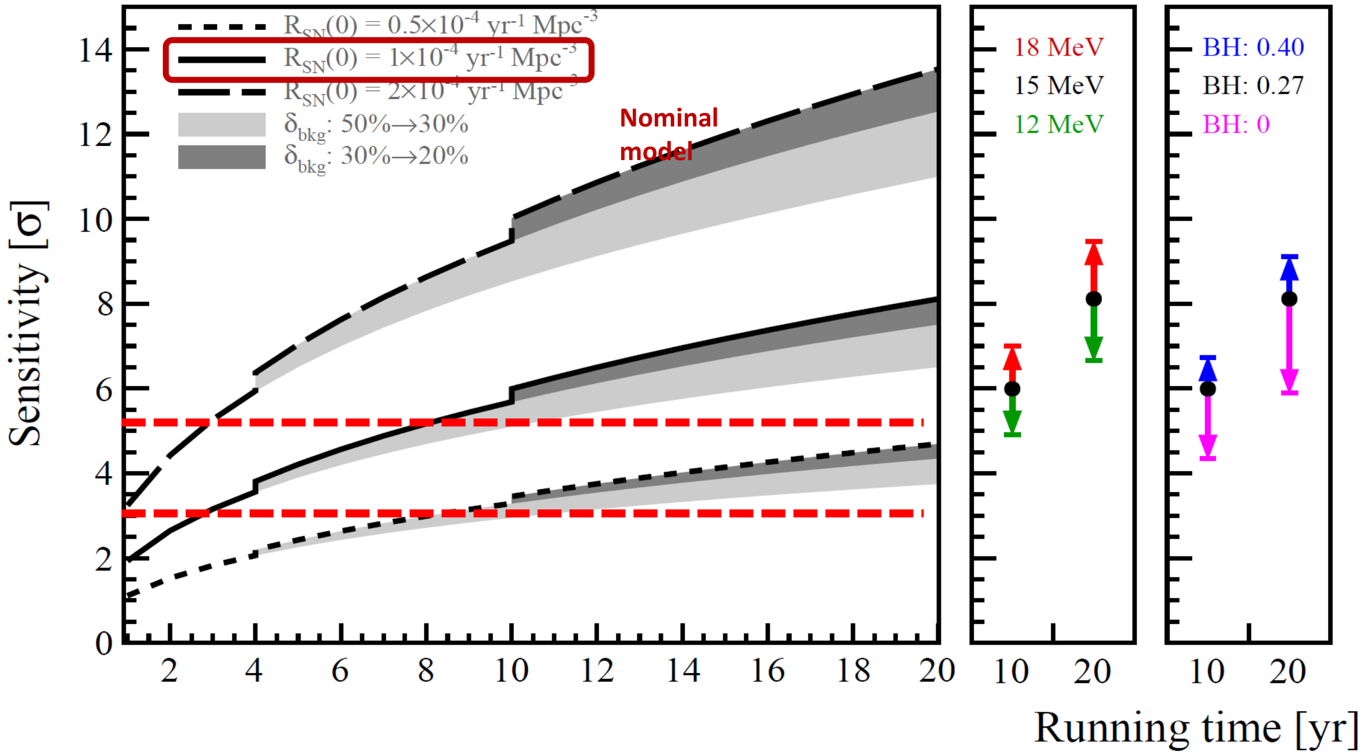
3 detection channels sensitive to all flavors

Excellent capability for early warning

220~400 kpc with 50% probability

10 ~ 30 ms for typical 10 kpc

Diffuse supernova neutrino background



JCAP 10 (2022) 033

S/B ratio improved from 2 to 3.5

Using the reference model

3σ in 3 years and $>5\sigma$ in 10 years

Solar and Terrestrial Neutrinos

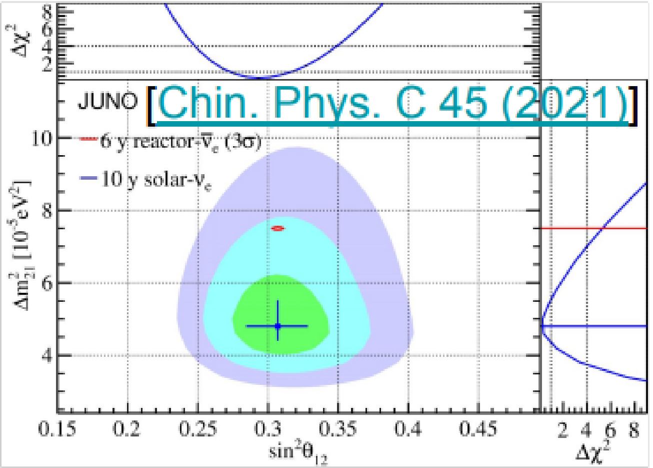
Measure θ_{12} by reactor and solar neutrinos to resolve the tension

