Variation of Reactor Antineutrino Yield at RENO

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VERI TAS LUX MEA

KNRC
Korea Neutrino Research Center

RENO Collaboration

Reactor Experiment for Neutrino Oscillation

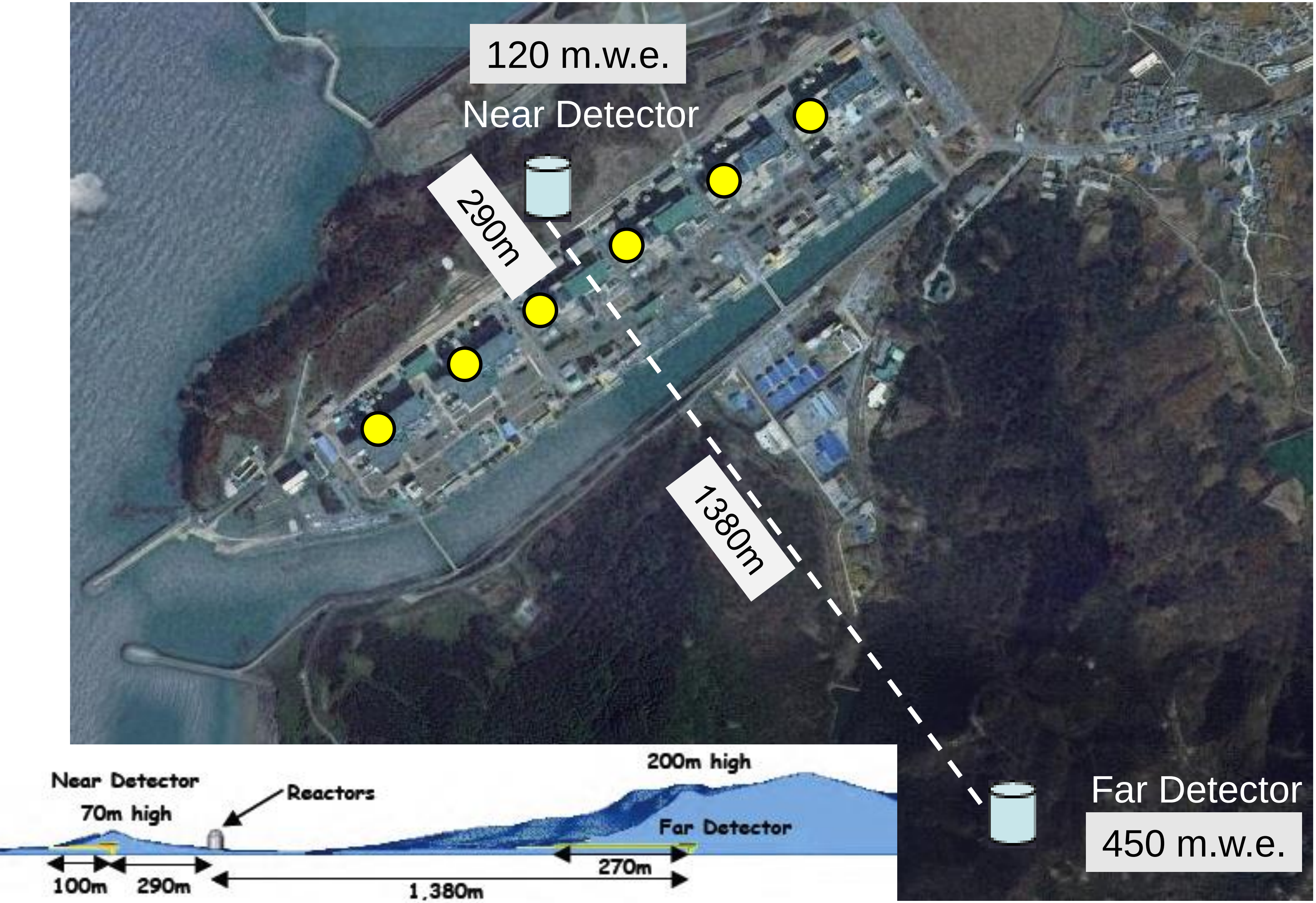
(9 institutions and 40 physicists)

- Chonnam National University
- Dongshin University
- GIST
- Gyeongsang National University
- 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) :

RENO Experimental Set-up



New Results from RENO

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

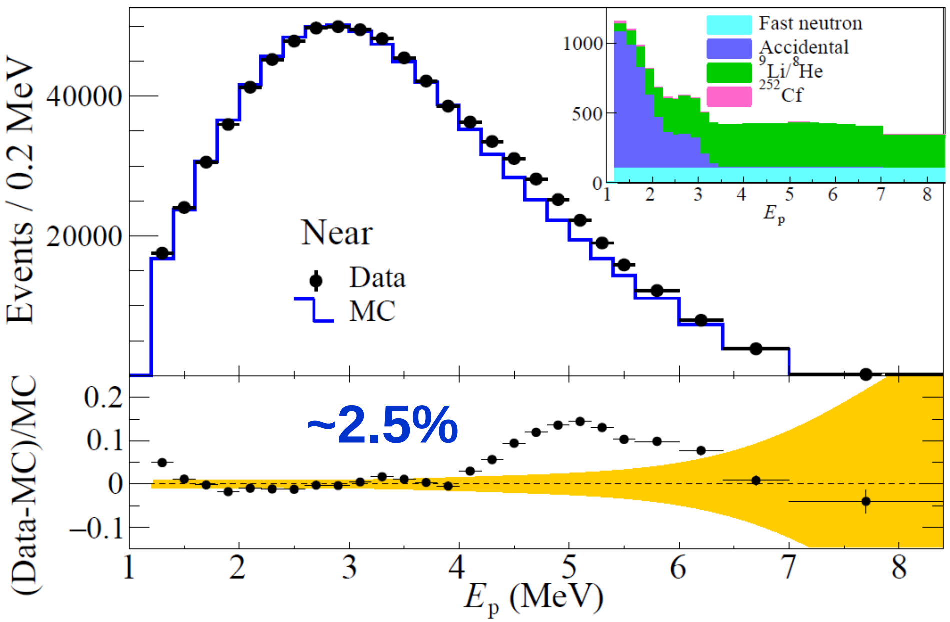
"Measurement of Reactor Antineutrino Oscillation Amplitude and Frequency at RENO" (Phys. Rev. Lett. 121, 201801 (2018. 11. 15))

