NuPhys2019: Prospects in Neutrino Physics

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Latest Results on Reactor Neutrino Experiments

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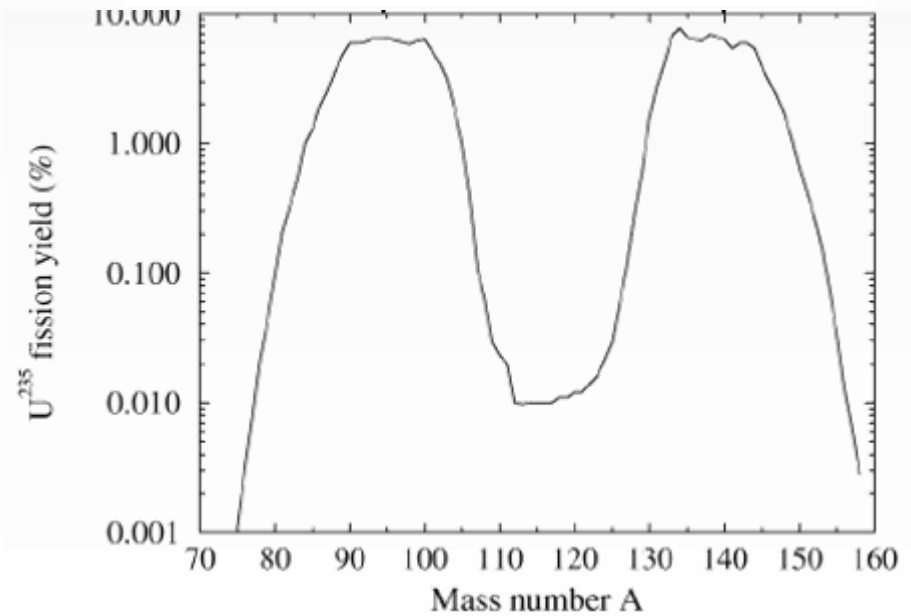
Outline

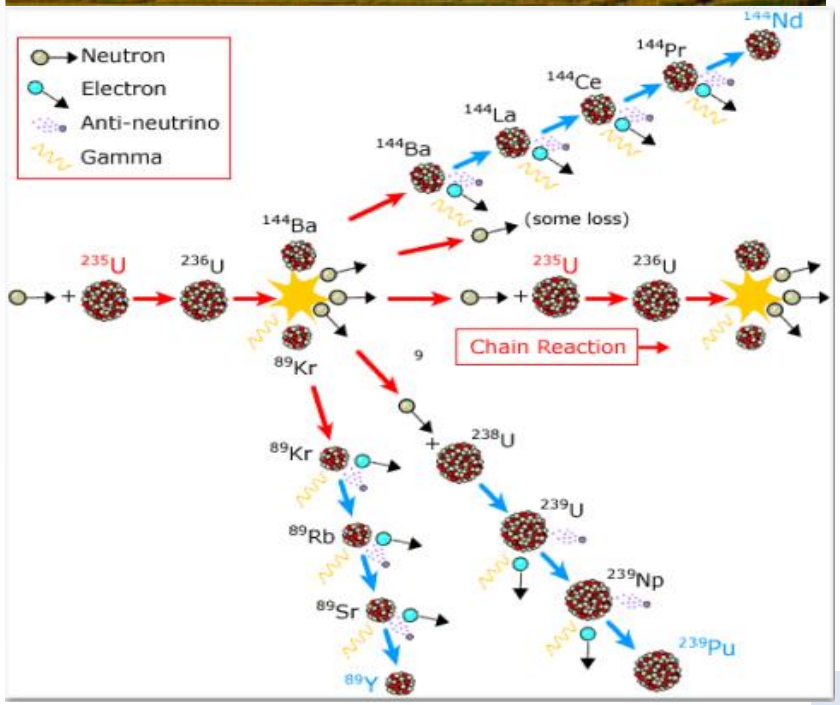
- Reactor neutrinos
  - Neutrino flux and detection
  - Neutrino oscillation
- Measurement of θ_{13}
  - Current experiments
  - Results
- Measurement of reactor neutrino flux
  - Reactor neutrino rate anomaly
  - Reactor neutrino spectrum deviation

Reactor neutrino flux

- Pure electron antineutrinos $\bar{\nu}_e$
- 2×10^{20} $\bar{\nu}_e$ /second/GW_{th}
- Produced by fission products from four major isotopes: ^{235}U, ^{238}U, ^{239}Pu, and ^{241}Pu
- ~ 6 $\bar{\nu}_e$ per fission

$$^{235}_{92}U + n \rightarrow X_1 + X_2 + 2n$$





Neutrino detection

Detect neutrino via inverse beta decay (IBD)

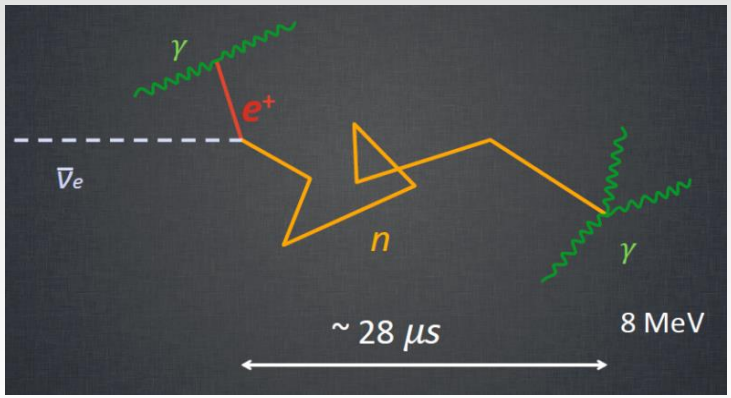
$\bar{\nu}_e + p \rightarrow e^+ + n$ (prompt)

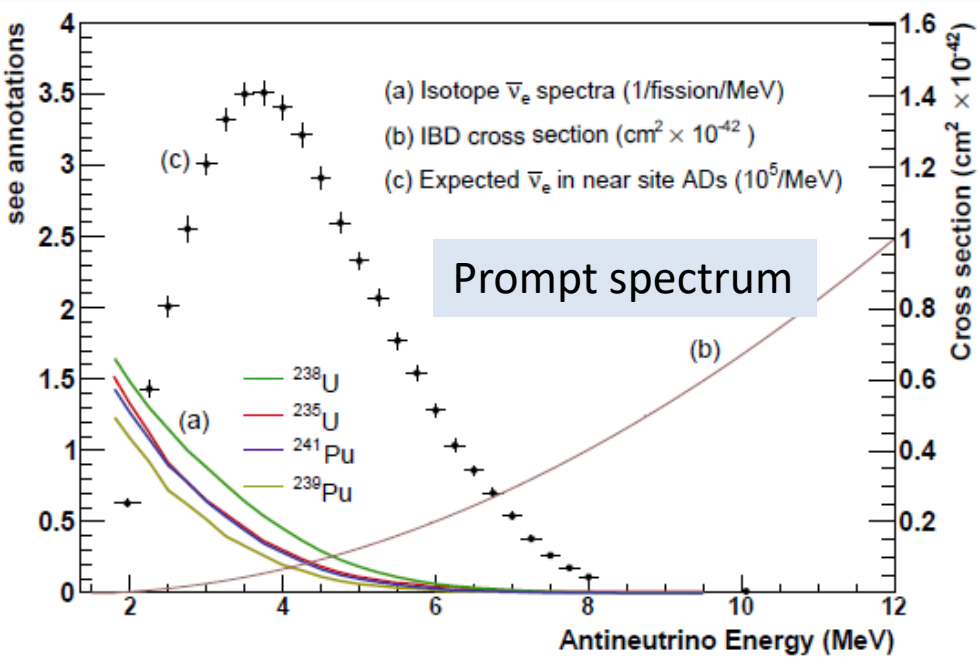
$\rightarrow +p \rightarrow D + \gamma$ (2.2 MeV delayed)

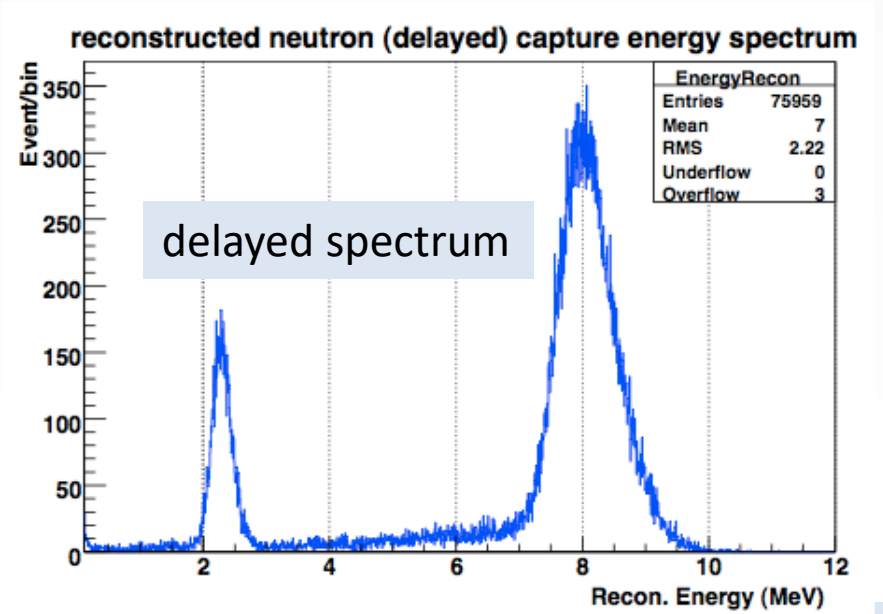
$\rightarrow + Gd \rightarrow Gd^*$

$\rightarrow Gd + \gamma$'s (8 MeV delayed)

Prompt signal: a proxy of neutrino energy
Delayed signal: a tag of neutrino event



