Results from RENO

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Seoul National University

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RENO Collaboration

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

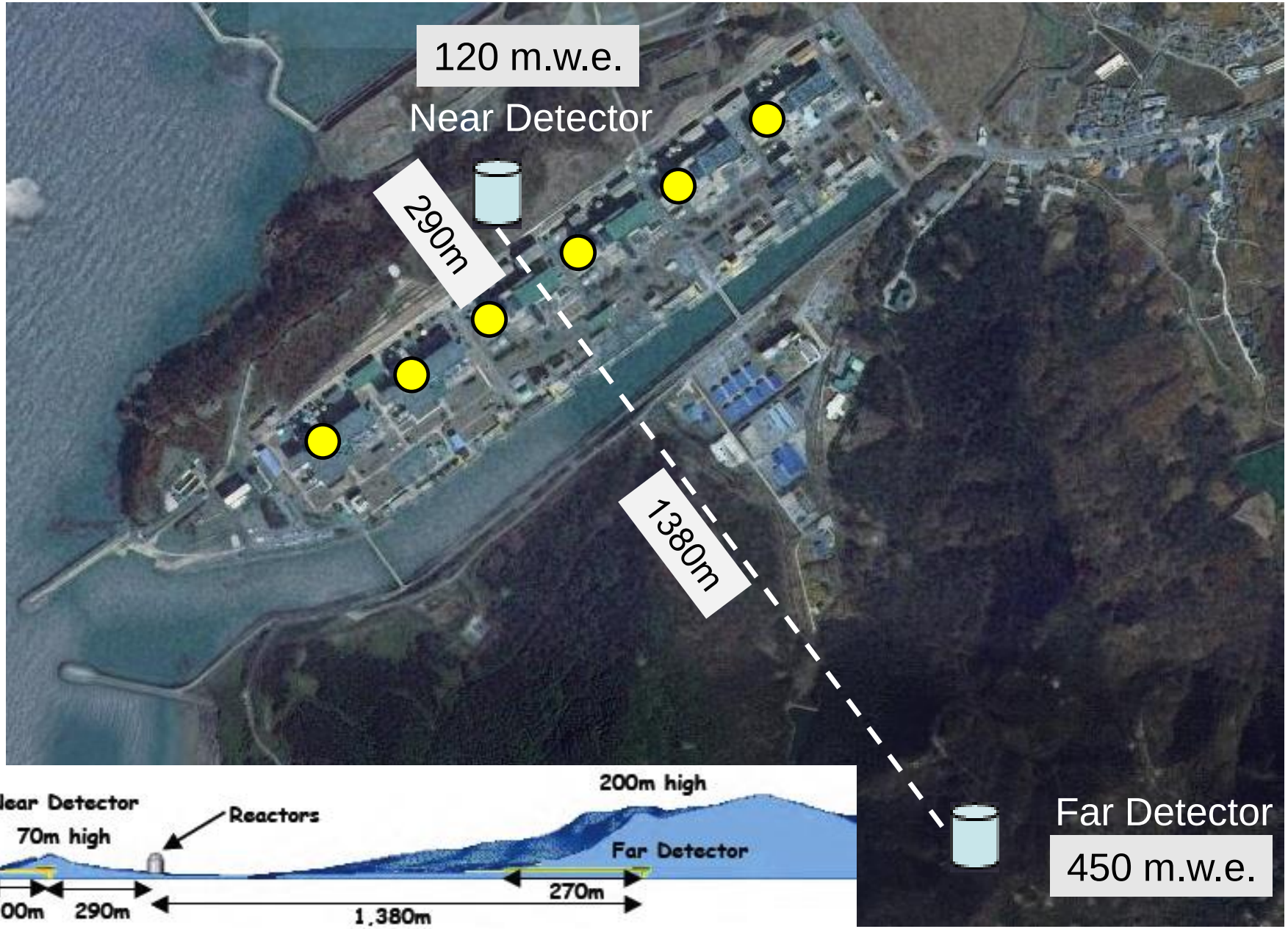
(8 institutions and 40 physicists)

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

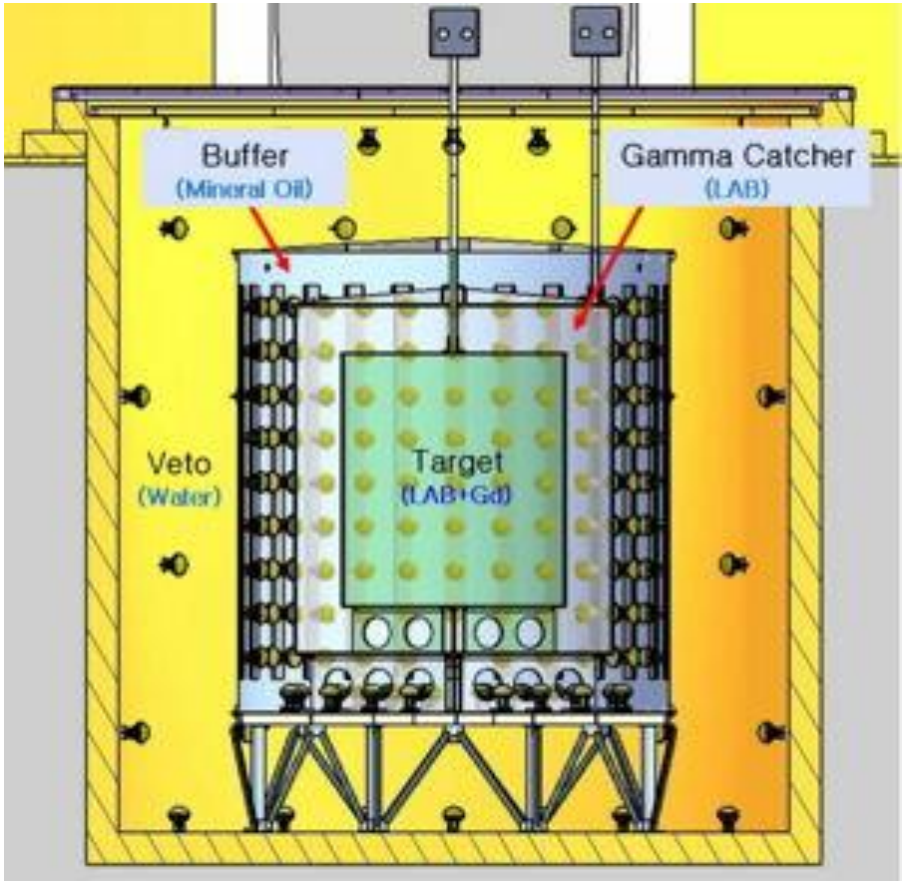
- Total cost : **$10M**
- Start of project : **2006**
- The first experiment running with both near & far detectors from **Aug. 2011**

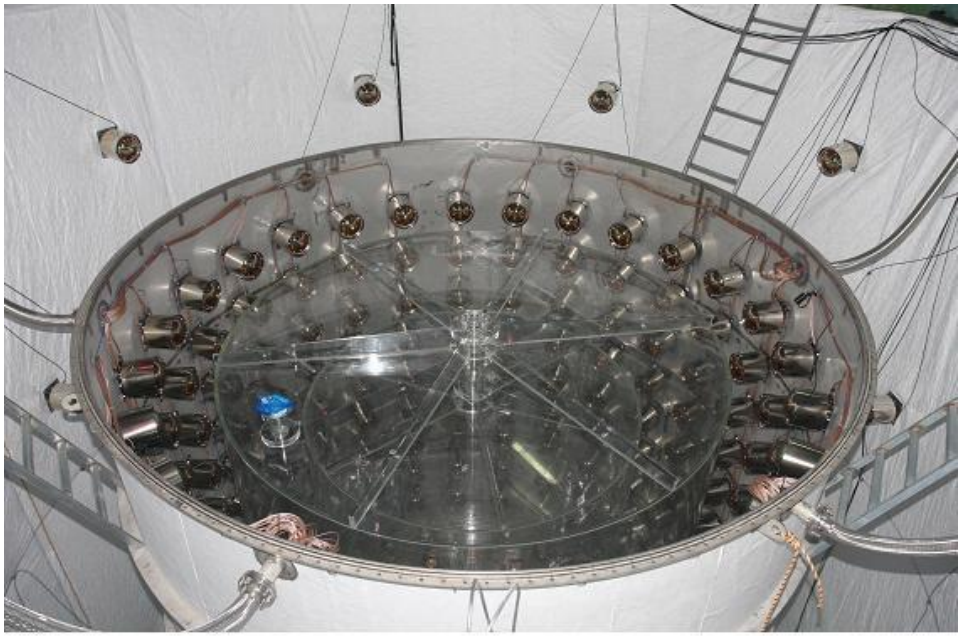
YongGwang (靈光) :

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

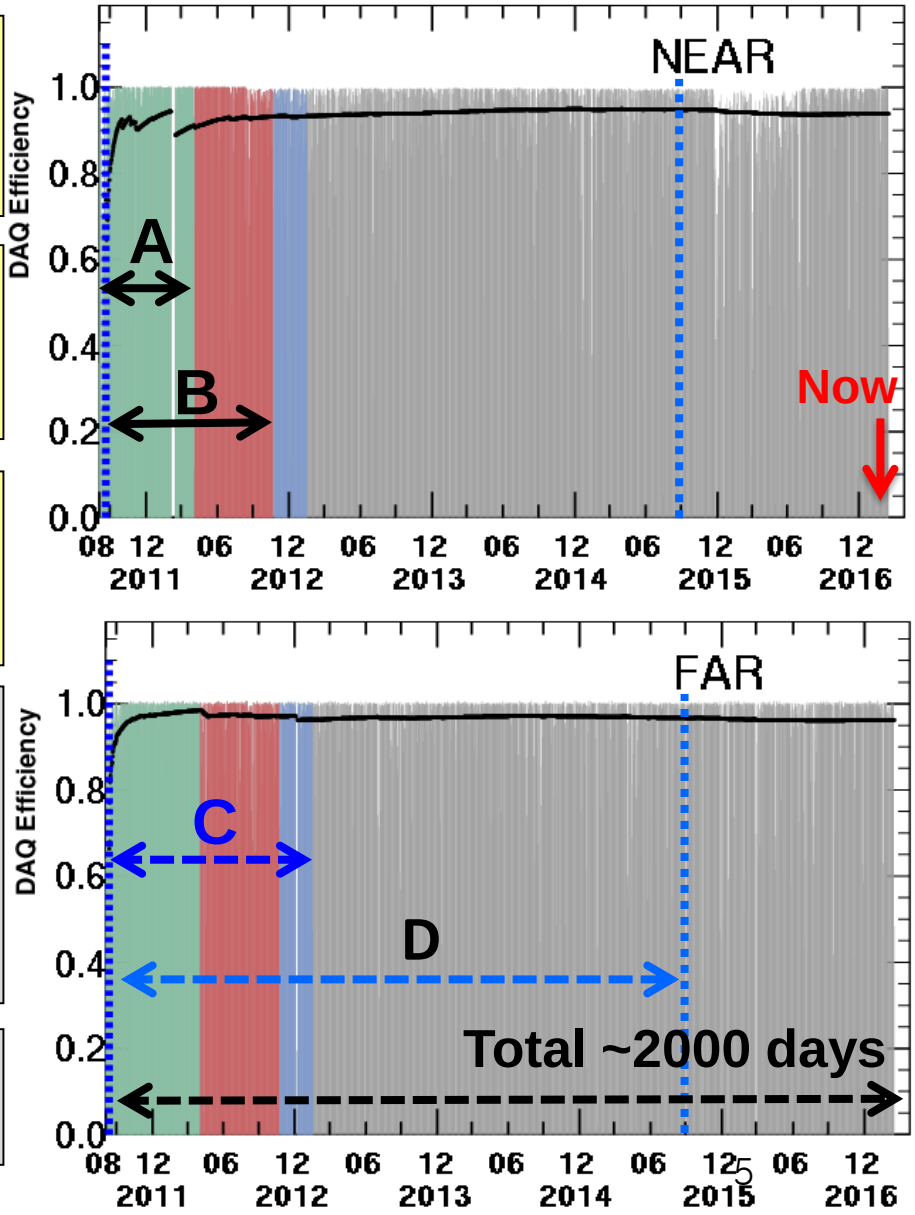
- Data taking began on Aug. 1, 2011 with both near and far detectors.
  (DAQ efficiency : ~95%)

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

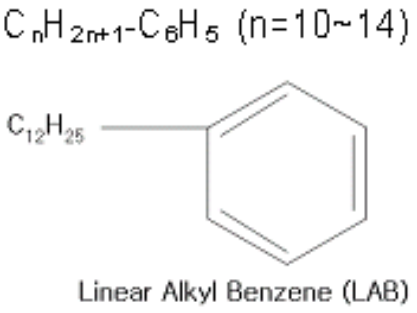
- **B (403 days)** : **Improved θ_{13} result**
  [11 Aug, 2011~13 Oct, 2012]
  NuTel 2013, TAUP 2013, WIN 2013

- **C (500 days)** : **New results**
  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 (1400 days)** : Spectrum
  [11 Aug, 2011 ~ 30 Sep,2015]



Detection of Reactor Antineutrinos



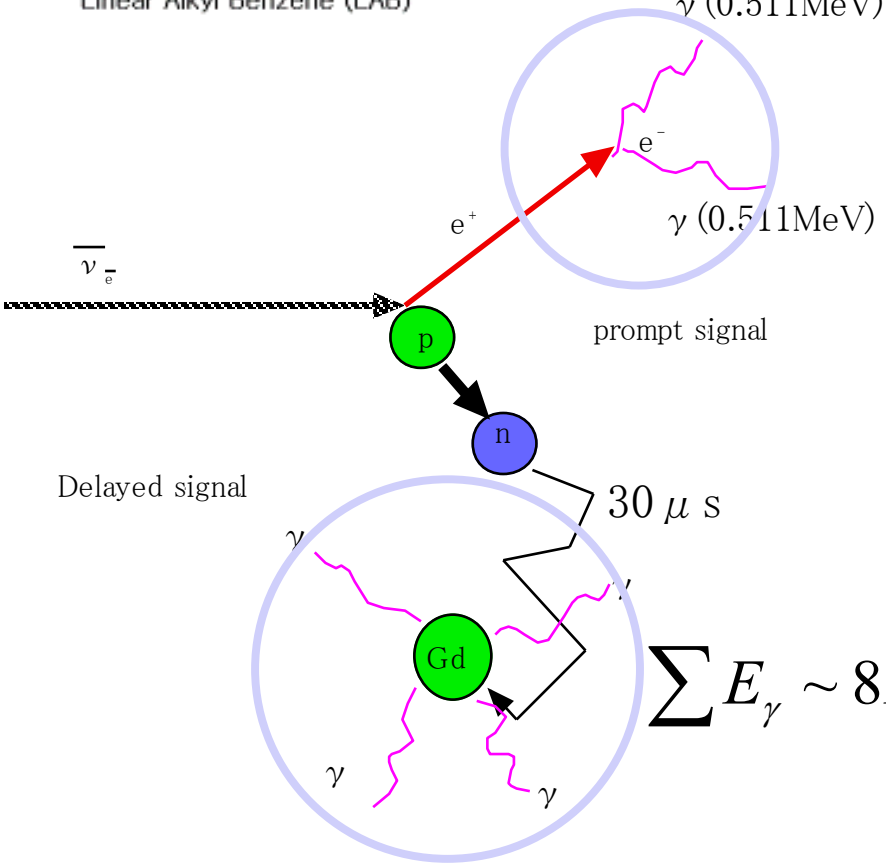
(prompt signal)

