JUNO Status and Prospects

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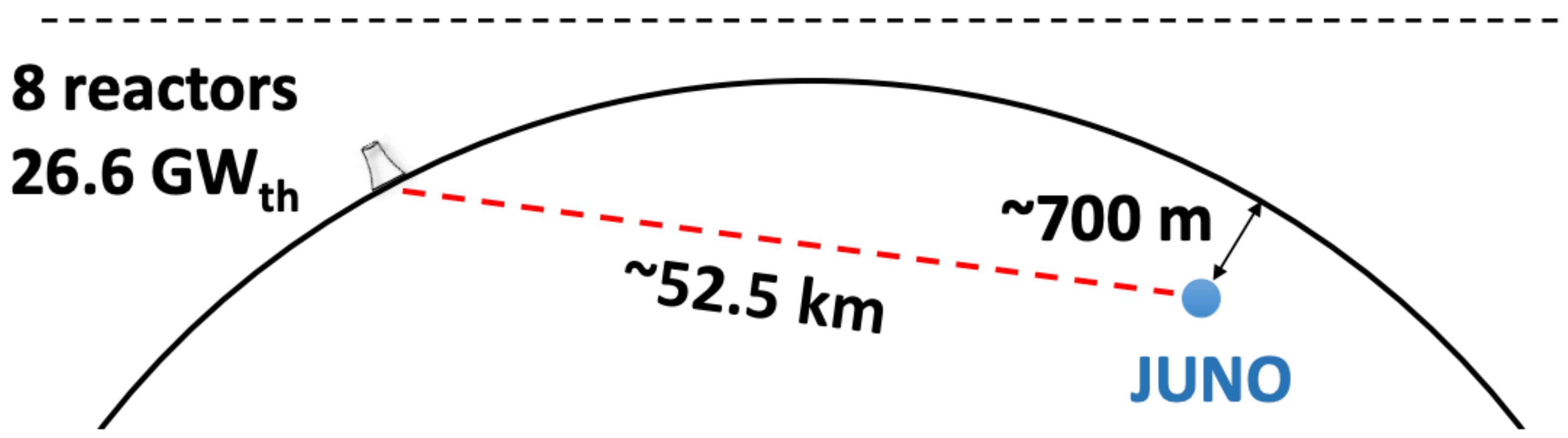
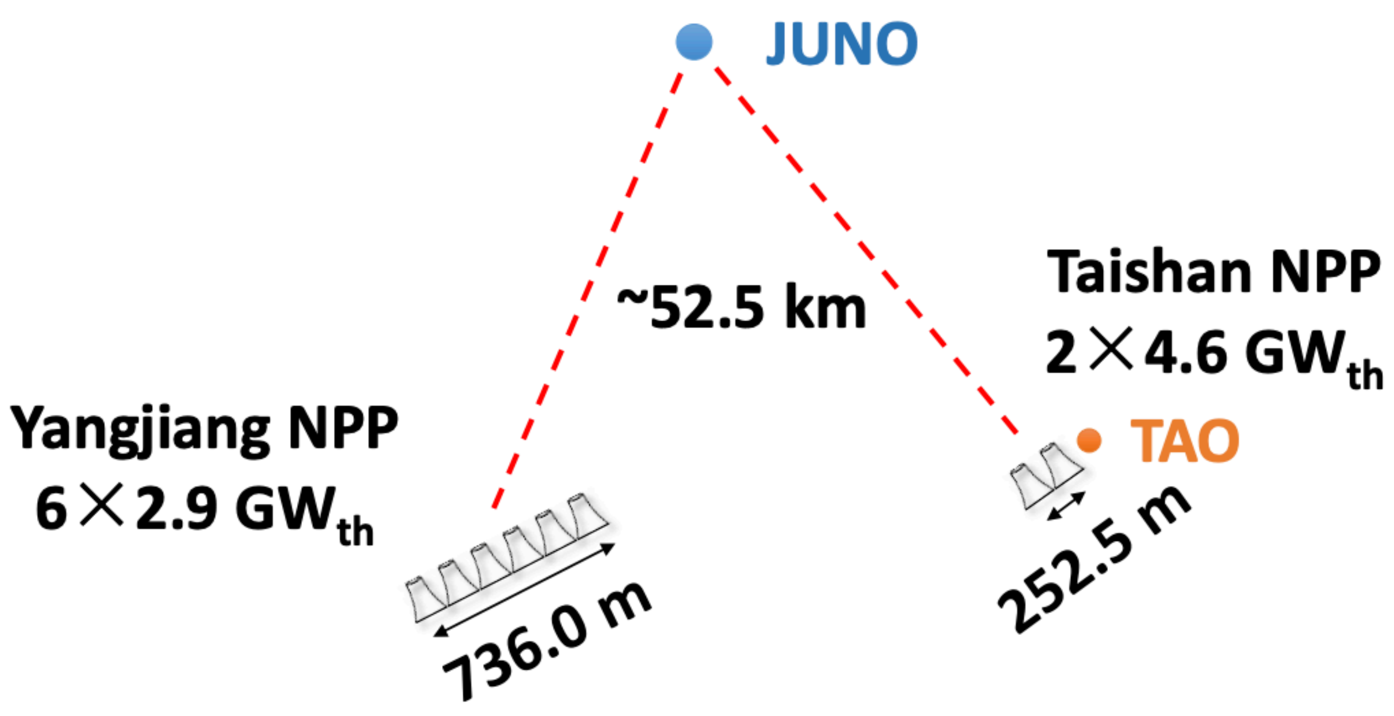
JUNO Overview

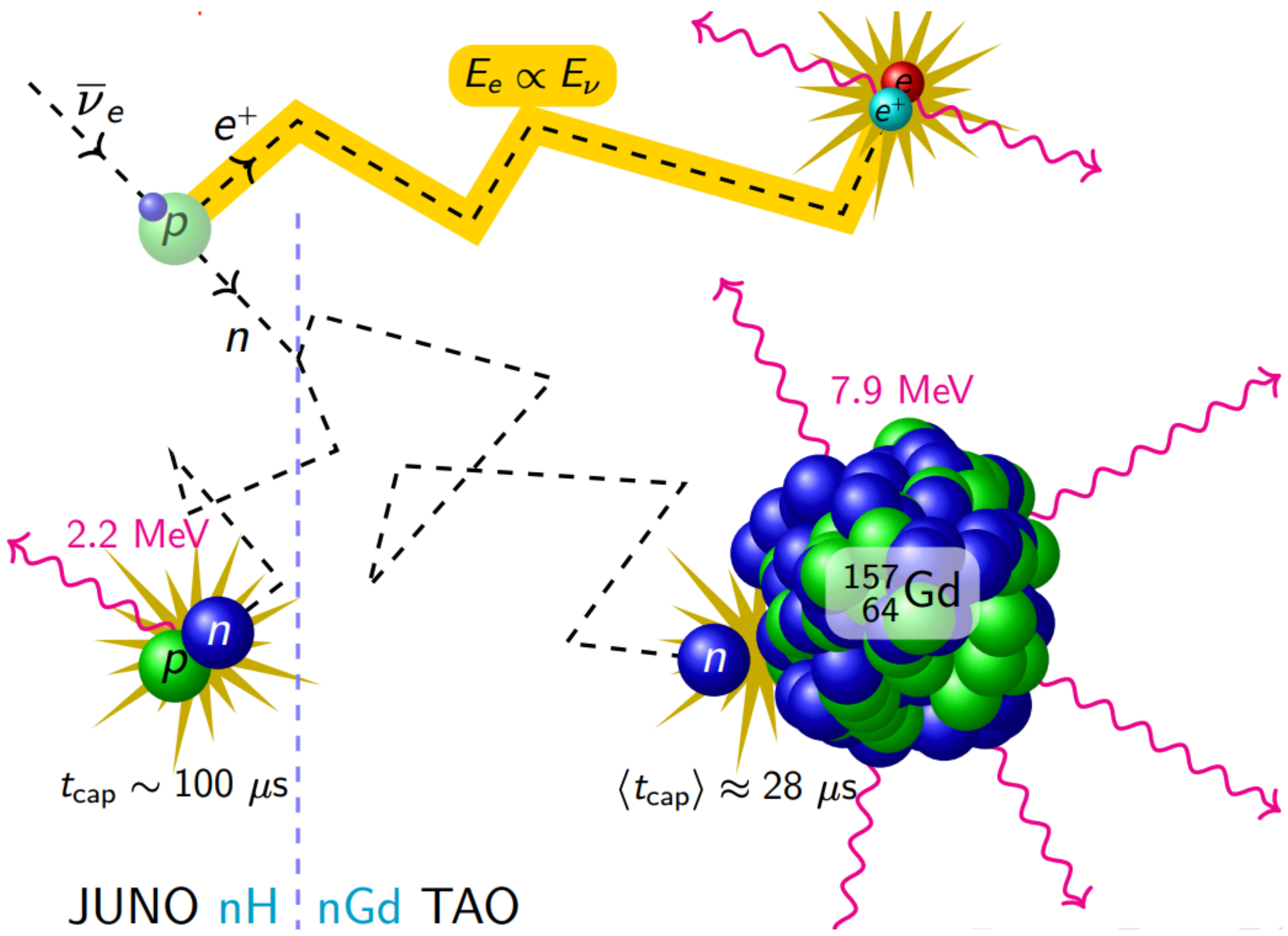




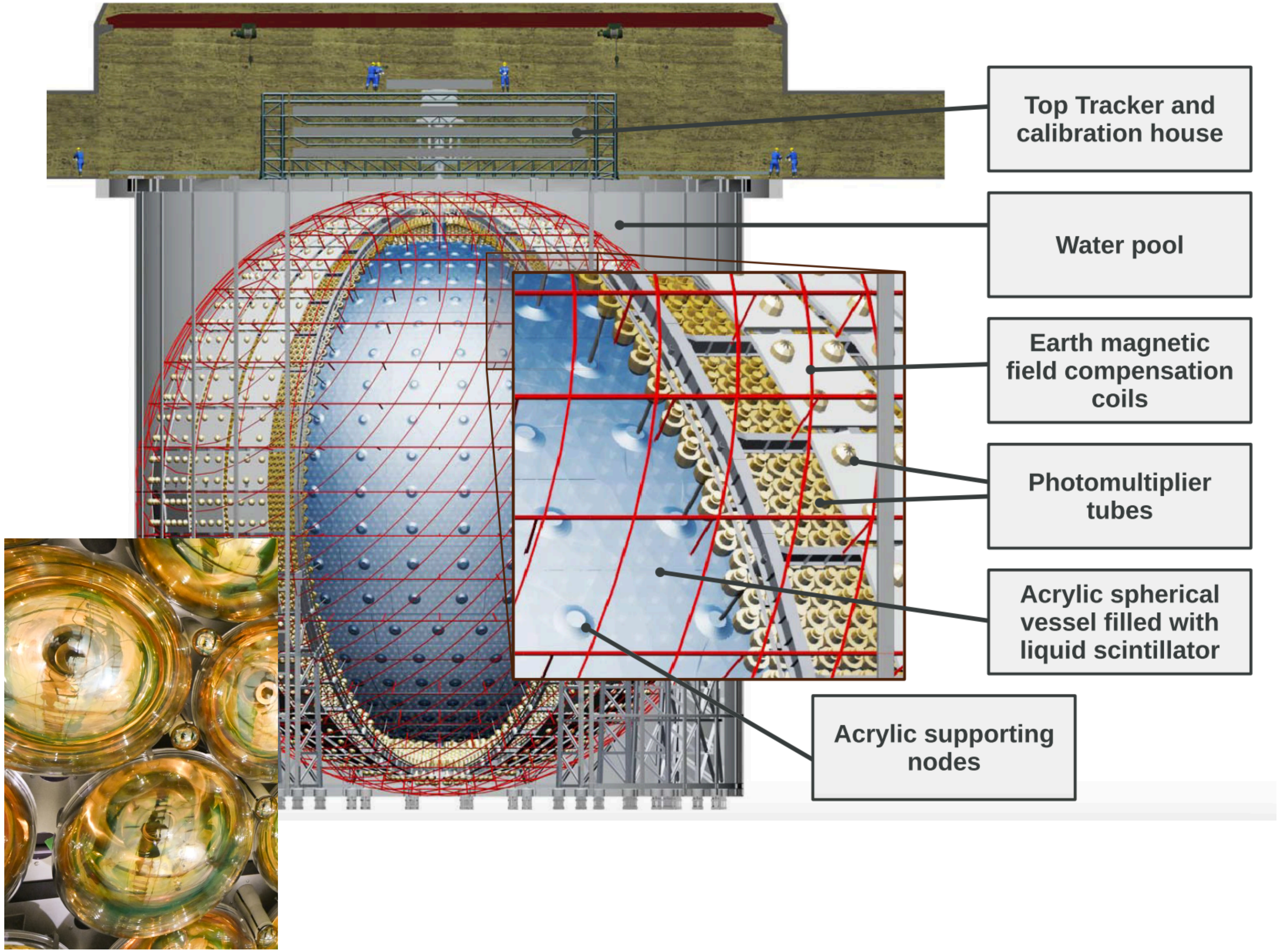
- The **J**iangmen **U**nderground **N**eutrino **O**bservatory (**JUNO**) is a 20 kton liquid scintillator neutrino detector, with ~700 m underground in southern China

- Placed 52.5 km from 8 nuclear reactors: **~10²⁰** $\bar{\nu}_e/s$ **per** GW_{th}

- Reactor $\bar{\nu}_e$ detected through Inverse Beta Decay (IBD) reaction: $\bar{\nu}_e + p \rightarrow e^+ + n$
  - Positron (prompt) signal followed by neutron capture (delayed) typically on H
  - Temporal and spatial coincidence of prompt and delayed signals is a powerful handle to extract reactor neutrino signal

