Recent Results from RENO

Hyunkwan Seo for the RENO Collaboration

Seoul National University

International Workshop on Next Generation Nucleon Decay and Neutrino Detectors

IHEP, Beijing, China, Nov. 3-5, 2016

KNRC

Korea Neutrino Research Center

RENO Collaboration

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

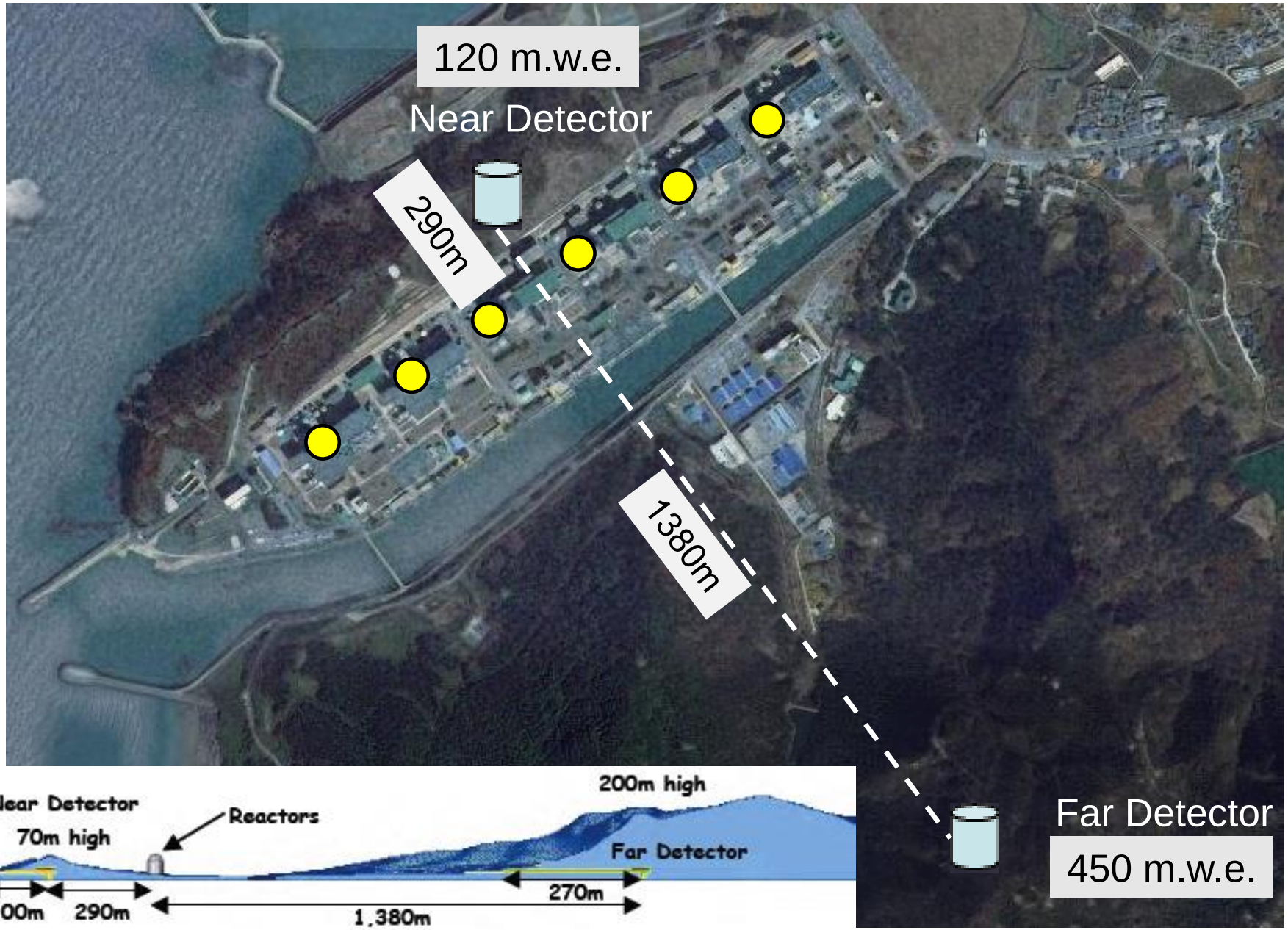
(8 institutions and 40 physicists)

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

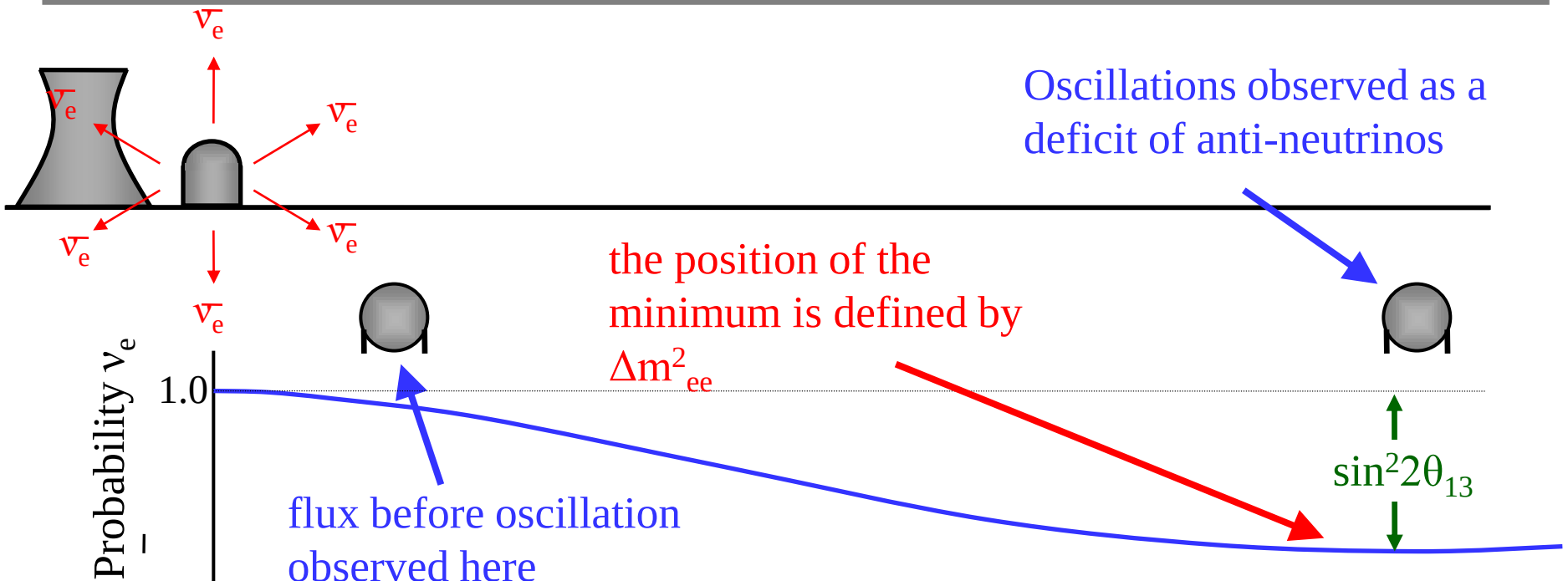
- Total cost : $10M
- Start of project : 2006
- The first experiment running with both near & far detectors from Aug. 2011

YongGwang (靈光) :

RENO Experimental Set-up



Reactor Neutrino Oscillations



$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$

$$\simeq 1 - \sin^2 2\theta_{13}\sin^2\Delta_{ee} - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$

$$\Delta_{ij} \equiv 1.267\Delta m^2_{ij} L/E$$

Distance

1200 to 1800 meters

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

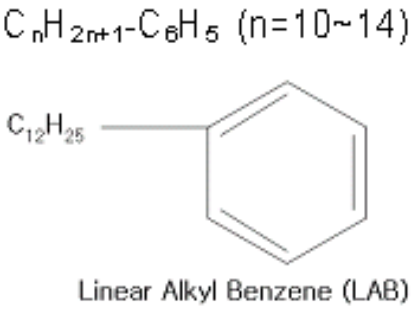
$$|\Delta m^2_{ee}| \simeq |\Delta m^2_{32}| \pm 5.21 \times 10^{-5}\text{eV}^2$$

$\cos^2\theta_{12}|\Delta m^2{}_{21}|$

+: Normal Hierarchy

−: Inverted Hierarchy

Detection of Reactor Antineutrinos



(prompt signal)

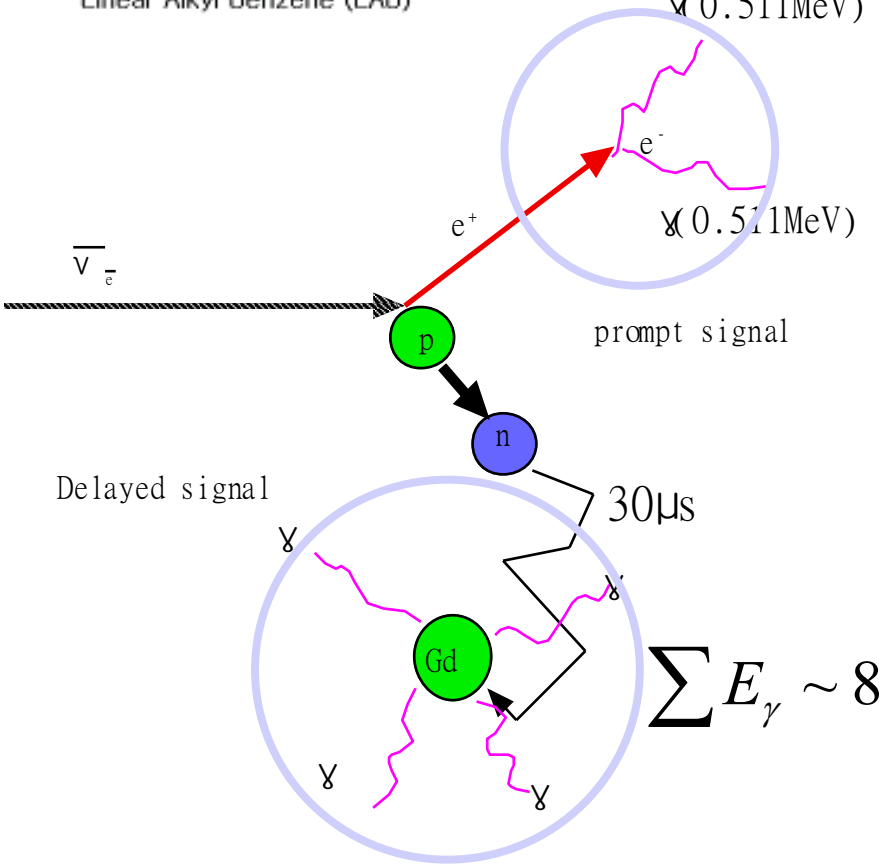
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

~180 μs (delayed signal)

+ p → D + γ (2.2 MeV)

~28 μs (0.1% Gd)

+ Gd → Gd + γ's (8 MeV)

