

New Results from RENO

DongHa Lee for the RENO Collaboration

Seoul National University

NuFact 2019

The Grand Hotel, Daegu, Korea, Aug. 26-31, 2019



KNRC
Korea Neutrino Research Center

RENO Collaboration



Reactor Experiment for Neutrino Oscillation

(8 institutions and 40 physicists)

- Chonnam National University
- Dongshin University
- GIST
- KAIST
- Kyungpook National University
- Seoul National University
- Seoyeong University
- Sungkyunkwan University

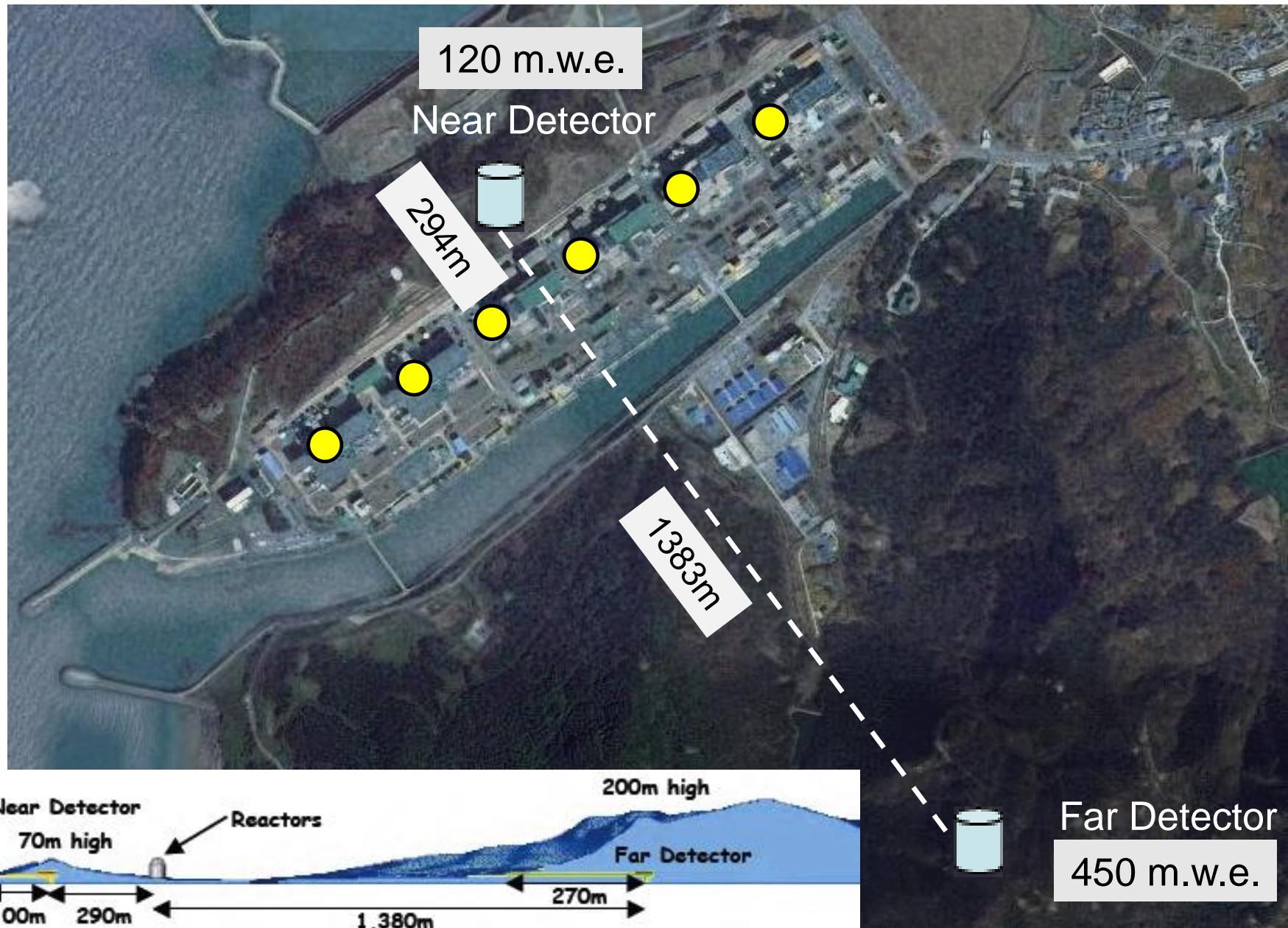
- Total cost : \$10M
- Start of project : 2006
- The first experiment running with both near & far detectors from Aug. 2011

YongGwang (靈光) :

16.8 GW (6 reactors)



RENO Experimental Set-up



New RENO Results

- Precise measurement of $|\Delta m_{ee}^2|$ and θ_{13} using ~2200 days of data (Aug. 2011 – Feb. 2018)

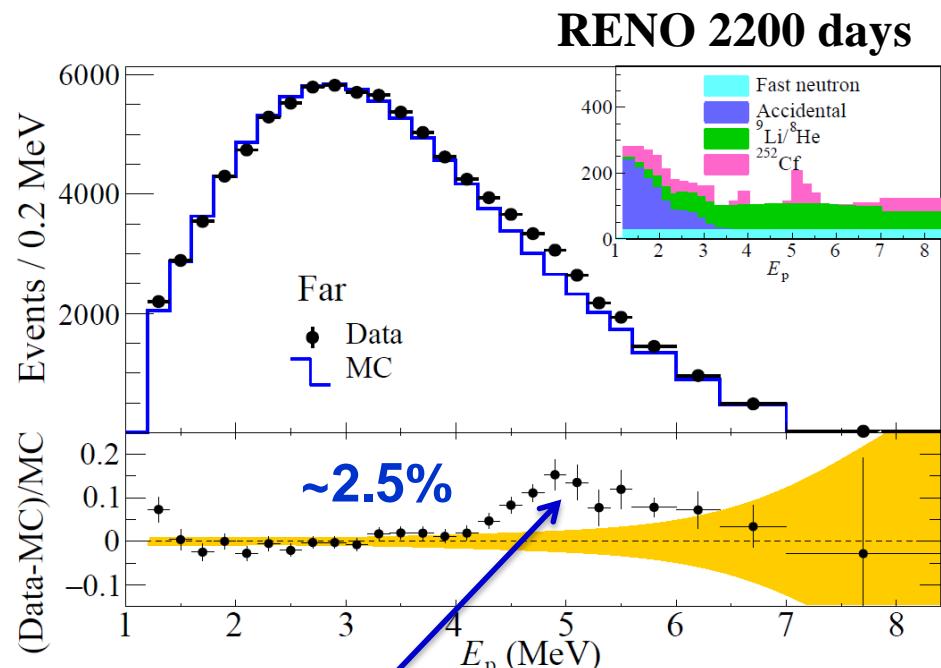
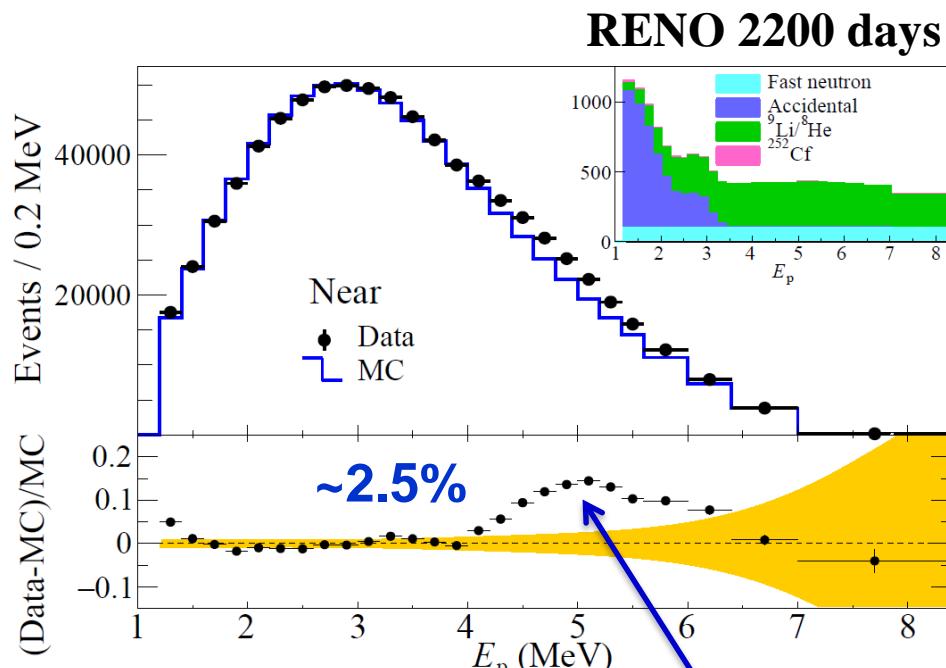
“Measurement of Reactor Antineutrino Oscillation Amplitude and Frequency at RENO” → Published in PRL (Phys. Rev. Lett. 121, 201801 (2018))

- Fuel-composition dependent reactor antineutrino yield → “Fuel-composition dependent reactor antineutrino yield and spectrum at RENO” → Published in PRL (Phys. Rev. Lett. 122, no.23, 232501 (2019))

- Independent measurement of $|\Delta m_{ee}^2|$ and θ_{13} with delayed n-H signals

