

Reactor Neutrinos

Part 2: The JUNO Experiment



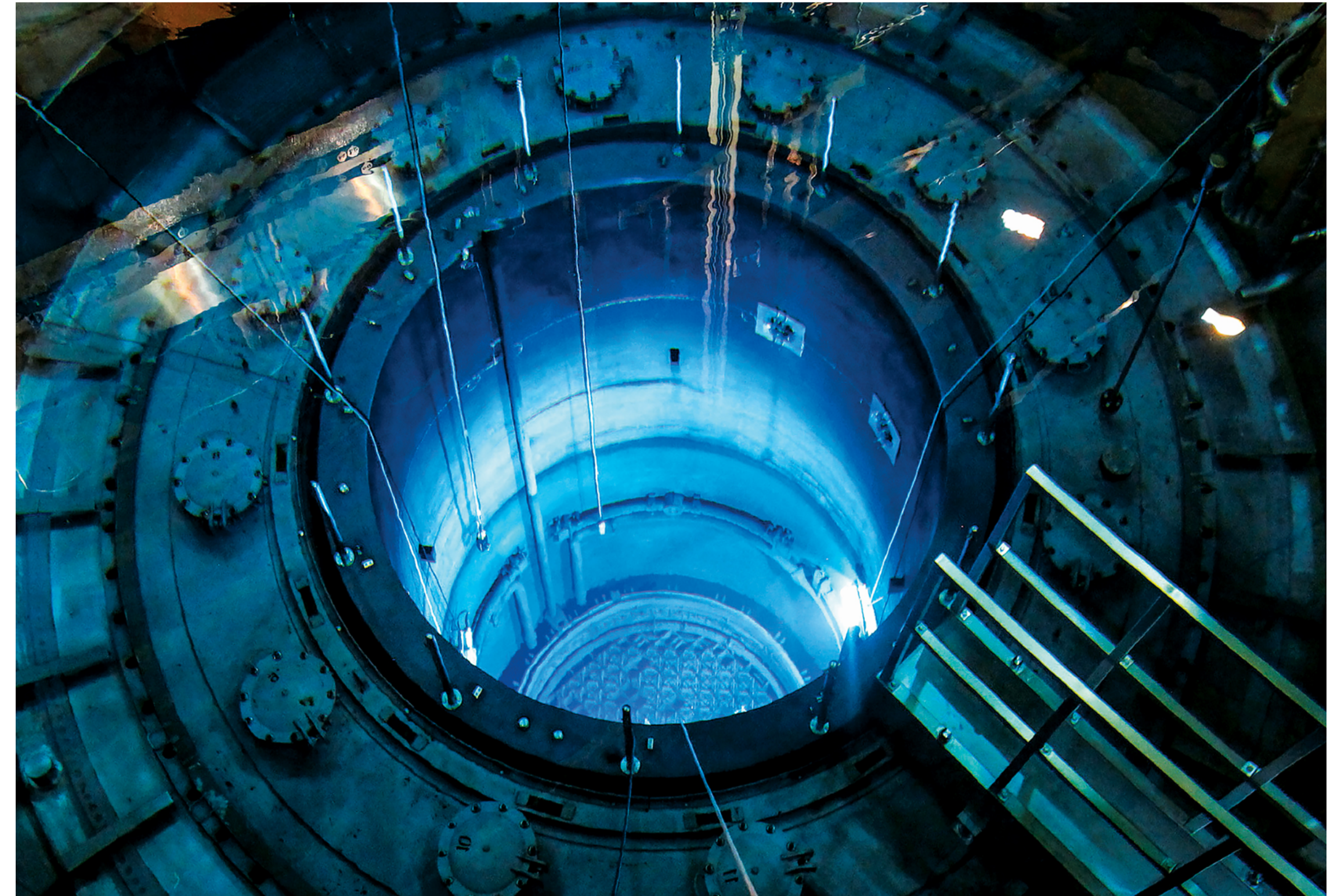
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J. Pedro Ochoa-Ricoux

International Neutrino Summer School
University of California, Santa Barbara
July 9, 2026

Outline

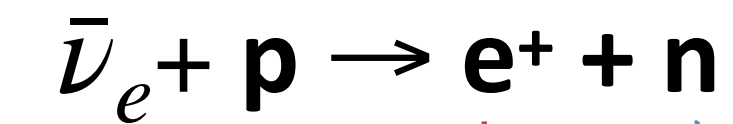
- Refresher from Part 1
- JUNO at a Glance
- Key Design Features and Construction of JUNO
- Latest Results from TAO and JUNO
- Outlook for JUNO and other projects
- Concluding Remarks



Refresher from Part 1

- Nuclear reactors are a flavor-pure ($\bar{\nu}_e$), **extremely intense** and well-understood source of electron antineutrinos
- Reactor neutrino experiments have been around since the beginning of the field
- If you know the operating conditions of a nuclear reactor, the antineutrino flux and spectral shape can be predicted to about ~2%
- The primary interaction channel is the IBD reaction:
 - The $\bar{\nu}_\mu$ and $\bar{\nu}_\tau$ resulting from oscillations do not have enough energy to trigger a similar interaction, so reactor experiments are $\bar{\nu}_e$ disappearance experiments

Inverse Beta Decay (IBD) Reaction:

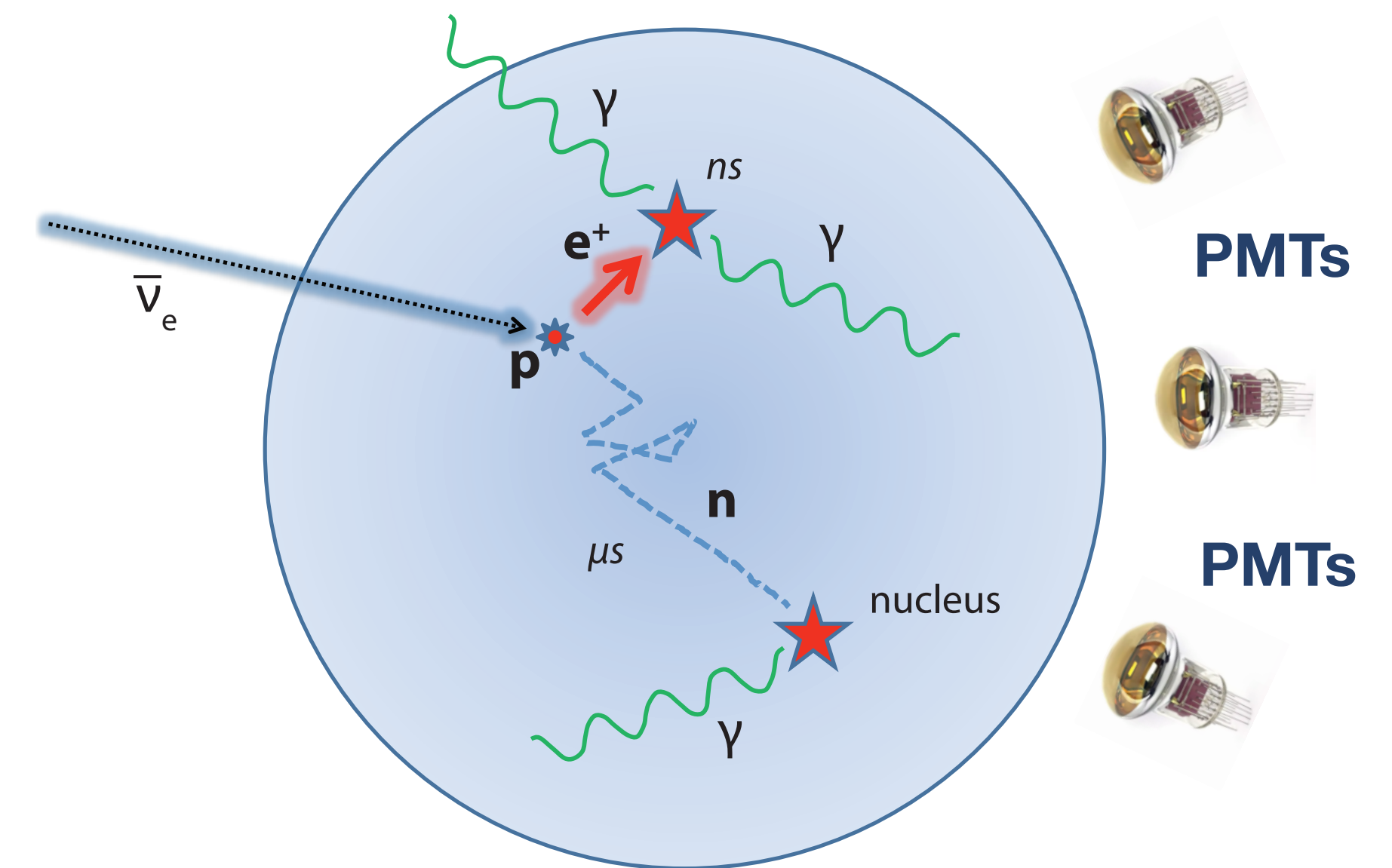


Prompt signal:

e^+ kinetic
energy loss +
annihilation

Delayed signal: n

capture on Hydrogen
(nH) or Gadolinium
(nGd) and subsequent
gamma-ray emission

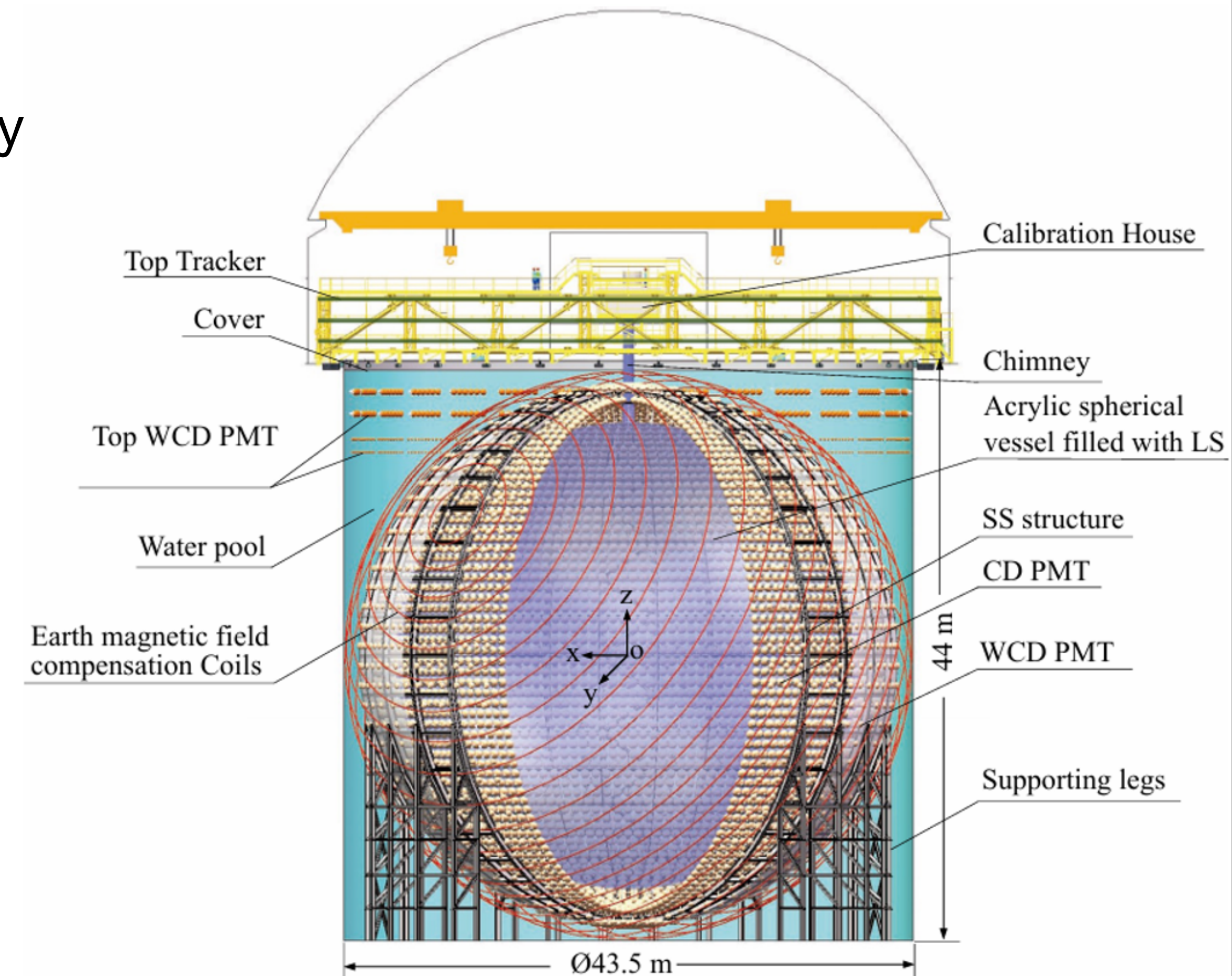
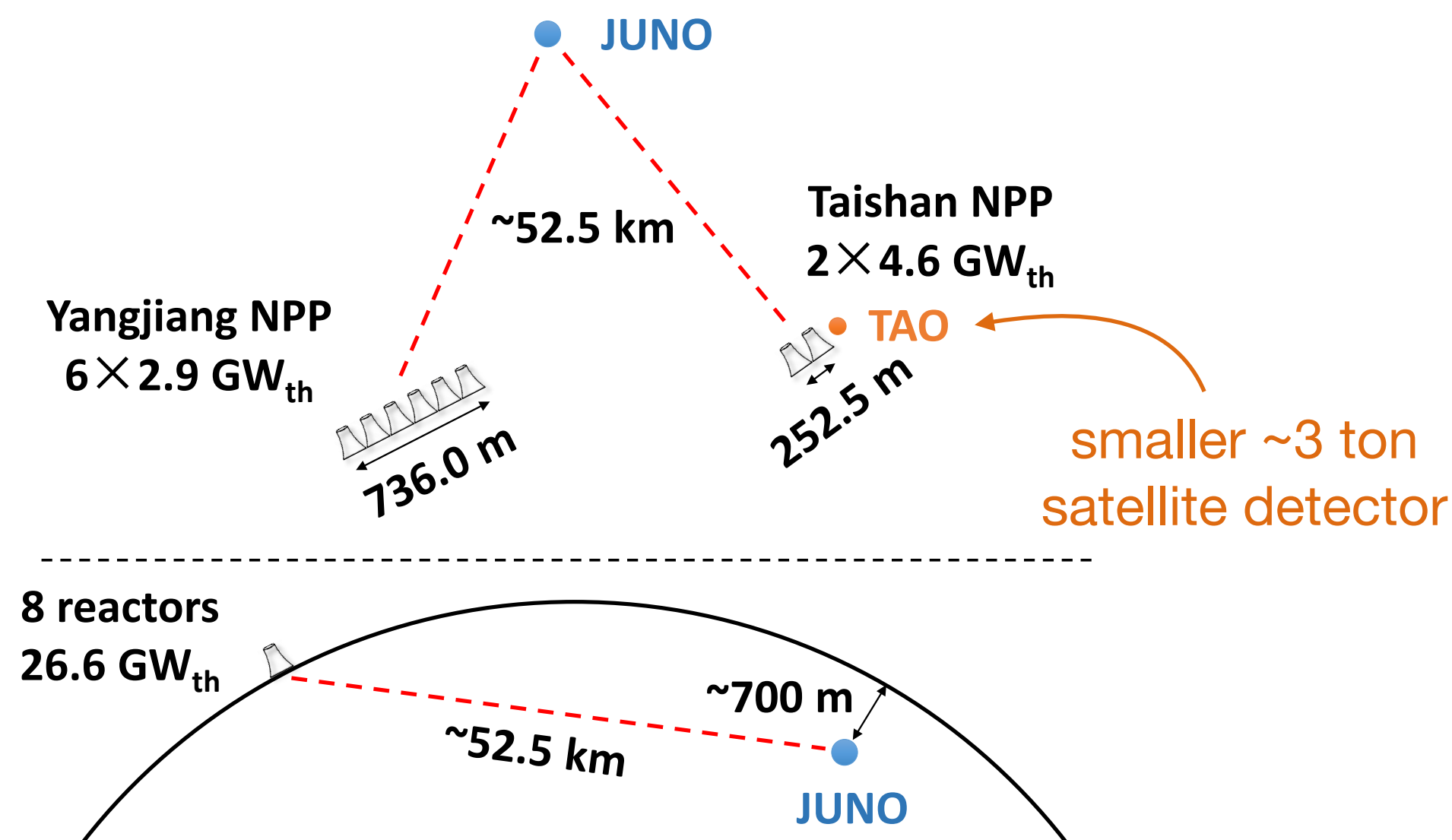


JUNO

The Basics

JUNO at a Glance

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



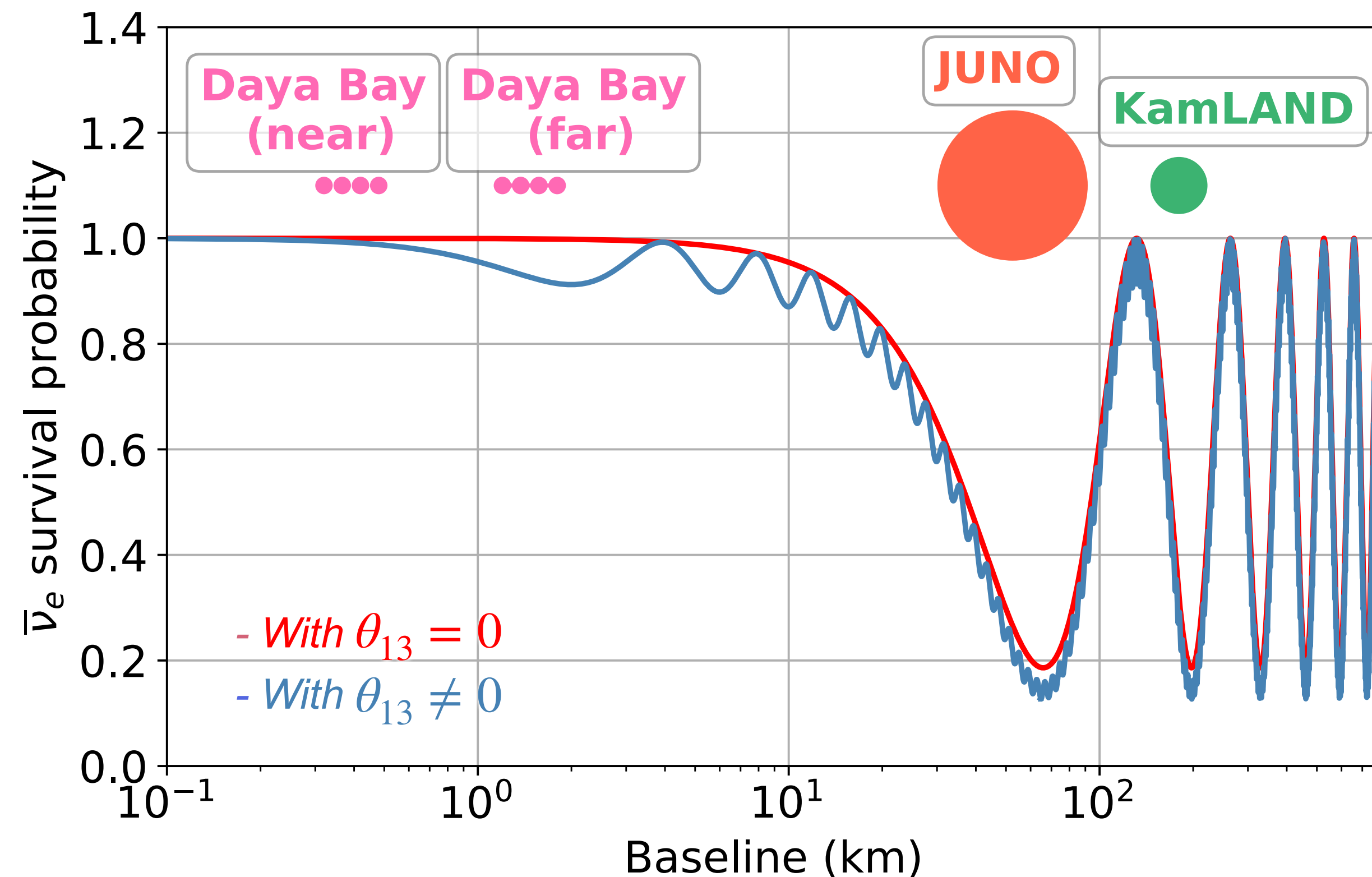
- 52.5 km from two major nuclear power plants (8 reactors)
- 35 m diameter sphere with 20 ktons of liquid scintillator (LS) surrounded by water Cherenkov detector
- Unprecedented energy resolution of 3% at 1 MeV

Reactor Antineutrino Oscillations

- Reactor neutrino experiments like JUNO study how reactor $\bar{\nu}_e$'s disappear into other flavors

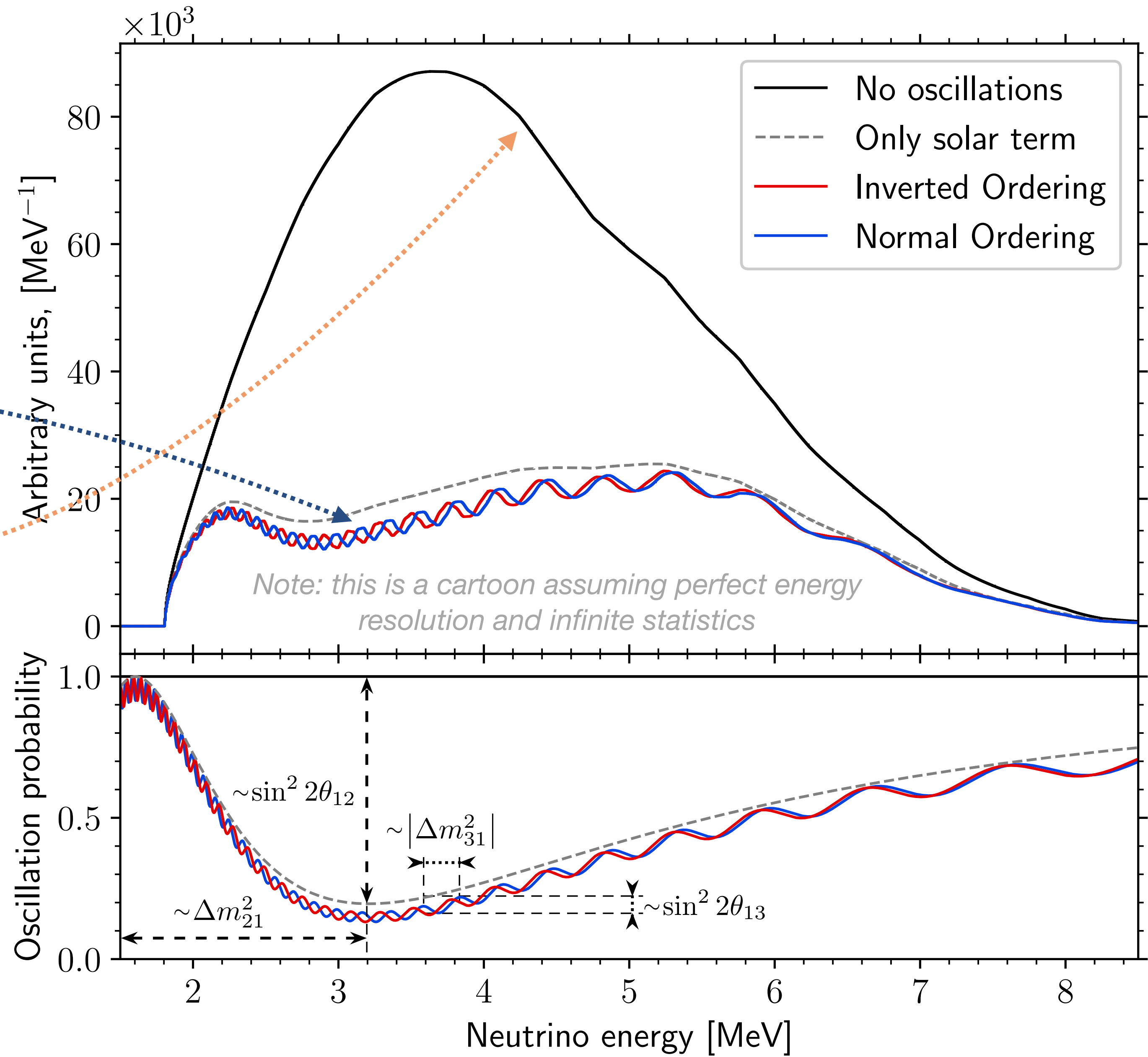
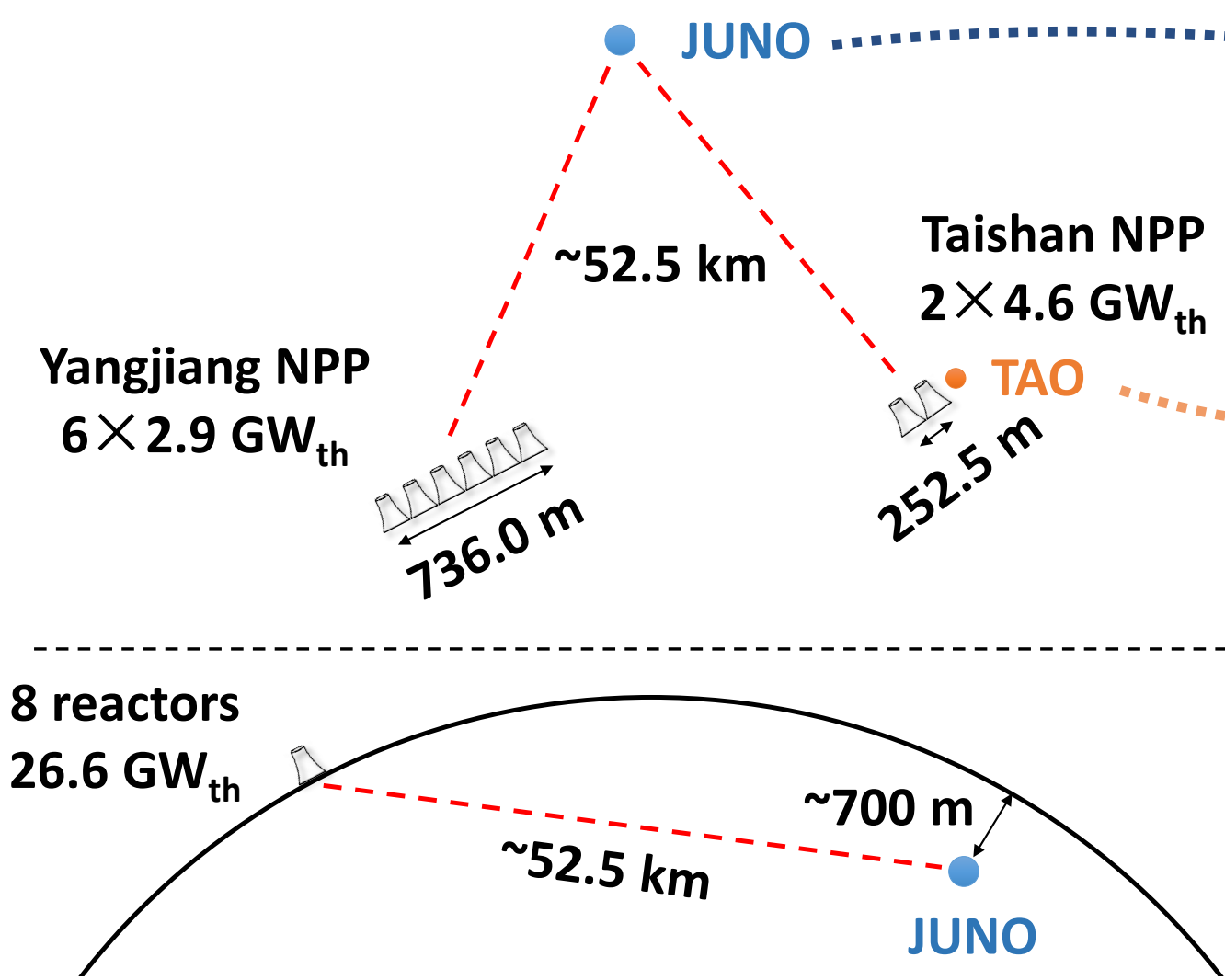
$$P_{\bar{\nu}_e \rightarrow \bar{\nu}_e}(L, E) = 1 - \sin^2 2\theta_{12} \cos^4 \theta_{13} \sin^2 \frac{\Delta m_{21}^2 L}{4E} - \sin^2 2\theta_{13} \left(\cos^2 \theta_{12} \sin^2 \frac{\Delta m_{31}^2 L}{4E} + \sin^2 \theta_{12} \sin^2 \frac{\Delta m_{32}^2 L}{4E} \right)$$

- Access to 4/6 oscillation parameters (θ_{12} , θ_{13} , Δm_{21}^2 , Δm_{31}^2) and the mass ordering
- No dependence on θ_{23} and δ_{CP}
- Baseline is set by physics goals



Basic Strategy

- JUNO measures the oscillated $\bar{\nu}_e$ spectrum
 - Mass ordering and 4 oscillation parameters can be extracted independently, with negligible correlations
- A satellite detector (JUNO TAO) constraints the shape of the unoscillated reactor $\bar{\nu}_e$ spectrum
 - Designed to attain even better energy resolution of 2% @ 1 MeV



Chin. Phys. C 49, 0033104 (2025)

The JUNO Detector

Key Design Features and Construction

Key Feature: High Statistics

What it takes: proximity to 8 nuclear reactors and **unprecedented size**

evolution of LS detectors

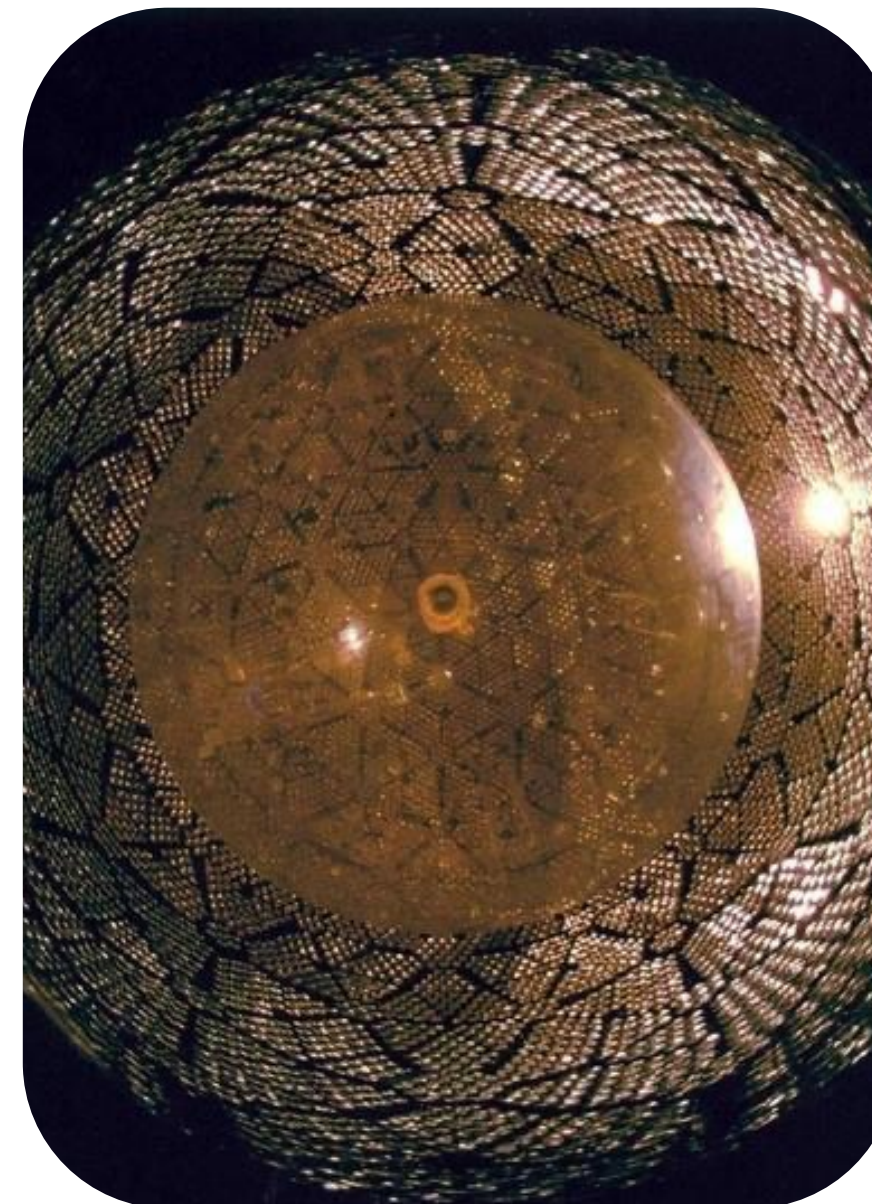
Reines &
Cowan
300 L



Daya Bay
8 x 20 t

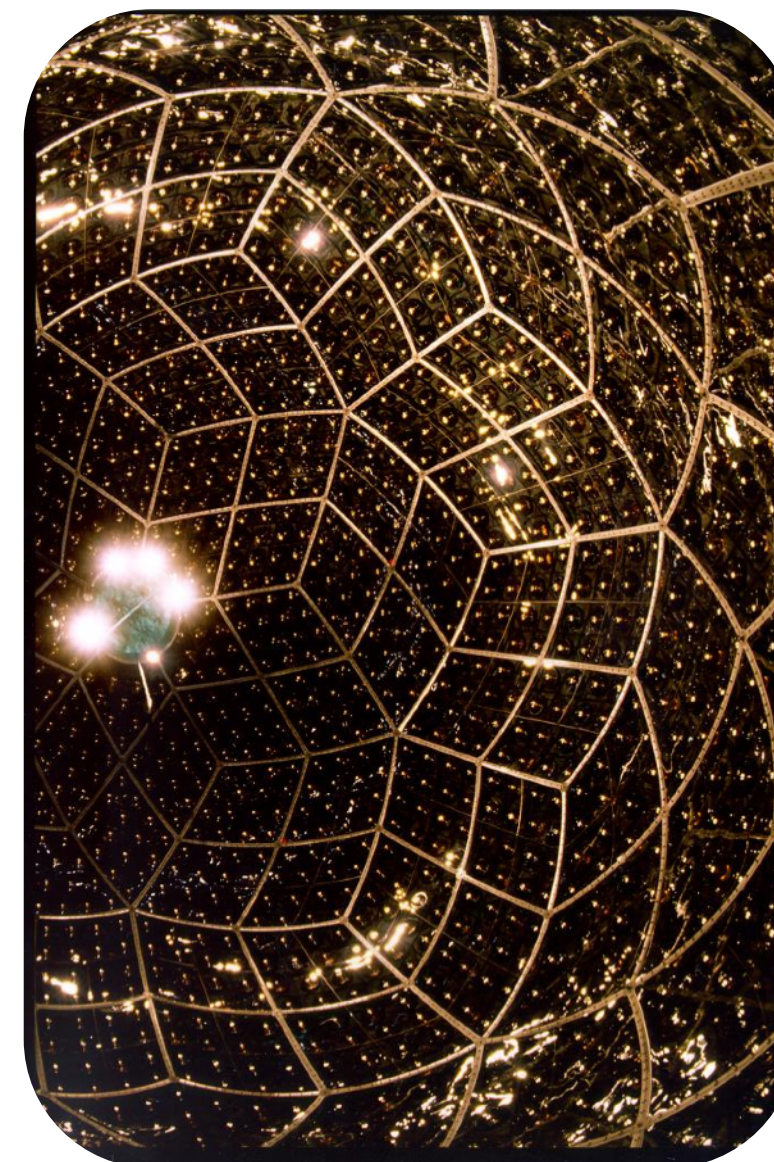


Borexino 300 t

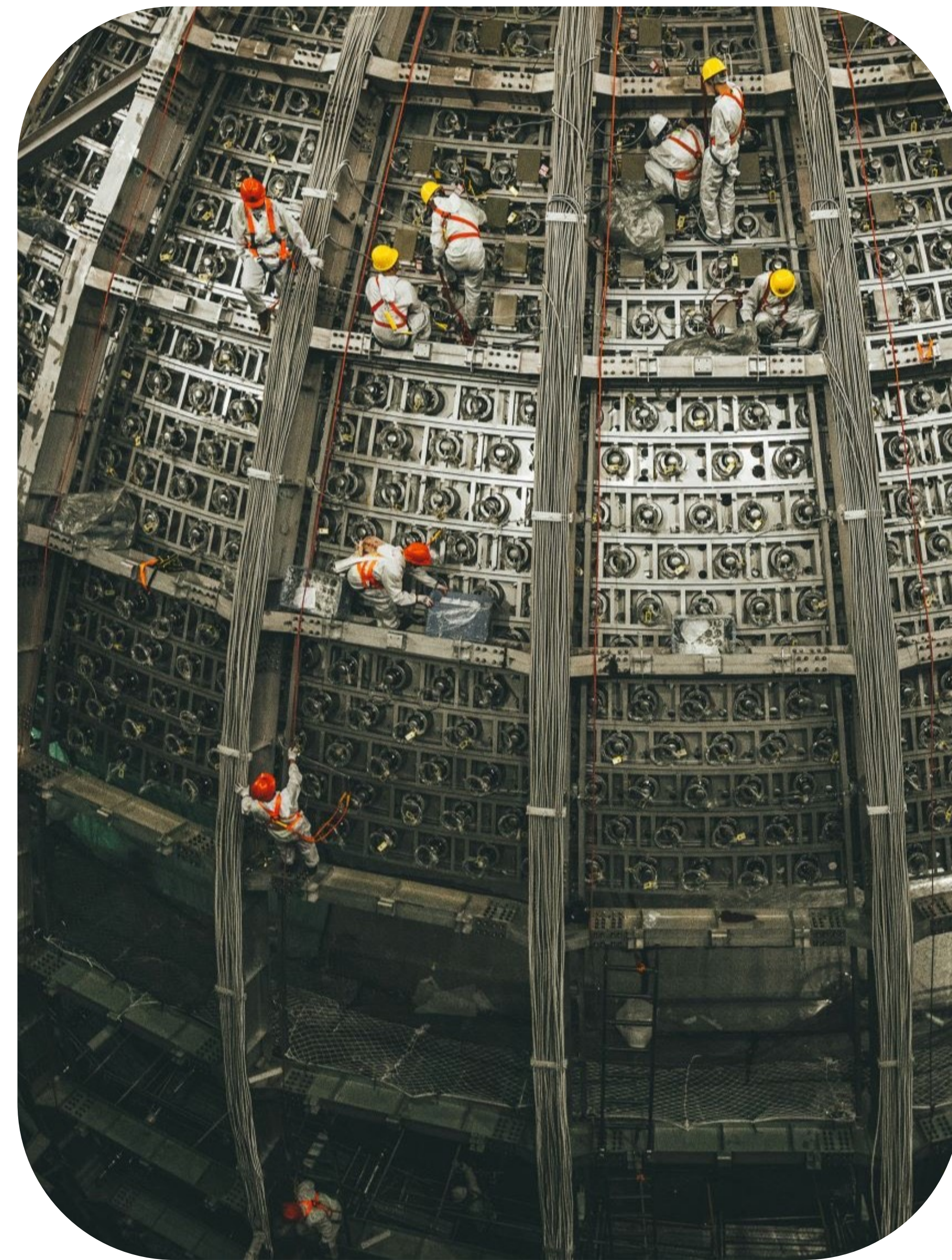


SNO+ 780 t

KamLAND 1,000 t



JUNO 20,000 t



Experimental Site

- JUNO campus had to be created from scratch at 52.5 km from the eight nuclear reactors
- Civil construction started in 2015, completed in 2021
- Challenging operation:
 - 650 m overburden
 - Encountered more water than anticipated



Key Feature: Energy Resolution

- With a target 3% @ 1 MeV, JUNO is the LS detector with the best energy resolution in history

What it takes: **high light yield** and **comprehensive calibration**

$$\frac{\sigma(E)}{E} = \sqrt{\frac{\sigma_{\text{stoch}}^2}{E} + \sigma_{\text{non-stoch}}^2}$$

stochastic term: depends on photostatistics

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

- Need to detect at least 1200 photoelectrons (PE) per MeV of energy deposition
 - No approach can singlehandedly provide all the light needed. Have to attack the problem from different angles:

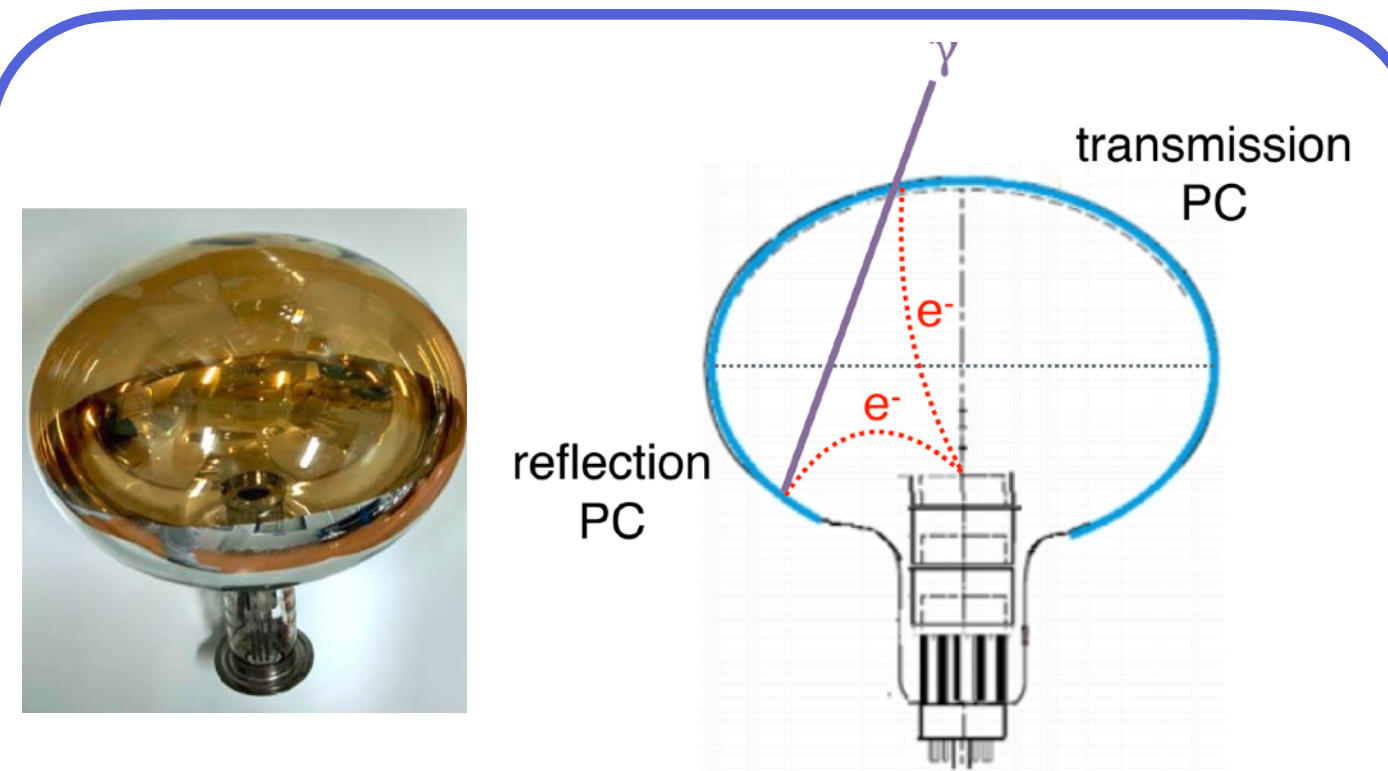
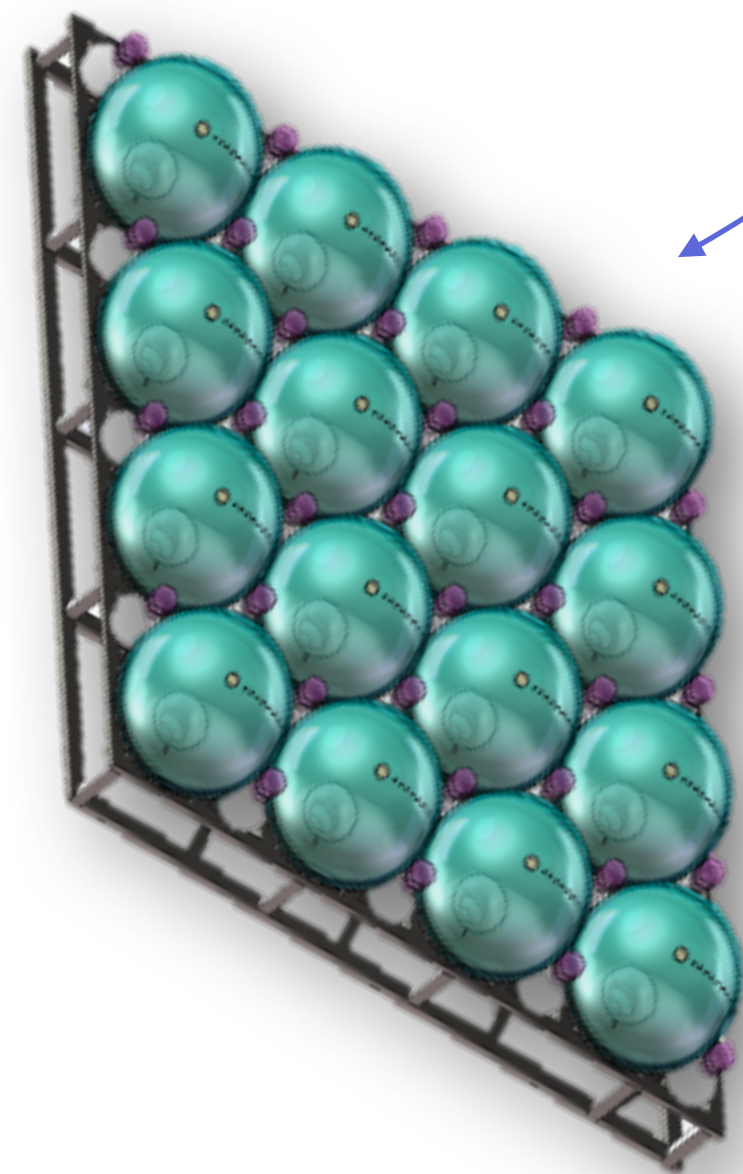
	KamLAND	JUNO	Relative Gain	use KamLAND as reference
Total light level	250 PE / MeV	>1200 PE / MeV	5	target
Photocathode coverage	34%	~78%	~2	lots of PMTs
Light yield	1.5 g/l PPO	2.5 g/l PPO	~1.5	optimized LS
Attenuation length / R	15/16 m	20/35 m	~0.8	
PMT QE×CE	20%×60% ~ 12%	~30%	~2	more efficient PMTs

Large and Small PMT Systems

17,596 large 20-inch PMTs serve as the main light-detection device

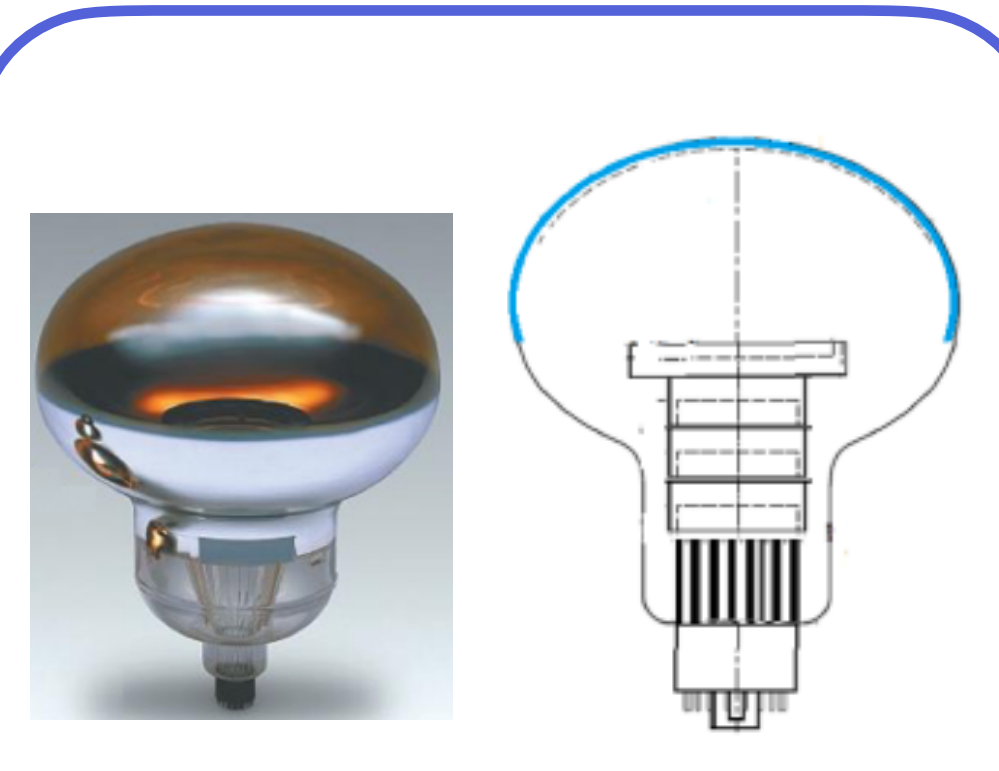
2 complementary (and new!) technologies:

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



Microchannel plate (MCP)-PMTs
(approximately 13,000)

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



Dynode-PMTs
(approximately 5,000)

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

Both reach detection efficiency ~ 30%!

