Latest Results from the Daya Bay Experiment

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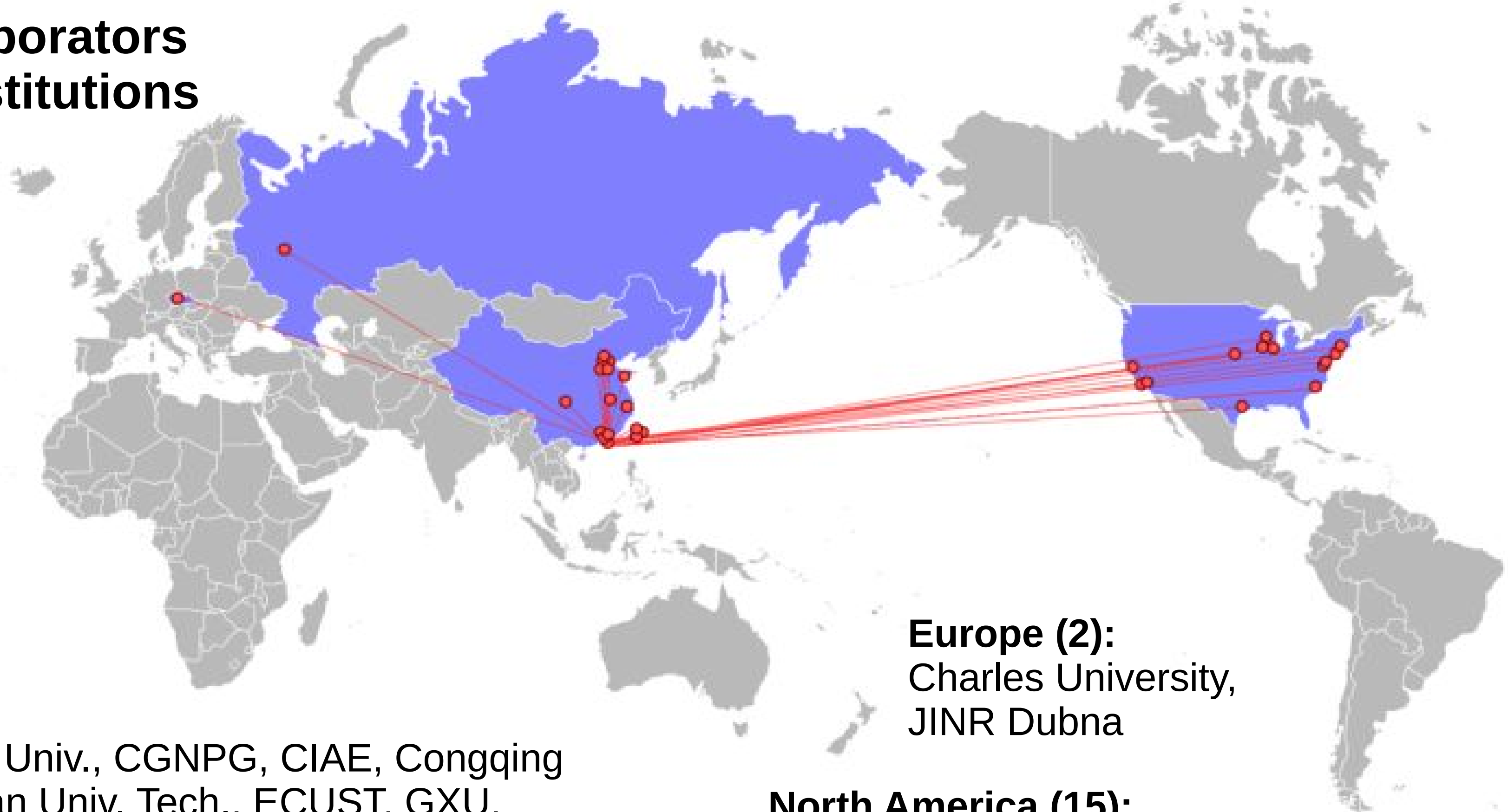
Charles University

**on behalf of the Daya Bay collaboration*

ICNFP 2020

The Daya Bay Collaboration

~230 Collaborators from 41 institutions



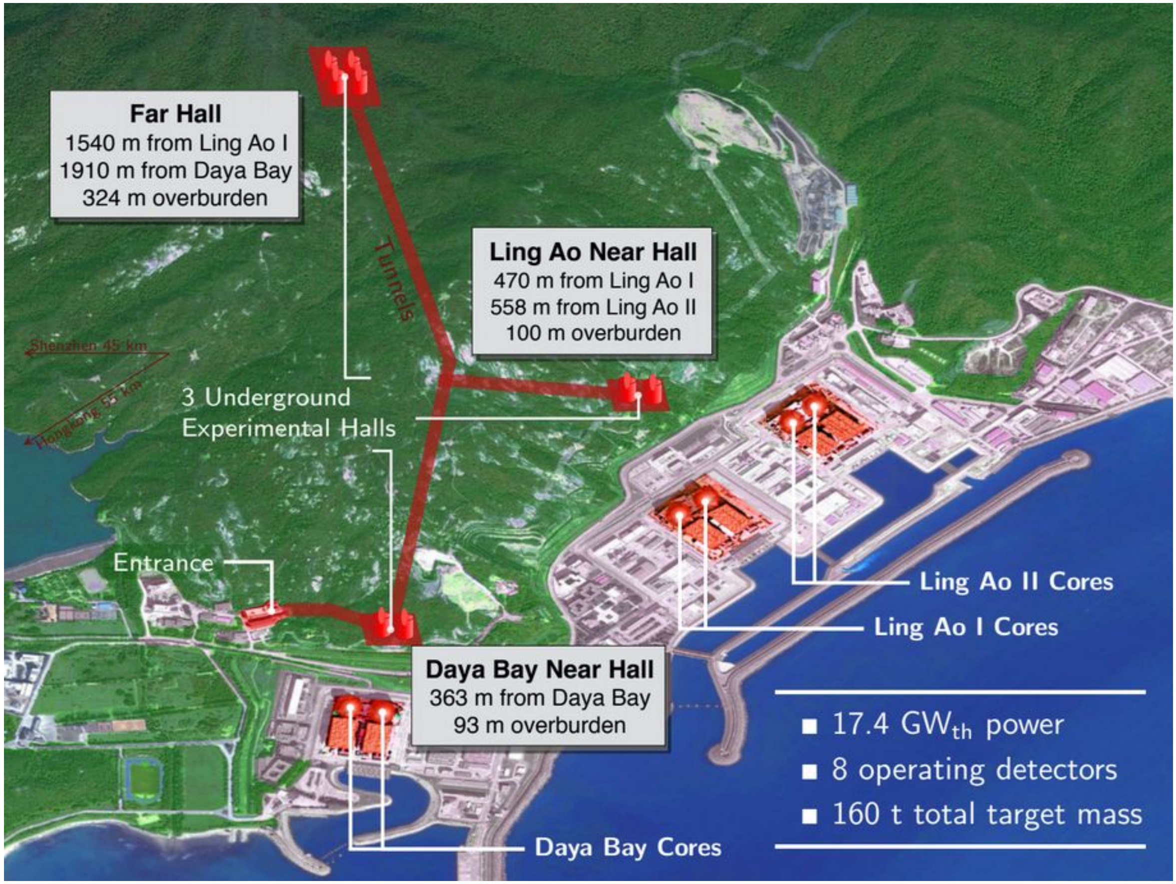
Asia (24):
Beijing Normal Univ., CGNPG, CIAE, Congqing Univ., Dongguan Univ. Tech., ECUST, GXU, IHEP, Nanjing Univ., Nankai Univ., NCEPU, NUDT, Shandong Univ., Shanghai Jiao Tong Univ., Shenzhen Univ., Tsinghua Univ., USTC, Xian Jiaotong Univ., Zhongshan (Sun Yat-sen) Univ., Chinese Univ. of Hong Kong, Univ. of Hong Kong, National Chiao Tung Univ., National Taiwan Univ., National United Univ.

