θ_{13} Reactor Neutrino Experiments

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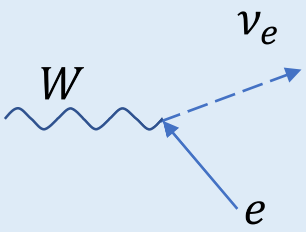
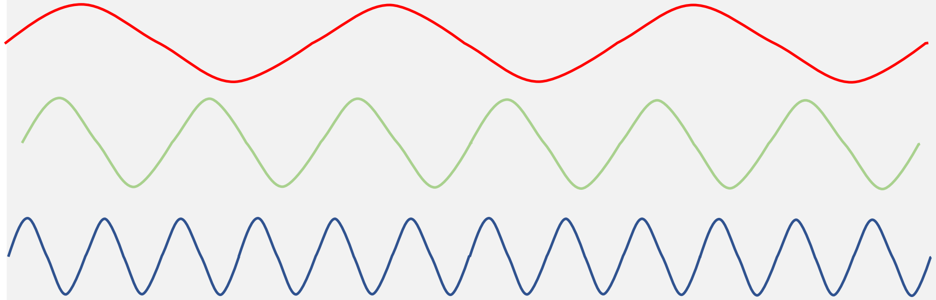
Neutrino Oscillations

Creation via
Weak Interaction



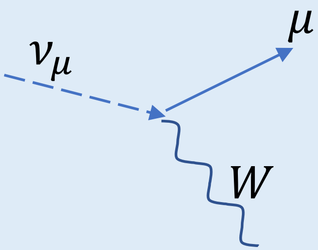
Flavor State $|\nu_\alpha\rangle$

Propagation determined by
mass-eigenstates $|\nu_i; p\rangle$



$$\omega_i = E_i = \sqrt{p^2 + m_i^2}$$

Detection via
weak interaction



Flavor State $|\nu_\beta\rangle$

$$|\nu_\alpha\rangle = \sum_{\alpha i} U_{\alpha i}^* |\nu_i; p\rangle$$

Different neutrino masses will create
phase differences after the time t

Lepton Sector

$$U_{PMNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

Quark Sector

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Neutrino Mixing and Oscillations

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$c_{ij} \equiv cos\theta_{ij}$

$s_{ij} \equiv sin\theta_{ij}$

two Majorana phases are omitted

atmospheric /accelerator

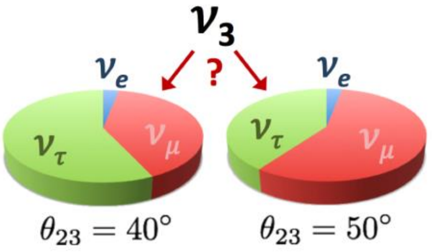
short-baseline reactor accelerator

Solar/ long-baseline reactor

$$|\Delta m^2_{32}| \approx |\Delta m^2_{31}| \sim 2.5 \times 10^{-3} eV^2$$

$$\Delta m^2_{21} \sim 7.5 \times 10^{-5} eV^2$$

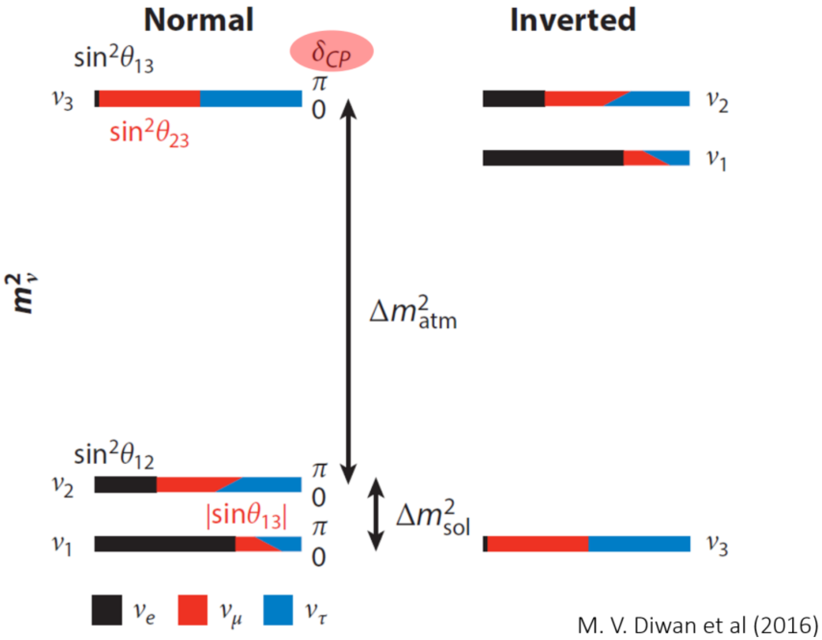
$\theta_{23} \sim 45^o$ θ_{23} Octant?



$\theta_{12} \sim 34^o$

$\theta_{13} \sim 8.4^o$

The last known oscillation angle,
Need sizable θ_{13} for CP violation measurement



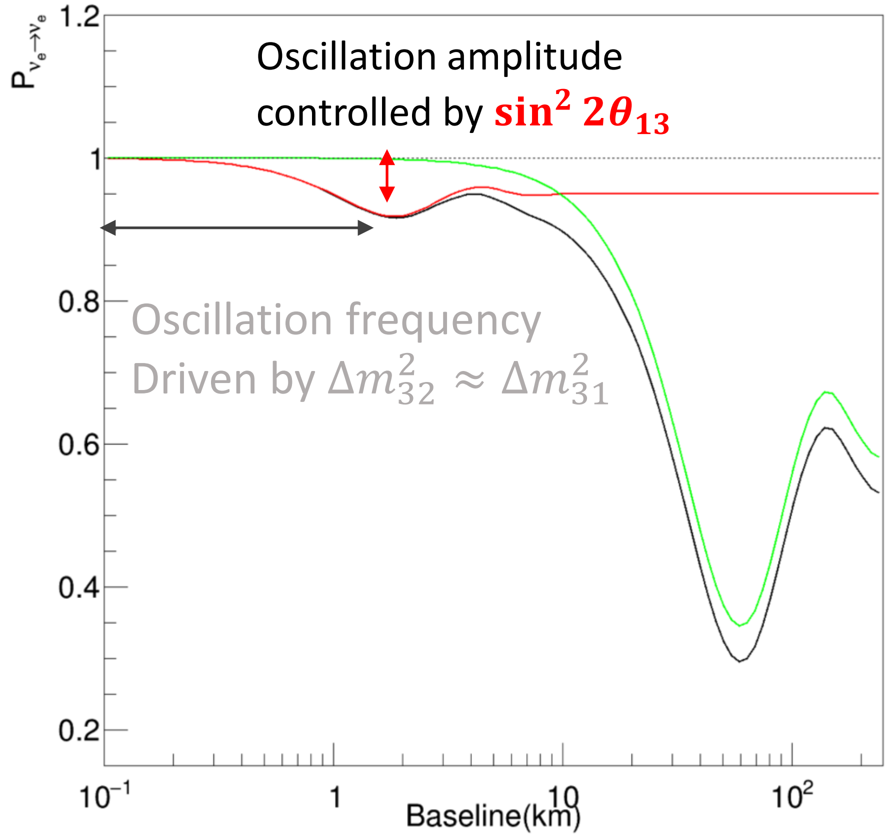
M. V. Diwan et al (2016)

θ_{13} Measurement Strategies

- Accelerator-Neutrinos exploring $P(\nu_\mu \rightarrow \nu_e)$
  - Leading term : $\sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \Delta_{31} + cos^2\theta_{13}\cos^2 \theta_{23} \sin^2 2\theta_{12} \sin^2 \Delta_{21}$
  - Higher order terms depend on δ_{cp} and mass ordering
- Reactor neutrinos @ ~ Km
  - A clean measurement of θ_{13}: No CP phase term , Negligible matter effect

Commentary approaches: θ_{13} measured in reactor experiments can serve as constrains in accelerator neutrino studies and helps to entangle the correlations among unknown parameters

