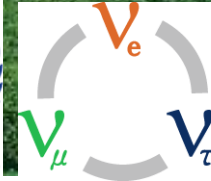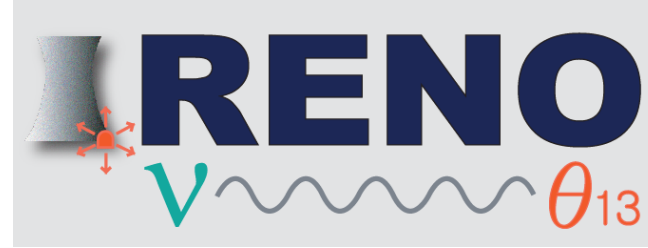# Variation of Reactor Antineutrino Yield at RENO

Hyunkwan Seo for the RENO Collaboration
Seoul National University

Lake Louise Winter Institute 2019
Chateau Lake Louise, AB, Canada, February. 10-16, 2019

ν_e
ν_μ ν_τ
KNRC
Korea Neutrino Research Center

RENO Collaboration

Reactor Experiment for Neutrino Oscillation
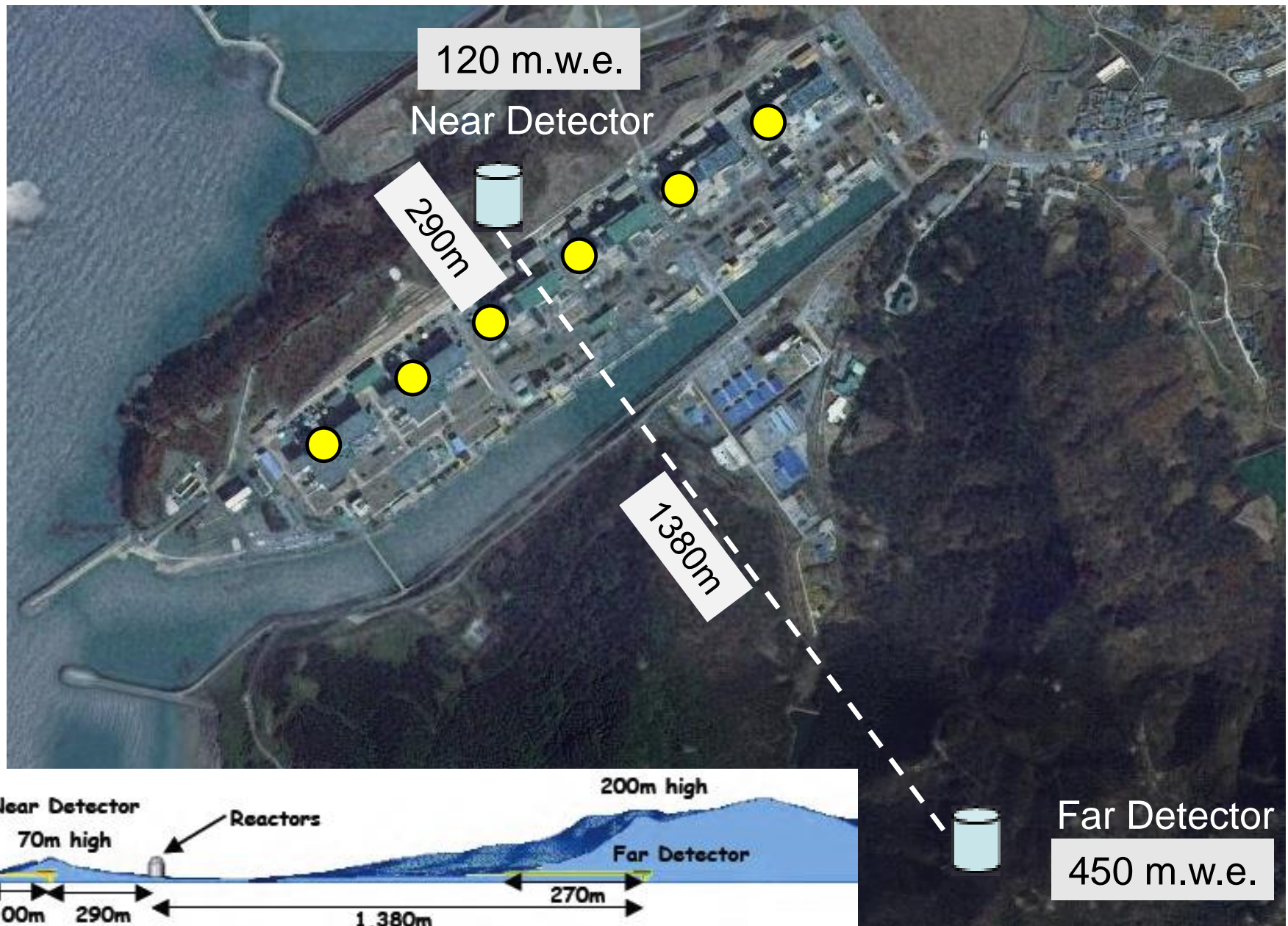
(9 institutions and 40 physicists)

- 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

120 m.w.e.

Near Detector

290m

1380m

Far Detector

450 m.w.e.

