Status of the JUNO experiment

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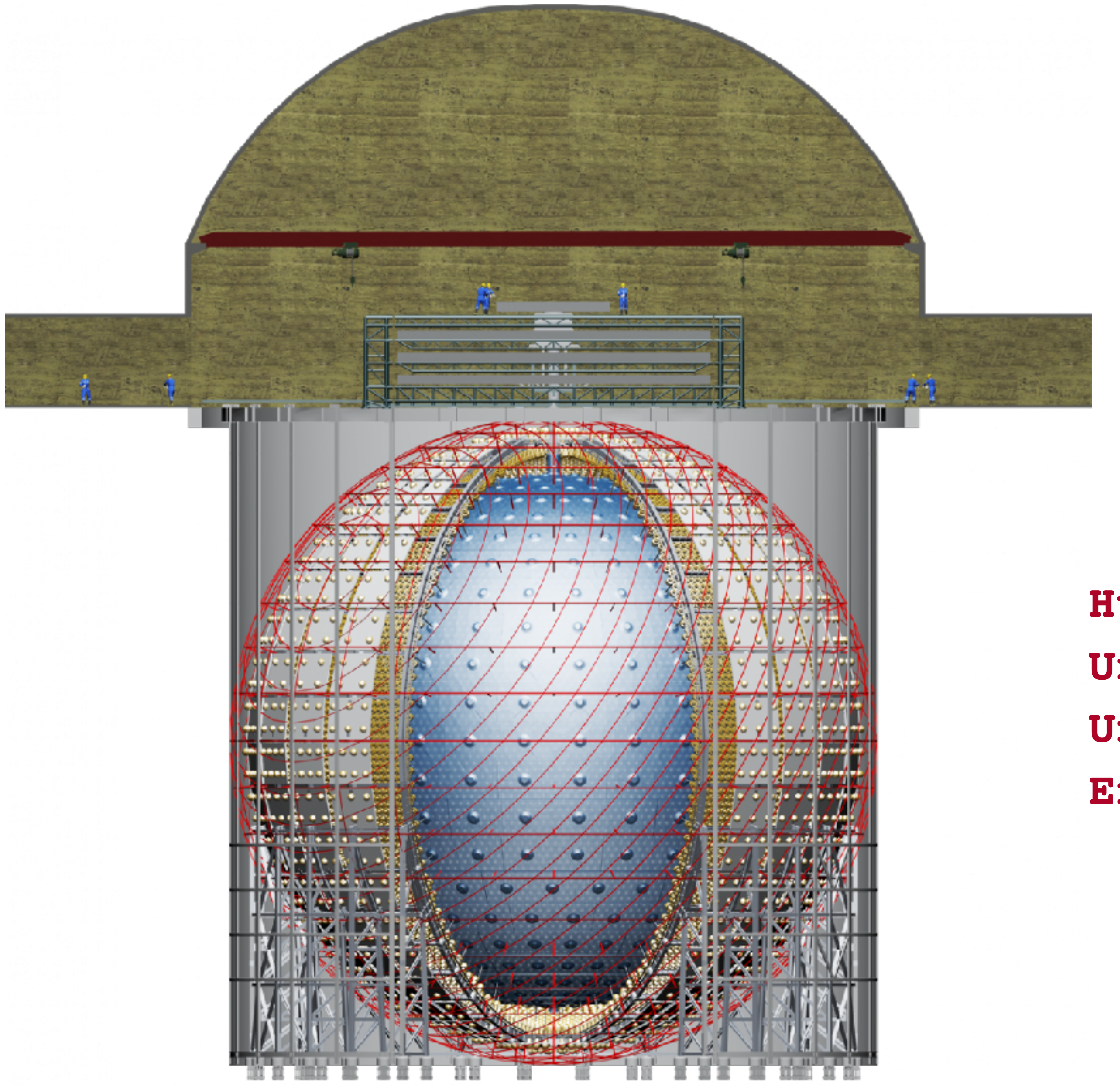
on behalf of the JUNO collaboration

IRN Neutrino meeting - 10 June 2021

Jiangmen Underground Neutrino Observatory

arXiv:2104.02565
JPG 43 (2016) 030401
arXiv:1508.07166

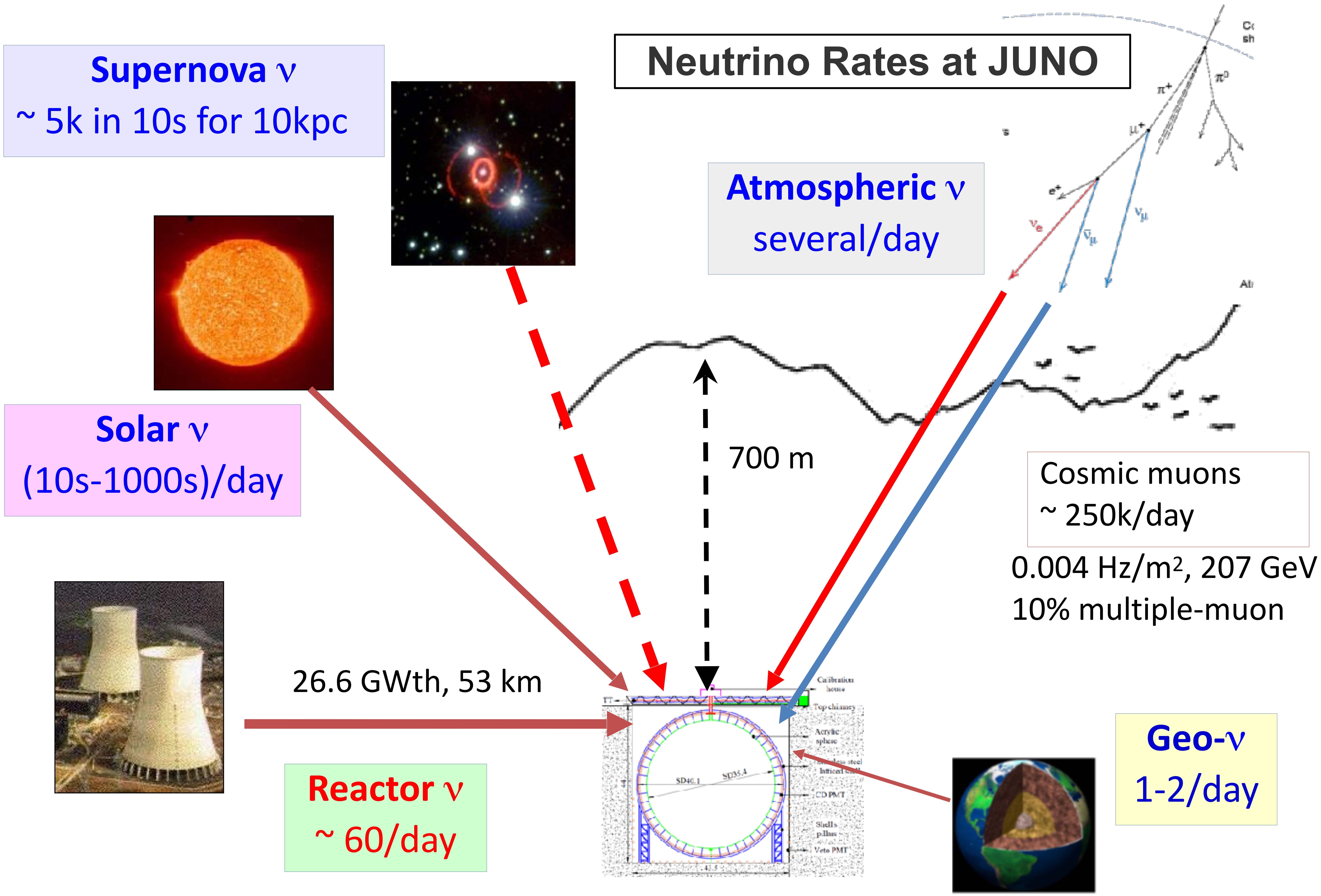


Main physics goal:
ν Mass Ordering determination

Huge mass: ~20 kton Liquid Scintillator (LS)
Underground: ~700 m overburden
Unprecedented energy resolution: 3% / √E (MeV)
Energy scale precision: < 1%

↳ rich physics possibilities

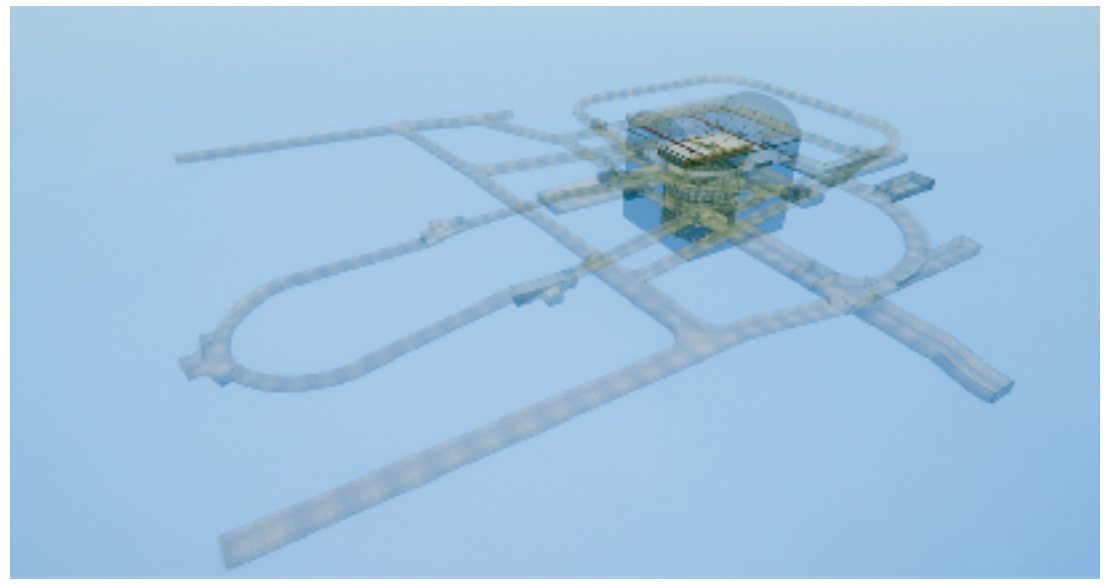
Jiangmen Underground Neutrino Observatory



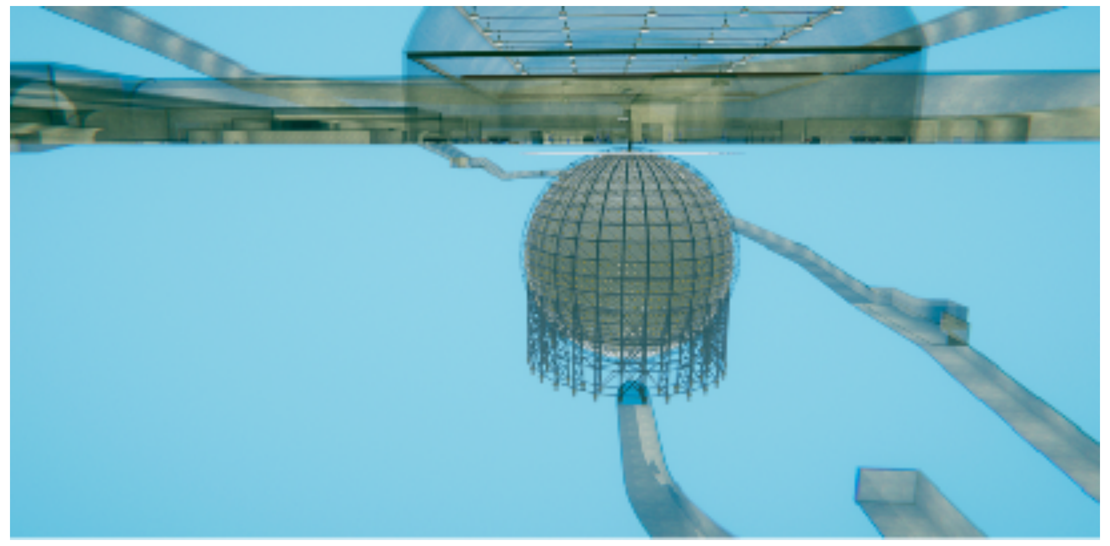
JUNO location

NPP	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	Operational	Planned	Planned	Operational	Operational / Planned
Power	17.4 GW	17.4 GW	17.4 GW	17.4 GW	9.2 GW / 18.4 GW

Total Power:
35.8 → 26.6 GWth

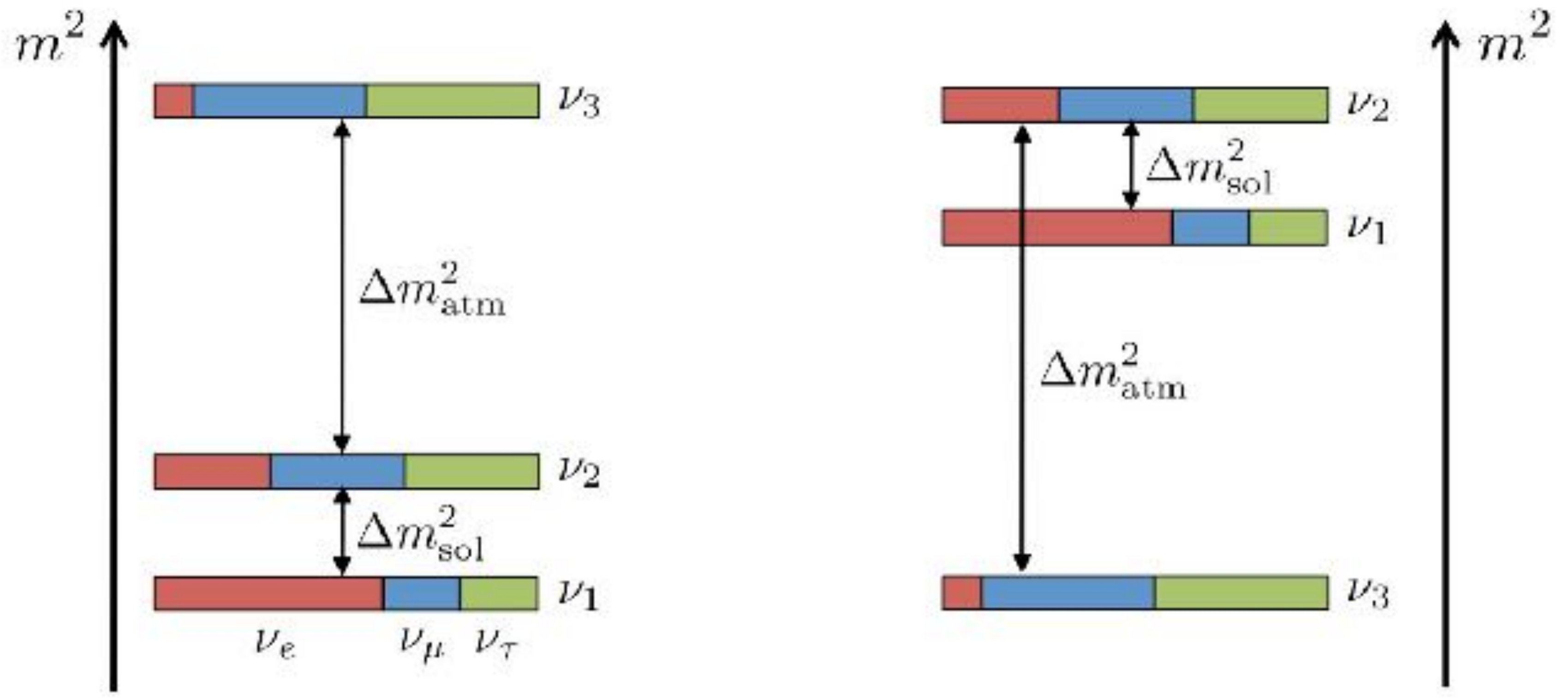


JUNO underground hall



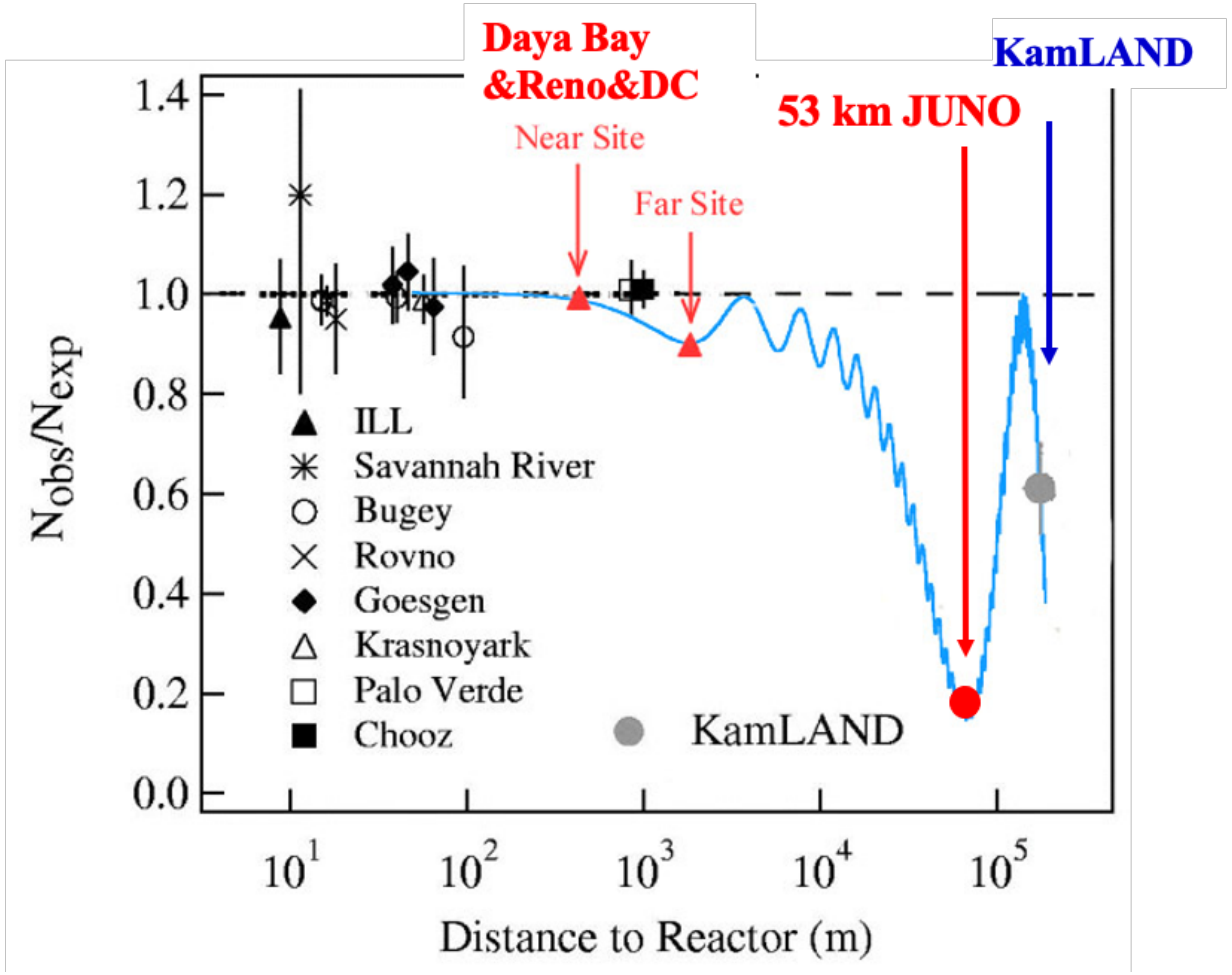
Neutrino mass ordering at reactors

normal ordering (NO) inverted ordering (NO)



NO: $|\Delta m^2_{31}| = |\Delta m^2_{32}| + |\Delta m^2_{21}|$

IO: $|\Delta m^2_{31}| = |\Delta m^2_{32}| - |\Delta m^2_{21}|$



$\bar{\nu}_e$ survival probability:

$$\Delta_{ij} \equiv \frac{\Delta m^2_{ij} L}{4E_\nu}$$

$$P_{ee}(L/E) = 1 - P_{21} - P_{31} - P_{32}$$

$$P_{21} = \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21})$$ → SLOW Δm_{sol}^2

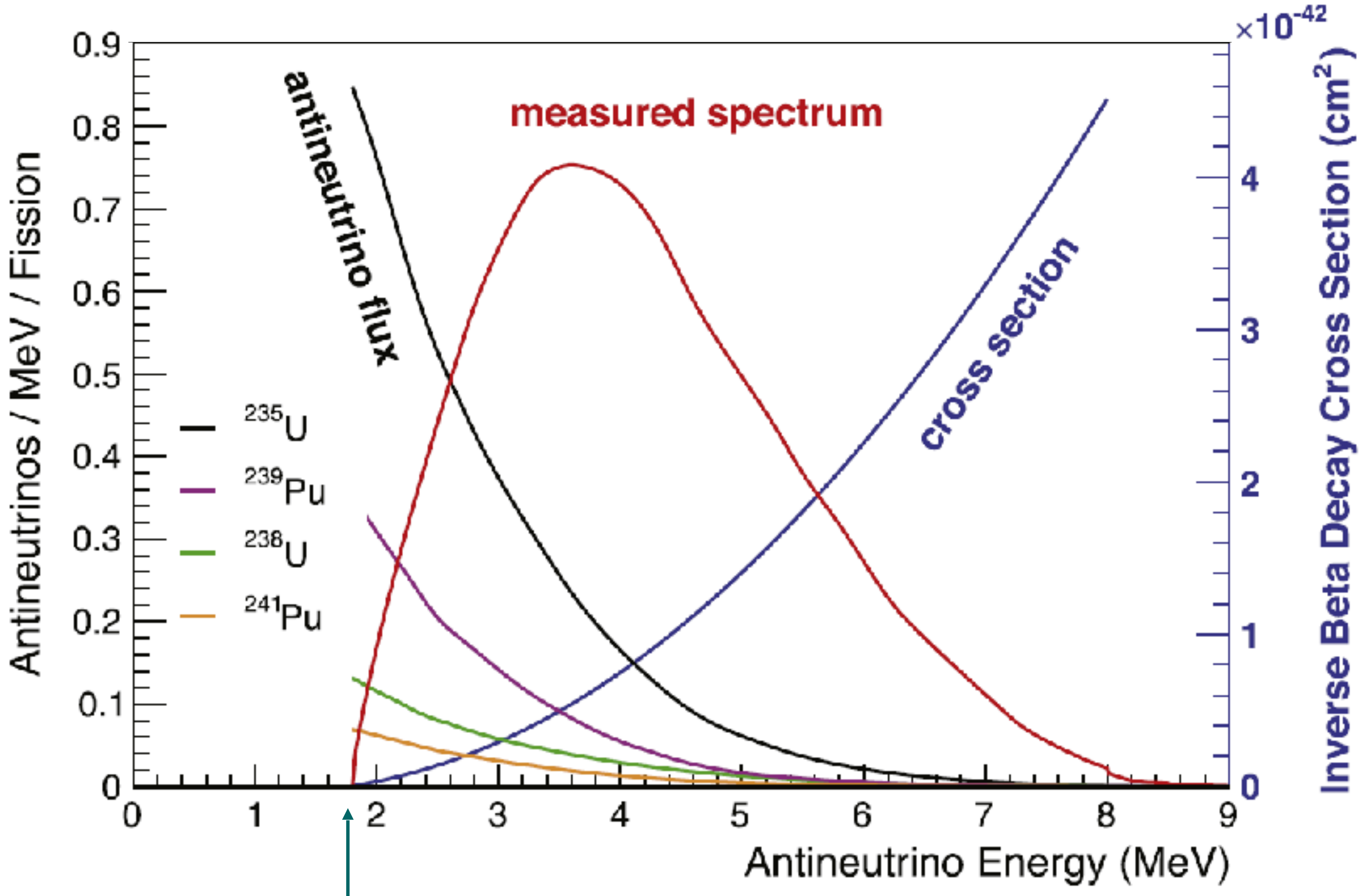
$$P_{31} = \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31})$$

$$P_{32} = \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32}),$$

→ FAST Δm_{atm}^2

→ Independent of θ_{23} and CP phase

Reactor antineutrino detection



Energy threshold: 1.8 MeV

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

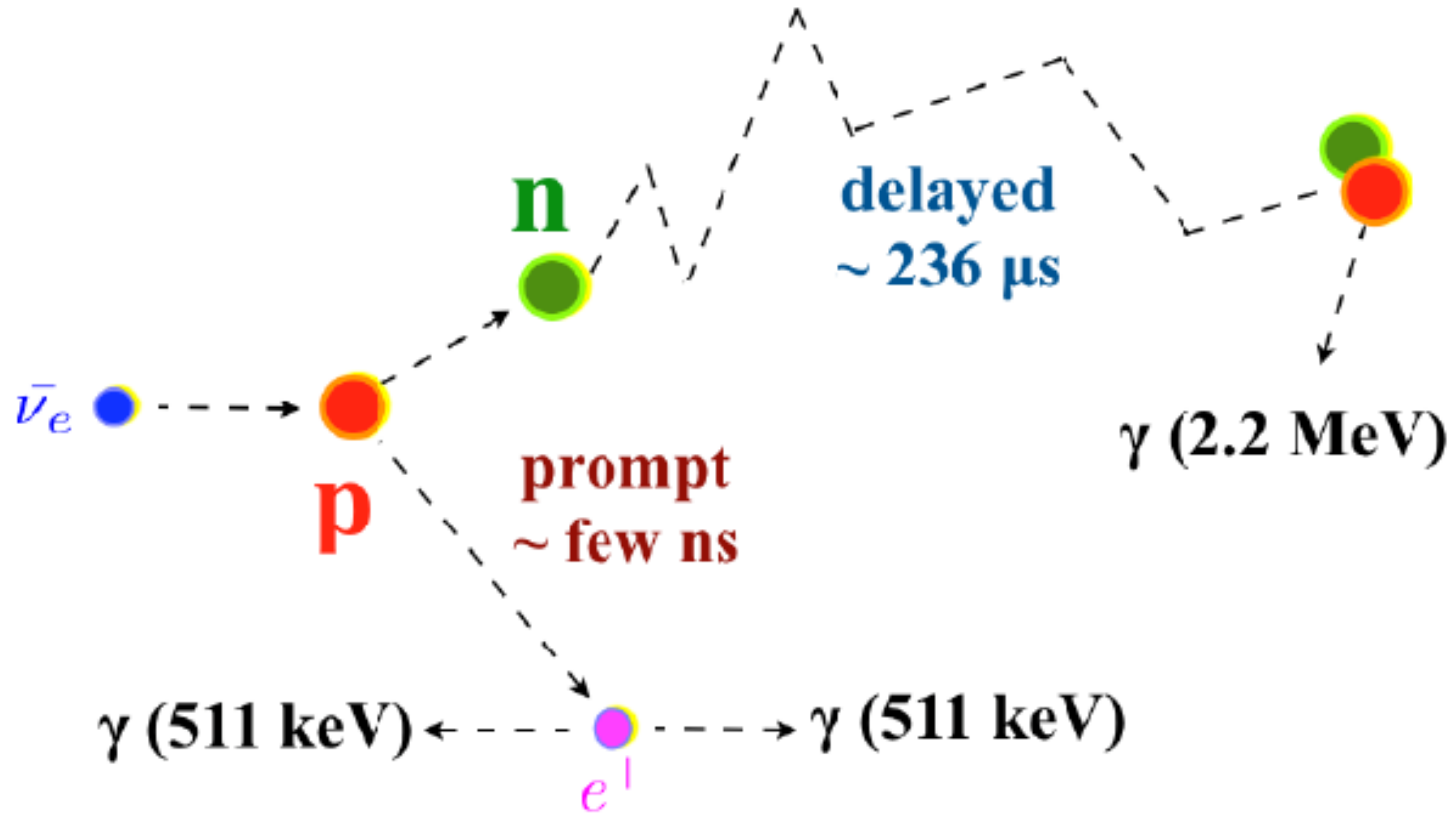
- E_{vis} (e+) ≃ E ($\bar{\nu}_e$) – 0.78 MeV
- Space-Time coincidences between prompt and delayed signals to reject uncorrelated background