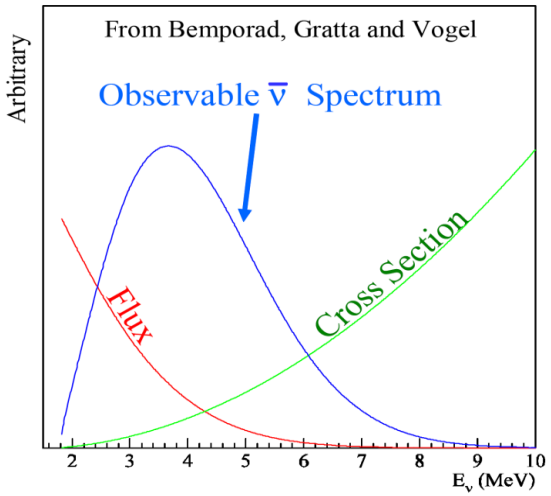


$$\sum E_\gamma \sim 8MeV$$

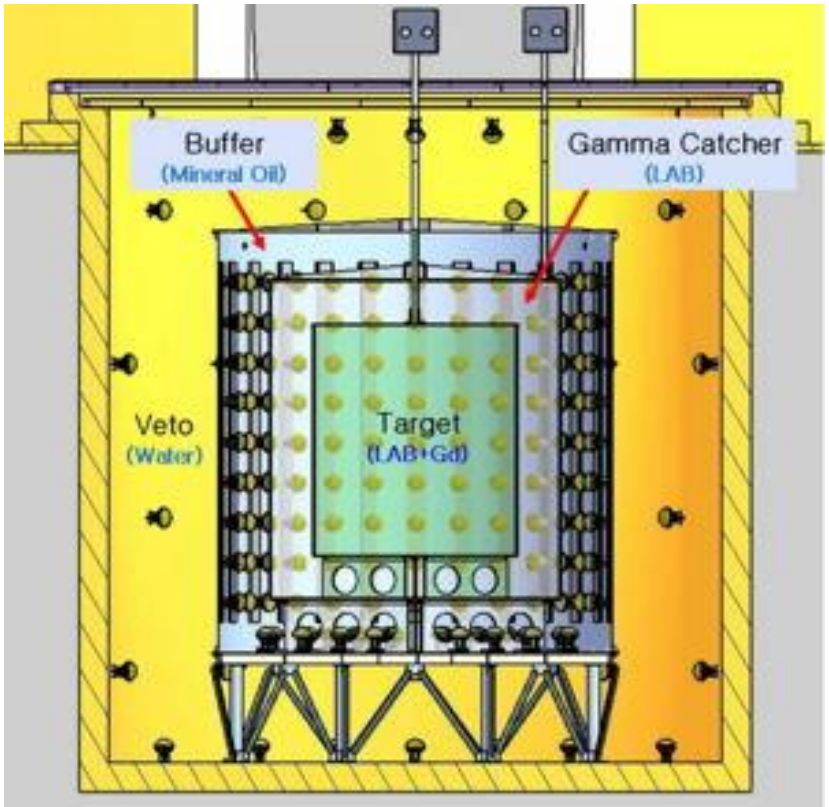
- **Neutrino energy measurement**

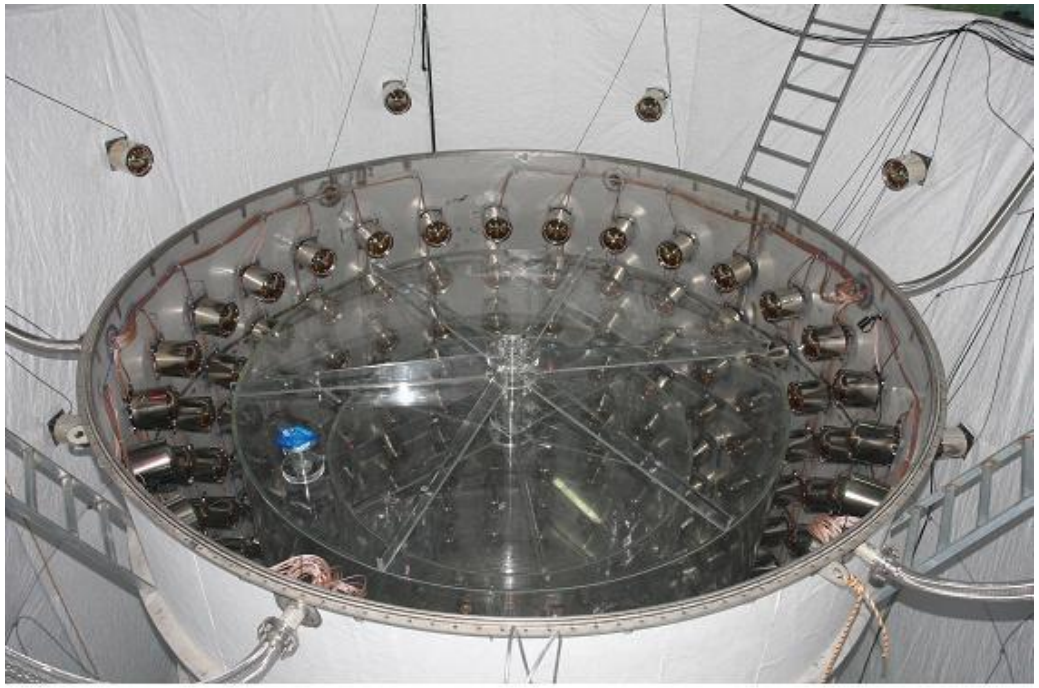
$$E_{\bar{\nu}} \cong T_{e^+} + T_n + (M_n - M_p) + m_{e^+}$$

10-40 keV *1.8 MeV*



RENO Detector



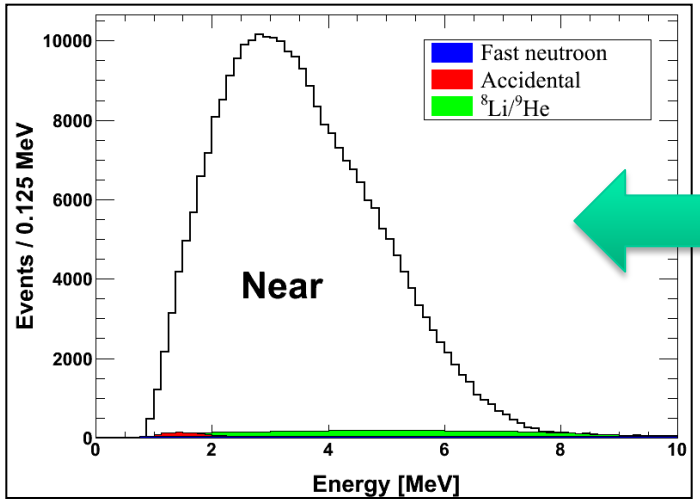


- 354 ID +67 OD 10” PMTs
- Target : 16.5 ton Gd-LS, R=1.4m, H=3.2m
- Gamma Catcher : 30 ton LS, R=2.0m, H=4.4m
- Buffer : 65 ton mineral oil, R=2.7m, H=5.8m
- Veto : 350 ton water, R=4.2m, H=8.8m

IBD signal: coincidence

Inverse beta decay ($\bar{\nu}_e + p \rightarrow e^+ + n$)

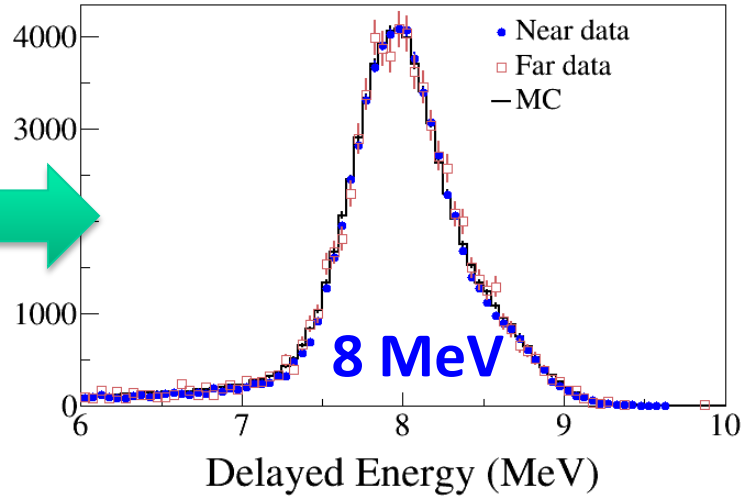
Prompt signal (S1)

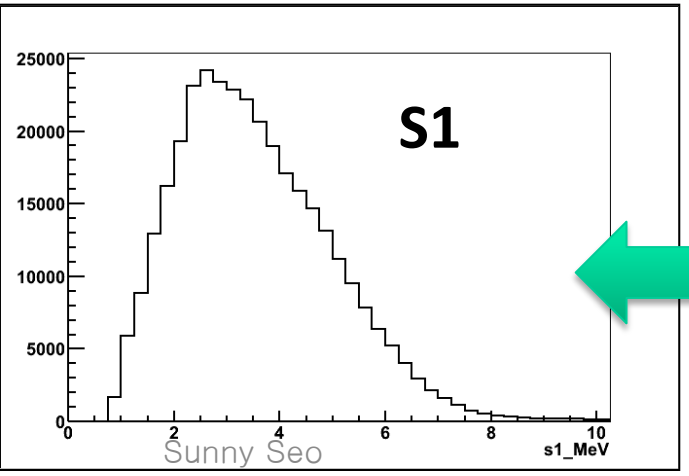


n-Gd IBD

~30 μs

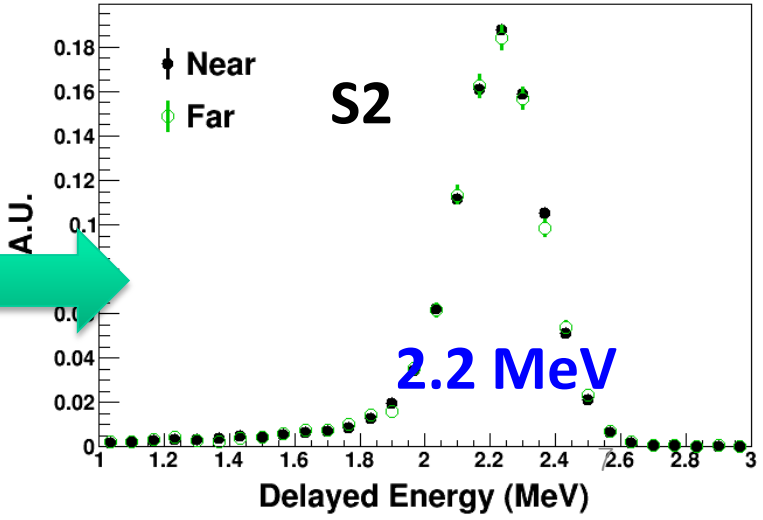
Delayed signal (S2)





n-H IBD

~200 μs



RENO Data-taking Status

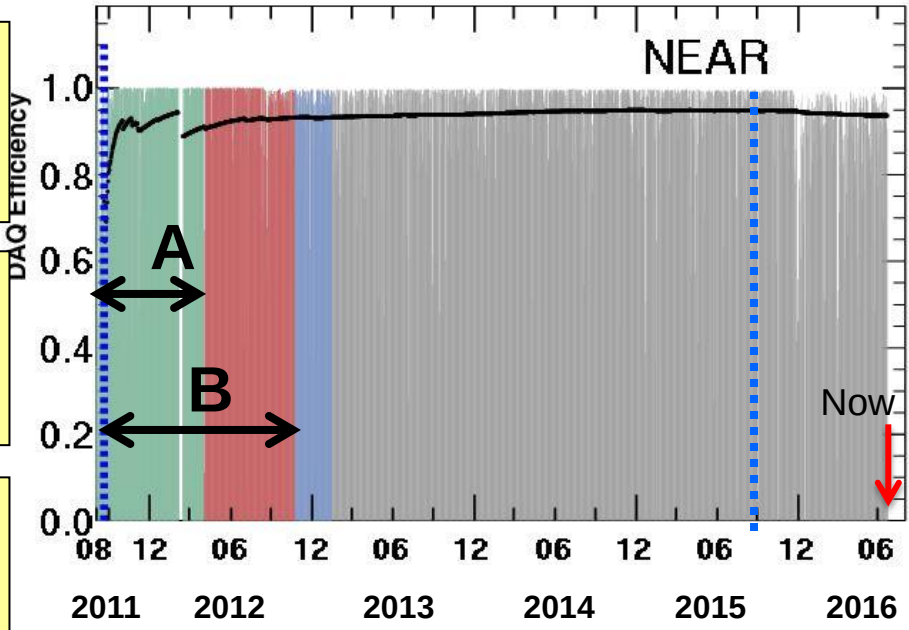
- Data taking began on Aug. 1, 2011 with both near and far detectors.
  (DAQ efficiency : ~95%)

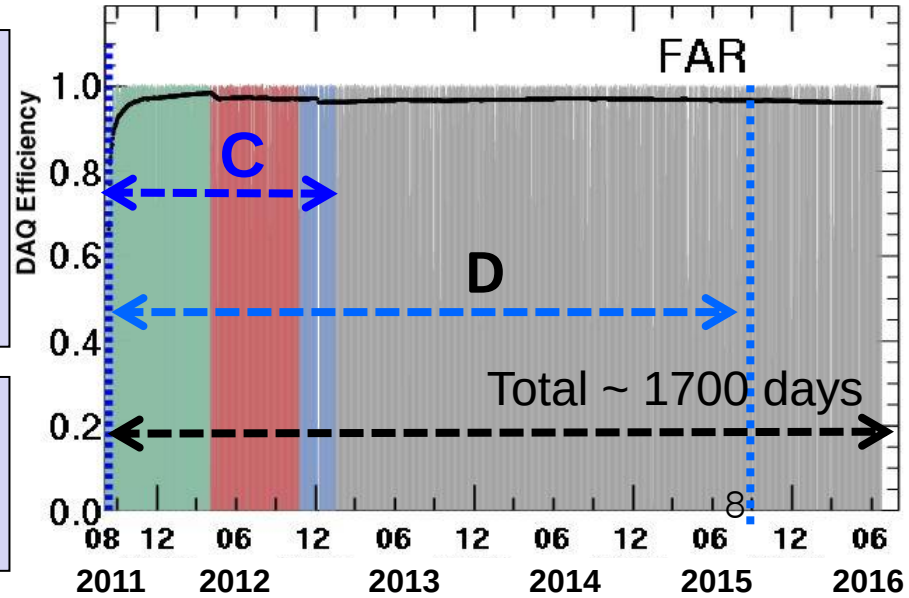
- **A (220 days)** : **First θ_{13} result**
  [11 Aug, 2011~26 Mar, 2012]
  PRL 108, 191802 (2012)

- **B (403 days)** : **Improved θ_{13} result**
  [11 Aug, 2011~13 Oct, 2012]
  NuTel 2013, TAUP 2013, WIN 2013

- **C (~500 days)** : New **result**
  Shape+rate analysis (θ_{13} **and** $|\Delta m_{ee}^2|$)
  [11 Aug, 2011~21 Jan, 2013]
  → Sterile neutrino search and updated n-H analysis in progress

