Daya Bay: Recent Results and Status

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**on behalf of the Daya Bay Collaboration*

NuFact 2019 - Daegu, S. Korea

Outline

- The Daya Bay Experiment
- Recent Results
  - Latest oscillation measurement
  - Search for sterile neutrino mixing*
  - Absolute measurements and their comparison with reactor antineutrino emission models
  - Search for a time-varying antineutrino signal
- Summary & Conclusions

* Please refer to this morning's plenary from Adam Aurisano and Zhuojun Hu

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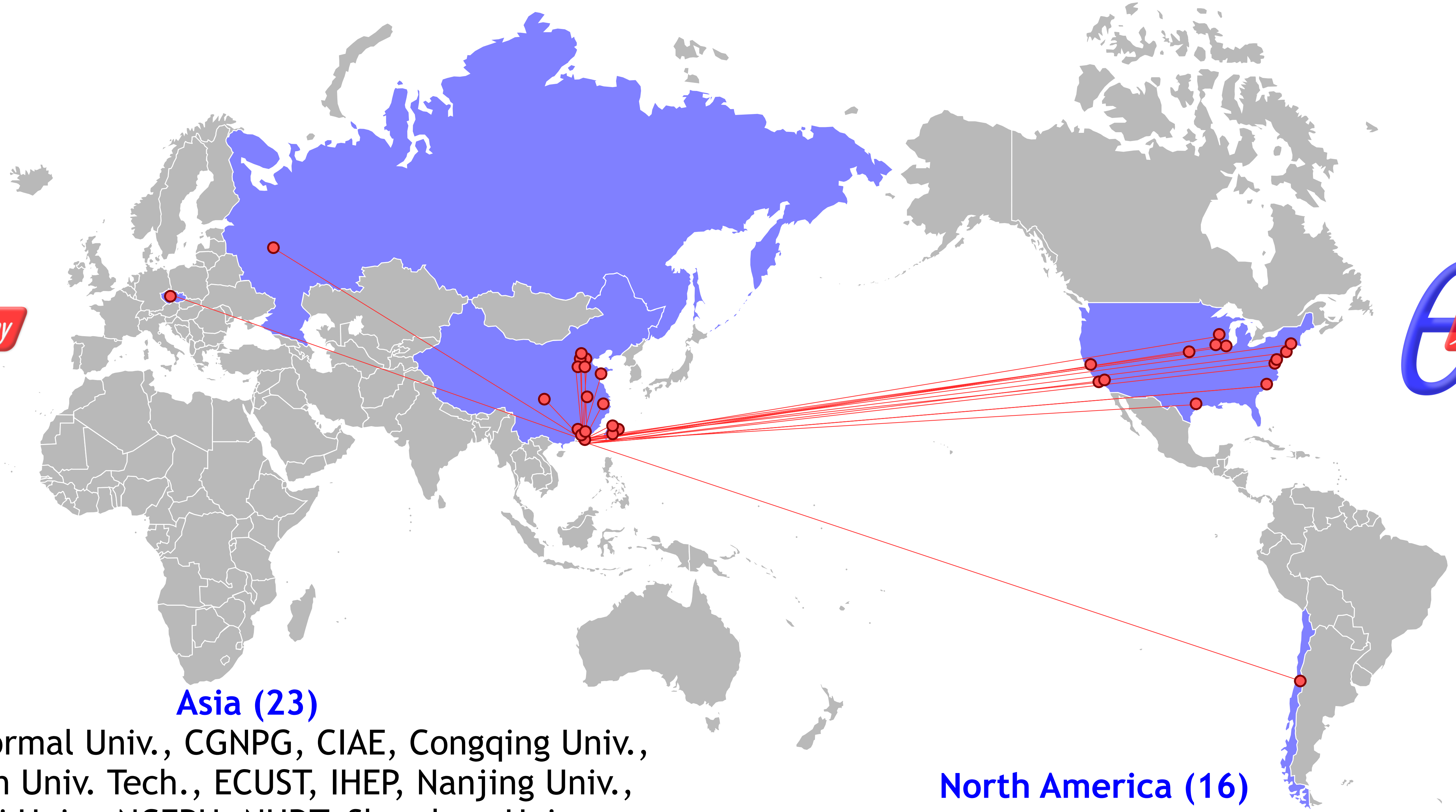
The Daya Bay Collaboration



Asia (23)

Beijing Normal Univ., CGNPG, CIAE, Congqing Univ., Dongguan Univ. Tech., ECUST, IHEP, Nanjing Univ., Nankai Univ., NCEPU, NUDT, Shandong Univ., Shanghai Jiao Tong Univ., Shenzhen Univ., Tsinghua Univ., USTC, Xian Jiaotong Univ., Zhongshan Univ., Chinese Univ. of Hong Kong, Univ. of Hong Kong, National Chiao Tung Univ., National Taiwan Univ., National United Univ.

Europe (2)

Charles University, JINR Dubna

North America (16)

Brookhaven Natl Lab, Illinois Institute of Technology, Iowa State, Lawrence Berkeley Natl Lab, Princeton, Siena College, Temple University, UC Berkeley, UC Irvine, Univ. of Cincinnati, Univ. of Houston, UIUC, Univ. of Wisconsin, Virginia Tech, William & Mary, Yale

South America (1)

