Latest Results from the Daya Bay Experiment

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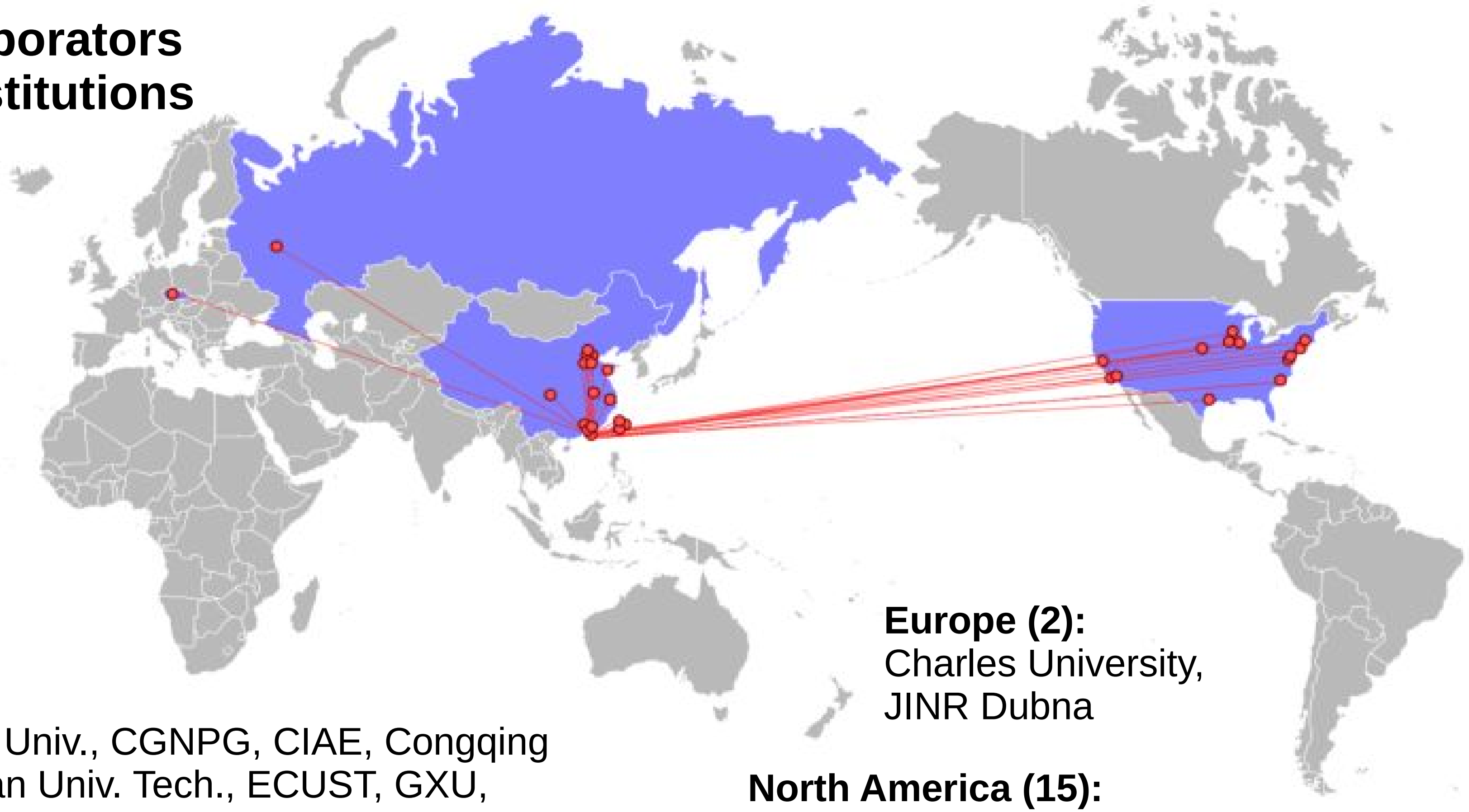
**on behalf of the Daya Bay collaboration*

ICRC 2021

The Daya Bay Collaboration

~200 Collaborators from 41 institutions



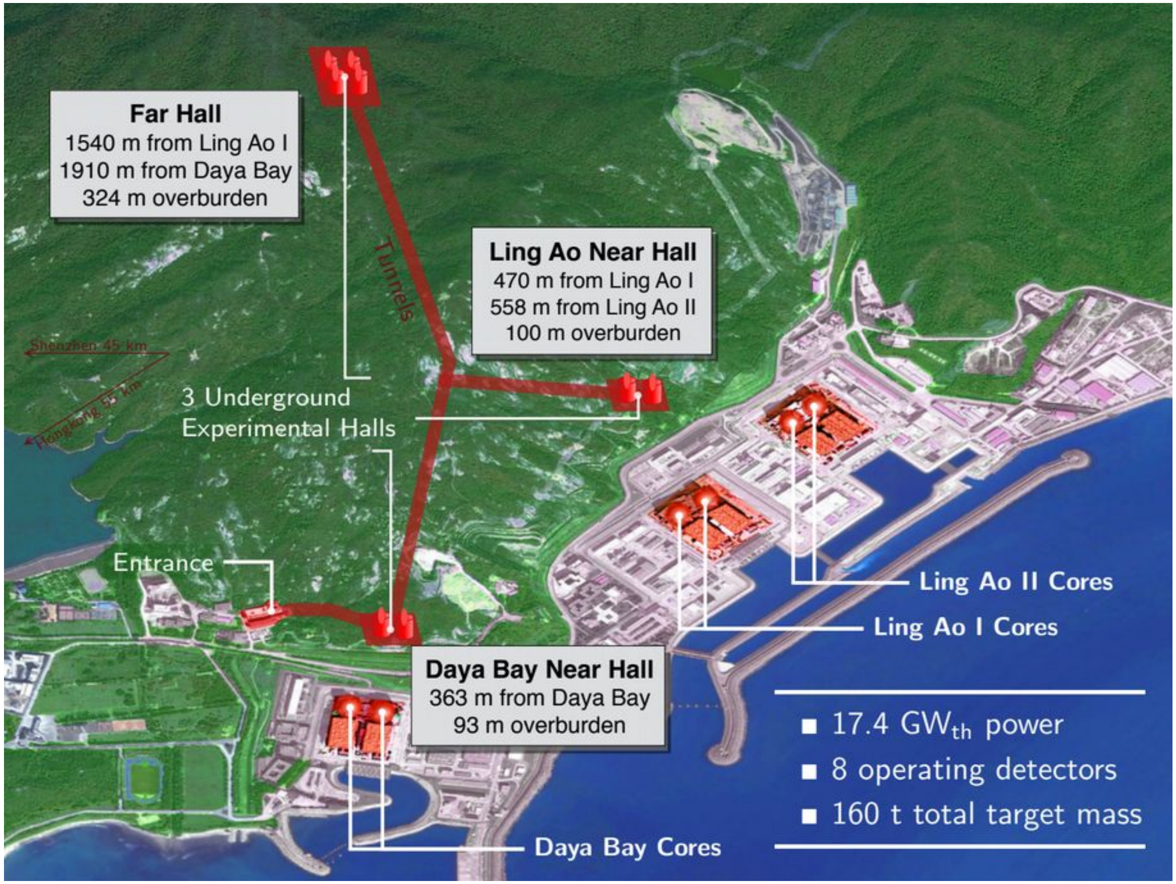
Europe (2):
Charles University, JINR Dubna

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.

