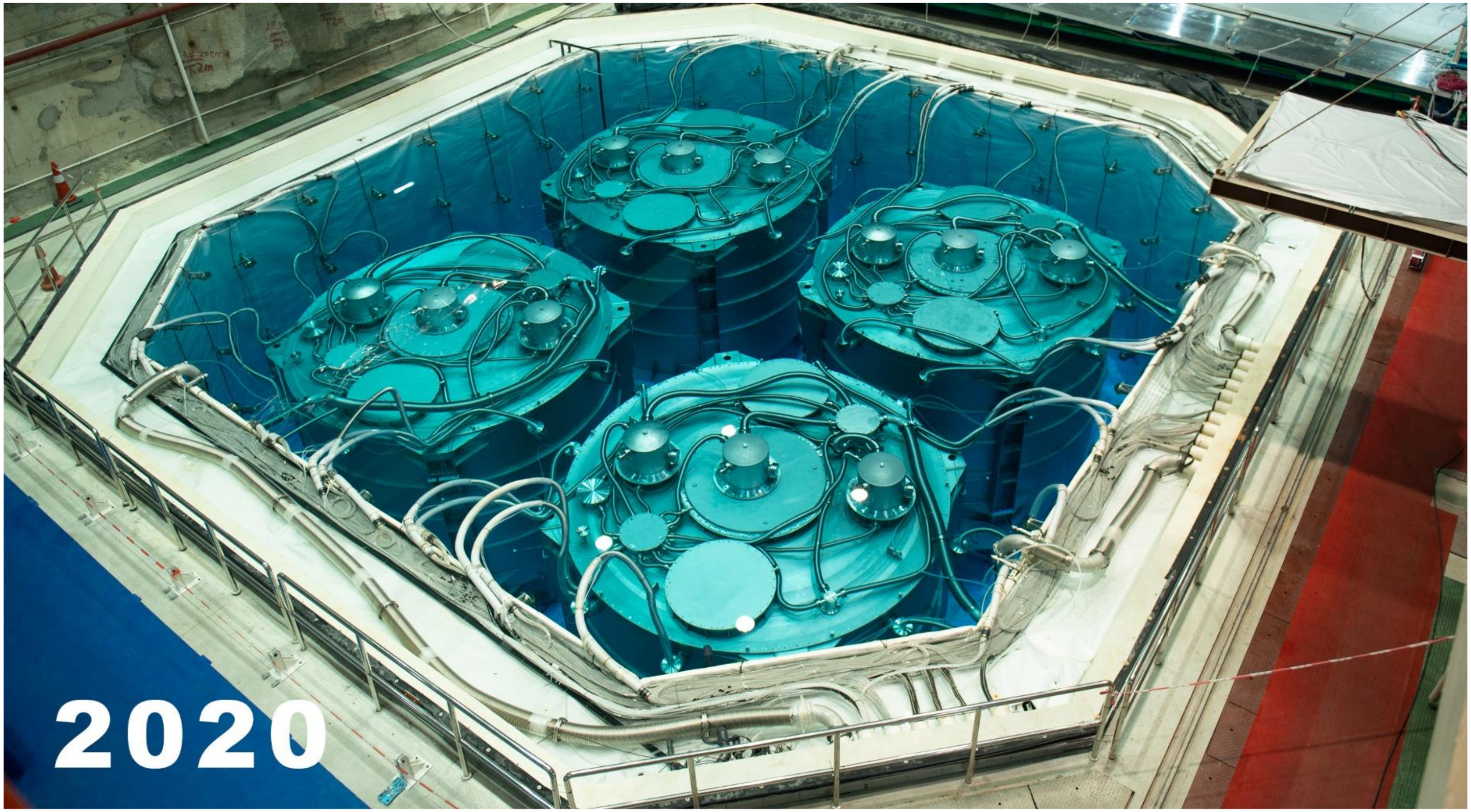
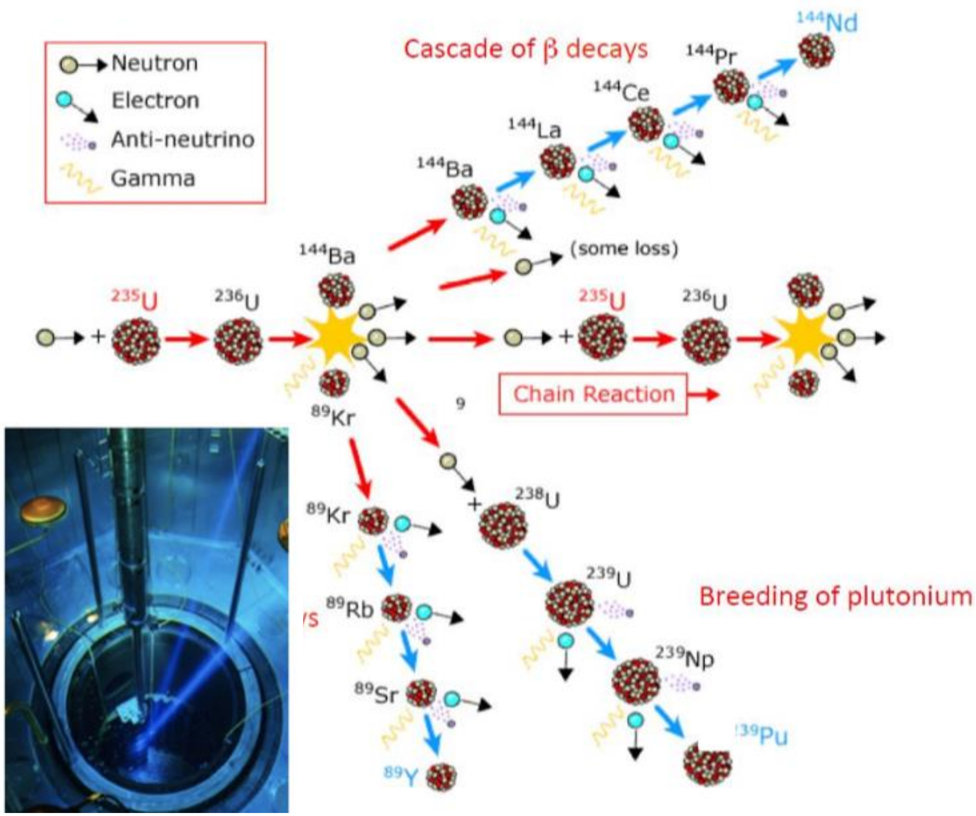
Latest Results from Daya Bay

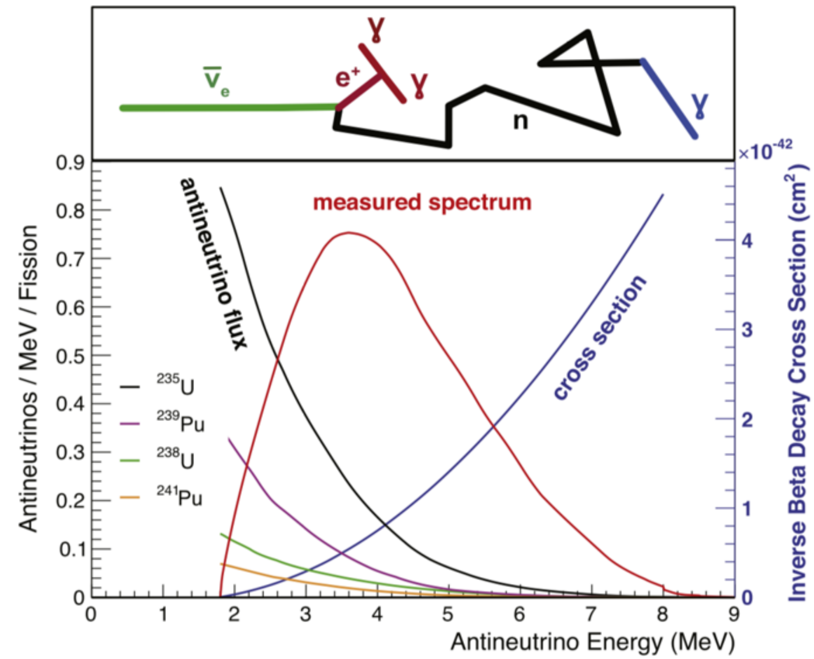


Jianrun Hu
On behalf of the Daya Bay Collaboration
Institute of High Energy Physics, China
XIX International Workshop on Neutrino Telescopes, 18-26 February 2021

Reactor Antineutrinos

- Electron antineutrinos produced in nuclear reactor cores
- Mainly from fission fragments of the fissile isotopes ^{235}U, ^{238}U, ^{239}Pu, and ^{241}Pu





Inverse β decay (IBD):

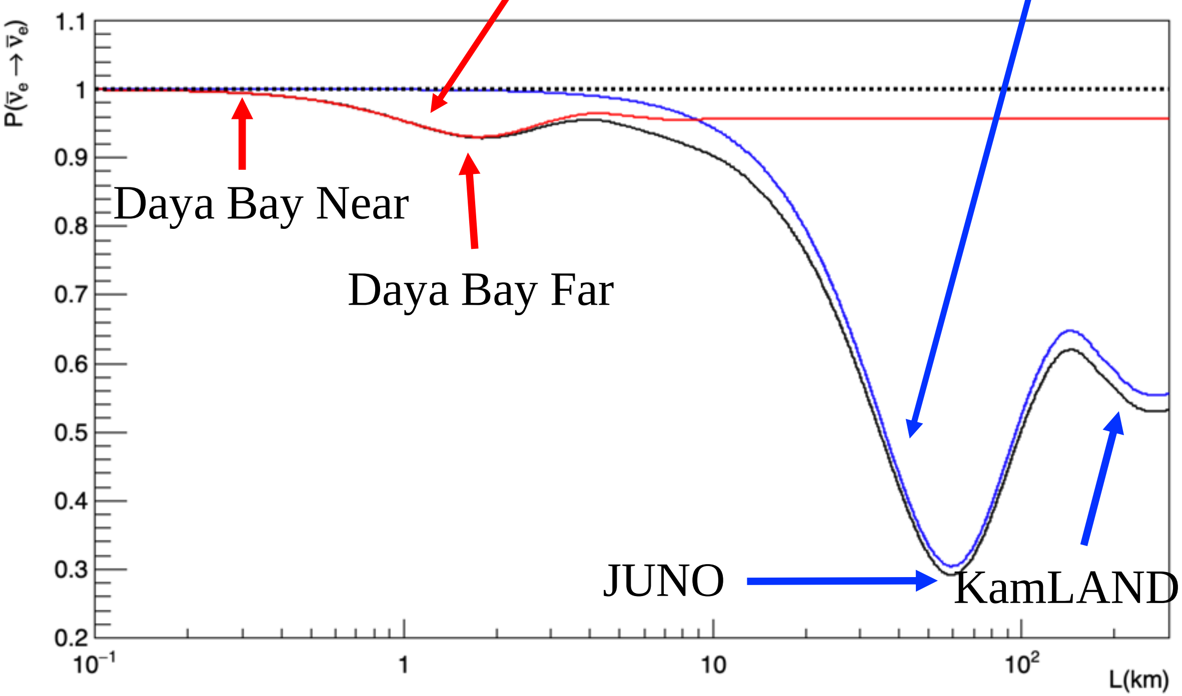
- Prompt: $E_{\text{prompt}} \approx E_{\nu} - 0.8$ MeV
- Delayed: nGd (~8 MeV)
  nH (~2.2 MeV)

Reactor Antineutrino Oscillation

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} (\cos^2\theta_{12} \sin^2\Delta_{31} + \sin^2\theta_{12} \sin^2\Delta_{32}) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\Delta_{21}$$

$$\approx 1 - \boxed{\sin^2 2\theta_{13} \sin^2\Delta_{ee}} - \boxed{\cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\Delta_{21}}$$

$$\Delta_{ij} = \Delta m^2_{ij} \frac{L}{4E}$$



Immune to CP violation and matter effects

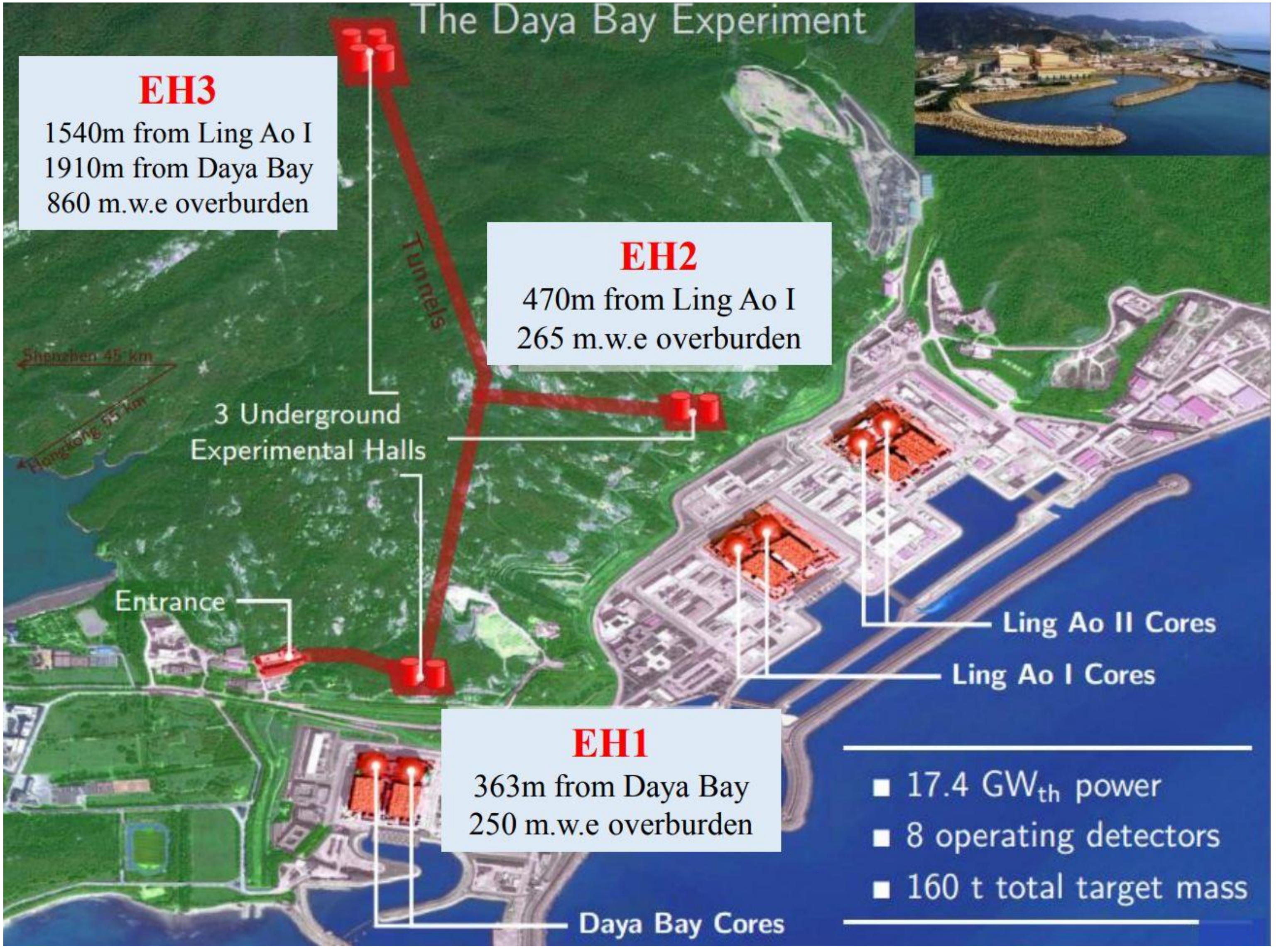
Key for a precise measurement:

- ✓ **Baseline Optimization**

$$L(\mathrm{m}) \sim \frac{\pi \cdot E\ (\mathrm{MeV})}{2.54 \cdot \Delta m^2 (\mathrm{eV}^2)}$$

- ✓ **Large statistics**
  - Large $\bar{\nu}_e$ flux
  - Large target mass (20 ton × 8)
- ✓ **Background control**
  - Large overburden
  - Detector shielding
  - Cosmic ray tagging
- ✓ **Systematics control**
  - Relative Far/Near measurement

Daya Bay Layout

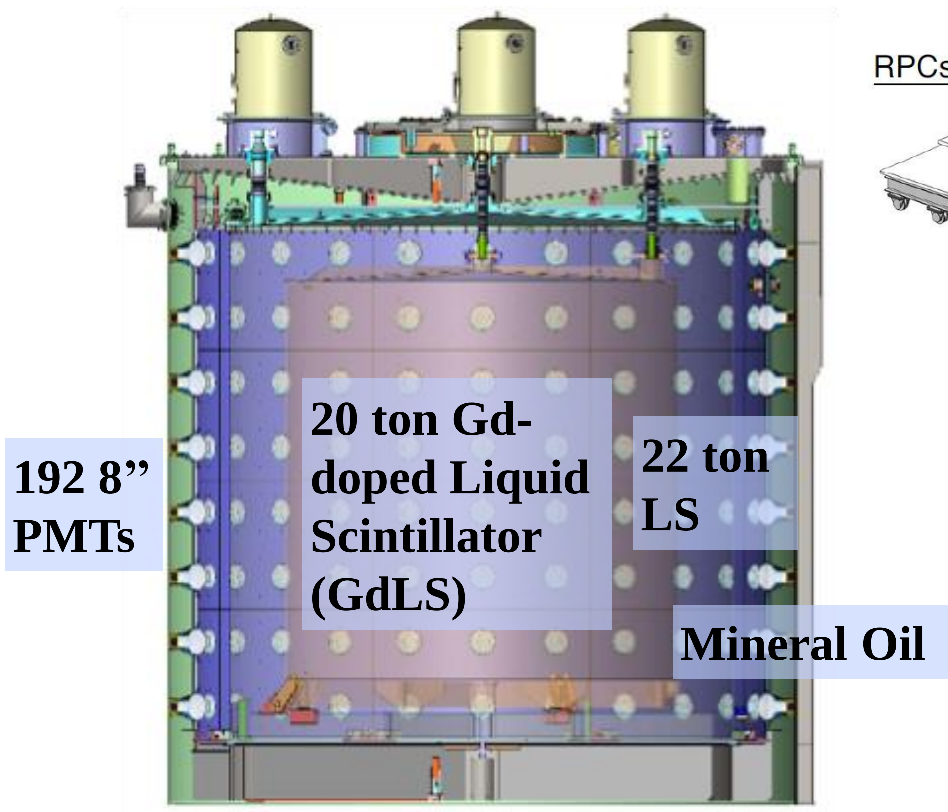


Detector System

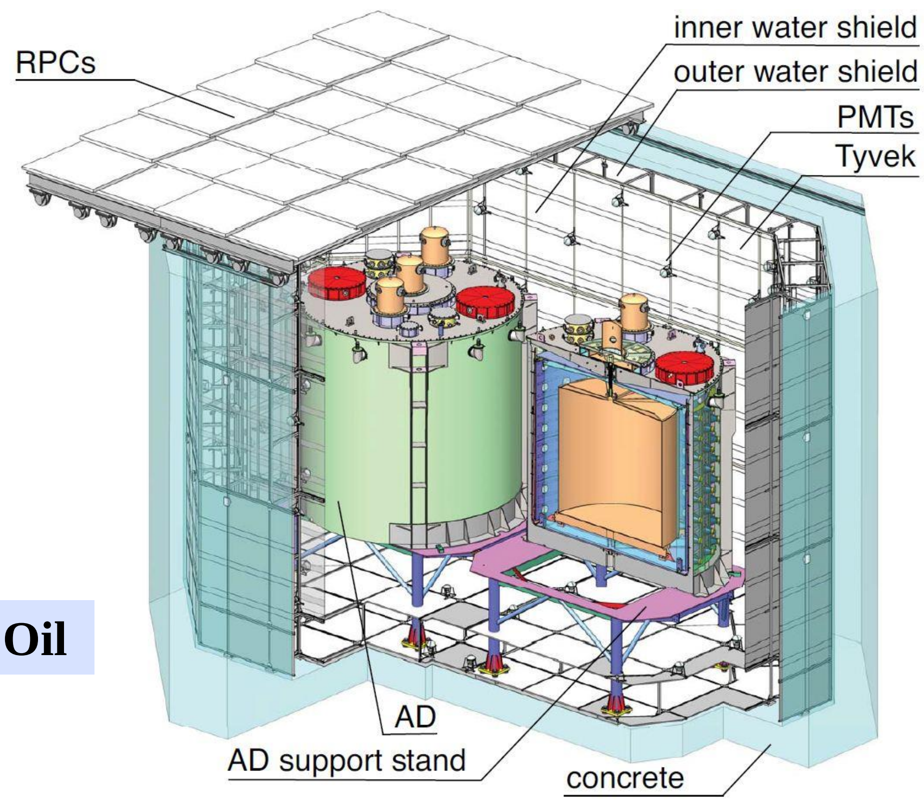
- Antineutrino Detectors (ADs):
  - "Three-zone" cylindrical modules

Energy resolution: $\sigma_E/E \cong 8.5\%/\sqrt{E[\mathrm{MeV}]}$

- Water Cherenkov Detector and RPCs:
  - Shield the ADs from natural radioactivity and neutrons
  - Veto cosmic-ray muons



*NIM A **811**, 133 (2016)*

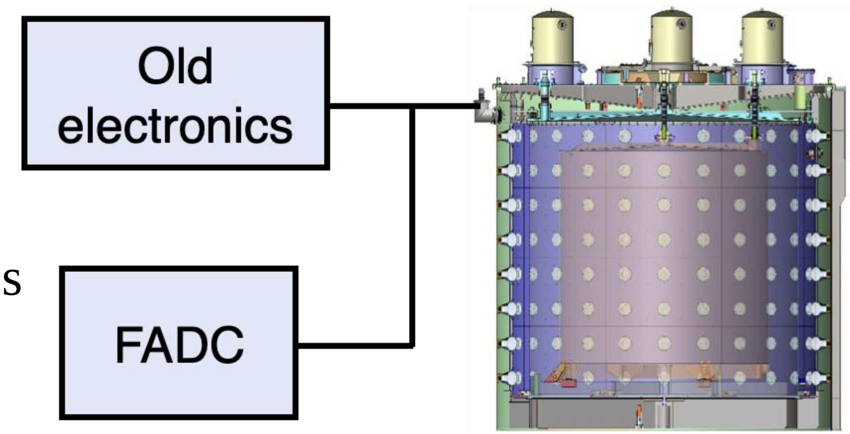


*NIM A **773**, 8 (2015)*

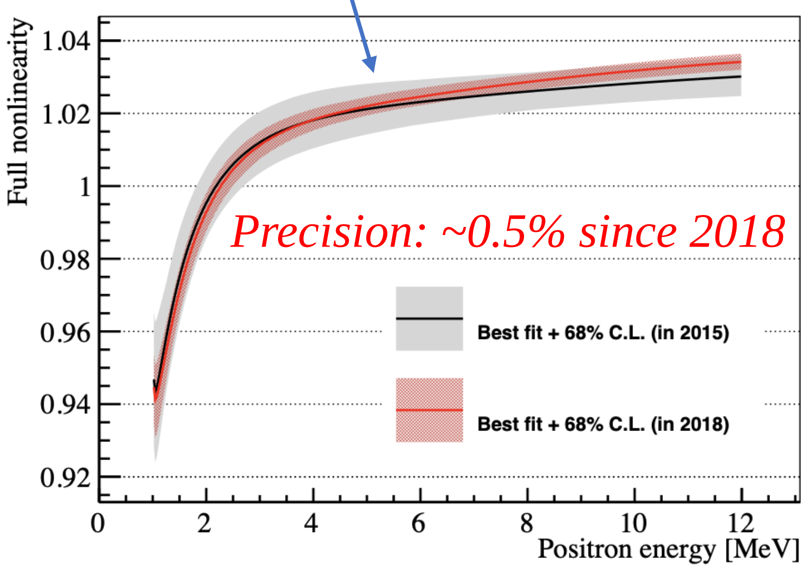
Energy Response

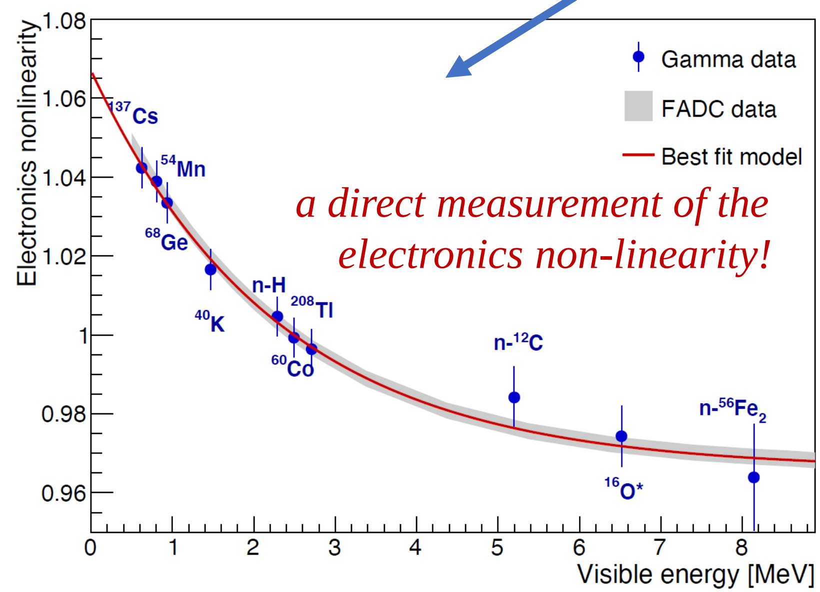
- Weekly calibration
  - ^{68}Ge, ^{241}Am^{13}C, ^{60}Co
- Special calibration campaign
  - ^{137}Cs, ^{54}Mn, ^{241}Am^{9}Be, ^{239}Pu^{13}C
- Special calibration in 2017: ^{60}Co sources with different enclosures
  - ➢ Optical shadowing effect
- Lead to <u>improvement on energy nonlinearity model</u>