Europe (2):
Charles University, 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

The Daya Bay Experiment Overview

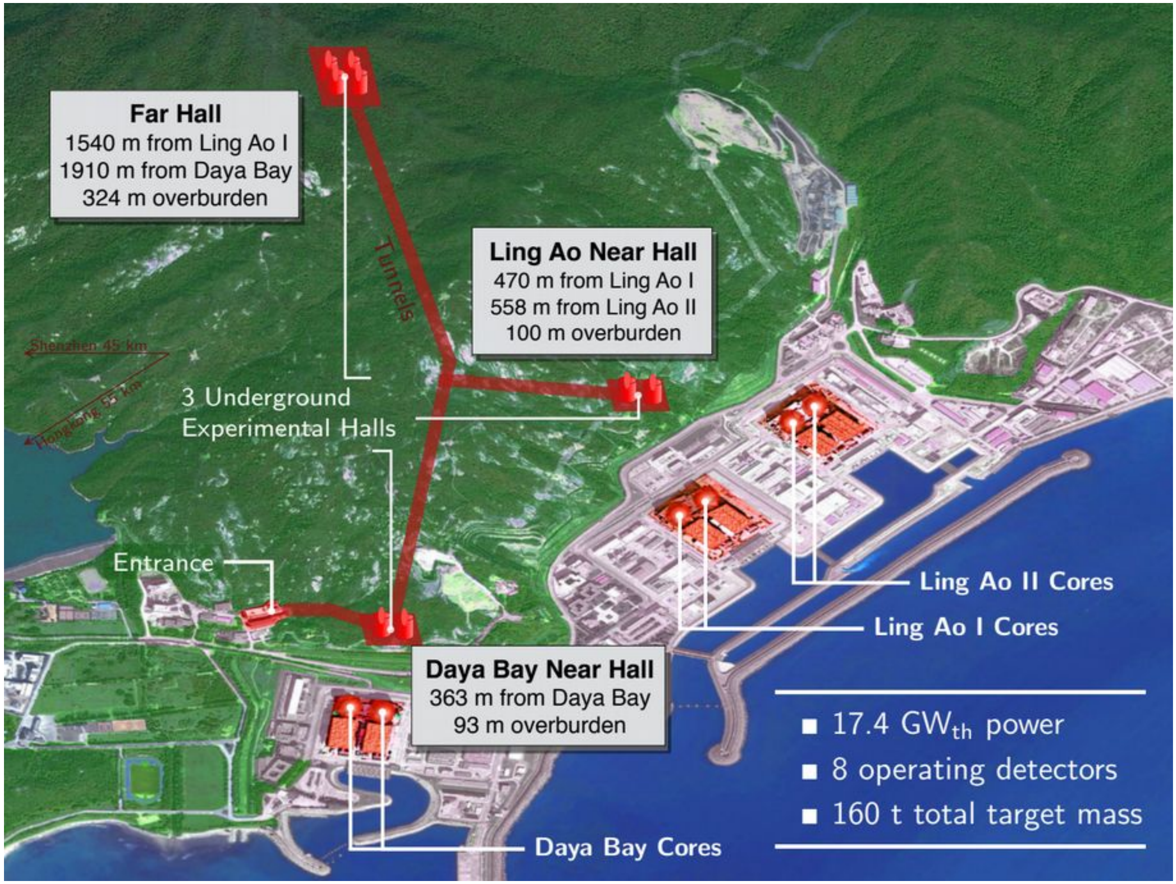
- The experiment is located in China, 55 km northeast from Hong Kong in proximity to Daya Bay & Ling Ao nuclear power plants
- 6 nuclear reactors serve as an intense and pure source of electron antineutrinos



With six 2.9 GW$_{th}$ reactors Daya Bay/Ling Ao is one of the most powerful nuclear complexes in the world, each reactor emitting ~ 6 x 10^{20} $\bar{\nu}_e$/s isotropically

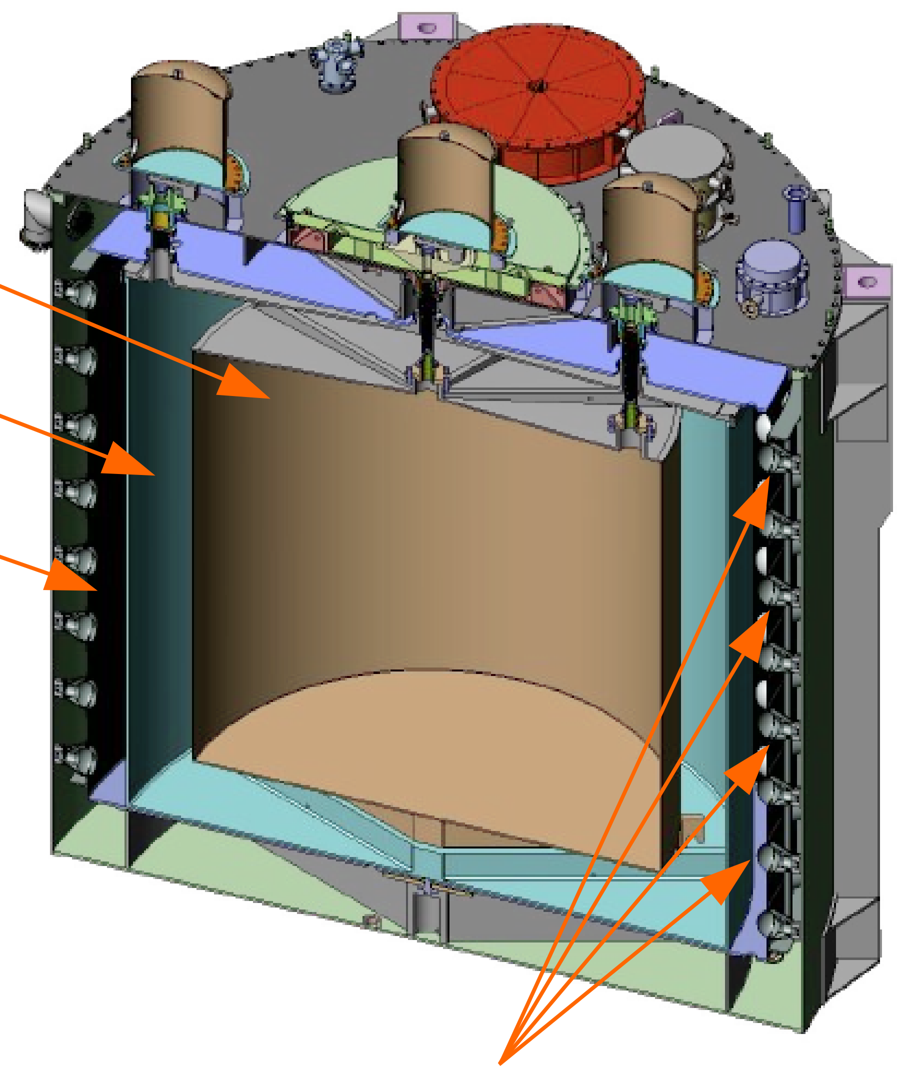
The Daya Bay Experiment Overview

- 8 functionally identical antineutrino detectors (ADs) located in 3 experimental halls
- Far hall location optimized in order to measure neutrino oscillation at the ~2 km baseline
- Placed underground for suppression of cosmic rays



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)



