Recent Results from RENO & Prospects with RENO-50

Soo-Bong Kim (KNRC, Seoul National University)

"NuSTEC School 2015"

Okayama University, Japan, Nov. 8-14, 2015"

NuSTEC
NuSTEC Training in Neutrino-Nucleus Scattering Physics
Nov.8-14, 2015, Okayama, Japan

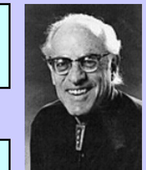
VERITAS LUX MEA

KNRC
Korea Neutrino Research Center

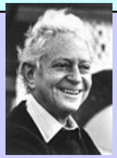
Summary of Developments in Neutrino Physics

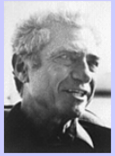
- 1930: Introduction of neutrino as an undetectable, neutral particle by Pauli

- 1956: Discovery of neutrino by Reines (1995 Nobel prize)



- 1962: Discovery of muon neutrino by Lederman et al. (1988 Nobel prize)





- 1967~1985: Detection of solar neutrinos by Davis (2002 Nobel prize)

- 1987: Detection of neutrino burst from Supernova (2002 Nobel prize)

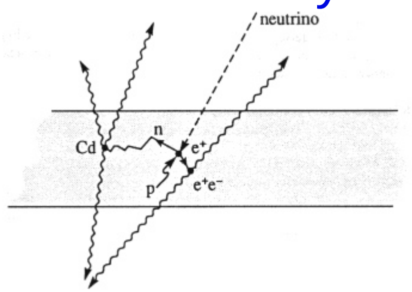
- 1998: Discovery of neutrino oscillation by Super-Kamiokande
(confirmed by accelerator neutrino beam at K2K in 2003) (2015 Nobel prize)

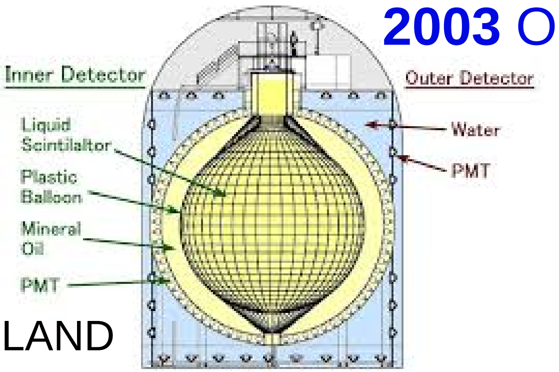

- 2001: Discovery of solar neutrino oscillation by SNO (2015 Nobel prize)
(confirmed by reactor neutrino oscillation at KamLAND in 2003)

- 2012: Discovery of reactor neutrino oscillation due to θ_{13} by Daya Bay and RENO

Neutrino Physics with Reactor

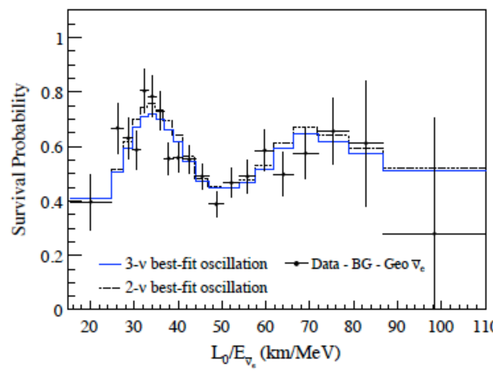
1956 Discovery of (anti)neutrino

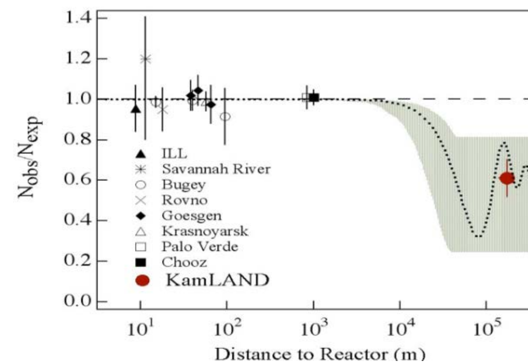




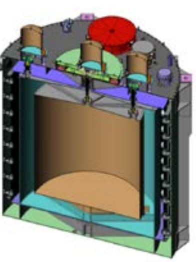
KamLAND

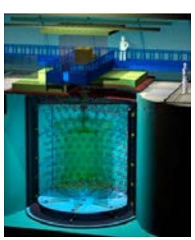
2003 Observation of reactor neutrino oscillation (θ_{12} & Δm_{21}^2)

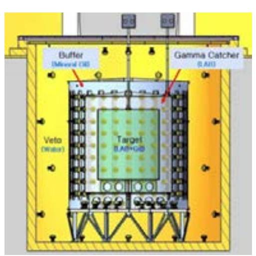


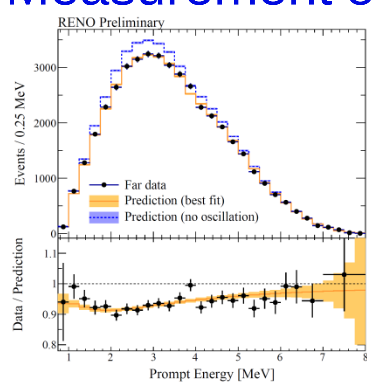


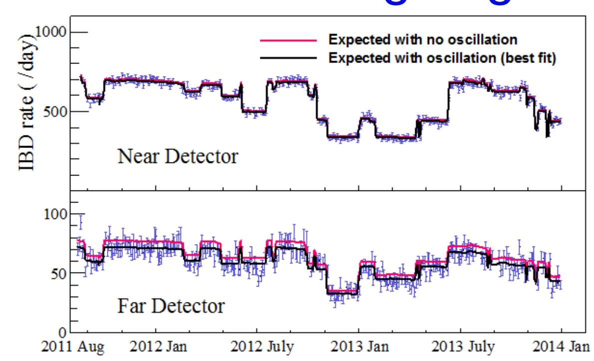
2012 Measurement of the smallest mixing angle θ_{13}



