Status of JUNO Experiment

On behalf of the JUNO collaboration

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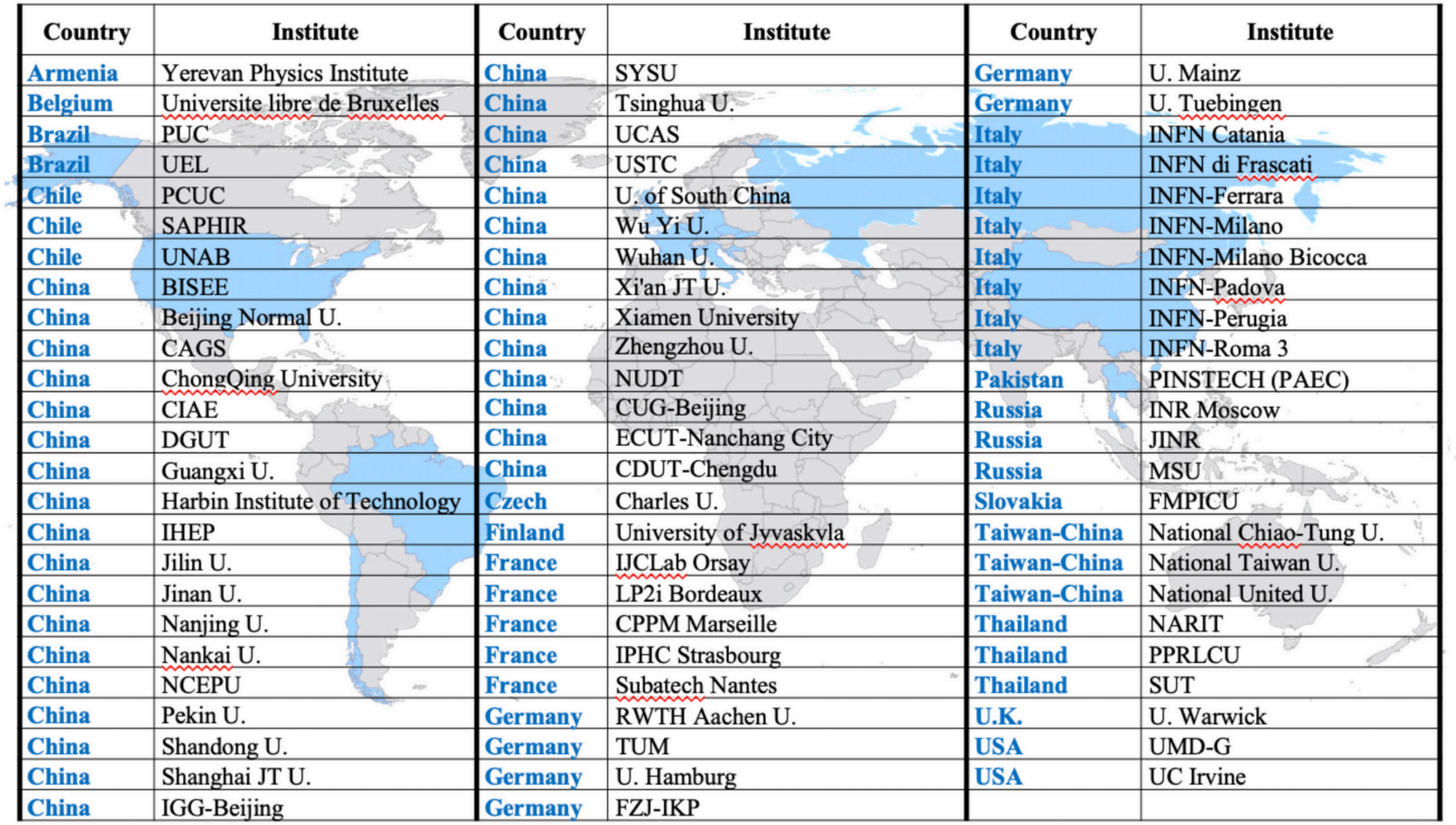
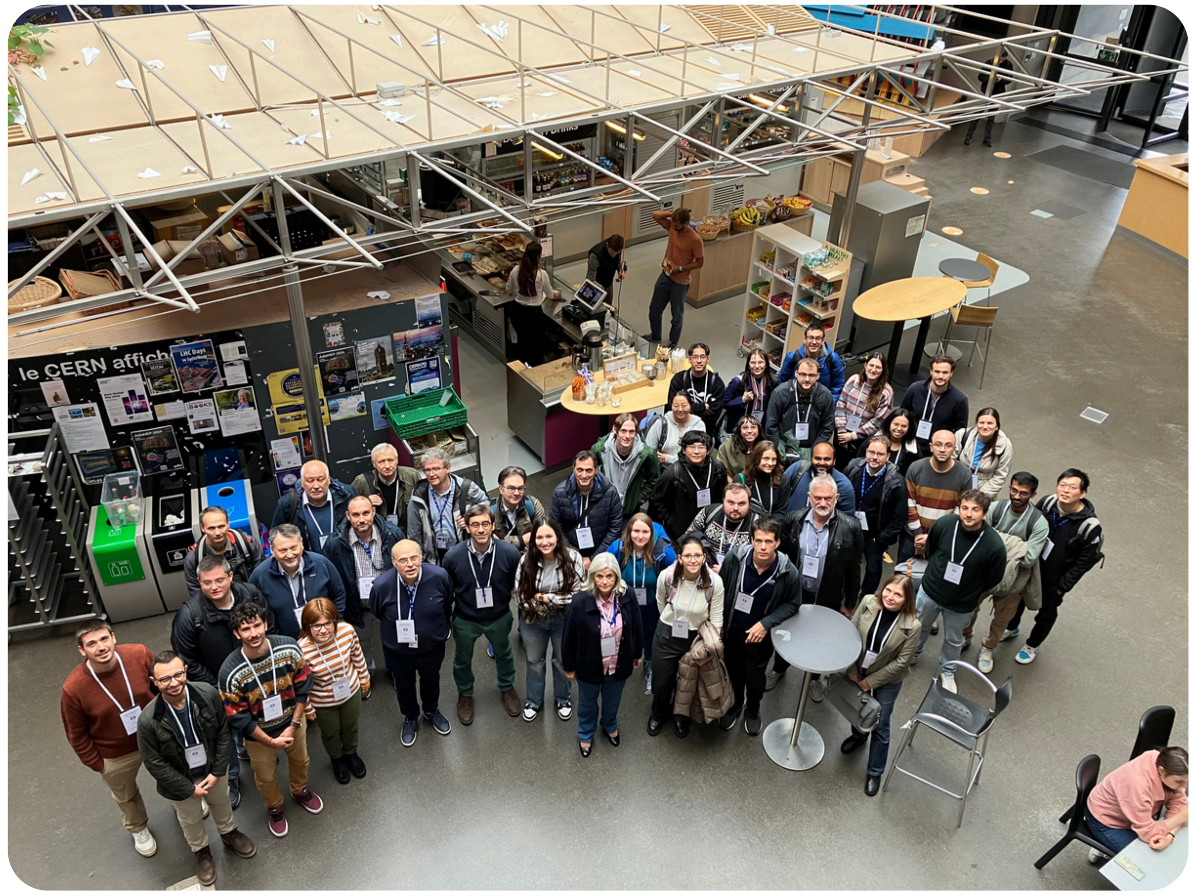
The JUNO collaboration

Collaboration was established in 2014.
We have now more than 700 collaborators from 74 institutions in 17 countries/region



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	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		

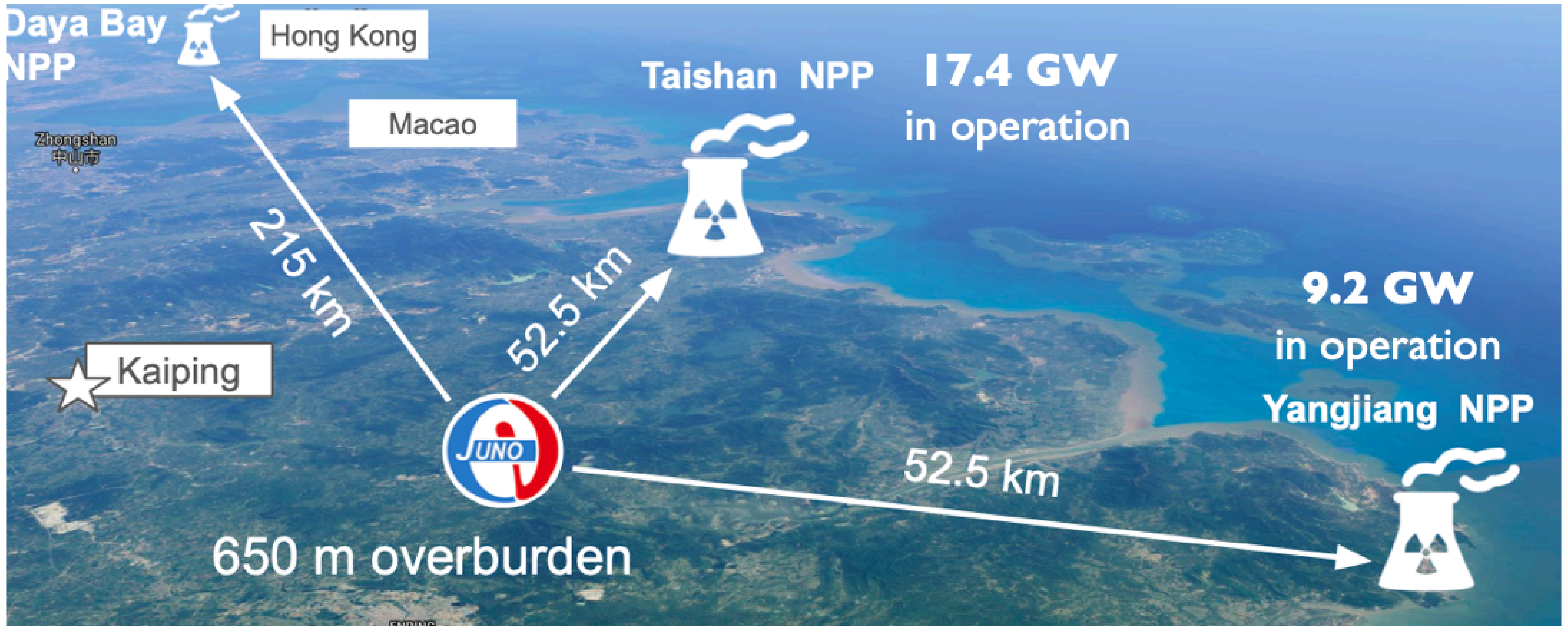
CERN recognised experiment with our first JUNO European + American collaboration meeting at CERN

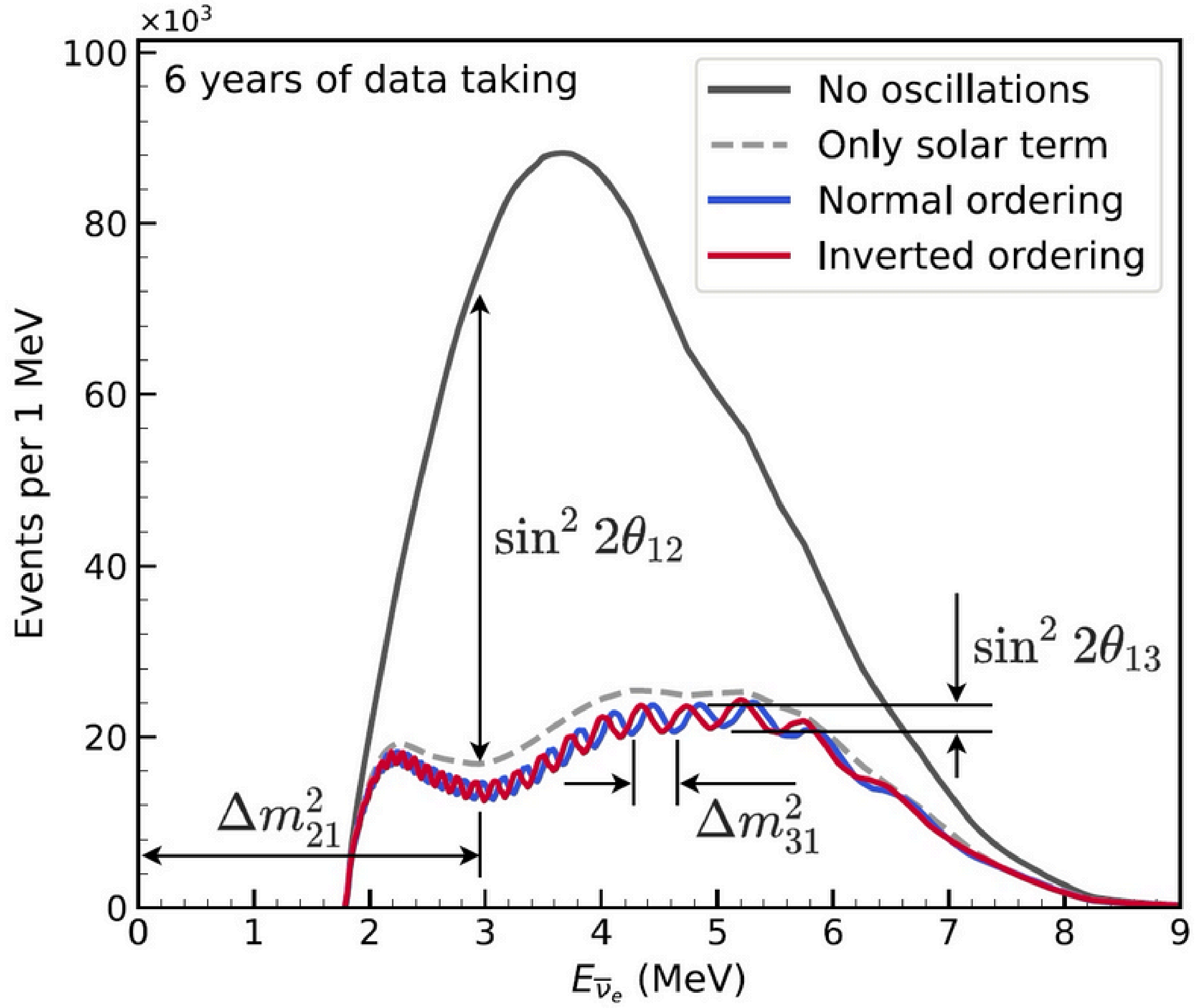


The **J**iangmen **U**nderground **N**eutrino **O**bservatory

JUNO is a state-of-the-art neutrino detector located in Jiangmen, China:

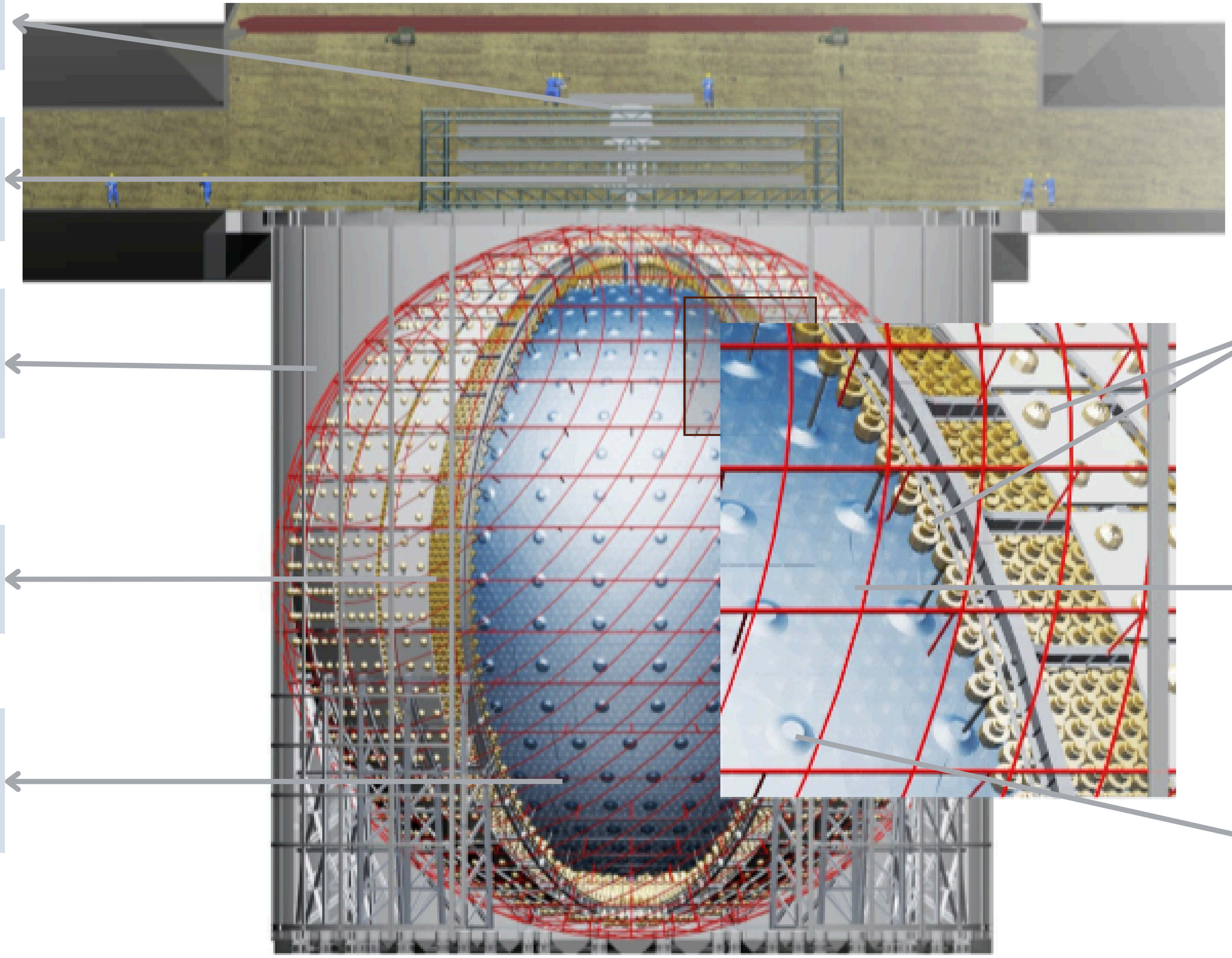
- Its position has been optimised to probe the Neutrino Mass Ordering (NMO)
- The main sources of (anti)neutrinos are 2 reactor power plants located exactly at 52.5 km from the detector