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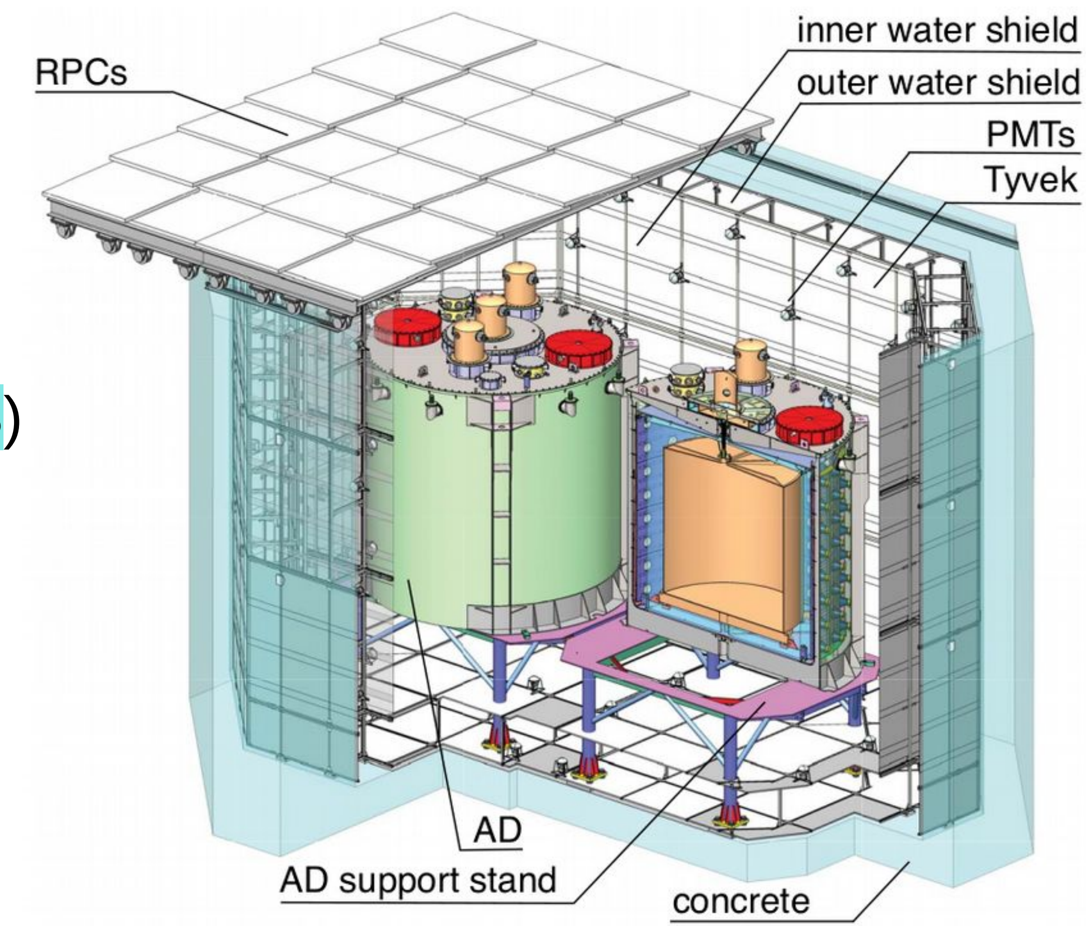
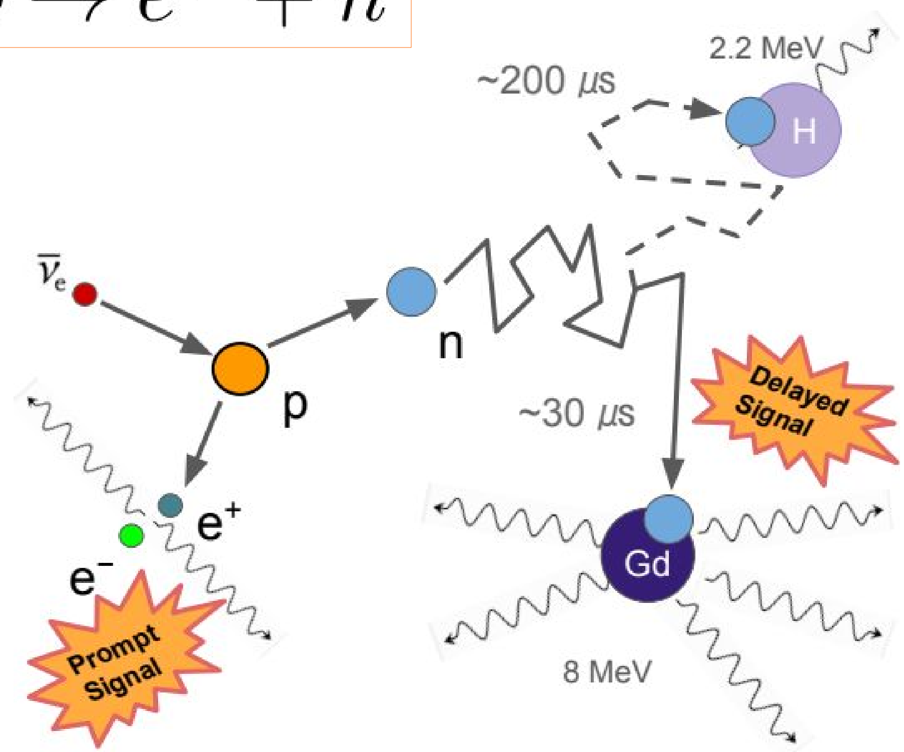


Antineutrino Detection

- 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: $E_{\overline{\nu}_e} \approx E_{prompt} + 0.8\,\mathrm{MeV}$



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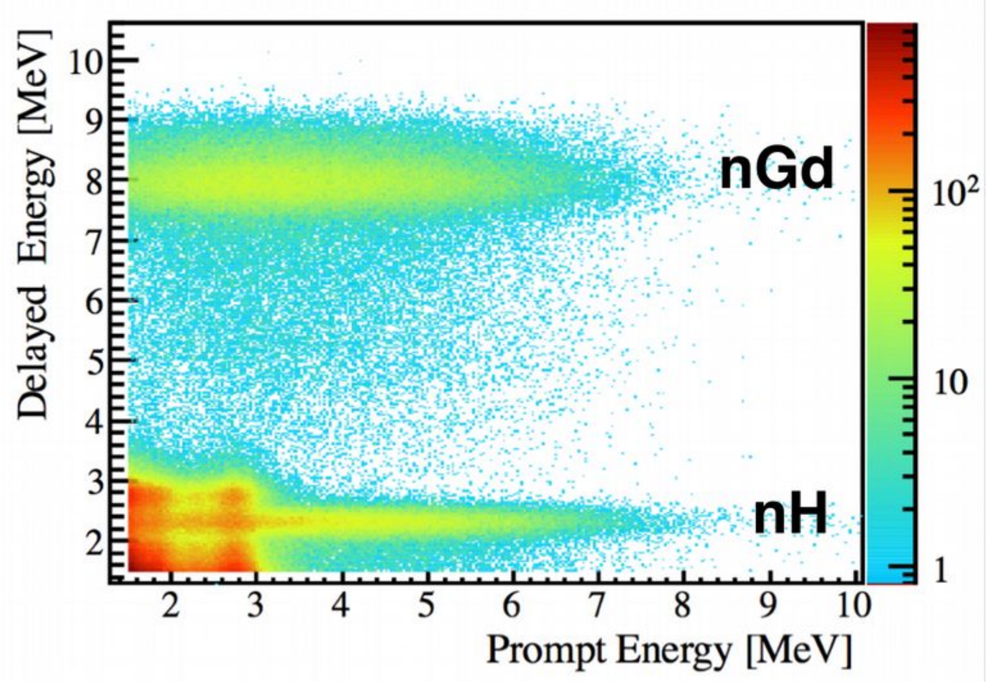