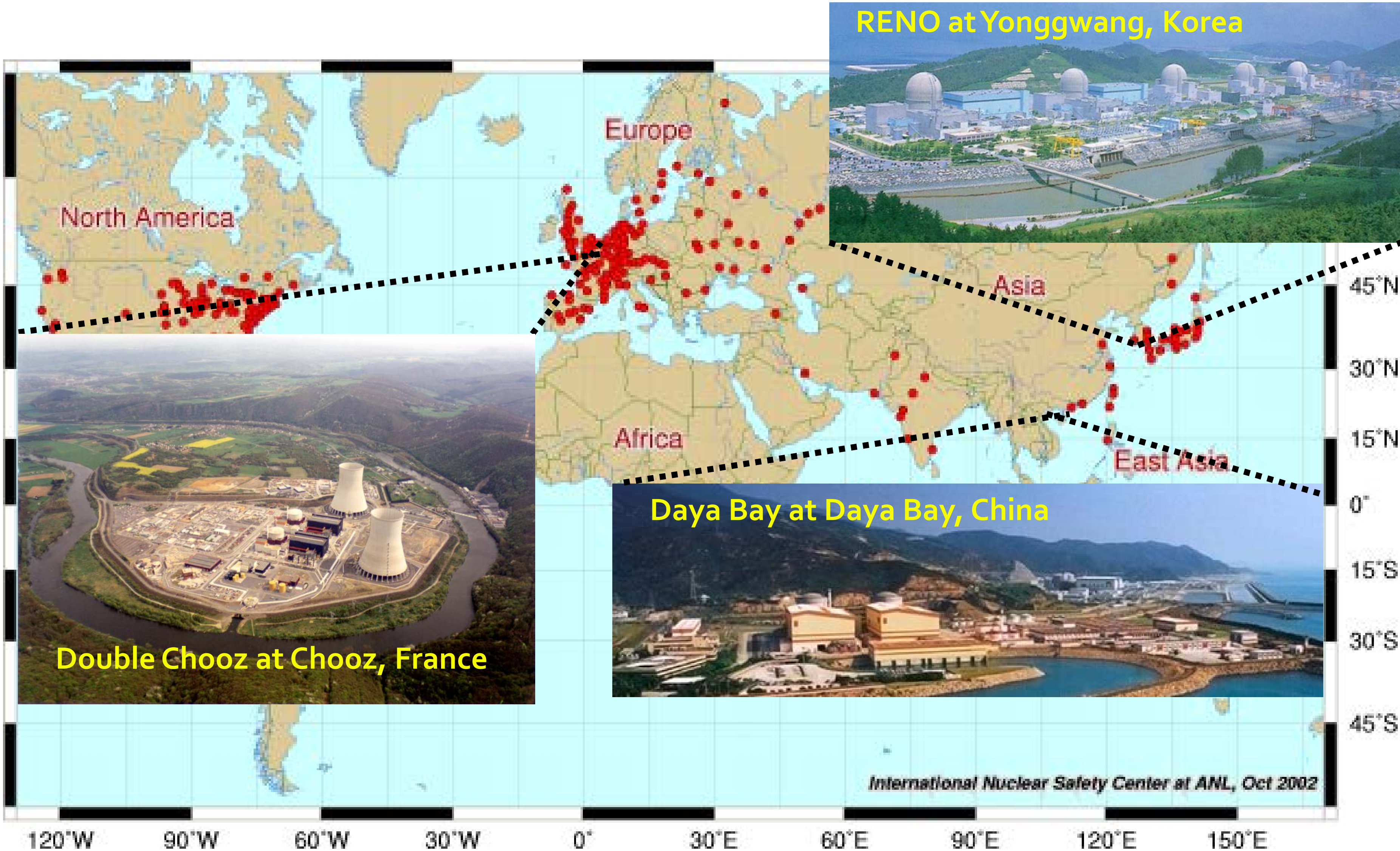




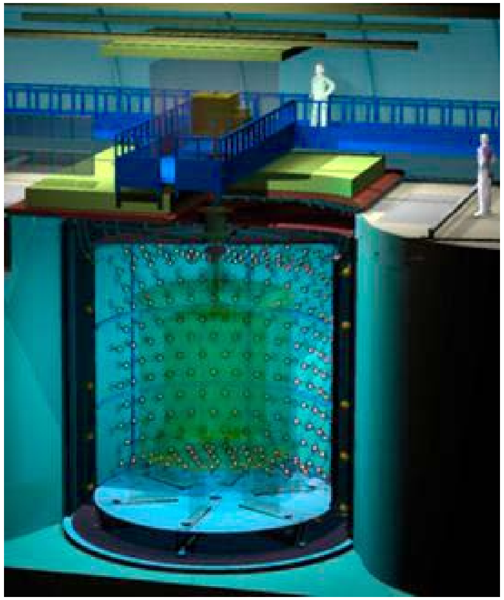


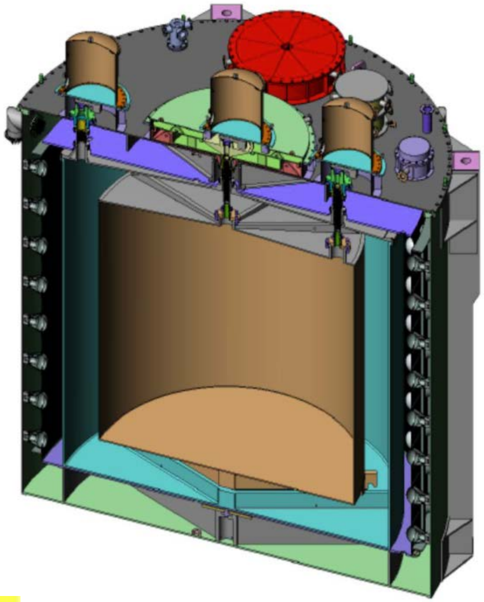


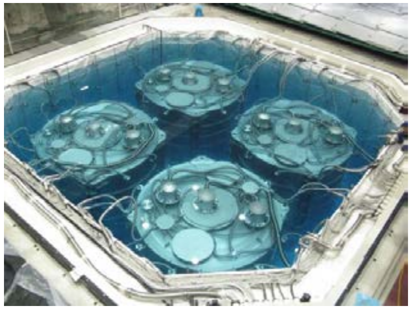
Reactor θ_{13} Experiments

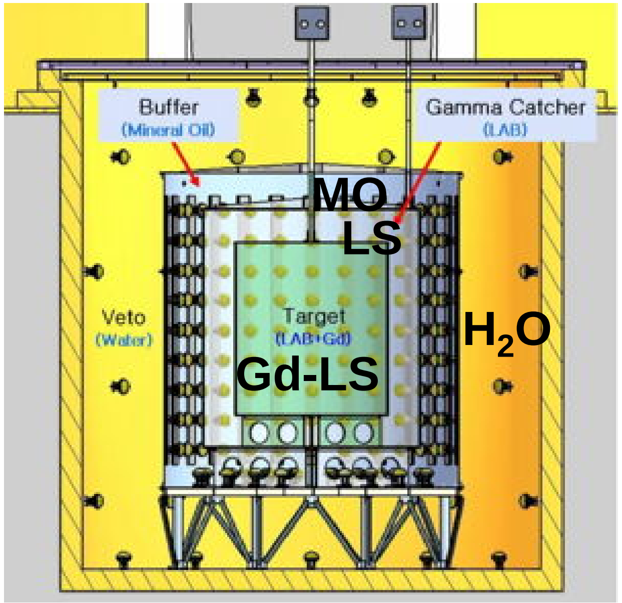


θ_{13} Reactor Neutrino Detectors



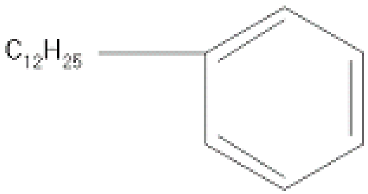






Detection of Reactor Antineutrinos

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



Linear Alkyl Benzene (LAB)

