Recent Results from RENO

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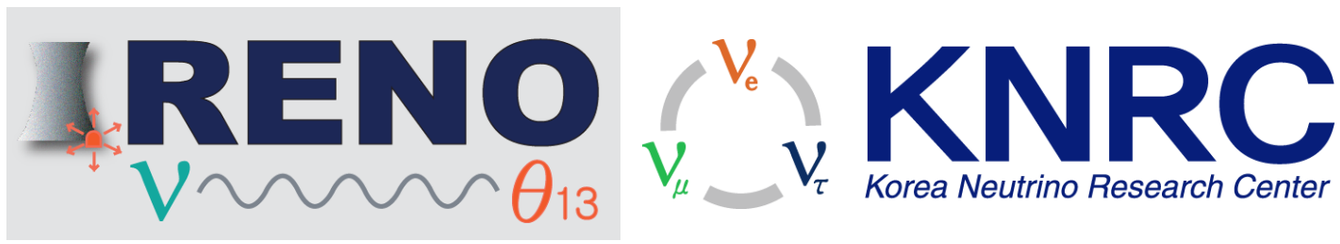
Dongshin University

The 19th International Workshop on Neutrinos from Accelerators (NUFACT 2017)



RENO (Reactor Experiment for Neutrino Oscillation) Collaboration

Eight institutions and 40 physicists

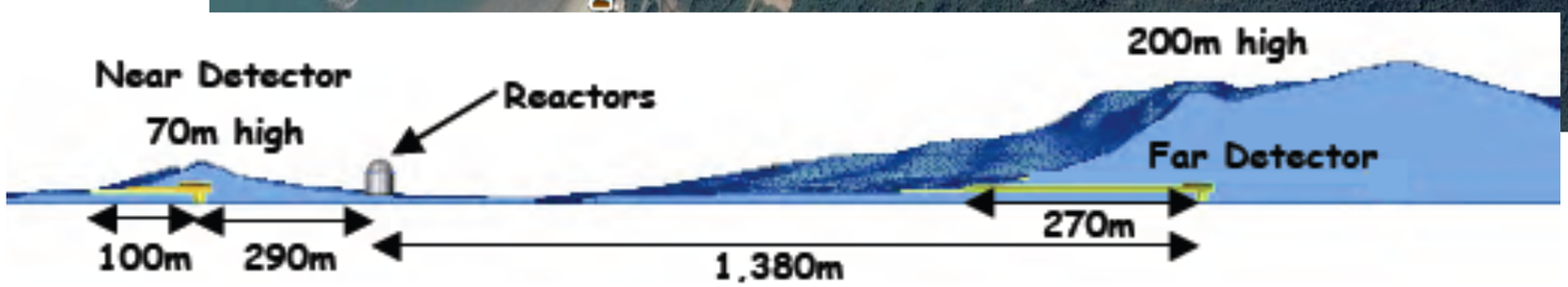
- Chonnam National University
- Dongshin University
- GIST
- Gyeongsang National University
- Kyungpook National University
- Seoul National University
- Seoyeong University
- Sungkyunkwan University

- **Total cost : $10M**
- **Start of project : 2006**
- **Start of data acquisition : Aug. 2011**

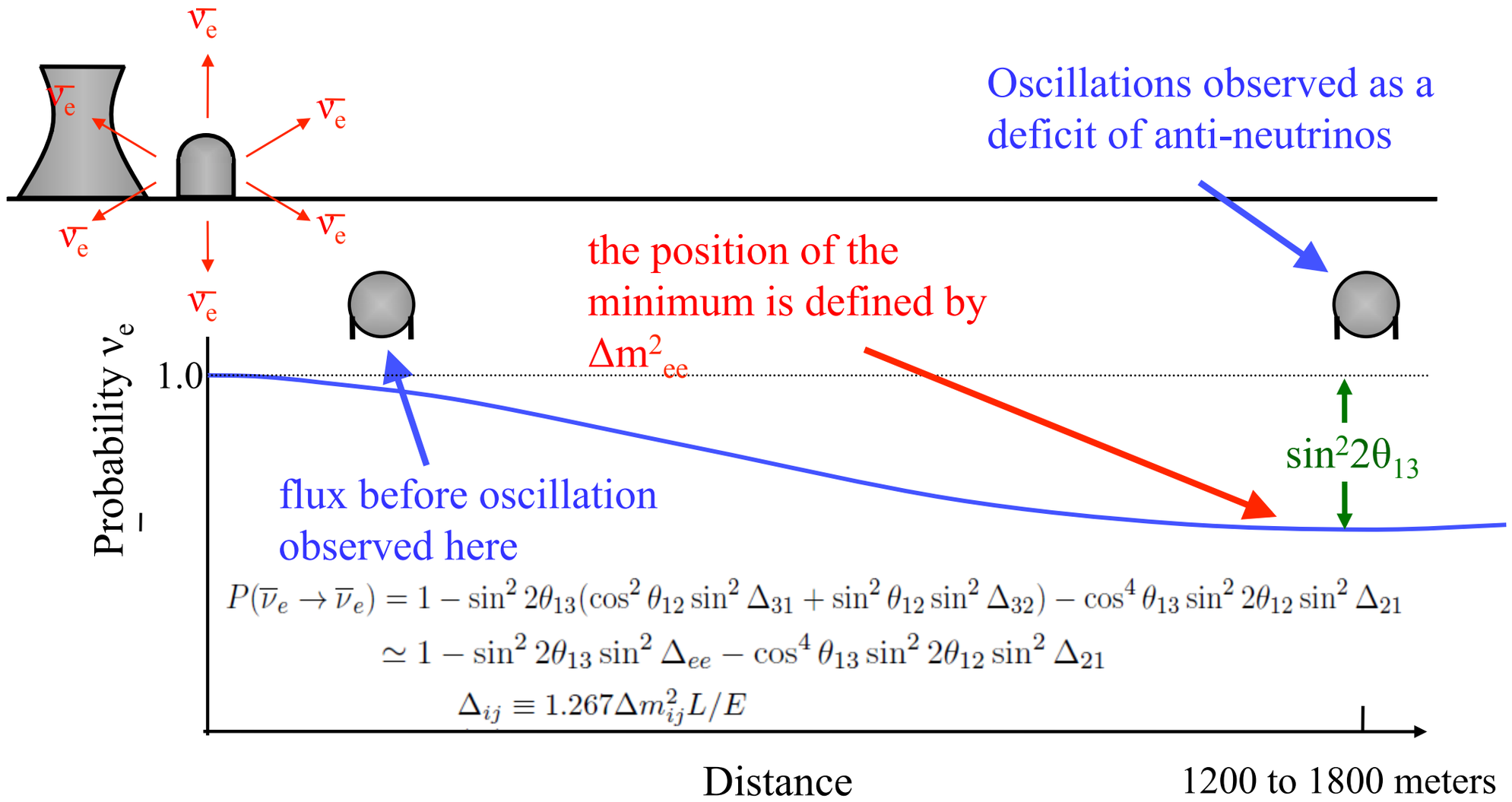
Habit Nuclear Power Plant

- six cores with maximum thermal output of 2.8 GW each
- in linear array spanning 1.3 km with equal spacing