Measured Spectra of IBD Prompt Signal

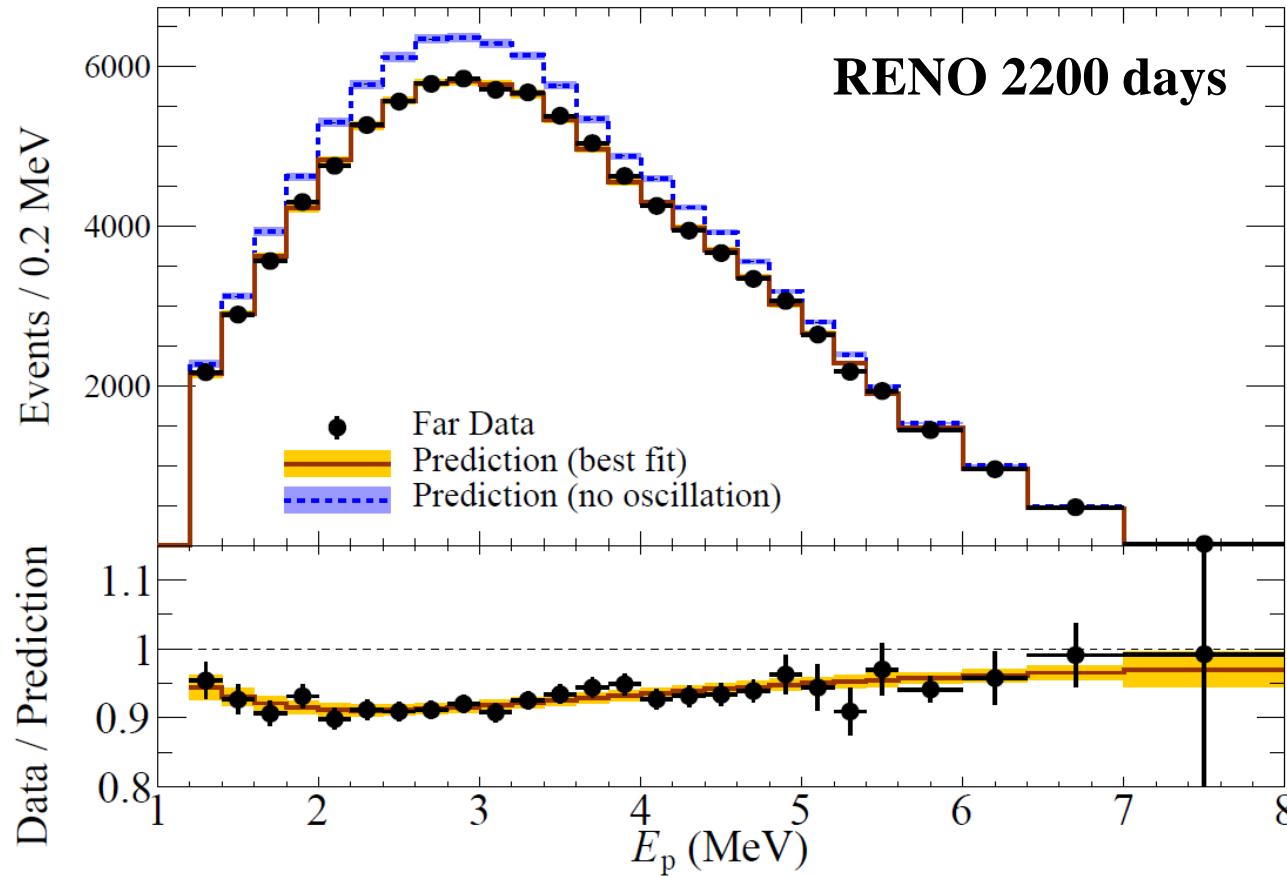
Clear excess at 5 MeV



In 2014, RENO showed the 5 MeV excess comes from reactors.

Far/Near Shape Analysis

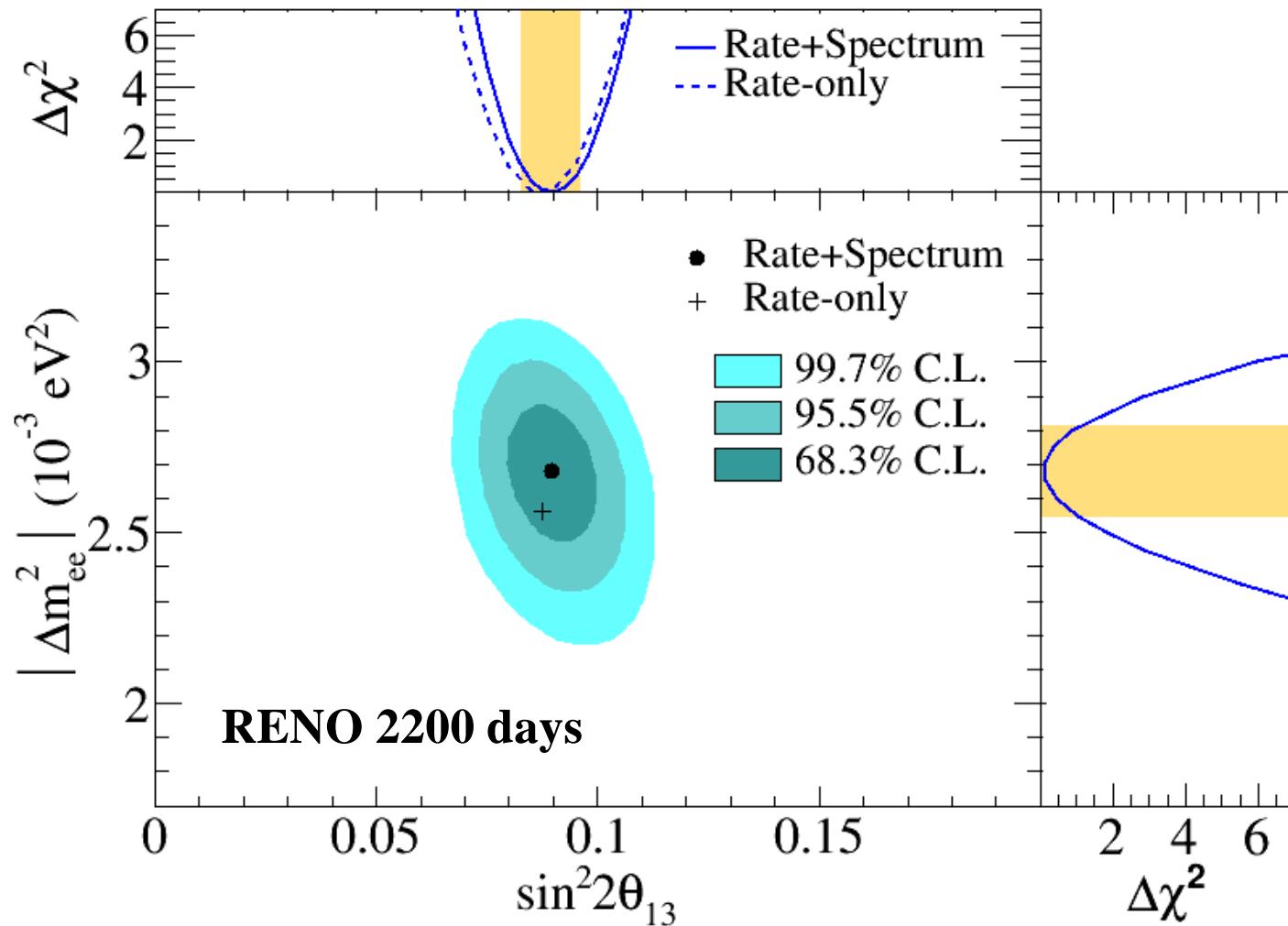
Energy-dependent disappearance of reactor antineutrinos



$$\sin^2 2\theta_{13} = 0.0896 \pm 0.0048(\text{stat.}) \pm 0.0047(\text{syst.}) \quad (\pm 7.6\%)$$

$$|\Delta m_{ee}^2| = 2.68 \pm 0.12(\text{stat.}) \pm 0.07(\text{syst.}) \times 10^{-3} \text{ eV}^2 \quad (\pm 5.2\%)$$

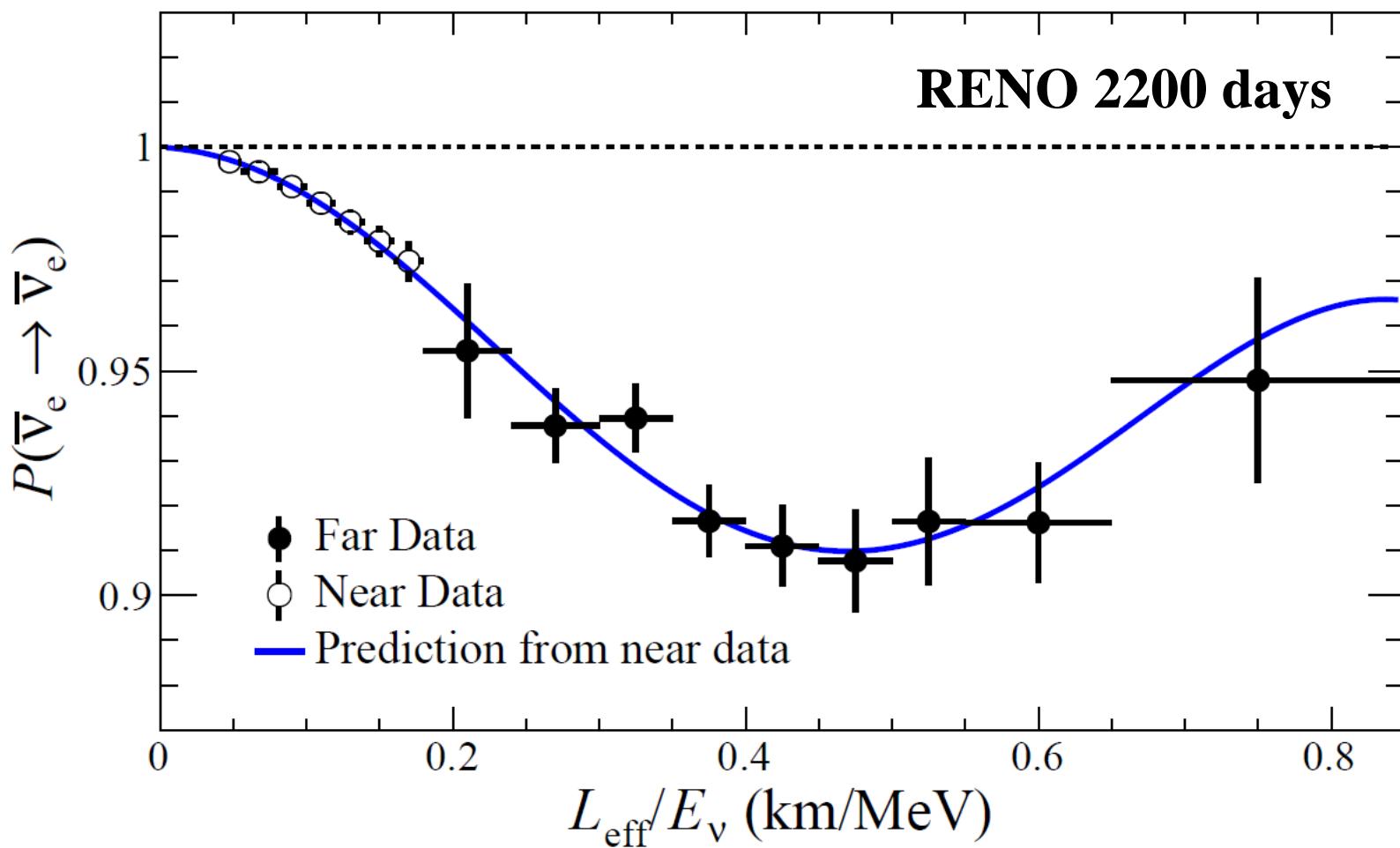
Results of θ_{13} and $|\Delta m^2_{ee}|$



$$\sin^2 2\theta_{13} = 0.0896 \pm 0.0048(\text{stat.}) \pm 0.0047(\text{syst.})$$