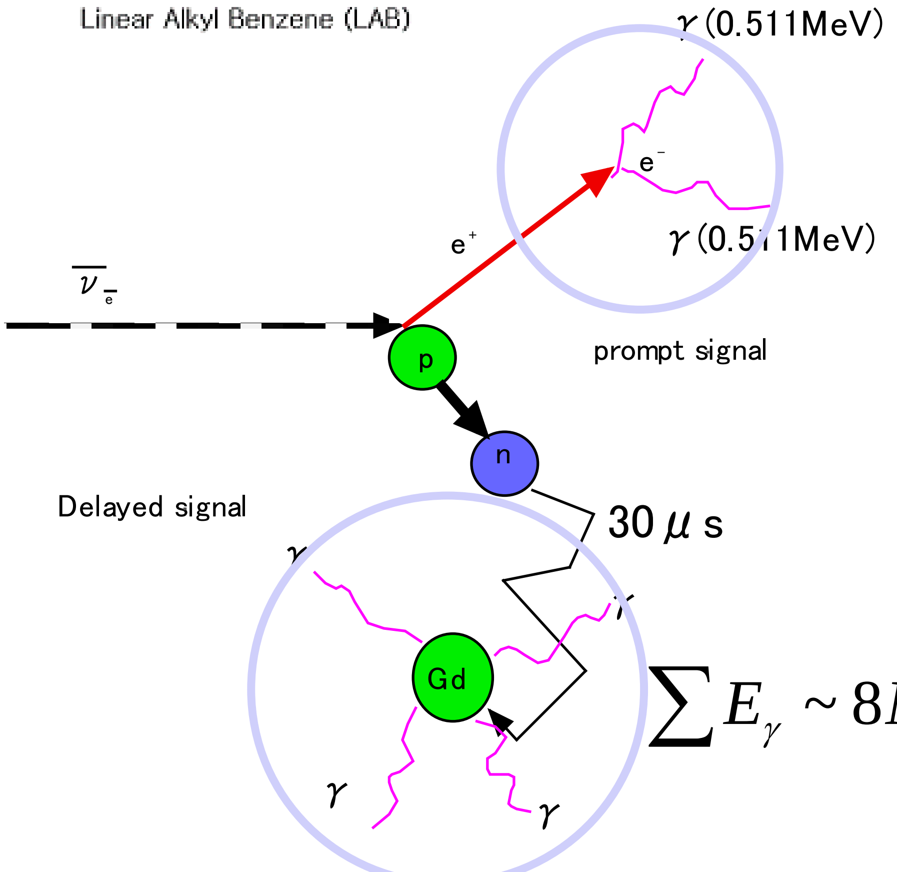
(prompt signal)

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

(delayed signal)

~180 μs: + p → D + γ (2.2 MeV)

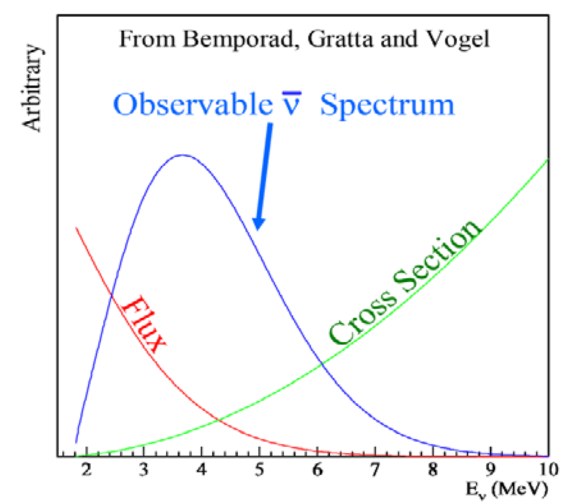
~28 μs (0.1% Gd): + Gd → Gd + γ's (8 MeV)



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

- **Neutrino energy measurement**

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



RENO Collaboration

Reactor Experiment for Neutrino Oscillation

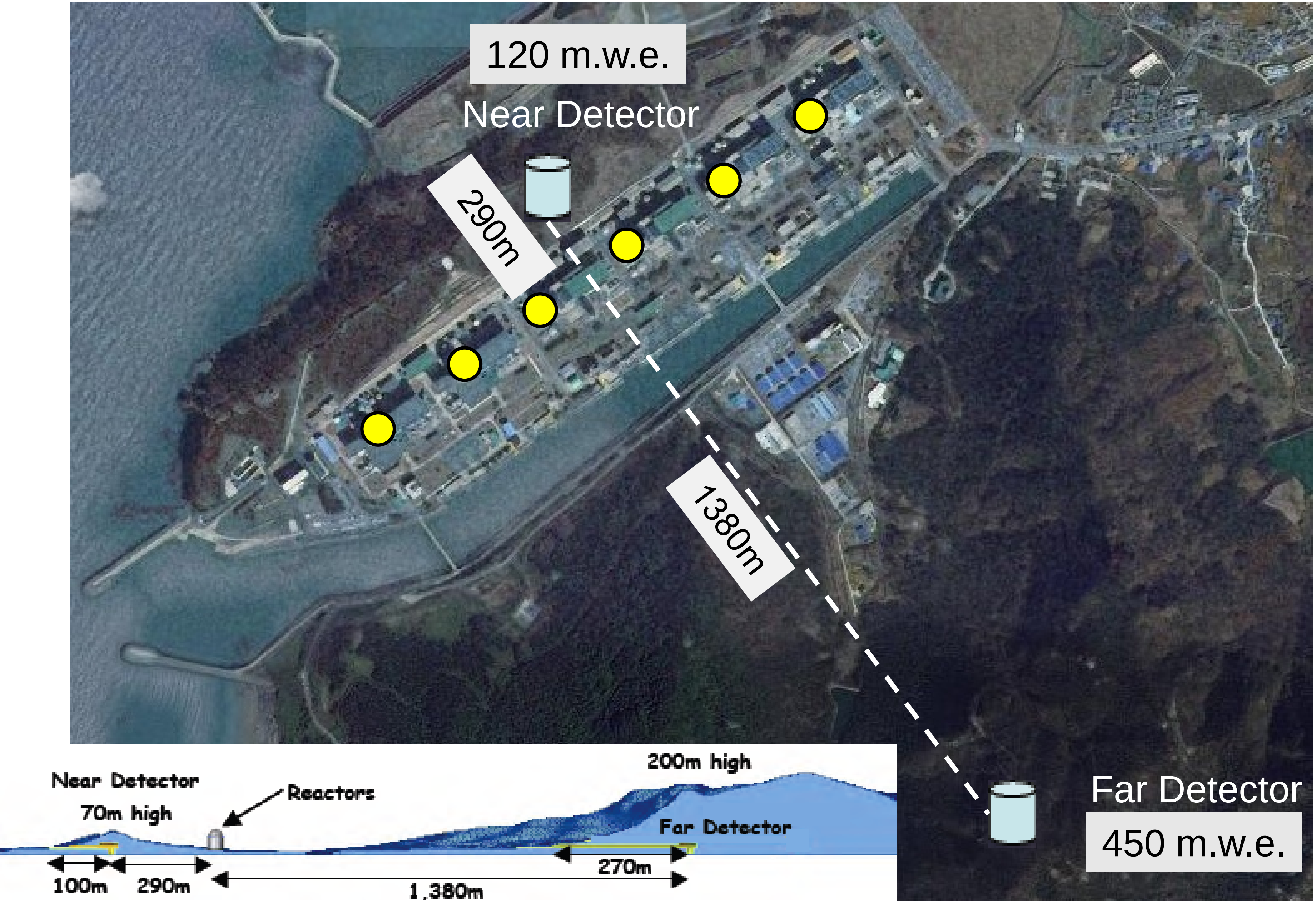
(10 institutions and 40 physicists)