25,600 3-inch PMTs are placed in between the large PMTs



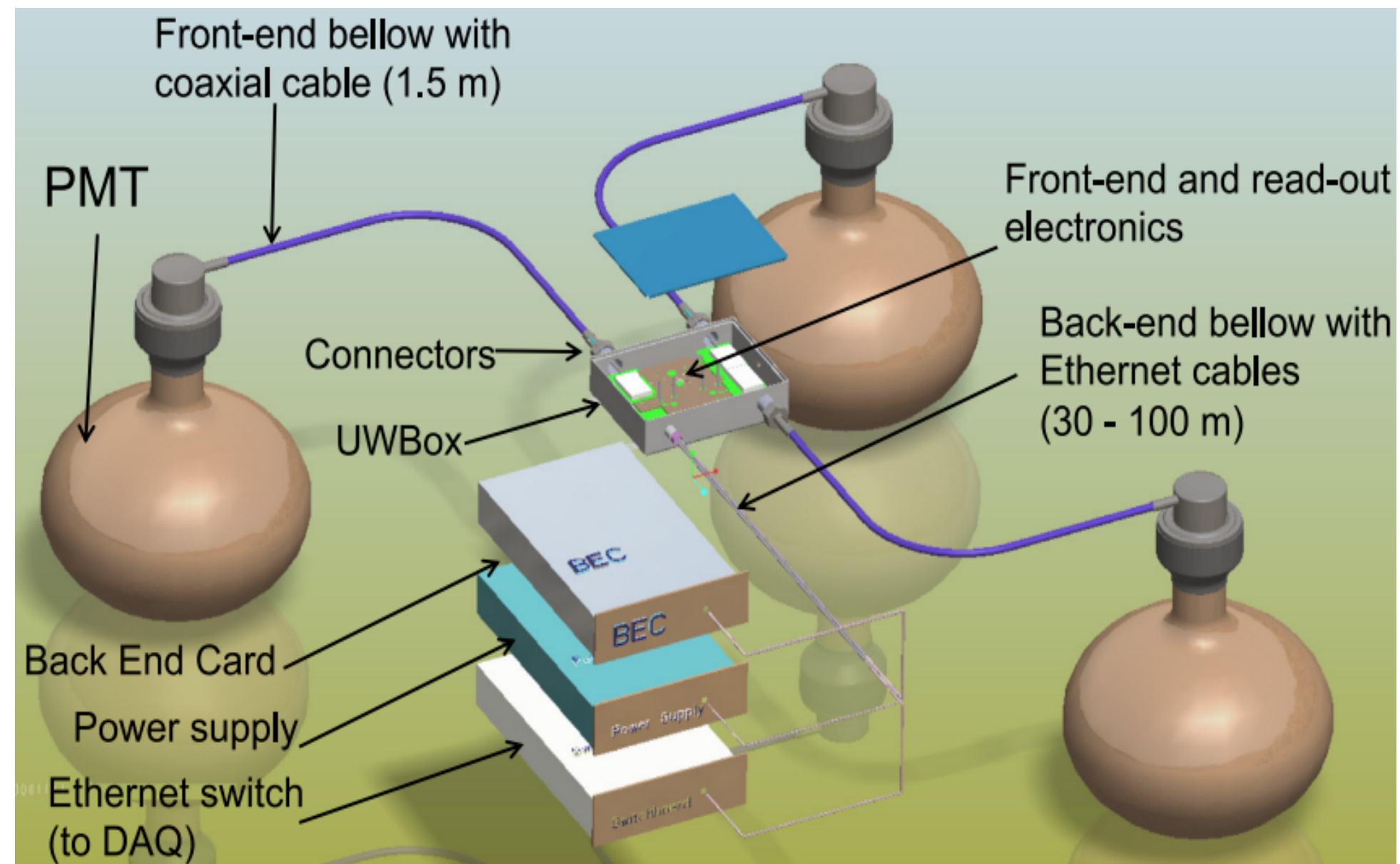
works with calibration system by serving as linear reference for large PMTs

+ increase light collection and enhance reconstruction capabilities

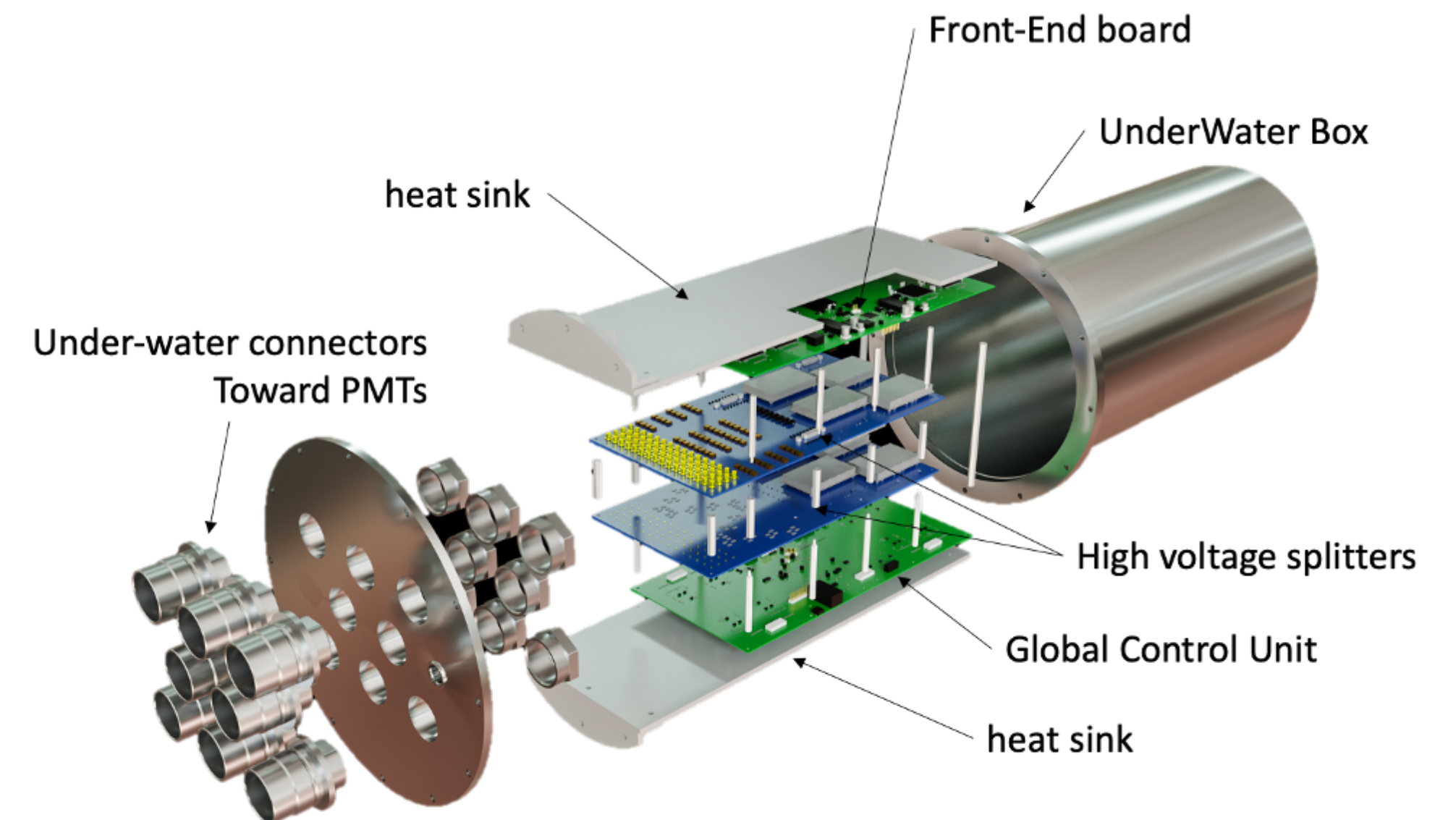
PMT Electronics

- For better signal to noise ratio, LPMT and sPMT frontend electronics are underwater
 - In stainless steel boxes connected to the surface via bellows
 - Power the PMTs, decouple signal from HV, process the analog signals and send the information to surface via digital cables

LPMT System
(3 LPMTs per underwater box)



sPMT System
(128 sPMTs per underwater box)

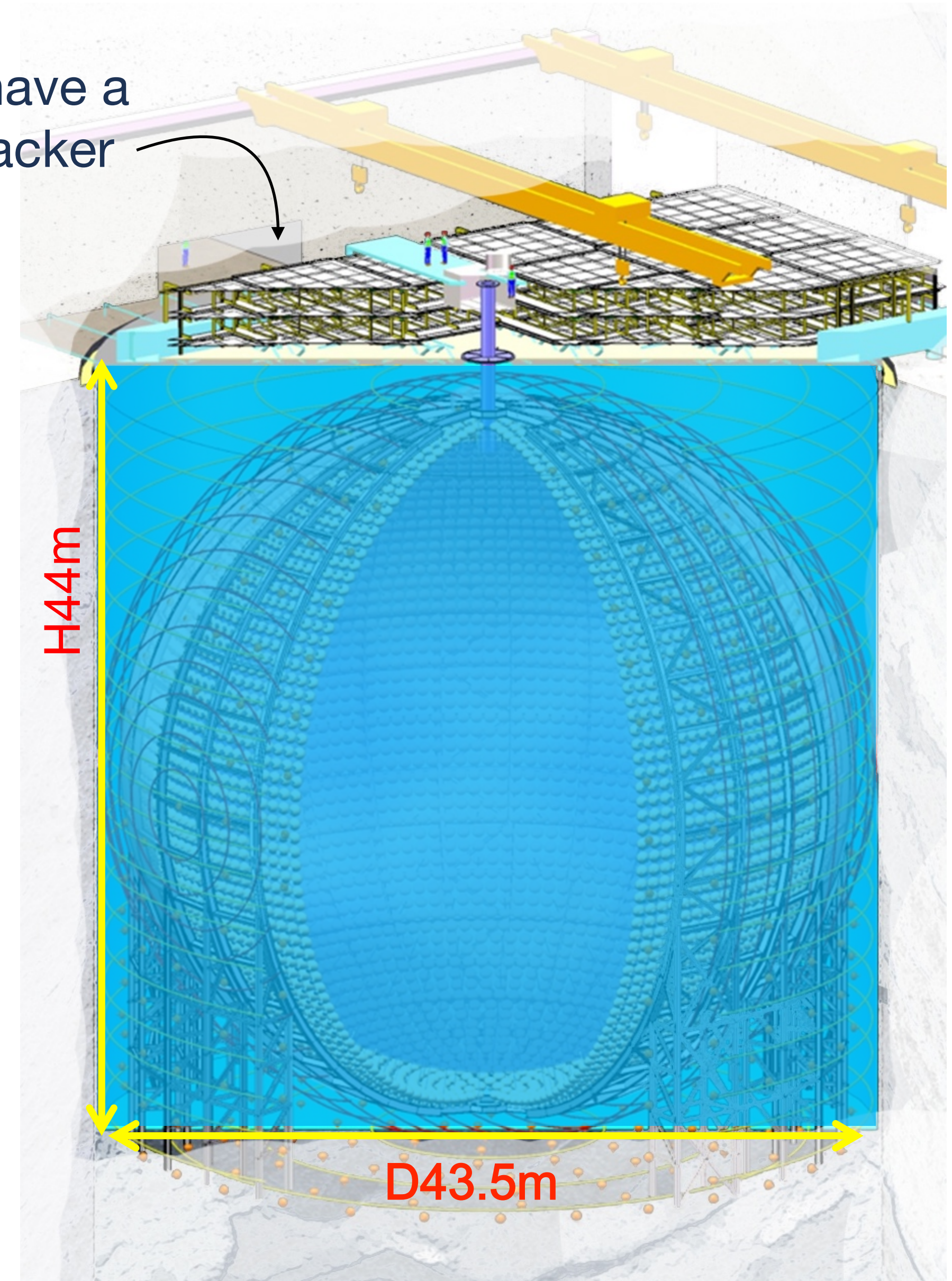


Key Feature: Low Background

What it takes: depth (650 m overburden),
radioactivity control, cleaning, veto system

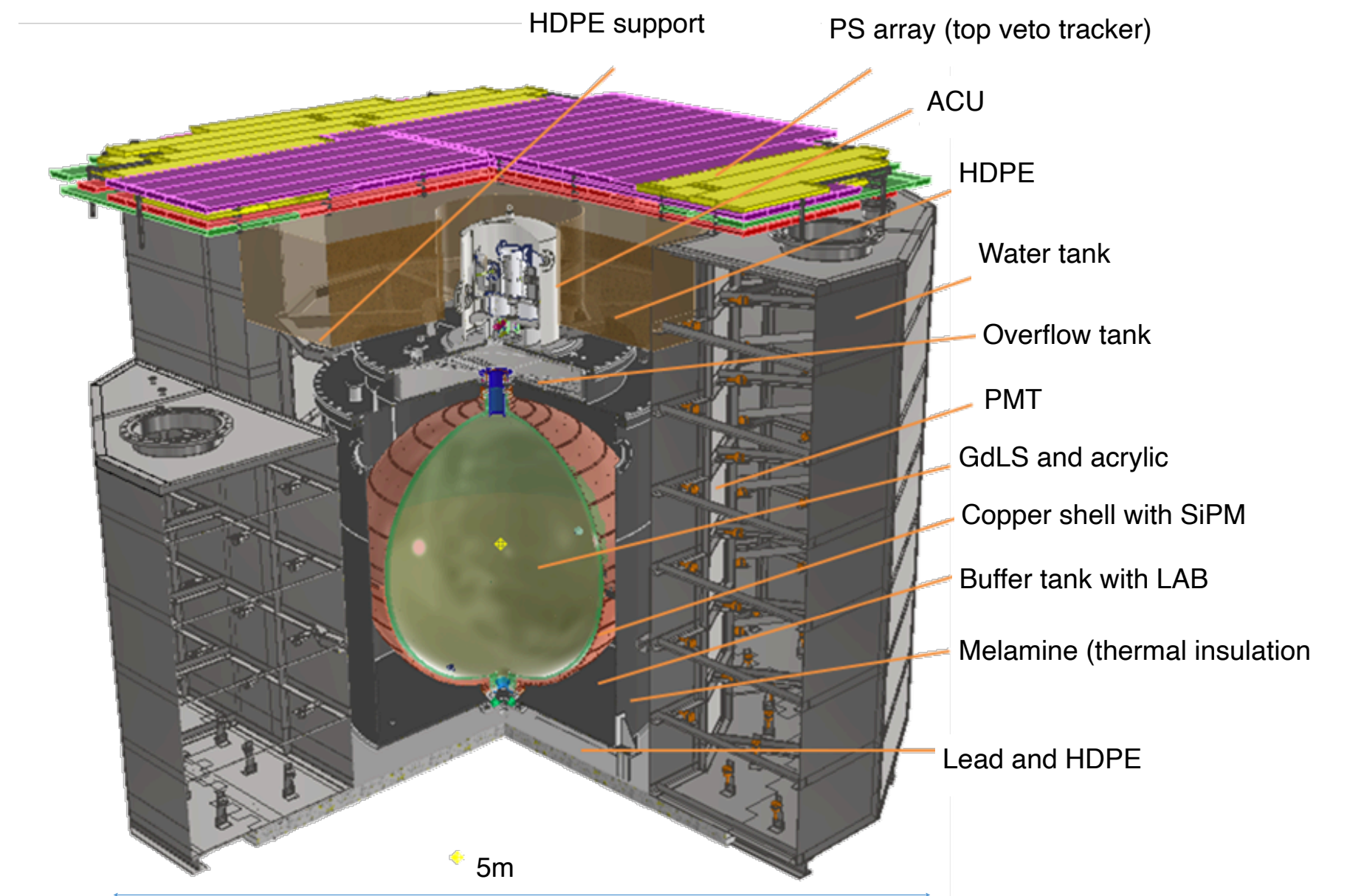
- Central detector is immersed in a cylindrical, instrumented water pool
 - Double purpose: shields the detector and allows to reconstruct cosmic-ray muons (>99.9% efficiency)
- Measures for radiopurity control:
 - Material screening, production handling, clean room during installation, acrylic surface treatment
- LS production chain includes four purification plants and stringent QA/QC

Also have a
top tracker



TAO Satellite Detector

- JUNO also deployed a satellite detector called the Taishan Antineutrino Observatory (TAO)
 - 44 m from one of the 4.6 GW_{th} reactors
 - 2.8 ton (1 ton fiducial) Gd-LS volume
 - SiPM and Gd-LS at -50°C
 - < 2% @ 1 MeV energy resolution



Main Goals:

- Measure reactor antineutrino spectrum with unprecedented energy resolution (reveal fine structure for the first time)
- Search for sterile neutrinos
- Isotopic yield and energy spectrum measurements

**Begun data
taking in
February 2026!!**

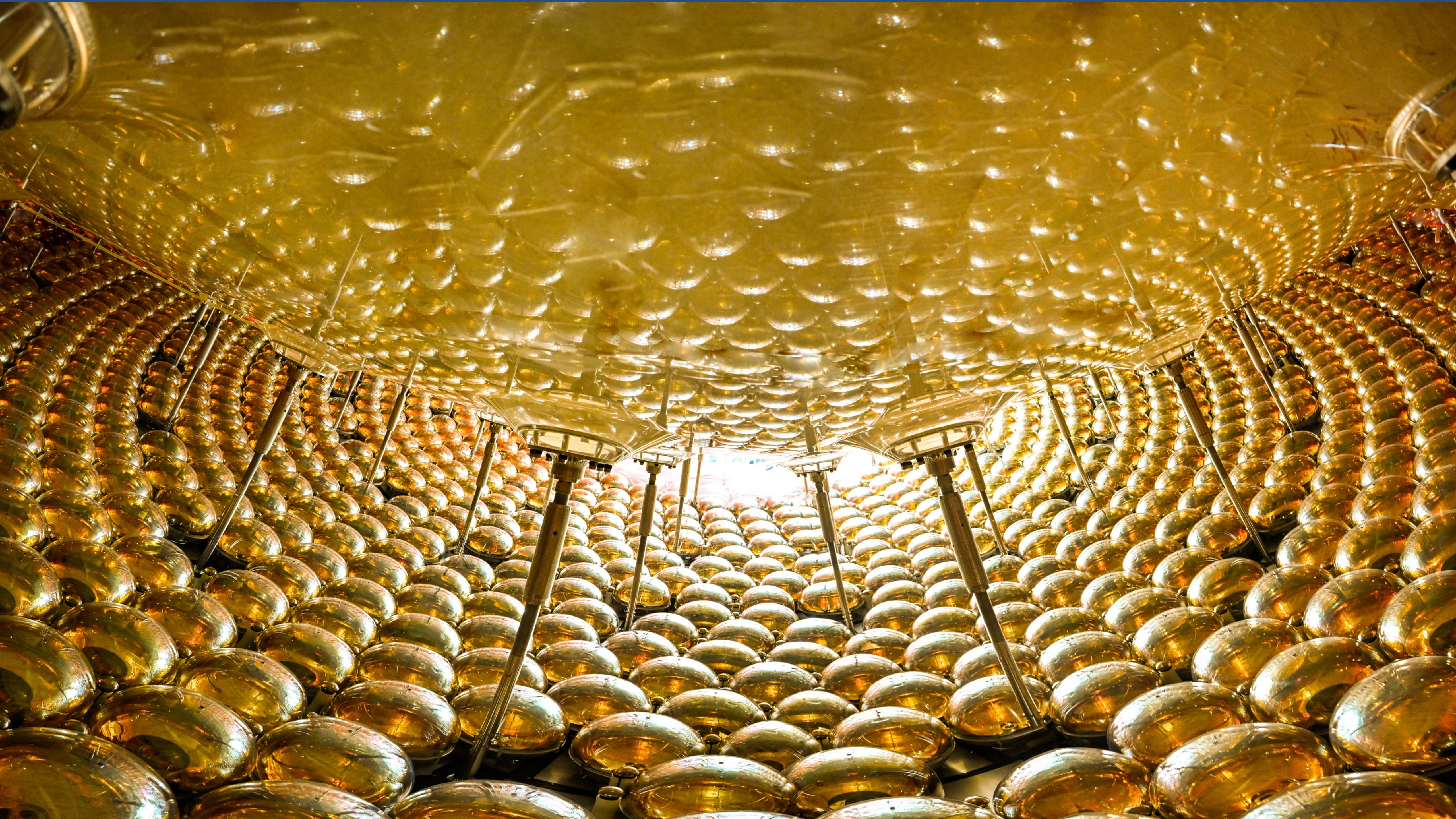


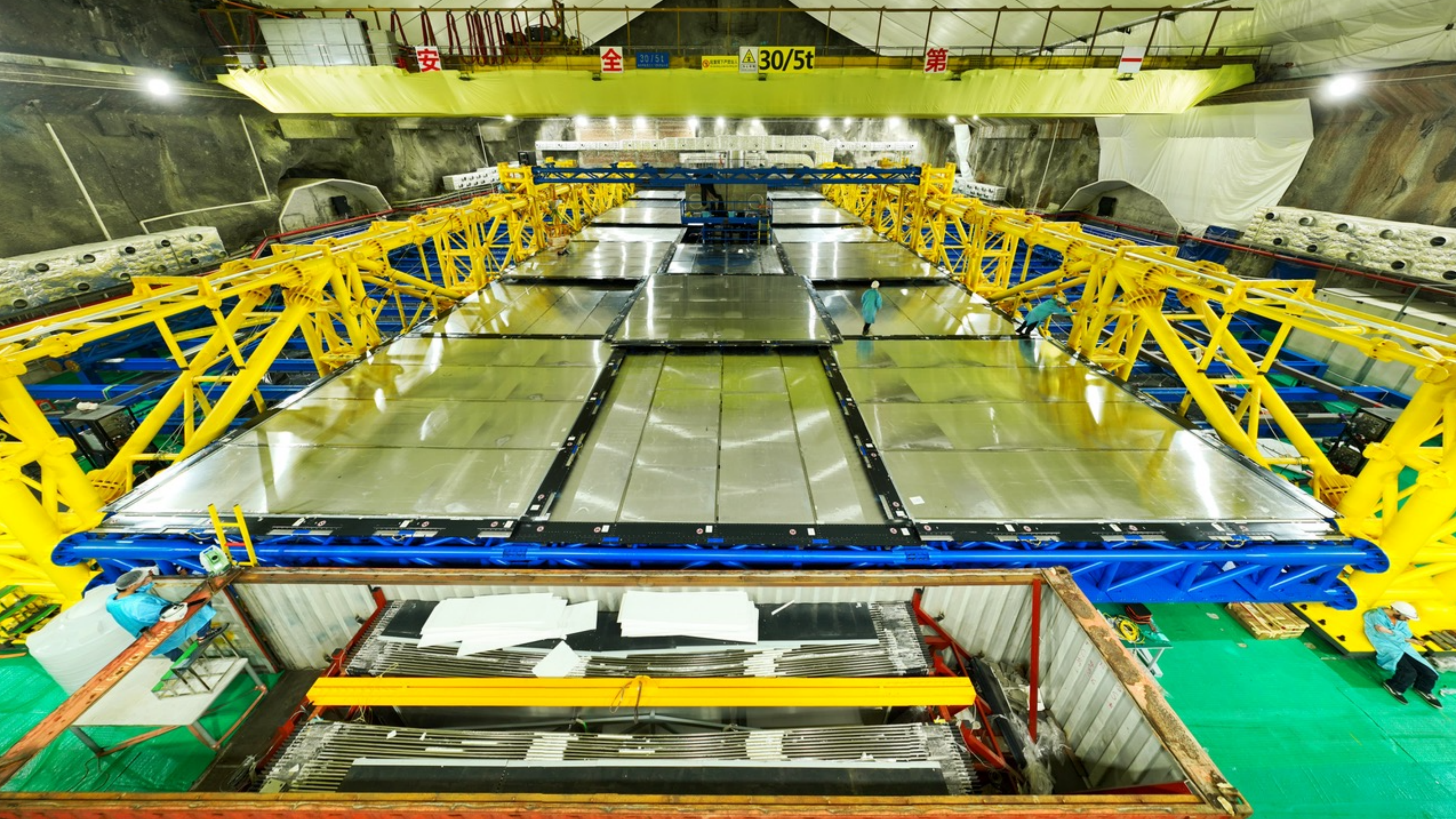
arXiv:2005.08745



Inside the Acrylic Sphere







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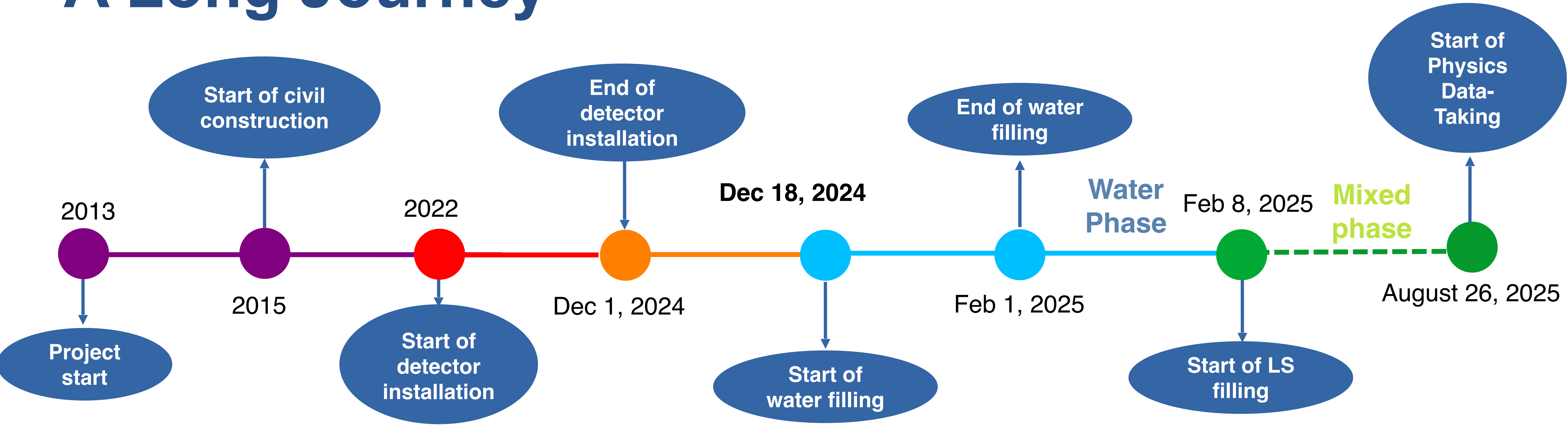
全

30/5t

30/5t

第

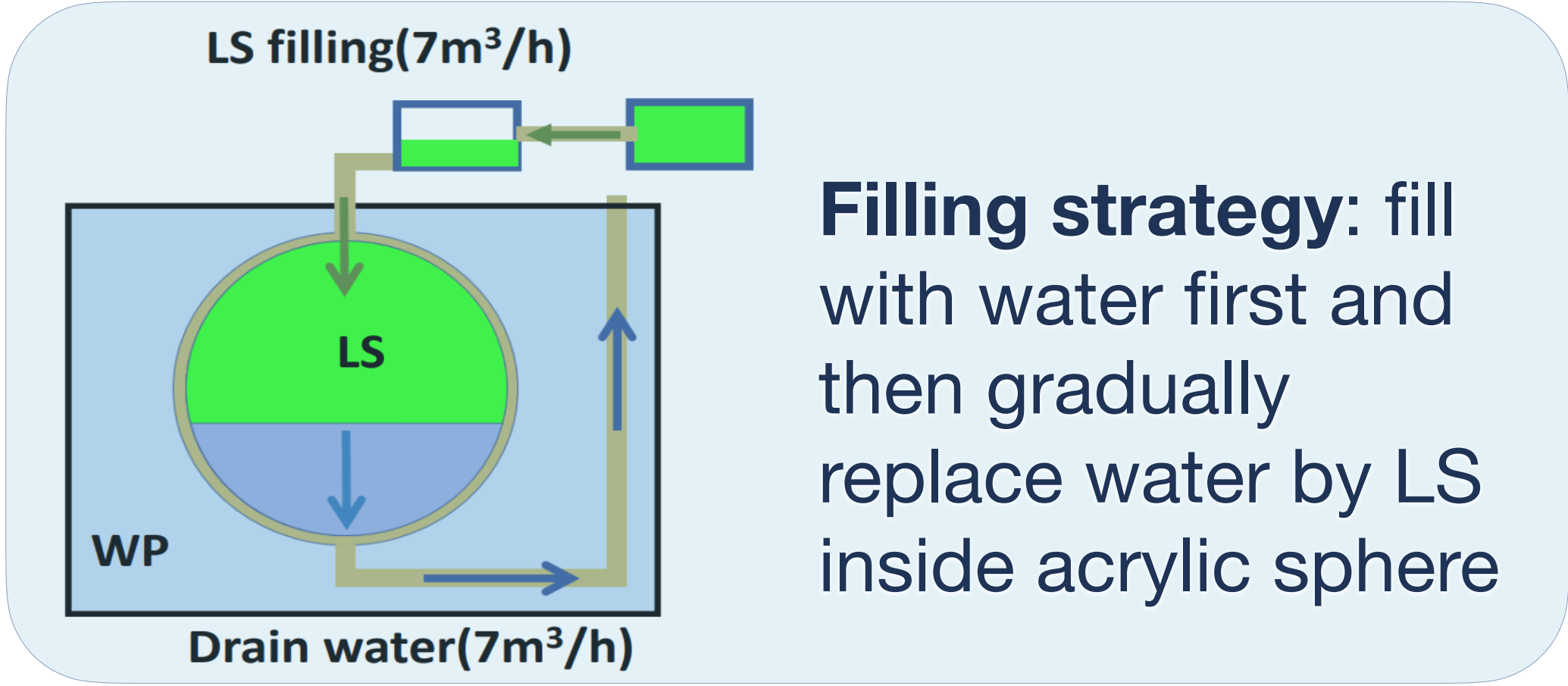
A Long Journey



Start of Detector Installation



Detector Ready for Filling

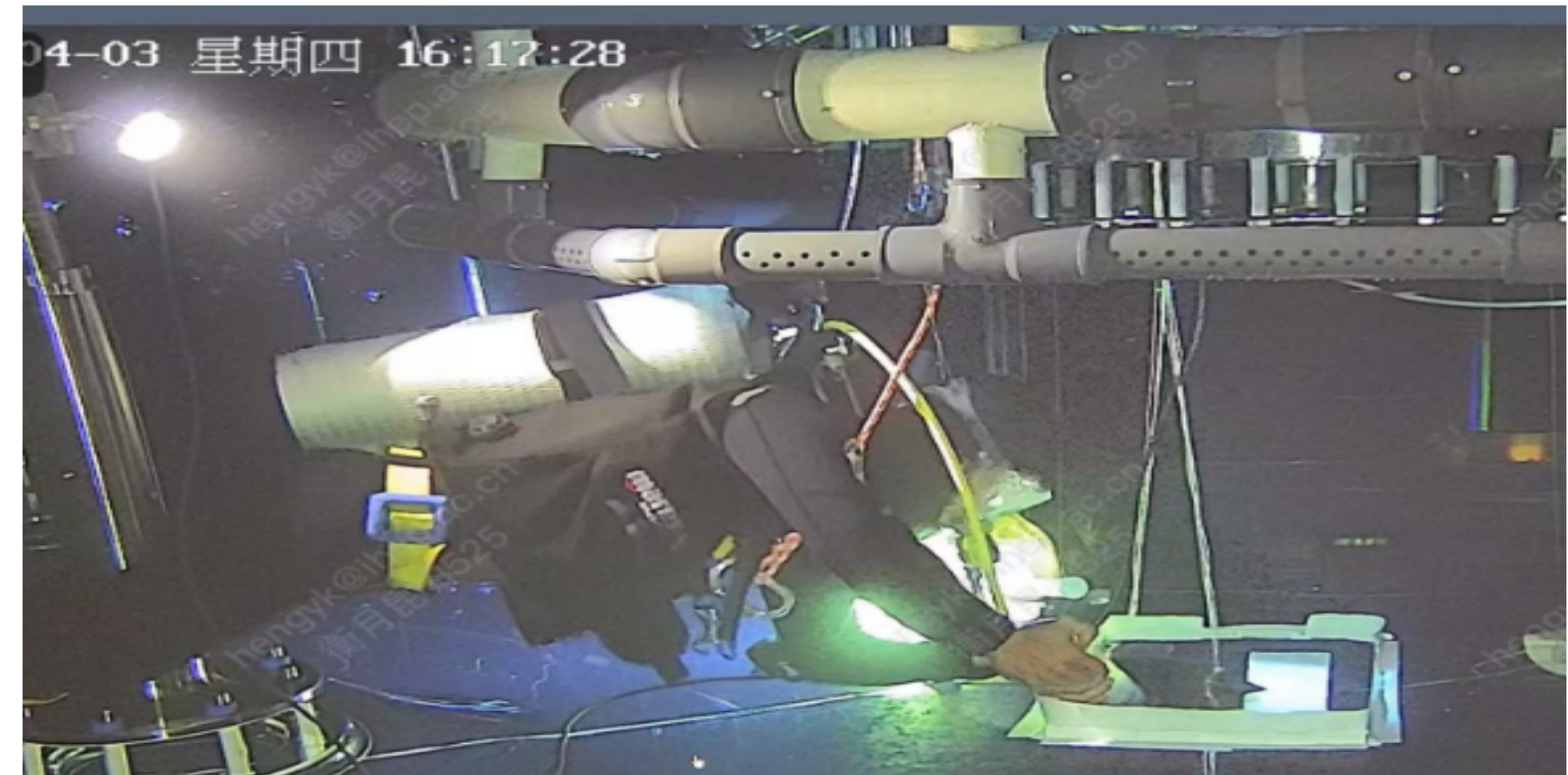


Detector Calibration and Performance

Latest Status

Acrylic Leaks

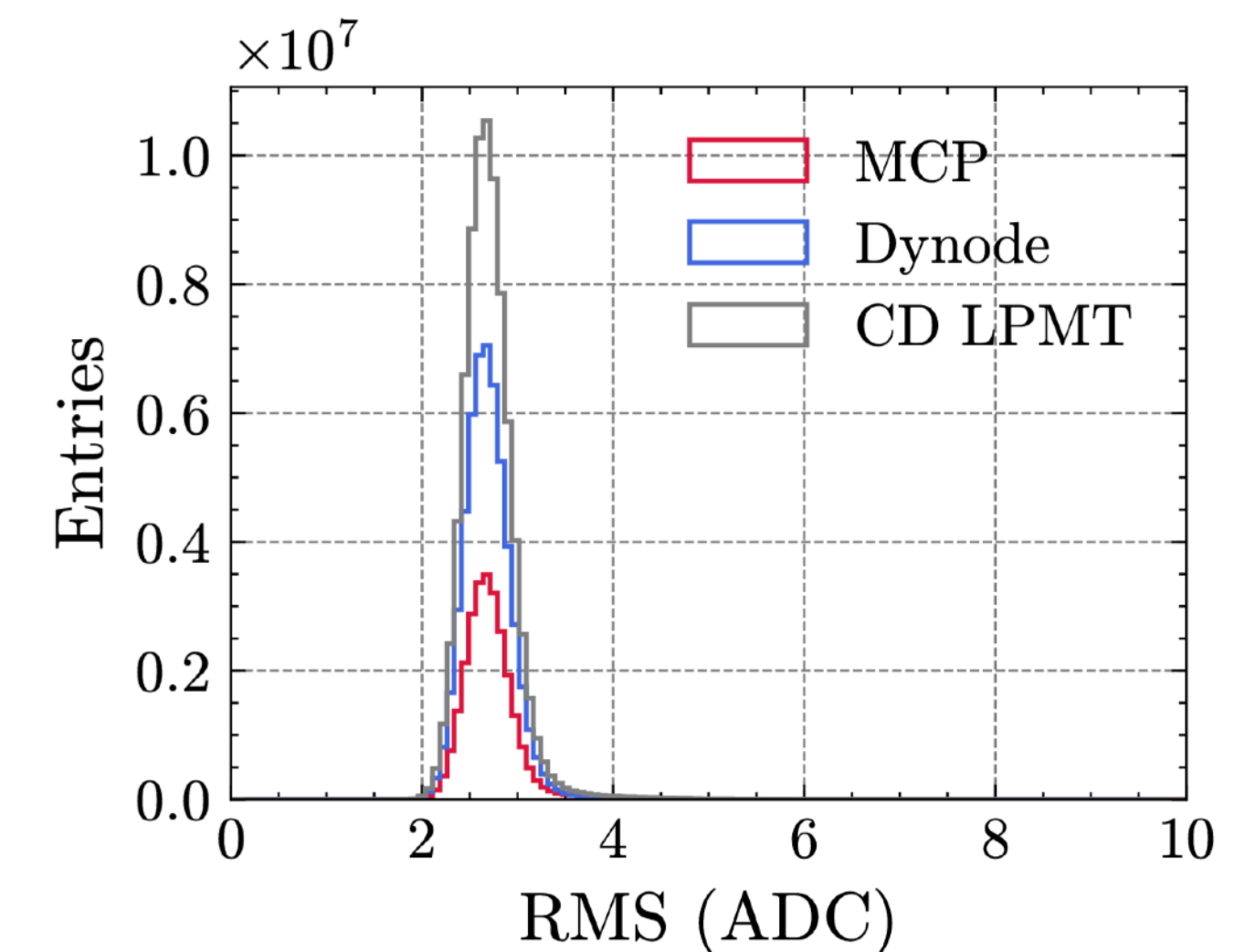
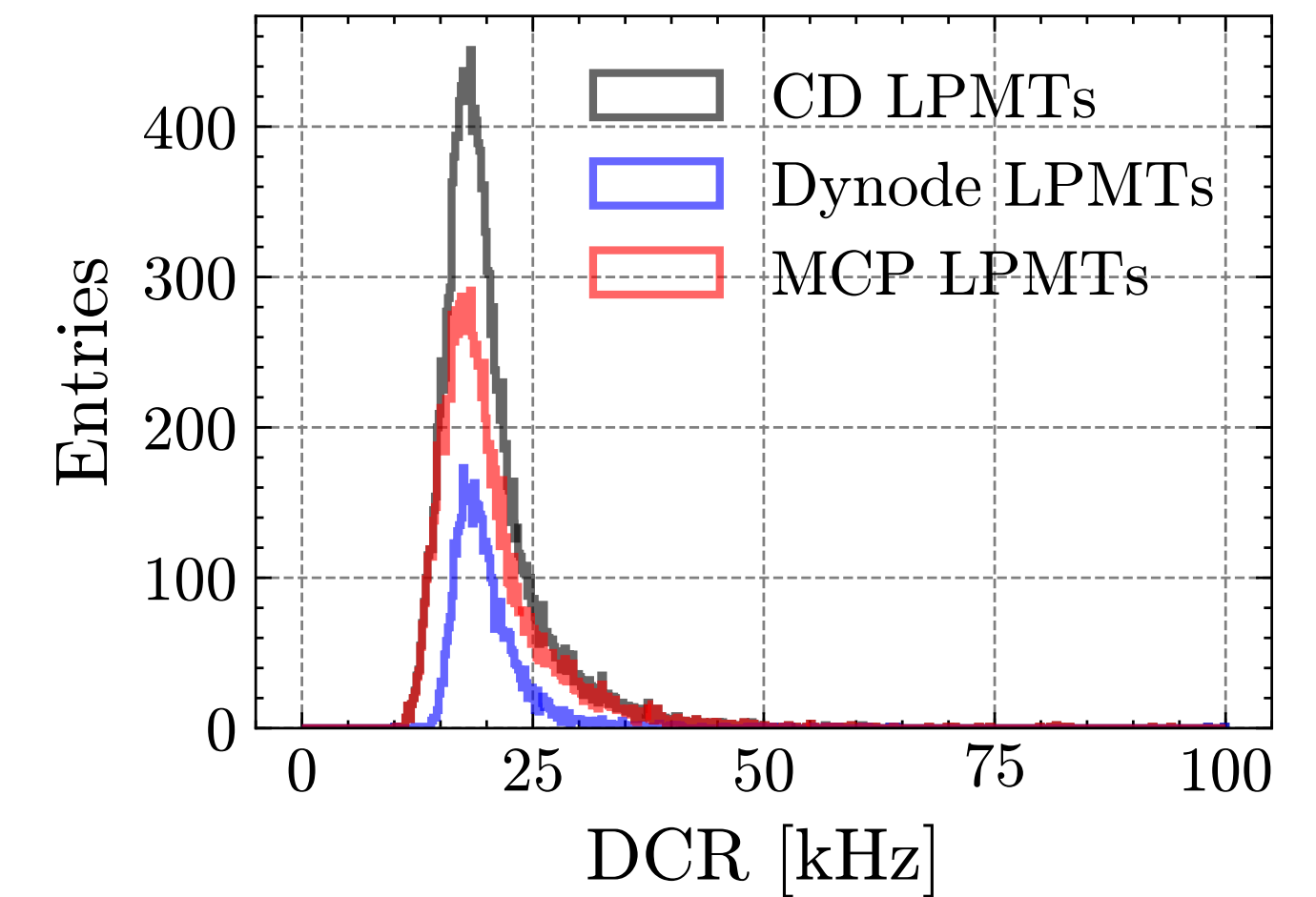
- Two leaks have appeared in the acrylic sphere so far
- First leak appeared on March 21, 2025
 - During filling
 - Stopped in 1 week by divers using epoxy and tape, further repaired using acrylic plate to reduce stress
- Second leak appeared on March 19, 2026
 - Leak stopped after 2 days by experienced divers, repaired in next 2 days
 - About 1 Bq of ^{222}Rn went into acrylic sphere, 13 days of data excluded
- Structure is safe, stress levels are within expectation



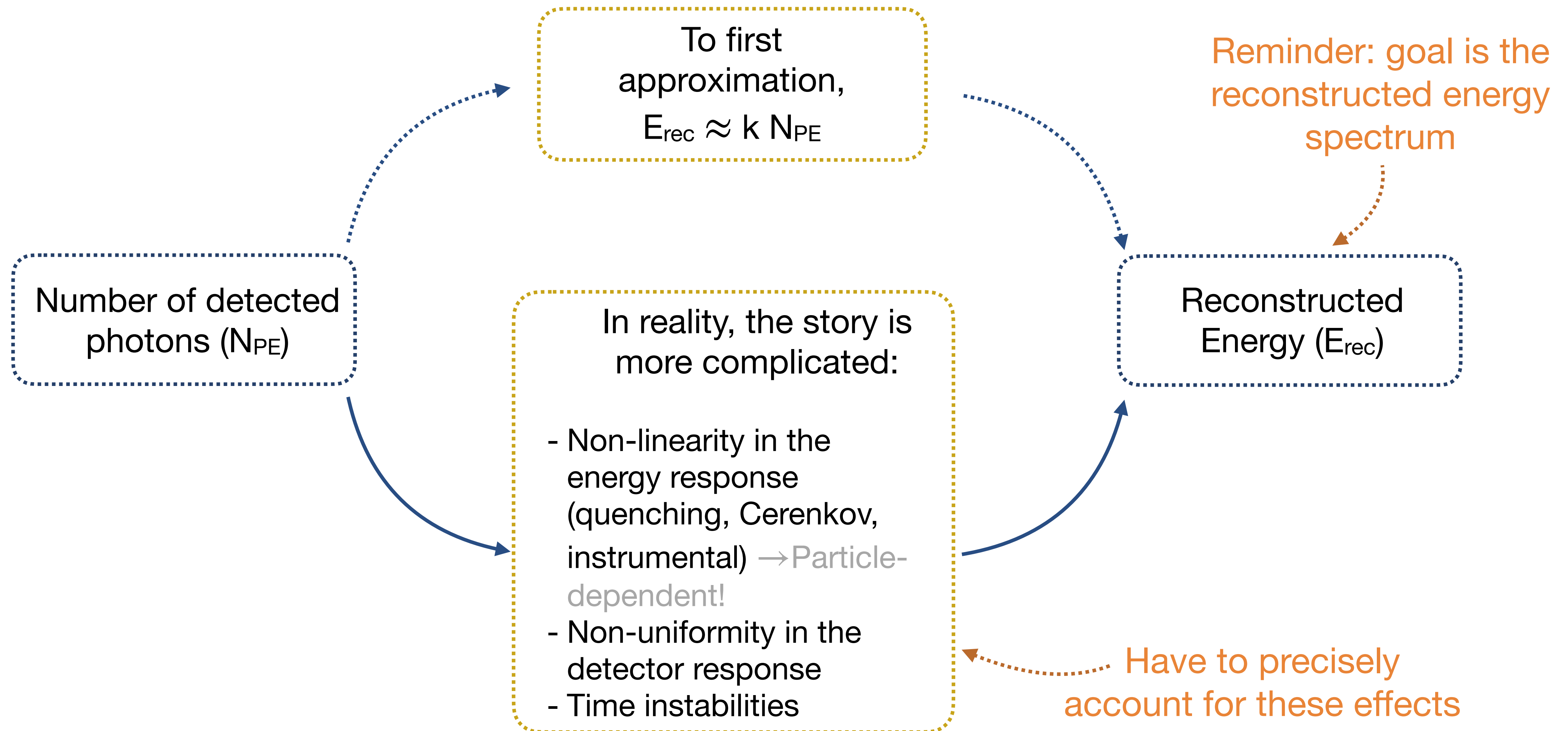
Low-Level Detector Performance

- Large PMTs (LPMTs):
 - Lost 16 LPMTs during installation in the Central Detector (CD)
 - Have lost a total of 26 LPMTs after installation (~ 1.2 / month)
 - Approximately 600 large PMTs flashing at any one time (turned off)
 - 20.6 kHz and 22.7 kHz of Dark Count Rate (DCR) for dynode and MCP-PMTs, respectively, but **decreasing**
- Electronics:
 - Low noise levels (around 2.8 ADC, roughly 0.055 PE)
 - Threshold at 0.2-0.3 PE
- Trigger:
 - Threshold at 200 keV

[arXiv:2511.14590](https://arxiv.org/abs/2511.14590)



Energy Reconstruction Basics



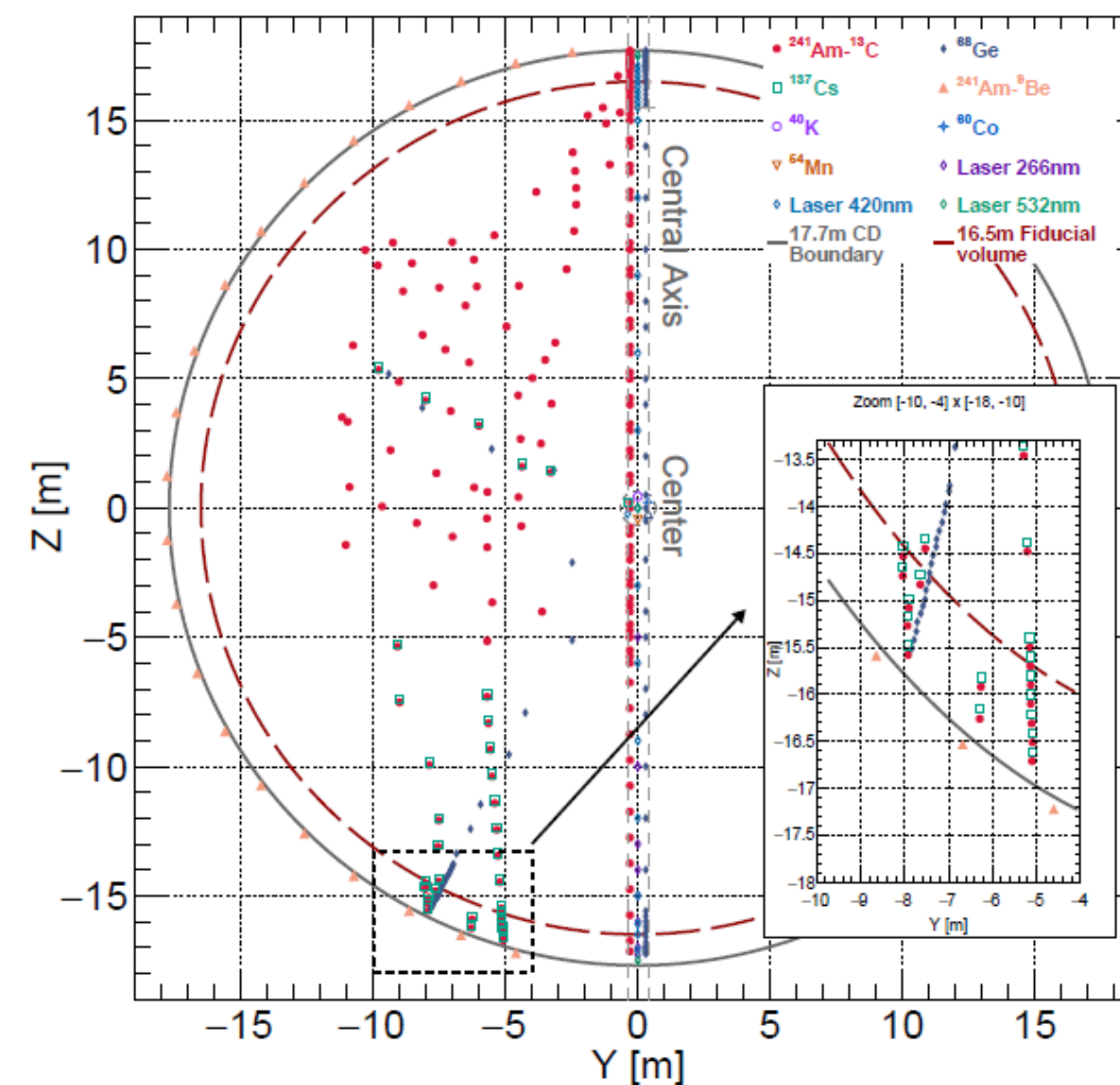
Calibration Source Deployment

- Multiple artificial calibration sources deployed around central axis (1D) and in 2D plane

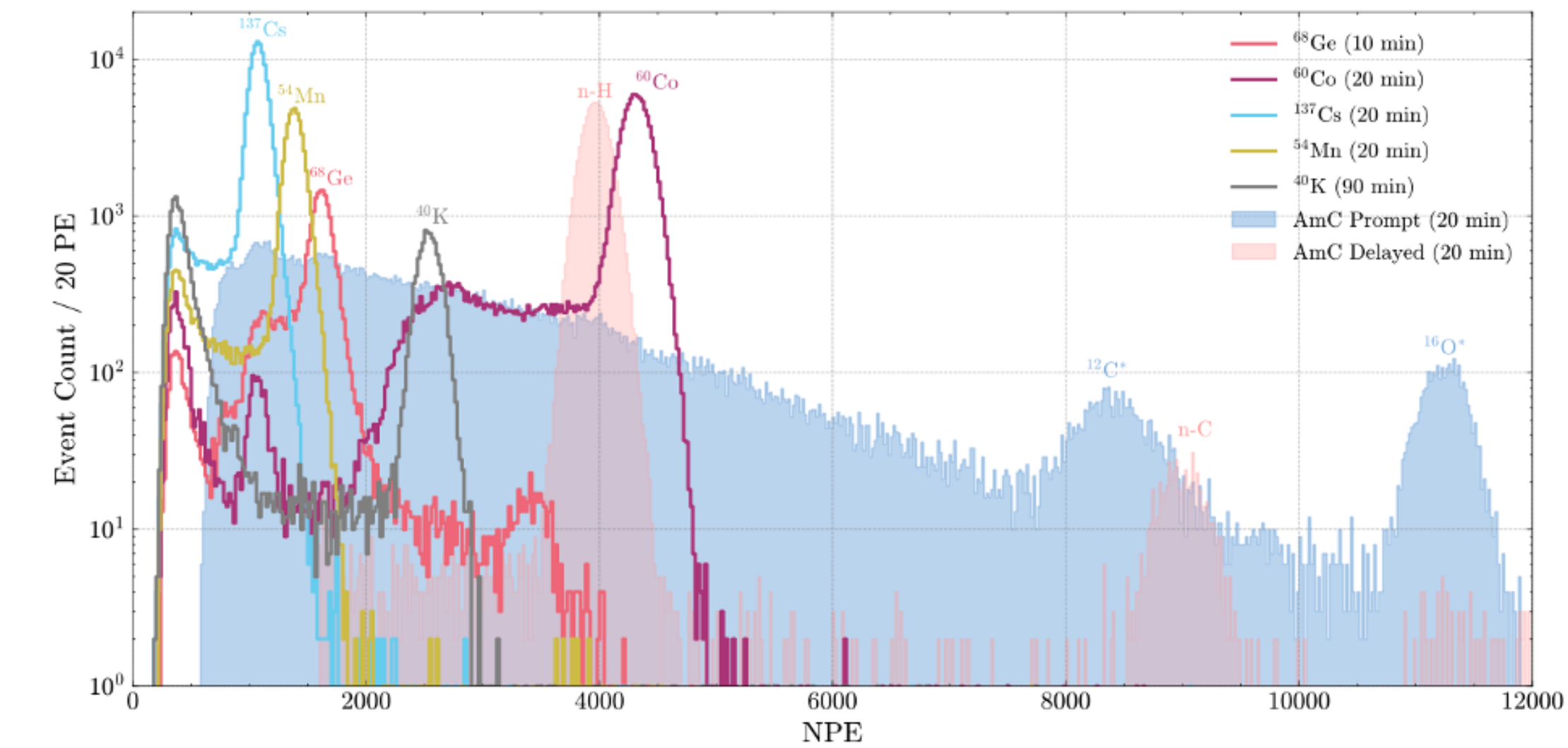
Calibration house on top of the detector



Source deployments so far



Charge distribution (total PE) of calibration points after DCR subtraction

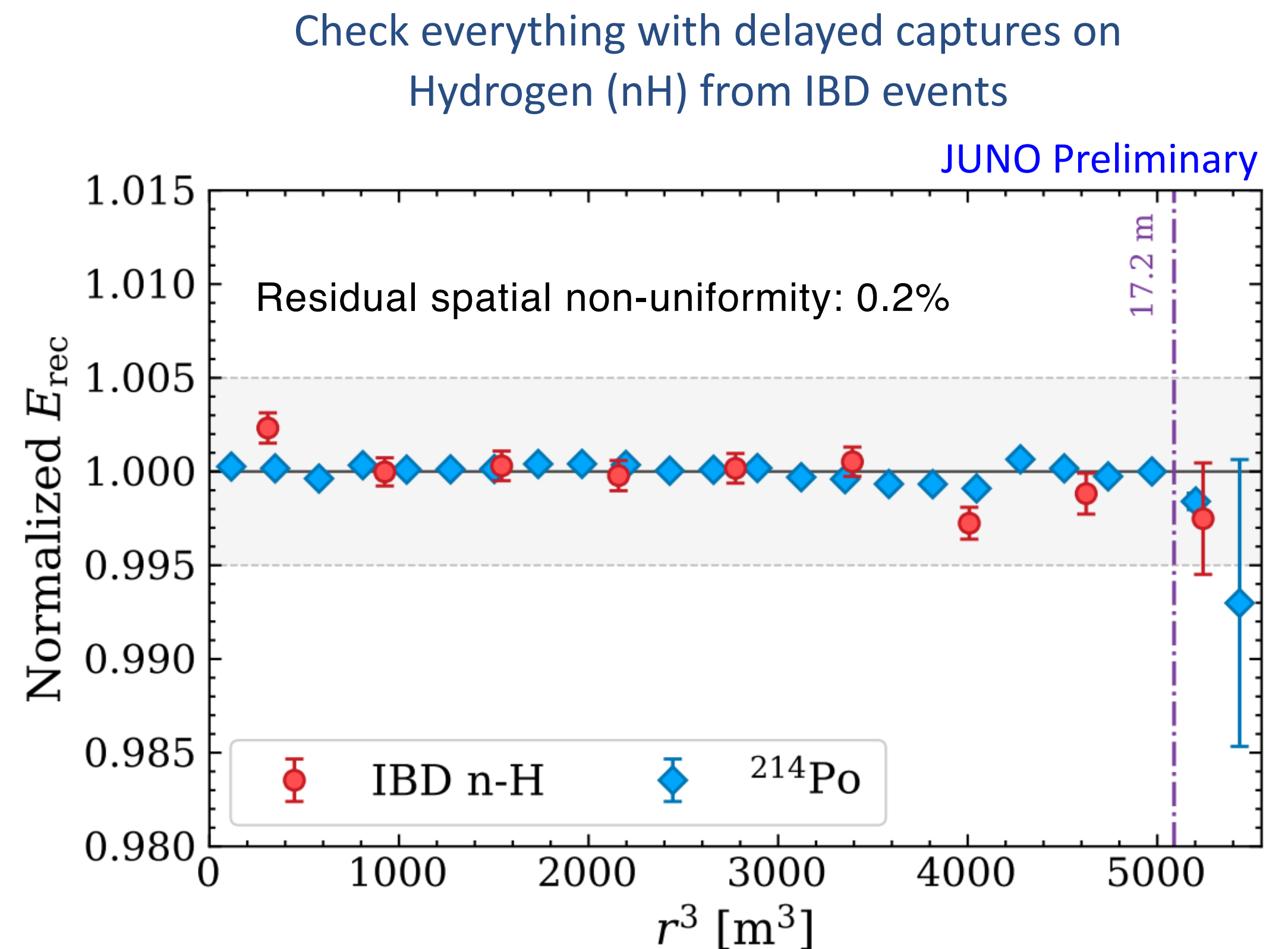
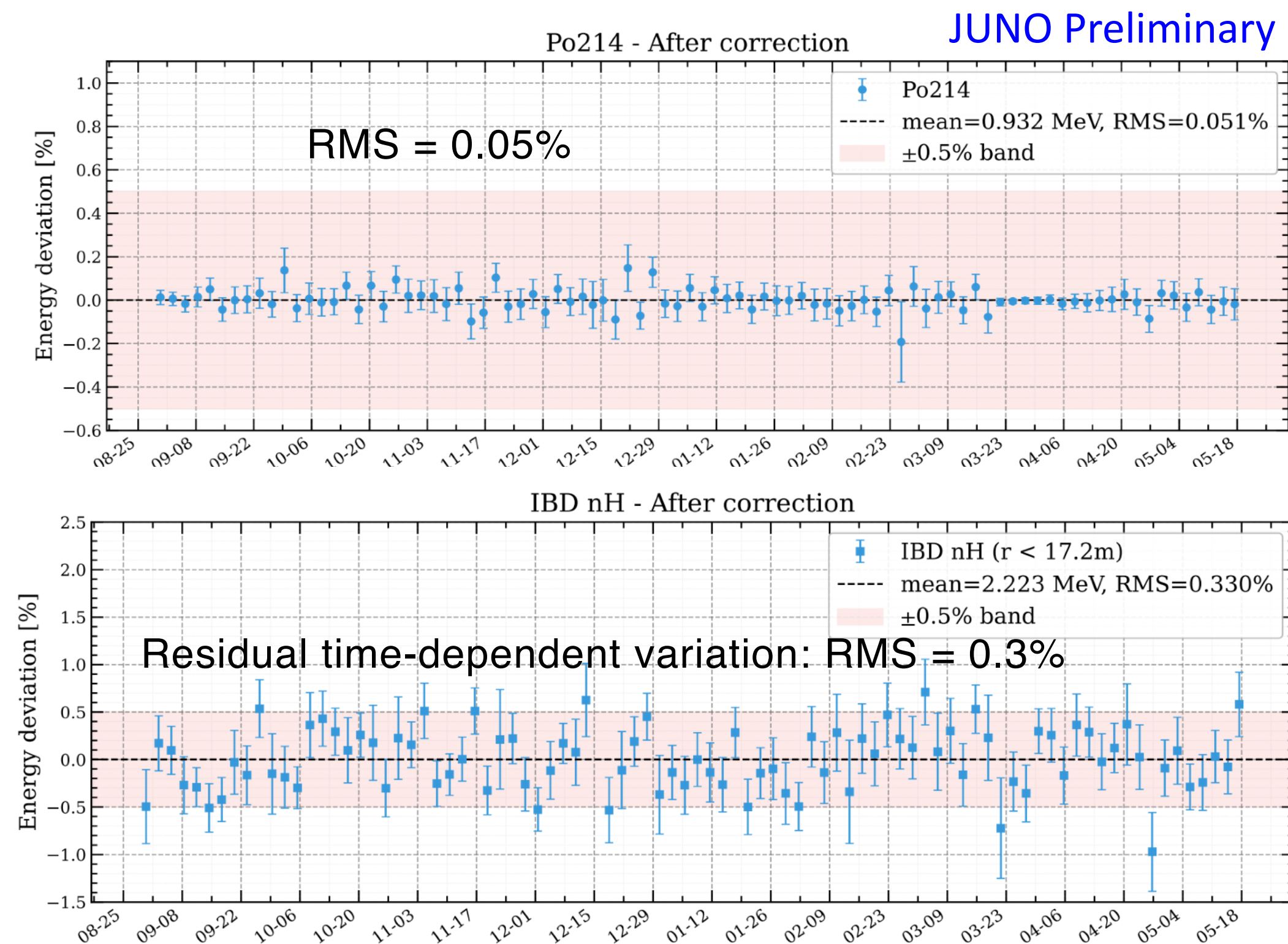


