UCI University of California, Irvine

Recent Advances in Reactor Neutrino Measurements

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Physics of the Two Infinities Conference, Tokyo, Japan, Nov. 2025

Basic Principles

of Reactor Neutrino Experiments

Neutrino Basics

- 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 oscillatory behavior is **beyond the Standard Model**
- The principle behind neutrino oscillations: neutrino mixing

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

How they interact (ν_e, ν_μ, ν_τ)

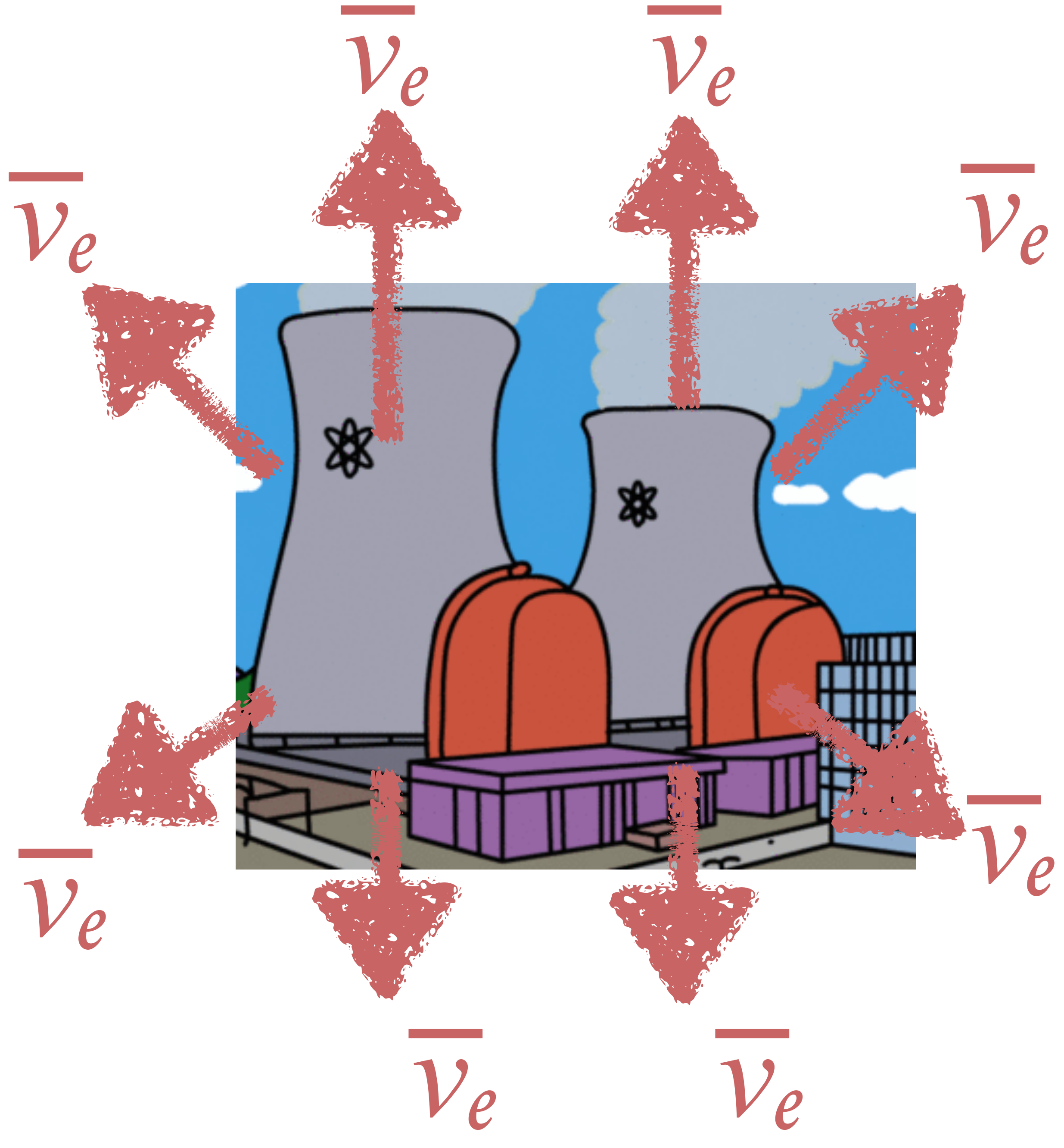
How they propagate (ν_1, ν_2, ν_3)

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

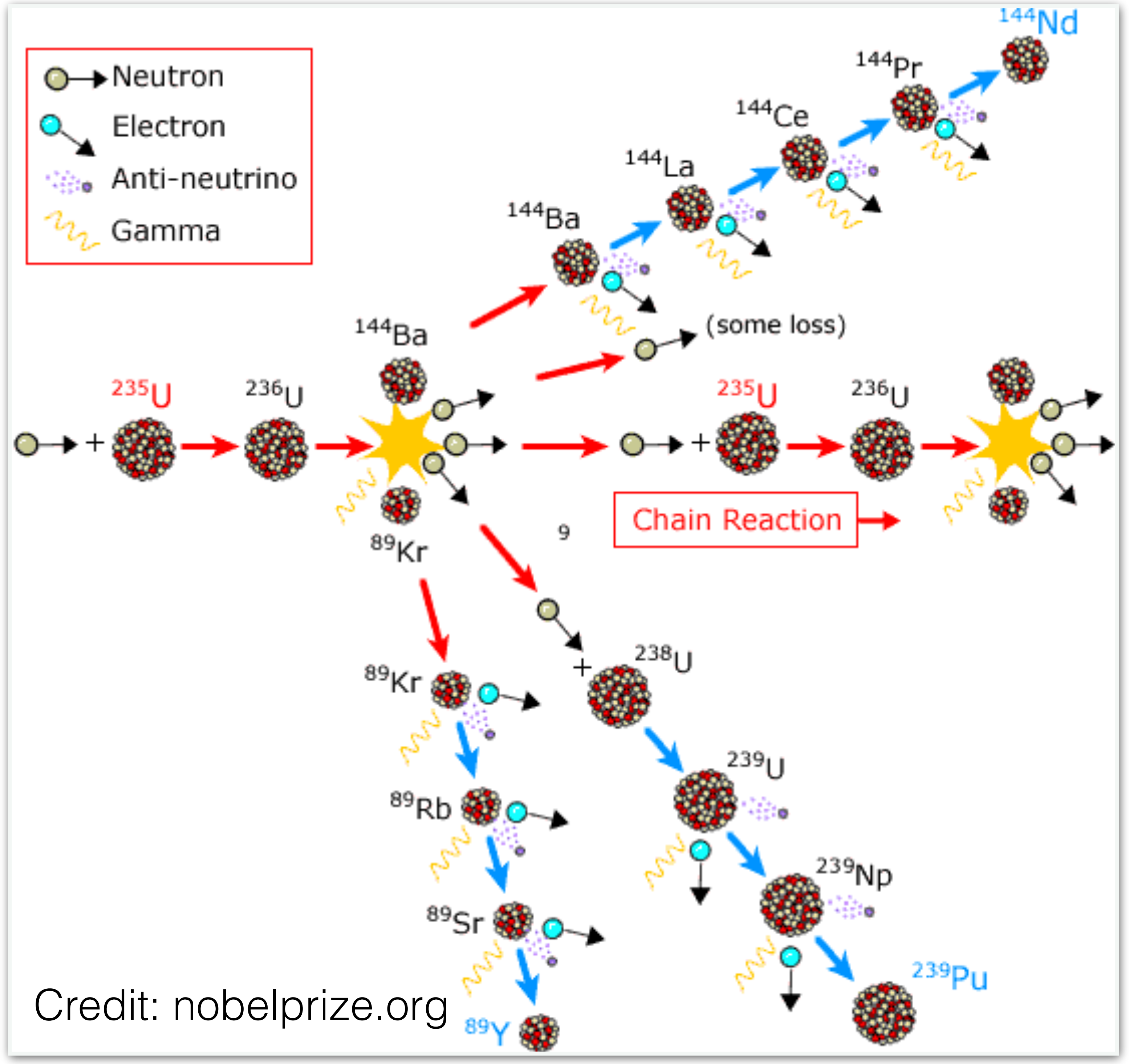
The **mass splittings** $\Delta m^2_{ij} = m^2_i - m^2_j$ determine the oscillation frequencies

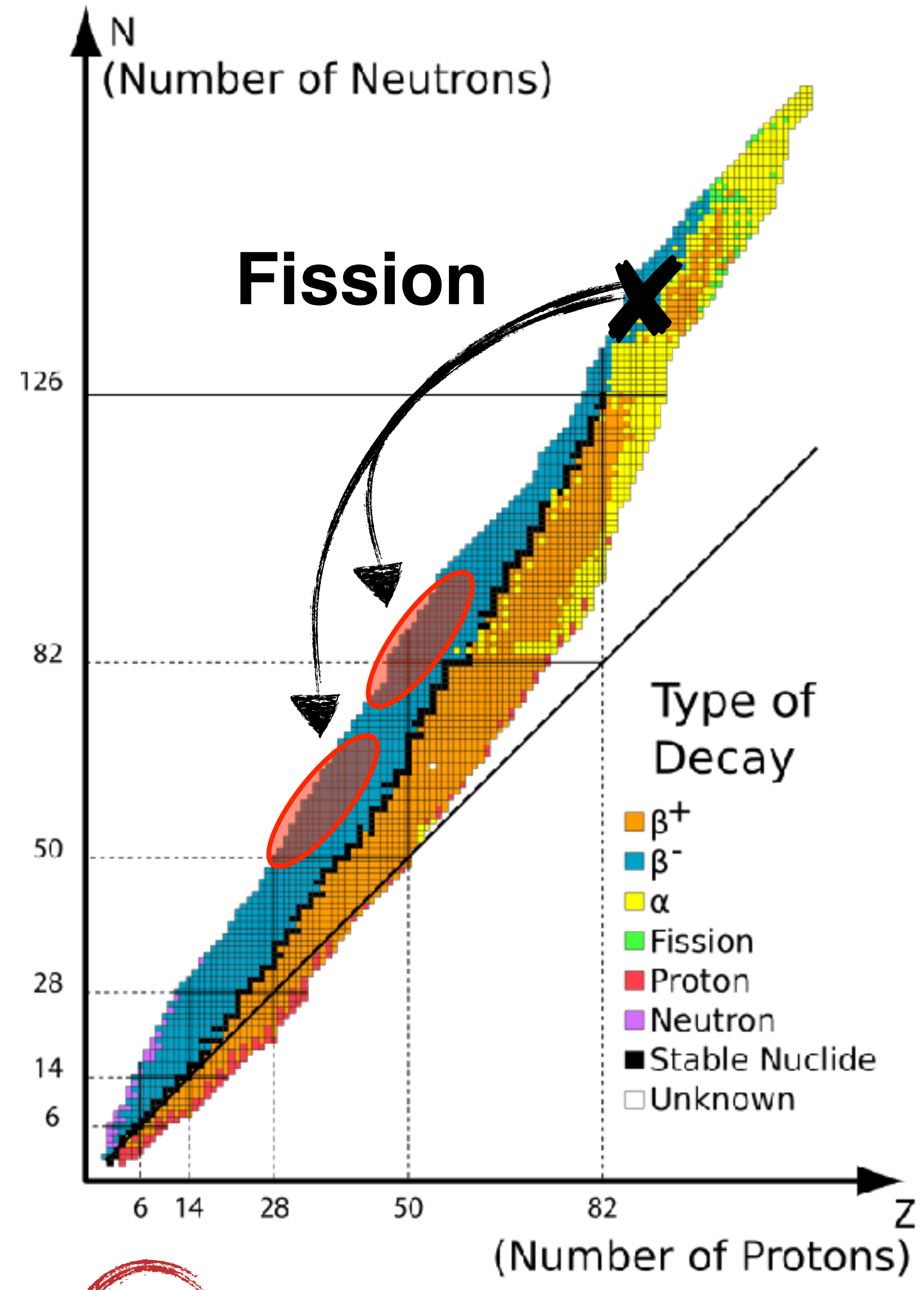
Reactor Antineutrinos

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



$\sim 10^{20}\ \bar{\nu}_e/(\mathrm{s}\cdot\mathrm{GW_{th}})$





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

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

Antineutrino Detection

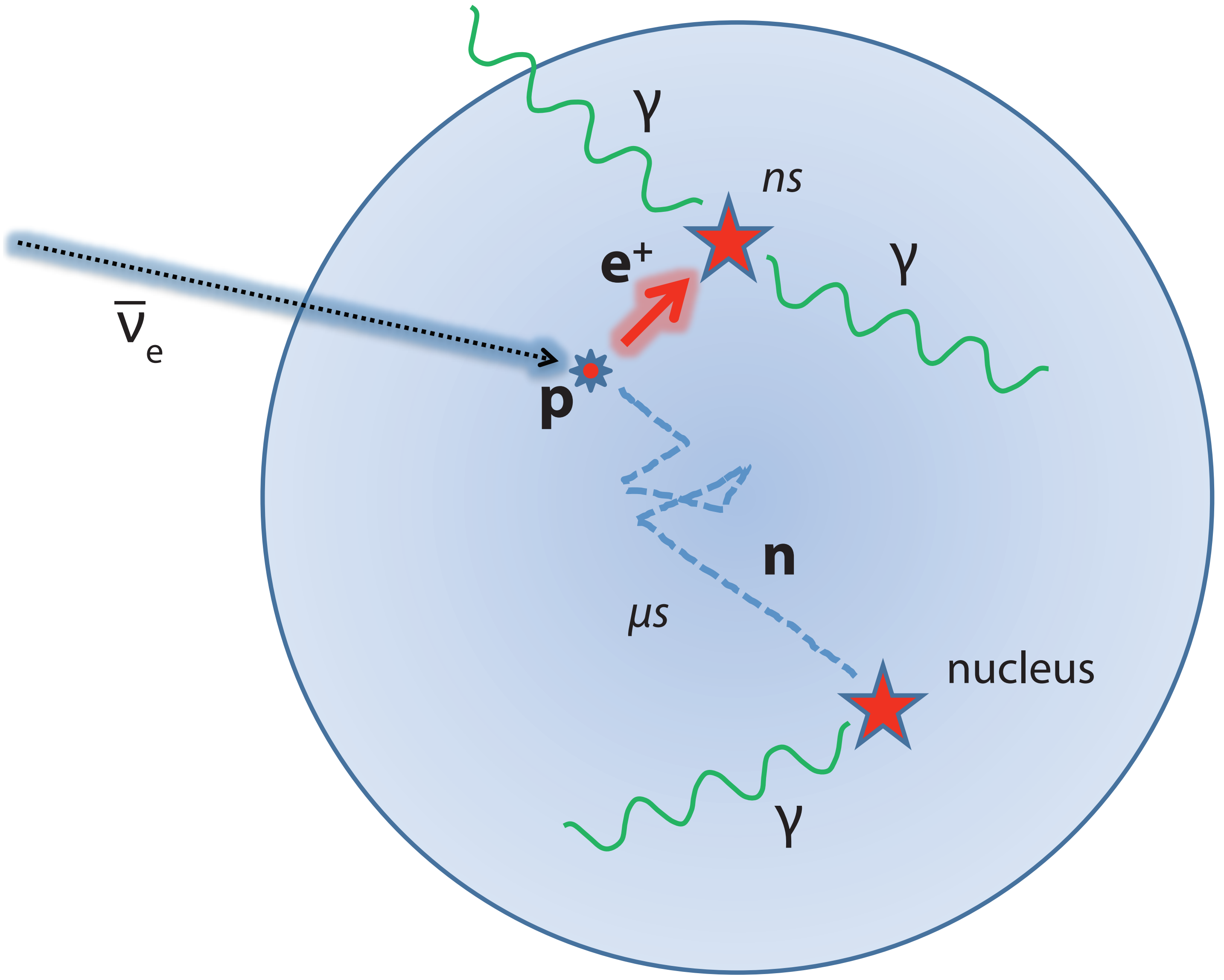
** Disclaimer: there is an emerging program using CEvNS to search for new physics at reactors, but time will not permit to cover it*

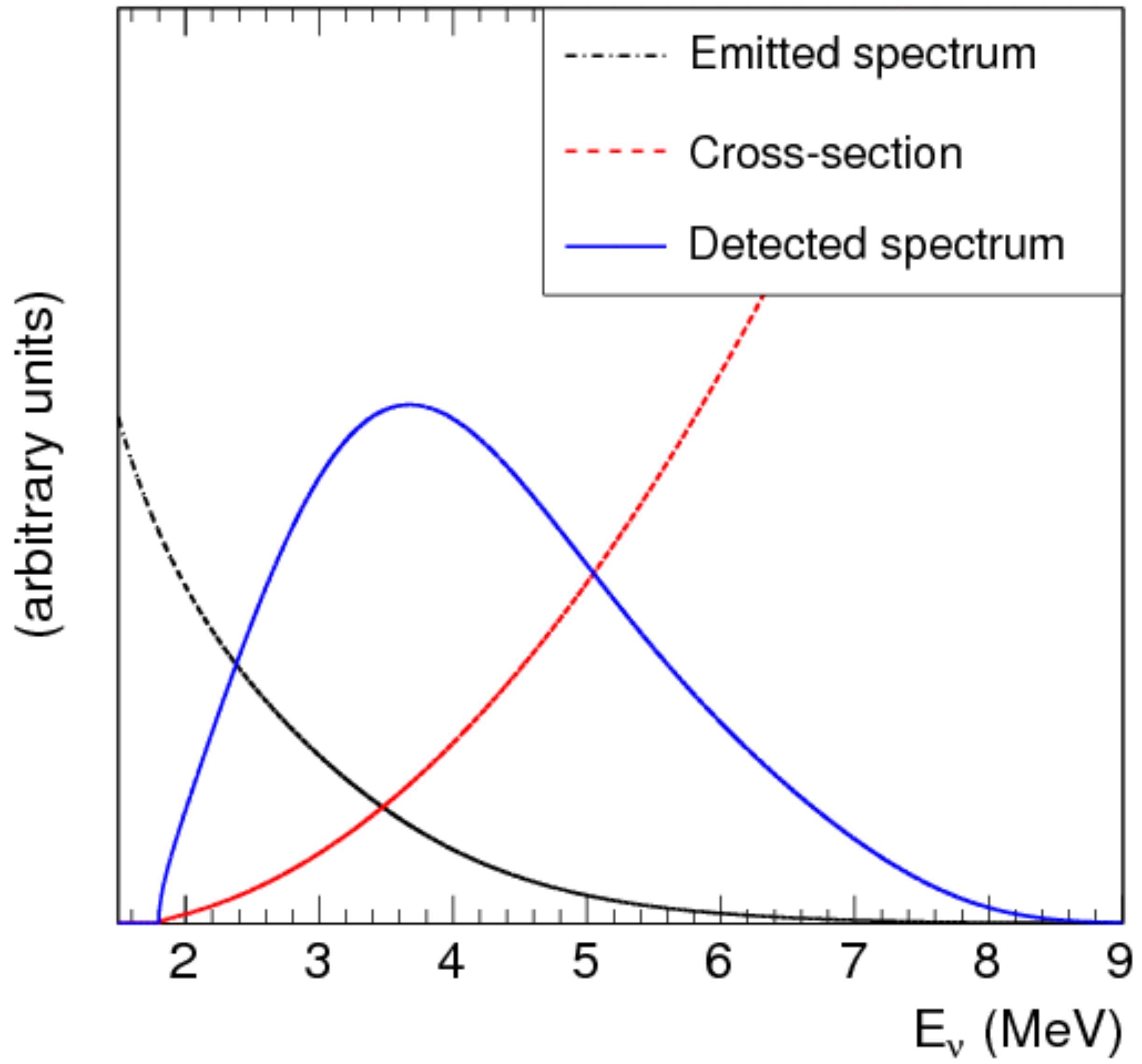
- Archetypical reactor $\bar{\nu}_e$ detector: liquid scintillator target surrounded by photomultiplier tubes (PMTs)
- The primary detection channel is the Inverse Beta Decay (IBD) reaction*:

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

Prompt signal: e^+ kinetic energy loss + annihilation

Delayed signal: n capture on Hydrogen (nH) or Gadolinium (nGd) 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 $\bar{\nu}_e$: $E_{\bar{\nu}_e} \approx E_{\text{prompt}} + 0.78\ \text{MeV}$