RENO Experimental Setup



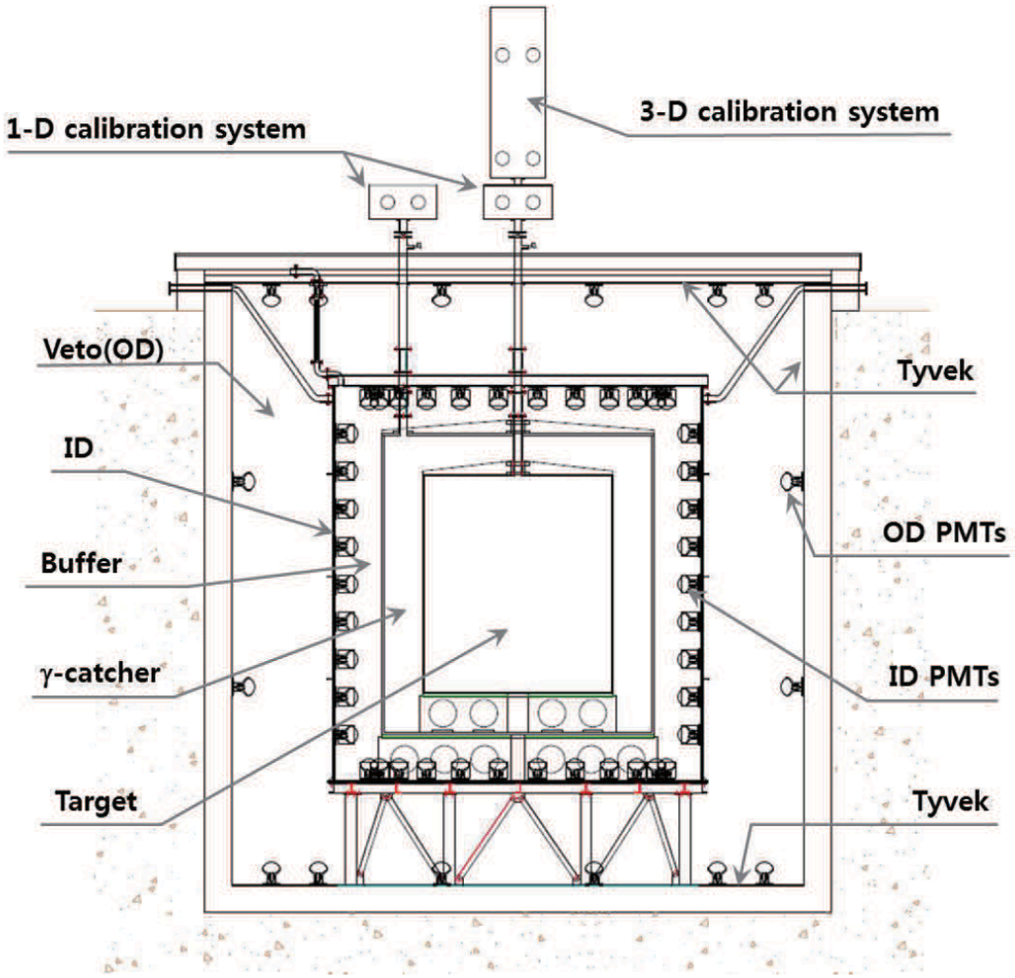
Reactor Neutrino Oscillation

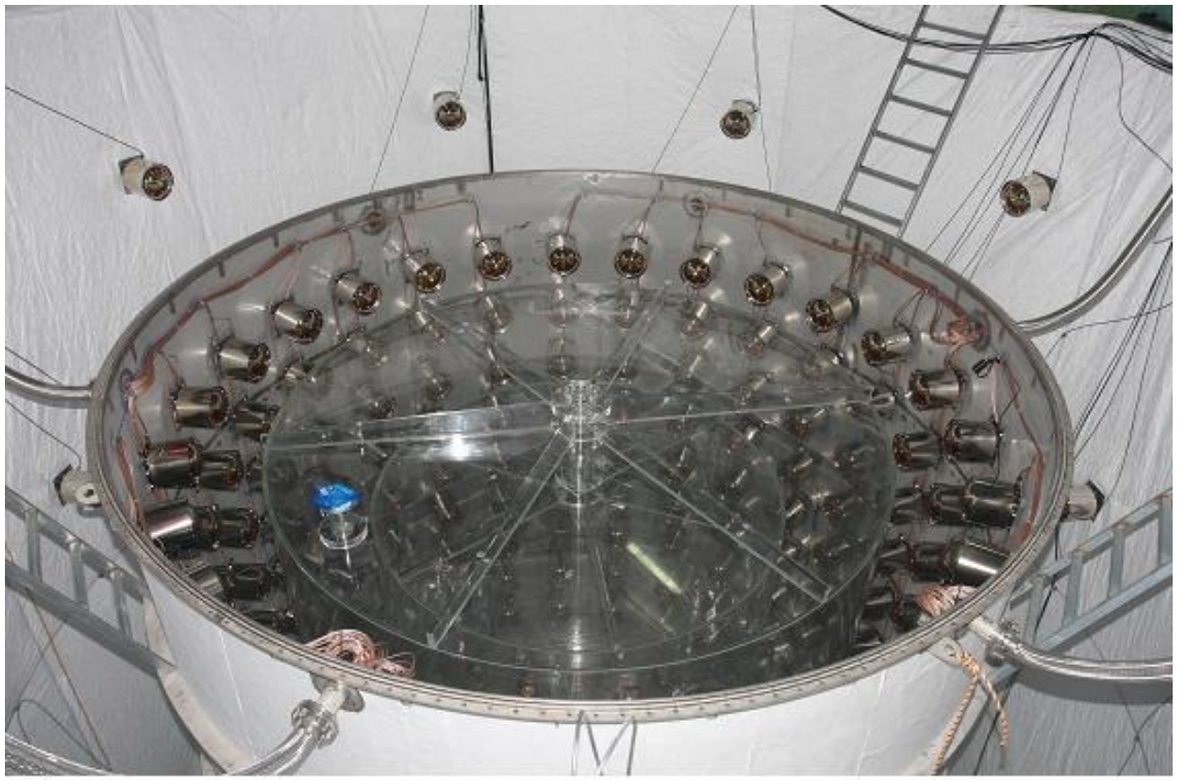


$$\Delta m^2_{ee} \equiv \cos^2\theta_{12}\Delta m^2_{31} + \sin^2\theta_{12}\Delta m^2_{32}$$ weighted squared mass difference

$\Delta m_{ee}^2 = \Delta m_{32}^2 \pm 5.21\times10^{-5}$ eV^2 (+ normal hierarchy, - inverted hierarchy)

RENO Detector

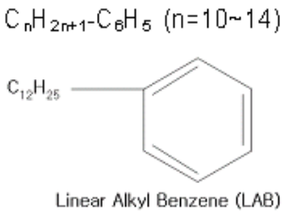


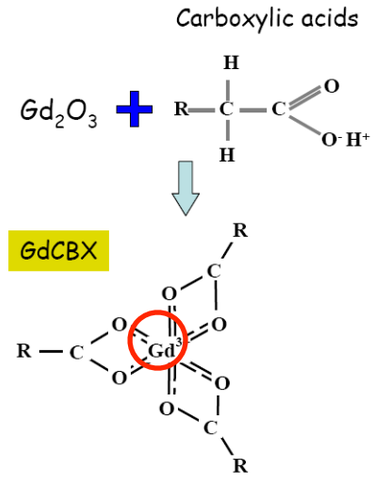


- 354 ID 10” PMTs
- 67 OD 10” PMTs

- Target : **16.5t Gd-LS** (R=1.4m, H=3.2m)
- Gamma Catcher : 30t LS (R=2.0m, H=4.4m)
- Buffer : 65t mineral oil (R=2.7m, H=5.8m)
- Veto : 350t water (R=4.2m, H=8.8m)

Detection of Reactor Antineutrinos





prompt signal

delayed signal

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

~180 μs

+ p → D + γ (2.2 MeV)

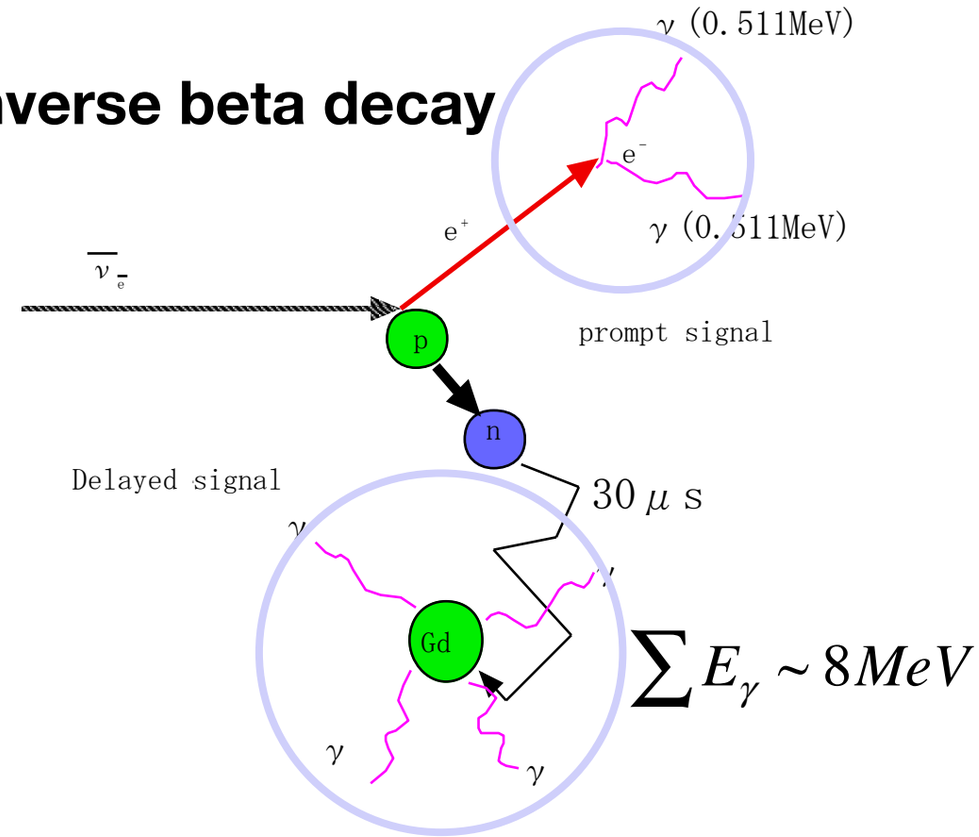
~28 μs

+ Gd (0.1%) → Gd + γ's (8 MeV

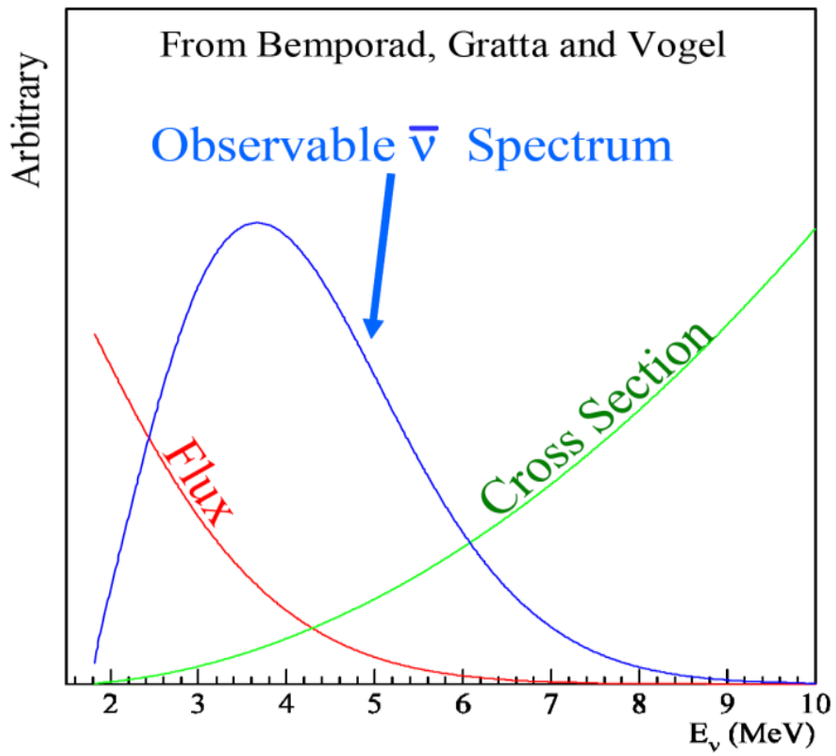
$$E_{\bar{\nu}} \cong T_{e^+} + T_n + (M_n - M_p) + m_{e^+}$$

10-40 keV ***1.8 MeV***

Inverse beta decay



$$\sum E_\gamma \sim 8MeV$$



Data Acquisition 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 (403 days)** : improved θ_{13} result

  [11 Aug, 2011~13 Oct, 2012]

  NuTel 2013, TAUP 2013, WIN 2013
- **C (500 days)** : first $|\Delta m_{ee}^2|$ result

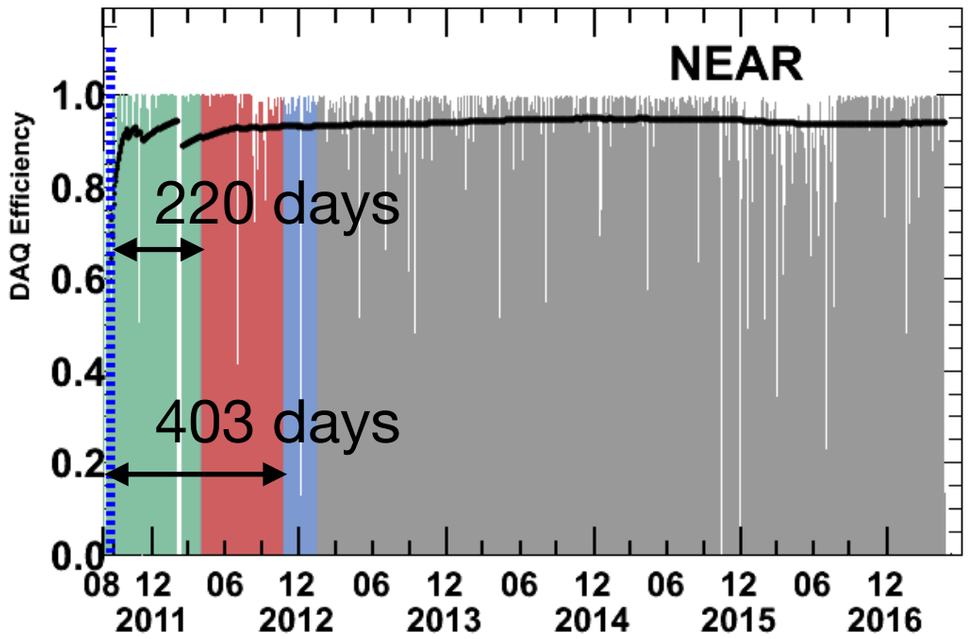
  rate+shape analysis (θ_{13} and $|\Delta m_{ee}^2|$)