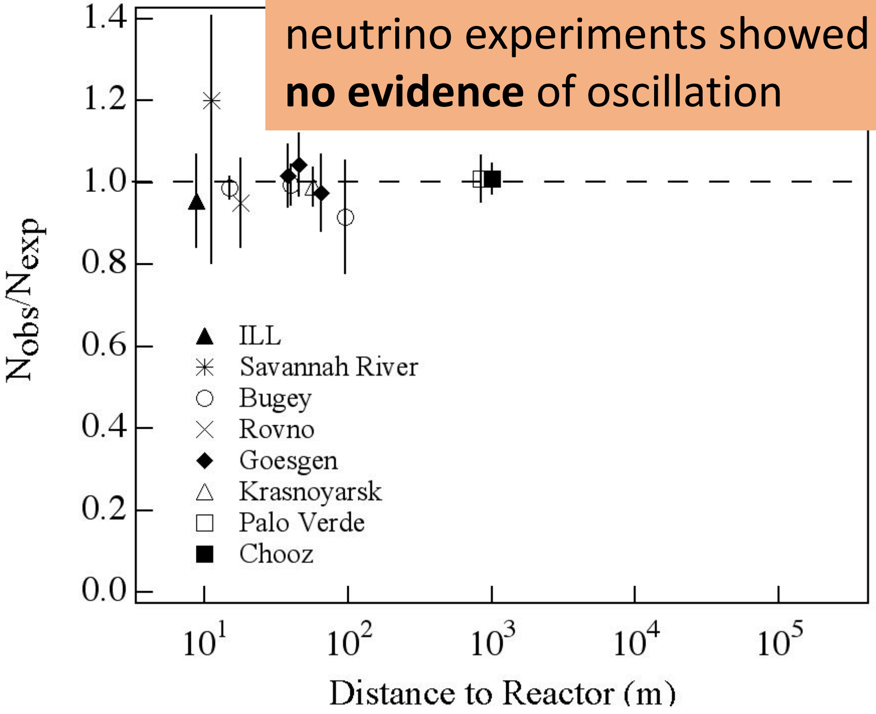
Measuring θ_{13} nearby reactors



Oscillation amplitude controlled by $\mathbf{\sin^2 2\theta_{13}}$

Oscillation frequency Driven by $\Delta m^2_{32} \approx \Delta m^2_{31}$

Previous short baseline reactor neutrino experiments showed **no evidence** of oscillation



Chooz and Palo Verde experiments determined $\theta_{13} < 11^o$ $(90\%\ C.L)$

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

$$\Delta_{\mathrm{ij}} \equiv \Delta m^2_{ij} L/4E \qquad -\sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32})$$

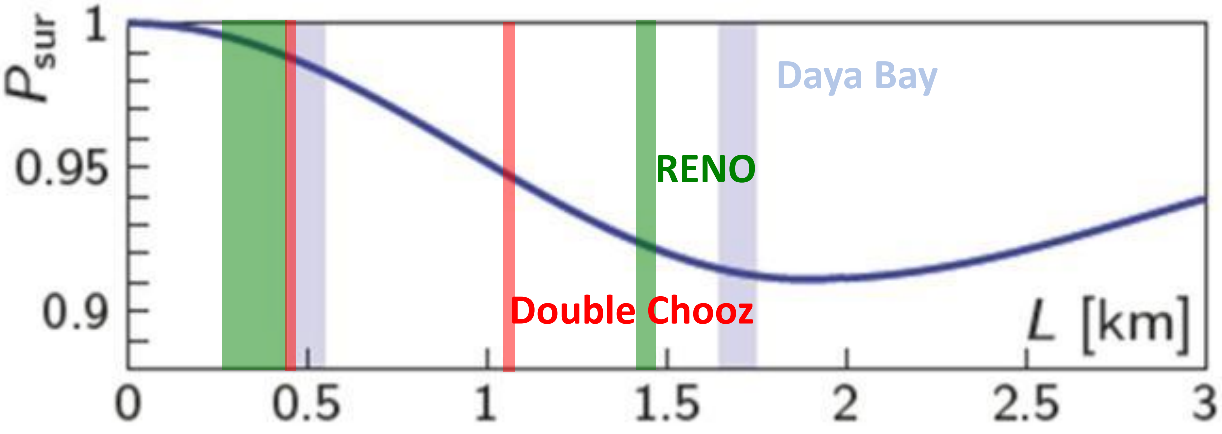
Improve the sensitivity

- Near/Far relative measurement

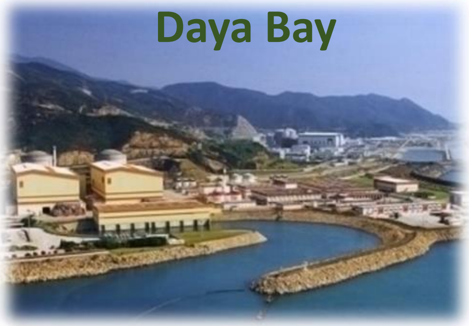
$$\frac{N_f}{N_n} = \left(\frac{N_{p,f}}{N_{p,n}}\right)\left(\frac{L_n}{L_f}\right)^2\left(\frac{\epsilon_f}{\epsilon_n}\right)\left[\frac{P_{sur}(\sin^2 2\theta_{13}, E, L_f)}{P_{sur}(\sin^2 2\theta_{13}, E, L_n)}\right]$$

  - First proposed by L.A Mikaelyan and V.V SineV , Phys. Atomic Nucl.63 1002(2000)
  - Minimal dependence on our knowledge of reactor neutrino flux: the largest uncertainty in previous measurements
- Powerful Reactors
- Optimize baseline
- Large overburden : lower the cosmogenic backgrounds
- Identical Detector Design:
  - Three zone design with Gd-doping