- Total observed reactor neutrino events as of today (1500 days)
  ~ 1.5M (Near), ~ **0.15M** (Far)





New Results from RENO

- New measured value of θ_{13} from rate-only analysis using ~500 days of data (Aug. 2011 ~ Jan. 2013)

- Observation of an excess at ~5 MeV in reactor neutrino spectrum

- Observation of energy dependent disappearance of reactor neutrinos to measure Δm_{ee}^2 and θ_{13}

"Observation of Energy and Baseline Dependent Reactor Antineutrino Disappearance in the RENO Experiment"

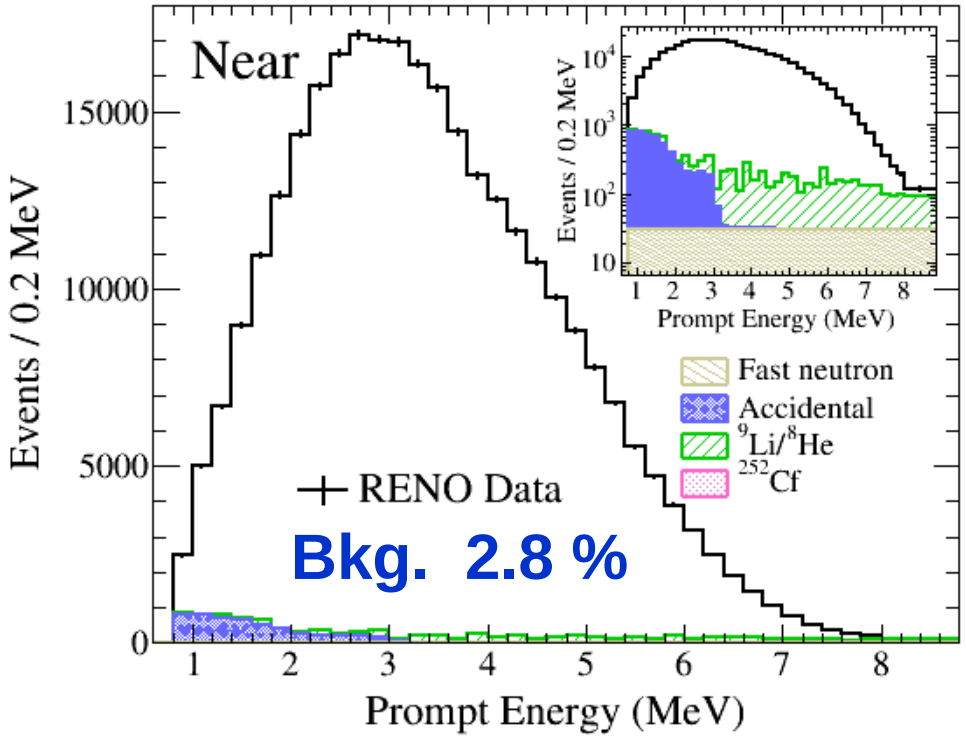
(published in **PRL 116, 211801, 2016**)

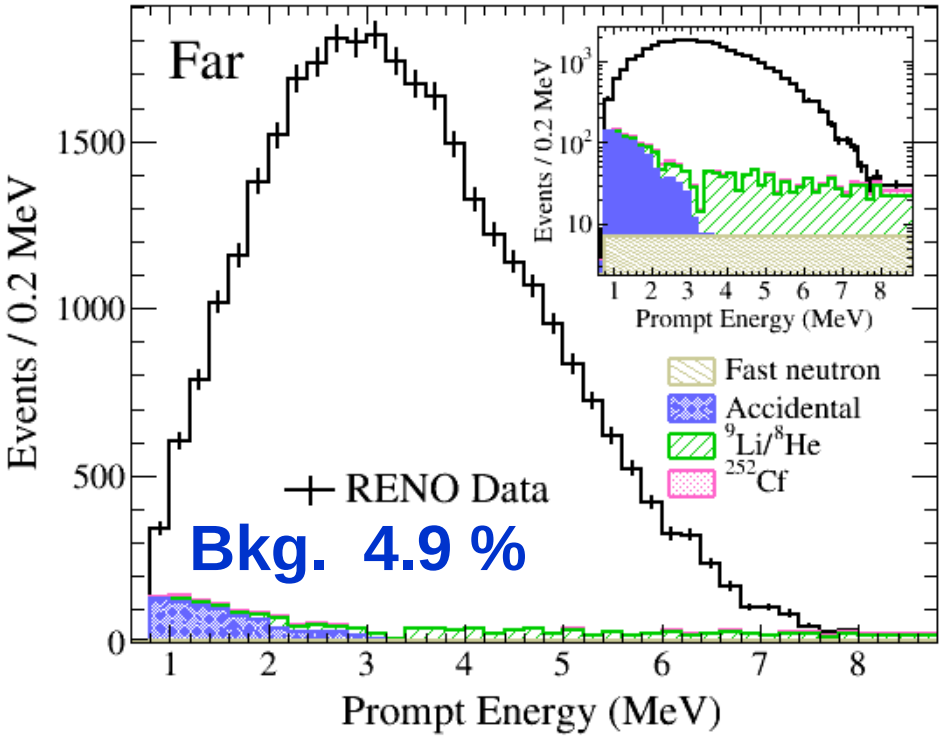
- Details can be found there & PRD to be submitted soon

- Independent measurement of θ_{13} with n-H for a delayed signal (additional background reduction in progress)

- Obtained result from sterile neutrinos search

Measured Spectra of IBD Prompt Signal



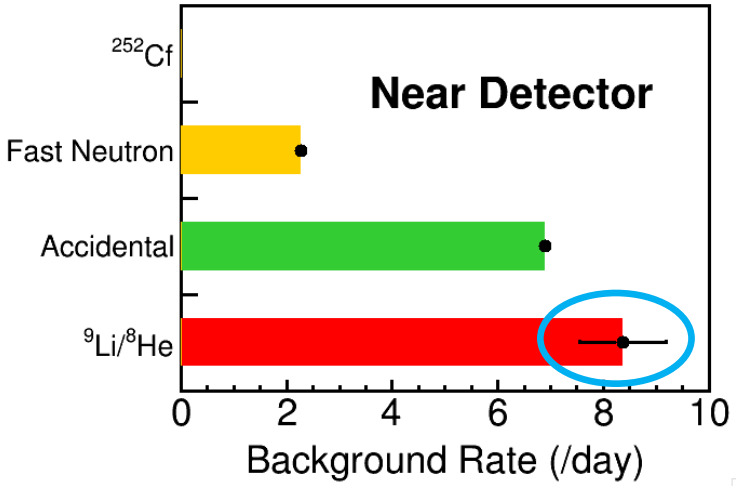


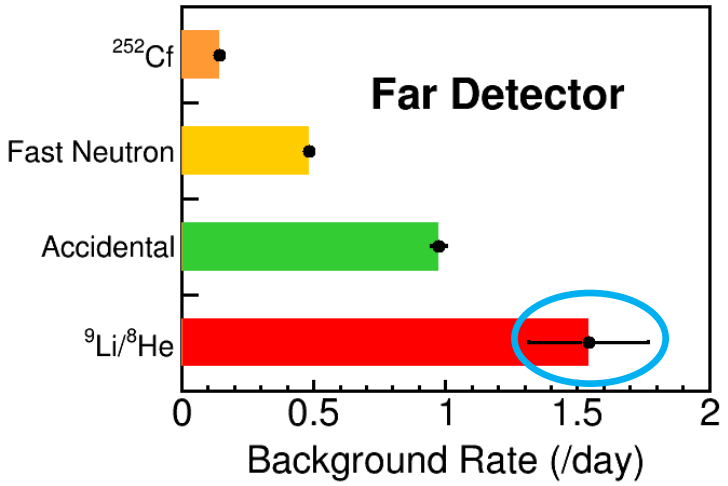
Near Live time = 458.49 days
# of IBD candidate = 290,775
# of background = 8,041 (2.8 %)

Far Live time = 489.93 days
# of IBD candidate = 31,541
# of background = 1,540 (4.9 %)

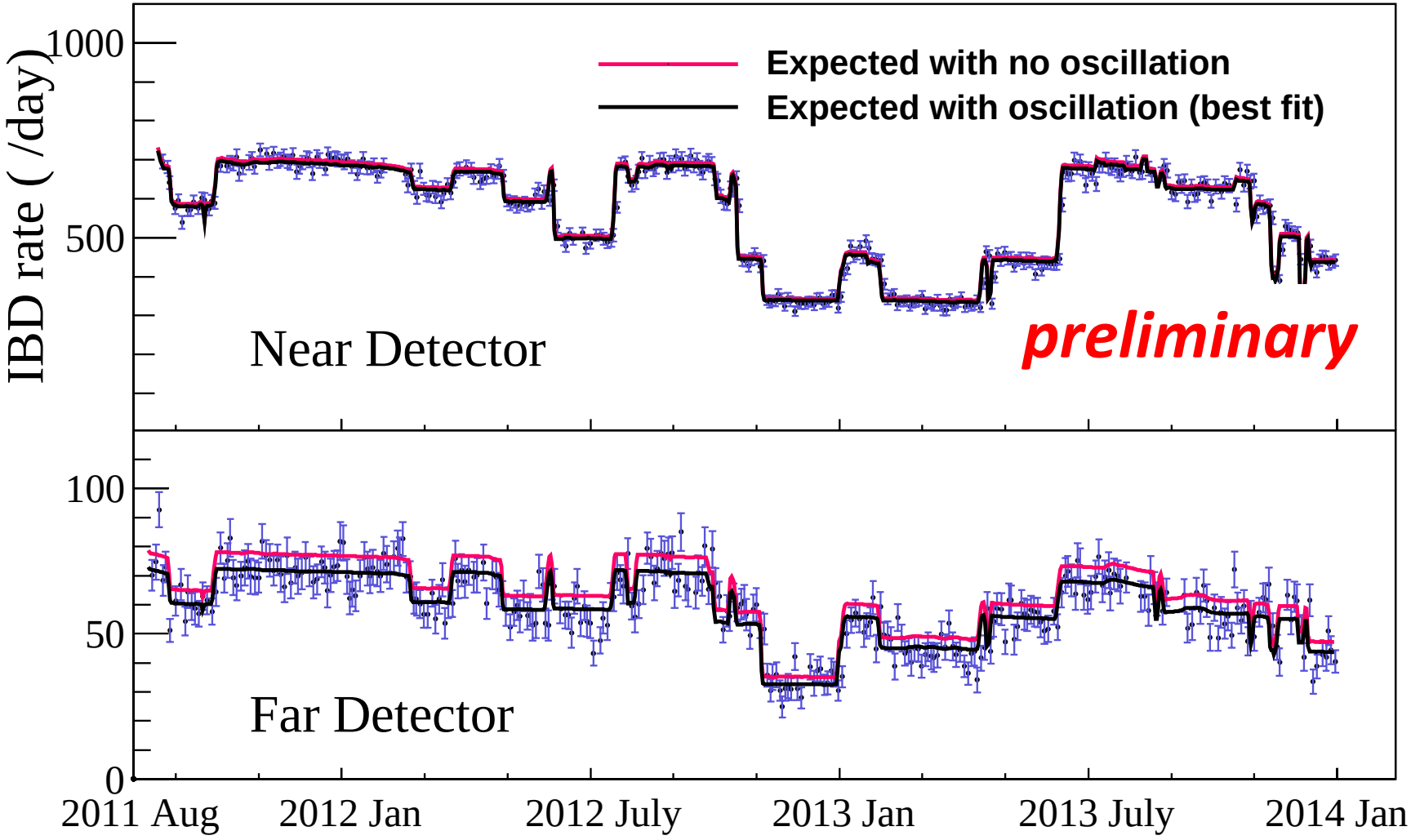
IBD Candidates & Backgrounds

	Near	Far
DAQ live time (days)	458.49	489.93
IBD candidates	290755	31541
Total BKG rate (/day)	17.54± 0.83	3.14± 0.21
IBD rate (/day) after BKG subtraction	616.67± 1.44	61.24± 0.42





