Status and Perspectives of the JUNO Experiment

Hongyue Duyang
Shandong University

On behalf of the JUNO Collaboration

22nd Lomonosov Conference on elementary particle physics

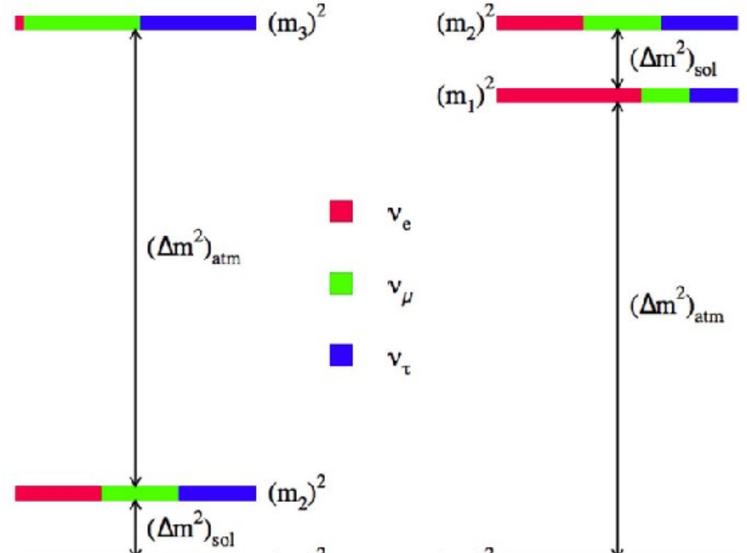
The Neutrino Ordering problem

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} \mathbf{U}^*_{\alpha i} |\nu_i\rangle$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$P_{\alpha\to\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2 \Delta_{ij} \qquad \Delta_{ij} = 1.27\Delta m^2_{ij} L/E$$

$$\pm 2\sum_{i>j} \mathrm{Im}(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin 2\Delta_{ij},$$



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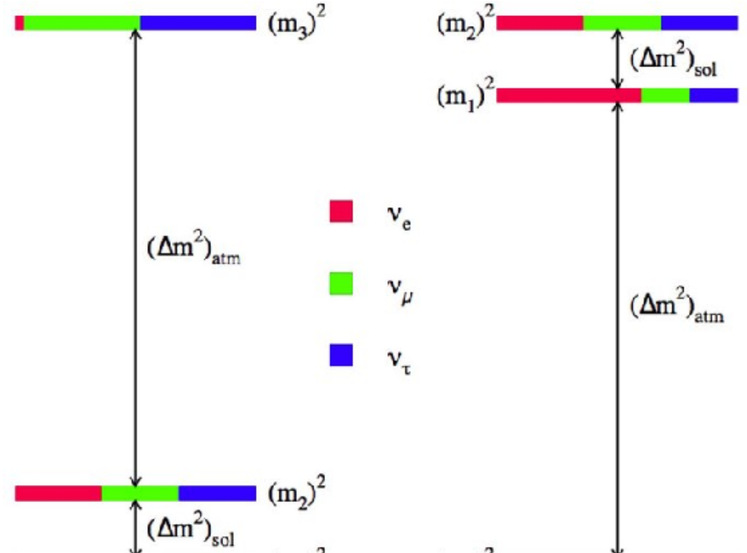

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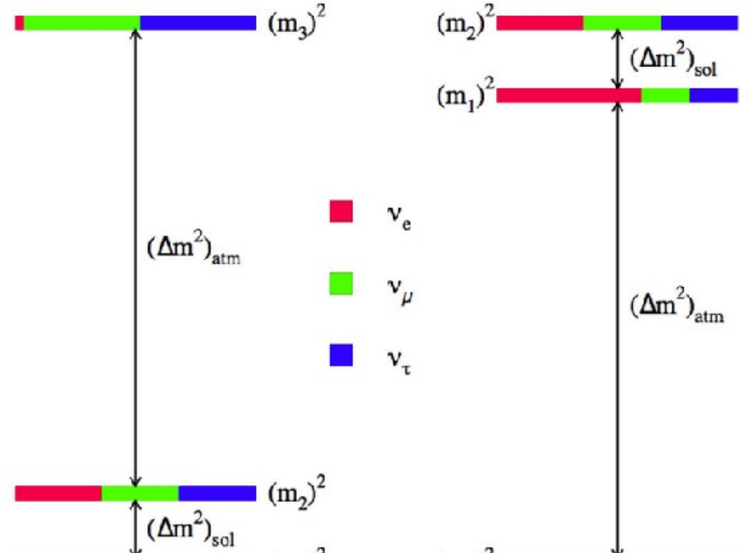

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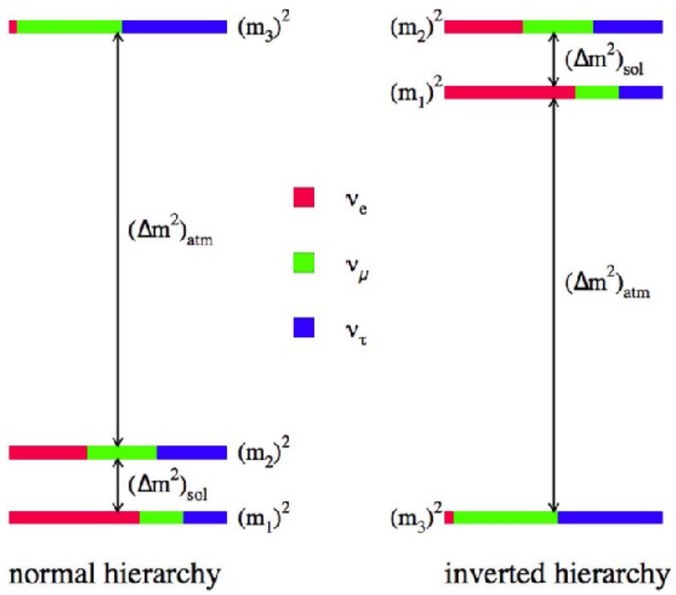
- Remaining questions about the neutrino mass:
  - Absolute mass scale?
  - Mass origin (Majorana or Dirac)?
  - **Which is the lightest neutrino mass state (the sign of Δm_{31} or Δm_{32})?**
    - Normal ordering (NO): $m_1<m_2<m_3$
    - Inverted ordering (IO): $m_3<m_1<m_2$

How to Determine Neutrino Mass Ordering?



normal hierarchy inverted hierarchy

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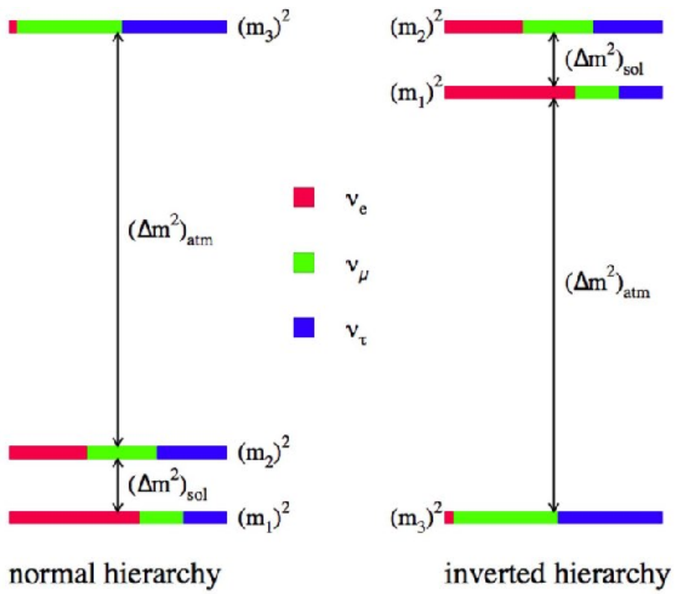

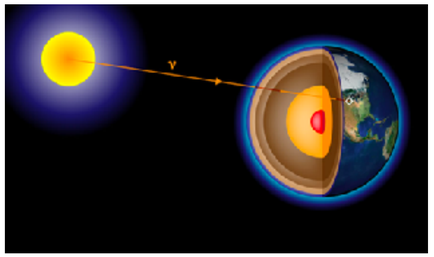

Solar neutrinos

- Historically, sign of Δm^2_{12} is determined by solar neutrinos with matter effects.

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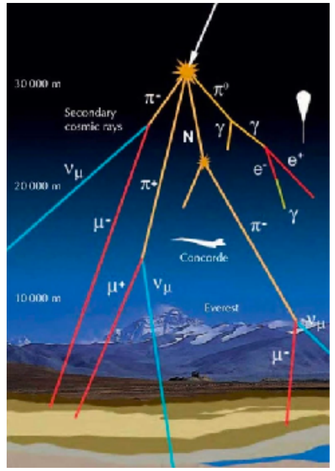
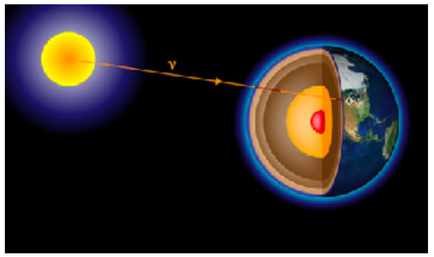


Atmospheric neutrinos



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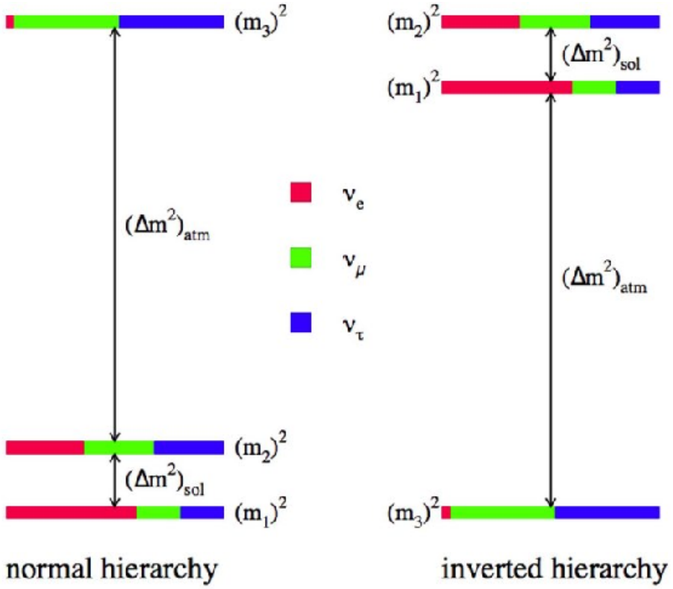
- Matter effects when neutrinos propagating through the earth.



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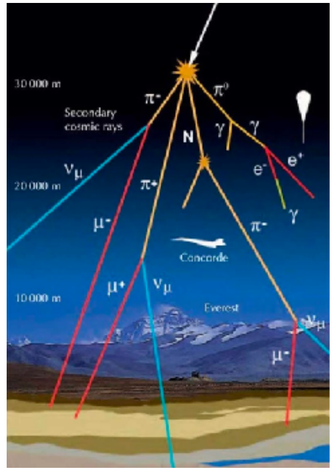

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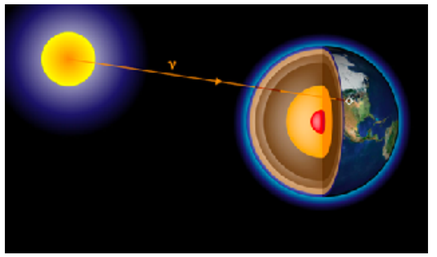

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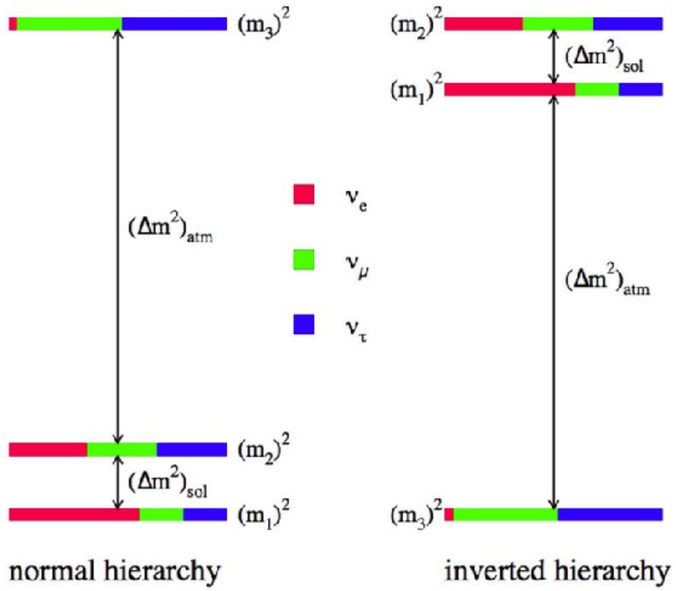

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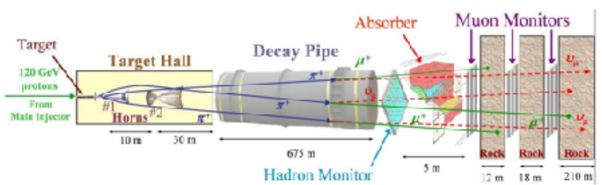

Accelerator neutrinos

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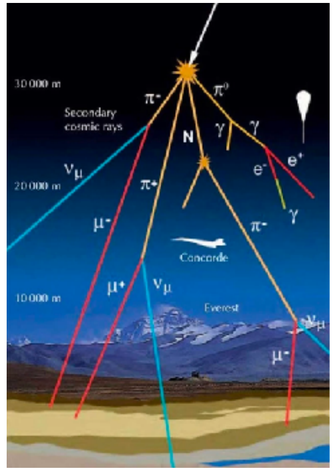

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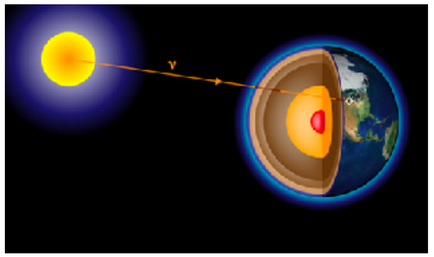

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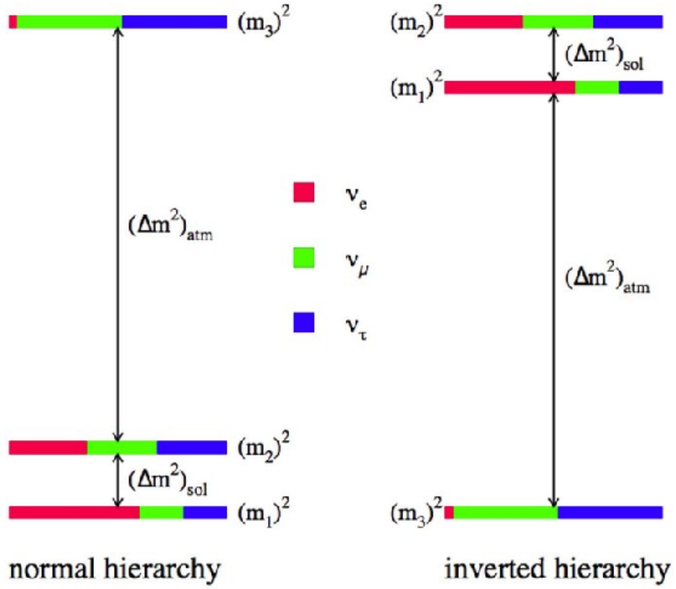

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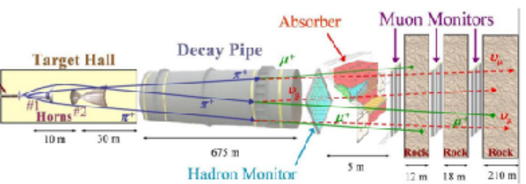


Accelerator neutrinos

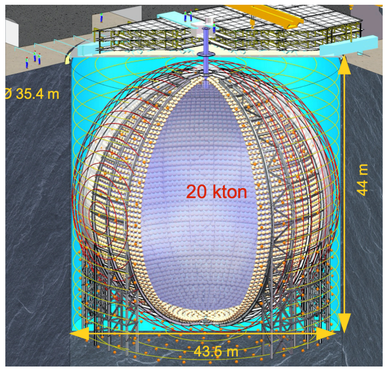
- Vacuum oscillation of $\bar{\nu}_e$ disappearance, interference between the Δm^2_{31} and Δm^2_{32} terms

Reactor neutrinos

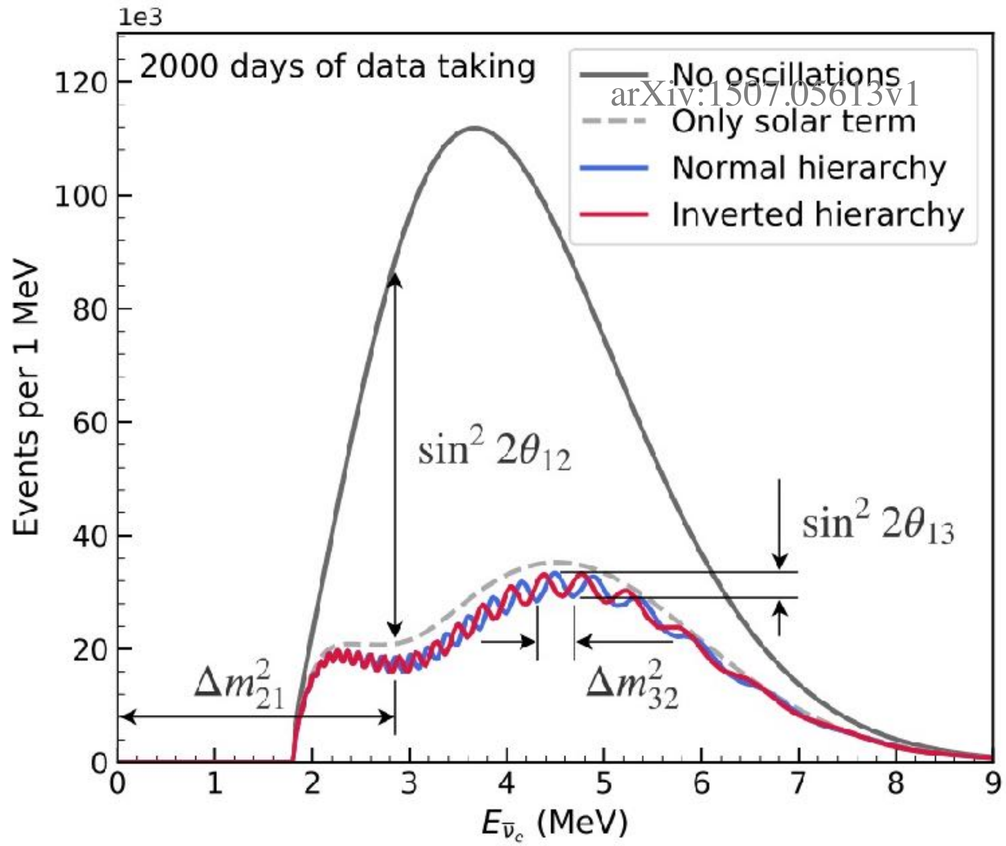
How to Determine NMO: Reactor Neutrinos

$\bar{\nu}_e$
$\bar{\nu}_e$
$\bar{\nu}_e$

Medium baseline maximizing the interference amplitude.