Neutrino Oscillation Measurement

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

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

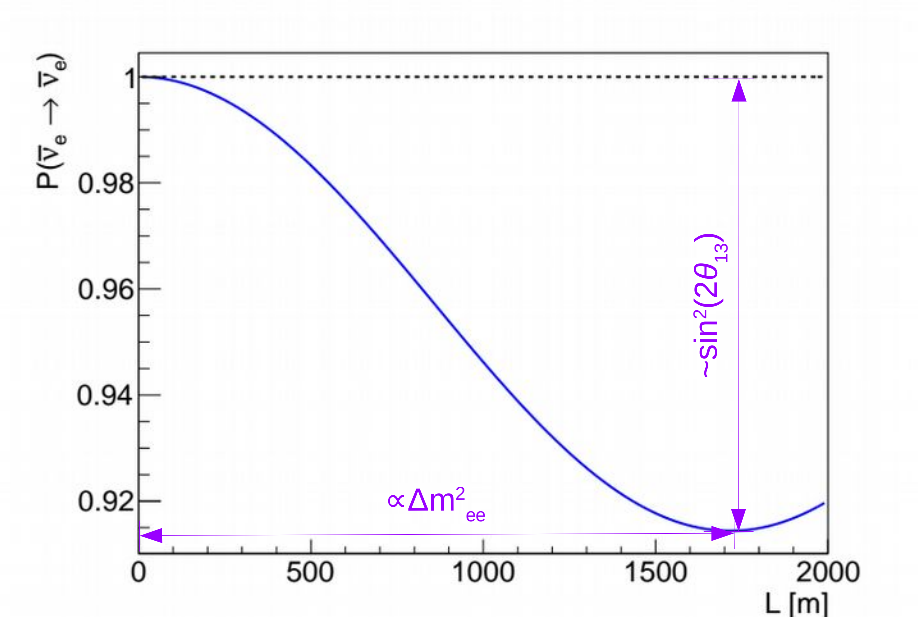
Short baseline

Medium baseline

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

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

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



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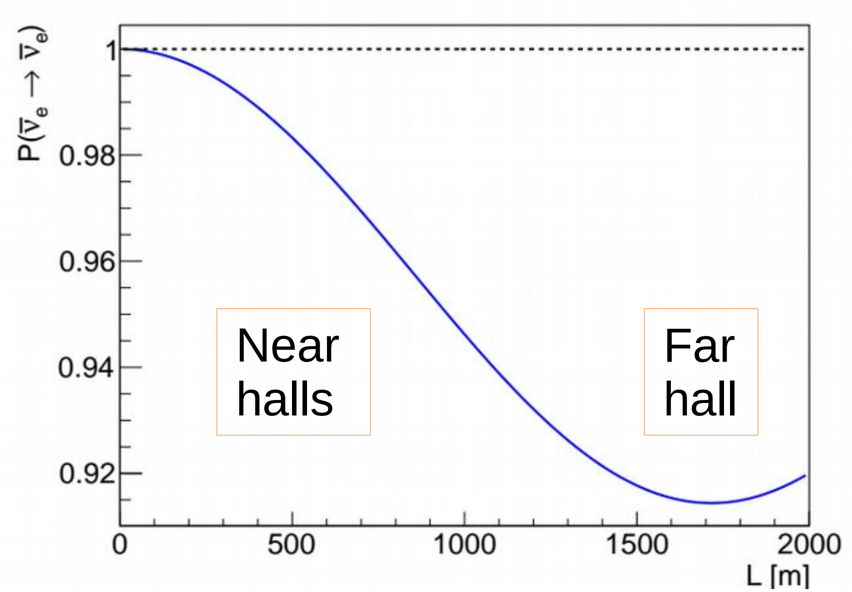
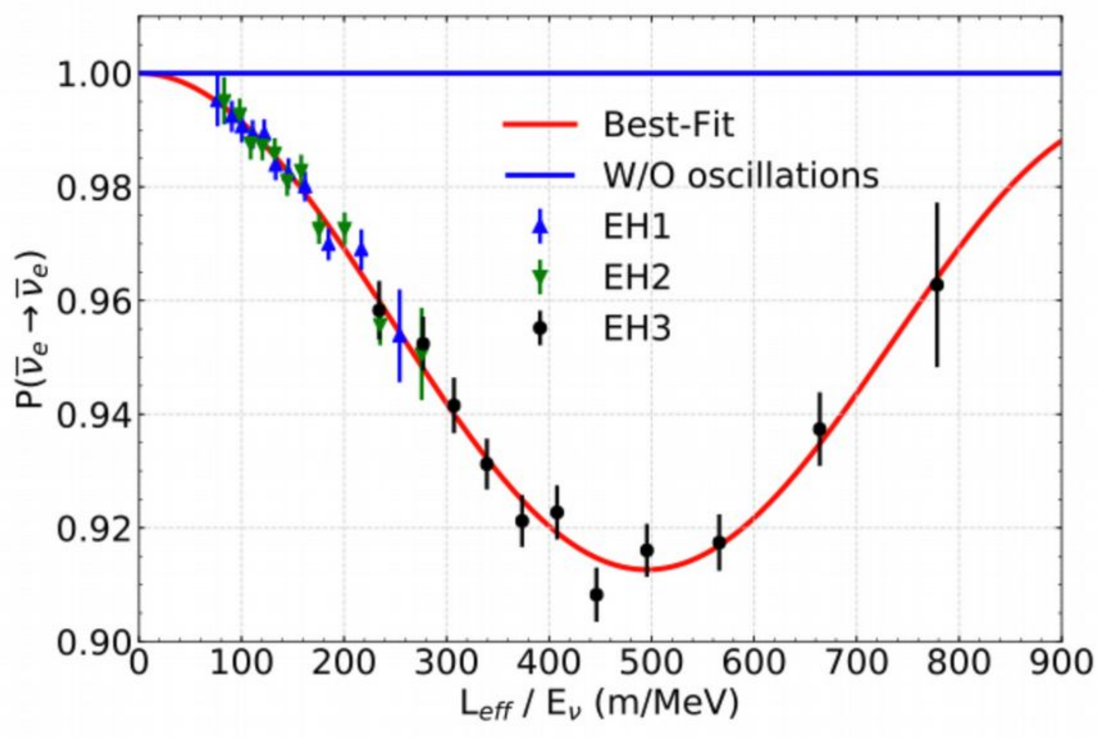


Oscillation Measurement with nGd

- Daya Bay discovered nonzero value of θ_{13} in 2012
- Latest results correspond to 1958 days of data taking (24.12.2011 – 30.8.2017)
- More than 3.9 million antineutrino candidates acquired
  - Almost 0.5 million in the far hall
  - World's largest reactor antineutrino data set



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

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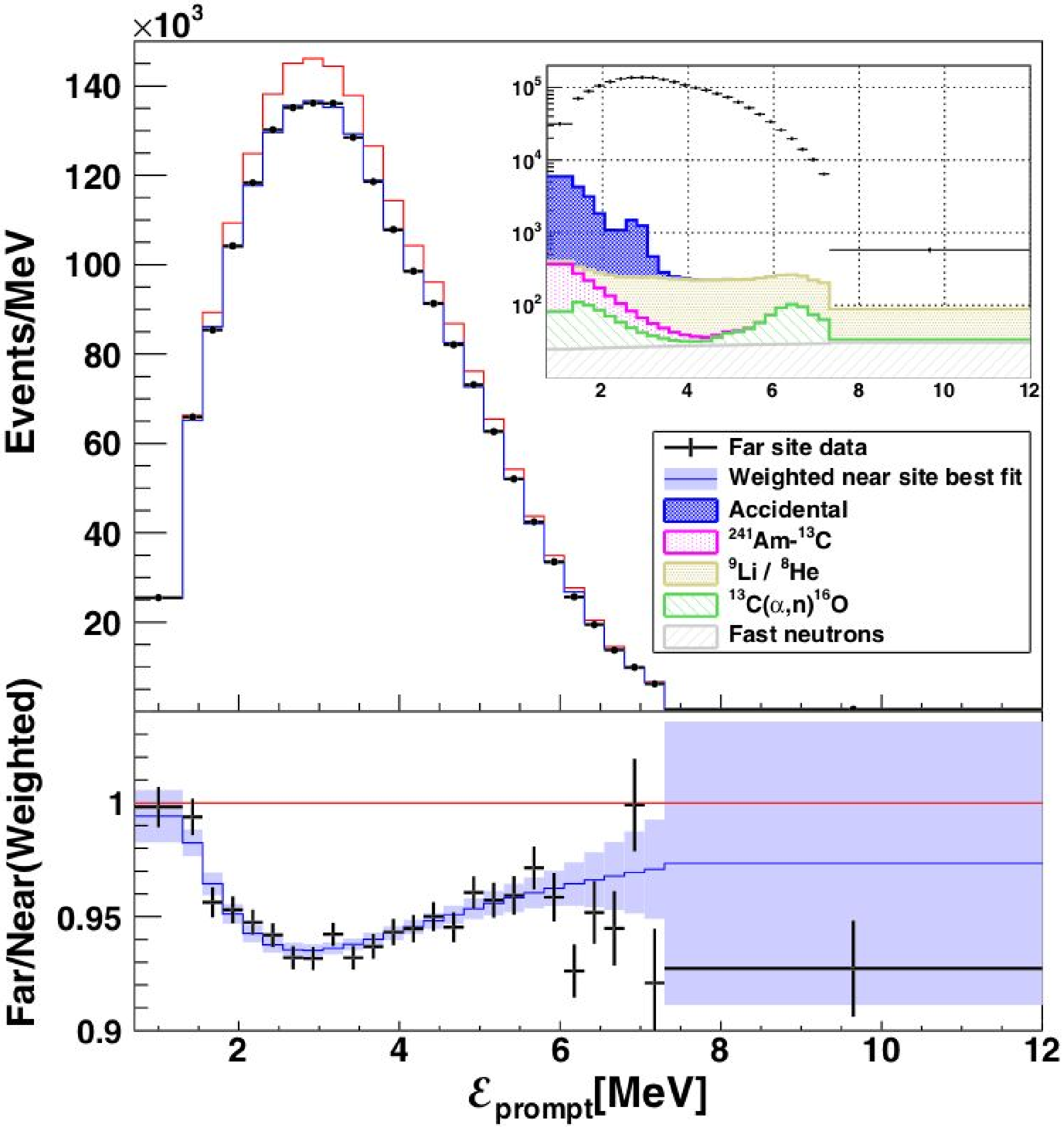


