Recent results from Daya Bay reactor neutrino Experiment

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TAUP 2017, July 24-28, Laurentian University,Sudbury

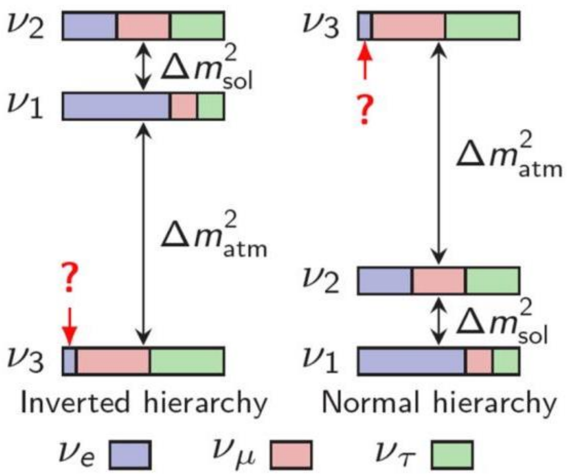
Outline

- Introduction
- Recent results from Daya Bay
  - Oscillation measurement
  - Reactor antineutrino flux and spectrum measurement
  - Evolution of the reactor antineutrino flux and spectrum
- Summary

Neutrino Mixing

In a 3-ν framework

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



$\Delta m^2_{sol} : \Delta^2 m_{21}$ $\Delta m^2_{atm} : \Delta^2 m_{31}, \Delta^2 m_{32}$

$$\mathrm{NH}: |\Delta m^2_{31}| = |\Delta m^2_{32}| + |\Delta m^2_{21}|, \quad |\Delta m^2_{31}| > |\Delta m^2_{32}|$$

$$\mathrm{IH}: |\Delta m^2_{31}| = |\Delta m^2_{32}| - |\Delta m^2_{21}|, \quad |\Delta m^2_{31}| < |\Delta m^2_{32}|$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

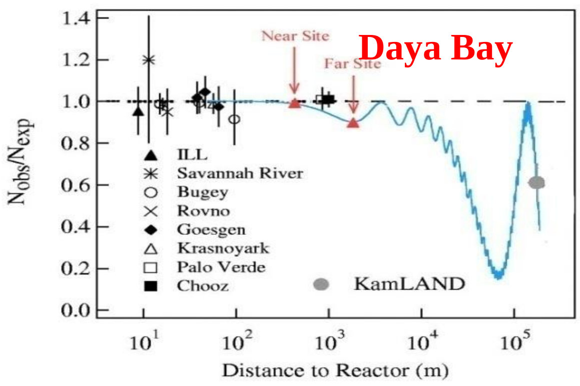
$\theta_{23} \sim 45°$
Atmospheric
Accelerator

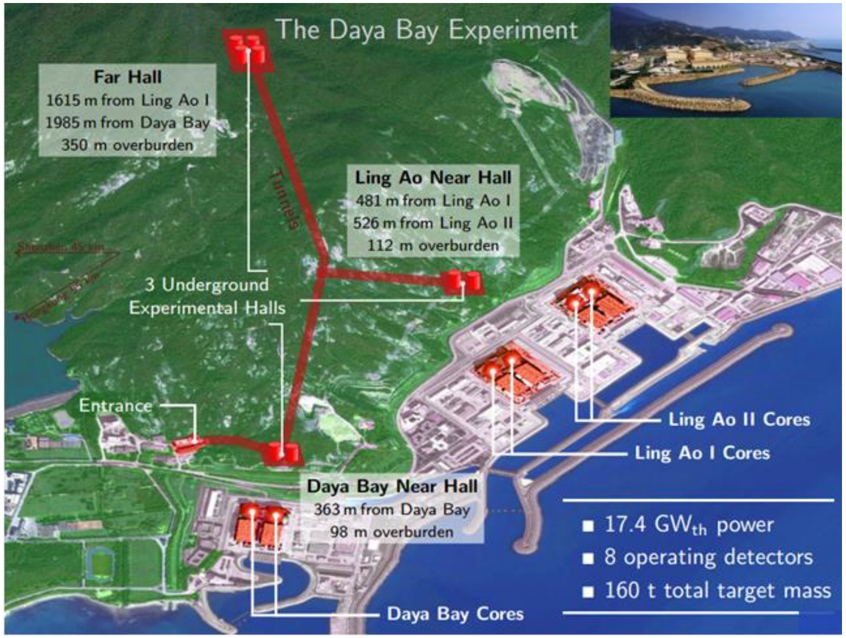
θ_{13} :The smallest and the last one to be determined
Reactor
Accelerator

$\theta_{12} \sim 34°$
Solar
Reactor

Daya Bay and Reactor Neutrino Oscillation

- DayaBay Reactor antineutrino experiment
  - In Shenzhen, southern China; ~55km to HK.
  - Discovery of disappearance by Inverse-β reaction to determine θ13.





- θ_{13} revealed by deficit of reactor antineutrinos at ~2 km. Mixing angle θ_{13} governs overall size of $\bar{\nu}_e$ deficit.
- Short-baseline reactor experiments insensitive to mass hierarchy can not discriminate 2 frequencies contributing to oscillation: $\Delta m^2_{31}, \Delta m^2_{32}$
- One effective oscillation frequency Δm^2_{ee} is measured:

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

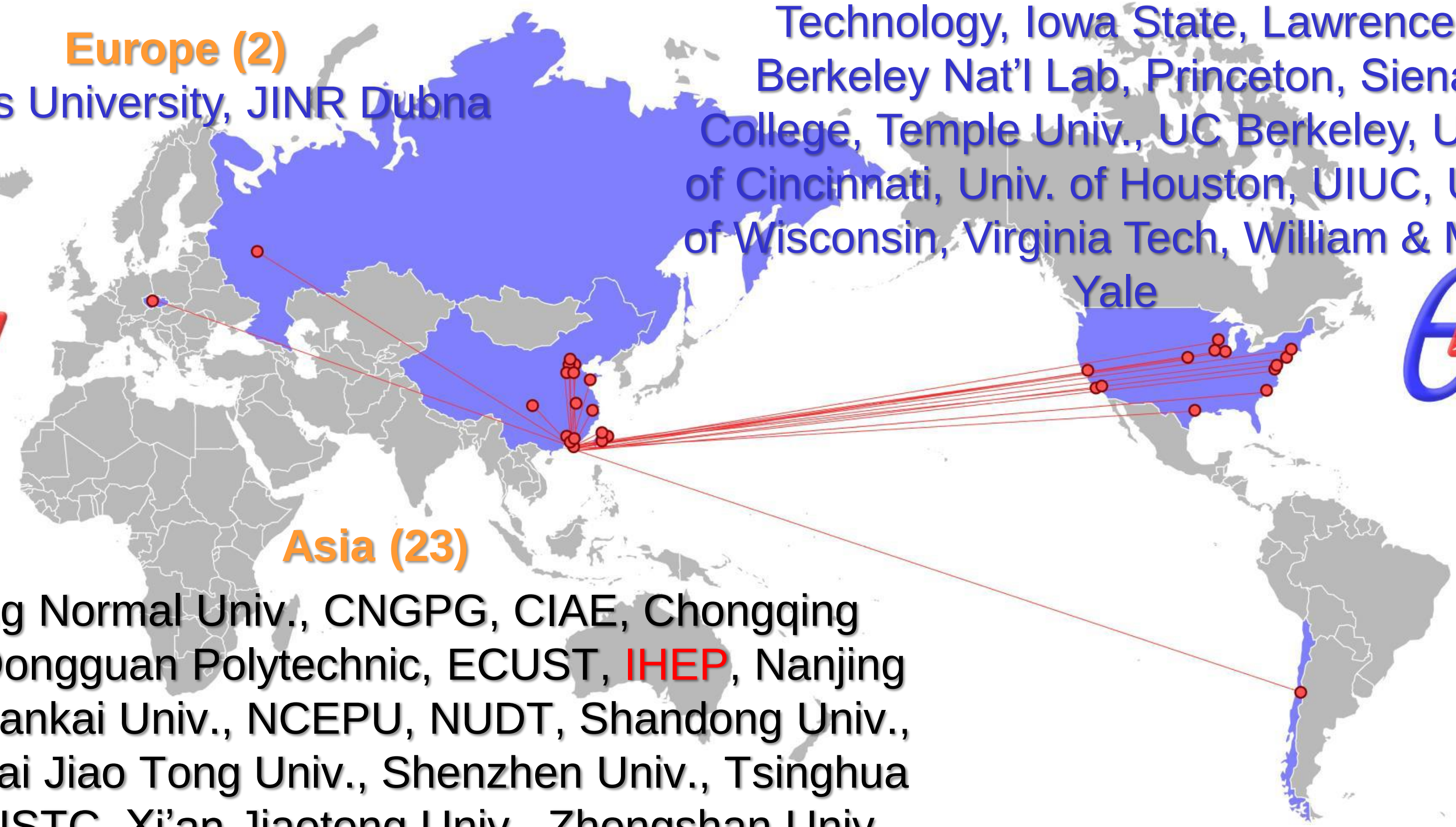
$$\sin^2(\Delta m^2_{ee} \tfrac{L}{4E}) \equiv \cos^2\theta_{12} \sin^2(\Delta m^2_{31} \tfrac{L}{4E}) + \sin^2\theta_{12} \sin^2(\Delta m^2_{32} \tfrac{L}{4E})$$

Daya Bay Collaboration

~230 collaborators from 41 institutions:

Europe (2)
Charles University, JINR Dubna

North America (15)
Brookhaven Nat'l Lab, Illinois Institute of Technology, Iowa State, Lawrence Berkeley Nat'l Lab, Princeton, Siena College, Temple Univ., UC Berkeley, Univ. of Cincinnati, Univ. of Houston, UIUC, Univ. of Wisconsin, Virginia Tech, William & Mary, Yale



Asia (23)
Beijing Normal Univ., CNGPG, CIAE, Chongqing Univ., Dongguan Polytechnic, ECUST, IHEP, Nanjing Univ., Nankai Univ., NCEPU, NUDT, Shandong Univ., Shanghai Jiao Tong Univ., Shenzhen Univ., Tsinghua Univ., USTC, Xi'an Jiaotong Univ., Zhongshan Univ., Chinese Univ. of Hong Kong, Univ. of Hong Kong, National Chiao Tung Univ., National Taiwan Univ., National United Univ.

South America (1)
Catholic Univ. of Chile

Detector design

Daya Bay Antineutrino Detectors (AD)

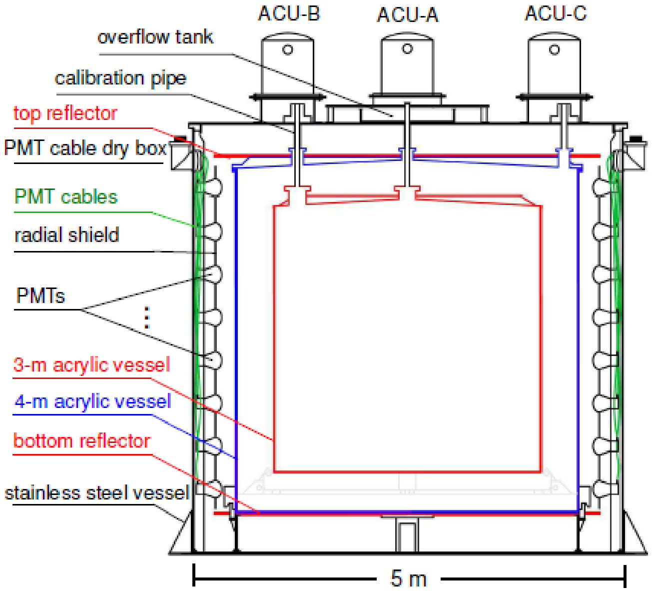
✓8 functionally identical detectors to reduce the detector relative errors

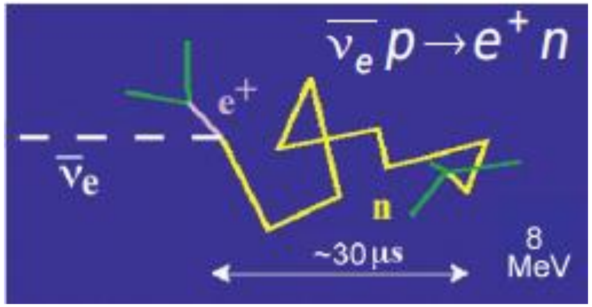
✓ Three zones modular structure

✓Reflector at top and bottom:

✓ Reflectors improve light collection and uniformity

Inverse beta decay(IBD) in Gd-doped liquid scintillator





Prompt signal

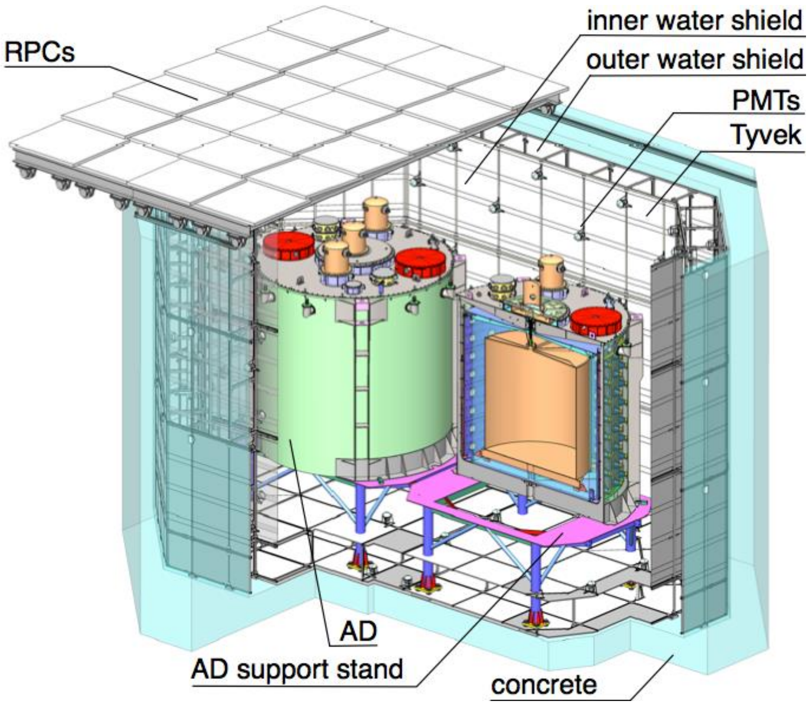
$$e^+ + e^- \to 2\gamma$$

$$\overline{\nu}_e + p \to e^+ + n$$

Delayed signal, Capture on Gd (8 MeV), ~30μs

Muon Tagging System

Dual tagging systems: 2.5 meter thick two-section water shield and RPCs



Two-zone ultrapure water cherenkov detector

- Outer layer of water veto (on sides and bottom) is 1m thick, inner layer >1.5m. Water extends 2.5m above ADs
  - 288 8” PMTs in each near hall
  - 384 8” PMTs in Far Hall
- 4-layer RPC modules above pool
  - 54 modules in each near hall
  - 81 modules in Far Hall
- Goal efficiency: > 99.5% with uncertainty <0.25%

Oscillation measurement(nGd)

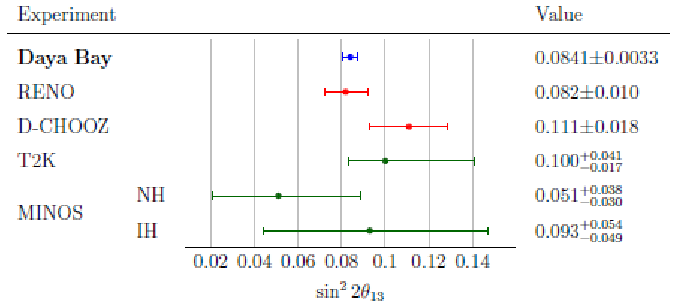
- 1230 days dataset
  - 217 days x 6AD + 1013 days x 8AD
- Strong confirmation of observed anti-neutrino deficit.

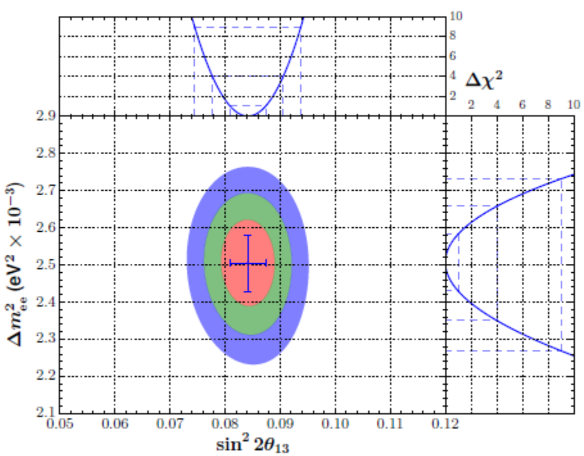
Phys. Rev D. **95**, 072006 (2017)

$$\sin^2 2\theta_{13} = 0.0841 \pm 0.0027(\text{stat.}) \pm 0.0019(\text{syst.})$$

$$\left|\Delta m^2_{ee}\right| = [2.50 \pm 0.06(\text{stat.}) \pm 0.06(\text{syst.})] \times 10^{-3}\,\text{eV}^2$$

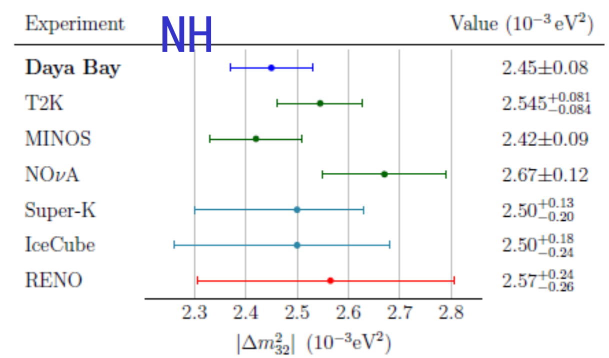
$$\chi^2 / NDF = 232.6 / 263$$

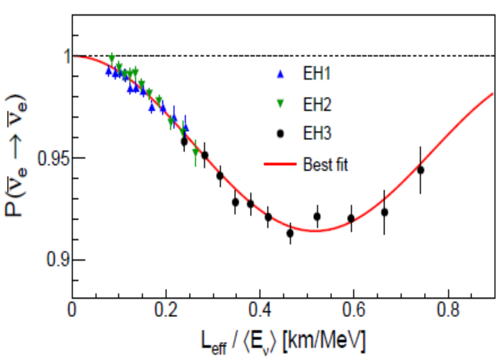




Most precise measurement:

- $\sin^2 2\theta_{13}$ uncertainty: 3.9%
- $\left|\Delta m^2_{ee}\right|$ uncertainty: 3.4%





Consistent with 3-neutrino oscillation framework.

