

Reactor Neutrinos

Part 1: Basic Principles and Previous Experiments



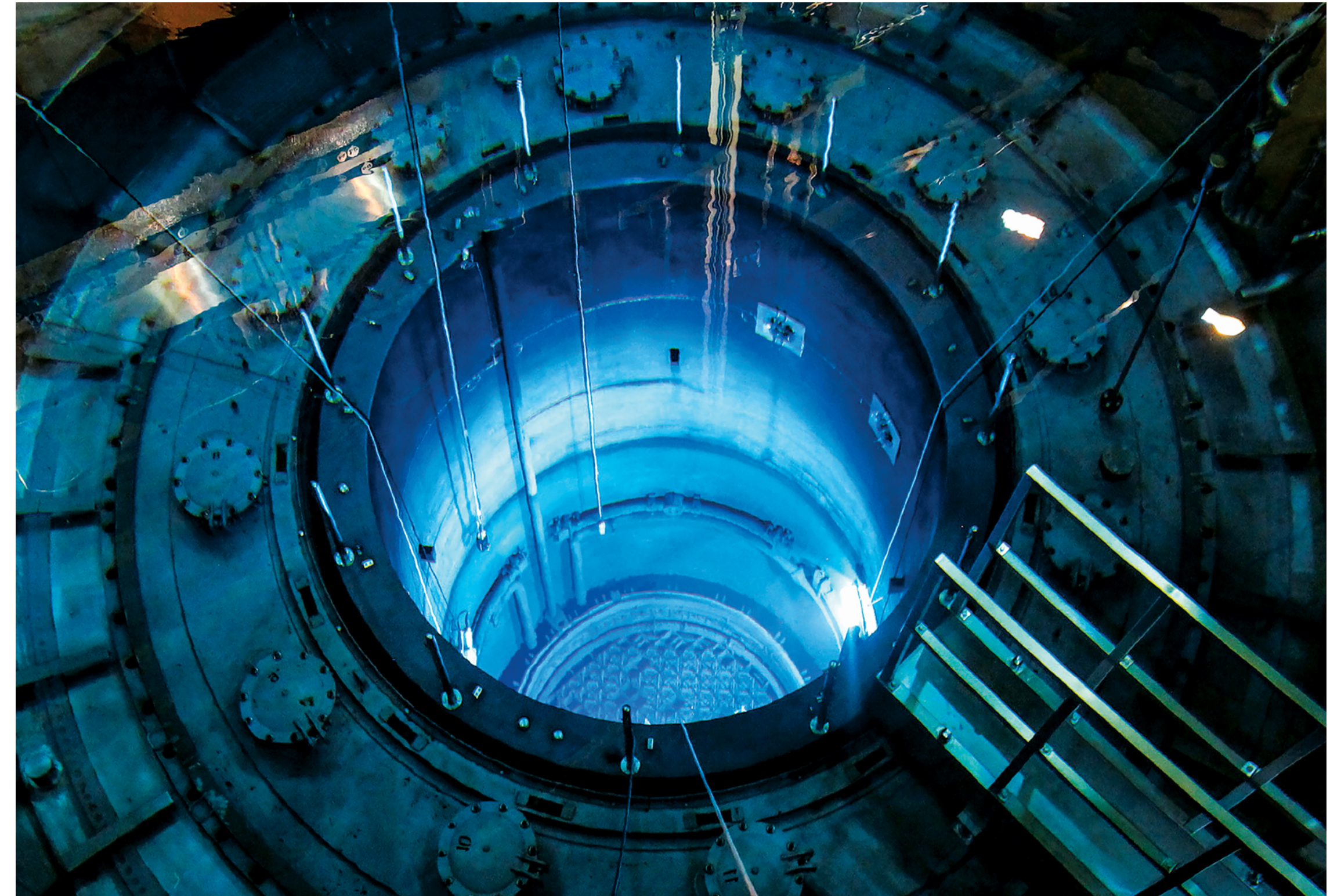
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International Neutrino Summer School
University of California, Santa Barbara
July 8, 2026

Outline

- Motivation
- Basic Principles of Reactor Neutrino Experiments
- Legacy Experiments
- The θ_{13} Generation of Experiments
- Data vs. Models and Short-Baseline Experiments
- Concluding Remarks (for now)



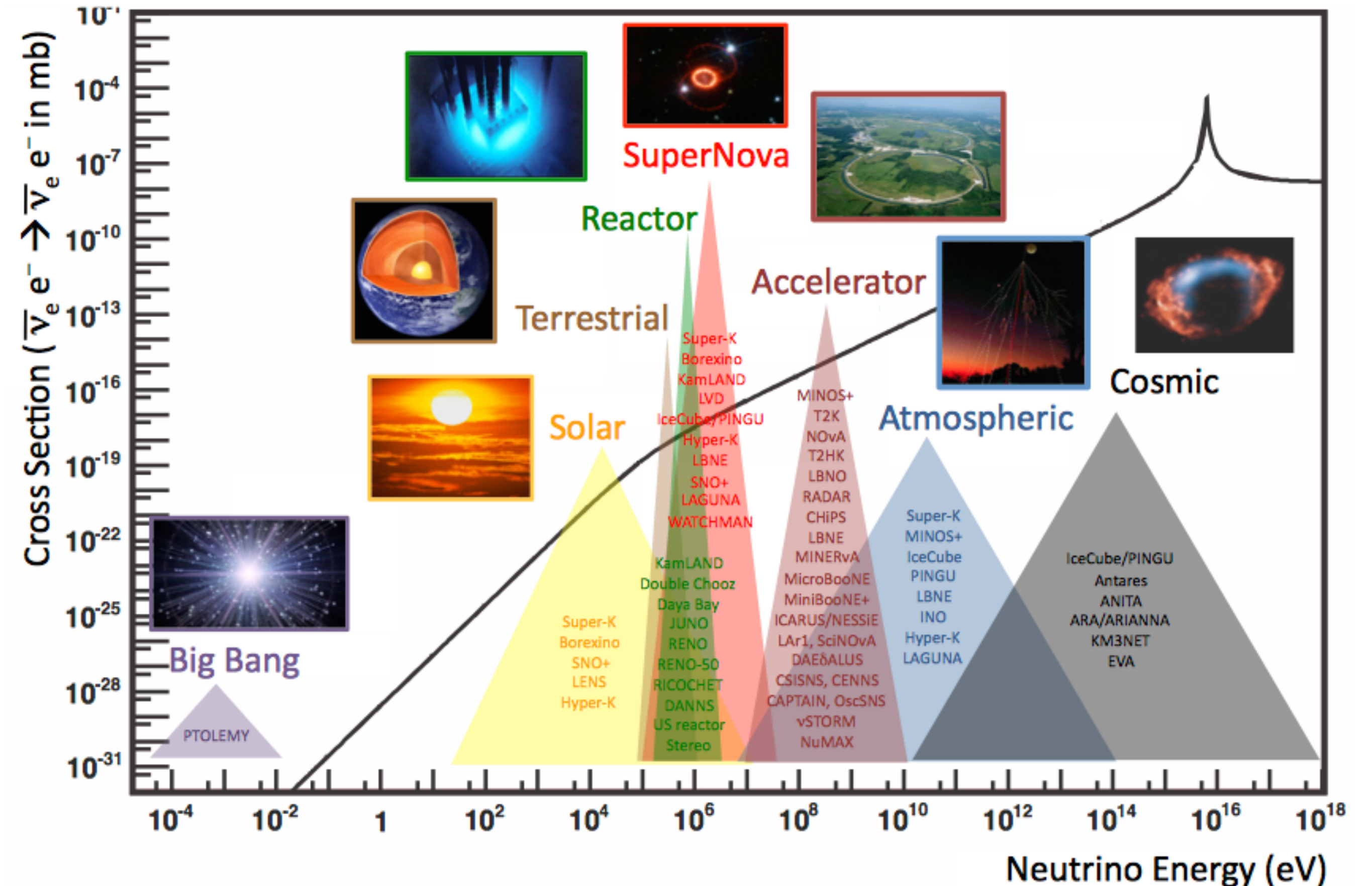
Motivation

for Reactor Neutrino Experiments

Big Picture

- We have key unknowns we want to answer **about** neutrinos:
 - The Standard Model (SM) needs to be extended to accommodate neutrino oscillations and neutrino masses
- We also have unknowns we want to answer **using** neutrinos:
 - For example, the physics involved in supernova explosions
- Reactor antineutrino experiments help with both types of questions!
 - Excellent laboratory for studying reactor neutrino oscillations, and more recently also a powerful tool for studying low-energy neutrinos from the Earth and the cosmos

Neutrinos are everywhere!



Refresher: Neutrino Oscillation

- The basic principle behind neutrino oscillations: neutrino mixing

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

How they interact

$(\nu_e, \nu_\mu, \nu_\tau)$

How they propagate

(ν_1, ν_2, ν_3)

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

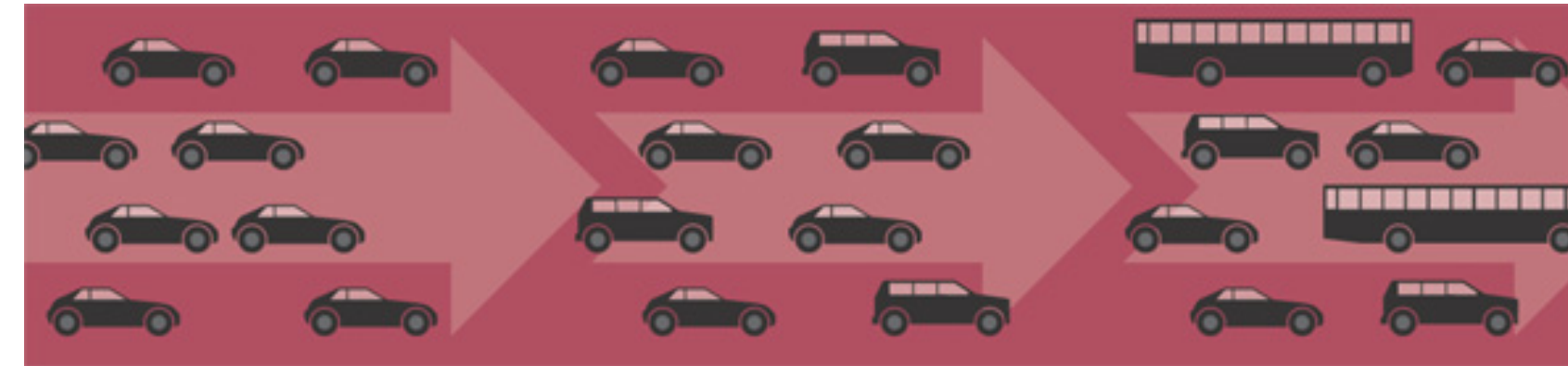
For example, as a rough approximation at short baselines, the $\bar{\nu}_e$ “survival” probability is:

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

amplitude frequency

(where $\Delta m_{ij}^2 = m_i^2 - m_j^2$ are the so-called “mass splittings”)

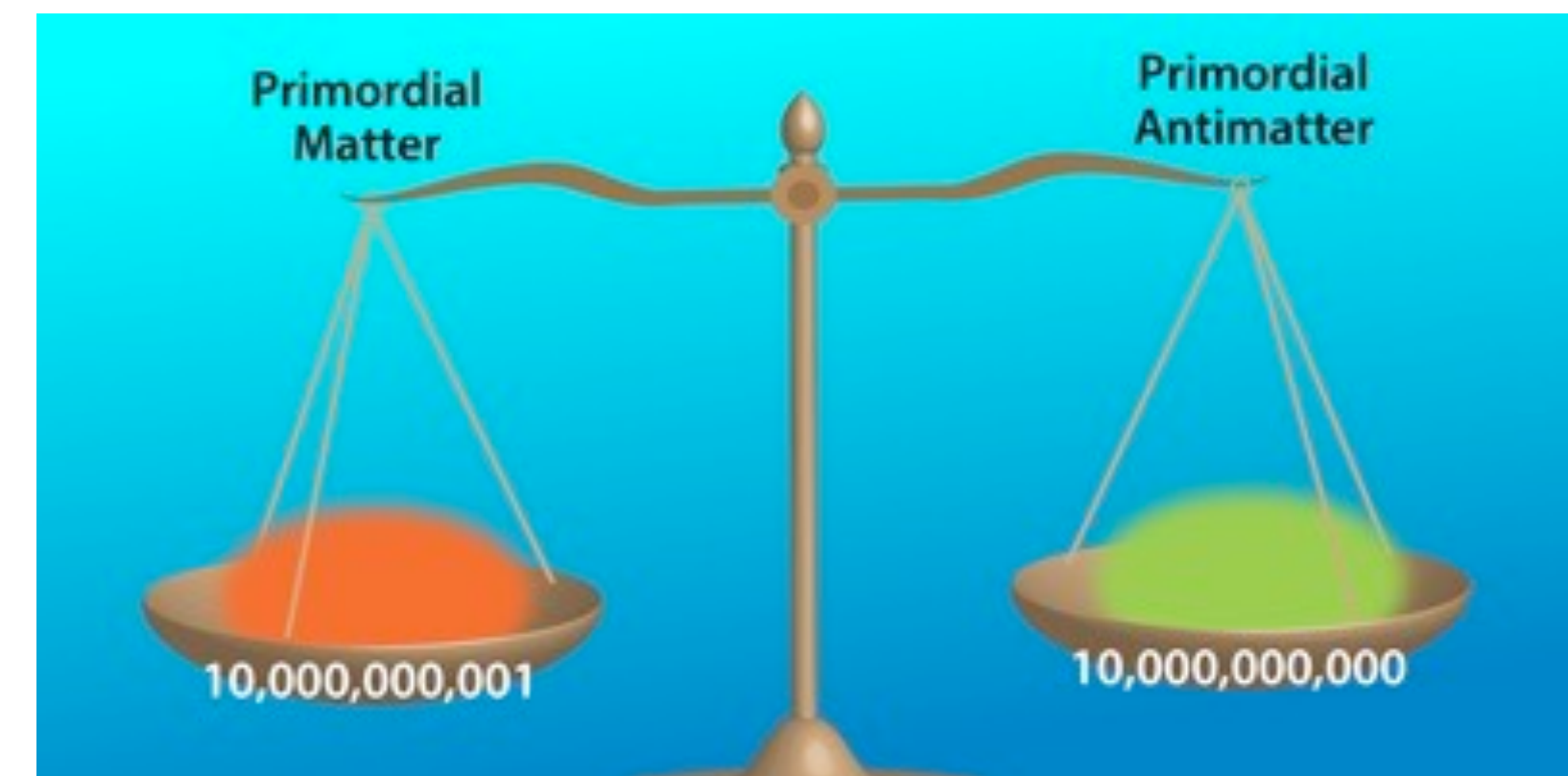
Illustration of neutrino oscillation:



Open Questions in Neutrino Oscillation Physics

- Most neutrino data collected across a wide range of energies and from many different sources are well described by the three-neutrino oscillation framework.
- However, key questions need to be answered before the picture can be considered complete:
 - What is the octant of θ_{23} ?
 - Do neutrinos obey the CP symmetry (is $\delta_{CP} = 0$)?

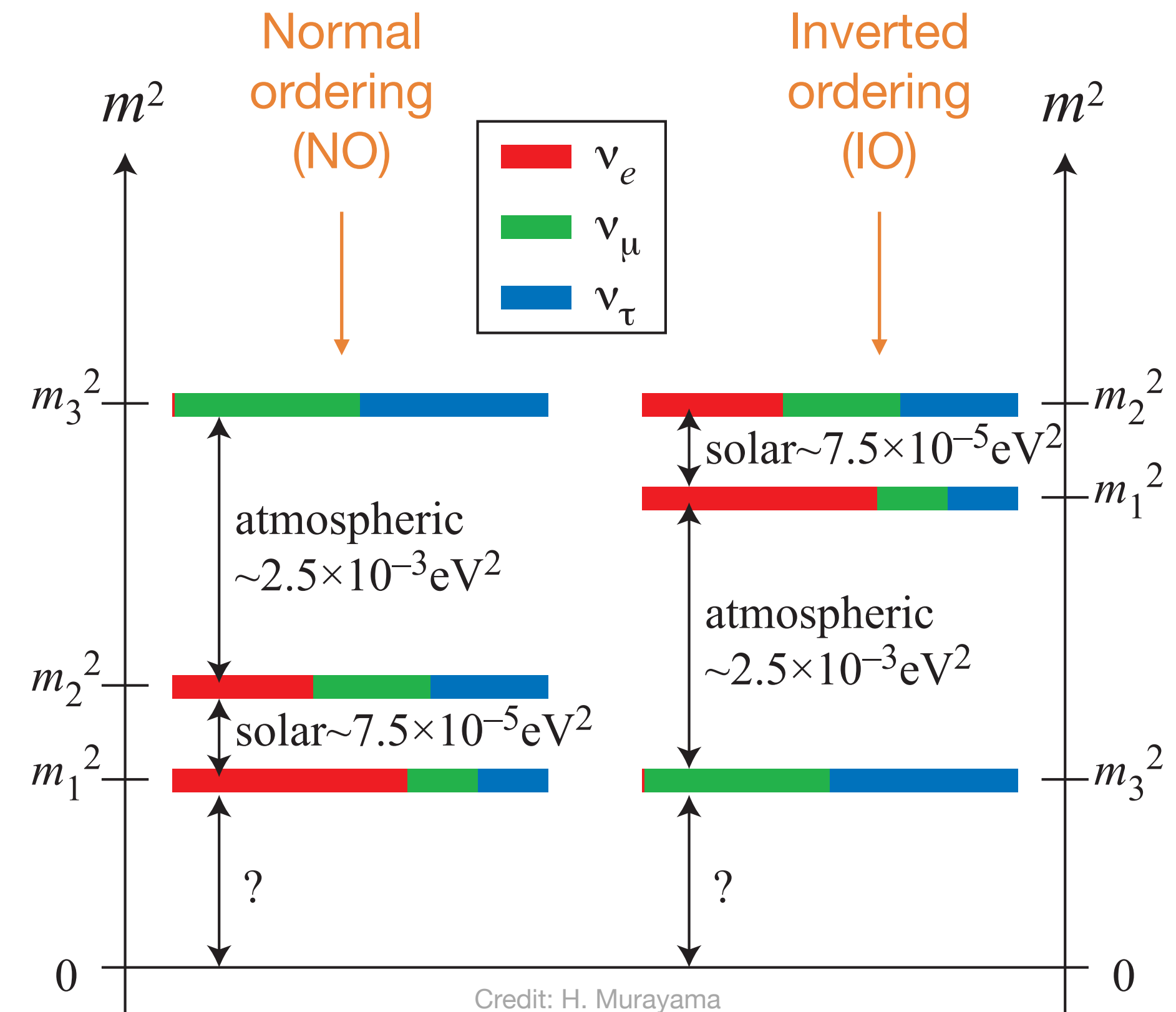
Big implications in cosmology!



Currently, we have some indications of CP violation but none definitive

Open Questions in Neutrino Oscillation Physics

- Most neutrino data collected across a wide range of energies and from many different sources are well described by the three-neutrino oscillation framework.
- However, key questions need to be answered before the picture can be considered complete:
 - What is the octant of θ_{23} ?
 - Do neutrinos obey the CP symmetry (is $\delta_{CP} = 0$)?
 - What is the ordering of the neutrino masses (i.e. sign of Δm_{32}^2)?



Currently, we have some indications of what is the mass ordering but none above 3σ

Open Questions

- We also want to know if the three-neutrino paradigm is the full story. For example:
 - Are there additional neutrino states?
 - Are there non-standard interactions?

Increasing the precision of our measurements is key



All oscillation parameters are currently **known to a few percent!**

From PDG 2025		Precision ↓
$\sin^2(\theta_{12})$	0.307 ± 0.013	4.2 %
Δm_{21}^2	$(7.53 \pm 0.18) \times 10^{-5} \text{ eV}^2$	2.4 %
$\sin^2(\theta_{23})$	$0.558^{+0.015}_{-0.021}$	3.2 %
Δm_{32}^2	$(2.455 \pm 0.028) \times 10^{-3} \text{ eV}^2$	1.1 %
$\sin^2(\theta_{13})$	0.0219 ± 0.0007	3.2 %

In addition to providing important key constraints for experiments and theoretical models, improved precision enables:

- Model-independent tests of the 3-neutrino framework (notably PMNS non-unitarity)
- Stringent cross-checks between different experiments

What we need

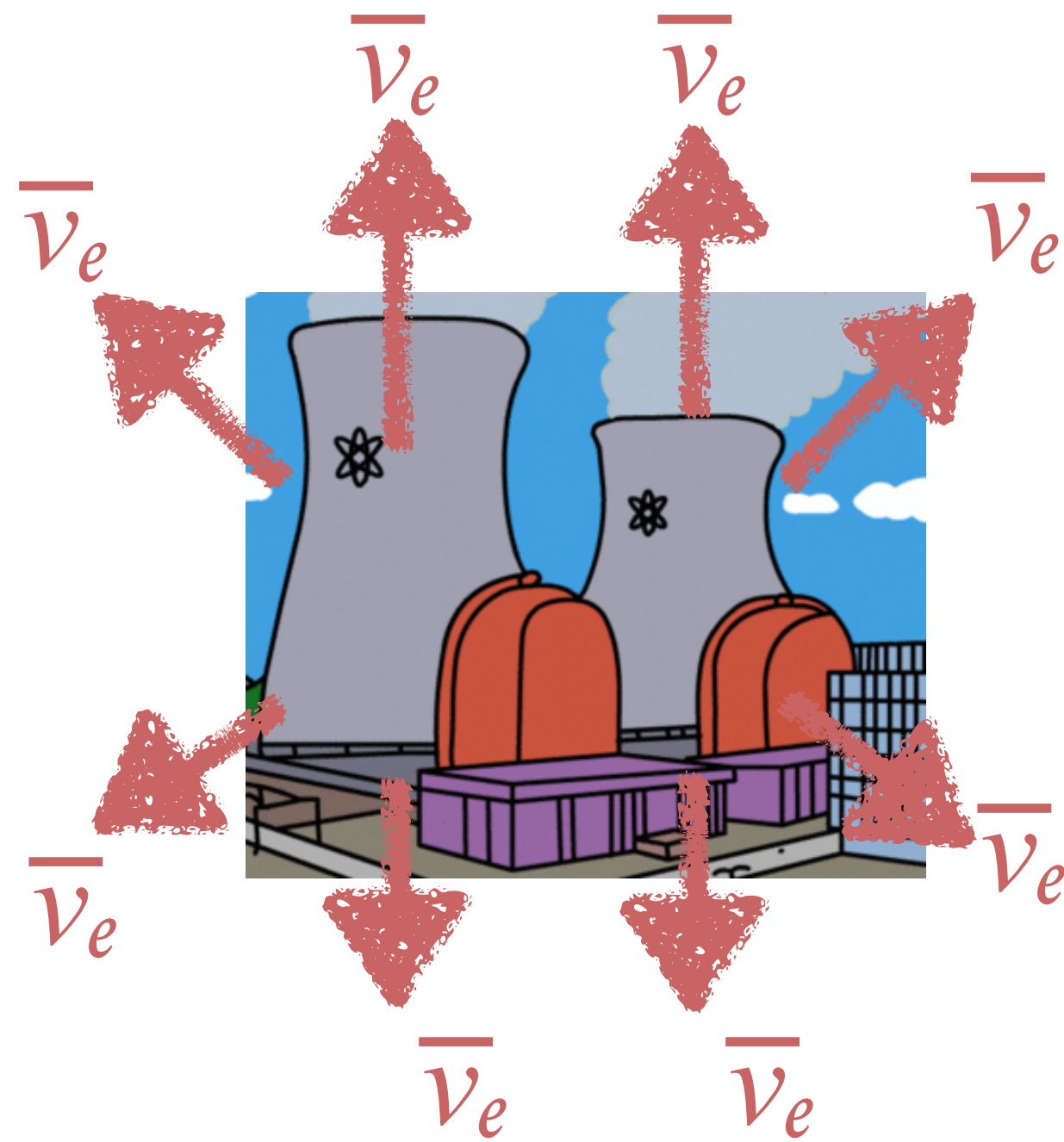
- To answer these questions, we need:
 - Very intense neutrino source
 - With well-understood flux(es)
- Nuclear reactors fit the bill!



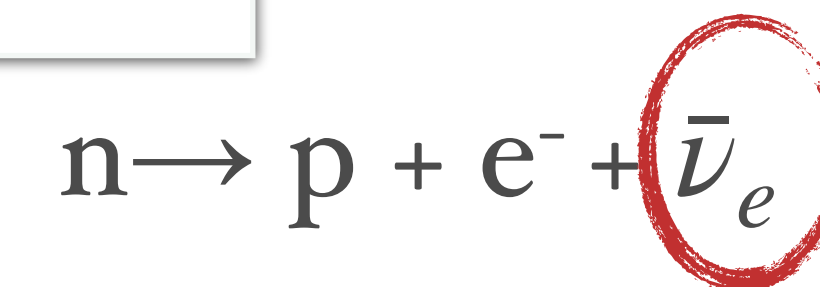
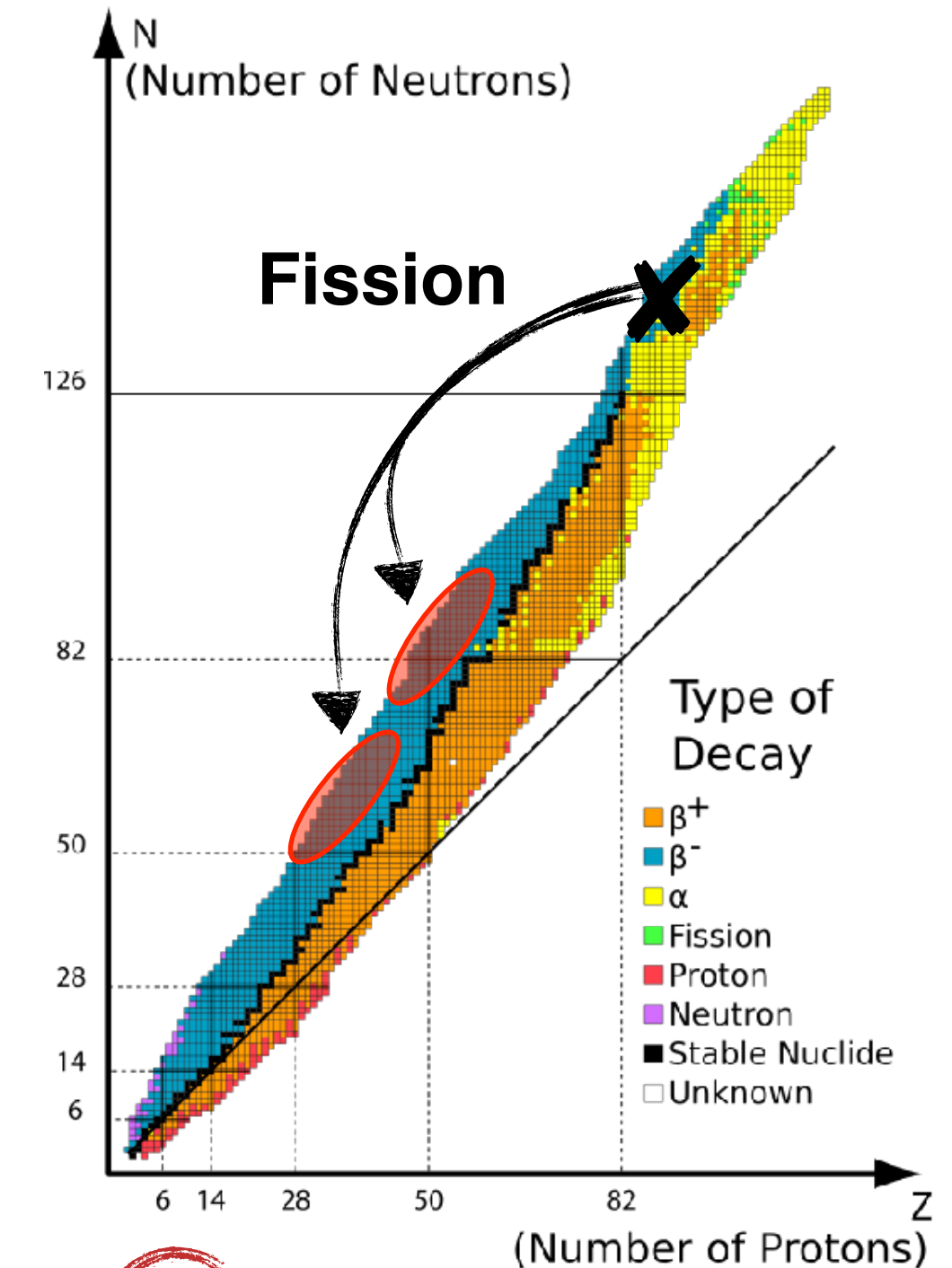
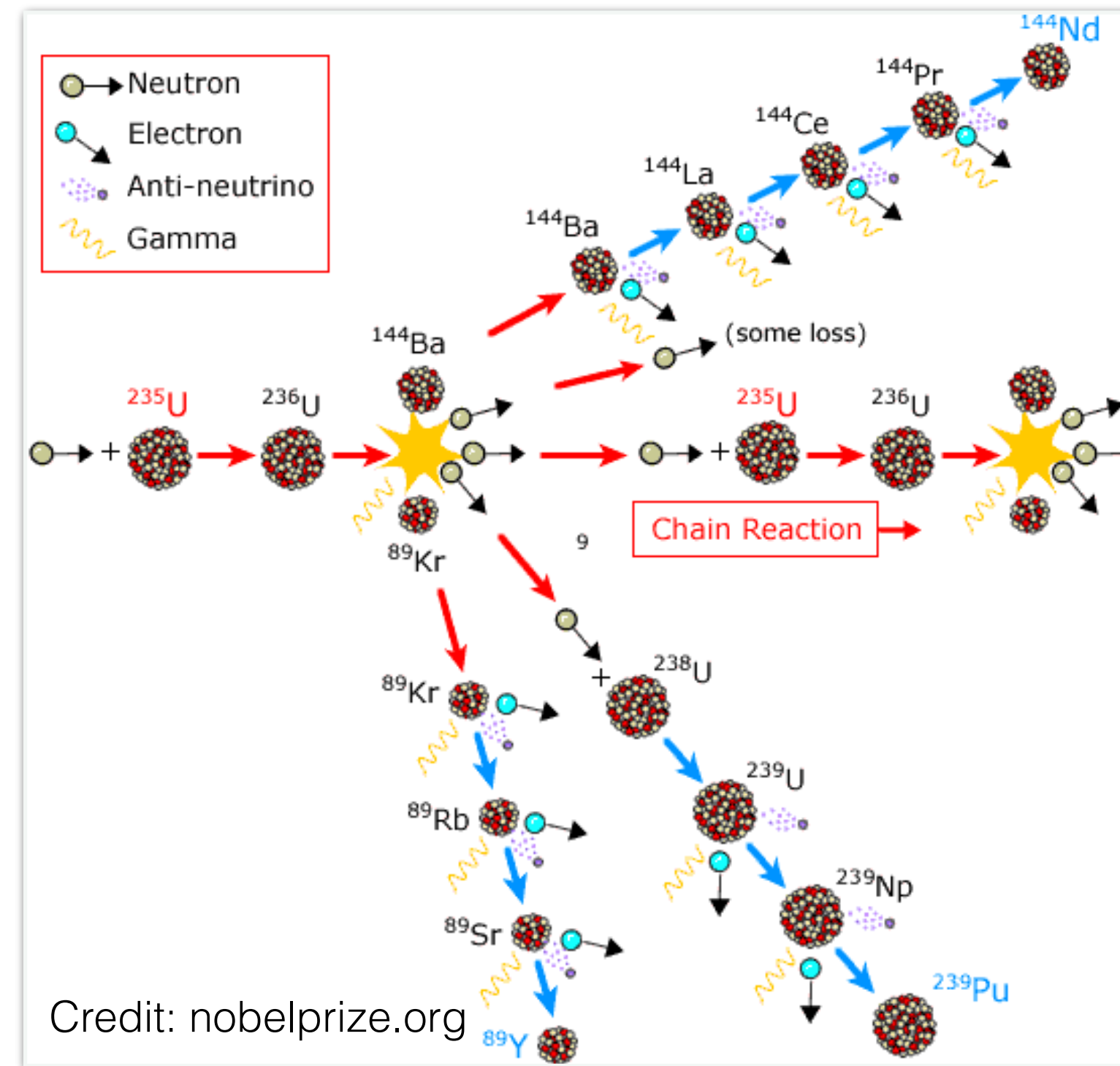
Basic Principles of Reactor Neutrino Experiments

Nuclear Reactors as Antineutrino Sources

- Nuclear reactors are a **flavor-pure** and **extremely intense** source of electron antineutrinos:



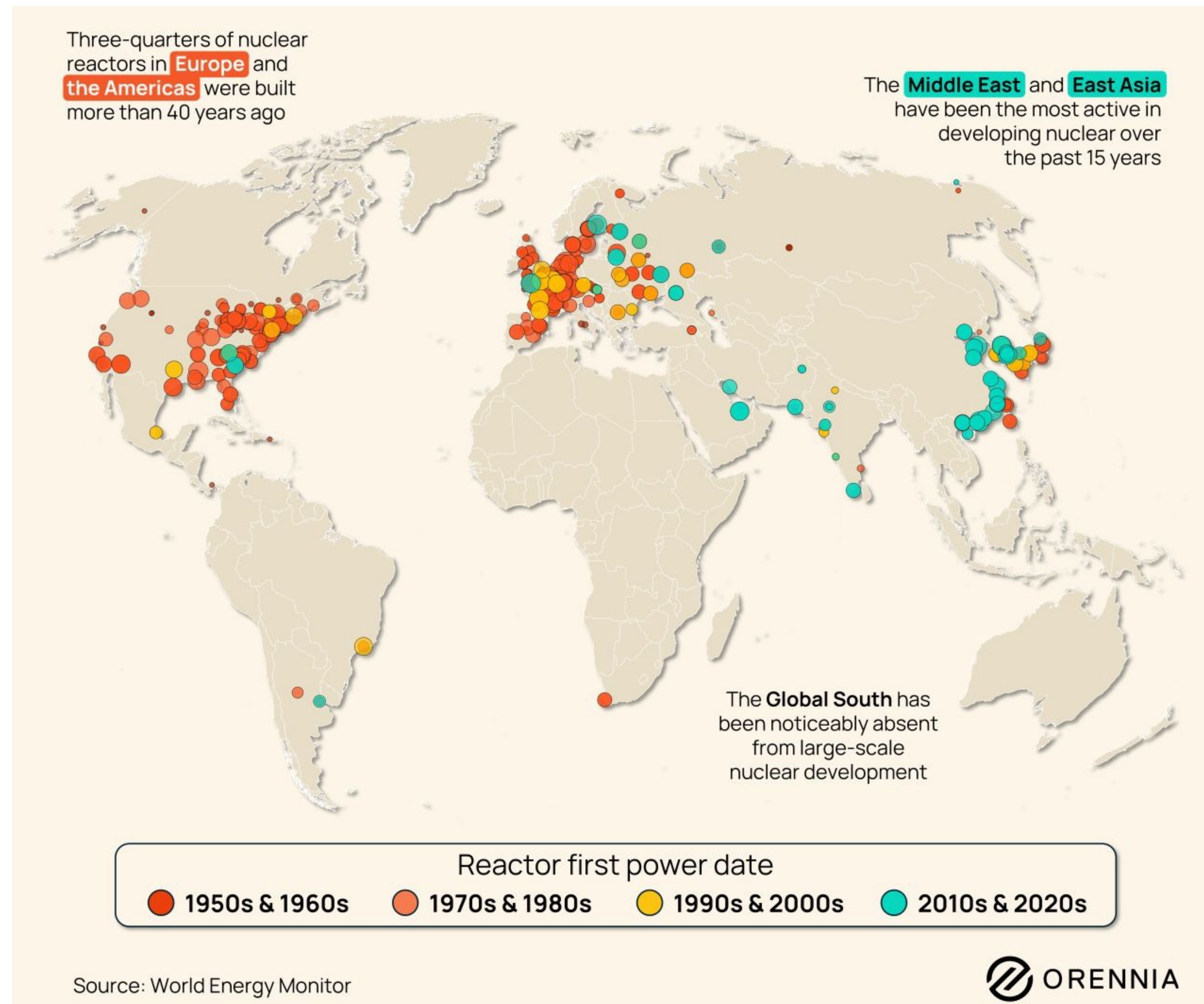
$$\sim 10^{20} \bar{\nu}_e / (\text{s} \cdot \text{GW}_{\text{th}})$$



