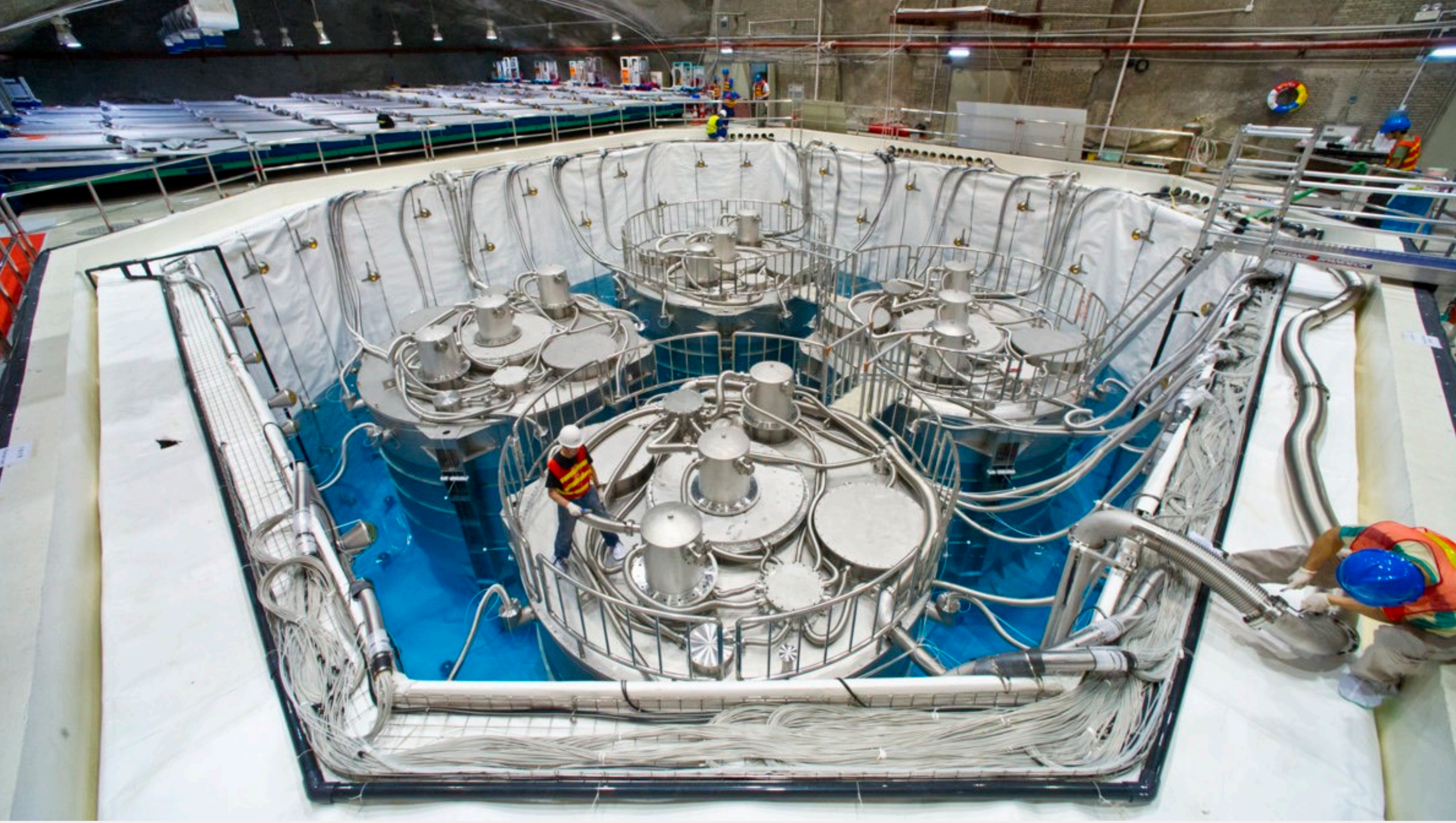

Overview of Recent Results from Daya Bay

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University of California at Irvine

***on behalf of the Daya Bay collaboration**

NuFact 2021 - Cagliari, Italy

Outline

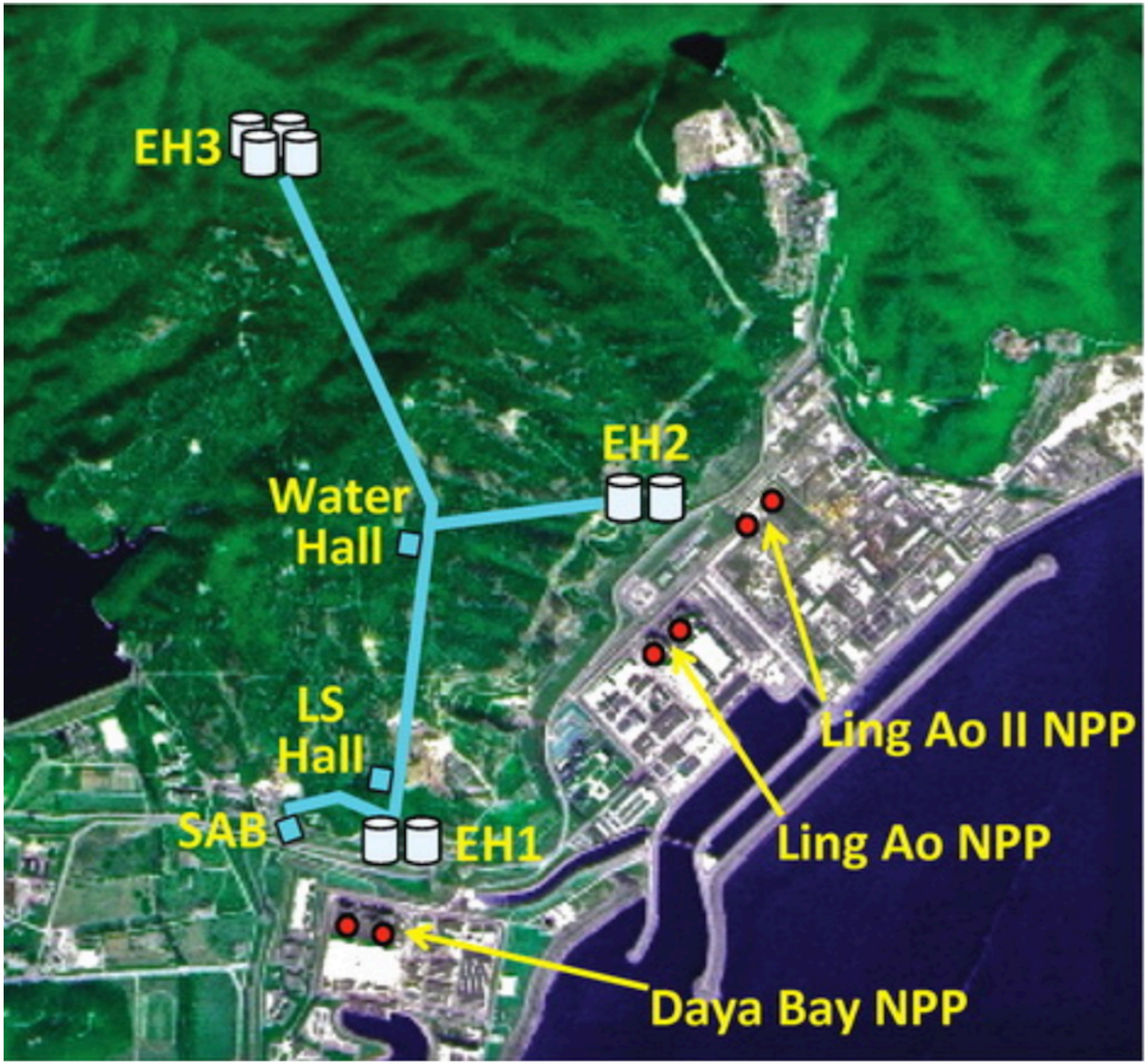
- The Daya Bay Experiment
- Recent Results
  - Latest oscillation measurement
  - Search for sterile neutrino mixing
  - Characterization of reactor antineutrino emission
- Summary & Conclusions

Daya Bay's Setup

- 8 identically designed detectors distributed in three underground experimental halls (EHs) beside the Daya Bay Power Plant in China

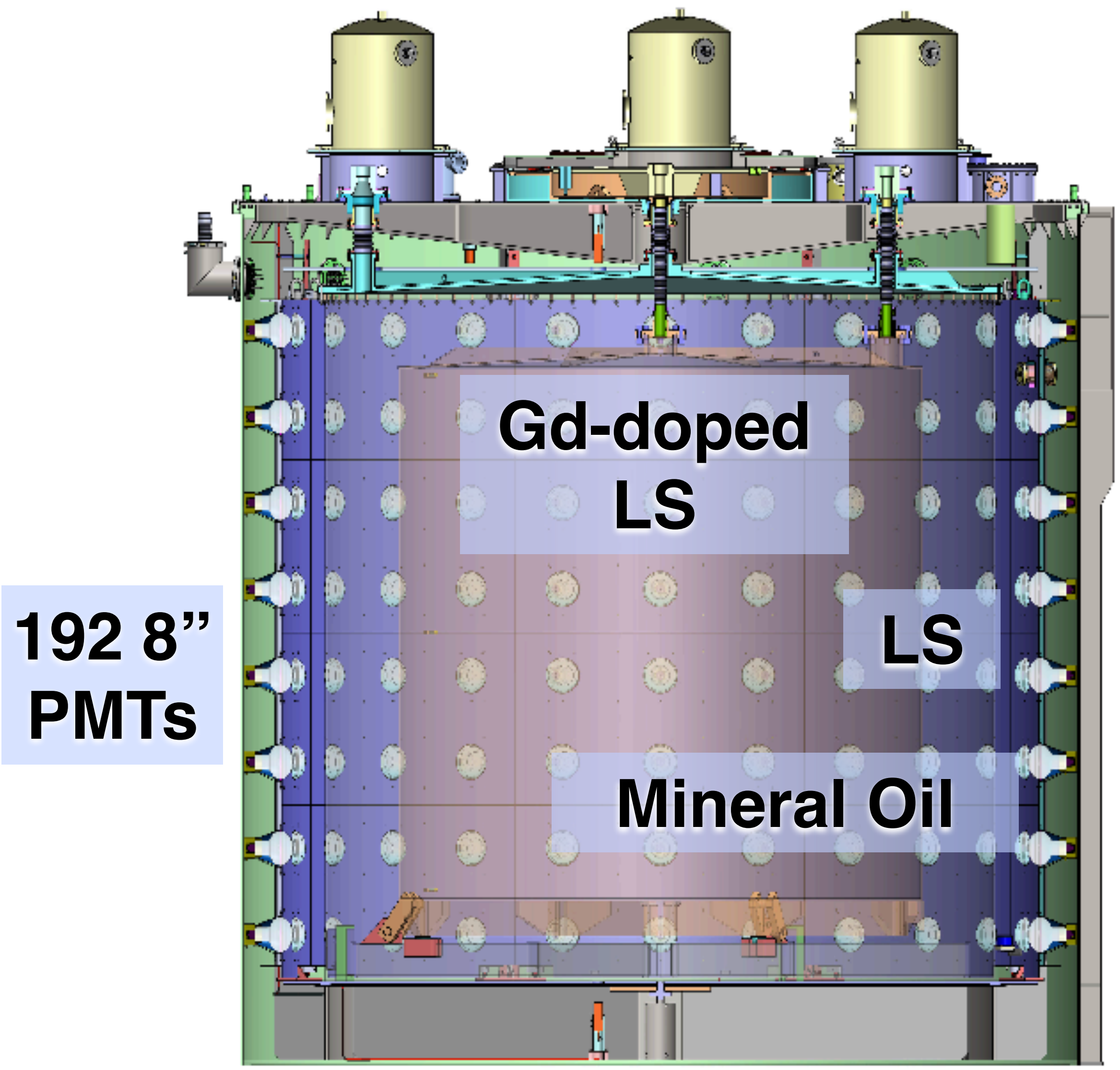
Six 2.9 GW_{th} reactors distributed in 3 Nuclear Power Plants (NPPs)

