New Results from RENO and Future RENO-50 Project

Soo-Bong Kim (KNRC, Seoul National University)

"Light Dark World International Forum 2016"

Daejeon, Korea, July 11-15, 2016"

KNRC
Korea Neutrino Research Center

Neutrino Mixing Angles

Atmospheric Neutrino Oscillation — θ_{23}

~45° (1998)
Super-K; K2K

Solar Neutrino Oscillation — θ_{12}

34° (2001)
SNO, Super-K; KamLAND

2015 Nobel Prize

Reactor Neutrino Oscillation — θ_{13}

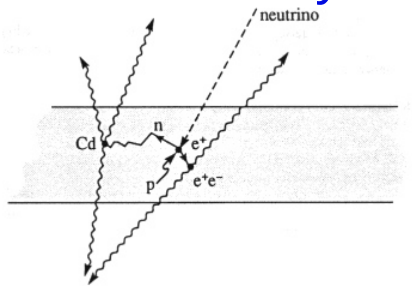
9° (2012)
Daya Bay, RENO
Double Chooz

"Neutrino has mass"

"Established three-flavor mixing framework"

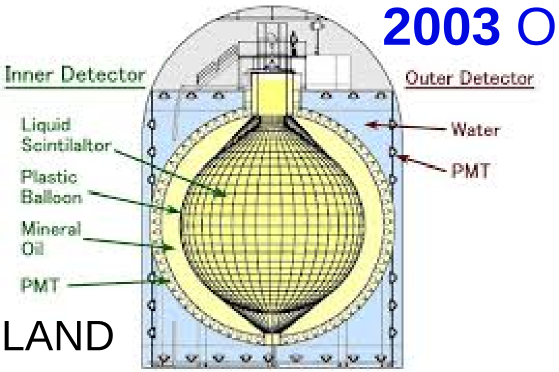
Neutrino Physics with Reactor

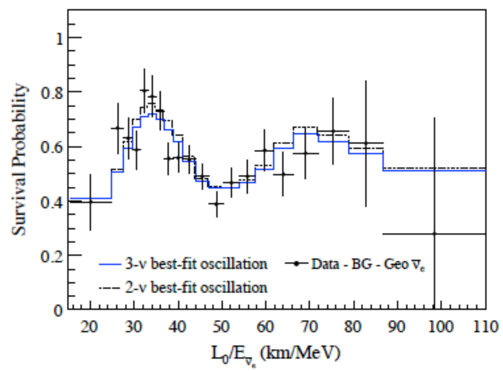
1956 Discovery of (anti)neutrino

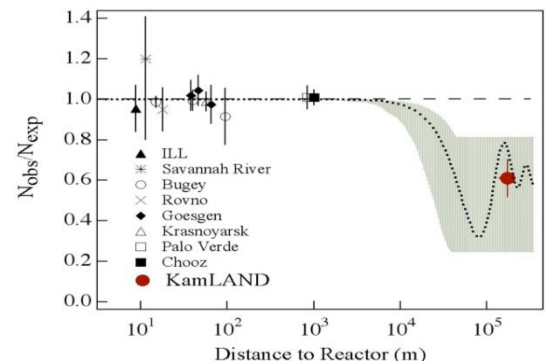


2003 Observation of reactor neutrino oscillation (θ_{12} & Δm_{21}^2)

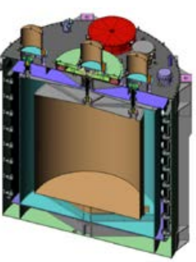
KamLAND

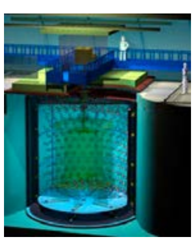


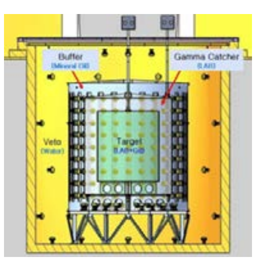


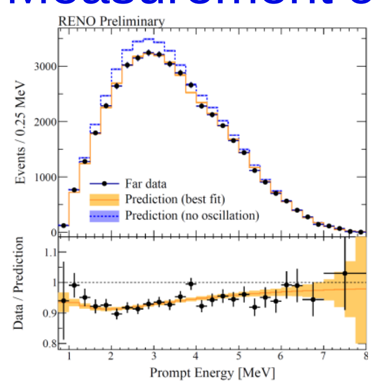


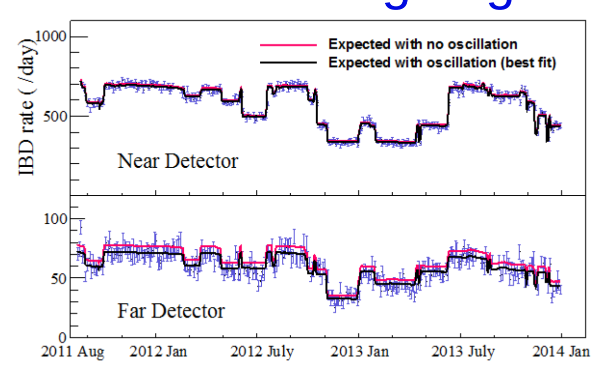
2012 Measurement of the smallest mixing angle θ_{13}



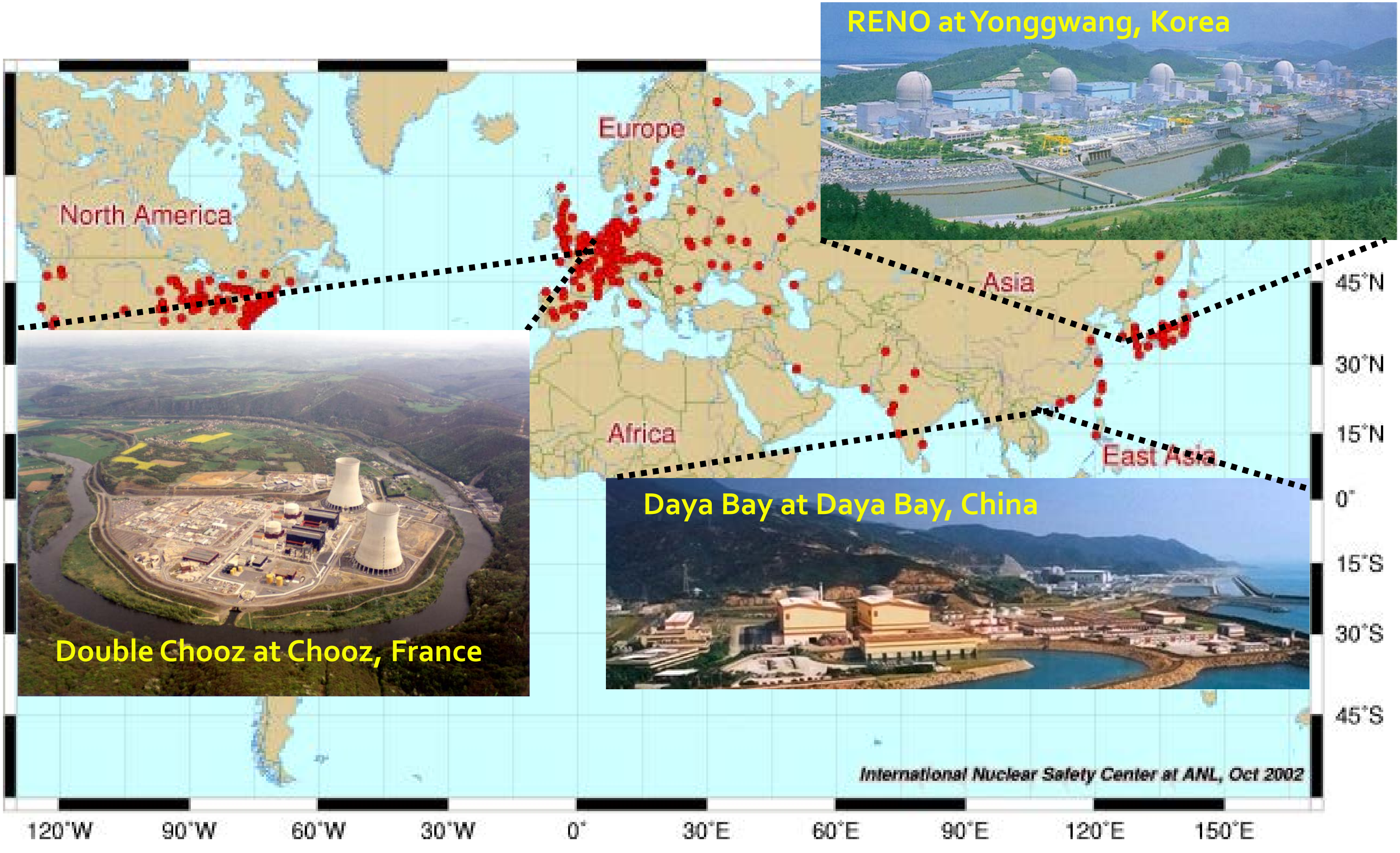






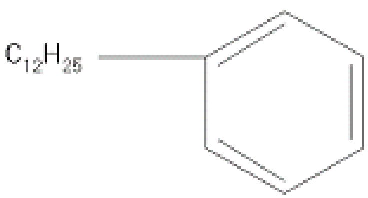


Reactor θ_{13} Experiments



Detection of Reactor Antineutrinos

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



Linear Alkyl Benzene (LAB)

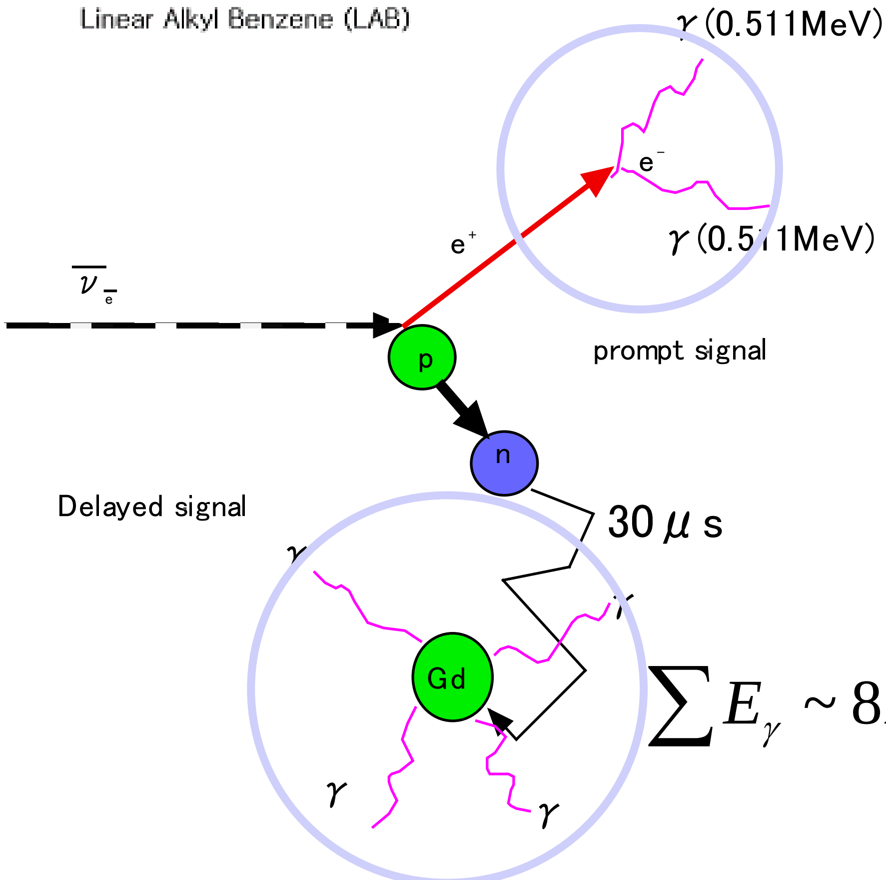
(prompt signal)

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

(delayed signal)

~180 μs: + p → D + γ (2.2 MeV)

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

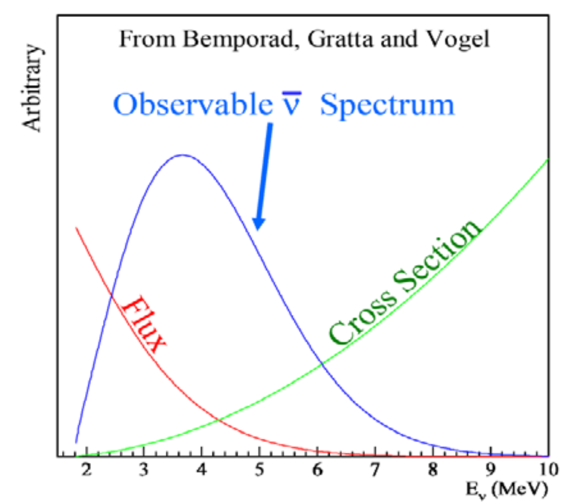


$$\sum E_\gamma \sim 8MeV$$

- **Neutrino energy measurement**

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

T_n: *10-40 keV*; $(M_n - M_p) + m_{e^+}$: *1.8 MeV*



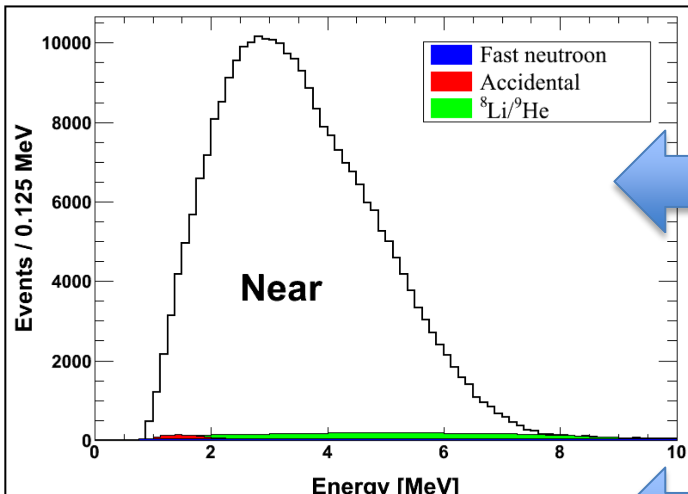
Coincidence of prompt and delayed signals

(prompt signal)