Consistent results with reactor and accelerator experiments.

Reactor antineutrino flux measurement

- 621 days data
  - 217 days x 6AD + 404 days x 8AD

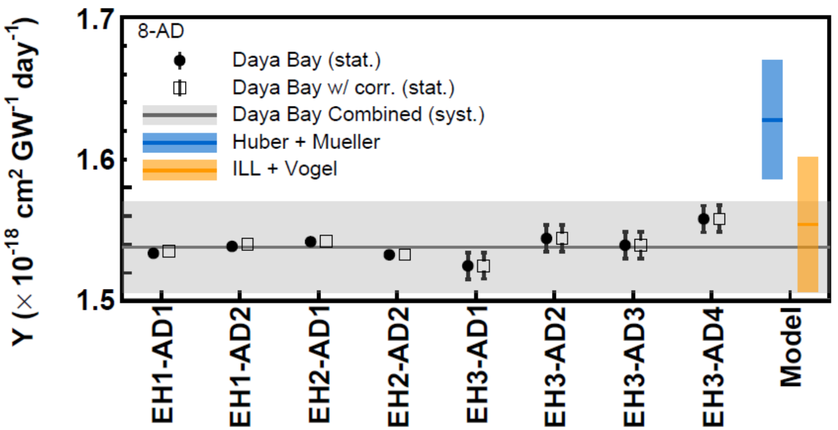
Chinese Physics C, 2017, 41(1): 13002-013002

IBD yield

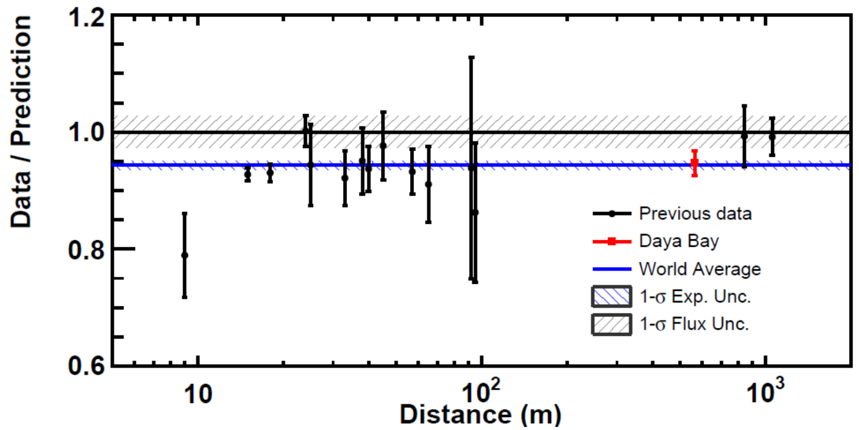
$$Y = (1.55 \pm 0.03) \times 10^{-18} cm^2 / GW / day$$

$$\sigma_f = (5.93 \pm 0.12) \times 10^{-43} cm^2 / \ fission$$

- Reactor antineutrino flux:
  - Data/Prediction (Huber+Mueller) :**0.946 ± 0.020**
    - Reactor antineutrino anomaly
  - Data/Prediction (ILL+Vogel): **0.992 ± 0.021**

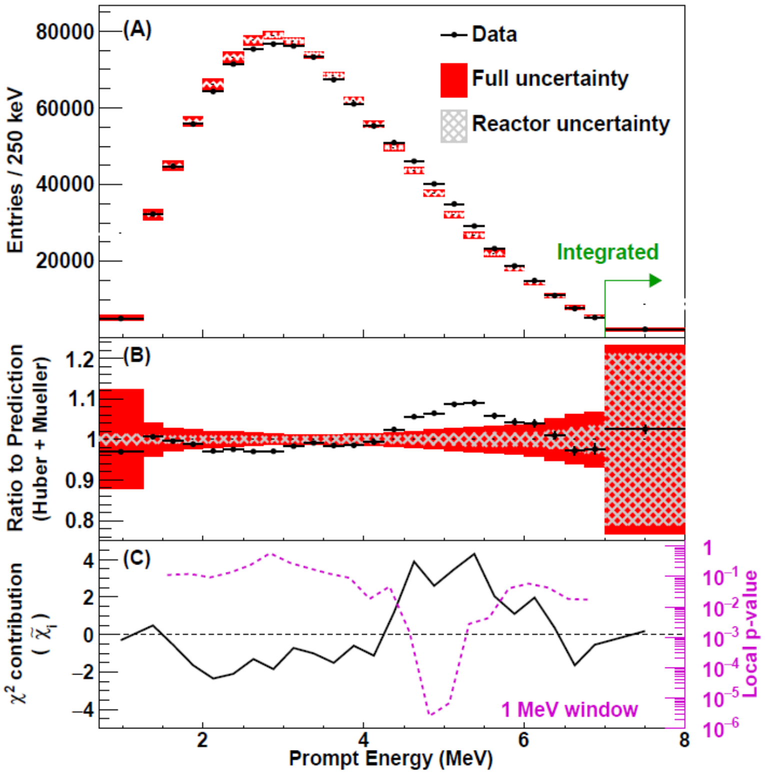


IBD yield measurement consistent among 8 ADs



Measurement consistent with the global average of the previous short baseline experiments

Reactor antineutrino spectrum measurement



Chinese Physics C, 2017, 41(1): 13002-013002

- 621 days data with more than 1.2 million IBD candidates
  - high-statistic reactor antineutrino spectrum measurement
- A 2.9 σ deviation compared to Huber+Mueller model prediction;
- Event excess in 4~6 MeV region(4.4 σ)
  - Excess events characteristics are same as IBD events, correlated with reactor power but time independent
  - Ruled out detector effects
    - There are no event excess for the spallation ^{12}B beta spectra at same energy range