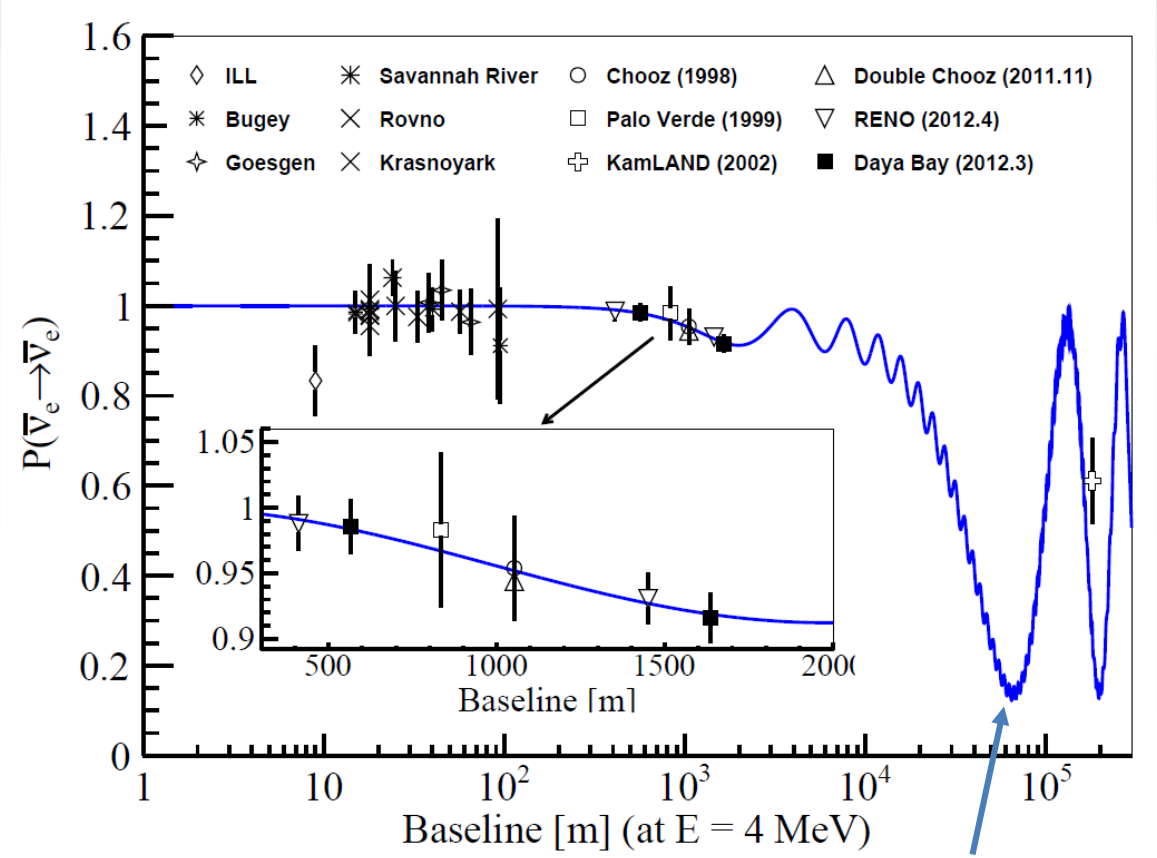




Reactor neutrino oscillation

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

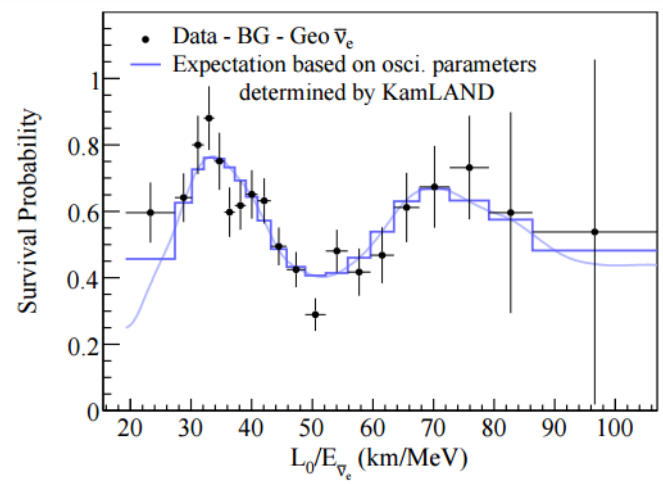
- $\bar{\nu}_e \rightarrow \bar{\nu}_e$ disappearance
- No dependence on CP phase and θ_{23}
- 2-km oscillation: θ_{13} and Δm^2_{ee}
- 50-km oscillation: θ_{12} and Δm^2_{21}
- JUNO can observe both Δm^2_{ee} and Δm^2_{21} driven oscillations, and is sensitivity to neutrino mass ordering (talk by Monica Sisti)

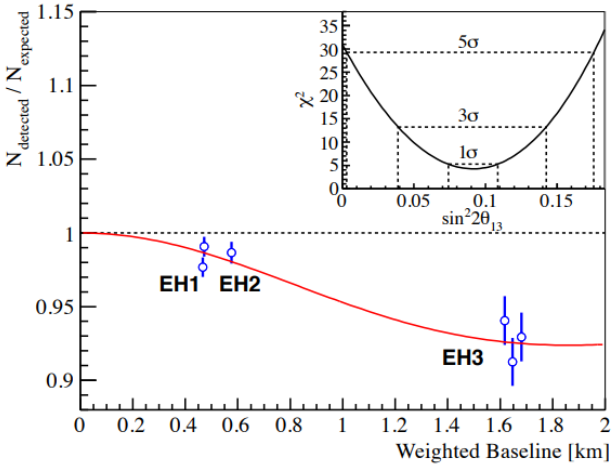


JUNO

Glorious history

- Discovery of neutrinos by Clyde L. Cowan and Frederick Reines in 1956
- First confirmation of solar neutrino oscillation by KamLAND in 2002
- Observation of non-zero θ_{13} at Daya Bay, RENO, Double Chooz in 2012