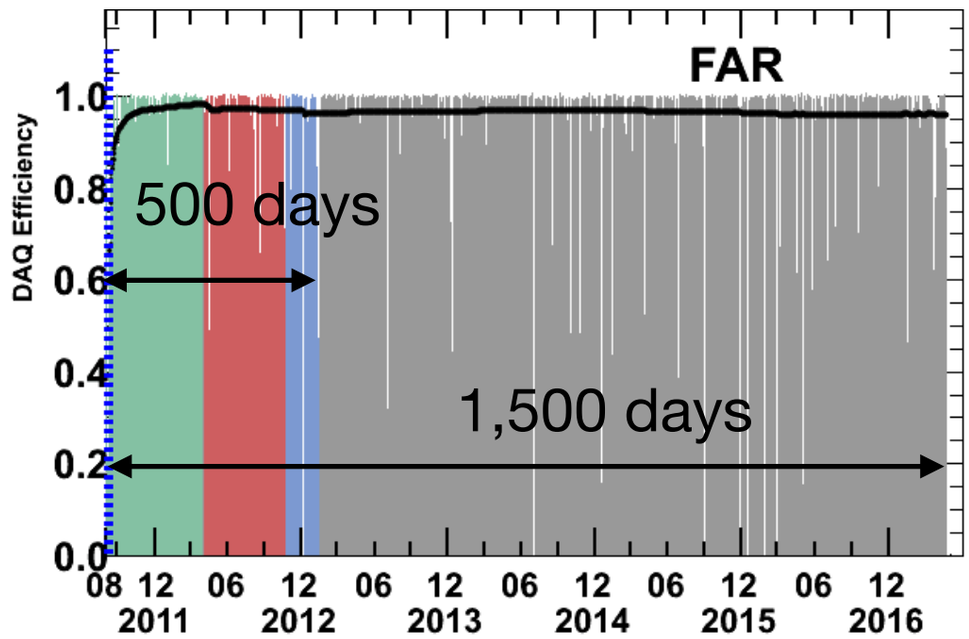
  [11 Aug, 2011 ~ 21 Jan,2013]

  PRL 116, 211801 (2016)

  submitted to PRD (arXiv:1610.04326)
- **D (1500 days)** : under analysis

  [11 Aug, 2011 ~ Sep, 2015]





Recent RENO Results and Status

- Observation of energy dependent disappearance of reactor neutrinos to measure $|\Delta m_{ee}^2|$ and θ_{13} using ~500 days of data

  - "Observation of Energy and Baseline Dependent Reactor Antineutrino Disappearance in the RENO Experiment" (PRL 116, 211801, 2016)

  - The detailed description has been submitted to PRD (arXiv:1610.04326)

- Measurement of **absolute reactor neutrino flux** (1,500 days)

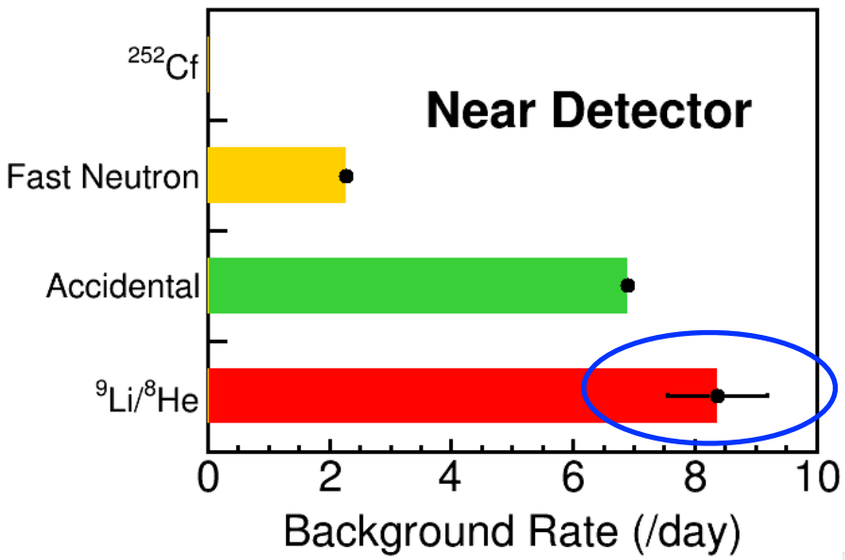
- Observation of an **excess at ~5 MeV** in reactor neutrino spectrum using ~1,500 days

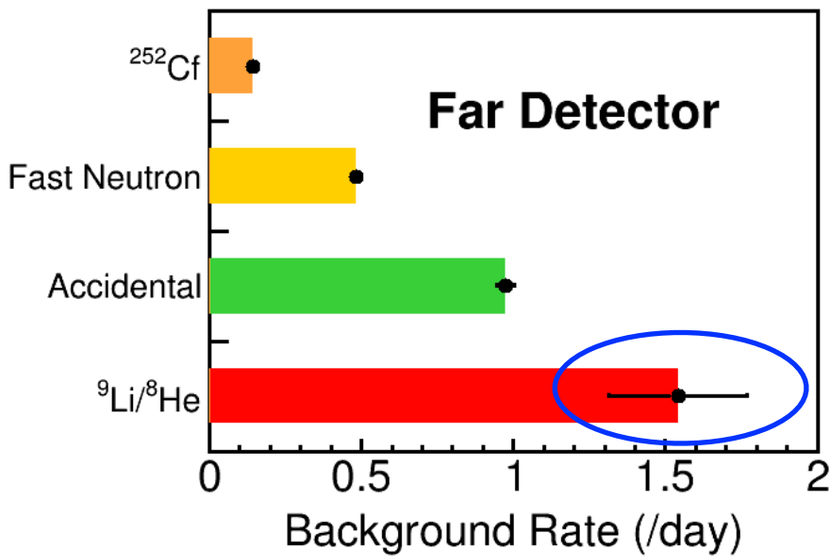
- independent measurement of **θ_{13} with n-H** for a delay signal (additoinal background reduction achieved)

- Obtained results from a **sterile neutrinos** search

IBD candidates and Backgrounds (500 days)

	Near	Far
DAQ live time	458.49	489.93
IBD candidates	290,755	31,541
Total BKG rate [day^{-1}]	17.54±0.83	3.14±0.21
IBD [day^{-1}] after BKG subtraction	616.67±1.44	61.24±0.42



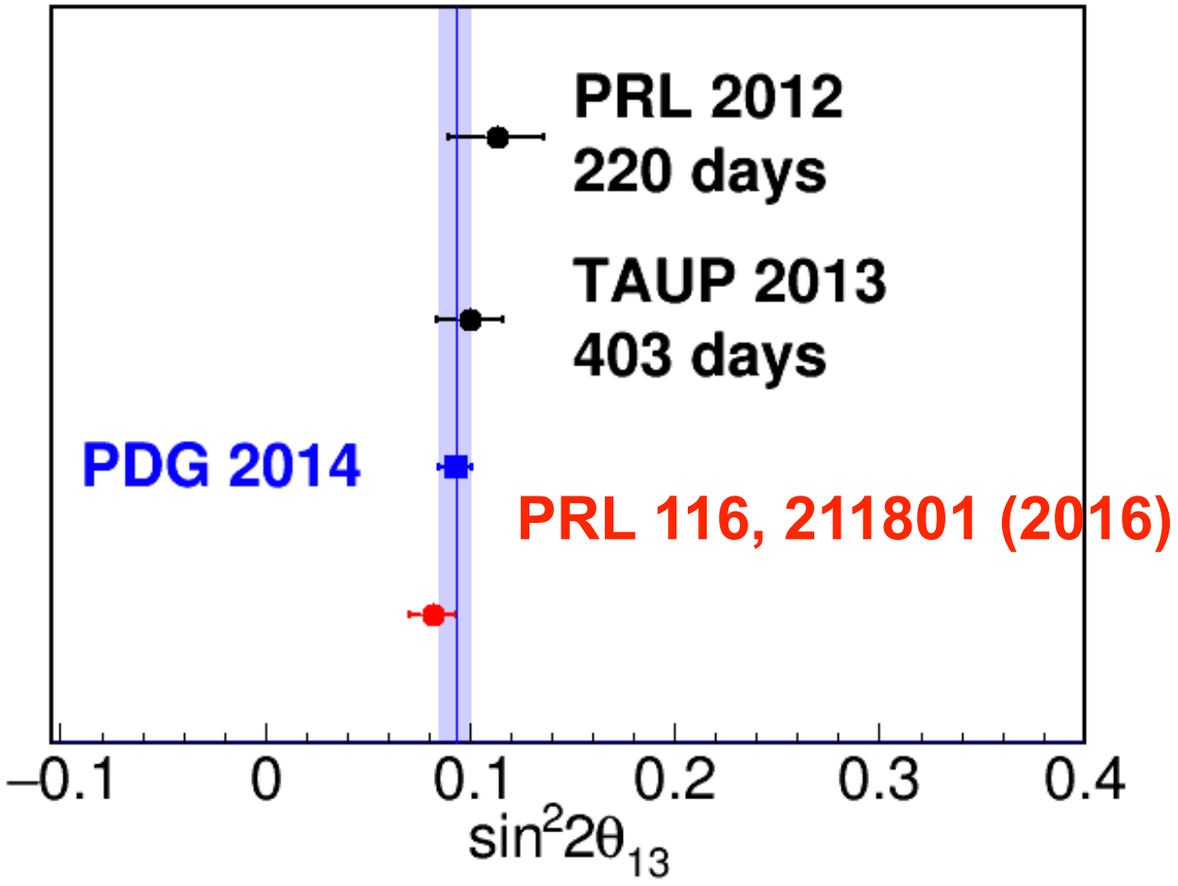


θ_{13} Measurement by Rate-Only Analysis (500 days)