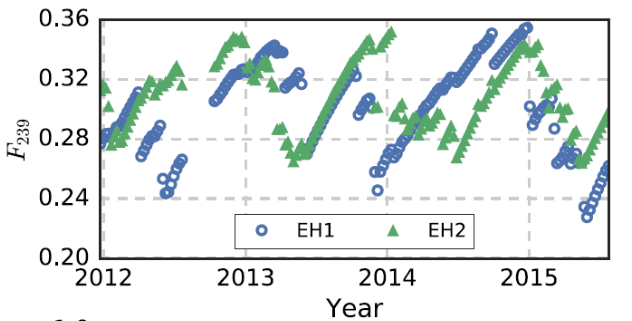
Reactor antineutrino flux evolution

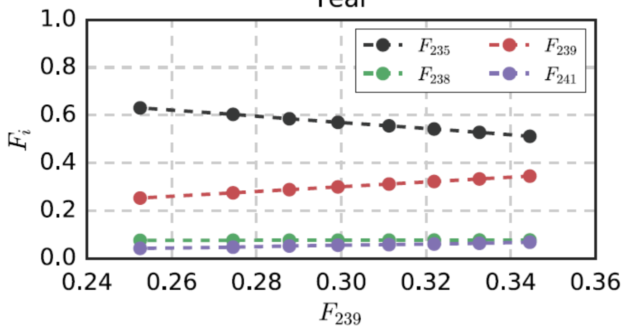
Analysis of dependence of IBD yield/fission σ_i for each fission isotope (i = ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu) on effective fission fraction.

Effective fission fraction (F_i): Weighted by power (*W*), *survival,* probability (*p*), *baseline (L) over 6* reactor cores

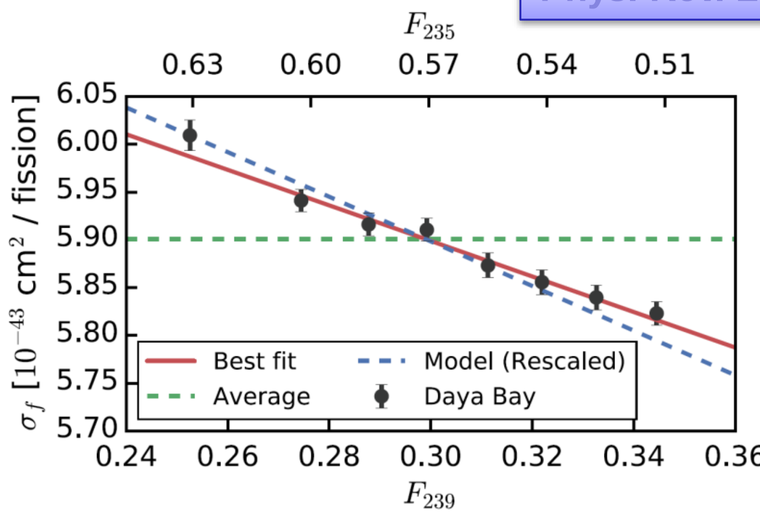
Phys. Rev. Lett. 118.251801

$$F_i(t) = \sum_{r=1}^{6} \frac{W_{\mathrm{th},r}(t)\bar{p}_r f_{i,r}(t)}{L_r^2 \overline{E}_r(t)} \Bigg/ \sum_{r=1}^{6} \frac{W_{\mathrm{th},r}(t)\bar{p}_r}{L_r^2 \overline{E}_r(t)}.$$





1230 days, near detectors

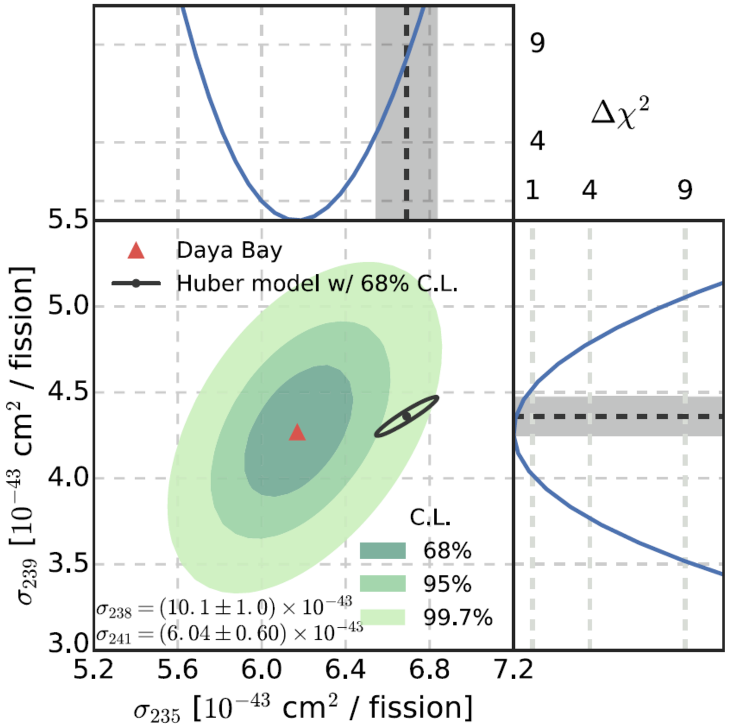


Unit $(\times 10^{-43} cm^2 / fission)$	$\overline{\sigma_f}$	$d\sigma_f/dF_{239}$
Daya Bay	5.90±0.13	-1.86±0.18
Huber-Mueller Model	6.22±0.14	-2.46±0.06

5.1% difference in predicted and measured in $\overline{\sigma_f}$.