- A 1 GW_{th} core produces in one minute more neutrinos than the NuMI and BNB beams produce in a typical year
- Caveat: antineutrinos are produced isotropically (in all directions)

Nuclear Reactors as Antineutrino Sources

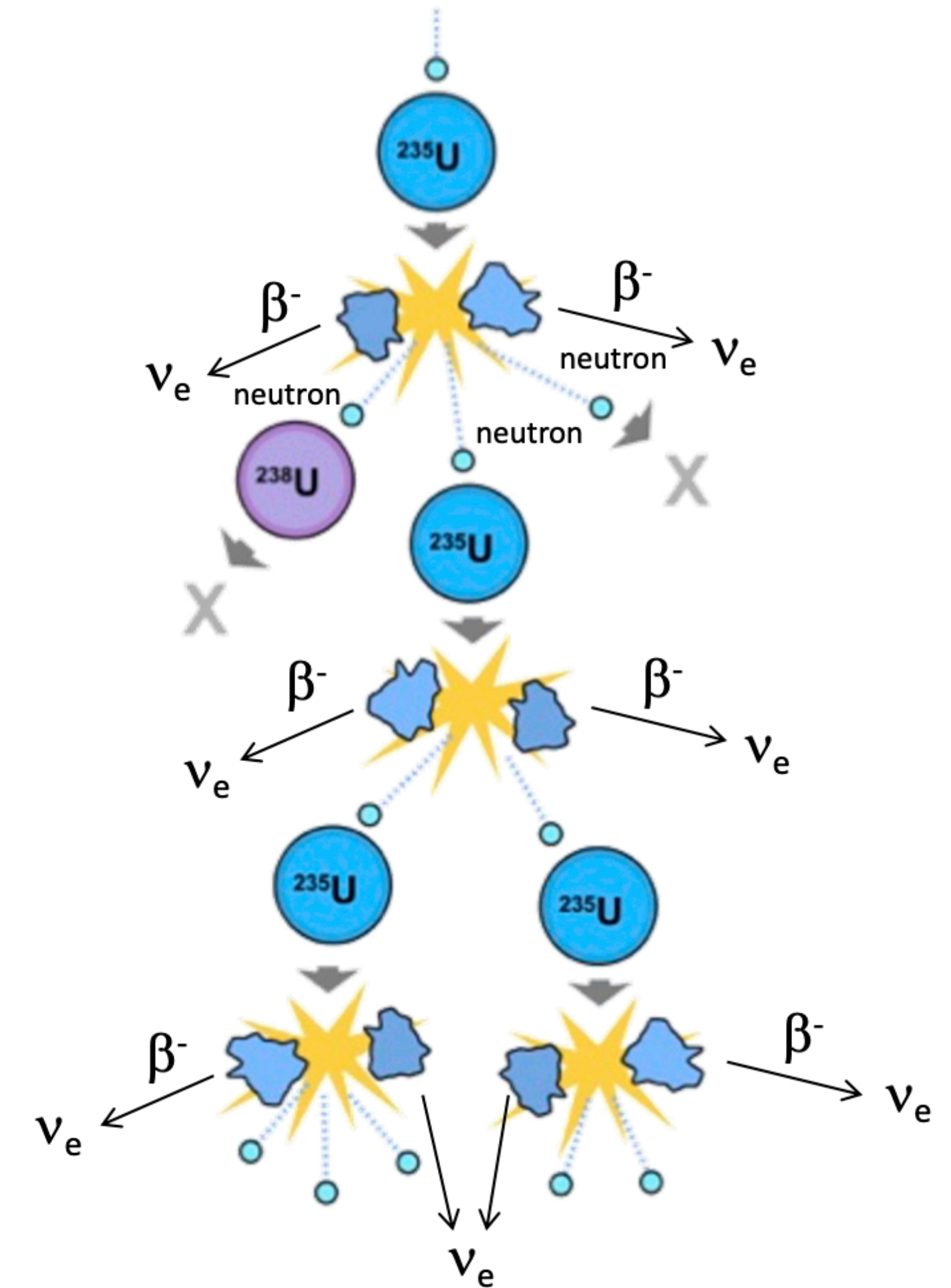
- Nuclear reactors are also **cost-effective** (for researchers) and **widely available**



Nuclear Reactors as Antineutrino Sources

- Finally, nuclear reactors are also a very **well-understood** source of antineutrinos:
 - Reactor antineutrino flux predictions have been greatly improved in the last years
 - And the last decade saw an explosion of measurements with unprecedented statistics
- If the operating conditions of a nuclear reactor are known, namely the thermal power and the fission fractions, the total antineutrino flux and spectral shape to the few-percent level
 - Caveat: discrepancies between model and measurement persist

(We will discuss this in more detail later in the talk)

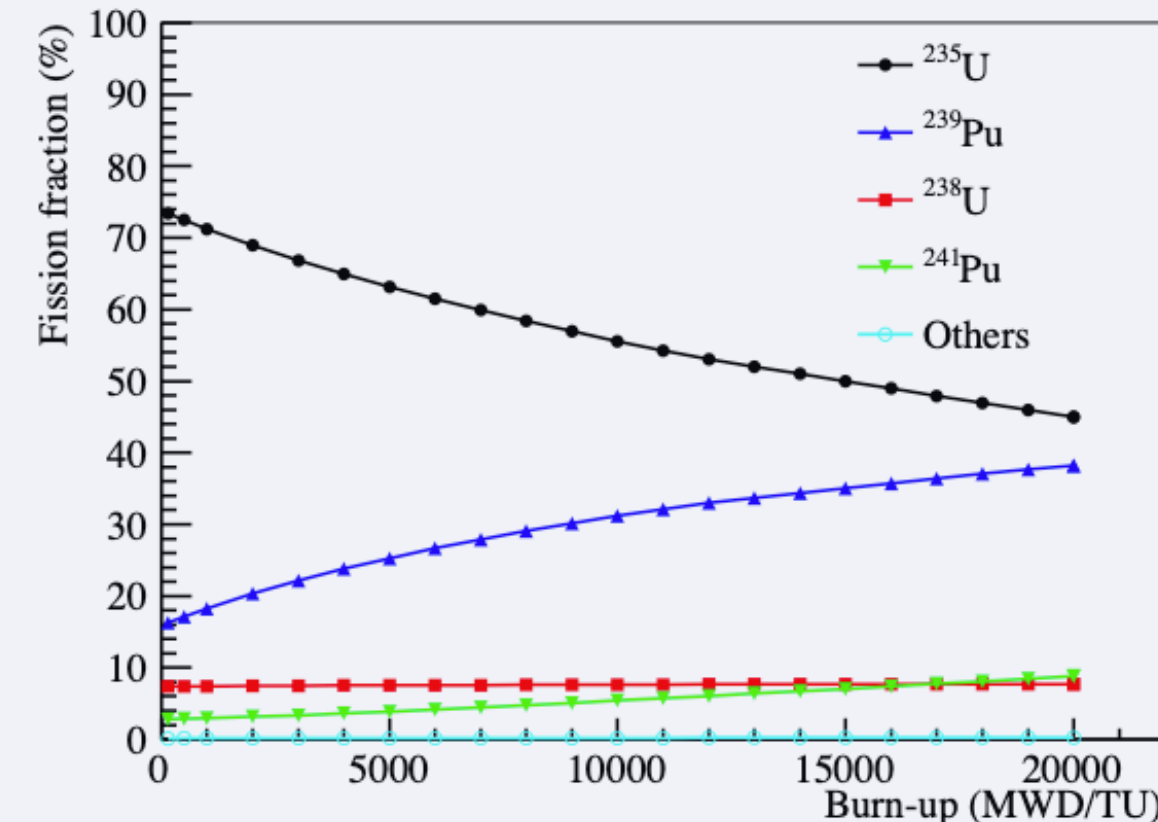


Types of Nuclear Reactors

- Nuclear reactors fall into two main categories:

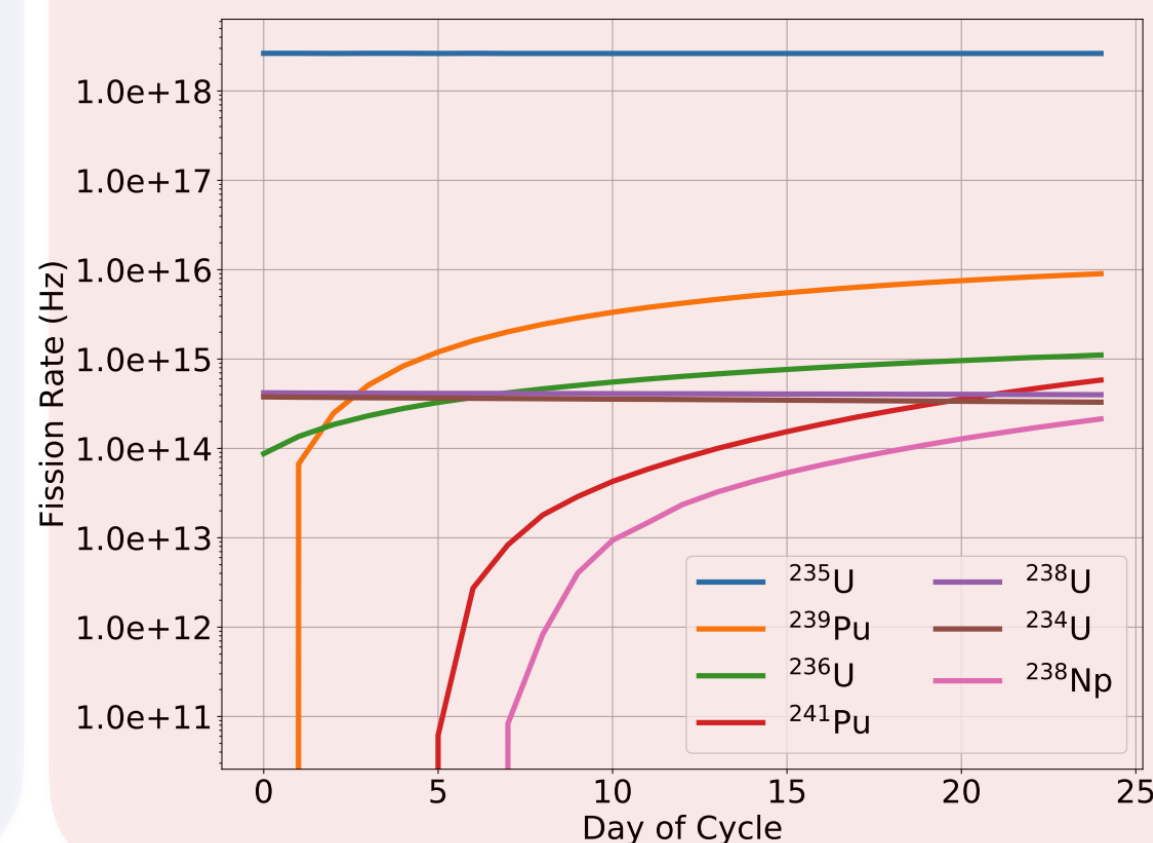
Low-Enriched Uranium (**LEU**)-fueled power reactors

- Commercial reactors
- Several GW of thermal power
- $\bar{\nu}_e$'s originate from fission products of 4 isotopes: ^{235}U , ^{239}Pu , ^{241}Pu and ^{238}U
- Fuel evolves as ^{235}U is consumed and $^{239,241}\text{Pu}$ is produced



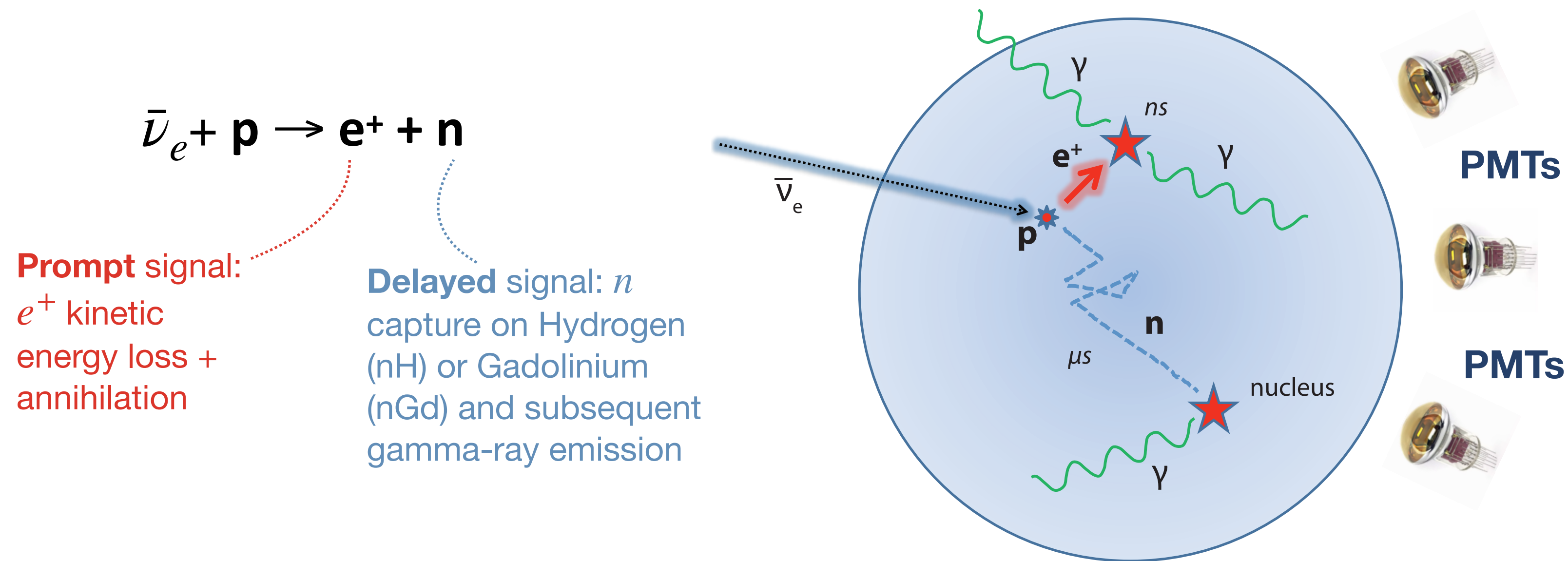
Highly-Enriched Uranium (**HEU**)-fueled reactors

- Research reactors
- 50-100 MW of thermal power
- Almost all fissions are ^{235}U



Antineutrino Detection

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



2) Light detection:

- This light is detected by extremely sensitive light detectors surrounding the LS volume, typically photomultiplier tubes (PMTs)

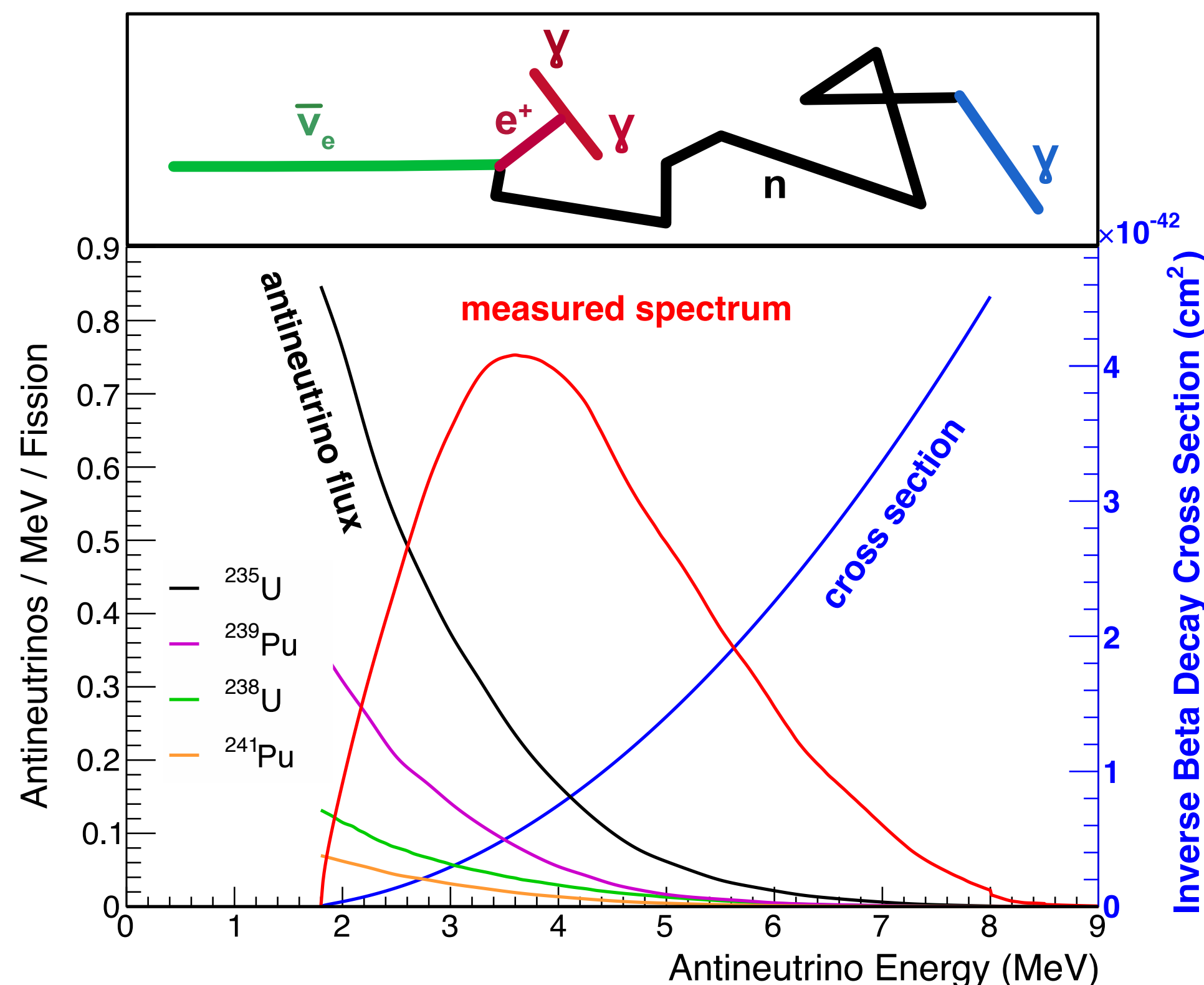
1) Light production:

- Ionizing particles produced as a result of the $\bar{\nu}_e$ interaction make the medium (typically liquid scintillator, or LS) “shine”
- Specifically, two flashes of light originating from the same region (within $\sim 1\text{m}$) and in short succession (mean lifetime of $\sim 200\ \mu\text{s}$) are produced

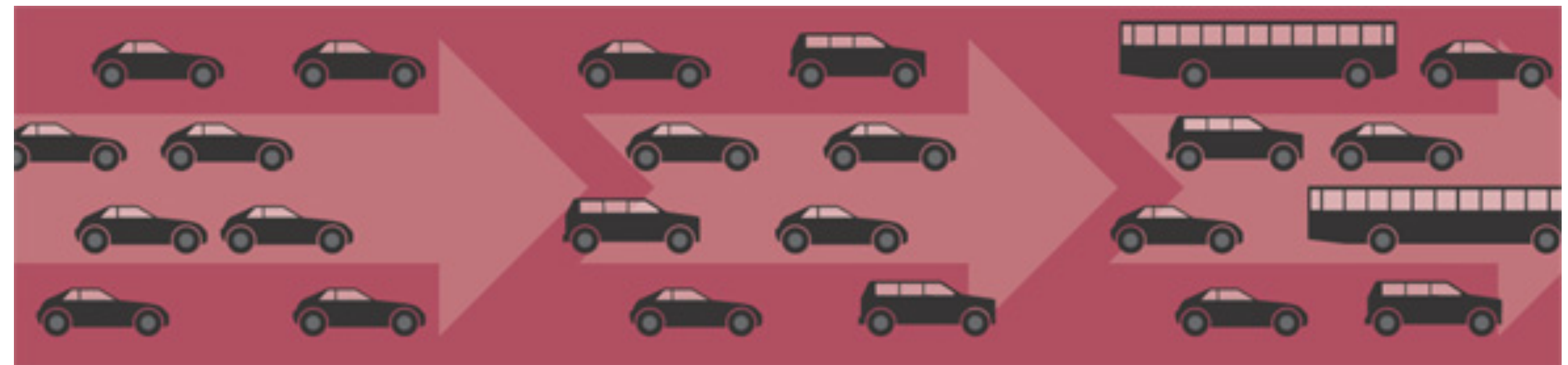
Spatial and temporal coincidence between e^+ and n signals allows for **powerful background rejection**

Antineutrino Detection

- Energy of positron preserves information about energy of incoming $\bar{\nu}_e$: $E_{\bar{\nu}_e} \approx E_{\text{prompt}} + 0.78 \text{ MeV}$
- The energy spectrum of reactor $\bar{\nu}_e$'s before oscillation peaks around 3.5 MeV



But only $\bar{\nu}_e$'s are detectable; other flavors are kinematically inaccessible



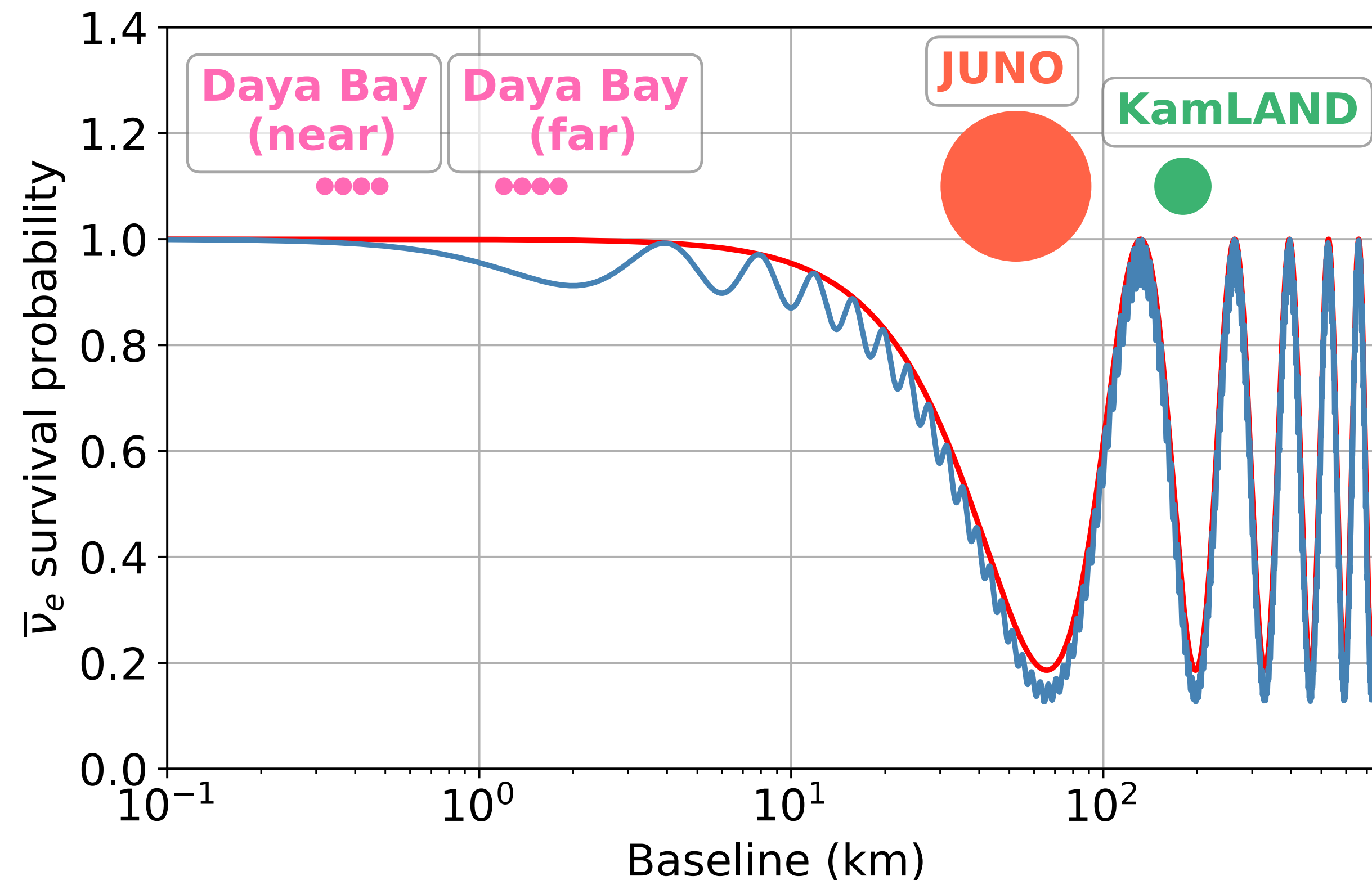
*If you only detect the neutrino flavor with which you started, it will look as if neutrinos are **disappearing***

Oscillation Probability

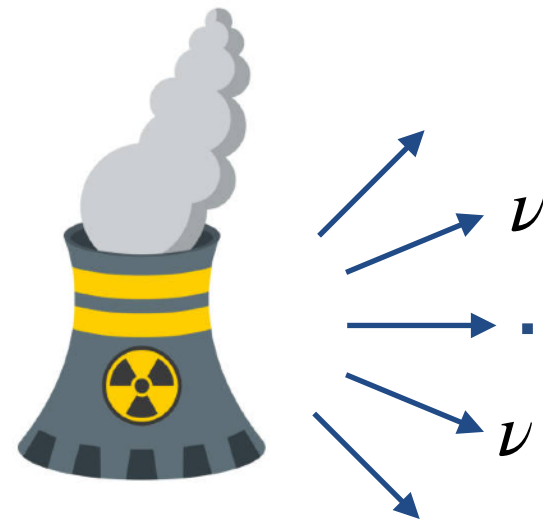
- Consequently, reactor neutrino experiments are “disappearance” experiments:

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

- Look at how $\bar{\nu}_e$'s oscillate (disappear) into other flavors
- Access to 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

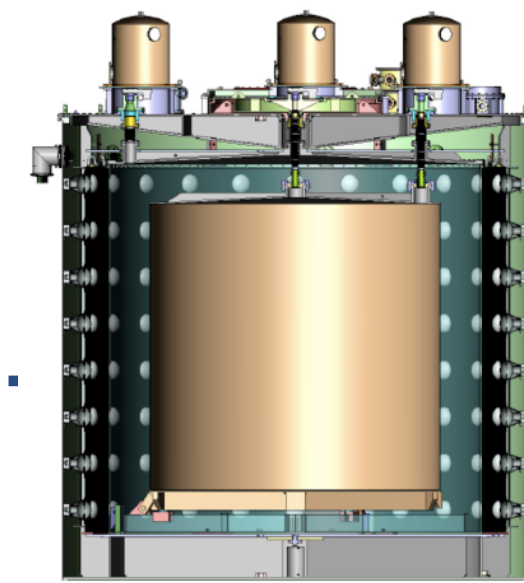
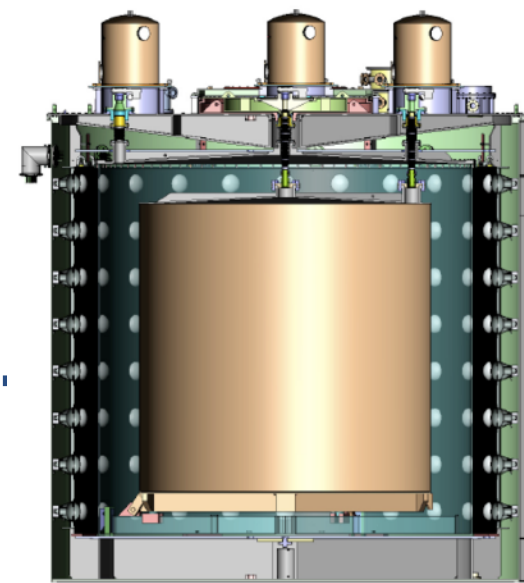


Anatomy of a Reactor Neutrino Experiment



$\bar{\nu}_e$'s are emitted isotropically (in all directions)

Can predict reactor antineutrino flux and shape to a few % precision

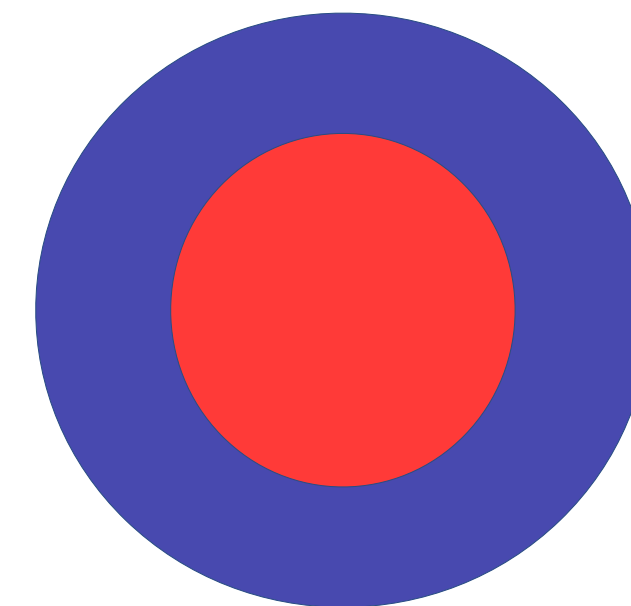


Note: using Daya Bay detectors for illustration

Sample the neutrino flux in at least one location:

- Sampling at multiple baselines $\rightarrow$ reduce flux uncertainties
- Using identical (or functionally-identical) detectors $\rightarrow$ reduce correlated detection systematics (e.g. efficiency and cross-section)

Reactor $\bar{\nu}_e$'s are $\sim$ MeV in energy, so need target material with high light yield



Typical reactor neutrino detector: a **liquid scintillator** target observed by photomultiplier tubes (PMTs) and surrounded by an **instrumented buffer and/or shield**

Thus, reactor neutrino detectors typically have low thresholds but limited topological information

see the surrounding and internal radioactivity, so need clean detectors

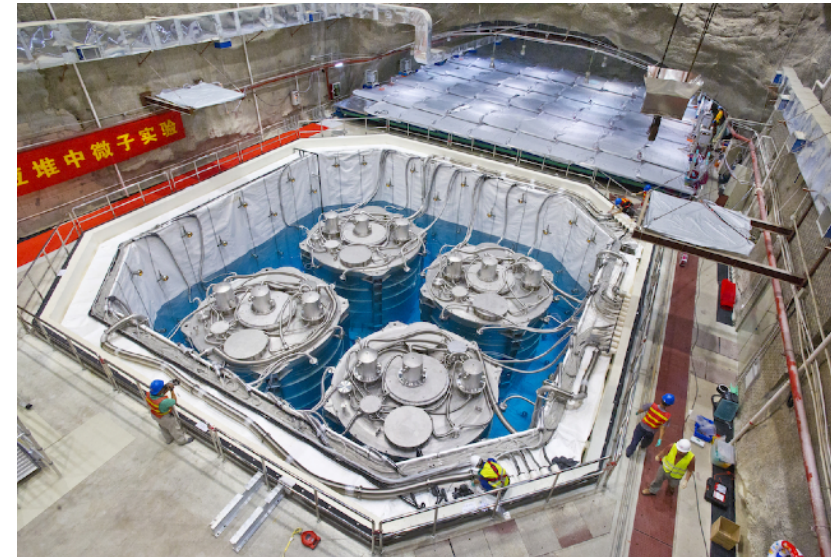
get total energy, time and position of event, but not detailed spatial structure

Several Generations of Reactor Neutrino Experiments



Discovery of the Neutrino (1956)

KamLAND
(2002-2011)



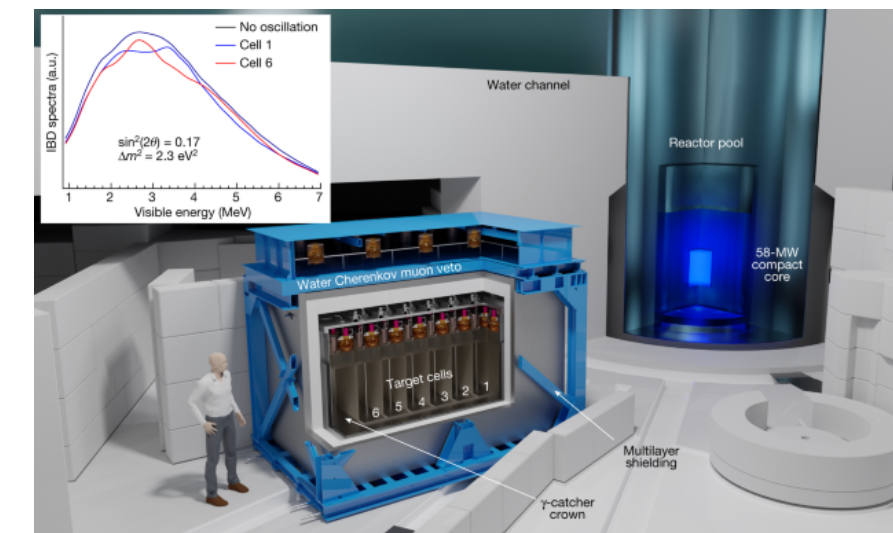
Short-Baseline Experiments
(~2015-2023)



JUNO (2025-present)

Focus of Part 2

The θ_{13} generation
(~2011-2023)



Focus of the rest of today's lecture

Legacy Experiments

Neutrino Discovery and KamLAND

Discovery of the Neutrino: First Attempt

- Even though neutrinos were proposed in 1930, they were not observed until several decades later by Frederick Reines and Clyde Cowan