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

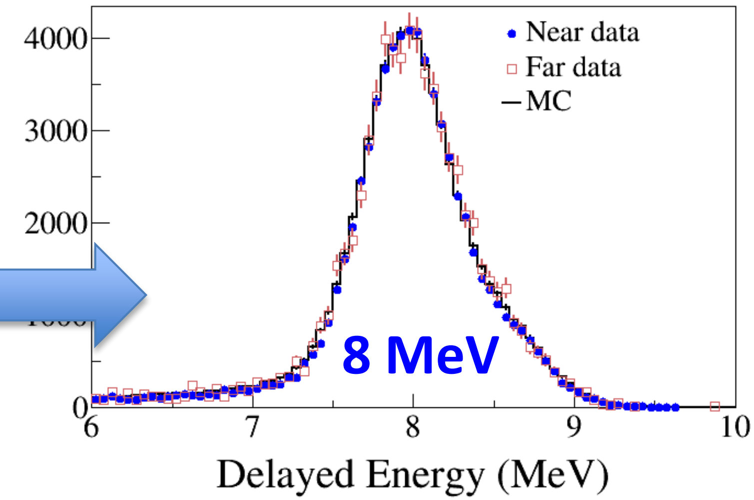
Prompt signal

Delayed signal



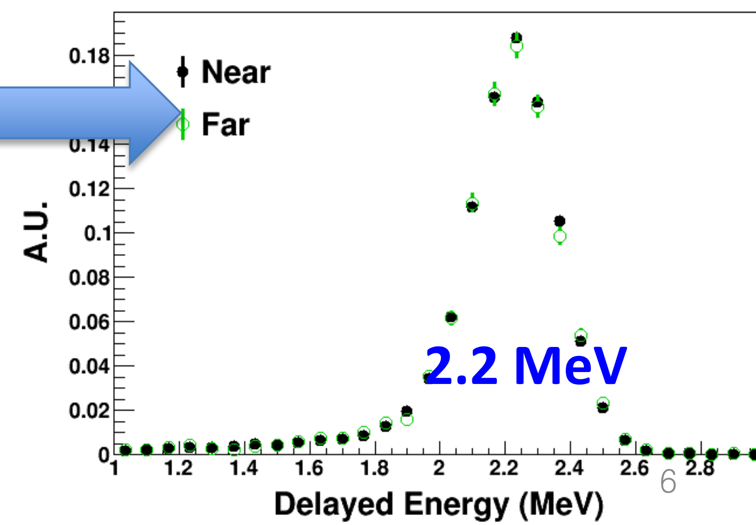
n-Gd IBD

~30 μs



~200 μs

n-H IBD



RENO Collaboration

Reactor Experiment for Neutrino Oscillation

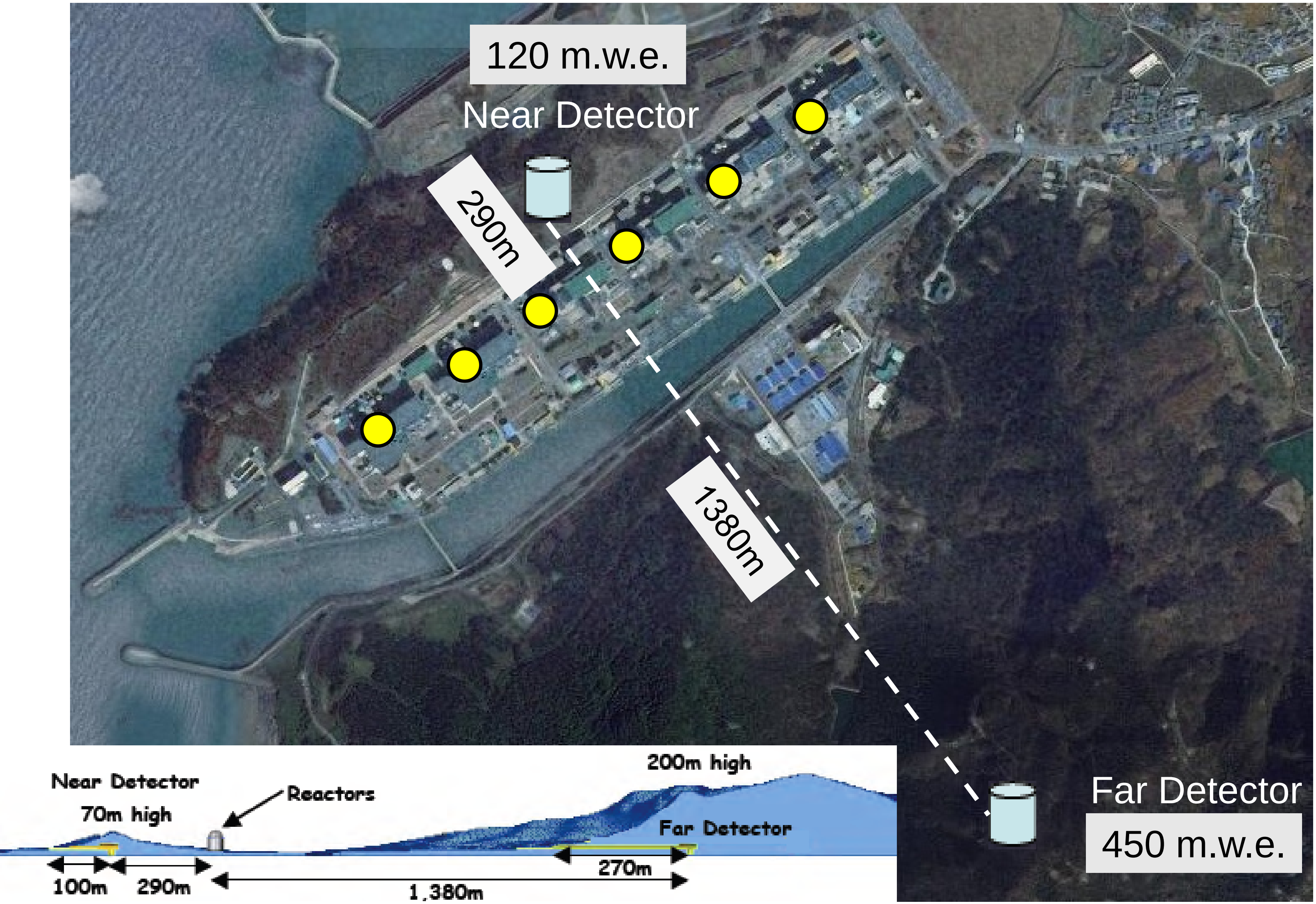
(9 institutions and 40 physicists)

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

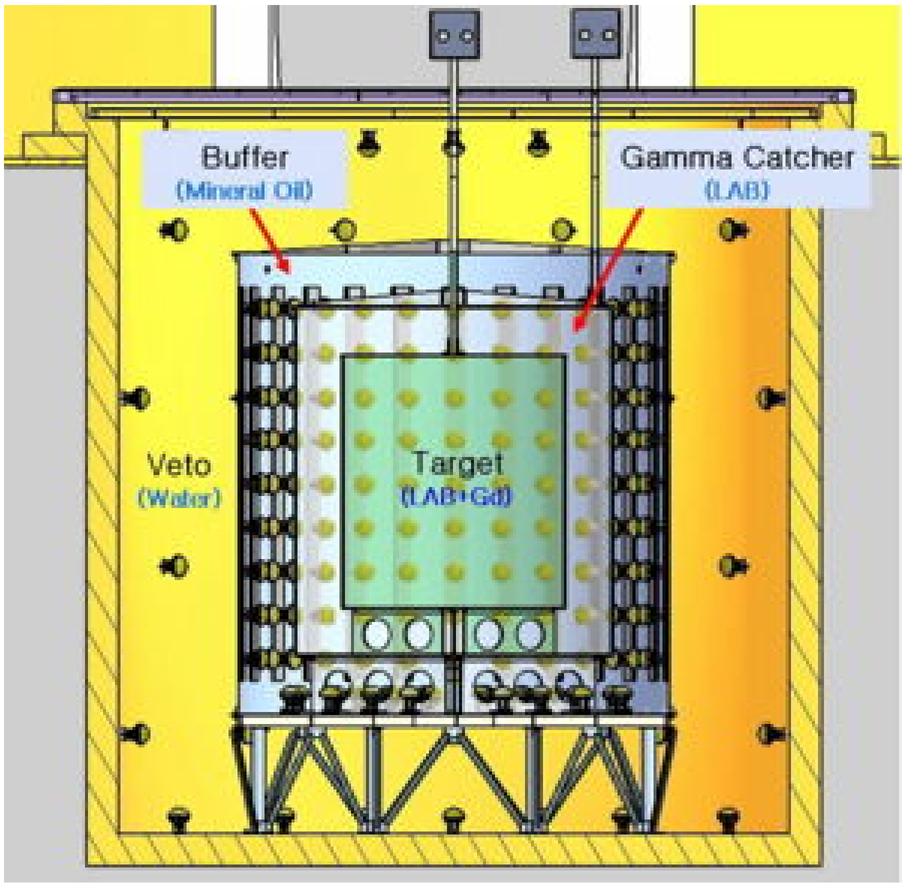
- Total cost : **$10M**
- Start of project : **2006**
- The first experiment running with both near & far detectors from **Aug. 2011**

YongGwang (靈光) :

RENO Experimental Set-up



RENO Detector



- 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)

- 354 ID 10” PMTs
- 67 OD 10” PMTs

RENO Data-taking Status

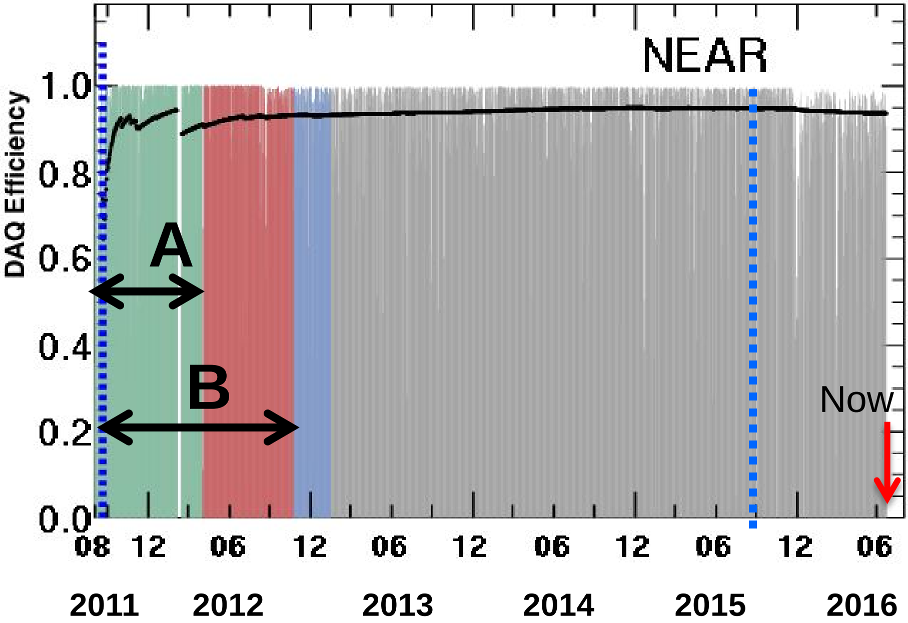
- Data taking began on Aug. 1, 2011 with both near and far detectors. (DAQ efficiency : ~95%)

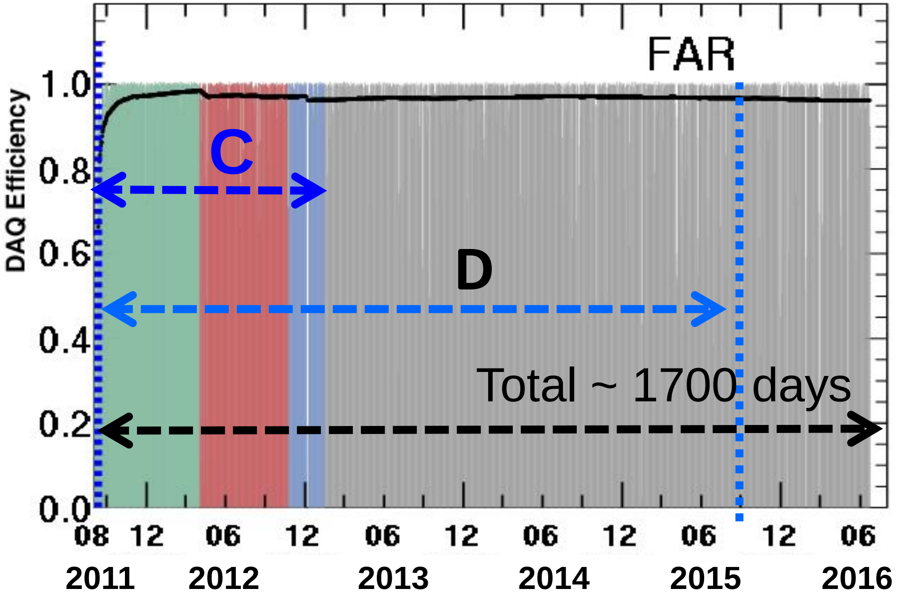
- **A (220 days)** : **First θ_{13} result**
  [11 Aug, 2011~26 Mar, 2012]
  PRL 108, 191802 (2012)

- **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]
  PRL 116, 211801 (2016)

- **D (~1400 days)** : Absolute reactor flux and spectrum
  [11 Aug. 2011~ 30 Sep, 2015]





New 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**)

- PRD to be submitted soon for details

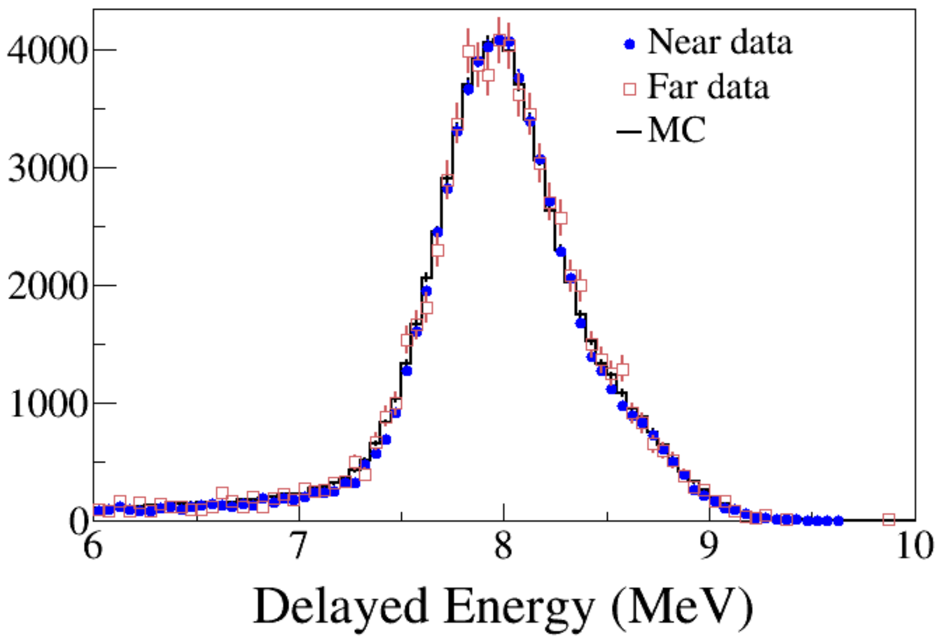
- Measurement of absolute reactor neutrino flux

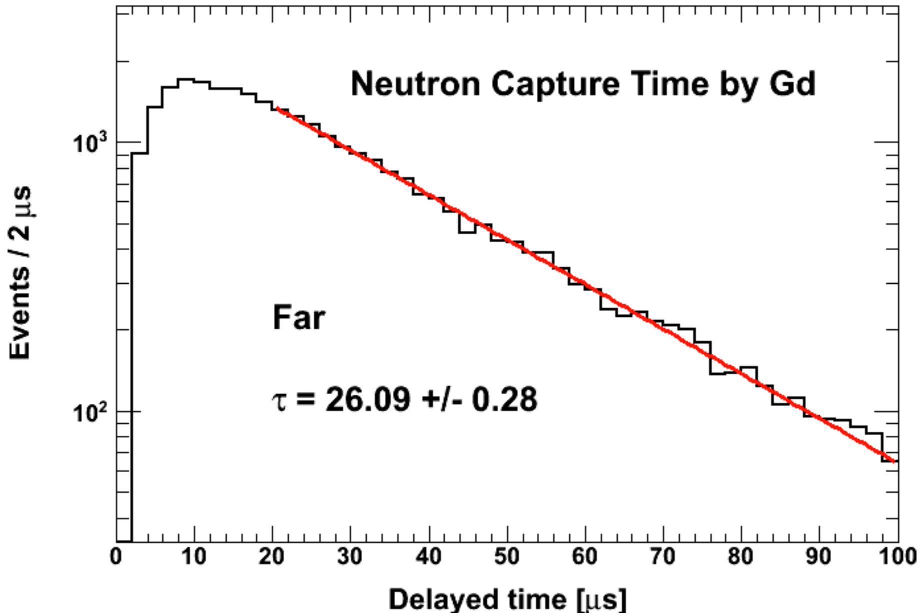
- Observation of an excess at ~5 MeV in reactor neutrino spectrum using ~1400 days of data