- End of 2015: installation of a full FADC readout system in EH1-AD1



EH1-AD1

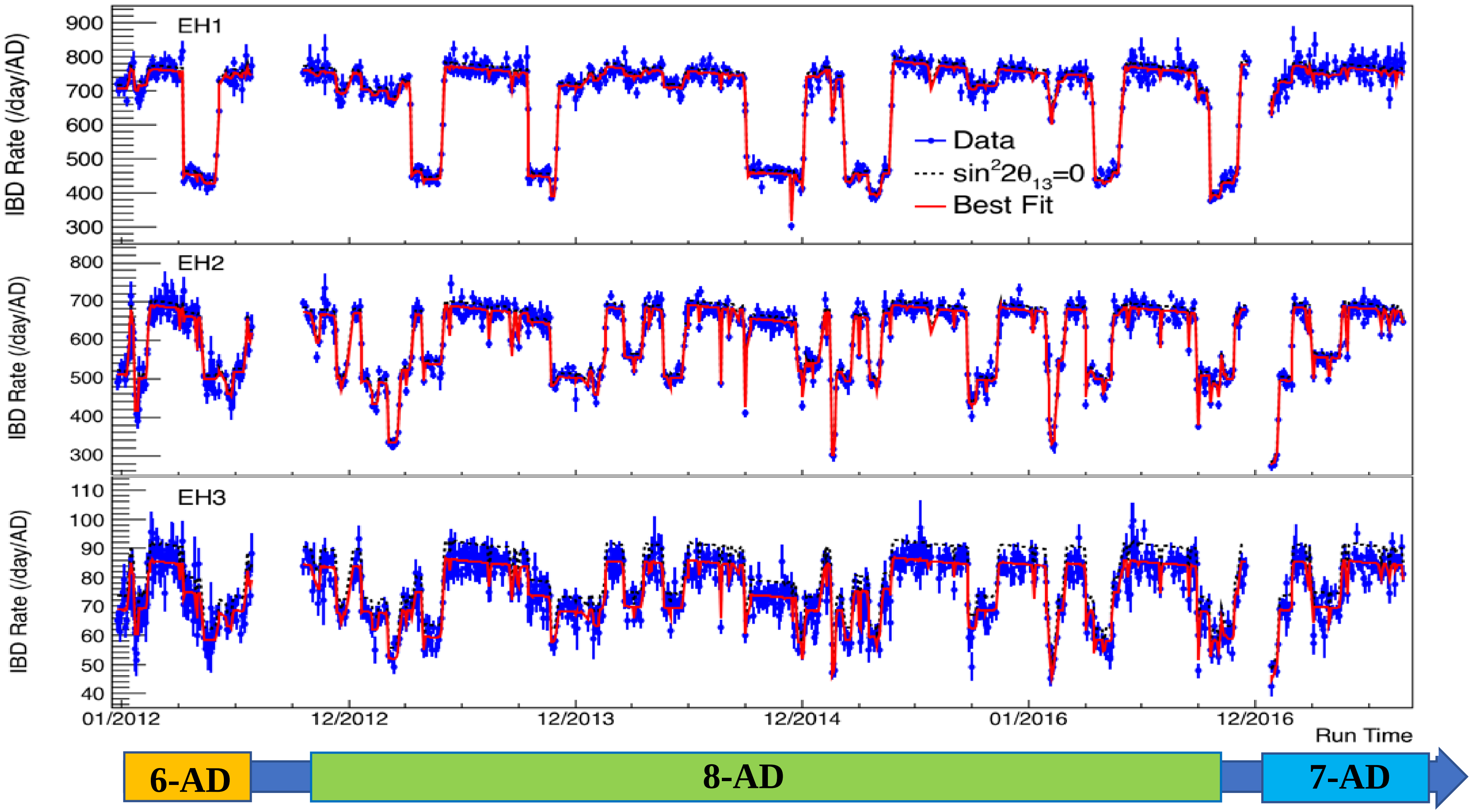




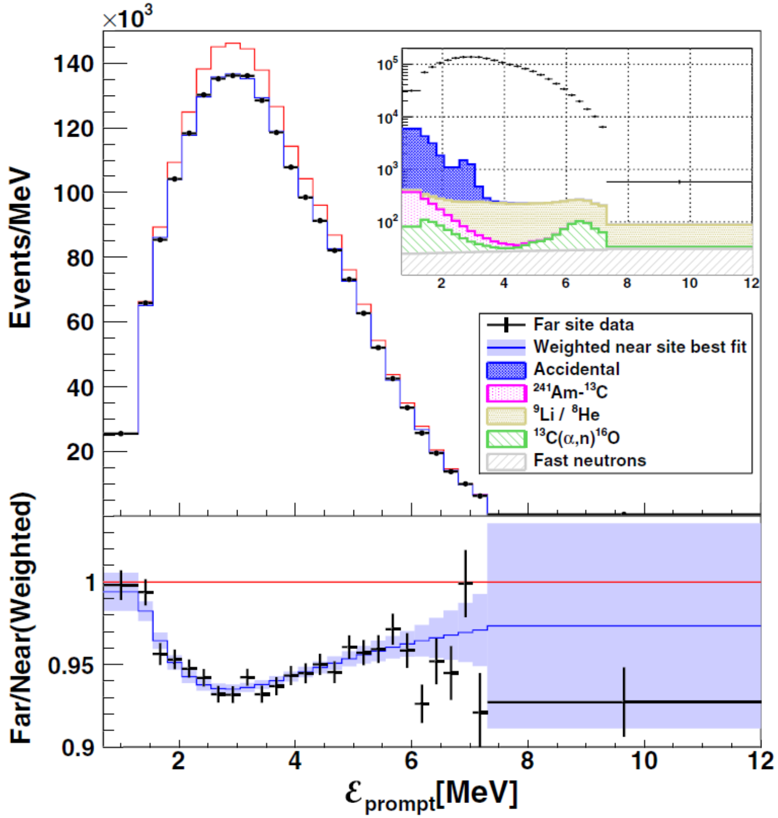
IBD Datasets

2011/12/24 – 2017/08/30 (1958 days)

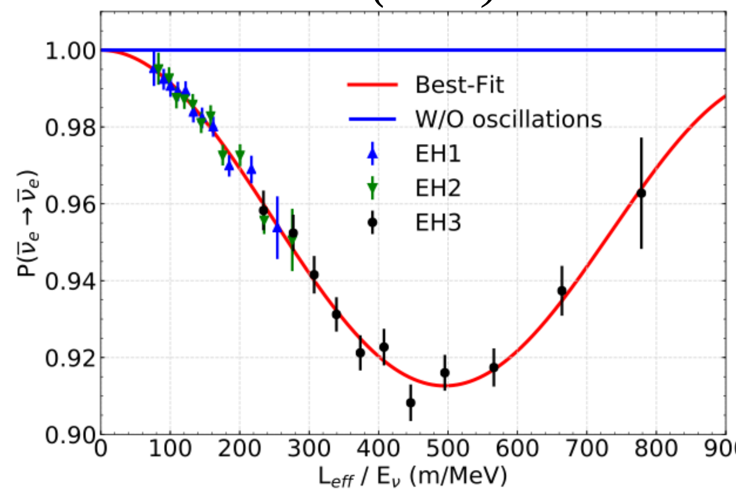
Site	EH1 (Near)	EH2 (Near)	EH3 (Far)
IBD candidates	1,794,417	1,673,907	495,421

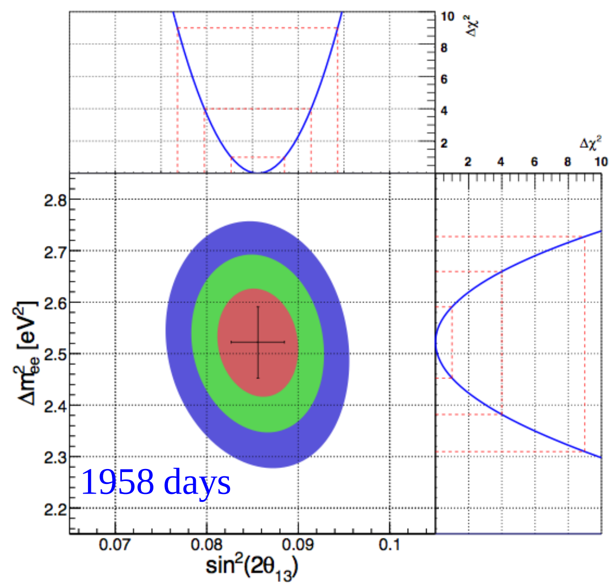


nGd Oscillation Results



PRL 121 (2018) 241805





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

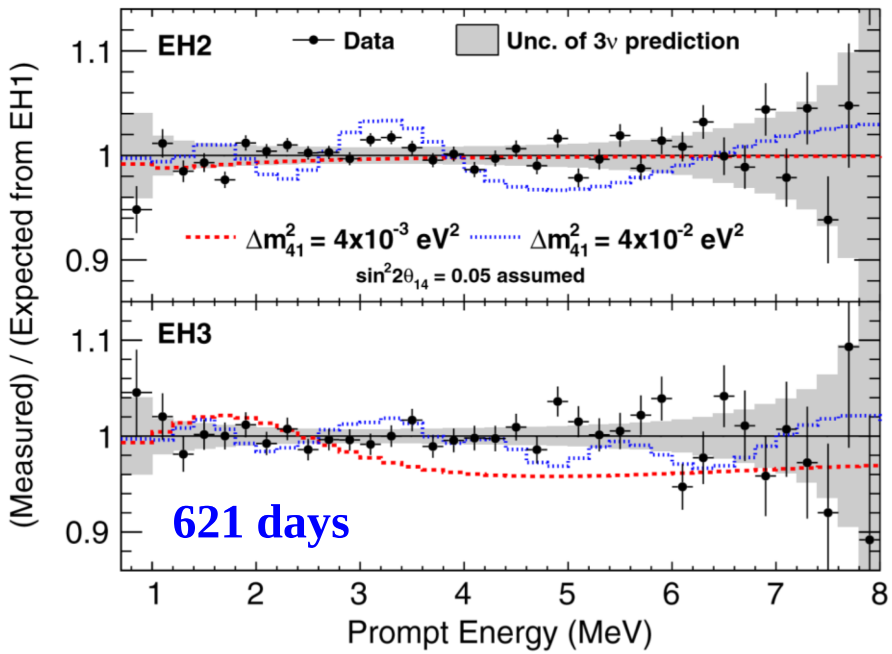
$$|\Delta m^2_{ee}| = (2.52 \pm 0.07) \times 10^{-3}\mathrm{eV}^2$$

$$\Delta m^2_{32} = (2.47 \pm 0.07) \times 10^{-3}\mathrm{eV}^2 \text{ (NO)}$$

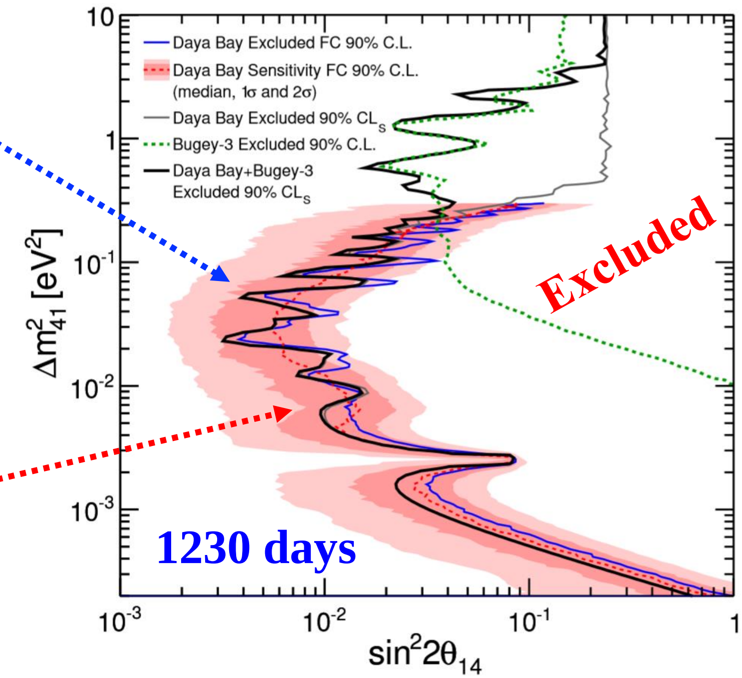
$$\Delta m^2_{32} = (-2.58 \pm 0.07) \times 10^{-3}\mathrm{eV}^2 \text{ (IO)}$$

Sterile Neutrino Search

PRL ***117*** *151802 (2016)*



PRL 125, 071801 (2020)



$$P(\bar{\nu}_e \to \bar{\nu}_e) \cong 1 - \cos^4\theta_{14}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{31}L}{4E_\nu}\right) - \sin^2 2\theta_{14}\sin^2\left(\frac{\Delta m^2_{41}L}{4E_\nu}\right)$$

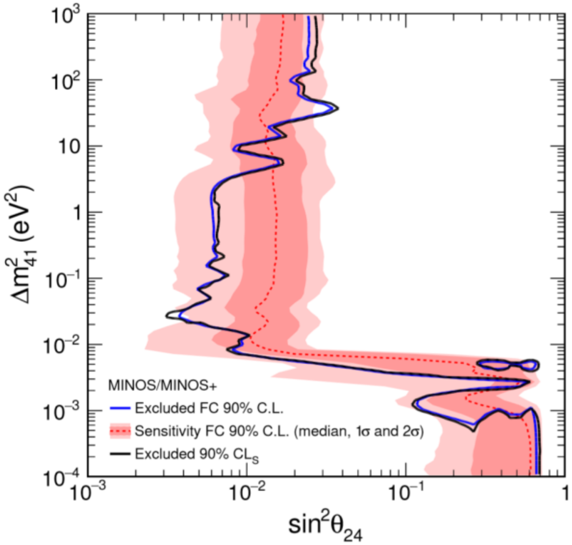
- Search for an additional oscillation frequency on top of established ones
- Data is consistent with 3-ν model; No light sterile neutrino signal observed
- Consistent results from Feldman-Cousins and CLs methods

The most stringent upper limit for light sterile neutrinos ($\Delta m^2 < 0.2$ eV^2)

