UCI University of California, Irvine

JUNO: Status & Prospects

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on behalf of the JUNO Collaboration

Fermilab Neutrino Seminar, April 11th 2023

Outline

- Physics Motivation
- JUNO Basics
- Physics Goals
- Design & Status
- Summary & Conclusions

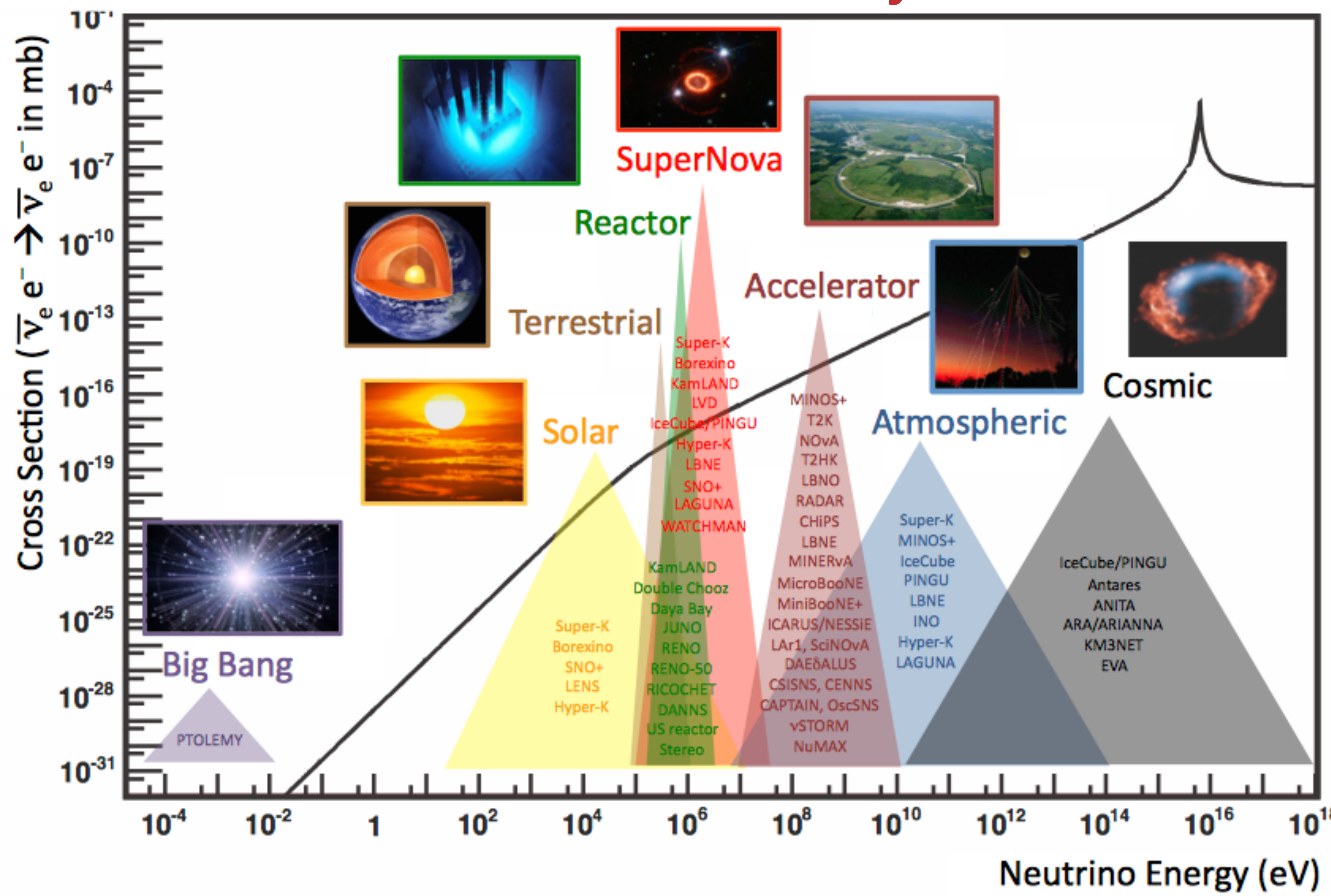
Physics Motivation

Status of the field

Neutrinos Matter!

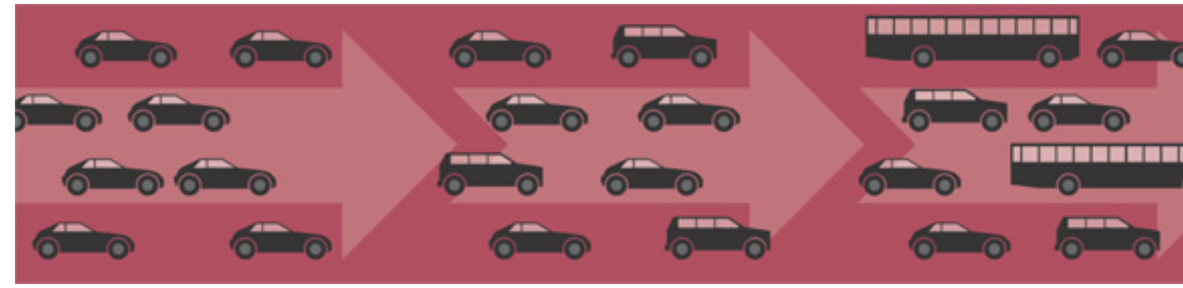
- We need to understand neutrinos if we want to understand our universe!
  - They are invaluable astronomical (and terrestrial) **messengers**
  - They are the second most **abundant** particle in the universe
  - Their behavior is **beyond the Standard Model**

Neutrinos are everywhere!



Neutrinos Oscillate!

Illustration of neutrino oscillation:



- The observation that neutrinos oscillate implies that they are massive:

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$$

How they interact (ν_e, ν_μ, ν_τ)

How they propagate (ν_1, ν_2, ν_3)

where the matrix *U* is parameterized in terms of three mixing angles (θ_{12},θ_{13},θ_{23}) and one CP-violating phase δ

For example, as a rough approximation at short baselines, the $\bar{\nu}_e$ "survival" probability is:

amplitude

frequency

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \cong 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{32} L}{4E}$$

(where $\Delta m^2_{ij} \equiv m^2_i - m^2_j$ are the so-called "mass splittings")

Completing the Picture

- Great progress has been achieved in the last two decades:

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Atmospheric **Reactor & CP** **Solar** **Majorana Phases**

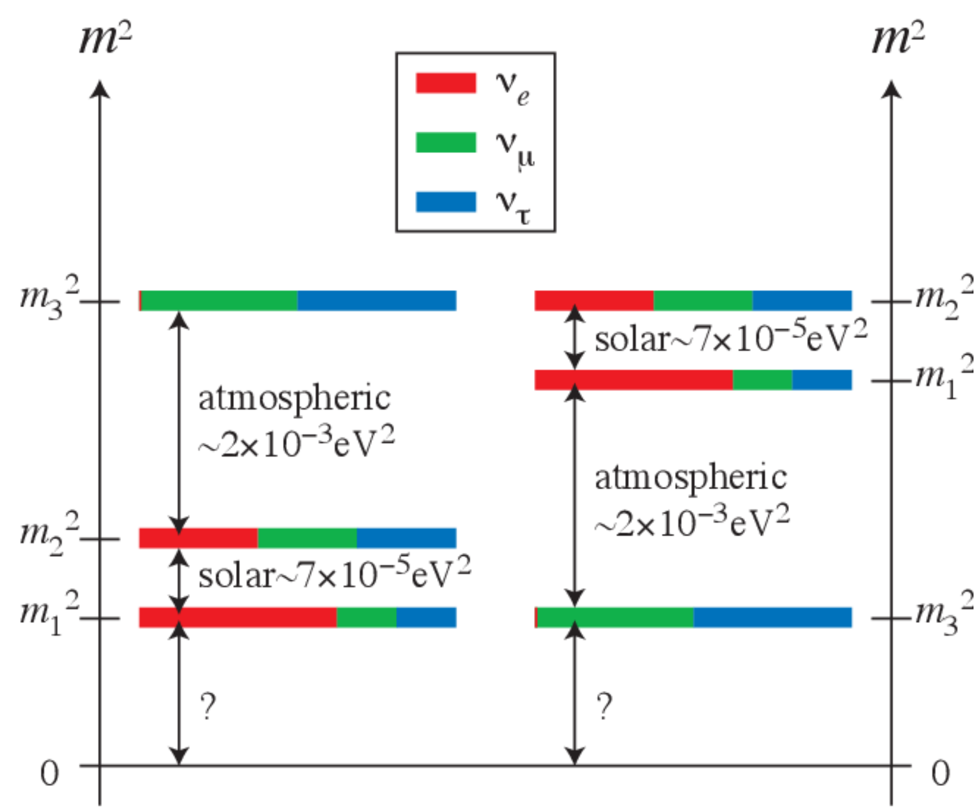
<u>Milestones</u>

1998: Atmospheric ν osc. ($\sin^2\theta_{23}$, $|\Delta m^2_{32}|$)

2002: Solar ν osc. ($\sin^2\theta_{12}$, Δm^2_{21})

2012: Reactor ν osc. ($\sin^2\theta_{13}$)

These 5 parameters are now known to better than 5%



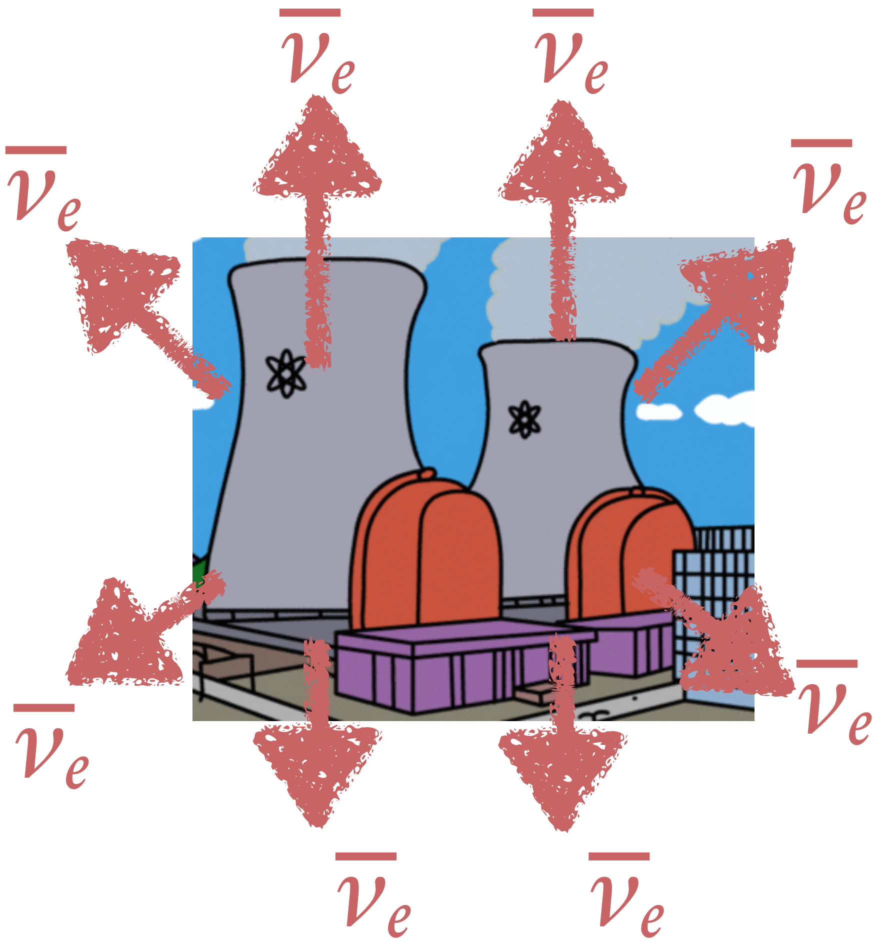
- But several questions still don't have an answer:
  - How are the neutrino masses ordered?
  - Do neutrinos violate CP symmetry?
  - Are there additional neutrino states?
  - What is the absolute mass of neutrinos?

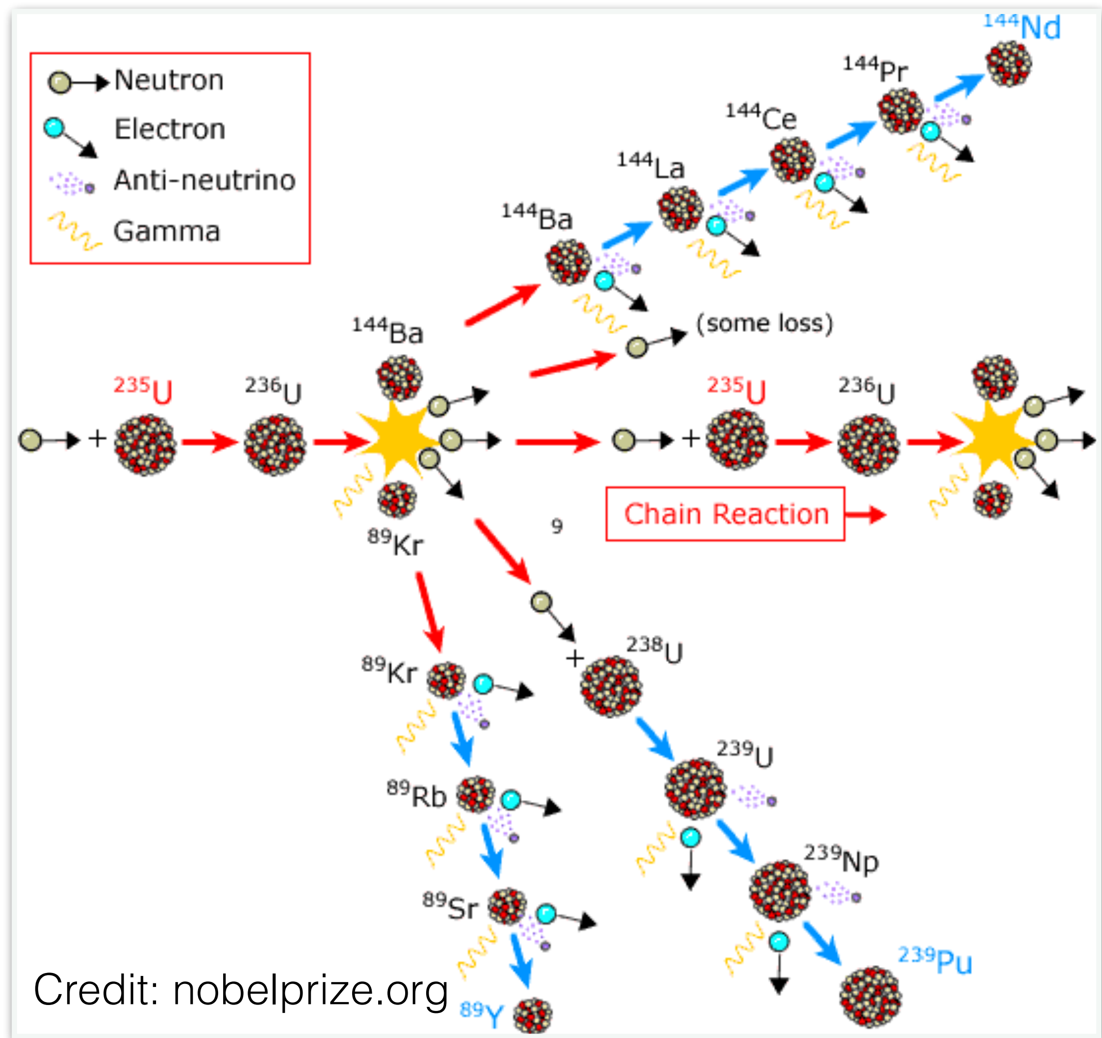
JUNO

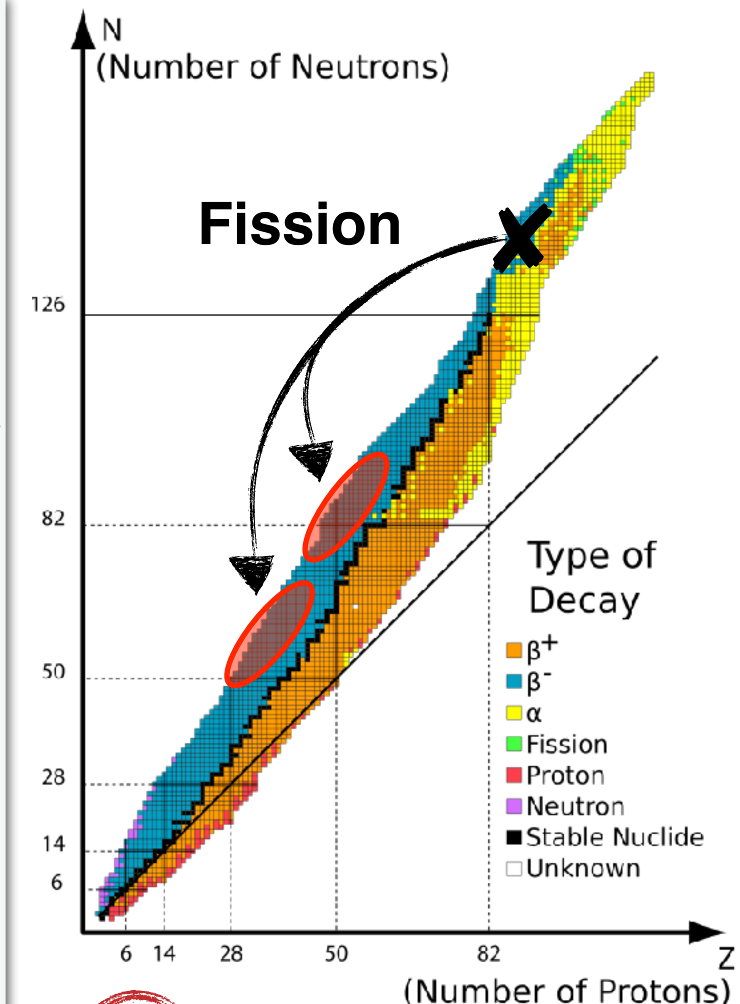
The Basics

Reactor Antineutrinos

- Nuclear reactors are a flavor-pure, widely available, cost-effective, **extremely intense** and well-understood source of electron antineutrinos:







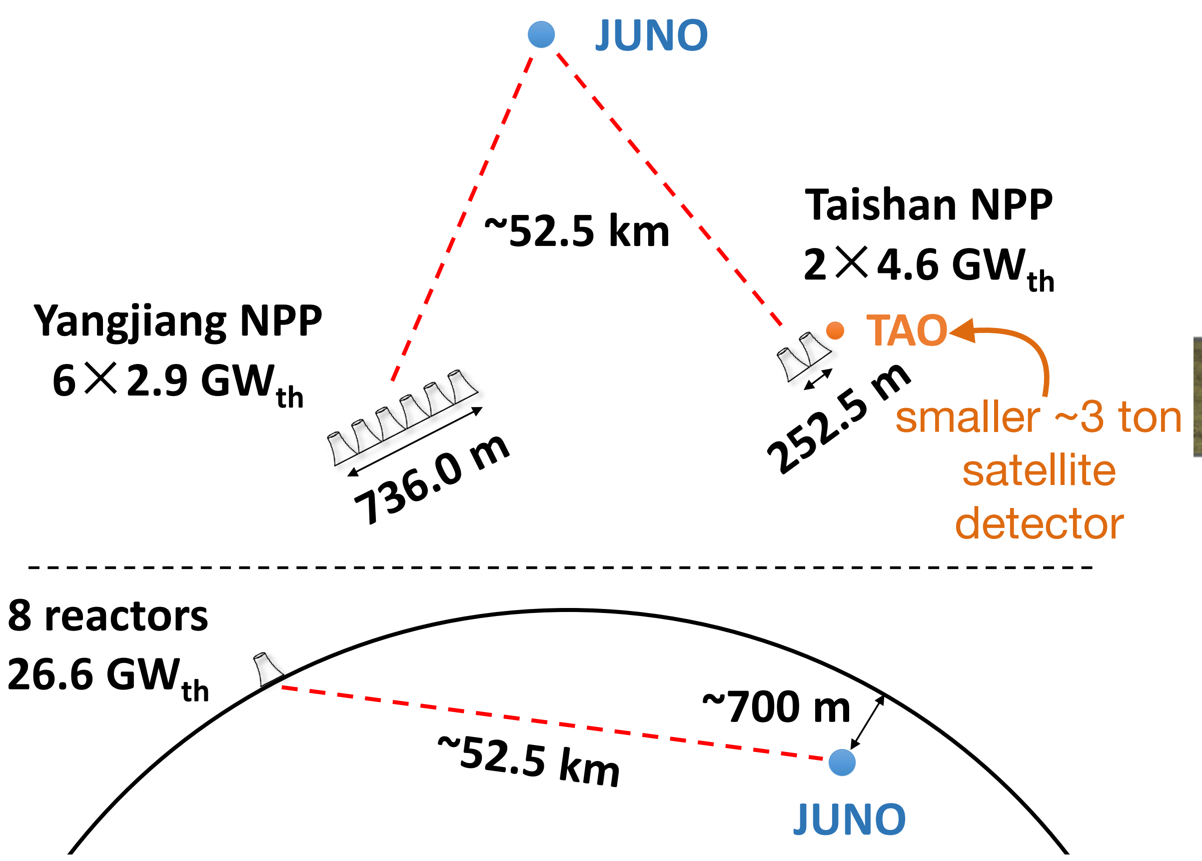
$\sim 10^{20}\ \bar{\nu}_e/\mathrm{GW_{th}}$

