UCI University of California, Irvine

Reactor Neutrinos

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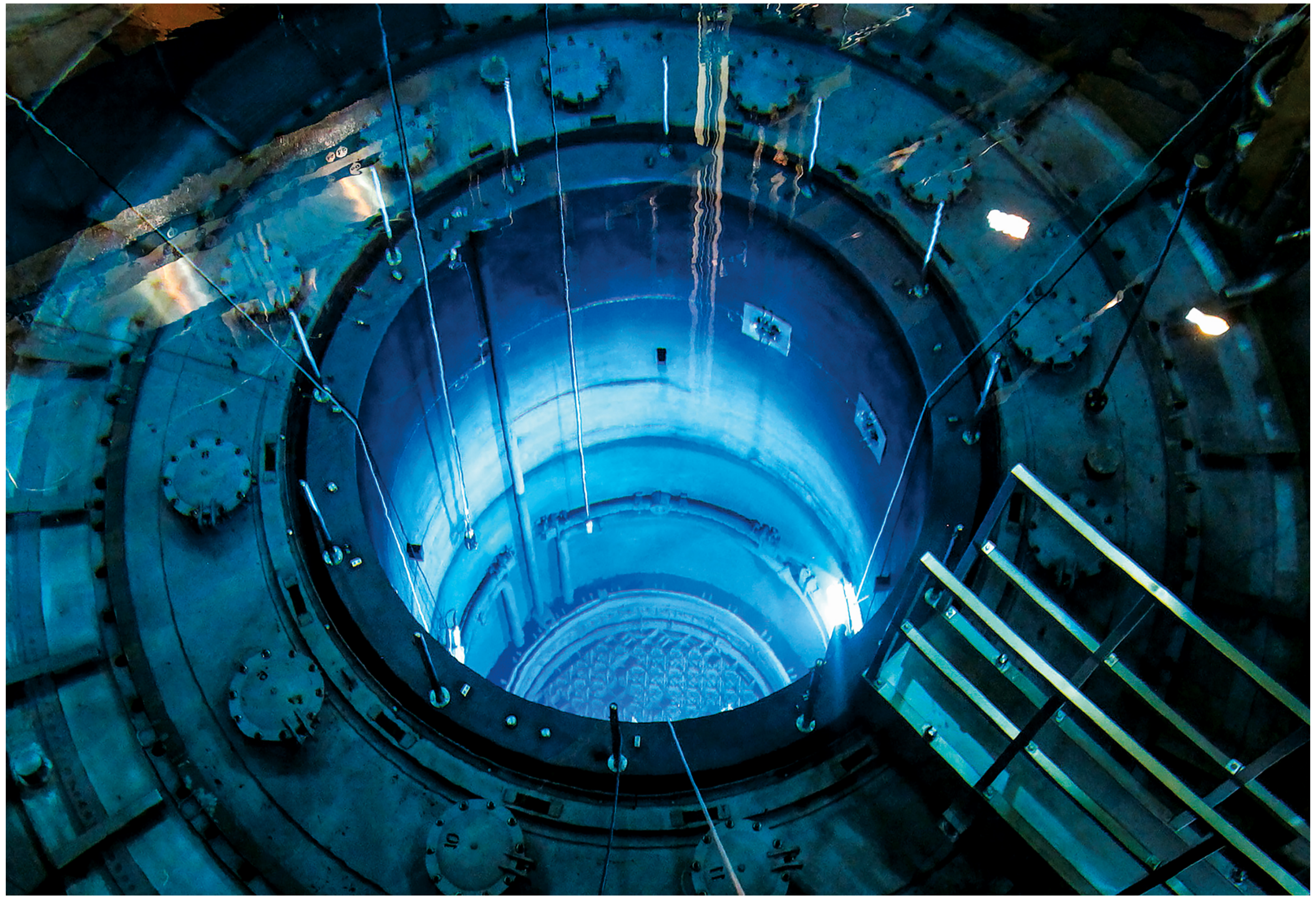
Outline

- Why study neutrinos?
- Basic Principles of Reactor Neutrino Experiments
- The θ_{13} Generation of Experiments
- Data vs. Models and Short-Baseline Experiments
- The Future: JUNO (and others)
- Concluding Remarks



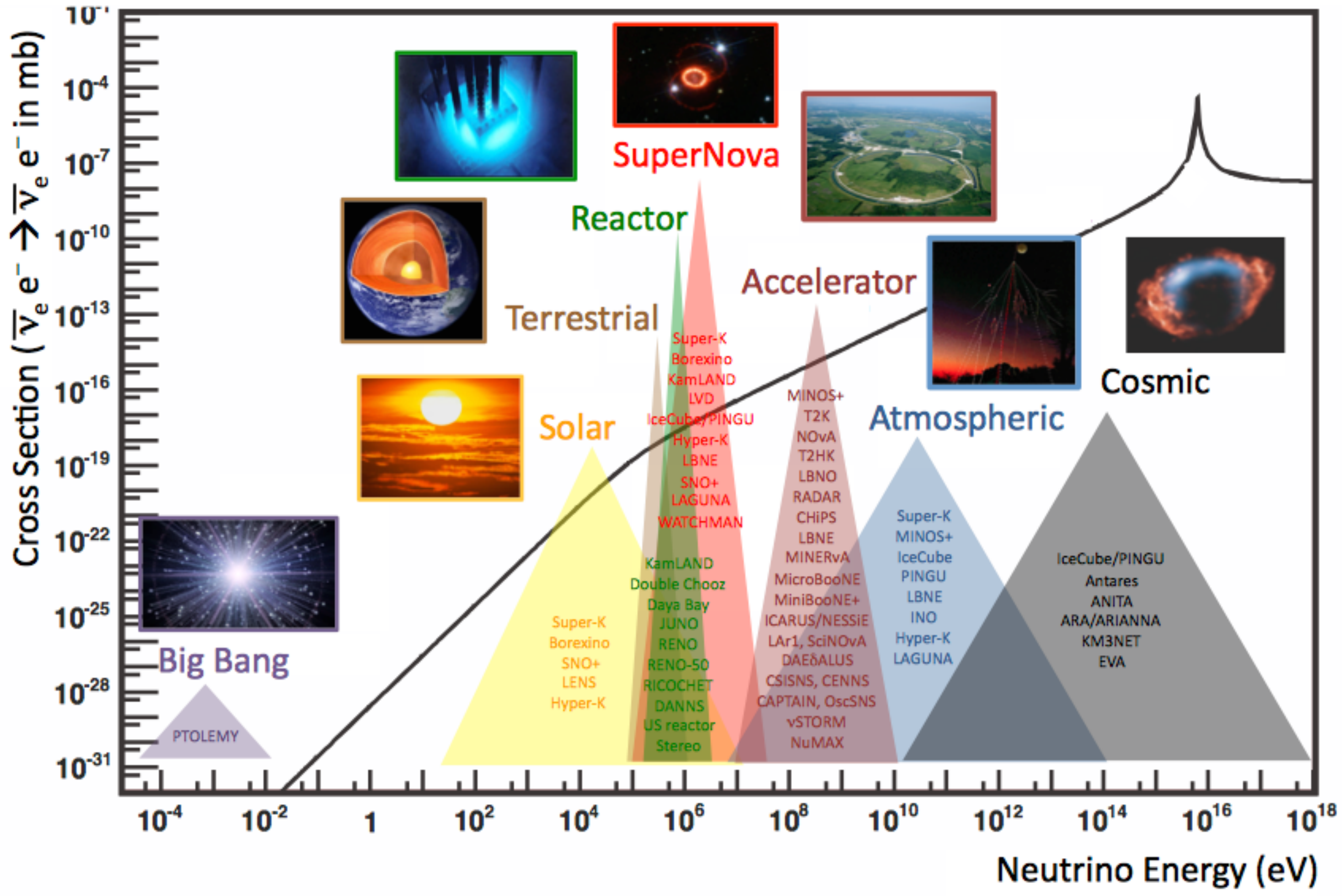
Why Study Neutrinos?

Brief Reminder

Why Study Neutrinos?

- 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**

Neutrinos are everywhere!



Neutrino Oscillation

- The basic principle behind neutrino oscillations: neutrino mixing

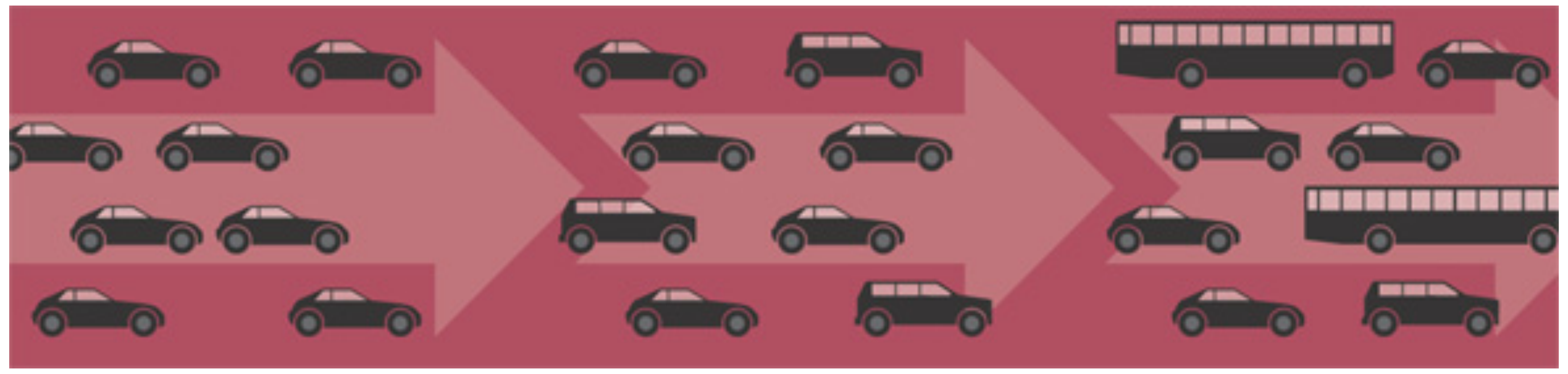
$$\left|\nu_\alpha\right\rangle = \sum_i U^*_{\alpha i}\left|\nu_i\right\rangle$$

How they interact
$(\nu_e,\ \nu_\mu,\ \nu_\tau)$

How they propagate
$(\nu_1,\ \nu_2,\ \nu_3)$

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

Illustration of neutrino oscillation:



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

amplitude   frequency

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

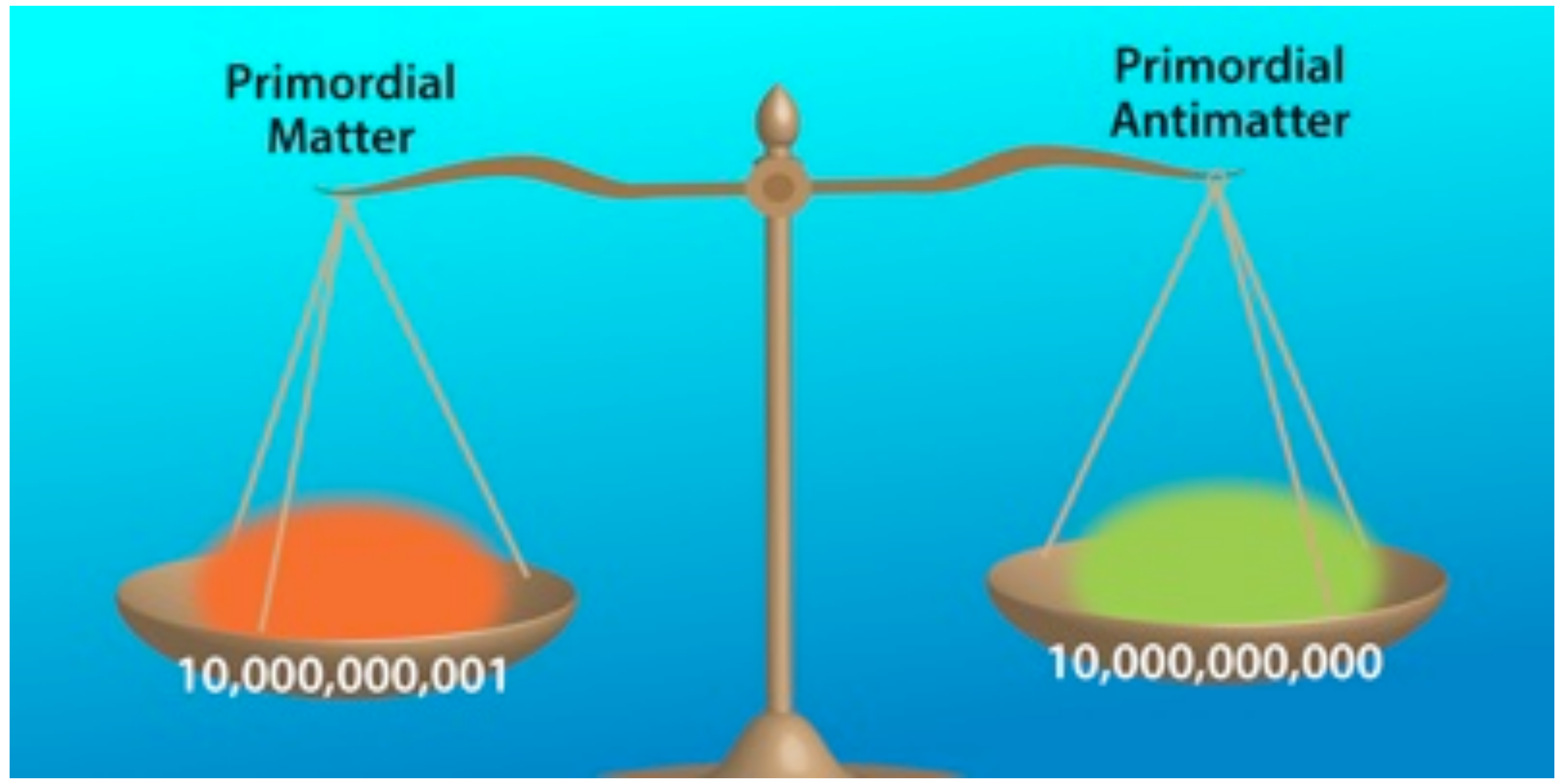
(where $\Delta m^2_{ij} = m^2_i - m^2_j$ are the so-called "mass splittings")

Open Questions

- 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!

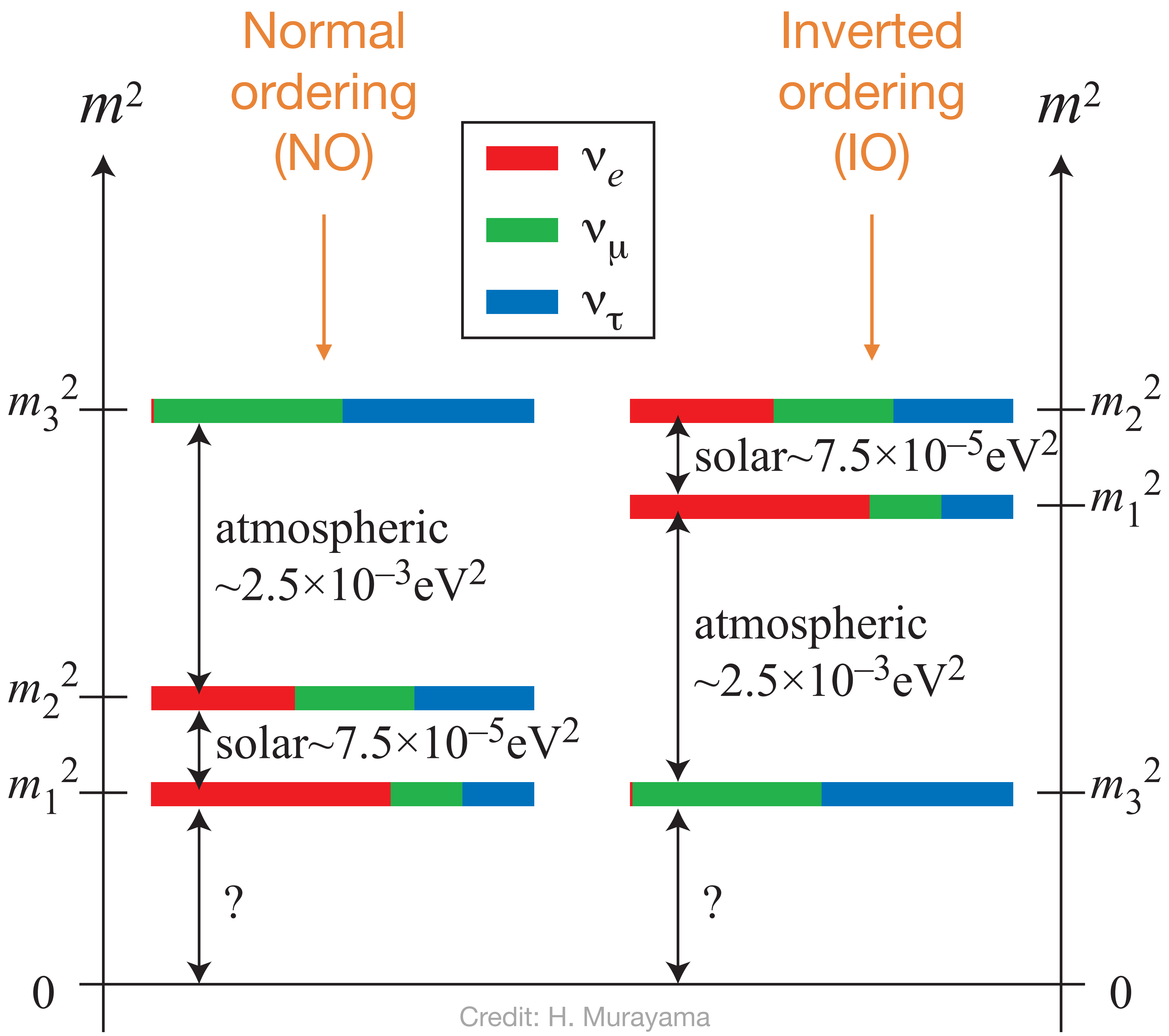


Currently, we have some indications of CP violation but none definitive

Open Questions

- 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^2_{32})?



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 2024

		Precision
$\sin^2(\theta_{12})$	0.307 ± 0.013	4.2 %
Δm^2_{21}	$(7.53 \pm 0.18) \times 10^{-5}\ \mathrm{eV}^2$	2.4 %
$\sin^2(\theta_{23})$	$0.558^{+0.015}_{-0.021}$	3.2 %
Δm^2_{32}	$(2.455 \pm 0.028) \times 10^{-3}\ \mathrm{eV}^2$	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:

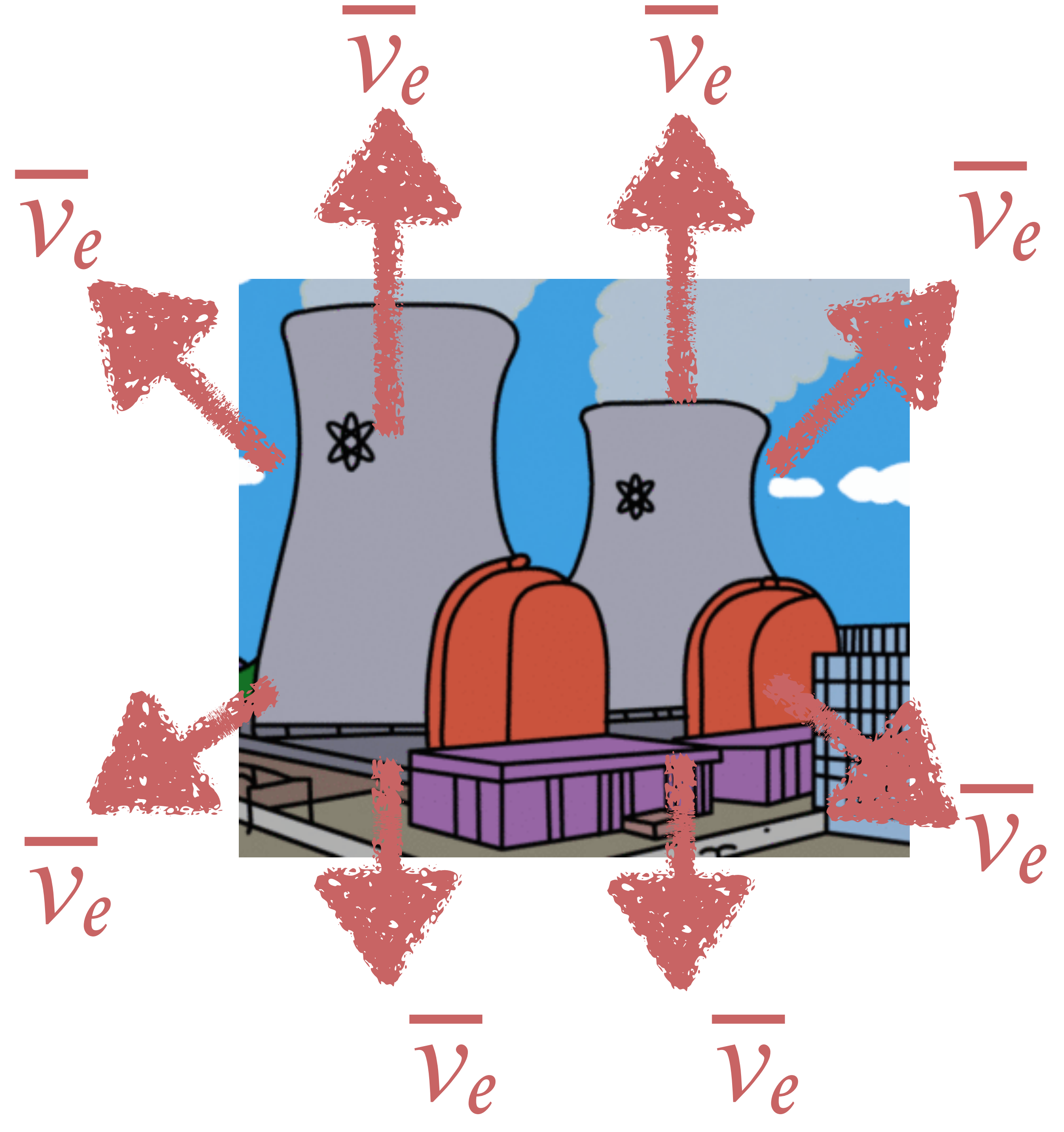
- Model-independent tests of the 3-neutrino framework (notably PMNS non-unitarity)
- Stringent cross-checks between different experiments