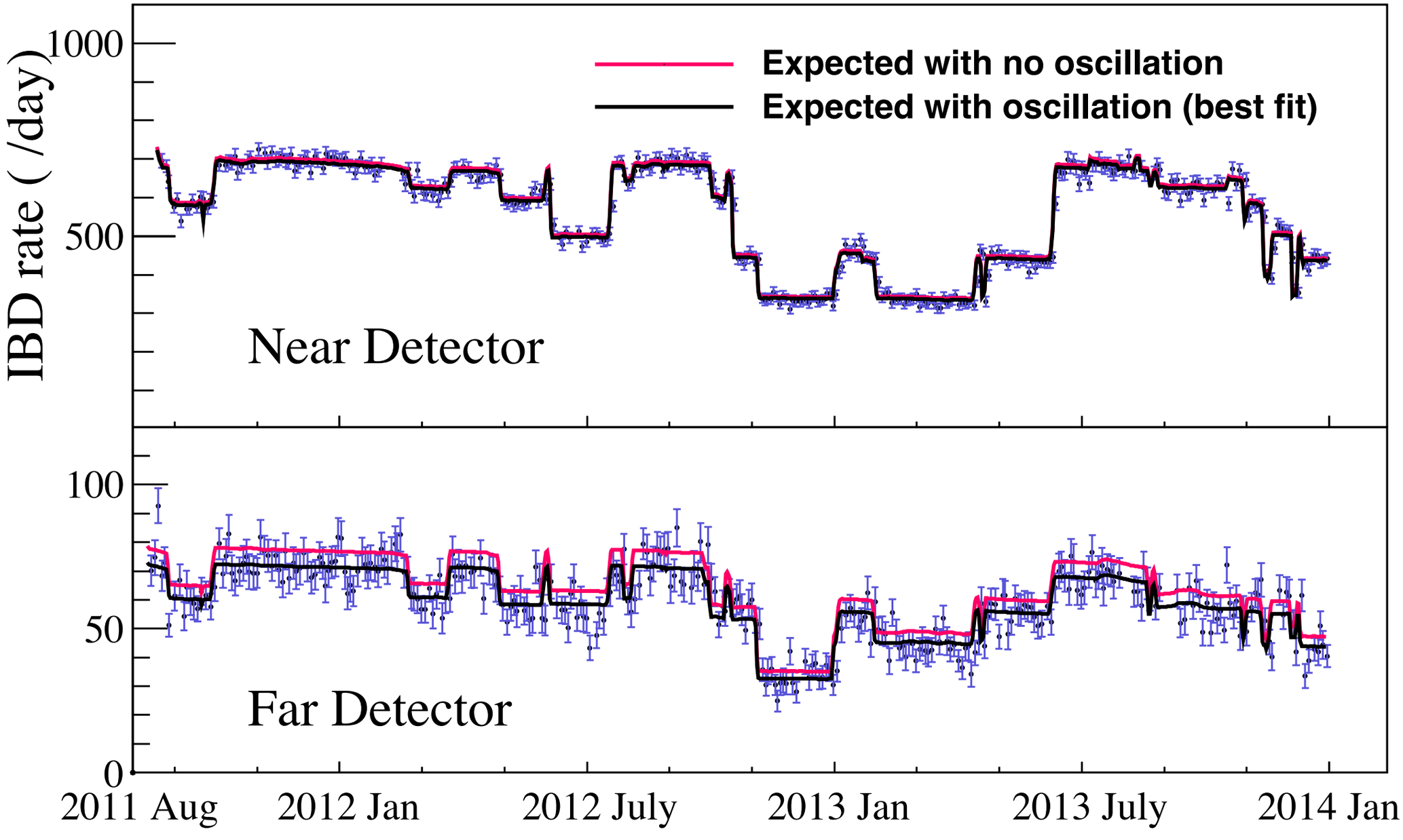
$$\sin^2 2\theta_{13} = 0.087 \pm 0.009(\text{stat.}) \pm 0.007(\text{syst.})$$

$|\Delta m_{ee}^2|$ = 2.49 x 10^{-3} eV^2 is used (PDG 2014)

By minimizing $\chi^2 = \dfrac{\left(O^{F/N} - T^{F/N}\right)^2}{\left(U\right)^2} + Pull\_Terms$

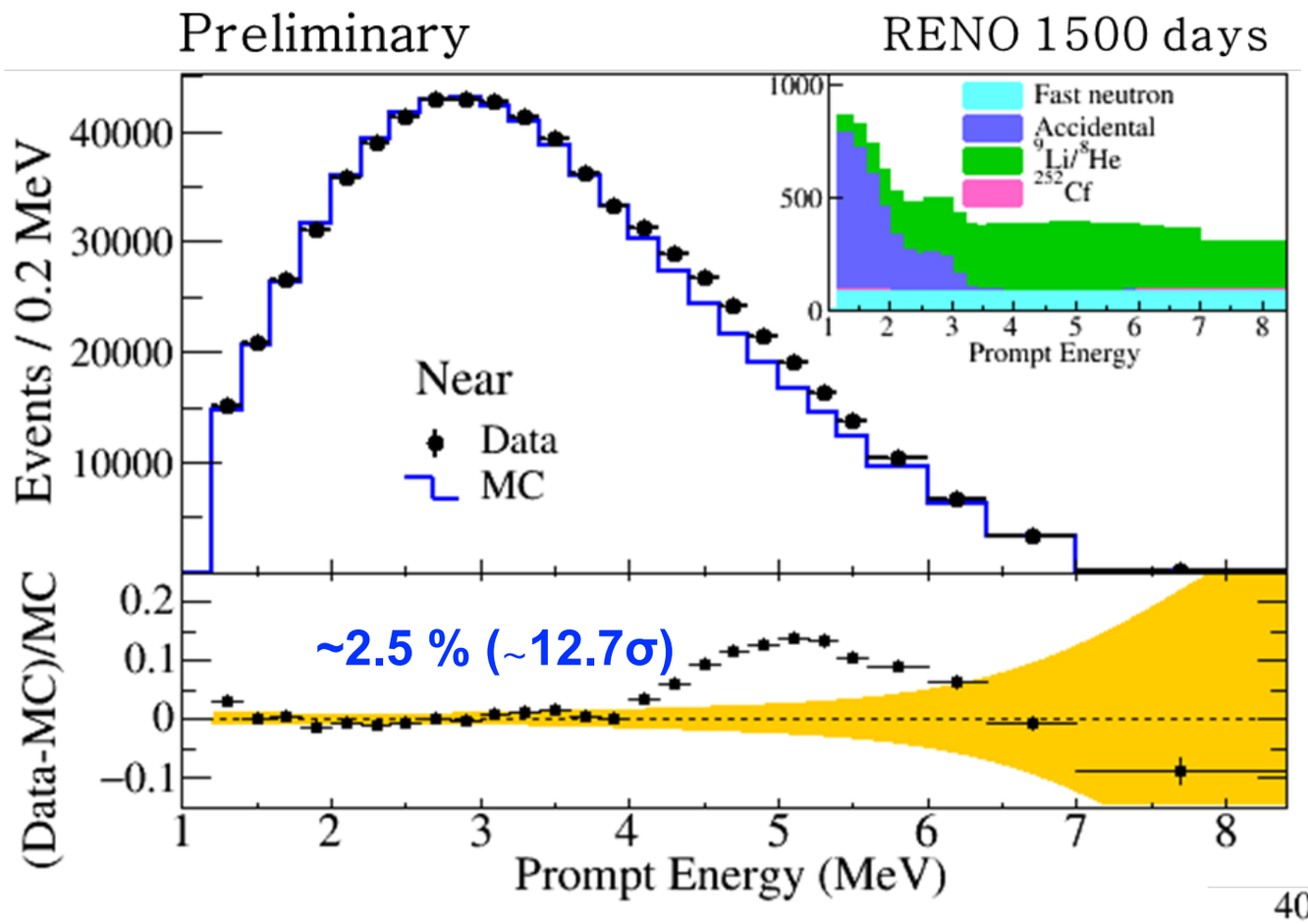


Observed Daily Averaged IBD Rate (~500 days)



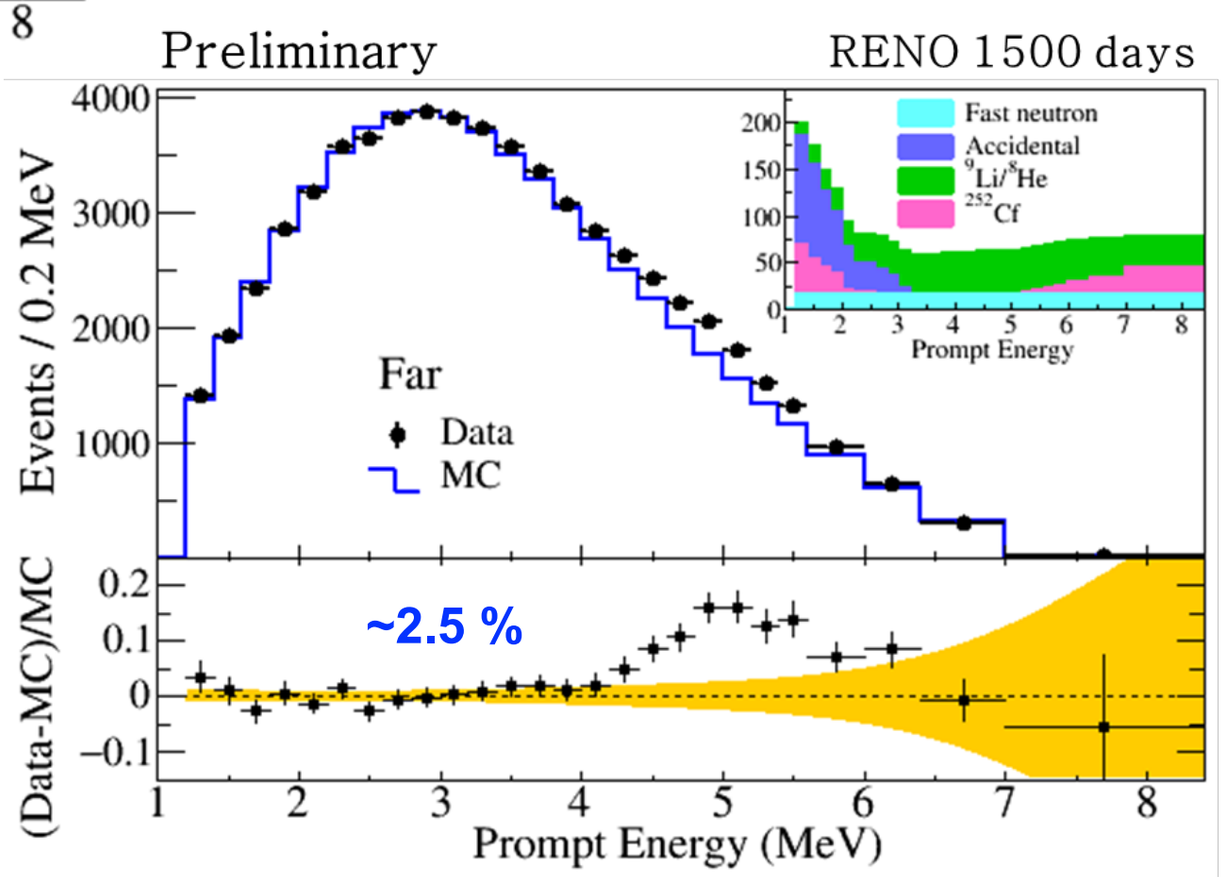
- Good agreement with observed rate and prediction.
- Accurate measurement of thermal power by reactor neutrinos

