New Results from RENO & Future RENO-50

Seon-Hee (Sunny) Seo
KNRC & Seoul National University
On behalf of the RENO Collaboration

"EPS 2015"
Vienna. Austria, July 22-29, 2015

KNRC
Korea Neutrino Research Center

RENO Collaboration

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

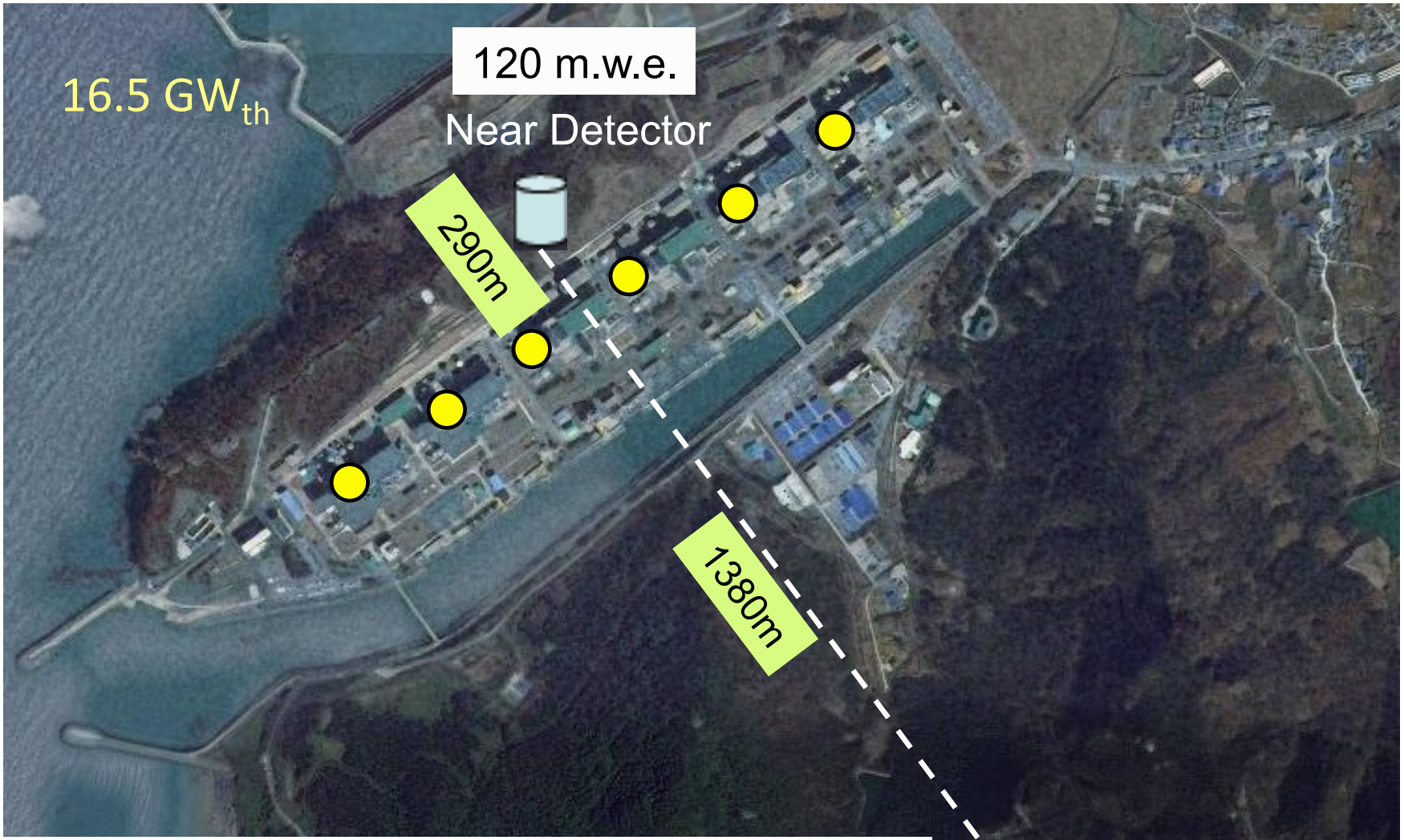
(10 institutions and 40 physicists)

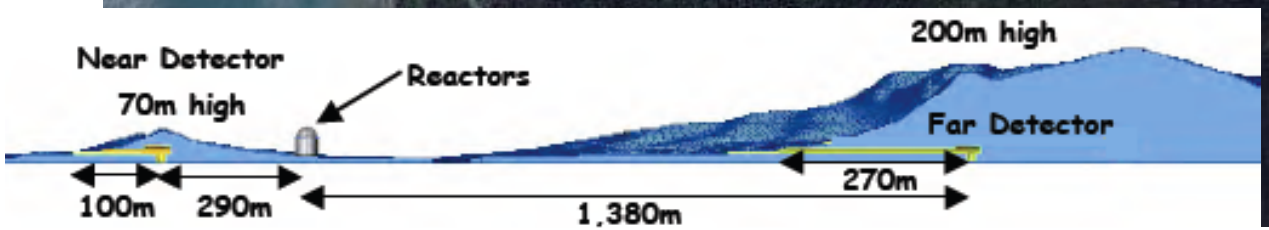
- Chonnam National University
- Chung-Ang University
- Dongshin University
- GIST
- Gyeongsang National University
- Kyungpook National University
- Sejong University
- Seoul National University
- Seoyeong University
- Sungkyunkwan University

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

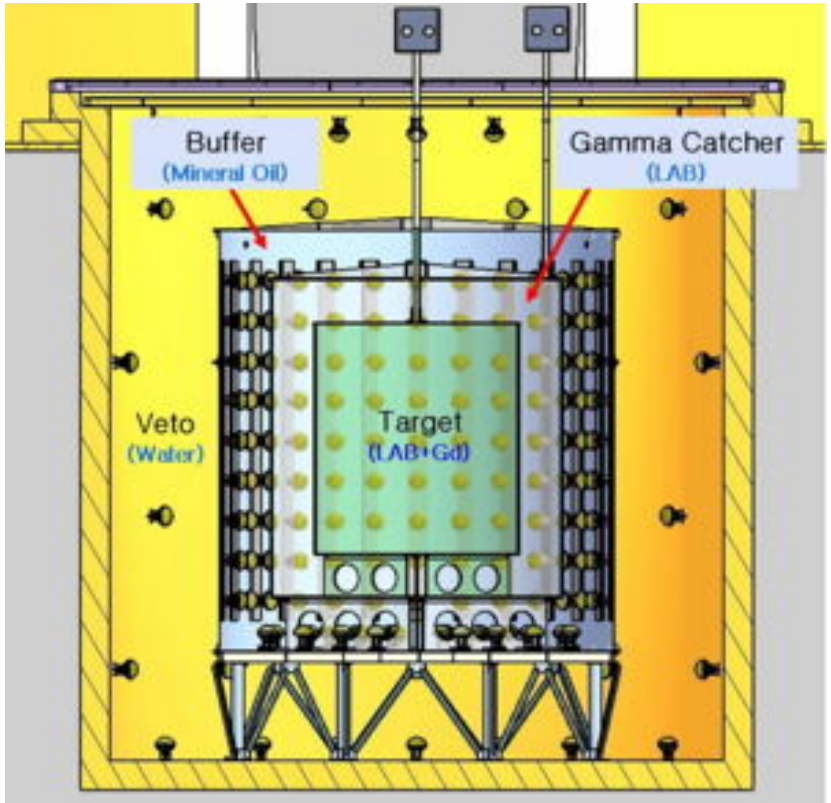
YongGwang (靈光) :

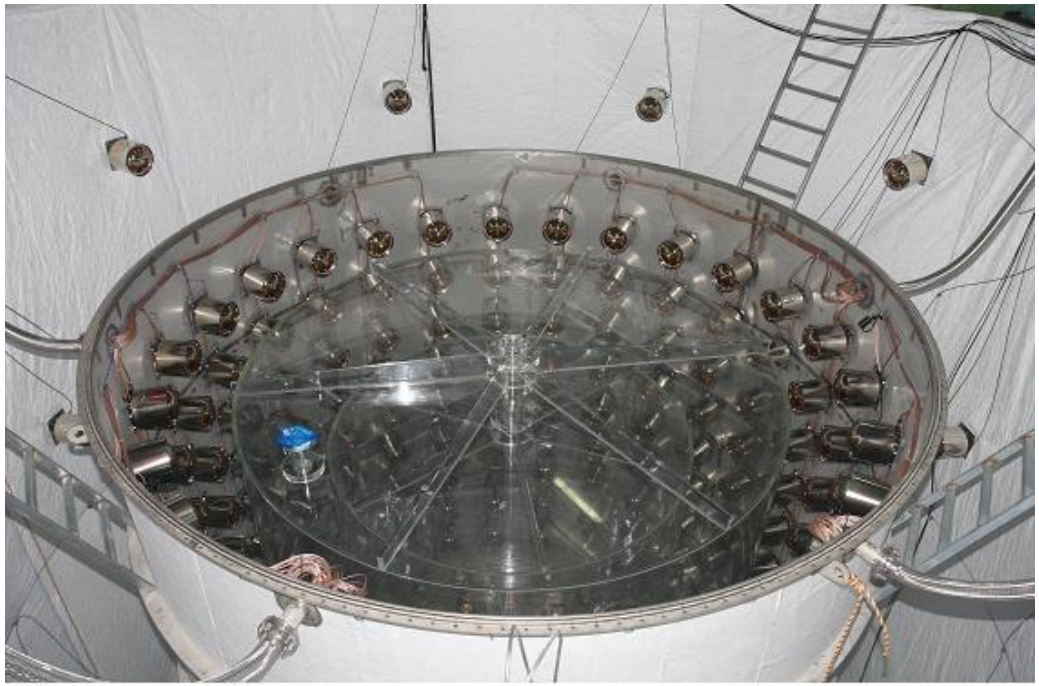
RENO Experimental Set-up





RENO Detector





- 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

RENO Data-taking Status

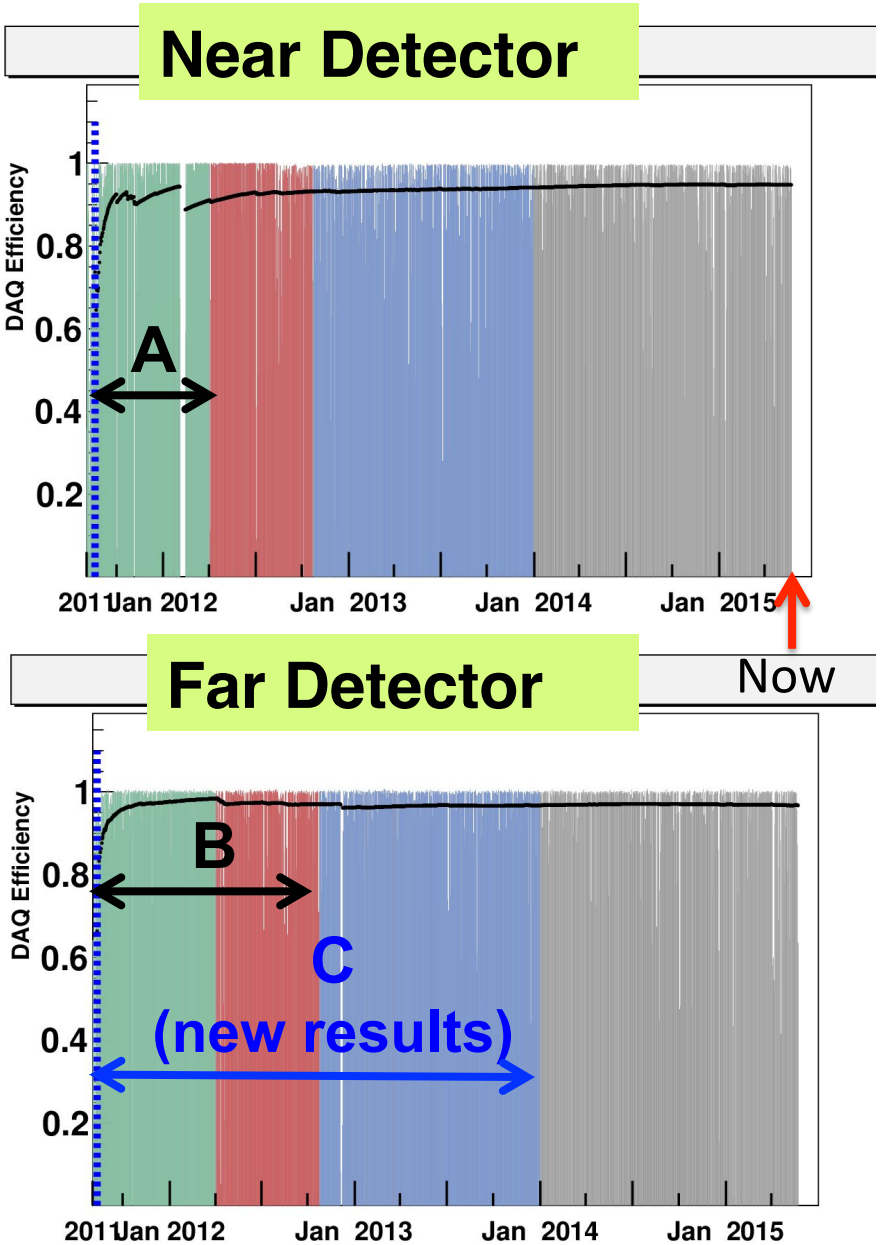
- Data taking began on Aug. 1, 2011 with both near and far detectors.
  (DAQ efficiency : ~95%)