Measurement of θ_{13}

Current experiments

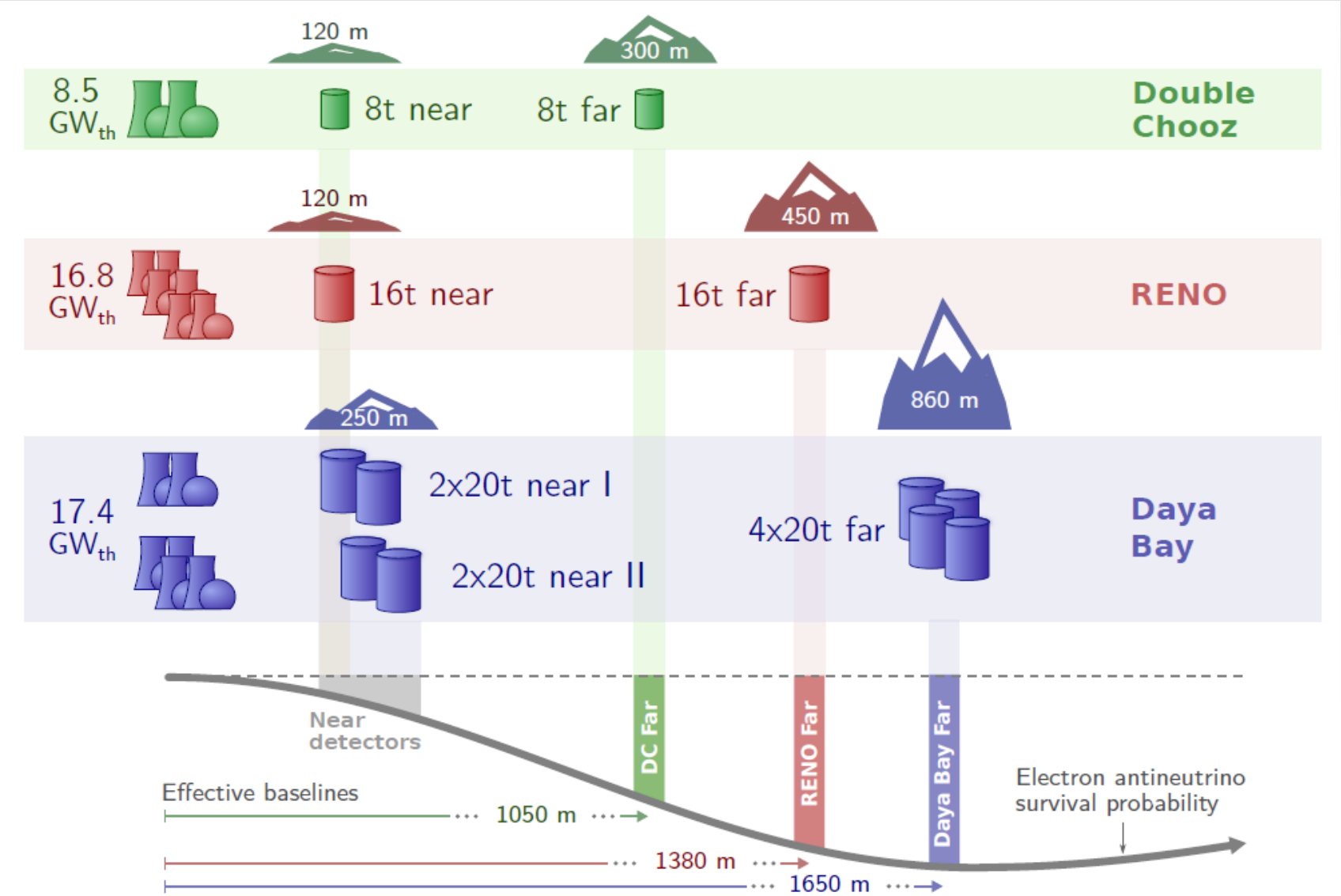
Daya Bay

RENO

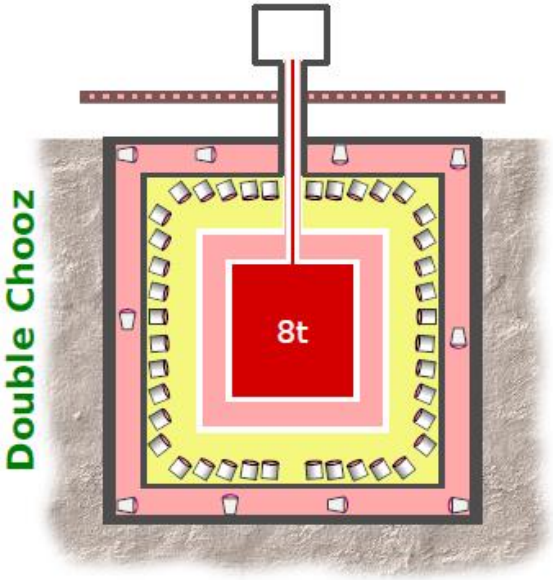
Double Chooz

Experiment layout

- Common feature: near/far relative measurement

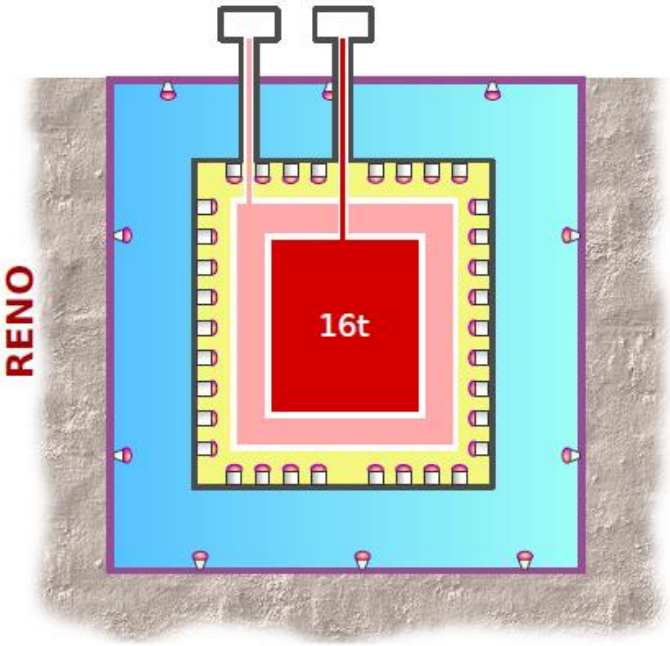


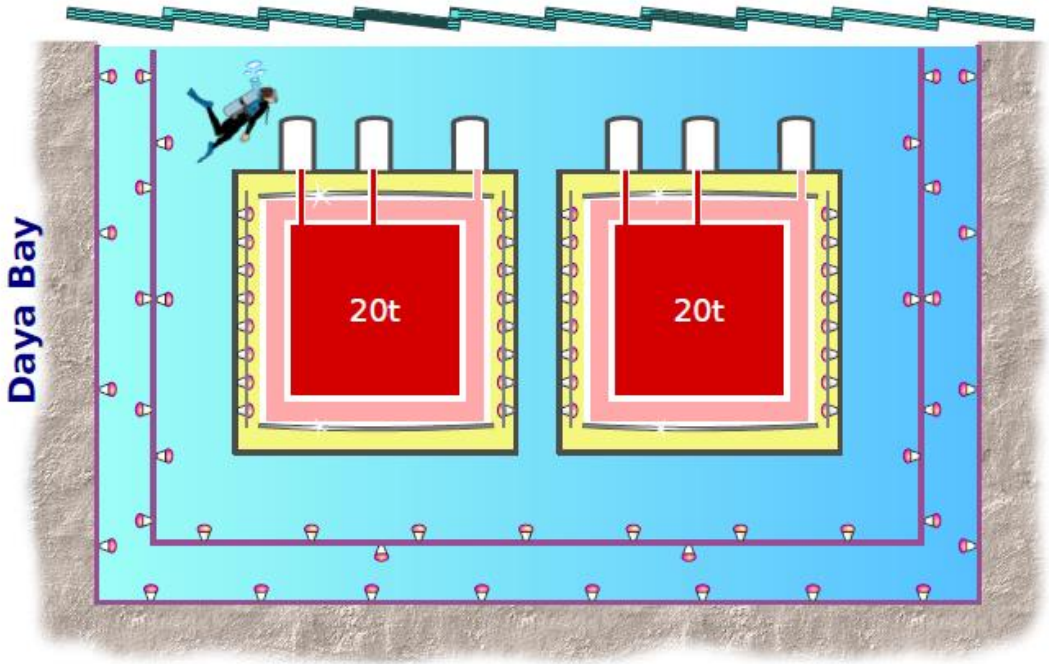
Detector design



	AD PMTs	Energy resolution	Muon PMTs
Double Chooz	390 x 10"	6% at 1 MeV	78 x 8"
RENO	354 x 10"	7% at 1 MeV	67 x 10"
Daya Bay	192 x 8"	8% at 1 MeV	288 x 8" (near) 388 x 8" (far)

- **Common three-zone design: GdLS – LS – Buffer**



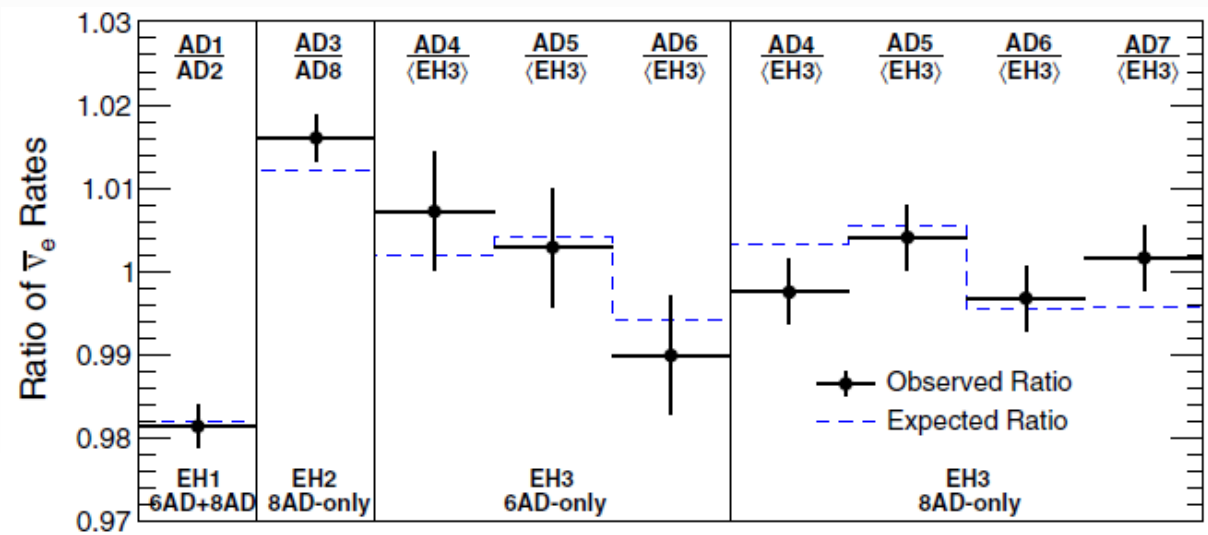


Near/far identical detector

- Near/far: reduce neutrino flux uncertainty
- Identical detector: cancel detection efficiency uncertainty

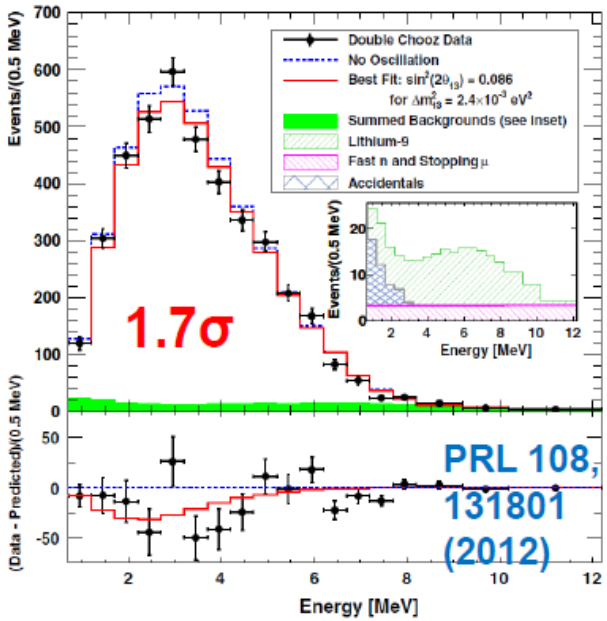
$$\frac{N_f}{N_n} = \left(\frac{N_{p,f}}{N_{p,n}}\right)\left(\frac{L_n}{L_f}\right)^2\left(\frac{\epsilon_f}{\epsilon_n}\right)\left(\frac{P_{sur}(E, L_f)}{P_{sur}(E, L_n)}\right)$$

- Unique feature in Daya Bay: side-by-side detectors ➔ Verification of identical detectors: side-by-side detectors observe 'equal' number of neutrinos (with correction of baseline difference).



Discovery of non-zero θ_{13}

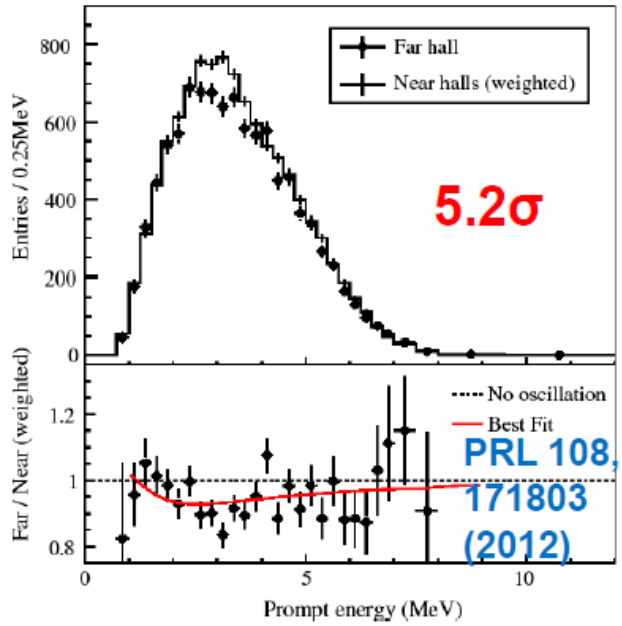
Double Chooz
with only a far detector
(Nov. 2011)



Rate+shape

$$\sin^2 2\theta_{13} = 0.086 \pm 0.041(\text{stat}) \pm 0.030(\text{syst})$$

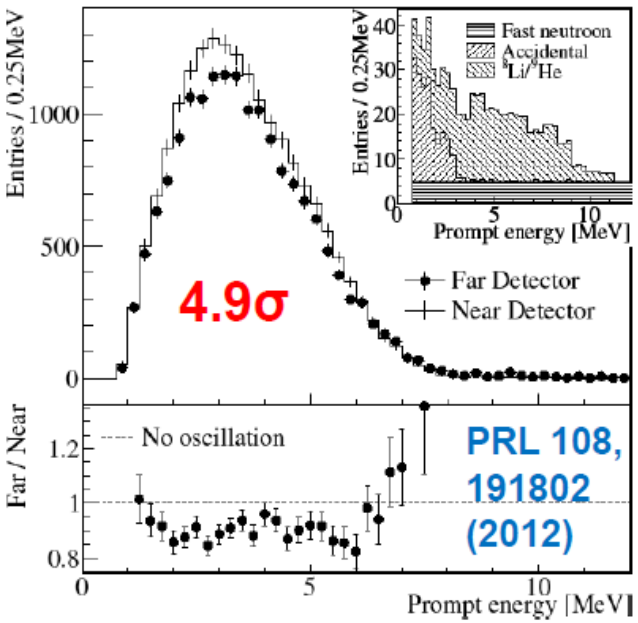
Daya Bay
(March 2012)



Rate only

$$\sin^2 2\theta_{13} = 0.092 \pm 0.016(\text{stat.}) \pm 0.005(\text{syst.})$$

RENO
(April 2012)