$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$



- Vacuum oscillation utilizing small differences in $|\Delta m^2_{31}|$ and $|\Delta m^2_{32}|$ for different MO.
- Independent from θ_{23} octant and δ_{CP}.
- Made possible by the relatively large θ_{13} value.
- Currently JUNO is the only experiment with such configuration.
  - Need excellent statistics, energy resolution and low-background!

Jiangmen Underground Neutrino Observatory

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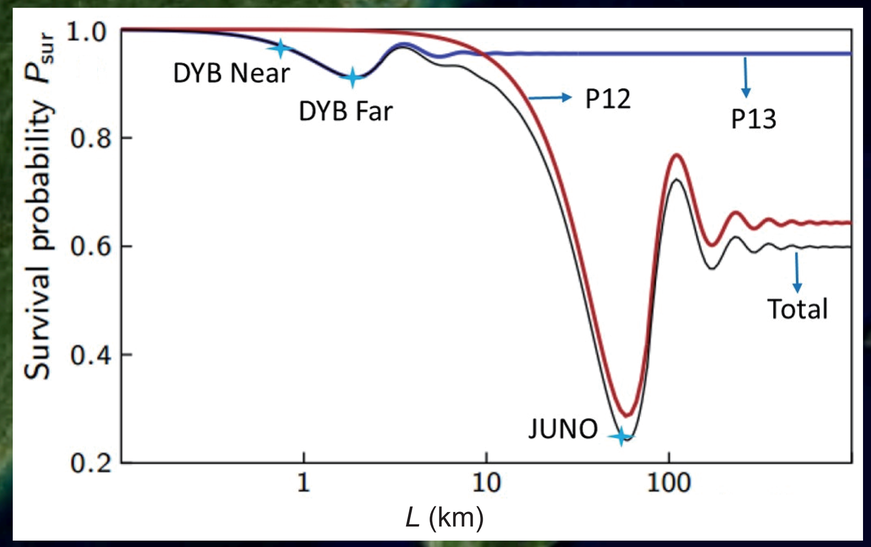


JUNO

DayaBay

53 km

53 km

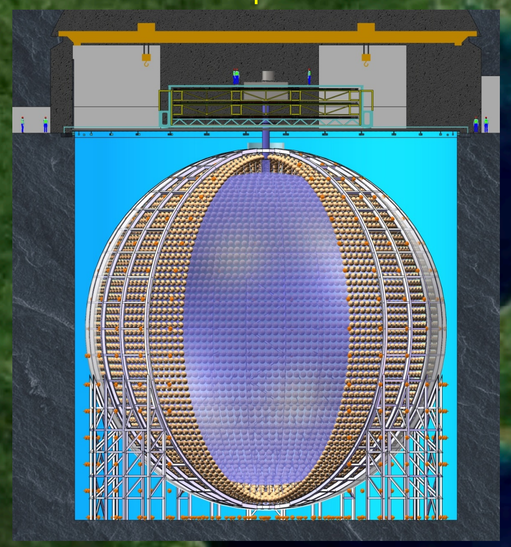
Taishan NPP

Yangjiang NPP

12

Jiangmen Underground Neutrino Observatory

700 m



20 kton LS detector

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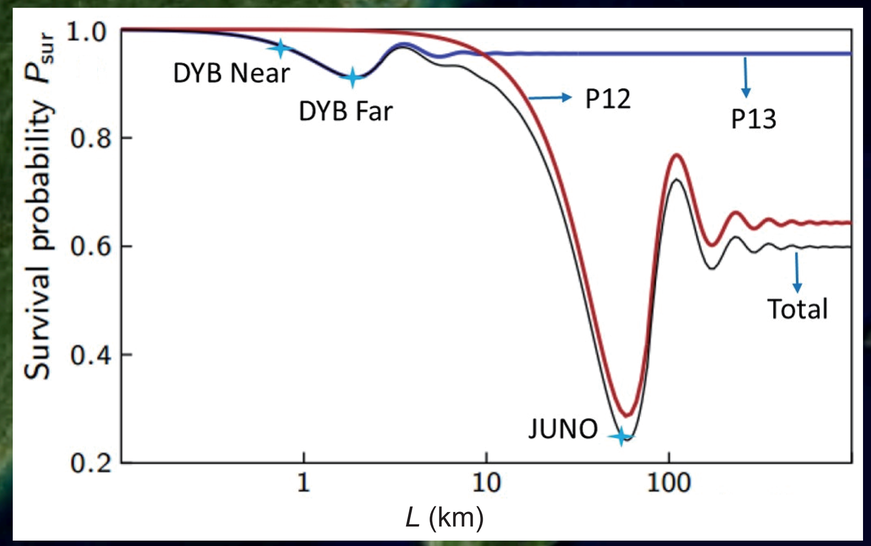

13

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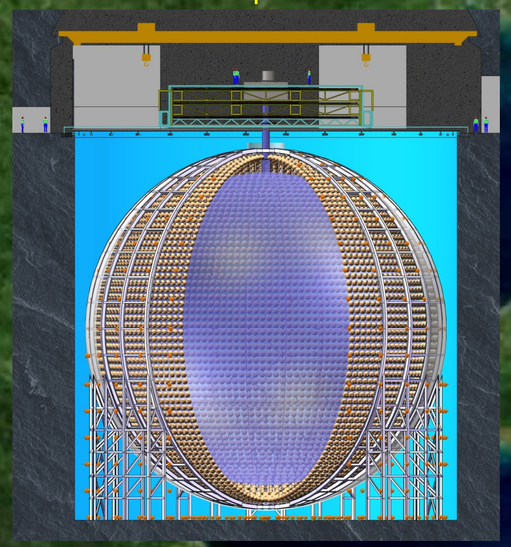

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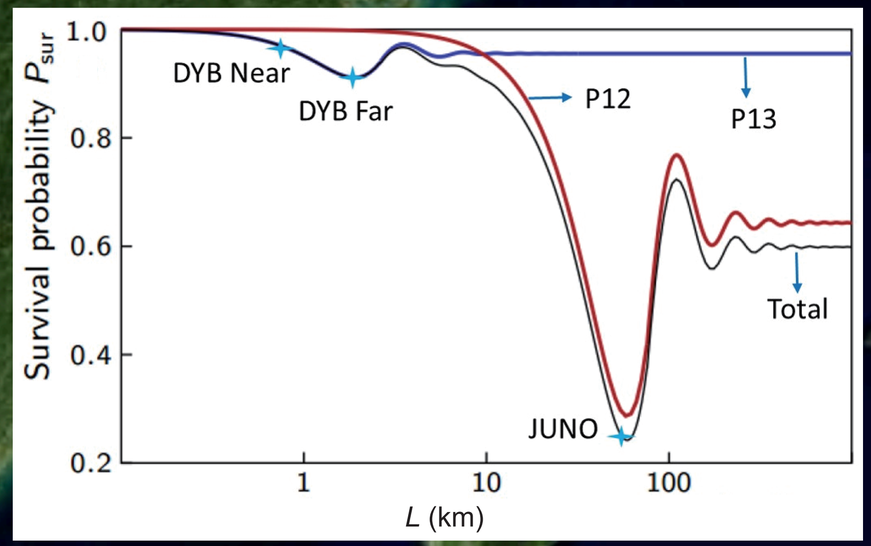

JUNO

DayaBay

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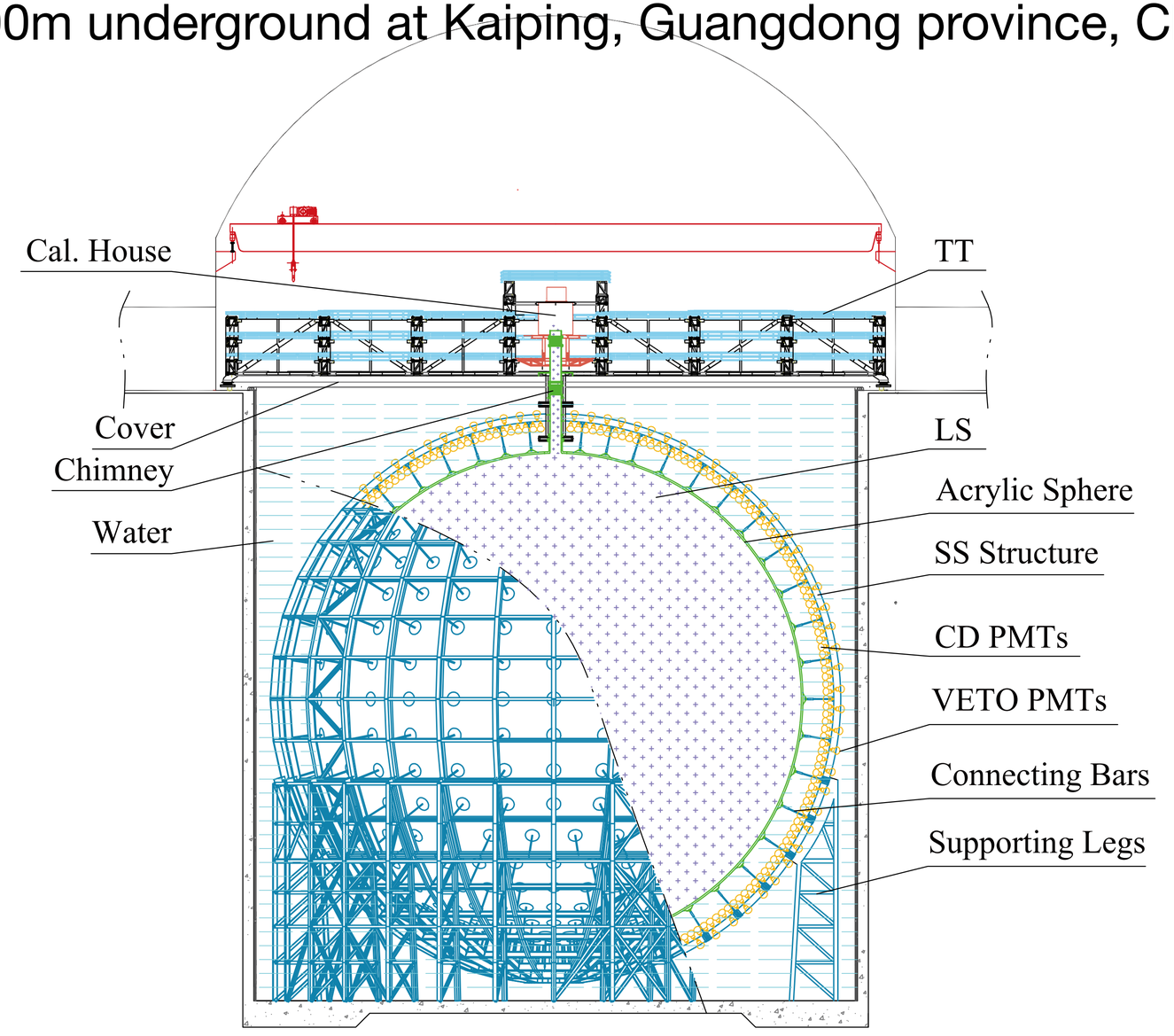
Beginning of the project	Civil construction	Detector construction	Filling start	Filling end
2013	2015	2022	2024.12	soon

14

The JUNO Detector

- 700m underground at Kaiping, Guangdong province, China



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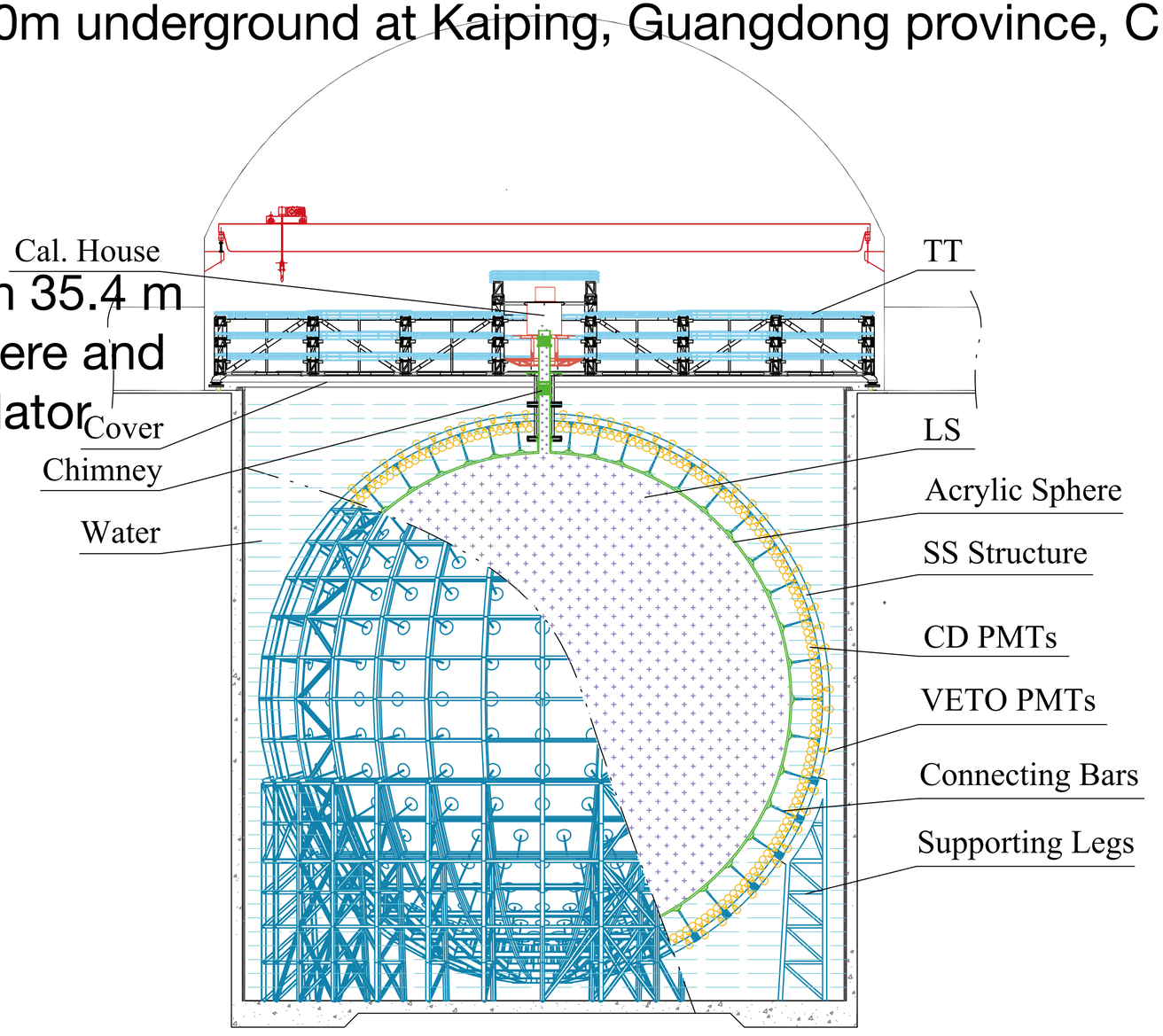
- Central detector with 35.4 m diameter acrylic sphere and 20k ton liquid scintillator



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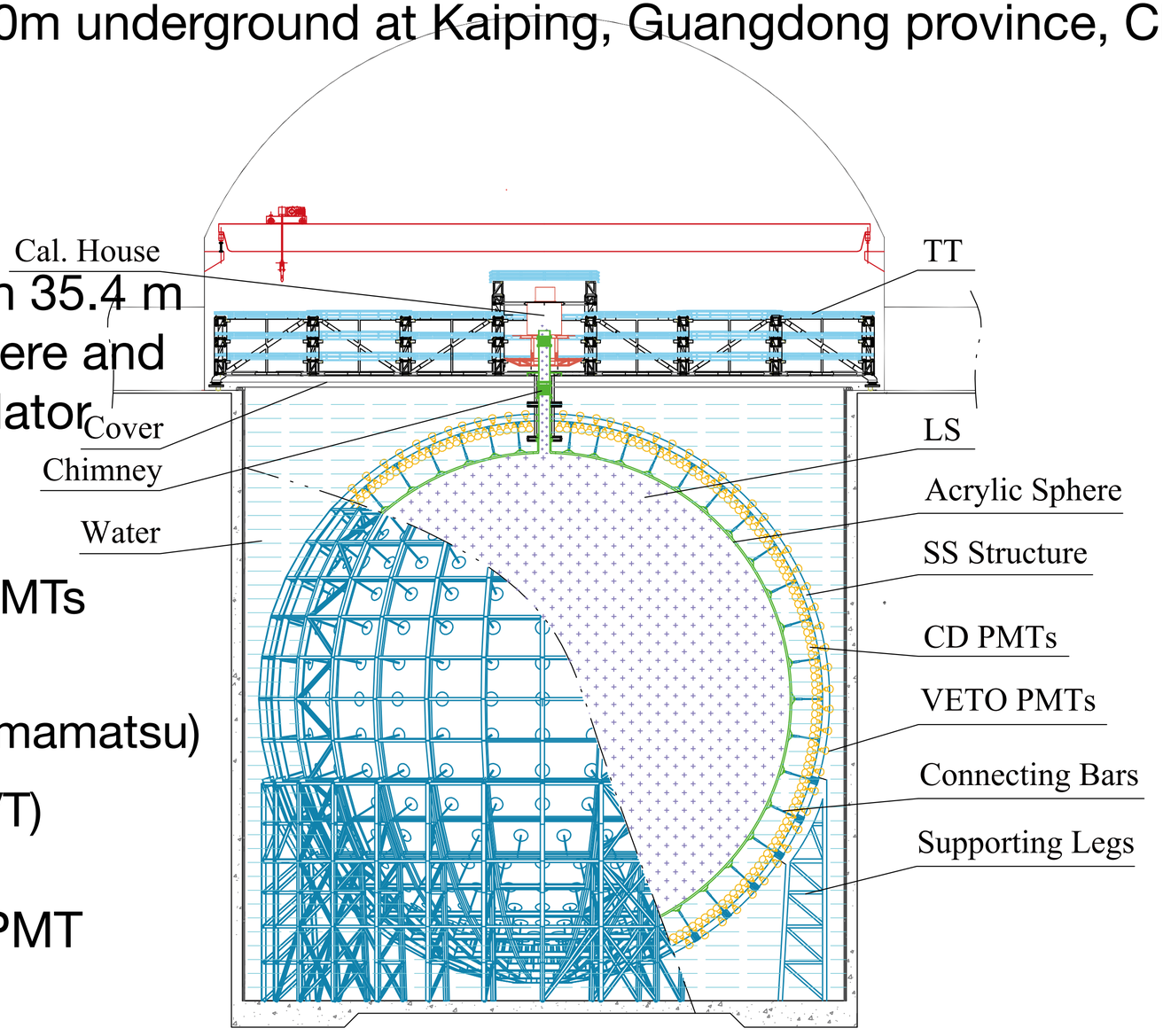