- **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 (~800 days)** : **New result**
  Shape+rate analysis (**θ_{13} and $|\Delta m_{ee}^2|$**)
  [11 Aug, 2011~31 Dec, 2013]

- Total observed reactor neutrino events as of today : **~ 1.5M** (Near), **~ 0.15M** (Far)
  → Absolute reactor neutrino flux measurement in progress
  [reactor anomaly & sterile neutrinos]



New RENO Results

First announced @NDM, June 2015

- ~800 days of data
- New measured-value of θ_{13} from rate-only analysis
- Observation of energy dependent disappearance of reactor neutrinos to measure $|\Delta m_{ee}^2|$ (work in progress)
- Observation of an excess at 5 MeV in reactor neutrino spectrum

Improvements after Neutrino 2014

- Relax Q_{max}/Q_{tot} cut : 0.03 → 0.07

  - allow more accidentals to increase acceptance of signal and minimize any bias to the spectral shape

- More precisely observed spectra of $^{9}Li/^{8}He$ background

  - reduced the $^{9}Li/^{8}He$ background uncertainty based on an increased control sample.

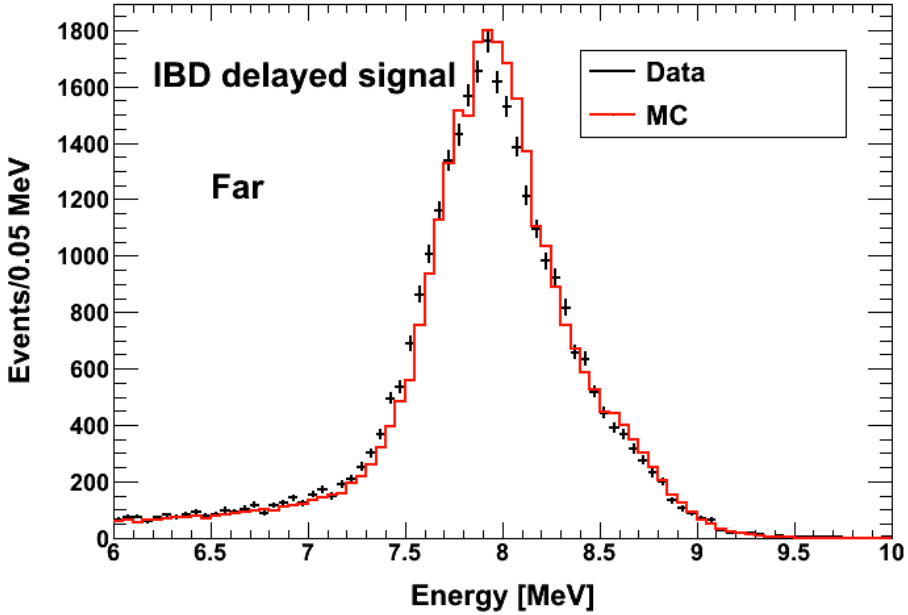
- More accurate energy calibration

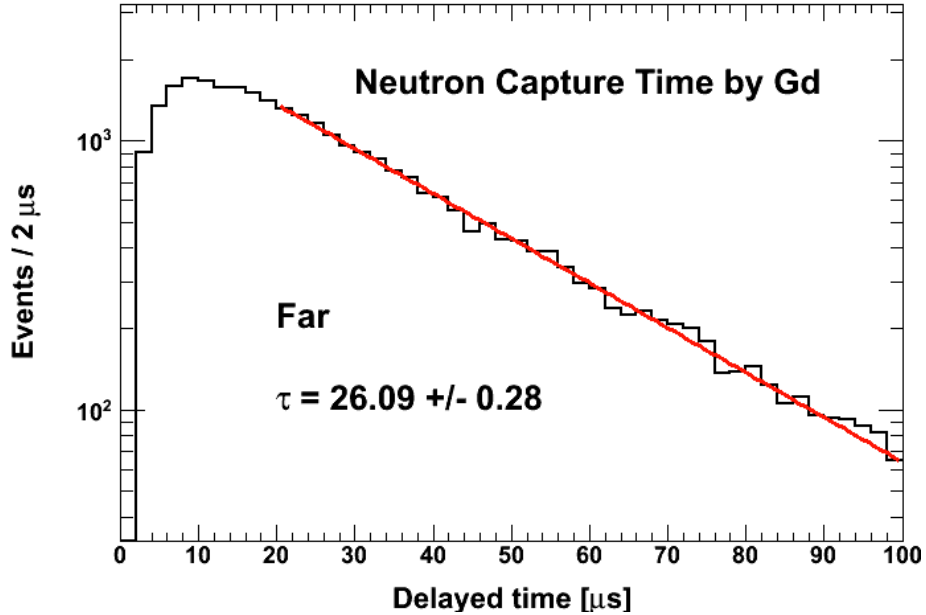
  - best efforts on understanding of non-linear energy response and energy scale uncertainty

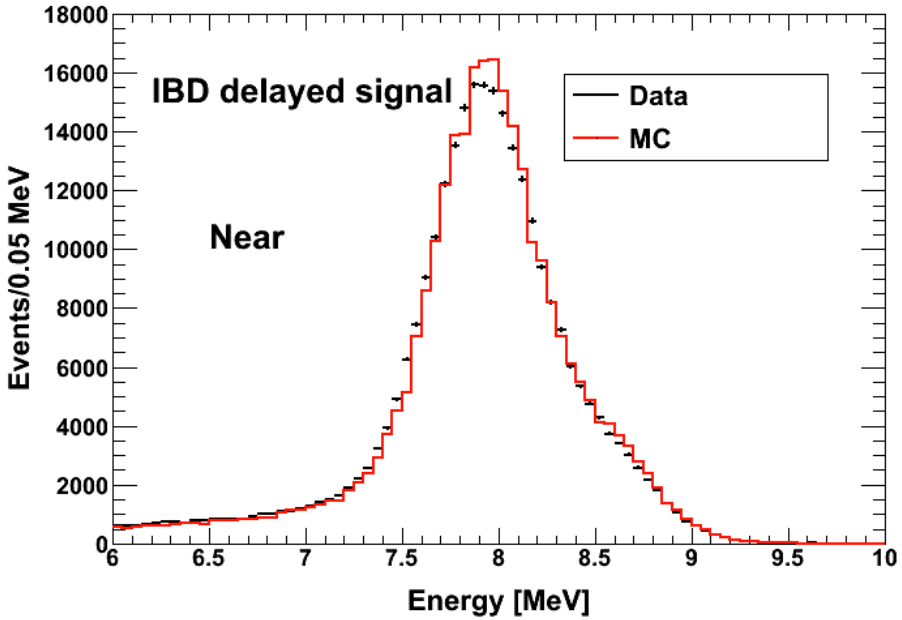
- Elaborate study of systematic uncertainties on a spectral fitter

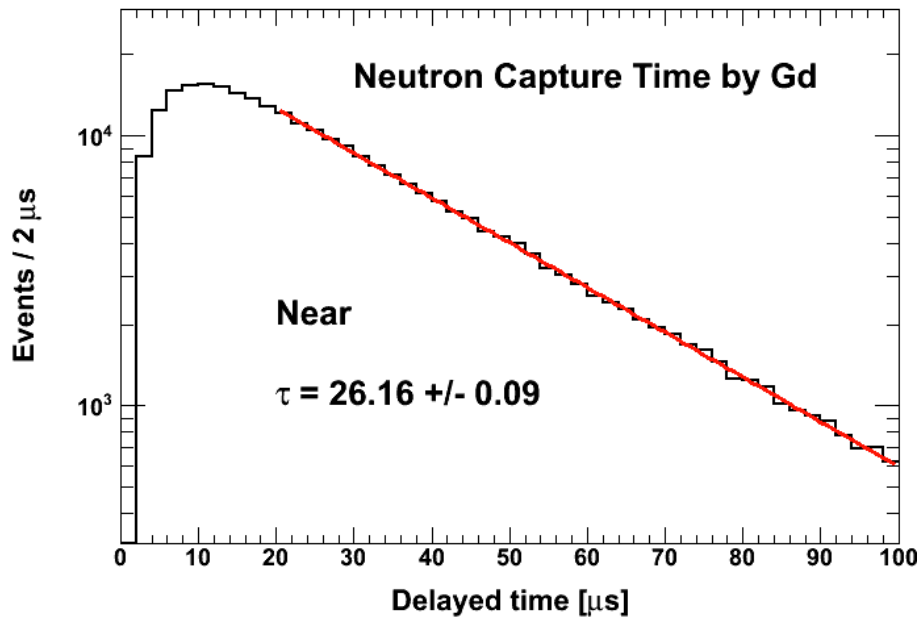
  - estimated systematic errors based on a detailed study of spectral fitter in the measurement of $|\Delta m_{ee}^2|$