^{8}B measurement
(in NC + CC + ES channels)

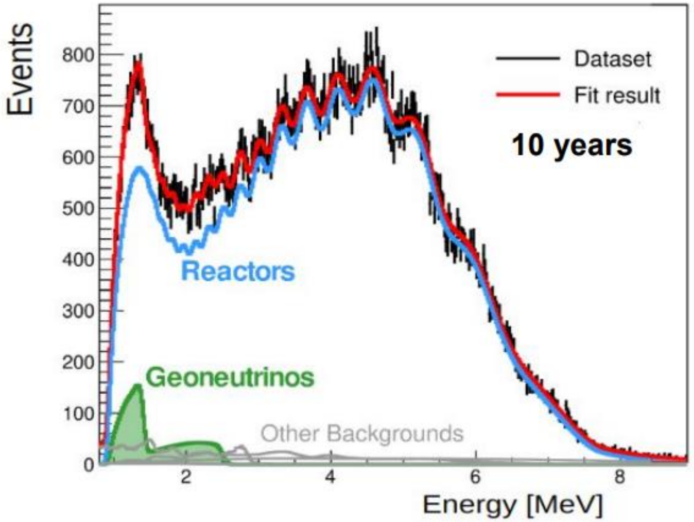
Expected precision:

^{8}B	5% (3% with SNO)
$\sin^2\theta_{12}$	8%
Δm^2_{21}	20%

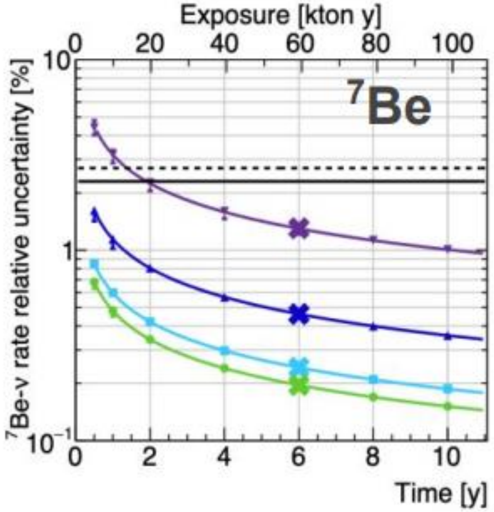
[arXiv:2210:08437]

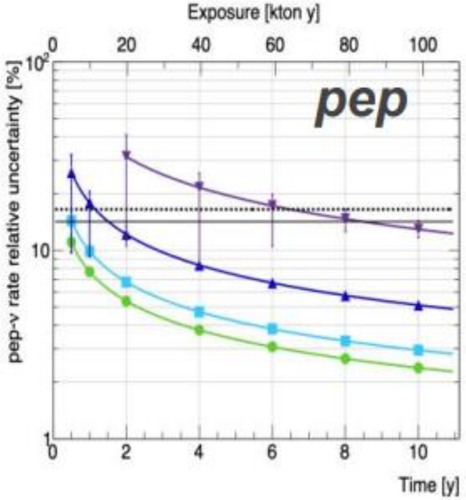


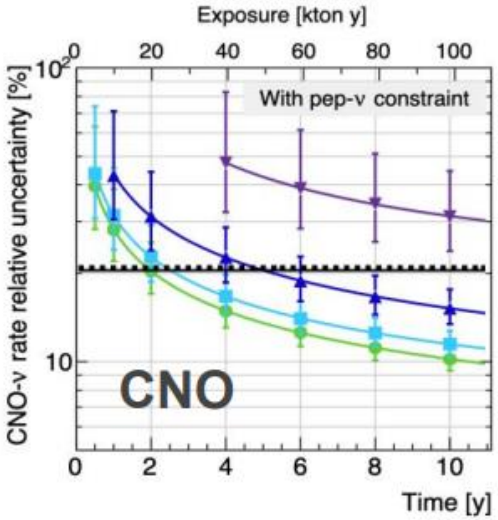
- **JUNO will collect the largest dataset of geoneutrinos with a precision of Th/U ratio ~8% in 10 years**
- **In comparison, KamLAND ~15%, Borexino ~17%**



Improve CNO and other solar neutrino measurement over Borexino







JUNO @ different radio-purity scenarios:
- min. requirement for NMO
- 10 x Borexino Phase-I
- Borexino Phase-I
- Borexino Phase-III (U/Th 10^{-17} g/g)