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

(delayed signal)

~180 μs: + p → D + γ (2.2 MeV)

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

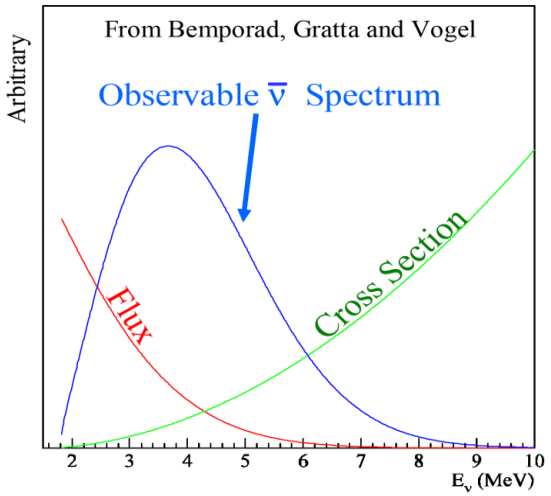


$$\sum E_\gamma \sim 8MeV$$

- **Neutrino energy measurement**

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

10-40 keV *1.8 MeV*



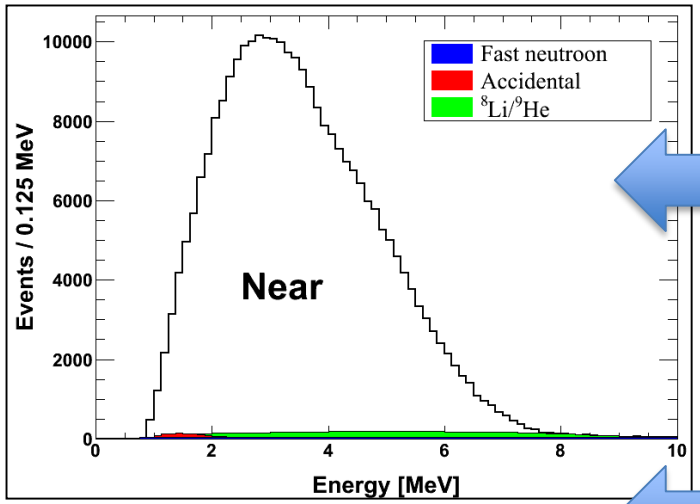
Coincidence of prompt and delayed signals

(prompt signal)

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

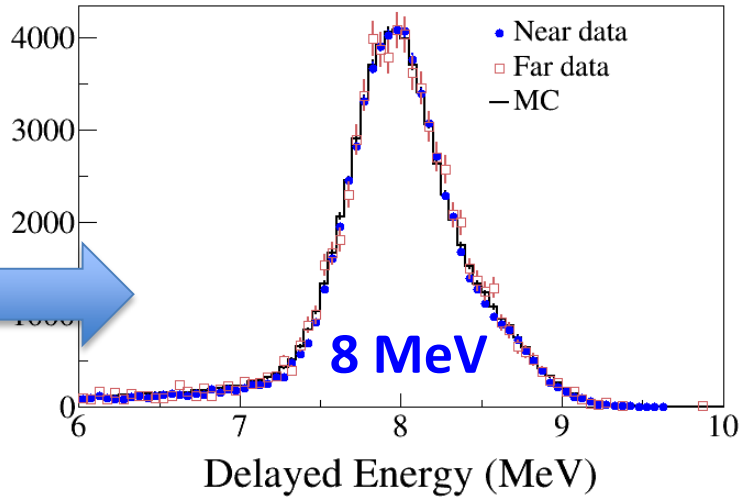
Prompt signal

Delayed signal



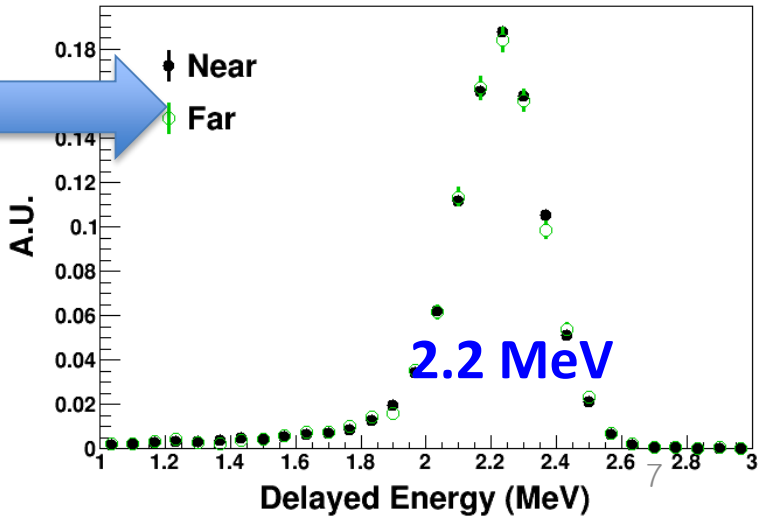
n-Gd IBD

~30 μs



~200 μs

n-H IBD



Results from RENO

- Observation of energy dependent disappearance of reactor neutrinos to measure Δm_{ee}^2 and θ_{13} using ~500 days of data (Aug. 2011 ~ Jan. 2013)

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

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

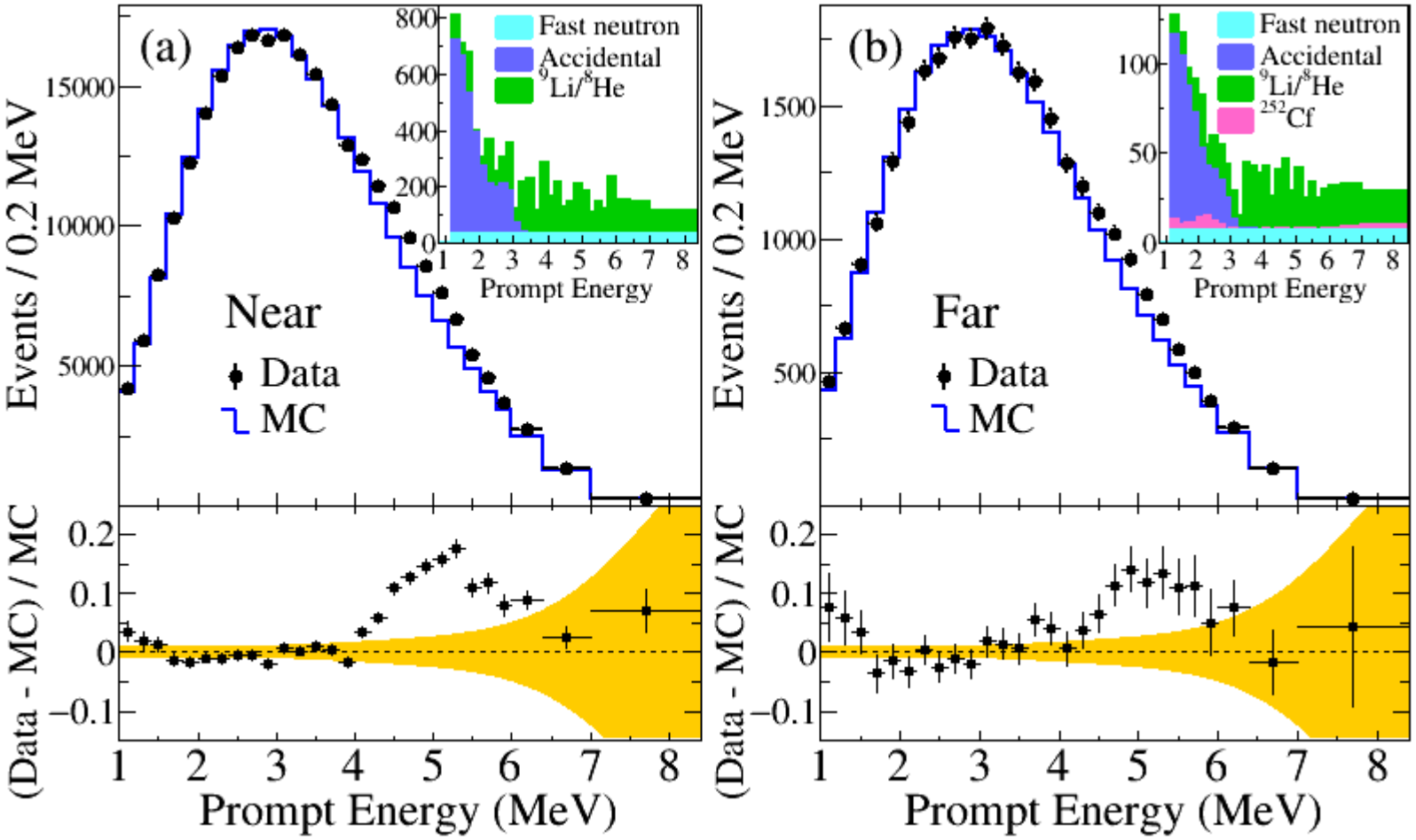
- Measurement of absolute reactor neutrino flux (500 days)

- Observation of an excess at ~5 MeV in reactor neutrino spectrum using ~1400 days of data

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

- Obtained results from a sterile neutrinos search

Measured Spectra of IBD Prompt Signal

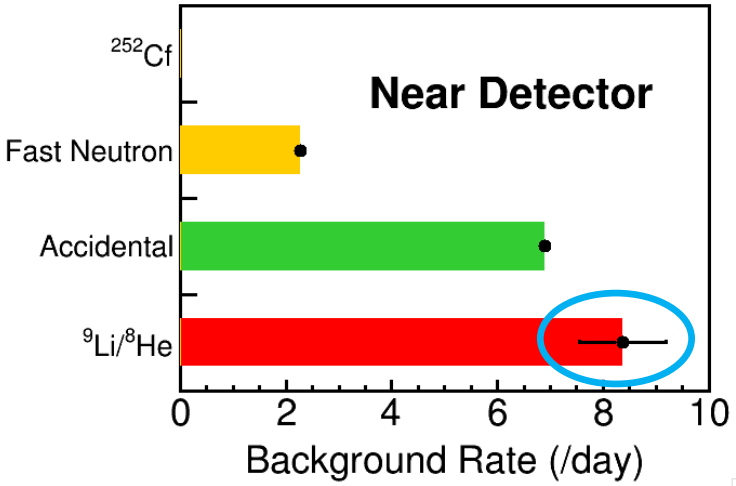


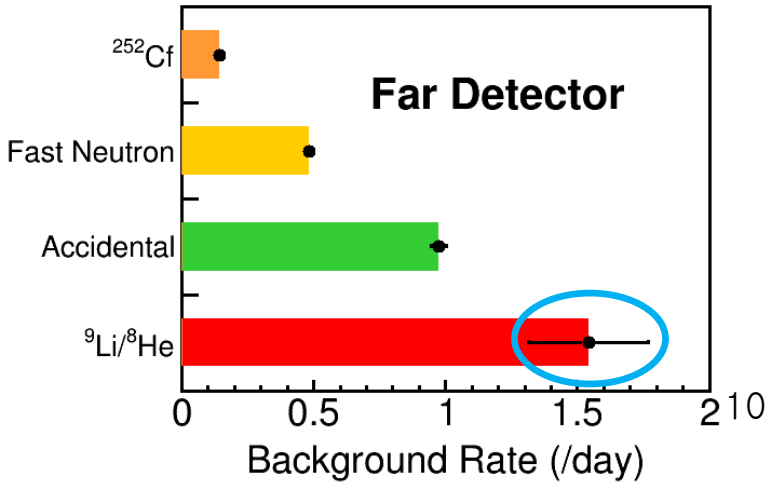
Near Live time = 458.49 days
# of IBD candidate = 290,775
# of background = 8,041 (2.8 %)

Far Live time = 489.93 days
# of IBD candidate = 31,541
# of background = 1540 (4.9 %)