Evolution of reactor antineutrino flux

- Fits to Individual Isotopes ^{235}U & ^{239}Pu
- Assume loose (10%) uncertainties on sub-dominant ^{238}U & ^{241}Pu (central values taken from Huber-Mueller model)



Unit $(\times 10^{-43} cm^2 / fission)$	σ_{235}	σ_{239}
Daya Bay	6.17 ± 0.17	4.27 ± 0.26
Huber-Mueller Model	6.69 ± 0.15	4.36 ± 0.11

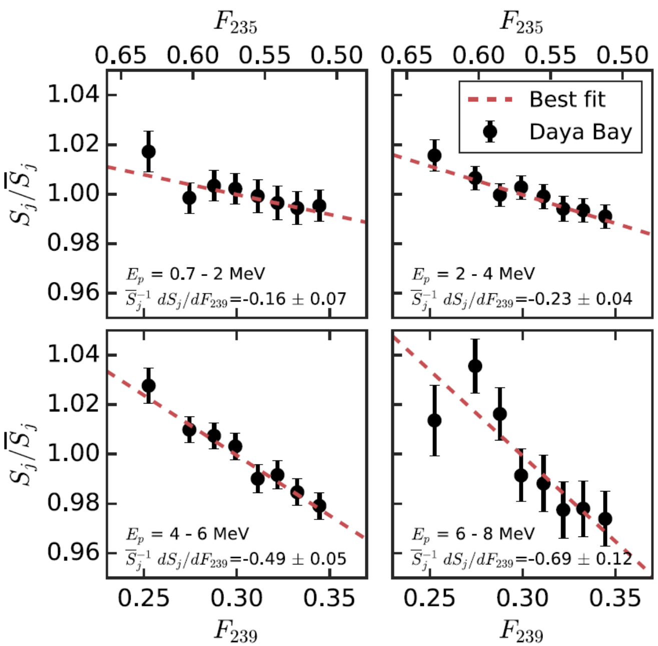
- Measurement of ^{235}U yield is 7.8% lower than predicted.
    - Significantly larger than the 2.7% measurement uncertainty
- Overestimated contribution from ^{235}U ?
- It may be the primary contributor to the reactor antineutrino anomaly.

Evolution of the reactor antineutrino Spectrum

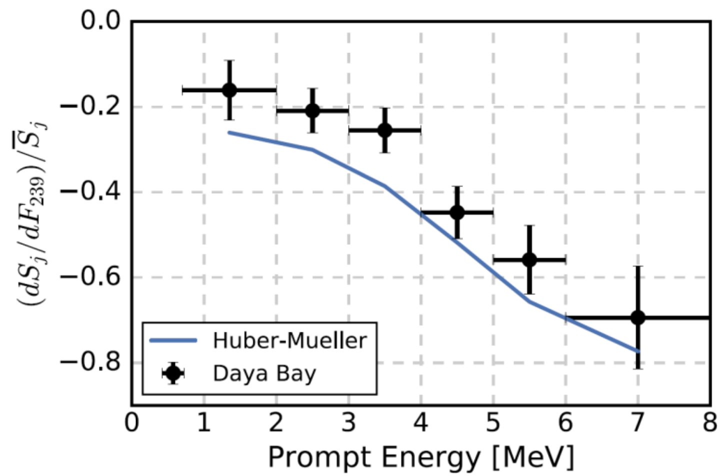
Observed IBD spectra per fission, S, $\sigma_f = \sum_j S_j$ the sum of IBD yields in all prompt energy bins.

$\bar{S}_j$: F239-averaged IBD yield per fission value.

Y axis is the ratio of $S_j / \bar{S}_j$.



4 different energy bins for the analysis



X axis: fractional variation in IBD yield. The trend is generally consistent with prediction

- Energy-dependent evolution is observed
- Change in spectral shape as fuel composition evolves.
- First unambiguous measurements of this Behavior

Summary

- **Reactor antineutrino oscillation results:**
  - **nGd, 1230 days' data**
    $$\sin^2 2\theta_{13} = 0.0841 \pm 0.0027(\text{stat.}) \pm 0.0019(\text{syst.})$$
    $$\left|\Delta m^2_{ee}\right| = [2.50 \pm 0.06(\text{stat.}) \pm 0.06(\text{syst.})] \times 10^{-3}\,\text{eV}^2$$
  - **nH, rate analysis** $\sin^2 2\theta_{13} = 0.071 \pm 0.011$ (Phys. Rev. D **93**, 0720 (2016))
- **Reactor antineutrino flux and spectrum**
  - Flux is consistent with previous short baseline experiments
  - Spectrum different from prediction with significance 4.4σ in 4-6 MeV energy region
- **Evolution of reactor antineutrino flux and spectrum**
  - IBD yield per fission from individual isotopes (^{235}U, ^{239}Pu, ^{238}U, ^{241}Pu) are measured
  - IBD yield of ^{235}U is 7.8% lower than prediction
- **Search for light sterile neutrino** **(Phys. Rev. Lett. 117 ,151802(2016); Phys. Rev. Lett. 117, 151801 (2016))**
  - No hint of light sterile neutrino observed. Most stringent limit for $|\Delta m^2_{41}| < 0.2\ \text{eV}^2$
  - Excluded parameter space allowed by MiniBooNE& LSND for $\Delta m^2_{41} < 0.8\ \text{eV}^2$
- **The experiment is expected to continue running until 2020.**
  - Expect to get uncertainty in oscillation parameters to below 3%