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  - 5000 dynode (Hamamatsu)
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- 25600 3-inch CD PMT (3% coverage)

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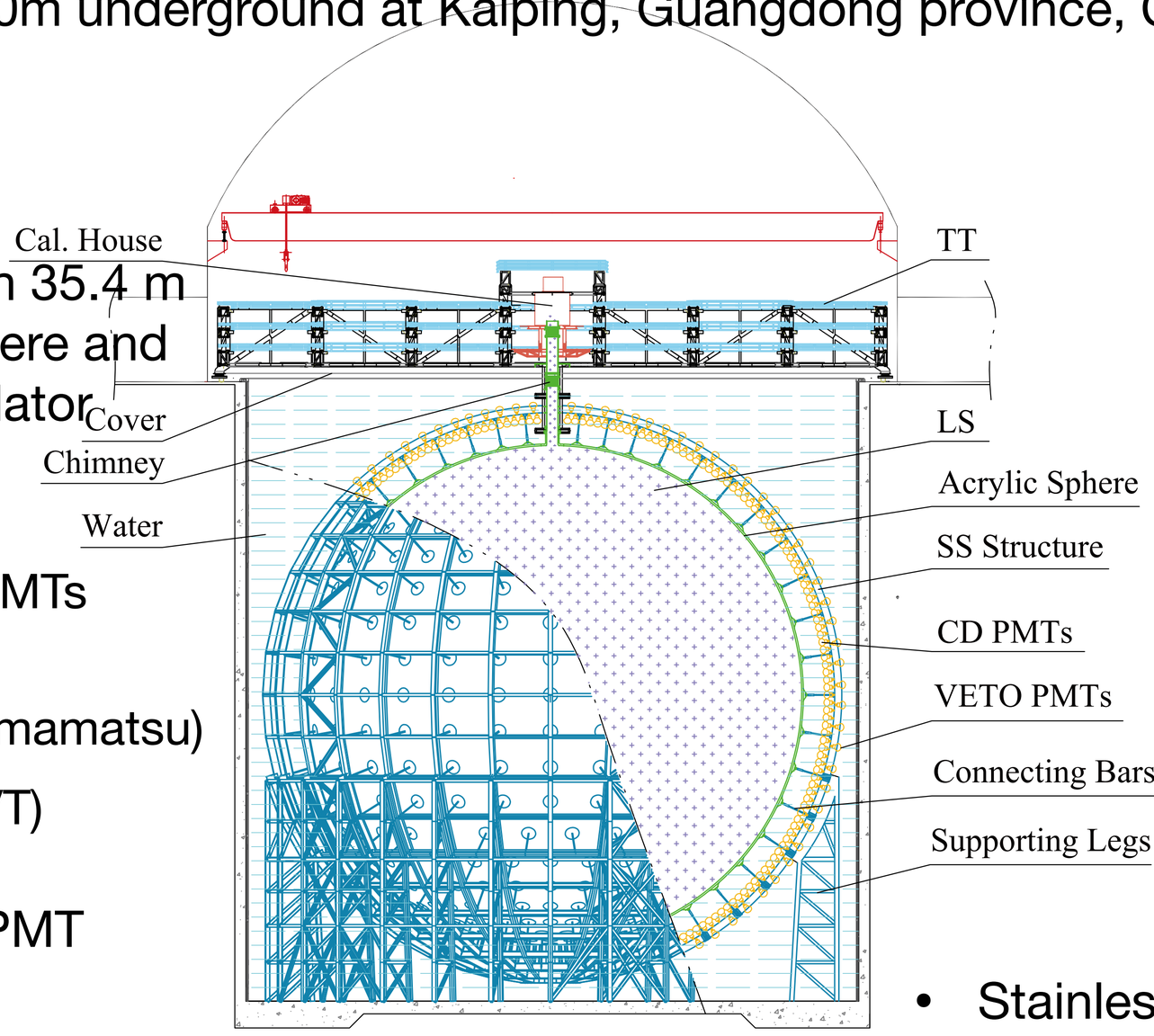

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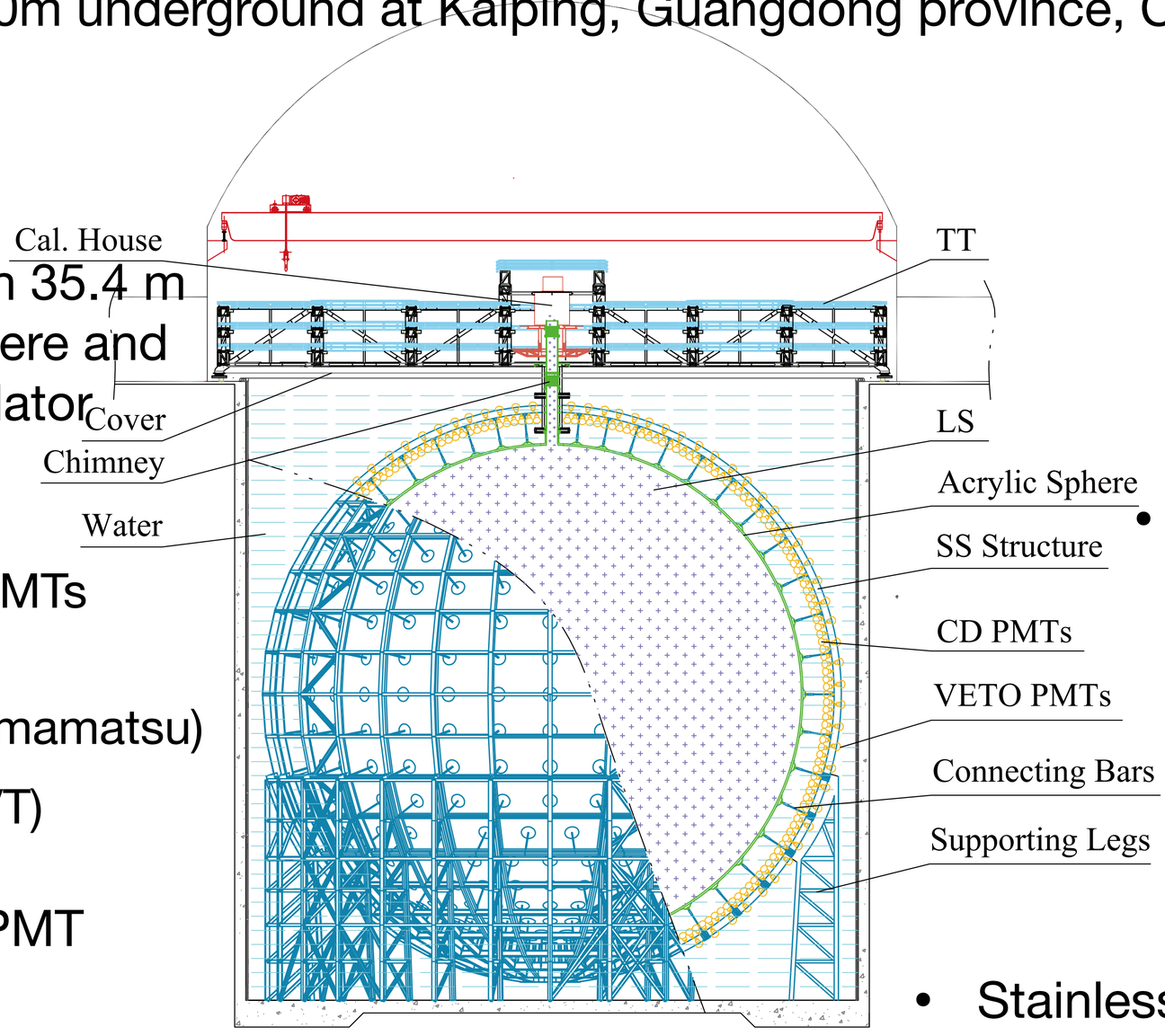

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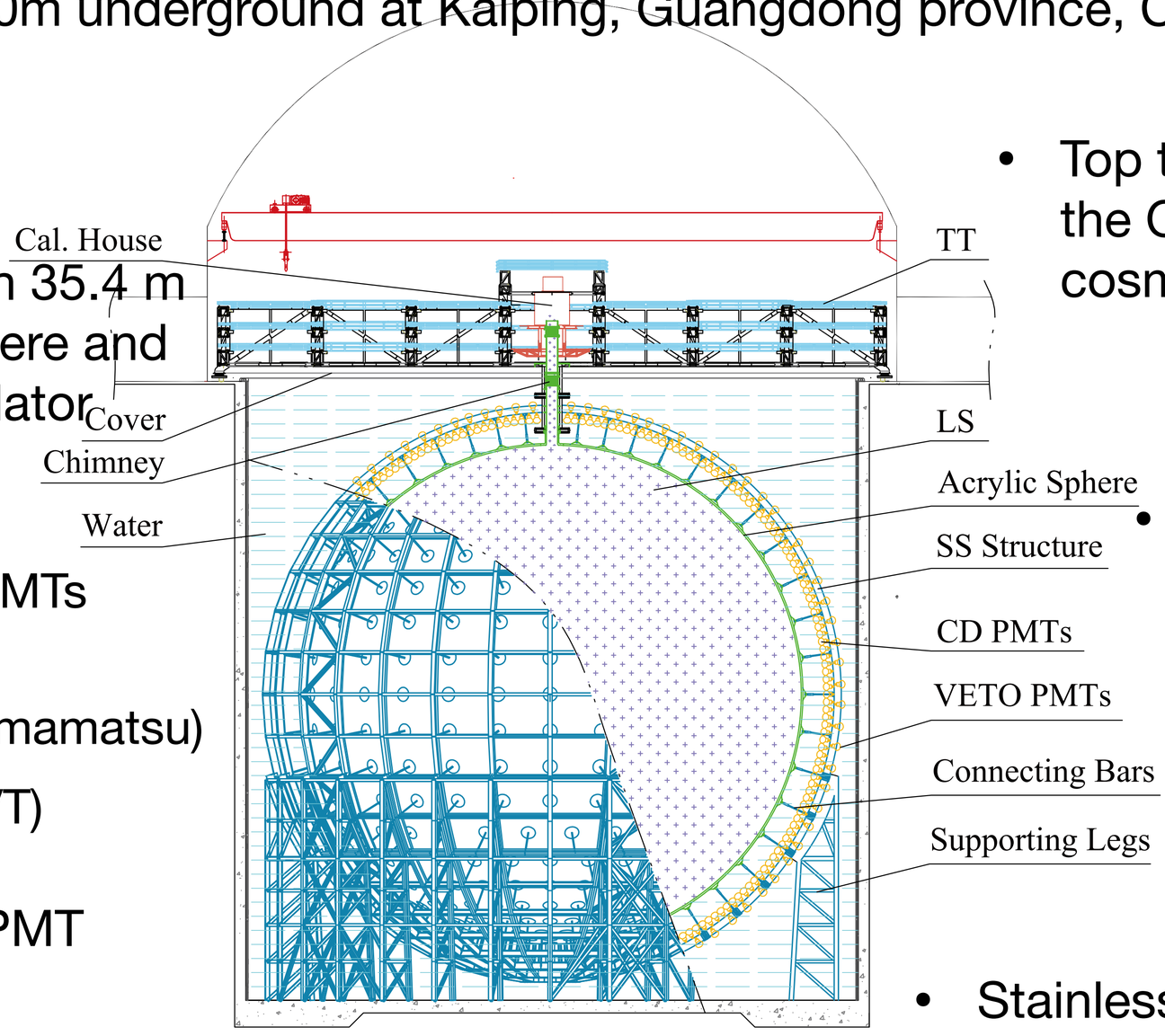

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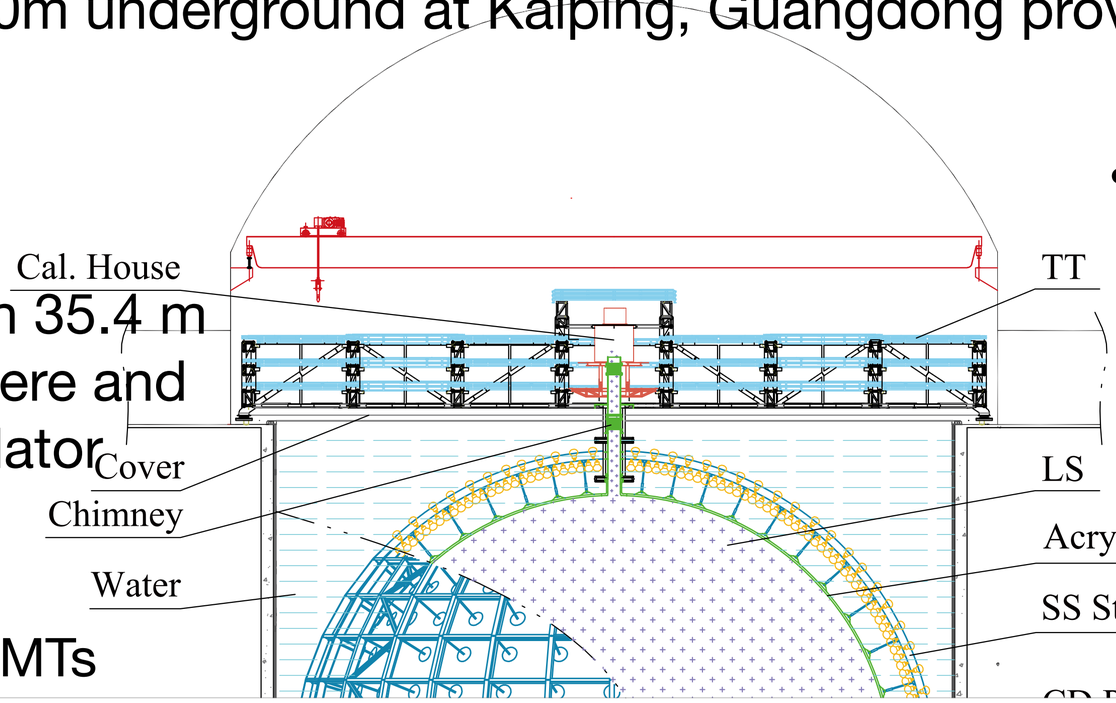

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  - 5
  - 1
- 25((3%

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ructure

Experiment	Daya Bay	BOREXINO	KamLAND	JUNO
Target mass	20 ton	~ 300 ton	~ 1 kton	**20 kton**
Energy resolution	7.5%/√E	5%/√E	6%/√E	**3%/√E**
Energy calibration	1,5%	~ 1%	2%	**< 1%**
Optical coverage	12%	34%	34%	**78%**
Light yield	160 p.e./MeV	500 p.e./MeV	250 p.e./MeV	**~1600 p.e./MeV**