Antineutrinos from reactors

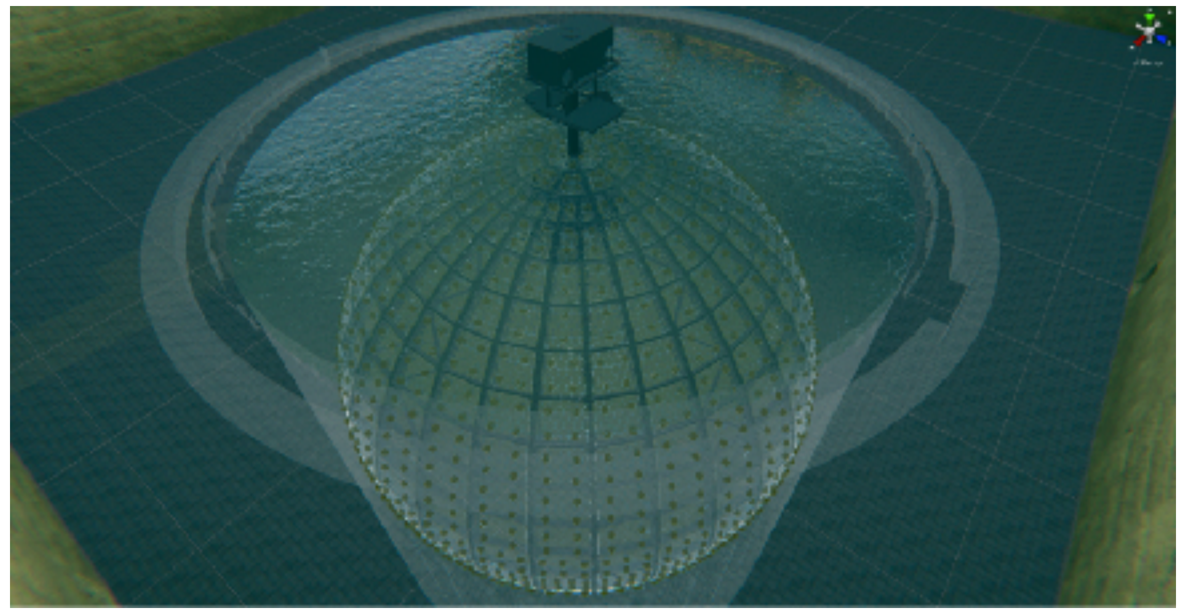
Cascade of beta decays from unstable fission fragments:

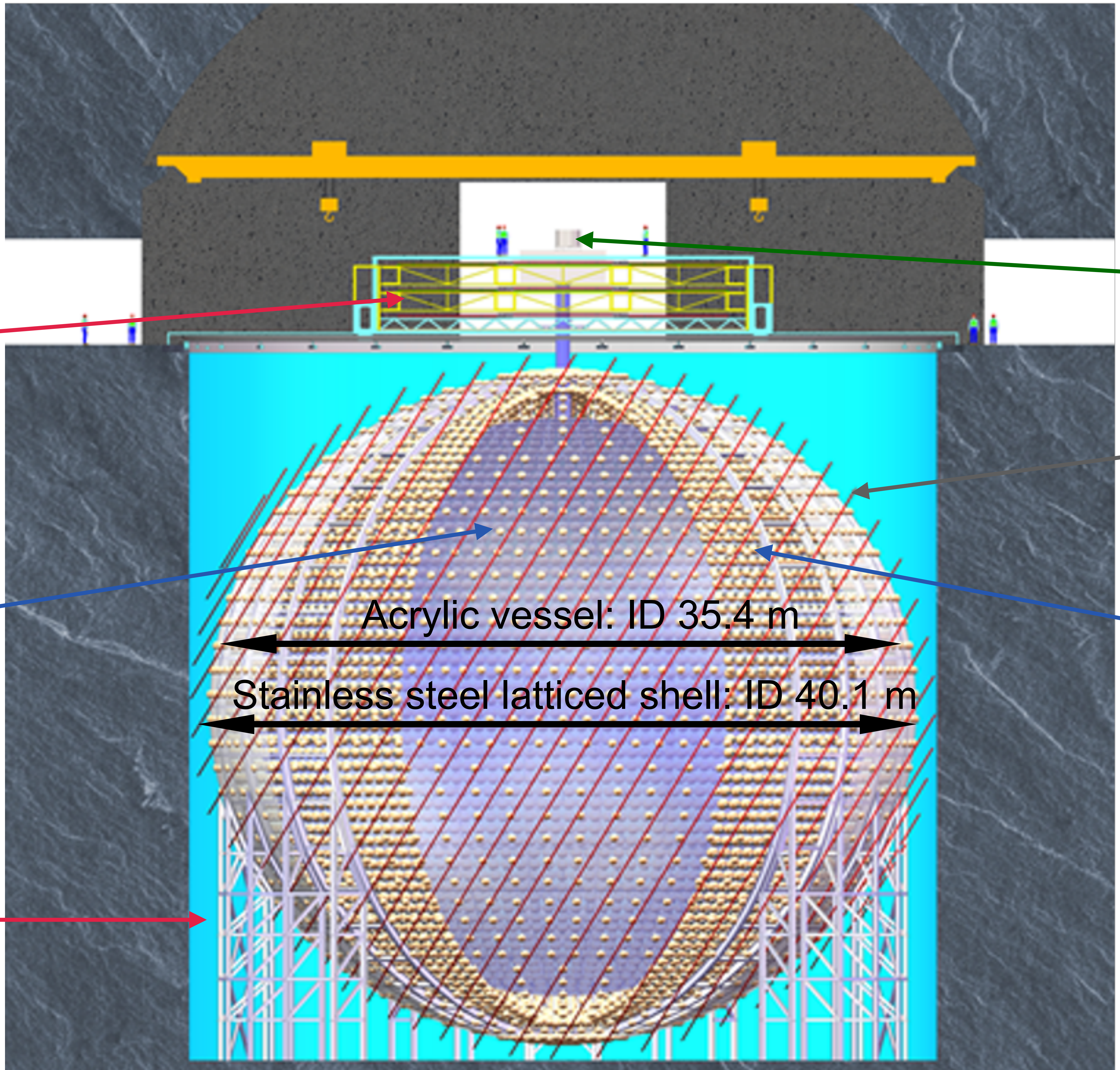
3 GW_{th} reactor → ~10^{21} $\bar{\nu}_e$/s

Inverse Beta Decay (IBD) reaction



Detector challenges





Top Tracker (TT):
3 plastic scintillator layers

Calibration house

Earth magnetic field shielding coils

Central Detector (CD):
Steel structure +
Acrylic vessel +
20 kton Liquid Scintillator (LS)

Light read-out:
~ 17612 20-inch PMTs
~ 25600 3-inch PMTs

Water Cherenkov Detector (WCD):
~ 2400 20-inch PMTs

Pool's dimensions
- height: 44 m
- diameter: 43.5 m
- water depth: 43.5 m

Experiment	Daya Bay	BOREXINO	KamLAND	JUNO
LS mass	20 ton	~ 300 ton	~ 1 kton	20 kton
Coverage	~ 12%	~ 34%	~ 34%	~ 78%
Energy	~ 7.5% /√E	~ 5% /√E	~ 6% /√E	~ 3% /√E
Light yield	~ 160 p.e. /MeV	~ 500 p.e. /MeV	~ 250 p.e. /MeV	~ 1300 p.e. /MeV

Overall detector design

Central detector:

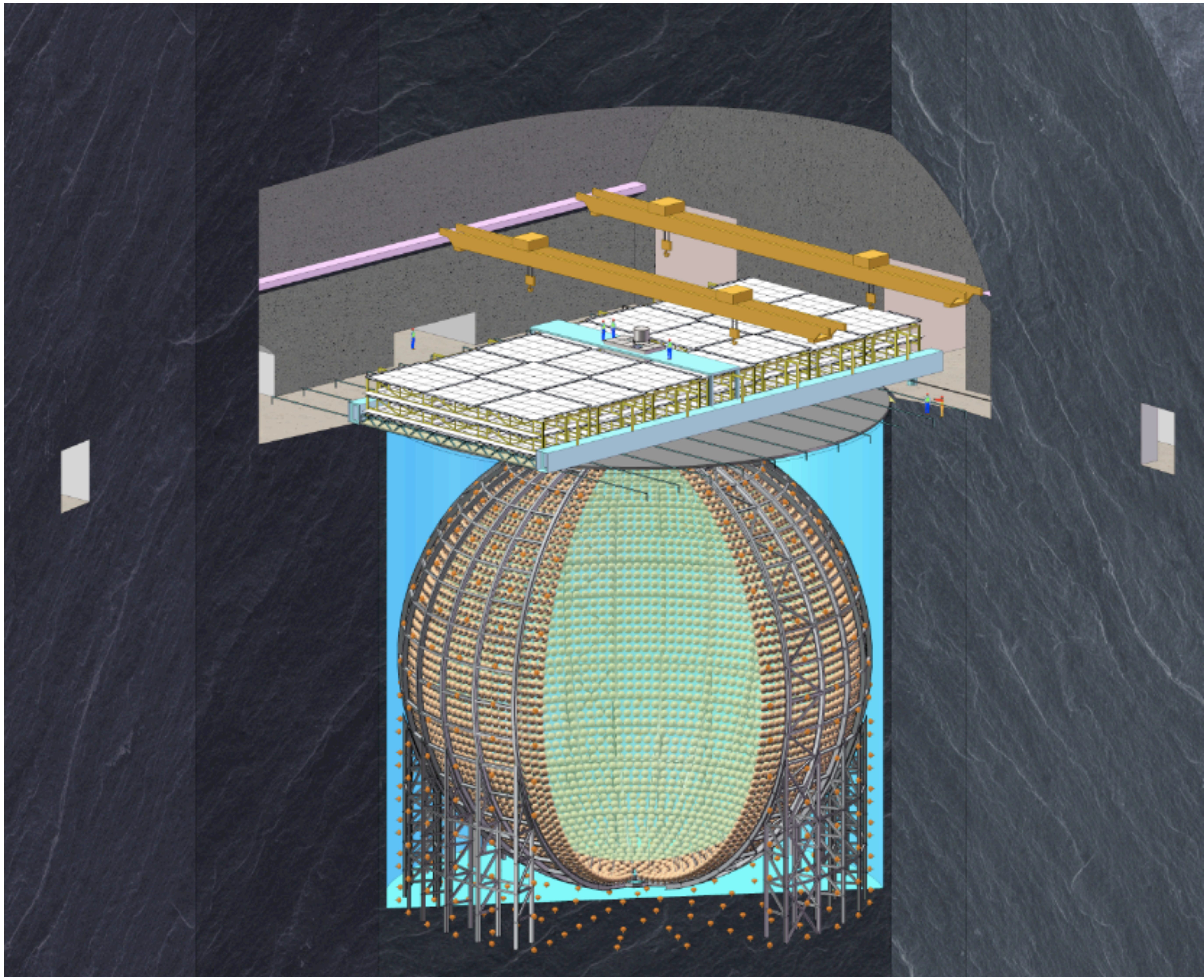
- acrylic vessel with liquid scintillator
- 17612 large PMTs (20-inch)
- 25600 small PMTs (3-inch)
- ~ 78% PMT coverage
- PMTs in water buffer

Water Cherenkov Detector (veto):

- 2400 20-inch PMTs
- 35 ktons ultra-pure water
- Muon detection efficiency > 99%

Top Tracker (veto):

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



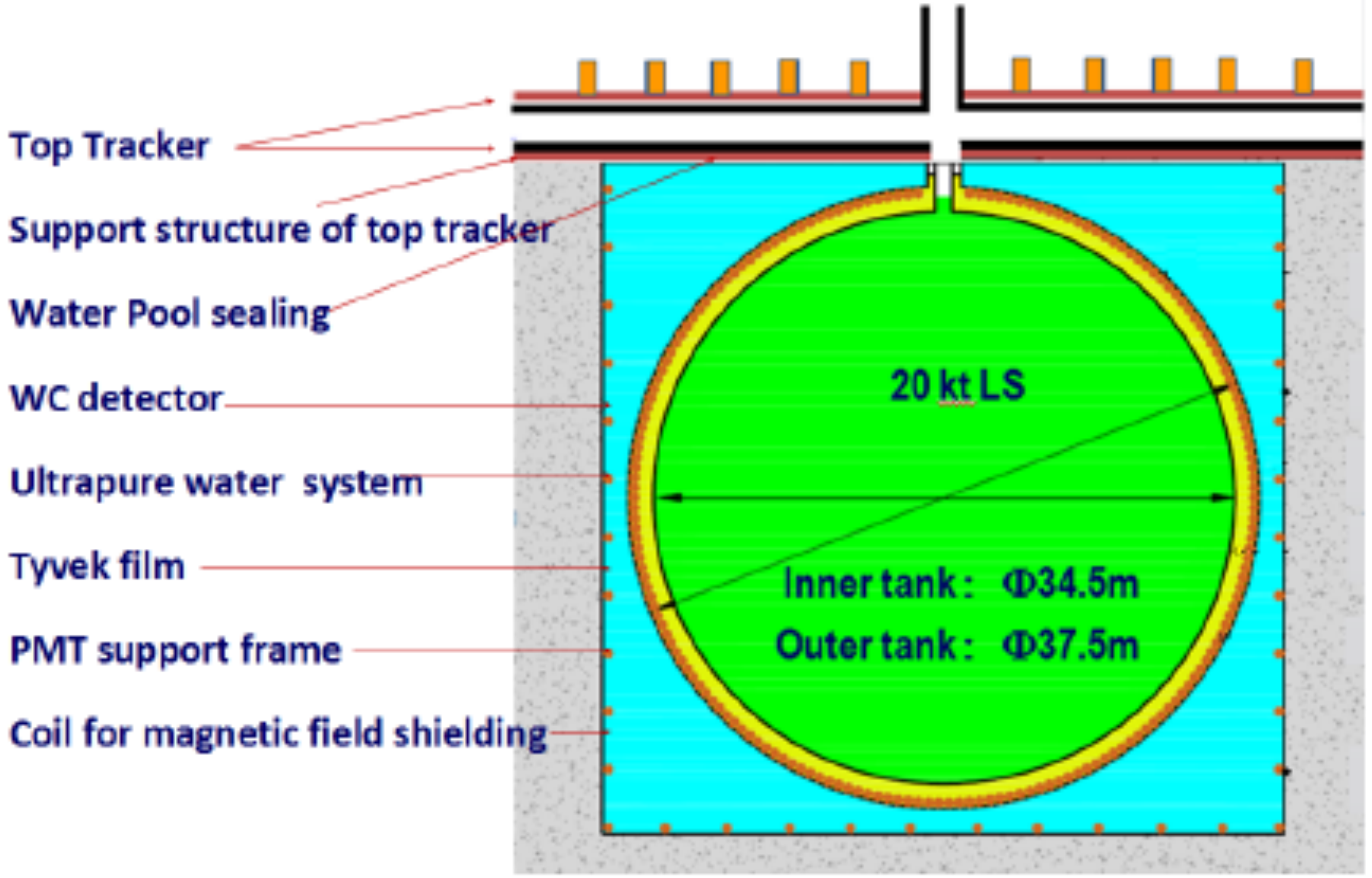
Muon Veto

Tasks:

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

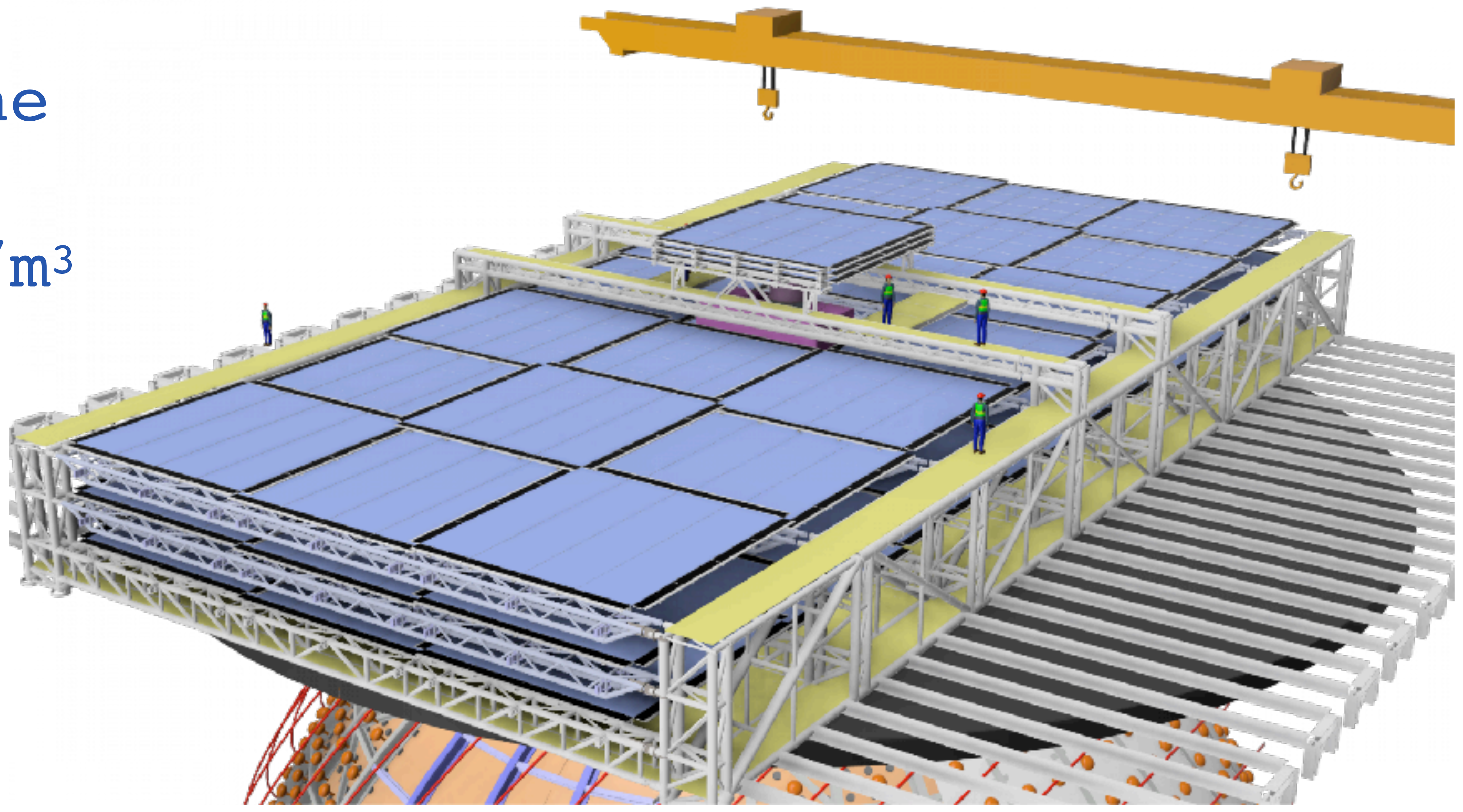
Detectors:

- Top tracker: refurbished OPERA scintillators
- Water Cherenkov detector



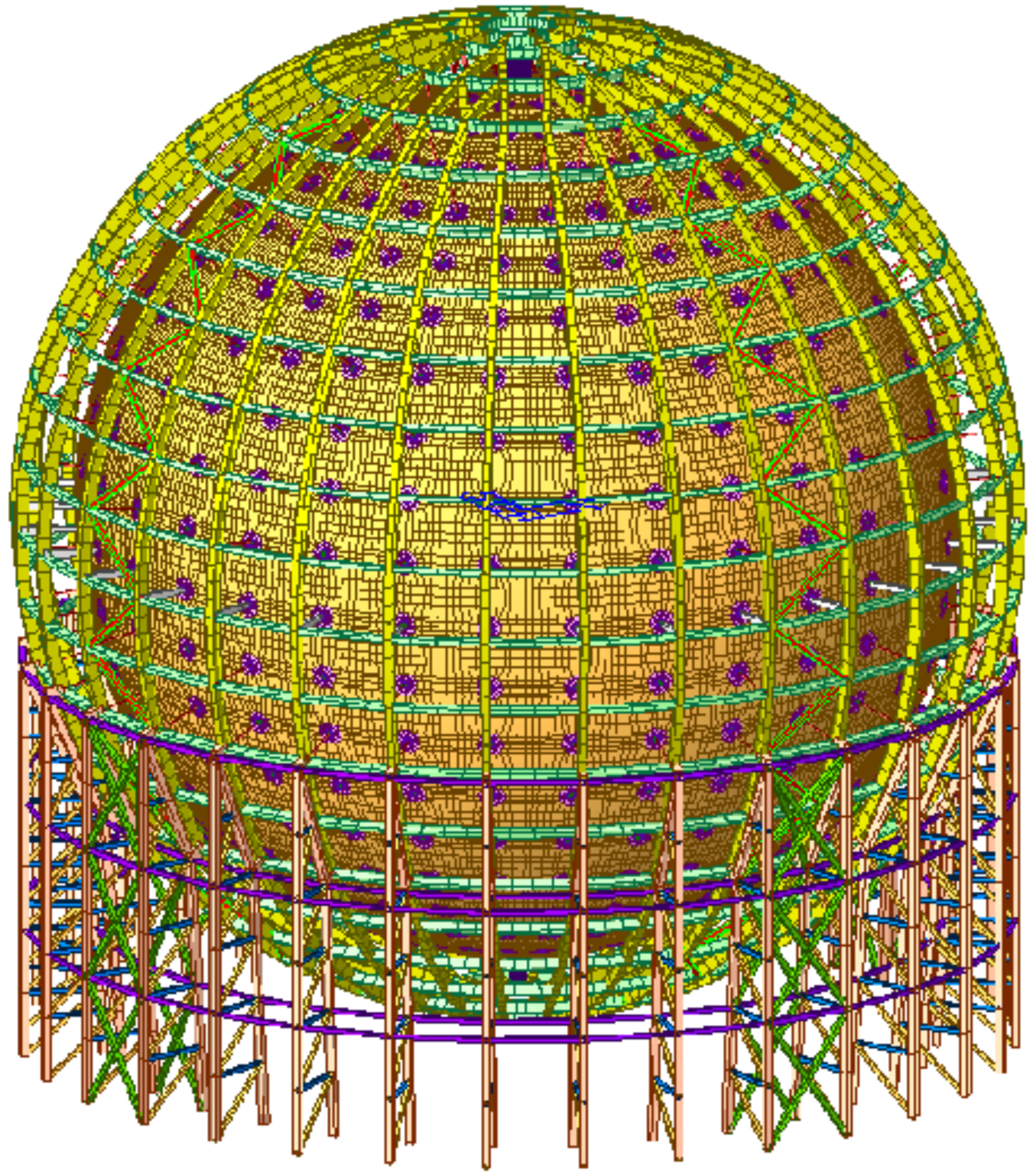
Main features:

- Careful temperature stabilization of the water at 21±1 °C
- Radon control in water → target 10 mBq/m^3
- Earth magnetic field compensation coil (needed for 20-inch PMTs)
- Pool lining: HDPE
- Pool sealing with a black rubber