Neutron Capture by Gd

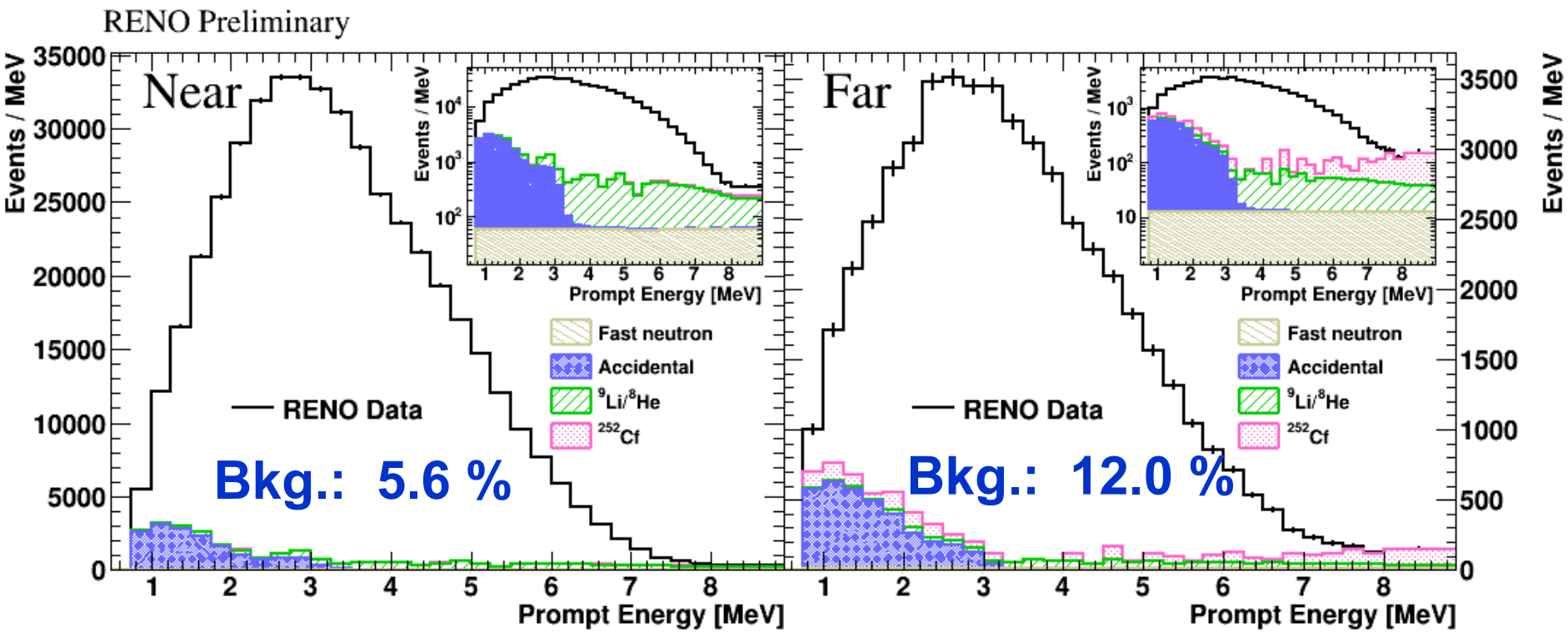








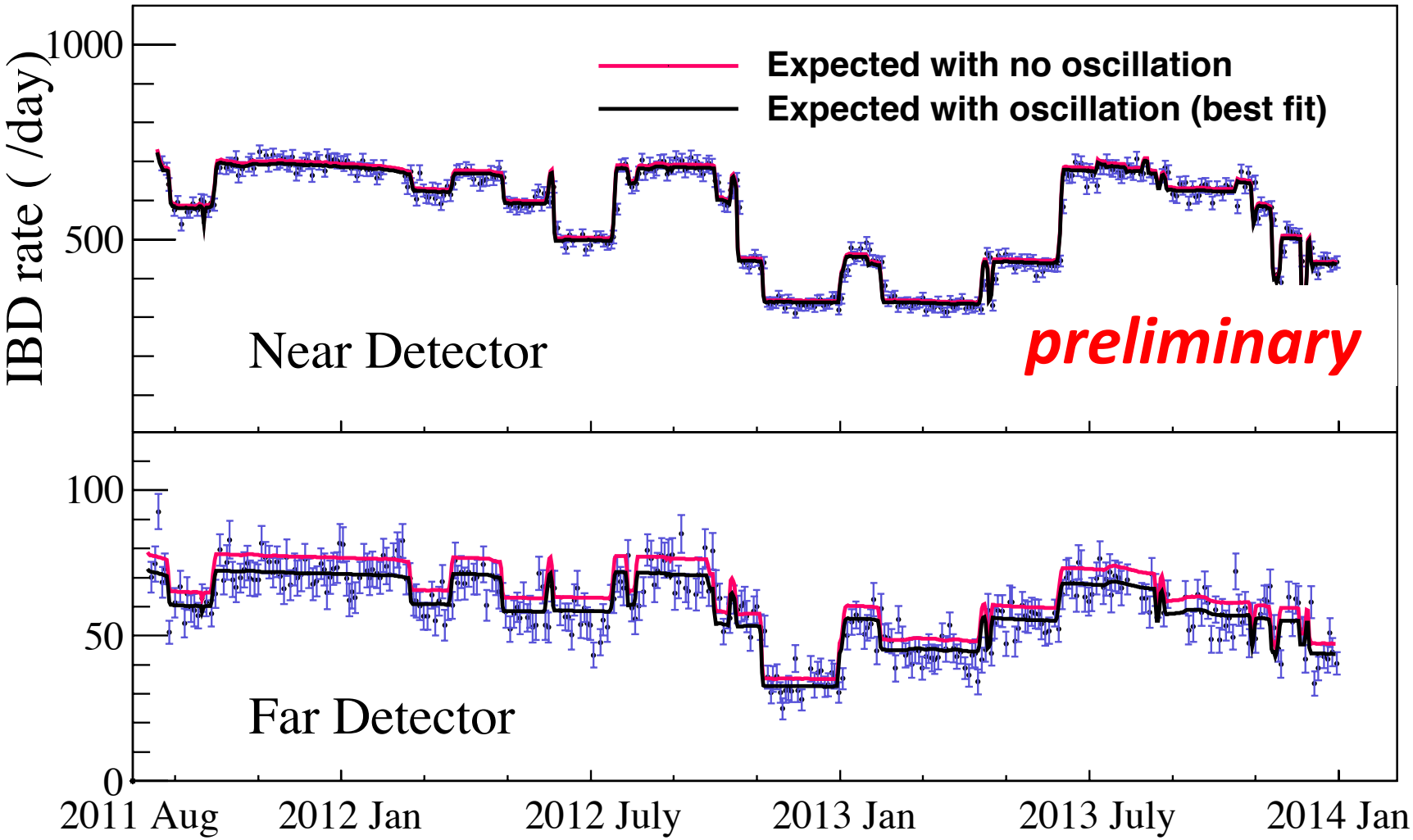
Measured Spectra of IBD Prompt Signal



Near Live time = 761.11 days
# of IBD candidate = 470,787
# of background = 26,375 (5.6 %)

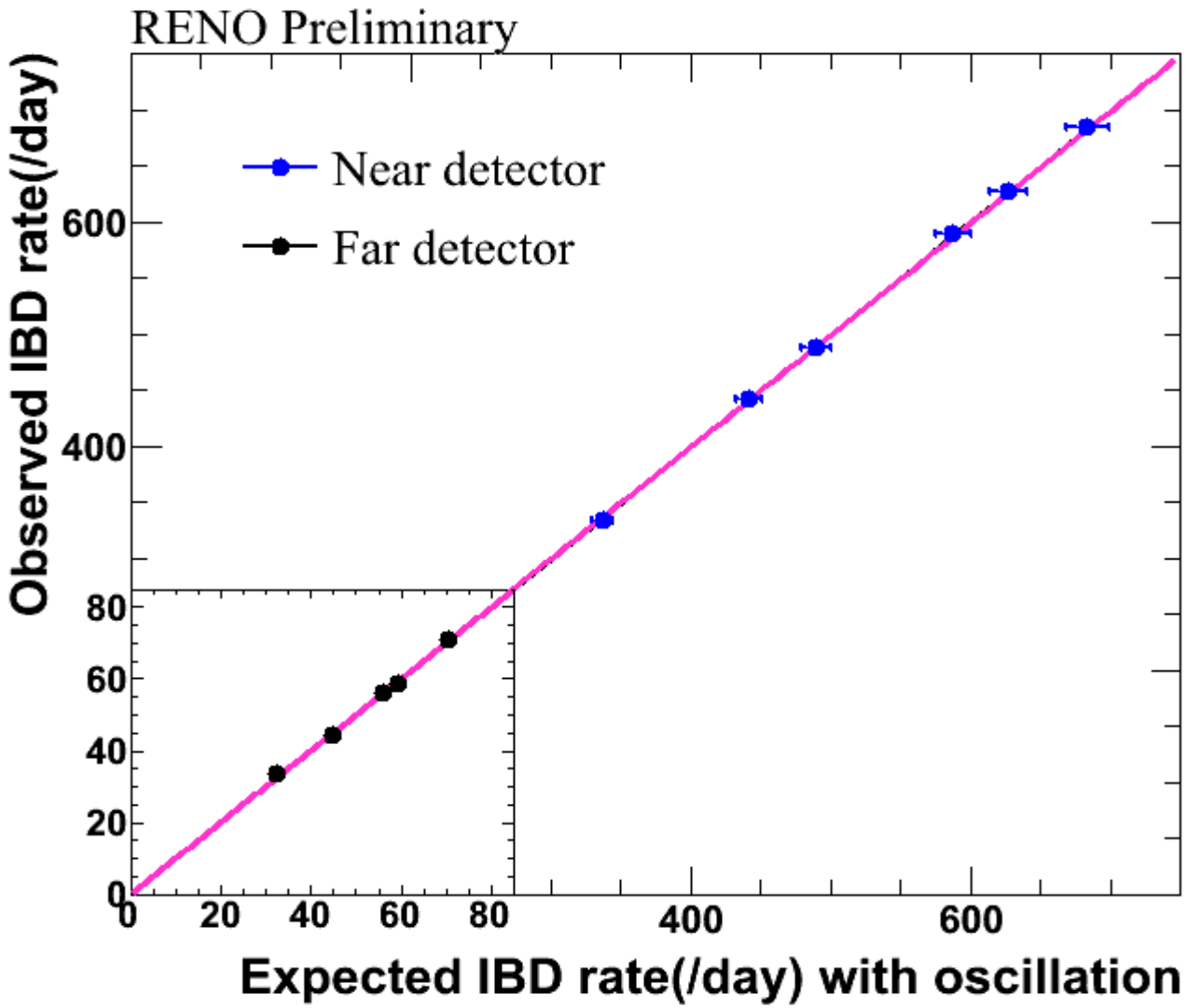
Far Live time = 794.72 days
# of IBD candidate = 52,250
# of background = 6,292 (12.0 %)

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

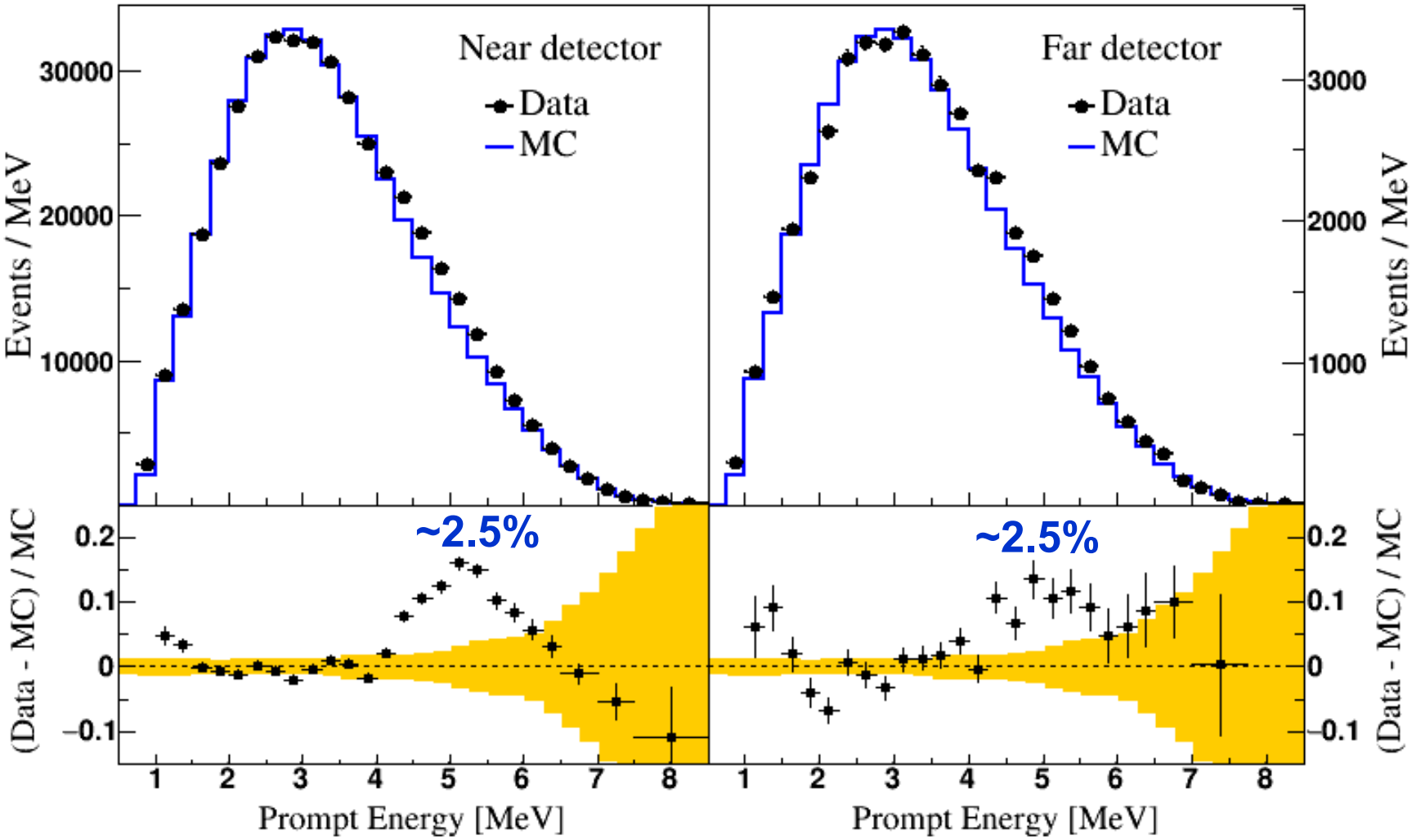
New θ_{13} Measurement by Rate-only Analysis