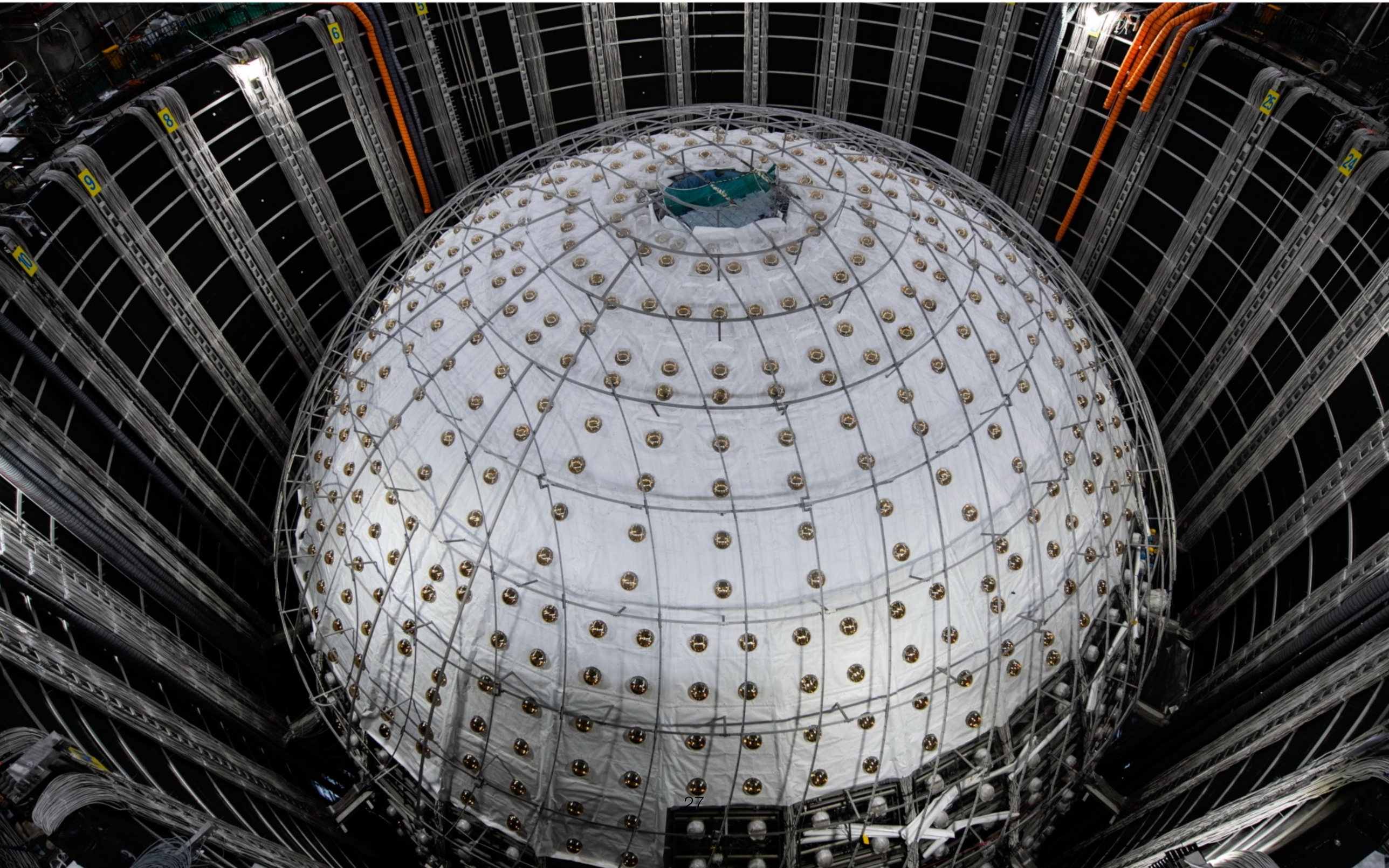
JUNO Collaboration

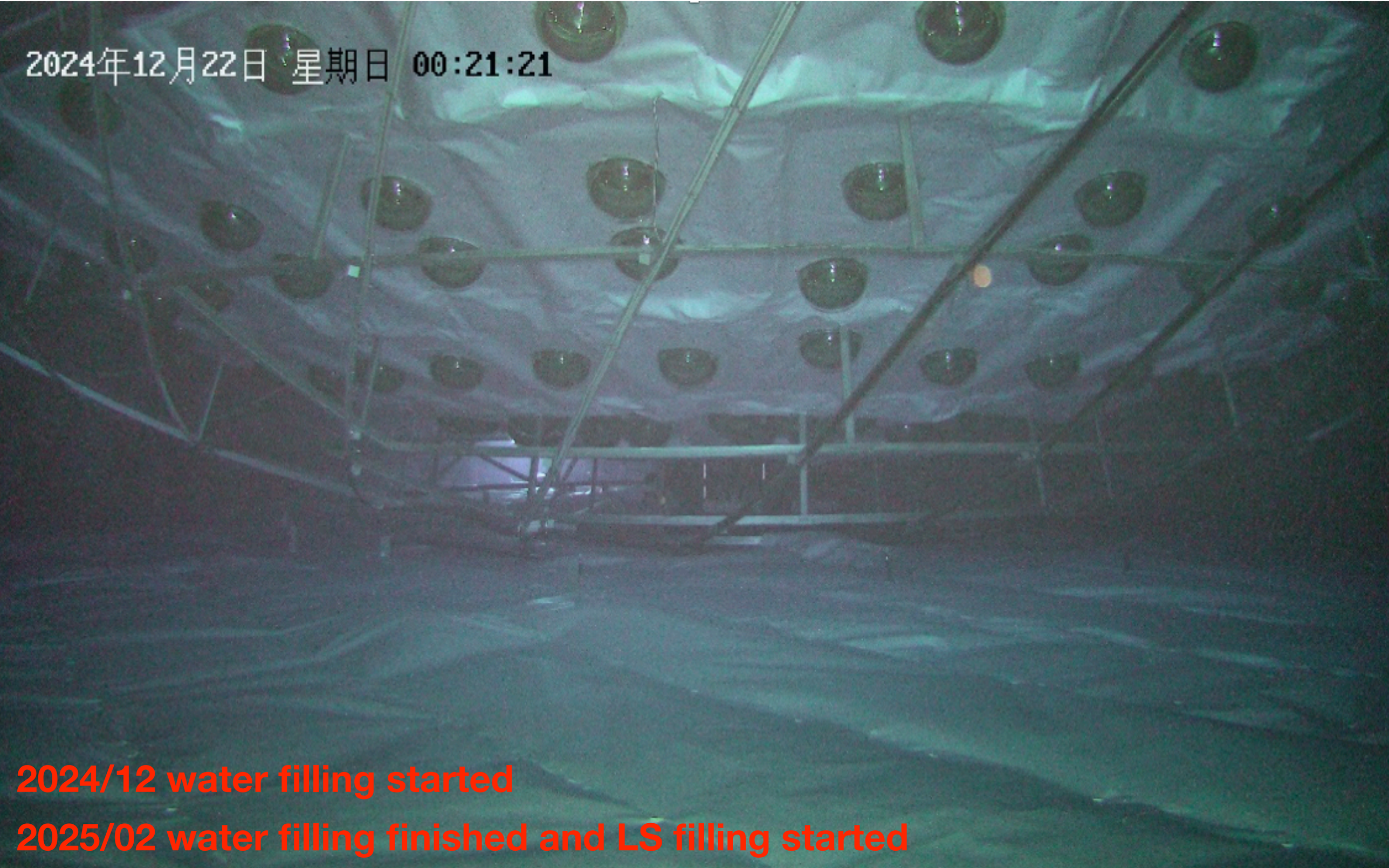
Country	Institute	Country	Institute	Country	Institute
Armenia	Yerevan Physics Institute	China	U. of South China	Italy	INFN Catania
Belgium	Universite Libre de Bruxelles	China	Wu Yi U.	Italy	INFN di Frascati
Brazil	PUC	China	Wuhan U.	Italy	INFN-Ferrara
Brazil	UEL	China	Xi'an JT U.	Italy	INFN-Milano
Chile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

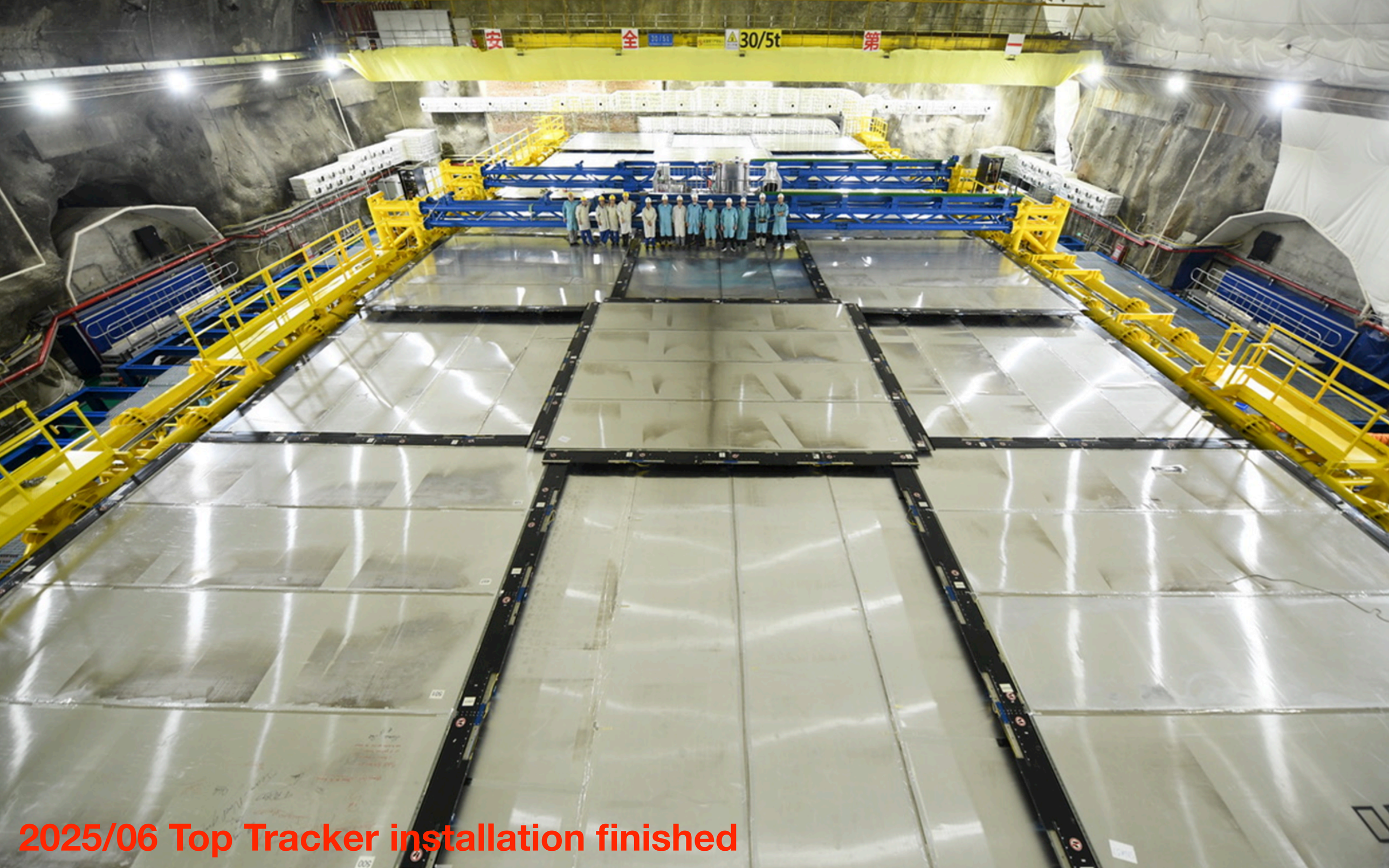
~700 collaborators from 69 institutes

Civil construction started in 2015

Detector construction started in 2022

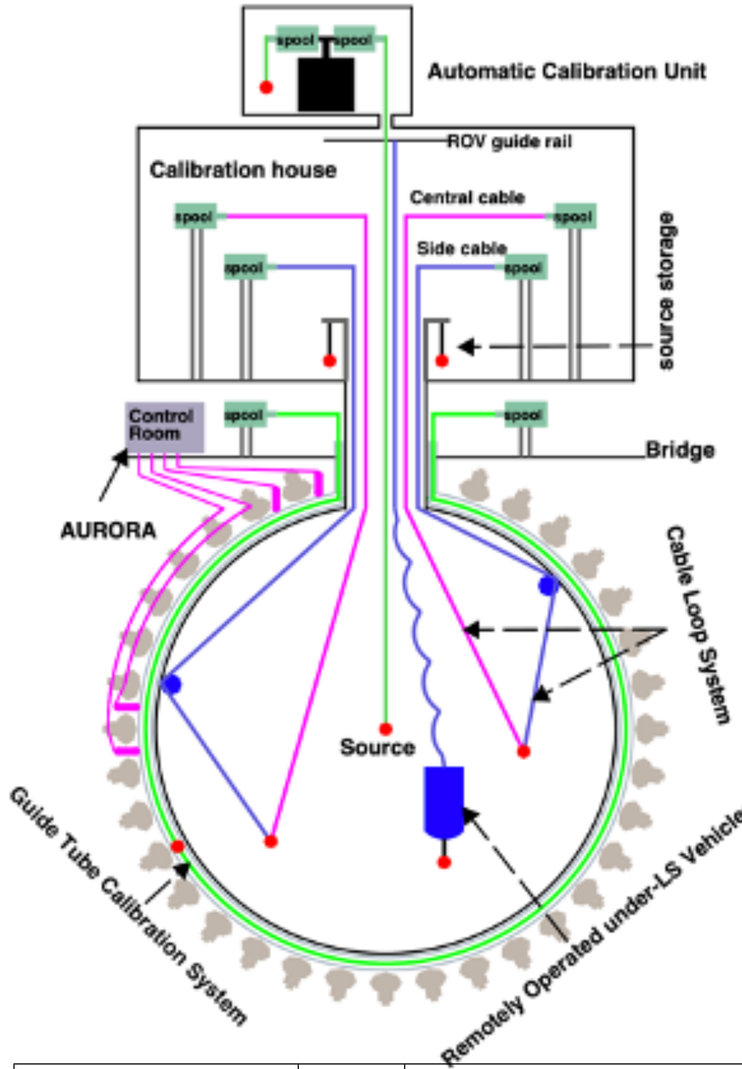



2024年12月22日 星期日 00:21:21
2024/12 water filling started
2025/02 water filling finished and LS filling started



2025/06 Top Tracker installation finished

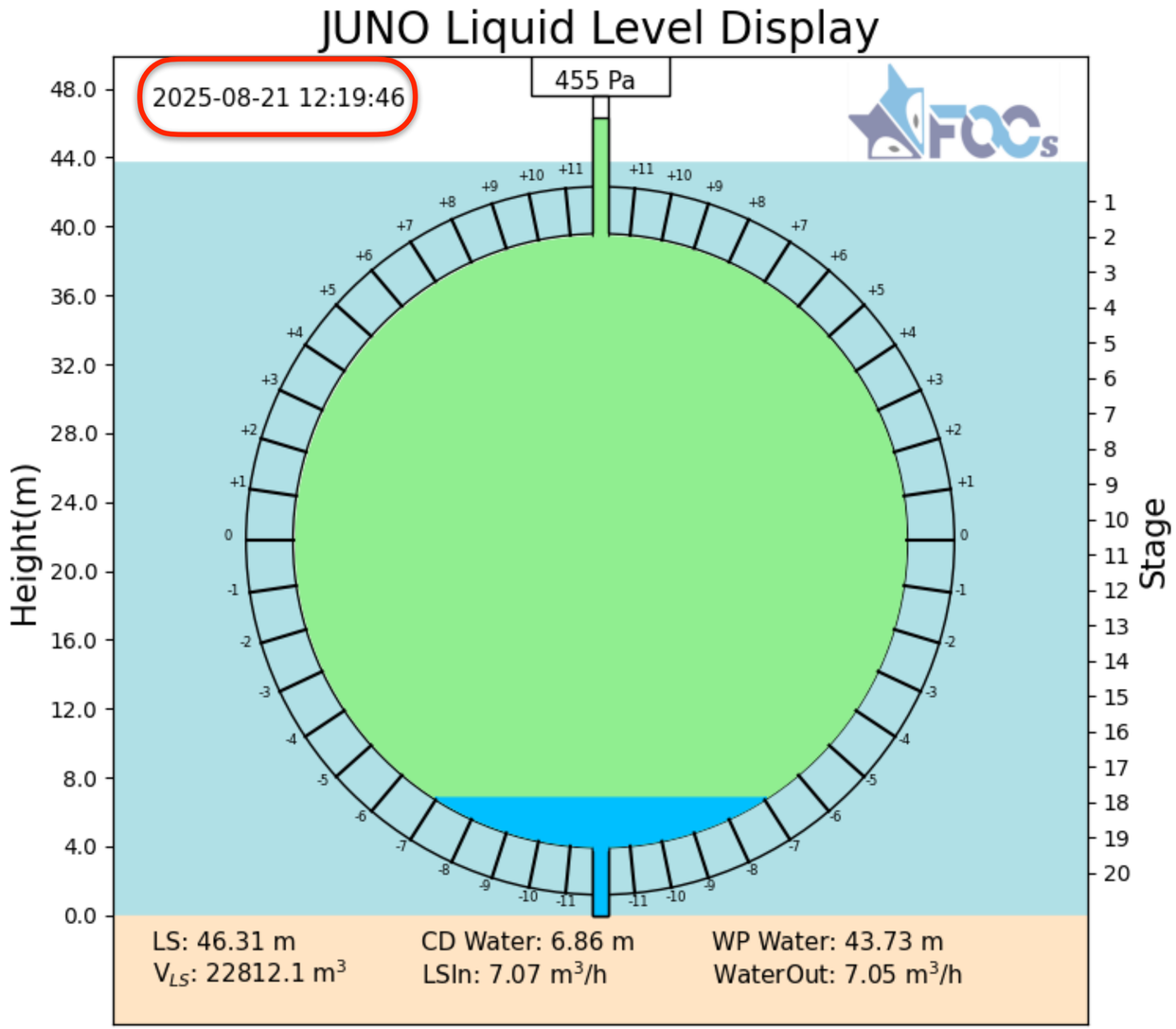
Calibration System



Sources/Processes	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

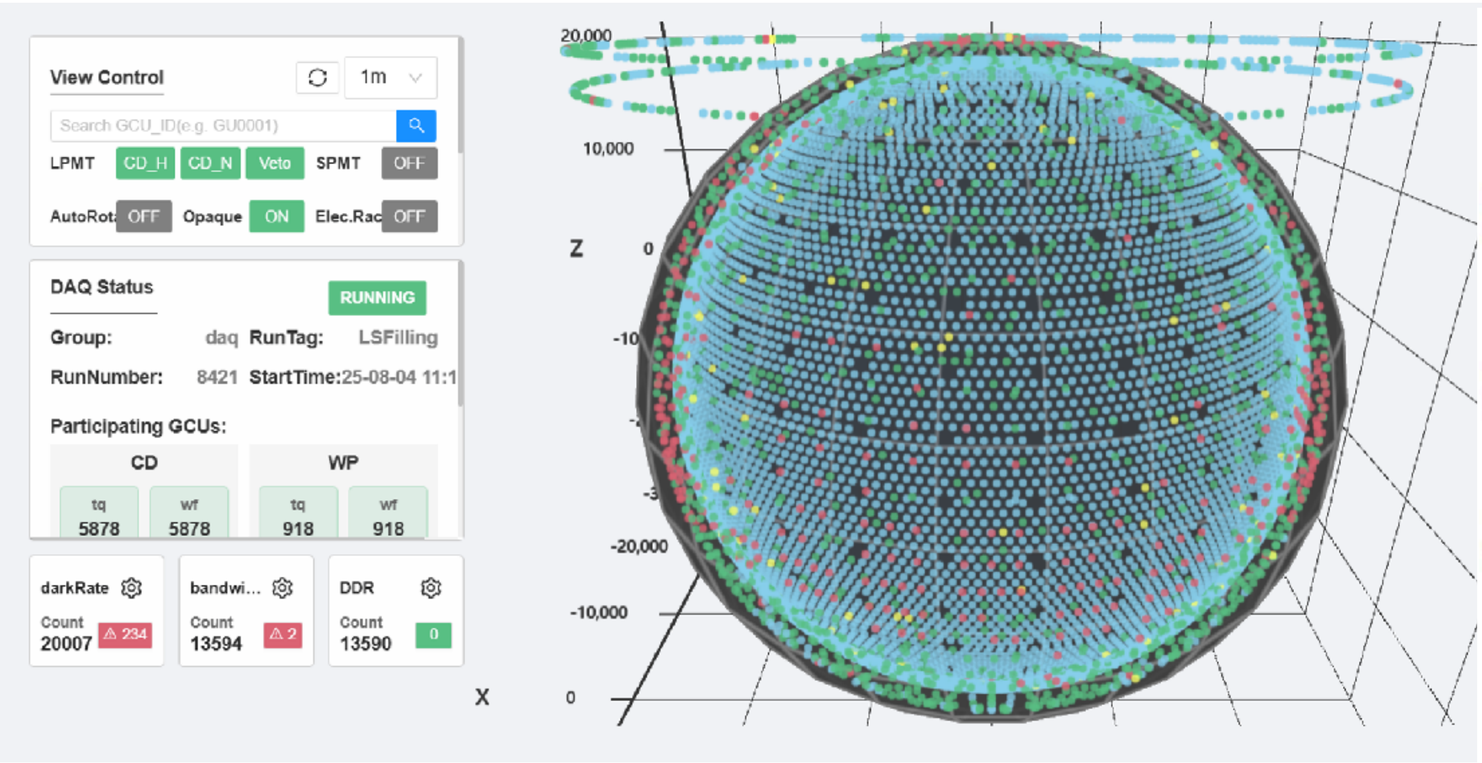
- Multiple calibration sources (^{68}Ge, ^{137}Cs, ^{54}Mn, ^{60}Co, ^{40}K, ^{241}Am-C, laser) with 1/2/3D locations to ensure the understanding of detector response.