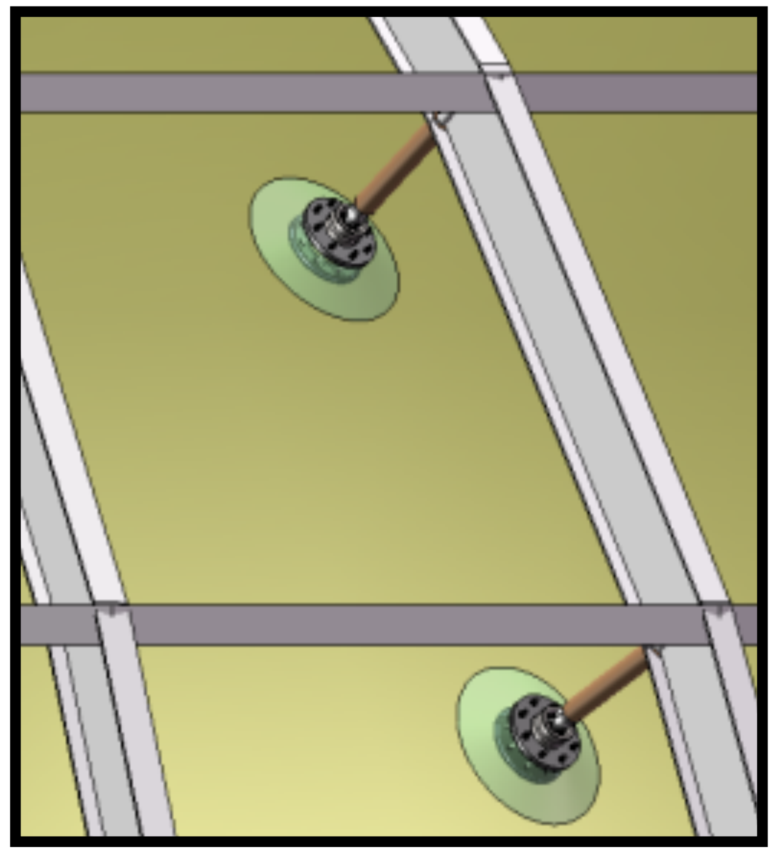


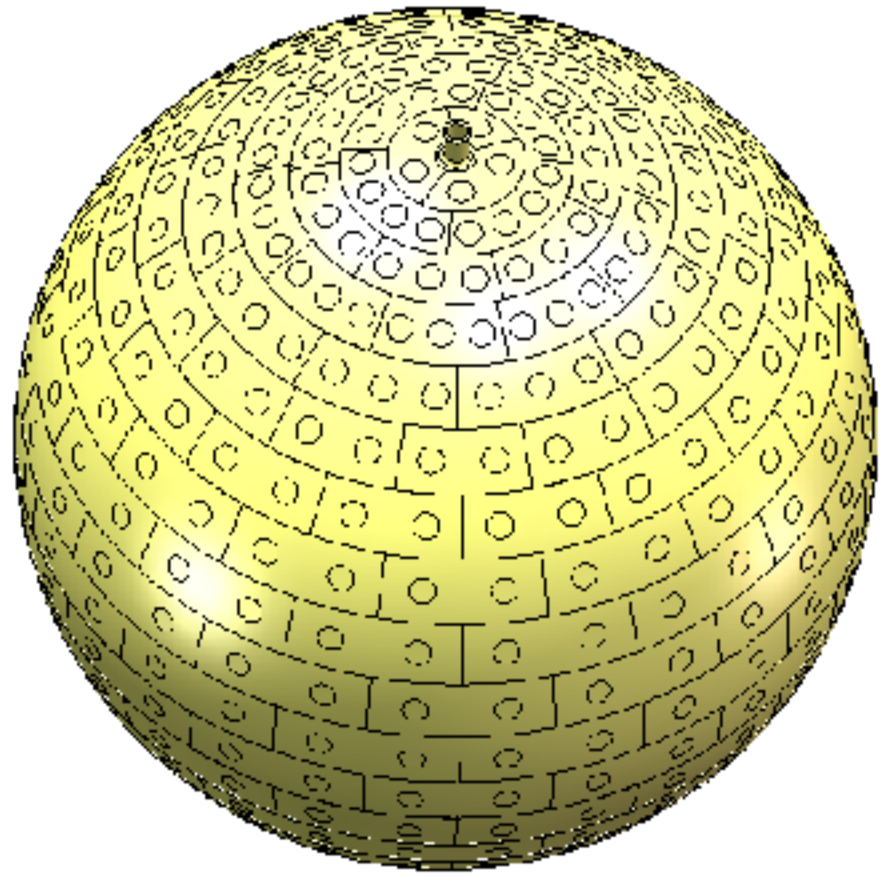
Central Detector: Steel Truss & Acrylic vessel

- **Stainless Steel Structure** to hold the acrylic sphere and to anchor the PMTs
  - rooted on the concrete floor of the water pool
  - supporting bars to hold the acrylic vessel
  - mechanical precision for 3 mm PMT clearance
  - earthquake-safe structure
  - Steel radiopurity U/Th/K: ≲ ppb



- **Acrylic Vessel** main issues:
  - built by bulk polymerization of 265 spherical panels
  - maximal stress < 3.5 MPa everywhere
  - thermal expansion matching: 21°C ± 1°C
  - transparency > 96%
  - Acrylic radiopurity U/Th/K: < 1 ppt

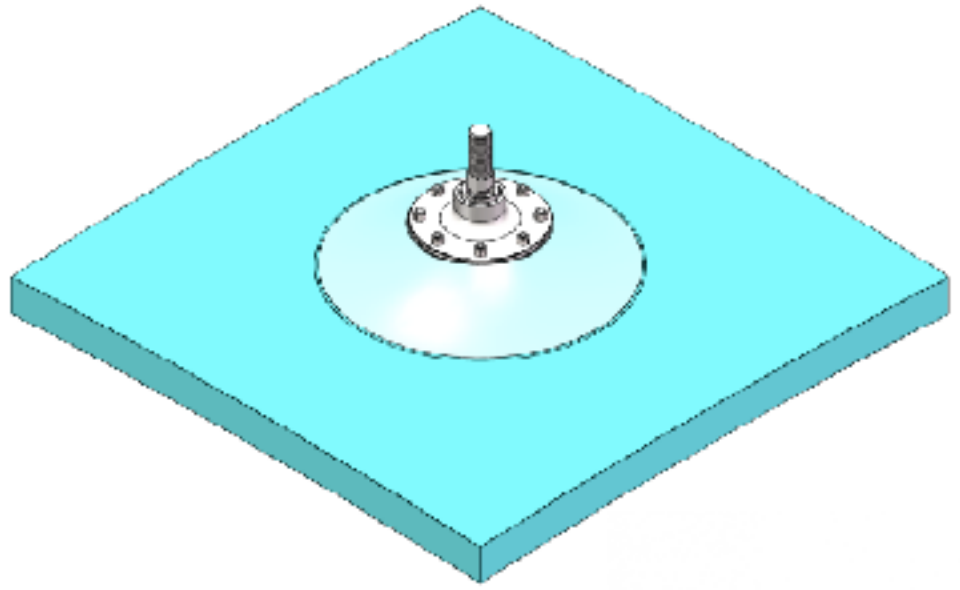


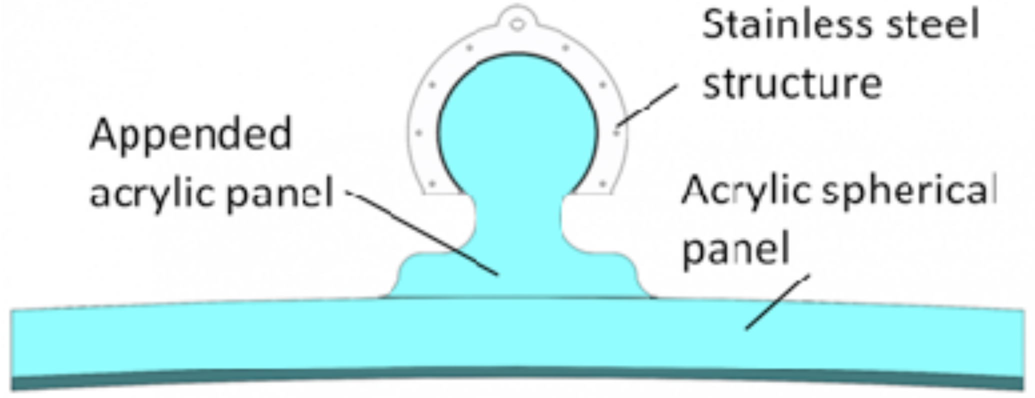


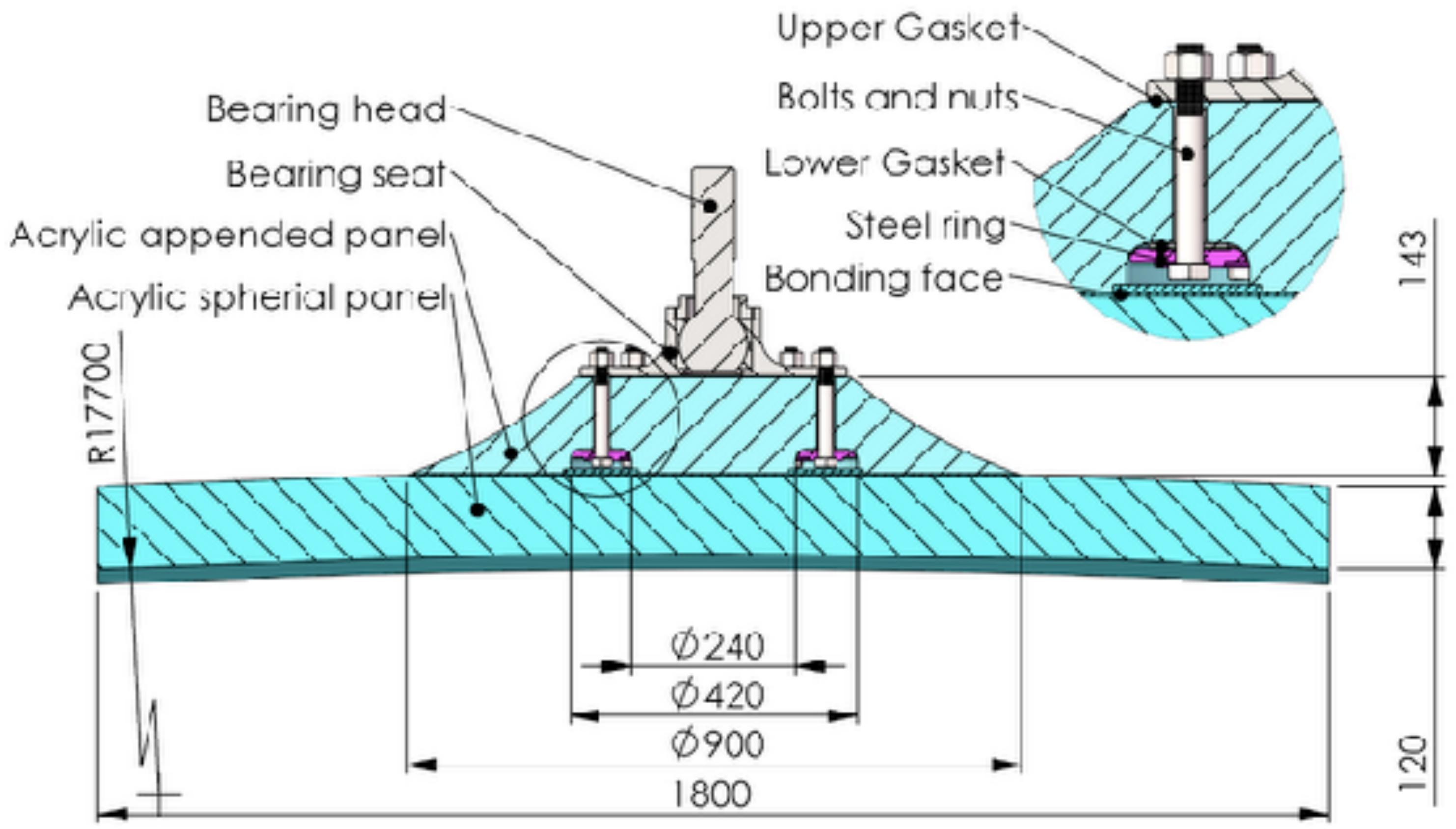
Central Detector: Steel Truss & Acrylic vessel

Acrylic panel mass production ongoing

Panel size: 3 m × 8 m × 120 mm



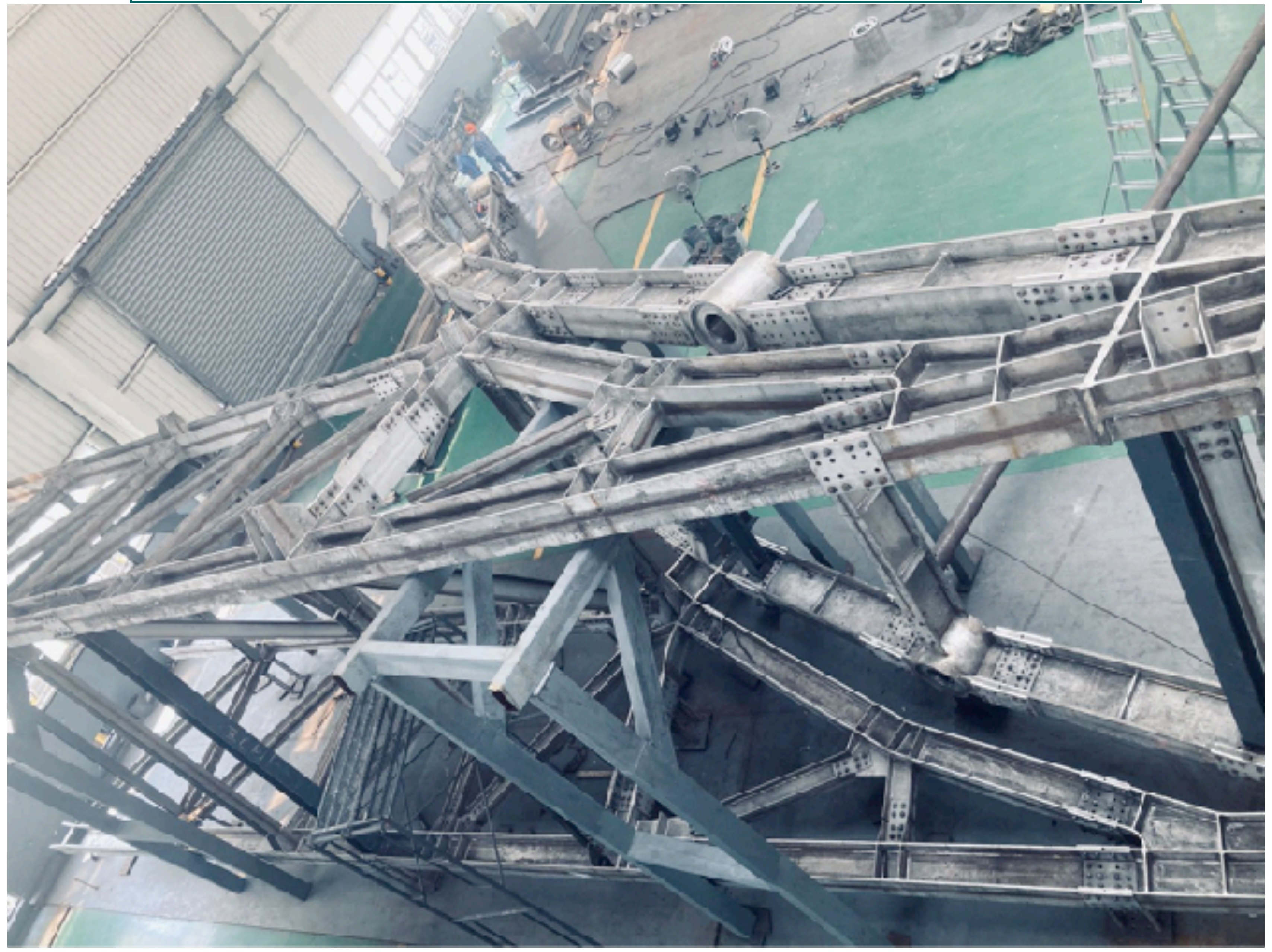




Pre-assemble of lifting platform

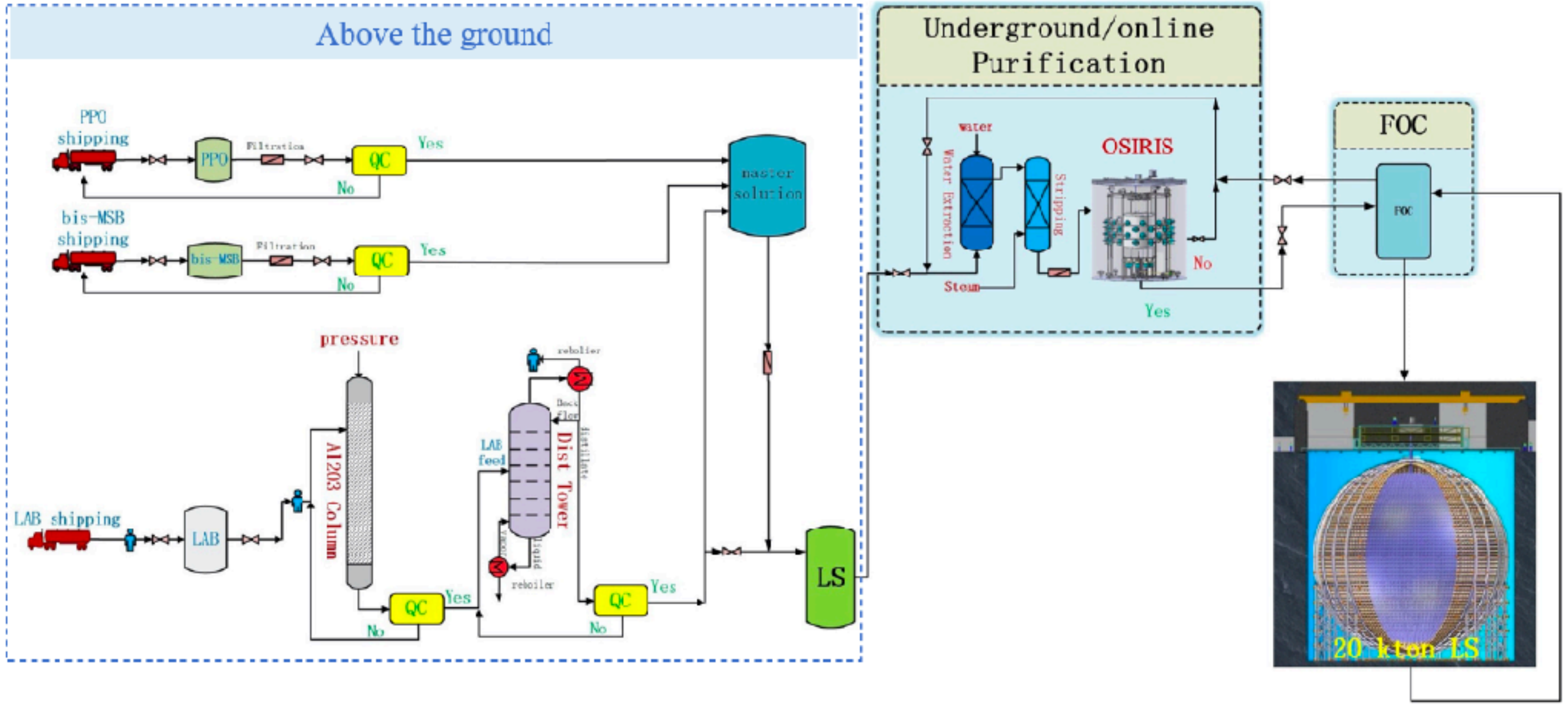
Acrylic panel assembly test

Production of stainless steel structure



Central Detector: Liquid Scintillator

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



Purification of LAB in 4 steps:

- Al_2O_3 filtration column
  - ➡ improvement of optical properties
- Distillation
  - ➡ removal of heavy metals
  - ➡ improvement of transparency
- Water Extraction (underground)
  - ➡ removal of radioisotopes from U/Th/K
- Steam / Nitrogen Stripping (underground)
  - ➡ removal of gaseous impurities (Ar, Kr, Rn)

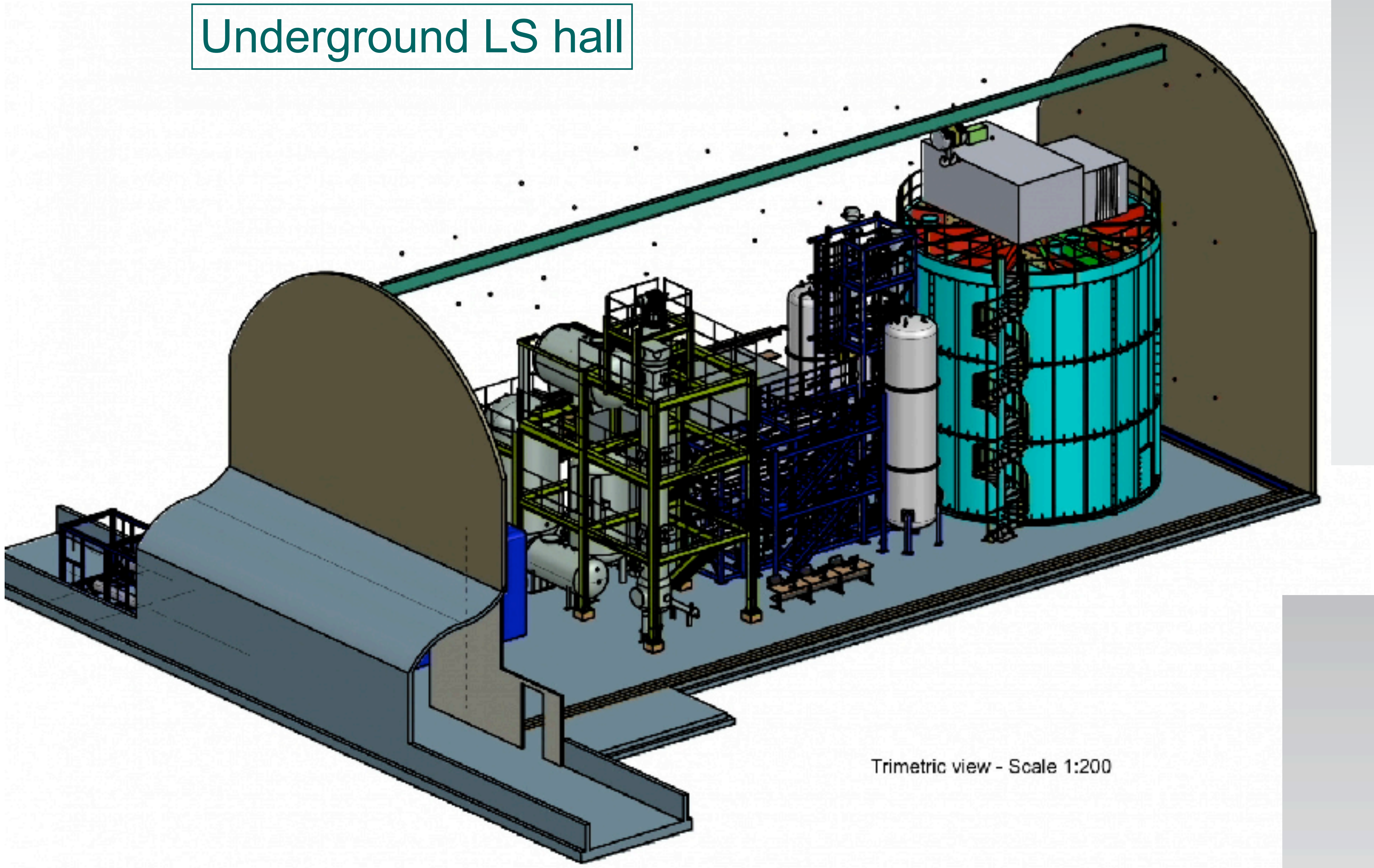
Required radiopurity:

➔ Reactor neutrinos:
^{238}U / ^{232}Th < 10^{-15} g/g
^{40}K < 10^{-16} g/g
^{210}Pb < 10^{-22} g/g