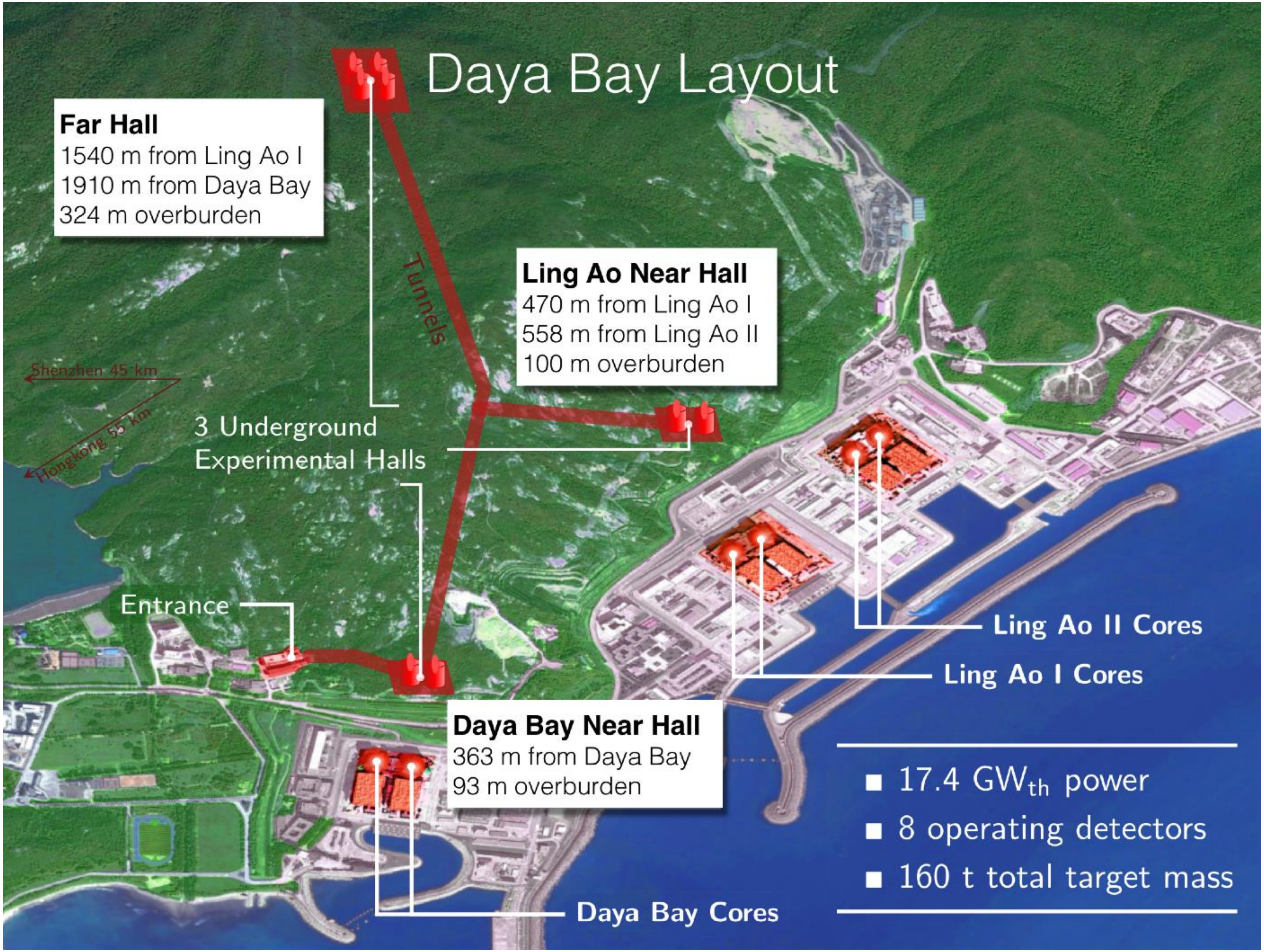
θ_{13} reactor neutrino experiments



	Reactor(GW)	Target(Ton)	Depth(m.w.e)
Double Chooz	8.5	16(2*8)	120/300 (near/far)
RENO	16.5	32(2*16)	120/450
Daya Bay	17.4	160(2*20)	250,300/870



Daya Bay Layout



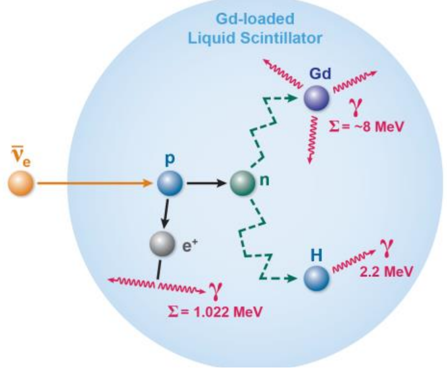
Far Hall
1540 m from Ling Ao I
1910 m from Daya Bay
324 m overburden

Ling Ao Near Hall
470 m from Ling Ao I
558 m from Ling Ao II
100 m overburden

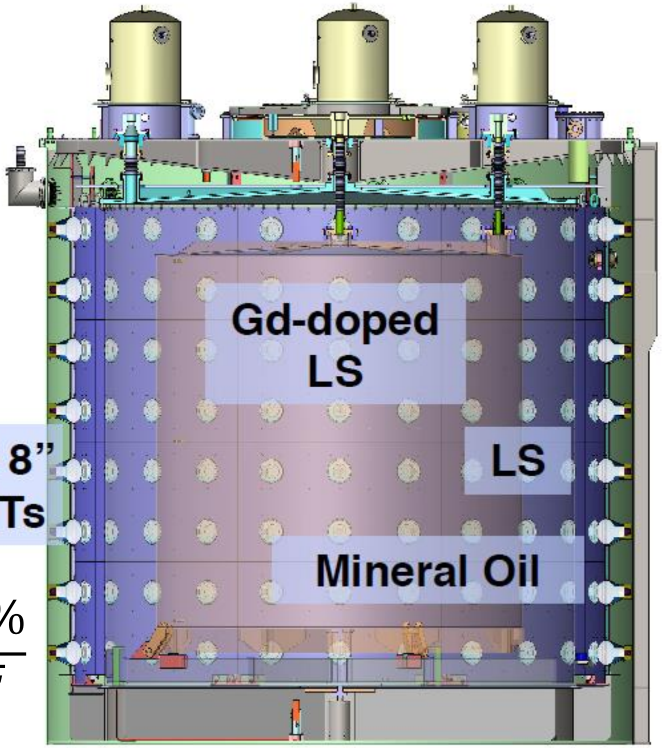
Daya Bay Near Hall
363 m from Daya Bay
93 m overburden

- 17.4 $\mathrm{GW_{th}}$ power
- 8 operating detectors
- 160 t total target mass

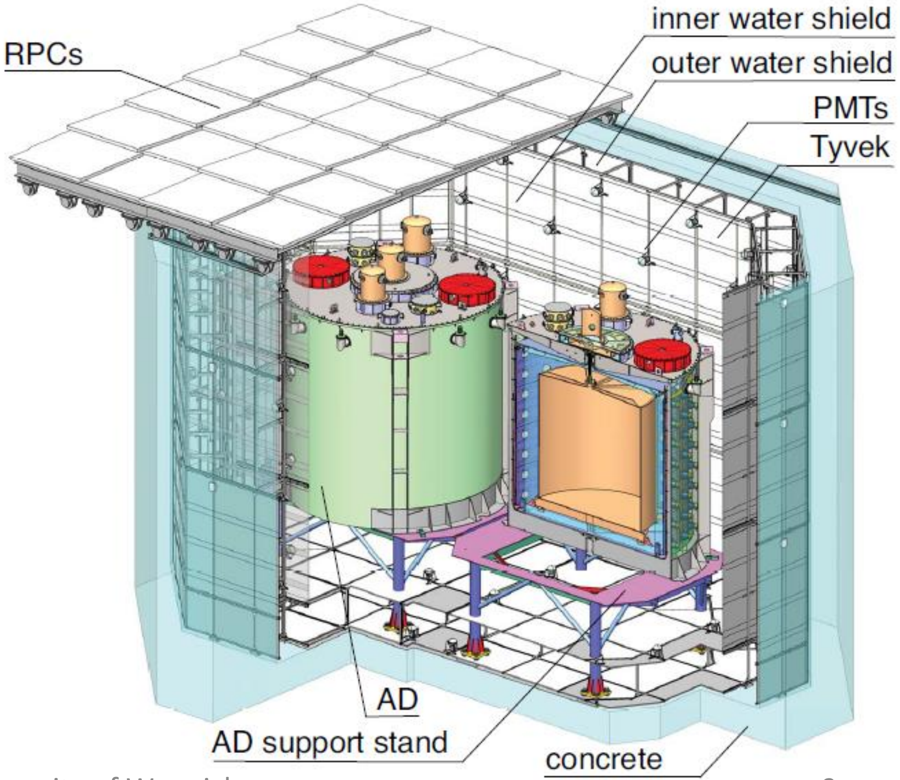
Antineutrino Detectors (AD)



- $\overline{\nu}_e$ are detected via Inverse Beta Decays (IBDs) :
  $\overline{\nu}_e + p \rightarrow e^+ + n$
- 3-zone detector module
- immersed in water pool, providing shielding and muon tagging



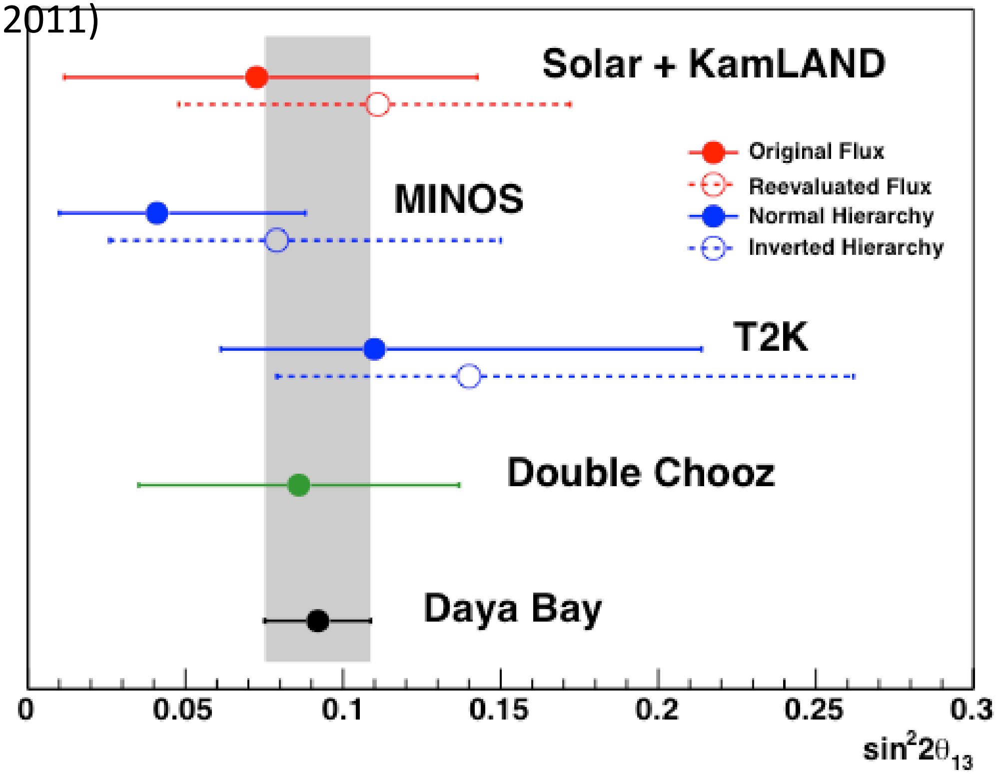
$$\frac{\sigma_E}{E} \approx \frac{8.5\%}{\sqrt{E}}$$