Among the most powerful nuclear power complexes in the world!



Antineutrino Detectors

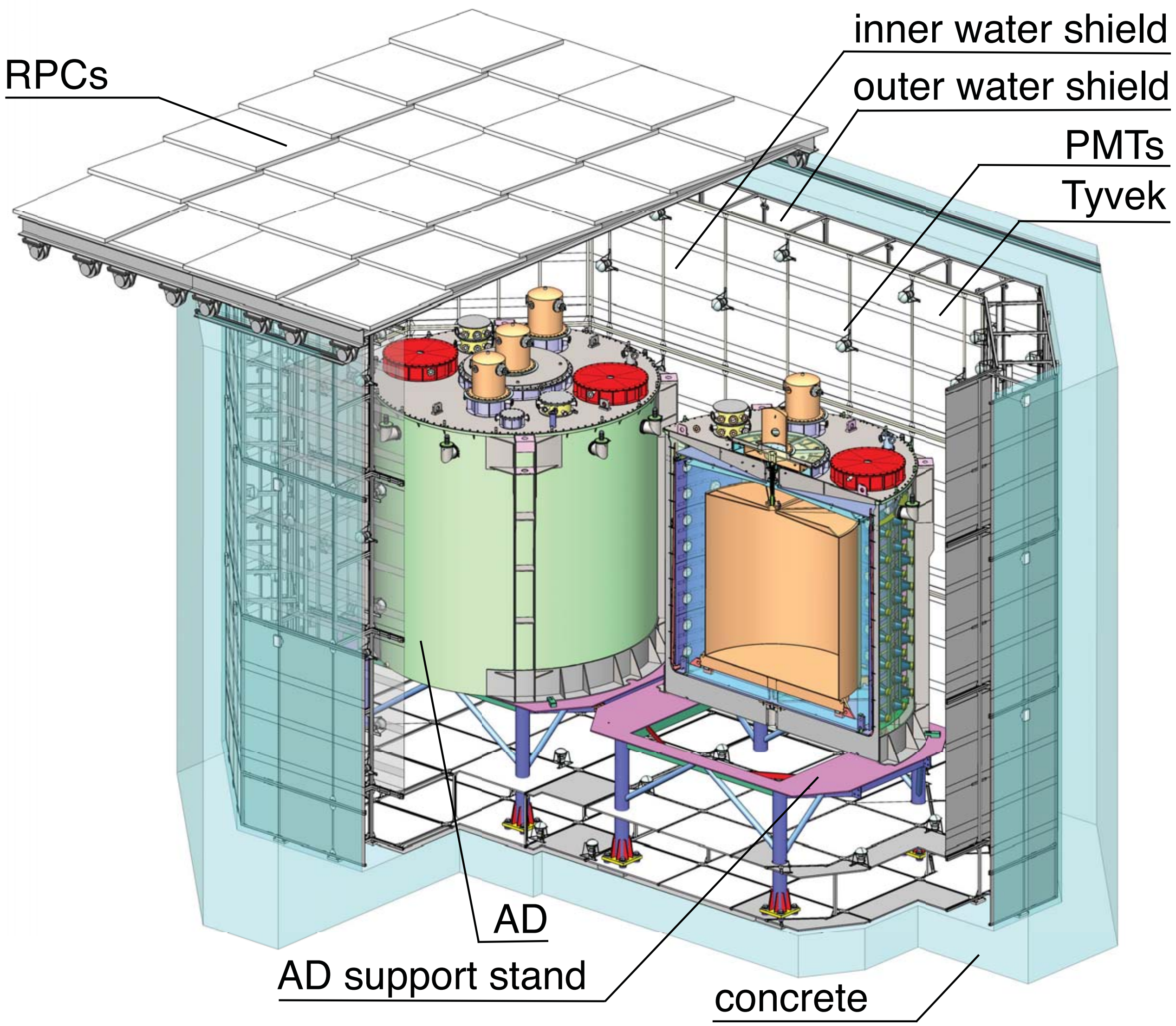
- Antineutrinos are detected via Inverse Beta Decay (IBD): $\overline{\nu}_e + p \rightarrow e^+ + n$
- The antineutrino detectors (ADs) are "three-zone" cylindrical modules immersed in water pools:



Energy resolution:

$\sigma_E/E \cong 8.5\%/\sqrt{E(\text{MeV})}$

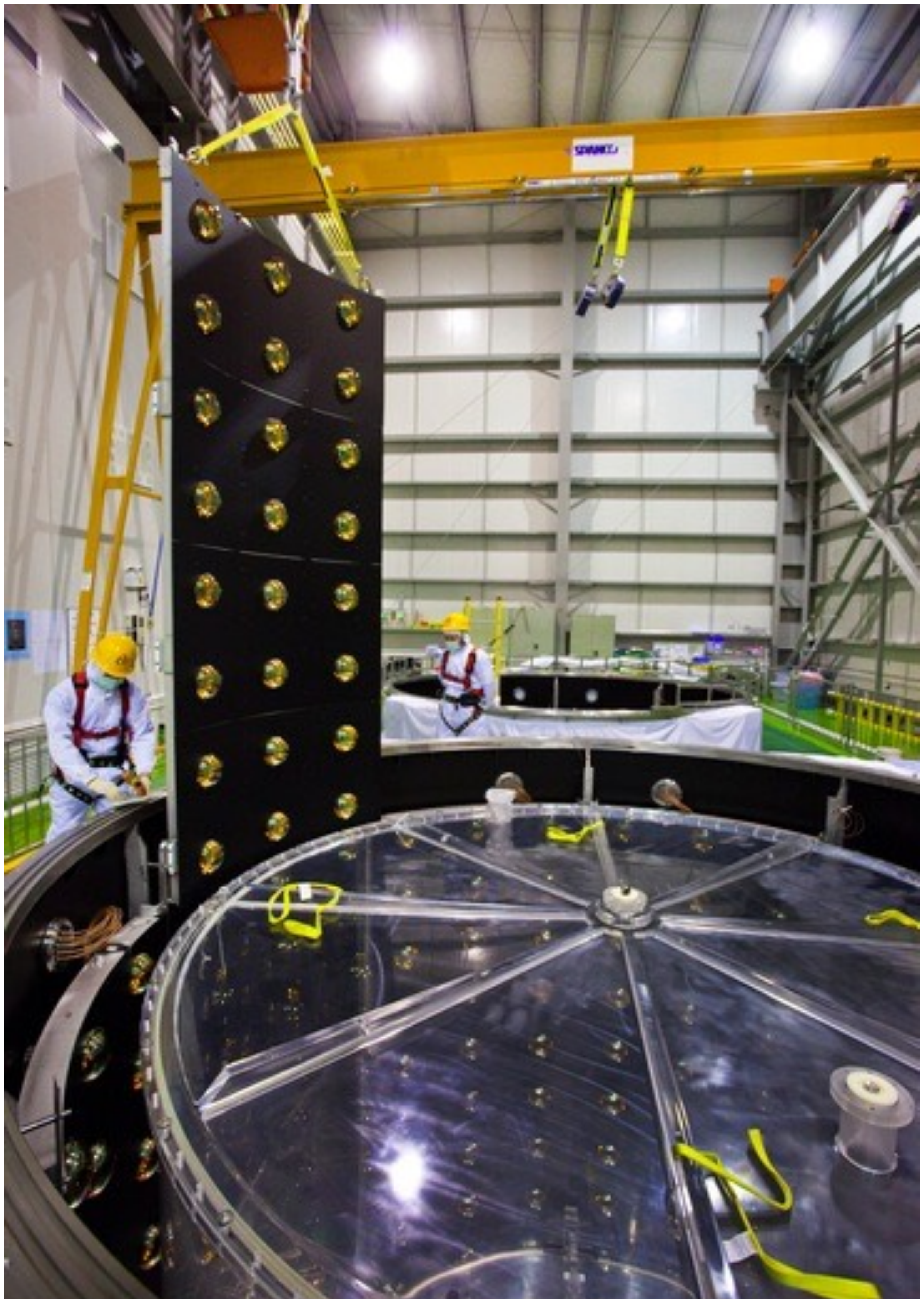
NIM A 811, 133 (2016)



Double purpose: shield the ADs and veto cosmic ray muons

NIM A 773, 8 (2015)

A Selection of Pictures



IBD Data Set

- Our latest oscillation results use **1958 days of data**
- IBD Selection strategy:

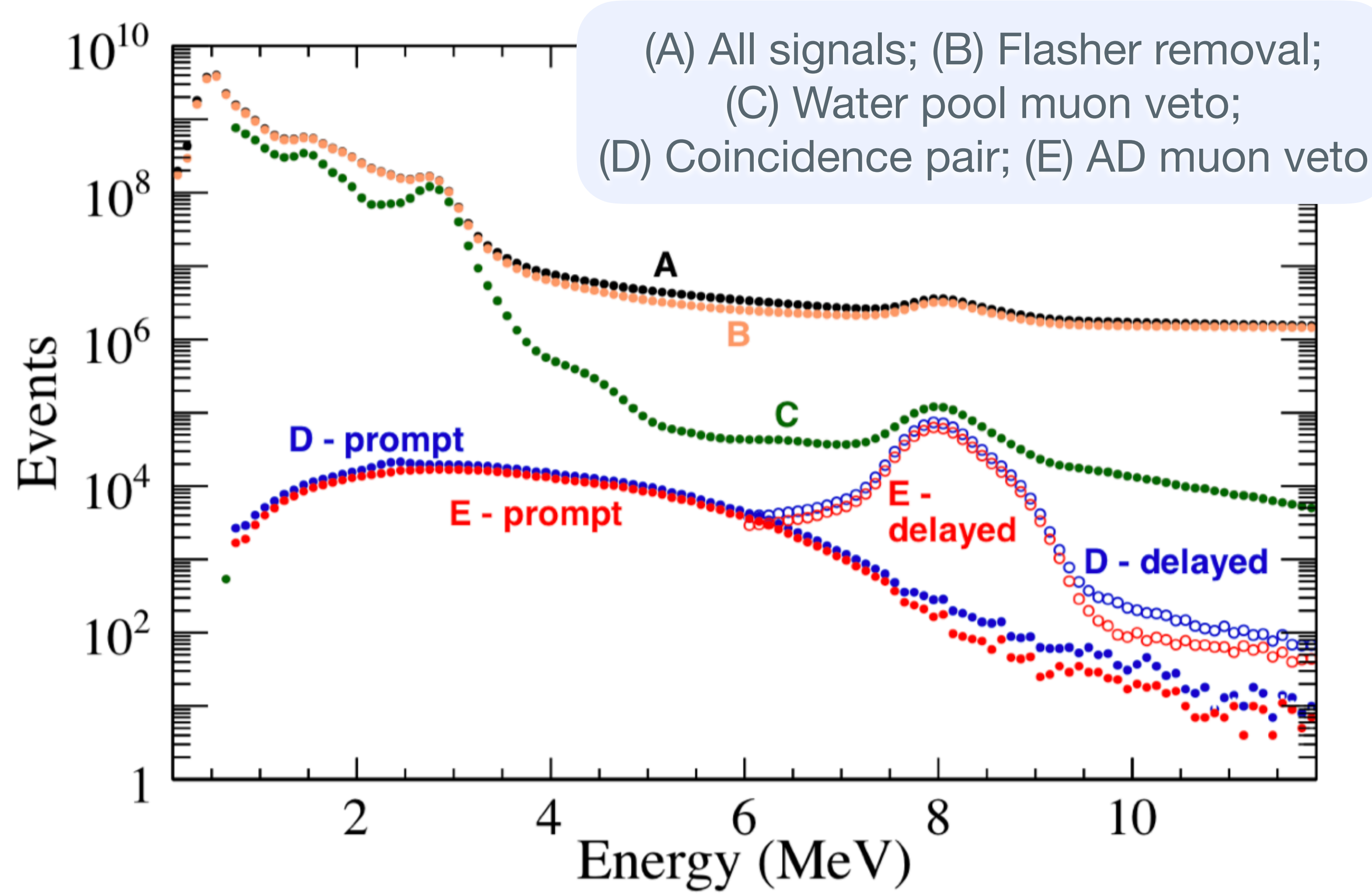
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

Select unambiguous prompt-delayed pairs with right energies and time separation, not in coincidence with a muon

1 μs < Δt < 200 μs

0.7 MeV < E_{prompt} < 12 MeV

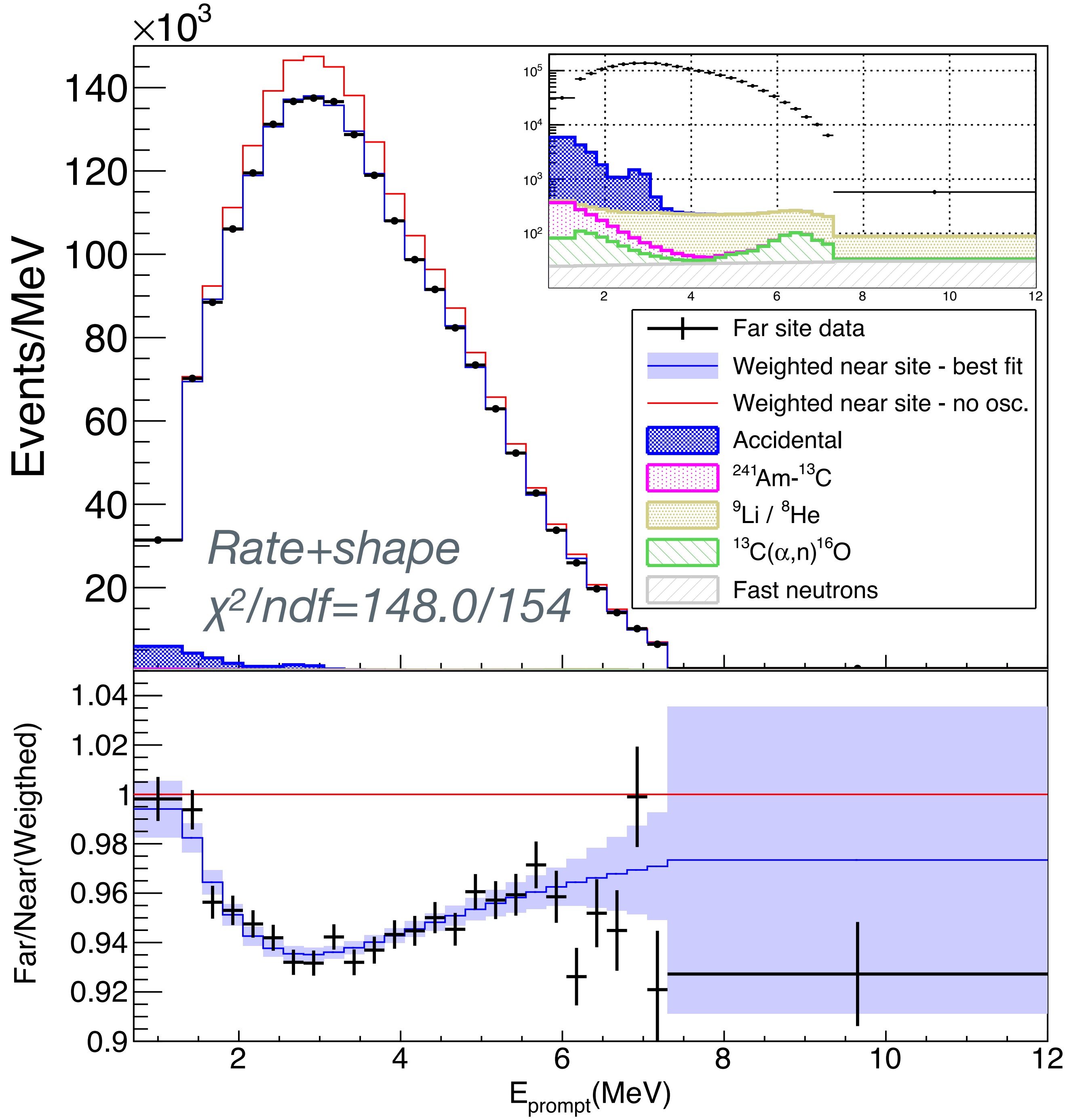
6 MeV < $E_{delayed}$ < 12 MeV



- Some highlights:
  - More than **3.9 million antineutrino interactions**
  - **< 2% background** in all halls
  - Relative efficiency uncertainty: 0.13% (all ADs)

Oscillation Results with 1958 Days

- See a clear rate and shape distortion that fits very well to the 3-neutrino hypothesis:



From rate and shape distortion can simultaneously measure $\sin^2 2\theta_{13}$ and $|\Delta m^2_{32}|$ to **3.4%** and **2.8%** respectively

$$\sin^2 2\theta_{13} = 0.0856 \pm 0.0029$$

$$\Delta m^2_{32} = (2.471^{+0.068}_{-0.070}) \times 10^{-3}\ \text{eV}^2\ (\text{NO})$$

$$\Delta m^2_{32} = -(2.575^{+0.068}_{-0.070}) \times 10^{-3}\ \text{eV}^2\ (\text{IO})$$

The statistical uncertainty contributes about 60% (50%) of the total θ_{13} (Δm^2) uncertainty.