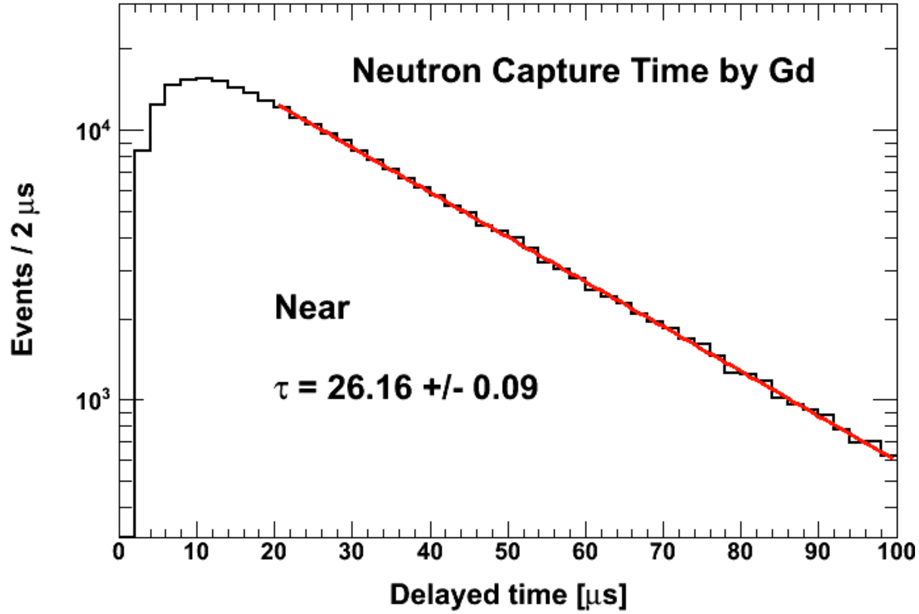
- Independent measurement of θ_{13} with n-H for a delayed signal (additional background reduction achieved)

- Obtained results from a sterile neutrinos search

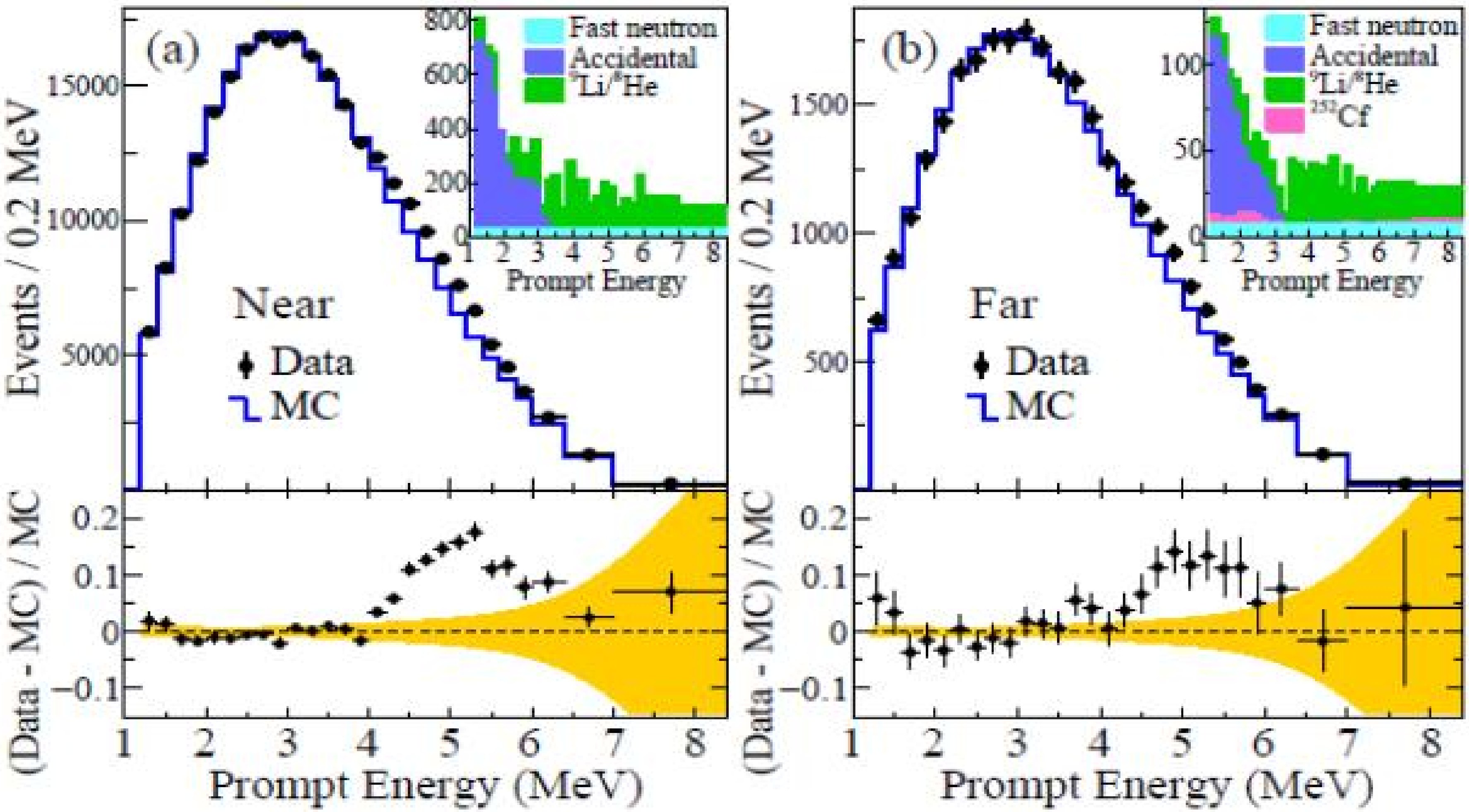
Delayed Signals from Neutron Capture by Gd







Measured Spectra of IBD Prompt Signal

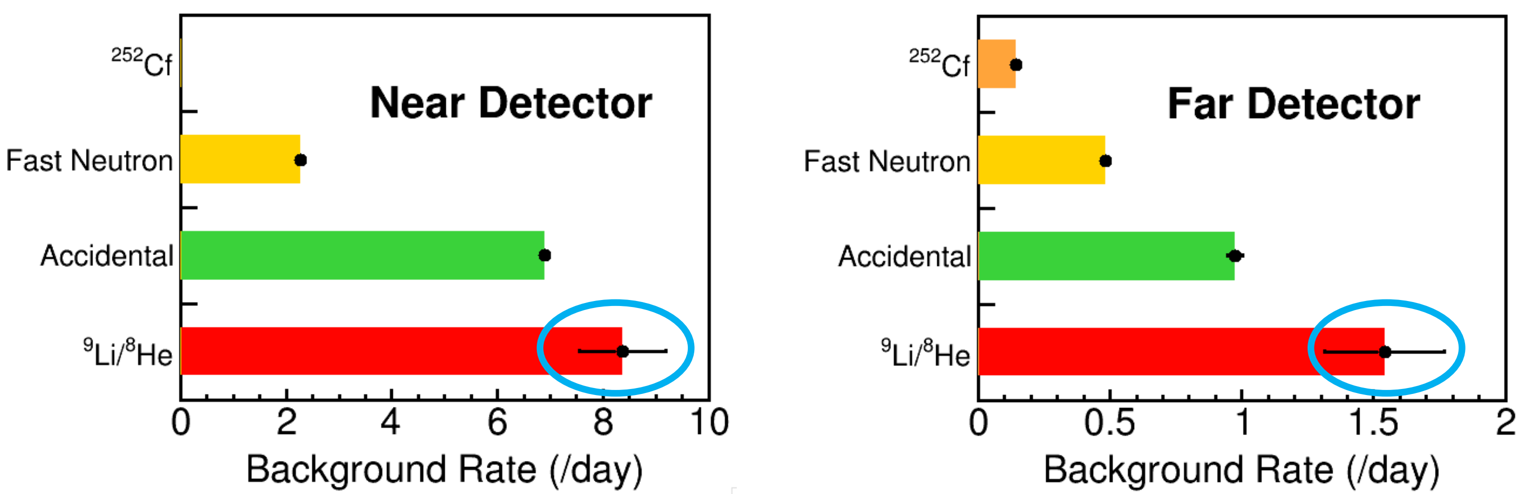


Near Live time = 458.49 days
# of IBD candidate = 290,775
# of background = 8,041 (2.8 %)

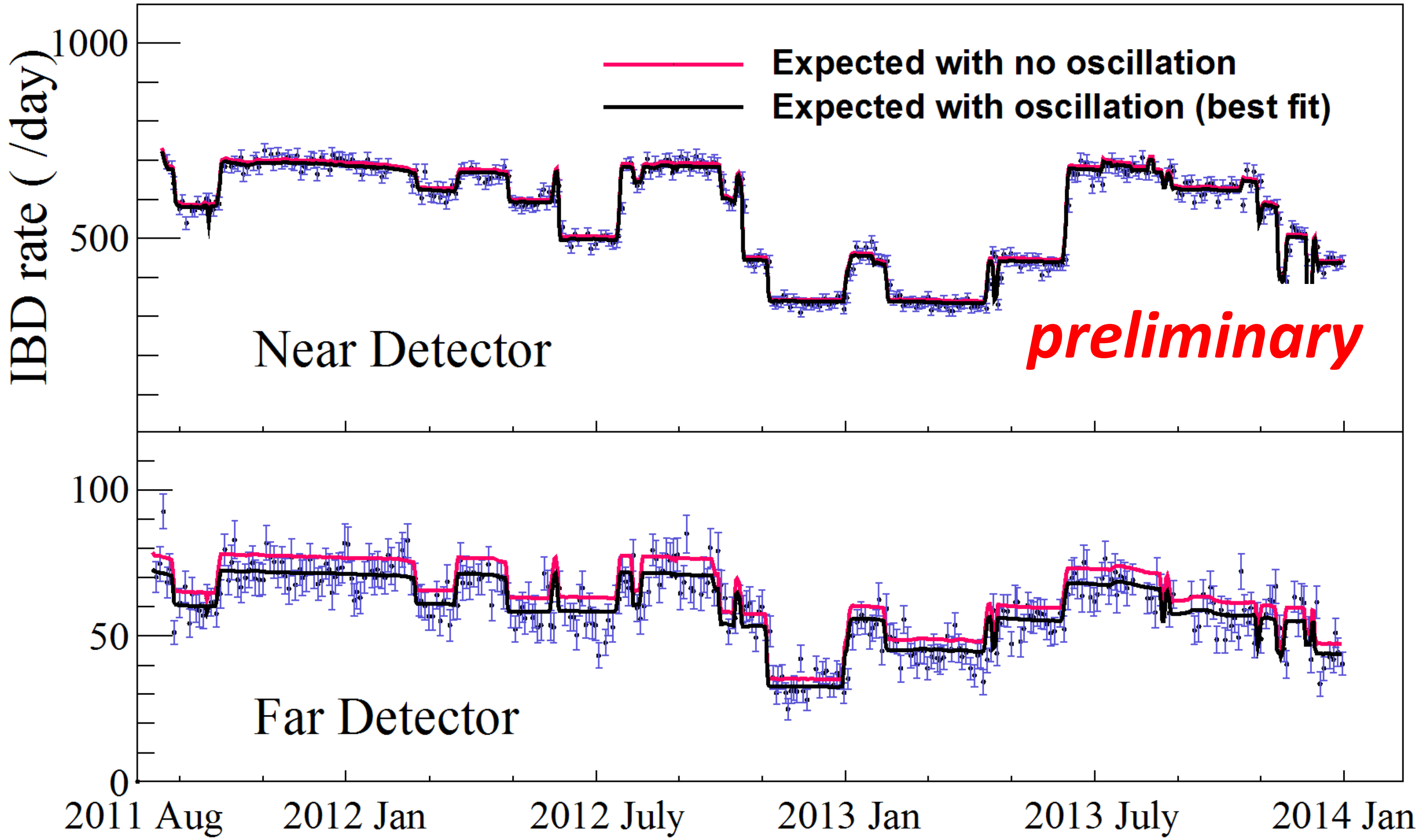
Far Live time = 489.93 days
# of IBD candidate = 31,541
# of background = 1540 (4.9 %)

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

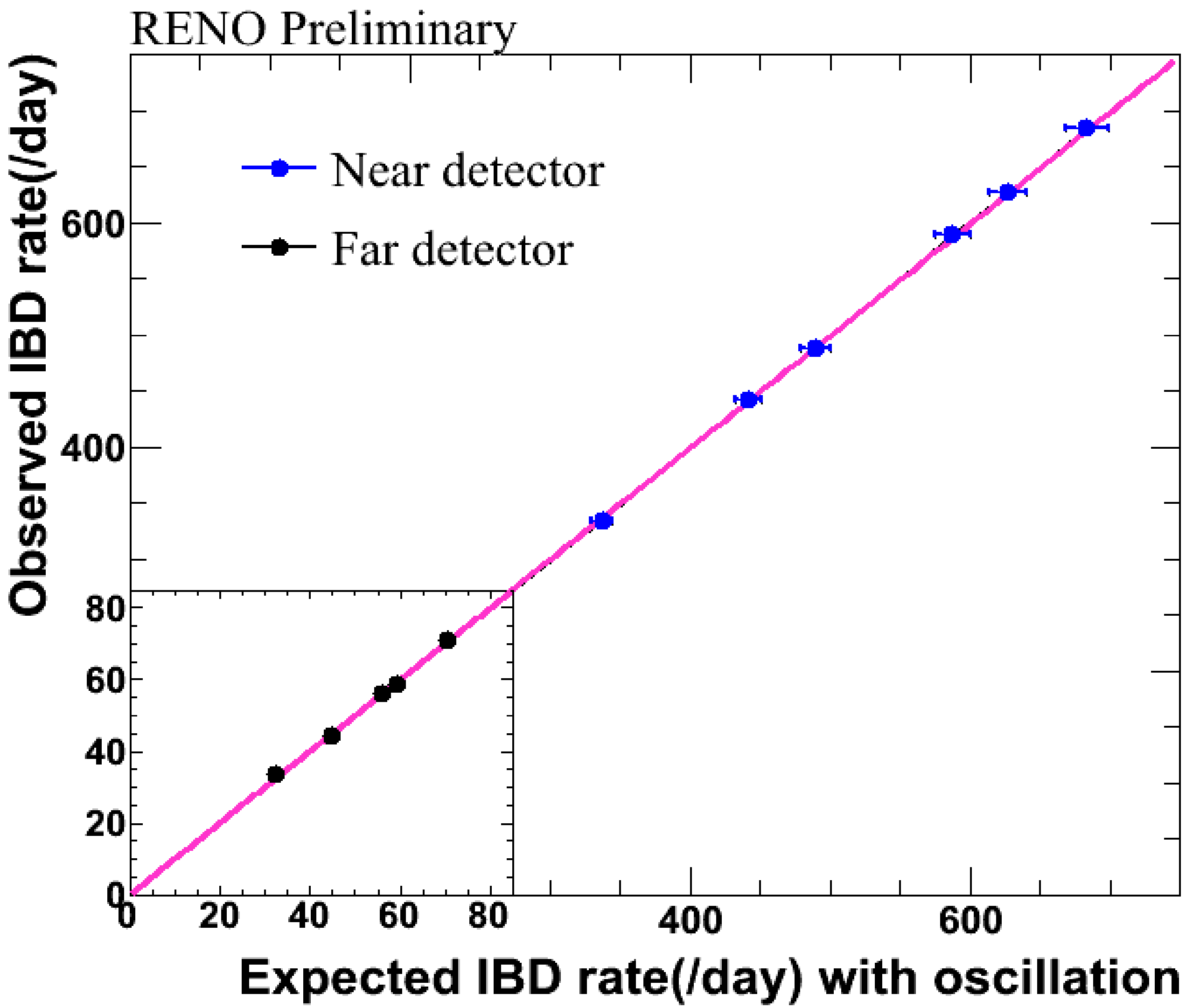


Observed Daily Averaged IBD Rate



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

Observed vs. Expected IBD Rates



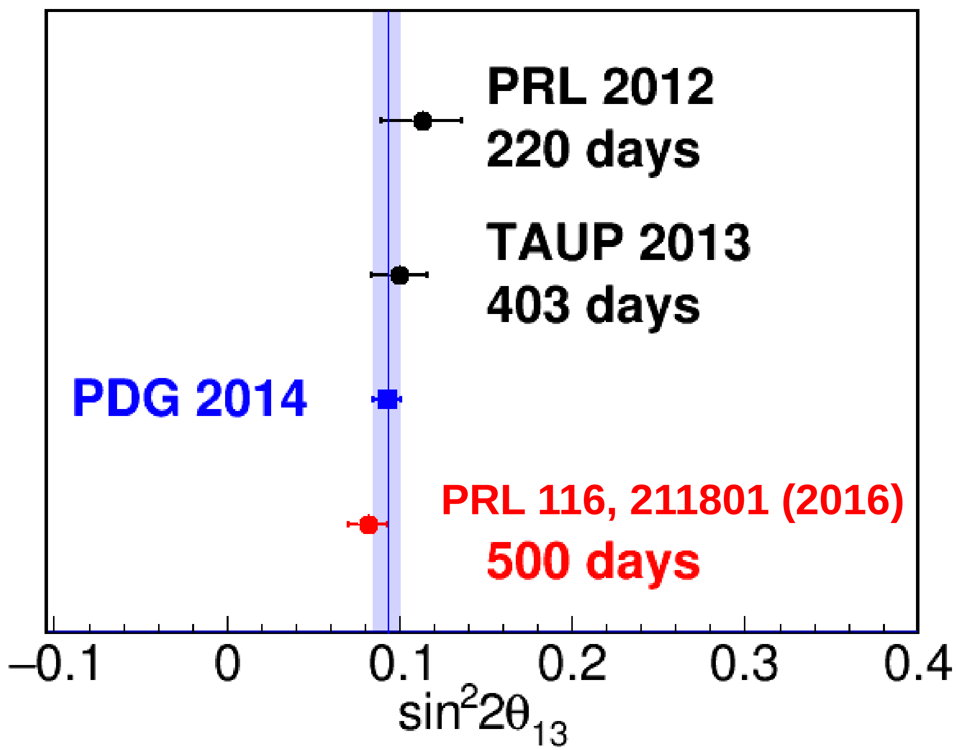
- Good agreement between observed rate & prediction
- Indication of correct background subtraction