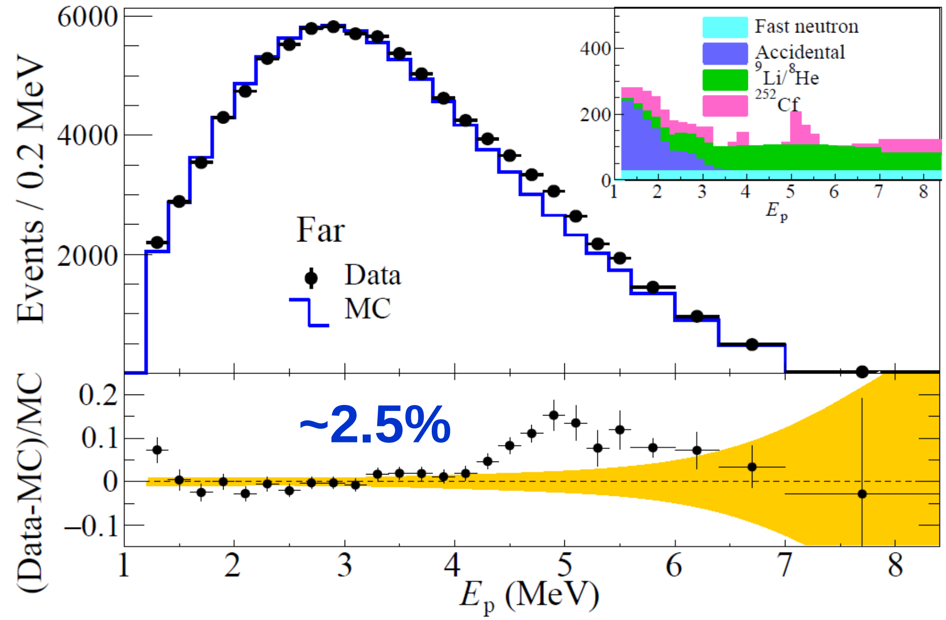
■ Fuel-composition dependent reactor antineutrino yield

"Fuel-composition dependent reactor antineutrino yield at RENO" (submitted to PRL (arXiv: 1806.00574))

Measured Spectra of IBD Prompt Signal

Clear excess at 5 MeV



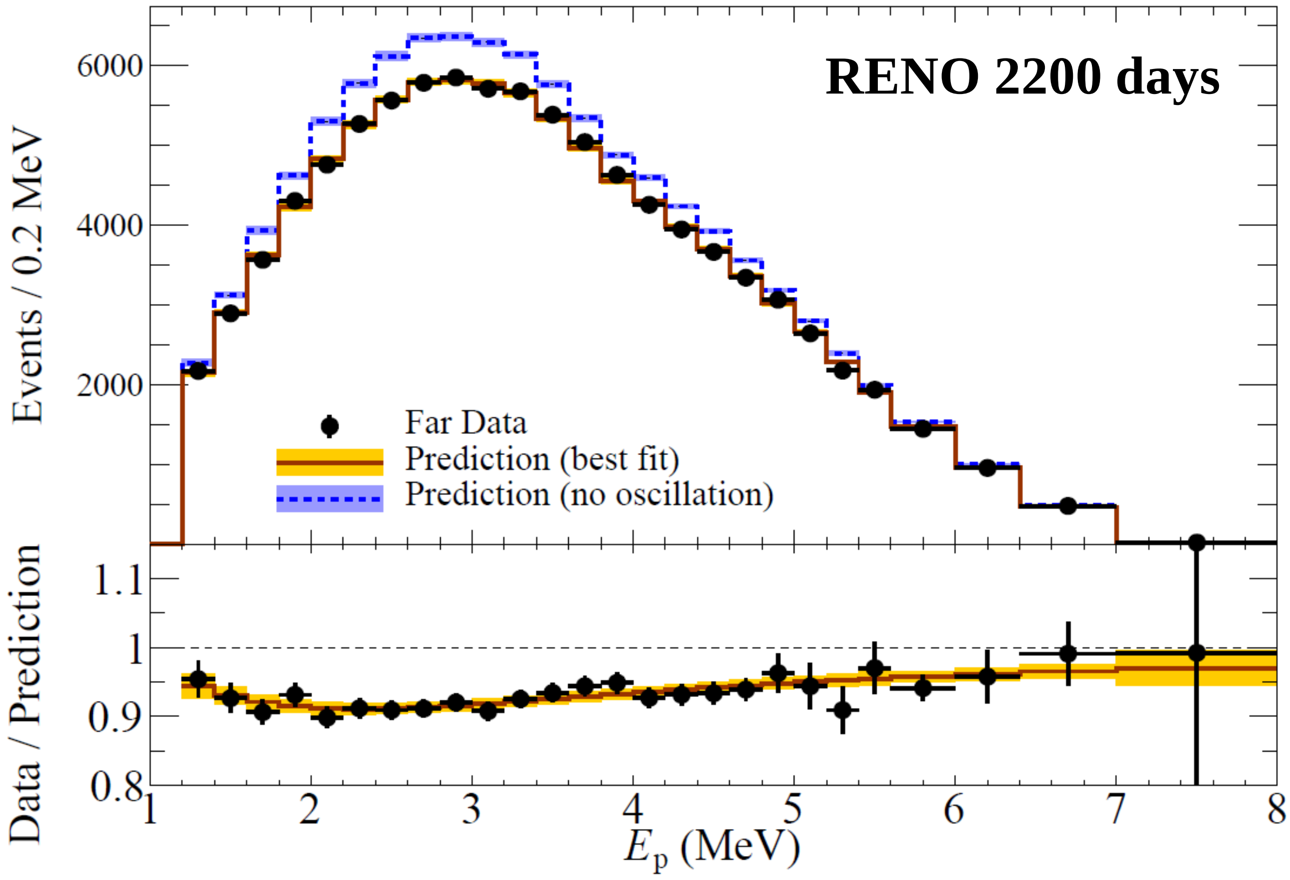


Near Live time = 1807.88 days
# of IBD candidate = 850,666
Background : 2.03±0.06%