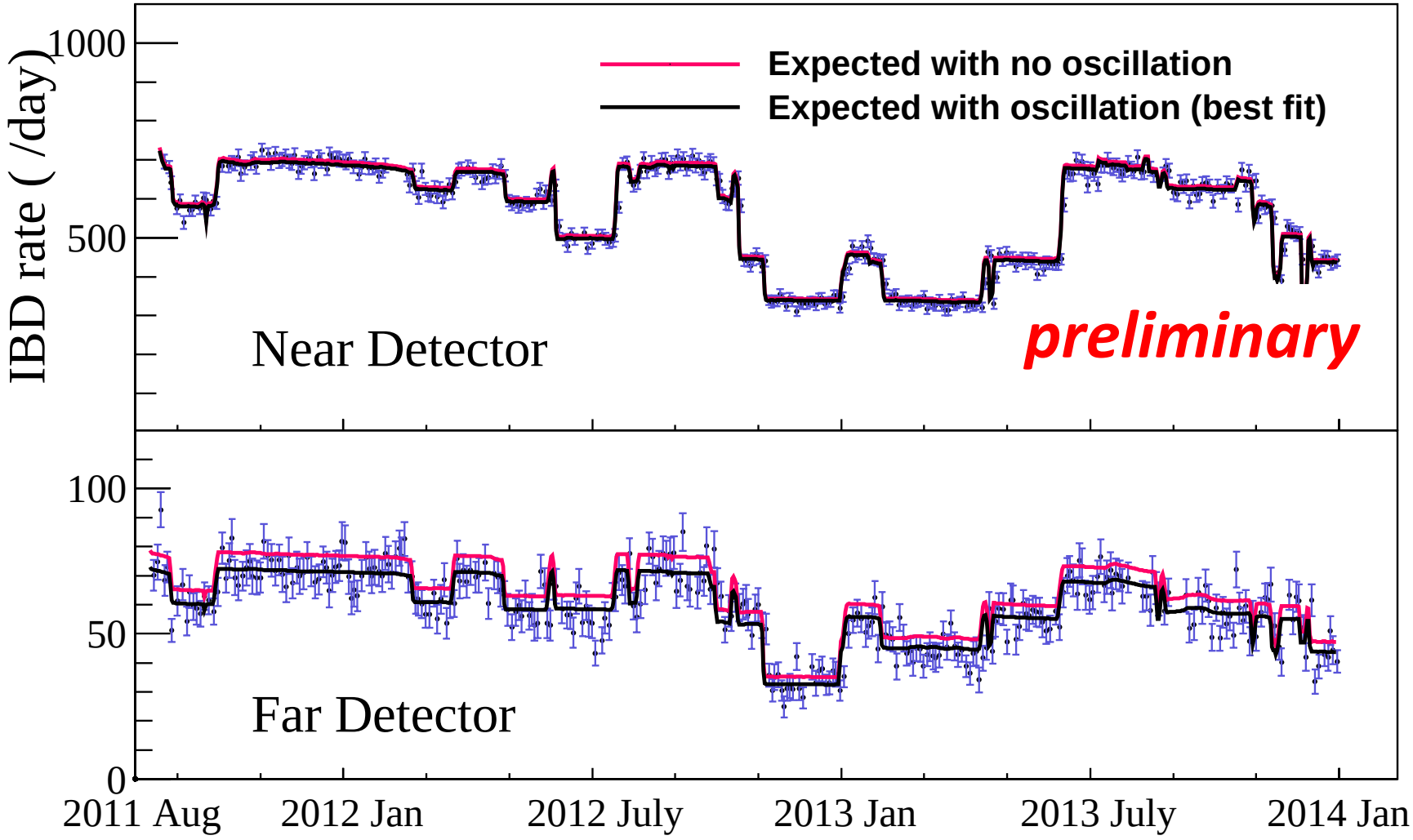
IBD Candidates & Backgrounds

	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

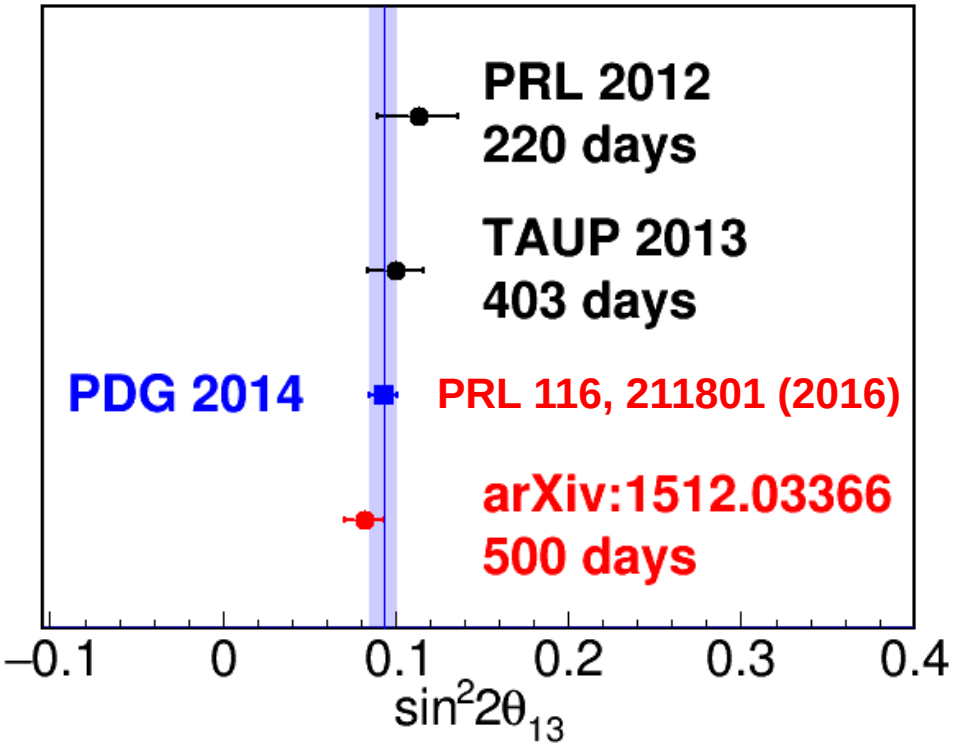
θ_{13} Measurement by Rate-only Analysis

Rate-only result

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

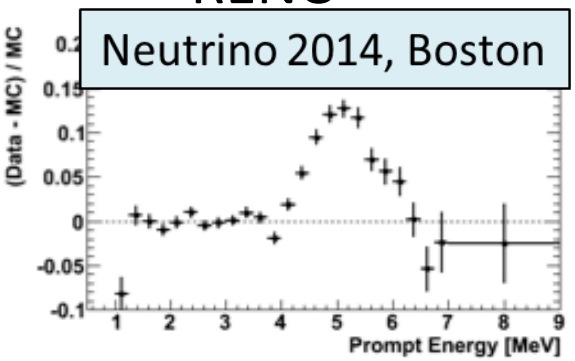
$|\Delta m_{ee}^2| = 2.49 \times 10^{-3}$ eV^2 is used (PDG 2014)

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

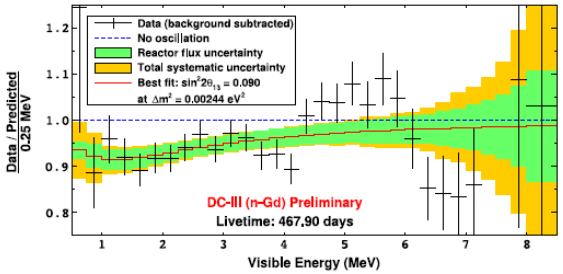


The 5 MeV Excess is there !

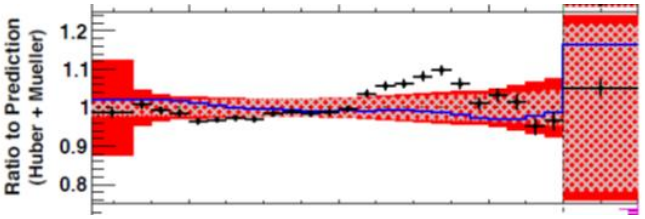
RENO



Double Chooz



Daya Bay

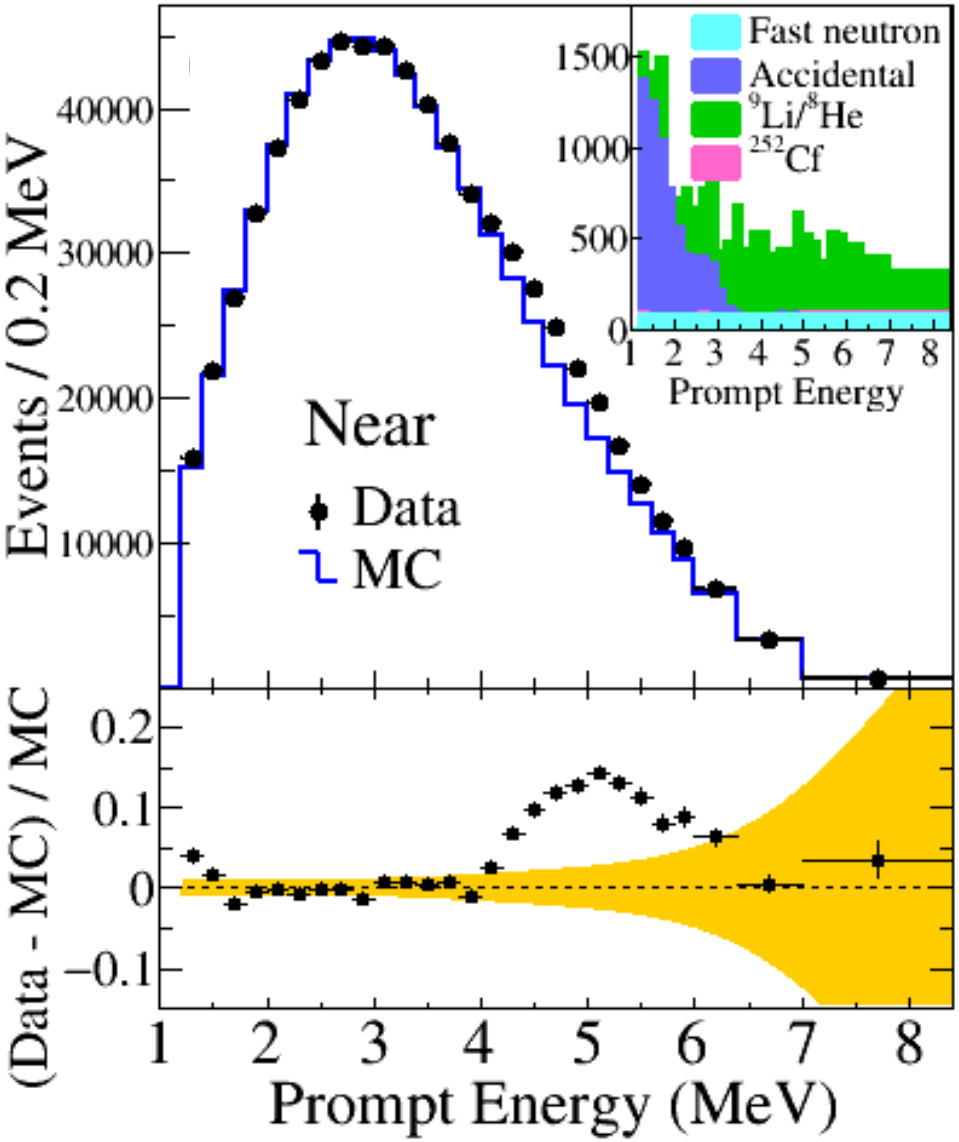


In 2014, RENO showed the 5 MeV excess comes from reactors.

Observation of an excess at 5 MeV

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

(Preliminary)

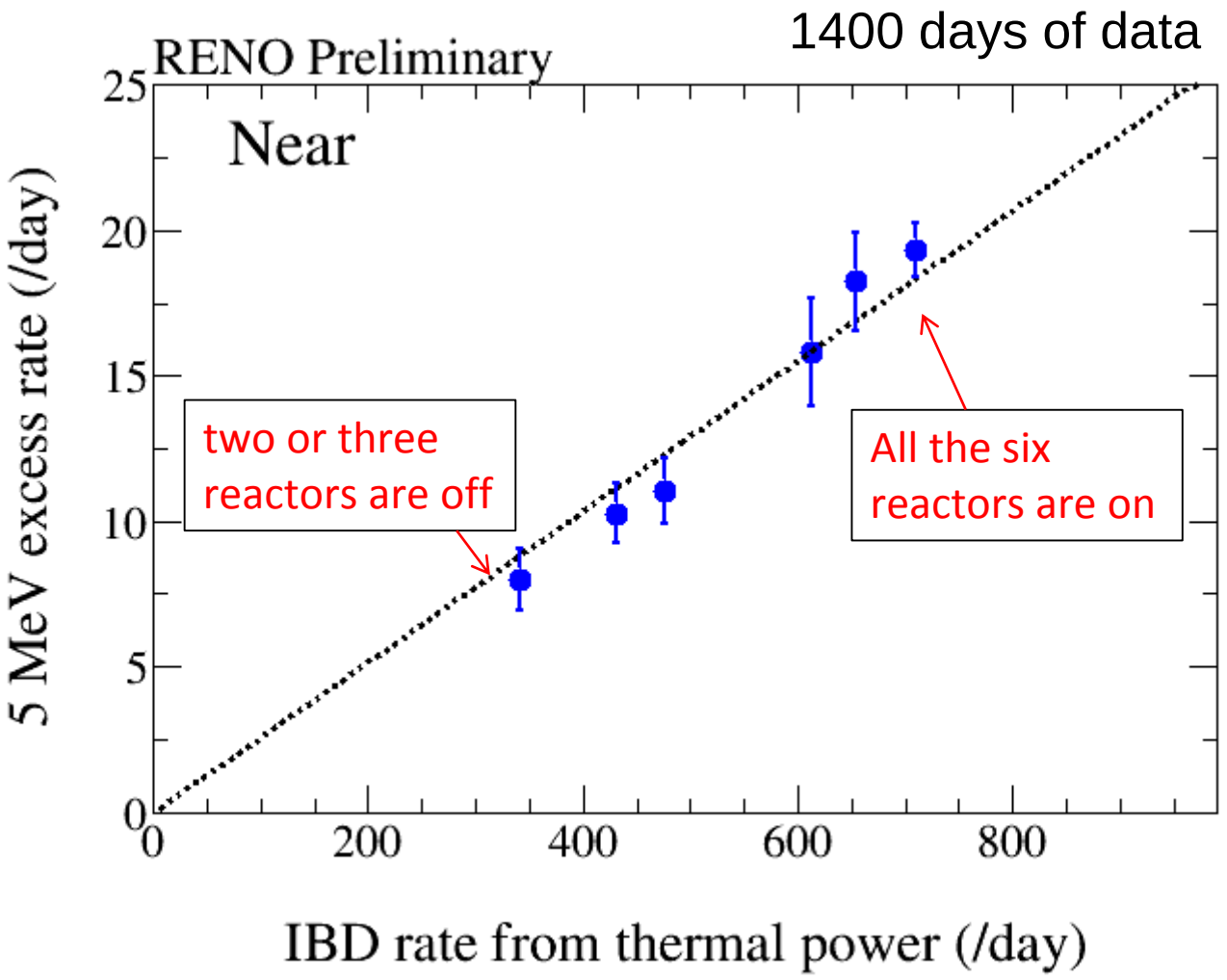


The measured near spectrum is compared with prediction using χ^2-square test.

Fraction of 5 MeV excess:
2.50 ± 0.21 (%)

Significance of the 5 MeV excess: **~12.7 σ**

Correlation of 5 MeV Excess with Reactor Power



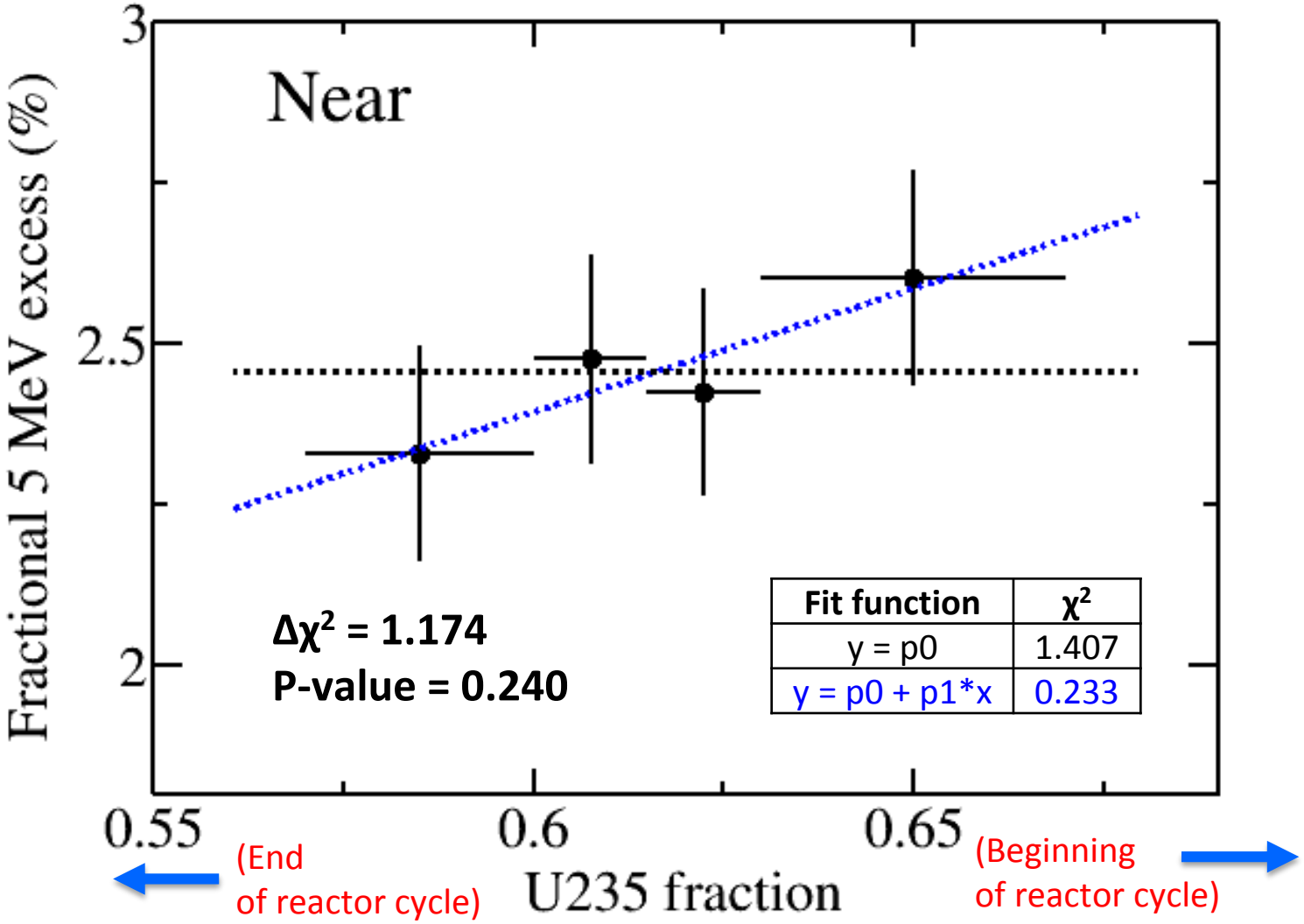
5 MeV excess has a clear correlation with reactor thermal power !