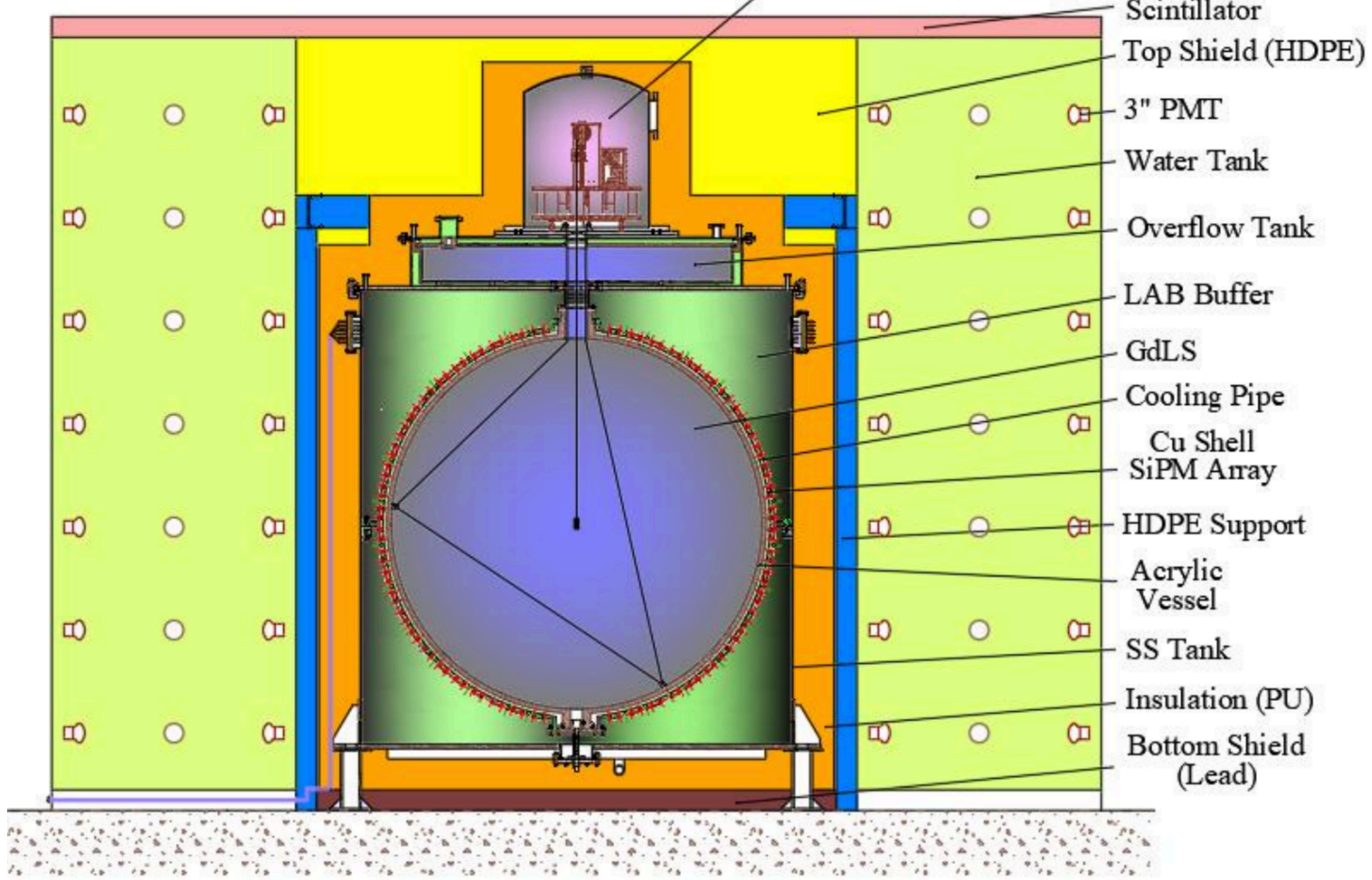


- 35.4 m diameter acrylic sphere filled with 20 kton of liquid scintillator (LS)
  - LS designed for high light yield and low attenuation
- Instrumented outer water tank and top scintillator panels
- 17,612 20” PMTs (LPMTs) and 25,600 3” PMTs (SPMTs)
  - ~78% photo-coverage
  - ~30% detection efficiency (LPMT)
- Unprecedented 3% energy resolution at 1 MeV

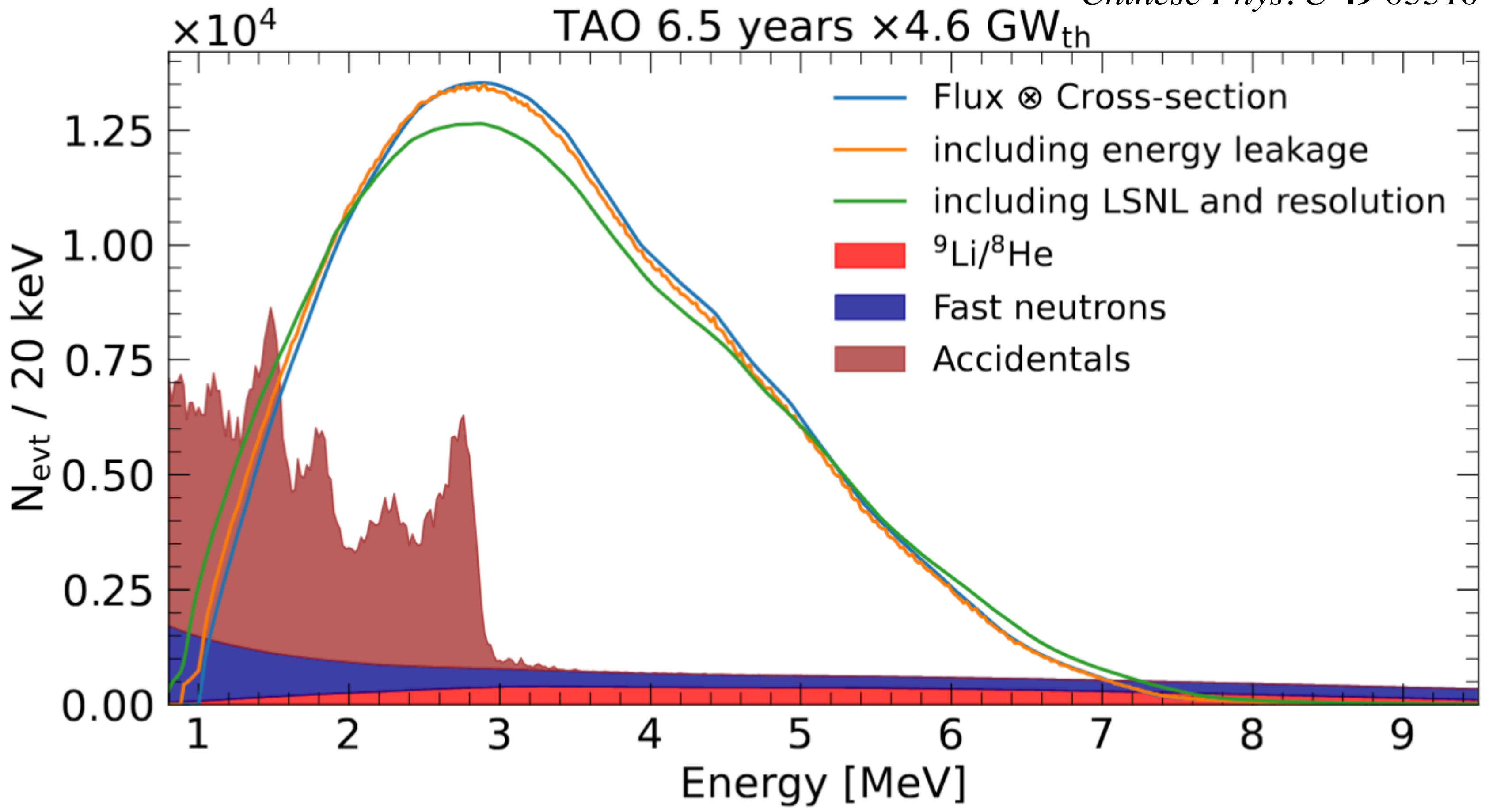


- JUNO-TAO (Taishan Antineutrino Detector) will be a satellite detector
  - 44 m from 4.6 GW_{th} reactor
  - ~1 ton GdLS fiducial volume
  - Instrumented with Silicon Photomultipliers (SiPMs) providing <2% at 1 MeV energy resolution and >95% photo-coverage
  - Operates at -50^{o}C
- **Measure reactor antineutrino energy spectrum** with unprecedented resolution
  - Expect to measure never-before-seen fine structure
  - Search for sterile neutrinos
  - Important inputs for experiments and nuclear databases

arXiv: 2005.08745



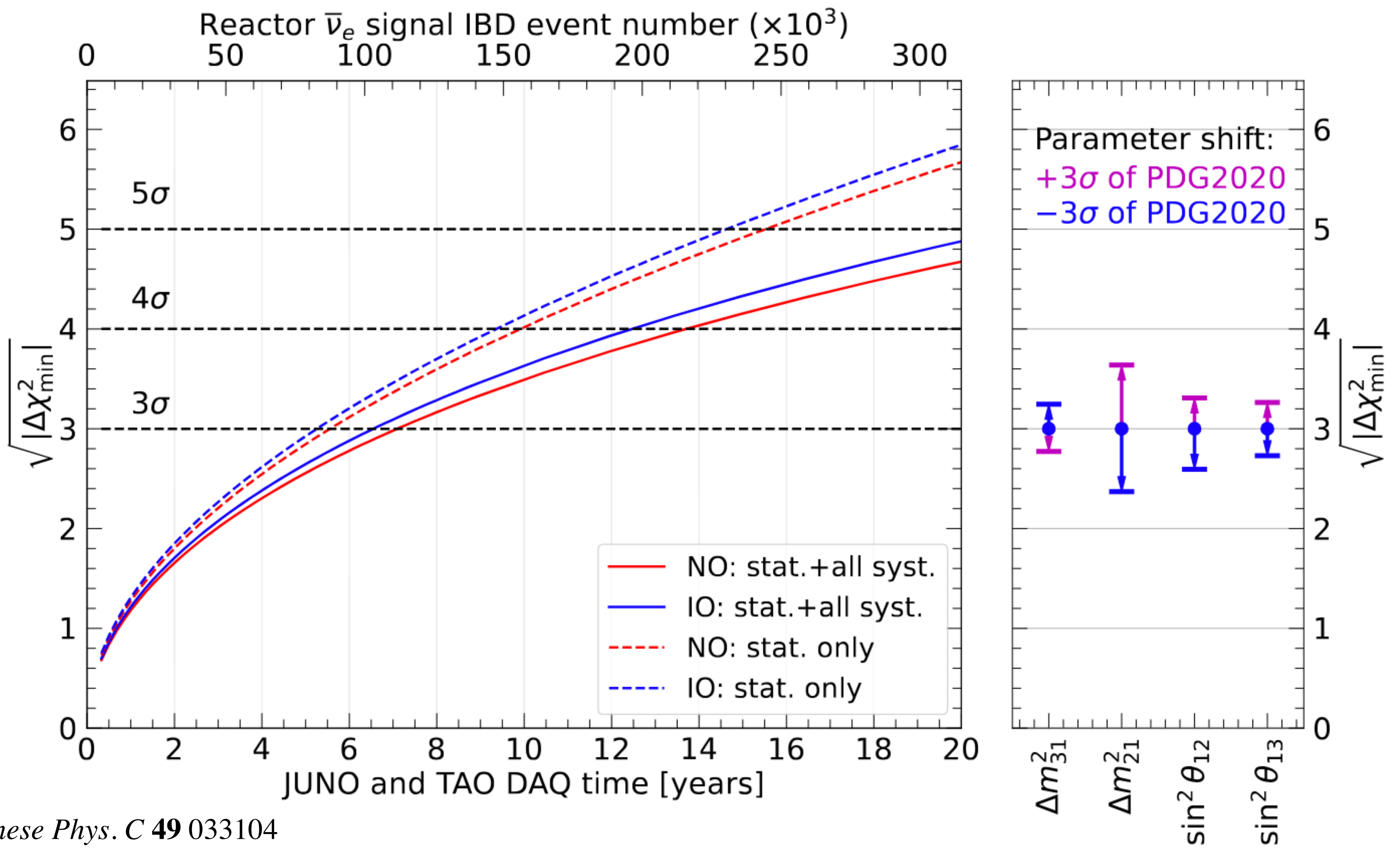
Chinese Phys. C **49** 033104




Solar ν's
Hundreds/
day
p
Cosmic muons
~ 250k/day
Atmospheric ν's
Several/day
Supernova ν's
5000 IBDs for
CCSN @10
kpc
~650 m
26.6 GWth, 53 km
reactor ν's
~ 60/day
Geo-ν's
1-2/day

JUNO $\bar{\nu}_e$ Oscillations

- Simultaneous observation of solar and atmospheric oscillations
- Determination of NMO through interference effects in fine structure of oscillated spectrum (allowed by large θ_{13})
    - Precise energy spectrum reference from JUNO-TAO
    - Complementary to accelerator and atmospheric measurements
    - Reach ~5σ in combination with other experiments (*PRD 101, 032006 (2019), Sci Rep 12, 5393 (2022)*)