[Phys. Rev. Lett. 121, 241805 (2018)]

Oscillation Measurement with nGd

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

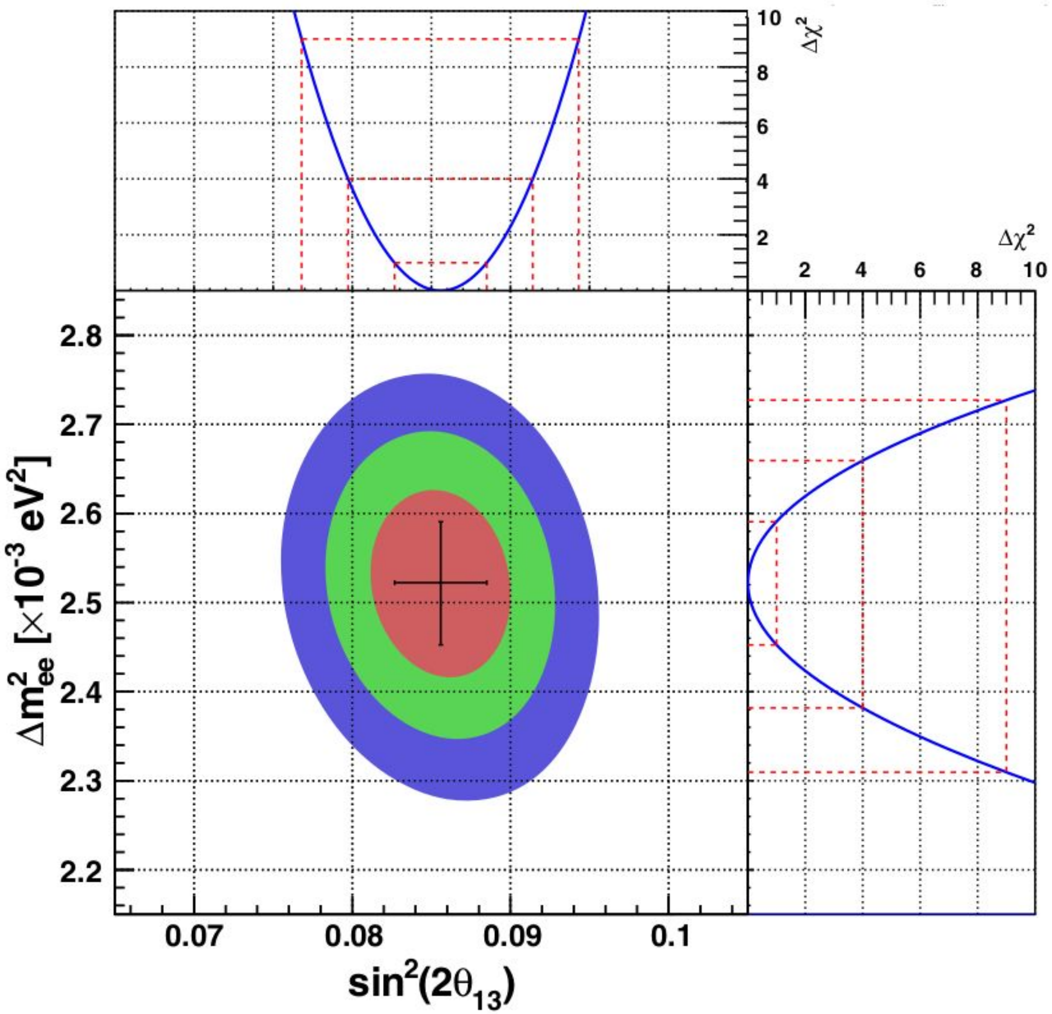
$$\sin^2(2\theta_{13}) = 0.0856 \pm 0.0029$$

- 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.



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

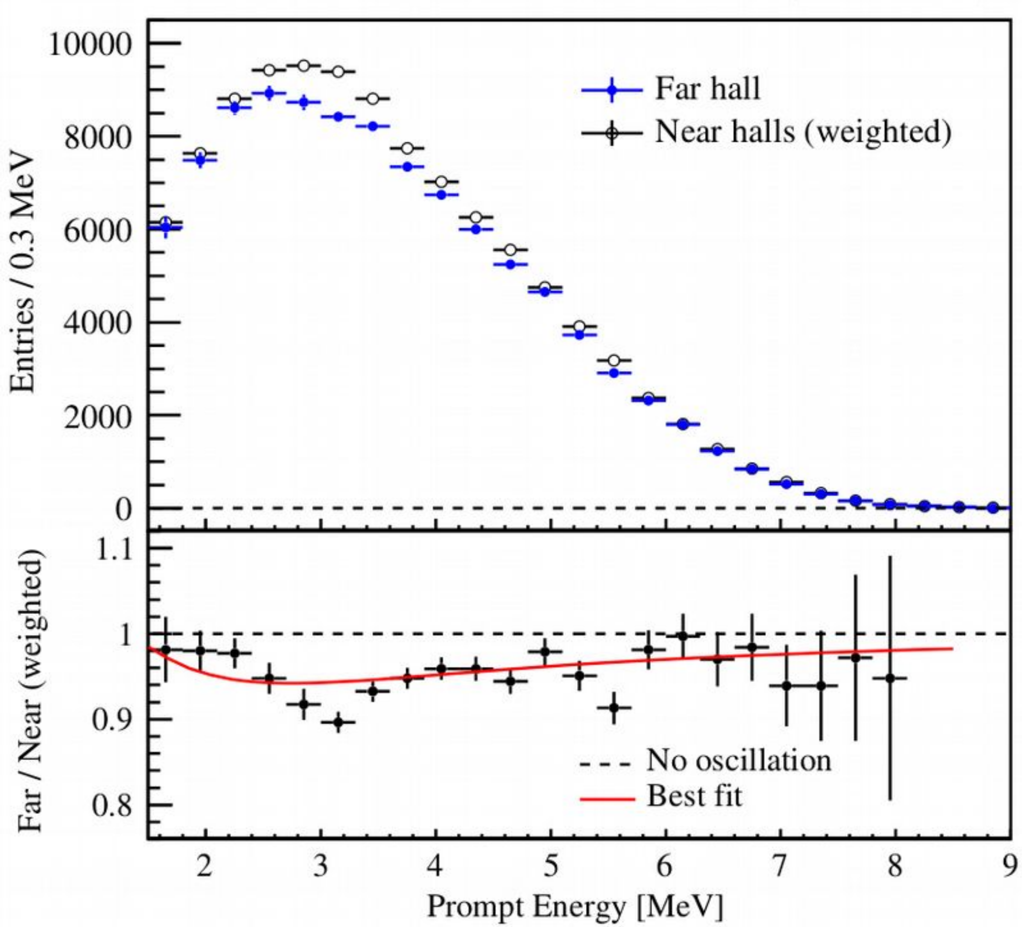
Oscillation Measurement with nH

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

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

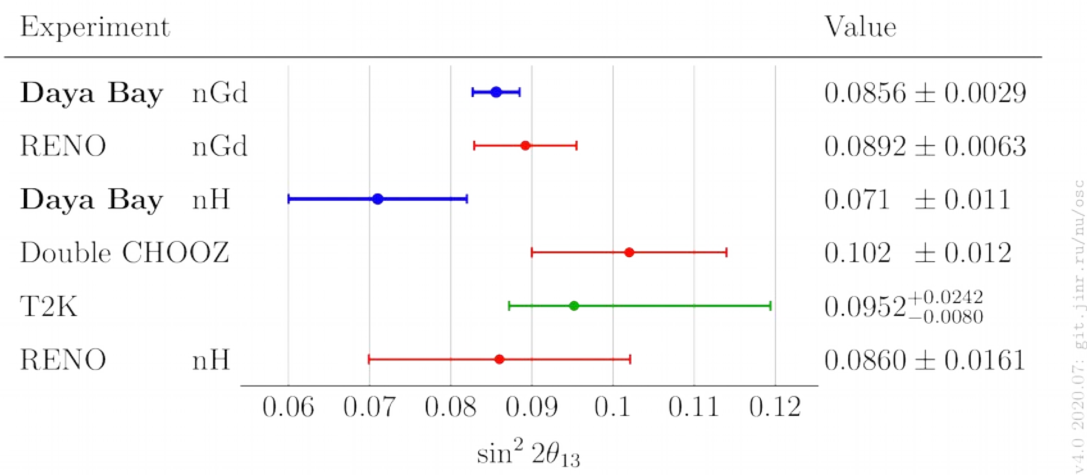
  - Based on 621 days data set
- Work on rate & shape analysis is in progress