The 5 MeV excess comes from reactors!

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

(Preliminary)

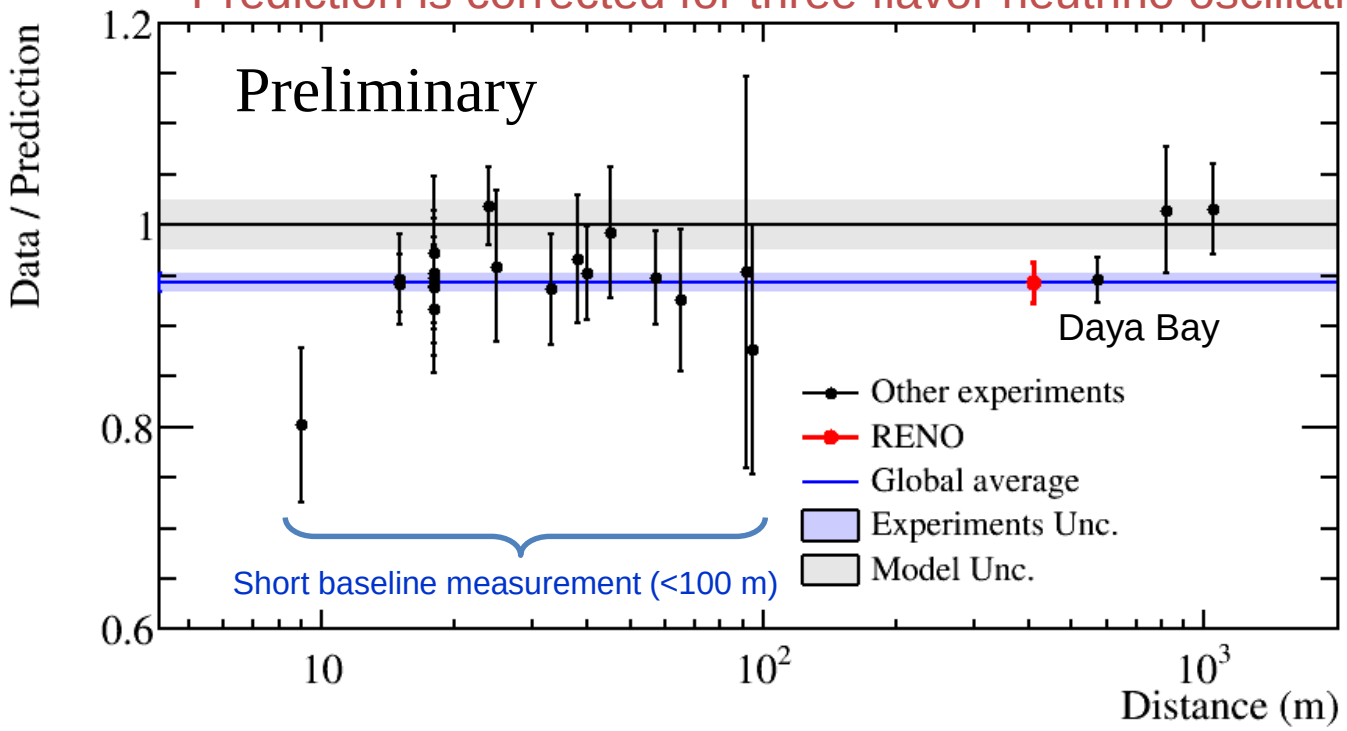
^{235}U fraction corresponds to freshness of reactor fuel



Measurement of Absolute Reactor Neutrino Flux

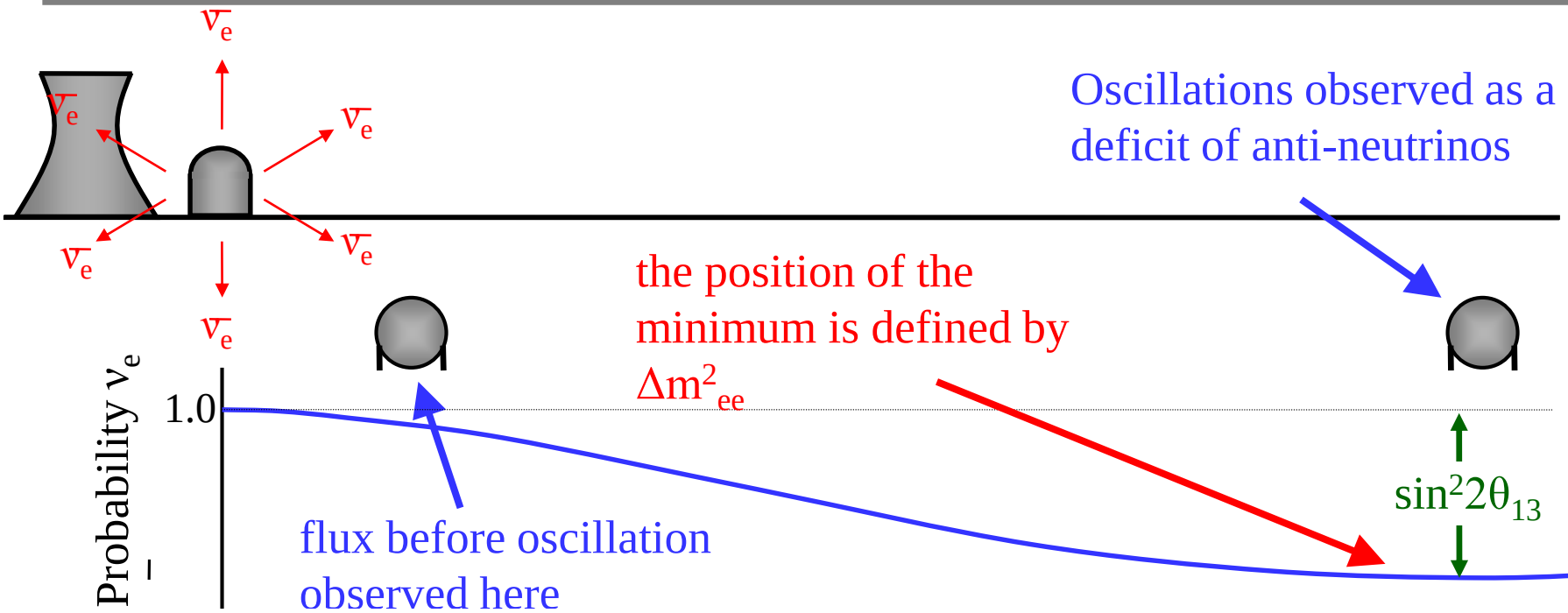
	Data / Prediction (Huber + Mueller)	Flux weighted baseline at near
RENO (500 days)	0.944 +- 0.021	411 m

*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

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

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

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

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

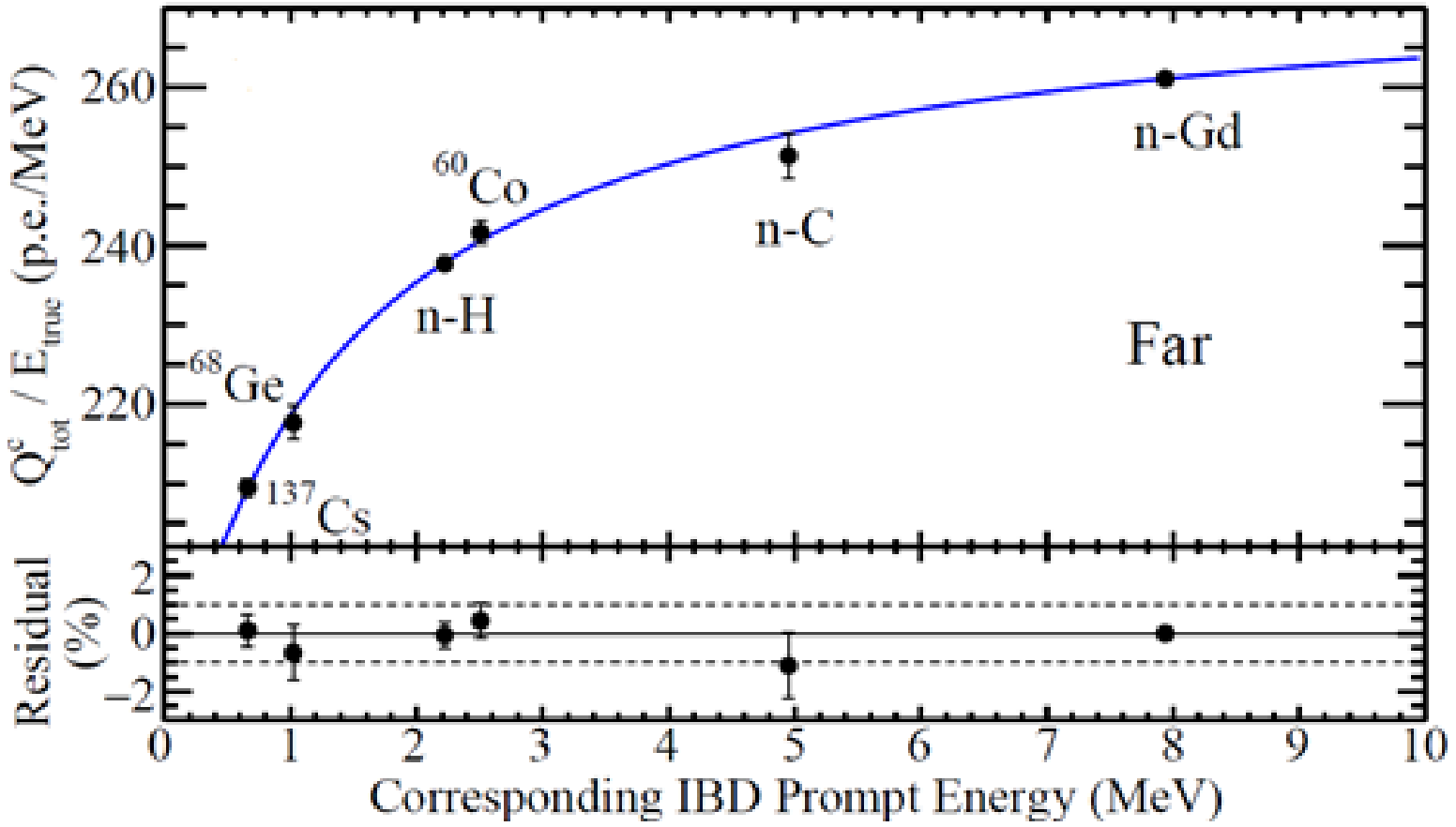
+: Normal Hierarchy

–: Inverted Hierarchy

H. Nunokawa et al, PRD72 013009 (2005)

Energy Calibration from γ-ray Sources

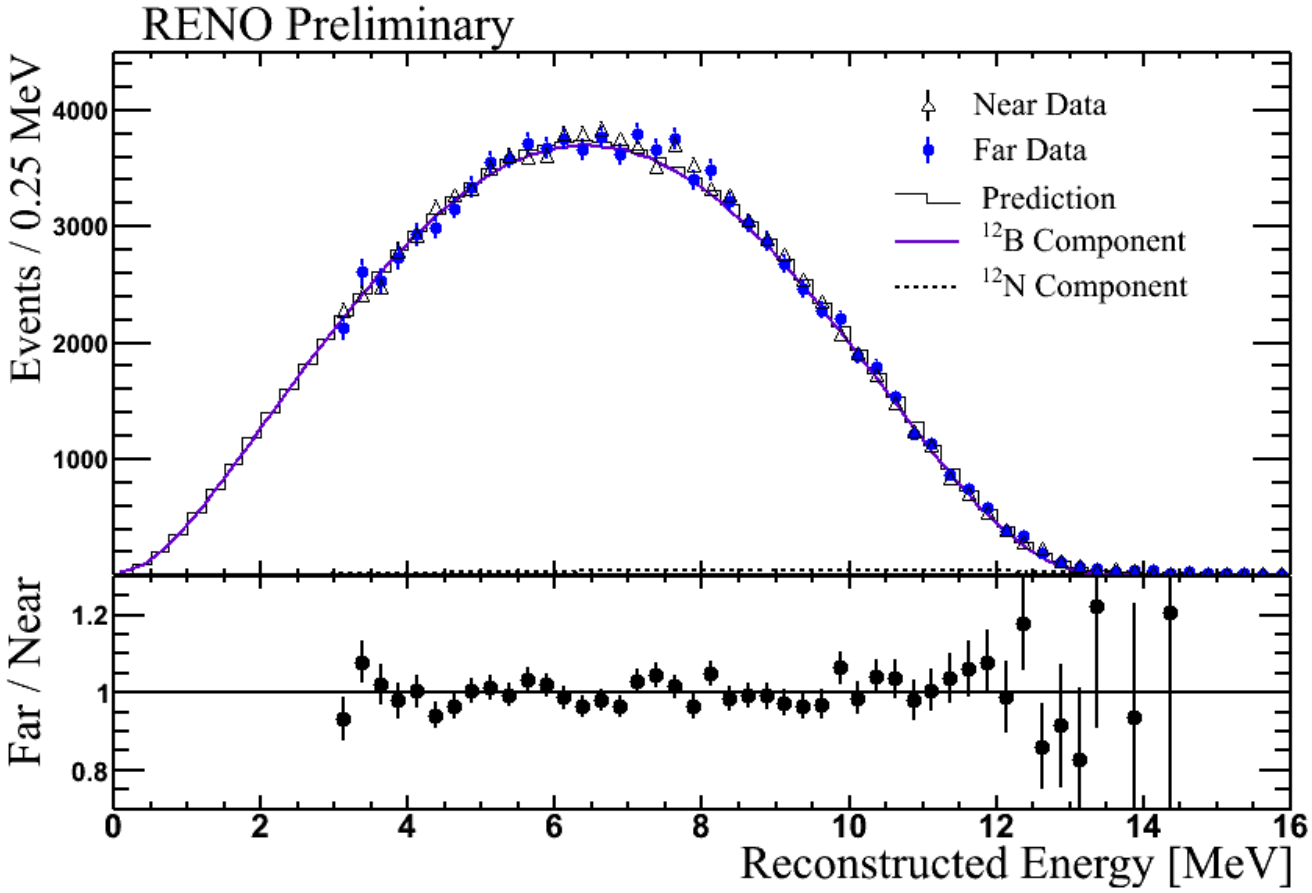
- Non-linear resonse of the scintillation energy is calibrated using γ-ray sources.
- The visible energy from γ-ray is corrected to its corresponding positron energy.