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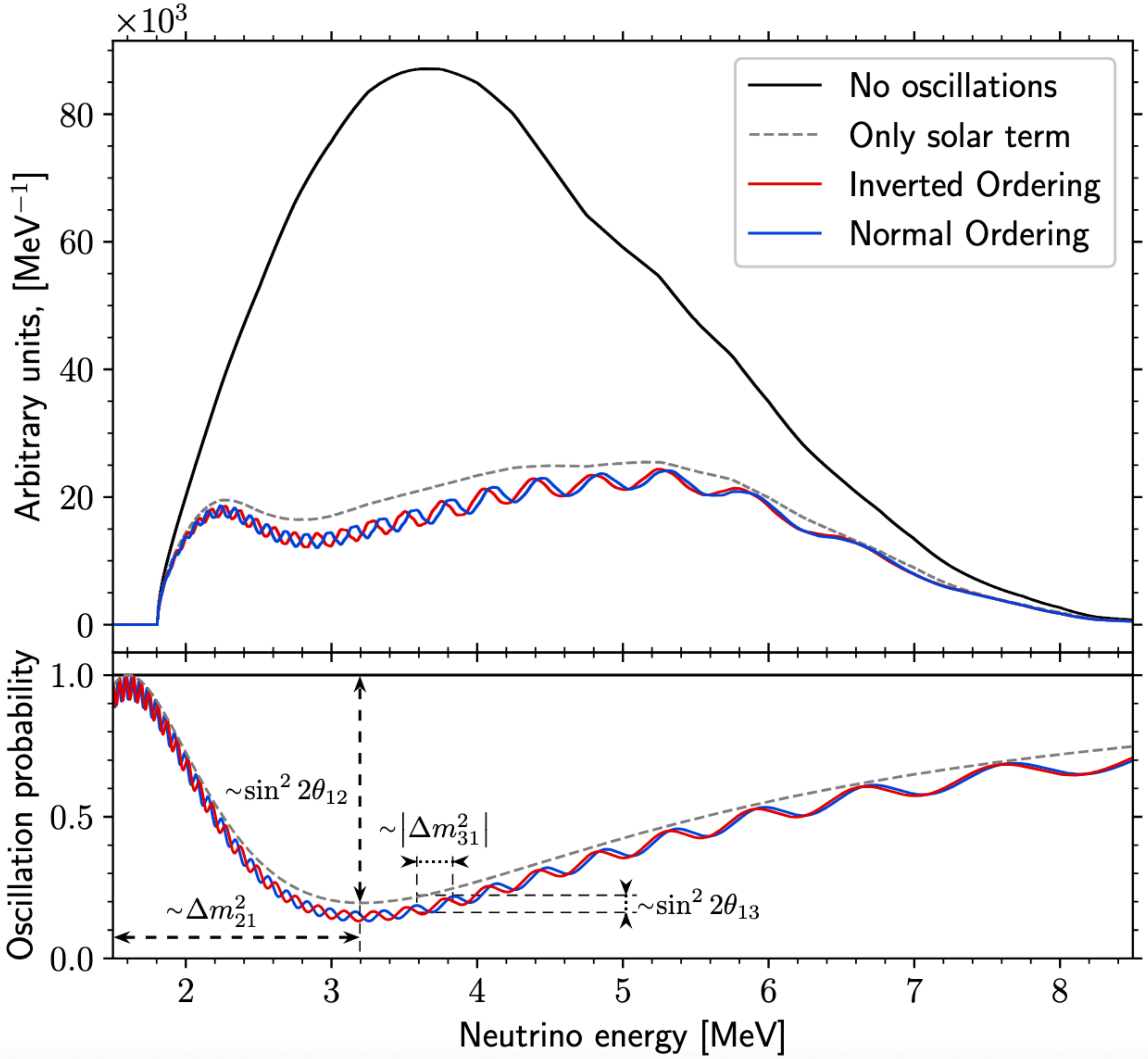
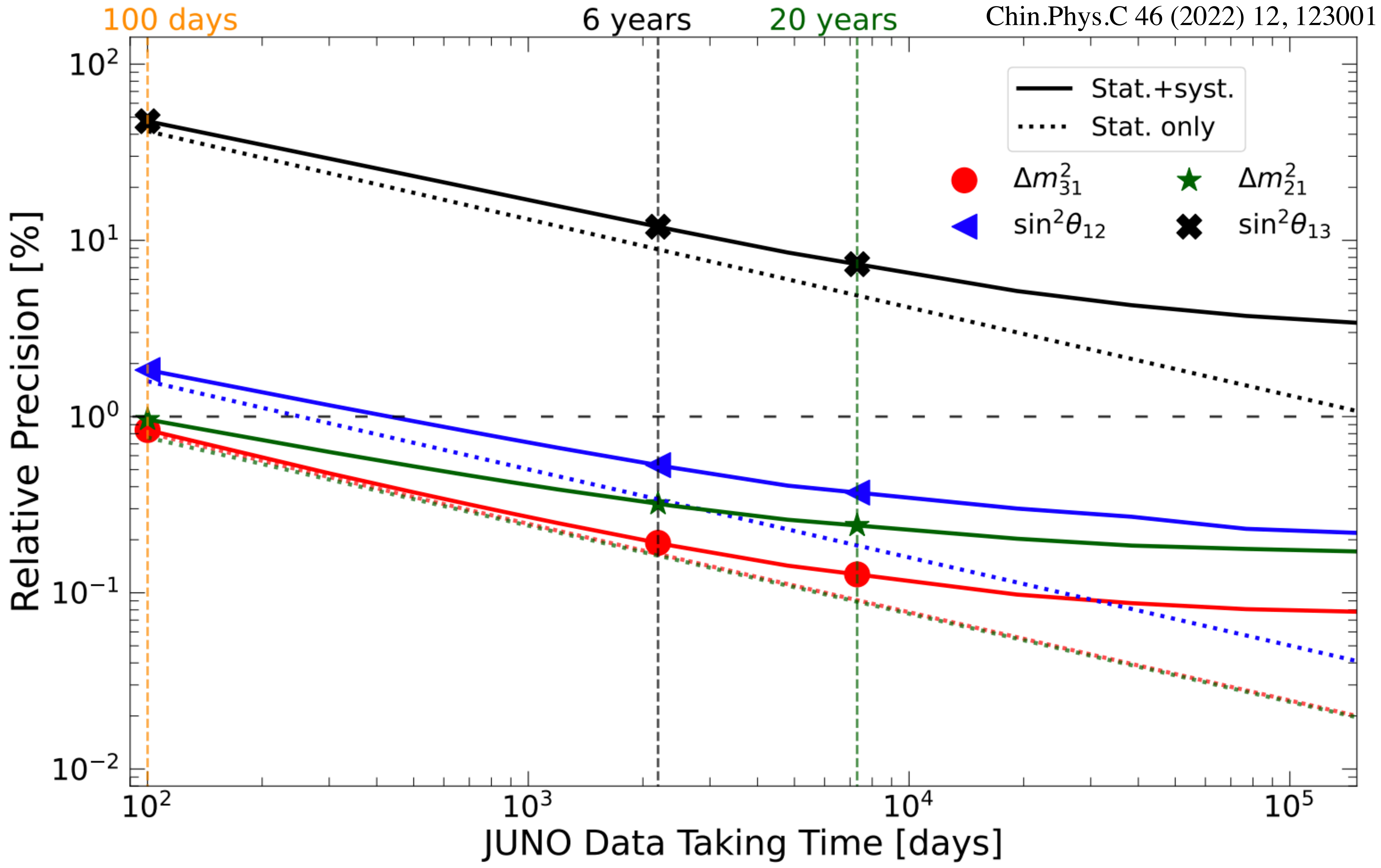


JUNO $\bar{\nu}_e$ Oscillations

- Measurement of $\sin^2\theta_{12}$, Δm^2_{21} and Δm^2_{31} to <= **0.5% precision with 6 years data**
  - Roughly one **order of magnitude improvement over existing constraints**
  - Precise tests of neutrino oscillations and U_{PMNS} unitarity (1%)

JUNO Relative Uncertainty vs. Current Precision

	Δm^2_{21}	Δm^2_{31}	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$
JUNO 100 days	0.8%	1%	1.9%	47.9%
JUNO 6 years	0.3%	0.2%	0.5%	12.1%
KamLAND	2.4%	-	-	-
T2K	-	2.6%	-	-
SNO+SK	-	-	4.5%	-
Daya Bay	-	-	-	3.4%



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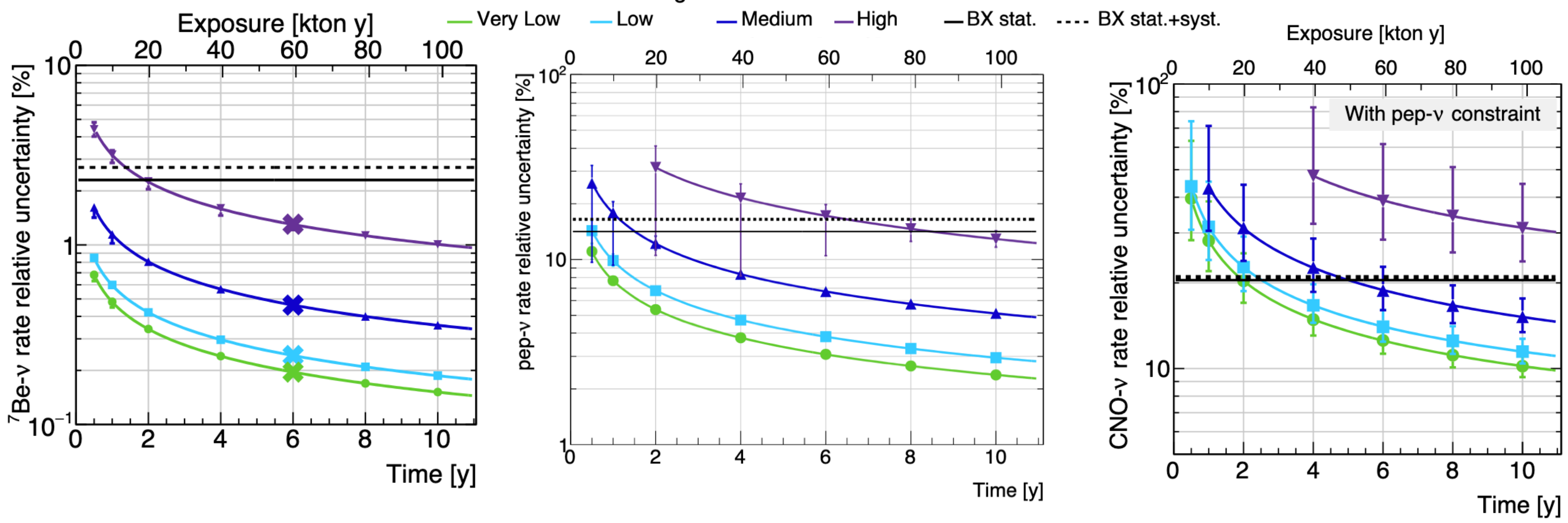
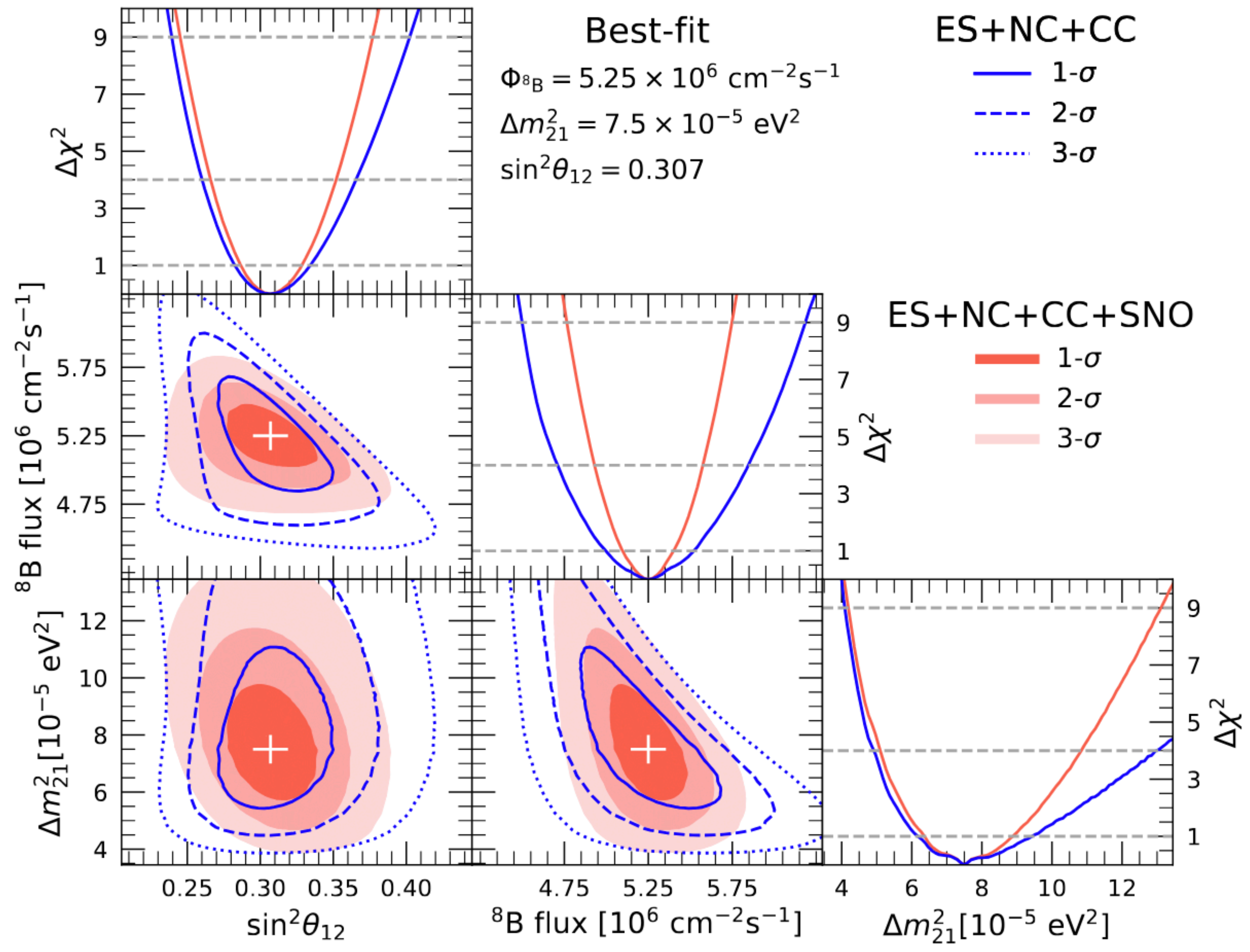


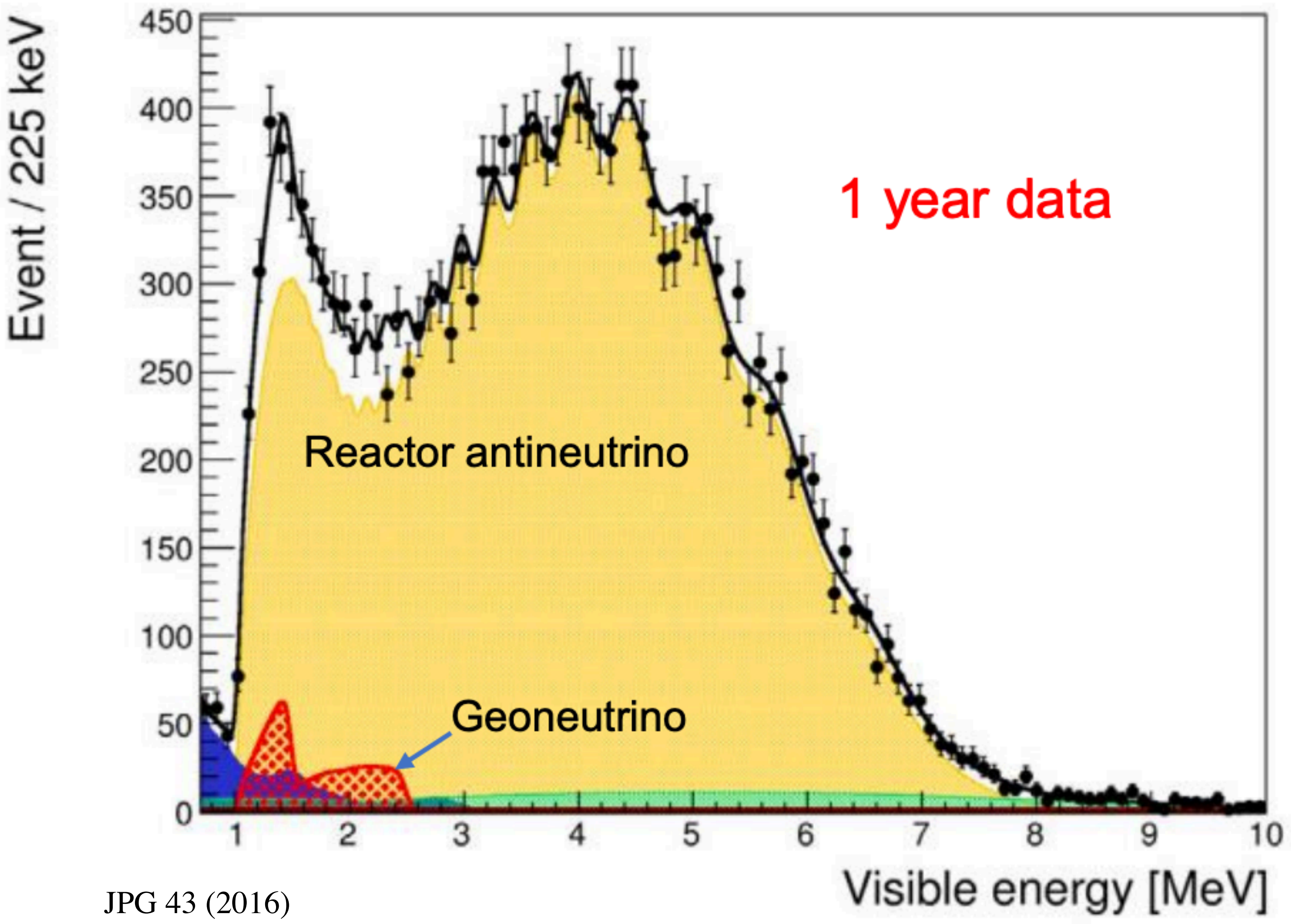
ApJ **965** 122



- JUNO has the potential to improve on ^7Be, pep, and CNO neutrino fluxes given strong control of radiopurity - ~10^{-17} g/g U/Th
- Measurement of ^8B neutrino flux: 5% precision in 10 years
- Measurement of Δm^2_{21}, $sin^2\theta_{12}$ with solar neutrino sample
  - Oscillation measurement with reactor and solar neutrinos in one detector