Basic Principles

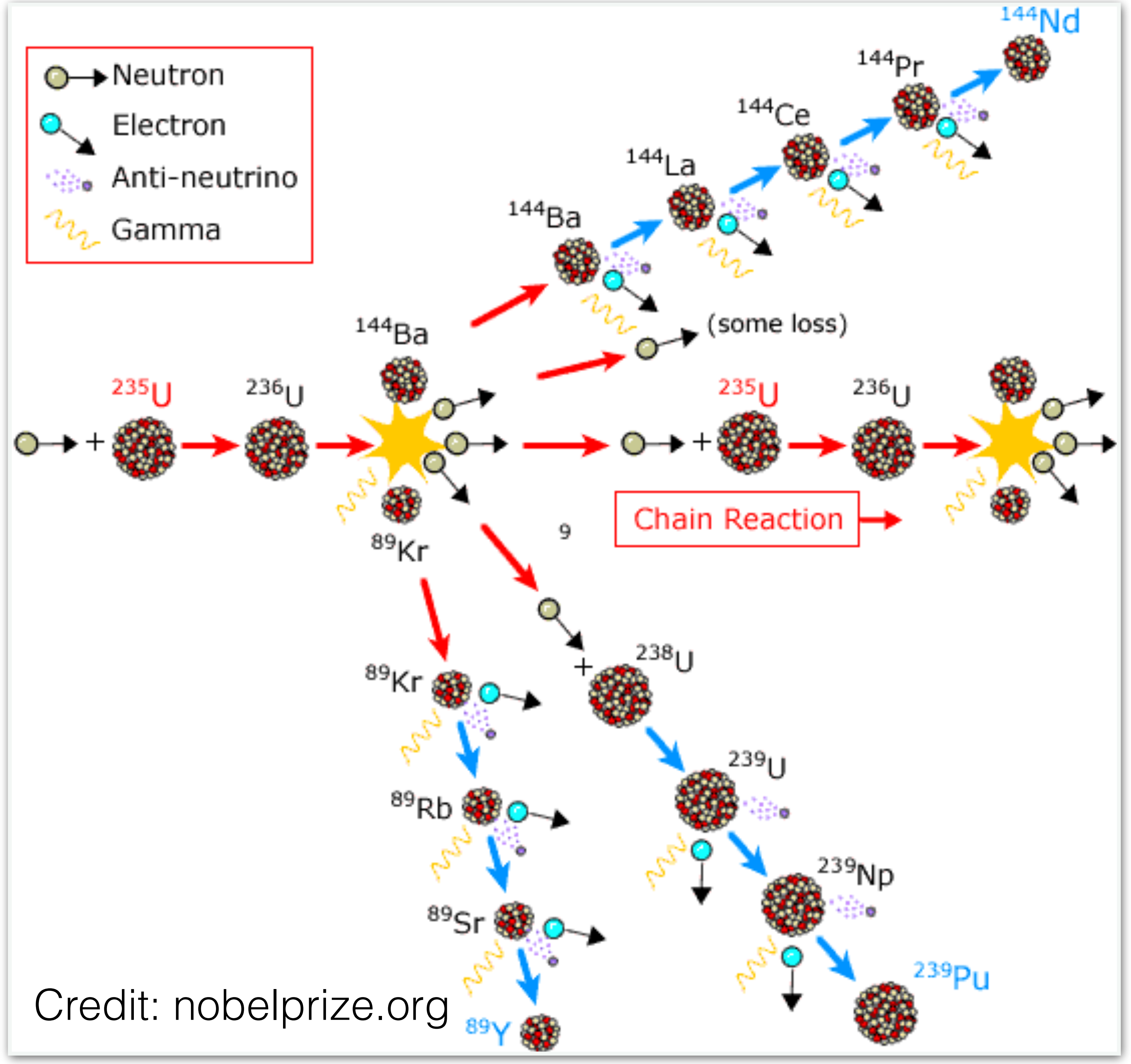
of Reactor Neutrino Experiments

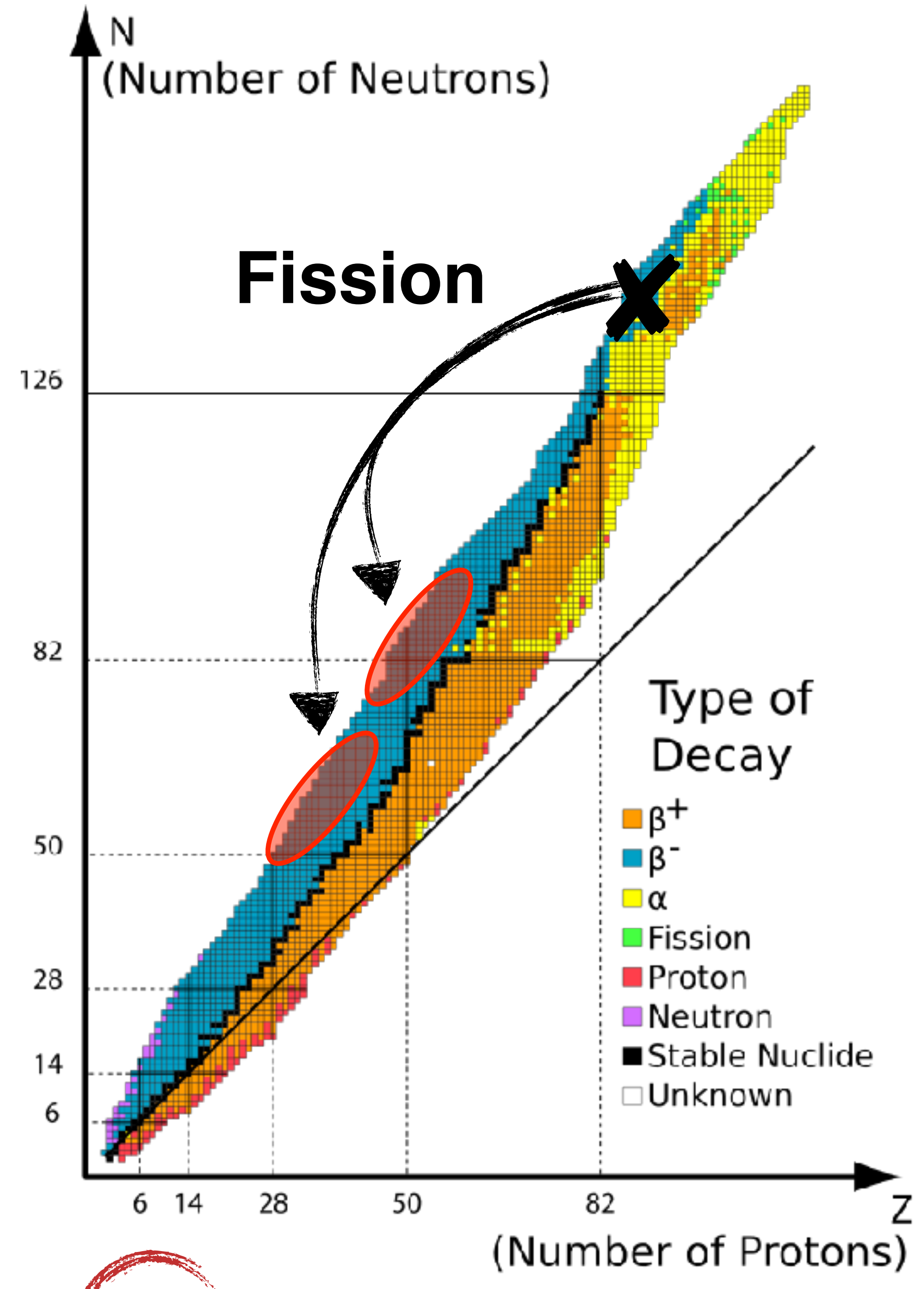
Reactor Antineutrinos

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



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





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

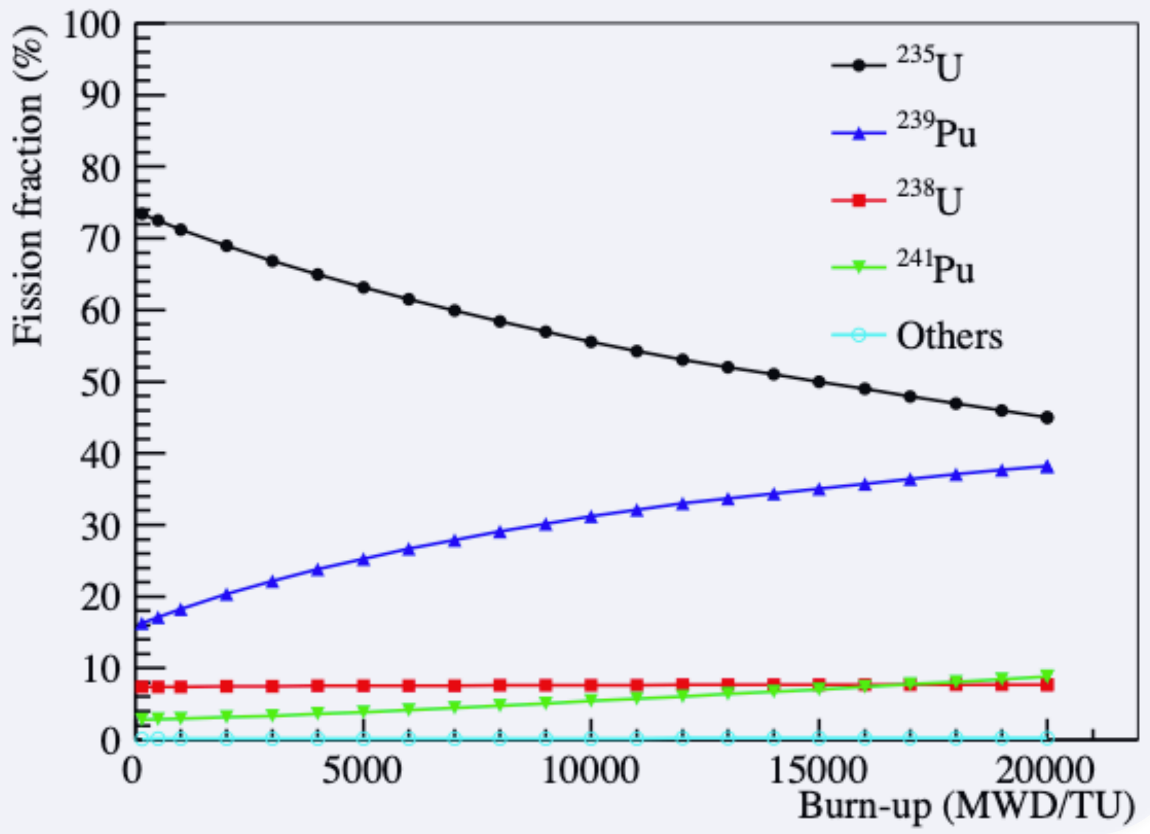
– A 1 $\mathrm{GW_{th}}$ core produces in one minute more neutrinos than the NuMI and BNB beams produce in a typical year

Types of Nuclear Reactors

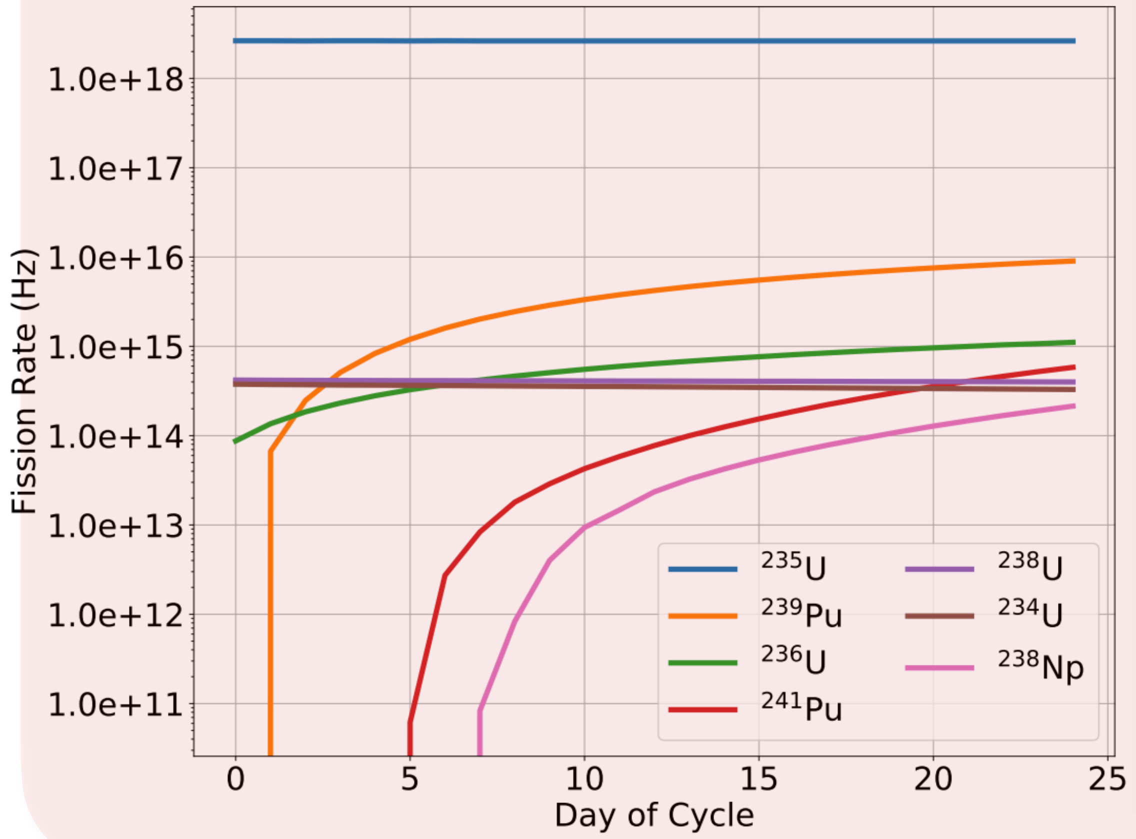
- Nuclear reactors fall into two main categories:

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}Pu is produced



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



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

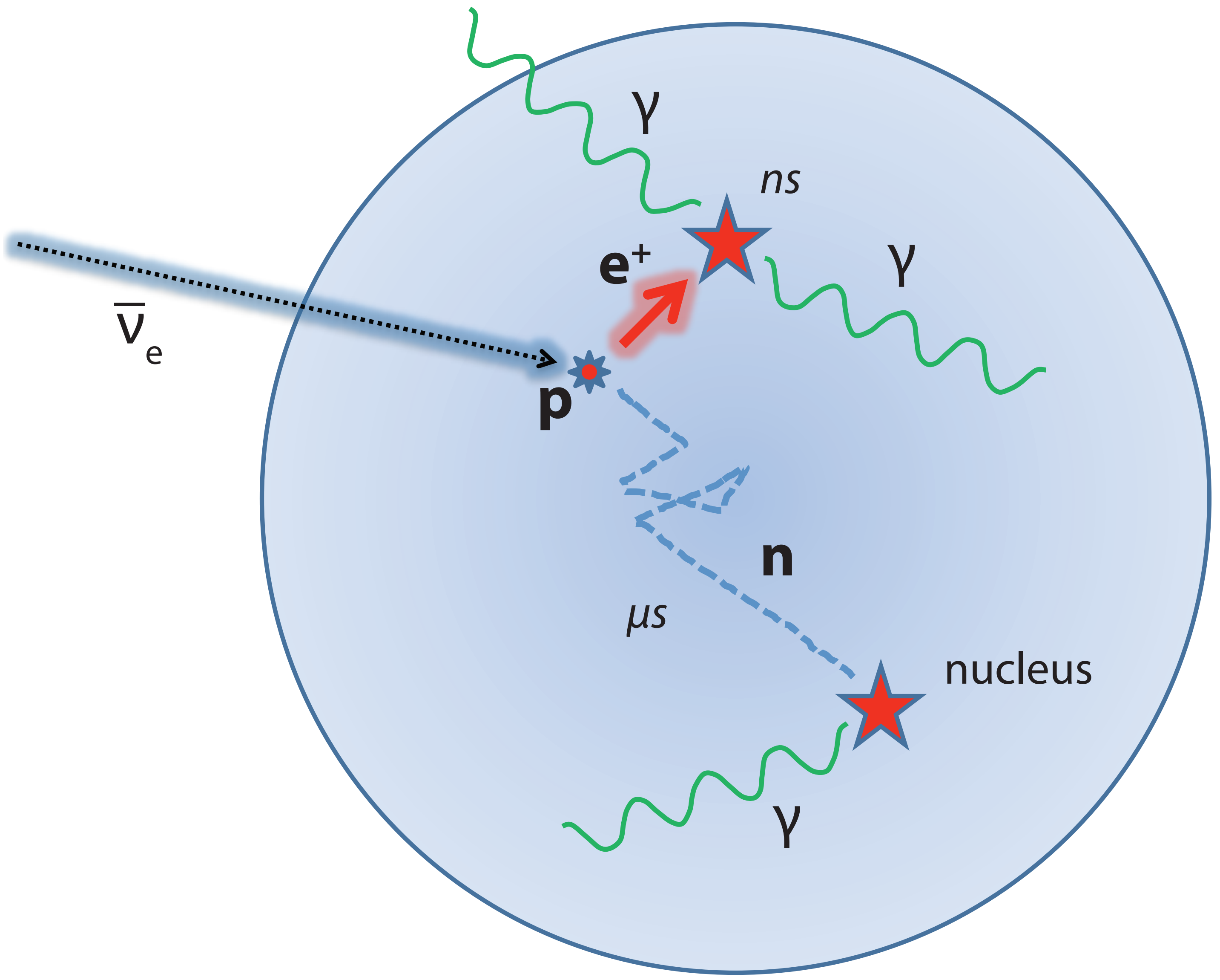
Antineutrino Detection

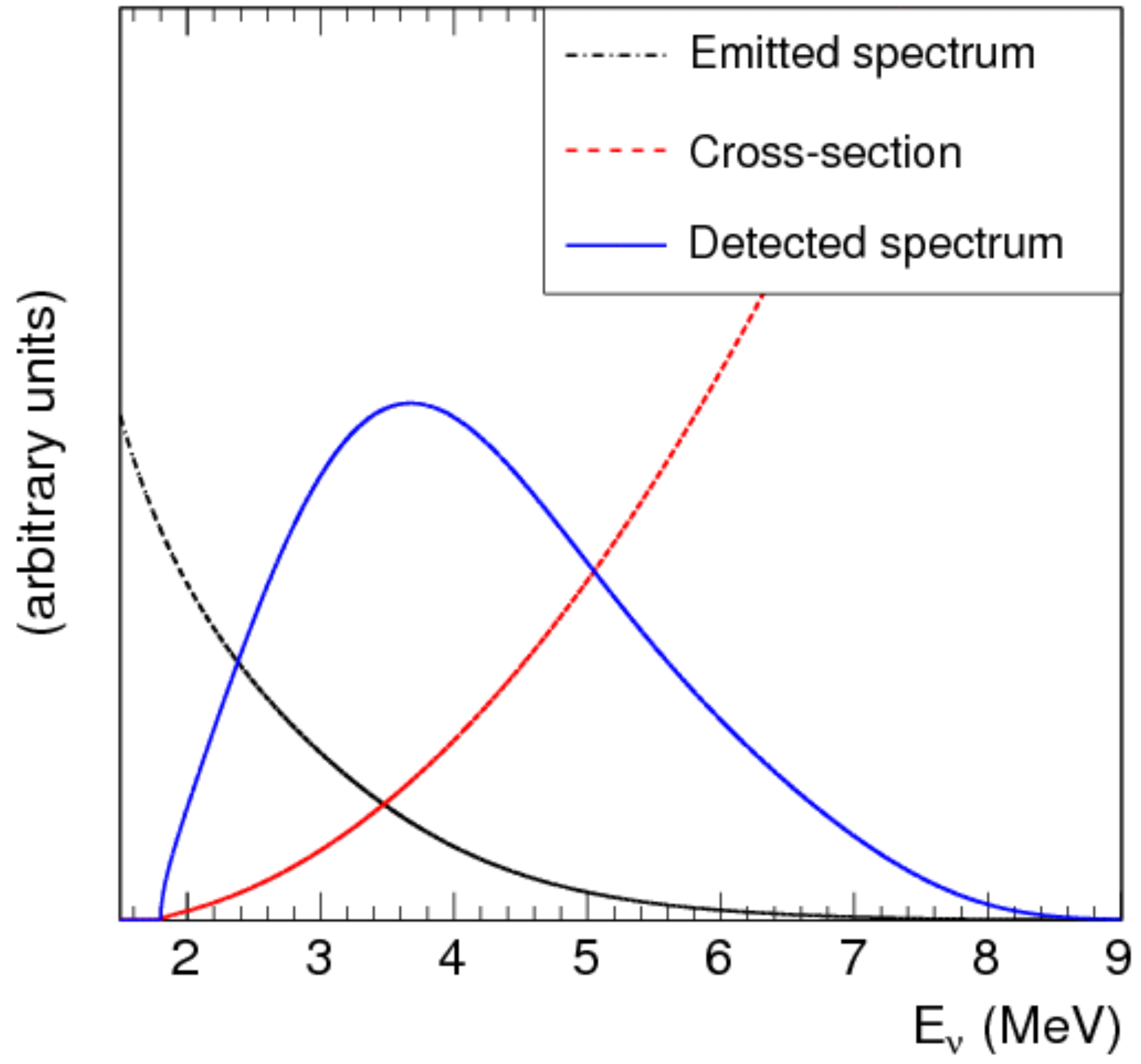
- The primary detection channel is the Inverse Beta Decay (IBD) reaction:

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

Prompt signal: e^+ kinetic energy loss + annihilation

Delayed signal: n capture on Hydrogen and subsequent gamma-ray emission





  – Coincidence between prompt positron and delayed neutron si **background rejection**

  – Energy of positron preserves information about energy of incoming $\bar{\nu}_e$: $E_{\bar{\nu}_e} \approx E_{\text{prompt}} + 0.78\ \text{MeV}$

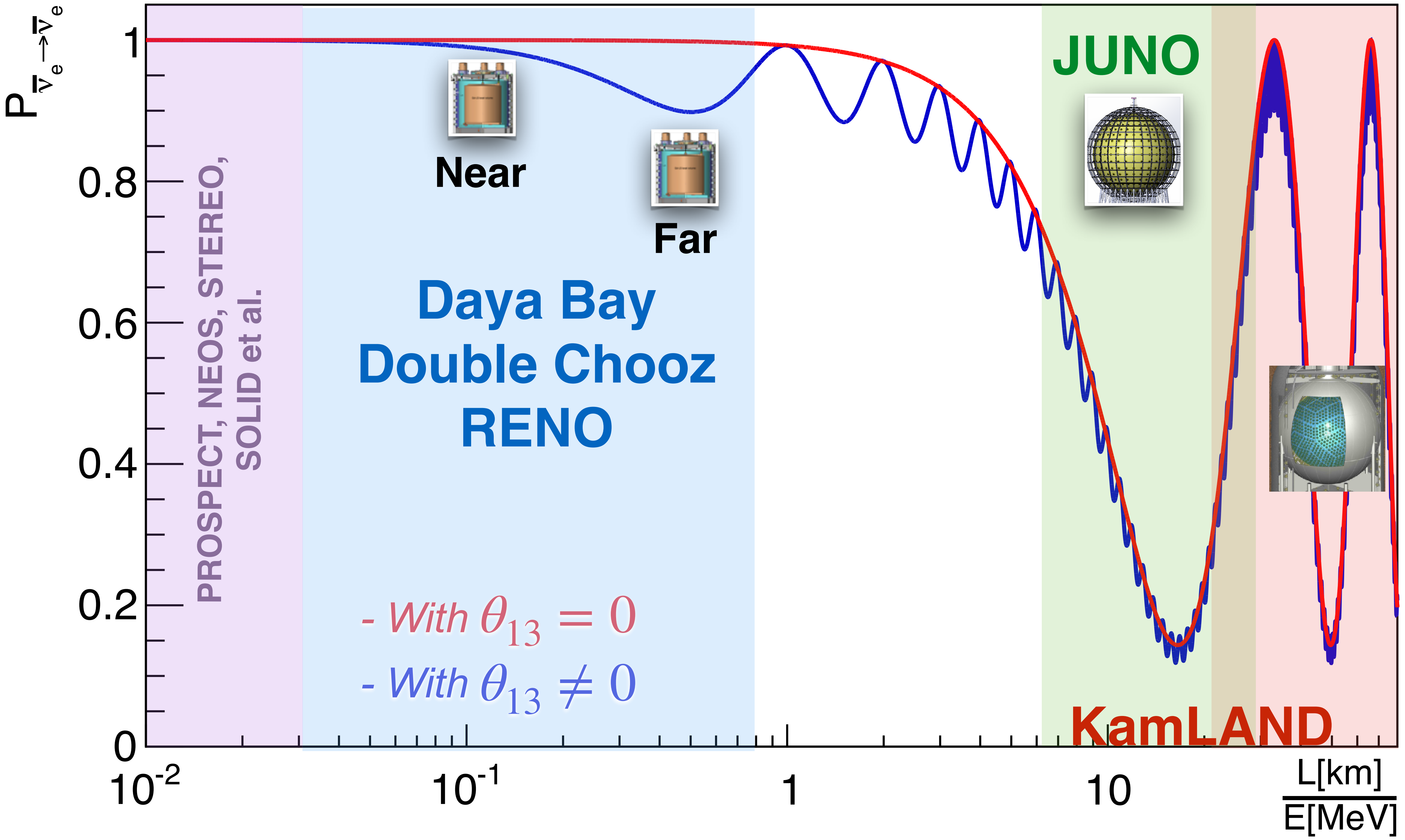
- Only $\bar{\nu}_e$'s are detectable via CC interactions; other flavors are kinematically inaccessible

Oscillation Probability

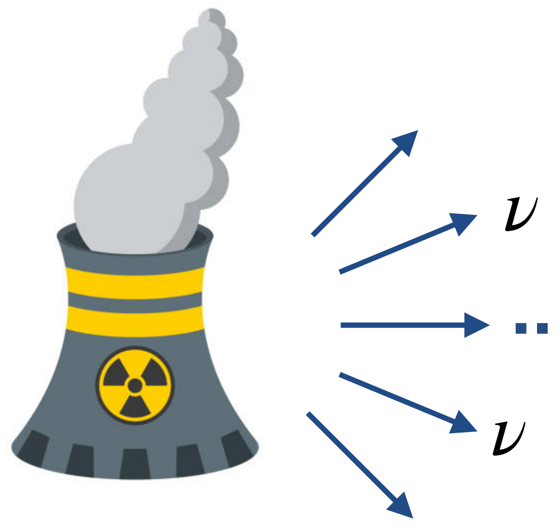
- Reactor neutrino experiments are "disappearance" experiments:

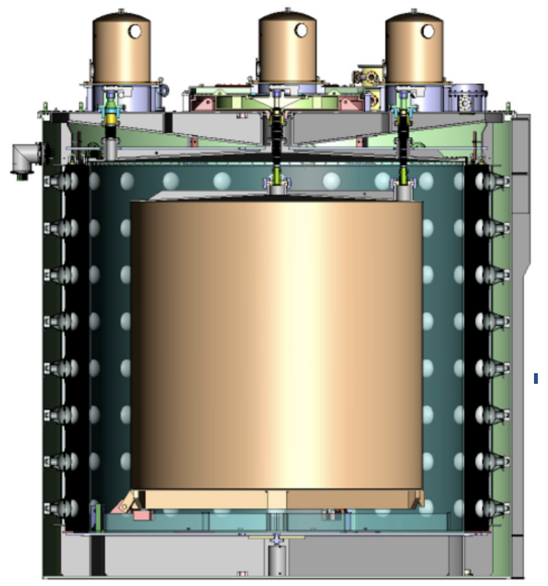
$$P_{\bar{\nu}_e \to \bar{\nu}_e}(L,E) = 1 - \boxed{\sin^2 2\theta_{12} \cos^4\theta_{13} \sin^2 \frac{\Delta m^2_{21} L}{4E}} - \sin^2 2\theta_{13} \left(\cos^2\theta_{12} \sin^2 \frac{\Delta m^2_{31} L}{4E} + \sin^2\theta_{12} \sin^2 \frac{\Delta m^2_{32} L}{4E} \right)$$

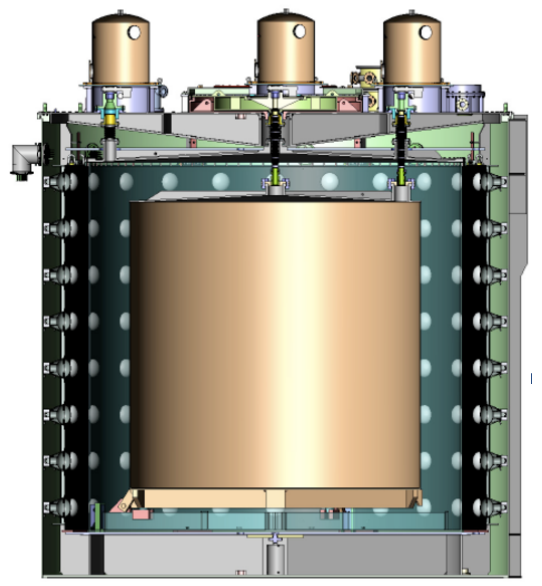
  - Look at how $\bar{\nu}_e$'s oscillate (disappear) into other flavors
  - Access to θ_{12}, θ_{13}, Δm^2_{21}, Δm^2_{31} and the mass ordering
  - No dependence on θ_{23} and δ_{CP}
  - Baseline is set by physics goals



Anatomy of a Reactor Neutrino Experiment







Note: using Daya Bay detectors for illustration

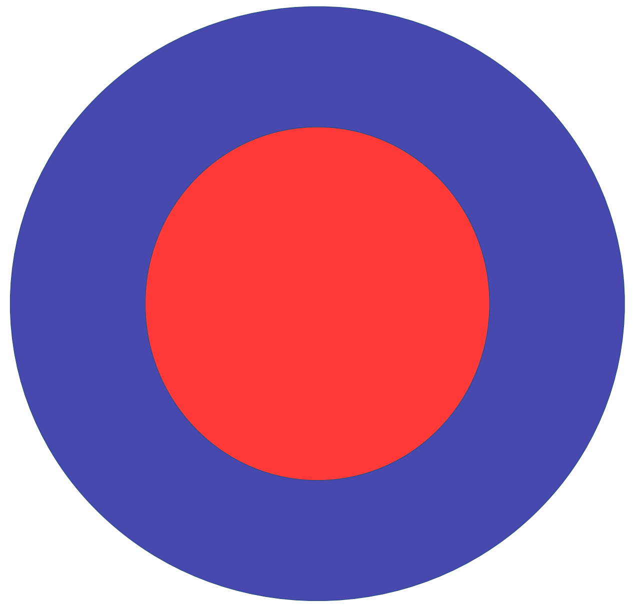
$\bar{\nu}_e$'s are emitted isotropically (in all directions)

