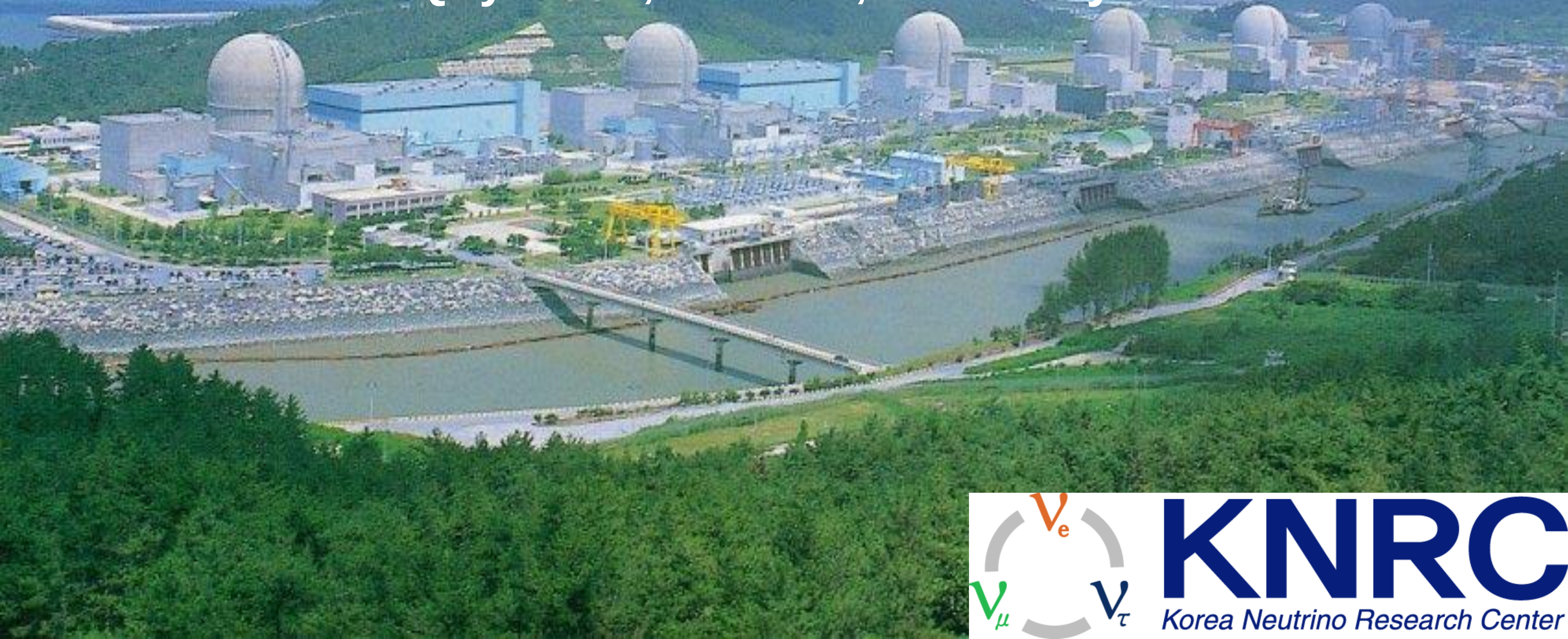
Results from RENO Experiment

“June Ho Choi (Dongshin University)”

“ Neutrinos”

“Quy Nhon, Vietnam, 16-22 July 2017”



KNRC
Korea Neutrino Research Center

RENO Collaboration

Reactor **E**xperiment for **N**eutrino **O**scillation

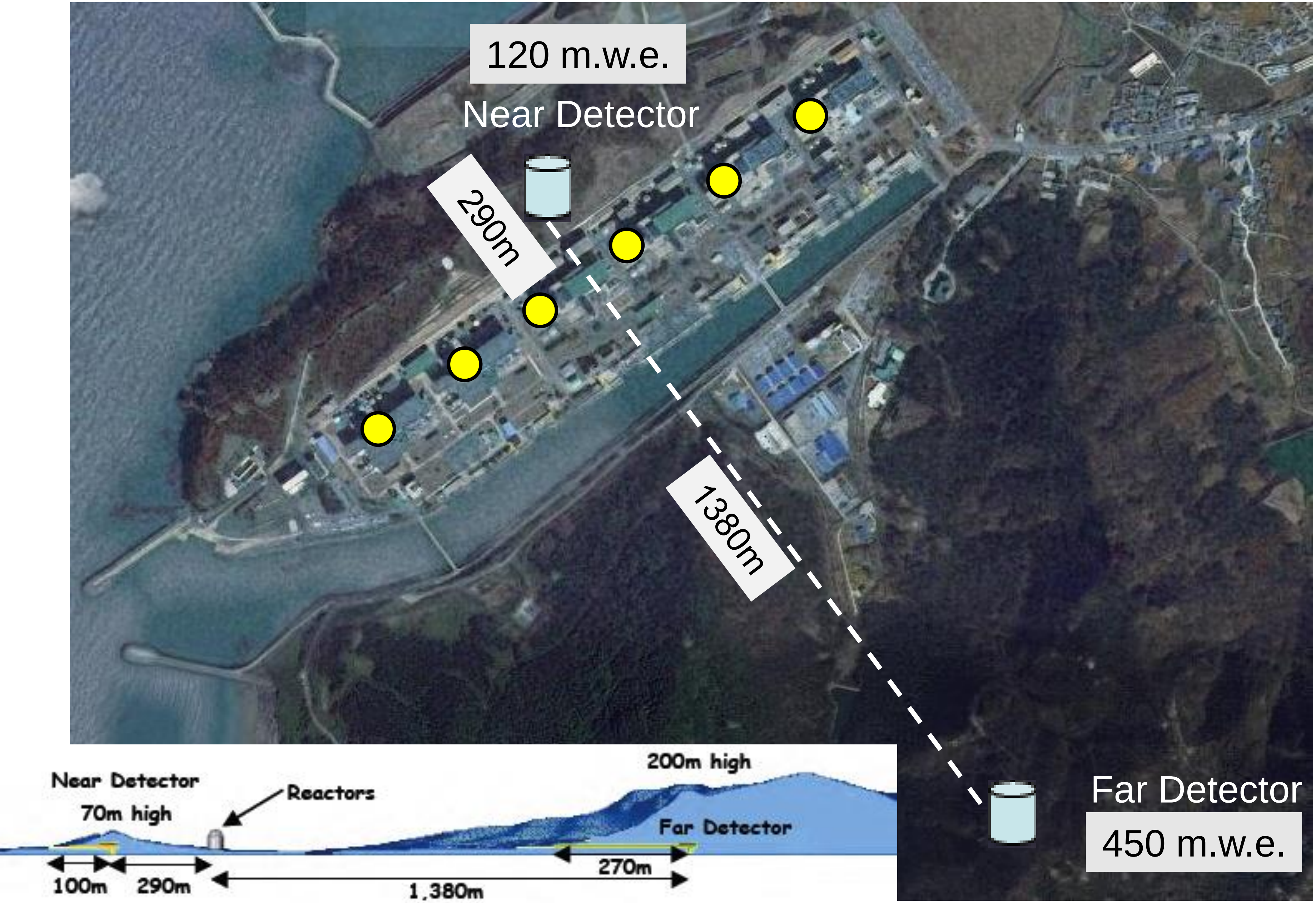
(8 institutions and 40 physicists)

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

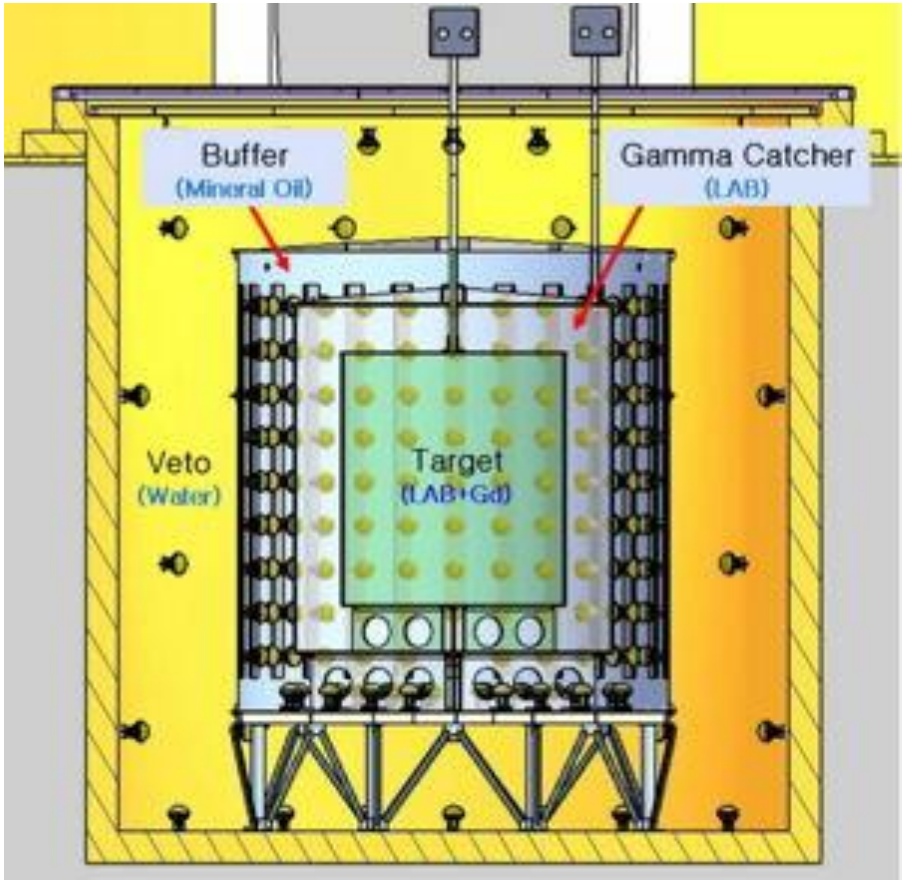
- Total cost : **$10M**
- Start of project : **2006**
- The first experiment running with both near & far detectors from **Aug. 2011**