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

The Daya Bay Experiment Overview

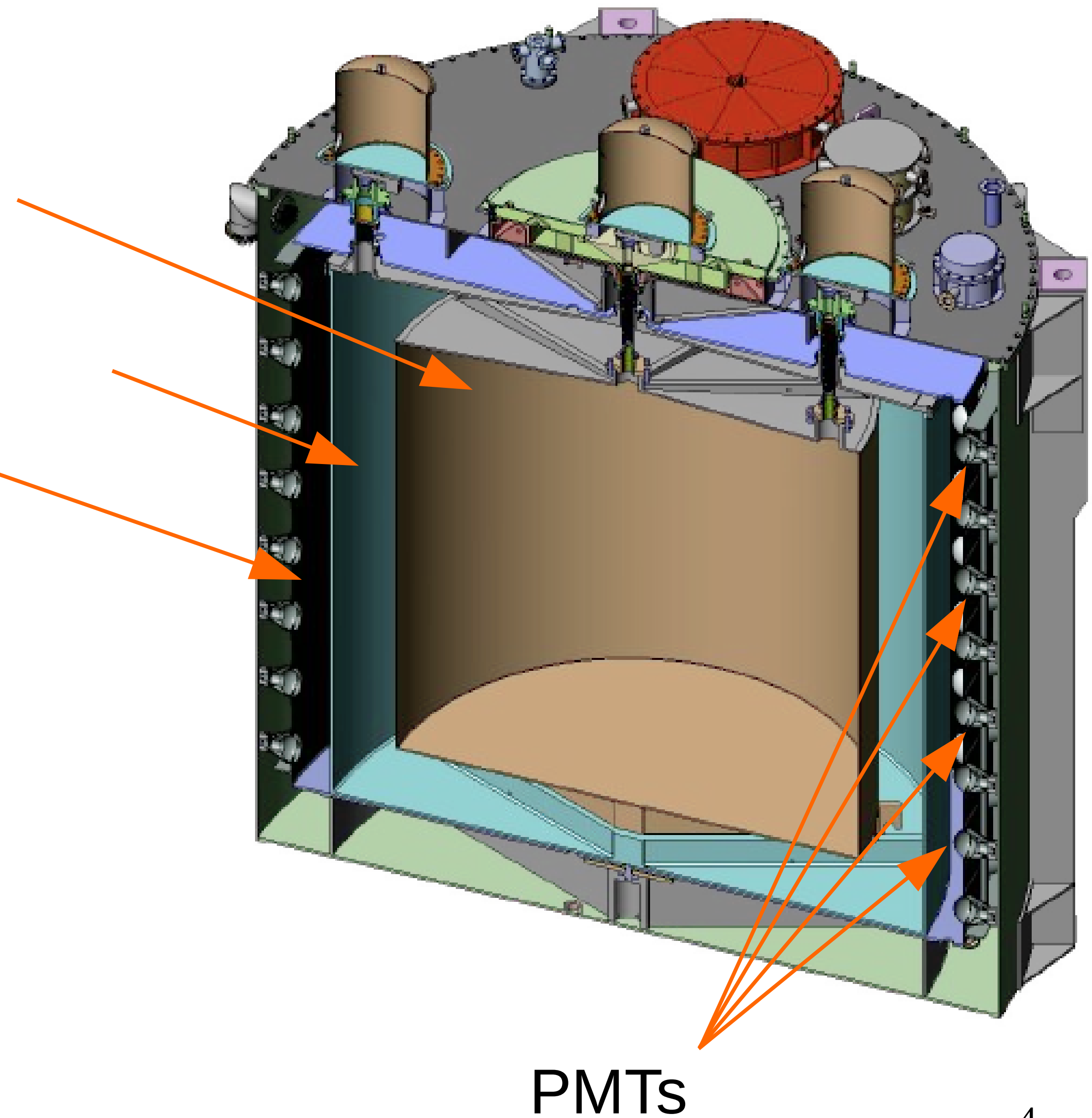
- The experiment is located in south China in proximity to Daya Bay & Ling Ao nuclear power plants
- 6 nuclear reactors serve as an intense and pure source of electron antineutrinos
- 8 functionally identical antineutrino detectors (ADs) located in 3 experimental halls (EHs)
- Placed underground for suppression of cosmic rays



Far hall location optimized in order to measure neutrino oscillation at the ~2 km baseline

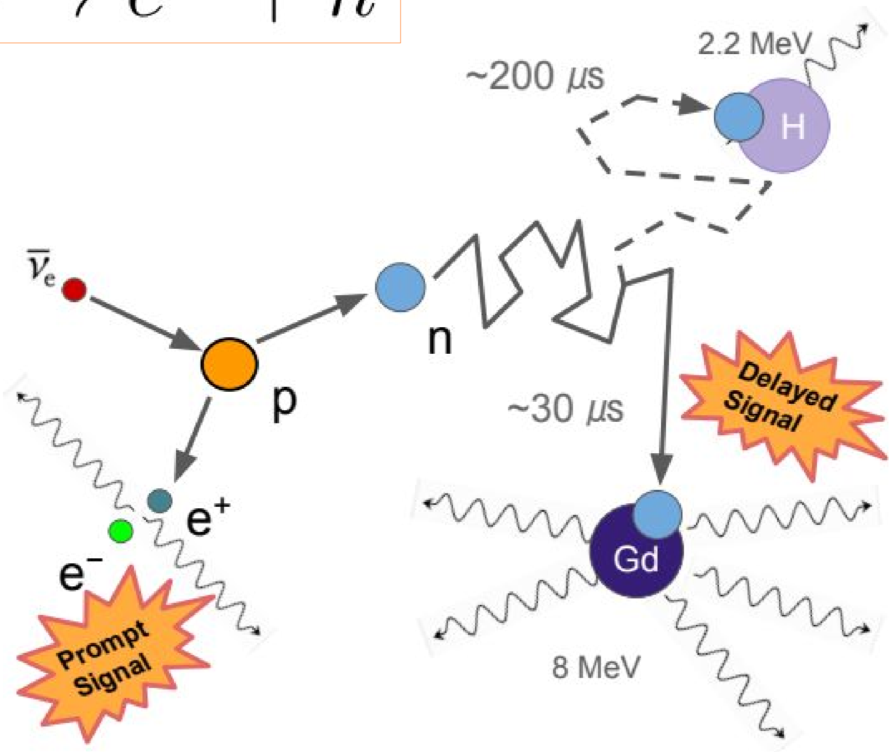
Antineutrino Detector (AD)

