New Results from RENO

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Seoul National University

NuFact 2019

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Korea Neutrino Research Center

RENO Collaboration

Reactor Experiment for Neutrino Oscillation

(8 institutions and 40 physicists)

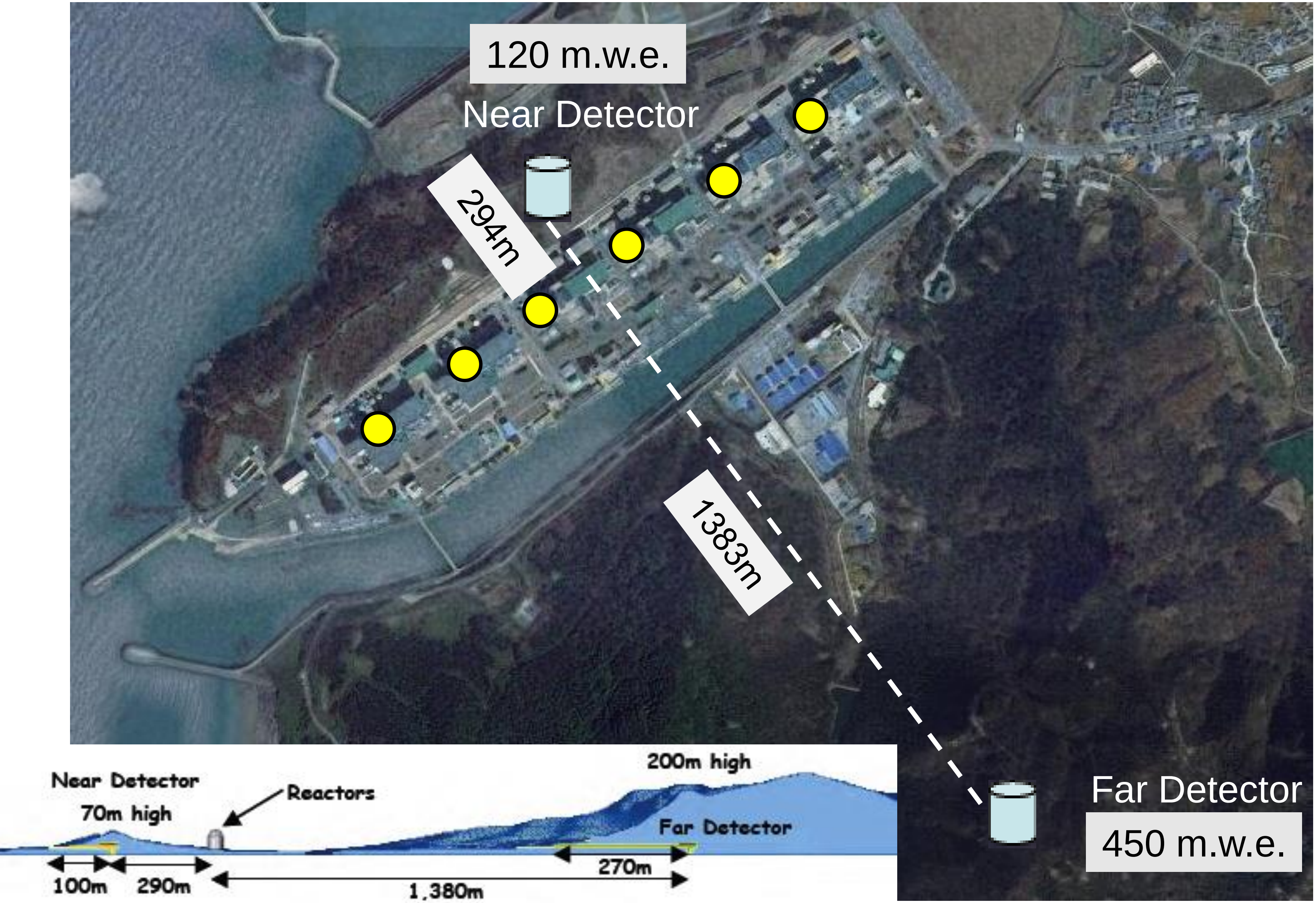
- Chonnam National University
- Dongshin University
- GIST
- KAIST
- Kyungpook National University
- Seoul National University
- Seoyeong University
- Sungkyunkwan University

- 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)

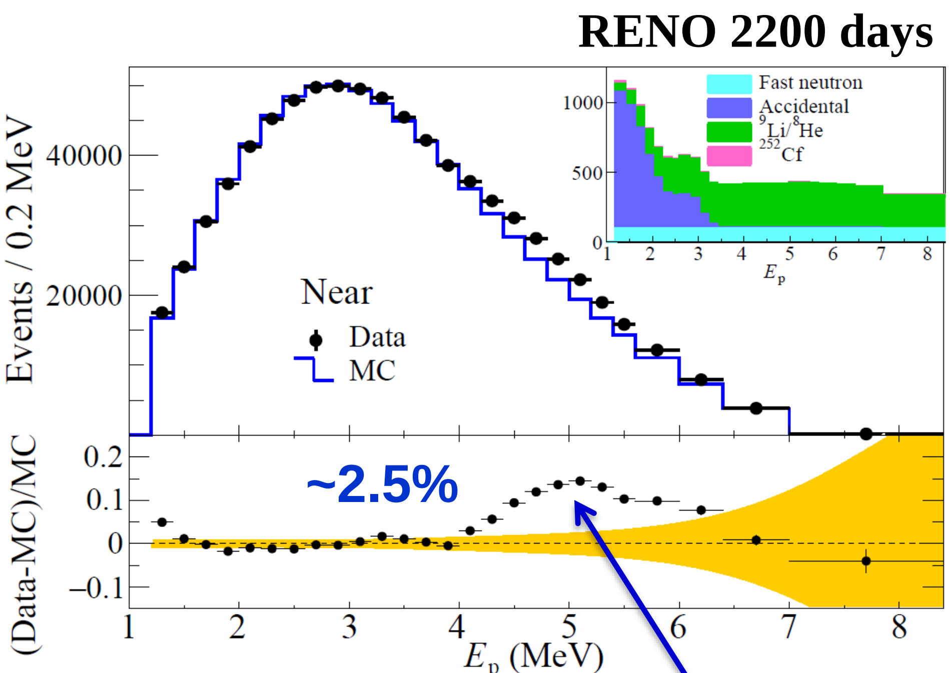
"Measurement of Reactor Antineutrino Oscillation Amplitude and Frequency at RENO" → Published in PRL (Phys. Rev. Lett. 121, 201801 (2018))

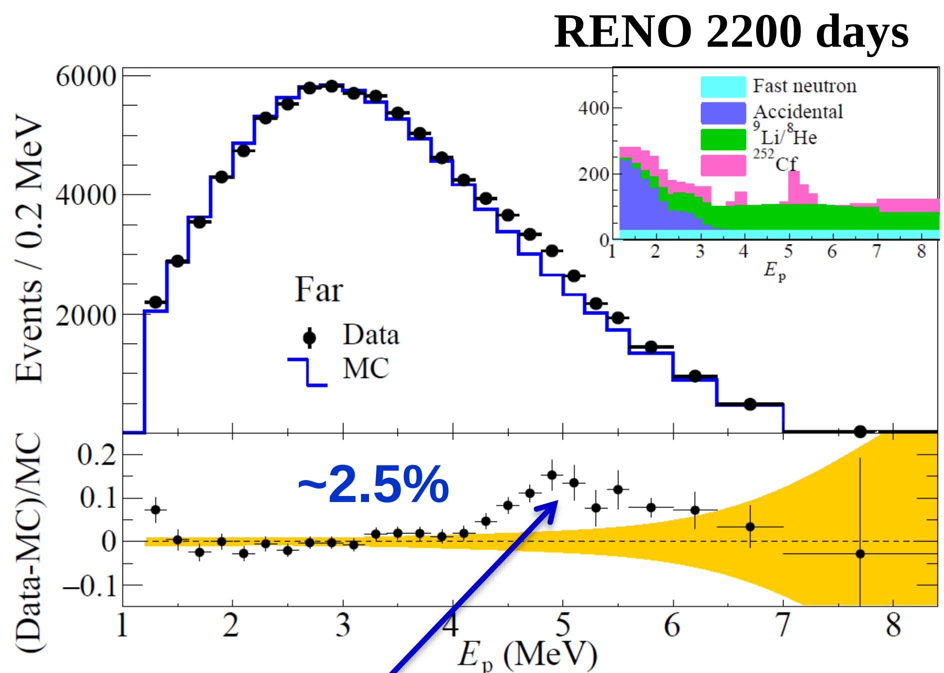
■ Fuel-composition dependent reactor antineutrino yield →
"Fuel-composition dependent reactor antineutrino yield and spectrum at RENO" → Published in PRL (Phys. Rev. Lett. 122, no.23, 232501 (2019))