Geoneutrinos and Atmospherics

- Geoneutrinos $\bar{\nu}_e$ from $^{238}U/^{232}Th$ in Earth's crust and mantle
  - Development of local crust model underway
- About 1 geoneutrino event per day:
  - Final sensitivity paper under preparation: expect ~8% precision on flux (fixed U/Th ratio) in 10 years
  - Will supersede combined KamLAND and Borexino statistics in less than a year
- Atmospheric Neutrinos: Independent constraint of NMO through matter effect



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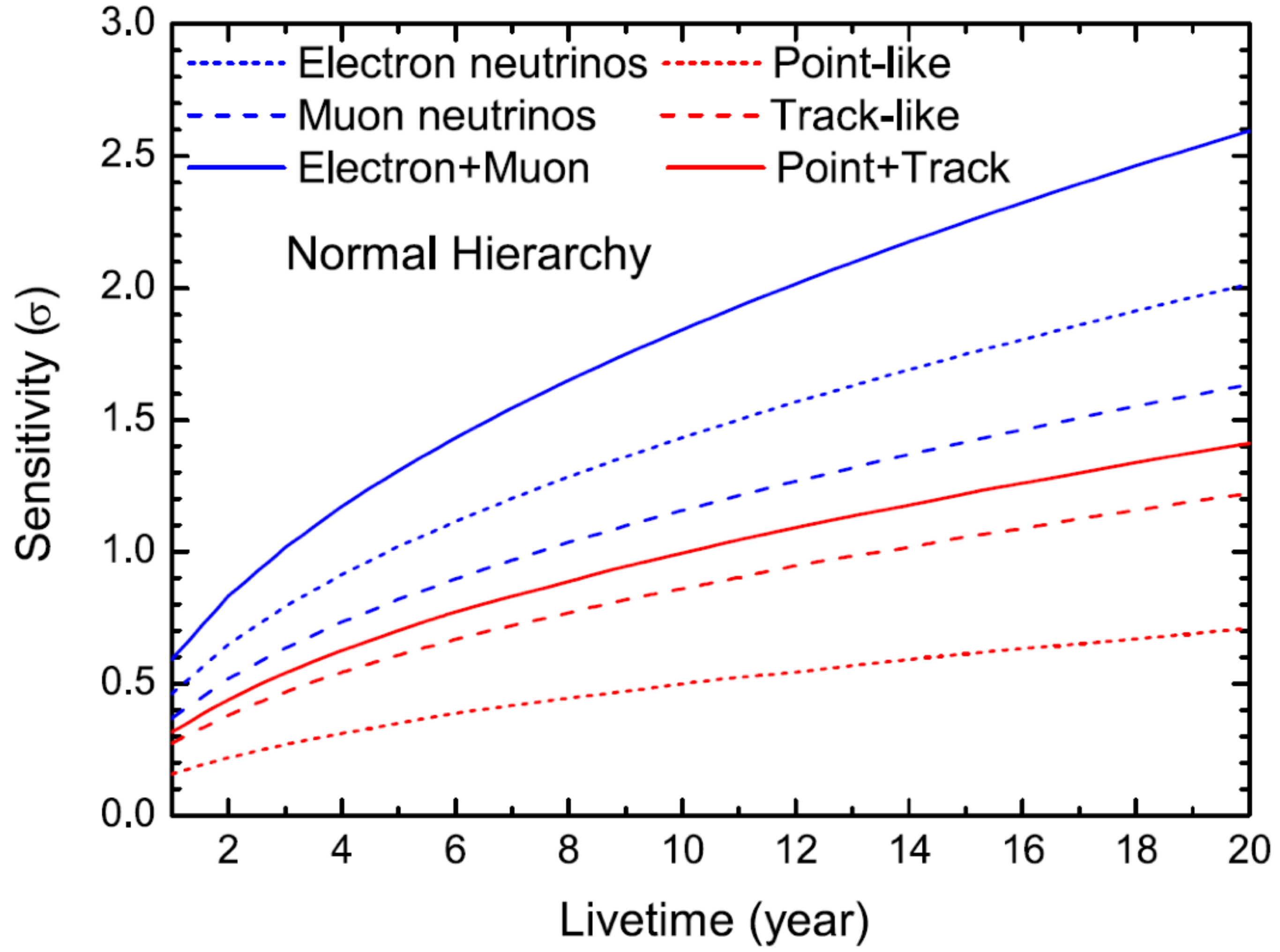
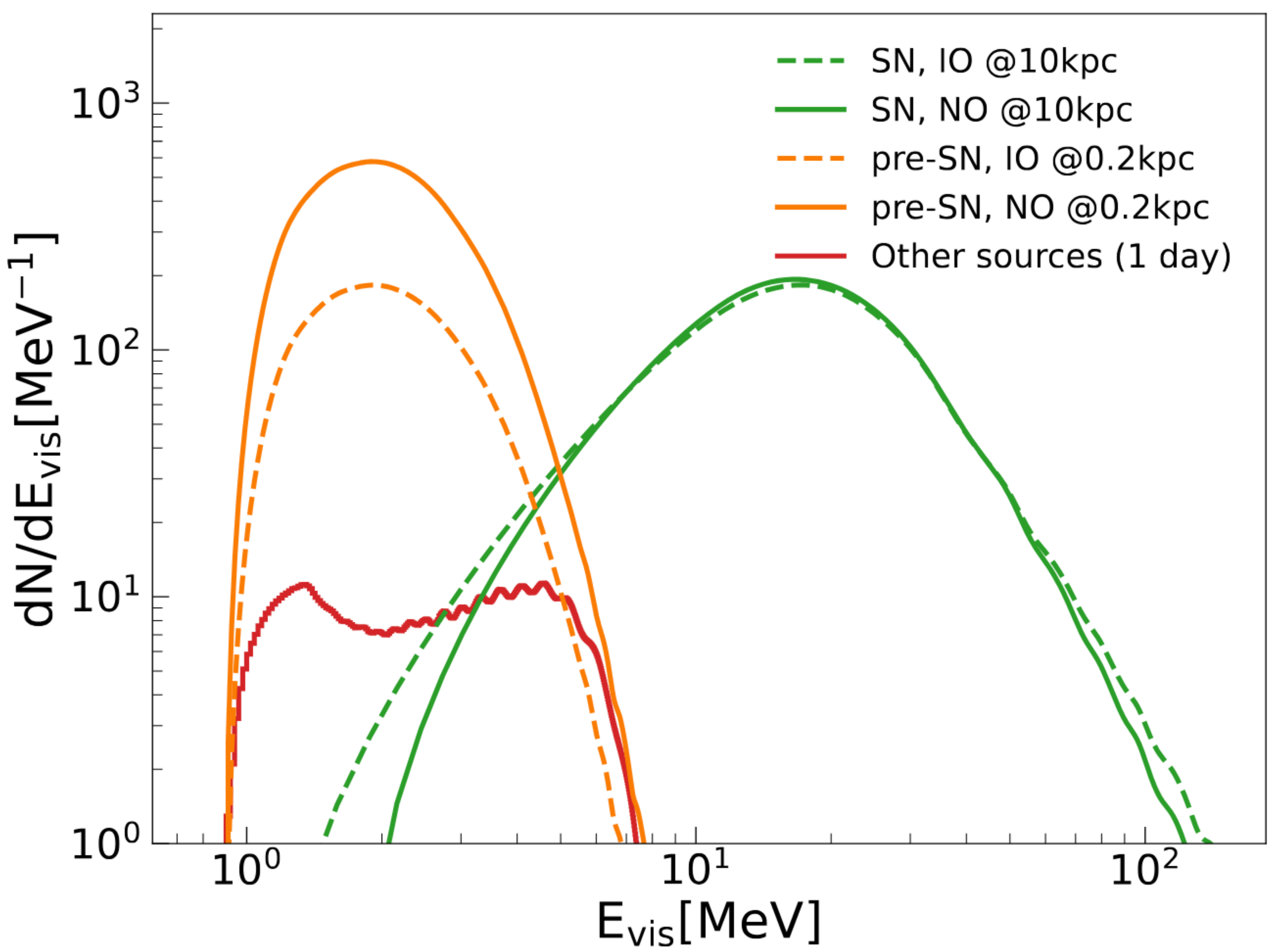
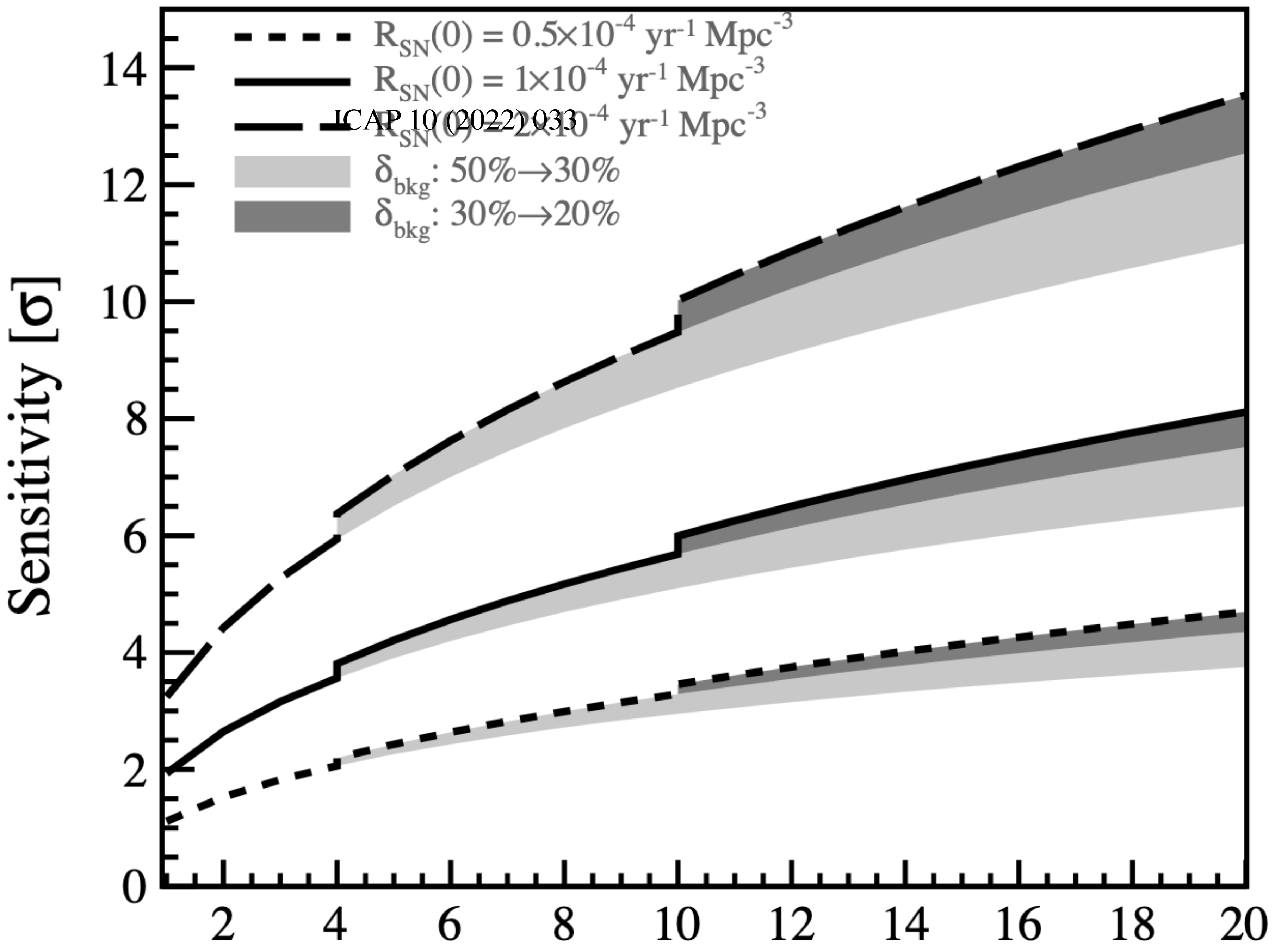