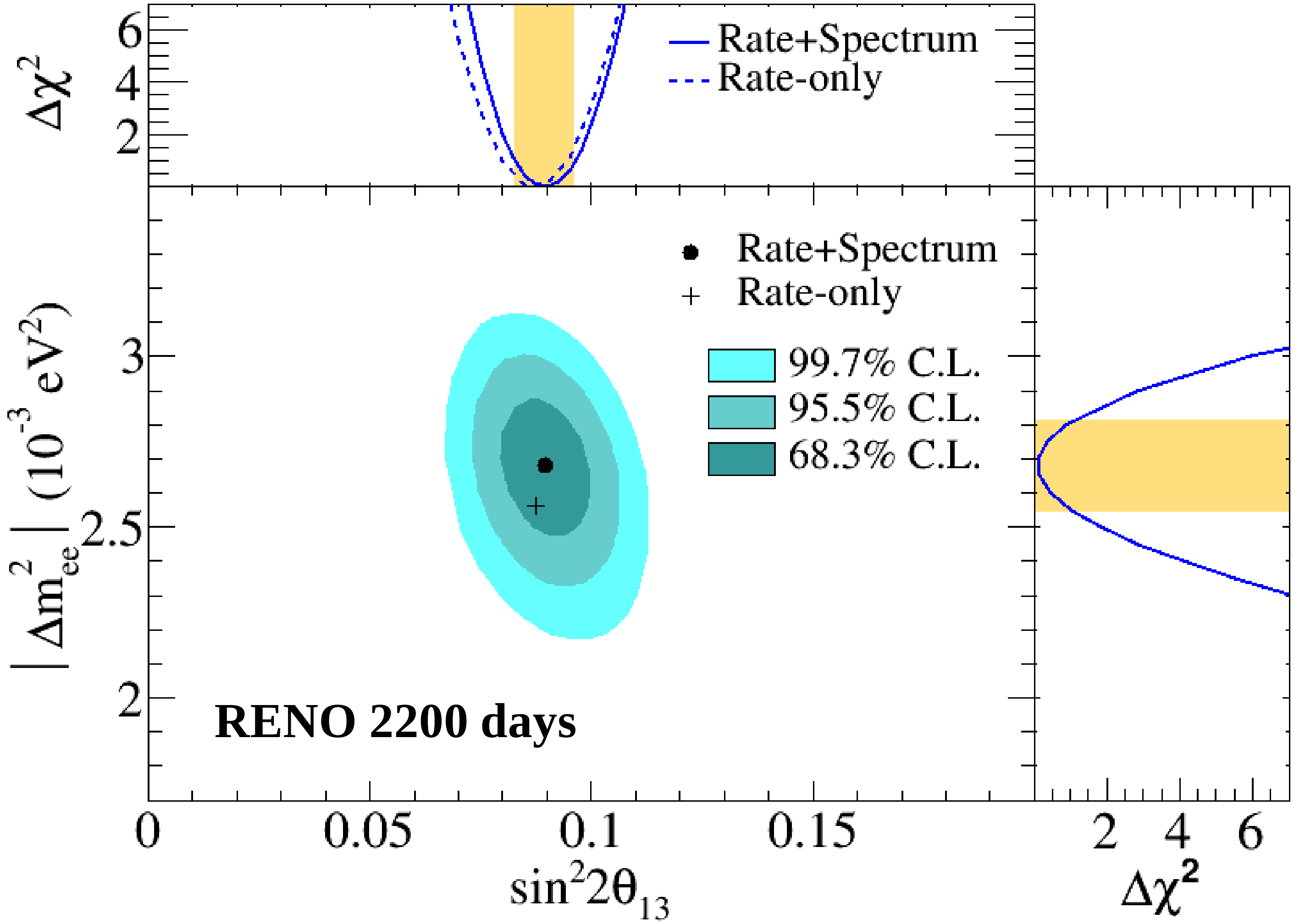
Far Live time = 2193.04 days
# of IBD candidate = 103,212
Background : 4.76±0.20%

Far/Near Shape analysis

Energy-dependent disappearance of reactor antineutrinos



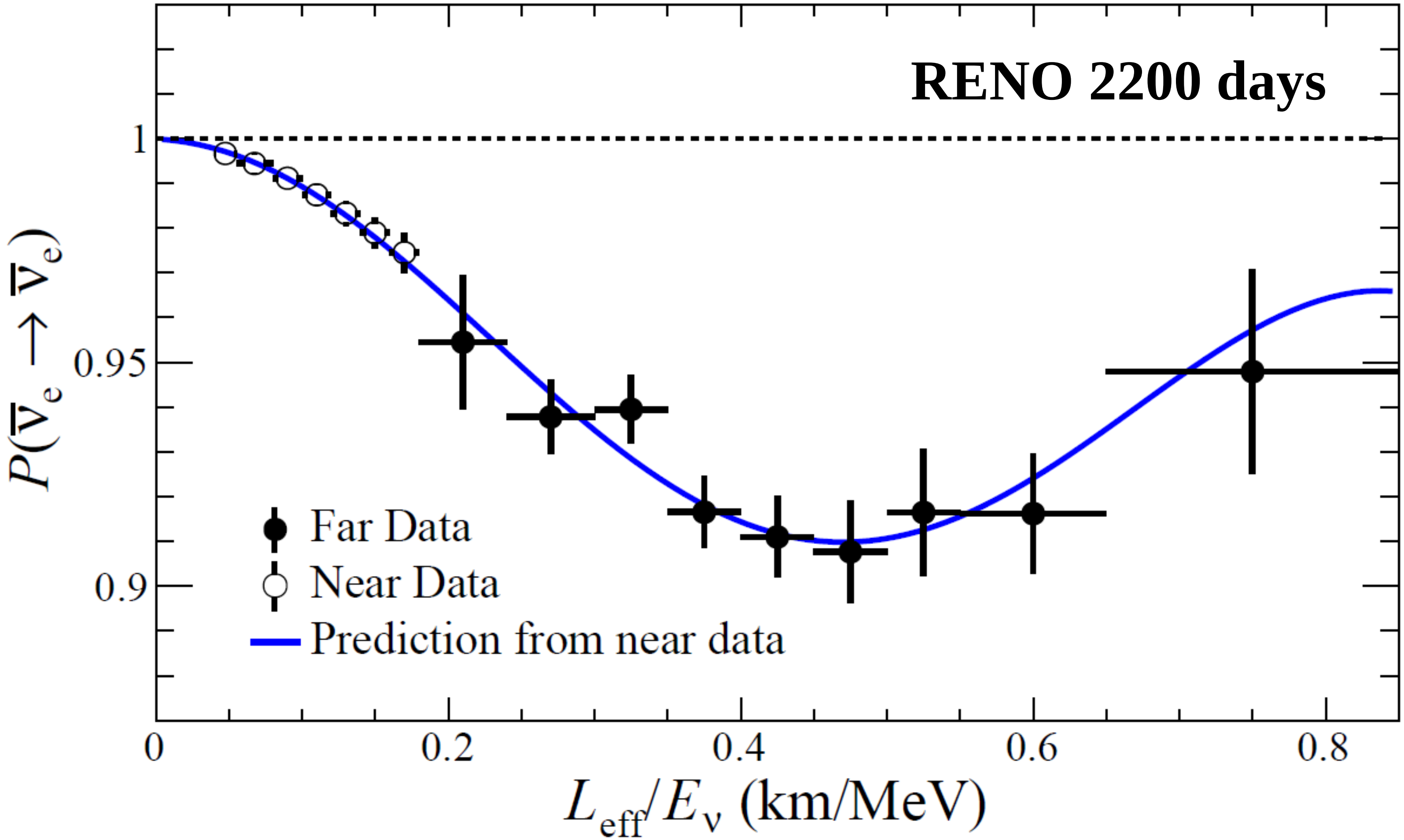
Results of θ_{13} and $|\Delta m^2_{ee}|$



