Reactor Neutrino Experiments: Status and Outlook

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Disclaimer: I am a Daya Bay and JUNO collaborator

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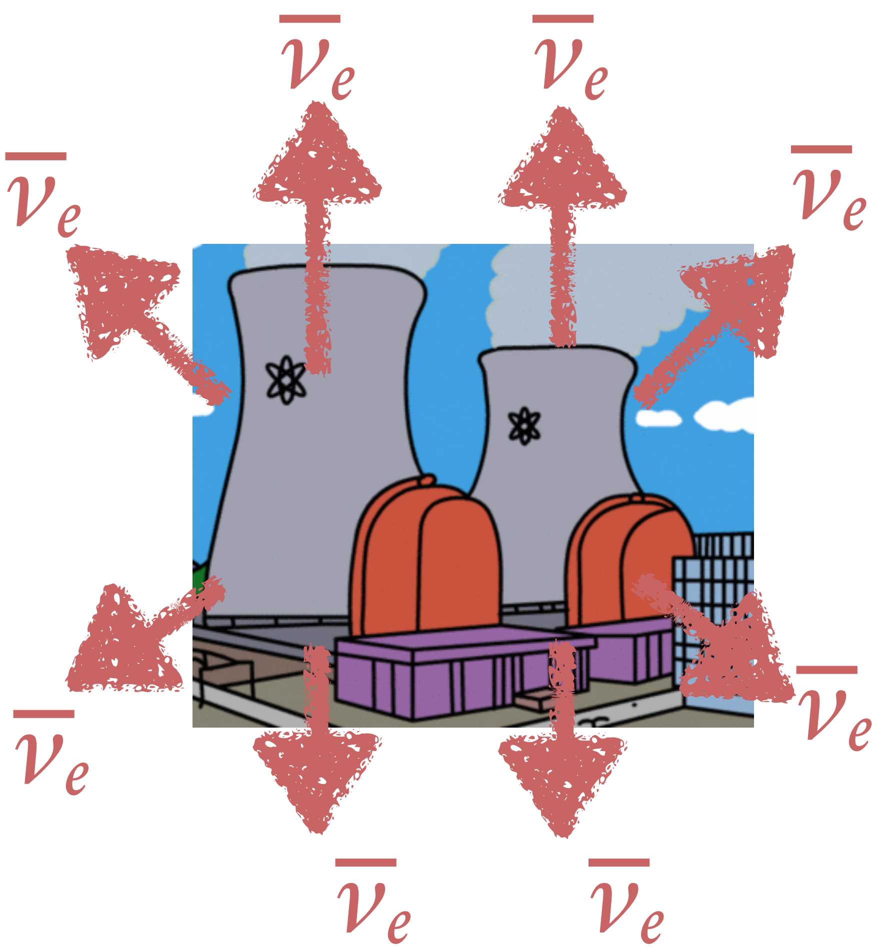
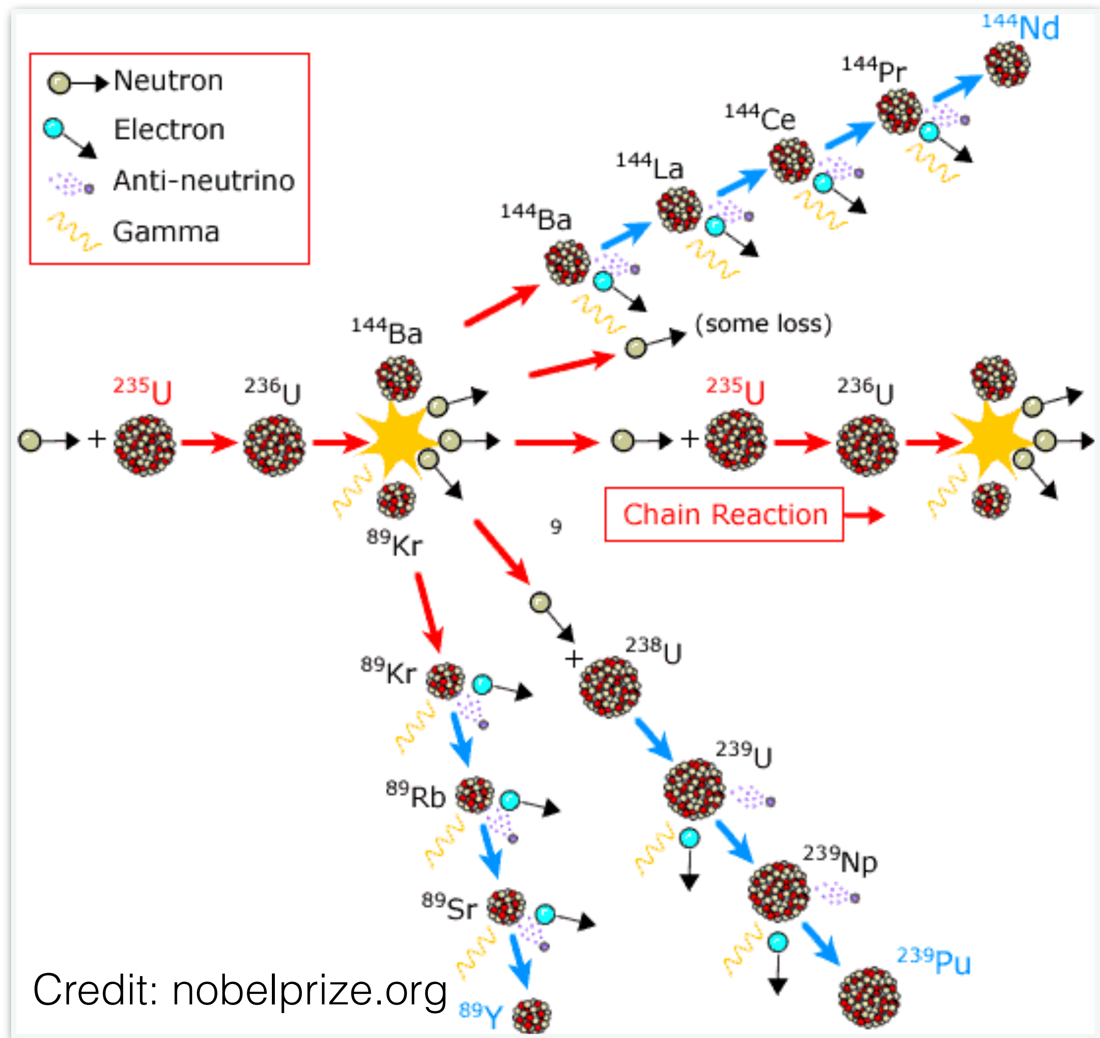
Basic Principles

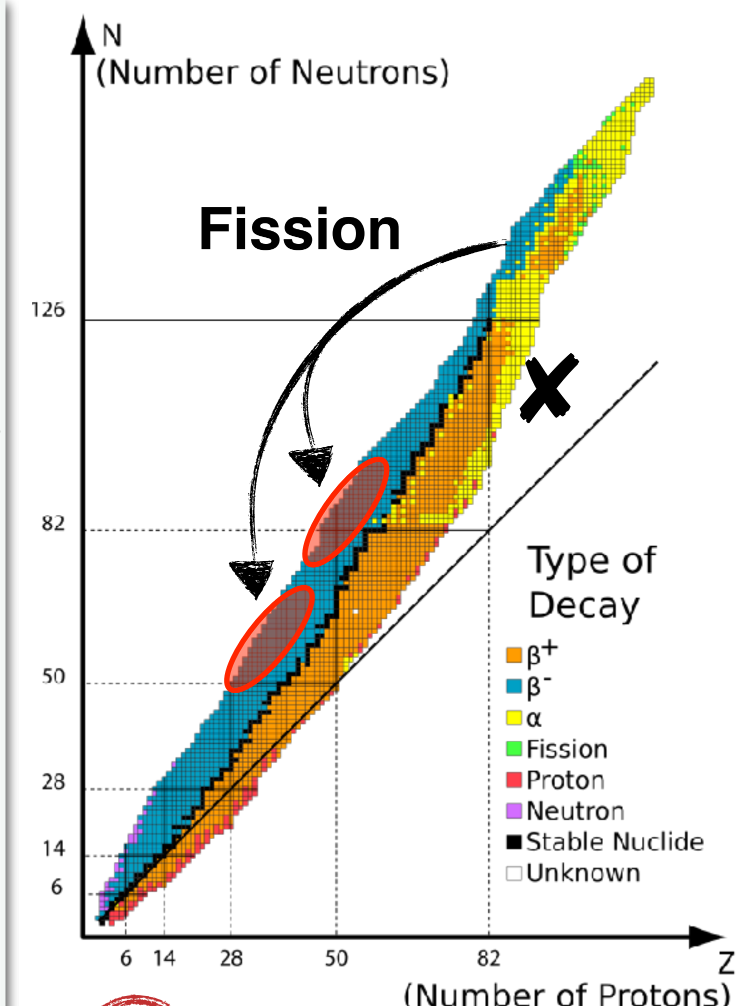
Reactor Antineutrinos

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



$\sim 10^{20}\ \bar{\nu}_e/\mathrm{GW_{th}}$





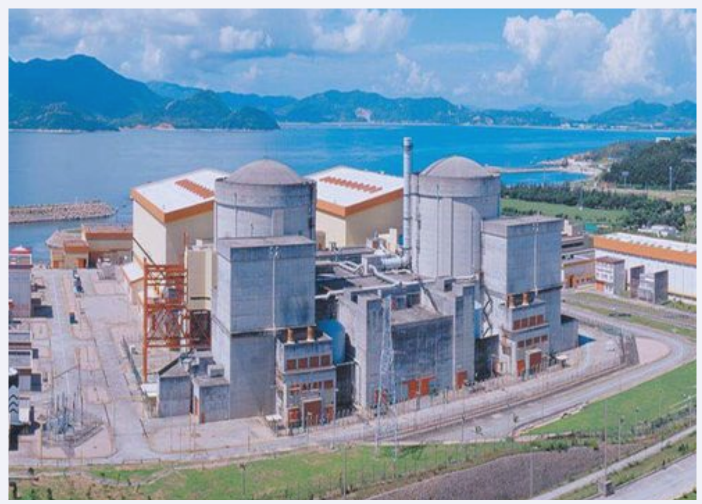
$$n \rightarrow p + e^- + \bar{\nu}_e$$

– A 1 $\mathrm{GW_{th}}$ core produces in one minute more neutrinos than the NuMI and BNB beams produced in all of 2018

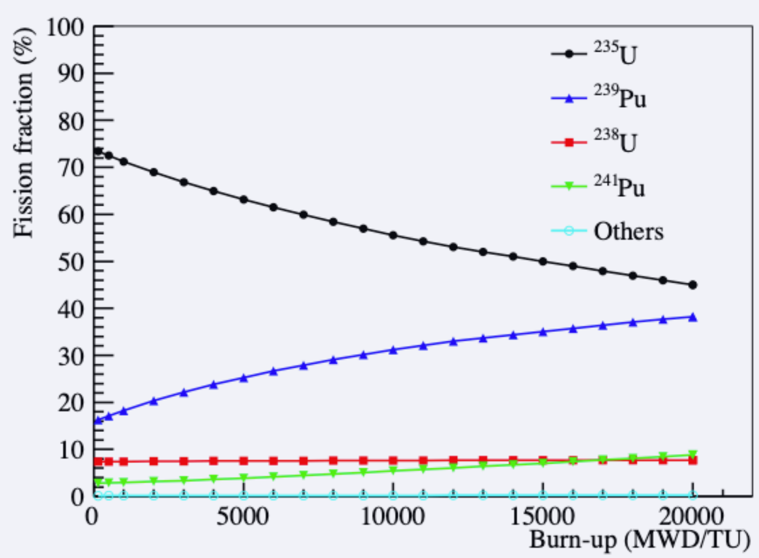
Types of Nuclear Reactors

- Nuclear reactors fall into two main categories:

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

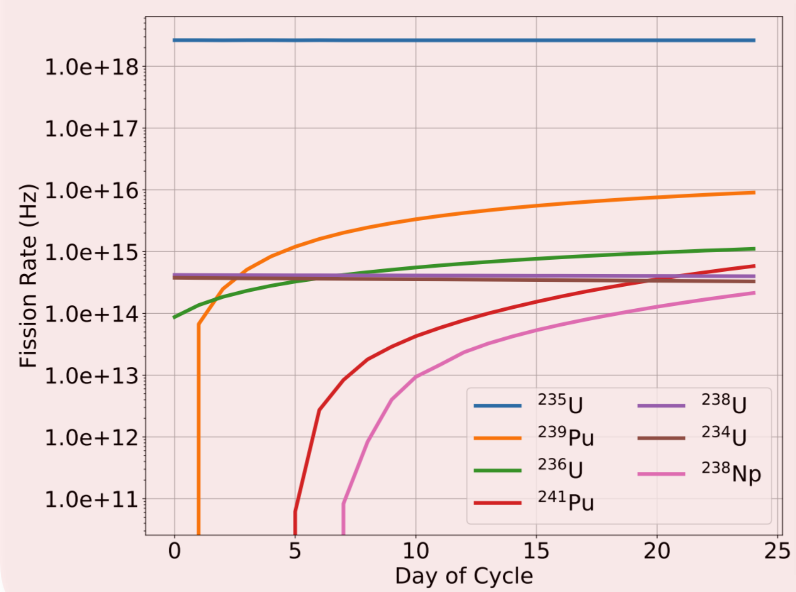


- Commercial reactors
- Several GW of thermal power
- $\bar{\nu}_e$'s originate from fission products of 4 isotopes: ^{235}U, ^{239}Pu, ^{241}Pu and ^{238}U
- Fuel evolves as ^{235}U is consumed and ^{239,241}Pu is produced



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

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



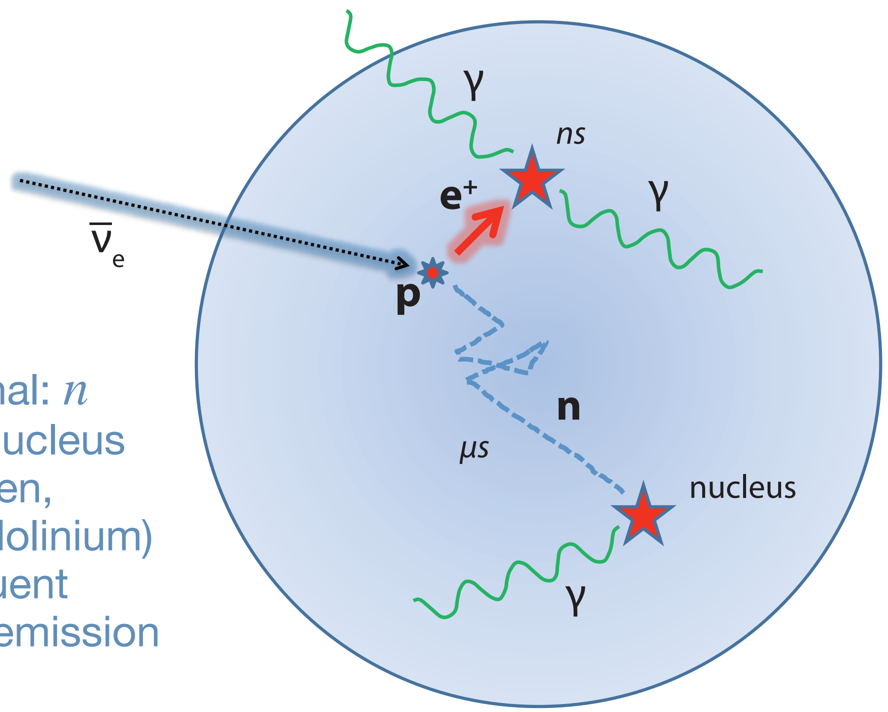
Antineutrino Detection

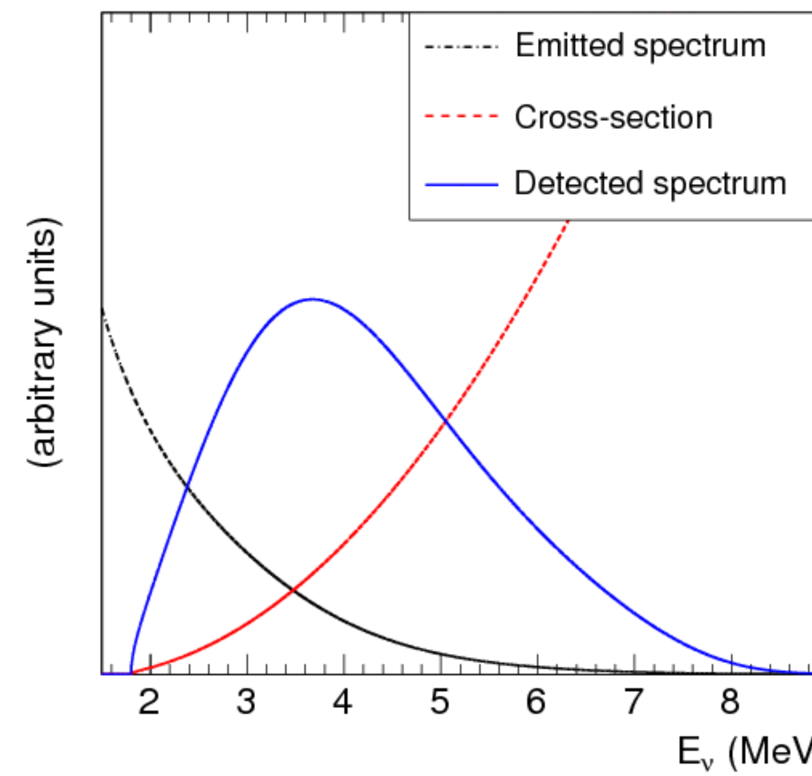
- The medium of choice for most of these experiments has been scintillator (plastic or liquid)
- The primary detection channel has been the Inverse Beta Decay (IBD) reaction:

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

Prompt signal: e^+ kinetic energy loss + annihilation

Delayed signal: n capture on nucleus (e.g. Hydrogen, Lithium, Gadolinium) 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 $\bar{\nu}_e$:

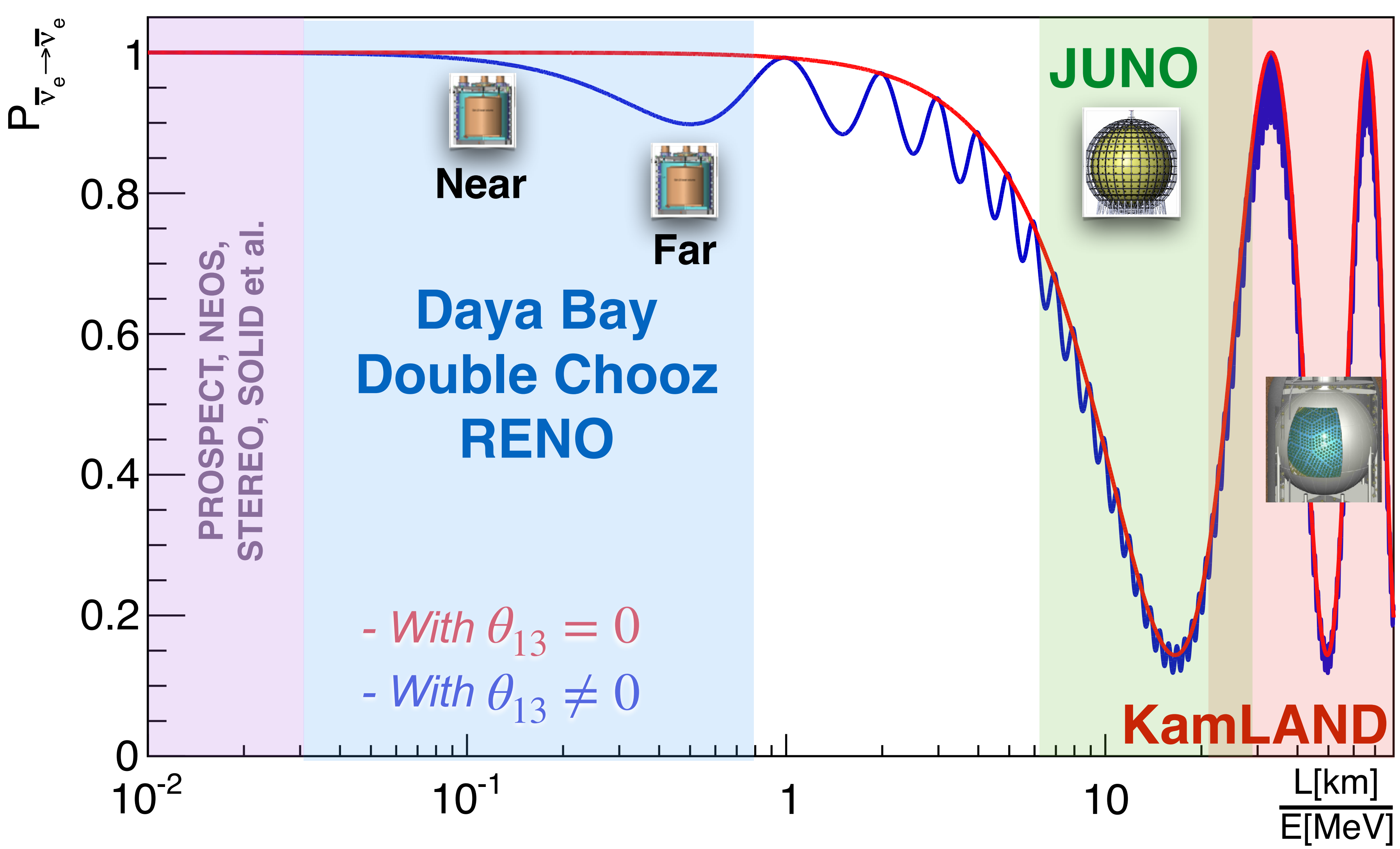
$$E_{\bar{\nu}_e} \approx E_{\text{prompt}} + 0.78\ \text{MeV}$$