- Natural calibration sources (e.g. spallation neutrons) also provide us with useful handles

[arXiv:2511.14590](https://arxiv.org/abs/2511.14590)

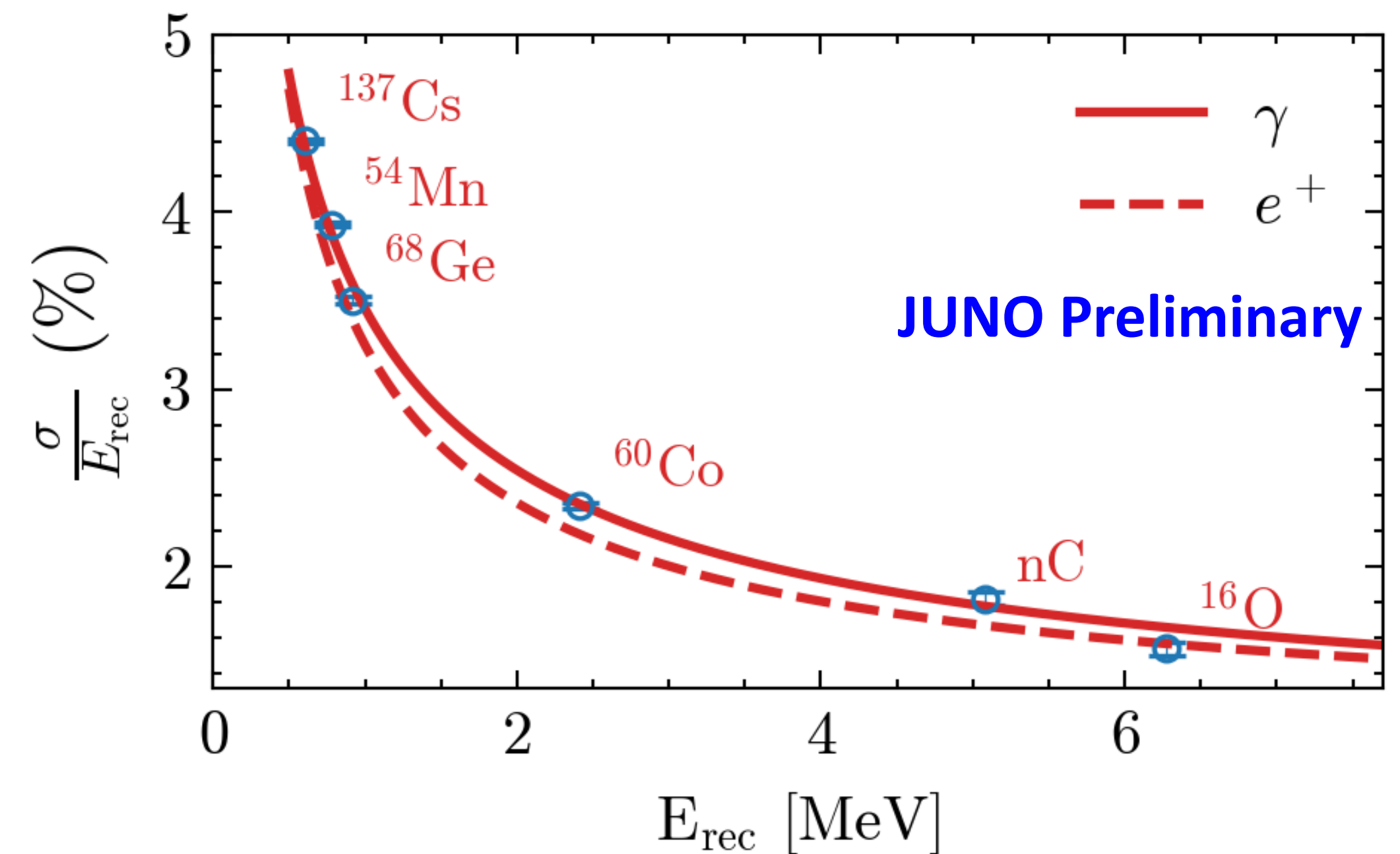
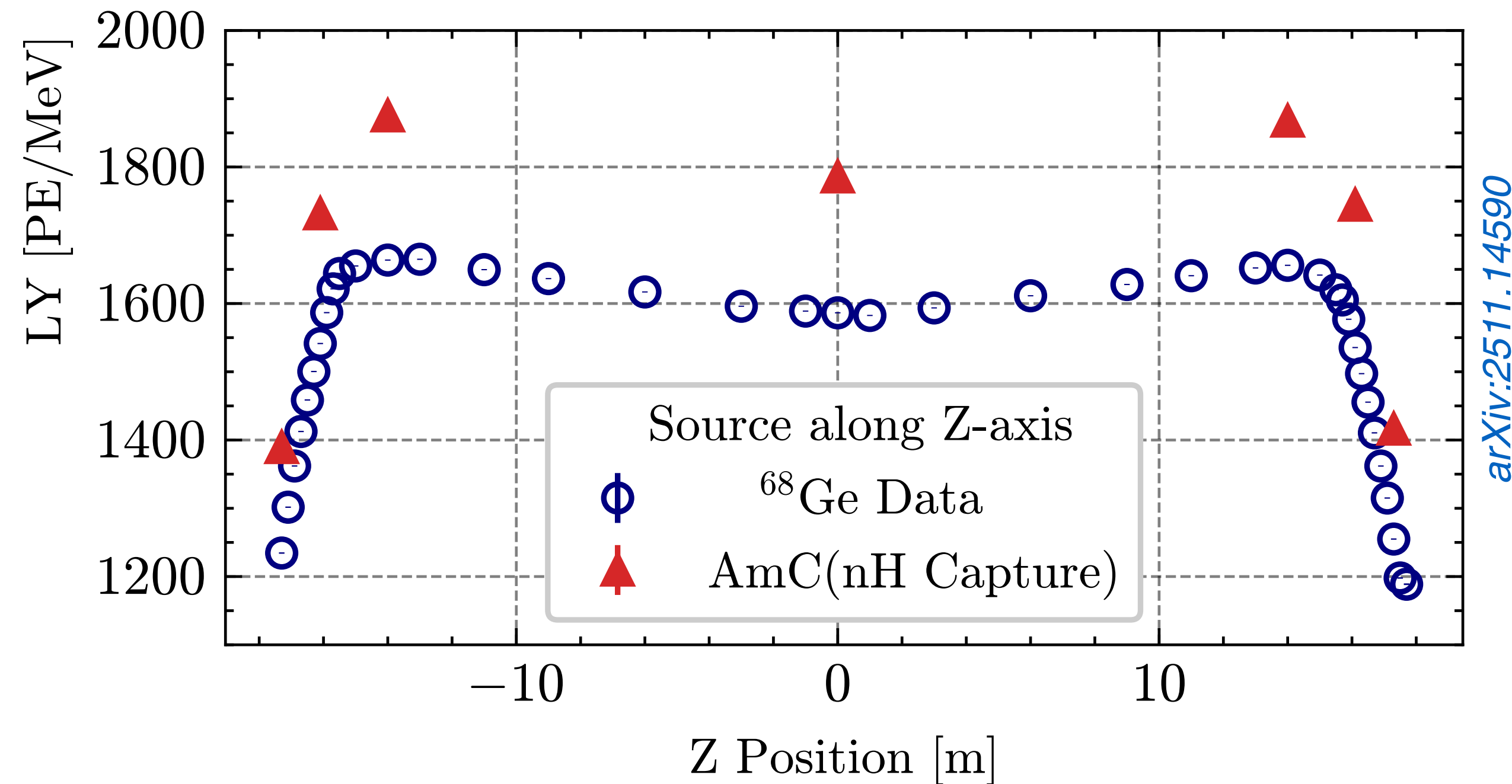
Energy Calibration

- Determine vertex and energy through maximum likelihood method that accounts for geometry, PMT response, and optical properties (benchmarked with calibration sources)
 - Also use alternative reconstruction approaches that give consistent results
- Time variations corrected using ^{214}Po in the whole volume, residual $\sim 1\%$ time-dependence in (r, θ) also corrected using ^{214}Po



Light-Yield and Energy Resolution

- Energy resolution is close to target level but not fully there yet:
 - Light level is higher than design: see **~1600 PE/MeV** with ^{68}Ge and **~1780 PE/MeV** for nH capture throughout most of the fiducial volume
 - Energy resolution of ^{68}Ge is **~3.5% @ 2×0.511 MeV** at the center, slightly worse than the expected 3.1%



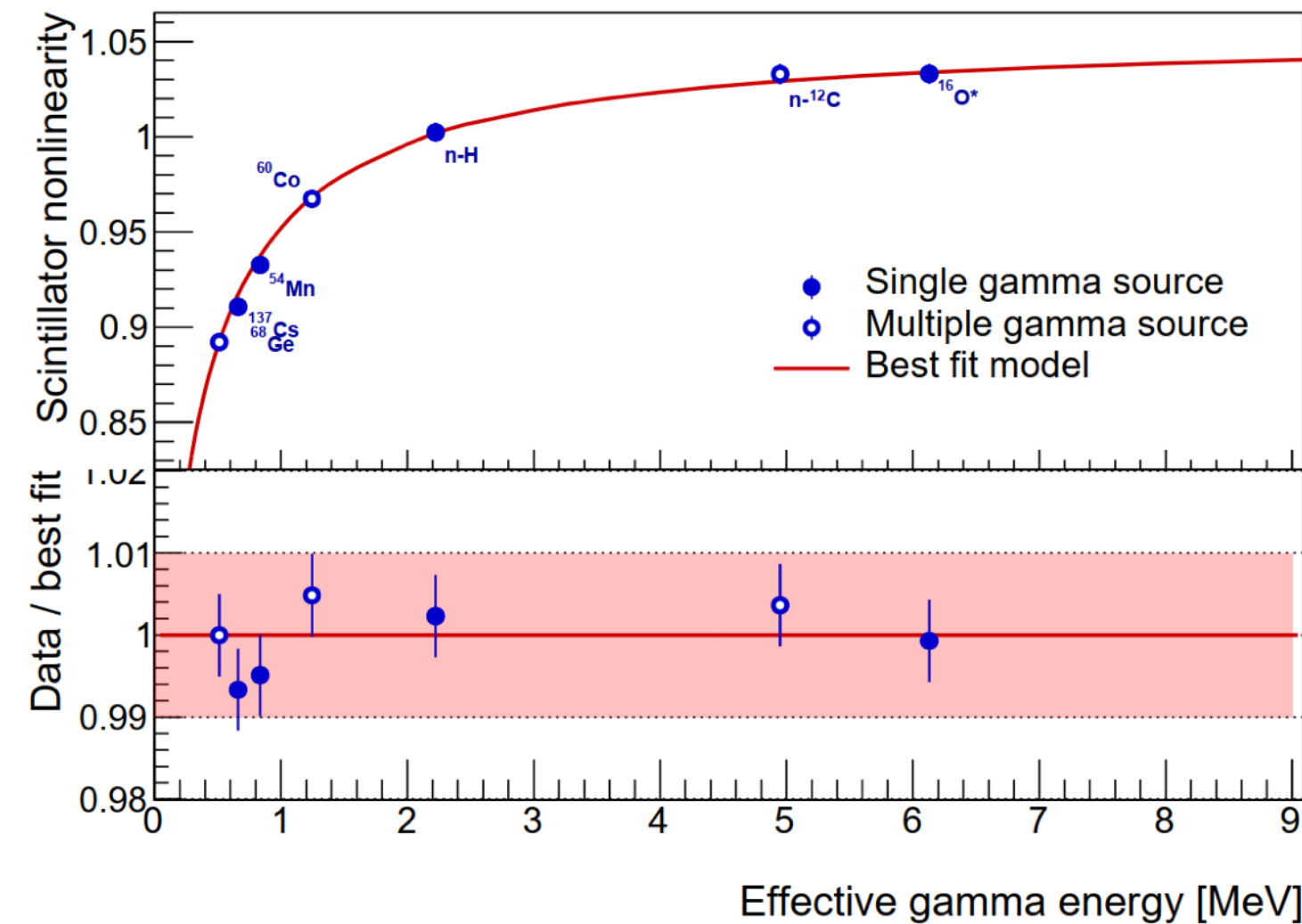
Several improvements under exploration, including additional calibration, better reconstruction, ^{14}C removal

Energy Non-Linearity

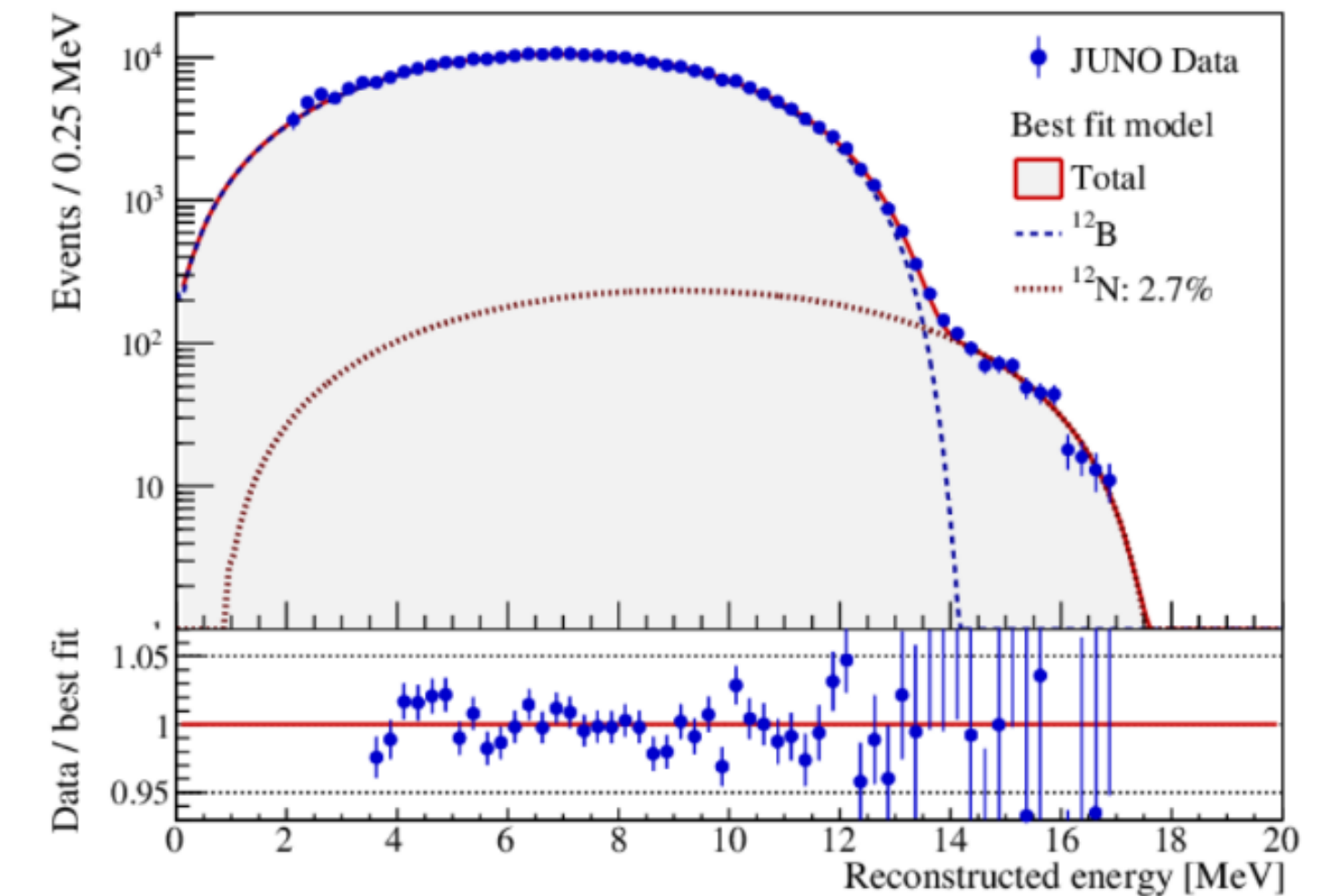
JUNO Preliminary

- Energy non-linearity (NL) characterized to better than **1% precision**
 - Simultaneous fit to gamma source data @ center and full volume cosmogenic samples $^{11}\text{C}(\text{e}^+)$, $^{10}\text{C}(\text{e}^+)$, $^{12}\text{B}(\text{e}^-)$, $^8\text{Li}(\text{e}^-)$, $^8\text{B}(\text{e}^+)$, $^6\text{He}(\text{e}^-)$
 - Use sPMTs to constrain LPMT instrumental non-linearity

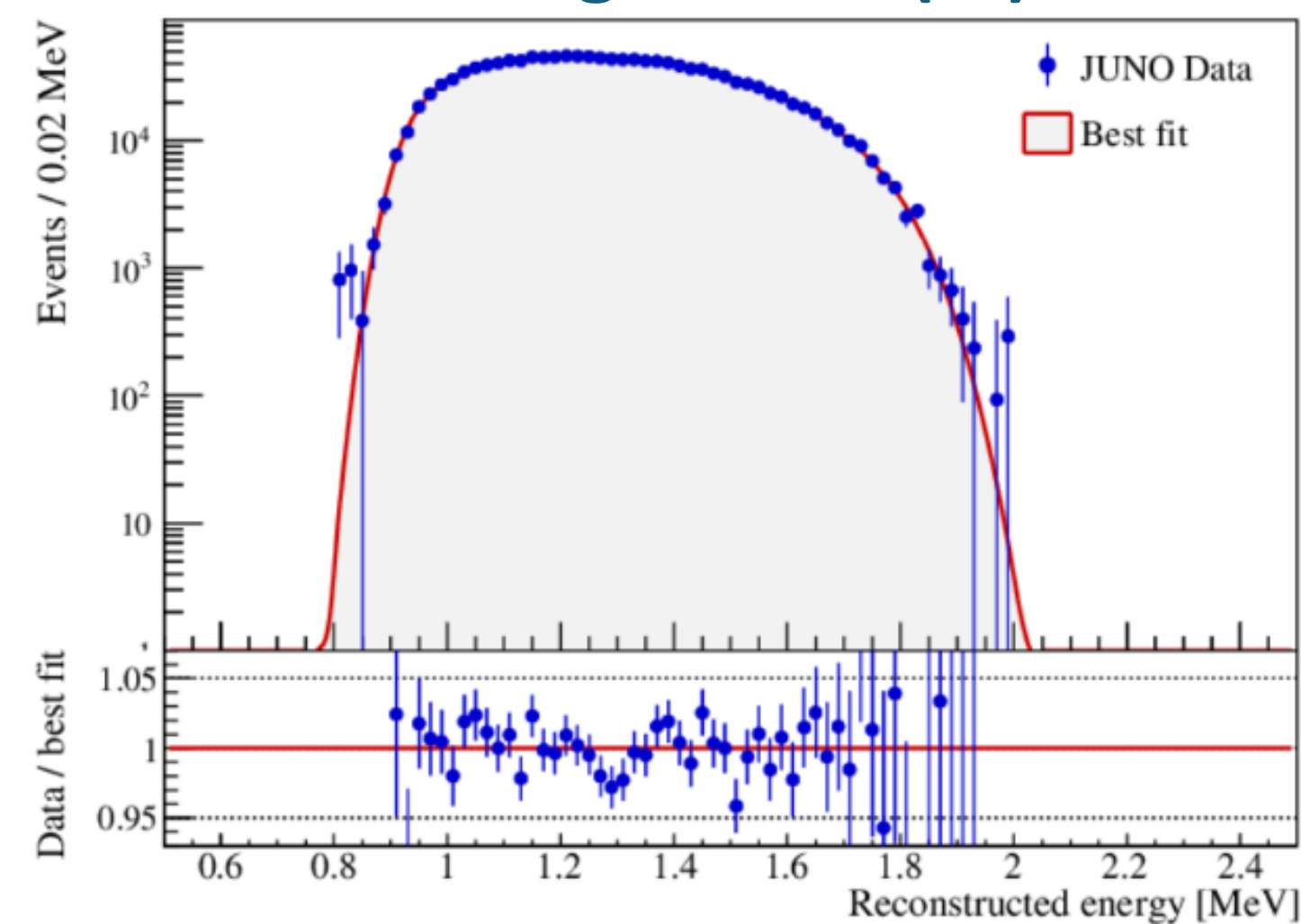
Gamma sources @Detector center



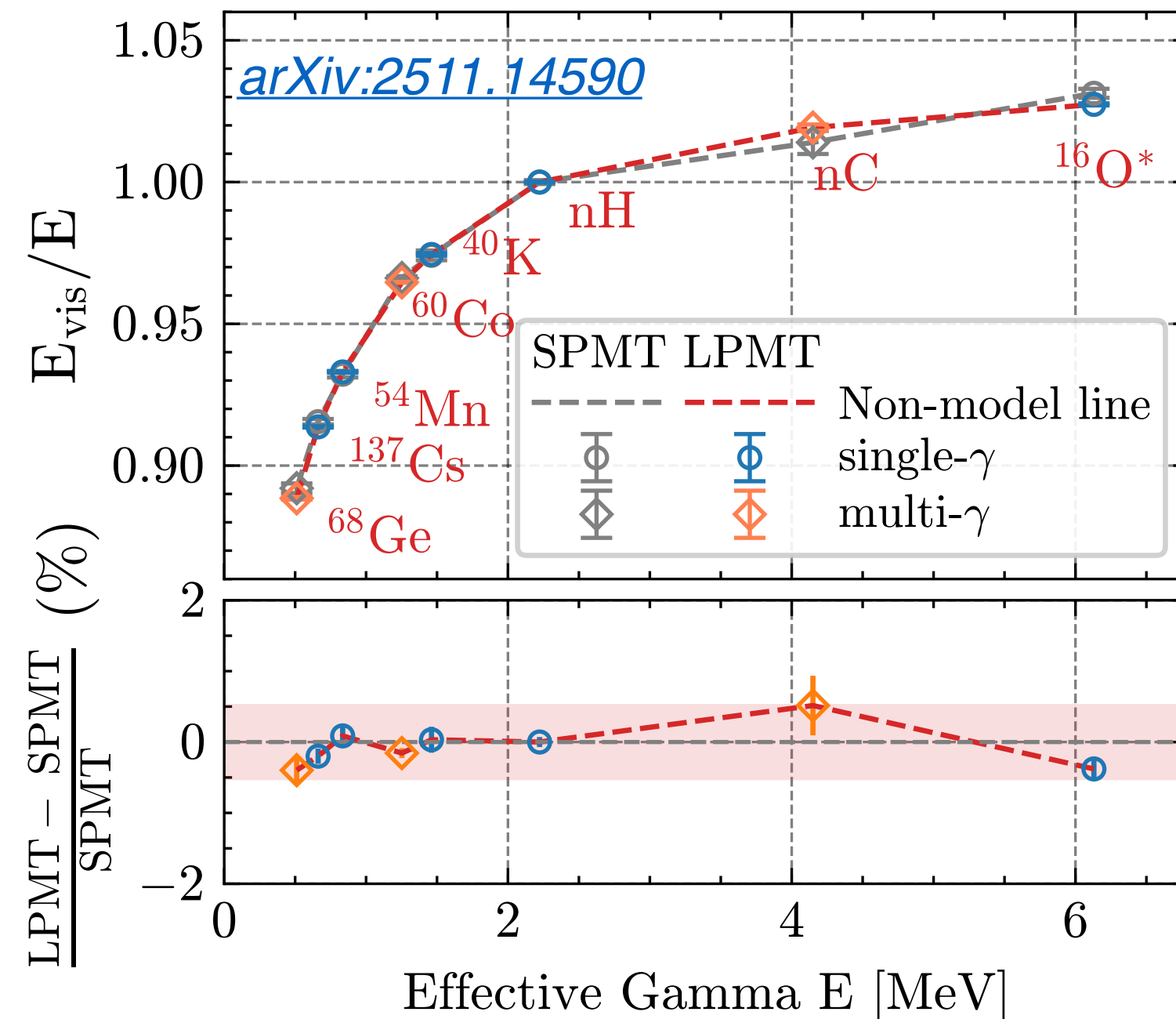
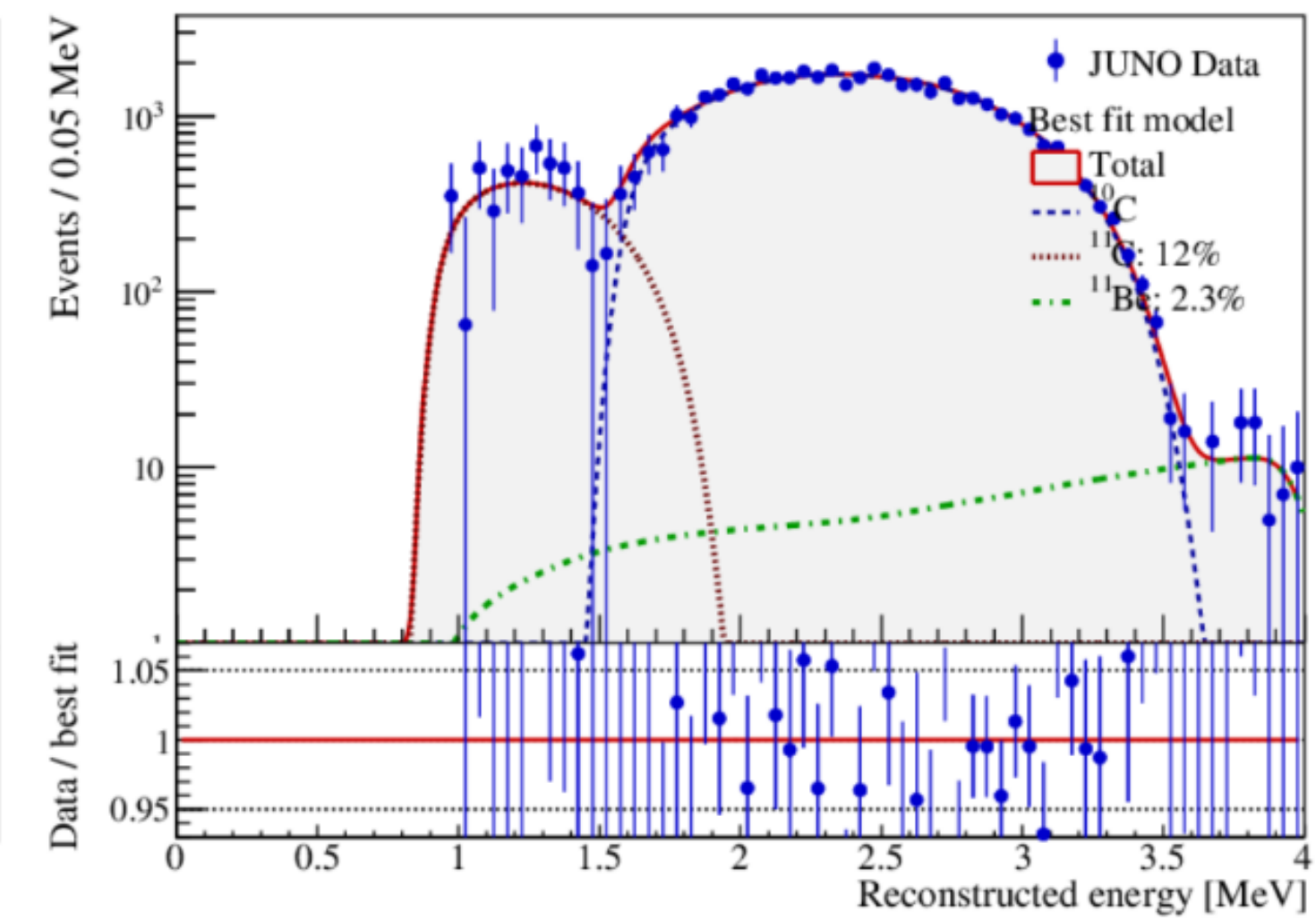
Cosmogenic $^{12}\text{B}(\text{e}^-)$



Cosmogenic $^{11}\text{C}(\text{e}^+)$



Cosmogenic $^{10}\text{C}(\text{e}^+)$



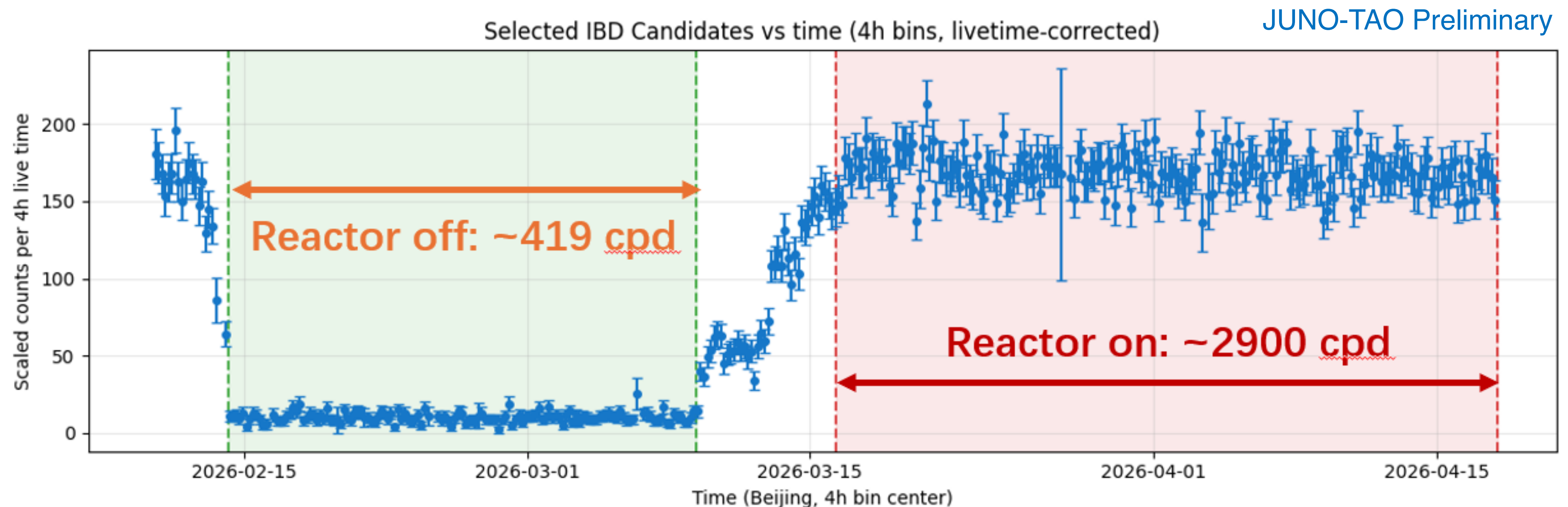
Results from TAO

with 30 days of Reactor ON data

TAO Data

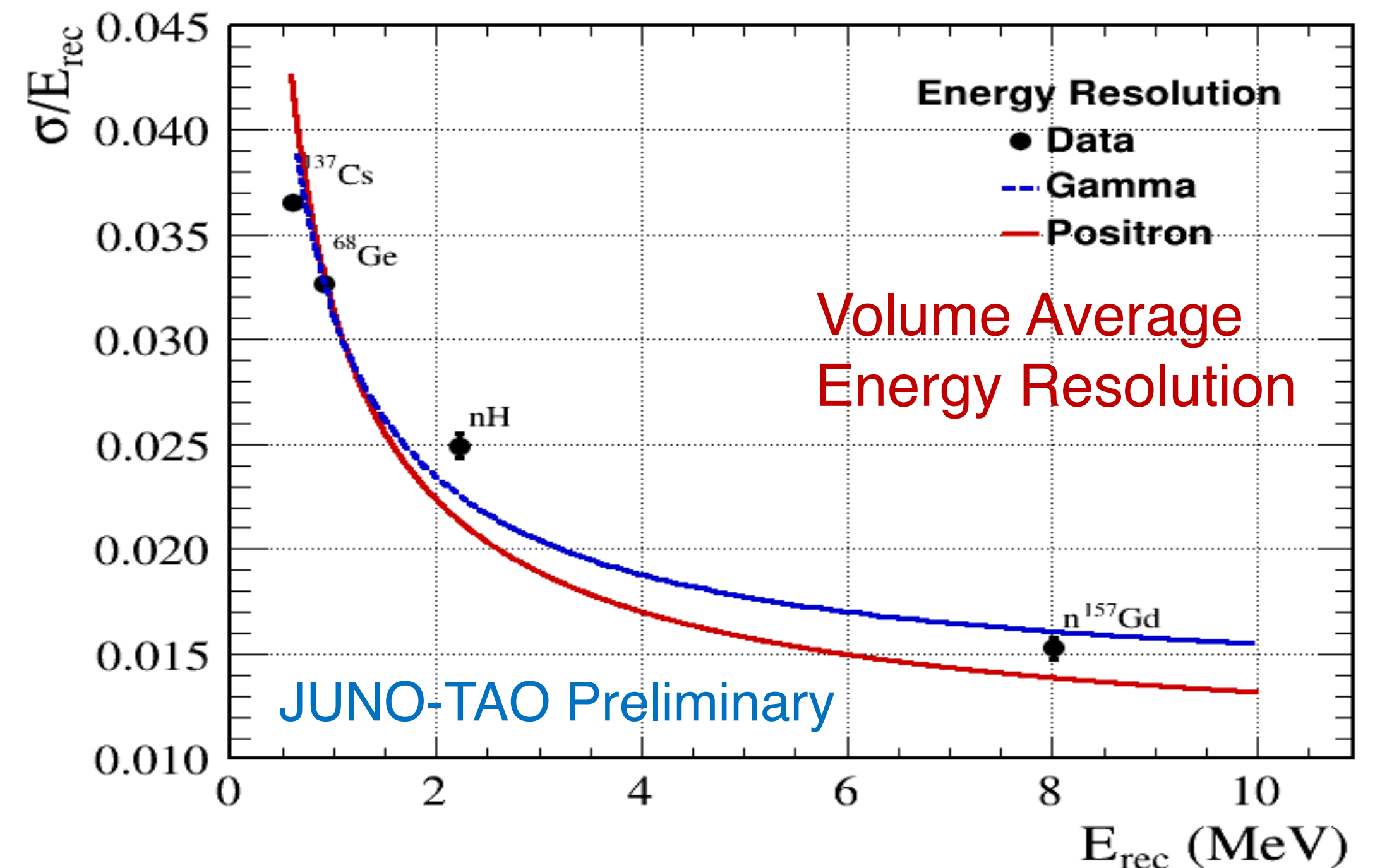
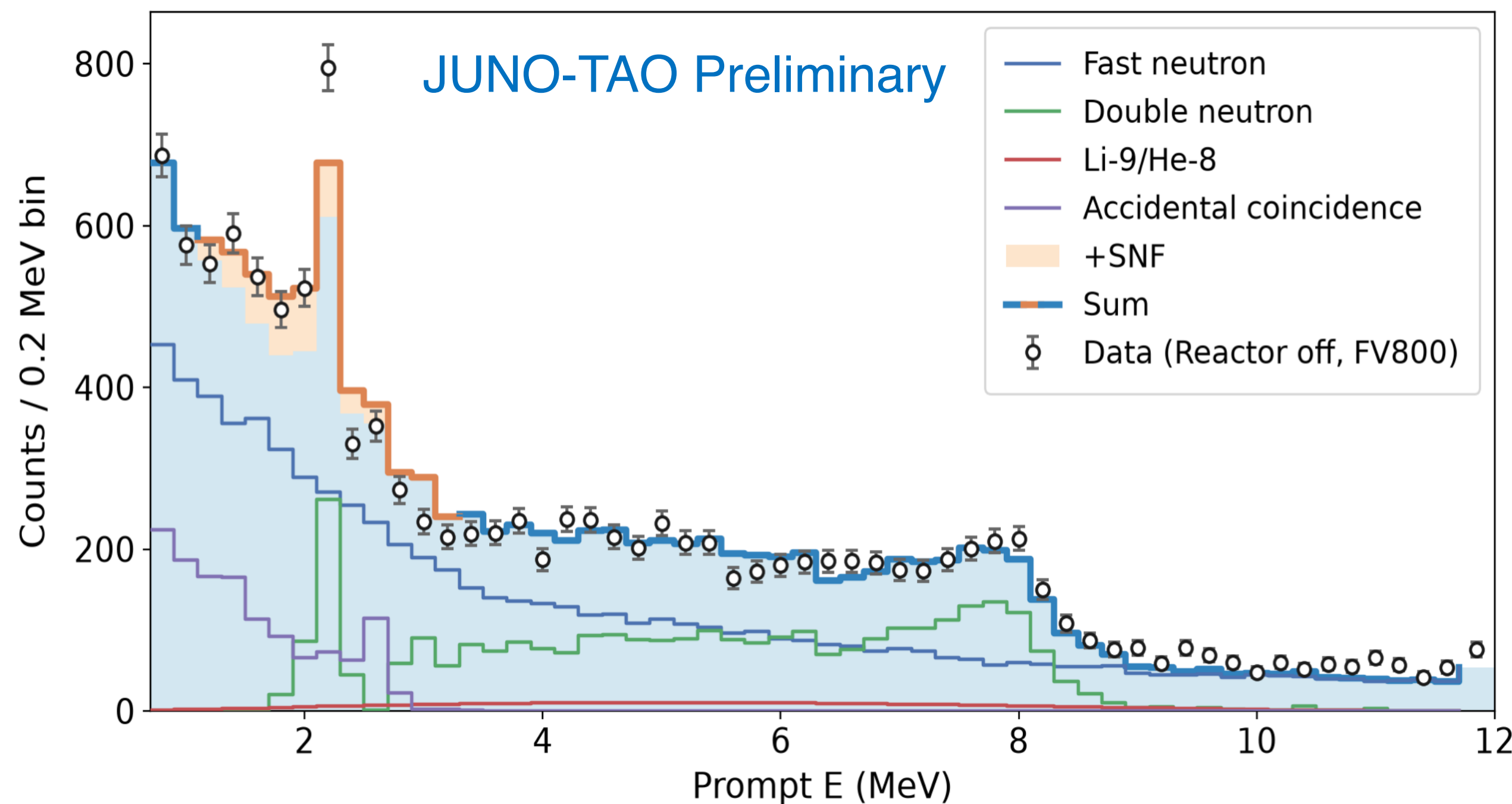
(for more details on the latest JUNO-TAO results, please see Yichen Li's [talk](#) at Neutrino 2026)

- TAO began operations in early February 2026
- Similar IBD selection strategy and detector response assessment as JUNO
- Around 2500 reactor IBDs / day
- Signal to background is about 6:1 (really good for an experiment at the surface!)
 - Will likely be further improved



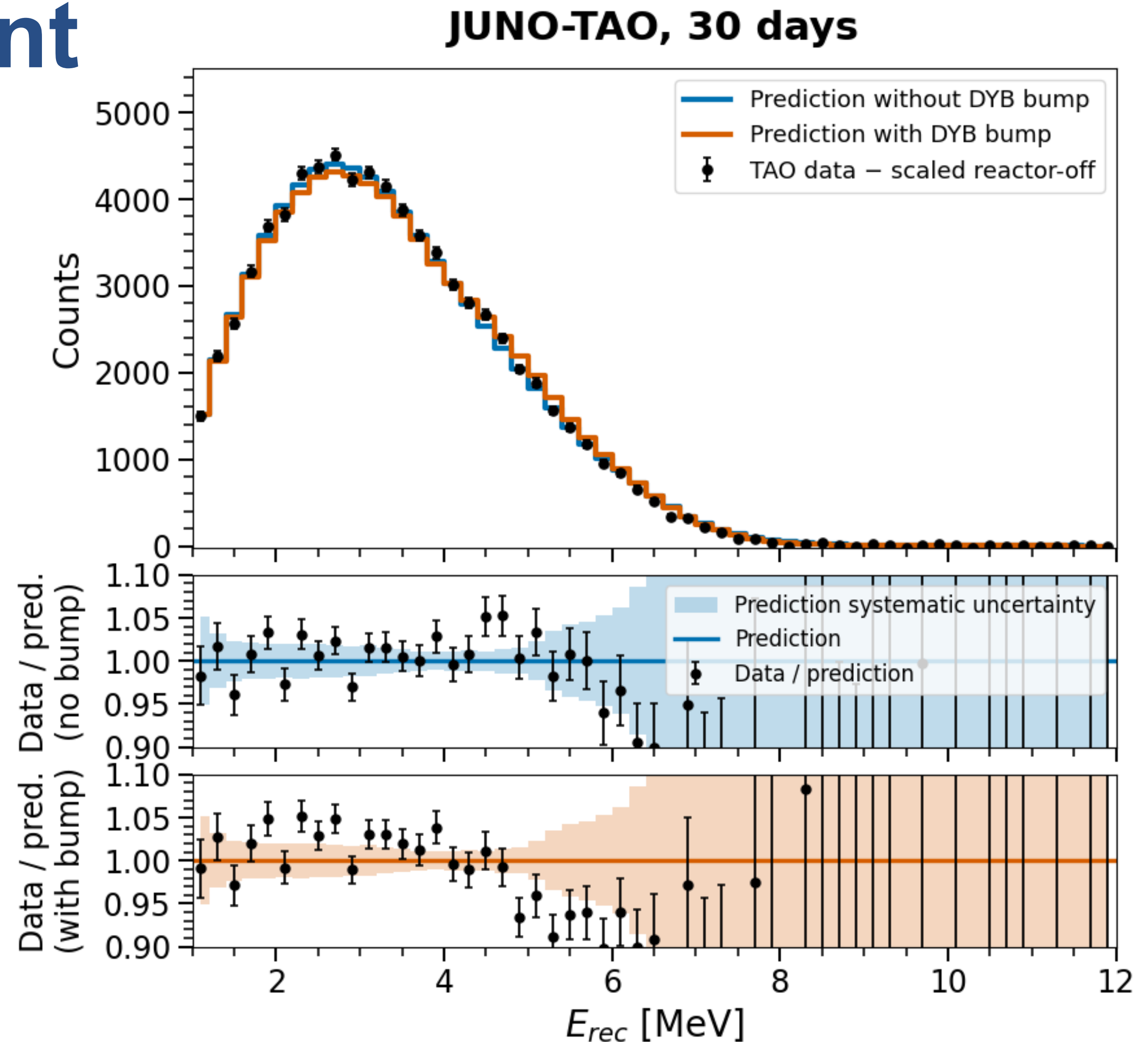
TAO Performance

- Reactor OFF data allows to measure the backgrounds essentially directly
 - Potential to directly measure the Spent Nuclear Fuel (SNF) contribution
- Energy resolution is already better than JUNO's: 2.8% @ 1 MeV with Ge68 at the center
 - Further improvements expected



First TAO Measurement

- Have produced a first measurement of the unoscillated reactor neutrino spectrum
 - First of its kind with such a good energy resolution
- Good agreement with model prediction
 - Indication of the 5 MeV bump, some differences in the high-energy tail
- Statistics still low to see fine structure
 - Uncertainty around 6-10% for most of the energy region of interest, still largely statistics dominated
 - But data already useful for JUNO to constrain any anomalously large fine structure

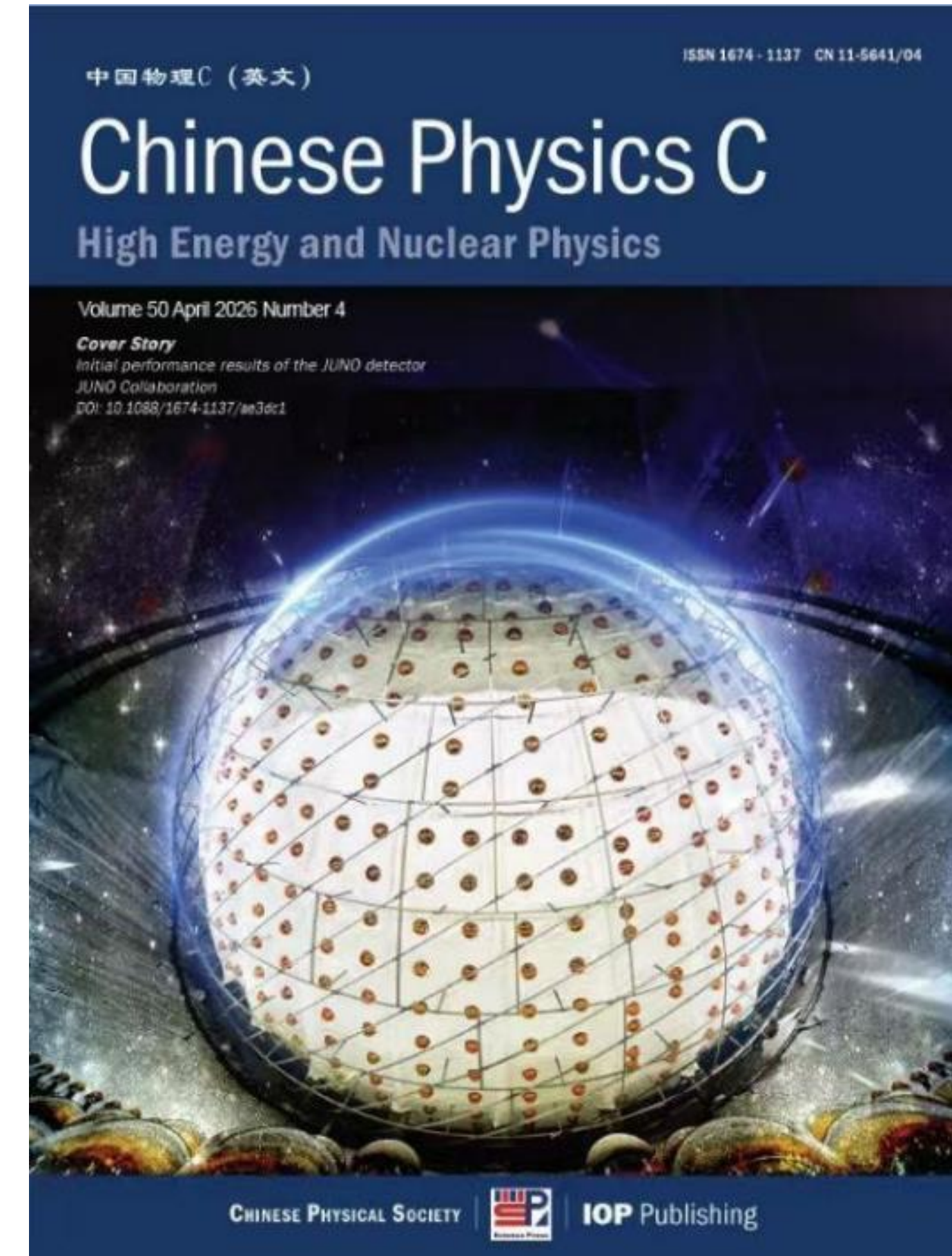


Latest Oscillation Results

with 207 days of JUNO data

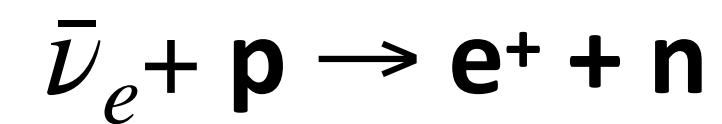
What's New?