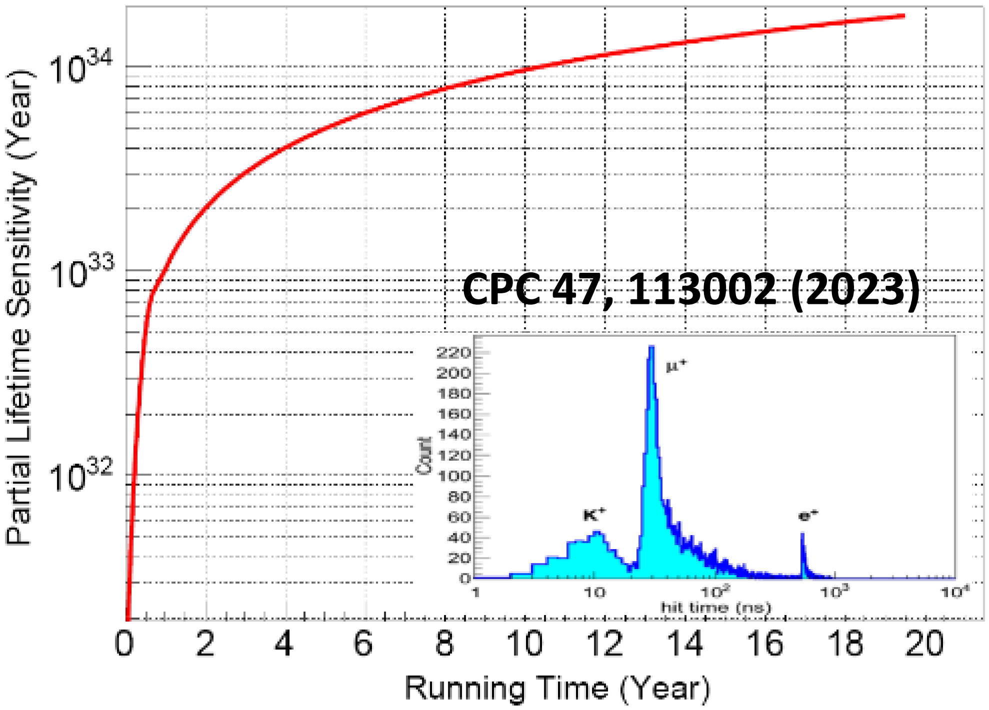
··· **Borexino result**

[arXiv:2303.03910, accepted by JCAP]

Nucleon Decays

Target mass: 20 kton LS → 1.45×10^{33} **free protons,** 5.30×10^{33} **bound protons/neutrons**

$p \to \bar{\nu} K^+$ **Triple coincidence**

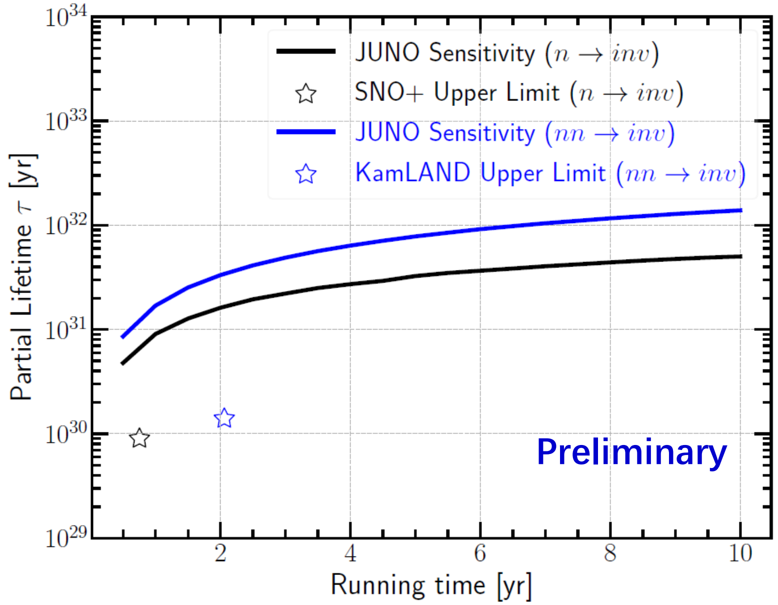


$\tau/B(p \to \bar{\nu} K^+) > 9.6 \times 10^{33}$ yrs/10 yrs

Best limit: 5.9×10^{33} **yrs from Super-K**

Neutron invisible decays

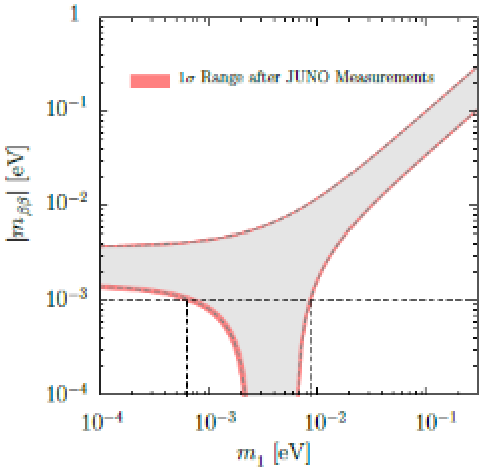
- $n \to inv$ $(^{12}\mathrm{C} \to {}^{11}\mathrm{C}^*)$
- $nn \to inv$ $(^{12}\mathrm{C} \to {}^{10}\mathrm{C}^*)$