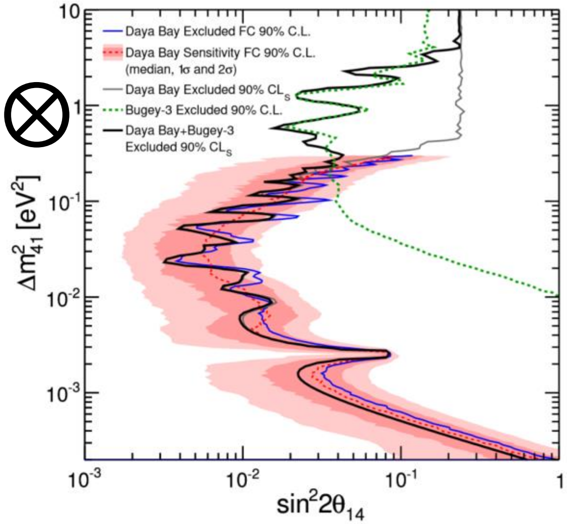
Joint Sterile Neutrino Searches

PRL ***122*** *091803 (2019)*

MINOS/MINOS+

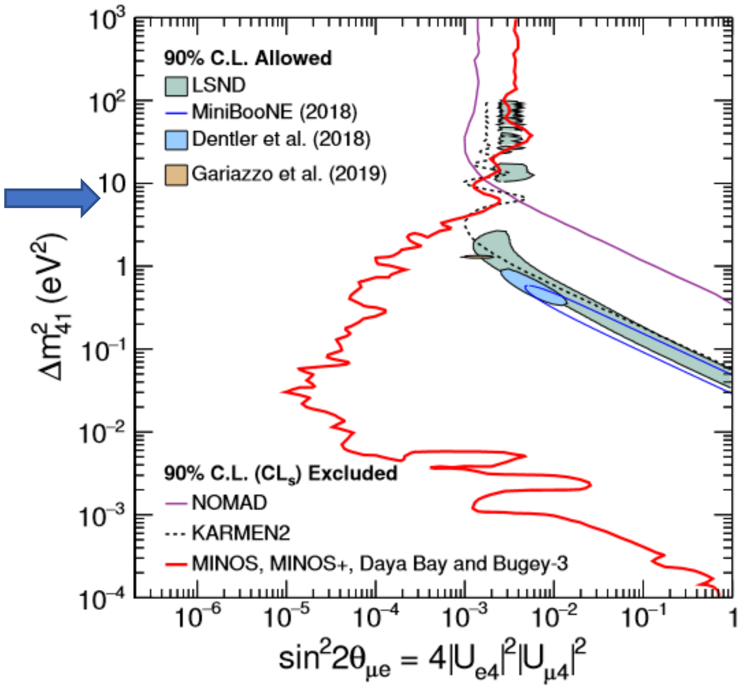


Daya Bay + Bugey-3



$$|U_{\mu 4}|^2 = \sin^2\theta_{24}\cos^2\theta_{14} \qquad |U_{e4}|^2 = \sin^2\theta_{14}$$

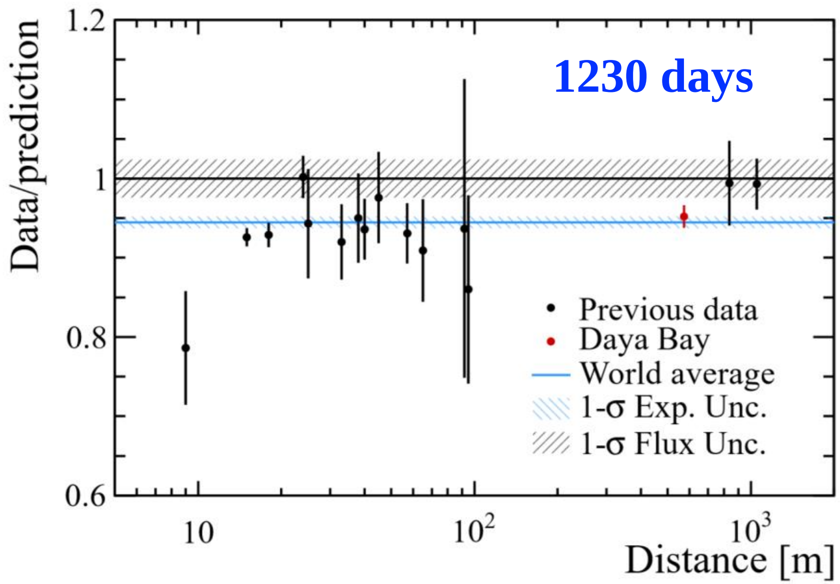
PRL 125, 071801 (2020)



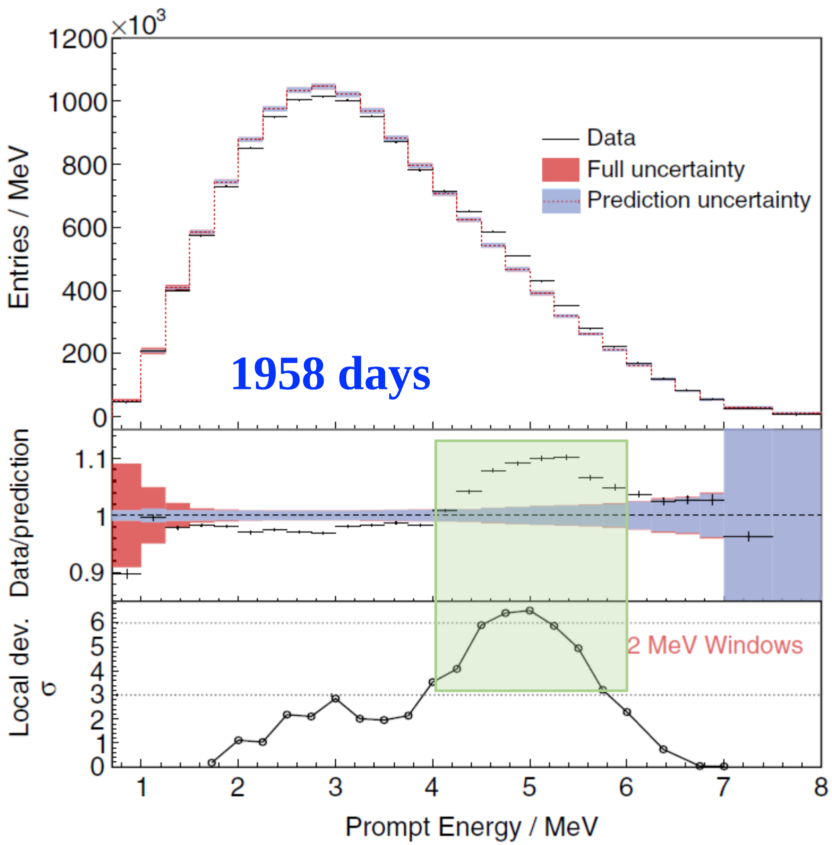
- The combined results can exclude the LSND and MiniBooNE signal region at $\Delta m^2_{41} < 5$ eV^2 at 90% C.L.
- Joint analysis with other experiments is underway.

Antineutrino Flux and Spectrum

*PRD **100** 052004 (2019)*



*PRL **123** 111801 (2019)*



$$R = \frac{data}{Model\ (Huber + Mueller)}$$

$$= 0.952 \pm 0.014(exp) \pm 0.023(model)$$

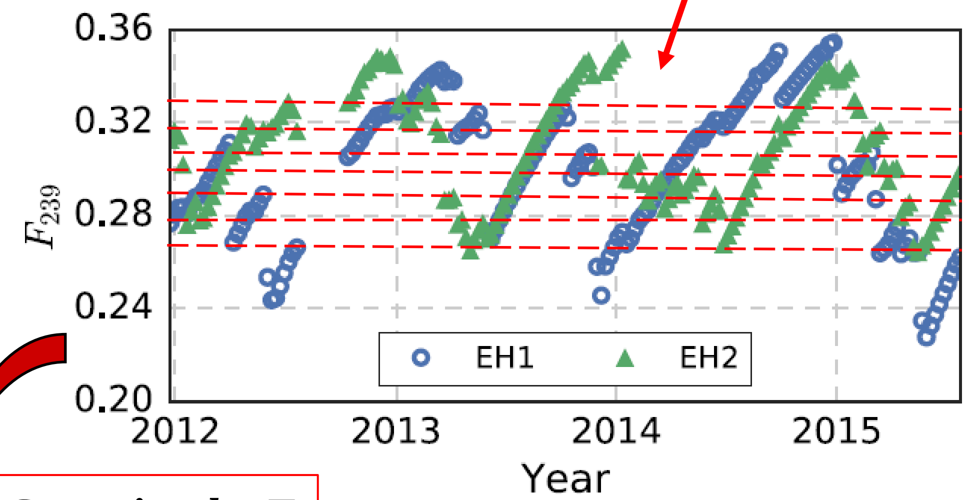
- Daya Bay result is consistent with previous experimental results
- Data/prediction spectrum shows an overall >5σ deviation, local deviation >6σ in maximum
- No effect on far/near relative measurement for θ_{13} and Δm^2_{ee}
- Spectral shape uncertainty (detector + background + statistic): ~0.5%

Fuel Evolution

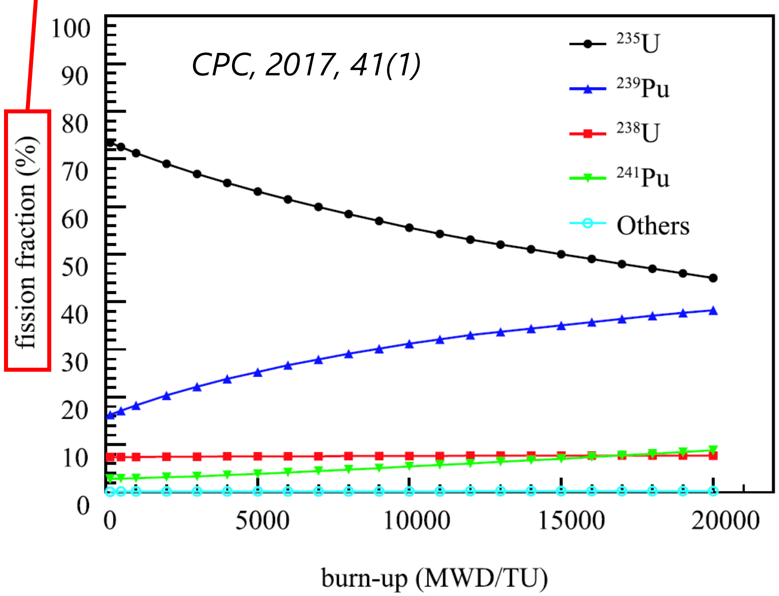
effective fission fraction

$$\sigma_f(t) = \sum_i \boxed{F_i(t)} \sigma_i$$

As the fuel burns in the reactors, the fission fractions and the antineutrino flux also evolve.

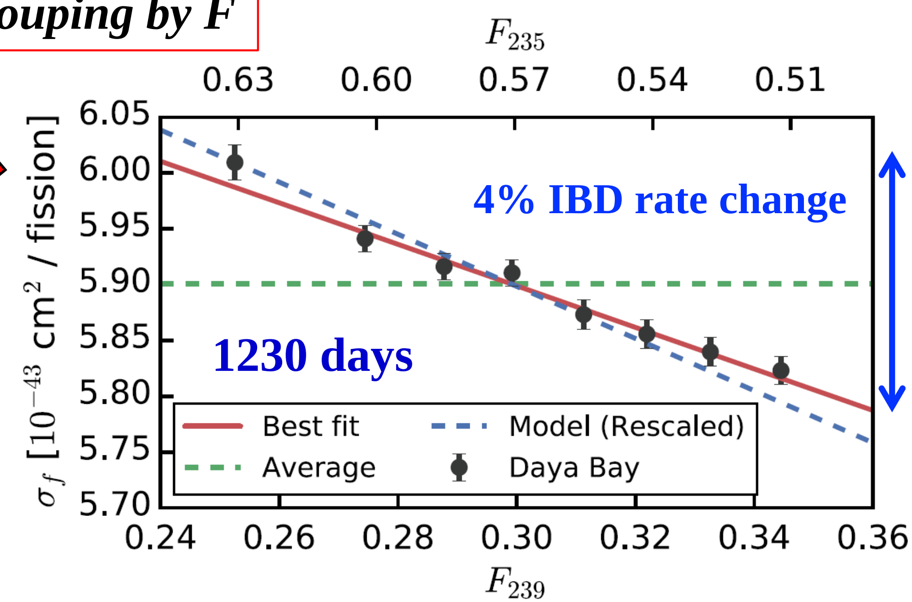


Contribution from different isotopes to the total neutrino flux.



Isotope fission fraction vs. burn-up from a simulation of a complete refueling cycle.