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

Sample the neutrino flux in at least one location:

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

Reactor $\bar{\nu}_e$'s are ~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

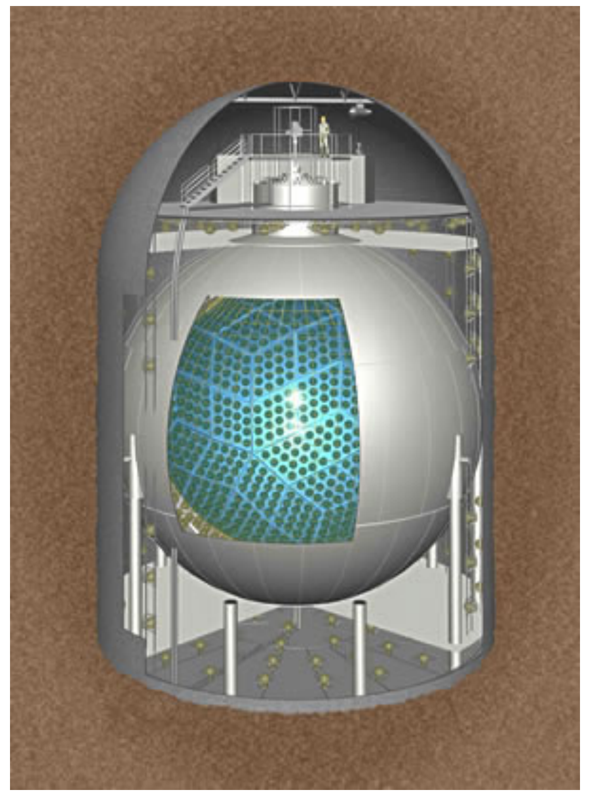
see the surrounding and internal radioactivity, so need clean detectors

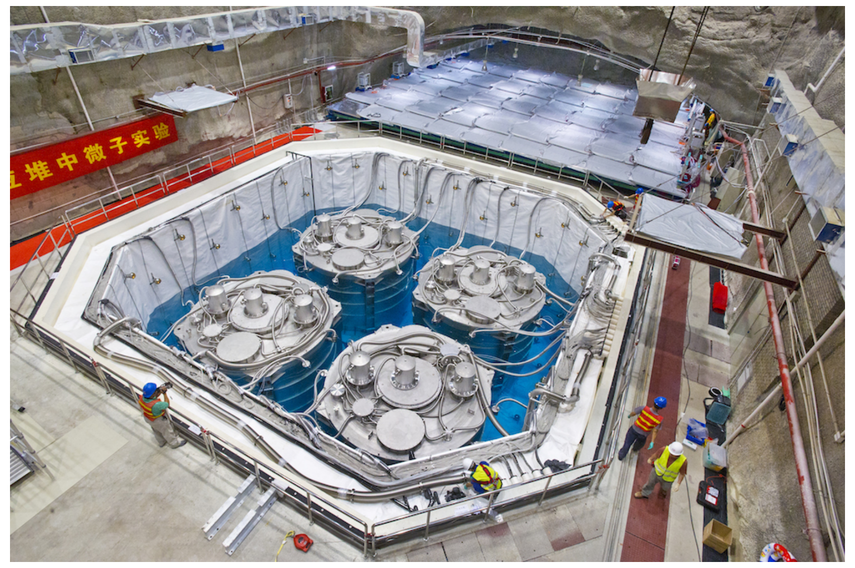
get total energy, time and position of event, but not detailed spatial structure

Several Generations of Reactor Neutrino Experiments

Discovery of the Neutrino (1956)

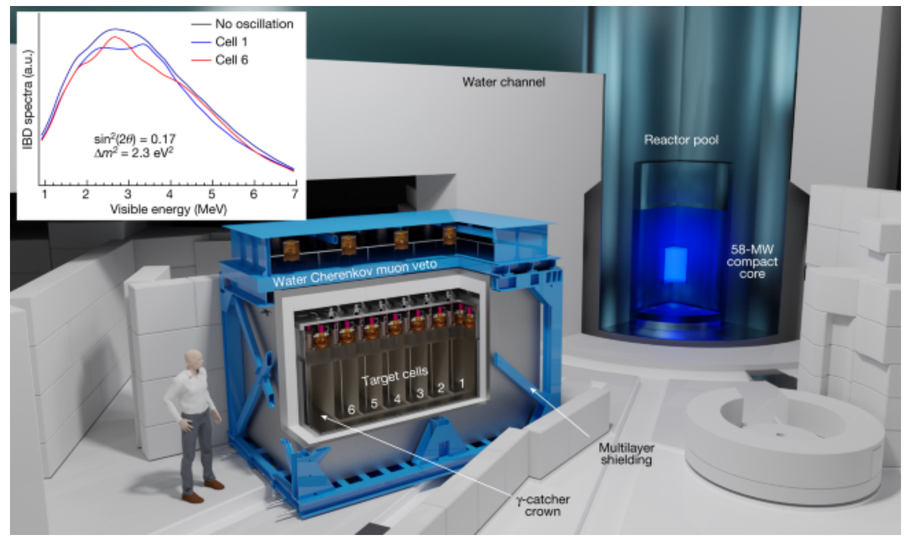
KamLAND (2002-2011)





The θ_{13} generation (~2011-2023)

Short-Baseline Experiments (~2015-2023)



JUNO (2025-?)

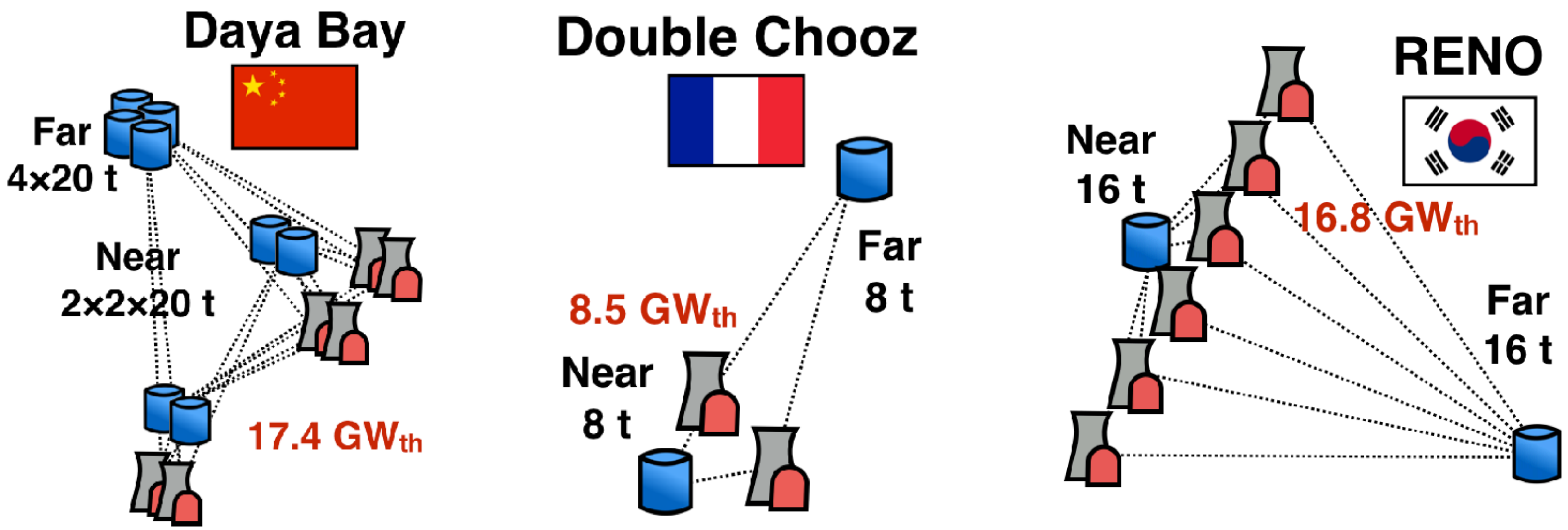
Focus of the rest of the talk

The θ_{13} Generation

of Reactor Neutrino Experiments

Basic Layout

- There are three θ_{13} reactor neutrino experiments:



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

 - < 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

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

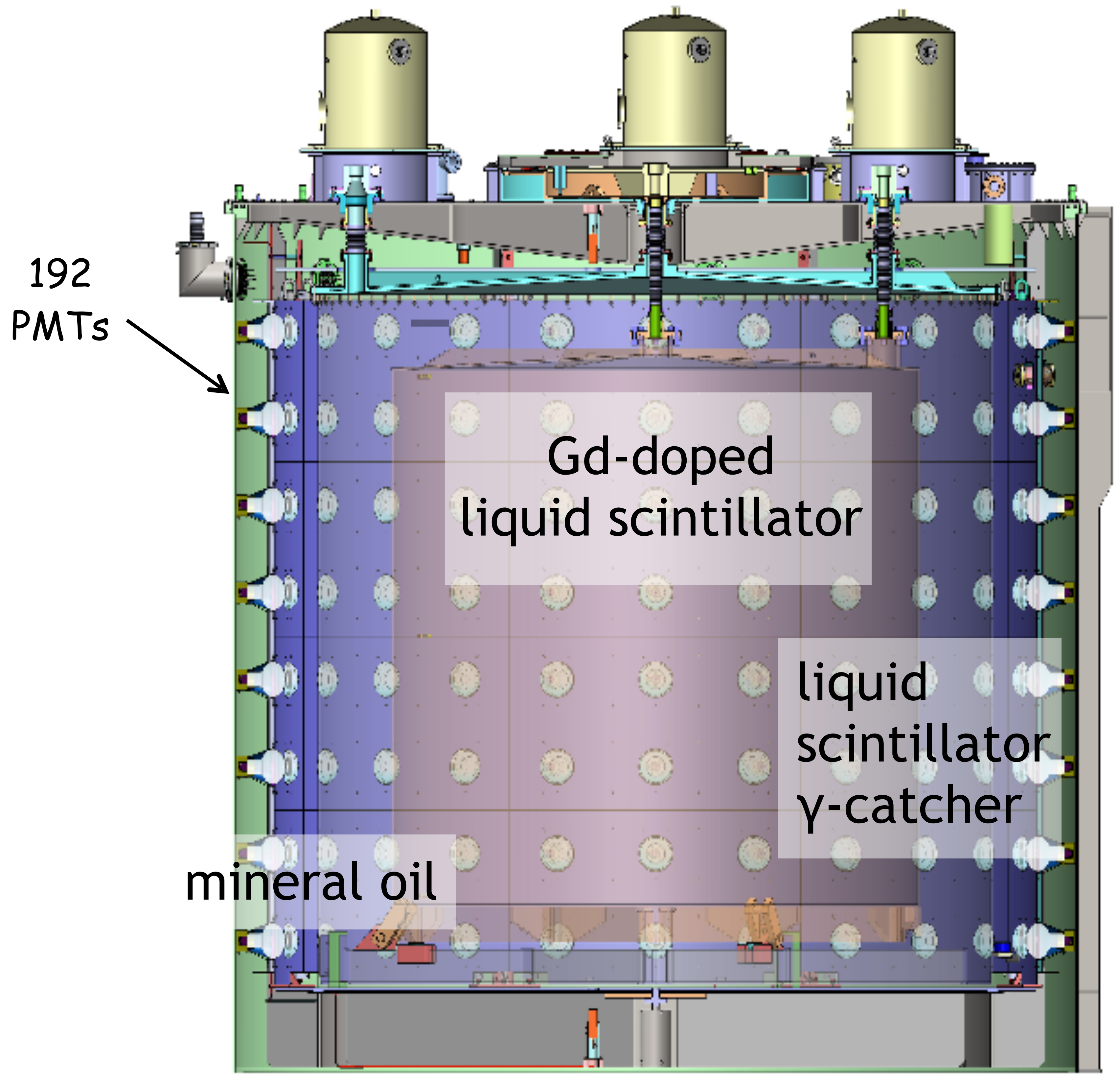
- Last unknown mixing angle in the PMNS matrix
- Intrinsically linked to the possibility of observing CP violation in the leptonic sector
- θ_{13}-driven oscillations offer a pathway for measuring the neutrino mass ordering

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

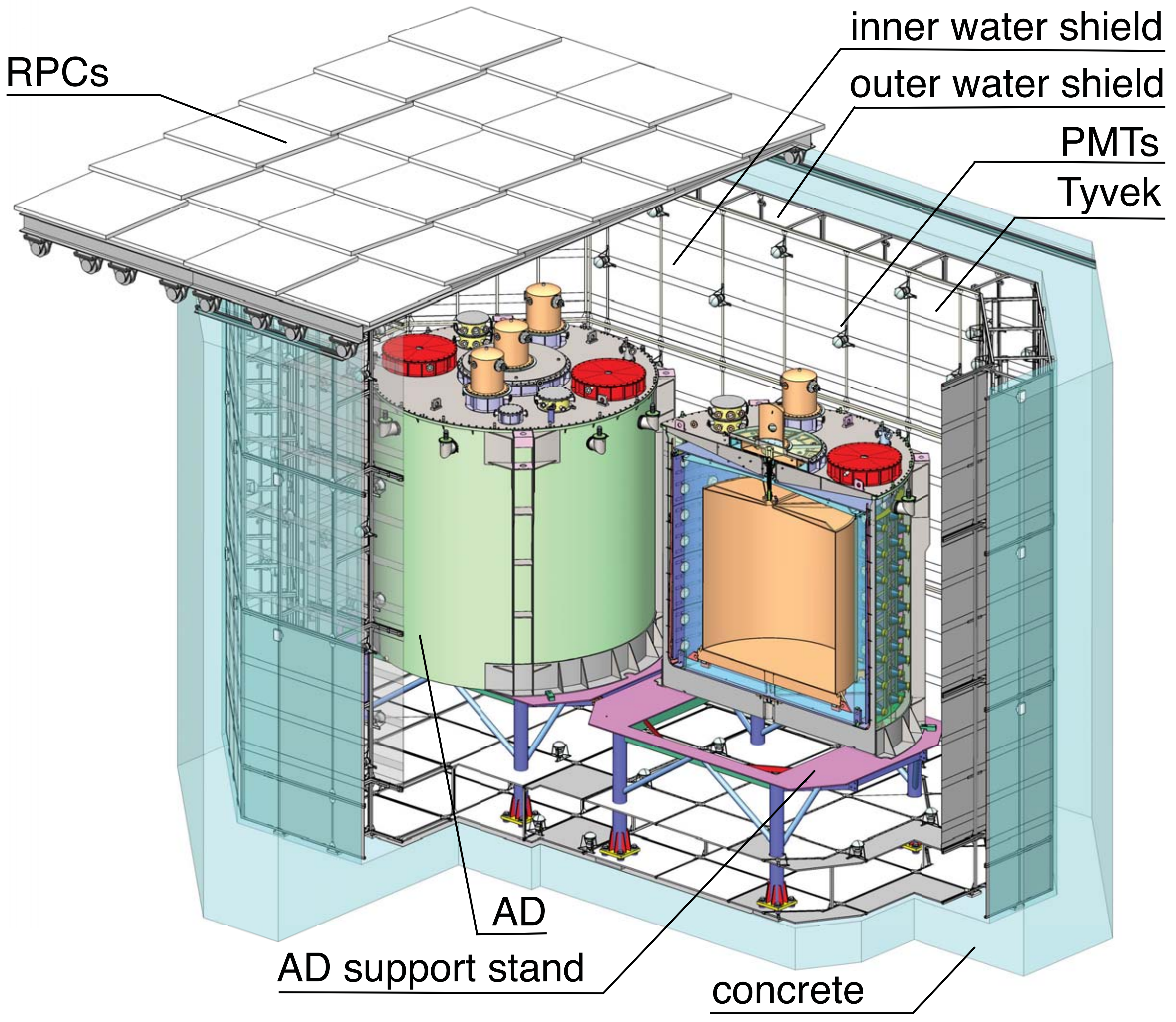
The Detectors

- 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

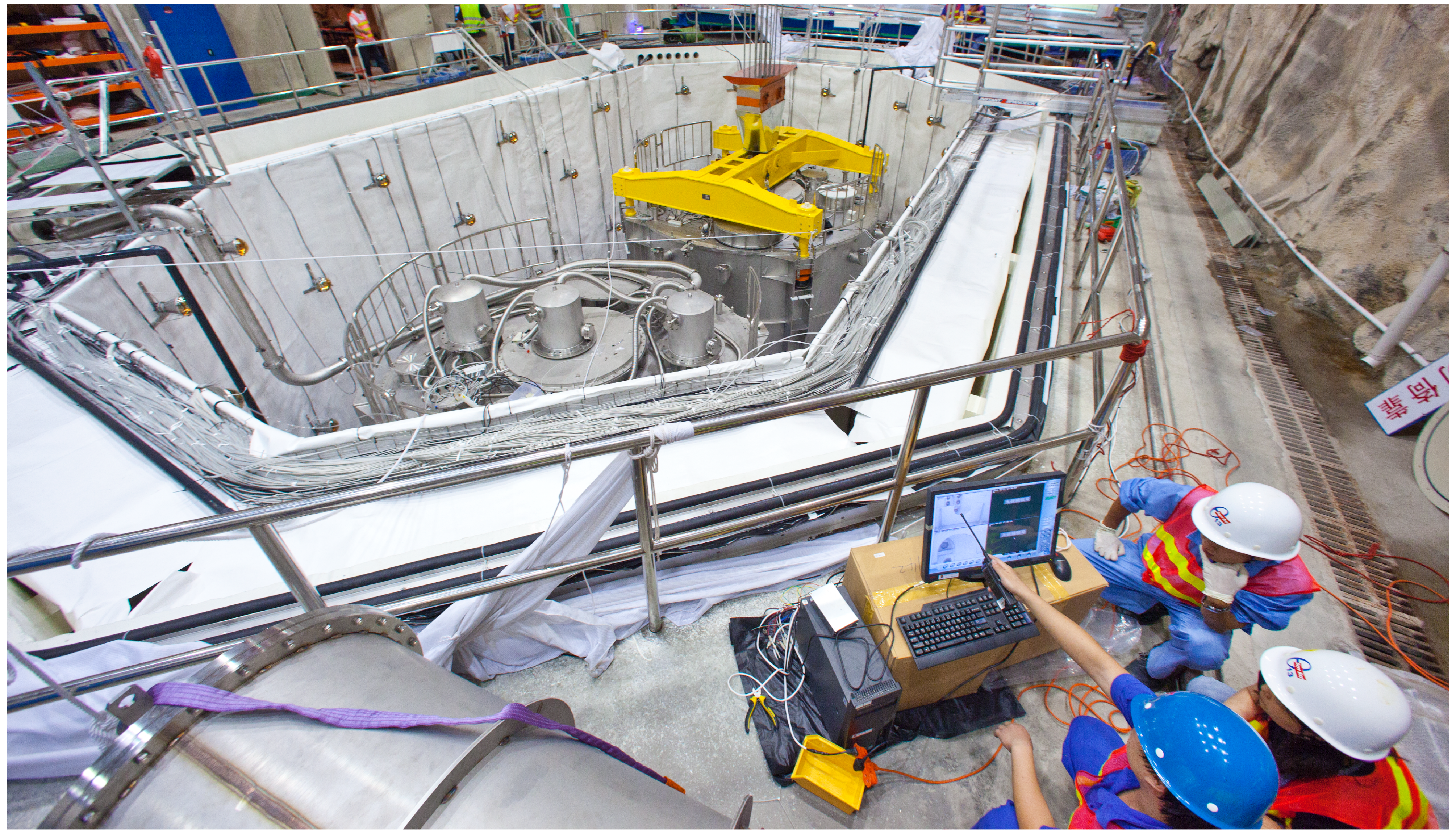


NIM A 811, 133 (2016)



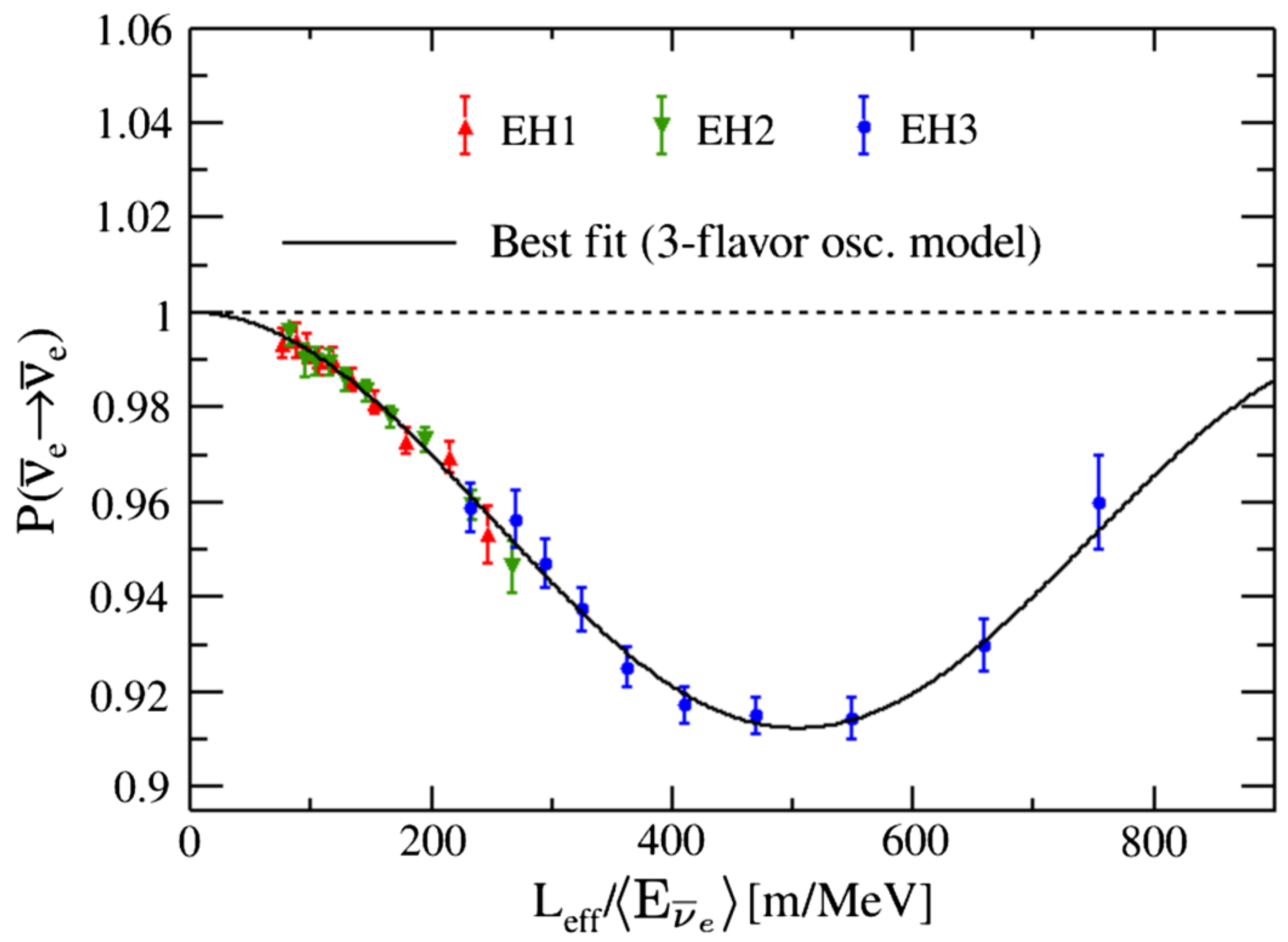
NIM A 773, 8 (2015)

Selection of Pictures

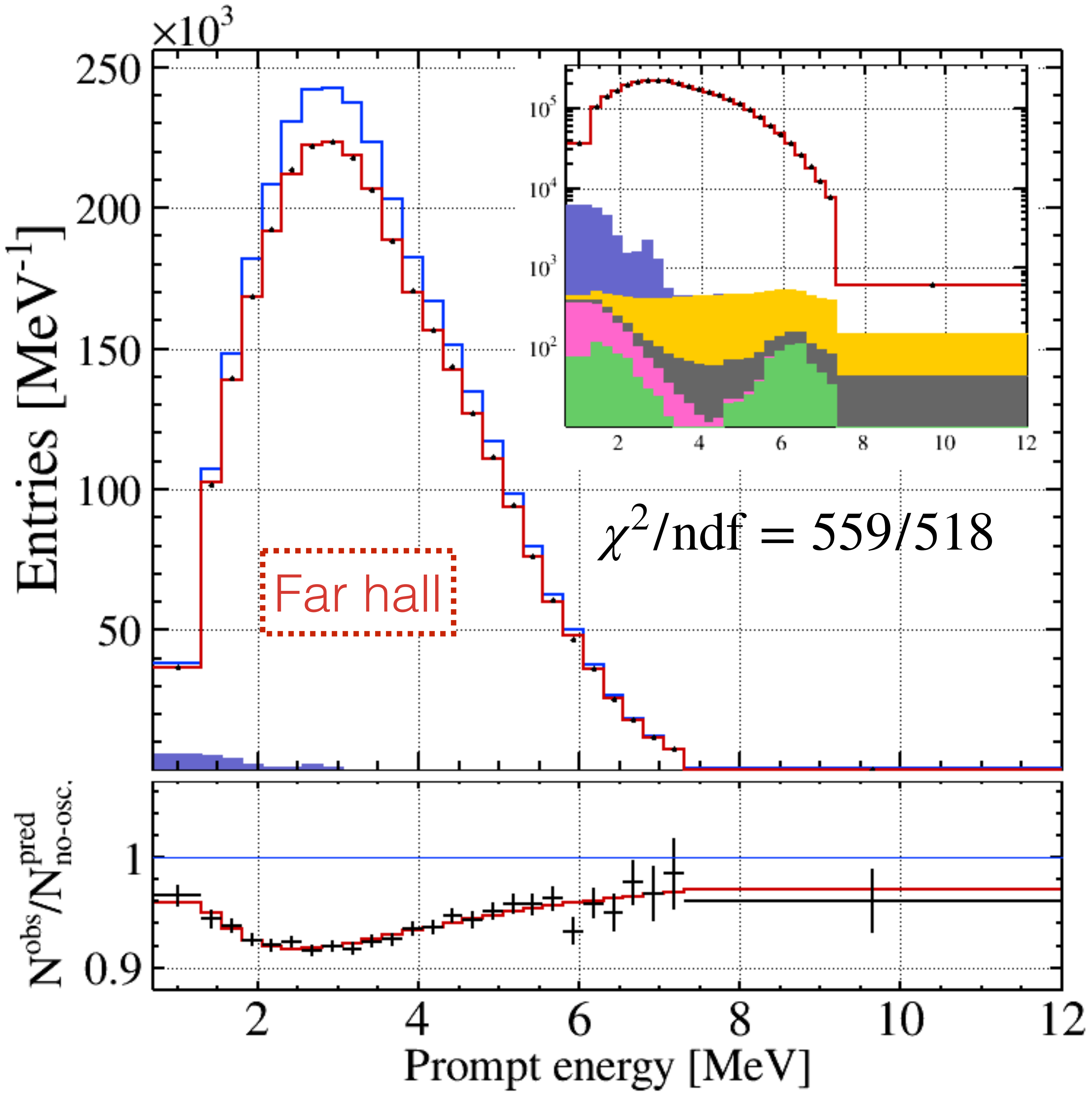


Oscillation Measurements

- As an example, these are the latest results from Daya Bay
  - 3158 days of data
  - From spectral distortion simultaneously extract $\sin^2(2\theta_{13})$ and Δm^2_{32}