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

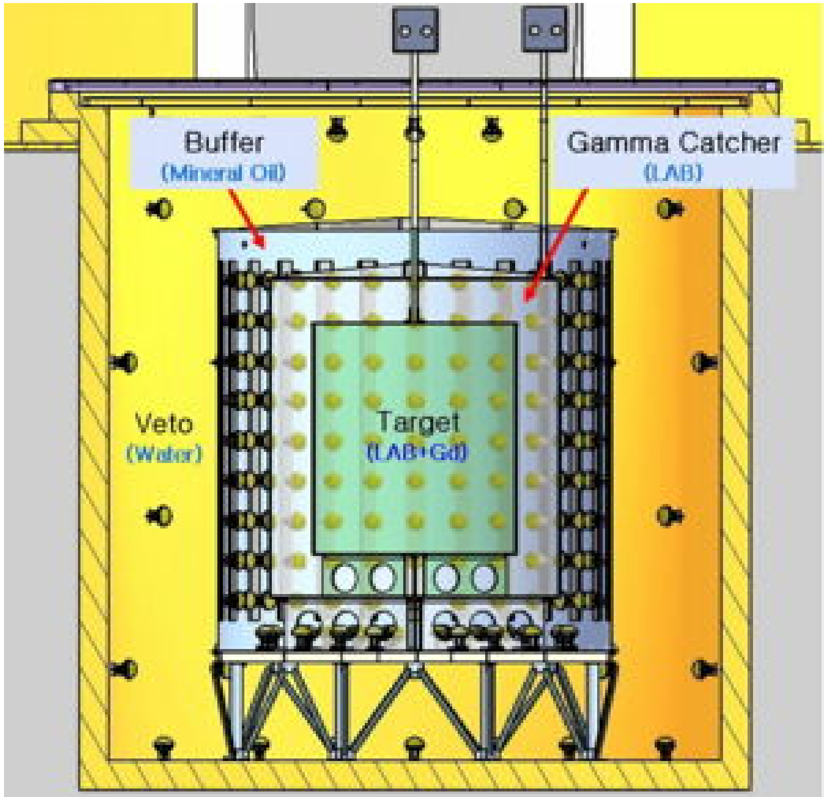
- Total cost : $10M
- Start of project : 2006
- The first experiment running with both near & far detectors from Aug. 2011

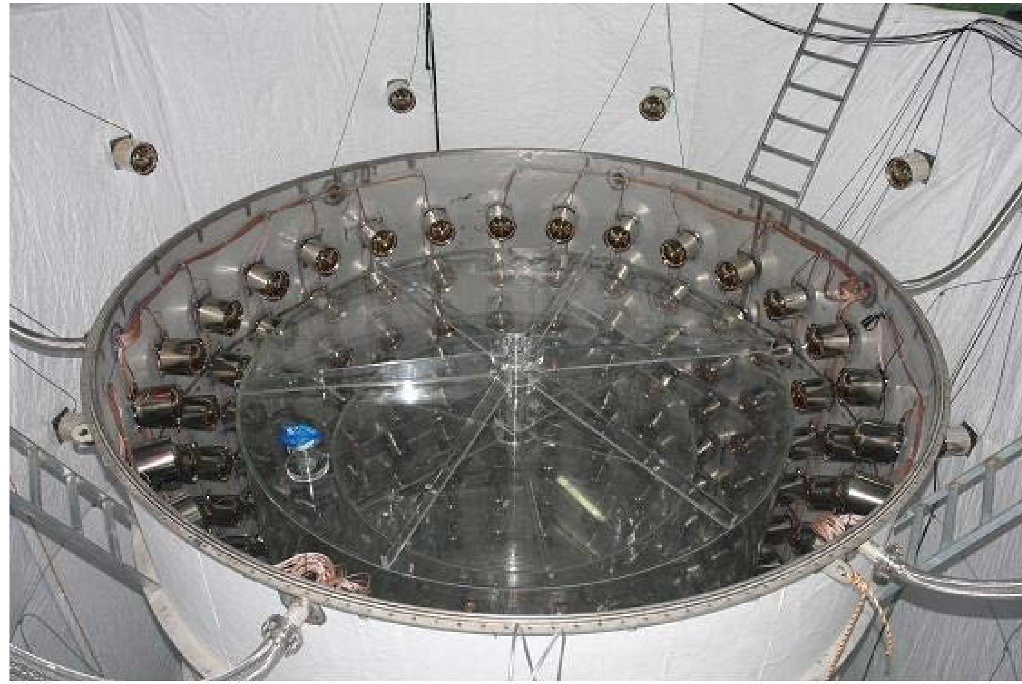
YongGwang (靈光) :