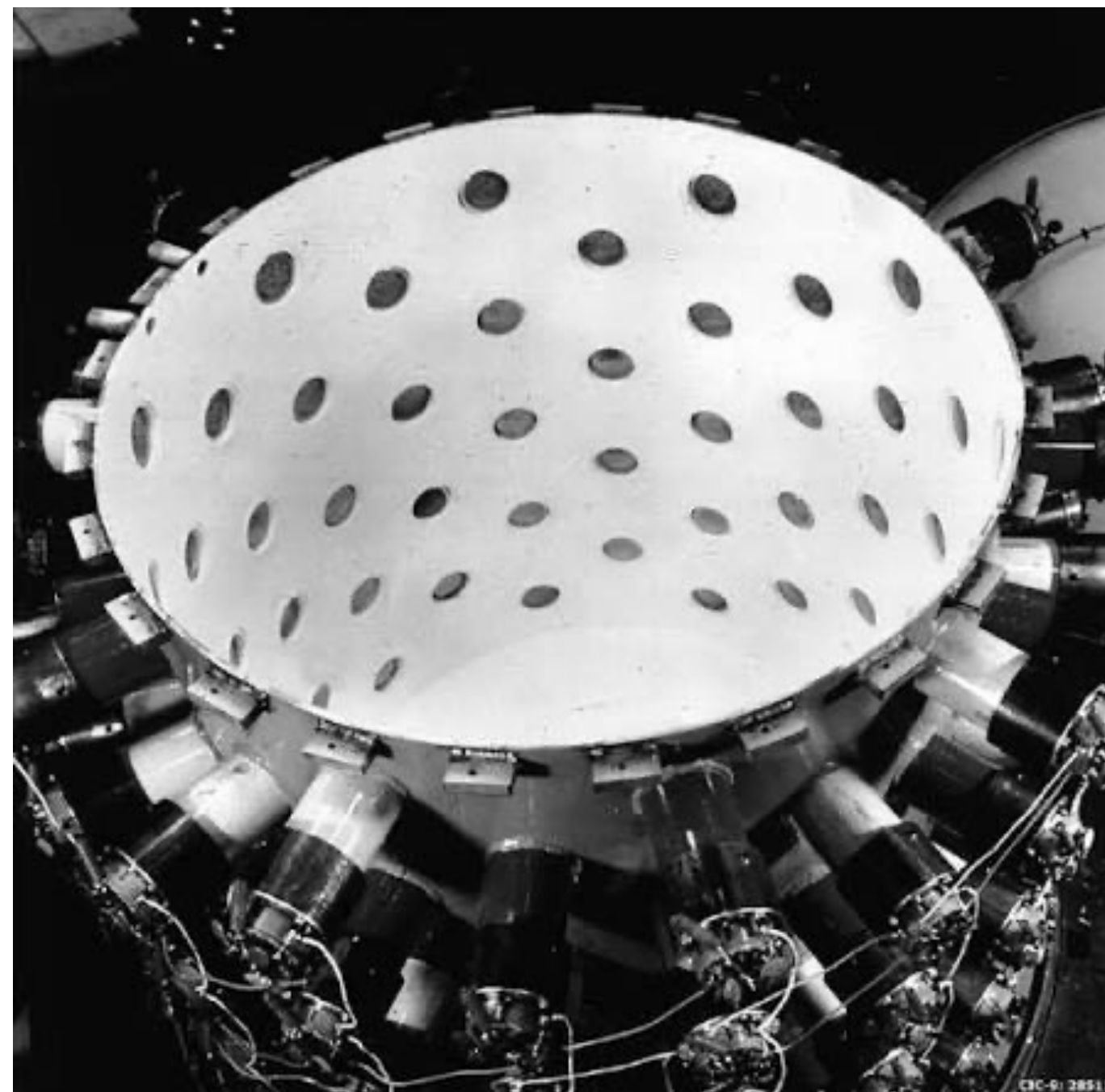
Had to wait until a strong enough source became available: a **nuclear reactor**

A first attempt was made in 1953 using a 300 liter LS target doped with Cadmium and surrounded by 45 2-inch PMTs near the Hanford Nuclear Reactor (250 MW_{th})

Reactor ON: 2.55 ± 0.15 count/min

Reactor OFF: 2.14 ± 0.13 count/min

Difference: 0.41 ± 0.20 count/min



Detection of the Free Neutrino*

F. REINES AND C. L. COWAN, JR.
*Los Alamos Scientific Laboratory, University of California,
Los Alamos, New Mexico*

(Received July 9, 1953; revised manuscript received September 14, 1953)

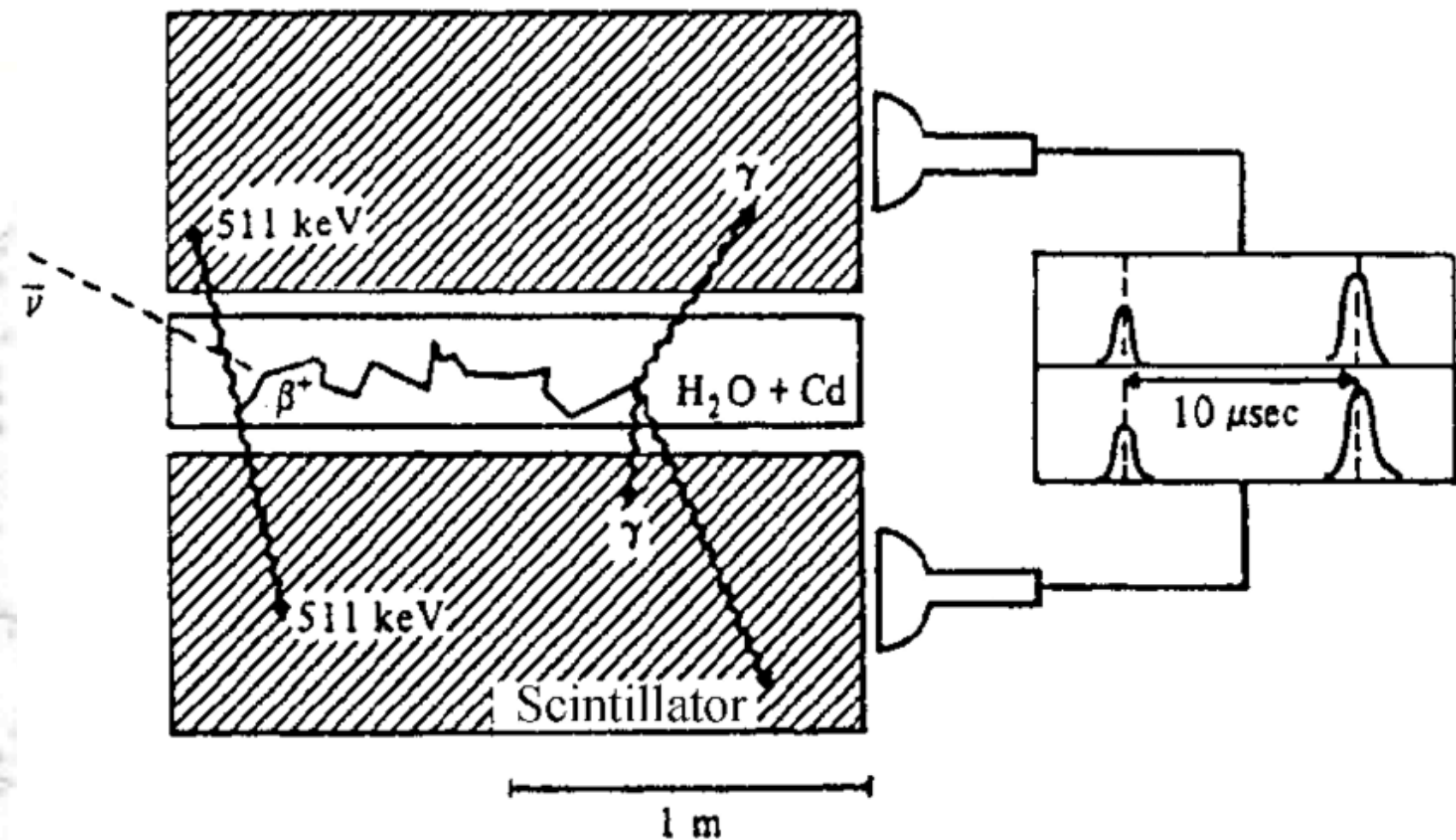
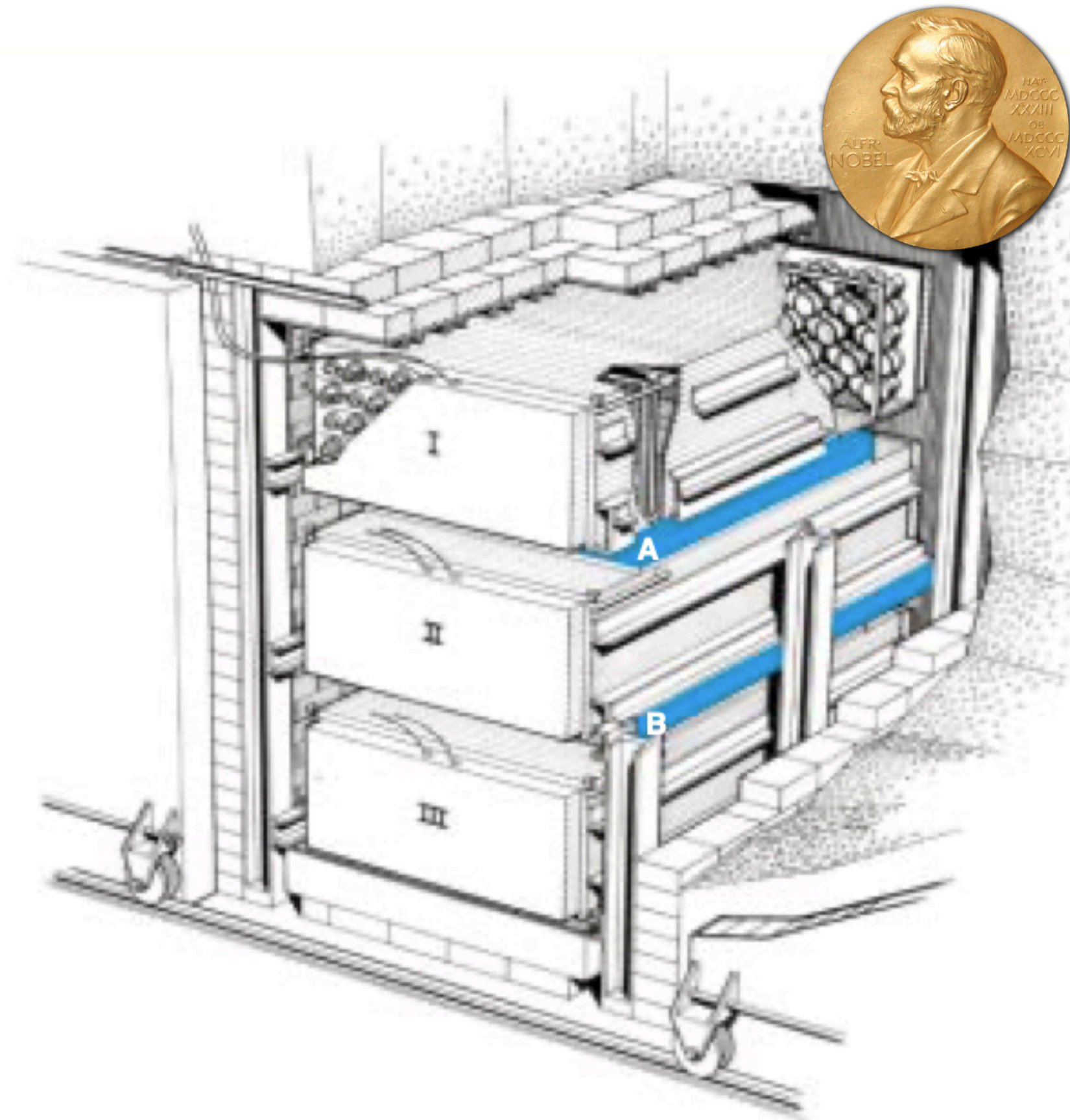
AN experiment¹ has been performed to detect the free neutrino. It appears probable that this aim has been accomplished although further confirmatory work is in progress. The cross section for the reaction employed,

$$\nu_{-} + p \rightarrow n + \beta^{+}, \quad (1)$$

Discovery of the Neutrino: Second Attempt

- A definite observation was made in 1956 with an improved experimental setup:

- Stronger reactor (Savannah River P-reactor, $\sim 700 \text{ MW}_{\text{th}}$)
- Better shielding
- Longer run time
- Better electronics



(I) A signal dependent upon reactor-power, 2.88 ± 0.22 counts/hr. in agreement with the predicted²⁰ cross-section ($6 \times 10^{-44} \text{ cm}^2$), was measured with a signal-to-reactor associated accidental background in excess of 20/1. The signal-to-reactor independent background ratio was 3/1.

Reines and Cowan, Nature 178, 446 (1956)

Aside: “El Monstro” (ca. 1951)

- Reines and Cowan’s original plan to detect neutrinos was to use a nuclear bomb as the neutrino source
 - A ~1 ton liquid scintillator (LS) detector surrounded by photomultiplier tubes in free-fall during a nuclear explosion
 - Concerning the detector, Reines’ wrote: “*The detector we dreamed up was a giant liquid scintillation device, which we dubbed ‘El Monstro’ (...) The biggest detector until Cowan and I came along was only a liter or so in volume*”

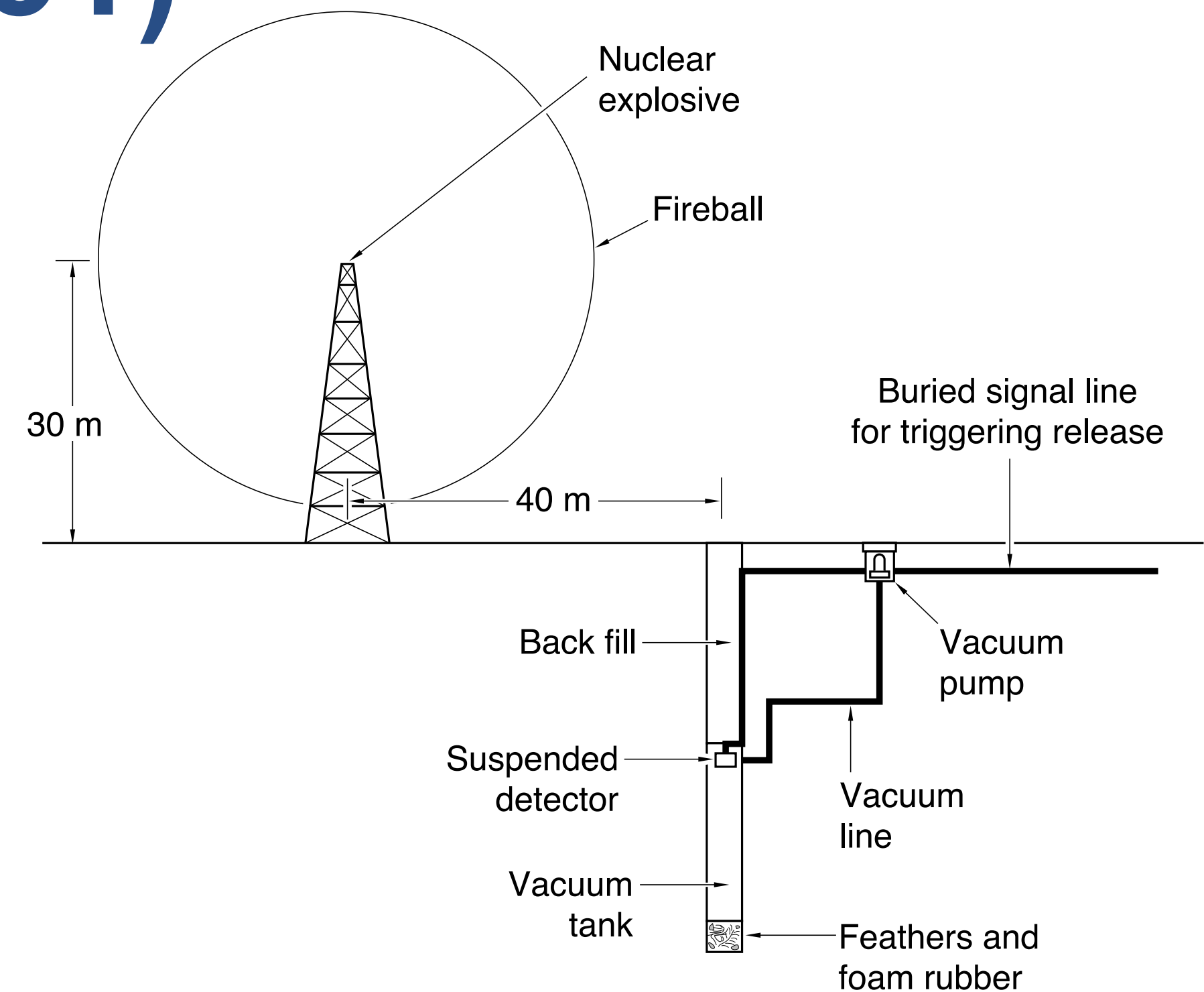
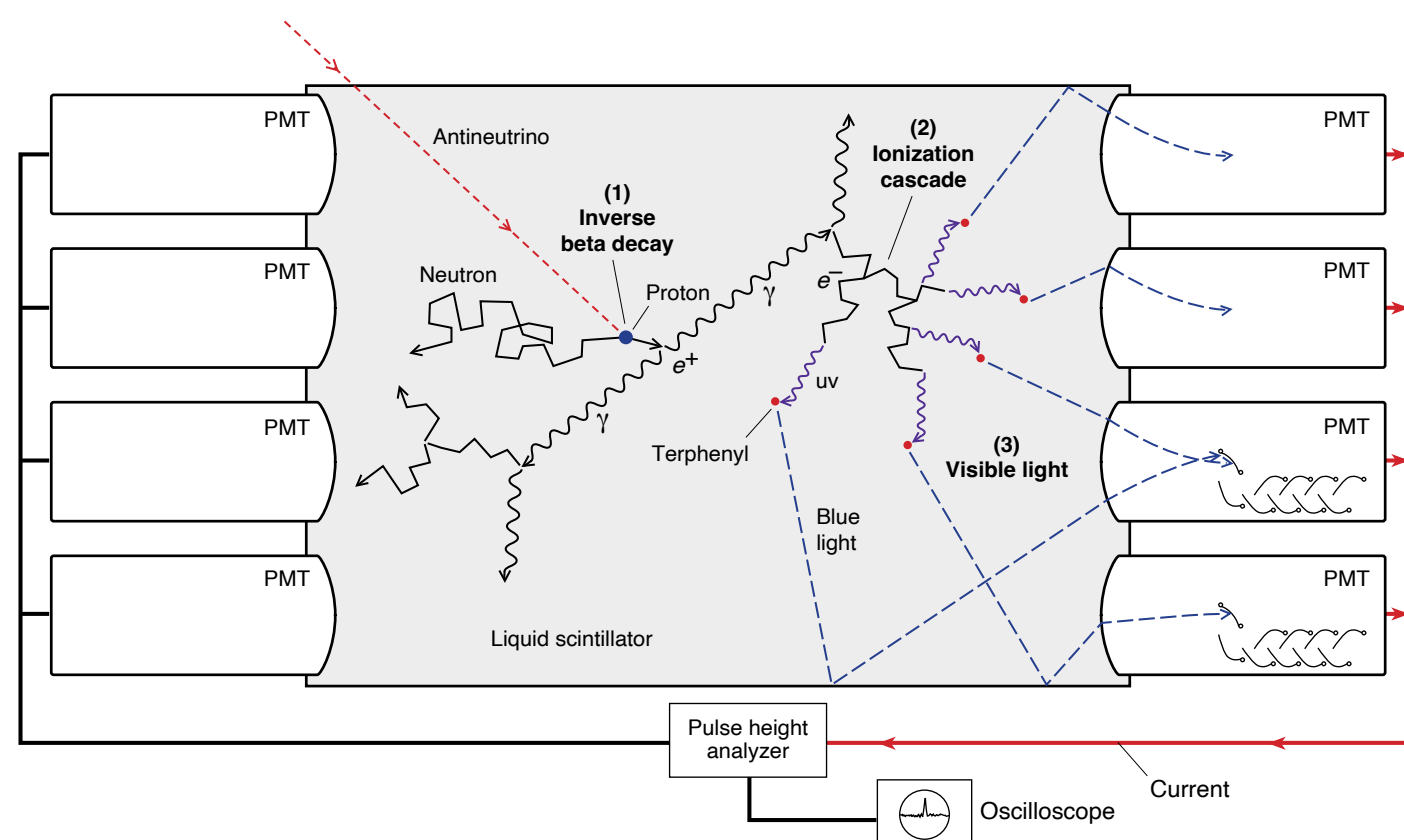
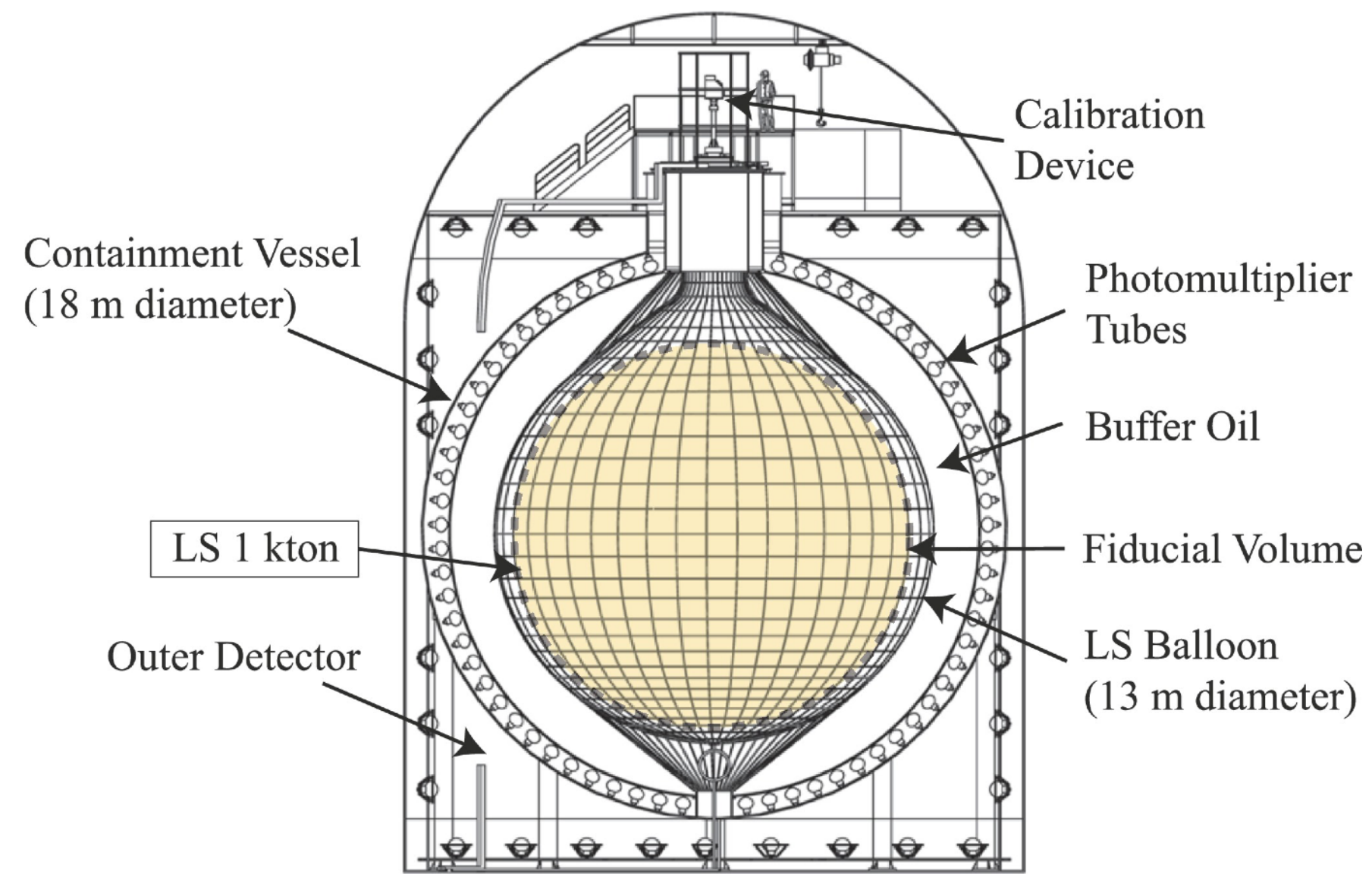


Figure 1. Detecting Neutrinos from a Nuclear Explosion

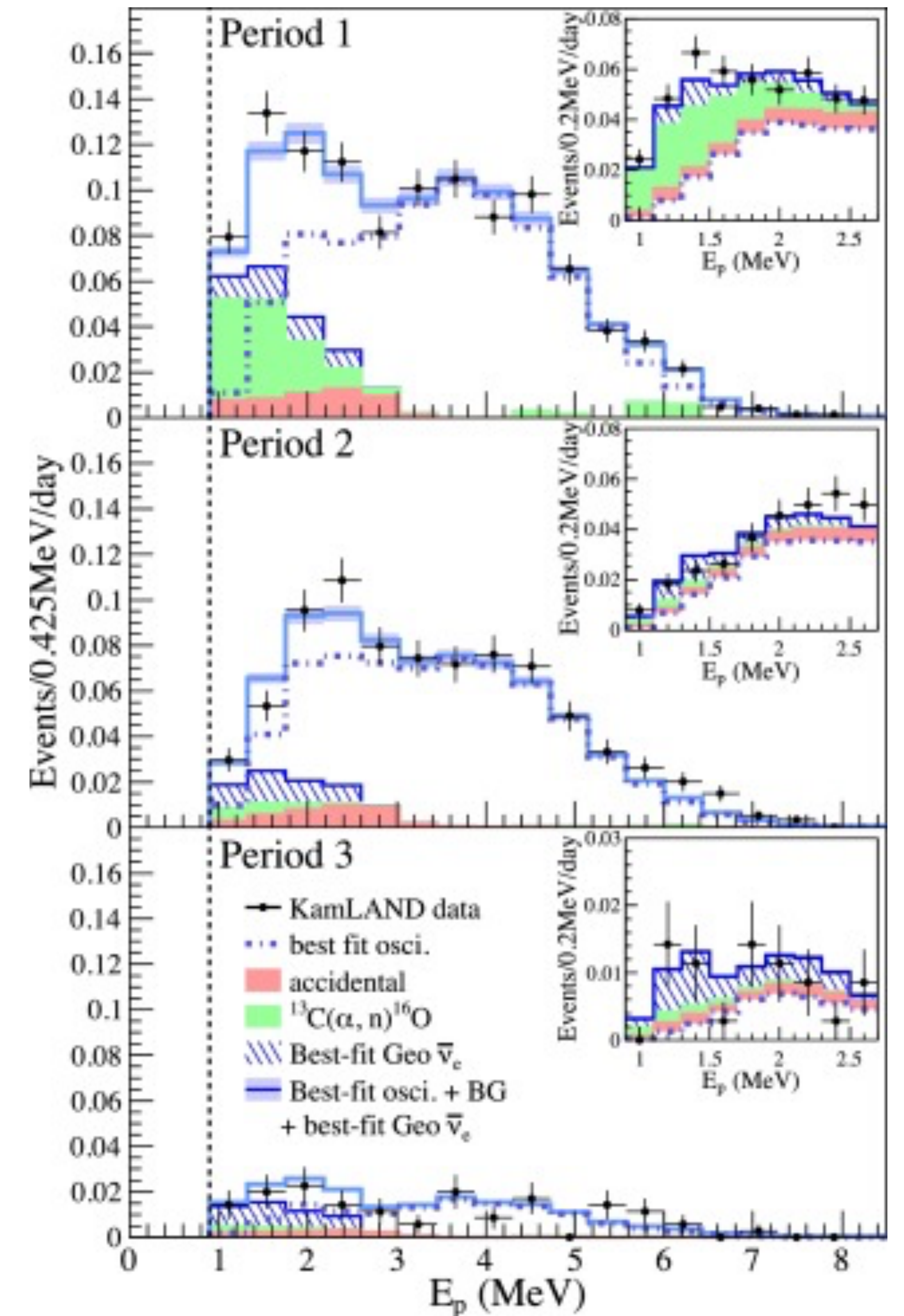
Antineutrinos from the fireball of a nuclear device would impinge on a liquid scintillation detector suspended in the hole dug below ground at a distance of about 40 meters from the 30-meter-high tower. In the original scheme of Reines and Cowan, the antineutrinos would induce inverse beta decay, and the detector would record the positrons produced in that process. This figure was redrawn courtesy of Smithsonian Institution.

(For more information, please see [here](#))

KamLAND

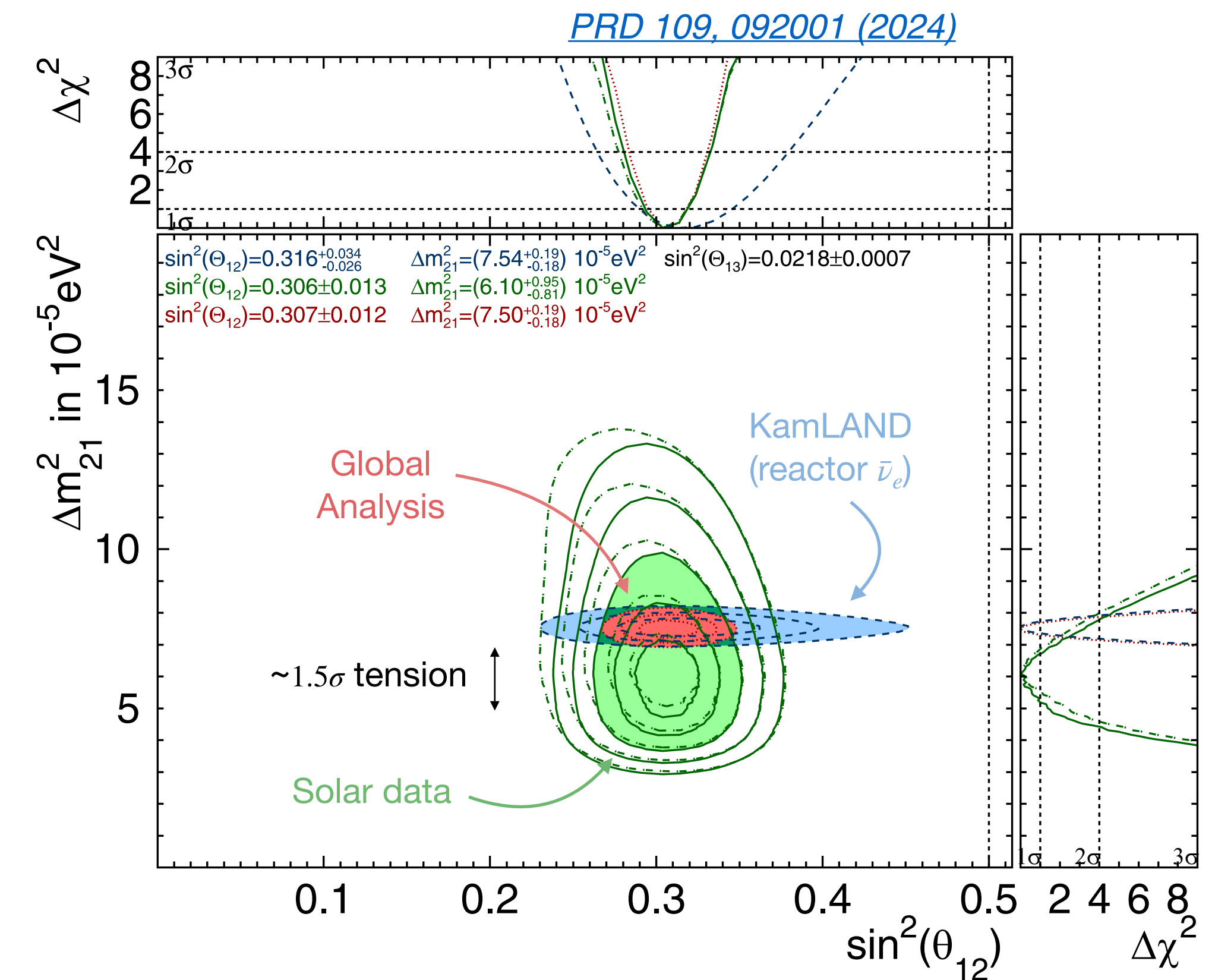
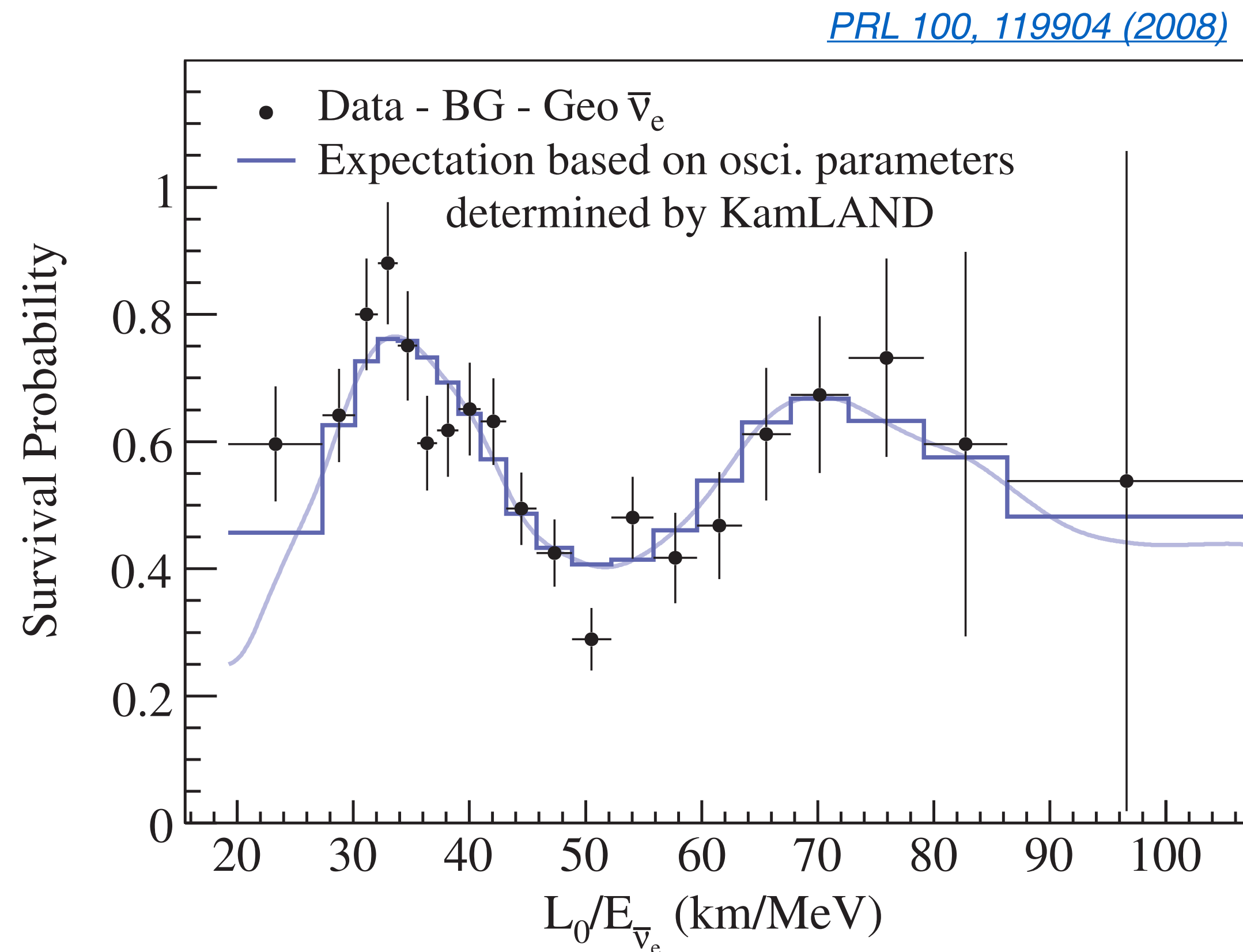