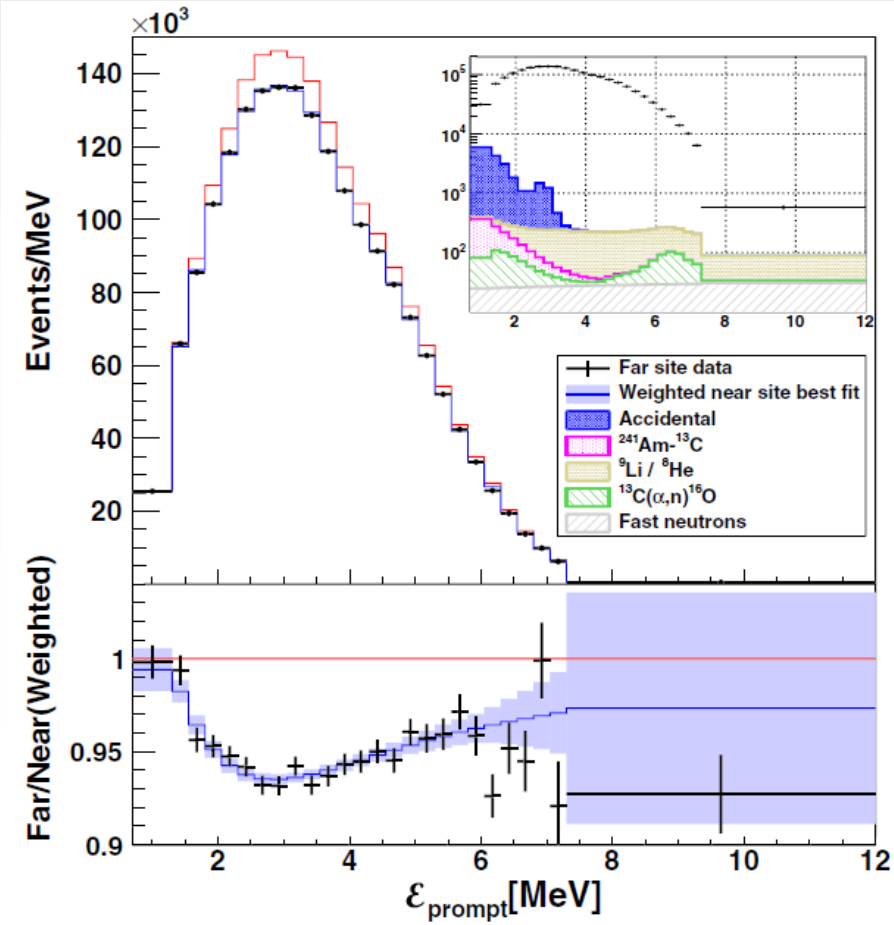


Rate only

$$\sin^2 2\theta_{13} = 0.103 \pm 0.013(\text{stat.}) \pm 0.011(\text{syst.})$$

1958-Day results of Daya Bay

- World-leading results: $\sin^2 2\theta_{13}$ uncertainty is 3.4% and $|\Delta m^2_{ee}|$ uncertainty is 2.8%
- Statistical uncertainty contributes 60% for $\sin^2 2\theta_{13}$ and 50% for $|\Delta m^2_{ee}|$



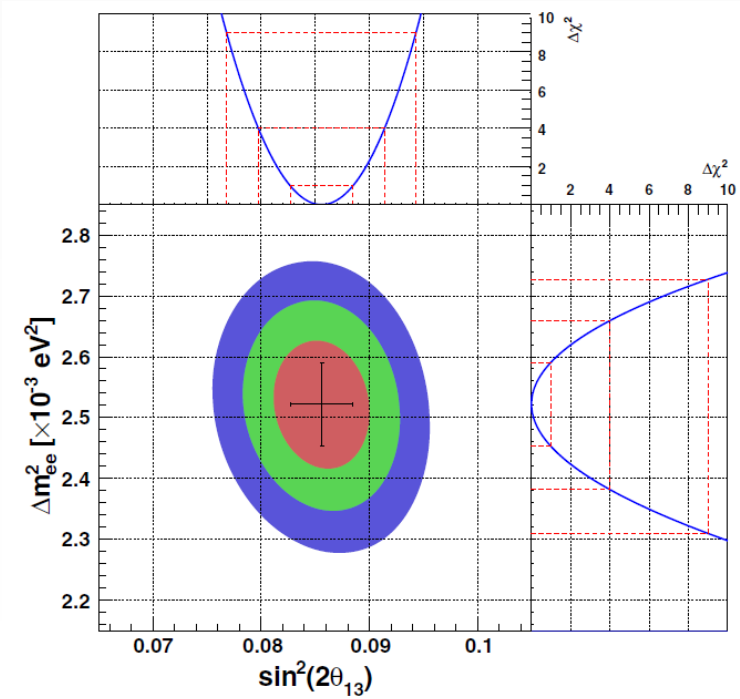
Phys.Rev.Lett, 121, 241805 (2018)

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

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

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

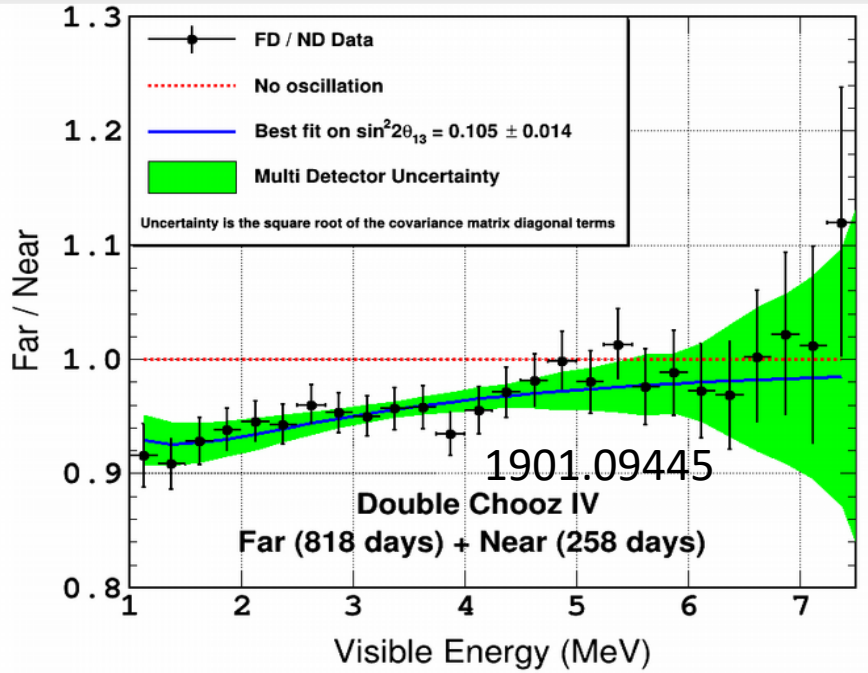
$$\Delta m^2_{32} = (-2.58 \pm 0.07) \times 10^{-3}\mathrm{eV}^2\ \text{(IO)}$$



Latest results of Double Chooz and RENO

- Double Chooz

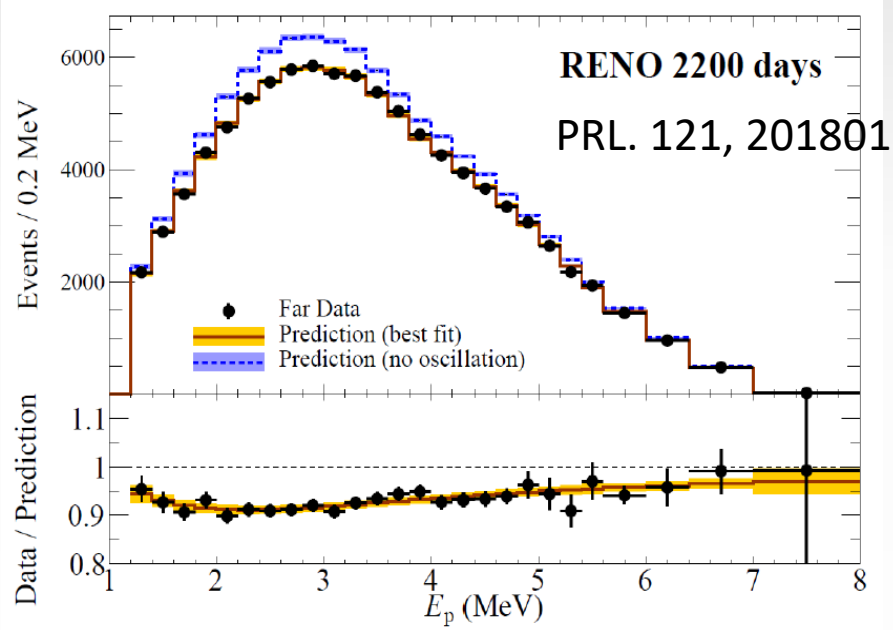
  $\sin^2 2\theta_{13} = 0.105 \pm 0.014$



- RENO

  $\sin^2 2\theta_{13} = 0.0896 \pm 0.0067$

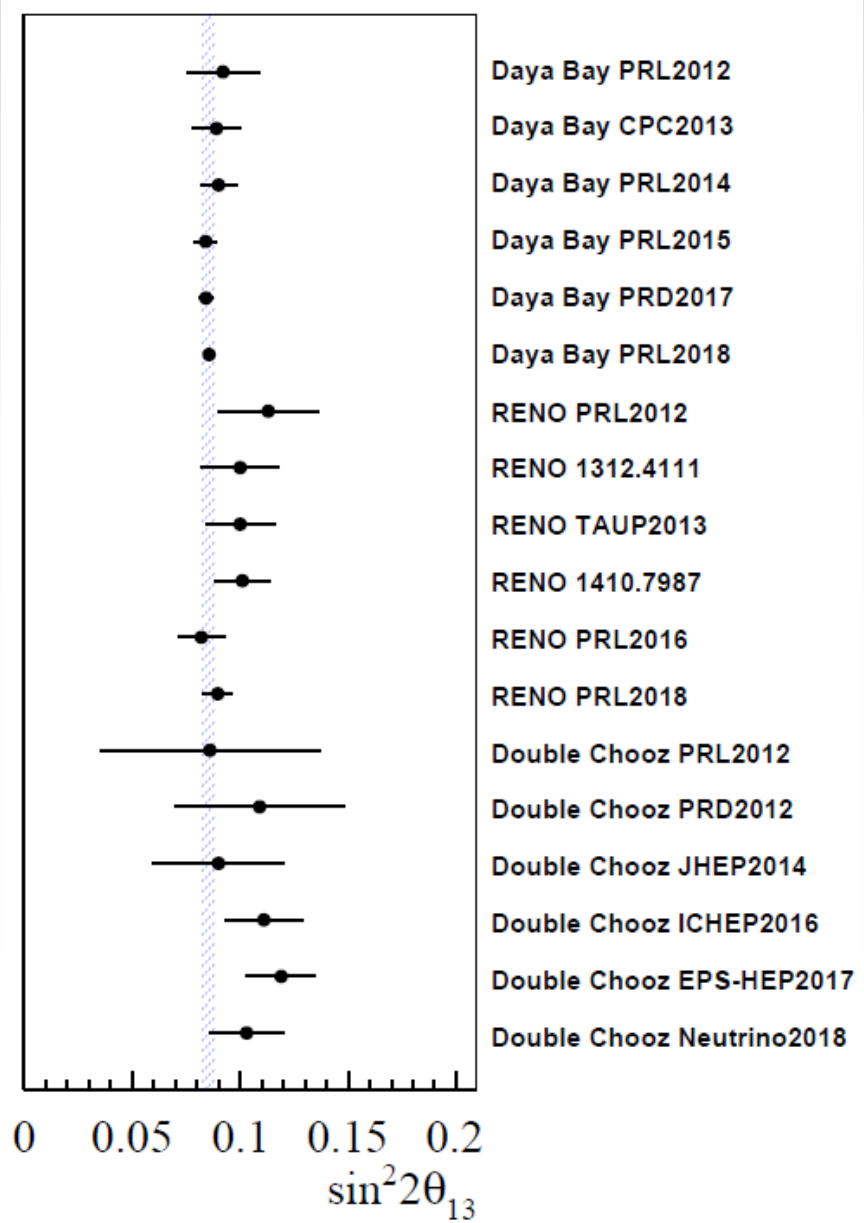
  $|\Delta m^2_{ee}| = 2.68 \pm 0.14\ (\times 10^{-3})\ \mathrm{eV}^2$