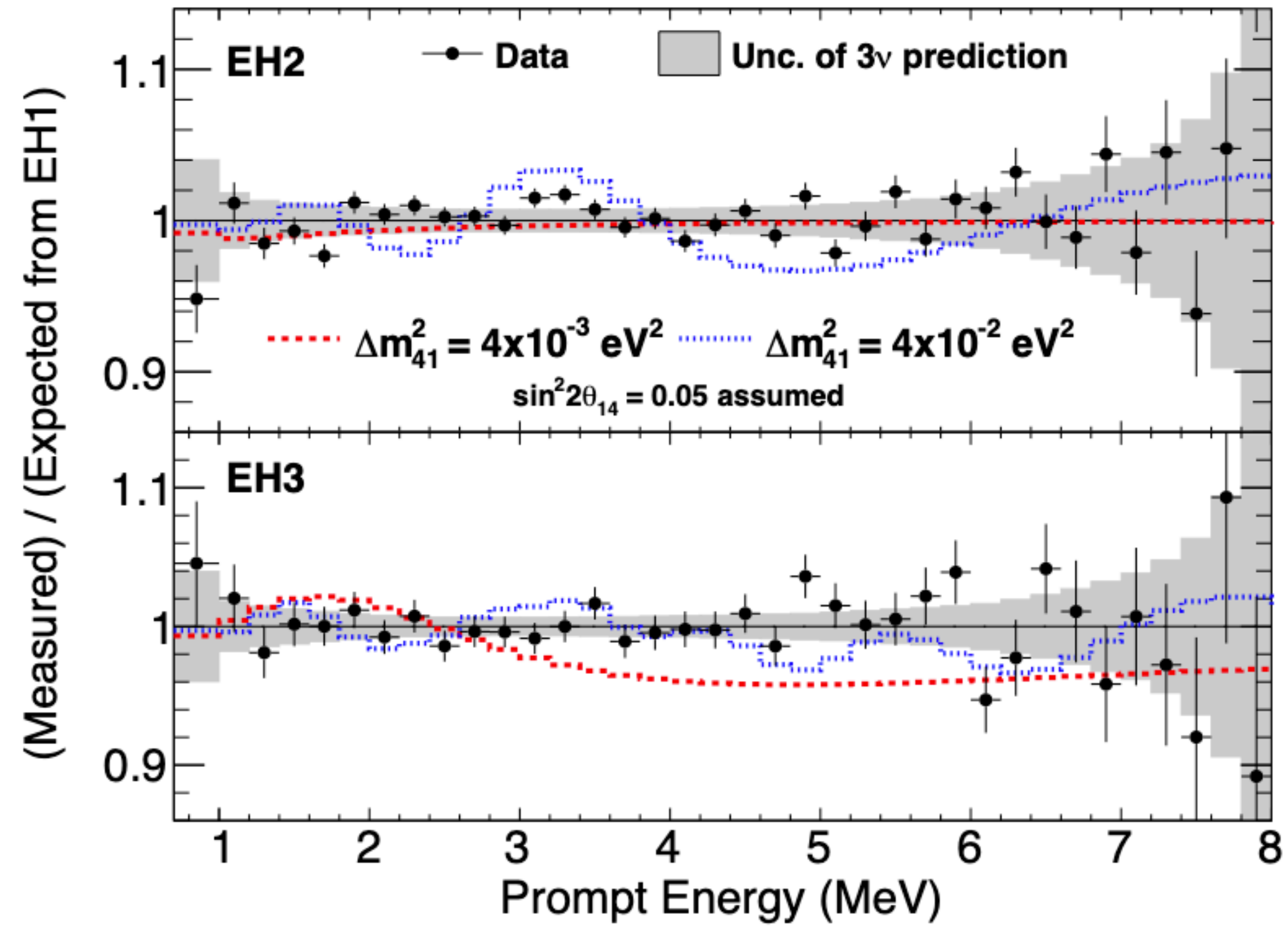
PRL 121, 241805 (2018)

Search for Sterile Neutrinos

- Daya Bay is also an excellent experiment to search for sterile neutrino mixing

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

$$P_{\bar{\nu}_e \to \bar{\nu}_e} \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{31} L}{4E} - \sin^2 2\theta_{14} \sin^2 \frac{\Delta m^2_{41} L}{4E}$$



- Combine with Bugey-3 and MINOS & MINOS+ to directly probe $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ observations from LSND & MiniBooNE:

For LSND & MiniBooNE: $$P^{SBL}_{\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e} = 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

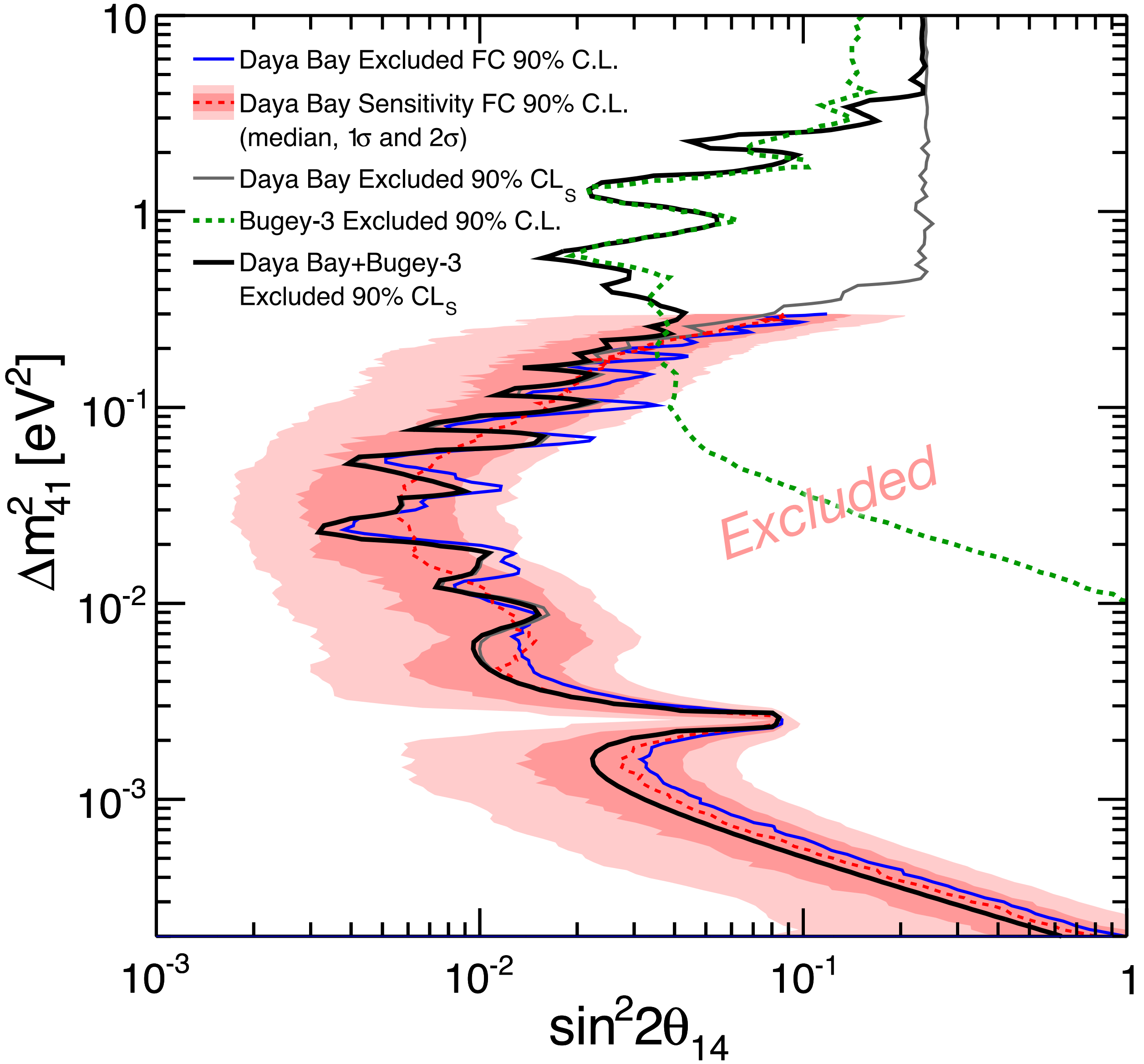
where: $$4|U_{e4}|^2|U_{\mu 4}|^2 = \sin^2 2\theta_{14} \sin^2 \theta_{24} \equiv \sin^2 2\theta_{\mu e}$$

Constrained by $\bar{\nu}_e$ disappearance (Daya Bay and Bugey-3)

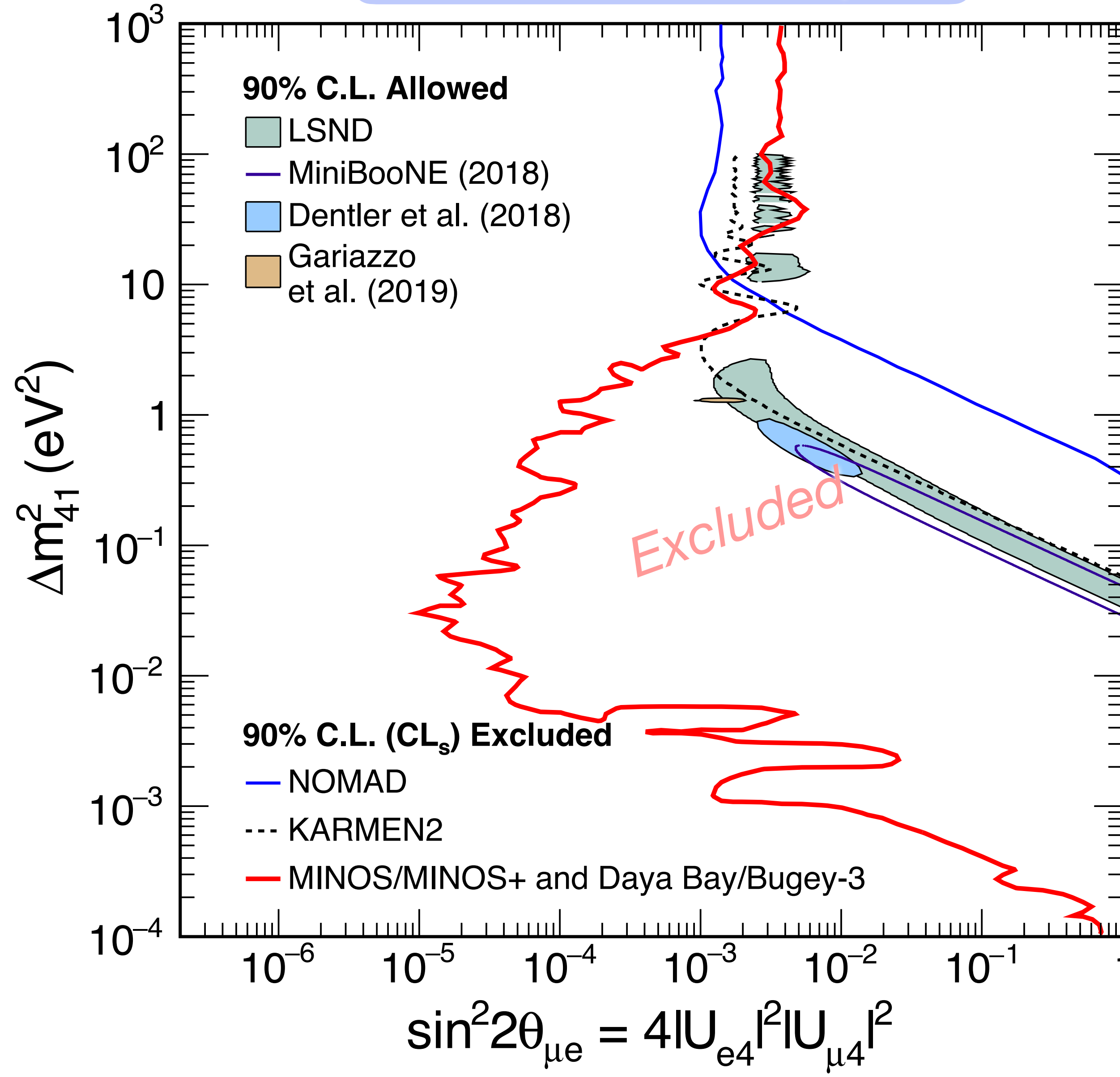
Constrained by $\overset{(-)}{\nu}_\mu$ disappearance (MINOS & MINOS+)