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

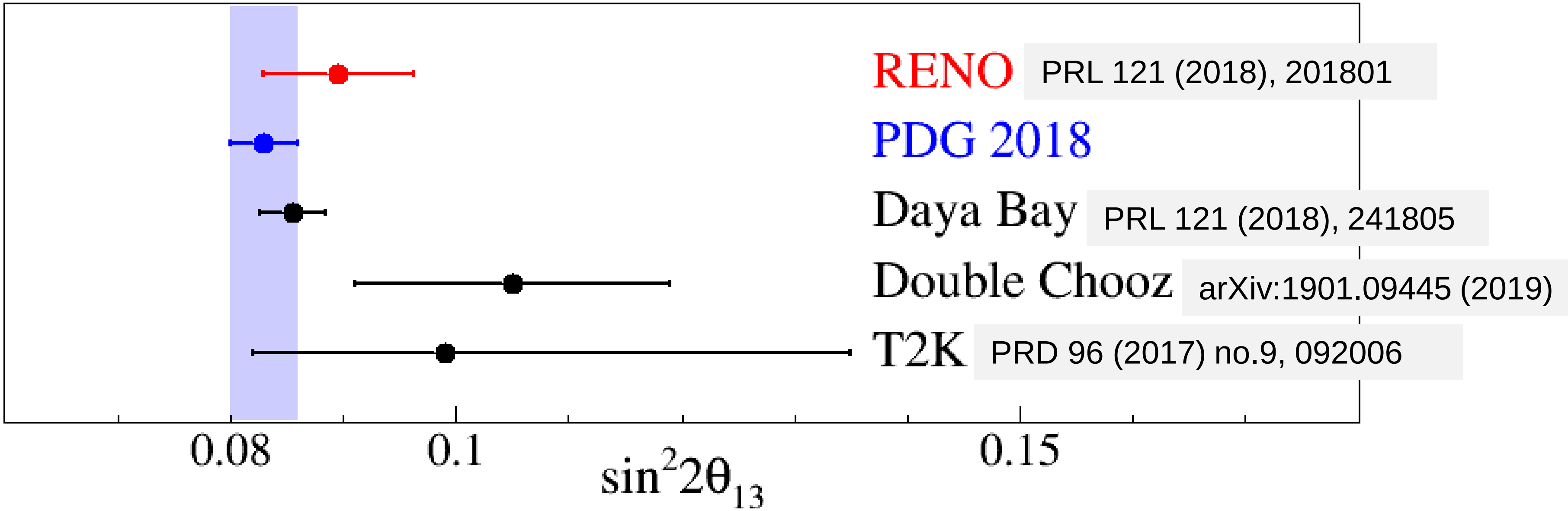
$|\triangle m_{ee}^2| = 2.68 \pm 0.12(\text{stat.}) \pm 0.07(\text{syst.})$ ($\times 10^{-3}$ eV^2) ($\pm$ 5.2 %)

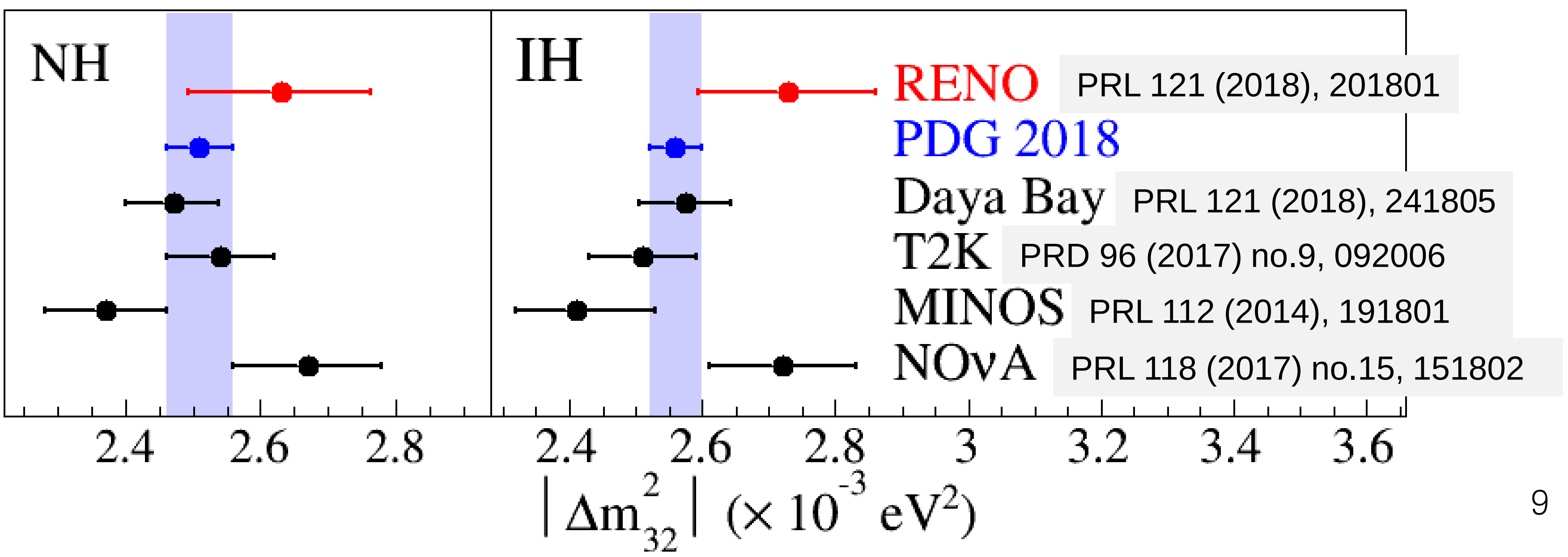
Observed L/E Dependent Oscillation



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

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)

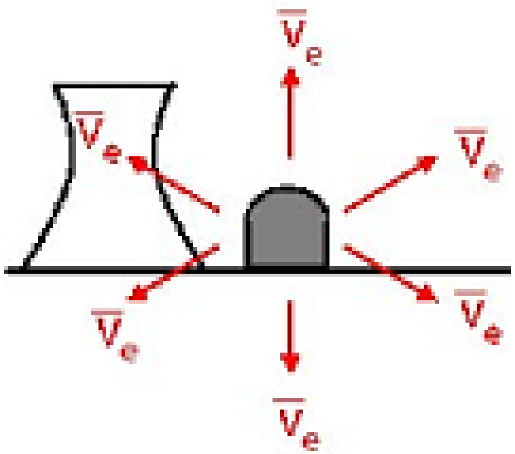
F. P. An et al. (Daya Bay Collaboration), PRL 118, 251801 (2017)

RENO Collaboration, arXiv:1806.00574 (submitted to PRL)