data sample in latest results

	Near detectors	Far detectors	B/S
Daya Bay	3.5 million	0.5 million	~ 2%
RENO	0.85 million	0.1 million	~ 5%
Double Chooz	0.21 million	0.09 million	~ 9%

$\sin^2 2\theta_{13}$ precision

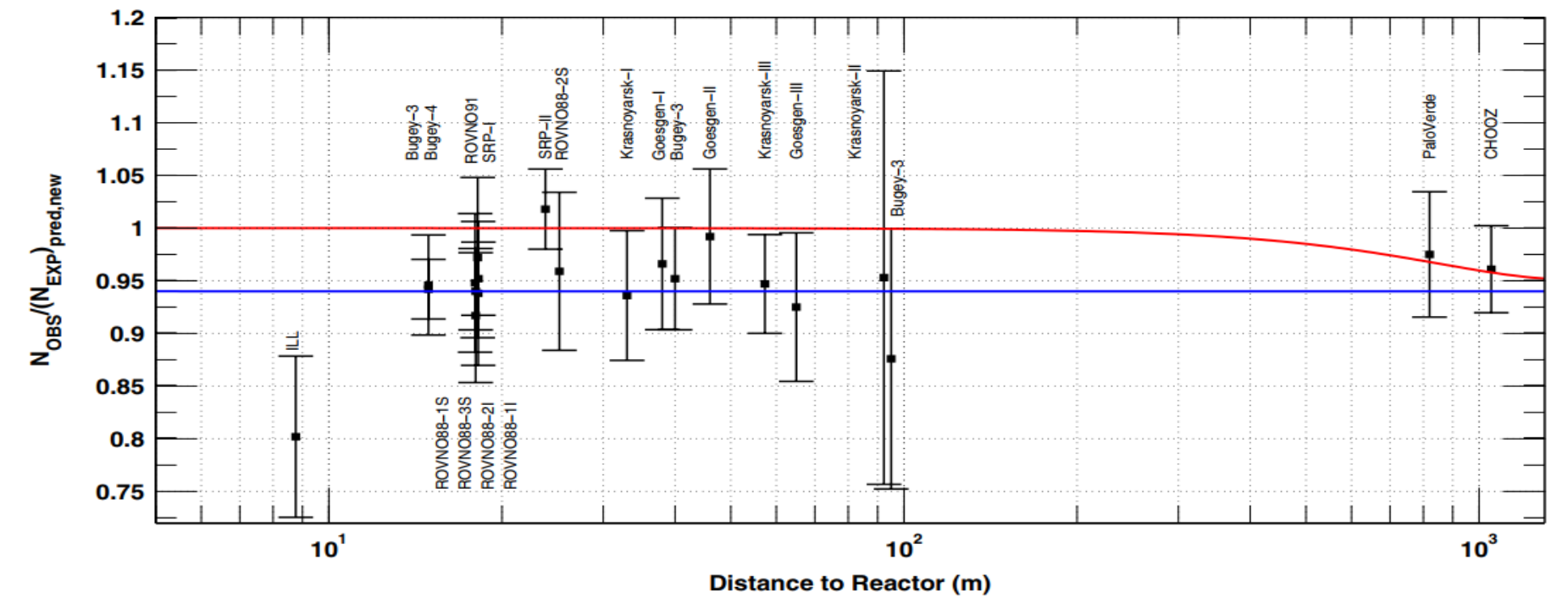


- Best precision at Daya Bay
- Still dominated by statistics
- Great success and rapid improvement on the precision: 20%➔3.4% from 2012 to 2019
- Measured Δm^2_{31} with spectral information
  - Comparable precision with T2K/MINOS
- More data taking
  - Daya Bay: 2011-2020
  - Double Chooz: 2011-2017
  - RENO: 2011-2021(?)
- Ultimate precision: 3% from Daya Bay

Measurement of reactor neutrino flux

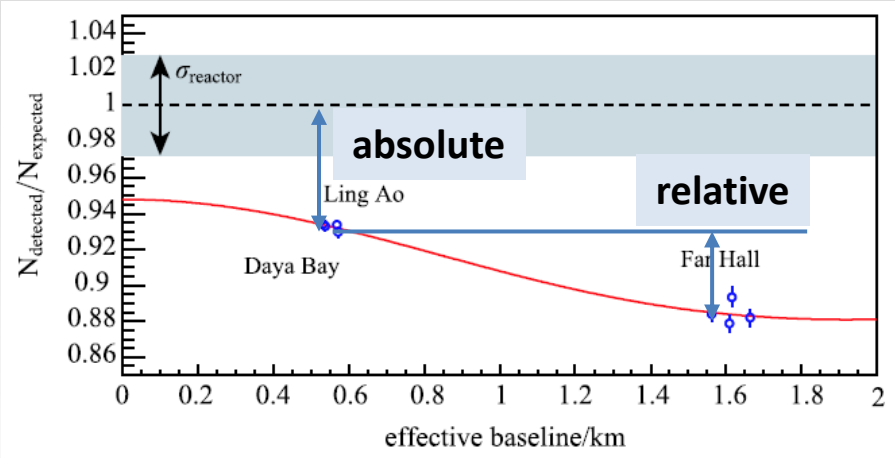
Reactor antineutrino anomaly

- New prediction of reactor neutrino flux in 2011: Huber-Mueller model
- Reactor Antineutrino Anomaly (RAA), *PRD 83 (2011) 073006*
  - Observation/prediction = 0.943, a 6% deficit.
- Possible reasons
  - Sterile neutrinos?
  - Incorrect model prediction? (uncertainty underestimated?)



Neutrino flux measurement

- Near/far relative measurements in oscillation cancel the flux uncertainty.
- The observed number of IBD events in near detectors yields absolute measurement of neutrino flux.
- Uncertainty dominated by detection efficiency
- Both Daya Bay and RENO confirmed the deficit in RAA

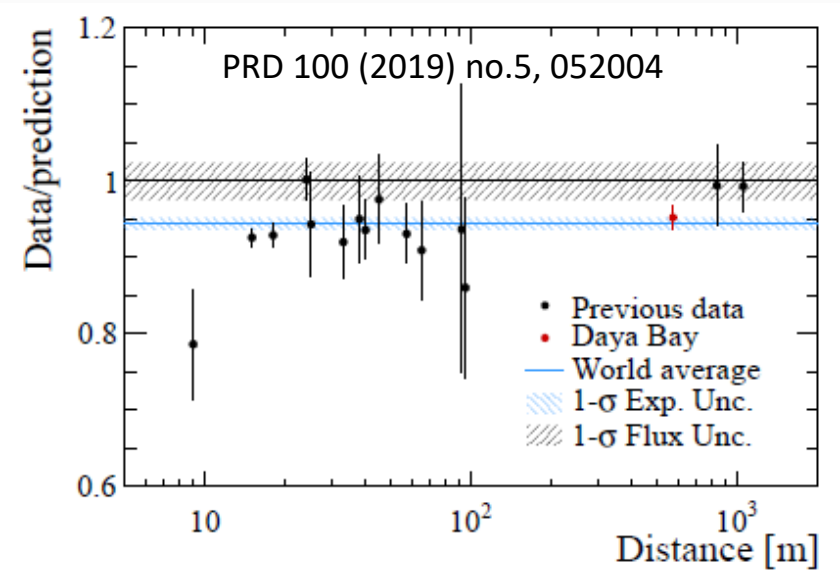


Daya Bay: Data/Huber-Mueller = 0.952 ±0.014(exp.)±0.023 (model)