- Our first results with 57 days of data were recently published
- In this new set of results:
 - More data: 57 days → 207 days
 - About 10% larger fiducial volume (16.5m → 17.2m)
 - Improvements in background reduction (accidentals) and estimation (^{214}Bi)

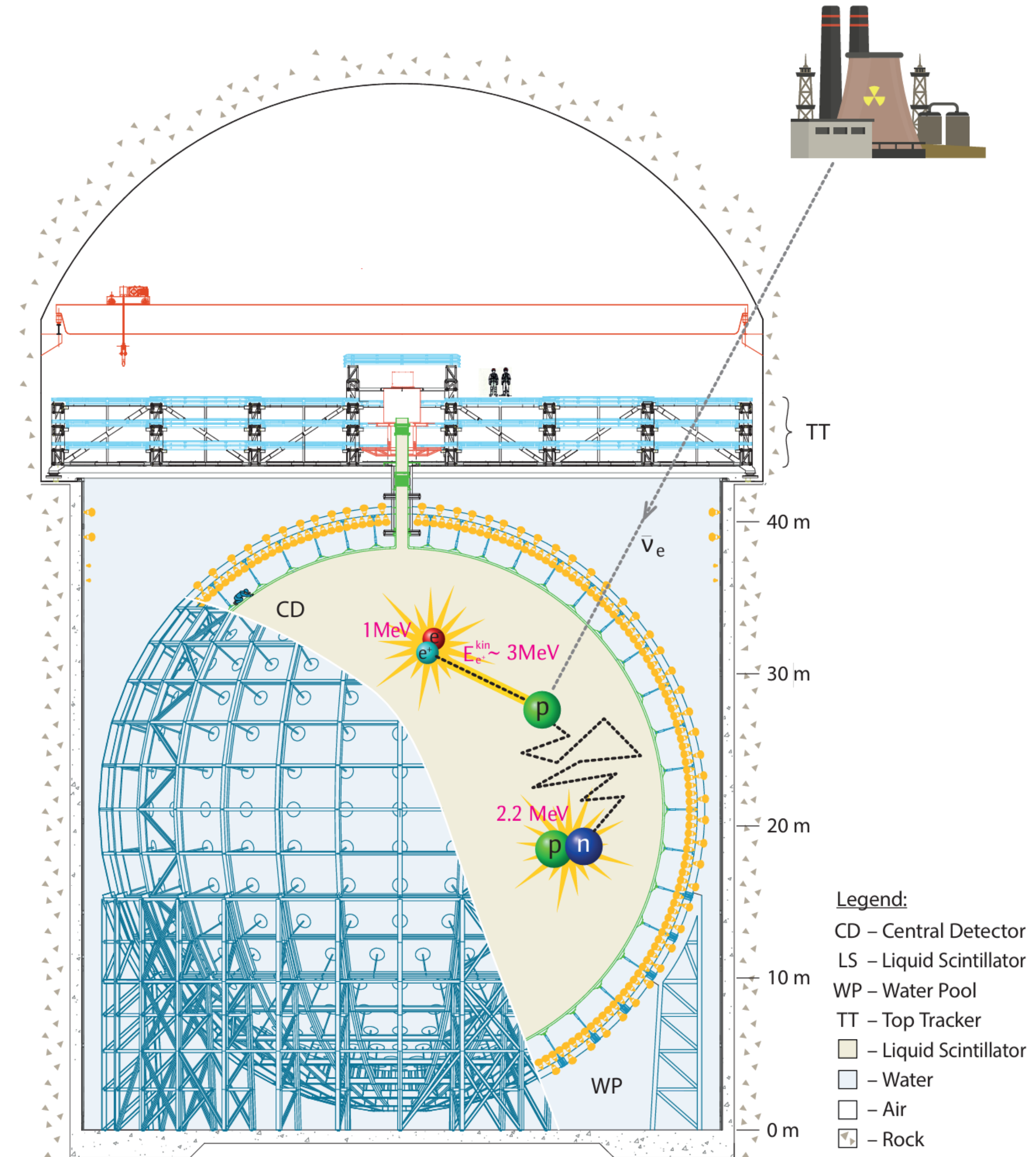


IBD Selection

- Reminder: we rely on the IBD reaction

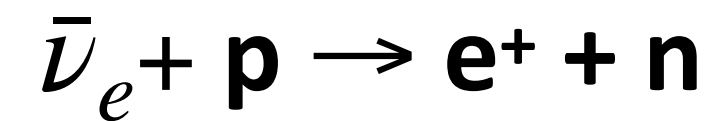


Looking for spatial and temporal coincidence of a positron-like (prompt) with a neutron-like (delayed) signal



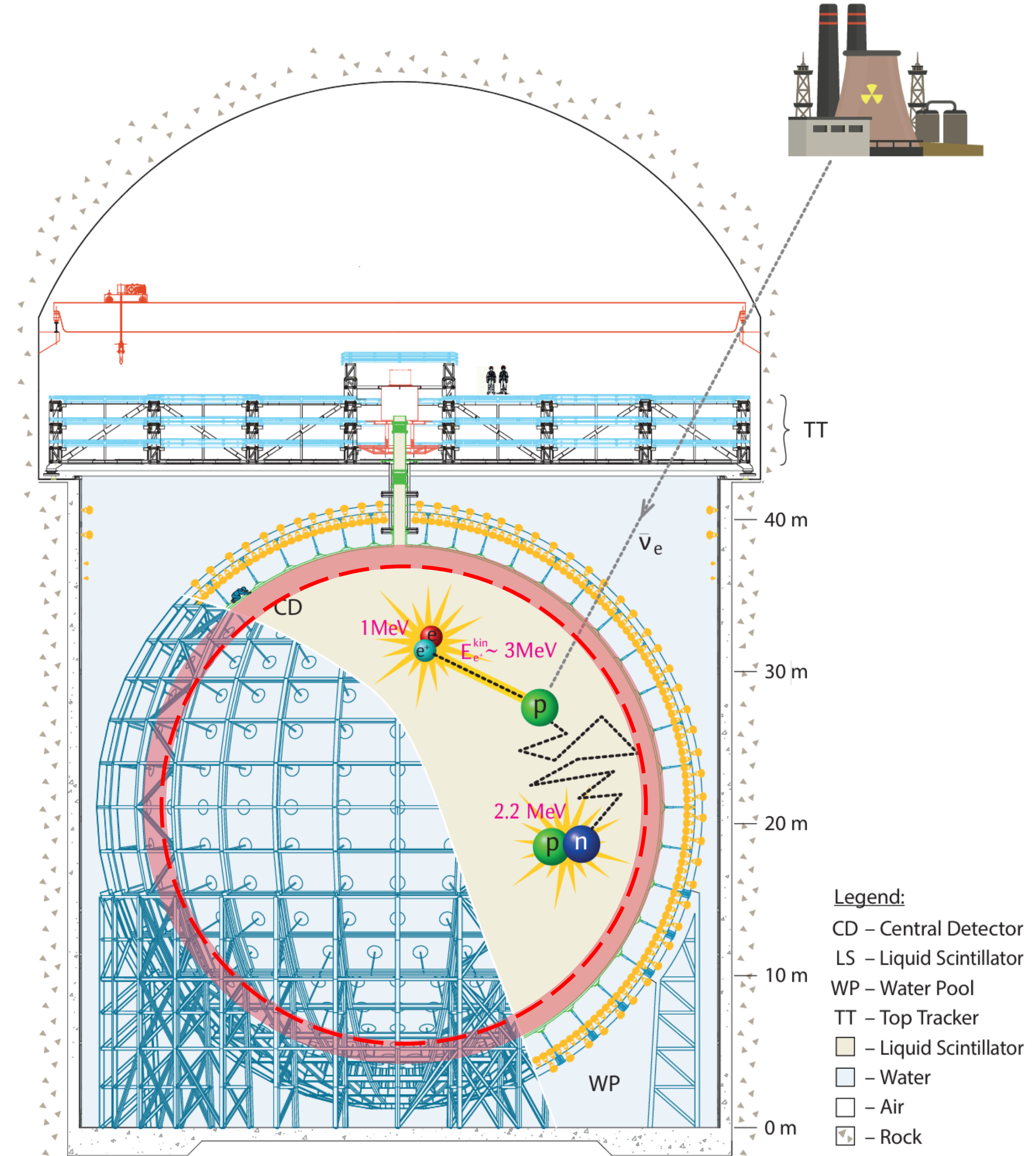
IBD Selection

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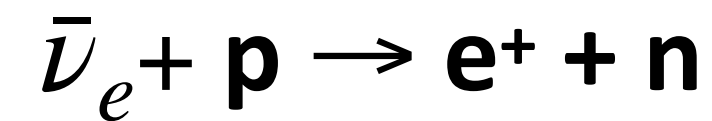
Looking for spatial and temporal coincidence of a positron-like (prompt) with a neutron-like (delayed) signal

- **Step #1:** remove events near the edge ($r > 17.2$ m) **(new!)**
 - That region contains higher backgrounds and has worse energy resolution



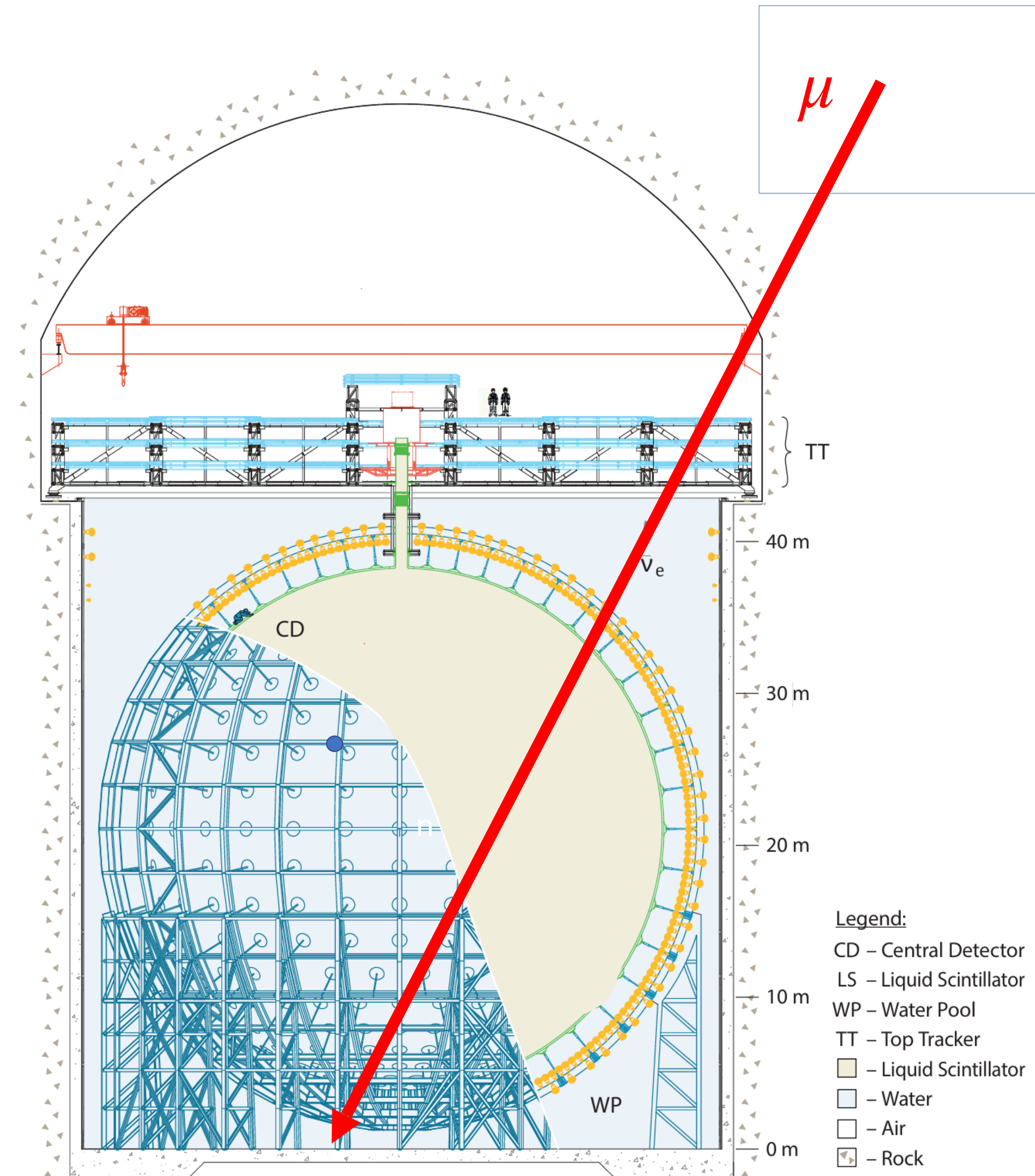
IBD Selection

- Reminder: we rely on the IBD reaction



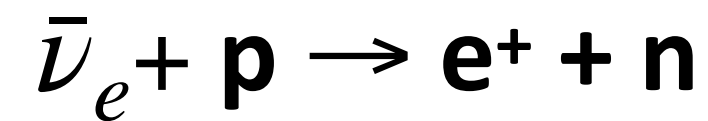
Looking for spatial and temporal coincidence of a positron-like (prompt) with a neutron-like (delayed) signal

- Step #2:** remove muons and correlated signals
 - Remove all events < 5 ms after muons seen by outer veto, inner detector, or both
 - Removes short-lived spallation products



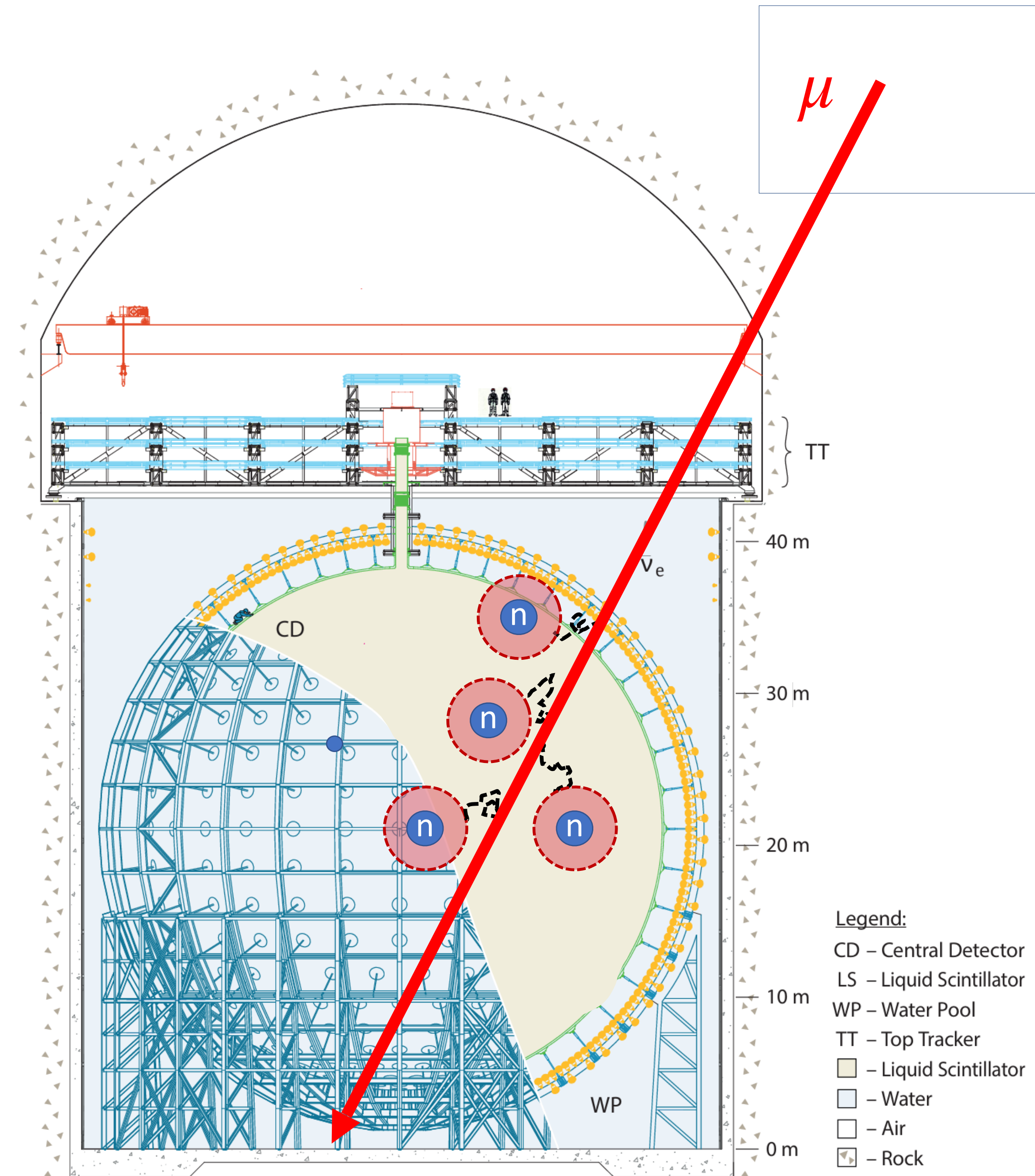
IBD Selection

- Reminder: we rely on the IBD reaction



Looking for spatial and temporal coincidence of a positron-like (prompt) with a neutron-like (delayed) signal

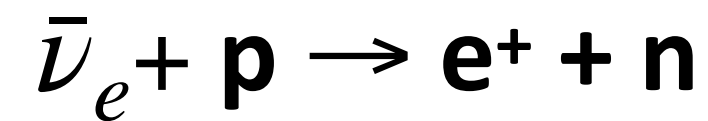
- Step #3:** apply a space-time veto around spallation neutrons and muon track
 - Suppresses (but does not completely eliminate) long-lived spallation products
 - Veto spherical regions of $r < 4\text{m}$ around spallation neutrons for $\Delta t = 1.2\text{ s}$



Legend:
CD - Central Detector
LS - Liquid Scintillator
WP - Water Pool
TT - Top Tracker
— Liquid Scintillator
— Water
— Air
— Rock

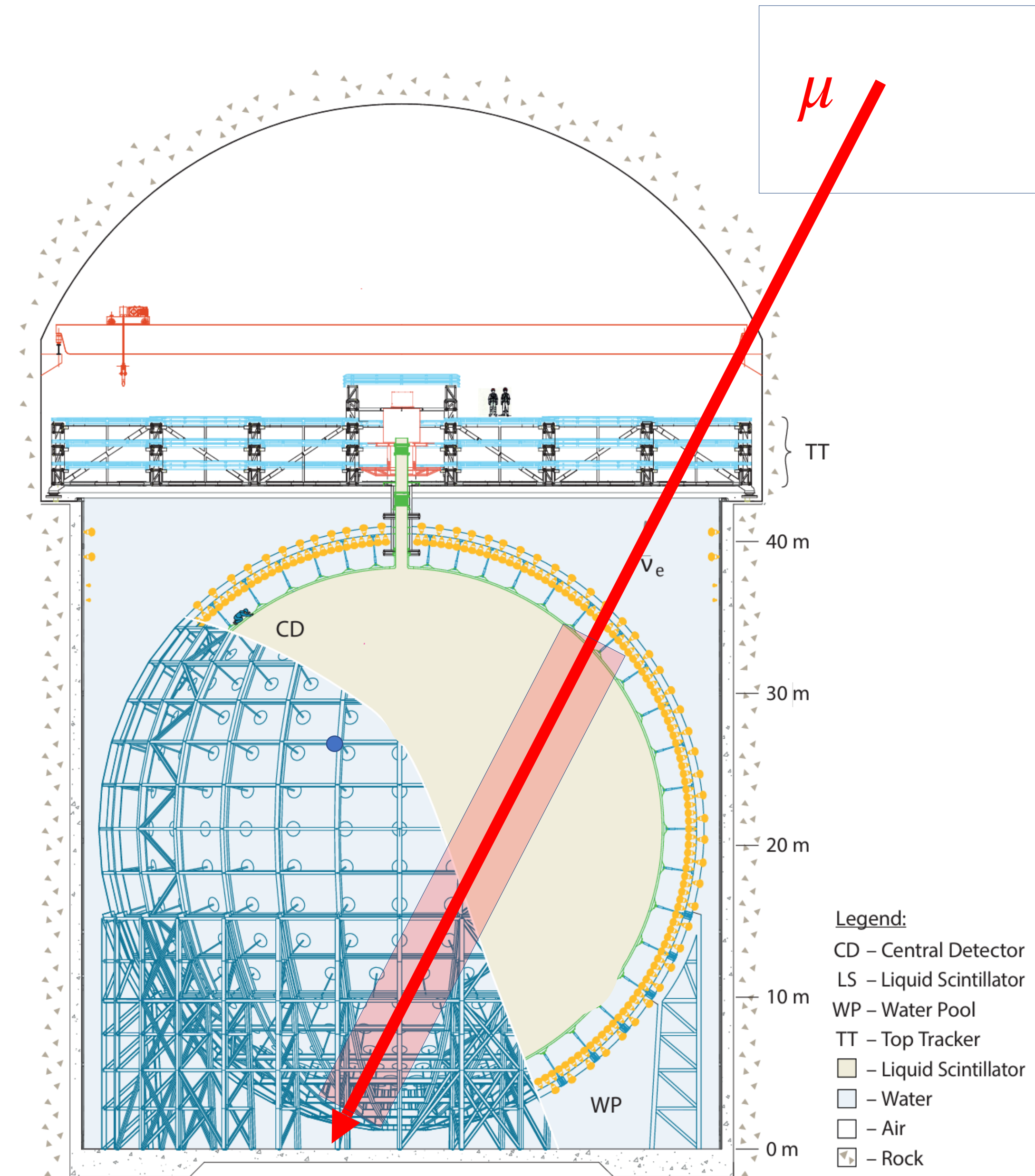
IBD Selection

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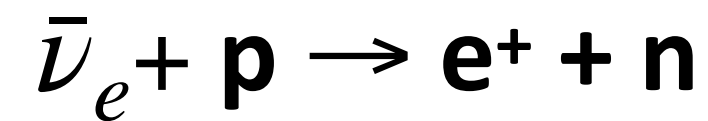
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 - Suppresses (but does not completely eliminate) long-lived spallation products
 - Veto spherical regions of $r < 4\text{m}$ around spallation neutrons for $\Delta t = 1.2\text{ s}$
 - Veto cylindrical region around the muon track (roughly equivalent to $r < 2.5\text{ m}$ for $\Delta t = 0.5\text{ s}$) **(new!)**



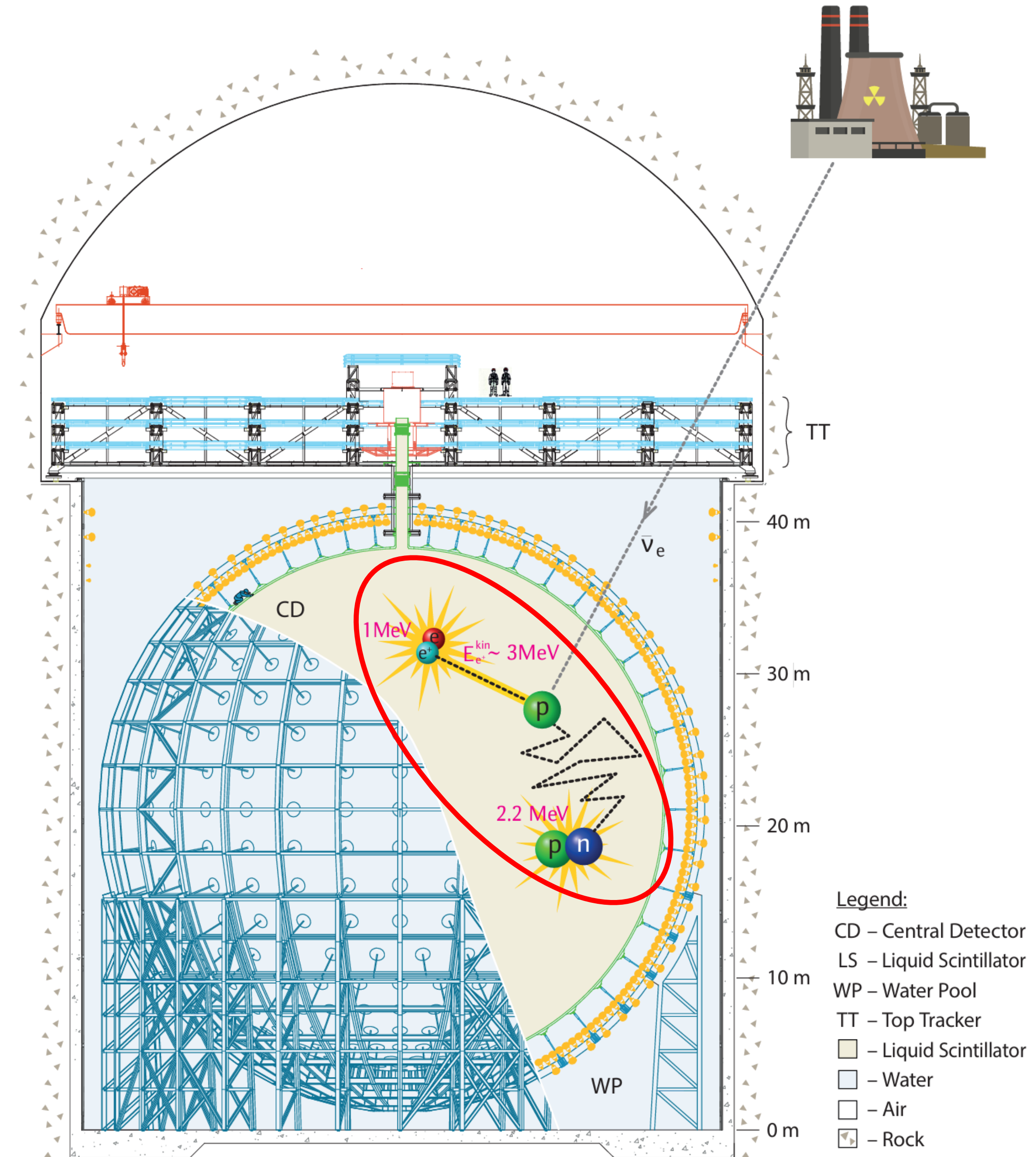
IBD Selection

- Reminder: we rely on the IBD reaction



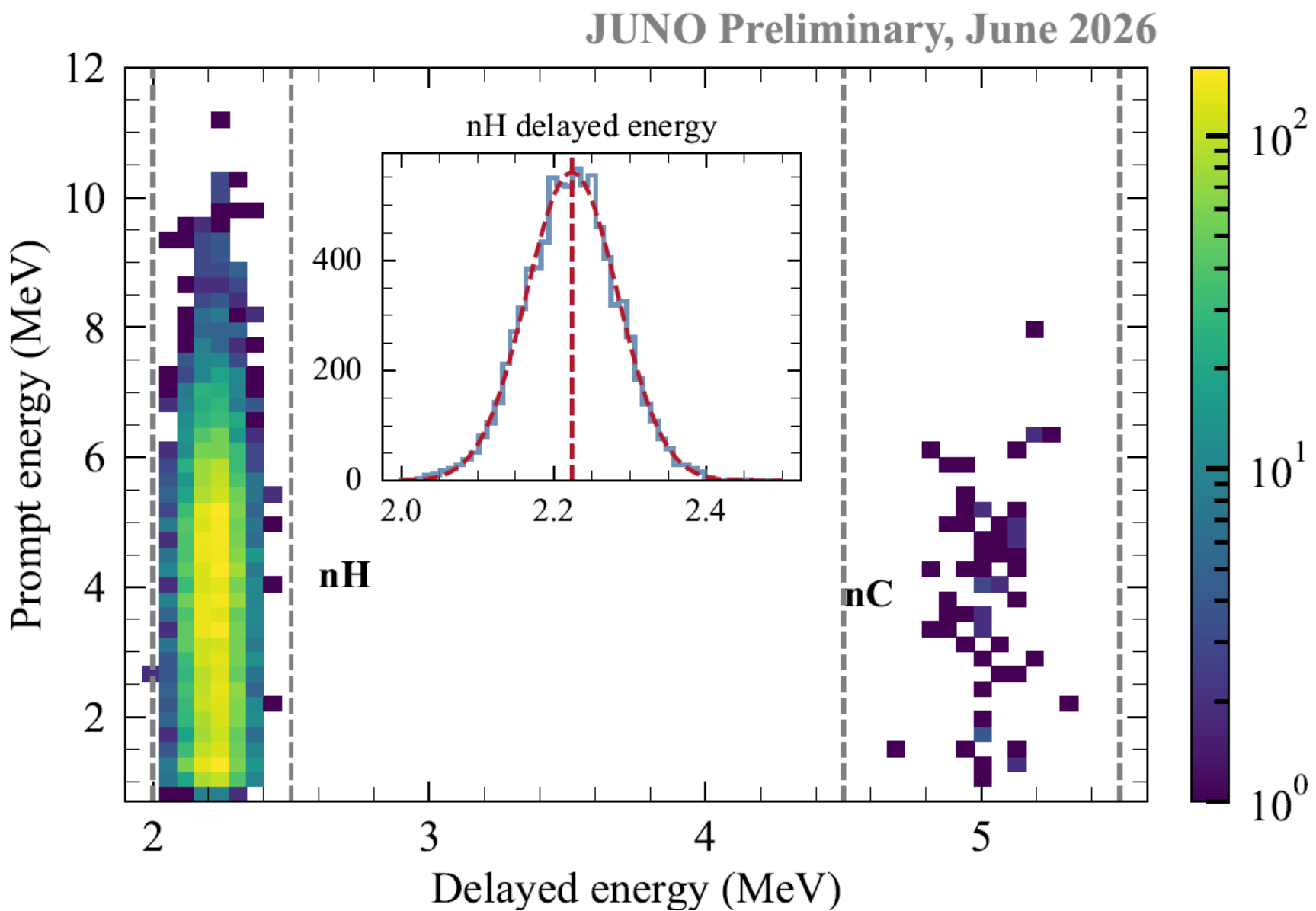
Looking for spatial and temporal coincidence of a positron-like (prompt) with a neutron-like (delayed) signal

- Step #4:** pair prompt-like and delayed-like events
 - Require $\Delta t < 1$ ms and $\Delta d < 1.5$ m
 - Apply a multiplicity cut to remove events where there's ambiguity

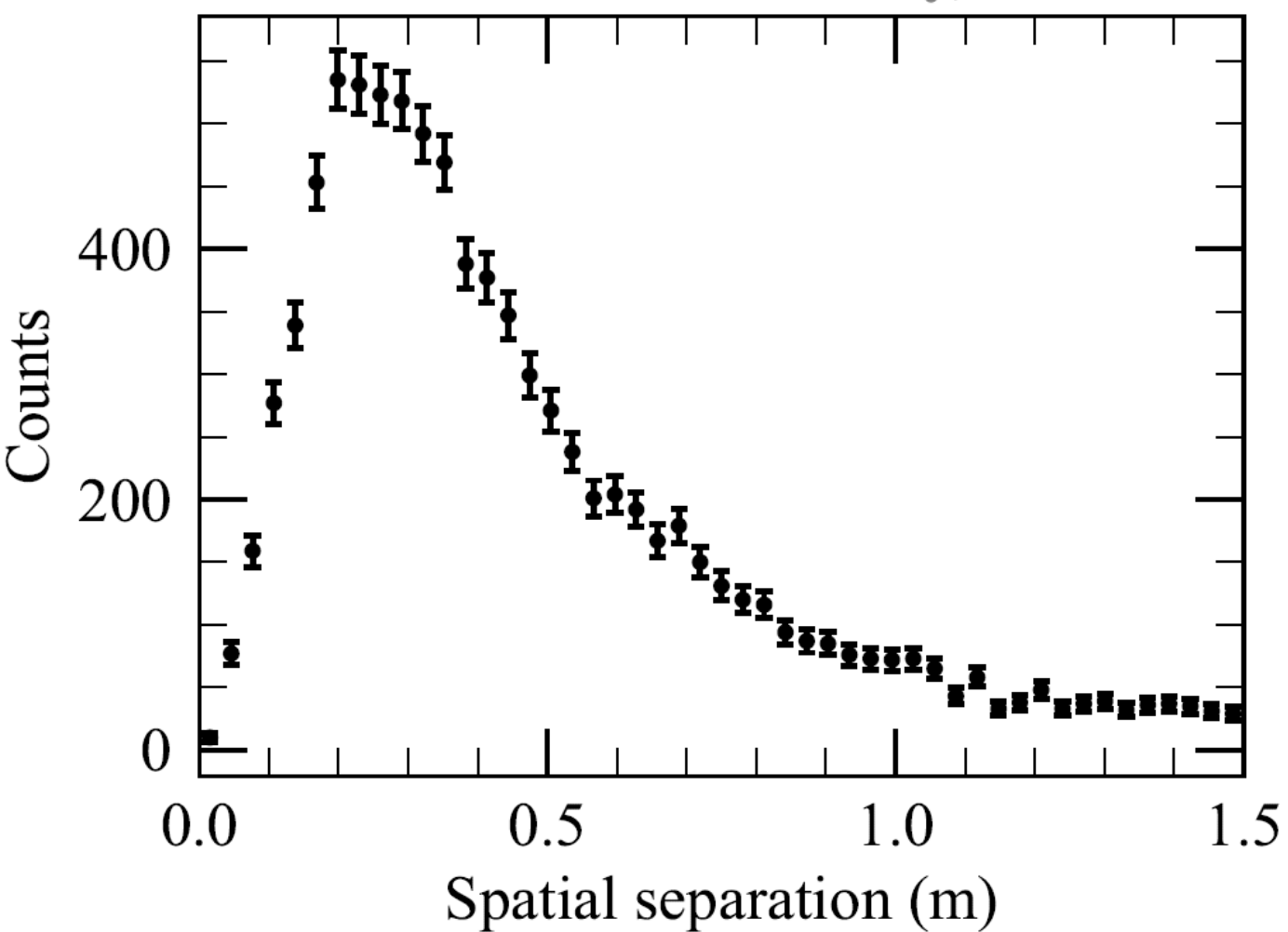
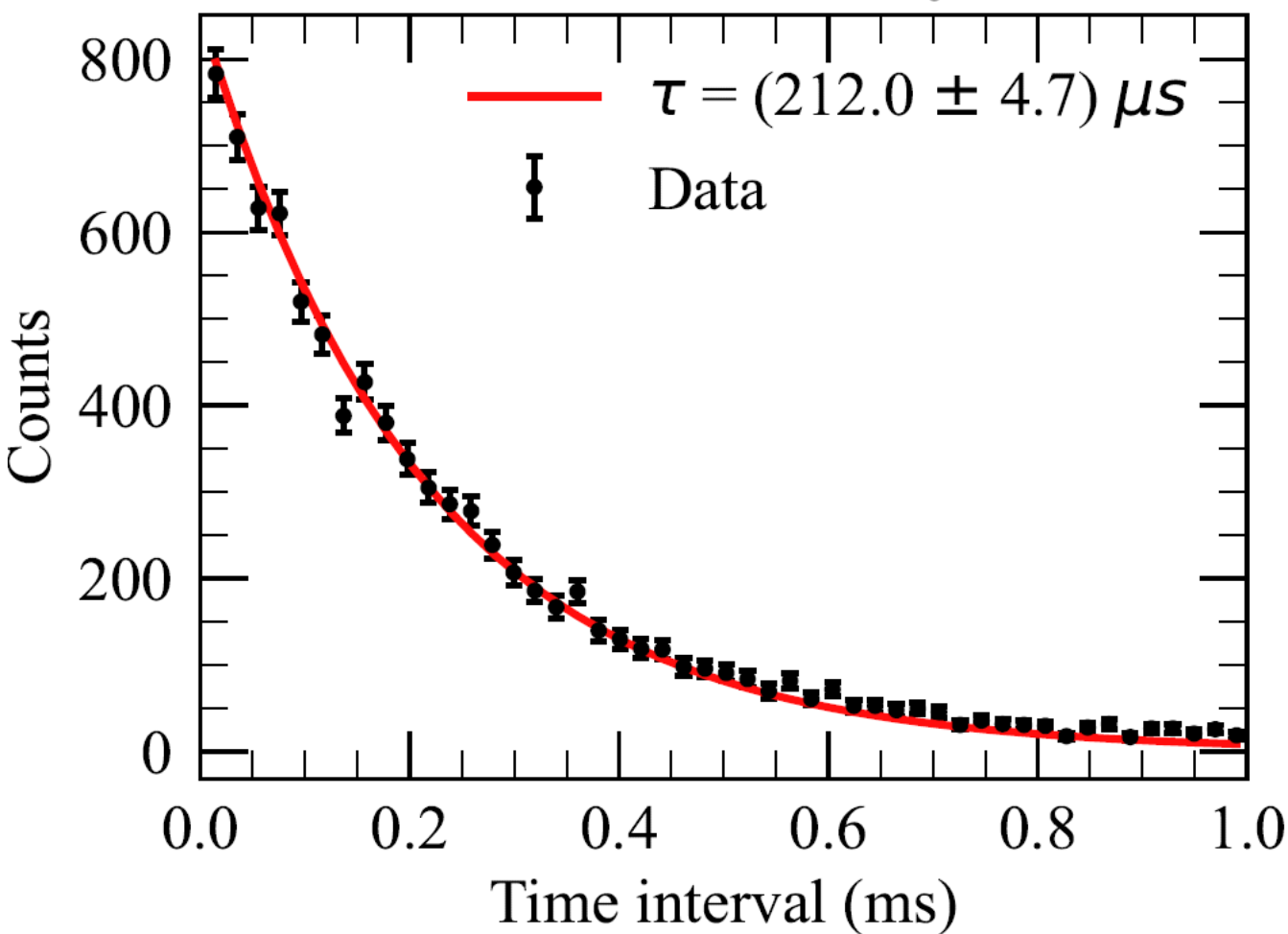


IBD Selection Highlights

- 207 days of good data:
 - From August 30th to May 18th
- Efficiency is estimated using data-driven methods
 - Reasonably high, around 74%

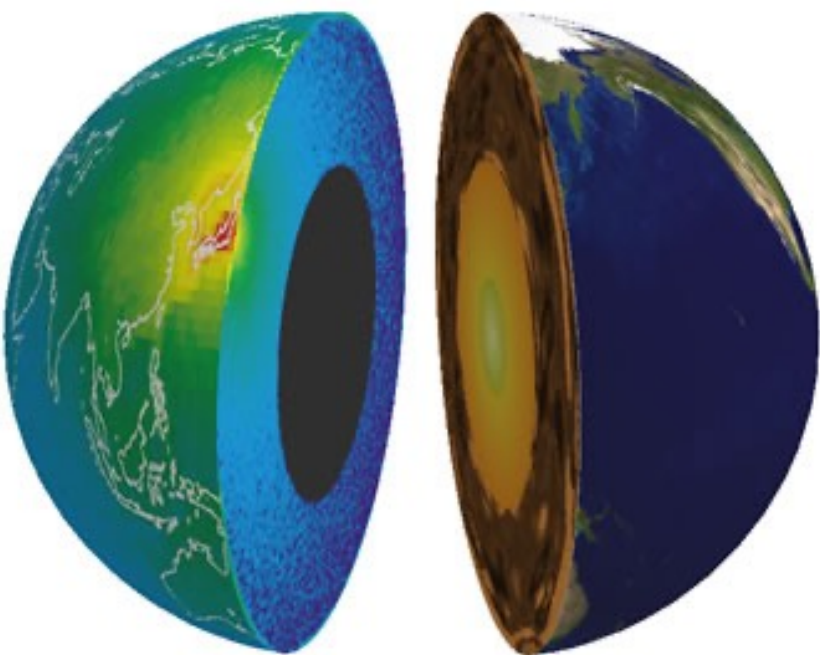
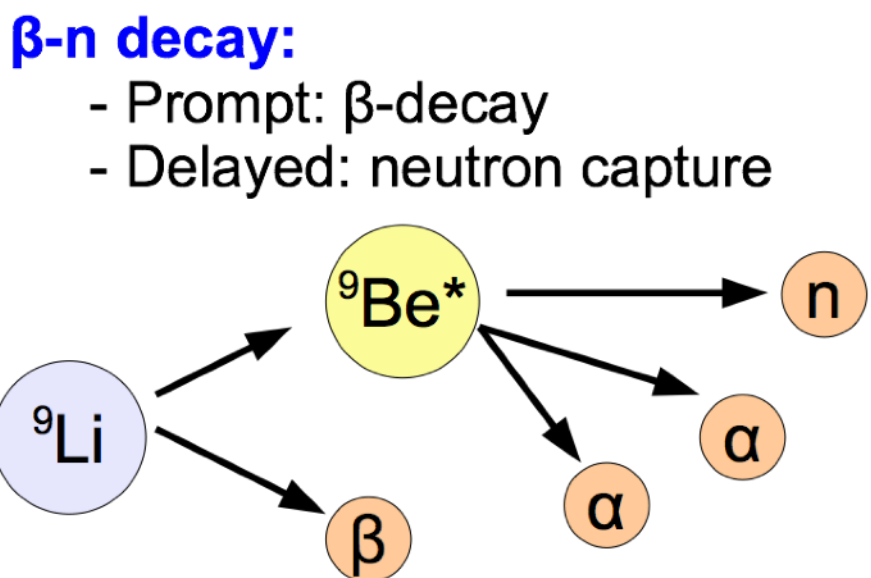


Antineutrinos ($\bar{\nu}_e$) Candidates Summary		
DAQ live time (days)	207.2	
$\bar{\nu}_e$ candidates	8294	
Selection Efficiencies (%)	ϵ	σ_{rel}
Fiducial volume	87.12%	0.96%
PMT flasher rejection	> 99.9%	Negligible
μ veto	93.67%	0.02%
Multiplicity cut	95.94%	negligible
Prompt-delayed coinc.	95.50%	0.32%
Correlated discriminator	98.99%	0.15%
Total efficiency (ϵ_{tot})	74.01%	1.02%

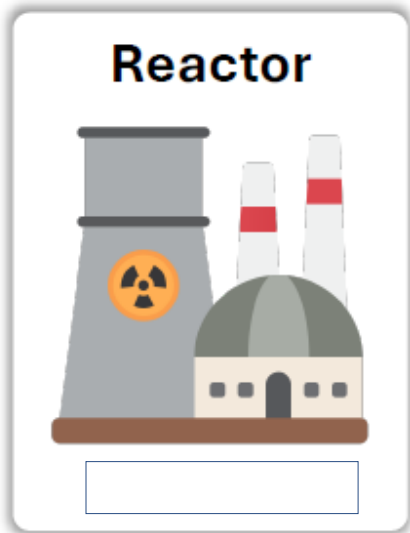
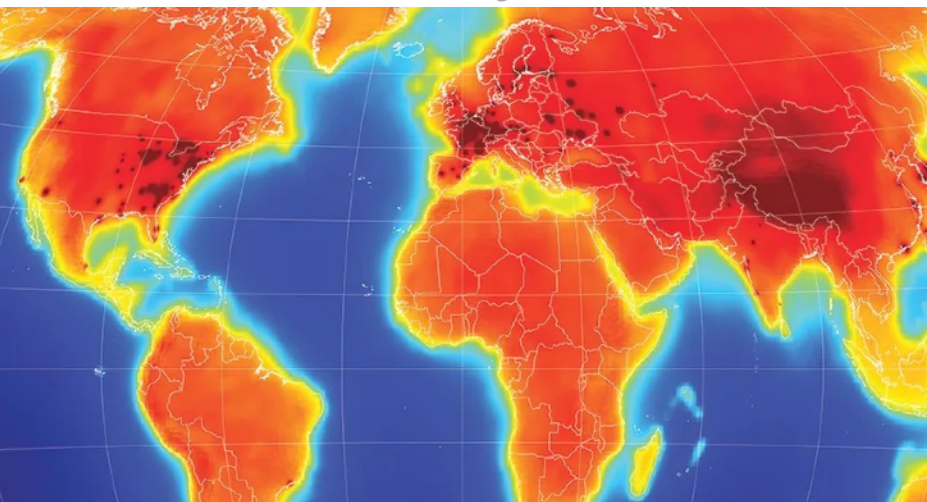


Backgrounds

- Backgrounds amount to **~15%** of the total candidate sample
- Main backgrounds:
 - Correlated $\beta - n$ signals from decay of long-lived ${}^9\text{Li}/{}^8\text{He}$
 - Geoneutrinos: emitted from the decay of U and Th in the Earth
 - Neutrinos from other nuclear power plants (World reactors)



(Global $\bar{\nu}_e$ map)



Backgrounds (cpd)	Pre-fit	Best-fit
${}^9\text{Li}/{}^8\text{He}$	1.05 ± 0.27	1.41 ± 0.26
Geoneutrinos	Free	2.12
World reactors	0.92 ± 0.09	0.92 ± 0.09
${}^{214}\text{Bi}-{}^{214}\text{Po}$	0.42 ± 0.31	0.57 ± 0.34
${}^{13}\text{C}(\alpha, n){}^{16}\text{O}$	0.05 ± 0.02	0.05 ± 0.02
Fast neutrons	0.02 ± 0.02	0.02 ± 0.02
Double neutrons	0.10 ± 0.10	0.13 ± 0.10
Atmospheric neutrinos	0.09 ± 0.04	0.11 ± 0.05
Accidentals	0.07 ± 0.01	0.07 ± 0.01

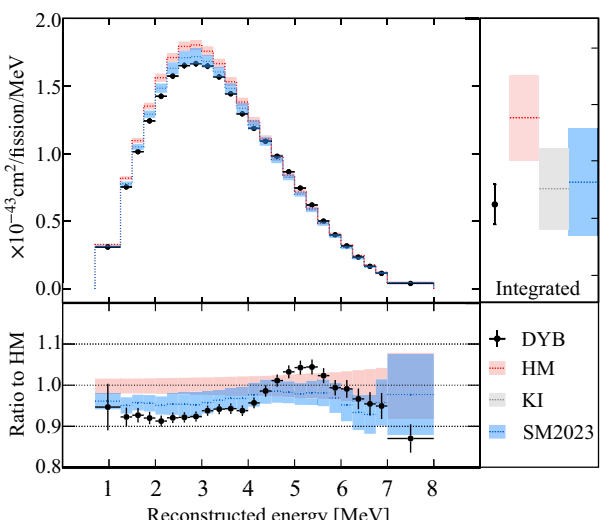
irreducible!

Signal IBD events: approx. 48 cpd
after efficiency correction

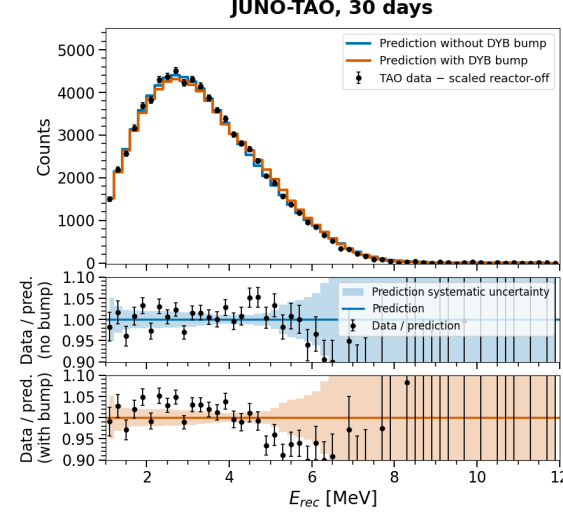
Nearly all backgrounds are assessed
using data-driven methods

Oscillation Fit

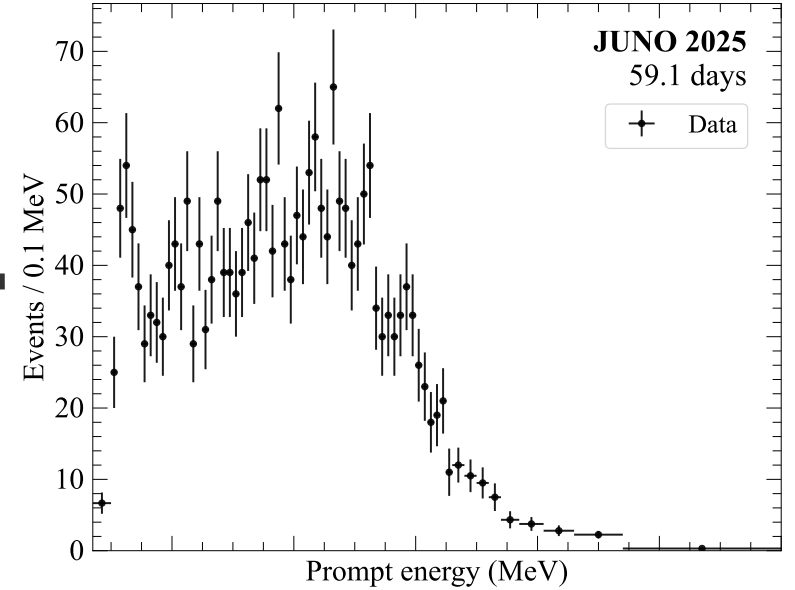
Daya Bay data



TAO data



JUNO data



Data

Huber-Mueller model

Reactor data
(fission fractions,
power, distance)

Energy non-linearity

Energy resolution

Data-driven or
analytical/MC

Shapes

Rates

Unoscillated
spectrum

Apply
oscillations

Detector
response

Backgrounds

Model

$\sin^2\theta_{12}$, Δm^2_{21} free

Fit/
minimize

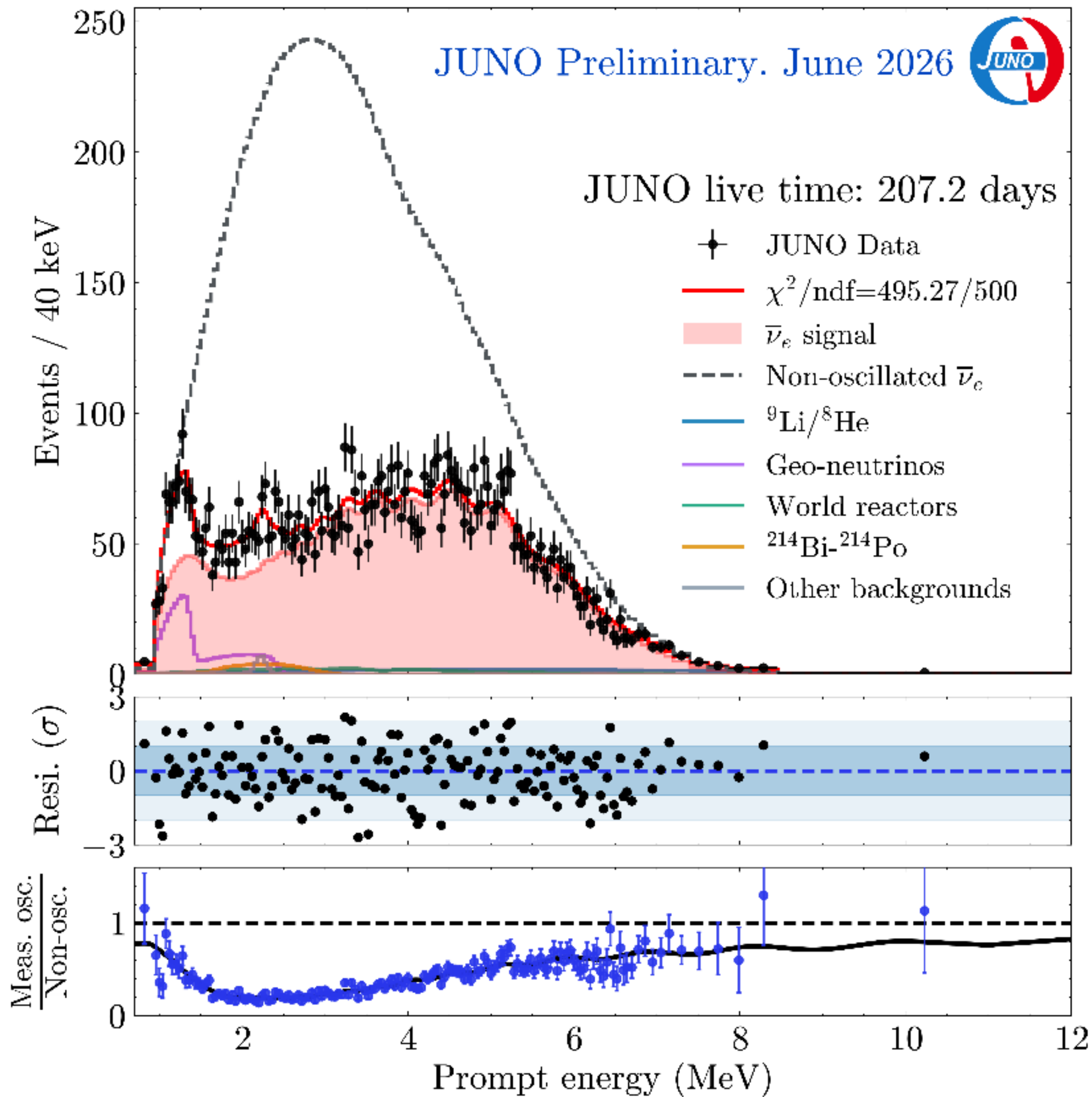
Oscillation Fit

- JUNO data are fit simultaneously with data from Daya Bay near detectors and TAO
 - Detector response accounted for individually for each detector
- Both solar oscillation parameters are estimated with world-leading precision

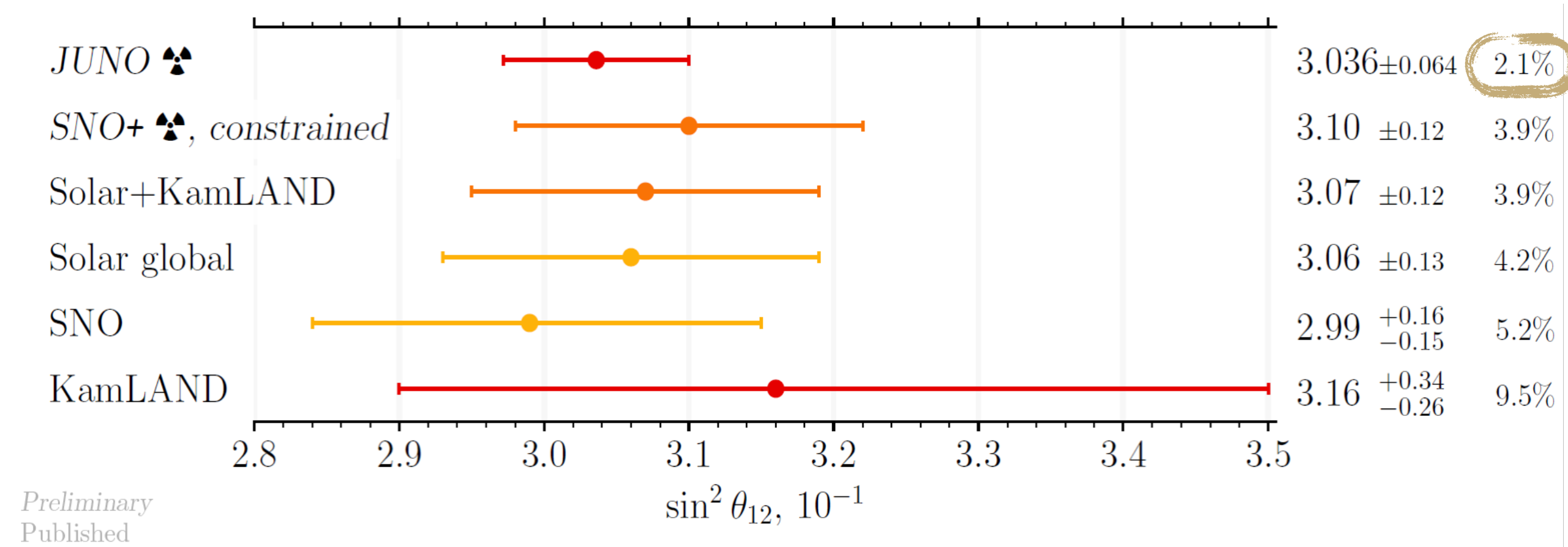
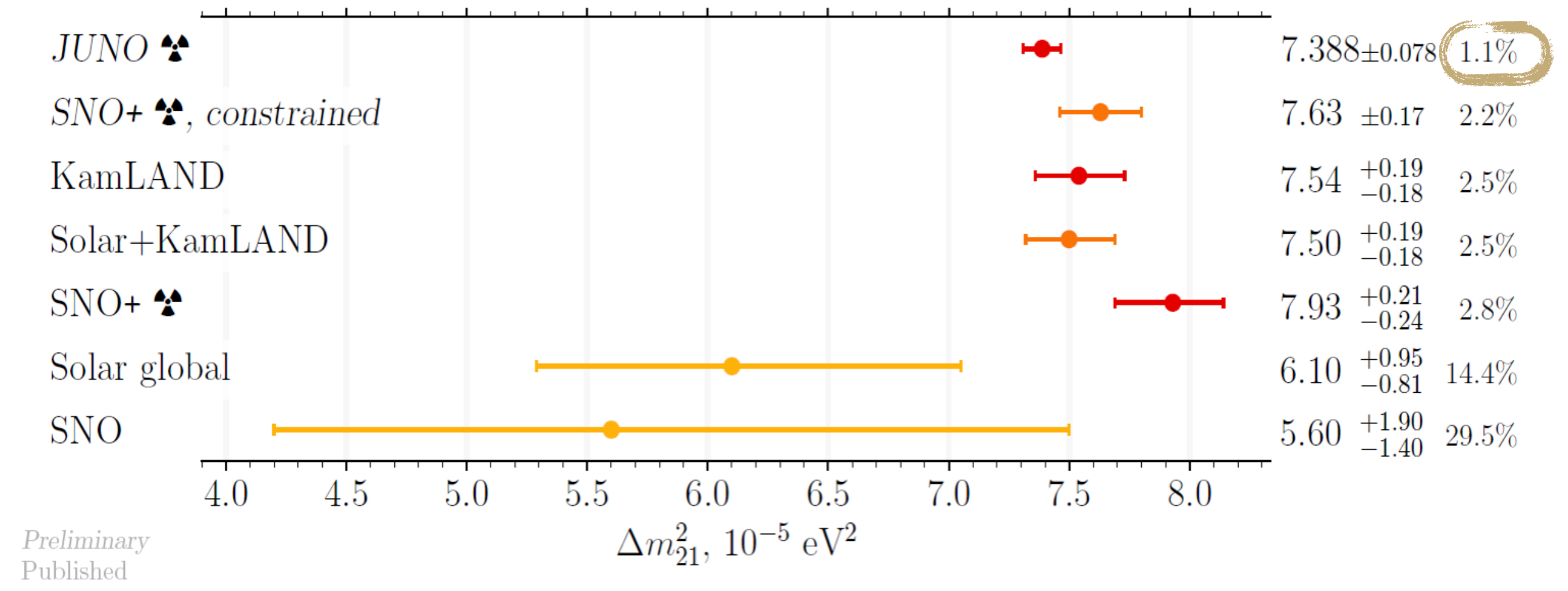
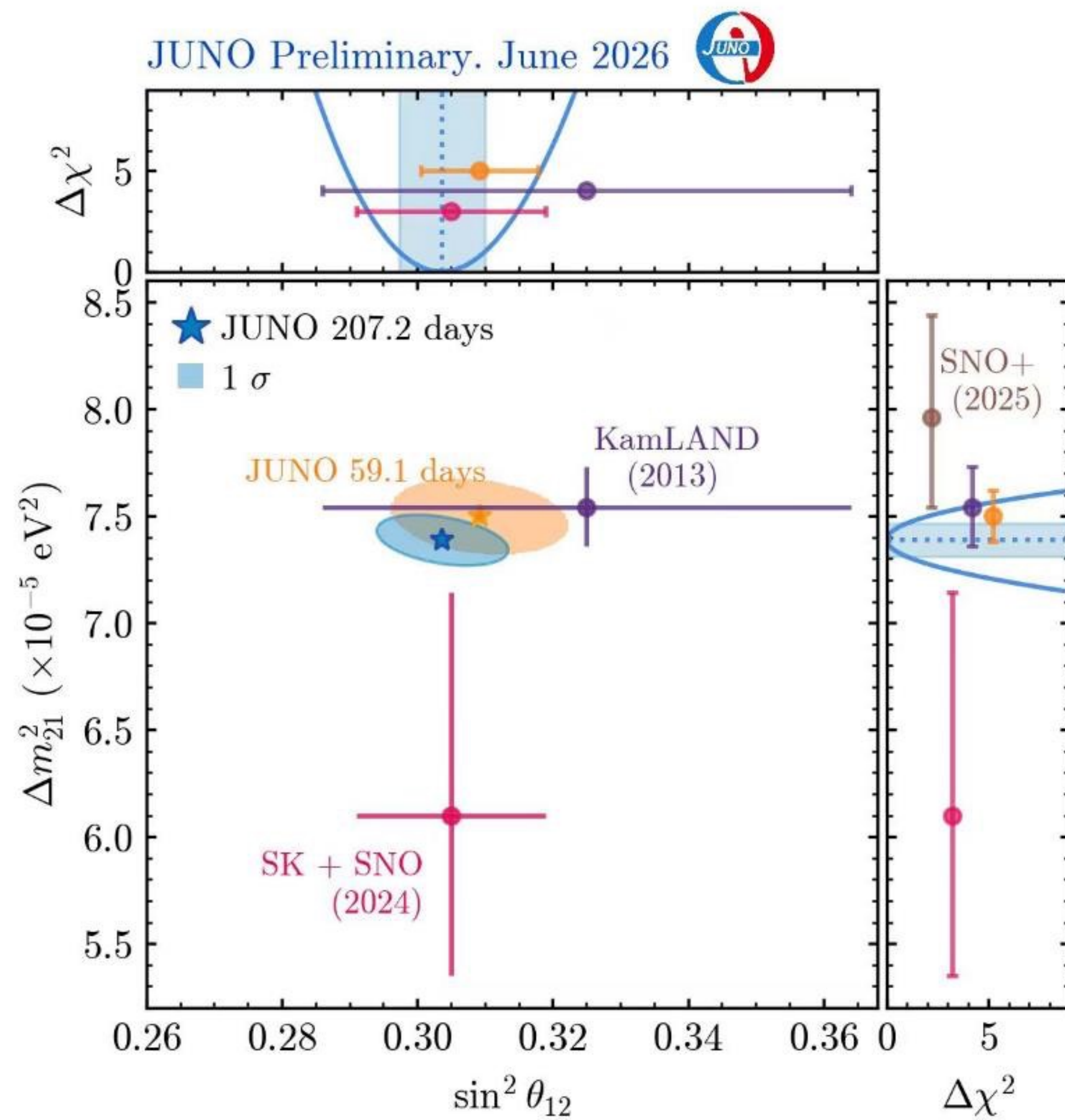
	Result	Precision
Δm_{21}^2	$7.388 \pm 0.078 \text{ eV}^2$	1.1 %
$\sin^2 \theta_{12}$	0.3036 ± 0.0064	2.1 %

- Results are still statistics dominated, but efficiency and background uncertainties are starting to become important

(for more details on the latest JUNO results, please see Yifang Wang's [talk](#) at Neutrino 2026)



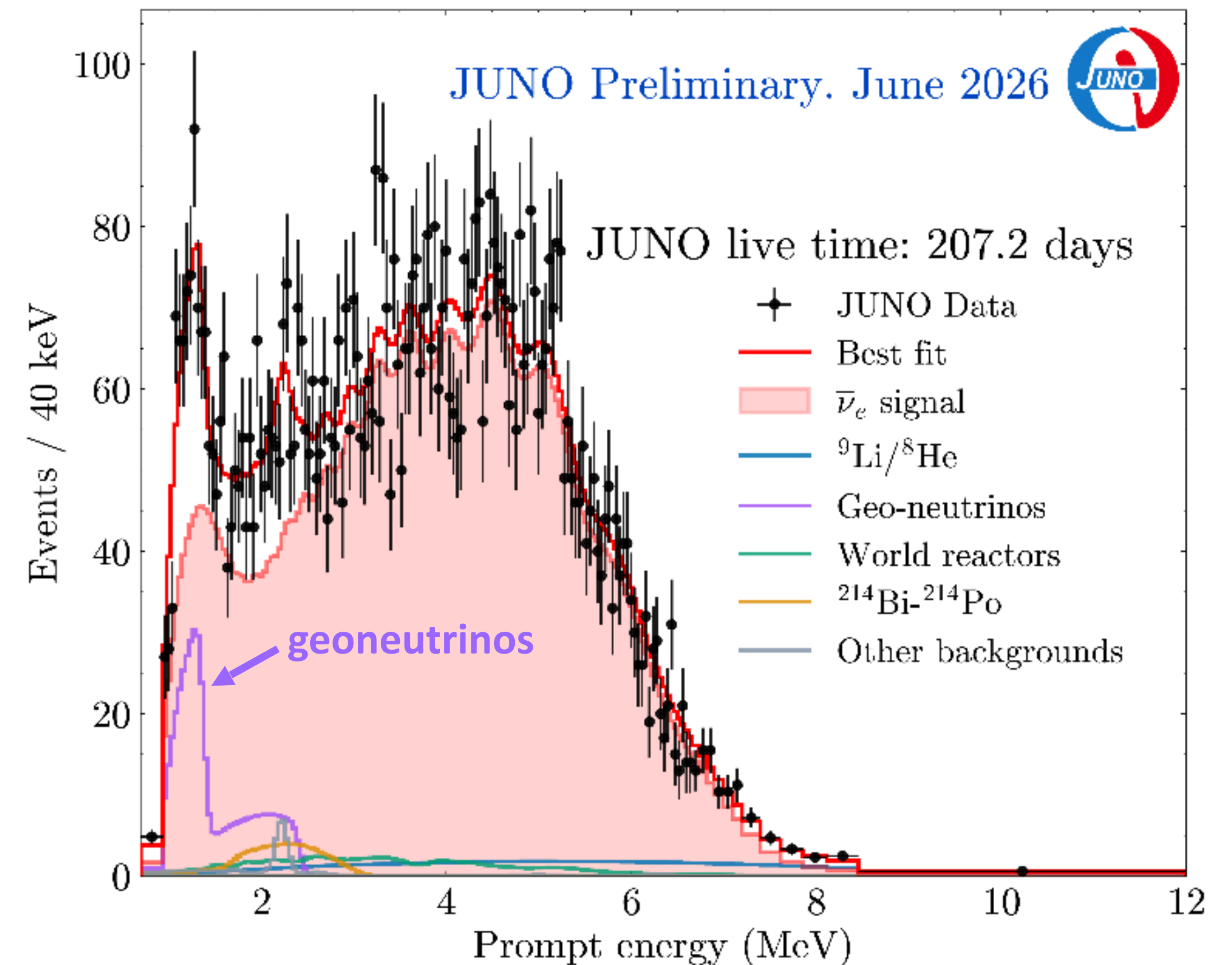
Solar Oscillation Parameters



Good agreement with previous results!