- Each AD consists of 3 nested cylindrical regions:
  - 20 t of liquid scintillator doped with gadolinium (GdLS)
  - 22 t of pure liquid scintillator (LS)
  - 40 t of mineral oil (MO)
- Scintillation light collected by 192 x 8'' PMTs
- ADs are submerged in instrumented water pool - passive shielding and active muon detector (veto)



Antineutrino Detection

- Inverse beta decay (IBD): $$\overline{\nu}_e + p \rightarrow e^+ + n$$
  - Prompt signal: e^+ loses energy and annihilates
  - Delayed signal: *n* thermalizes and is captured on Gd (nGd) or H (nH) – two independent data sets
  - Temporal (and spatial) correlation of prompt and delayed signal leads to great suppression of background
  - Antineutrino energy can be deduced from prompt energy: $$E_{\overline{\nu}_e} \approx E_{prompt} + 0.8\,\mathrm{MeV}$$



Neutrino Oscillation Measurement

- Looking at neutrino flux as a function of distance and energy
- Disappearance of some $\overline{\nu}_e$'s due to neutrino oscillation:

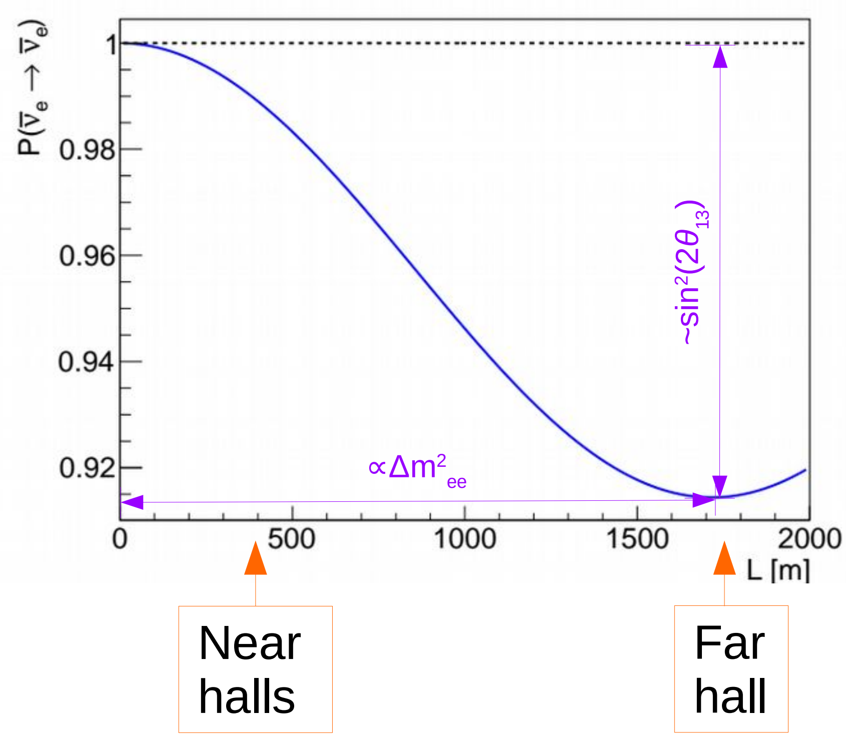
$$P(\overline{\nu}_e \to \overline{\nu}_e) = 1 - \sin^2 2\theta_{13}\left(\cos^2\theta_{12}\sin^2\frac{\Delta m^2_{31}L}{4E} + \sin^2\theta_{12}\sin^2\frac{\Delta m^2_{32}L}{4E}\right) - \sin^2 2\theta_{12}\cos^4\theta_{13}\sin^2\frac{\Delta m^2_{21}L}{4E}$$

Short baseline Medium baseline

- Daya Bay optimized for short baseline measurement of θ_{13} where:

$$P(\overline{\nu}_e \to \overline{\nu}_e) \simeq 1 - \sin^2(2\theta_{13})\sin^2\left(\frac{\Delta m^2_{ee}L}{4E}\right)$$

$$\sin^2\frac{\Delta m^2_{ee}L}{4E} \simeq \cos^2\theta_{12}\sin^2\frac{\Delta m^2_{31}L}{4E} + \sin^2\theta_{12}\frac{\Delta m^2_{32}L}{4E}$$



Oscillation Measurement with nGd

- Measurement of $\sin^2 2\theta_{13}$ with world-leading 3.4% precision:

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

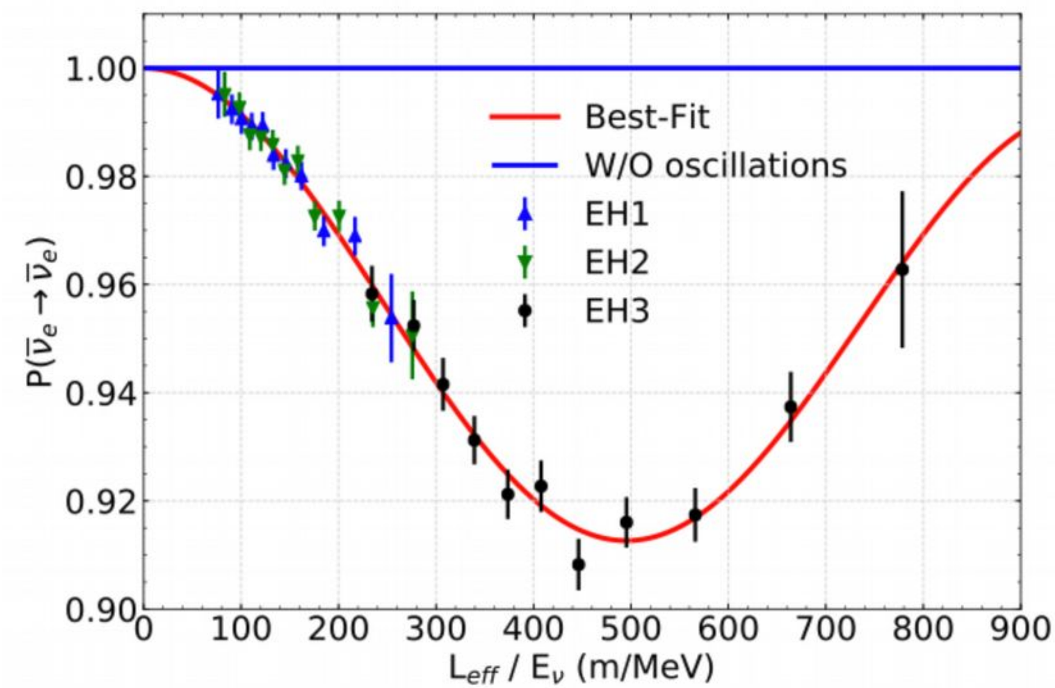
- Measurement of Δm^2_{ee} with 2.8% precision, comparable to accelerator experiments:

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

$$\Delta m^2_{32} = (2.471^{+0.068}_{-0.070}) \times 10^{-3}\,\mathrm{eV}^2 \text{ (Normal mass ordering)}$$
$$\Delta m^2_{32} = -(2.575^{+0.068}_{-0.070}) \times 10^{-3}\,\mathrm{eV}^2 \text{ (Inverted mass ordering)}$$

- Statistics contribute 60% (50%) to the total uncertainty in the $\sin^2 2\theta_{13}$ (Δm^2_{ee}) measurement.

World's largest data set of of almost 4 million antineutrino candidates collected (1958 days)



[Phys. Rev. Lett. 121, 241805 (2018)]

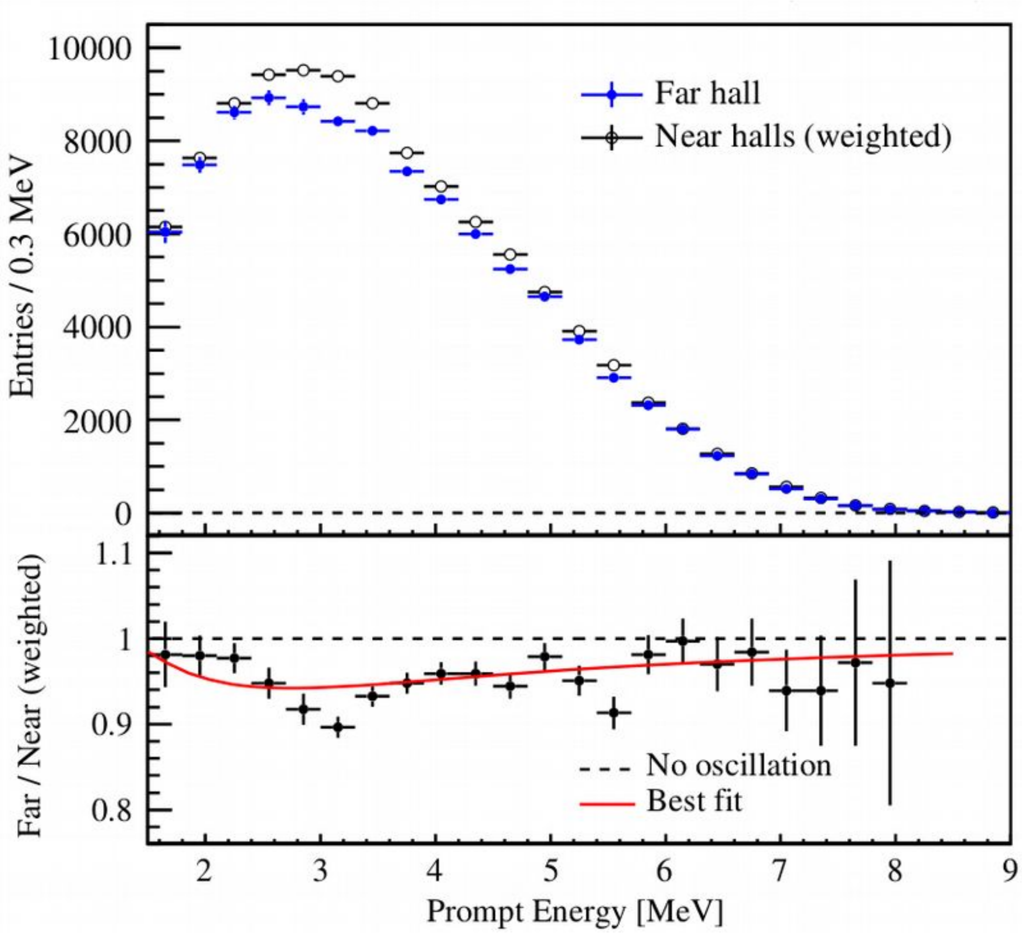
Oscillation Measurement with nH

- Largely independent measurement from nGd:
  - Different statistics
  - Mostly independent (and larger) systematics
  - Larger background
- Rate-only analysis:

$$\sin^2(2\theta_{13}) = 0.071 \pm 0.011$$

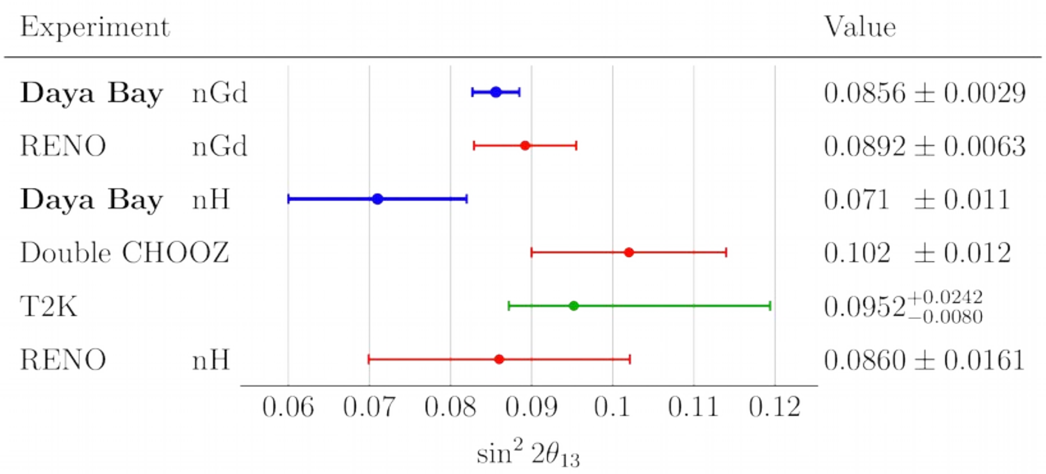
  - Based on 621 days data set
- Work on rate & shape analysis is in progress