Oscillation Probability

- Reactor experiments are an excellent ground to measure neutrino oscillations
- Electron antineutrino survival probability:

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

- Access to 4/6 oscillation parameters: θ_{12}, θ_{13}, Δm^2_{21}, and Δm^2_{31} (Δm^2_{32})
- Independent of θ_{23} and δ_{CP}
- Physics goals drive choice of baseline

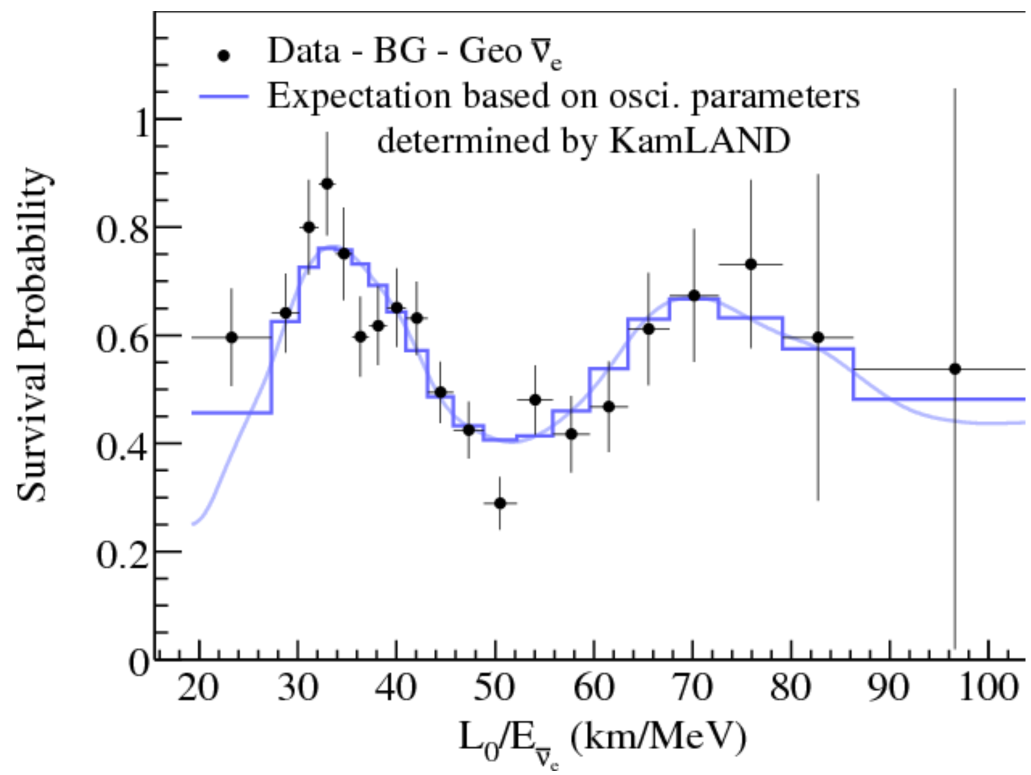


A Rich History

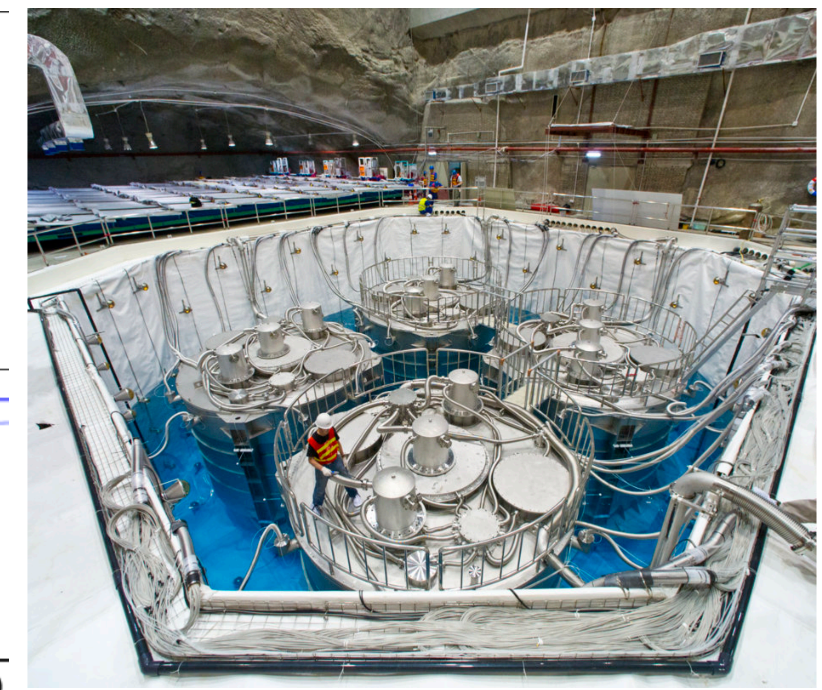
- Reactor antineutrino experiments have a very rich history of contributions to neutrino physics:

Discovery of the neutrino (Reines & Cowan, 1953-1956)

Phys. Rev. Lett. 100, 221803 (2008)



First observation of neutrino oscillation with terrestrial neutrinos (KamLAND, 2002)



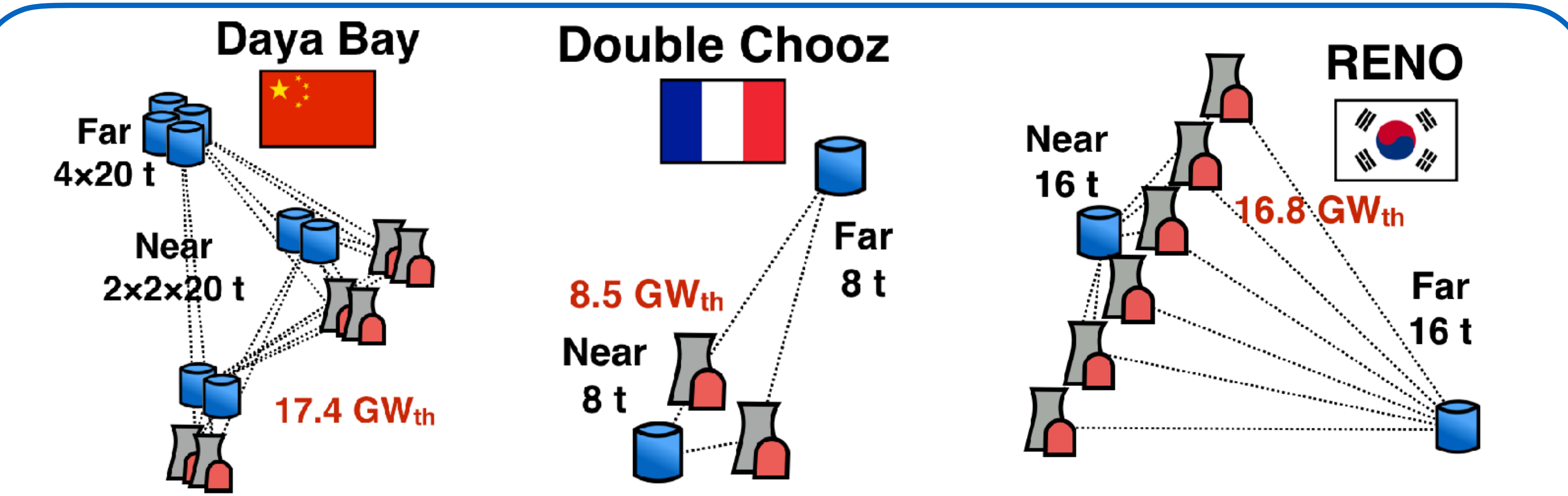
First definite observation of non-zero θ_{13} mixing angle

Current-Generation Reactor Neutrino Experiments

θ_{13} Experiments

- The current generation of reactor experiments fall roughly into two categories:

  1) Experiments designed to measure the θ_{13} mixing angle:



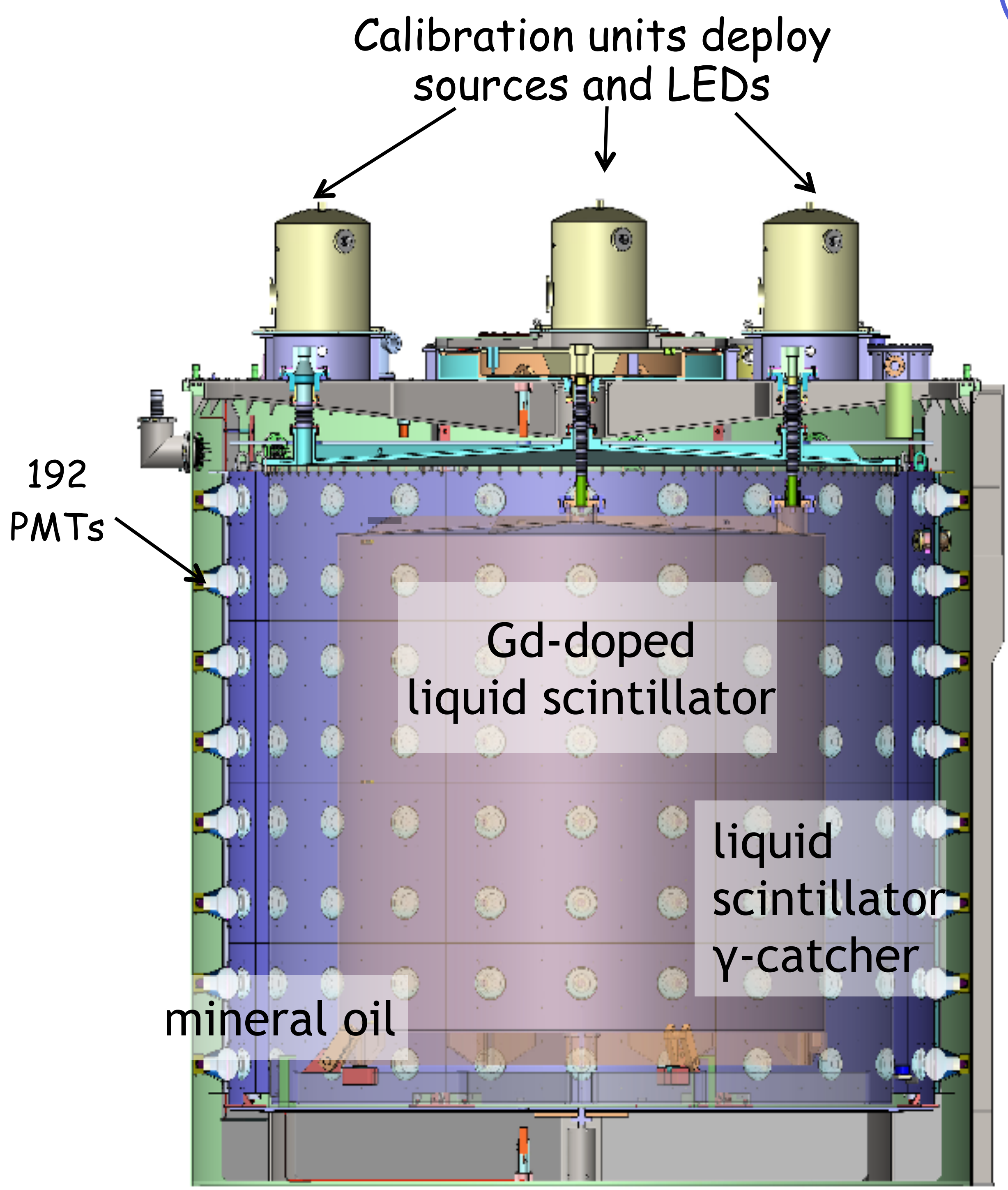
Data taking: 2011 - 2020 Data taking: 2011 - 2017 Data taking: 2011 - present

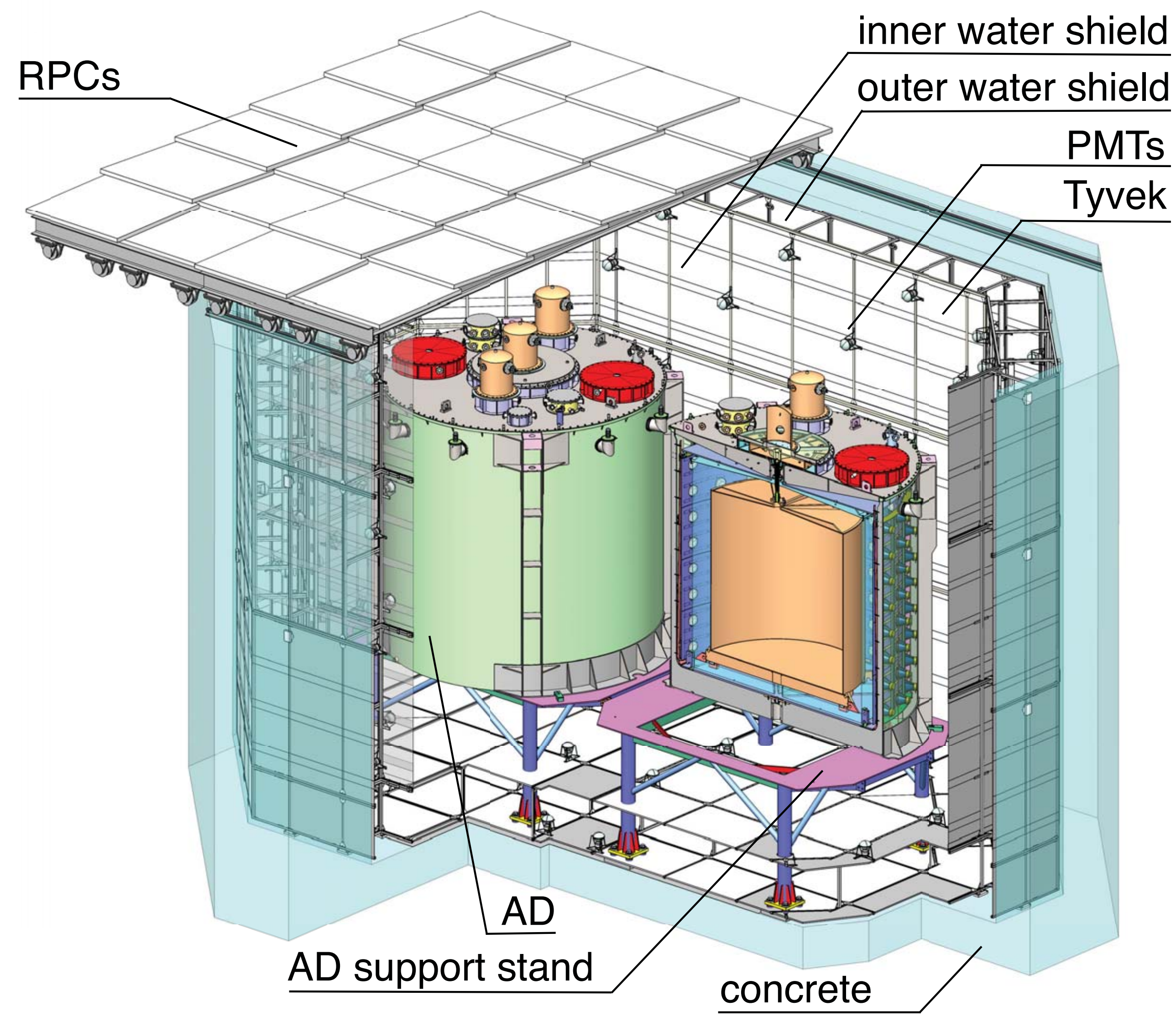
Notes: all reactors are LEU; flags indicate location of experiment, not composition of collaboration

  – < 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

θ_{13} Experiments

- Similar detection technologies:
  - Three-zone detectors
  - Surrounded by instrumented shields (water or LS) that also veto muons
  - LS doped with Gadolinium to enhance capture signal





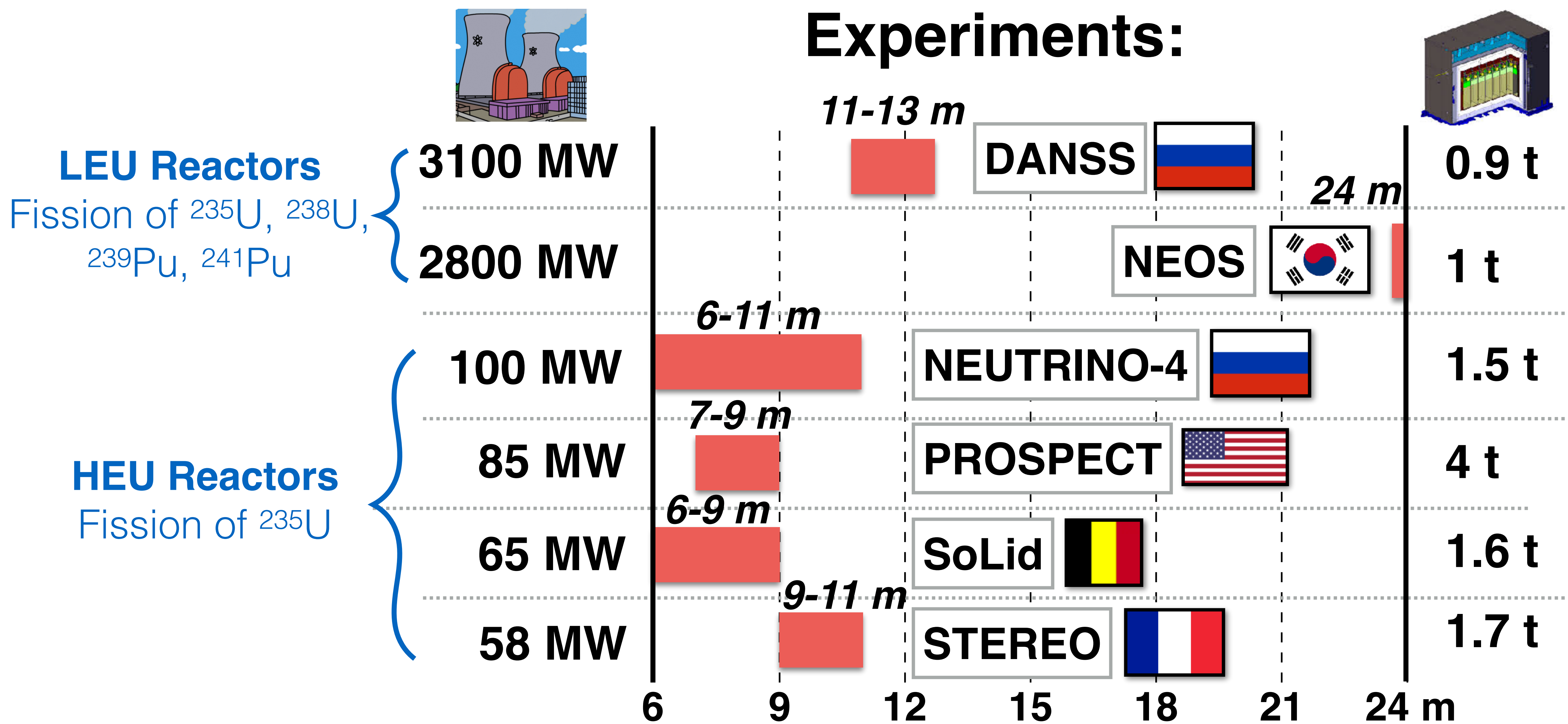
(using Daya Bay as an illustration)

SBL Experiments

2) Short-Baseline (SBL) Experiments

- Primary goal: search for a sterile neutrino with O(10 m) baselines

Motivation: anomalies in neutrino physics that can be explained by sterile neutrino mixing with $\Delta m^2_{41} \sim 1\ \mathrm{ev}^2$, including the reactor antineutrino anomaly (explained later)



+ (mini-)CHANDLER, NuLAT

(chart courtesy of B. Roskovec)