Catholic University of Chile

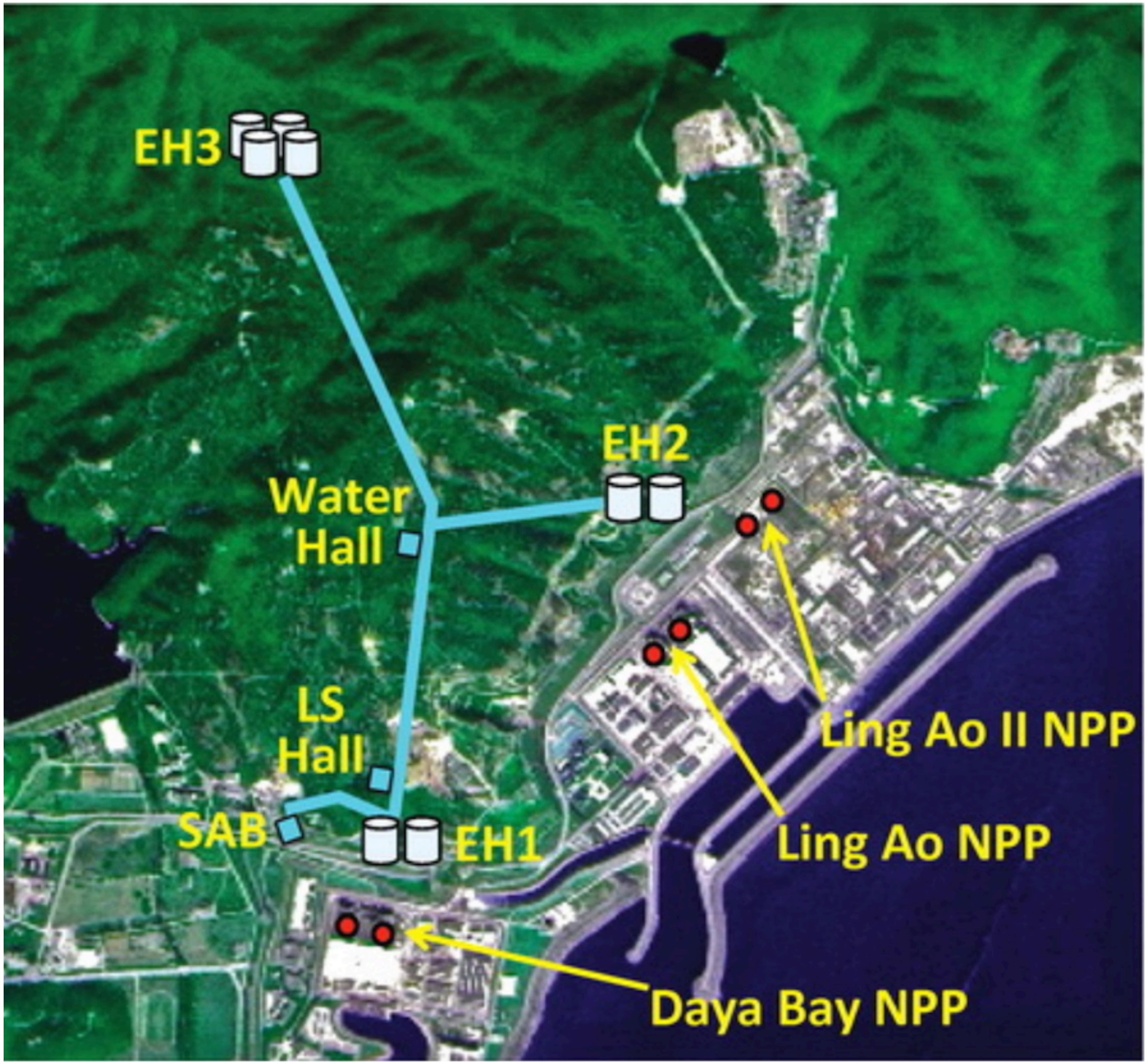
~190 Collaborators

Experimental Setup

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

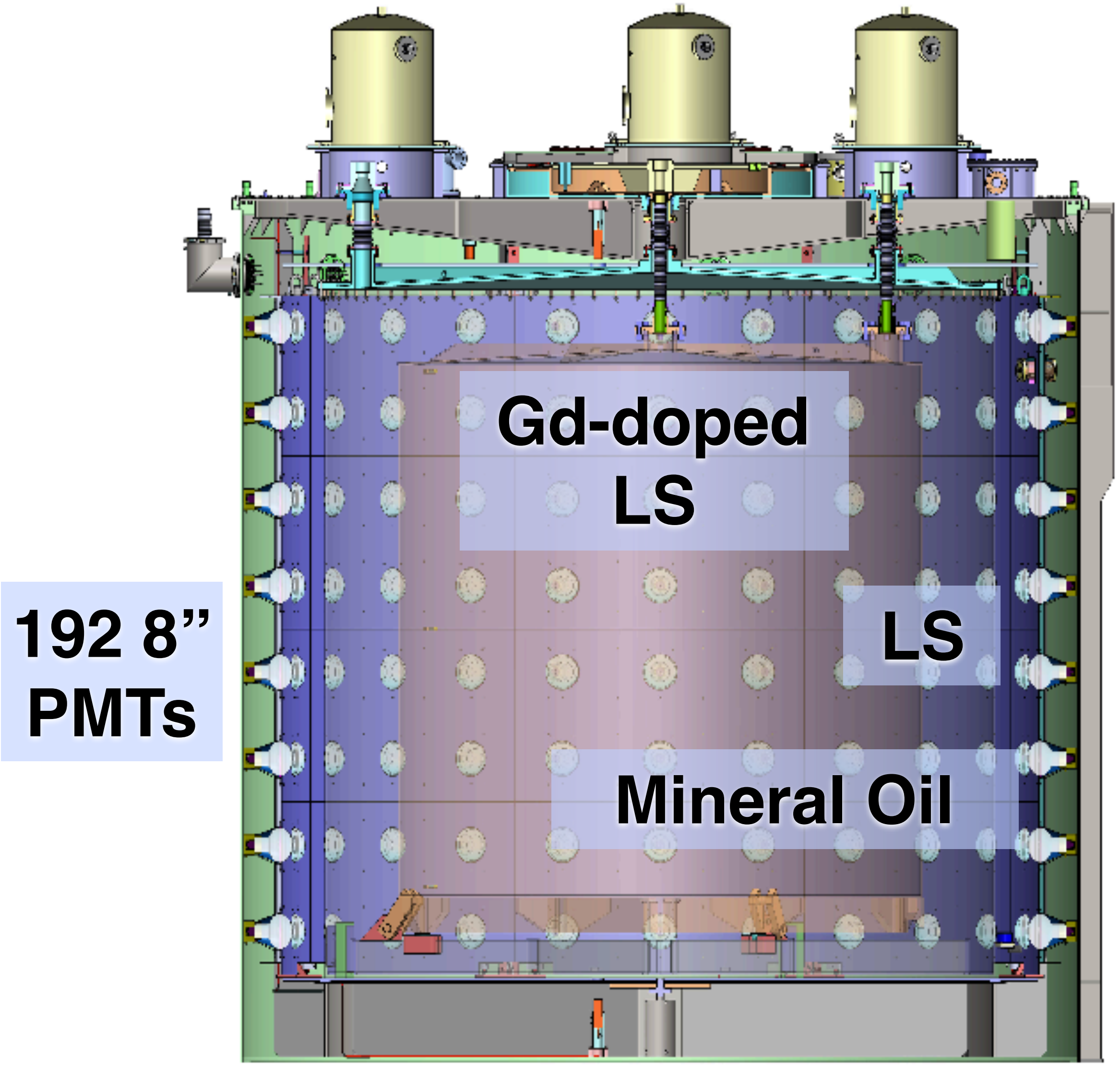
Six 2.9 GW_{th} reactors distributed in 3 Nuclear Power Plants (NPPs)

Among the most powerful nuclear power complexes in the world!



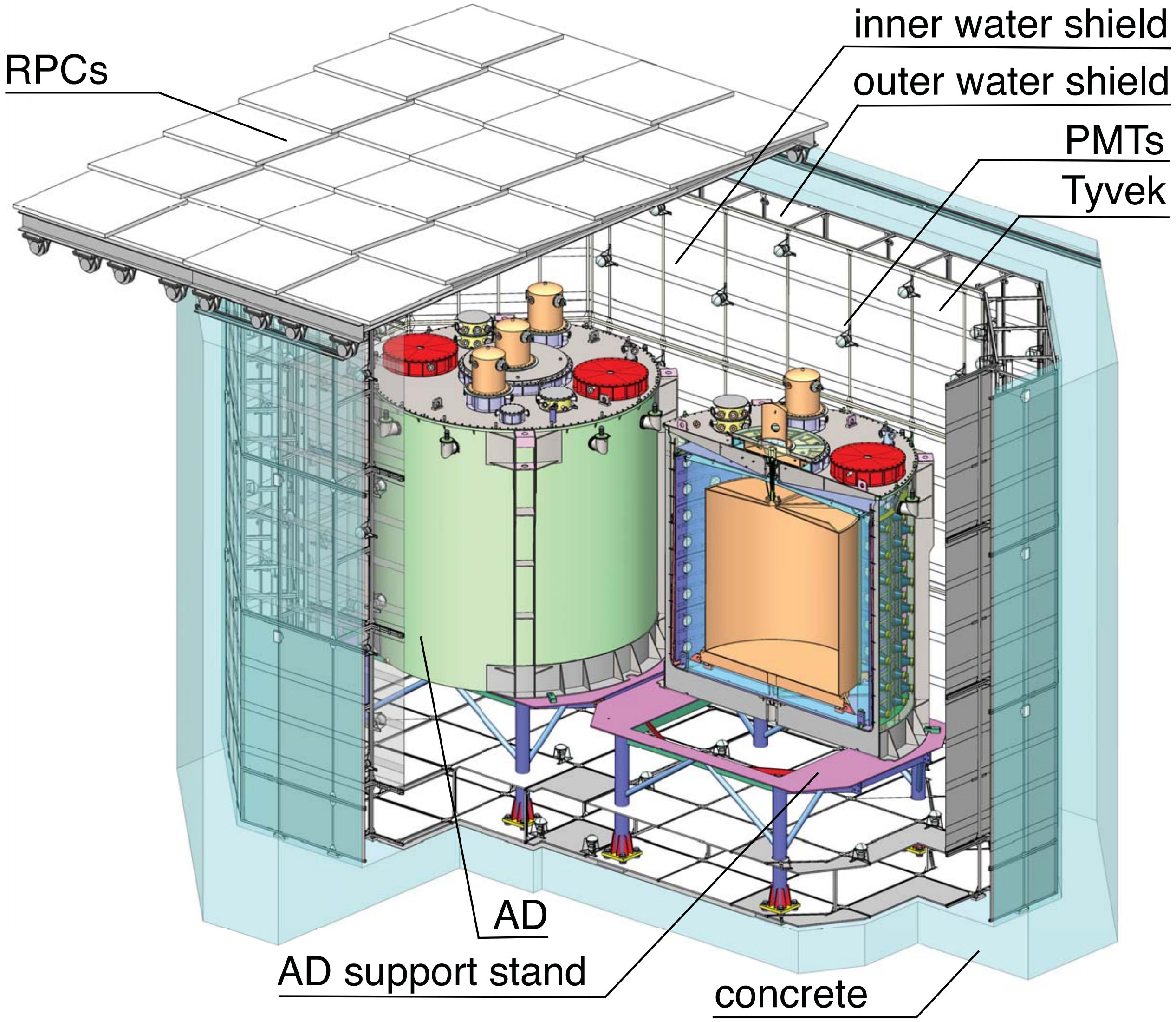
Antineutrino Detectors

- 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:
$\sigma_E/E \cong 8.5\%/\sqrt{E(\mathrm{MeV})}$

NIM A 811, 133 (2016)



Double purpose: shield the ADs and veto cosmic ray muons

NIM A 773, 8 (2015)

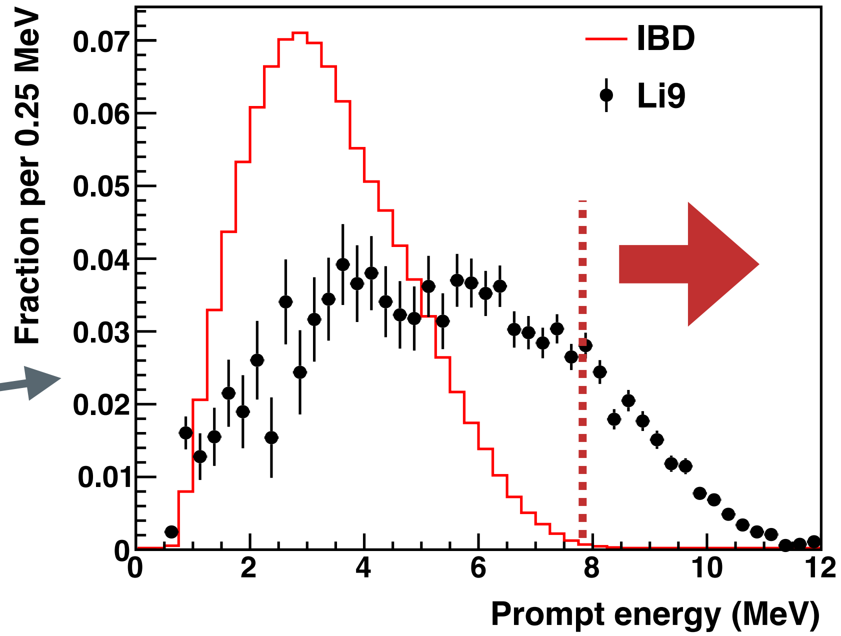
A Selection of Pictures

Improvements on Latest Oscillation Results

- Our latest oscillation results were obtained with **1958 days of data**
  - More than **3.9 million antineutrino interactions** (0.5 million at far site)
  - Roughly **60% increase in statistics** with respect to previous result
- Also incorporated three main systematic improvements:

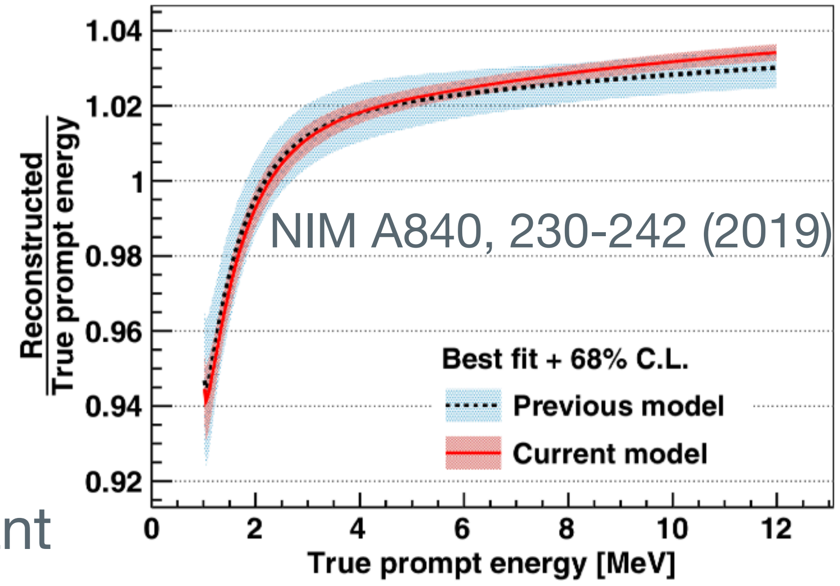
1) Reduced uncertainty in ^{9}Li/^{8}He background estimation

How: determine shape from data and apply a prompt energy cut to enhance ^{9}Li/^{8}He fraction when fitting time-since-last-muon distributions



2) Halved uncertainty of absolute energy scale to ~0.5%

How: installation of FADC readout in one AD and special calibration runs acquired using ^{60}Co sources with different encapsulating materials



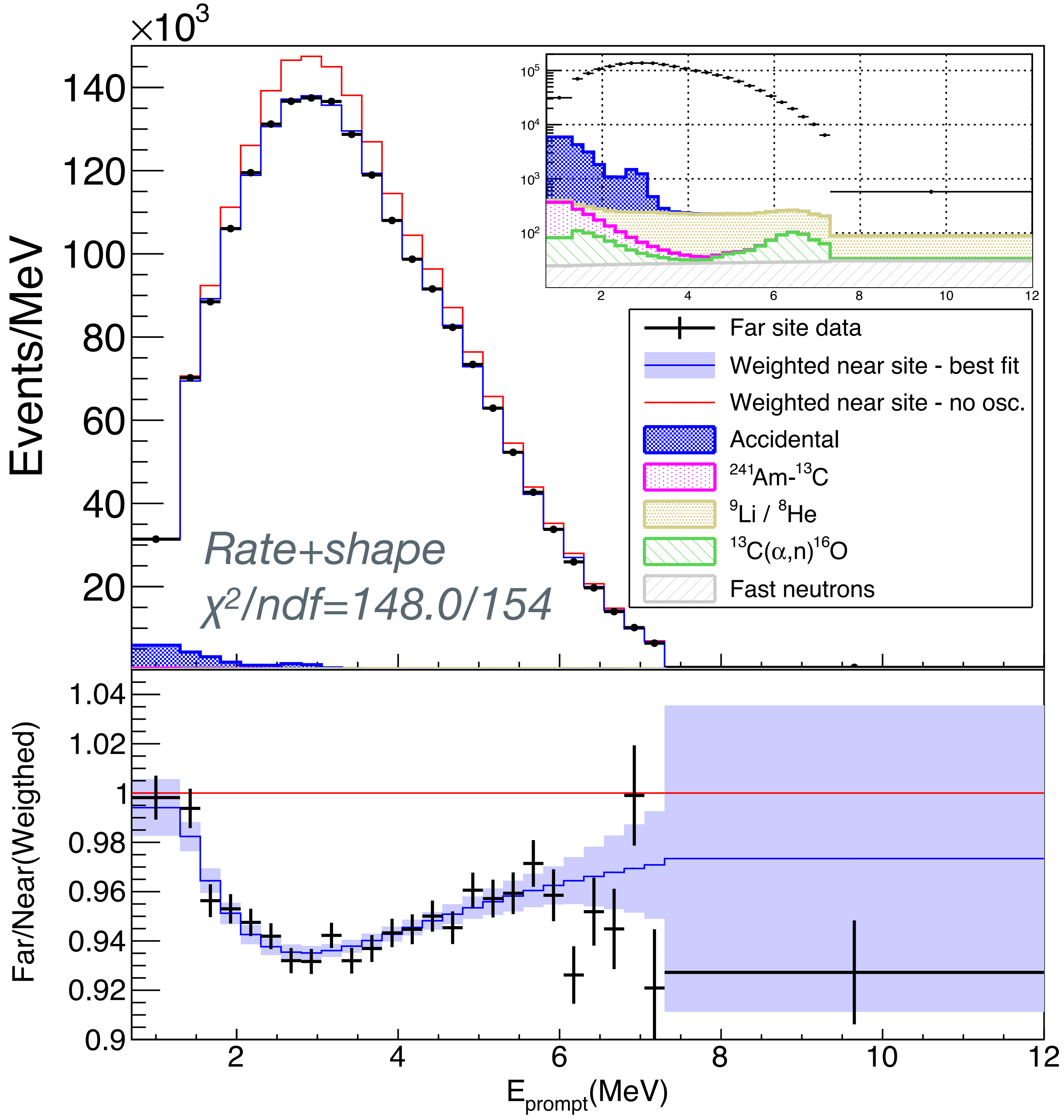
NIM A840, 230-242 (2019)

3) Reduced uncertainty of spent nuclear fuel (SNF) from 100% to 30%

How: detailed review of SNF history from power plant

Data Set

- From rate and shape distortion can simultaneously extract $\sin^2 2\theta_{13}$ and Δm^2:
  - Very good fit to 3ν hypothesis
  - Most info on θ_{13} is from relative rate comparison
- Some highlights of our relative rate uncertainties:
  - Statistical error in $\overline{\nu}_e$ rates: ~0.11% (near ADs), ~0.29% (far ADs)
  - Background uncertainty in $\overline{\nu}_e$ rates: ~0.12% (all ADs)
  - Relative efficiency uncertainty: 0.13% (all ADs)



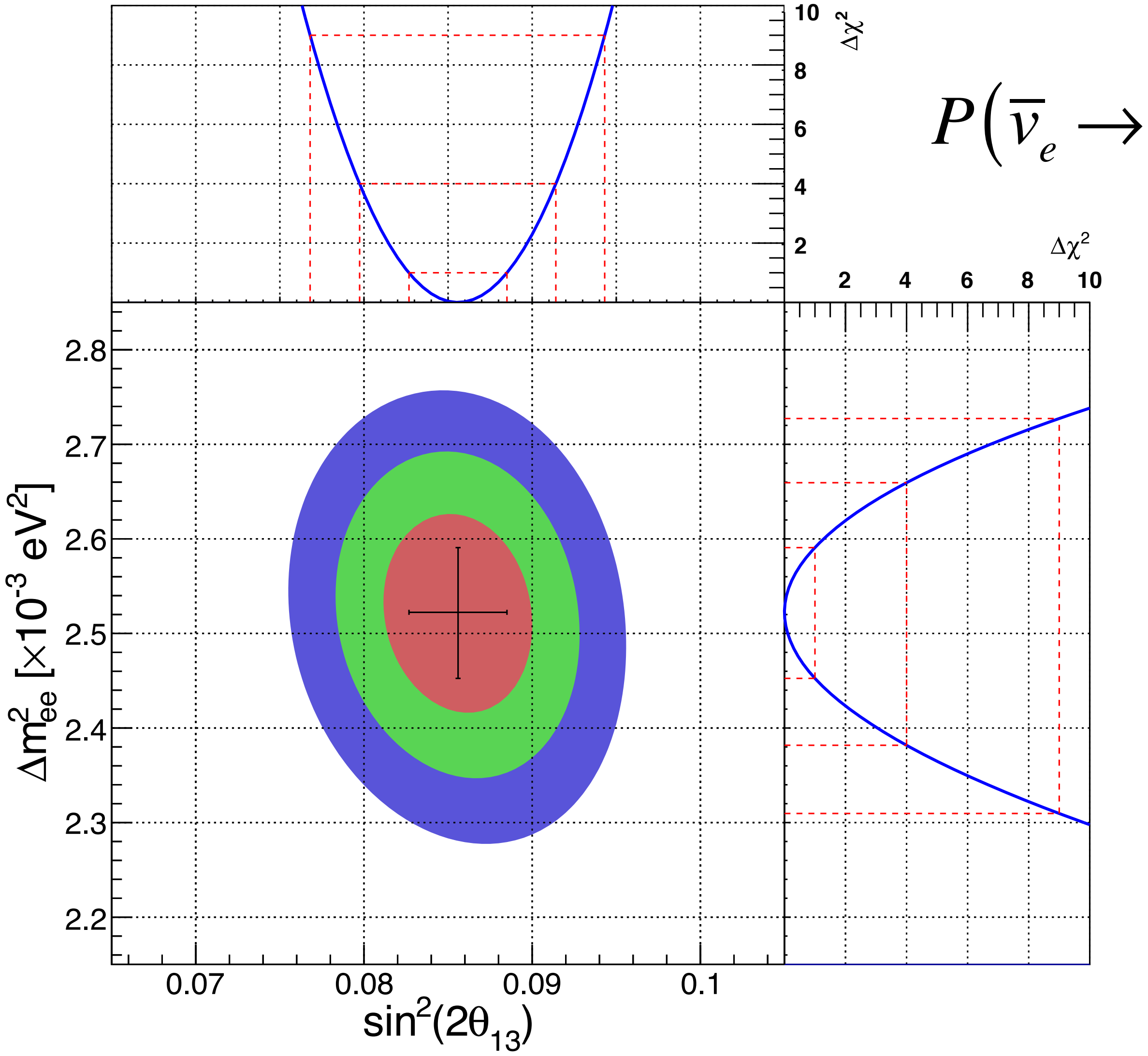
PRL 121, 241805 (2018)