- Distance requires large enough mass (**20kt liquid scintillator target**)
- **Unprecedented energy resolution** (3% at 1 MeV) to seperate mass orederings

JUNO Detector Design



Calibration room
multi-dimension calibration systems

Top Tracker
3 layers of plastic scintillators strips
(cover ~50% of Water Pool)

Water Pool (WP)
35 kt pure water
~2000 20" MCP PMT
Muon and external radioactivity veto

Central Detector (CD)
Stainless Stell Structure (SSS)
Acrylic Sphere

Liquid Scintillator (LS)
High light yield: 1665 PE/MeV
High transparency: ~20 m attenuation length at 430 nm

PhotoMultipliers (PMTs)
17612 20" PMTs (LPMTs)
25600 3" PMTs (SPMTs)
~78% Photo coverage

Acrylic Vessel
Filled with 20 kt of LS
96% transparency
High radiopurity

Acrylic Nodes
Connecting bars to the SS structure to support the acrylic

Central Detector Construction

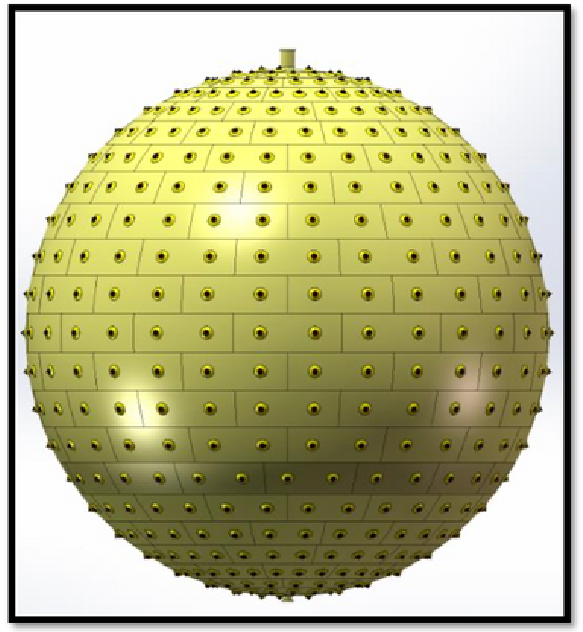
The Central Detector is made of the Acrylic vessel containing the LS and the SS structure supporting the acrylic

Acrylic panels production:

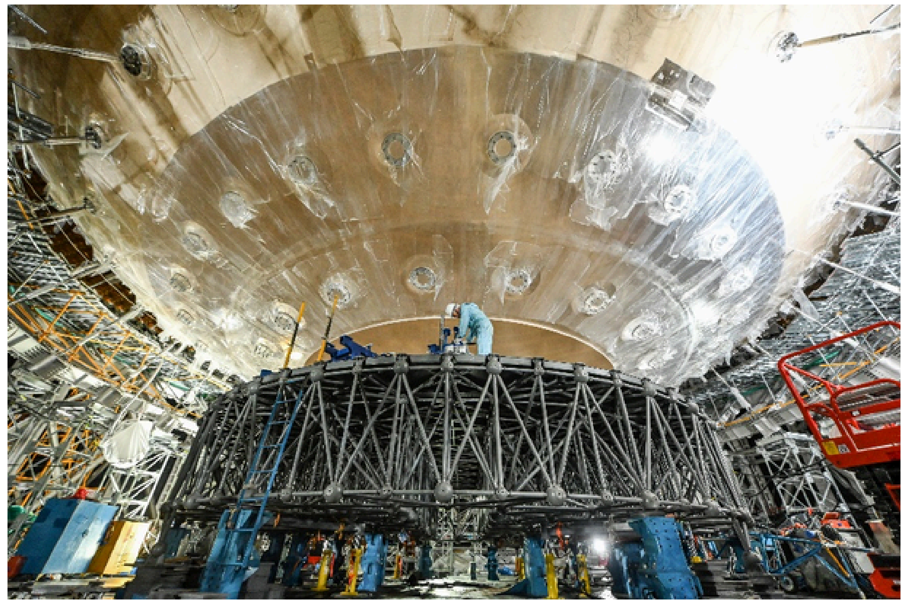
- **265 pieces** of spherical panels
- Thickness of 12 cm and net weight of **~600 tons**

Acrylic requirements:

- Transparency of >96%
- Radiopurity U/Th/K < 1ppt



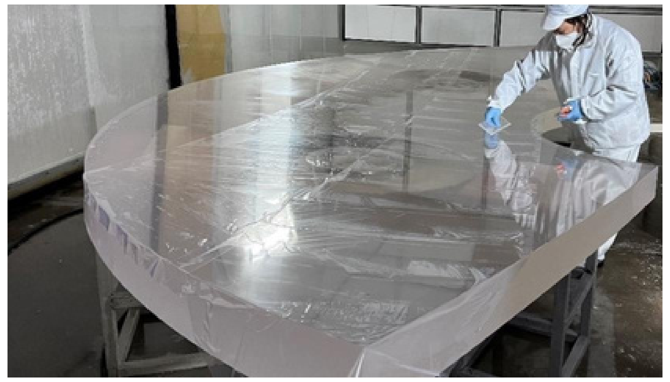
View of the Acrylic vessel from the bottom of the water pool



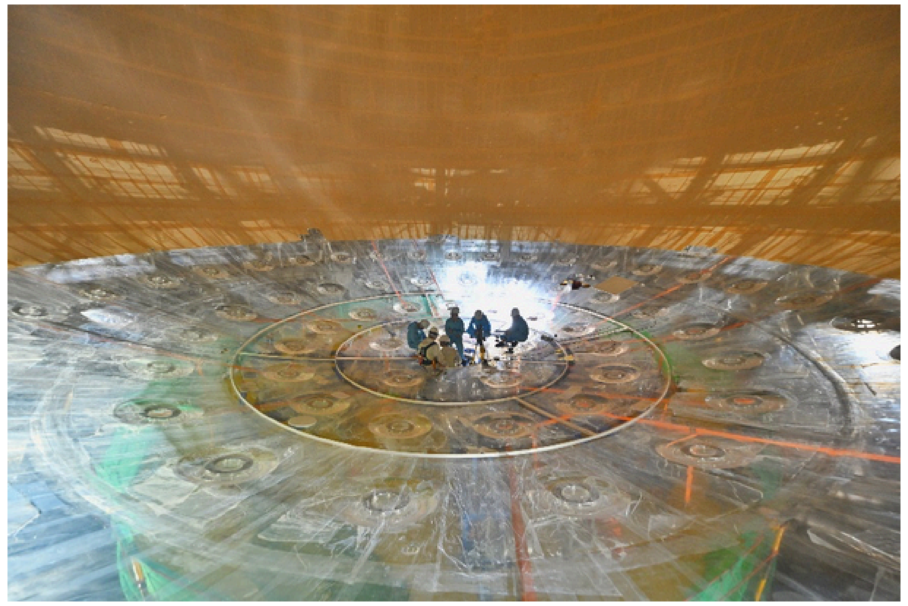
Polishing

Cleaning

50um PE protection film



Last 2 layers in positionning



Acrylic construction is completed

Defects were repaired

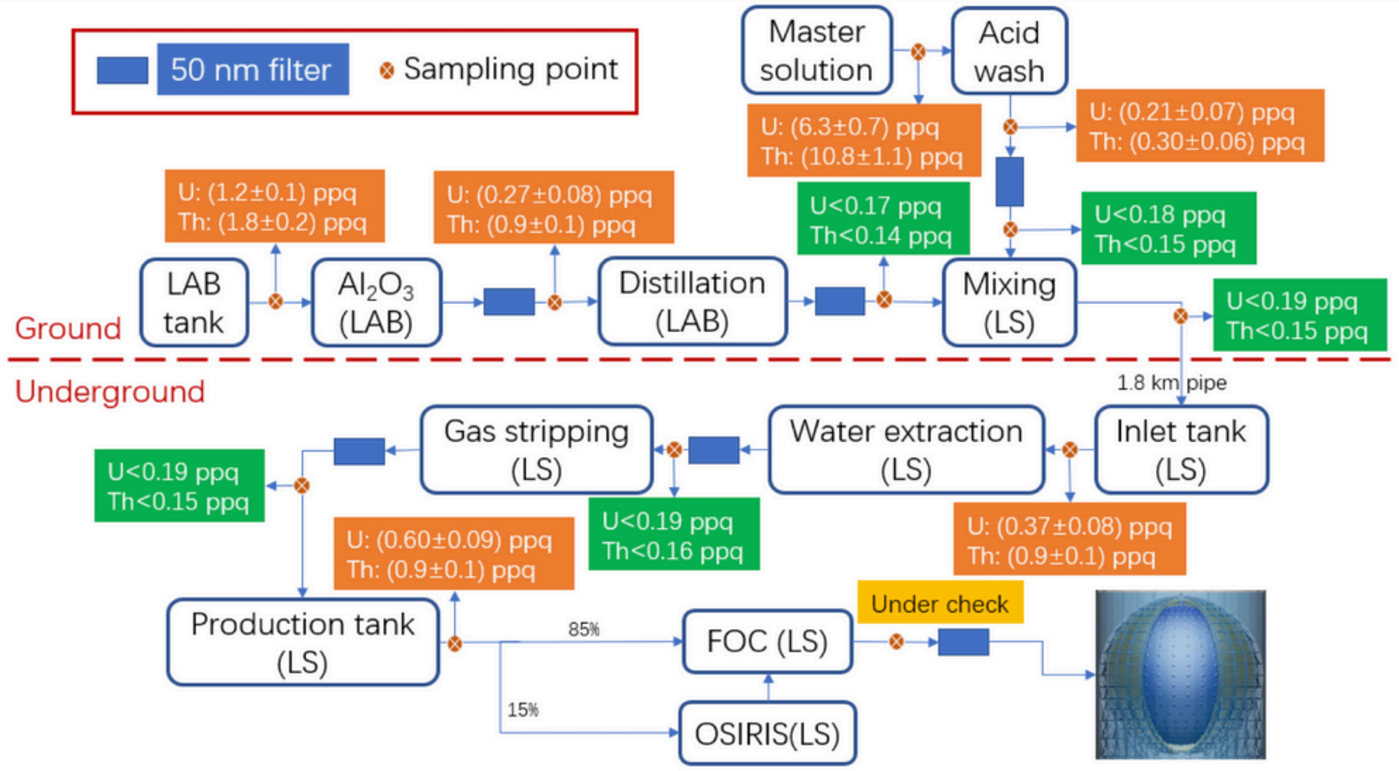
Last SS bars connecting acrylic to SS structure to be installed

Liquid Scintillator and OSIRIS

- Liquid Scintillator recipe: LAB (*solvant*) + 2.5 g/L PPO (*fluor*) + 3 mg/L bis-MSB (*wavelength shifter)*
- Before filling, the LS undergoes purification processes to enhance optical properties and remove radioactivity contaminants

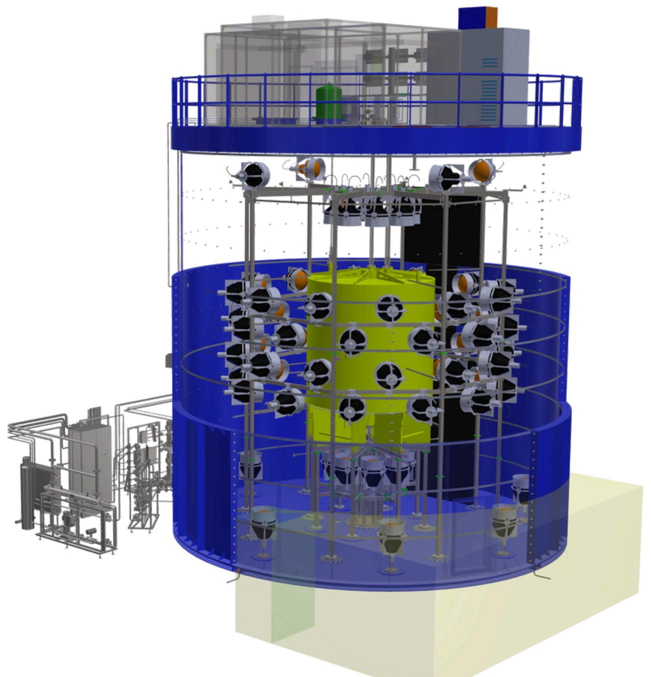
4 purification steps

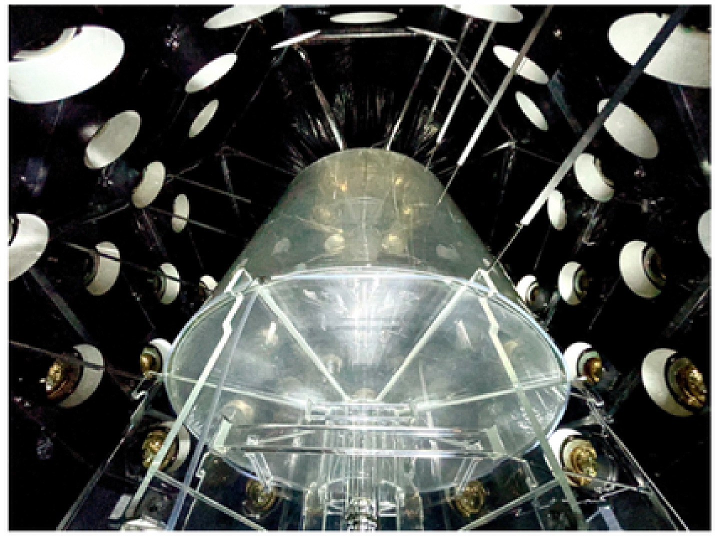
- Al_2O_3 filtration column (*optical properties improvement)*
- Distillation tower (*remove heavy element and improve transparency)*
- Water extraction (*remove U/Th/K isotopes)*
- Steam or Nitrogen stripping (*remove gaseous impurities from Ar/Kr/Rn)*



OSIRIS

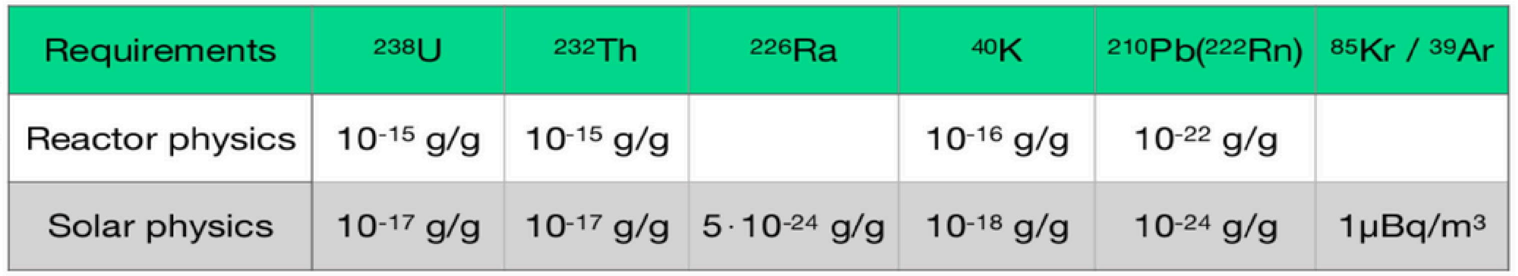
Online Scintillator Internal Radioactivity Investigation System





OSIRIS

- 17t liquid scintillator detector to monitor radiopurity levels of LS
- 3x3 m acrylic vessel surrounded by 76 MCP-PMTs + 3m of water shielding
- U/Th tagging by searching for Bi-Po coincidence



Requirements	^{238}U	^{232}Th	^{226}Ra	^{40}K	$^{210}Pb(^{222}Rn)$	^{85}Kr / ^{39}Ar	
Reactor physics	10^{-15} g/g	10^{-15} g/g		10^{-16} g/g	10^{-22} g/g		✓
Solar physics	10^{-17} g/g	10^{-17} g/g	$5 \cdot 10^{-24}$ g/g	10^{-18} g/g	10^{-24} g/g	1μBq/m^3	⌛