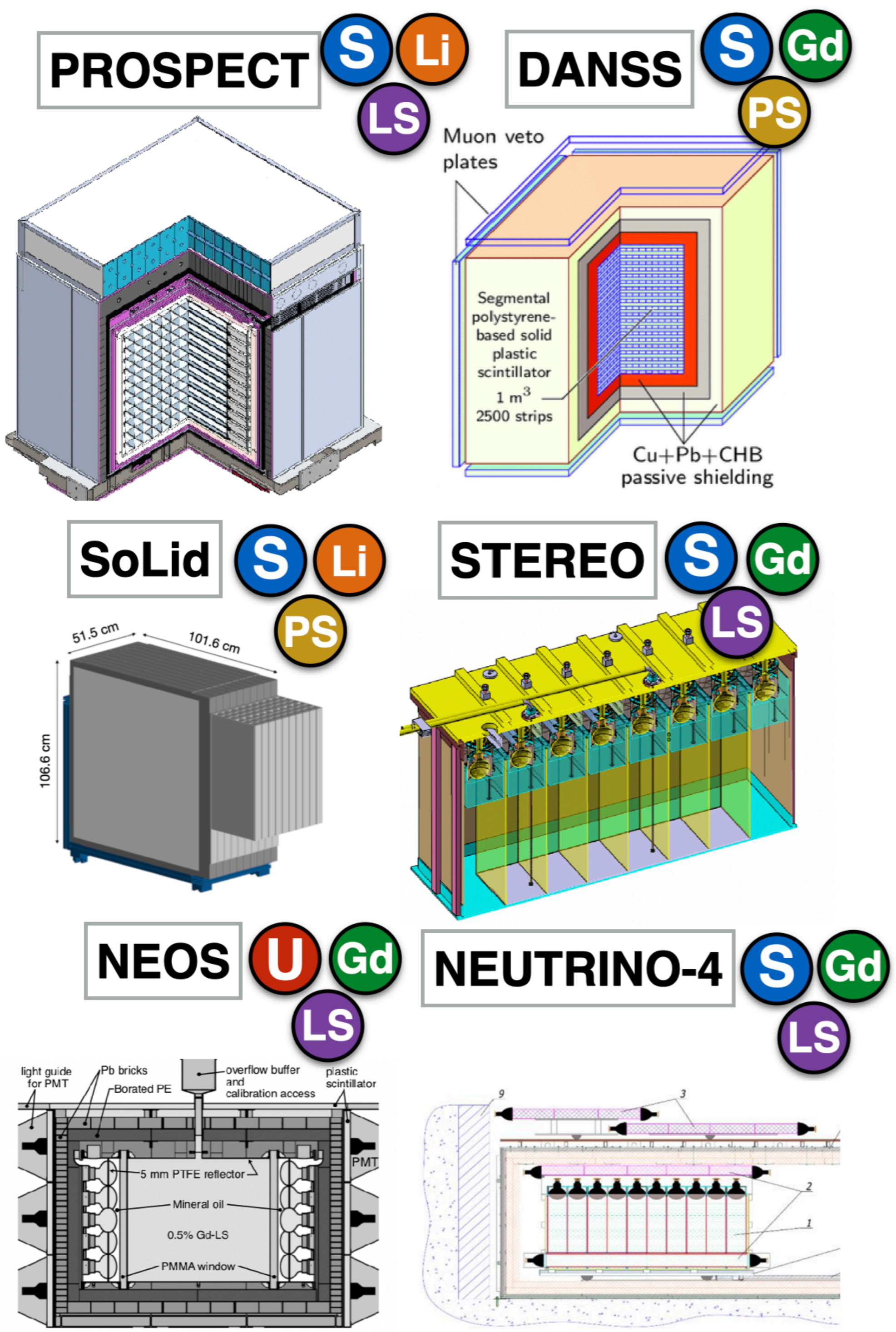
SBL Experiments

- Wide range of detection media and approaches:

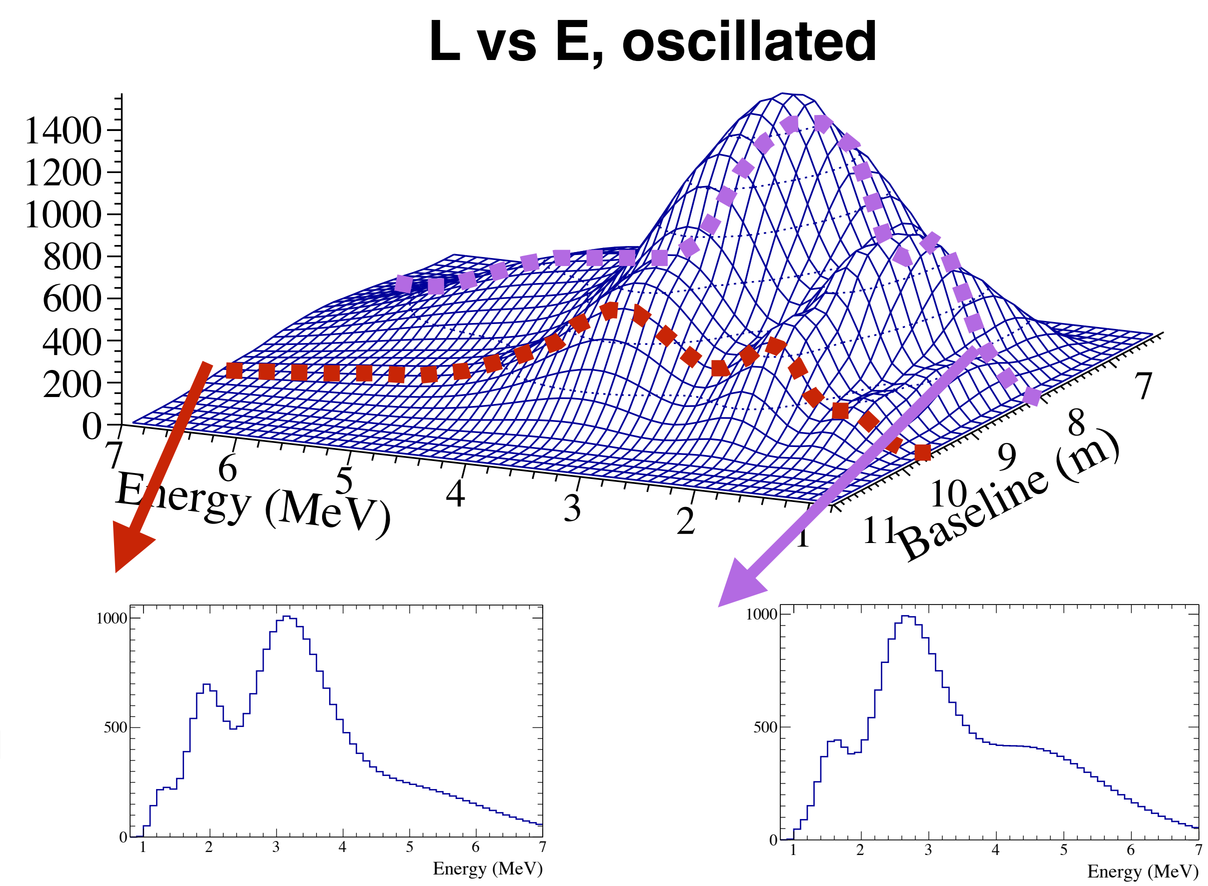
Segmentation:
S Segmented
U Unsegmented

Doping:
Gd Gadolinium
Li Lithium

Scintillator:
LS Liquid
PS Plastic



Segmentation/movability allows to make a **relative** measurement within/with the same detector



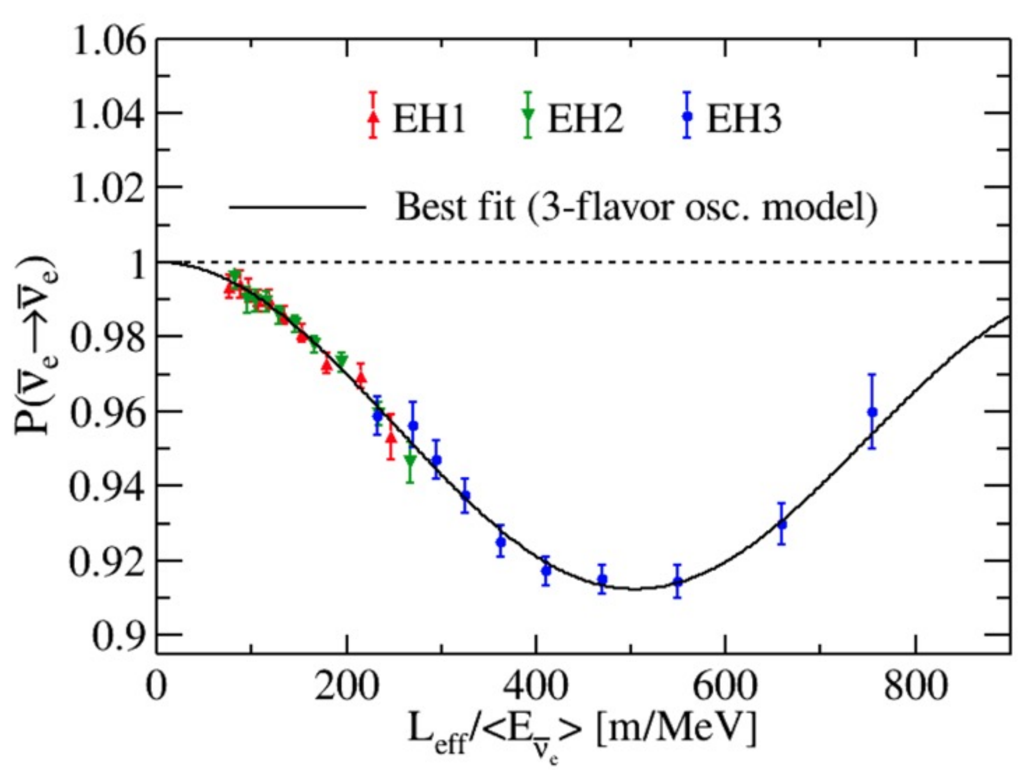
(from B. Littlejohn's seminar at FNAL)

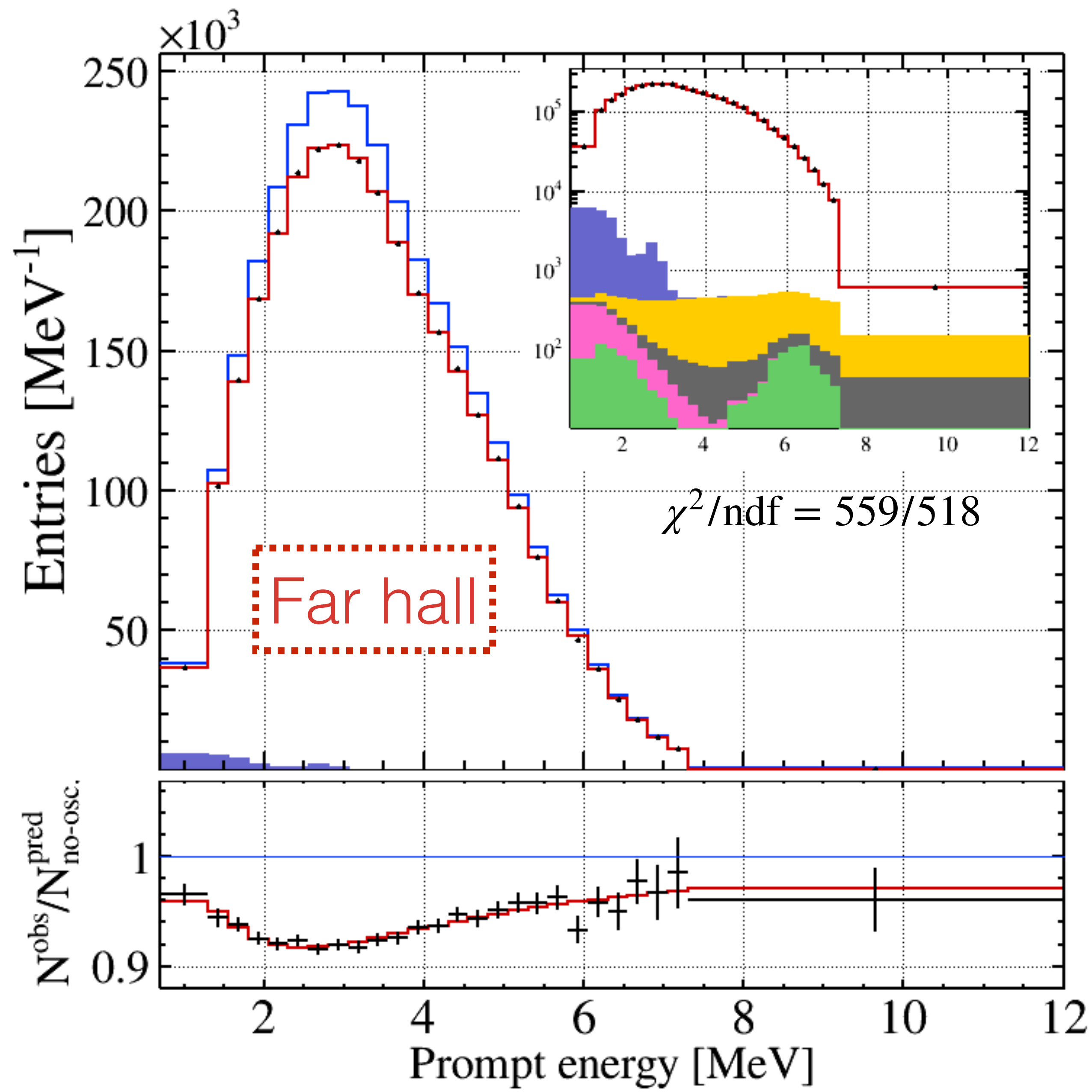
Makes measurement largely independent of reactor prediction models!

Recent Oscillation Results Highlights

Three-Neutrino Oscillation Measurements

- The most precise measurements of θ_{13} come from reactor experiments
- As an example, these are the latest results from Daya Bay (released in May 2022)
  - 3158 days of data
  - From spectral distortion simultaneously extract $\sin^2(2\theta_{13})$ and Δm^2_{32}



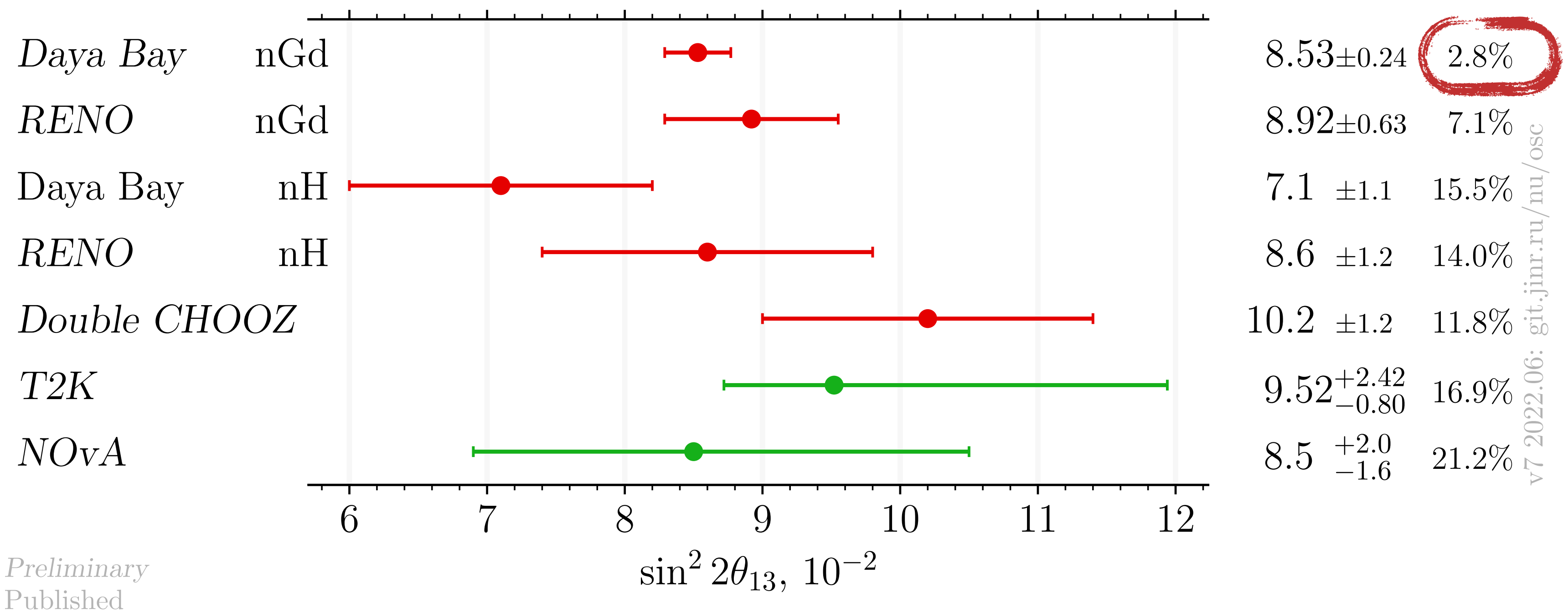


  - Excellent fit to standard three-neutrino framework

10.5281/zenodo.6683712

Global Landscape

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

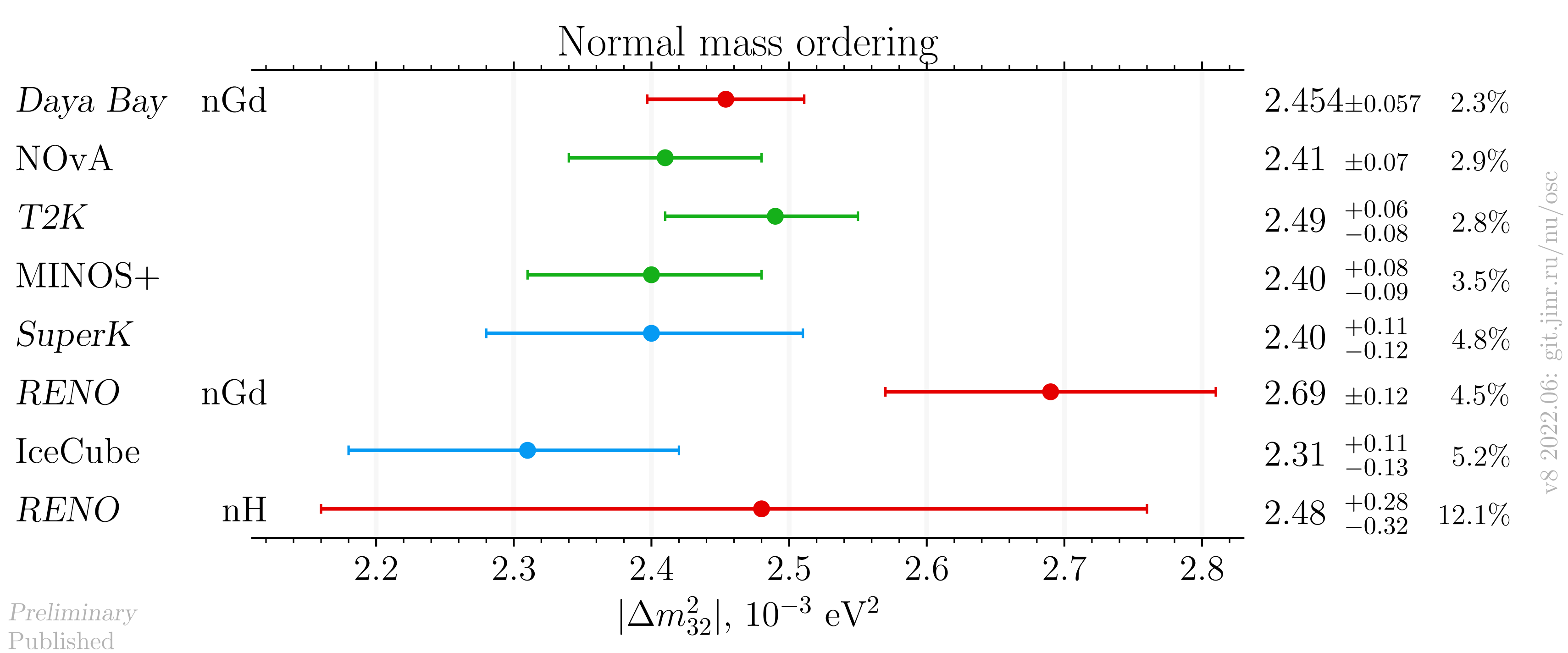


2.8% precision in $\sin^2 2\theta_{13}$

Currently the best known angle in the PMNS matrix, but this will likely change

(see A. Cabrera's talk for the role that θ_{13} will play in future unitarity tests)

- Reactor experiments also have excellent sensitivity to Δm^2_{32}:



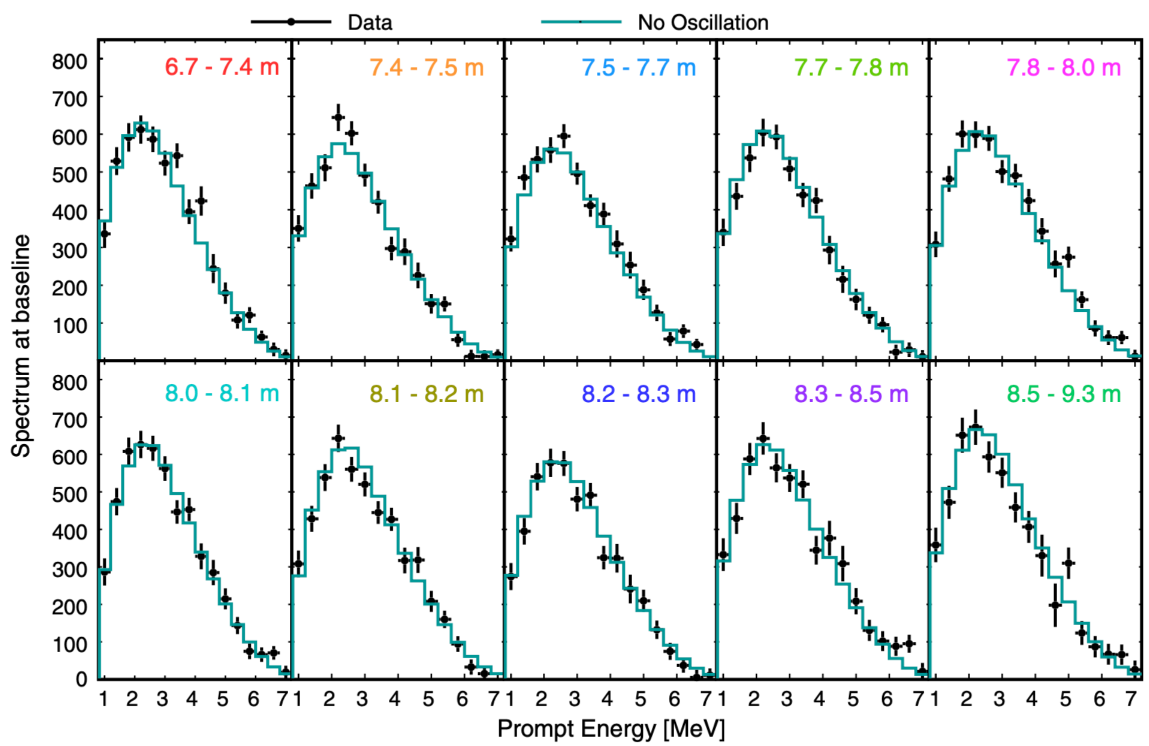
Great agreement between very different experimental approaches!