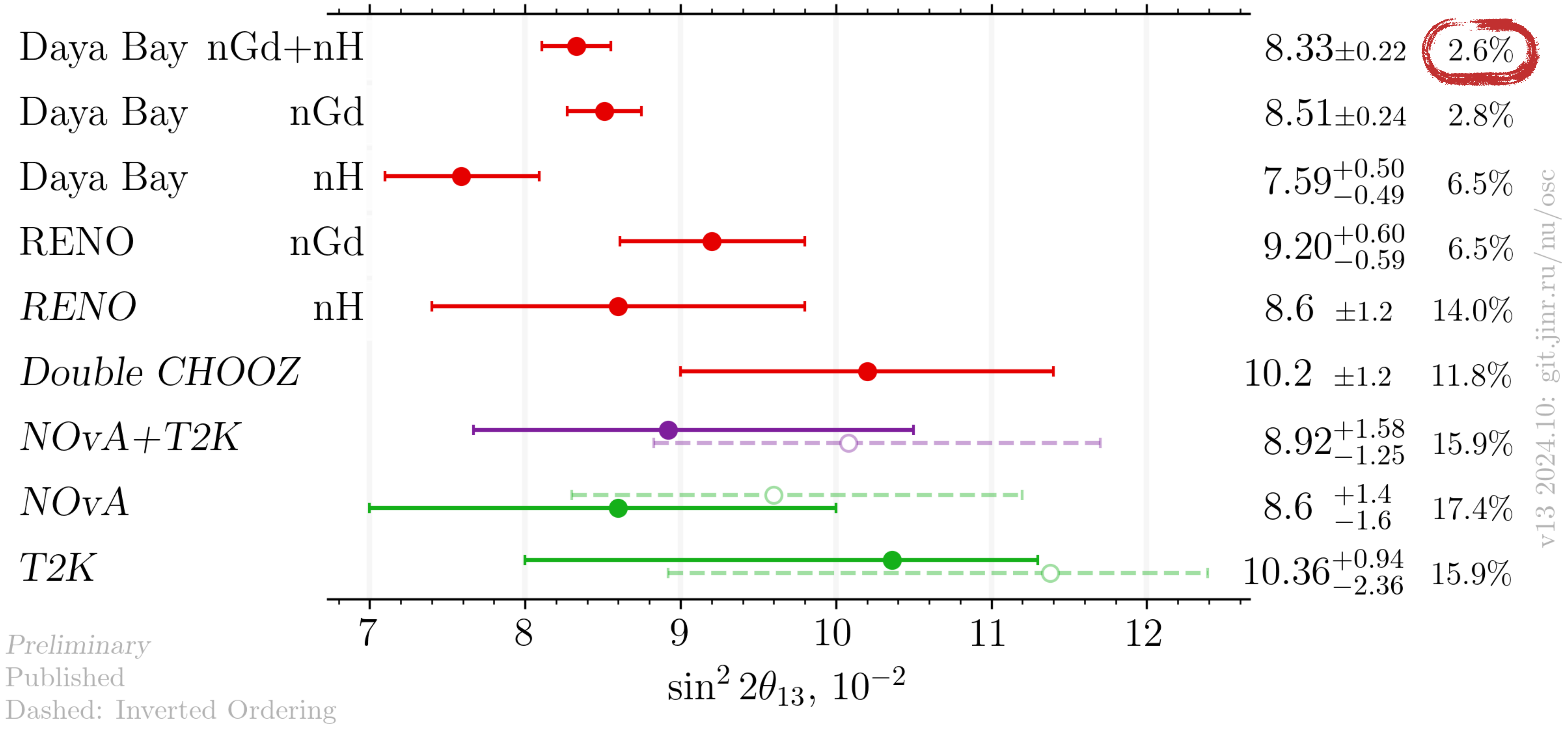


  - Excellent fit to standard three-neutrino framework

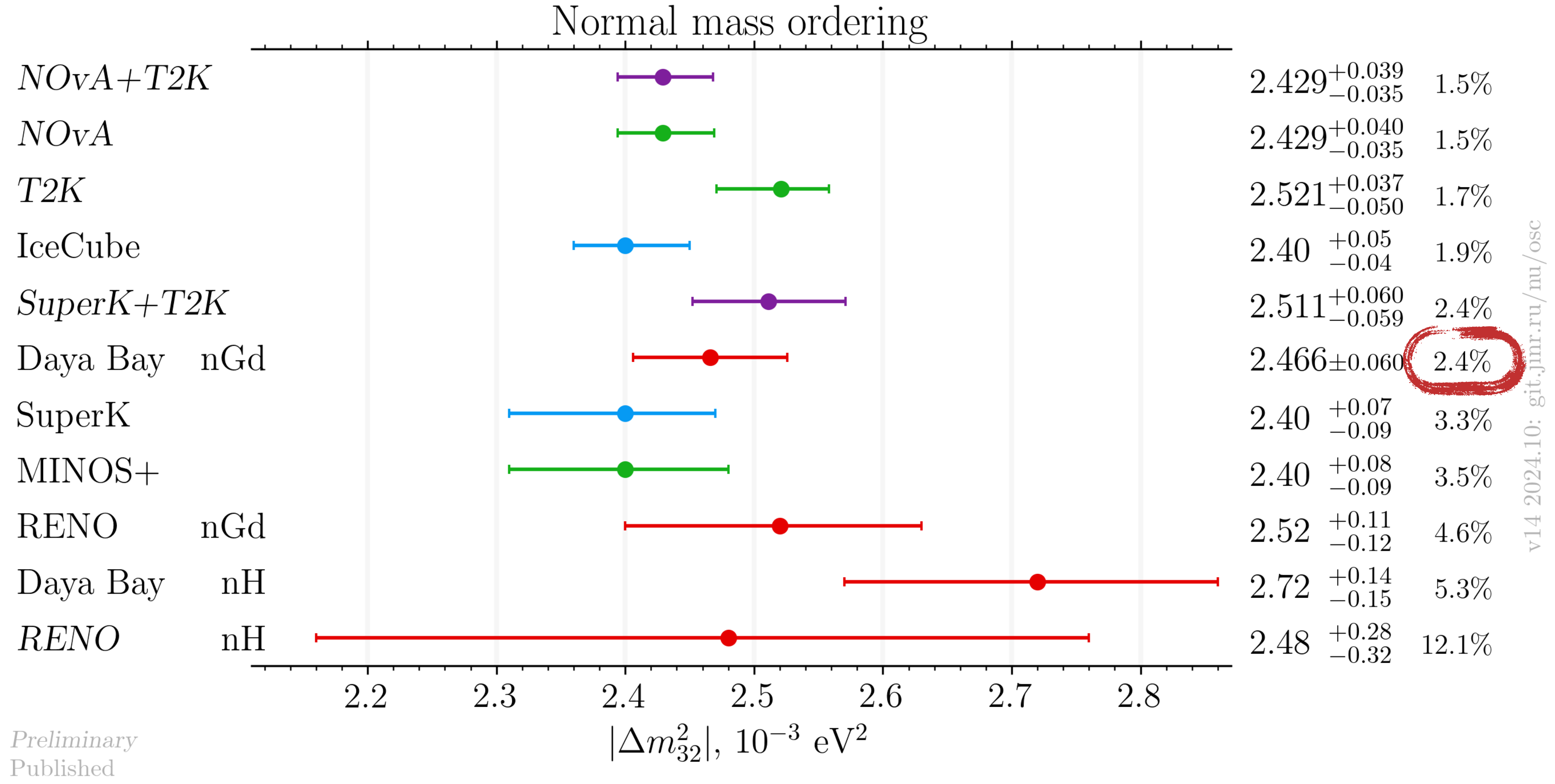


Global Landscape

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



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



Great agreement with accelerator experiments!

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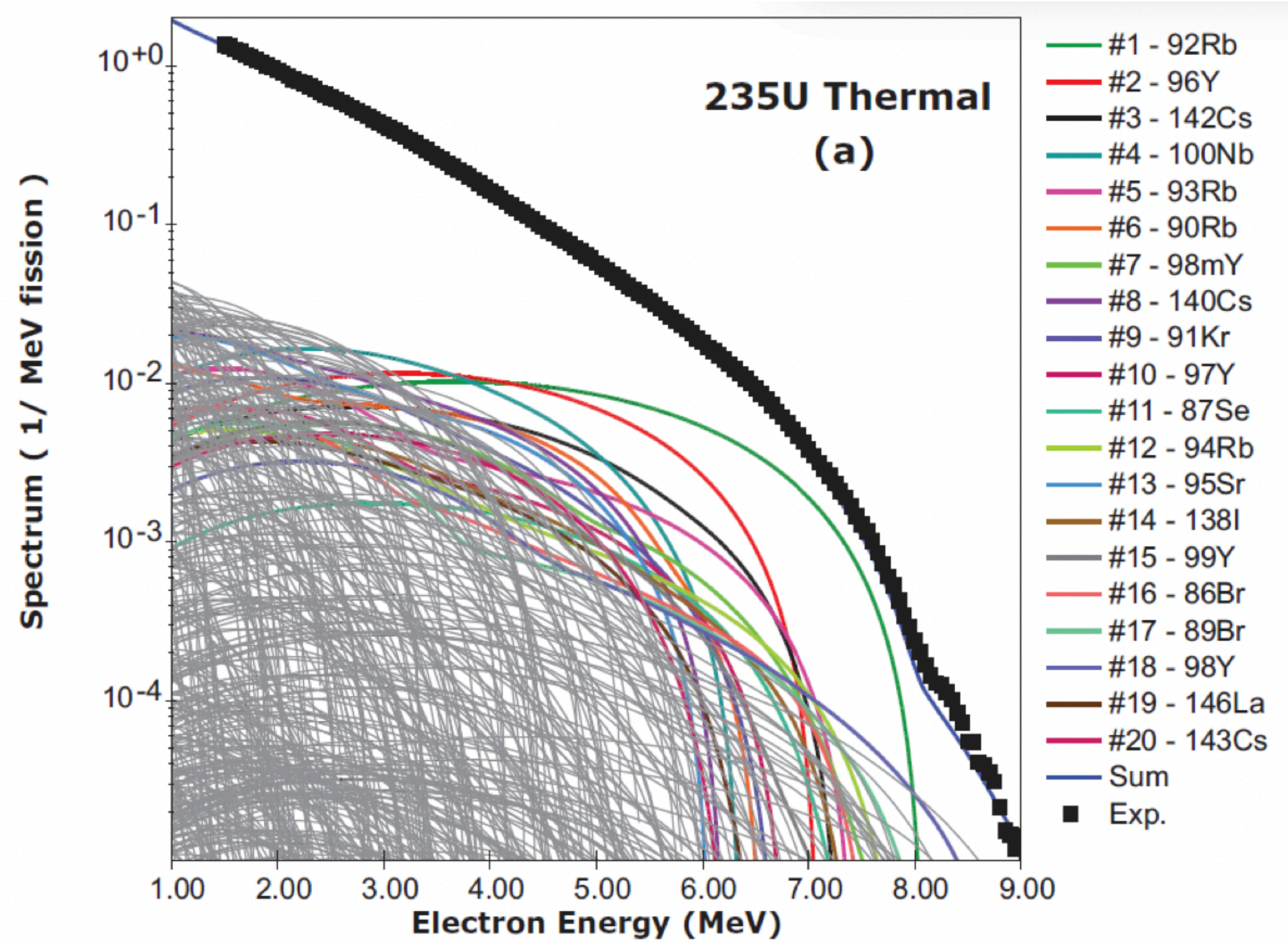
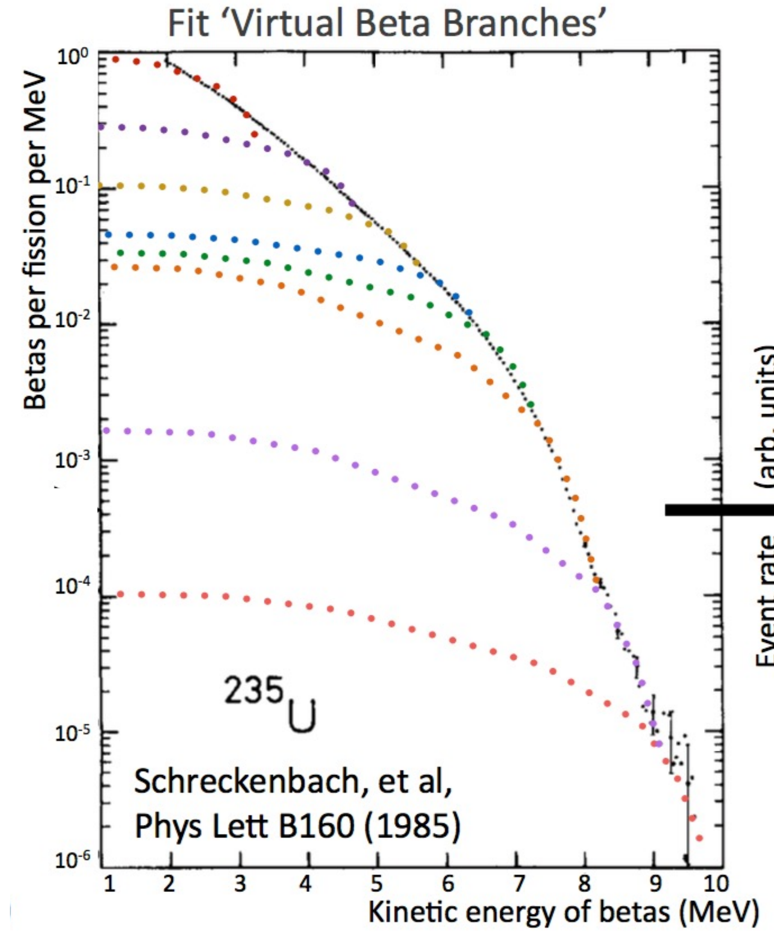
Data vs. Models

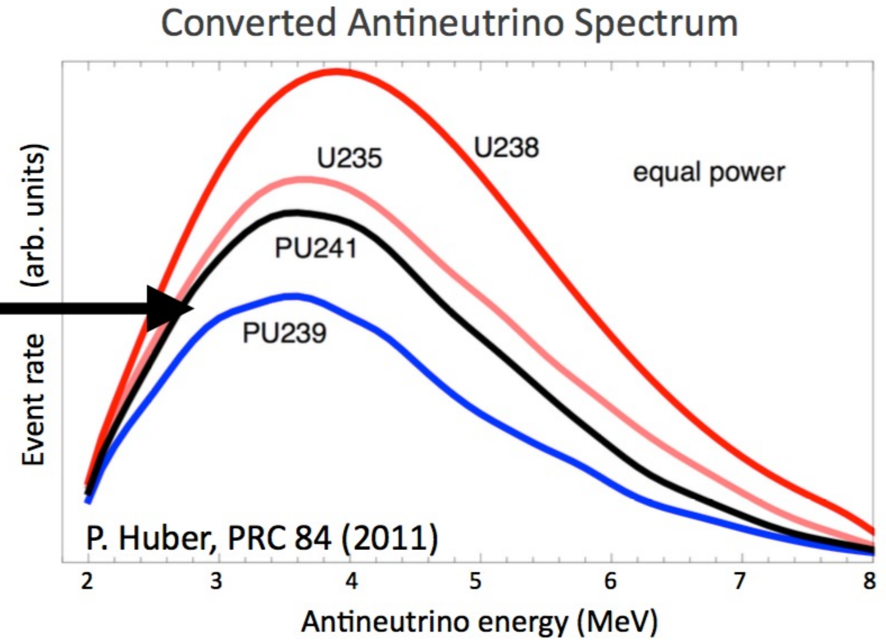
and Sterile Neutrino Searches

Characterizing $\bar{\nu}_e$ emission

- 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:
  - **Summation** (ab-initio) method:
    - Bottom-up calculation using fission yields, Q values and decay branching ratios from nuclear data bases
    - A recent implementation is the **SM2023** model
  - **Conversion** method:
    - Converting measured beta spectra from thermal-neutron induced fission (^{235}U, ^{239}Pu, ^{241}Pu) at ILL in the 1980s to $\bar{\nu}_e$ spectra
    - Smaller estimated uncertainties (few %)
    - Latest implementation is the so-called **Huber+Mueller (HM)** model



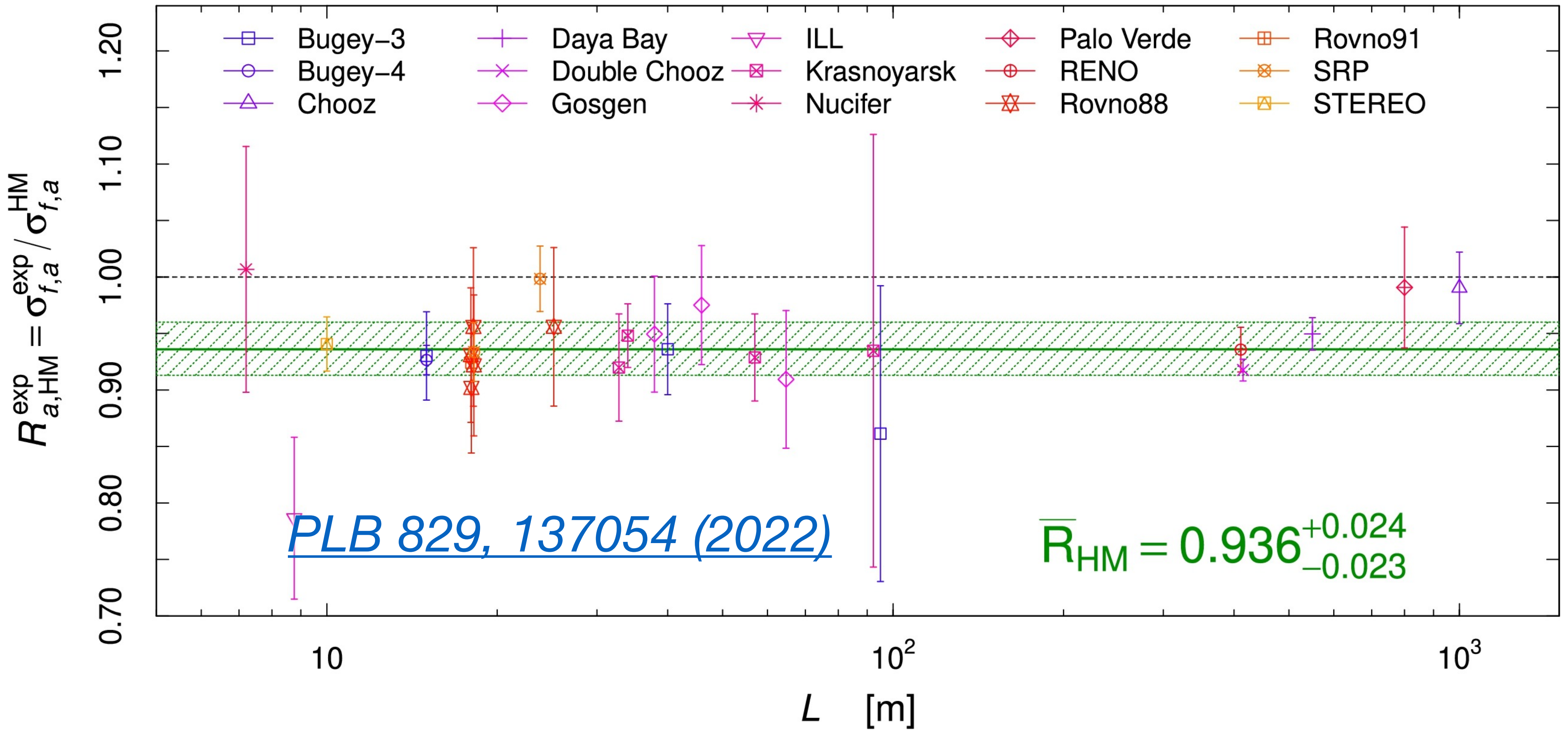




Disagreements with Predictions

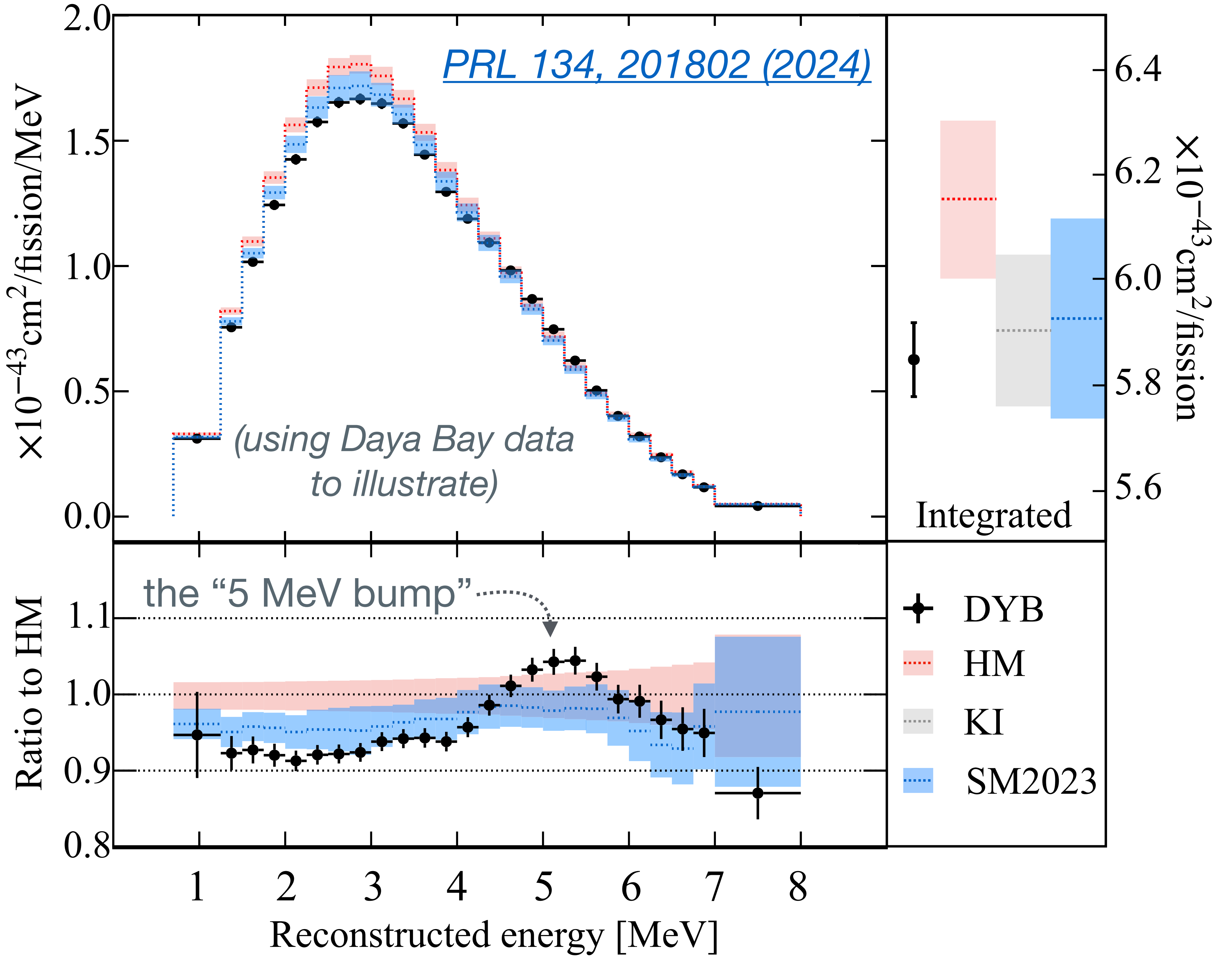
- These experiments exposed significant disagreements with prediction models during the last decade

Rate



- ~6% deficit in total flux with respect to the HM model at short baselines is known as the **"reactor antineutrino anomaly"** (RAA)
- Primary motivation for SBL sterile neutrino searches
- Not seen with recent summation models

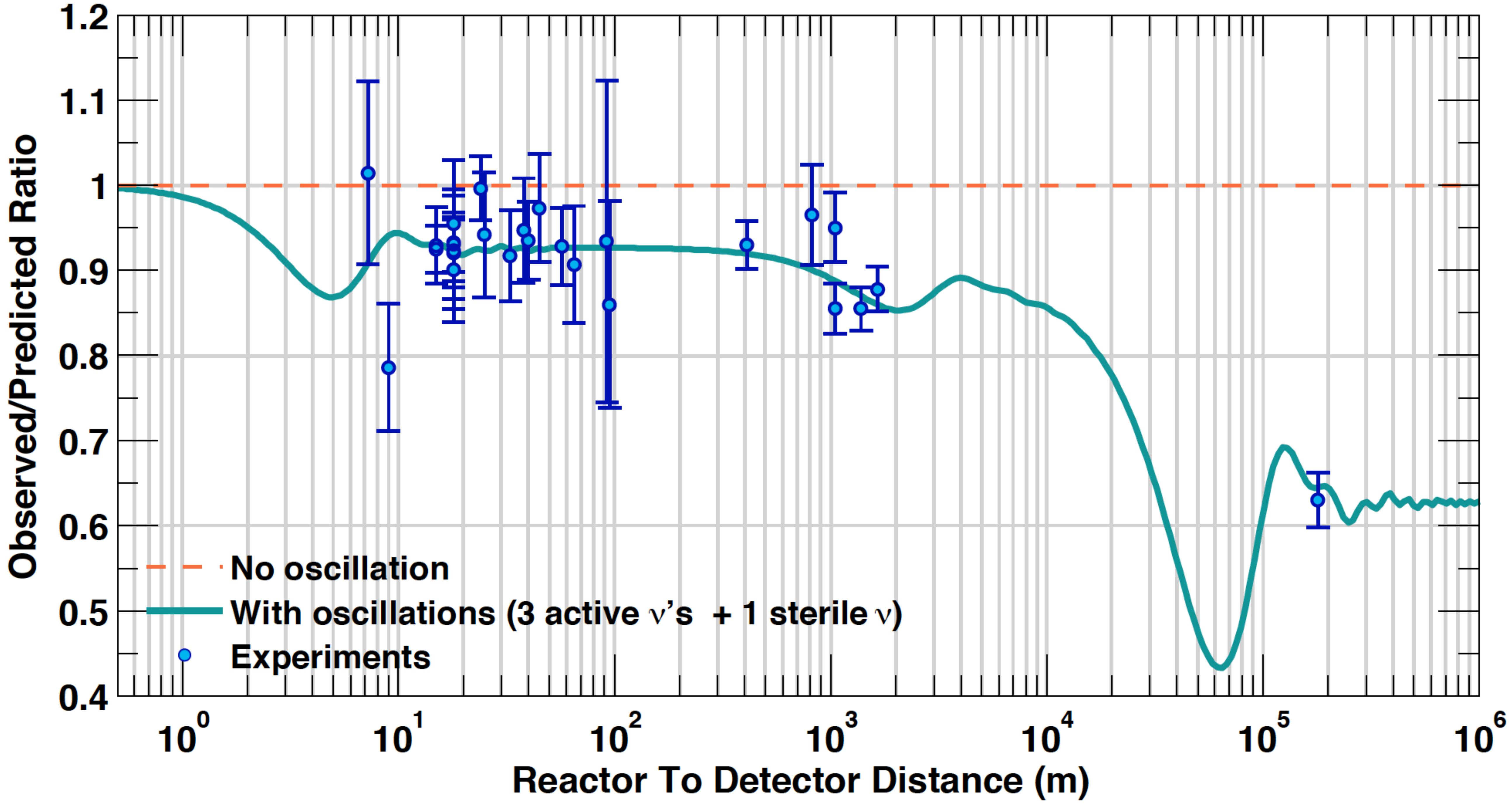
Shape



- Main disagreement is often referred to as "the 5 MeV bump"
- Seen with both summation and conversion models

Causes?