(Preliminary)

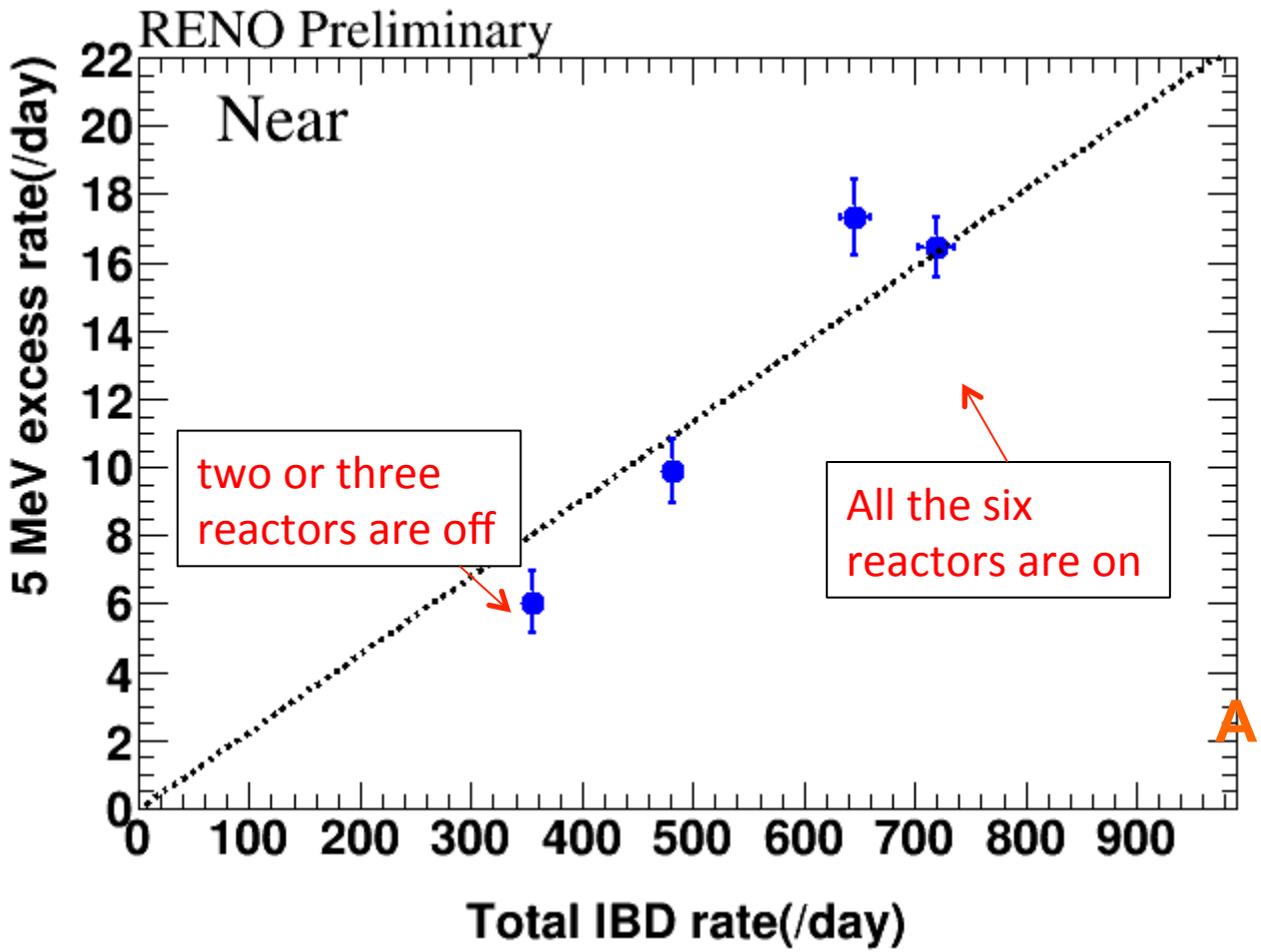
$$\sin^2 2\theta_{13} = 0.087 \pm 0.008(\text{stat.}) \pm 0.008(\text{syst.})$$

Uncertainties sources	Uncertainties (%)	Errors of $\sin^2 2\theta_{13}$ (fraction)
Statistics (near) (far)	0.21 % 0.54 %	**0.0080**
Systematics (near) (far)	0.94% 1.06%	**0.0081**
Reactor	0.9 %	0.0032 (39.5 %)
Detection efficiency	0.2 %	0.0037 (45.7 %)
Backgrounds (near) (far)	0.14 % 0.51 %	0.0070 (86.4 %)

Observation of an excess at 5 MeV



Correlation of 5 MeV Excess with Reactor Power



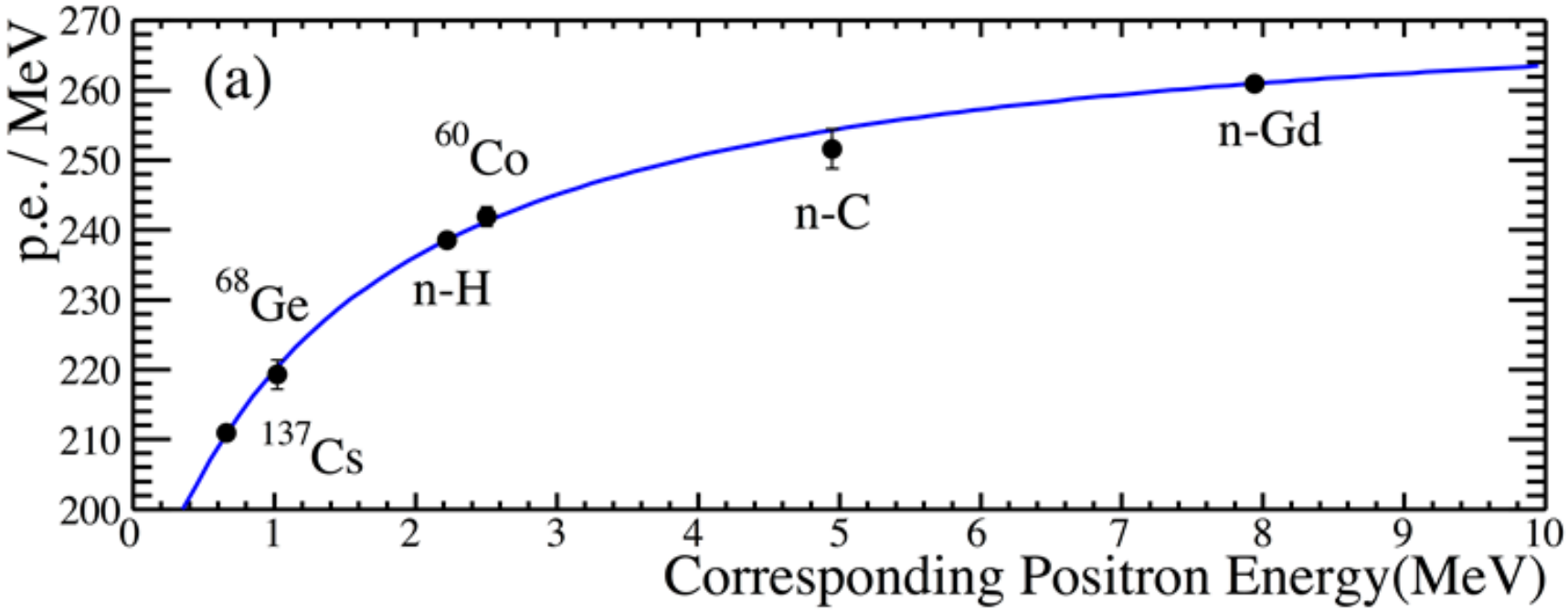
5 MeV excess has a clear correlation with reactor thermal power !

A new reactor neutrino component !!

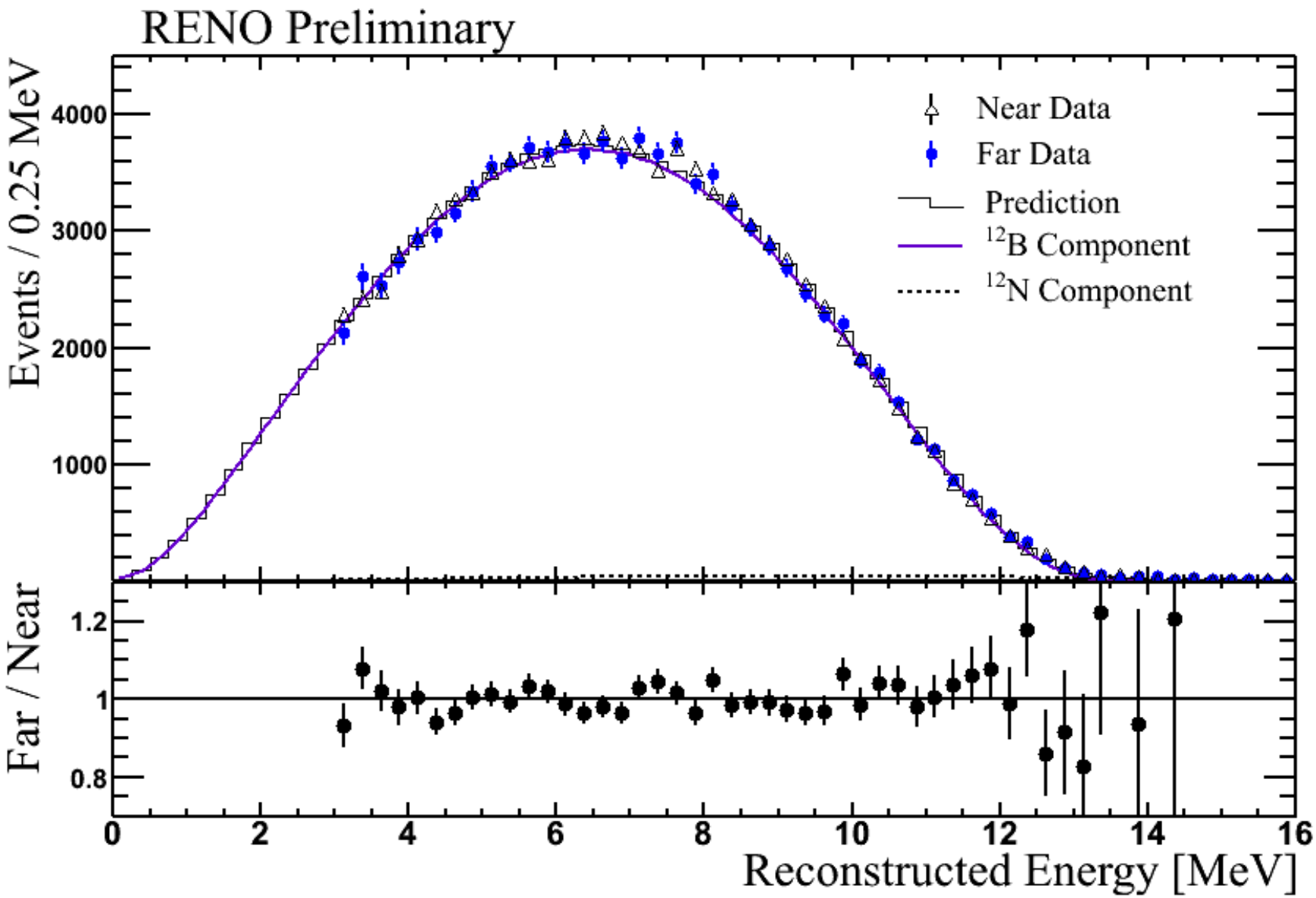
** Recent ab initio calculation [D. Dwyer and T.J. Langford, PRL 114, 012502 (2015)] :