■ 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

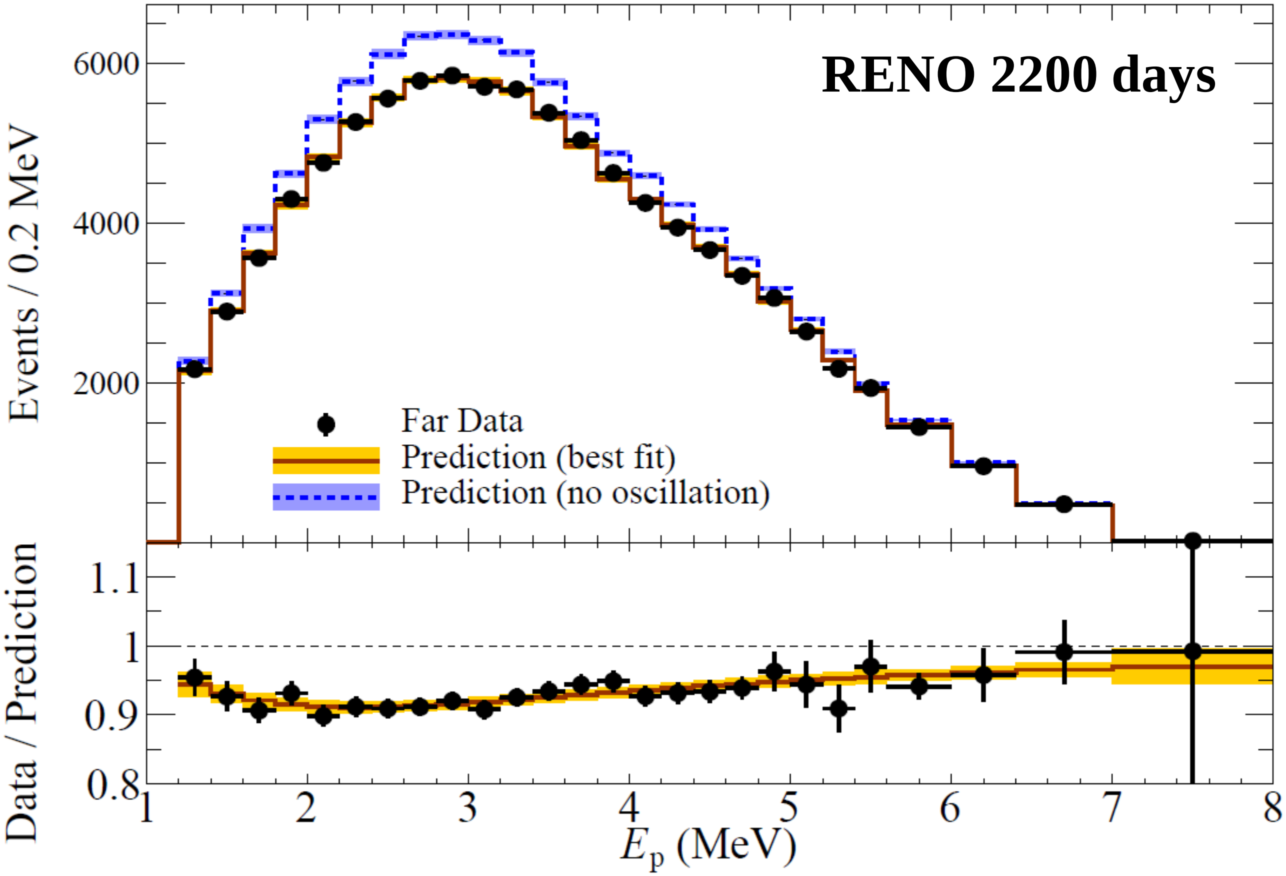




In 2014, RENO showed the 5 MeV excess comes from reactors.

Far/Near Shape Analysis

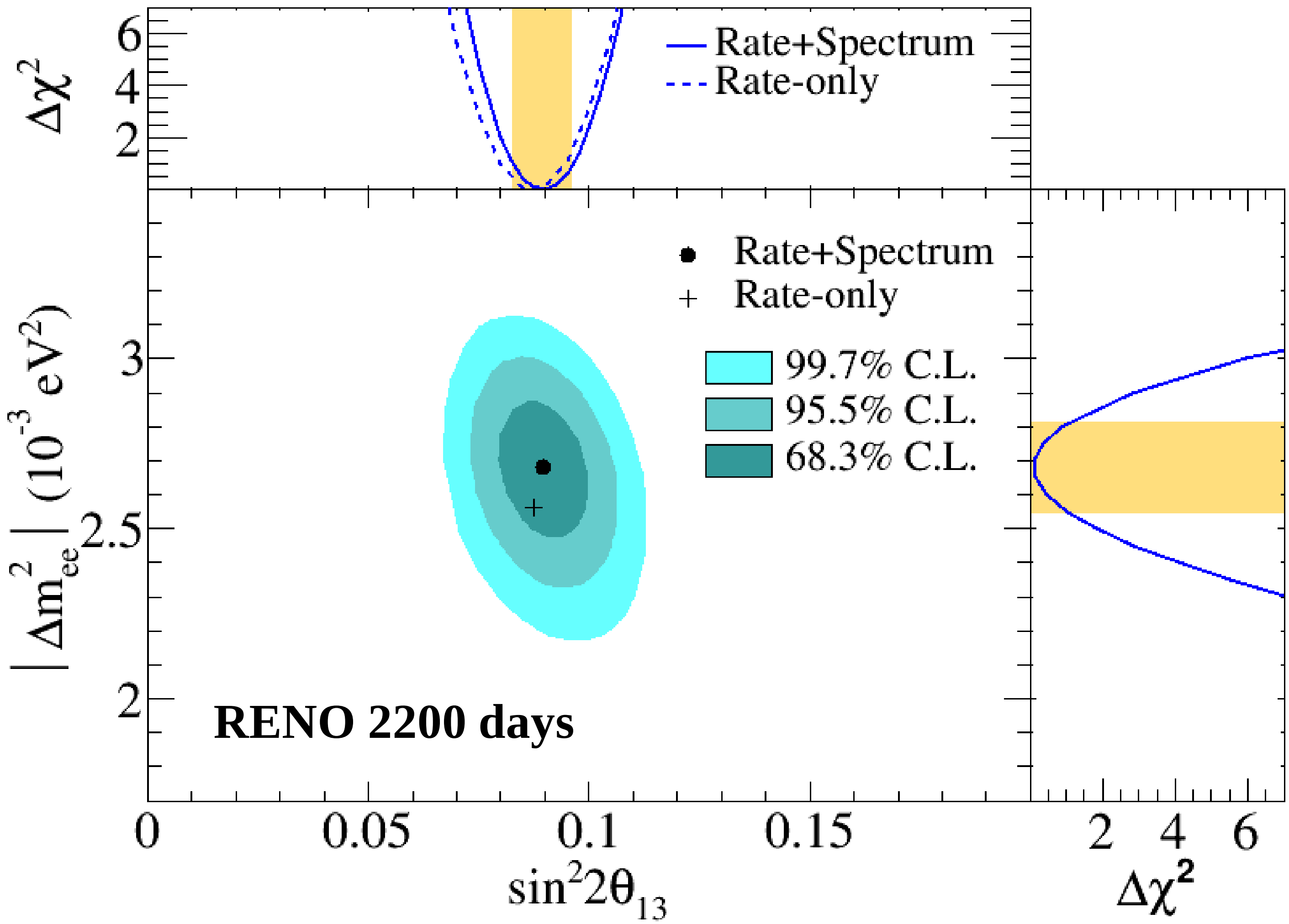
Energy-dependent disappearance of reactor antineutrinos



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

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

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



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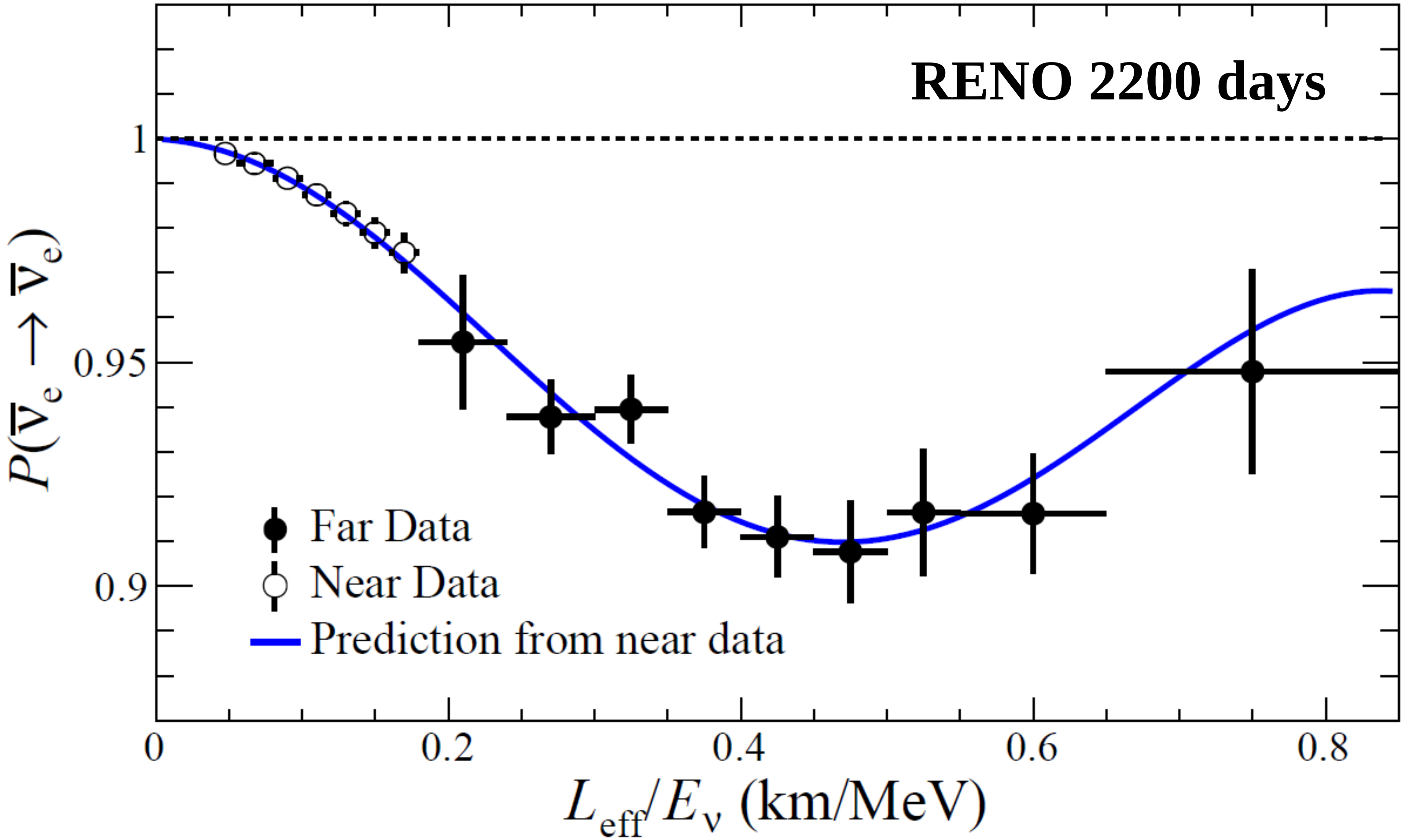
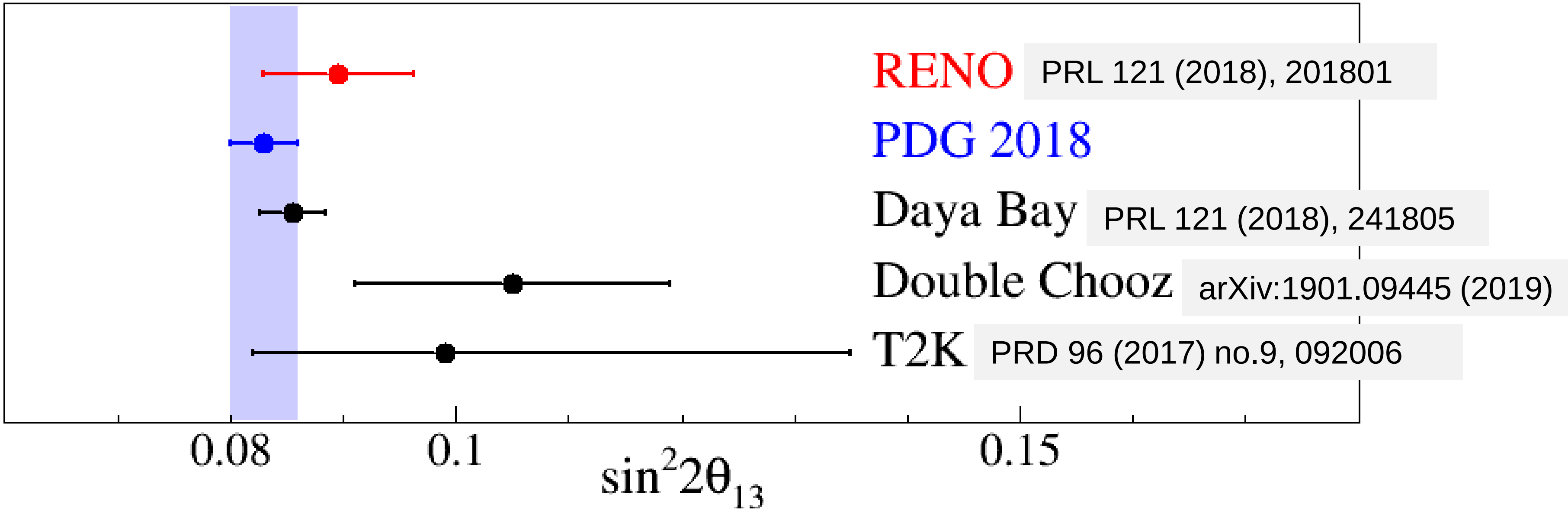
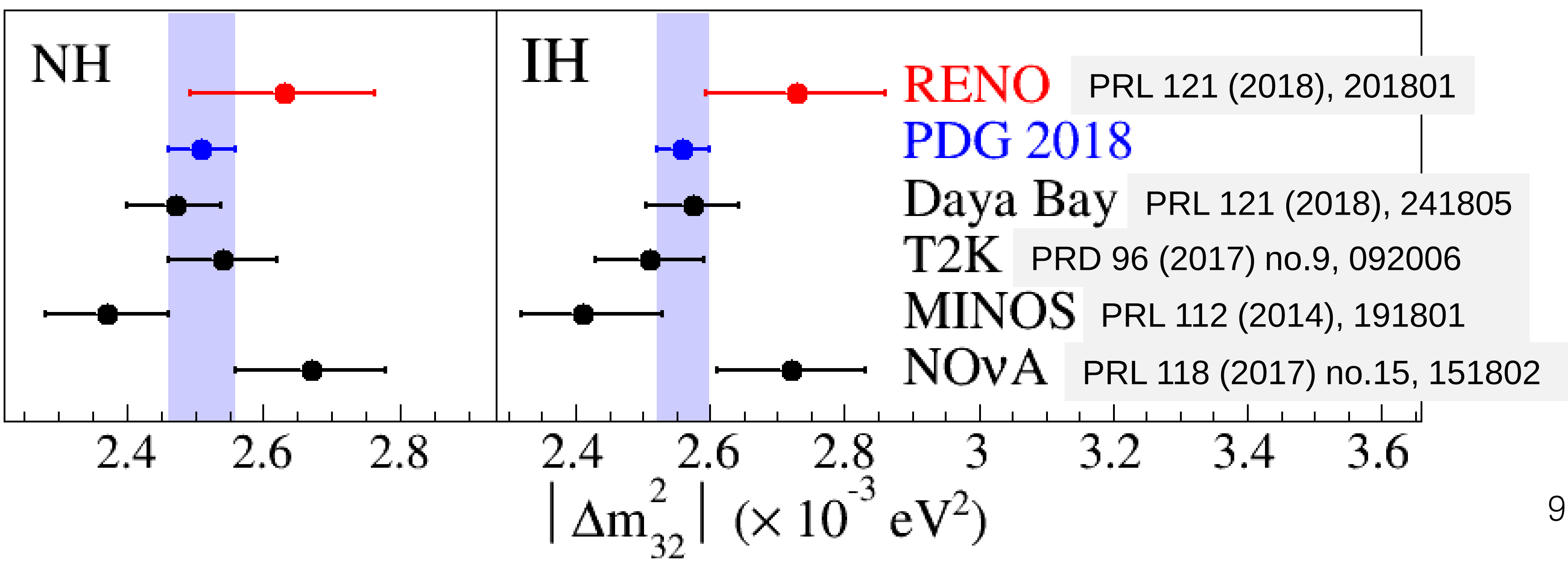
Observed L/E Dependent Oscillation