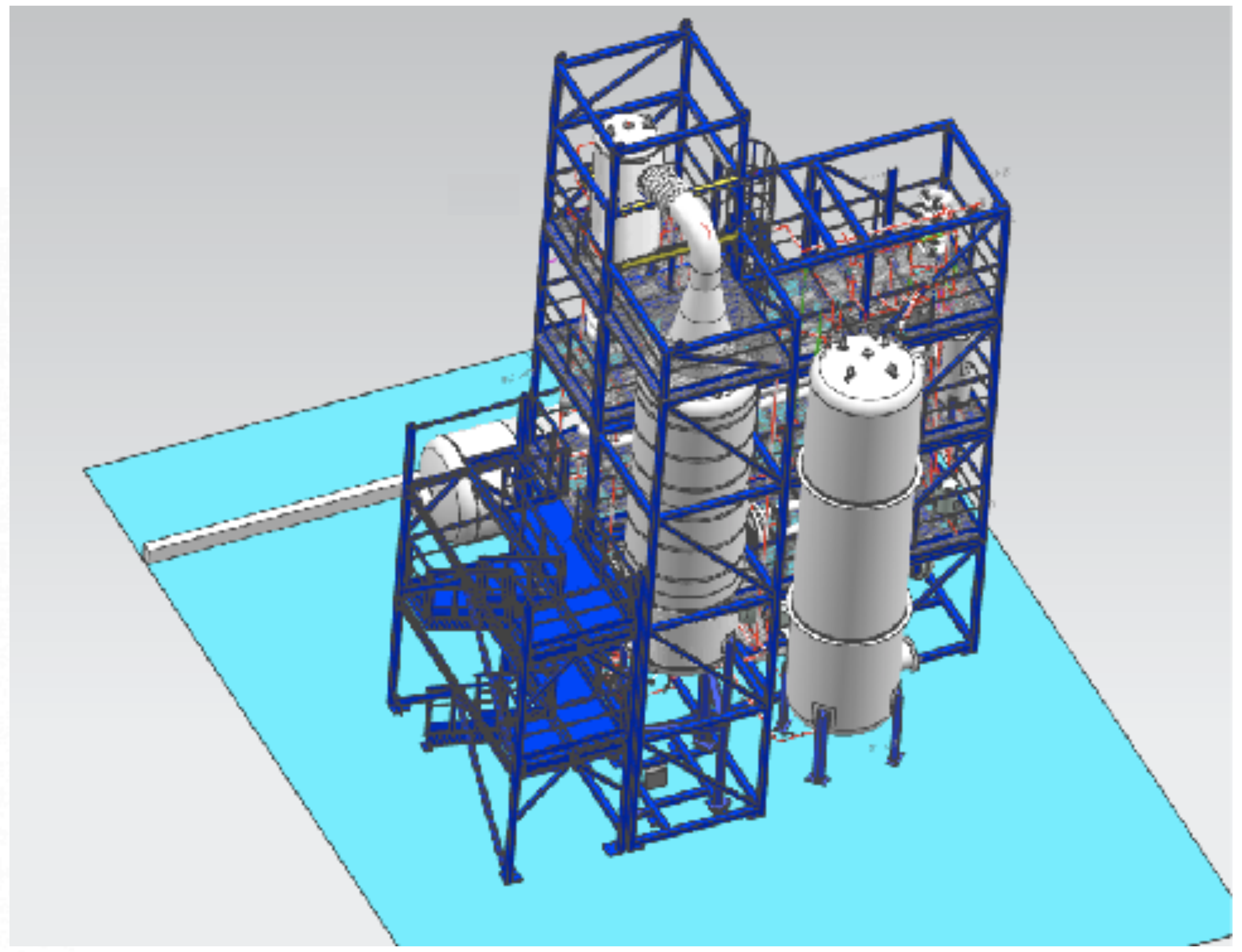
➔ Solar neutrinos:
^{238}U / ^{232}Th < 10^{-17} g/g
^{40}K < 10^{-18} g/g
^{210}Pb < 10^{-24} g/g

Central Detector: Liquid Scintillator

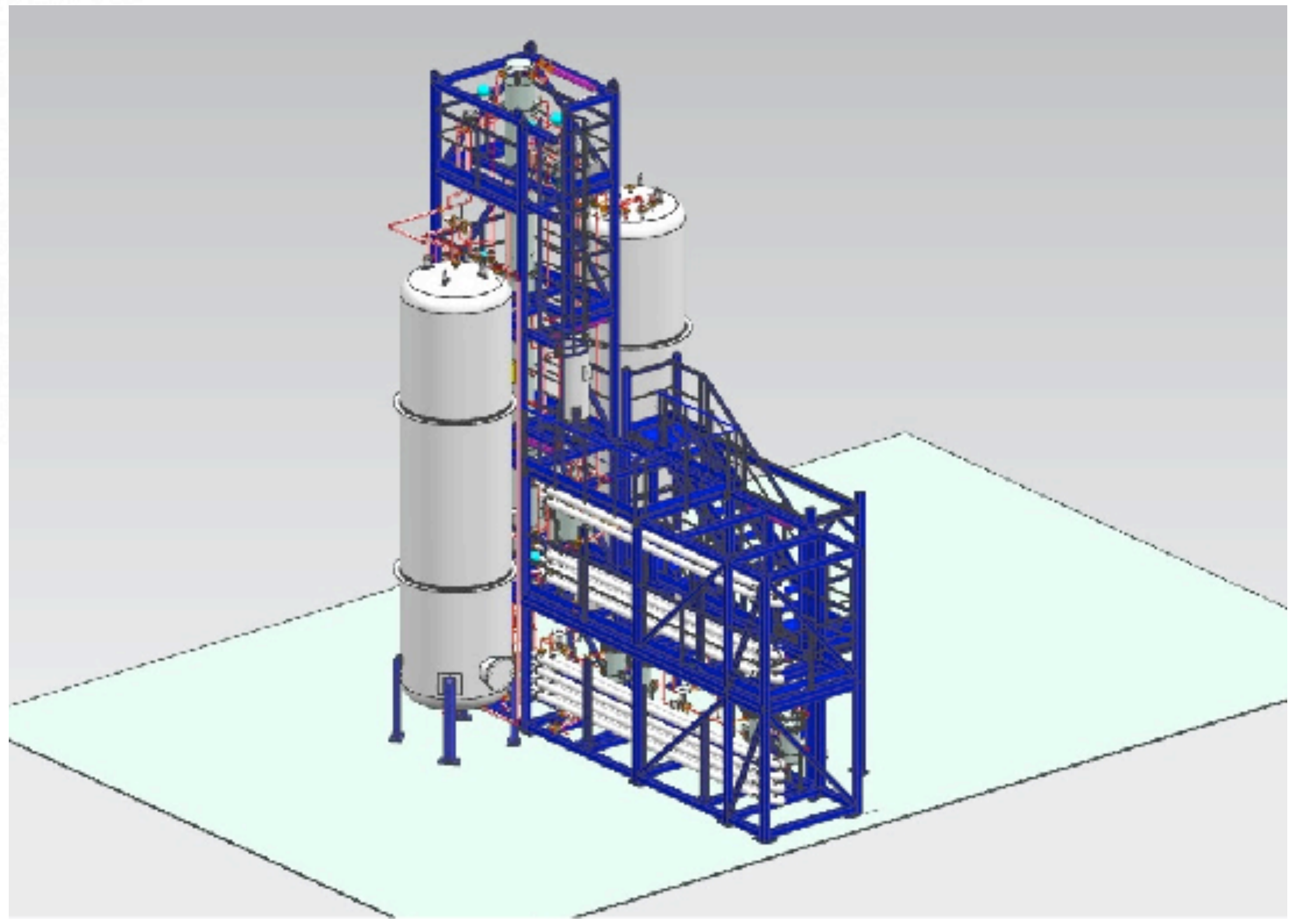
Underground LS hall



Distillation plant

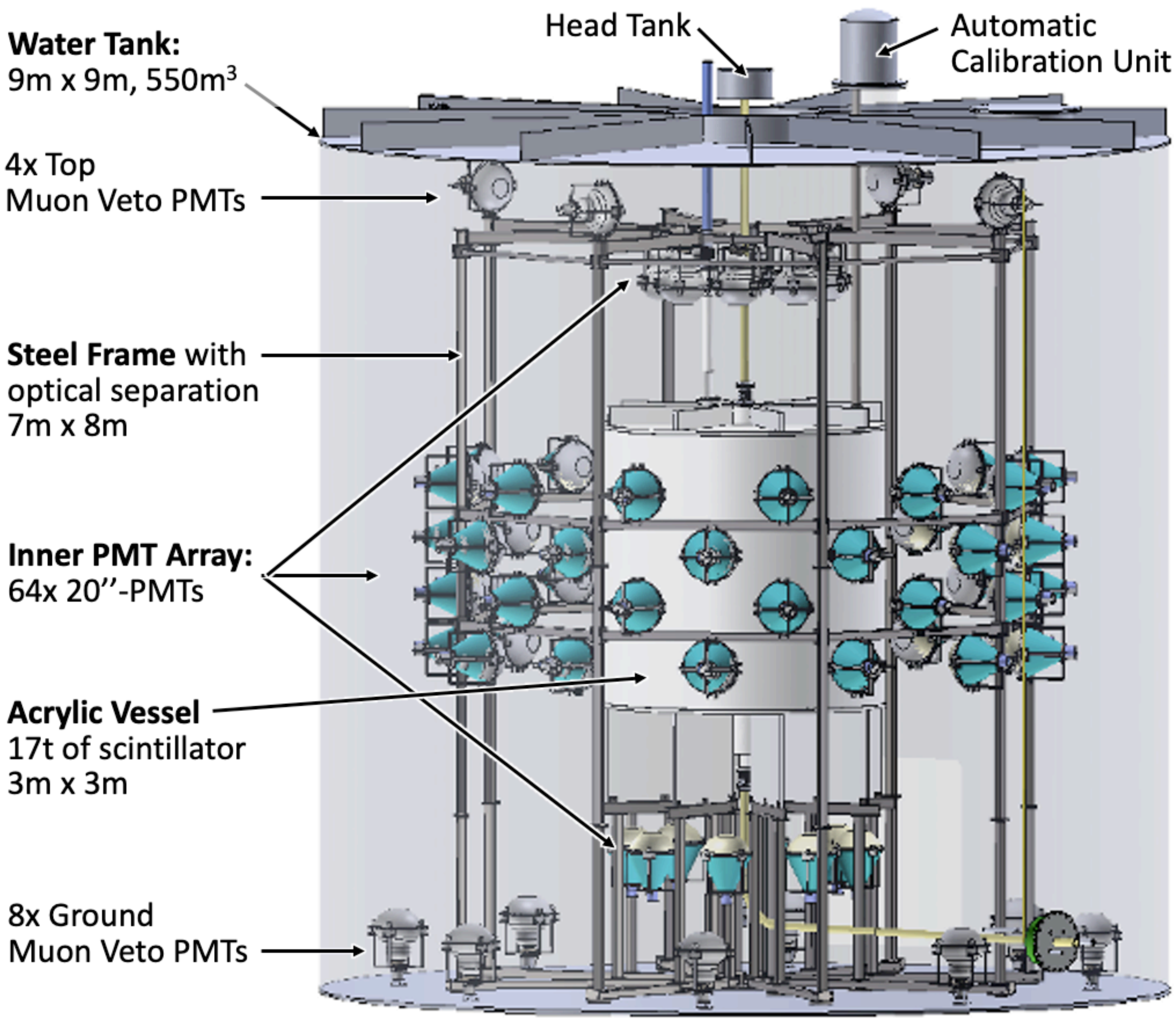


Stripping plant



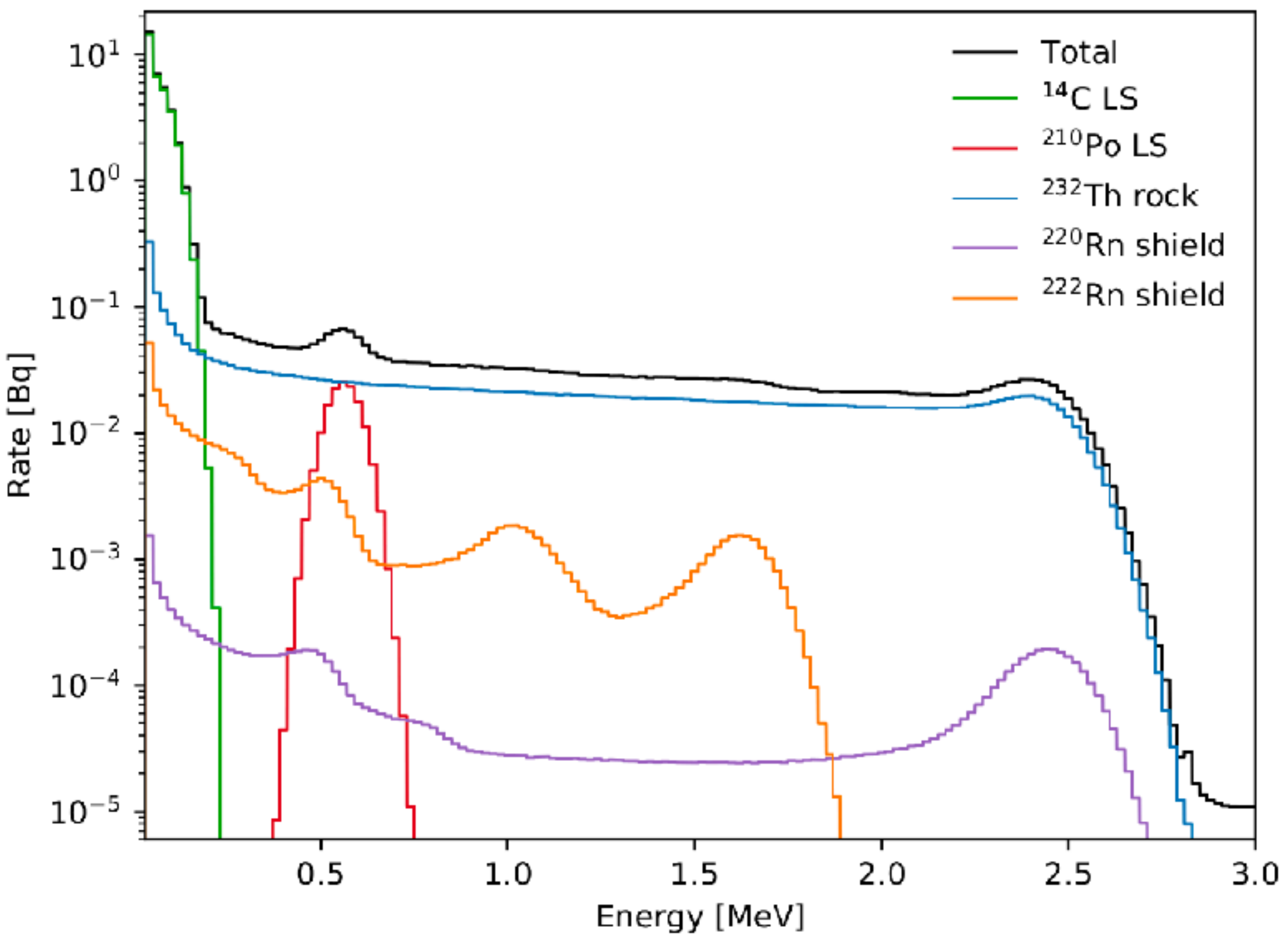
OSIRIS Detector

Online Scintillator Internal Radioactivity Investigation System



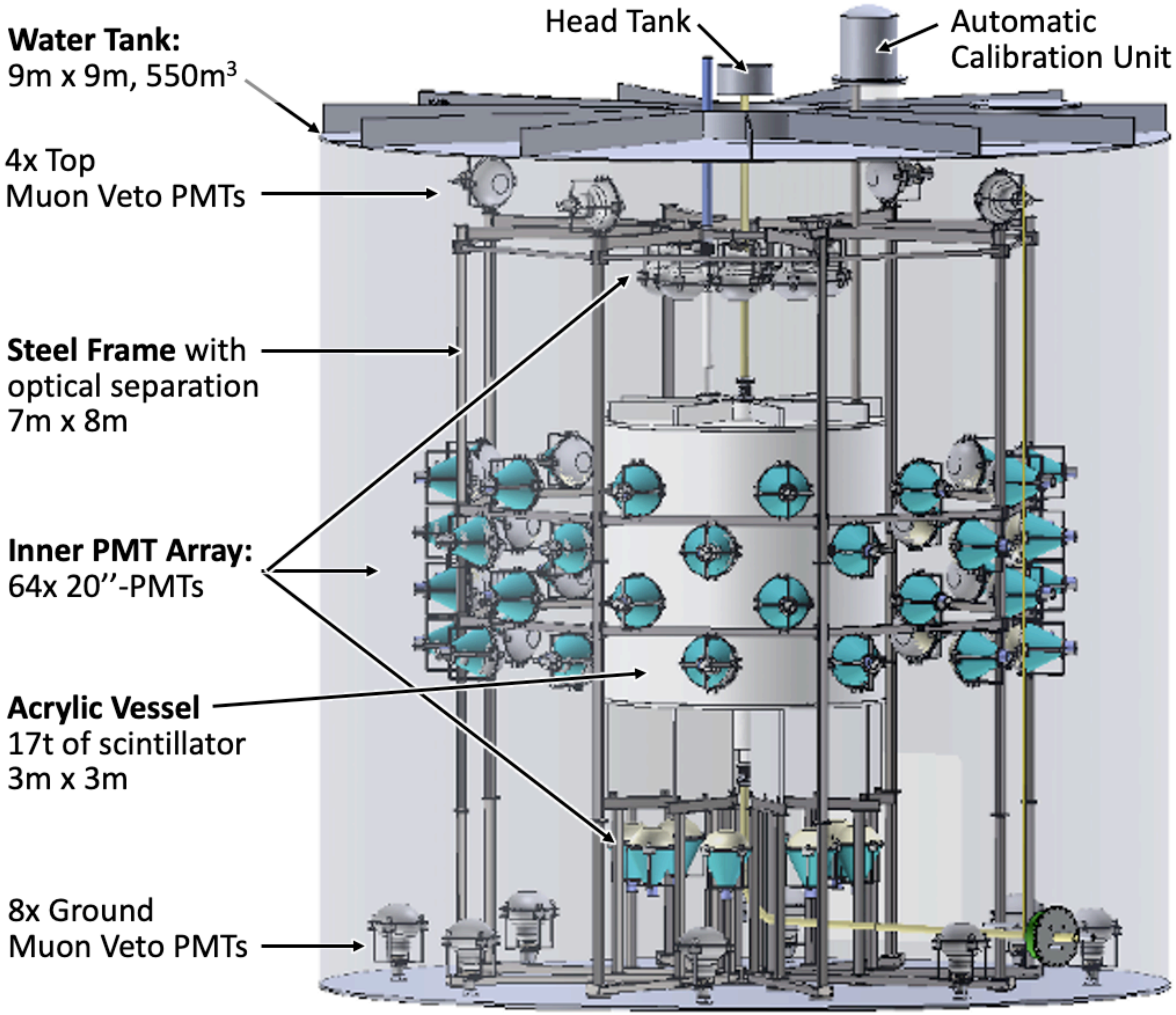
- Exploit fast coincidences in the ^{238}U and ^{232}Th chains
- 18 ton LS volume (Ø=3 m, H=3 m)
- Instrumentation:
  68x 20″ PMTs for the scintillator
  12x 20″ PMTs for the muon veto

Total expected background contribution in OSIRIS

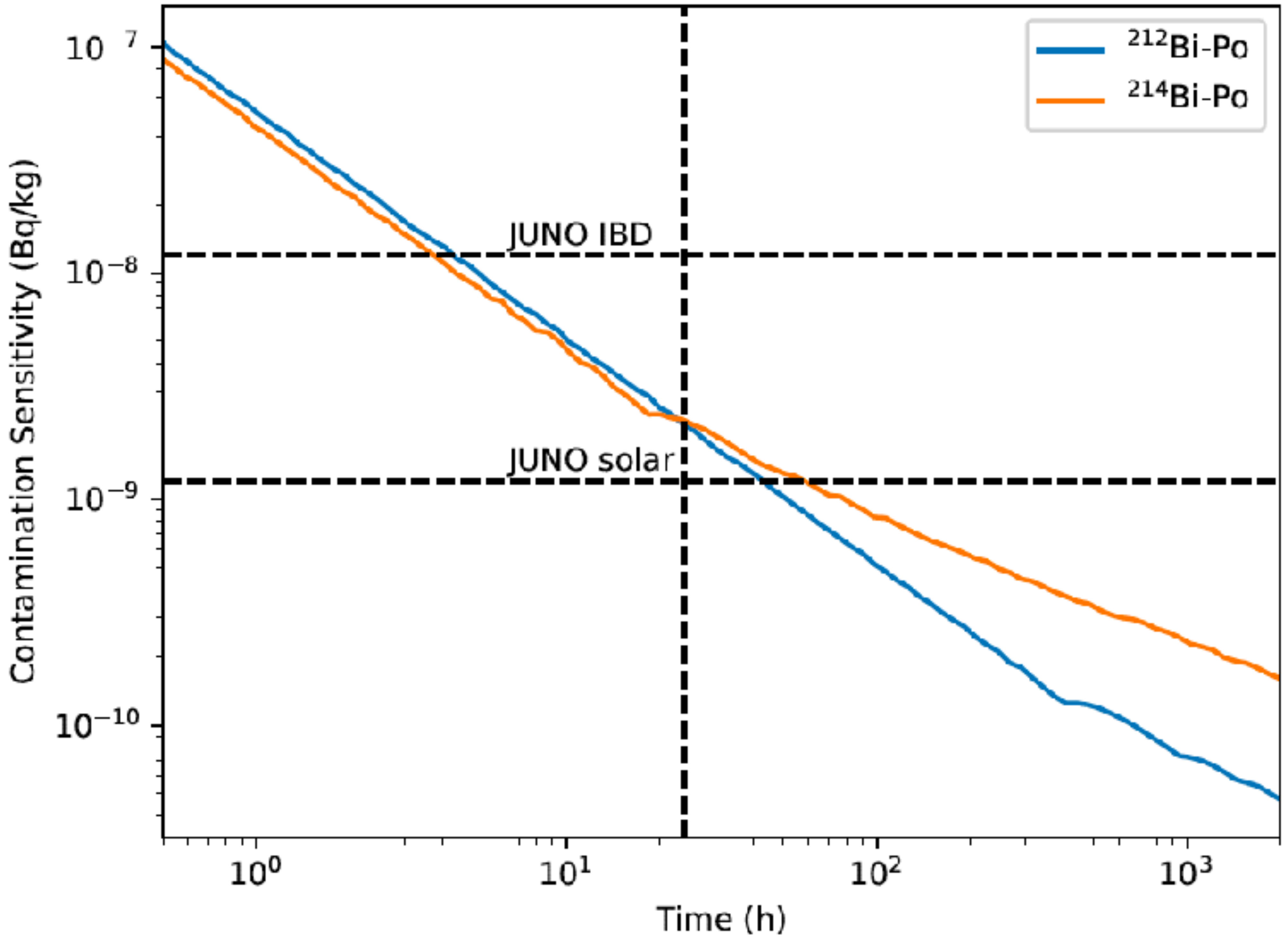


OSIRIS Detector

Online Scintillator Internal Radioactivity Investigation System



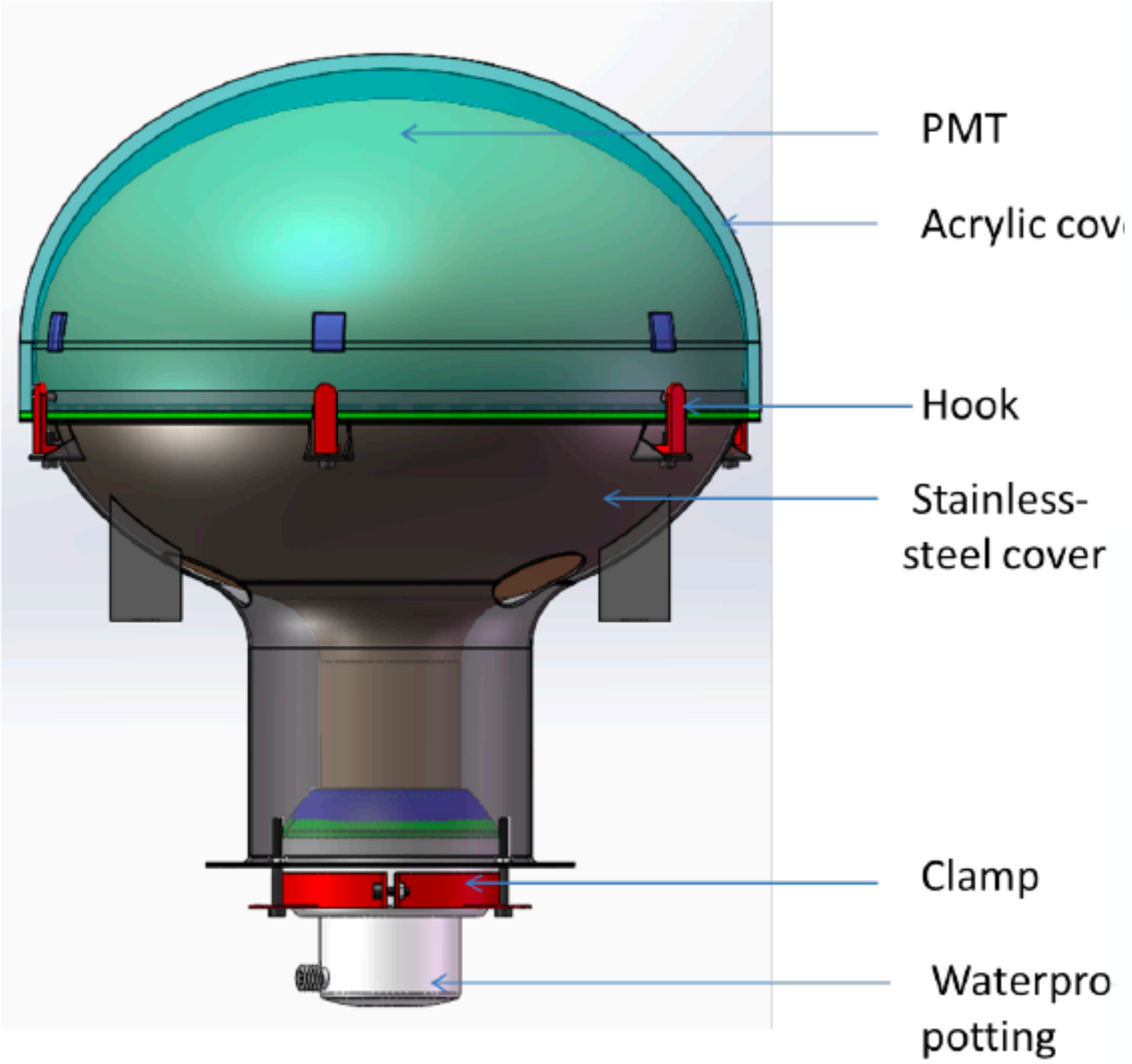
Few hours to verify compliance to JUNO IBD requirements