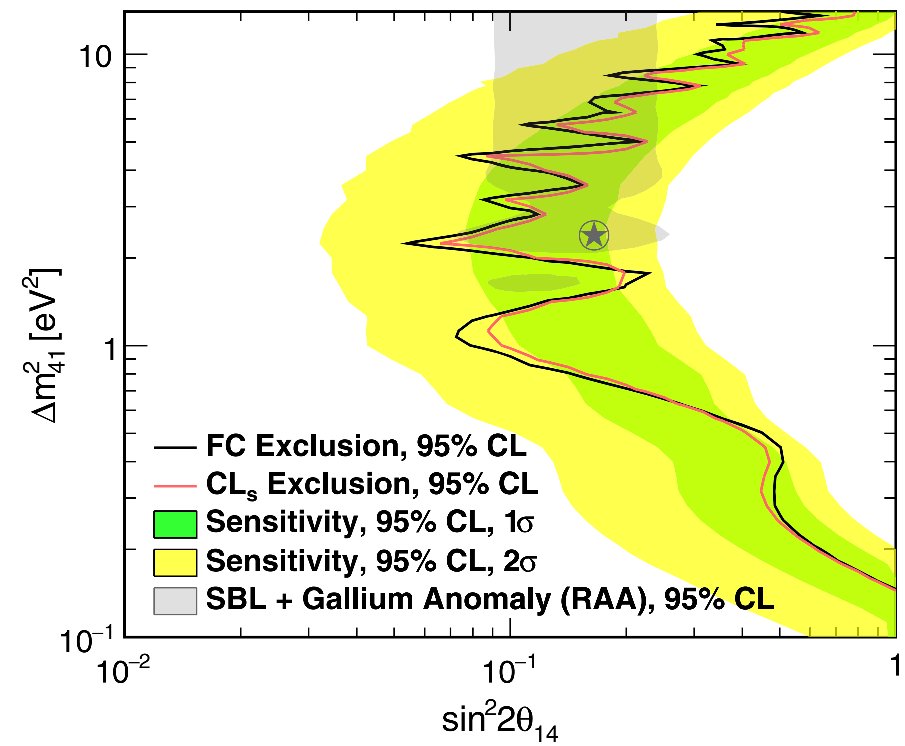
JUNO will further carry the torch (see later)

SBL Experiments

- Almost all SBL experiments have released results by now
- As an example, these are the 2021 results from PROSPECT

No evidence of spectral distortion vs. baseline →

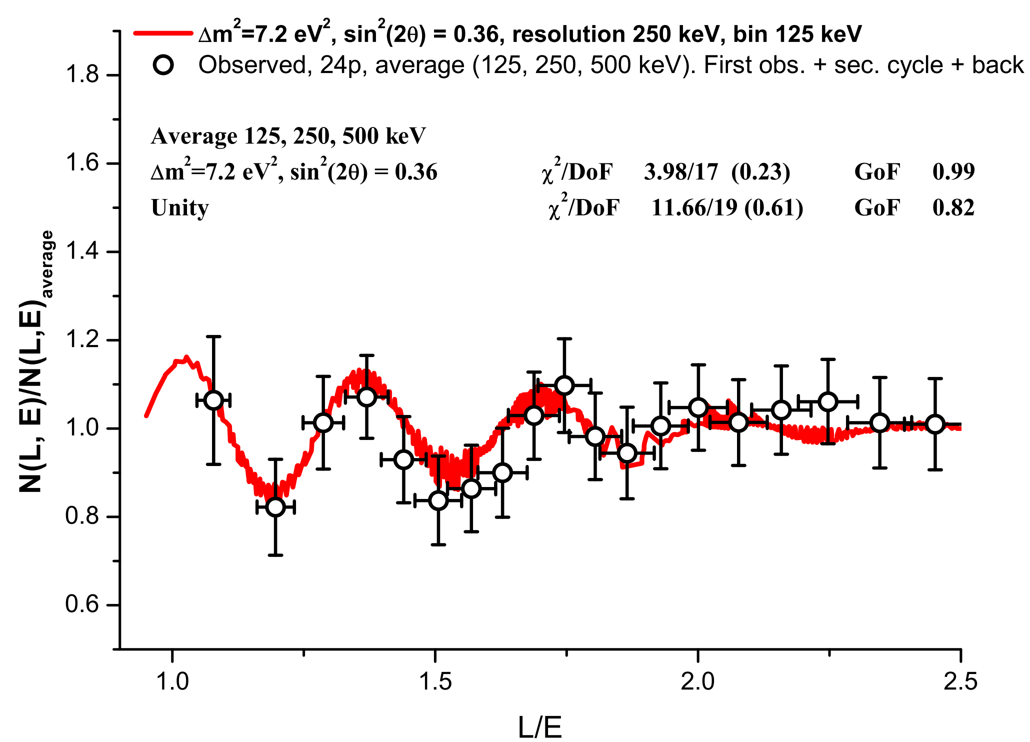


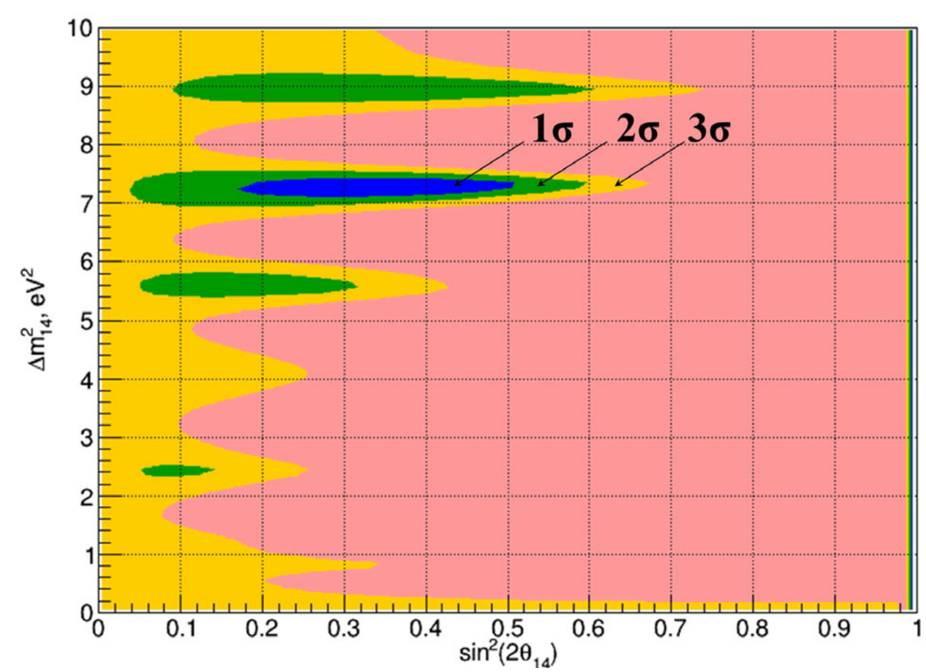


PRD 103, 032001 (2021)

- There is a ~2.7σ claim of a positive signal from Neutrino-4:

Heavily disputed (e.g. PLB 816, 136214 (2021)) →





PRD 104, 032003 (2021)

Non-Standard Flavor Mixing Landscape

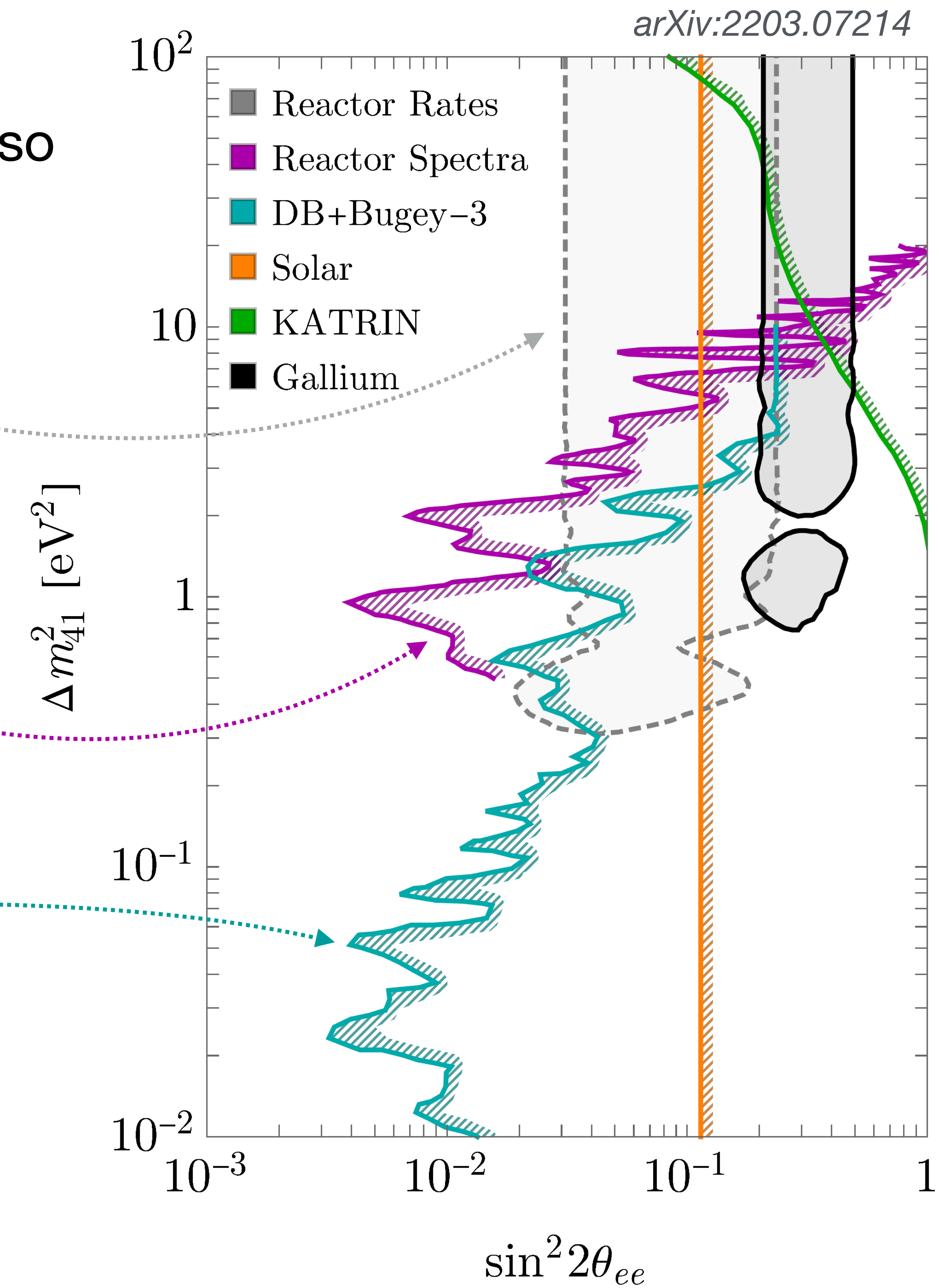
- In general, no significant evidence so far for non-standard flavor mixing

Parameter space motivated by the reactor antineutrino anomaly (see next section)

Exclusion curve from global fit of SBL spectral measurements (DANSS, NEOS, Neutrino-4, PROSPECT, STEREO)

Exclusion limit from combination of Daya Bay and Bugey-3

(Daya Bay's longer baseline of ~2 km makes it sensitive to lower values of Δm^2_{41}; Bugey-3 operated at several <100 m baselines)

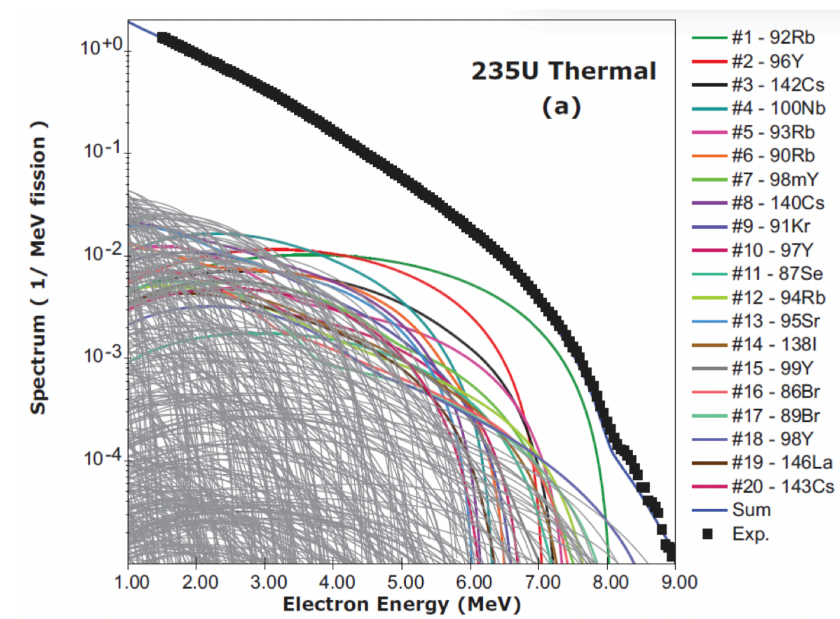


Reactor Antineutrino “Anomalies”: Data vs. Model Comparisons

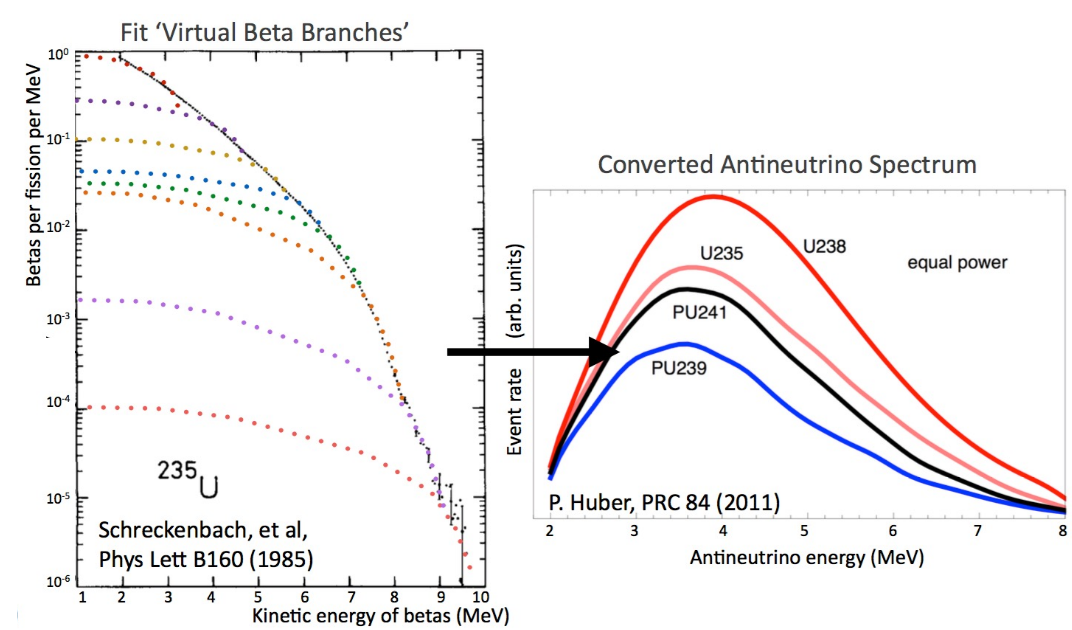
Characterizing Reactor $\bar{\nu}_e$ Emission

- Existing data can be also be used to characterize the emission of antineutrinos from nuclear reactors and to compare with prediction models:
  - Important for fundamental physics, non-proliferation applications, and as a stringent test of nuclear data inputs

- Two methods to predict the reactor $\bar{\nu}_e$ rate and spectral shape:
  - Ab-initio method:
    - Bottom-up calculation using fission yields, Q values and decay branching ratios from nuclear data bases
  - 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



Sonzogni AAP 2019

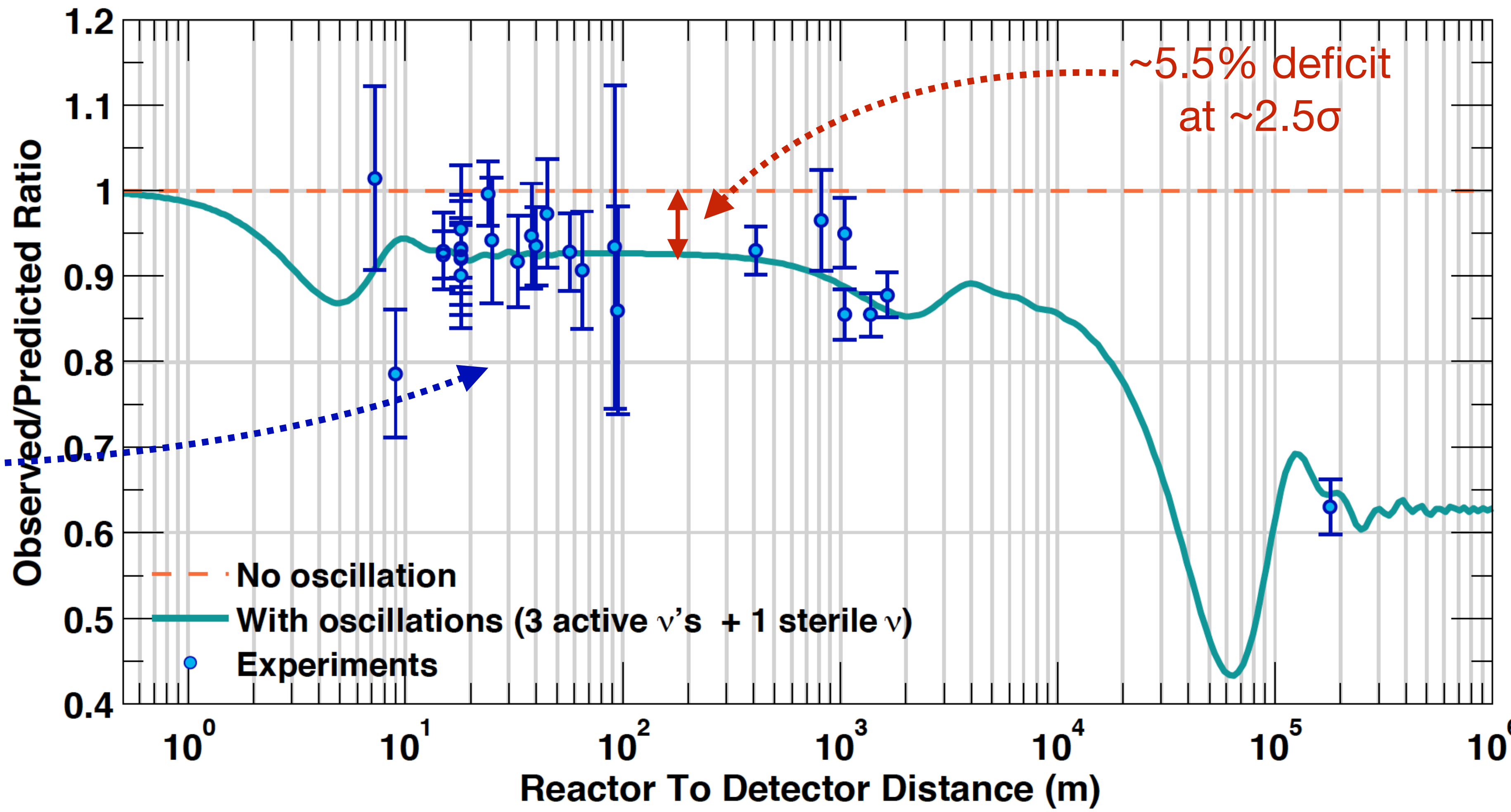


The “Rate Anomaly”

- Historically, the comparison of the observed vs. predicted $\bar{\nu}_e$ rate came first:

Rate = total yield, i.e. time-averaged yield from all isotopes

Most precise measurements come from Double Chooz (~1%), Bugey4 (~1.4%), and Daya Bay (~1.5%)



PRD 83, 073006 (2011)