- KamLAND is an experiment in Japan that studied the neutrinos from over 50 nuclear reactors
 - 1 kton liquid scintillator (LS) detector
 - Average baseline of ~ 180 km



KamLAND Key Results

- Best measurement of Δm_{21}^2 (until last year)
- First clear observation of L/E_ν dependence in neutrino oscillations
- First observation of neutrinos from the Earth (geoneutrinos)



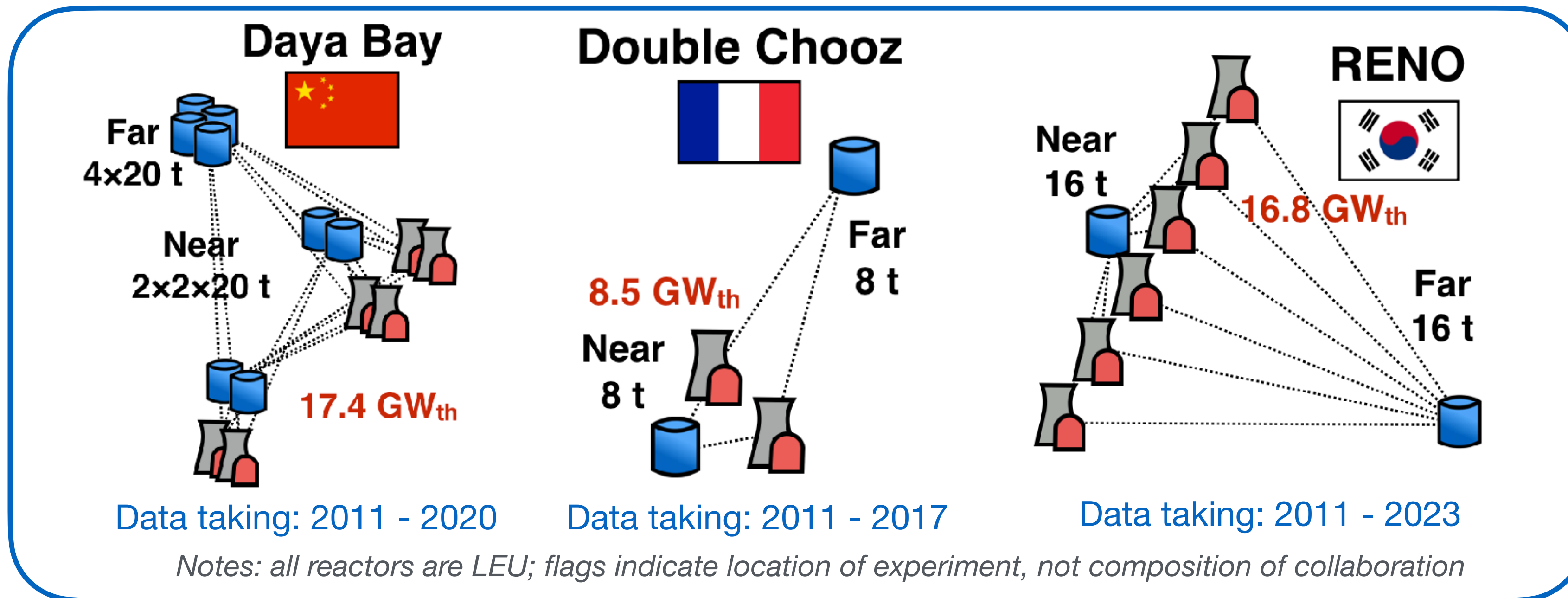
- The experiment has now been reconfigured to search for neutrinoless double-beta decay

The θ_{13} Generation

of Reactor Neutrino Experiments

Basic Layout

- There are three θ_{13} reactor neutrino experiments that recently stopped operating:



Background: understanding if θ_{13} was different from zero was a priority in 2012

- Last unknown mixing angle in the PMNS matrix
- Intrinsically linked to the possibility of observing CP violation in the leptonic sector
- θ_{13} -driven oscillations offer a pathway for measuring the neutrino mass ordering

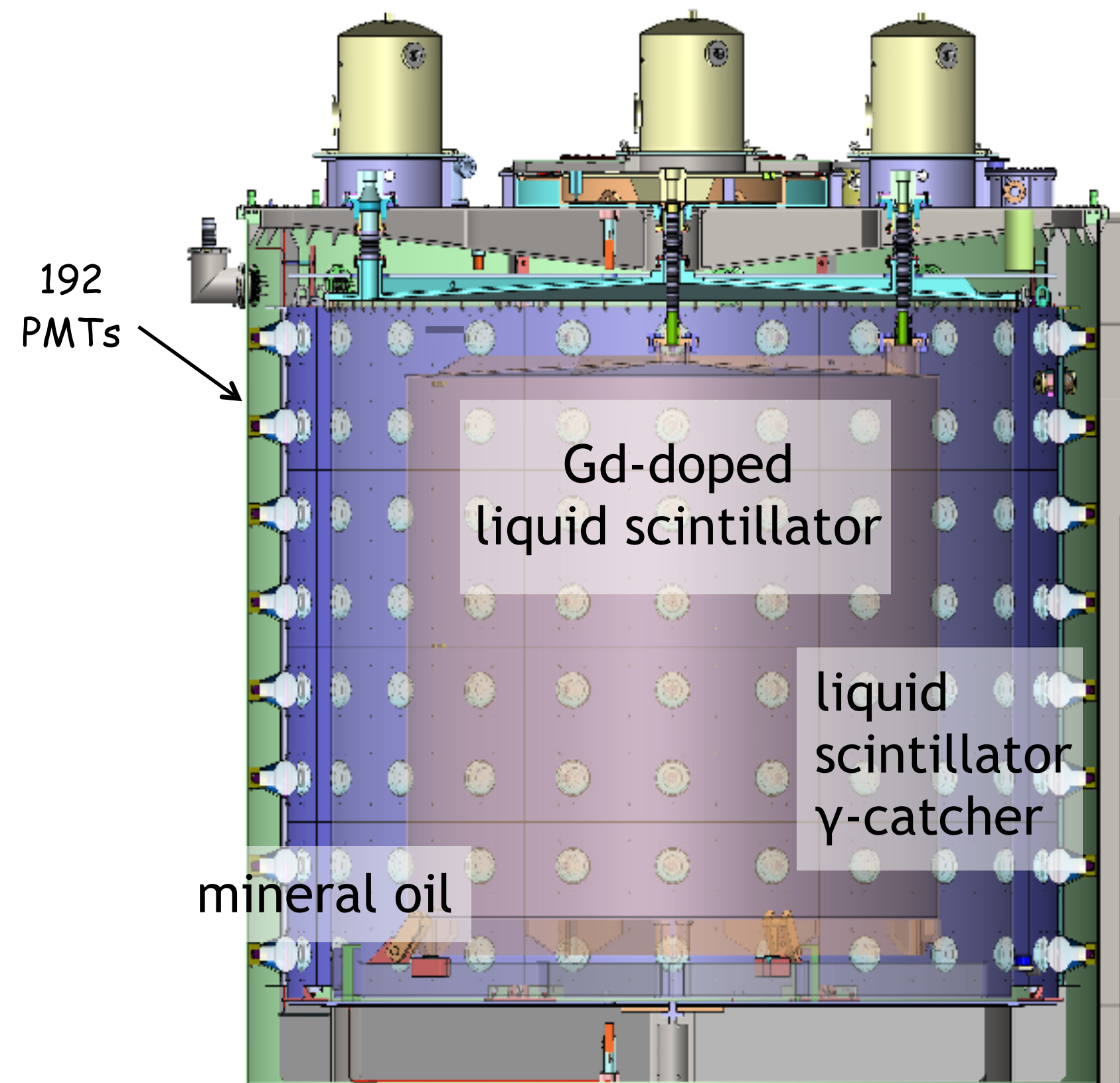
The discovery that $\theta_{13} \neq 0$ set in motion the next-generation program under preparation (DUNE, HyperK, JUNO)

- < 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 essentially cancel uncertainties in flux prediction and correlated detection efficiencies

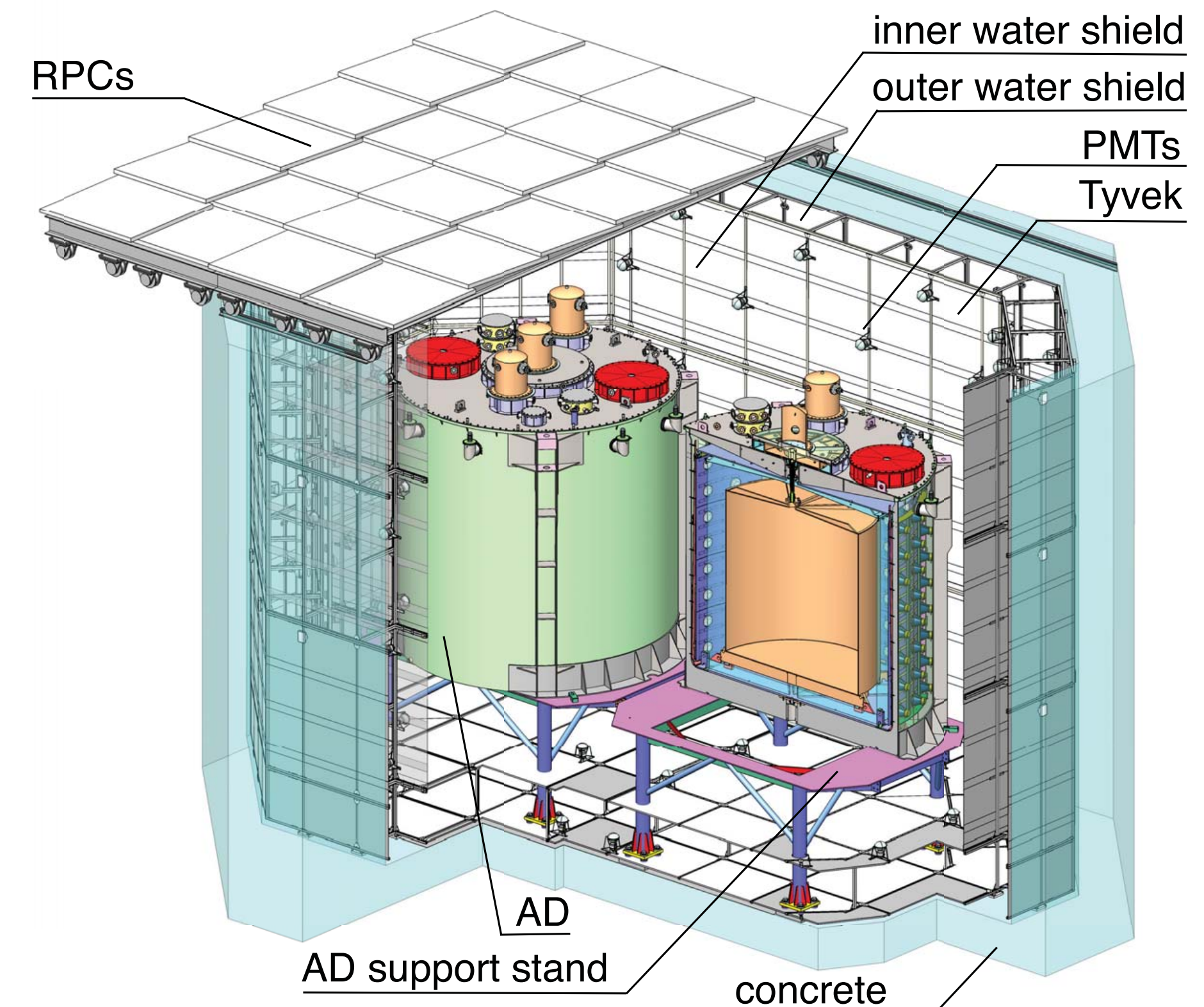
The Detectors

- The three experiments use very similar technology. Here we show Daya Bay:

- Three-zone detectors
- Surrounded by instrumented shields that also veto muons
- LS doped with Gadolinium (GdLS) to enhance capture signal

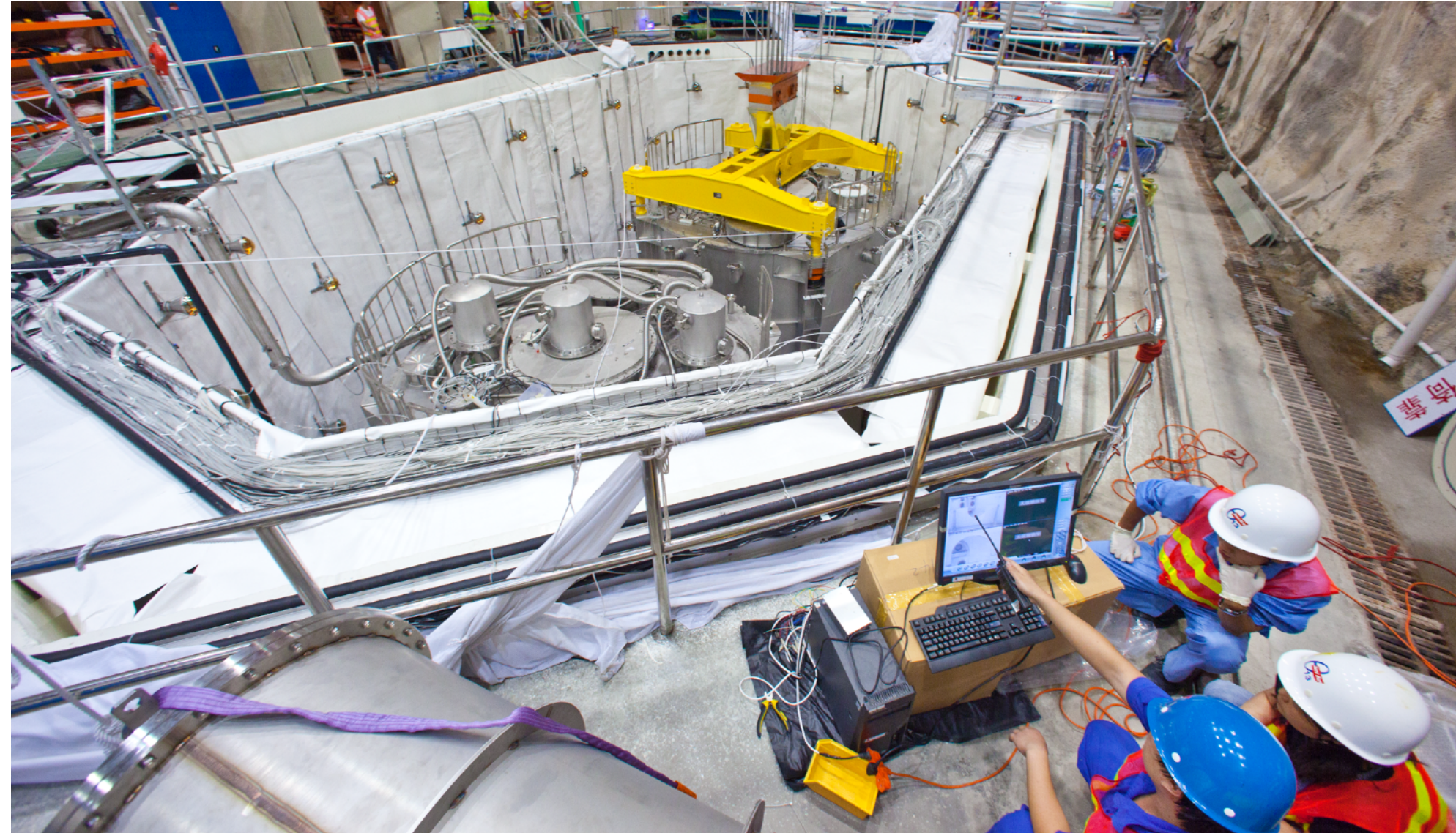


NIM A 811, 133 (2016)



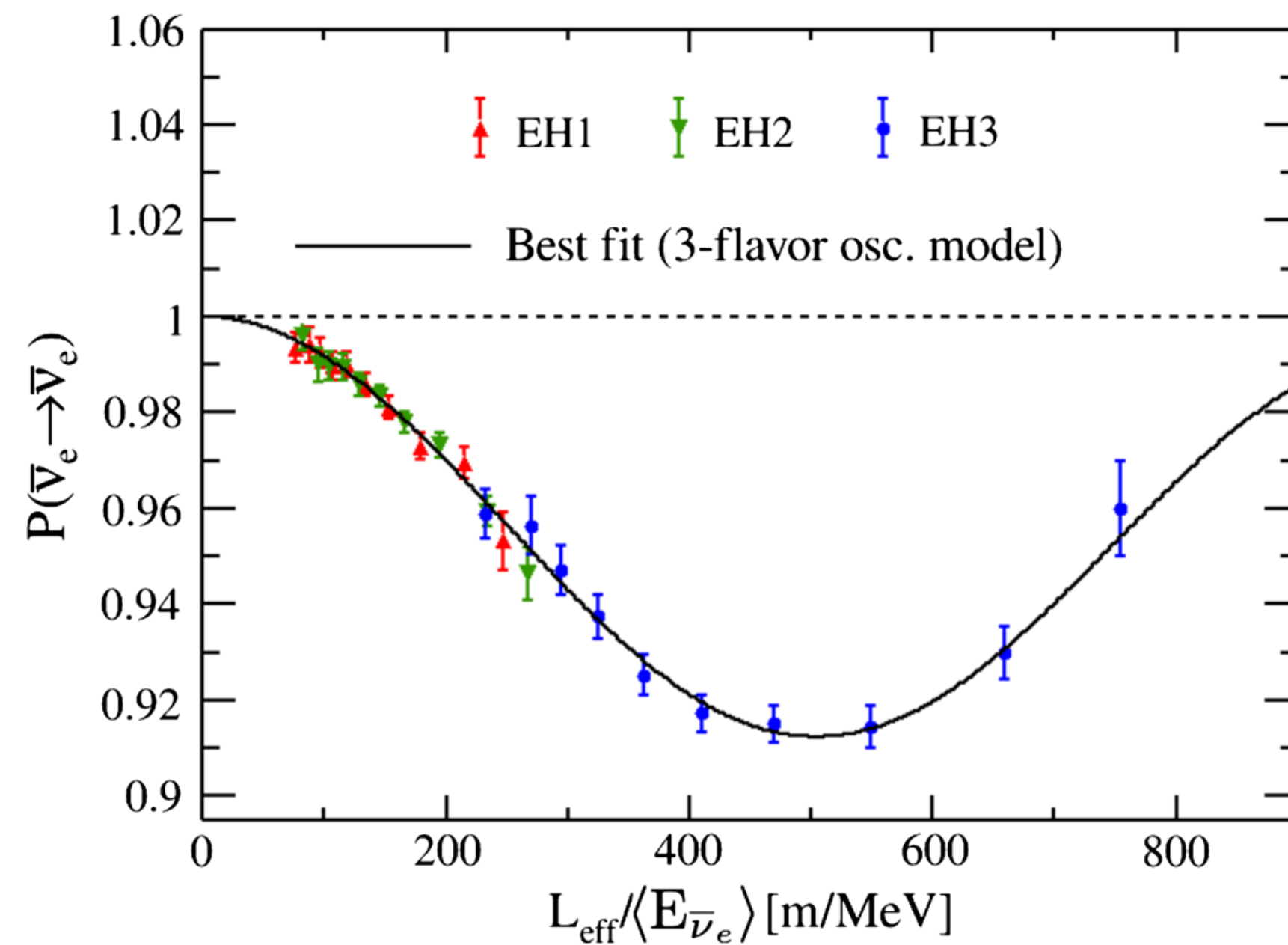
NIM A 773, 8 (2015)

Selection of Pictures

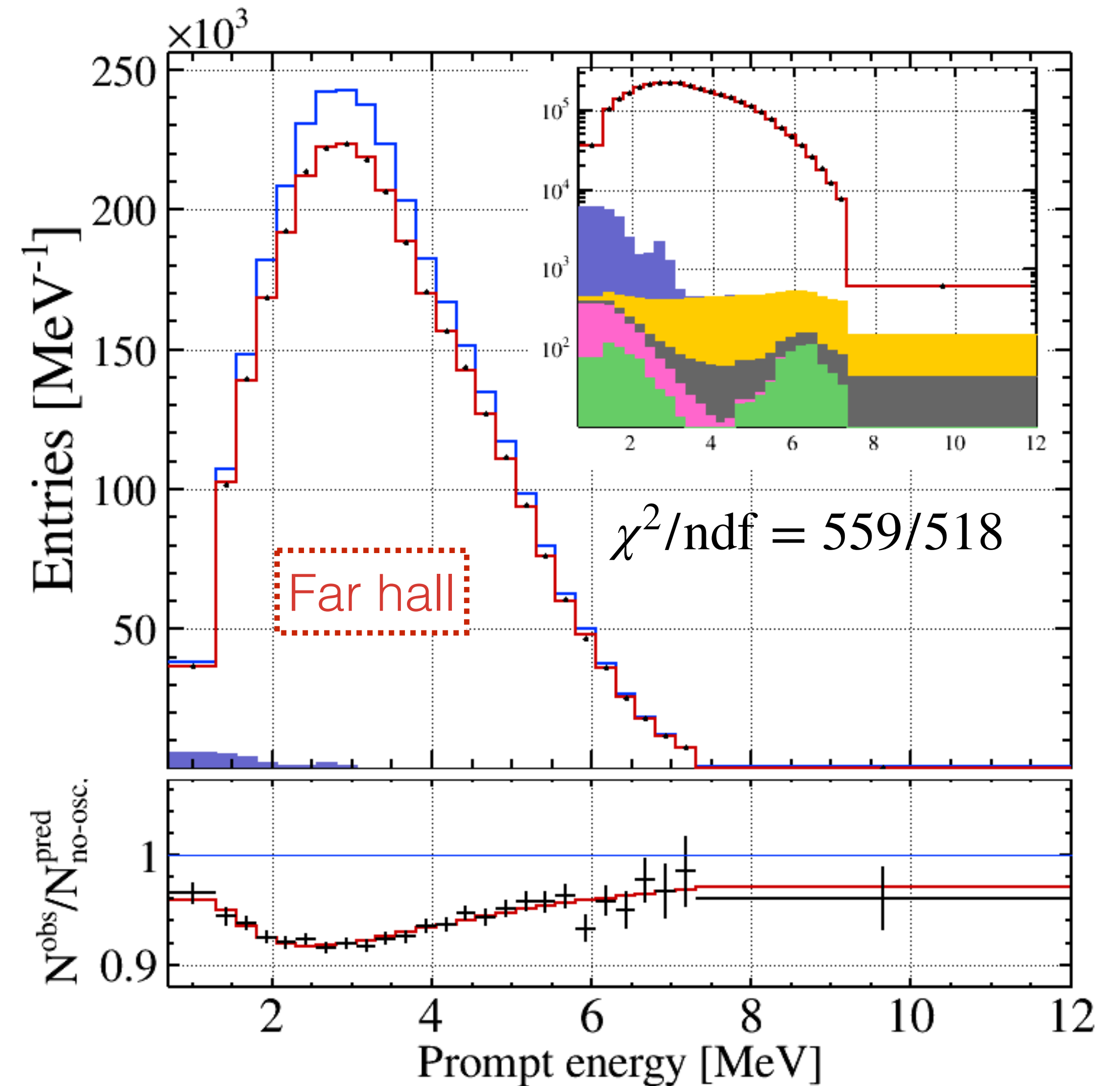


Oscillation Measurements

- These are the latest results from Daya Bay (with neutron capture on Gadolinium):
 - 3158 days of data
 - From spectral distortion simultaneously extract $\sin^2(2\theta_{13})$ and Δm_{32}^2



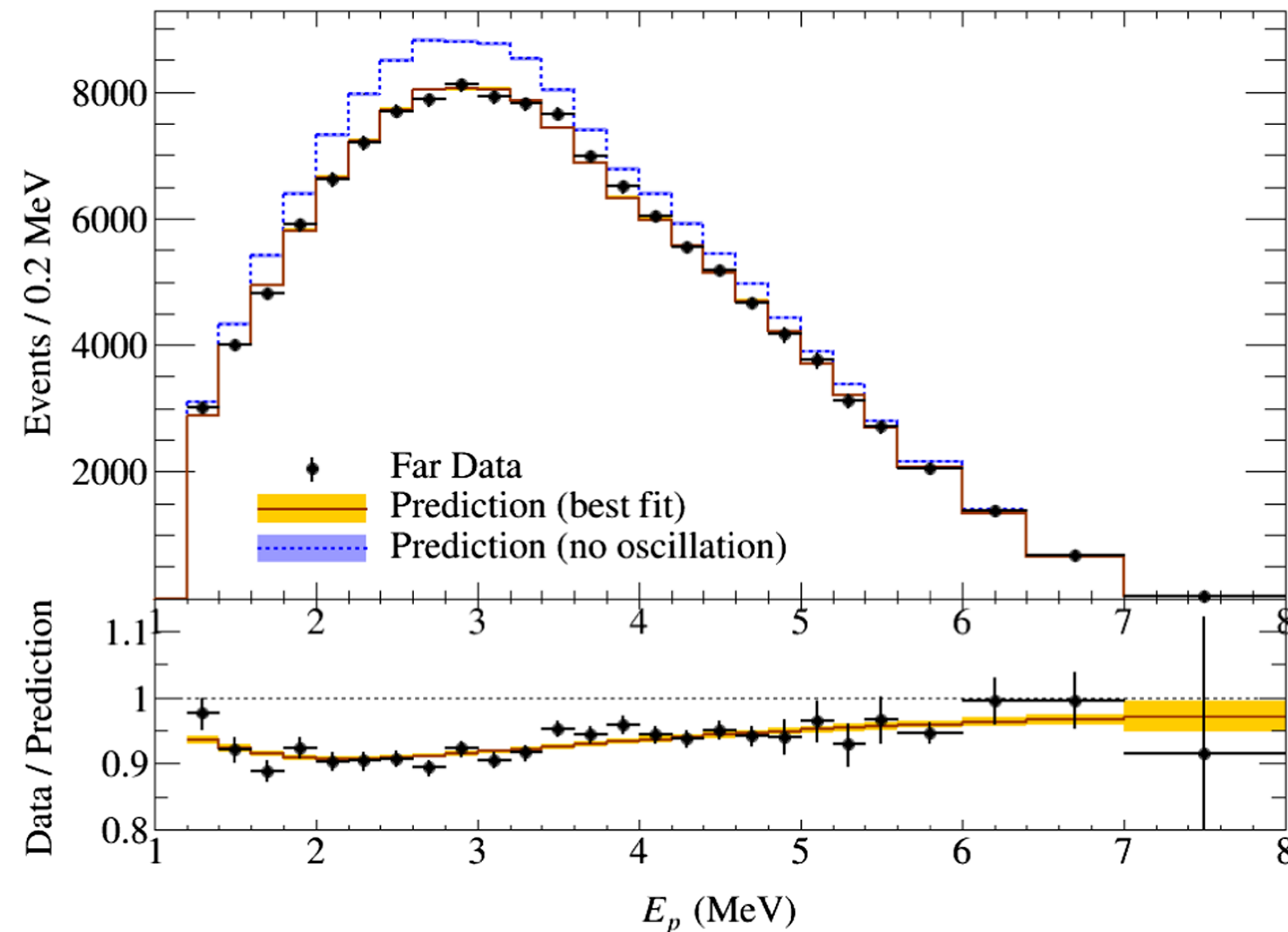
- Excellent fit to standard three-neutrino framework



Oscillation Measurements

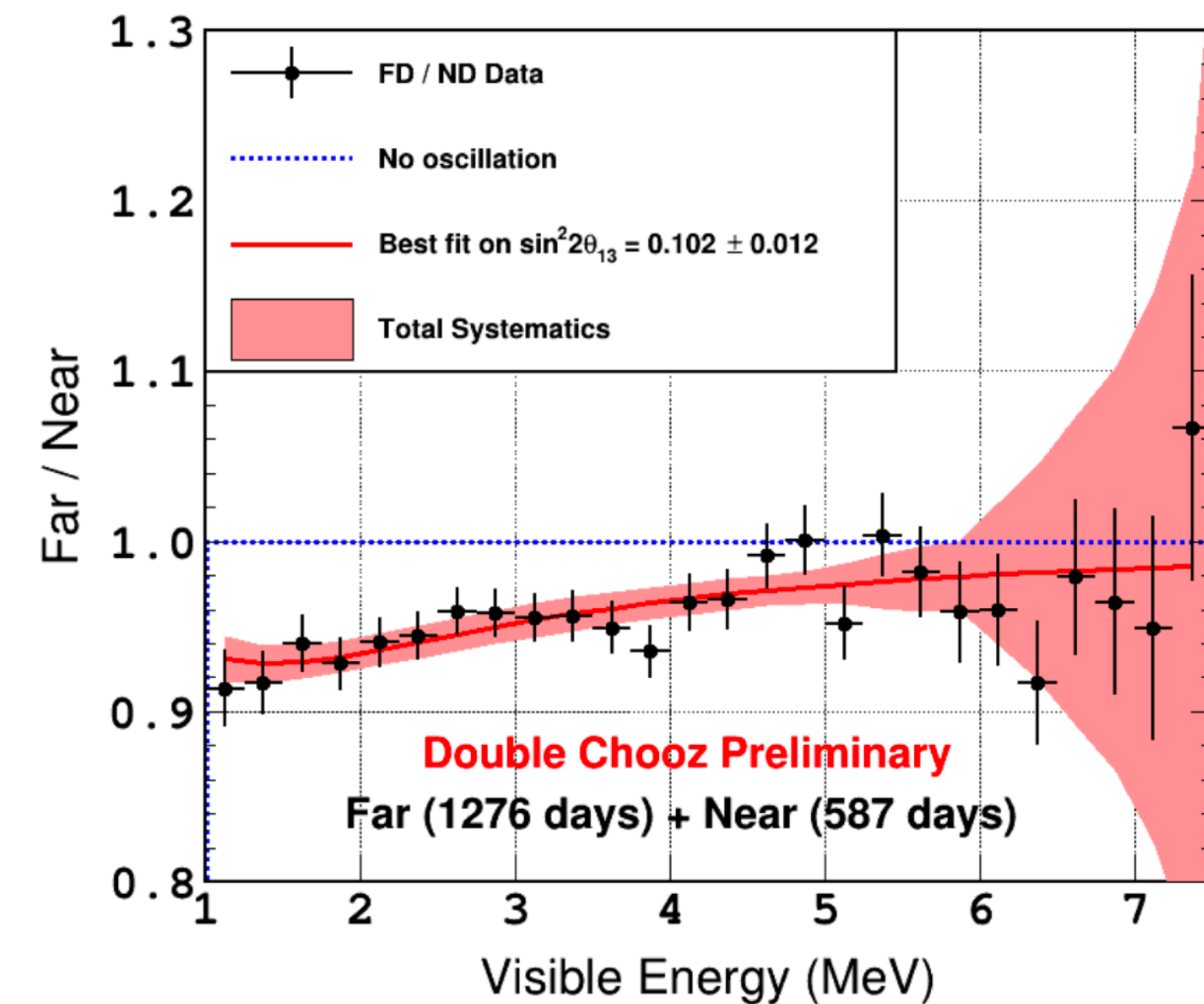
- Latest results from RENO and Double Chooz:

[Phys. Rev. D 111, 112006 \(2025\)](#)



RENO
(capture on Gd)

[Nature Phys. 16, 558-564 \(2020\)](#) and
[10.5281/zenodo.4157464](#)

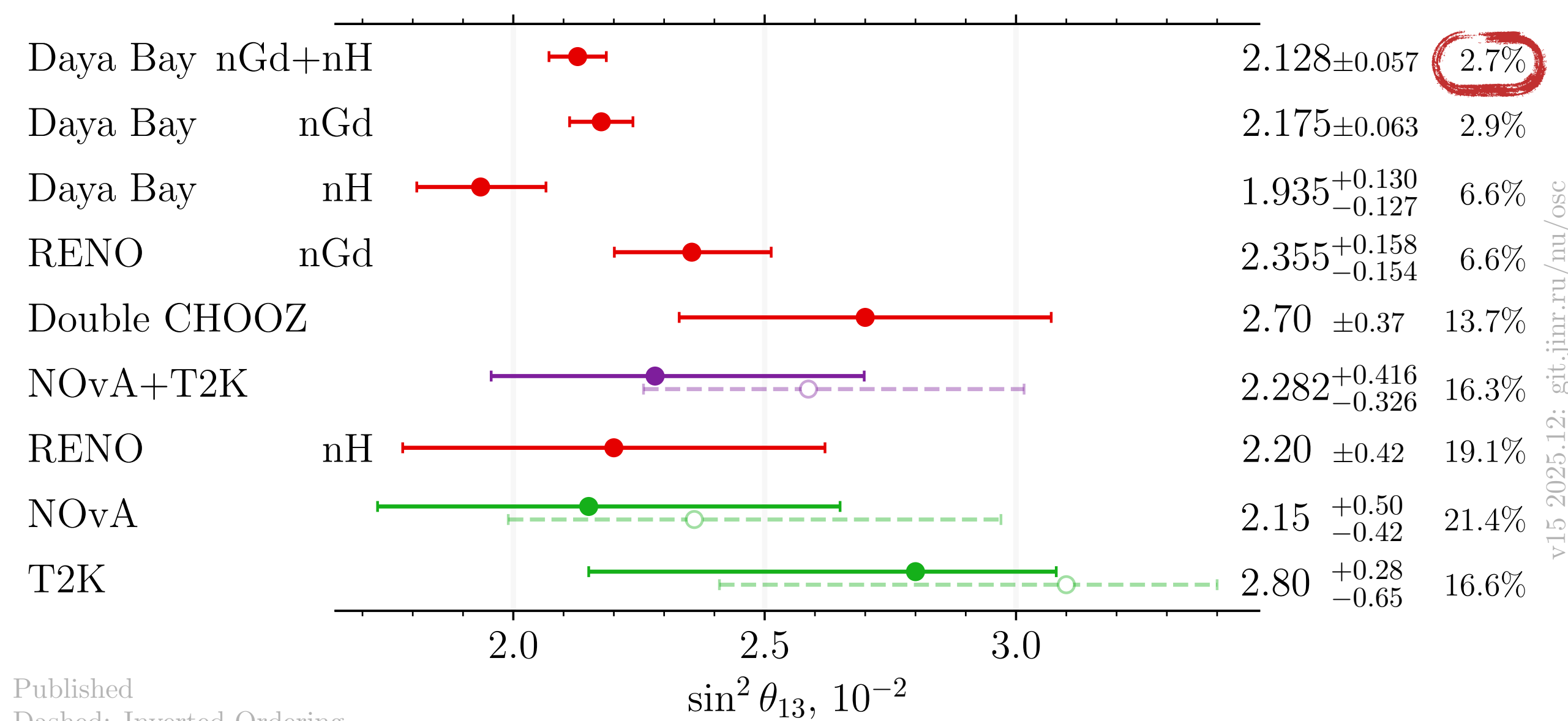


Double Chooz
(capture on H, C and Gd)