The discovery of nonzero θ_{13}

hints in 2011:

- **Solar + KamLAND**: Phys. Rev. D 84, 053007 (2011)
- **MINOS**: Phys. Rev. Lett. 107, 181802 (2011)
- **T2K**: Phys. Rev. Lett. 107 041801 (2011)
- **Double CHOOZ**: arXiv:1112.6353

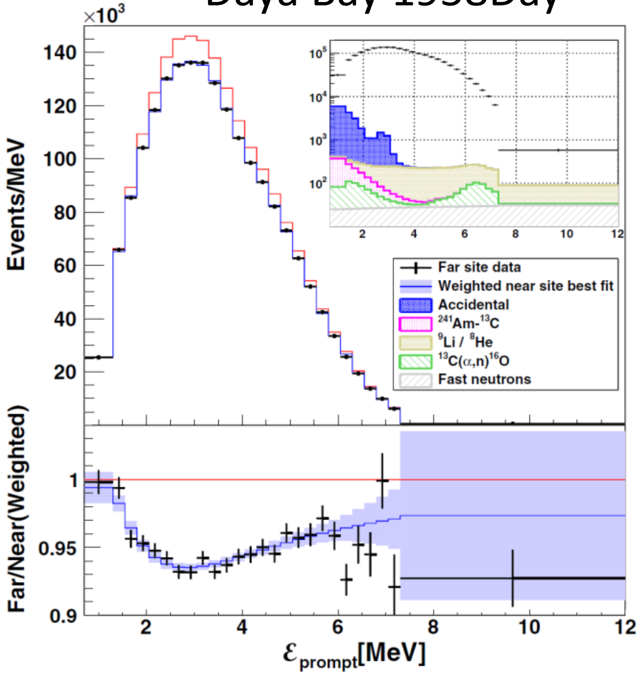


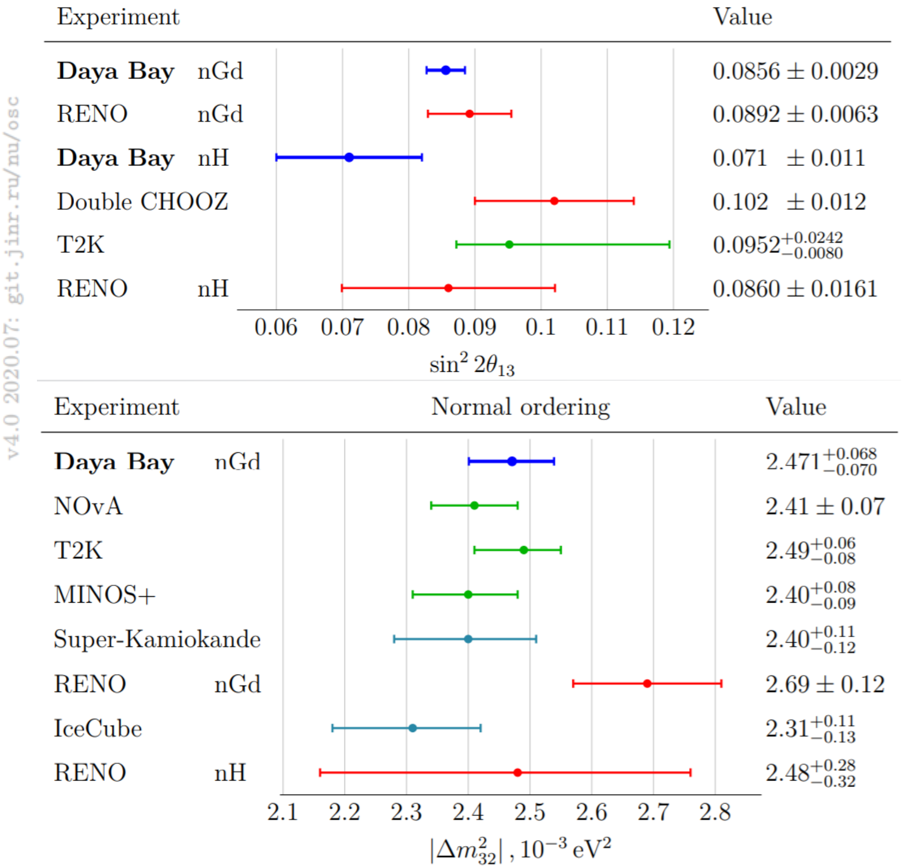
Daya Bay: Nonzero θ_{13} @ 5.2 σ PRL 108,171803(2012)

Reno: Confirms nonzero θ_{13} PRL 108,191802(2012)

Latest Oscillation Results

Daya Bay 1958Day





$$\sin^2 2\theta_{13} = 0.0856 \pm 0.0029$$
$$\Delta m^2_{32} = (2.471^{+0.068}_{-0.070}) \times 10^{-3} eV^2$$
$$\Delta m^2_{32} = (-2.575^{+0.068}_{-0.070}) \times 10^{-3} eV^2$$

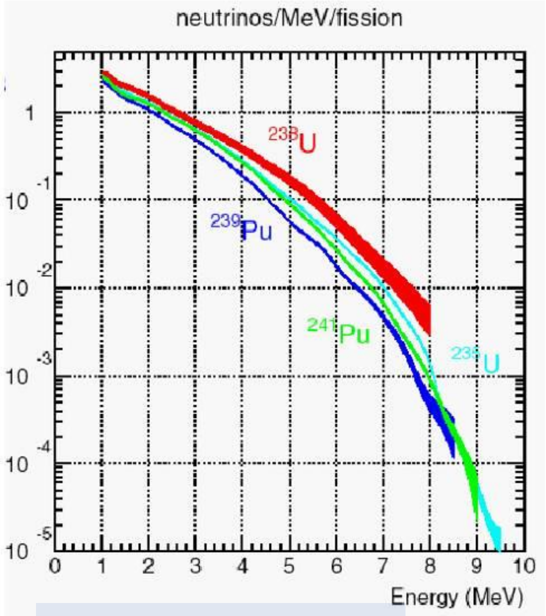
Daya Bay dominates the global precision

Phys.Rew.Lett. 121, 241805 (2018)