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Photomultipliers system

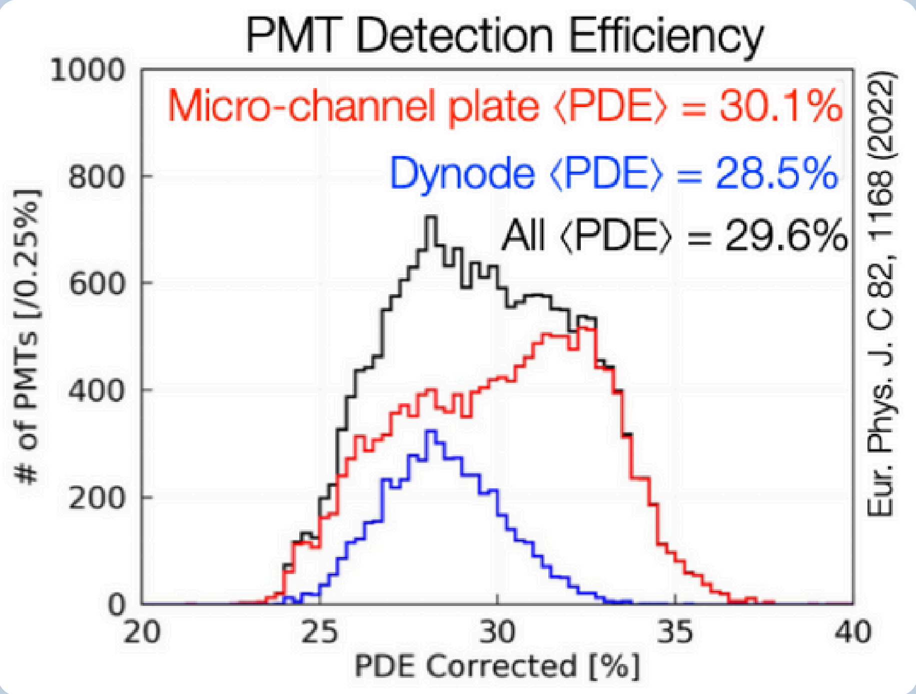
- To ensure high photo statistics and reach required energy resolution, JUNO is equipped with 2 PMT systems

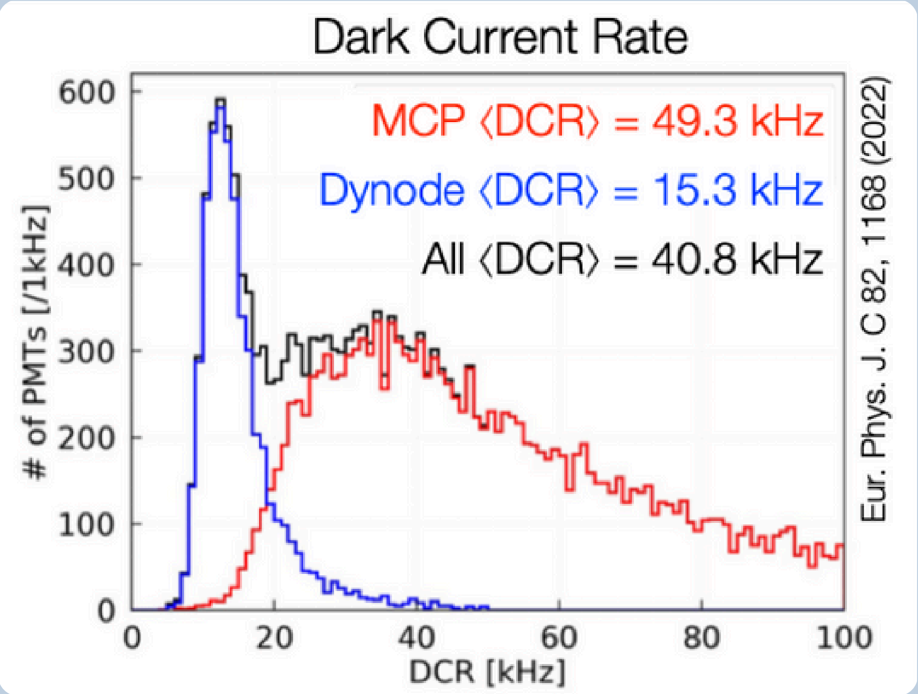
	20" PMTs (LPMT)		3" PMTs (SPMT)
Quantity	**5000**	**12612**	**25600**
Manufacturer	Hamamatsu (JP)	NNVT (CN)	HZC (CN)
Charge collection	Dynode	Micro-channel plate	Dynode
Transit Time Spread	1.3 ns	7.0 ns	1.5 ns
Light Yield	1665 p.e/MeV		
Coverage	~ 75 %		~ 3%

arXiv:2405.18008

NIM.A 1005 (2021) 165347

20 “ PMTs

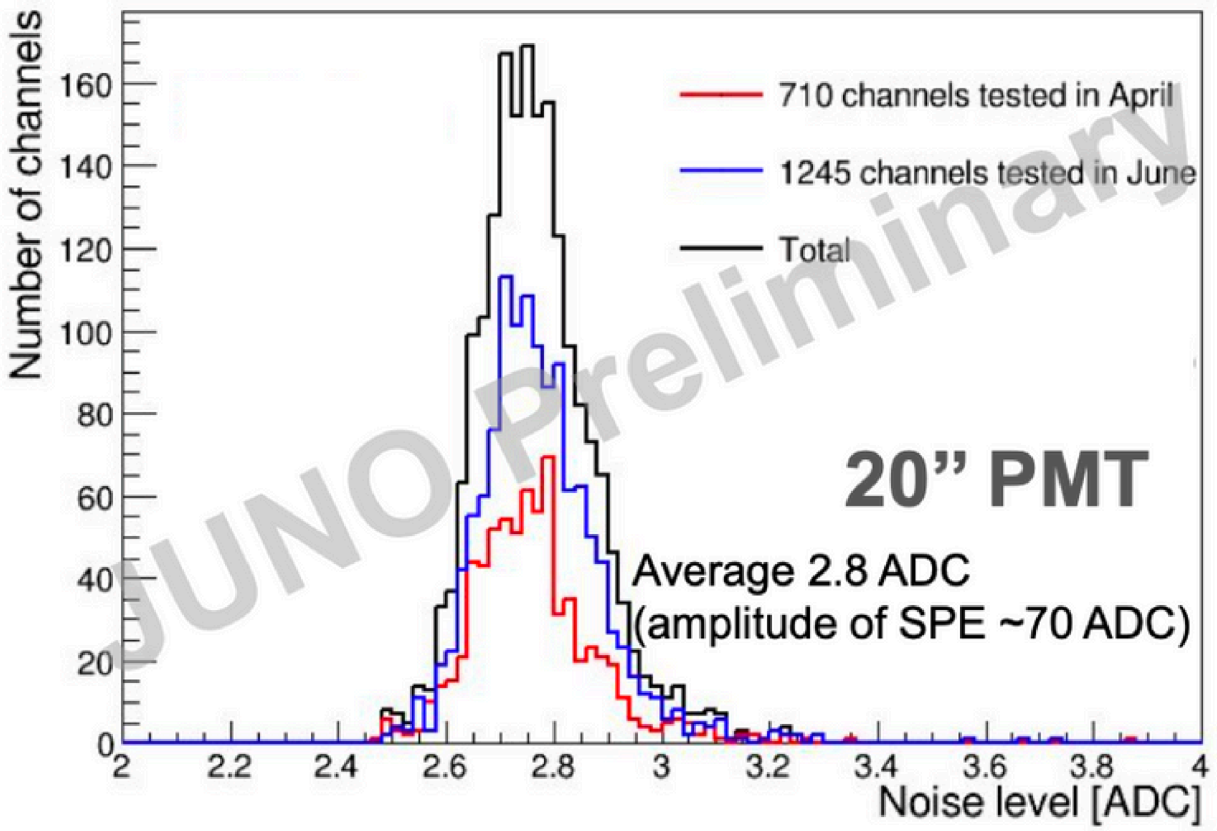




- MCP PMTs have better PDE than Hamamatsu dynode PMTs but worse TTS
- MCP PMTs are more suited for energy measurements and dynode PMTs are crucial for tracking and vertex reconstruction

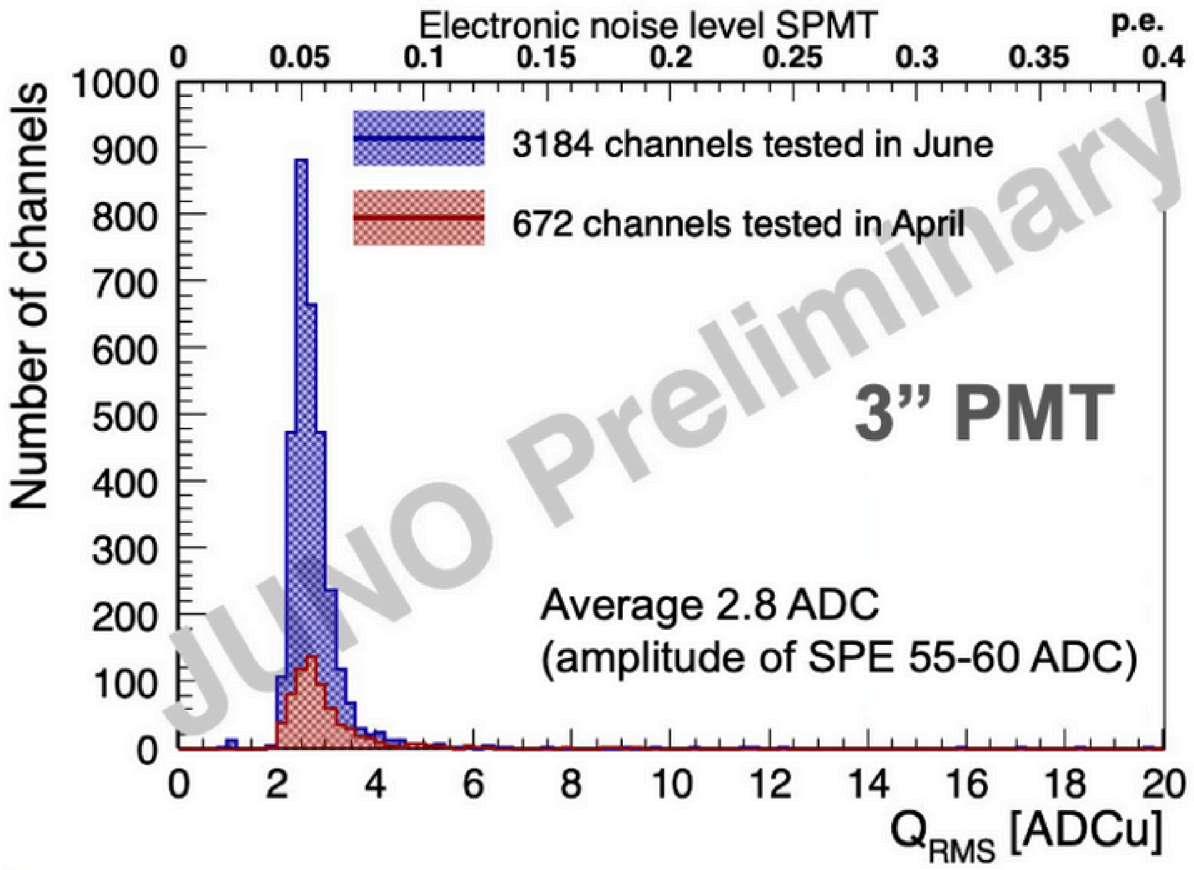
Photomultipliers system commissioning

- Regular light-off tests during detector assembly:
  - Light off tests: full data taking and processing chain with PMT HV on
  - Light on tests: joint elec./trigger/DAQ/DCS test with PMT HV off
- Very good electronics, shielding and grounding
- All tested PMTs were working well



Electronics noise is 2.8 ADC counts, 4% of SPE

↳ Much better than the design of 10%



Electronics noise is 2.8 ADC counts, 5% of SPE

↳ Much lower than the trigger threshold of 1/3 p.e

Photomultiplier tubes installation

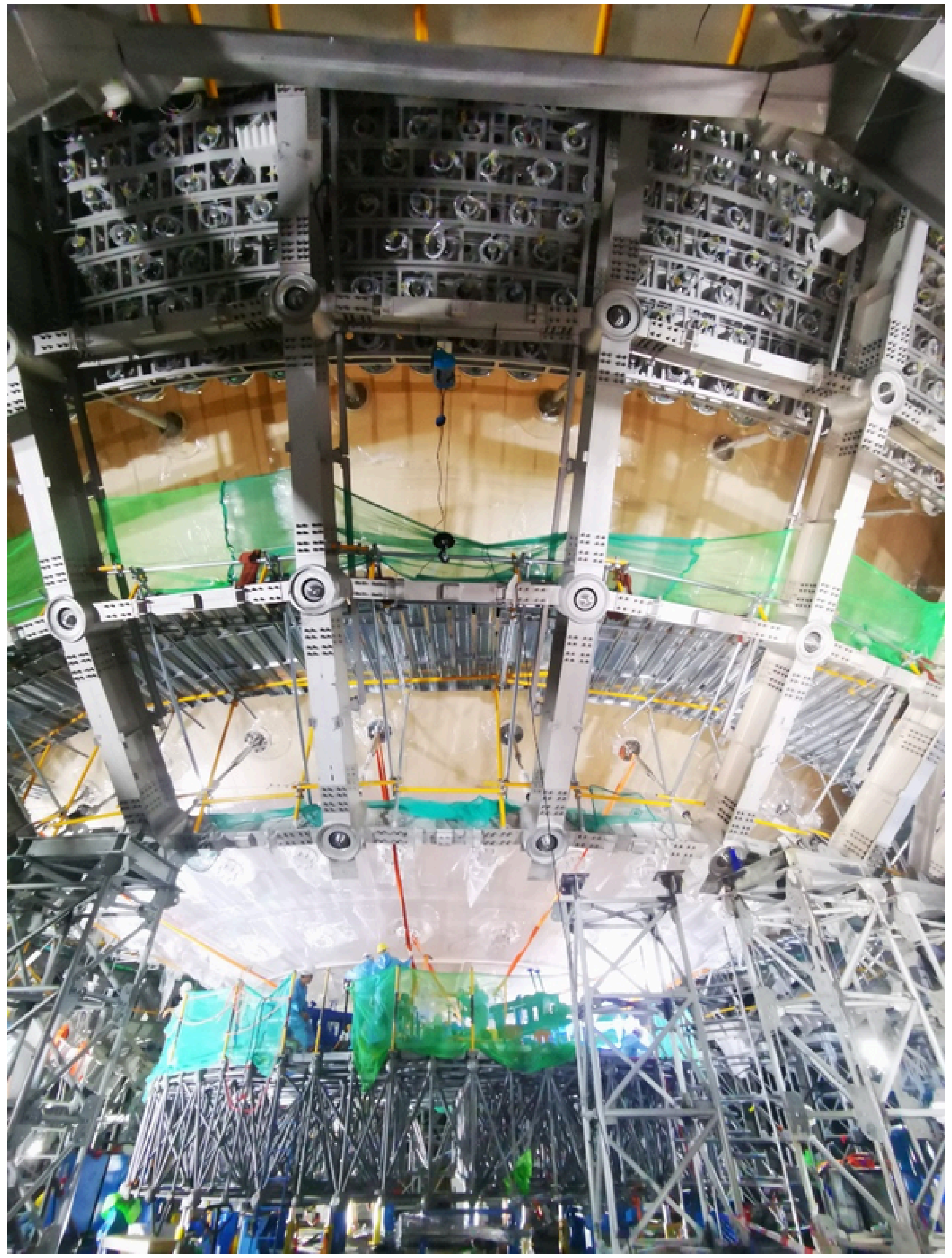
The PMTs installation follows closely the acrylic construction

As of September 2024:

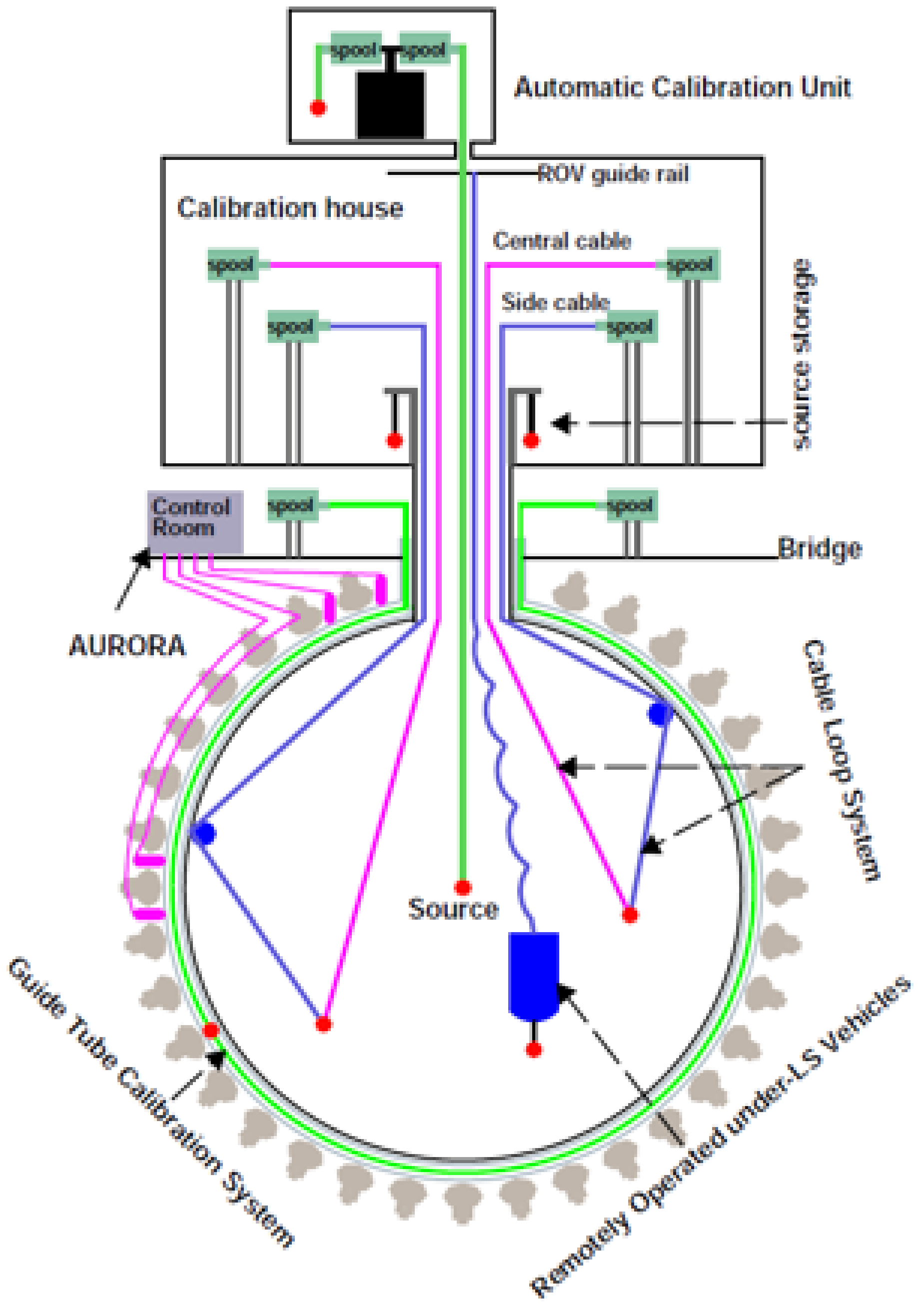
- 14866 LPMTs installed (~84% of 17612)
- 22207 SPMTs installed (~87% of 25600)

Electronics installation:

- Under Water Boxes (UWB) containing the electronics have been installed (85%)
- Some channels in UWB located in upper layers have electronics noises and are under investigation



Energy Scale calibration



A systematic error of less than 1% is obtained by the means of the calibration system composed by four systems exploiting γ , β and neutron sources:

- **Automatic Calibration Unit (ACU)**: 1D along the vertical axis (*Scan central axis*)
- **Cable Loop System (CLS)**: 2D plane inside the acrylic vessel (*Scan CD vertical plane*)
- **Guide Tube (GT):** 2D plane outside acrylic vessel (*Scan CD outer surface*)
- ***Remotely Operated Vehicle (ROV)**: 3D anywhere inside the detector*

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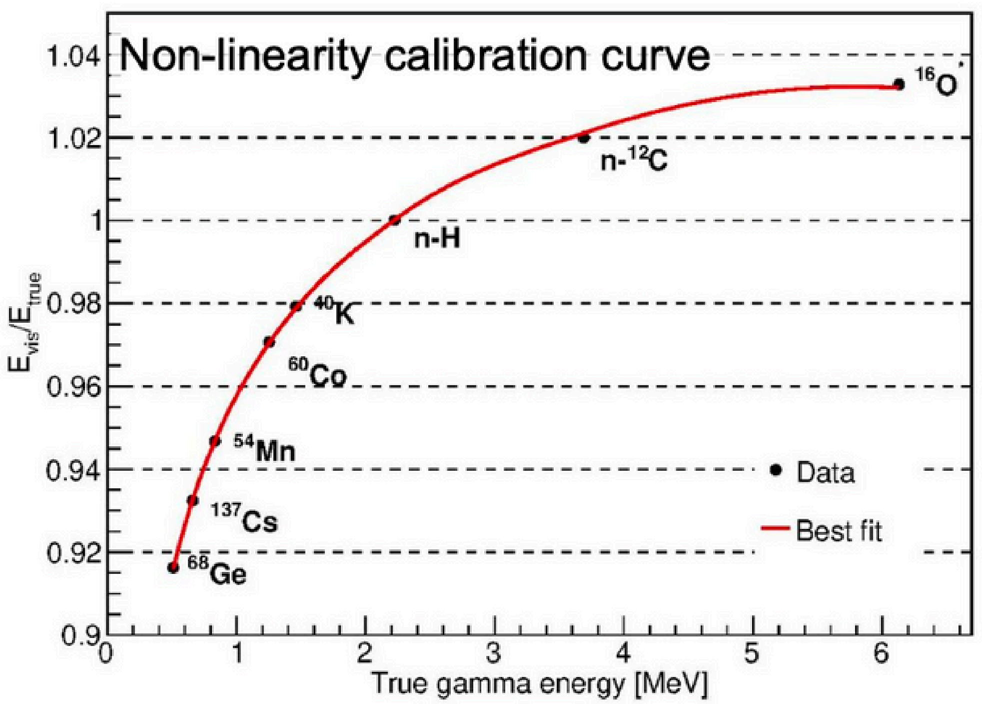
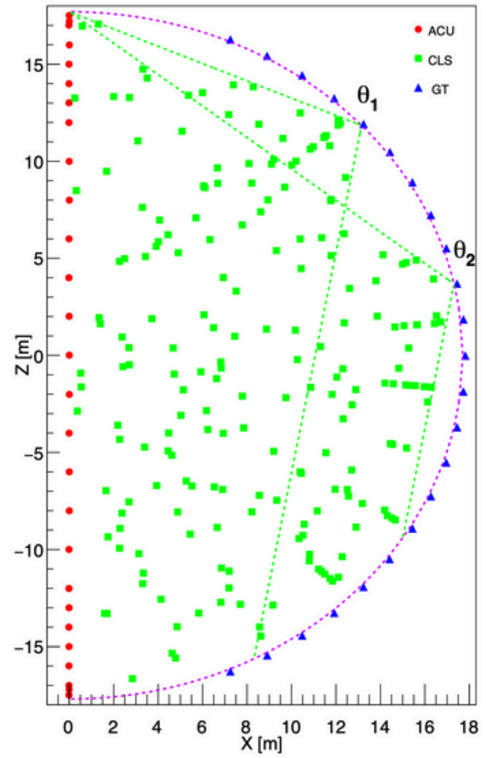
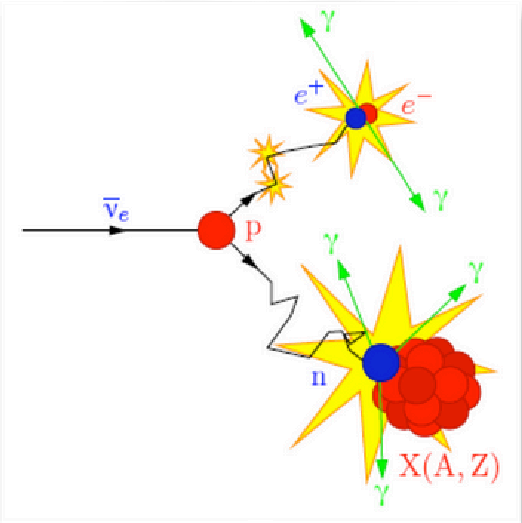


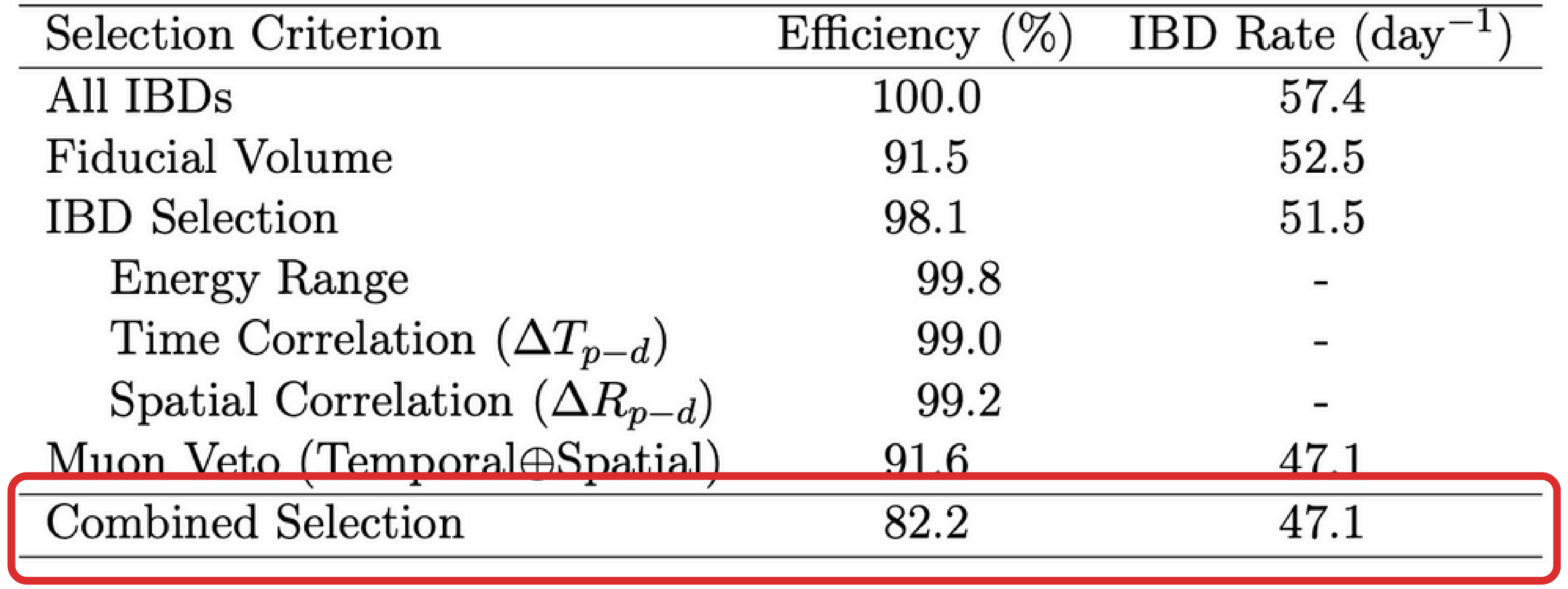


Signal and Background in JUNO

Inverse Beta Decay (IBD)

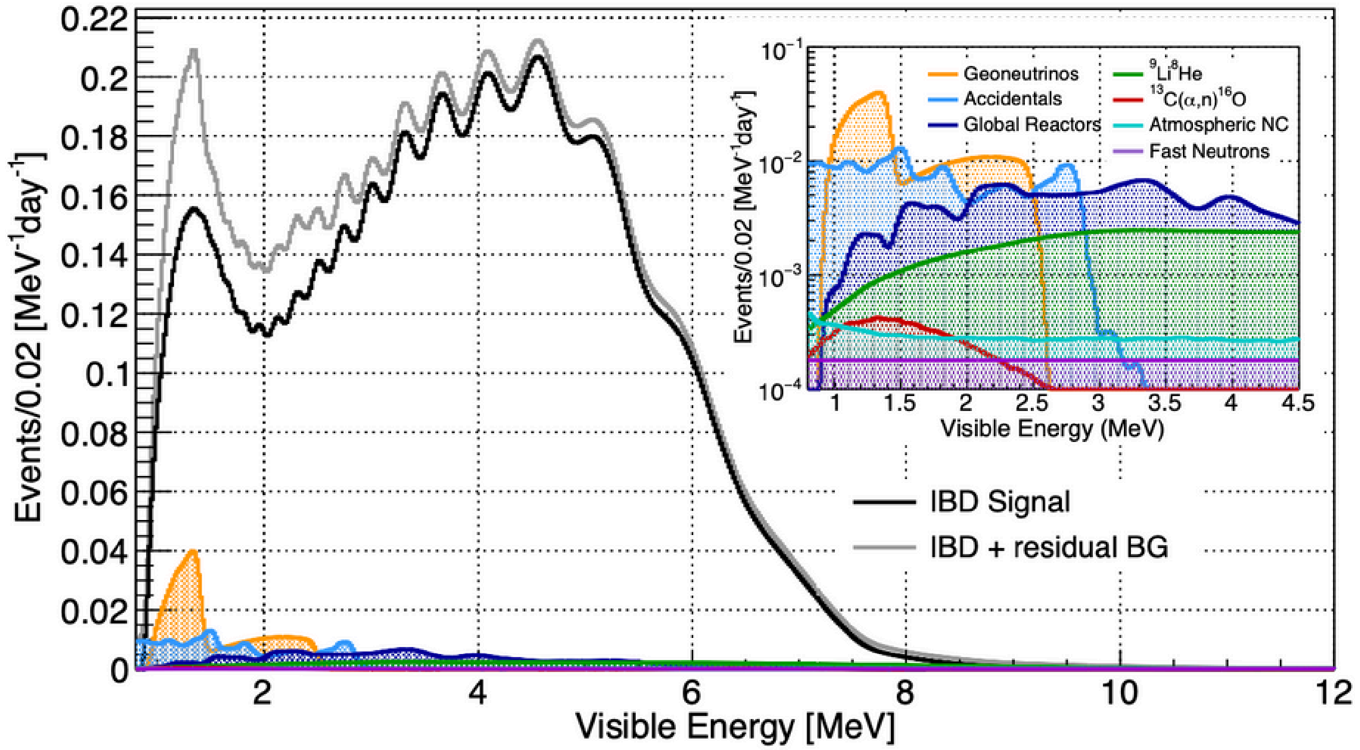
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

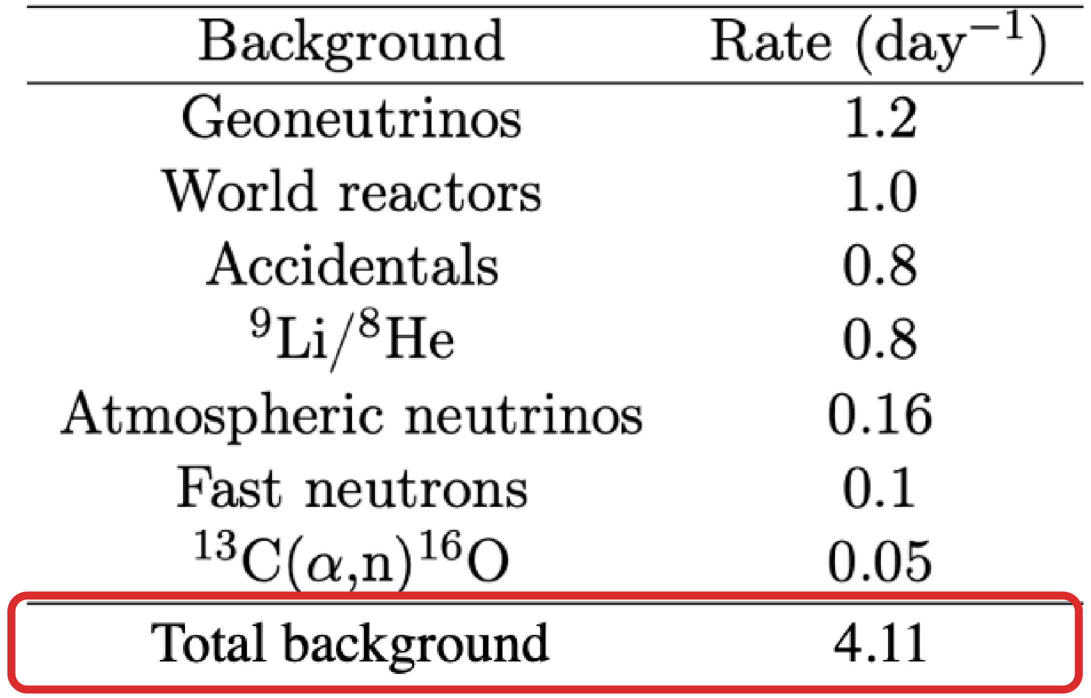




Selection Criterion	Efficiency (%)	IBD Rate (day^{-1})
All IBDs	100.0	57.4
Fiducial Volume	91.5	52.5
IBD Selection	98.1	51.5
Energy Range	99.8	-
Time Correlation (ΔT_{p-d})	99.0	-
Spatial Correlation (ΔR_{p-d})	99.2	-
Muon Veto (Temporal⊕Spatial)	91.6	47.1
Combined Selection	82.2	47.1