- The excess may be explained by addition of eight isotopes, such as ^{96}Y and ^{92}Rb

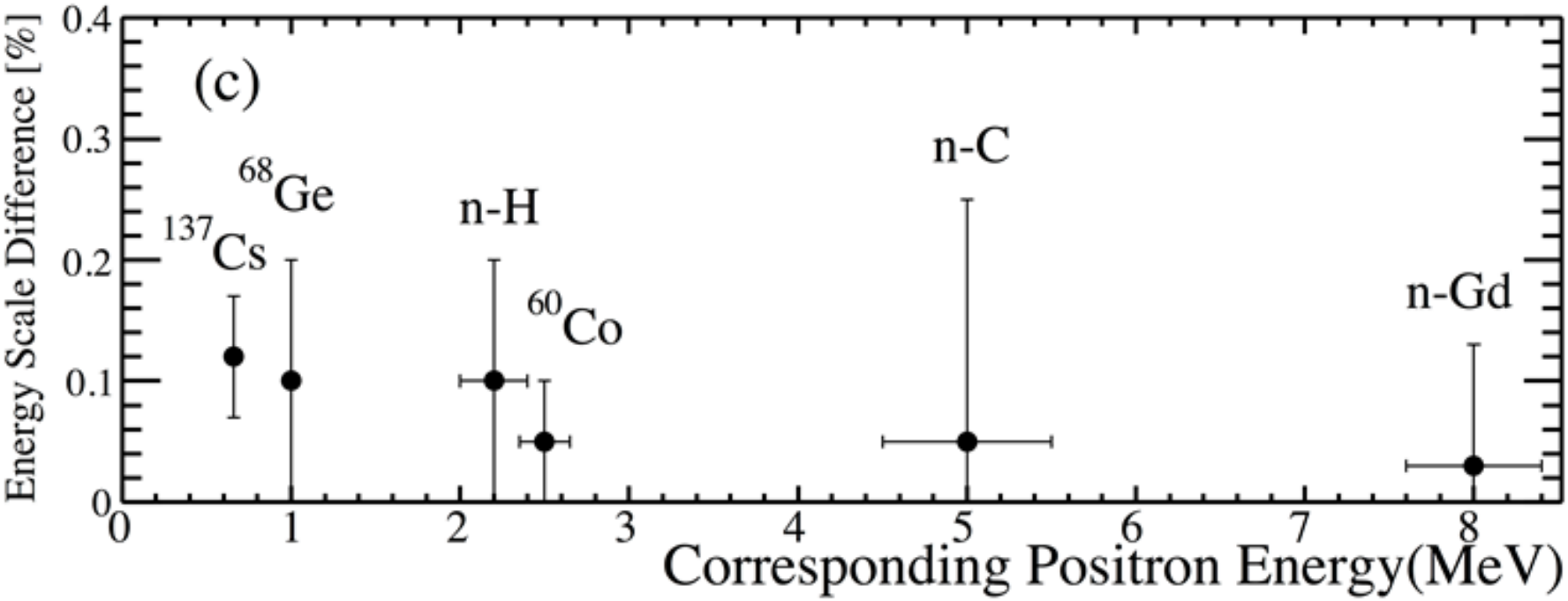
Energy Calibration from γ-ray Sources



^{12}B Energy Spectrum (Near & Far)

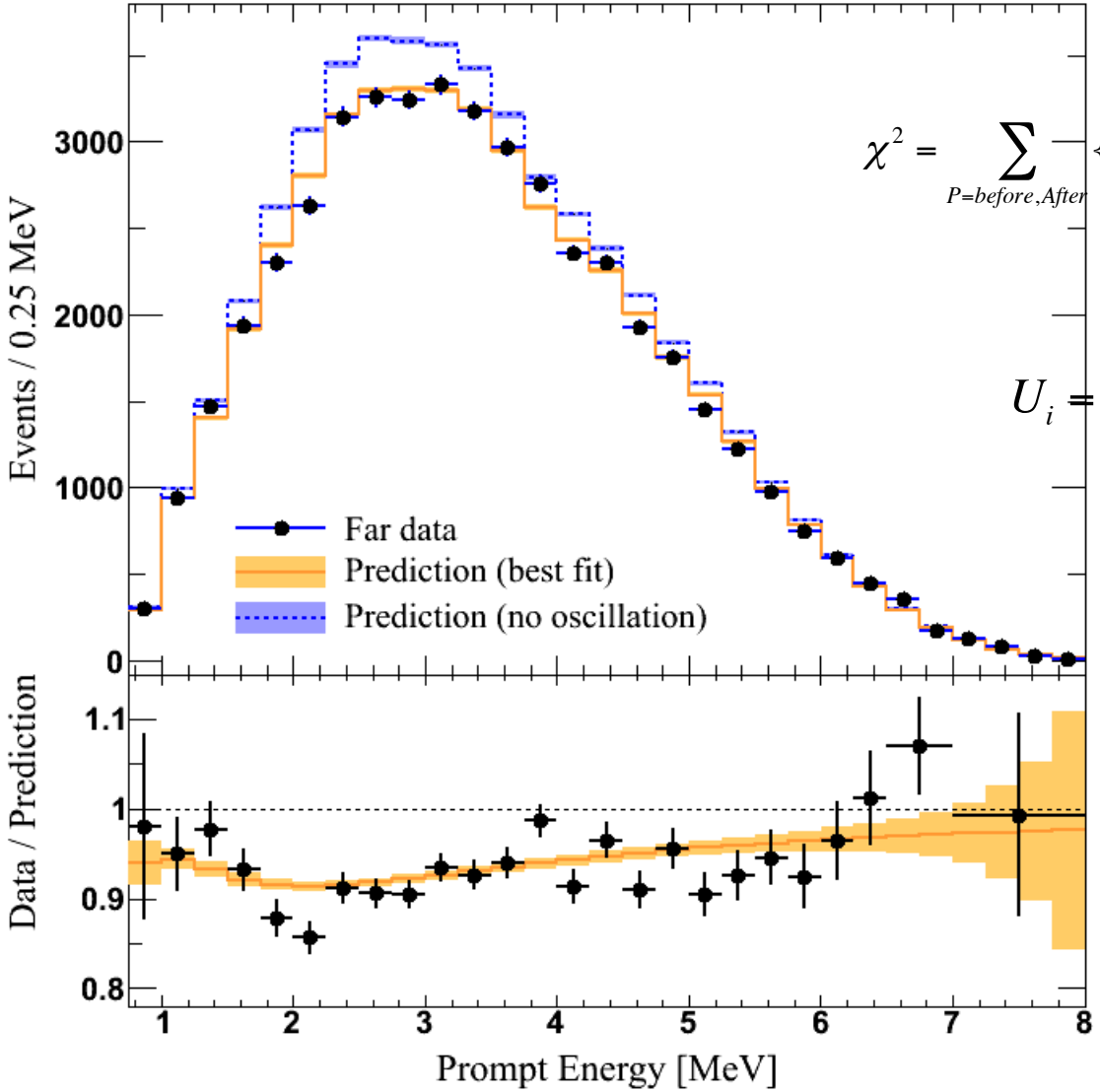


Energy Scale Difference between Near & Far



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

(work in progress)

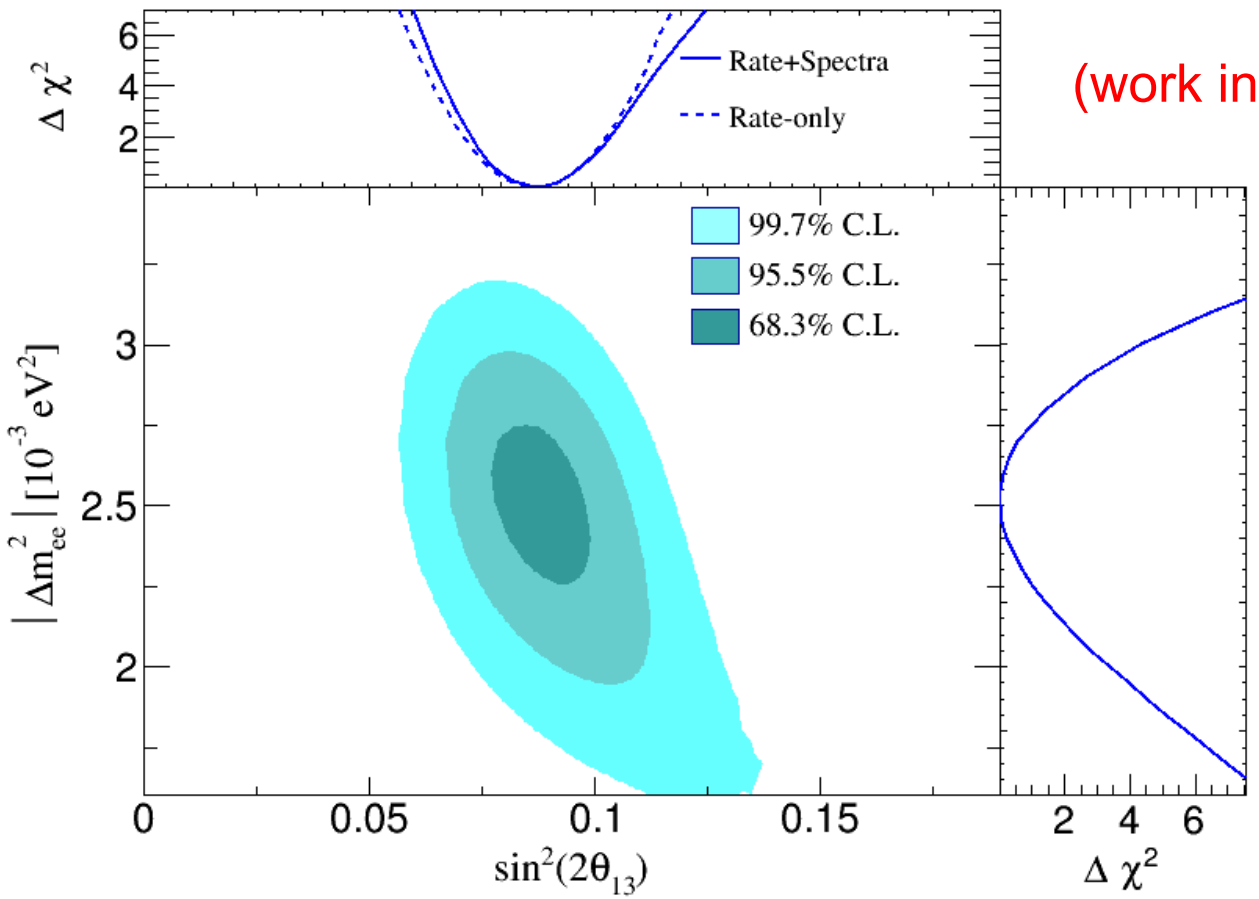


Minimize X^2 Function

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

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

Results from Spectral Fit



(work in progress)

$$\Delta m_{ee}^{2} = [2.52 \pm 0.19(\text{stat}) \pm 0.17(\text{syst})] \times 10^{-3}\ \text{eV}^{2}$$

$$\sin^{2} 2\theta_{13} = 0.088 \pm 0.008(\text{stat}) \pm 0.007(\text{syst})$$

Systematic Errors of θ_{13} & Δm_{ee}^2

(work in progress)

$$\sin^2 2\theta_{13} = 0.088 \pm 0.008(\text{stat}) \pm 0.007(\text{syst})$$

$$\Delta m_{ee}^2 = [2.52 \pm 0.19(\text{stat}) \pm 0.17(\text{syst})] \times 10^{-3}\ \text{eV}^2$$

Uncertainties sources	Uncertainties (%)	Errors of $\sin^2 2\theta_{13}$	Errors of Δm_{ee}^2 (x 10^{-3} eV^2)
Statistics (near) (far)	0.21 % 0.54 %	**0.008**	**0.19**
Total Systematics	0.94 % 1.06 %	**0.007**	**0.17**
Reactor	0.9 %	0.0025 (34.2 %)	-
Detection efficiency	0.2 %	0.0025 (34.2 %)	-
Energy scale diff.	0.15 %*	0.0015 (15.6 %)	0.07
Backgrounds (near) (far)	0.14 % 0.51 %	0.0060 (82.2 %)	0.15