Observed Daily Averaged IBD Rate



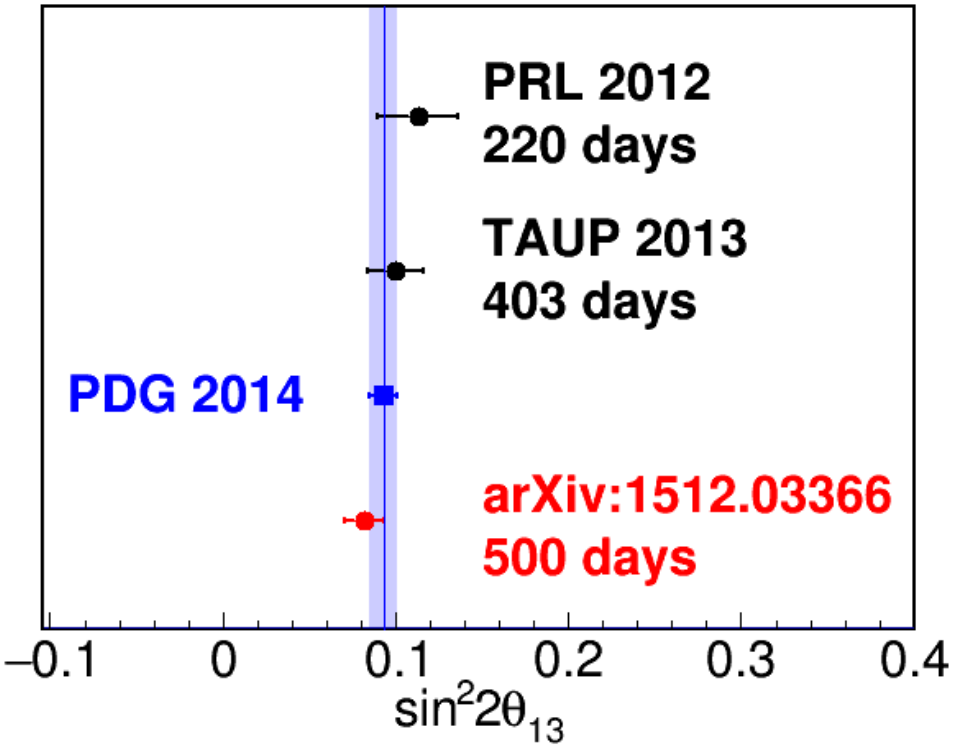
- Good agreement with observed rate and prediction.
- Accurate measurement of thermal power by reactor neutrinos

New θ_{13} Measurement by Rate-only Analysis

Rate-only new result

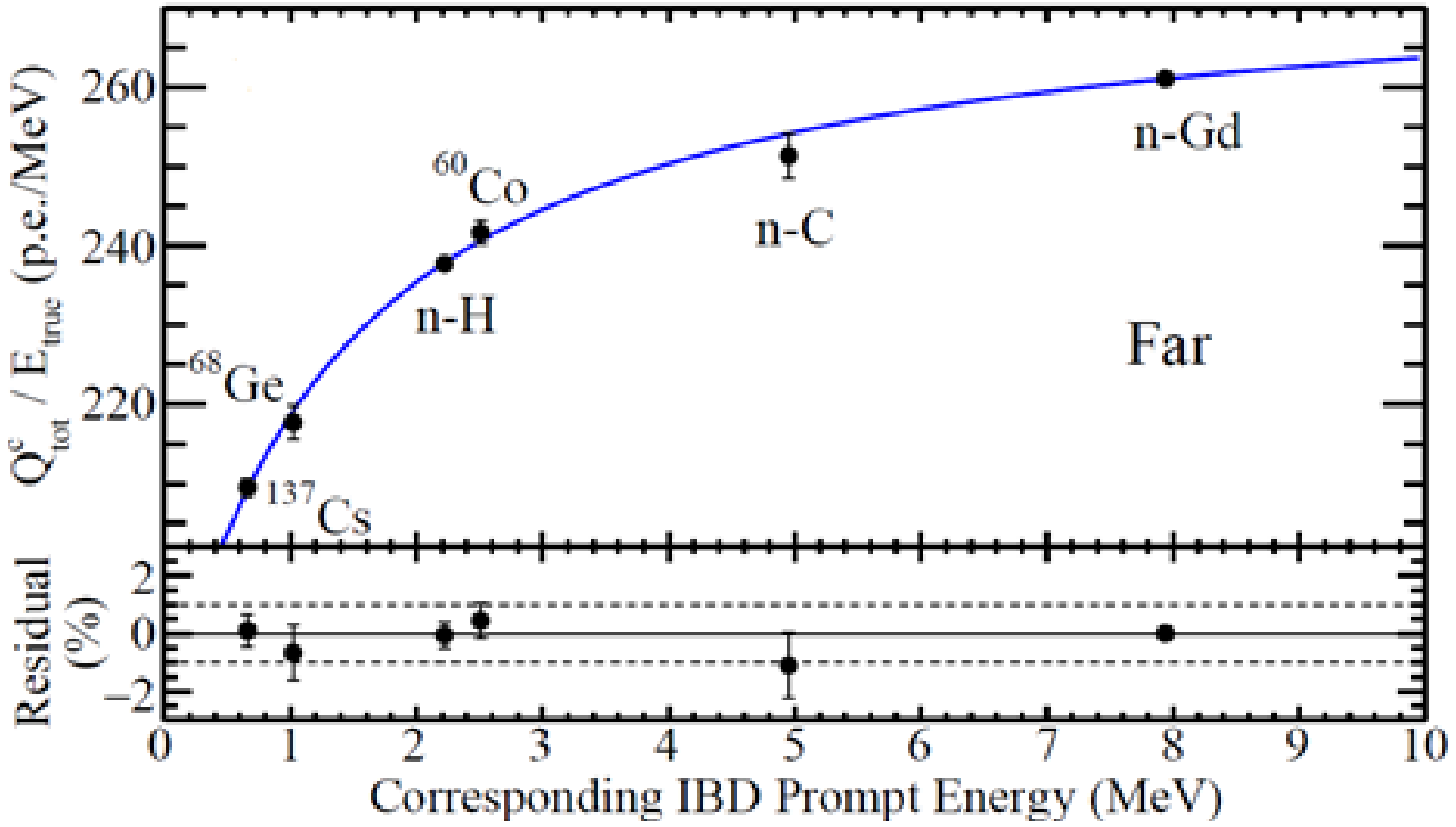
$$\sin^2 2\theta_{13} = 0.087 \pm 0.009(\text{stat.}) \pm 0.007(\text{syst.})$$

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



Energy Calibration from γ-ray Sources

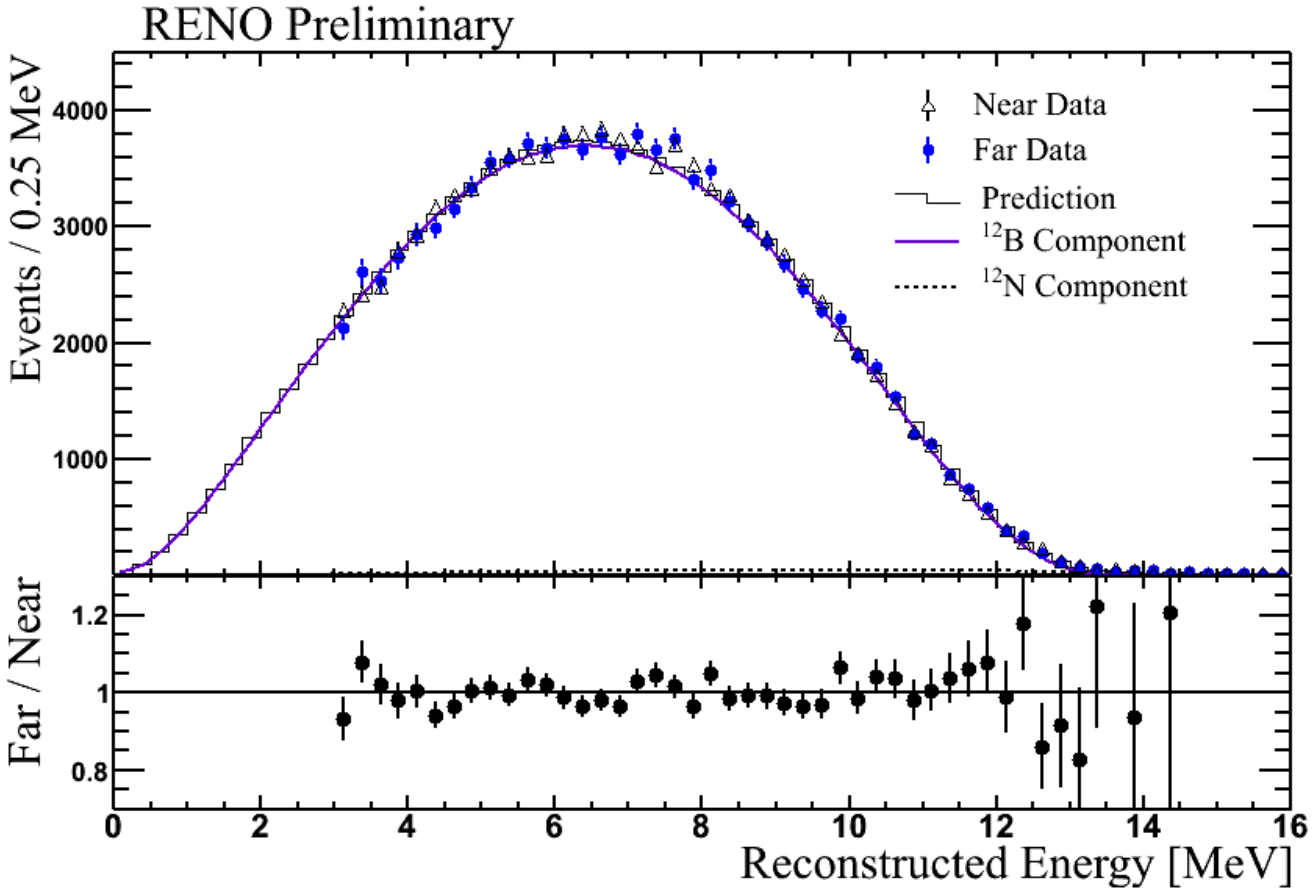
- Non-linear resonse of the scintillation energy is calibrated using γ-ray sources.
- The visible energy from γ-ray is corrected to its corresponding positron energy.



Fit function : $E_{vis}/E_{true} = a - b/(1 - \exp(-cE_{true} - d))$

B12 Energy Spectrum (Near & Far)

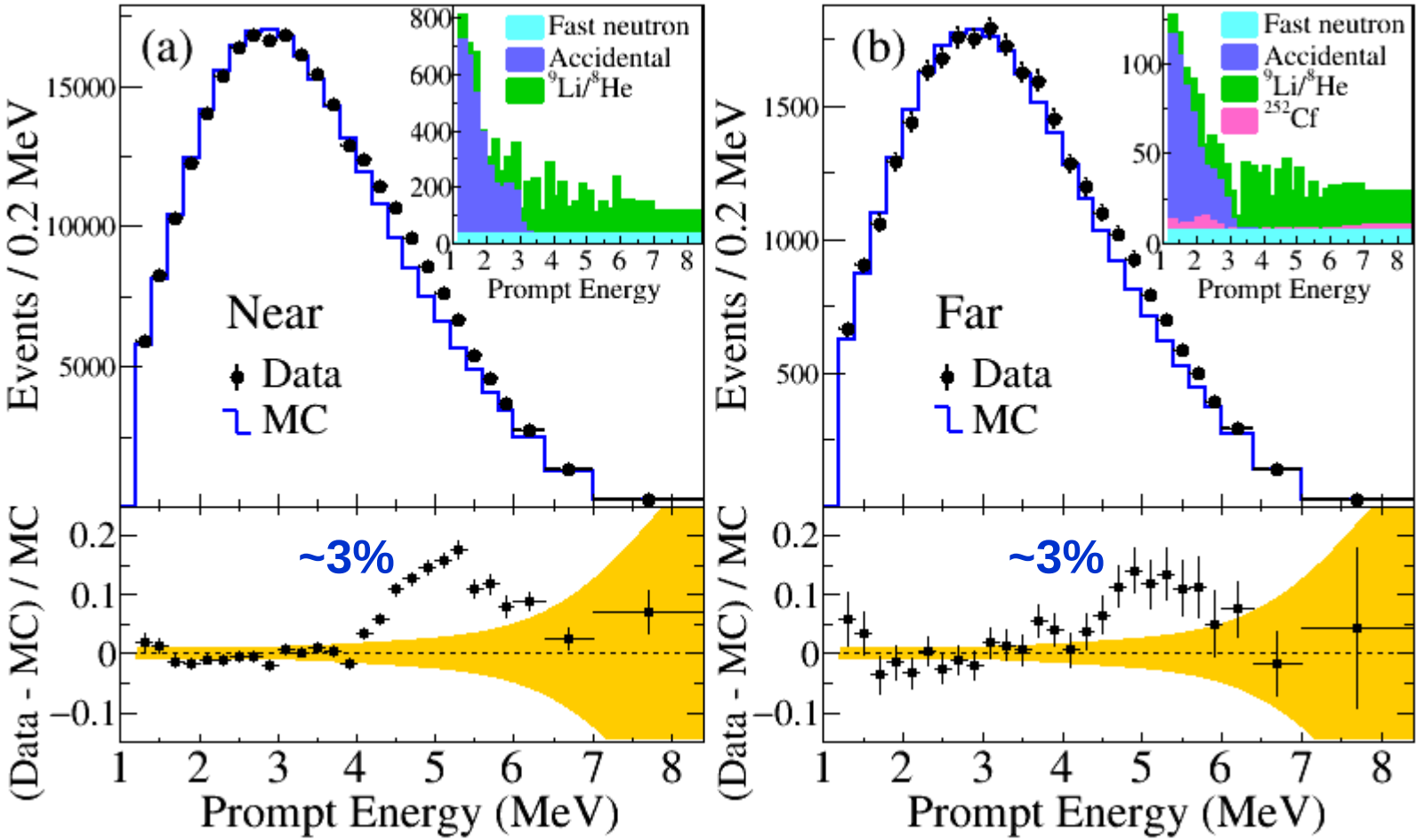
- Electron energy spectrum from β-decays from ^{12}B and ^{12}N, which are produced by comic-muon interactions.