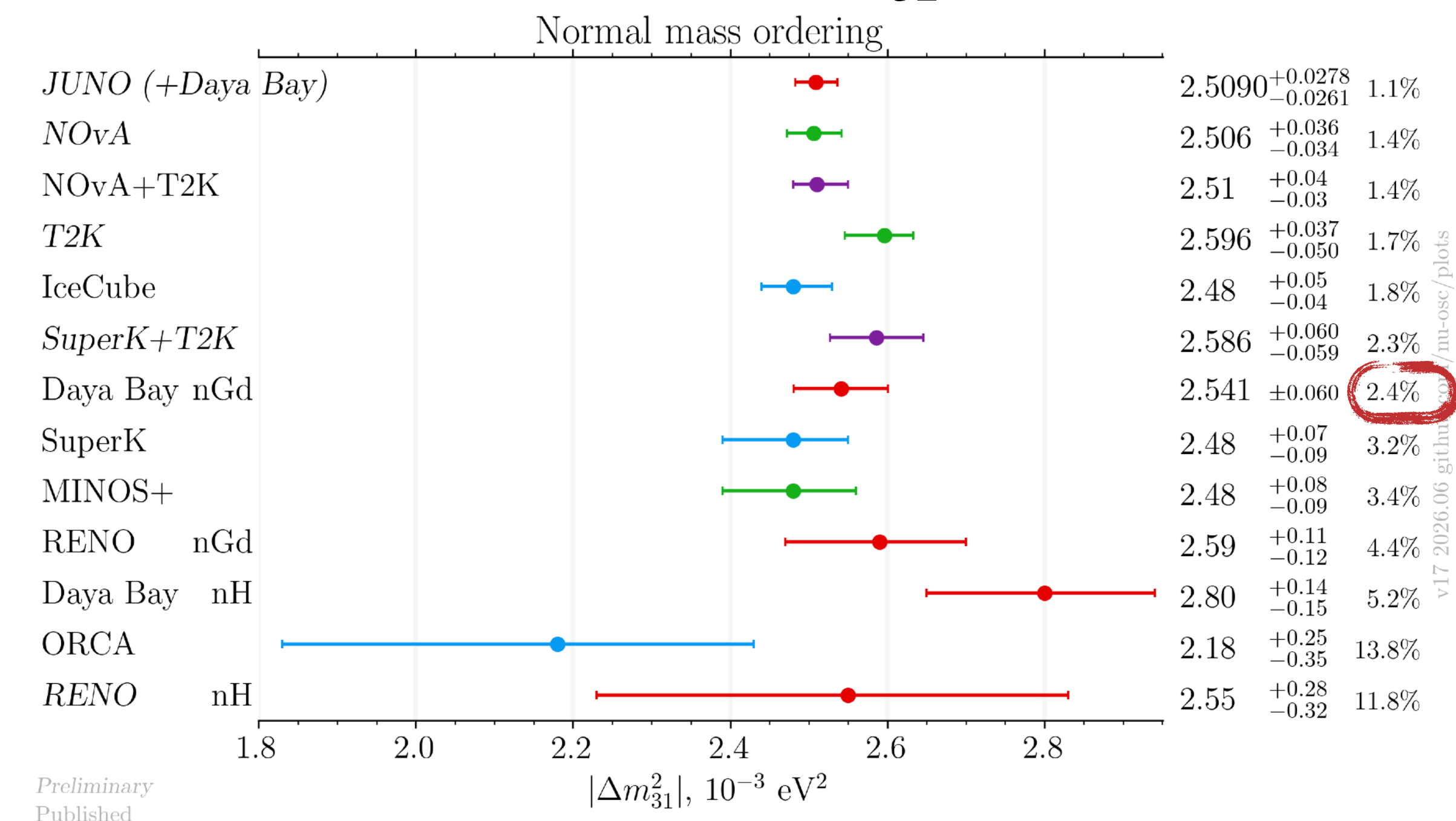
- RENO and Daya Bay also have independent measurements done entirely with capture on Hydrogen (H)

Global Landscape

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



These experiments also have good sensitivity to Δm_{32}^2

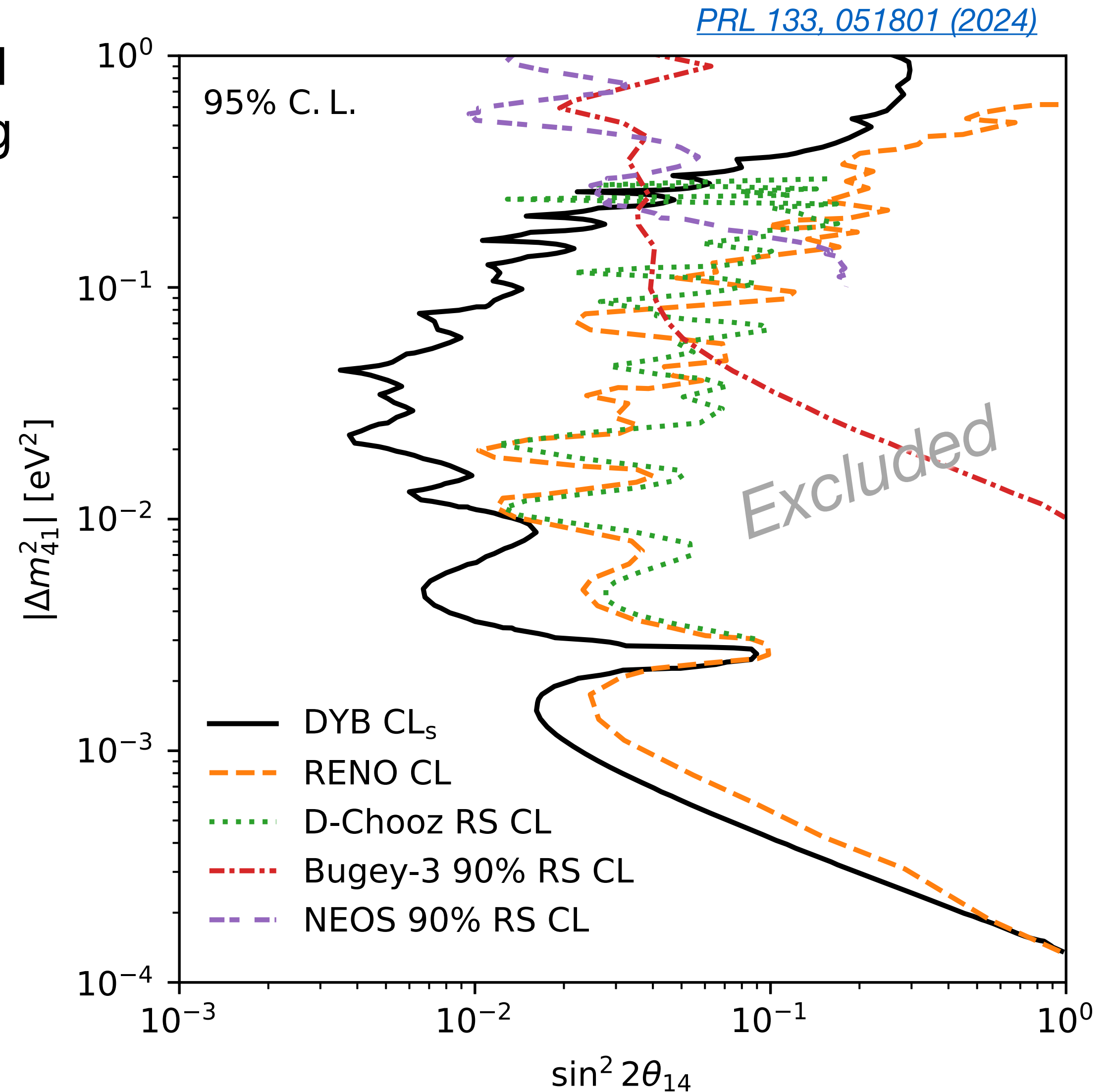
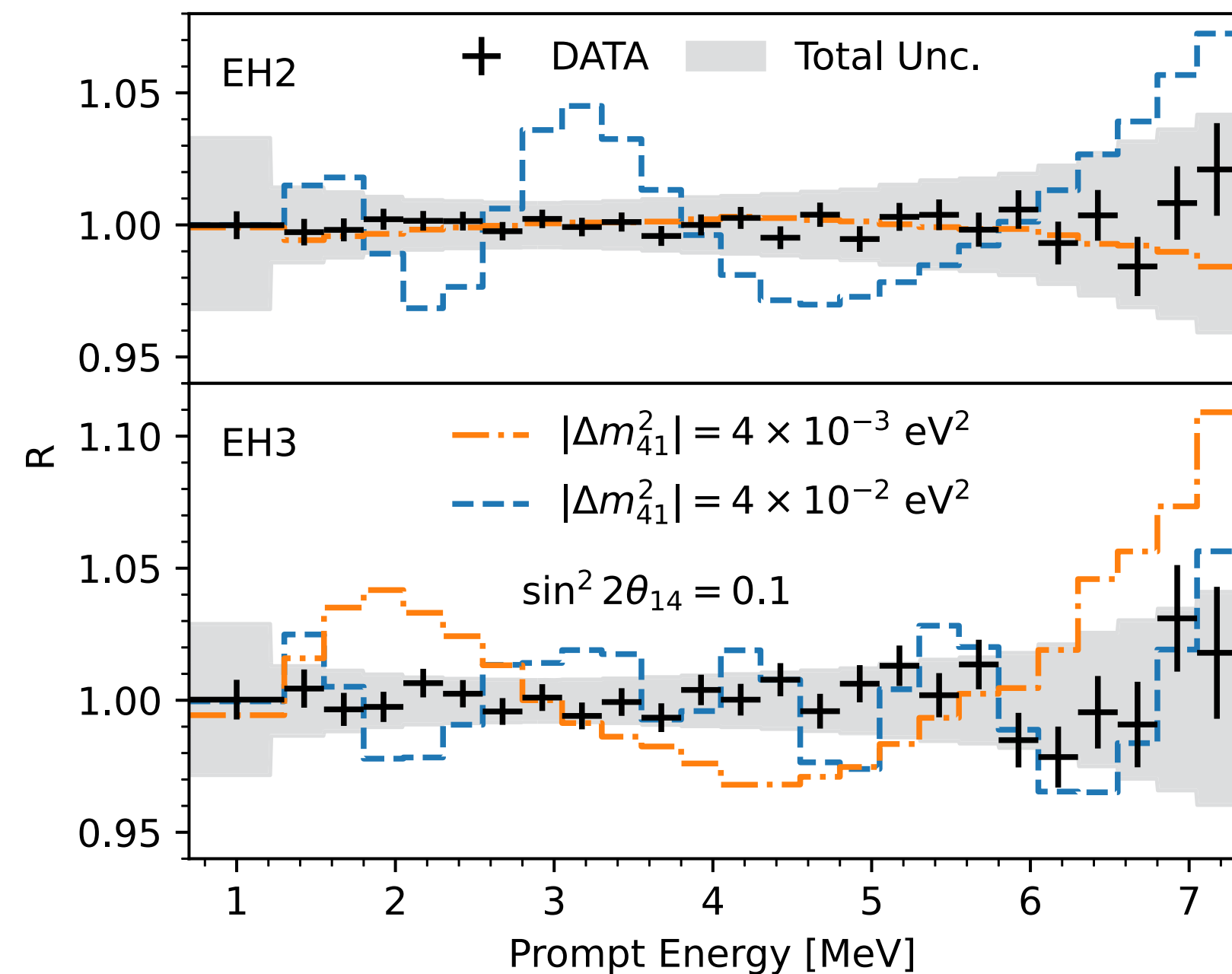


Great agreement with accelerator experiments!

Searches for Sterile Neutrinos

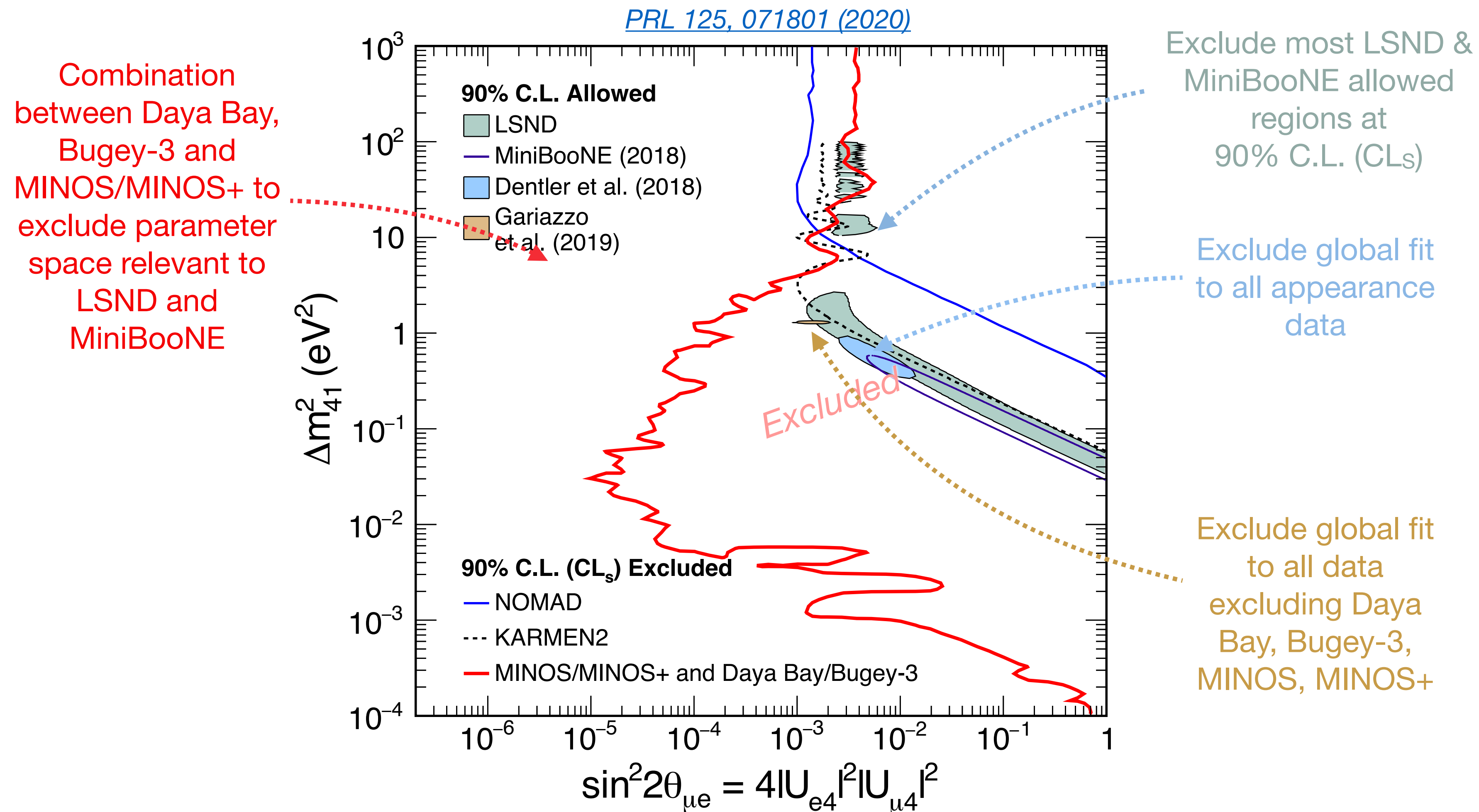
- These experiments are also an ideal ground to search for sub- eV^2 sterile neutrino mixing

To first order, signal would appear as an **additional spectral distortion** with a frequency Δm_{41}^2 different from standard 3- ν oscillations



Combination with Other Experiments

- These experiments have also combined their measurements with those of accelerator experiments
- Most notable example:



Data vs. Models

and Sterile Neutrino Searches

Characterizing $\bar{\nu}_e$ emission

- Given a reactor's operating conditions, it is possible to predict the antineutrino flux emitted by it
 - The million dollar question: does the prediction match the data?
- The θ_{13} experiments have greatly advanced the characterization of the reactor antineutrino emission and the comparison with prediction models:
 - Important for fundamental physics, non-proliferation applications, and as a stringent test of nuclear data inputs
- Two main approaches for predicting the reactor $\bar{\nu}_e$ rate and spectral shape (next two slides)
 - Summation (ab-initio) method
 - Conversion method

Summation (ab-initio) Method

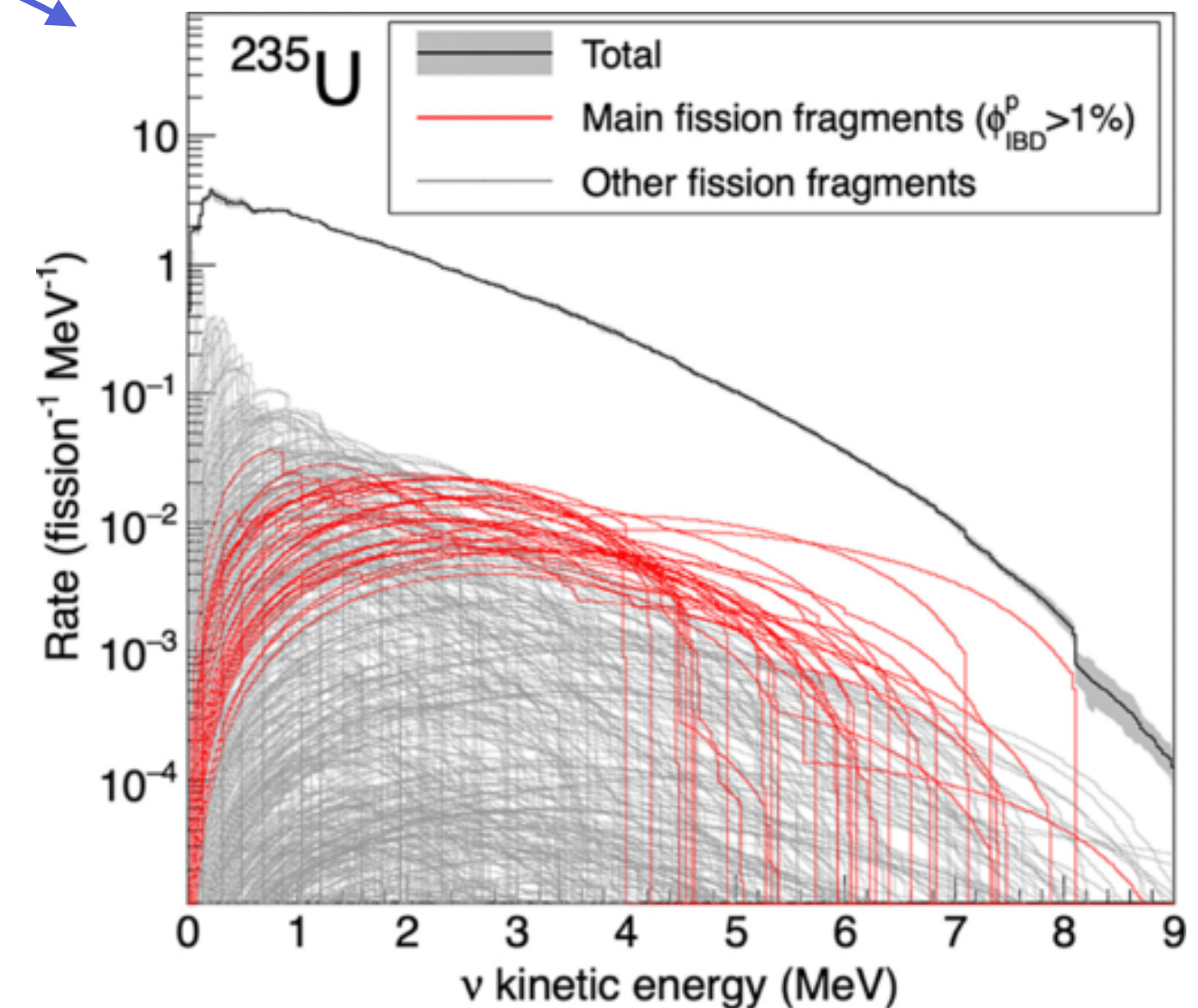
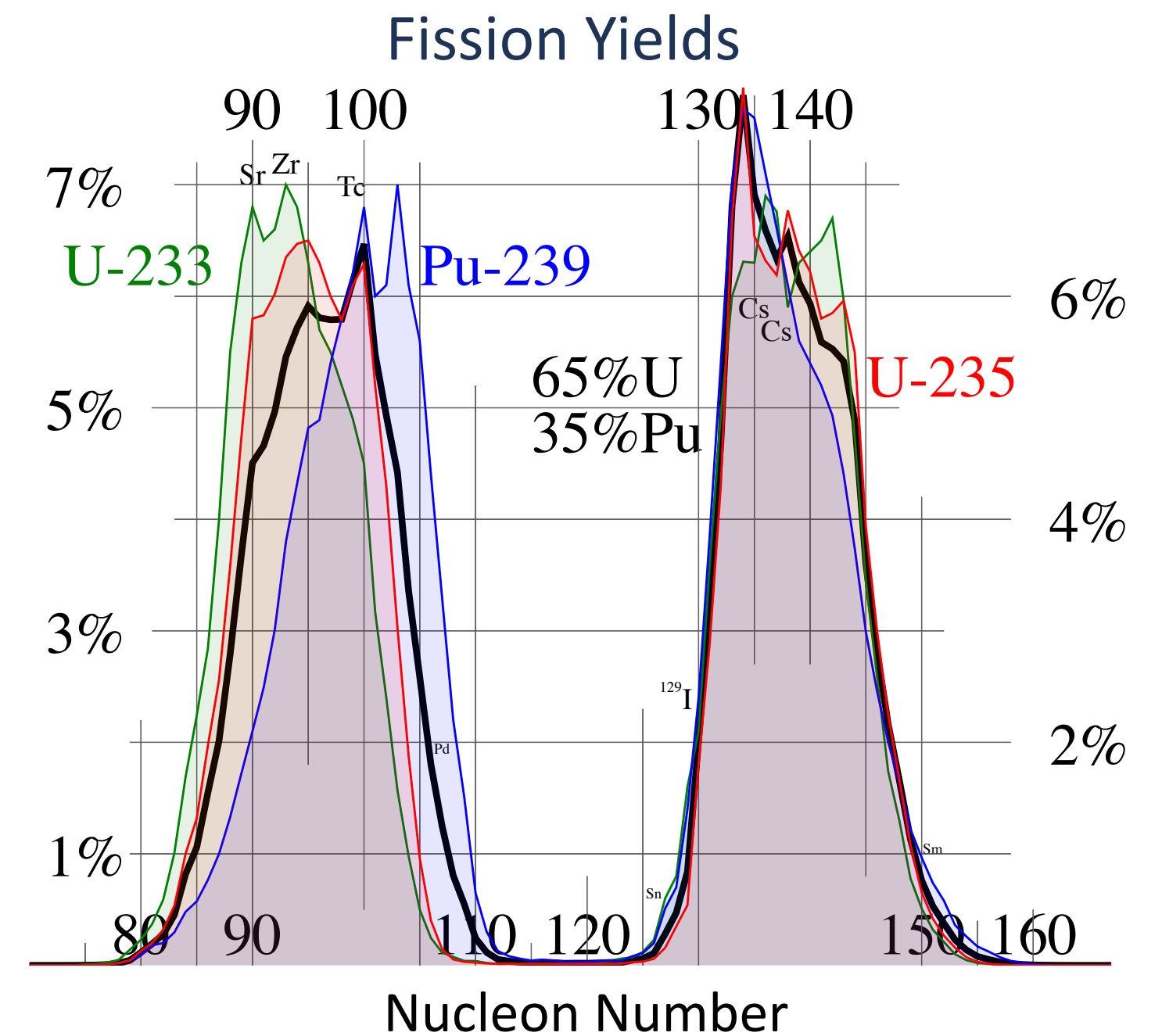
- Summation method: build the spectrum from the bottom-up: fission yields and beta decay branching ratios from nuclear databases

$$\frac{d\phi_i}{dE_\nu} = \sum_n Y_n(Z, A, t) \left(\sum_m b_{n,m} P(E_\nu, E_0, Z) \right)$$

Fission Yields
beta decay branches
antineutrino spectra
($E_\nu = E_0 - E_e$)

A recent implementation is the **SM2023** model

- Challenges:
 - Incomplete database data (~10% of decays)
 - Forbidden decays (poorly known energy-dependent shape factors, affects ~30% of decays)
 - Pandemonium effect (bias in traditional beta decay measurements with HPGe detectors)
 - Difficult to ascertain uncertainties



~800
fission
products,
> 10k
decay
branches

Conversion Method

- Conversion method: convert measured beta spectra from thermal-neutron induced fission (^{235}U , ^{239}Pu , ^{241}Pu) to $\bar{\nu}_e$ spectra

- Use beta spectra measured at Institut Laue-Langevin (ILL) in the 1980s
- Fit with ~ 30 virtual beta decay branches with endpoint energies equally spaced across the spectra

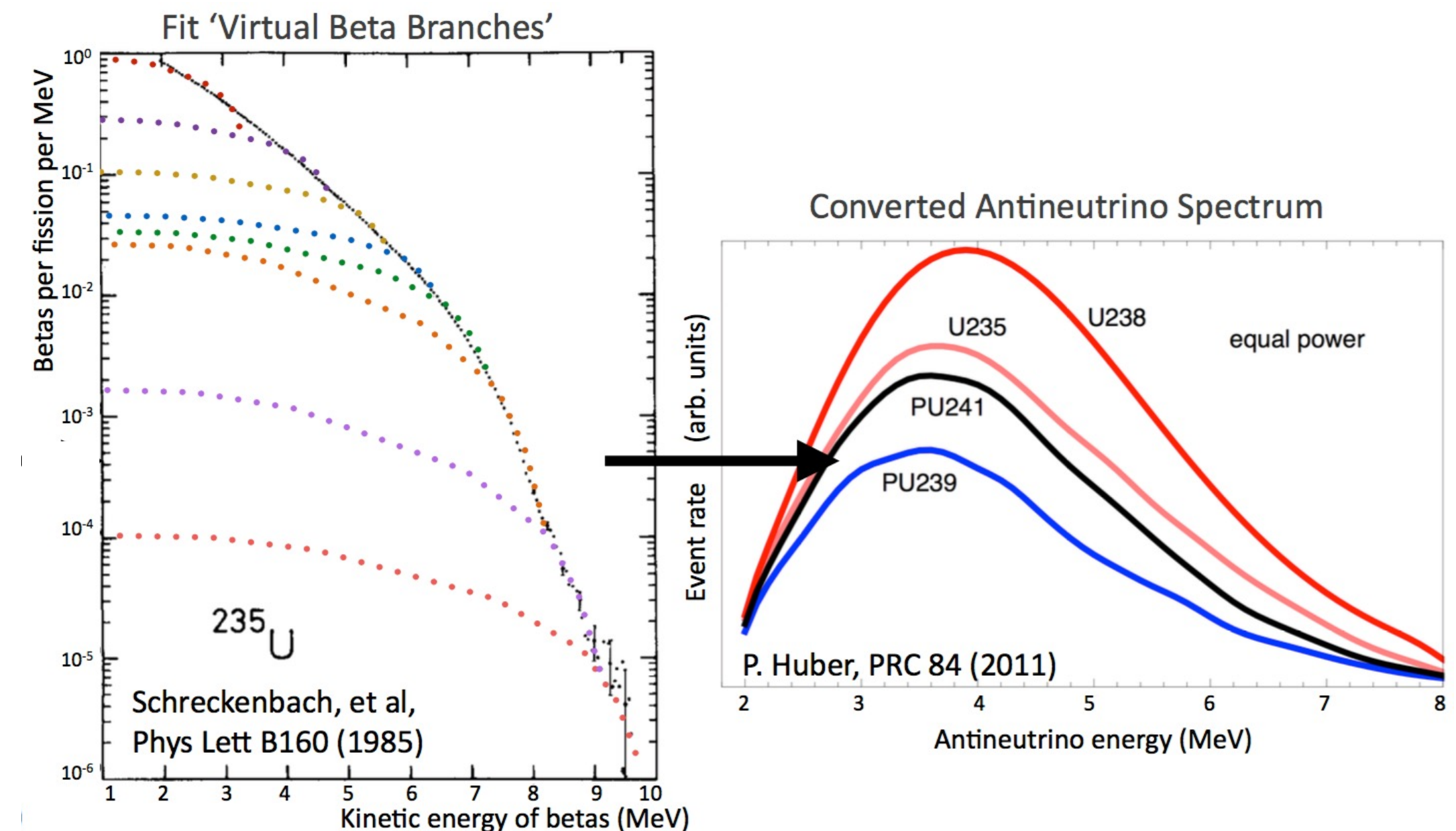
Latest implementation is the so-called Huber+Mueller (HM) model

- Advantages:

- Smaller, well-defined uncertainty ($\sim 2.7\%$)

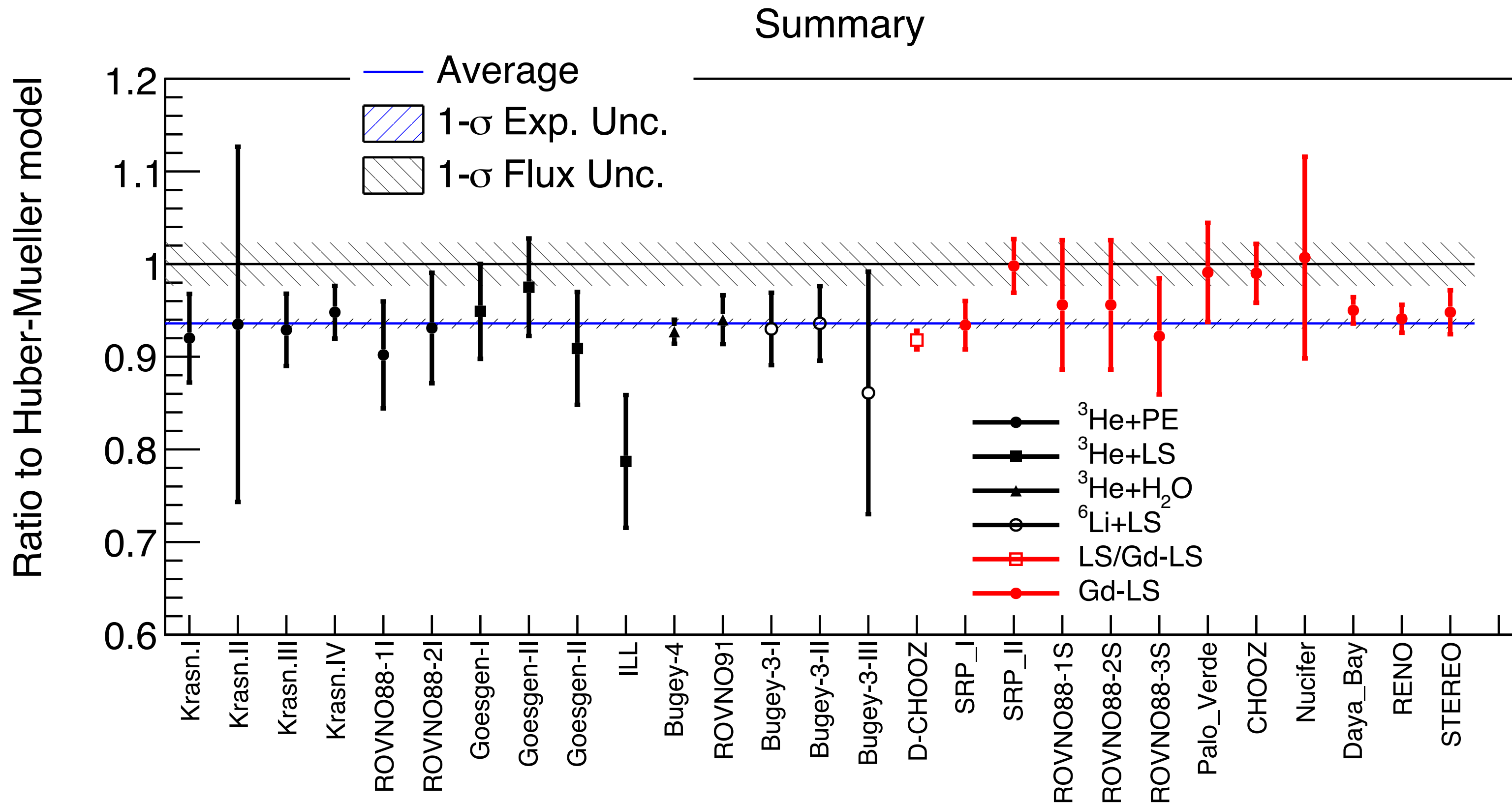
- Caveats:

- Relies on one and only measurement @ ILL
- Requires correction for non-equilibrium effects (small impact)
- Requires correction of nuclear effects on beta spectra (Coulomb, forbidden-transition shape factors, weak magnetism... etc)



Comparison with Data: Total Flux

- First thing to try: compare the total predicted flux with the measured one

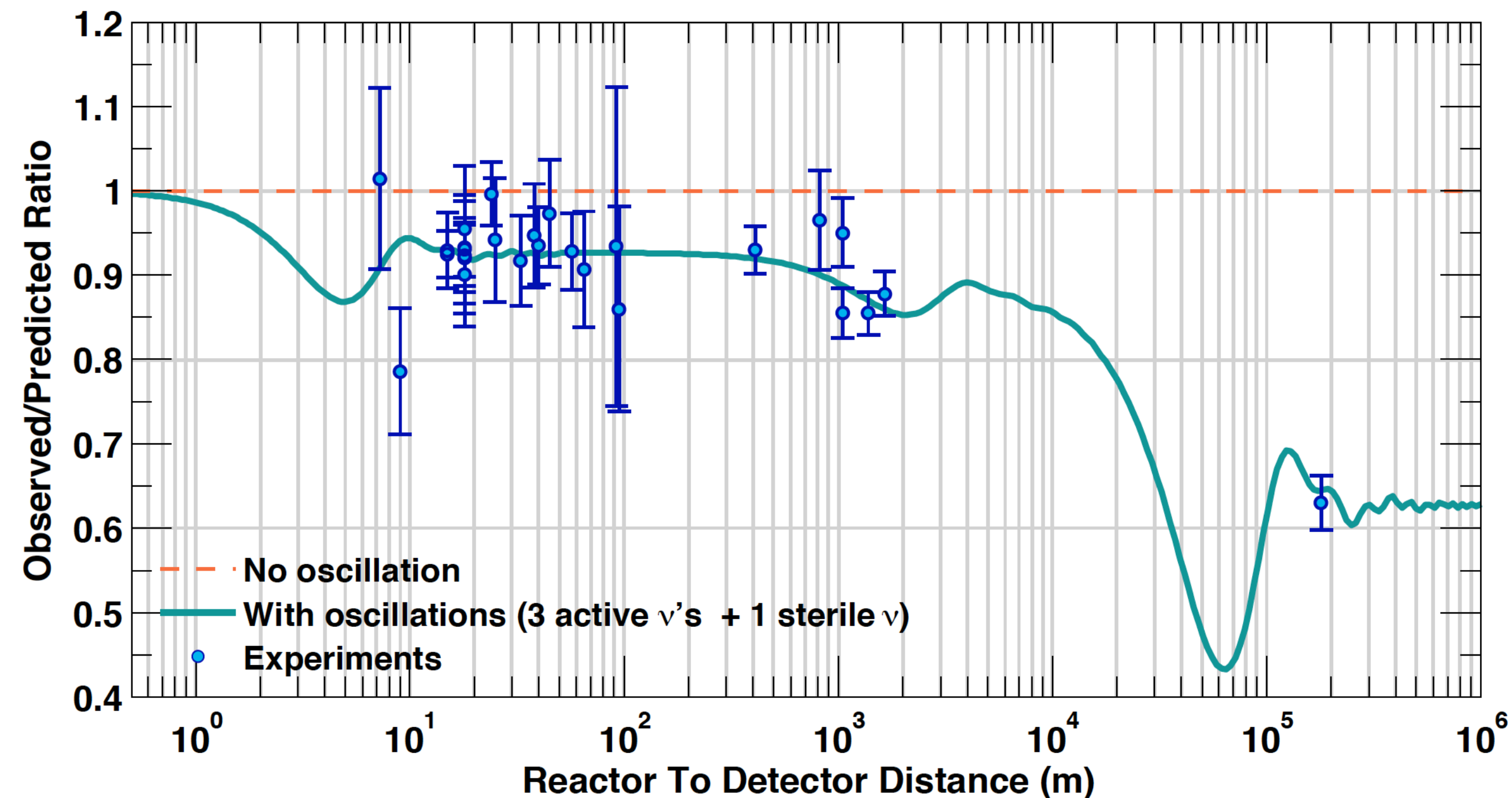


[PPNP 136, 104106 \(2024\)](#)

- 27 measurements at short (<1 km) baselines since 1980
- ~6% deficit in total flux with respect to the HM model at short baselines is known as the “reactor antineutrino anomaly” (RAA)
- About 2.6σ significant
- Not seen with recent summation models
- Primary motivation for short baseline (SBL) sterile neutrino searches

Causes of the RAA?