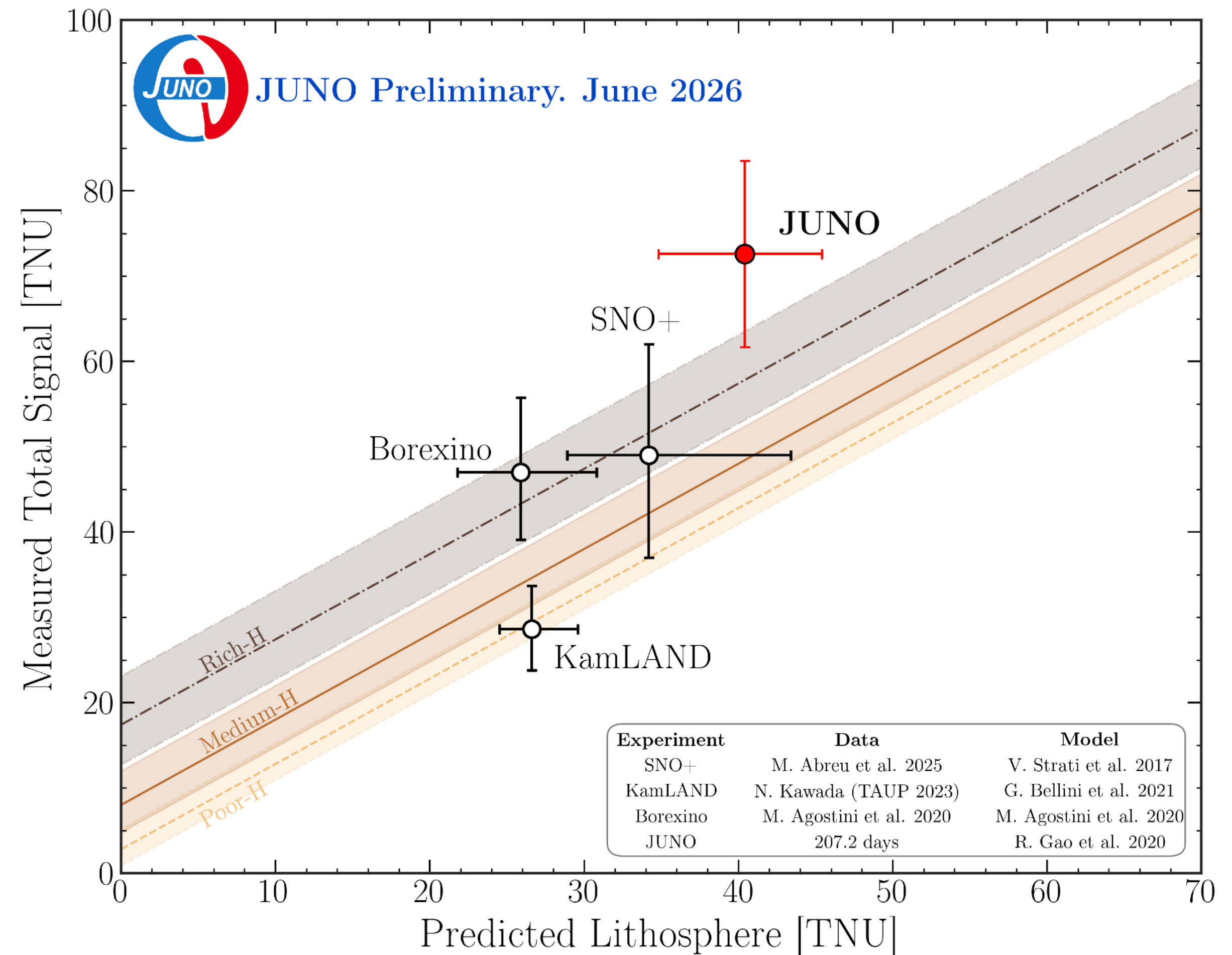
Geoneutrino Results

- Reminder: geoneutrinos are $\bar{\nu}_e$'s emitted by the decay of radioactive isotopes in the Earth
 - Provide a direct probe of the Earth's radiogenic heat production
 - Unique information about the composition and thermal evolution of our planet
- JUNO collects more geoneutrinos every year than all the geoneutrinos ever detected by other experiments
- These neutrinos cannot be distinguished on an individual basis from reactor antineutrinos
 - They are mixed with reactor $\bar{\nu}_e$'s in our spectrum, but have a distinctive spectral shape and energy range
 - The fit is able to disentangle the amount of geoneutrinos in our spectrum with some uncertainty (currently 15%)



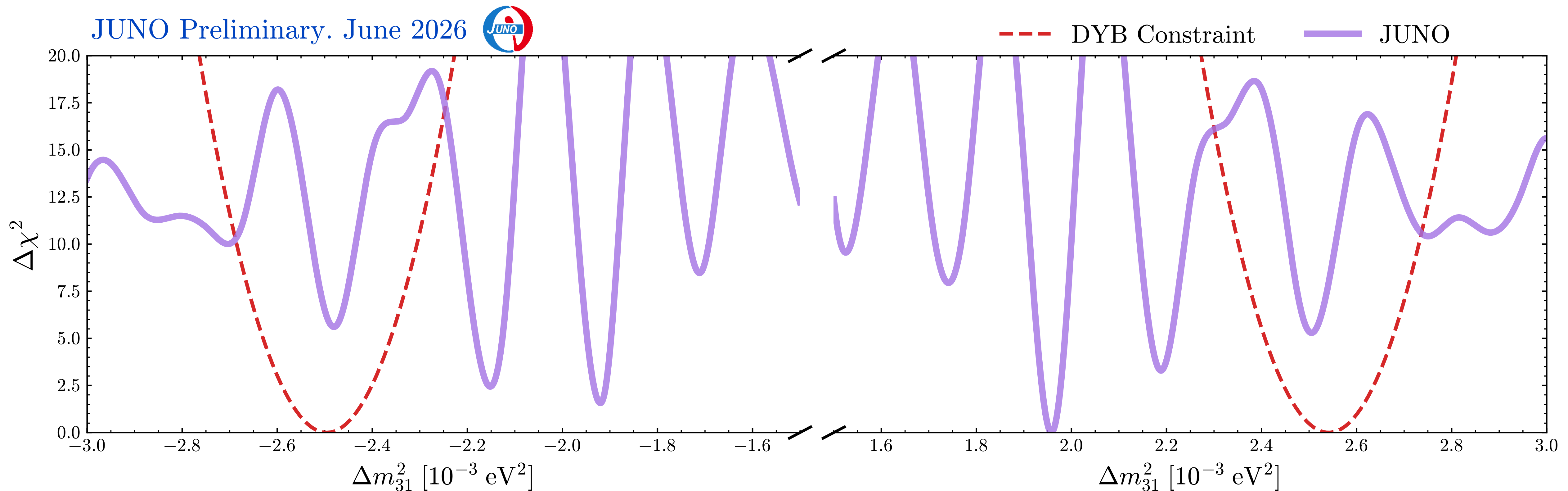
Geoneutrino Results

- Geoneutrino rates are normally reported in Terrestrial Neutrino Units (TNU):
 - 1 TNU = 1 IBD per 10^{32} free protons per year with 100% detector efficiency
- In our most recent measurement, we are seeing a very clear geoneutrino signal
 - Corresponds to 73 ± 11 TNU
 - World-leading precision of 15%
- Higher than expectation from existing geological models, but still with limited statistical significance
- Need more JUNO data and refined geological models to elucidate



Atmospheric Mass Splitting Δm_{31}^2

- JUNO's current measurement of Δm_{31}^2 has degeneracies due to the low statistics

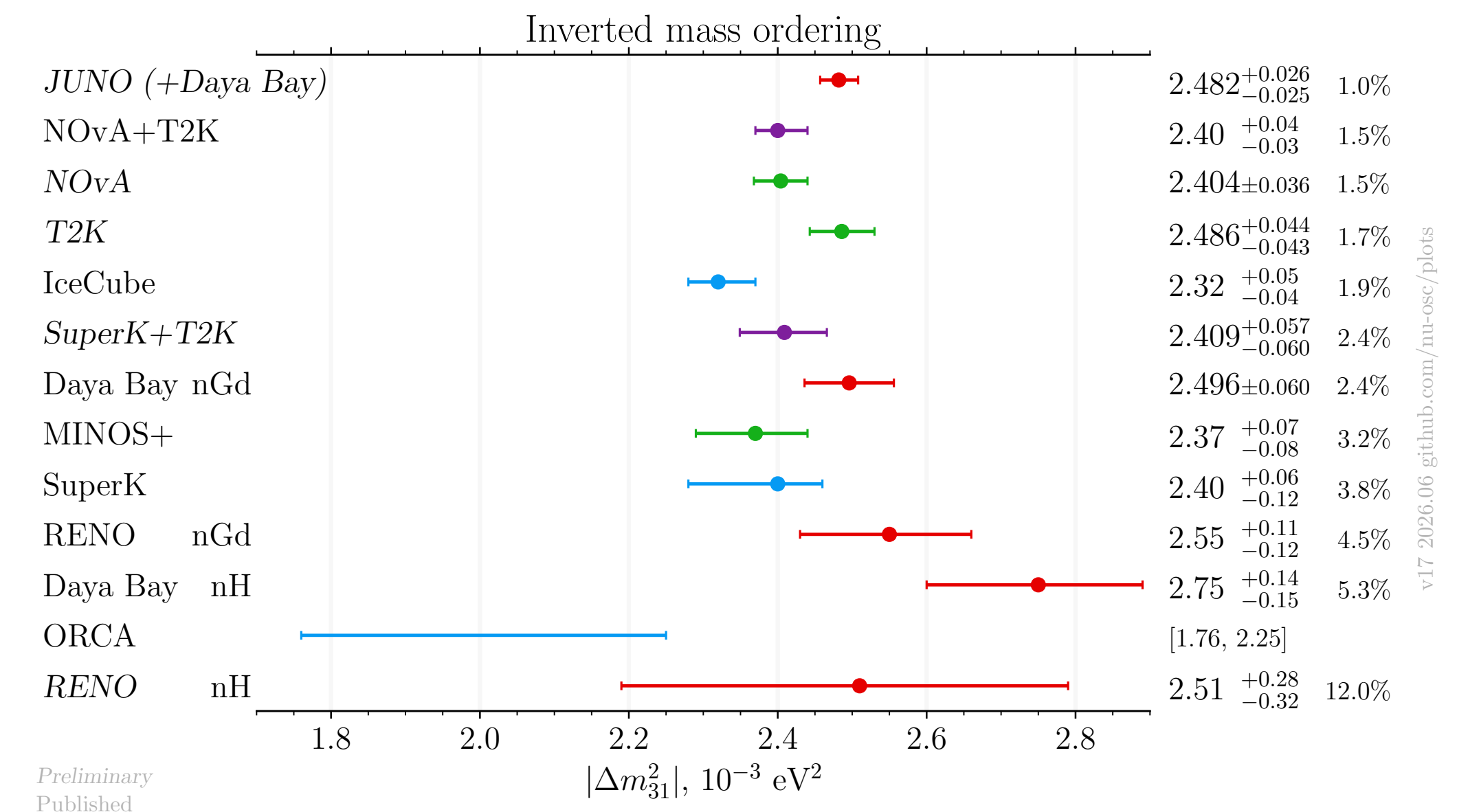
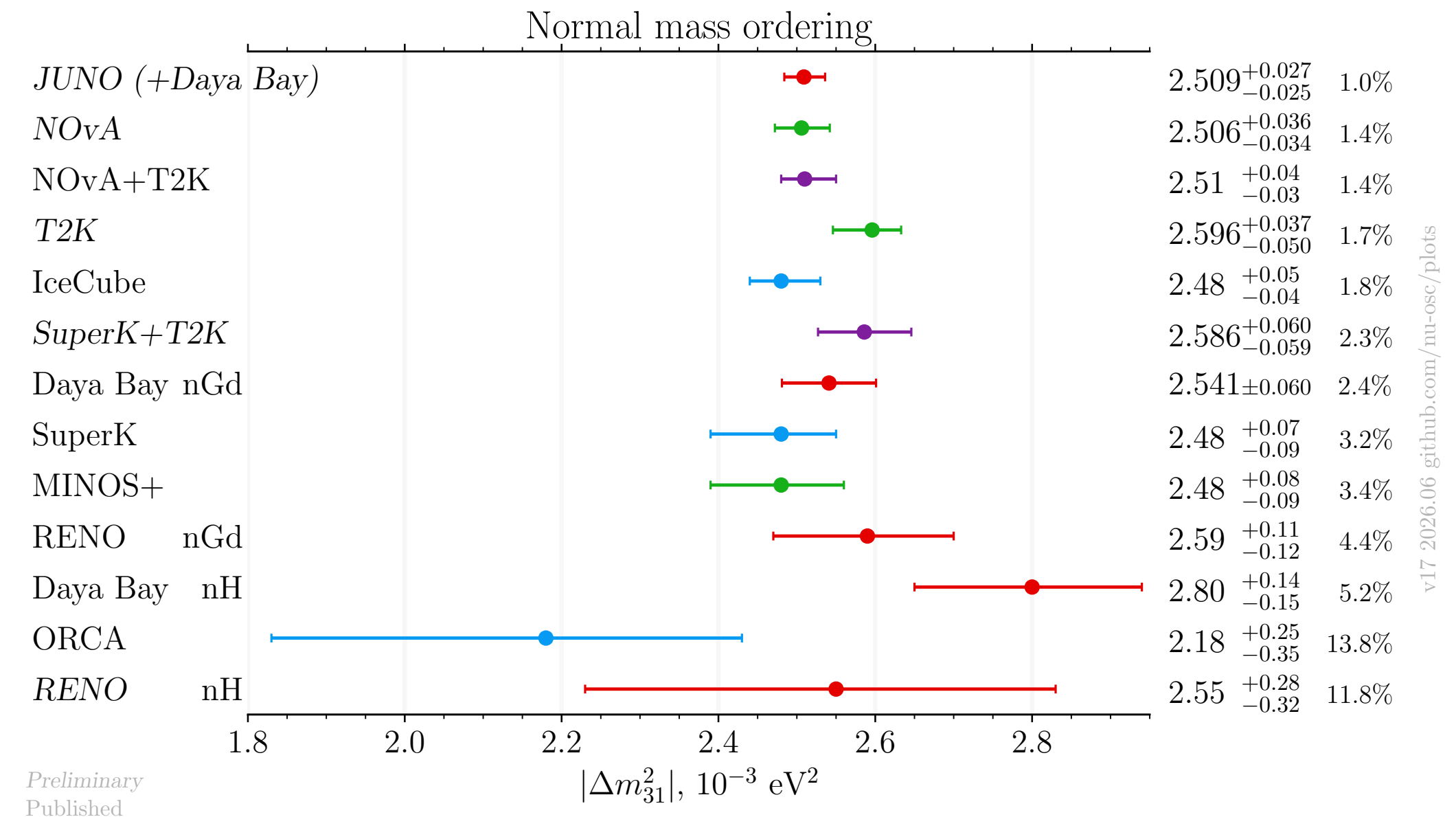
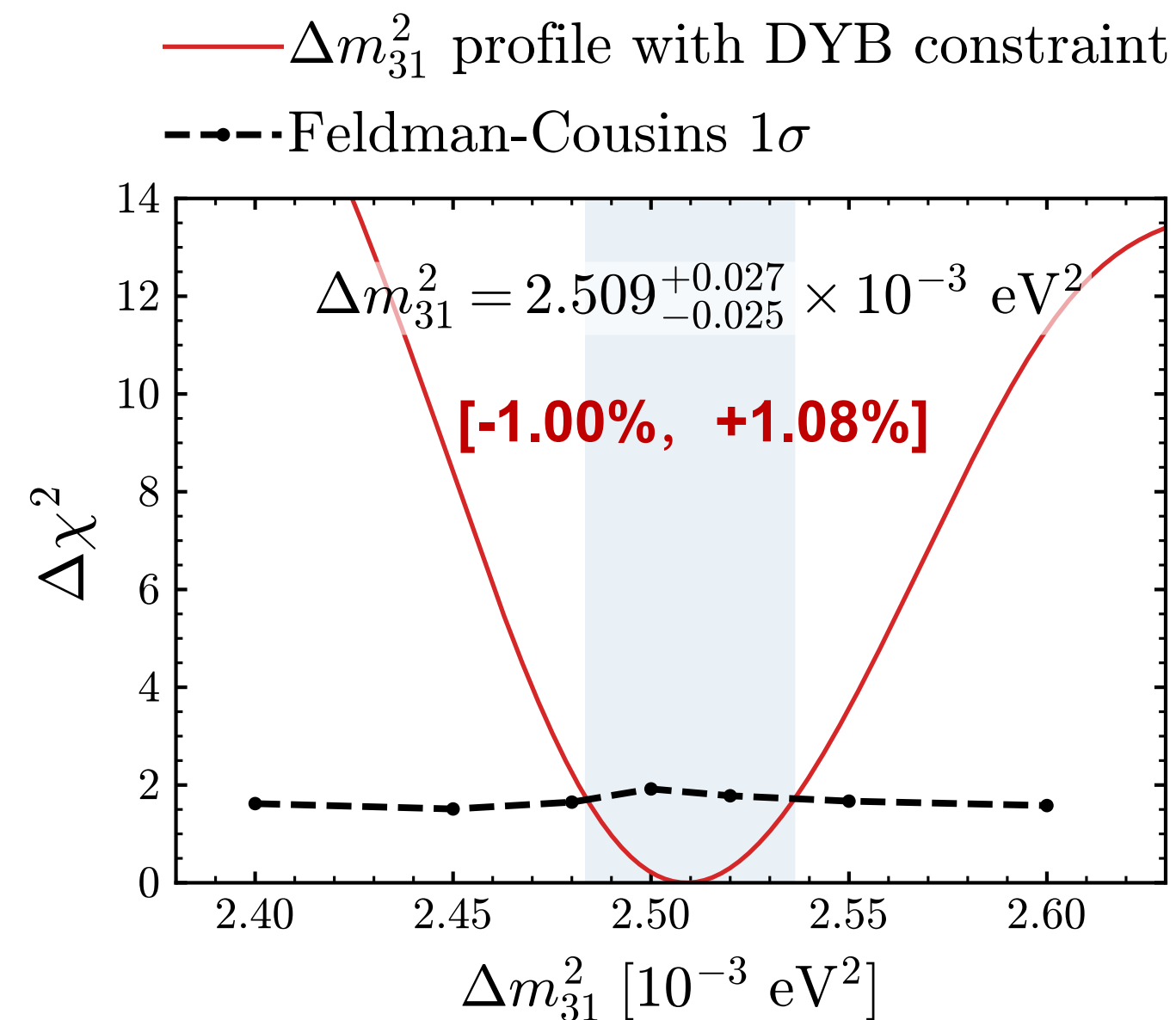
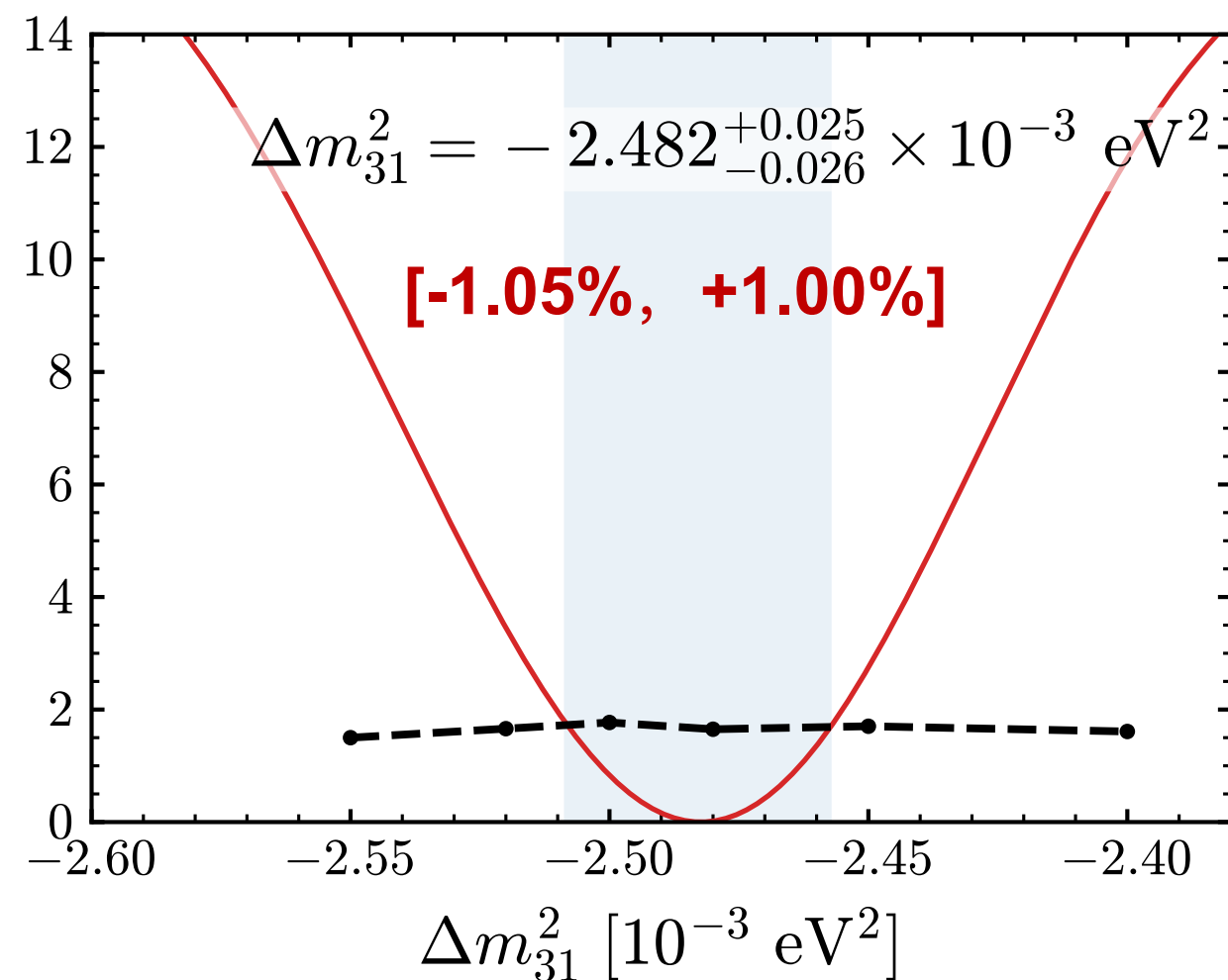


- Multiple minima will disappear as more data are accumulated, leaving only the one minimum
- For now, Daya Bay's measurement is used as an external constraint so the fit focuses on the "right" minimum

Δm_{31}^2 Mass Splitting

- The error bars are determined using the Feldman-Cousins method
 - World-leading precision between 1.0 and 1.1%
- We can further exploit this measurement to shed light on the mass ordering (next slides)

JUNO Preliminary. June 2026 



v17 2026.06 github.com/nu-osc/plots

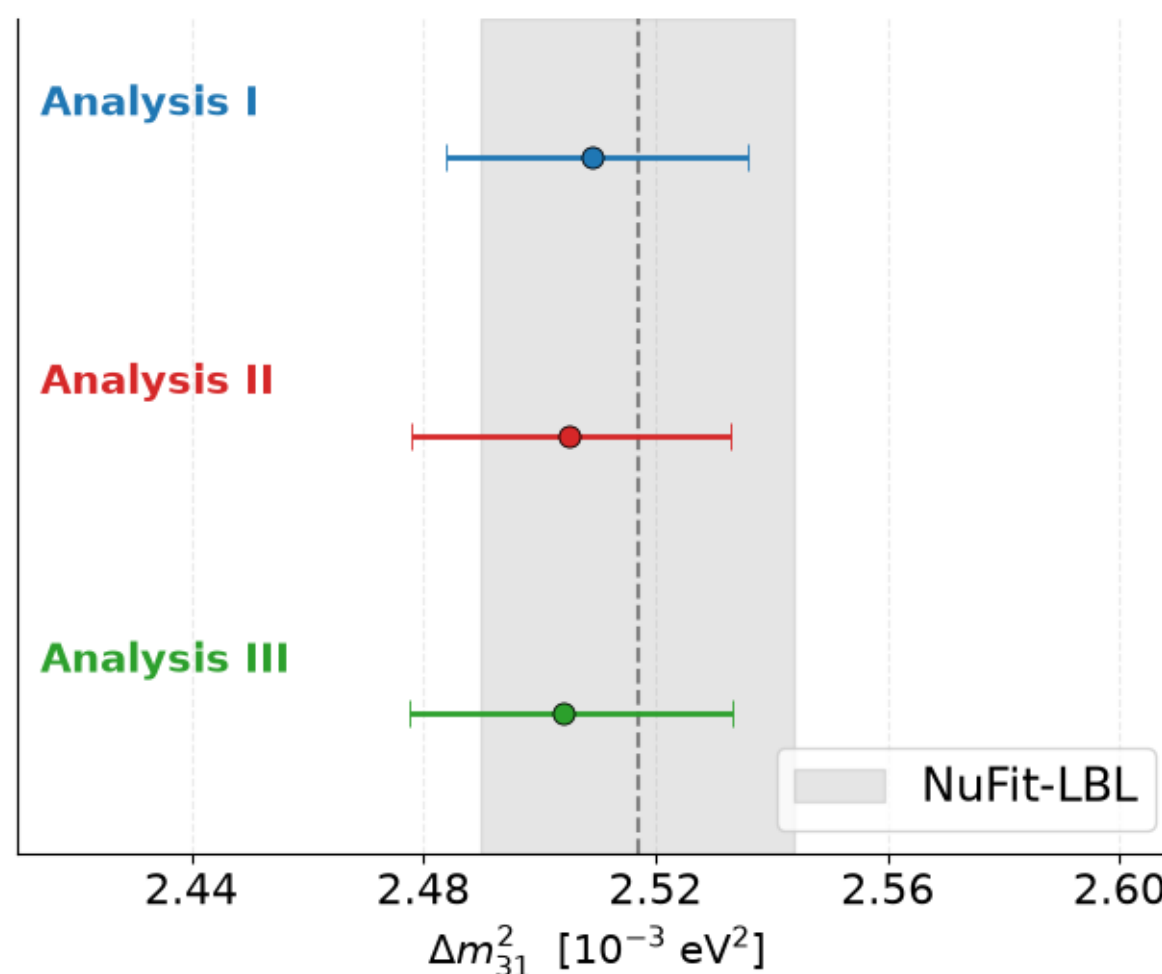
v17 2026.06 github.com/nu-osc/plots

Constraining the Mass Ordering

- Have 3 independent analyses that yield consistent results (independent reconstruction, fiducial volume, selection, background assessment, and oscillation fitters)

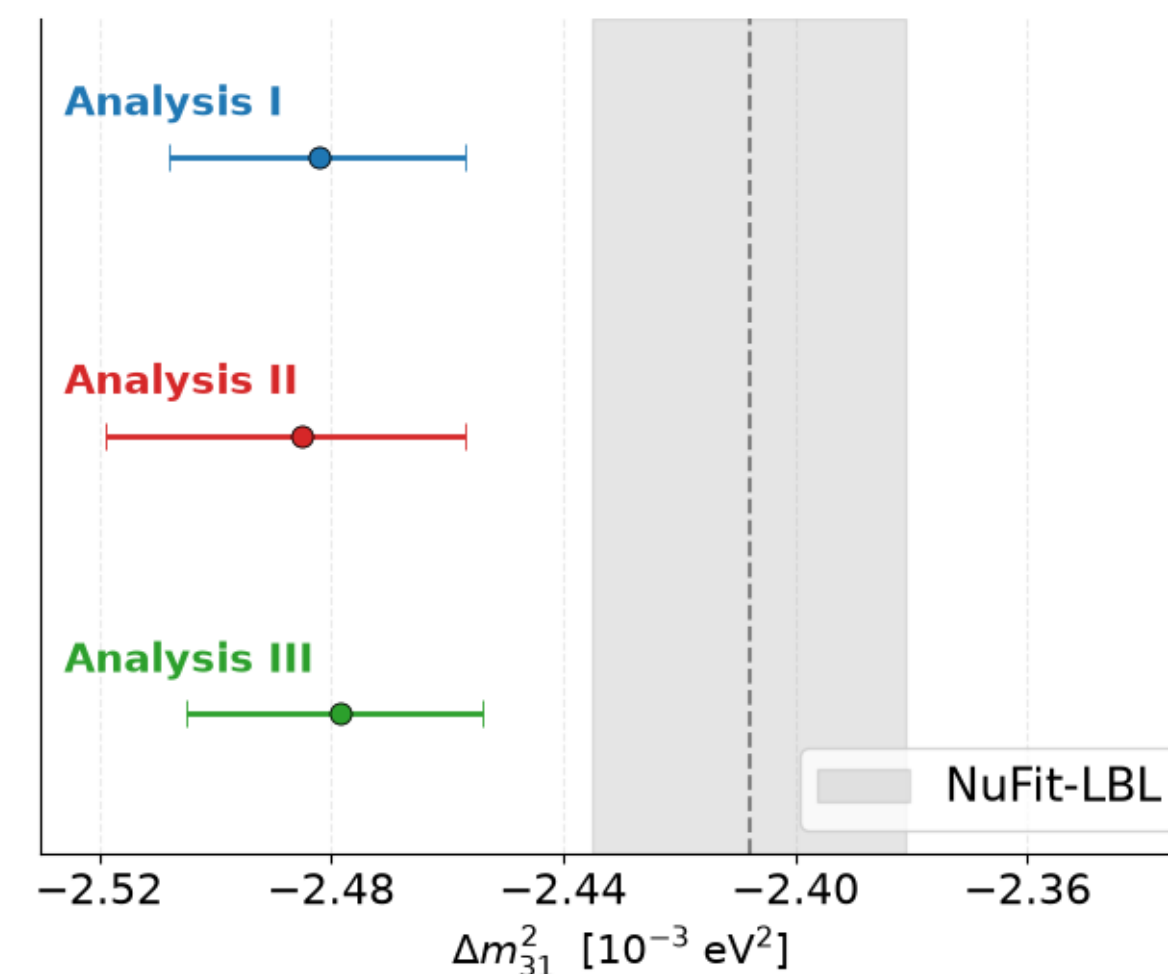
JUNO+DYB Feldman-Cousins

Normal Ordering

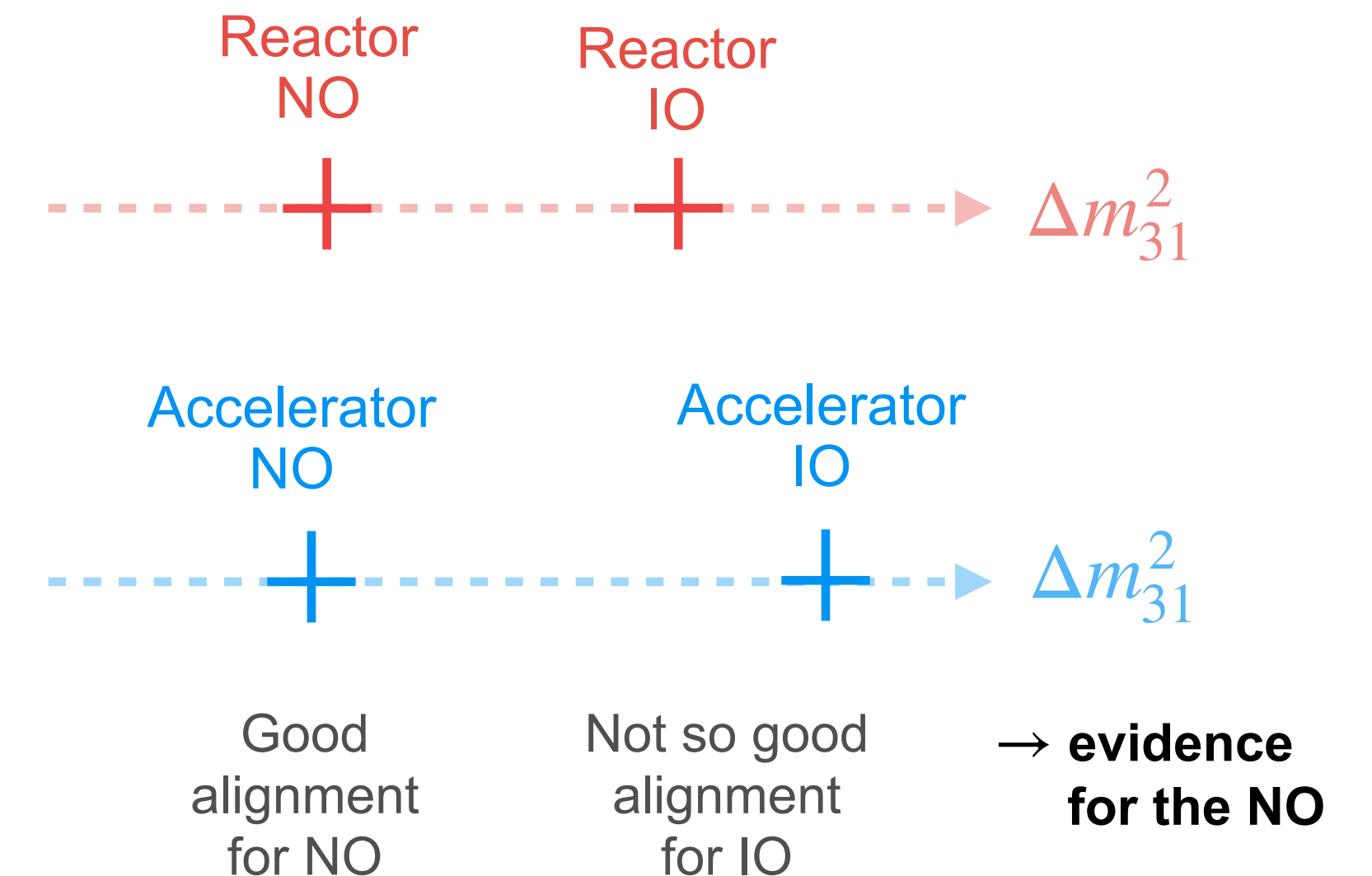


JUNO Preliminary. June 2026

Inverted Ordering



Basic principle: Measurements of Δm_{31}^2 from $\bar{\nu}_e$ disappearance and $\nu_\mu/\bar{\nu}_\mu$ disappearance expected to **align** for the right mass ordering but not for the wrong one



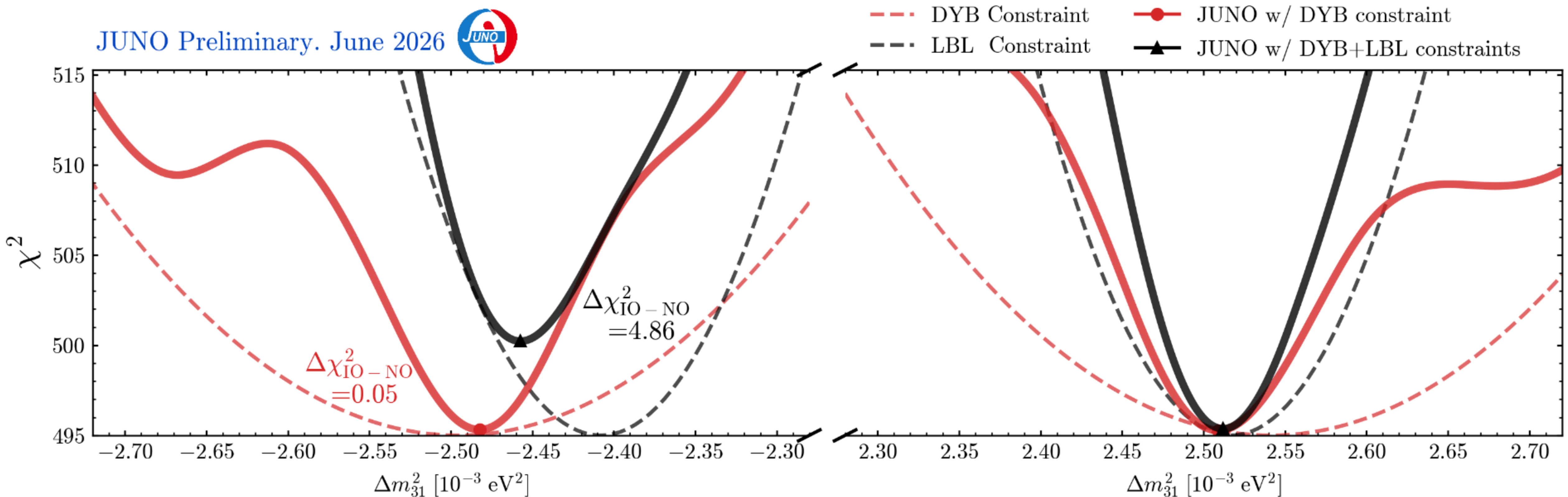
- Comparing our measurement with that of accelerator experiments provides additional information on the mass ordering

— Adopt estimate from NuFit for long-baseline (LBL) experiments for this comparison

Cartoon is just for illustration purposes, but inspired from current situation

Constraining the Mass Ordering

JUNO Preliminary. June 2026 



Measurements do not align so well for the inverted ordering (IO)

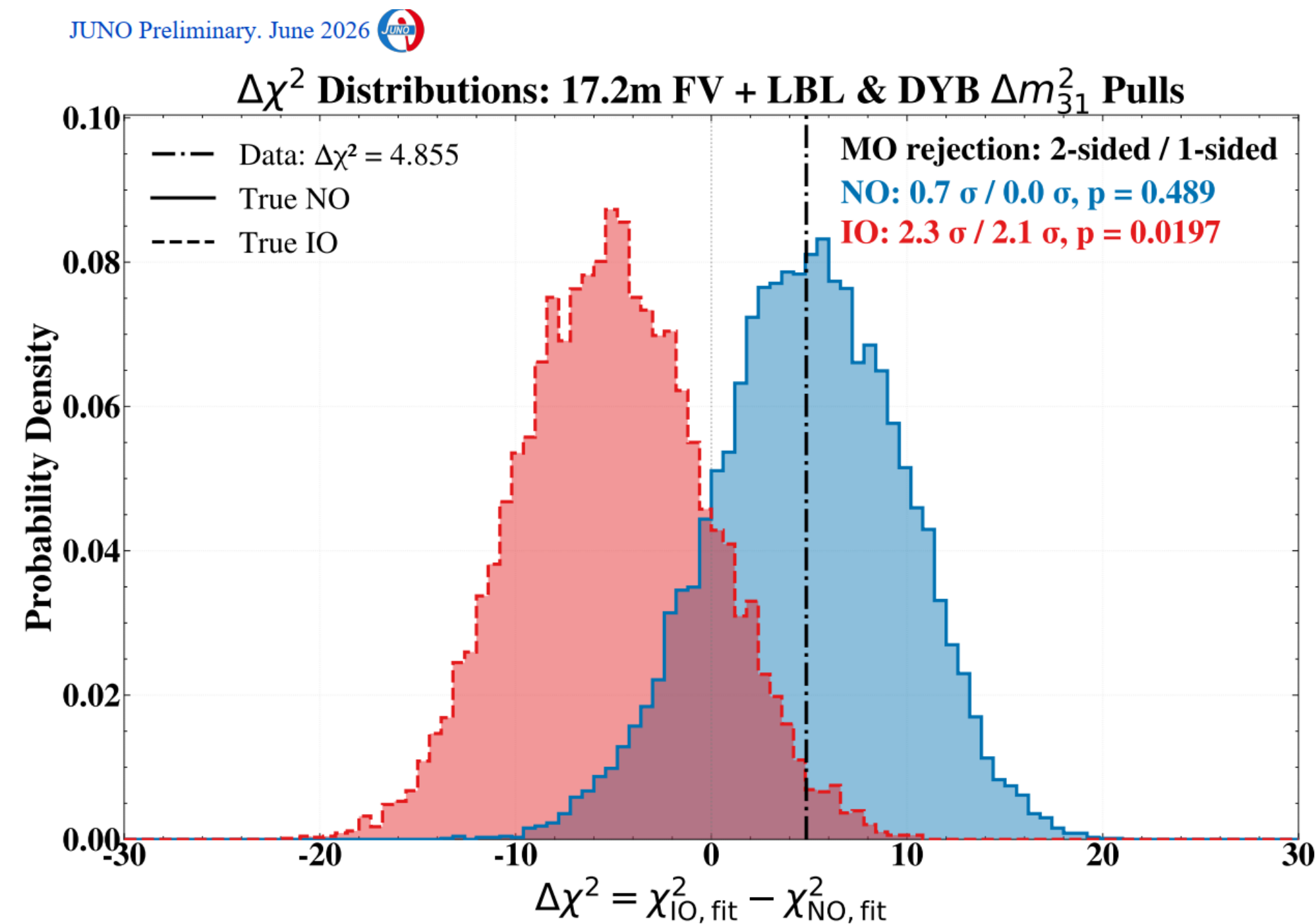
But they do for the normal ordering (NO)

→ Normal mass ordering favored at $\Delta\chi^2 = 4.86$

Mass Ordering Significance

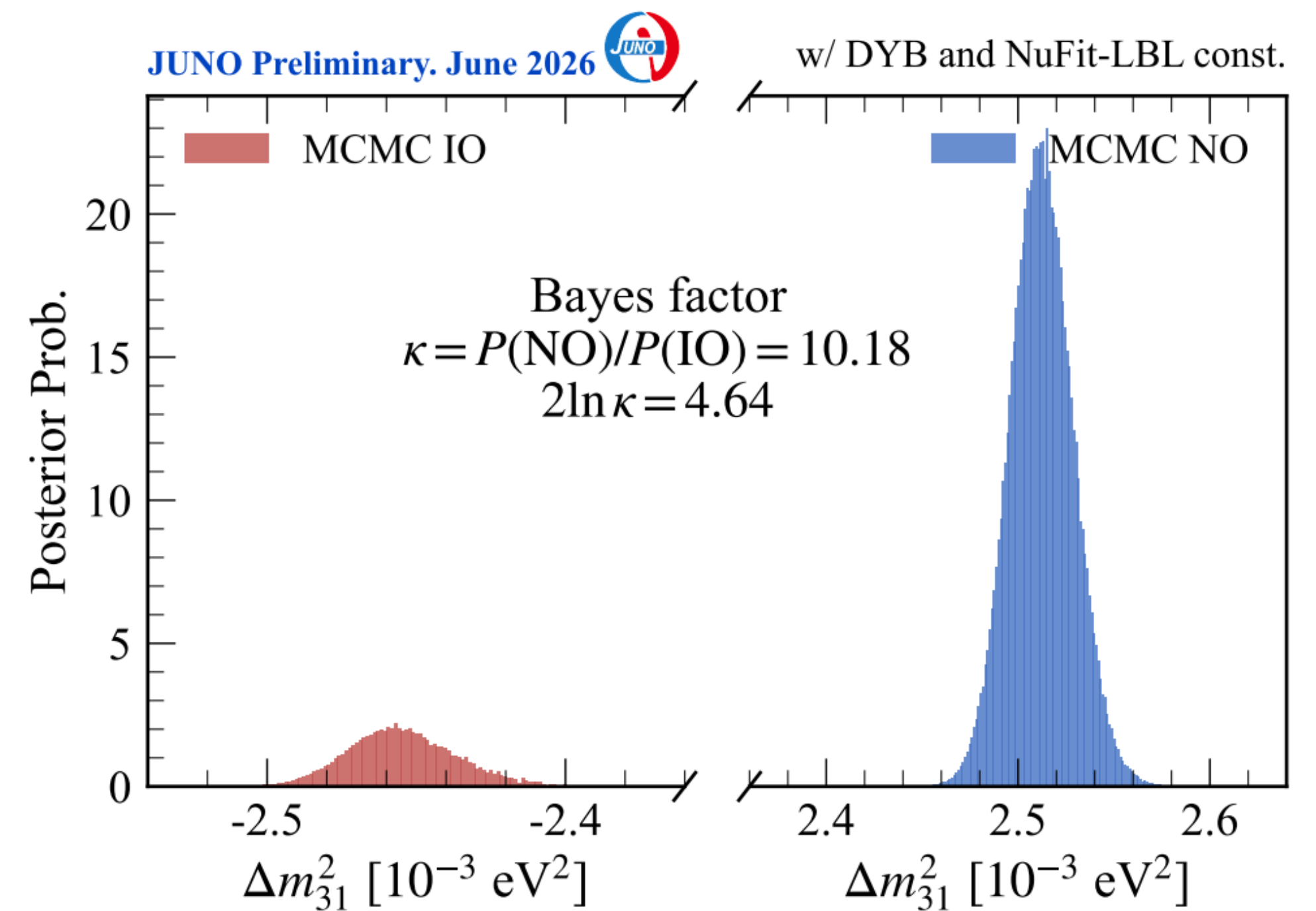
- Use two approaches to calculate the significance of the observed NO preference:

Frequentist Approach



- Relies on the generation of many pseudo-experiments
- Normal ordering favored at **2.3 σ**

Bayesian Approach



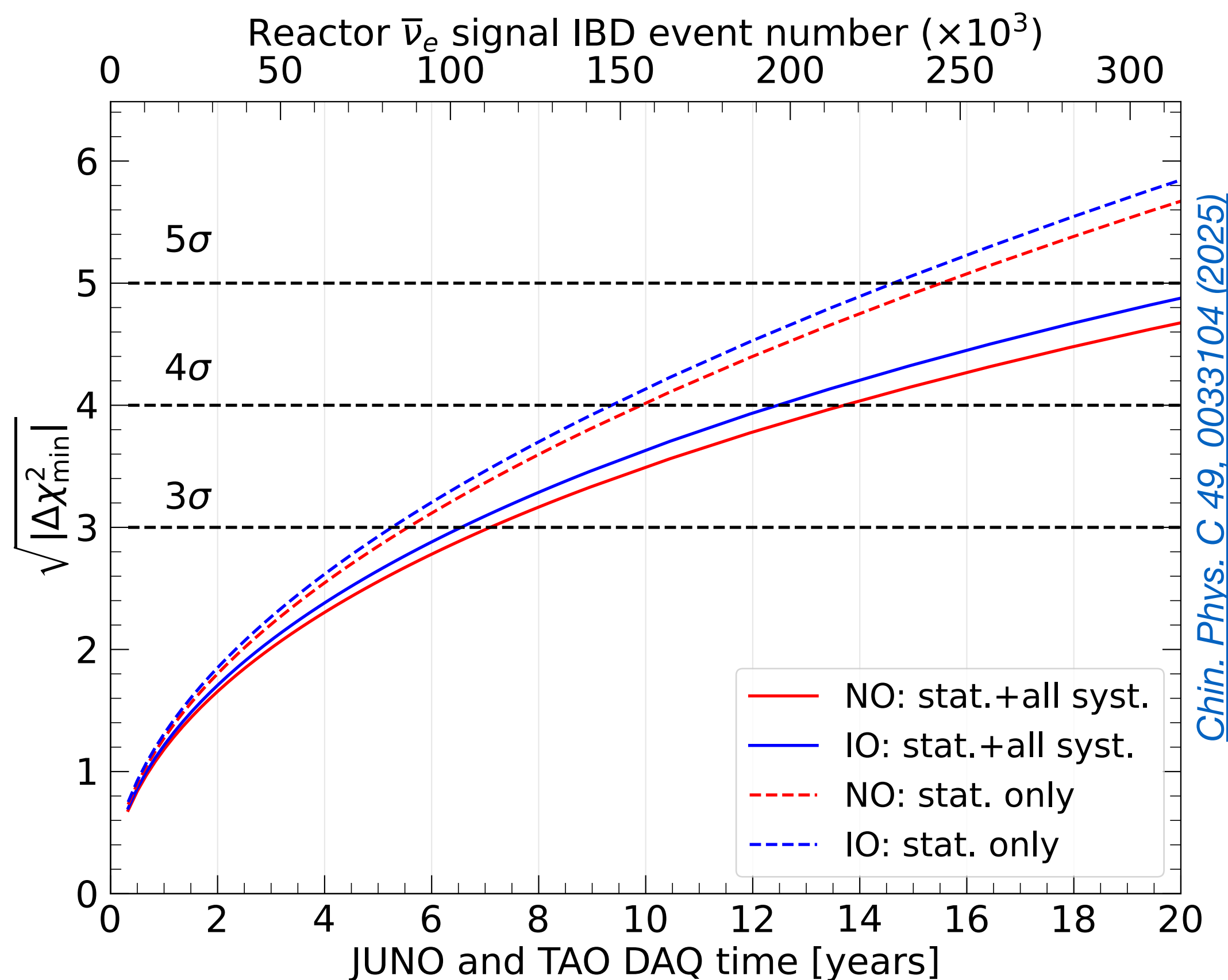
- Relies on Markov Chain Monte Carlo
- Normal ordering favored with **Bayes factor of 10.18**

Looking Forward

Prospects for JUNO and Other Experiments

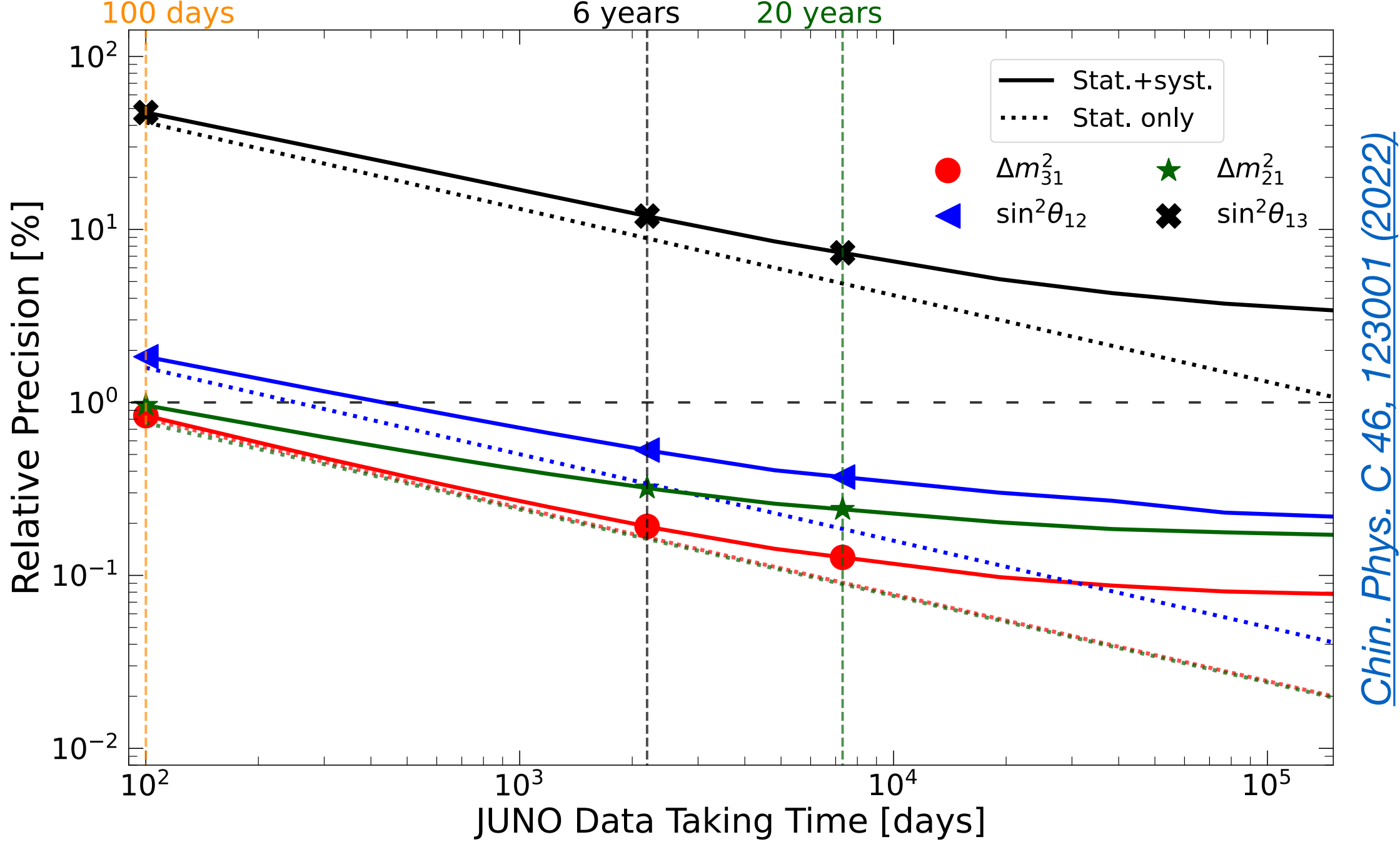
Oscillation Physics with Reactor $\bar{\nu}_e$'s

JUNO-only NMO sensitivity:



Unique measurement at 3σ significance with about 7 years of data

Sensitivity to Δm_{21}^2 , $\sin^2 \theta_{12}$, Δm_{31}^2 and $\sin^2 \theta_{13}$



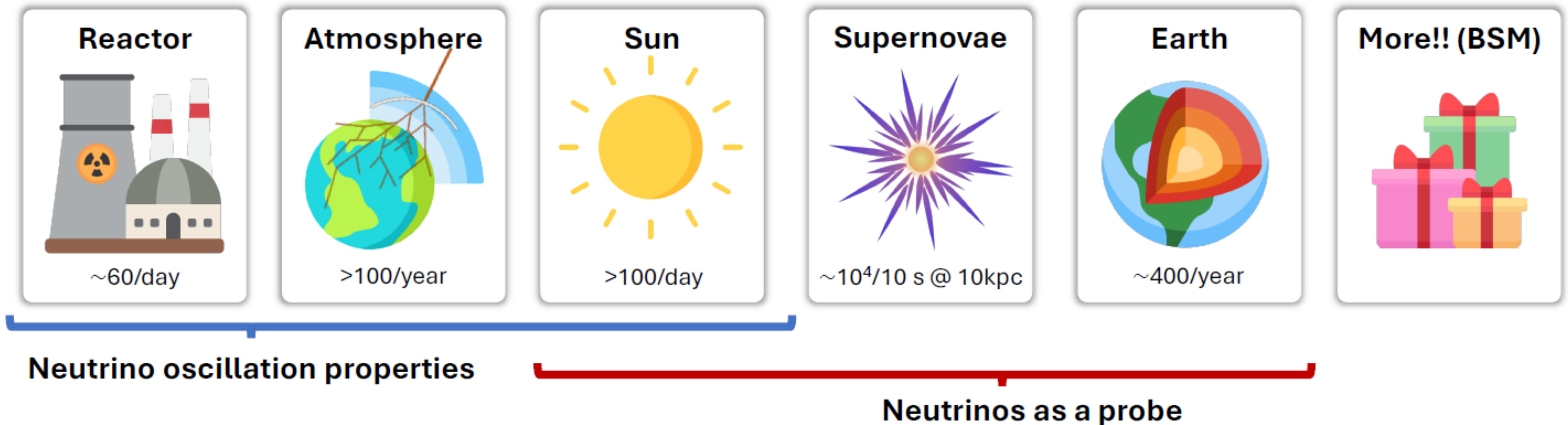
Parameter	$\sin^2 \theta_{12}$	Δm_{21}^2	Δm_{32}^2	$\sin^2 \theta_{13}$
Precision before JUNO*	3.9%	2.5%	1.3%	2.8%
JUNO 6 years	0.5%	0.3%	0.2%	12.1%

* from PDG 2025

Roughly one order of magnitude improvement over existing precision for 3 parameters with 6 years of data!