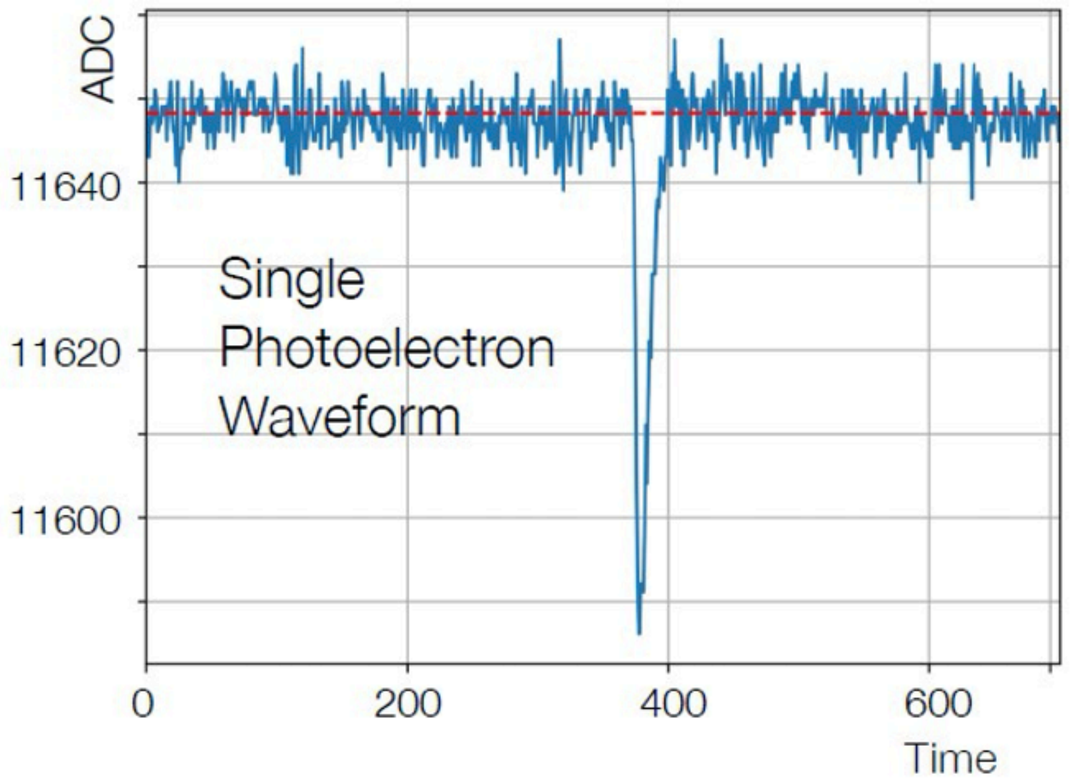
Detector Status



- Now at the final stage of the LS filling which is to be fully finished very soon!

Detector Status





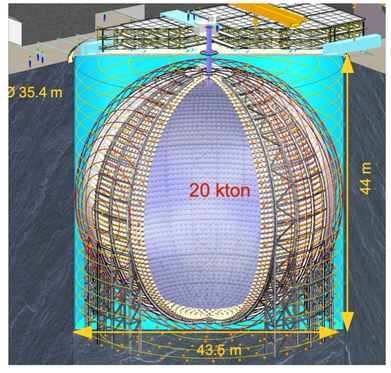
- The detector is under commissioning data-taking during water-phase and mixed-phase.
  - PMTs/electronics/calibration systems etc. working well

Signal and Background

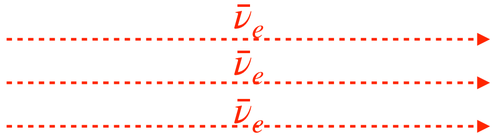
$\bar{\nu}_e$

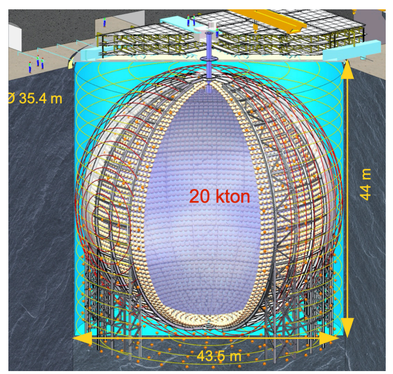
$\bar{\nu}_e$

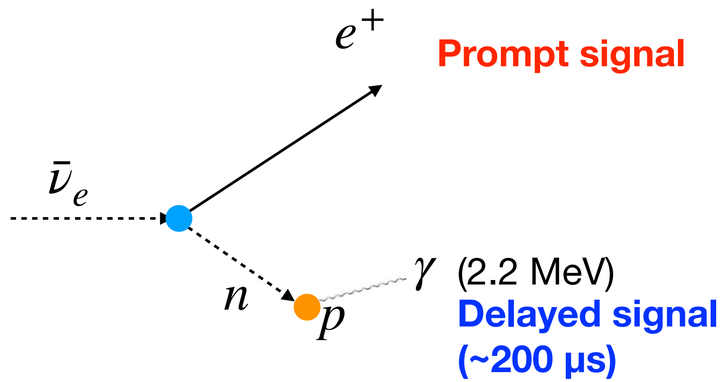
$\bar{\nu}_e$



Signal and Background





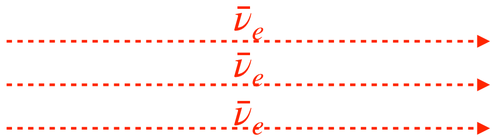


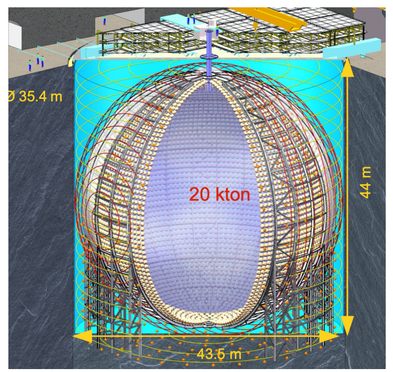
- Signal: electron antineutrino Inverse bete decay (IBD):

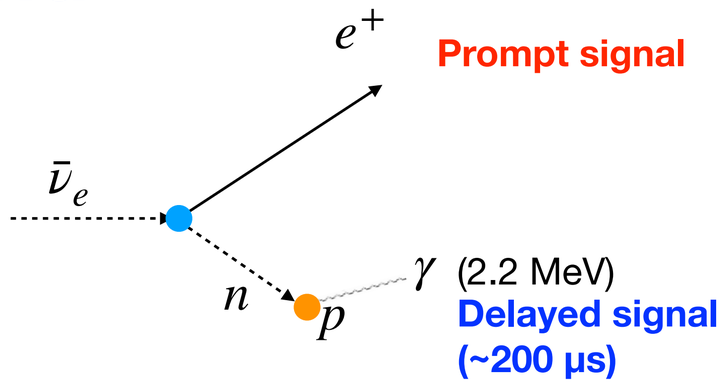
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

- coincident of prompt (positrons) and delayed signals (n-captures).
- Expected rate: 47/day (after event selection)

Signal and Background







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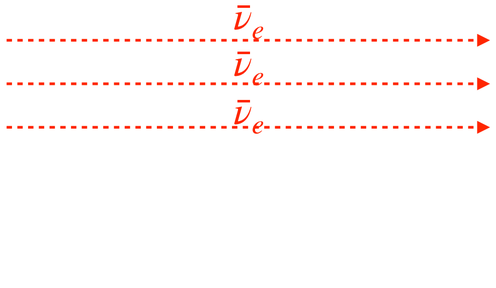
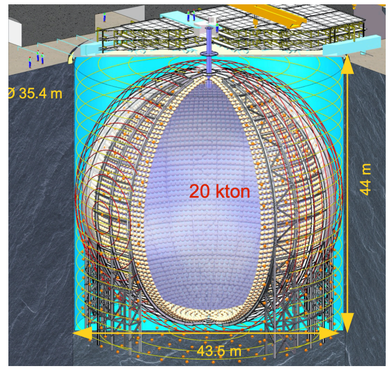
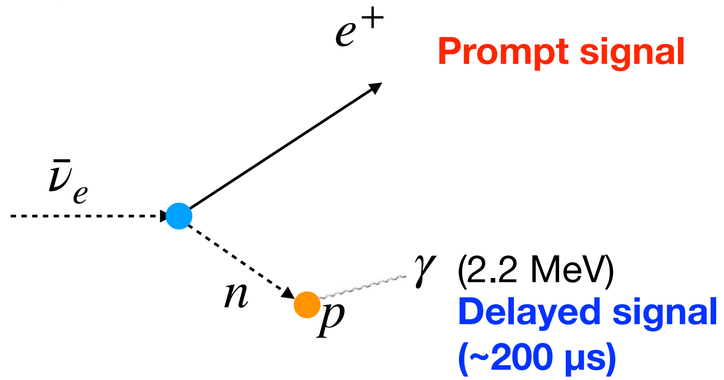
  - coincident of prompt (positrons) and delayed signals (n-captures).
  - Expected rate: 47/day (after event selection)
- Backgrounds: Geoneutrinos, world reactors, cosmogenic isotopes, fast neutrons etc.
  - Expected rate: 4/day (after event selection)

Signal and Background







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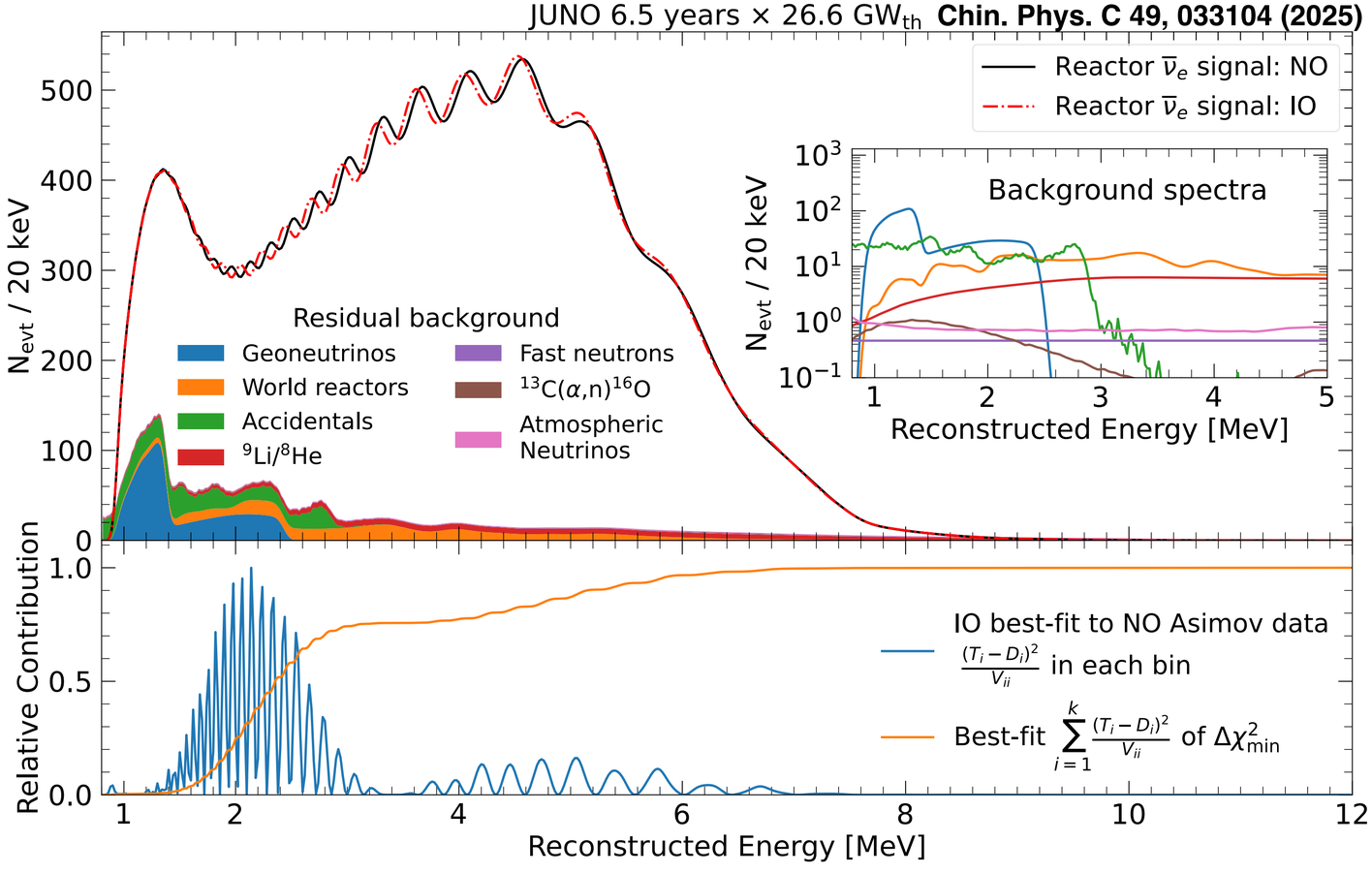
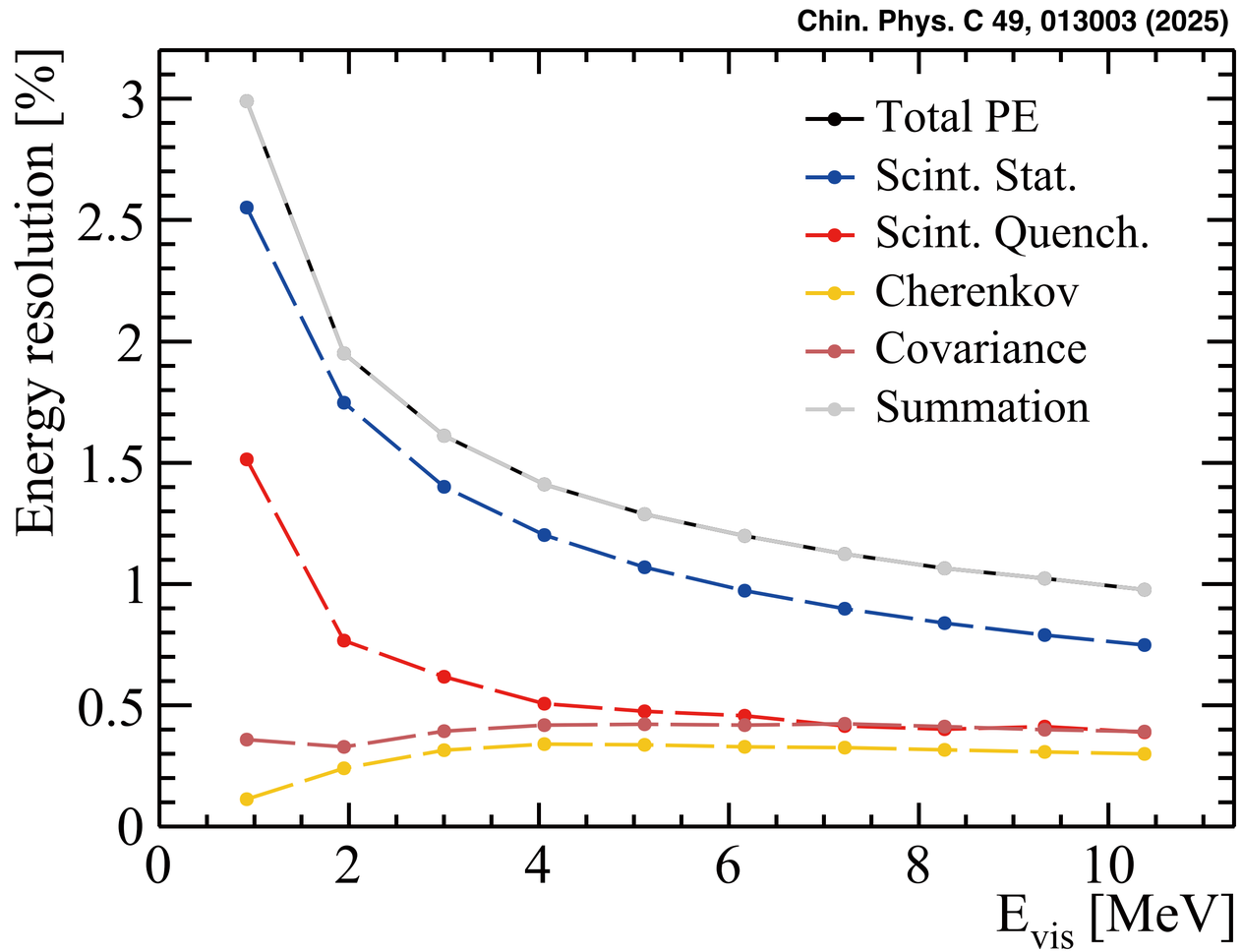
  - Expected rate: 4/day (after event selection)