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 Status

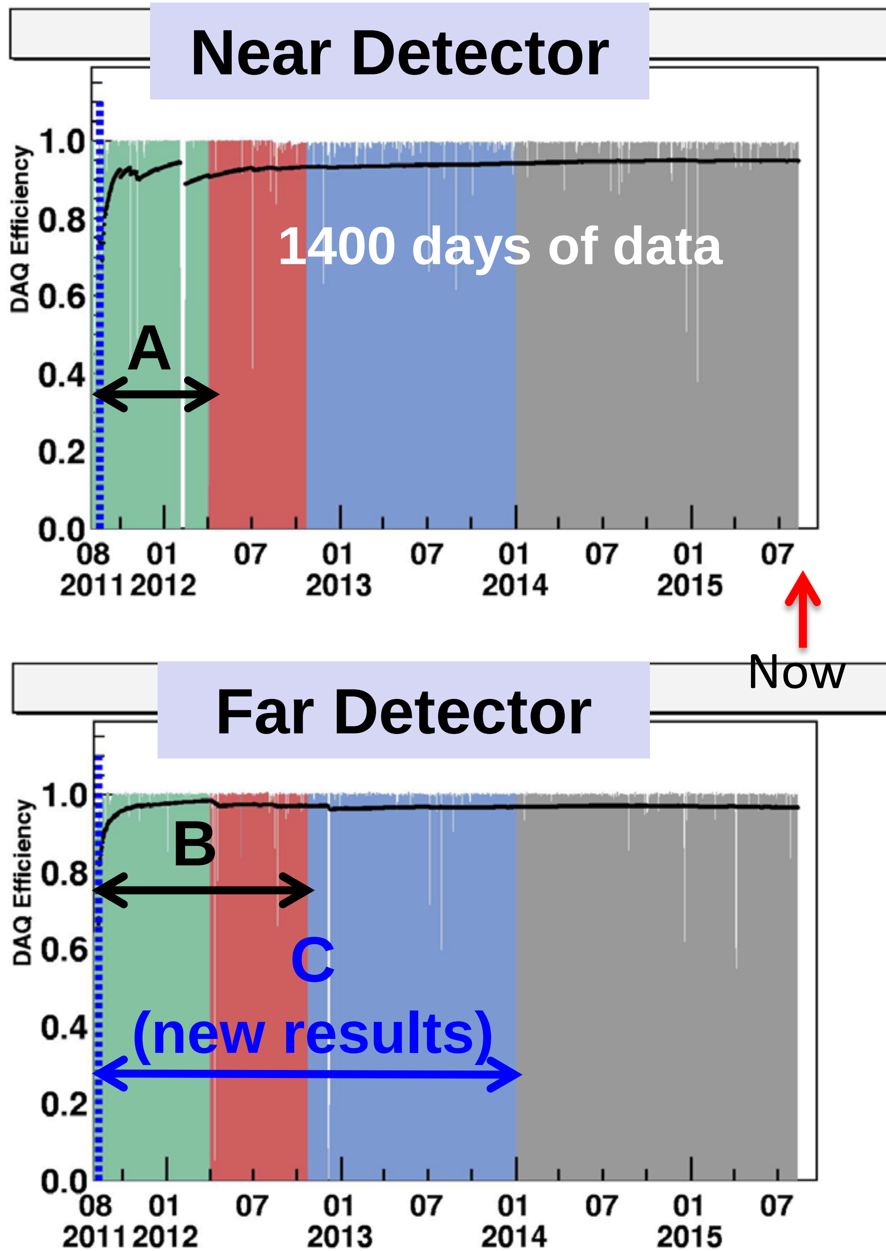
- Data taking began on Aug. 1, 2011 with both near and far detectors.
  (DAQ efficiency : ~95%)

- **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 Δm_{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]



Recent RENO Results and Status

- ~800 days of data
- New measured-value of θ_{13} from rate-only analysis
- Observation of energy dependent disappearance of reactor neutrinos to measure Δm_{ee}^2 and θ_{13} (to be submitted)
- Observation of an excess at 5 MeV in reactor neutrino spectrum
- Independent measurement of θ_{13} with n-H for a delayed signal (additional background reduction in progress)
- Search for sterile neutrinos in progress