New θ_{13} Measurement by Rate-only Analysis

Rate-only new result

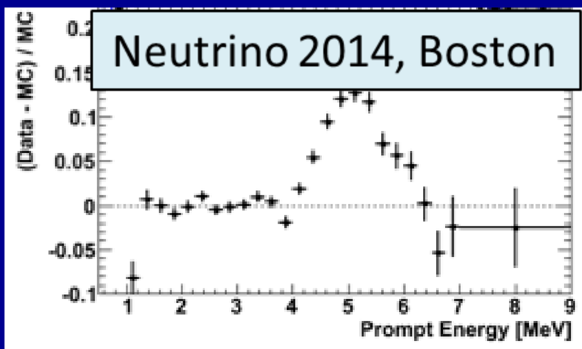
$$\sin^2 2\theta_{13} = 0.087 \pm 0.009(\text{stat.}) \pm 0.007(\text{syst.})$$

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

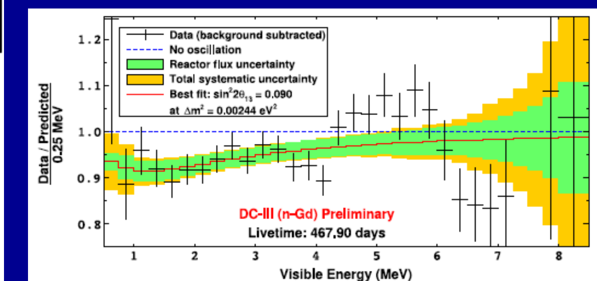


The 5 MeV Excess is there !

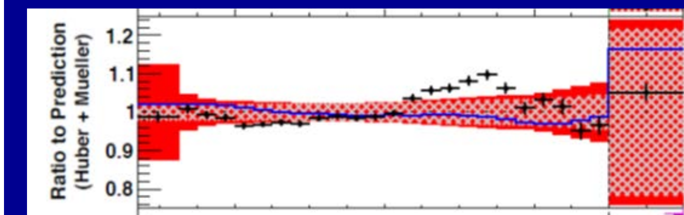
RENO



Double Chooz



Daya Bay

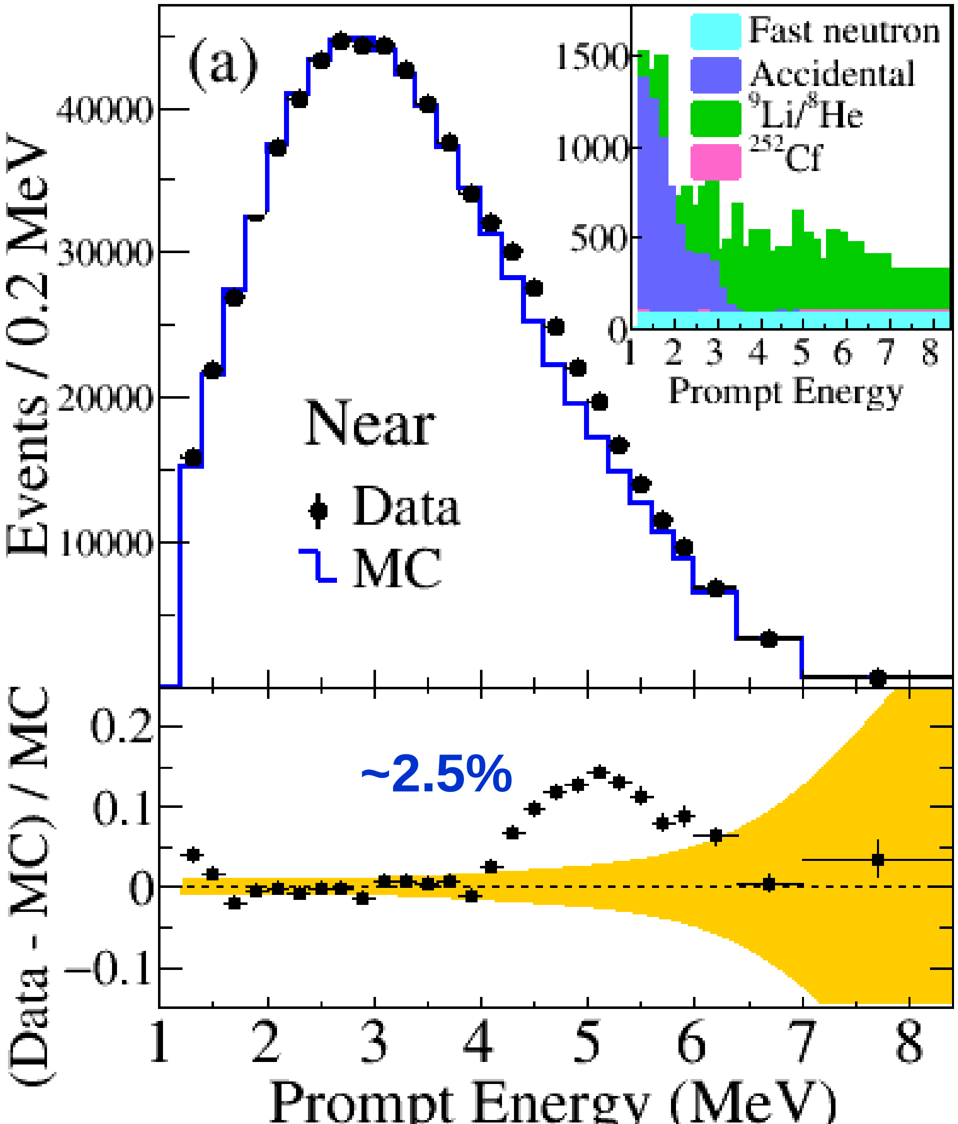


In 2014, RENO showed the 5 MeV excess comes from reactors.

Observation of an excess at 5 MeV

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

(Preliminary)



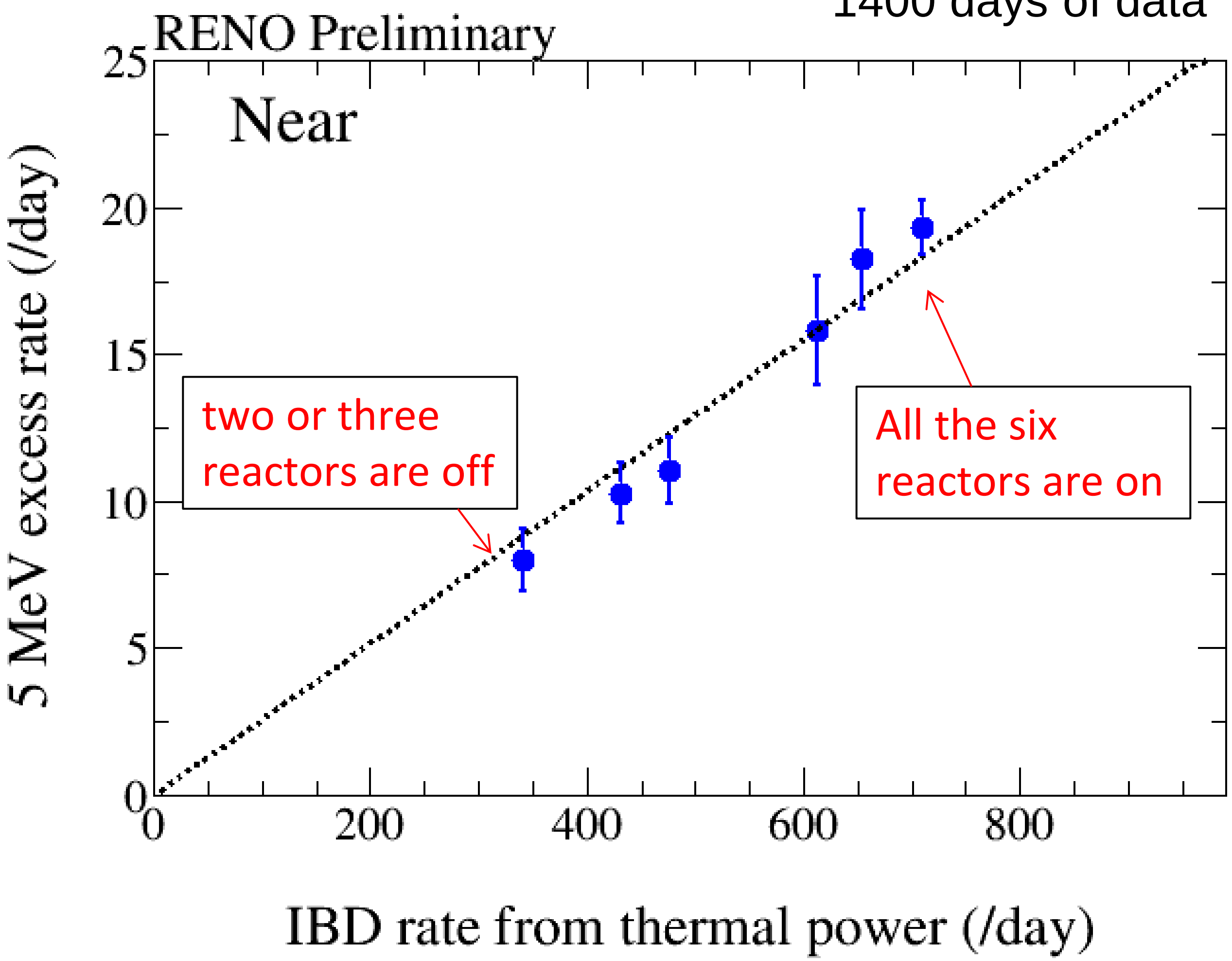
The measured near spectrum is compared with prediction using χ^2-square test.

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

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

Correlation of 5 MeV Excess with Reactor Power

1400 days of data



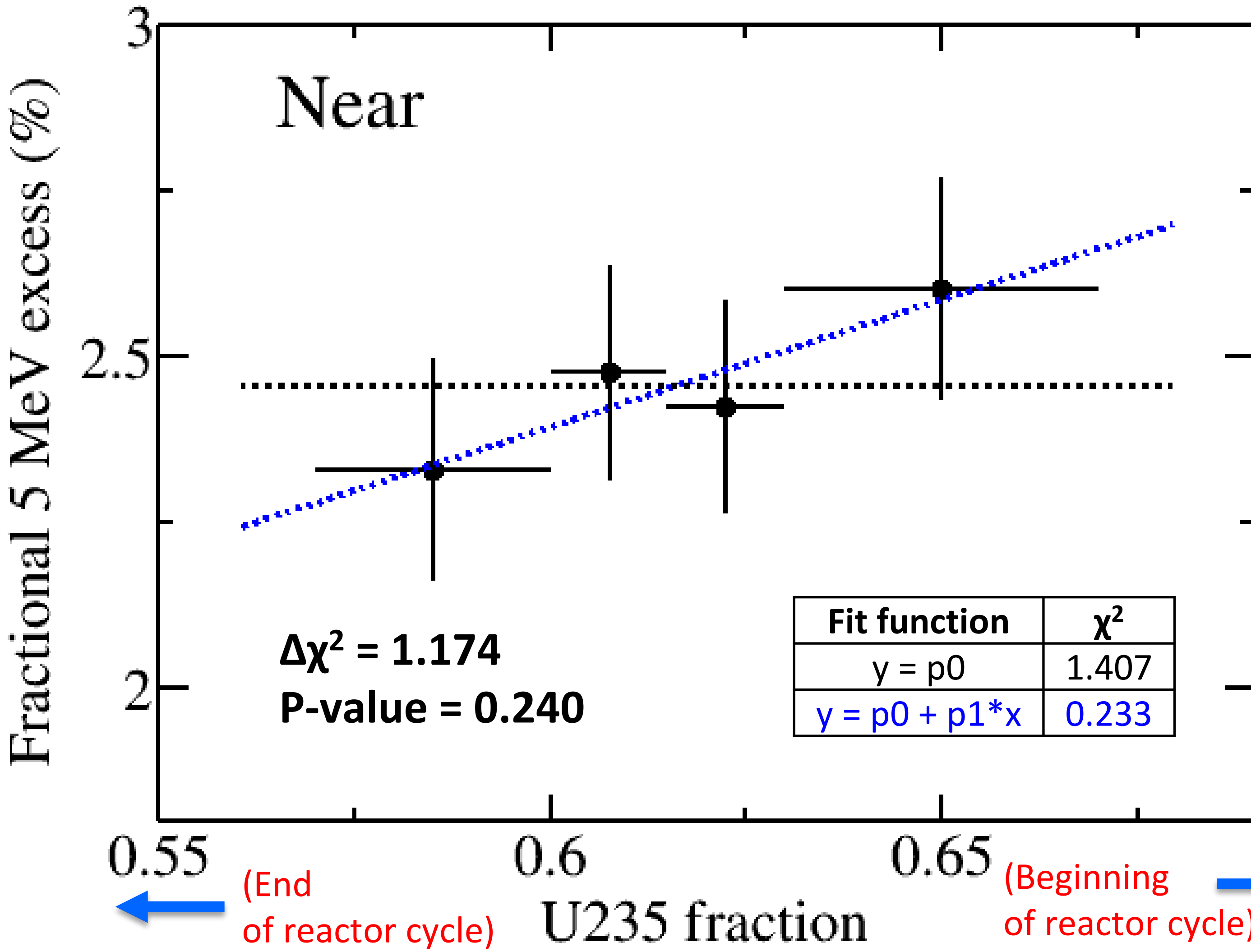
5 MeV excess has a clear correlation with reactor thermal power !