Sterile Neutrino Search Results

$\bar{\nu}_e$ disappearance
(Bugey-3 & Daya Bay)



Combined Results
(Bugey-3, Daya Bay,
MINOS & MINOS+)



PRL 125,071801 (2020)

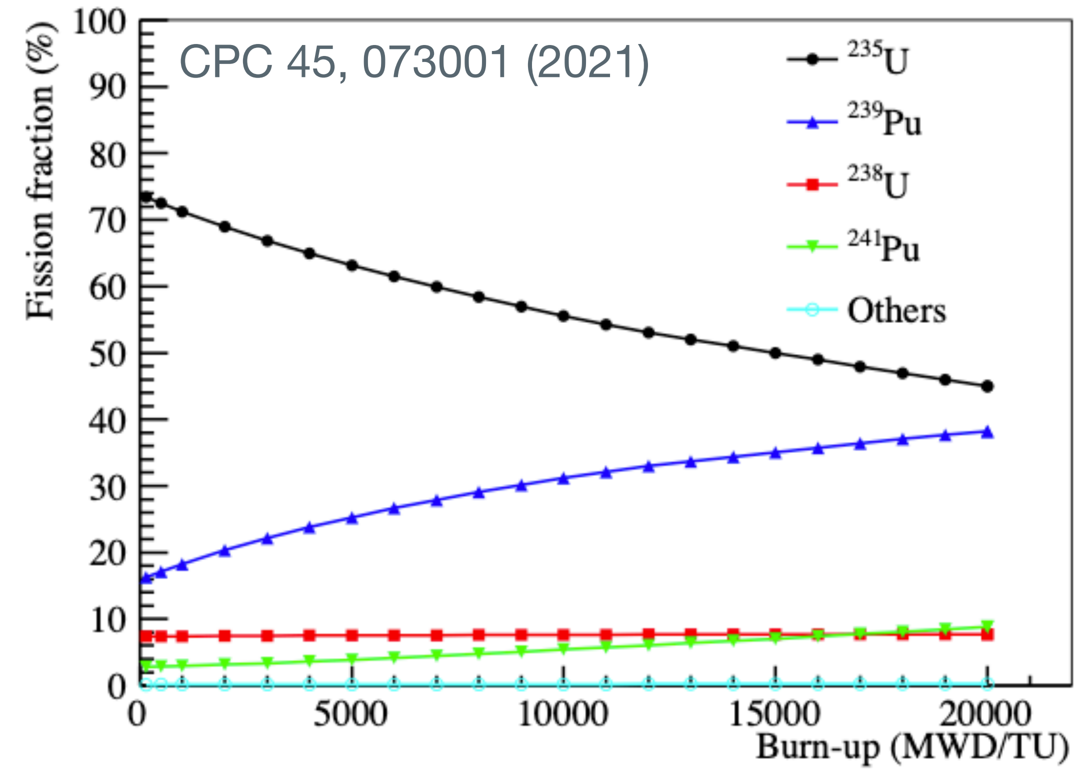
Most stringent limits on $\theta_{\mu e}$ to date over 5 orders of magnitude in Δm^2_{41}

(essentially rule out the "sterile neutrino-only" interpretation of anomalous results)

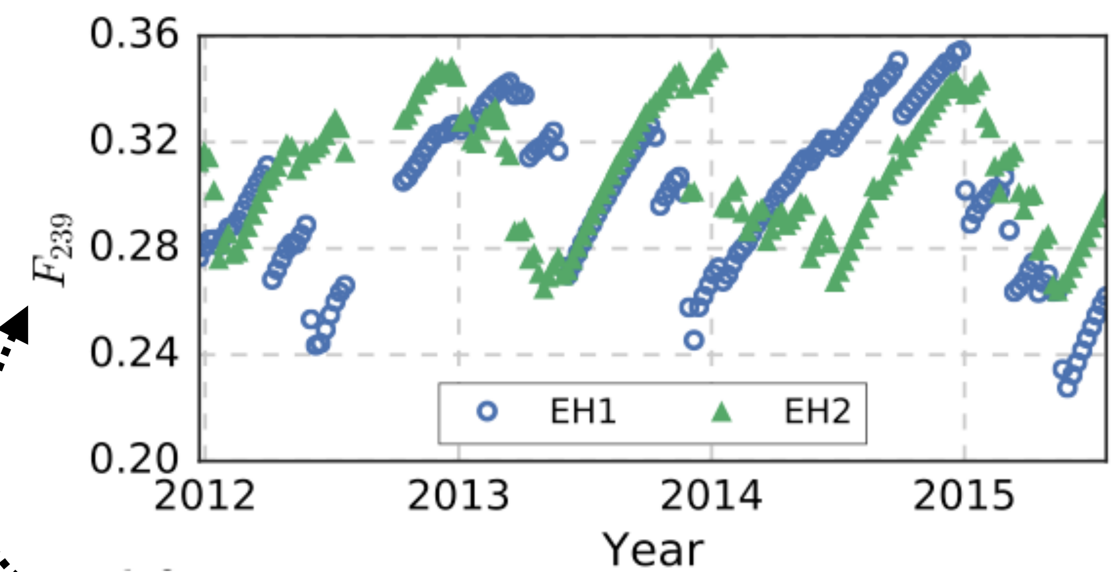
Reminder: Reactor Antineutrino Emission

- Around 99.7% of reactor antineutrinos are produced from the fission of 4 isotopes: ^{235}U, ^{239}Pu, ^{238}U and ^{241}Pu
  - Yield (basically $\bar{\nu}_e$'s per fission) and shape vary from isotope to isotope
  - Therefore, $\bar{\nu}_e$ rate and shape depends on fission fractions (percentage of fissions from a given isotope)
- Two methods to predict the $\bar{\nu}$ rate and spectral shape:
  - Ab-initio method:
    - Use fission yields, Q values and decay branching ratios from nuclear databases
  - Conversion method (preferred):
    - Use measured beta spectra from thermal-neutron induced fission (^{235}U, ^{239}Pu, ^{241}Pu) performed at ILL in the 1980s
    - Latest implementation is the so-called Huber+Mueller (HM) model

Evolution of fission fractions with burn-up:



^{239}Pu effective fission fraction at Daya Bay:

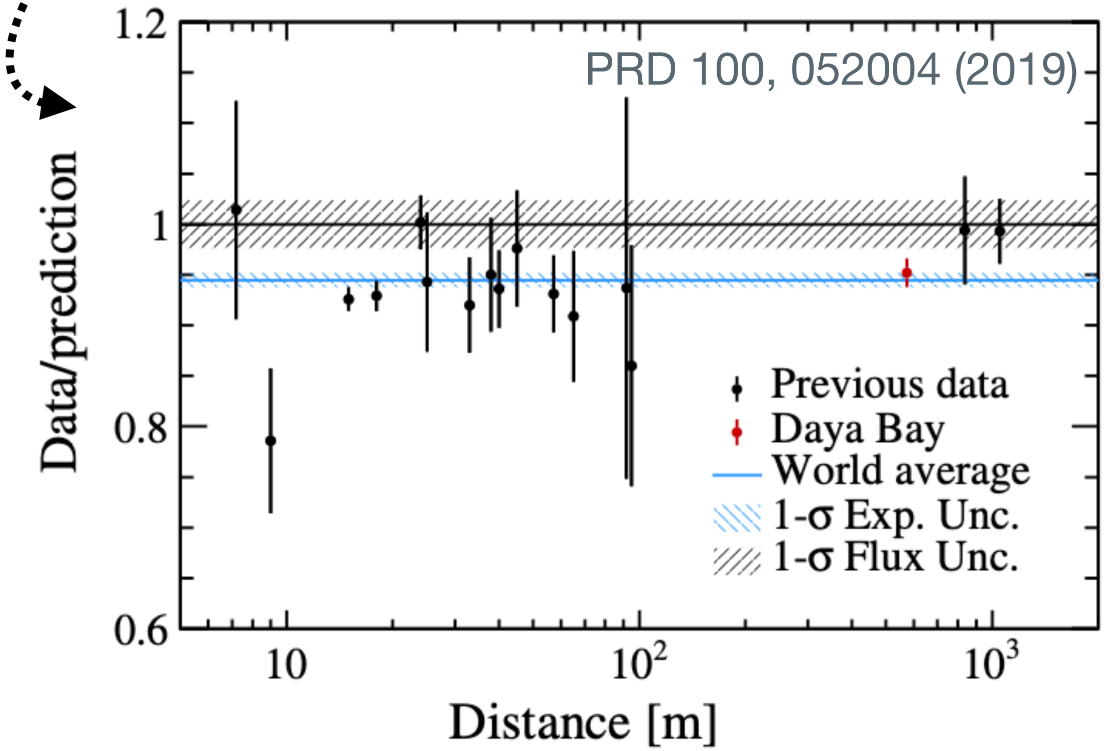


F_i = effective fission fraction for isotope i

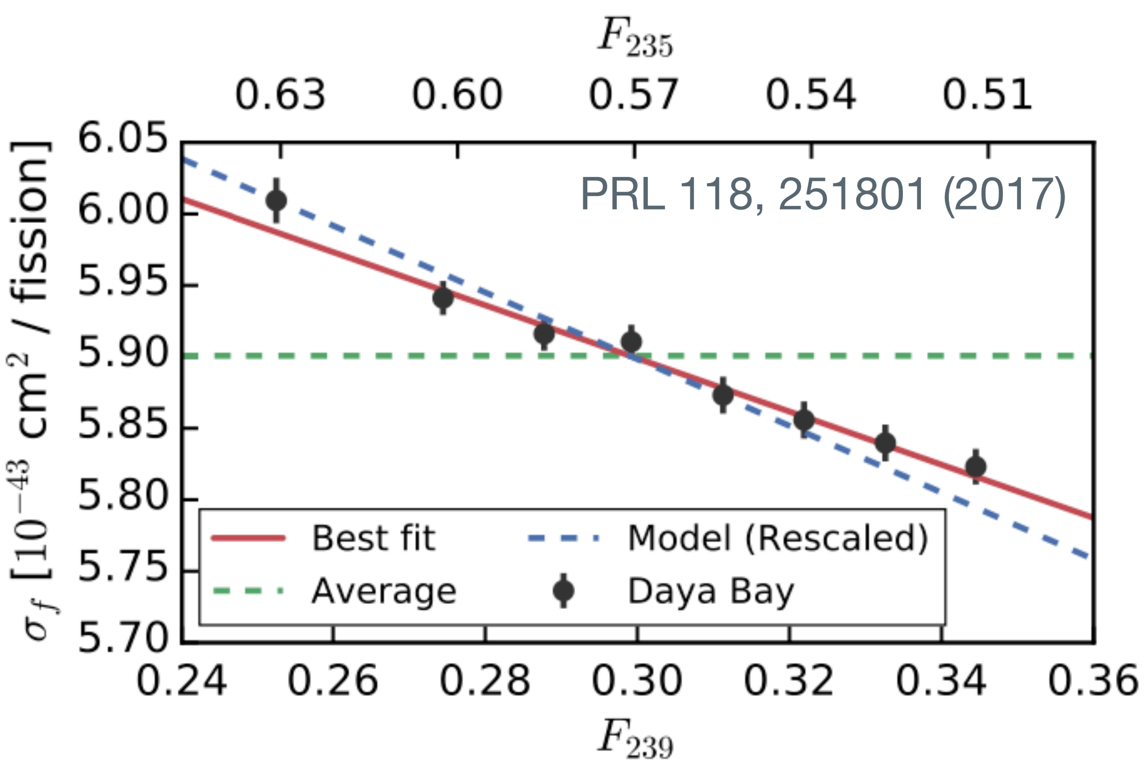
Discrepancies Between Data and Prediction

the "Reactor Antineutrino Anomaly"

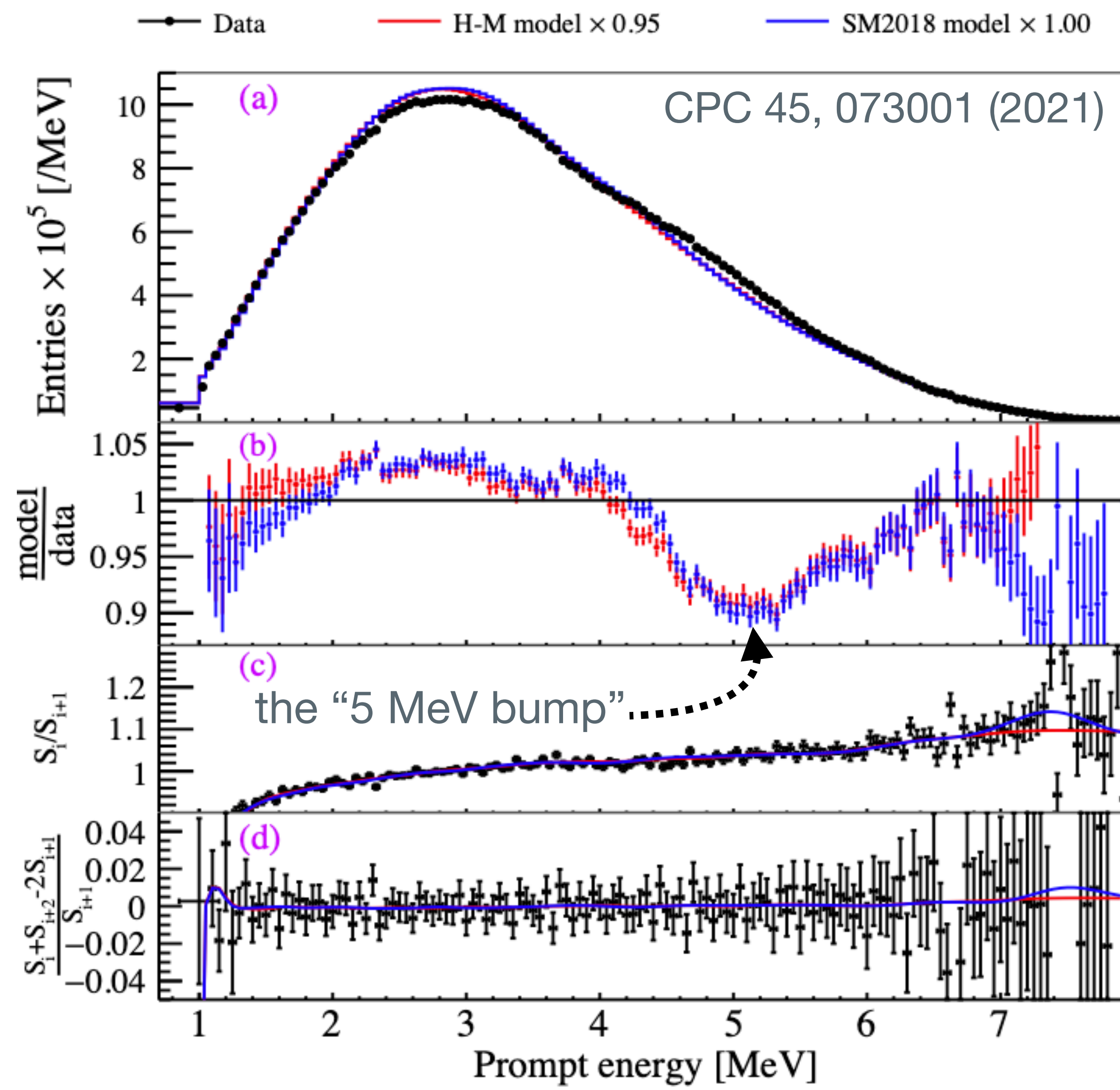
Rate



Rate vs. F_{239}



Spectral Shape

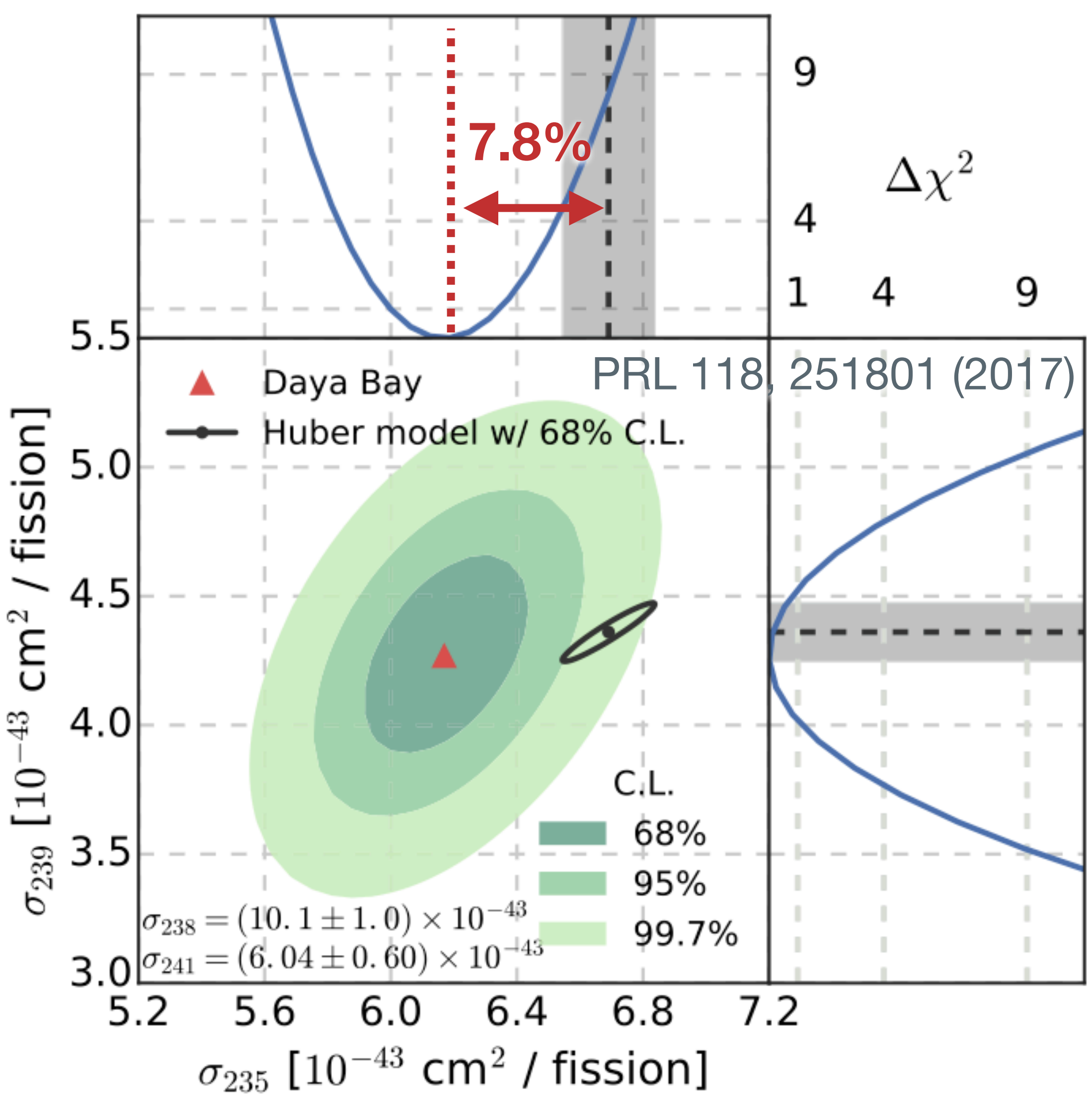


Note: if confirmed, recent beta spectra measurements at Kurchatov Institute could resolve these discrepancies except for the 5 MeV bump (arXiv:2103.01684).