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

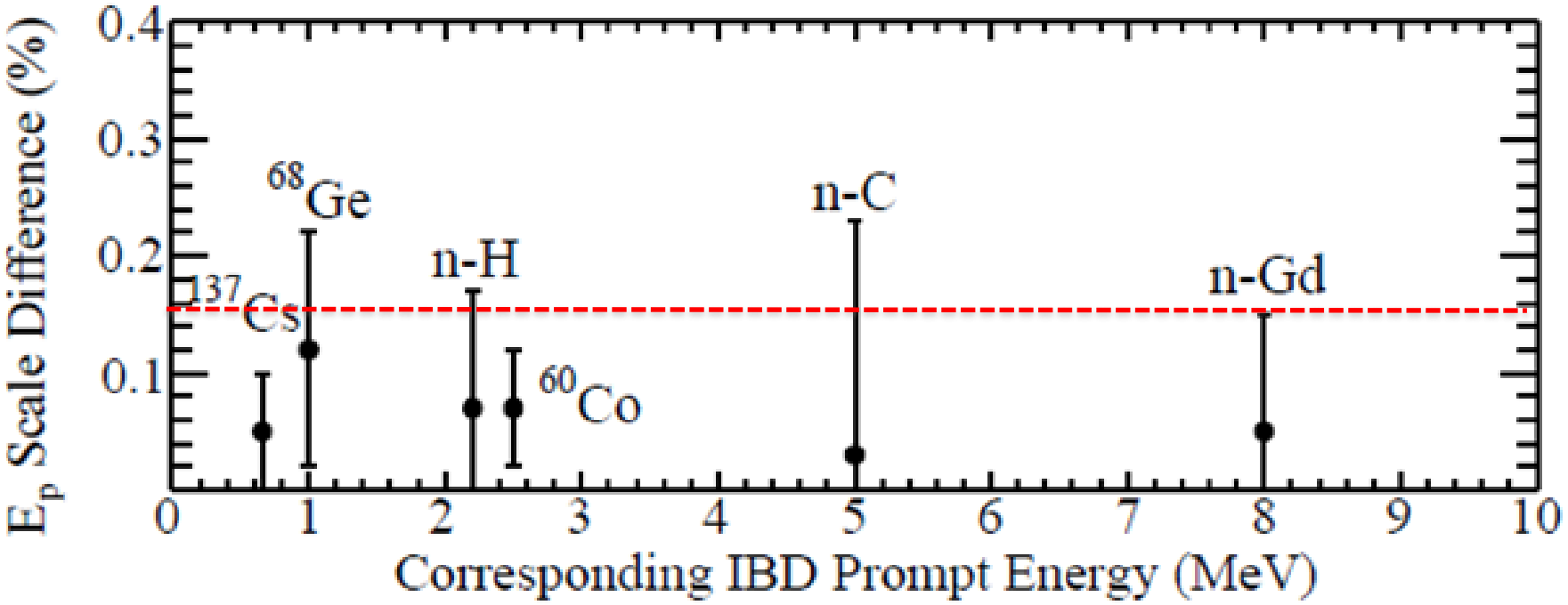
B12 Energy Spectrum (Near & Far)

- 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!

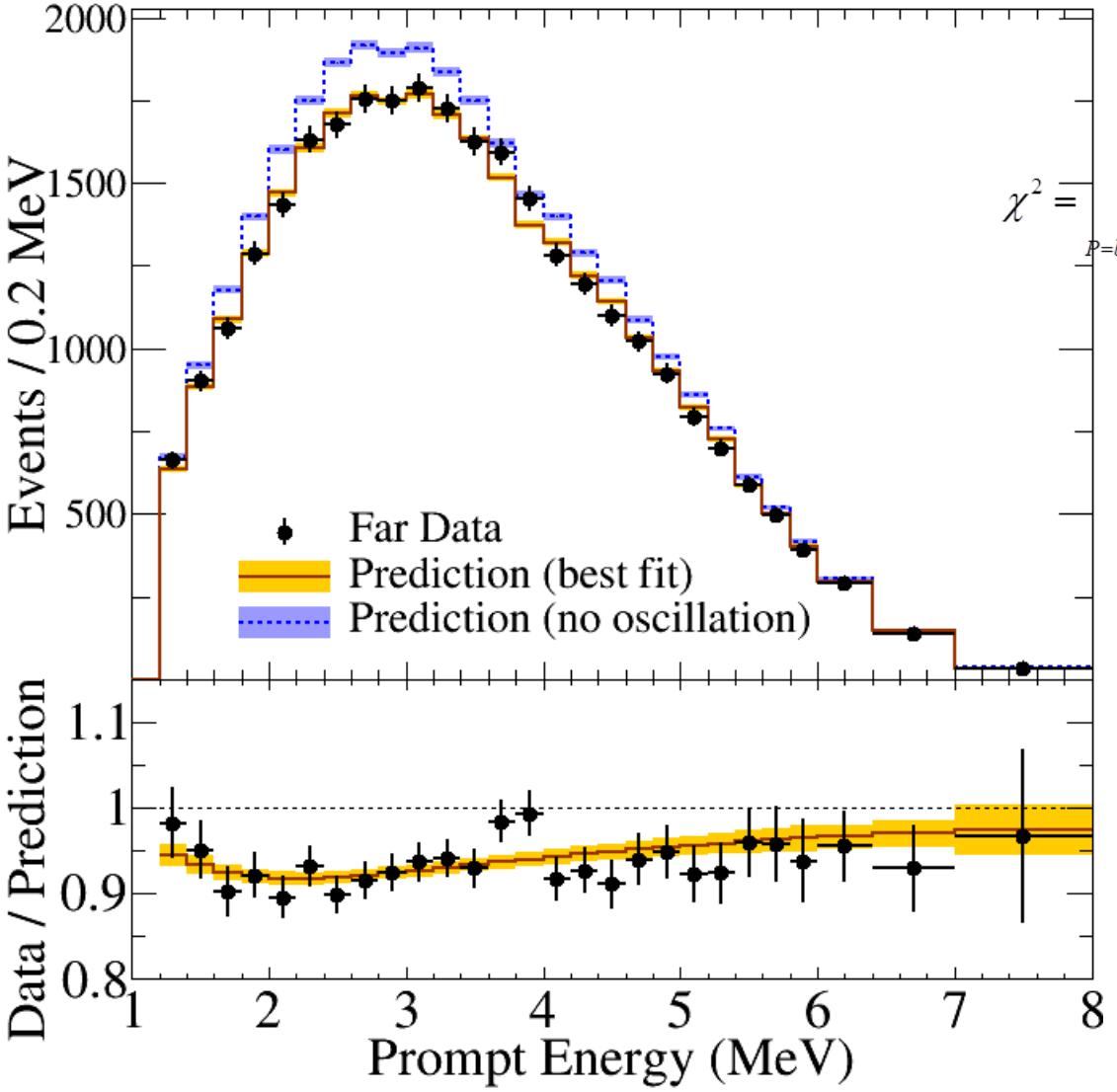
Energy Scale Difference between Near & Far



Energy scale difference < 0.15%

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

PRL 116, 211801, 2016

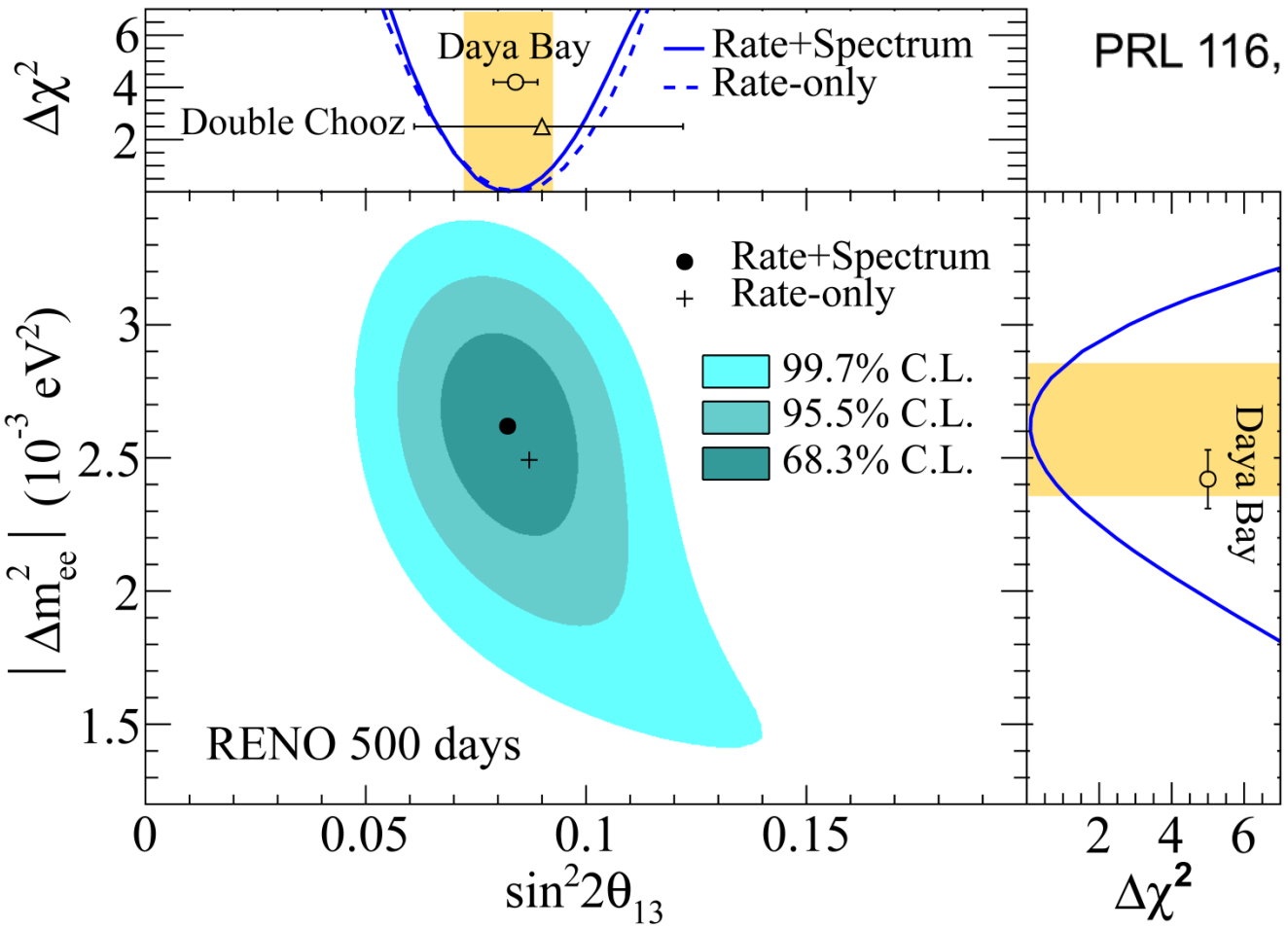


Minimize X^2 Function

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

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

Results from Spectral Fit



PRL 116, 211801, 2016

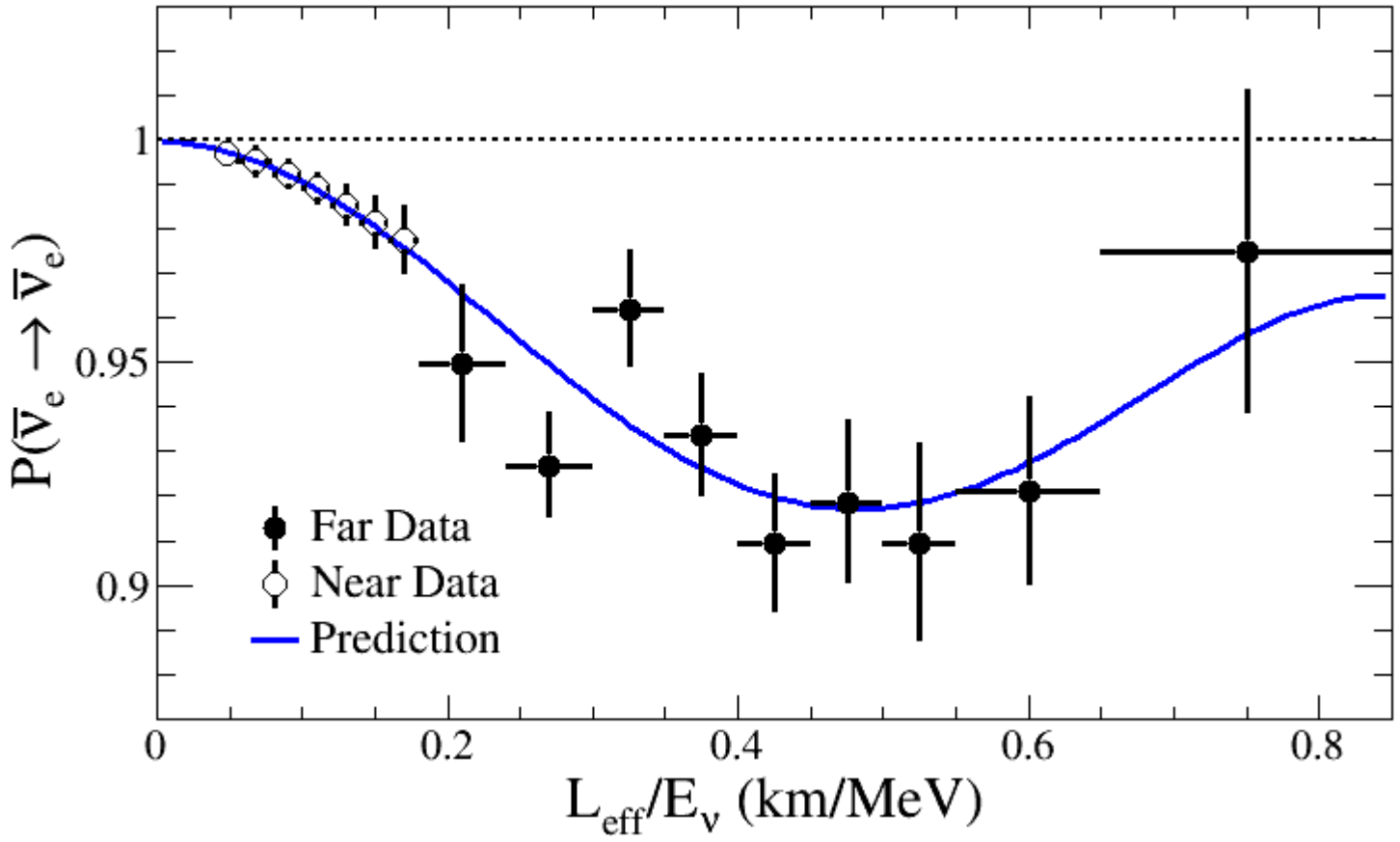
Rate+shape results

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

PRL 116, 211801, 2016



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

RENO Results

	Rate-only		Rate+shape
Data set	220 days (2012)	500 days(2015)	500 days (2015)
$\|\Delta m_{ee}^2\|$ [x10^{-3} eV^2]	2.32 (PDG 2010)	2.49 (PDG 2014)	$2.62^{+0.21}_{-0.23}(\text{stat.})^{+0.12}_{-0.13}(\text{syst.})$
$\sin^2(2\theta_{13})$	0.113	**0.087**	**0.082**
Stat. error	0.013	0.009	0.009
Syst. error	0.019	0.007	0.006
Total error	0.023	**0.011**	**0.011**
Significance	4.9 σ	7.9 σ	7.5 σ

^{9}Li/^{8}He BKG uncertainty reduced greatly !