Energy Resolution

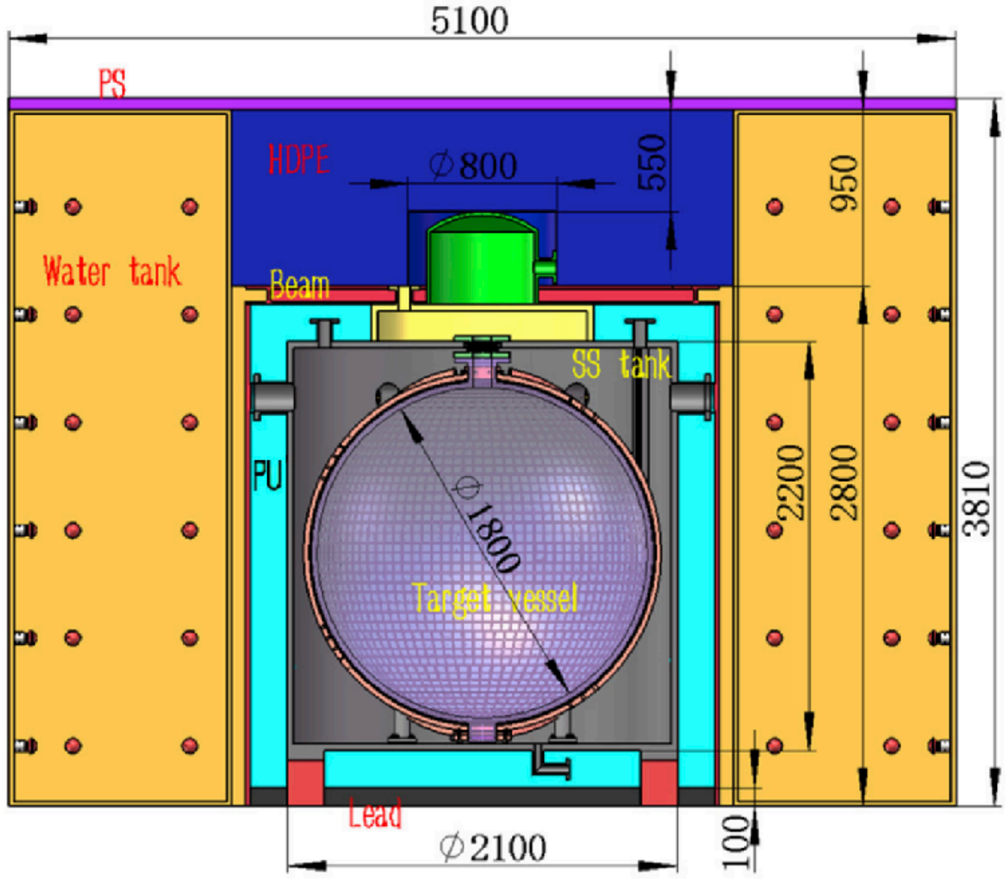
$$\frac{\sigma}{E_{\text{vis}}} = \sqrt{\left(\frac{a}{\sqrt{E_{\text{vis}}}}\right)^2 + b^2 + \left(\frac{c}{E_{\text{vis}}}\right)^2}.$$

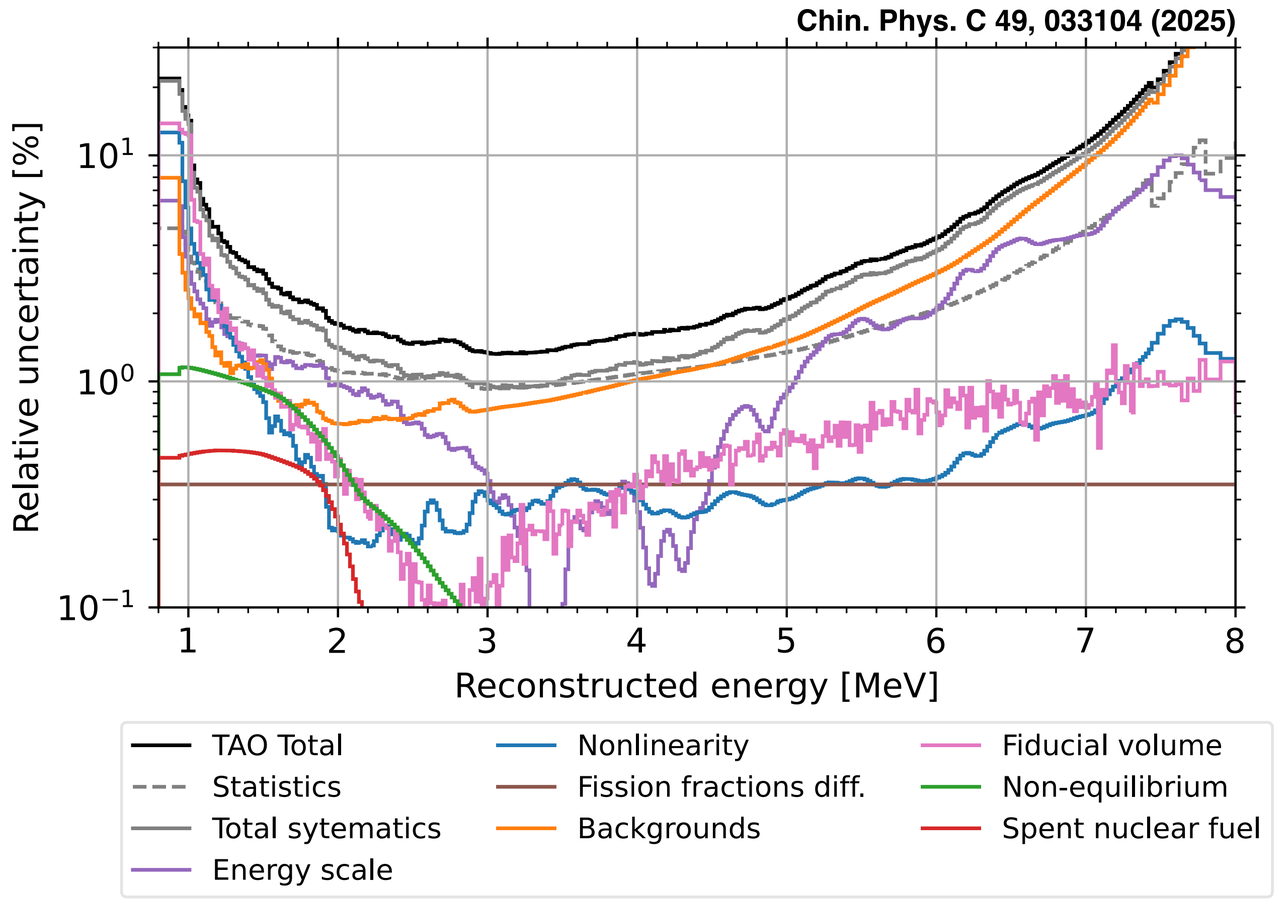
- a: statistical term mainly driven by the Poisson statistics of detected PE
- b: constant, independent of energy and mostly contributed by the scintillation quenching effect, Cherenkov radiation, and energy non-uniformity
- c: the PMT dark noise and positron annihilation γs



- Light yield: 1665 PE/MeV (CD center).
- Energy reconstructed by a data-driven likelihood method.
- Estimated energy resolution: 2.95% @1MeV.

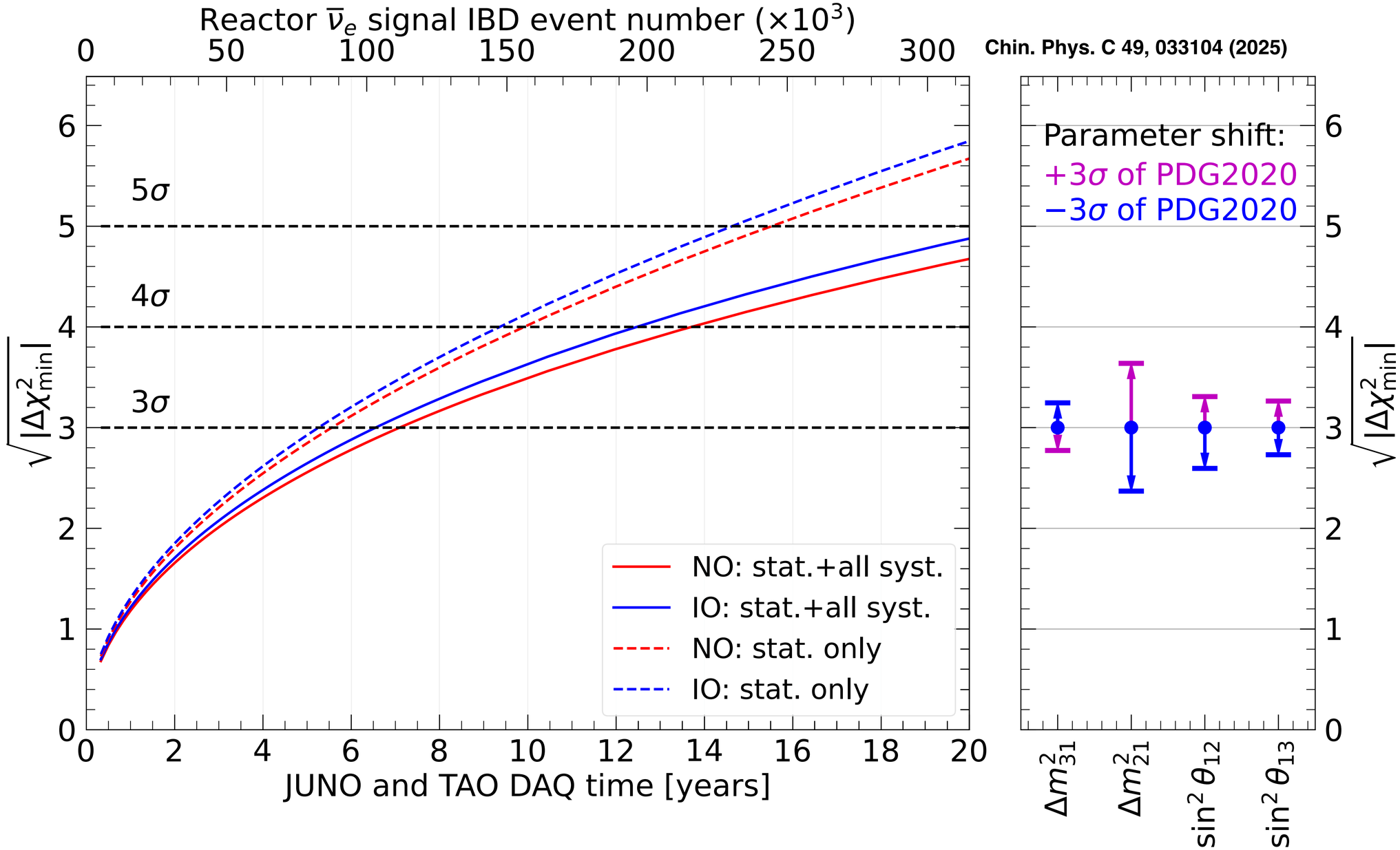
A Near Detector for Flux: JUNO-TAO





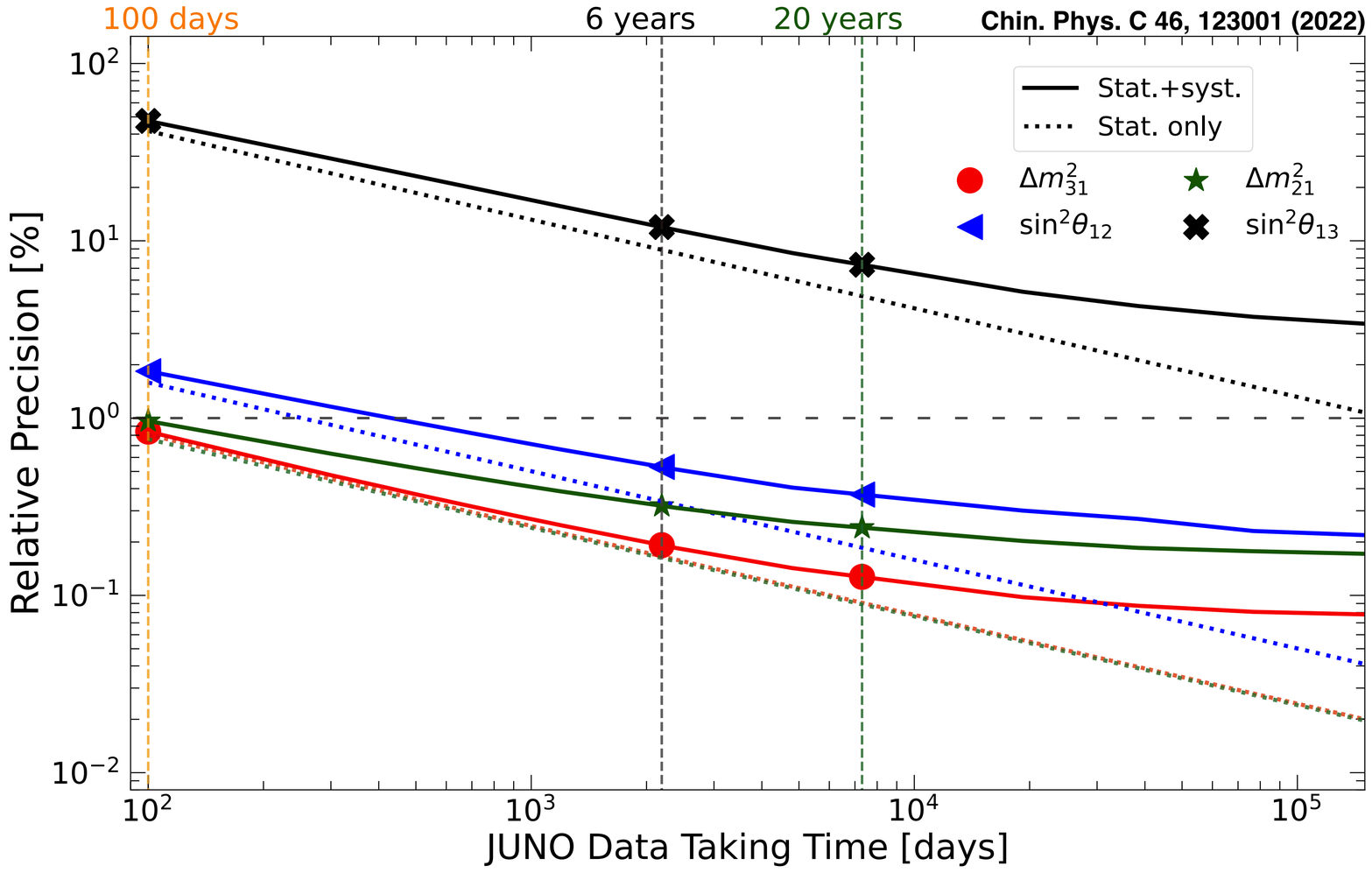
- 2.8 ton Ga doped LS detector with SiPM (94% coverage) by the Tanshan NPP.
- Energy resolution better than 2% @ 1 MeV.
- Measurement of reactor $\bar{\nu}_e$ spectrum with no oscillation.
- Provides model-independent reference spectrum for JUNO with subpercent shape uncertainty.
- Physics potential for sterile neutrinos etc. by itself. **Talk by L. Delgadillo Franco, Aug 22nd afternoon**

Sensitivity to NMO



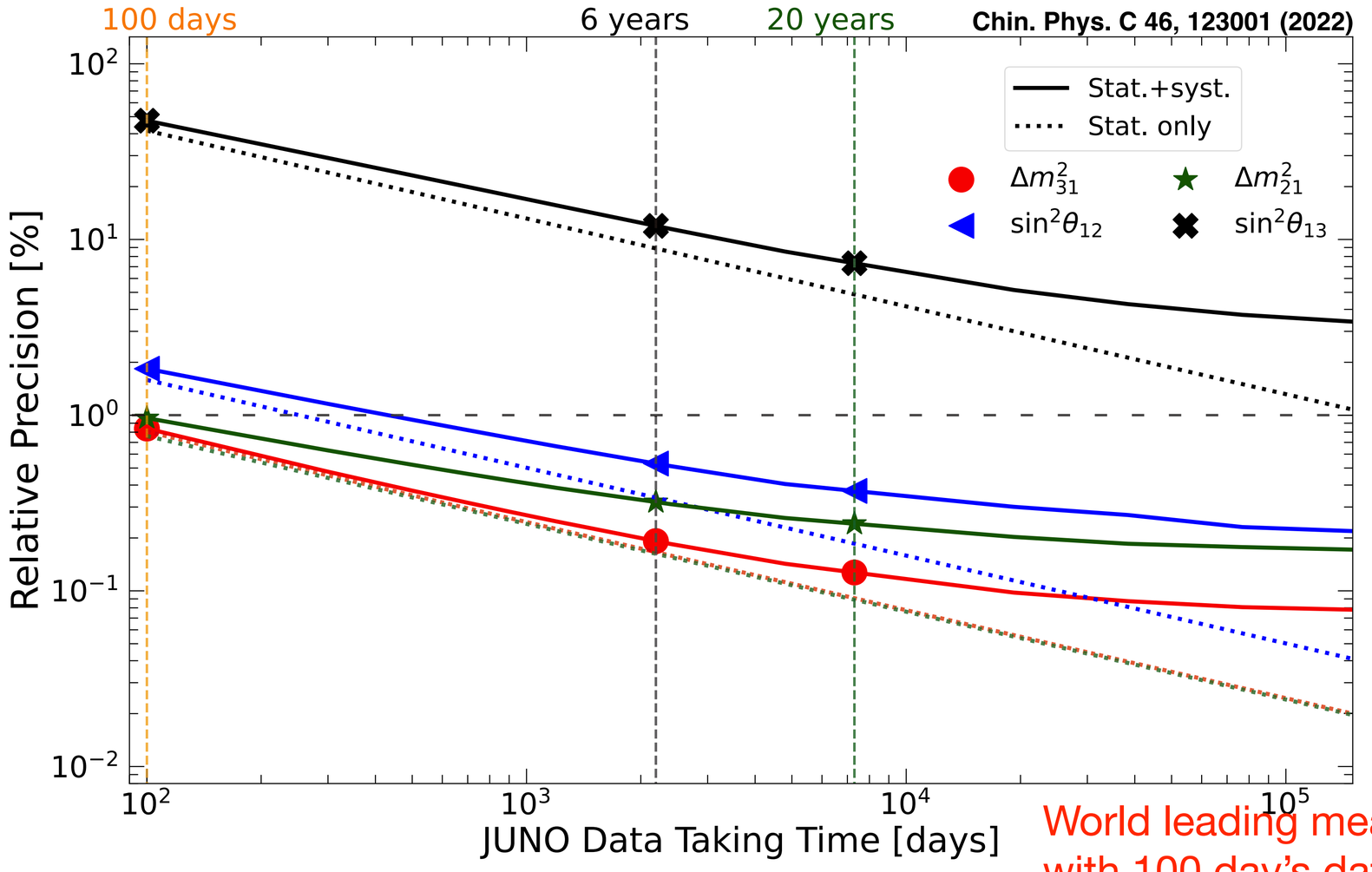
- 3σ measurement of NMO in ~6 years.