Central Detector: Large (20”)PMT system

- 15000 MCP-PMTs from NNVT (Northern Night Vision Technology)
- 5000 dynode PMTs from Hamamatsu (R12860 HQE)
- 17612 PMTs will collect the scintillation light of the CD
- In production since 2016
- Bare PMT testing completed

Specifications	Unit	MCP-PMT (NNVT)	R12860 Hamamatsu HQE
Det. Efficiency (QE*CE) (PDE)	%	26.9% (new Type: 30.1%)	28.1%
Peak to Valley of SPE		3.5, (>2.8)	3, (>2.5)
TTS on the top point	ns	12, (<15)	2.7, (<3.5)
Rise time / Fall Time	ns	RT~2, FT~12	RT~5, FT~9
Anode Dark Count	kHz	20, (<30)	10, (<50)
After Pulse Rate	%	1, (<2)	10, (<15)
Radioactivity (glass)	ppb	^{238}U: 200 ^{232}Th: 120 ^{40}K: 4	^{238}U: 400 ^{232}Th: 400 ^{40}K: 40



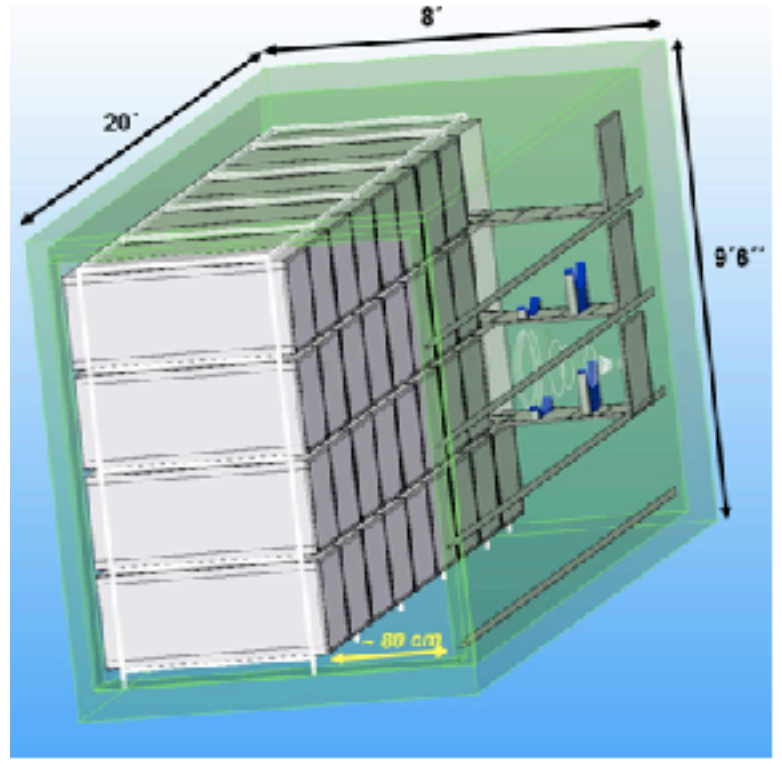
Hamamatsu PMT

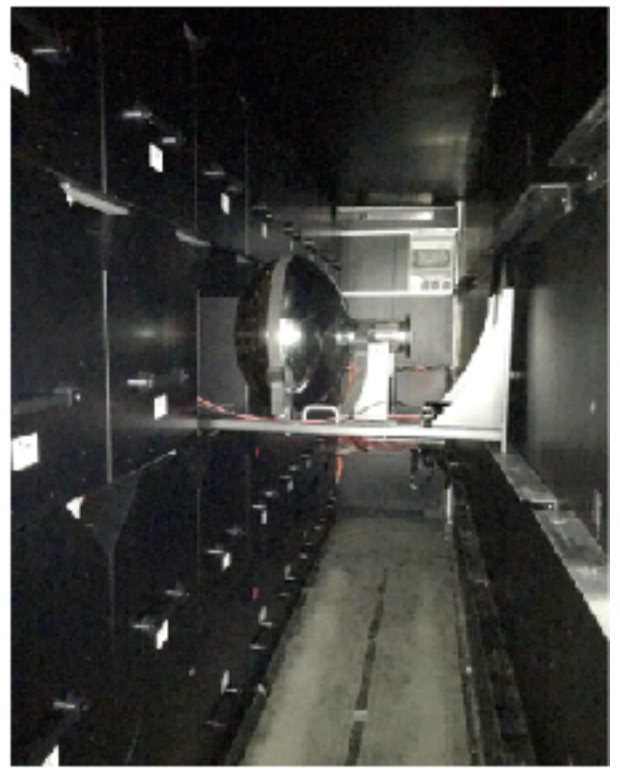
NNVT PMT

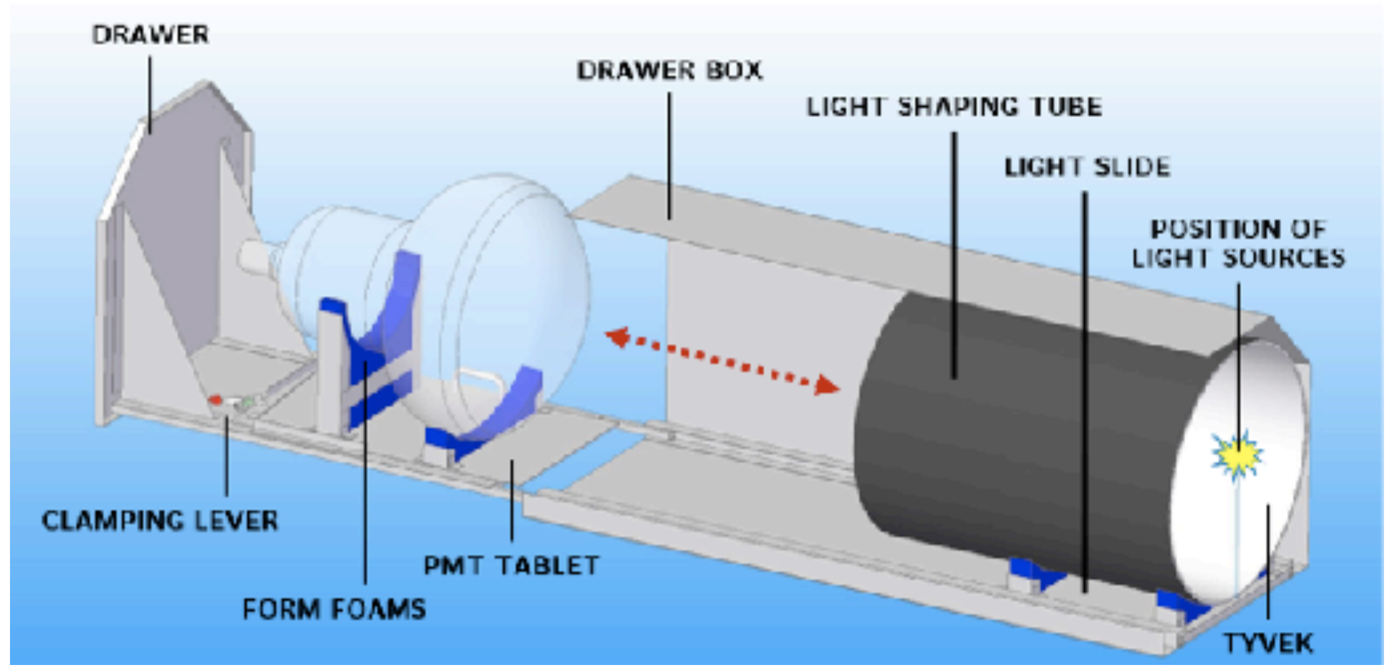
Large PMT testing facility

PMT Testing Containers (all PMTs):

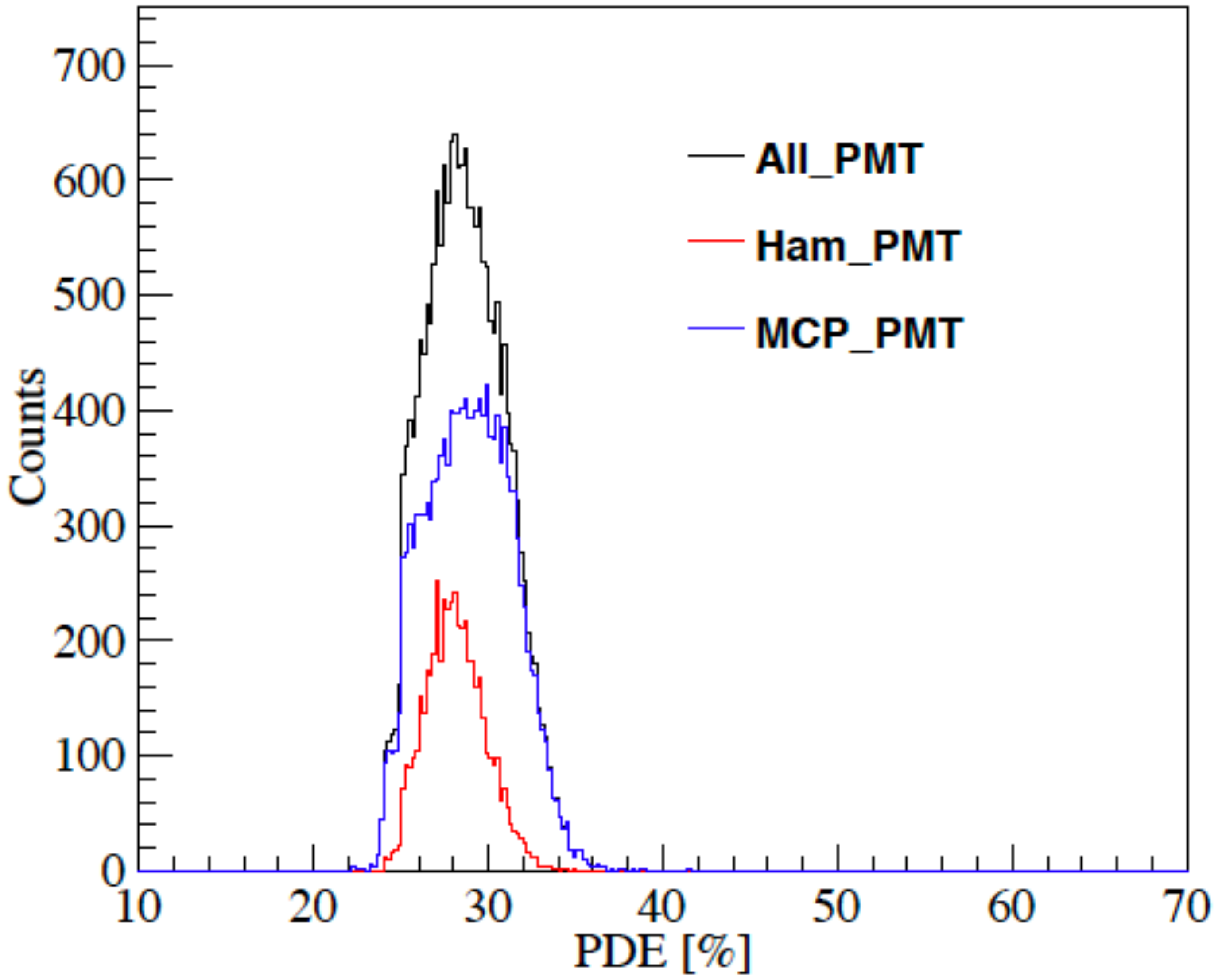
- Capacity: 36 (-5) PMTs per Container
- Relative PDE Measurement:
  1 fixed & 4 rotating reference PMTs
- Magnetic shielding: 10% EMF
- Climate control systems





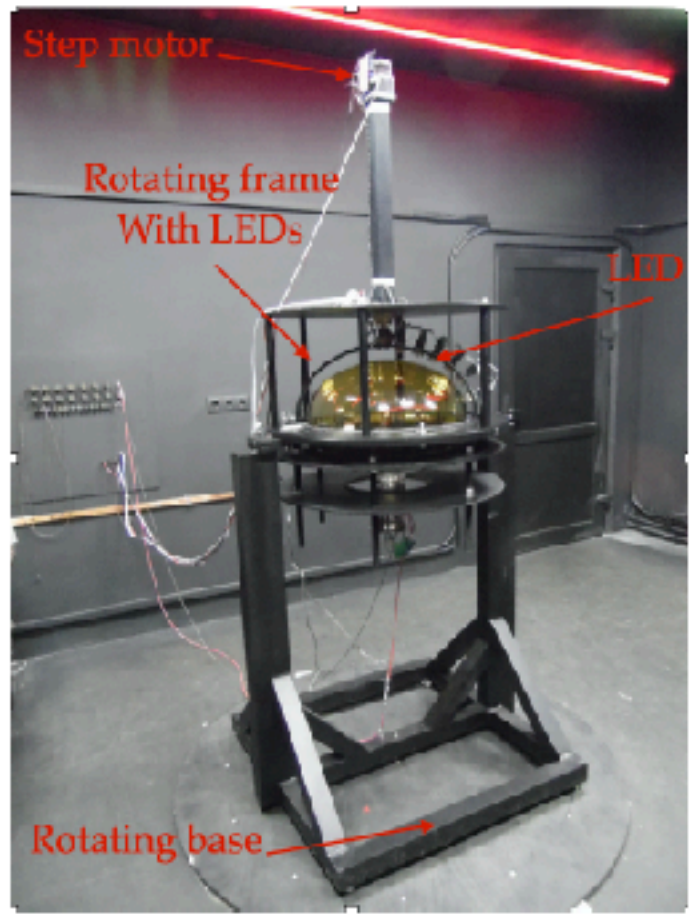


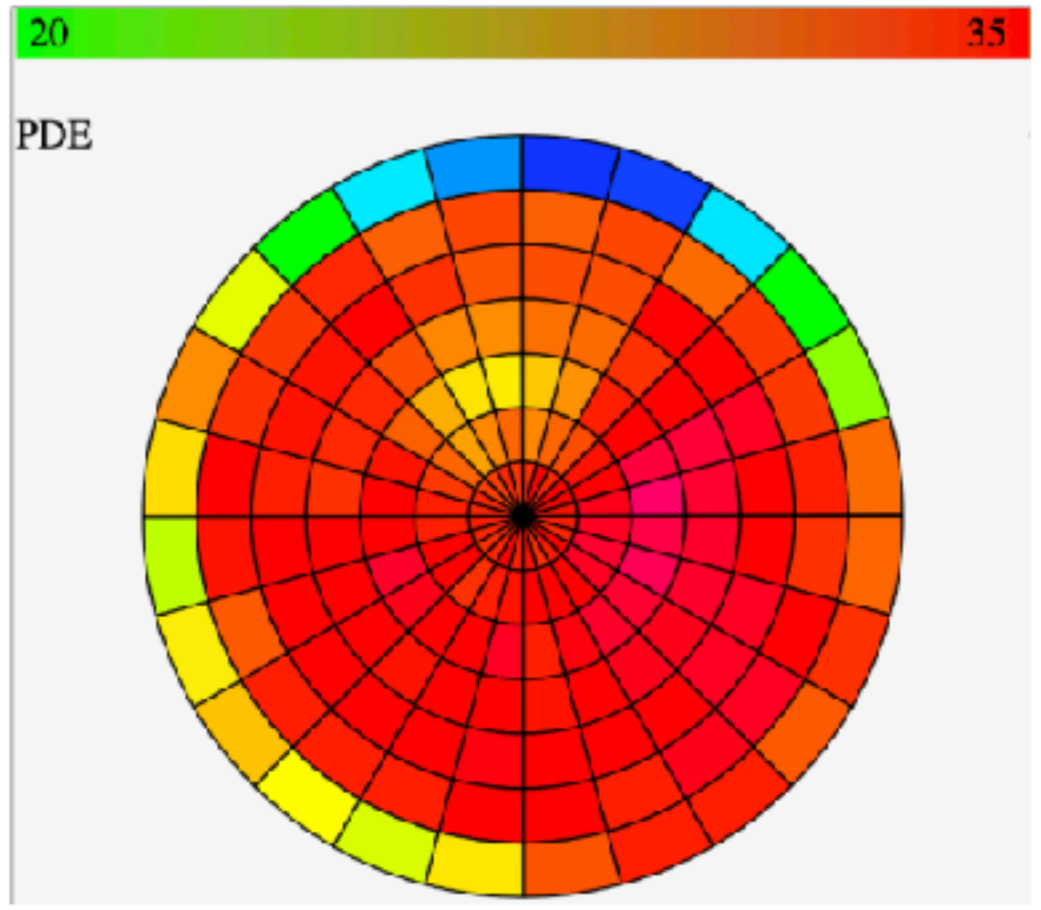
Average PDE for all PMTs: 29.1%



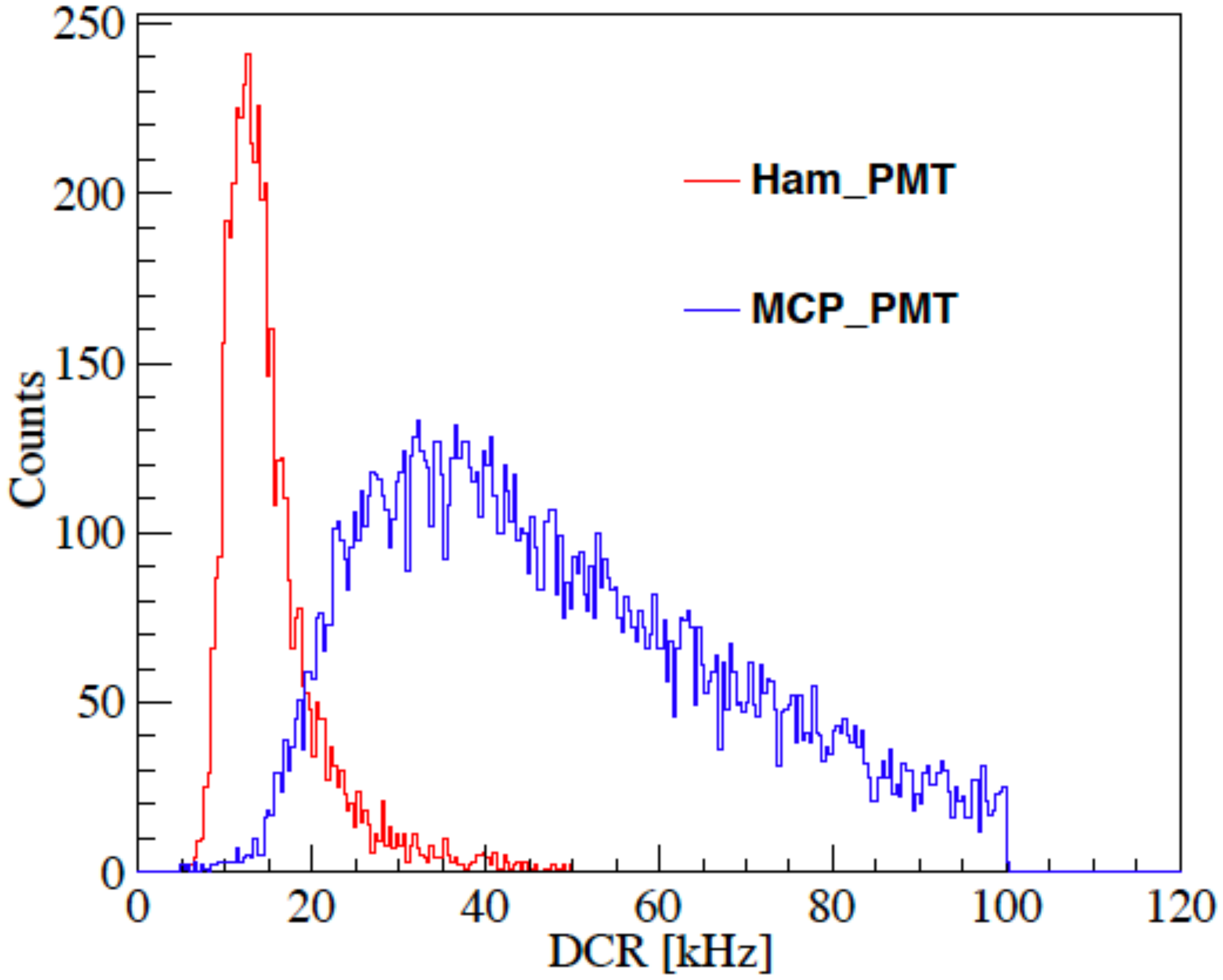
Scanning Station (5-10% of PMTs):

- Provide non-uniformity measurement of PMT parameters
- Study dependence of PMT performance on magnetic field
- Provide a tool for precise PMT studies and cross calibration



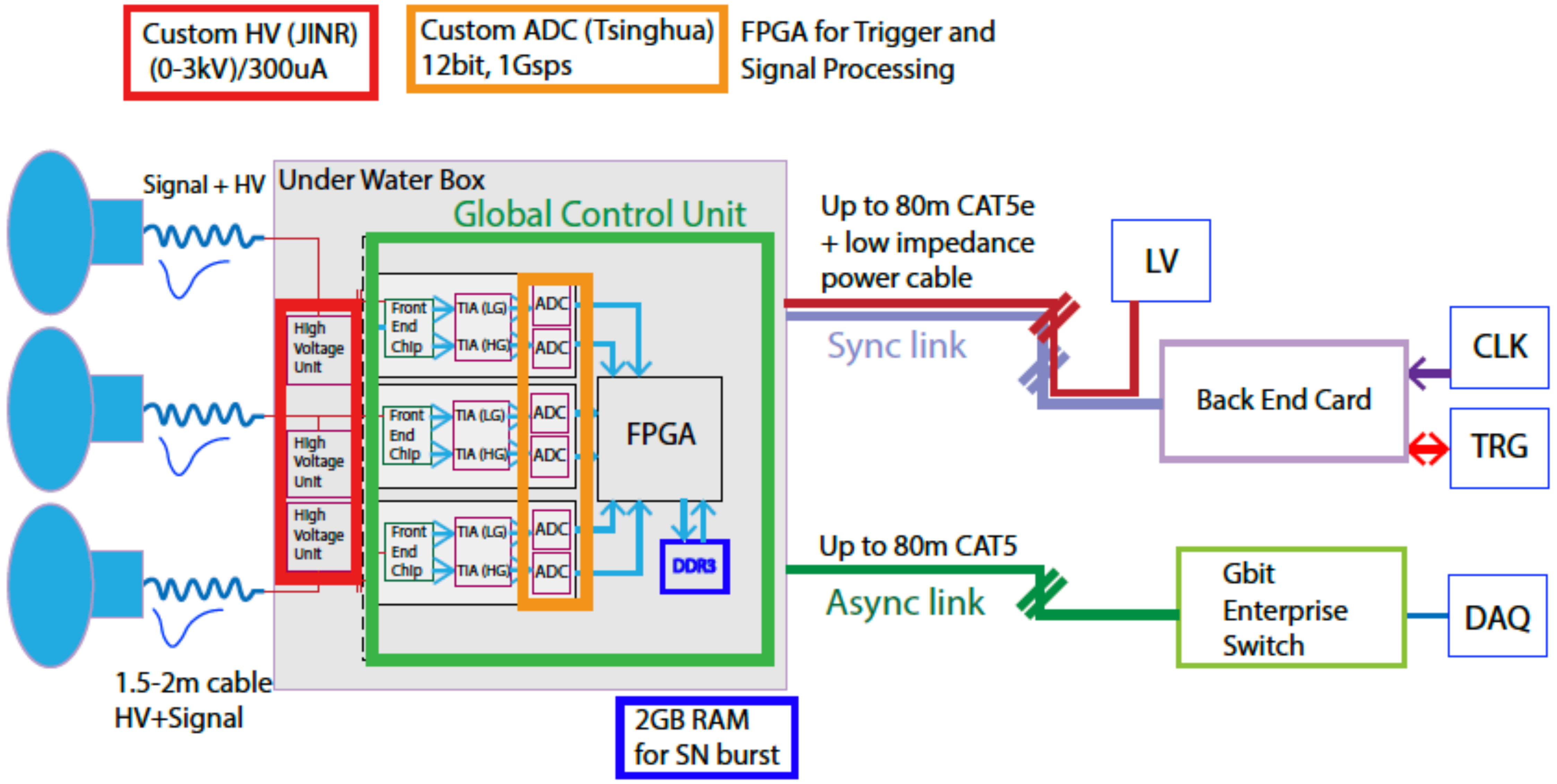


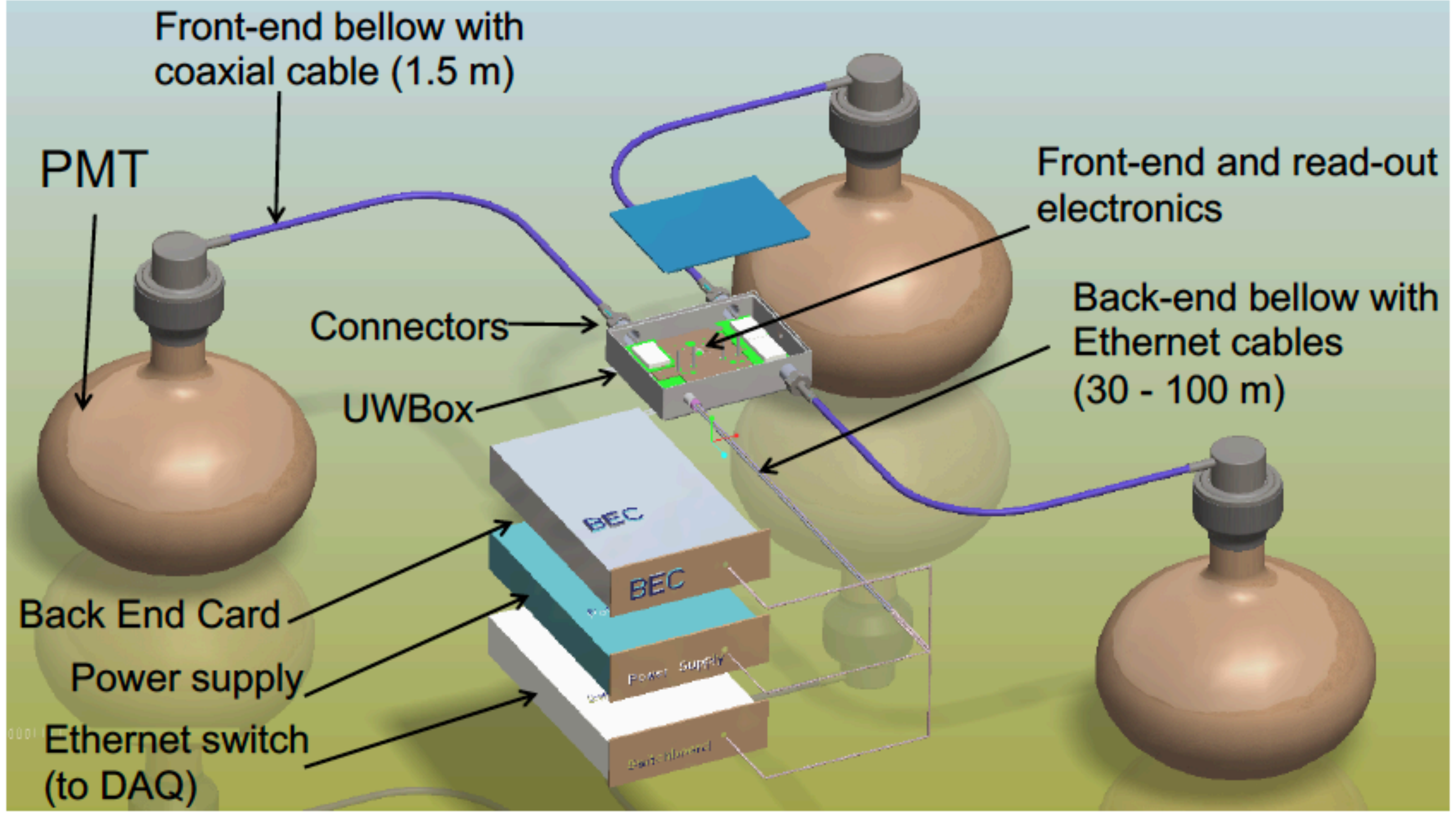
Average DCR < 50 kHz for all PMTs



Large PMT electronics

- 20000 ch. for LPMT
- Final solution:
  - 1 GHz sampling FADC in a small under water box (UWB) in water (×3 ch.)
  - all cables in corrugated pipes
- Cable length:
  - 1.5 m from PMT to UWB
  - 30 to 100 m cable from UWB to back-end
- Dynamic range: 1- 4000 PE
- Noise: < 10% @ 1 PE
- Resolution: 10% at 1 PE, 1% at 100 PE
- Failure rate: < 0.5% over 6 years