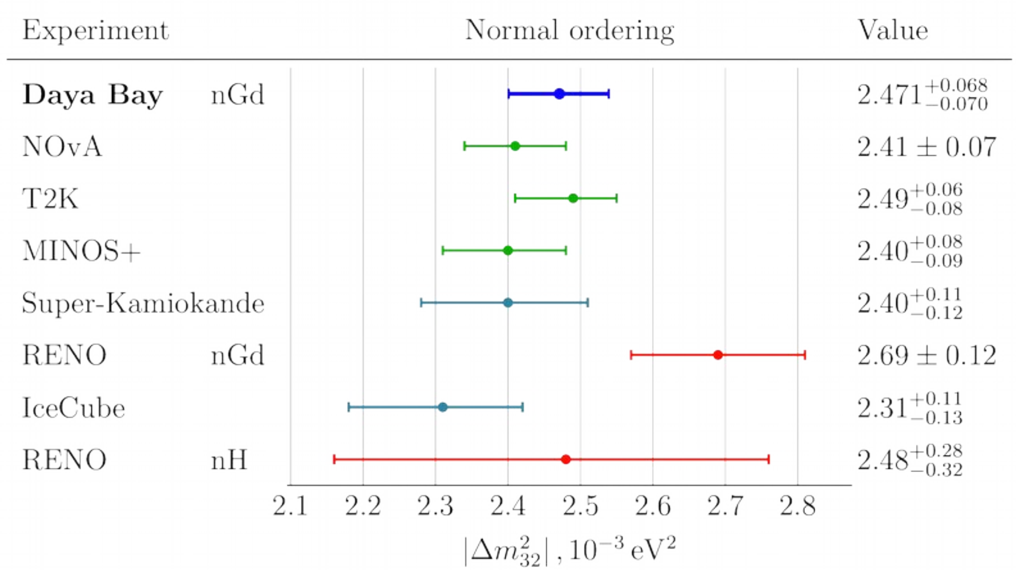
→ It will likely be one of the leading measurements of $\sin^2 2\theta_{13}$ in the world

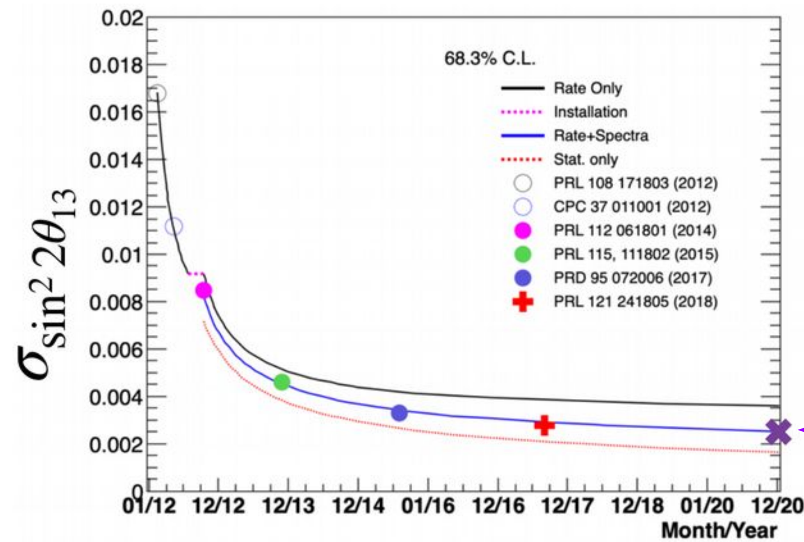


[Phys. Rev. D 93, 072011 (2016)]

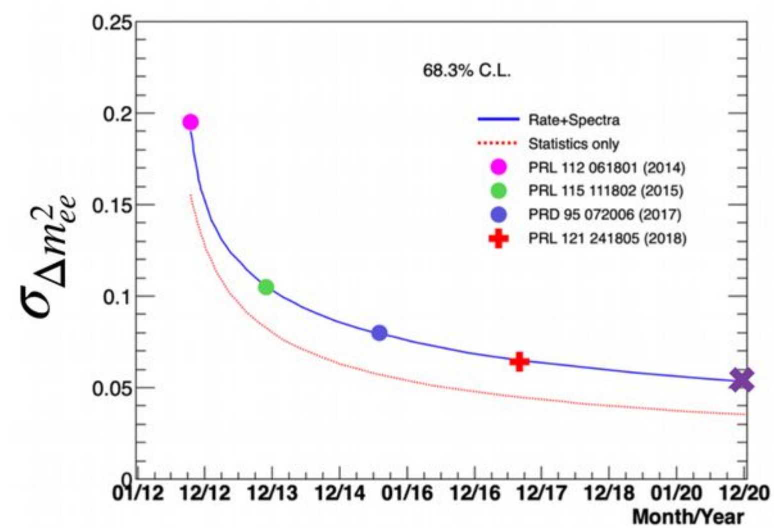
Global Comparison: $\sin^2 2\theta_{13}$ & Δm^2_{ee}