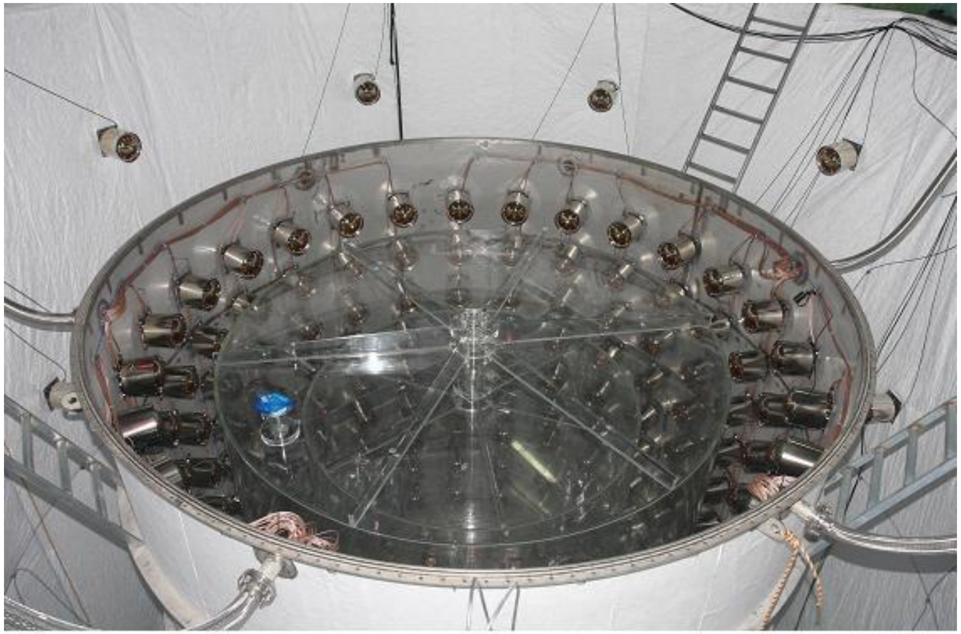
YongGwang (靈光) :

RENO Experimental Set-up



RENO Detector





- 354 ID 10” PMTs
- 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

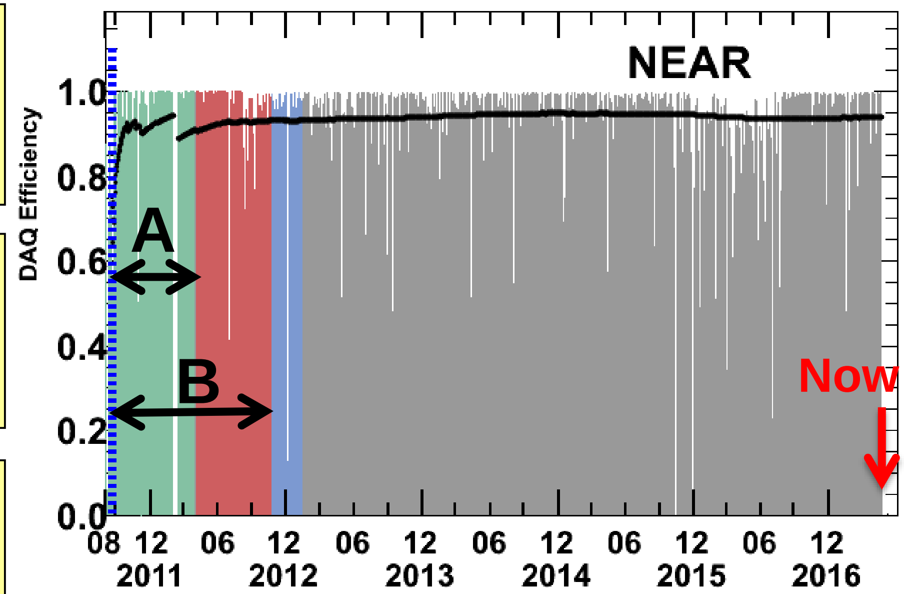
- Data taking began on Aug. 1, 2011 with both near and far detectors.
  (DAQ efficiency : ~95%)

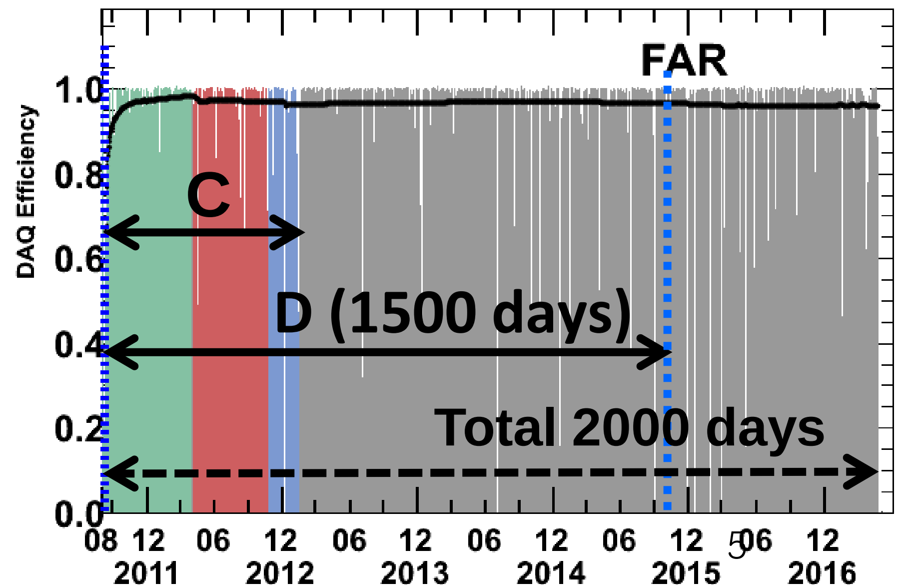
- **A (220 days)** : **First θ_{13} result**
  [11 Aug, 2011~26 Mar, 2012]
  PRL 108, 191802 (2012)

- **B (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)** : **New results**
  [11 Aug, 2011 ~ Sep, 2015]





New Results from RENO

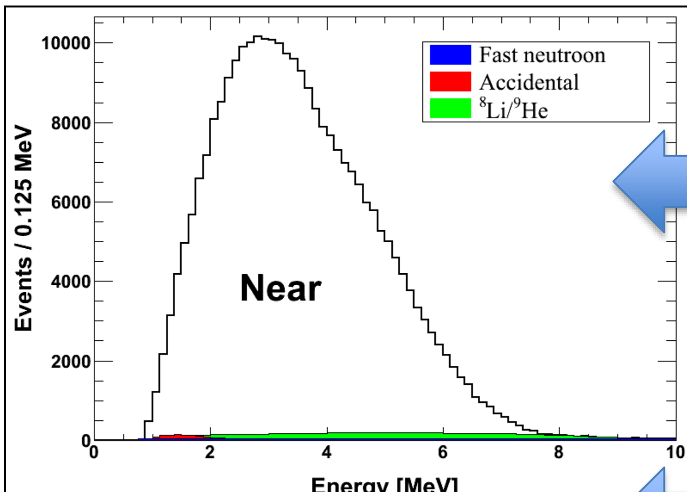
- Observation of energy dependent disappearance o f reactor neutrinos to measure Δm_{ee}^2 and θ_{13} using 1500 live days of data (Aug. 2011 ~ Sep. 2015)
- Observation of an excess at ~5 MeV in reactor neu trino spectrum using 1500 days of data
- Measurement of absolute reactor neutrino flux usin g 1500 days

Coincidence of prompt and delayed signals

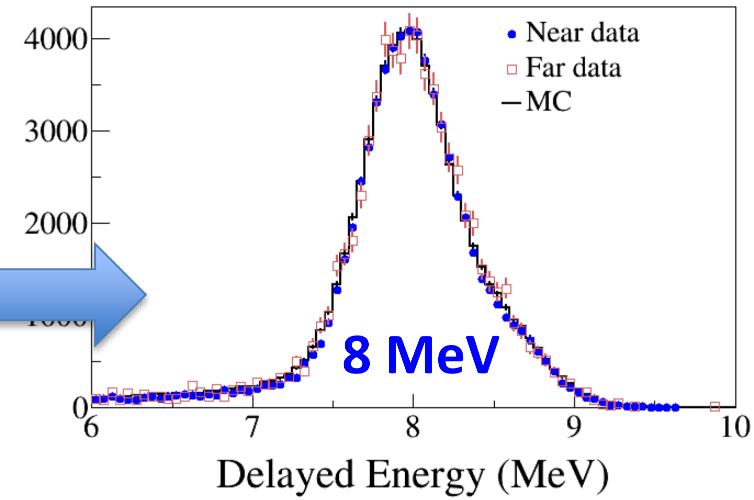
(prompt signal)

$$\bar{\nu}_e + p \rightarrow e^+ + n$$ (delayed signal)