Oscillation Results with 1958 Days

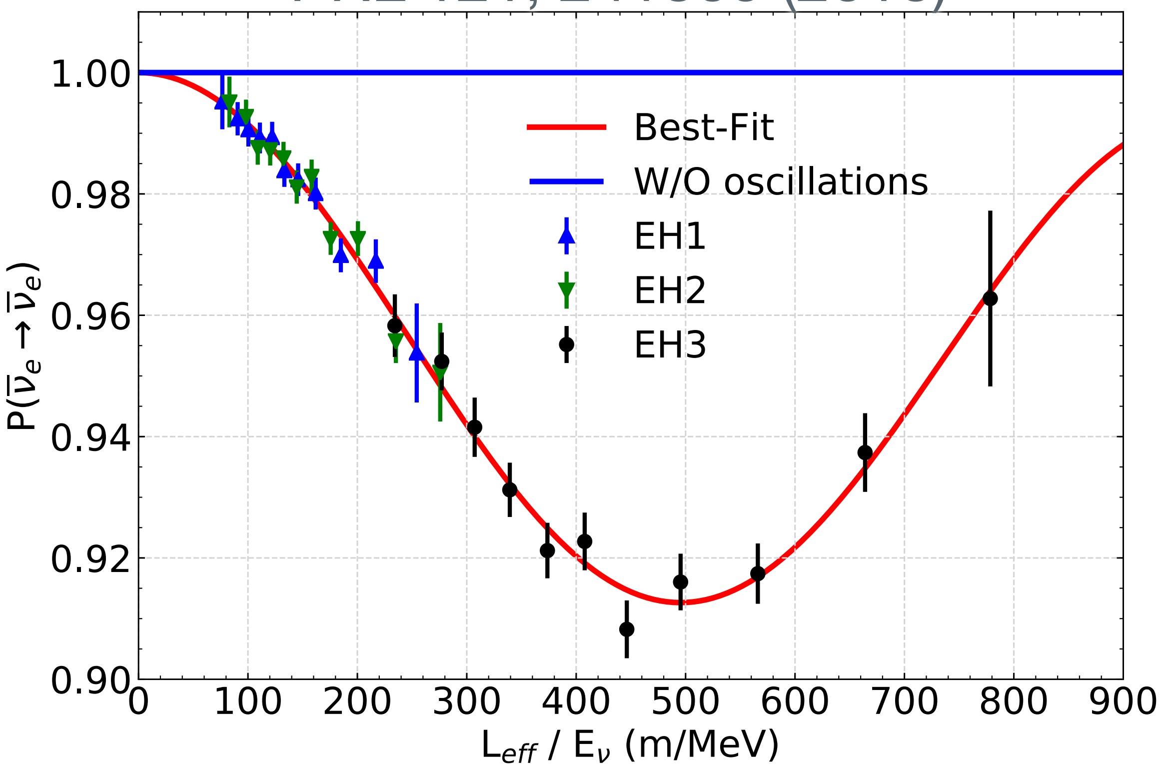
- Measure $\sin^2 2\theta_{13}$ and $|\Delta m^2_{ee}|$ to **3.4%** and **2.8%** respectively:

effective mass splitting

$$P(\overline{\nu}_e \rightarrow \overline{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2 \frac{\boxed{\Delta m^2_{ee}} L}{4E} - \text{solar term}$$



PRL 121, 241805 (2018)



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

$$|\Delta m^2_{ee}| = (2.522^{+0.068}_{-0.070}) \times 10^{-3}\ \text{eV}^2$$

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

- Consistent results obtained with sample tagged via neutron capture on H

[PRD 93, 072011 (2016)]

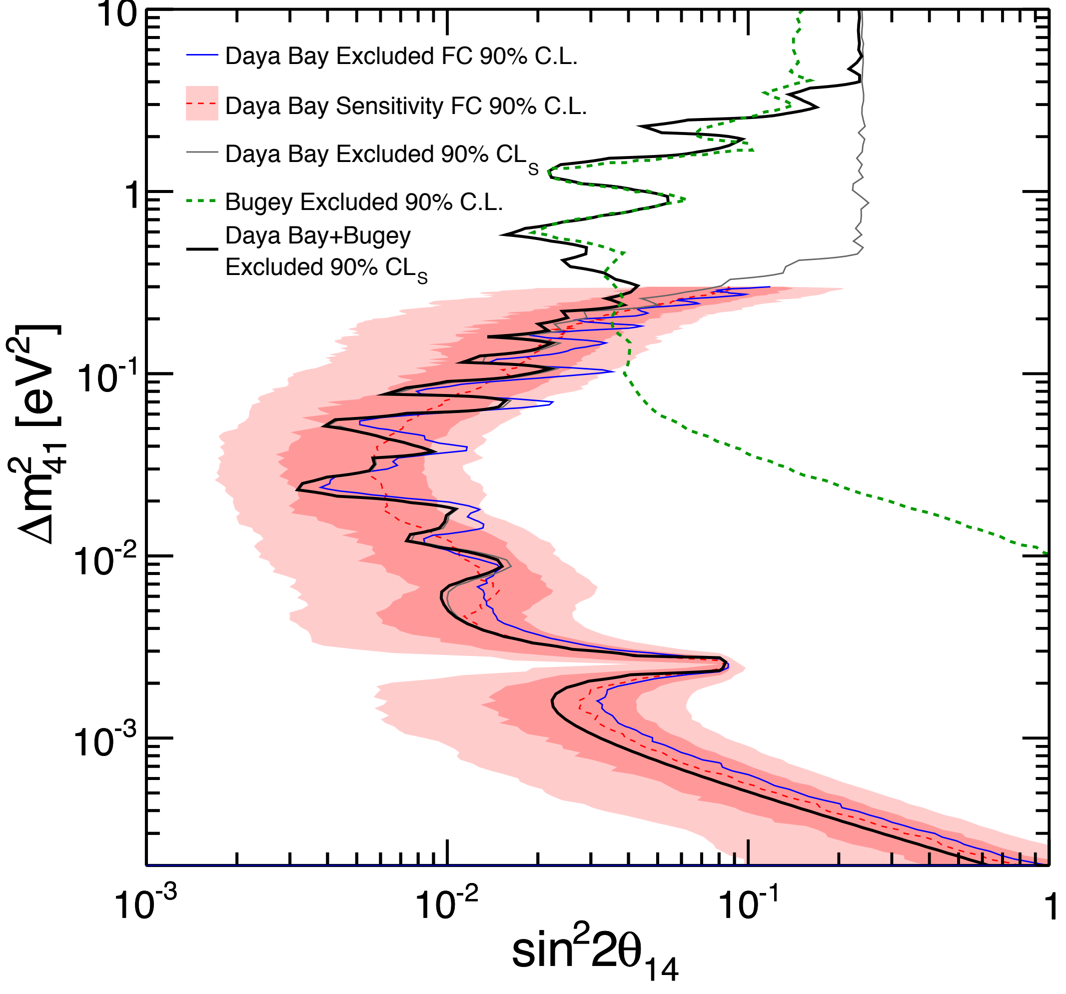
New Sterile Neutrino Search

- The results for a new search for sterile neutrino mixing are being released at this conference:

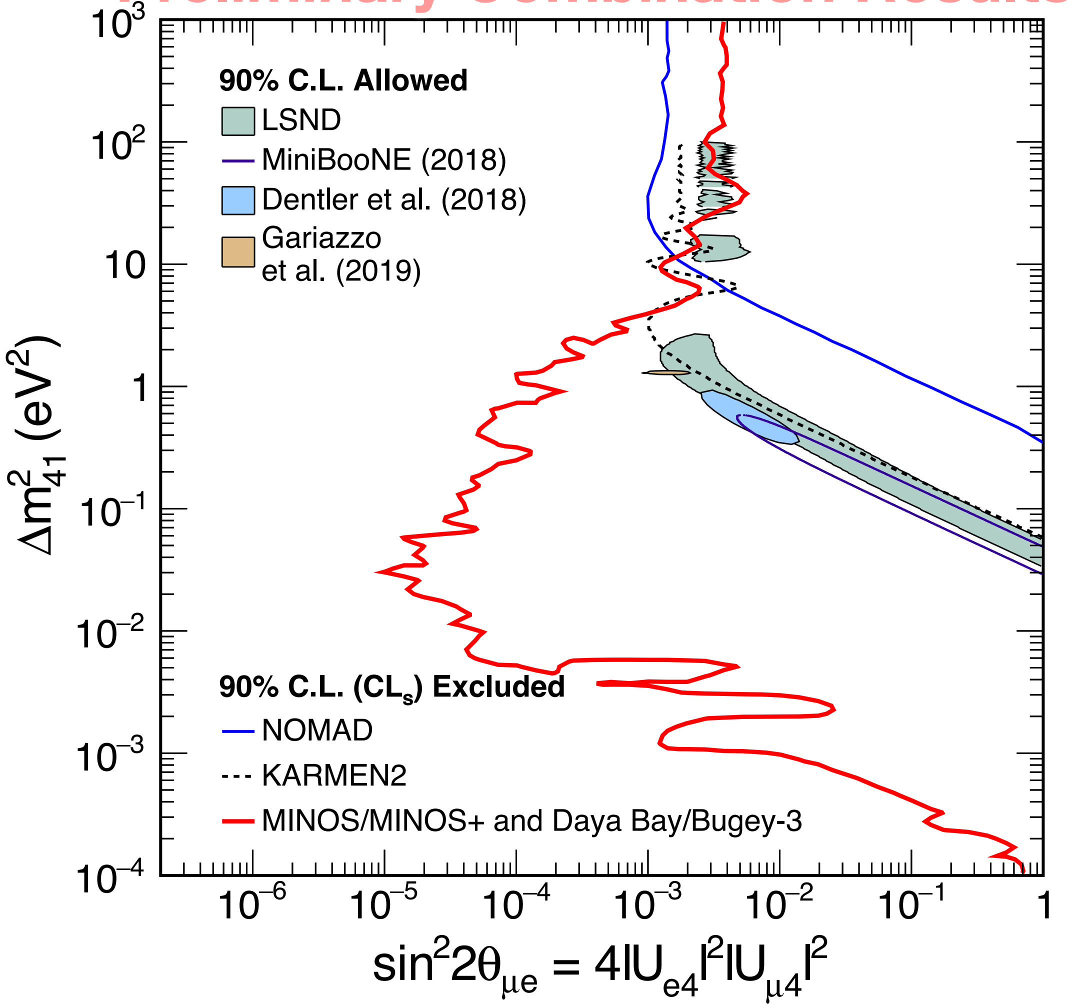
- Several systematic improvements and double the statistics from previous result