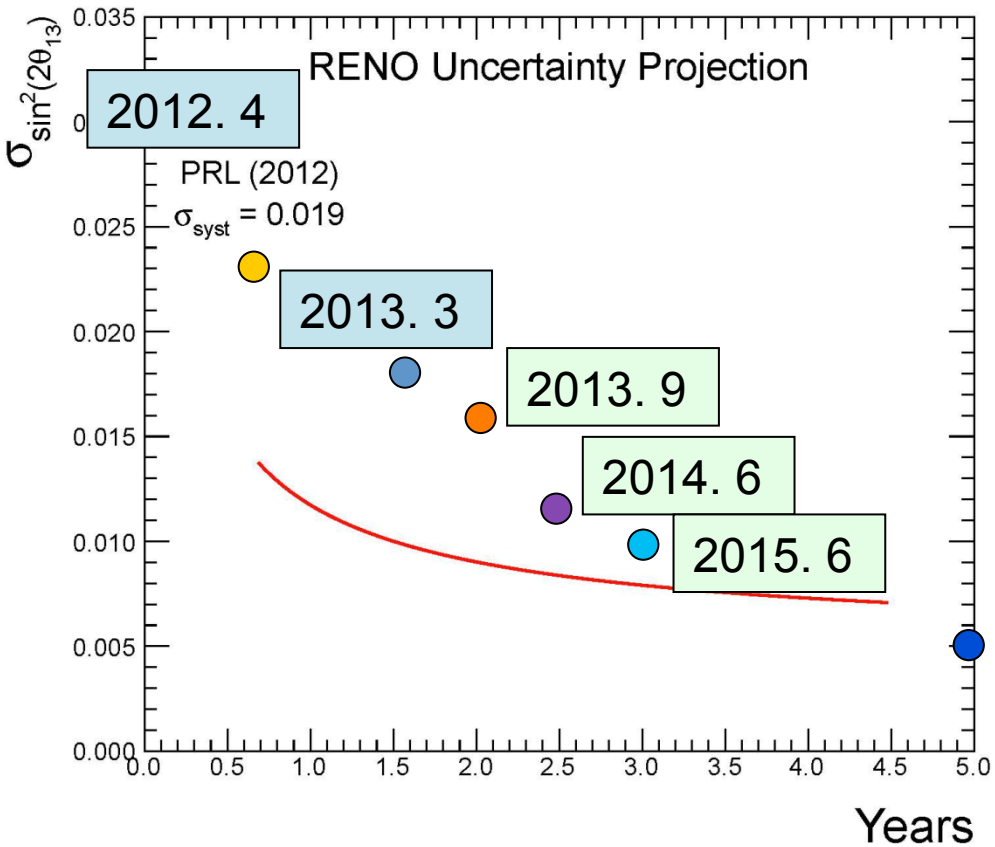
(* tentative)

Projected Sensitivity of θ_{13} & Δm_{ee}^2

NDM 2015 $\sin^2 2\theta_{13} = 0.088 \pm 0.011$ (~800 days)

± 0.005 (5 % precision) (5 years of data)

* Expected precision of $|\Delta m_{ee}^2|$: ~ 0.1×10^{-3} eV^2



(5 % precision)

(sensitivity goal of θ_{13})

Results from n-H IBD sample

Very preliminary
Rate-only result

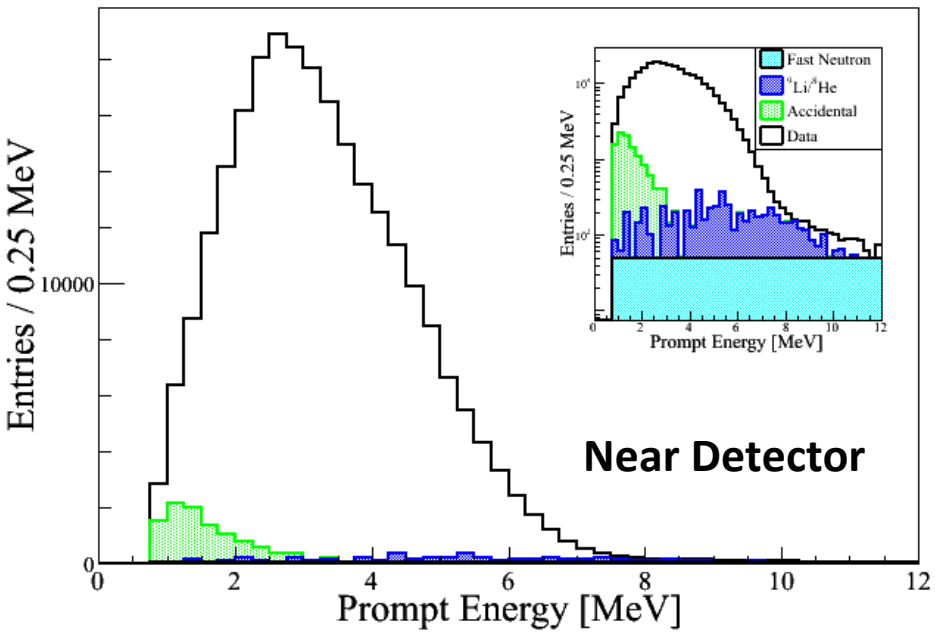
(B data set, ~400 days)

$$\sin^2 2\theta_{13} = 0.103 \pm 0.014(\text{stat.}) \pm 0.014(\text{syst.})$$

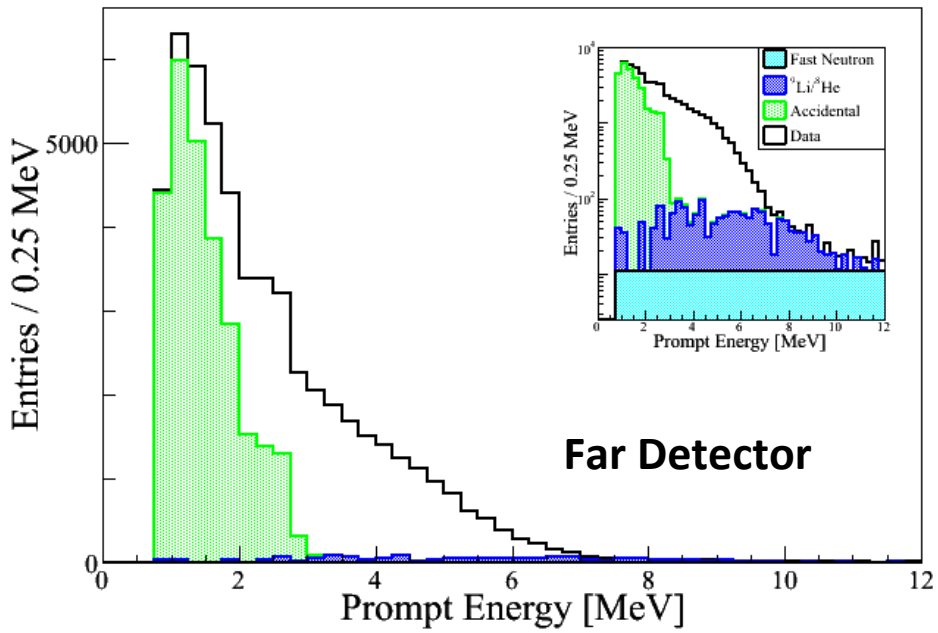
(Neutrino 2014) $\sin^2 2\theta_{13} = 0.095 \pm 0.015(\text{stat.}) \pm 0.025(\text{syst.})$

← *Removed a soft neutron background*
and reduced the uncertainty of the accidental background

preliminary



preliminary



Summary

- Observed an excess at 5 MeV in reactor neutrino spectrum
- New measurement of θ_{13} by rate-only analysis

$$\sin^2 2\theta_{13} = 0.087 \pm 0.008(\text{stat}) \pm 0.008(\text{syst})$$

(preliminary)

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

$$\sin^2 2\theta_{13} = 0.088 \pm 0.008(\text{stat}) \pm 0.007(\text{syst})$$

$$\Delta m_{ee}^2 = [2.52 \pm 0.19(\text{stat}) \pm 0.17(\text{syst})] \times 10^{-3}\ \text{eV}^2$$

(work in progress)

- Measurement of θ_{13} from n-H IBD analysis

$$\sin^2 2\theta_{13} = 0.103 \pm 0.014(\text{stat}) \pm 0.014(\text{syst})$$

(preliminary)

- $\sin(2\theta_{13})$ to 5% accuracy
  $|\Delta m_{ee}^2|$ to 0.1×10^{-3} eV^2 accuracy within 3 years