Good agreement between data and MC spectrum!

Observation of an excess at 5 MeV

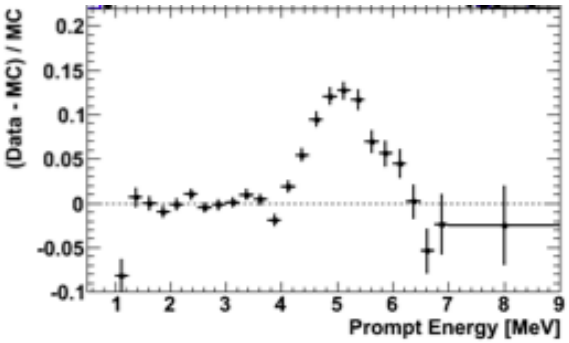
PRL 116, 211801, 2016



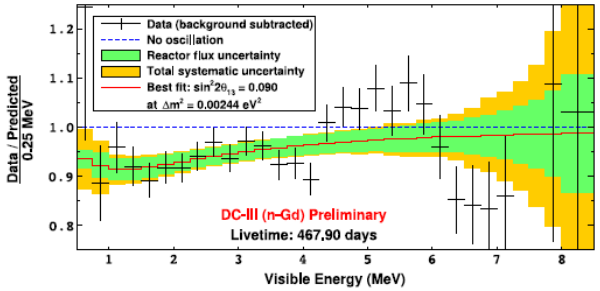
In Neutrino 2014, RENO showed the 5 MeV excess is from reactor neutrinos.

The 5 MeV Excess is there !

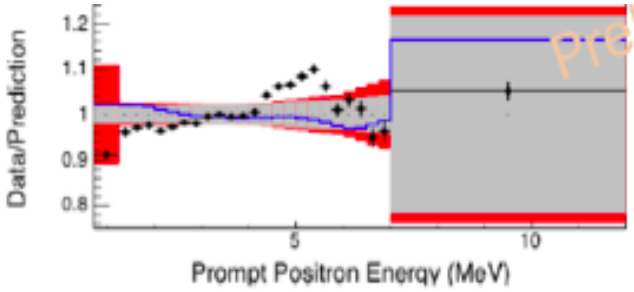
RENO



Double Chooz



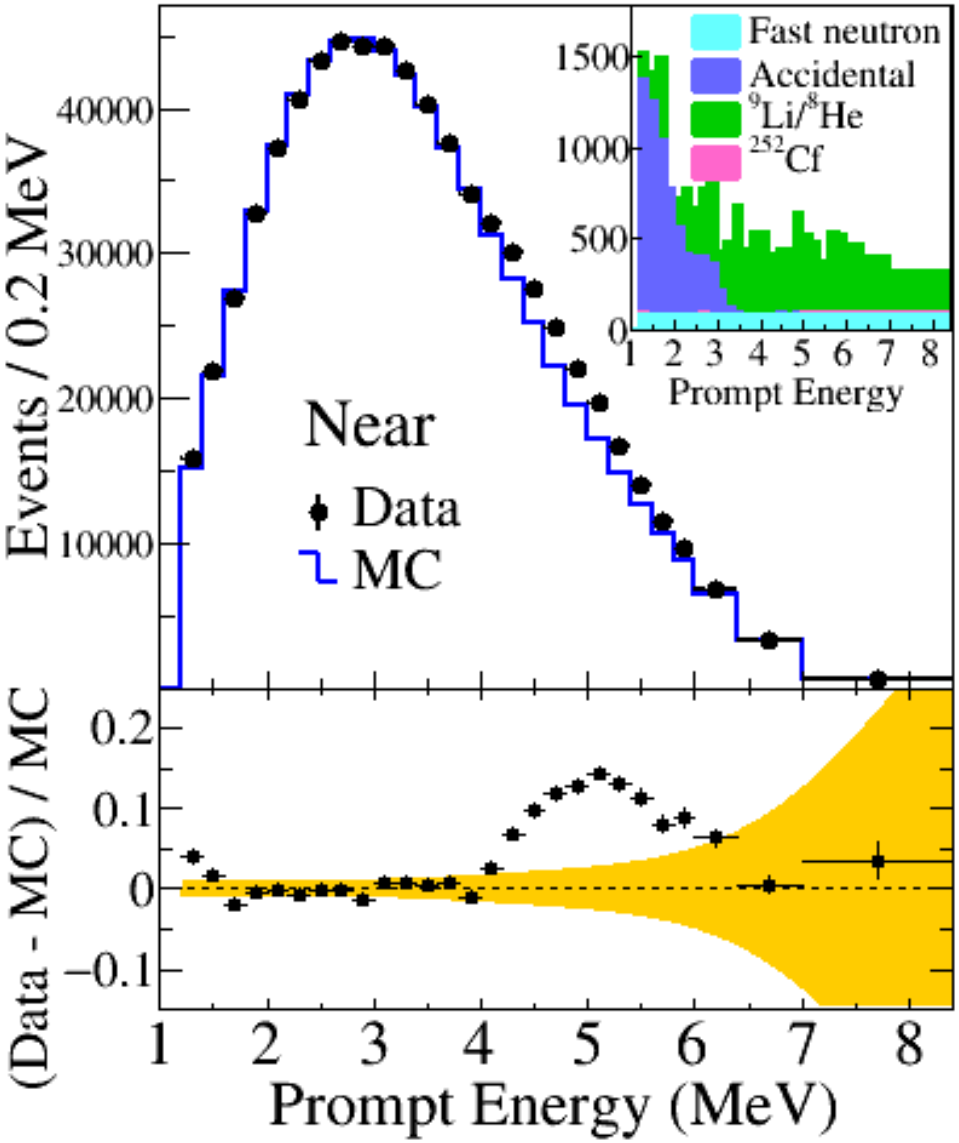
Daya Bay



In 2014, RENO showed the 5 MeV excess is from reactor neutrinos.

Observation of an excess at 5 MeV

RENO 1400 days of data (Aug. 2011 – Sep 2015) (Preliminary)



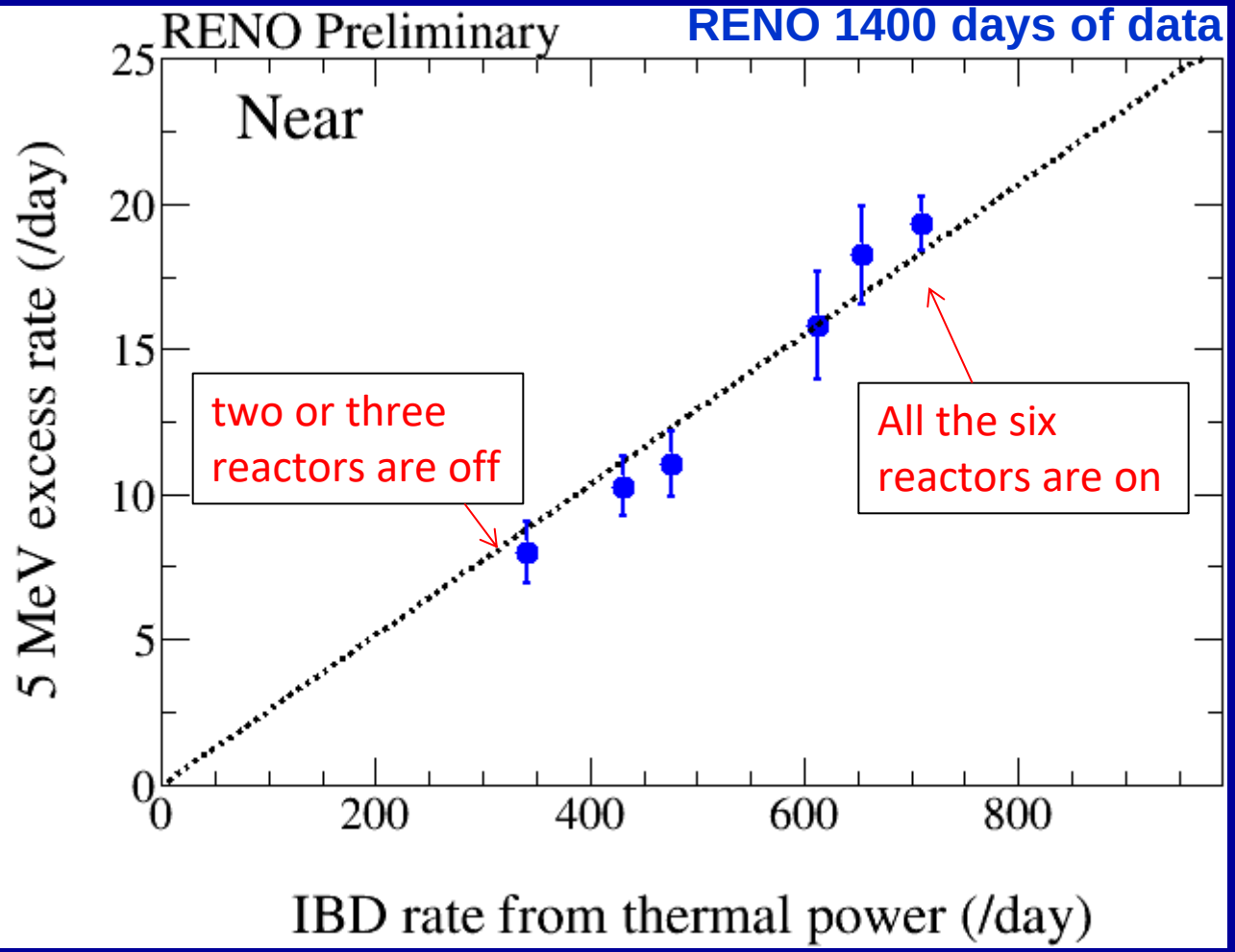
The measured near spectrum is compared with prediction using χ^2-square test.

Fraction of 5 MeV excess:
2.46 ± 0.27 (%)

Significance of the 5 MeV excess: **~9 σ**

Correlation of 5 MeV Excess with Reactor Power

PRL 116, 211801, 2016



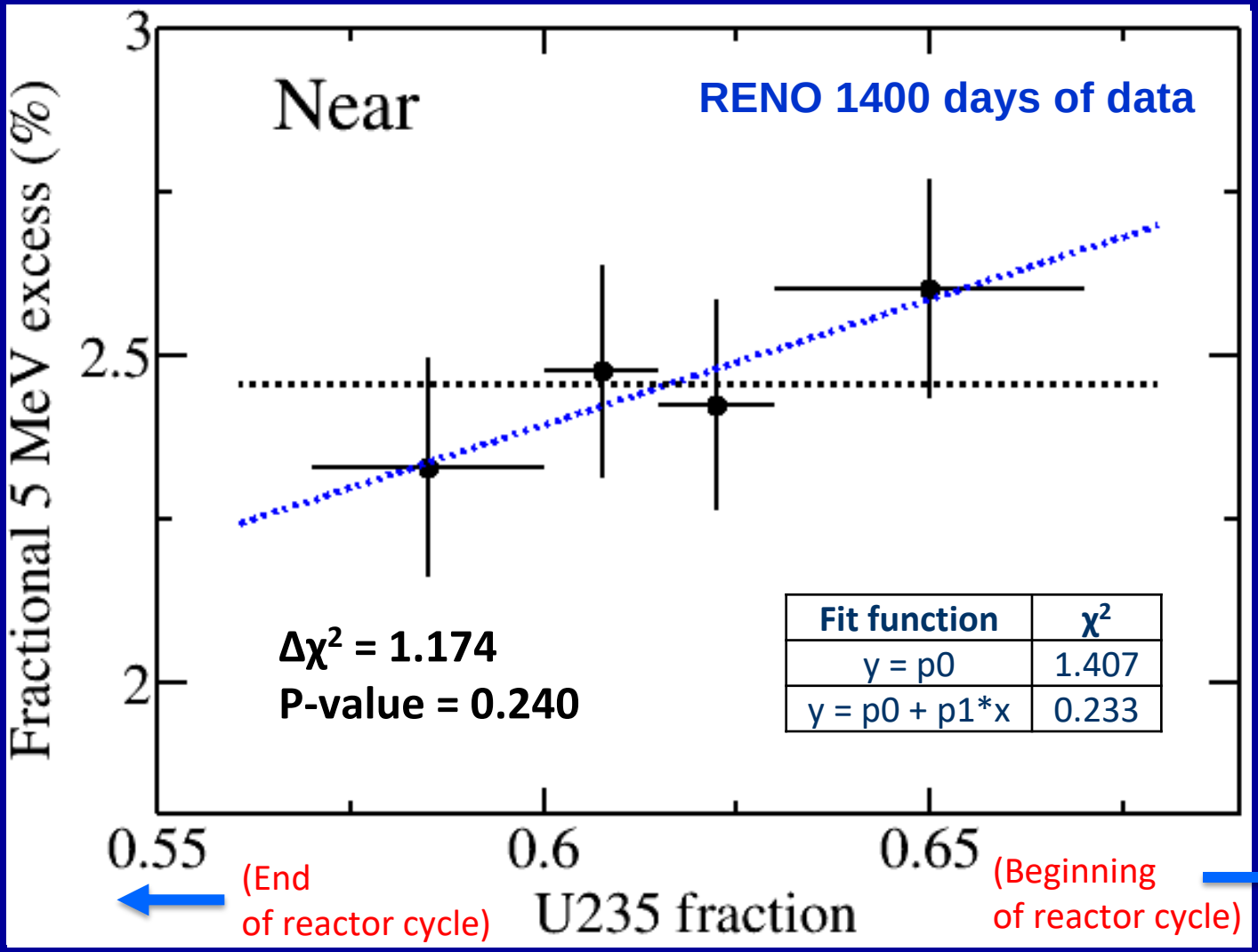
5 MeV excess has a clear correlation with reactor thermal power !