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 Li/He background

  - reduced the Li/He background uncertainty based on an increased control sample

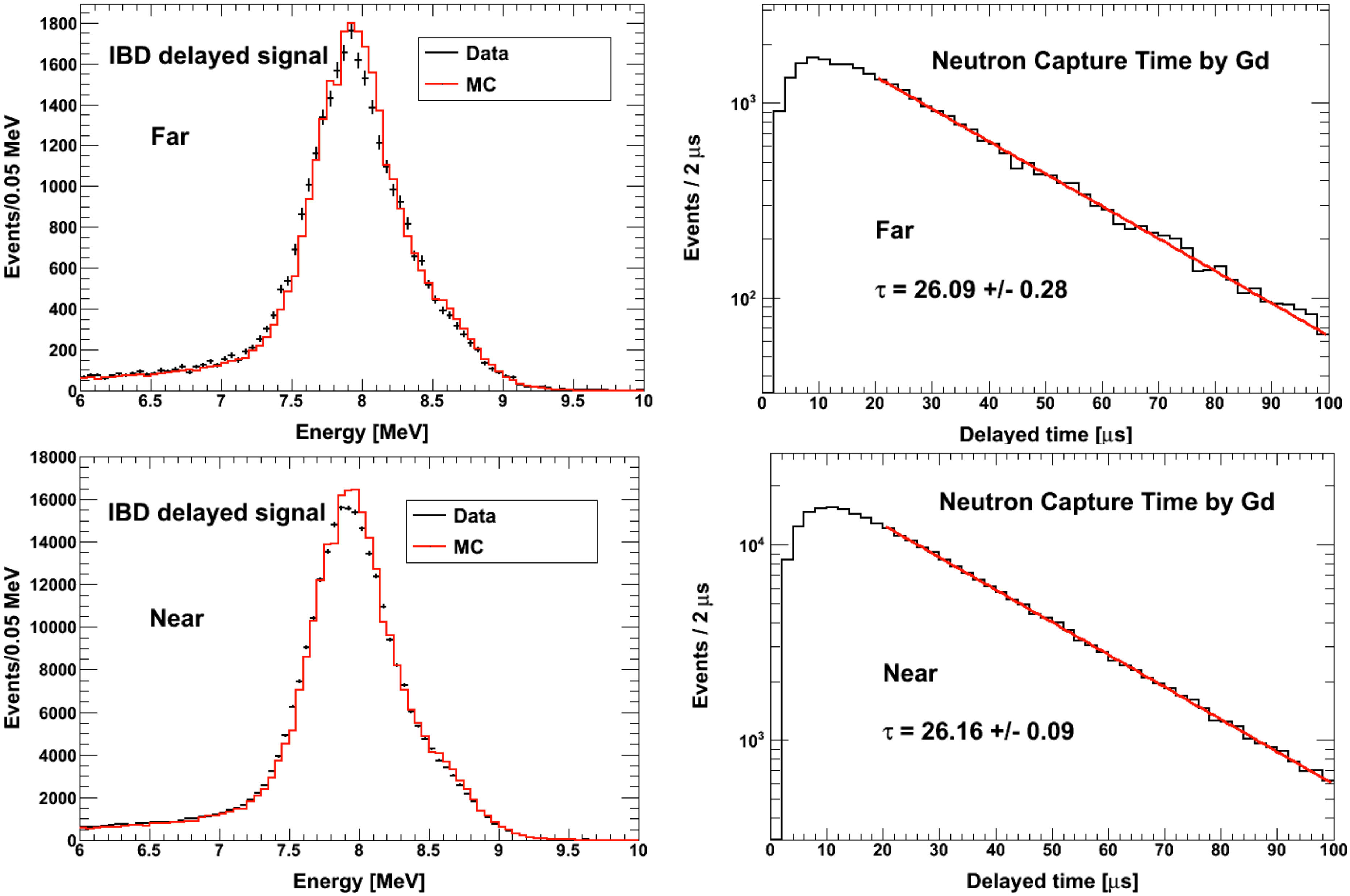
- More accurate energy calibration

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

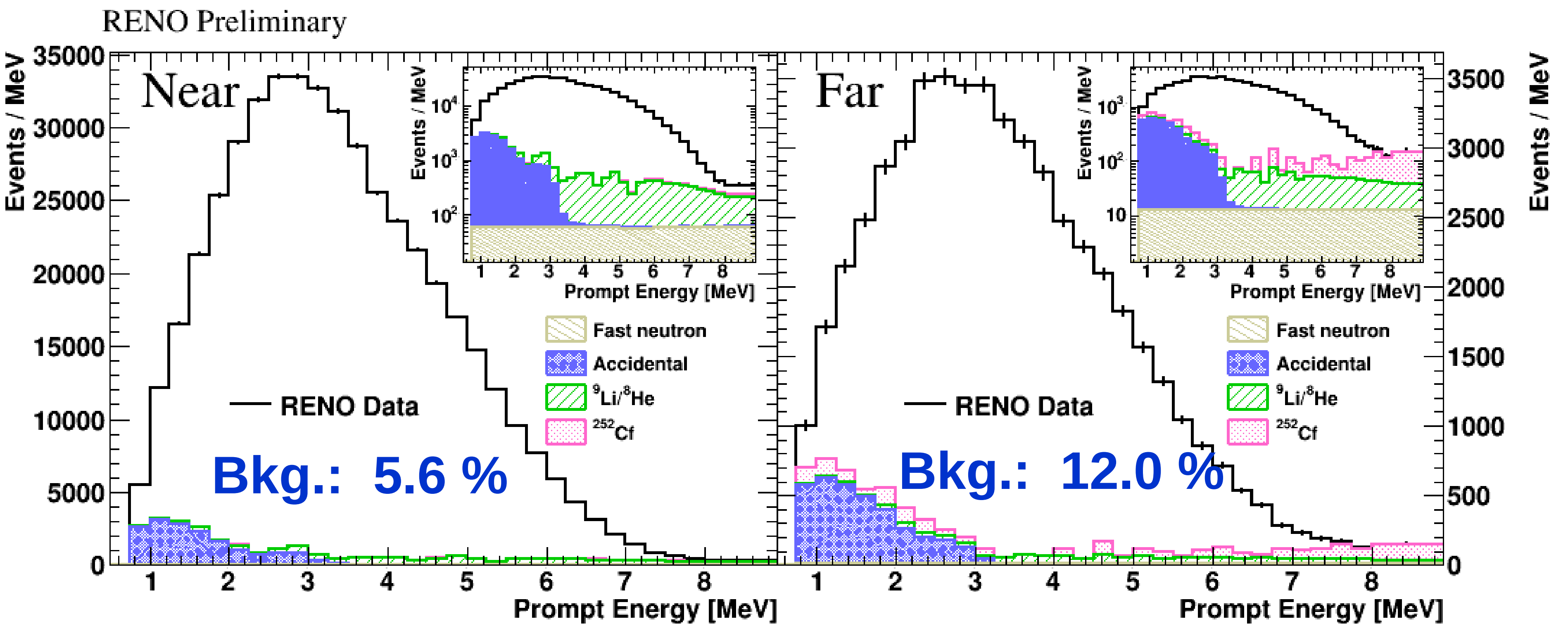
- Elaborate study of systematic uncertainties on a spectral fitter

  - estimated systematic errors based on a detailed study of spectral fitter in the measurement of Δm_{ee}^2