$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\Delta m^2_{ee} \frac{L}{4E_\nu}\right)$$

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.**

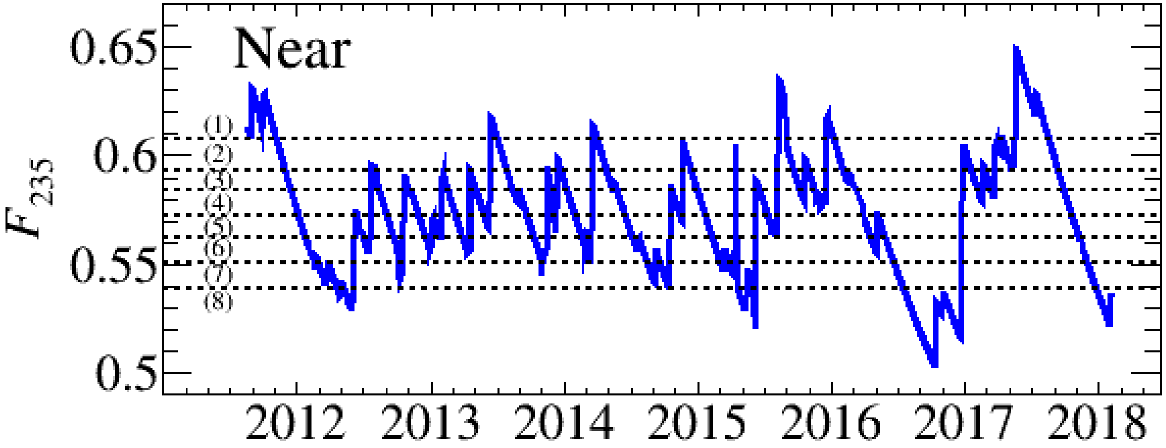
C. Giunti, Phys. Lett. B 764, 145 (2017)

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

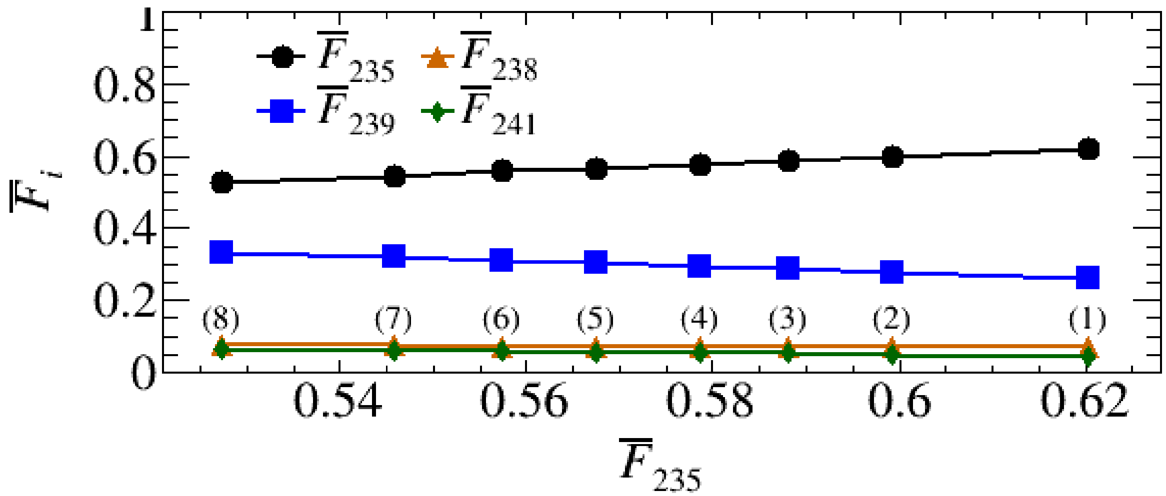
- **RENO Collaboration, Phys. Rev. Lett. 122, no.23, 232501 (2019)**

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)



8 groups of near IBD samples with equal statistics according to ^{235}U isotope fraction

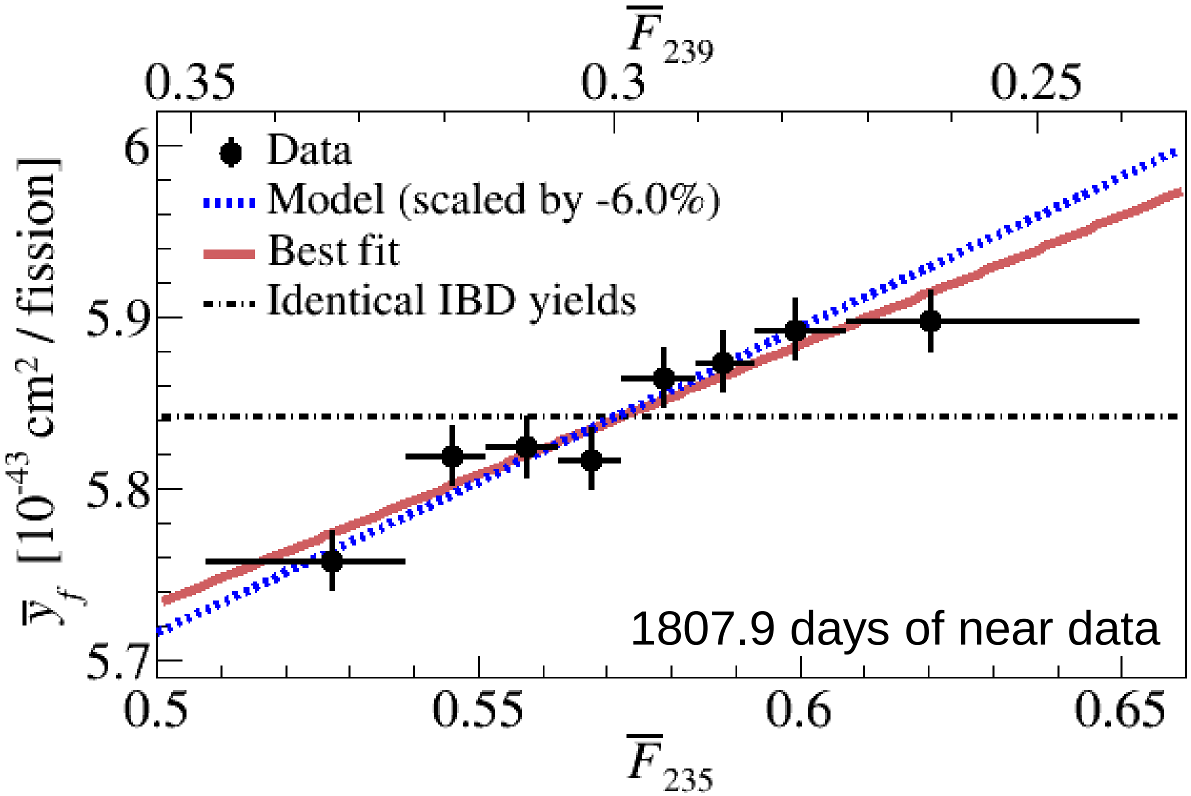
Effective Fission fraction for each isotope