$\sin^2 2\theta_{13}$ uncertainty **3.4%** → **2.7%**

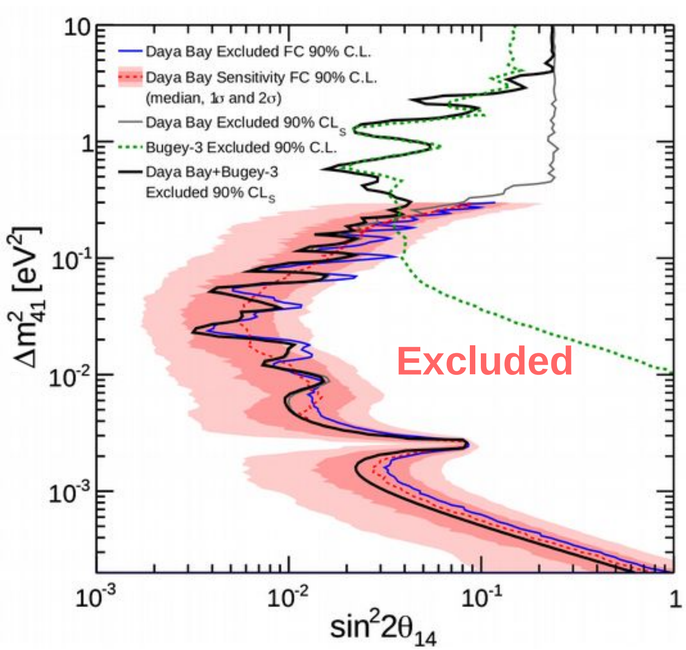


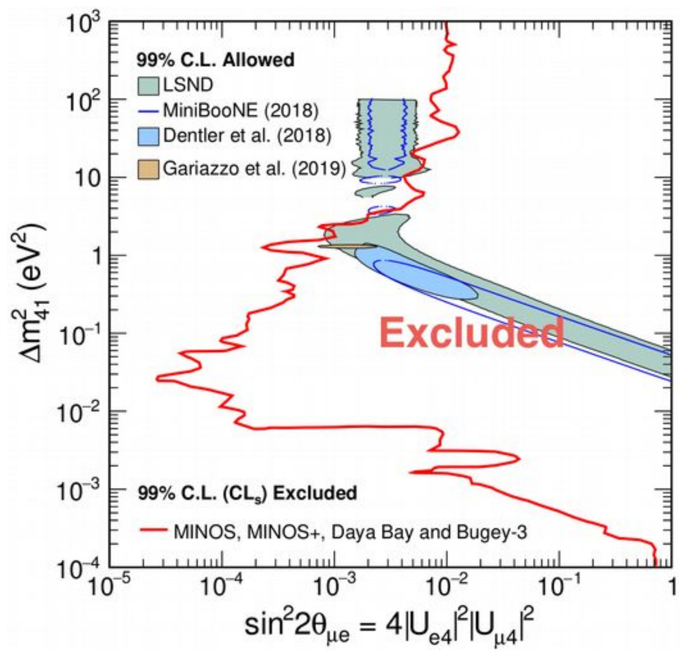
Δm^2_{ee} uncertainty **2.8%** → **2.1%**

End of Daya Bay data taking

Sterile Neutrino Search

- Motivated (among other things) by LSND & MiniBooNE observed excess of ν_e ($\bar{\nu}_e$) in ν_μ ($\bar{\nu}_\mu$) beam inconsistent with 3ν oscillation
- Daya Bay results consistent with 3ν model, no additional oscillation driven by Δm^2_{41} and $\sin^2 2\theta_{14}$ observed (1230 days)





Combined analysis with Bugey-3, MINOS, MINOS+ excluded LSND and MiniBooNE 99% C.L. allowed regions at 99% CL_s for $\Delta m^2_{41} < 1.6\ \text{eV}^2$

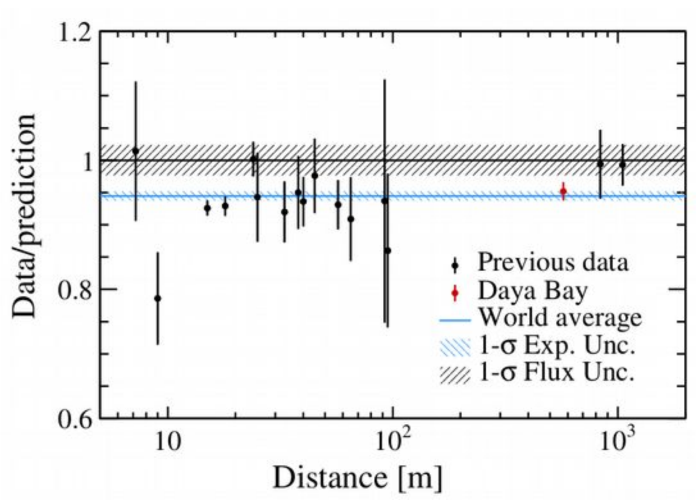
Daya Bay imposed the most stringent limits on $\sin^2 2\theta_{14}$ for $\Delta m^2_{41} < 0.2\ \text{eV}^2$

[Phys. Rev. Lett. 125, 07180 (2020)]

Reactor Antineutrino Flux & Spectrum

- Flux: Daya Bay consistent with previous experimental results, but ~1.8 σ below the best prediction up to date (Huber-Mueller model)
- Spectrum: comparison with Huber-Mueller model shows a total >5σ deviation, especially significant in 4-6 MeV 'bump' region (>6σ)

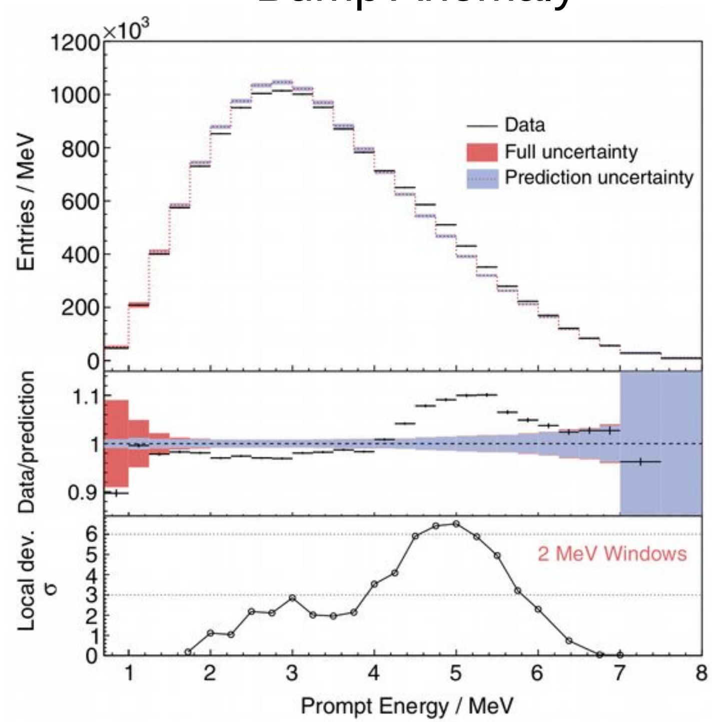
Reactor Antineutrino Anomaly



Yield comparison with Huber-Mueller model:
$R_{data/HM}$ = 0.952 ± 0.014(exp.) ± 0.023(model)

[Phys. Rev. D 100, 052004 (2019)]