Measured Spectra of IBD Prompt Signal

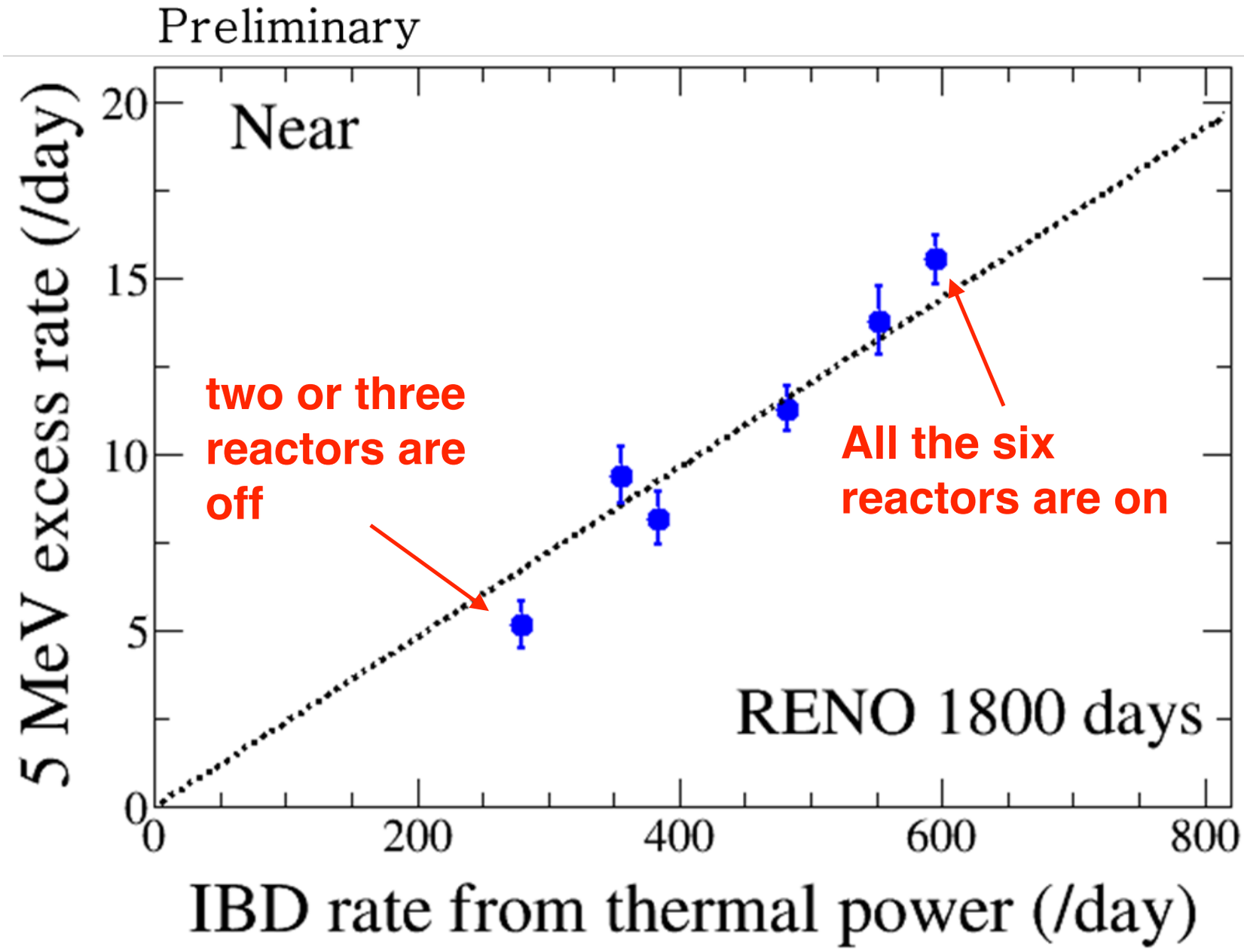


Clear excess at 5 MeV

RENO's observation of 5 MeV excess



Correlation of 5 MeV Excess with Reactor Power

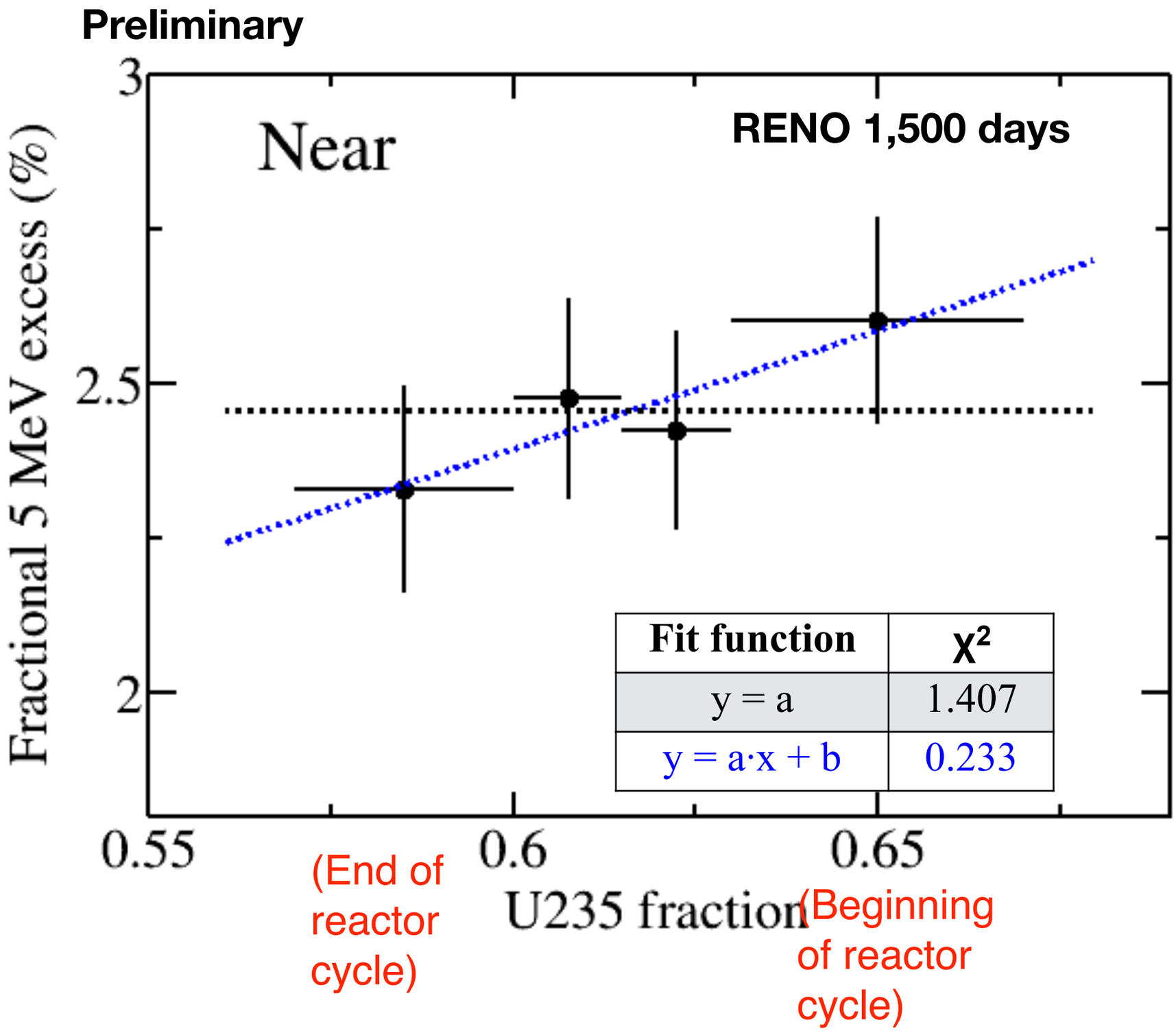


5 MeV excess has a clear correlation with reactor thermal power !

The 5 MeV excess comes from reactors!

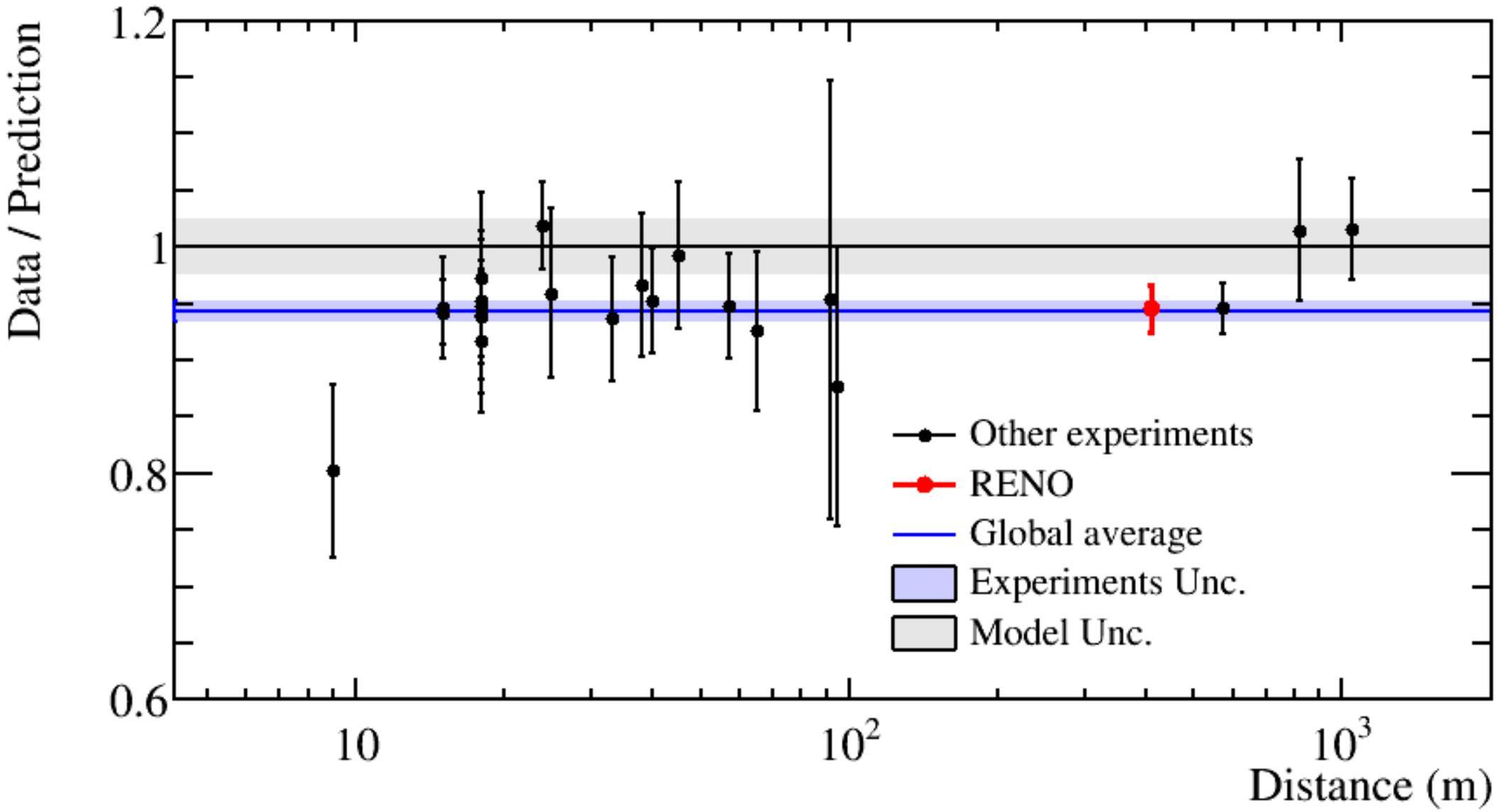
Correlation of 5 MeV Excess with ^{235}U Isotope Fraction