Prompt signal



Delayed signal

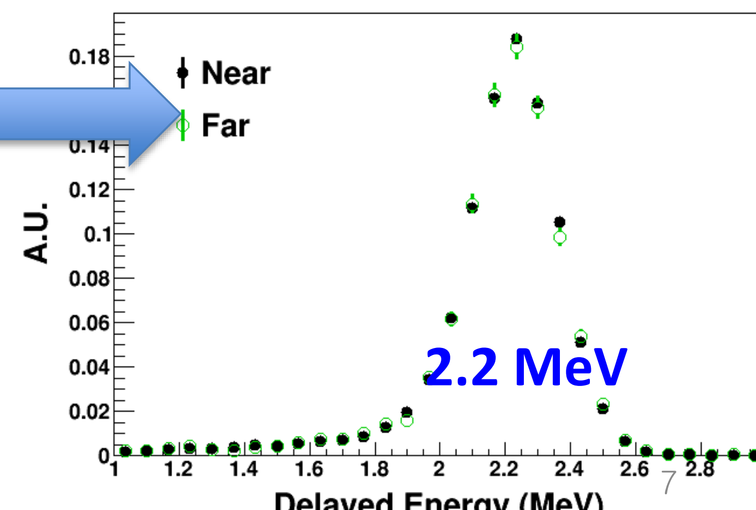


n-Gd IBD

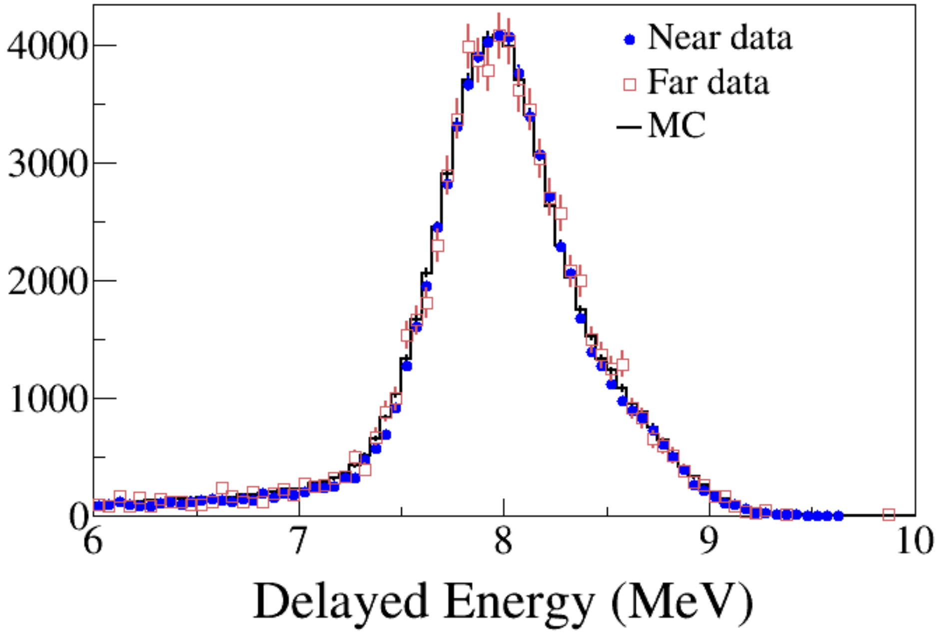
~30 μs

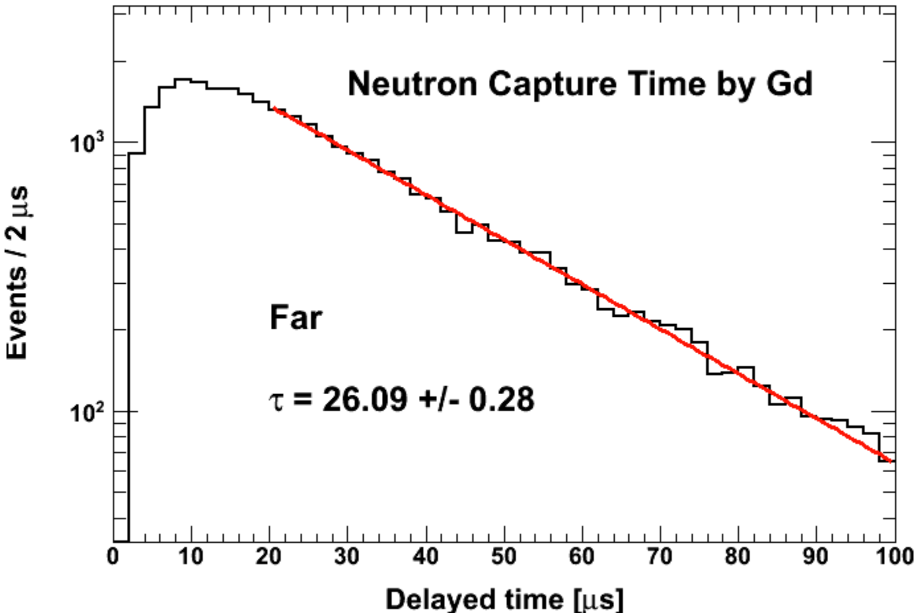
~200 μs

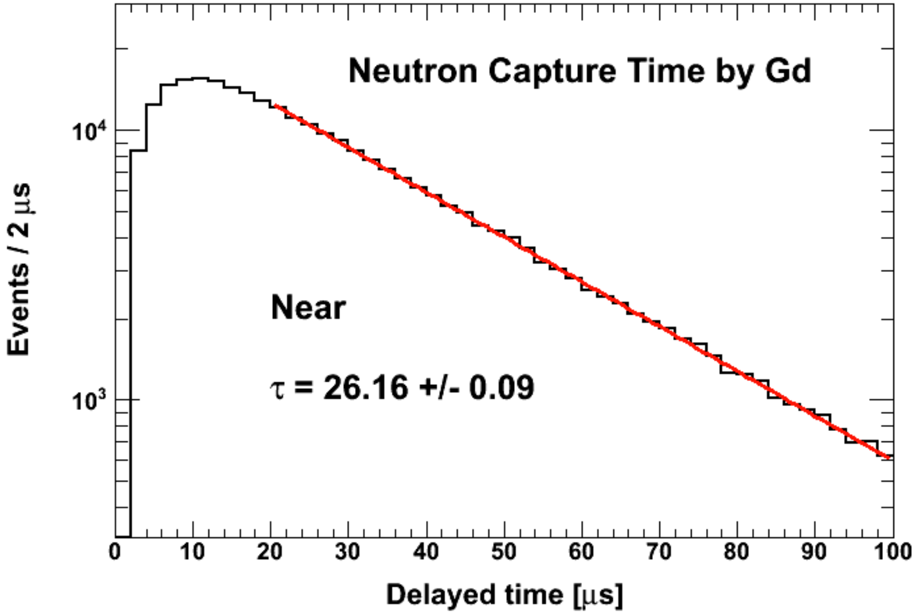
n-H IBD



Delayed Signals from Neutron Capture by Gd

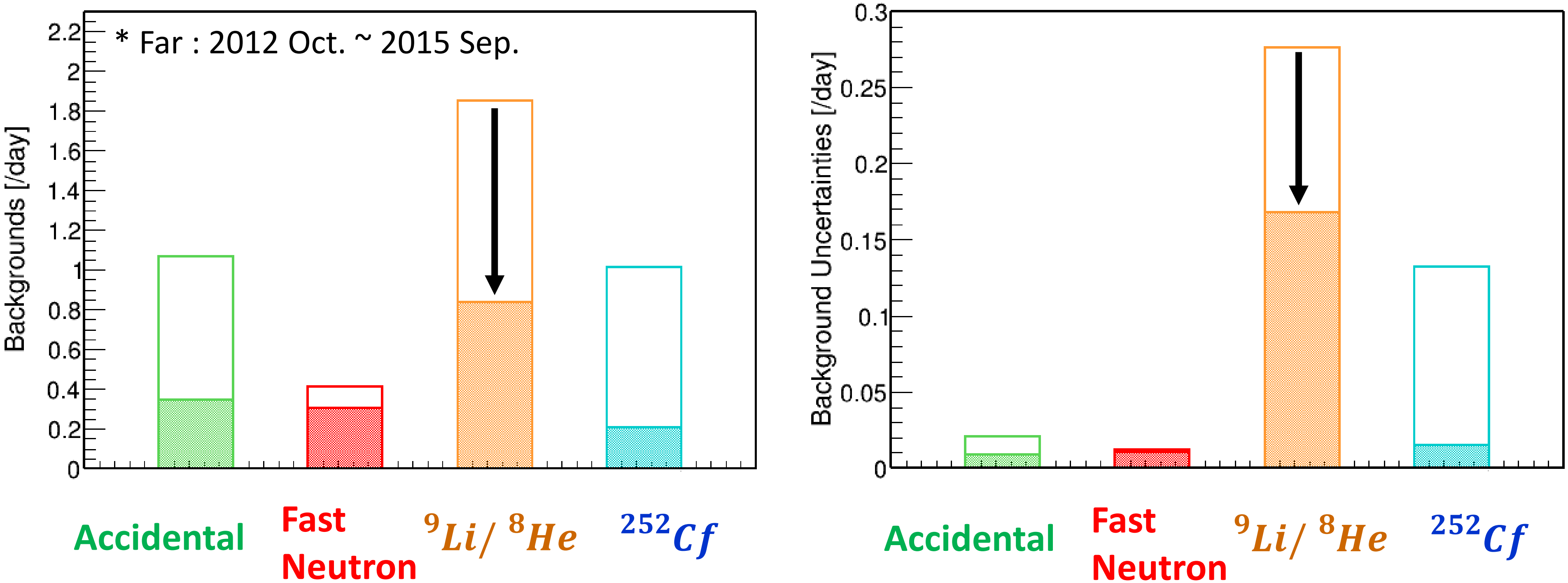






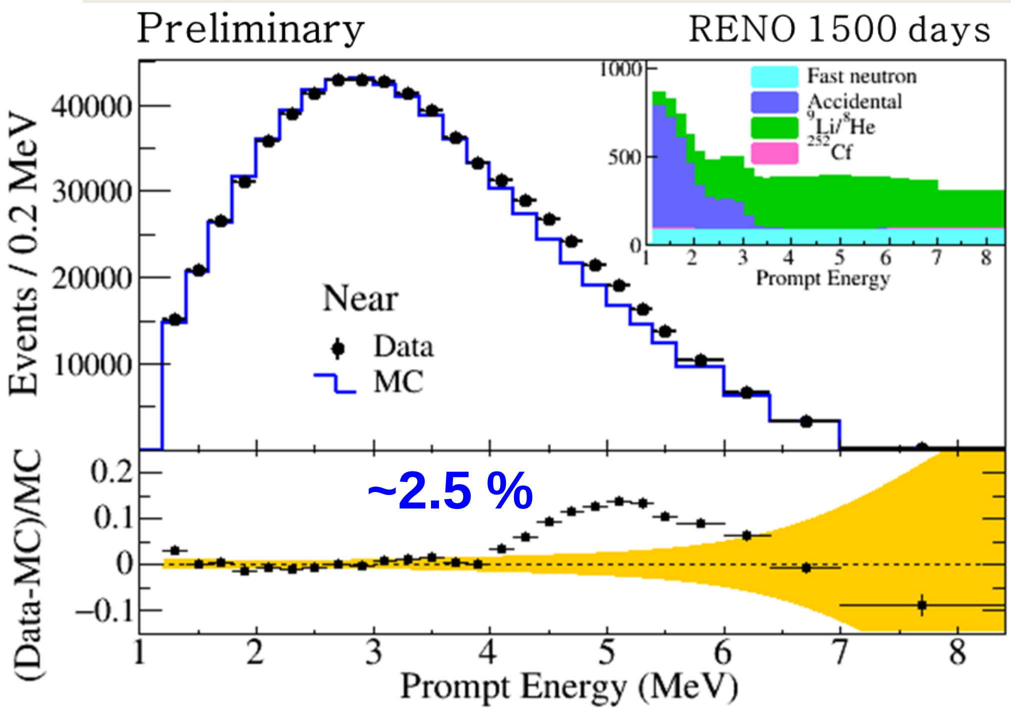
Reduction of background rates & uncertainties