Precise Measurements on Oscillation Parameters



	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%)

Precise Measurements on Oscillation Parameters



World leading measurements with 100 day's data!

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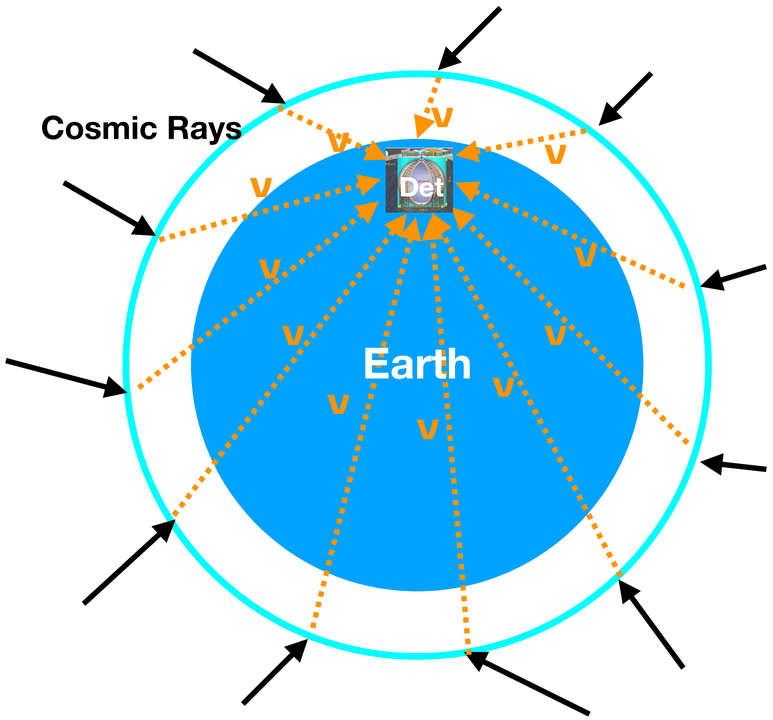
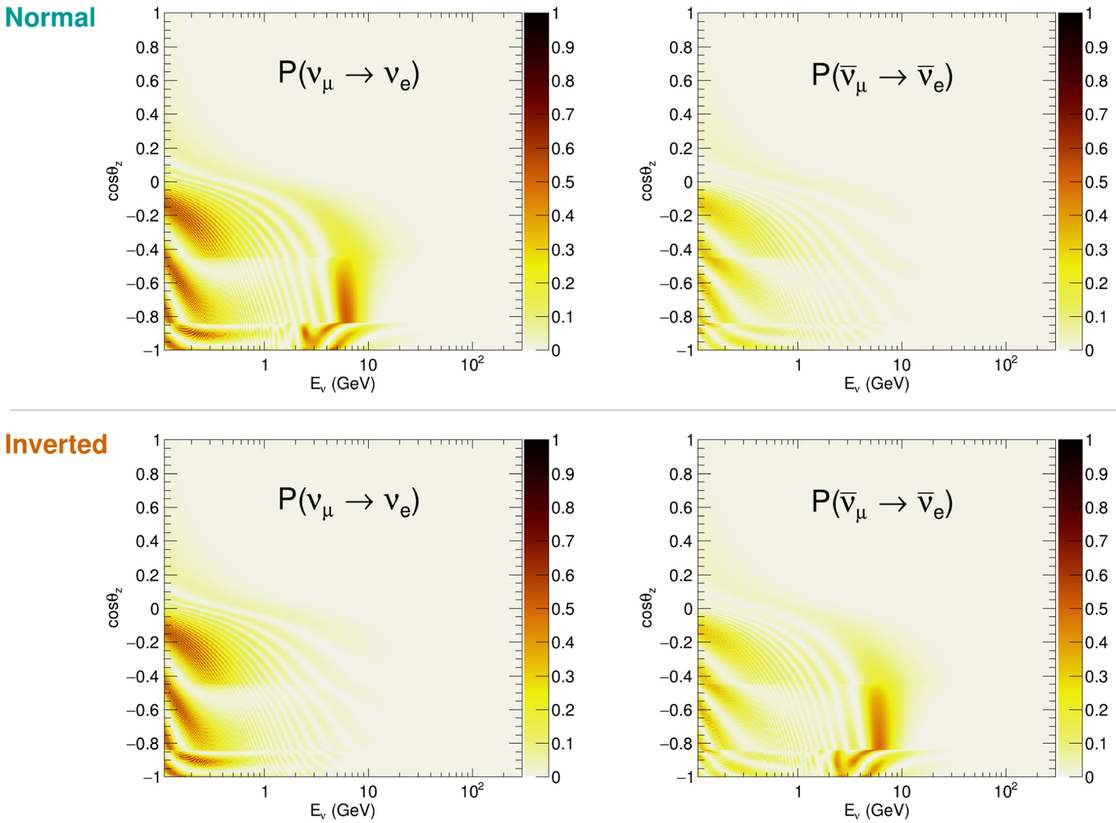
More for NMO: Atmospheric Neutrinos





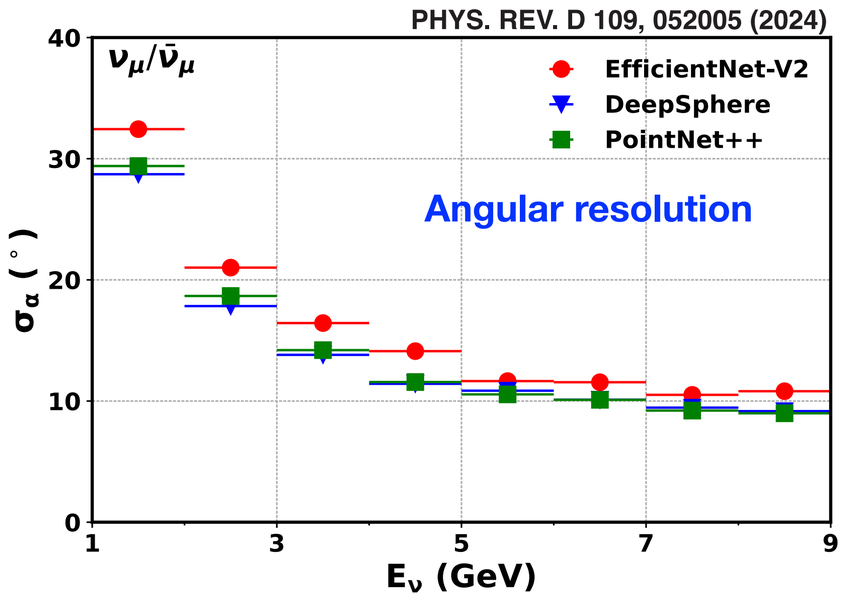
Sensitivity benchmarked by $\Delta\chi^2 = |\chi^2_{NO} - \chi^2_{IO}|$

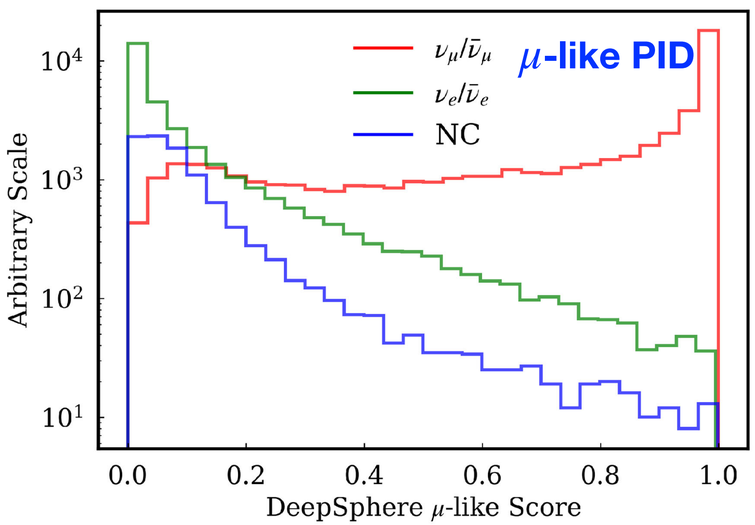
- Atmospheric neutrinos are sensitive to NMO via matter effects.
- Requires measurements of neutrino directionality and flavor identification.
- Traditionally not measured in a LS detector.

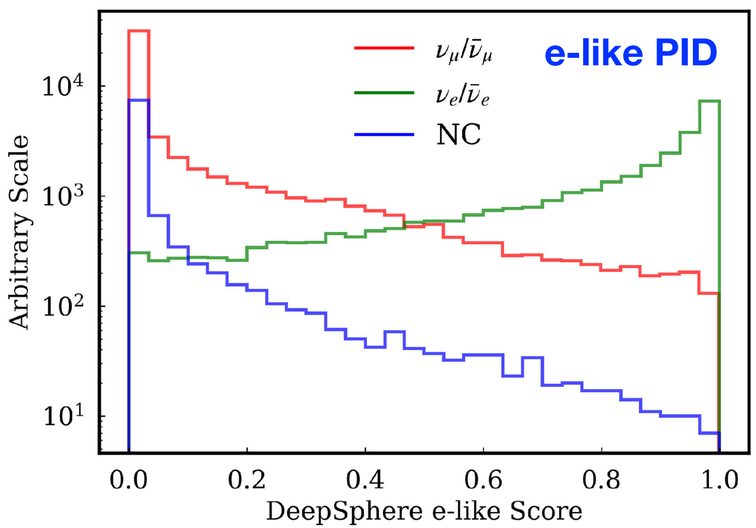
More for NMO: Atmospheric Neutrinos

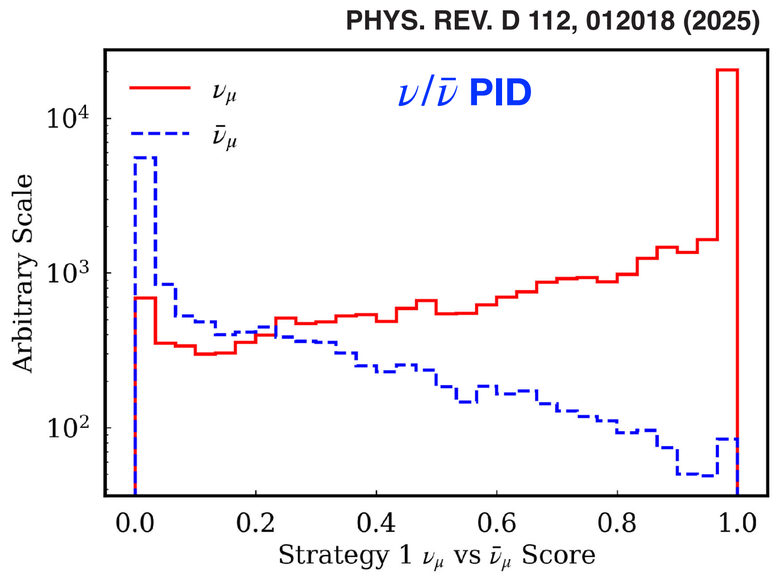
- Novel machine learning techniques developed for atmospheric neutrinos' direction reconstruction, flavor identification, and $\nu/\bar{\nu}$ discrimination.

- Joint reactor and atmospheric neutrino oscillation measurements may further increase JUNO's total sensitivity to NMO.

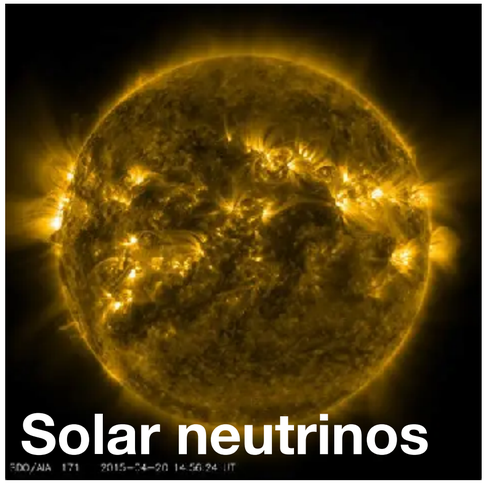




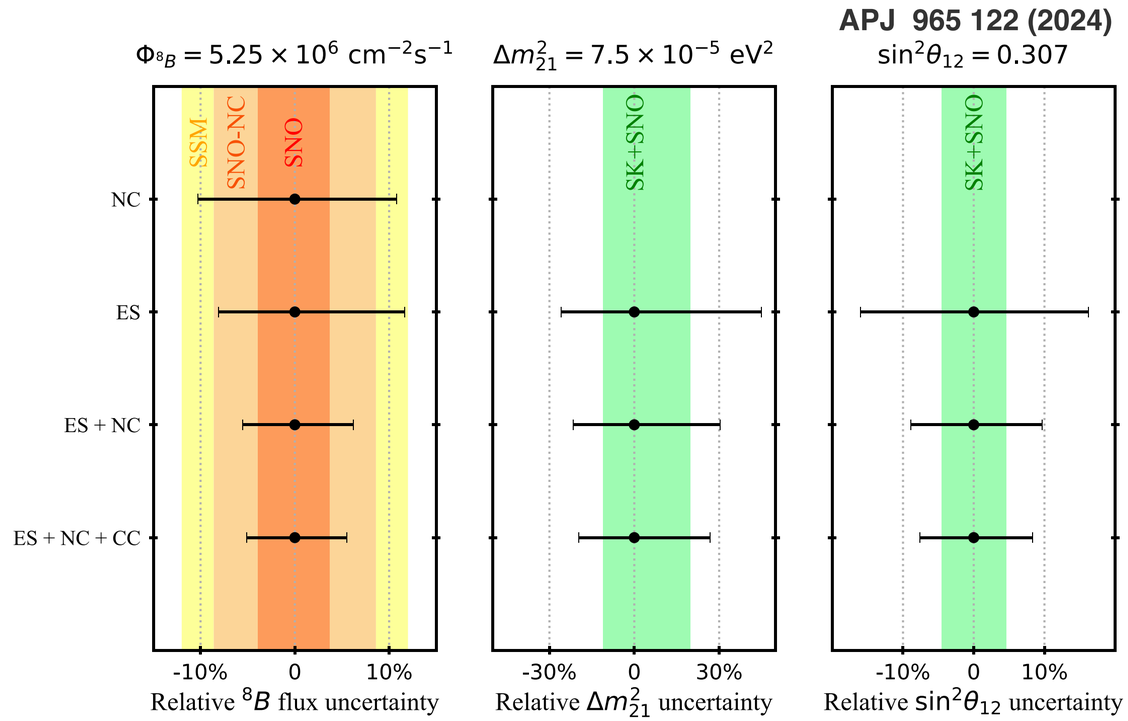




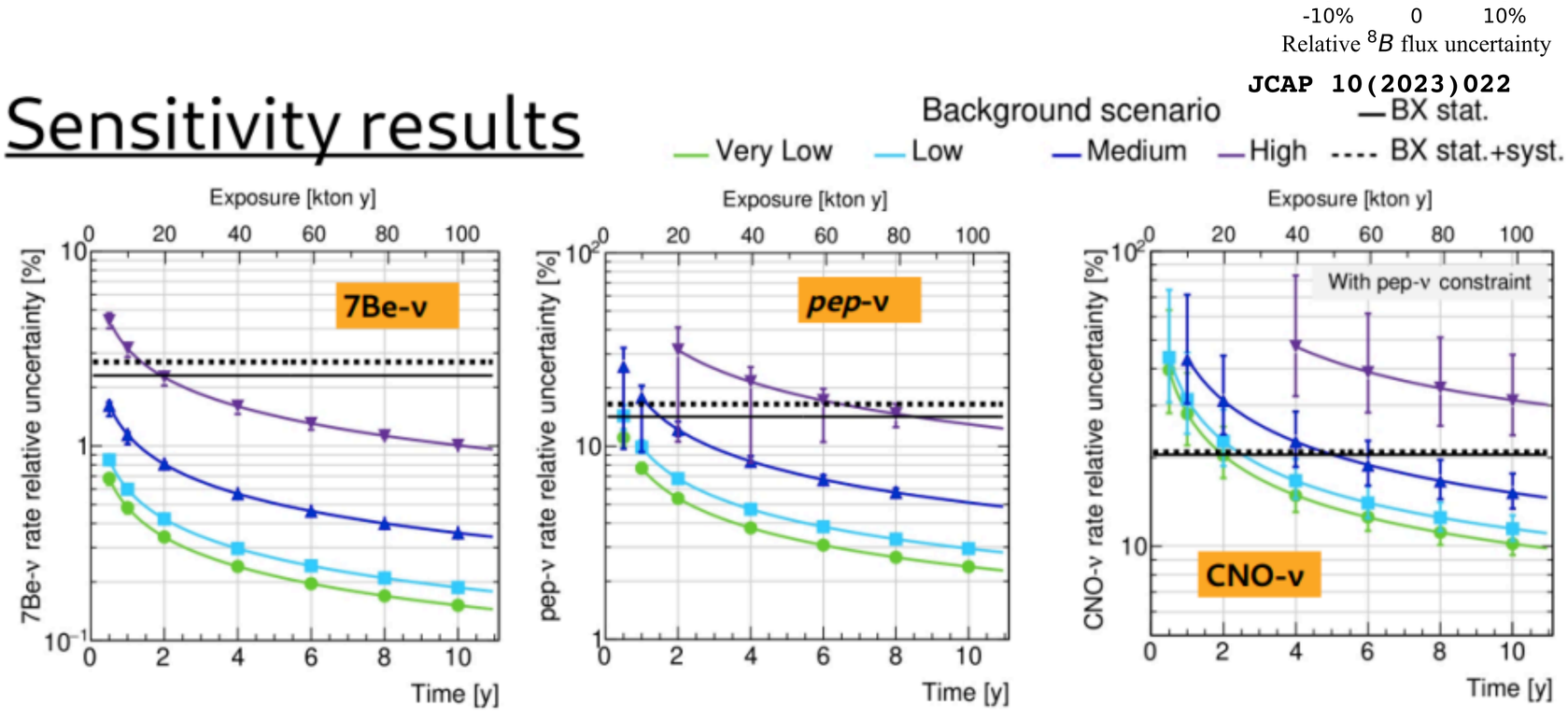
A Multi-Purpose Experiment: Solar Neutrinos



- Solar neutrino oscillations with ES+NC+CC channels for Δm^2_{21} and θ_{12} measurements