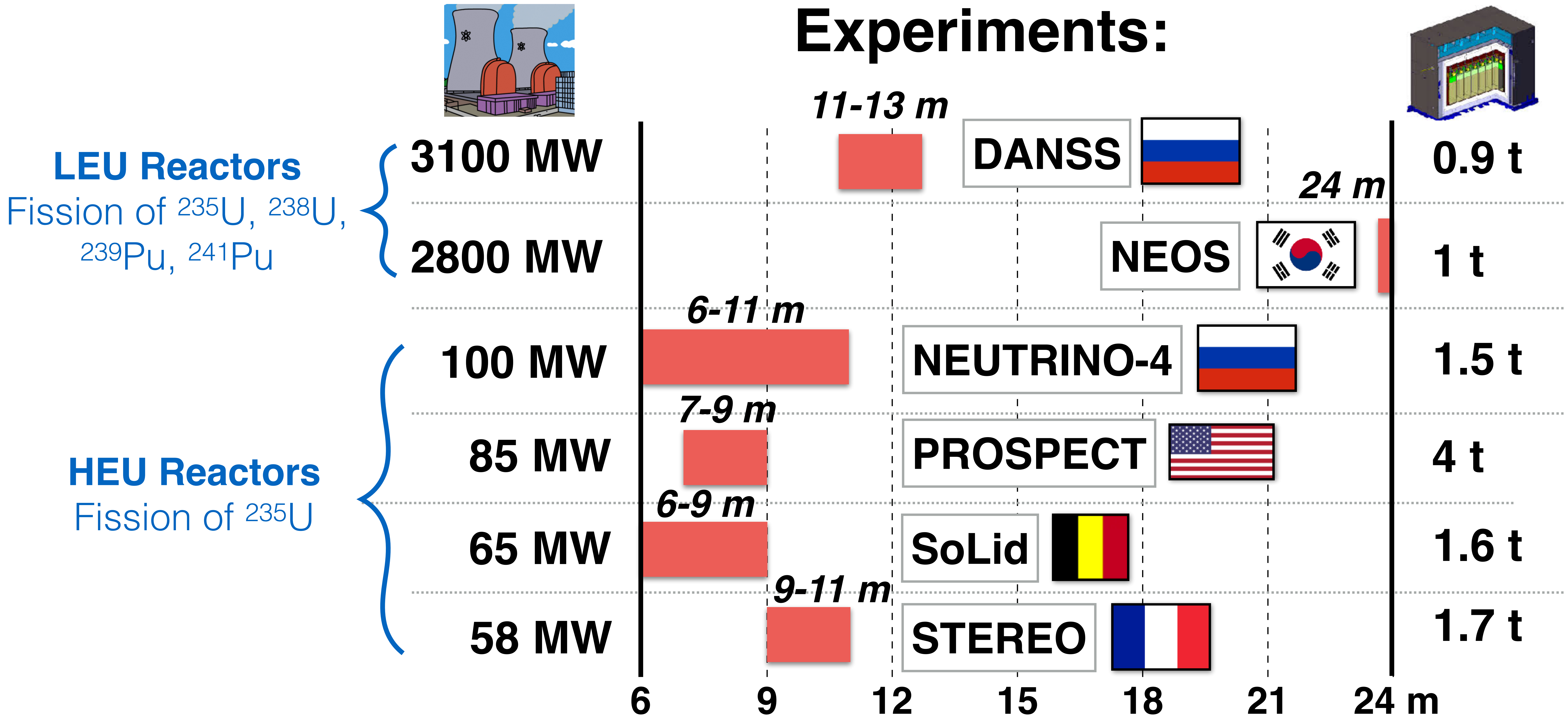
- What could be behind the reactor antineutrino anomaly?
  - Experimental systematics? **Extremely unlikely**…
  - New Physics (oscillations to a ~eV sterile neutrino)? **Maybe…**



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

Short Baseline (SBL) Experiments

- It is possible to test the sterile neutrino hypothesis by placing a detector at a O(10 m) baseline from a reactor

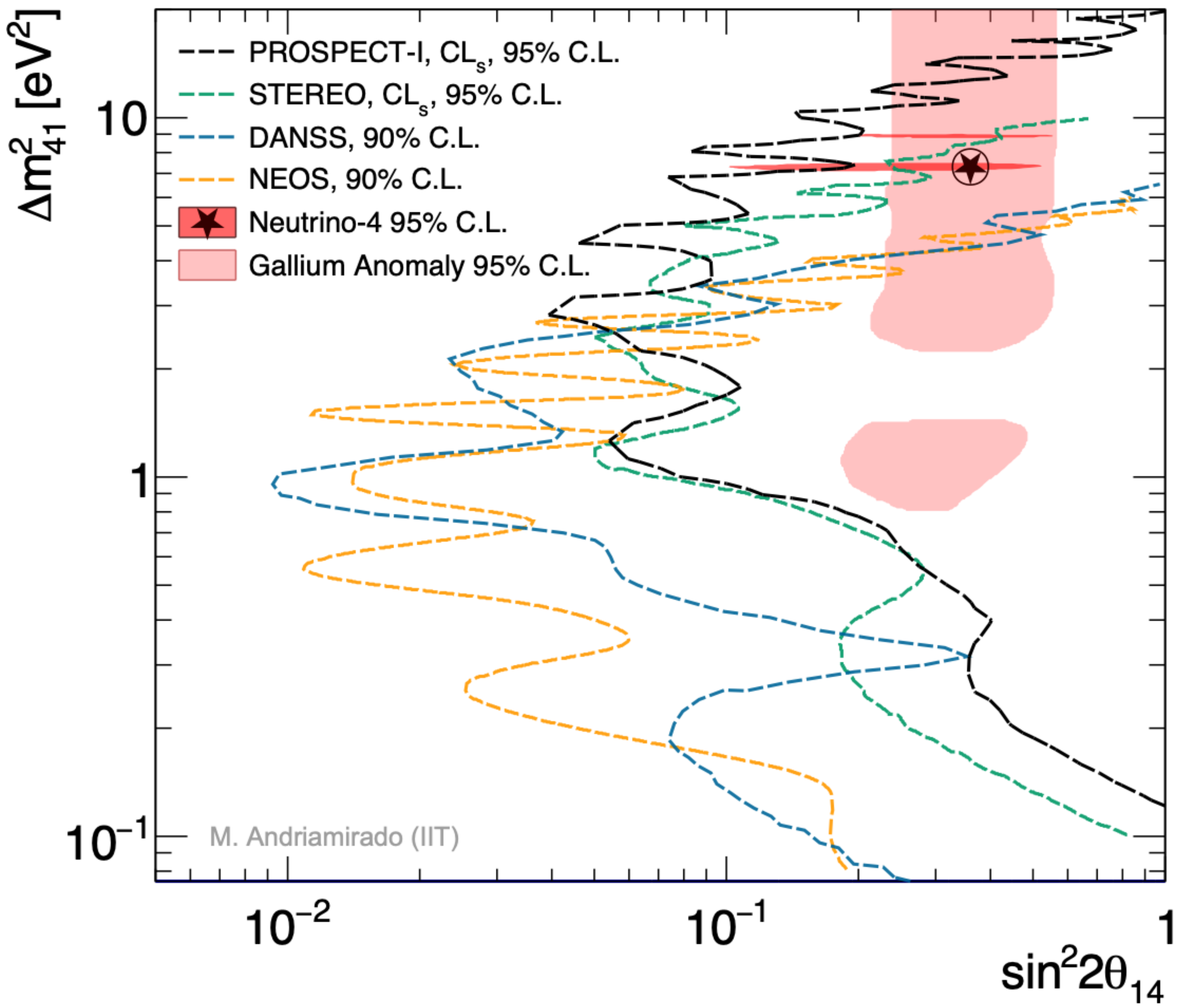


(chart courtesy of B. Roskovec)

+ (mini-)CHANDLER, NuLAT

Non-Standard Flavor Mixing Landscape

- All SBL experiments have released results by now
  - 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. right plot)



From D. Lhuillier's talk at Neutrino 2024

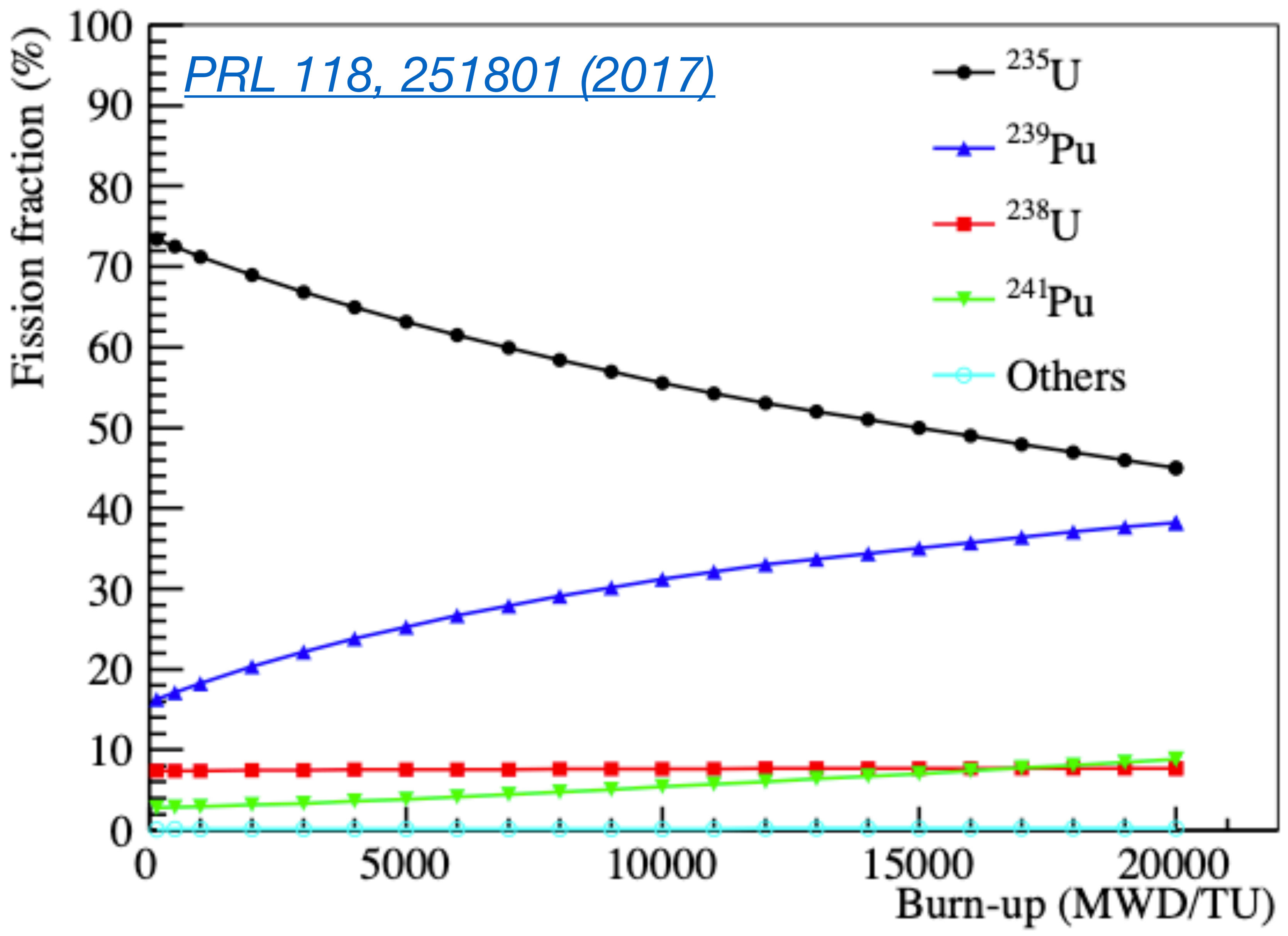
- No significant evidence so far for non-standard flavor mixing from either SBL or km-scale experiments

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:

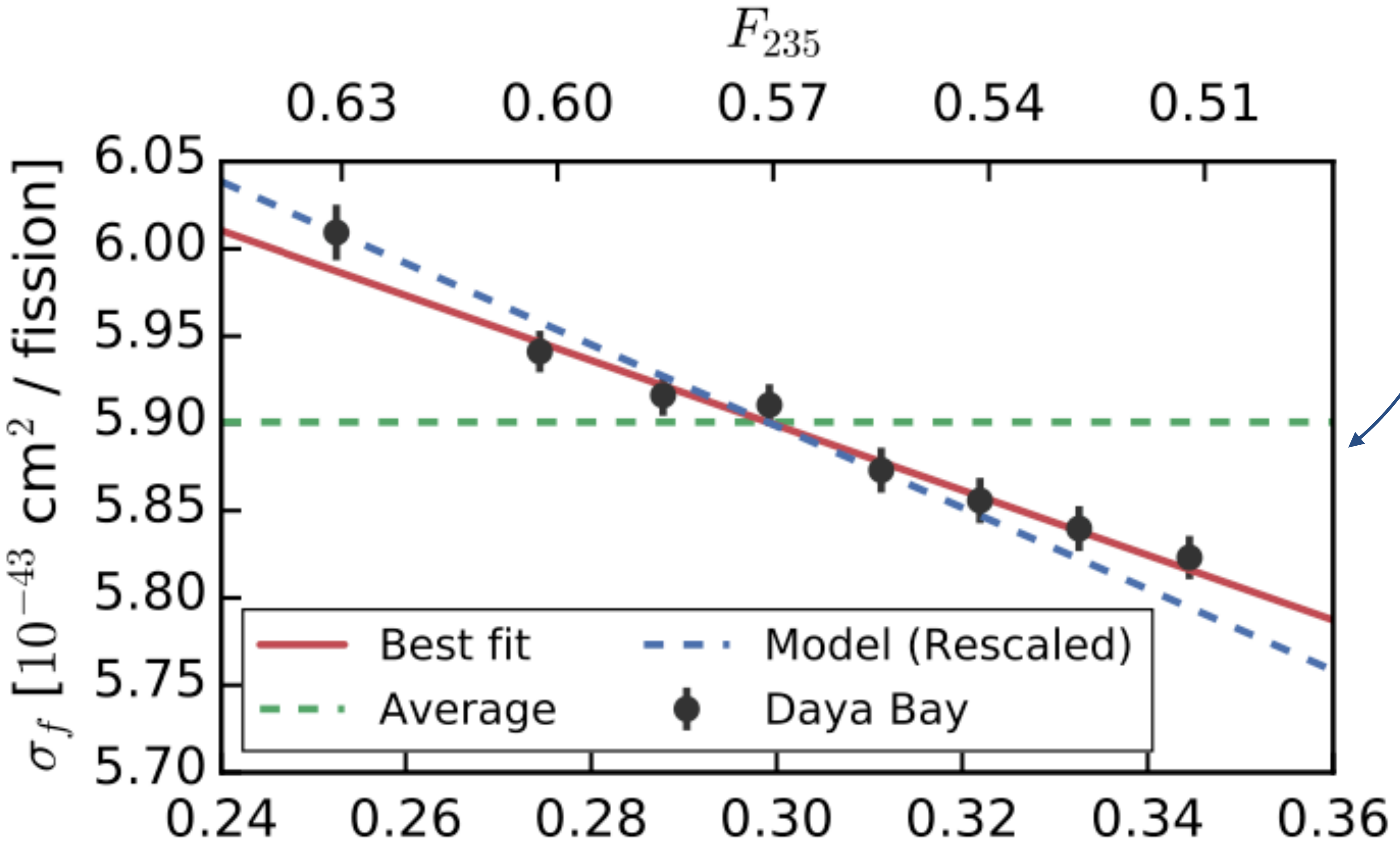


(fission fraction F_X = fraction of fissions from isotope X)

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



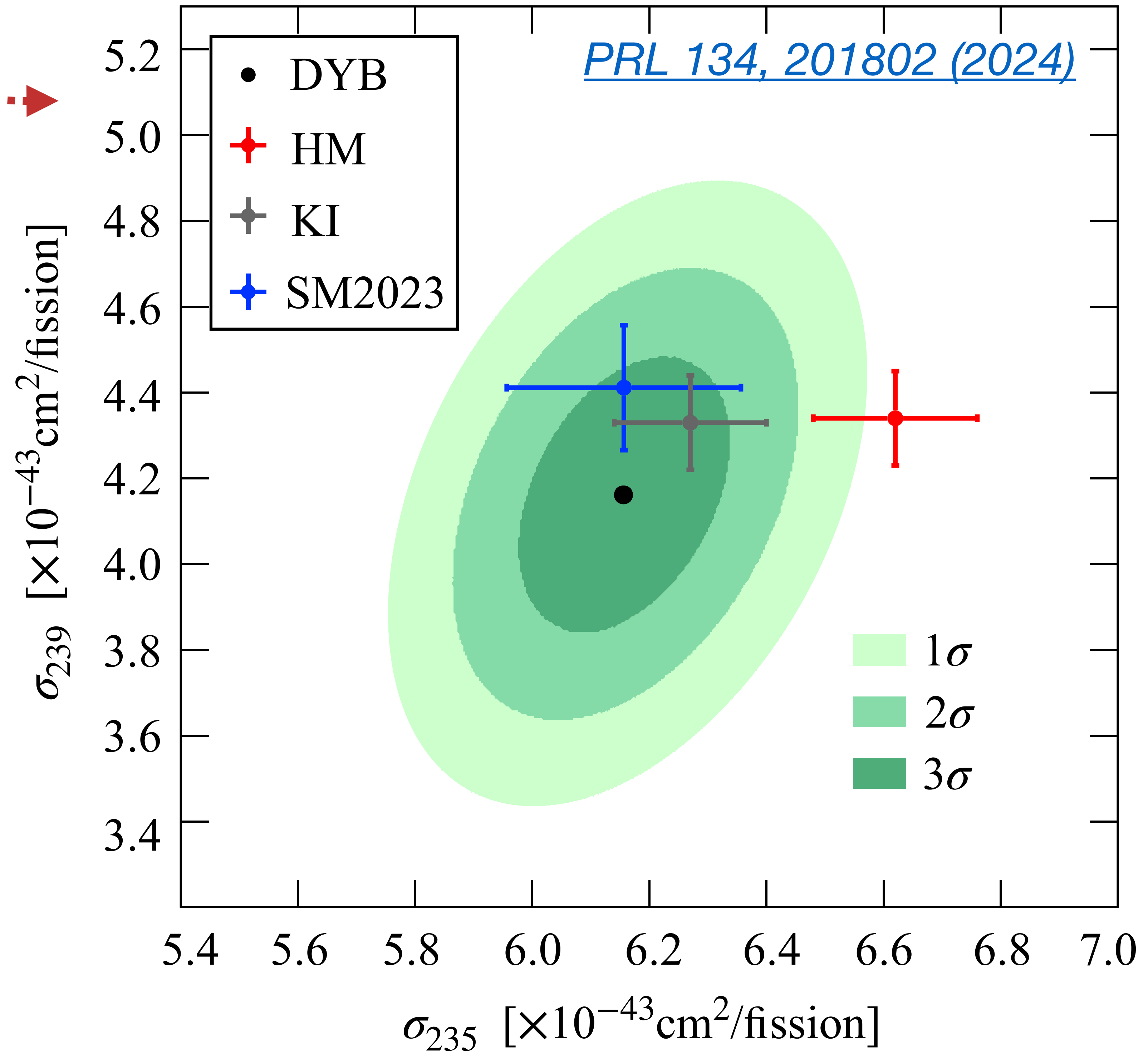
fission fraction for ^{239}Pu $\rightarrow$ F_{239}

Yield Measurements

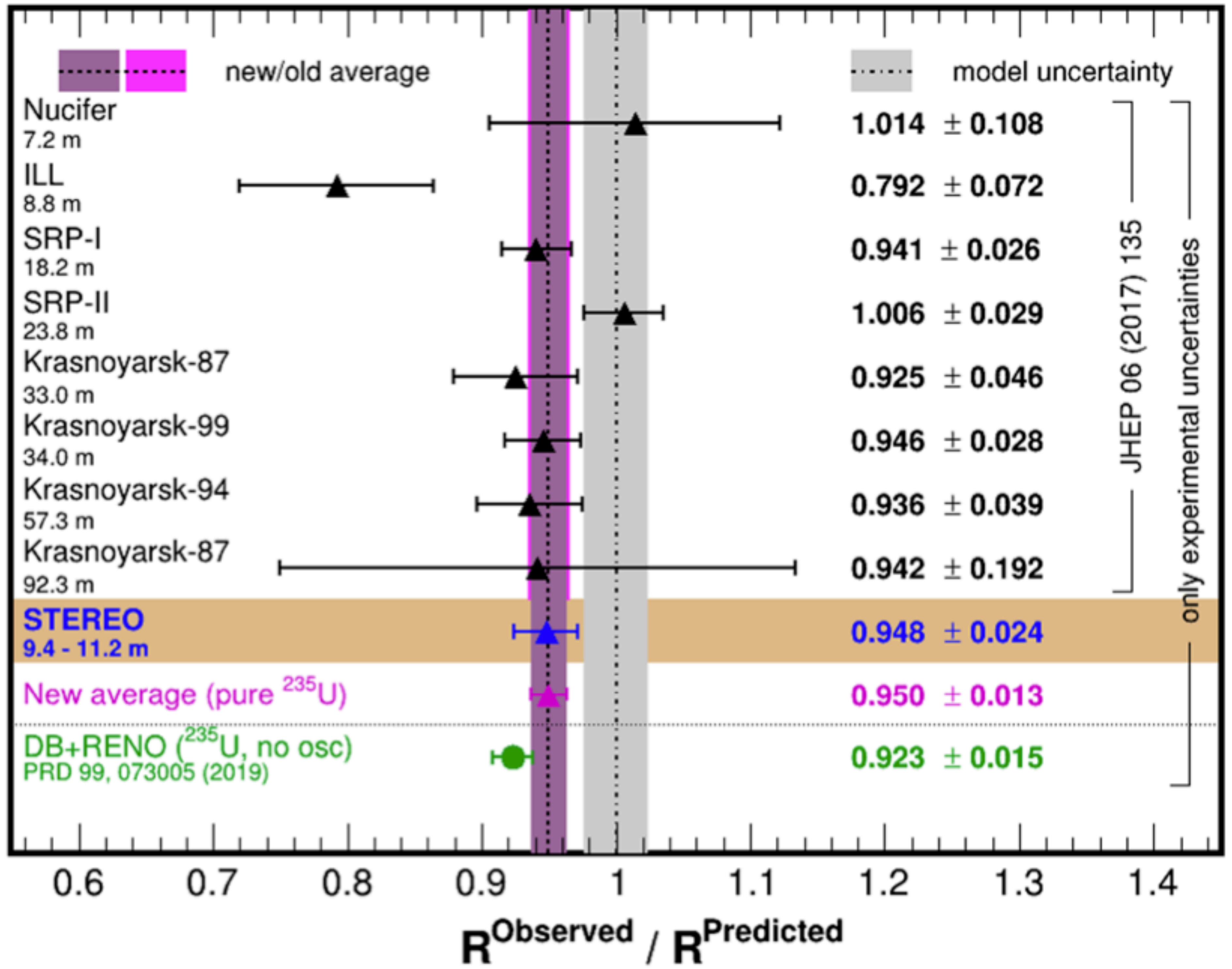
Showing Daya Bay as an example, but RENO also makes this measurement

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

Note: from these measurements it is also possible to extract the reactor $\bar{\nu}_e$ spectra for ^{235}U and ^{239}Pu fissions (not shown here)



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



Get a **consistent story**: the HM model overestimates the predicted $\bar{\nu}_e$ flux from ^{235}U fission