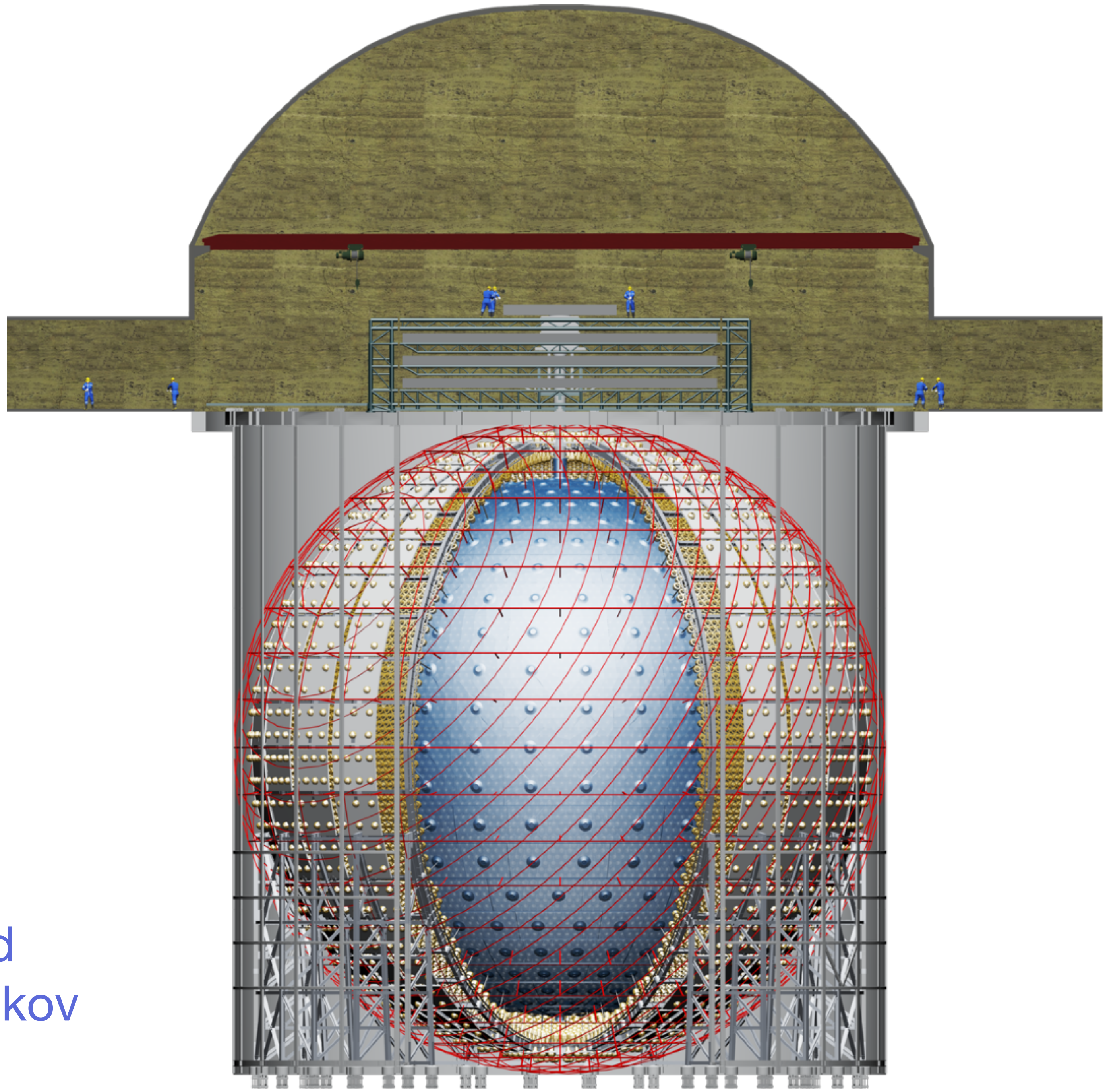
$$n \rightarrow p + e^- + \bar{\nu}_e$$

– A 1 $\mathrm{GW_{th}}$ core produces in one minute more neutrinos than the NuMI and BNB beams produce in a typical year

JUNO at a Glance

- The **J**iangmen **U**nderground **N**eutrino **O**bservatory (JUNO) is a large multi-purpose experiment under construction in China:





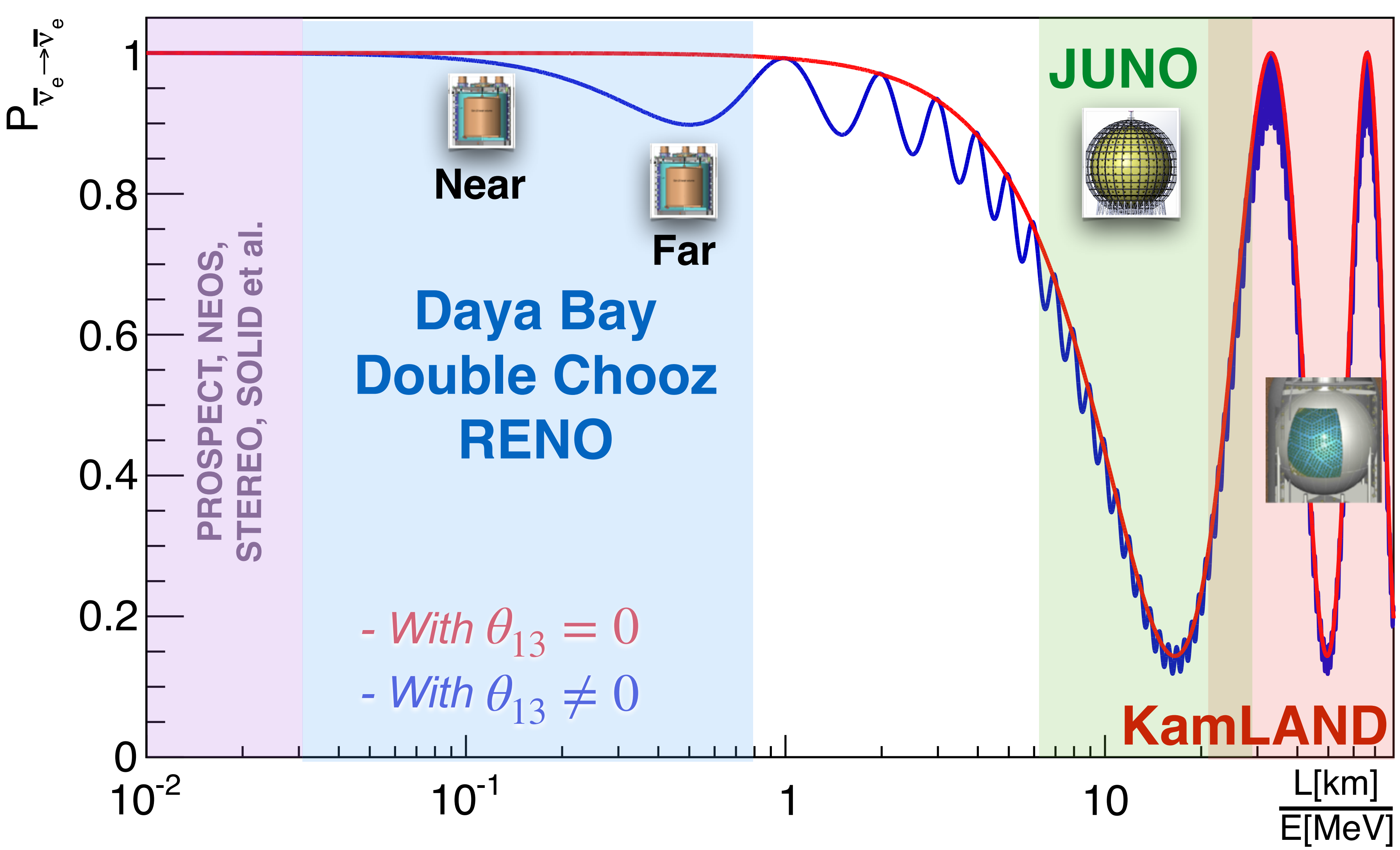
- 53 km from two major nuclear power plants (8 reactors)
- 35 m diameter sphere with 20 ktons of liquid scintillator (LS) surrounded by water Cherenkov detector
- Unprecedented energy resolution of 3% at 1 MeV

Oscillation Probability

- Electron antineutrino survival probability:

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

- Access to θ_{12}, θ_{13}, Δm^2_{21}, Δm^2_{32} and Δm^2_{31}
- First experiment to observe so-called “solar” and “atmospheric” oscillations simultaneously
- Independent of θ_{23} and δ_{CP}



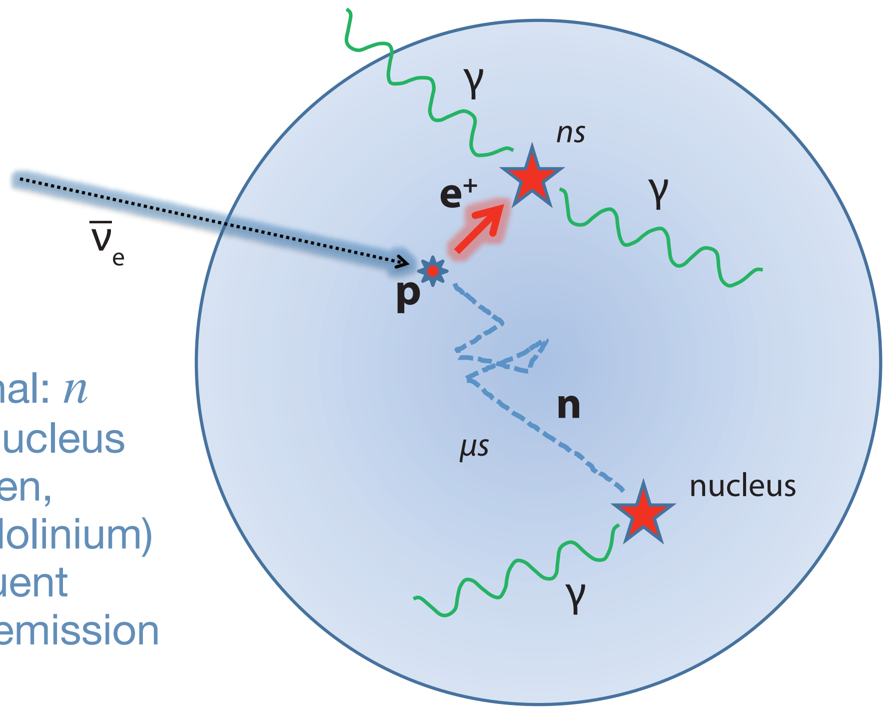
Antineutrino Detection

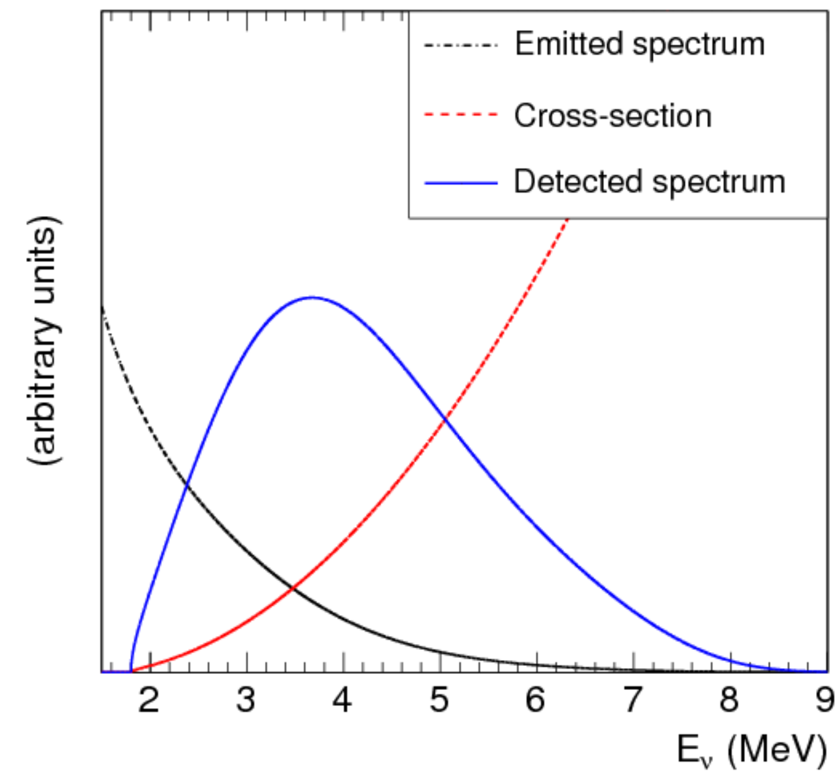
- The primary detection channel is the Inverse Beta Decay (IBD) reaction:

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

Prompt signal: e^+ kinetic energy loss + annihilation

Delayed signal: n capture on nucleus (e.g. Hydrogen, Lithium, Gadolinium) and subsequent gamma-ray emission





  – Coincidence between prompt positron and delayed neutron signals allows for **powerful background rejection**
  – Energy of positron preserves information about energy of incoming $\bar{\nu}_e$:

$$E_{\bar{\nu}_e} \approx E_{\text{prompt}} + 0.78\ \text{MeV}$$

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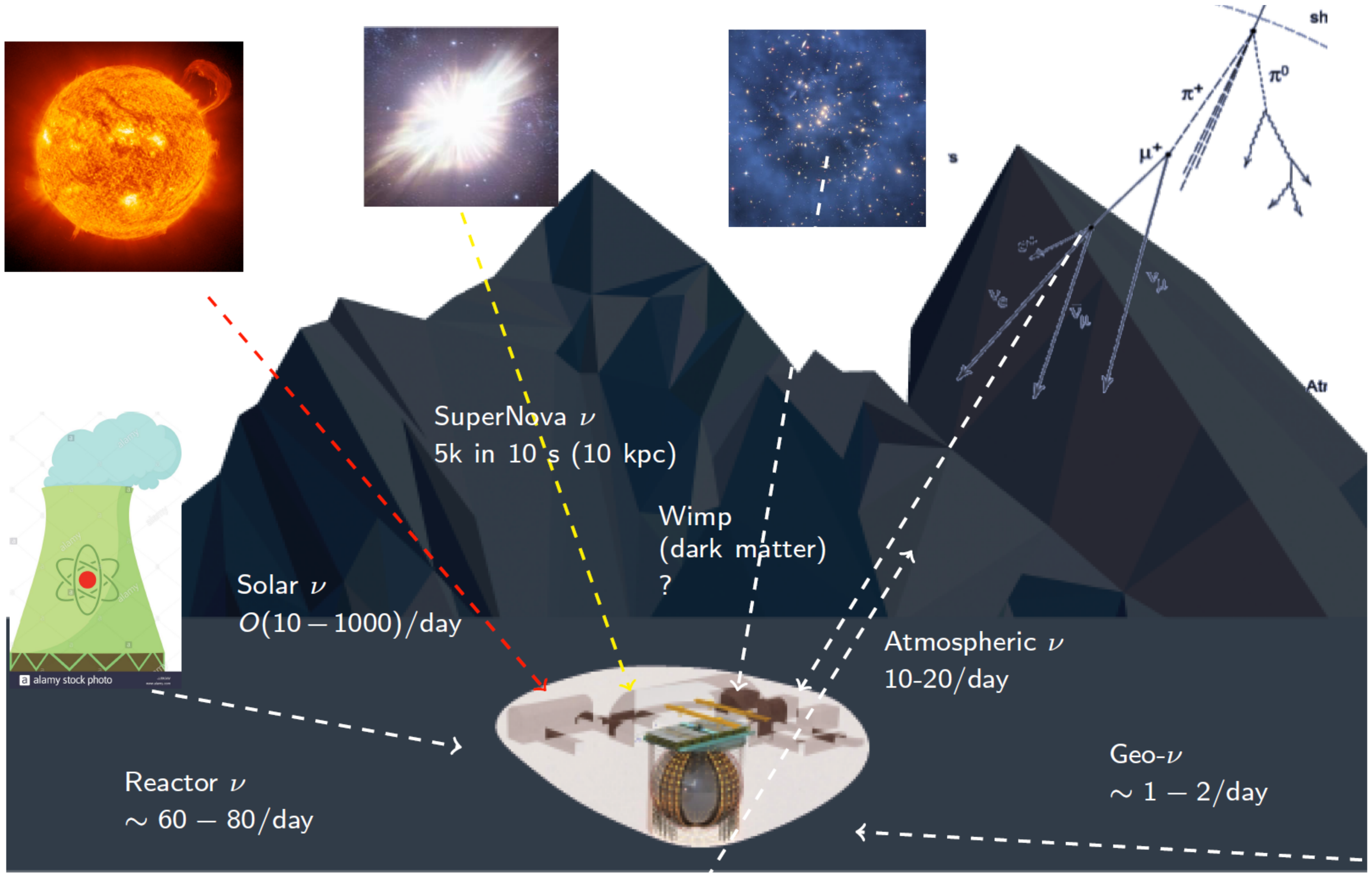
Prospects

Physics Capabilities

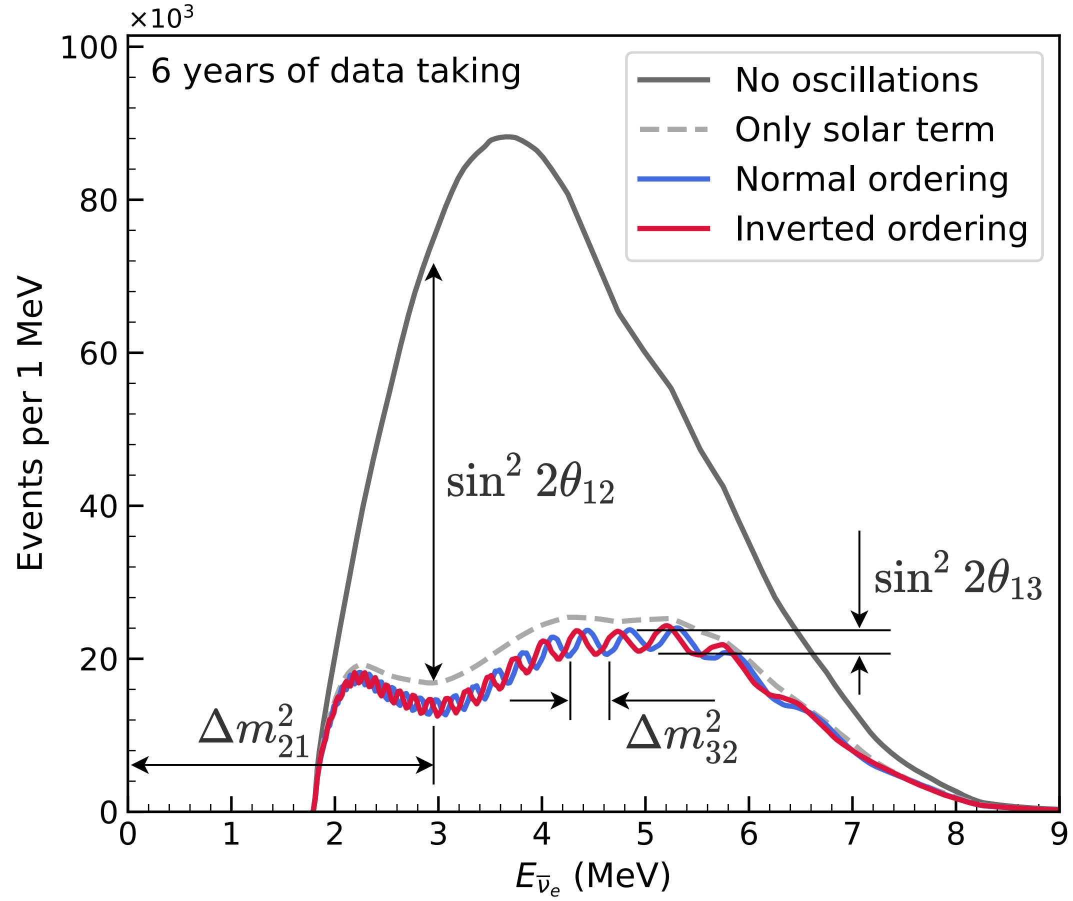
A Multi-Purpose Neutrino Observatory

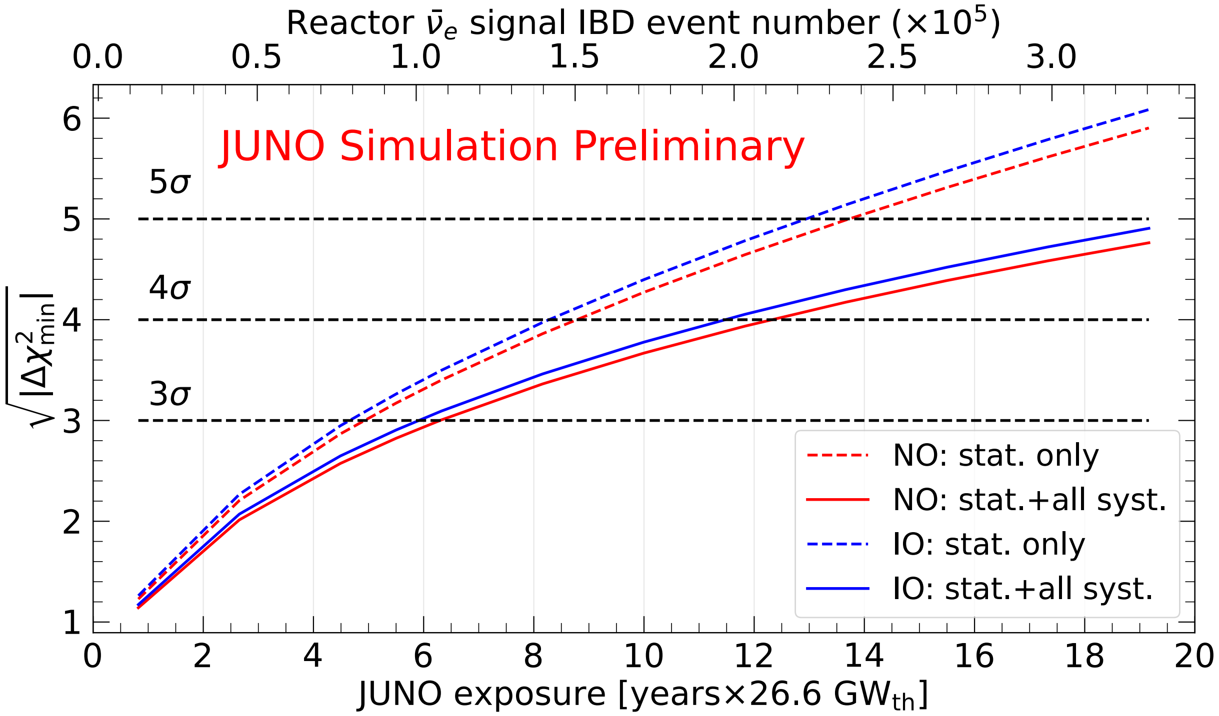


Oscillation Physics with Reactor $\bar{\nu}_e$'s

- The oscillated spectrum contains a wealth of information
- Can determine the neutrino mass ordering (NMO)
  - Exploit interference effects in the fine structure of the oscillated spectrum
  - **3σ** sensitivity within ~6 years
    - Reassessment with full simulation and updated inputs about to be released
  - Independent of θ_{23} and δ_{CP}
    - Complementary information to that of other experiments
    - Can achieve ~5σ in combination with other experiments (e.g. PRD 101, 032006 (2019), Sci Rep 12, 5393 (2022))

Fitting with the wrong ordering yields the wrong Δm^2_{31} value. Therefore, external constraints can help!