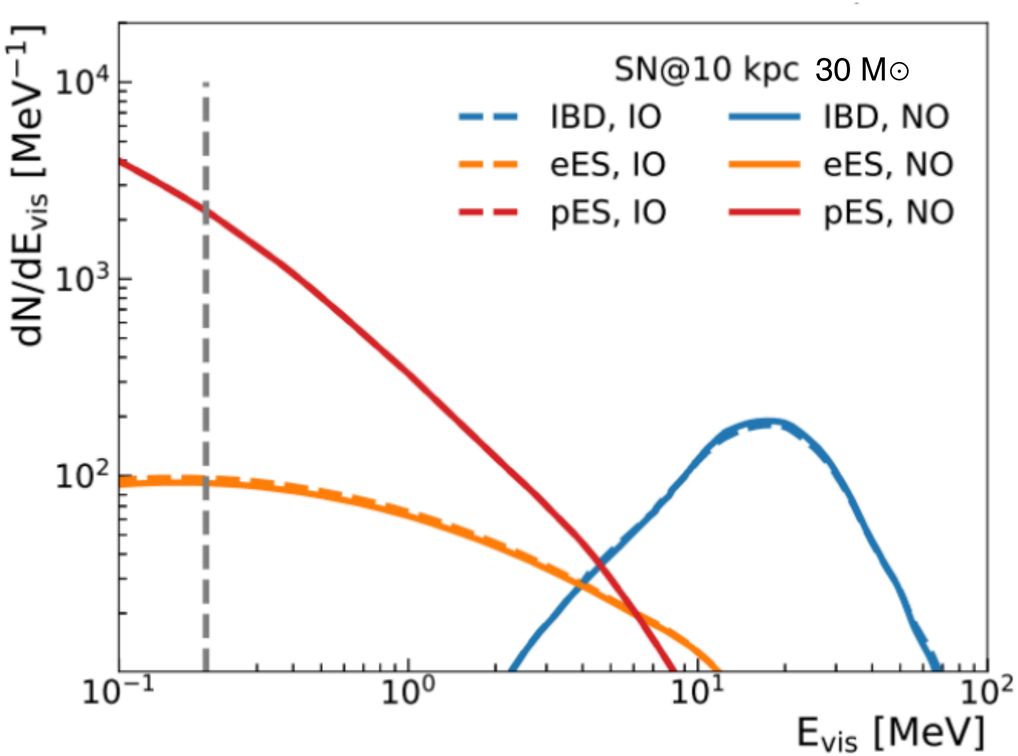


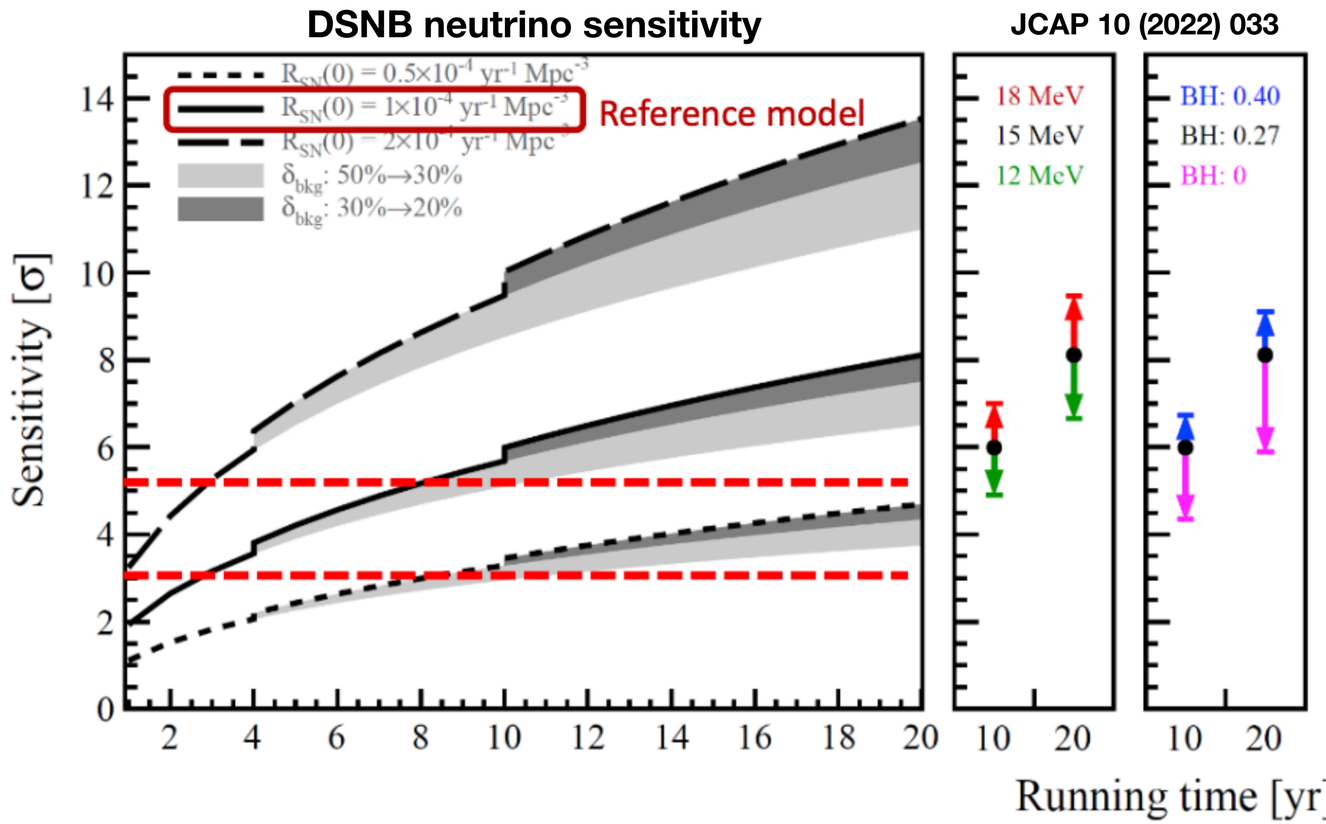
Sensitivity results



- Improves measurement on ^{7}Be, pep, CNO neutrino flux.

A Multi-Purpose Experiment: Supernova Neutrinos

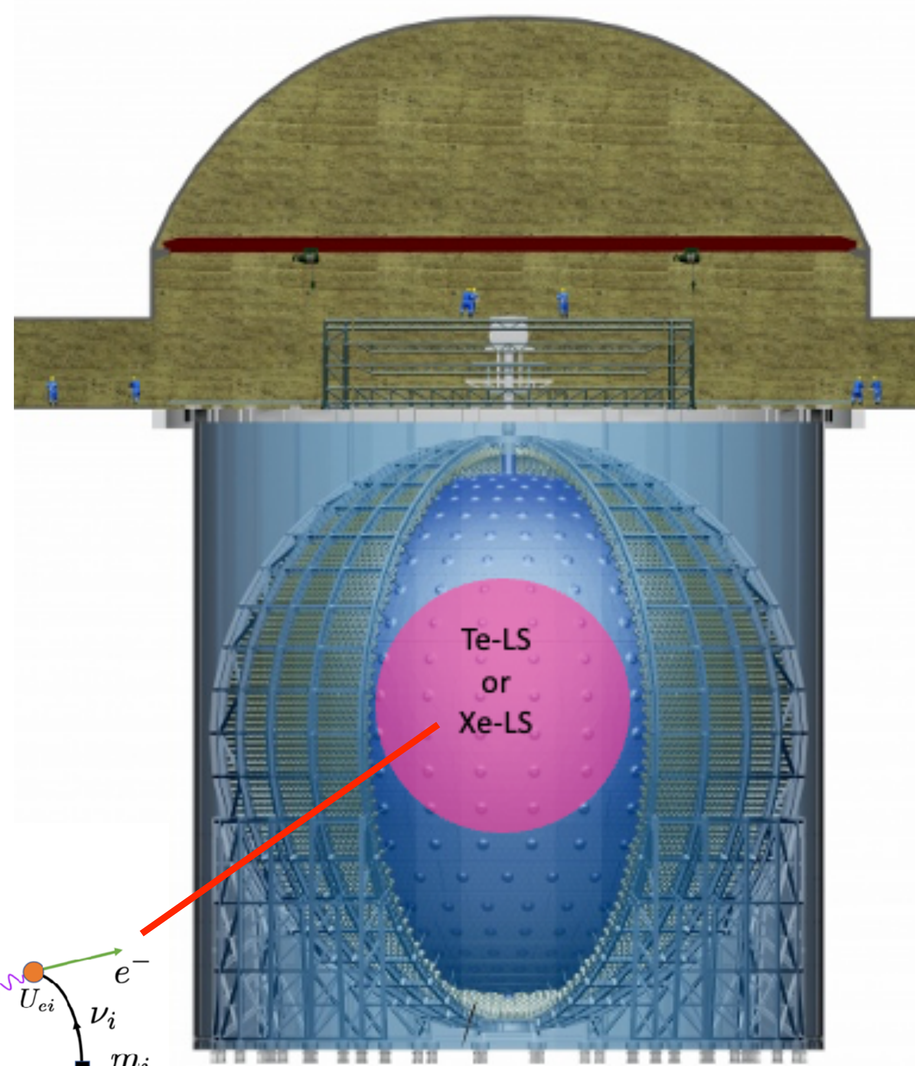


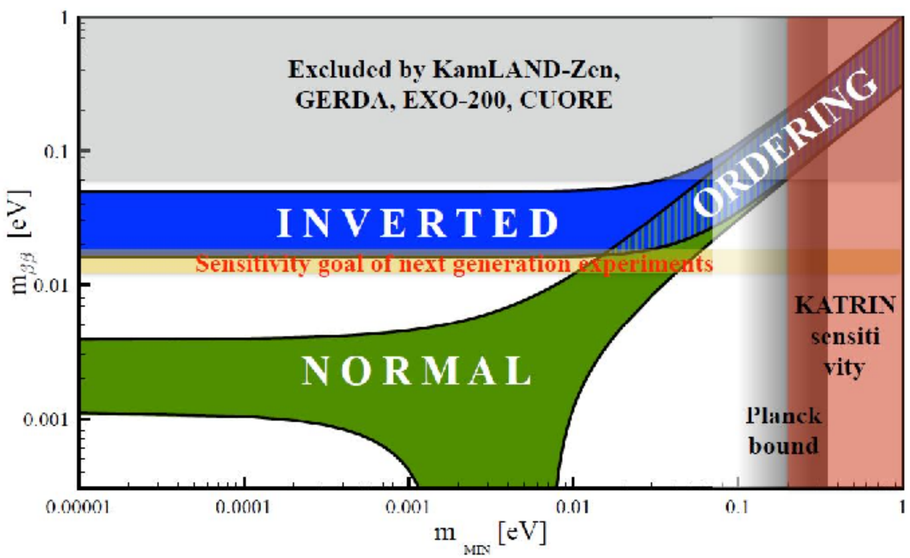


- Supernova burst neutrinos: 3 detection channels sensitive to all flavors (JCAP01 (2024) 057)
  - Excellent capability for early warning
- Diffused supernova background: 3σ in 3 years and 6σ in 10 years (JCAP 10 (2022) 033).
- More topics not covered in this talk: geoneutrino, proton decay etc.

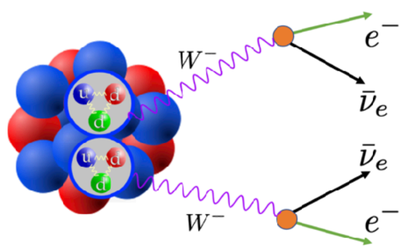
Future Upgrade: Neutrino-less Double Beta Decay Search

- Possible for future 100-ton scale isotope loading
- Good energy resolution (< 3% @ 1 MeV)
- LS shielding for low background.
- Potential to explore normal mass ordering parameter space of Majorana neutrino mass.
- R&D in progress.

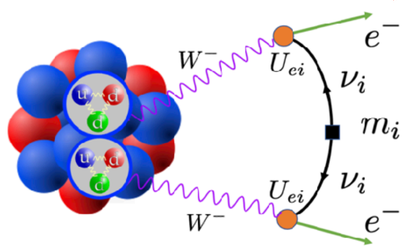




2νββ



0νββ

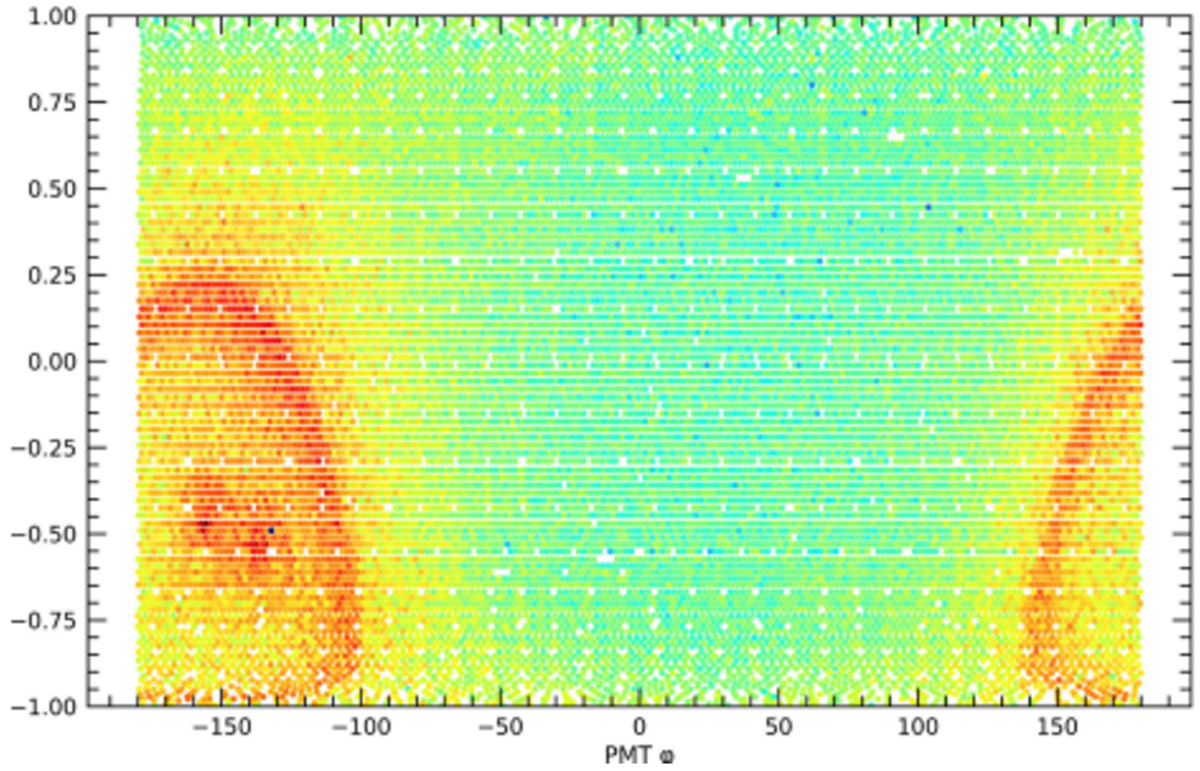


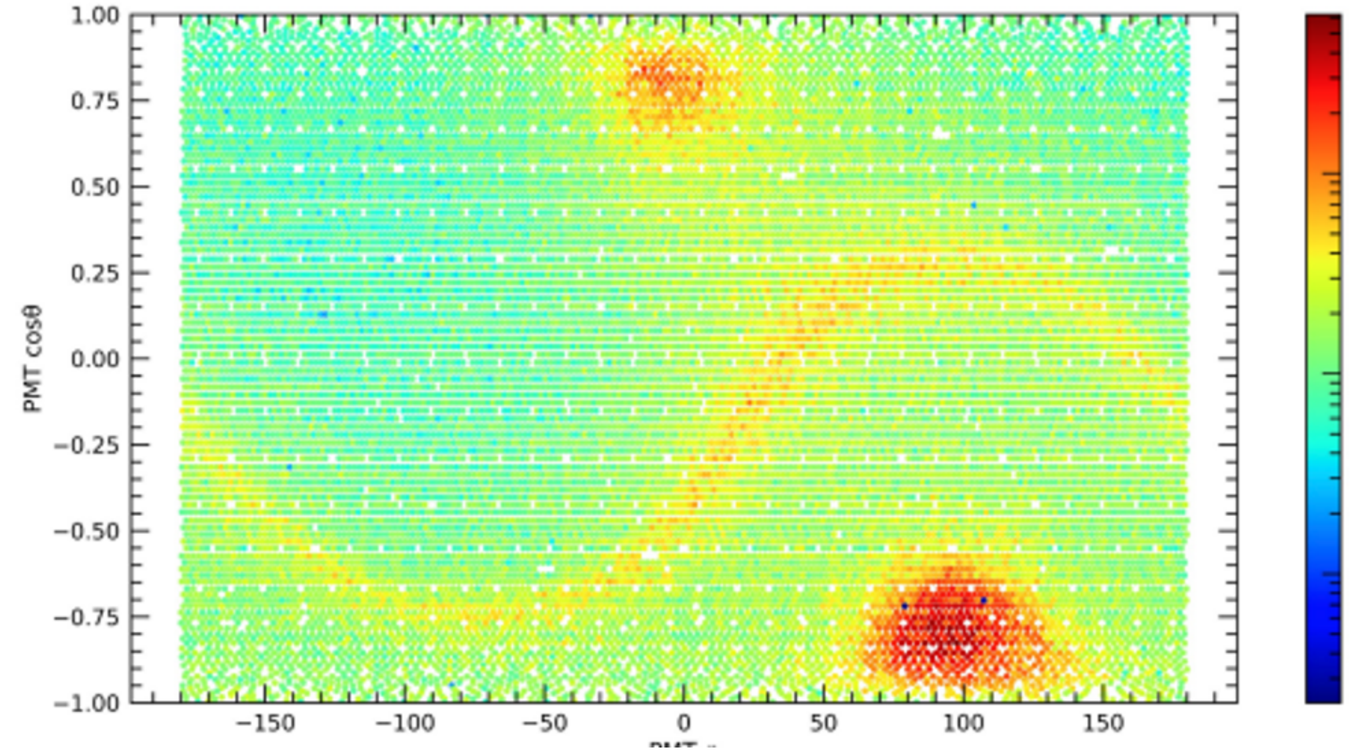
Summary

- **JUNO is the largest LS detector ever build with rich physics programs: NMO and more.**
- **A very exciting moment: finishing the final LS filling.**
- **Detector in good shape with commissioning data-taking.**
- **Physics data-taking very soon.**
- **Stay tuned!**

Back up slides

Events with Commissioning Data





- Cosmic muons candidates in water phase commissioning data.