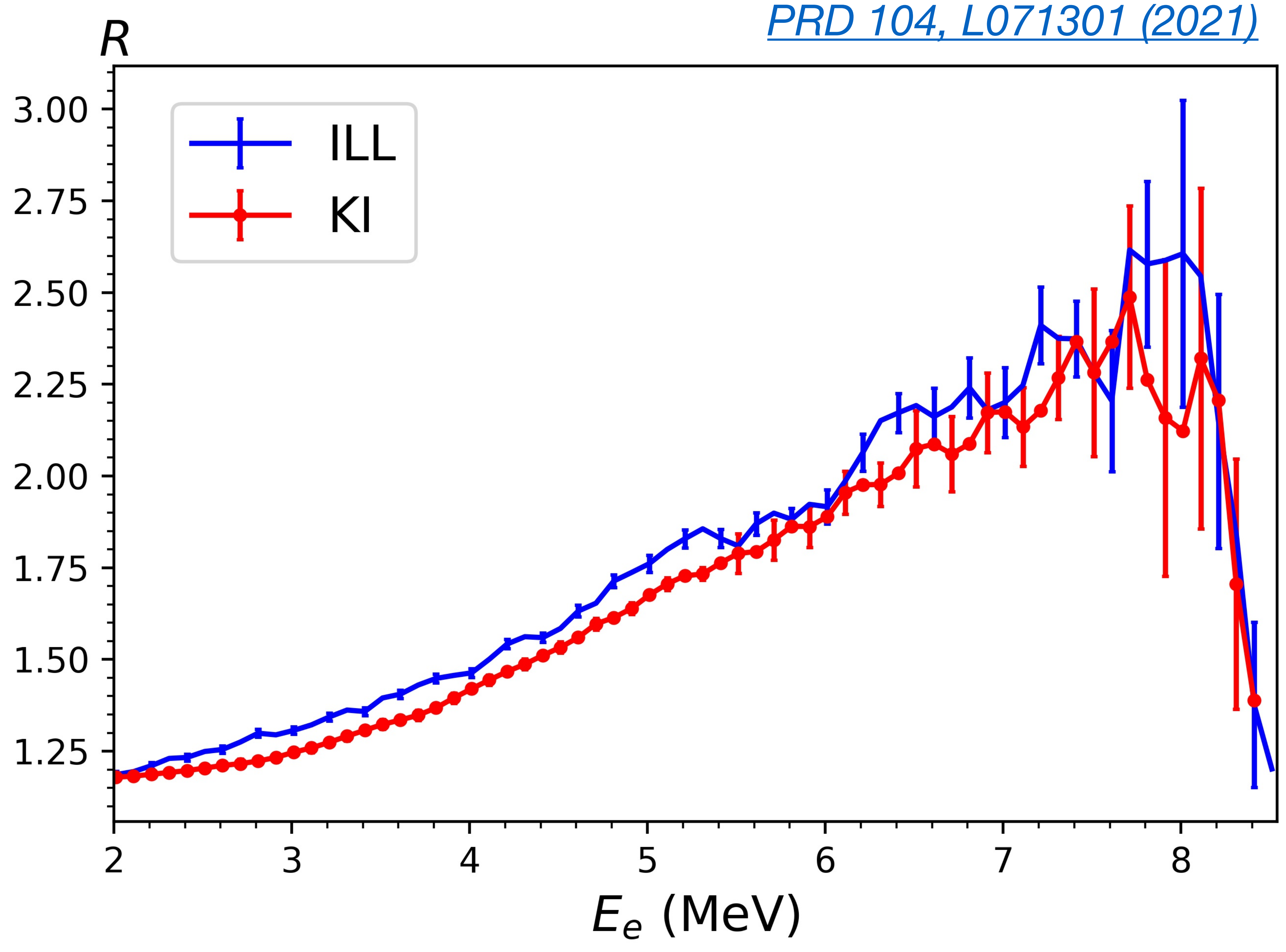
Recent Beta Ratio Measurement

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

$$R = \frac{^{e}S_{235}}{^{e}S_{239}}$$

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

PRD 104, L071301 (2021)



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

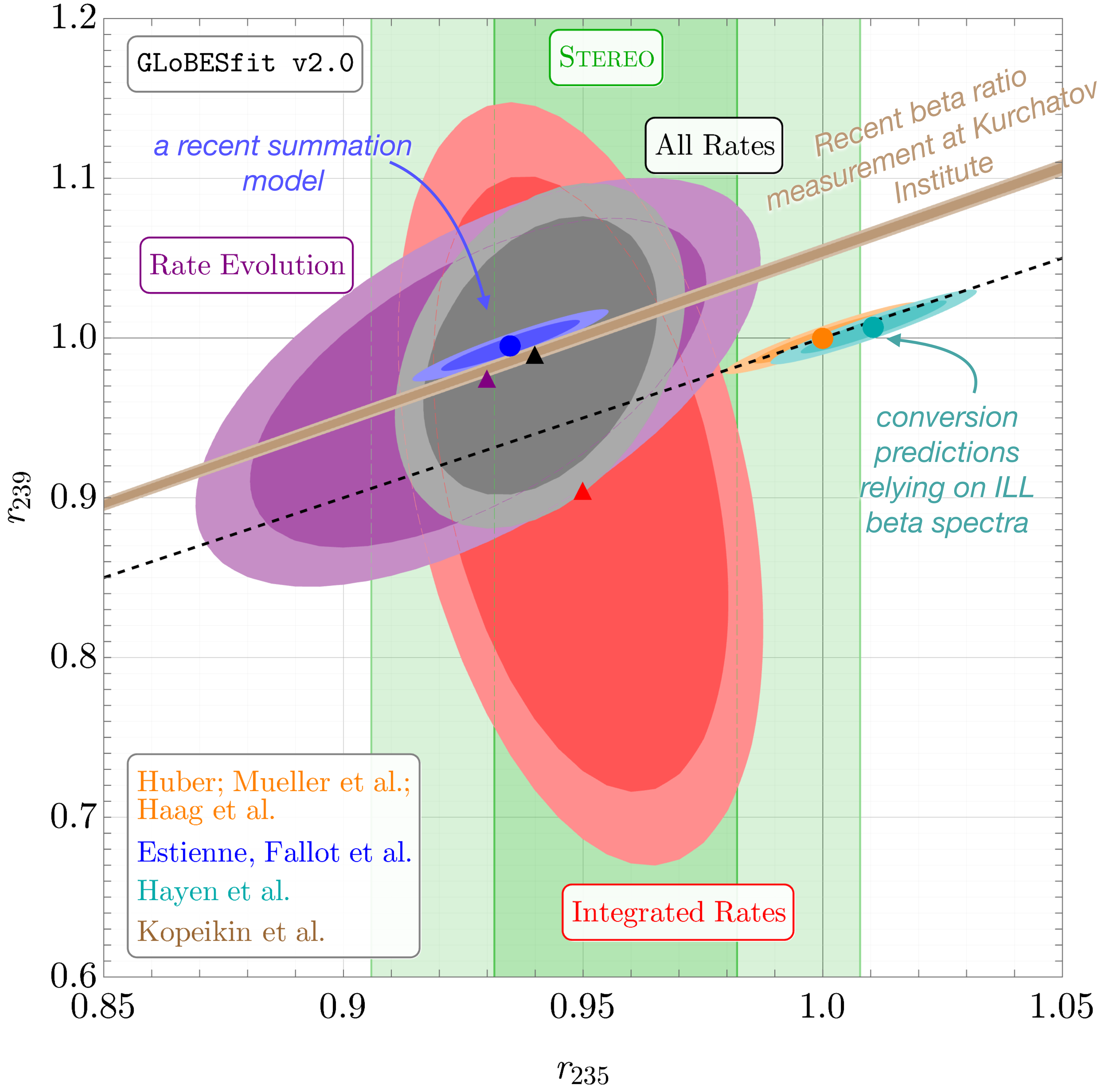
Current Situation

- 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 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

r_X = ratio of measured over predicted rate for isotope X with respect to the HM prediction

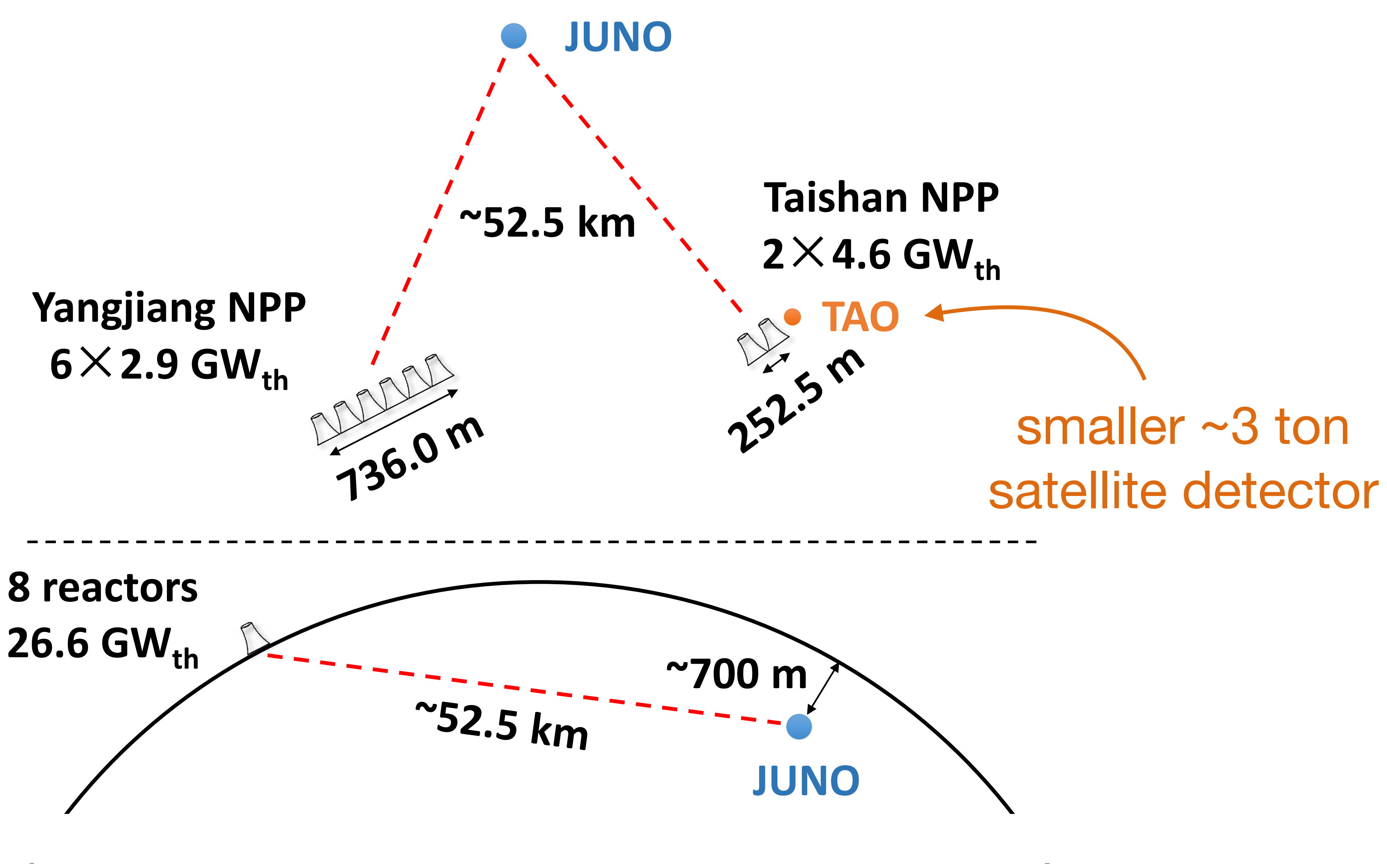


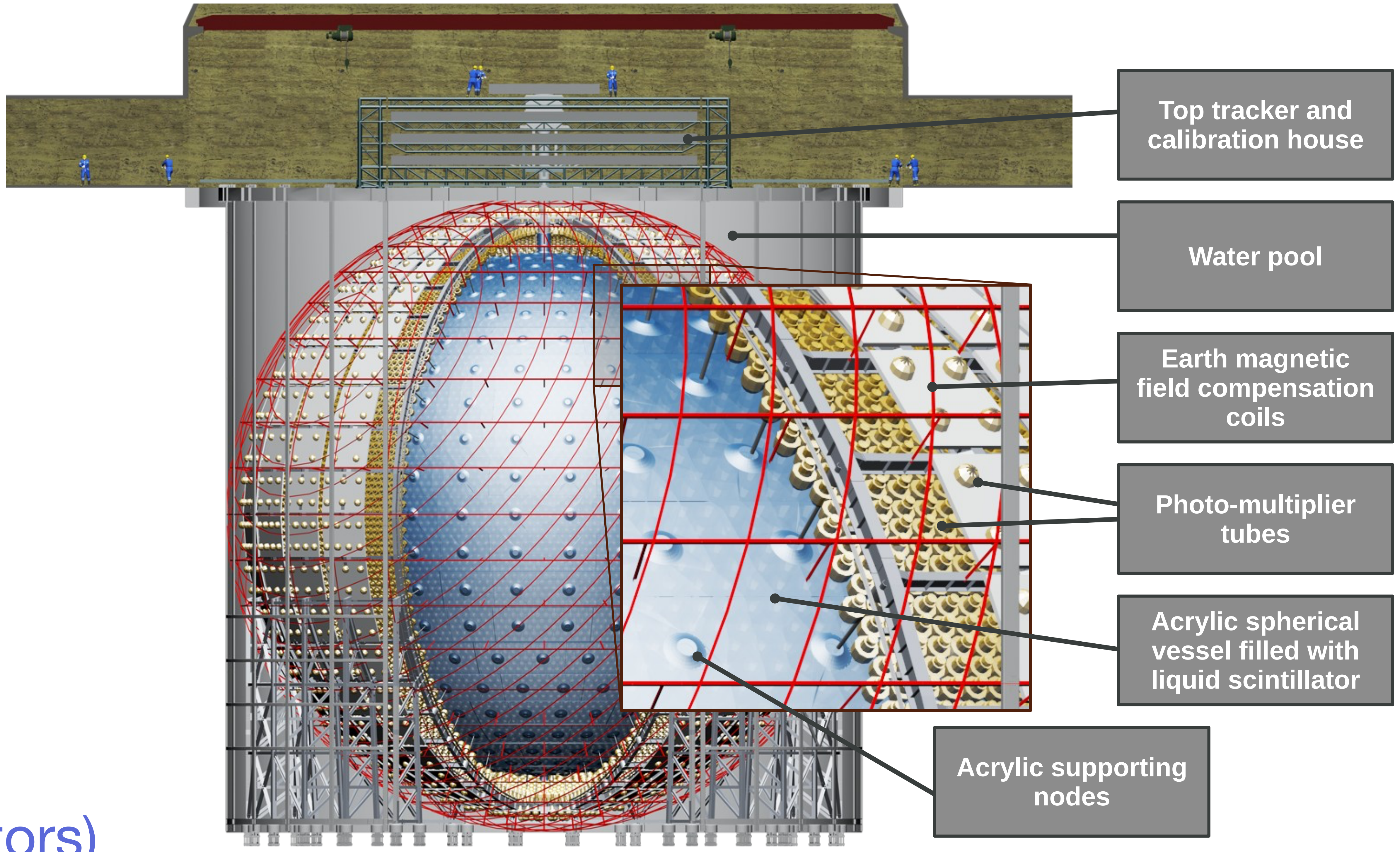
Outlook

The JUNO Experiment

JUNO at a Glance

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



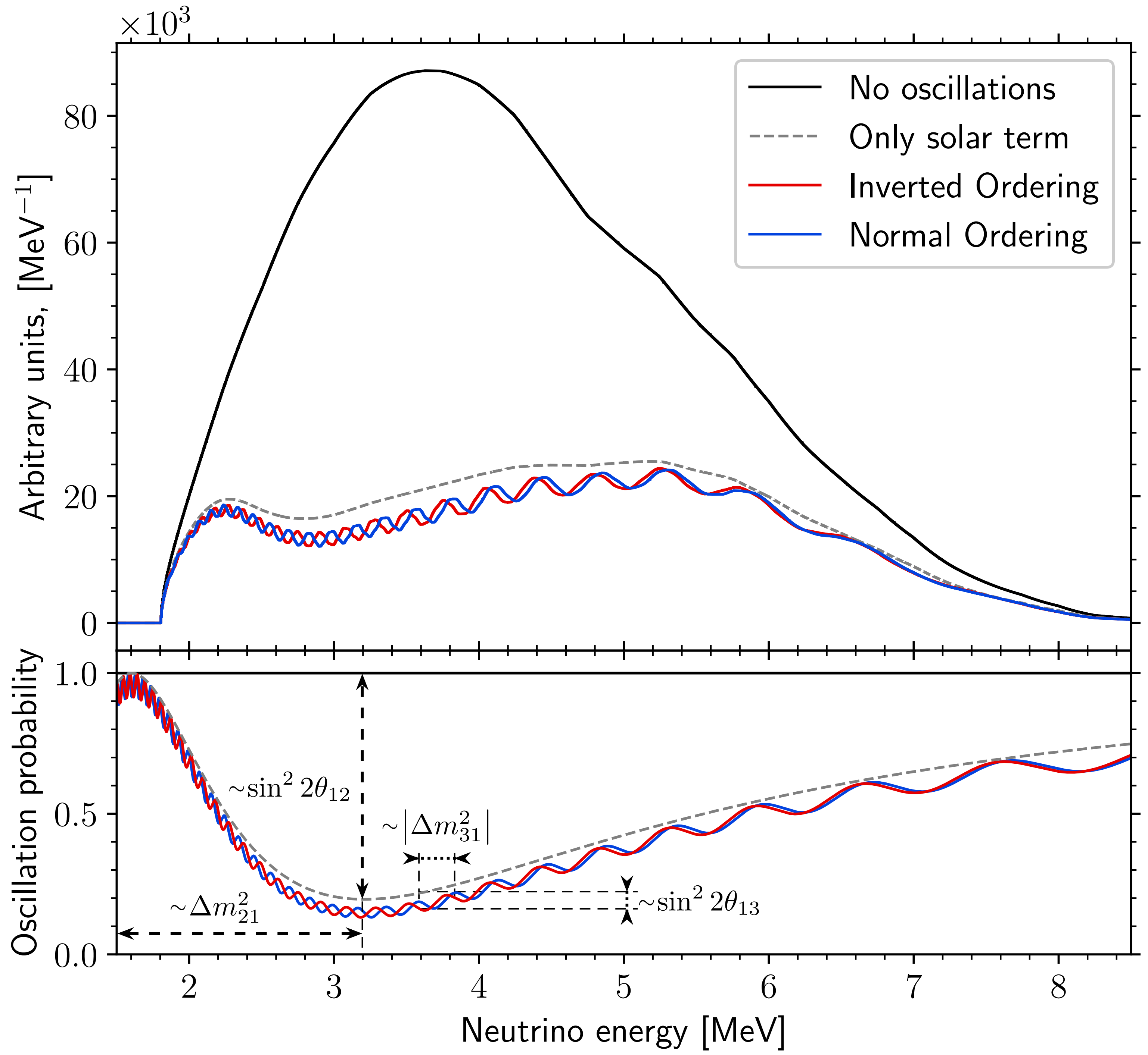


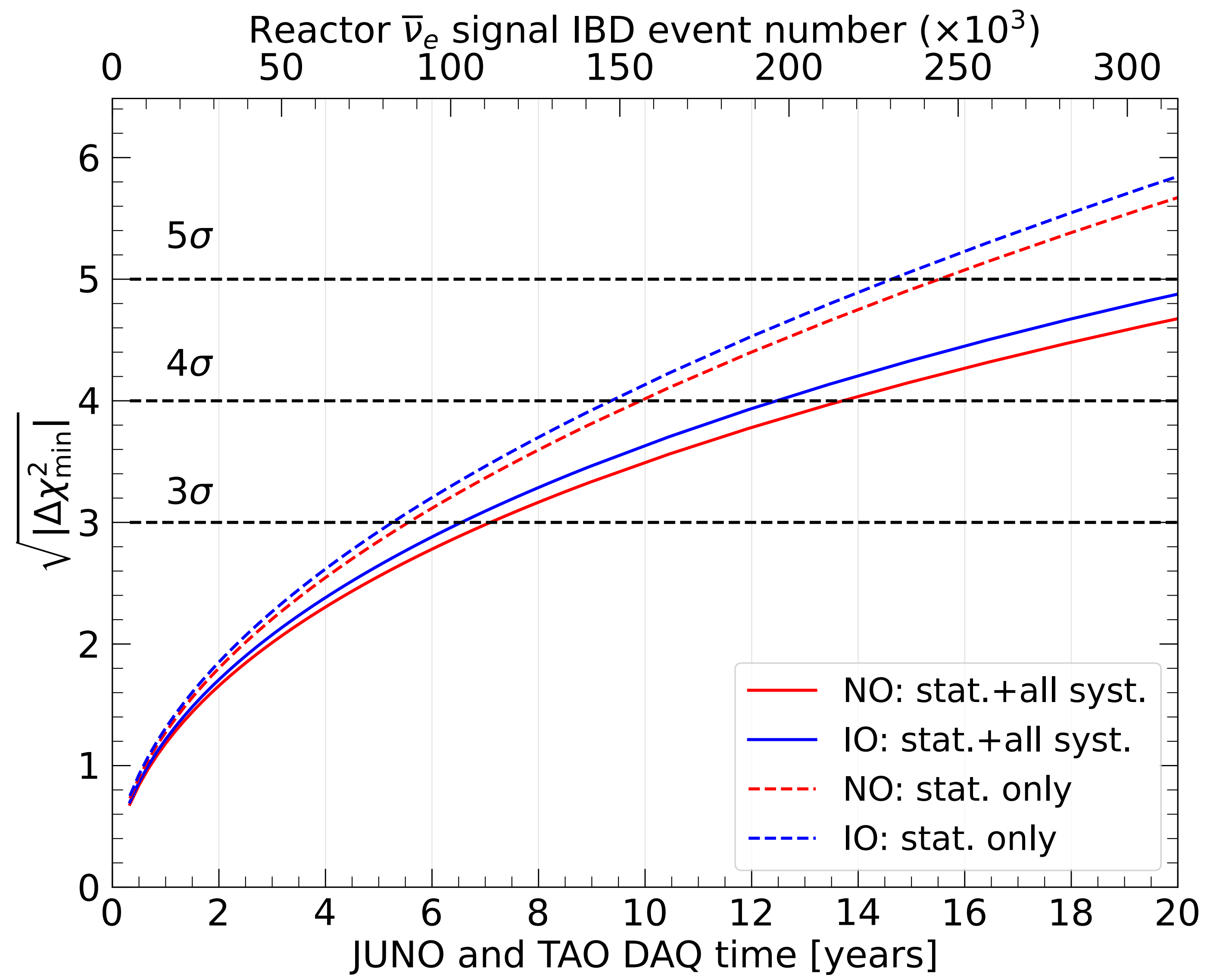
- 53 km from two major nuclear power plants (8 reactors)
- 35 m diameter sphere with 20 ktons of liquid scintillator (LS) surrounded by water Cherenkov detector
- Unprecedented energy resolution of 3% at 1 MeV

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

- The oscillated spectrum contains a wealth of information, including key signatures of the Neutrino Mass Ordering (NMO)
  - Exploit interference effects in the fine structure of the oscillated spectrum
  - **3σ** sensitivity within ~7 years
  - High complementarity with other experiments
    - Independent of θ_{23} and δ_{CP}, no reliance on matter effects
    - Unique energy and baseline
    - Unique information that provides a **stringent test of the three-neutrino** framework and can be combined with other experiments to reach ~5σ (e.g. [PRD 101, 032006 (2019)](), [Sci Rep 12, 5393 (2022)]())

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





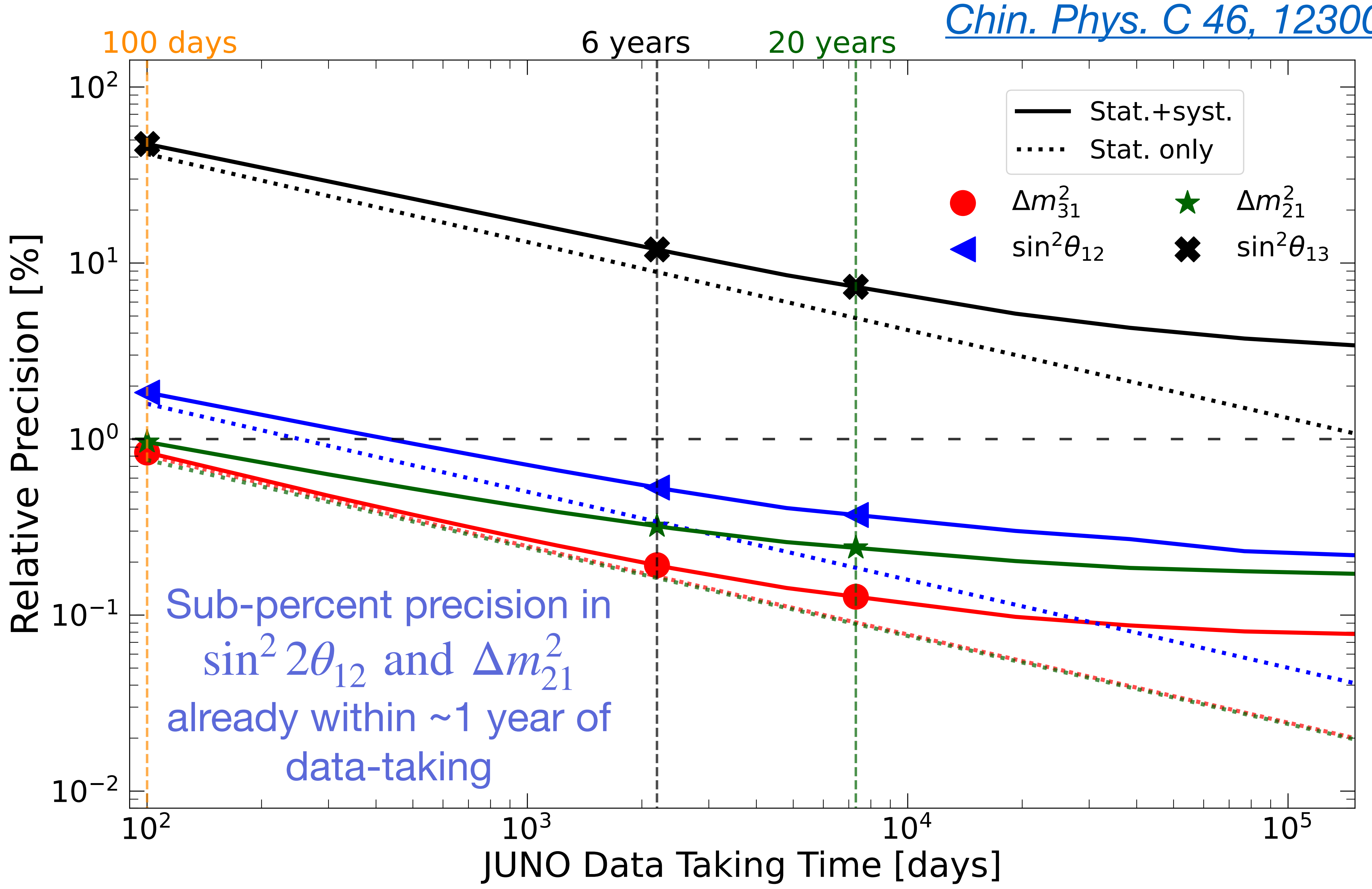
Chin. Phys. C 49, 0033104 (2025)

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

- JUNO will also measure $\sin^2\theta_{12}$, Δm^2_{21} and Δm^2_{31} to better than 0.5% in 6 years
  - Important input for the neutrino community:
    - Powerful discrimination of neutrino mass & mixing models
    - Constraints for other experiments (e.g. narrow down parameter space for $0\nu\beta\beta$ searches)
  - Will allow to **test three-neutrino framework well beyond current limits**
    - Model independent tests of the three-neutrino oscillation framework (notably, U_{PMNS} unitarity)
    - Comparison with other experiments will be a powerful test of our understanding of neutrino oscillations with potential for discovery