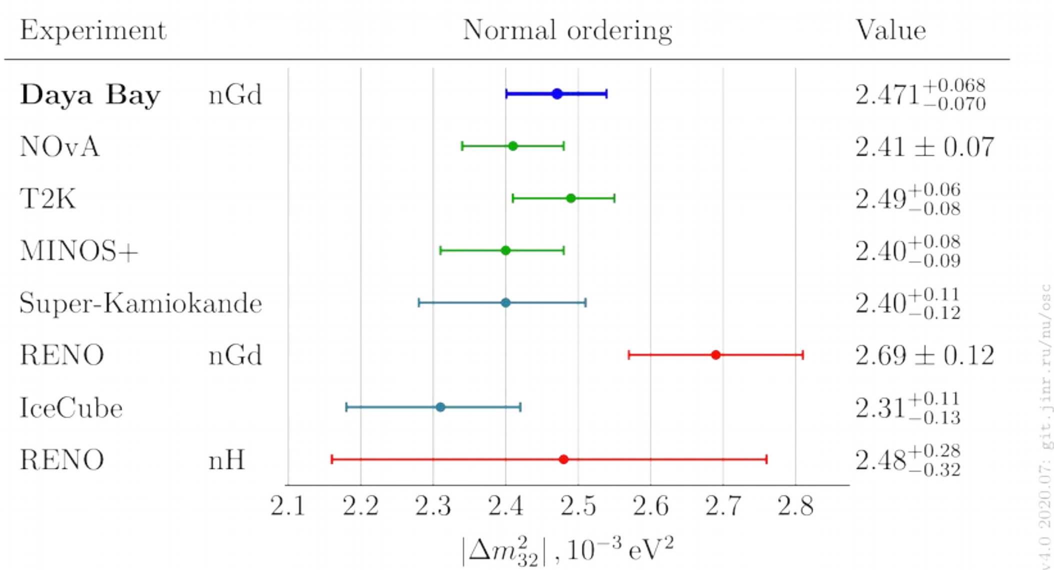
→ Will likely become the 2nd most precise measurement of $\sin^2 2\theta_{13}$ in the world

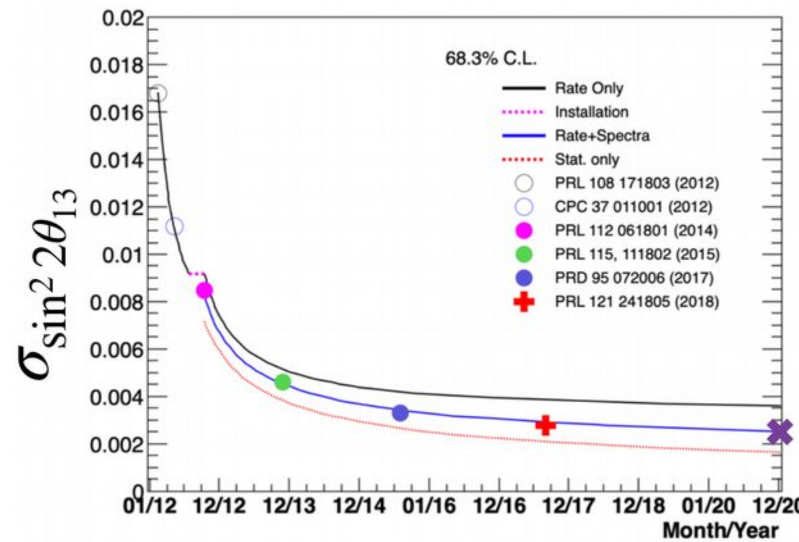


[Phys. Rev. D 93, 072011 (2016)]