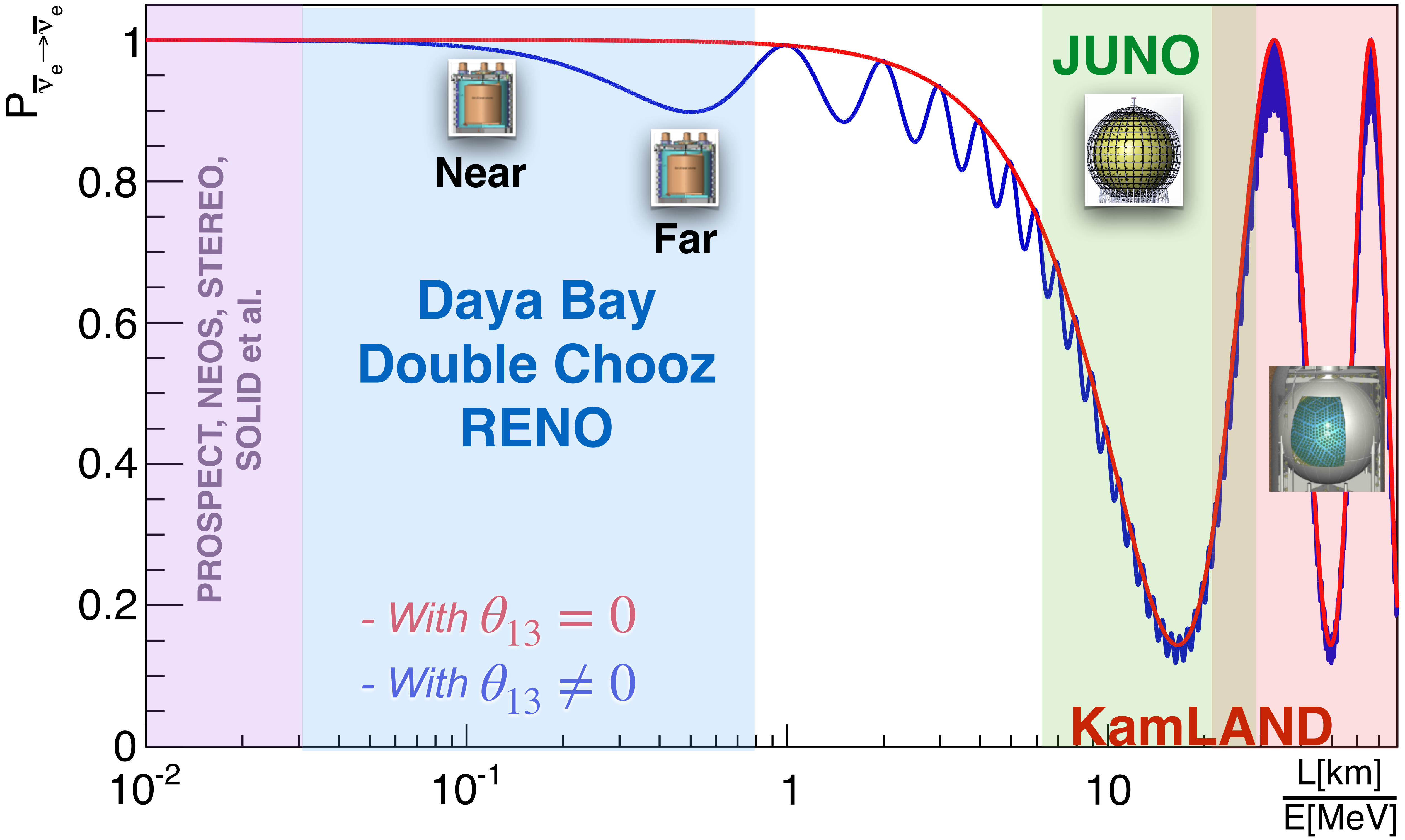
- Only $\bar{\nu}_e$'s are detectable via CC interactions; other flavors are kinematically inaccessible

Reactor Antineutrino Oscillations

- Reactor neutrino experiments provide an excellent platform to make precision measurements of neutrino oscillation:

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

  - Look at how $\bar{\nu}_e$'s oscillate (disappear) into other flavors
  - Access to θ_{12}, θ_{13}, Δm^2_{21}, Δm^2_{31} and the mass ordering
  - No dependence on θ_{23} and δ_{CP}
  - Baseline is set by physics goals



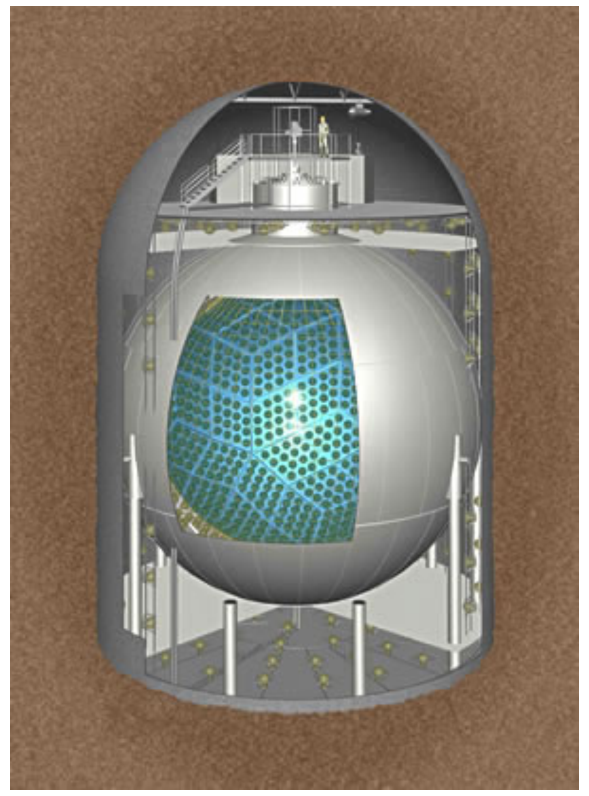
(chart courtesy of B. Roskovec)

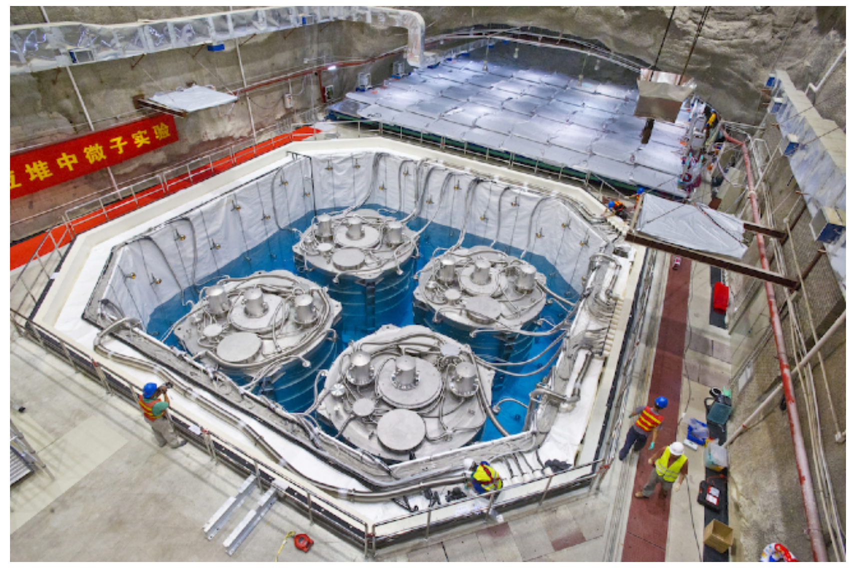
Several Generations of Reactor Neutrino Experiments

New results just released yesterday!!

Discovery of the Neutrino (1956)

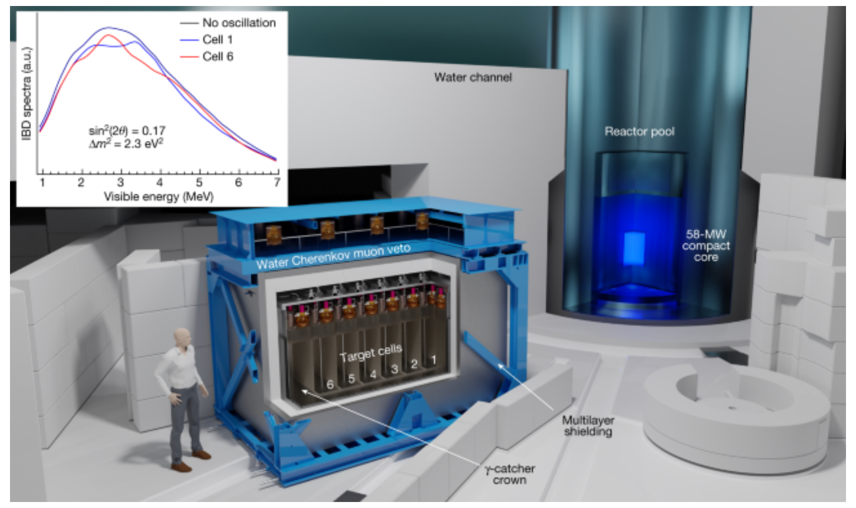
KamLAND (2002-2011)





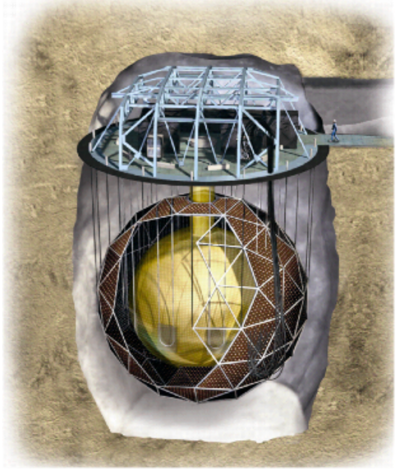
The θ_{13} generation (~2011-2023)

Short-Baseline Experiments (~2015-2023)



Still producing results!

Next generation



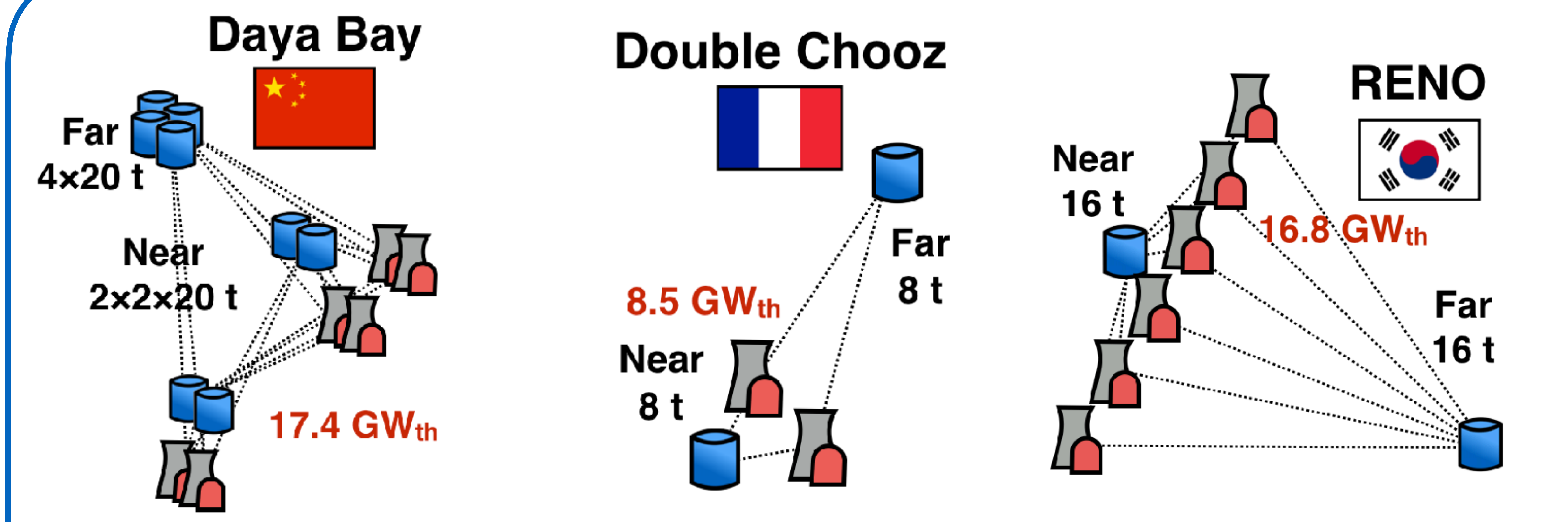
Disclaimer: there is also exciting R&D happening (e.g. LiquidO) that unfortunately there is no time to cover

Highlights of Recent Results

from the previous generation of experiments

θ_{13} Experiments

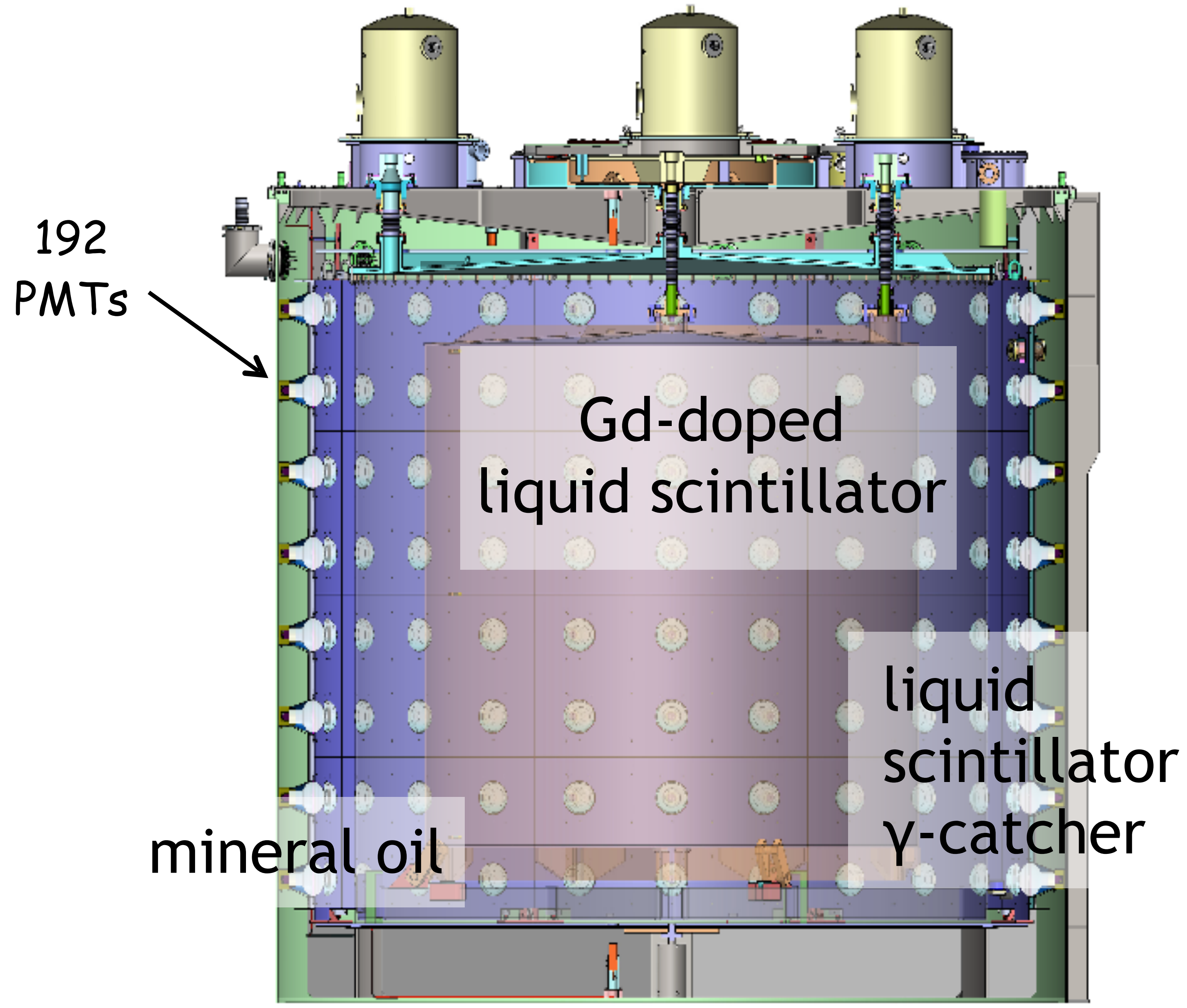
- There are three experiments dedicated to precisely measuring θ_{13}:



Data taking: 2011 - 2020 | Data taking: 2011 - 2017 | Data taking: 2011 - 2023

Notes: all reactors are LEU; flags indicate location of experiment, not composition of collaboration

- Three-zone detectors
- Surrounded by instrumented shields



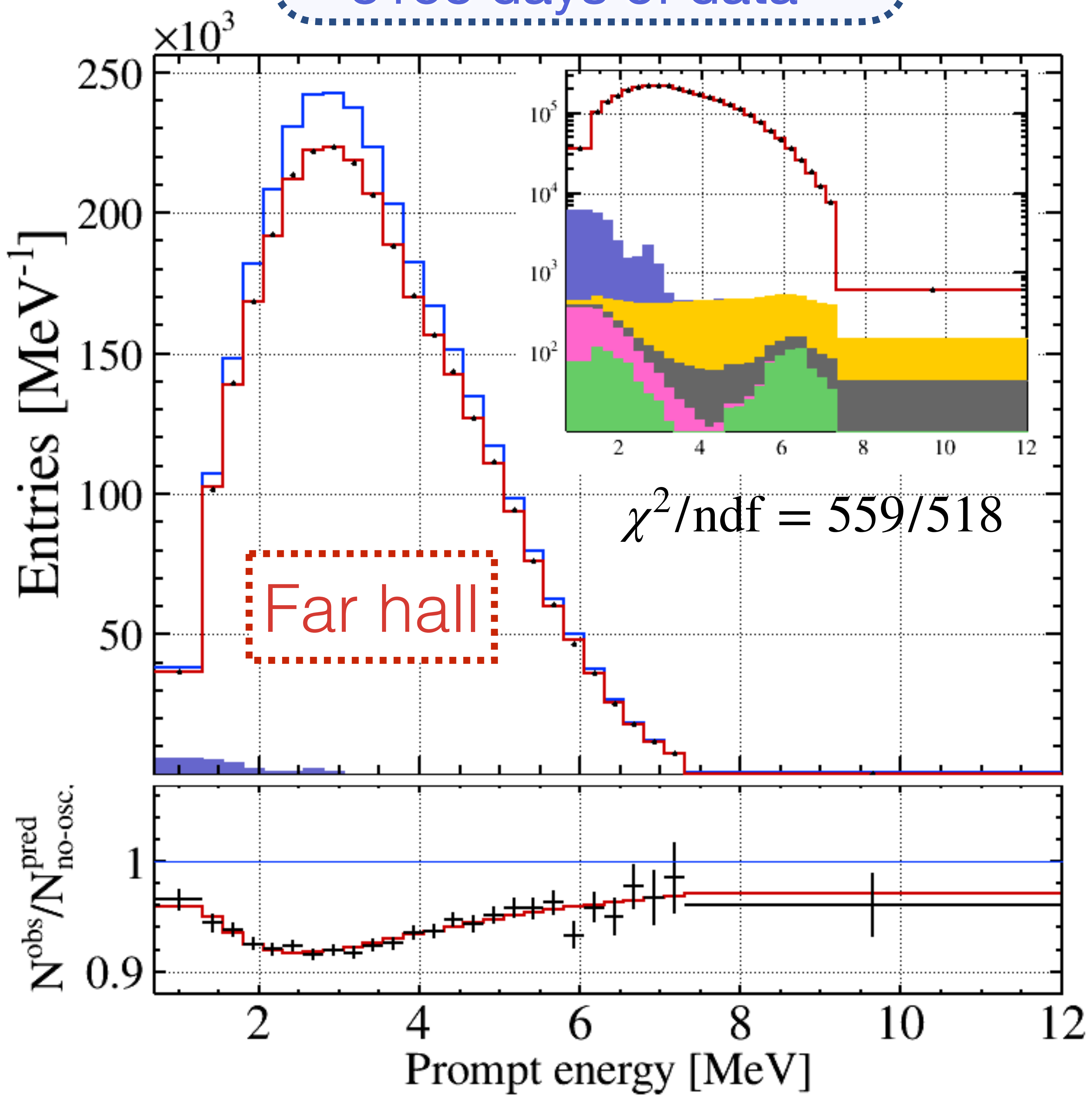
Using Daya Bay as an example (NIM A 811, 133 (2016))