Case in point: comparison with DUNE's NMO and Δm^2_{31} measurement (also sub-percent precision)

Chin. Phys. C 46, 123001 (2022)

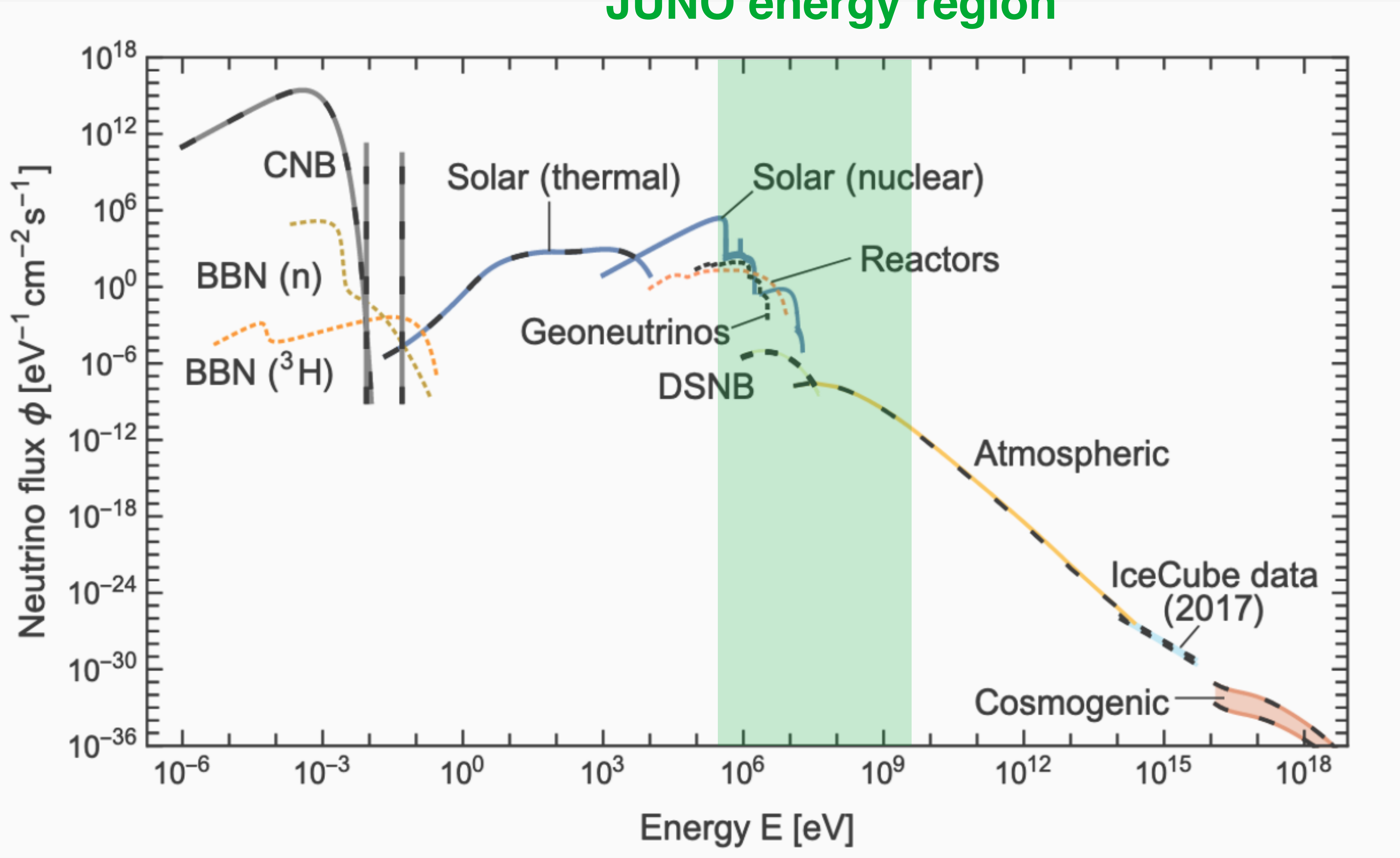


Parameter	$\sin^2\theta_{12}$	Δm^2_{21}	Δm^2_{32}	$\sin^2\theta_{13}$
Current Precision*	4.2%	2.4%	1.5%	3.2%
JUNO 6 years	0.5%	0.3%	0.2%	12.1%

* from PDG 2022

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

A Multipurpose Neutrino Observatory

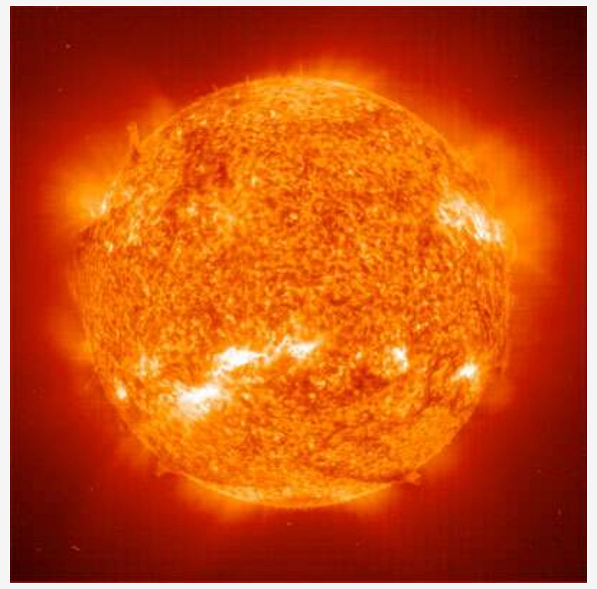


E. Vitagliano et al., Rev. Mod. Phys. 92 (2020) 045006
Note: fluxes are averaged

Reactor

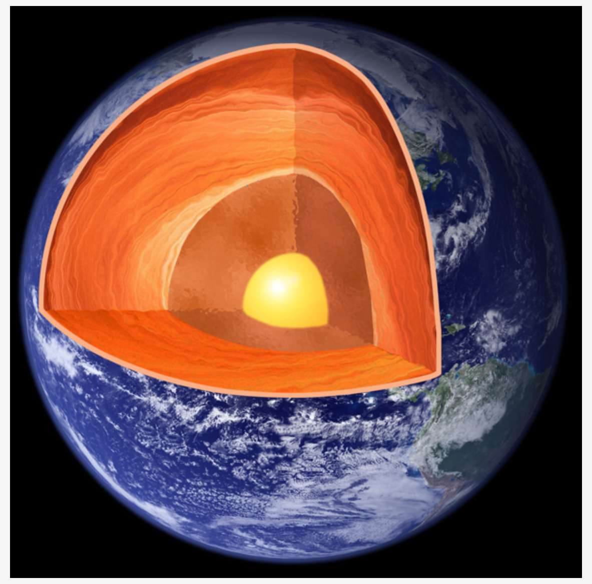
~50/day

Solar



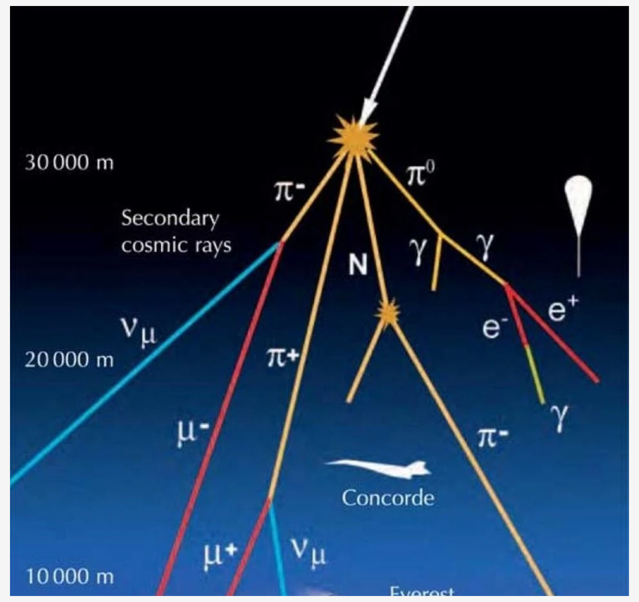
~2000/day

Geo



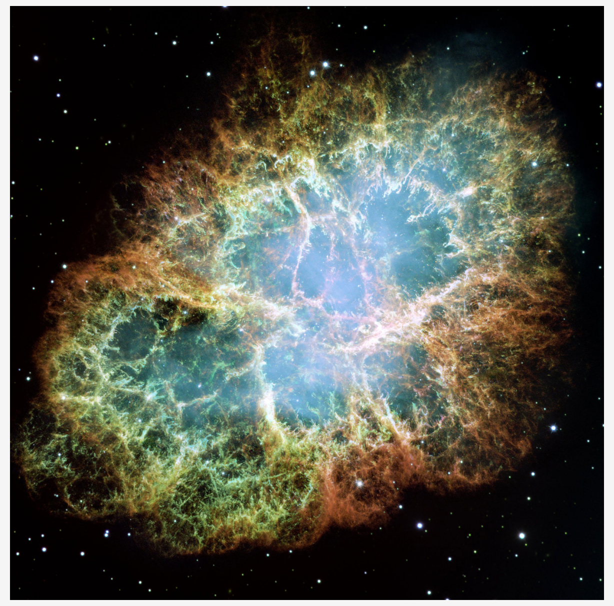
~1/day

Atmospheric



10-20/day

Supernova



O(1000)/s for core-collapse SN @10 kpc
DSNB: few/year

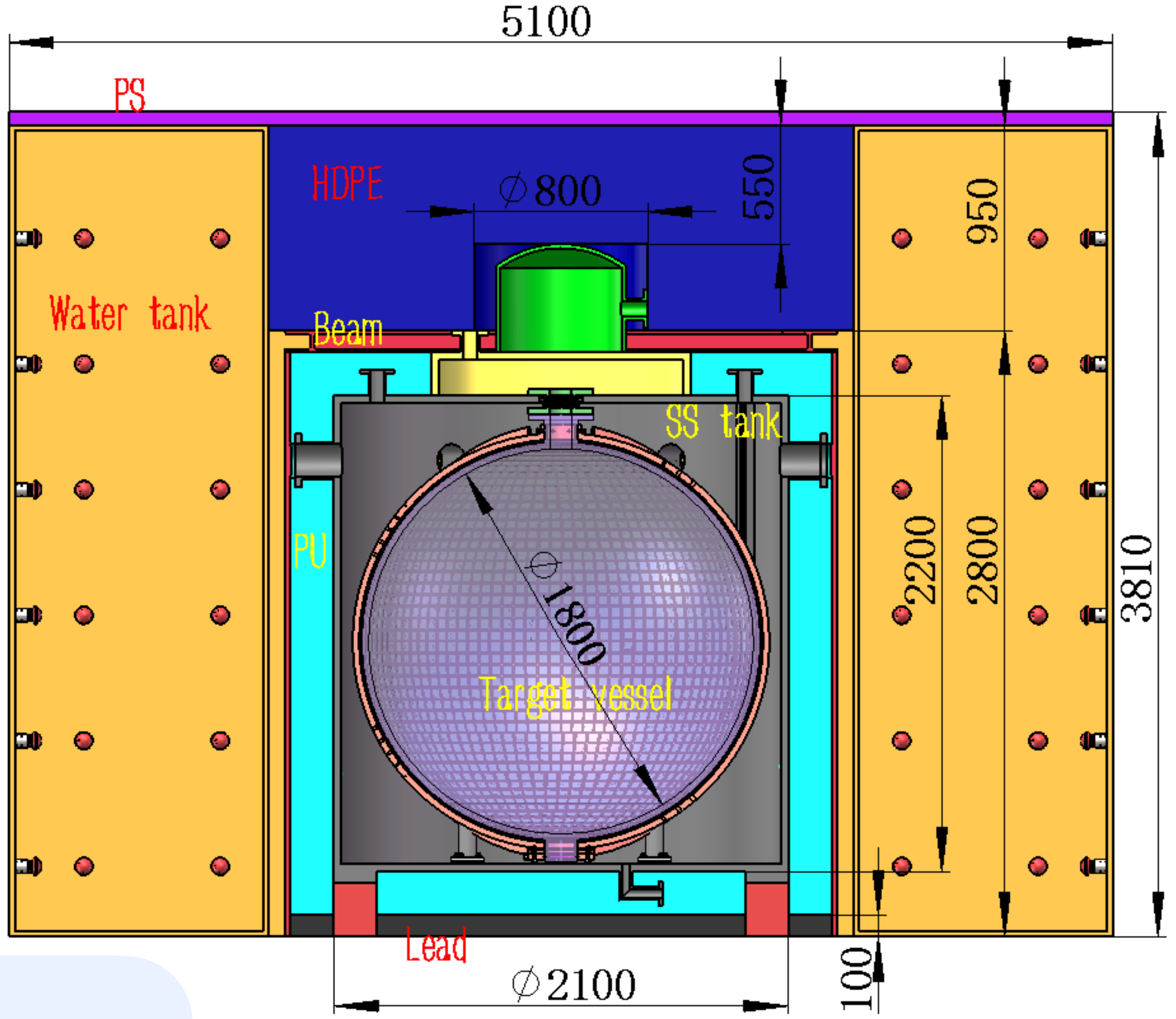
+ New Physics

Proton decay, Non-standard interactions, Sterile neutrinos, Neutrino magnetic moment, etc.

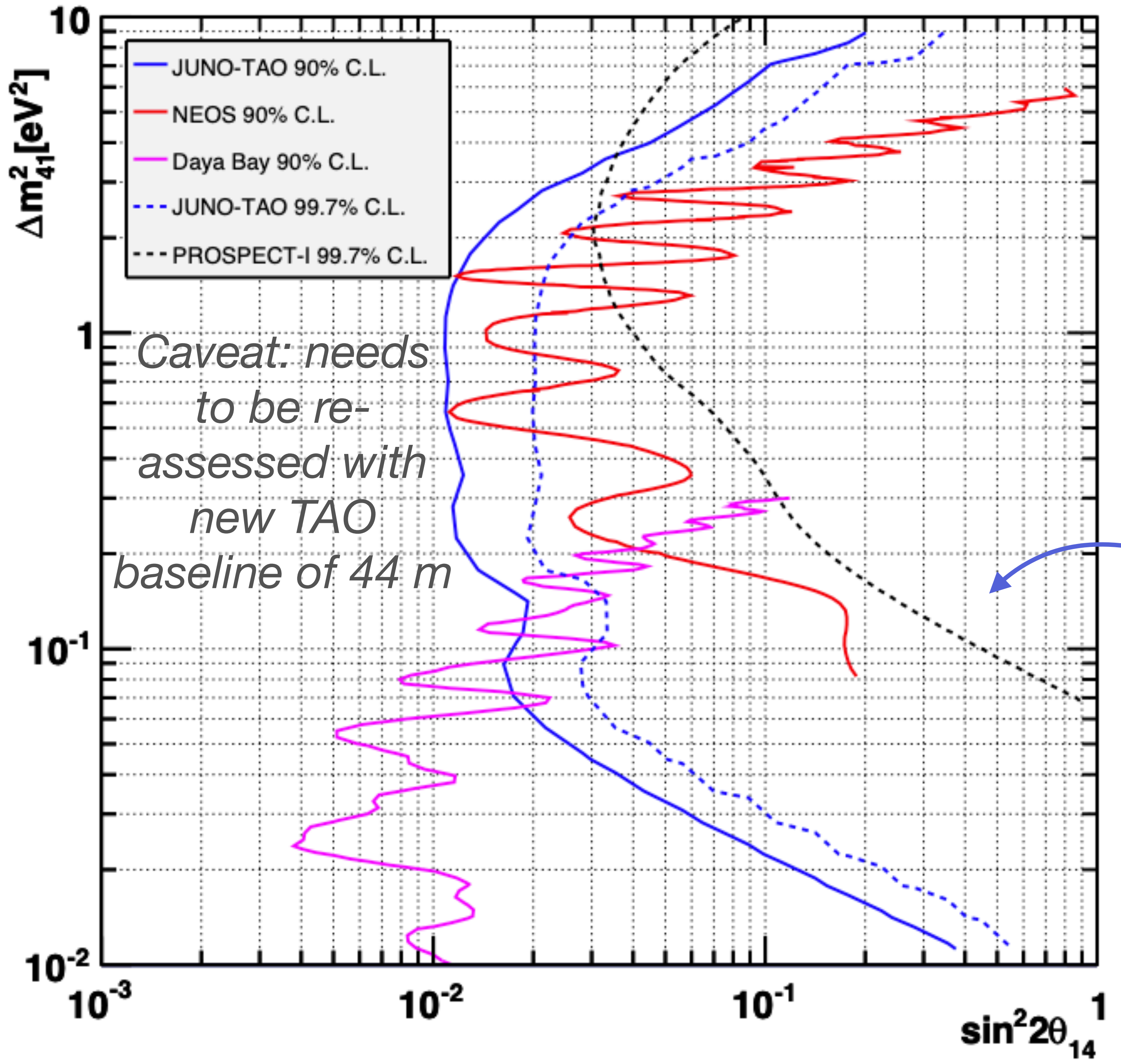
There's no time to cover this in any detail, but JUNO's features also make it an ideal detector to study neutrinos from other sources

Physics with TAO

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

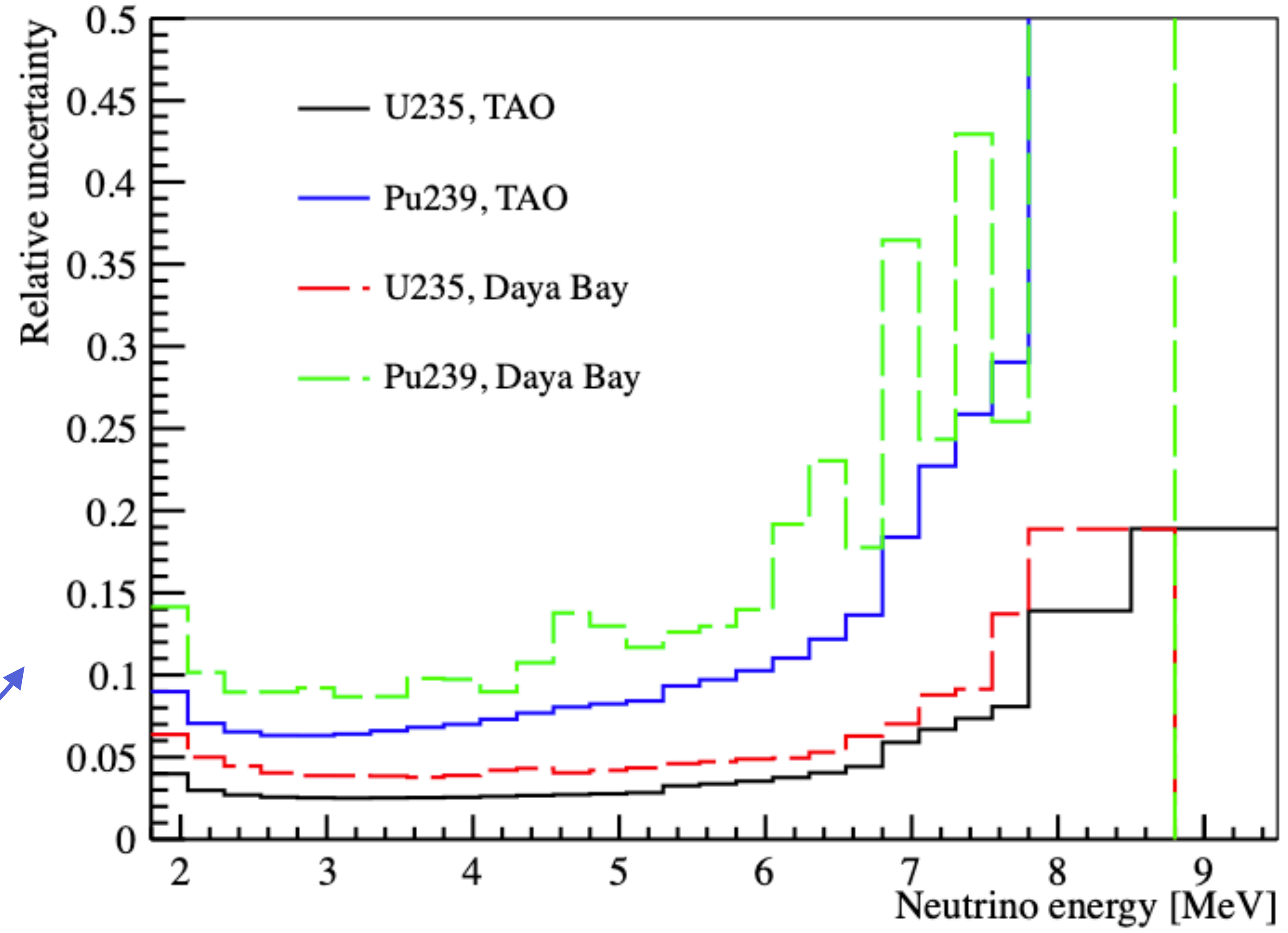


arXiv:2005.08745



Main Goals:

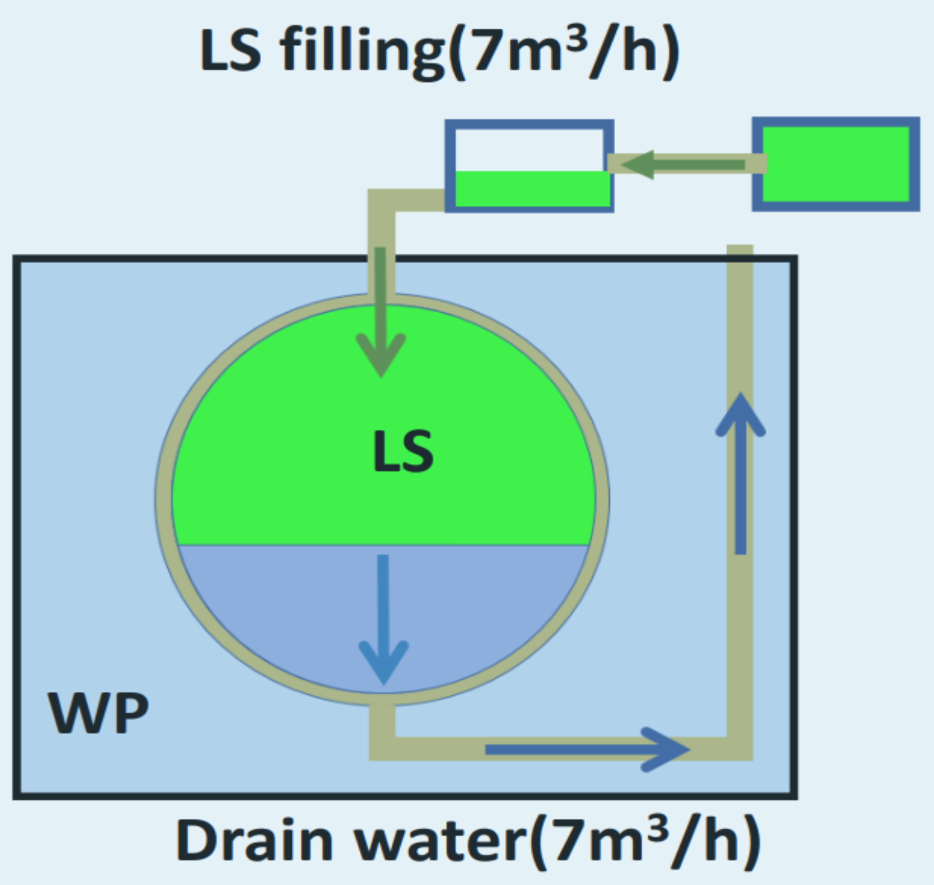
- Measure reactor antineutrino spectrum with unprecedented energy resolution (reveal fine structure for the first time)
- Search for sterile neutrinos
- Isotopic yield and energy spectrum measurements