Bump Anomaly

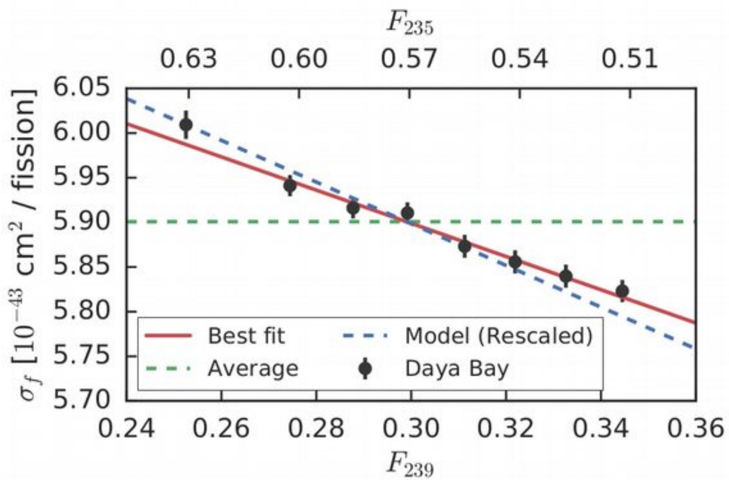


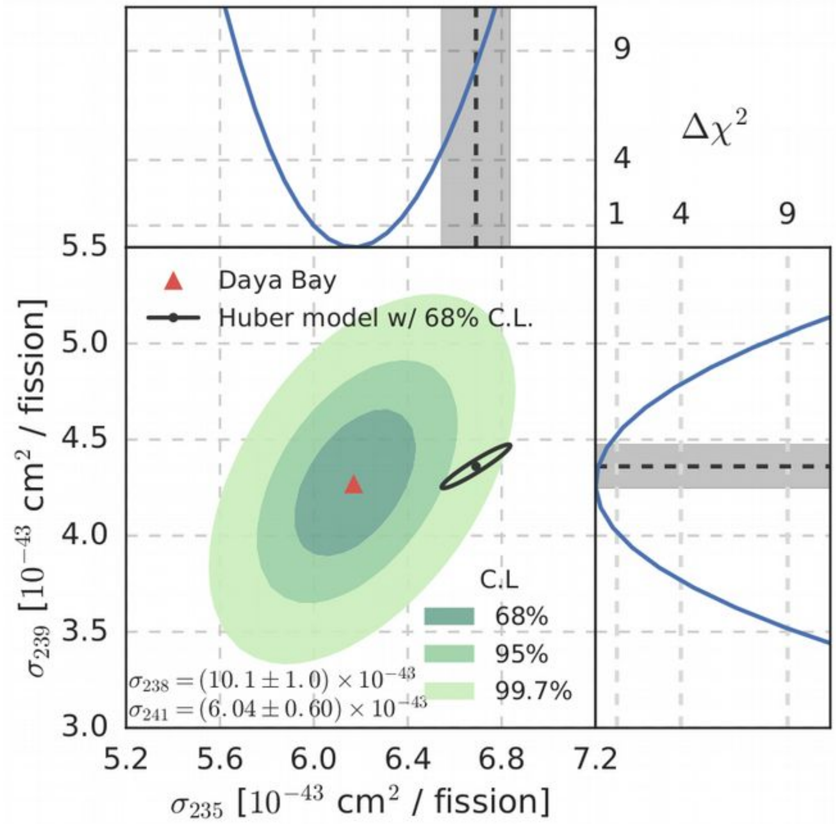
Daya Bay spectrum vs. Huber-Mueller prediction

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

Isotopic Yield Measurement

- Reactor $\bar{\nu}_e$ come from fission of 4 main isotopes: ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu
- Clear change of total $\bar{\nu}_e$ flux with reactor fuel composition observed
- Individual yields for ^{235}U and ^{239}Pu extracted





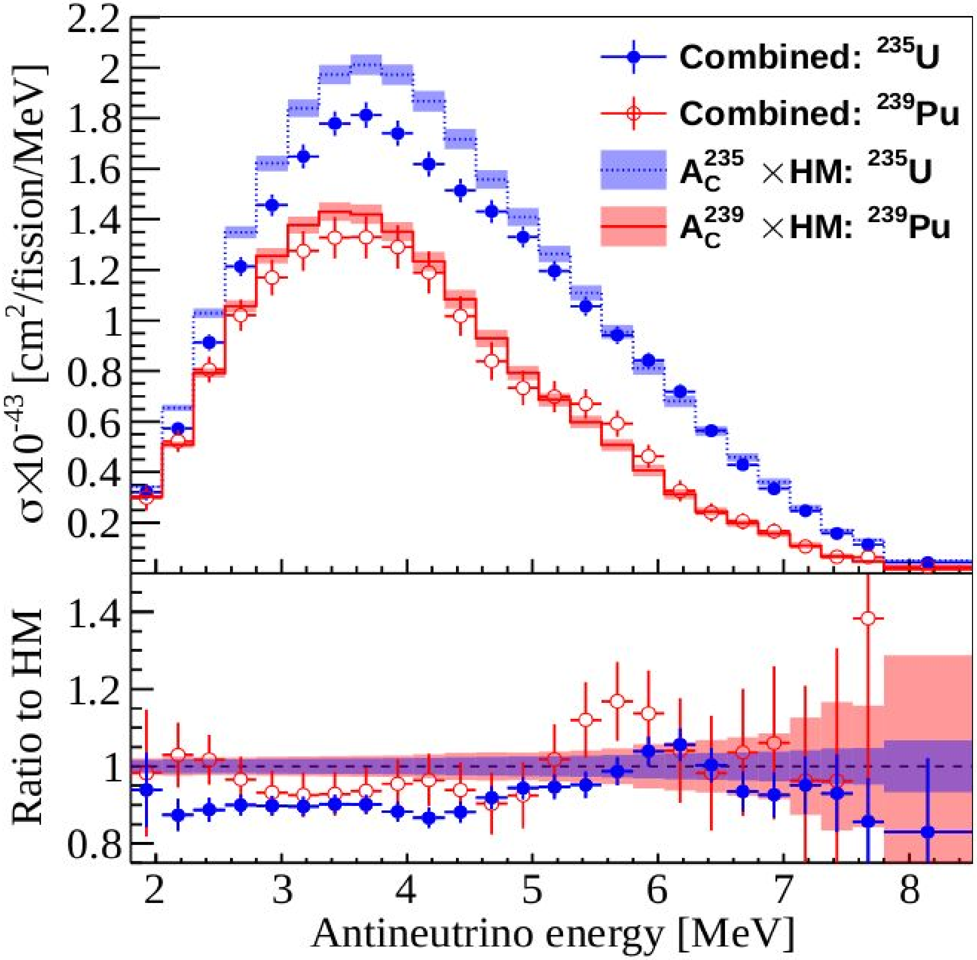
Result points to ^{235}U being mainly responsible for the deficit of observed $\bar{\nu}_e$'s compared to Huber-Mueller model