Yields and Spectra

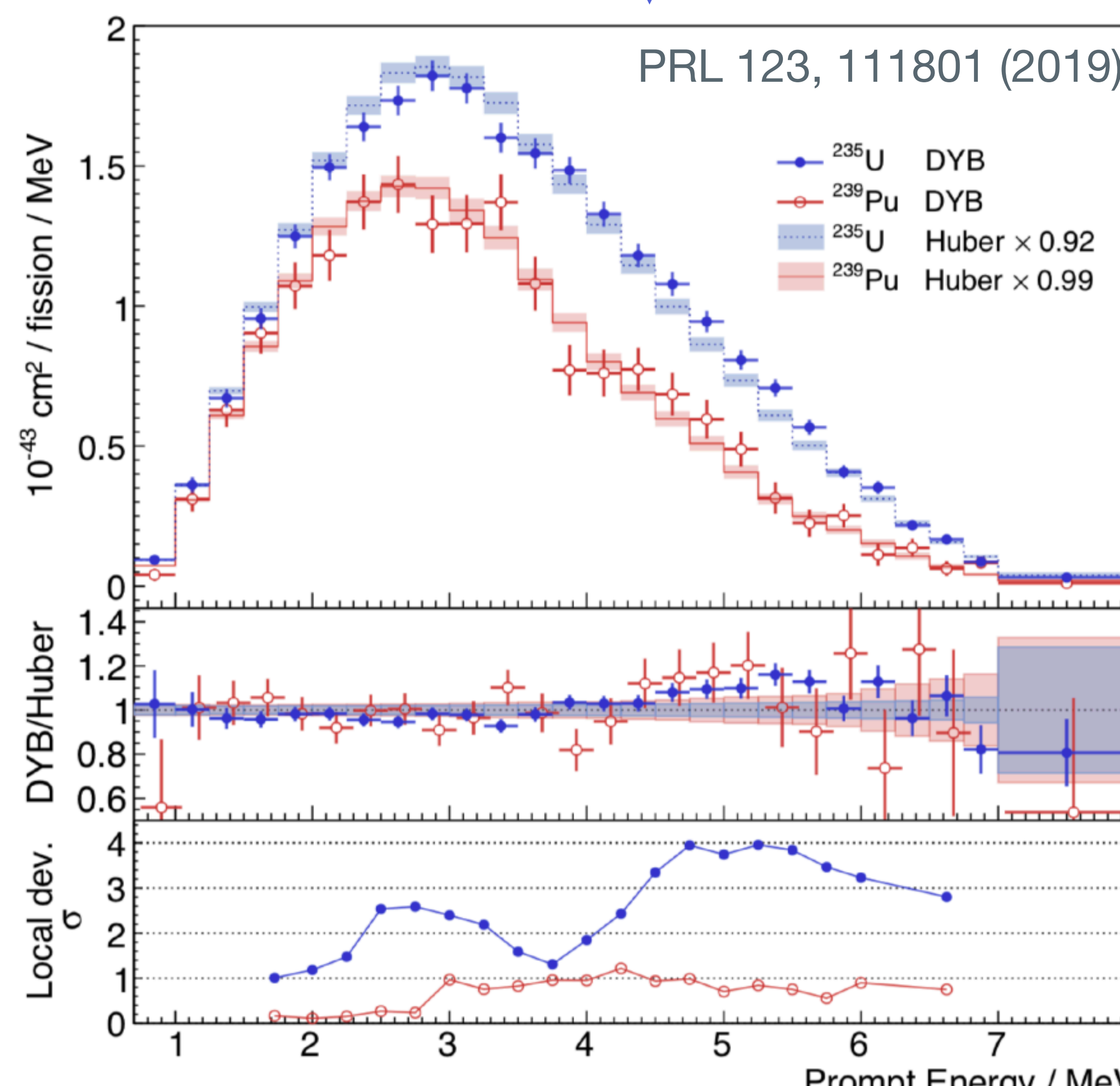
- The evolution with fuel composition allows to extract the individual yields and spectra for the two main isotopes: ^{235}U and ^{239}Pu

Total yield per fission



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

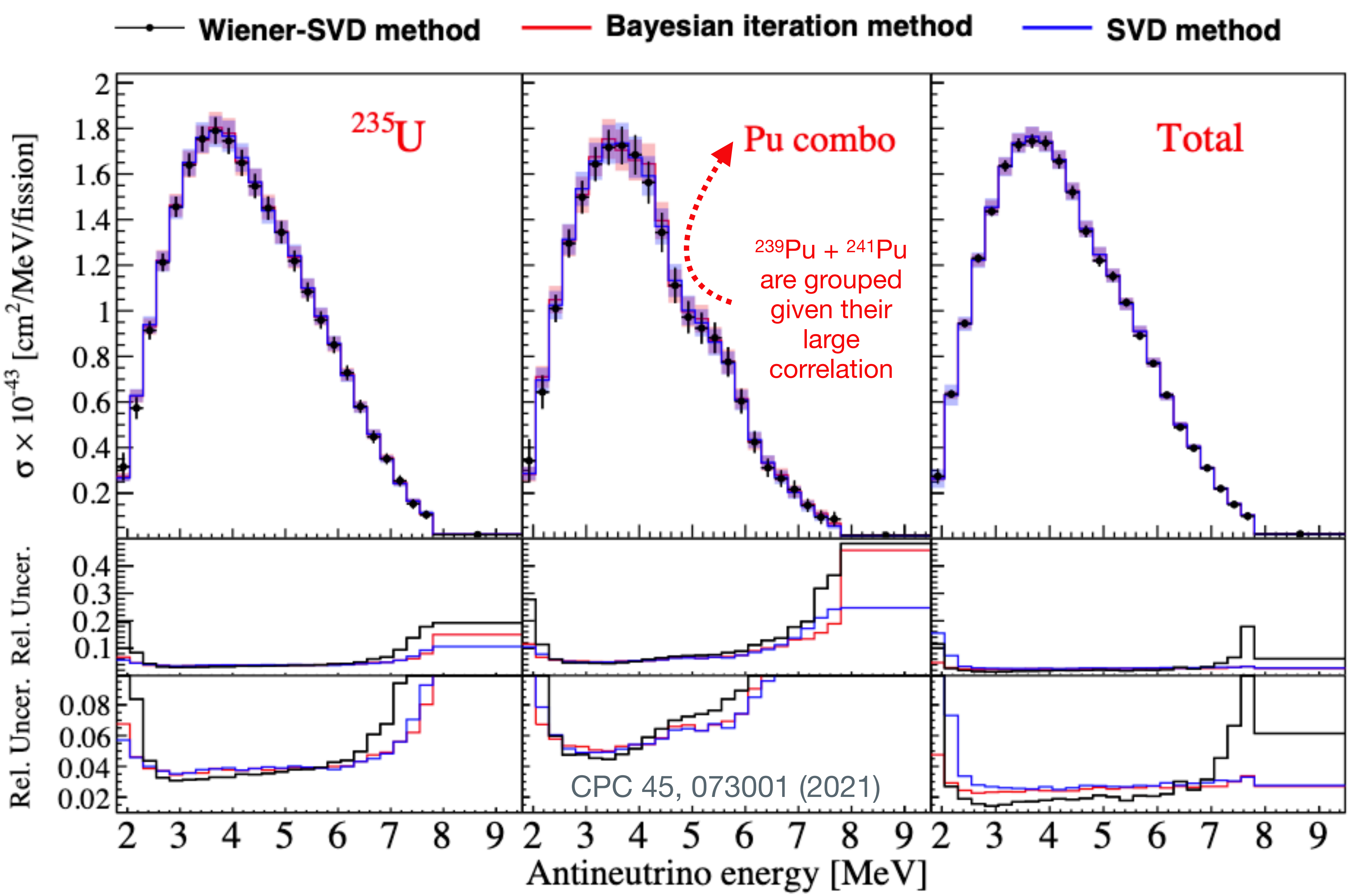
Energy Spectra



First decomposition of individual spectra with commercial reactors

Spectrum Unfolding

- Can "remove" the detector response by unfolding the spectra ($E_{\text{prompt}} \rightarrow E_{\bar{\nu}_e}$)



Unfolded Isotopic Spectra (3 methods)

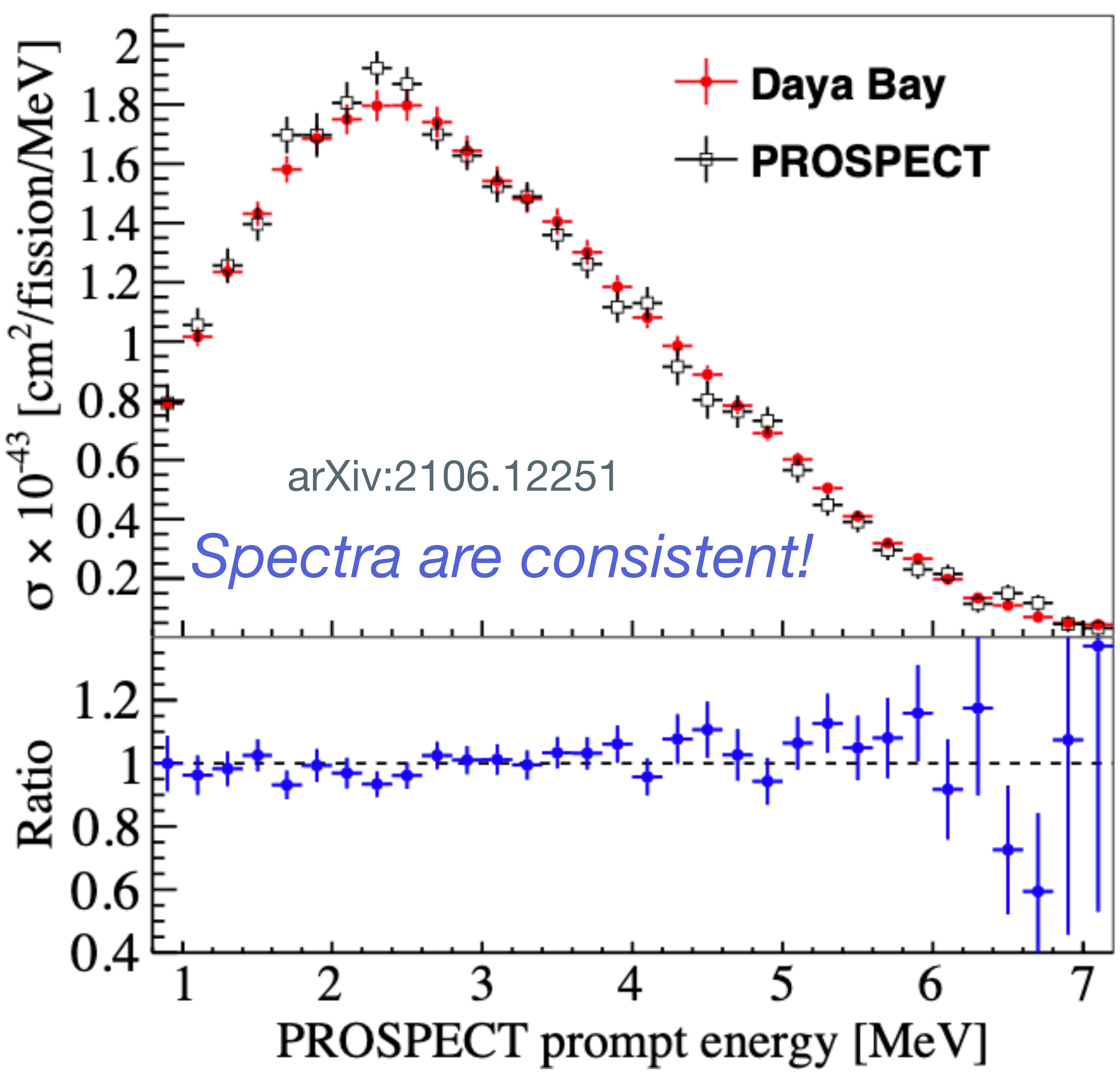
Provide a **data-based** spectrum prediction for other experiments with different fission fractions to **2% precision**