The 5 MeV excess comes from reactors!

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

(Preliminary)

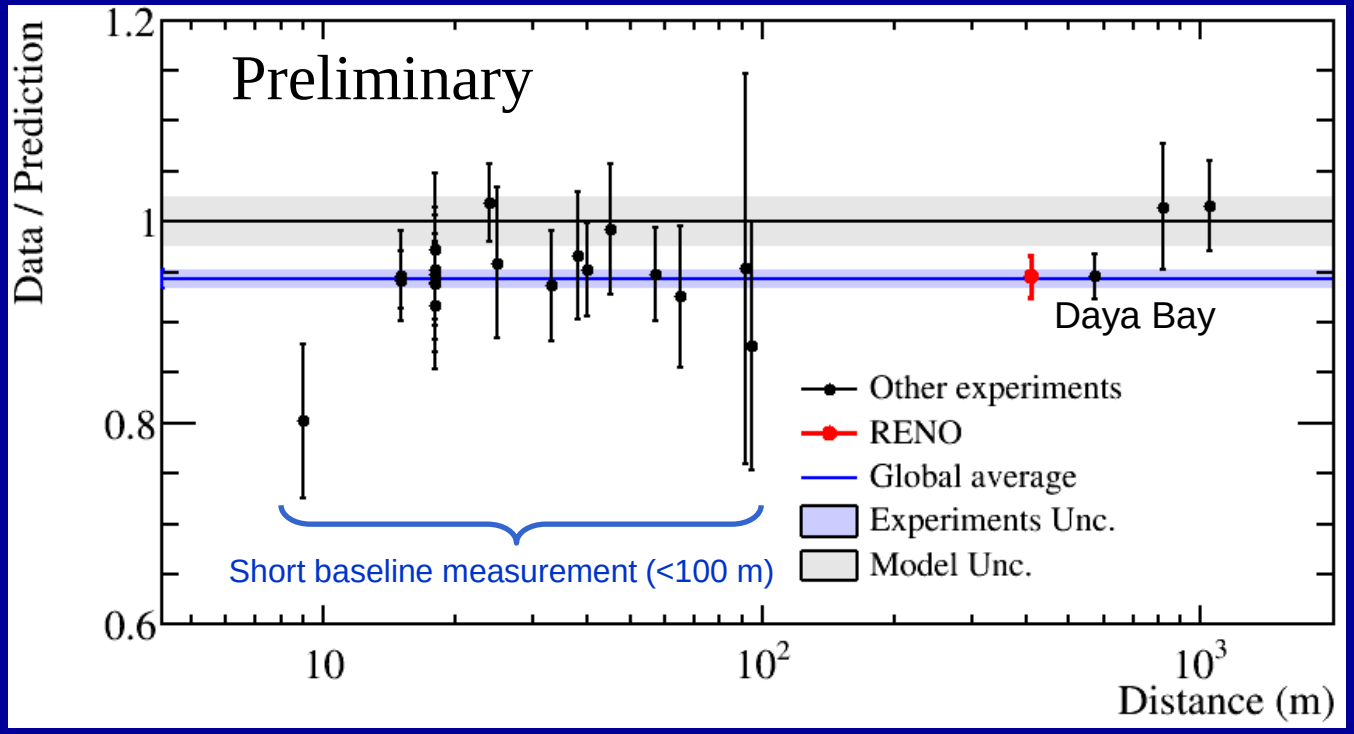
^{235}U fraction corresponds to freshness of reactor fuel



Measurement of Absolute Reactor Neutrino Flux

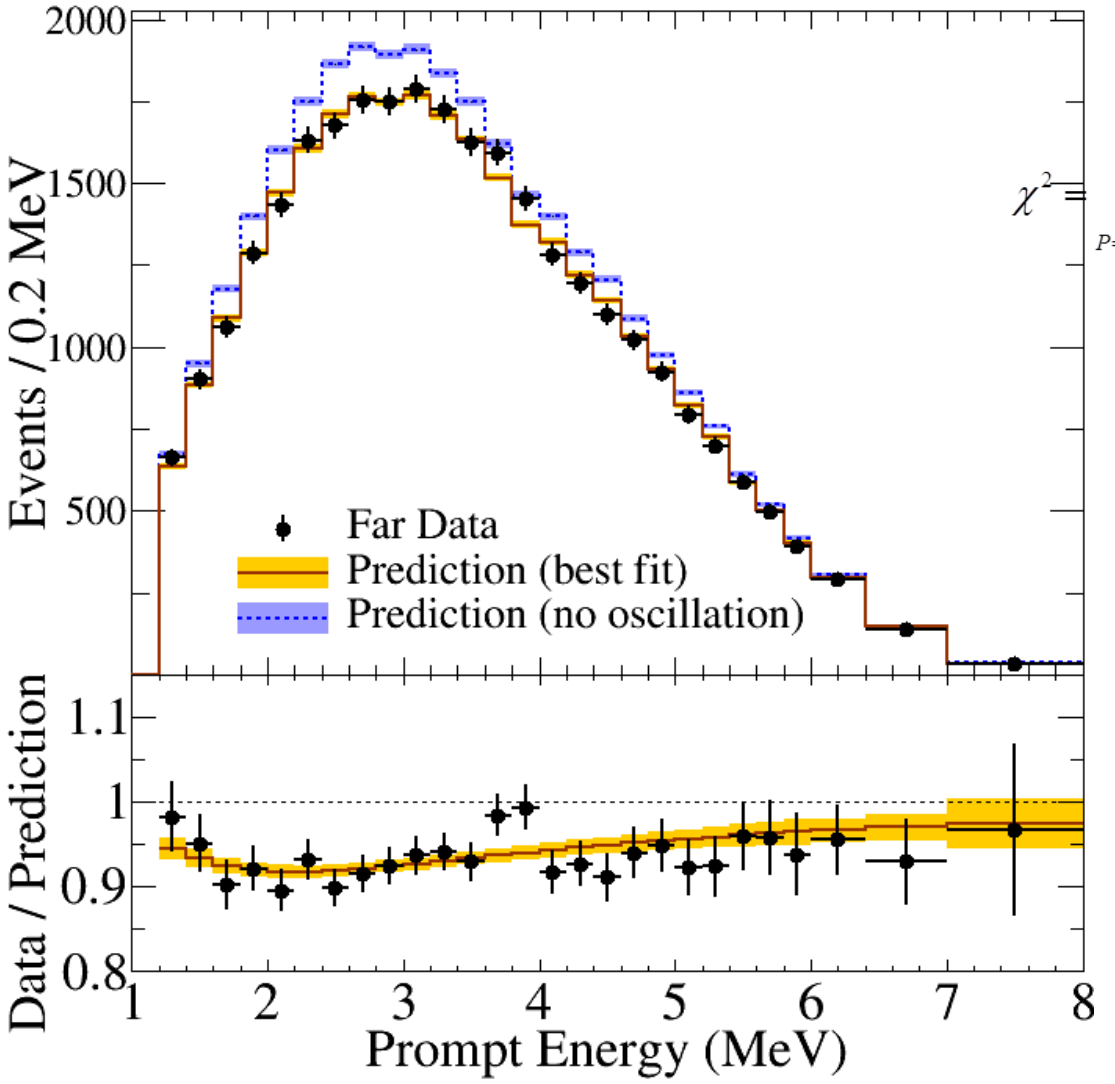
	Data / Prediction (Huber + Mueller)	Flux weighted baseline at near
RENO (500 days)	0.944 ± 0.021	411 m