Reactor for Antineutrino Source

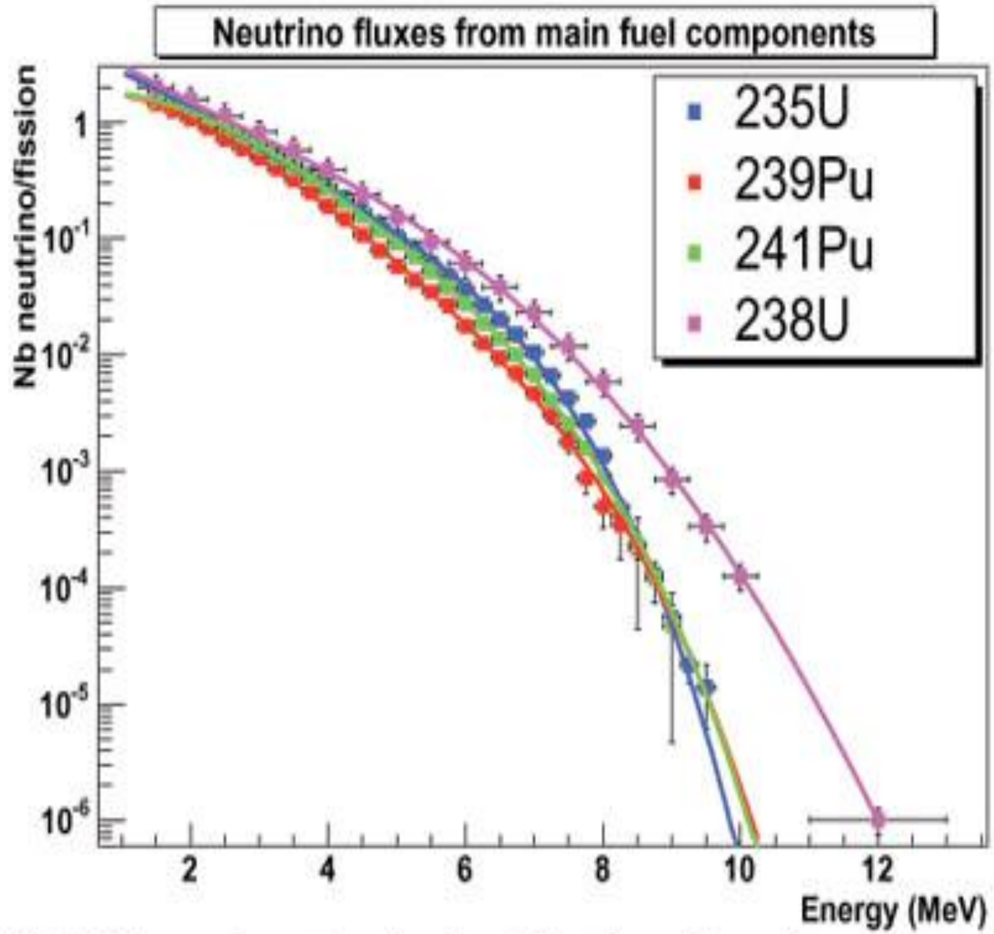
Reactor: A copious and isotropic source of electron antineutrinos

~3 GW_{th} or ~1 GW_{elec} per reactor



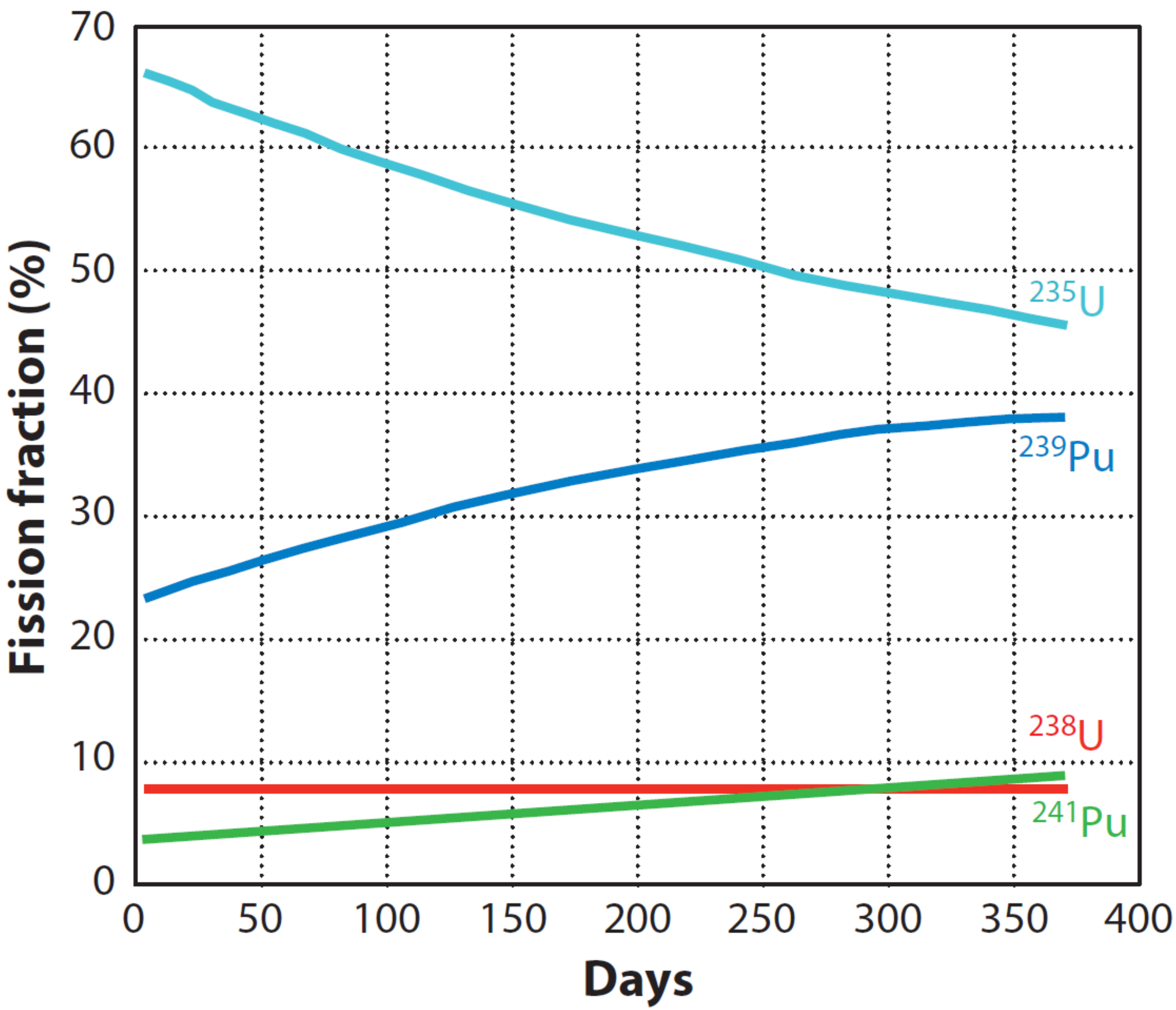
3 GW_{th} reactor
→ ~6×10^{20} $\bar{\nu}_e$/sec