In Daya Bay, signal would primarily appear as an additional spectral distortion with a frequency different from standard 3ν oscillations

Daya Bay Preliminary (1230 days)



Preliminary Combination Results



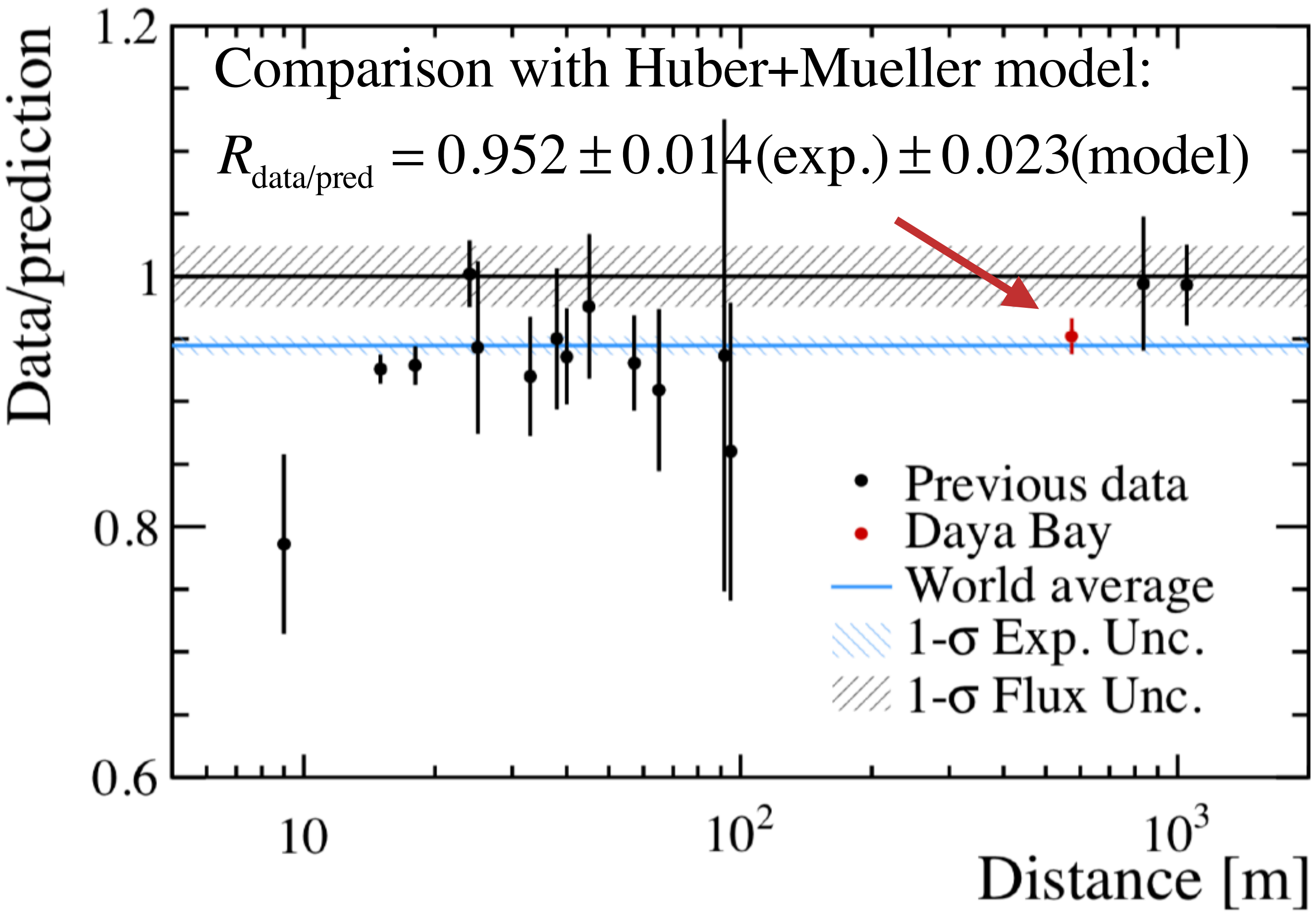
- Combination with ν_μ disappearance results allows to constrain $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ oscillations*

* Please refer to this morning's plenary from Adam Aurisano and Zhuojun Hu for more details

Reactor Antineutrino Flux

- Our data can be compared with the predictions from reactor antineutrino emission models
  - Allows to better understand reactors and the inputs that go into the predictions, as well as to search for new physics
- We recently released an improved measurement of the reactor $\overline{\nu}_e$ flux:
  - Measurement is systematics-dominated
  - Uncertainty in absolute detection efficiency was significantly reduced through extensive calibration campaign

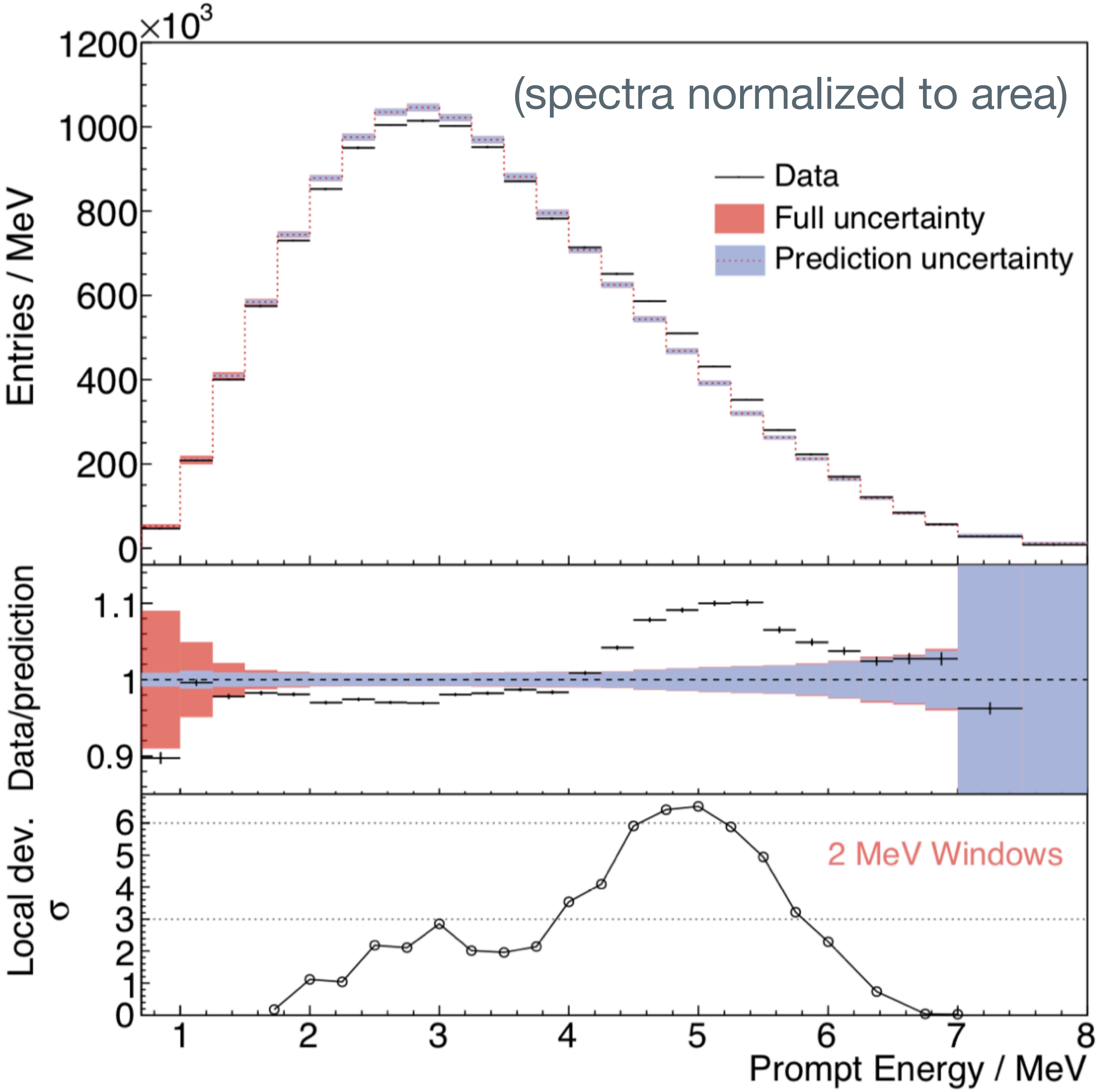
See details in arXiv:1808.10836 (accepted by PRD)



- This ~2.5σ flux anomaly could be due to mixing with a sterile neutrino and/or to problems with the prediction

Reactor Antineutrino Spectral Shape

- Have also recently updated our **high-statistics measurement** of the spectral shape of reactor antineutrinos:
  - Comparison with the Huber + Mueller prediction reveals a 5.3σ discrepancy overall (**6.3σ in the 4-6 MeV "bump" region**)
  - Bump events have all the IBD characteristics and are reactor power correlated
  - Bump does not appear in ^{12}B spectra (disfavoring detector effects).
- This shape anomaly cannot be explained with sterile neutrino mixing