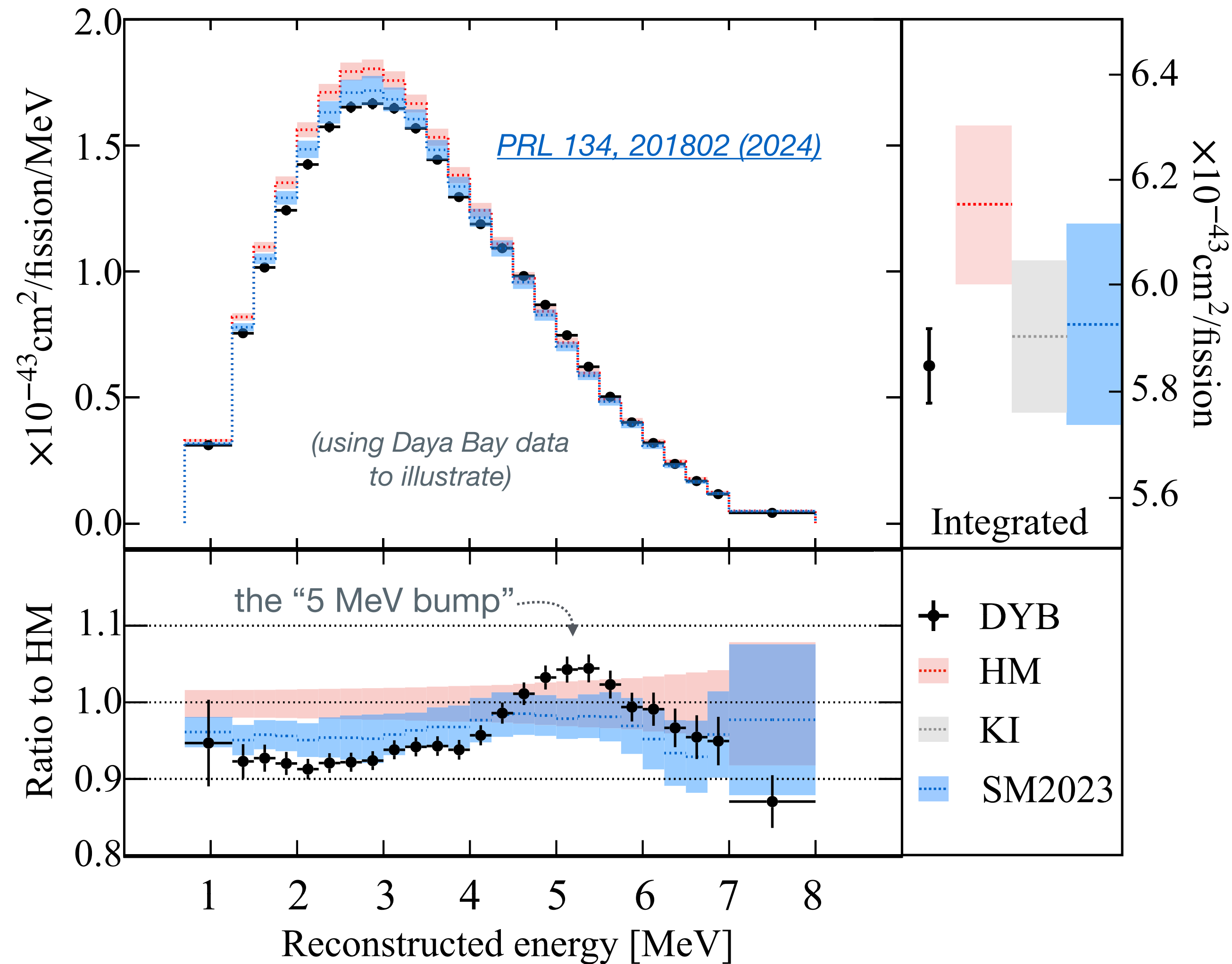
- What could be behind the reactor antineutrino anomaly?
 - Experimental systematics? **Extremely unlikely...**
 - New Physics (oscillations to a $\sim$ eV sterile neutrino)? **Maybe...**



- Unaccounted systematics and/or biases in the prediction? **Likely...** see next slides

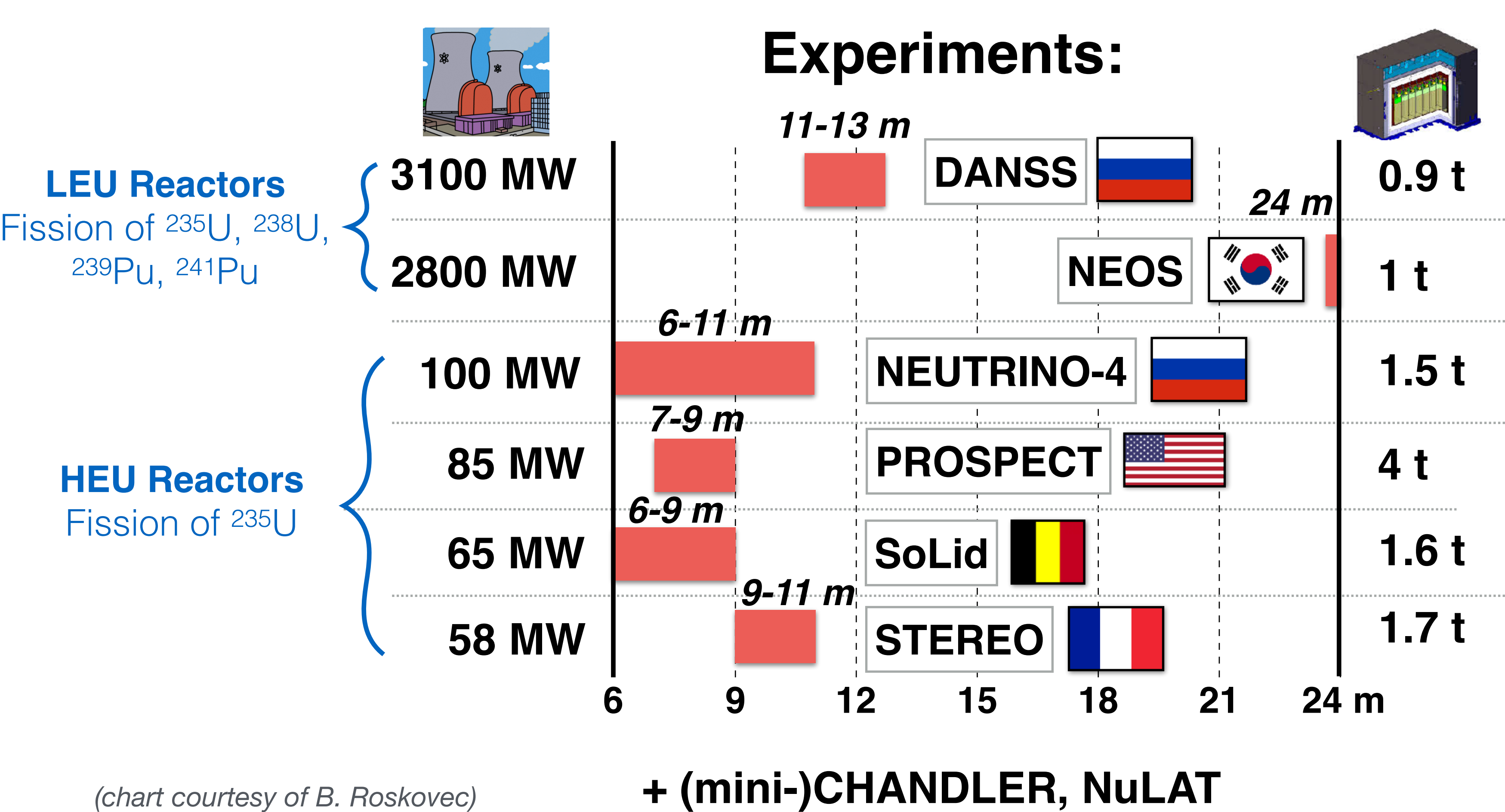
Comparison with Data: Spectral Shape

- The θ_{13} experiments were the first to measure the spectral shape of reactor antineutrinos with unprecedented statistics
 - Main disagreement found is often referred to as “the 5 MeV bump”
 - Seen with both summation and conversion models
 - Cannot be explained with sterile neutrino oscillations
 - Now seen by over 10 experiments (see backup)



Short Baseline (SBL) Experiments

- It is possible to test the sterile neutrino explanation of the RAA by placing a detector at a $O(10\text{ m})$ baseline from a reactor



Looking for a smoking gun for sterile neutrino oscillations: a **spectral distortion in L/E**

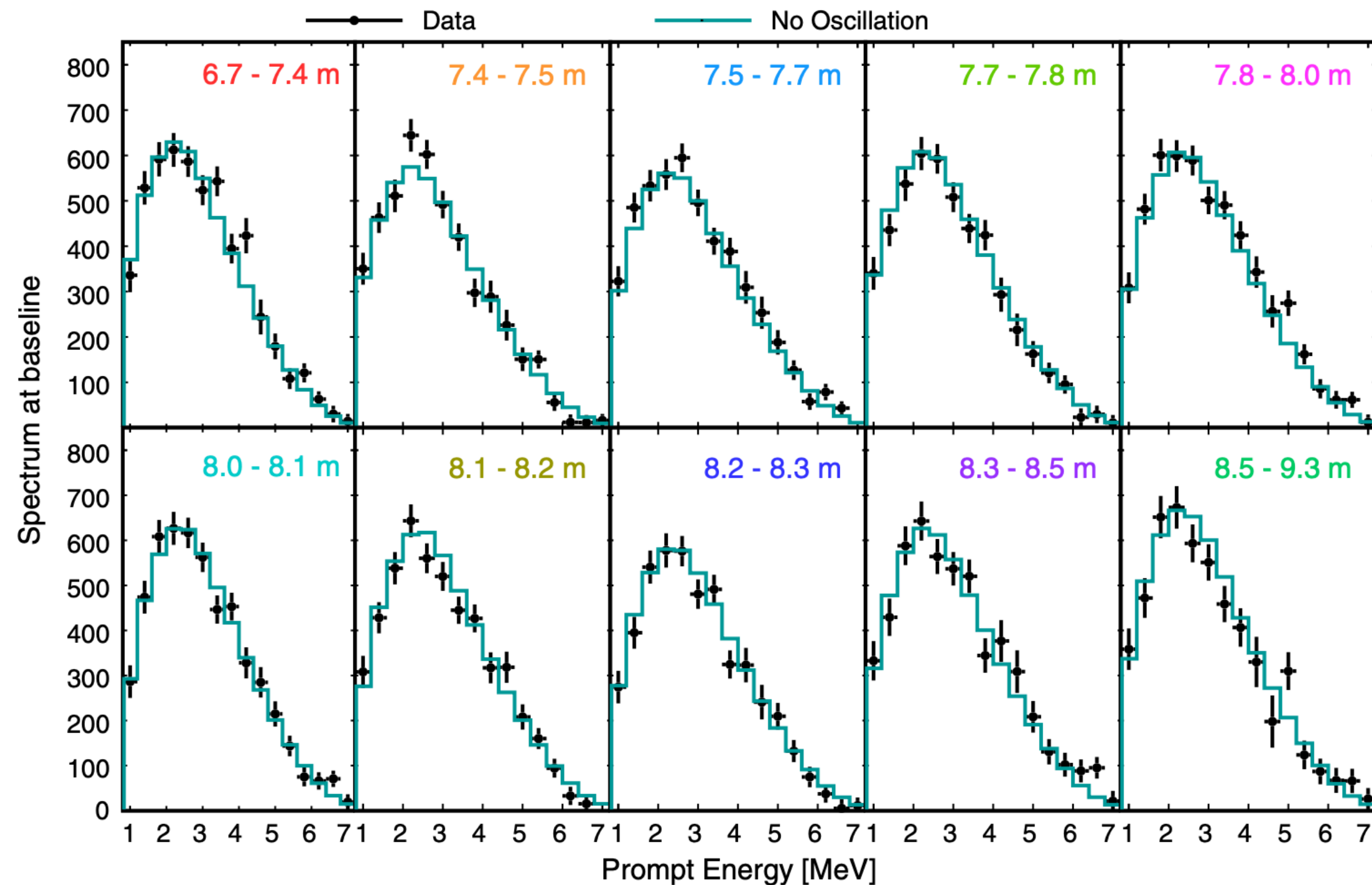


Main strategy: avoid reliance on model prediction; instead, search for relative spectrum distortion at different baselines (by **segmenting** the detector or making it **movable**)

SBL Null Results

- All SBL experiments have released results by now. For example:

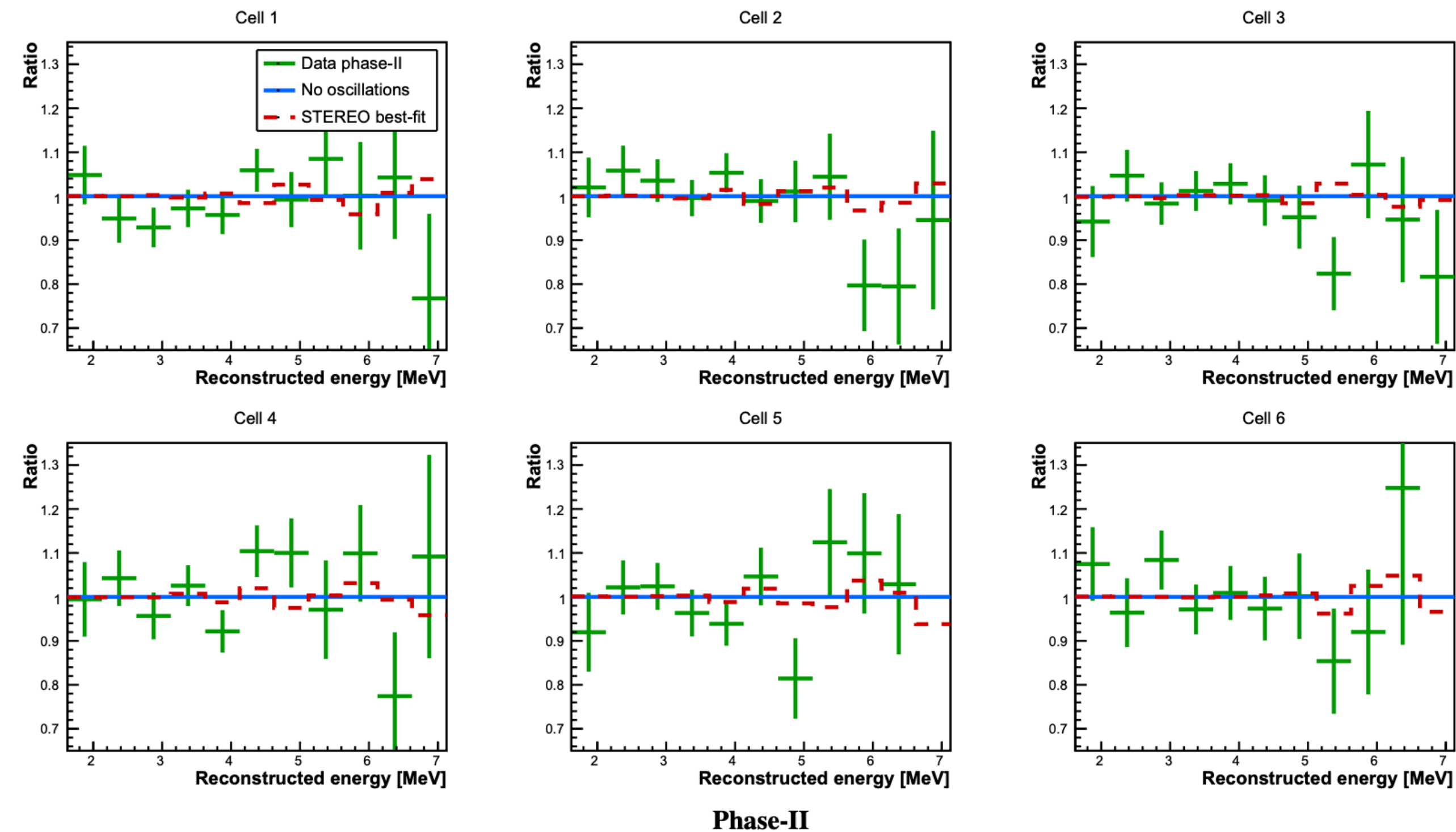
PROSPECT



[Phys. Rev. D 103, 032001 \(2021\)](#)

(More recent results available in [Phys. Rev. Lett. 134, 151802 \(2025\)](#))

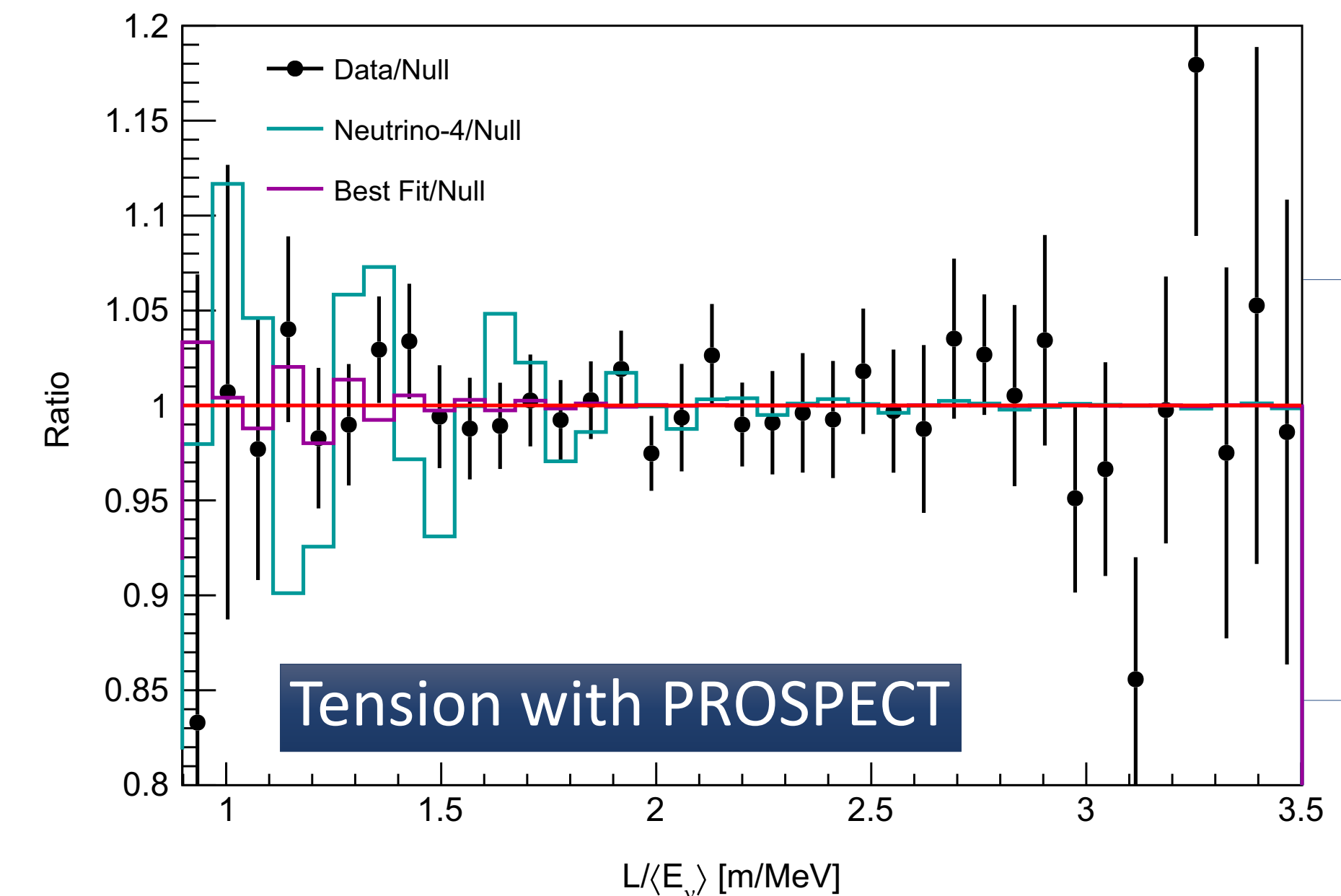
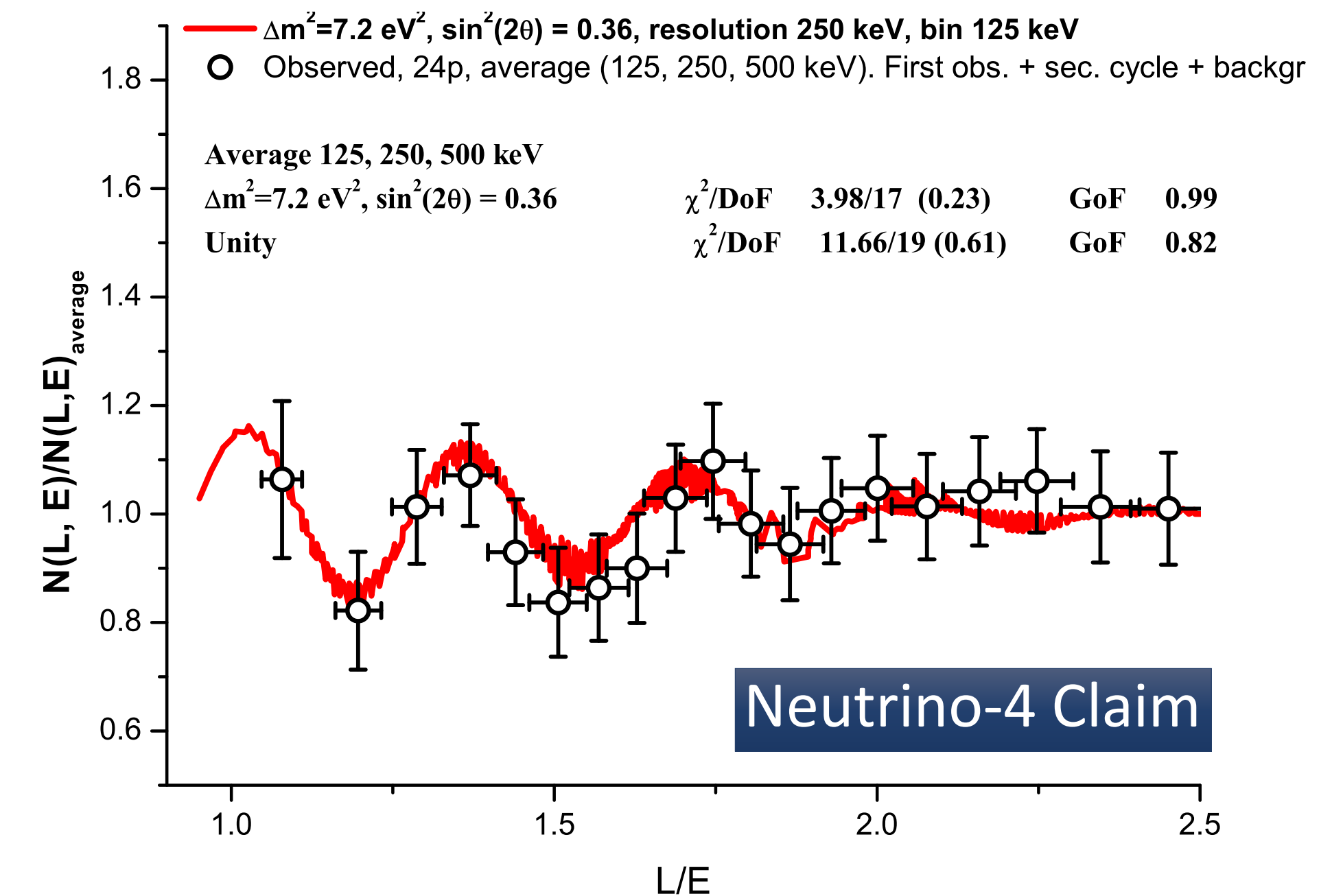
STEREO



[Nature 613, 257 \(2023\)](#)

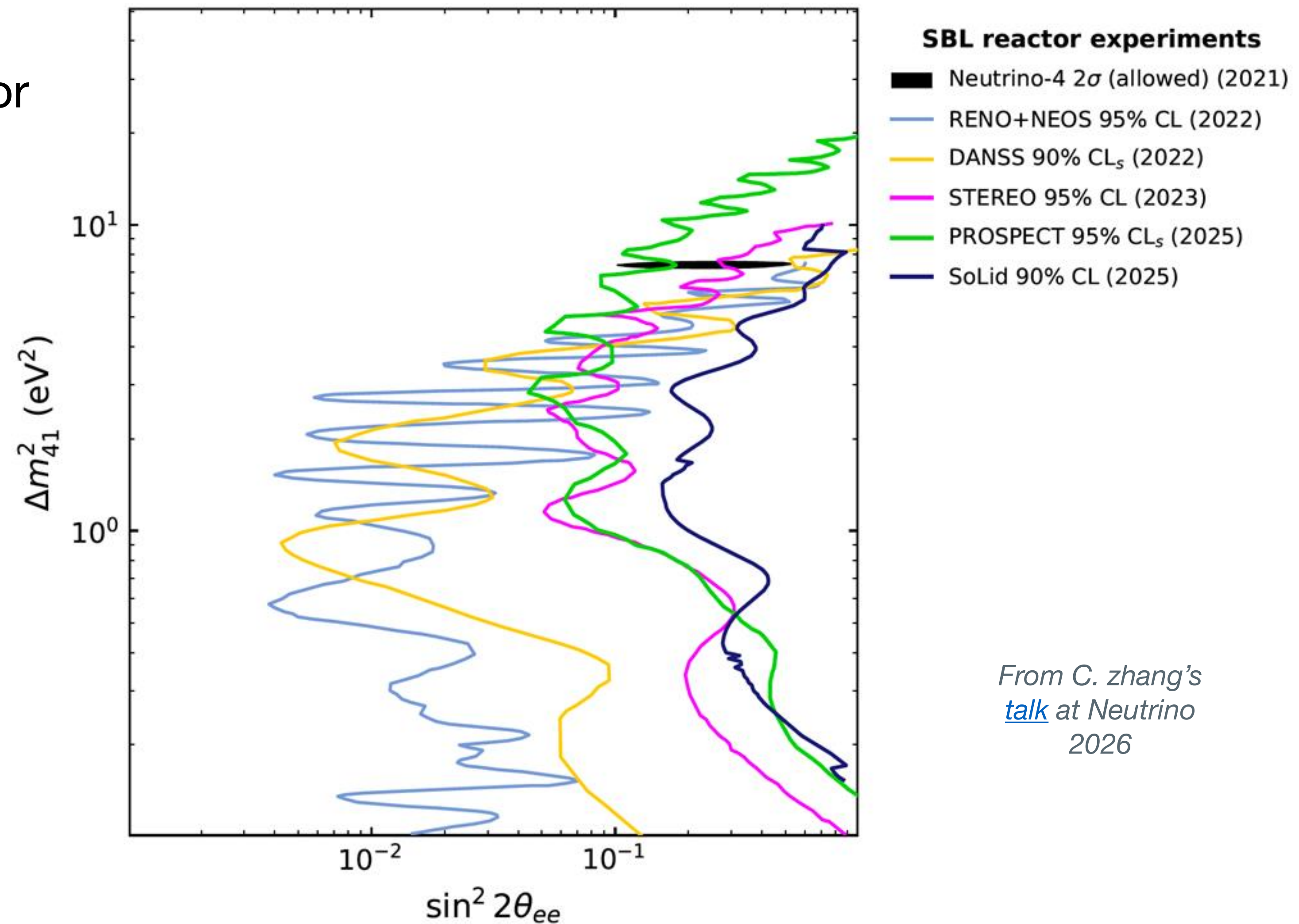
Neutrino-4 Claim

- Only one of these experiments has claimed an observation: Neutrino-4 ([PRD 104, 032003 \(2021\)](#))
- Comments about Neutrino-4's claim:
 - It is 2.7σ
 - It is controversial (e.g. [PLB 816, 136214 \(2021\)](#) and [arXiv:2006.13639](#))
 - It is in strong tension with null results from other experiments (e.g. bottom plot)



Non-Standard Flavor Mixing Landscape

- Conclusion so far: no significant evidence so far for non-standard flavor mixing from either SBL or km-scale experiments
- Question remains: if not sterile neutrinos, what causes the RAA then?
 - Additional data have come to light that give us a tentative answer (see next slides)



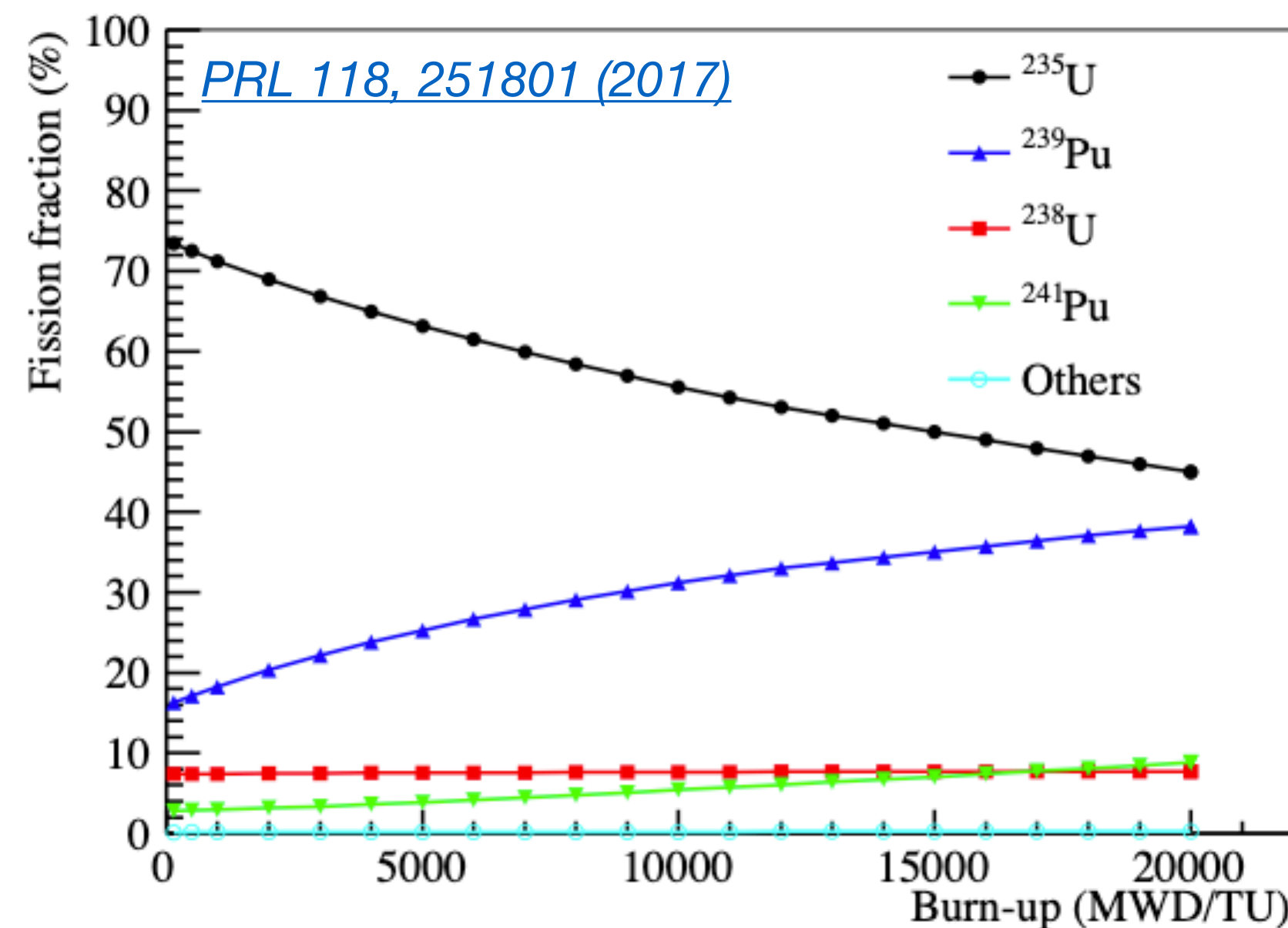
From C. Zhang's
[talk](#) at Neutrino
2026

Evolution with fuel composition

- θ_{13} experiments brought an additional handle to the table for understanding the RAA: evolution with fuel composition

Refresher: neutrinos from commercial nuclear reactors created from fission of ^{235}U , ^{239}Pu , ^{241}Pu , ^{238}U