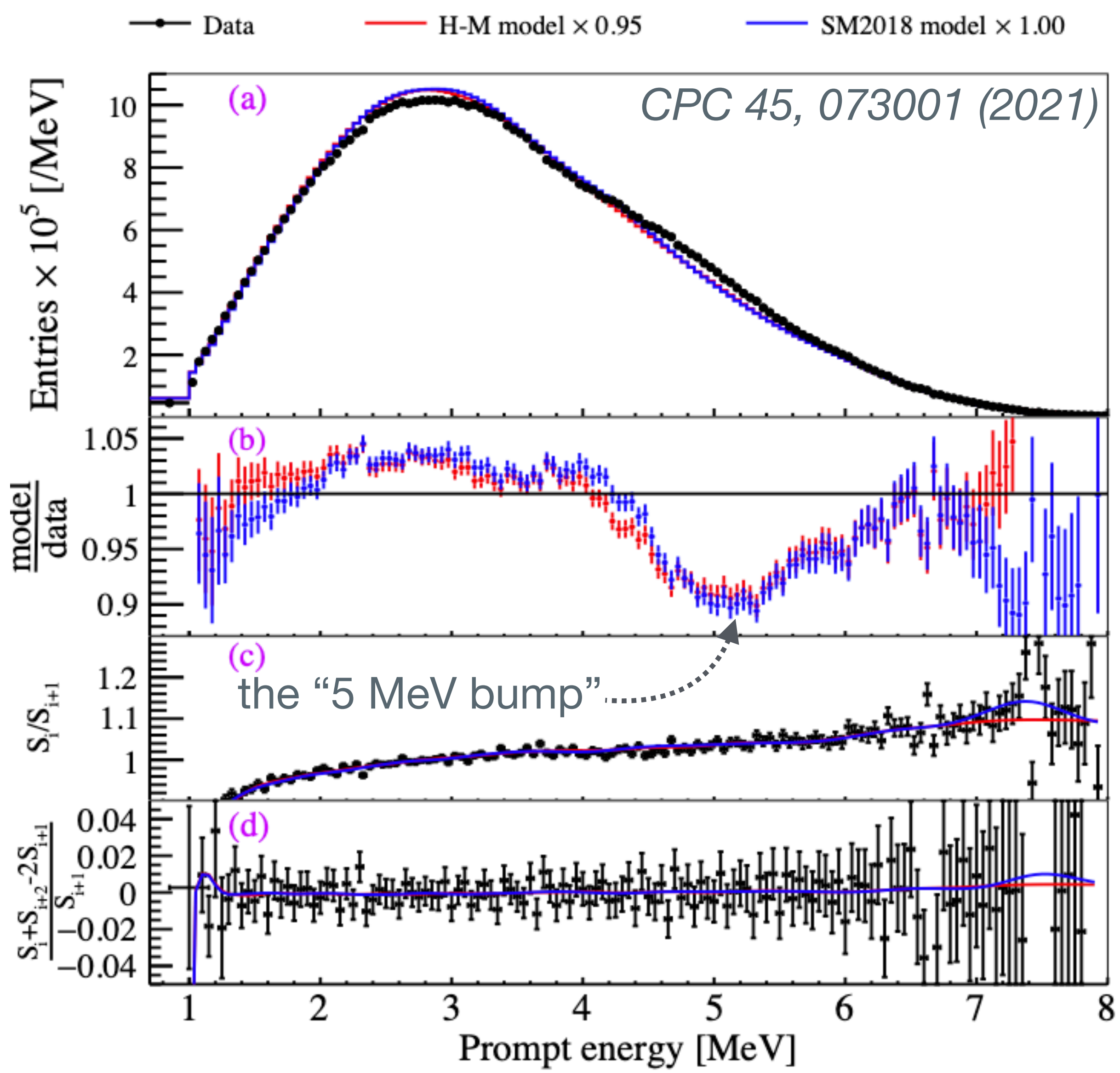
  - This is the “**reactor antineutrino anomaly**”: a ~5% deficit in total rate with respect to the Huber Mueller (HM) model at short baselines

- Causes of the anomaly?
  - Experimental systematics? **Extremely unlikely**…
  - New Physics (oscillations to a ~eV sterile neutrino)? **Maybe…**
  - Unaccounted systematics and/or biases in the prediction? **Likely**…

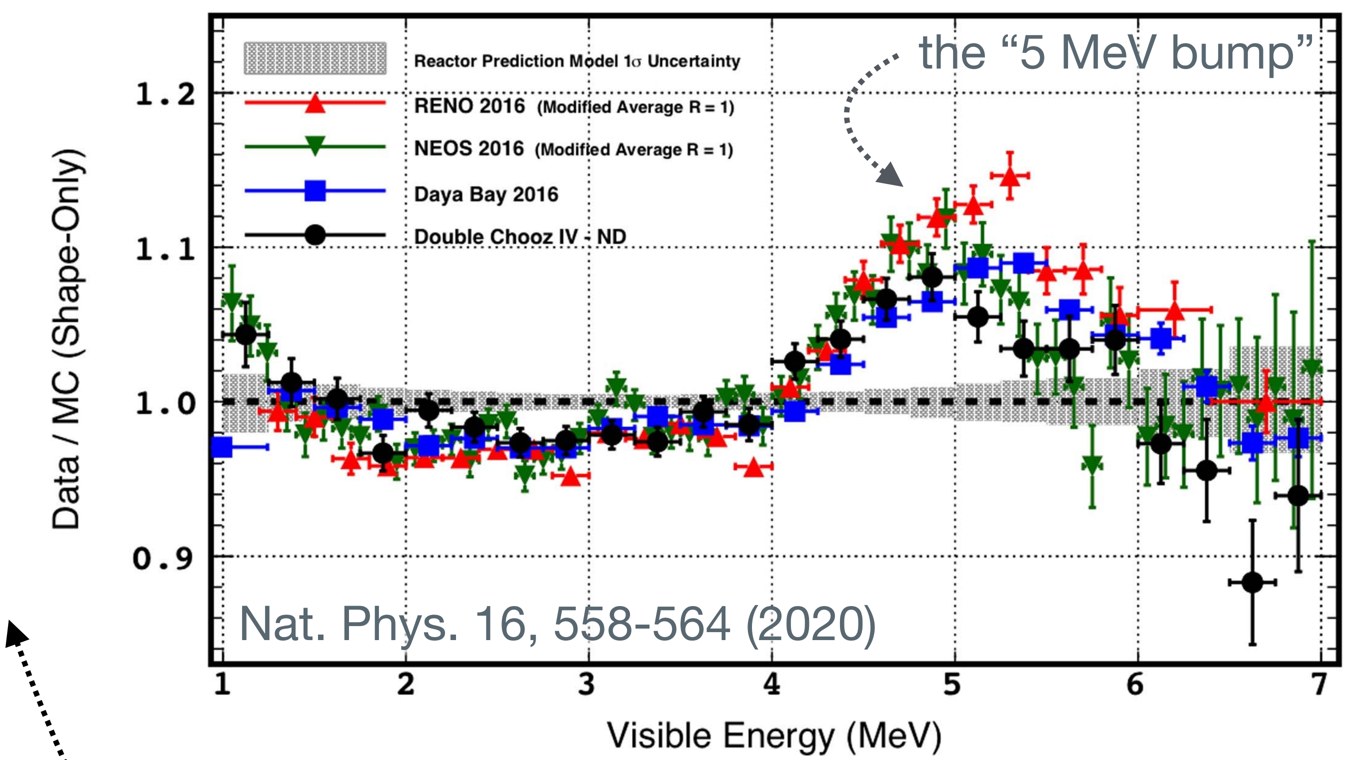
The “Shape Anomaly”

- With recent reactor experiments it became possible to also make a precise comparison of the observed vs. predicted spectral shape of reactor $\bar{\nu}_e$’s:

Spectral Shape
(Daya Bay)



Data/Model comparison
for several experiments



See a “5 MeV bump” (4-6 MeV excess) that is roughly consistent among experiments

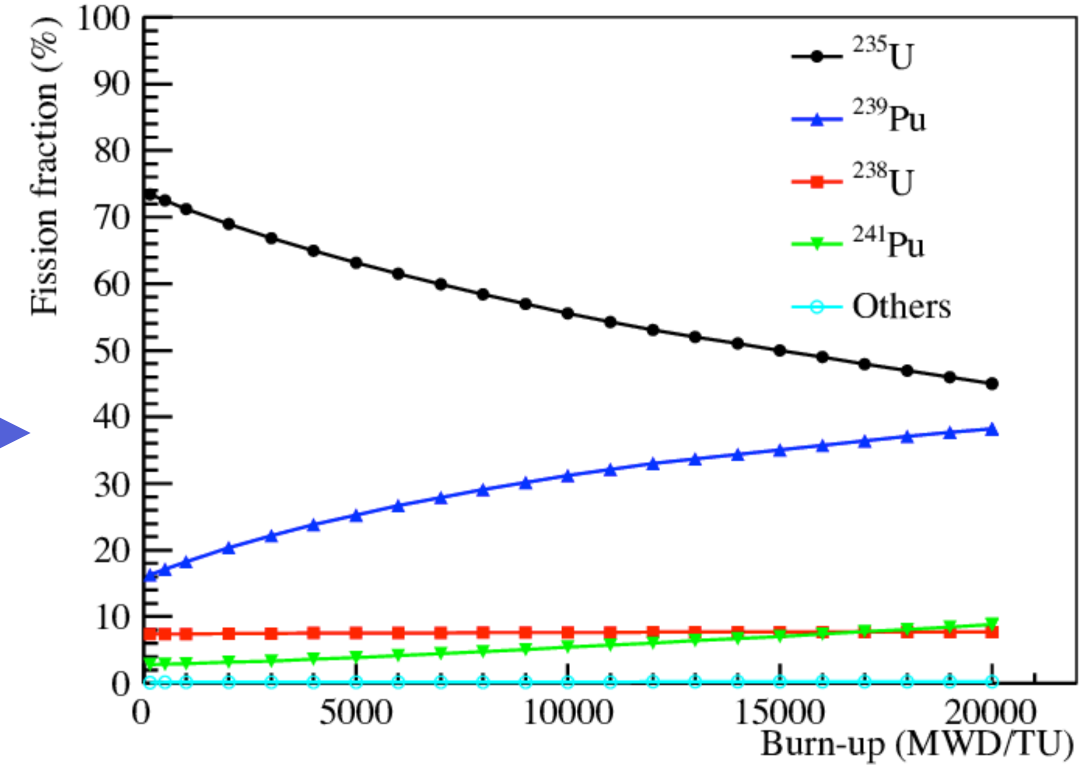
Bump appears when comparing with both conversion (HM) and summation (SM2018) models

The "Evolution Anomaly"

- The question arises: **can these anomalies be traced to a particular isotope?**

Reminder: neutrinos from nuclear reactors originate from the fission of ^{235}U, ^{239}Pu, ^{241}Pu, ^{238}U

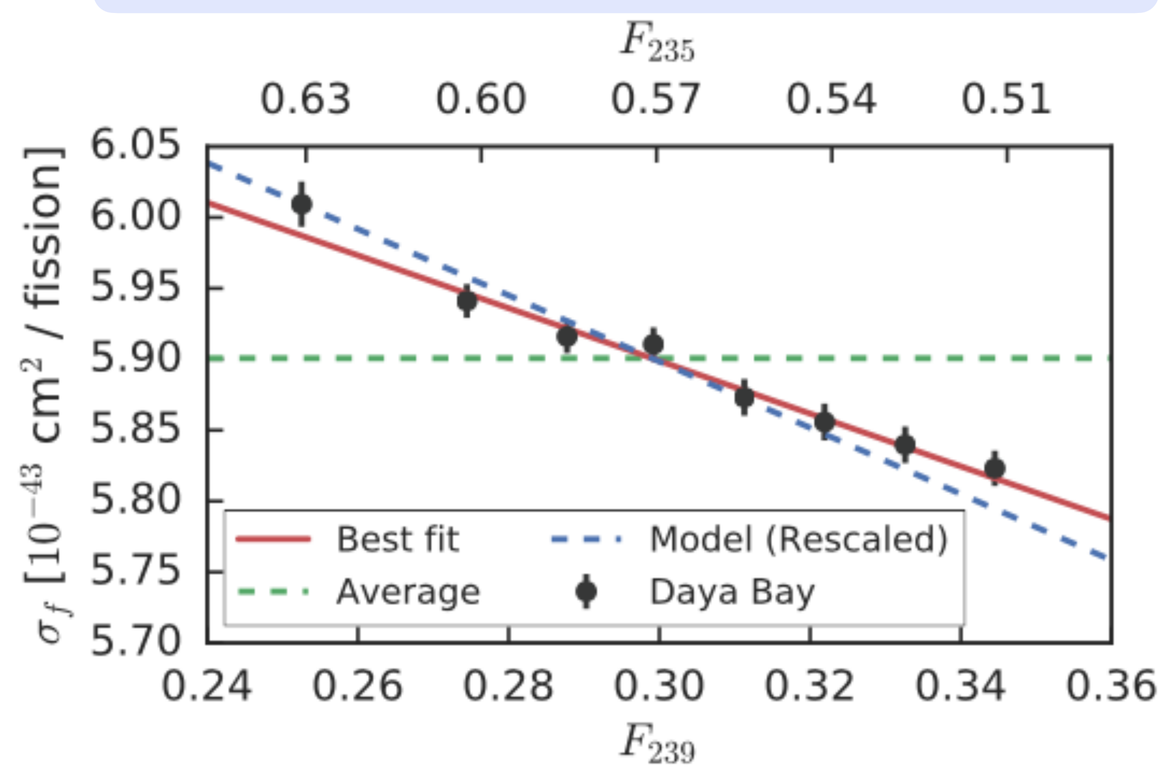
(fission fraction F_X = fraction of fissions from isotope X)



- Neutrino yield of ^{239}Pu (σ_{239}) is lower than that of ^{235}U (σ_{235}):
  - Expect a decrease in the observed total yield vs. ^{239}Pu fission fraction that is observed ✔
  - Find yet **another "anomaly"**: observed and predicted slopes differ at ~3σ ×

These data contain information on the individual yields!

Total yield with fission fraction (Daya Bay)

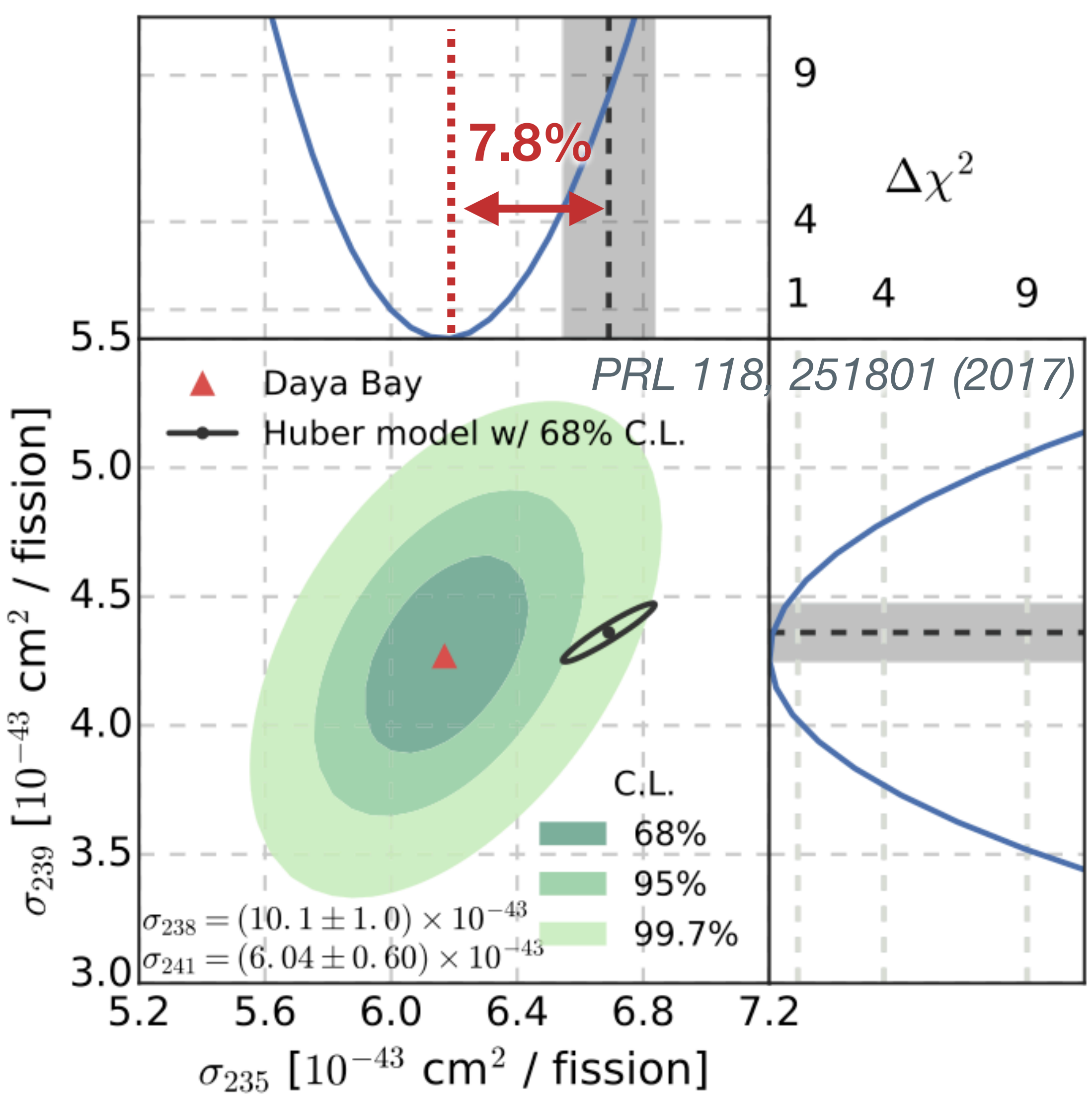


PRL 118, 251801 (2017)

Isotopic Yields and Spectra

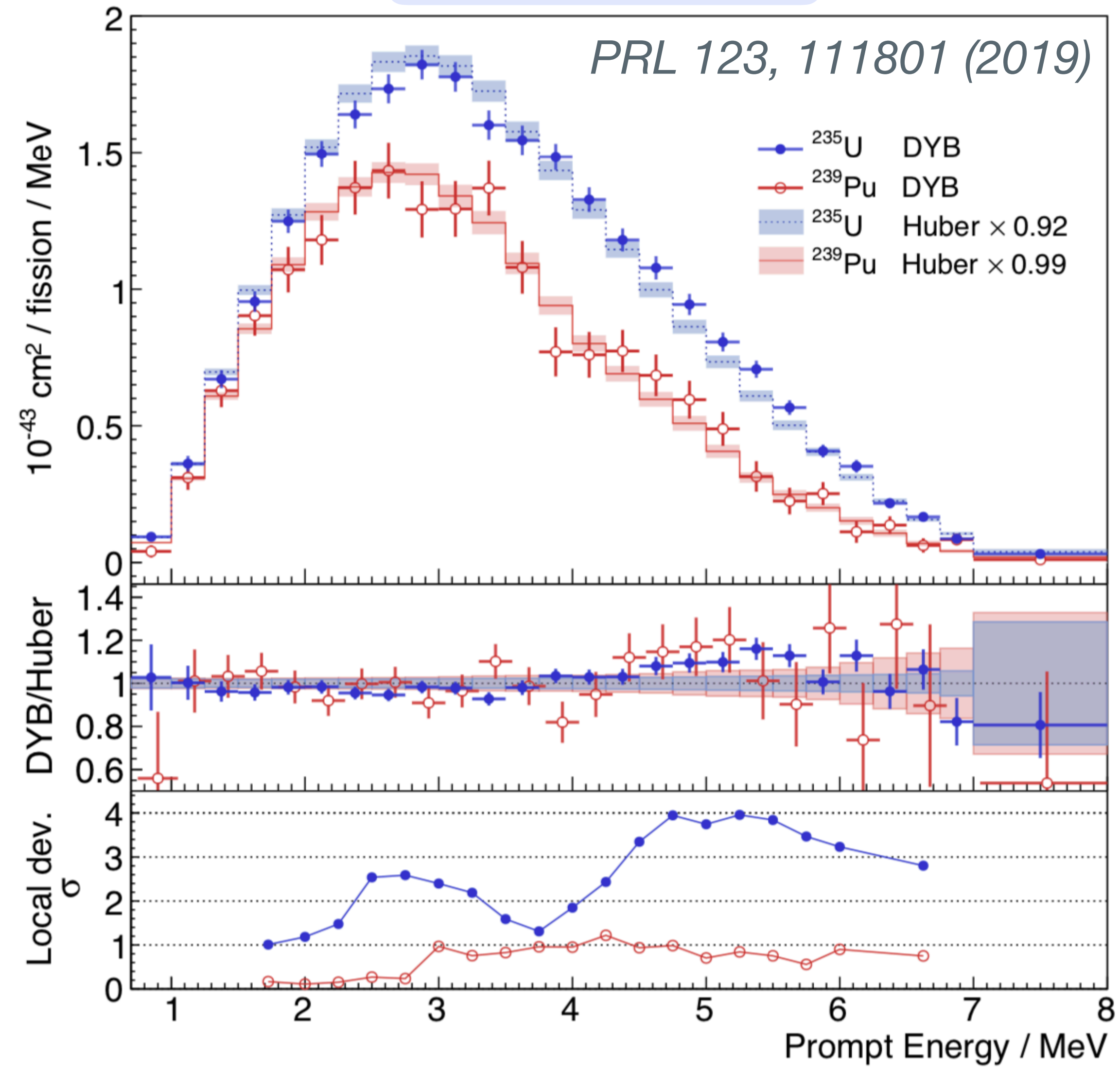
- The evolution with fuel composition allows to extract the individual yields and spectra for the two main isotopes: ^{235}U and ^{239}Pu

Isotopic Yields
(Daya Bay)



Suggests ^{235}U is main contributor to Reactor Antineutrino Anomaly

Isotopic Spectra
(Daya Bay)