	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%

flux measurement

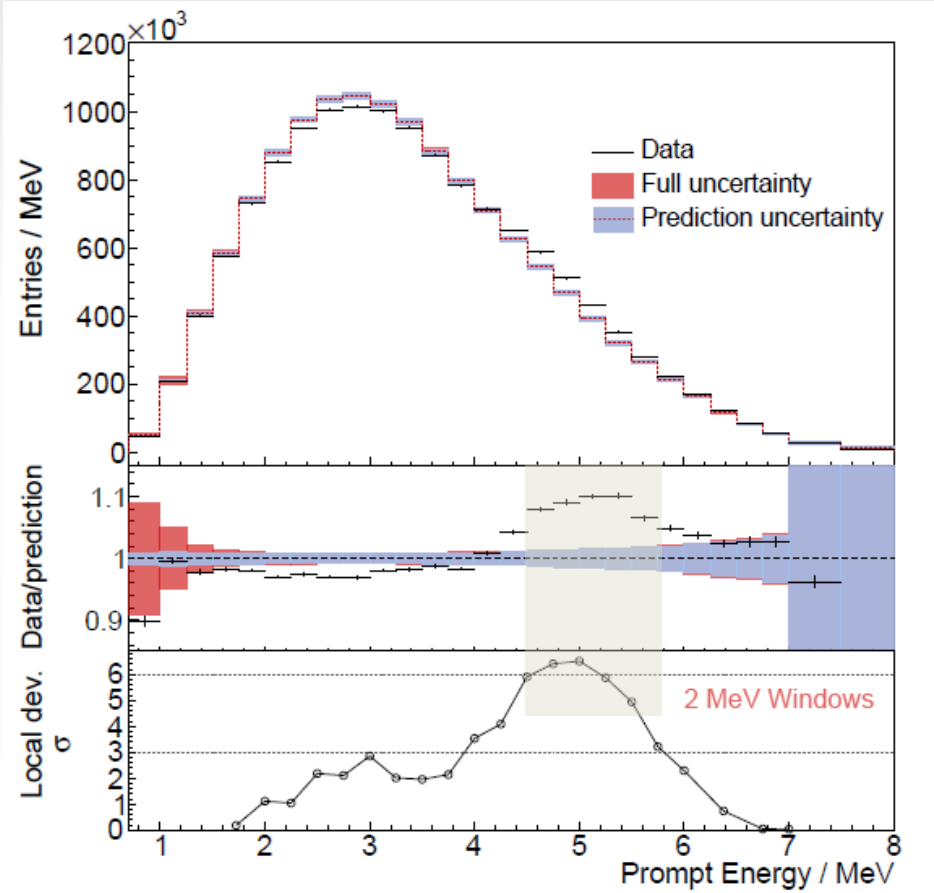
osc. measurement

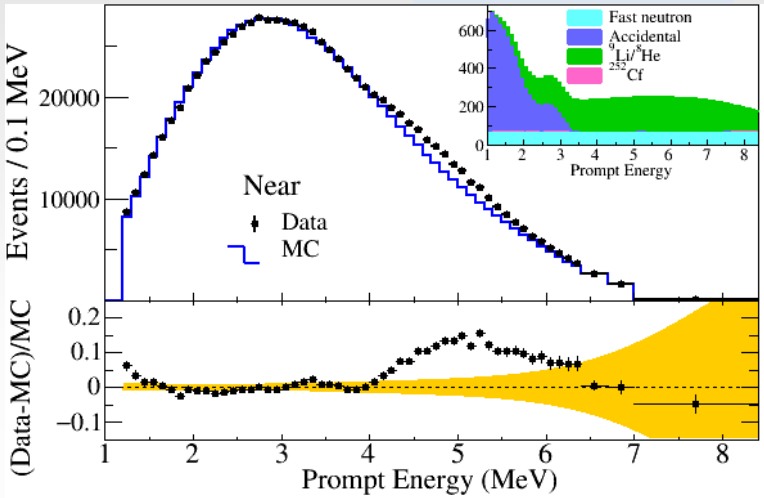


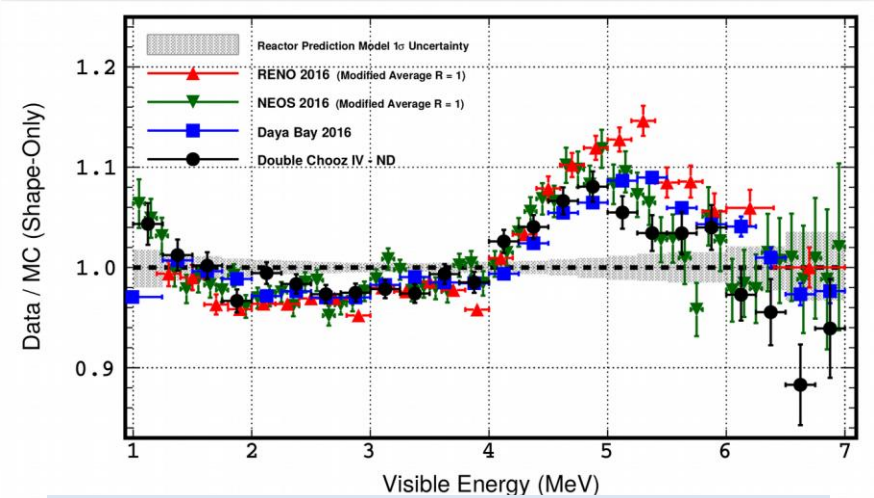
Spectrum measurement

- Absolute spectral shape is NOT consistent with the prediction. A bump is observed in 4-6 MeV of the prompt energy.

RENO, AAP2019





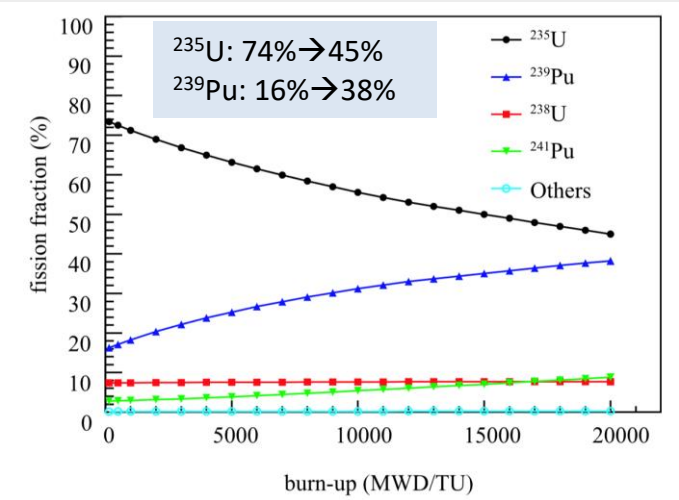


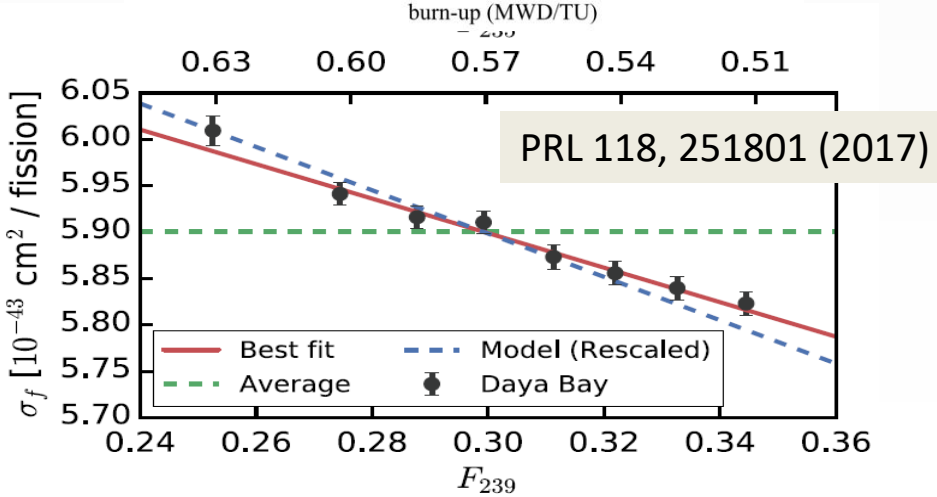
Daya Bay: PRL 123 (2019) no.11, 111801

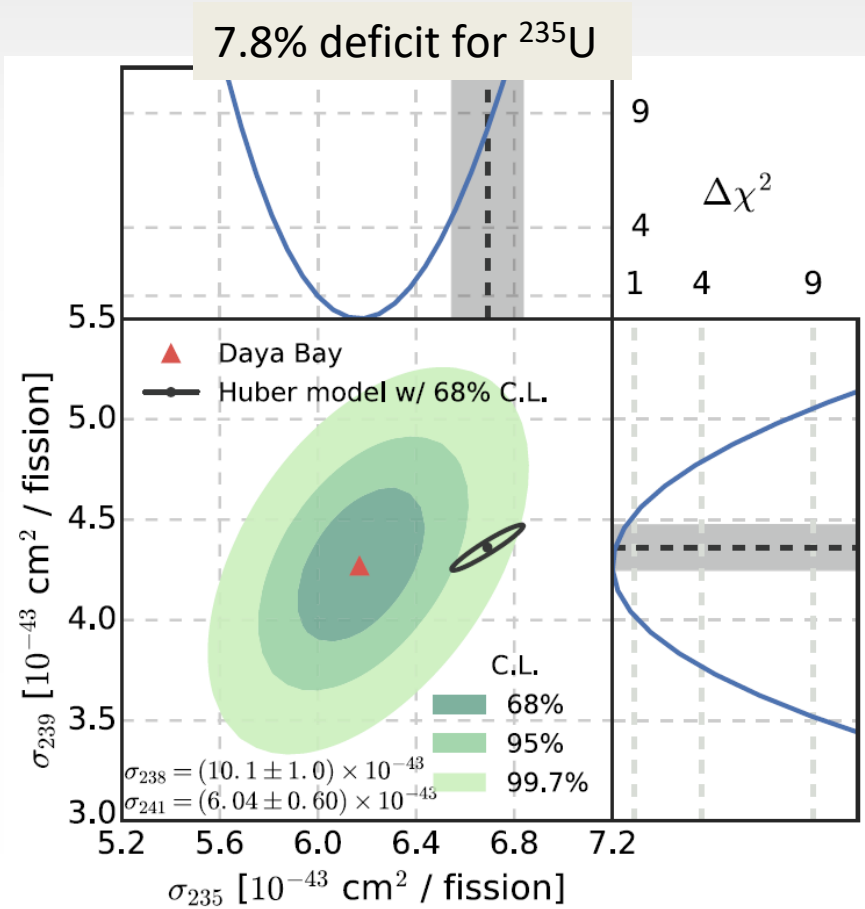
Also observed at Double Chooz, NEOS

Reactor Fuel Evolution in Daya Bay

- Which isotope(s) is (are) responsible for anomalies: ^{235}U, ^{239}Pu, ^{238}U, and ^{241}Pu
- IBD yield depends on F_{239}, negative slope
- ^{235}U is the main contributor to the reactor flux anomaly