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

Fuel-Composition Dependent Reactor Neutrino Yield

Measured total averaged IBD yield per fission ($\overline{y}_f$)
= (5.84 ± 0.13)×10^{-43} cm^2/fission

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



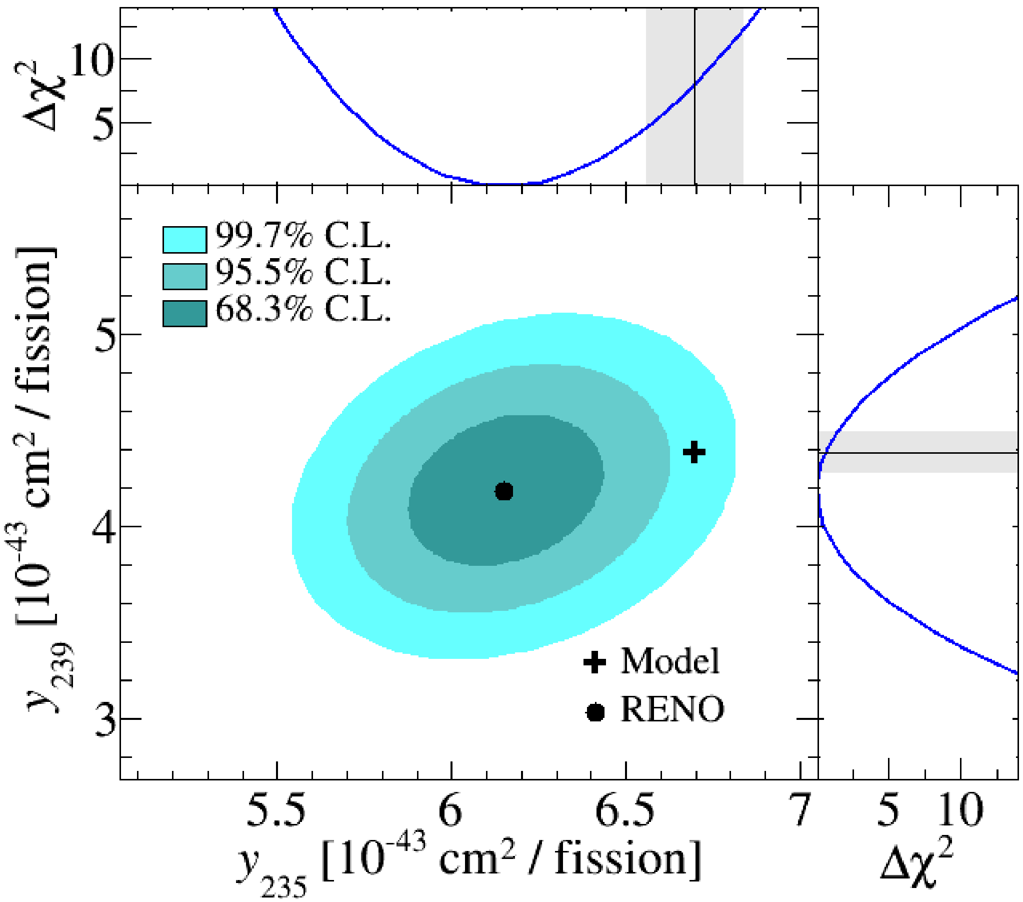
Averaged IBD yield per fission ($\overline{y}_f$) vs $\overline{F}_{i,j}$
→ slope means **different neutrino yield** for each isotope
→ rules out the no fuel-dependent variation at **6.6σ**

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

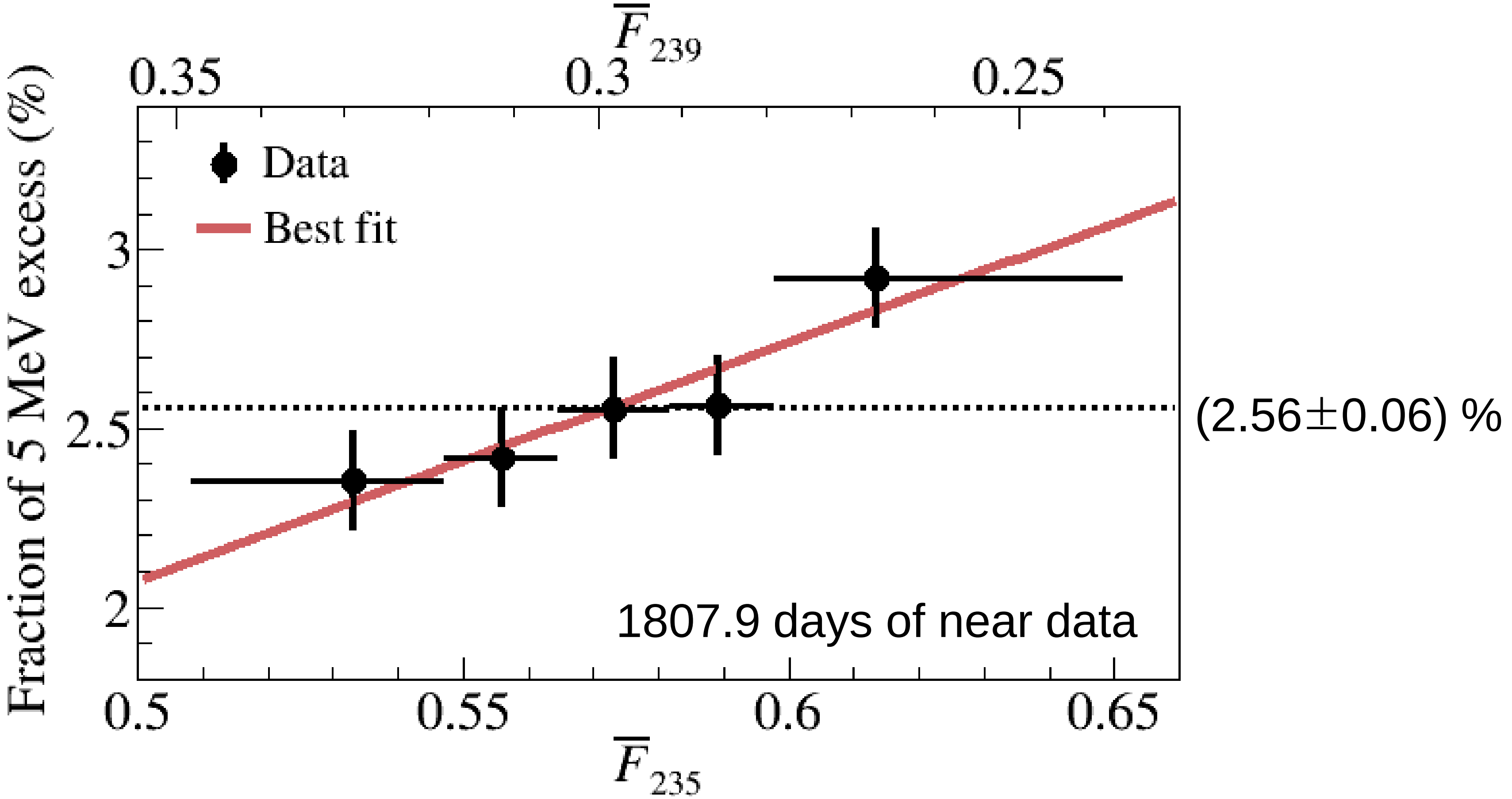
H-M model

y_{235} = 6.70 ± 0.14
y_{239} = 4.38 ± 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

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



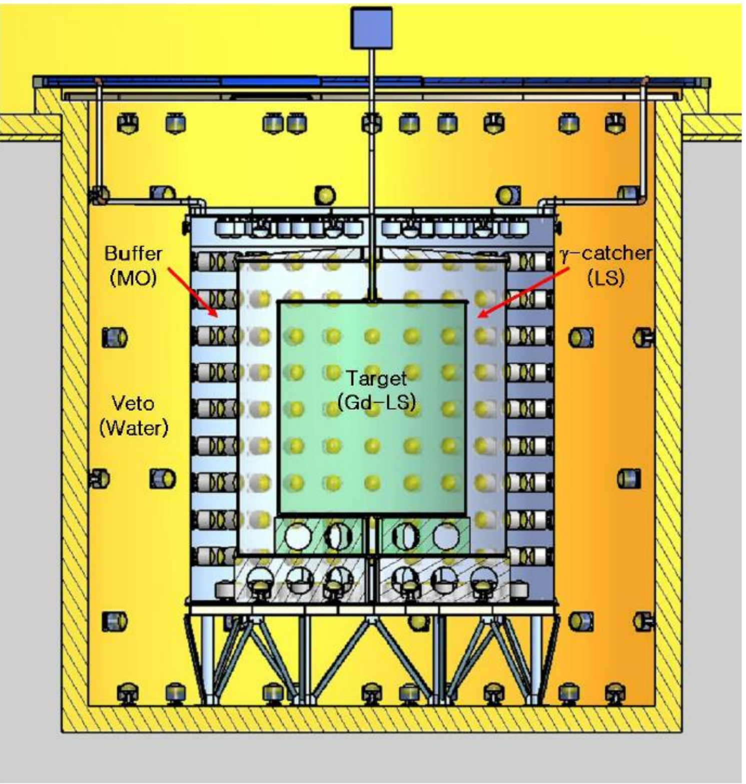
(End of reactor cycle)

(Beginning of reactor cycle)