Near Detector
70m high

Reactors

200m high

Far Detector

100m   290m

1,380m

270m

Motivation

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 Fuel Isotope Fraction

Average fission fraction
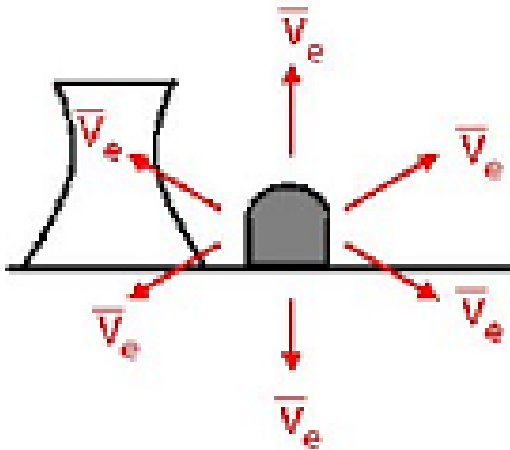$f_{235}: f_{239}: f_{238}: f_{241}= 0.573 : 0.299 : 0.073 : 0.055$
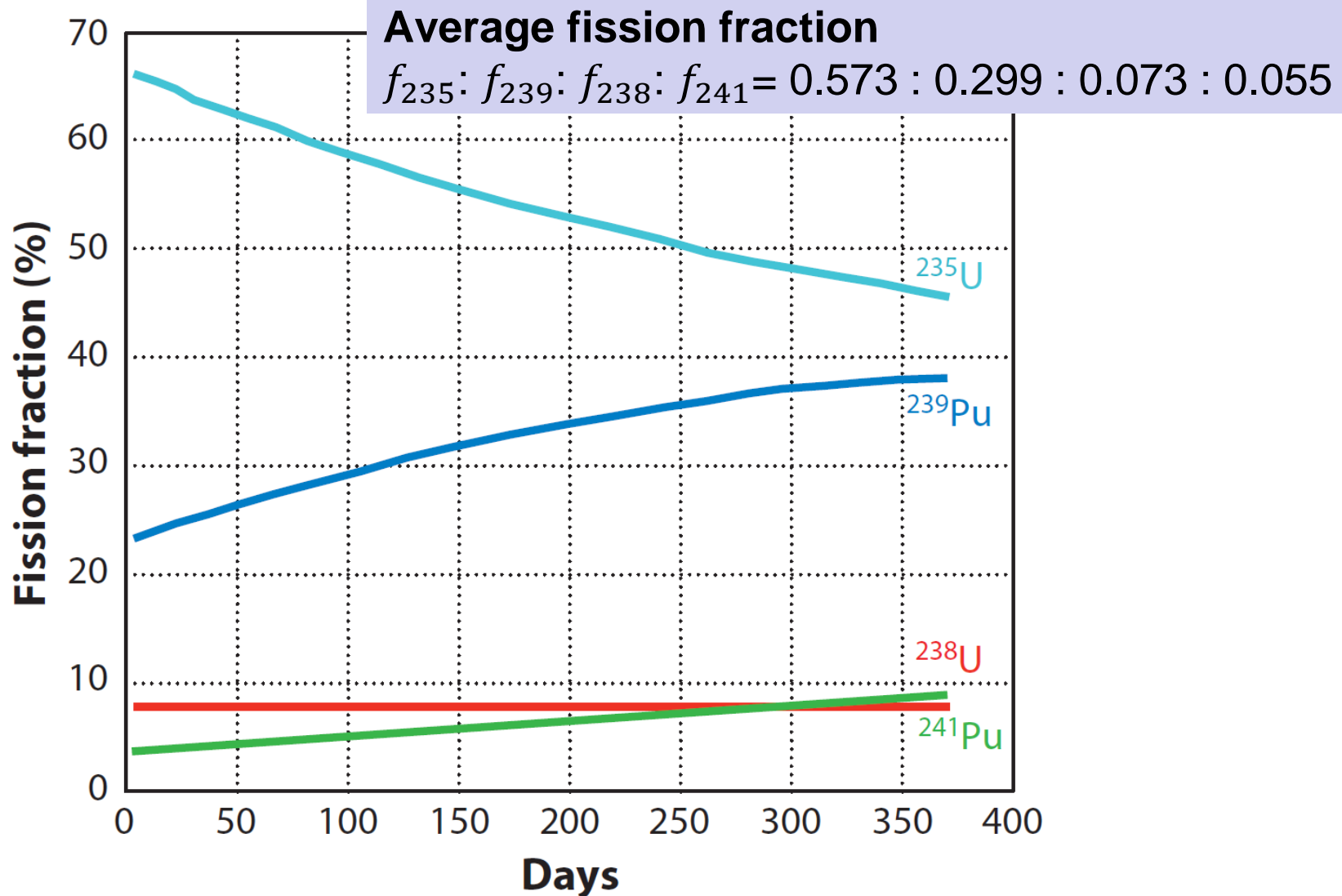
The **Fission fraction** of an isotope varies with **fuel-burning**