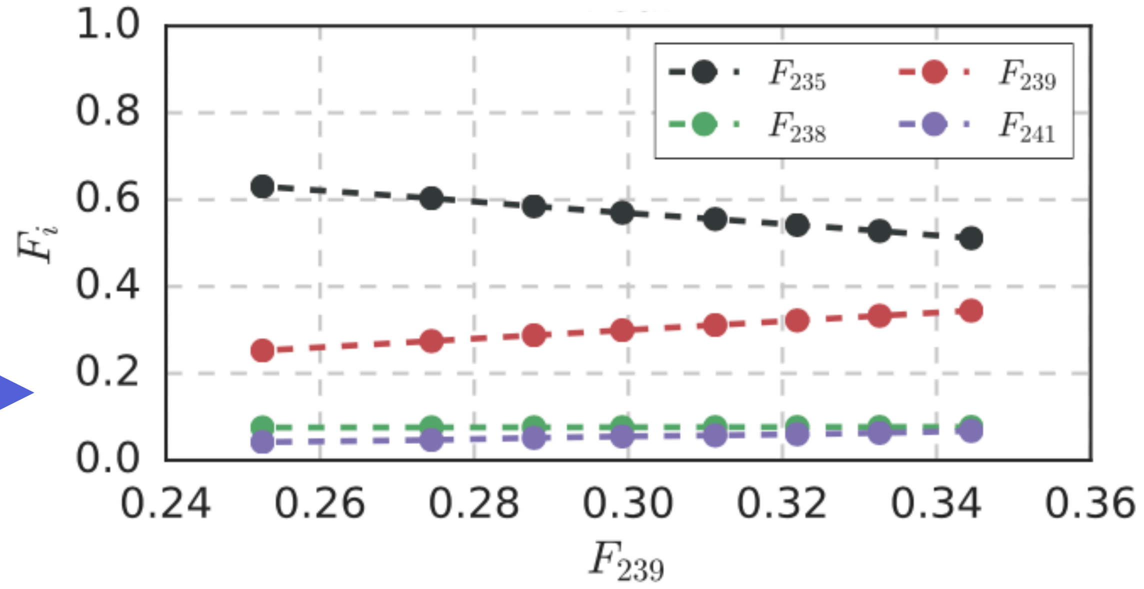


arXiv:1904.07812 (accepted by PRL)

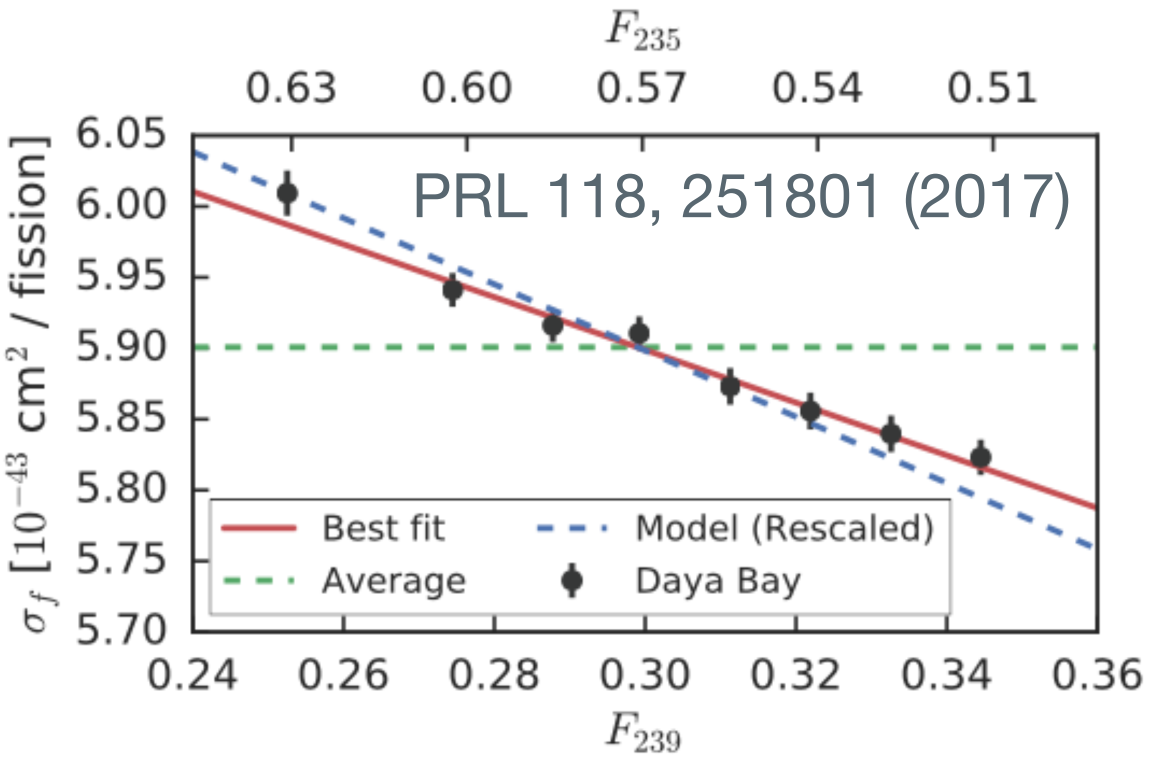
Evolution with Fuel Composition

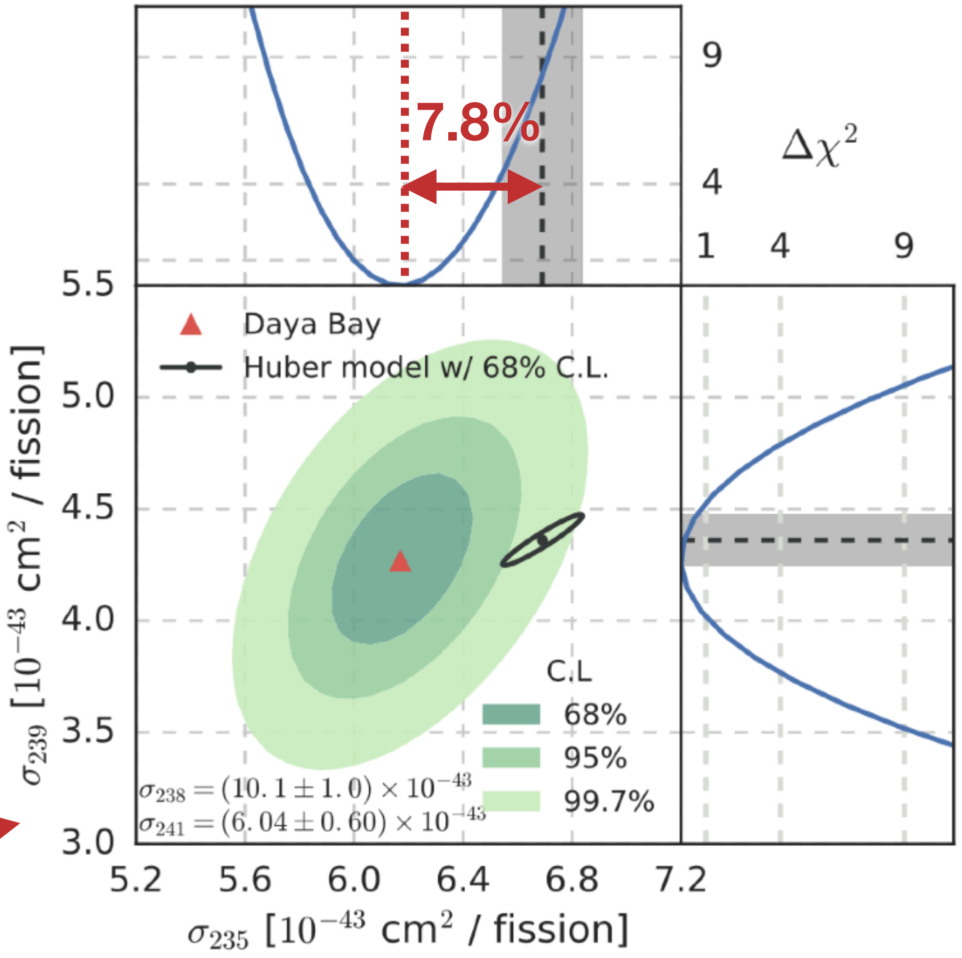
- The question arises: **can these anomalies be traced to a particular isotope?**

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



- A study of how the total flux changes with fuel composition allowed to extract the individual antineutrino yield σ of ^{235}U and ^{239}Pu:



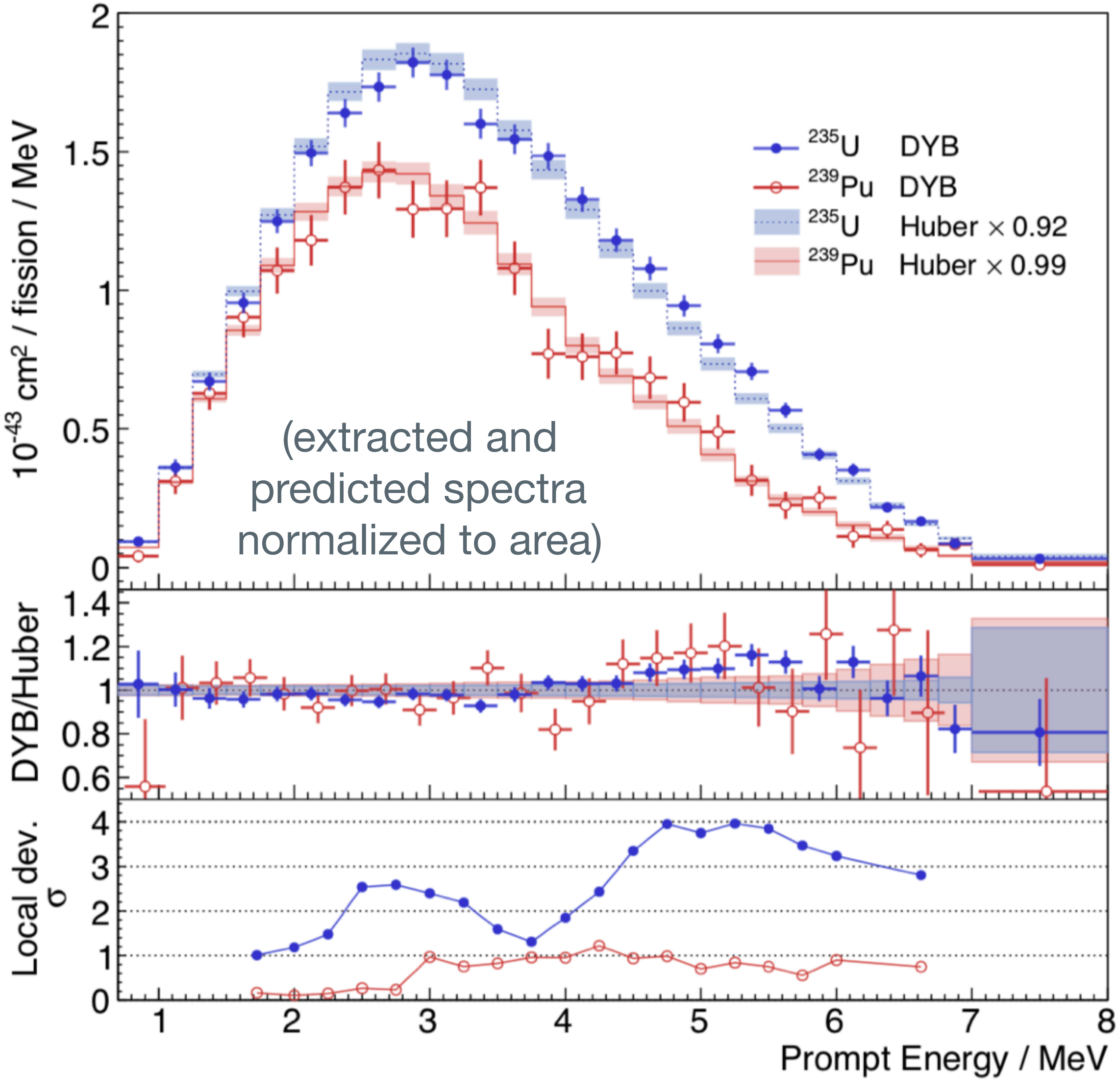


Our data suggest ^{235}U is the primary contributor to the flux anomaly

New: Extraction of Individual Spectra

- Similarly, the individual ^{235}U and ^{239}Pu spectra can be simultaneously extracted from the evolution of the spectrum with fuel composition:

Divide1958-day data set into 20 groups ordered by ^{239}Pu fission fraction, and fit ^{235}U and ^{239}Pu as the two dominant components



<u>Highlights:</u>

- Similar bump excess seen with both ^{235}U and ^{239}Pu:
- Local deviations:
  - 4σ for ^{235}U
  - 1.2σ for ^{239}Pu (larger uncertainty)

This is the **first measurement** of the individual ^{235}U and ^{239}Pu spectra with commercial reactors

arXiv:1904.07812 (accepted by PRL)

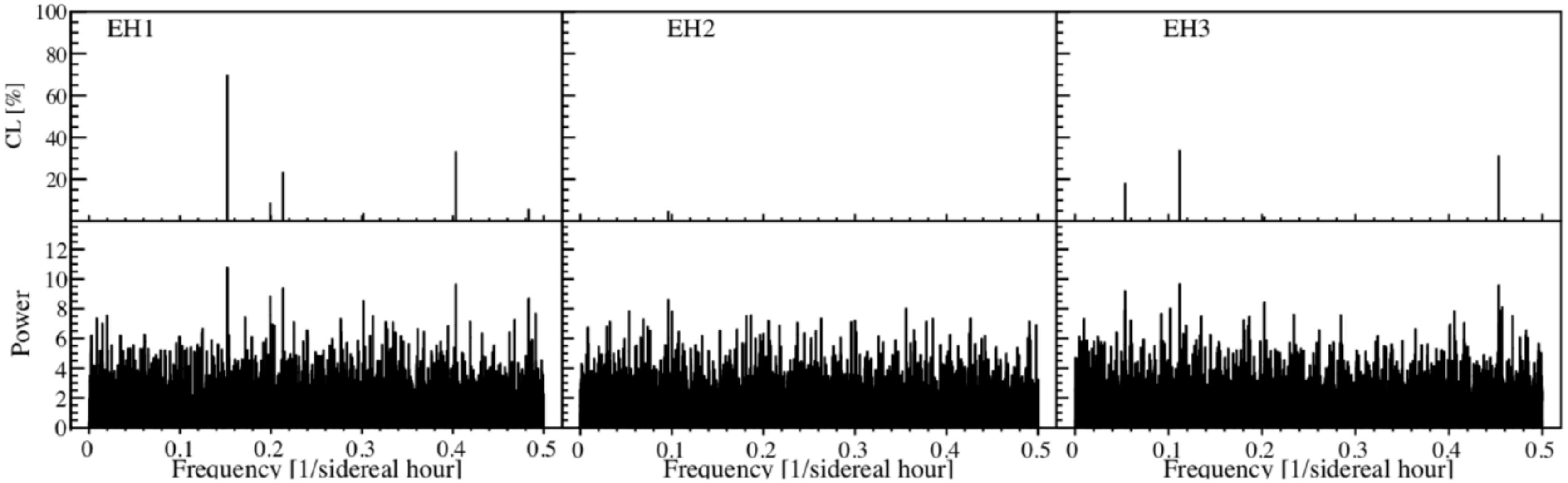
Search for Time-Varying Antineutrino Signal

- We also recently performed a search for a time-varying $\overline{\nu}_e$ signal over 704 calendar days
  - Motivated by models with ultralight dark matter coupling to neutrinos, as well as Lorentz and CPT violation.
- Searched for any periodicity with a Lomb-Scargle (LS) periodogram:

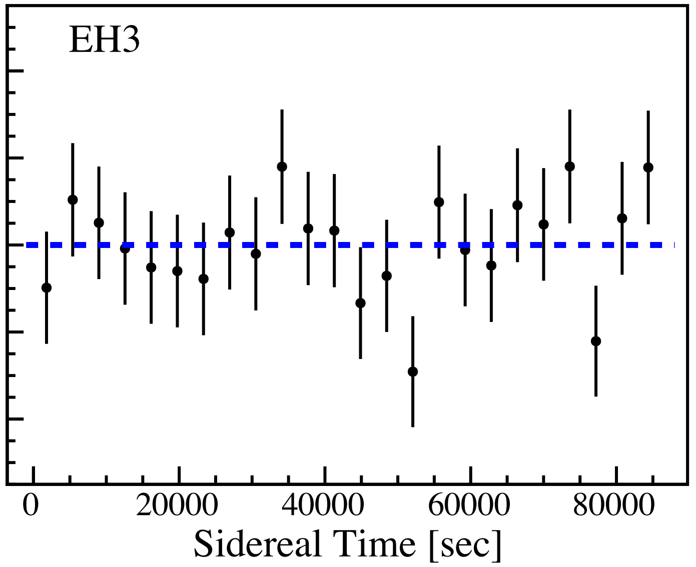
Highest LS powers in each hall

Hall	Frequency	Period	Confidence Level
EH1	0.15 hr^{-1}	6.6 hr	69.8%
EH2	0.10 hr^{-1}	10.4 hr	5.1%
EH3	0.11 hr^{-1}	8.9 hr	33.9%

No signal found



- Also searched for a sidereal modulation in the context of the Standard Model Extension (SME):
  - Thanks to its multiple directions and high-statistics, Daya Bay is able to disentangle the complex relationship between sidereal amplitudes and individual SME coefficients



PRD 98, 092013 (2018)

Summary & Outlook

- Have recently updated many results and released some new ones:

Latest oscillation results →

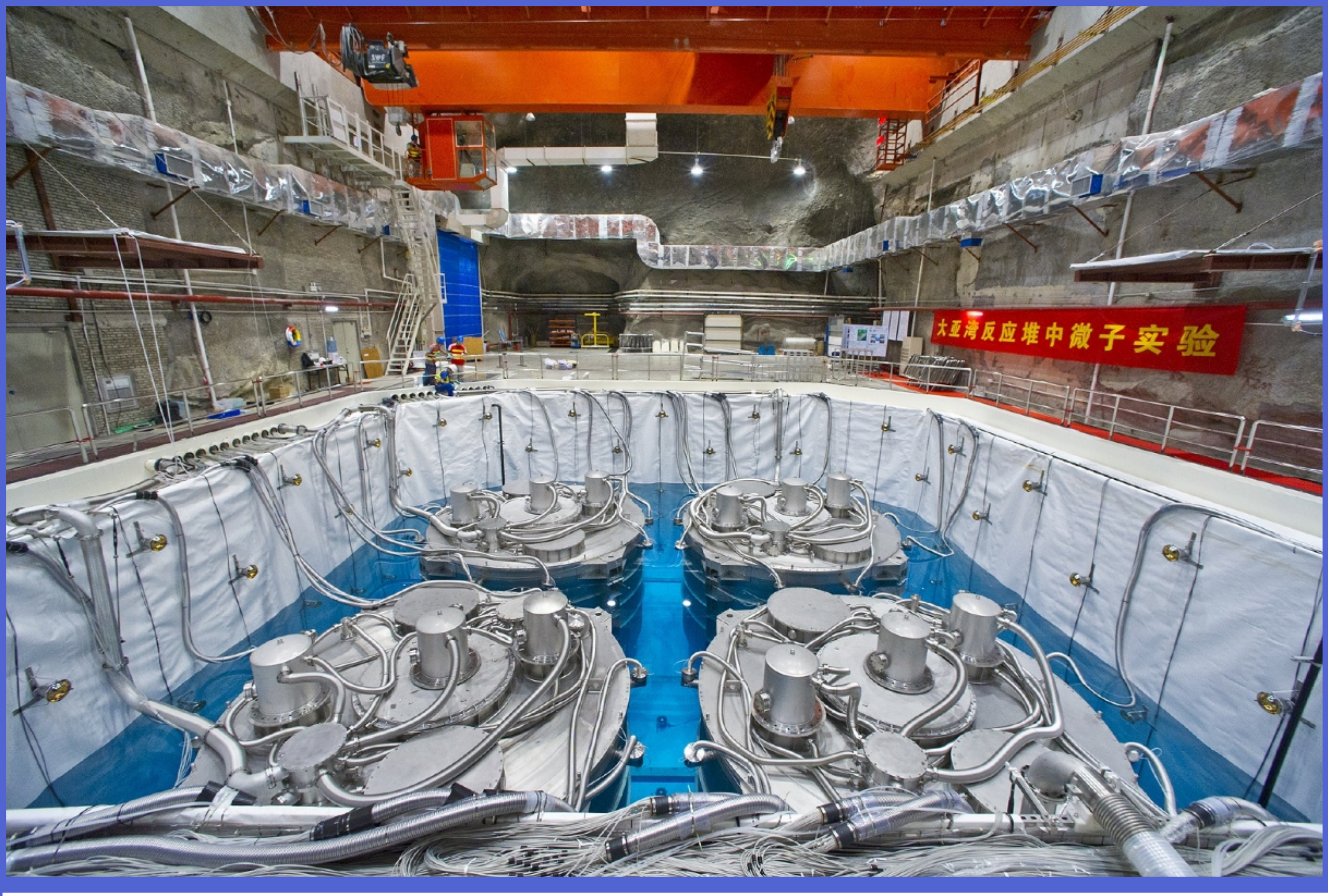
$$\sin^2 2\theta_{13} = 0.0856 \pm 0.0029$$