Isotopic spectra uncertainties dominated by statistics and ^{238}U & ^{241}Pu model uncertainties

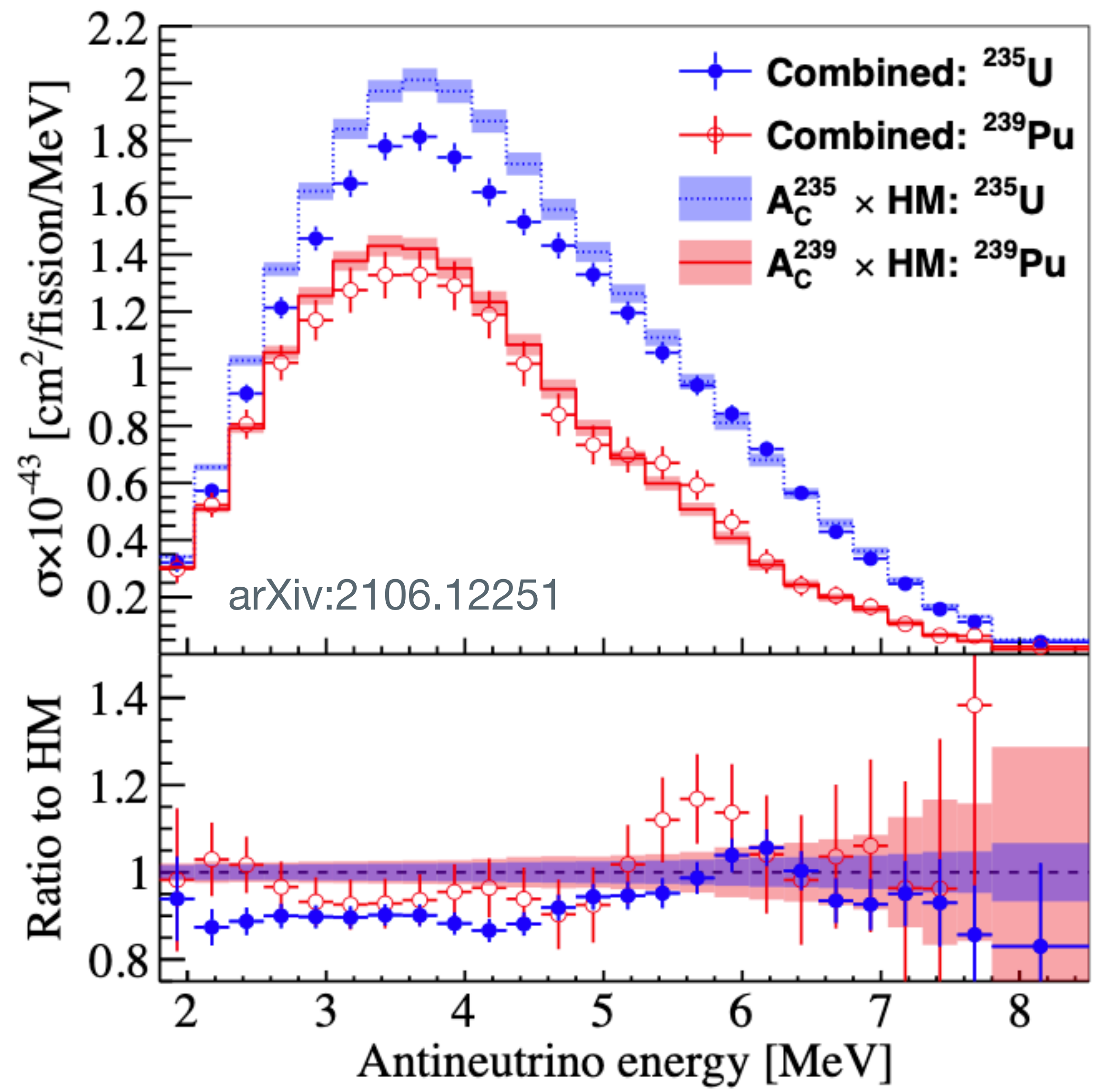
Combination with PROSPECT

- Have combined with the PROSPECT experiment, which makes a direct measurement of the ^{235}U spectrum by being very close to a Highly Enriched Uranium (HEU) reactor

Comparison of ^{235}U Spectral Measurements



Combined Unfolded ^{235}U Spectral Measurement

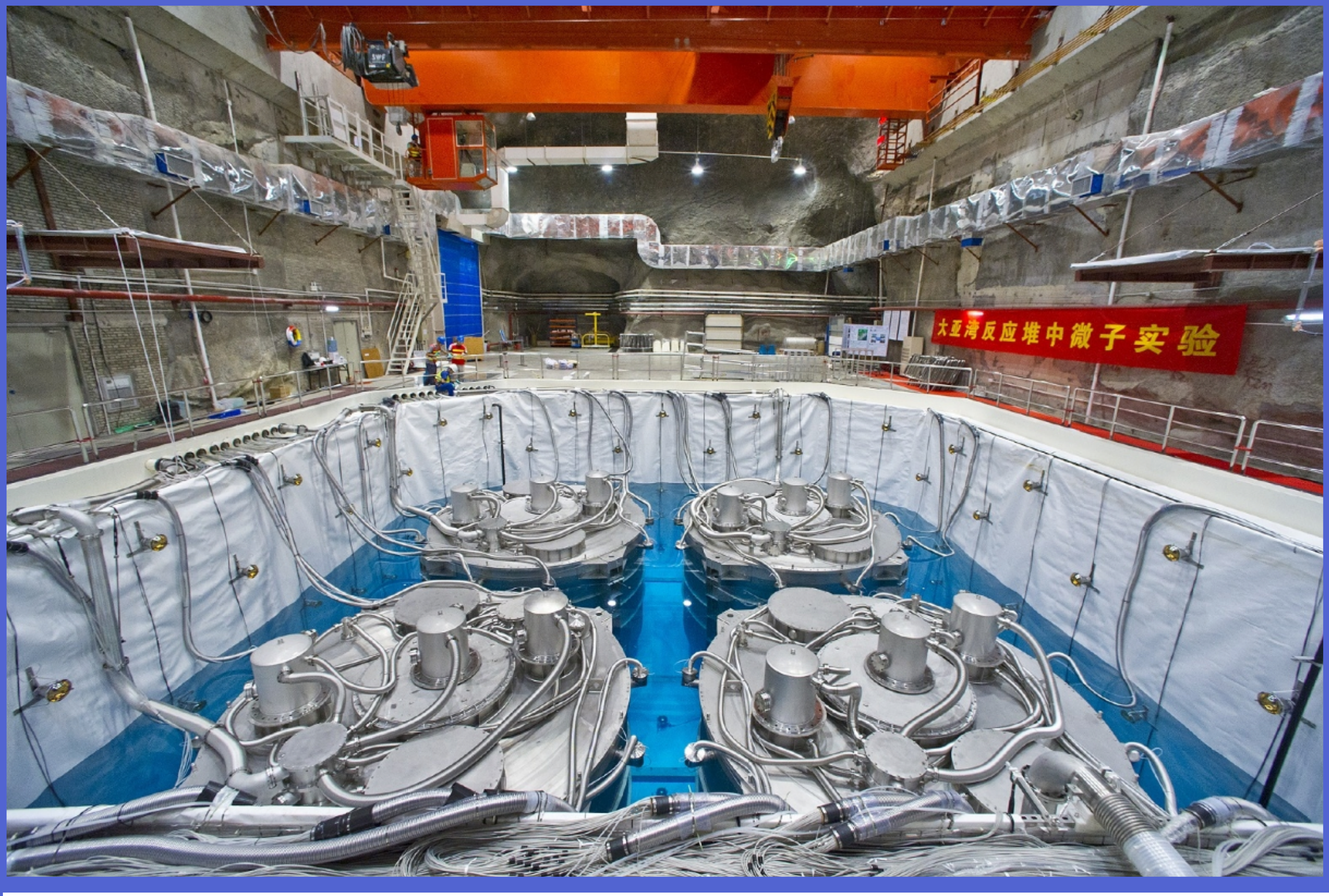


^{235}U spectrum uncertainty in 2-5 MeV region is reduced to about 3% in the combination

Summary & Outlook

- Daya Bay has produced some of the most significant measurements in reactor antineutrino physics.
- The experiment stopped operating on December 12, 2020 after roughly 9 years and has now been decommissioned
  - Over 3,000 days of data were collected in total!
- Many results with the final data set are in preparation:
  - Determination of $\sin^2 2\theta_{13}$ to < 3%, sterile neutrino search with ~2x more data, oscillation measurement using neutron capture on hydrogen with ~4x more data, among others

Stay tuned!



Thank you for your attention!