JCAP 01 (2024)057



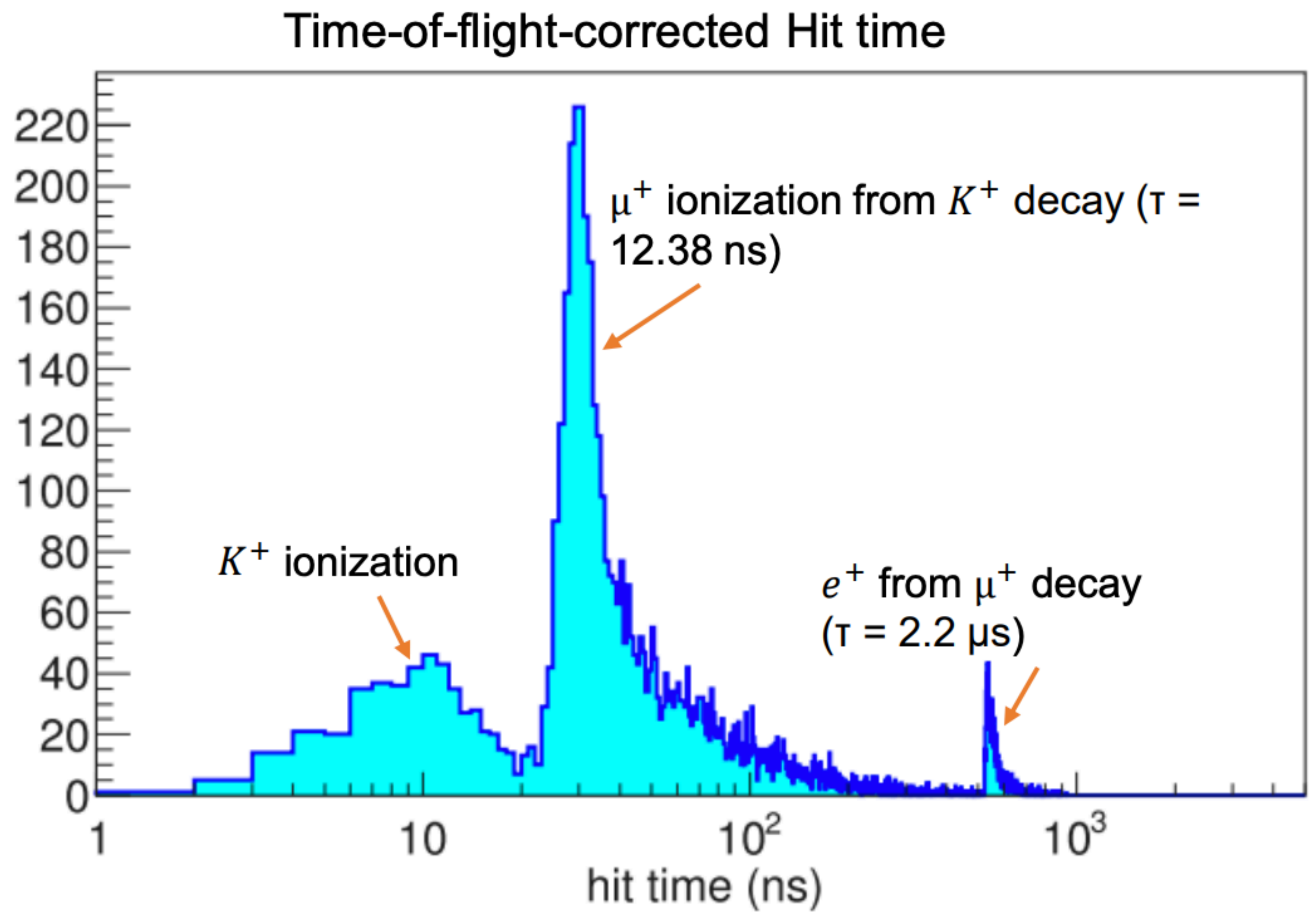
JCAP 10 (2022)033



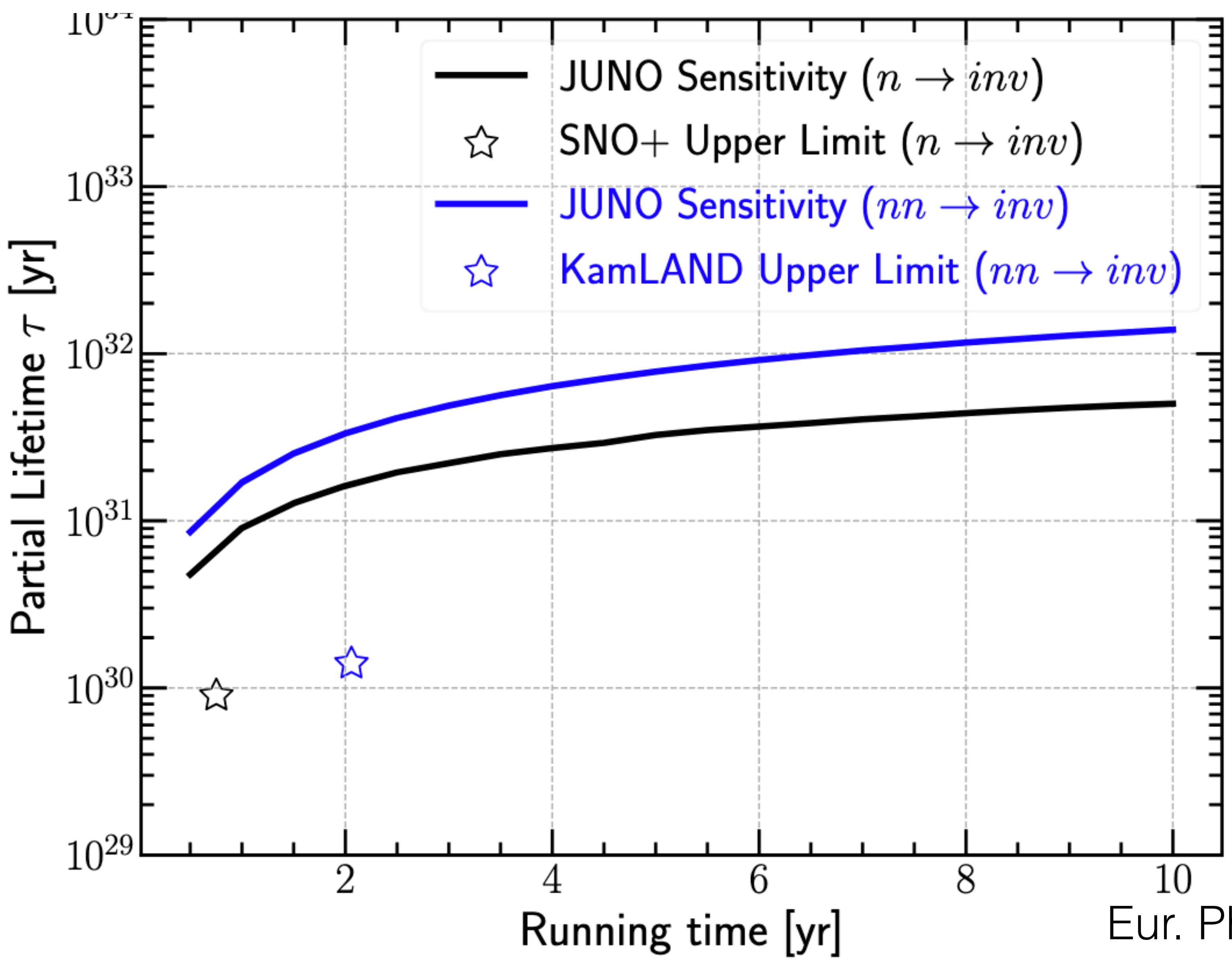
- Study of flavor composition, time evolution, and energy spectrum of supernova (SN) burst neutrinos
  - Low detection threshold (sub-MeV)
  - For SN @ 10 kpc: ~5000 IBDs, ~2000 pES ~300 eES
- Potential first observation of Diffuse Supernova Neutrino Background
  - Expected detection significance of ~3σ (nominal model) after 10 years

Nucleon Decay

- **Proton decay search** will exploit triple coincidence in $p \to \bar{\nu} + K^+ \to \nu_\mu + \mu^+ \to \bar{\nu}_\mu + \nu_e + e^+$
  - Good sensitivity: 8.34×10^{33} s 90% CL in 10 years for $p \to \bar{\nu} + K^+$ channel



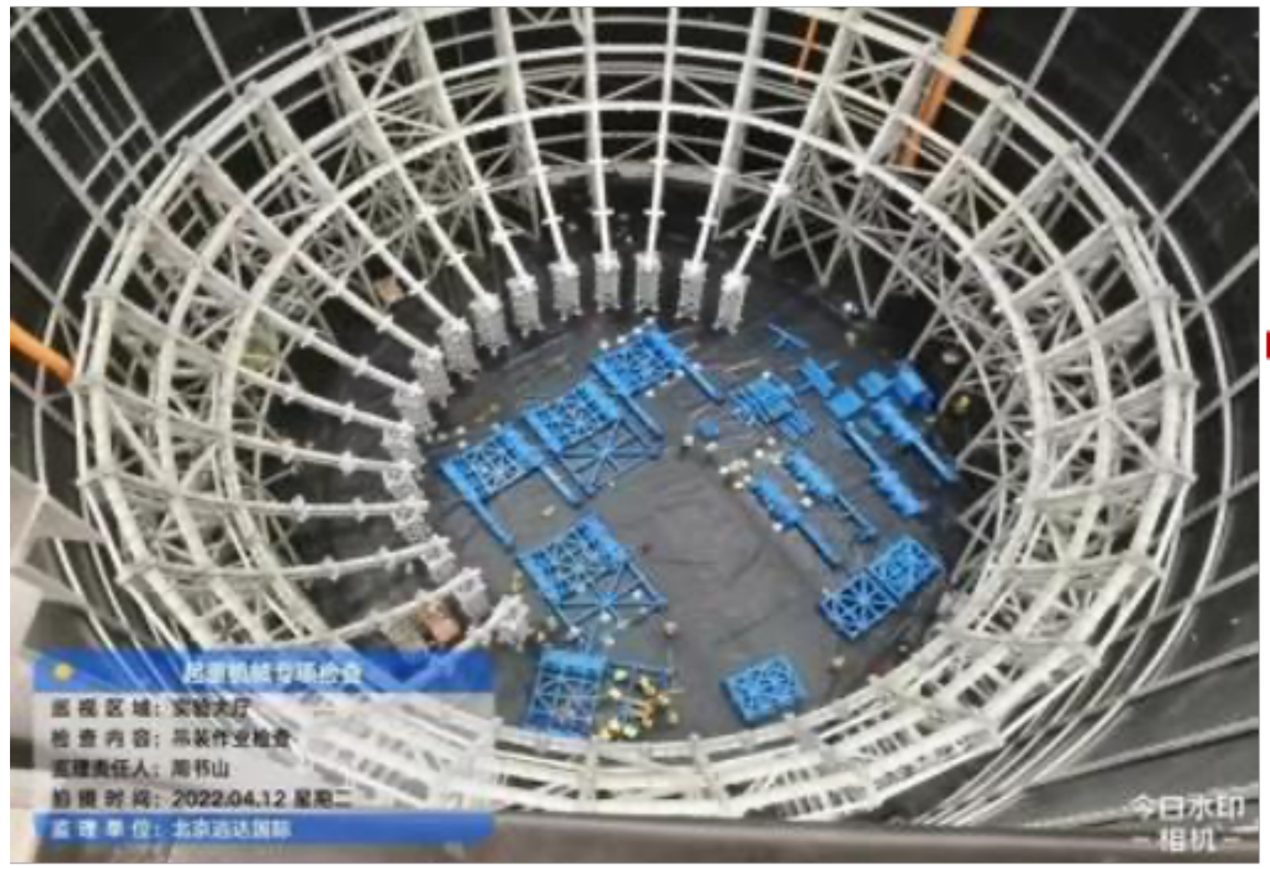
- Look for **neutron decays:** invisible decays of bounded neutrons in ^{12}C through nucleus de-excitation
  - $n \to inv :^{12} C \to^{11} C^*$
  - $nn \to inv :^{12} C \to^{10} C^*$
  - **Order of magnitude improvement over existing limits in 2 years of data-taking**



Eur. Phys. J. C 85, 5 (2025).

Status

Steel + Acrylic Structures



Bottom structure

Platform for Acrylic assembly

Top structure

5 layers of Acrylic

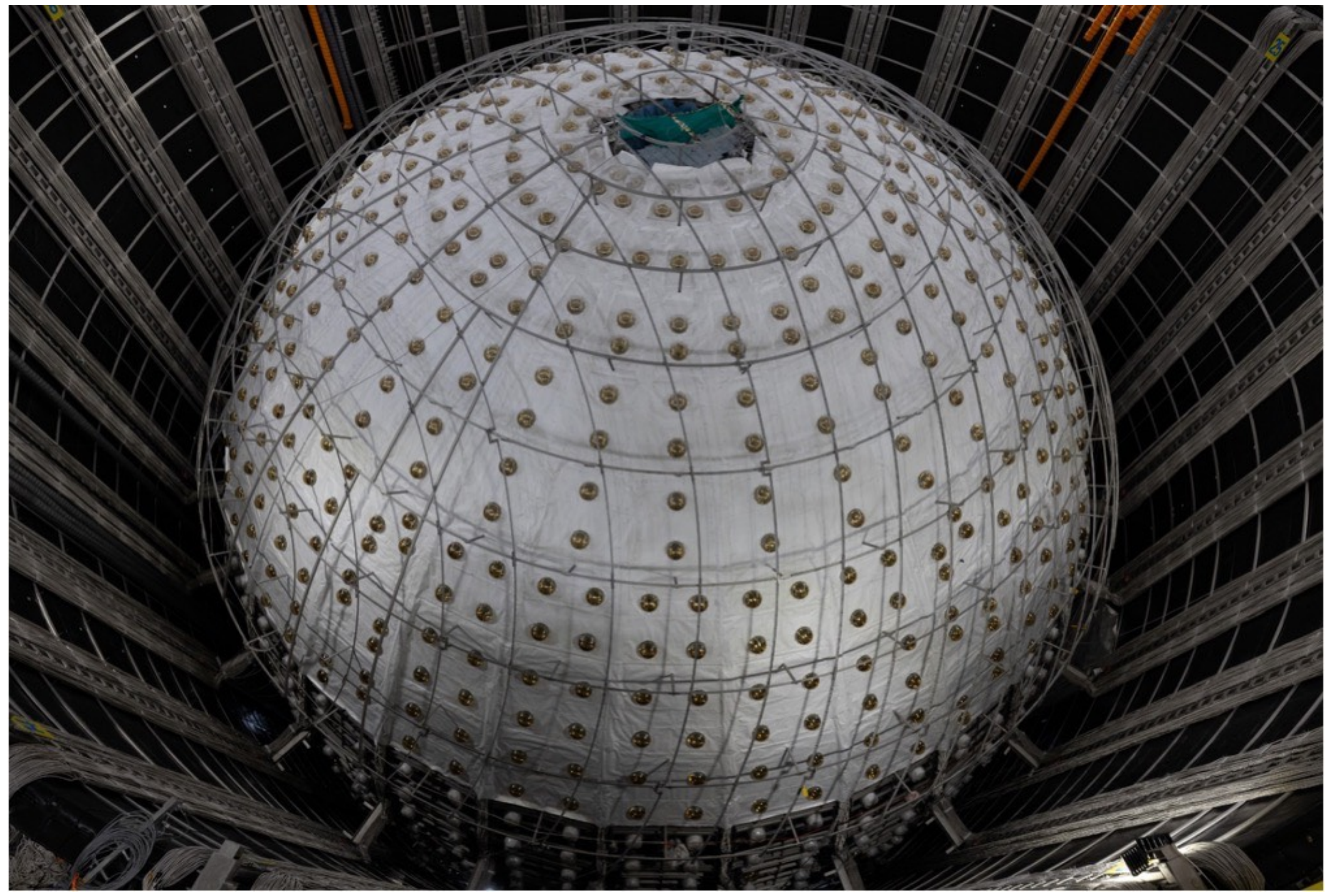
20 layers of Acrylic

23 layers of acrylic

Instrumentation Installation

- As acrylic layers were finished, sPMT and LPMTs + underwater electronics were installed

- Periodic lights-off tests found no major issues and provided us with valuable system experience