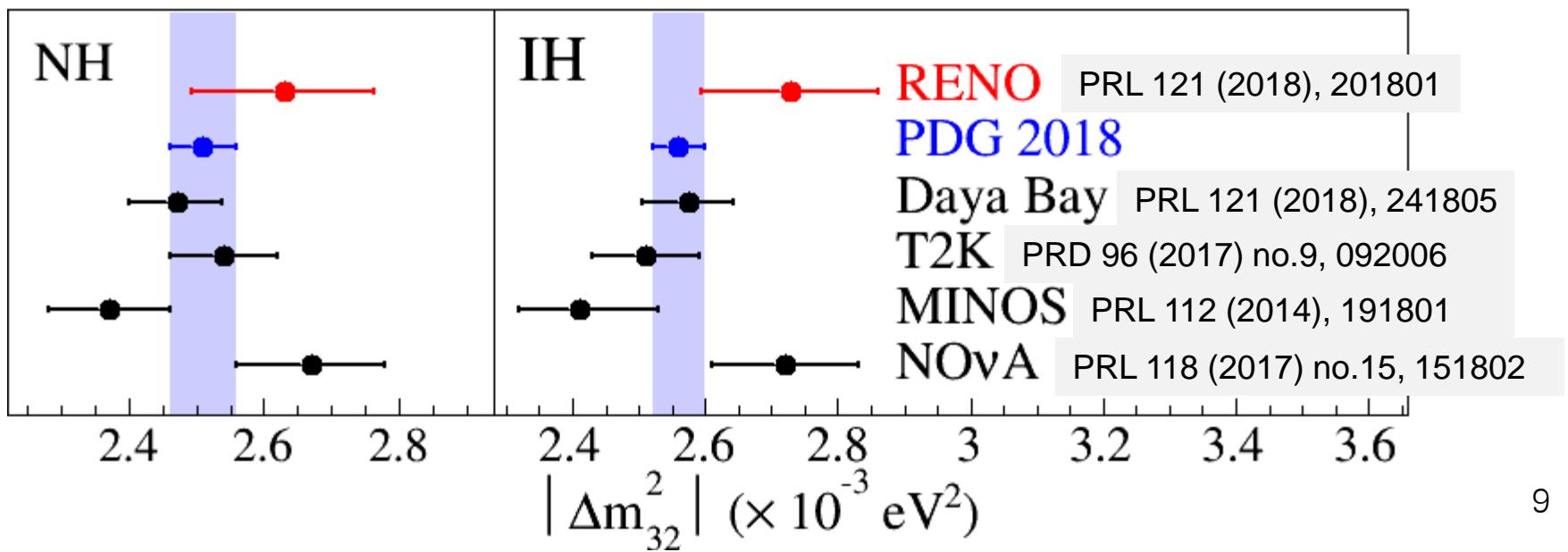
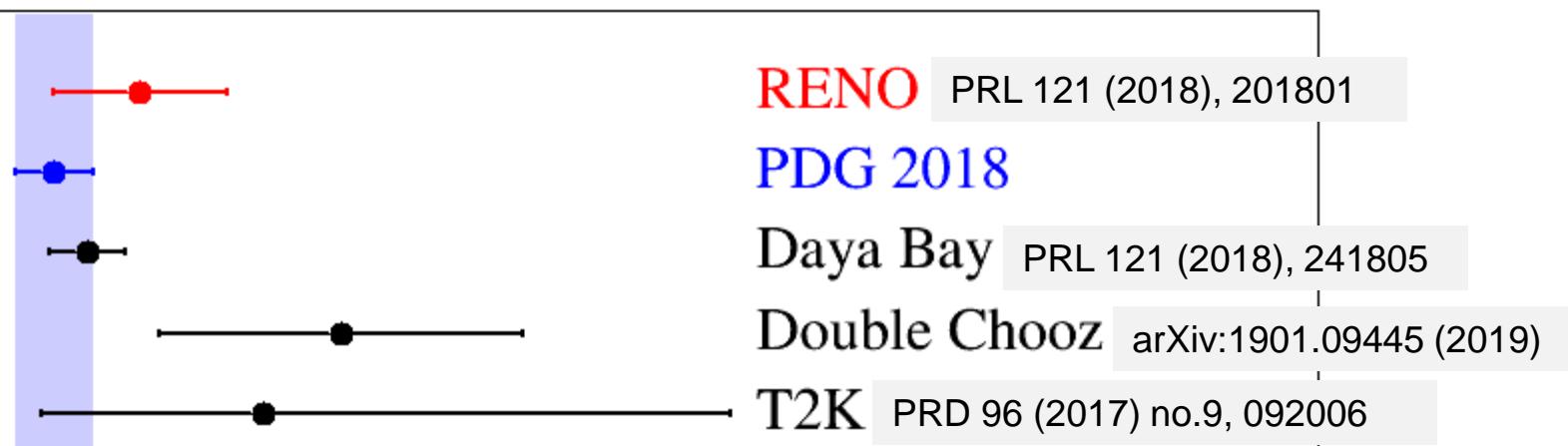
$$|\Delta m^2_{ee}| = 2.68 \pm 0.12(\text{stat.}) \pm 0.07(\text{syst.}) (\times 10^{-3} \text{ eV}^2)$$

Observed L/E Dependent Oscillation



$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2 2q_{13} \sin^2 \left(Dm_{ee}^2 \frac{L}{4E_n} \right)$$

Comparison of θ_{13} and $|\Delta m^2_{ee}|$



Motivation for the study of fuel composition dependent reactor antineutrino yield

Reactor Antineutrino Anomaly

- ~6% deficit of measured reactor neutrino flux compared to the prediction with new predicted flux evaluation in 2011 by Huber and Mueller.
- Deficit of observed reactor neutrino fluxes relative to the prediction (Huber + Mueller model) indicates an overestimated flux or possible oscillation to sterile neutrinos.



The possibility that reactor anomaly is due to miscalculation of one or more of the ^{235}U , ^{239}Pu , ^{238}U and ^{241}Pu antineutrino fluxes is investigated by observing **fuel-composition dependent variation of reactor antineutrino yield and spectrum**.

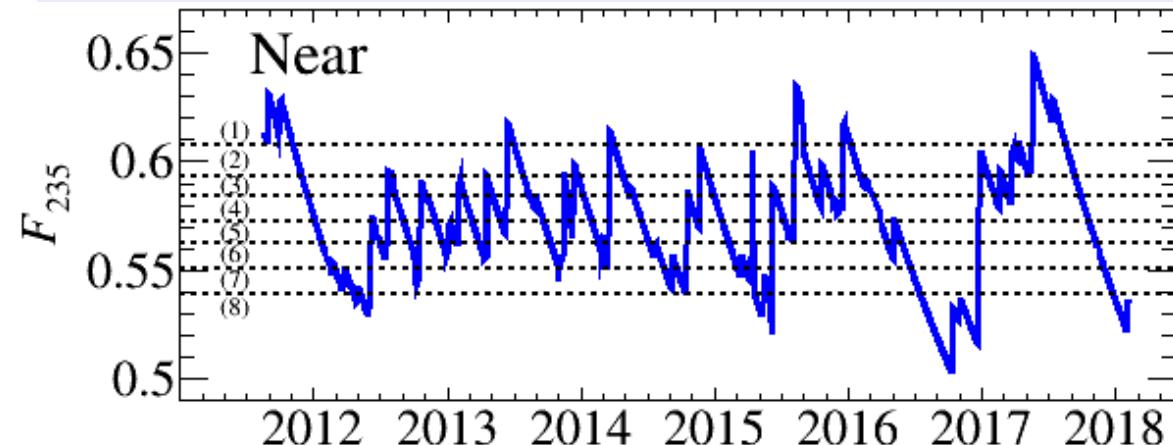
C. Giunti, Phys. Lett. B 764, 145 (2017)

F. P. An et al. (Daya Bay Collaboration), PRL 118, 251801 (2017)

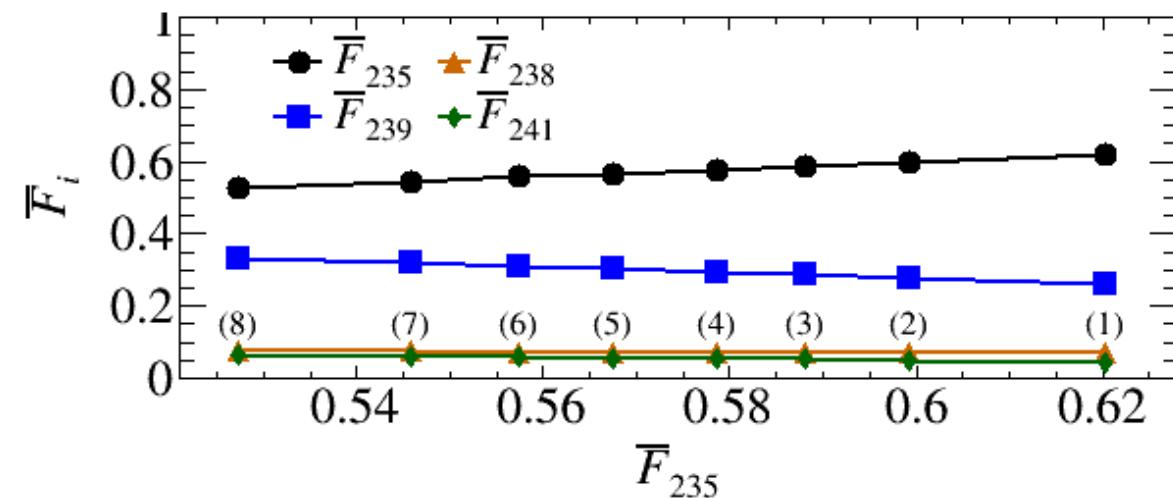
- RENO Collaboration, Phys. Rev. Lett. 122, no.23, 232501 (2019)

Evolution of Fuel Composition at RENO

Average fission fraction $f_{235} : f_{239} : f_{238} : f_{241} = 0.573 : 0.299 : 0.073 : 0.055$



Effective fission fraction of ^{235}U
(weighted by each reactor's thermal power and baseline)



Effective Fission fraction for each isotope

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

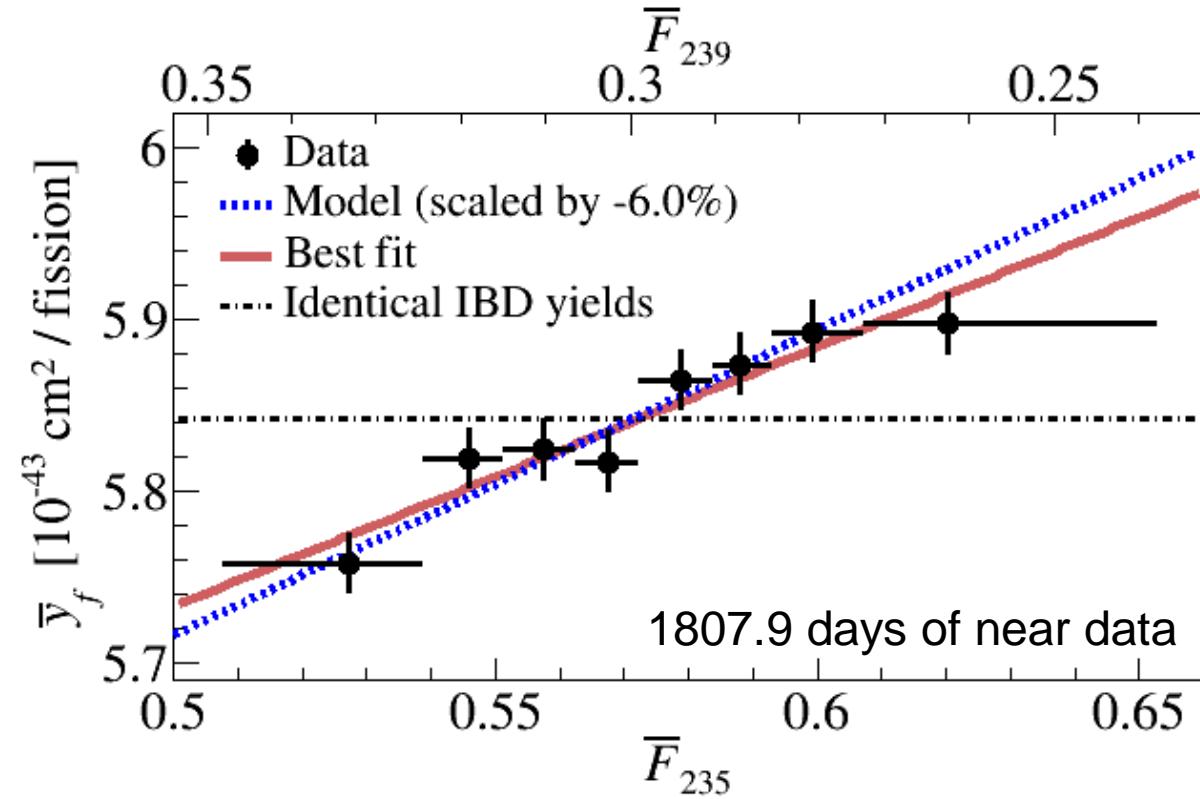
Fuel-Composition Dependent Reactor Neutrino Yield