- < 2 km baseline means only need "small" detectors (tens or hundreds of tons)
- Looking for small (<10%) disappearance, so **key is keeping systematics under control**
- Near/far **relative** comparison allows to largely cancel uncertainties in flux prediction and correlated detection efficiencies

Final Oscillation Measurements

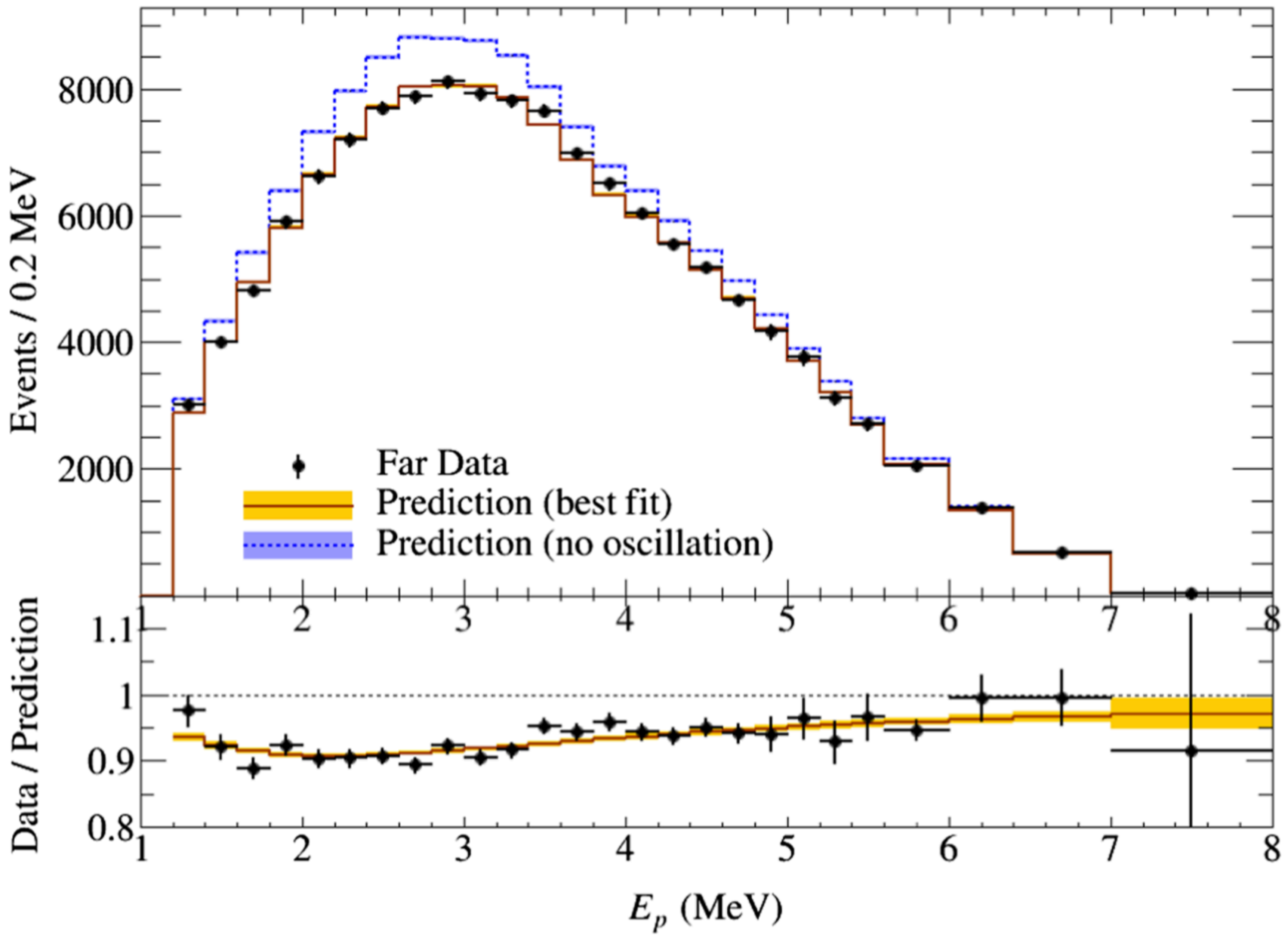
- Extract θ_{13} and Δm^2_{32} from relative near/far rate and spectral distortion

Daya Bay
3158 days of data



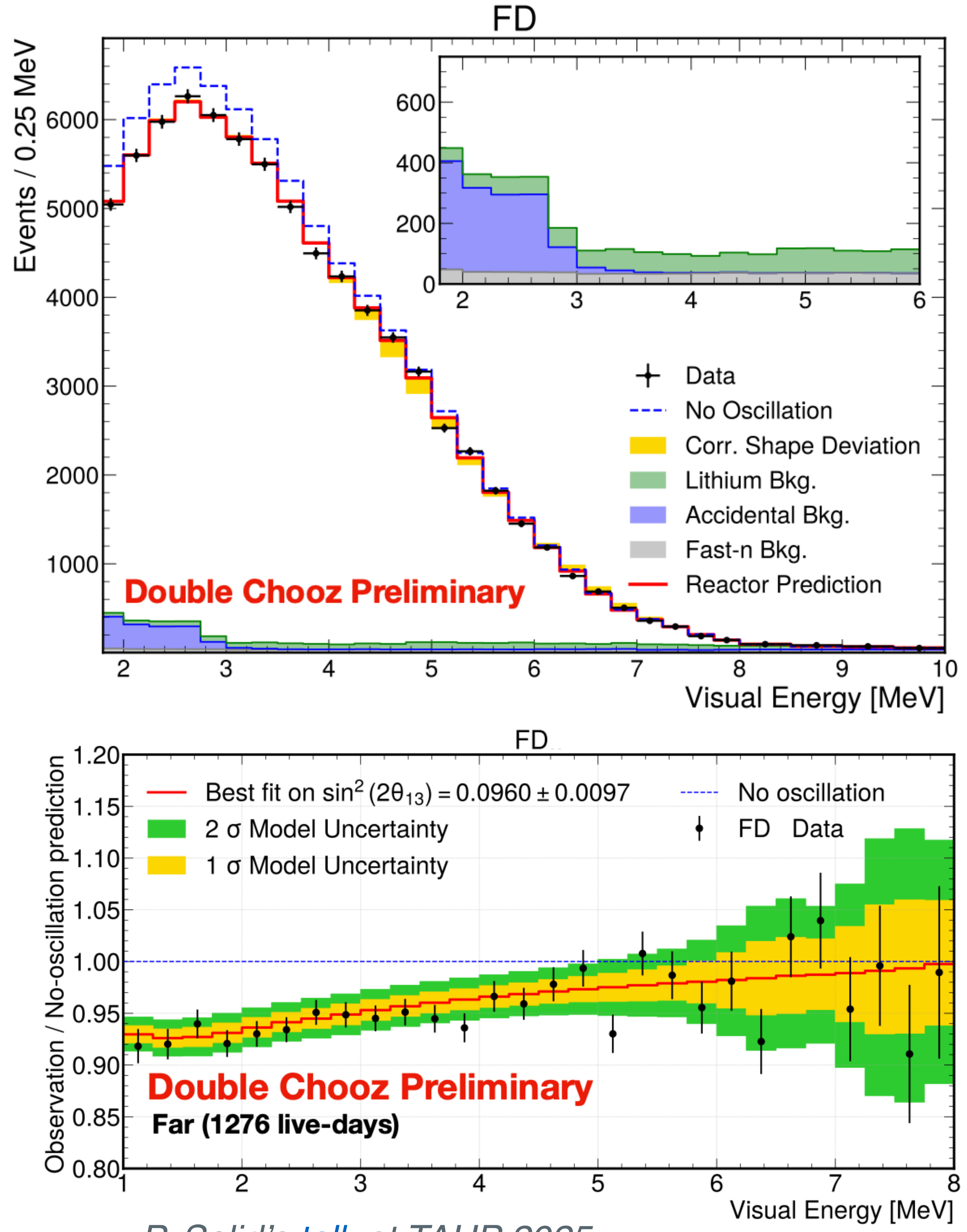
PRL 103, 161802 (2023)

RENO
3800 days of data



PRD 111, 112006 (2025)

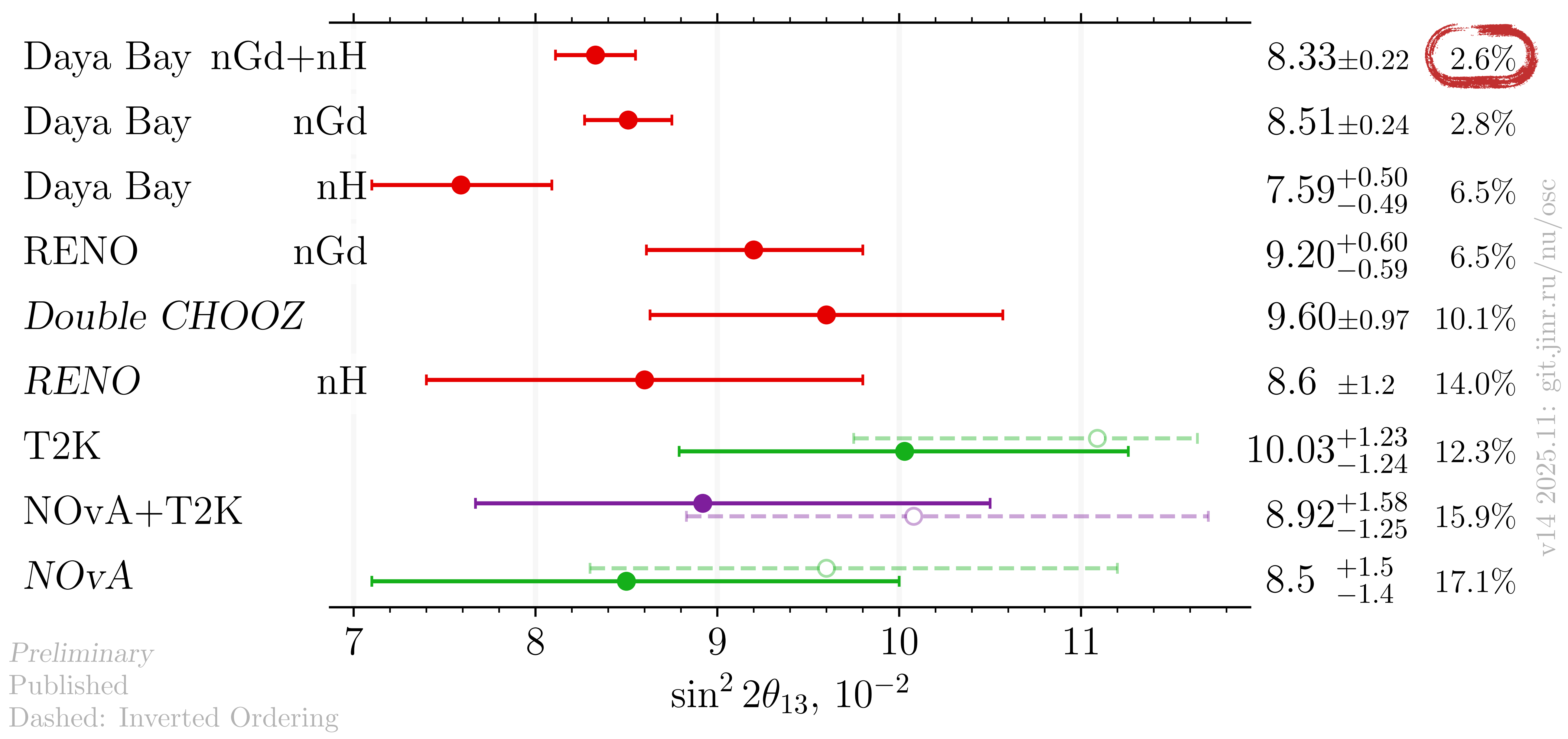
Double Chooz
1276 live-days of data



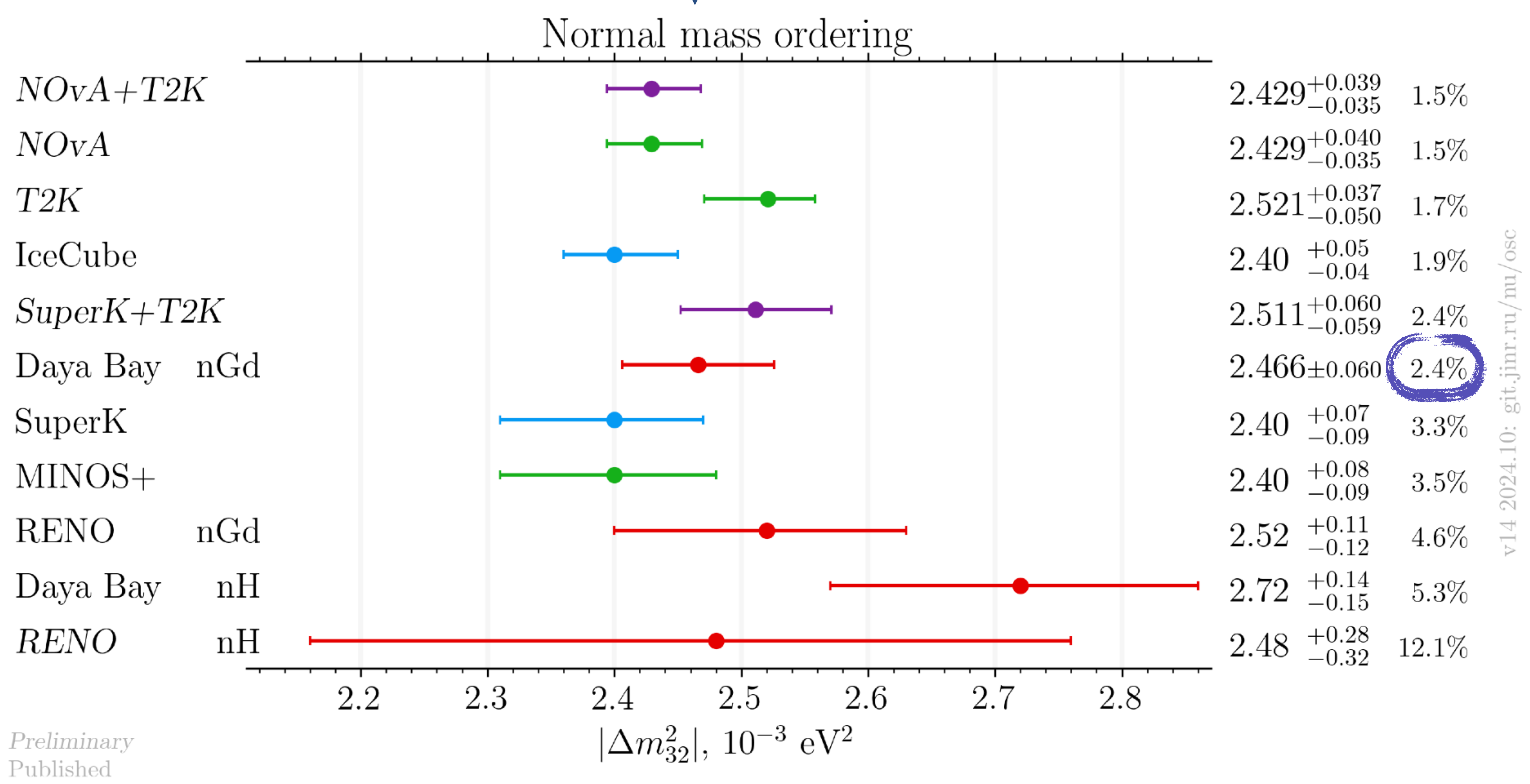
P. Solid's talk at TAUP 2025

Global Landscape for $\sin^2 2\theta_{13}$ and $|\Delta m^2_{32}|$

Current reactor measurements of θ_{13} will likely remain the most precise for a long time



Consistent Results with Accelerator Experiments for $|\Delta m^2_{32}|$

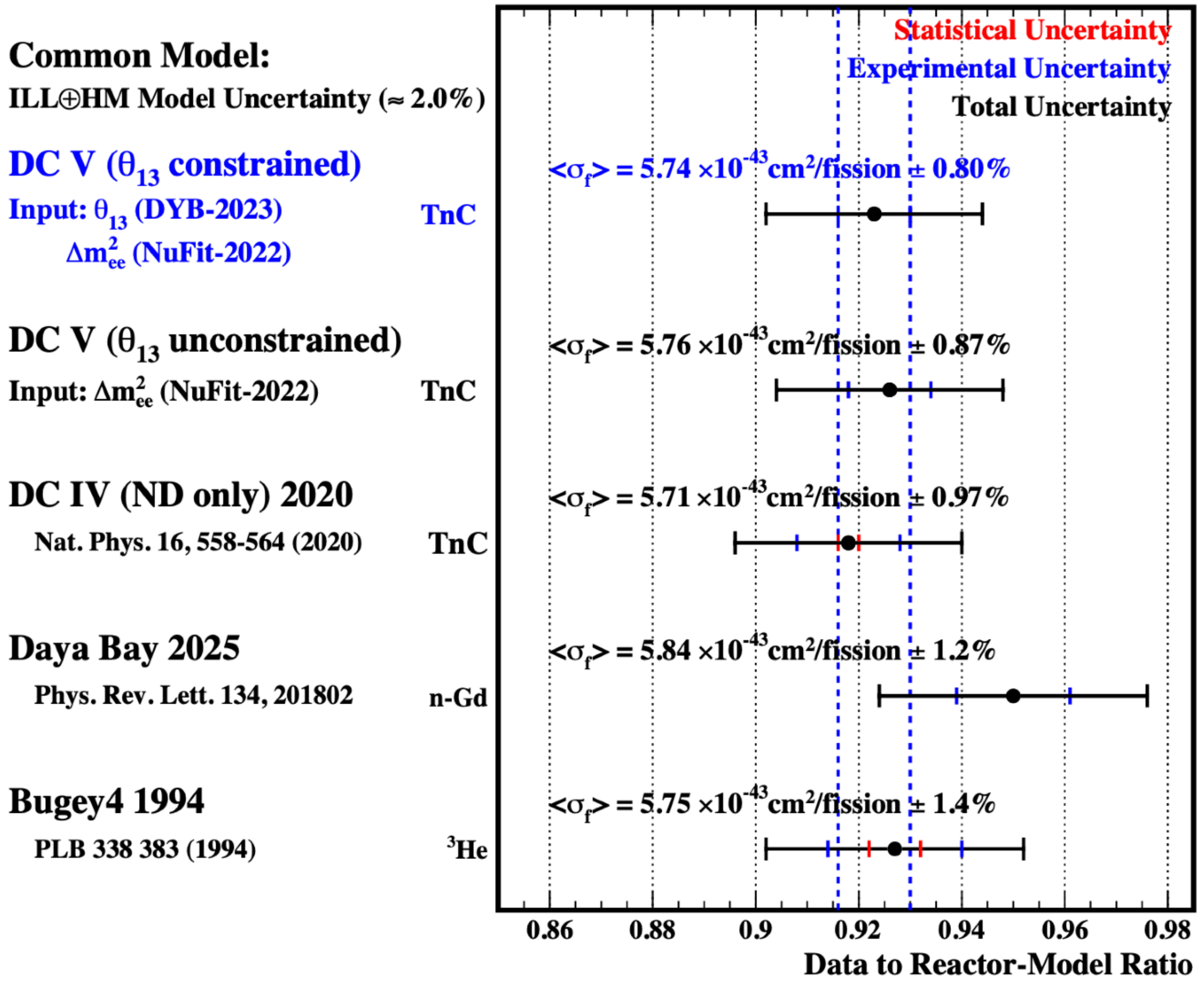


There is a proposal for a next-generation θ_{13} experiment using LiquidO technology called SuperChooz that there is no time to cover

Reactor $\bar{\nu}_e$ Emission Characterization

- Double-Chooz and Daya Bay have recently released new results with their full data sets:

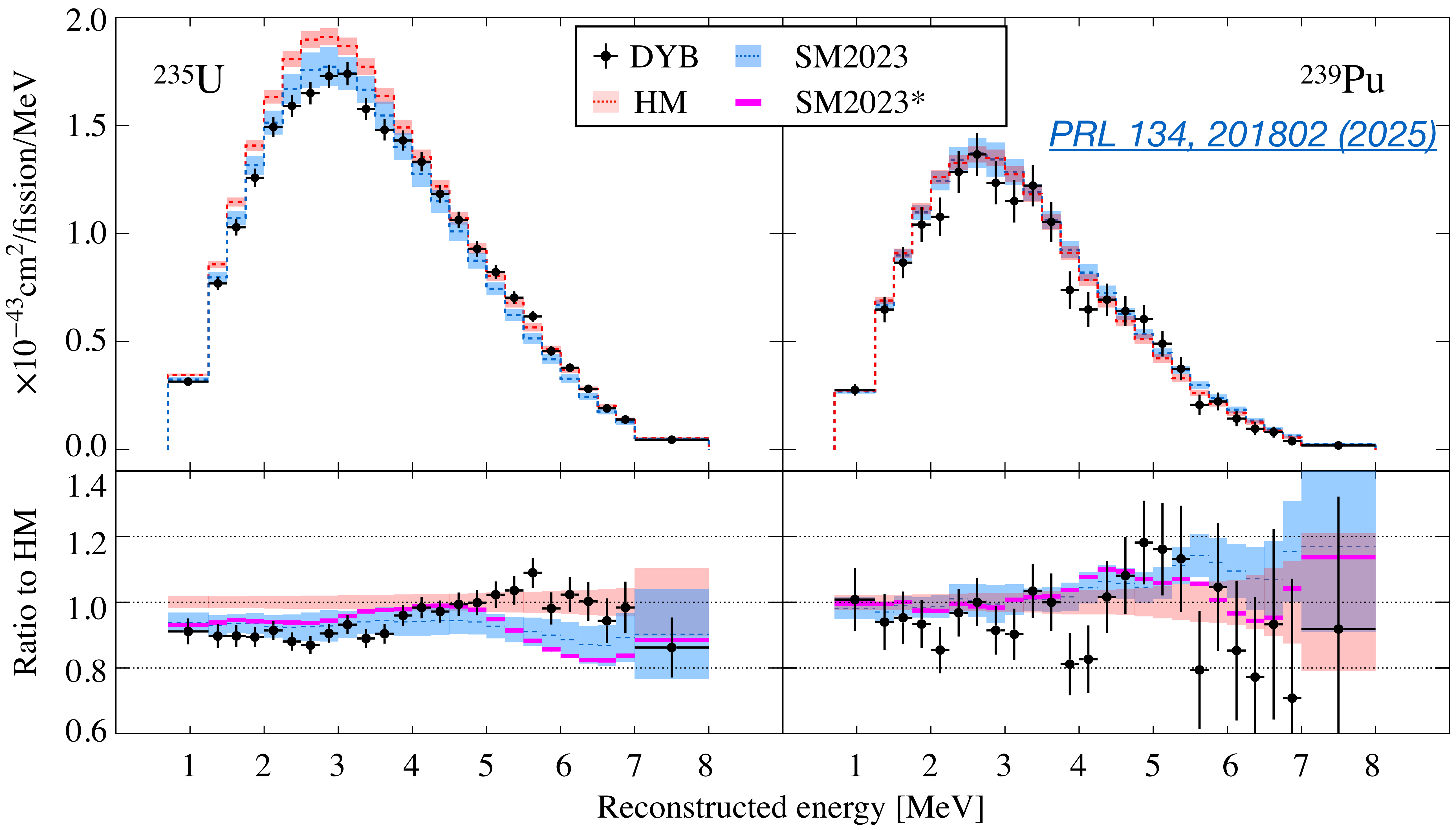
Double Chooz
Most precise IBD yield σ
(0.8% precision)



P. Solid's talk at TAUP 2025

~7% deficit in total flux with respect to the Huber-Mueller (HM) model at short baselines is known as the "Reactor Antineutrino Anomaly" (RAA)

Daya Bay
Most precise total, ^{235}U and ^{239}Pu spectra
(1.3%, 3% and 8% precision at 3 MeV, respectively)



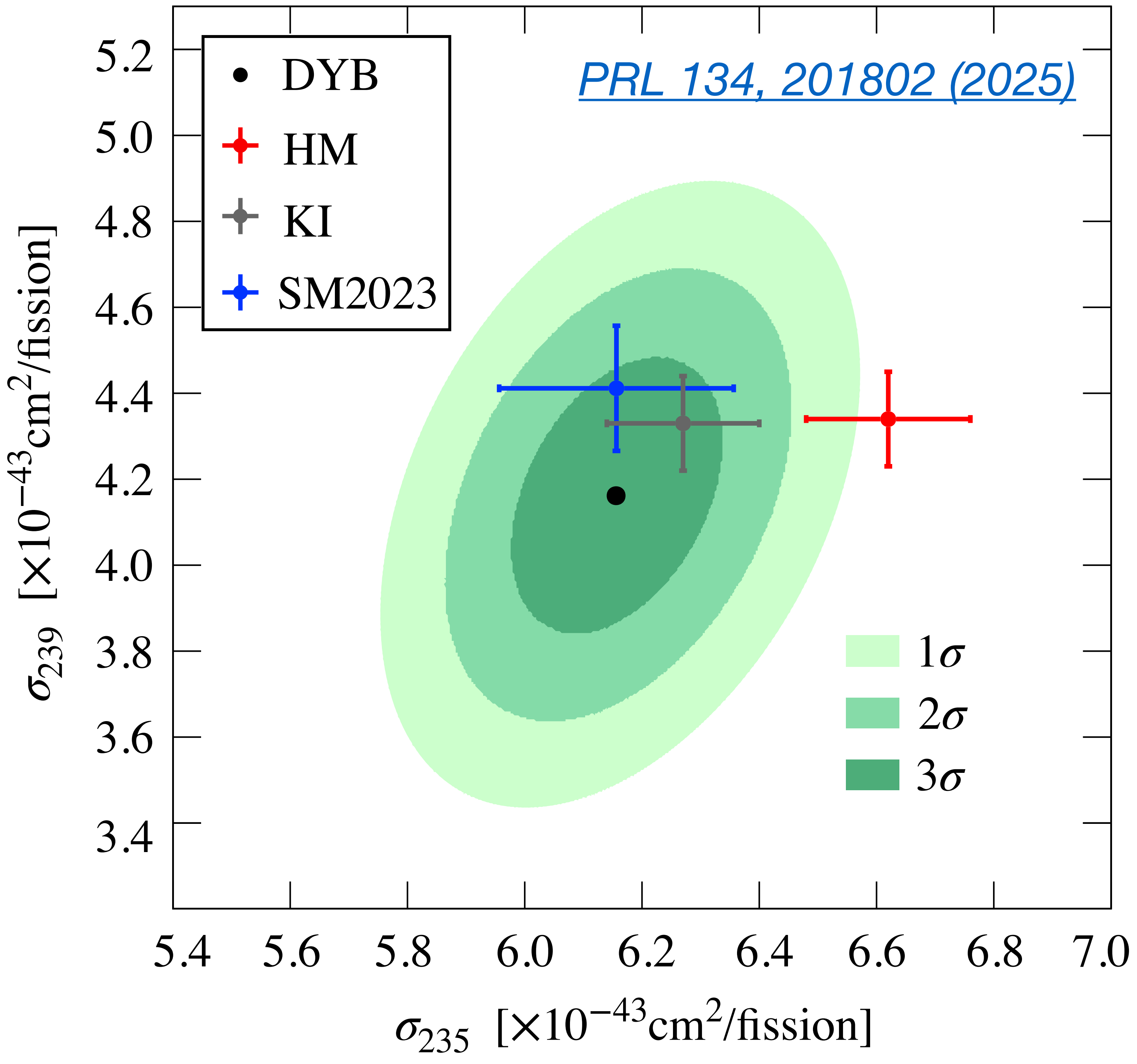
PRL 134, 201802 (2025)

Reminder: in LEU reactors, fissions originate from ^{235}U, ^{239}Pu, ^{241}Pu and ^{238}U fissions

The RAA and Sterile Neutrinos

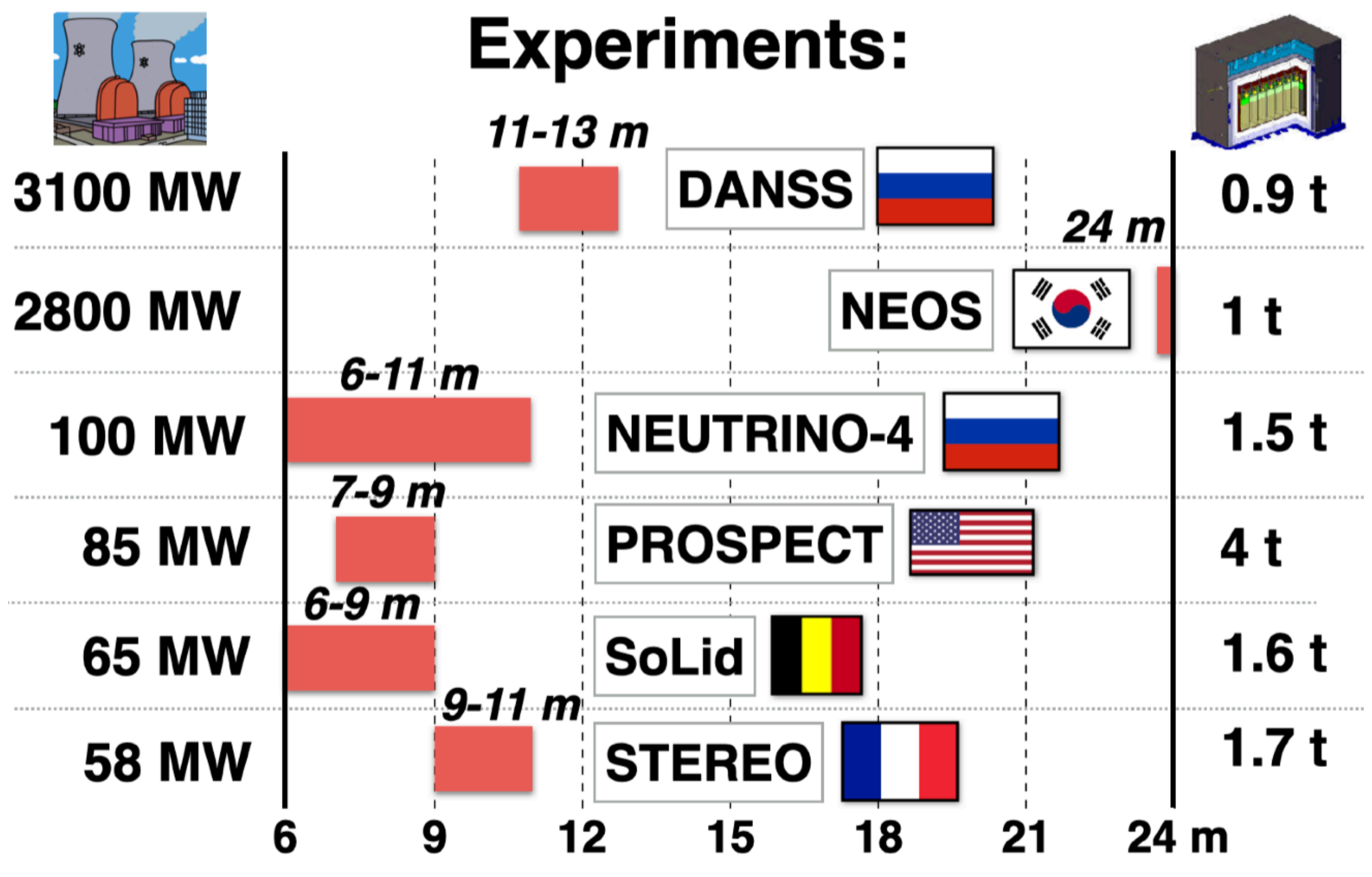
- Sterile neutrino hypothesis as explanation of RAA remains disfavored:

Daya Bay
^{239}Pu vs. ^{235}U IBD yields



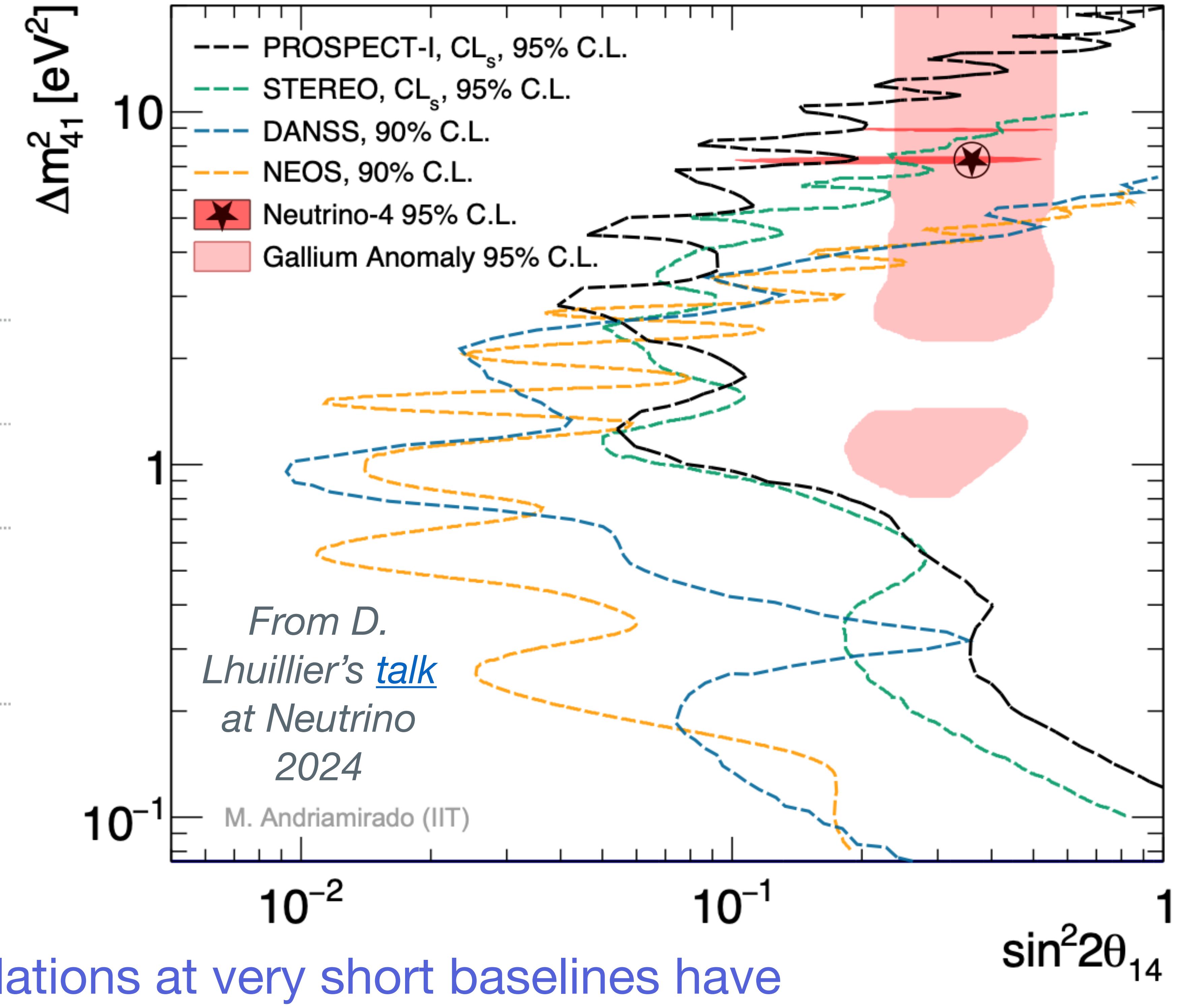
All isotopes as contributors to RAA disfavored at 1.4σ

Short-Baseline Reactor Neutrino Program



(chart courtesy of B. Roskovec)

Sterile Neutrino Searches at Short Baselines



Experiments searching for oscillations at very short baselines have mostly come up empty handed. There is a claim from Neutrino-4 that is in $> 5\sigma$ tension with PROSPECT and STEREO