Precision Projection: $\sin^2 2\theta_{13}$ uncertainty 3.4%→2.7%

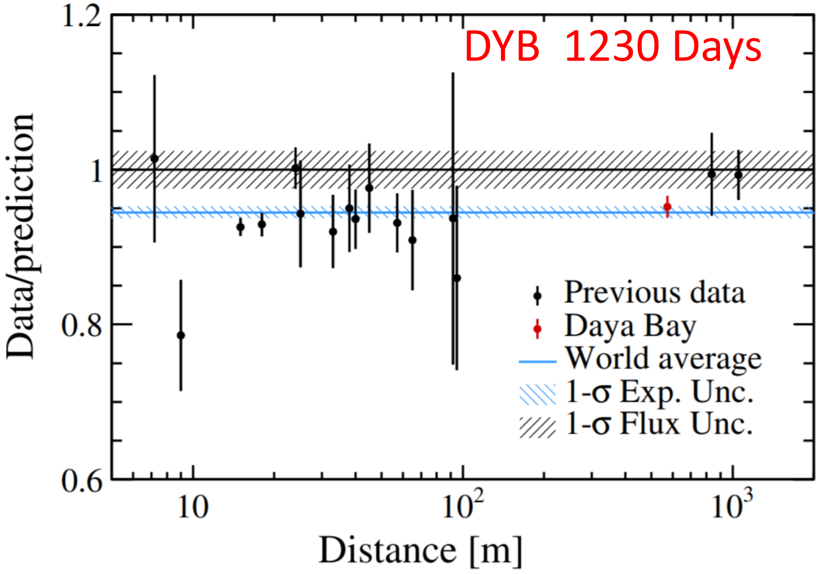
Δm^2_{ee} uncertainty 2.8% → 2.1%

Reactor Neutrino Flux Measurements



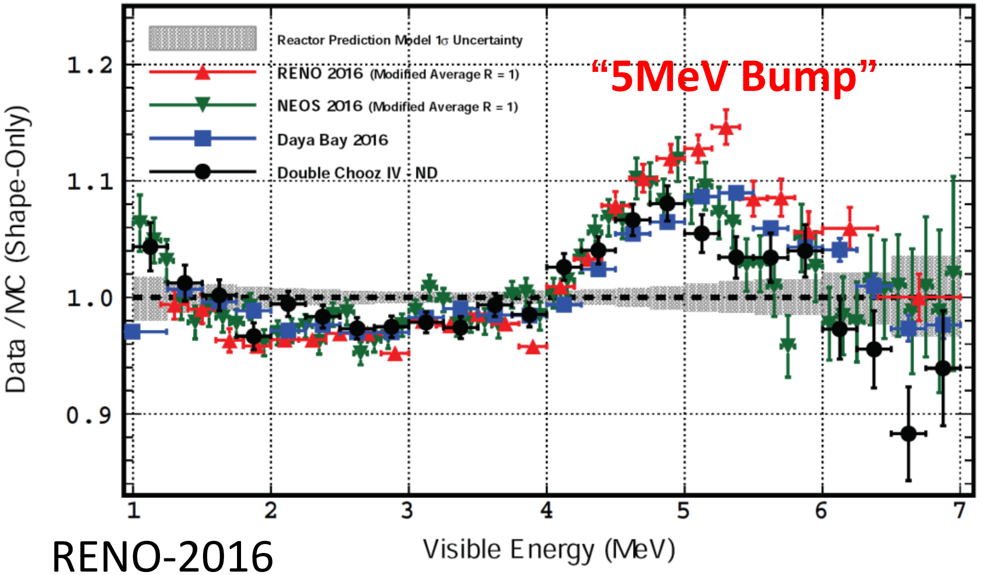
Old(ILL + Vogel)

Phys. Rev.D 100, 052004(2019)



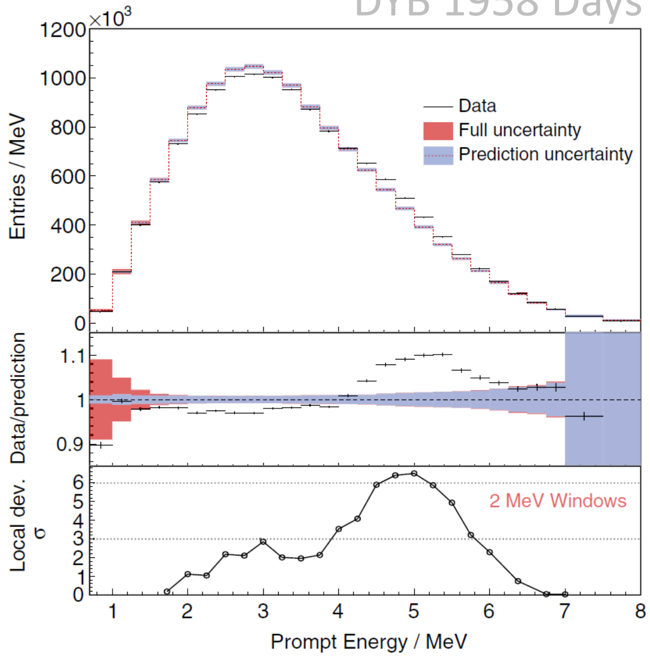
- IBD yield agree with other short baseline experiments, agree with old reactor flux model , but is about 95% of Huber+Muller (“Reactor Antineutrino Anomaly”)
- Where do neutrinos go?
  - Experimental Efforts
  - Theoretical Efforts

Spectra Shape Measurement



RENO-2016

DYB 1958 Days



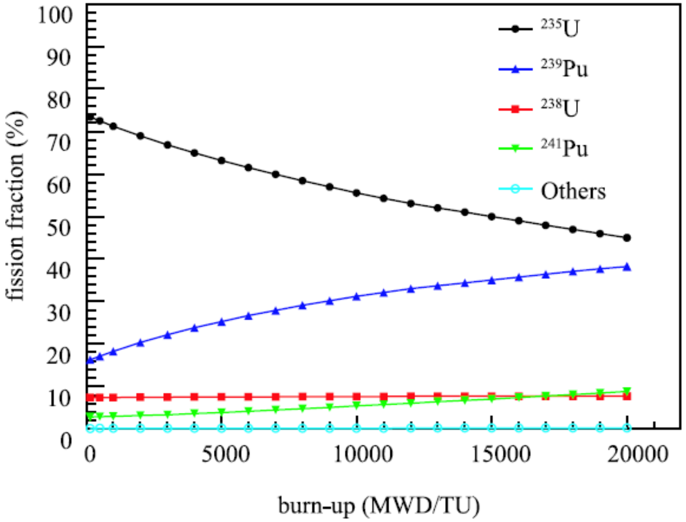
PRL 123, 111801(2019)

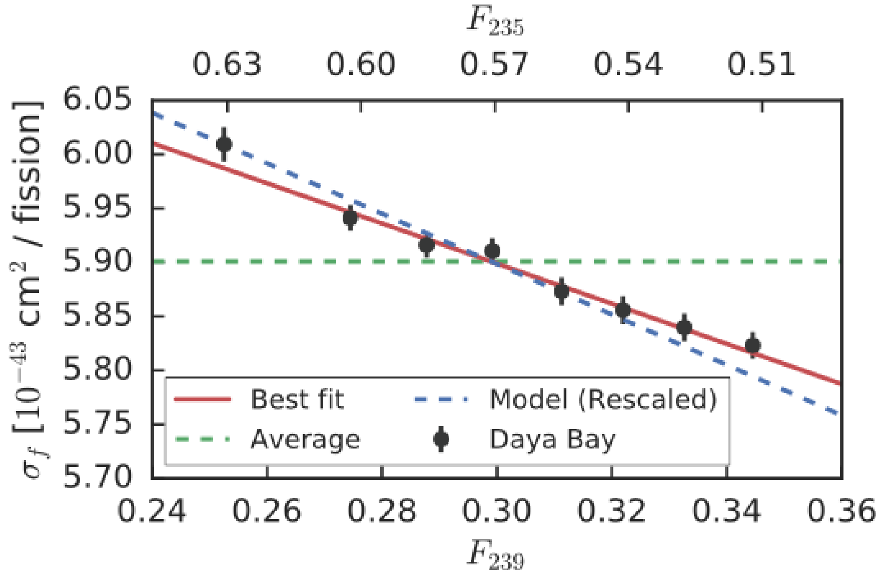
The measured IBD positron energy spectrum deviates from spectral prediction (Huber + Muller)