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

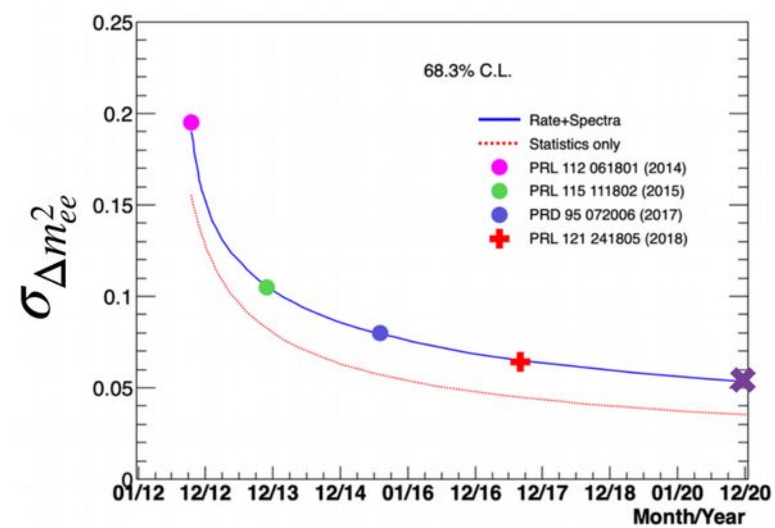






$\sin^2 2\theta_{13}$ uncertainty **3.4%** → **2.7%**

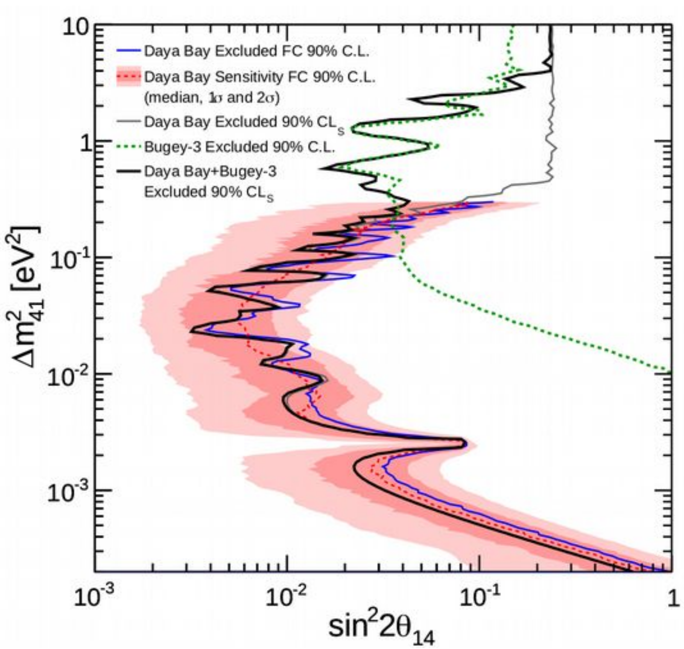
End of Daya Bay data taking

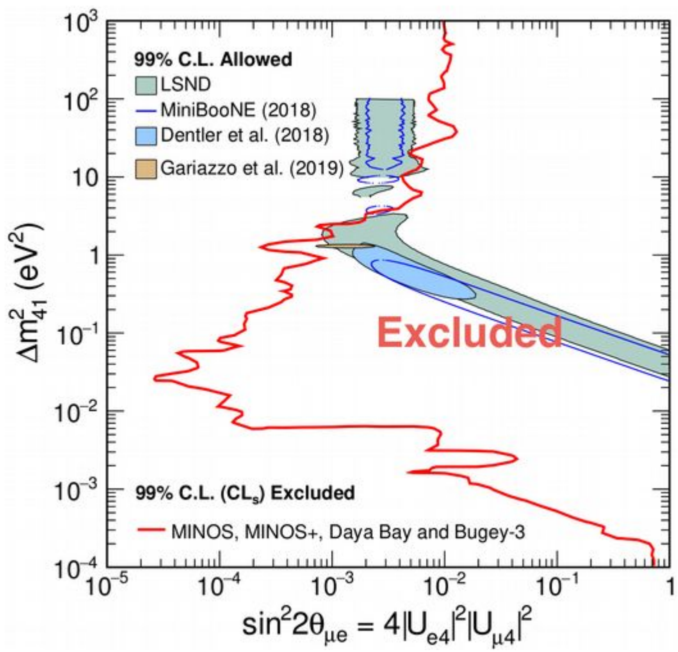


Δm^2_{ee} uncertainty **2.8%** → **2.1%**

Sterile Neutrino Search

- Motivated (among other things) by LSND & MiniBooNE observing excess of ν_e ($\bar{\nu}_e$) in ν_μ ($\bar{\nu}_\mu$) beam inconsistent with 3ν model
- 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 $\Delta m^2_{41} < 1.6$ eV^2

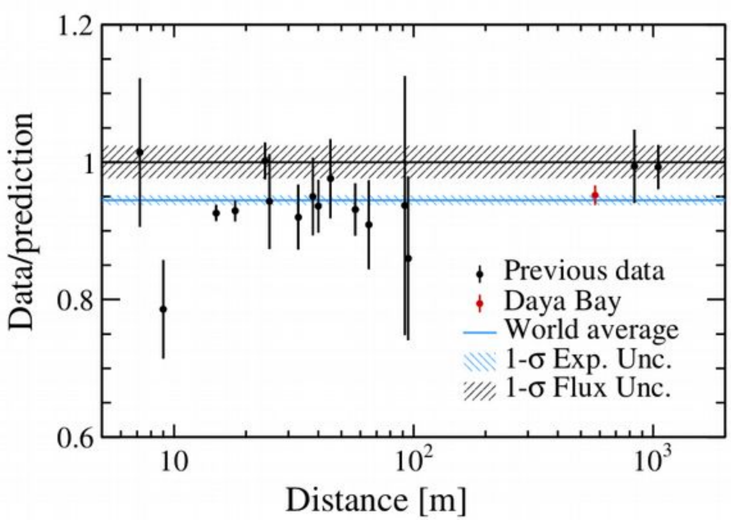
Daya Bay imposed the most stringent limits on $\sin^2 2\theta_{14}$ for $\Delta m^2_{41} < 0.2$ eV^2

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

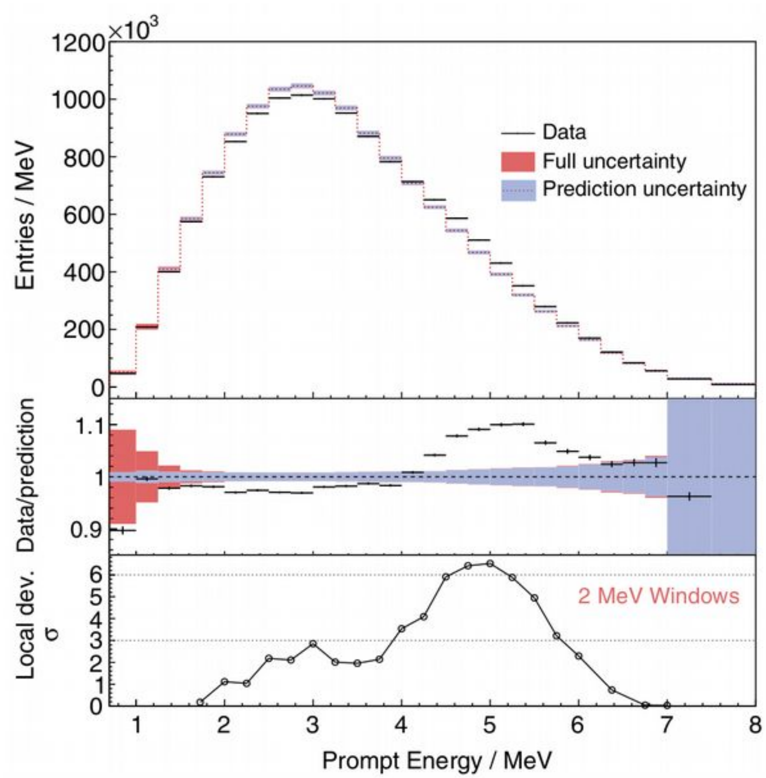
Reactor Antineutrino Flux & Spectrum

- 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)

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



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

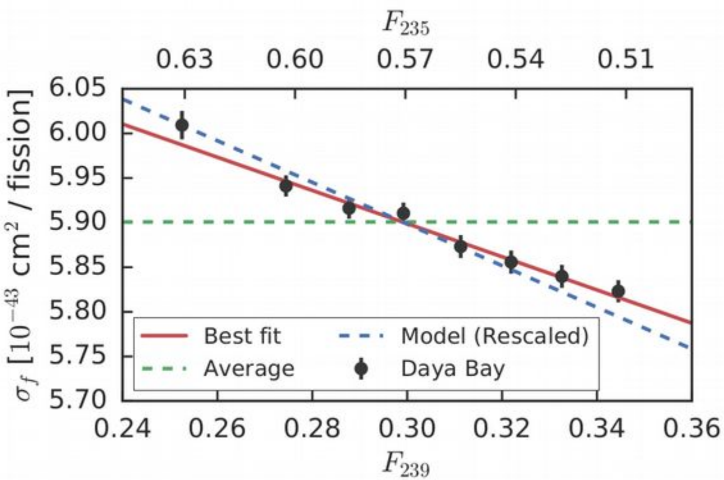


Daya Bay spectrum vs. Huber-Mueller prediction

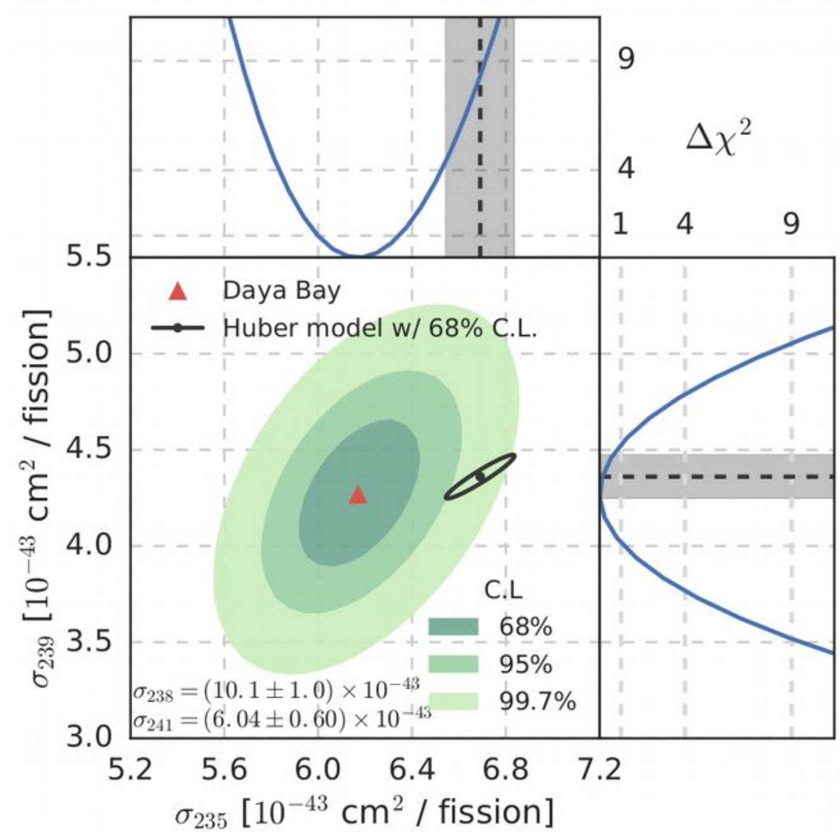
[Phys. Rev. Lett. 123, 111801 (2019)]