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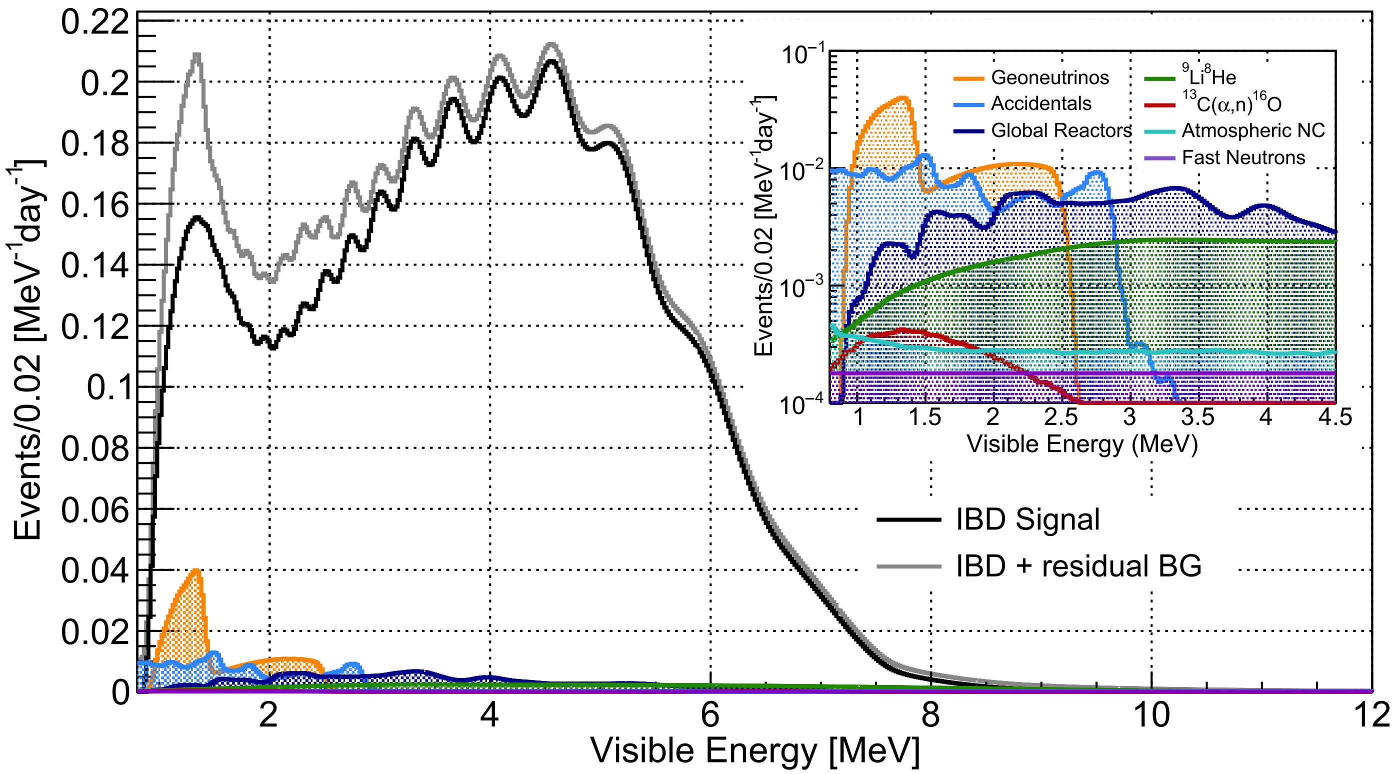
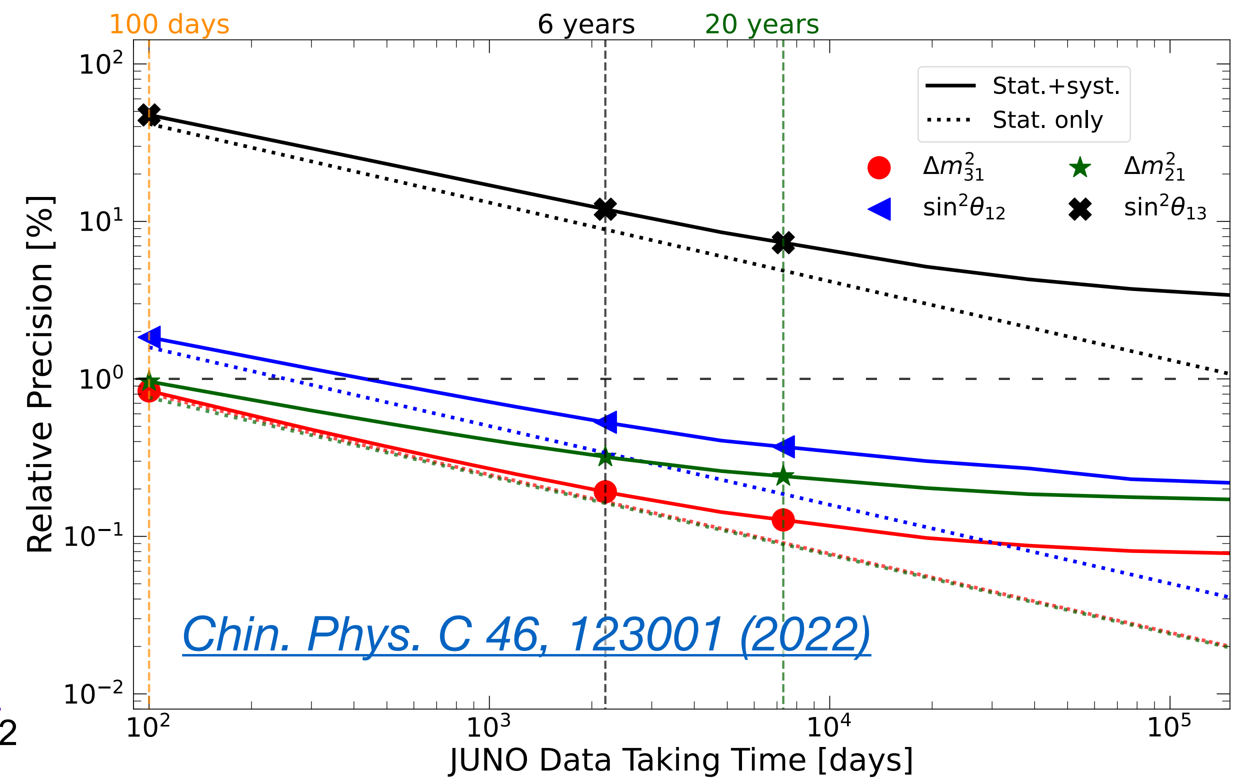
Oscillation Physics with Reactor $\bar{\nu}_e$'s

- JUNO will also measure $\sin^2\theta_{12}$, Δm^2_{21} and Δm^2_{31} to better than 0.5% in 6 years





- Important input for the neutrino community:
  - New era of precision for neutrino mass & mixing models
  - Model independent tests of the three-neutrino oscillation framework (U_{PMNS} unitarity tests)
  - Narrow down parameter space for $0\nu\beta\beta$ searches

Parameter	$\sin^2\theta_{12}$	Δm^2_{21}	Δm^2_{32}	$\sin^2\theta_{13}$
Current Precision*	4.2%	2.4%	1.5%	3.2%
JUNO 6 years	0.5%	0.3%	0.2%	12.1%

* from PDG 2020

Roughly one order of magnitude improvement over existing precision for 3 parameters!

Sub-percent precision in $\sin^2 2\theta_{12}$ and Δm^2_{21} already within ~1 year of data-taking

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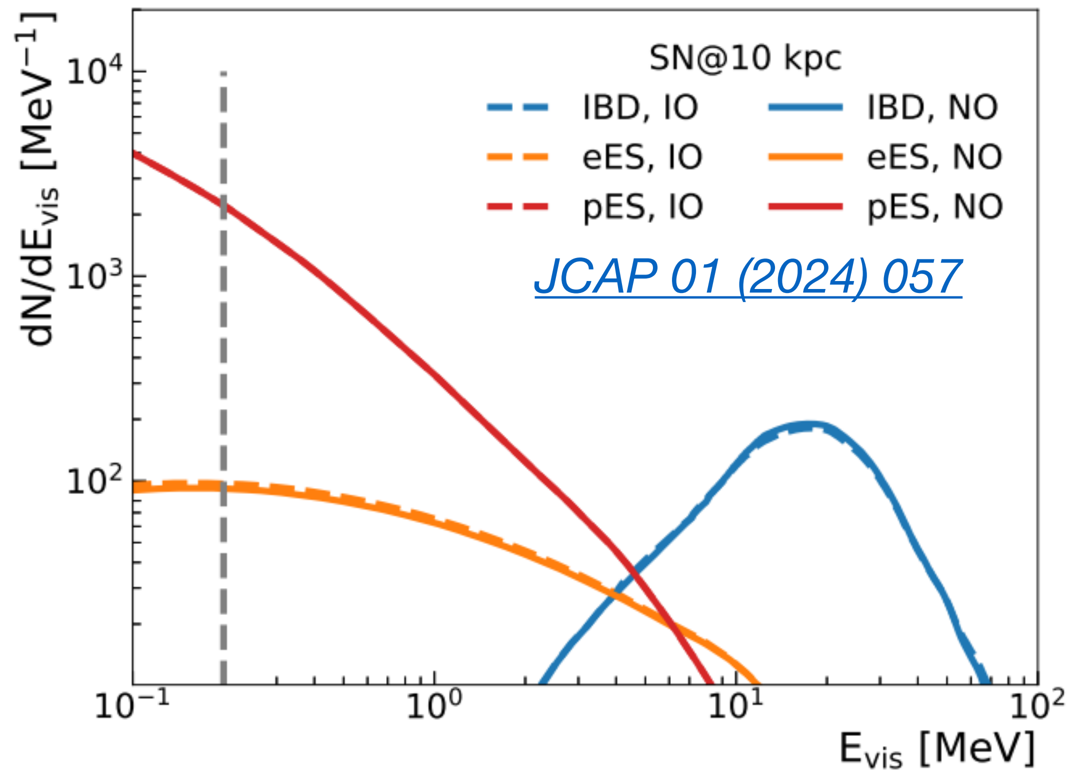
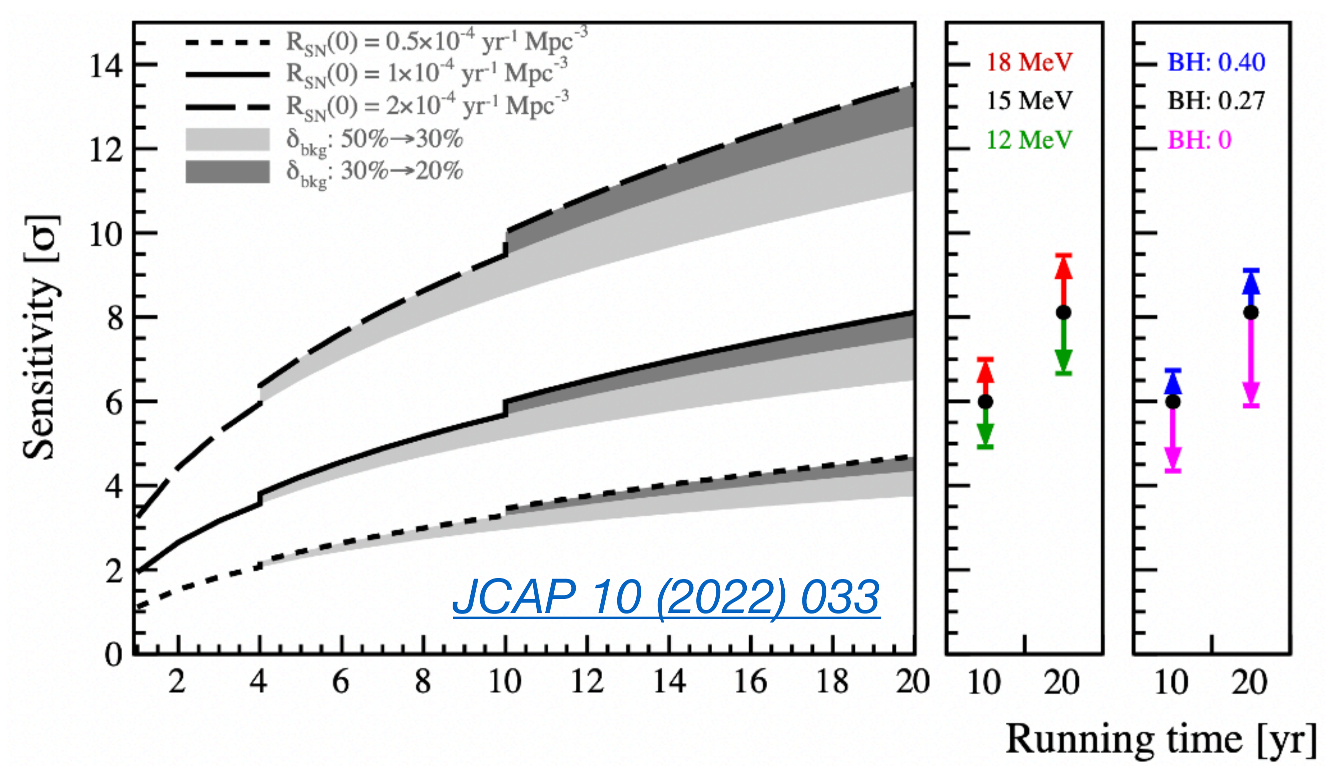
Supernova (SN) Neutrinos

- Able to determine flavor content, energy spectrum and time evolution of supernova (SN) burst neutrinos
  - 10^4 detected events (5000 IBDs) for SN @ 10 kpc
  - 3 detection channels sensitive to all flavors, low threshold ~0.2 MeV
  - Sensitivity to pre-SN neutrinos up to ~1.6 (0.9) kpc for normal (inverted) ordering
- Also sensitive to diffuse SN neutrino background (DSNB)
  - Expected detection significance of 3σ after ~3 years of data for nominal model
  - Provide leading constraint if DSNB is not observed



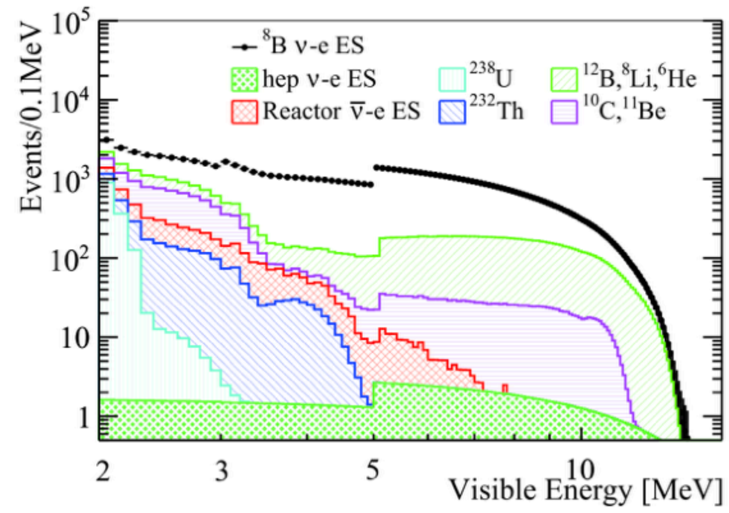


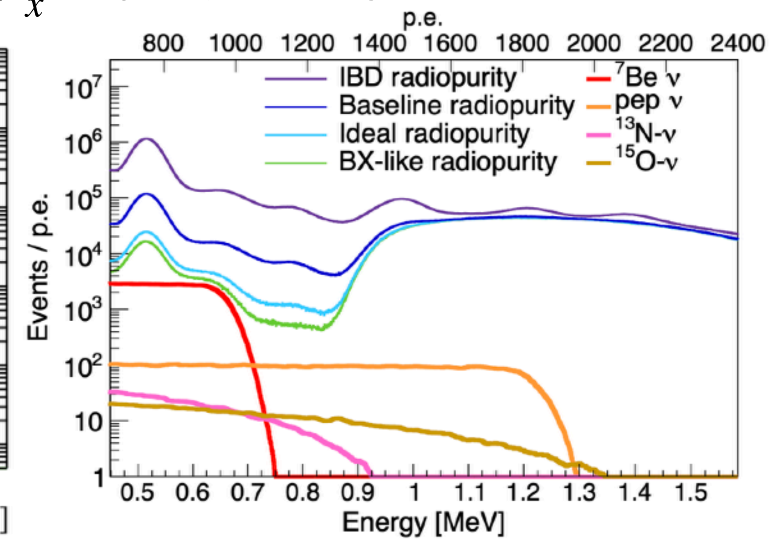
Solar Neutrinos

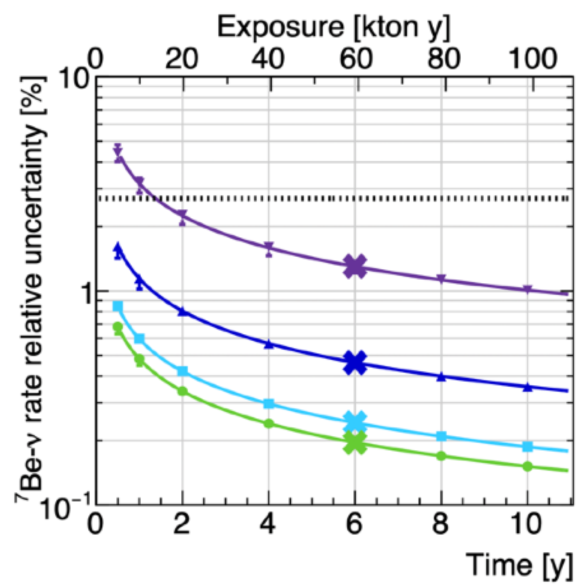
CPC 45, 023004 (2021) and arXiv:2303.03910 (accepted by JCAP)