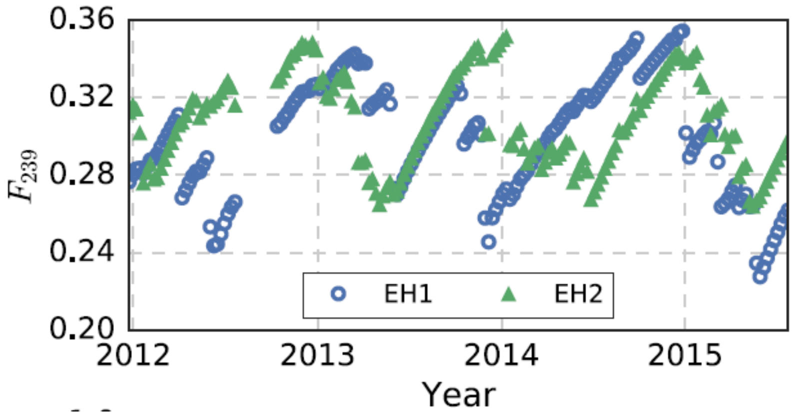
Last result shows an overall > 5 σ discrepancy and maximal local deviation of > 6σ

No effects on oscillation study which employs near/far relative measurement strategy

IBD Yield Study Using Fuel Evolution







DYB : Phys. Rev. Lett. 118, 251801(2017)

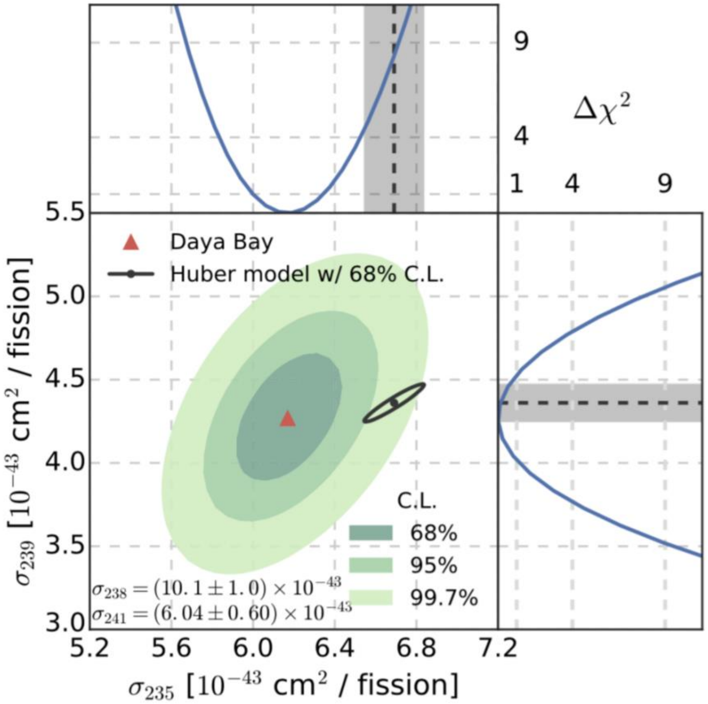
- Clear correlation between $\overline{\nu}_e$ yield and fuel evolution

- **inconsistent with Huber+Muller model at 3 σ, indicating non-equal fractional deficit of the 4 isotopes , that results to the overall measured flux deficit compared with theory prediction**

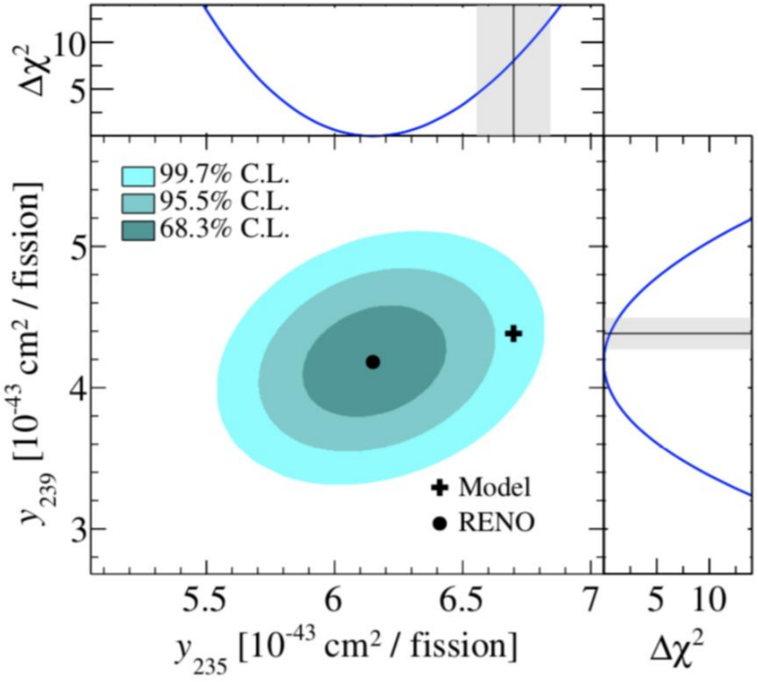
IBD Yield Study Using Fuel Evolution

Extract individual yield for the two dominant isotopes(^{235}U, ^{239}Pu) using constraints from two minor ones (^{238}U,^{241}Pu)

Identified ^{235}U as the primary source for the RAA

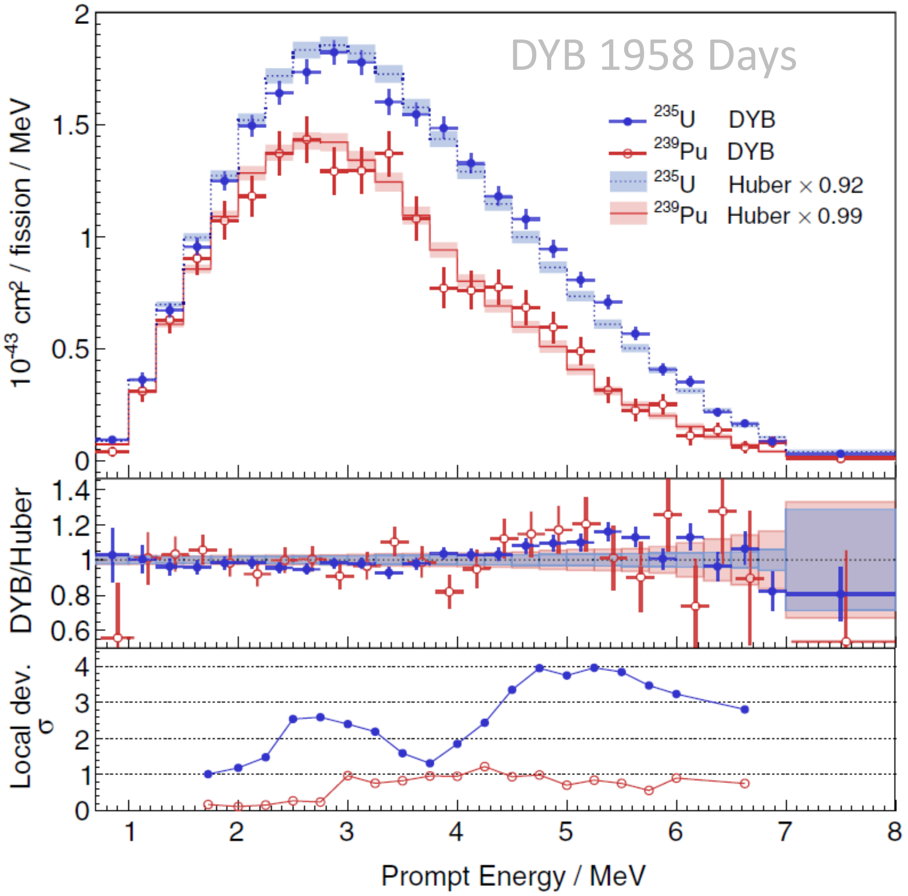


DYB :Phys.Rev.Lett. 118, 251801(2017)



RENO: Phys. Rev.Lett. 122, 232501 (2019)

Spectra Measurement Using Fuel Evolution



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

First measurement of ^{235}U , ^{239}Pu Spectra from commercial reactors by Daya Bay