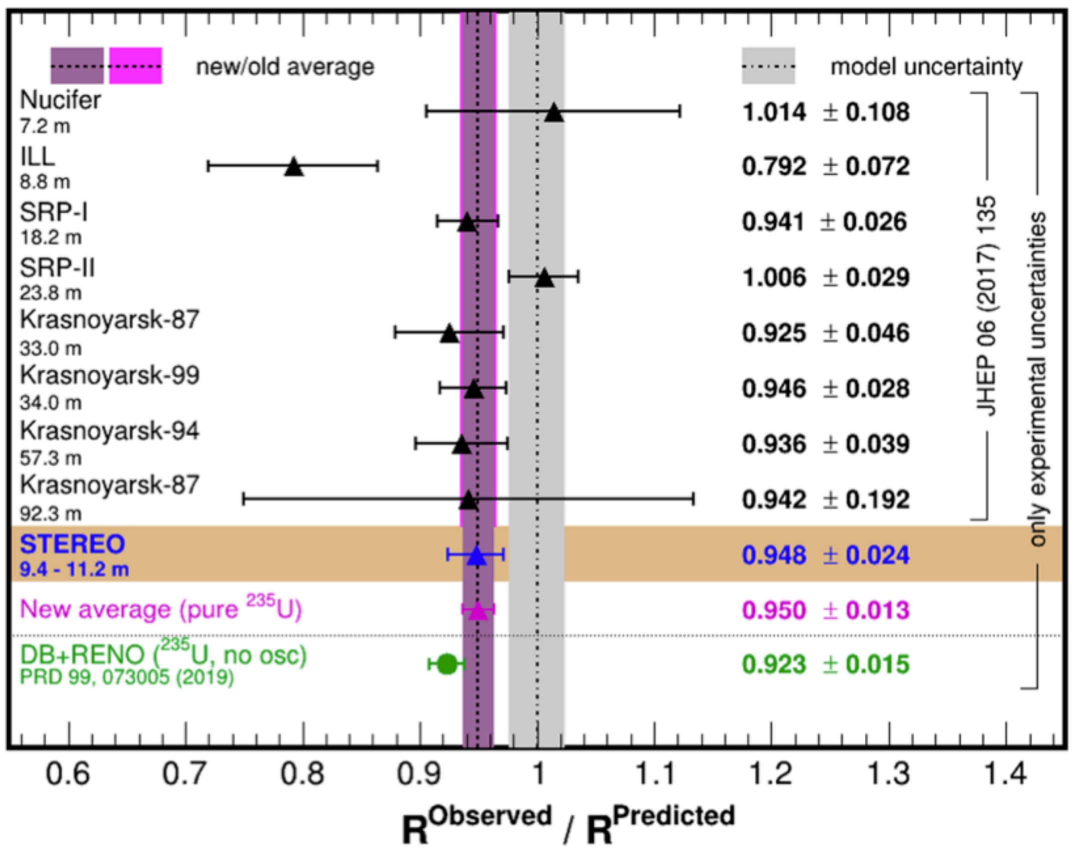
Data are consistent with "5 MeV bump" in both ^{235}U and ^{239}Pu spectra

Comments: have to make conservative assumptions about the contributions from ^{238}U and ^{241}Pu. RENO and NEOS-II have released consistent yields in PRL 122, 232501 (2019) and 10.5281/zenodo.6680618, respectively

Consistent Picture

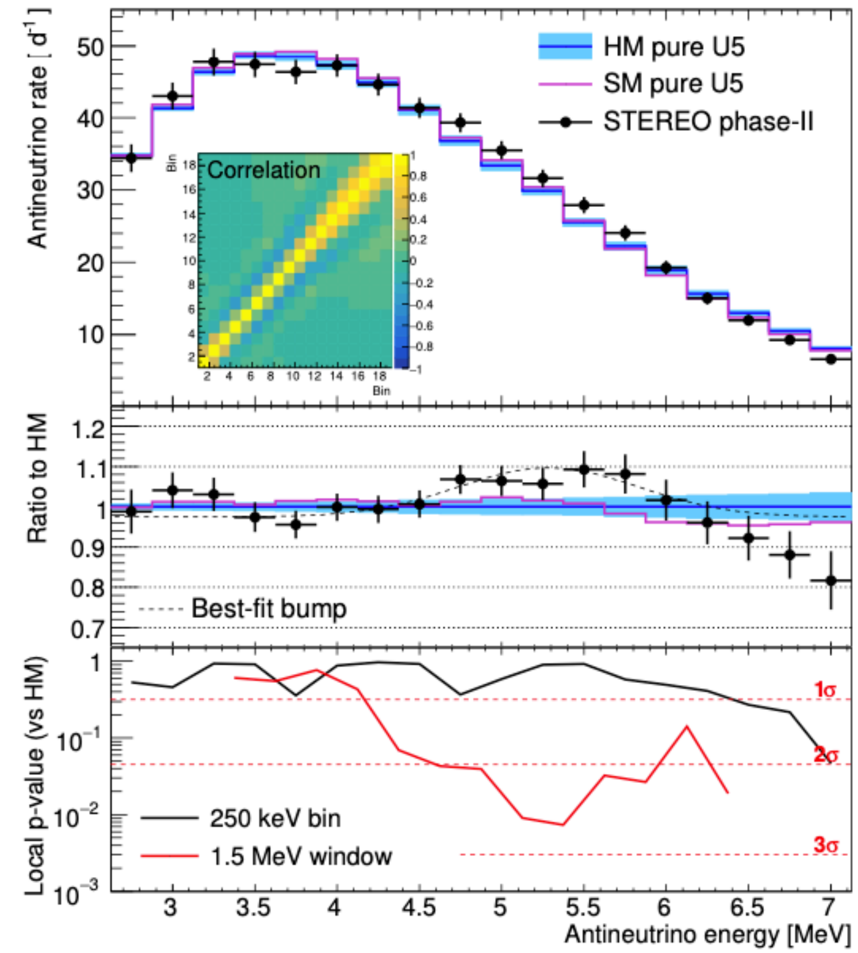
- Get a consistent story from HEU experiments:

^{235}U Yield Data/Prediction



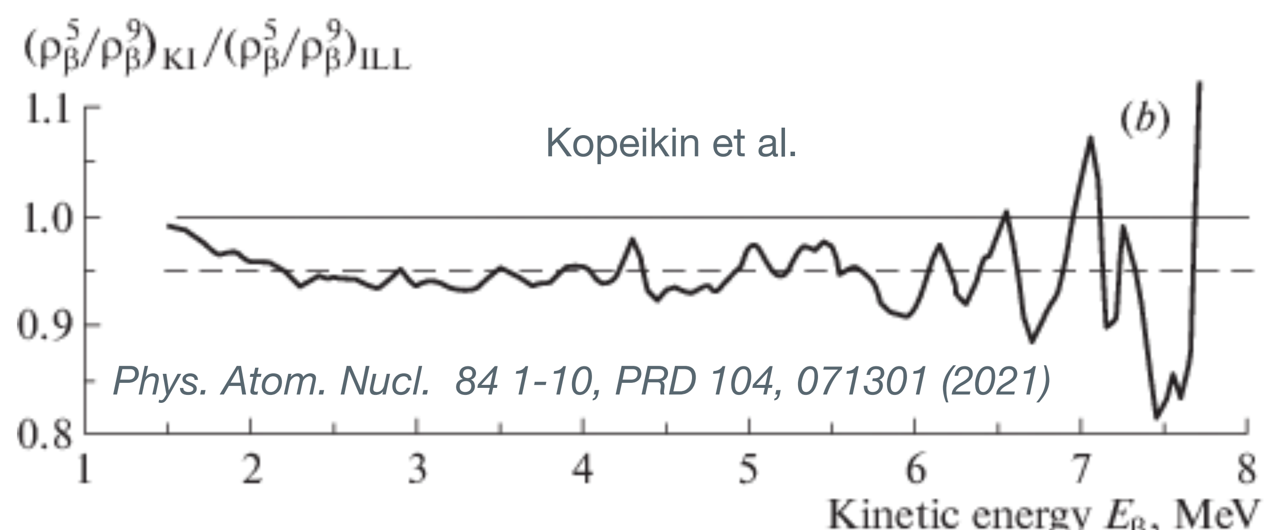
PRL 125, 201801 (2020)

^{235}U Spectral Measurement (STEREO)



J. Phys. G 48, 075107

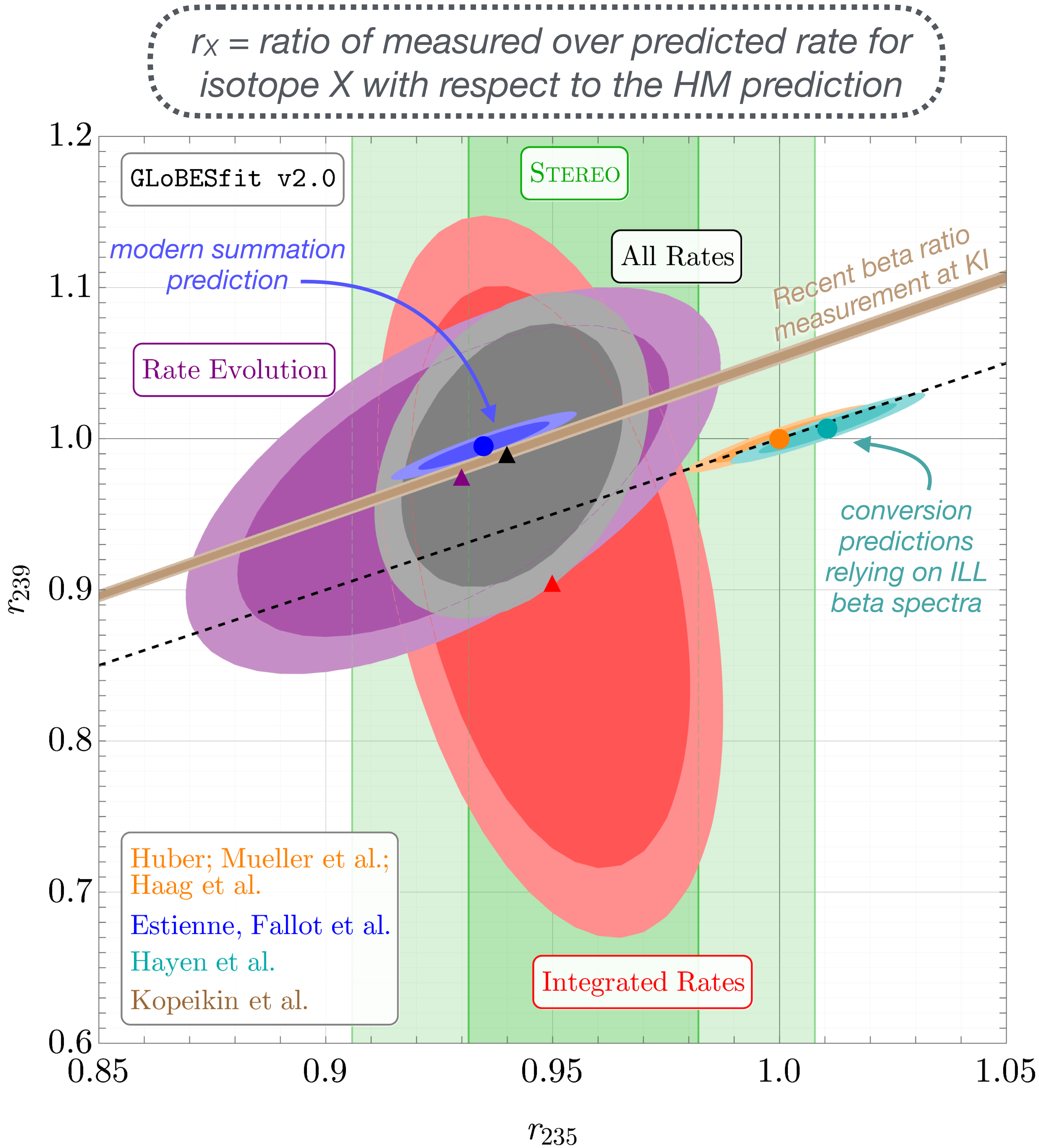
- And from recent re-evaluation of the ^{235}U /^{239}Pu ratio of cumulative fission beta spectra at Kurchatov Institute (KI):
  - Almost constant offset of about ~5% with respect to ILL!
  - No indication of a “5 MeV bump”



Phys. Atom. Nucl. 84 1-10, PRD 104, 071301 (2021)

Putting it All Together

- Main conclusions:
  - Convergence of multiple lines of evidence suggests that ^{235}U beta spectrum from ILL (which underlies 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**

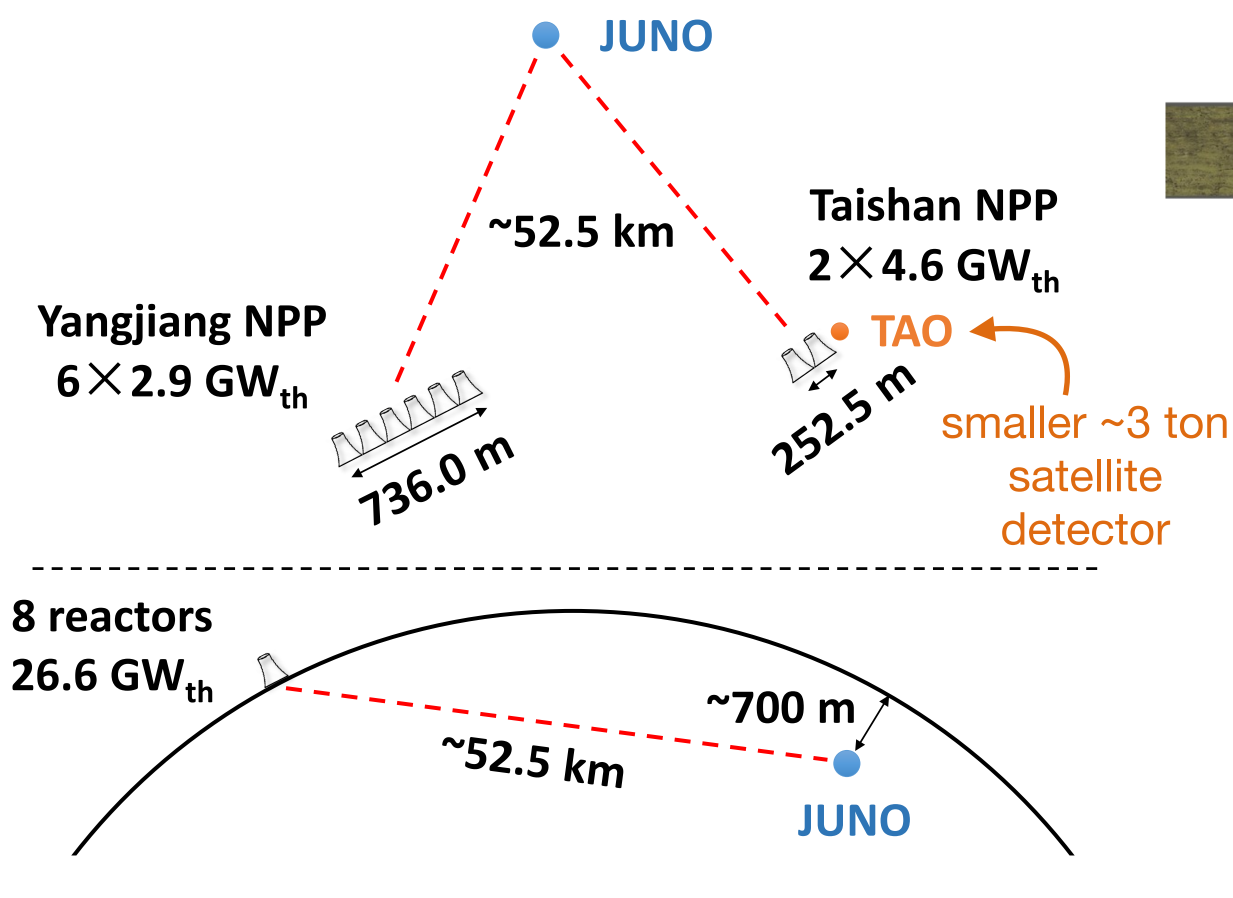


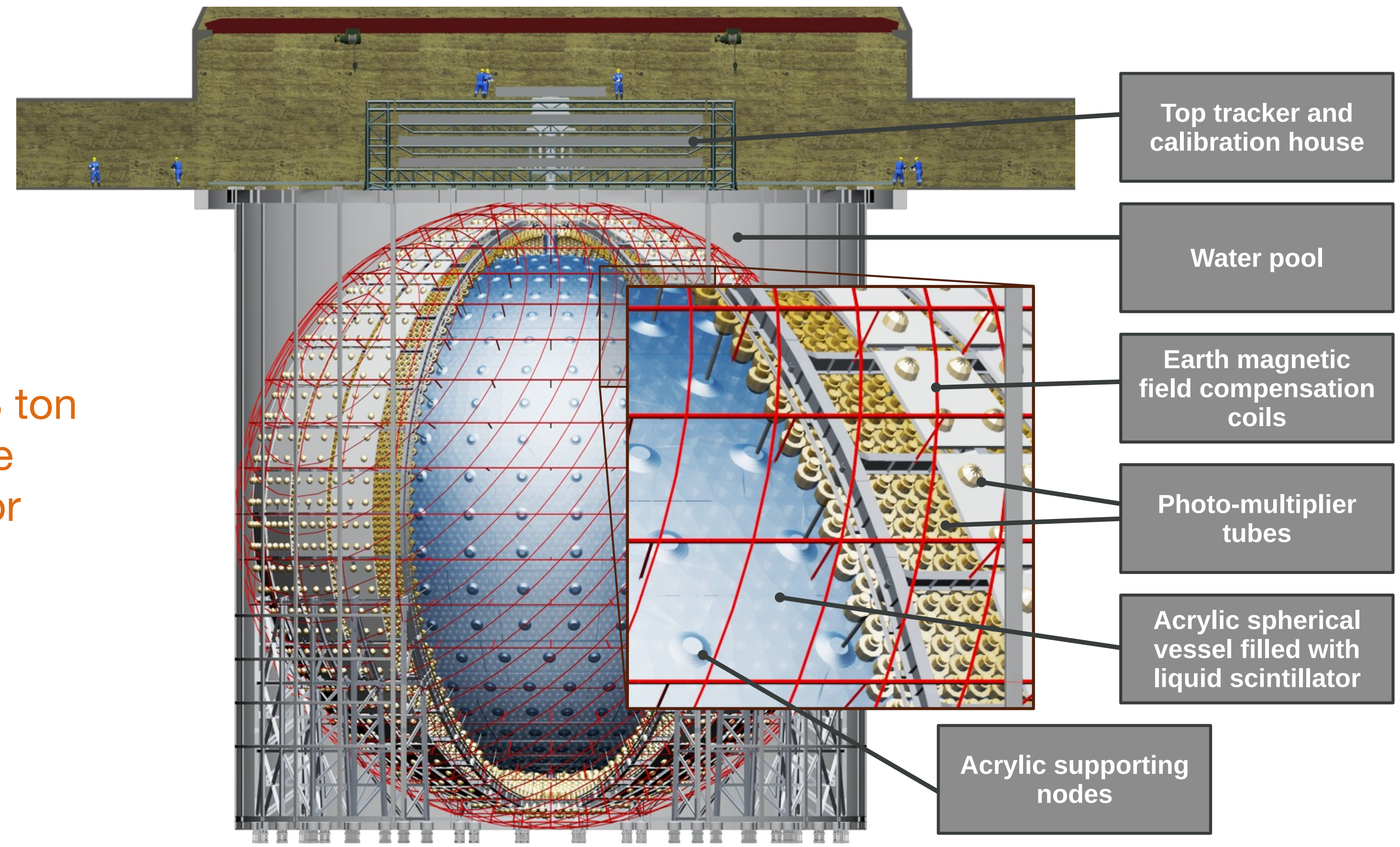
arXiv:2203.07214

The Future

The JUNO Experiment

- There is a large, next-generation reactor neutrino experiment under construction in China: the **J**iangmen **U**nderground **N**eutrino **O**bservatory (JUNO)





- 53 km from 8 reactors in two major nuclear power plants (NPPs)
- 35 m diameter sphere with 20 ktons of liquid scintillator (LS) surrounded by 17,612 large (20-inch) and 25,600 small (3-inch) photomultiplier tubes (PMTs)
- Energy resolution of 3% at 1 MeV

unprecedented for a detector of this type!