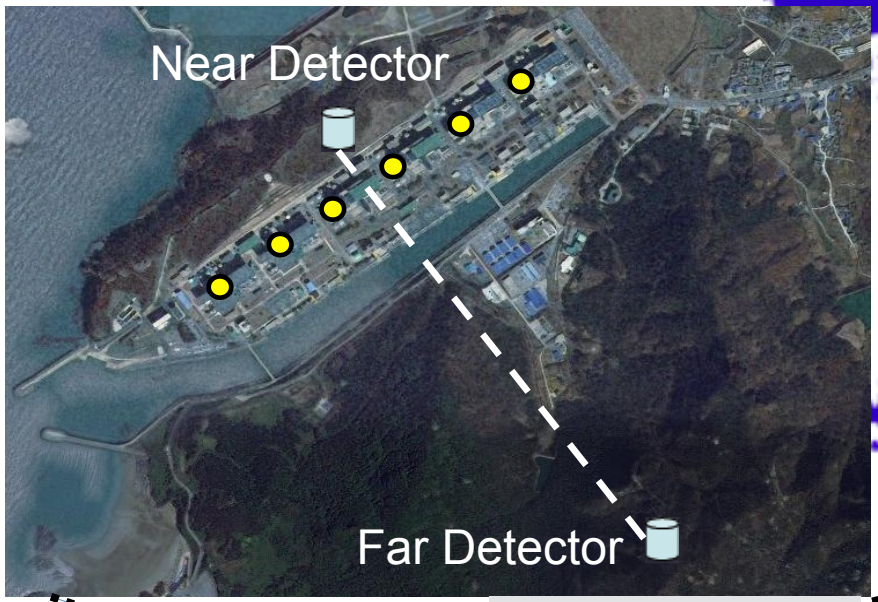
Overview of Future RENO-50

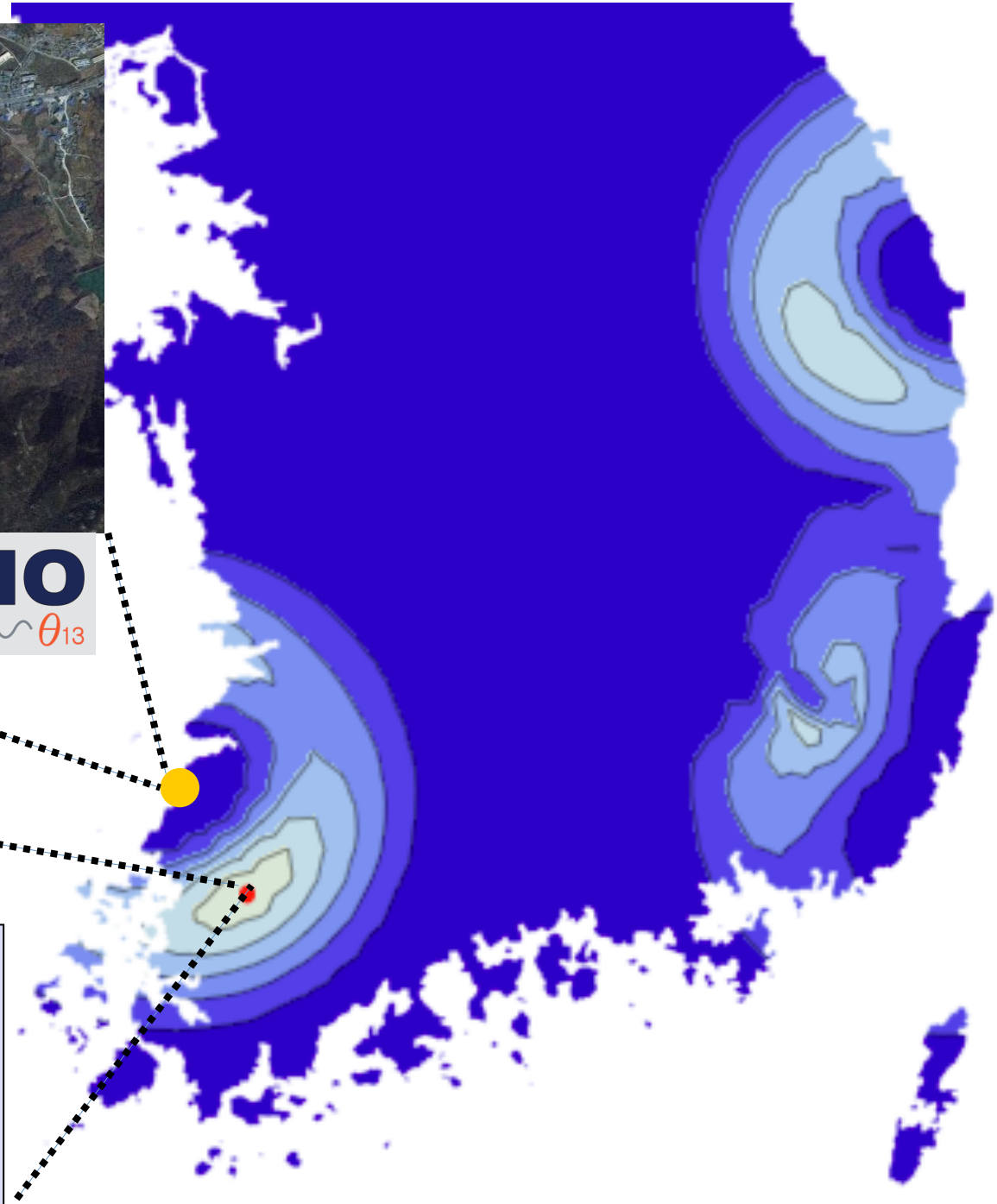
- **RENO-50** : An underground detector consisting of **18 kton** ultra-low-radioactivity liquid scintillator & **15,000 20" PMTs, at 50 km** away from the Hanbit(Yonggwang) nuclear power plant

- **Goals** : - Determination of neutrino mass hierarchy
- High-precision measurement of θ_{12}, Δm^2_{21} and Δm^2_{31}
- Study neutrinos from reactors, the Sun, the Earth, Supernova, and any possible stellar objects

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

- **Schedule** : 2015 ~ 2020 : Facility and detector construction
2021 ~ : Operation and experiment





RENO

ν θ_{13}

RENO-50 Site

18 kton LS Detector
~47 km from YG reactors

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

Physics Goals with RENO-50

- Determination of neutrino mass hierarchy

  - 3 σ sensitivity from 5 years of data

- Precise measurement of θ_{12}, Δm^2_{21} and Δm^2_{32}

$$\frac{\delta \sin^2\theta_{12}}{\sin^2\theta_{12}} < 1.0\%(1\sigma) \quad (\leftarrow 5.4\%) \qquad \frac{\delta \Delta m^2{}_{21}}{\Delta m^2{}_{21}} < 1.0\%(1\sigma) \quad (\leftarrow 2.4\%) \qquad \frac{\delta \Delta m^2{}_{32}}{\Delta m^2{}_{32}} < 1.0\%(1\sigma) \quad (\leftarrow 2.8\%)$$

- Neutrino burst from a Supernova in our Galaxy

  - ~5,600 events (@8 kpc) (* NC tag from 15 MeV deexcitation γ)

- Geo-neutrinos : ~ 1,000 geo-neutrinos for 5 years

  - Study the heat generation mechanism inside the Earth

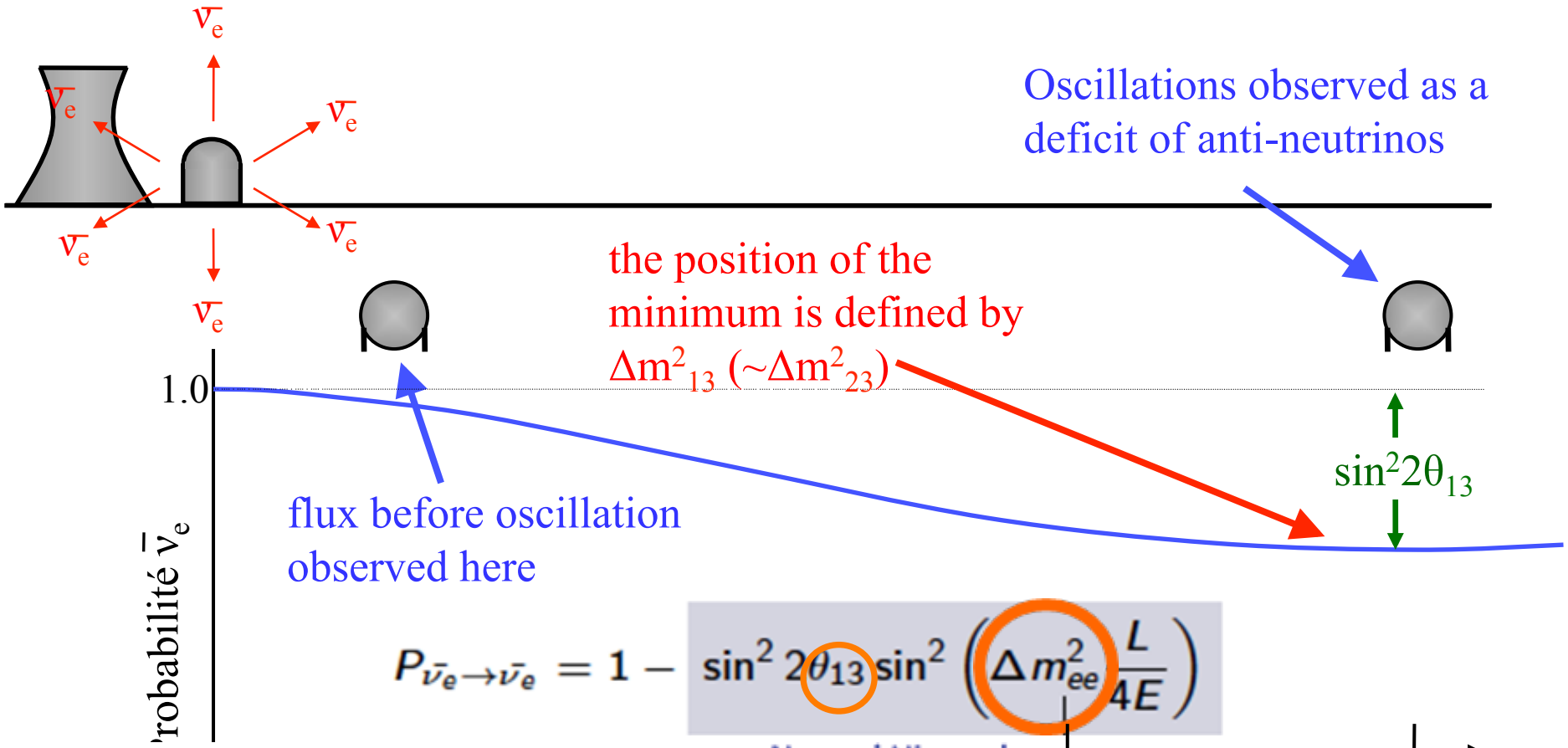
- Solar neutrinos : with ultra low radioacitivity

  - MSW effect on neutrino oscillation and solar models

- Detection of J-PARC beam : ~200 events/year

Thank you very much
for your attention !

Reactor Neutrino Oscillations



$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \sin^2 2\theta_{13} \sin^2\left(\Delta m^2_{ee} \frac{L}{4E}\right)$$

+: Normal Hierarchy
−: Inverted Hierarchy

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

cos↑2 θ↓12 |Δm2↓21↑|

$$\sin^2(\Delta m^2_{ee} \tfrac{L}{4E}) \equiv \cos^2\theta_{12} \sin^2(\Delta m^2_{31} \tfrac{L}{4E}) + \sin^2\theta_{12} \sin^2(\Delta m^2_{32} \tfrac{L}{4E})$$

Why n-H IBD Analysis?

Motivation:

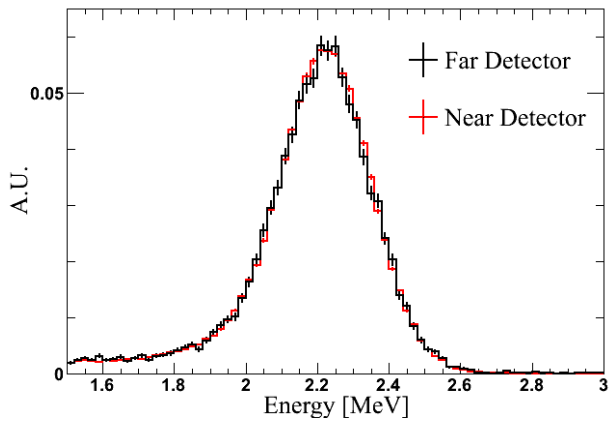
1. Independent measurement of θ_{13} value.
2. Consistency and systematic check on reactor neutrinos.

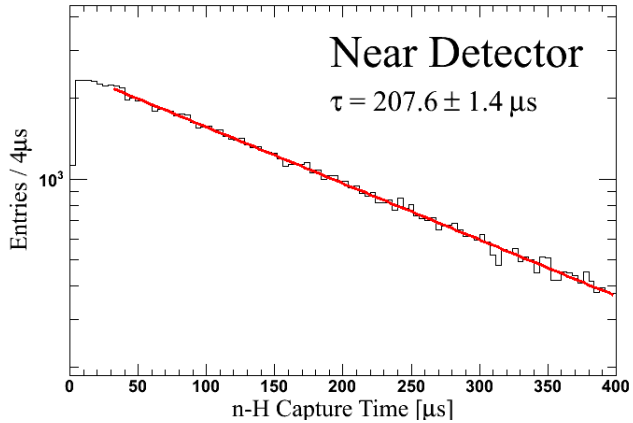
* RENO's low accidental background makes it possible to perform n-H analysis.

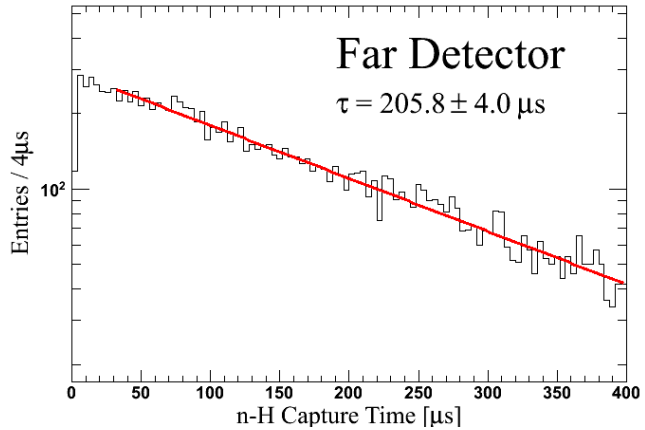
  -- low radioactivity PMT
  -- successful purification of LS and detector materials.