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



Fit function	χ^2
y = p0	1.407
y = p0 + p1*x	0.233

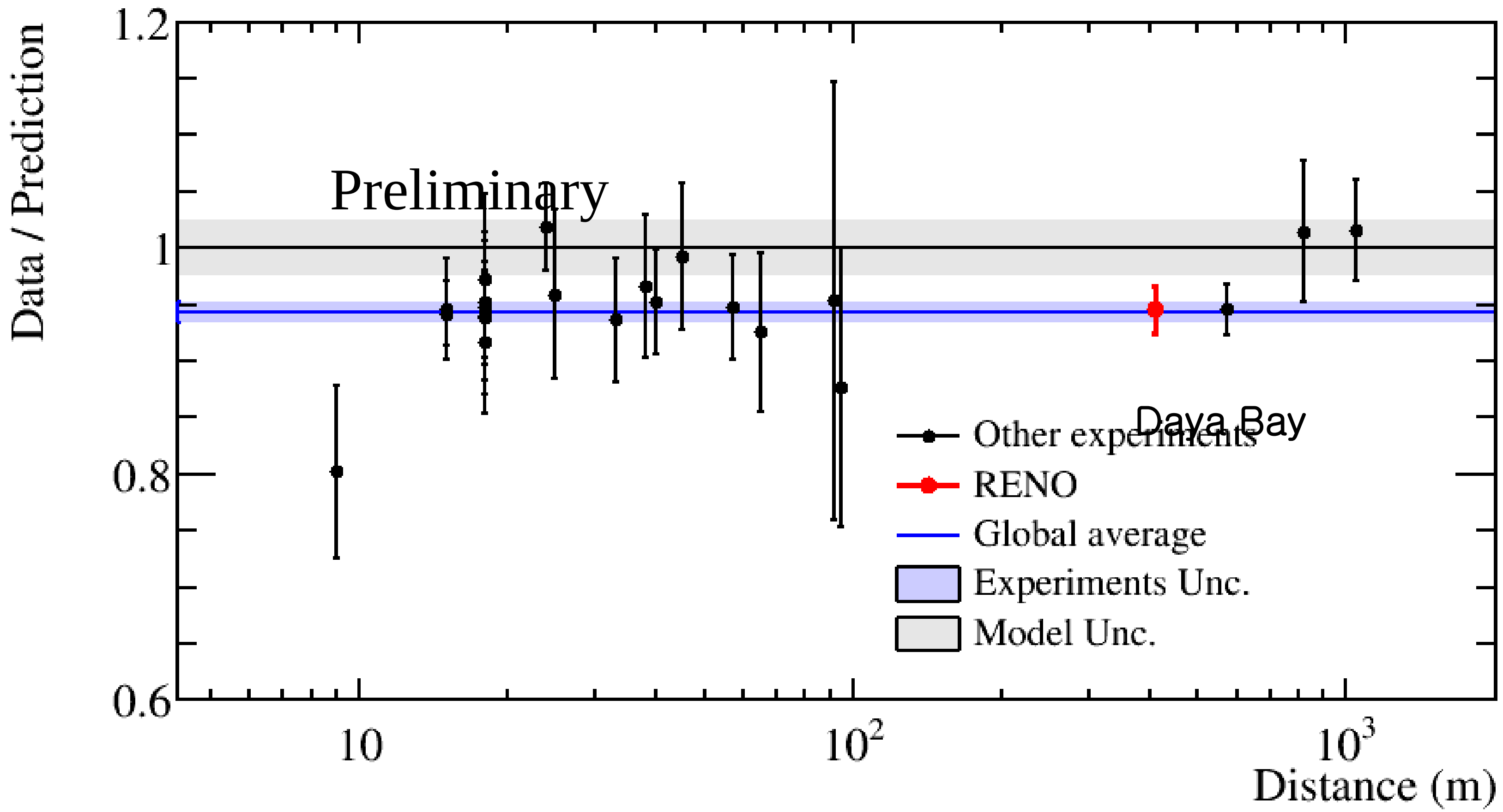
(End of reactor cycle)

(Beginning of reactor cycle)

Measurement of Absolute Reactor Neutrino Flux

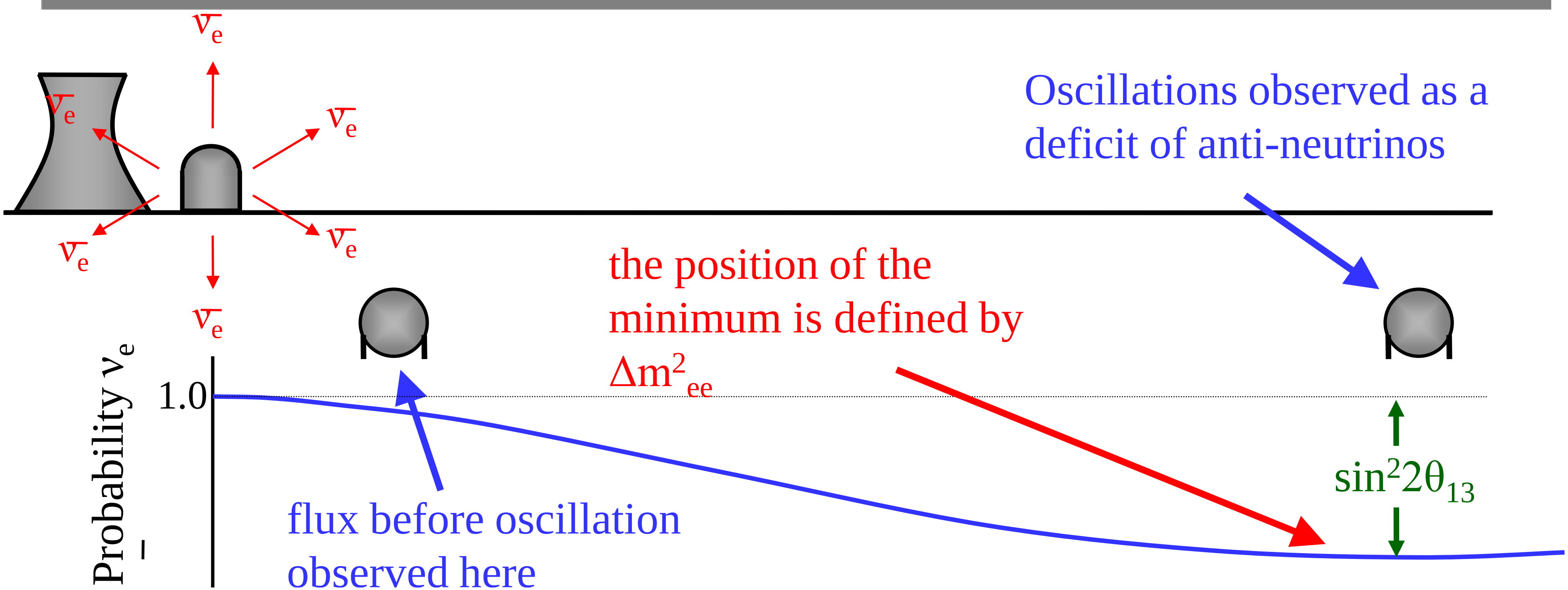
R (data/prediction) = 0.946 ± 0.021 (500 days)

- The flux prediction is with Huber + Mueller model
- Flux weighted baseline at near : 411 m



*Prediction is corrected for three flavor neutrino oscillation

Reactor Neutrino Oscillations



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

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

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

Distance

1200 to 1800 meters

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

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

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

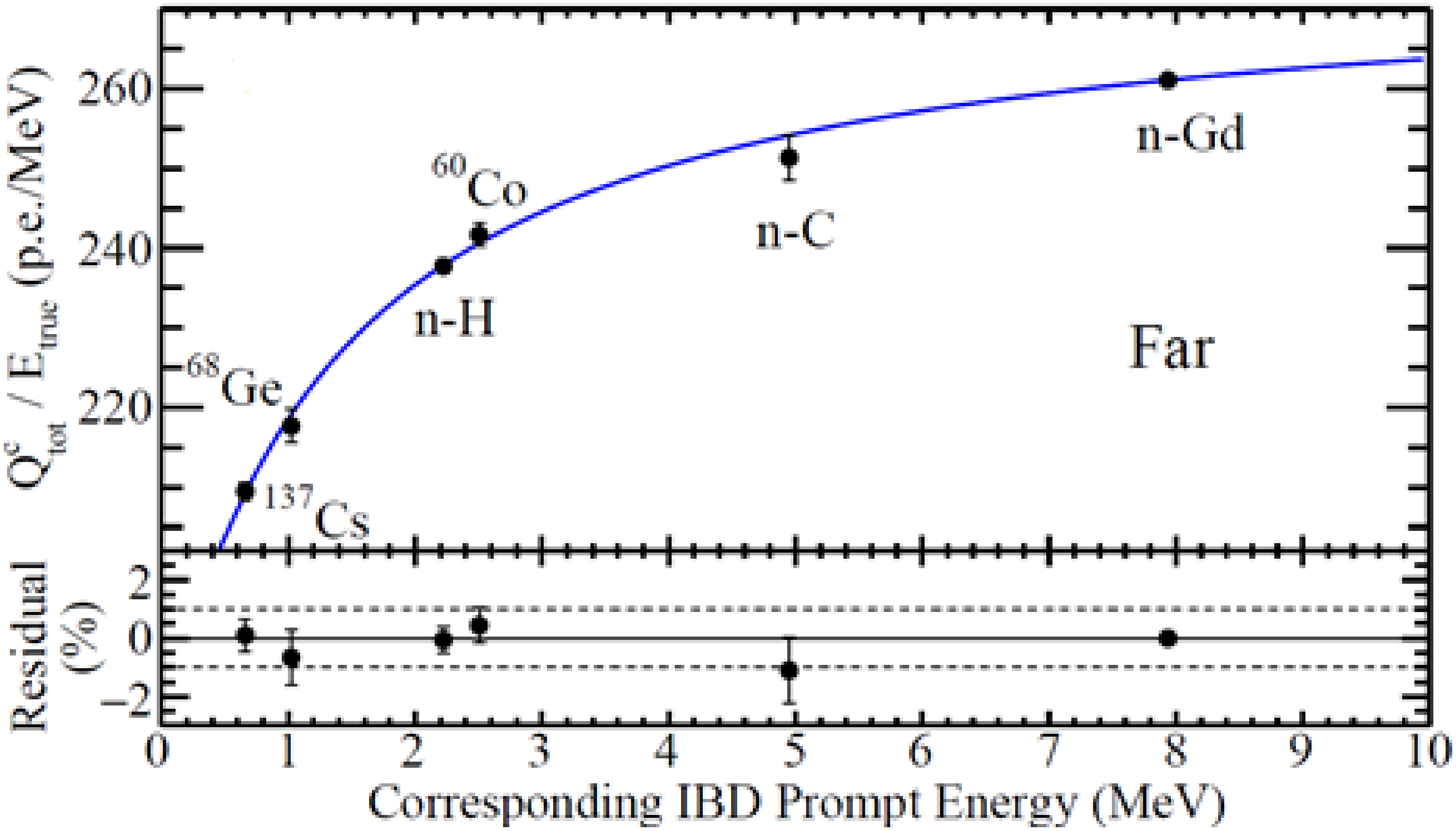
+: Normal Hierarchy

−: Inverted Hierarchy

H. Nunokawa et al, PRD72 013009(2005)

Energy Calibration from γ-ray Sources

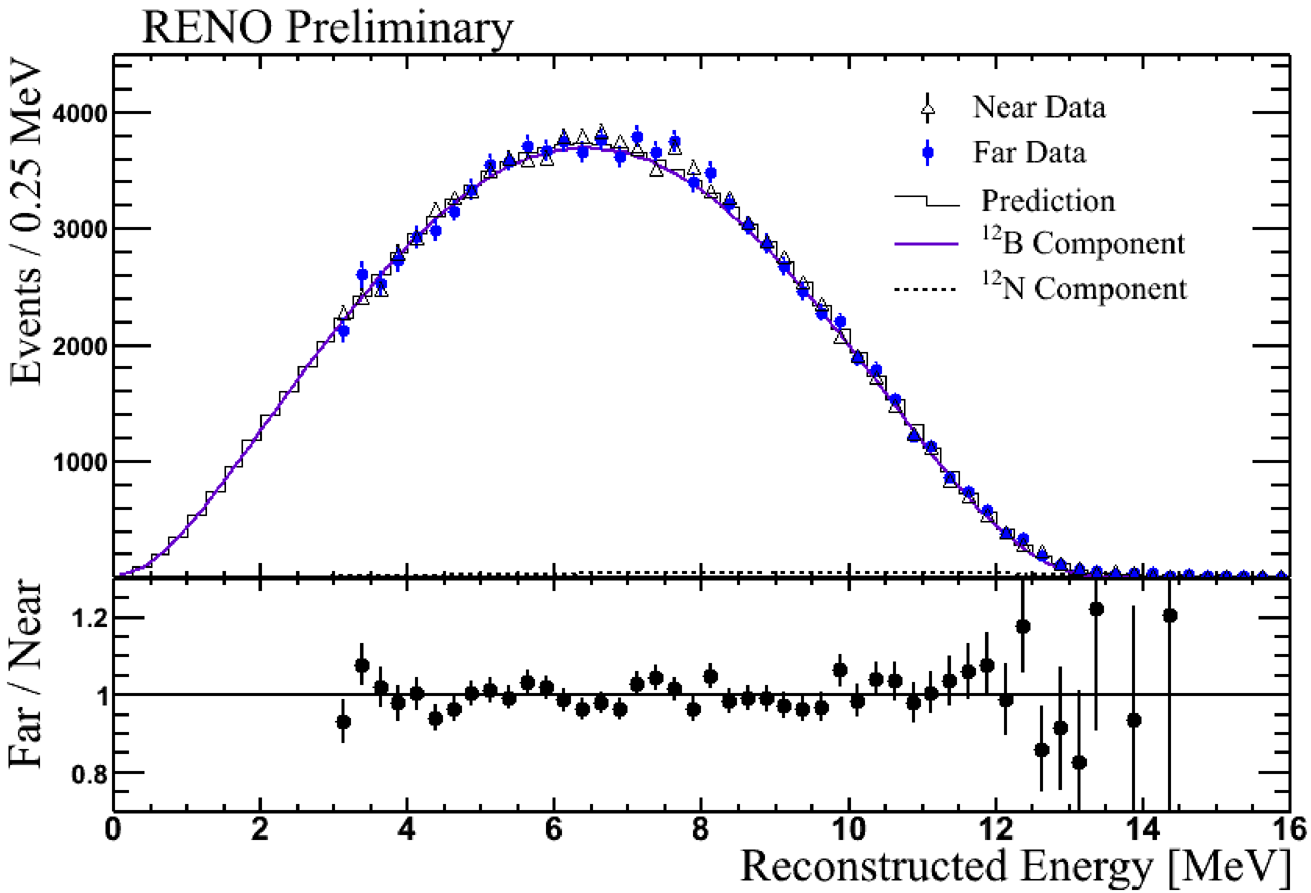
- Non-linear resonse of the scintillation energy is calibrated using γ-ray sources.
- The visible energy from γ-ray is corrected to its corresponding positron energy.