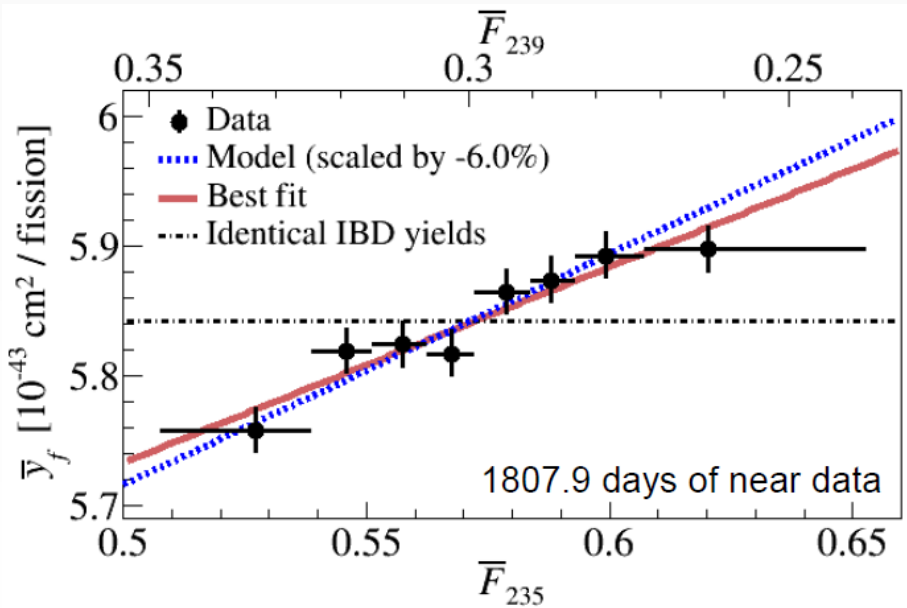


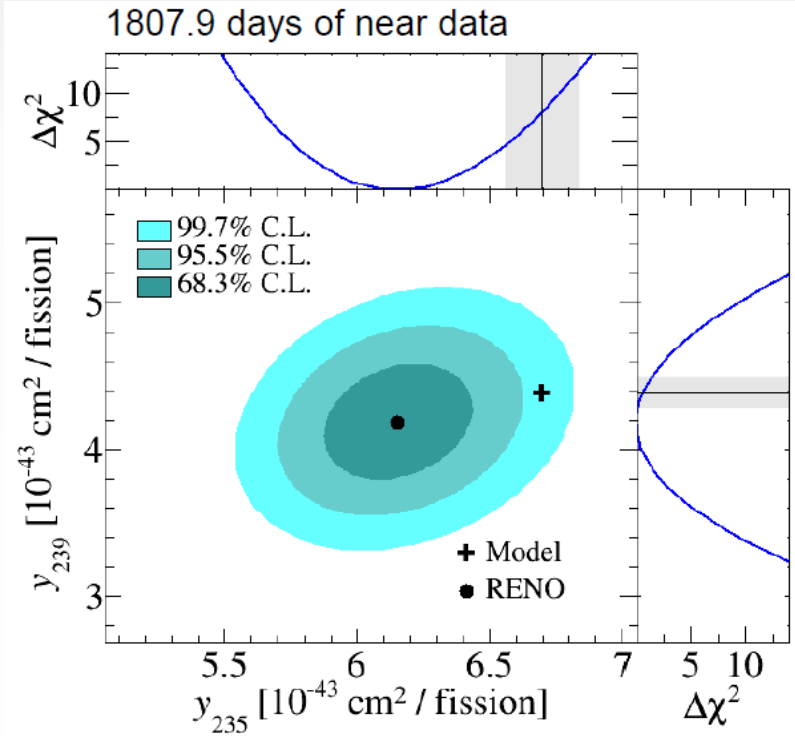


Reactor Fuel Evolution in RENO

Ratio (Data /H-M model) for the total average IBD yield
= 0.940 ± 0.021 → (6.0 ± 2.1)% deficit

- Similar conclusions observed in RENO
  - Negative (positive) slope of IBD yield vs. F_{239} (F_{235}) is observed
  - Larger ^{235}U deficit than ^{239}Pu



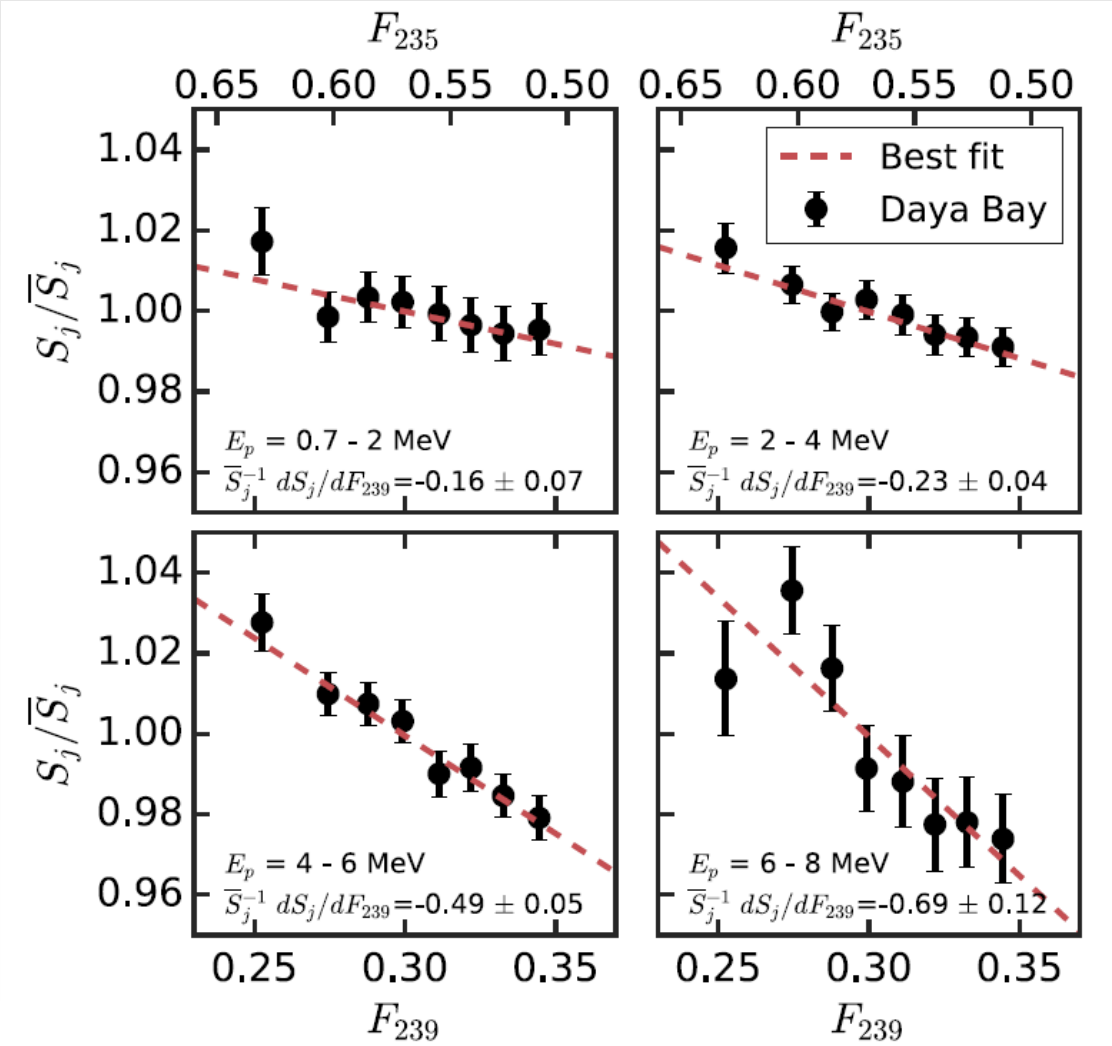


y_{235} = 6.15 ± 0.19 (2.8σ deficit)
y_{239} = 4.18 ± 0.26 (0.8σ deficit)

PRL 122 (2019) no.23, 232501

Spectrum Evolution in Daya Bay

- Antineutrino spectrum depends on fission fraction



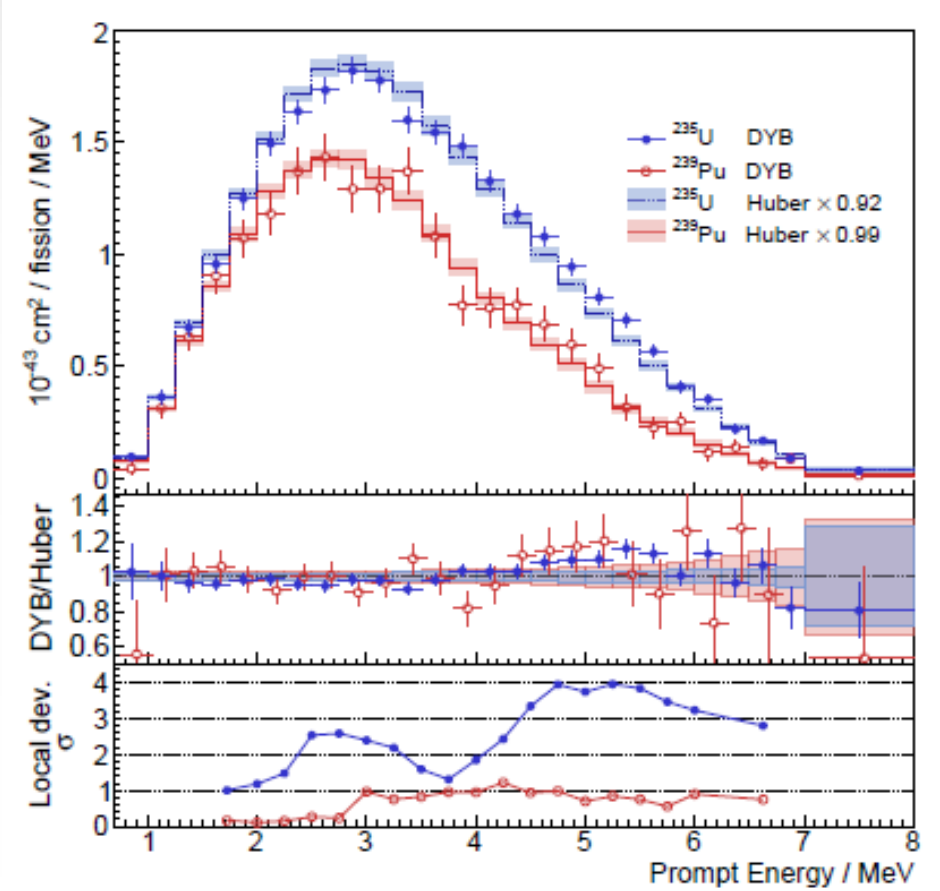
Results in
PRL 118 251801 (2017)