*Prediction is corrected for three flavor neutrino oscillation



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

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

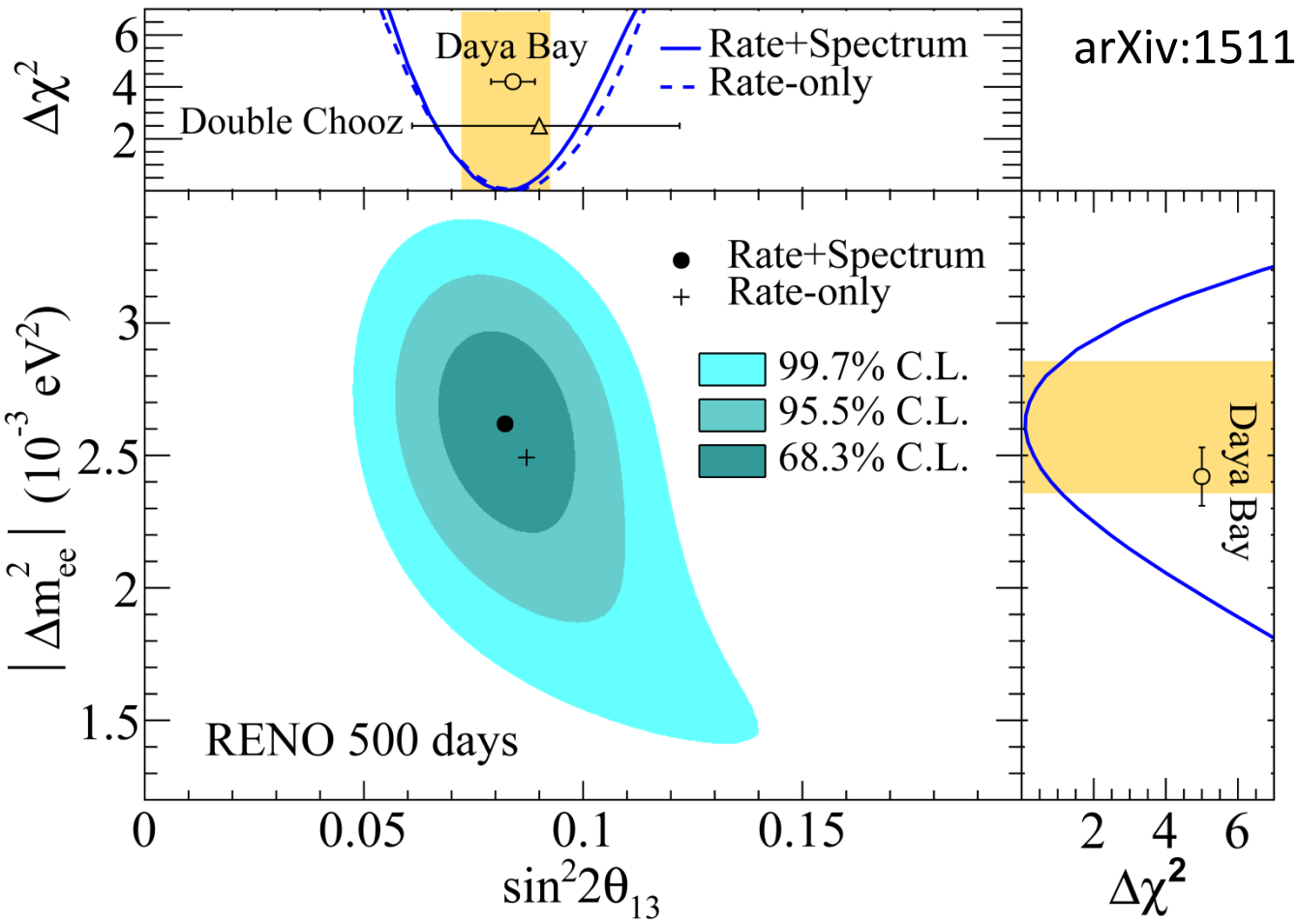


Minimize X^2 Function

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

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

Results from Spectral Fit



arXiv:1511.05849.v2

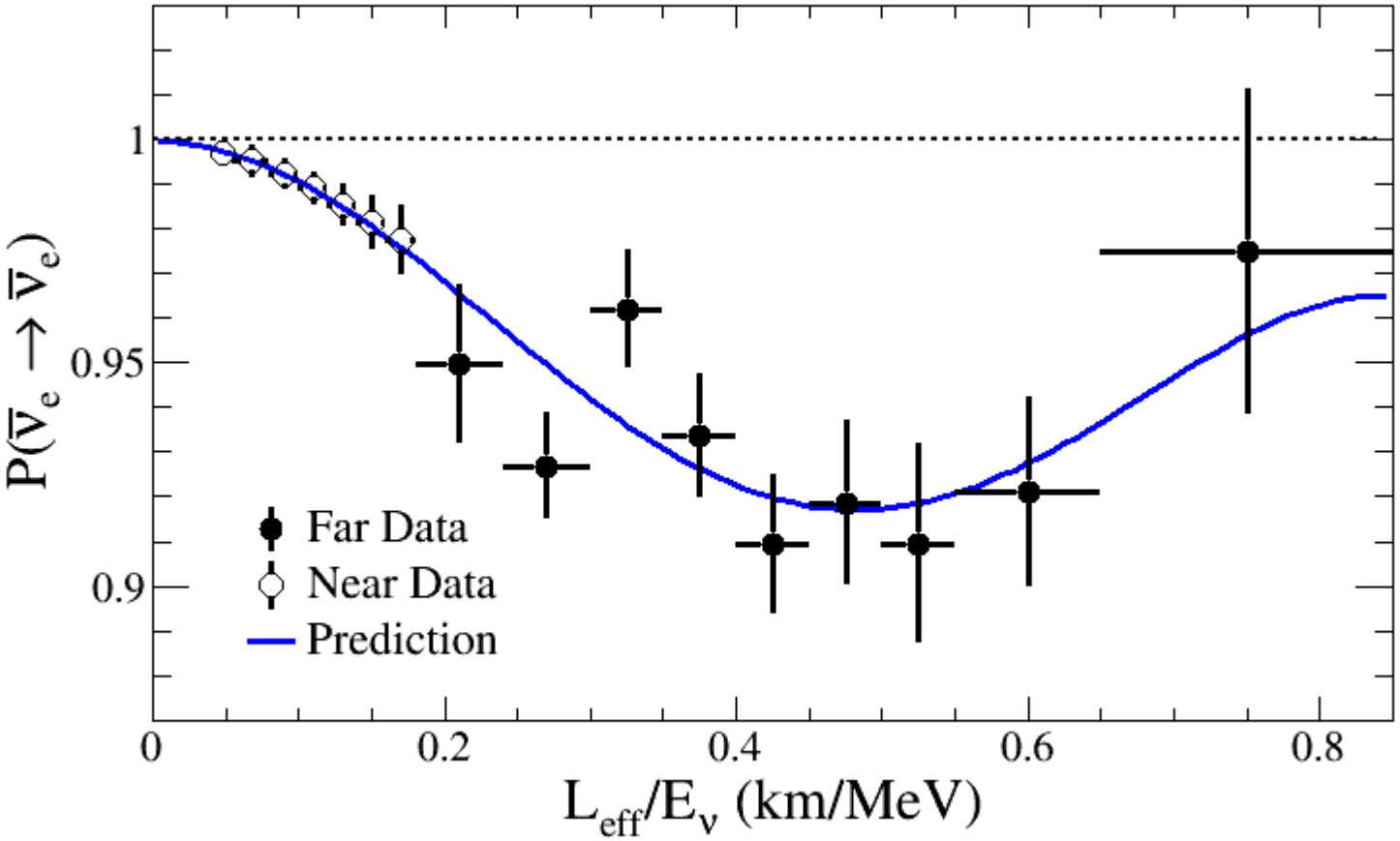
Rate+shape new results

$$\sin^2 2q_{13} = 0.082 \pm 0.009(\text{stat.}) \pm 0.006(\text{syst.})$$ (± 12 %)

$$\left|Dm^2_{ee}\right| = 2.62^{+0.21}_{-0.23}(\text{stat.})^{+0.12}_{-0.13}(\text{syst.}) \ (\acute{}\ 10^{-3} eV^2)$$ (± 10 %)

Observed L/E Dependent Oscillation

arXiv:1511.05849.v2



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

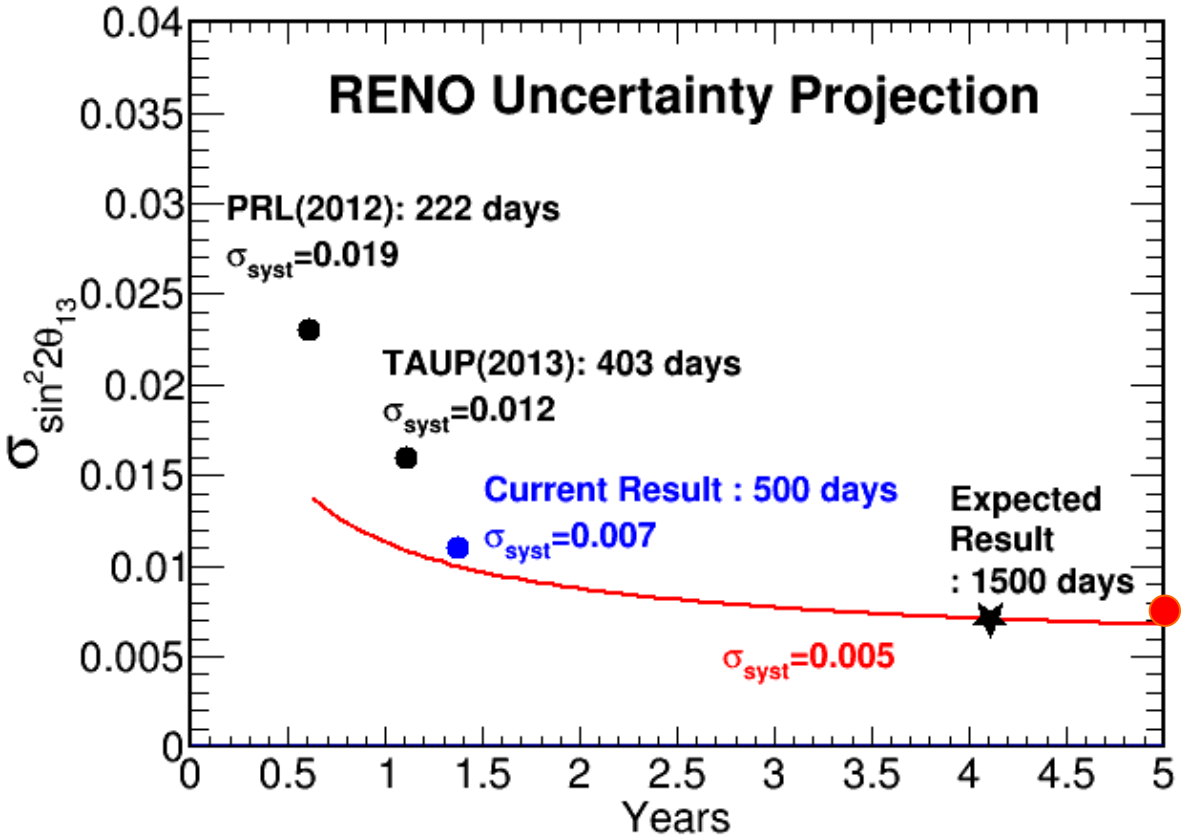
Projected Sensitivity of θ_{13} & $|\Delta m_{ee}^2|$

$\sin^2 2\theta_{13} = 0.082 \pm 0.011$ (±12%) ⇨ ± 0.005 (±6 %)

$\left|\Delta m^2_{ee}\right| = (2.62^{+0.24}_{-0.26}) \times 10^{-3}\,\mathrm{eV}^2$ (±10%) ⇨ $\pm 0.15 \times 10^{-3}\,\mathrm{eV}^2$ (±6 %)

(~500 days)

(5 years of data)



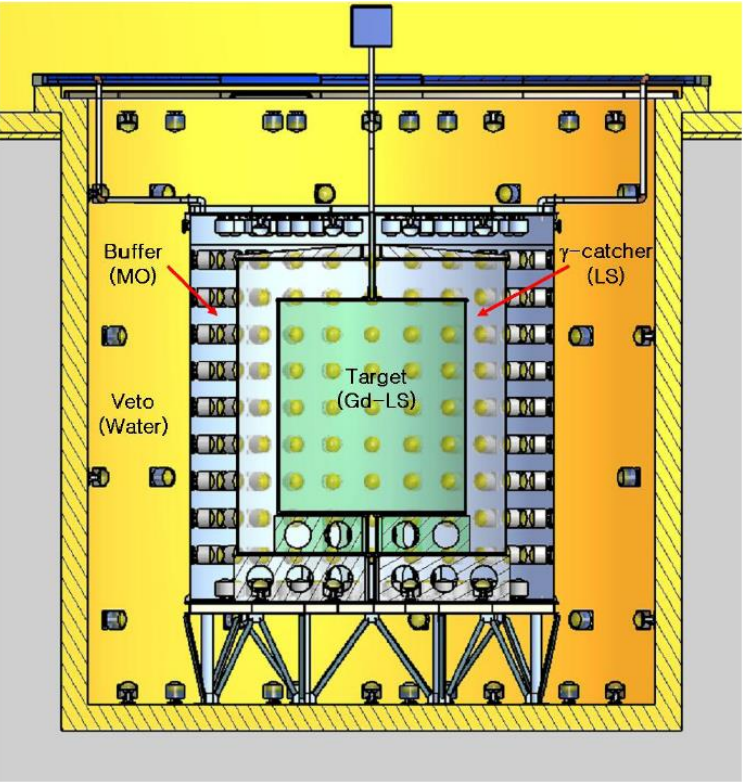
(6 % precision)

(sensitivity goal of θ_{13})

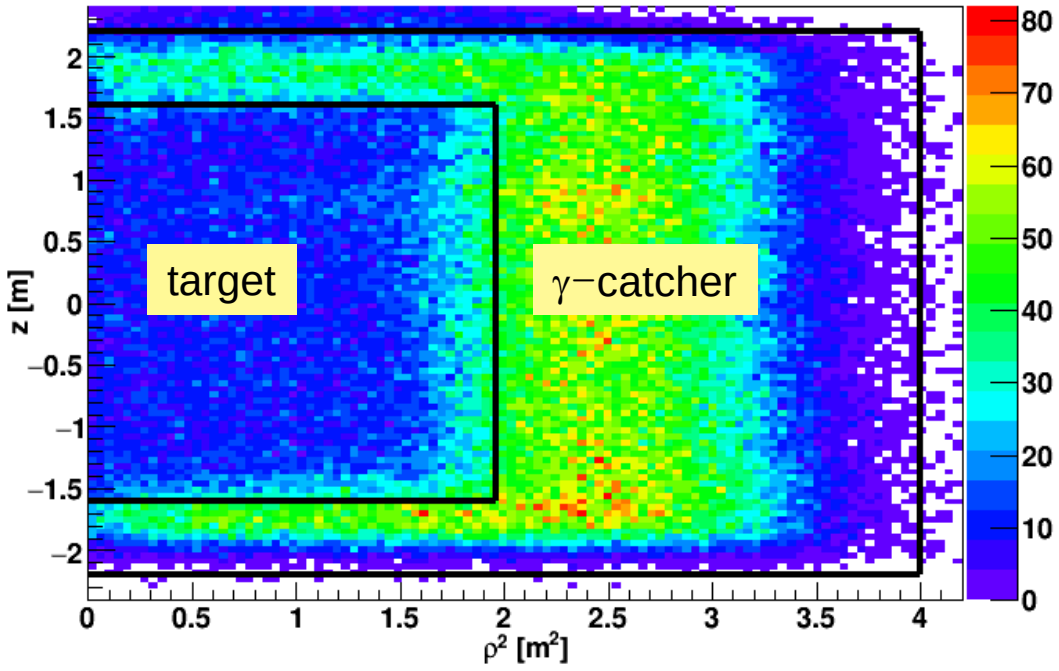
n-H IBD Analysis

Motivation:

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



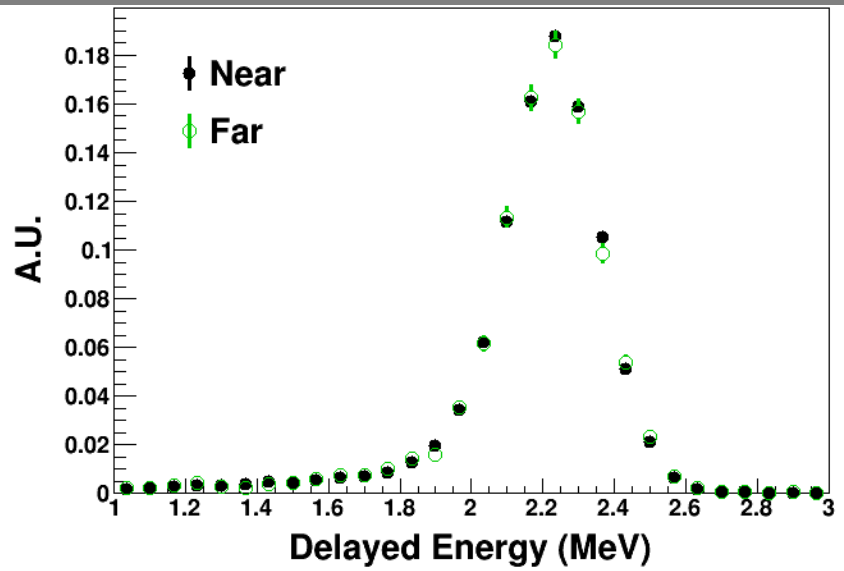
n-H IBD Event Vertex Distribution



Poster: "Measurement of θ_{13} using RENO reactor neutrino events with neutron capture on hydrogen" (C. D. Shin)