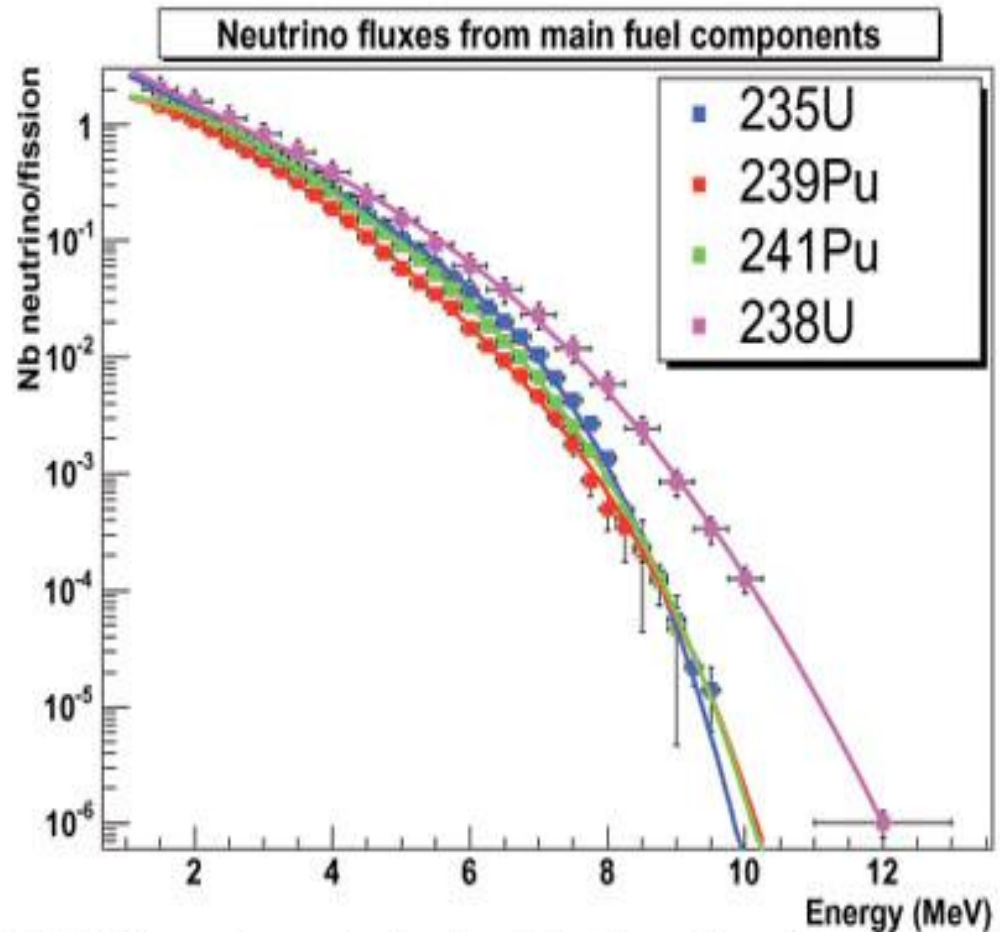# Reactor for Antineutrino Source

Reactor: A copious and isotropic source of electron antineutrinos

~3 GW$_{th}$ or ~1 GW$_{elec}$ per reactor

3 GW$_{th}$ reactor
→ ~6x10^{20} $\bar{\nu}_e$/sec

Neutrino fluxes from main fuel components

- 235U
- 239Pu
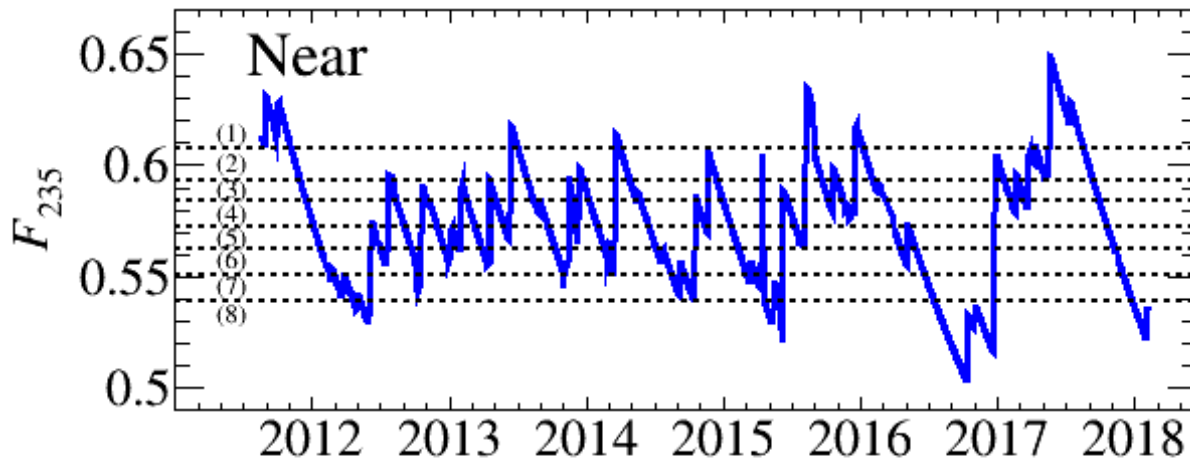- 241Pu
- 238U

Nb neutrino/fission

Energy (MeV)

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

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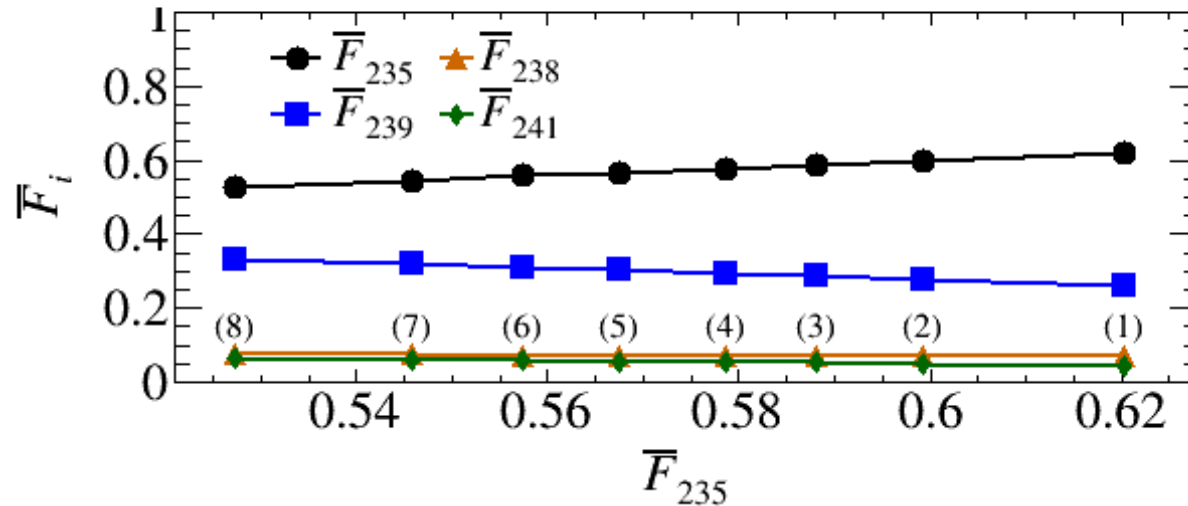T. Mueller *et al.*, Phys. Rev. C83, 054615 (2011)]