Observed spectrum evolution in a coarse binning

Extracted ^{235}U and ^{239}Pu Spectra

Daya Bay: PRL 123 (2019) no.11, 111801

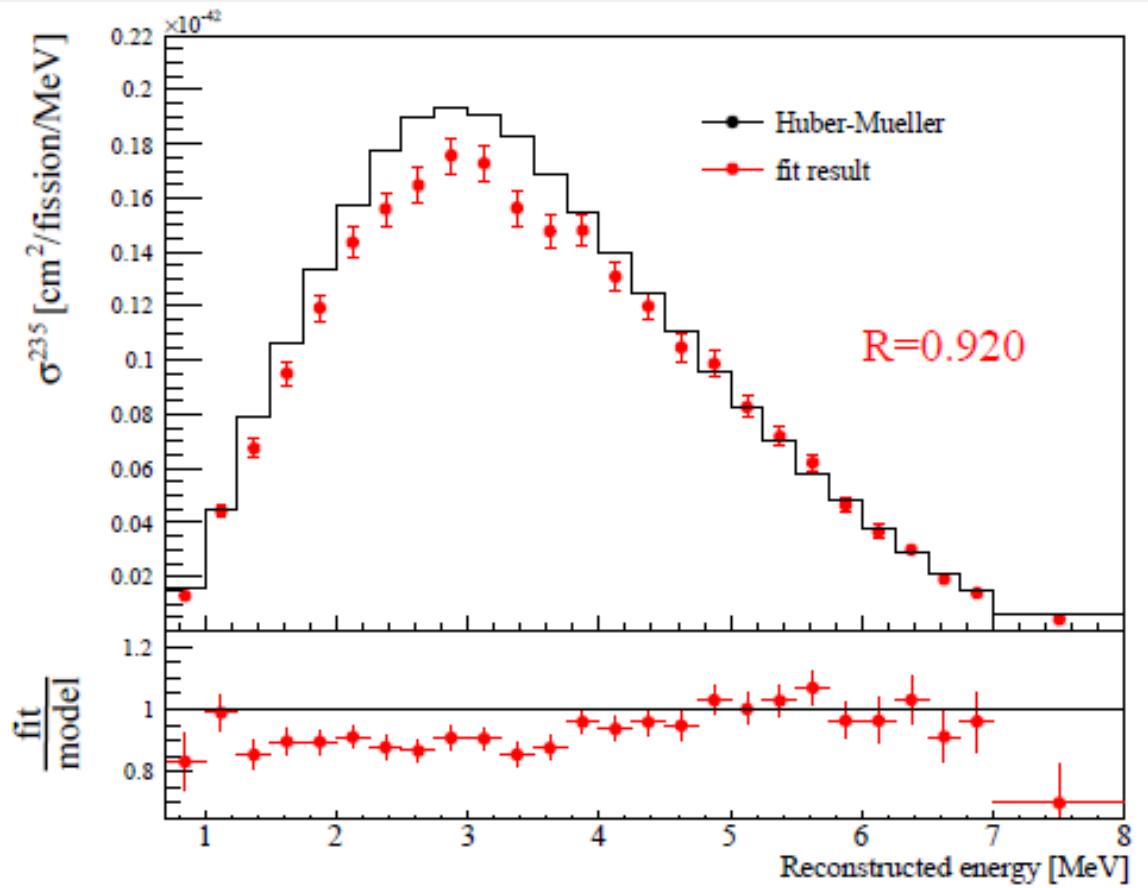
- IBD yield comparison
  - ^{235}U: data/prediction = 0.92 $\pm$0.023(exp.) $\pm$0.021(model)
  - ^{239}Pu: data/prediction = 0.99 $\pm$0.057(exp.) $\pm$0.025(model)



- First measurement of ^{235}U spectrum in commercial reactors
- First measurement of ^{239}Pu spectrum
- Spectral shape comparison after normalizing the model
  - Similar bump excess for ^{235}U and ^{239}Pu in 4—6 MeV
  - Significance of local deviations: 4σ for ^{235}U, only 1.2σ for ^{239}Pu due to larger uncertainty

Bump or Deficit?

- Compare the spectrum without normalization for ^{235}U
  - The 8% deficit of ^{235}U depends on the energy
  - 11% deficit below 4 MeV (4σ) for ^{235}U spectrum ➔8% overall rate deficit



Sterile neutrinos?

- Reactor Antineutrino Anomaly
- LSND anomaly: excess of events in neutrino beam, similar results in MiniBooNE.
- Gallium anomaly: deficit of ν_e at meter level

Search for light (1 eV^2) sterile neutrinos, details in other talks at this conference

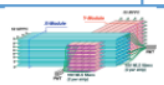
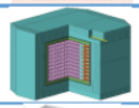
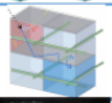
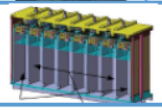
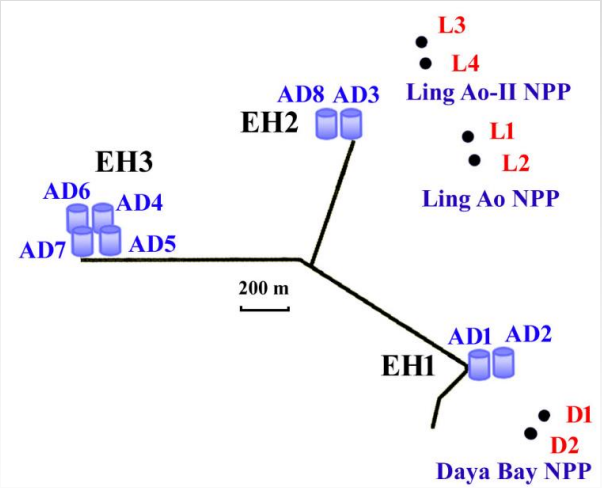
Experiment	Reactor Power/Fuel	Overburden (mwe)	Detection Material	Segmentation	Optical Readout	Particle ID Capability
DANSS (Russia) 	3000 MW LEU fuel	~50	Inhomogeneous PS & Gd sheets	2D, ~5mm	WLS fibers.	Topology only
NEOS (South Korea) 	2800 MW LEU fuel	~20	Homogeneous Gd-doped LS	none	Direct double ended PMT	recoil PSD only
nuLat (USA) 	40 MW ^{235}U fuel	few	Homogeneous ^{6}Li doped PS	Quasi-3D, 5cm, 3-axis Opt. Latt	Direct PMT	Topology, recoil & capture PSD
Neutrino4 (Russia) 	100 MW ^{235}U fuel	~10	Homogeneous Gd-doped LS	2D, ~10cm	Direct single ended PMT	Topology only
PROSPECT (USA) 	85 MW ^{235}U fuel	few	Homogeneous ^{6}Li-doped LS	2D, 15cm	Direct double ended PMT	Topology, recoil & capture PSD
SoLid (UK Fr Bel US) 	72 MW ^{235}U fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm multiplex	WLS fibers	topology, capture PSD
Chandler (USA) 	72 MW ^{235}U fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm, 2-axis Opt. Latt	Direct PMT/ WLS Scint.	topology, capture PSD
Stereo (France) 	57 MW ^{235}U fuel	~15	Homogeneous Gd-doped LS	1D, 25cm	Direct single ended PMT	recoil PSD

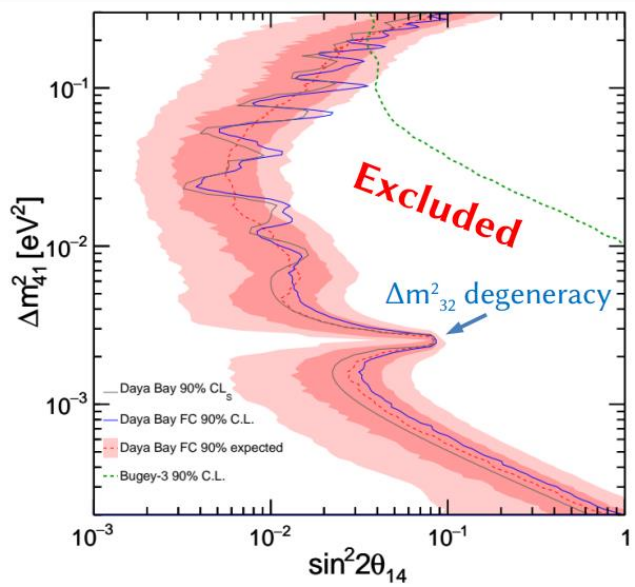
Table from Nathaniel Bowden @ Neutrino 2016

Sterile neutrino search in ~km experiments

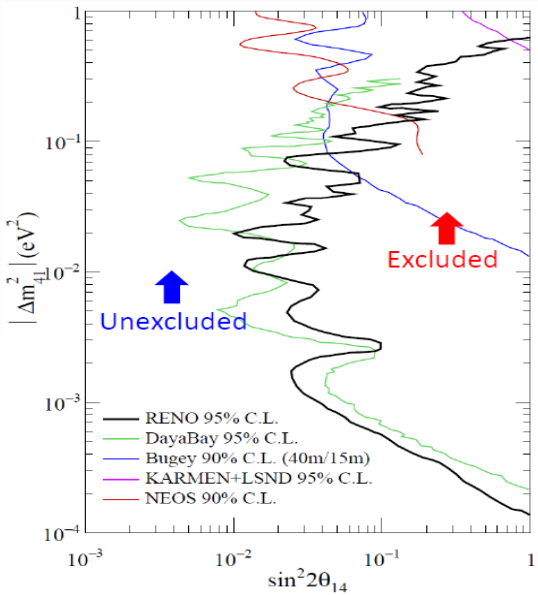
- Multiple-baseline in Daya Bay has potential in search for sterile neutrinos
- Improved sensitivity when combined with accelerator experiments
- Reject the regions (< 2 eV^2) in LSND and two global fit results with 99% C.L.



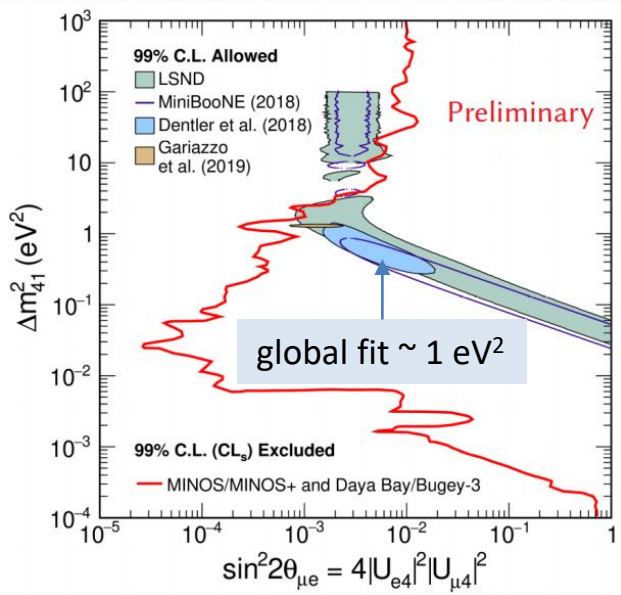
Daya Bay, Nufact 2019



RENO, AAP 2019



Daya Bay + MINOS, Nufact 2019



Summary

- Great success and rapid progress in the measurement of $\sin^2 2\theta_{13}$ with ~km reactor neutrino experiments
  - Ultimate precision on $\sin^2 2\theta_{13}$ to reach 3%
- Anomalies observed both in the reactor neutrino rate and spectrum suggest problems in the model predictions.
- Experiments to search for sterile neutrinos at 10s meter baselines are active.
- JUNO with goal to determine the neutrino mass ordering is under construction, and is expected to take data in 2021.

Thanks