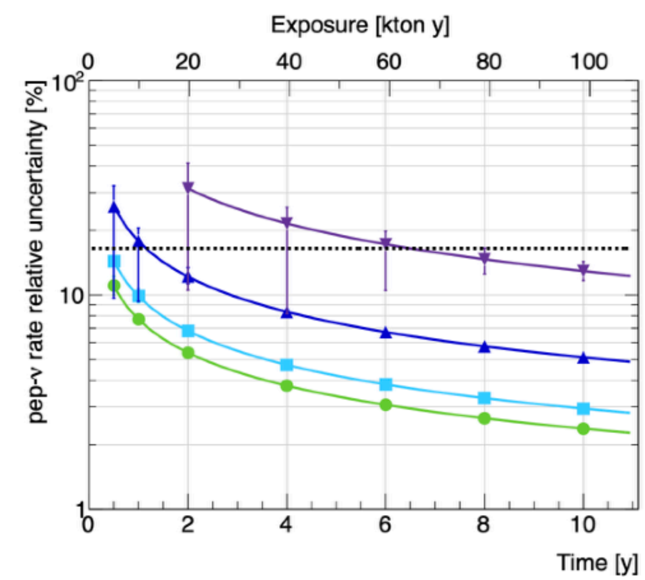
$\nu_x + e^- \rightarrow \nu_x + e^-$ channel

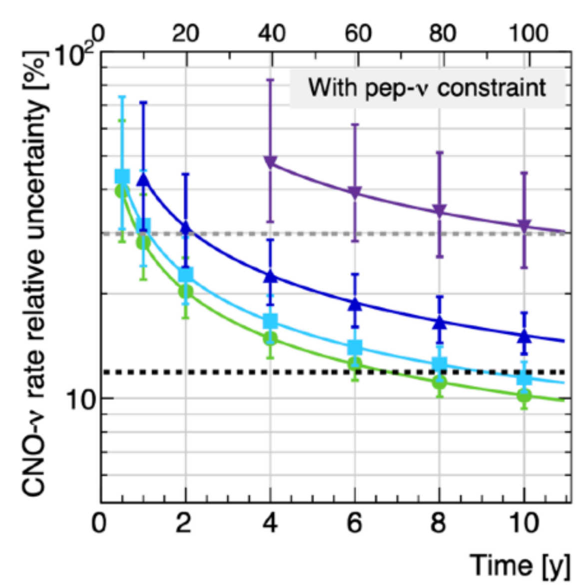
- Solar neutrinos in JUNO:
  - Unique assets:
    - Large size, low threshold, and high resolution
  - Main challenge: radiogenic and cosmogenic backgrounds
  - Will collect large sample of ^{8}B neutrinos
    - Flux measurement in CC, NC and ES channels with 5% precision (3% with SNO) in 10 years
    - Day night asymmetry (2-3σ in 10 years)
    - Measure osc. parameters with solar and reactor neutrinos in the same detector
  - Good sensitivity to solar neutrinos below 1.5 MeV (^{7}Be, pep and CNO)
    - Reach depends strongly on scintillator radiopurity











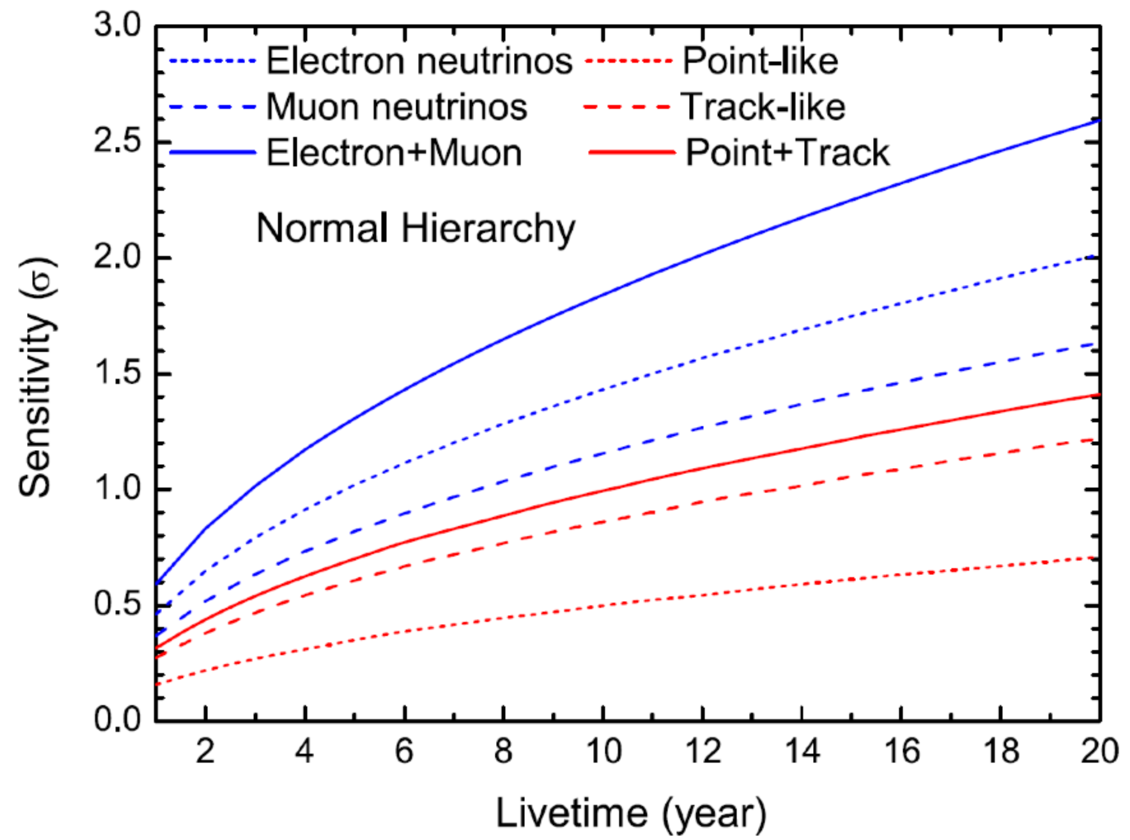
Different radiopurity scenarios:

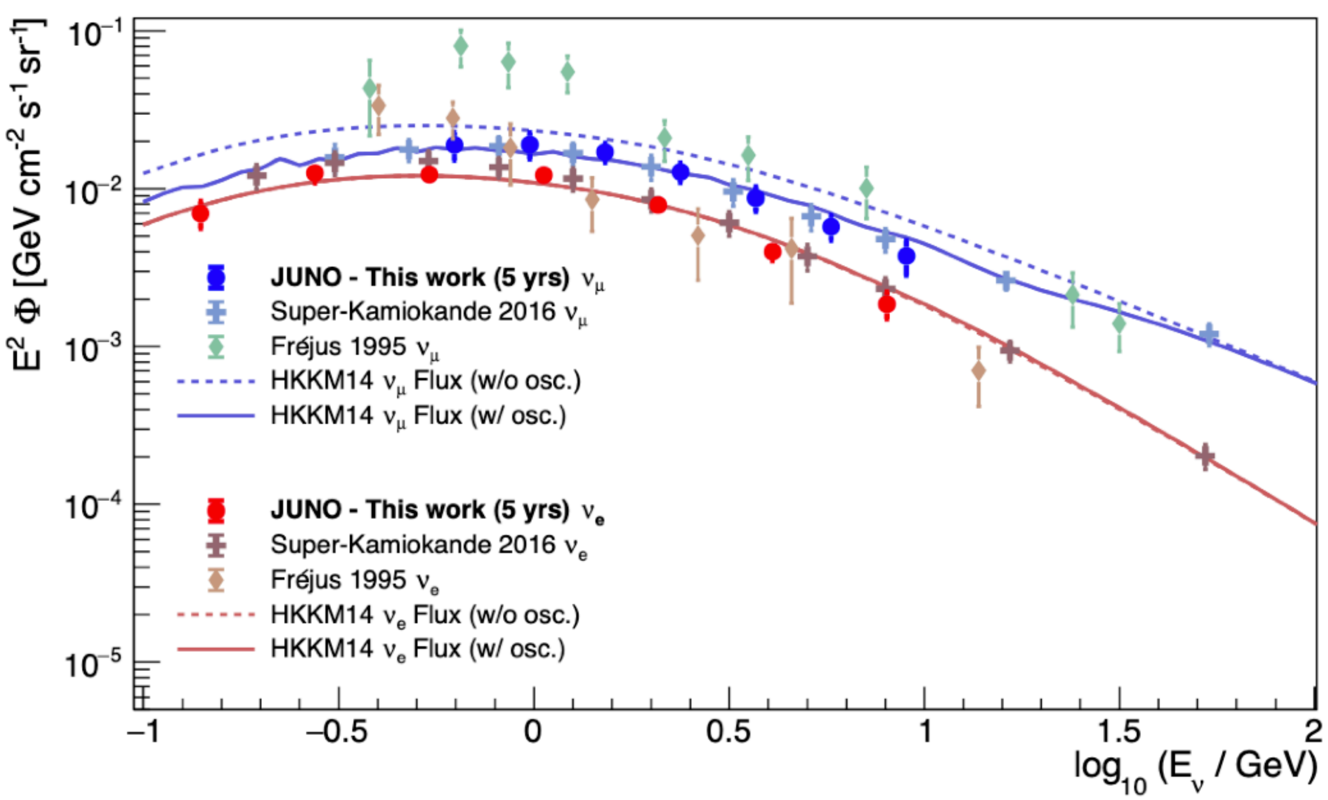
- min. requirement for NMO
- 10 x Borexino Phase-I
- Borexino Phase-I
- Borexino Phase-III (U/Th 10^{-17} g/g)

(dashed horizontal lines are the Borexino results)

Atmospheric Neutrinos

- Some oscillation information:
  - Independent measurement of NMO via matter effect
    - Complementary information to that from reactor antineutrinos
    - ~1σ sensitivity in 6 years
  - Significant progress on reconstruction and selection
    - Reevaluation of sensitivity in progress
- Have good ability to reconstruct atmospheric neutrino spectrum
  - Very good performance in "low energy" region (100 MeV - 10 GeV)
  - Provide important constraints to models





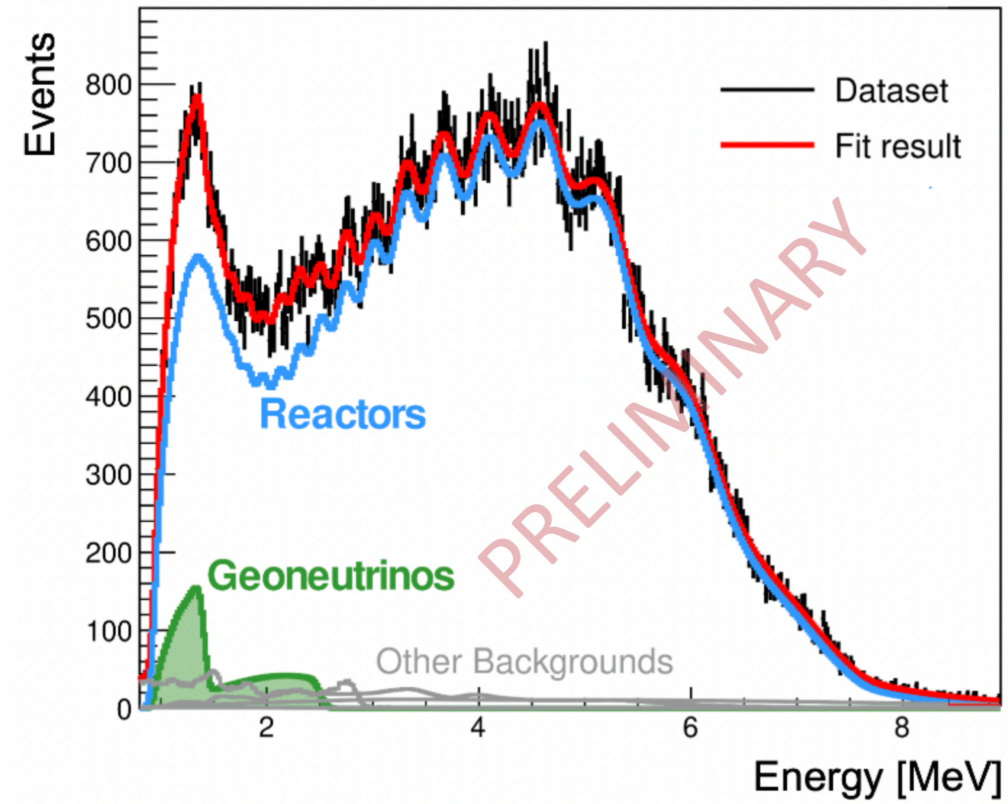
J Phys G 43, 03041 (2016), Eur Phys J C 81, 887 (2021)

Geoneutrinos and Nucleon Decay

- With 1-2 events per day, will collect largest sample of geoneutrinos in ~1 year
  - Precision of ~8% in 10 years with fixed Th/U mass ratio (current precision from KamLAND and Borexino is 15% and 17%, respectively)
  - Precision of U and Th components:

^{232}Th	~35%
^{238}U	~30%
^{232}Th+^{238}U	~15%
^{232}Th/^{238}U	~55%

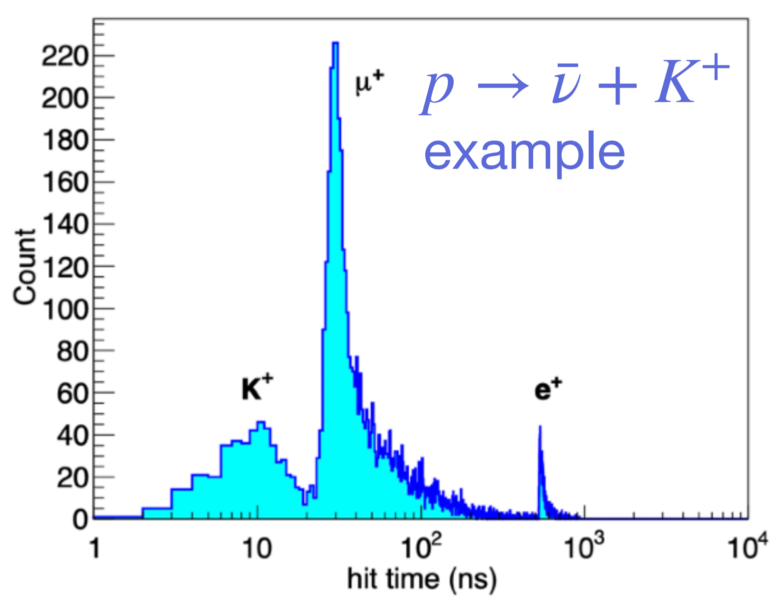
PRELIMINARY

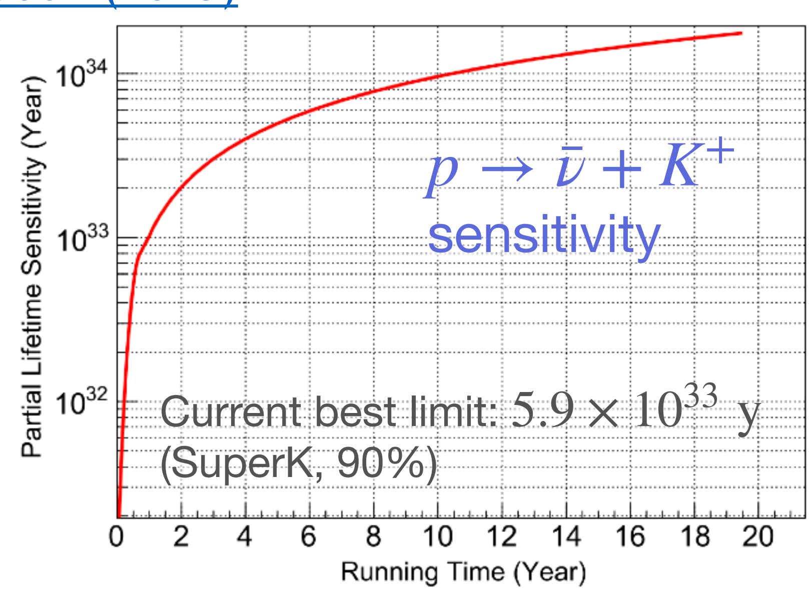


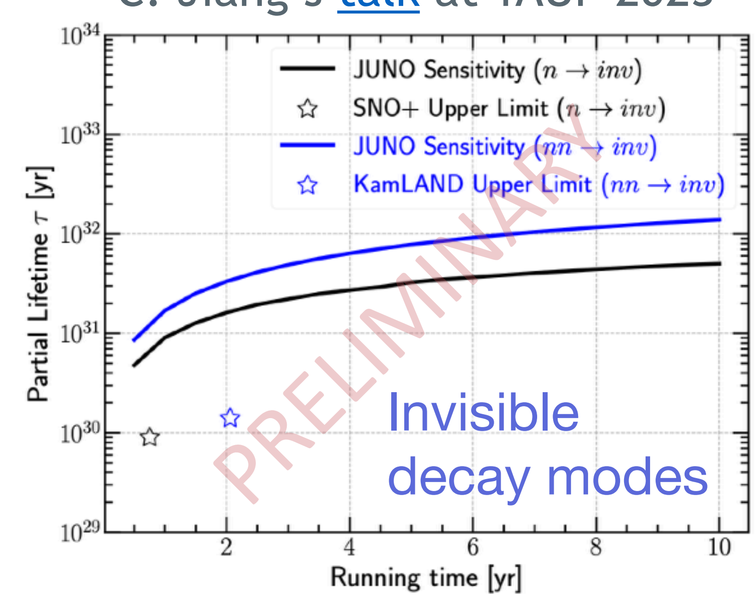
- Competitive sensitivity to nucleon decay, particularly in modes where LS enables triple coincidence

CPC 47, 113002 (2023)

C. Jiang's talk at TAUP 2023







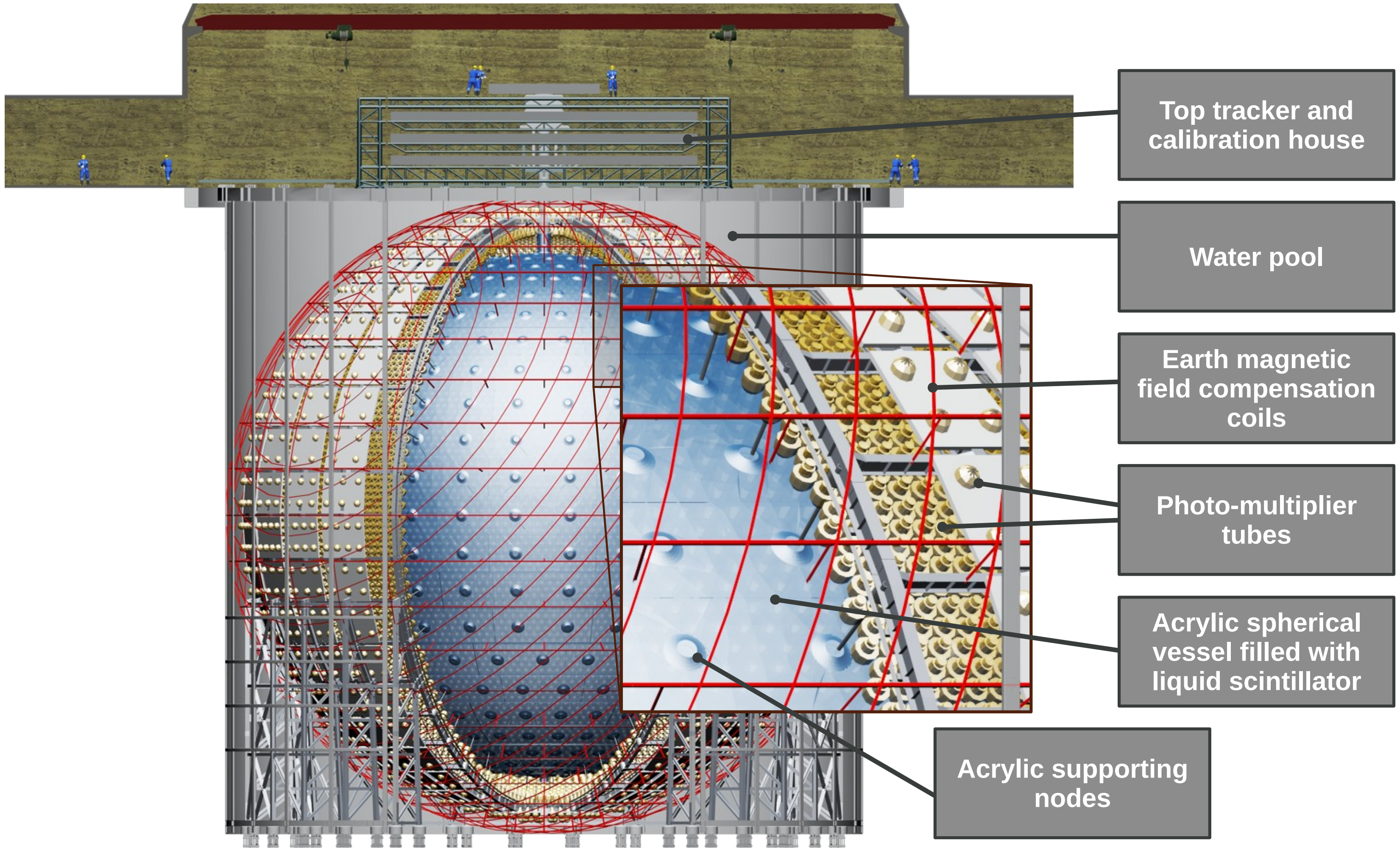
Design & Status

Overview of the Project

Detector Concept

- Keys to fulfilling the physics goals:

  - Optimal baseline
  - High statistics
  - Superb energy resolution
  - Excellent control of energy response systematics
  - Background reduction

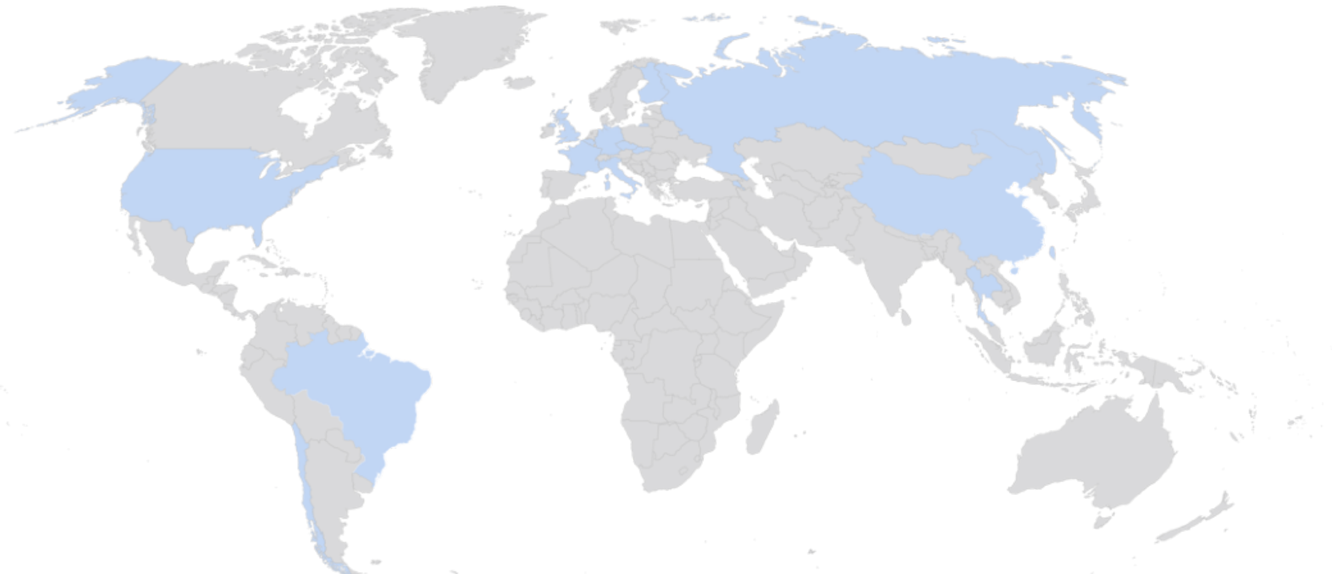


Similar concept to previous LS experiments, but much **LARGER** and **MORE PRECISE**

LS Detectors	Target mass
Daya Bay	**20 t x 8**
Borexino	**300 t**
KamLAND	**1 kt**
JUNO	**20 kt**

JUNO Project

- Collaboration established in 2014
- Now > 700 collaborators from 74 institutions in 17 countries/ regions



Civil Construction

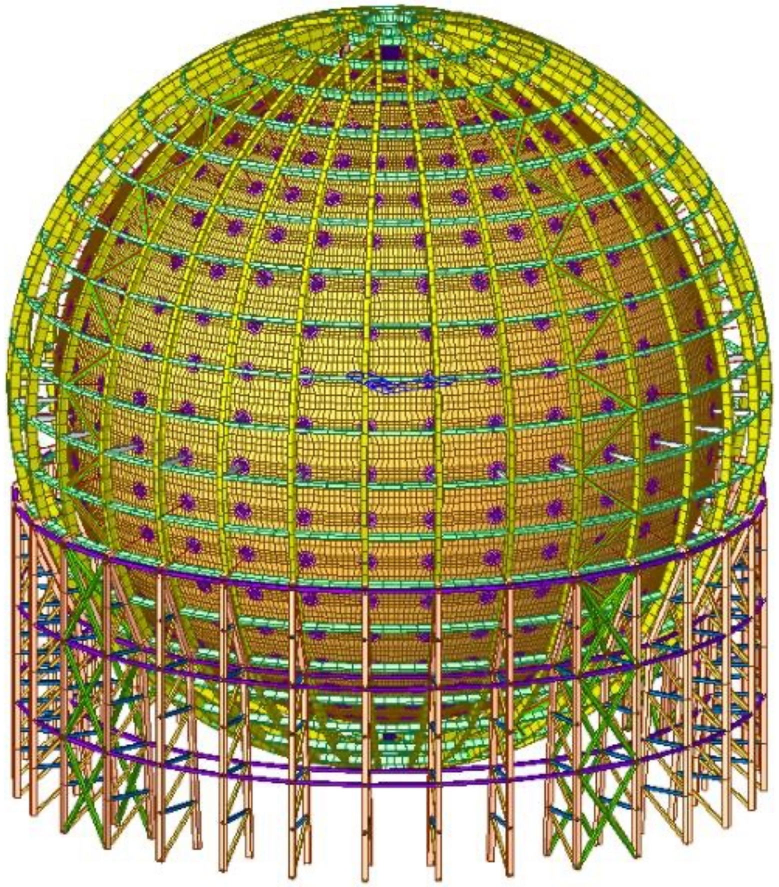
- Civil construction started in 2015, completed in 2021
- Challenging operation:
  - 650 m overburden
  - Saw more water than anticipated
- Have our own campus with > 200 people

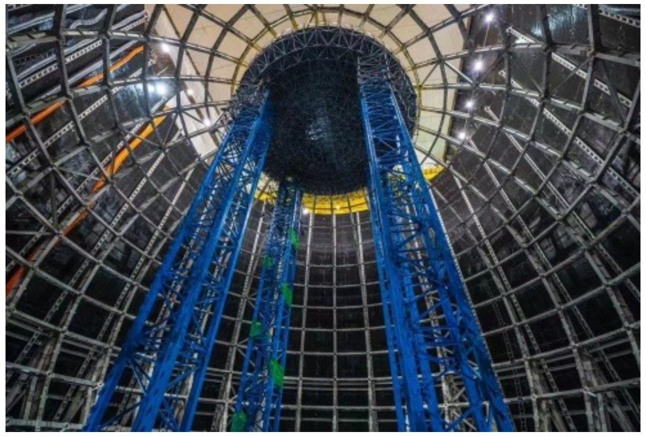
Overview of Installation Process

Central Detector (CD)

arXiv:2311.17314

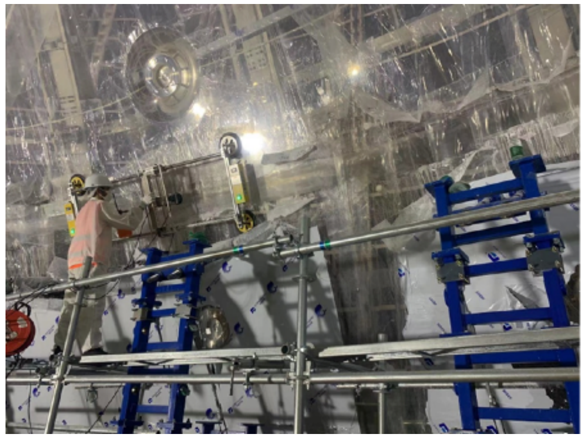
- Use stainless steel (SS) frame to hold acrylic sphere and mount PMTs
  - Fully complete except for bottom 4 layers
- Production of acrylic panels is complete
  - 263 panels in total, 12 cm in thickness
  - Special production line for low backgrounds (< 1 ppt U/Th/K)
- Acrylic sphere construction well underway
  - Built from the top
  - Stainless steel bars connecting acrylic and structure, sensors for stress monitoring
  - 15/23 layers finished and defects repaired



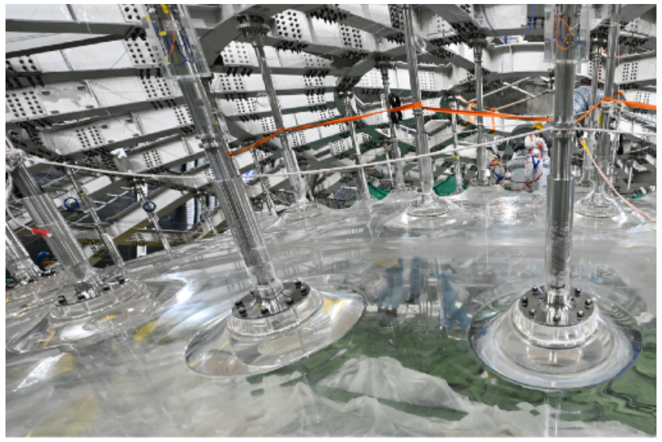


Hydraulic Lifting platform

The first five layers of Acrylic

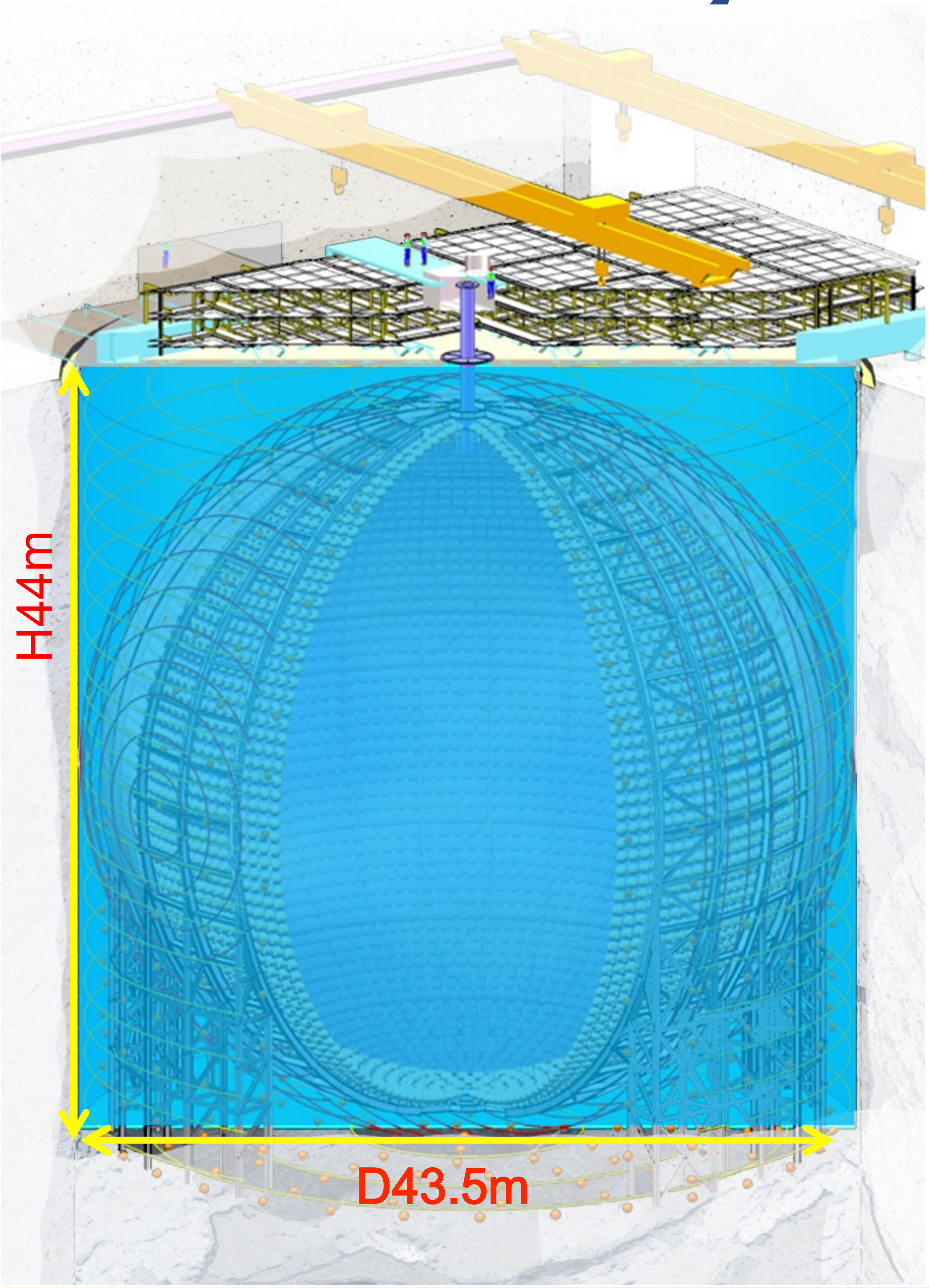


Sanding and polishing



Bars between SS and acrylic

Muon Veto System



- The CD will be immersed in a cylindrical, instrumented water pool:
    - 35 kton ultrapure water with a circulation system (U/Th/K<10^{-14} g/g and Rn<10 mBq/m^3, attenuation length>40 m)

Double-purpose:

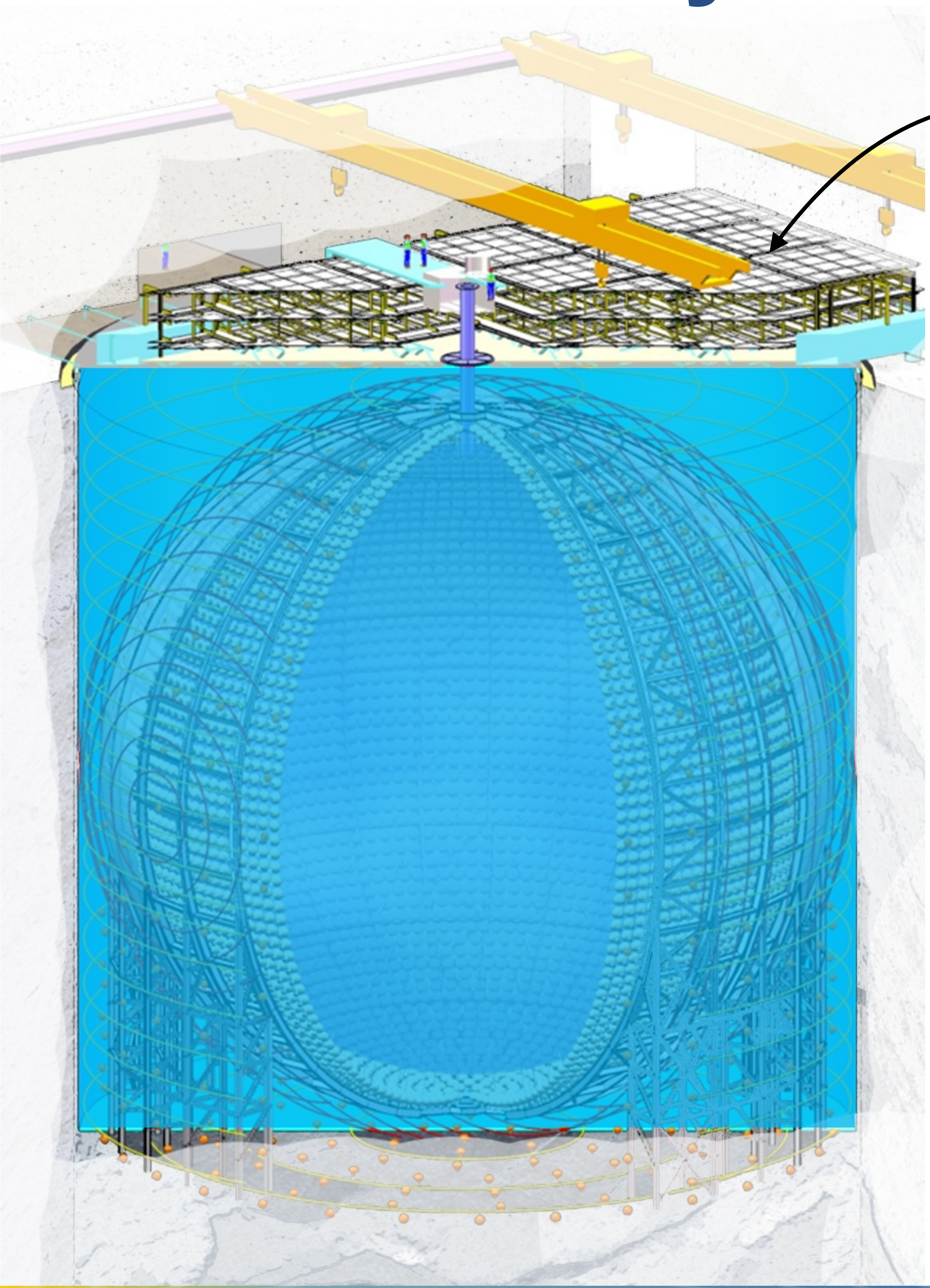
→ Shield central detector against radioactivity from rock and neutrons from cosmic rays

→ Reconstruct and veto cosmic-ray muons

Critical to keeping the cosmogenic backgrounds under control

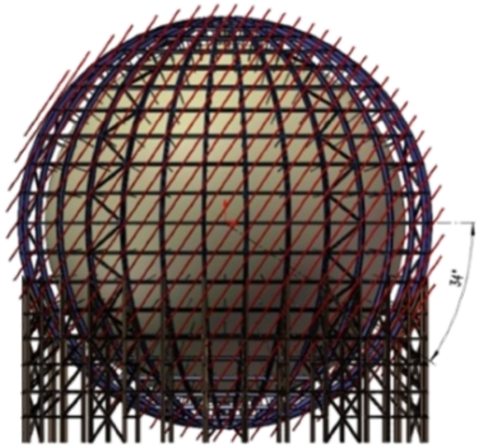
- Some details about the water pool:
    - 2,400 20-inch PMTs
    - 5 mm HDPE lining to stop Rn from rock
    - Detection efficiency expected to be > 99%

Muon Veto System



- The muon veto system will also have a top tracker:
  - 3-layers of plastic scintillators
  - Reuse of OPERA's target tracker

  - About 60% partial coverage
- There will also be a magnetic field (EMF) shielding system



Pushing the Limits

$$\frac{\sigma(E)}{E} = \sqrt{\frac{\sigma^2_{STOCH}}{E} + \sigma^2_{NON-STOCH}}$$

stochastic term: depends on photostatistics

non-stochastic term: residual issues (stability, uniformity, linearity) after calibration

- With 3% @ 1 MeV, JUNO will be the LS detector with the best energy resolution in history

- Most obvious (although not sufficient) requirement for achieving the target energy resolution: **seeing enough photons**.
  - No approach can singlehandedly provide all the light needed. Have to attack the problem from different angles:

	KamLAND	JUNO	Relative Gain
Total light level	**250 p.e. / MeV**	**>1200 p.e. / MeV**	**5**
Photocathode coverage	34%	~78%	~2
Light yield	1.5 g/l PPO	2.5 g/l PPO	~1.5
Attenuation length / R	15/16 m	20/35 m	~0.8
PMT QE×CE	20%×60% ~ 12%	~30%	~2

use KamLAND as reference

target

lots of PMTs

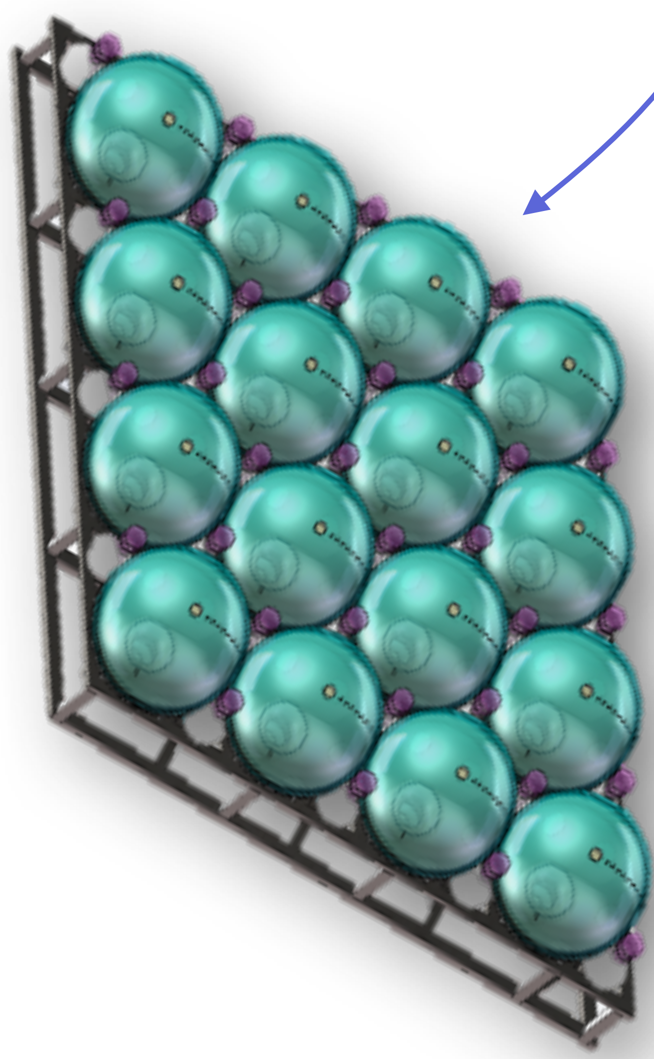
optimized LS

more efficient PMTs

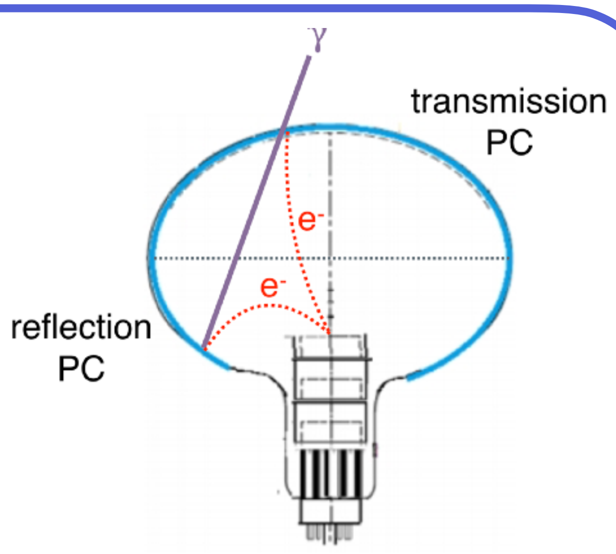
Large PMT System

- JUNO uses large 20-inch PMTs as its main light-detection device:

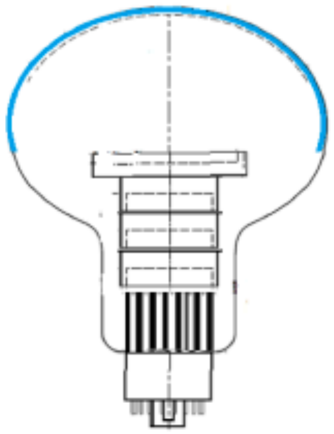
Arranged as tightly as possible, with a clearance of 3 mm



2 complementary (and new!) technologies:



Microchannel plate (MCP)-PMTs



Dynode-PMTs

- Developed for/by JUNO
- Use of transmission + reflection cathodes to increase QE
- Good price
- Mass-produced by NNVT (China)

- R12860 from Hamamatsu
- New type of Super Bialkali photocathode
- Excellent TTS (2.7 ns FWHM)

Both reach QE x CE ~ 30%!