Allows precise measurements of $sin^2 2\theta_{13}$ and Δm^2_{ee}



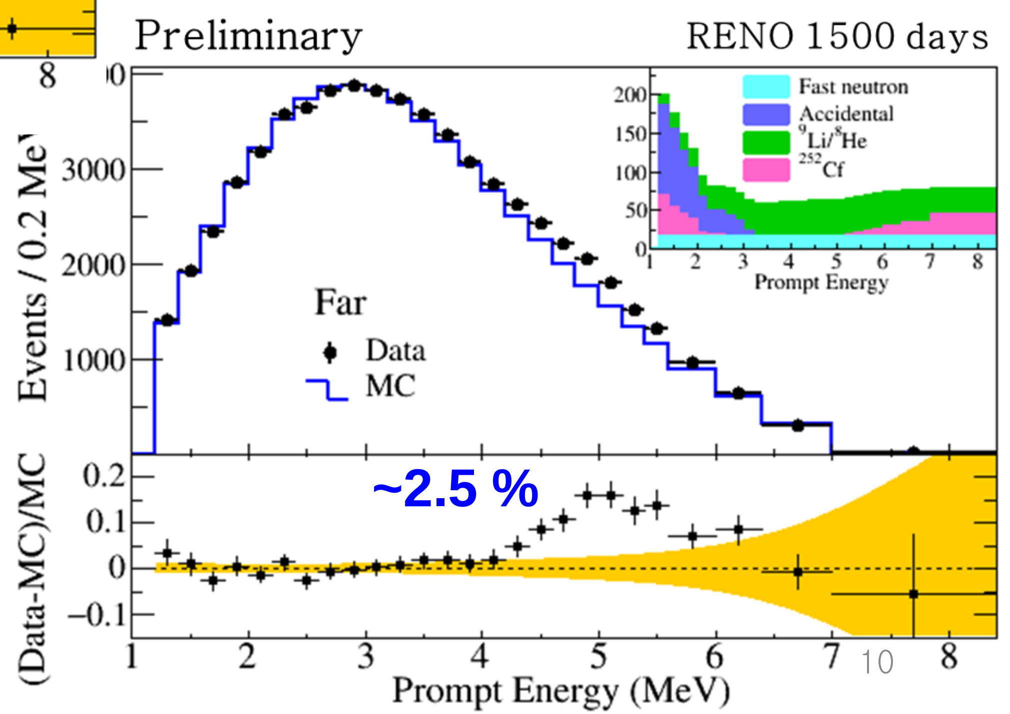
- Accidentals : Additional cuts and improved flashing-PMT removal algorithms
- Cosmogenic $^9Li/\,^8He$: Optimized muon veto criteria
- ^{252}Cf contamination : Improved multiple-neutron removal algorithms

Measured Spectra of IBD Prompt Signal

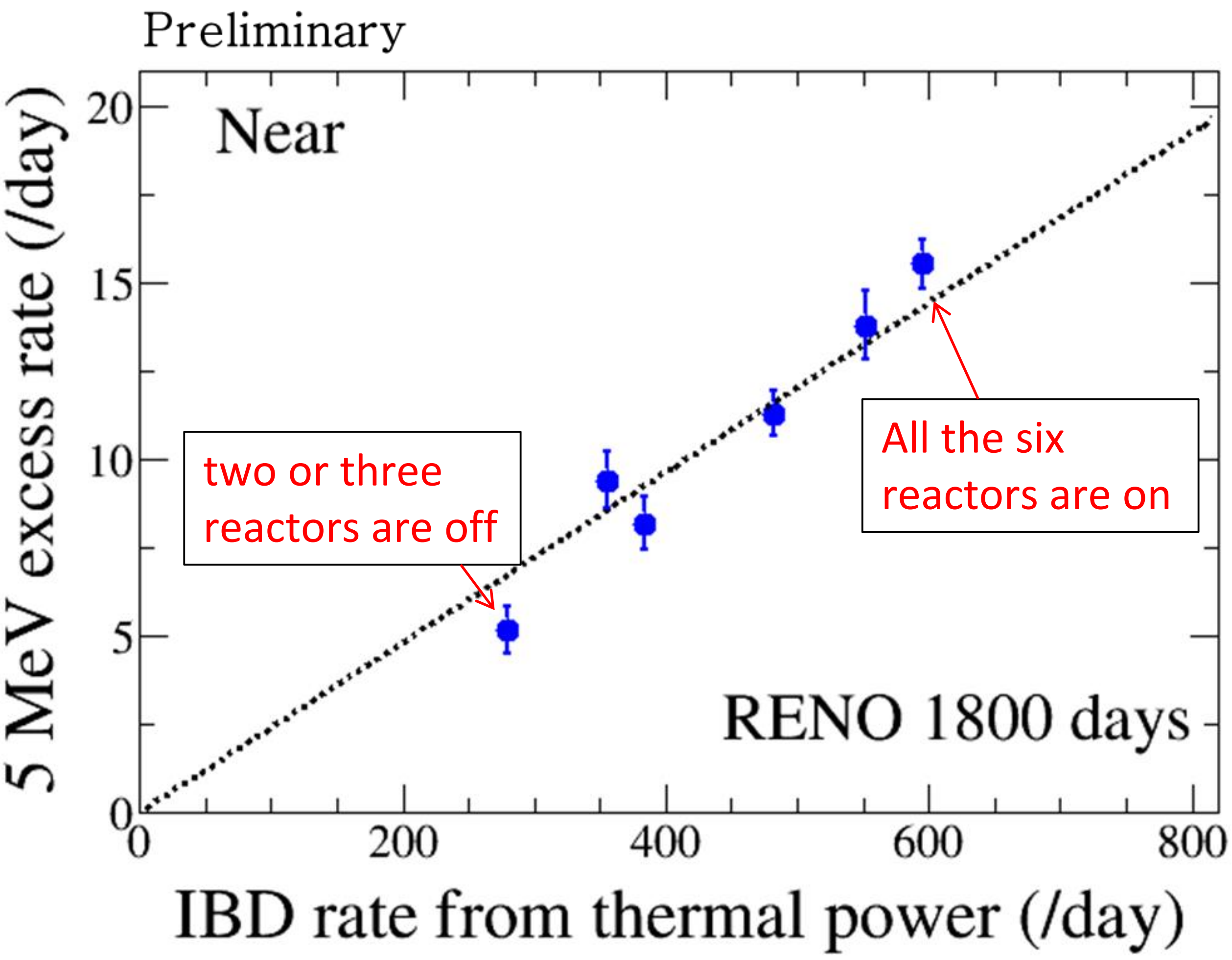


RENO's observation of 5 MeV excess

Clear excess at 5 MeV



Correlation of 5 MeV Excess with Reactor Power

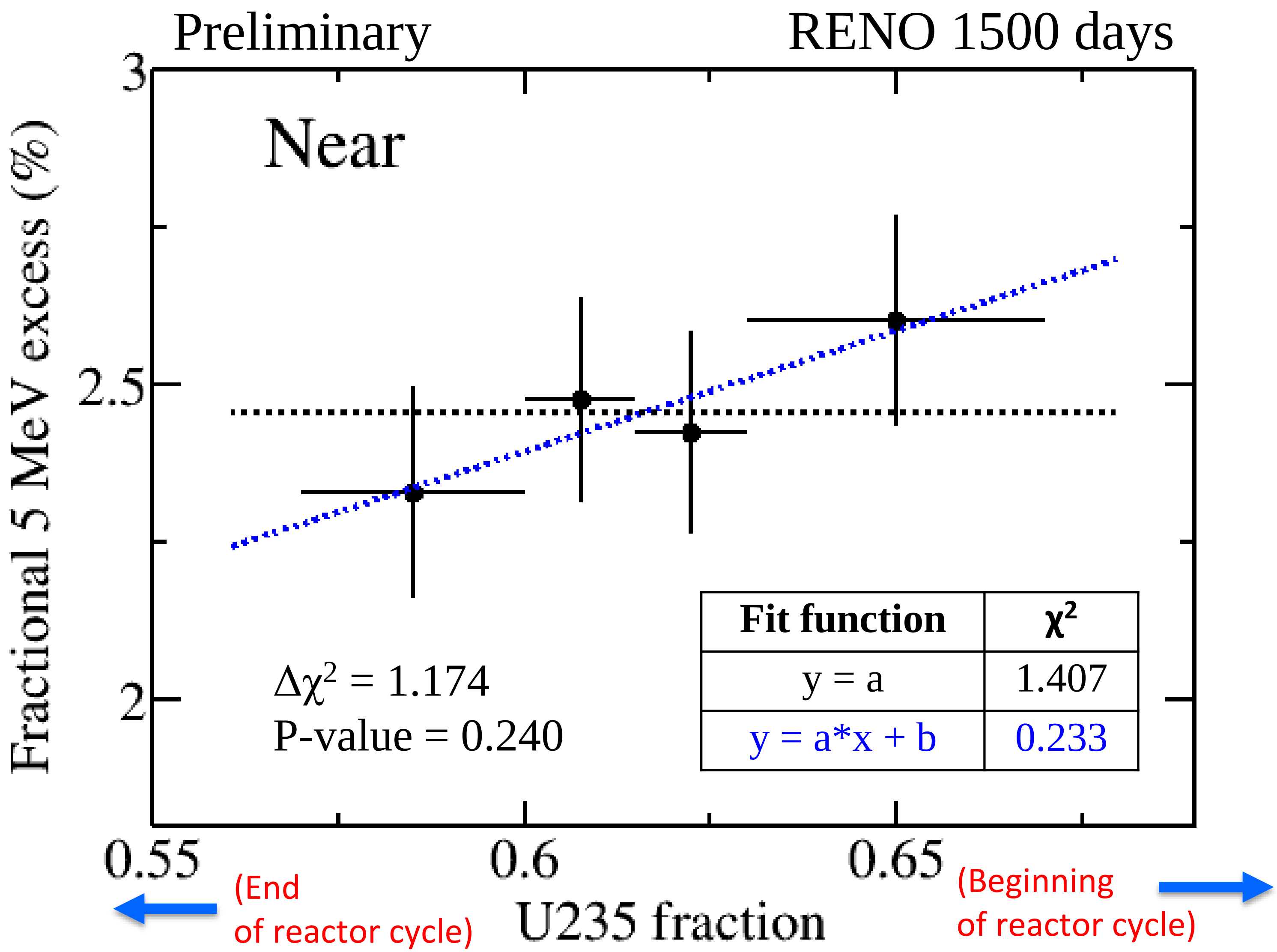


5 MeV excess has a clear correlation with reactor thermal power !

The 5 MeV excess comes from reactors!