Measured total averaged IBD yield per fission (\bar{y}_f)

$$= (5.84 \pm 0.13) \times 10^{-43} \text{ cm}^2/\text{fission}$$

Ratio (Data /H-M model) for the total average IBD yield

$$= 0.940 \pm 0.021 \rightarrow (6.0 \pm 2.1)\% \text{ deficit}$$



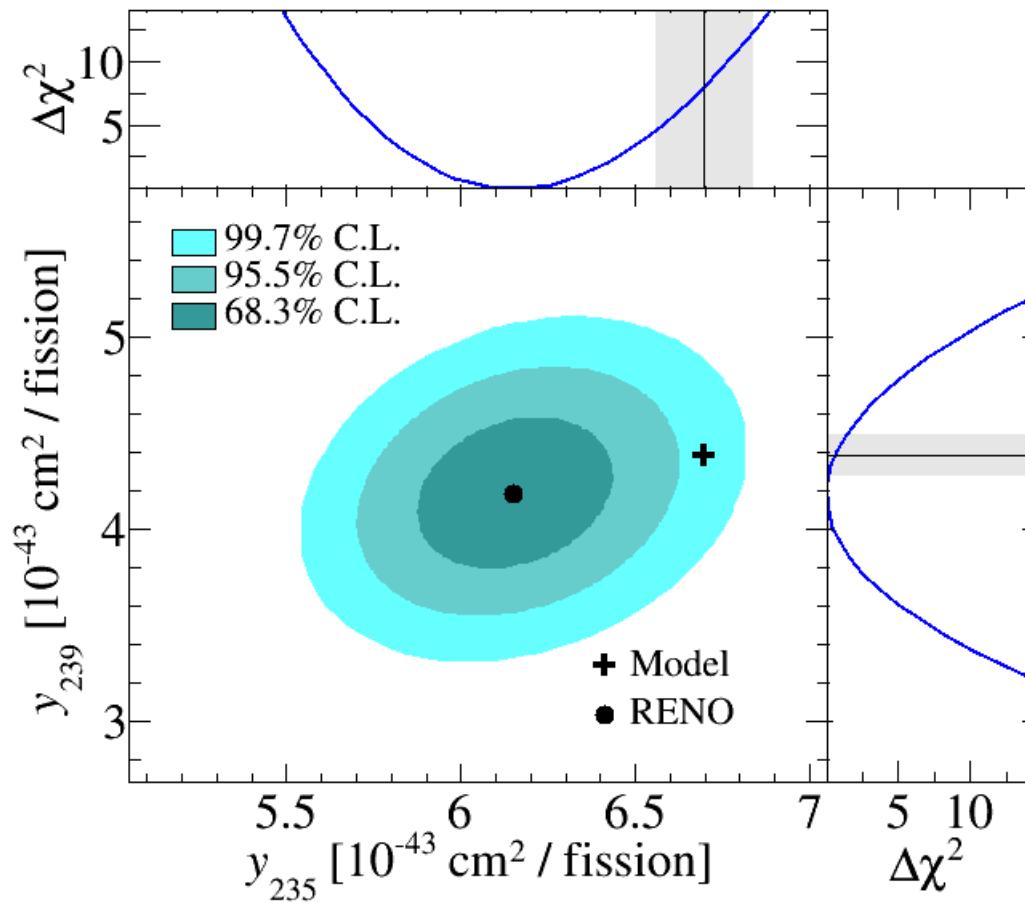
Averaged IBD yield per fission (\bar{y}_f) vs $\bar{F}_{i,j}$
→ slope means **different neutrino yield** for each isotope
→ rules out the no fuel-dependent variation at **6.6σ**

The scaled model indicates the **reactor antineutrino anomaly**

Measurement of y_{235} and y_{239}

The best-fit measured yields per fission of ^{235}U and ^{239}Pu

1807.9 days of near data



The best-fit values

$$y_{235} = 6.15 \pm 0.19 \text{ (2.8}\sigma\text{ deficit)}$$
$$y_{239} = 4.18 \pm 0.26 \text{ (0.8}\sigma\text{ deficit)}$$

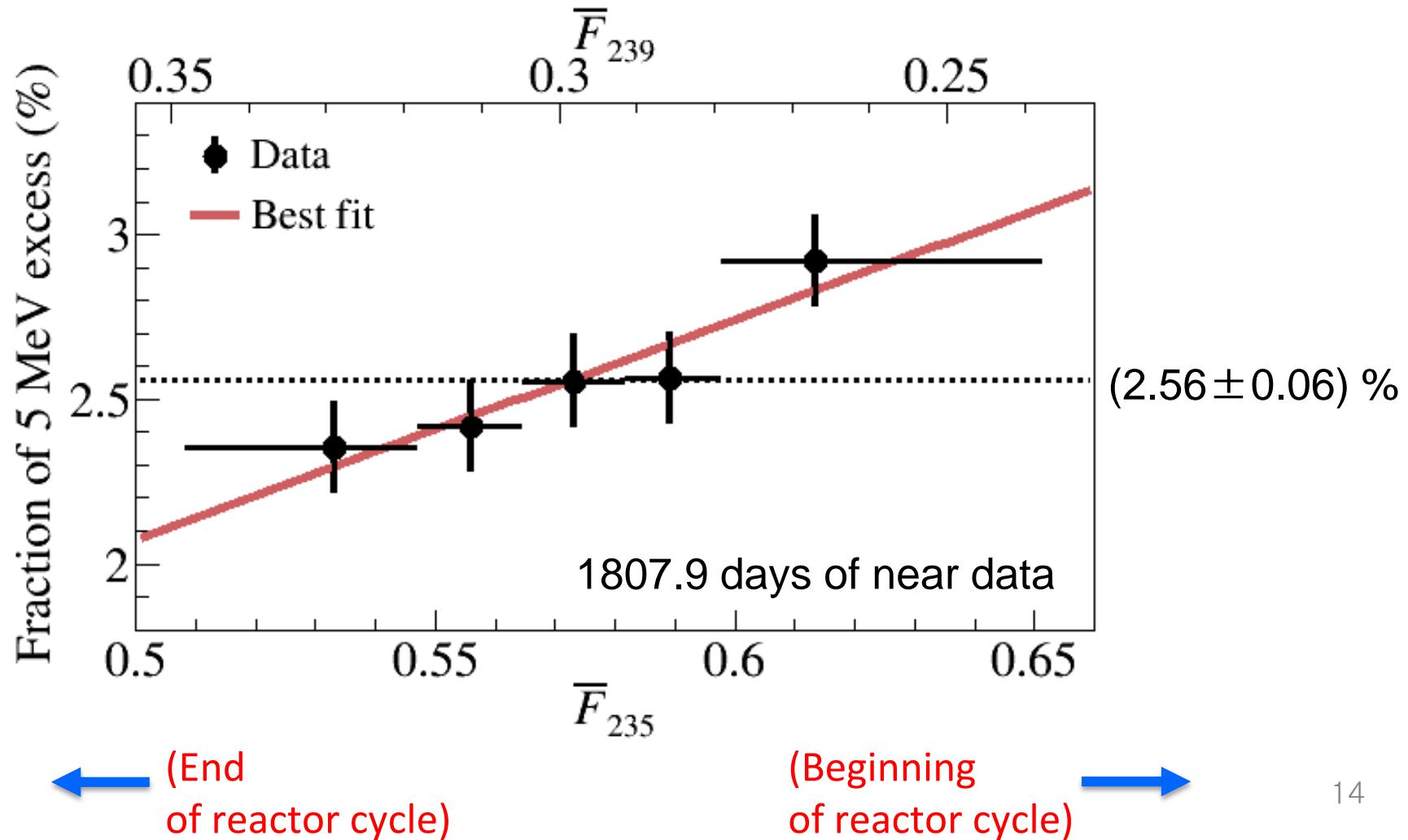
H-M model

$$y_{235} = 6.70 \pm 0.14$$
$$y_{239} = 4.38 \pm 0.11$$

Reevaluation of the y_{235} may **mostly solve** the reactor antineutrino **anomaly**. But ^{239}Pu is **not entirely** ruled out as a possible source of the anomaly.

Correlation of 5 MeV excess with fuel ^{235}U

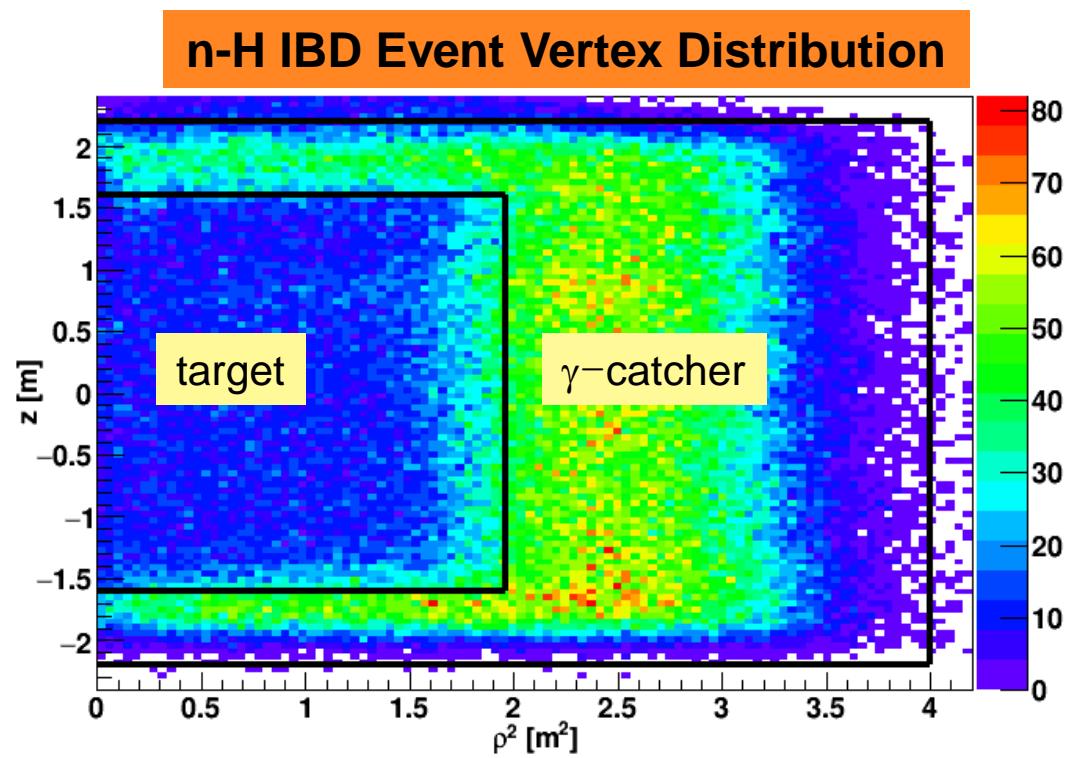
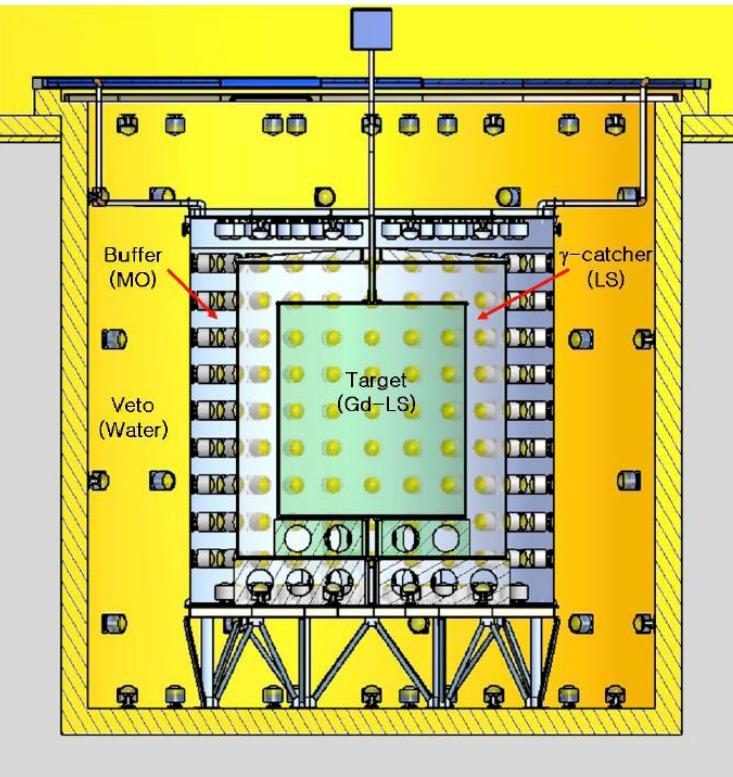
2.9 σ indication of 5 MeV excess coming from ^{235}U fuel isotope fission !!