From Bemporad, Gratta and Vogel

Observable ν̄ Spectrum

Flux

Cross Section

E_ν (MeV)

Arbitrary
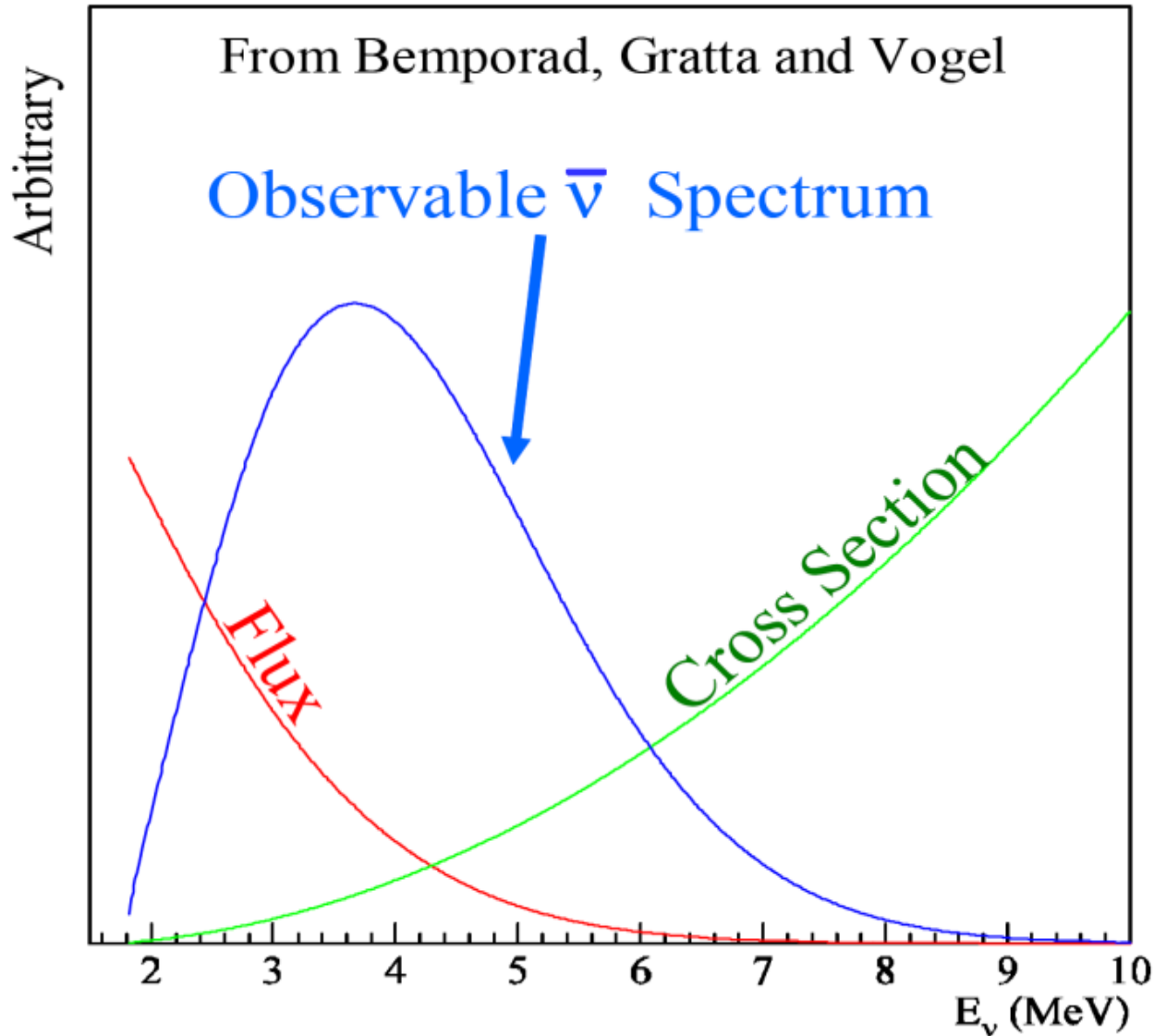
Evolution of Fuel Composition at RENO