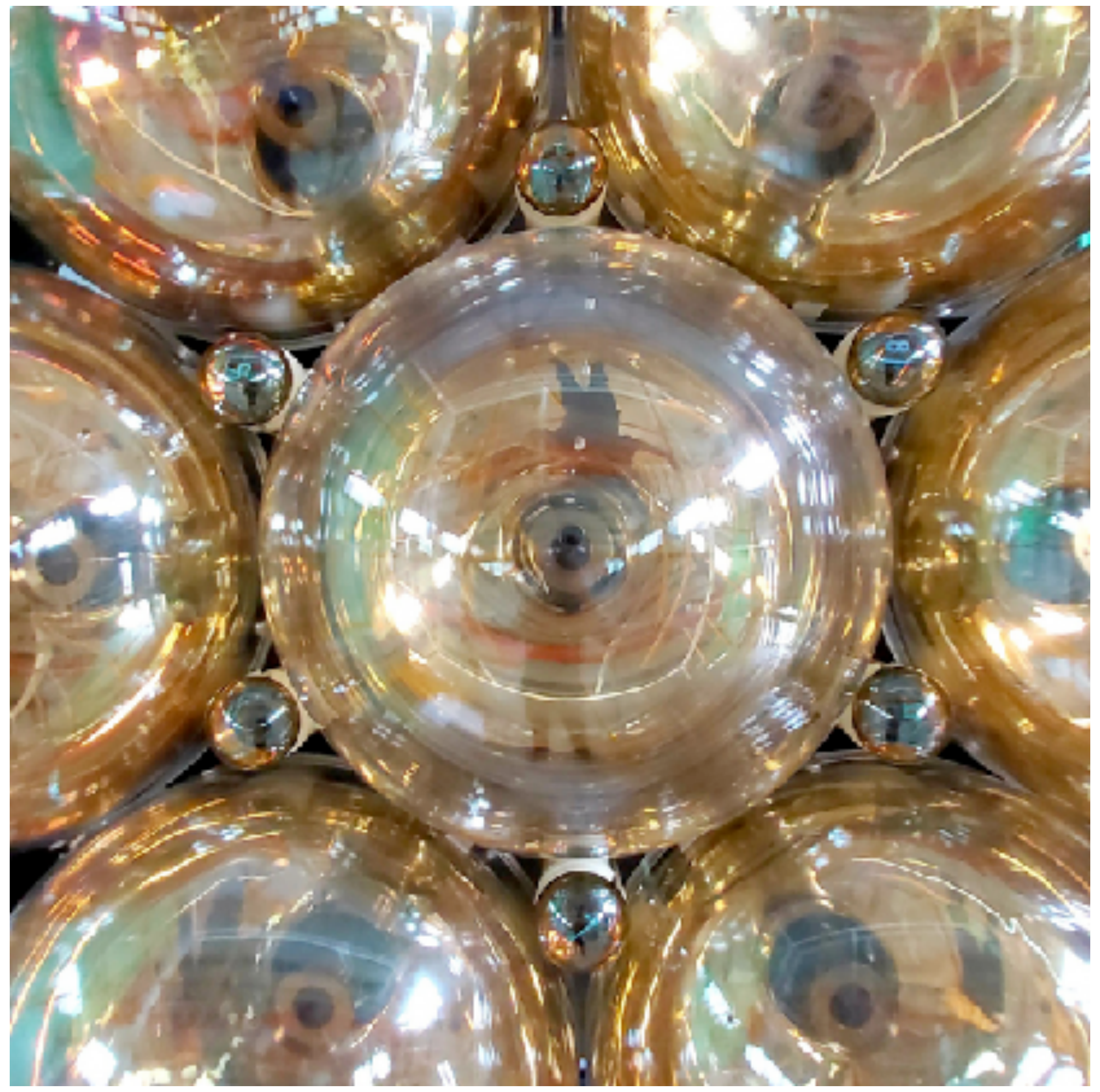
Central Detector: Small (3”) PMT system

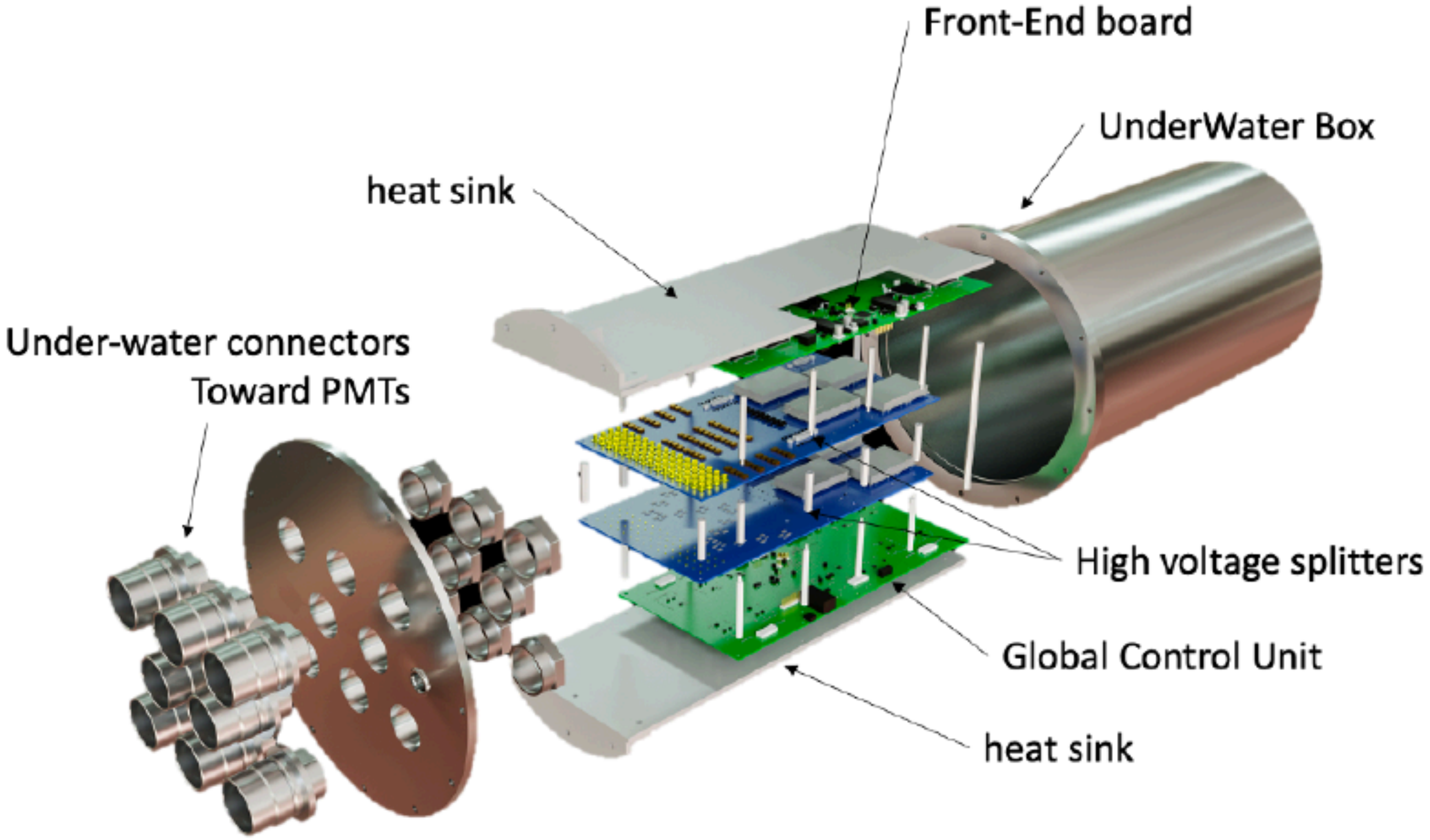
- **Double calorimetry**

- Always in **photon counting mode** in 1~10 MeV range
- **Almost no instrumental non-linearity:** calibration of large PMT array
- **Mitigate saturation effects** at high energies

- **25600 small PMTs** in the Central Detector
  - 2.7% coverage
  - Provided by HZC Photonics (Hainan,PR China)

- **Independent physics measurements:**
  - Muon tracking (+ shower muon calorimetry)
  - Solar oscillation parameter measurement
  - Supernova readout

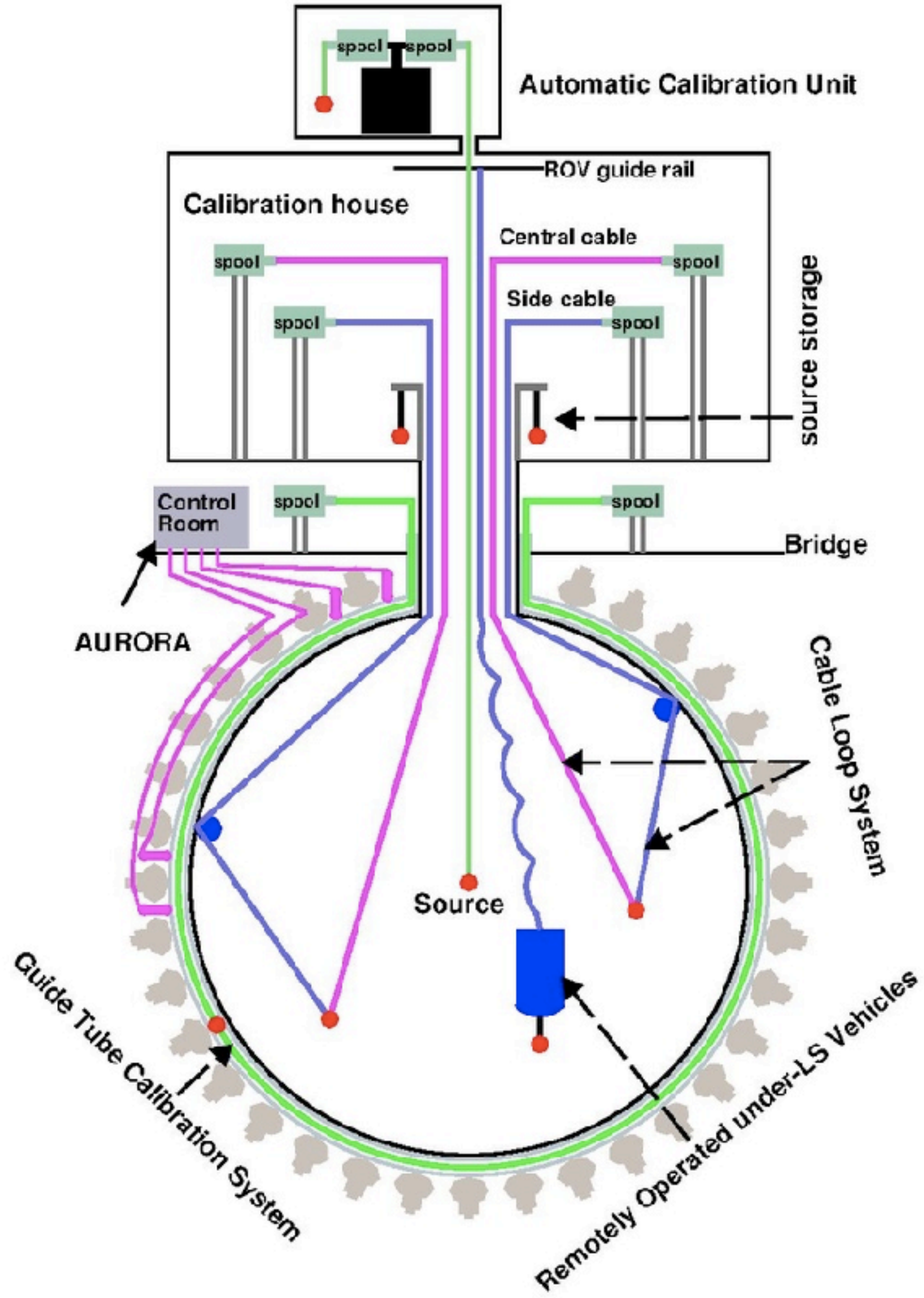


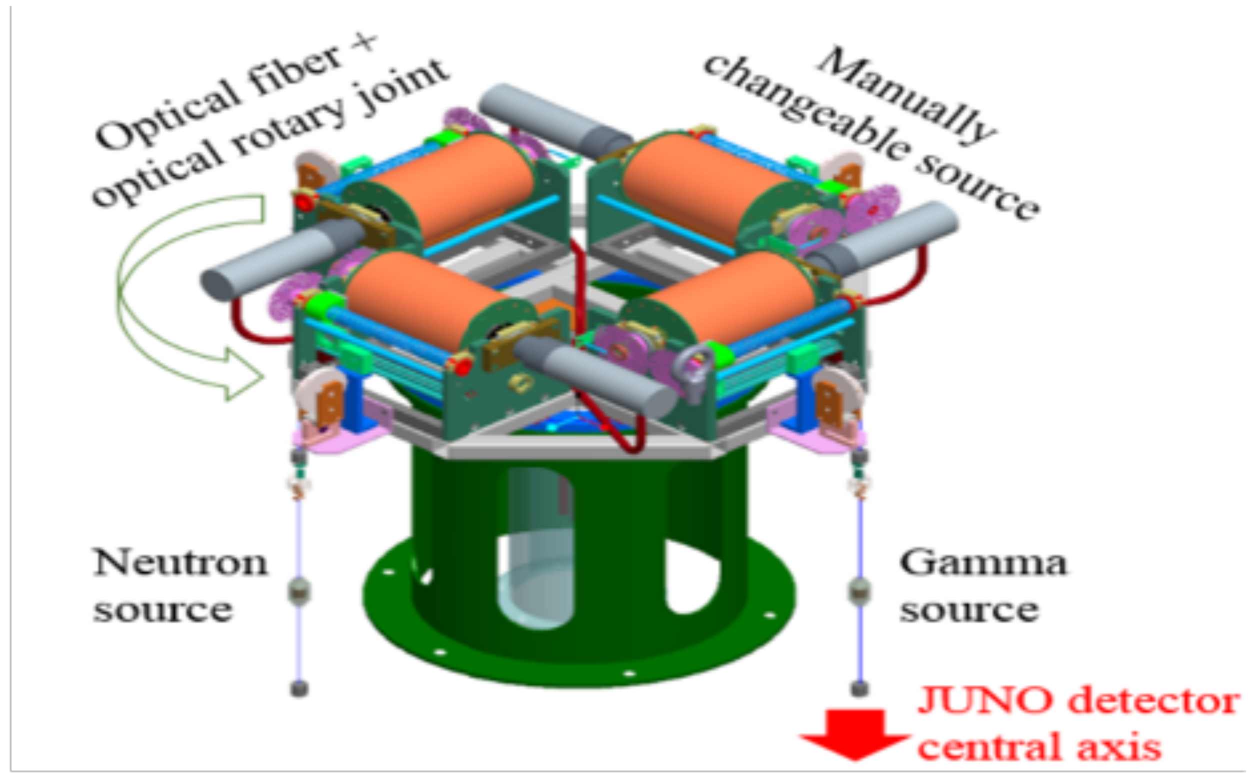


Calibration system

Strategy:

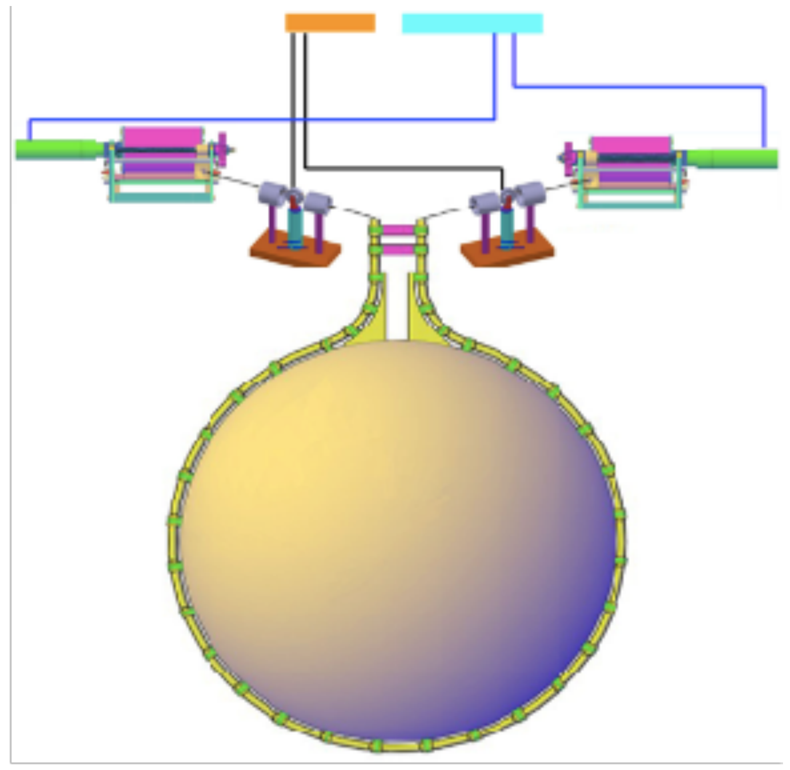
- Many sources (LS non-linearity)
- Tunable photon source (electronics non-linearity)
- Many locations (detector non-uniformity)



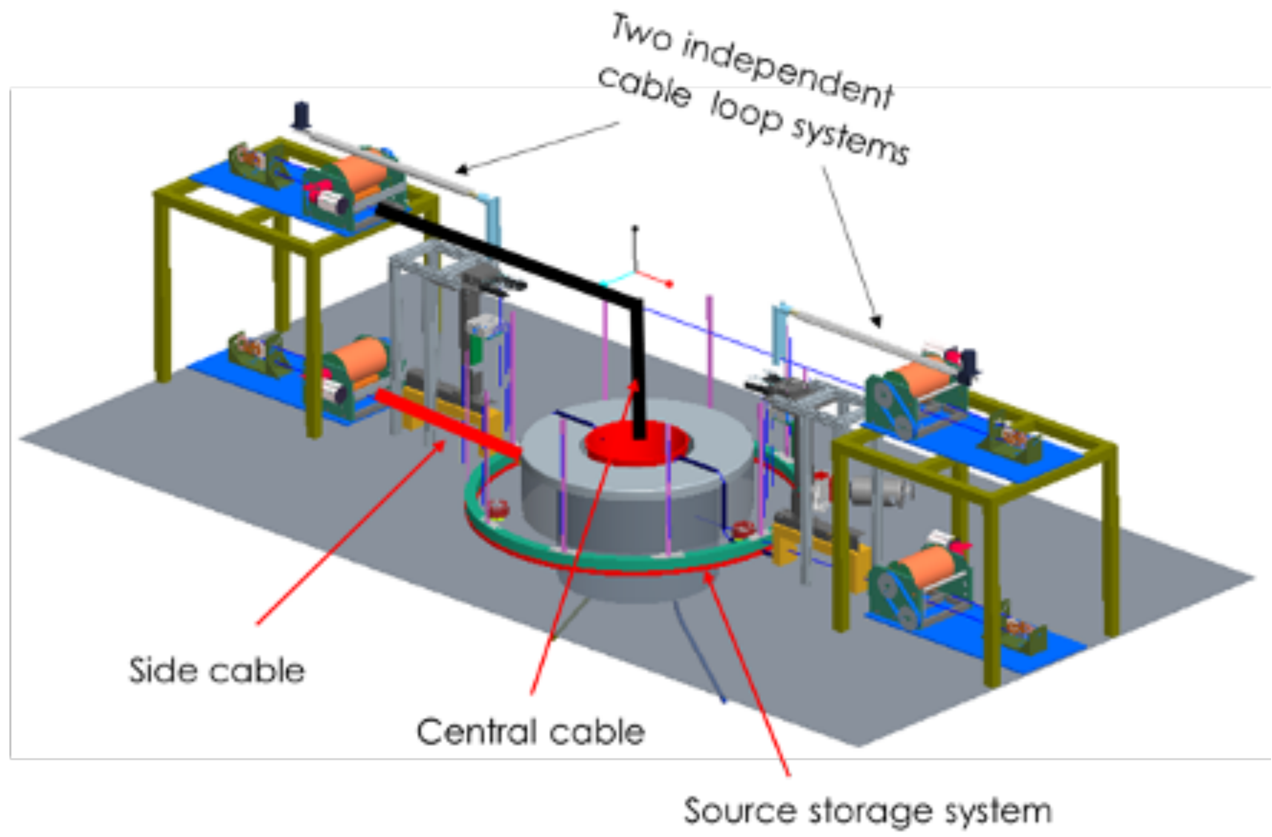


ACU (Automatic Calibration Unit)

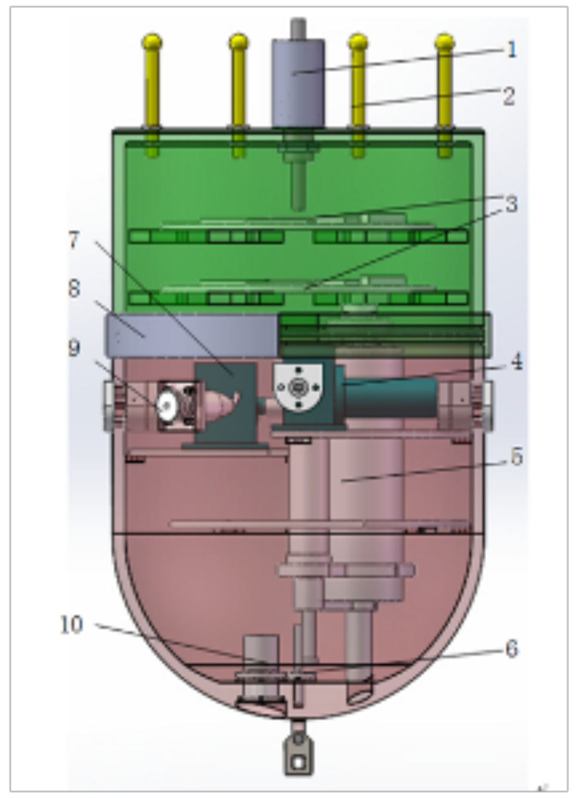
Source	Type	Radiation
^{137}Cs	γ	0.662 MeV
^{54}Mn	γ	0.835 MeV
^{60}Co	γ	1.173 + 1.333 MeV
^{40}K	γ	1.461 MeV
^{68}Ge	e^+	annihilation 0.511 + 0.511 MeV
^{241}Am-Be	n, γ	neutron + 4.43 MeV (^{12}C*)
^{241}Am-^{13}C	n, γ	neutron + 6.13 MeV (^{16}O*)
(n,γ)p	γ	2.22 MeV
(n,γ)^{12}C	γ	4.94 MeV or 3.68 + 1.26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