- 3-4% accurate neutrino source
- 0.13% uncertainty of IBD cross section



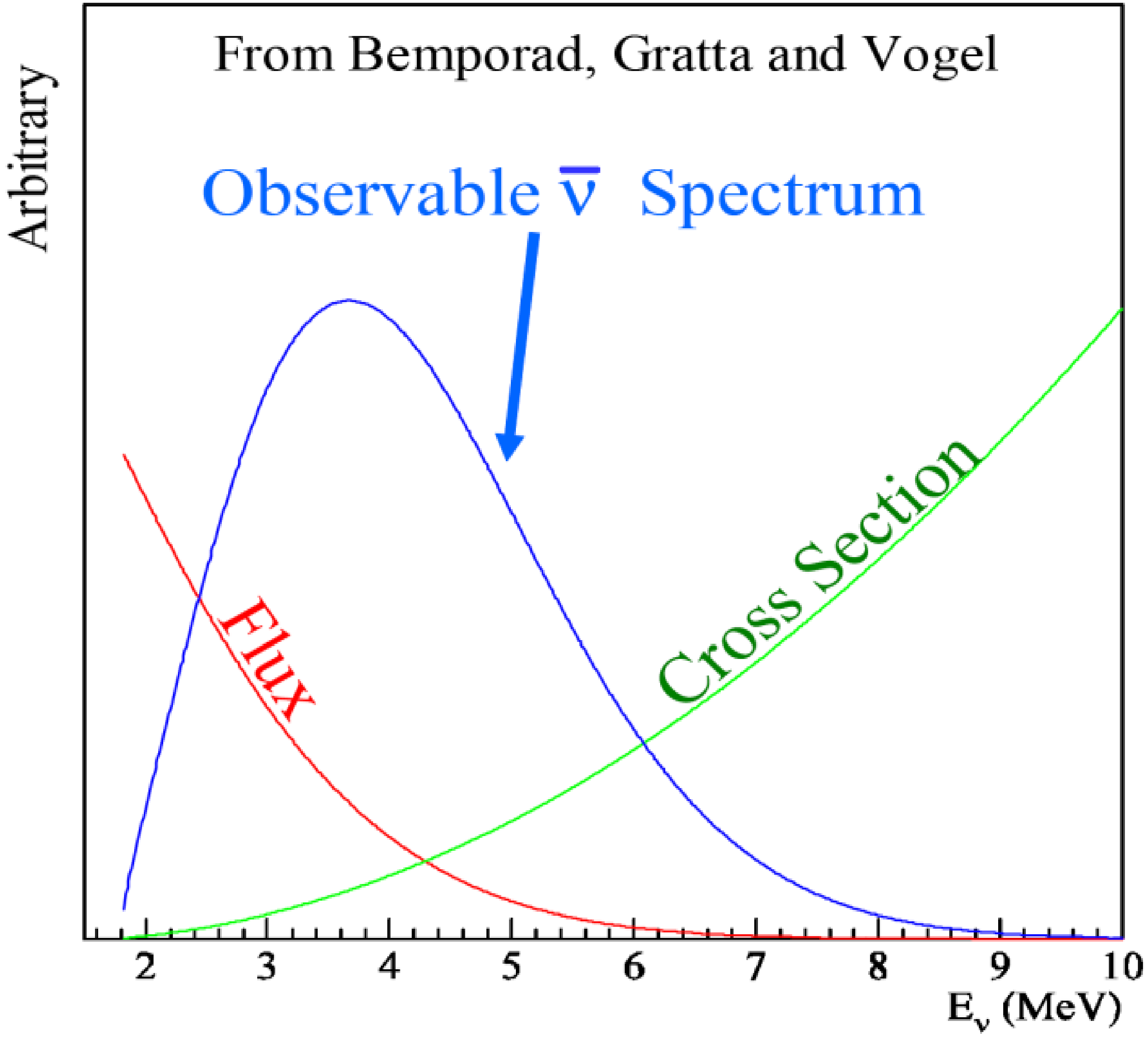
[* P. Huber, Phys. Rev. C84, 024617 (2011)
T. Mueller *et al*., Phys. Rev. C83, 054615 (2011)]

Evolution of Fuel Isotope Fraction in Single Reactor



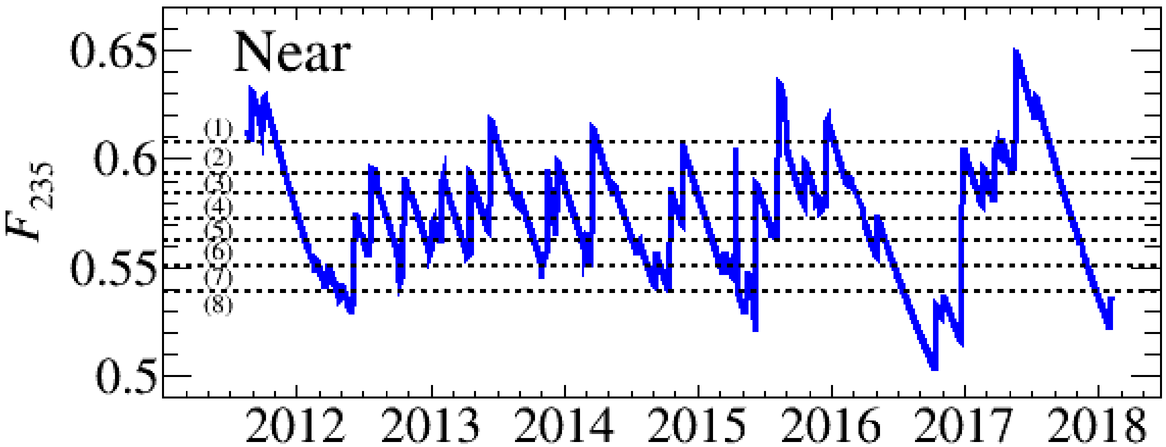
The **Fission fraction** of an isotope varies with **fuel-burning**