Correlation of 5 MeV excess with ^{235}U isotope fraction

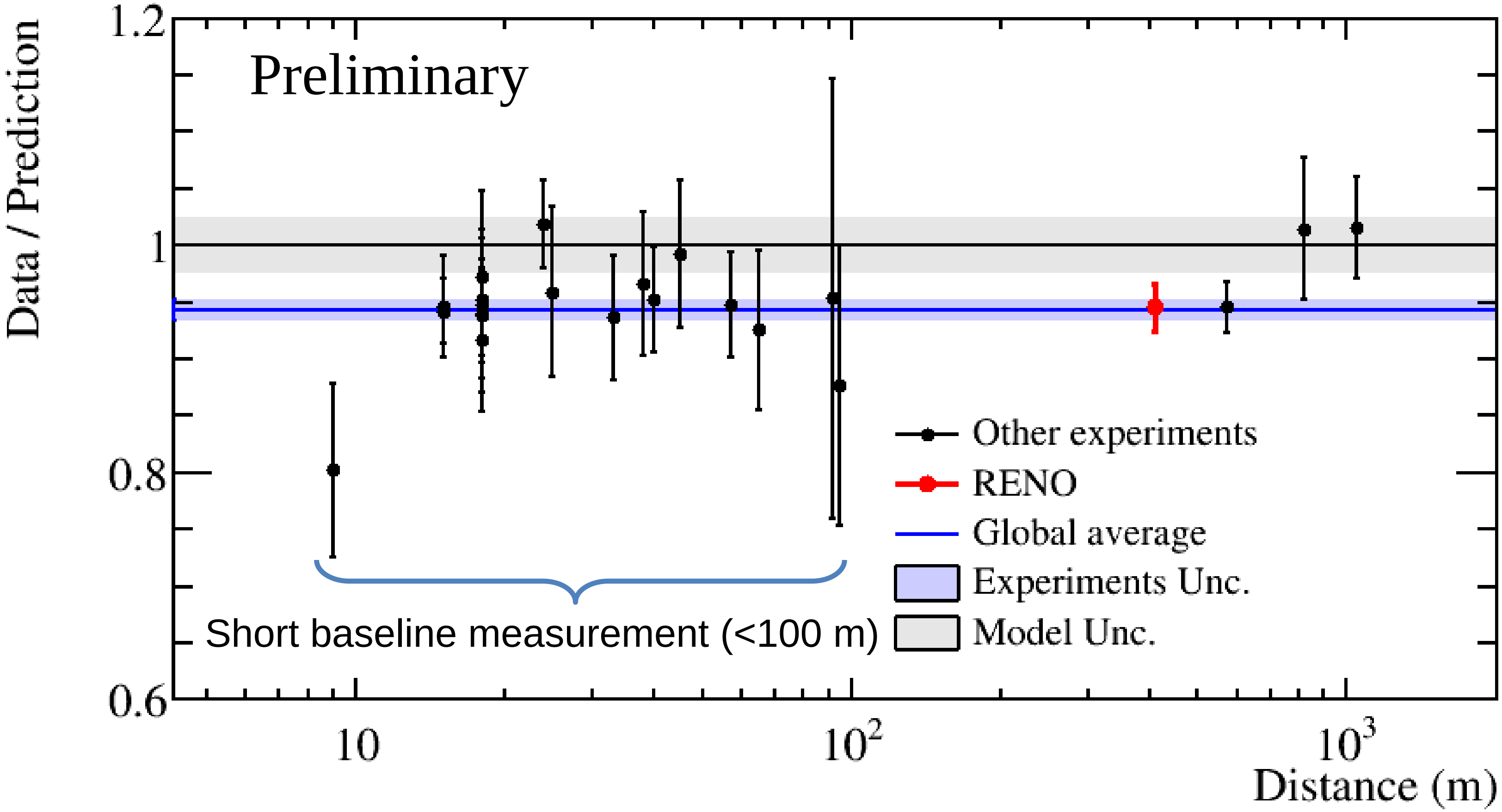
^{235}U fraction corresponds to freshness of reactor fuel



Fit function	χ^2
y = a	1.407
y = a*x + b	0.233

Measurement of Absolute Reactor Neutrino Flux

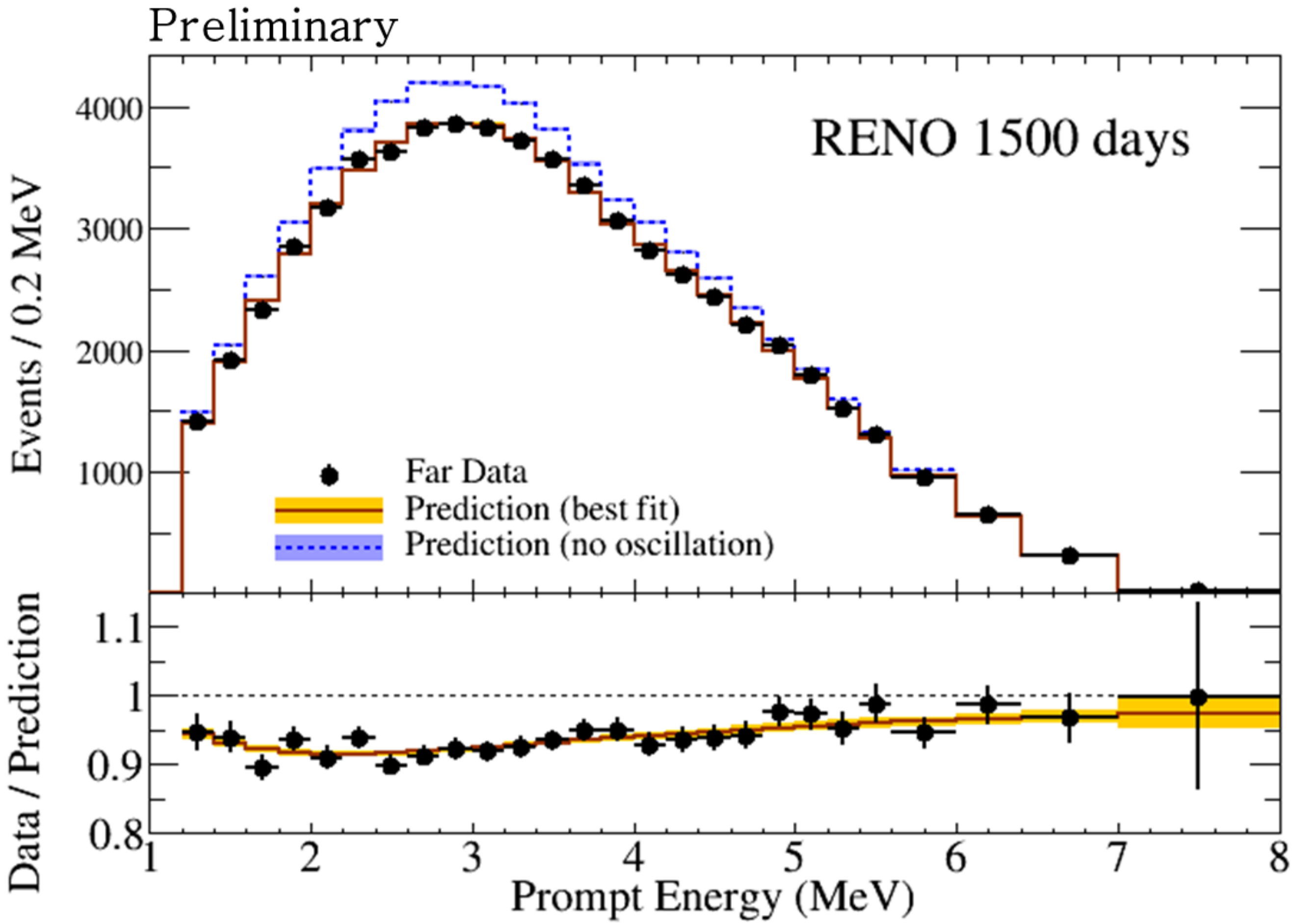
RENO 1500 days at near (411 m)	Data / Prediction (Huber + Mueller)
	0.946 +- 0.021