A Multi-Purpose Observatory for Neutrino Physics and Astrophysics

- JUNO has unique features that make it extremely well-suited for other physics goals
- Rich scientific program spanning a wide range of sources and research topics



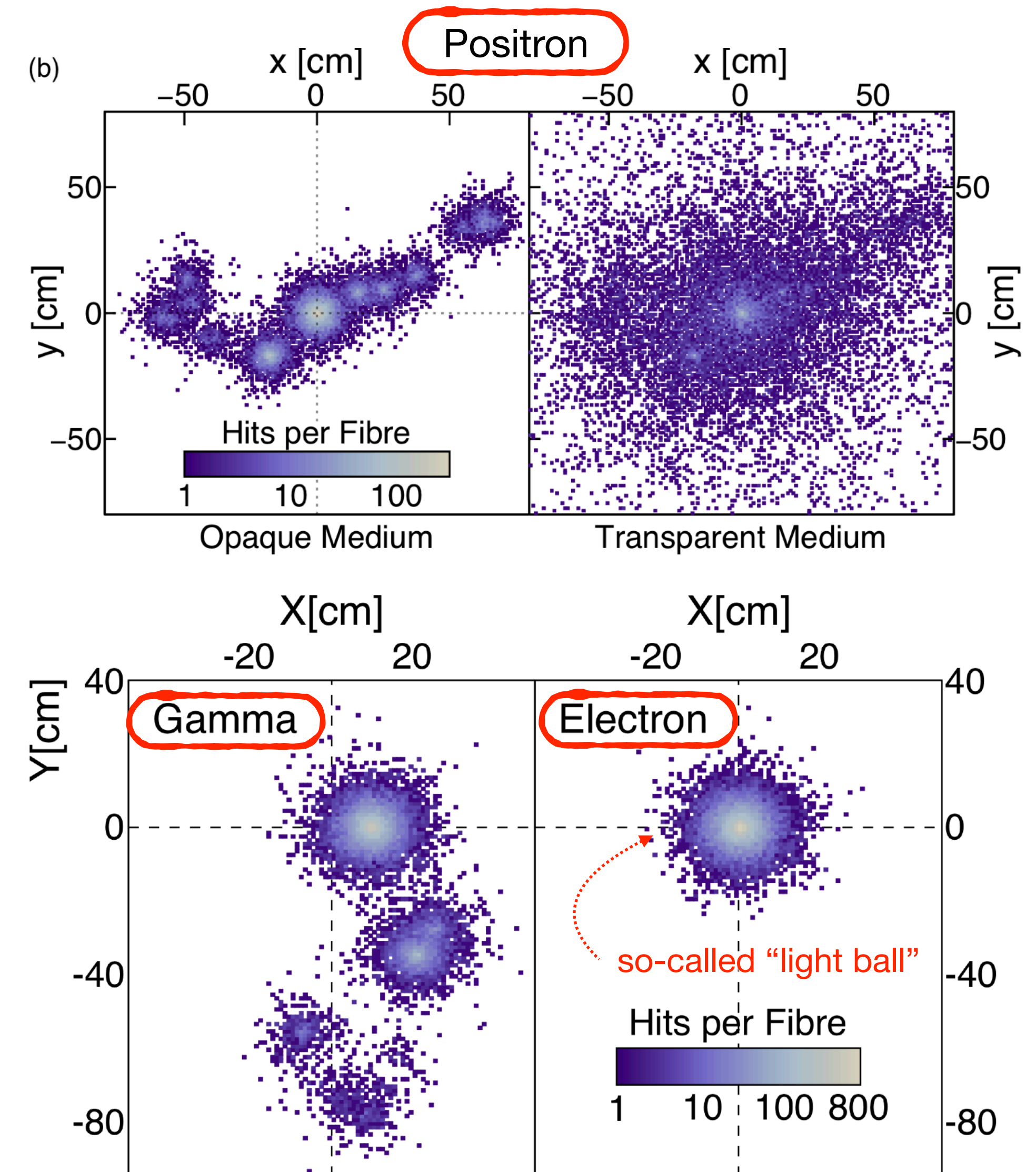
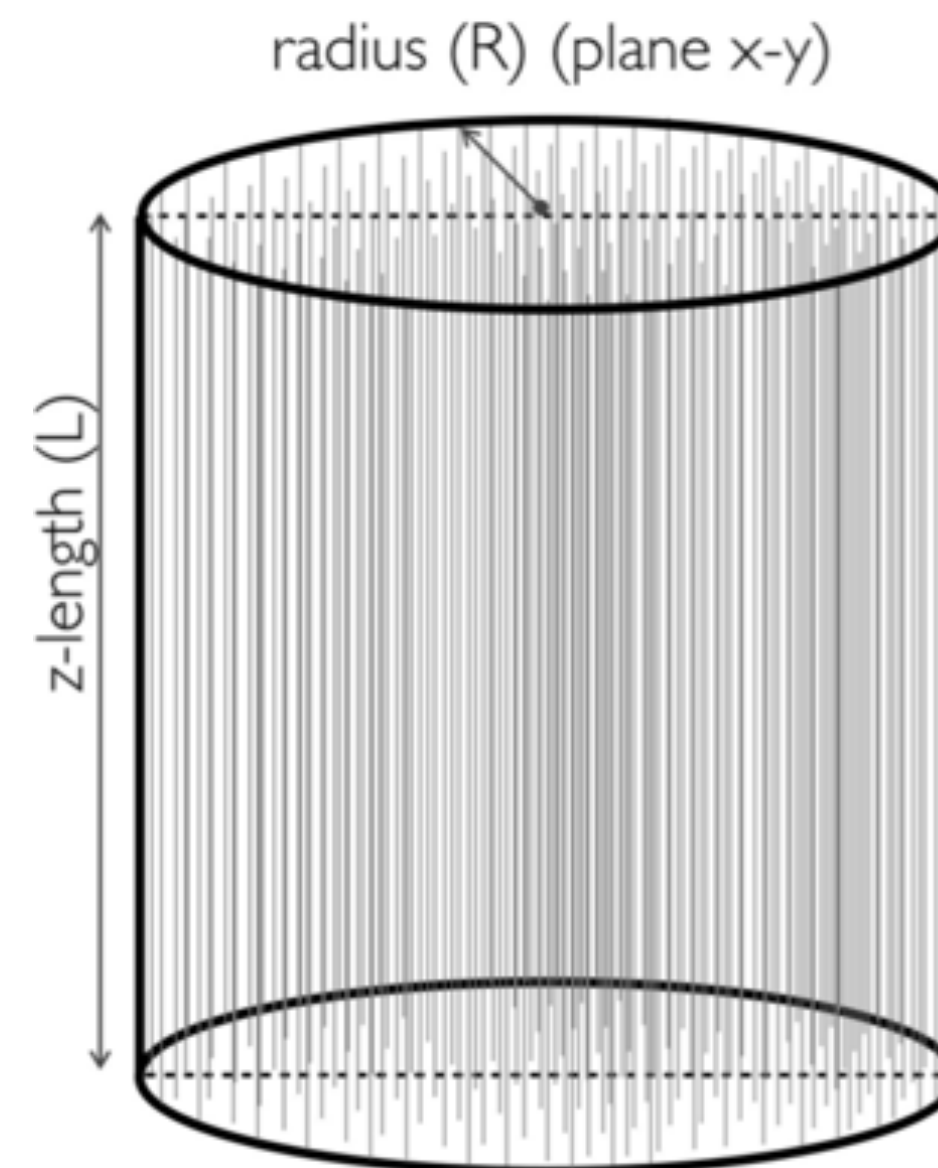
More information in backup; can discuss as needed

LiquidO: a New Approach

- In conventional scintillator detectors like Daya Bay and JUNO, the light travels through transparent volumes to photosensors in the periphery
- New detector concept: opaque medium traversed by dense array of fibers

Key Advantages:

- Event-by-event ID of events that are currently indistinguishable in traditional liquid scintillator detectors (e^- , e^+ , γ)
- High affinity for loading thanks to the opacity

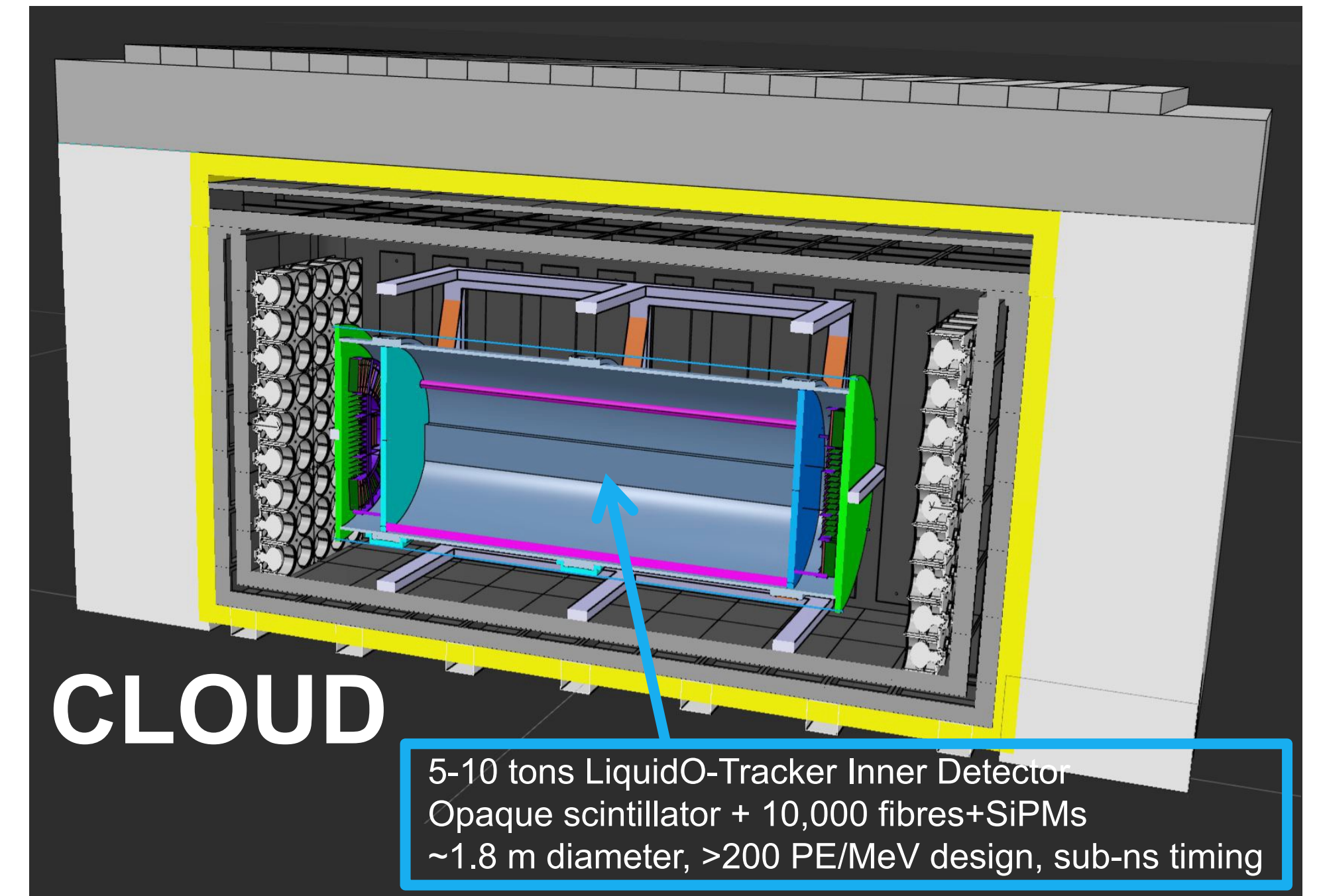


See [arXiv:2503.02541](https://arxiv.org/abs/2503.02541) for the latest results from a prototype

Each of these panels assumes a 1cm fiber pitch, one pixel per fibre, 2MeV of energy

CLOUD and SuperChooz

- Demonstrator called “CLOUD” funded: ~30 m from CHOOZ reactor in France



- There is a proposal for a next-generation θ_{13} reactor experiment called SuperChooz
 - Soon to become the most poorly known mixing angle
 - LiquidO technology, ~ 10 kton mass, ~ 1 km baseline from Chooz reactors

CEvNS at Reactors

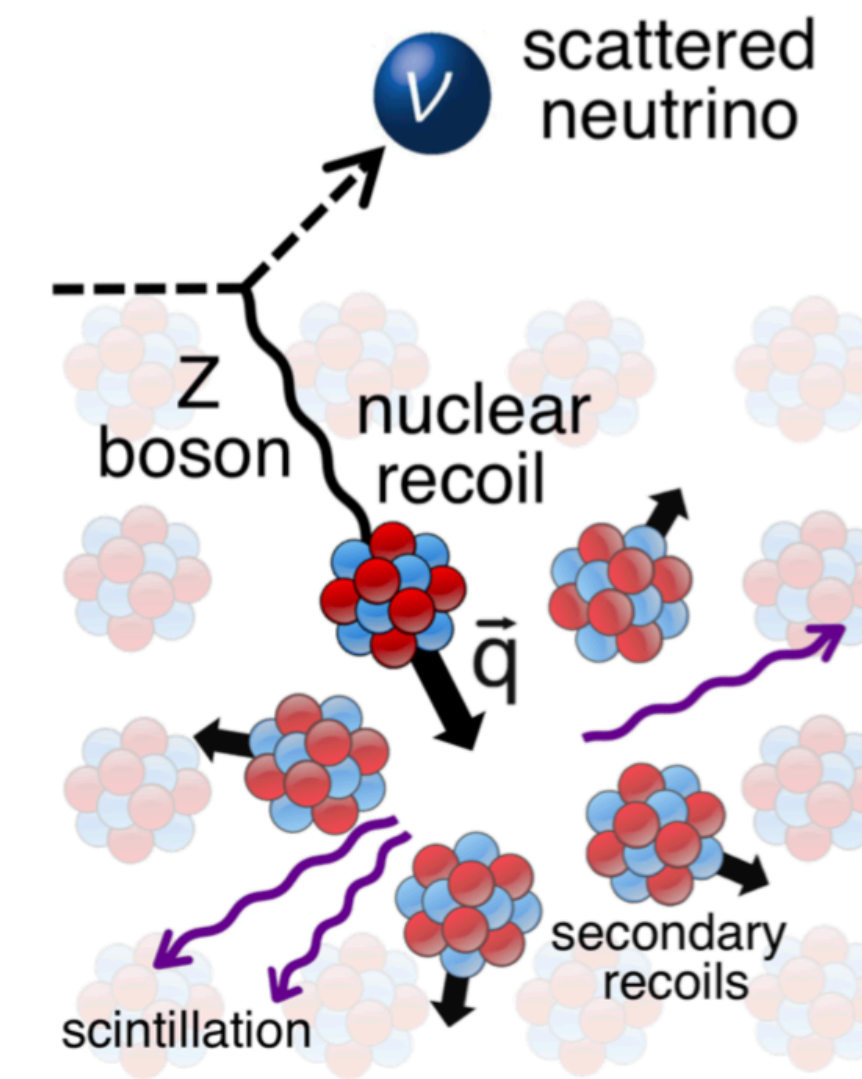
- An exciting new program using CEvNS at reactors is well underway

- Pro: very high cross-section (can be orders of magnitude higher than IBD)
- Con: very difficult to detect (only signal is low-energy recoiling nucleus)

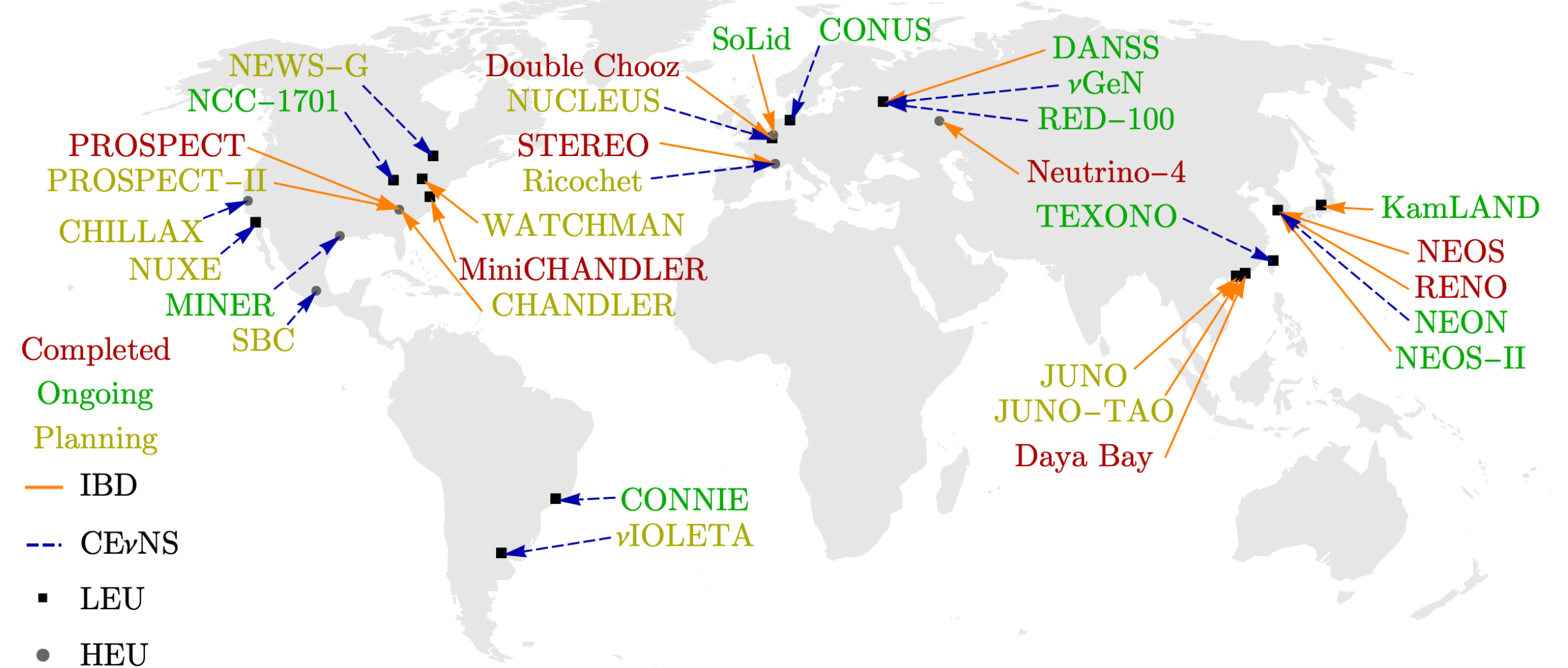
- Search for deviations from Standard Model, hidden sector particles & interactions

- The race is on!

- Vibrant effort in many reactors throughout the world with different technologies
- The CONUS+ experiment has reported a 3.7σ observation ([Nature 643, 1229-1233 \(2025\)](#))



Global Landscape of Reactor Neutrino Experiments



[arXiv:2203.07214](#) and [arXiv:2203.07361](#)

Concluding Remarks

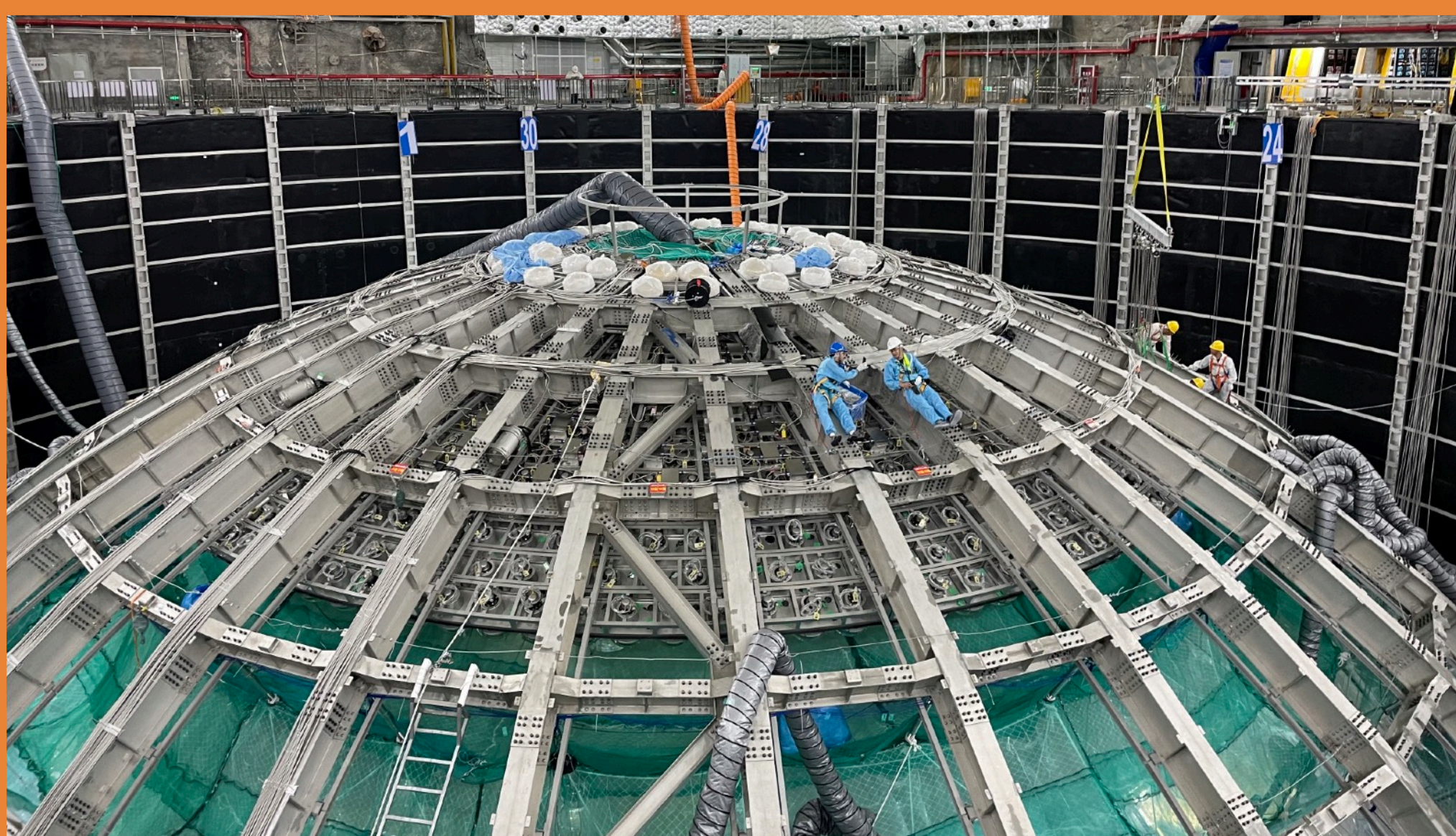
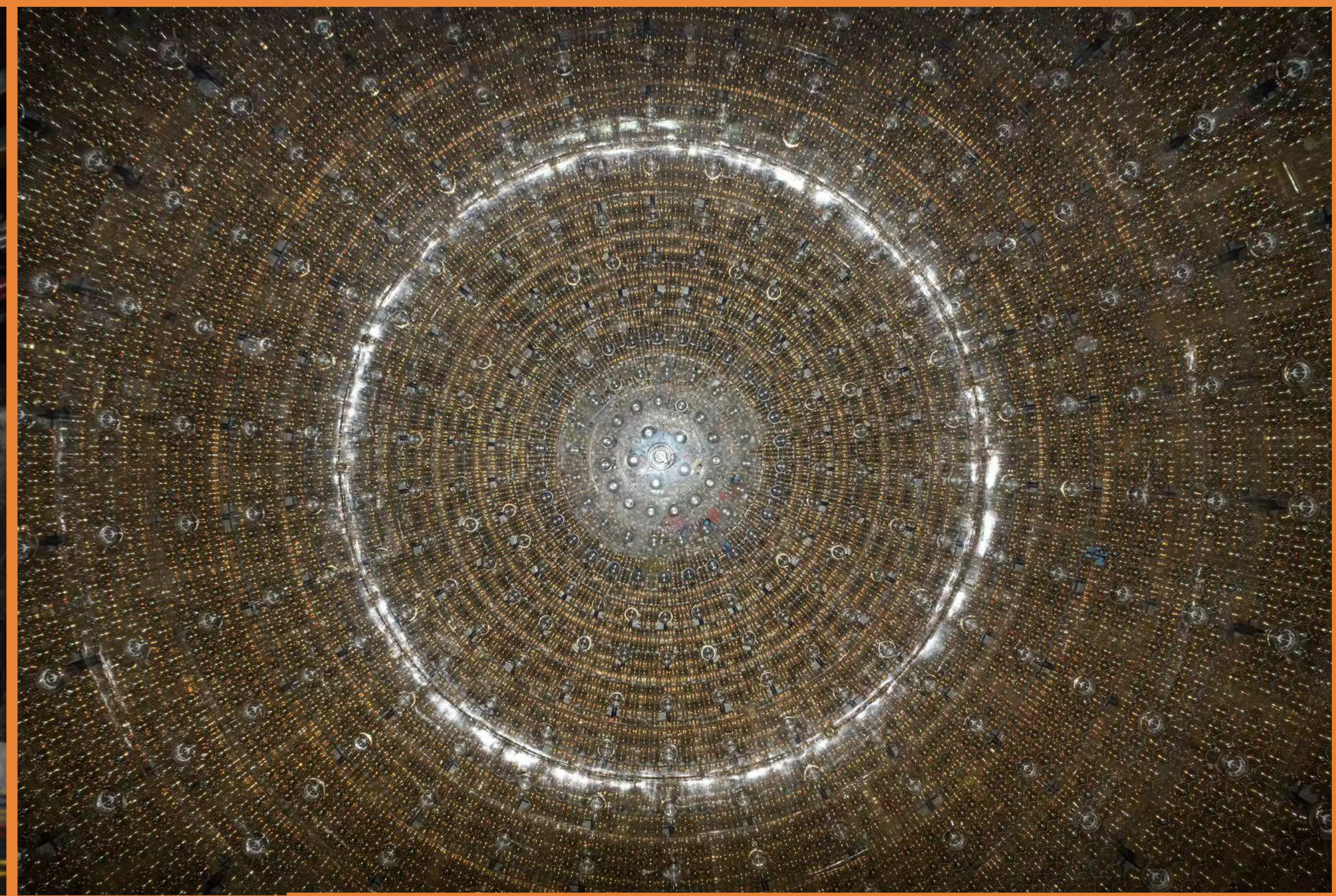
Summary & Conclusions

- Nuclear reactors are excellent neutrino sources
- Reactor neutrino experiments have made key contributions to experimental neutrino physics
- JUNO is the largest reactor neutrino experiment ever constructed and features the best energy resolution ever achieved in a detector of its kind
 - Designed primarily for reactor antineutrino oscillation physics, but also has a rich program with neutrinos from other Earthly and cosmic sources
- JUNO has released new oscillation results with 207 days of data
 - World-leading precision on $\sin^2 \theta_{12}$, Δm_{21}^2 and Δm_{31}^2
 - Preference of 2.3σ for the normal mass ordering
 - Geoneutrino flux measured to 15%
- More to come! Anticipate some exciting results (and maybe some surprises?)

Stay tuned!



Support from NSF is gratefully acknowledged



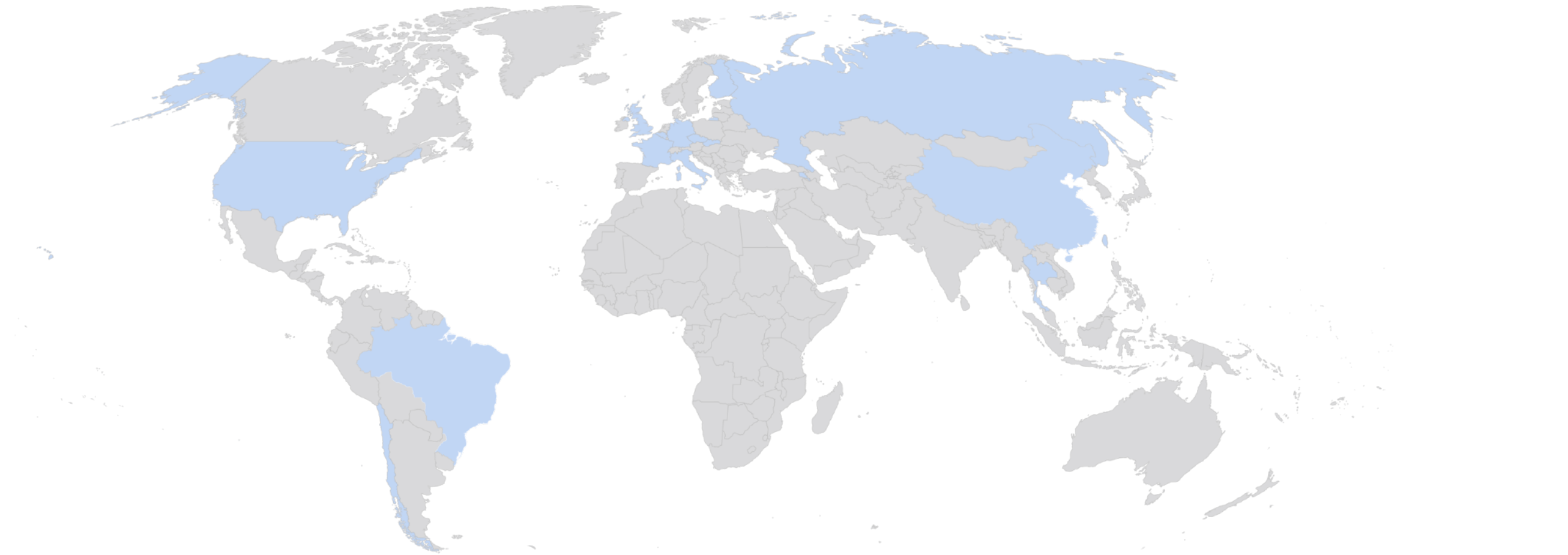
*Thank you
for your
attention!*



Backup

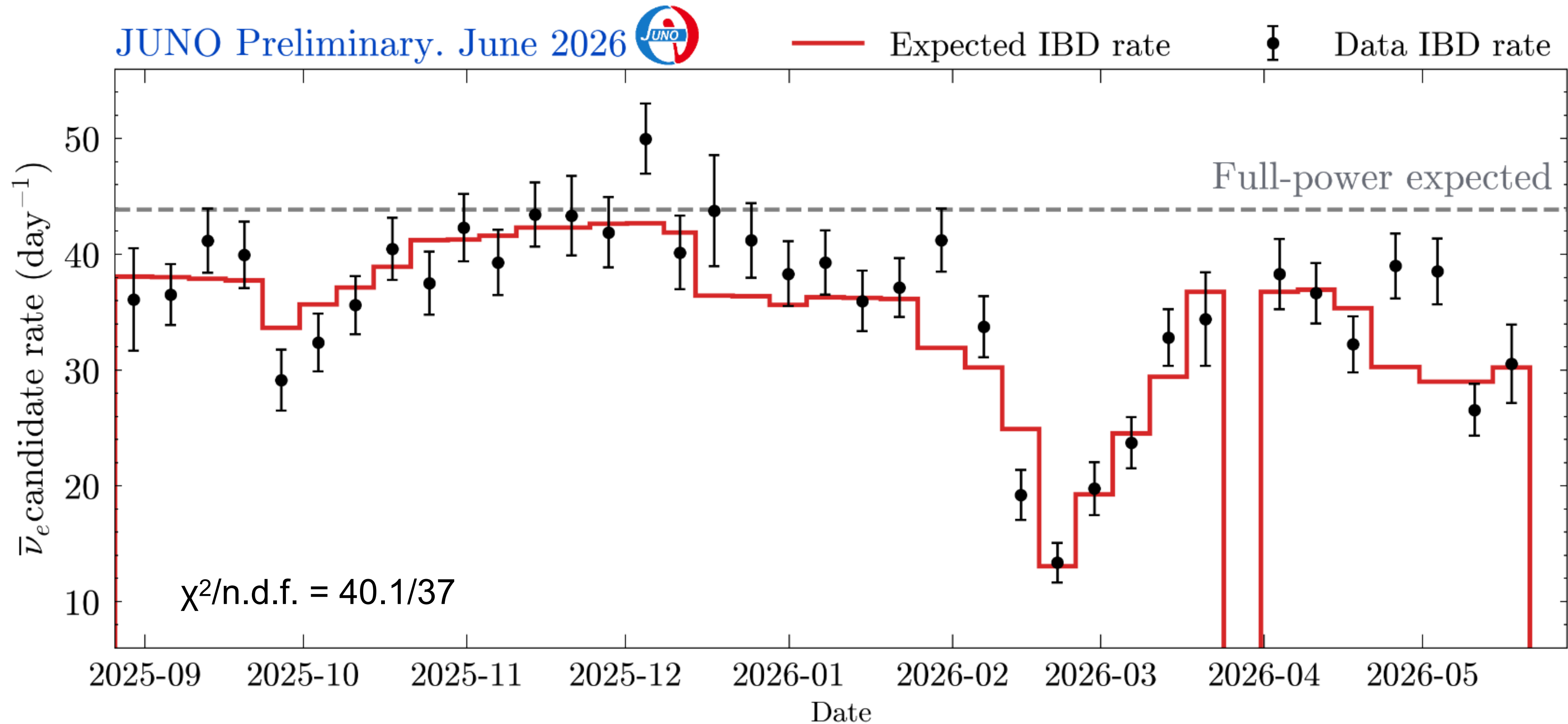
JUNO Project

- Collaboration established in 2014
- Now > 650 collaborators from 74 institutions in 17 countries/regions

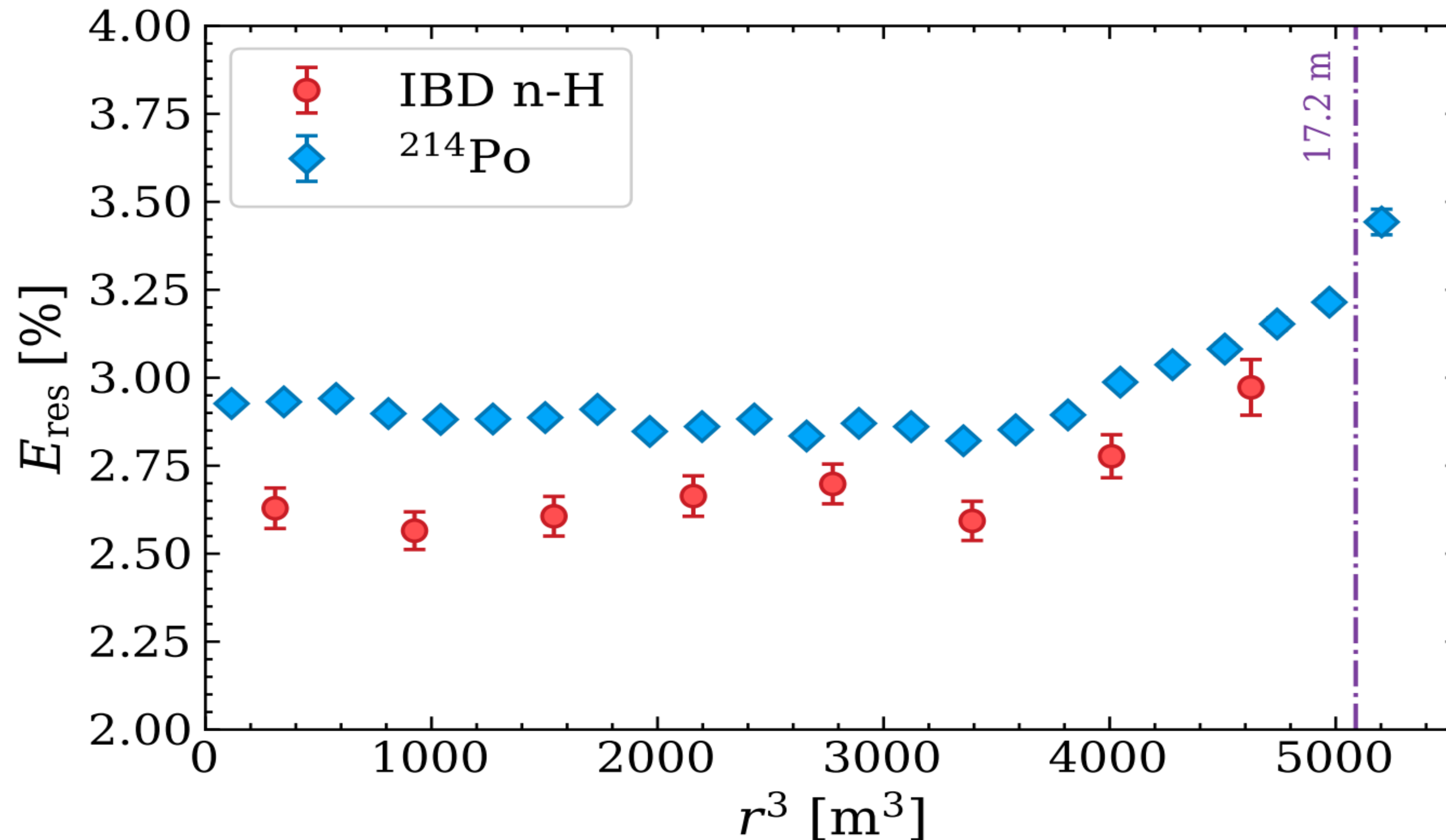


IBD Rate vs. Time

Good correlation between predicted and expected reactor IBD rate after background subtraction

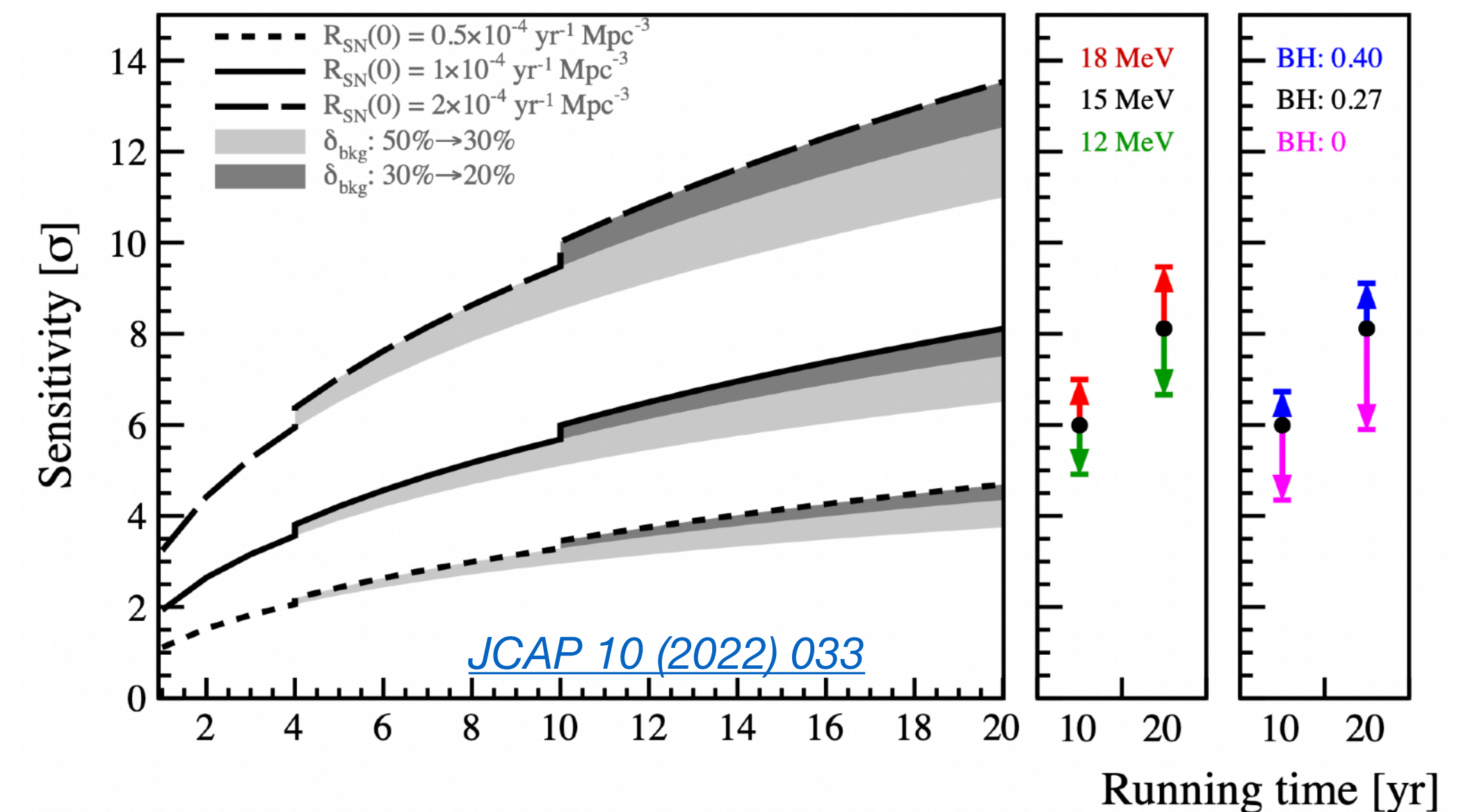
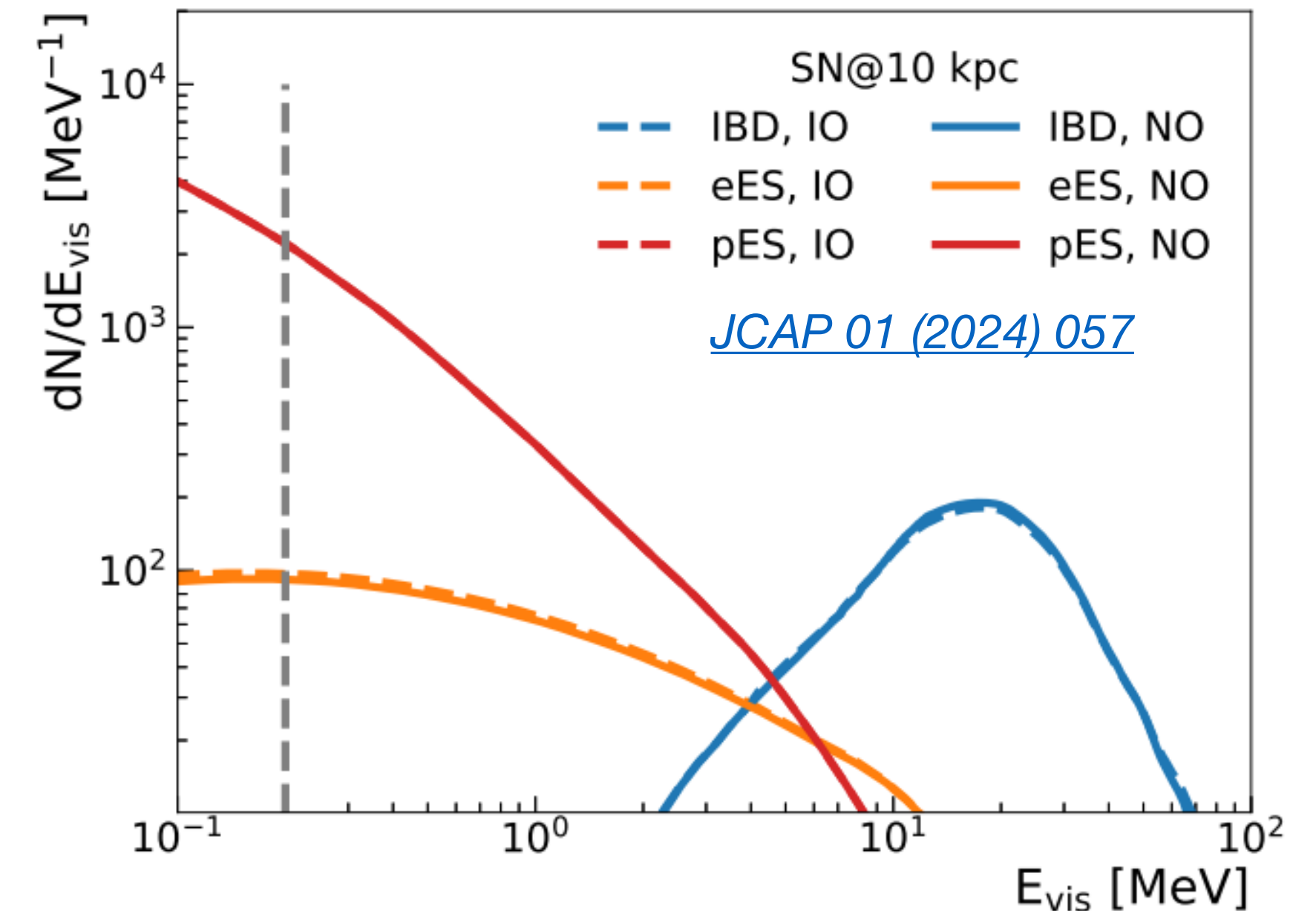


Energy Resolution for ^{214}Po and IBD nH



Supernova (SN) Neutrinos

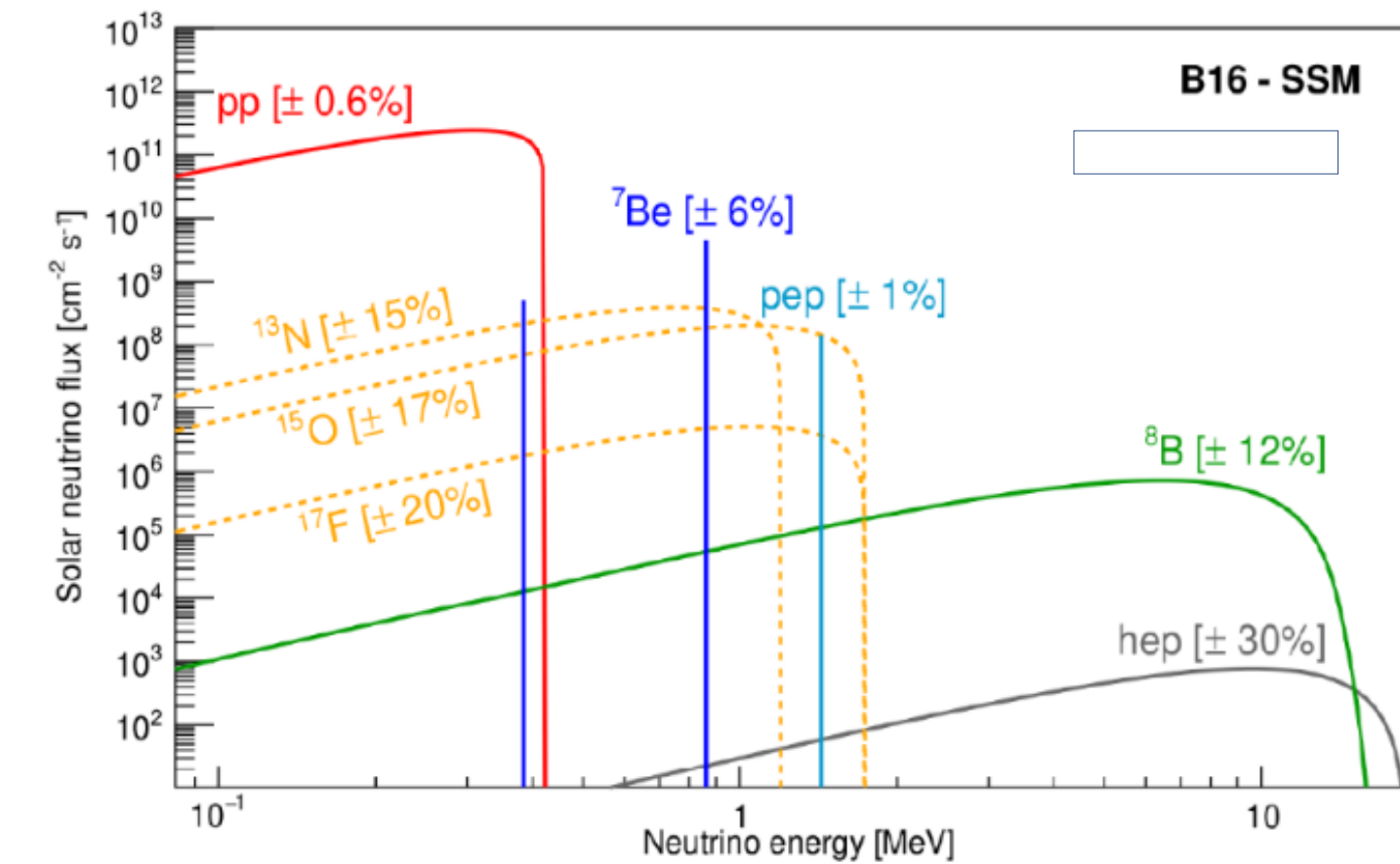
- Able to determine flavor content, energy spectrum and time evolution of supernova (SN) burst neutrinos
 - Order of 10^4 detected events for SN @ 10 kpc
 - 3 detection channels sensitive to all flavors, low threshold ~ 0.2 MeV
 - Sensitivity to pre-SN neutrinos up to ~ 1.6 (0.9) kpc for normal (inverted) ordering
- Also have leading sensitivity 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