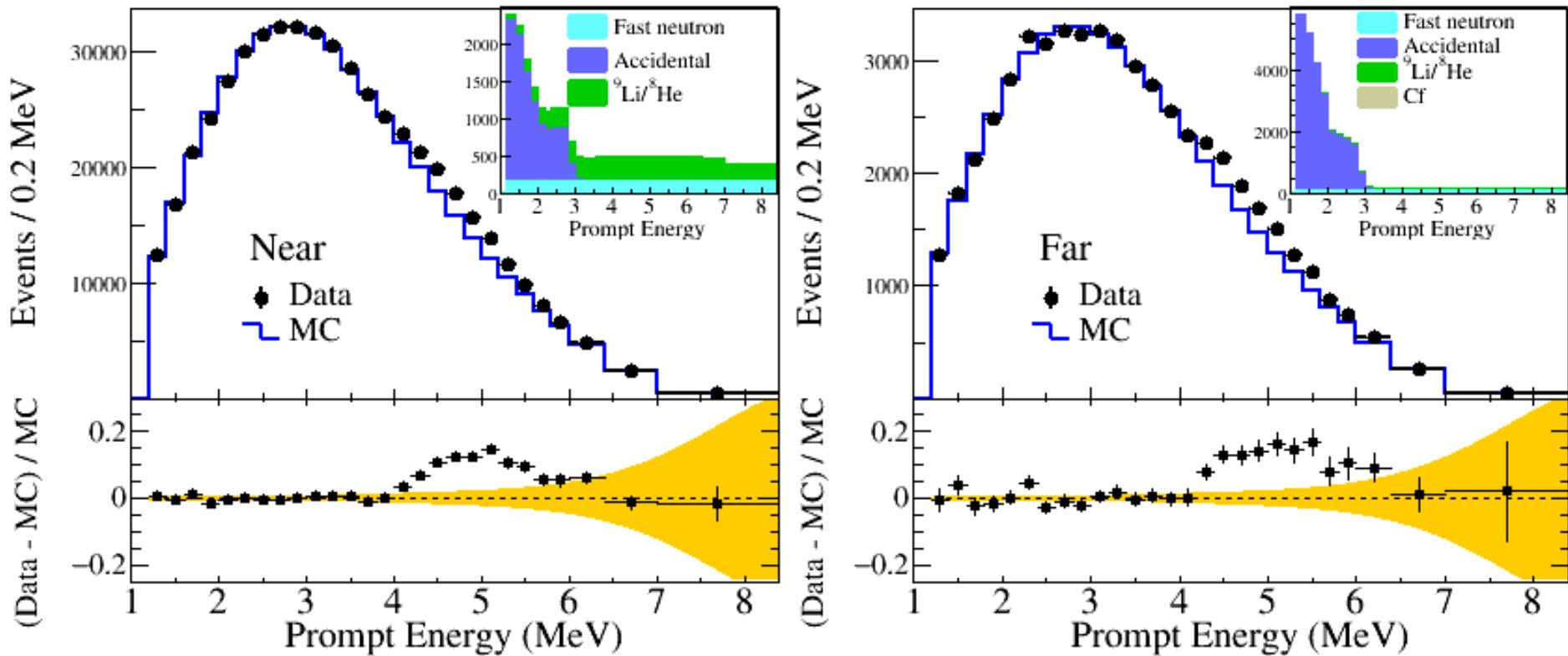
n-H IBD Analysis

Motivation:

1. Independent measurement of θ_{13} and $|\Delta m_{ee}^2|$.
2. Consistency and systematic check on reactor neutrinos.

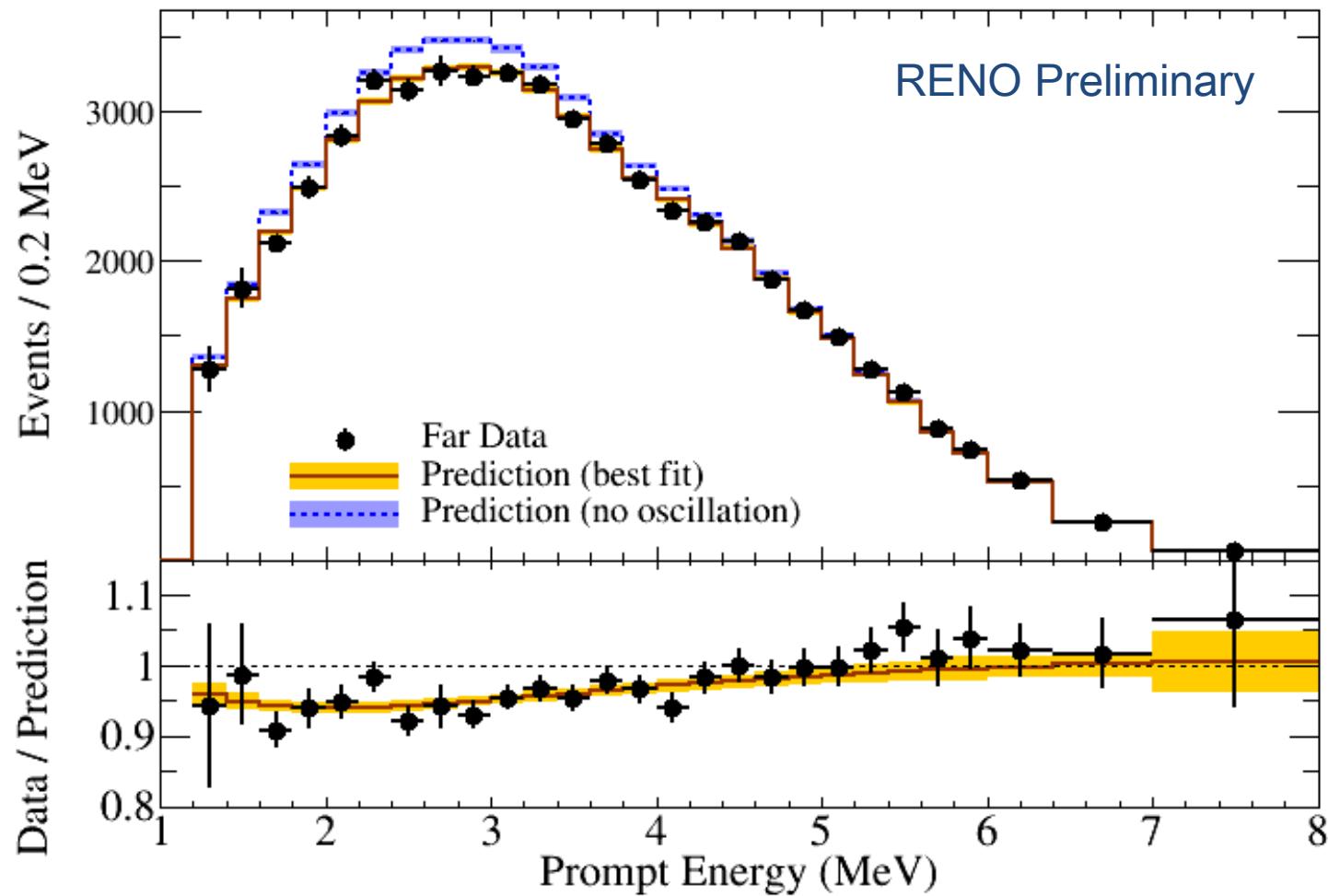


θ_{13} Measurement with n-H



$$\sin^2 2\theta_{13} = 0.085 \pm 0.008(\text{stat.}) \pm 0.012(\text{syst.})$$

θ_{13} and $|\Delta m^2_{ee}|$ Measurement with n-H



$$\sin^2 2\theta_{13} = 0.094^{+0.012}_{-0.010} (\text{stat}) \pm 0.009 (\text{syst})$$

$$|\Delta m^2_{ee}| = 2.53^{+0.25}_{-0.28} (\text{stat.})^{+0.13}_{-0.16} (\text{syst.}) (\times 10^{-3} \text{ eV}^2)$$

Summary

- More precise measurement of $|\Delta m_{ee}^2|$ and θ_{13} using 2200 days of data