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

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

Effective Fission fraction for each isotope

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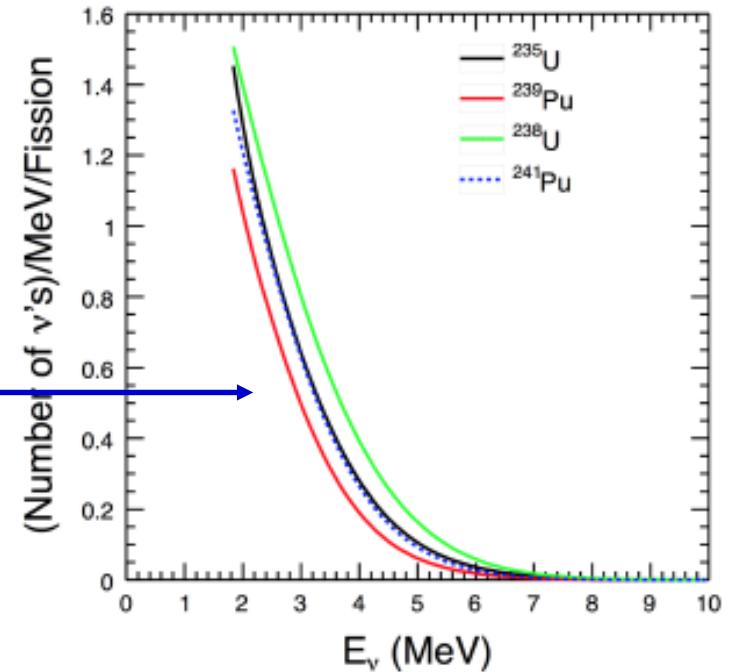
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Predicted IBD Yield per Fission

IBD yield per fission for each isotope

(Total # of produced IBD events)

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

IBD cross   Antineutrino
section   spectrum

(i : each isotope)   (H-M model)

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

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Measurement of IBD Yield per Fission

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

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

# of Observed IBD

$$N_j = \overline{y}_{f,j} \sum_{r=1}^{6} \frac{N_{\mathrm{p}}}{4\pi L_r^2} \int dt \left[\frac{W_{\mathrm{th},r}(t)\overline{P}_r(t)}{\sum_i f_{i,r}(t)E_i} \right] \epsilon_{\mathrm{d}}(t)$$

# of Target proton

# of fission

Detection Efficiency

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

Average IBD yield per fission
(for each 8 group, j)

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

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

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

= (5.84 $\pm$ 0.13)$\times$10^{-43} cm²/fission

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

= 0.940 $\pm$ 0.021 $\rightarrow$ (6.0 $\pm$ 2.1)% deficit
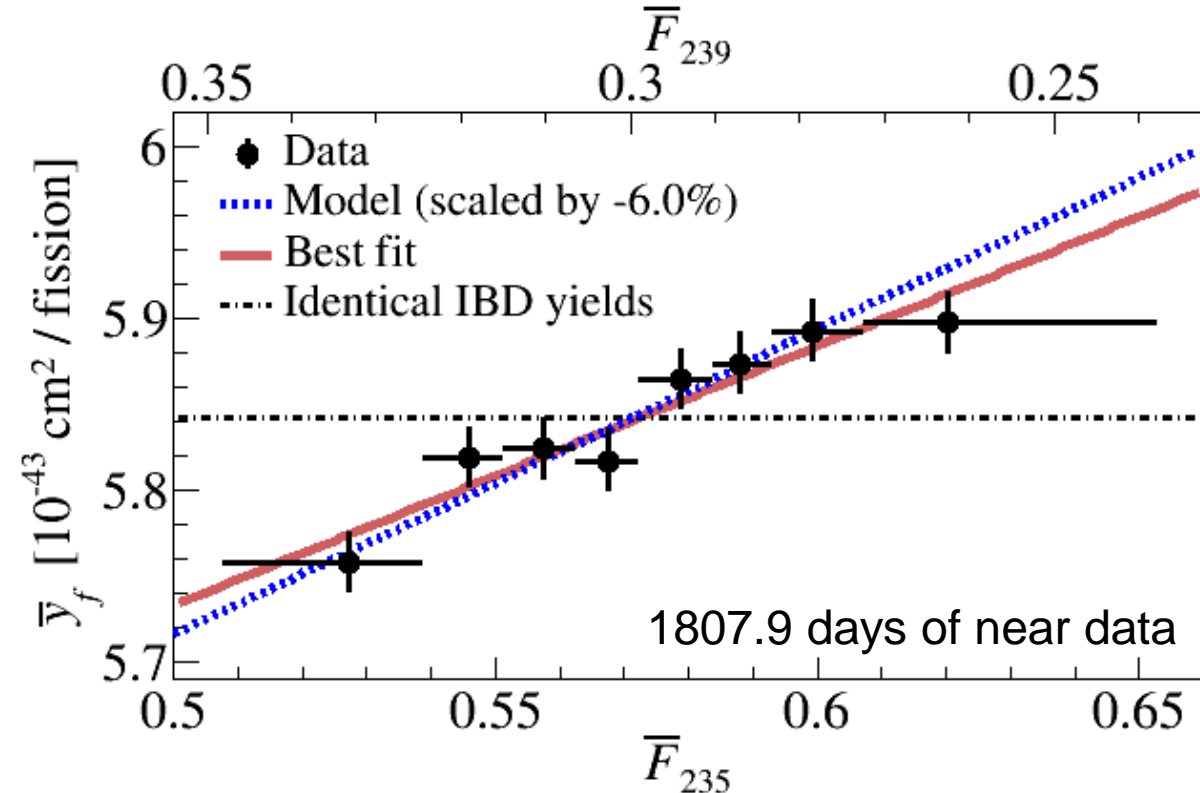
Averaged IBD yield per fission ($\overline{y}_f$) vs $\overline{F}_{i,j}$