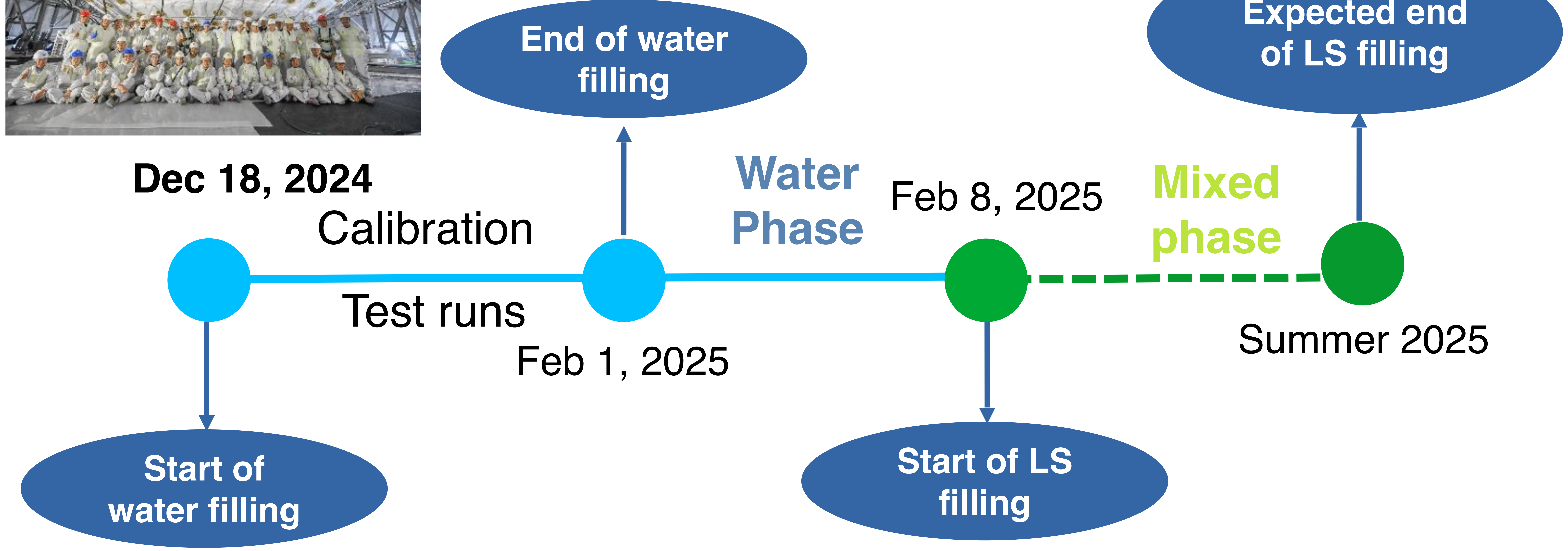
Completing the Acrylic Sphere

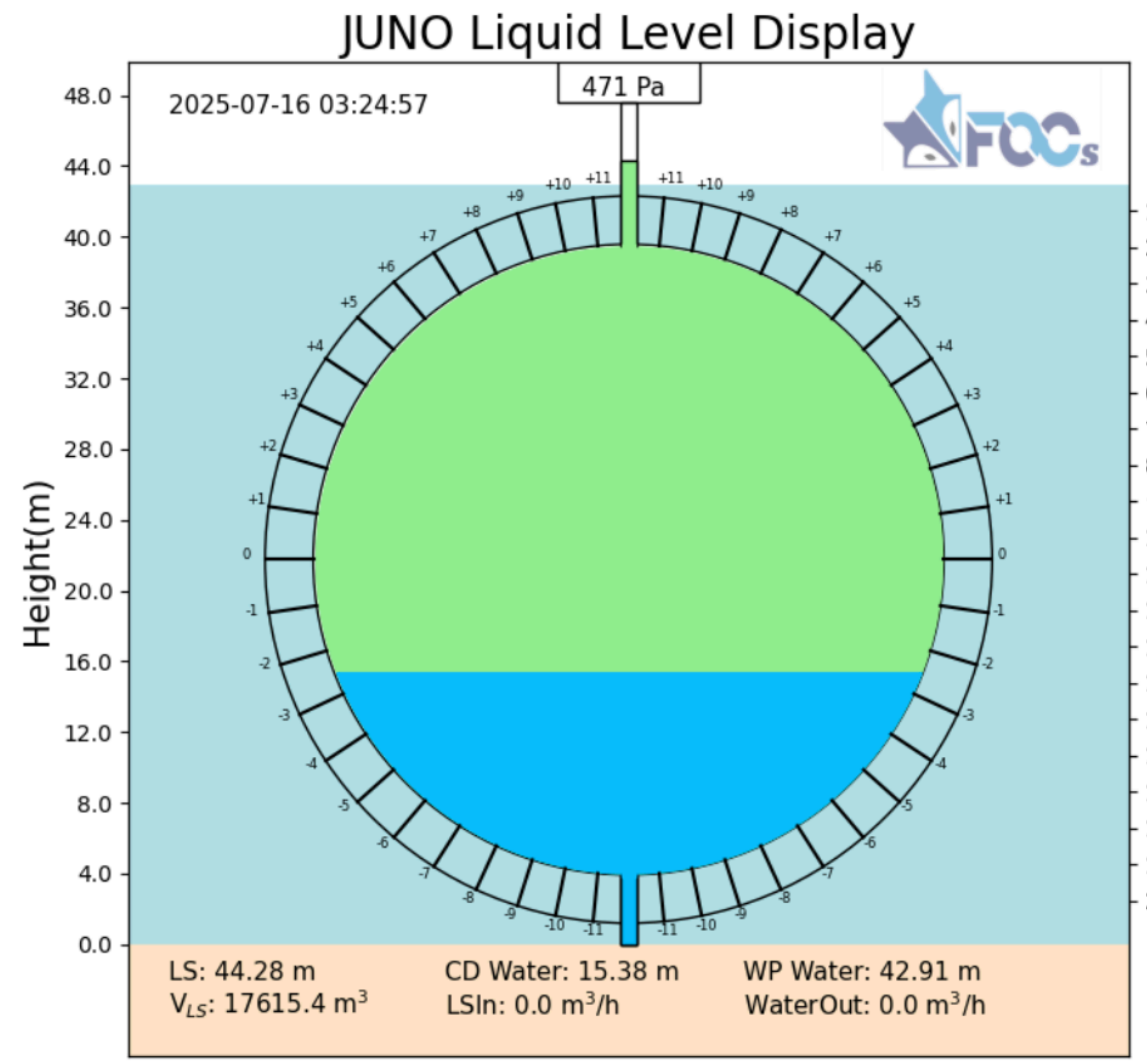
Current Status

- Filling with water has been completed
  - Good detector performance
- Now filling with liquid scintillator
  - Start of physics data-taking by end of summer



Filling strategy: fill with water first and then gradually replace water by LS inside acrylic sphere





Status as of July 15, 2025

Outlook

LiquidO and CEvNS at Reactors

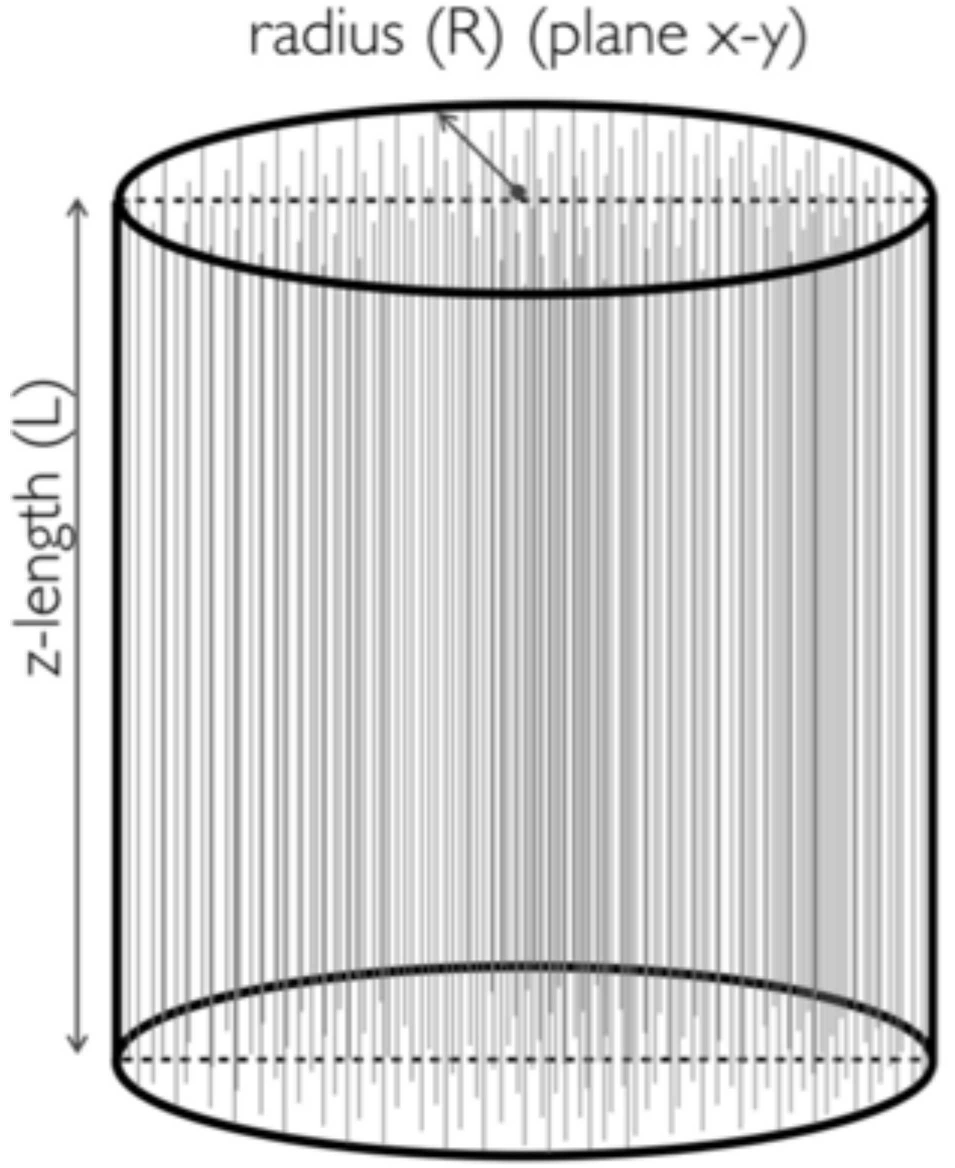
[Comm. Phys. 4, 273 (2021)](#)

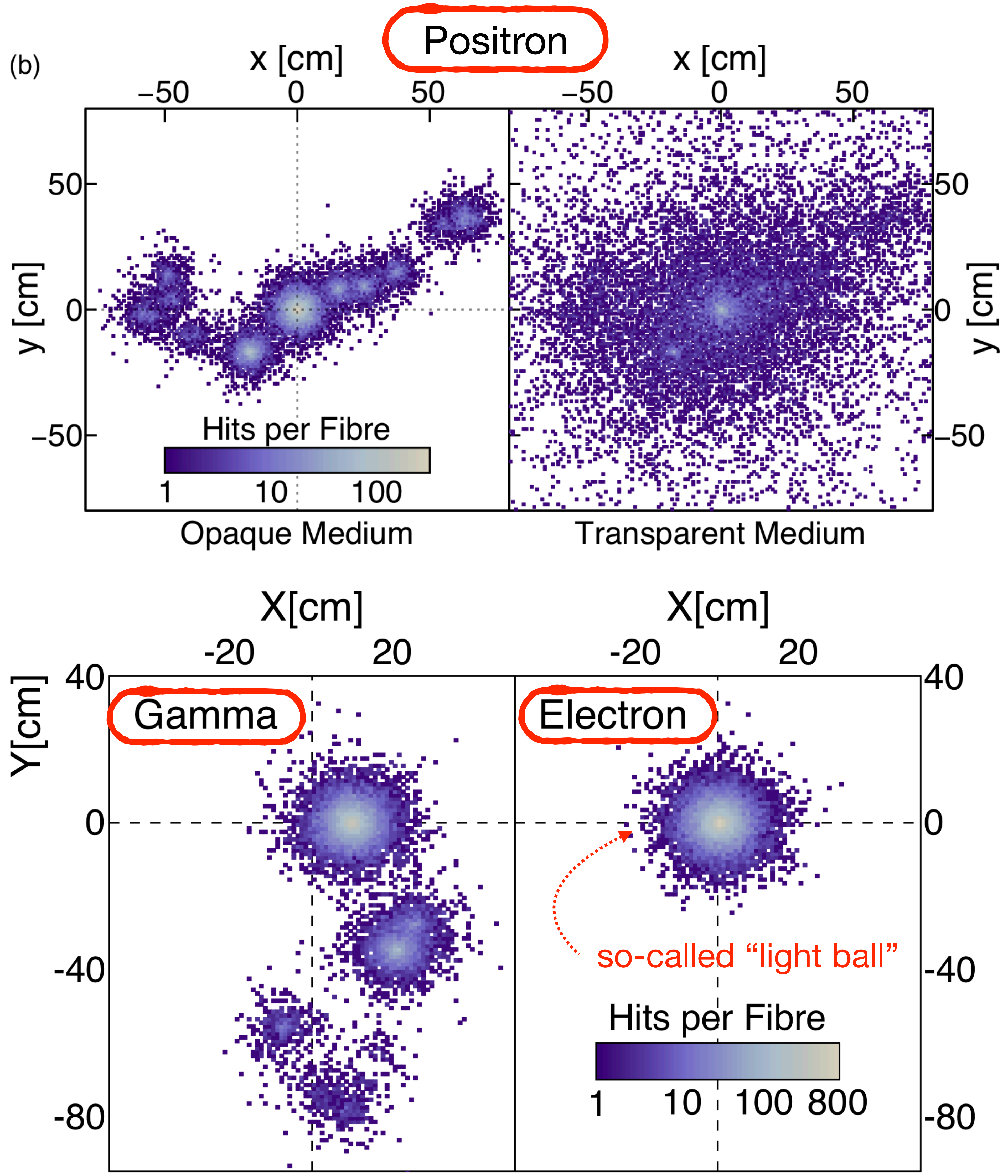
LiquidO: a New Approach

- 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



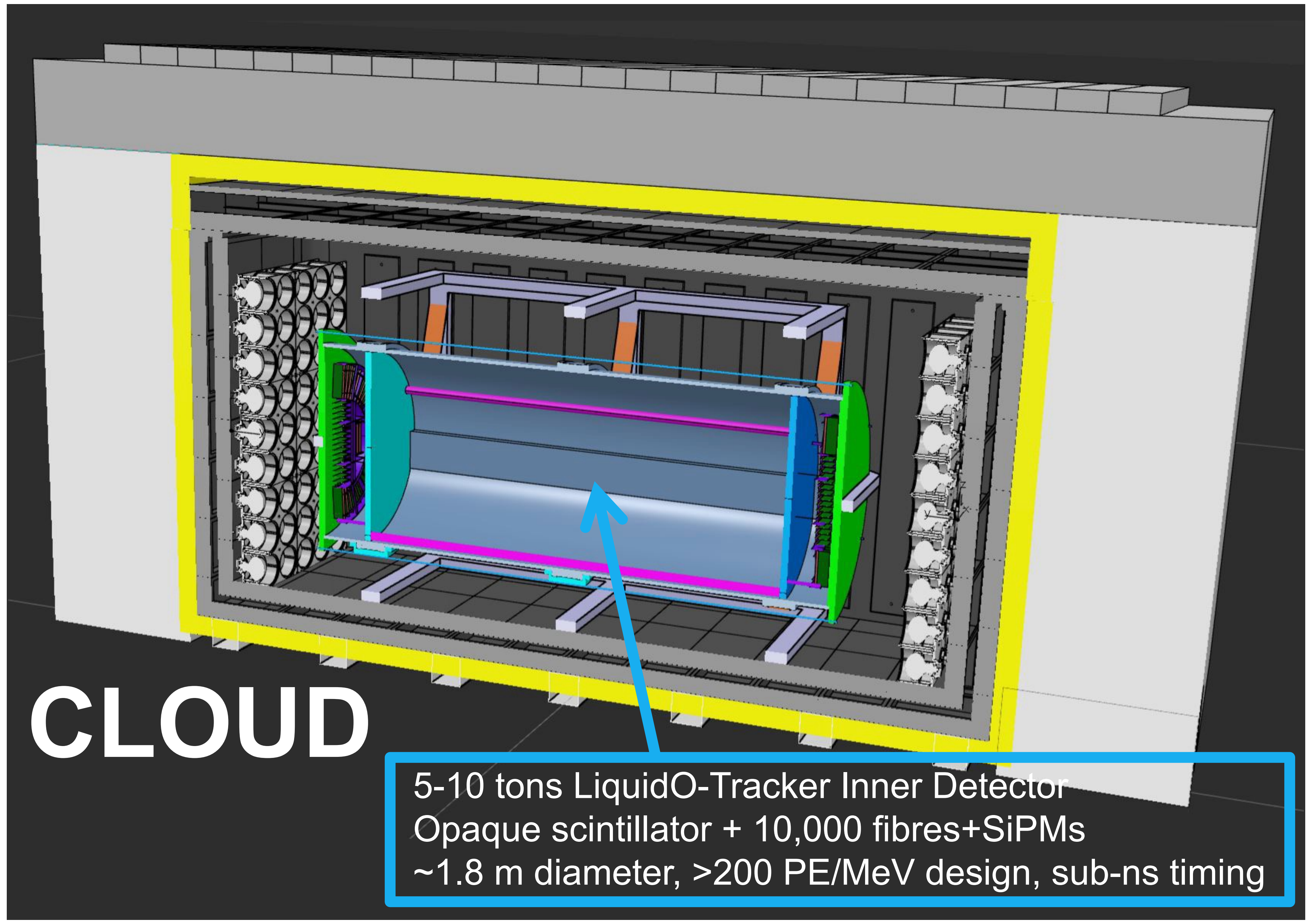


Each of these panels assumes a 1cm fiber pitch, one pixel per fibre, 2MeV of energy

See arXiv:2503.02541 for the latest results from a prototype

CLOUD and SuperChooz

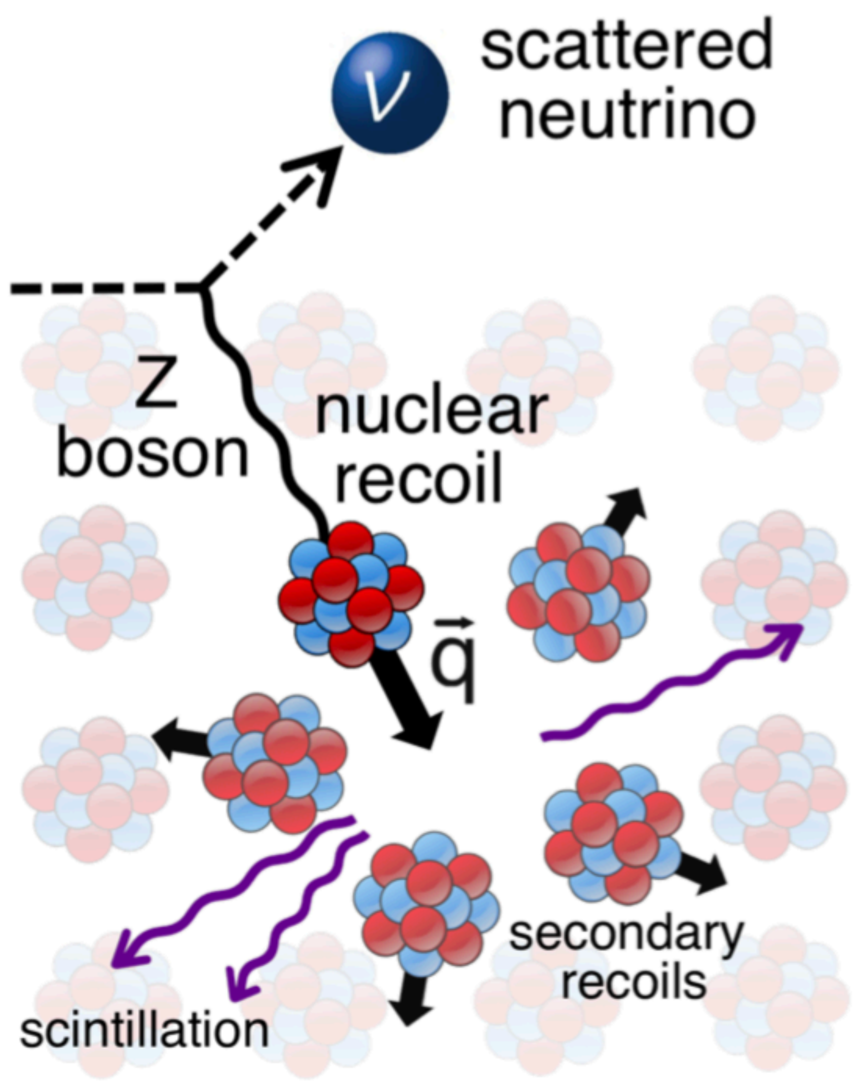
- Demonstrator called “CLOUD” funded: ~30 m from CHOOZ reactor in France



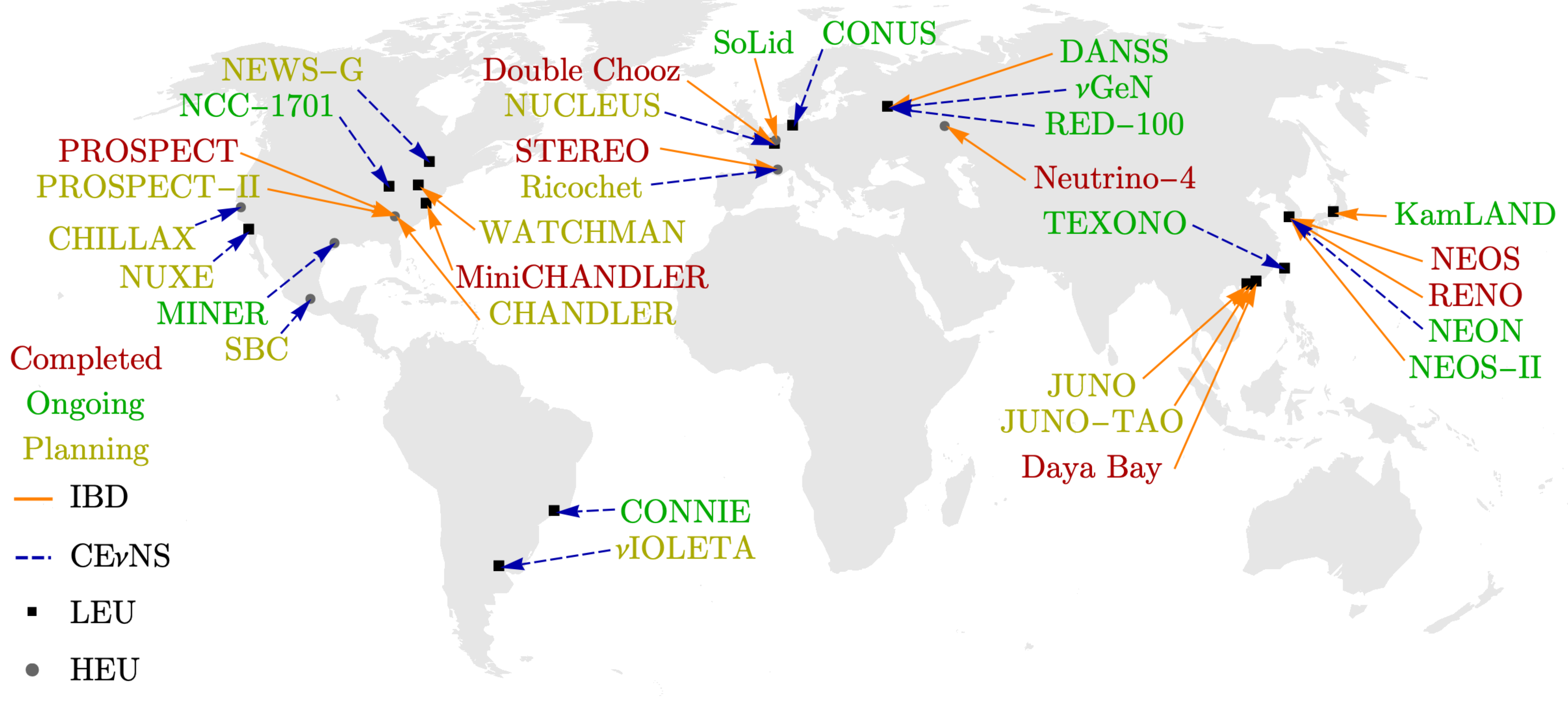
- There is a proposal for a next-generation θ_{13} reactor experiment called SuperChooz
  - Soon to become the most poorly known mixing angle
  - LiquidO technology, ~10 kton mass, ~1 km baseline from Chooz reactors

CEvNS at Reactors

- An exciting new program using CEvNS at reactors is in its early stages
    - 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 recently reported a 3.7σ observation (arXiv:2501.05206)



Global Landscape of Reactor Neutrino Experiments



arXiv:2203.07214 and arXiv:2203.07361

Concluding Remarks

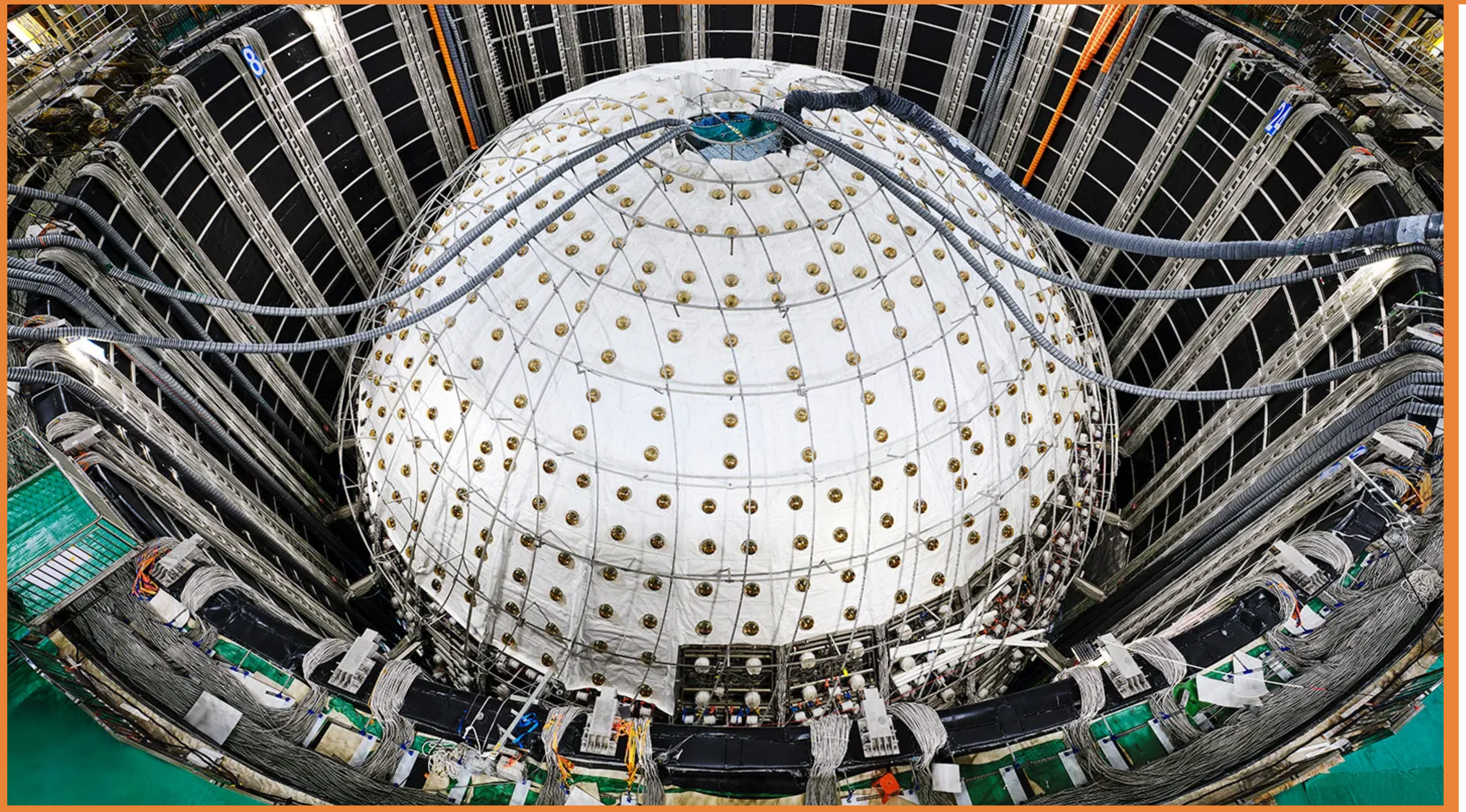
Parting Thoughts

- Nuclear reactors are excellent neutrino sources
- Reactor neutrino experiments continue to make unique contributions to the field
  - Leading precision for 4 out of 6 oscillation parameters
  - Unique measurement of neutrino mass ordering
  - Searches for physics beyond standard 3-neutrino mixing
- A bright future is on the horizon
  - A vibrant next-generation experimental program is under preparation that includes a very large multi-purpose detector
  - Expect some exciting results and, hopefully, some surprises

Stay tuned!

Support from NSF and DOE is gratefully acknowledged





Thank you for your attention!