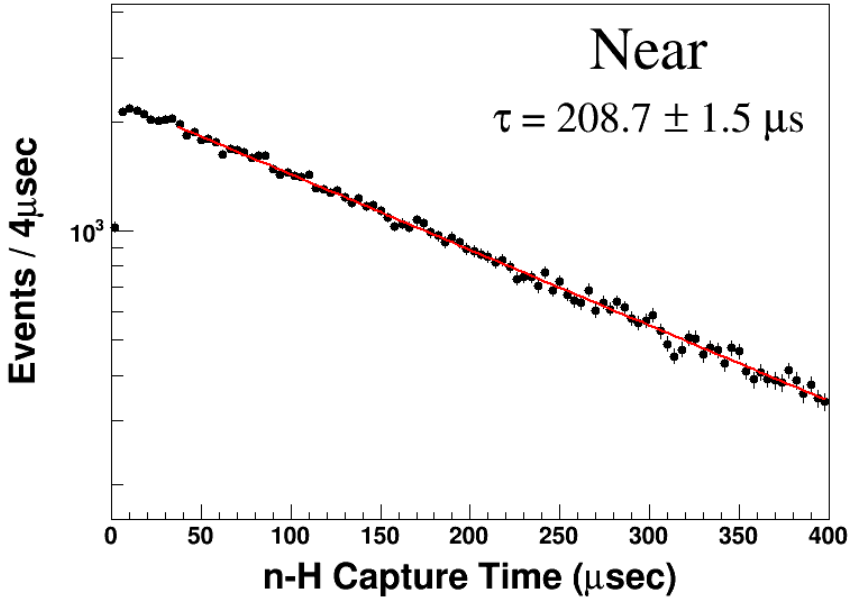
Delayed spectrum and capture time

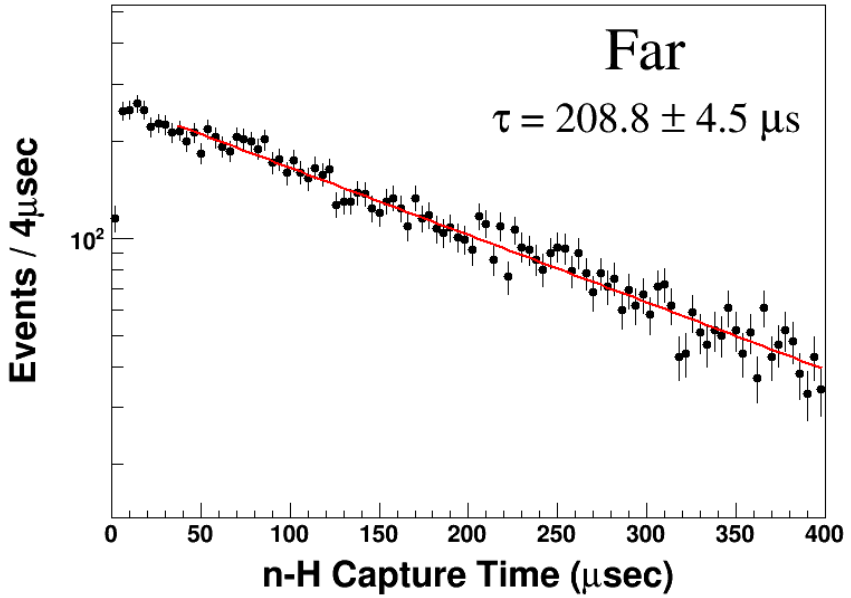
- Delayed signal peak:
  ~2.2 MeV
- Mean coincidence time:
  ~ 200 μs



Capture time (n-H)

Far and near data match very well





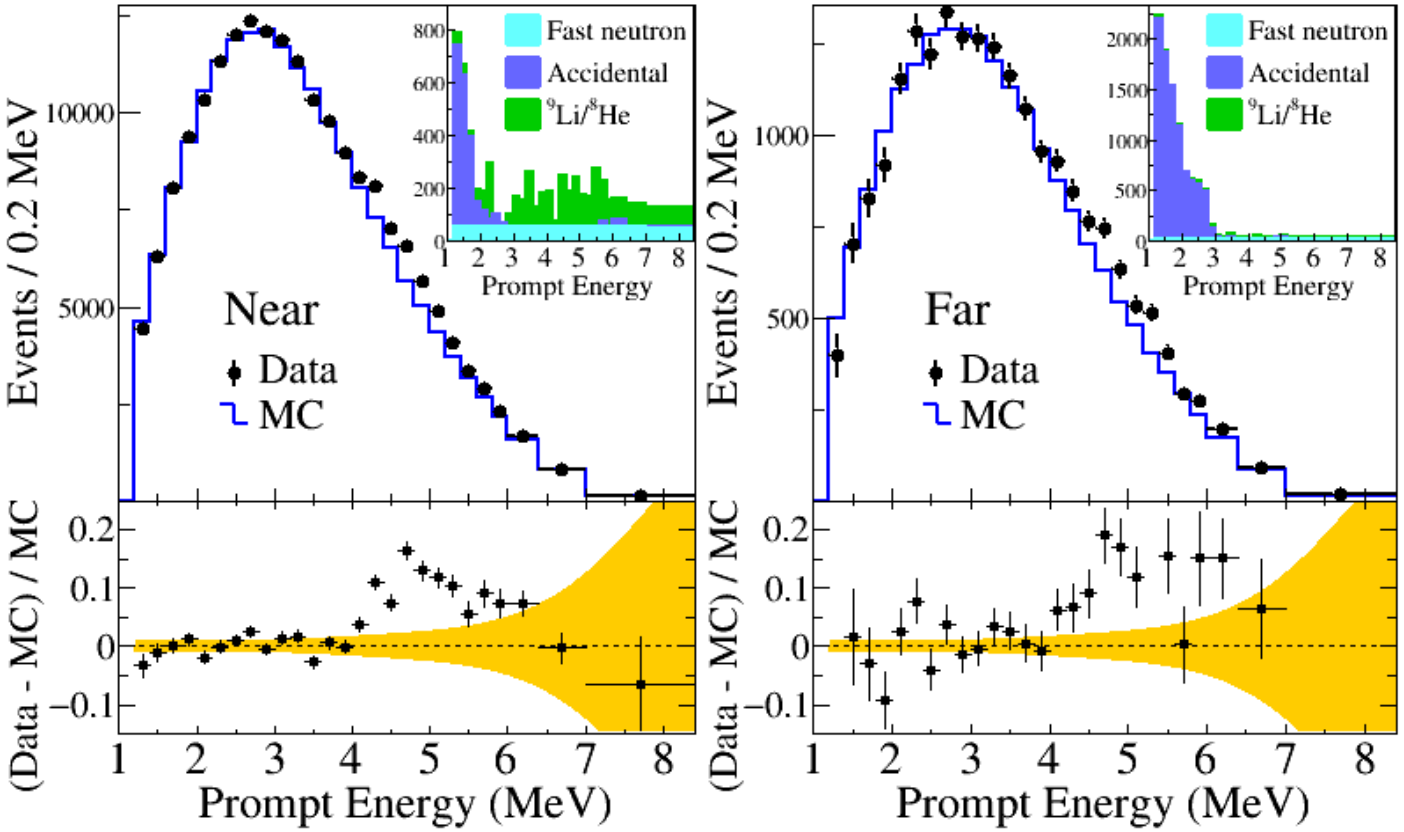
θ_{13} Measurement with n-H

Data set : 2011/08 ~ 2013/01 (~500 days)

Preliminary rate only analysis results is

$$\sin^2 2\theta_{13} = 0.086 \pm 0.012(\text{stat.}) \pm 0.015(\text{syst.})$$

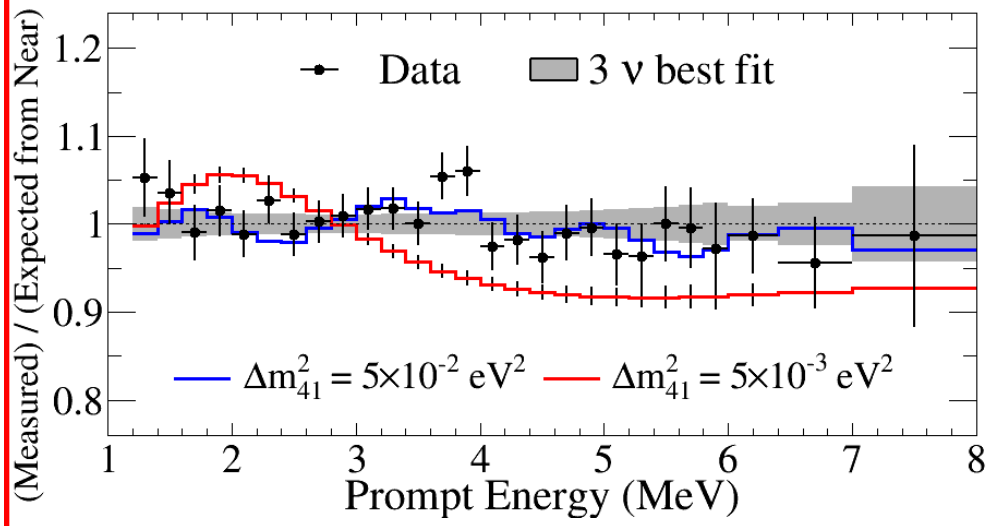
	Uncertainty
Detection efficiency	0.59%
Thermal power	0.5 %
Isotope fraction	0.7 %
Background	Near : 0.2% Far : 0.8%

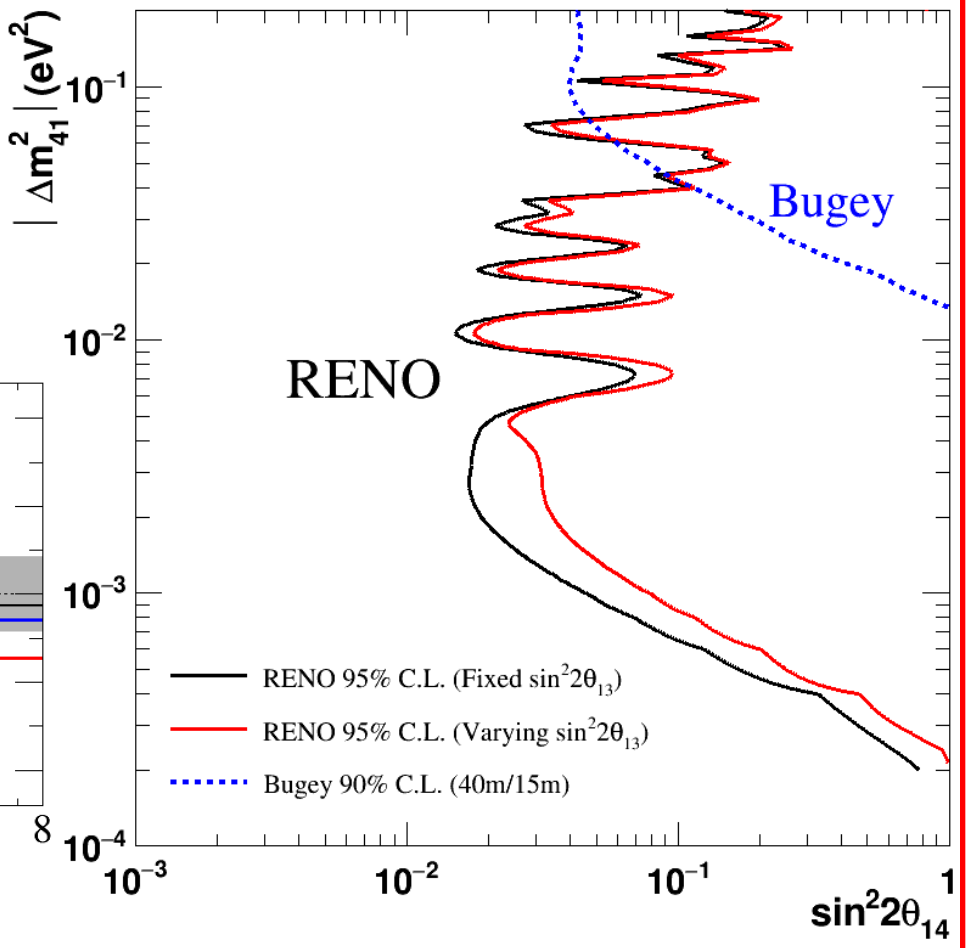


Light Sterile Neutrino Search Results

- All 500 days of RENO data
- Consistent with standard 3-flavor neutrino oscillation model
- Able to set stringent limits in the region $10^{-3}\,\mathrm{eV}^2 < \Delta m^2_{41} < 0.1\,\mathrm{eV}^2$

(Preliminary)





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

Paper now in preparation

Summary

- New results are presented
  - More precise measurement of θ_{13} value ($\pm$12%)
  - Clear observation of 5 MeV excess
  - First measurement of Δm_{ee}^2 ($\pm$10%)
  - Absolute antineutrino flux measurement (R = 0.944 +- 0.021)
  - Independent measurement of θ_{13} with n-H
  - Excluded region for sterile neutrinos

Thanks for your attention!