- Veto PMTs + Magnetic field compensating coils installed

Liquid Scintillator Production

5000 m^3 LAB tank

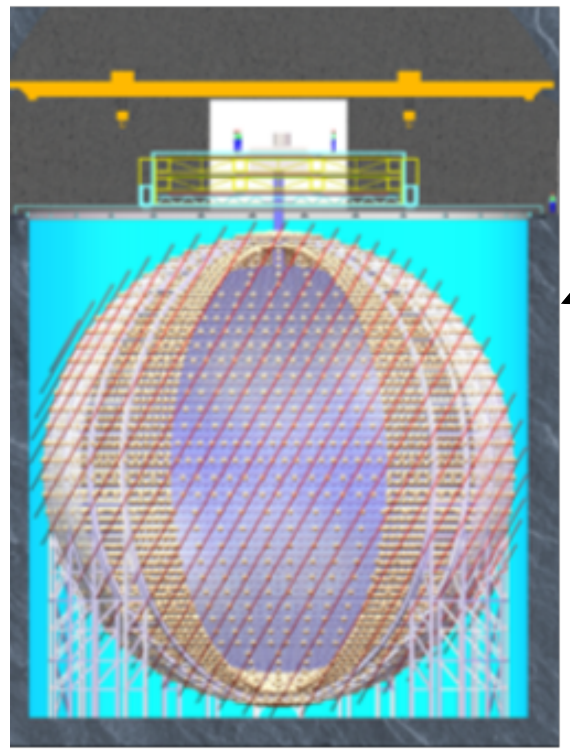
Al_2O_3 to remove particles

Distillation to remove radioactive impurities

Add 2.5 g/L PPO and 3 mg/L bis-MSB

Water extraction to remove radioactive impurities

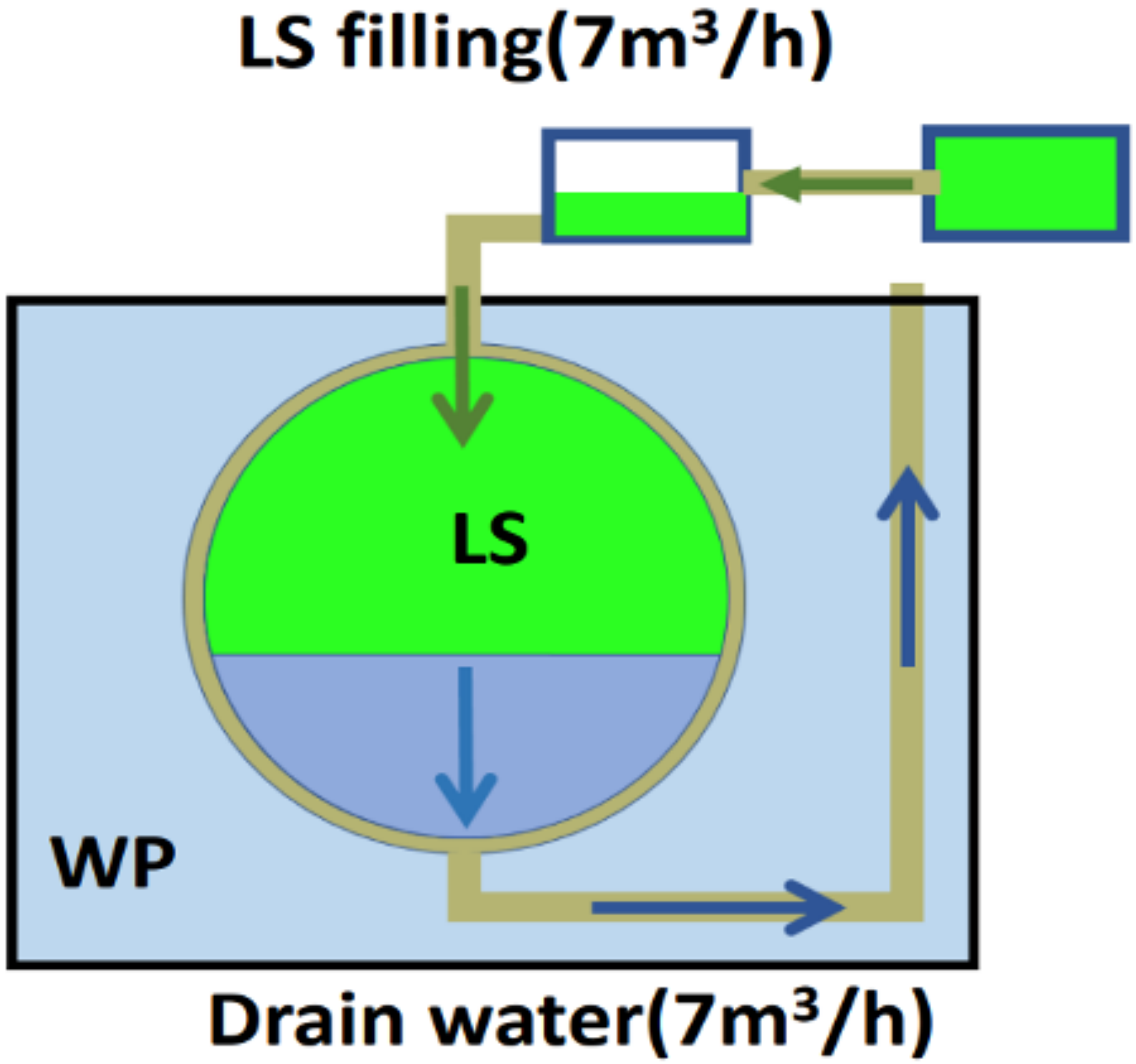
Gas stripping to remove Rn and O_2



- Four purification plants on-site to achieve radio-purity and transparency goals

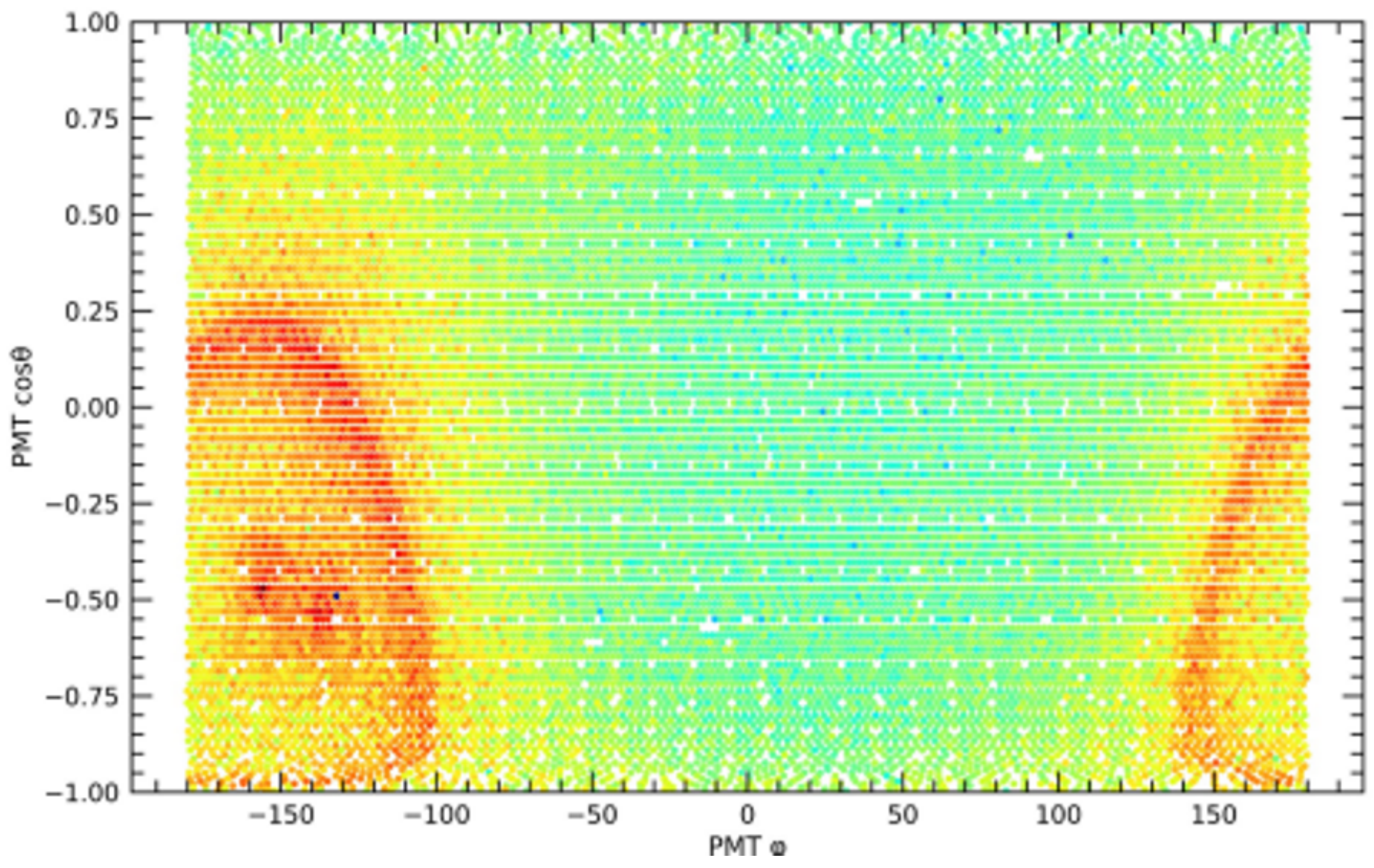
Filling Strategy

- After final cleaning, fill outer pool and central detector with water
- Explore detector performance, calibration, etc. underwater
- Gradually drain central detector water and replace with LS

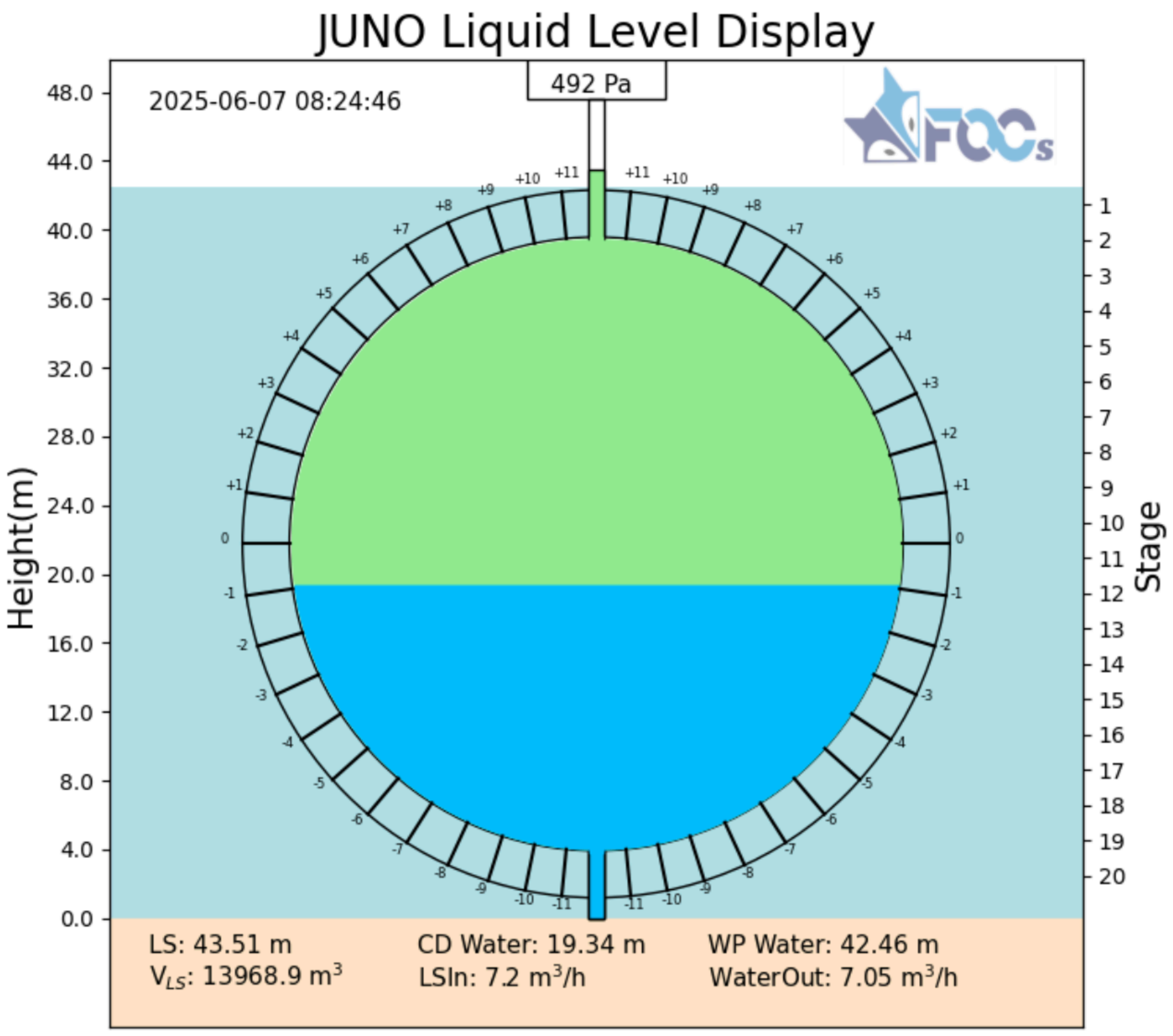


- Gain, time calibration of 20'' PMTs using laser data
  - <0.1% loss at installation
- Probed low energy threshold using neutron sources (AmBe, AmC)
- **First muon candidate events!!**

Muon candidate event in water

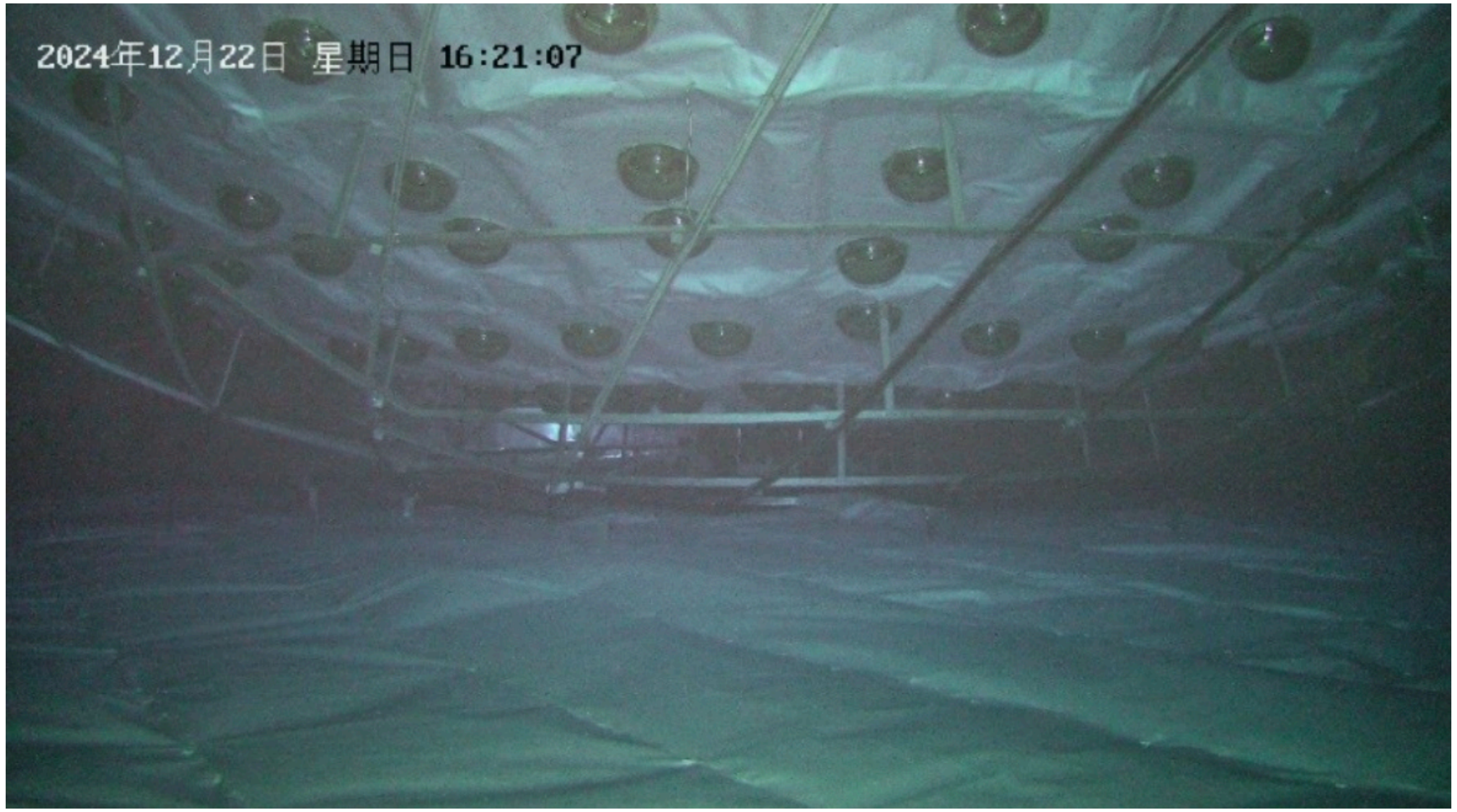


- Water filling completed and meets requirements
  - ◆ Attenuation length: >60m
  - ◆ Particle counts: ~800/20mL
  - ◆ Resistivity: ~4 MW cm
  - ◆ U/Th<10-15 g/g
  - ◆ 222Rn<10 mBq/m3
  - ◆ 226Ra<10 uBq/m3
- Currently filling with LS, expected to complete by end of summer