Next Generation

of Reactor Neutrino Experiments

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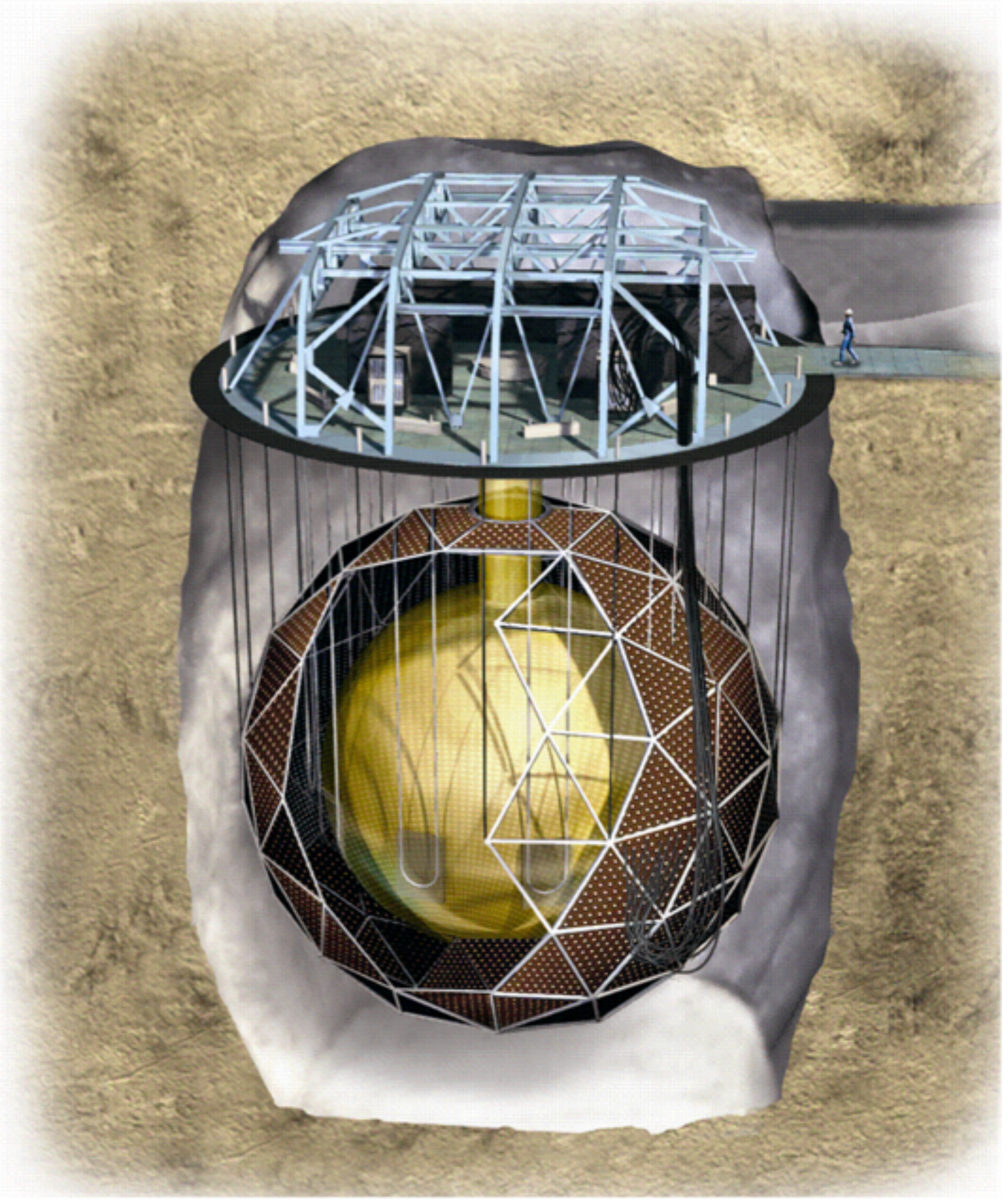
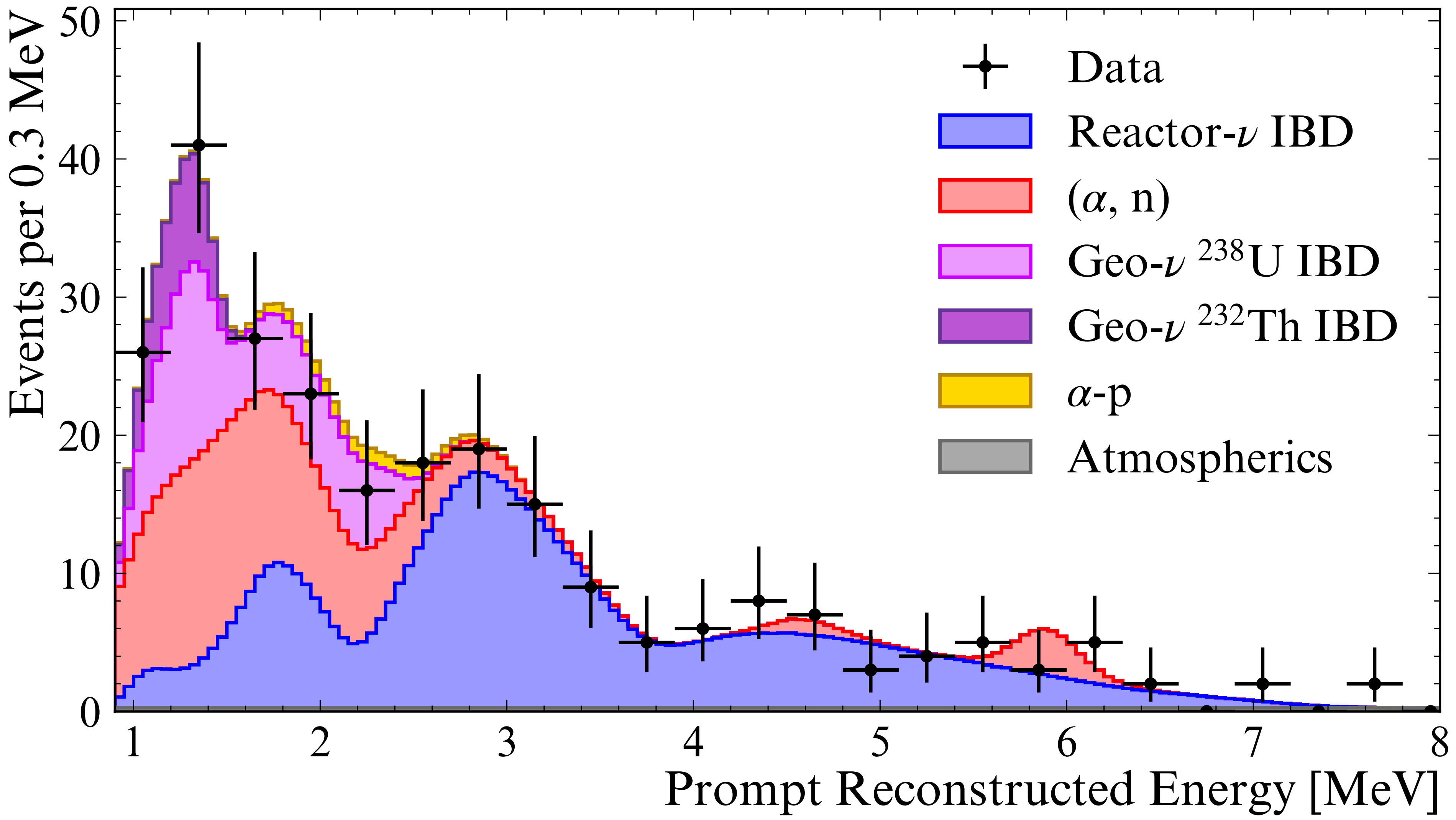
Reactor Antineutrinos in SNO+

- SNO+ is a multi-purpose liquid scintillator detector at SNOLAB in Canada



  - Same as SNO but filled with liquid scintillator (LS) instead of heavy water
  - 2.1 km underground, 9362 PMTs, 0.780 kton of LS
  - 60% of reactor $\bar{\nu}_e$'s from three nuclear complexes in Ontario at 240 km, 350 km and 355 km



SNO+

Data from May 2022 to July 2025

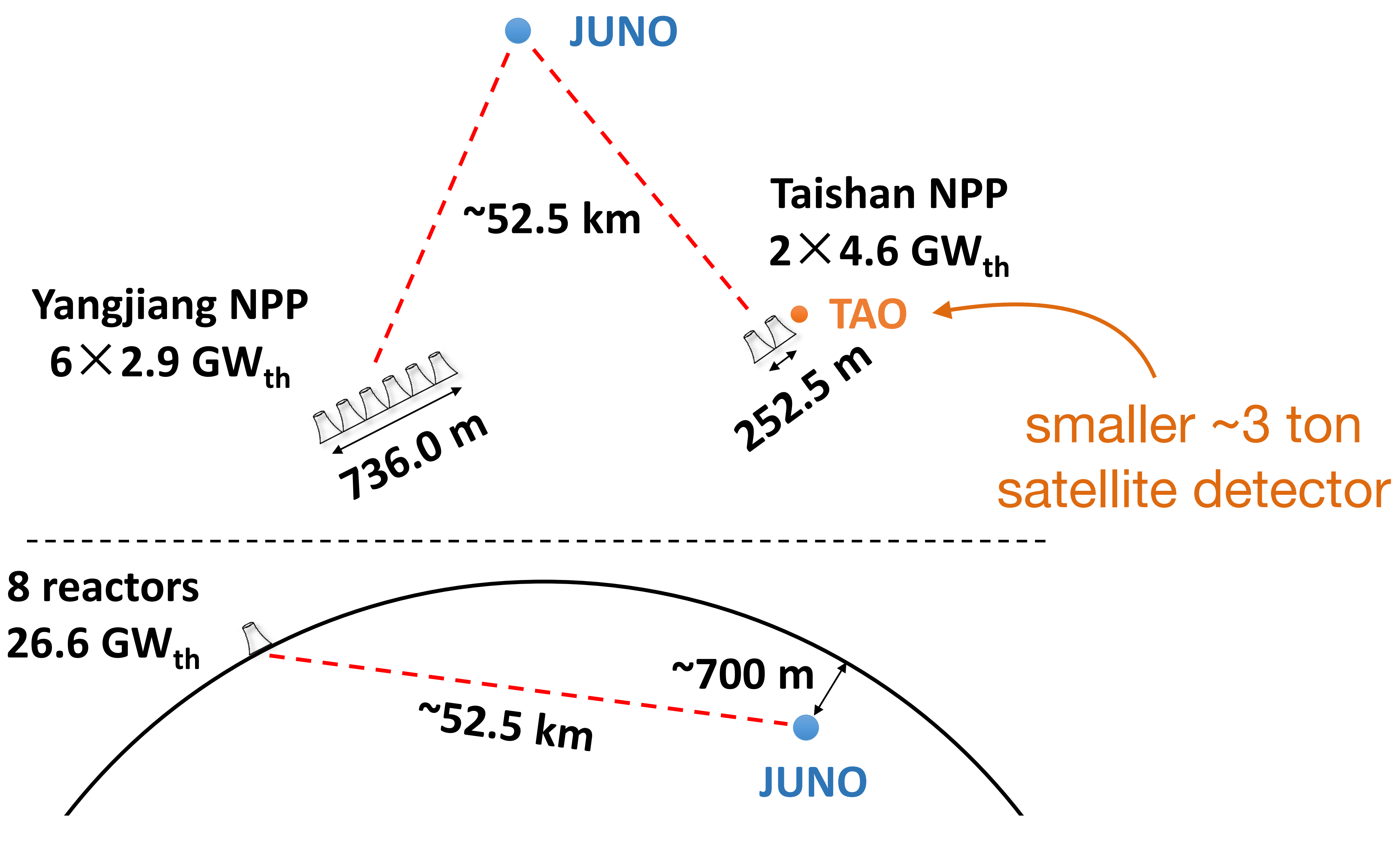
	Fit
Δm^2_{21} [$\times 10^{-5}$eV^2]	$7.93^{+0.21}_{-0.24}$
$\sin^2\theta_{12}$	0.505 ± 0.134
Geo-$\bar{\nu}$ [TNU]	60^{+23}_{-22}
Geo-$\bar{\nu}$ U/Th	$3.38^{+1.39}_{-1.41}$

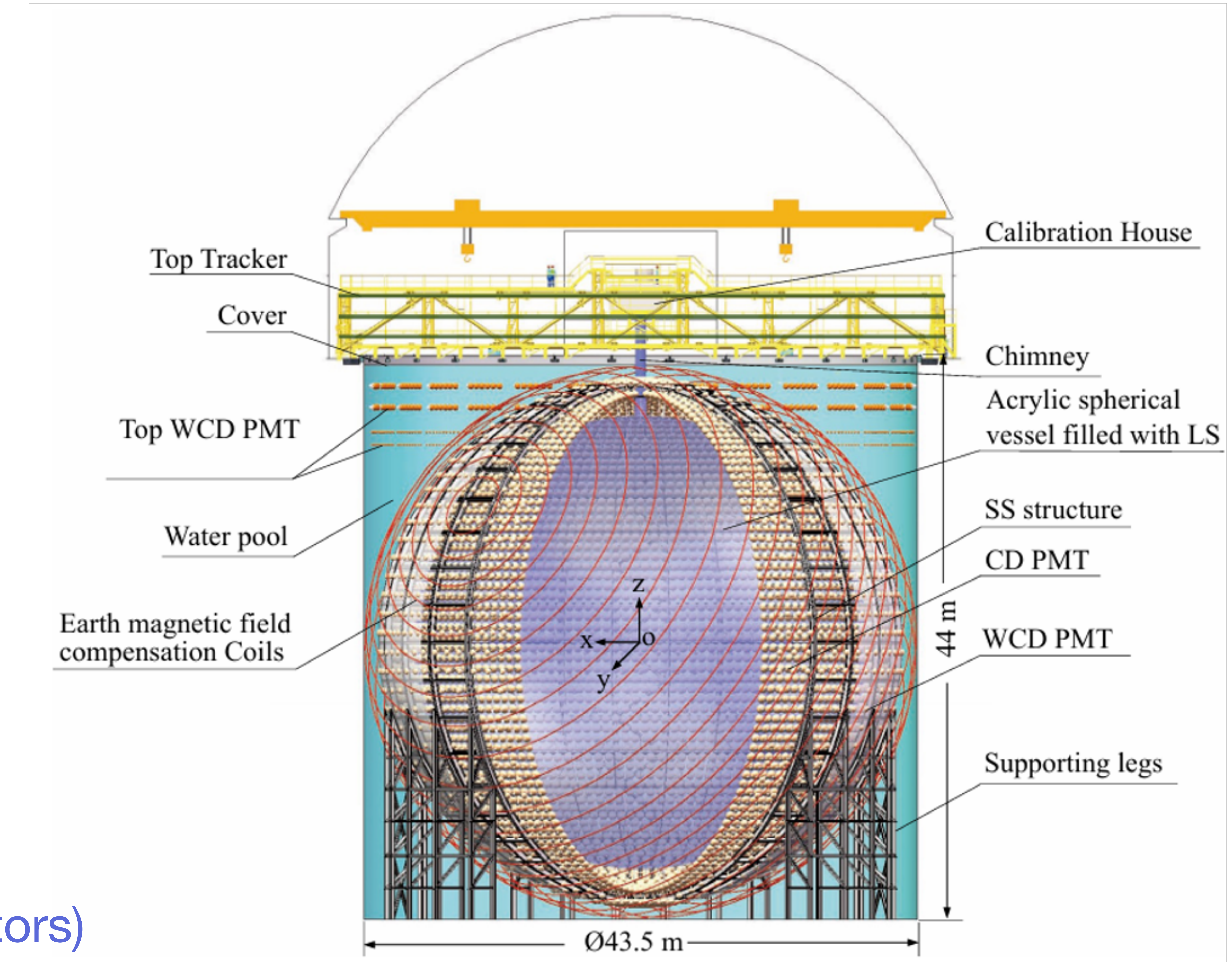
arXiv:2511.11856

JUNO at a Glance

Details about the experiment were provided by Luca Pelicci on Monday

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



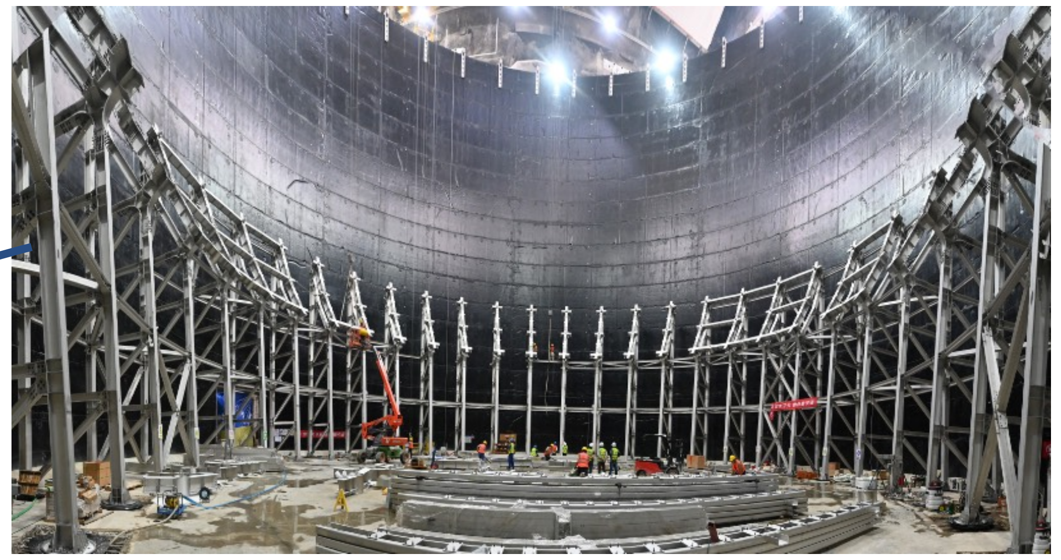


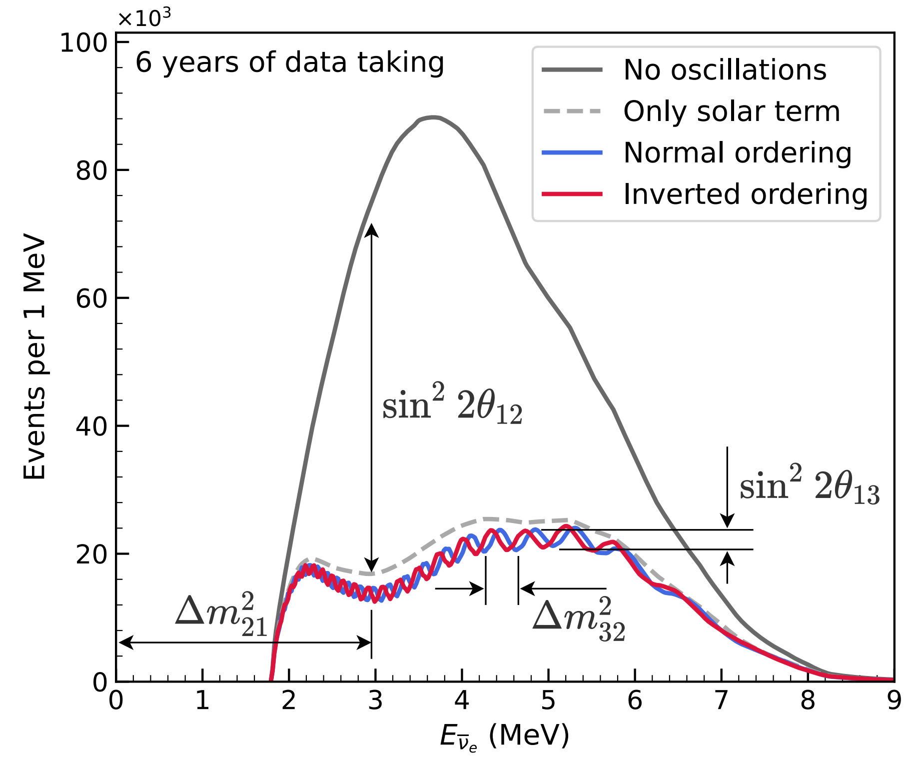
- 52.5 km from two major nuclear power plants (8 reactors)
- 35 m diameter sphere with 20 ktons of liquid scintillator (LS) surrounded by water Cherenkov detector
- Unprecedented energy resolution of 3% at 1 MeV

A Long Journey

Tunnel Digging

Start of Detector Installation



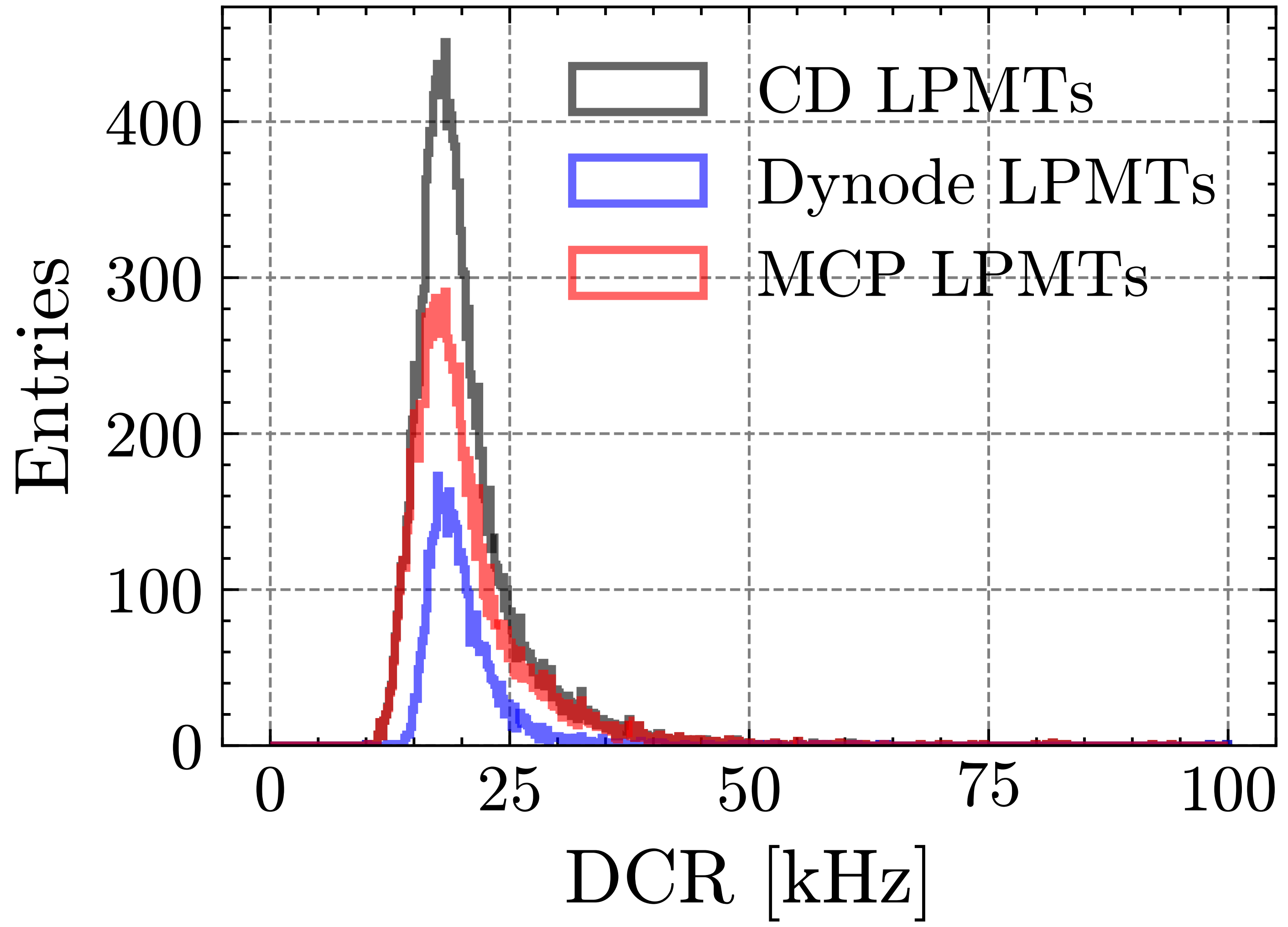


- **2013** — **Project start**
- **2015** — **Start of civil construction**
- **2022** — **Beginning of detector installation**
- **Dec 2024** — **End of detector installation**
- water filling
- **Feb 2024** — **End of water filling**
- LS filling
- **Aug 2025** — **End of LS filling**
- physics data
- **November 19, 2025** — **First Results Announced!**