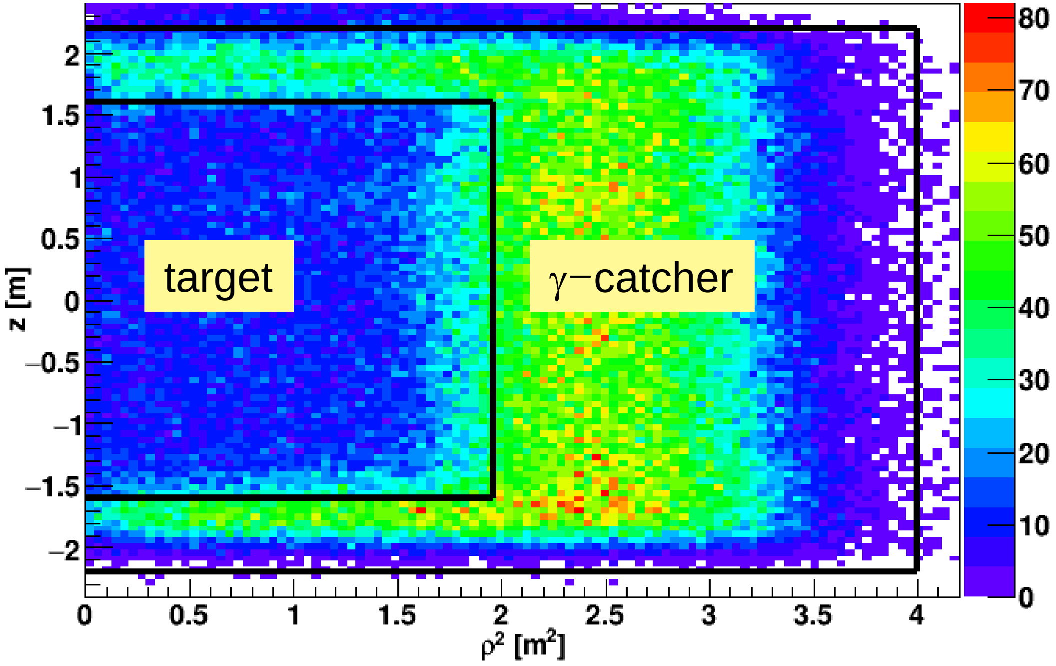
n-H IBD Analysis

<u>Motivation:</u>

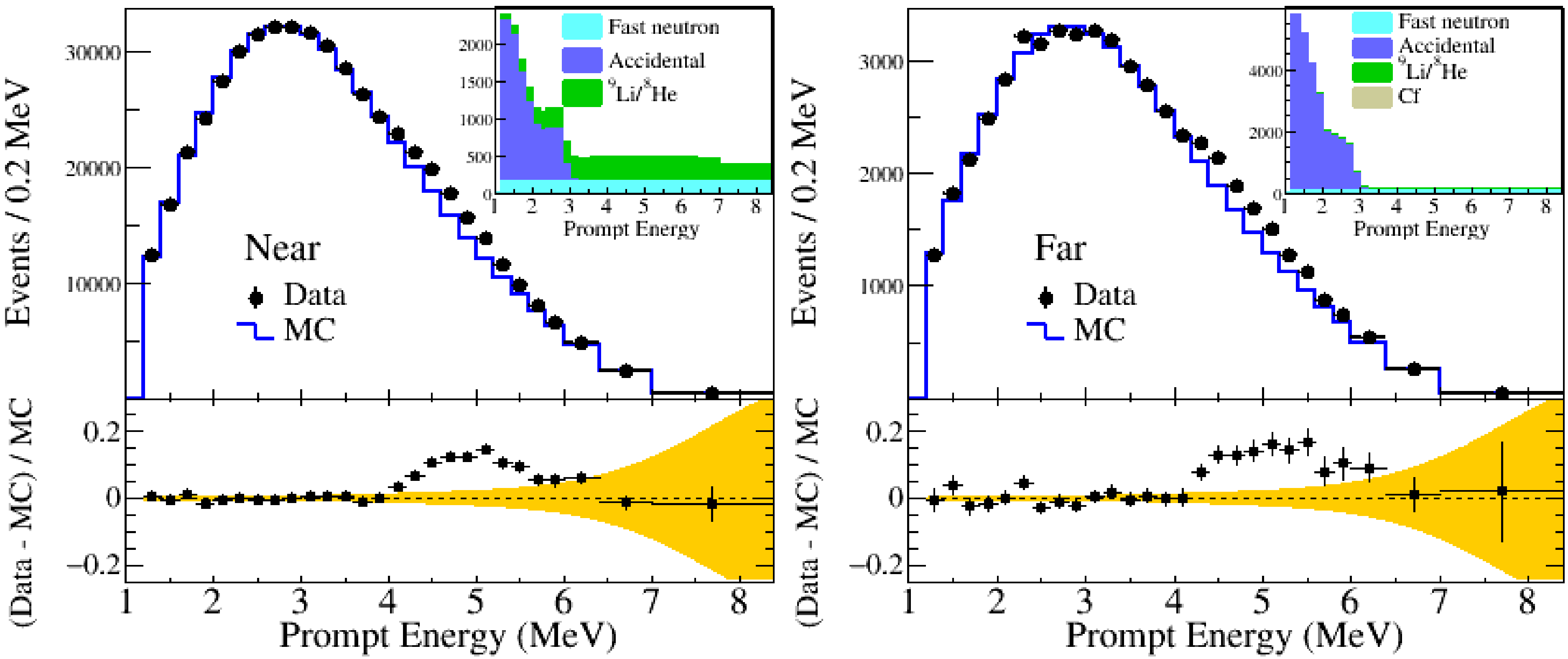
1. Independent measurement of θ_{13} and $|\Delta m_{ee}^2|$.
2. Consistency and systematic check on reactor neutrinos.



n-H IBD Event Vertex Distribution

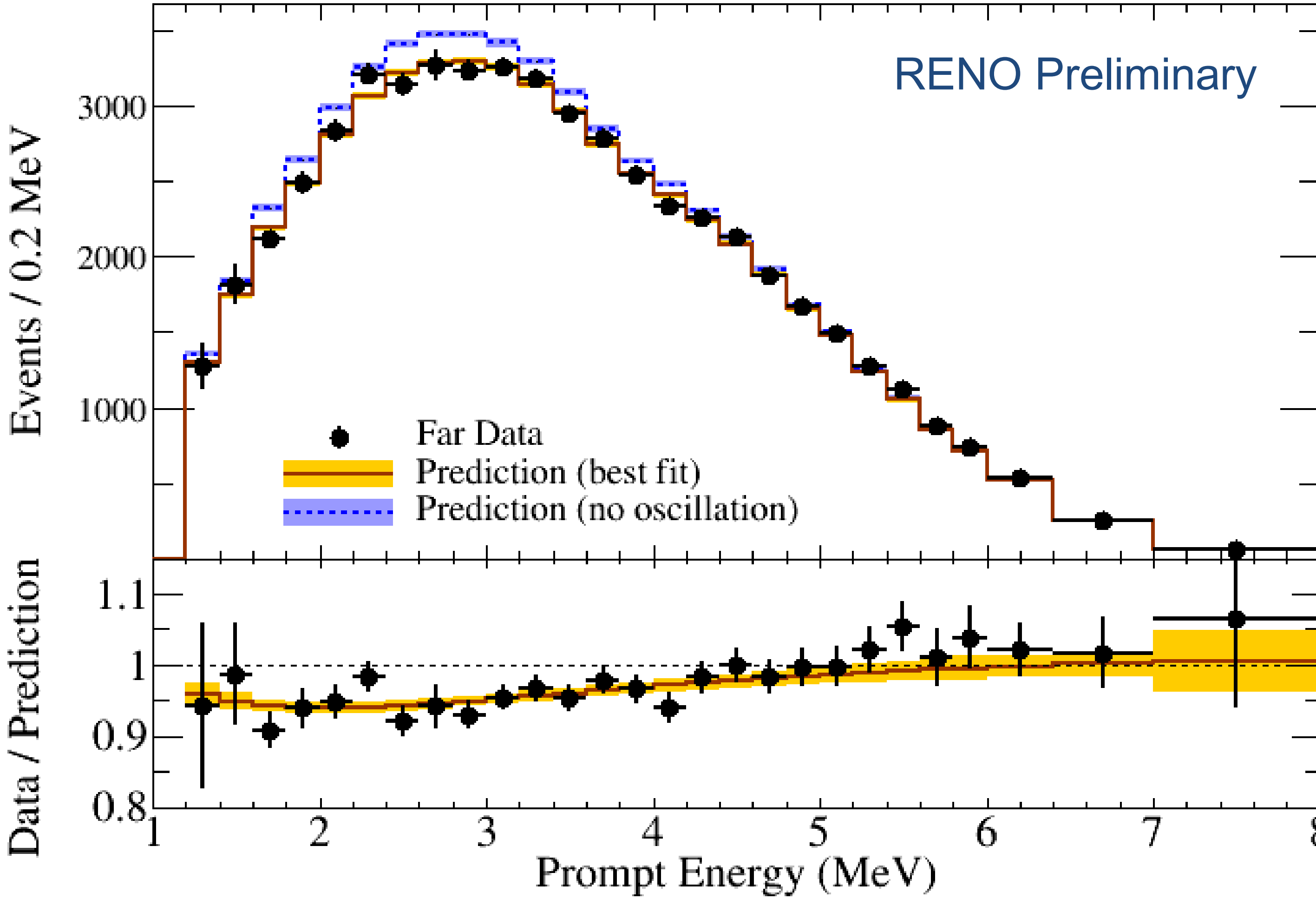


θ_{13} Measurement with n-H



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

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

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

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

- Observation of fuel composition dependent IBD yield at 6.6σ CL

- Measured IBD yield per fission (10^{-43} cm^2)

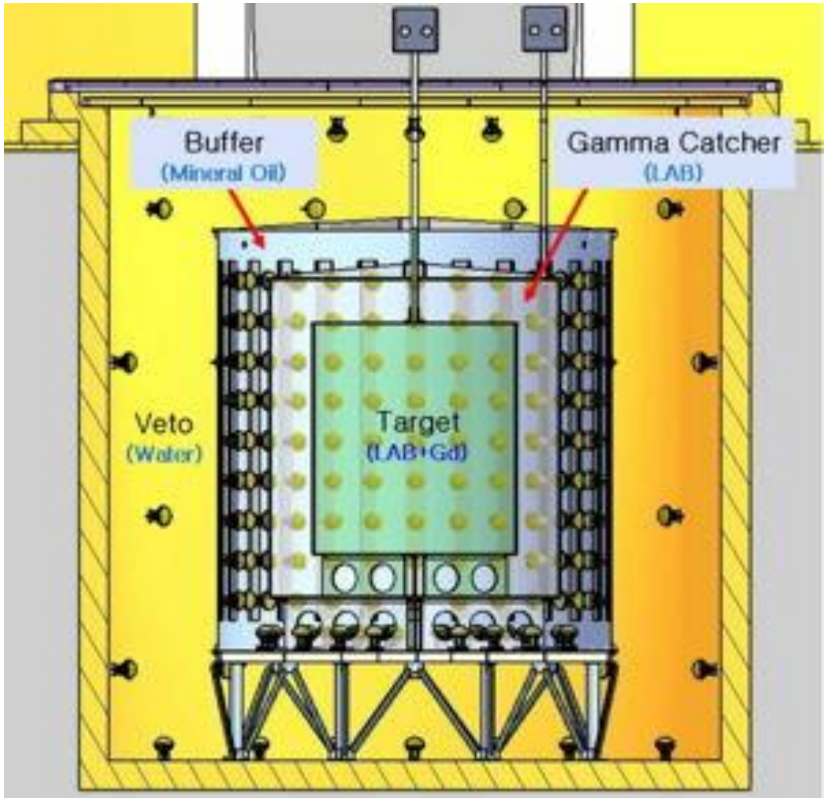
^{235}U : 6.15 ± 0.19 (smaller than the H-M prediction at 2.8σ)
^{239}Pu : 4.18 ± 0.26 (smaller than the H-M prediction at 0.8σ)