$\rightarrow$ slope means **different neutrino spectrum** for each isotope

$\rightarrow$ 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
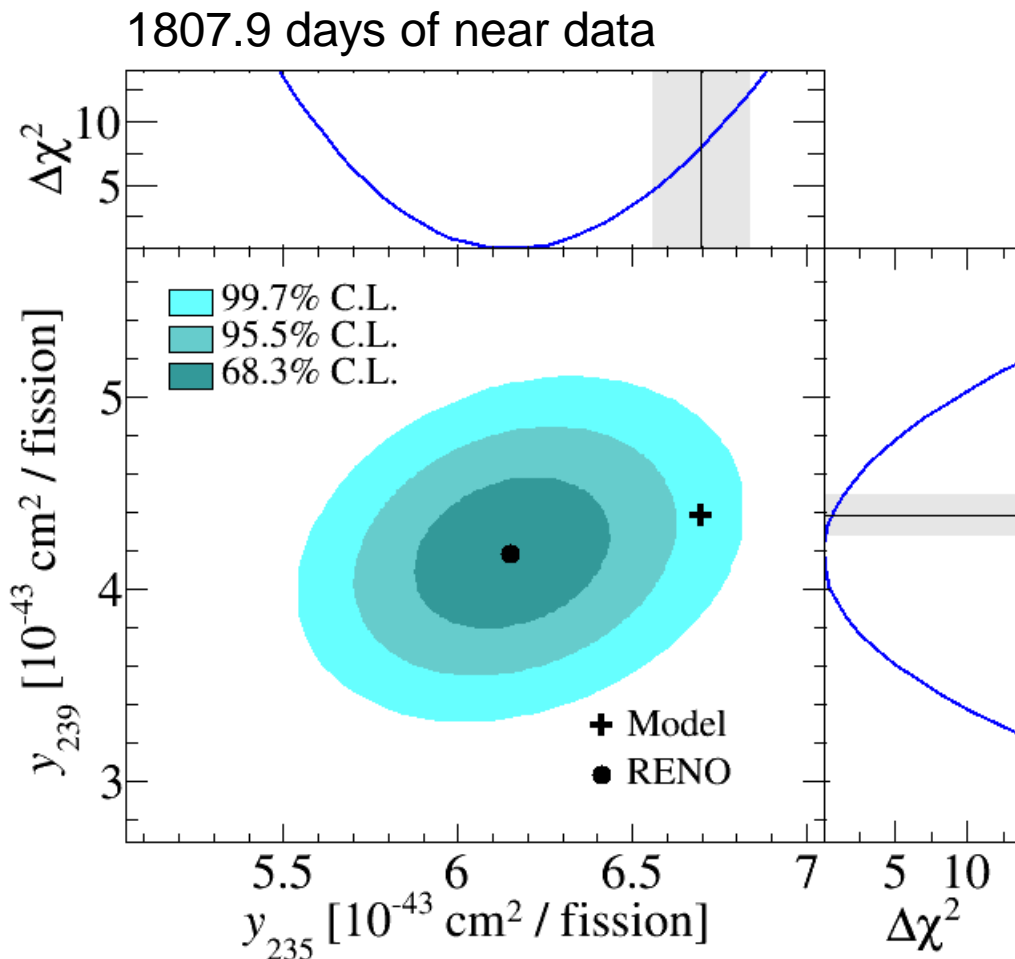
The best-fit values

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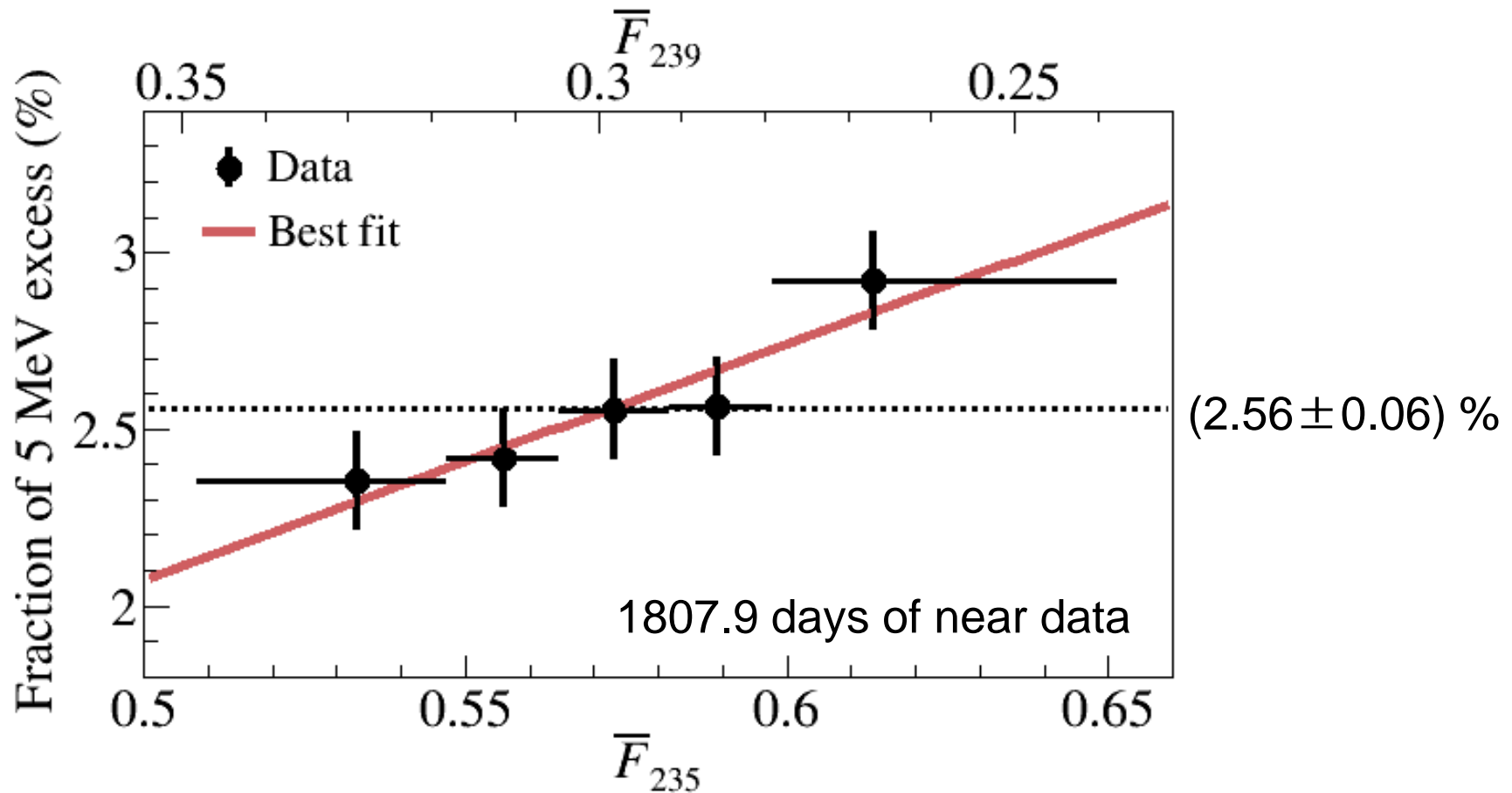
H-M model