Observable Reactor Neutrino Spectrum

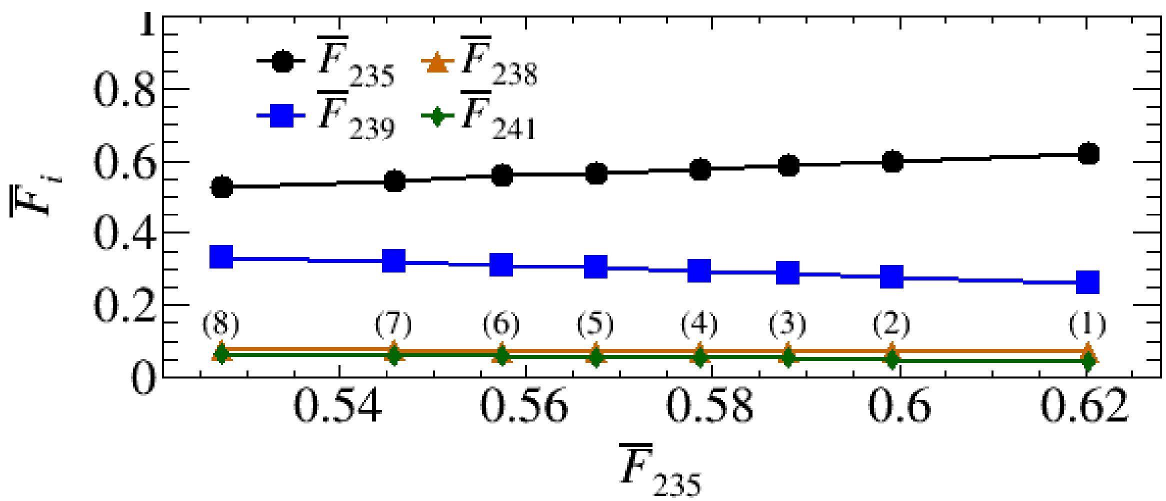


Evolution of Fuel Composition at RENO

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

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

Predicted IBD Yield per Fission

IBD yield per fission for each isotope

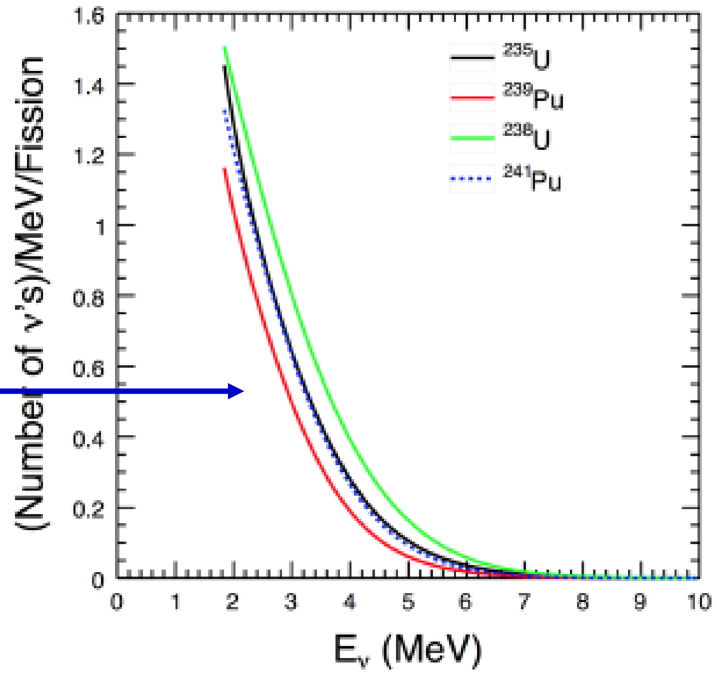
(Total # of produced IBD events)

$$y_i = \int \sigma(E_\nu)\phi_i(E_\nu)dE_\nu$$

IBD cross section

Antineutrino spectrum (H-M model)

(i : each isotope)



Average IBD yield per fission

(for each 8 group, j)

$$\bar{y}_{f,j} = \sum_{i=1}^{4} \bar{F}_{i,j} y_i$$

$\overline{F}_{i,j}$: Effective Fission fraction for each isotope

	H-M model (10^{-43} cm²/fission)
y_{235}	6.70 +- 0.14
y_{239}	4.38 +- 0.11
y_{238}	10.07 +- 0.82
y_{241}	6.07 +- 0.13

Measurement of IBD Yield per Fission using RENO data

Measurement of IBD yield per fission ($\bar{y}_{f,j}$) for each group

- Number of IBD events after subtracting background is obtained for each group, j. Then $\bar{y}_{f,j}$ is determined by solving the following equation.

$$N_j = \bar{y}_{f,j} \sum_{r=1}^{6} \frac{N_p}{4\pi L_r^2} \int dt \left[\frac{W_{th,r}(t) \bar{P}_{sur}^{r}(t)}{\sum_i f_{i,r}(t) E_i} \right] \epsilon_d(t)$$

N_j: # of Observed IBD

N_p: # of Target proton

$\frac{W_{th,r}(t) \bar{P}_{sur}^{r}(t)}{\sum_i f_{i,r}(t) E_i}$: # of fission

$\epsilon_d(t)$: Detection Efficiency

'Measured IBD yield per fission' corresponding to average IBD yield per fission

Average IBD yield per fission

(for each 8 group, j)

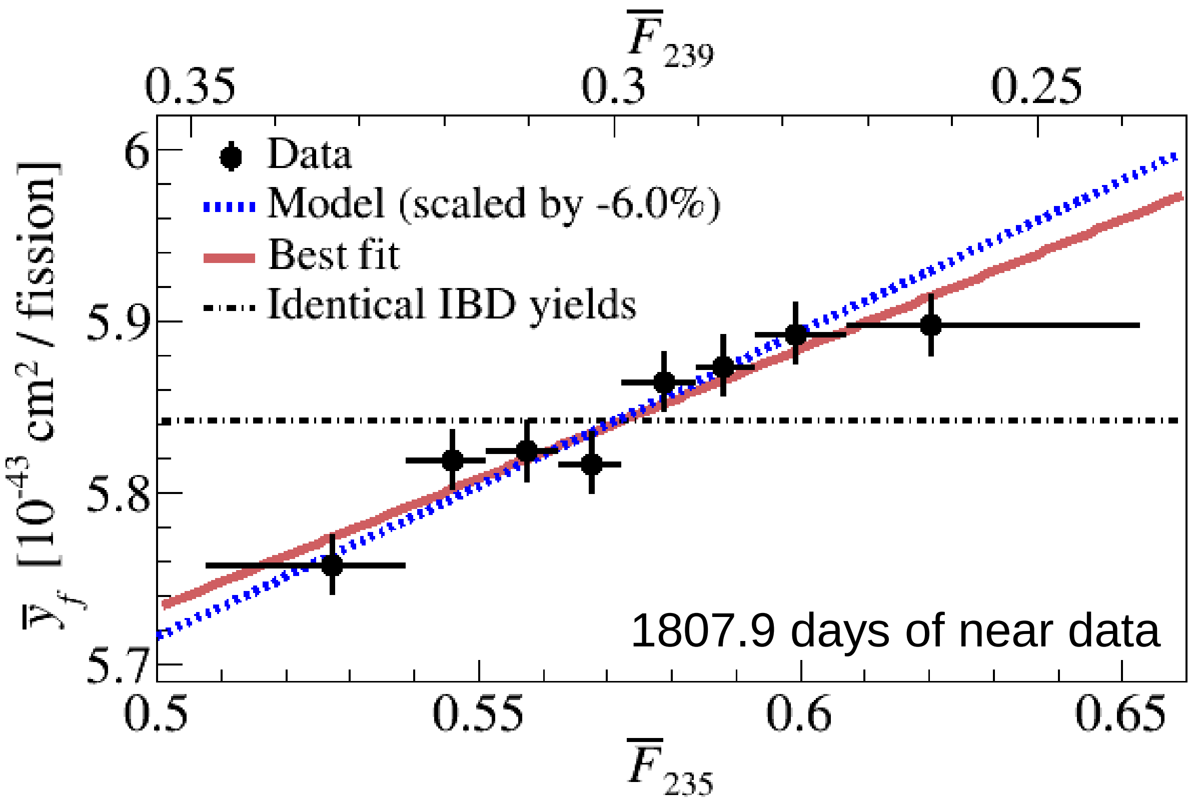
$$\bar{y}_{f,j} = \sum_{i=1}^{4} \bar{F}_{i,j} y_i$$