JUNO's central detector uses 13,000 MCP-PMTs and 5,000 Dynode-PMTs

Small PMT System

- JUNO will also have to keep the non-stochastic term of the resolution under control (≲1%)

$$\frac{\sigma(E)}{E} = \sqrt{\frac{\sigma^2_{STOCH}}{E} + \sigma^2_{NON-STOCH}}$$

< 1% never achieved before!

- 25,600 3-inch PMTs will operate predominantly in photon-counting mode:

Basic principle: look at the same events with two sets of "eyes" that have different systematics
(e.g. nonlinearity)

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- The small PMTs also bring other nice benefits to the table:
  - Aid to position reconstruction and muon track reconstruction
  - Aid to supernova neutrino measurement
  - Independent physics (e.g. measurement of solar parameters)
  - Others (a little extra light, larger dynamic range… etc).

XP72B22

HZC PHOTONICS

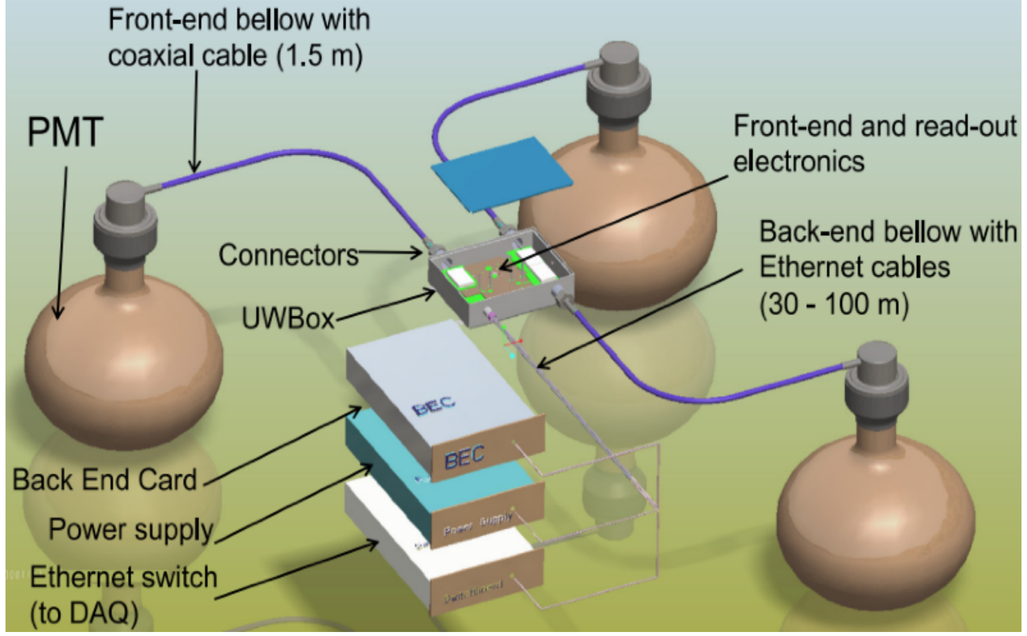
A custom design for JUNO!

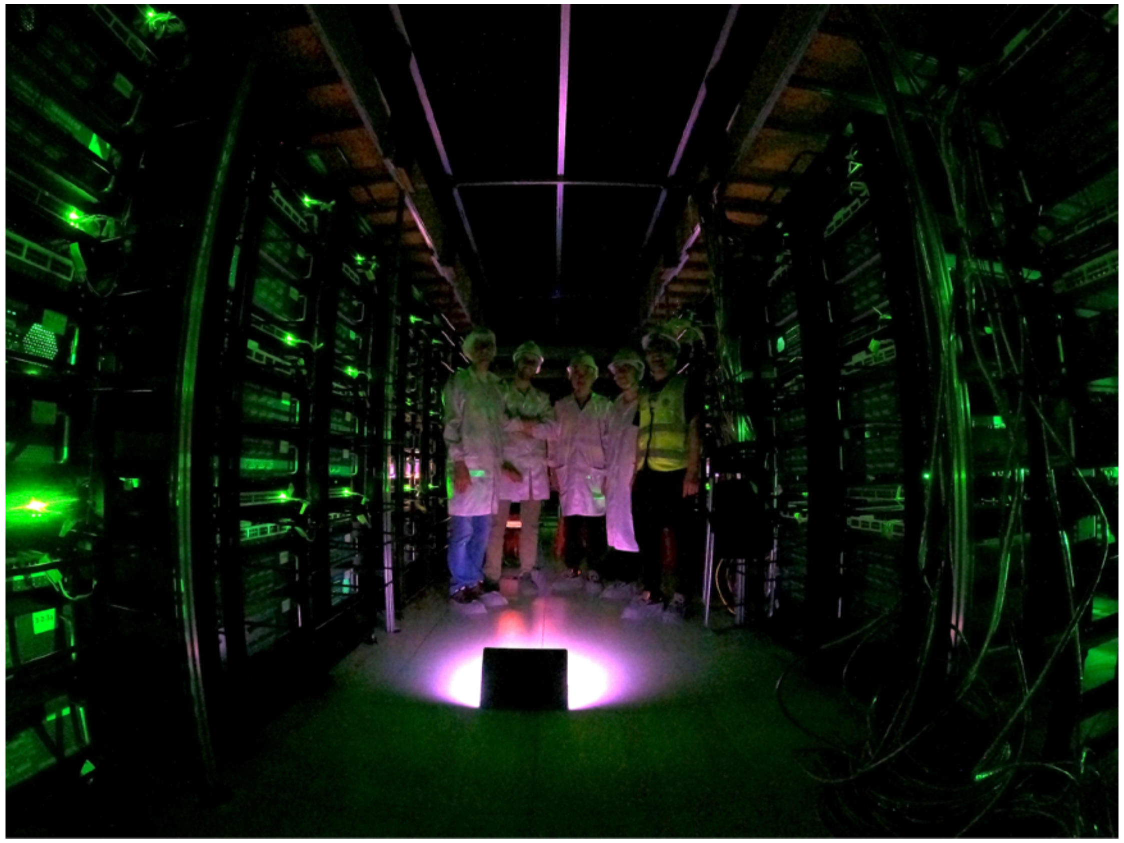
University of California, Irvine

Electronics

- LPMT and sPMT frontend electronics are housed in SS underwater boxes
  - Power the PMTs, decouple signal from HV, process the analog signals and send the information to surface via digital CAT5 cables

LPMT System (3 LPMTs per underwater box)

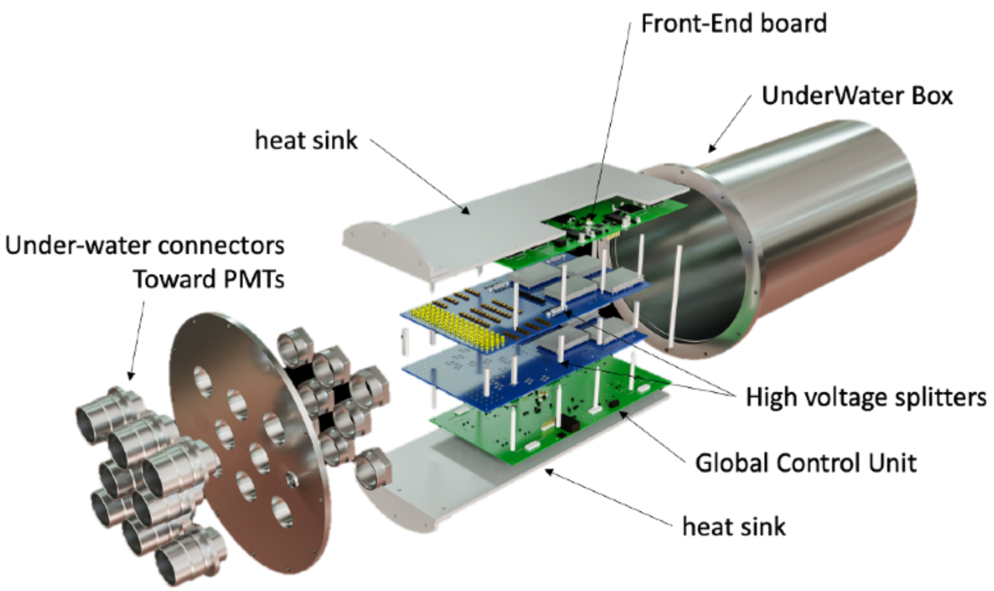




About 2/5 of all PMTs have been installed

Have performed several commissioning dry-runs with lights-off & high-voltage on to ensure integrity of PMTs + electronics after installation

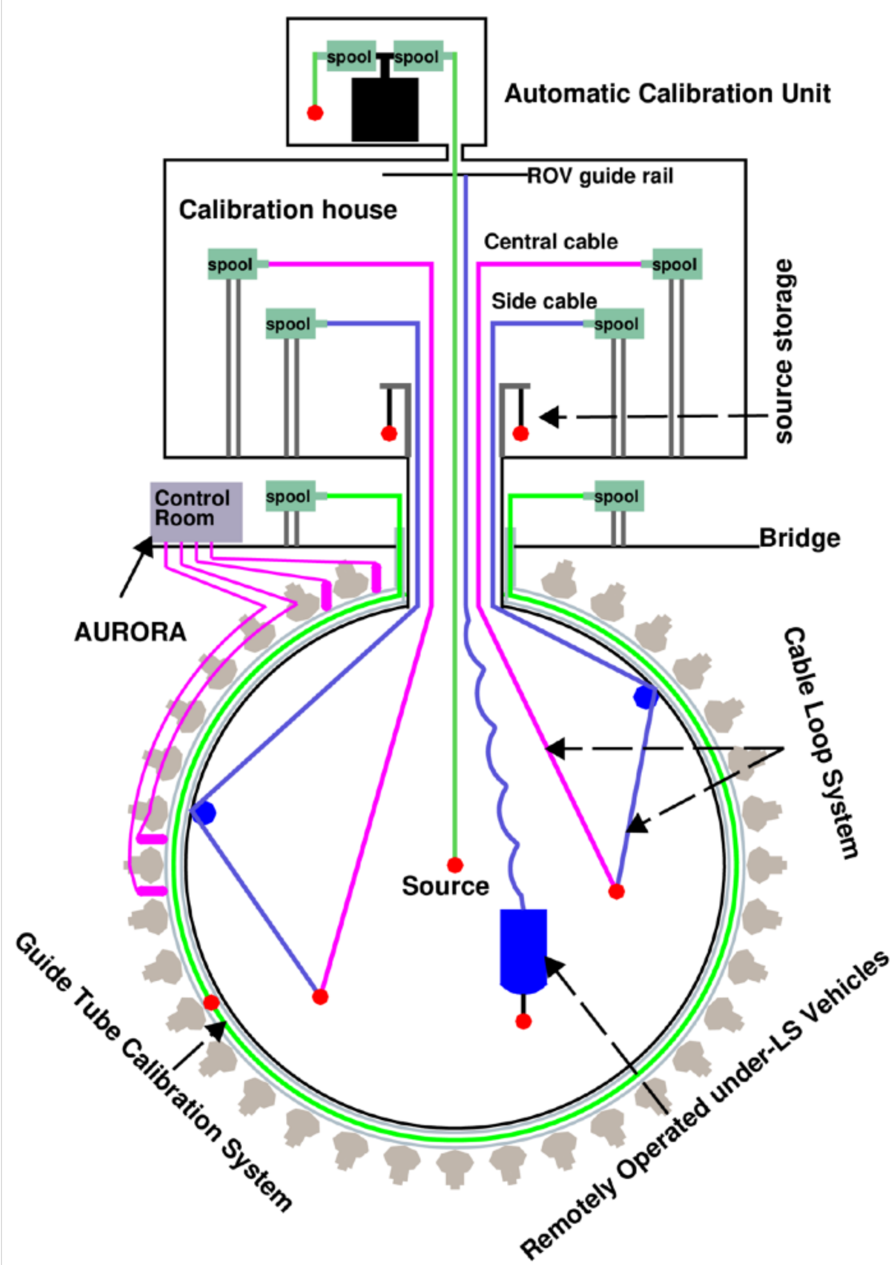
sPMT System (128 sPMTs per underwater box)



Calibration System

- Achieving a light level of 1200 p.e. / MeV is not enough. Also have to **keep the systematics under control**

JHEP 2021, 04 (2021)



- Have an **comprehensive calibration program** consisting of 4 mutually complementary systems:
  - **1D**: Automated Calibration Unit (ACU) deploys radioactive and laser (1ns, keV-TeV range) sources along the central axis
  - **2D**: Cable Loop System (CLS) to scan vertical planes
  - **2D**: Guide Tube to scan the outer surface of the central detector (where the CLS cannot reach)
  - **3D**: Remotely Operated Vehicle (ROV) operating inside the LS to scan the full volume