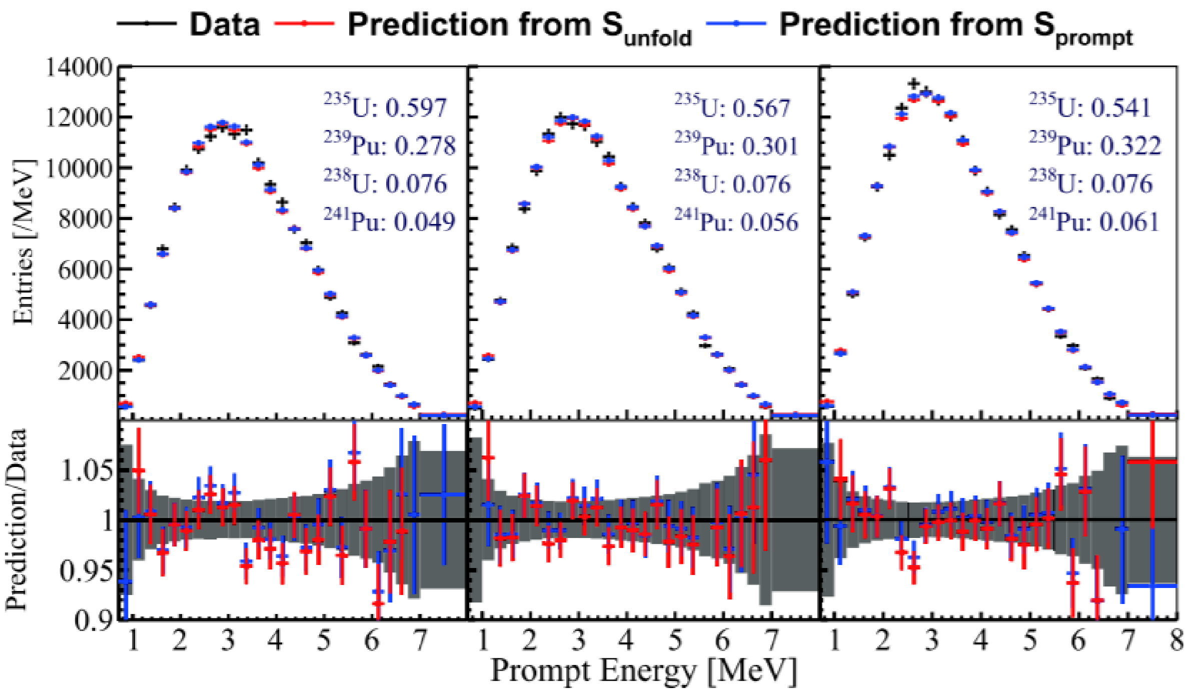
Similar bump excess for ^{235}U and ^{239}Pu in 4-6MeV :

- Local spectral deviation from prediction:

  up to 4 σ for ^{235}U
  ~ 1.2 σ for ^{239}Pu

Data-Driven reactor neutrino flux prediction

- Total and individual $\bar{\nu}_e$ energy spectra are unfolded by Wiener-SVD method
- Given a reactor fission fractions, one can predict the energy spectrum to a 2% precision

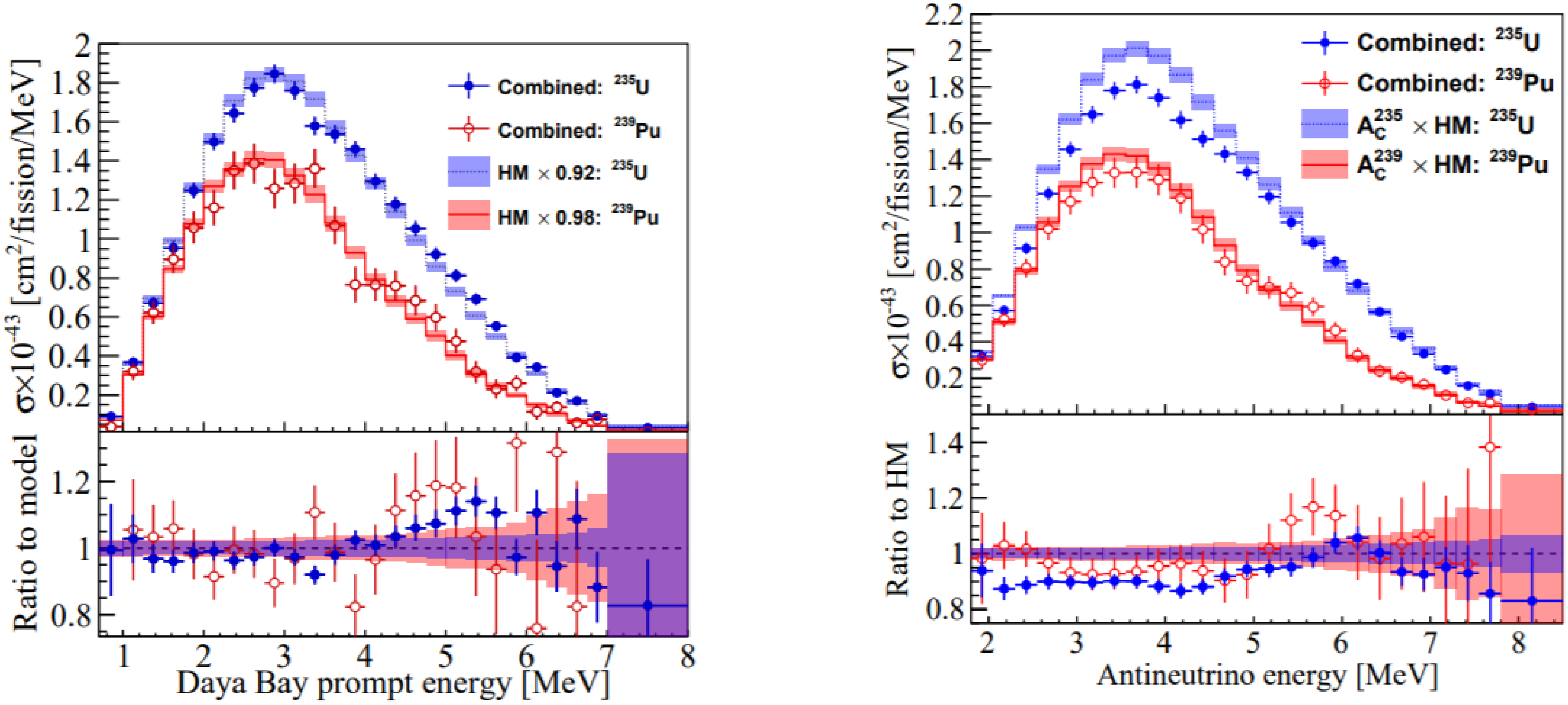


CPC 45,073001(2021)

Improve spectral measurement with joint analysis by Daya Bay and PROSPECT

PROPECT data provides constrains on ^{235}U spectrum

Relative uncertainty of the spectral shape of ^{235}U improved 3.5%->3.0% around 3MeV



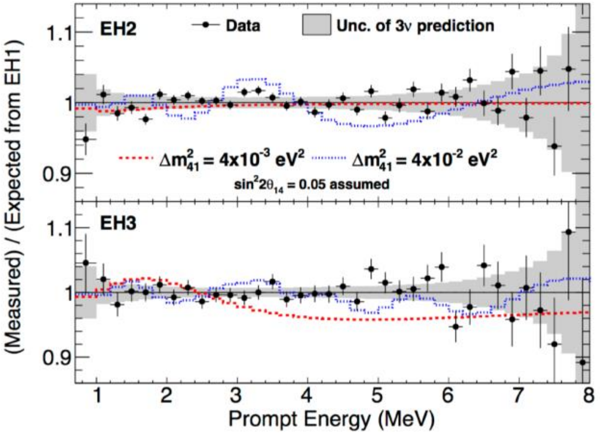
arXiv: 2106.12251

Summary

- DC, Reno, DYB have provided an unambiguous measurement of θ_{13} .Final precision of 2.7% on $\sin^2 2\theta_{13}$ is expected from Daya Bay. This will be the standard for decades to come.
- With high precision, large statistics , θ_{13} reactor experiments have precisely measured reactor neutrino flux and spectra. The deviation from theory is evoking active study on reactor flux both theoretically and experimentally.
- θ_{13} reactor experiments are reaching to their life circles. Final results are coming . Stay tuned.