Guide Tube System



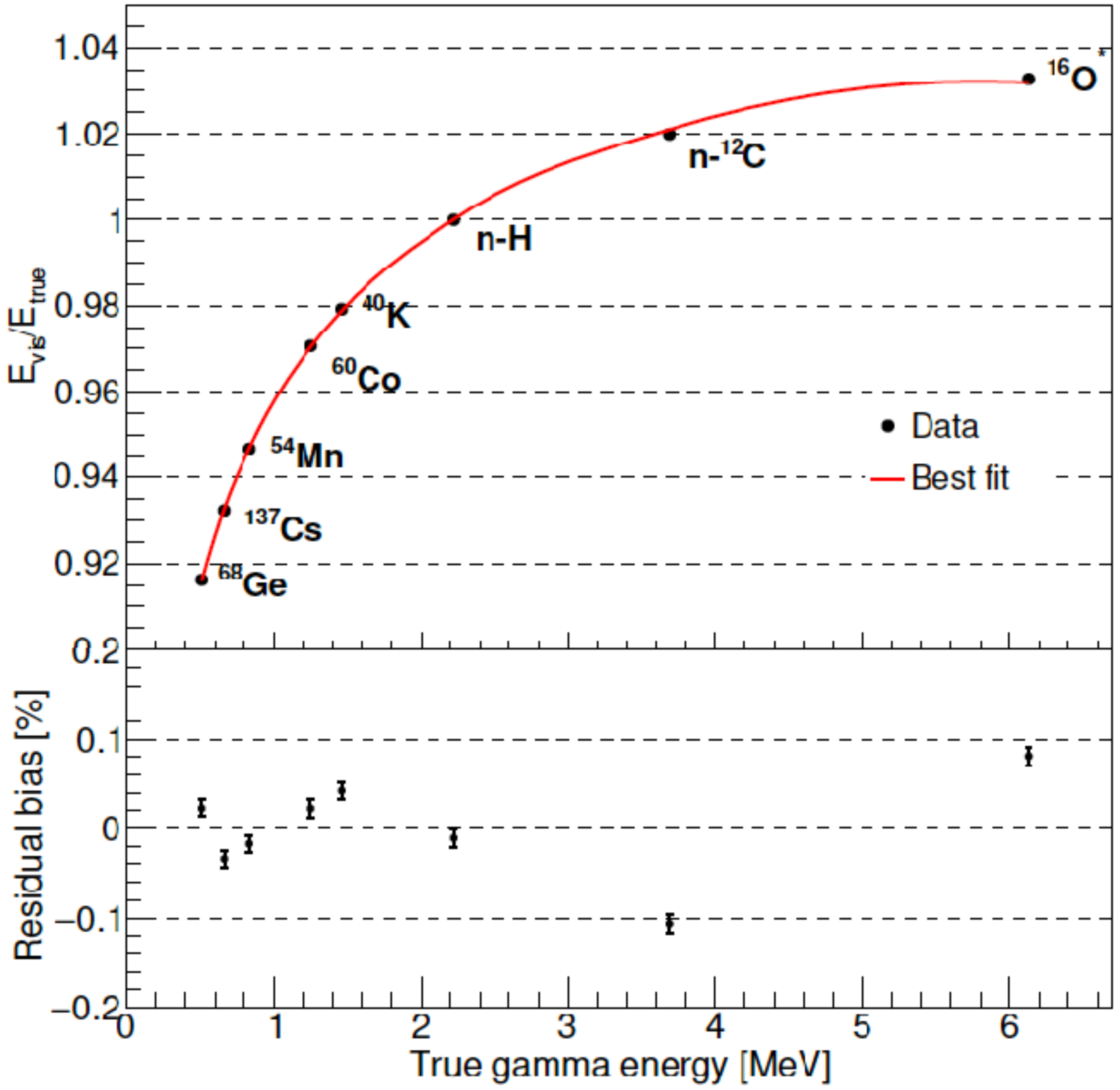
Cable Loop System



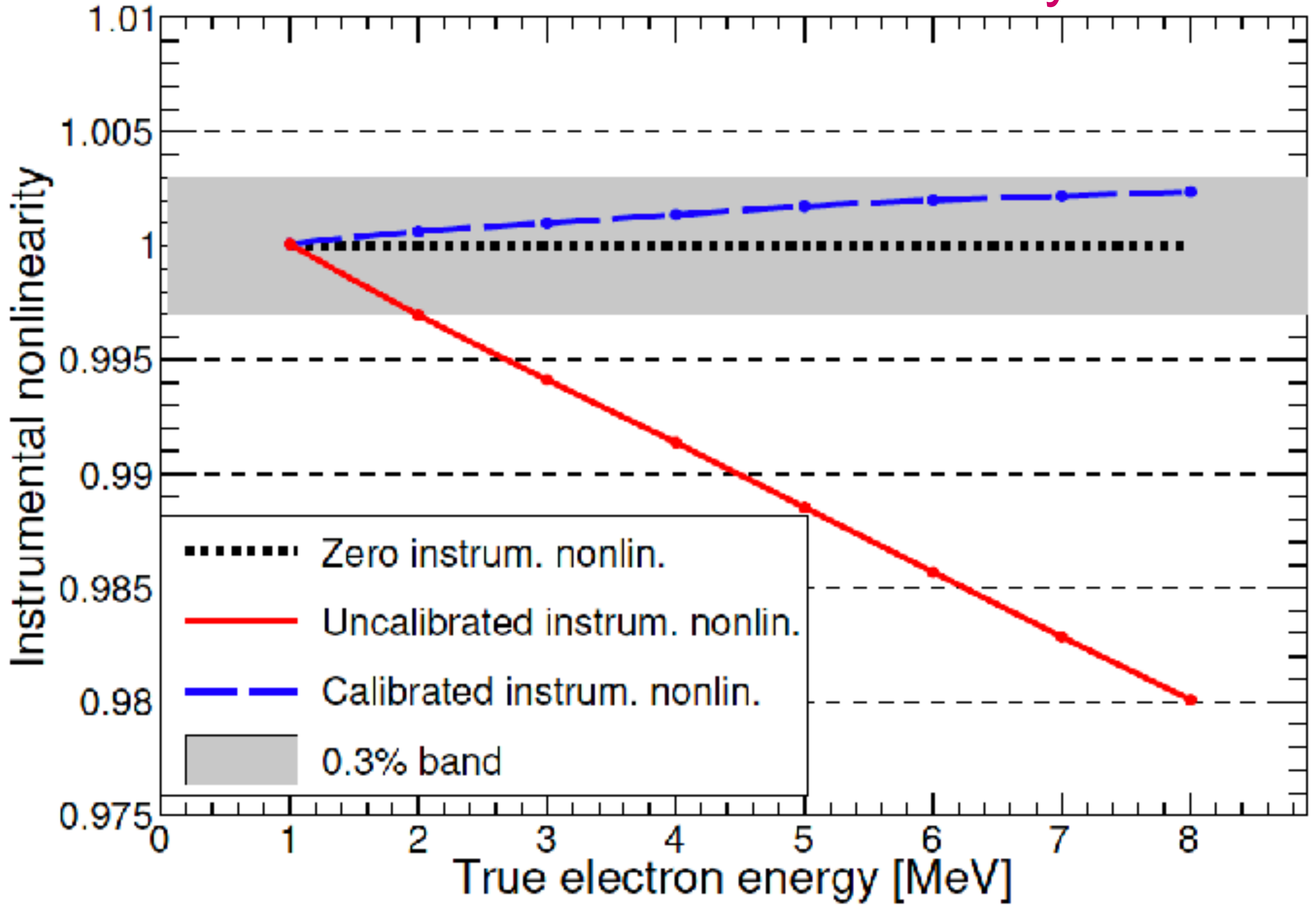
ROV
(Remotely Operated Vehicle)

Expected calibration performance

Simulated scintillator non-linearity



Instrumental non-linearity



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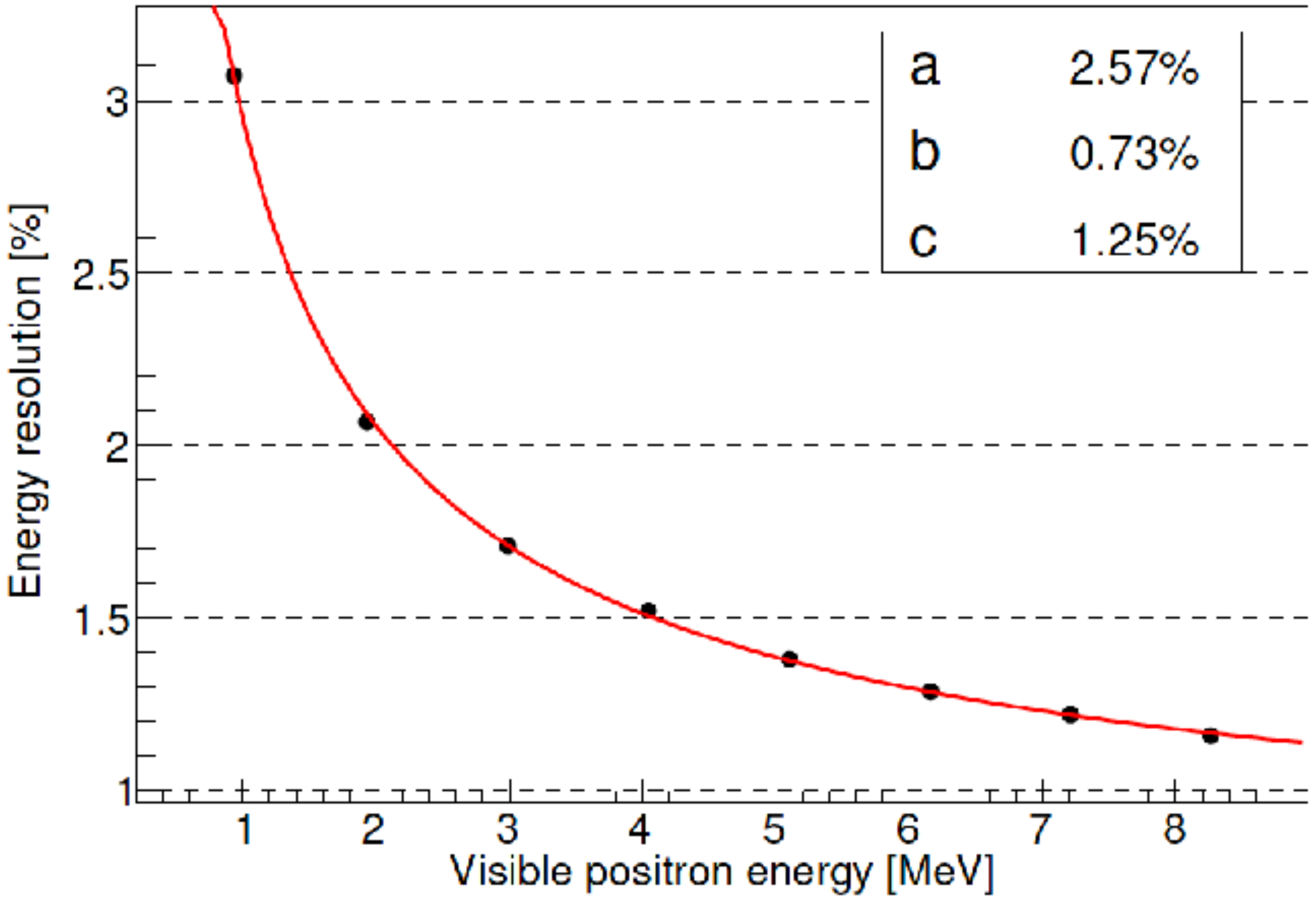
Energy resolution

$$\frac{\sigma_{E_{\text{vis}}^{\text{prompt}}}}{E_{\text{vis}}^{\text{prompt}}} = \sqrt{\left(\frac{a}{\sqrt{E_{\text{vis}}^{\text{prompt}}}}\right)^2 + b^2 + \left(\frac{c}{E_{\text{vis}}^{\text{prompt}}}\right)^2}$$



Civil construction

Tunnel, 3 February 2021

Water pool, 2 February 2021

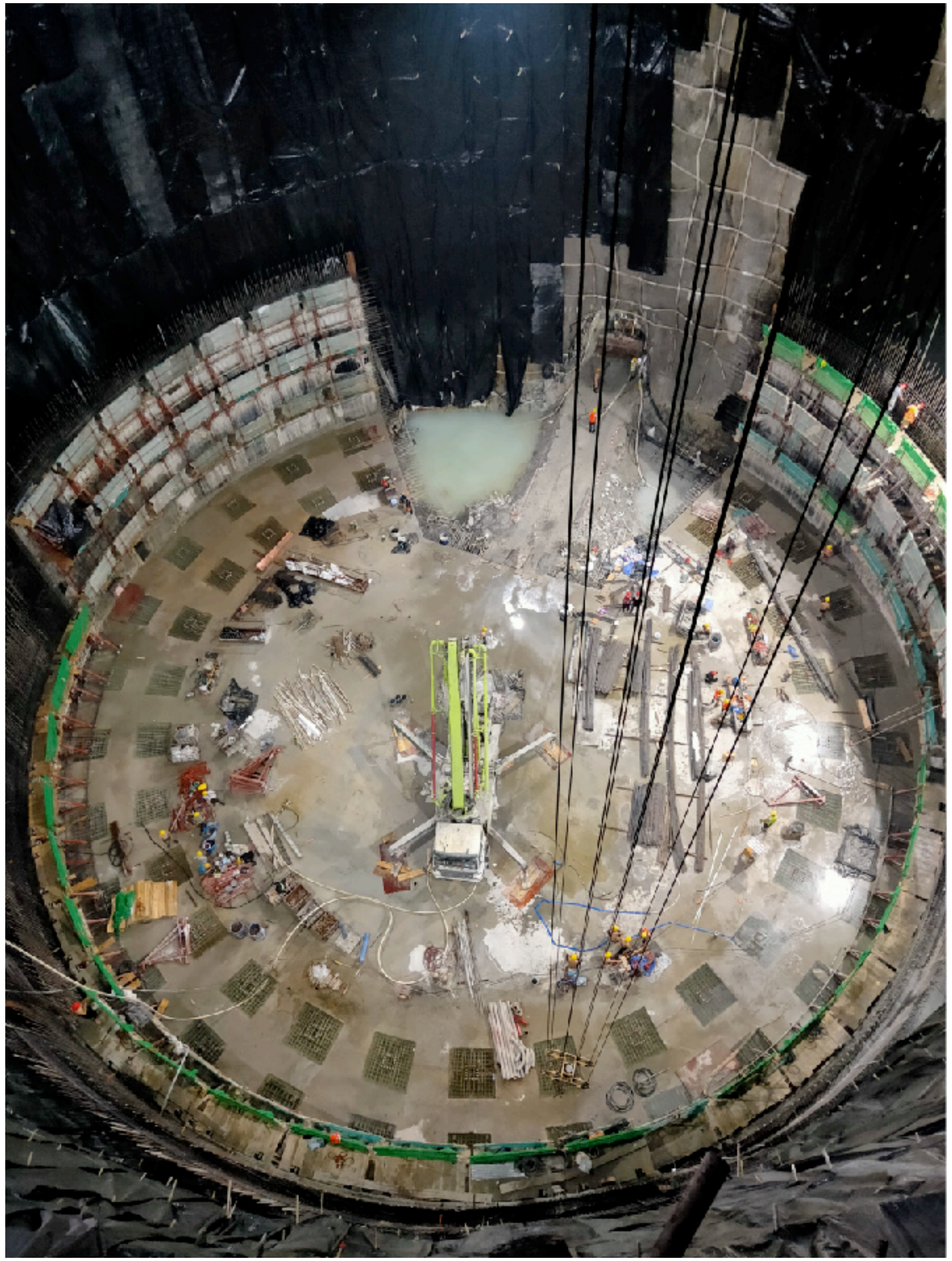
Campus, 28 January 2021

Preparation for side wall concrete, 15 April 2021

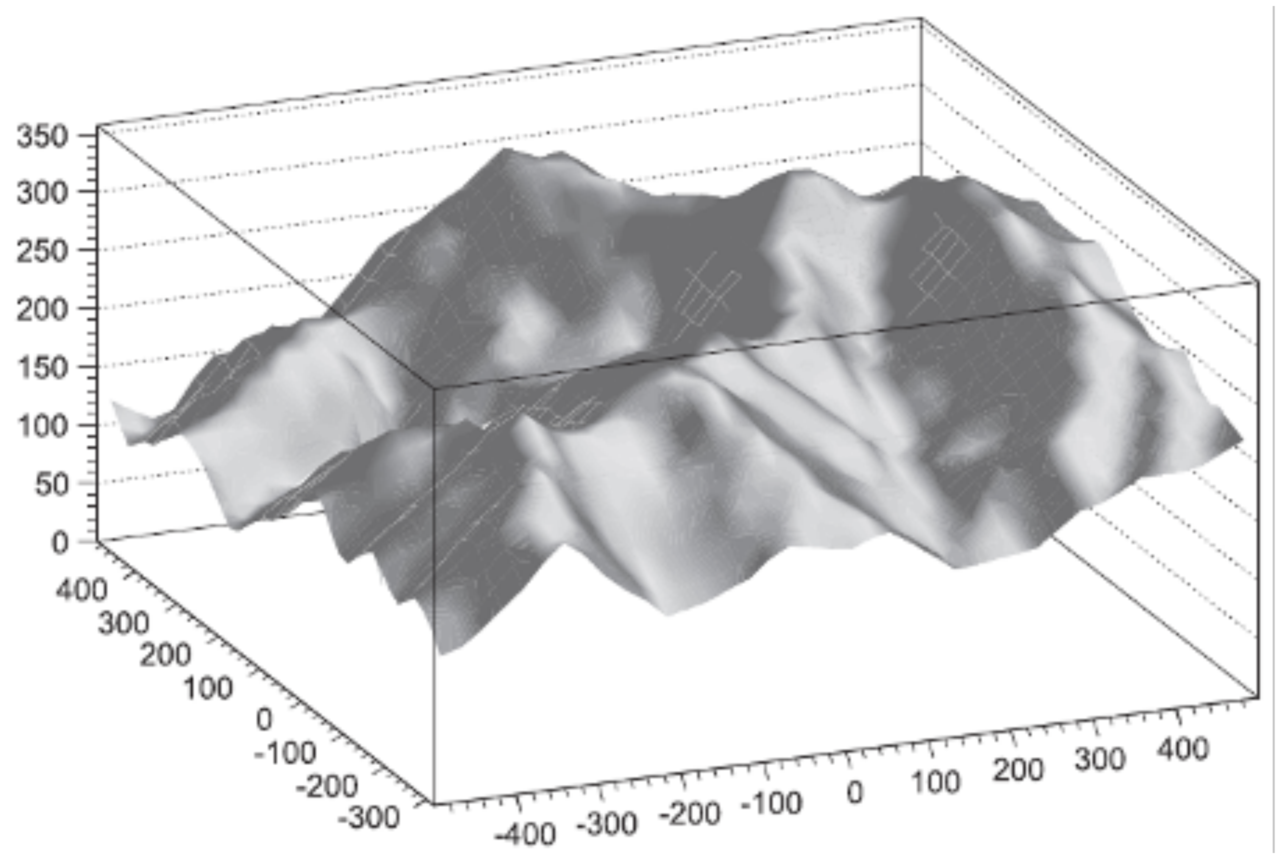
Civil construction

Water pool, 9 March 2021

Water pool, 2 May 2021



Cosmic Muons



JUNO site

~ 700 m overburden, 1800 m.w.e.

Expected muon rate

- The muon flux at the JUNO site is ~0.004 Hz/m^2 with a mean energy of 207 GeV
- The rate of muons passing through the liquid scintillator is 3.6 Hz
- The rate of muons passing through the ultra pure water is 10 Hz

Tagging efficiency in the liquid scintillator: ~100%

Muon veto strategies using WCD and TT to cope with induced background impact requirements

Muon induced background

Fast neutron background

- Neutrons are produced by muons passing through rock and detector materials: if they reach the liquid scintillator (fast neutrons) they may induce a prompt proton recoil and then be captured by H or C → can mimic an IBD event
- **Muon tagging** removes this background (99.8% efficiency of Water Cherenkov detector)
- Fast neutron background < 0.1 c/day (even lower if including Top Tracker tagging)

Cosmogenic background

- Muons and muon showers interact with ^{12}C in LS producing $Z \leq 6$ isotopes by hadronic or electromagnetic processes: β–n decaying nuclides are produced that can mimic IBD signal
- ^{9}Li and ^{8}He are the most dangerous correlated background sources
- Various **physics-driven models** for veto strategies to reduce the impact of cosmogenic background in the different JUNO physics channels

Natural radioactivity background

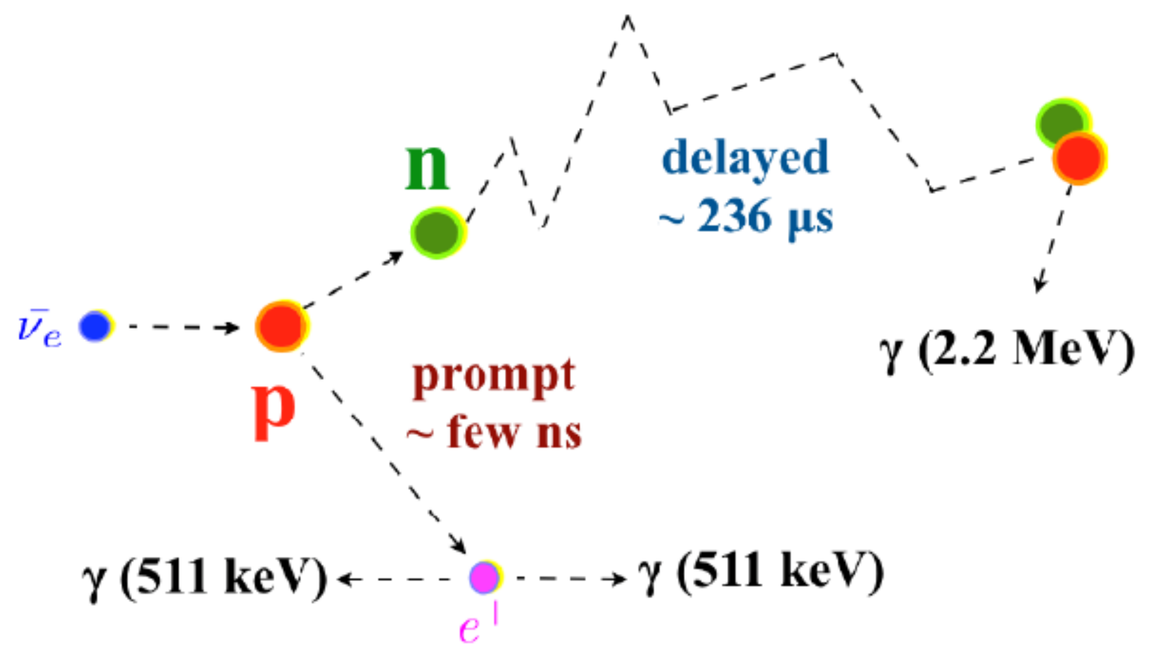
Must be controlled at the lowest possible level to reduce accidental count rate.