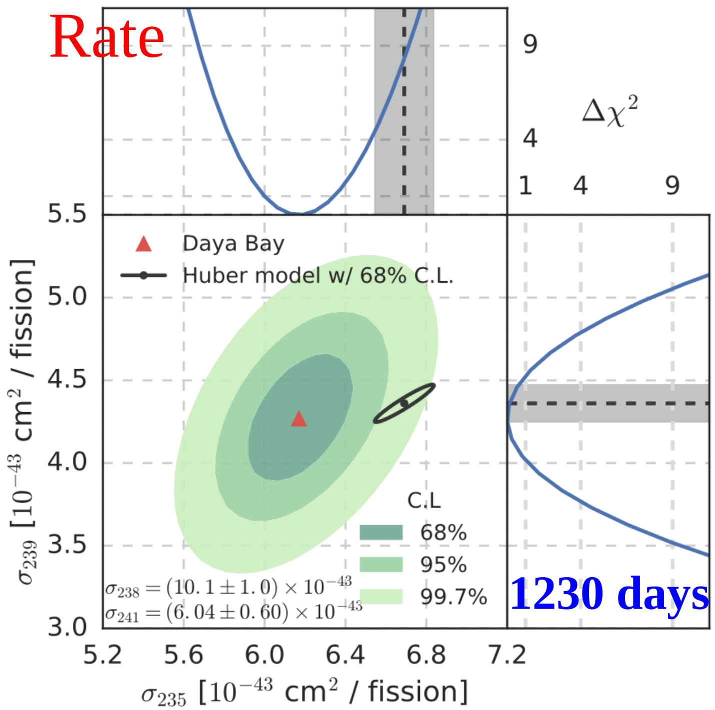
Grouping by F



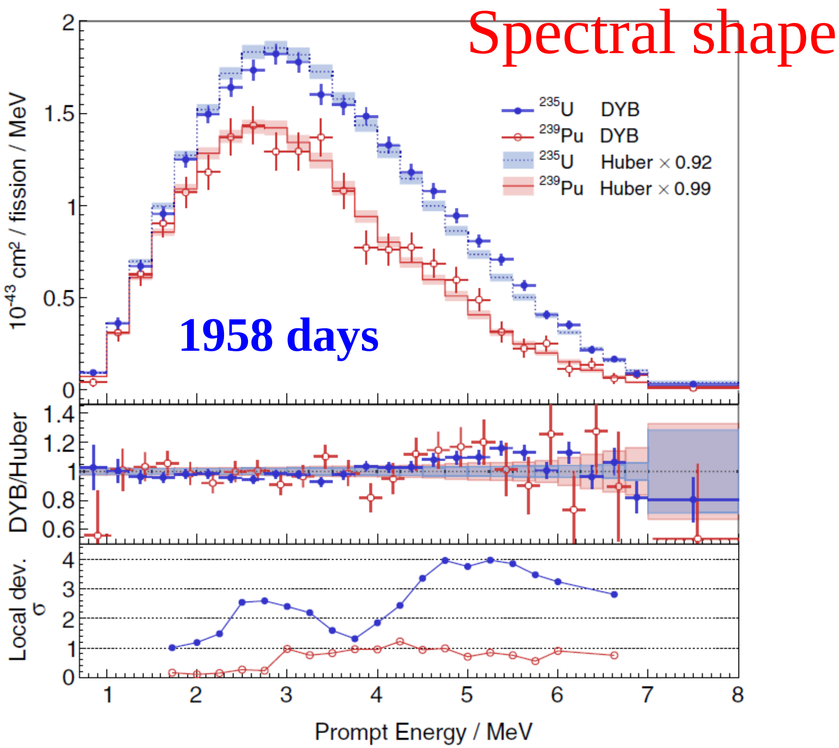
- Disfavor sterile neutrino only hypothesis at 2.6σ

Isotopic Yields and Spectra Measurements from Fuel Evolution Study

*PRL **118** 251801 (2017)*



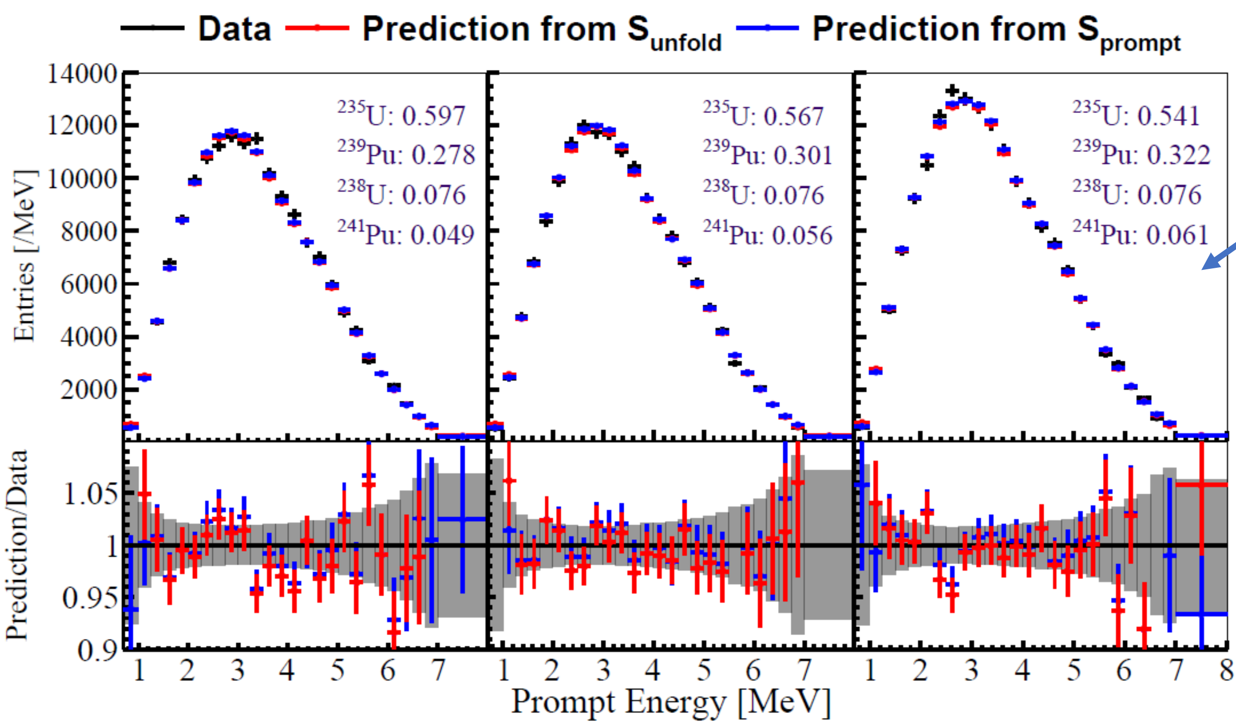
*PRL **123** 111801 (2019)*



- Daya Bay data suggest ^{235}U is mainly responsible for the Reactor $\bar{\nu}_e$ Anomaly
- First measurement of ^{235}U and ^{239}Pu spectra from commercial reactors
- Similar bump excess for ^{235}U and ^{239}Pu in 4~6 MeV
- Local spectral deviation from prediction: ^{235}U (4σ) and ^{239}Pu (1.2σ)
- Plan a joint fit with PROSPECT to have a better measurement of the ^{235}U spectral shape

Data-based Prediction for Other Experiments

- Provide a data-based prediction for other reactor antineutrino experiments.
  - With known reactor fission fractions, the technique can predict the energy spectrum to a 2% precision.
- Total and isotopic antineutrino energy spectra is unfolded by Wiener-SVD method.



Example: giving predictions for Daya Bay itself given different fission fractions.

arXiv:2102.04614. Supplemental materials and examples are provided.

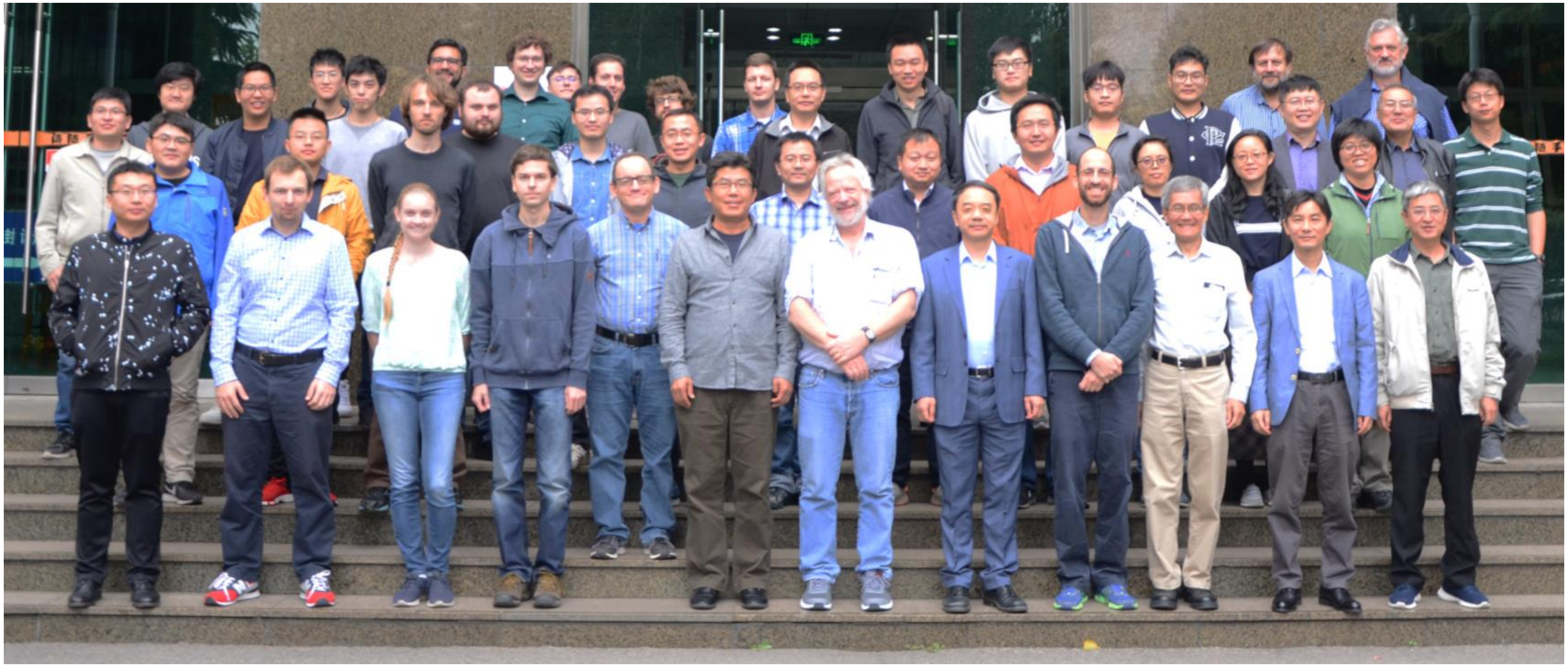
Summary

- Daya Bay has made the most precise measurements on $\sin^2 2\theta_{13}$ and $|\Delta m^2_{ee}|$ with ~3% precision
  - Expected final precision of **2.7%** on $\sin^2 2\theta_{13}$ is likely to be the standard for decades to come
  - $|\Delta m^2_{32}|$ has a precision comparable to that of accelerator experiments
- Set the most stringent upper limit for light sterile neutrino with $\Delta m^2_{41} < 0.2\ \mathrm{eV}^2$
- Reactor fuel evolution is observed
  - Disfavor sterile neutrino as the main explanation of Reactor Antineutrino Anomaly
  - First measurement of ^{235}U and ^{239}Pu spectra from commercial reactor
- Antineutrino energy spectra are unfolded to provide data-based prediction for other experiments.
- $\bar{\nu}_e$ associated with GW events is searched. Refer to backup.

Prospect

- After 9 years' data taking, Daya Bay has fulfilled its historic mission and was shut down at the end of 2020.
- Final Daya Bay results expected by 2022

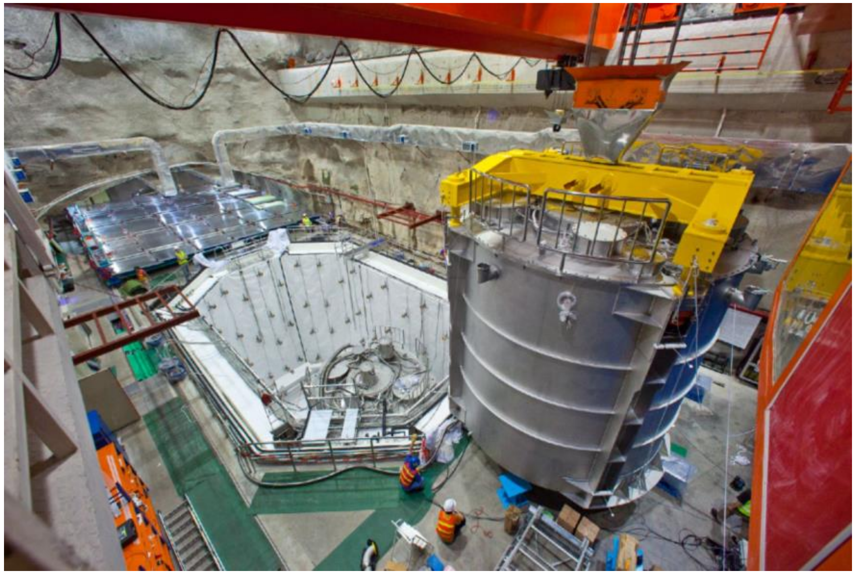
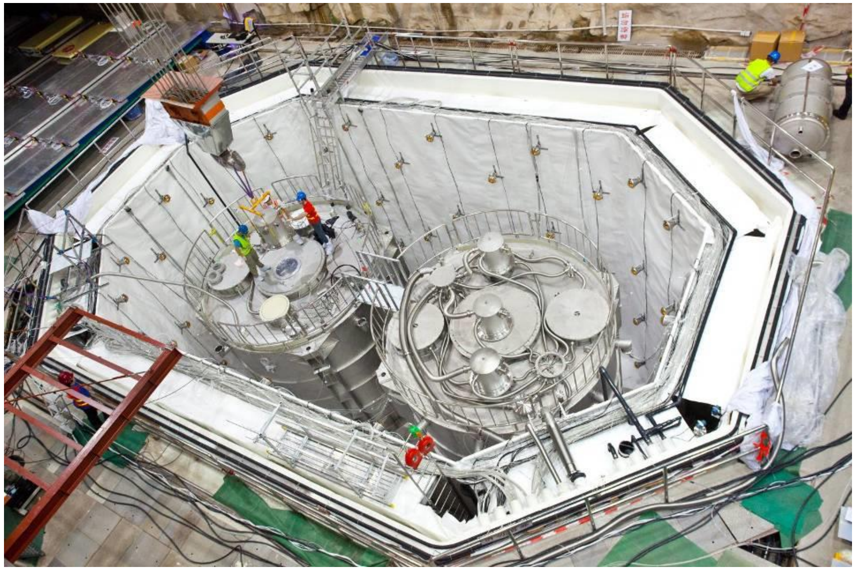
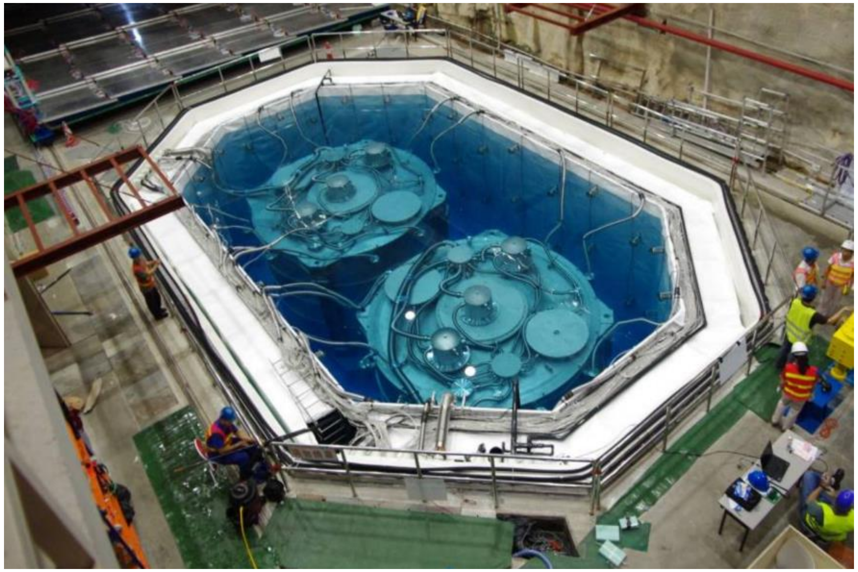
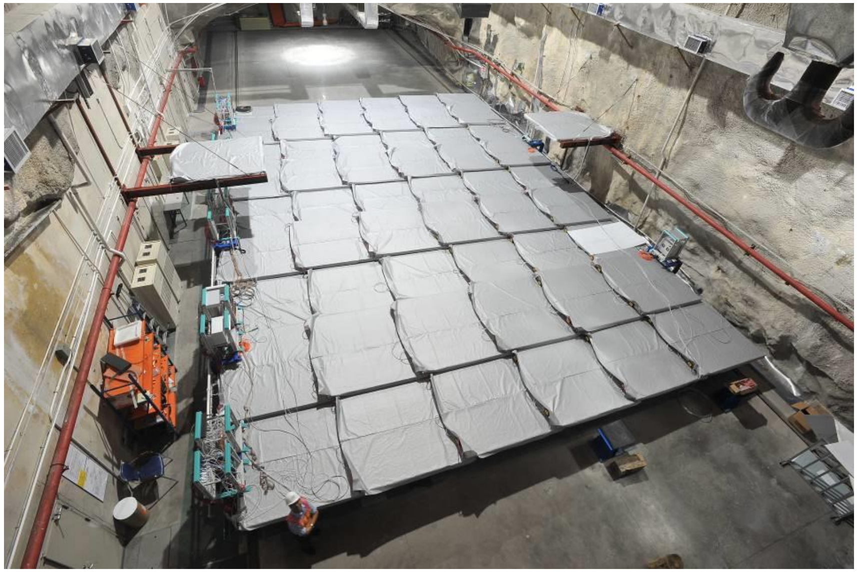
Thank you for your attention!