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



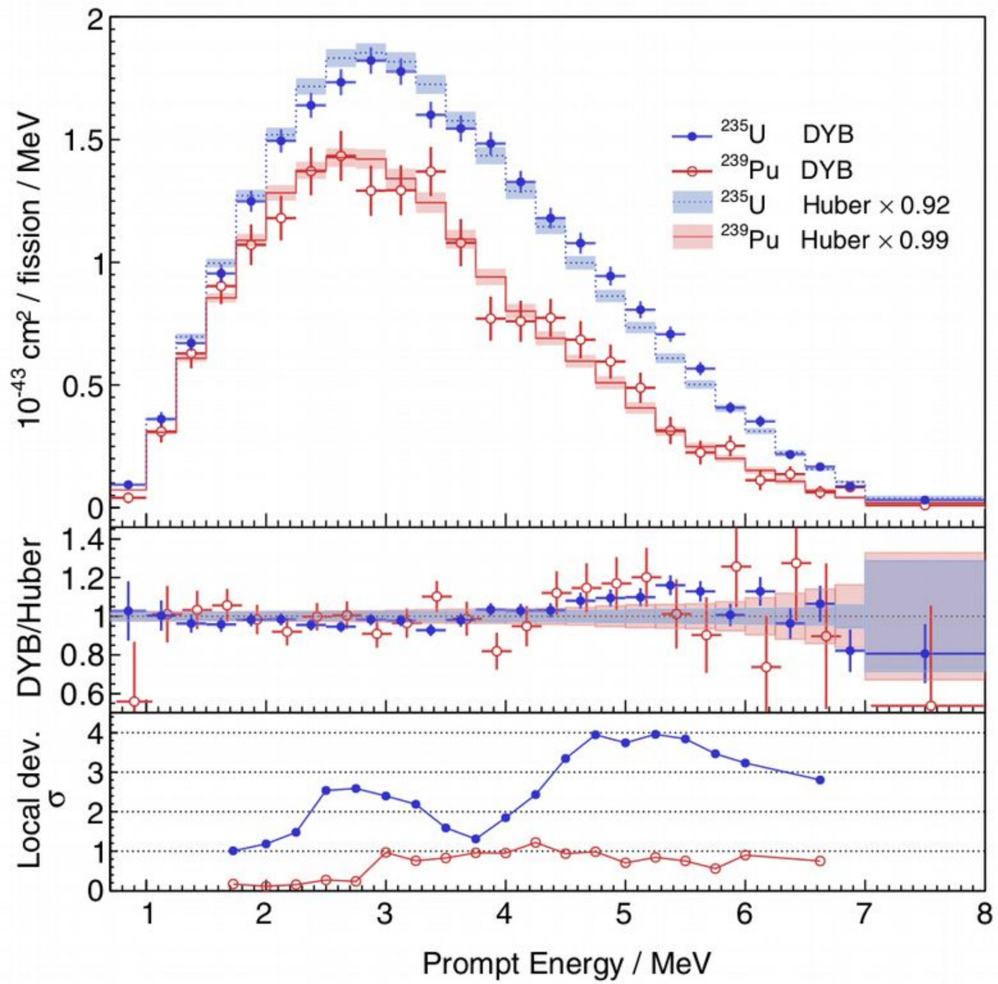
Result points to ^{235}U being mainly responsible for the deficit of observed $\bar{\nu}_e$'s compared to Huber-Mueller model



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

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

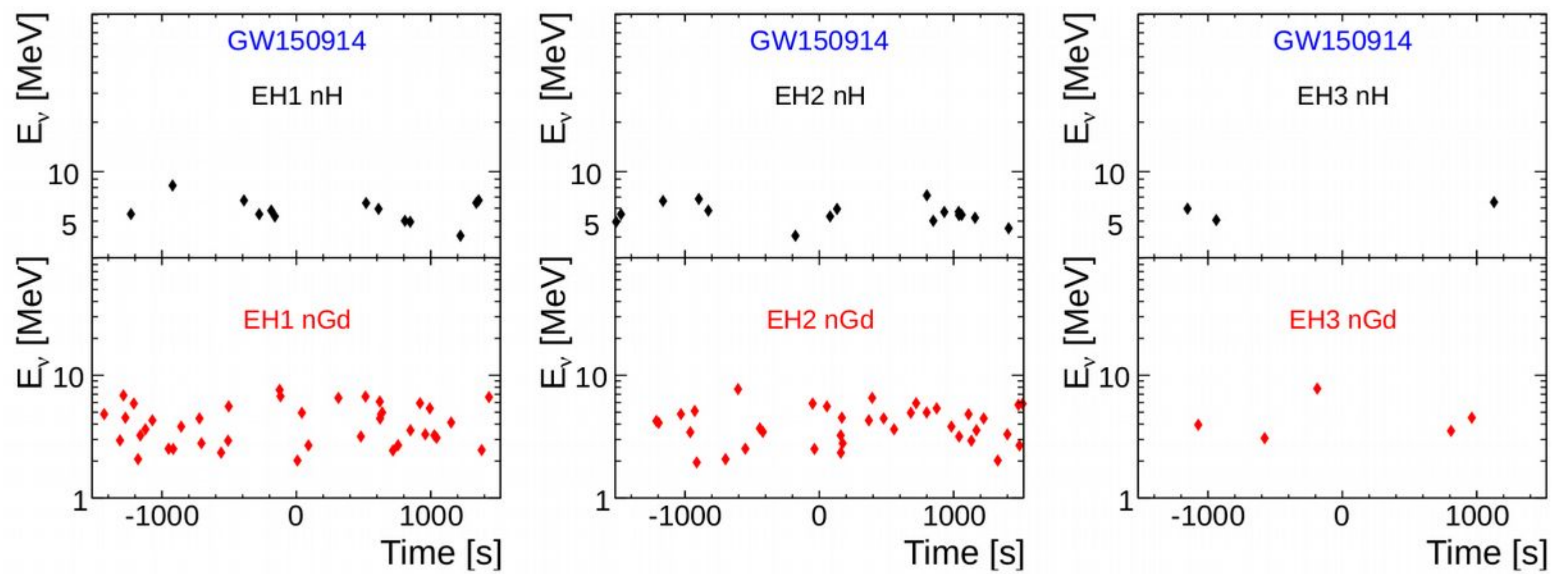
- Individual prompt spectra of ^{235}U and ^{239}Pu extracted using the evolution of the prompt spectrum as a function of the isotope fission fractions
- First measurement of ^{235}U and ^{239}Pu spectra from a commercial reactor
- Results consistent with 4-6 MeV bump in both spectra
- 4σ discrepancy of ^{235}U spectrum compared to Huber-Mueller model



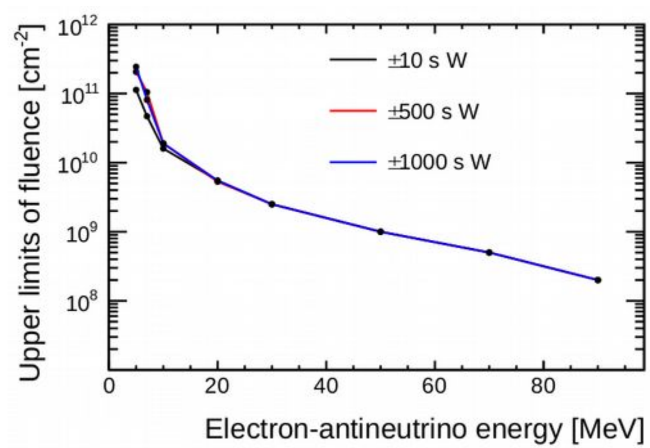
[Phys. Rev. Lett. 123, 111801 (2019)]

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

- No significant $\bar{\nu}_e$ event excess within ±10/500/1000 s time window of gravitational wave event observed



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



[arXiv:2006.15386]

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 signal region
- Reactor neutrino flux and spectrum measured, using fuel evolution ^{235}U and ^{239}Pu yields and spectra decoupled
- No IBD excess associated with gravitational waves observed
- **Daya Bay finishes 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!