Summary

- JUNO is a next-generation, precision, multi-purpose experiment with a rich physics program:
  - Neutrino oscillations
  - Supernovae
  - Geoneutrinos
  - Solar neutrinos
- Using its reactor $\bar{\nu}_e$ dataset:
  - NMO measurement to 3σ with about 6 years of data-taking
  - Sub-percent precision for $\sin^2\theta_{12}$, Δm^2_{21} and Δm^2_{31} with as little as O(100) days of data
- Currently in filling stage - **LS data-taking starting this year!**

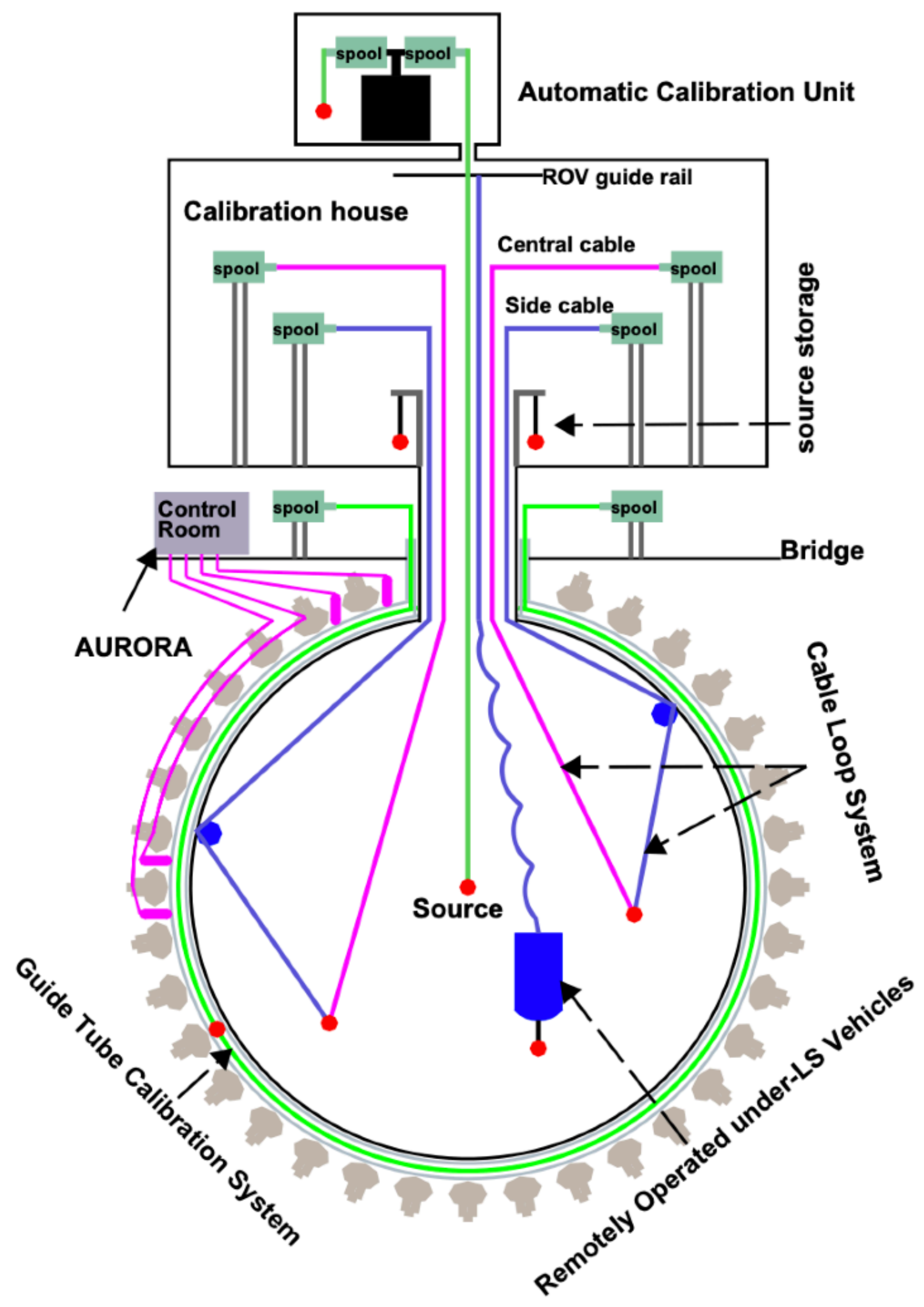



Thank you!
JUNO

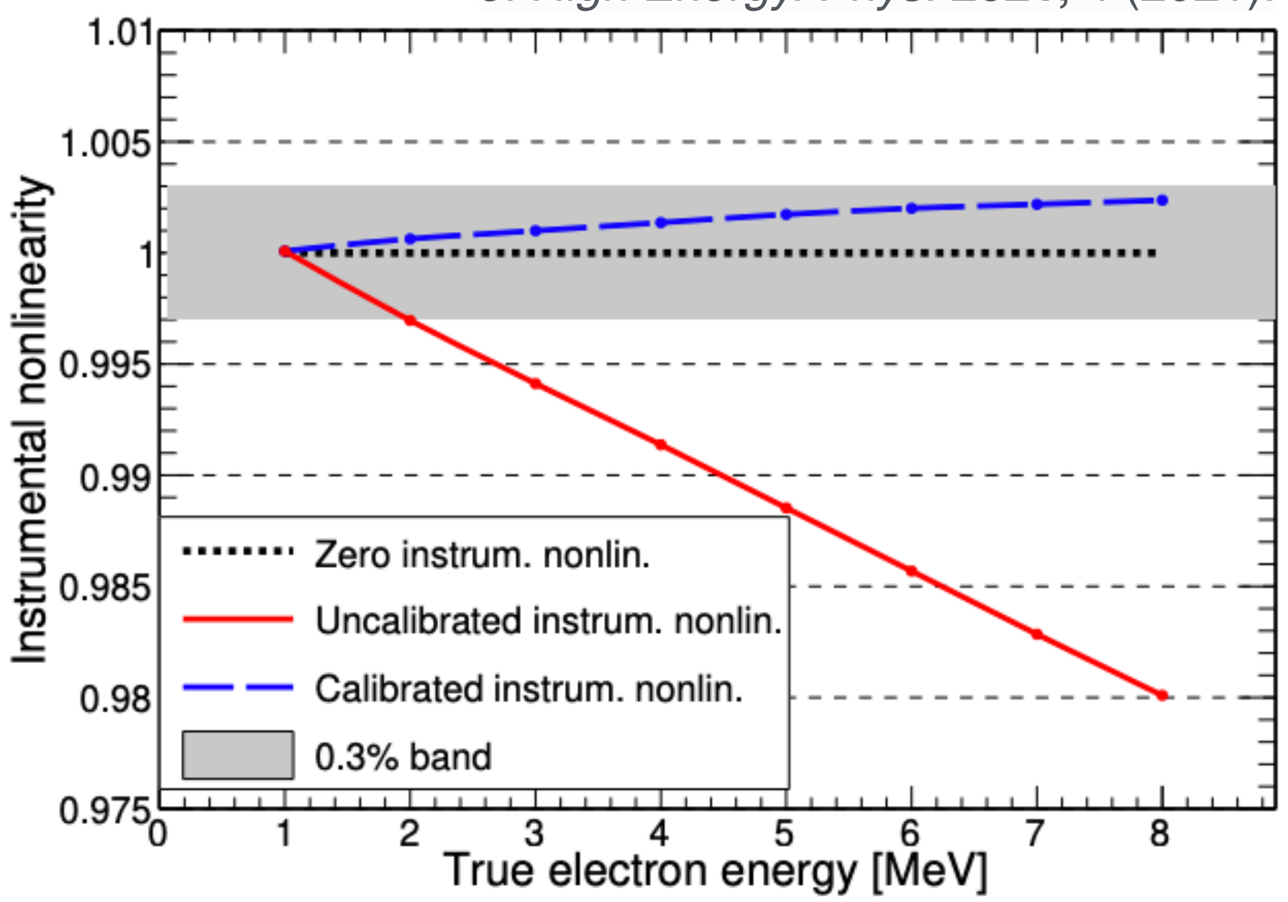
BACKUP

Calibration

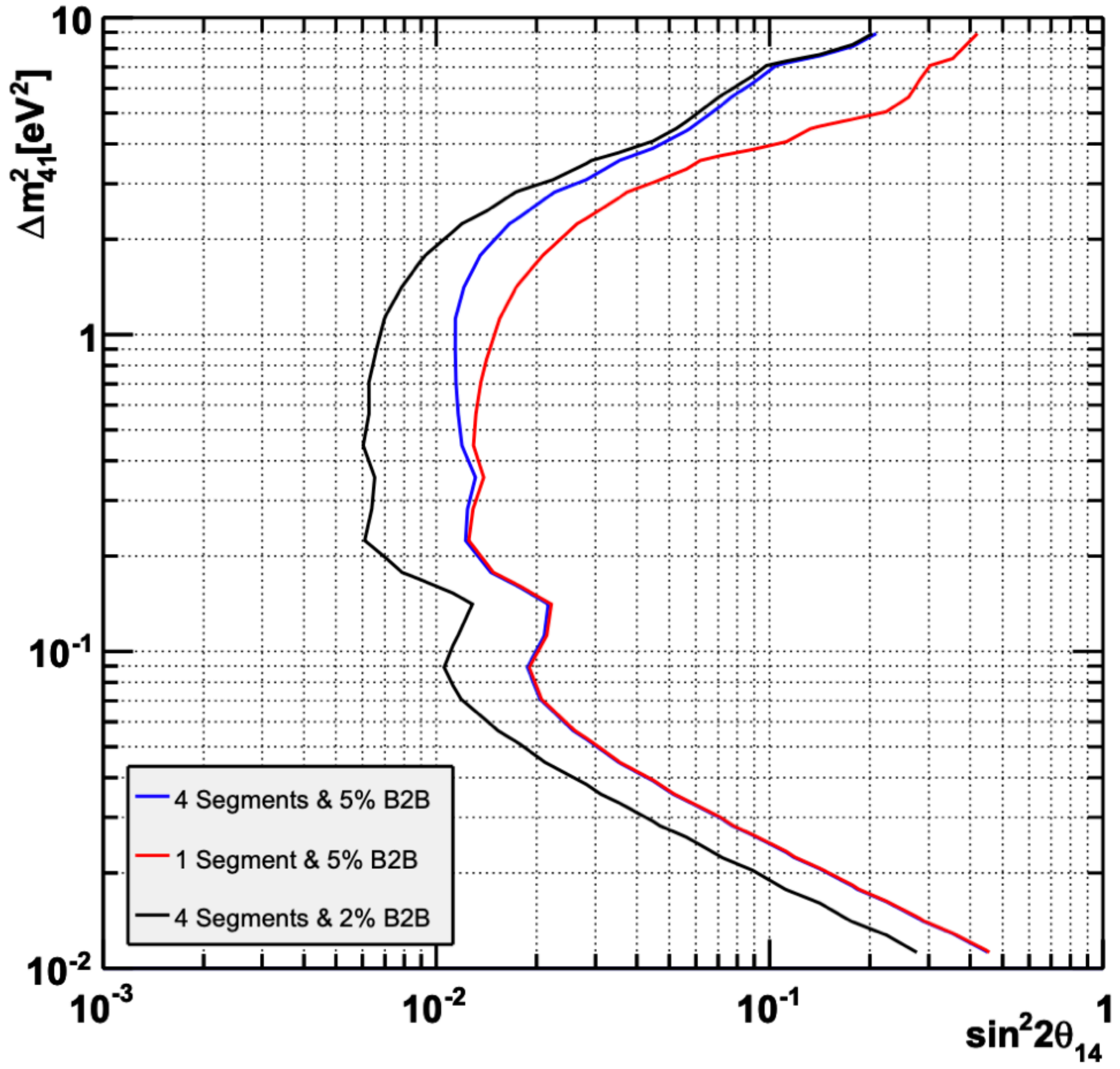
- Comprehensive calibration strategy
  - Gamma/neutron sources, cosmogenic ^{12}B and UV laser
  - Multi-positional source deployment
- SPMTs serve as linear reference for LPMT non-linearity
  - Operate in photon-counting mode for ~1-10 MeV
- Dual Calorimetry Calibration compares LPMT charge to SPMT charge under same source
  - Channel-wise LPMT charge vs. total SPMT charge
  - UV laser energies span region of interest
  - Gamma sources match time profile of neutrino (positron) signal
  - Absolute energy scale uncertainty <1%