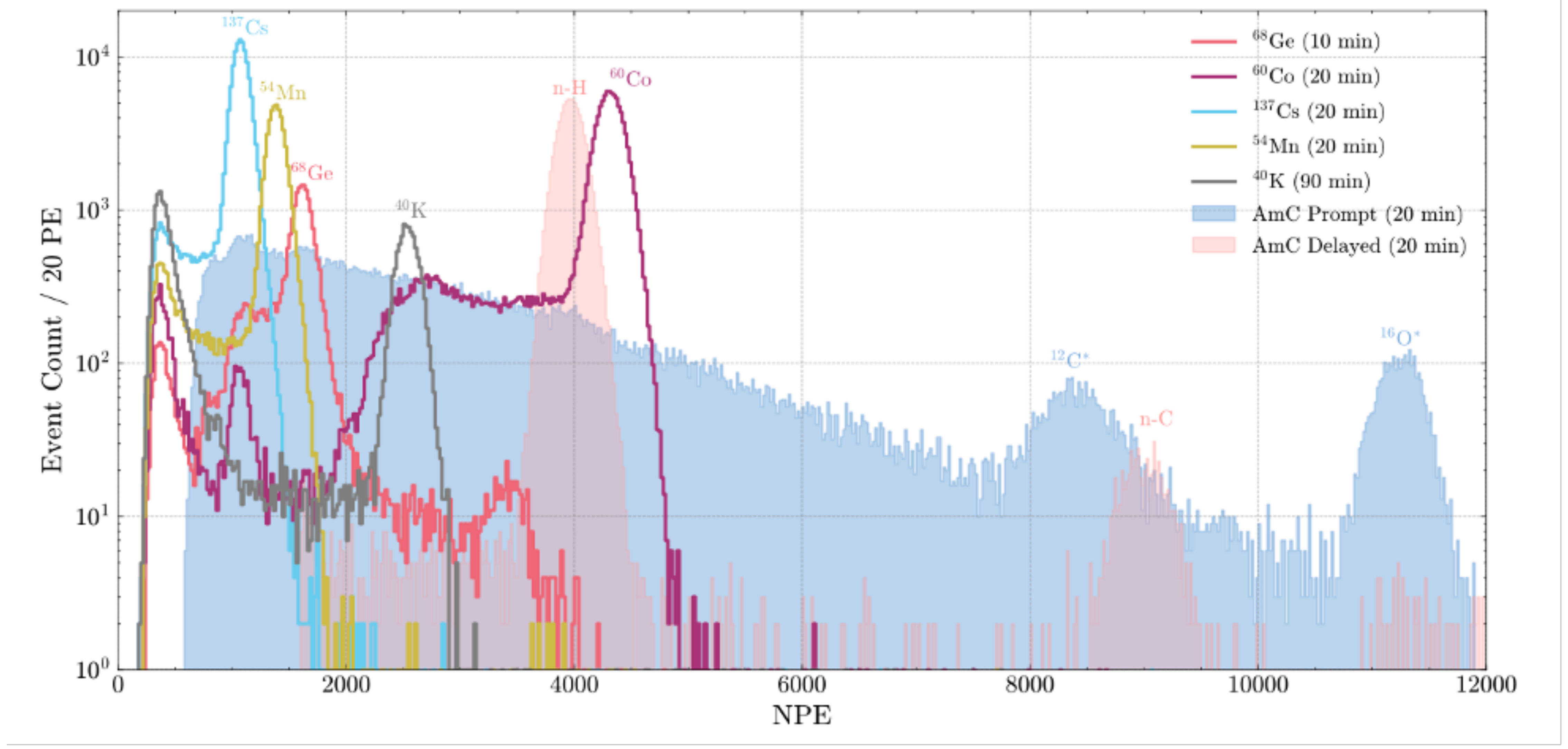
Low-Level Detector Performance

[arXiv:2511.14590]

- Large PMTs (LPMTs):
  - Lost 16 LPMTs during installation in the Central Detector (CD)
  - As of now, have lost an additional 22 LPMTs (0.1%)
  - Approximately 300 large PMTs flashing at any one time
  - 20.6 kHz and 22.7 kHz of Dark Count Rate (DCR) for dynode and MPC-PMTs, respectively
- Electronics:
  - Low noise levels (roughly 0.055 PE)
  - Threshold at 0.2-0.3 PE
- Trigger:
  - Threshold at 200 keV
- Calibration:
  - Multiple artificial calibration sources deployed around central axis (1D) and in 2D plane

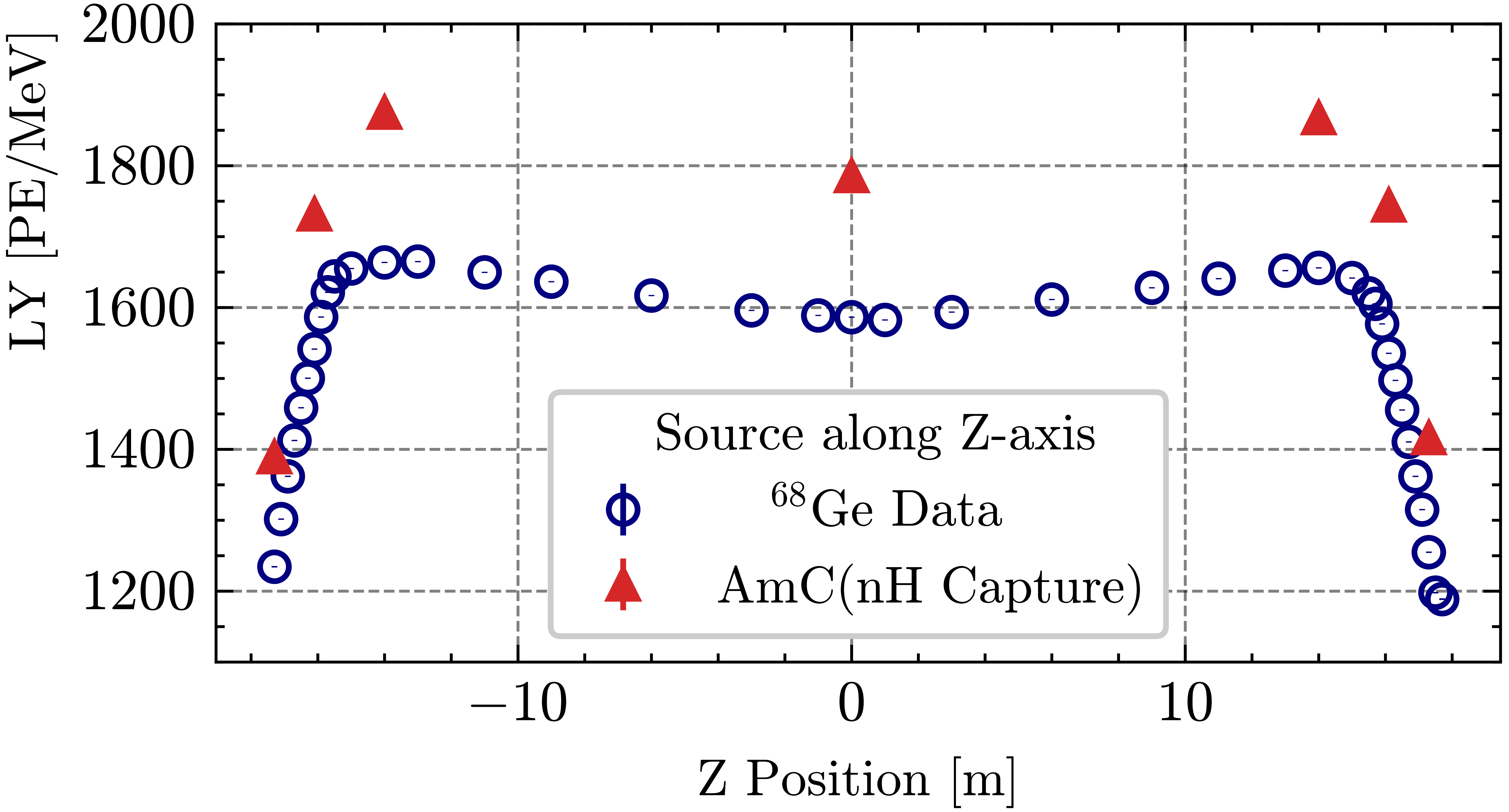


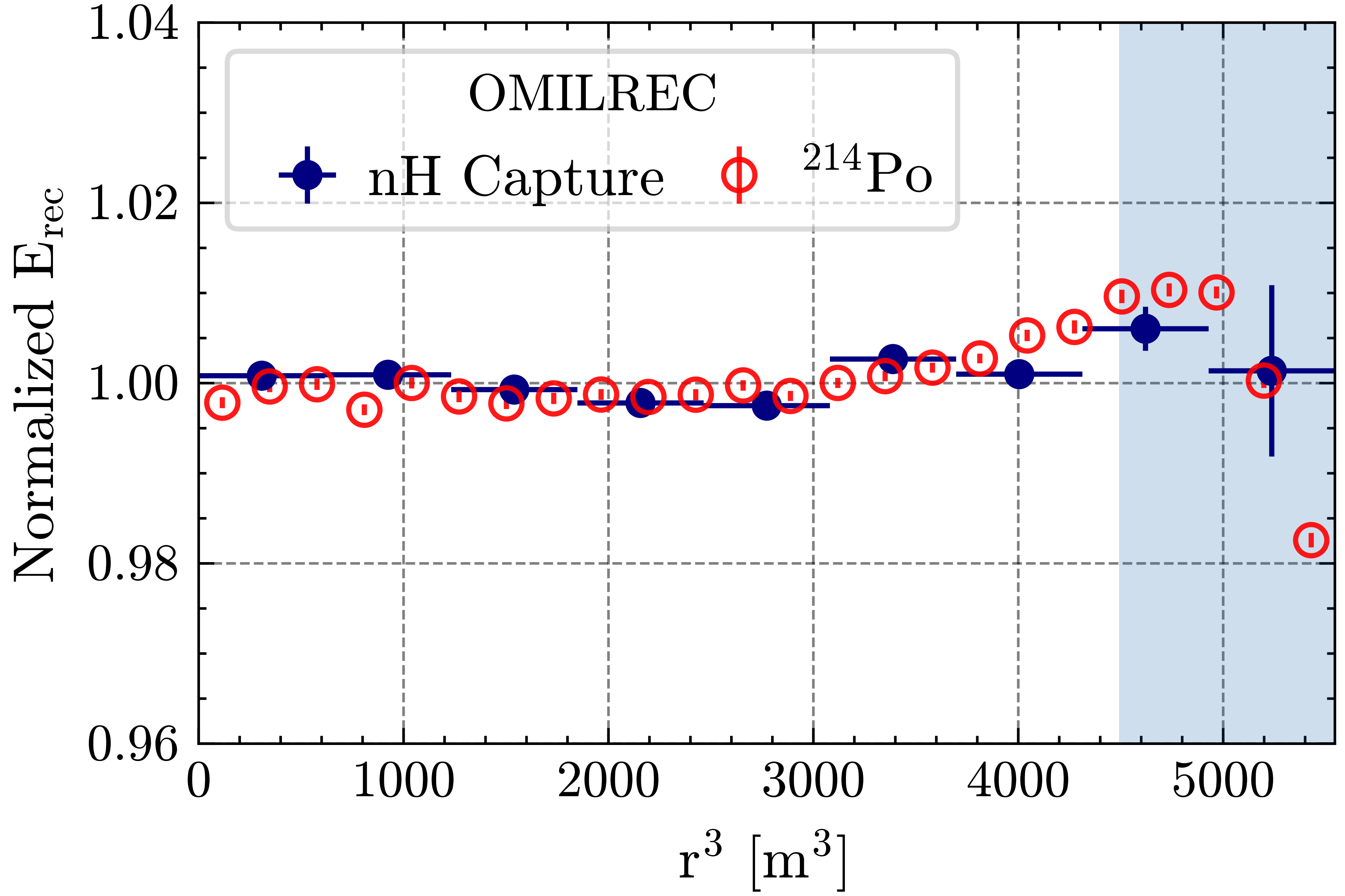
Charge distribution (total PE) of calibration points after DCR subtraction



Light-Yield and Residual Non-Uniformity

- Light-yield and residual non-uniformity are essential to achieve the target energy resolution for the mass ordering measurement
  - See **~1600 PE/MeV** with ^{68}Ge and **~1780 PE/MeV** for nH capture throughout most of the fiducial volume, higher than design
  - Residual non-uniformity is well **within ±1%** in the r<16.5 fiducial volume



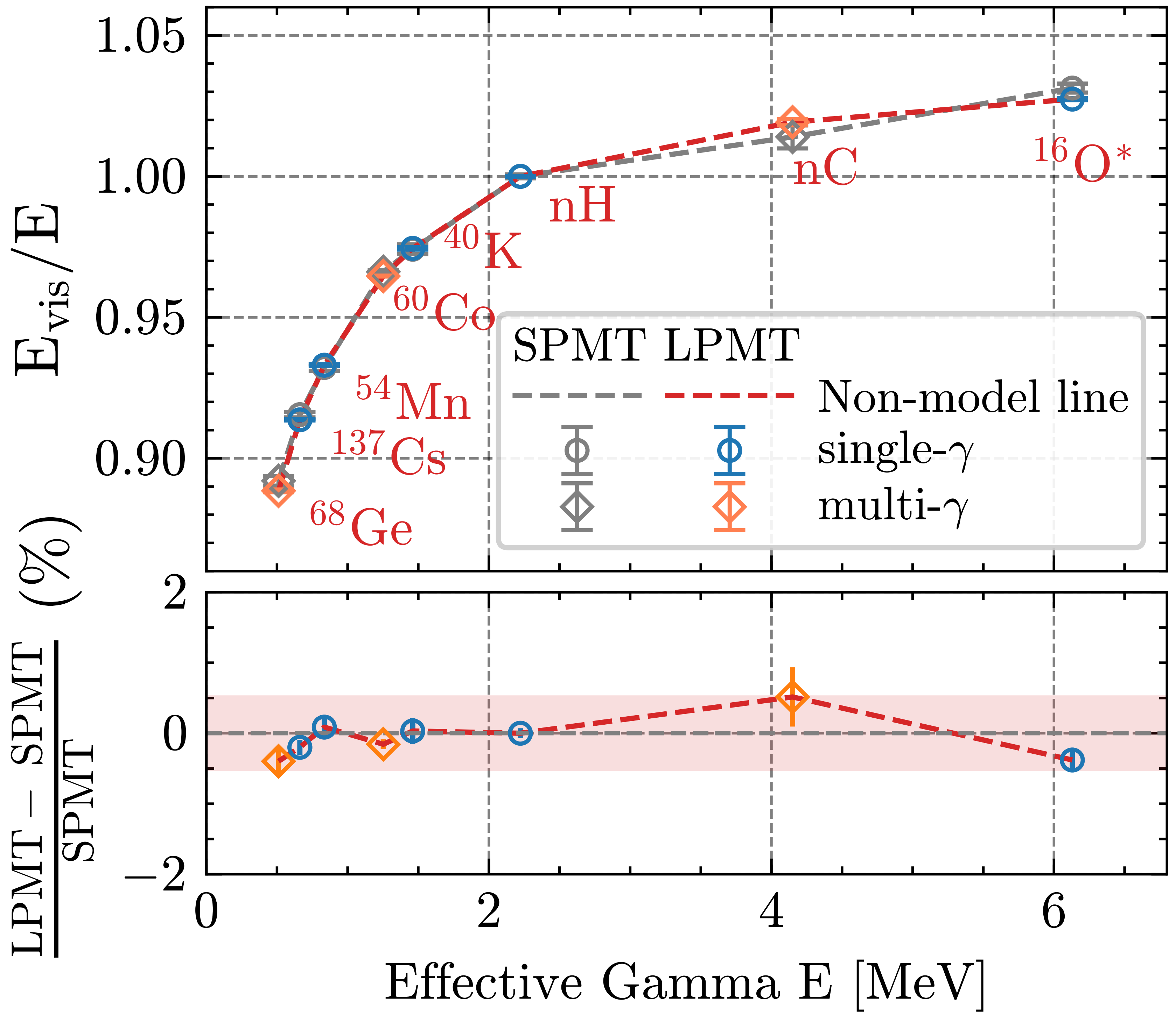


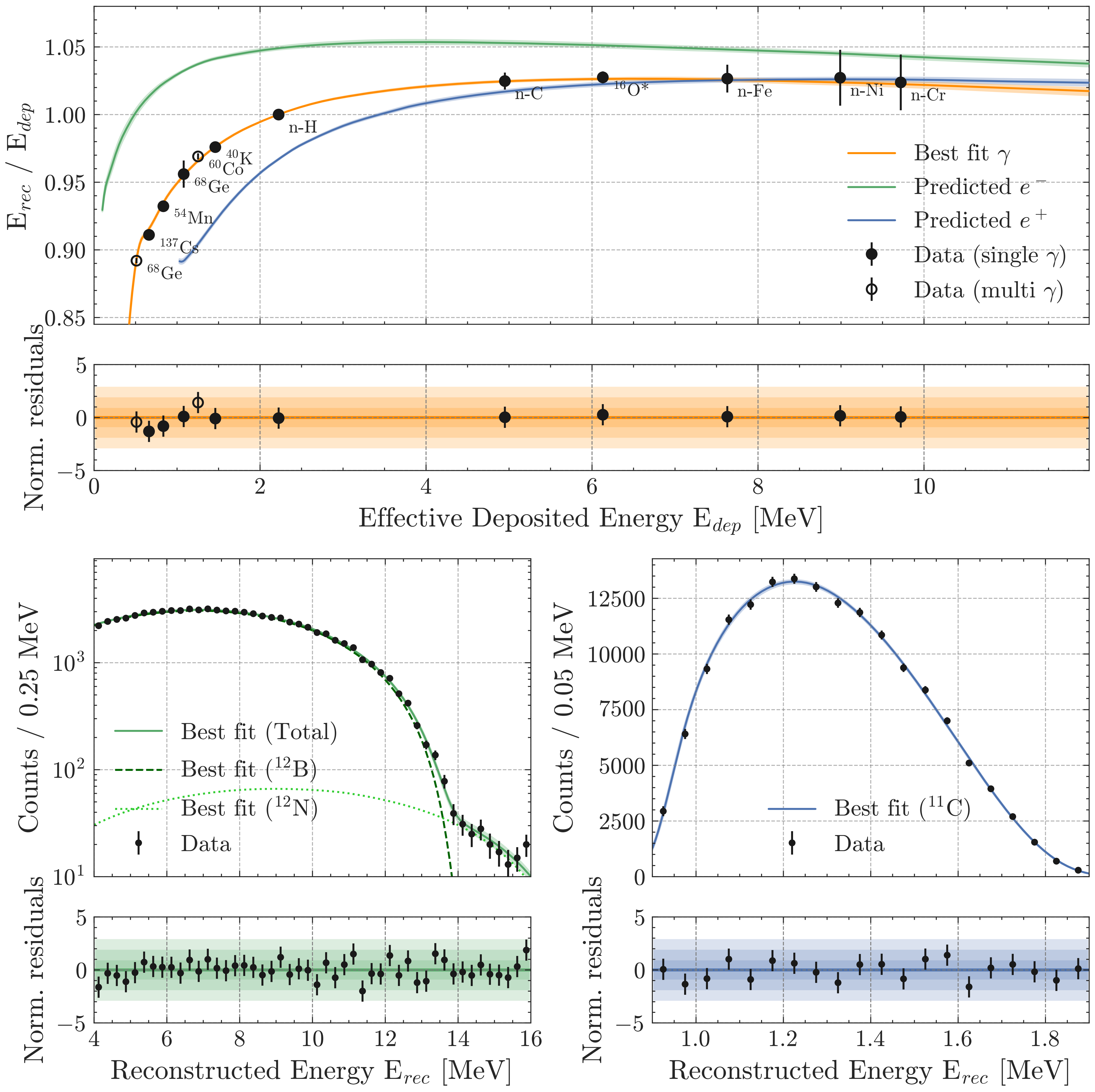
arXiv:2511.14590

Energy Non-Linearity

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

- Energy non-linearity (NL) characterized to better than **1% precision**
  - Good agreement between NL measured with LPMTs and small PMTs (which are virtually linear)