$\overline{F}_{i,j}$: Effective Fission fraction for each isotope

Fuel-Composition Dependent Reactor Neutrino Yield

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



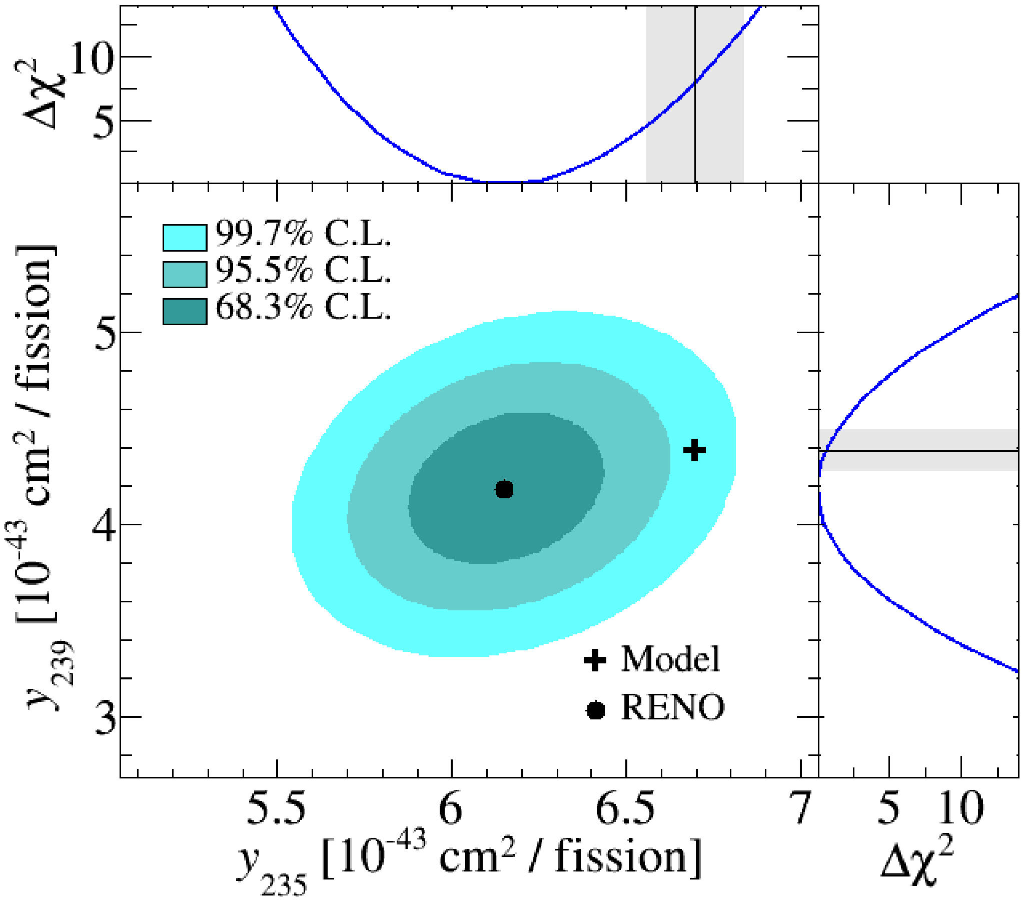
Averaged IBD yield per fission ($\bar{y}_f$) vs $\overline{F}_{i,j}$
→ slope means **different neutrino yield** for each isotope
→ rules out the no fuel-dependent variation at **6.6σ**

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)

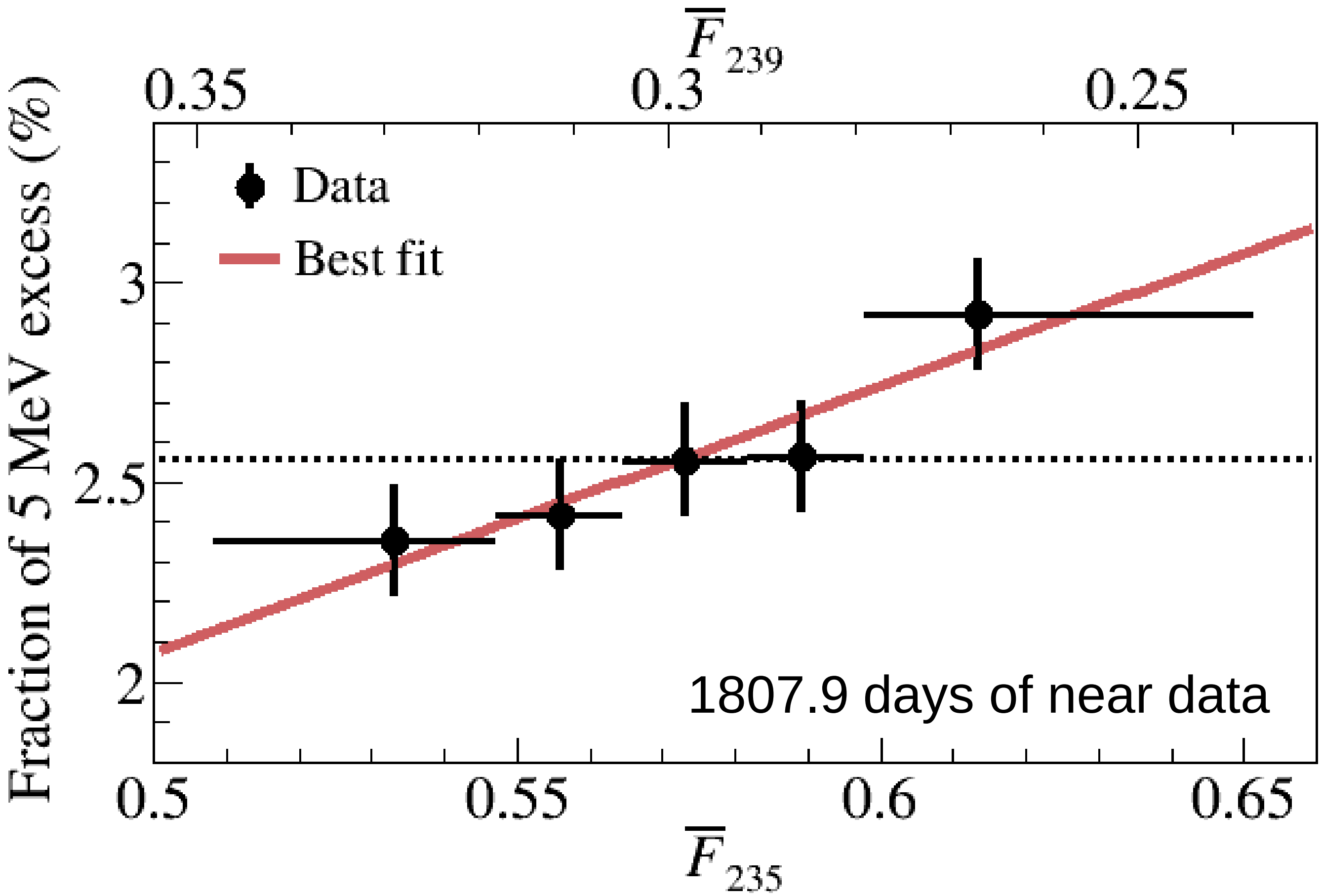
H-M model

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 !!



(2.56±0.06) %

(End of reactor cycle)

(Beginning of reactor cycle)

Summary

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

$\sin^2 2\theta_{13} = 0.0896 \pm 0.0068$ **(7.6 %)**

$|\triangle m_{ee}^2| = 2.68 \pm 0.14\ (\times 10^{-3}\ eV^2)$ **(5.2 %)**

- **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 **2.8*σ***)

^{239}**Pu :** 4.18 ± 0.26 (smaller than the H-M prediction at **0.8*σ***)

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

Thanks for your attention!