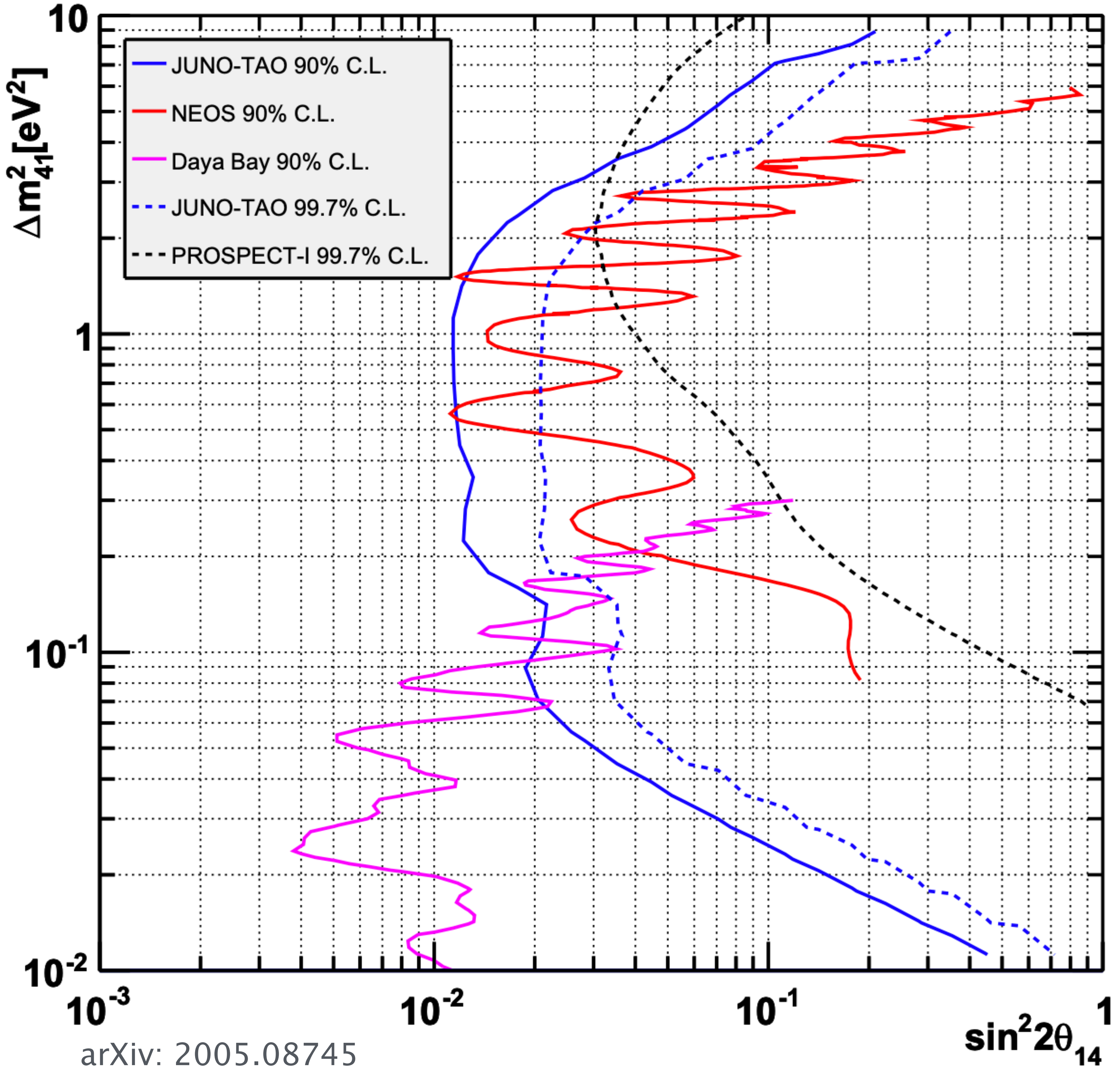


J. High Energy. Phys. **2021,** 4 (2021).



- With its short baseline, TAO has great potential in sterile oscillation searches
  - Sensitivity improved by virtual segmentation of detector



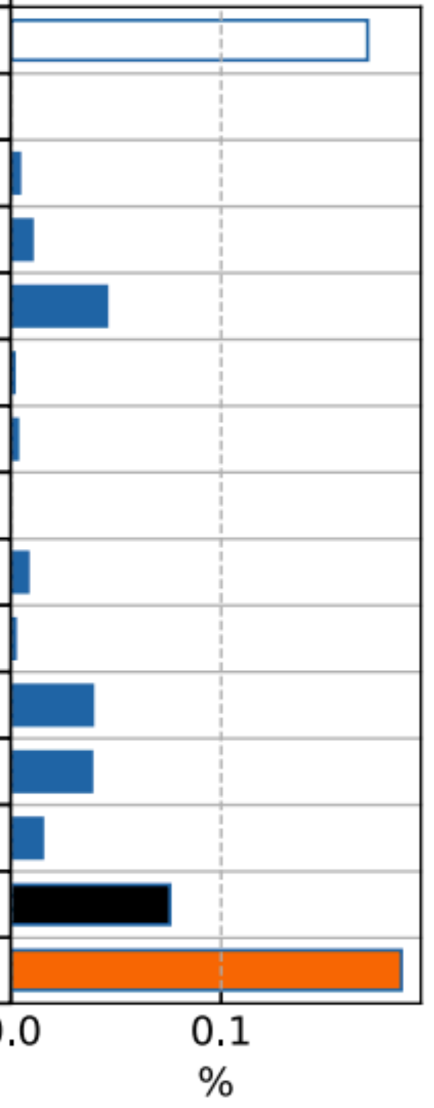


arXiv: 2005.08745

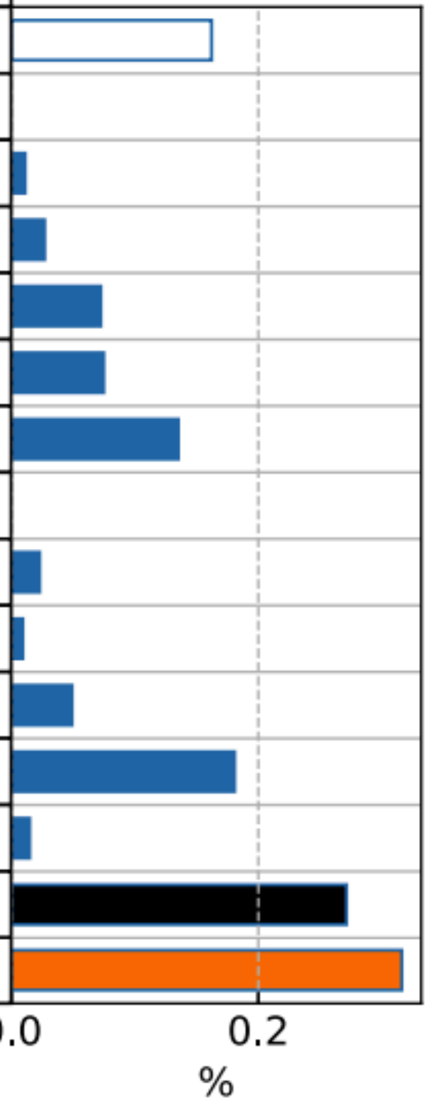
Systematics

- Updated treatment of systematics
    - Values for 6 year exposure shown
- Rate systematics mitigated by spectral shape constraint on normalization

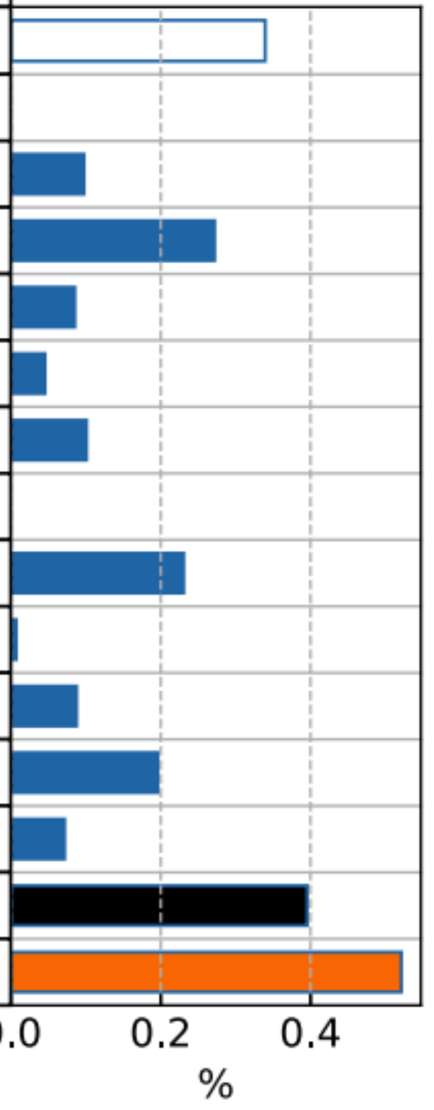
Δm^2_{31}	1σ (%)
Statistics	0.17
Reactor:	
- Uncorrelated	< 0.01
- Correlated	0.01
- Reference spectrum	0.05
- Spent Nuclear Fuel	< 0.01
- Non-equilibrium	< 0.01
Detection:	
- Efficiency	0.01
- Energy resolution	< 0.01
- Nonlinearity	0.04
- Backgrounds	0.04
Matter density	0.01
All systematics	0.08
Total	0.19



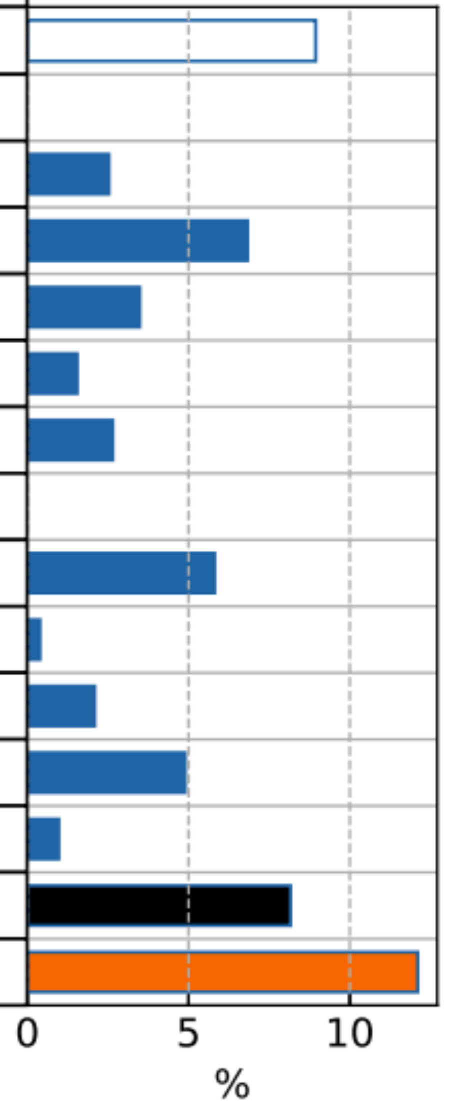
Δm^2_{21}	1σ (%)
Statistics	0.16
Reactor:	
- Uncorrelated	0.01
- Correlated	0.03
- Reference spectrum	0.07
- Spent Nuclear Fuel	0.07
- Non-equilibrium	0.14
Detection:	
- Efficiency	0.02
- Energy resolution	0.01
- Nonlinearity	0.05
- Backgrounds	0.18
Matter density	0.01
All systematics	0.27
Total	0.32



$\sin^2\theta_{12}$	1σ (%)
Statistics	0.34
Reactor:	
- Uncorrelated	0.10
- Correlated	0.27
- Reference spectrum	0.09
- Spent Nuclear Fuel	0.05
- Non-equilibrium	0.10
Detection:	
- Efficiency	0.23
- Energy resolution	0.01
- Nonlinearity	0.09
- Backgrounds	0.20
Matter density	0.07
All systematics	0.40
Total	0.52



$\sin^2\theta_{13}$	1σ (%)
Statistics	8.94
Reactor:	
- Uncorrelated	2.53
- Correlated	6.83
- Reference spectrum	3.48
- Spent Nuclear Fuel	1.55
- Non-equilibrium	2.65
Detection:	
- Efficiency	5.81
- Energy resolution	0.39
- Nonlinearity	2.09
- Backgrounds	4.89
Matter density	0.98
All systematics	8.16
Total	12.11

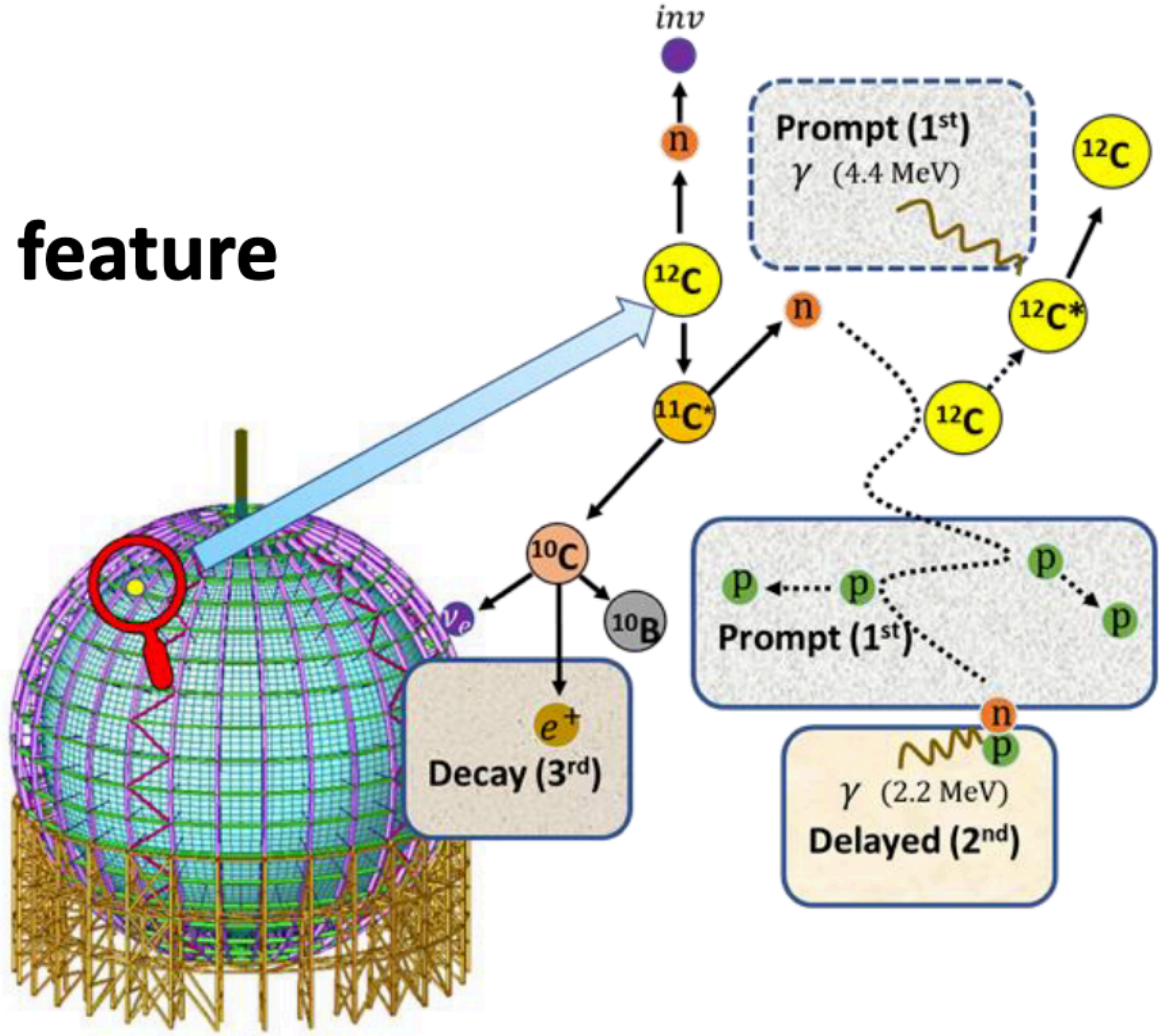


Invisible Neutron Decay

- Bounded neutrons in ^{12}C : two invisible decay modes
  - $n \rightarrow inv \ (^{12}C \rightarrow {}^{11}C^{*})$
  - $nn \rightarrow inv \ (^{12}C \rightarrow {}^{10}C^{*})$
- De-excitation modes have **triple coincidence feature**

$$^{11}C^{*} \rightarrow n + {}^{10}C \quad (Br_{n1} = 3.0\%)$$
$$^{11}C^{*} \rightarrow n + \gamma + {}^{10}C \quad (Br_{n2} = 2.8\%)$$
$$^{10}C^{*} \rightarrow n + {}^{9}C \quad (Br_{nn1} = 6.2\%)$$
$$^{10}C^{*} \rightarrow n + p + {}^{8}B \quad (Br_{nn2} = 6.0\%)$$

Yuri Kamyshkov, Edwin Kolbe PRD 67, 076007 (2003)



C. Jiang CoSSURF 2024