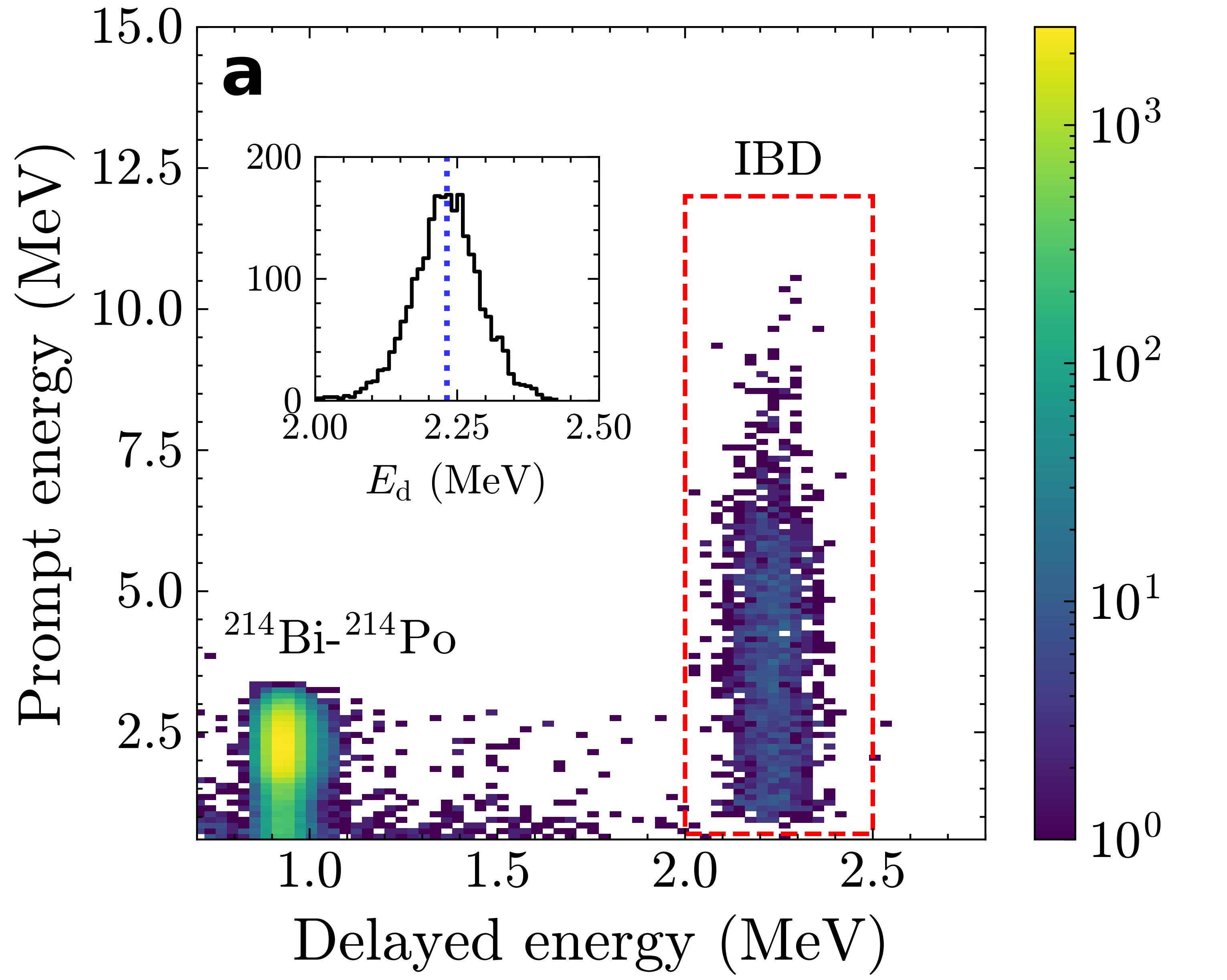
IBD Selection

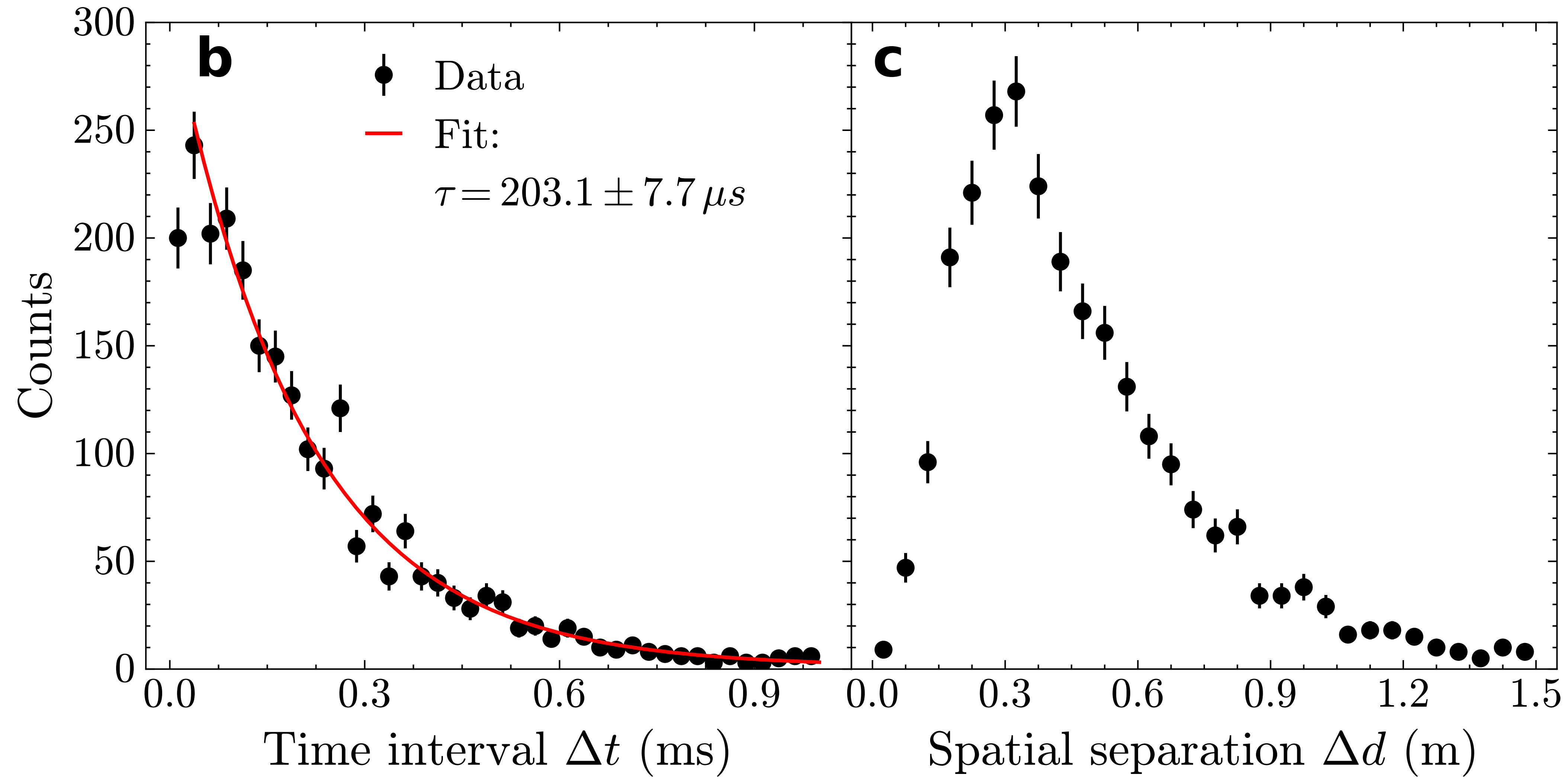
- 59.1 days of good data:
  - From August 30th to November 2nd
- Exploit temporal and spatial coincidence of prompt and delayed events to extract signal
  - Muon and multiplicity vetos
  - Energy cut
  - Time (Δt) and space (Δd) coincidence

Antineutrinos ($\overline{\nu}_e$) Candidates Summary		
DAQ live time (days)	59.1	
$\overline{\nu}_e$ candidates	2379	
Selection Efficiencies (%)	ε	σ_{rel}
Fiducial volume	80.6	1.6
PMT flasher rejection	>99.9	negligible
μ veto	93.6	negligible
Multiplicity	97.4	negligible
Prompt-delayed coinc.	95.1	0.13
Total efficiency (ε_{tot})	69.9	1.6
$\overline{\nu}_e$ signal (cpd[1])		
w/o ε_{tot} corrected	33.5 ± 1.7	
w/ ε_{tot} corrected	47.9 ± 2.6	
Non-oscillated $\overline{\nu}_e$	150.9 ± 2.7	

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

arXiv:2511.14593



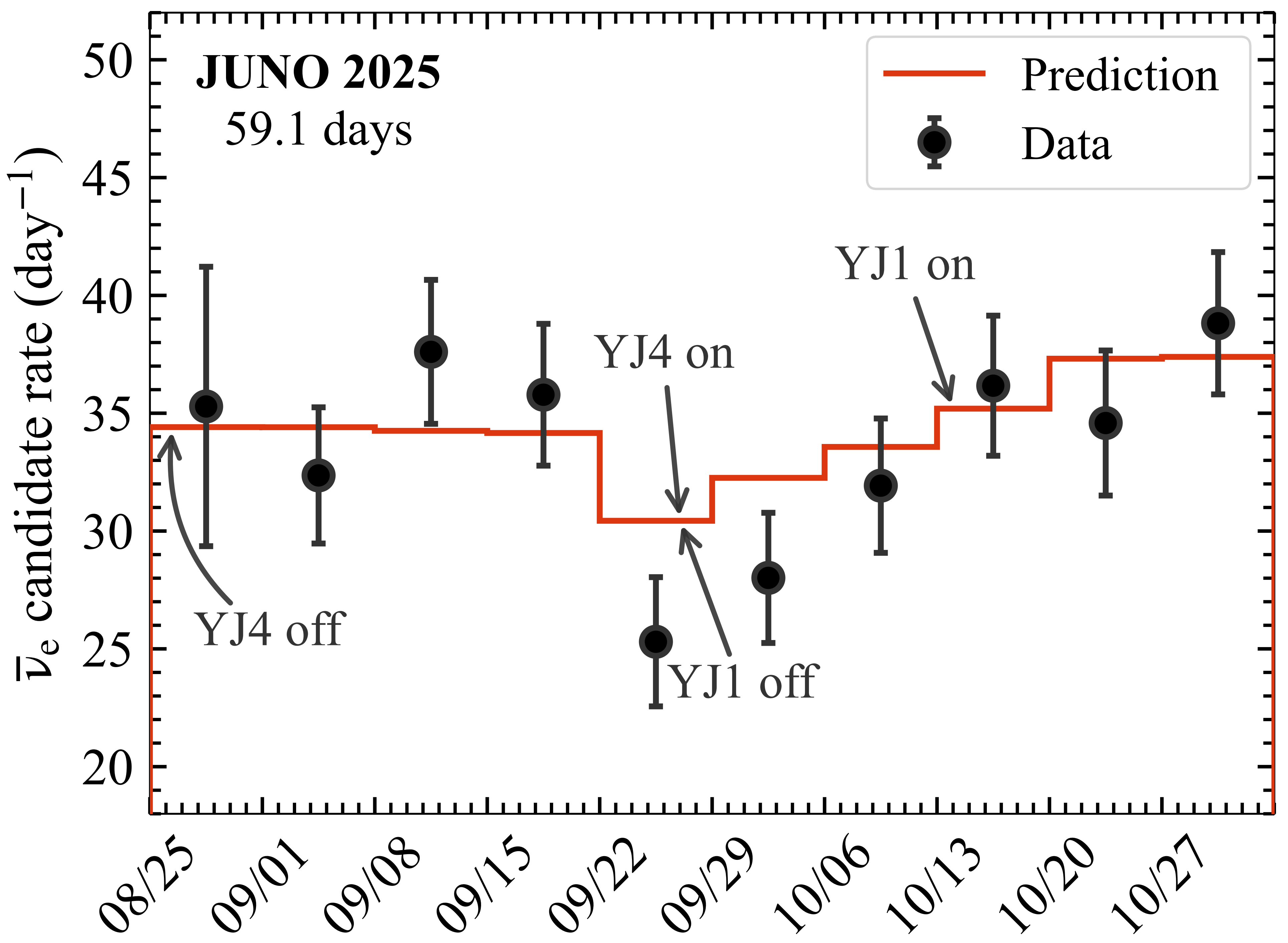


Backgrounds

- Backgrounds amount to **~14%** of reactor IBDs
- Main backgrounds:
  - Correlated $\beta - n$ signals from decay of long-lived ^{9}Li/^{8}He
  - Geo-neutrinos: emitted from the decay of U and Th in the Earth
  - Neutrinos from other nuclear power plants (World reactors)

Backgrounds (cpd)	Pre-fit	Best-fit
^{9}Li/^{8}He	4.3 ± 1.4	3.9 ± 0.6
Geoneutrinos	1.2 ± 0.5	1.4 ± 0.4
World reactors	0.88 ± 0.09	0.88 ± 0.09
^{214}Bi-^{214}Po	0.18 ± 0.10	0.20 ± 0.10
^{13}C$(\alpha$, n$)^{16}$O	0.04 ± 0.02	0.04 ± 0.02
Fast neutrons	0.02 ± 0.02	0.02 ± 0.02
Double neutrons	0.05 ± 0.05	0.07 ± 0.05
Atmospheric neutrinos	0.08 ± 0.04	0.07 ± 0.04
Accidentals $(\times 10^{-2})$	4.9 ± 0.3	4.9 ± 0.3

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



Note: YJ stands for Yangjiang, a Nuclear Power Plants with 6 reactors seen by JUNO

First JUNO Results
(presented by Luca Pelicci)

Oscillation Fit

- Consistent results from three independent analyses:
  - Own selections, reconstructions, background estimations, detector response characterizations, and fitting implementation
- Unoscillated $\bar{\nu}_e$ spectrum constrained through joint fit with released Daya Bay data
  - Detector response accounted for individually for JUNO and Daya Bay
- Frequentist analysis with binned χ^2

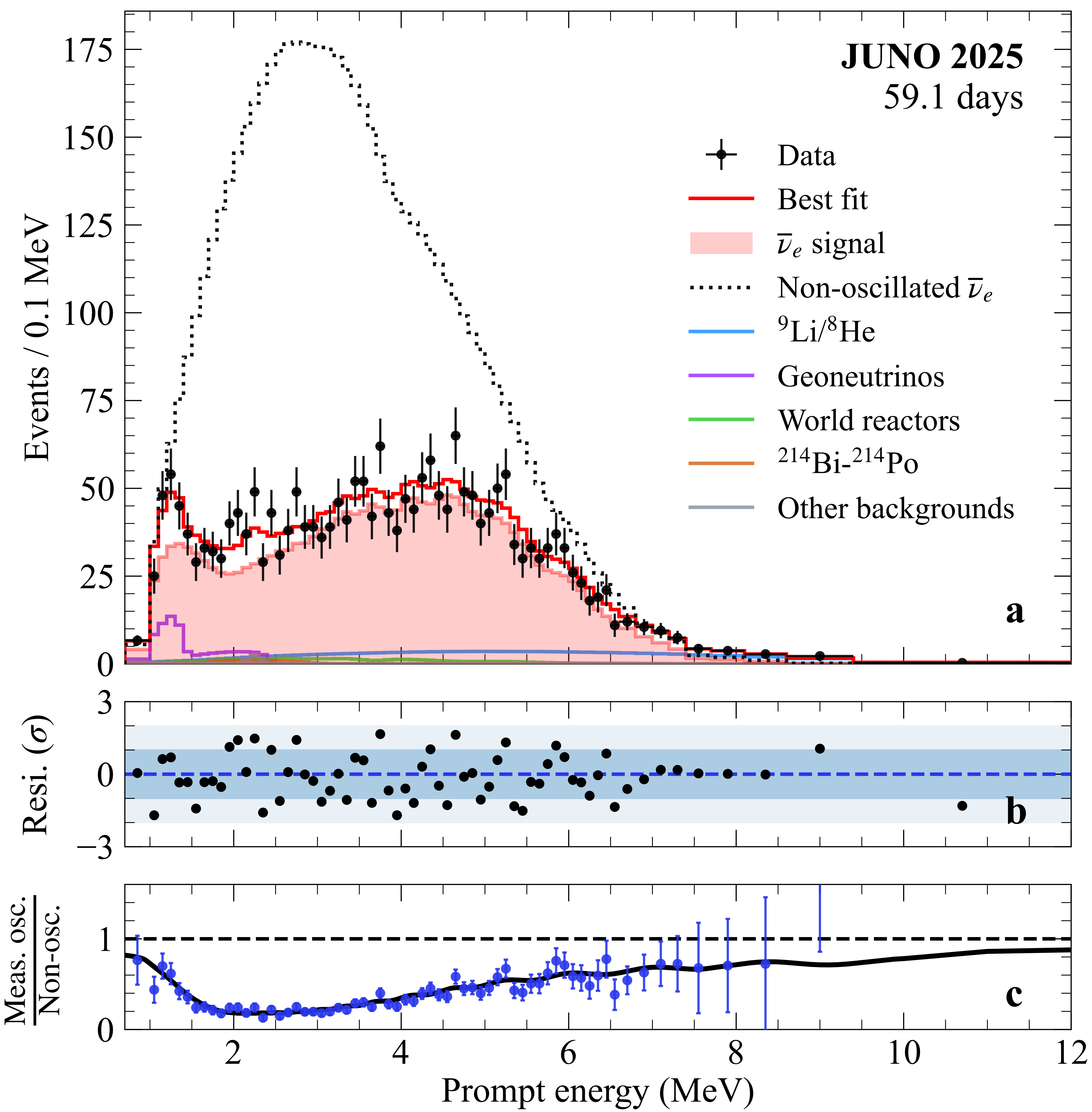
$$\sin^2\theta_{12} = 0.3092 \pm 0.0087 \ (2.81\%)$$

$$\Delta m^2_{21} = (7.50 \pm 0.12) \times 10^{-5}\ \text{eV}^2 \ (1.55\%)$$

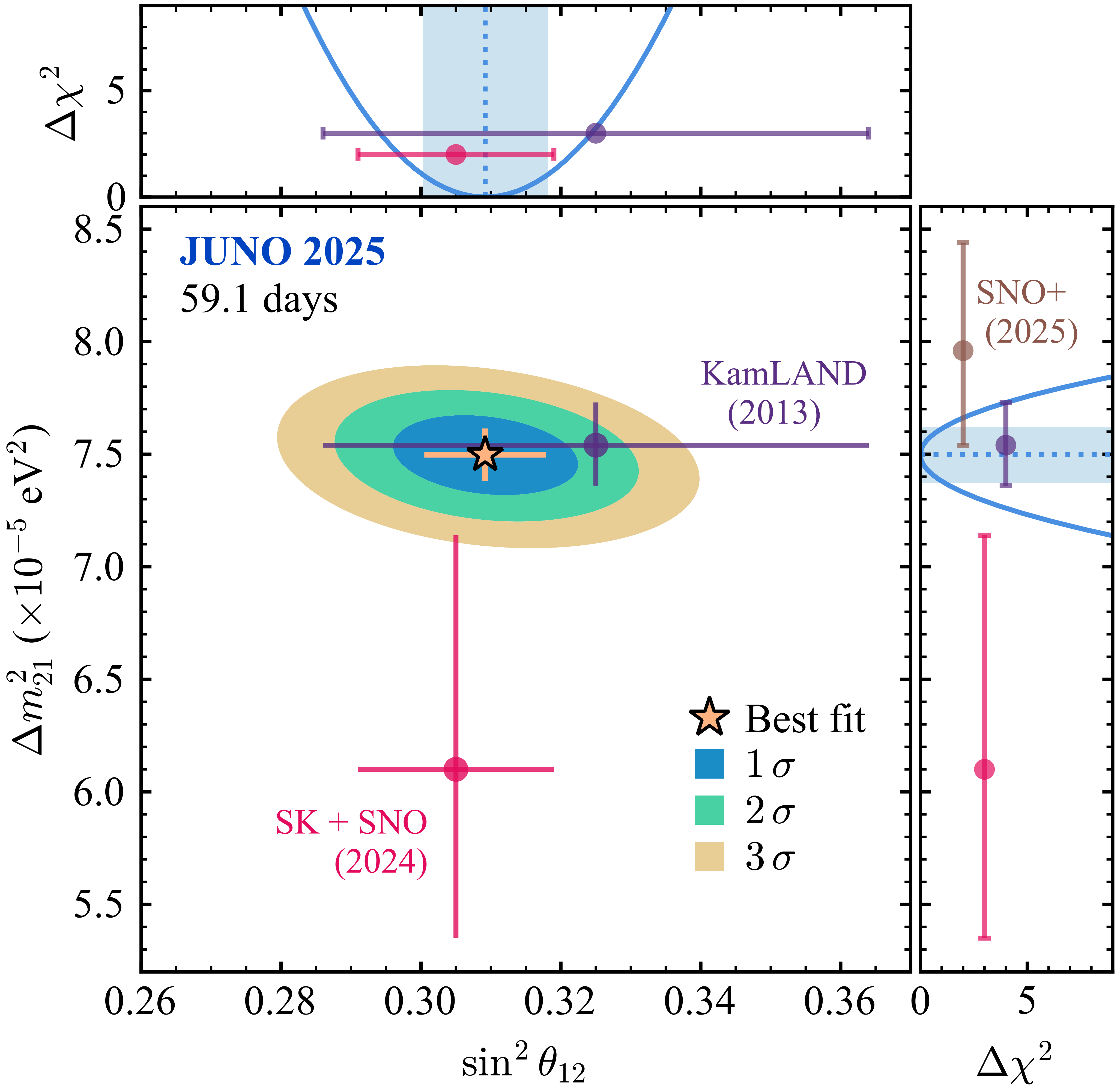
	PDG 2025	JUNO
Δm^2_{21}	2.5%	1.6%
$\sin^2\theta_{12}$	3.9%	2.8%