Near: 12.45 ± 5.93/day (48%)
Far: 2. 59 ± 0.75/day (29%)
(220 days)

Near: 8.36 ± 0.82/days (10%)
Far 1.54 ± 0.23/day (15%)
(500 days)

Expected θ_{13} & $|\Delta m_{ee}^2|$ measurement

Current results (~500 days)

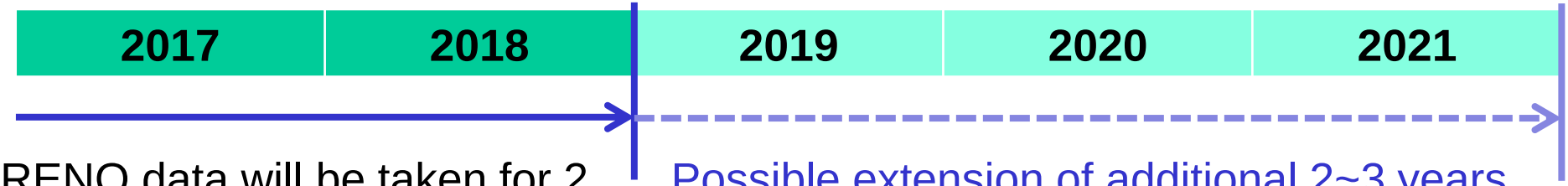
$\sin^2 2\theta_{13} = 0.082 \pm 0.010$ (±12%)

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

Precision measurement results based on ~2000 days of data will be reported soon (~8 % precision)

~6% is our ultimate goal

Plan for RENO data taking



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

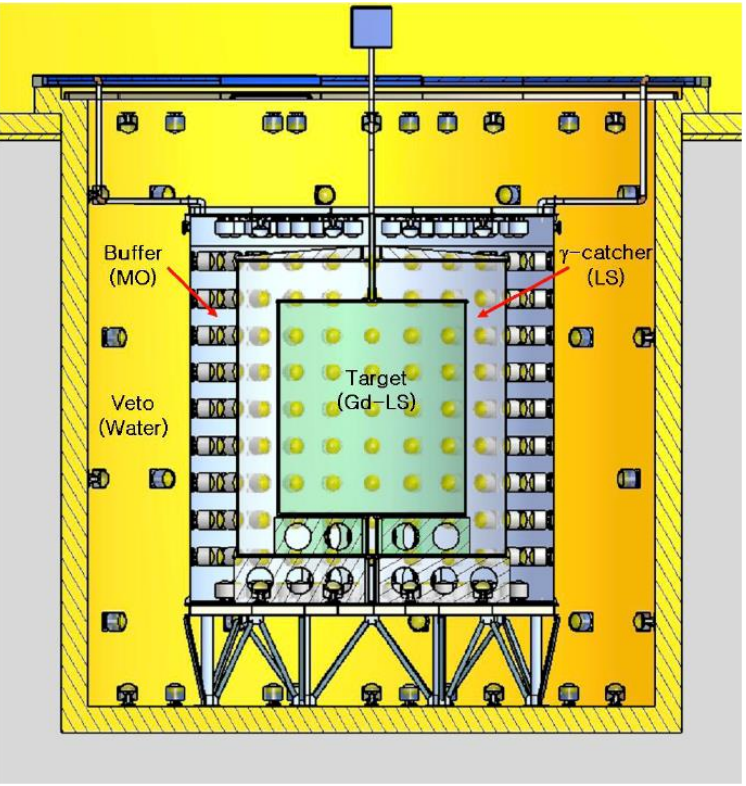
According to our recent study, the systematic error of $|\Delta m_{ee}^2|$ is smaller than the statistical error.

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

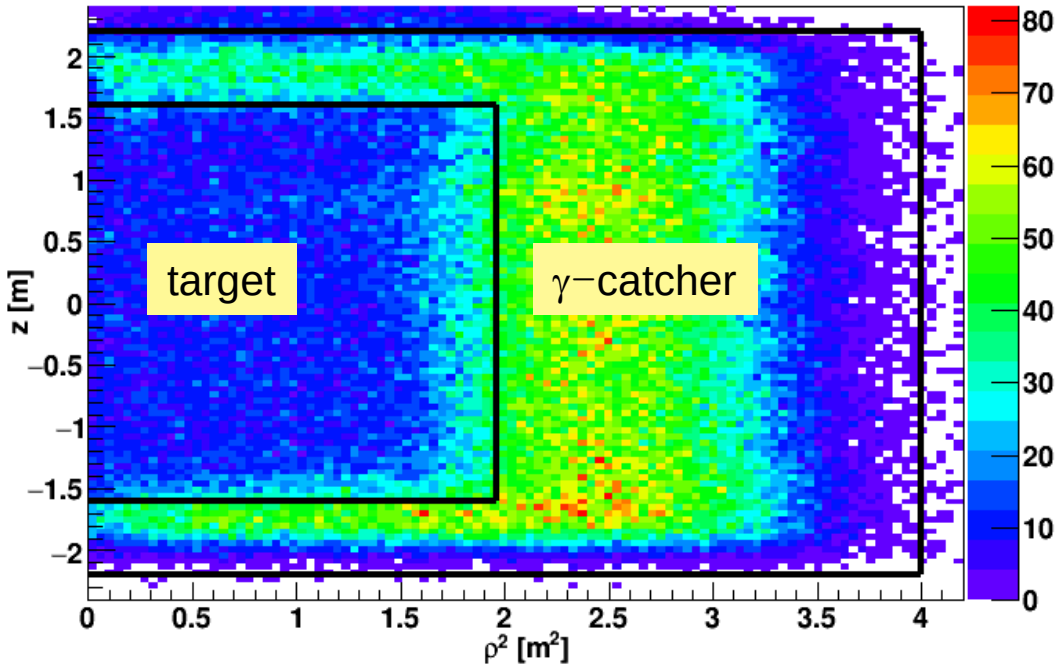
n-H IBD Analysis

Motivation:

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

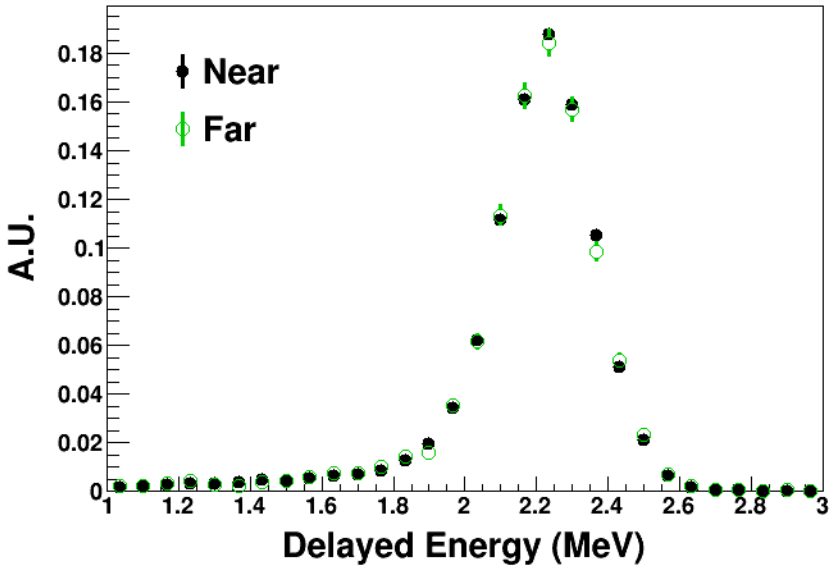


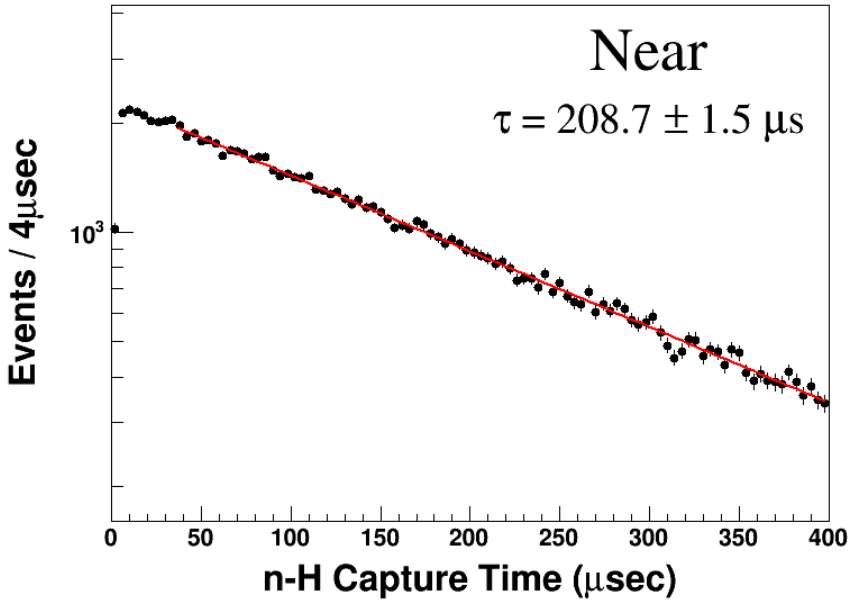
n-H IBD Event Vertex Distribution

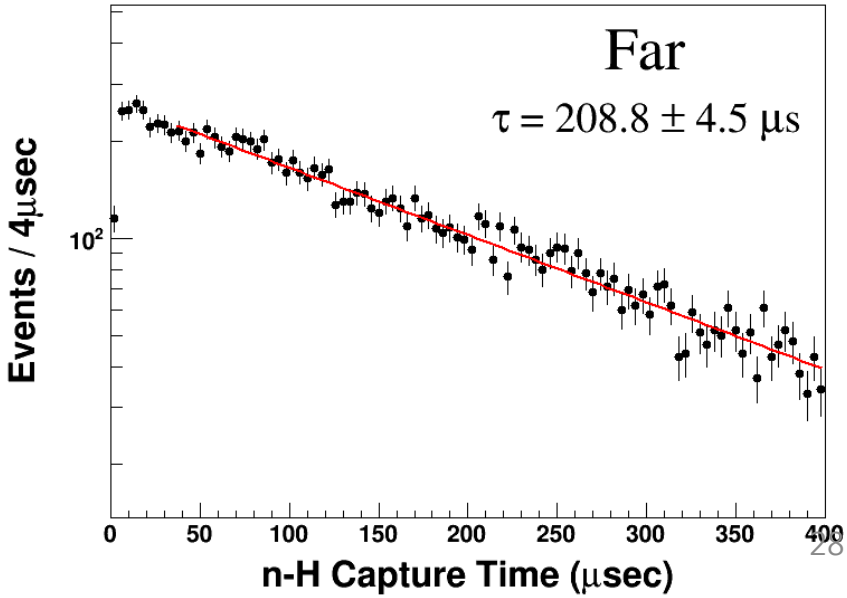


Delayed Spectrum and Capture Time

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







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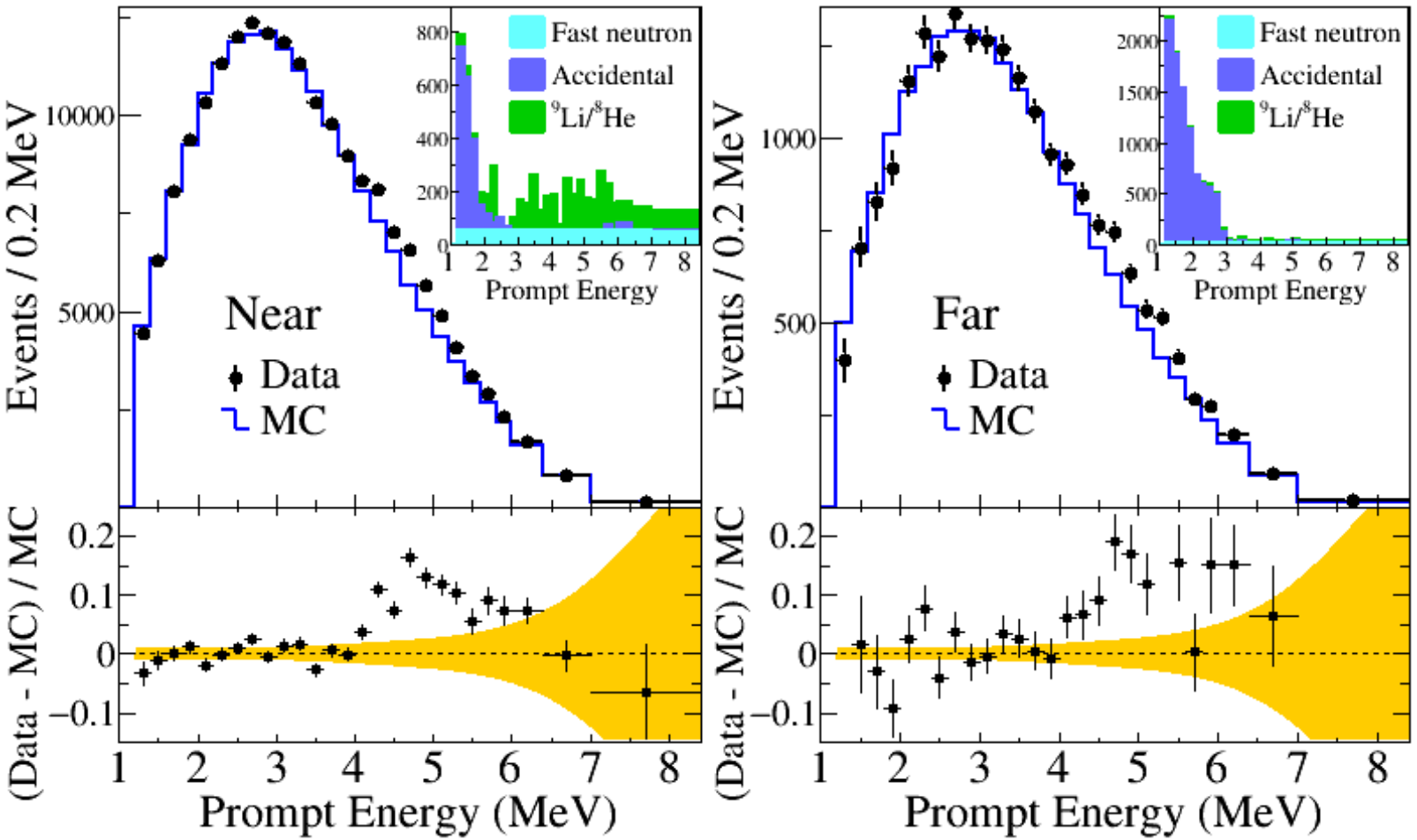
θ_{13} Measurement with n-H

(Preliminary, 500 days)