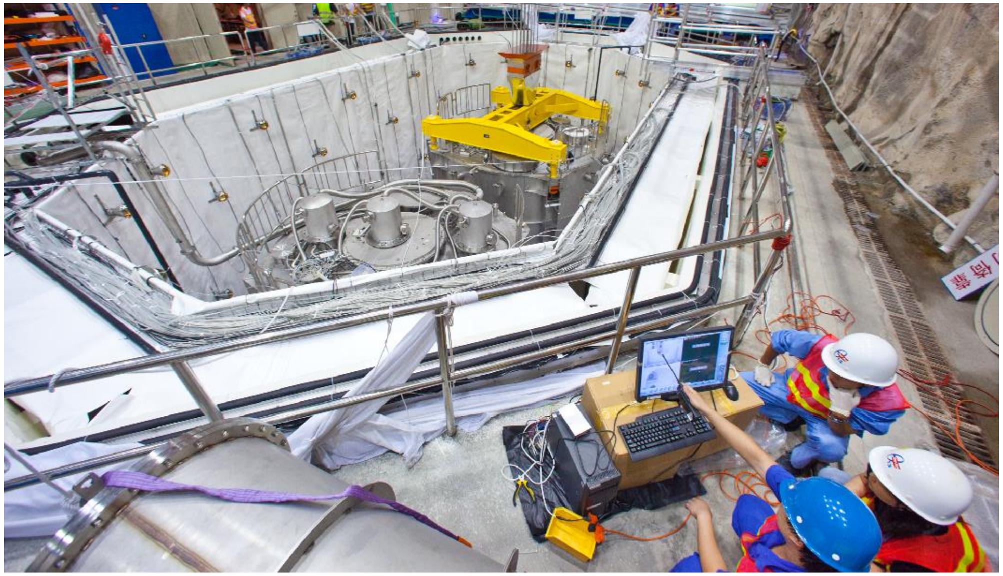
The Daya Bay Collaboration

Backup

A Selection of Pictures

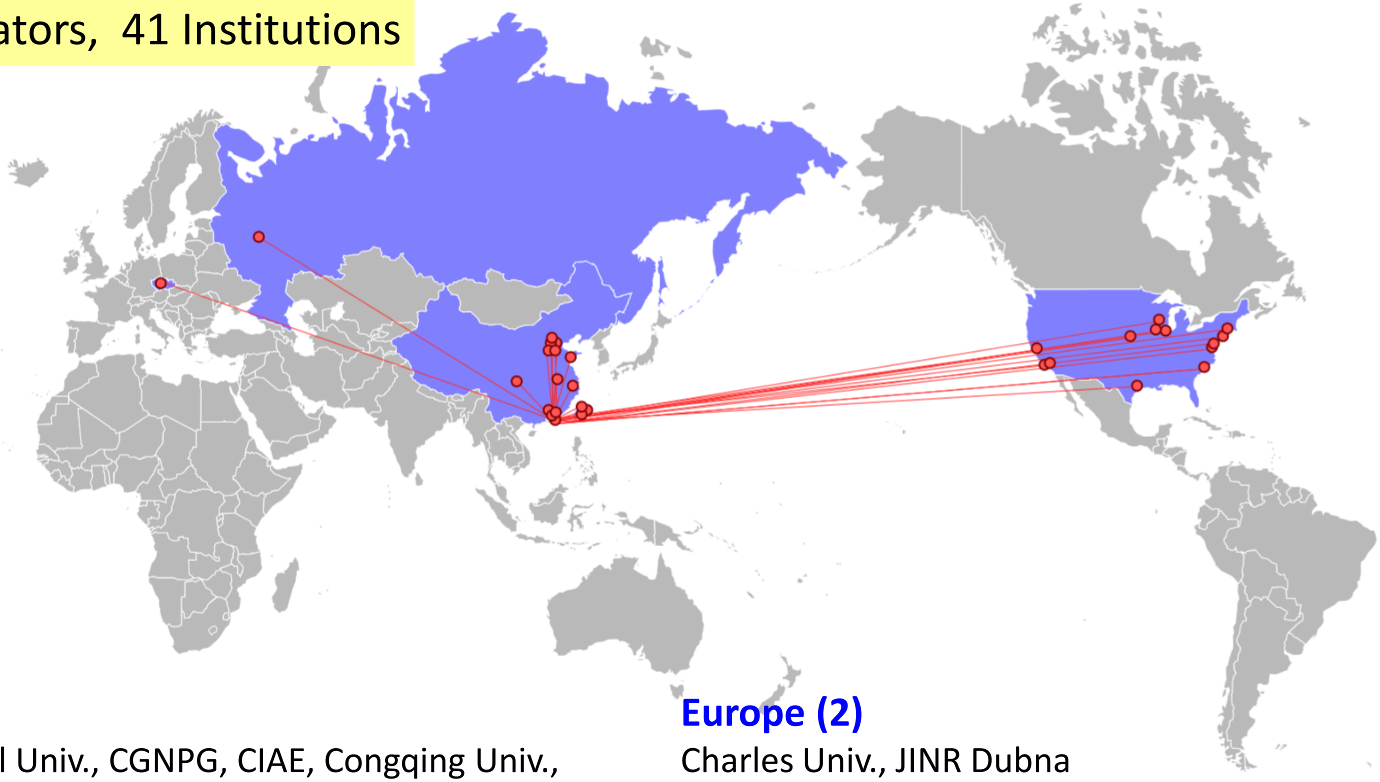





A Selection of Pictures



The Daya Bay Collaboration

191 Collaborators, 41 Institutions



Asia (24)

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

Europe (2)

Charles Univ., JINR Dubna

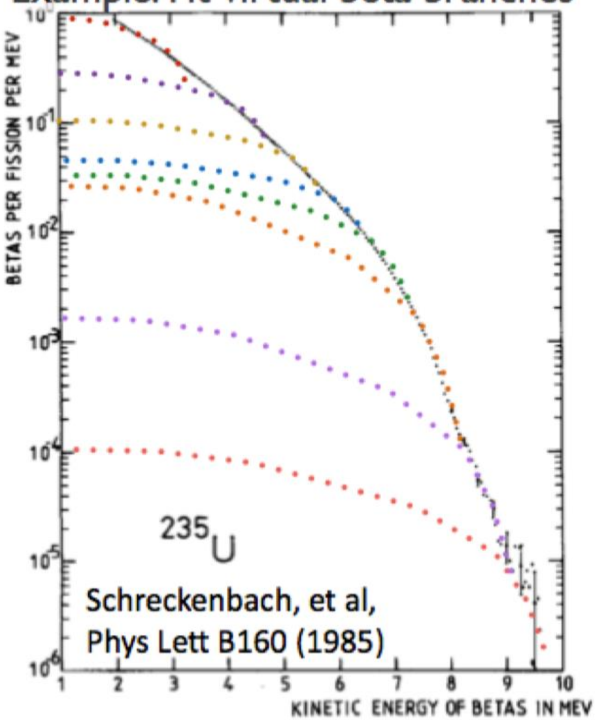
North America (15)

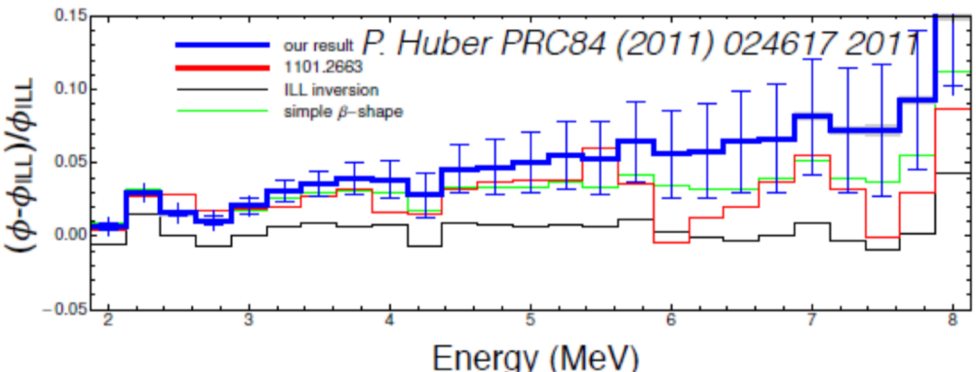
Brookhaven Natl Lab, Illinois Institute of Technology, Iowa State, Lawrence Berkeley Natl Lab, Princeton, Siena College, Temple University, UC Berkeley, Univ. of Cincinnati, Univ. of California Irvine, UIUC, Univ. of Wisconsin, Virginia Tech, William & Mary, Yale

Reactor $\bar{\nu}_e$ Flux Prediction

- Summation (ab initio) method
  - > 6000 decay branches
  - Missing data in the nuclear database
  - ~30% forbidden decays
  - ~ 10% uncertainty
- Conversion method
  - Convert ILL measured ^{235}U, ^{239}Pu and ^{241}Pu β spectra to $\bar{\nu}_e$ with >30 virtual β-decay branches
  - Old: ILL + Vogel (^{238}U) model (1980s)
  - New: Huber + Mueller (^{238}U) model (2011)
  - ~ 2.4% uncertainty

Example: Fit virtual beta branches

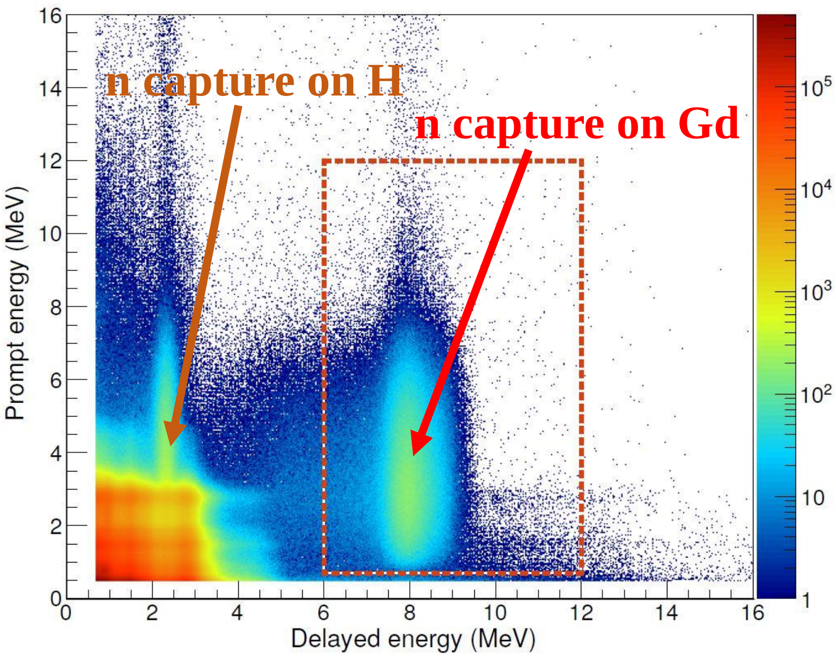




IBD Selection (nGd)

Prompt-delayed pairs:

- $1\ \mu s < \Delta t < 200\ \mu s$
- $0.7\ MeV < E_{prompt} < 12\ MeV$
- $6\ MeV < E_{delayed} < 12\ MeV$