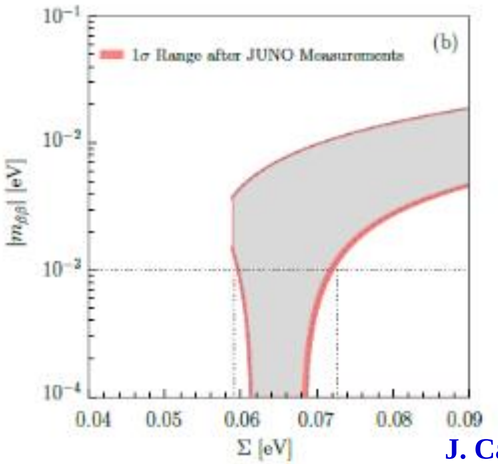


An order of magnitude improvement to the current best limits in 2 years data taking

JUNO-ββ

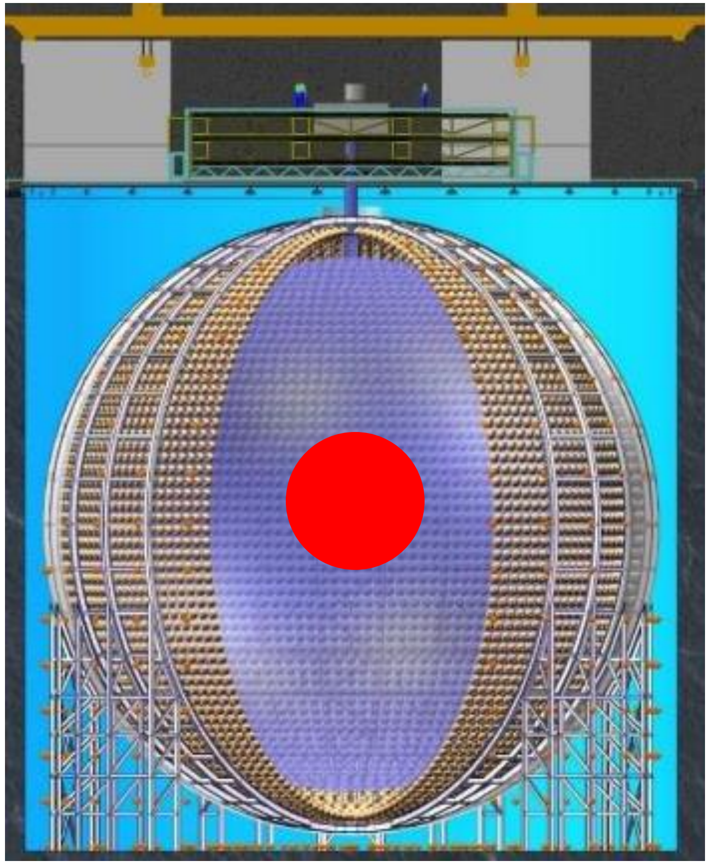
- In ten years from now, oscillation parameters will all be measured
- 0ν ββ decay will be the next focus:





J. Cao et al., arXiv:1908.08355

	Isotope	Mass(t)	$<m_{\beta\beta}>$,meV
SNO+	^{130}Te	8	19-46
KamLAND2-Zen	^{136}Xe	1	~20
NEXT-HD	^{136}Xe	1	14-40
nEXO	^{136}Xe	5	7-22
Darwin/Panda-nT	^{136}Xe	3-5	7-22
LEGEND-1000/CDEX-1t	^{76}Ge	1	10-40
AMoRE-II	^{100}Mo	0.1	12-22
CUPID	^{100}Mo	0.24	12-20
CUPID-1T	^{100}Mo	1	4-7
JUNO-ββ	^{136}Xe	50	4-10
	^{130}Te	100	3-14



Insert a balloon filled with ^{136}Xe-loaded LS(or ^{130}Te) into the JUNO detector

Zhao et al., arXiv: 1610.07143, CPC 41（2017）5

Summary

- JUNO construction near completion, overcoming challenges
- Component quality exceeding the design value, performance may surpass expectations
- Neutrino mass ordering may be known within this decade
- Anticipate groundbreaking results in particle and astro-particle physics from JUNO