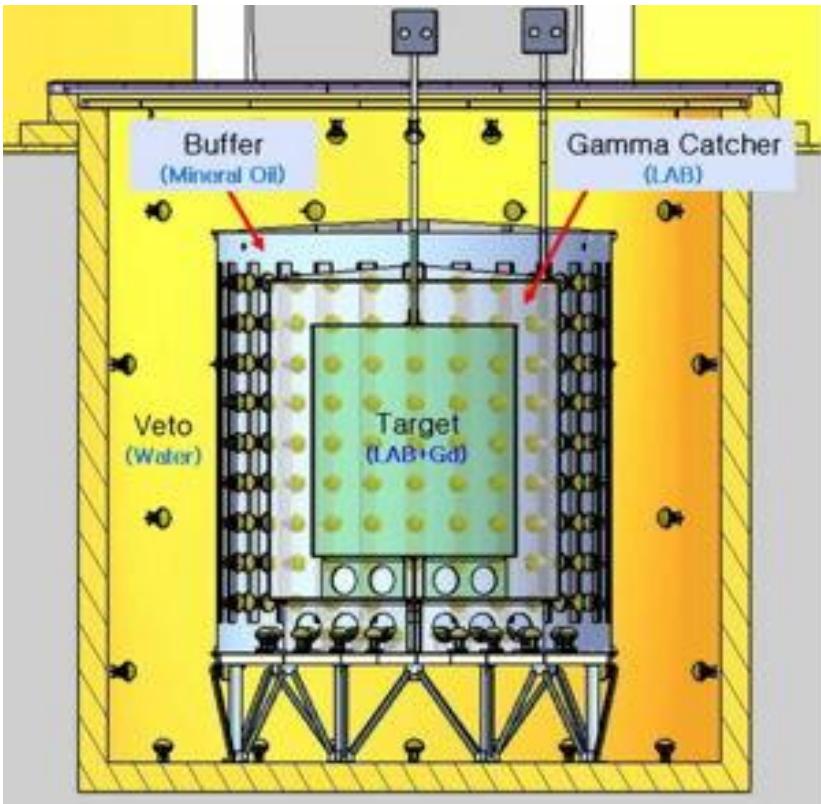
$$\sin^2 2\theta_{13} = 0.0896 \pm 0.0048(\text{stat.}) \pm 0.0047(\text{syst.}) \quad \pm 0.0068 \quad 7.6 \% \text{ precision}$$

$$|\Delta m_{ee}^2| = 2.68 \pm 0.12(\text{stat.}) \pm 0.07(\text{syst.}) (\times 10^{-3} \text{ eV}^2) \quad \pm 0.14 \quad 5.2 \% \text{ precision}$$

- Observation of fuel composition dependent IBD yield at 6.6σ CL
- Measured IBD yield per fission (10^{-43} cm^2)
 - ^{235}U : 6.15 ± 0.19 (smaller than the H-M prediction at 2.8σ)
 - ^{239}Pu : 4.18 ± 0.26 (smaller than the H-M prediction at 0.8σ)
- First hint for 2.9σ correlation between 5 MeV excess and ^{235}U fission fraction
- Measurement of $|\Delta m_{ee}^2|$ and θ_{13} using n-H IBD analysis

Thanks for your attention!

RENO Detector



- 354 ID +67 OD 10" PMTs
- Target : 16.5 ton Gd-LS, R=1.4m, H=3.2m
- Gamma Catcher : 30 ton LS, R=2.0m, H=4.4m
- Buffer : 65 ton mineral oil, R=2.7m, H=5.8m
- Veto : 350 ton water, R=4.2m, H=8.8m



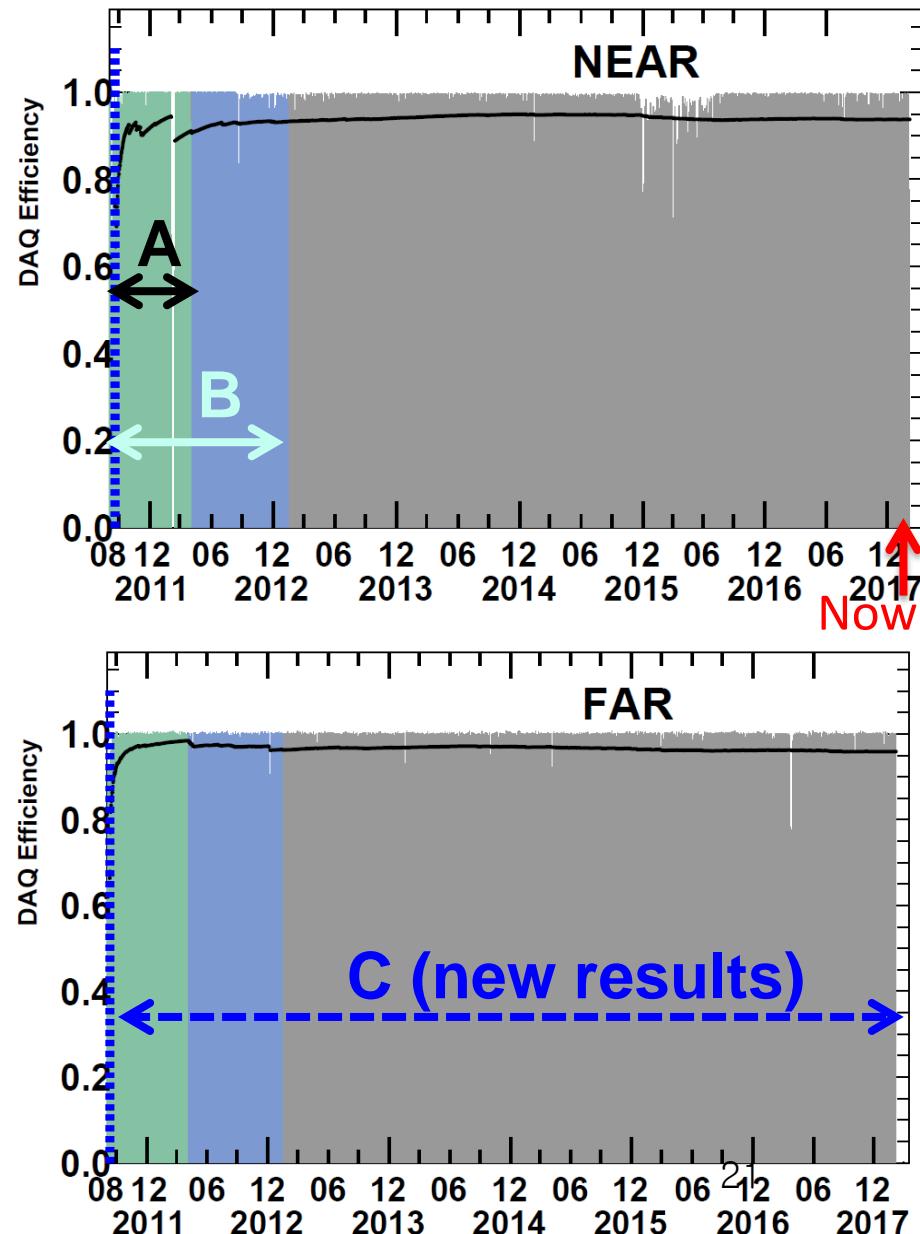
RENO Data-taking Status

- Data taking began on Aug. 1, 2011 with both near and far detectors.
(DAQ efficiency : ~95%)

- A (220 days) : First θ_{13} result
[11 Aug, 2011~26 Mar, 2012]
PRL 108, 191802 (2012)

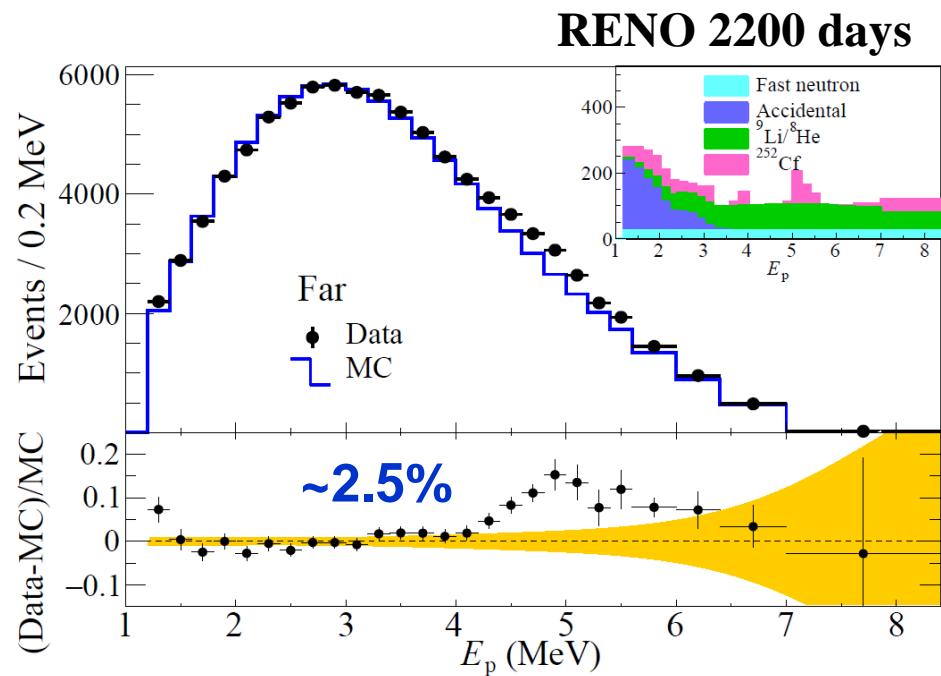
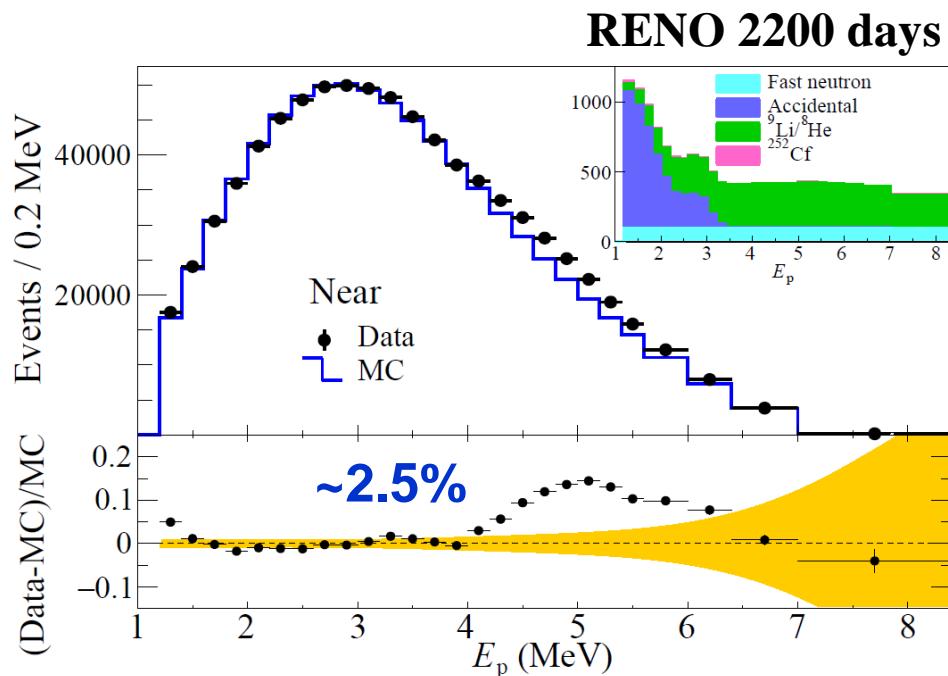
- B (~500 days) : Recent results
Rate+shape analysis (θ_{13} and $|\Delta m_{ee}^2|$)
[11 Aug, 2011~21 Jan, 2013]
→ PRL 116, 211801 (2016)
accepted to PRD (arXiv:1610.04326)

- C (~2200 days) : New results
Rate+shape analysis (θ_{13} and $|\Delta m_{ee}^2|$)
[11 Aug, 2011~7 Feb, 2018]
→ submitted to PRL (arXiv:1806.00248)