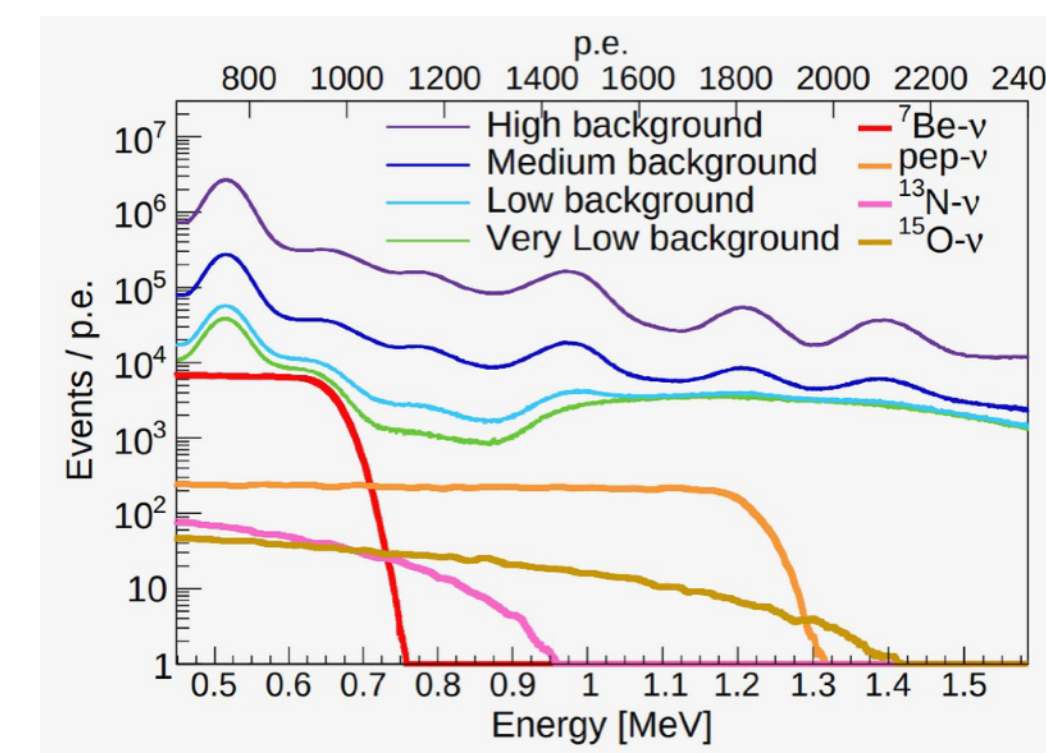
Solar Neutrinos

- Solar neutrinos in JUNO:
 - Unique assets:
 - Large size, low threshold, and high resolution
 - Will collect large sample of high energy (^8B) neutrinos
 - Precise measurement of the flux
 - Measure osc. parameters with solar and reactor neutrinos in the same detector
 - Day night asymmetry ($2-3\sigma$ in 10 years)
 - Good sensitivity to solar neutrinos below 1.5 MeV (^7Be , pep and CNO)
 - Expect results to be world-leading once enough data are collected

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



Low Energy (^7Be , pep, CNO)



Sensitivity (6 years)

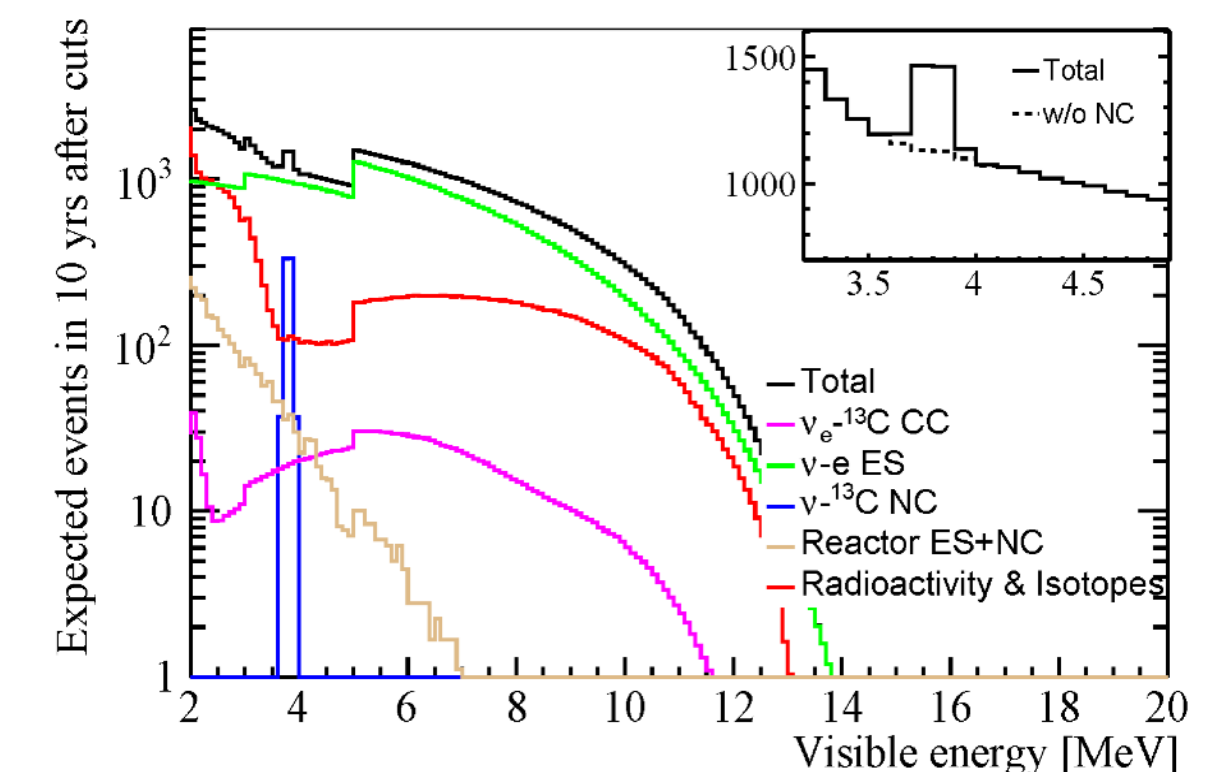
^7Be : ~0.3%

pep : ~4%

CNO: ~12%

(low background
10⁻¹⁷g_{U,Th}/g_{LS} scenario)

High Energy (^8B)



Sensitivity (10 years)

$\Phi_{8\text{B}}$: 5%

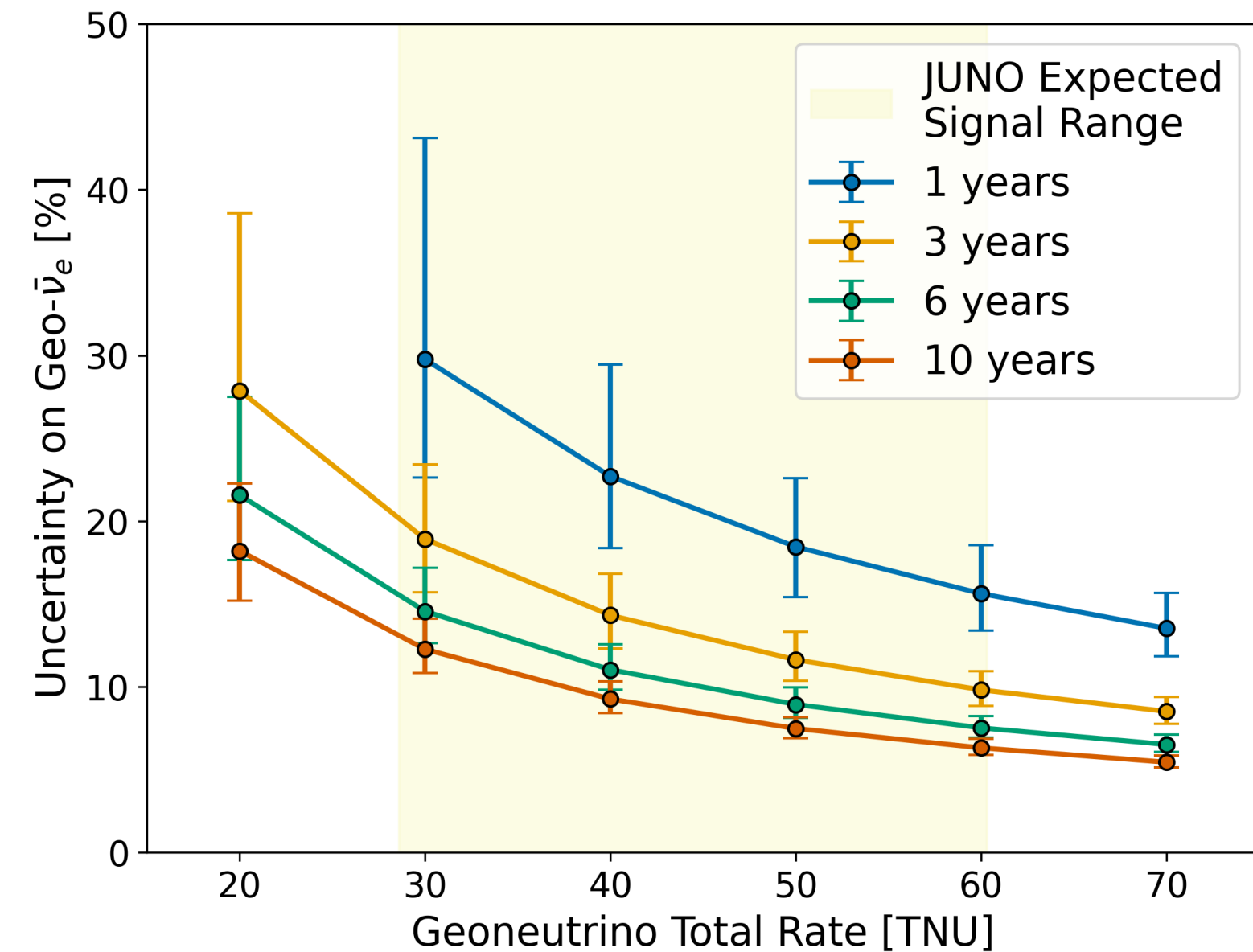
$\sin^2 \theta_{12}$: 8%

Δm_{21}^2 : 20%

Geo-neutrinos and Nucleon Decay

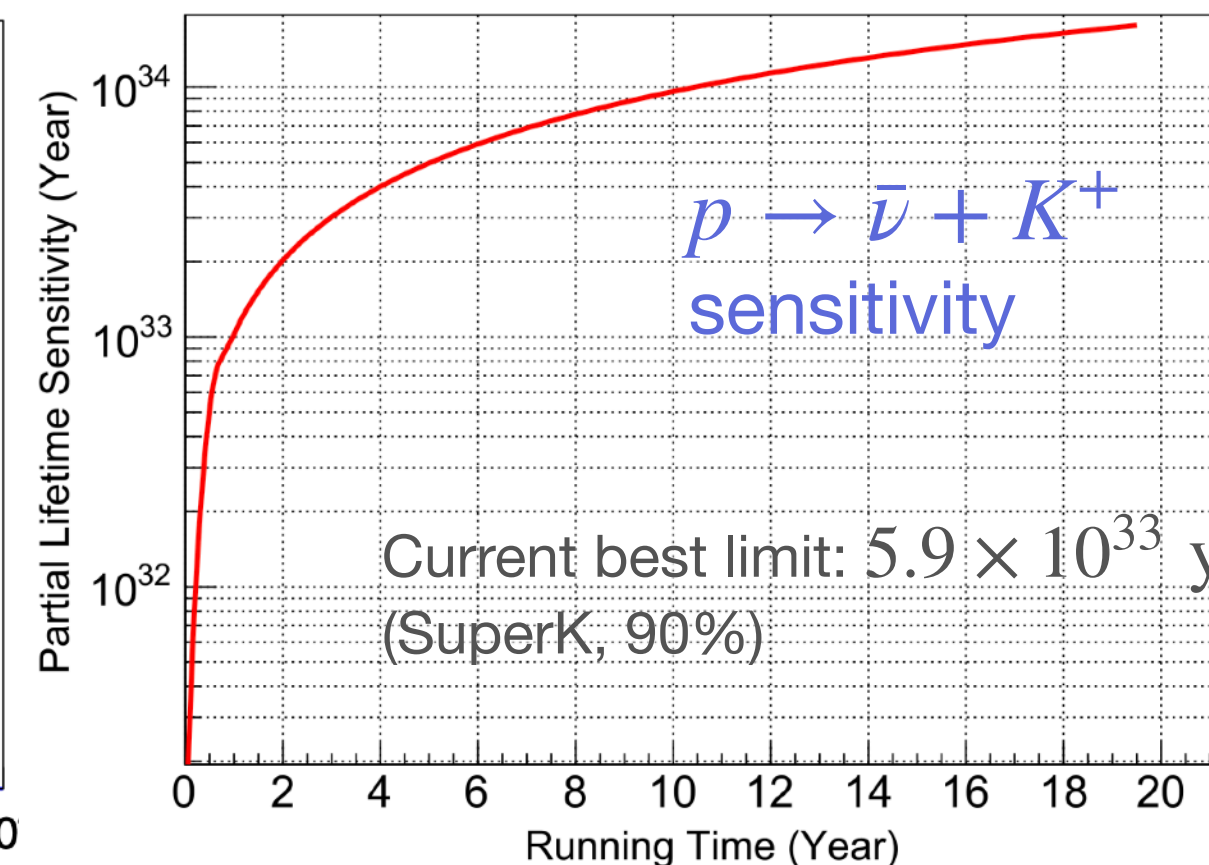
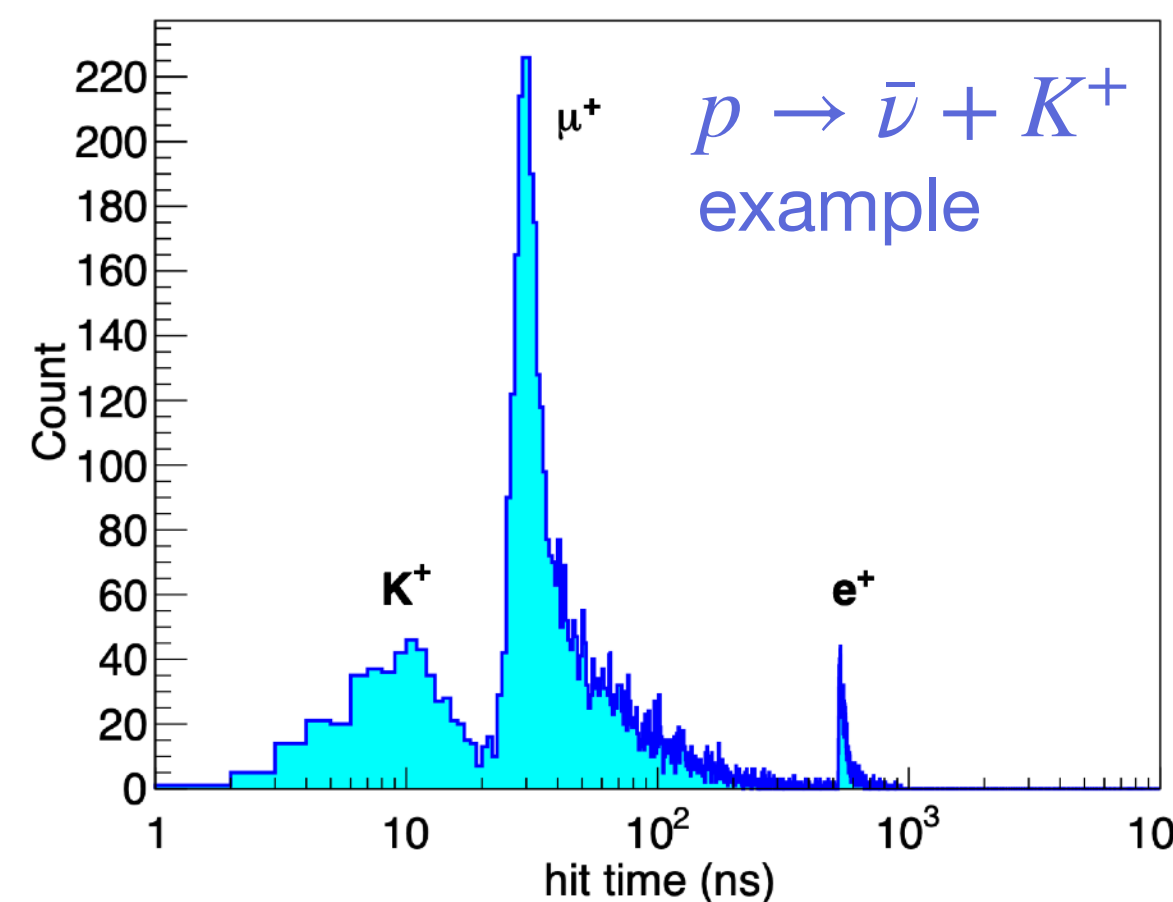
- With 1-2 events per day, will collect largest available sample of geoneutrinos in ~1 year
 - Precision of ~8% in 10 years with fixed Th/U mass ratio (current precision is around 15%)
 - Separation of U and Th components with unprecedented precision
- Competitive sensitivity to nucleon decay, particularly in modes where LS enables triple coincidence

Sensitivity to total geo- ν signal, fixed Th/U ratio:

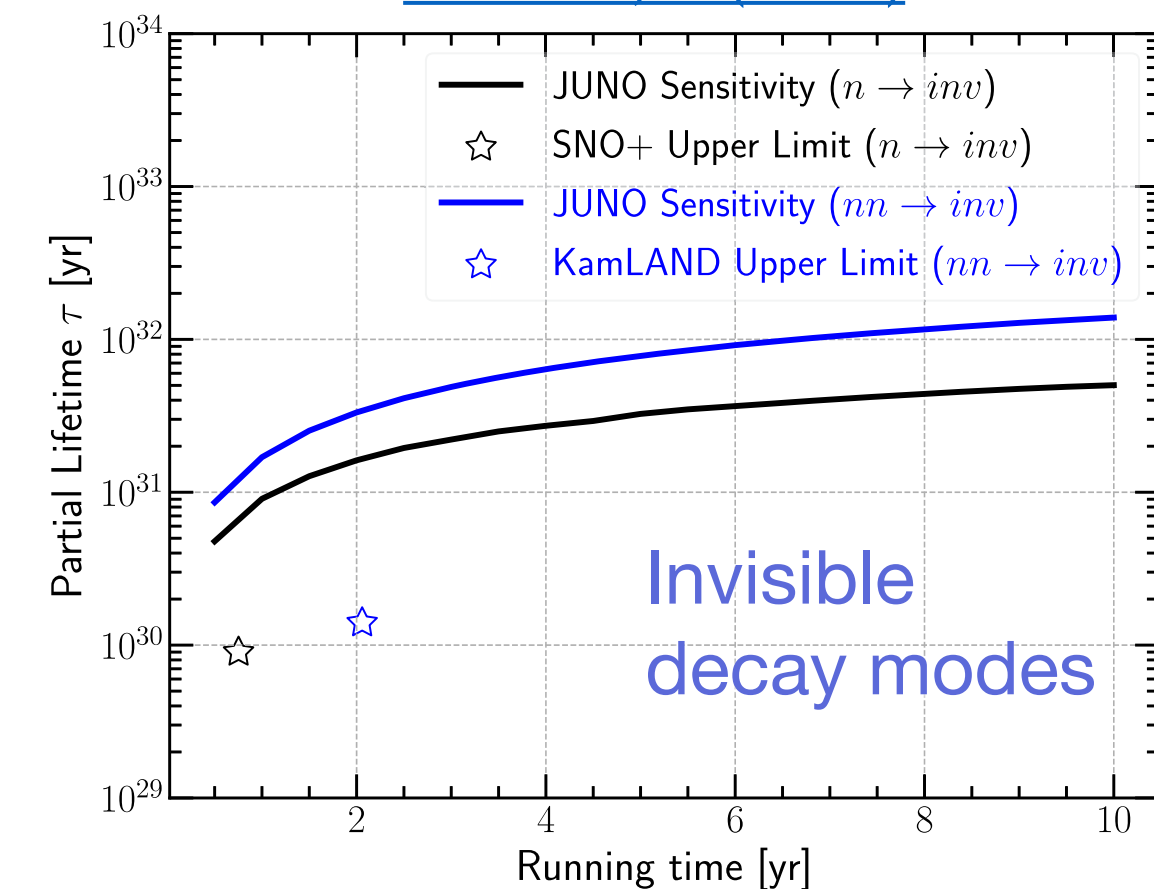


arXiv:2511.07227

CPC 47, 113002 (2023)

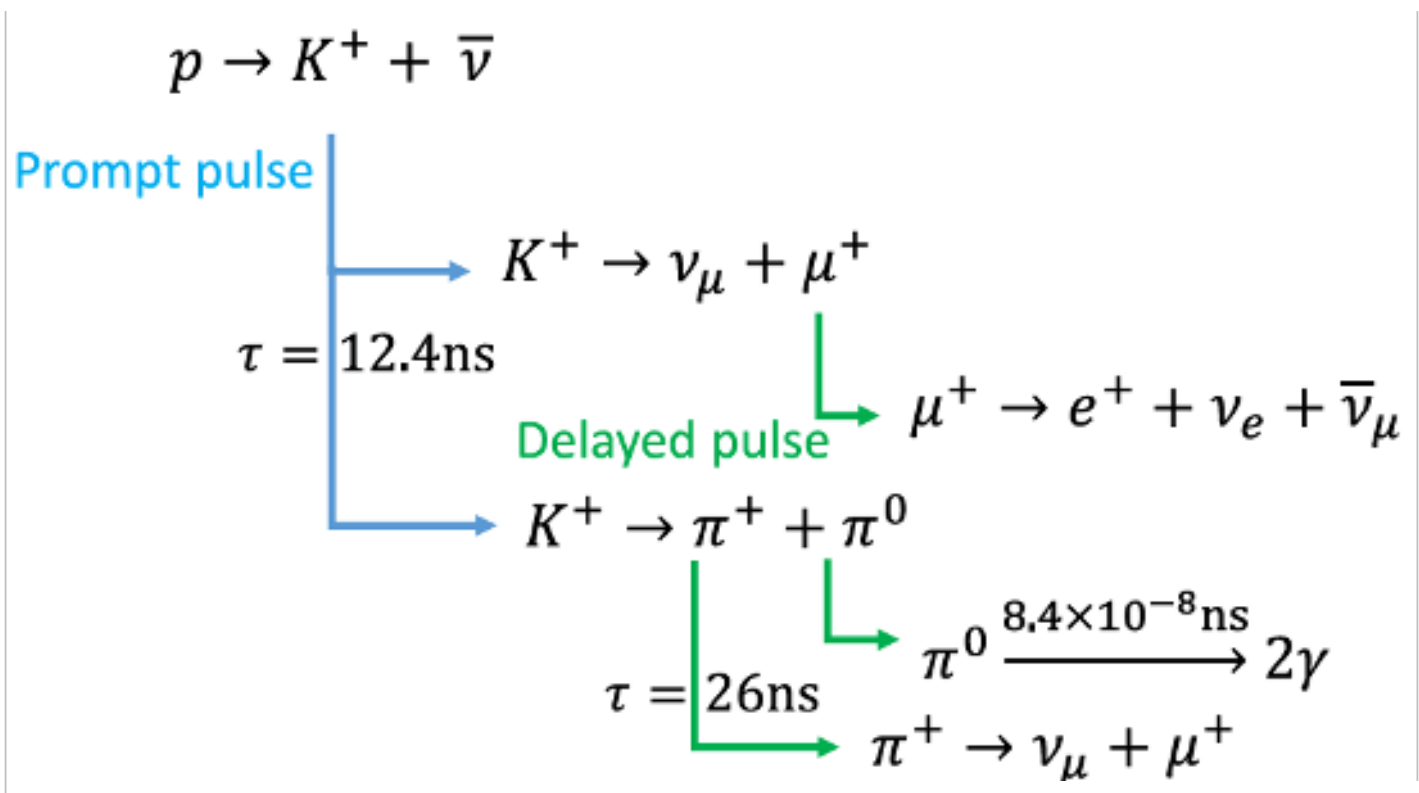


EPJC 85, 5 (2025)



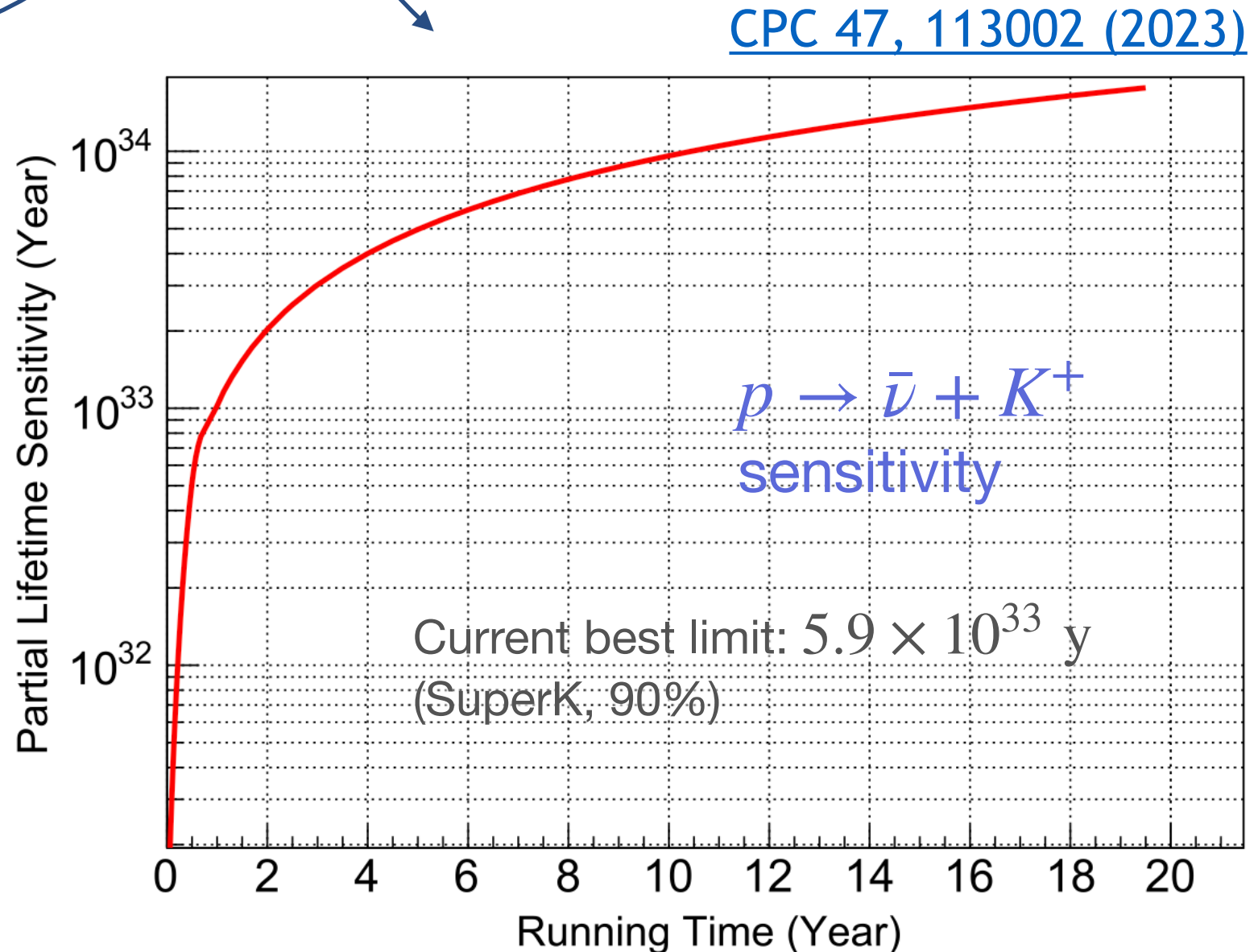
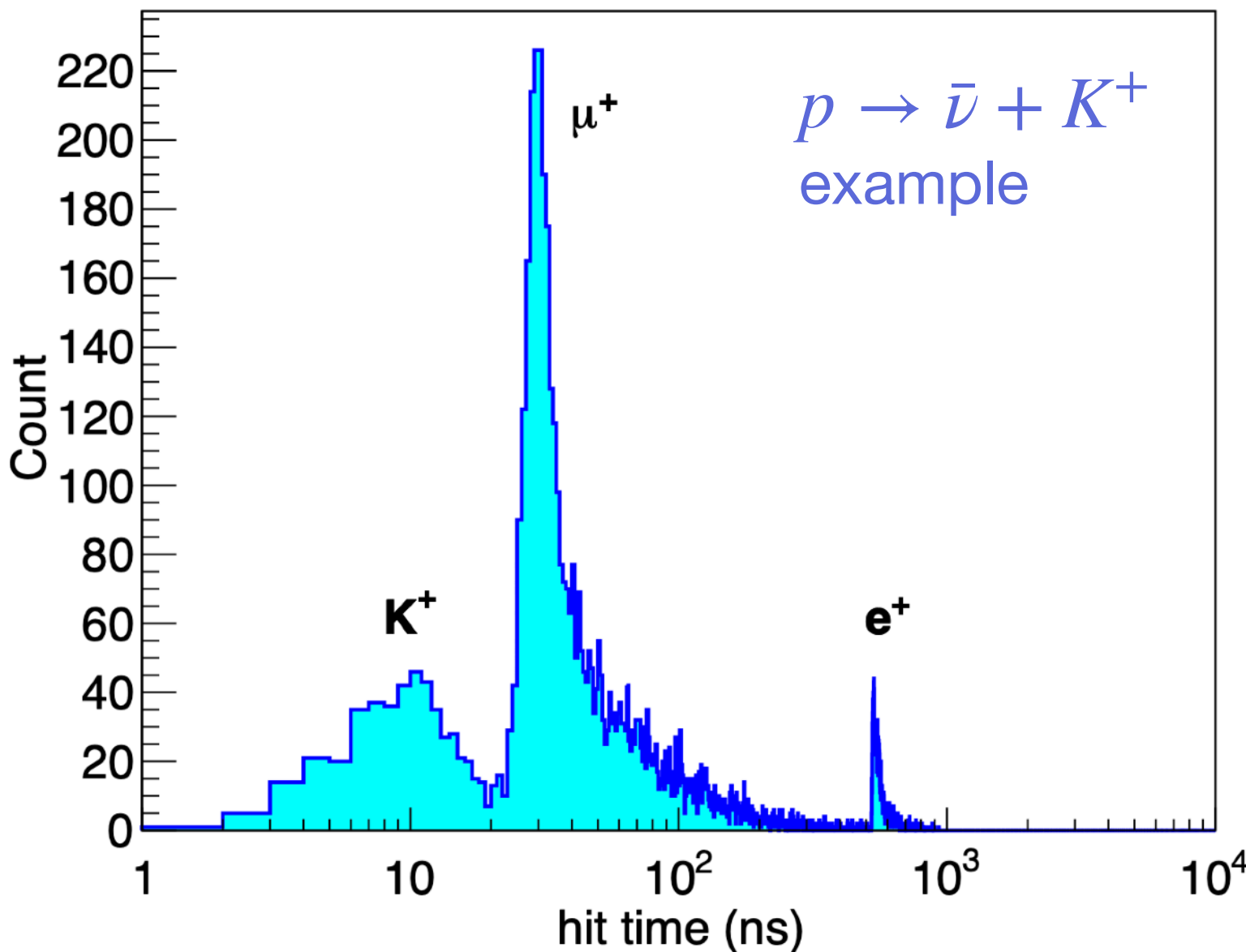
Proton Decay

- Competitive sensitivity, particularly in modes where LS enables triple coincidence signal



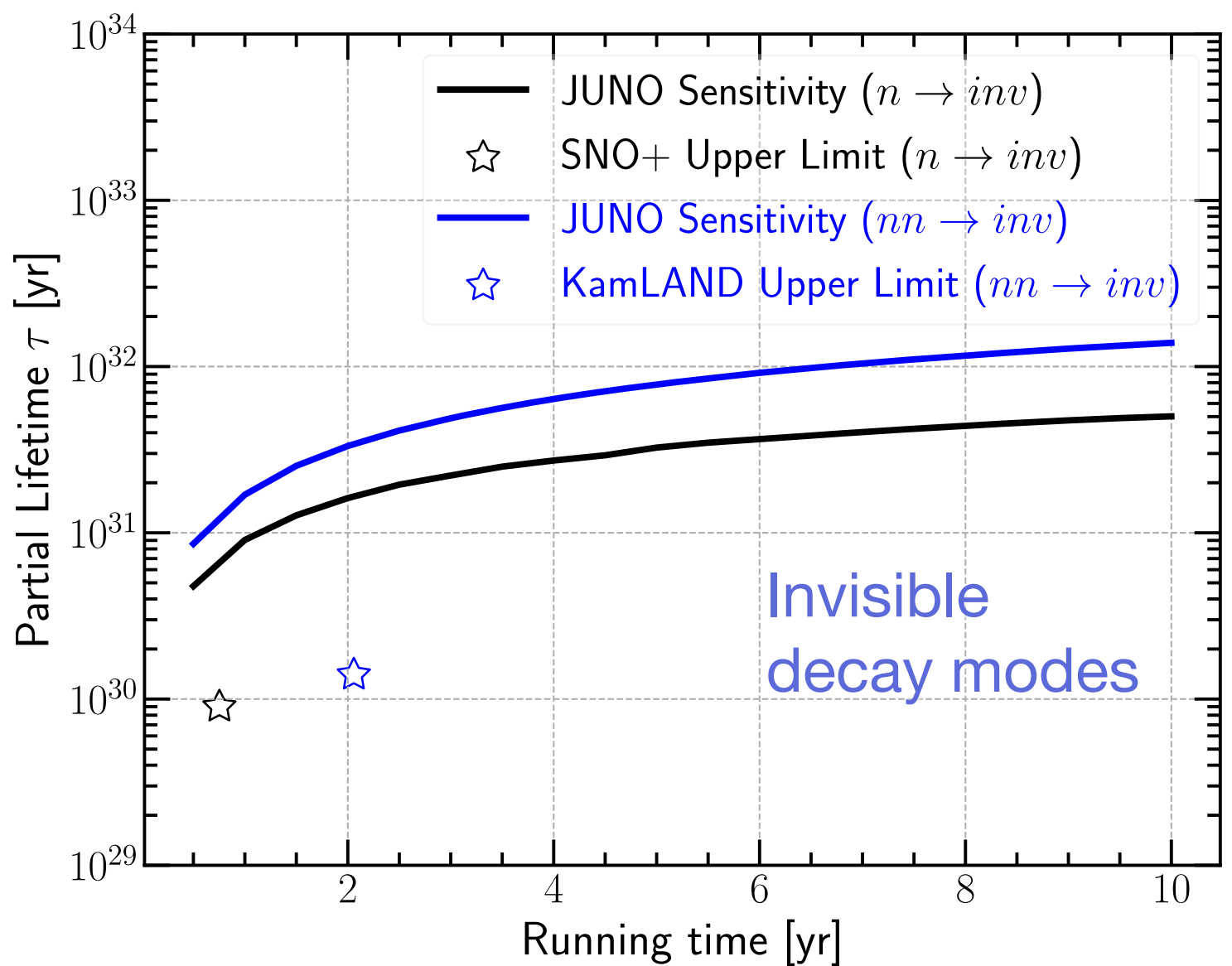
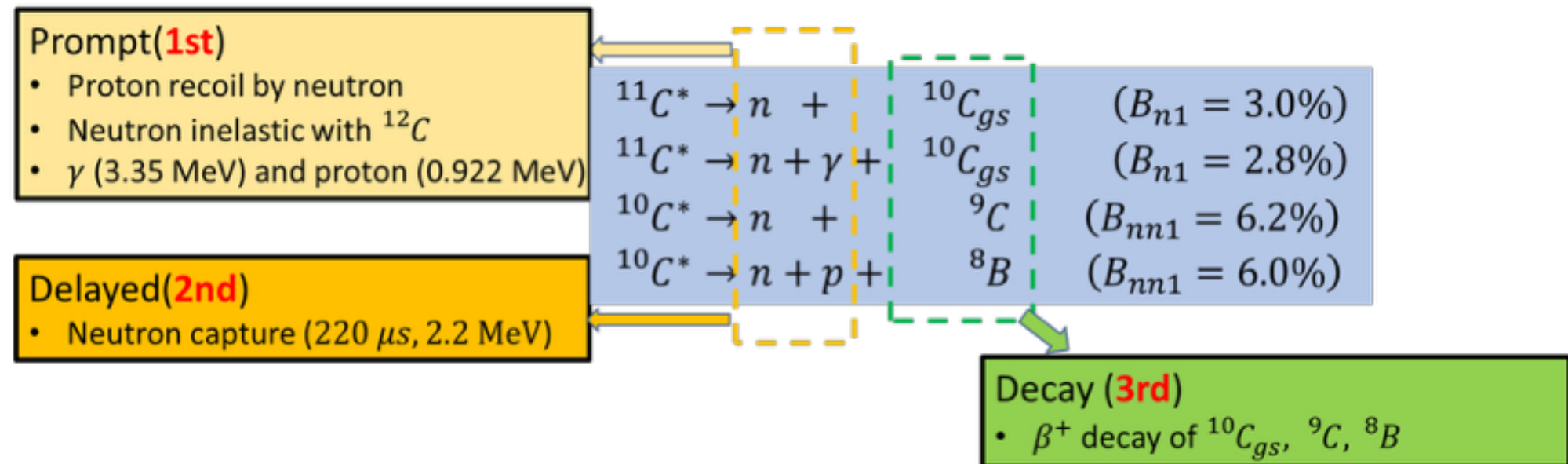
$p \rightarrow \bar{\nu} + K^+$

Detect K^+ and decay daughters



$n \rightarrow \text{inv}$ and $nn \rightarrow \text{inv}$

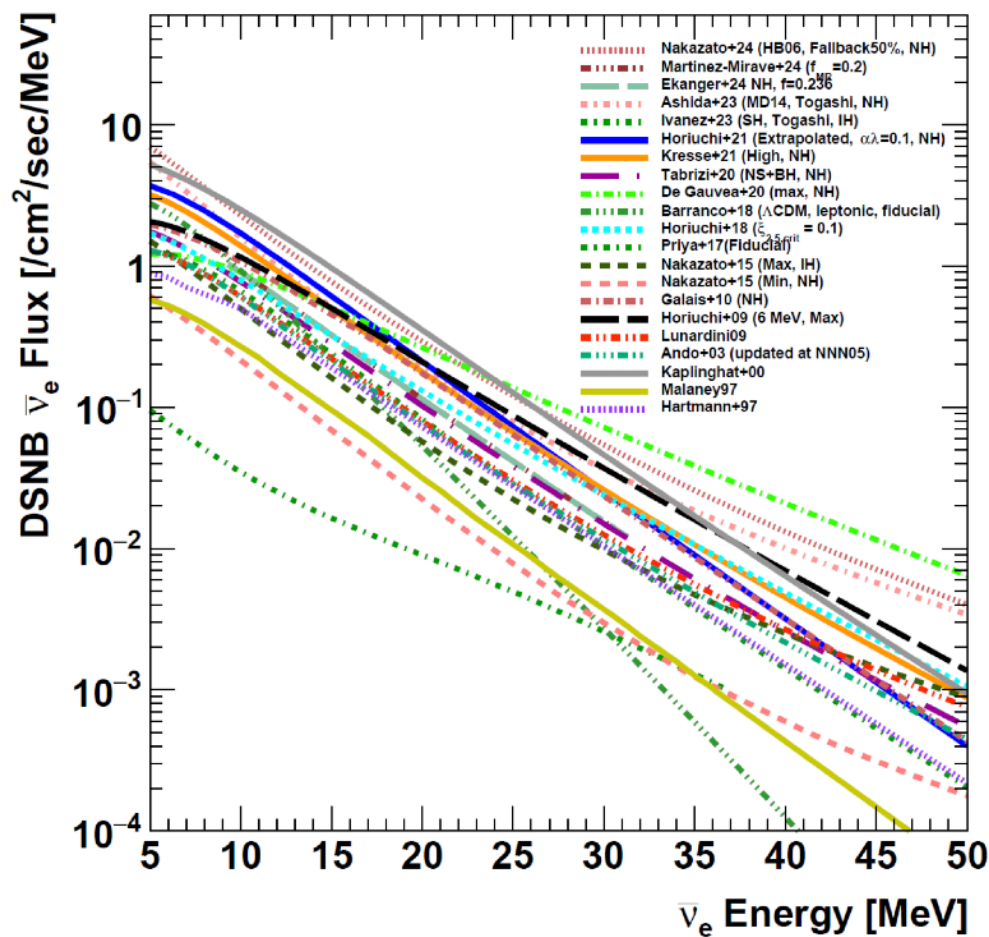
Detect de-excitation of the excited nucleus



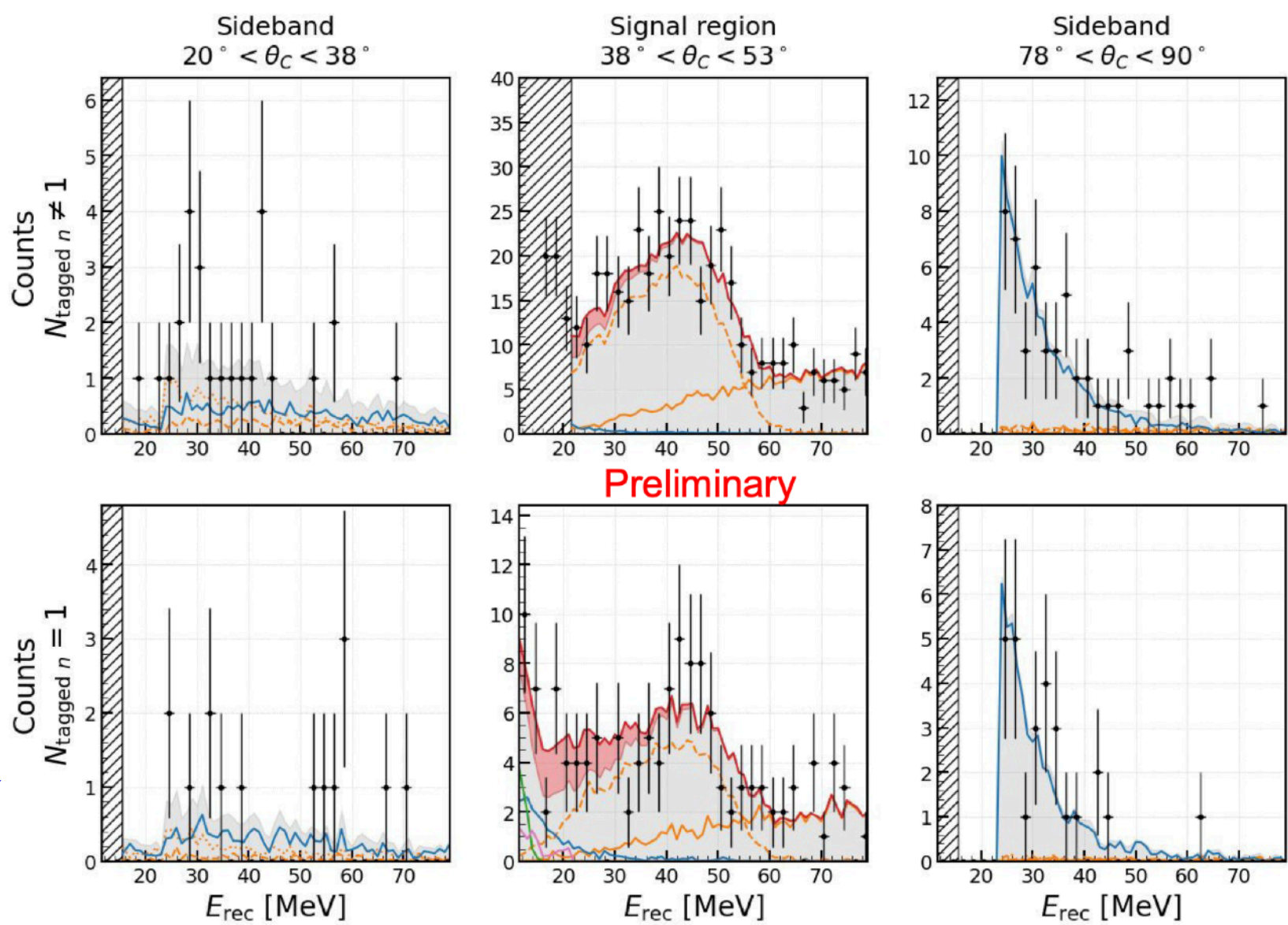
EPJC 85, 5 (2025)

Diffuse Supernova Neutrino Background (DSNB)

- DSNB = cumulative flux of neutrinos and antineutrinos emitted by all core-collapse supernovae (SN) explosions throughout the history of the universe
- Unique probe of SN physics and cosmic history, including:
 - Average core-collapse SN energy spectrum
 - Cosmic star formation rate
 - Fraction of failed (black-hole forming) SN
- Faint signal, very hard to detect
 - In JUNO, expect 2-3 events per year (compared to about 50 reactor antineutrinos per day)
- A 2.6σ significant observation has just been [reported at Neutrino 2026](#) by Super-Kamiokande



Large spread in prediction from models



- + Data (SK-IV + V + VI + VII + VII.5 + VIII)
- DSNB (Horiuchi+09, 6 MeV, max)
- All backgrounds
 - Atmos ν_e CC
 - Atmos decay e
 - Atmos μ/π
 - Atmos NC γ
 - Spall ^9Li
 - Accidental coincidence

IBD event rate for $E_\nu > 13.3$ MeV ($E_{\text{rec}} > 11.5$ MeV)
Best-fit: $4.8^{+2.2}_{-2.0}$ events/yr
Predicted: 2.9 - 5.2 events/yr (Horiuchi+09, 6MeV, min - max)

DSNB flux for $E_\nu > 13.3$ MeV ($E_{\text{rec}} > 11.5$ MeV)
Best-fit: $3.6^{+1.6}_{-1.5}$ $\text{cm}^{-2} \text{s}^{-1}$
Predicted: 2.1 - 3.9 $\text{cm}^{-2} \text{s}^{-1}$ (Horiuchi+09, 6MeV, min - max)

JUNO and the DSNB

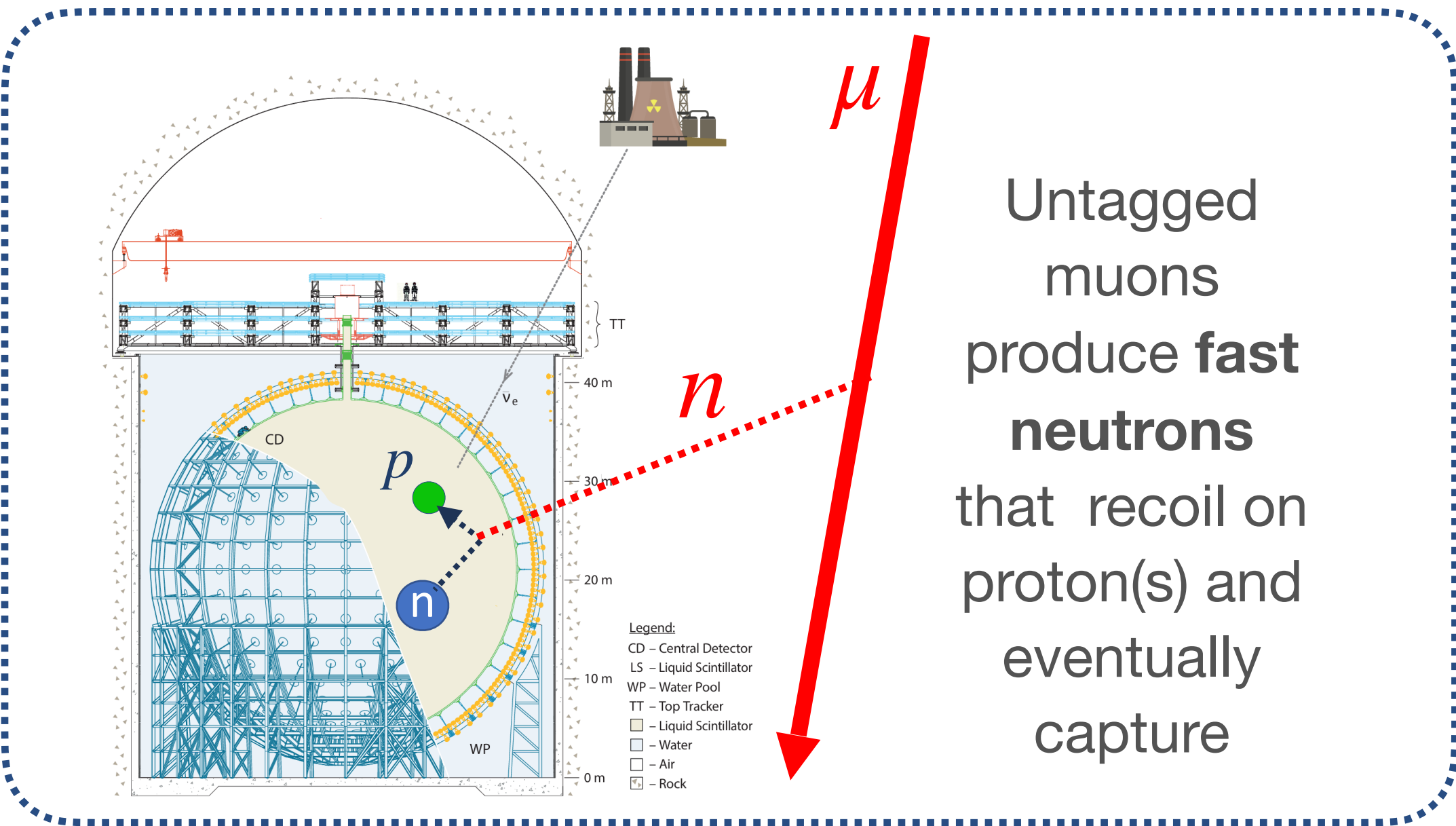
- JUNO is an excellent detector to search for the DSNB
 - High energy resolution and low threshold (resulting eg. in neutron tagging efficiency > 98%)
 - Low backgrounds and with multiple rejection tools at its disposal (next slide)

Designed to for low-energy antineutrino detection, but also extremely large!