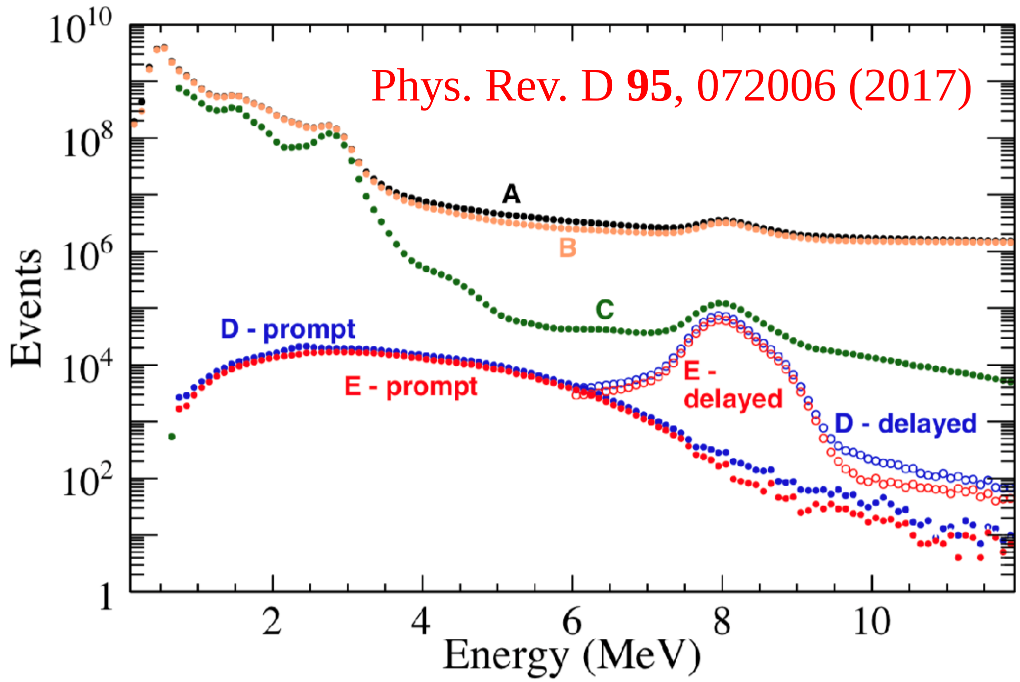


- **Selection:**

(A) All signals (B) Flasher removal

(C) Water-pool muon veto

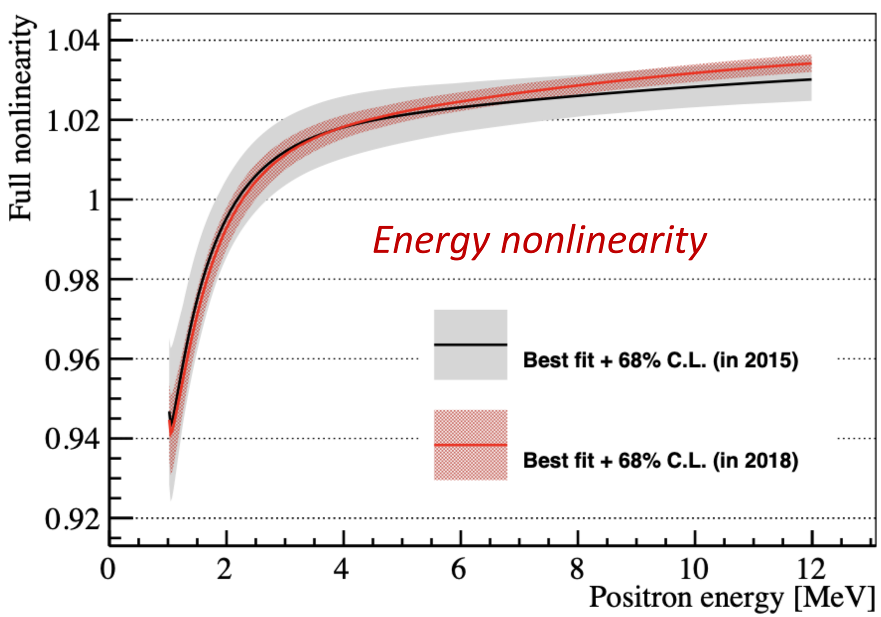
(D) Coincidence pair (E) AD muon veto



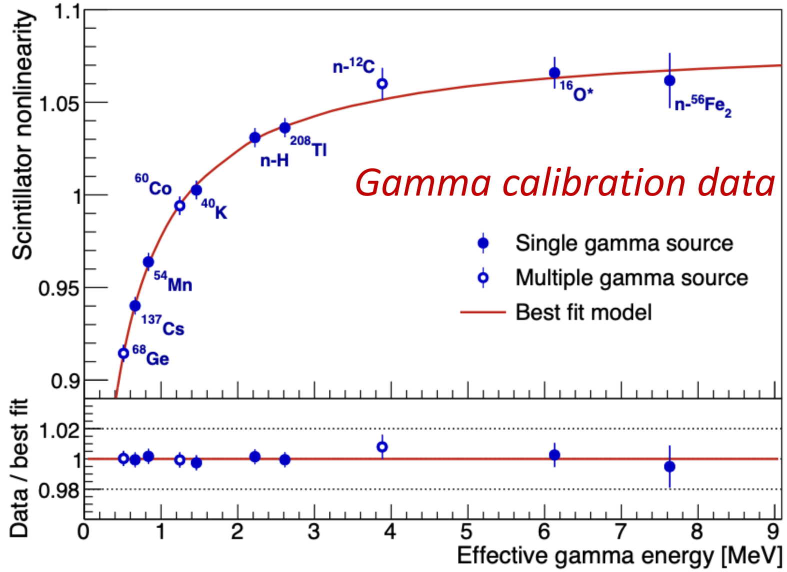
- < 2% background in all ADs
- Background uncertainty in $\bar{\nu}_e$ rates: ~0.12% (all ADs).

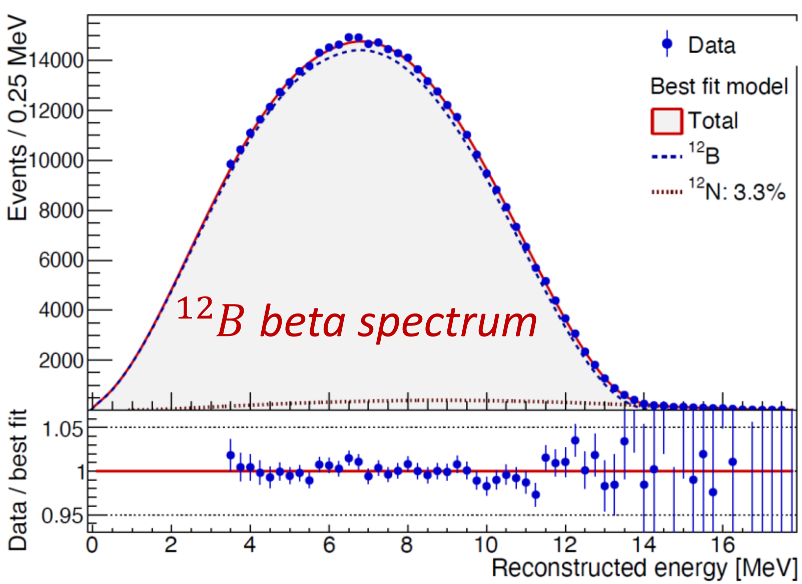
Energy Nonlinearity Model

- Model built by a combined fit to mono-energetic gamma lines and ^{12}B beta-decay spectrum
- Improved uncertainty of nonlinearity energy model: ~1% → ~0.5% since 2018.



NIMA 230-242,940(2019)



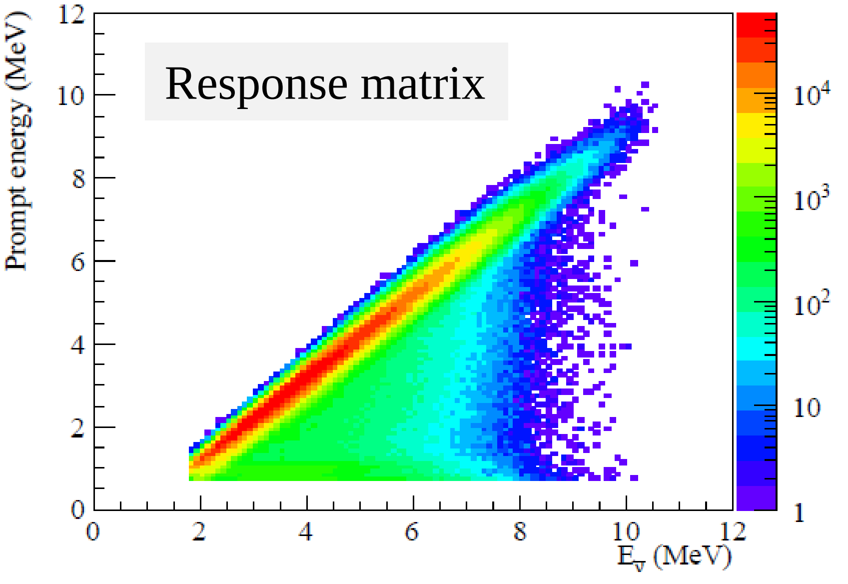


Detector Response

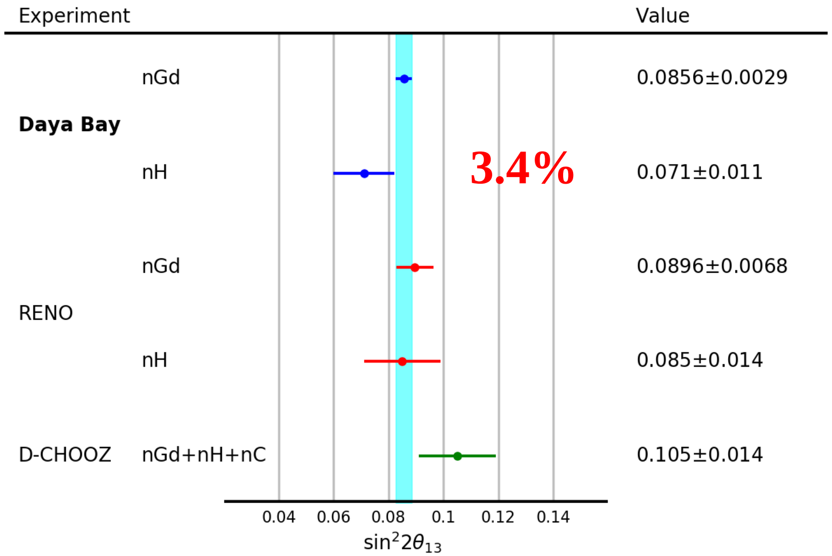
- Detector response includes effects of
  - IBD neutron recoiling
  - IAV effect: energy loss in inner acrylic vessel
  - Nonlinearity (scintillation quenching, electronics response)
  - Energy Resolution: ~8.5% at 1 MeV

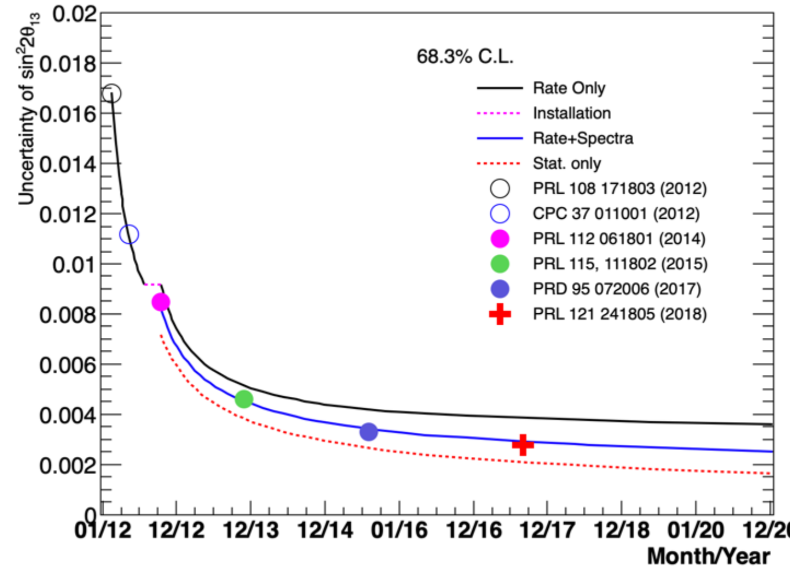
Detection efficiency

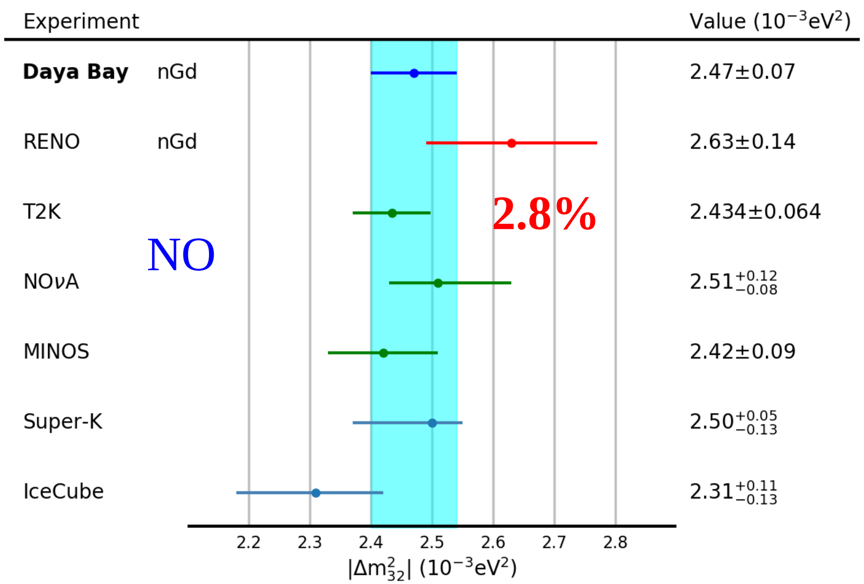
	Efficiency	Uncertainty	
		Correlated	Uncorrelated
Target protons	-	0.92%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Prompt Energy cut	99.8%	0.10%	0.01%
Multiplicity cut	-	0.02%	0.01%
Capture time cut	98.7%	0.12%	0.01%
Delayed neutron cut	81.48%	0.74%	0.13%
Live time	-	0.002%	0.01%
Combined	80.2%	1.2%	0.13%