Neutron Capture by Gd



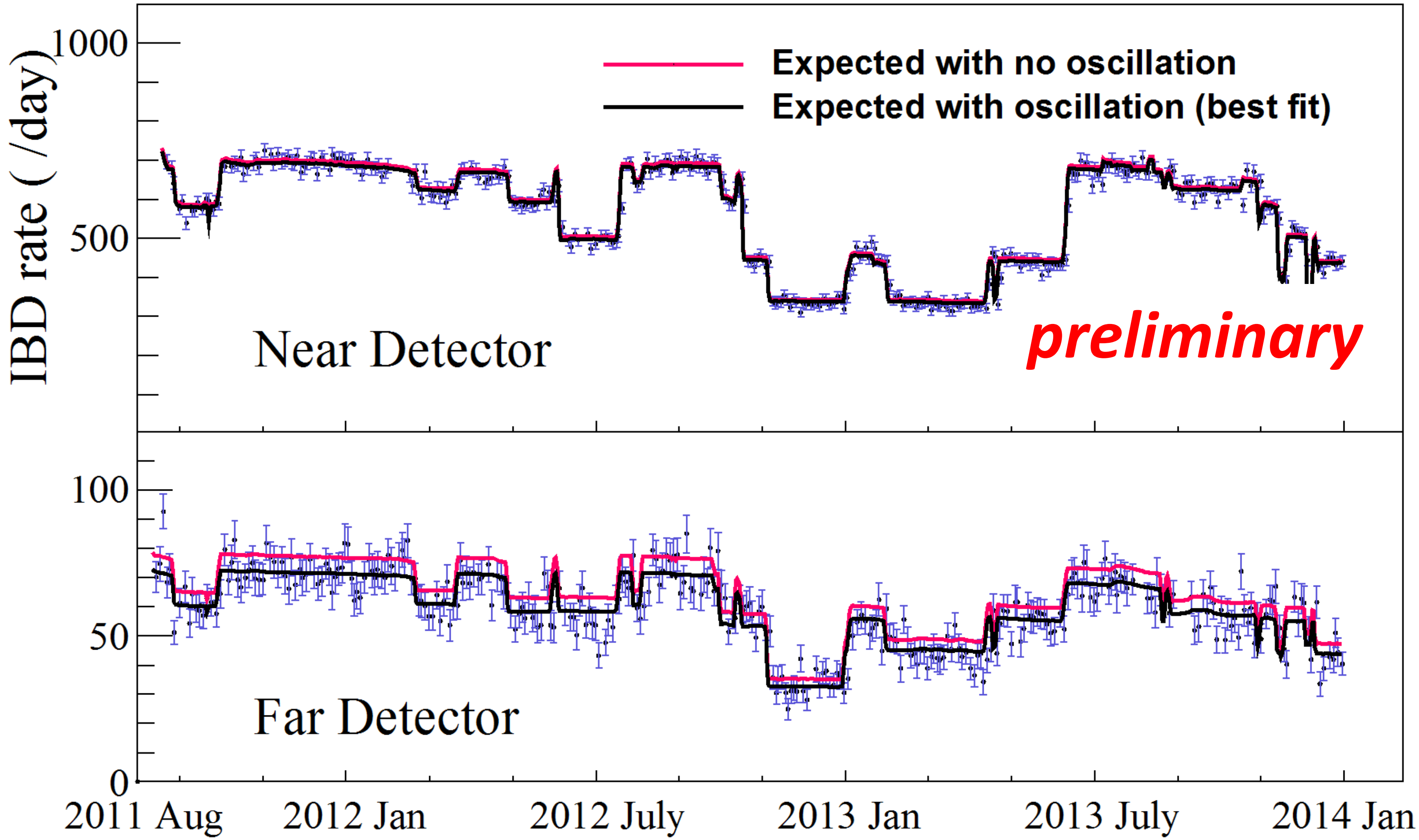
Measured Spectra of IBD Prompt Signal



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

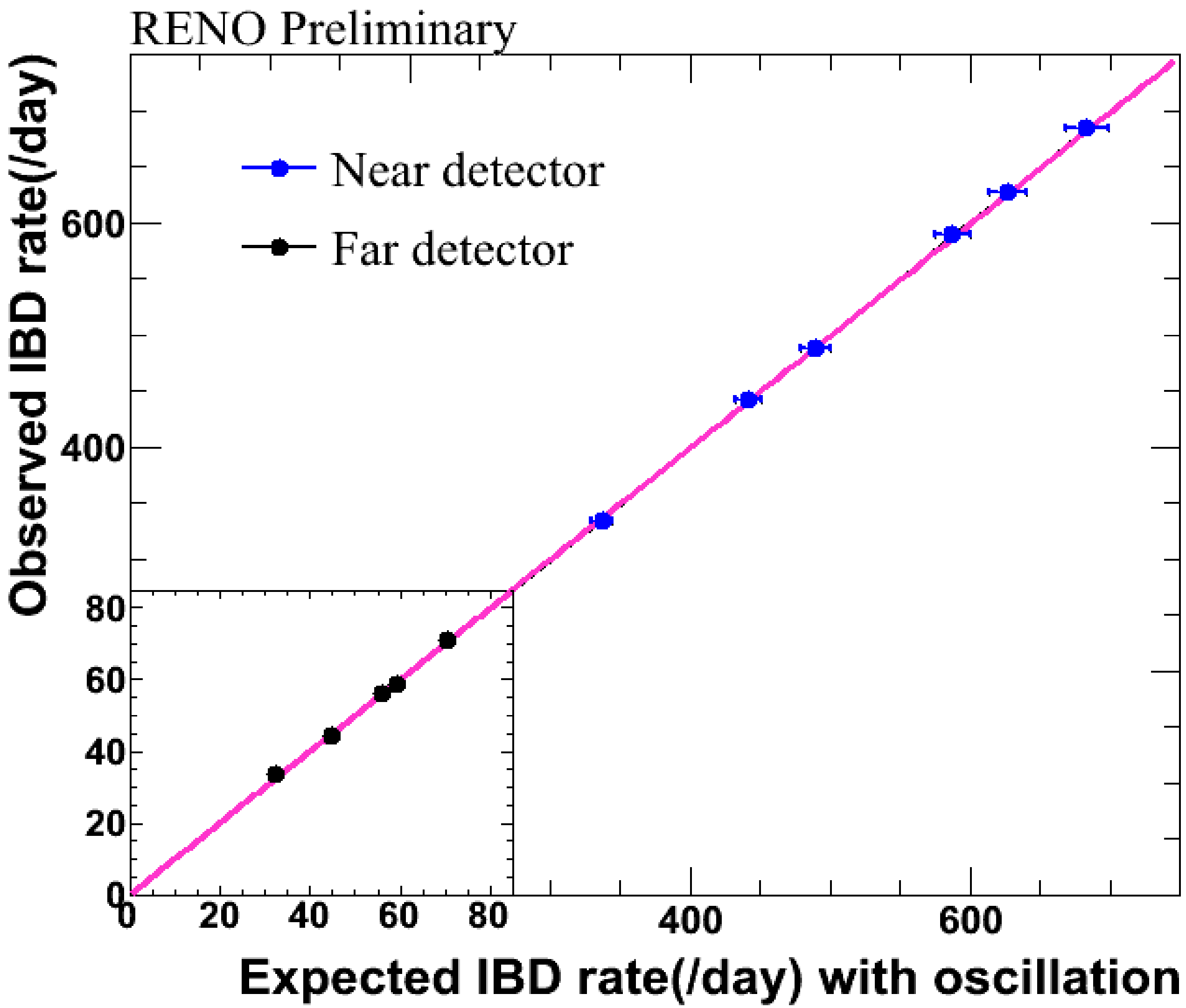
Far Live time = 794.72 days
# of IBD candidate = 52,250
# of background = 6,292 (12.0 %)

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

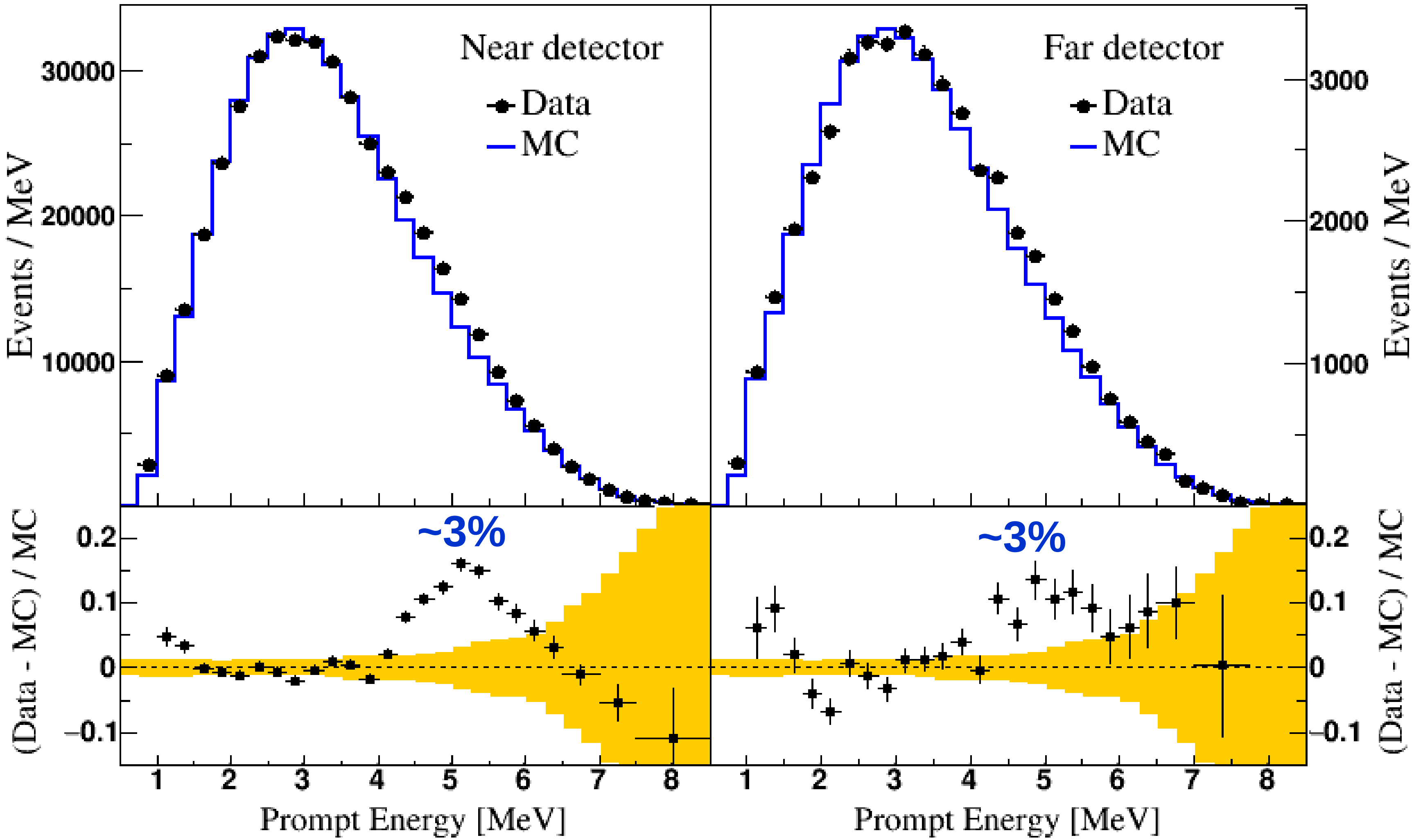
New θ_{13} Measurement by Rate-only Analysis