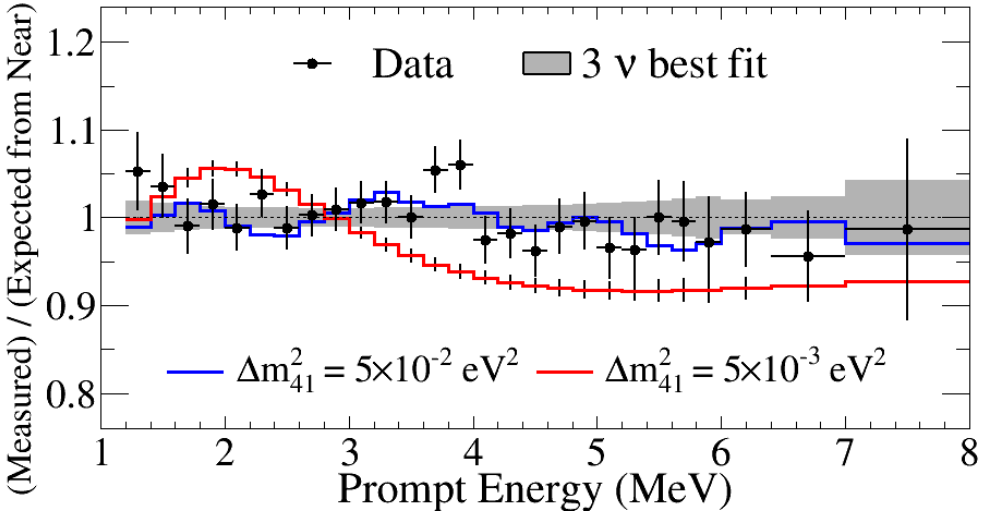
$$\sin^2 2\theta_{13} = 0.086 \pm 0.012(\text{stat.}) \pm 0.015(\text{syst})$$

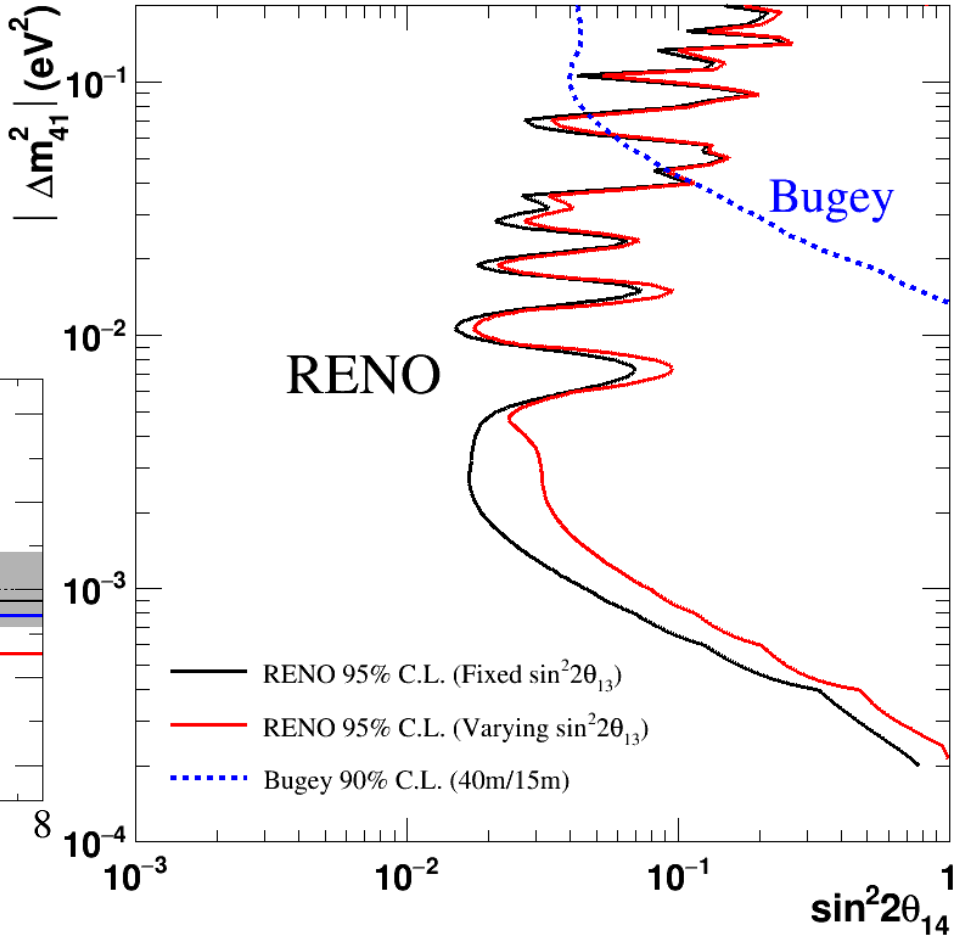


Light Sterile Neutrino Search Results

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

(Preliminary)





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

Summary

- Observation of energy dependent disappearance of reactor neutrinos and our first measurement of Δm_{ee}^2

$$\sin^2 2\theta_{13} = 0.082 \pm 0.009(\text{stat}) \pm 0.006(\text{syst})$$ ± 0.010 12 % precision

$$\left|\Delta m^2_{ee}\right| = 2.62^{+0.21}_{-0.23}(\text{stat.})^{+0.12}_{-0.13}(\text{syst.})\,(\times 10^{-3}\,\text{eV}^2)$$ ± 0.26 10 % precision

- Measured absolute reactor neutrino flux : R= 0.944±0.021
- Observed an excess at 5 MeV in reactor neutrino spectrum
- Measurement of θ_{13} using n-H IBD analysis : 0.086±0.019
- Obtained an excluded region from a sterile neutrino search
- $\sin^2(2\theta_{13})$ 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!

Neutrino Mixing Angles

Atmospheric Neutrino Oscillation → θ_{23} → ~45° (1998) **Super-K;** K2K

Solar Neutrino Oscillation → θ_{12} → 34° (2001) **SNO, Super-K;** KamLAND

Reactor Neutrino Oscillation → θ_{13} → 9° (2012) **Daya Bay, RENO** Double Chooz

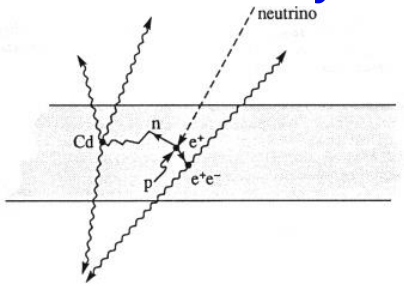
2015 Nobel Prize

"Neutrino has mass"

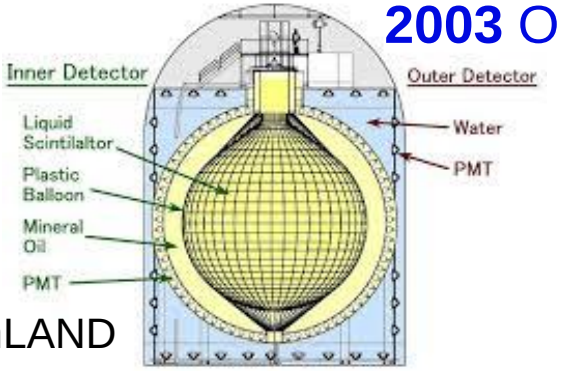
"Established three-flavor mixing framework"

Neutrino Physics with Reactor

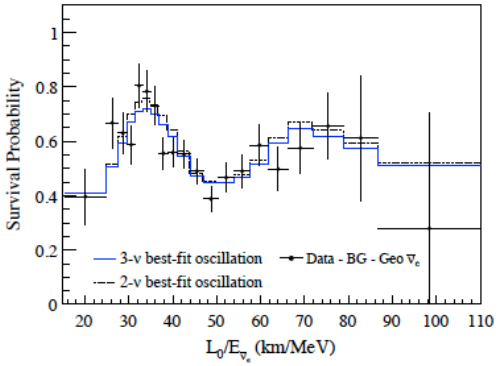
1956 Discovery of (anti)neutrino

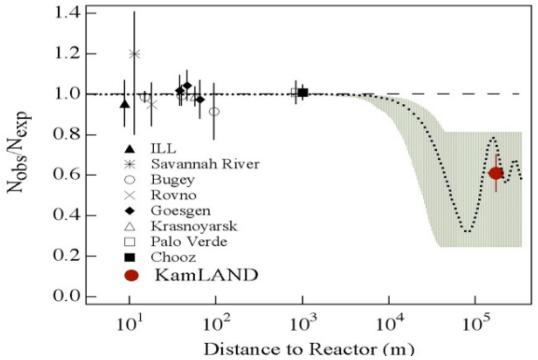


2003 Observation of reactor neutrino oscillation (θ_{12} & Δm_{21}^2)

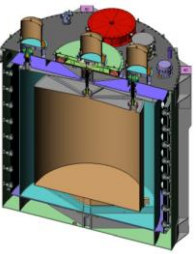


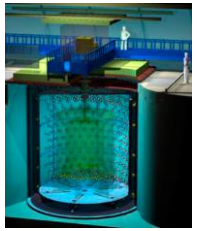
KamLAND

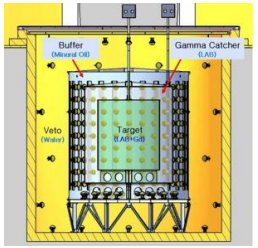


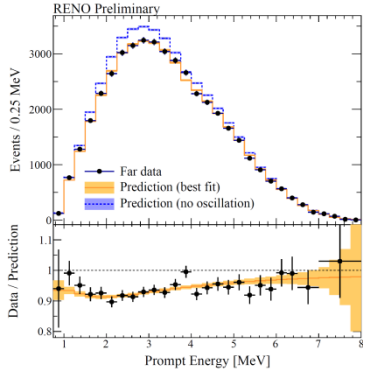


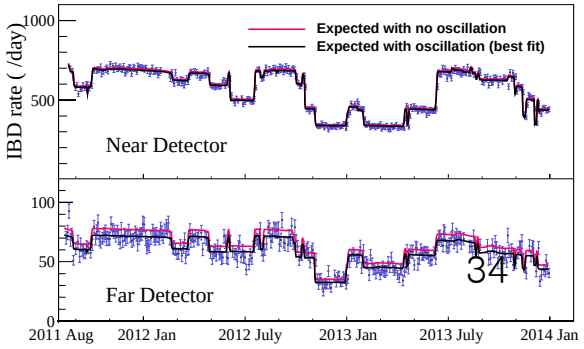
2012 Measurement of the smallest mixing angle θ_{13}