Target: < 10 Hz in Fiducial Volume (FV)

Current background budget

Material	Mass	Target impurity concentration					Singles in ROI	
		^{238}U	^{232}Th	^{40}K	^{210}Pb/^{222}Rn	^{60}Co	ALL	FV
	[t]	[ppb]	[ppb]	[ppb]		[mBq/kg]	[Hz]	[Hz]
LS	20 k	10^{-6}	10^{-6}	10^{-7}	10^{-13} ppb		2.5	2.2
Acrylic	610	10^{-3}	10^{-3}	10^{-3}			8.4	0.4
SS truss and nodes	1 k	0.2	0.6	0.02		1.5	15.8	1.1
dynode-LPMT glass	33.5	400	400	40				
MCP-LPMT glass	100.5	200	120	4			26.2	2.8
dynode-SPMT glass	2.6	400	400	200				
Water	35 k				10 mBq/m^3		1.0	0.06
Other							5	0.6
Sum							59	7.2

Signal and background



Preliminary antineutrino selection criteria:

- fiducial volume: r < 17.2 m
- prompt energy: 0.7 MeV < E_p < 12 MeV
- delayed energy: 1.9 MeV < E_d < 2.5 MeV
- prompt-delay time difference: $\Delta t_{p\text{-}d}$ < 1.0 ms
- prompt-delay distance: $D_{p\text{-}d}$ < 1.5 m

+ muon veto criteria

Modified from JPG 43 (2016) 030401

Selection	IBD efficiency	IBD	Geo-νs	Accidental	^{9}Li/^{8}He	Fast n	(α, n)
-	-	62	1.5	-	84	-	-
Fiducial volume	91.8%	57	1.4	410	77	0.1	0.05
Energy cut	97.8%	55	1.3		71		
Time cut	99.1%						
Vertex cut	98.7%			1.1			
Muon veto	83%	45	1.1	0.9	1.6		
Combined	73%	45	3.55				

Neutrino mass ordering at JUNO

Neutrino MO estimator:

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

In 6 years of data taking (~100k IBD events):

Expected: $\Delta\chi^2 \sim 10$

Significance: $\sim 3\sigma$

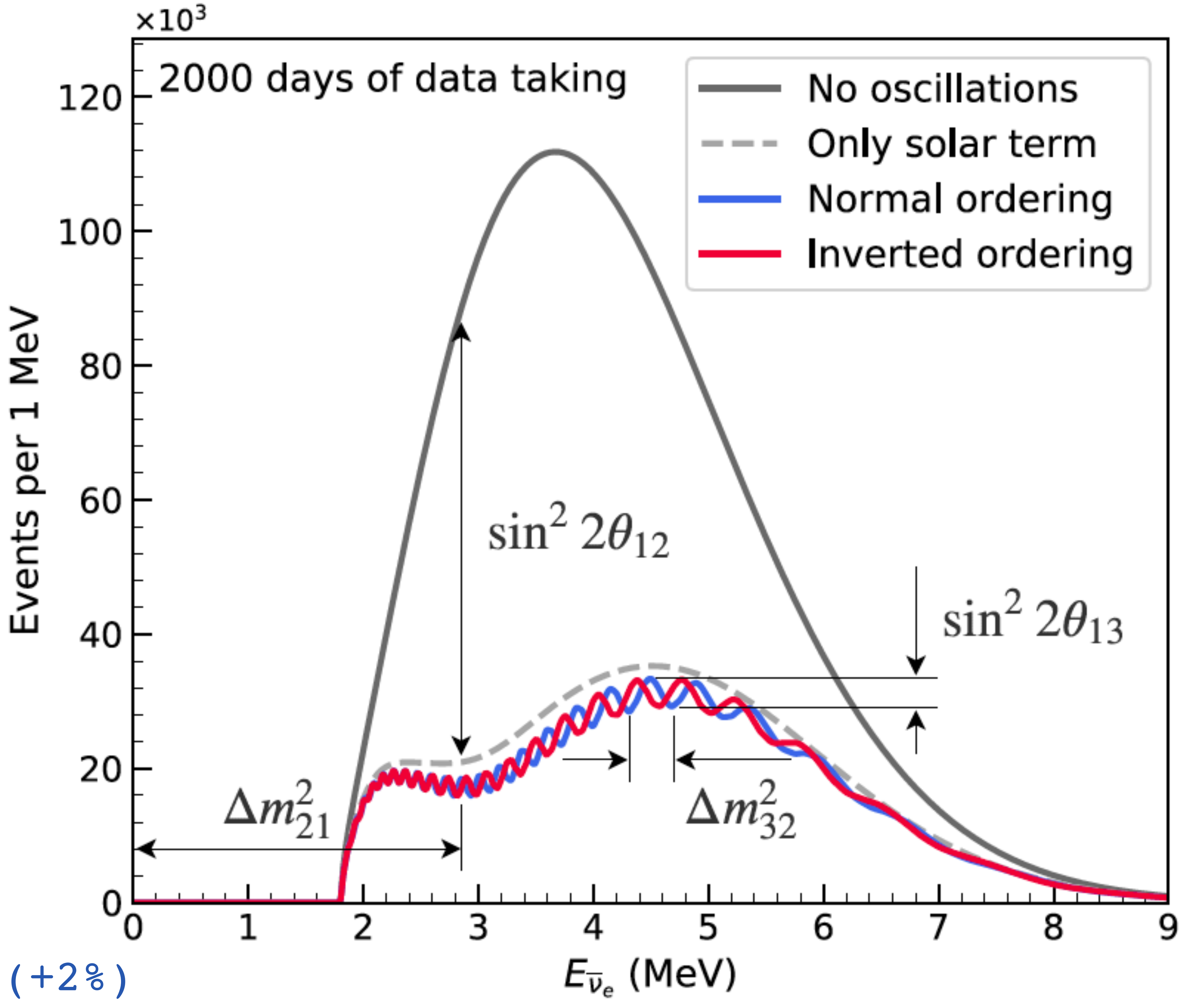
$\Delta\chi^2$ increase:

- 25% reactor power reduction
- exp. hall shift → overburden reduction (+30% muons)

$\Delta\chi^2$ decrease:

- measured PMT detection efficiency better than design (+2%)
- new optical model: higher photo-e- yield
- input reactor spectrum better constrained by TAO detector
- more efficient event selection: live time increase (+10%)

JUNO is the first experiment to see both Δm² at the same time

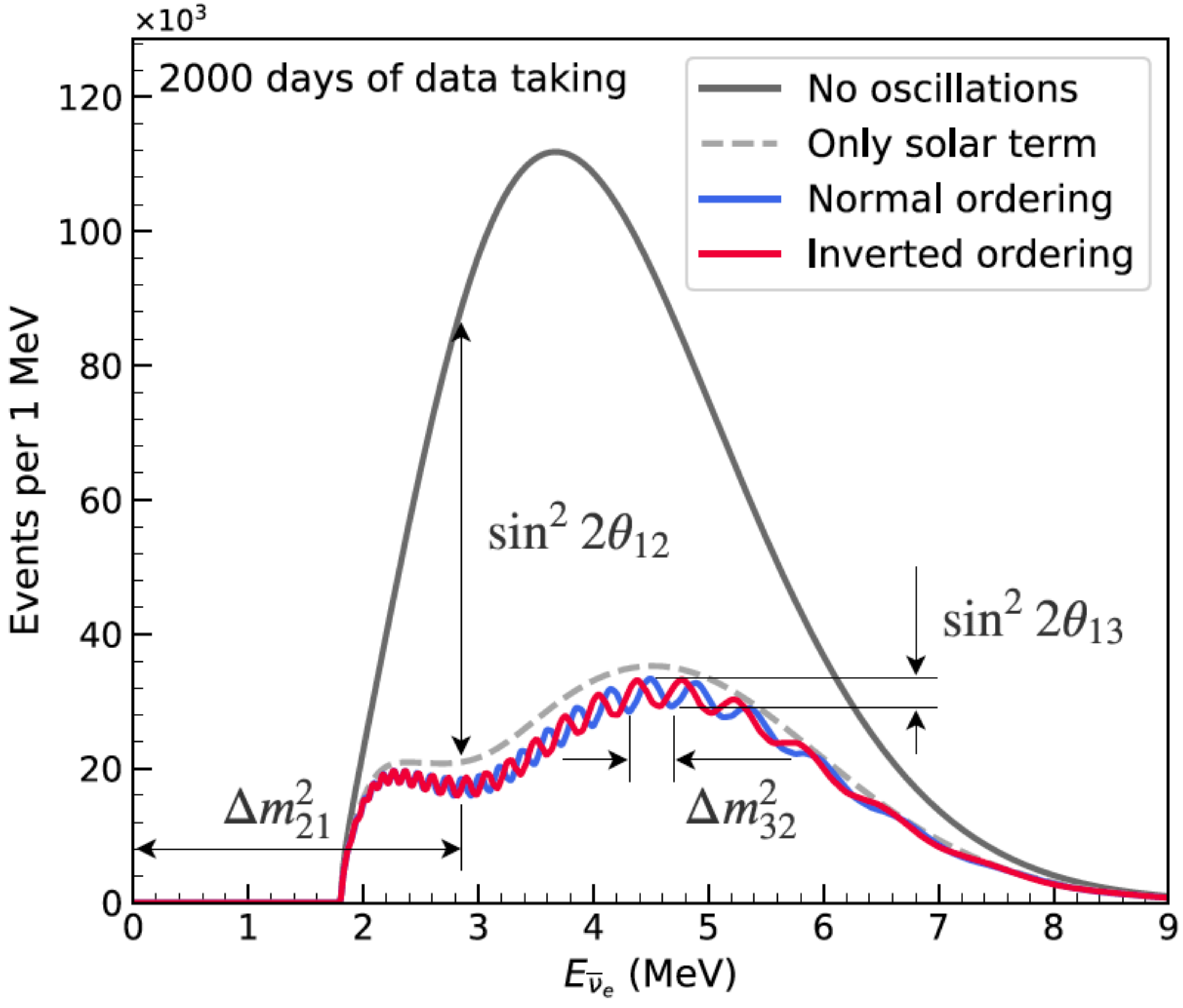


Sensitivity basically unchanged w.r.t. JUNO Yellow Book *J. Phys. G 43, 030401 (2016)*

Neutrino oscillation parameters at JUNO

Unique peculiarity of JUNO: simultaneous estimation of the four oscillation parameters

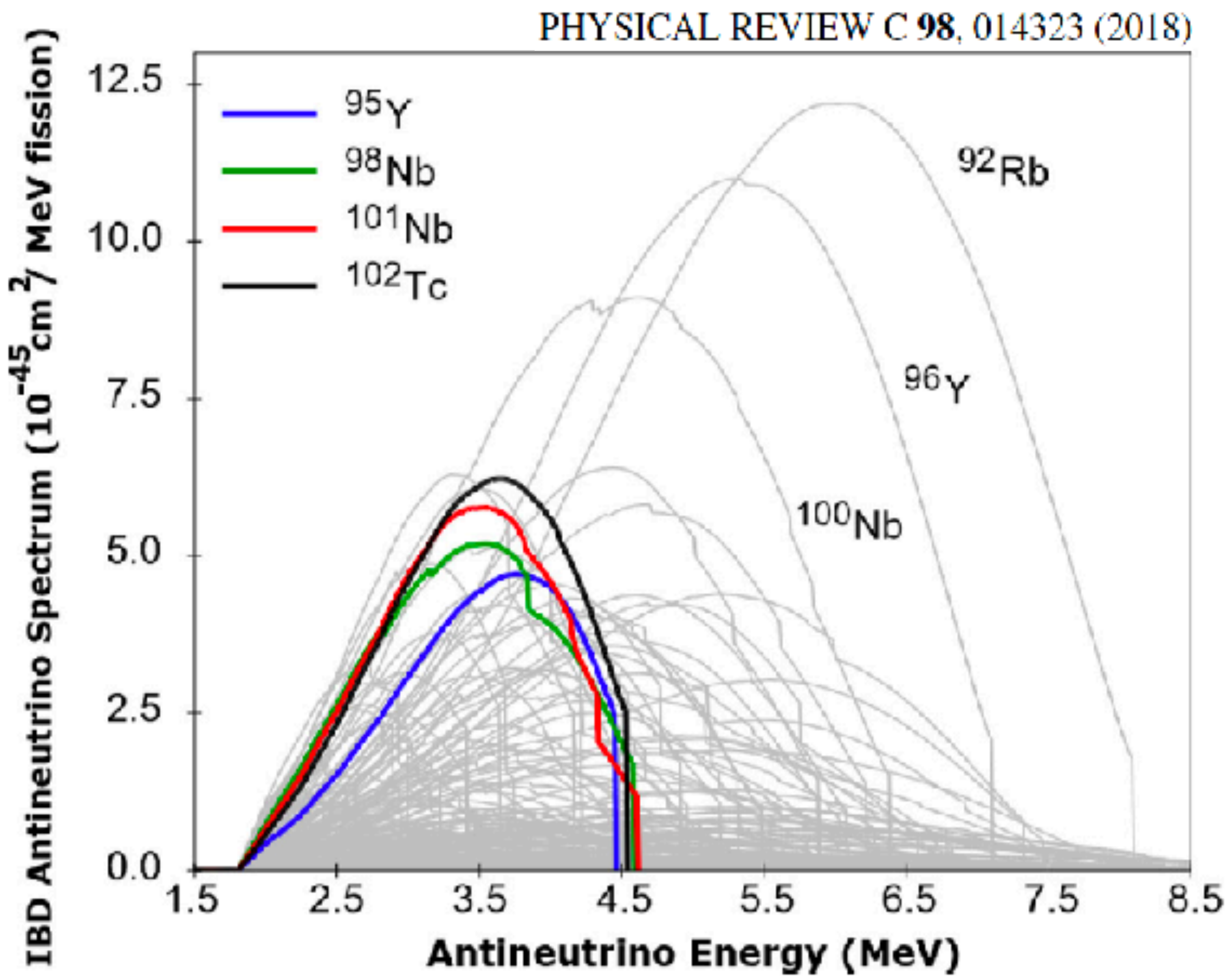
JUNO is the first experiment to see both Δm^2 at the same time



$\sin^2 2\theta_{12}$, Δm^2_{21}, and $|\Delta m^2_{32}|$
will be determined with a precision of ≲0.6% in 6 years of exposure

A new detailed study is ongoing to incorporate several updates to the analysis of the JUNO Yellow Book. Results will be soon released.

Spectral uncertainties



- Large scale fine structures constrained by Daya Bay experiment
- **A known fine structure does not hurt JUNO mass ordering determination**

  ⇒ Tested with multiple spectra with fine local structure from ab initio calculation (PRL 114:012502, 2015) → no major effect on JUNO sensitivity
- ***Unknown fine structure might have a larger impact***

⬇

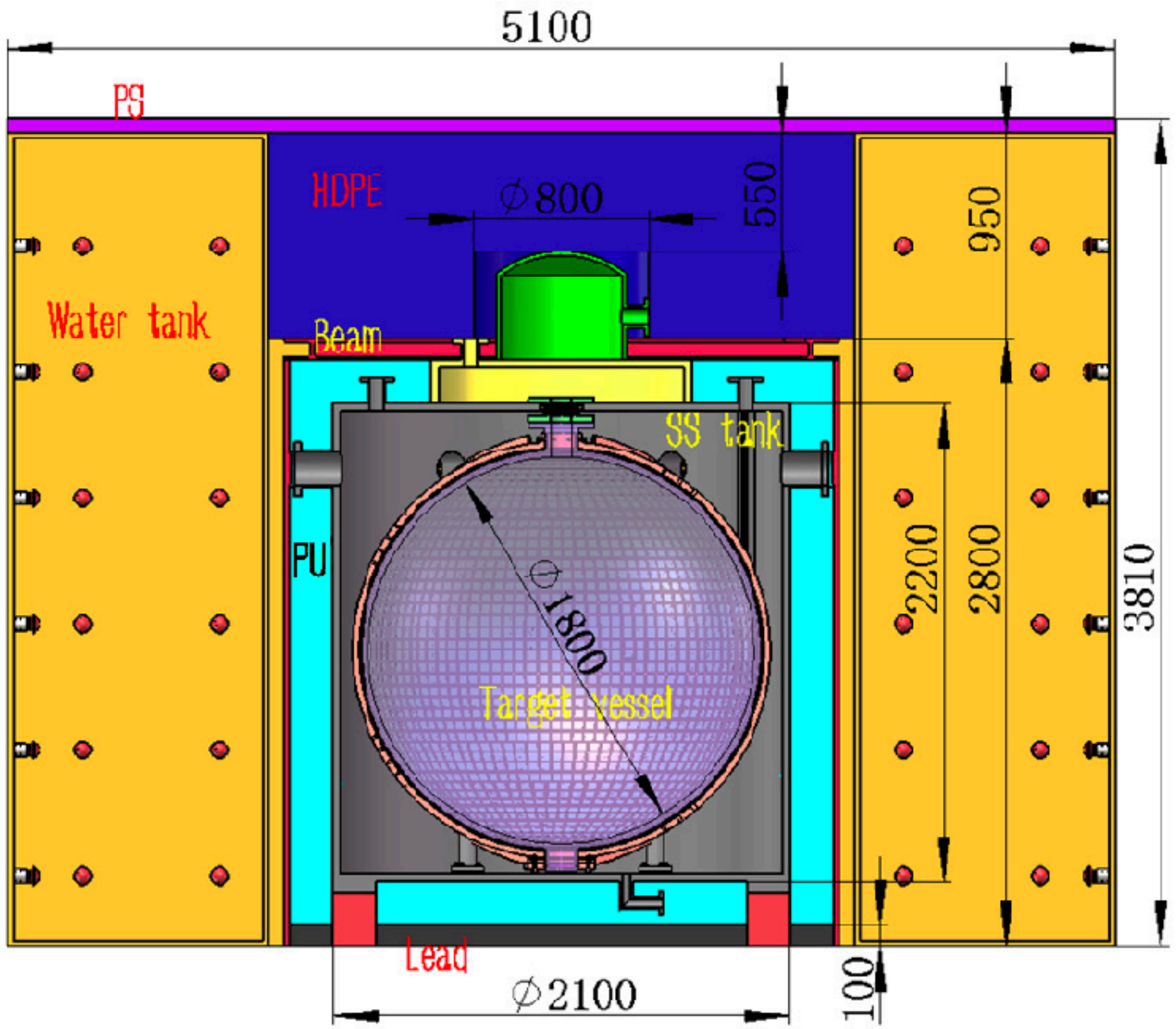
Taishan Antineutrino Observatory (TAO)

A satellite experiment of JUNO to measure reactor neutrino spectrum with unprecedented energy resolution: < 2% / $\sqrt{E}$ [MeV]

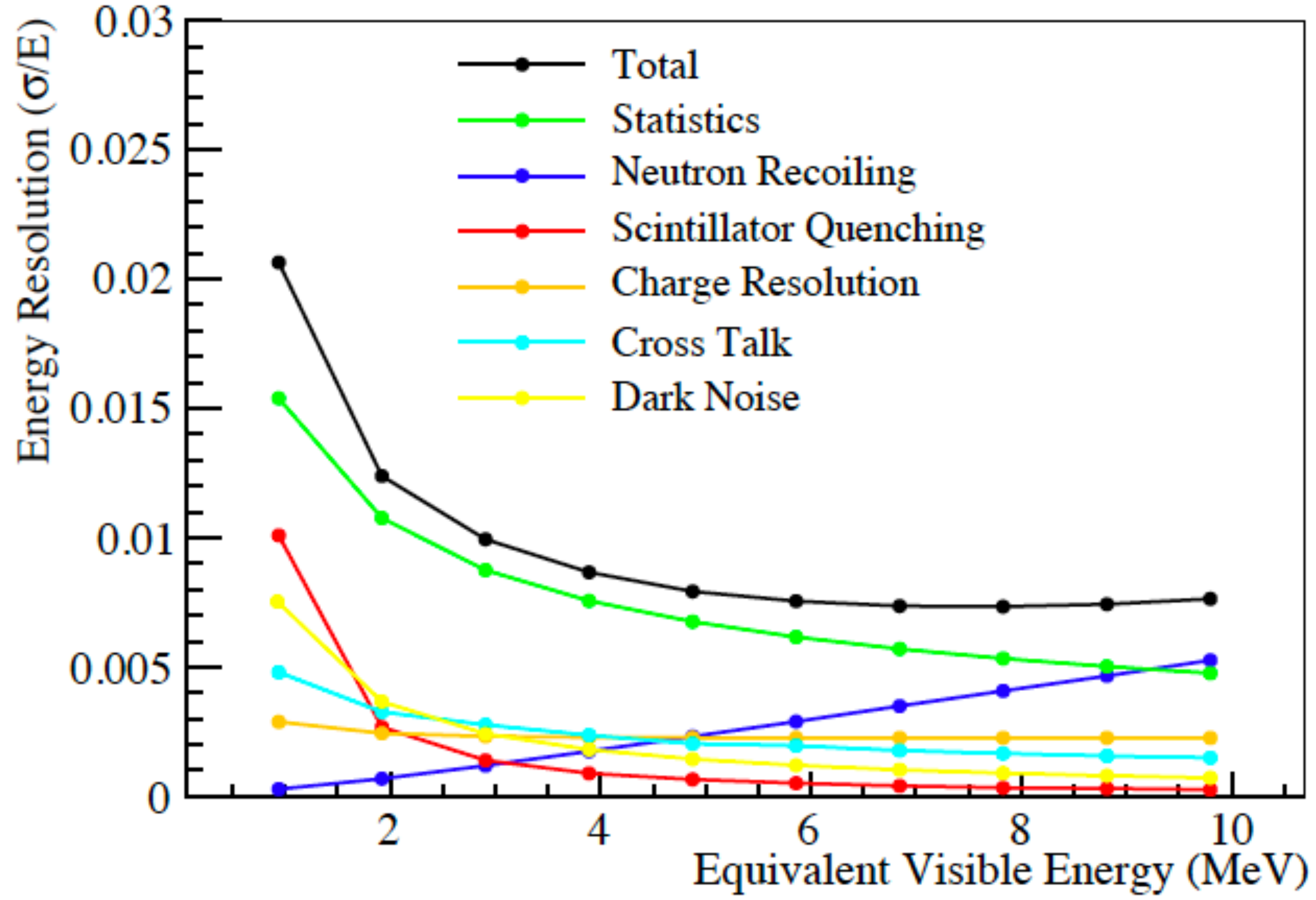
⇒ provides model-independent reference spectrum for JUNO

TAO detector

arXiv:2005.08745

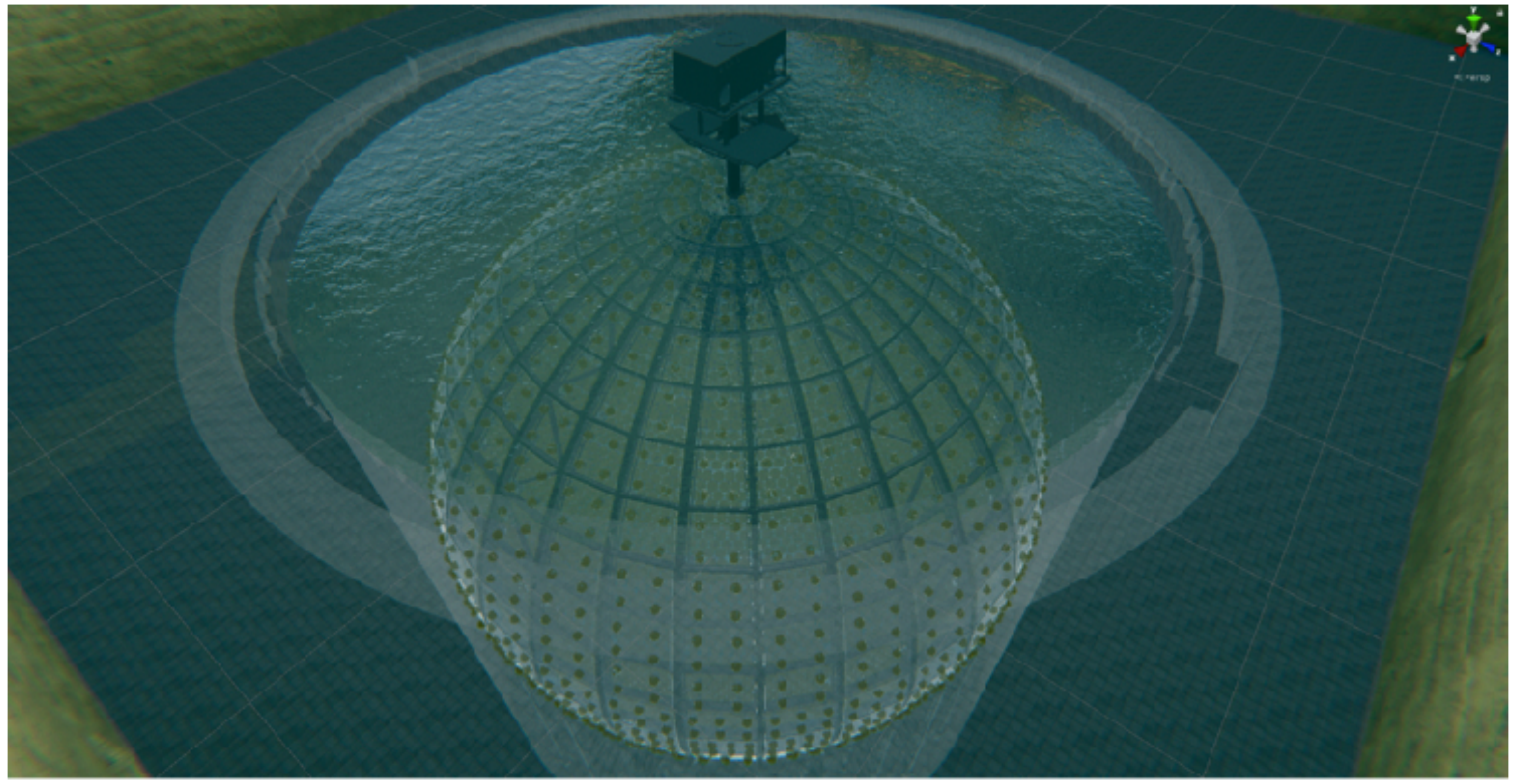


- 2.8 ton Gd-LS in acrylic vessel
- 10 m^2 SiPM for light detection on a spherical copper shell
- Operated at -50 °C
- High energy resolution
- 3.45 ton buffer liquid
- Cylindrical stainless steel tank insulated with 20 cm thick polyurethane (PU)
- Muon veto: water tank + PMTs on side and plastic scintillators on top
- 30 m from Taishan core (4.6 GW_{th})



Expected event rates

IBD signal	2000 events/day
Muon rate	70 Hz/m^2
Singles from radioactivity	< 100 Hz
Fast neutron background after veto	< 200 events/day
Accidental background rate	< 190 events/day
^{8}He/^{9}Li background rate	~ 54 events/day



Summary

- JUNO will be the largest neutrino observatory ever built with unprecedented energy resolution for detectors of this type
- Main goal: determine the neutrino mass ordering with a sensitivity of 3σ (may improve if combined with other experiments)
- First detector to see many oscillation cycles in the same experiment
- Sub-percent measurement of neutrino mixing parameters
- Very rich parallel physics program, including Supernova neutrinos, atmospheric neutrinos, solar neutrinos, geo-neutrino, nucleon decays, and exotic searches
- Detector construction to be completed by 2022

List of members

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	UTFSM	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
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China	Nankai U.	France	CPPM Marseille	Taiwan-China	National United U.
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China	Shandong U.	Germany	FZJ-ZEA	Thailand	SUT
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