World leading precision

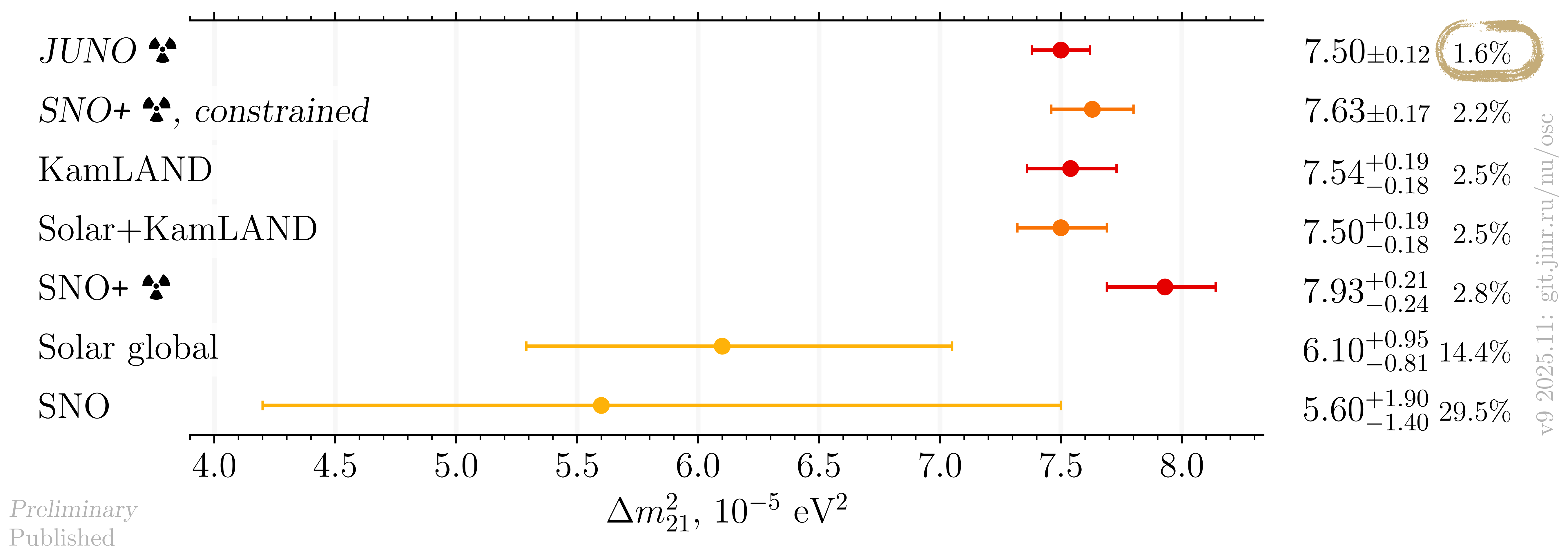
arXiv:2511.14593

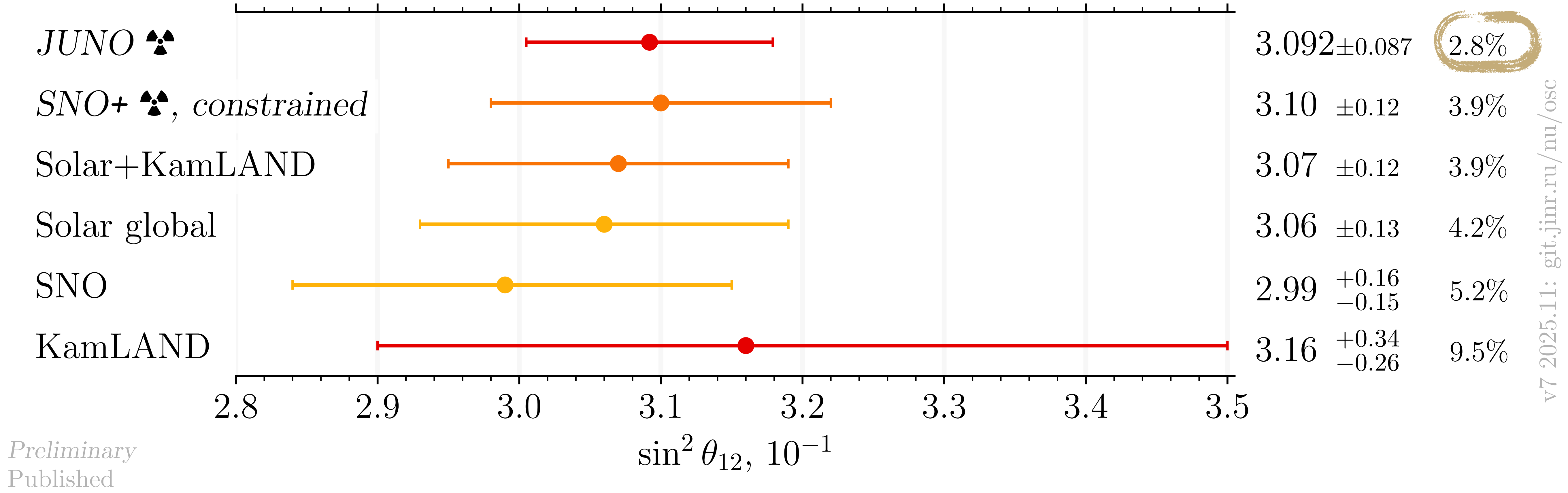


Contours and Global Landscape



[arXiv:2511.14593](https://arxiv.org/abs/2511.14593)

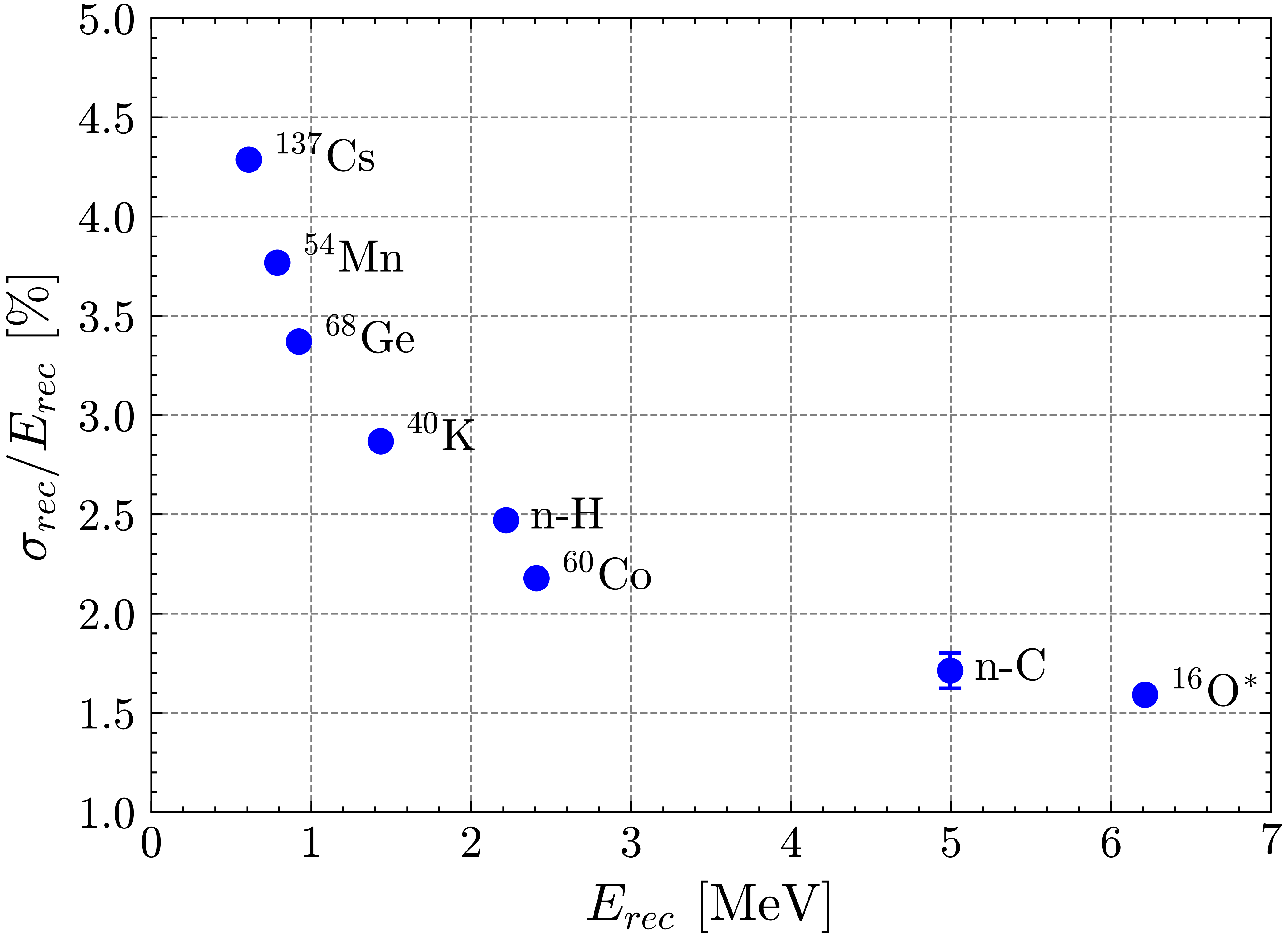


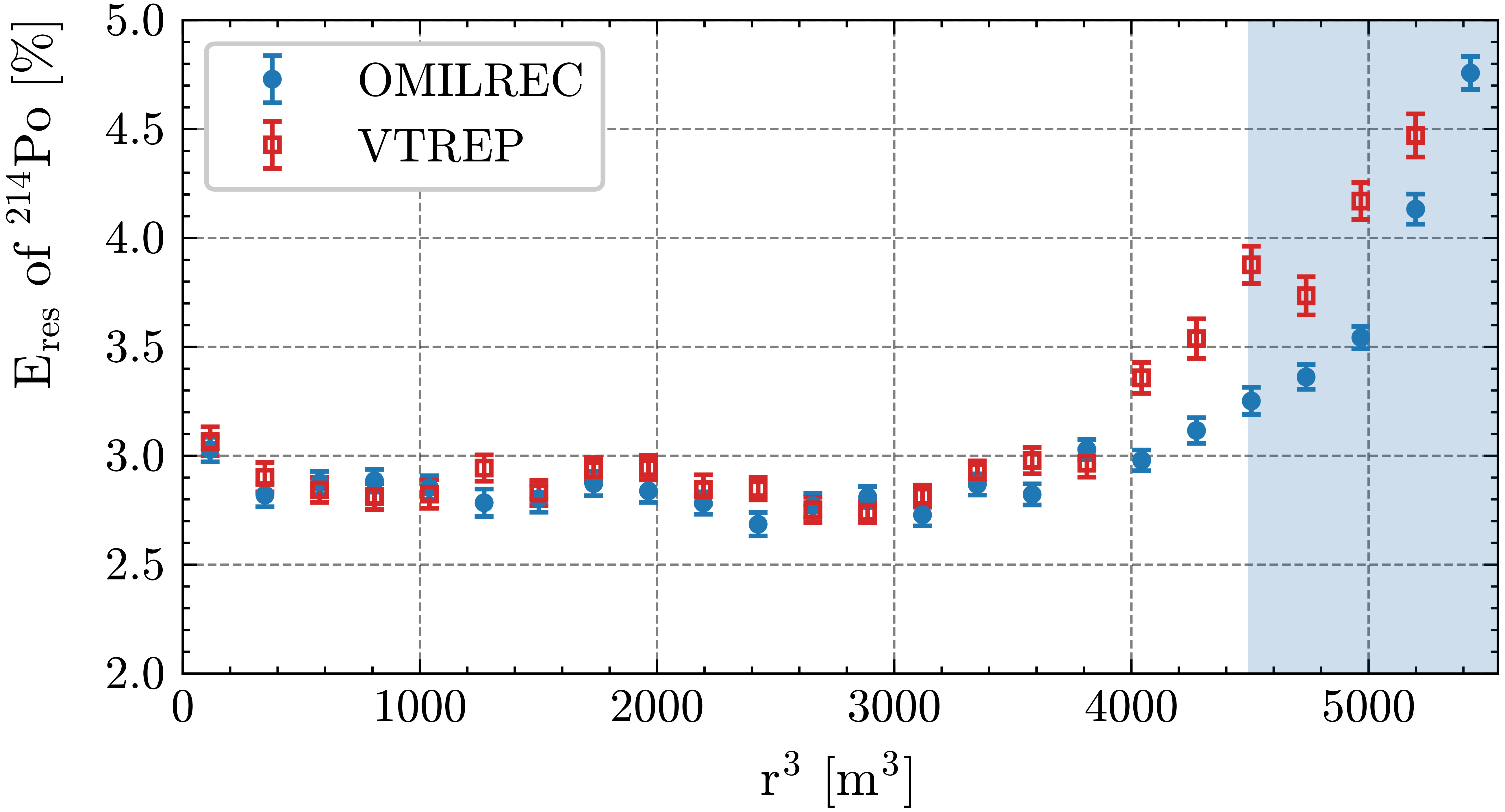


Good agreement with previous results!

Looking Forward

- More is coming!
  - Energy resolution is almost at design level; further improvements expected with better calibration and energy reconstruction





  - Will enable measurements of Δm^2_{31} and the mass ordering (in addition to higher precision on Δm^2_{21} and $\sin^2\theta_{12}$)

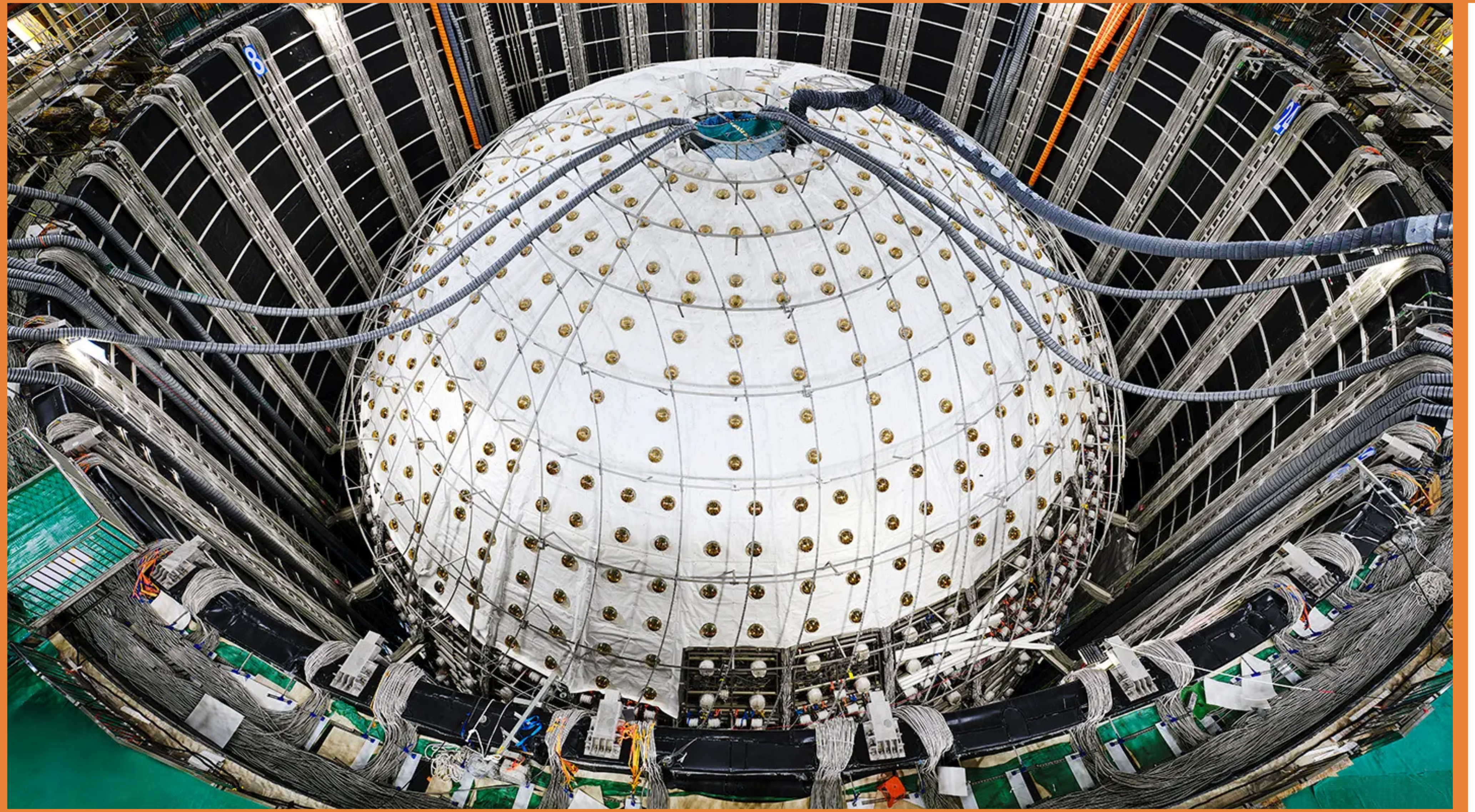
Concluding Remarks

Parting Thoughts

- Nuclear reactors are excellent neutrino sources
- Our empirical knowledge of reactor $\bar{\nu}_e$ emission continues to improve
  - Important for fundamental physics, non-proliferation applications, and as a stringent test of nuclear data inputs
- Reactor neutrino experiments continue to make unique contributions to the field:
  - As of yesterday, reactor experiments have leading precision for 3 out of 6 oscillation parameters
  - Also expected to have leading precision for $|\Delta m^2_{31}|$ and to make a unique measurement of neutrino mass ordering
- A bright future is on the horizon
  - Expect some exciting results and, hopefully, some surprises

Stay tuned!

Support from NSF and DOE is gratefully acknowledged



Thank you
for your
attention!