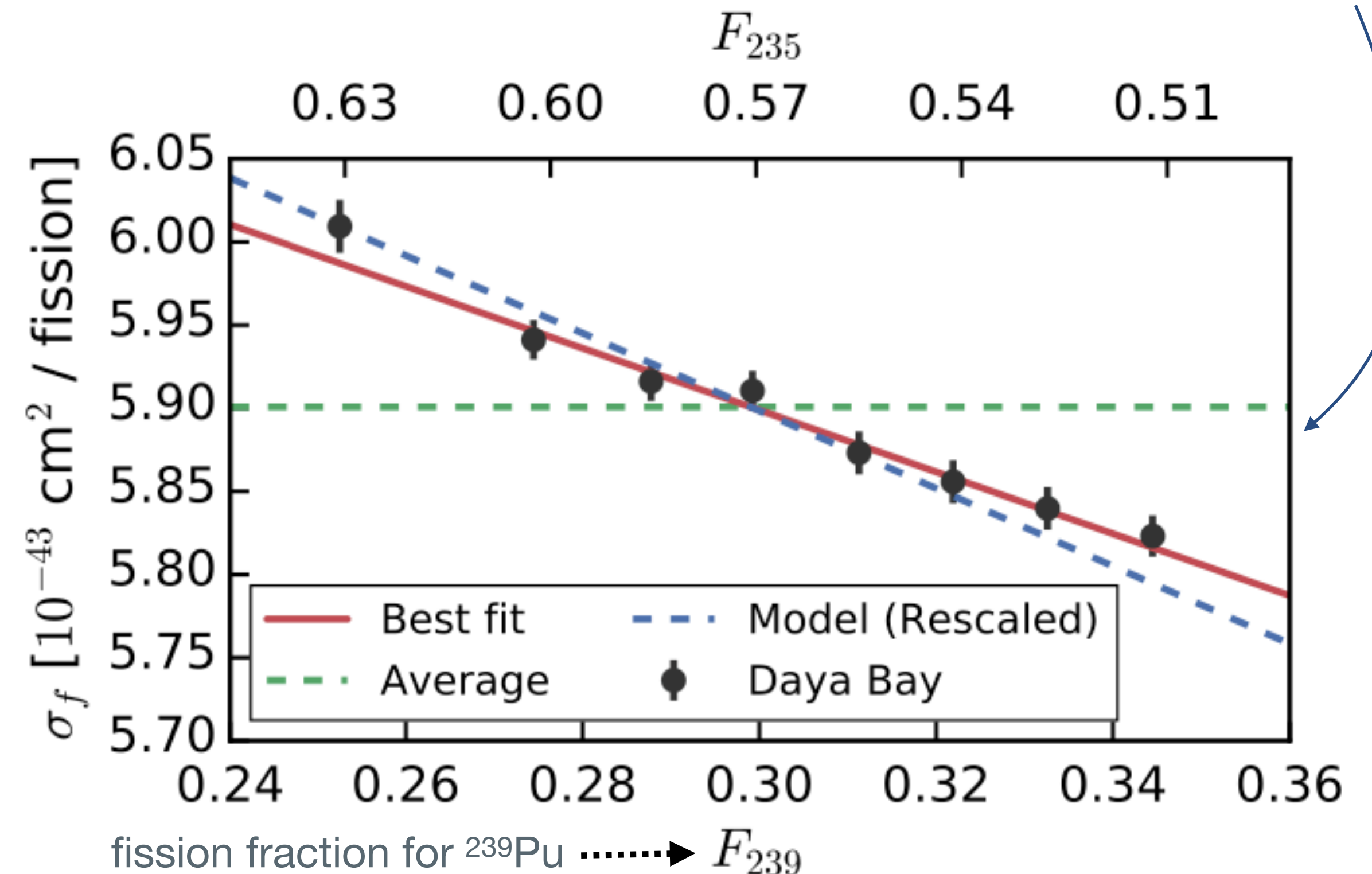
Evolution of fission fractions with burn-up:



(fission fraction F_X = fraction of fissions from isotope X)

Yield (basically $\bar{\nu}_e$'s per fission) and shape vary from isotope to isotope

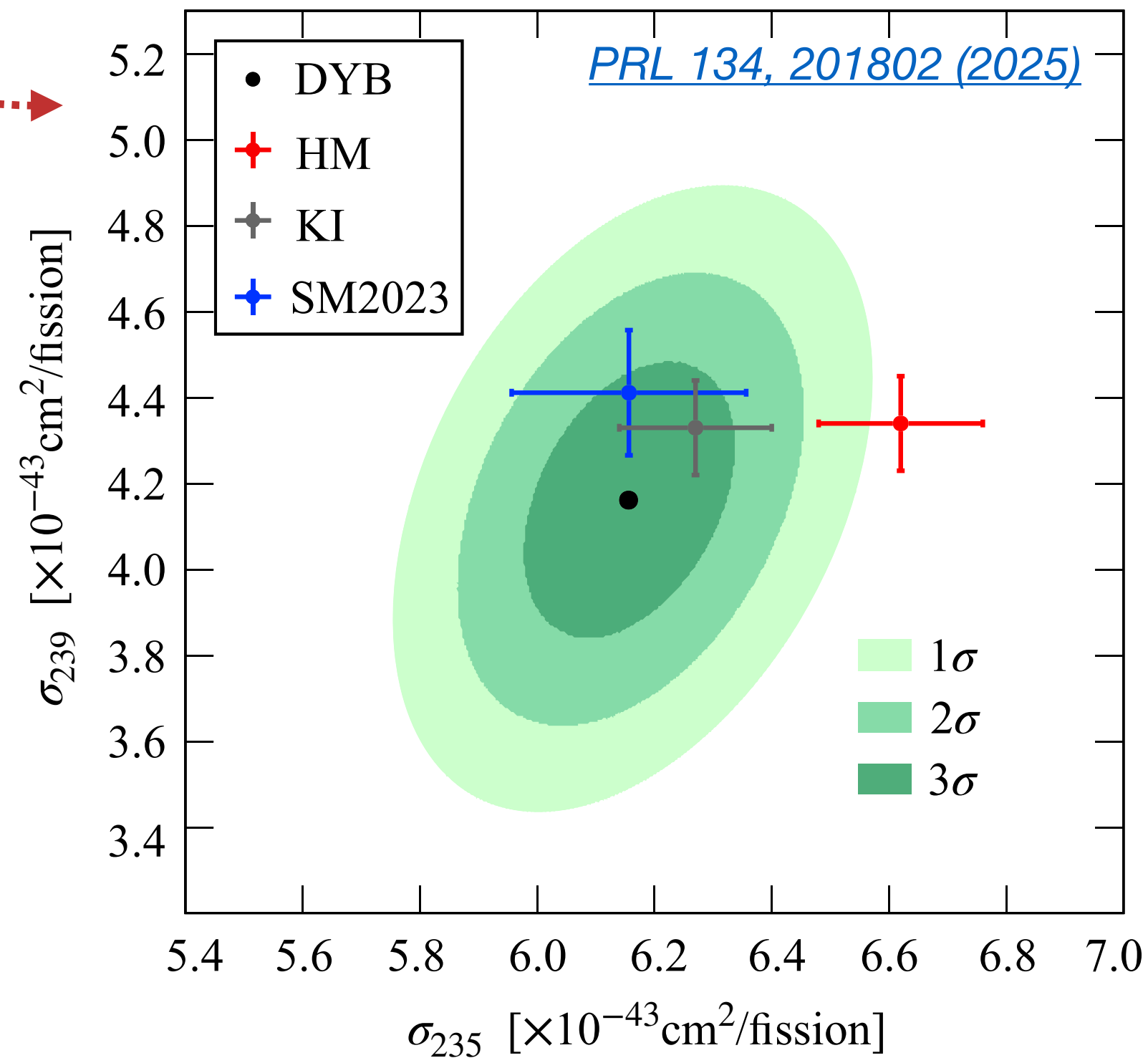
In particular, yield of ^{235}U is larger than that of ^{239}Pu .
Therefore, $\bar{\nu}_e$ rate (total yield) goes down as reactor burns fuel



Yield Measurements

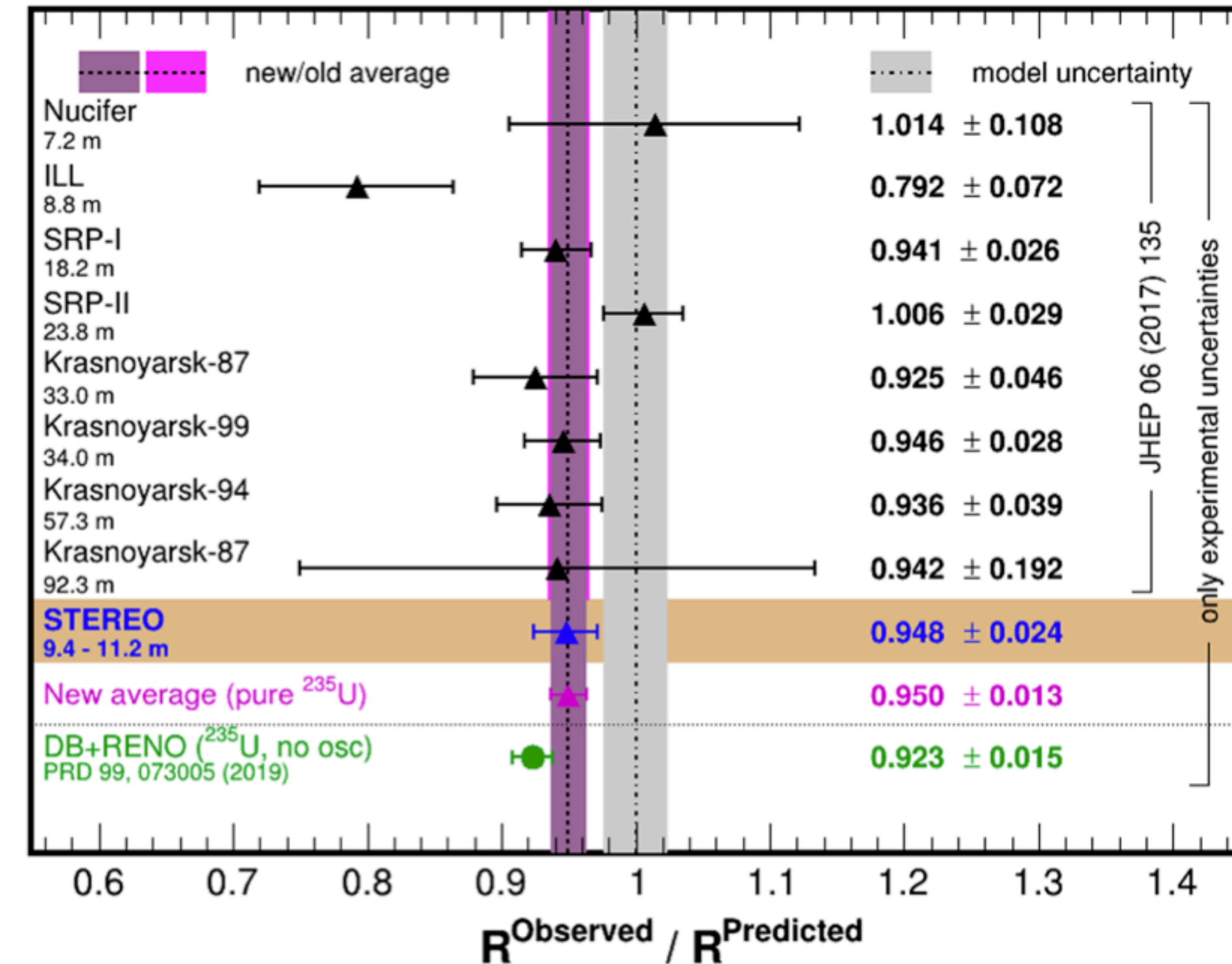
From the evolution data it is possible to extract the yield σ of the two main isotopes: ^{235}U and ^{239}Pu

Showing Daya Bay as an example, but RENO also makes this measurement



From SBL experiments at HEU reactors it is also possible to measure the ^{235}U yield

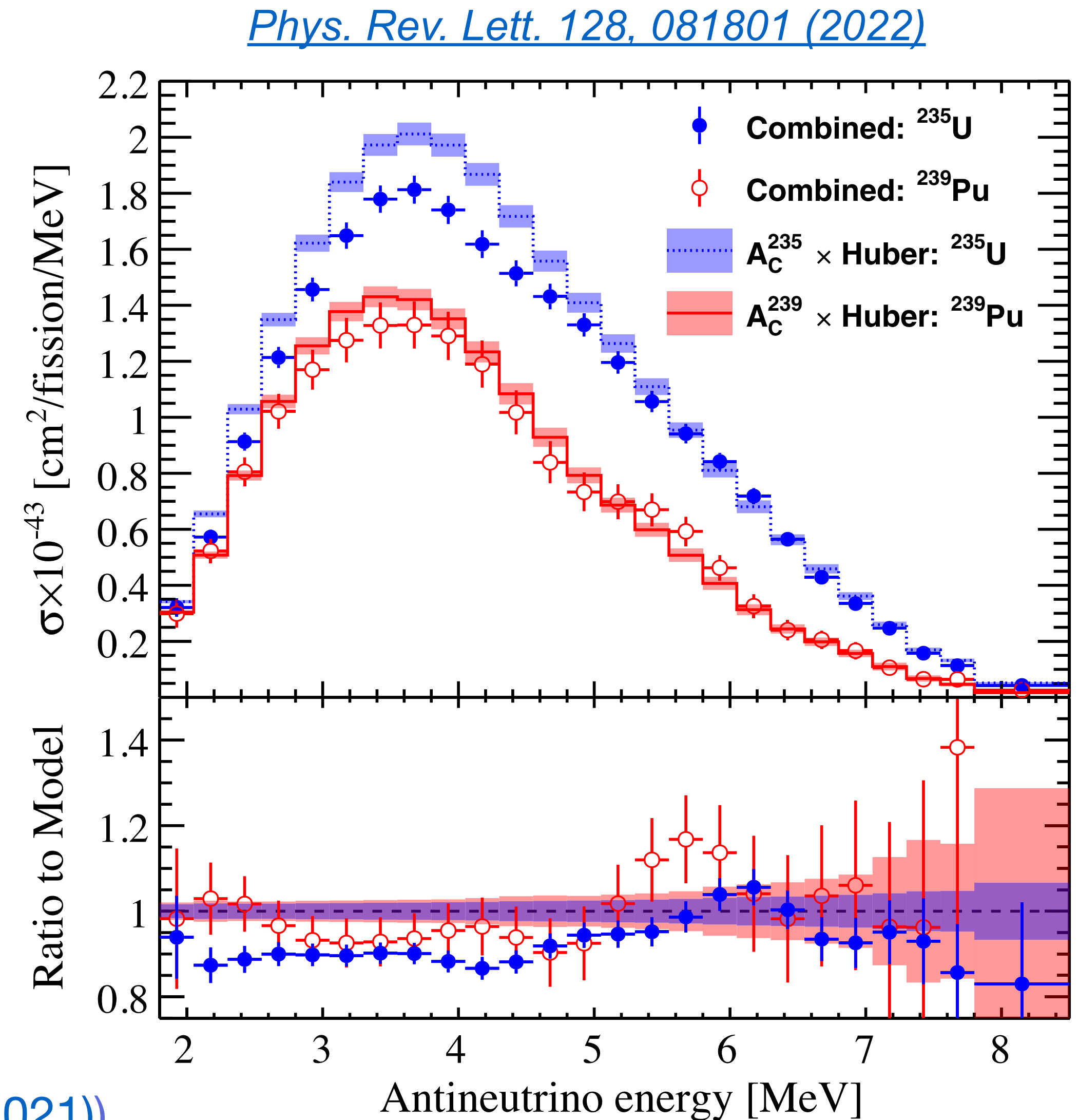
[PRL 125, 201801 \(2020\)](#)



Get a **consistent story**: the HM model overestimates the predicted $\bar{\nu}_e$ flux from ^{235}U fission by about 6% (inconsistent with sterile neutrino interpretation, under which deficit should not depend on the isotope considered)

Aside: ^{235}U and ^{239}Pu Spectra

- This same procedure can be done as a function of energy to extract the spectra for the two main isotopes: ^{235}U and ^{239}Pu
- The ^{235}U spectrum can also be measured directly in HEU experiments like PROSPECT and STEREO
 - Here showing the combined result from Daya Bay and PROSPECT →
- The “5 MeV bump” is visible in both spectra
 - Suggests a common origin, such as inaccurate shape factors from forbidden decays
- Important: these measurements can be used to constrain the reactor antineutrino flux at other experiments
 - Can achieve a ~2% precision (c.f. [Chin. Phys. C 45, 7 \(2021\)](#))



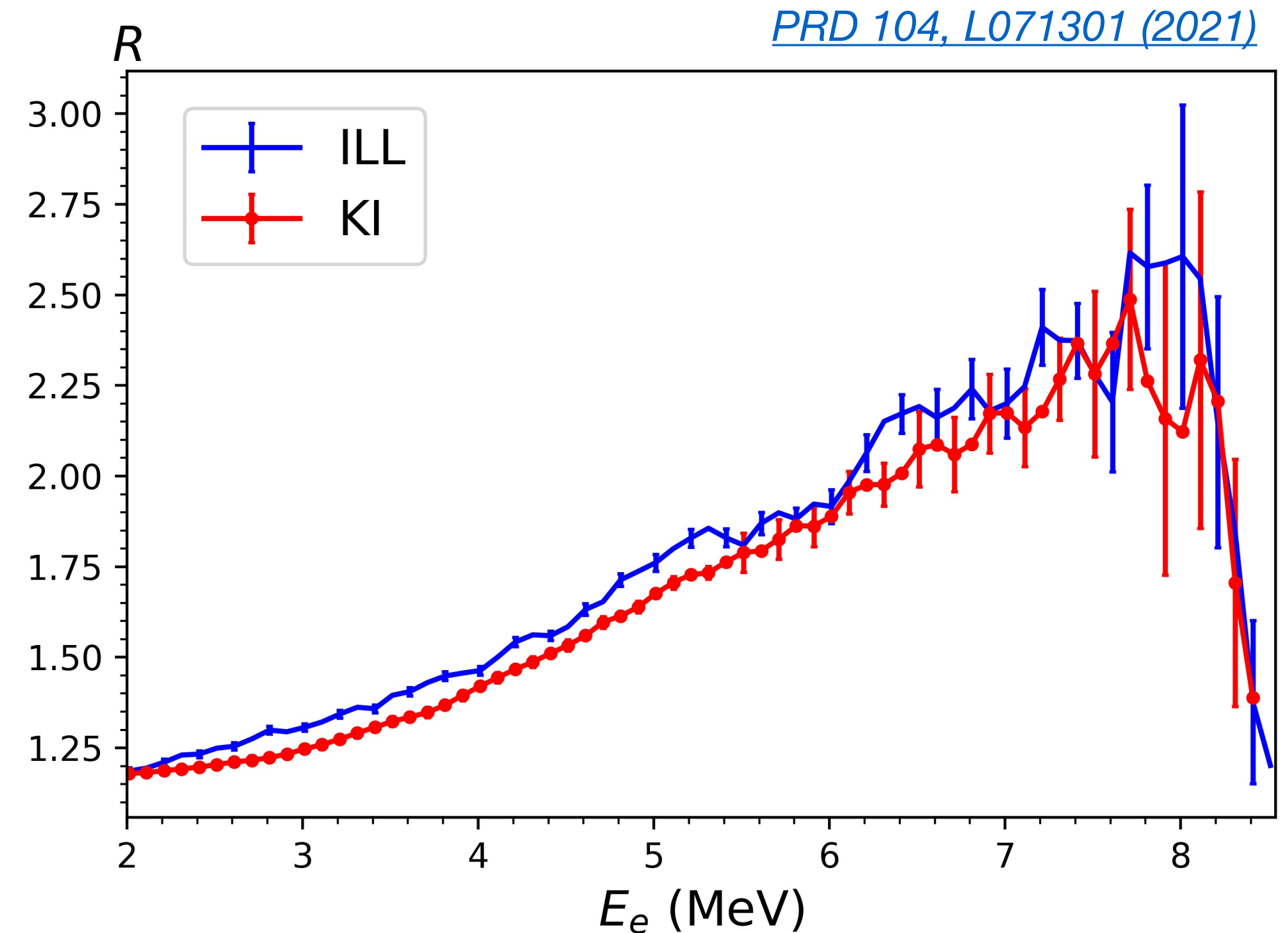
Recent Beta Ratio Measurement

- Another important piece of the puzzle:

- A new measurement of the beta spectra ratio between ^{235}U and ^{239}Pu was performed at the Kurchatov Institute (KI)

$$R = \frac{{}^eS_{235}}{{}^eS_{239}}$$

- Shows a discrepancy with ILL data: new measurement is ~5.4% lower
 - In agreement with measurements from Daya Bay, RENO and STEREO
- However: no significant difference in spectral shape with respect to ILL, so this cannot explain the 5 MeV bump



Reminder: measured beta spectra from thermal-neutron induced fission (^{235}U , ^{239}Pu , ^{241}Pu) at ILL in the 1980s undergirds conversion predictions like the HM model

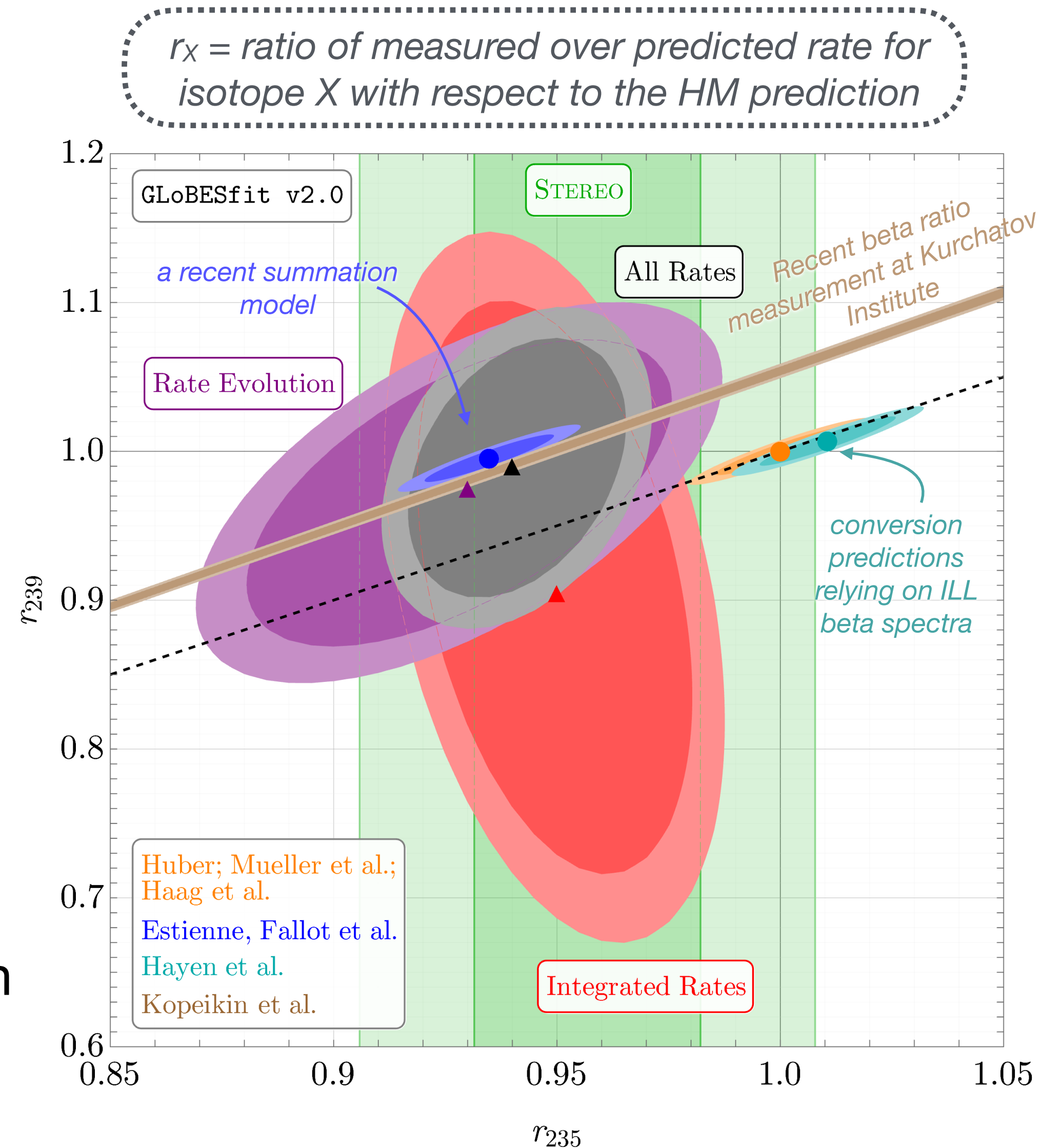
Current Situation

- In conclusion, we have made good progress in understanding the Reactor Antineutrino Anomaly:

- Recent data suggests that ^{235}U beta spectrum from ILL underlying all conversion predictions is largely responsible for reactor antineutrino anomaly
- Shape anomaly remains unexplained and is caused by a yet unknown issue affecting both conversion and summation predictions
- All in all, sterile neutrino hypothesis **not ruled out, but weakened**

See [arXiv:2203.07214](https://arxiv.org/abs/2203.07214) for a detailed description

- All these measurements give us tight constraints on the rate and spectral shape of $\bar{\nu}_e$'s emitted by nuclear reactors

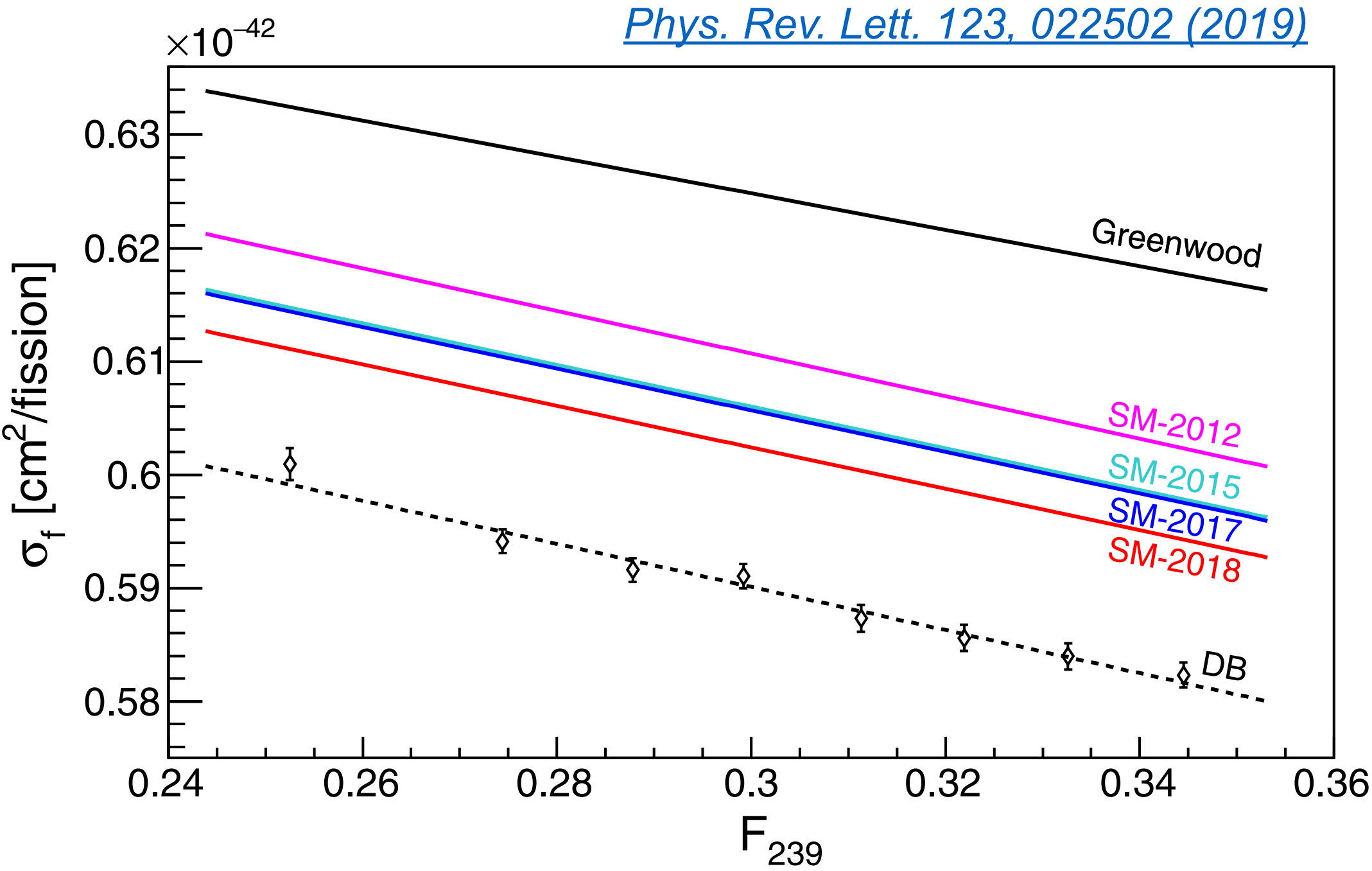


Model Improvements

- Summation models have been steadily improving in the last decade
 - Incorporation of new Total Absorption Gamma-Ray Spectroscopy (TAGS) data
 - Free of pandemonium effect!
 - Comprehensive uncertainty treatment
 - Notably, BESTIOLE implementation in [Phys. Rev. C 108, 055501 \(2023\)](#)

Source	Uncertainty (%)	Methods
Residual Pandemonium	2.1–2.6	Evaluated from 81 measured nuclides and applied to ~29 nuclides
Tengblad integral β conversion	1.4–1.7	Evaluated from 23 TAGS and apply to 44 nuclides;
Fission yield	1.1–1.3	Cumulative uncertainty (JEFF-3.3), kept uncorrelated
Nuclides with no data	0.6–1.3	Statistical “Pool method”
Model correction (ξ -approximation, WM, etc.)	0.4–0.6	estimated against a few transitions that can be calculated exactly
Branching ratio + β^- intensity	0.3–0.4	ENSDF BR/intensity uncertainties, Monte Carlo propagated

From C.
zhang’s [talk](#) at
Neutrino 2026



Summation Model	New TAGS nuclei added	TAGS reference
SM-2012	Greenwood (49 nuclides) + 102,104,105,106,107Tc, 105Mo and 101Nb	PRL 105, 202501 (2010)
SM-2015	92,94Rb and 87,88Br	PRL 115, 102503 (2015), PRC 95, 024320 (2017)
SM-2017	91Rb, 86Br	PRC 96, 014320 (2017)
SM-2018 (EF)	100,100m,102,102mNb	PRL 122, 042502 (2019)
BESTIOLE-2023 (CEA)	28 new nuclides	ORNL+ post-2019 campaigns

- On the conversion side, we would like to see a full repeat of the ILL measurements

Conclusions

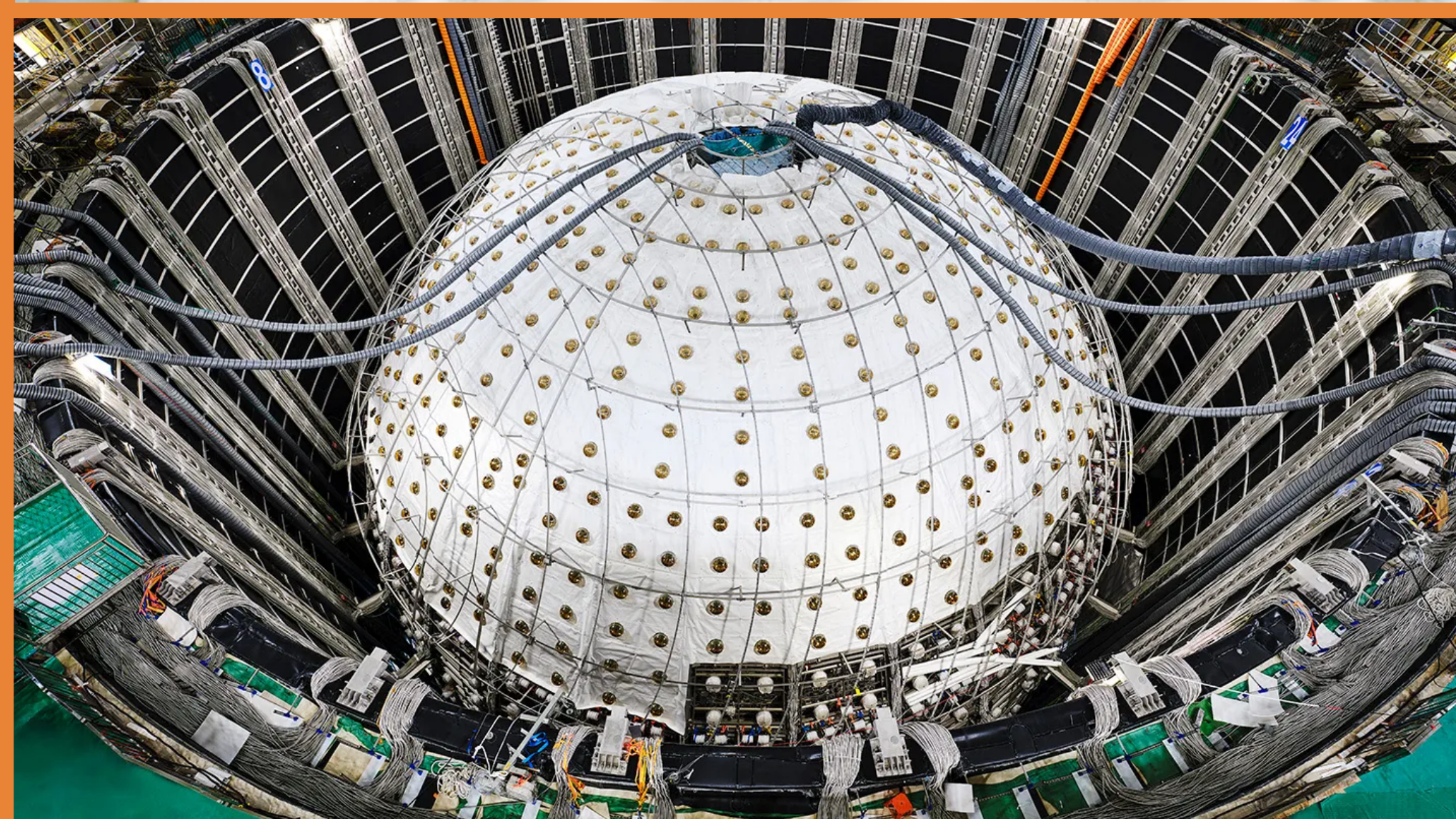
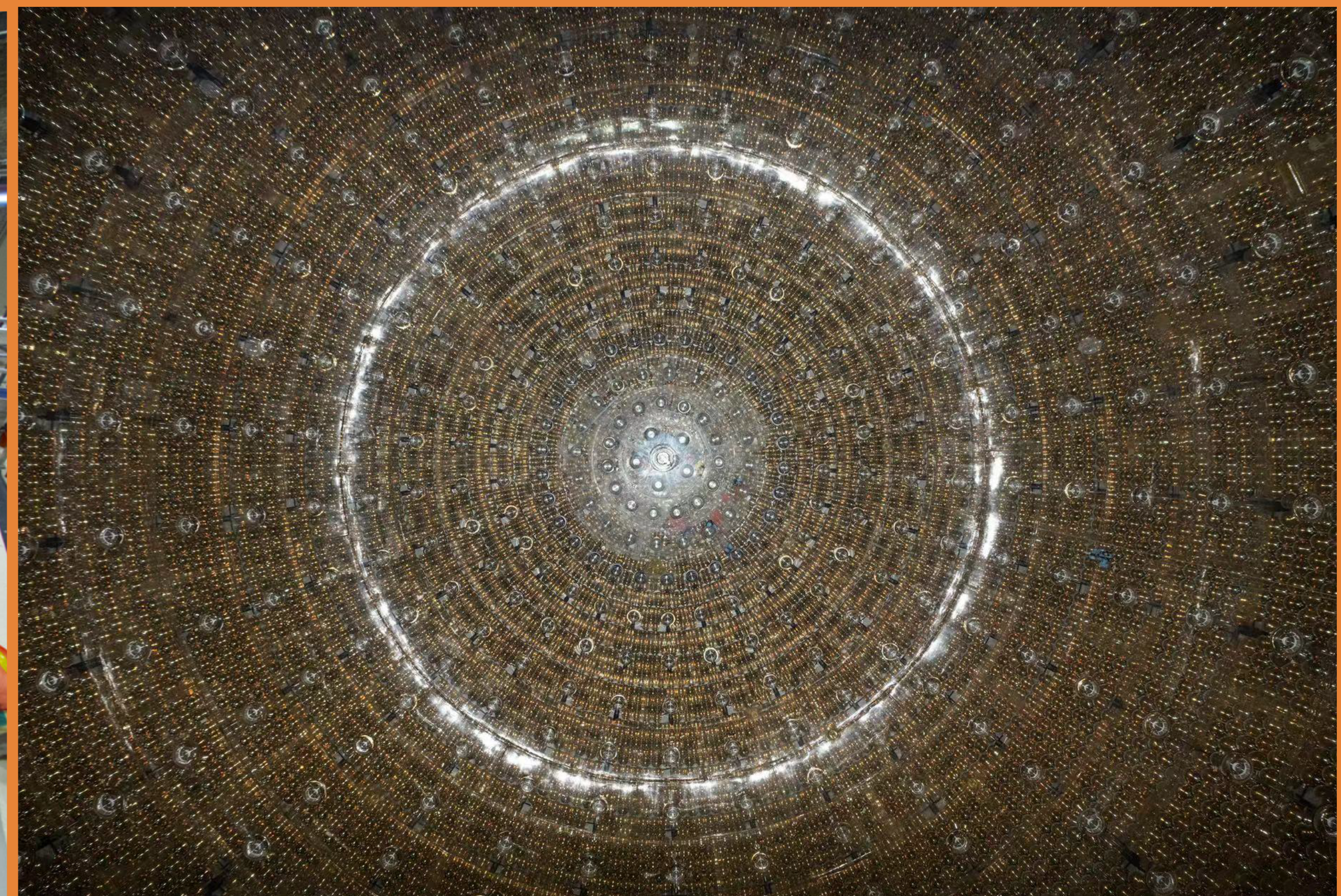
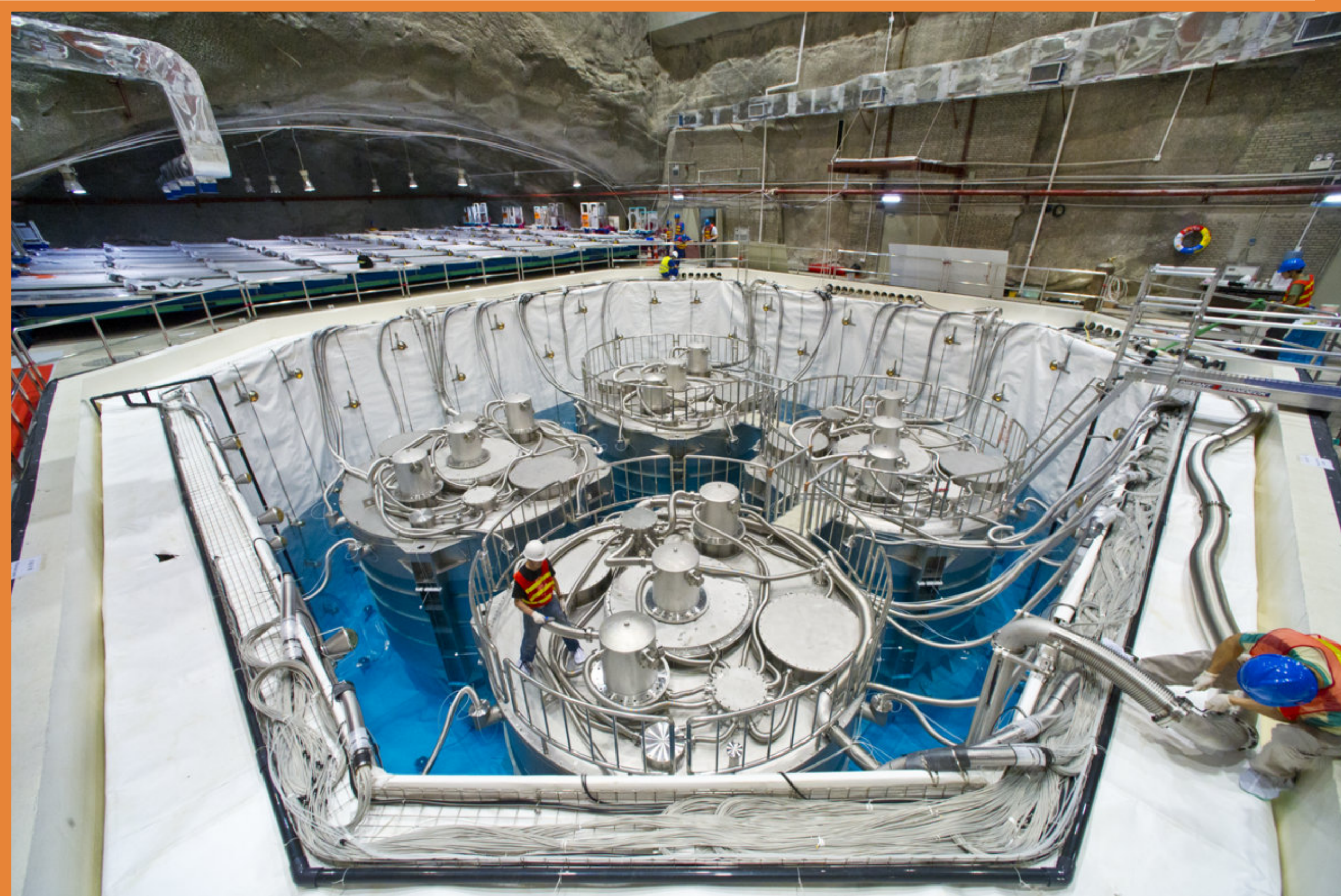
so far....