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

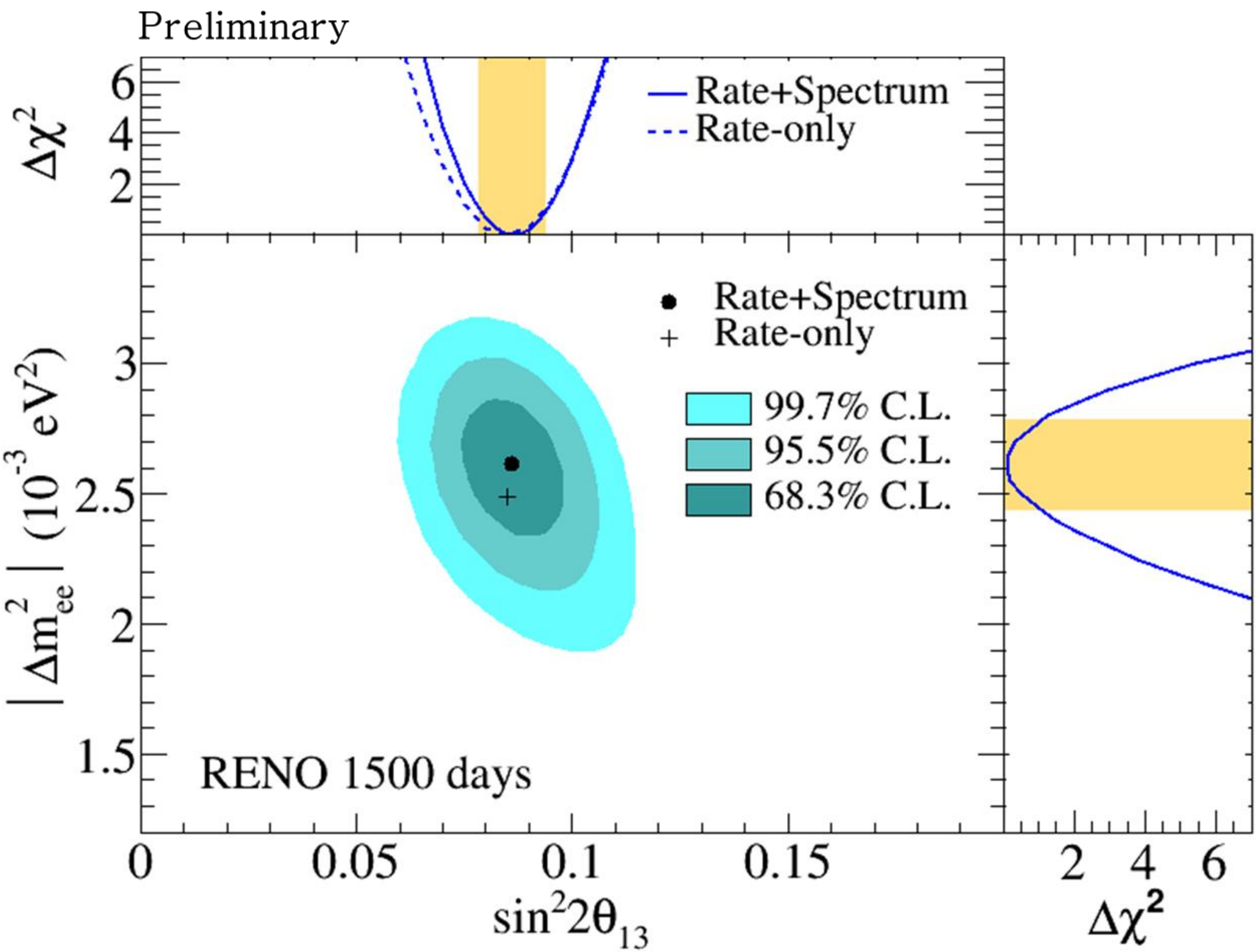
Energy-dependent disappearance of reactor antineutrinos



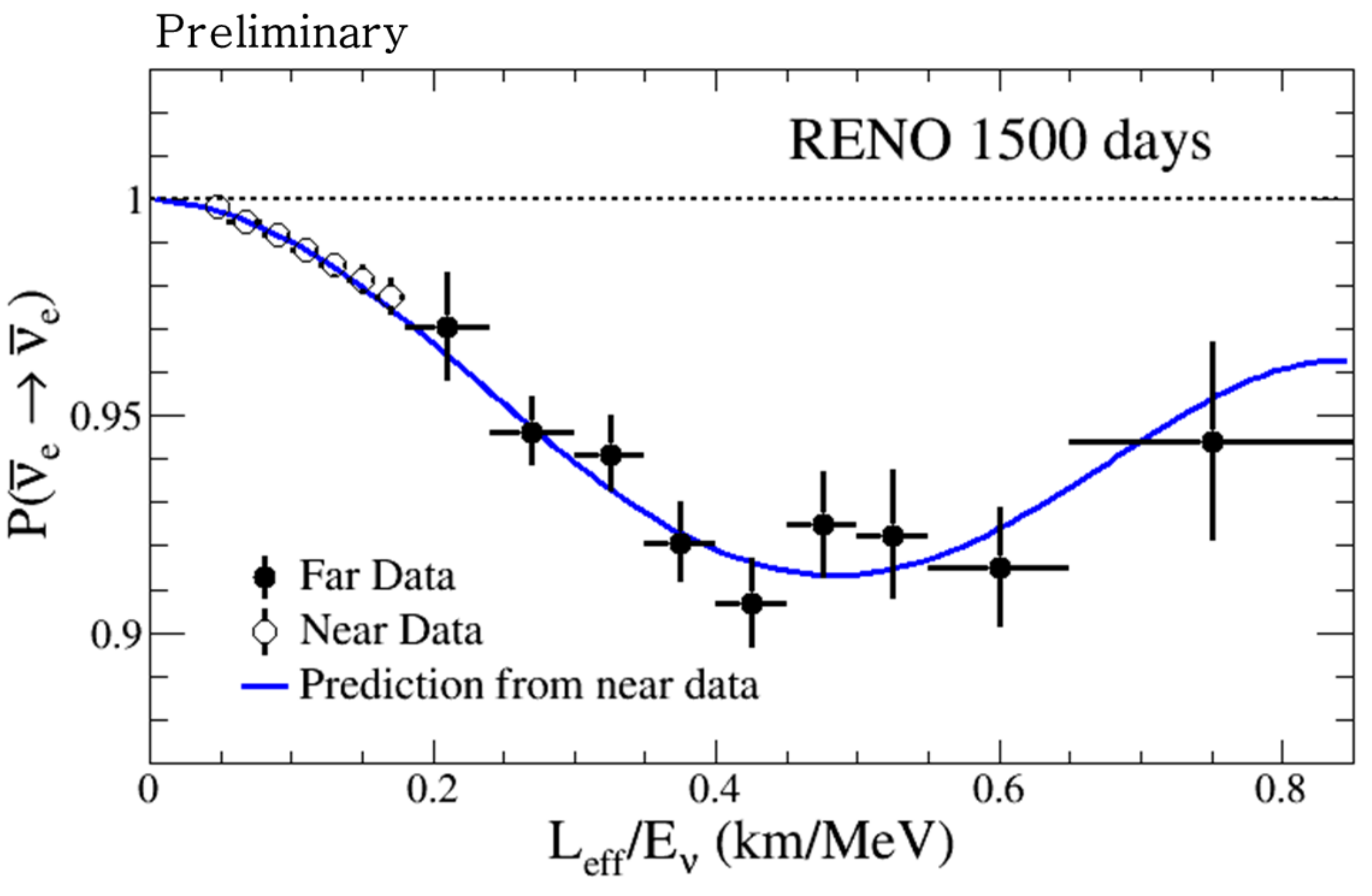
$$\sin^2 2\theta_{13} = 0.086 \pm 0.006(\text{stat.}) \pm 0.005(\text{syst.})$$ (± 9 %)

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

Allowed regions in $|\Delta m_{ee}^2|$ and $\sin^2 2\theta_{13}$



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

RENO : Plan and Prospects

Plan for RENO data taking

2017	2018	2019	2020	2021

RENO data will be taken for 2 more years from now and it will take 3 additional years for the analysis.

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.

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

	500 days Measured	1500 days Measured (preliminary)	~3500 days Expected
$\sin^2 2\theta_{13}$	12 %	9 %	6 ~ 7 %
$\|\Delta m_{ee}^2\|$	10 %	7 %	4 ~ 5 %

Summary

- More precise measurements of θ_{13} and Δm_{ee}^2 energy dependent disappearance of reactor neutrinos

(Preliminary)

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

$$\left|\Delta m_{ee}^2\right| = 2.61^{+0.15}_{-0.16}(\text{stat.})^{+0.09}_{-0.09}(\text{syst.}) \ (\times 10^{-3}\text{eV}^2)$$ ± 0.18 (7 %)

(Preliminary)

- Measured absolute reactor neutrino flux : R= 0.946±0.021

- Observed an excess at 5 MeV in reactor neutrino spectrum

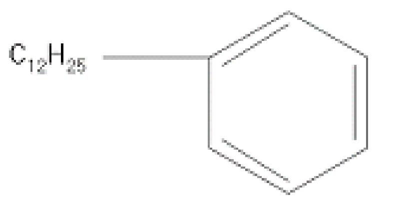
- $\sin^2(2\theta_{13})$ and Δm_{ee}^2 to 6% accuracy after 2 more years data taking

- Additional 2~3 years of data taking under consideration to improve Δm_{ee}^2 accuracy

Thanks for your attention!

Detection of Reactor Antineutrinos

C_nH_{2n+1}-C_6H_5 (n=10~14)



Linear Alkyl Benzene (LAB)

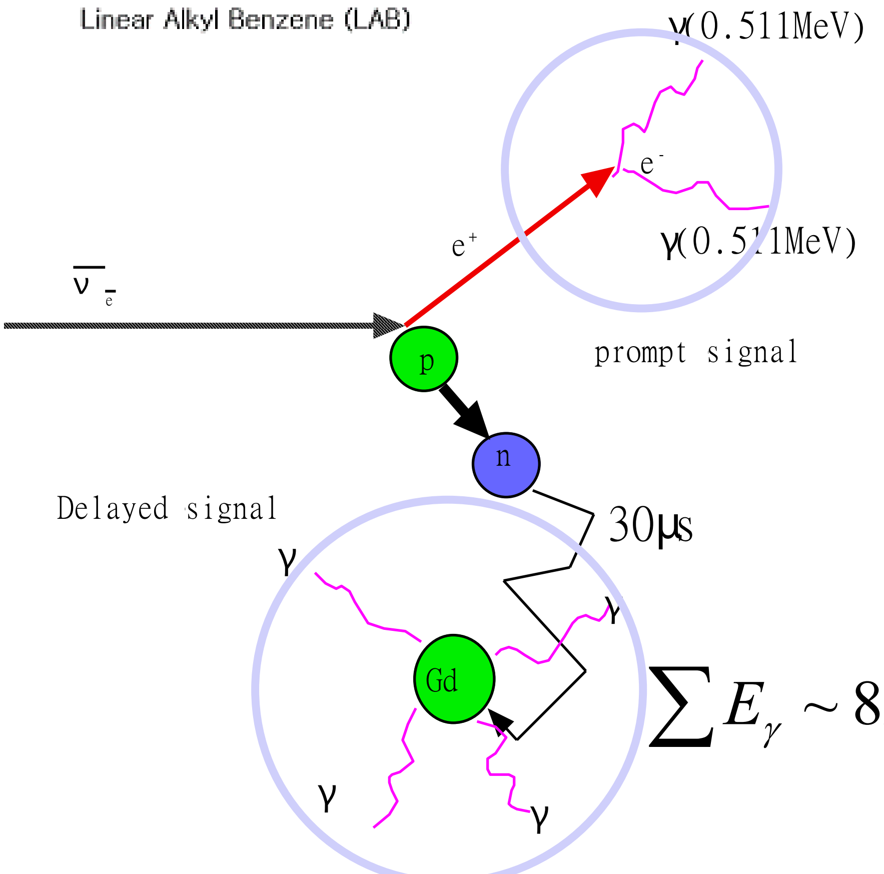
(prompt signal)