[Phys. Rev. Lett. 118, 251801 (2017)]

^{235}U & ^{239}Pu Spectra Measurement

- Individual prompt spectra of ^{235}U and ^{239}Pu extracted using the evolution of the prompt spectrum as a function of the isotope fission fractions
  - First measurement of ^{235}U and ^{239}Pu spectra from a commercial reactors
- Joint analysis with the PROSPECT experiment done
  - ^{235}U spectra consistent
  - ^{235}U spectrum obtained with better precision
  - Correlation between ^{235}U and ^{239}Pu spectra reduced

Daya Bay & PROSPECT:

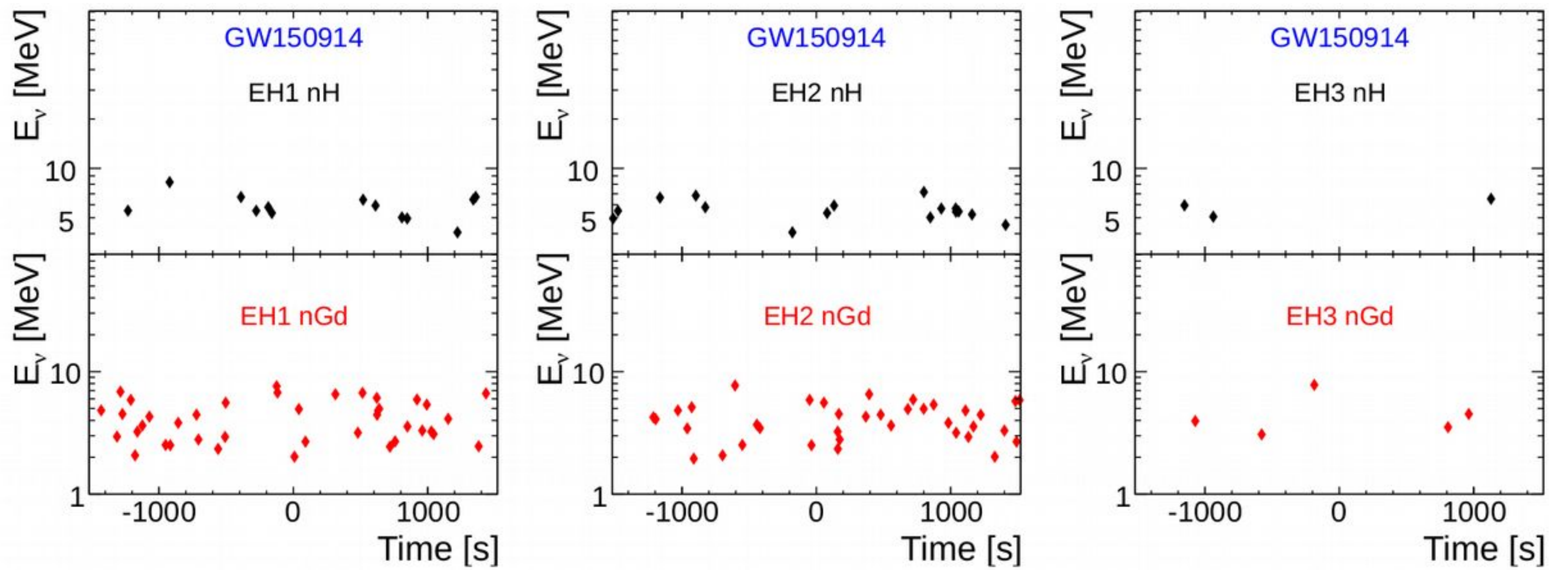


[arXiv:2006.15386]

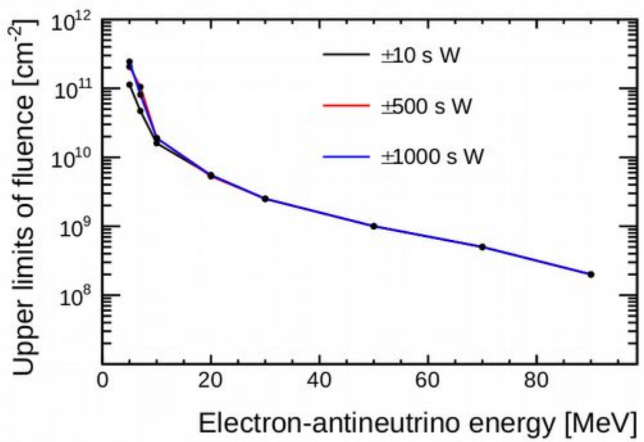
[Phys. Rev. Lett. 123, 111801 (2019)]

$\bar{\nu}_e$'s Associated with Gravitational Waves

- No significant $\bar{\nu}_e$ event excess within ±10/500/1000 s time window of gravitational wave event observed
  - GW150914
  - GW151012
  - GW151226
  - GW170104
  - GW170608
  - GW170814
  - GW170817



- Upper limits (90% C.L.) on $\bar{\nu}_e$ fluence determined:



[Chinese Phys. C 45, 055001 (2021)]

Summary & Outlook

- The latest Daya Bay reactor neutrino oscillation results:

$\sin^2(2\theta_{13}) = 0.0856 \pm 0.0029$ $\Delta m^2_{ee} = (2.522^{+0.068}_{-0.070}) \times 10^{-3}\,\mathrm{eV}^2$

- Daya Bay imposed the most stringent limits on sterile neutrino mixing angle $\sin^2 2\theta_{14}$ for $\Delta m^2_{41} < 0.2$ eV^2
  - Together with MINOS/MINOS+ excluded most of LSND / MiniBooNE allowed region
- Reactor antineutrino flux and spectrum measured as well as individual yields and spectra of ^{235}U and ^{239}Pu, joint analysis with PROSPECT
- No $\bar{\nu}_e$ excess associated with gravitational waves observed, limits on $\bar{\nu}_e$ fluence placed
- **Daya Bay finished data taking at the end of 2020**
  - Final results will include the best determination of $\sin^2 2\theta_{13}$ for the foreseeable future (uncertainty < 3%) and more

Thank you for your attention!