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

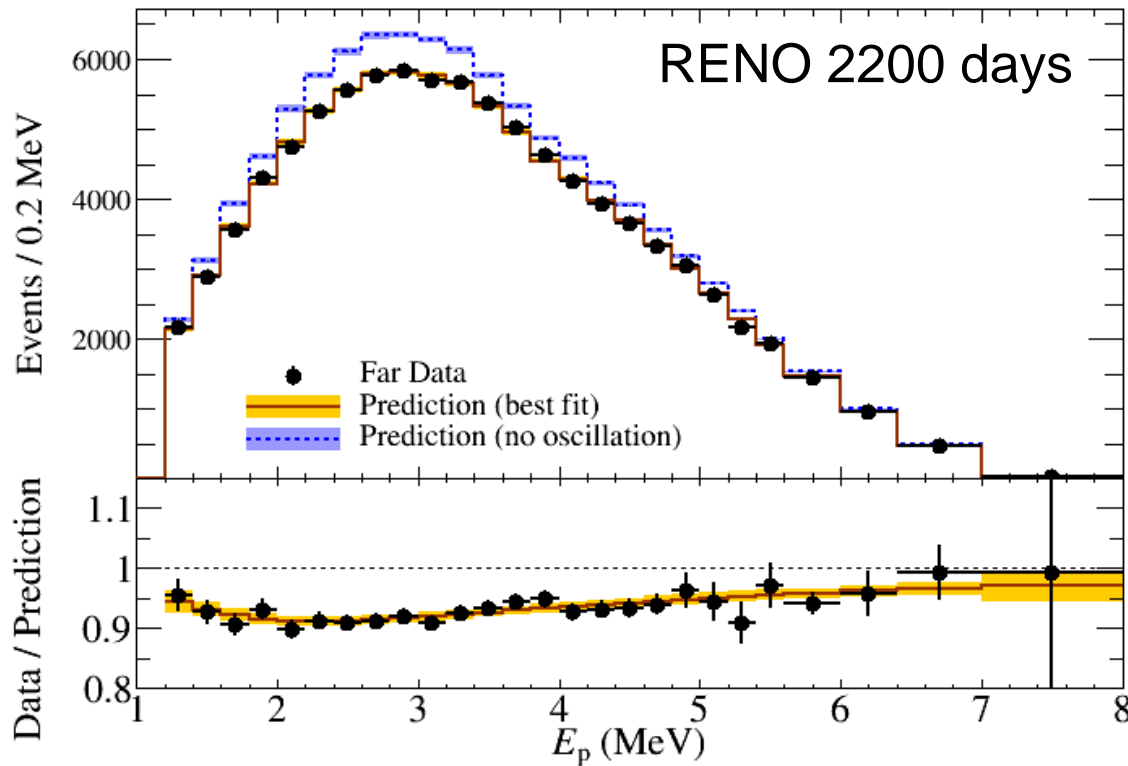2.9σ indication of 5 MeV excess coming from ^{235}U fuel isotope fission !!

$\overline{F}_{239}$

(2.56±0.06) %

1807.9 days of near data

$\overline{F}_{235}$

(End of reactor cycle)

(Beginning of reactor cycle)

θ₁₃ and |Δm²ₑₑ| in RENO

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

$|\triangle m_{ee}^2| = 2.68 \pm 0.14$ ($\times 10^{-3}$ eV²) (5.2 %)
$\quad 2.68 \pm 0.12(\text{stat.}) \pm 0.07(\text{syst.})$