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

(delayed signal)

~180 μs: + p → D + γ (2.2 MeV)

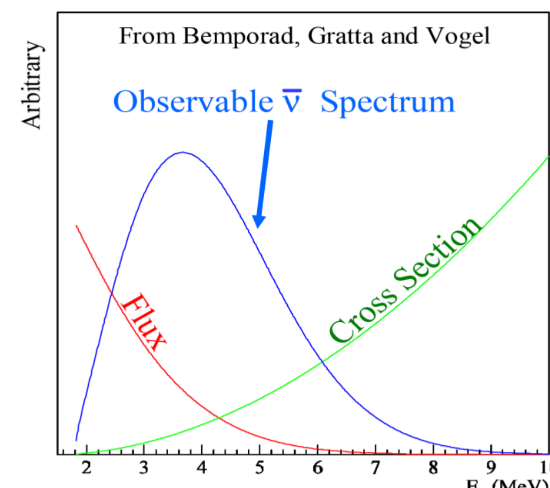
~28 μs (0.1% Gd): + Gd → Gd + γ's (8 MeV)



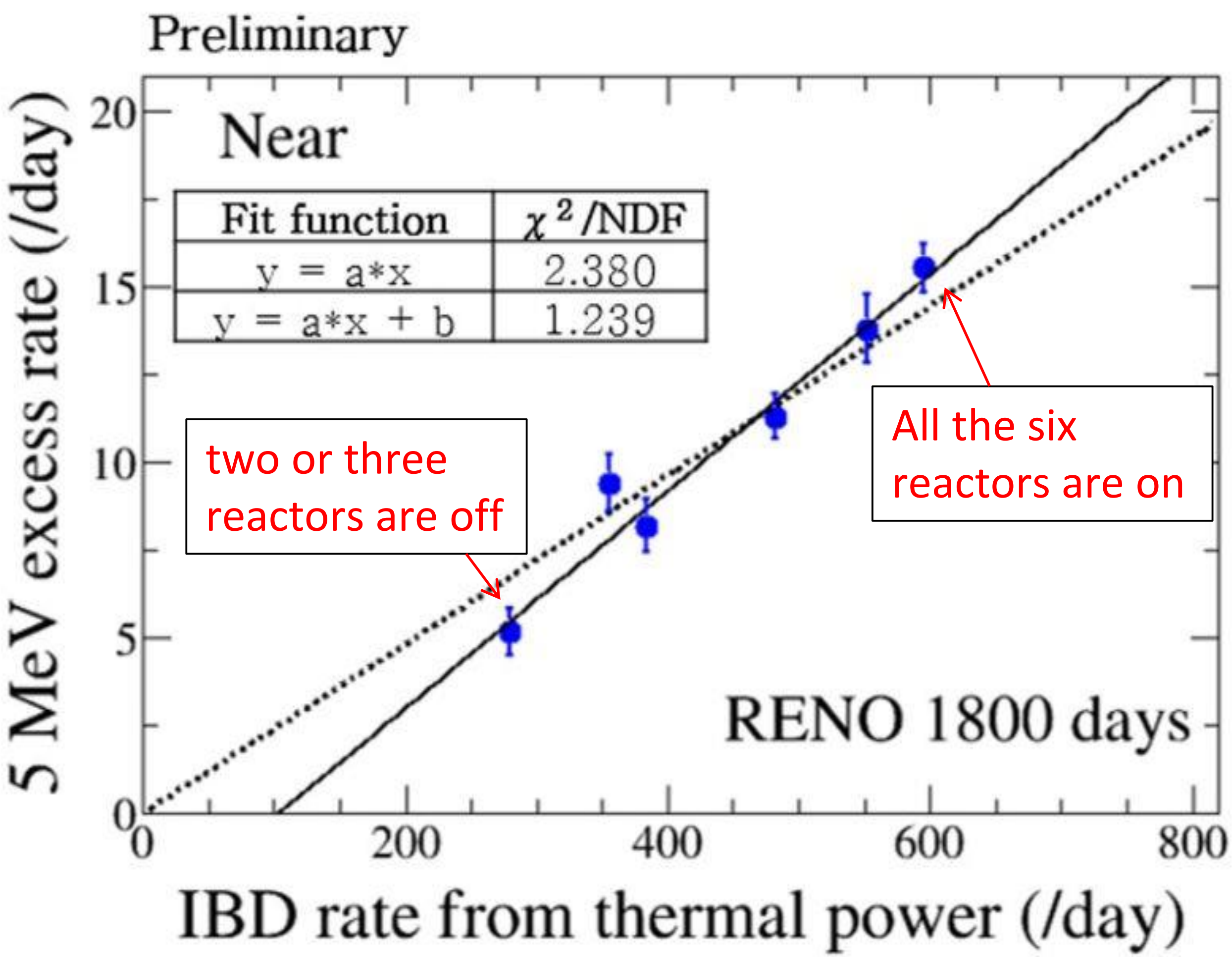
$$\sum E_\gamma \sim 8MeV$$

- **Neutrino energy measurement**

$$E_{\bar{\nu}} \cong T_{e^+} + \underbrace{T_n}_{10\text{-}40\ keV} + \underbrace{(M_n - M_p) + m_{e^+}}_{1.8\ MeV}$$



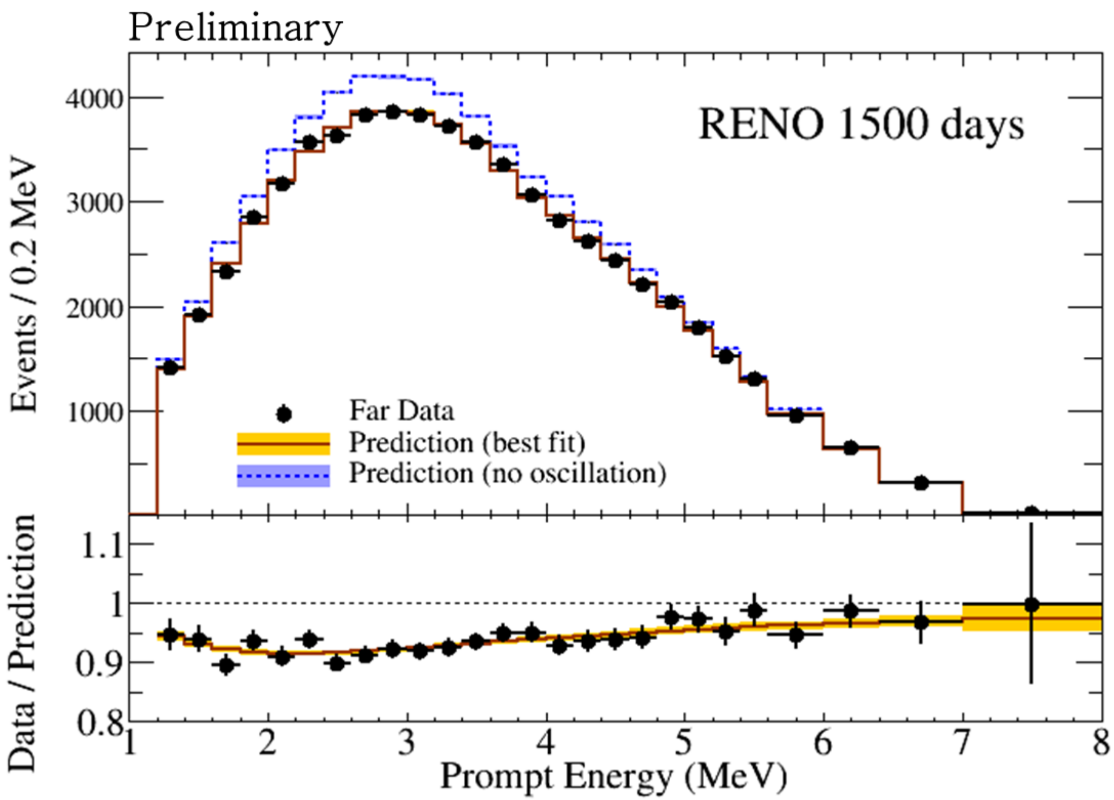
Correlation of 5 MeV Excess with Reactor Power



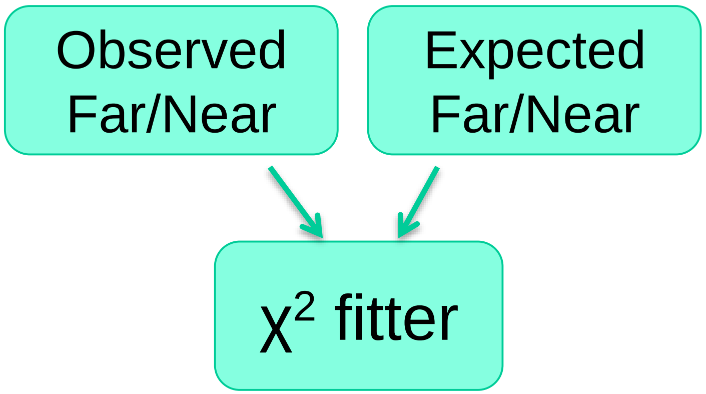
5 MeV excess has a clear correlation with reactor thermal power !

The 5 MeV excess comes from reactors!