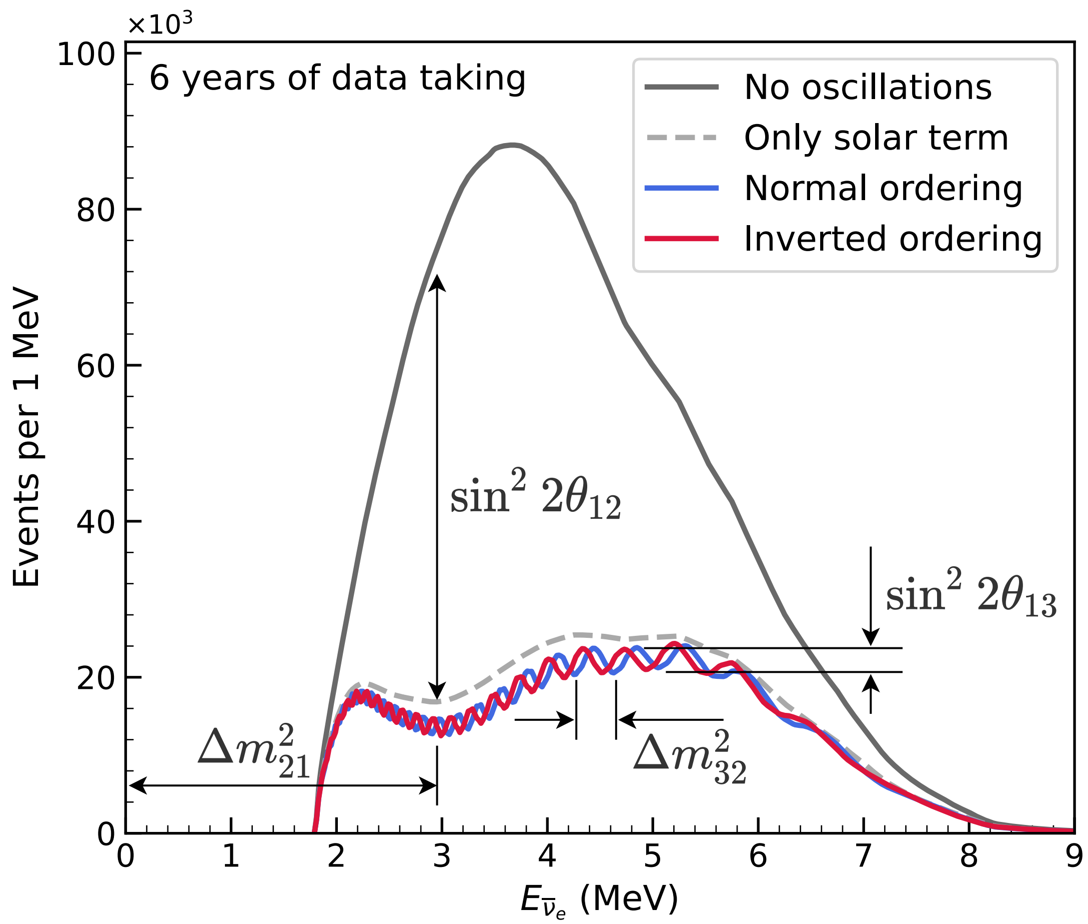
Pushing the Limits

- Most obvious (although not unique) requirement for achieving the target energy resolution: **seeing enough photons**.
  - No approach can singlehandedly provide all the light needed. Have to attack the problem from different angles:

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

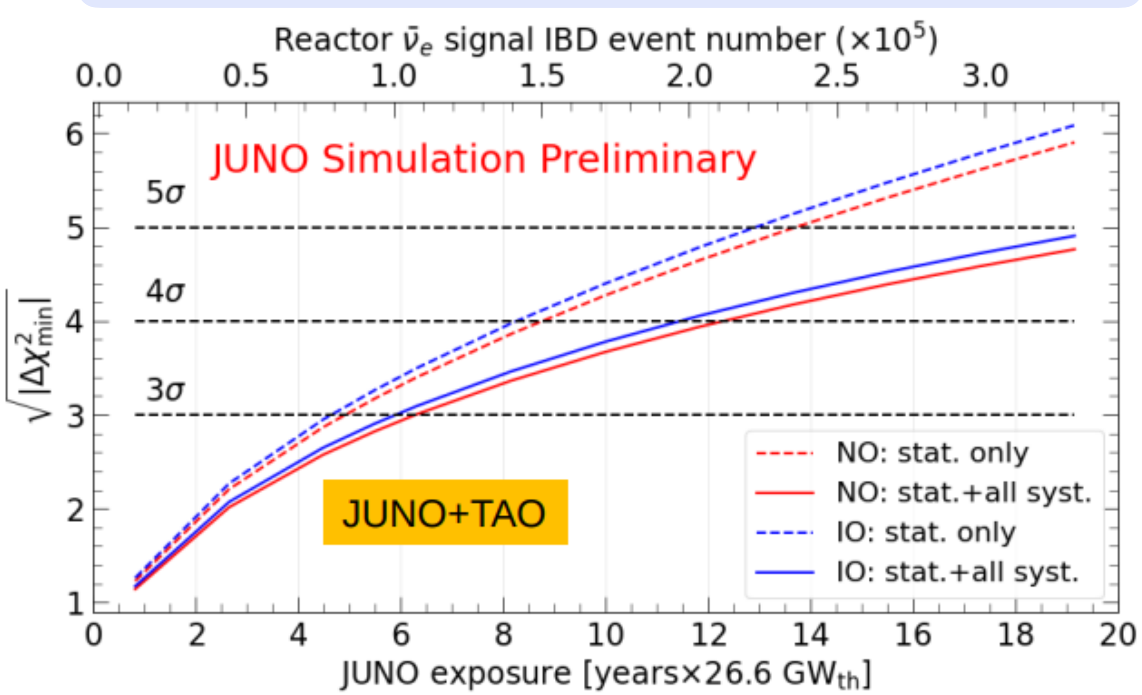
- Also need to control the non-stochastic term of the energy resolution to ≲1%
  - Have a comprehensive calibration program including two complementary types of PMTs

JUNO's Oscillation Goals



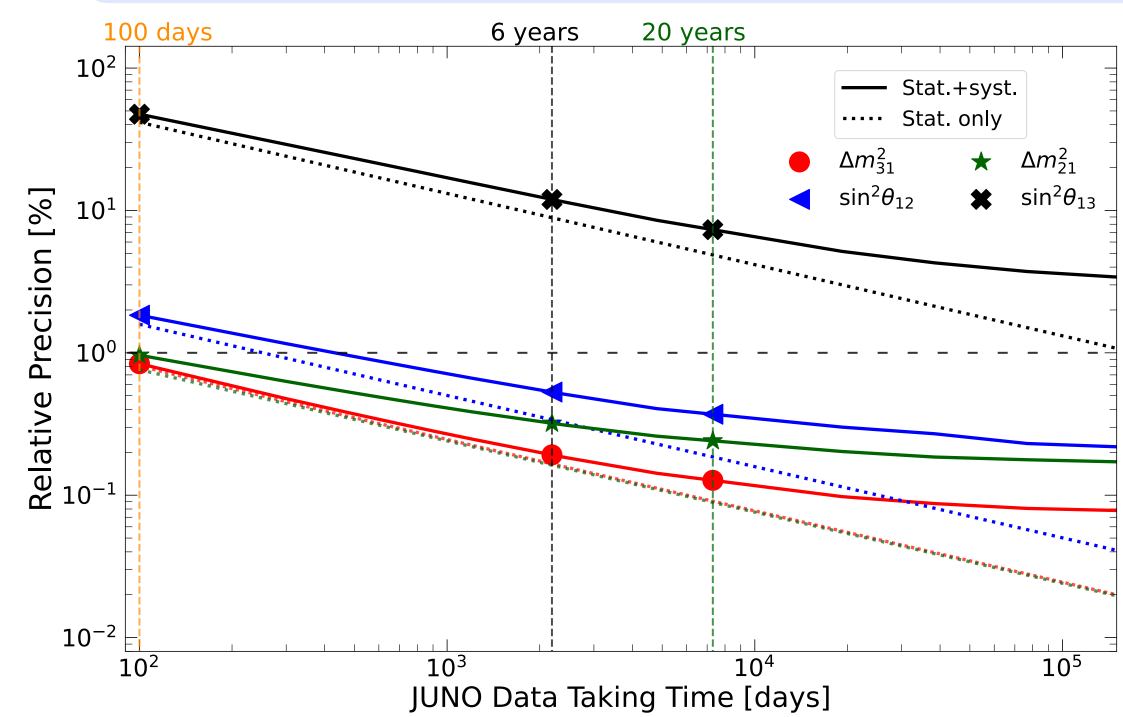
- Why such a good energy resolution? To measure the fine structure in the oscillated reactor neutrino spectrum at 52.5 km
  - Extract the neutrino mass ordering (3σ in ~6 years)
  - Measure four oscillation parameters (≲0.5% precision in 6 years for $\sin^2\theta_{12}$, Δm^2_{21} and Δm^2_{31})

Mass ordering sensitivity vs. time



10.5281/zenodo.6683749

Sensitivity to the osc. parameters vs. time



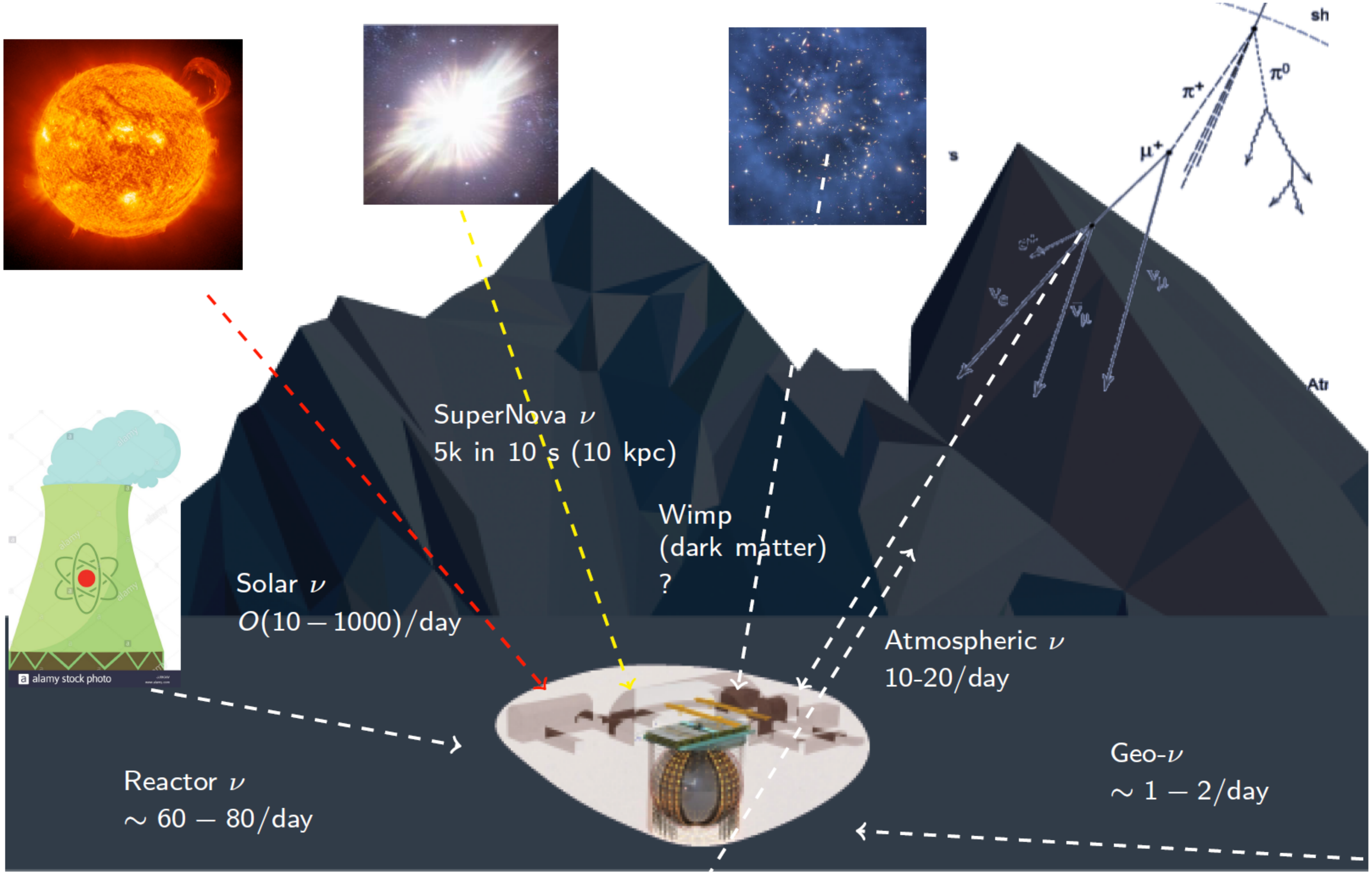
arXiv:2204.13249

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

* from PDG 2020

Other Goals and Status

- JUNO also has a very rich program in other areas:



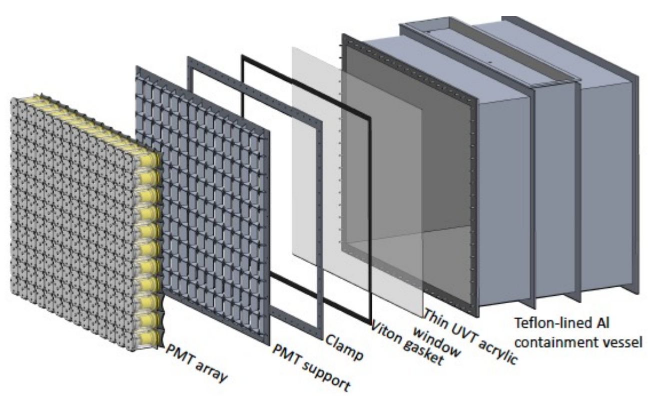
- Detector construction is already ongoing and expected to be completed by 2023

(for more details please see A. Garfagnini's talk on JUNO later today)

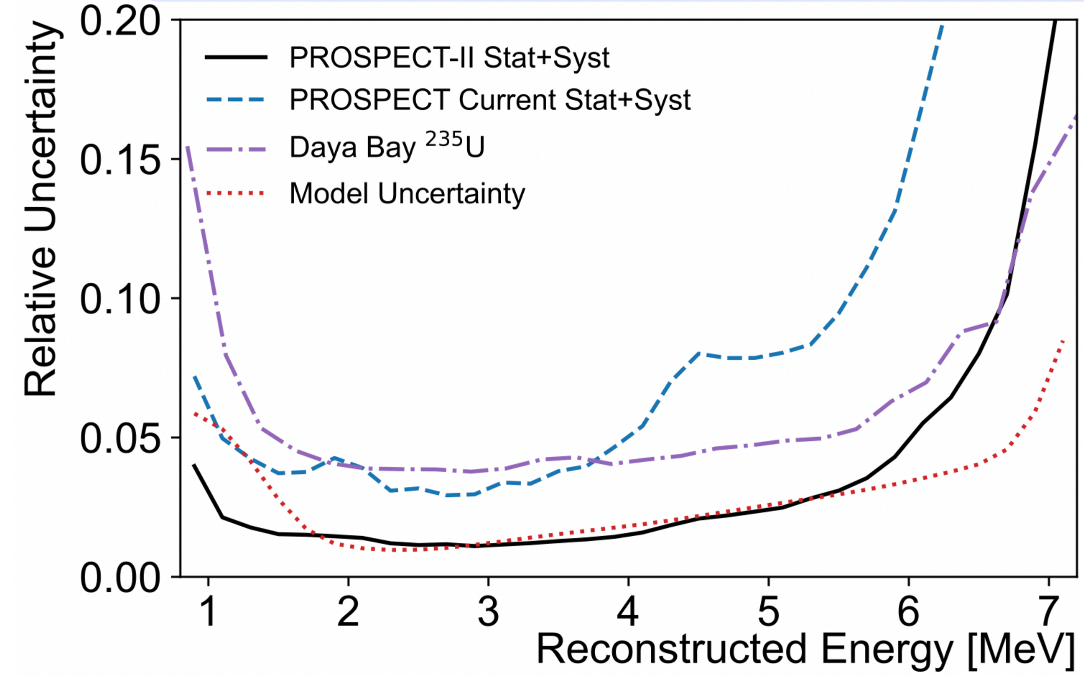
Other Future Experiments

Future SBL Experiments

- There are also at least four new SBL experiments/upgrades in preparation:
  - DANSS and Neutrino-4 are being upgraded
  - There is a proposal for a PROSPECT-II detector:
    - Address technical challenges of PROSPECT-I
    - Able to relocate between HEU and LEU reactors

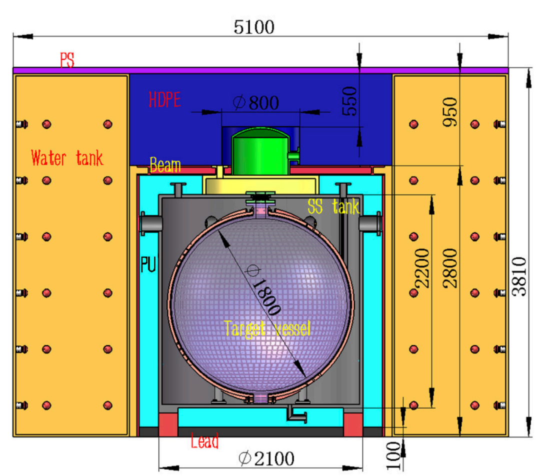


PROSPECT-II ^{235}U spectrum uncertainty

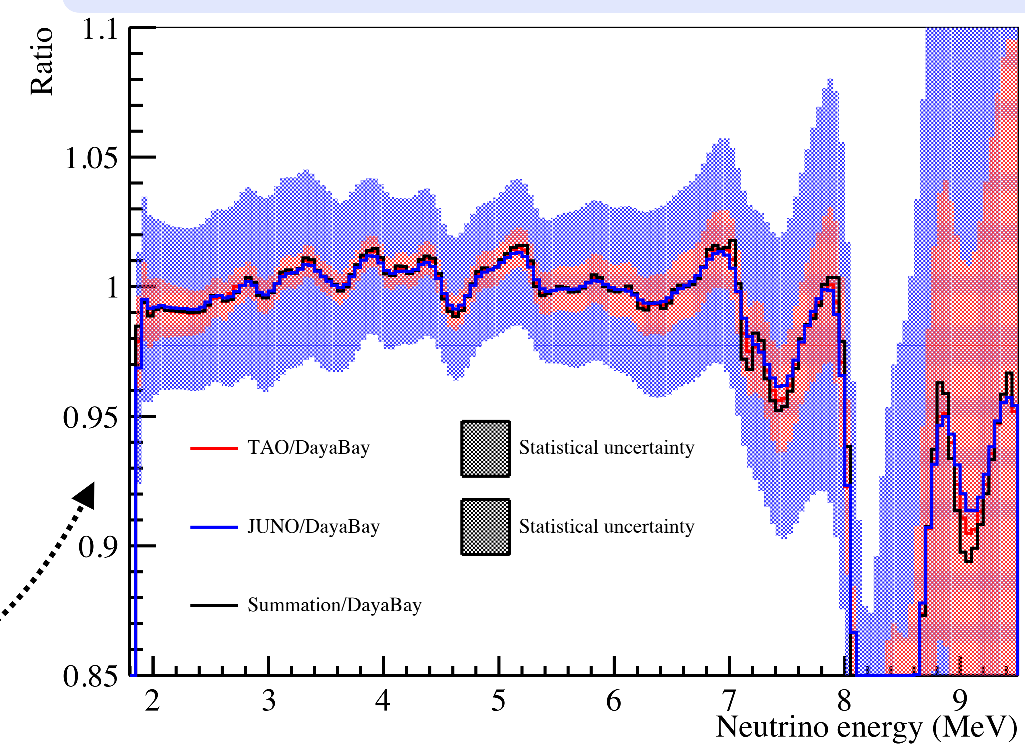


arXiv:2107.03934

  - JUNO will deploy a satellite detector called “TAO” at 30 m from one of the 4.6 GWth Taishan reactors
    - <2% energy resolution @ 1 MeV



TAO’s sensitivity to fine structure in spectrum



arXiv:2005.08745

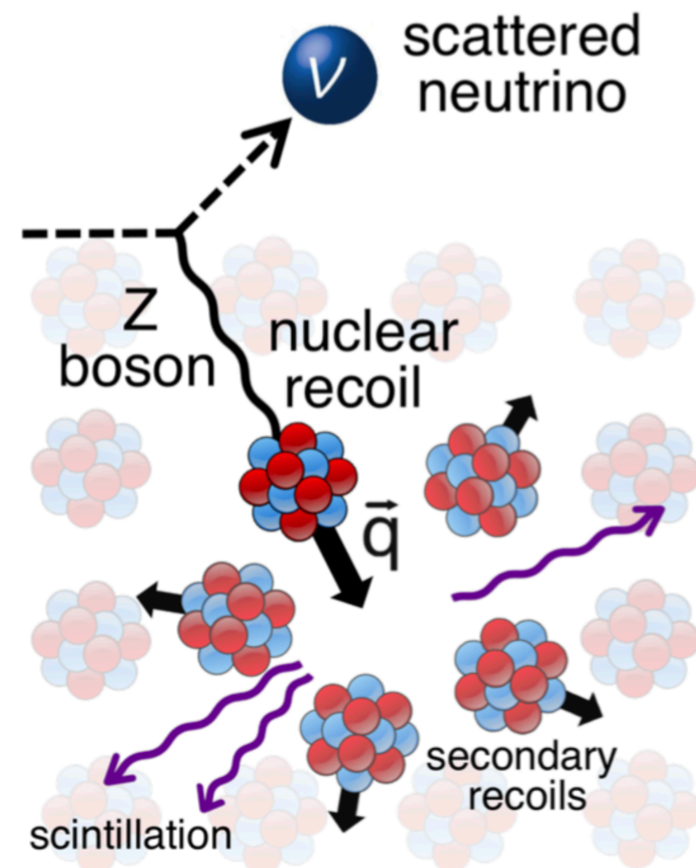
  - All these experiments will search for sterile ν’s
    - TAO and PROSPECT-II will also improve our knowledge of the isotopic yields and spectra
    - TAO will see the fine structure for the first time