Measured Spectra of IBD Prompt Signal

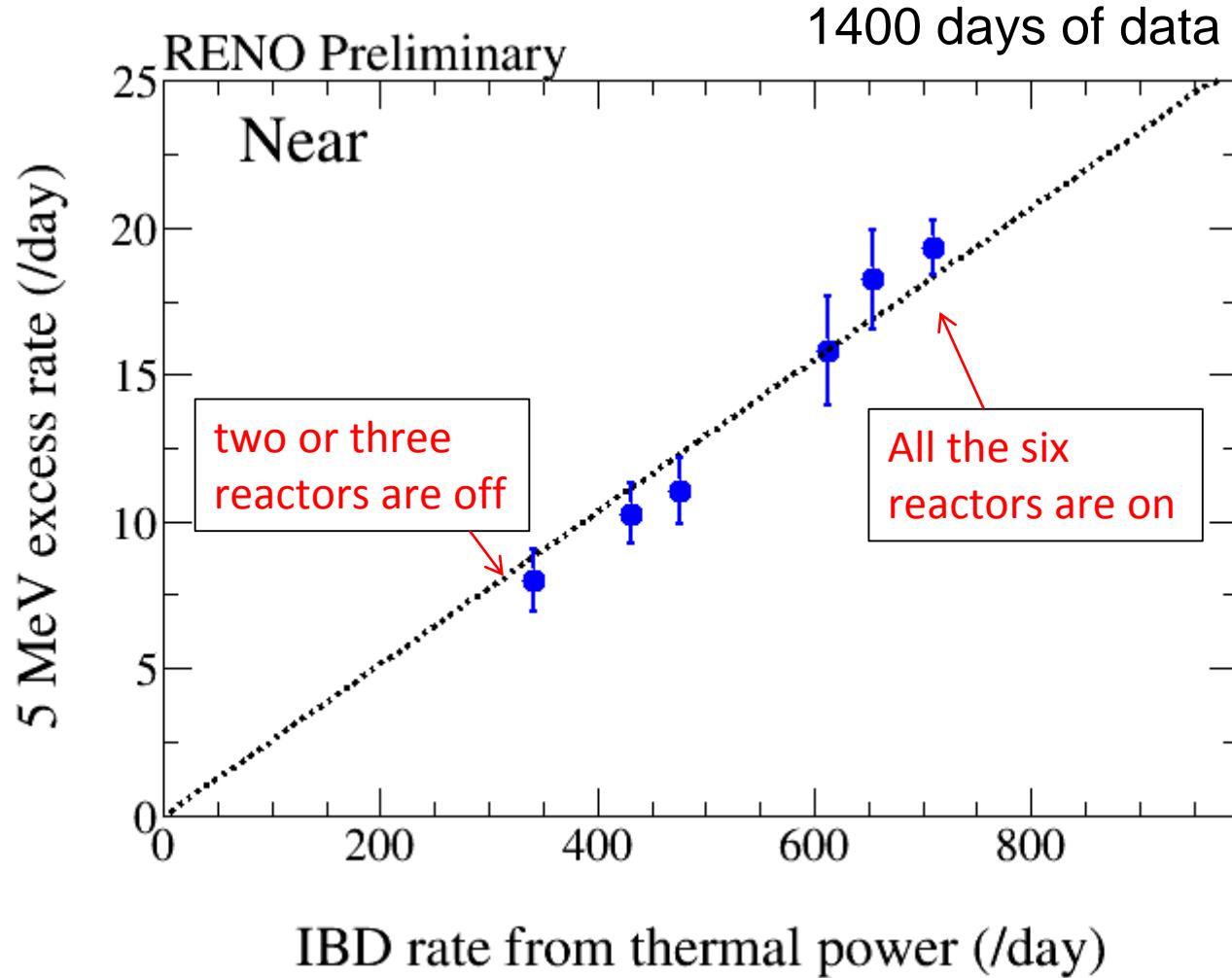
Clear excess at 5 MeV



Near Live time = 1807.88 days
of IBD candidate = 850,666
of background = 17,233 (2.0%)

Far Live time = 2193.04 days
of IBD candidate = 103,212
of background = 4,879 (4.8%)

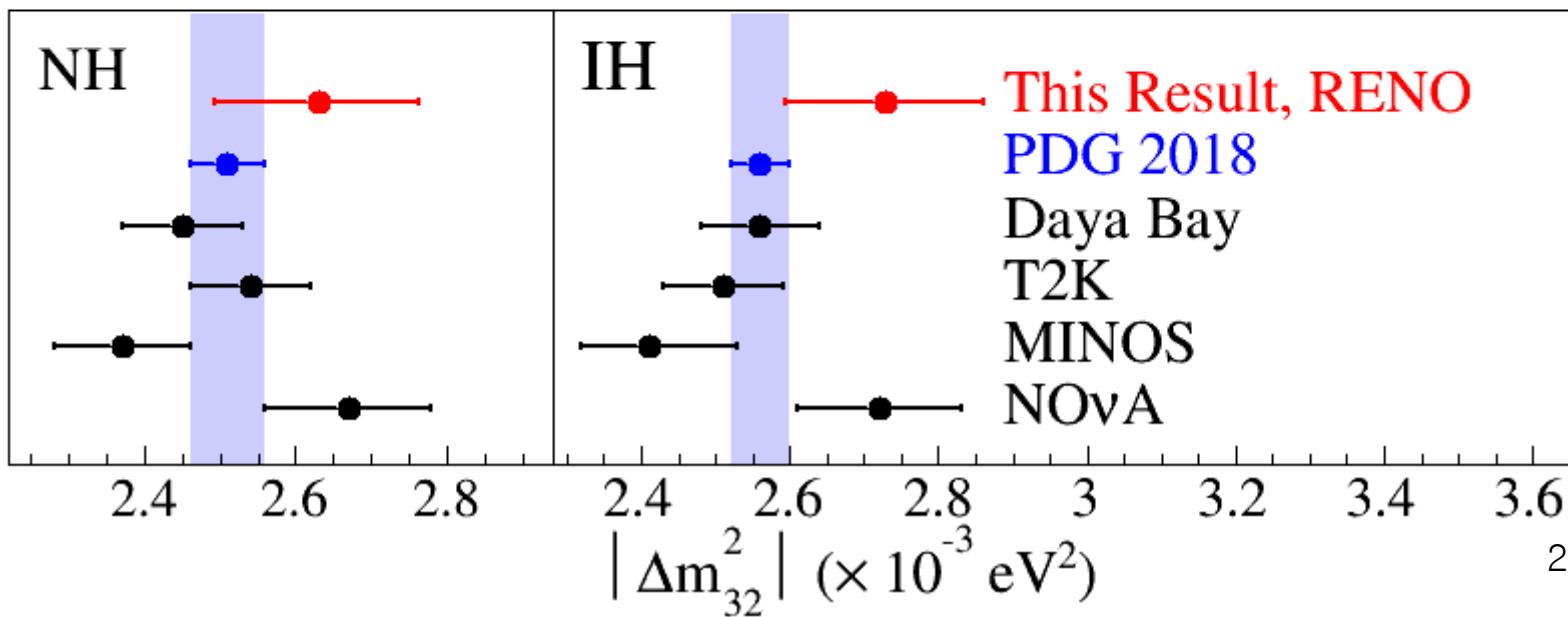
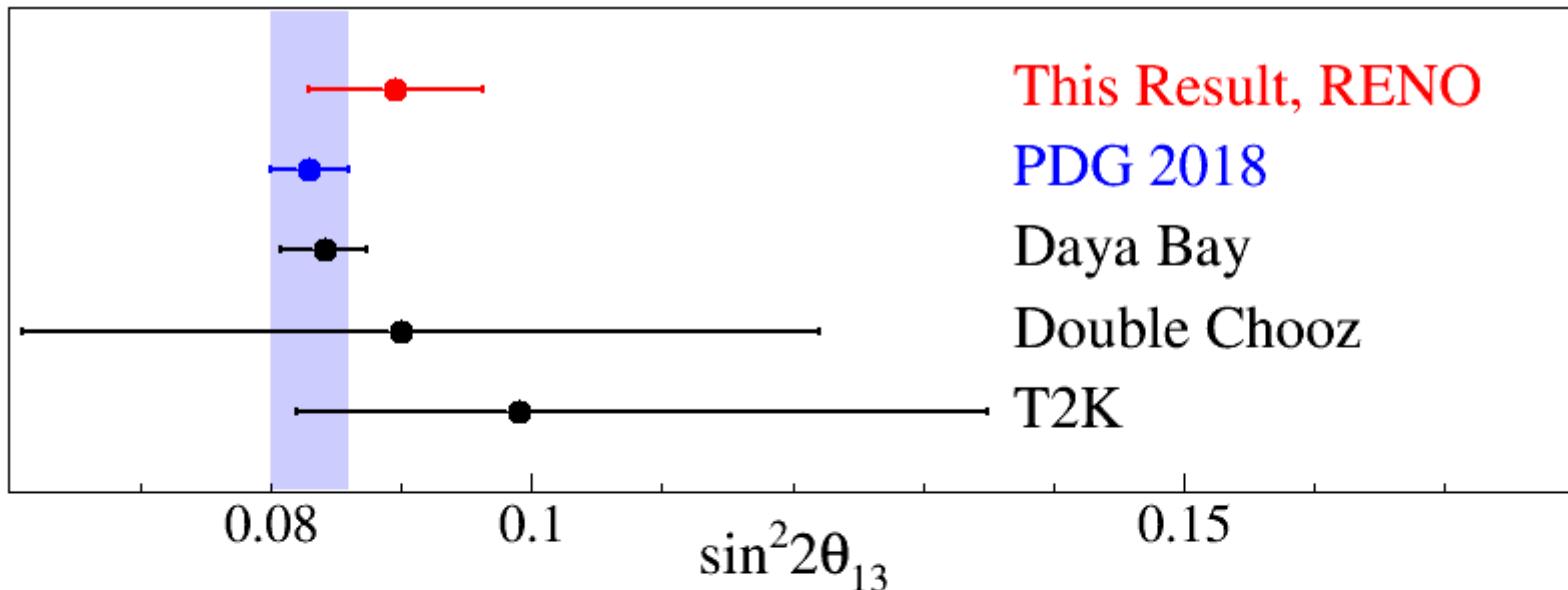
Correlation of 5 MeV Excess with Reactor Power