CPC 46 (2022) 12, 123001



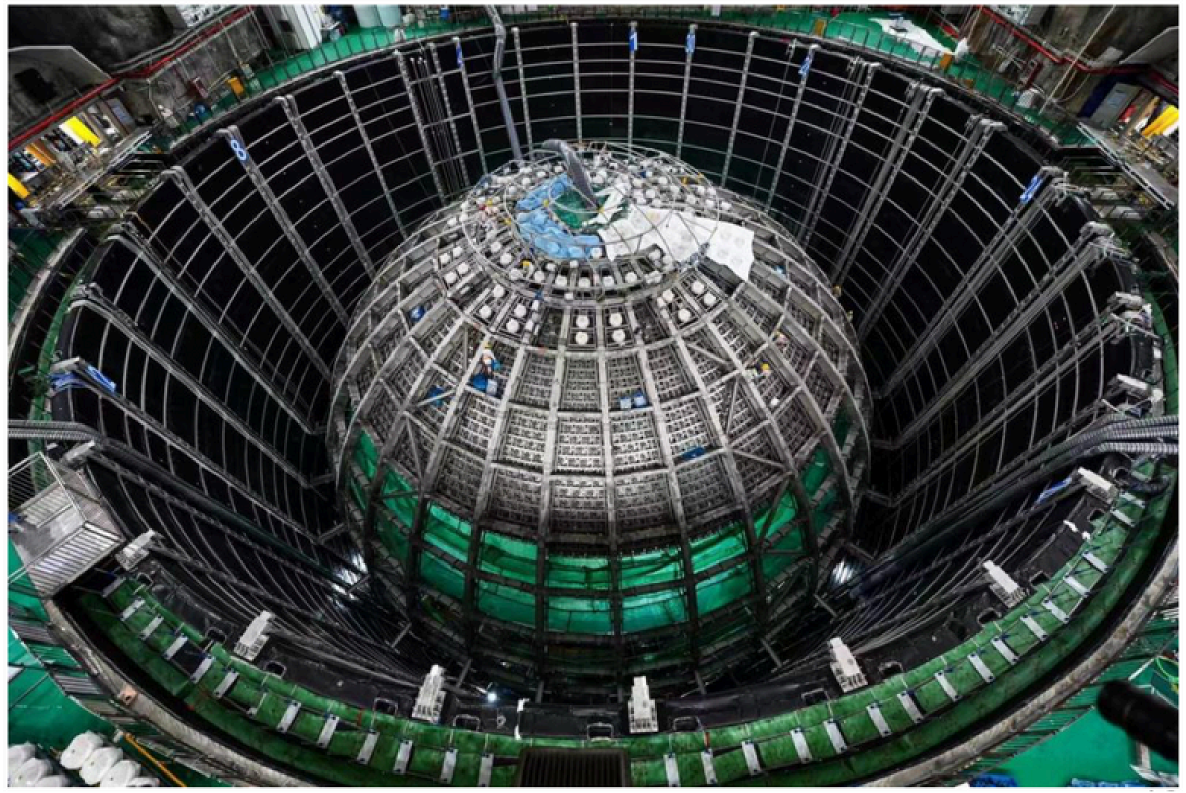


Background	Rate (day^{-1})
Geoneutrinos	1.2
World reactors	1.0
Accidentals	0.8
^{9}Li/^{8}He	0.8
Atmospheric neutrinos	0.16
Fast neutrons	0.1
^{13}C(α,n)^{16}O	0.05
Total background	4.11

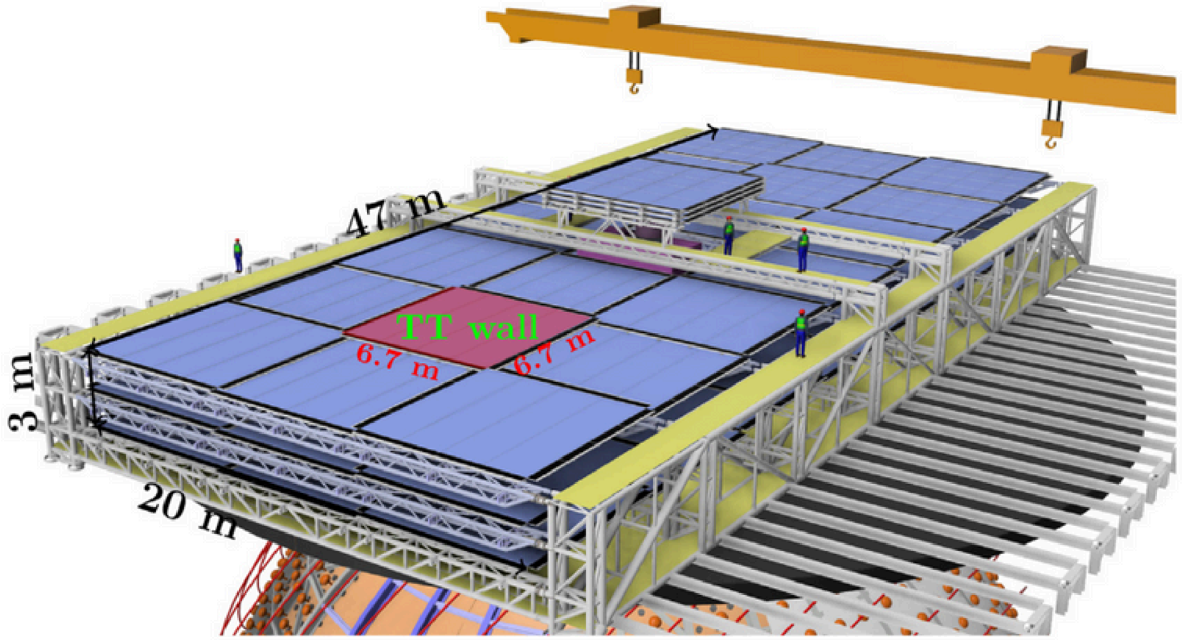
Veto Design and Installation

- 650m overburden corresponding to 1800 m.w.e

- Water pool (WP):
  - 35 kton of ultrapure water and 2400 MCP-PMTs are used to form the Water Cherenkov Detector (~50% of PMTs have been installed)
  - Water pool lining: 5mm of HDPE to serve as Rn barrier and keep the water clean
  - 100t/h ultrapure water production system:
    - Rn < 10mBq/m^3
    - temperature controlled to (21 ± 1 °C)



- TopTracker (TT):
  - Reusing **plastic scintillator from OPERA** Target Tracker
  - ~ 50% coverage on the top. Three layers to reduce accidental coincidence
  - Control muon samples to validate track reconstruction and study cosmogenic backgrounds
  - Bridge has been assembled and installation is on-going

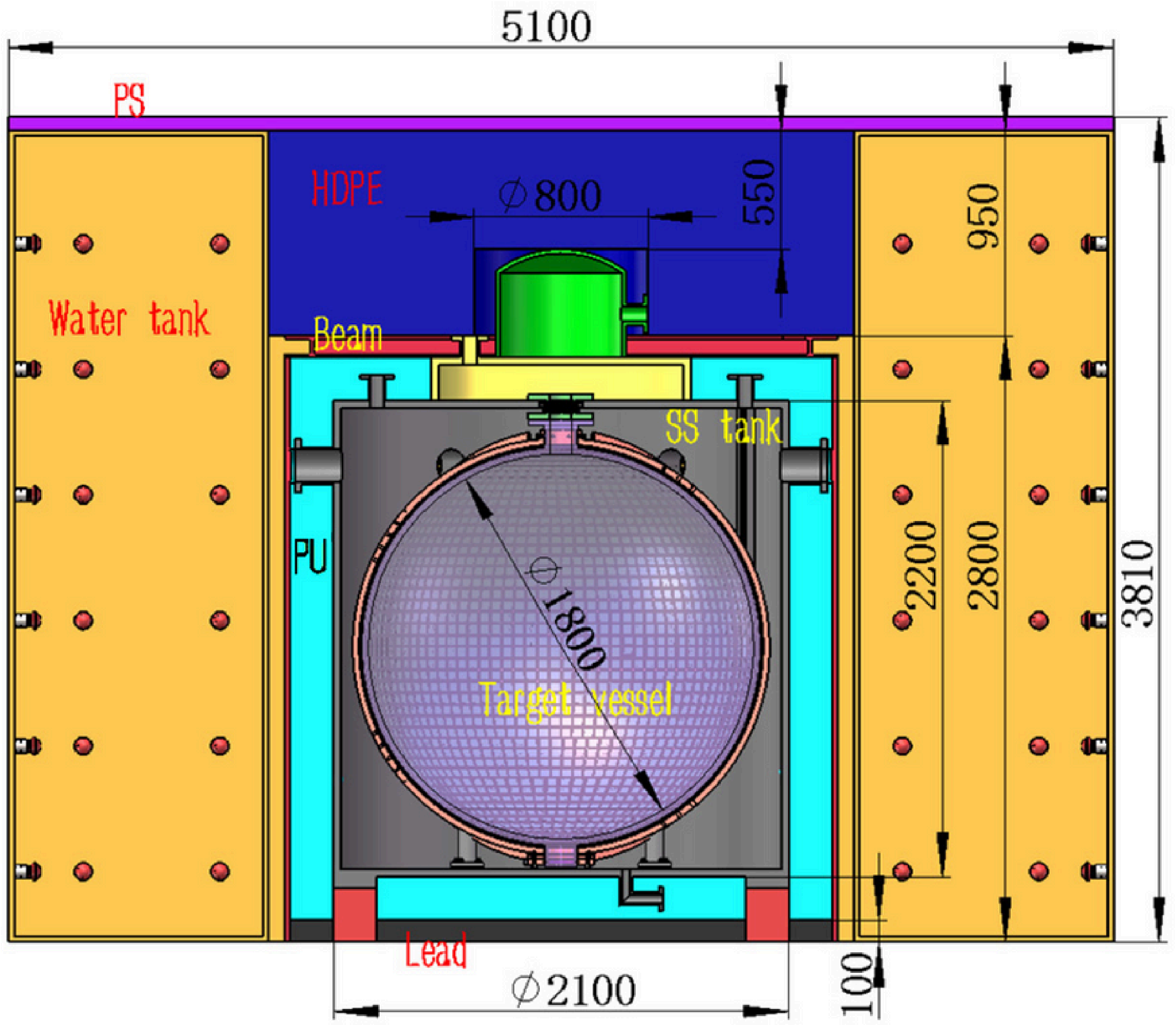


JUNO-TAO

Taishan **A**ntineutrino **O**bservatory (TAO) is a high energy resolution LS detector located at 30m from one of Taishan's reactor cores (4.6 GW_{th}).
This satellite detector will measure the fine structure of the reactor neutrino spectrum and **eliminate the model dependence** of JUNO Neutrino Mass Ordering (NMO).

Detector Design

- 2.8t of Gd-doped LS in an acrylic vessel
- Water Cherenkov veto + plastic scintillator (PS) tagger
- Working temperature: -50°C
- Covered with SiPM tiles (PDE ~50%) for ~94% coverage
- 4500 p.e/MeV corresponding to 2% energy resolution at 1 MeV

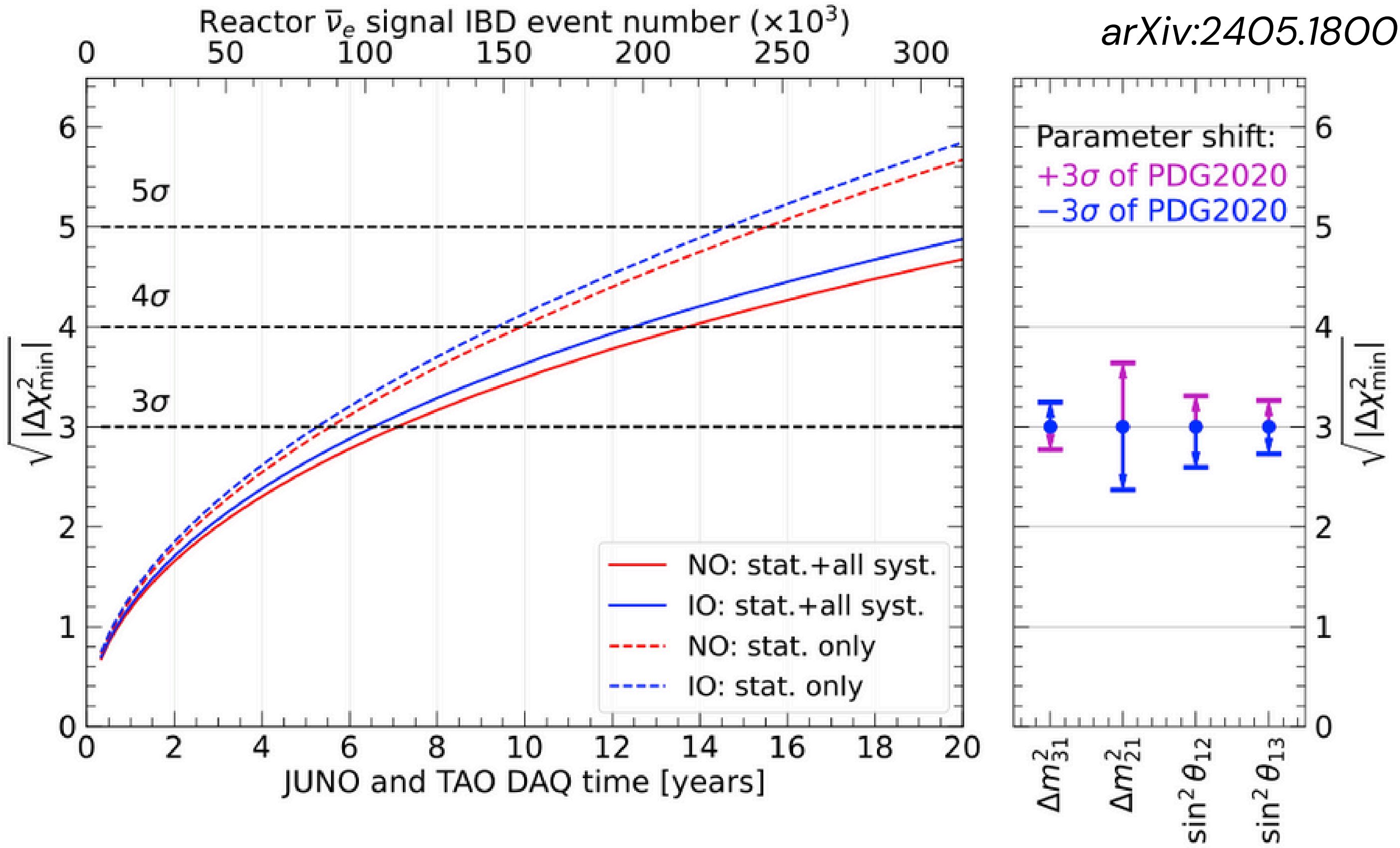


JUNO Physics reach

Physics goals:

- Neutrino mass ordering
- Mesure other oscillation parameters at sub-% precision

arXiv:2405.18008



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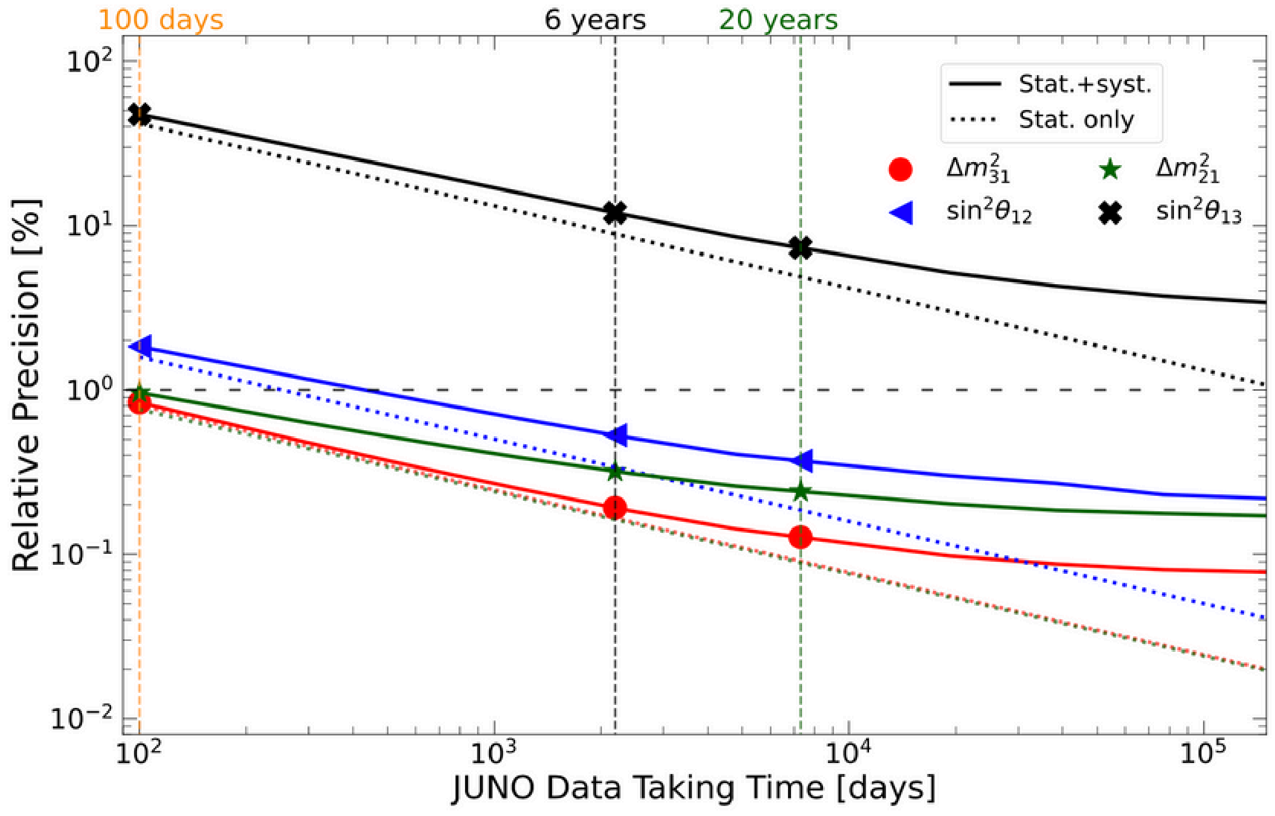