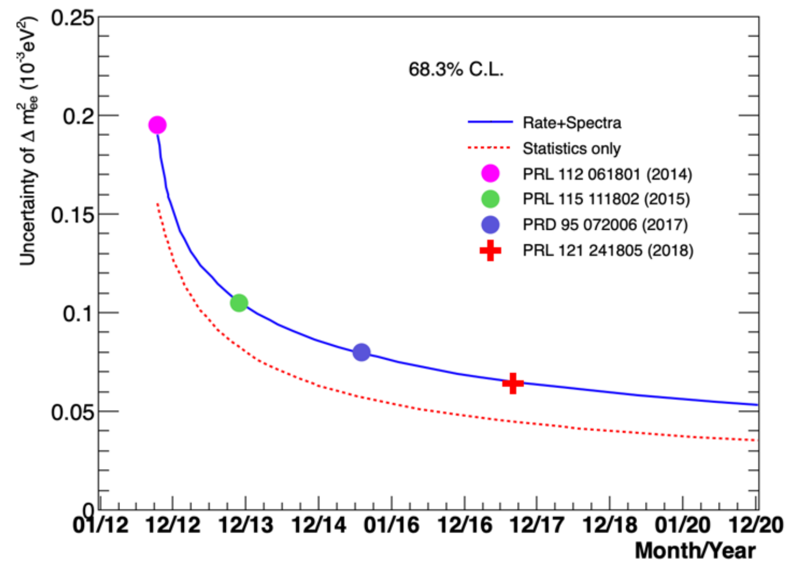


Precision Measurements









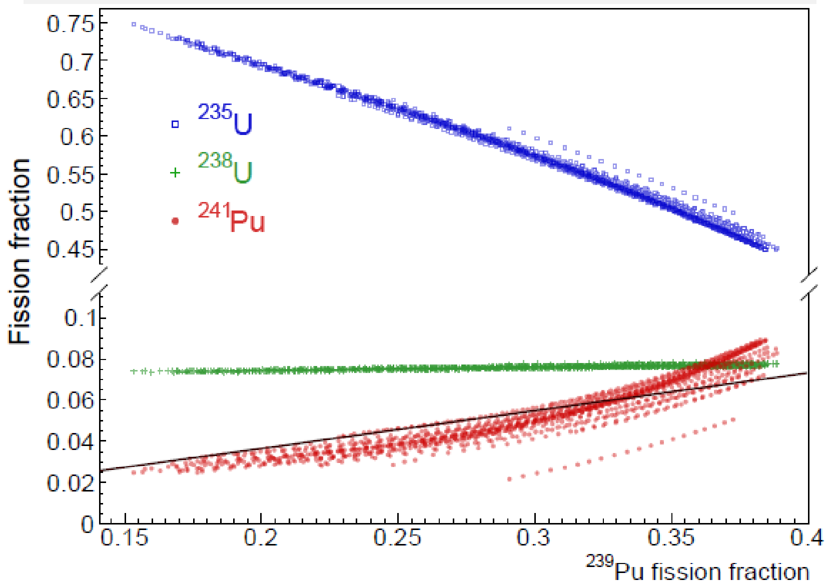
Combined ^{239}Pu and ^{241}Pu Spectrum

- Reduce the Pu spectrum uncertainty by combining ^{239}Pu and ^{241}Pu according to their fission fraction ratio

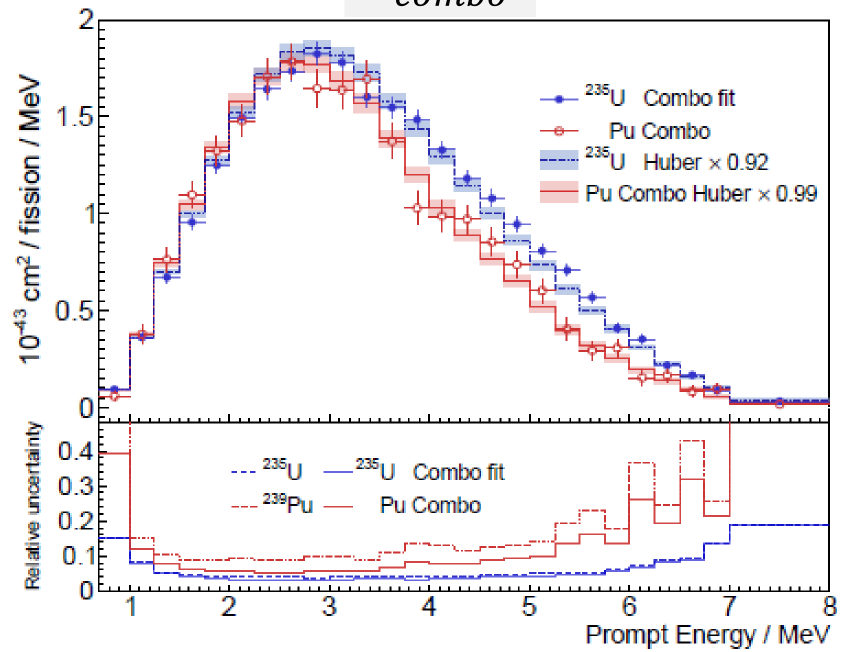
$$s_{\text{combo}} = s_{239} + 0.183 \times s_{241}$$

- Dependence on the input of ^{241}Pu largely removed
- Combined Pu spectrum uncertainty: 6% (9% for Pu239-only)

Residual S_{241} is corrected when fission fraction ratio deviates from 0.183



S_{combo}

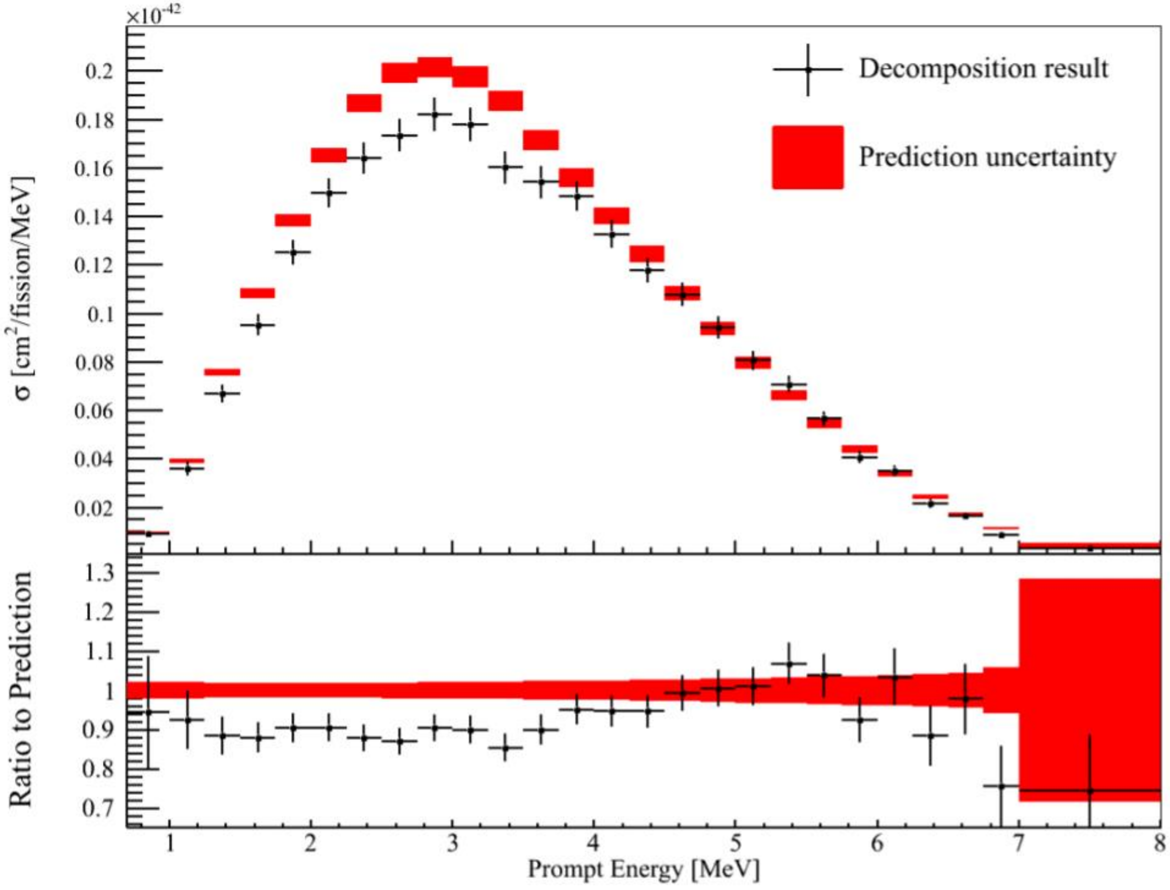


Phys. Rev. Lett. 123, 111801 (2019)

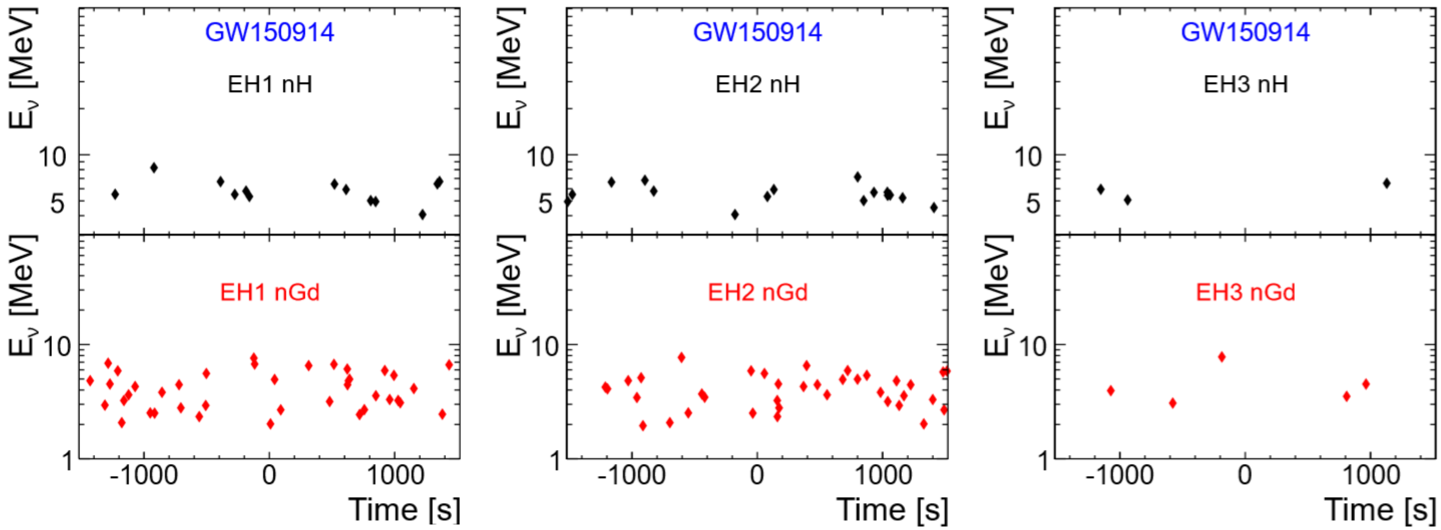
Absolute Spectrum Comparison for ^{235}U

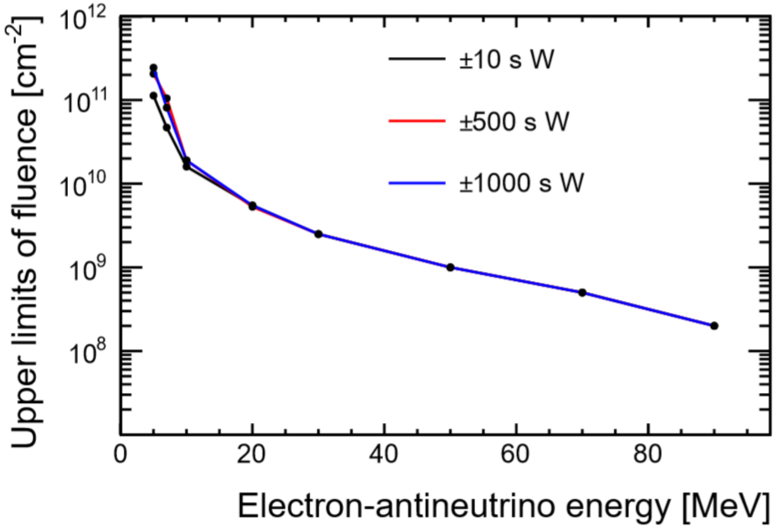
Compare the spectrum without normalization

- The 8% deficit of ^{235}U depends on the energy
- 11% deficit below 4 MeV for ^{235}U spectrum → 8% overall rate deficit



$\bar{\nu}_e$ Search associated with Gravitational Wave (GW) Events





- Search GW associated $\bar{\nu}_e$ with joint fit of IBDs with both nGd and nH capture at different energy regions
- No significant IBD event excess within $\pm$10/500/1000 s time window of GW event

arXiv:2006.15386