5 MeV excess has a clear correlation with reactor thermal power !

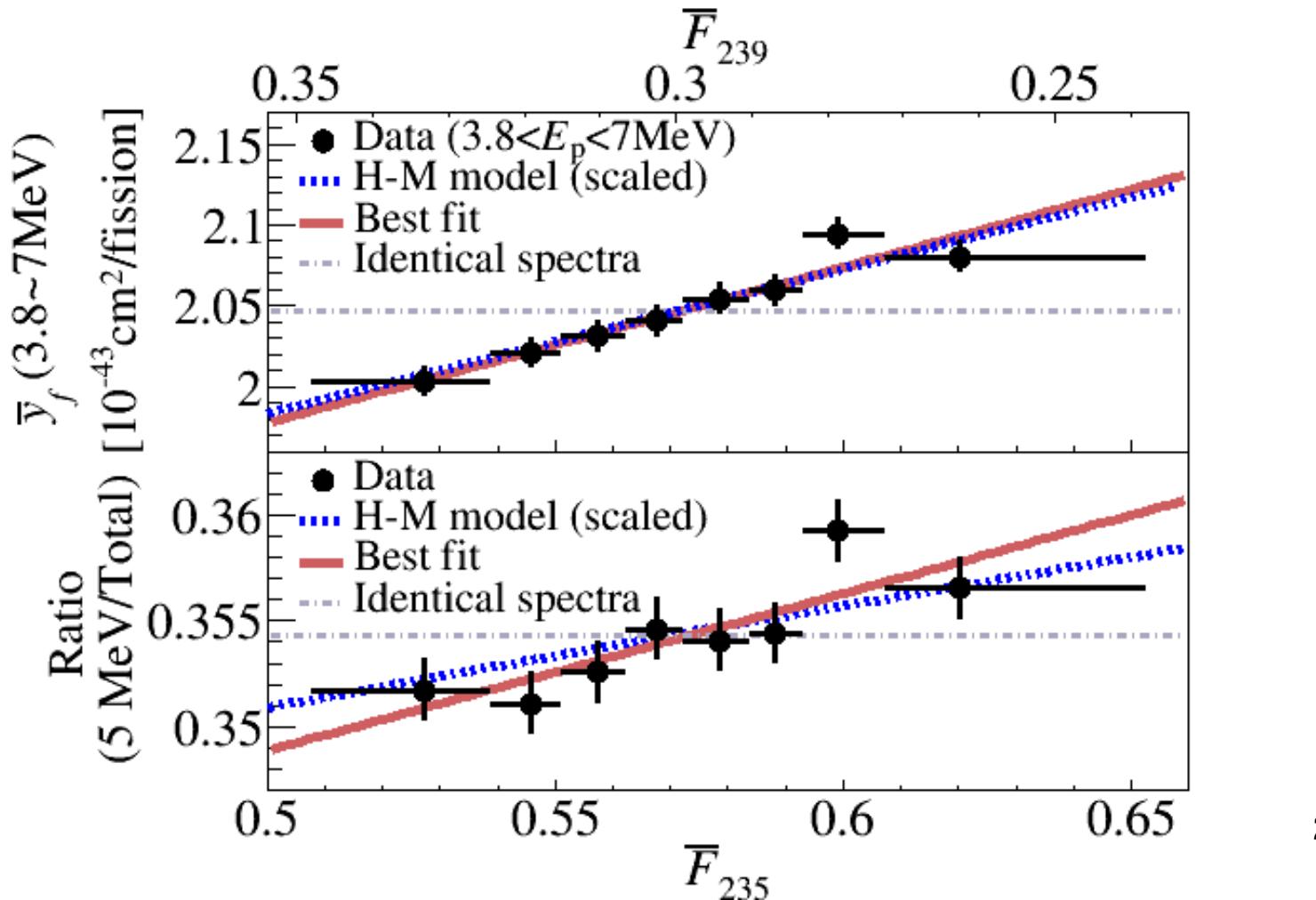
The 5 MeV excess comes from reactors!

Comparison of θ_{13} and $|\Delta m^2_{ee}|$



IBD Yield Variation of 5 MeV Excess Region

Ratio of IBD yield per fission between “5 MeV excess region” and “total” → Weak indication of enhanced yield in 5 MeV excess region due to ^{235}U isotope fraction increase....



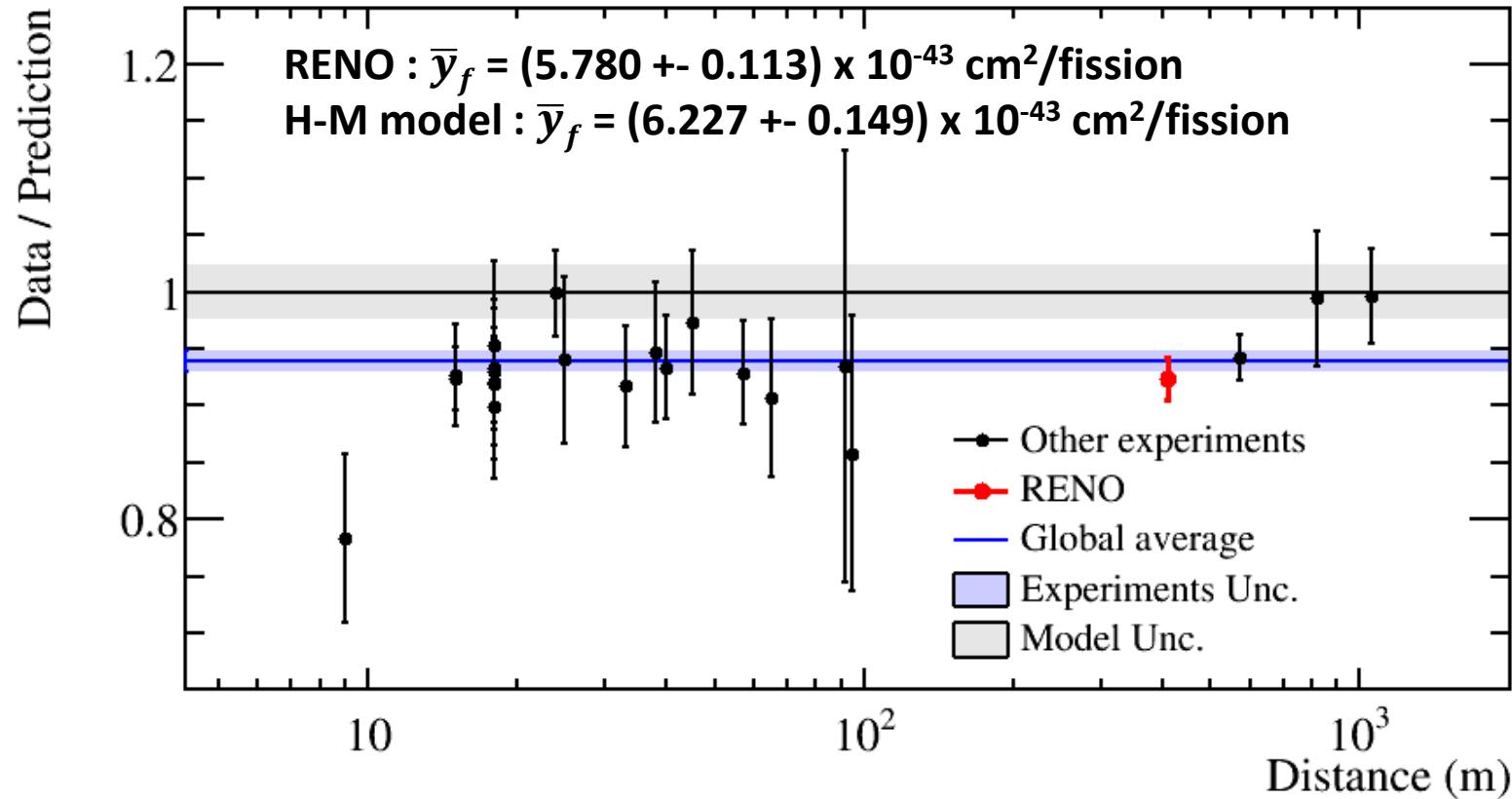
Measurement of Absolute Reactor Neutrino Flux

Cross section calculation

- Vogel 84 formalism
- $\tau_n = 880.2\text{s}$ (PDG2017)

Data / Prediction, RENO 2200 days at near detector

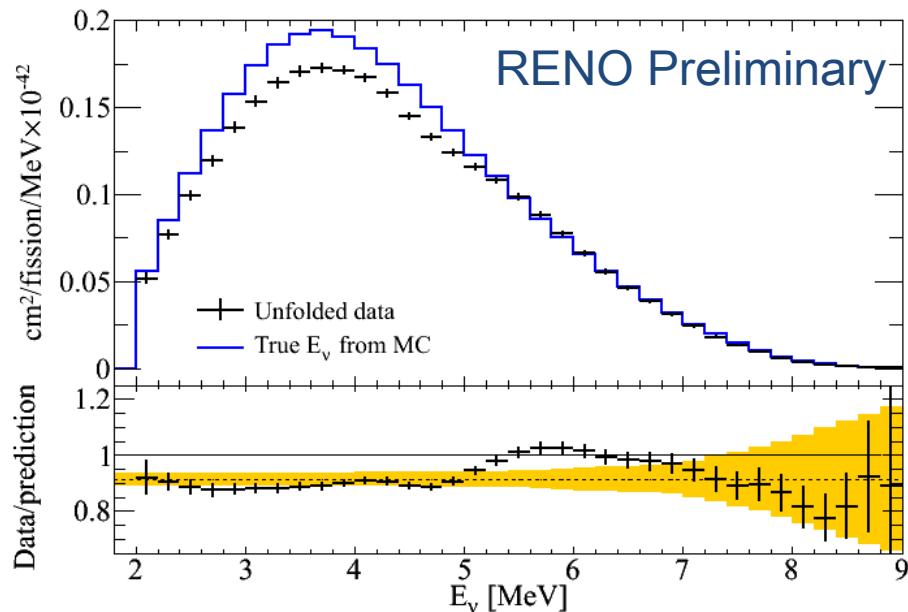
0.924 ± 0.018 (for Huber + Mueller model)
 0.966 ± 0.019 (for ILL + Vogel model)



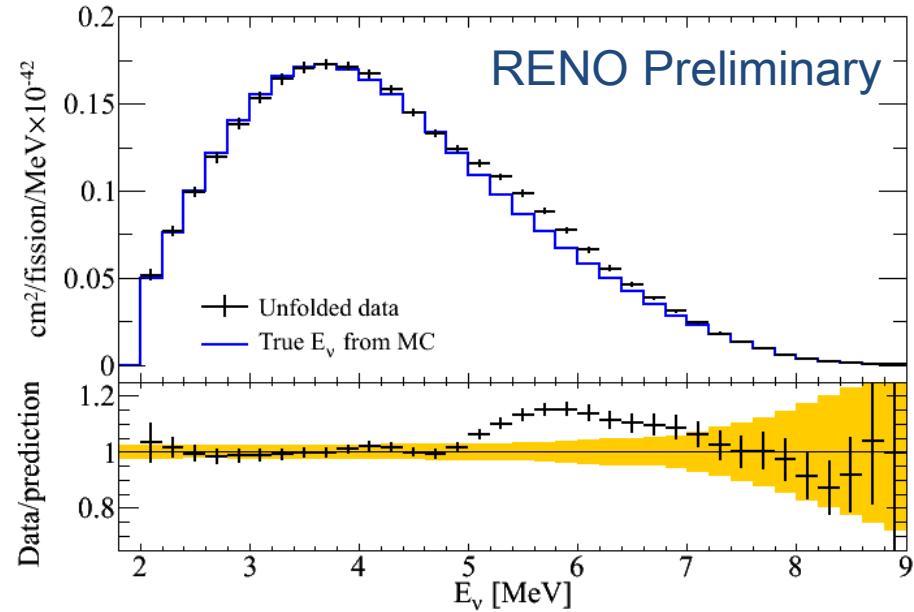
Deficit of observed reactor neutrino fluxes relative to the prediction (Huber + Mueller model) indicates an overestimated flux or possible oscillation to sterile neutrinos

Unfolded Reactor Antineutrino Spectrum

Measured spectrum
vs. H-M prediction



Spectral comparison



* MC is normalized to data in the region excluding $3.6 < E_p < 6.6$ MeV

- Unfolding using iterative method in *RooUnfold*