^{235}U fraction corresponds to freshness of reactor fuel



Measurement of Absolute Reactor Neutrino Flux (preliminary)

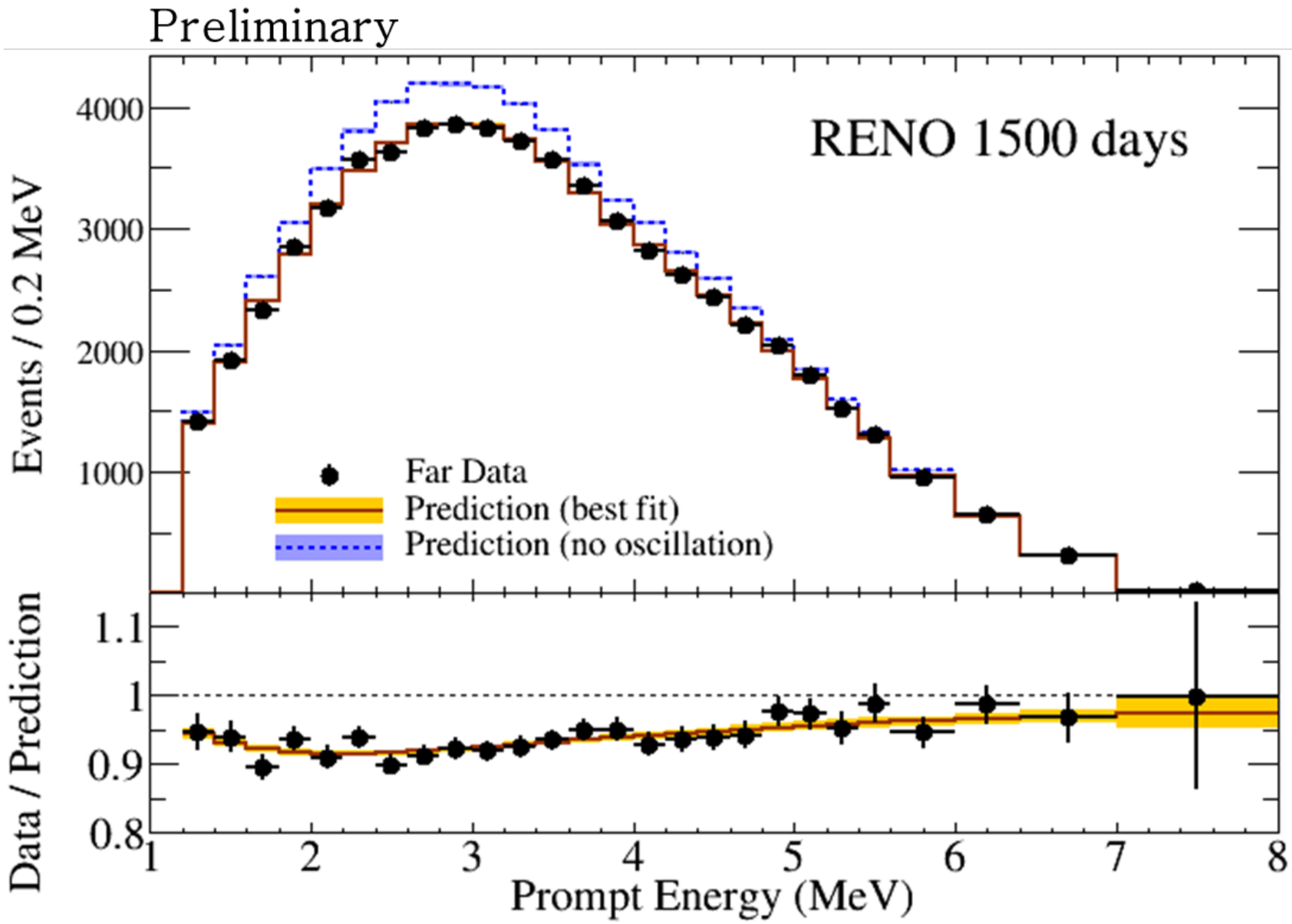
RENO 1500 days at near (411 m)	Data / Prediction (Huber + Mueller)
	0.946 +- 0.021



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

Results from Spectral Fit (1,500 days)

Energy-dependent disappearance of reactor antineutrinos



Fit using far-to-near ratio

Observed Far/Near

Expected Far/Near

χ^2 fitter

Minimize X^2 Function

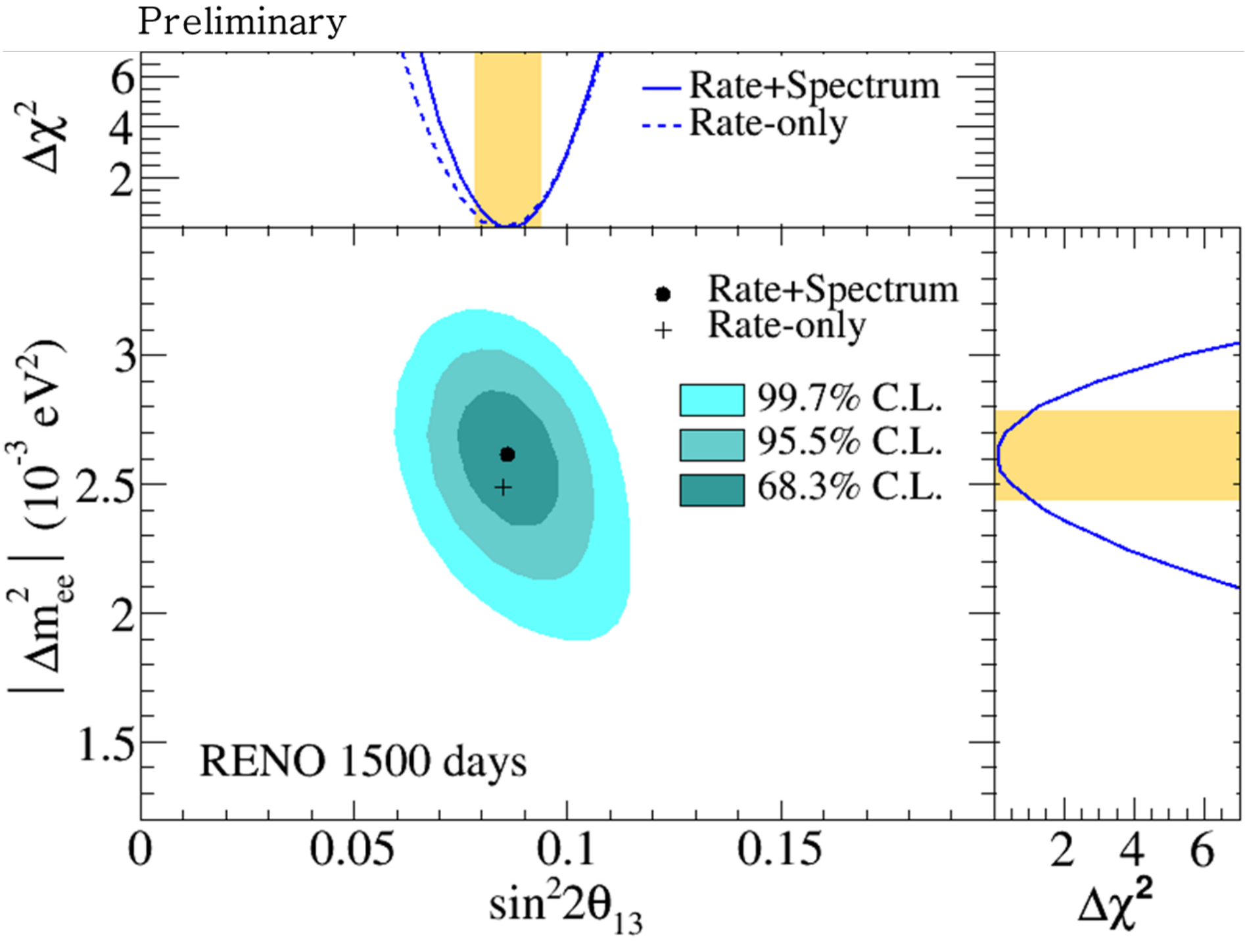
$$\chi^2 = \sum_{P=before,After} \left\{ \sum_{i=1\sim N_b} \frac{\left(\frac{N_{obs}^{F,P,i}}{N_{obs}^{N,P,i}} - \frac{N_{Exp}^{F,P,i}}{N_{Exp}^{N,P,i}} \right)^2}{\left(U_i\right)^2} \right\} + Pull\_Terms$$

$$U_i = \frac{N_{obs}^{F,i}}{N_{obs}^{N,i}} \cdot \sqrt{\frac{N_{obs}^{F,i} + N_{bkg}^{F,i}}{(N_{obs}^{F,i})^2} + \frac{N_{obs}^{N,i} + N_{bkg}^{N,i}}{(N_{obs}^{N,i})^2}}$$