$$|\Delta m^2_{ee}| = (2.522^{+0.068}_{-0.070}) \times 10^{-3}\ \mathrm{eV}^2$$

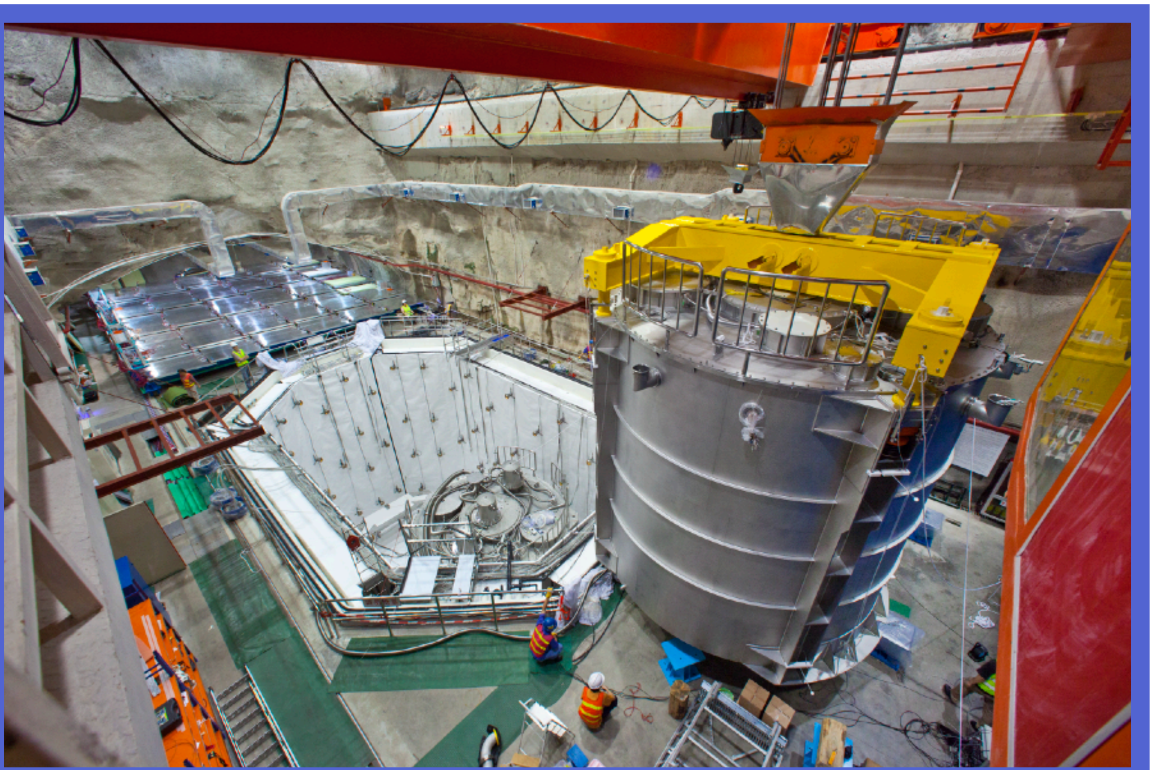
+ high-statistics absolute reactor antineutrino flux and shape measurements and evolution with fuel composition, searches for new physics, … etc.

- Daya Bay will run until 2020 and produce many other important results:
  - New oscillation measurement with **$\sin^2 2\theta_{13}$ uncertainty below 3%**
  - Results from campaign to study liquid scintillator recipes and purification methods with EH1-AD1, which was dedicated permanently to this purpose
  - Other measurements in preparation including:
    - New unfolded reactor antineutrino spectrum
    - Improved measurement of θ_{13} and Δm^2_{ee} via neutron capture on H
    - Search for ν signals coincident with gravitational wave events

Stay tuned!



Thank you for your attention!



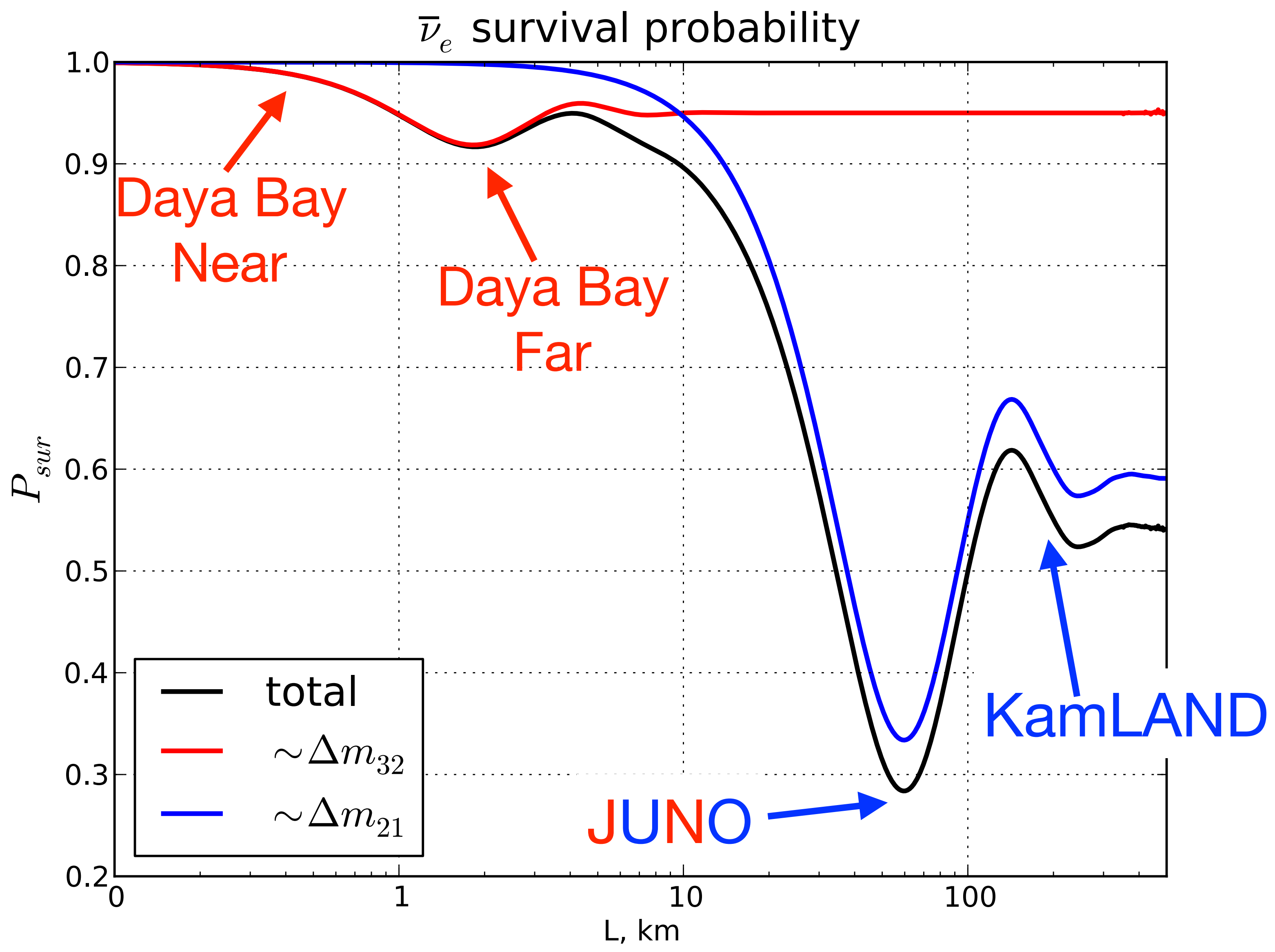
Backup

Daya Bay Basics

- Daya Bay was designed to measure the θ13 mixing angle:

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

- Keys to a precise measurement:
  - High-statistics
  - Suppressing backgrounds
  - **Keeping systematics under control**
    - Relative near/far measurement
    - Make detectors as similar as possible (design, construction & calibration)



With > 5 years of data, controlling **systematic uncertainties** becomes increasingly important

EH1-AD1

- After the special calibration campaign in early 2017, EH1-AD1 was taken down permanently and its Gd-LS replaced with JUNO LS
  - Loss of this detector will only impact $\sin^2 2\theta_{13}$ precision by $< 0.05\%$
  - Carrying out measurements on LS R&D in conjunction with subset of JUNO collaboration
    - Evaluating performance of purification methods and of different LS recipes, among other activities