IBD Sample with n-H

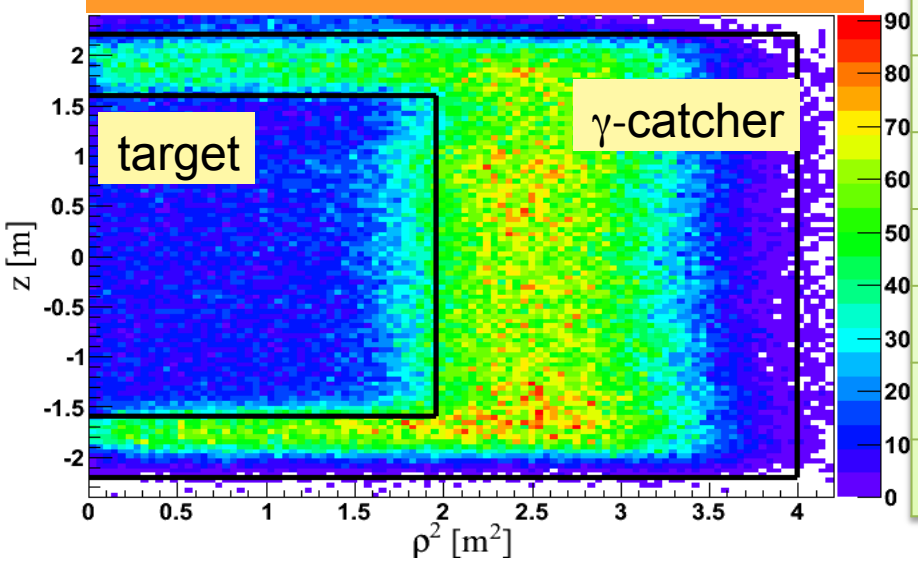
preliminary







n-H IBD Event Vertex Distribution



	Near	Far
Live time(day)	379.663	384.473
IBD Candidate	249,799	54,277
IBD(/day)	619.916	67.823
Accidental (/day)	25.16±0.42	68.90±0.35
Fast Neutron(/day)	5.62±0.30	1.30±0.08
LiHe(/day)	9.87±1.48	3.19±0.37

Expected Energy Dependent Oscillation

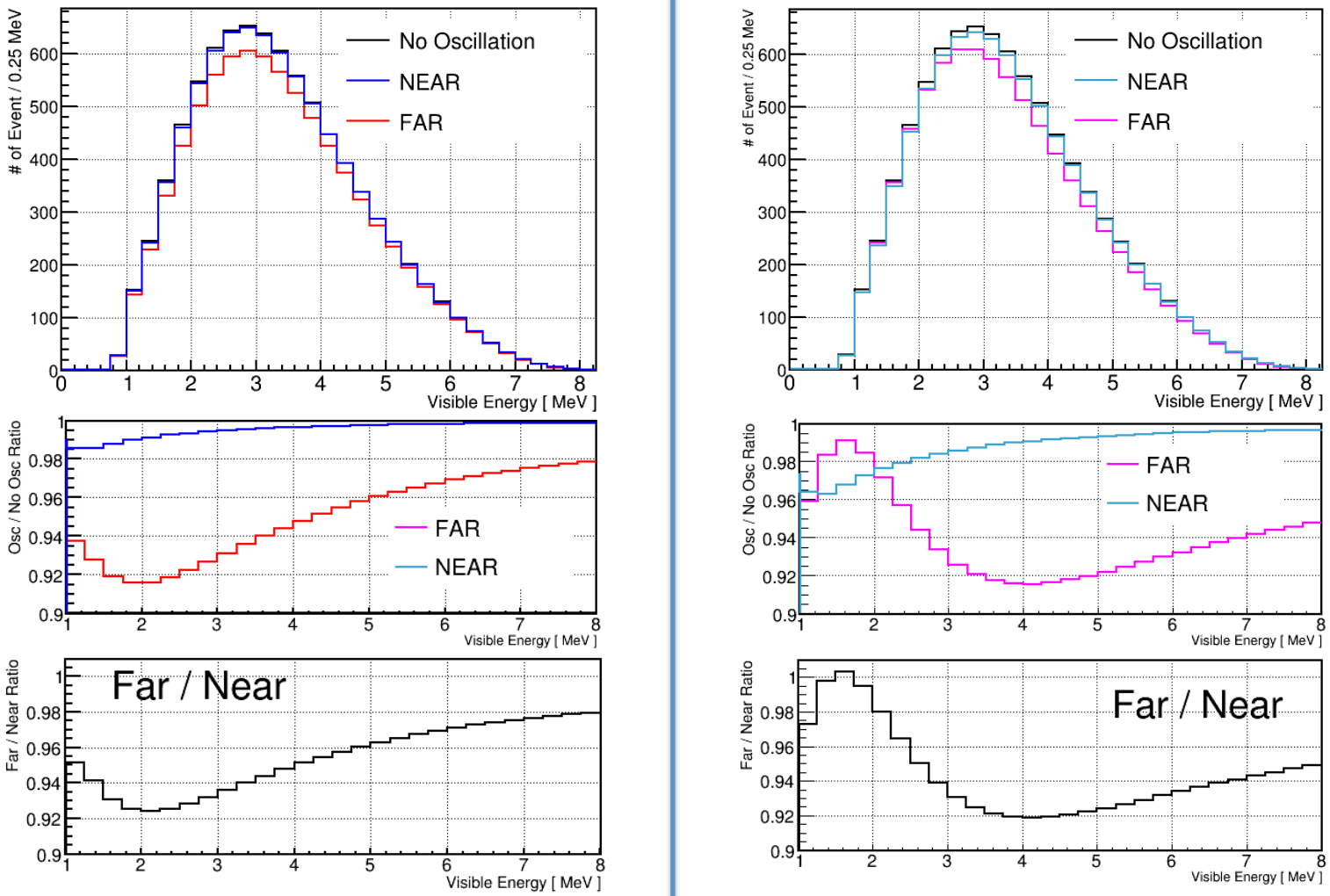
$$\left|\Delta m_{ee}^2\right| = 2.5\times10^{-3}\,eV^2$$

$$\left|\Delta m_{ee}^2\right| = 4.3\times10^{-3}\,eV^2$$

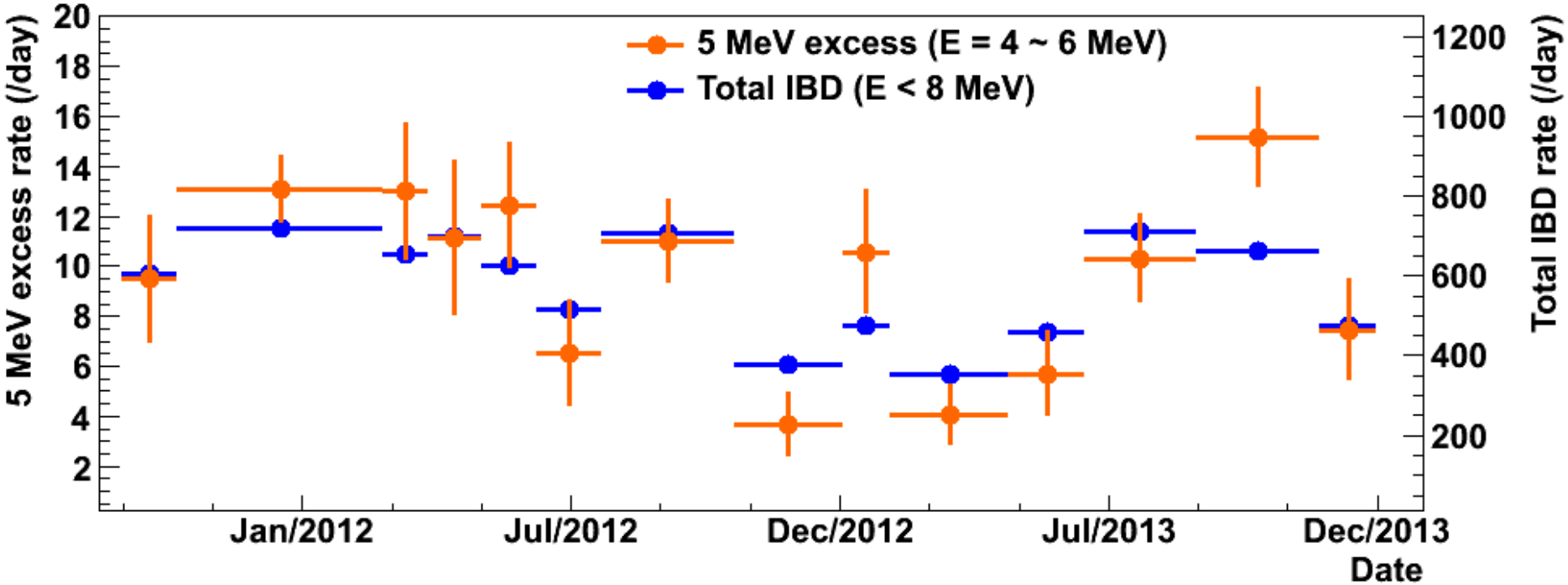
Expected oscillated spectra

Ratio of osc, / no osc.

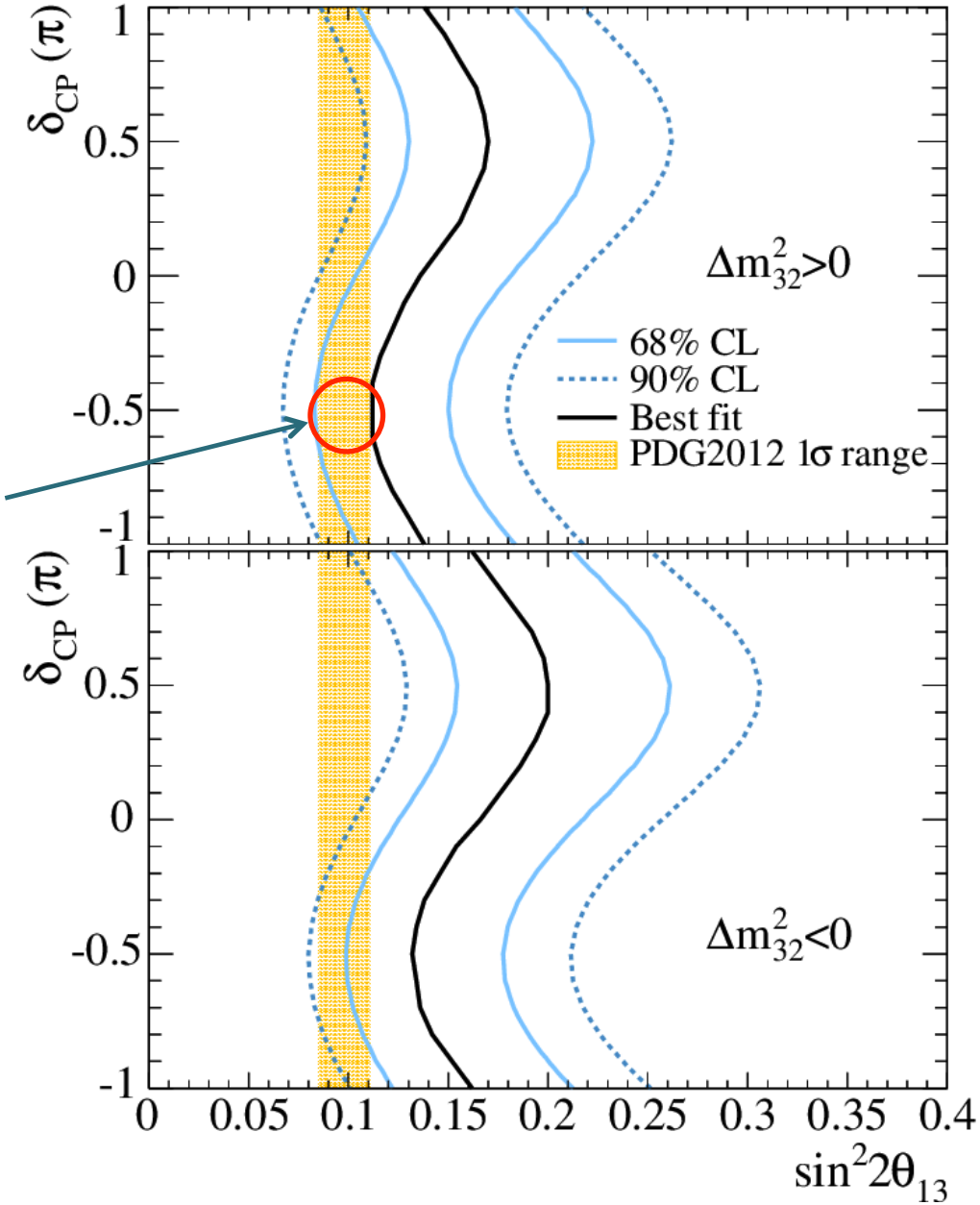
Ratio of Far / Near



Correlation of 5 MeV Excess with Reactor Power



θ_{13} from Reactor and Accelerator Experiments



First hint of δ_{CP} combining Reactor and Accelerator data

Best overlap is for Normal hierarchy & $\delta_{CP} = -\pi/2$

Is Nature very kind to us?
Are we very lucky?
Is CP violated maximally?

Strong motivation for anti-neutrino run and precise measurement of θ_{13}

(T2K: PRL 112, 061802, 2014)