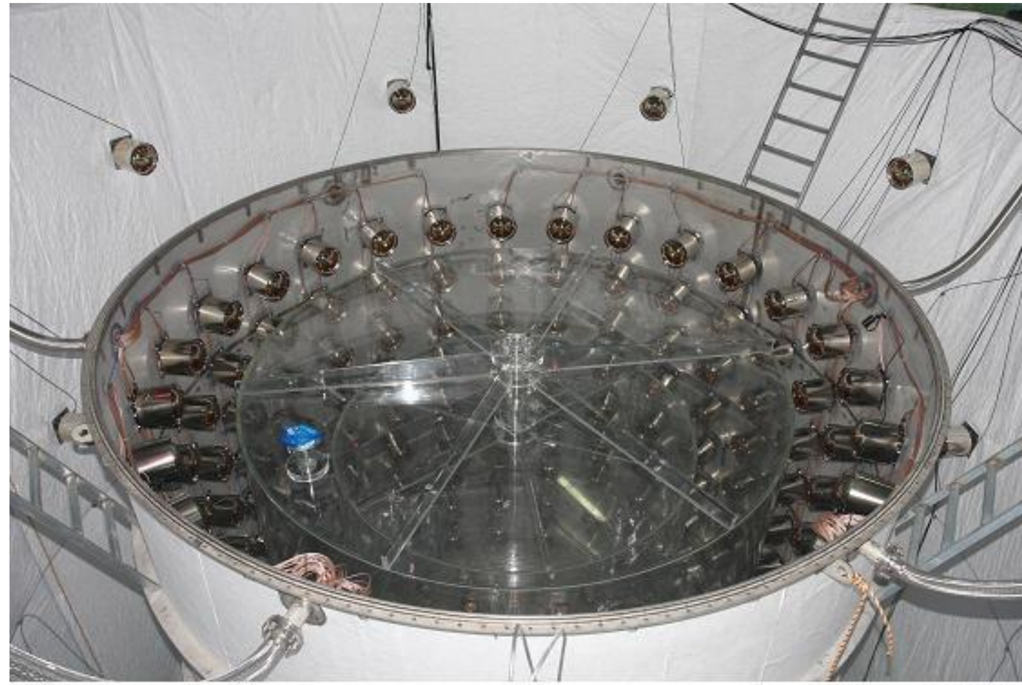
- First hint for 2.9σ correlation between 5 MeV excess and ^{235}U fission fraction

- 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

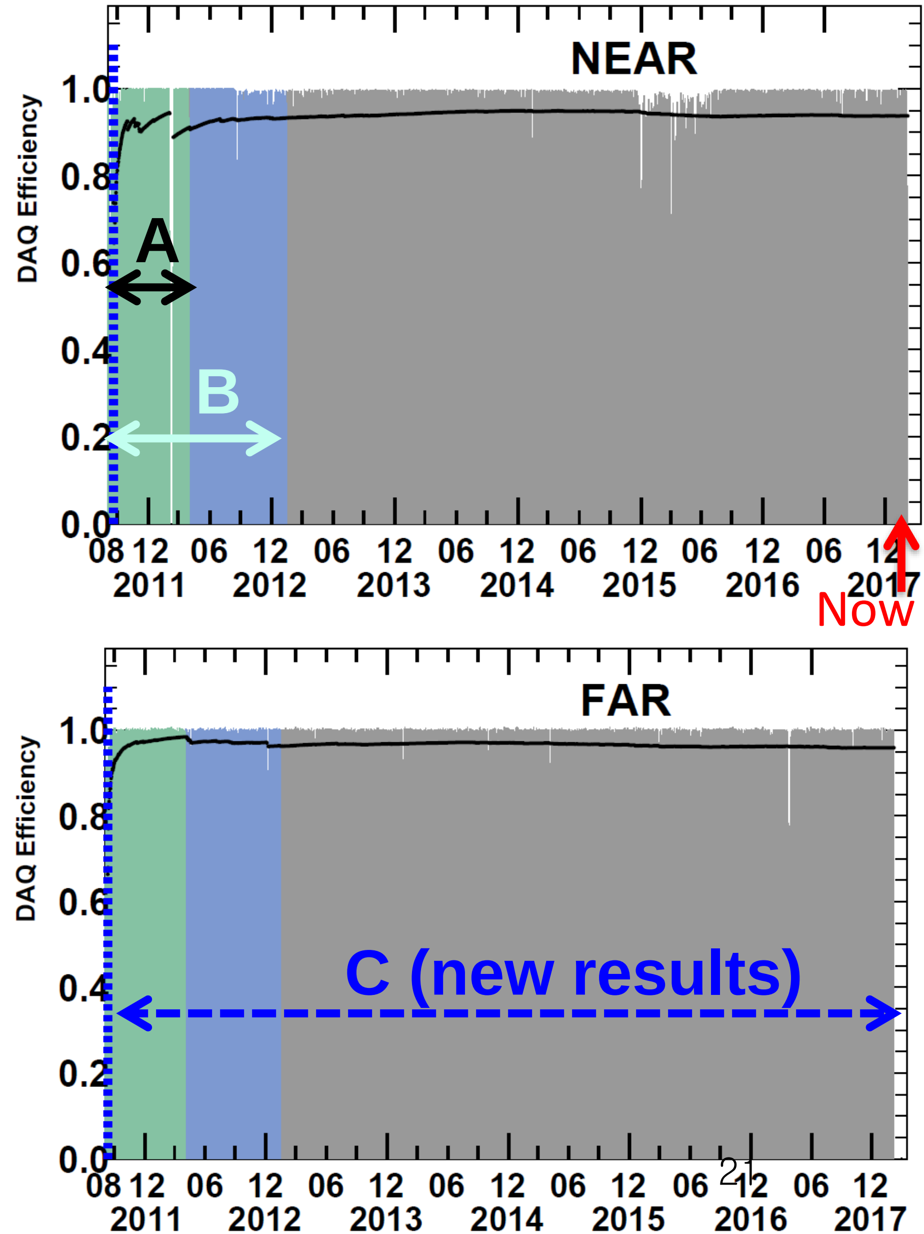
RENO Data-taking Status

- 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)

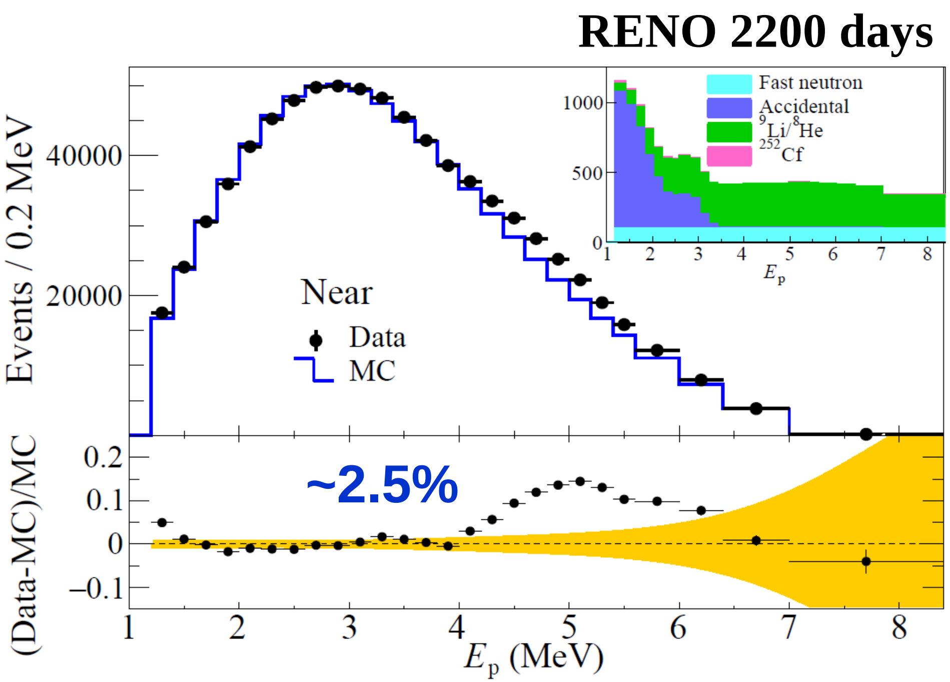
- **B (~500 days)** : **Recent results**
  Rate+shape analysis (**θ_{13} and $|\Delta m_{ee}^2|$**)
  [11 Aug, 2011~21 Jan, 2013]
  → PRL 116, 211801 (2016)
  accepted to PRD (arXiv:1610.04326)