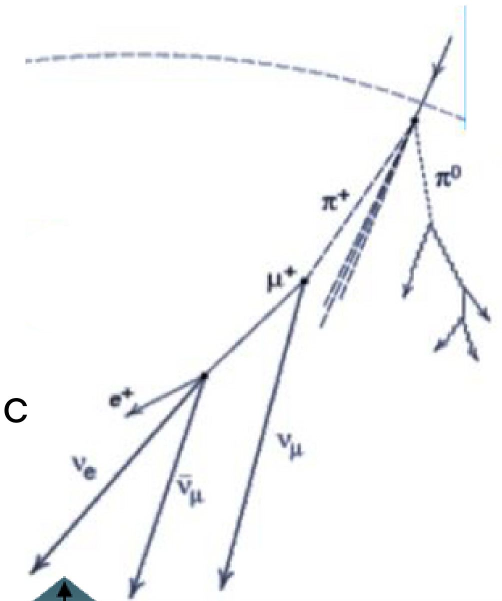
		Central Value	PDG2020	100 days	6 years	20 years
●	Δm^2_{31} ($\times10^{-3}$ eV^2)	2.5283	±0.034 (1.3%)	±0.021 (0.8%)	±0.0047 (0.2%)	±0.0029 (0.1%)
★	Δm^2_{21} ($\times10^{-5}$ eV^2)	7.53	±0.18 (2.4%)	±0.074 (1.0%)	±0.024 (0.3%)	±0.017 (0.2%)
◀	$\sin^2\theta_{12}$	0.307	±0.013 (4.2%)	±0.0058 (1.9%)	±0.0016 (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%)

- JUNO aims toward determining the mass ordering with over **3σ significance level after 6.7 years** of data taking.
- A 5σ significance level could be reached by accounting for external constraints from long-baseline experiments

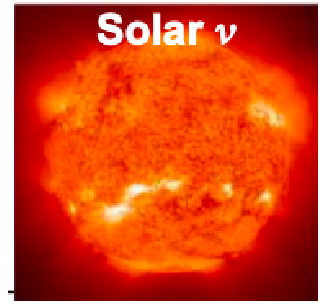
JUNO Physics reach

JUNO is sensitive to a large panel of neutrino sources that makes it a multi-purpose Neutrino Observatory

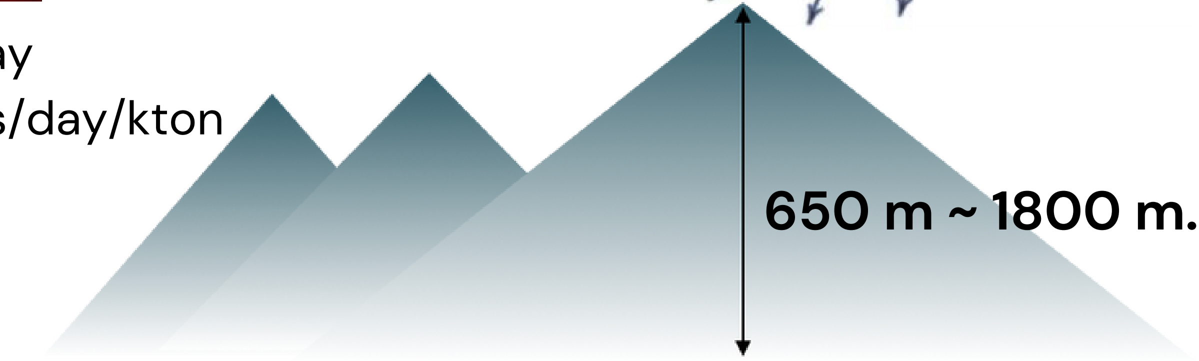
CCSN: 10^4evts at 10 kpc
DSNB: 2-4 evts/year



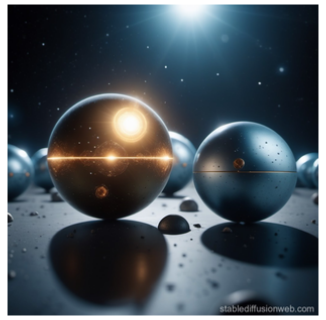
Less than 100 evts/day



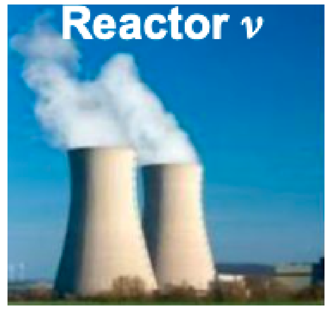
^{8}B: 16 evts/day
^{7}Be: 490 evts/day/kton



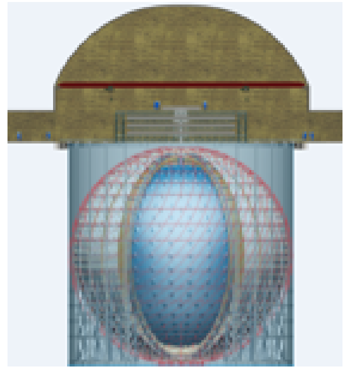
650 m ~ 1800 m.w.e



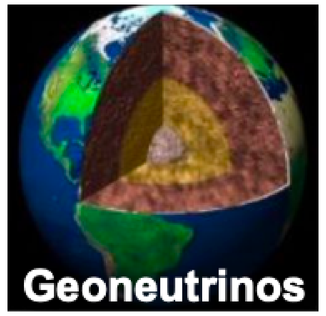
Proton decays: $p \rightarrow \bar{\nu} + K^+$
Lifetime: 10^{34} years



~ 47 evts/day



~400 evts/year



Summary and Conclusion

- JUNO is a state-of-the-art reactor neutrino detector with the largest mass ever built (20 kt of LS) and an unmatched energy resolution (3% @ 1 MeV)
- JUNO's construction is still ongoing but very close to completion
- Components quality exceed the predicted design and may increase the performance
- Filling and start of data taking is scheduled for 2025
- The satellite detector TAO will increase our knowledge of the reactor neutrino flux
- Neutrino mass ordering measurement will be obtained in 6 years x 26.6 GWth with:
  - ~3σ with reactor neutrinos only
  - ~5σ by accounting for long baseline experiments constraints
- Sub-percent measurement of other parameters of the PMNS matrix (Δm^2_{31} , Δm^2_{21} , $\sin^2\theta_{12}$)
- JUNO also has a large panel of astrophysics program

BACK UP

Neutrino Oscillation

PMNS mixing matrix links neutrino flavour eigenstates with their mass eigenstates:

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

$s_{ij} = \sin(\theta_{ij})$

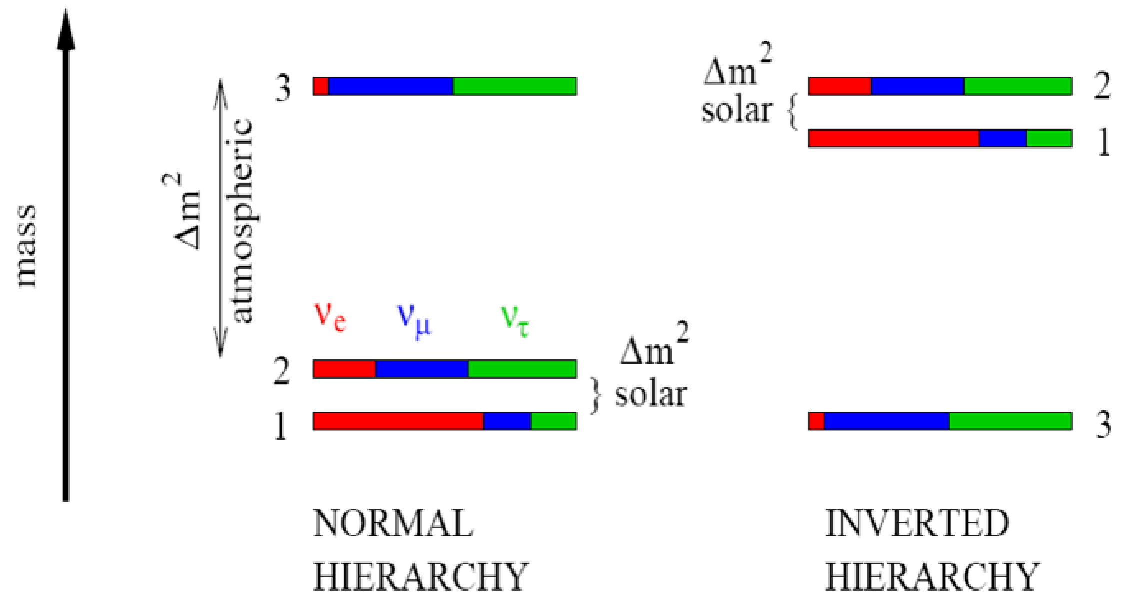
$c_{ij} = \cos(\theta_{ij}) \qquad i,j = (1,2,3)$

$\delta = phase\ CP$

$\xi_{ij} = Majorana\ phase$

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \times \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{bmatrix} \times \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} e^{i\xi_1/2} & 0 & 0 \\ 0 & e^{i\xi_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Most of the parameters have been measured with a precision > 1%



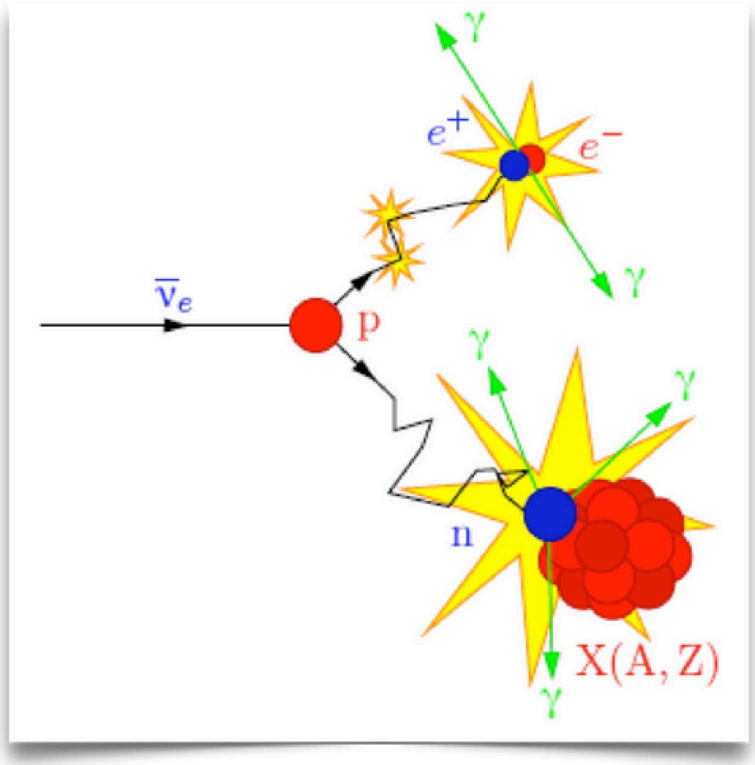
PDG 2022

	Ref. [188] w/o SK-ATM	
NO	Best Fit Ordering	
Param	bfp $\pm 1\sigma$	3σ range
$\frac{\sin^2\theta_{12}}{10^{-1}}$	$3.10^{+0.13}_{-0.12}$	$2.75 \rightarrow 3.50$
$\theta_{12}/°$	$33.82^{+0.78}_{-0.76}$	$31.61 \rightarrow 36.27$
$\frac{\sin^2\theta_{23}}{10^{-1}}$	$5.58^{+0.20}_{-0.33}$	$4.27 \rightarrow 6.09$
$\theta_{23}/°$	$48.3^{+1.2}_{-1.9}$	$40.8 \rightarrow 51.3$
$\frac{\sin^2\theta_{13}}{10^{-2}}$	$2.241^{+0.066}_{-0.065}$	$2.046 \rightarrow 2.440$
$\theta_{13}/°$	$8.61^{+0.13}_{-0.13}$	$8.22 \rightarrow 8.99$
$\delta_{CP}/°$	222^{+38}_{-28}	$141 \rightarrow 370$
$\frac{\Delta m^2_{21}}{10^{-5}\ eV^2}$	$7.39^{+0.21}_{-0.20}$	$6.79 \rightarrow 8.01$
$\frac{\Delta m^2_{32}}{10^{-3}\ eV^2}$	$2.449^{+0.032}_{-0.030}$	$2.358 \rightarrow 2.544$

What is the sign of Δm^2_{32} ?

Mass hierarchy determination using reactors neutrinos

- Nuclear reactors are an intense source of anti-neutrinos
- They come from beta-fission fragments from the fission of U and Pu isotopes
- For 1 GW reactor (thermal power) we expect $2 \times 10^{20} \nu / s$ emitted in 4π solid angle



- Reactor anti-neutrinos are detected via **Inverse Beta Decay (IBD):**

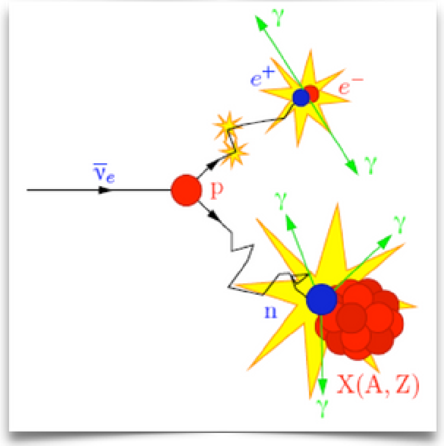
$$\boxed{\bar{\nu}_e + p \rightarrow e^+ + n}$$

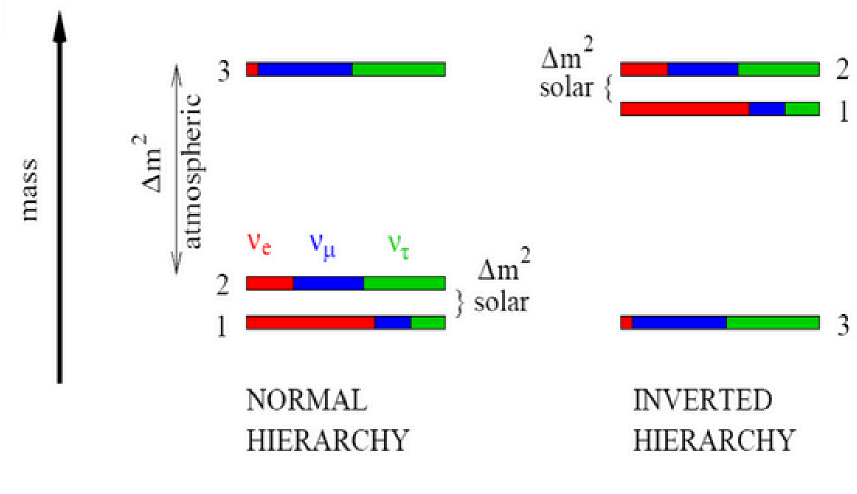
- The signal signature is given by the coincidence between:
  - **Prompt** photons from **e+** ionisation and annihilation (1-8 MeV)
  - **Delayed** photon from **n** capture on H (2.2 MeV)
  - **Time correlation τ** = 200µs

- **Only the disappearance is observable** using reactor anti-neutrinos where the oscillation do not rely on δ_{CP} and θ_{23}