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

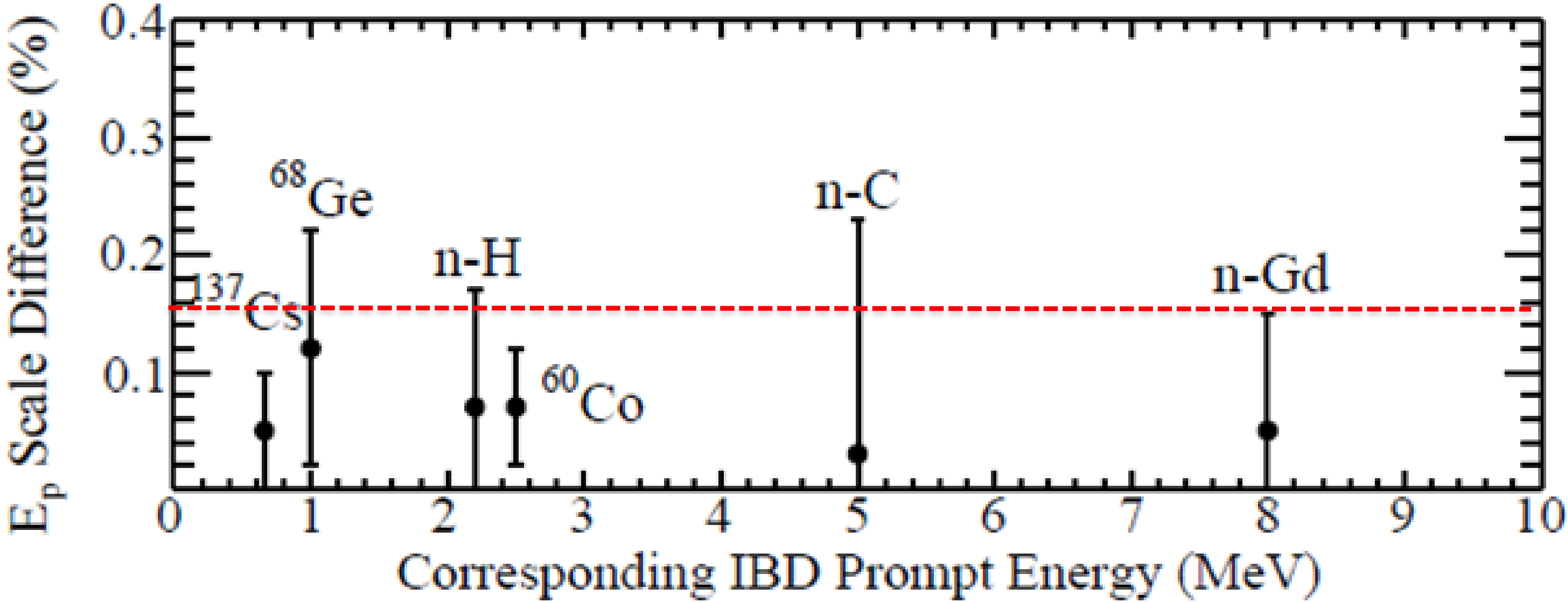
B12 Energy Spectrum (Near & Far)

- 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!

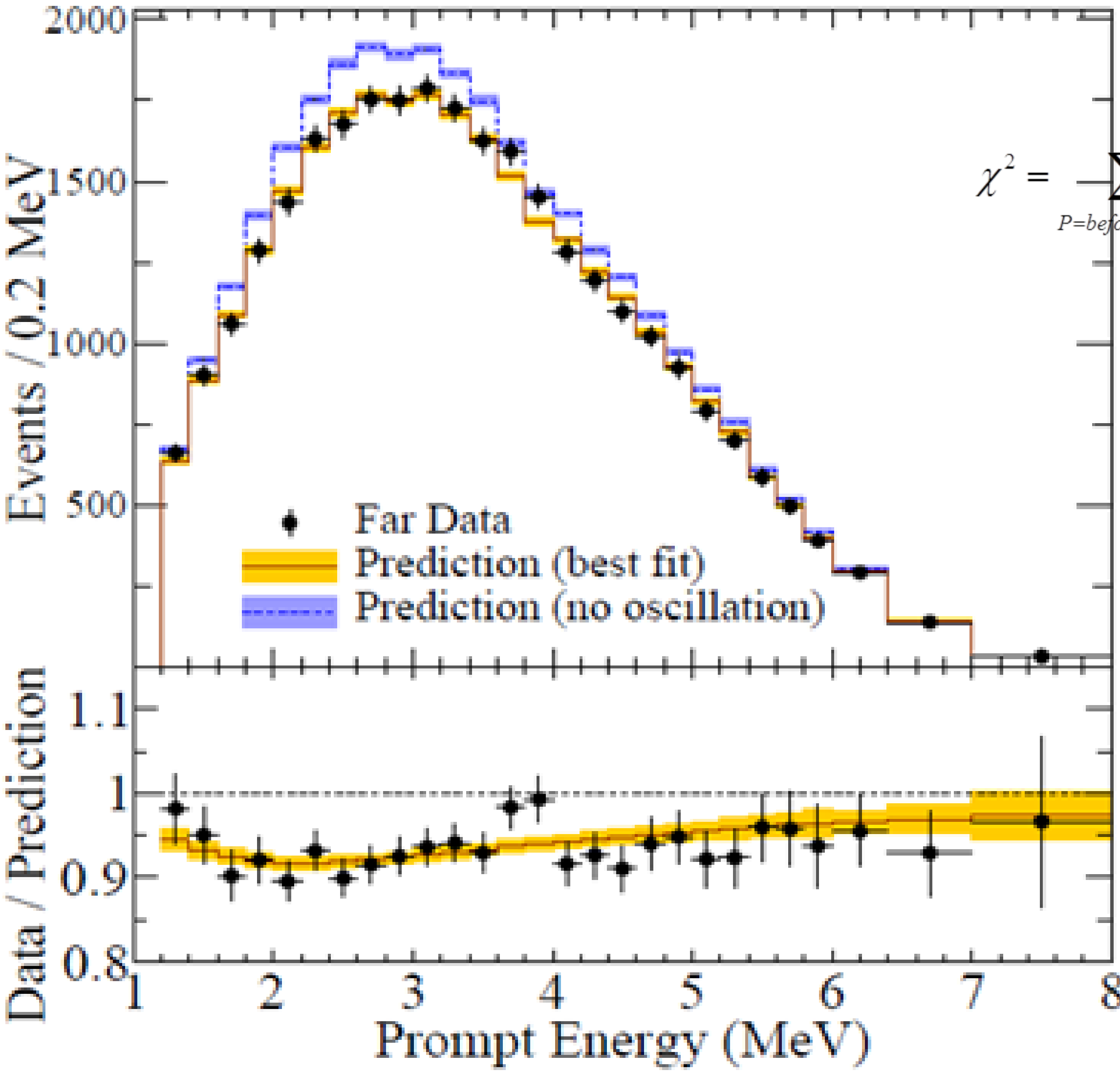
Energy Scale Difference between Near & Far



Energy scale difference < 0.15%

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

PRL 116, 211801, 2016



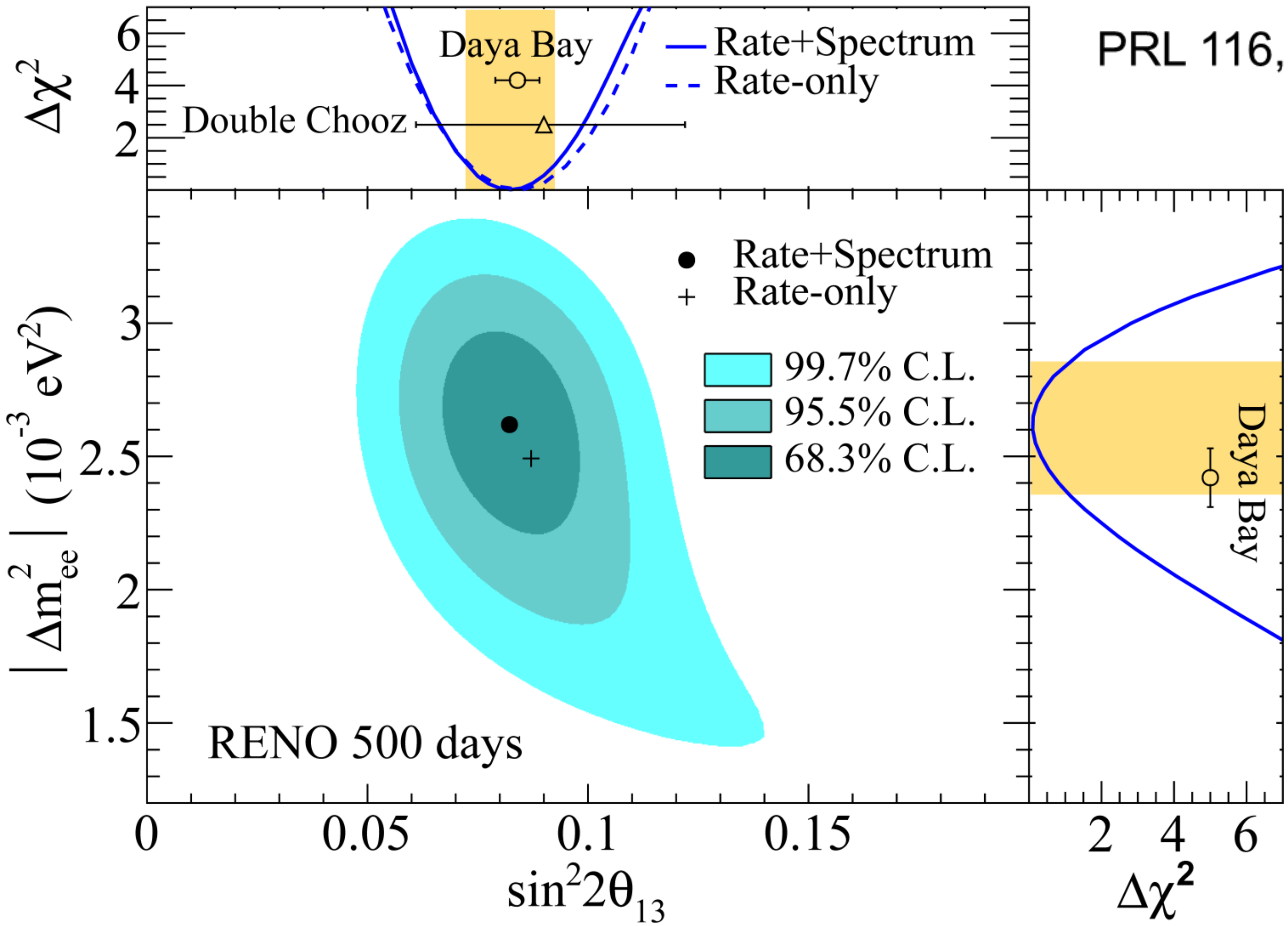
Minimize X^2 Function

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

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

Results from Spectral Fit

PRL 116, 211801, 2016



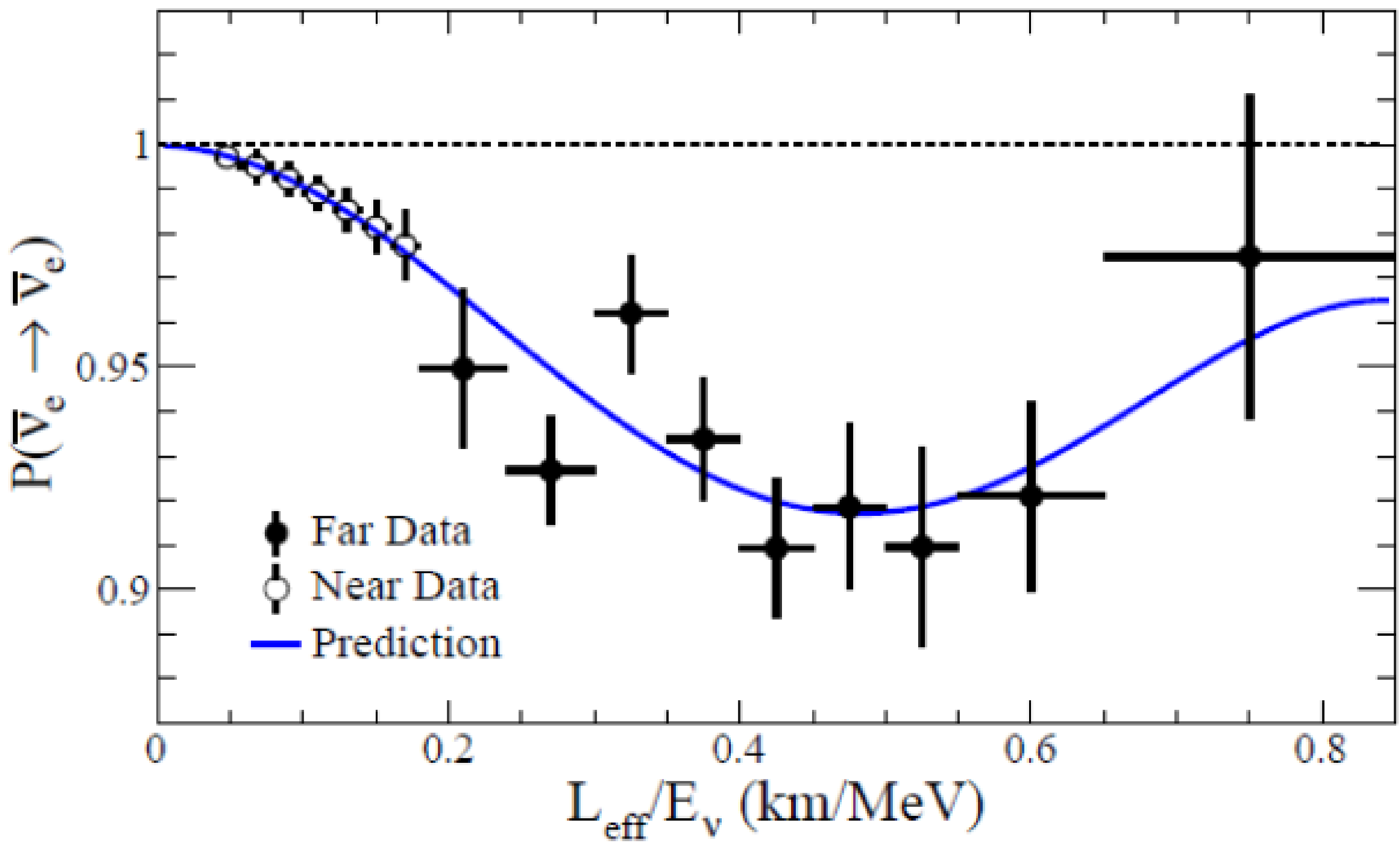
Rate+shape new results

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

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

Observed L/E Dependent Oscillation

PRL 116, 211801, 2016



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

RENO New Results

	Rate-only		Rate+shape
Data set	220 days (2012)	500 days(2015)	500 days (2015)
$\|\Delta m_{ee}^2\|$ [$\times 10^{-3}$ 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

$^9Li/^8He$ 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)