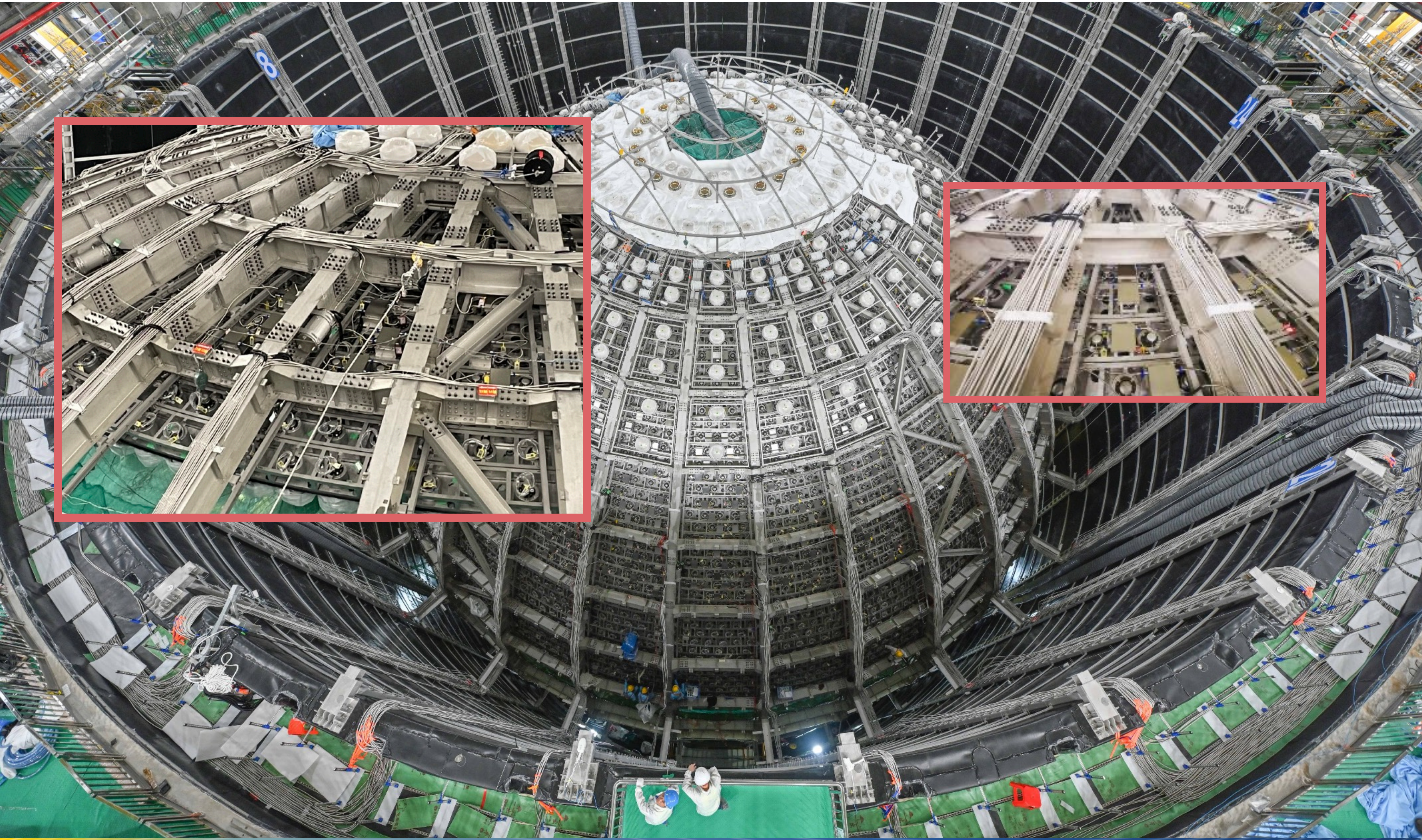
+ sPMT system

Goal is to keep the energy scale uncertainty < 1%

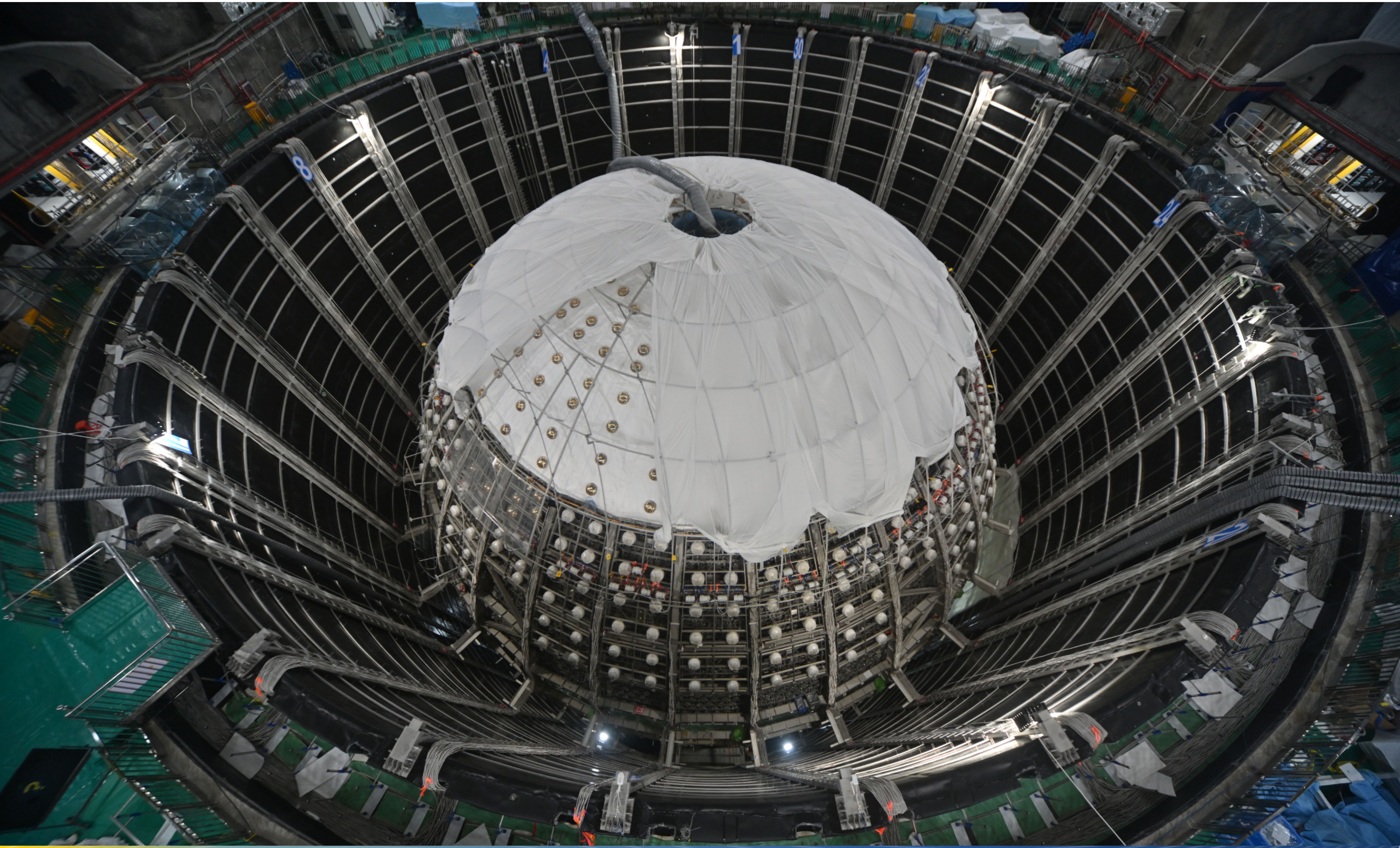
University of California, Irvine

Bird’s Eye View of the Detector

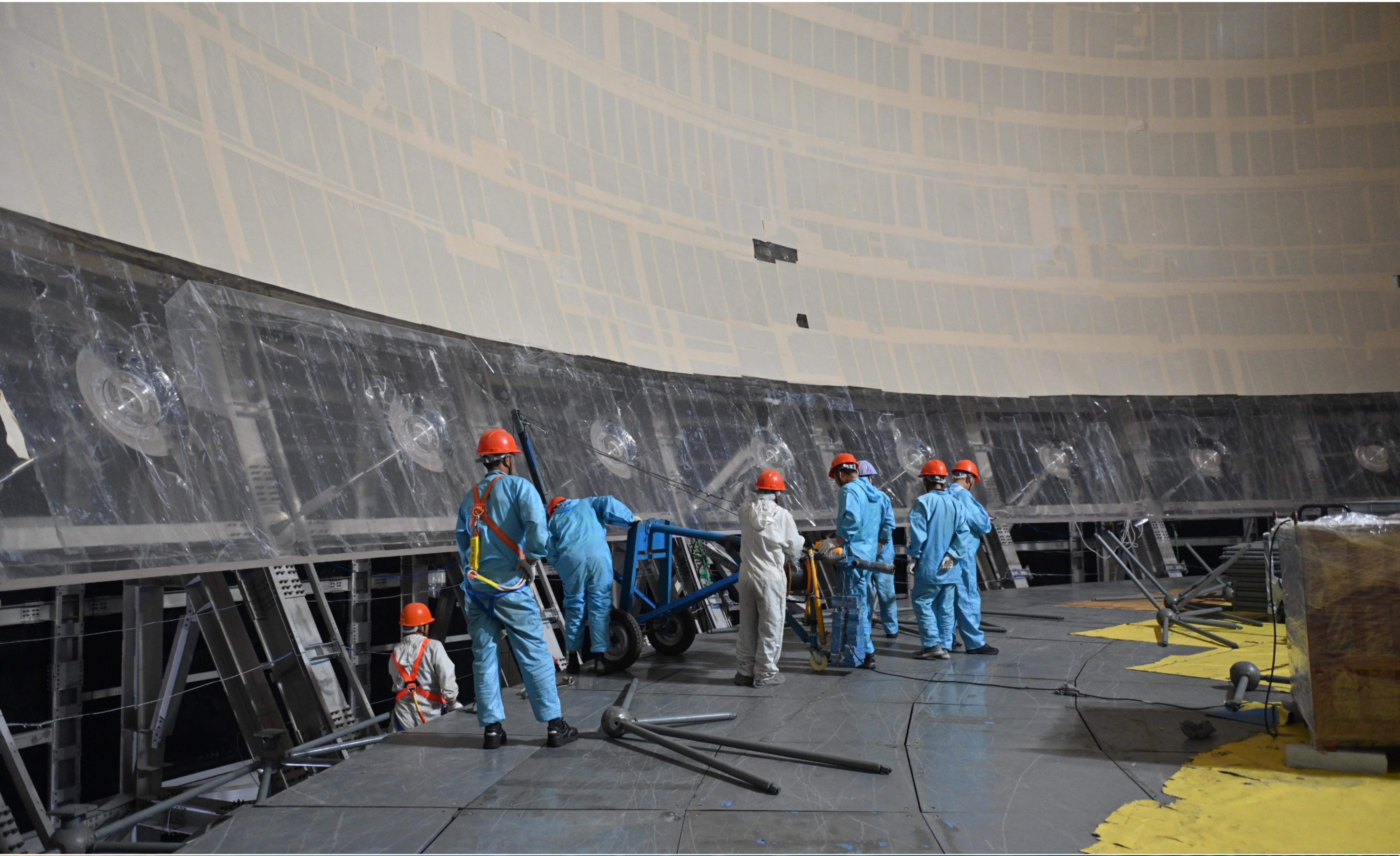
Bird’s Eye View of the Detector



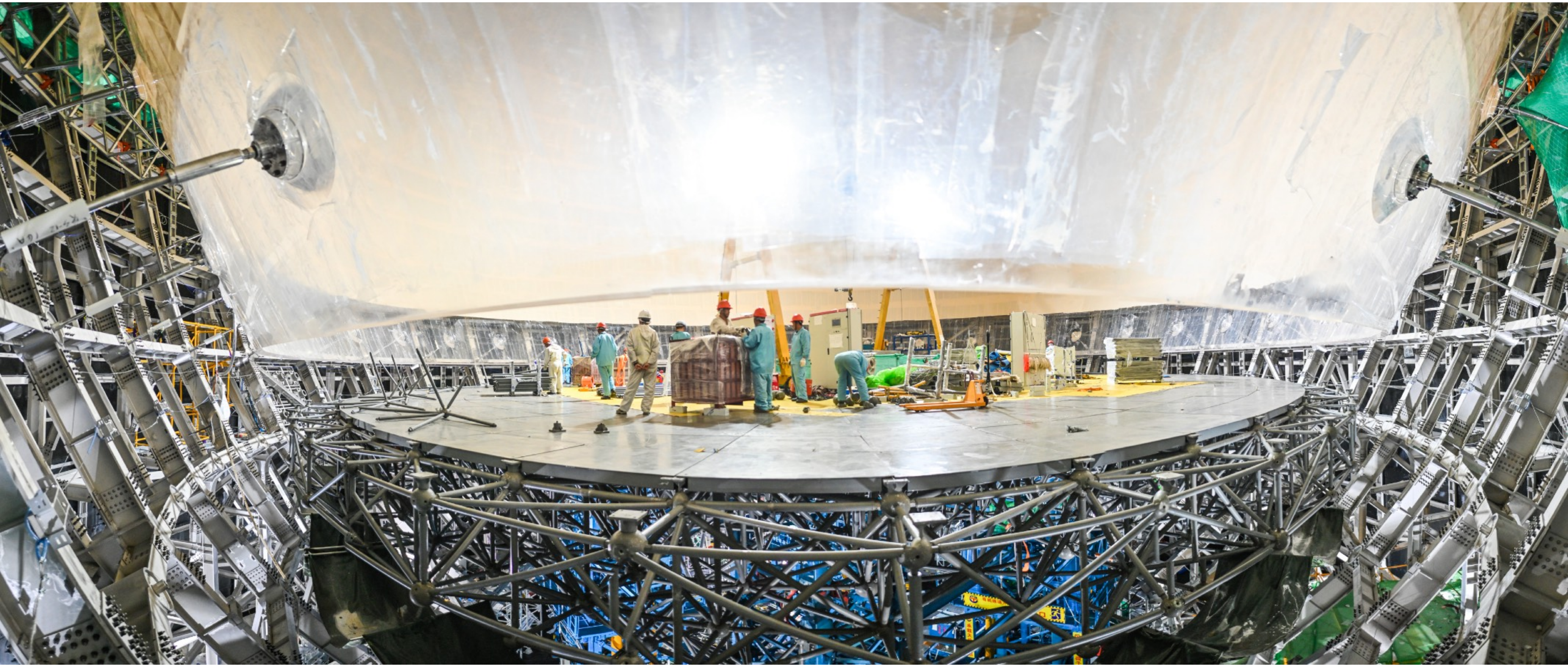
Bird's Eye View of the Detector



Inside the Acrylic Sphere



Inside the Acrylic Sphere



Between the Acrylic and the PMTs

Radiopurity & Cleanliness

- Radiopurity of raw materials stringently controlled:
  - Material screening
  - Production handling

Better than spec by ~15%

- Have achieved good environmental cleanliness
  - Radon concentration below 200 Bq/m³ requirement
  - Cleanliness: class 20,000
  - Very challenging to control cleanliness of such a big volume

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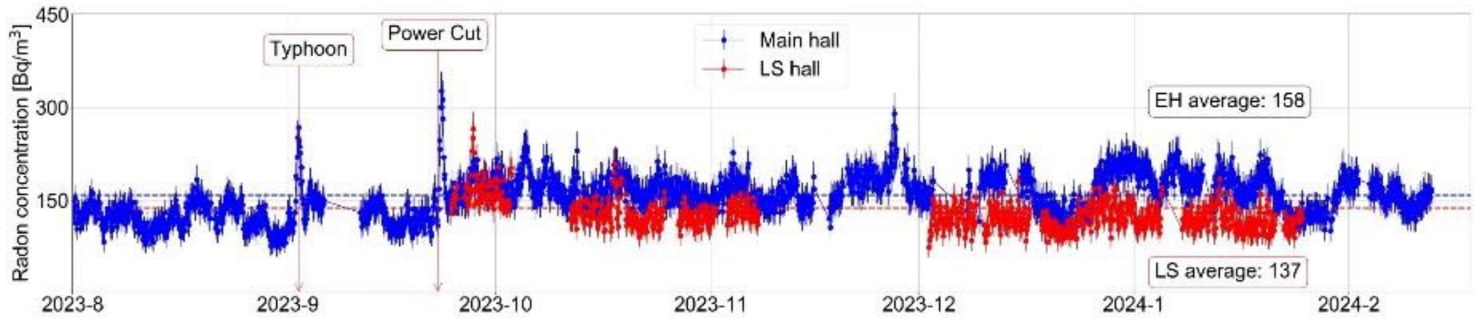
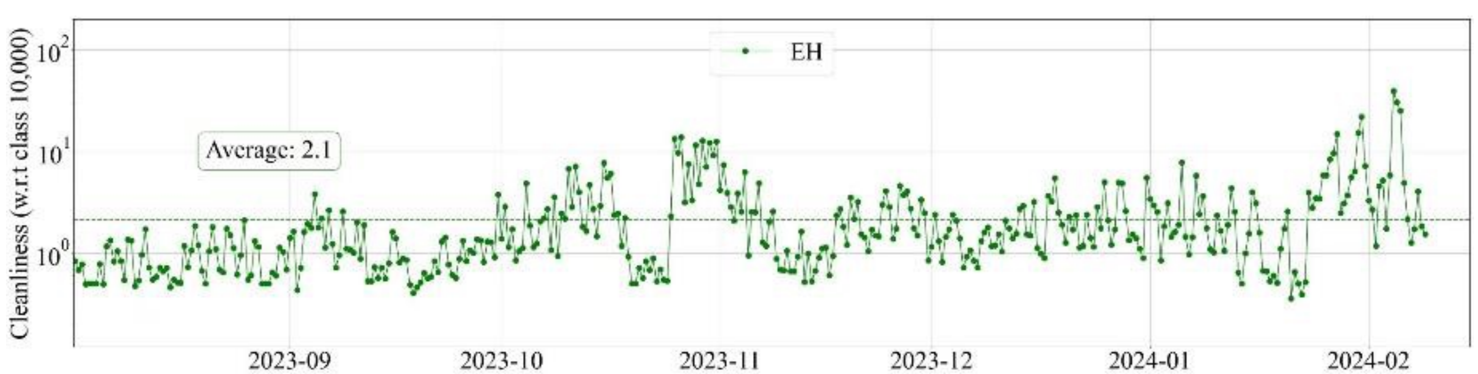
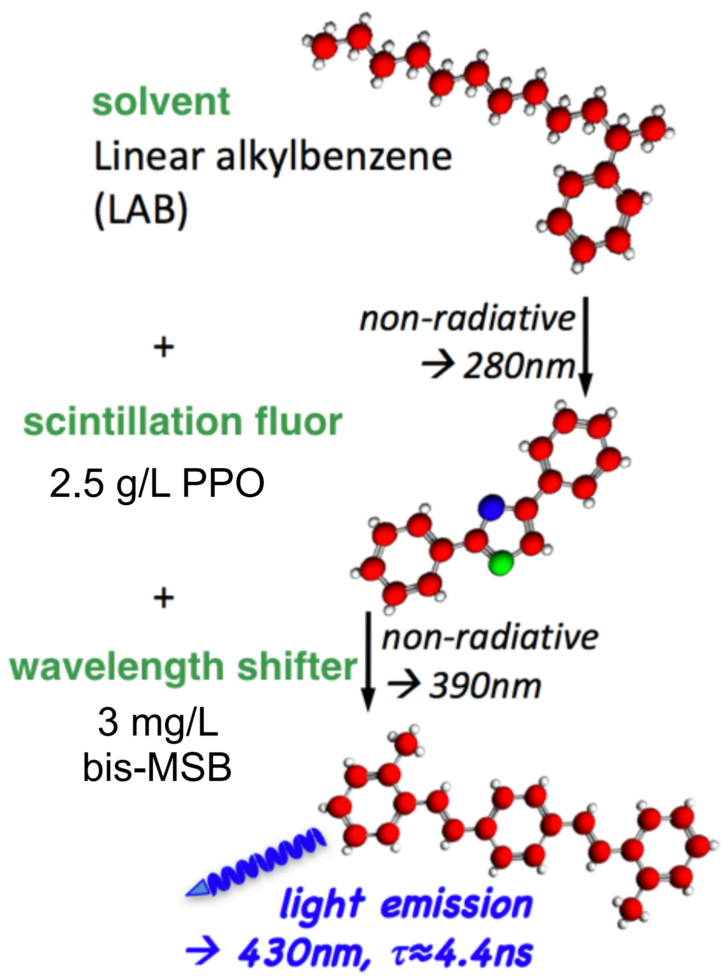
Singles (R < 17.2 m, E > 0.7 MeV)	Design [Hz]	Change [Hz]	Comment
LS	2.20	0	
Acrylic	3.61	-3.2	10 ppt -> 1 ppt
Metal in node	0.087	+1.0	Copper -> SS
PMT glass	0.33	+2.47	Schott -> NNVT/Ham
Rock	0.98	-0.85	3.2 m -> 4 m
Radon in water	1.31	-1.25	200 mBq/m³ -> 10 mBq/m³
Other	0	+0.52	Add PMT readout, calibration sys
Total	8.5	-1.3	





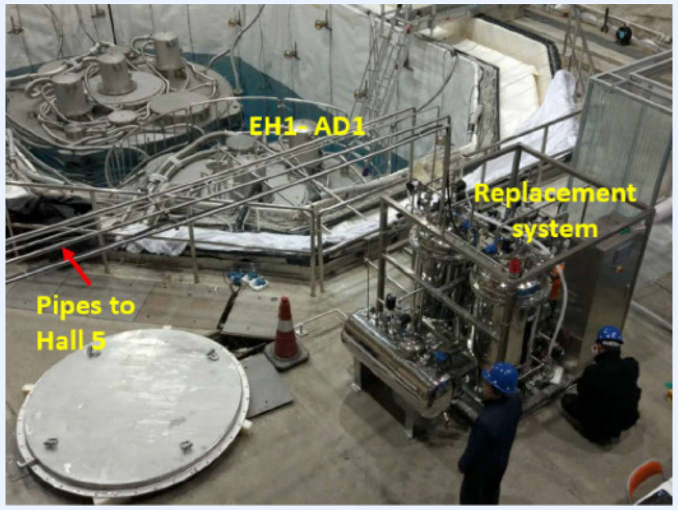
Liquid Scintillator

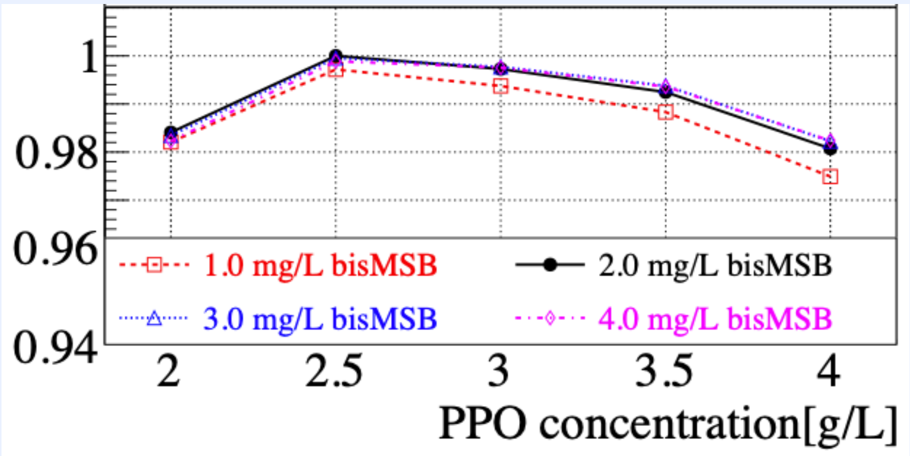
- Main requirements: high light yield, high transparency and high radiopurity
- Using a recipe inspired from Daya Bay's experience



- No doping, large fluor concentration

Recipe optimized with a decommissioned Daya Bay detector whose results were extrapolated to JUNO size using a new optical model





NIMA 998, 164823 (2021)

Recent measurements: LAB attenuation length > 24 m, LS attenuation length > 20 m

LS Production and Purification

- Full chain includes four purification plants, LS mixing, QA/QC equipment, high-purity N_2 and water production systems

5000 m3 LAB storage tank

1) Al_2O_3 for optical transparency

2) Distillation for radiopurity

Mixing LAB with PPO and bis-MSB

1.8 km SS pipes to underground

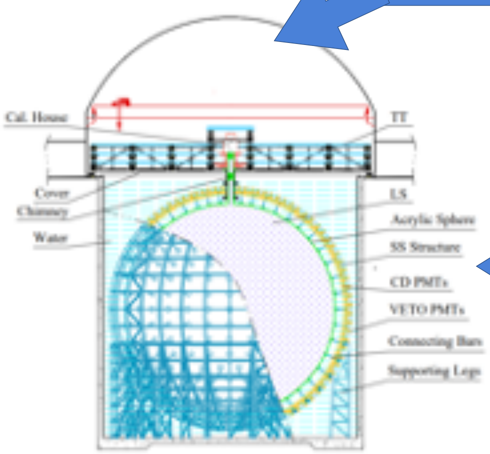
3) Water extraction to remove radioactive impurities

4) Gas stripping to remove Rn and O_2

15%

OSIRIS for LS qualification

85%



JUNO filling

- Recently had a successful commissioning run with all equipment running simultaneously