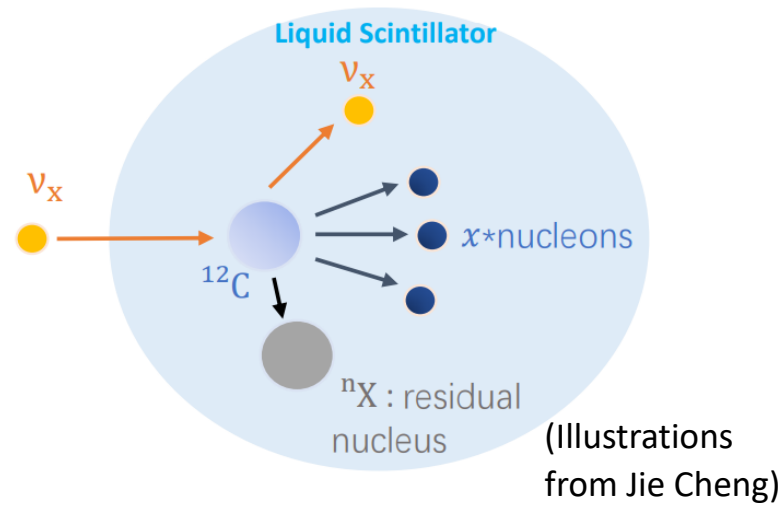
- Strategy:
 - Rely on the IBD reaction, with its characteristic double-coincidence signal
 - Look in the 12-30 MeV energy range to avoid reactor antineutrinos and ${}^9\text{Li}/{}^8\text{He}$ background

Note: also small background from atmospheric $\bar{\nu}_e$ Charged Current (CC) interactions

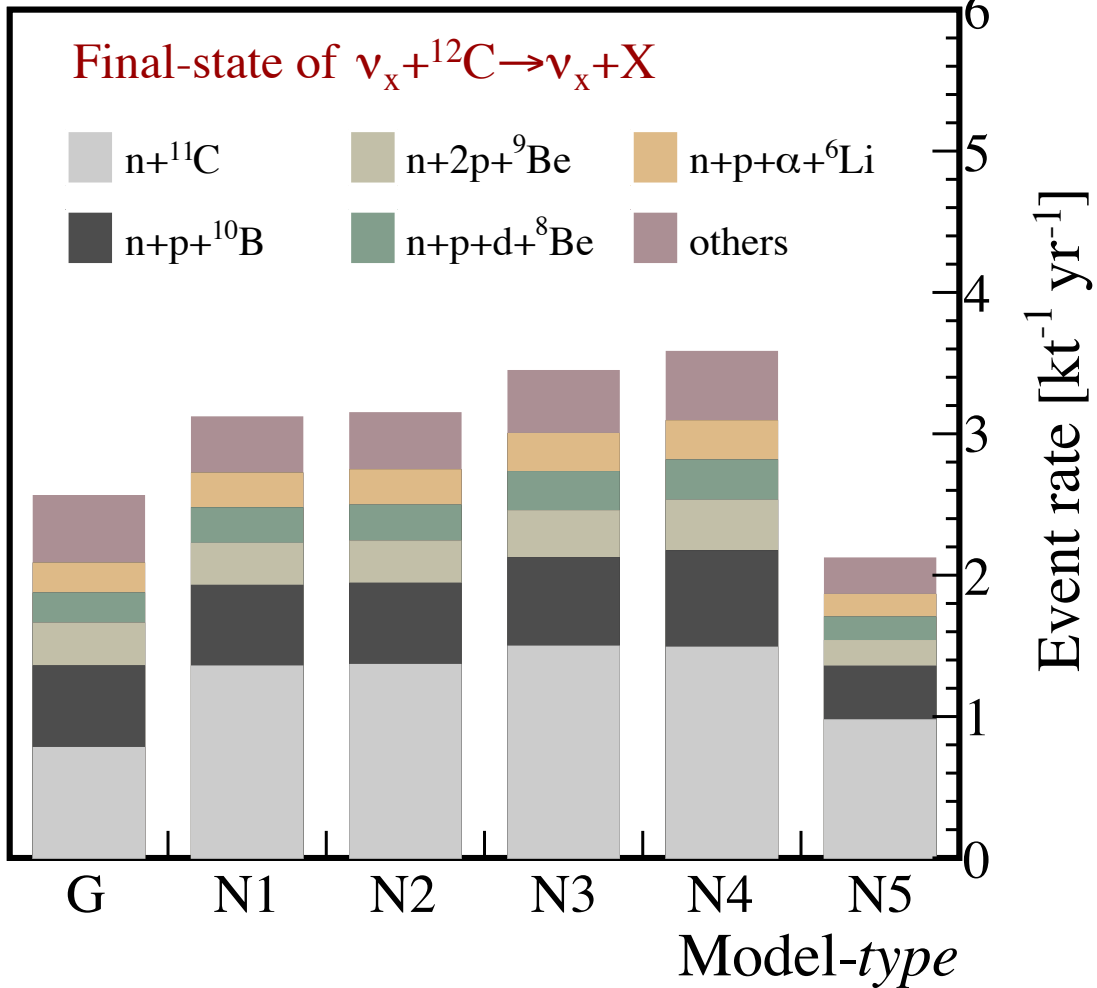
End up with 2 main types of backgrounds:



Atmospheric Neutrino Neutral Current (NC) interactions



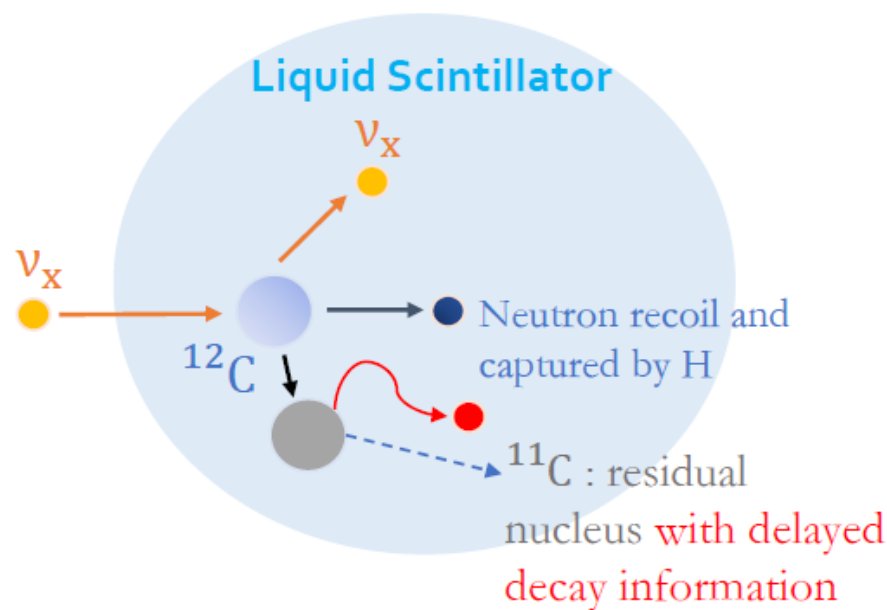
$n + C^{11}$ is dominant



Background Suppression

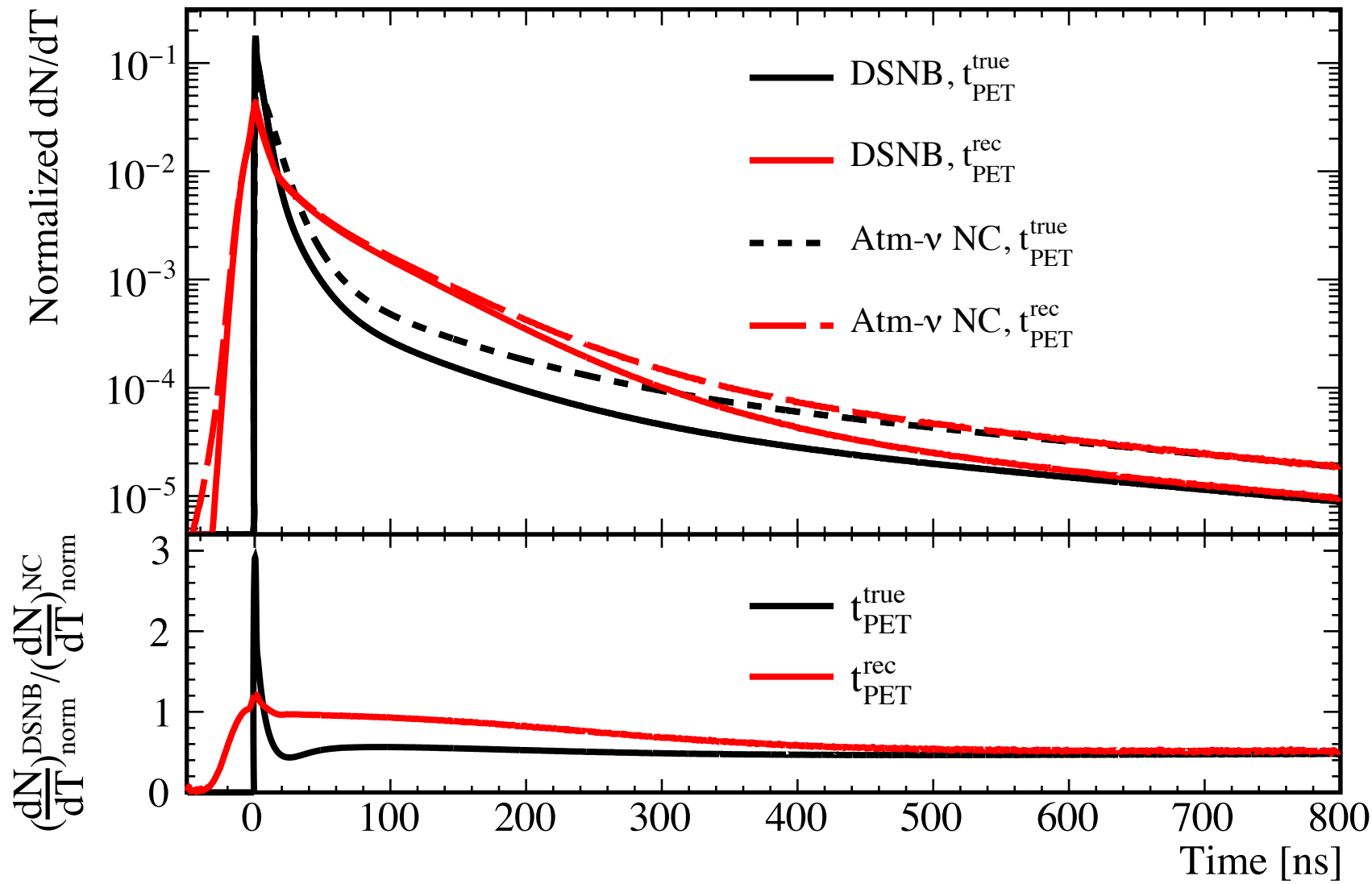
- Use mainly two approaches to further mitigate DSNB backgrounds
 - **Pulse-Shape Discrimination (PSD):** exploit differences in time profiles between particles
 - **Triple Coincidence (TC):** exploit decay of resulting ^{11}C nucleus

Expect efficiency uncertainty to improve with time as studies are done on natural and artificial calibration samples

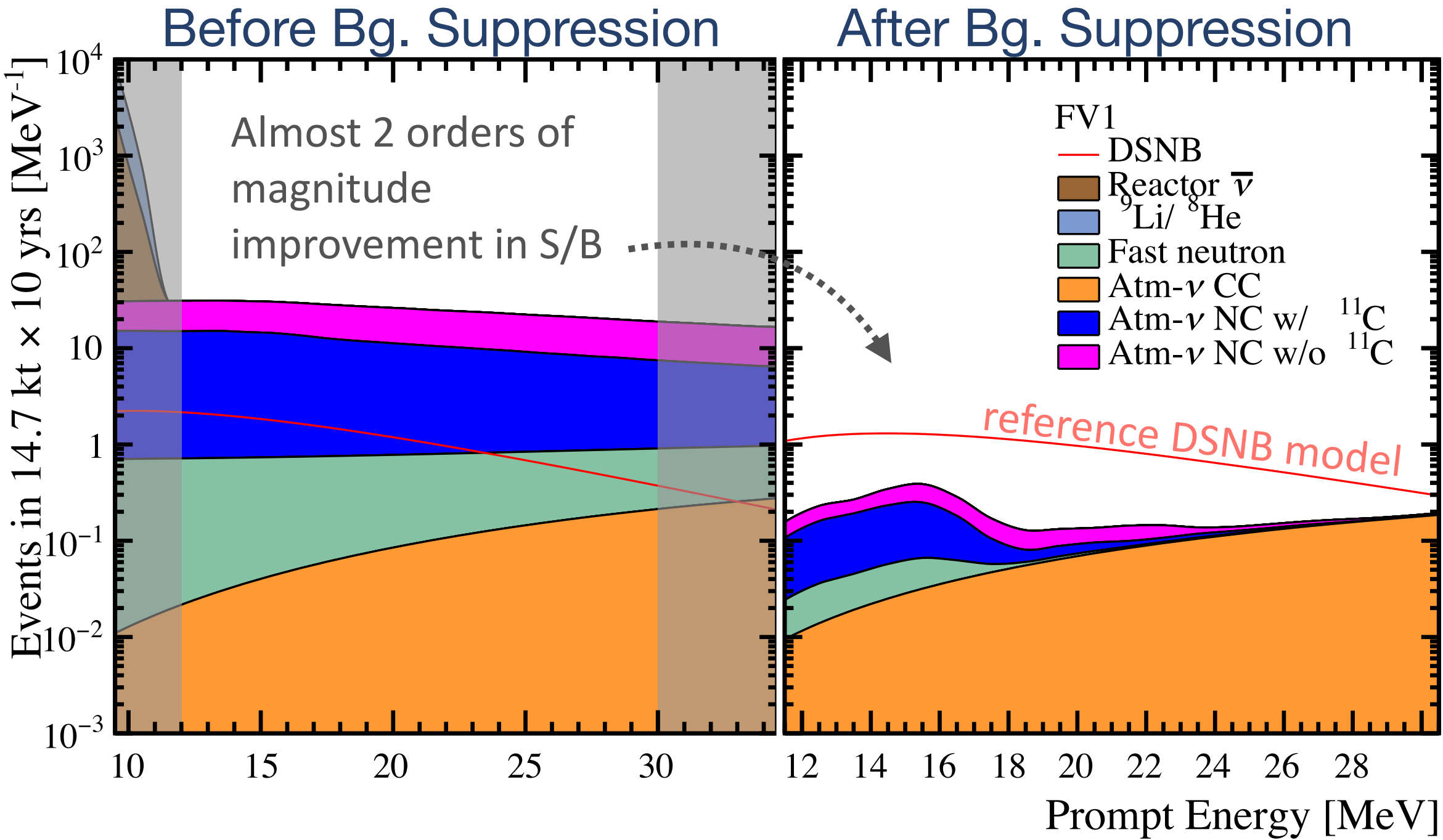


Signal efficiency of ~80% with background inefficiency of ~1%

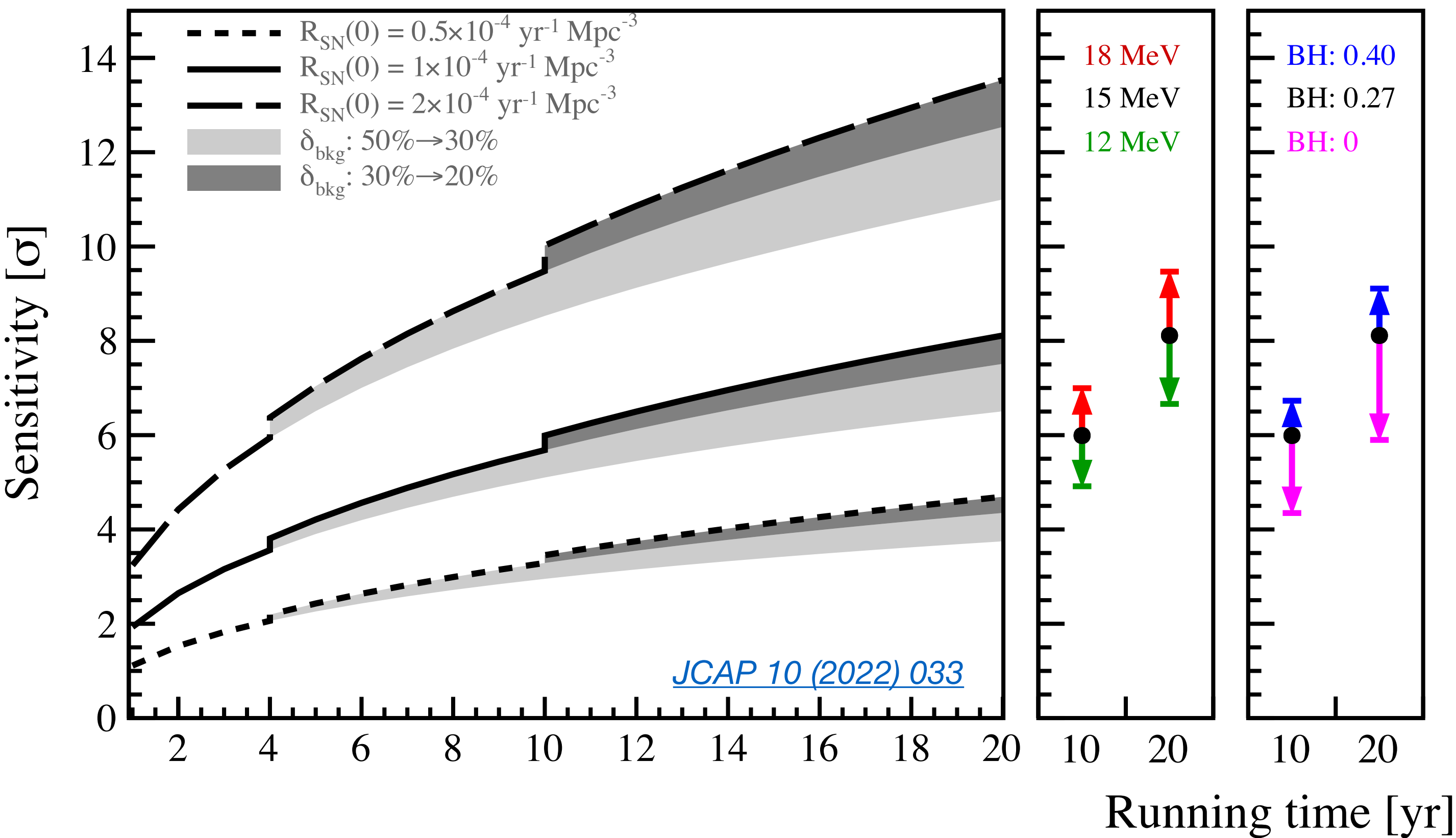
Uncertainty on this background also expected to decrease with time with *in situ* measurement ([PRD 103, 053002 \(2021\)](#))



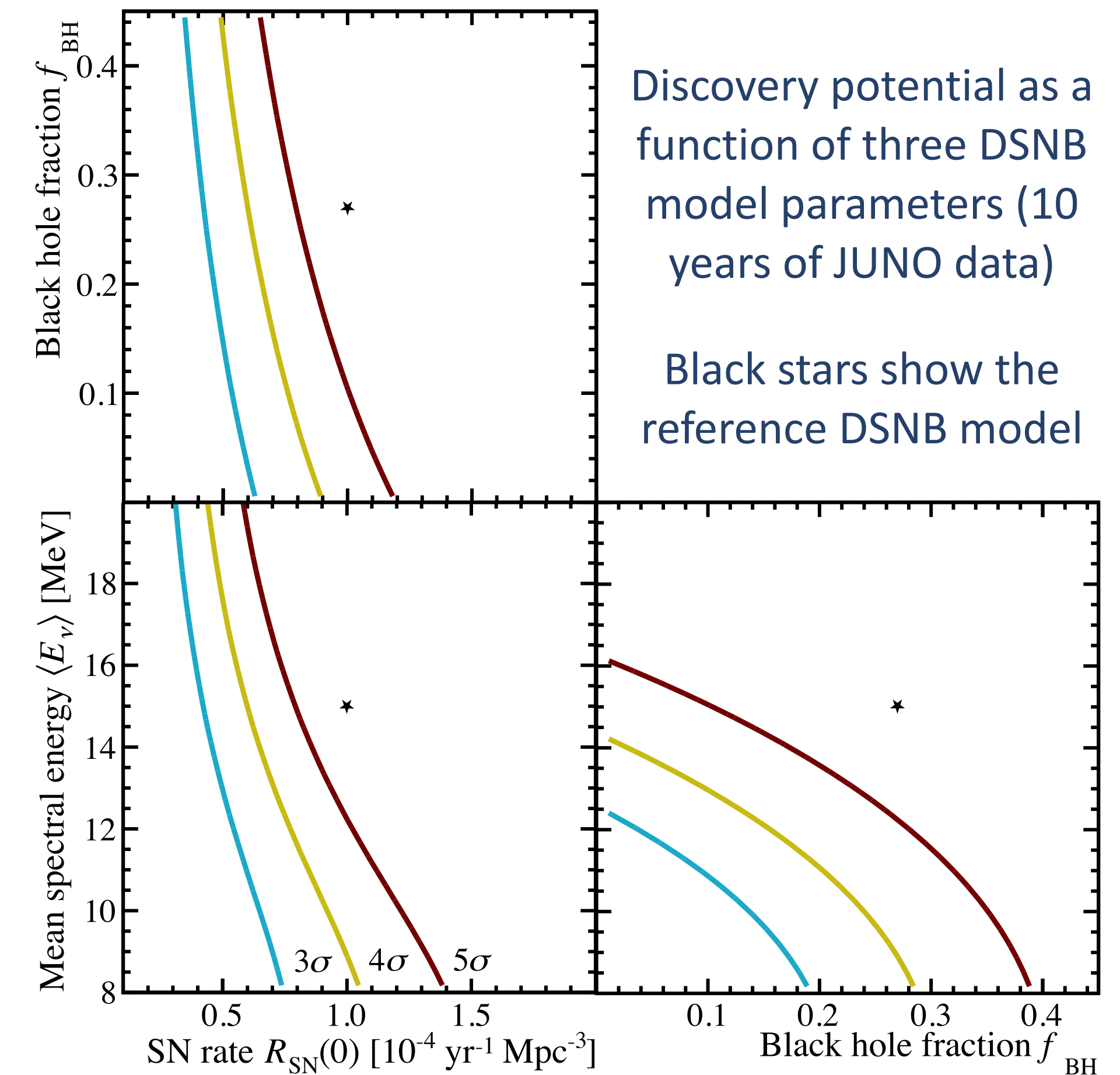
Average Photon Emission Time (PET)



DSNB Discovery Potential



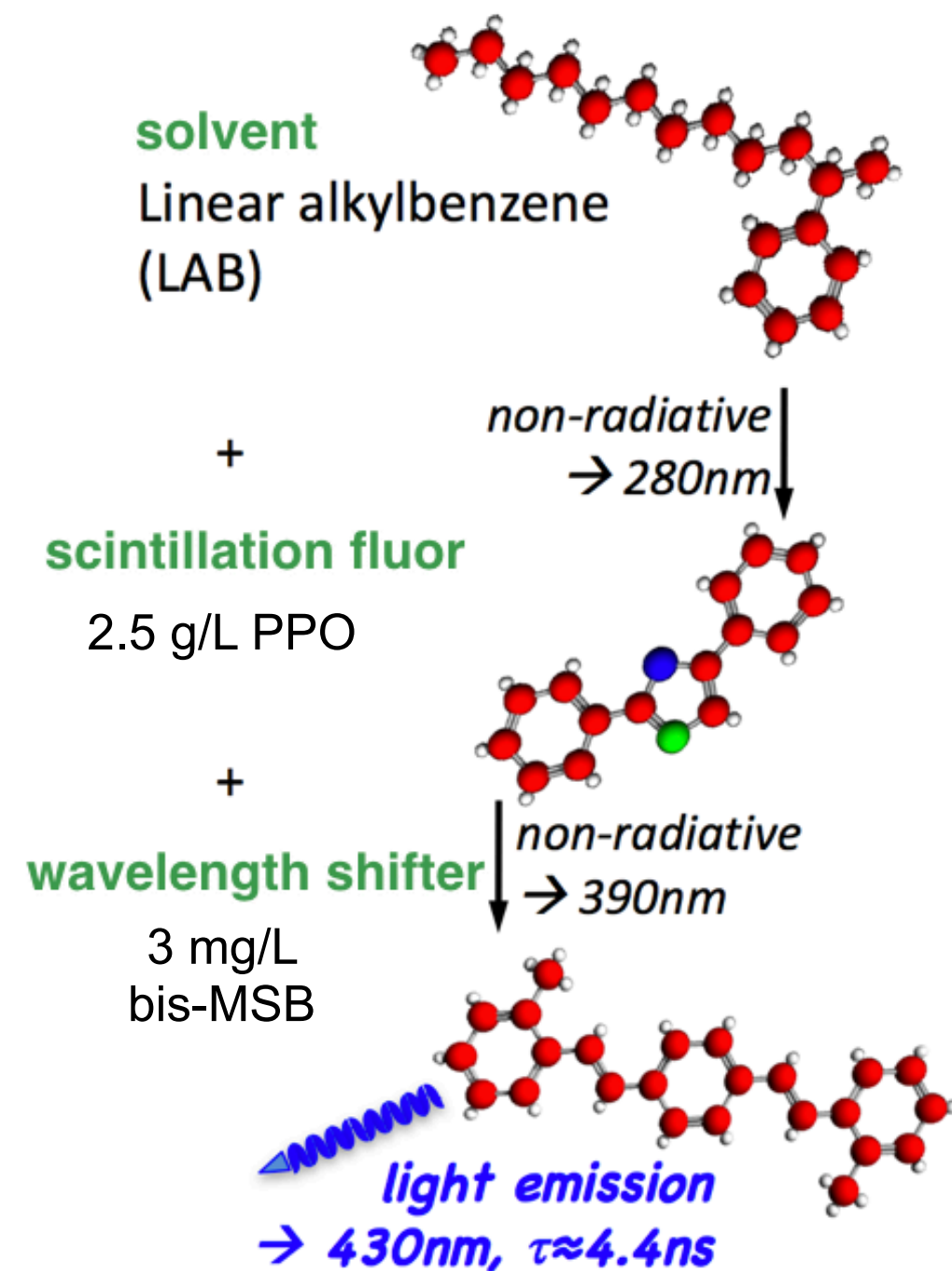
- Expected detection significance of 3σ after ~ 3 years of data for nominal model
- Provide leading constraint if DSNB is not observed



Better than 5σ discovery potential for broad region of parameter space

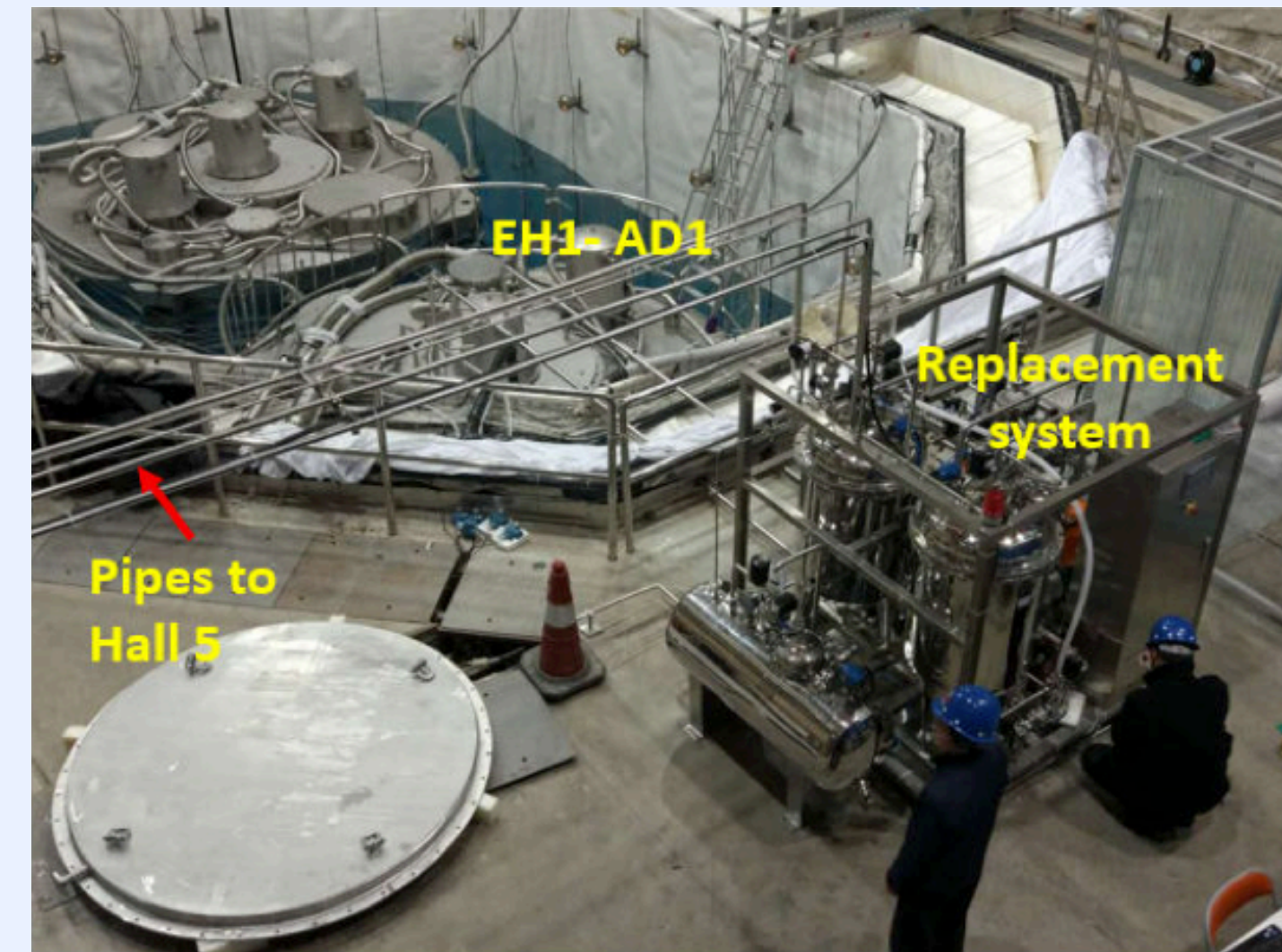
Liquid Scintillator (LS)

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

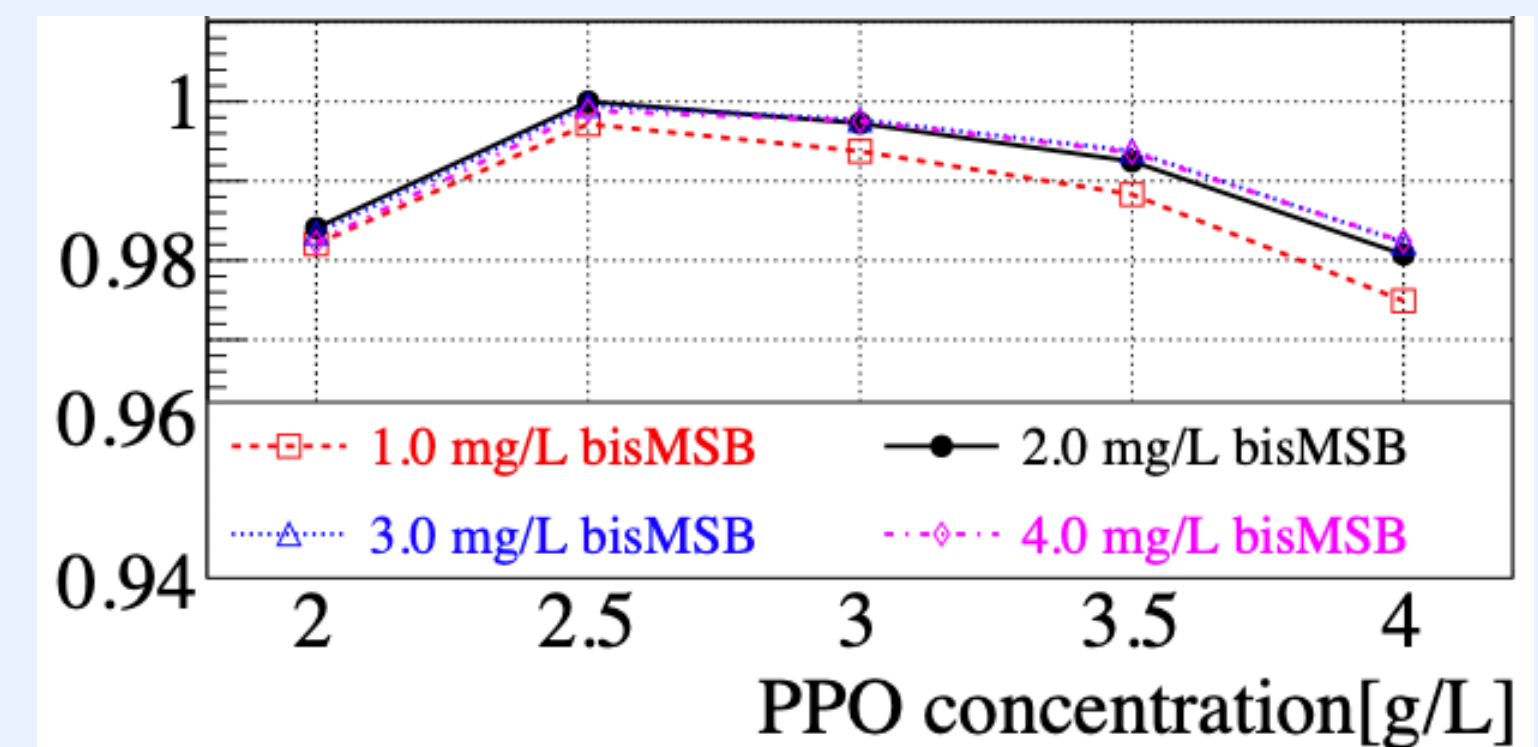


- No doping, large fluor concentration

LS Recipe optimized with a decommissioned Daya Bay detector



[NIMA 998, 164823 \(2021\)](#)



Key Feature: Energy Resolution

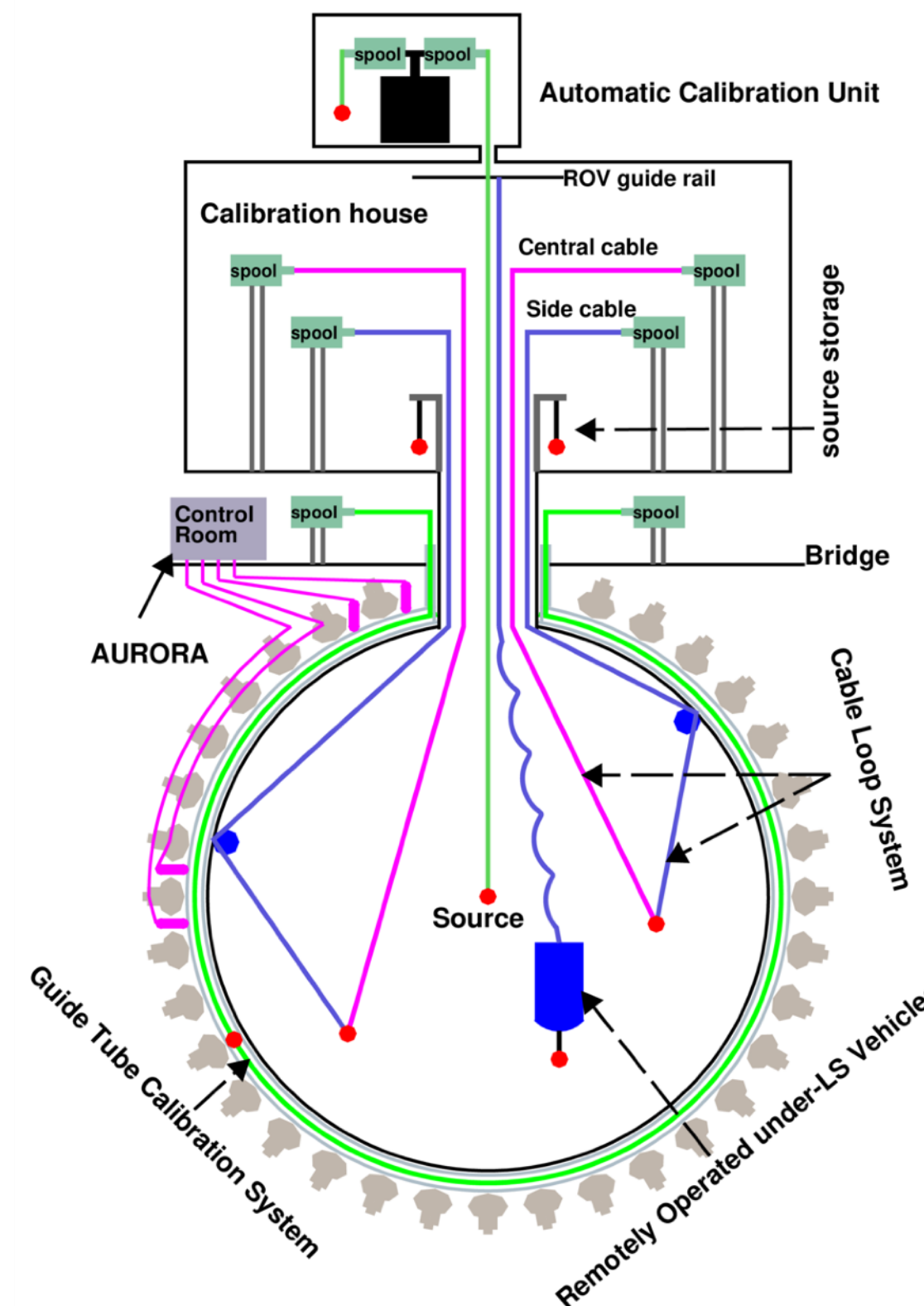
What it takes: **high light yield** and **comprehensive calibration**

Summarizing the previous slide, we need:

- **Lots of PMTs!!**

Two types of 20-inch PMTs packed as tightly as possible, with 3-inch PMTs in the space between them

- Tuned and highly transparent liquid scintillator
- PMTs with almost double the detection efficiency compared to the previous generation



[JHEP 2021, 04 \(2021\)](#)

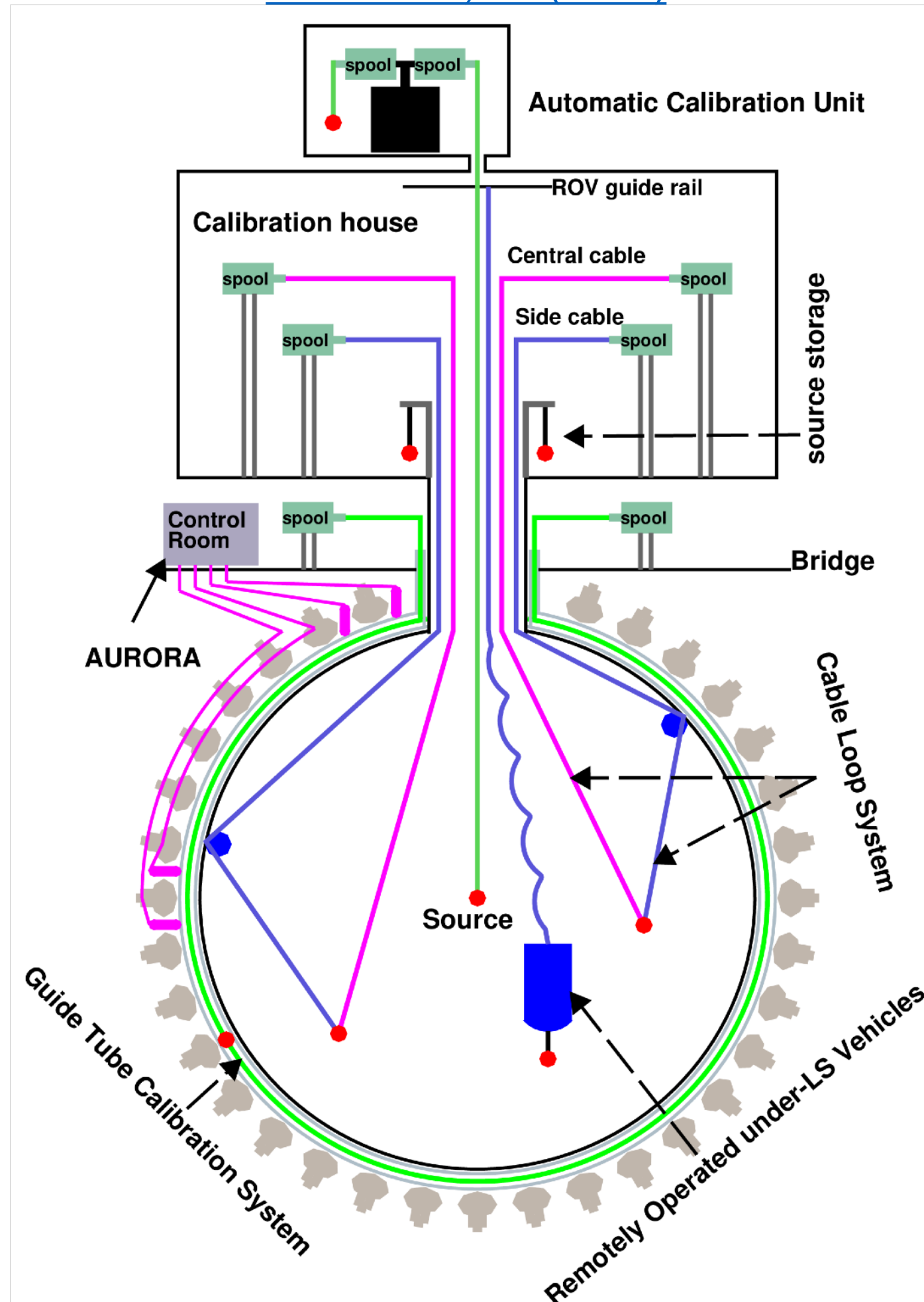
Need to **minimize residual effects after calibration**

- Comprehensive calibration system allowing to position sources everywhere inside and around the detector
- Works in sync with small PMT system, which serves as linear reference

Calibration System

- JUNO also needs to **keep the systematics under control**

JHEP 2021, 04 (2021)



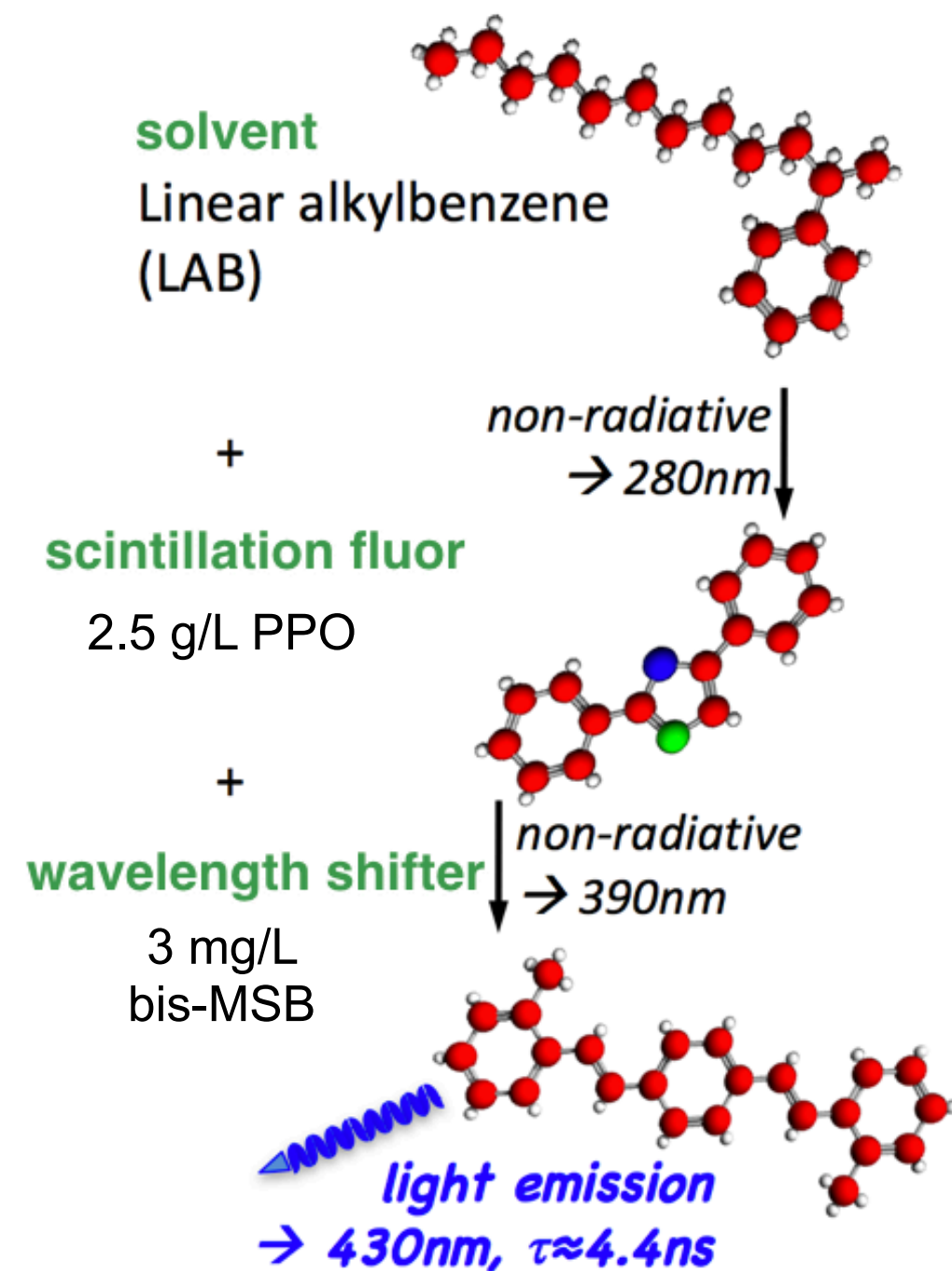
- Have an **comprehensive calibration program** consisting of 4 mutually complementary systems:
 - **1D**: Automated Calibration Unit (ACU) deploys radioactive and laser (1ns, keV-TeV range) sources along the central axis
 - **2D**: Cable Loop System (CLS) to scan vertical planes
 - **2D**: Guide Tube 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 $< 1\%$

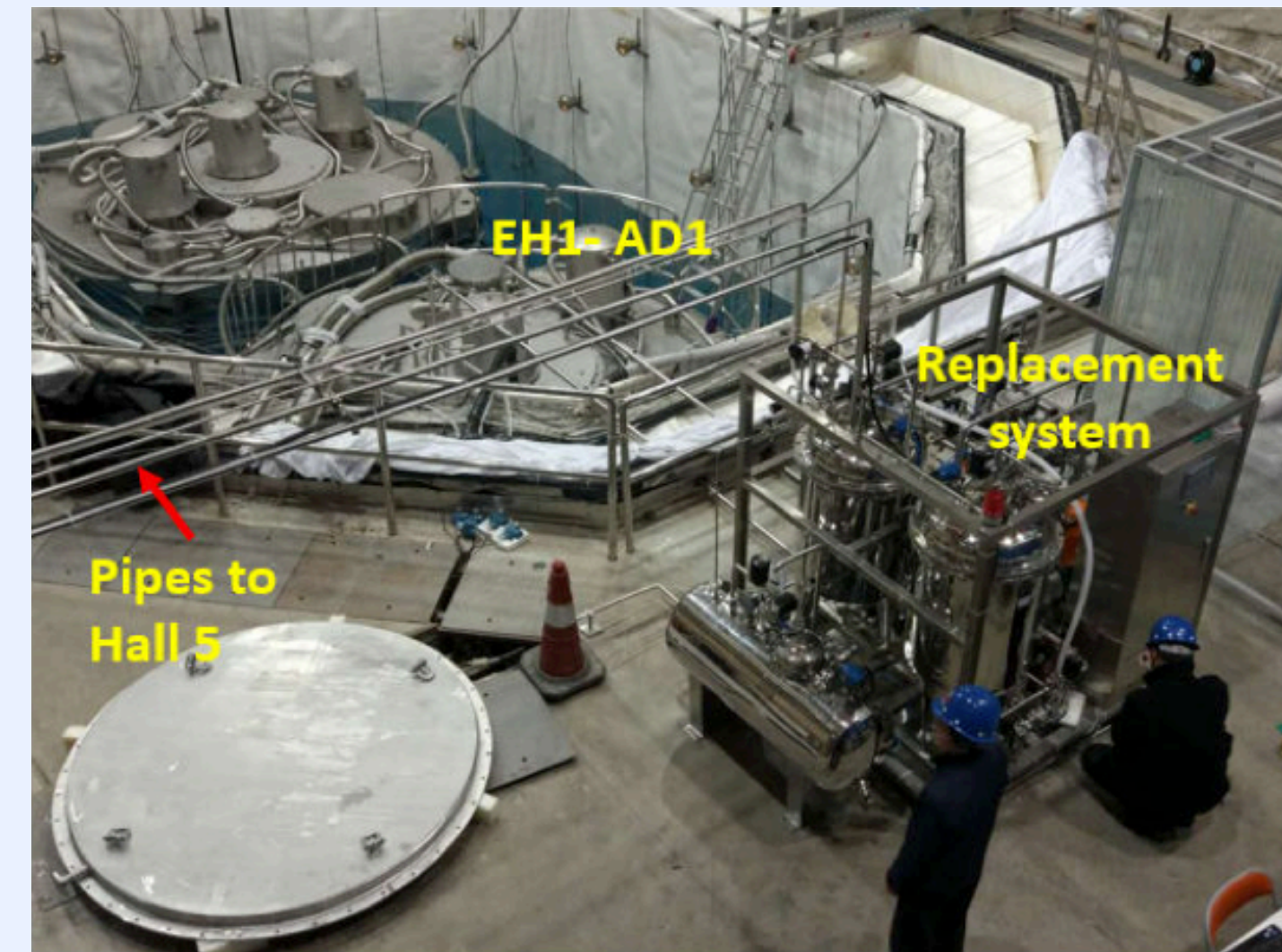
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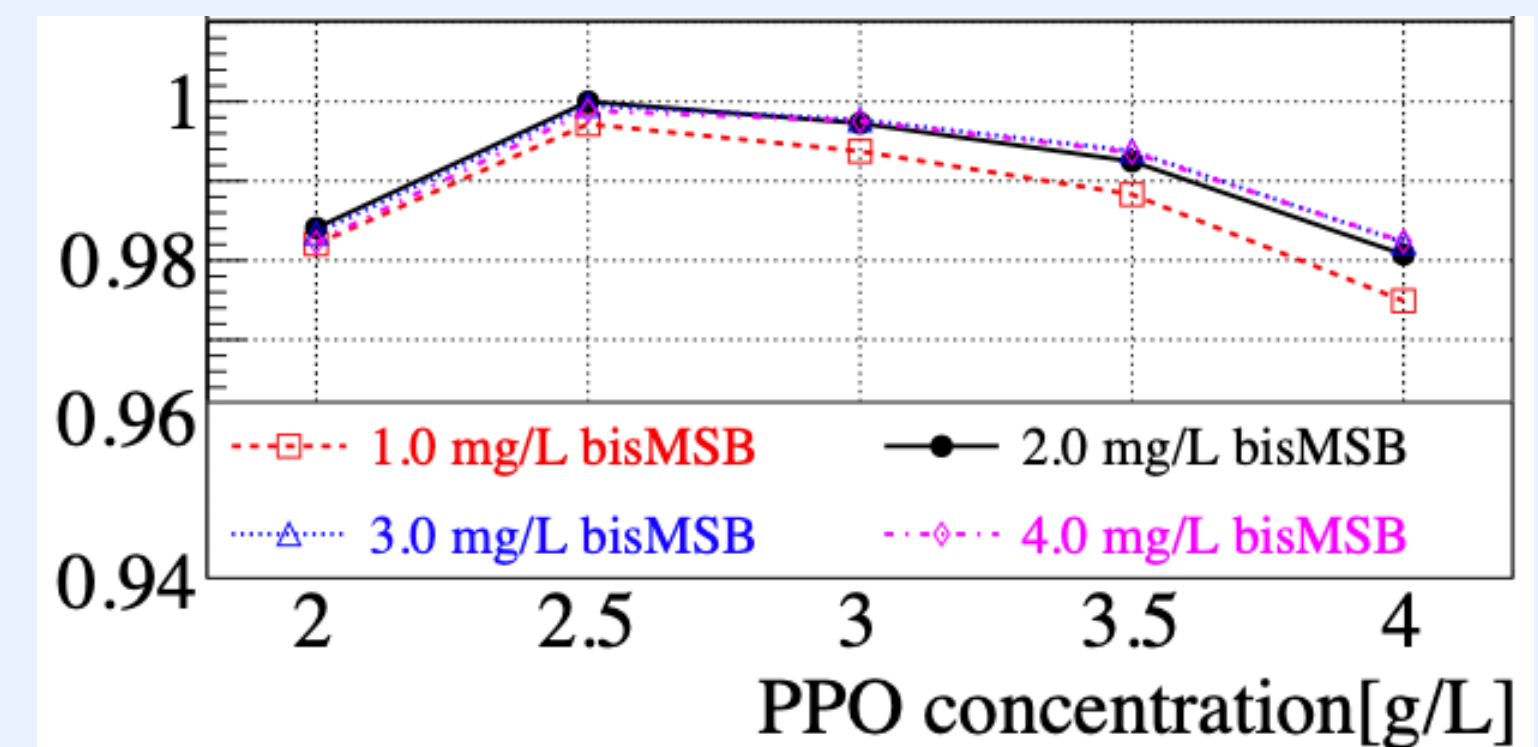


- No doping, large fluor concentration

LS Recipe optimized with a decommissioned Daya Bay detector



[NIMA 998, 164823 \(2021\)](#)



Muon Veto System

The CD is immersed in a cylindrical, instrumented water pool:

- 35 kton ultrapure water with a circulation system

Double-purpose:

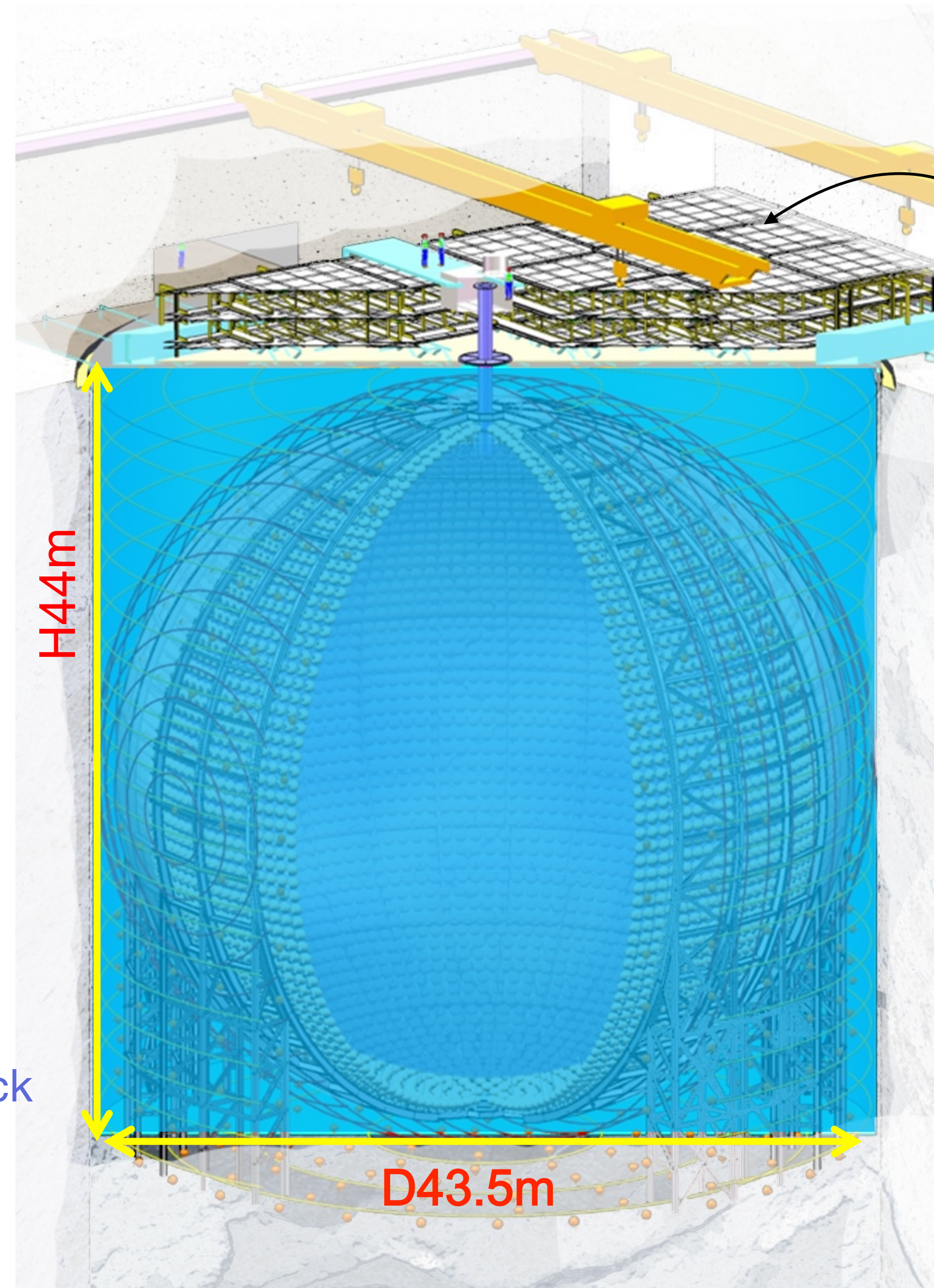
Shield central detector against radioactivity from rock and neutrons from cosmic rays

Reconstruct and veto cosmic-ray muons

Critical to keeping the cosmogenic backgrounds under control

Some details about the water pool:

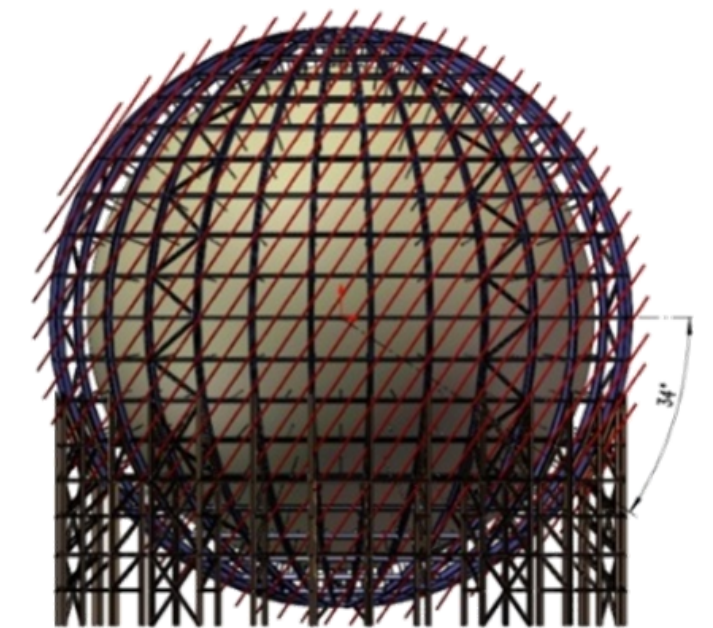
- 2,400 20-inch PMTs
- 5 mm HDPE lining to stop Rn from rock
- Detection efficiency > 99.9%



Also have a top tracker:

- 3-layers of plastic scintillators
- Reuse of OPERA's target tracker

and a magnetic field (EMF) shielding system



Detector Construction (Video)