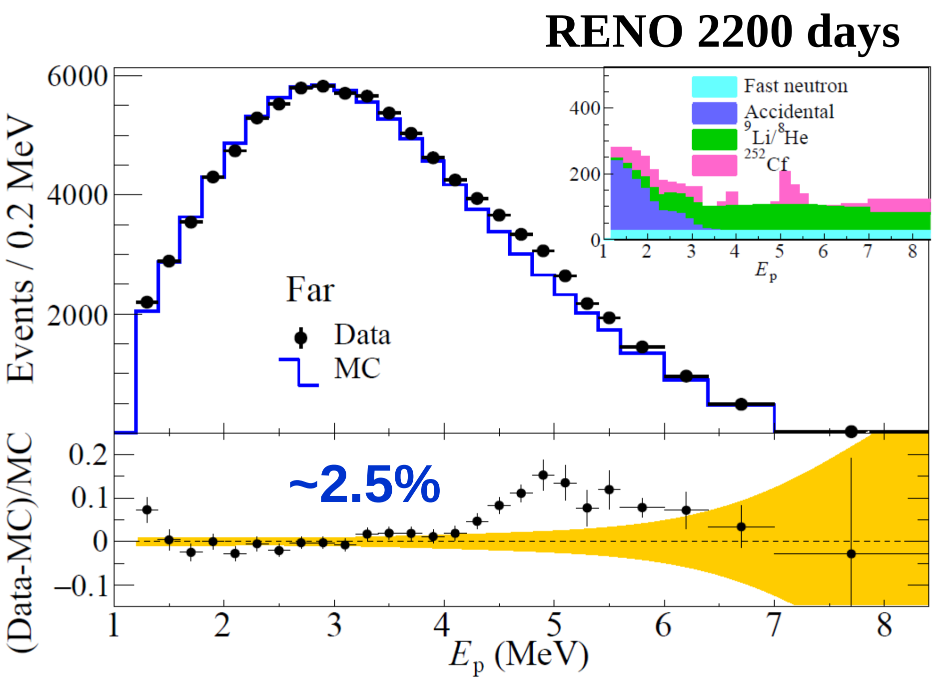
- **C (~2200 days)** : **New results**
  Rate+shape analysis (**θ_{13} and $|\Delta m_{ee}^2|$**)
  [11 Aug, 2011~7 Feb, 2018]
  → submitted to PRL (arXiv:1806.00248)



Measured Spectra of IBD Prompt Signal

Clear excess at 5 MeV

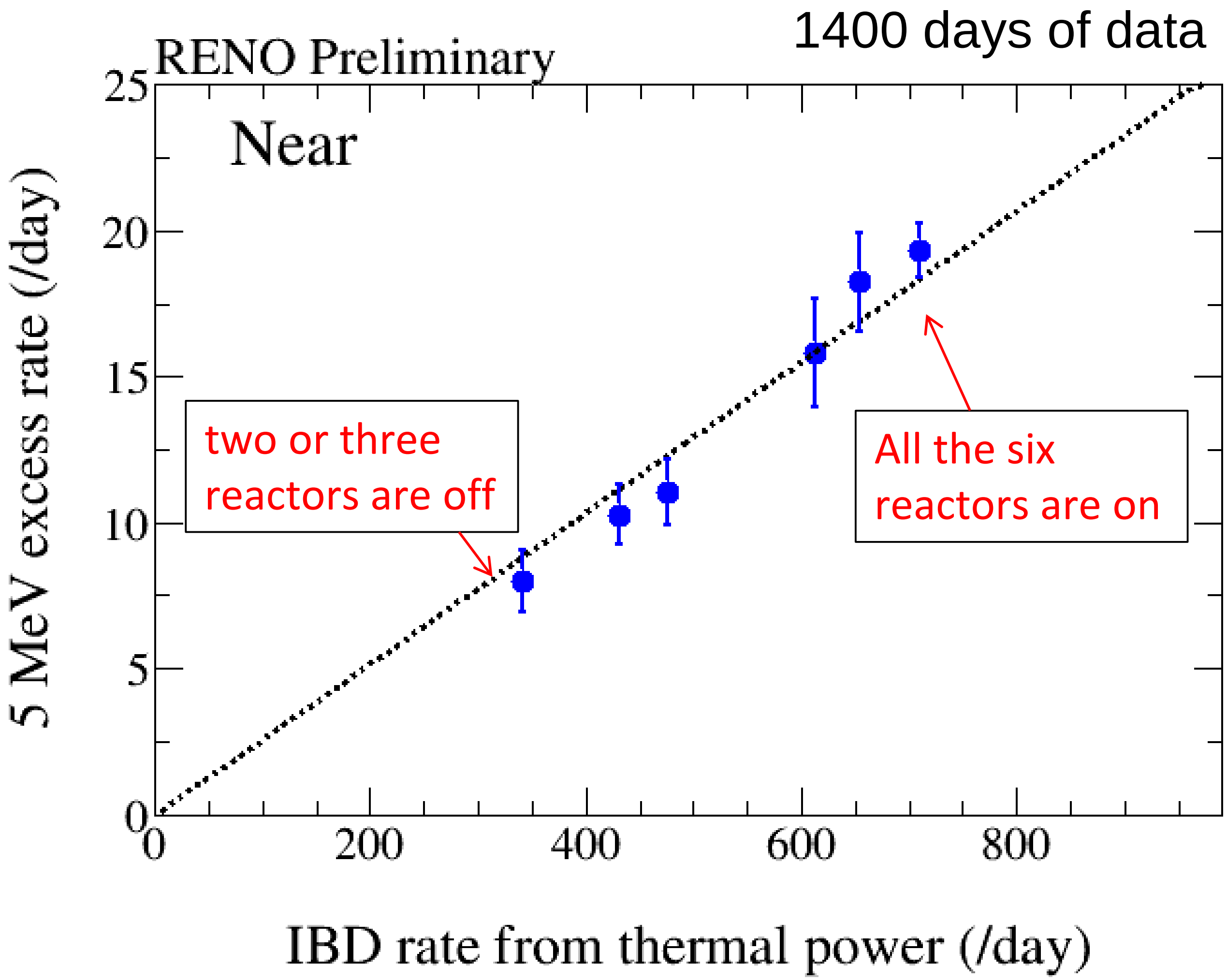




Near Live time = 1807.88 days
# of IBD candidate = 850,666
# of background = 17,233 (2.0 %)

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

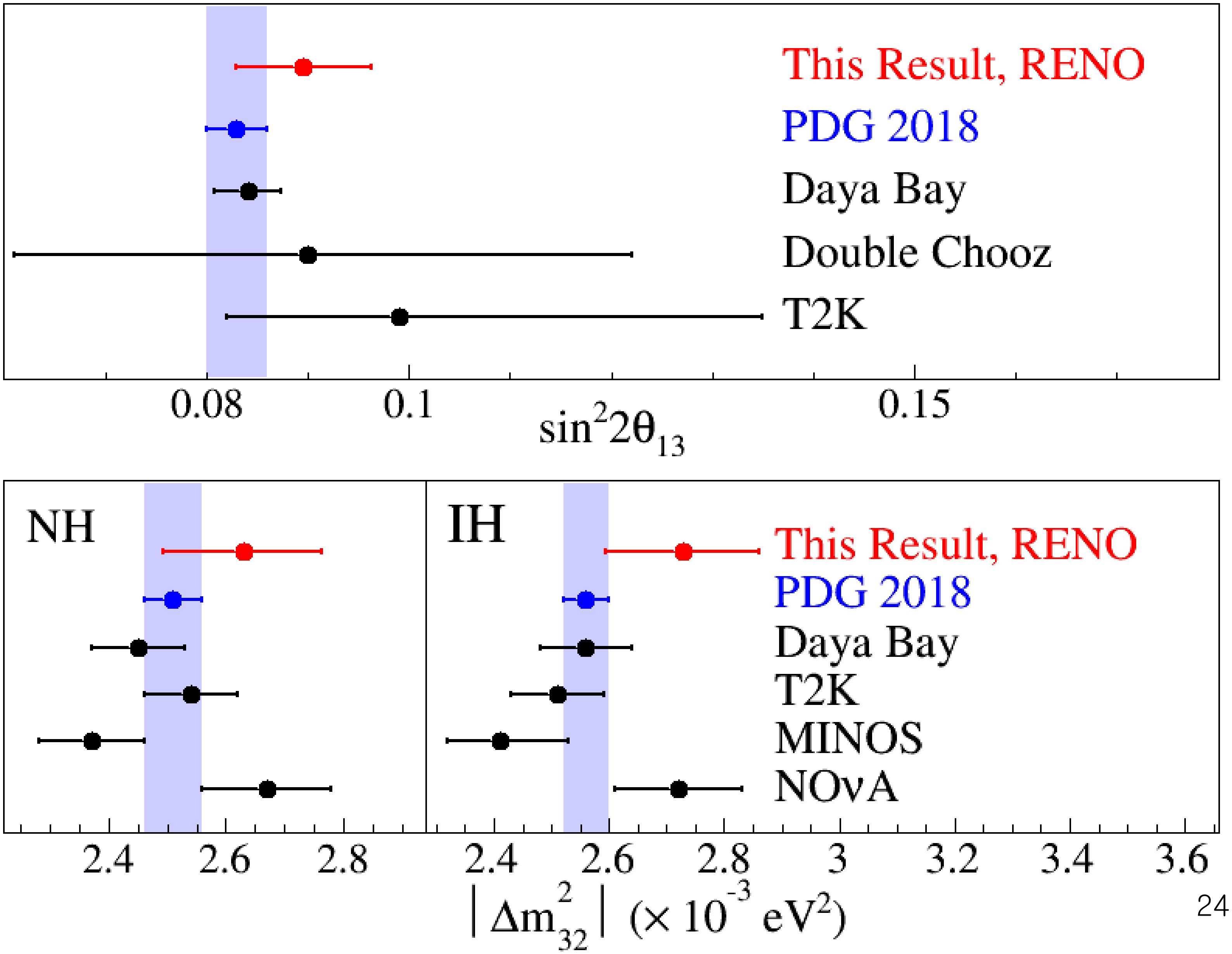
Correlation of 5 MeV Excess with Reactor Power