OSIRIS and Filling Strategy

- Just filled first batch of JUNO LS into OSIRIS pre-detector on March 11

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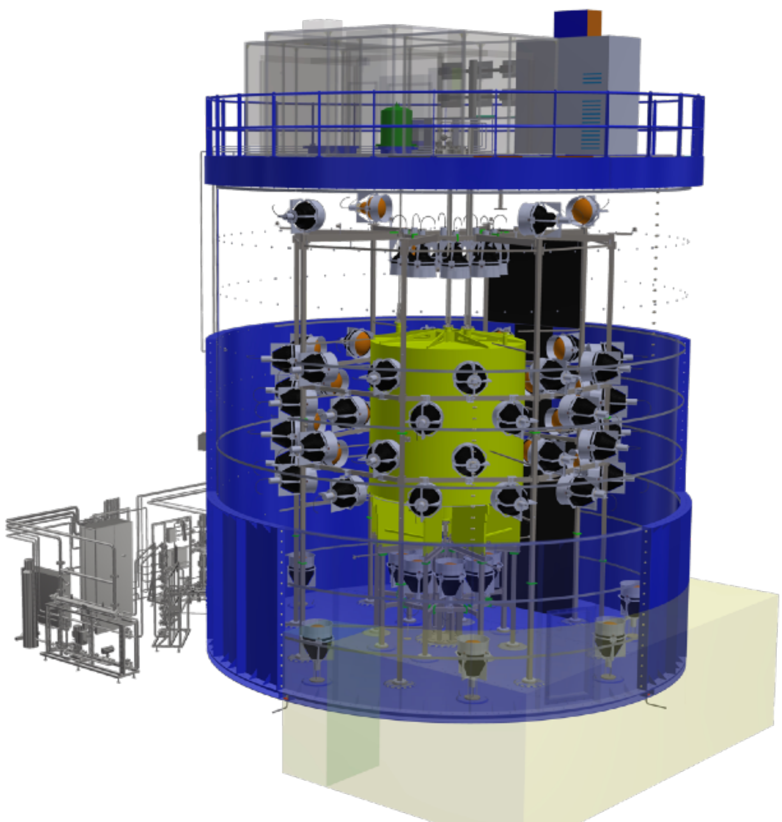
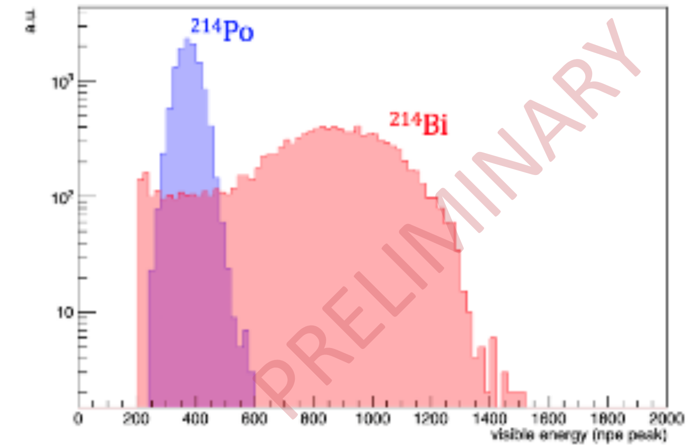
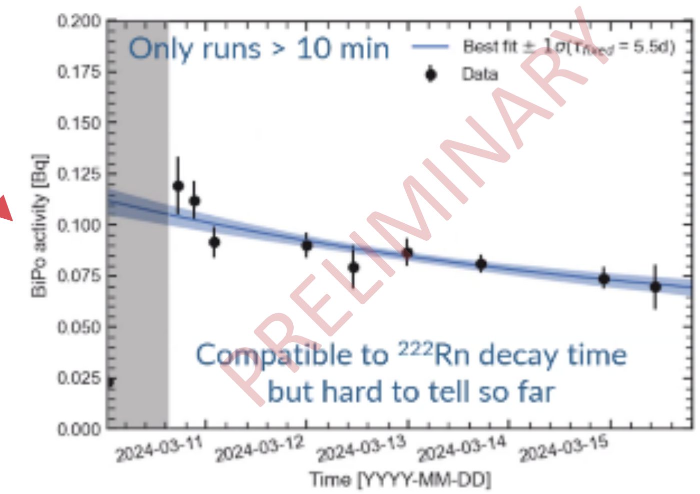


- 3 m x 3 m acrylic vessel, 76 MCP-PMTs, 3m of water shielding
- U/Th estimation by Bi-Po-214 coincidence tagging

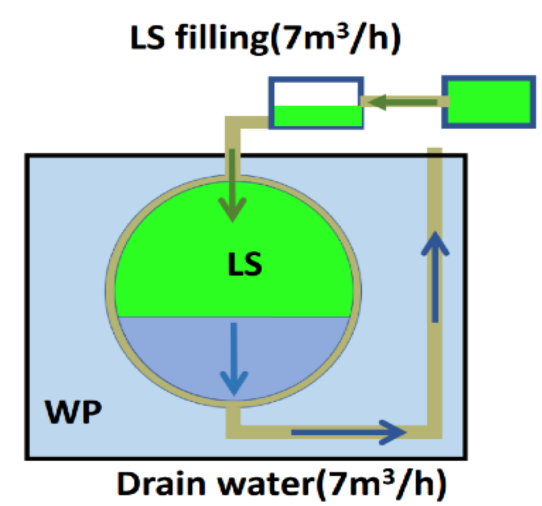
Study in progress; decays dominated by ^{222}Rn

- Analysis for other isotopes (e.g. ^{14}C, ^{210}Po) in progress





- Gearing up for filling as soon as detector installation is complete (this year!)
  - Seal and wait for ~2 weeks (achieve class 1,000)
  - Remove acrylic's protective film and wash with high-pressure water spray
  - Fill with water and then gradually replace acrylic sphere with LS



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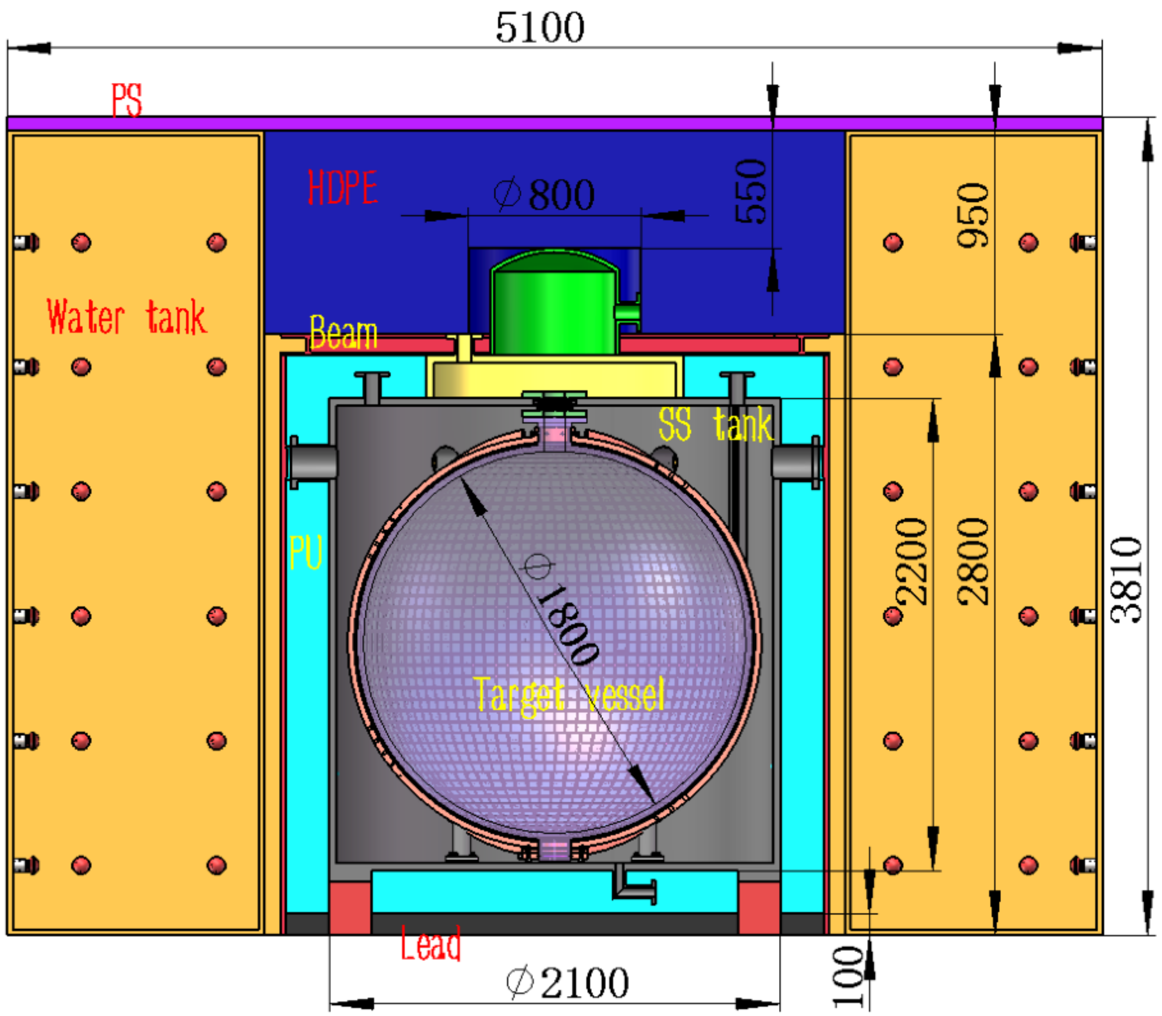
JUNO-TAO

- JUNO will also deploy a satellite detector called TAO (Taishan Antineutrino Observatory)
  - 44 m from a 4.6 GW_{th} reactor
  - 2.8 ton (1 ton fiducial) Gd-LS volume
  - 700k IBDs/year, ~10% background
  - SiPM and Gd-LS at -50°C
  - < 2% @ 1 MeV energy resolution

Main goals: measure the reactor antineutrino spectrum with unprecedented resolution

- Start of operations around the same time as the main JUNO detector



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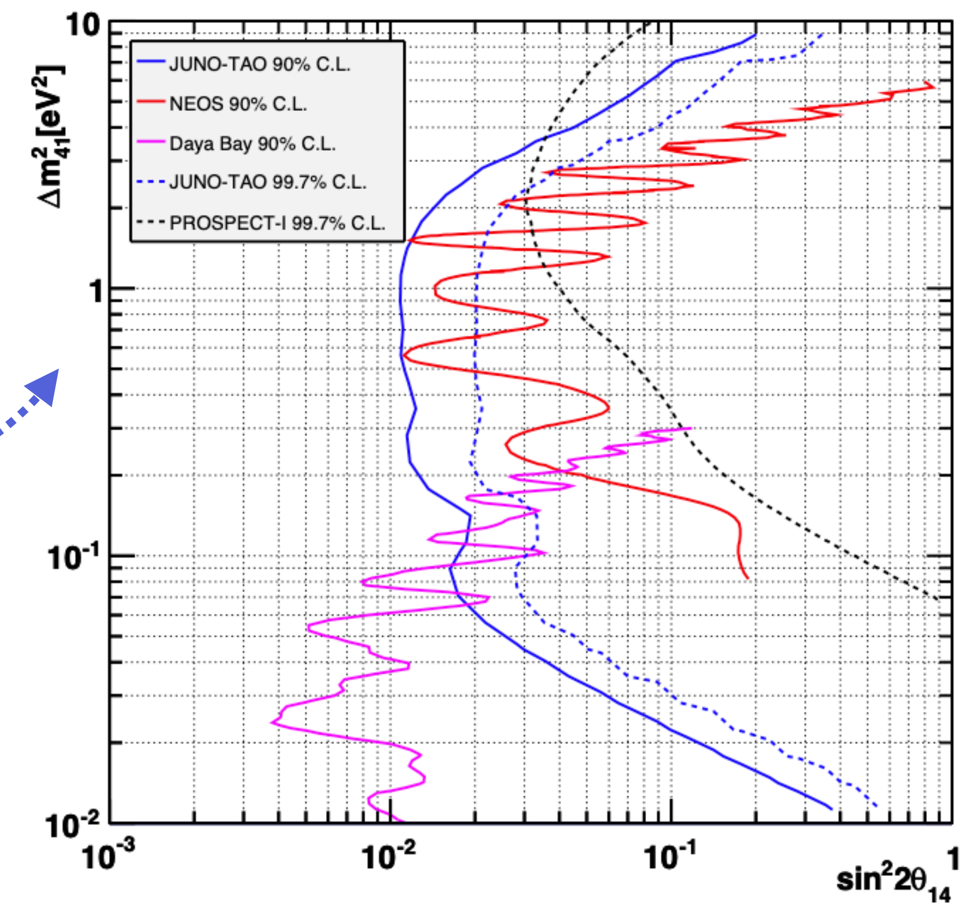
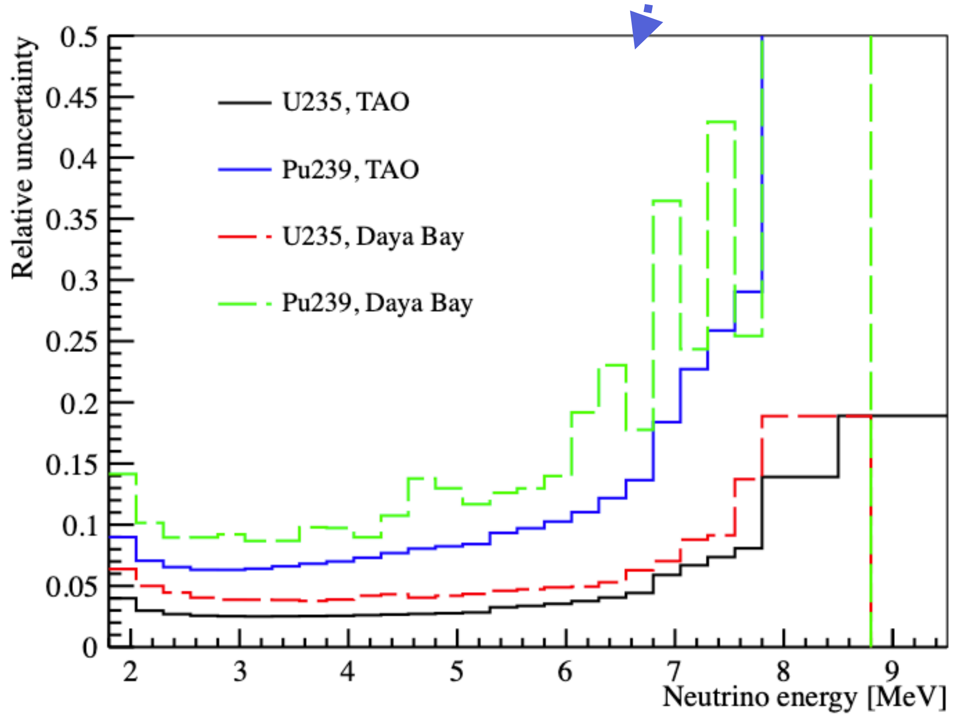
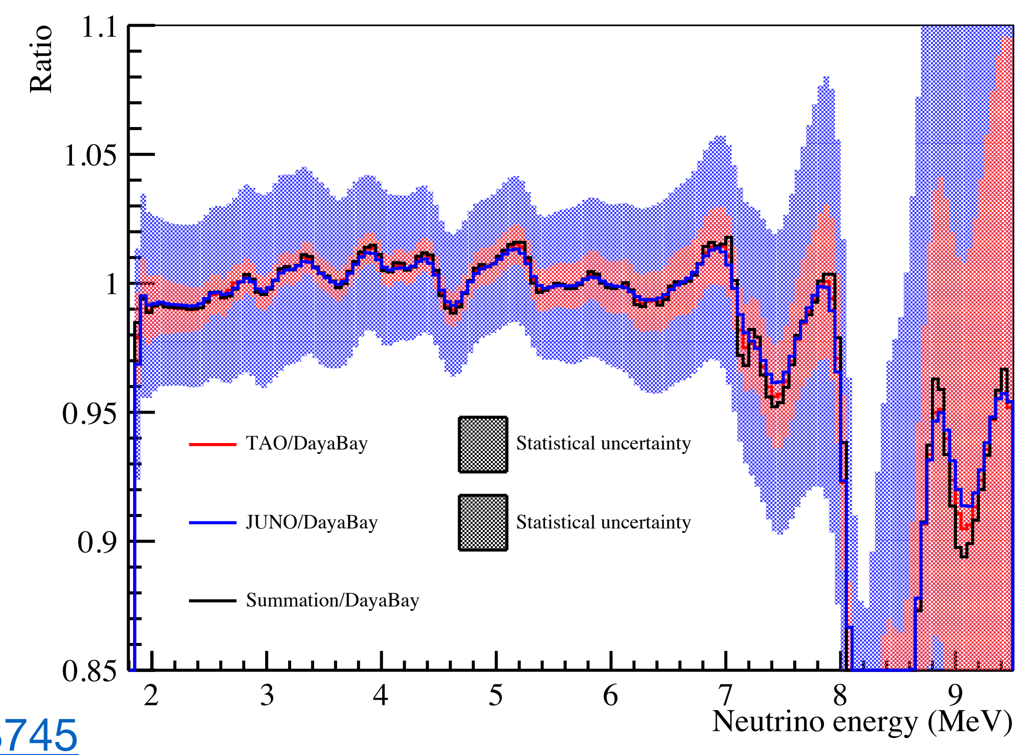
JUNO-TAO Physics

- TAO’s physics goals:
  - See fine structure due to Coulomb corrections
  - Serve as benchmark for JUNO, other experiments, and nuclear databases
  - Search for sterile neutrinos
  - Study flux and shape change with fuel evolution & decompose isotope spectra



Note: needs to be re-assessed with new TAO baseline of 44 m



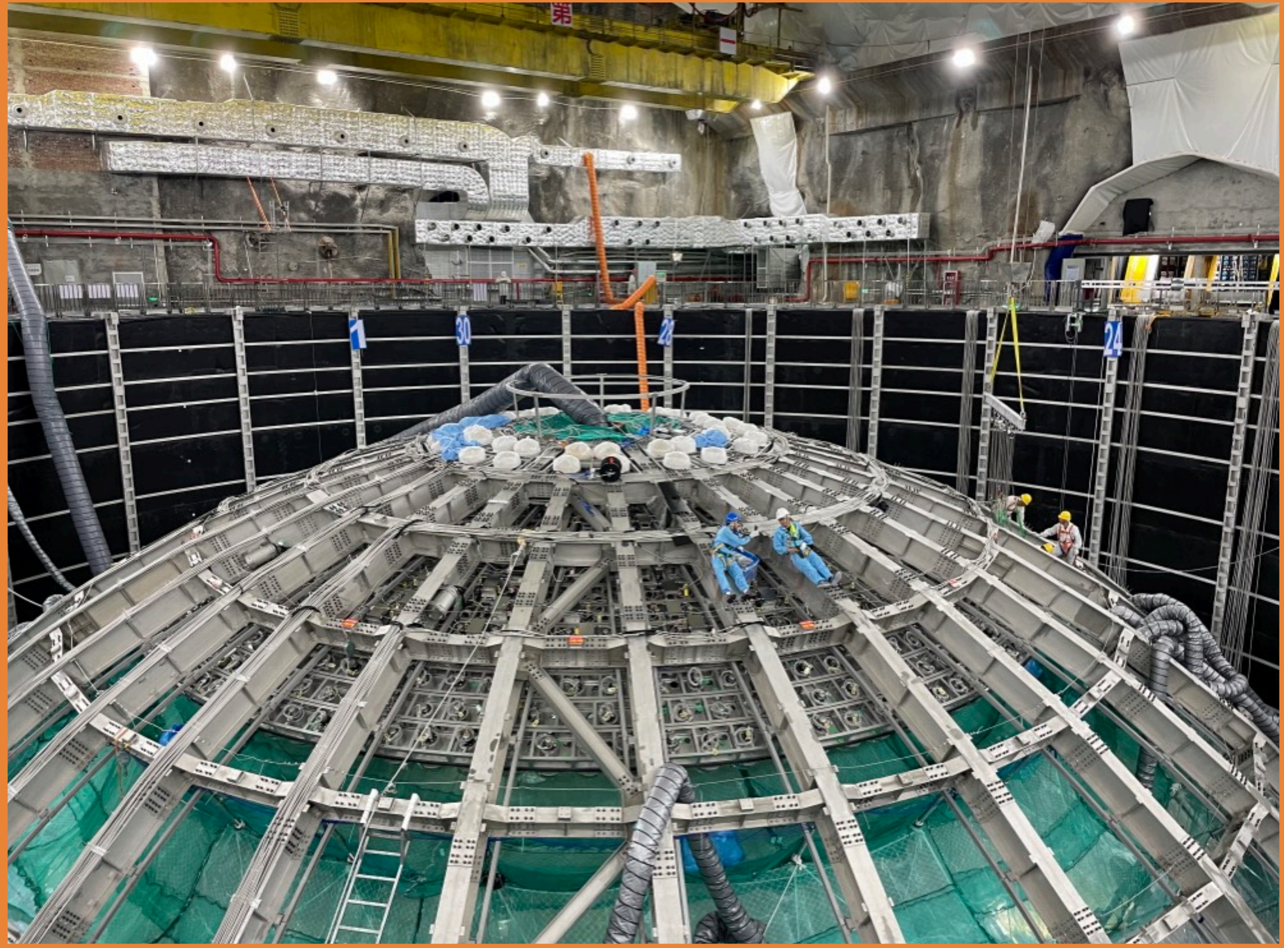


arXiv:2005.08745

Summary & Conclusions

Summary & Conclusions

- JUNO is a multipurpose neutrino observatory with a rich program in neutrino physics and astrophysics
  - Neutrino mass ordering, oscillation parameters, supernova ν's, solar ν's, atmospheric ν's, geo-ν's, nucleon decay, and others
- JUNO is pushing the limits in liquid scintillator detection technology
  - New solutions in terms of PMT technology, liquid scintillator properties and detector construction
  - Developing some unique approaches to calibration and to the reduction of systematic uncertainties
- Progress is well underway, and expect to begin filling this year
- Anticipate some exciting results (and maybe some surprises?)



Thank you for your attention!