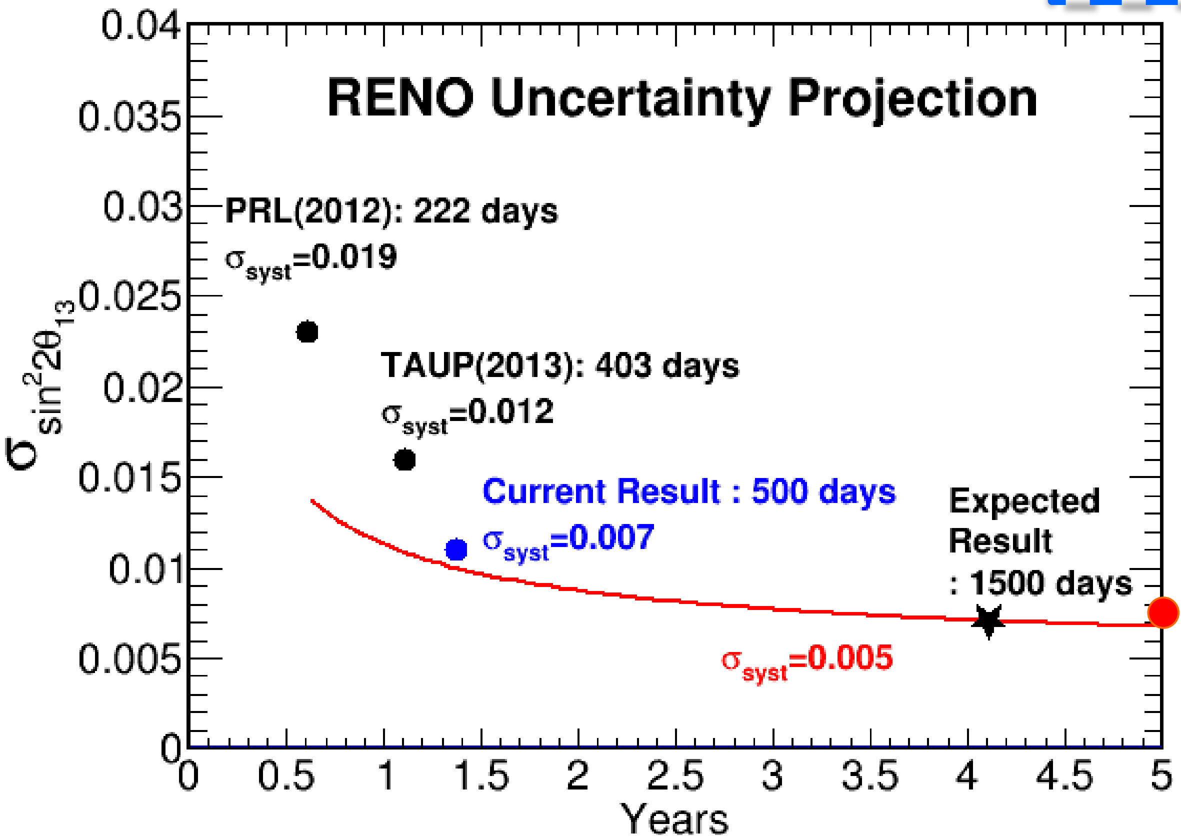
Projected Sensitivity of θ_{13} & $|\Delta m_{ee}^2|$

$\sin^2 2\theta_{13} = 0.082 \pm 0.010$ (±12%) → ± 0.005 (±6 %)

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

(~500 days)

(5 years of data)



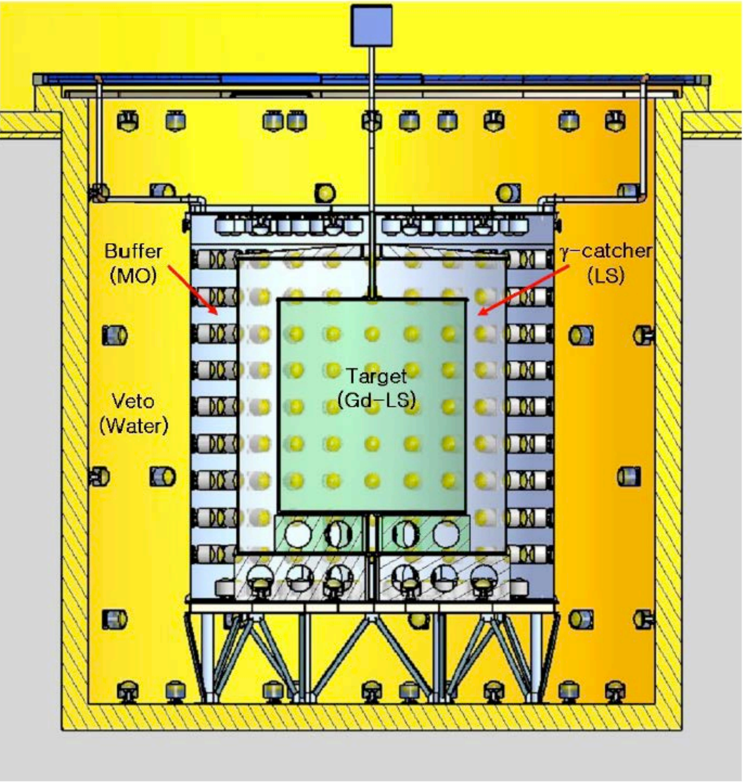
(6 % precision)

(sensitivity goal of θ_{13})

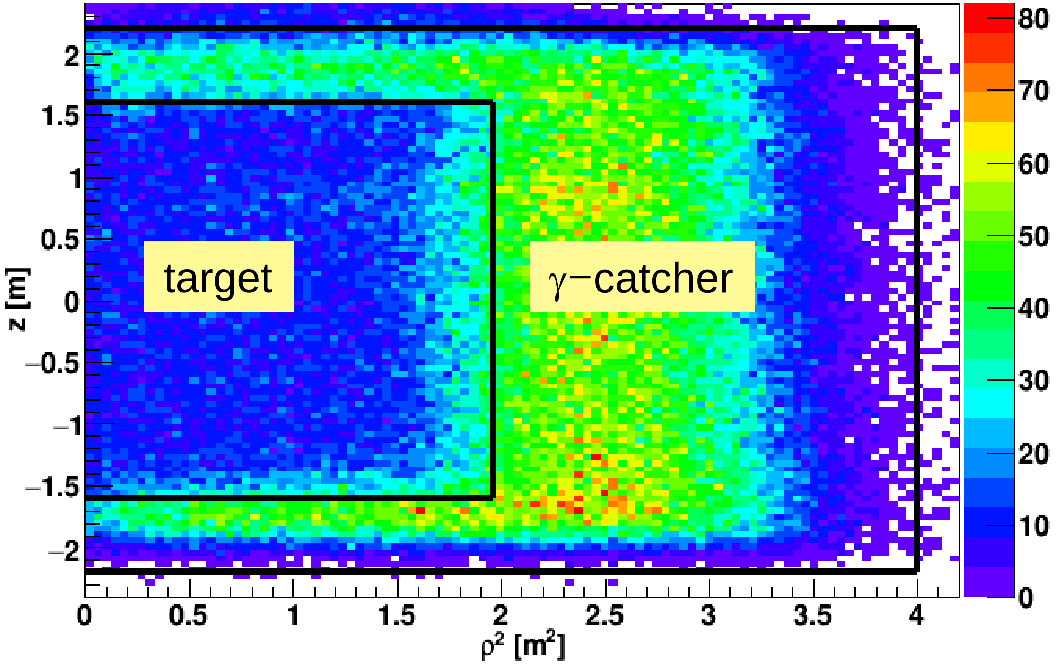
n-H IBD Analysis

Motivation:

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

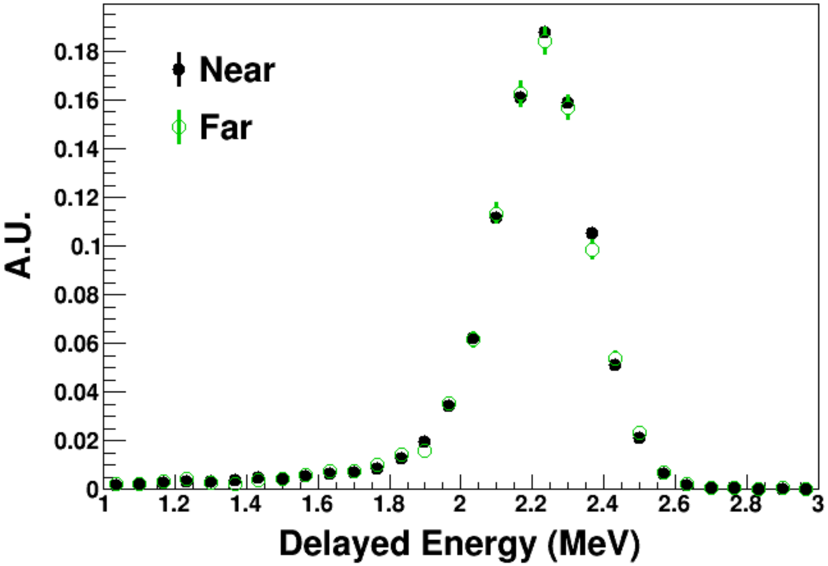


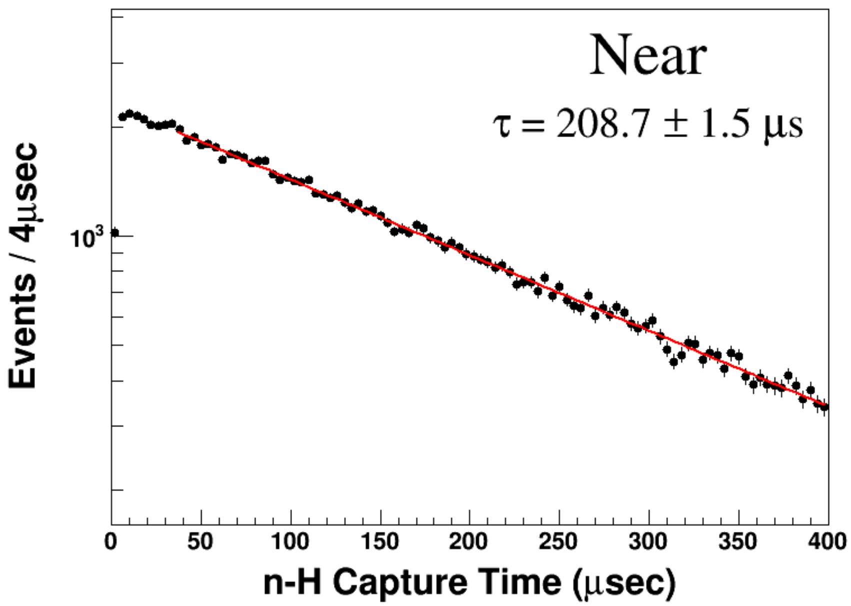
n-H IBD Event Vertex Distribution

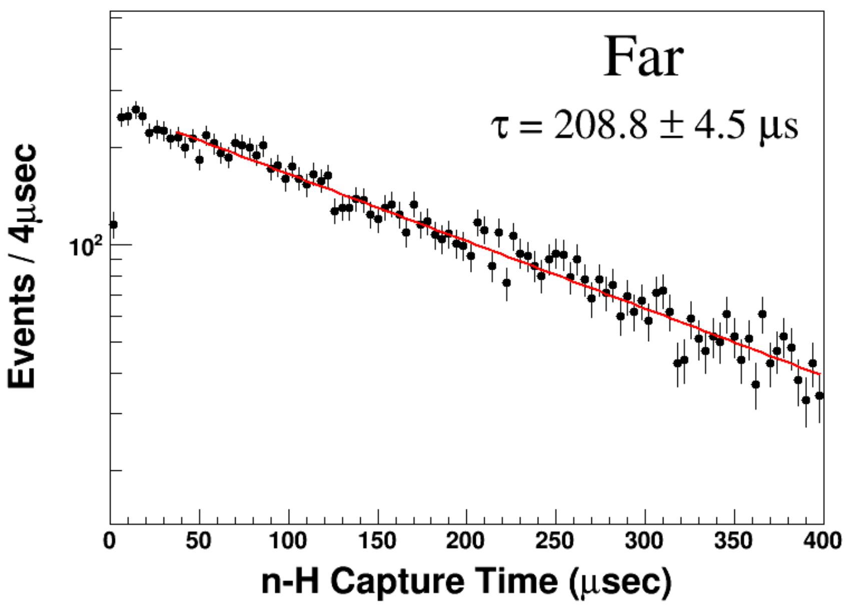


Delayed Spectrum and Capture Time

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



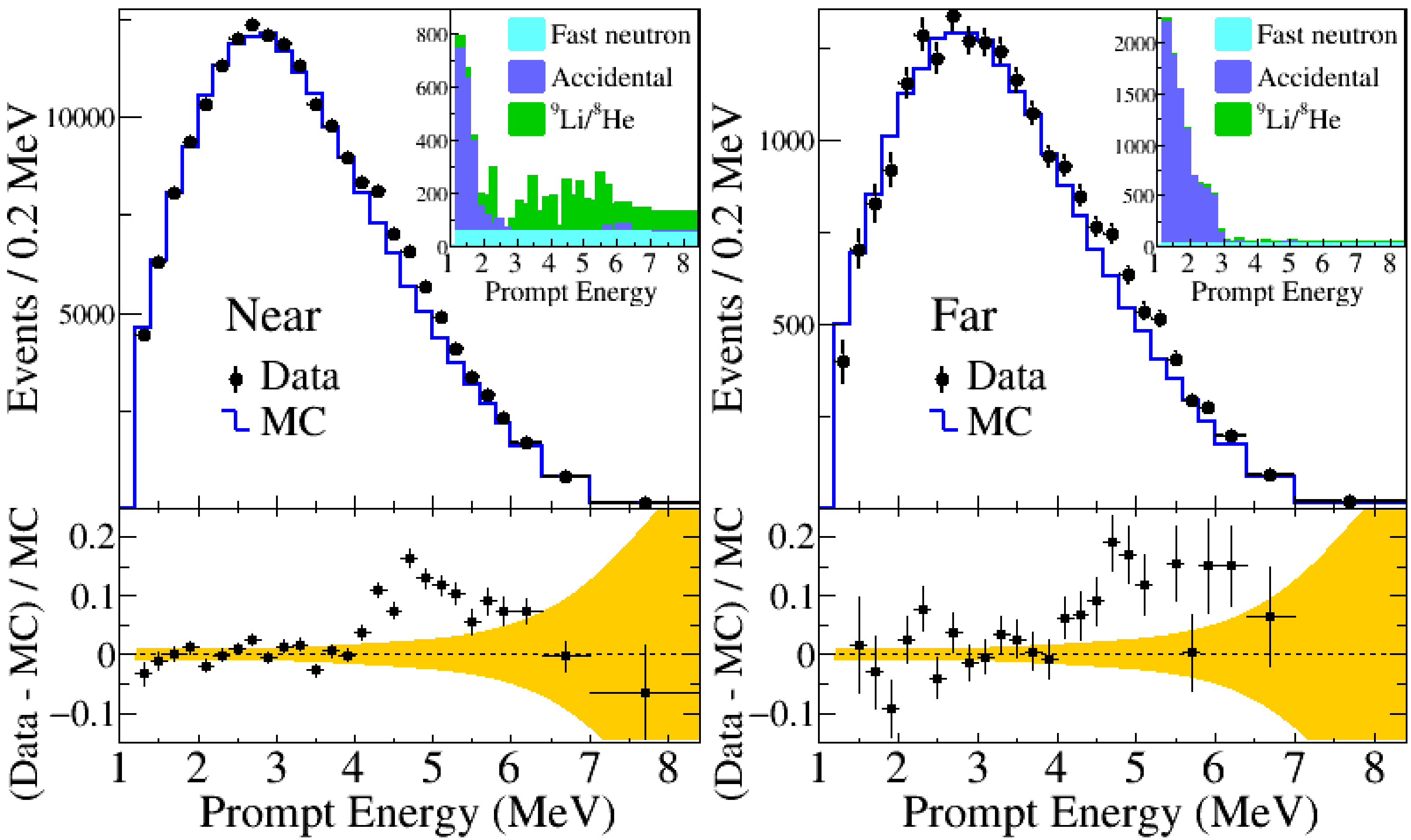




θ_{13} Measurement with n-H

(Preliminary, 500 days)

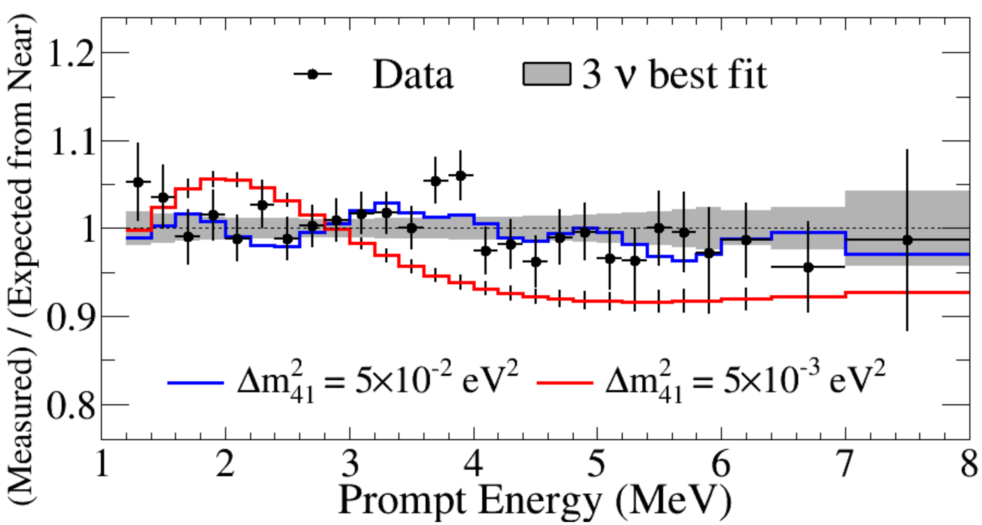
$$\sin^2 2\theta_{13} = 0.086 \pm 0.012(\text{stat.}) \pm 0.015(\text{syst.})$$