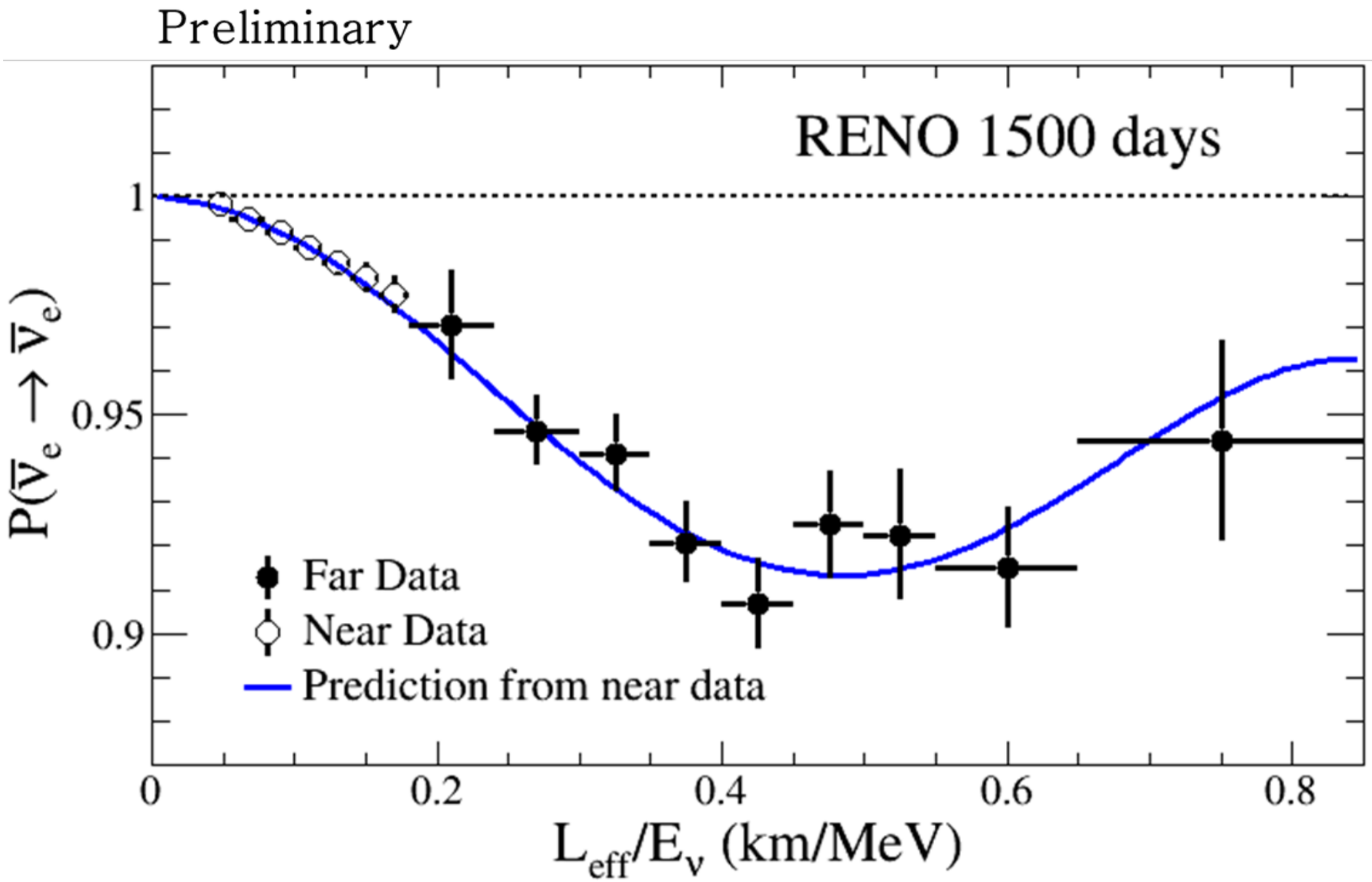
$$\sin^2 2\theta_{13} = 0.086 \pm 0.006(\text{stat.}) \pm 0.005(\text{syst.}) \textbf{(± 9%)}$$

$$\left|\Delta m^2_{ee}\right| = 2.61^{+0.15}_{-0.16}(\text{stat.})^{+0.09}_{-0.09}(\text{syst.})\,(\times 10^{-3}\text{eV}^2) \quad \textbf{(± 7%)}$$

Allowed Regions in $|\Delta m^2_{ee}|$ and $\sin^2 2\theta_{13}$ Plane



Observed L/E Dependent Oscillation



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

More Precise Measurement of θ_{13} and $|\Delta m_{ee}|^2$

PRL 116, 211801 (2016), Submitted to PRD (arXiv:1610.04326)

500 days	Mean	Stat.	Sys.	Precision
$\sin^2 2\theta_{13}$	0.082	+0.009 -0.009	+0.006 -0.006	12%
$\|\Delta m_{ee}^2\|$ ($\times 10^{-3}$ eV^2)	2.62	+0.21 -0.23	+0.12 -0.13	10%

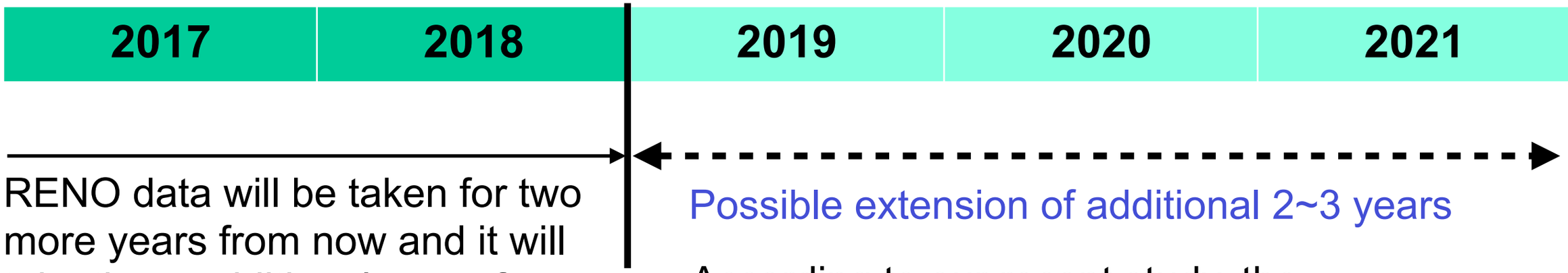
New results (preliminary)

1500 days	Mean	Stat.	Sys.	Precision
$\sin^2 2\theta_{13}$	0.086	+0.006 -0.006	+0.005 -0.005	**9%**
$\|\Delta m_{ee}^2\|$ ($\times 10^{-3}$ eV^2)	2.61	+0.15 -0.16	+0.09 -0.09	**7%**

- Systematic errors are reduced due to background reduction and larger statistics of control samples.

Plan and Prospect

Plan for RENO Data Taking



RENO data will be taken for two more years from now and it will take three additional years for the analysis.

$\sin^2 2\theta_{13}$ and $|\Delta m_{ee}^2|$ will approach to **~6% precision** (our design goal).

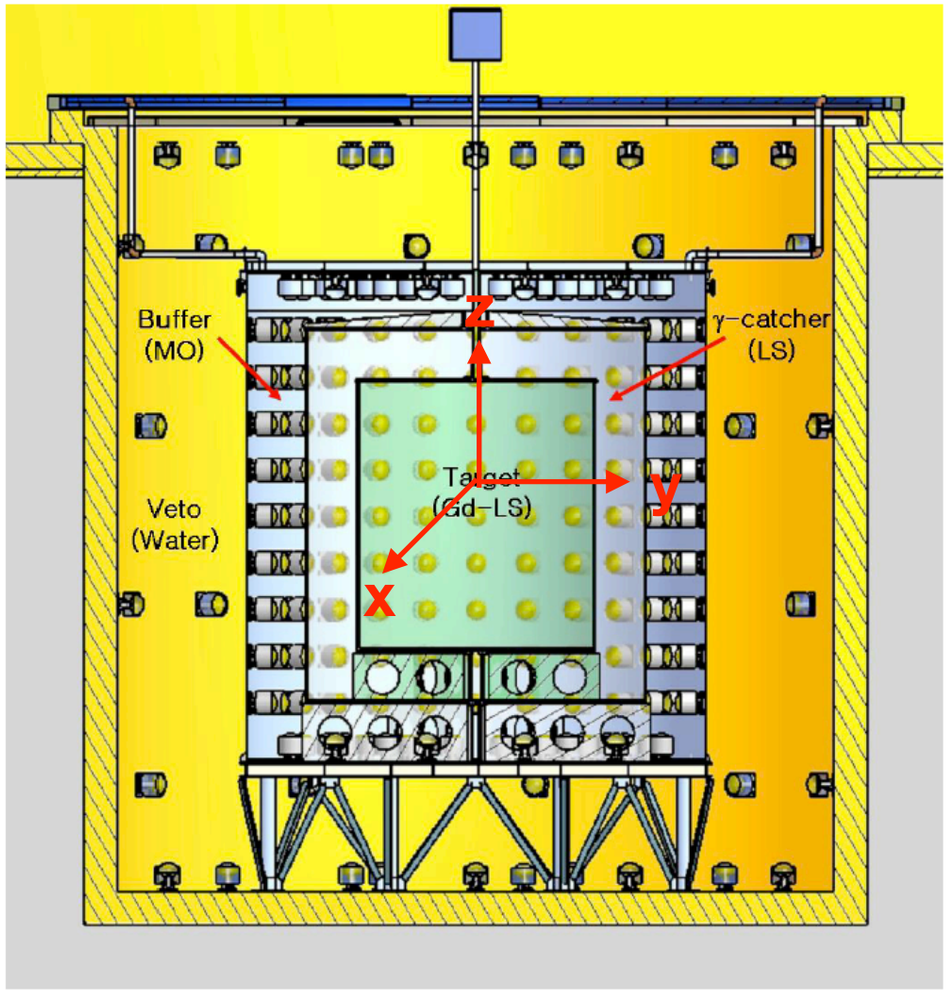
Possible extension of additional 2~3 years

According to our recent study, the systematic error of $|\Delta m_{ee}|^2$ is smaller than the statistical error.