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

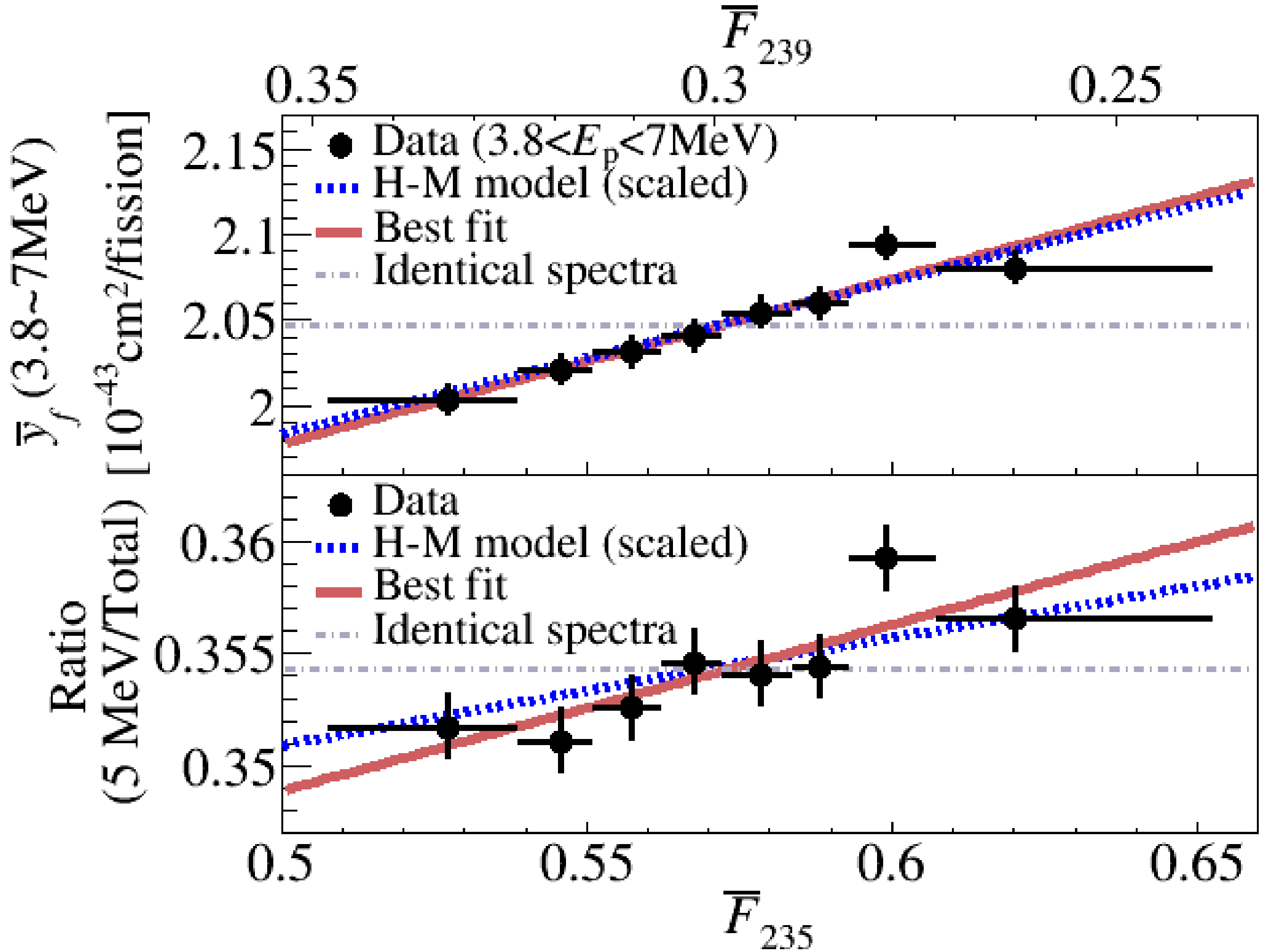
The 5 MeV excess comes from reactors!

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



IBD Yield Variation of 5 MeV Excess Region

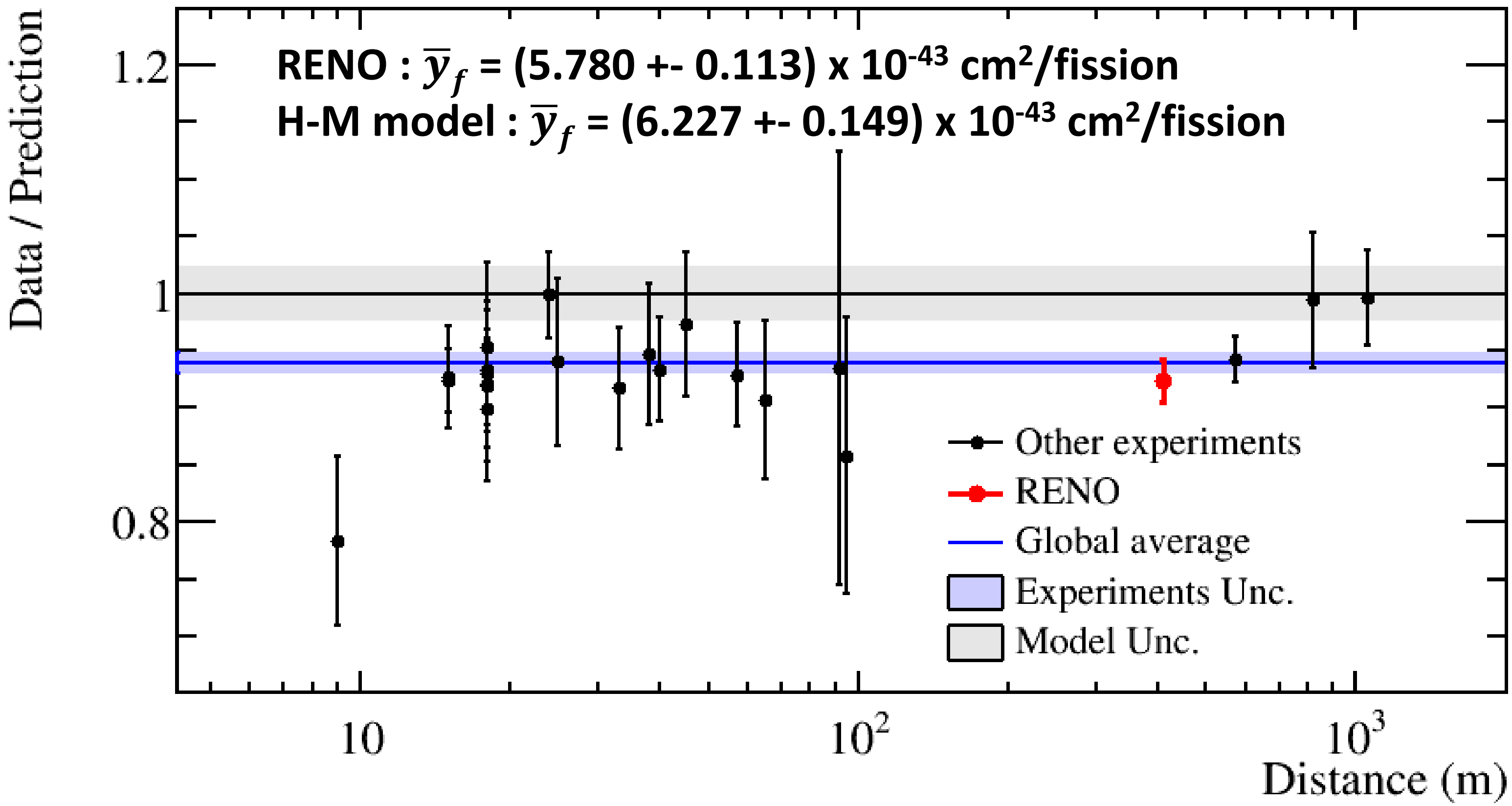
Ratio of IBD yield per fission between "5 MeV excess region" and "total" → Weak indication of enhanced yield in 5 MeV excess region due to ^{235}U isotope fraction increase….



Measurement of Absolute Reactor Neutrino Flux

Cross section calculation
- Vogel 84 formalism
- τ_n= 880.2s (PDG2017)

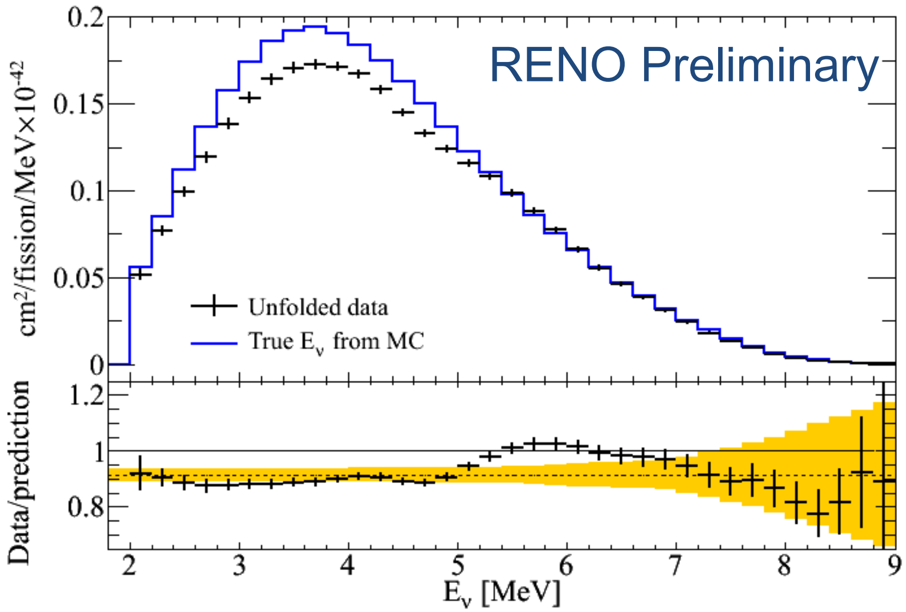
Data / Prediction, RENO 2200 days at near detector
0.924 +- 0.018 (for Huber + Mueller model) 0.966 +- 0.019 (for ILL + Vogel model)



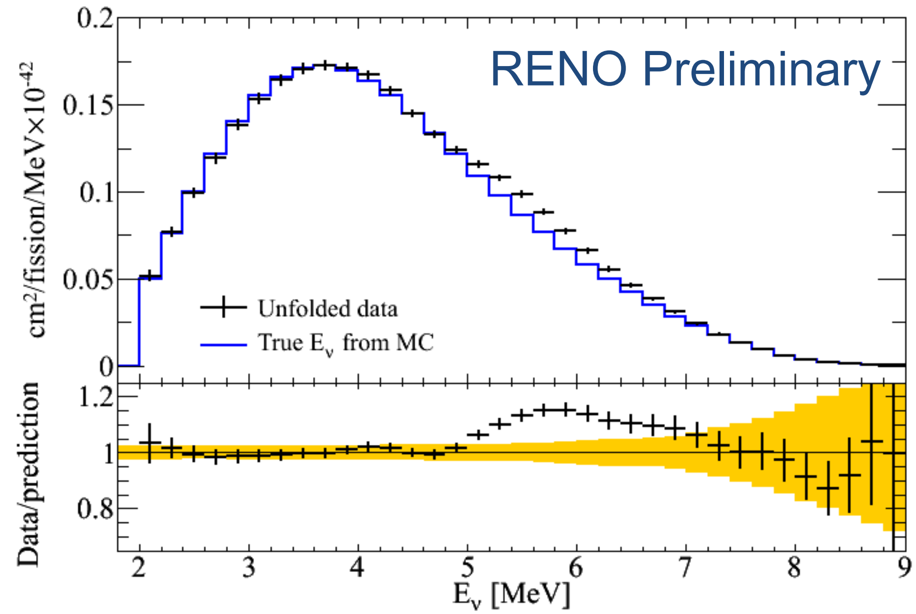
Deficit of observed reactor neutrino fluxes relative to the prediction (Huber + Mueller model) indicates an overestimated flux or possible oscillation to sterile neutrinos

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*