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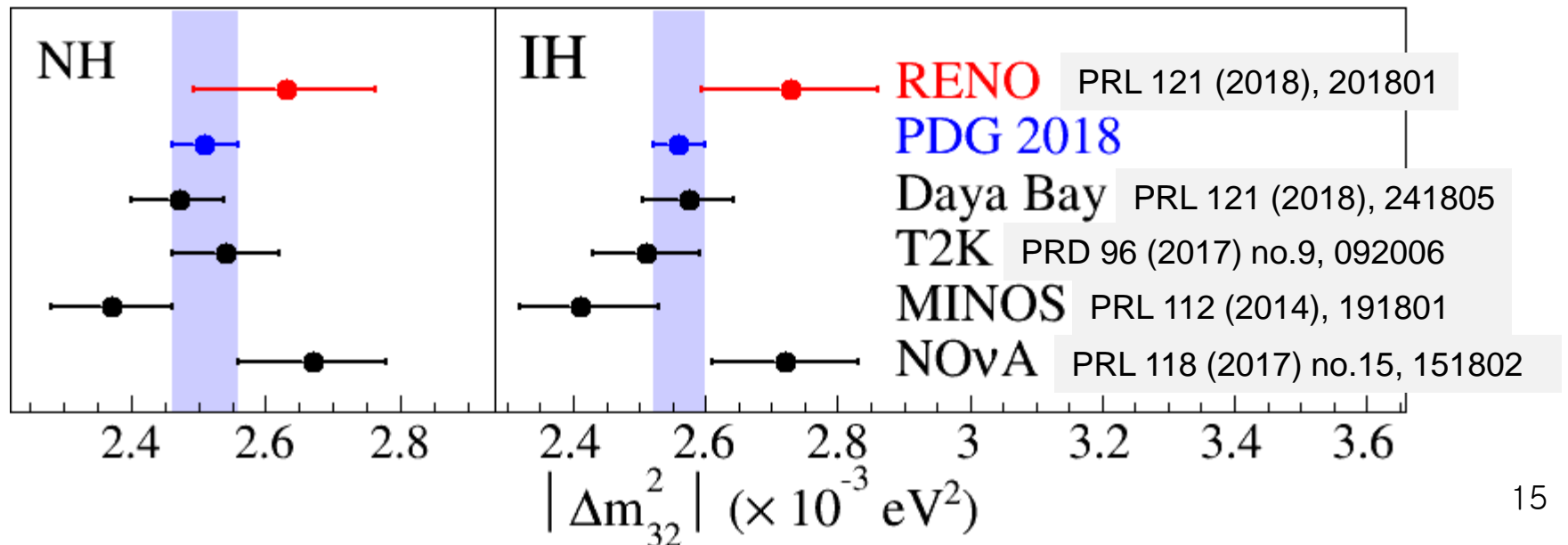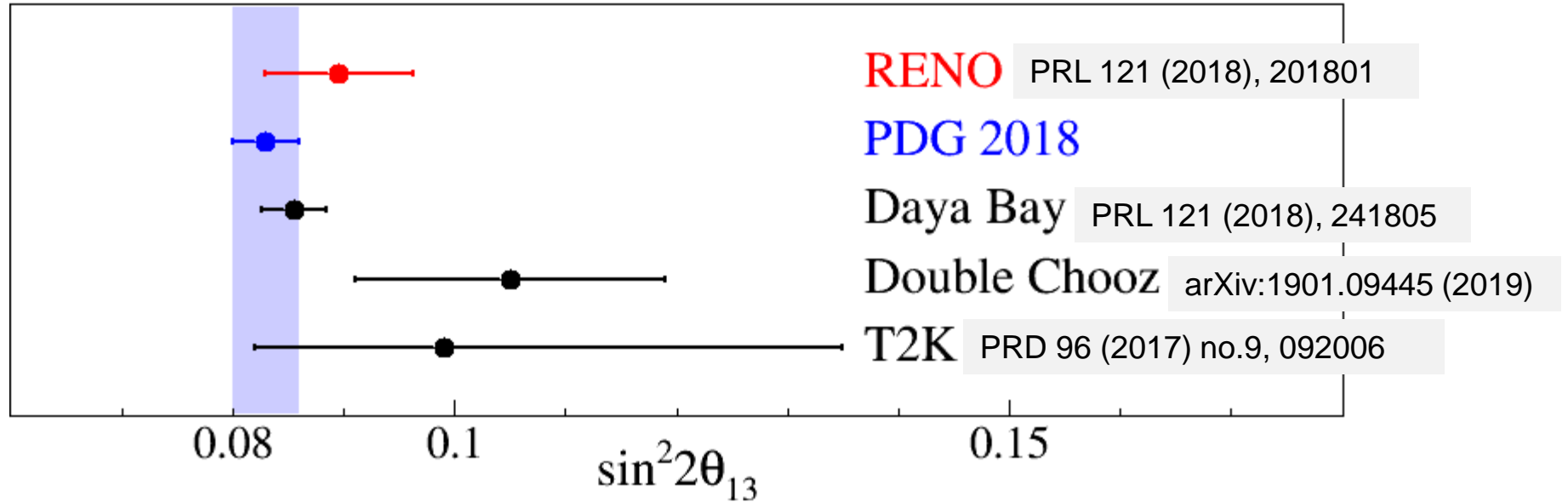
Summary

- RENO report a fuel-dependent IBD yield and energy spectrum using 1807.9 live days (Aug. 2011 – Feb. 2018) of near detector data

- Rules out the no fuel-dependent variation at **6.6σ**

- Measured IBD yield per fission for individual isotope

$y_{235} = 6.15 \pm 0.19 \rightarrow$ 2.8σ deficit compared to H-M model (6.70 ± 0.14)
$y_{239} = 4.18 \pm 0.26 \rightarrow$ 0.8 σ deficit compared to H-M model (4.38 ± 0.11)

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

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

Thanks for your attention!