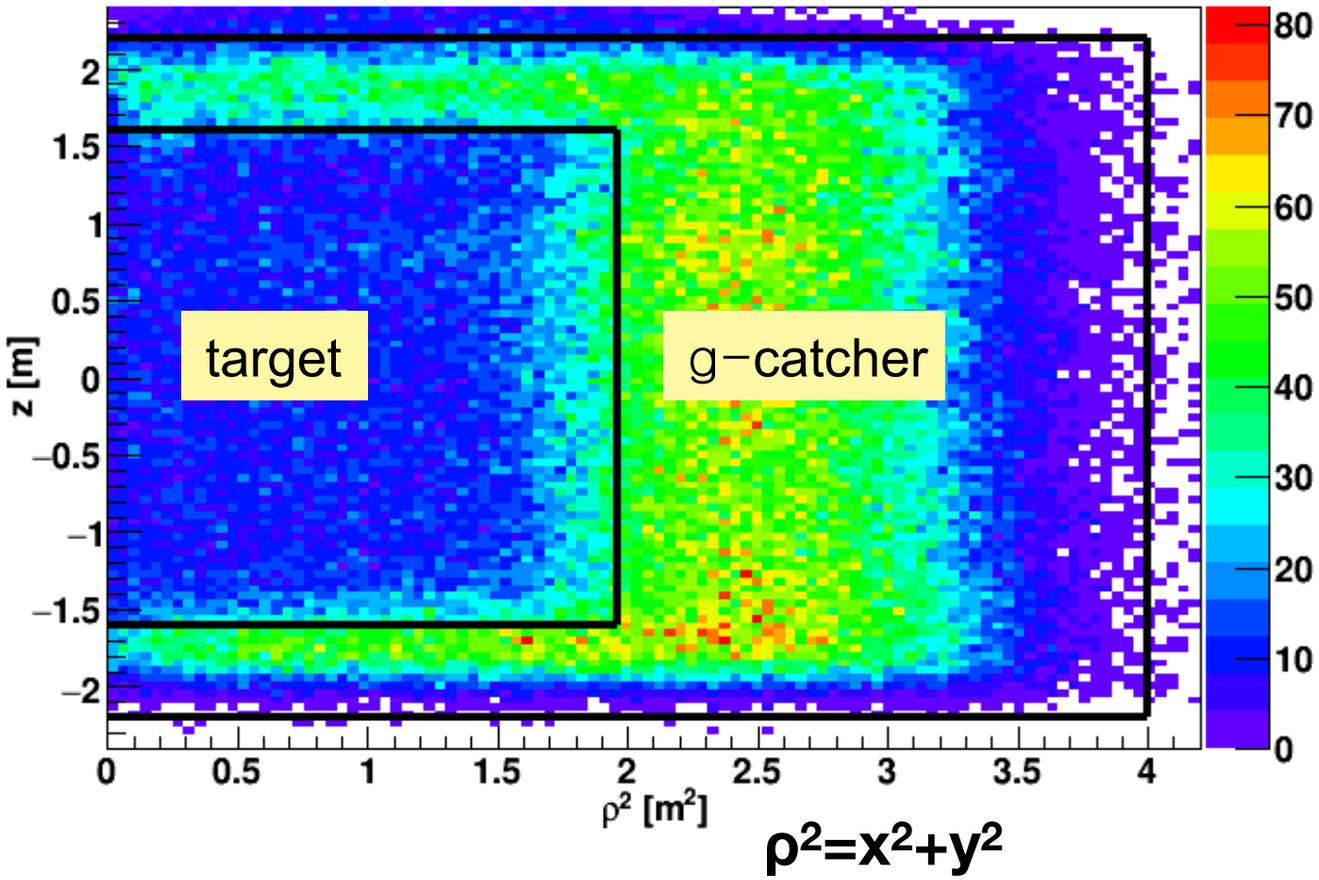
	500 days	1,500 days	~3,500 days
$\sin^2 2\theta_{13}$	12%	9%	6 ~ 7 %
$\|\Delta m_{ee}^2\|$	10%	7%	4 ~ 5 %

n-H IBD Analysis (preliminary)

- Independent measurement of θ_{13} value.
- Consistency and systematic check on reactor neutrinos



n-H IBD Event Vertex Distribution



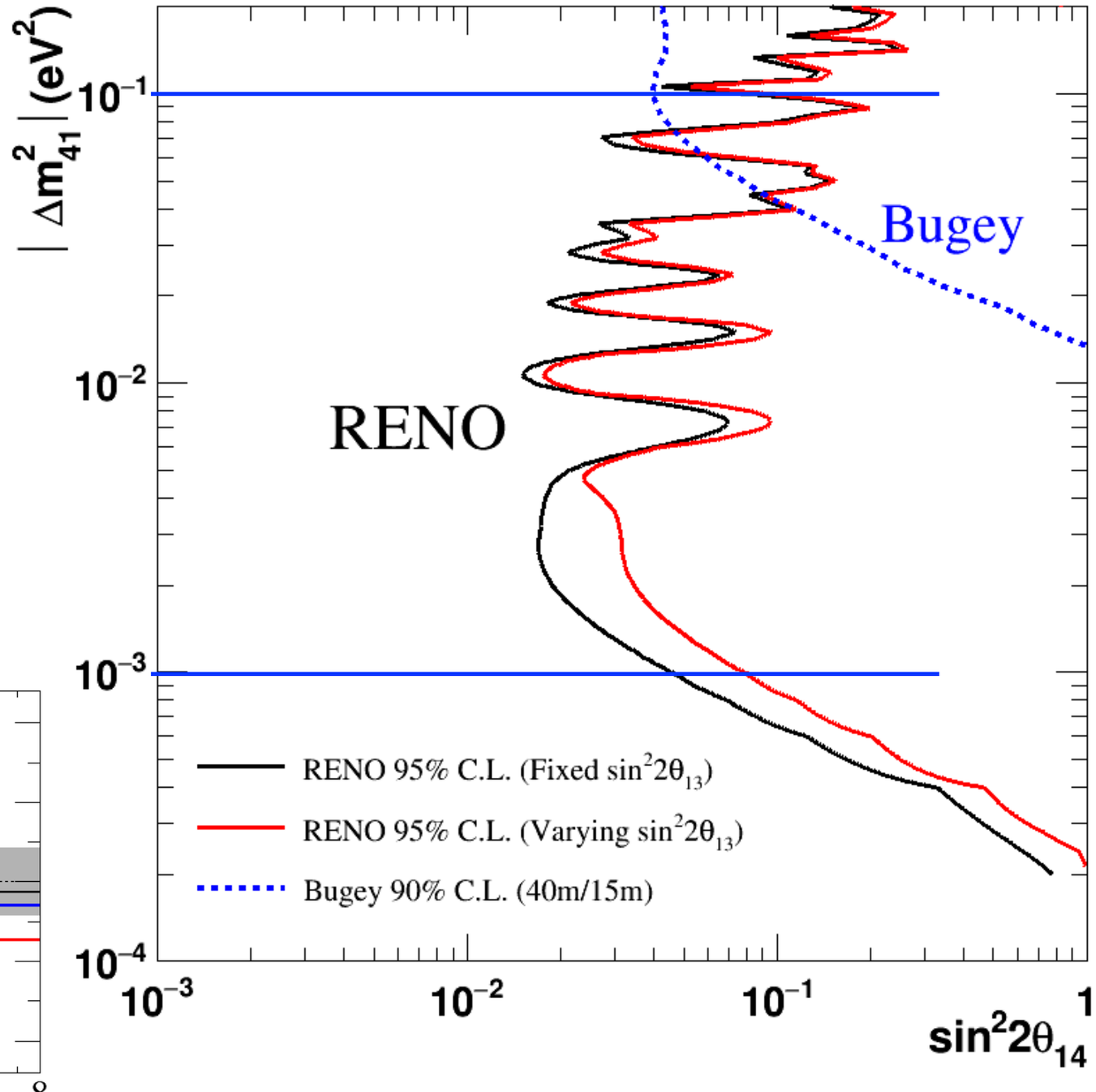
$\rho^2=x^2+y^2$

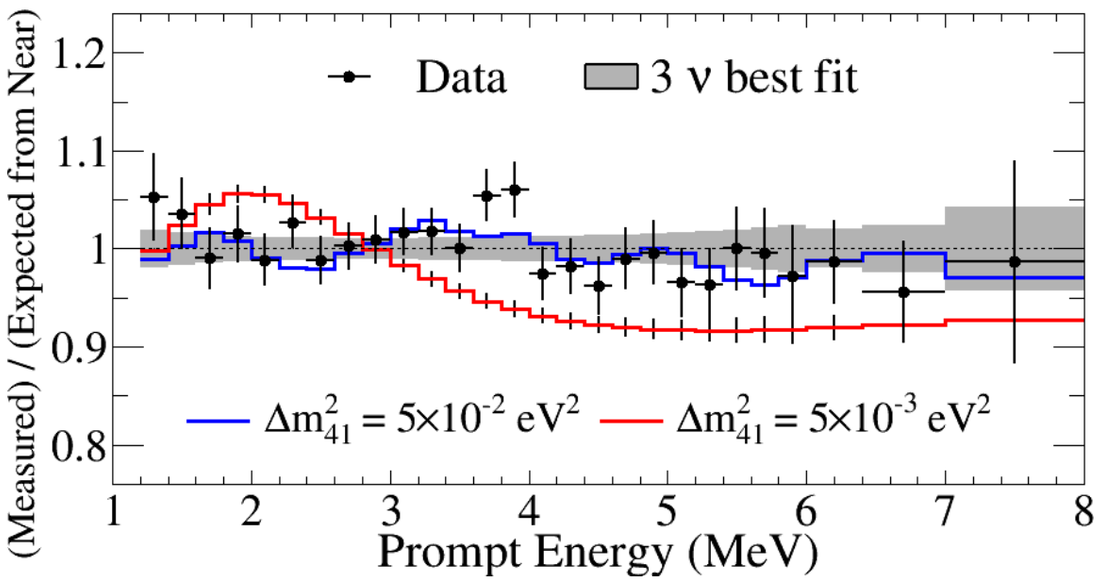
400 days of data before ^{252}Cf contamination

$$\sin^2 2\theta_{13} = 0.097 \pm 0.013(\text{stat.}) \pm 0.015(\text{syst.})$$

Light Sterile Neutrino Search Results (preliminary)

- All 500 days of RENO data
- Consistent with standard 3-flavor neutrino oscillation model
- Able to set stringent limits in the region $10^{-3} < \Delta m_{ee}^2 < 0.1\ eV^2$





full curves assumes $\sin^2 2\theta_{14} = 0.1$

Summary

- More precise measurements of θ_{13} and $|\Delta m_{ee}^2|$ energy dependent disappearance of reactor neutrinos (preliminaries)

$$\sin^2 2\theta_{13} = 0.086 \pm 0.006(\text{stat.}) \pm 0.005(\text{syst.}) \quad \pm 0.008\ (9\%)$$

$$\left|\Delta m^2_{ee}\right| = 2.61^{+0.15}_{-0.16}(\text{stat.})^{+0.09}_{-0.09}(\text{syst.}) \quad \pm 0.18\ (7\%)$$

- Measured absolute reactor neutrino flux : R= 0.946 ± 0.021
- Observed an excess at 5 MeV in reactor neutrino spectrum
- $\sin^2 2\theta_{13}$ and $|\Delta m_{ee}^2|$ to 6% accuracy after 2 more years data taking
- Additional 2~3 years of data taking under consideration to improve $|\Delta m_{ee}^2|$ accuracy