Summary so far...

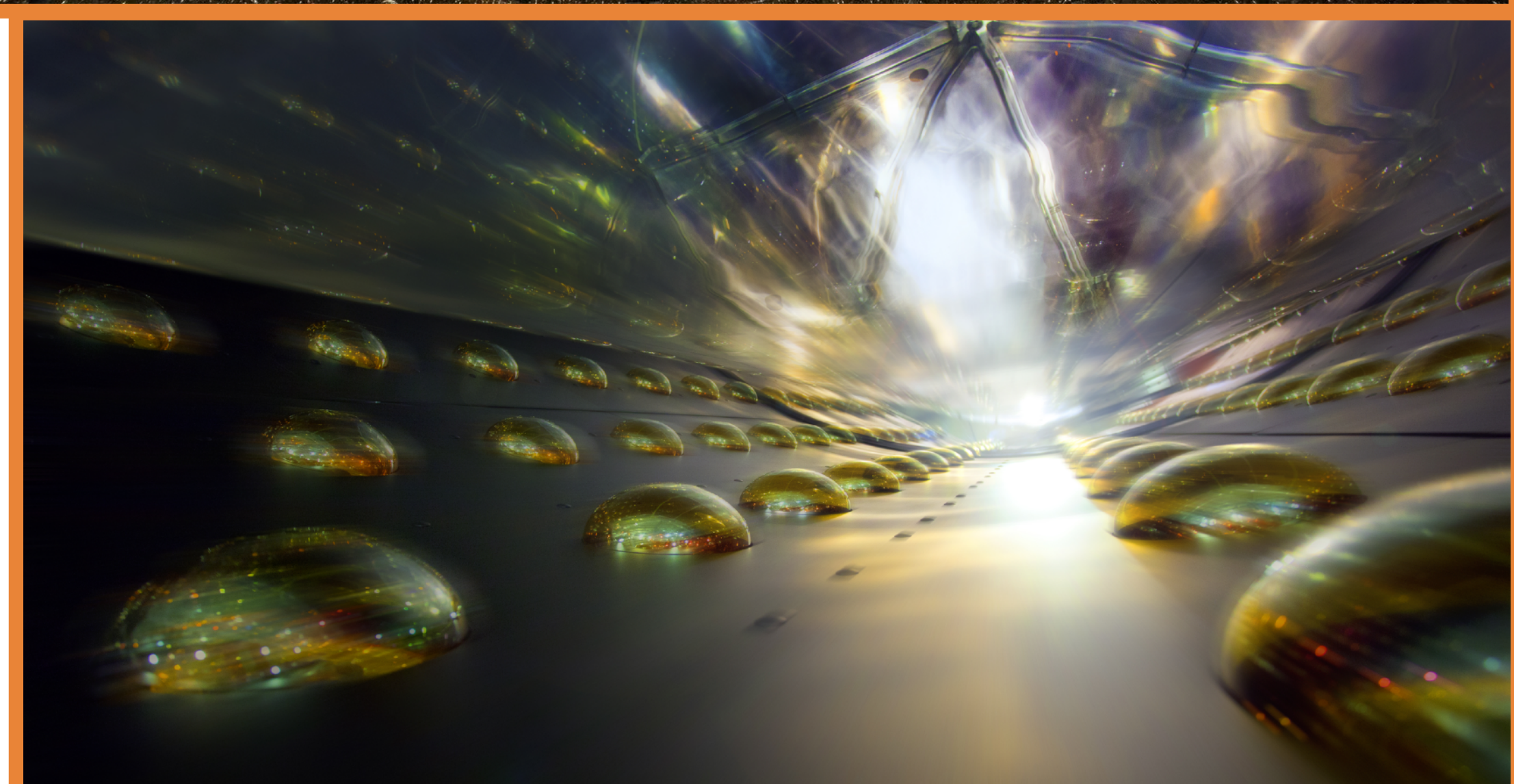
- Nuclear reactors are excellent neutrino sources
- Reactor neutrino experiments have made unique contributions to the field
 - From the discovery of the neutrino to the discovery of a non-zero value of θ_{13}
- Great progress has been made in the last decade in predicting and measuring the reactor antineutrino flux and spectral shape in the last decade
 - Have an explanation for the Reactor Antineutrino Anomaly, although 5 MeV bump remains unexplained
 - Existing combination of models and data allow to predict reactor antineutrino flux and shape to $\sim 2\%$
 - Have not seen significant evidence for sterile neutrino mixing
- Of the three large next-generation experiments, one is a reactor experiment and recently began producing results
 - Focus of part 2 of this lecture (tomorrow)



*Support from NSF and
DOE is gratefully
acknowledged*



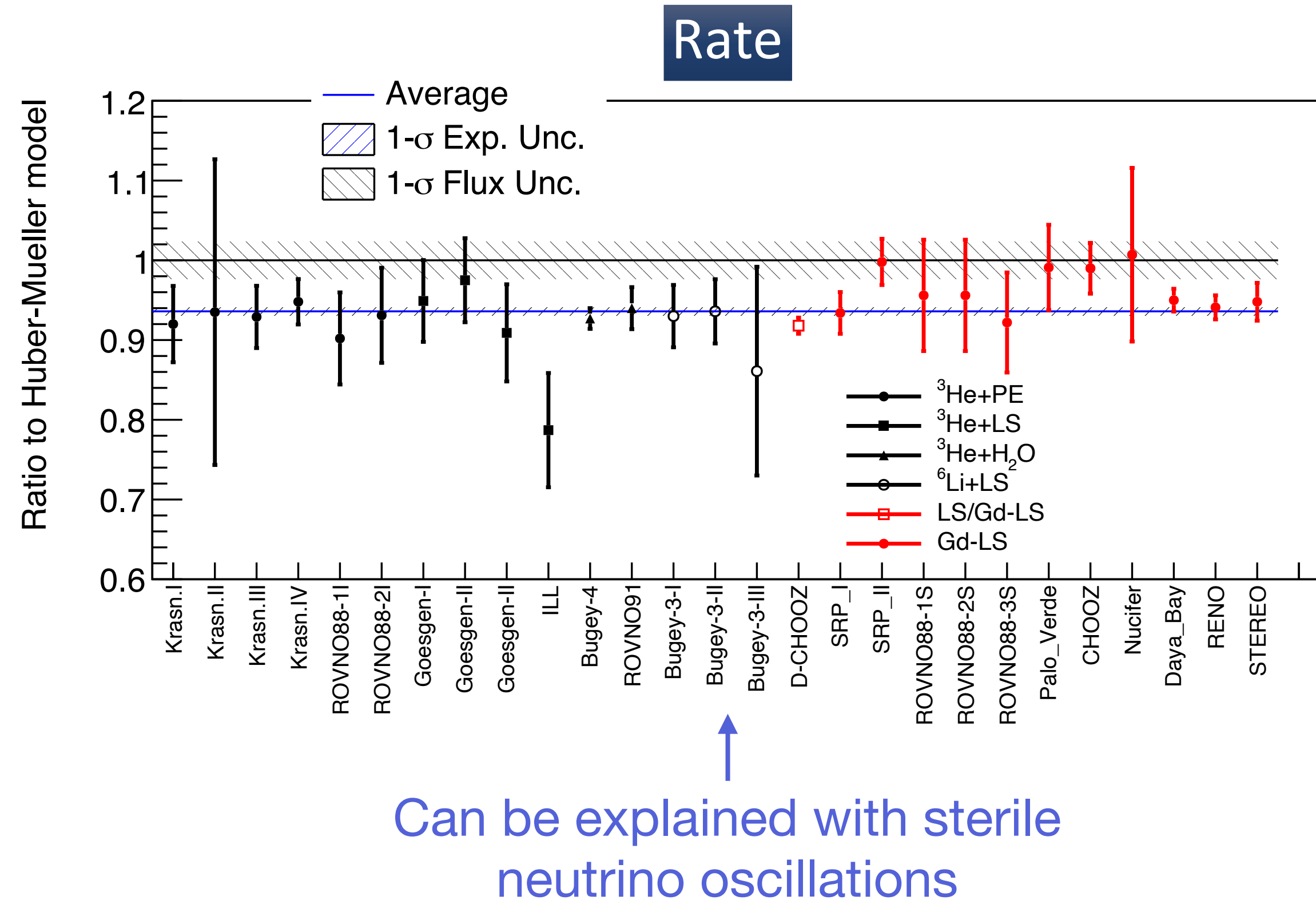
*Thank you
for your
attention!*



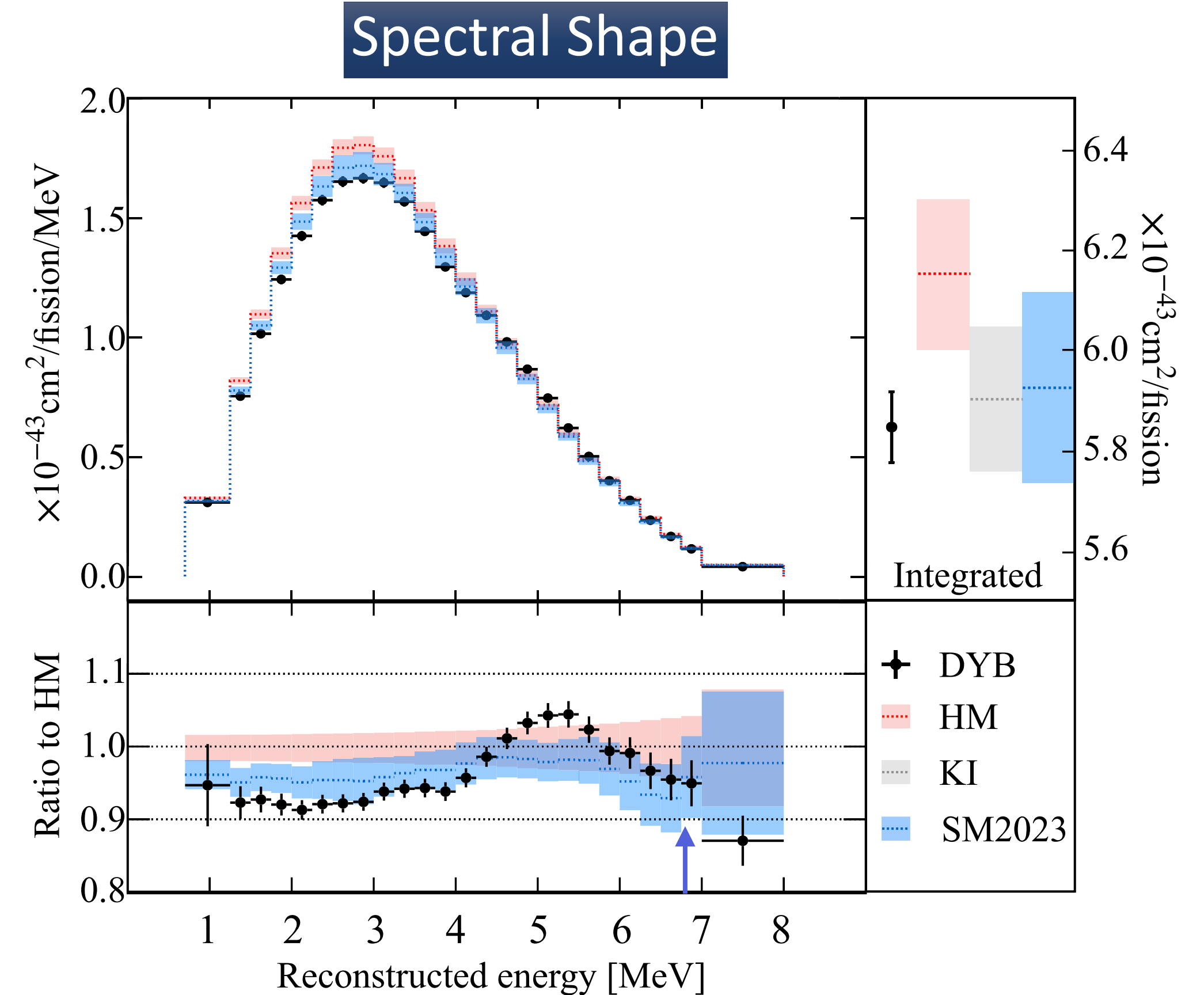
Backup

Recap

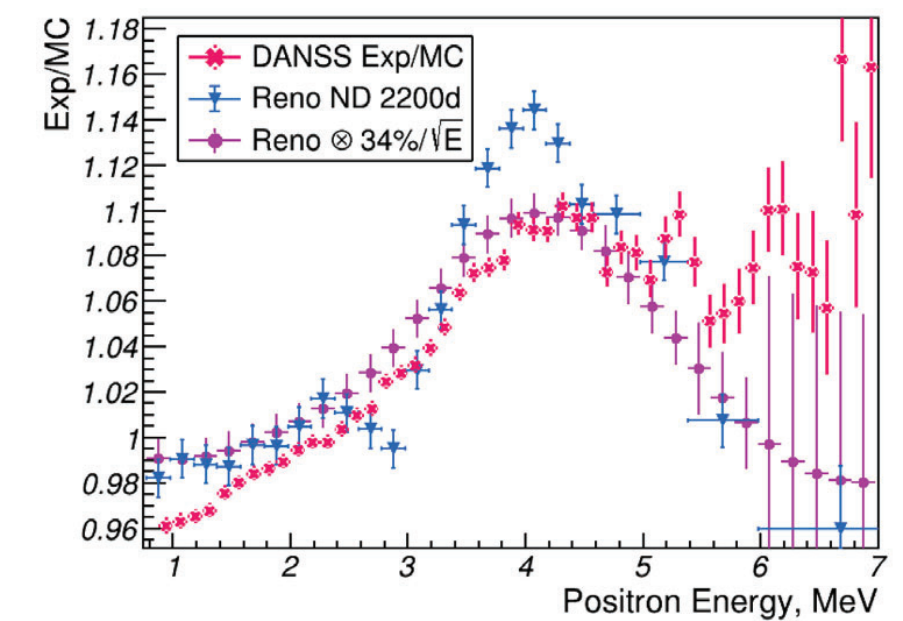
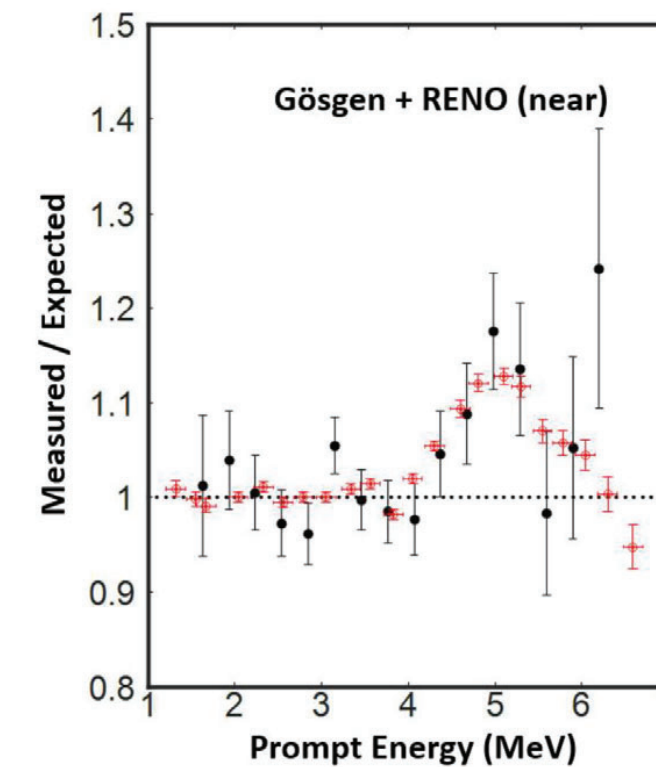
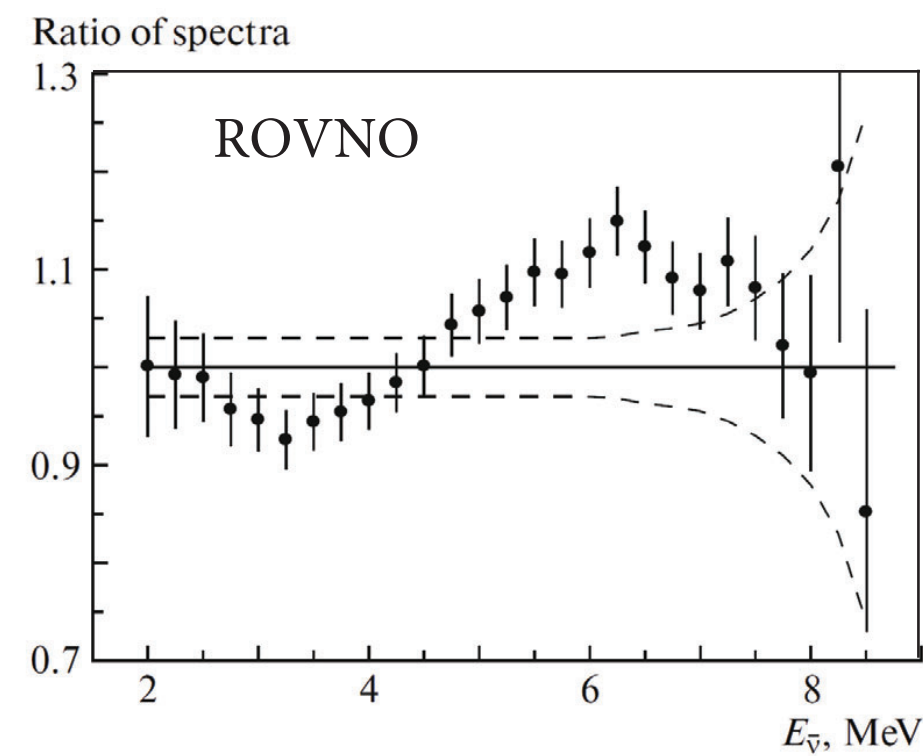
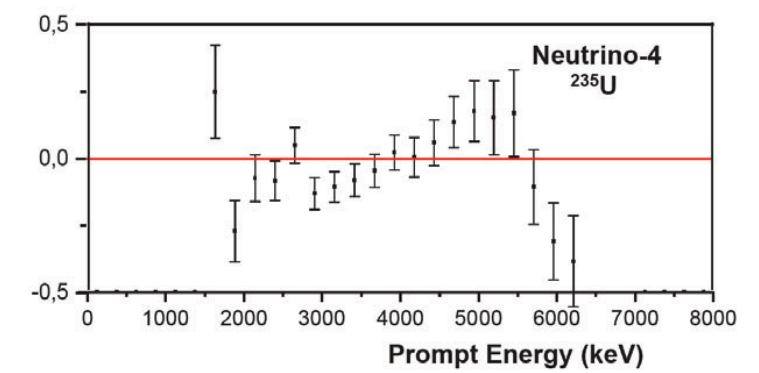
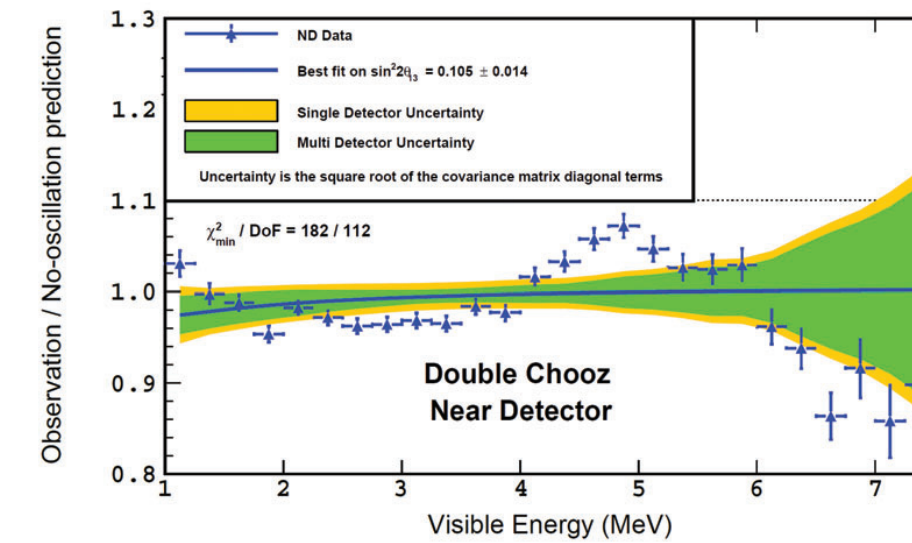
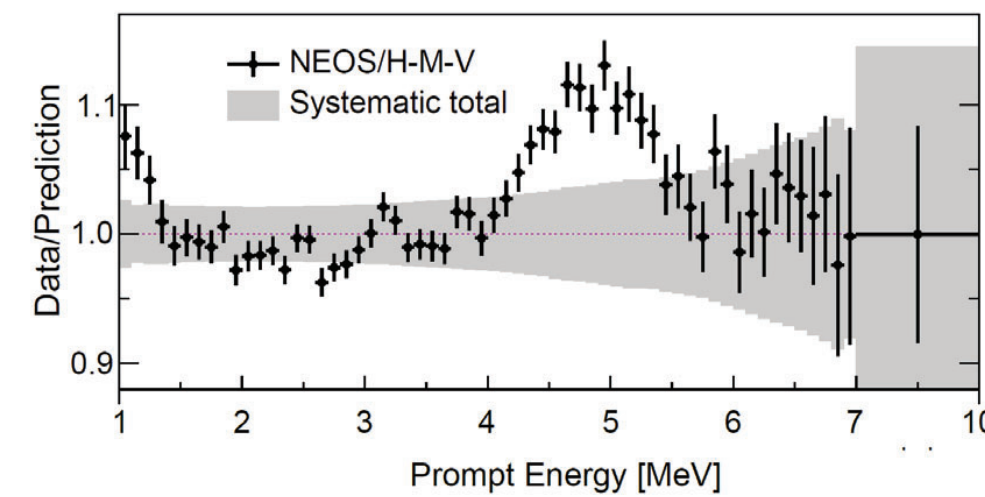
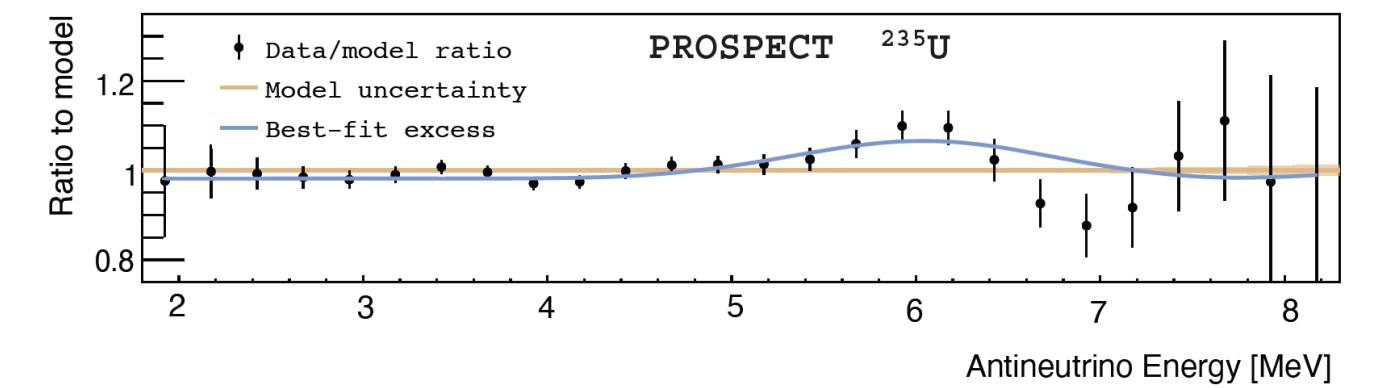
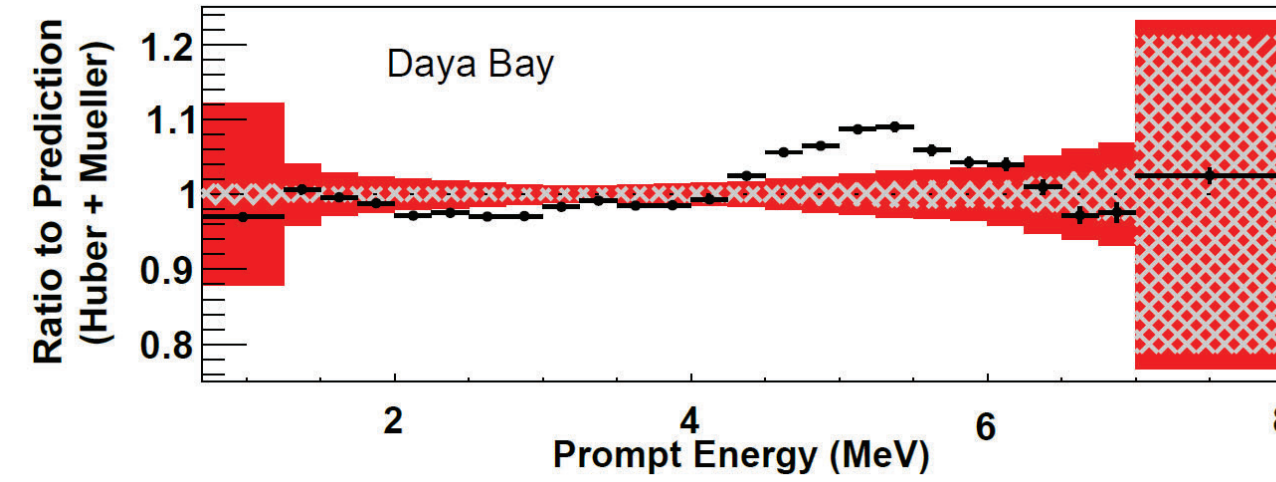
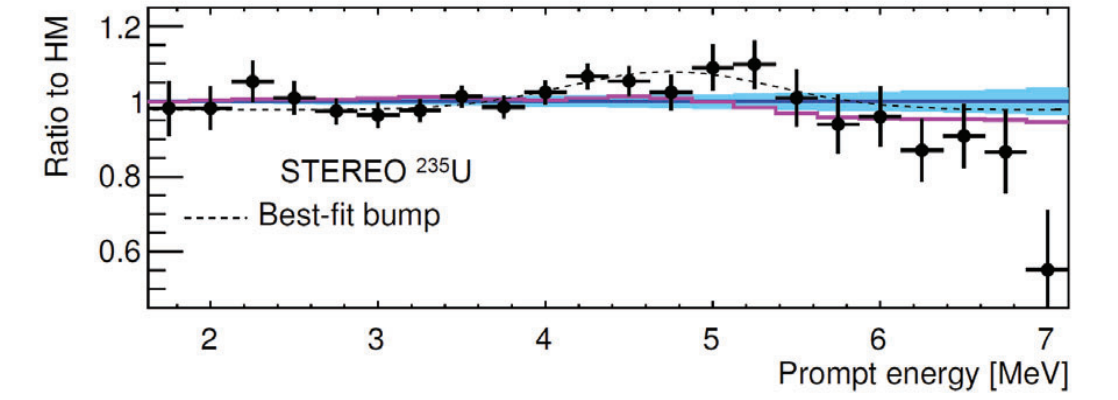
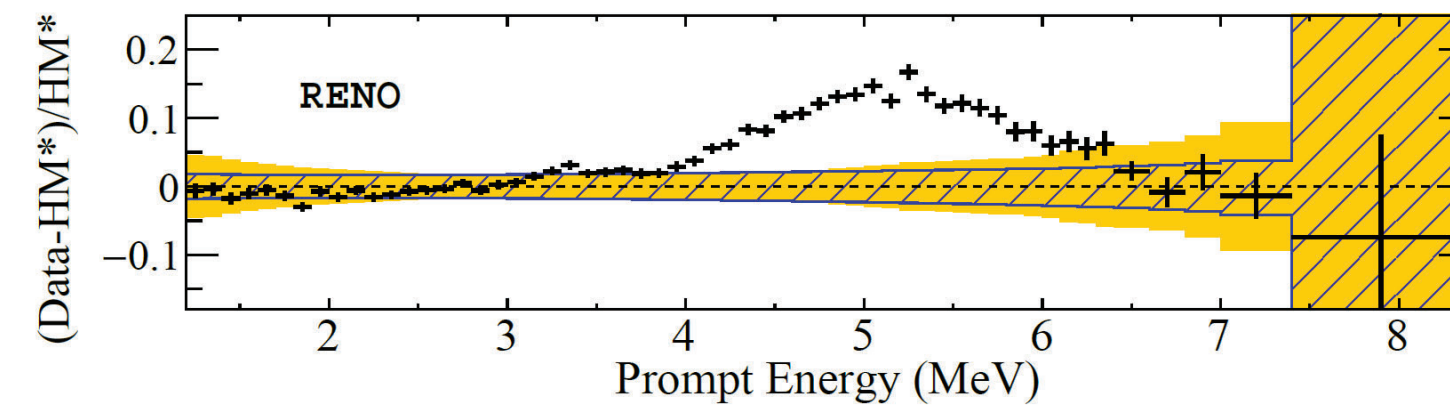
- Two anomalies have come to light when comparing the predicted reactor antineutrino flux to the measured one



However, sterile neutrino searches have come out empty. What explains these anomalies then?



Comparison with Data: Spectral Shape



Scope of Reactor Neutrino Experiments

- Some types of experiments have traditionally been more effective at probing certain sectors of the PMNS matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_{23} & \sin \theta_{23} \\ 0 & -\sin \theta_{23} & \cos \theta_{23} \end{pmatrix}}_{\text{Atmospheric (+Accelerator)}} \underbrace{\begin{pmatrix} \cos \theta_{13} & 0 & \sin \theta_{13} e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin \theta_{13} e^{i\delta_{CP}} & 0 & \cos \theta_{13} \end{pmatrix}}_{\text{Reactor (+Accelerator)}} \underbrace{\begin{pmatrix} \cos \theta_{12} & \sin \theta_{12} & 0 \\ -\sin \theta_{12} & \cos \theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar (+Reactor)}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- Main areas where reactor neutrino experiments have a big impact and/or make a unique contribution:
 - Precision measurement of oscillation parameters (reactor experiments will provide leading precision on 4 out of 6 oscillation parameters)
 - Determination of the neutrino mass ordering
 - Searches for new physics beyond standard 3-neutrino mixing