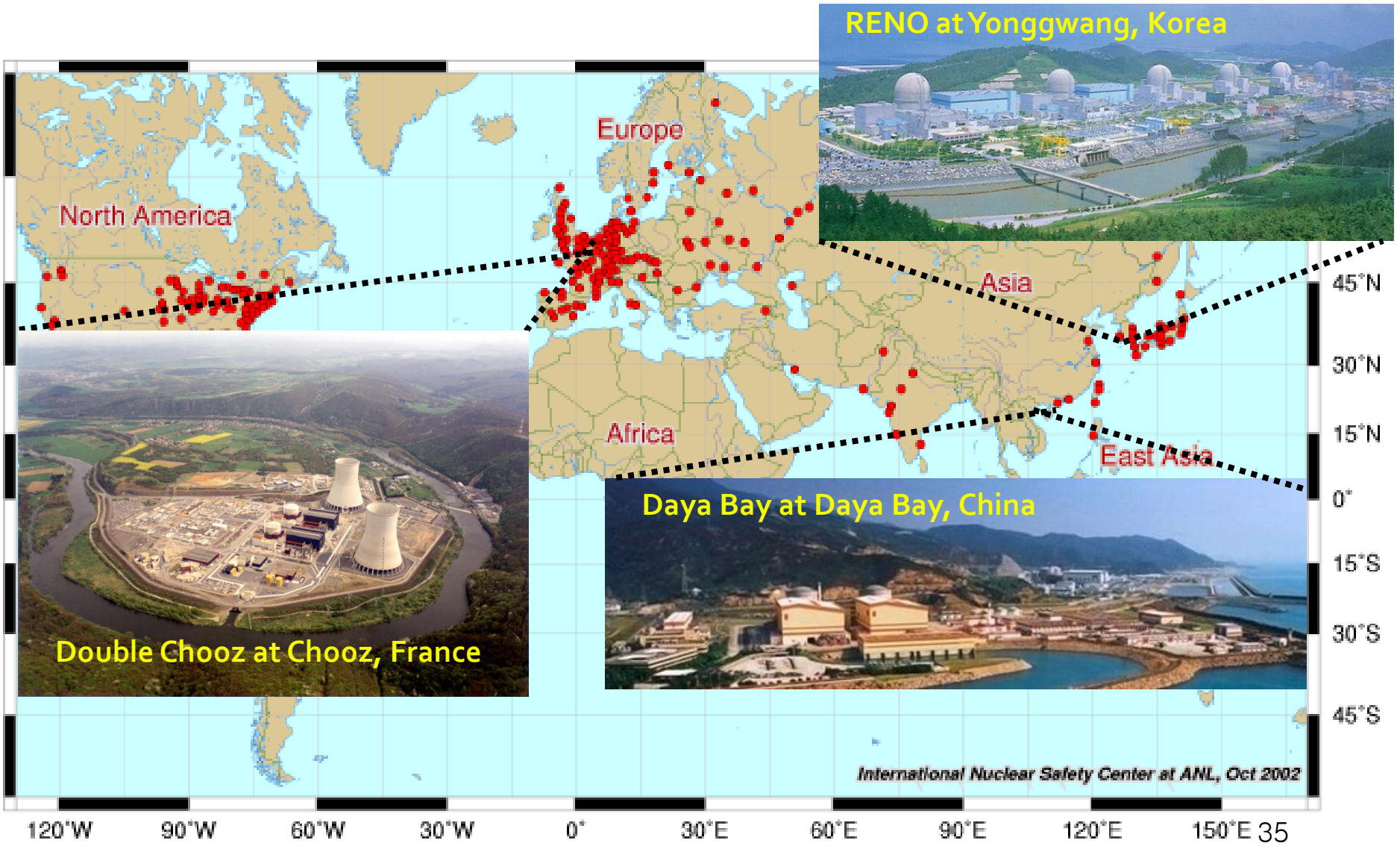




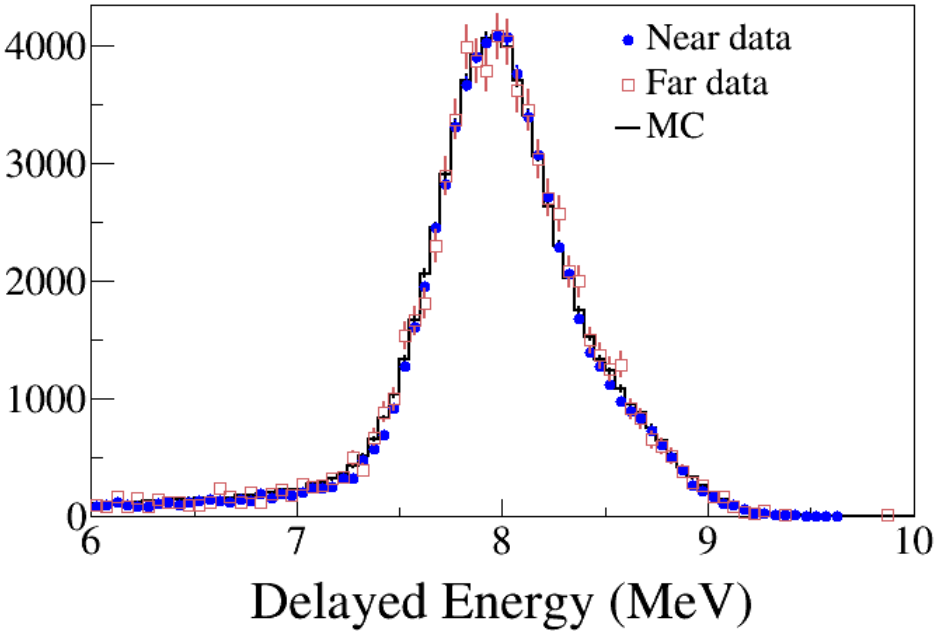


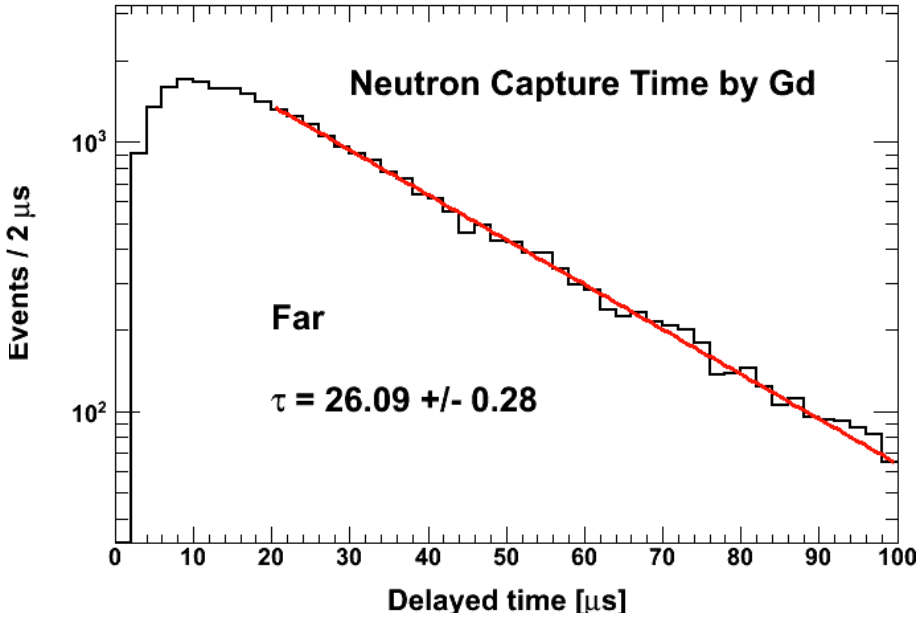


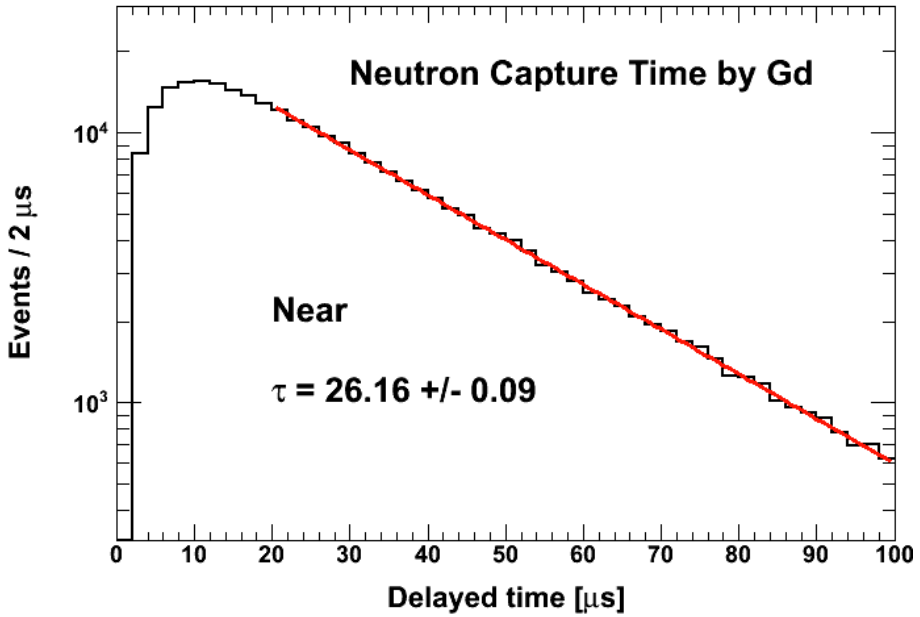
Reactor θ_{13} Experiments



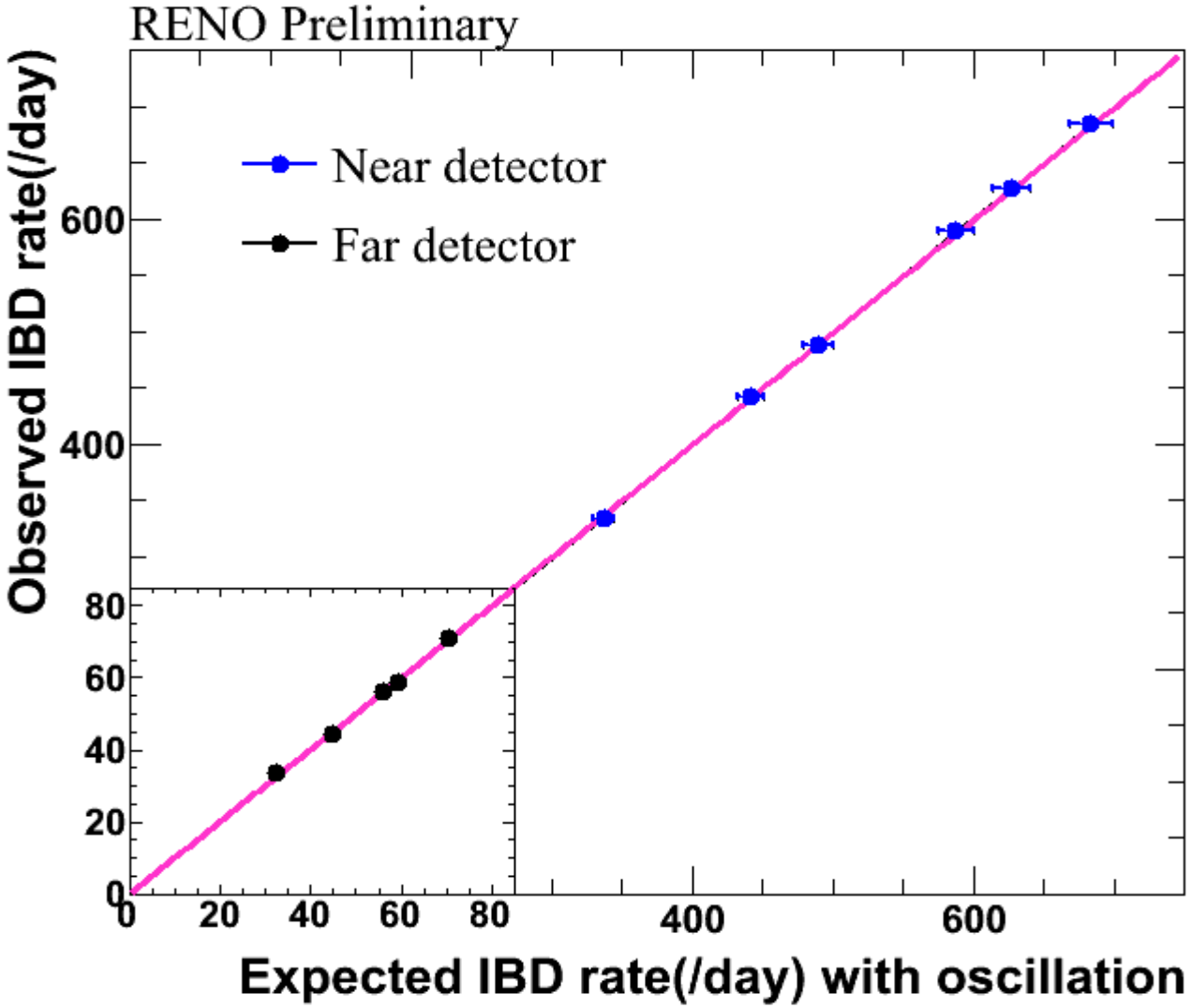
Delayed Signals from Neutron Capture by Gd







Observed vs. Expected IBD Rates



- Good agreement between observed rate & prediction
- Indication of correct background subtraction

χ^2 equation for 5 MeV excess

$$\chi^2 = \sum_i \frac{\left(N^i_{obs} - N^i_{exp}\right)^2}{N^i_{obs} + N^i_{bkg}} + \sum_{k,i} \left(\frac{b^{k,i}_{uncor}}{\sigma^{k,i}_{b,uncor}}\right)^2 + \sum_k \left(\frac{b^k_{cor}}{\sigma^k_{b,cor}}\right)^2 + \left(\frac{\epsilon}{\sigma_{scale}}\right)^2 + \left(\frac{\epsilon_{5MeV}}{\sigma^{5MeV}_{scale}}\right)^2$$
$$+ \sum_{iso}\sum_i \left(\frac{\gamma^{i,iso}}{\sigma^{i,iso}_{\gamma}}\right)^2 + \sum_i \left(\frac{g^i}{\sigma^i_g}\right)^2 + \sum_{r=1}^{6} \left(\frac{f^r_{uncor}}{\sigma_{f,uncor}}\right)^2 + \left(\frac{f_{cor}}{\sigma_{f,cor}}\right)^2 + \left(\frac{\xi_{uncor}}{\sigma_{\xi,uncor}}\right)^2$$
$$+ \left(\frac{\xi_{cor}}{\sigma_{\xi,cor}}\right)^2$$

where

$$N^i_{exp} = R\Bigg[\sum_r \left(1 + \xi_{cor} + \xi_{uncor} + f_{cor} + f^r_{uncor}\right) \sum_{iso} \left(1 + \gamma_{i,iso}\right) T^{i,r,iso}_{exp}$$
$$+ \left(1 + \xi_{cor} + \xi_{uncor}\right) \alpha N^i_{5MeV} + \delta N^{5MeV,i}_{uncor} g^i_{uncor}$$
$$+ \epsilon_{5MeV} \left(\delta E \frac{\partial N^i_{5MeV}}{\partial E}\right) + \sum_r \epsilon \left(\delta E \frac{\partial T^{i,r}_{exp}}{\partial E}\right)\Bigg]$$
$$+ \sum_k \left(\frac{\left(\delta B^{k,i}_{uncor}\right)^2}{\sqrt{\sum_i \left(\delta B^{k,i}_{uncor}\right)^2}} b^k_{uncor}\right) + \sum_k \left(\delta B^{k,i}_{cor} b^k_{cor}\right)$$

Determination of normalization factor, R

A normalization factor R (= Data/Absolute Prediction) is determined using the χ^2 fitting

$$\chi^2 = \sum_{d=N,F} \frac{\left[O_d + b^d - R\sum_{r=1}^{6}\left(1+\xi_{cor}+\xi_{uncor}+f^r_{uncor}+f_{cor}\right)T^r_d\right]^2}{O_d}$$

$$+ \sum_{d=N,F}\left(\frac{b^d}{\sigma^d_{bkg}}\right)^2 + \sum_{r=1}^{6}\left(\frac{f^r_{uncor}}{\sigma_{f,uncor}}\right)^2 + \left(\frac{f_{cor}}{\sigma_{f,cor}}\right)^2 + \left(\frac{\xi_{uncor}}{\sigma_{\xi,uncor}}\right)^2 + \left(\frac{\xi_{cor}}{\sigma_{\xi,cor}}\right)^2$$

O_d : number of observed IBD events
b_d : number of background
T_d : number of expected IBD events
R : normalization factor
σ_b : uncertainty for background
$\sigma_{\xi,cor}$: correlated uncertainty for detection efficiency (1.04 %)
$\sigma_{\xi,uncor}$: uncorrelated uncertainty for detection efficiency (0.13 %)
$f_{r,uncor}$: uncorrelated uncertainty for reactor
f_{cor} : correlated uncertainty for reactor (2.0 %)
ξ_{cor}, ξ_{uncor}, $f_{r,uncor}$, f_{cor} are corresponding pull parameters to the above uncertainties

- The χ^2 does not use far-to-near ratio in order to determine the normalization factor, R
- Pull parameter for correlated detection efficiency and reactor are included unlike far-to-near ratio analysis

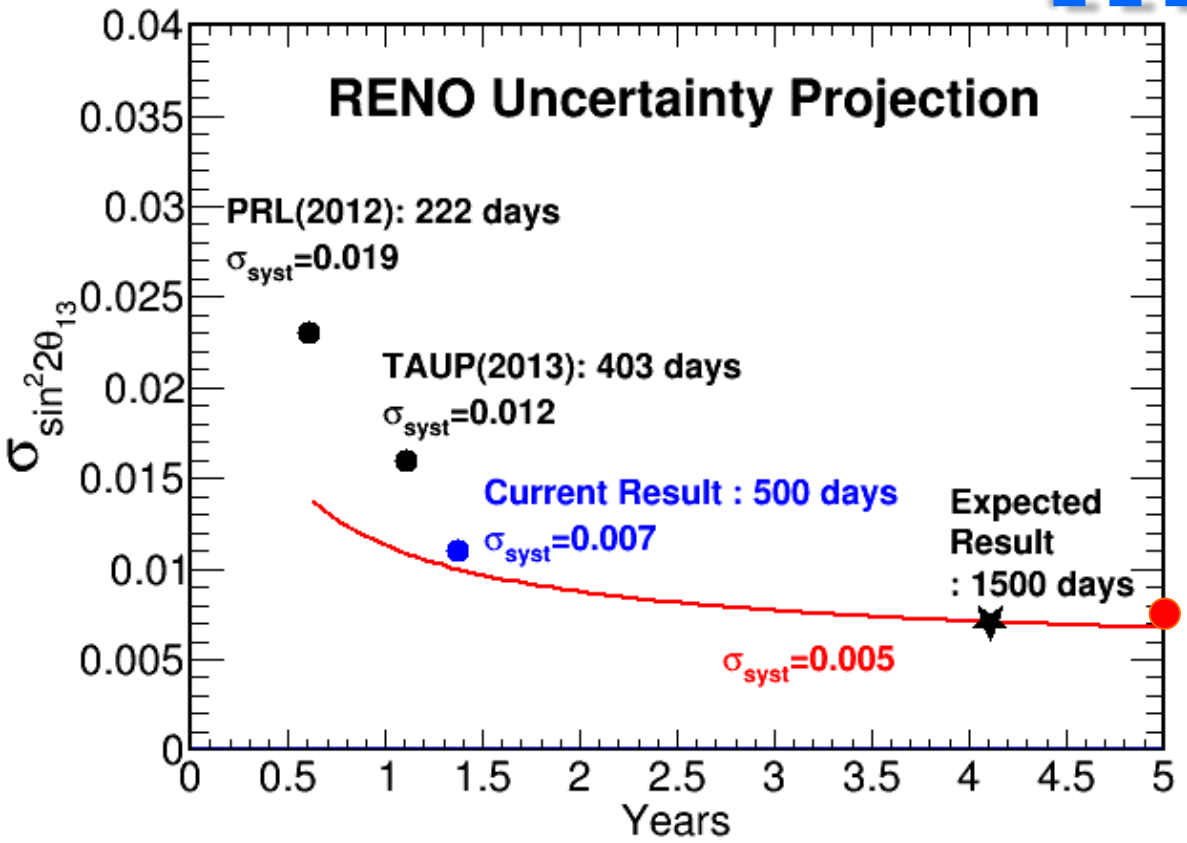
Projected Sensitivity of θ_{13} & $|\Delta m_{ee}^2|$

$\sin^2 2\theta_{13} = 0.082 \pm 0.010$ (±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})