Thanks

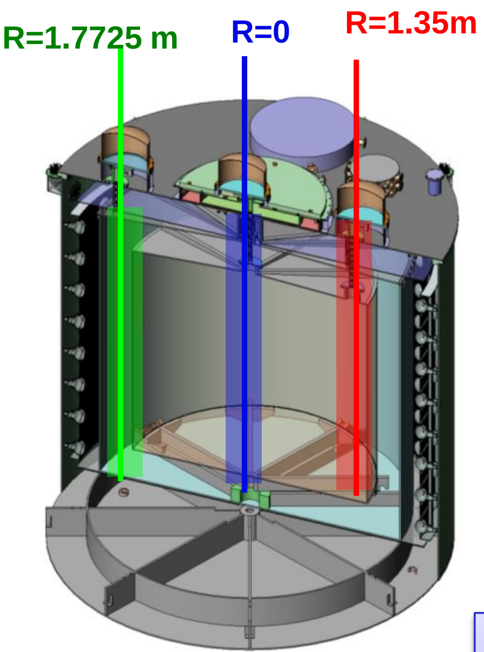
- Backup

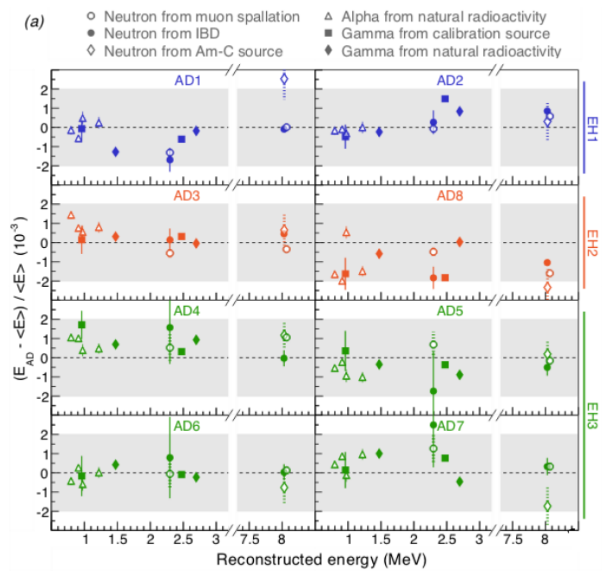
Energy Calibration

3 Automatic calibration units (ACUs) on each detector

Use different sources to calibrate the neutrino detector.

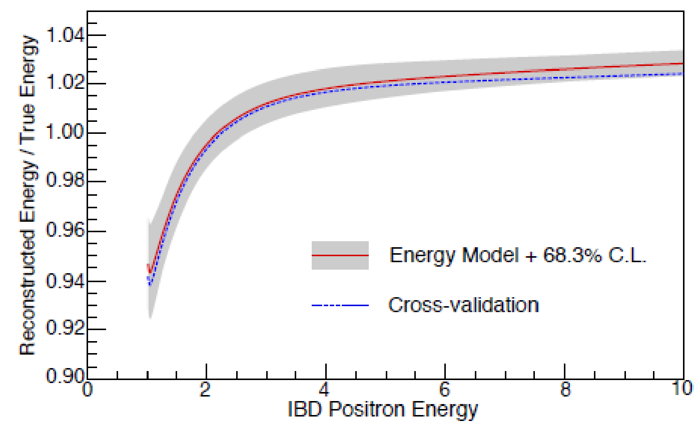
Energy scale, time variation, non-uniformity, non-linearity.





Check with various sources from 0.8MeV to 8MeV;
Relative energy scale uncertainty for nGd analysis: 0.2%

Energy non-linearity calibration



Nominal energy model: fit to mono-energetic gamma lines and ^{12}B beta-decay spectrum

Cross-validation model: fit to ^{208}Th, ^{212}Bi, ^{214}Bi beta-decay spectrum, Michel electron

Use two methods and get the consistent results.

<1% uncertainty in most energy ranges (>2MeV)

Uncertainty Summary

	Efficiency	Correlated	Uncorrelated
Target protons	-	0.92%	0.03%
Flasher cut	99.98%	0.01%	0.01%
Delayed energy cut	92.7%	0.97%	0.08%
Prompt energy cut	99.8%	0.10%	0.01%
Multiplicity cut		0.02%	0.01%
Capture time cut	98.7%	0.12%	0.01%
Gd capture fraction	84.2%	0.95%	0.10%
Spill-in	104.9%	1.00%	0.02%
Livetime	-	0.002%	0.01%
Combined	80.6%	1.93%	0.13%

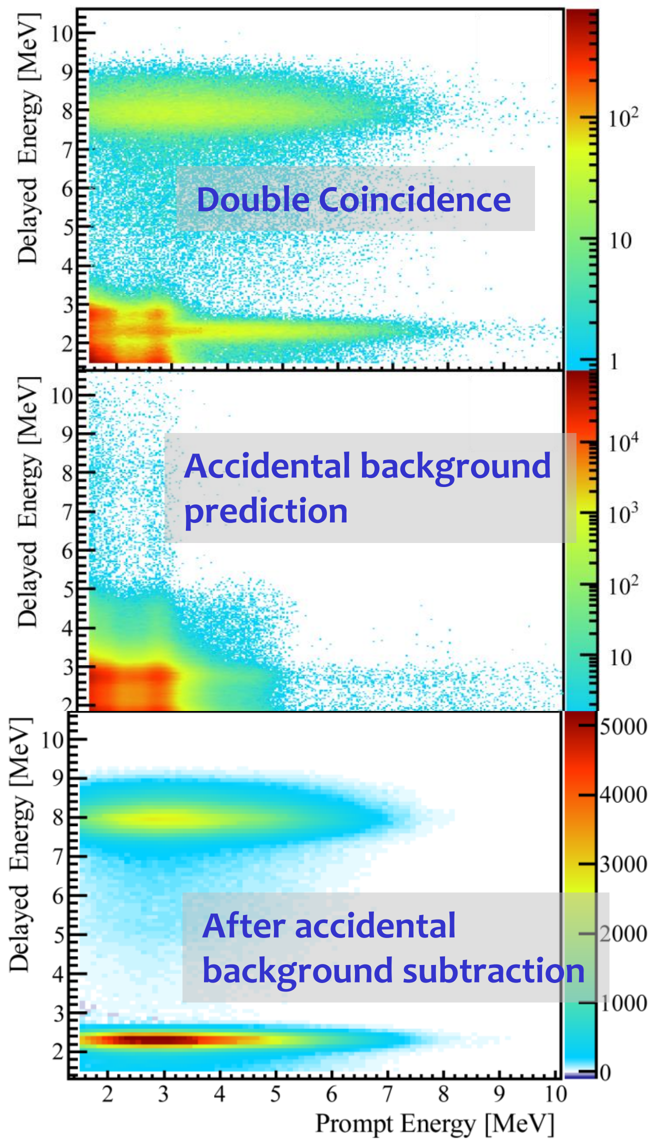
For near/far oscillation, only uncorrelated uncertainties are used.