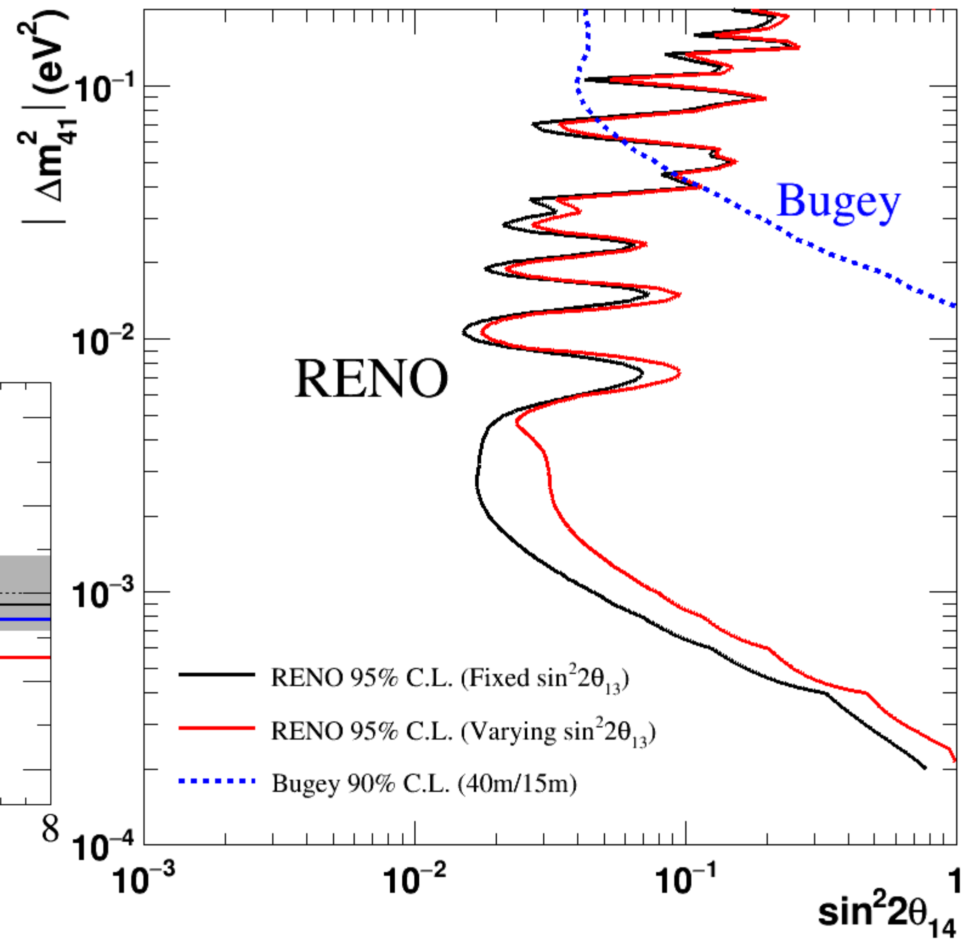
Light Sterile Neutrino Search Results

(Preliminary)

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



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

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

± 0.26 10 % precision

- Measured absolute reactor neutrino flux : R= 0.946±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
- $\sin(2\theta_{13})$ to 6% accuracy
  Δm_{ee}^2 to 0.15×10^{-3} eV^2 (6%) accuracy for final sensitivity

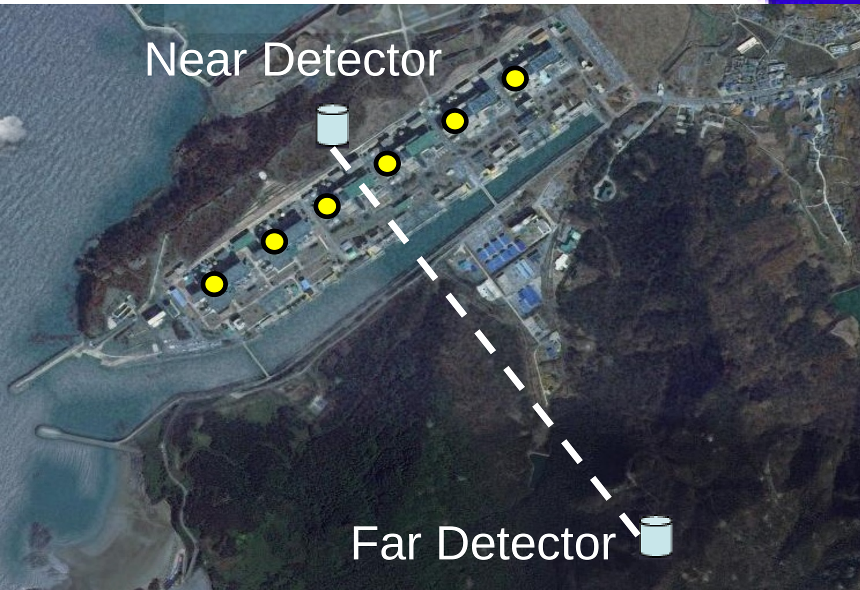
Overview of RENO-50

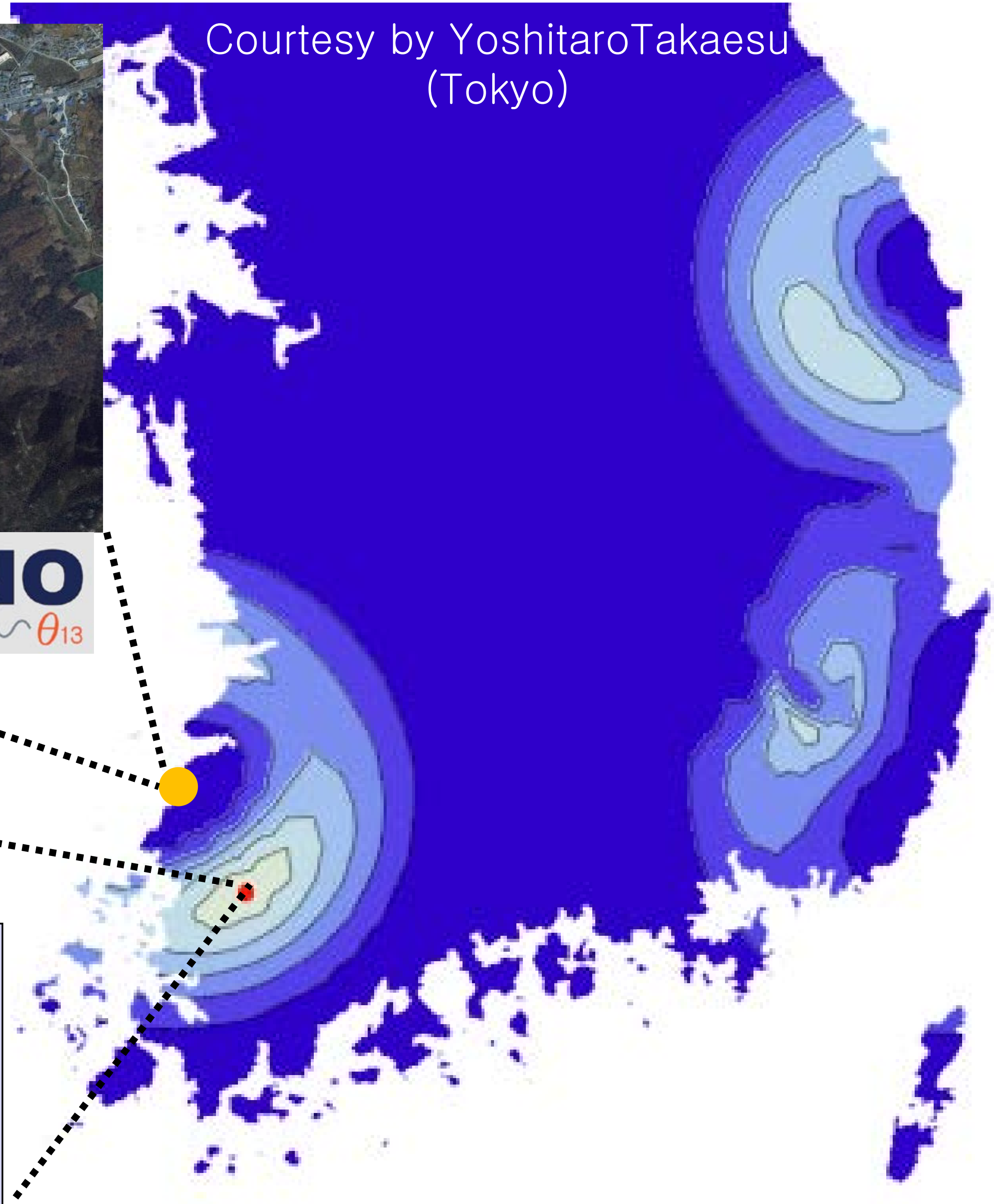
- **RENO-50** : An underground detector consisting of 18 kton ultra-low-radioactivity liquid scintillator & 15,000 20" PMTs, at 50 km away from the Hanbit(Yonggwang) nuclear power plant

- **Goals** : - Determination of neutrino mass ordering
  - High-precision measurement of θ_{12}, Δm^2_{21} and Δm^2_{ee}
  - Supernova neutrinos, Geo neutrinos, Sterile neutrino search, ….

- **Budget** : $ 100M for 6 year construction
  (Civil engineering: $ 15M, Detector: $ 85M)

- **Schedule** : 2016 ~ 2021 : Facility and detector construction
  2022 ~ : Operation and experiment





(NEAR Detector)

(FAR Detector)

RENO-50

18 kton LS Detector
~47 km from YG reactors

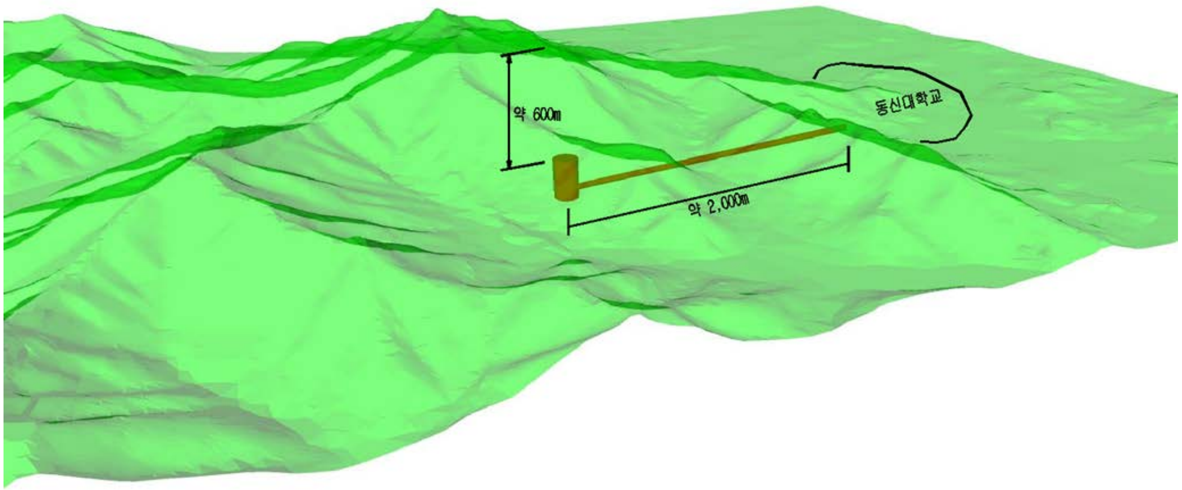
Mt. Guemseong (450 m)
~900 m.w.e. overburden

Various Physics with RENO-50

- Determination of neutrino mass ordering
  - 3σ sensitivity with 10 years of data
- Precise (~0.5%) measurement of θ_{12}, Δm^2_{21} and Δm^2_{ee}
  - An interesting test for unitarity & essential for the future discoveries
- Neutrino burst from a Supernova in our Galaxy
  - ~5,600 events (@8 kpc)
  - Study the core collapsing mechanism with neutrino cooling
- Geo-neutrinos : ~ 1,500 geo-neutrinos for 5 years
  - Study the heat generation mechanism inside the Earth
- Solar neutrinos
  - MSW effect on neutrino oscillation
- Sterile neutrino search : reactor / radioactive sources / IsoDAR
- Detection of J-PARC beam : ~200 events/year

RENO-50 Candidate Site

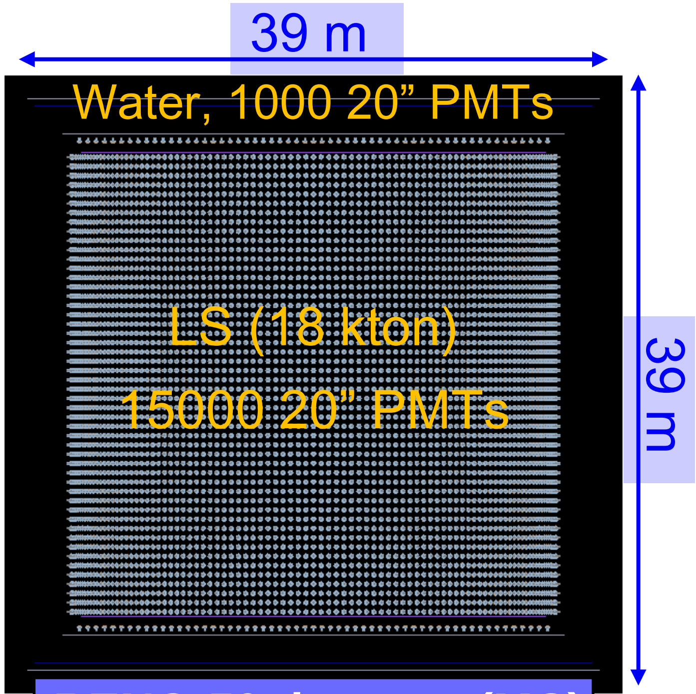
Geological Survey for Underground Facility



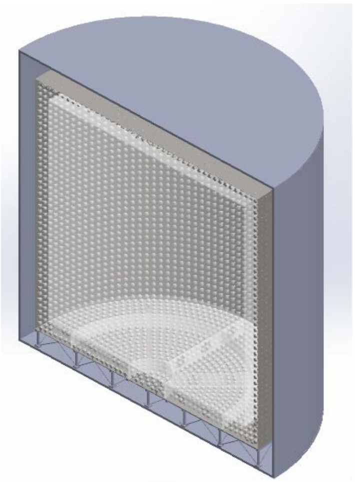
Cost estimation for RENO-50 underground facility (in progress)

- Geological survey for design of tunnel and experimental hall
- Cost estimation to be obtained soon

Conceptual Design of RENO-50 Detector



RENO-50 detector (MC)



RENO-50 R&D Status

(1) Development of DAQ electronics is on-going

(2) Develop techniques of LS purification is on-going

(3) Mechanical design of detector is on-going

(4) Measurement of radioactivity for the detector materials is on-going

(5) Upgrade of measurement device for absolute LS attenuation length is on-going

SAMSUNG 삼성미래기술육성재단

- An R&D funding (US $2M for 3 years of 2015-2017) is given by the Samsung Science & Technology Foundation.

- Efforts on obtaining a full construction fund

Thanks for your attention!