Far/Near Shape Analysis for $|\Delta m_{ee}^2|$



Fit using far-to-near ratio



Minimize X^2 Function

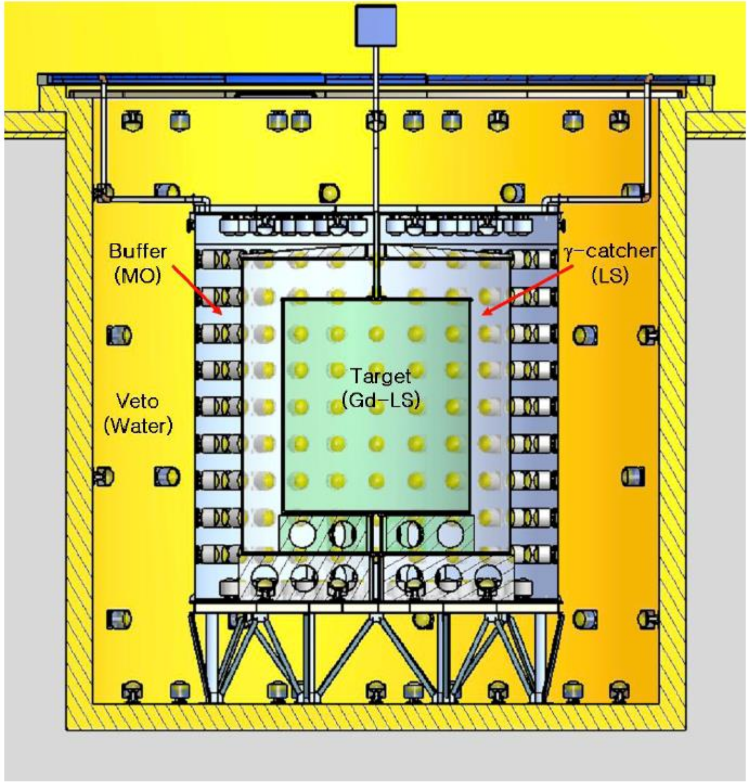
$$\chi^2 = \sum_{P=before,After} \left\{ \sum_{i=1\sim N_b} \frac{\left(\frac{N_{obs}^{F,P,i}}{N_{obs}^{N,P,i}} - \frac{N_{Exp}^{F,P,i}}{N_{Exp}^{N,P,i}} \right)^2}{\left(U_i\right)^2} \right\} + Pull\_Terms$$

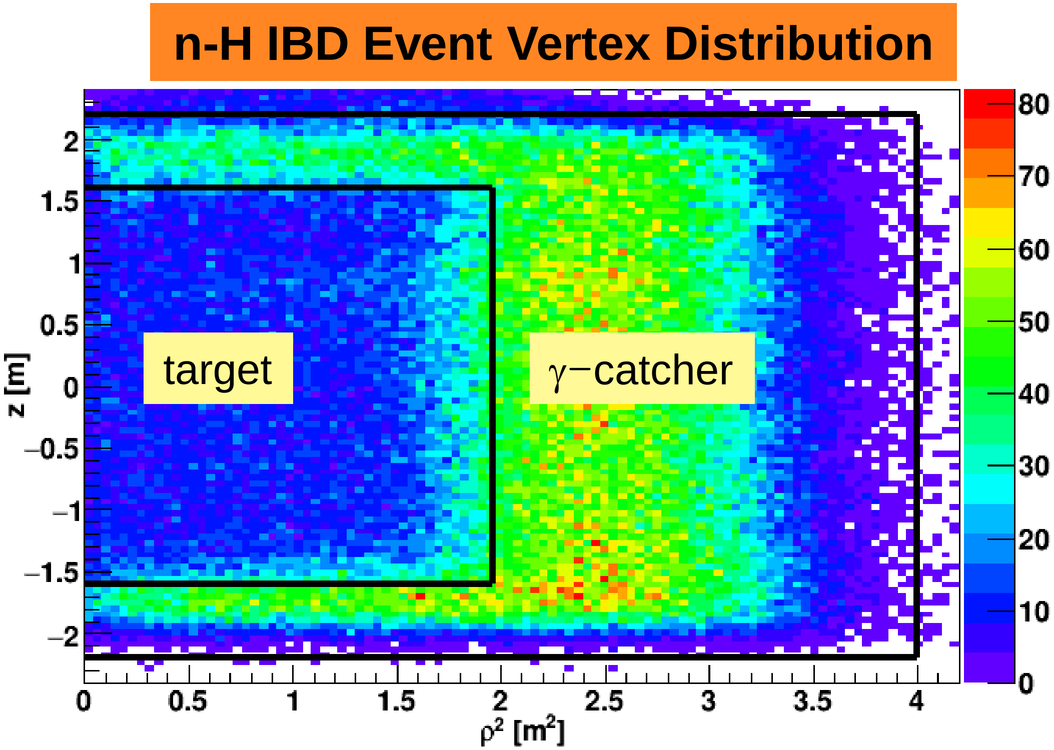
$$U_i = \frac{N_{obs}^{F,i}}{N_{obs}^{N,i}} \cdot \sqrt{\frac{N_{obs}^{F,i} + N_{bkg}^{F,i}}{(N_{obs}^{F,i})^2} + \frac{N_{obs}^{N,i} + N_{bkg}^{N,i}}{(N_{obs}^{N,i})^2}}$$

Energy-dependent disappearance of reactor antineutrionos

n-H IBD Analysis

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





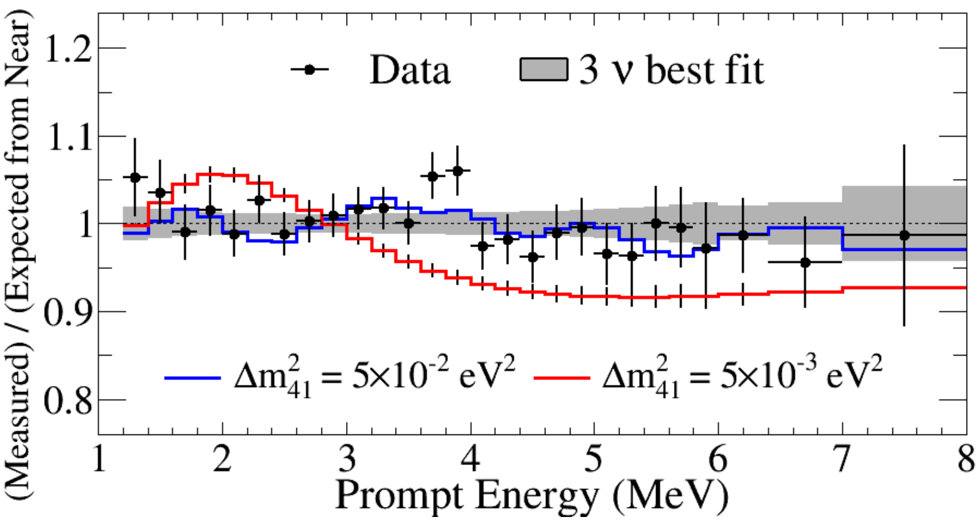
(Work in progress) 400 days of data before ^{252}Cf contamination

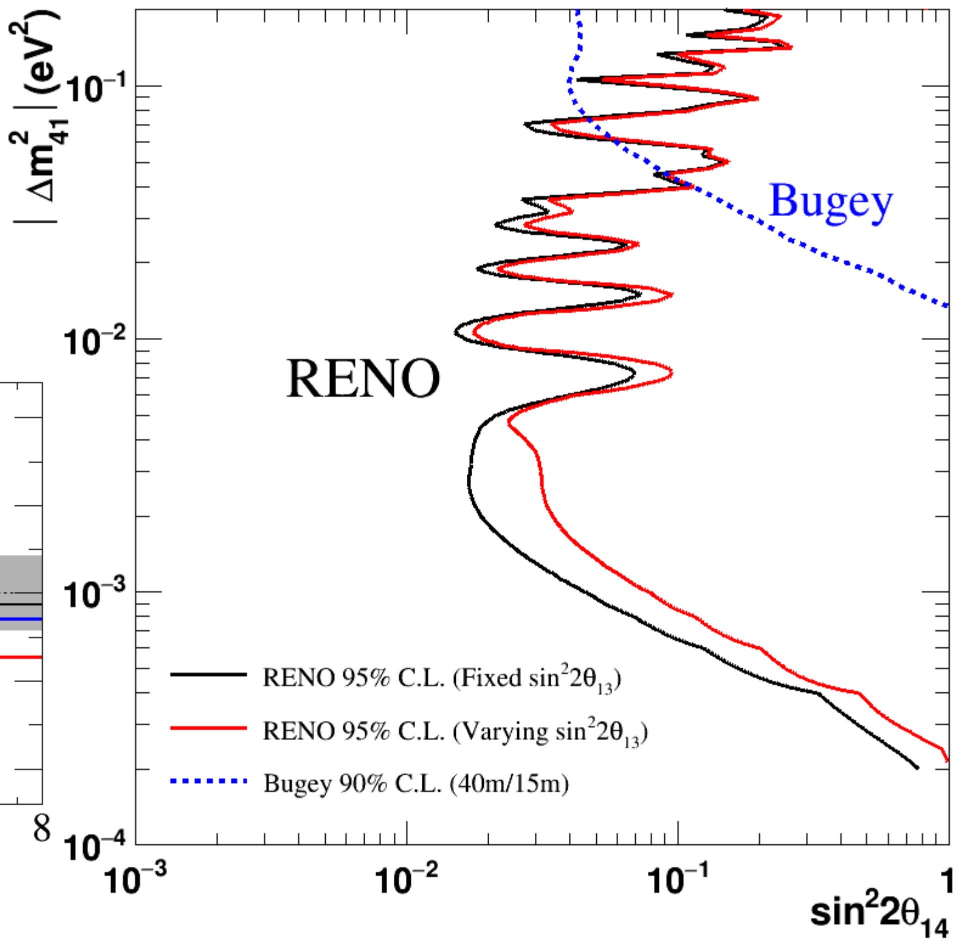
$$\sin^2 2\theta_{13} = 0.097 \pm 0.013(\text{stat.}) \pm 0.015(\text{syst.})$$

Light Sterile Neutrino Search Results

- 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

(Preliminary)





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