CEvNS at Reactors

- An exciting new program using CEvNS at reactors is in its first stages

CEvNS: a neutrino scatters off a nucleus whose nucleons recoil in phase

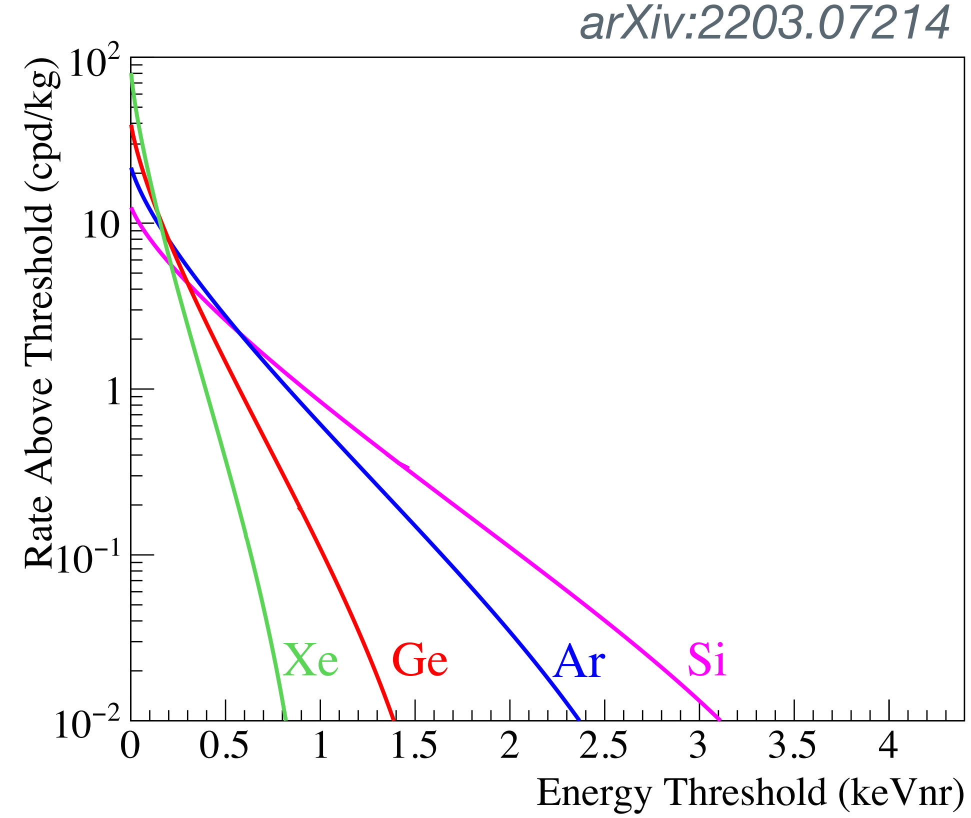
  - Pro: very high cross-section (can be orders of magnitude higher than IBD)
  - Con: very difficult to detect (only signal is low-energy recoiling nucleus)



- Main challenge: achieving a low enough detection threshold (and background)
  - Need $\lesssim$1 keV threshold to have enough statistics

Integrated CEvNS rate expected in detector 25 m away from 1 GW_{th} reactor

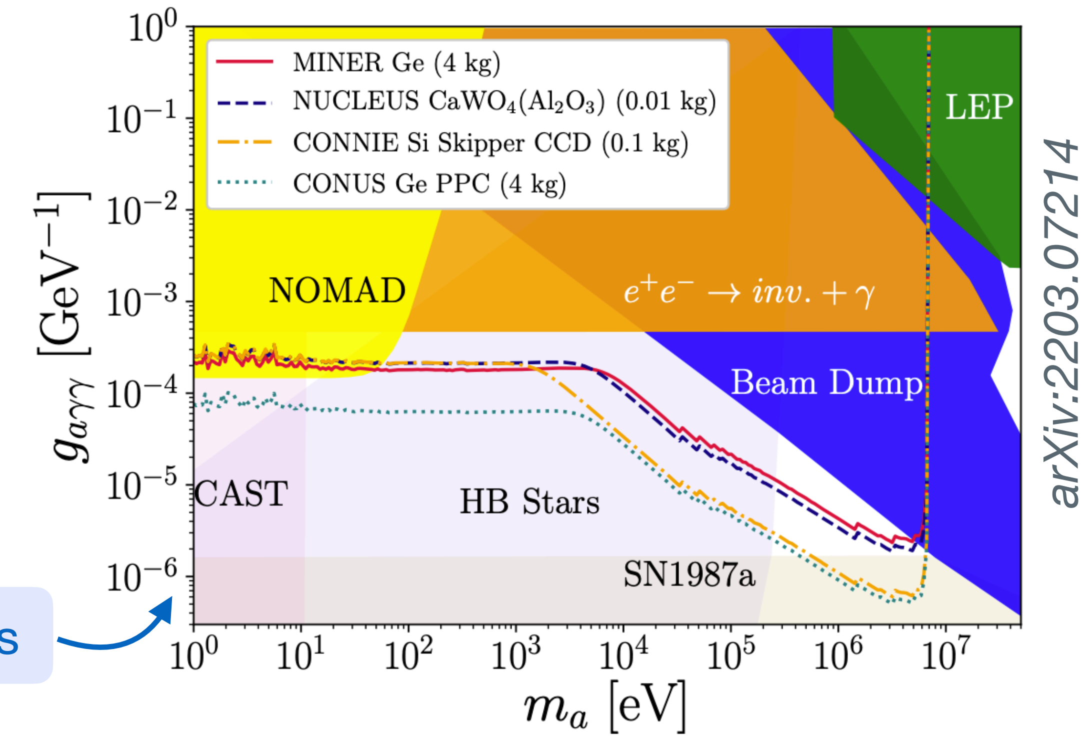
arXiv:2203.07214



CEvNS at Reactors

- Can do great physics:
  - Measure CEvNS cross-sections at low momentum transfer and search for deviations from SM prediction
  - Search for hidden sector particles and interactions
  - Develop small detectors for reactor monitoring

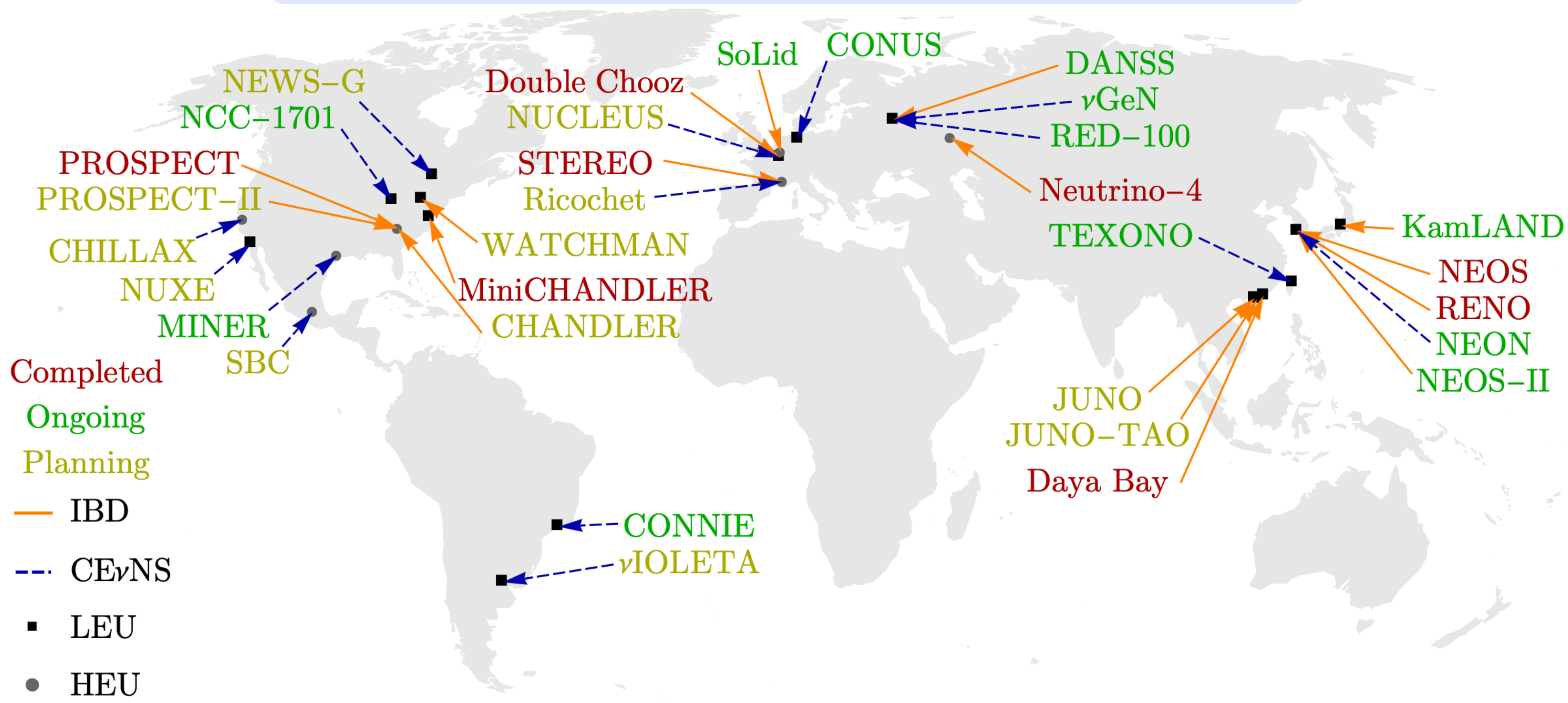
Example: sensitivity to axion searches for different experiments



- The race is on!
  - Vibrant effort in many reactors throughout the world with different technologies
  - First detection of CEvNS from reactors expected soon

(for more details please see J. Hempfling's talk on CONUS later today)

Global Landscape of Reactor Neutrino Experiments

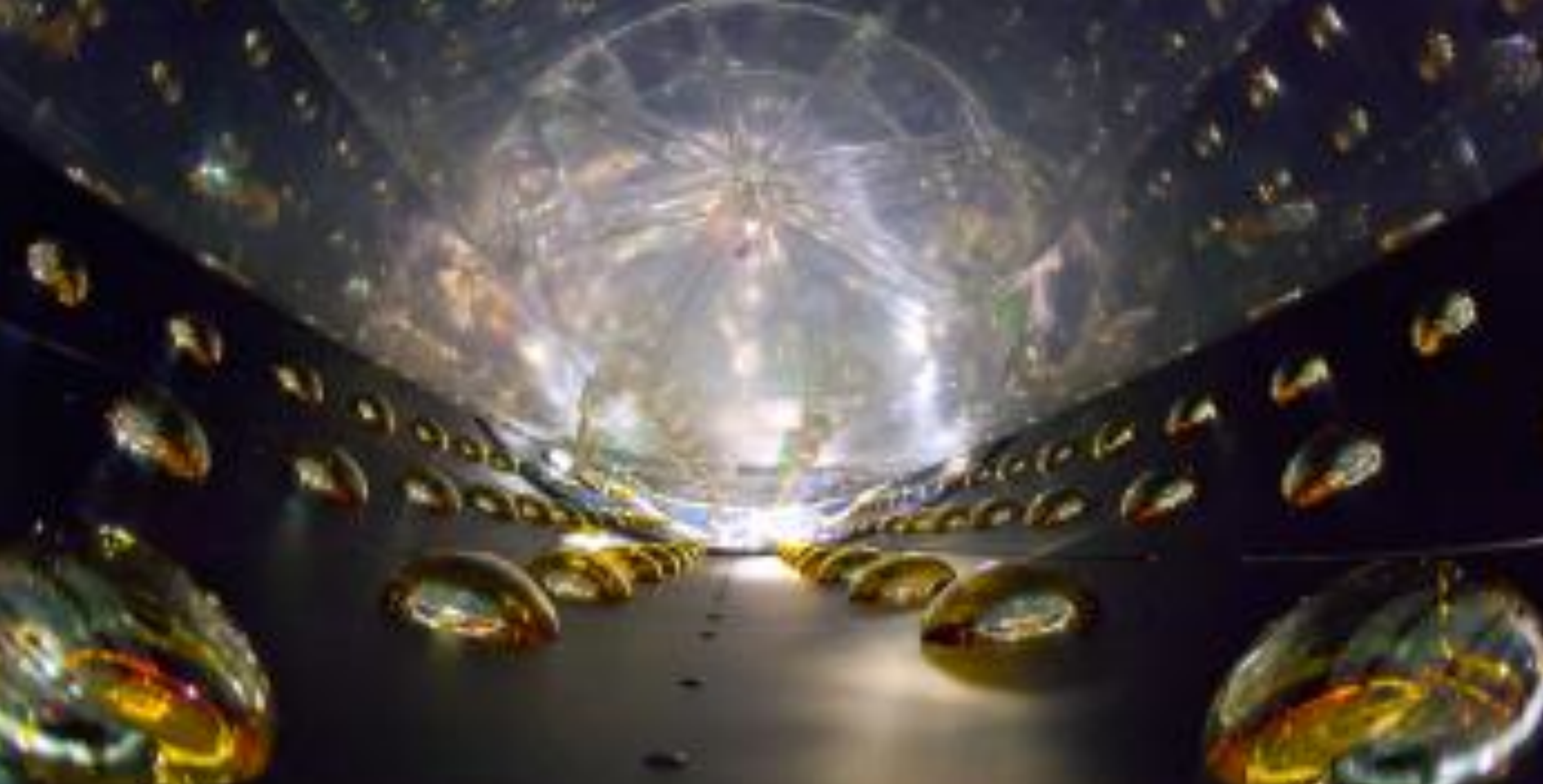


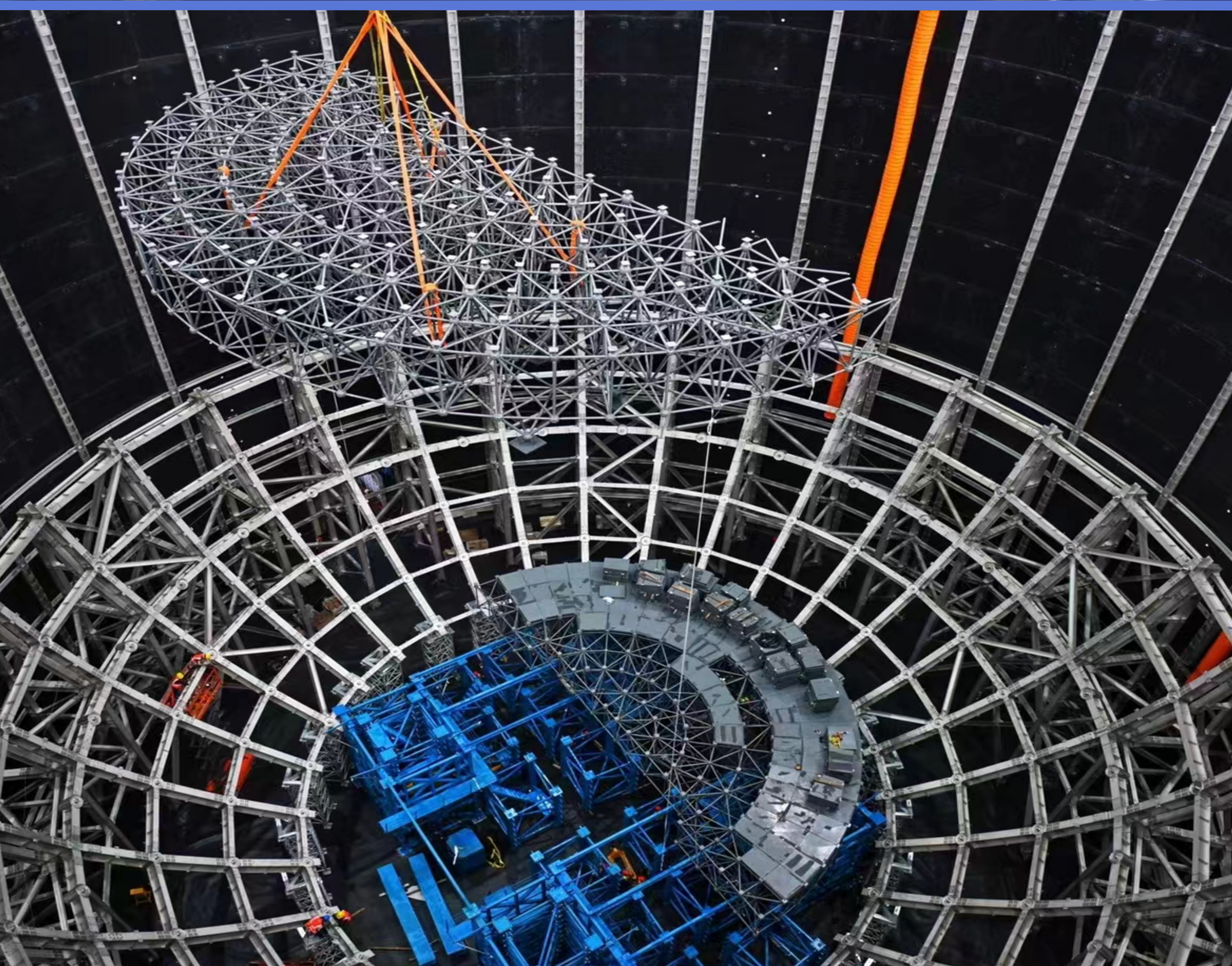
arXiv:2203.07214 and arXiv:2203.07361

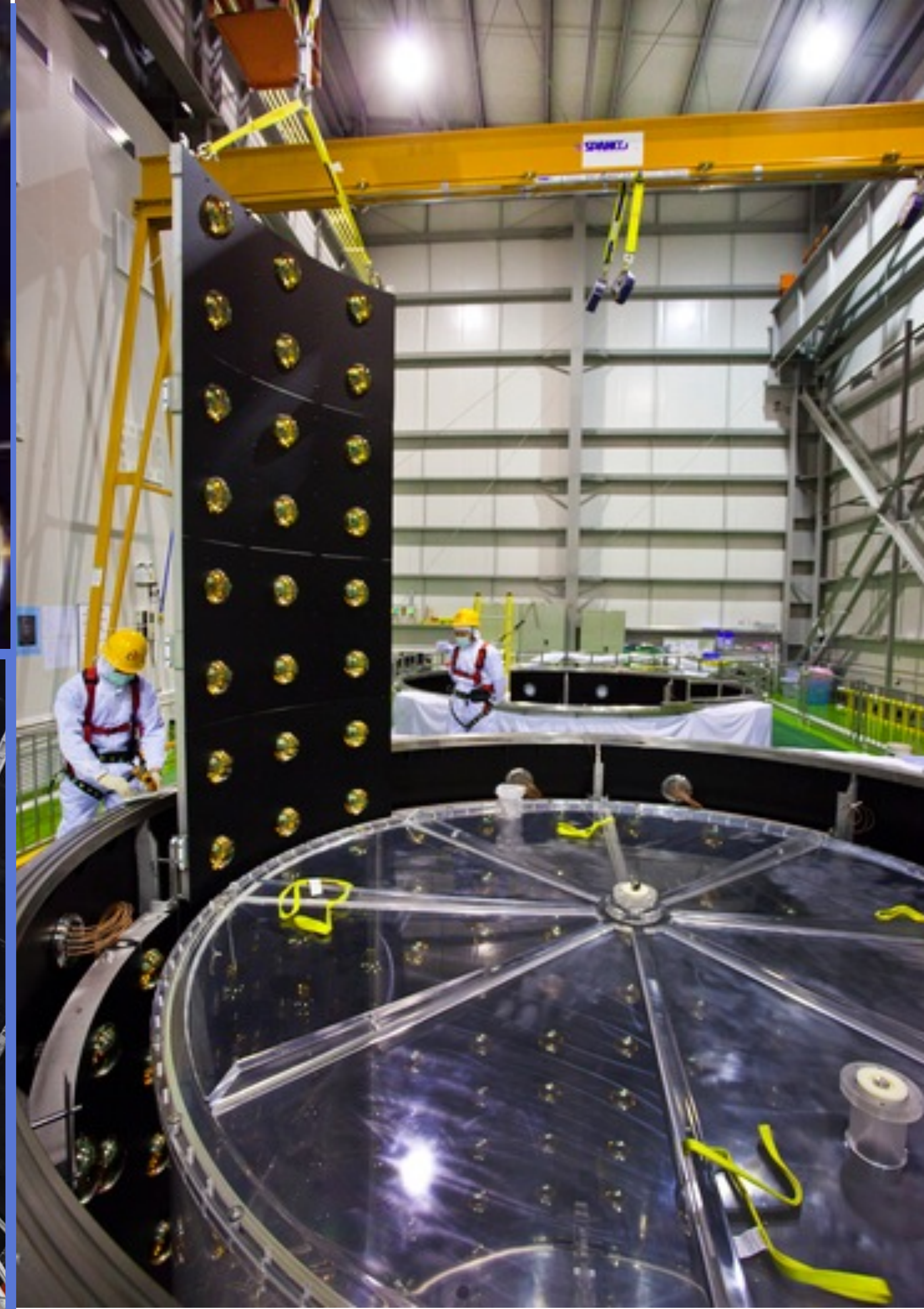
Summary & Conclusions

Summary & Conclusions

- Nuclear reactors are excellent neutrino sources
- Cutting-edge neutrino physics continue to be done with reactor neutrinos:
  - Leading precision in oscillation parameters, searches for sterile neutrinos, high-precision measurements of reactor antineutrino flux and spectral shape, among others.
- A bright future is on the horizon for this subfield of neutrino physics:
  - A vibrant next-generation experimental program is under preparation that includes a very large multi-purpose detector, new/upgraded SBL experiments, and a new window to search for physics beyond the Standard Model
  - Expect some exciting results and, hopefully, some surprises







Thank you for your attention!