BACK UPS

Sterile Neutrino searches



- Minimally extended 4ν scenario
- Searching for an additional spectral distortion with a frequency different from the standard 3 ν oscillation
- Sensitive to mass square differences in sub-eV range

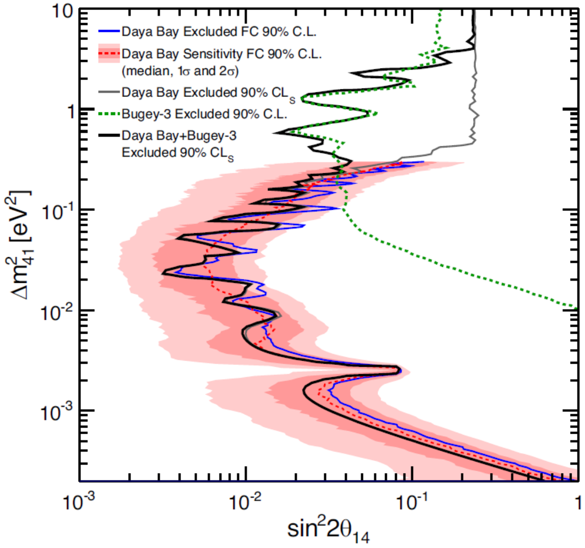
$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2 \Delta_{31} - \sin^2 2\theta_{14} \sin^2 \Delta_{41}$$

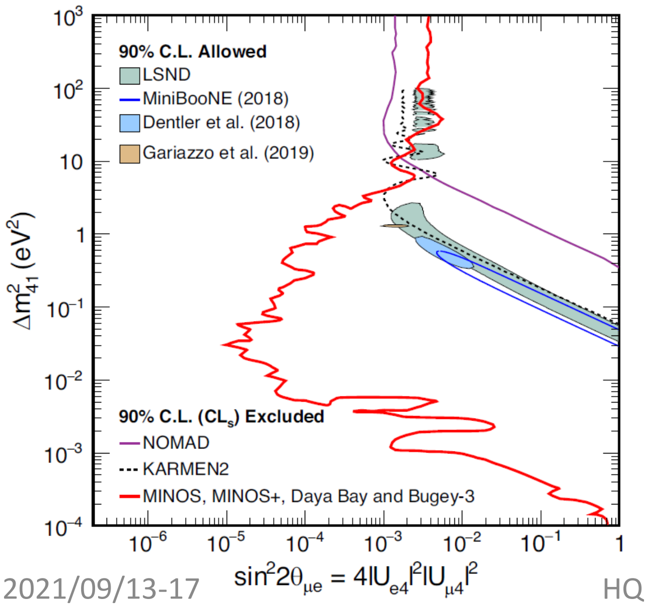
For LSND & miniBooNE: $P^{SBL}_{\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e} \approx 4|U_{e4}|^2 |U_{\mu 4}|^2 \sin^2 \Delta_{41}$

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

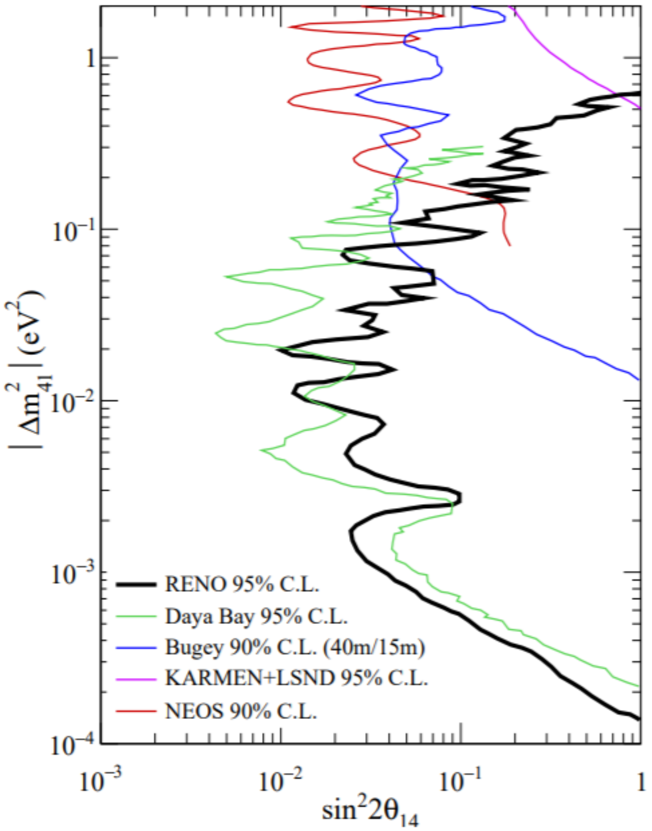
Sterile Neutrino searches

Phys.Rev.Lett 125, 071801(2020)





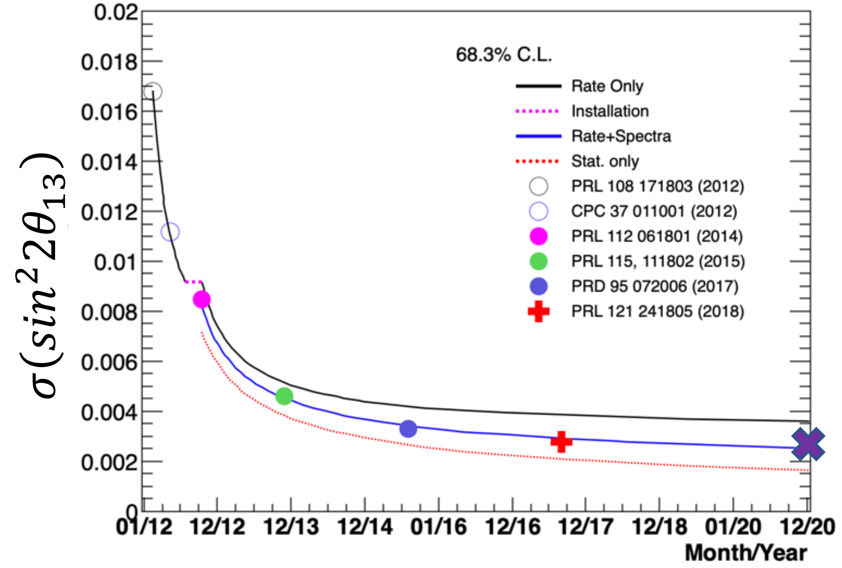
RENO 2200Days



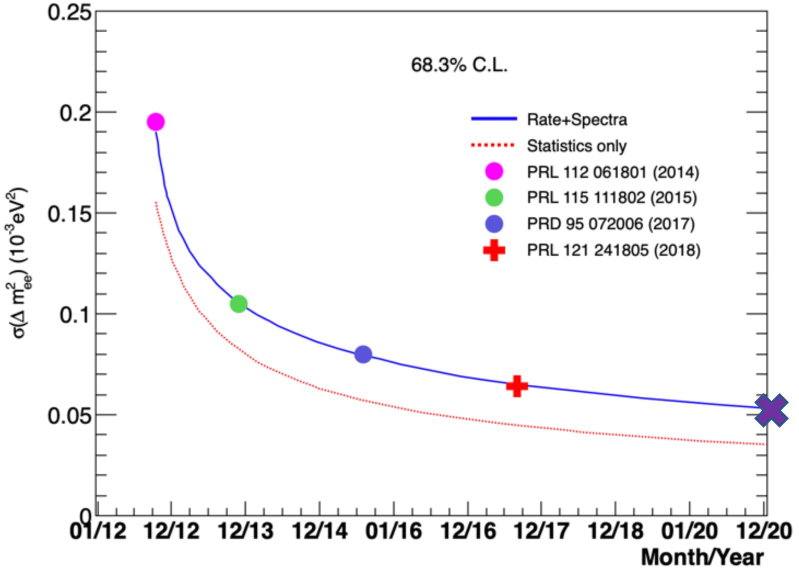
Phys. Rev. Lett. 125, 191801 (2020)

Oscillation Measurement Prospects

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



Δm^2_{ee} uncertainty 2.8% → 2.1%



- Daya Bay and Double Chooz have stopped data taking
- High statistic reactor neutrino data provides a good opportunity to study the reactor neutrino flux, which contains complications by itself.