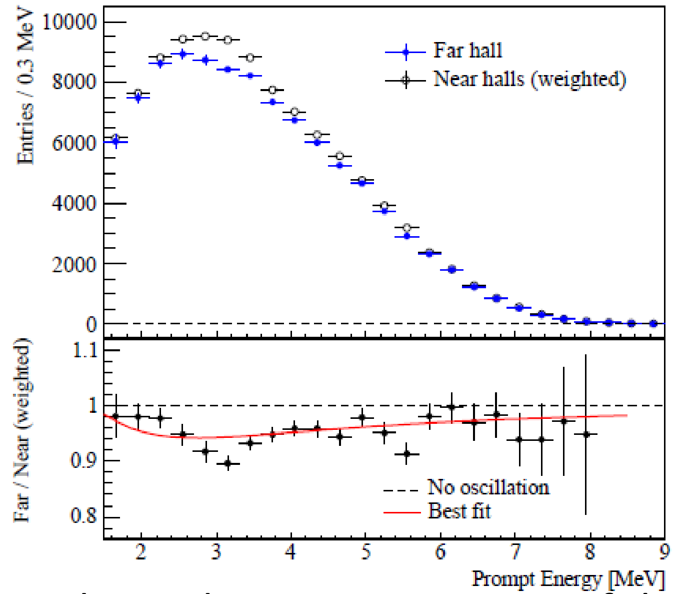
Reactor			
Correlated		Uncorrelated	
Energy/fission	0.2%	Power	0.5%
$\overline{\nu}_e$/fission	3%	Fission fraction	0.6%
		Spent fuel	0.3%
Combined	3%	Combined	0.8%

Influence of uncorrelated reactor systematics reduced by far vs. near measurement.

Oscillation measurement(nH)

Phys. Rev. D **93**, 0720 (2016)





- Independent measurement of theta13
- Challenge of the analysis
  - High accidental background and more energy leakage at the edge of detector
  - Increase energy threshold, consider the correlation in space , details study the backgrounds
- Rate only results

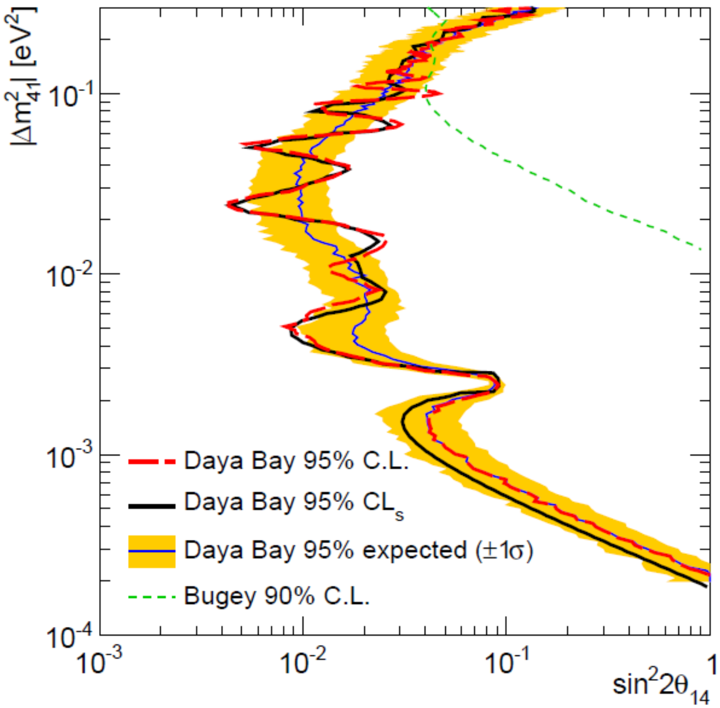
$$\sin^2 2\theta_{13} = 0.071 \pm 0.011$$

$$\chi^2 / NDF = 6.3/6$$

Search for light sterile neutrino

- **Sterile neutrino(3+1)**

Phys. Rev. Lett. 117 ,151802(2016)



Obtain world's best limits in region spanning more than three orders of magnitude:

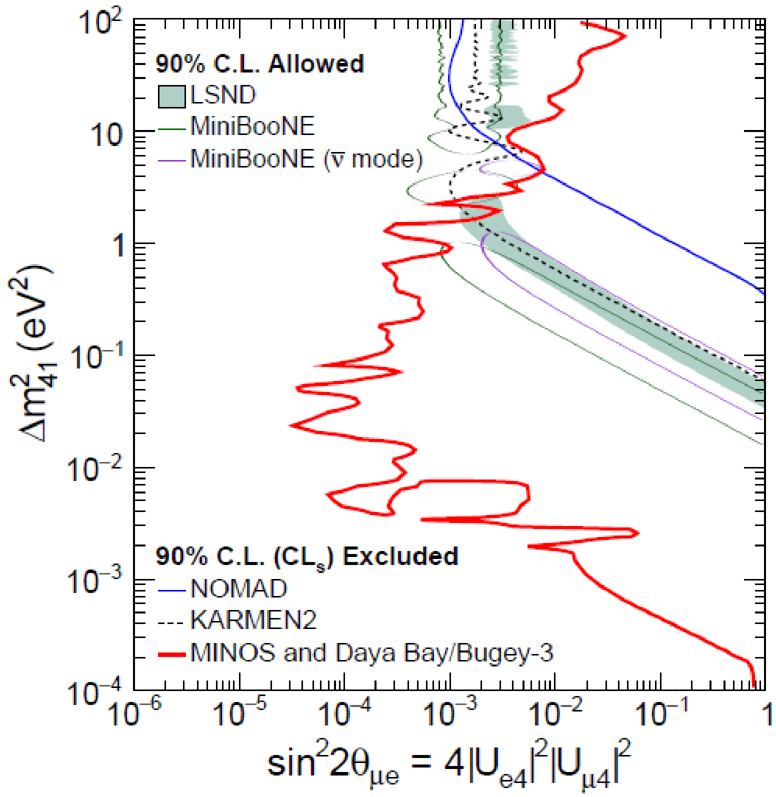
$$2\times10^{-4}\mathrm{eV}^2 < \leq |\Delta m^2_{41}| < 0.3\mathrm{eV}^2$$

No hint of light sterile neutrino observed.

•Most stringent limit for $|\Delta m^2_{41}| < 0.2\mathrm{eV}^2$

Phys. Rev. Lett. 117, 151801 (2016)

DayaBay + MINOS + Bugey-3



Excluded parameter space allowed by MiniBooNE& LSND for $\Delta m^2_{41} < 0.8\mathrm{eV}^2$