Mass hierarchy determination using reactor neutrinos

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





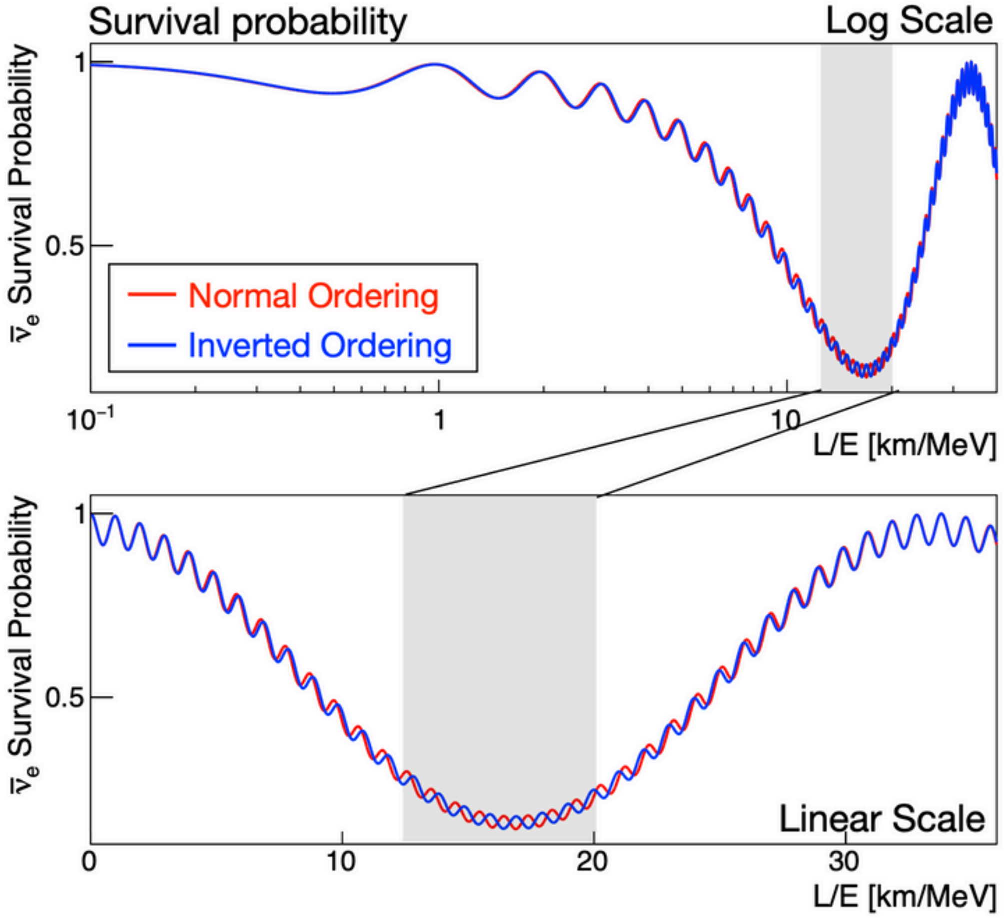
The survival probability of electronic anti-neutrinos is given by:

+ Normal hierarchy

- Inverted hierarchy

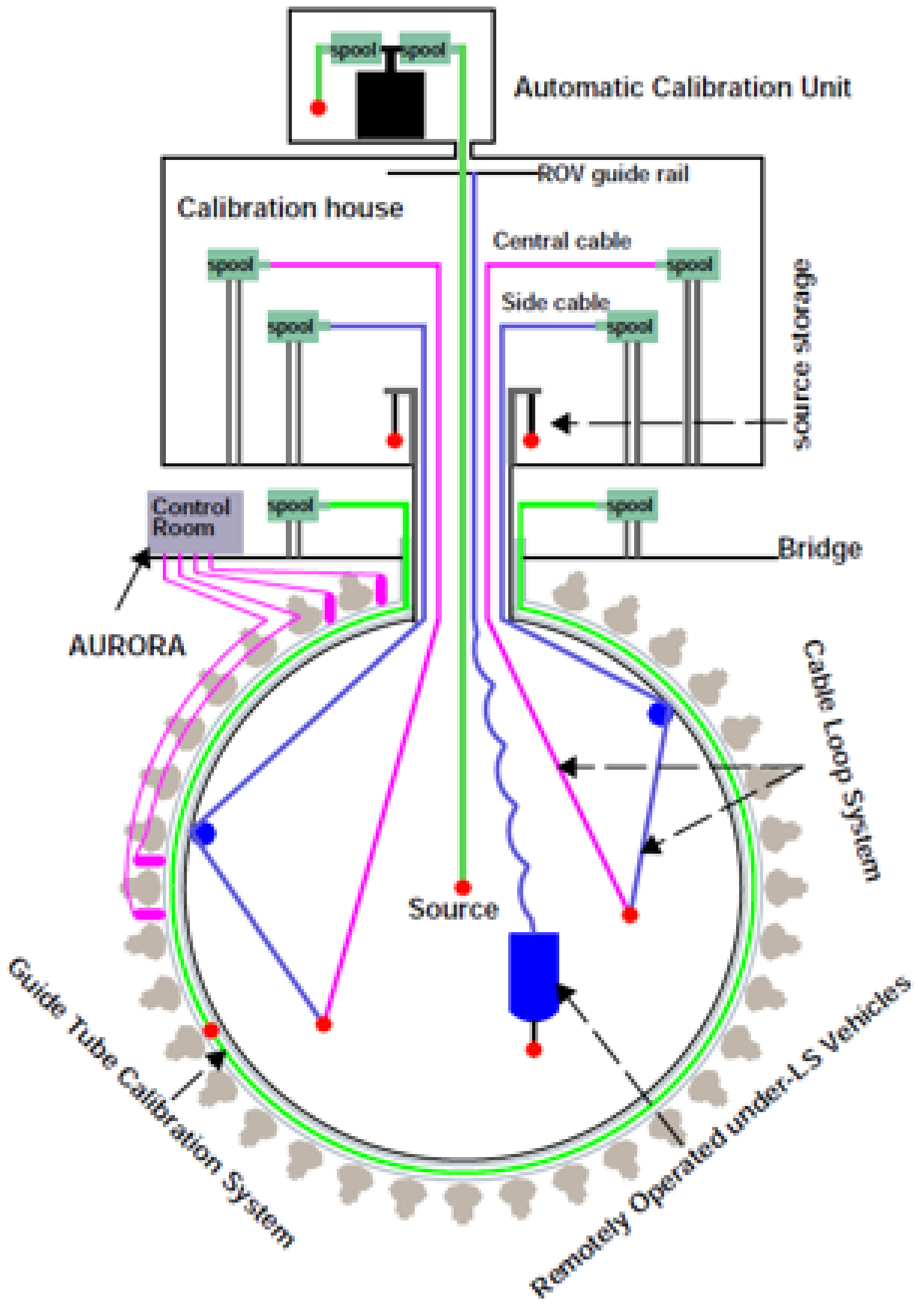
$$
\begin{aligned}
P_{ee} = 1 &- \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2(\Delta_{21}) \\
&- \sin^2 2\theta_{13}\sin^2(|\Delta_{31}|) \\
&- \sin^2\theta_{12}\sin^2 2\theta_{13}\sin^2(\Delta_{21})\cos(2|\Delta_{31}|) \\
&\textcircled{$\pm$}\frac{\sin^2\theta_{12}}{2}\sin^2 2\theta_{13}\sin(2\Delta_{21})\sin(2|\Delta_{31}|)\,,
\end{aligned}
$$

$$
\Delta_{ij} \equiv \frac{\Delta m^2_{ij} L}{4E_\nu}, \quad (\Delta m^2_{ij} \equiv m_i^2 - m_j^2)
$$



- Several **conditions on baseline and energy resolution** are required to determine the neutrino mass hierarchy
- At ~50 km the oscillation are dominated by $(\Delta m^2_{21}, \theta_{12})$
- With a high energy resolution it is possible to see the oscillation dominated by $(\Delta m^2_{32}, \theta_{13})$

Energy Scale calibration



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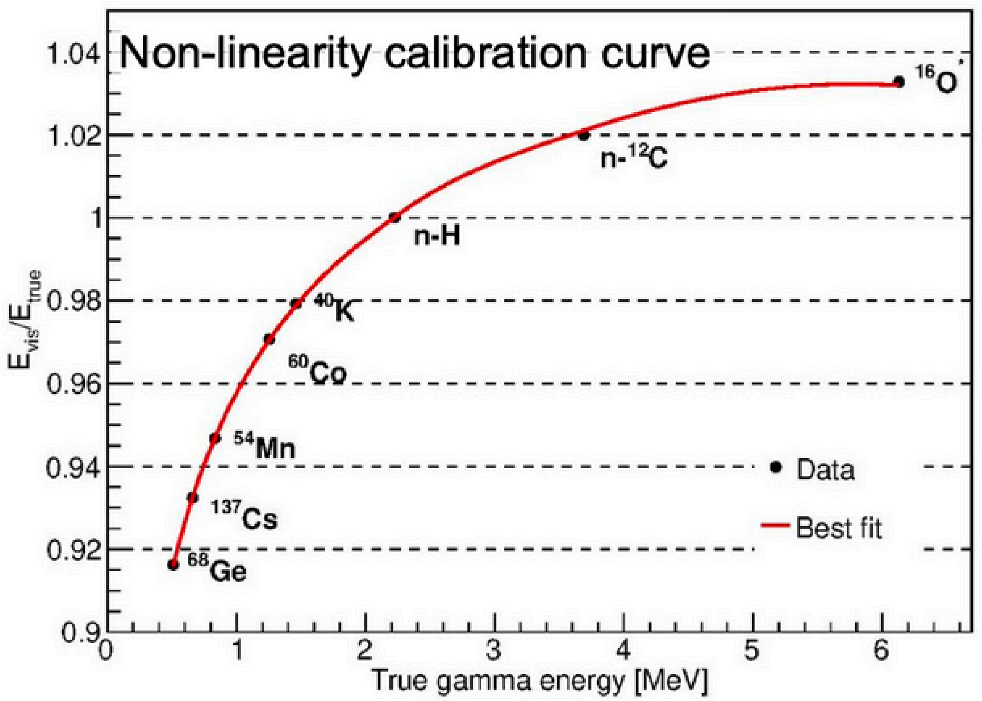

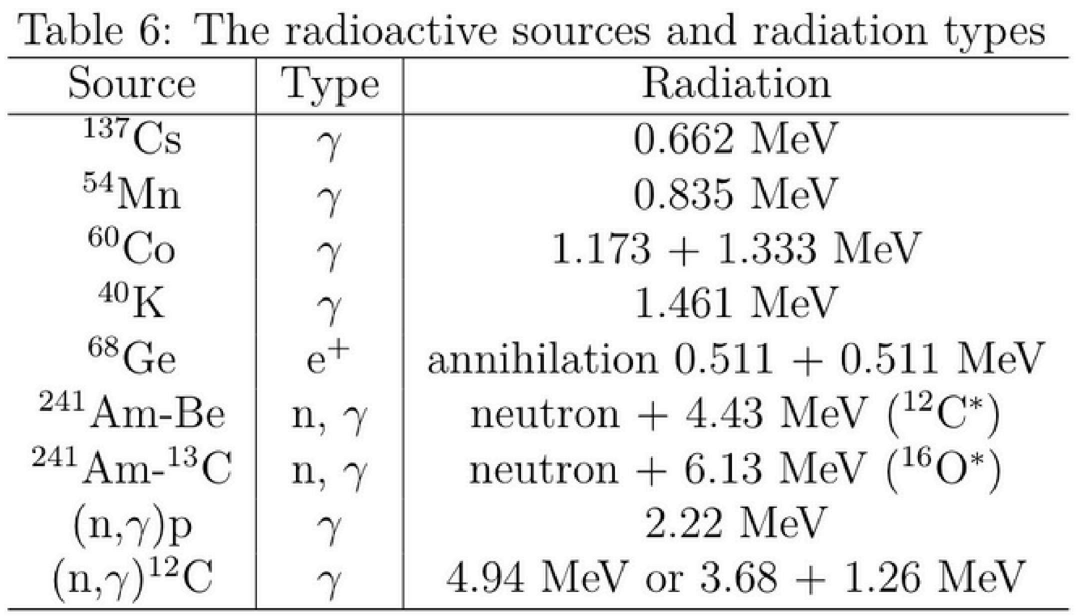

Table 6: The radioactive sources and radiation types

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

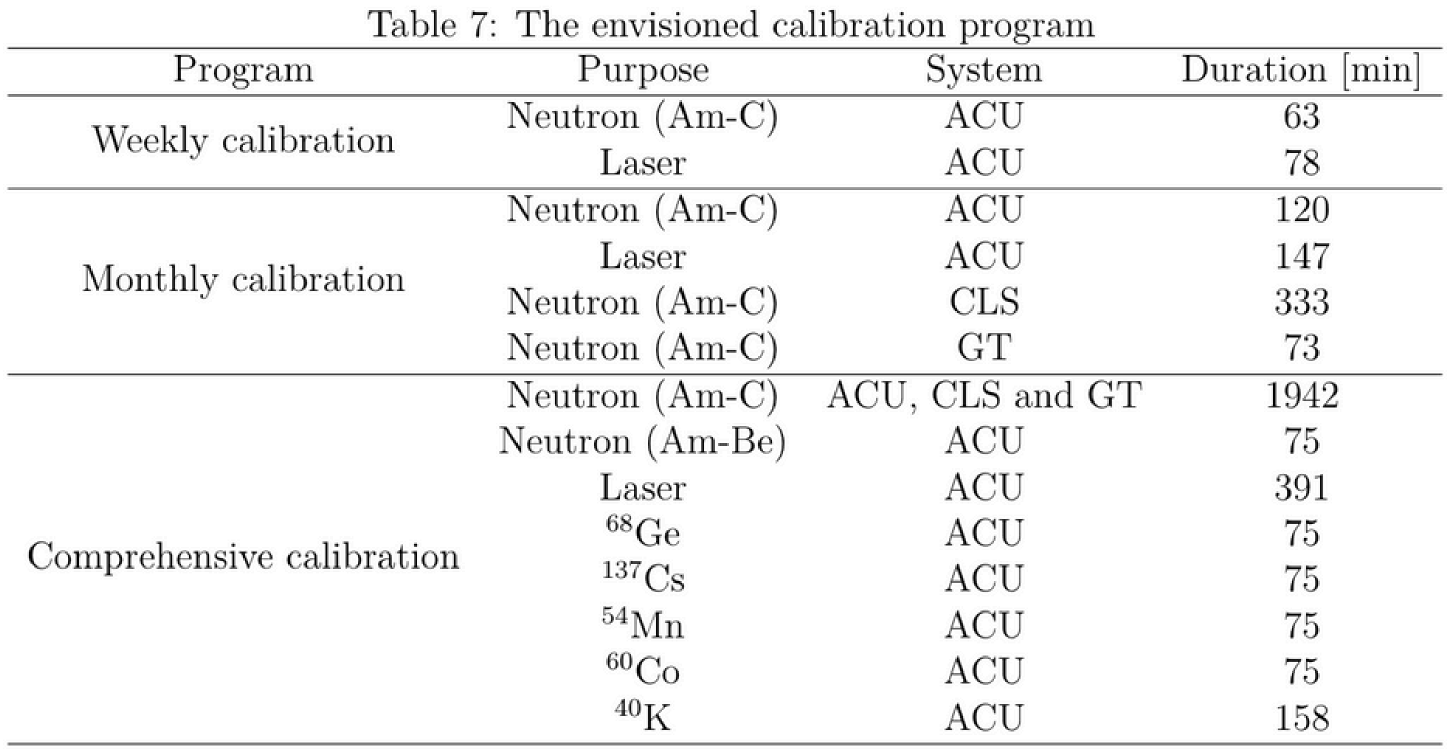

Table 7: The envisioned calibration program

Program	Purpose	System	Duration [min]
Weekly calibration	Neutron (Am-C)	ACU	63
	Laser	ACU	78
Monthly calibration	Neutron (Am-C)	ACU	120
	Laser	ACU	147
	Neutron (Am-C)	CLS	333
	Neutron (Am-C)	GT	73
Comprehensive calibration	Neutron (Am-C)	ACU, CLS and GT	1942
	Neutron (Am-Be)	ACU	75
	Laser	ACU	391
	^{68}Ge	ACU	75
	^{137}Cs	ACU	75
	^{54}Mn	ACU	75
	^{60}Co	ACU	75
	^{40}K	ACU	158

Atmospheric neutrinos

- JUNO design allows good separation between ν_e / ν_μ
- Good capabilities to measure atmospheric neutrino flux
- Help constrain discrepancies between models
- Matter effect acting for neutrinos crossing the Earth provides a complementary measurement of neutrino mass ordering

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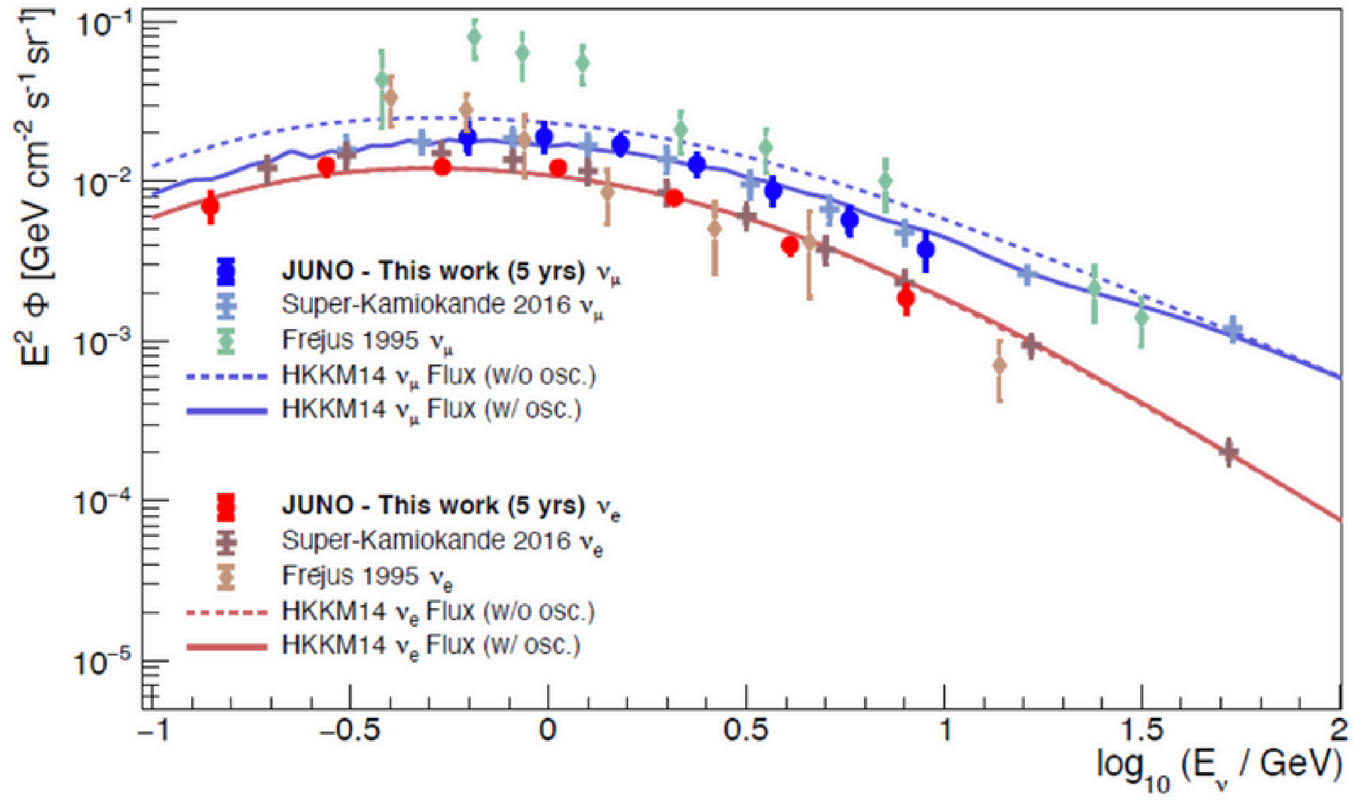

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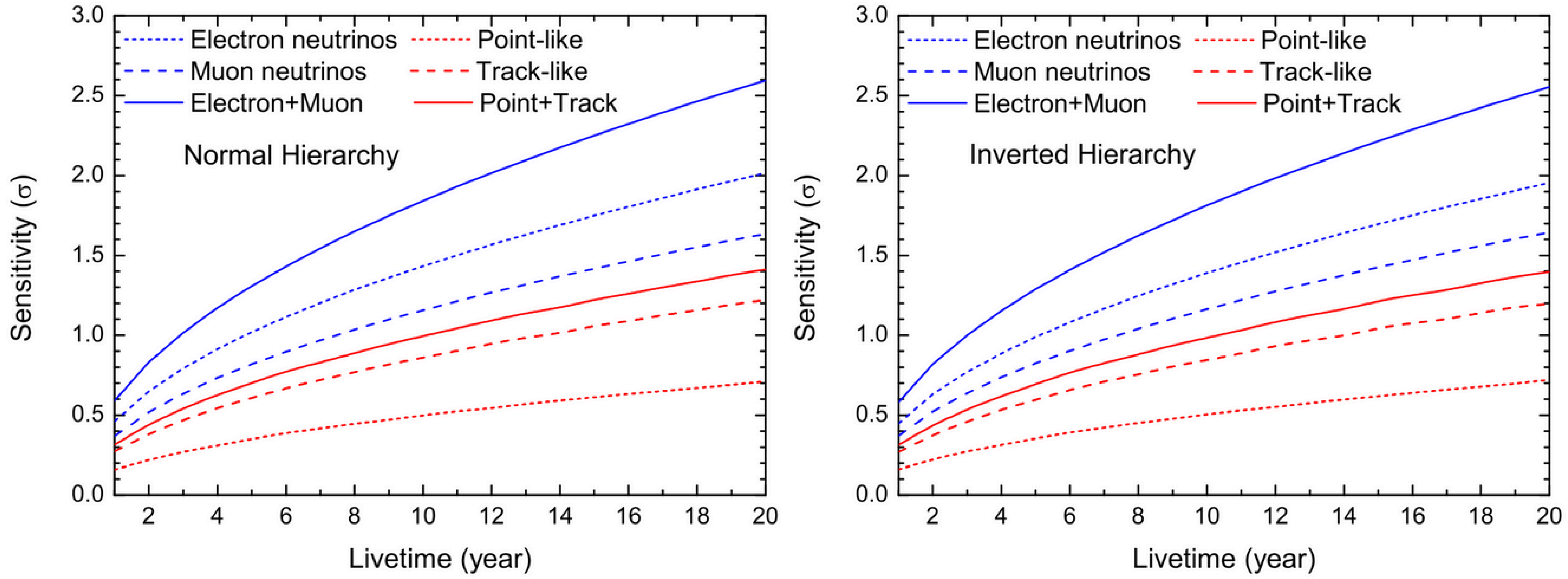

~1σ NMO sensitivity reachable in ~2 years using atm. neutrinos only

Solar and Geo Neutrinos

- Solar neutrinos studies are highly dependent on radiopurity levels
- In all radiopurity scenarios, JUNO will be able to reduce Borexino uncertainty
- Shed light on Δm^2_{12} and θ_{12} tension between solar and reactor neutrinos measurement

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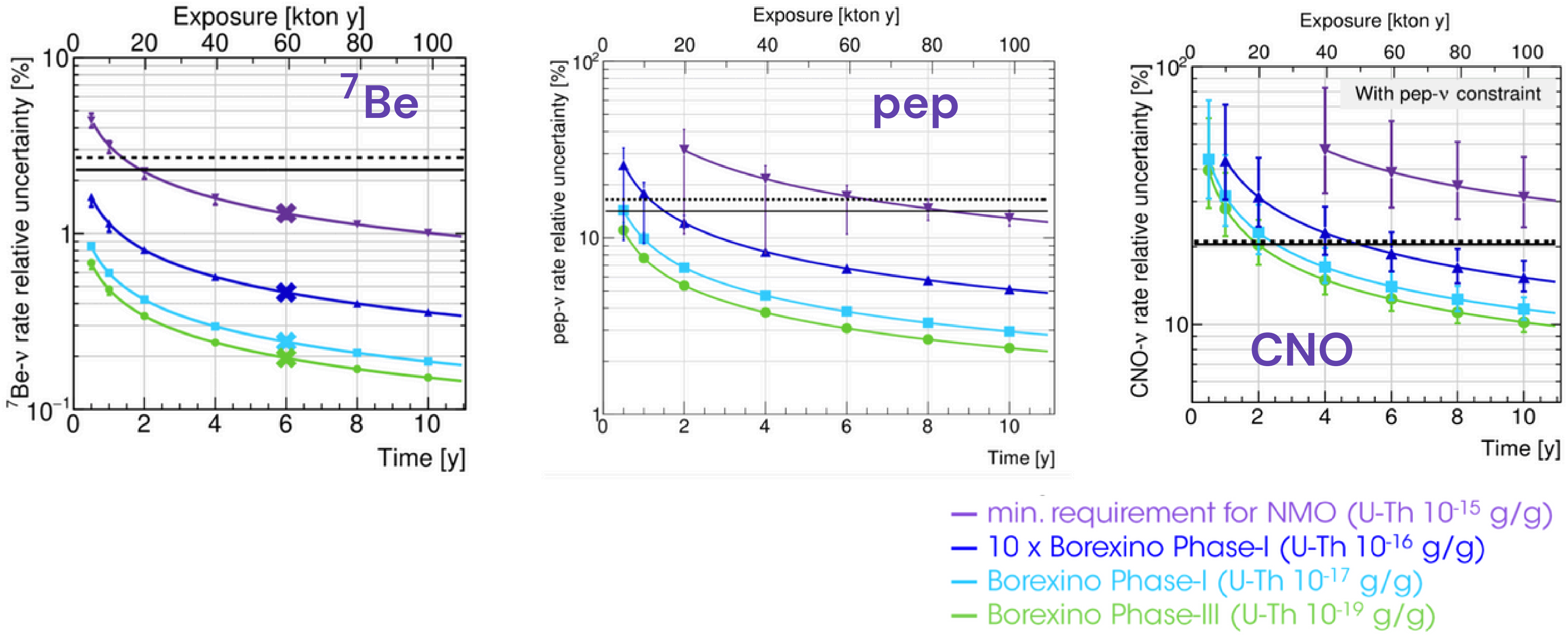
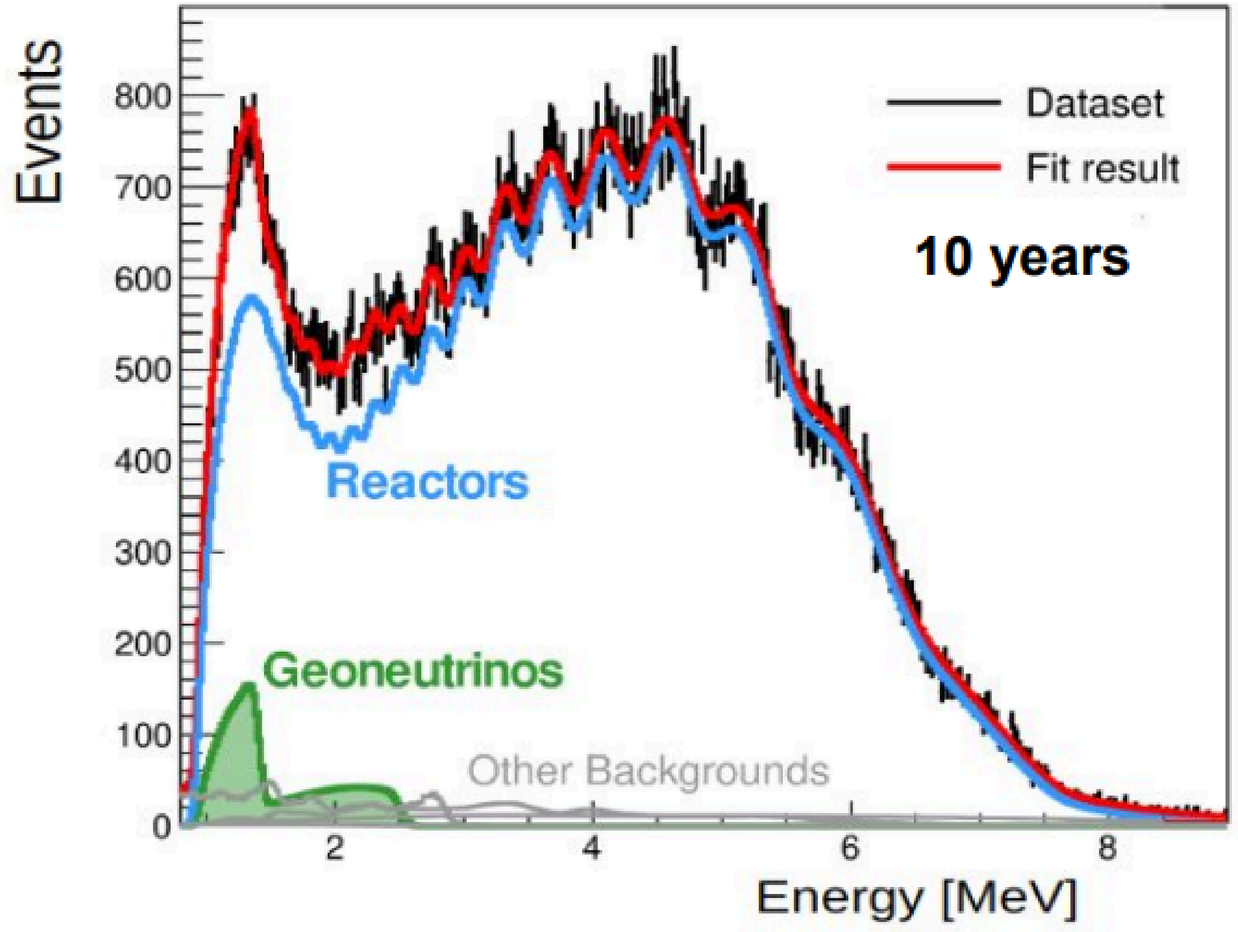


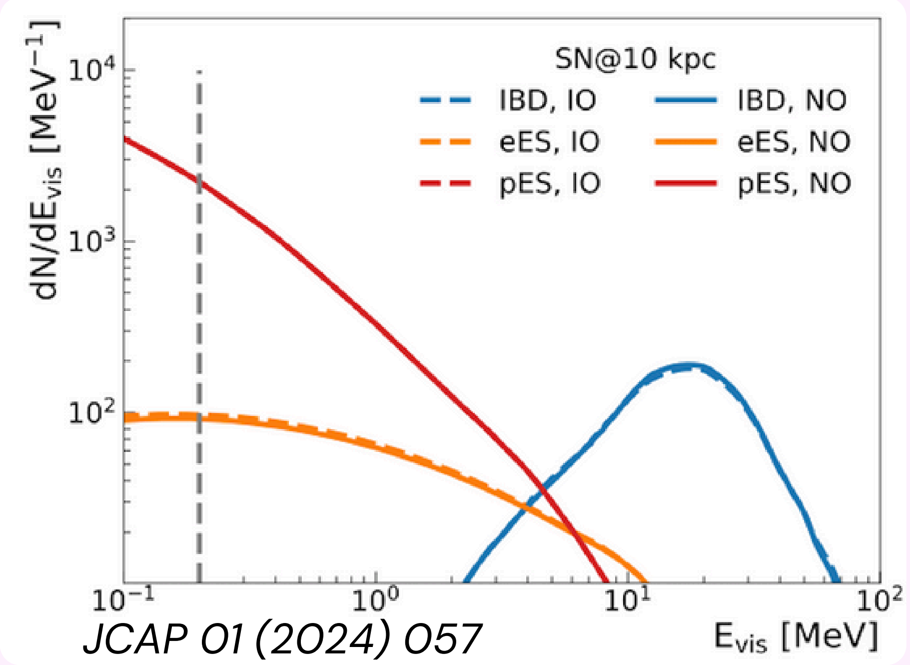


- Largest dataset of geo-neutrinos ever measured (~400 evts/year)
- Total precision ~8% in 10 years with Th/U ratio fixed (KamLAND ~15%, Borexino ~17%)
- Geonetrinos are detected by IBD (threshold of 1.8 MeV)
- Main background are reactor neutrinos

Supernova Neutrinos

Core-Collapse Supernova

- SN emits 99% of their energy in the form of neutrinos and antineutrinos
- 3 main detection channels sensitive to **all flavors**
- Expected SN rates at 10kpc : 5000 *sn*IBD, 2000 pES, 300 eES



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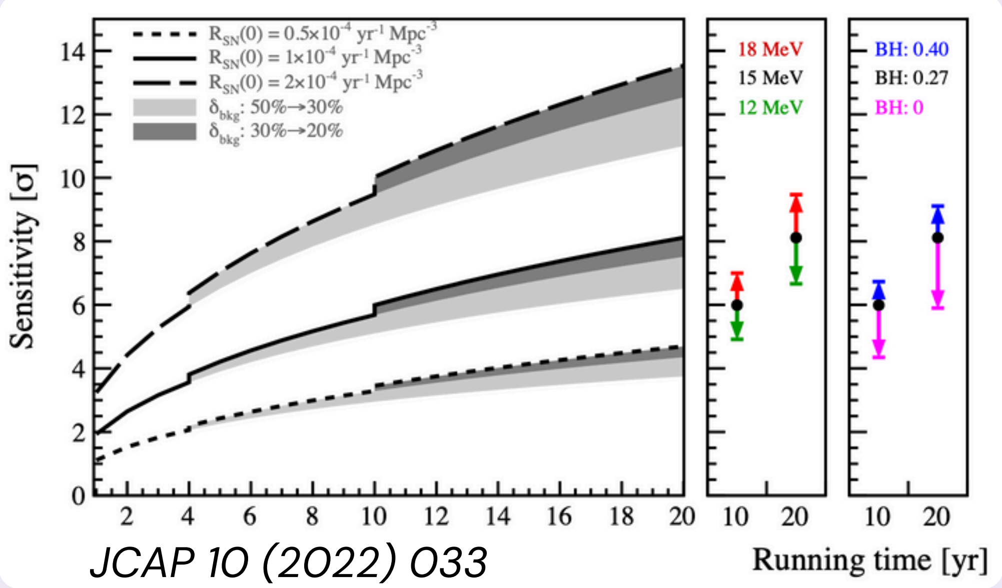
Diffuse Supernova Background (DSNB)

- Many backgrounds: dominance from NC atm. neutrinos interaction with ^{12}C nuclei (more than one order magnitude over DSNB)
- Good background rejection expected
- 3σ significance after 3 years and 5σ significance after 10 years



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