(Preliminary)

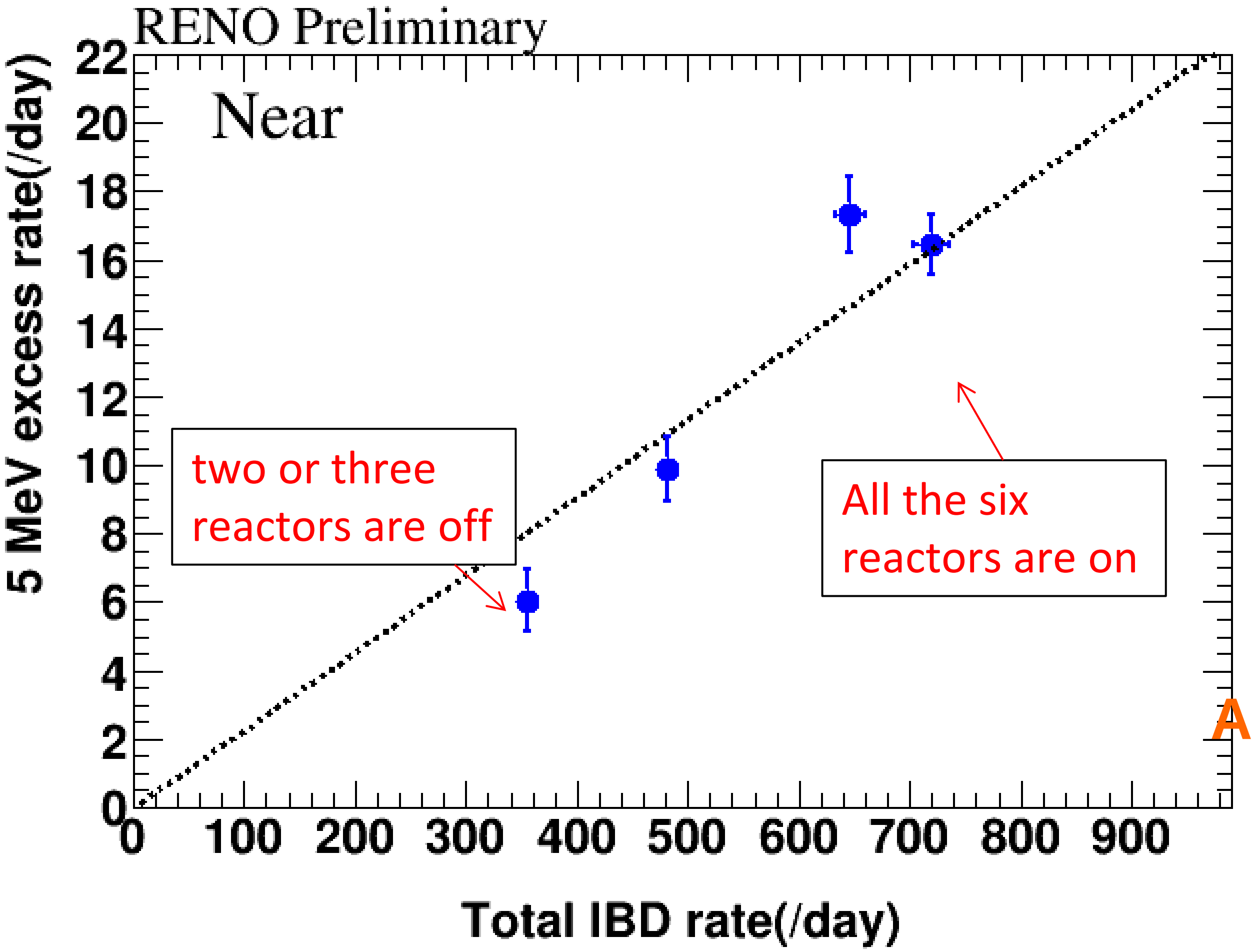
$$\sin^2 2\theta_{13} = 0.087 \pm 0.008(\text{stat.}) \pm 0.008(\text{syst.})$$

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

Why n-H IBD Analysis?

Motivation:

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

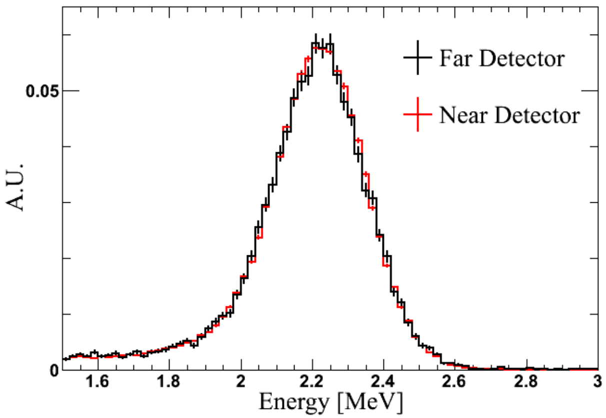
* RENO's low accidental background makes it possible to perform n-H analysis.

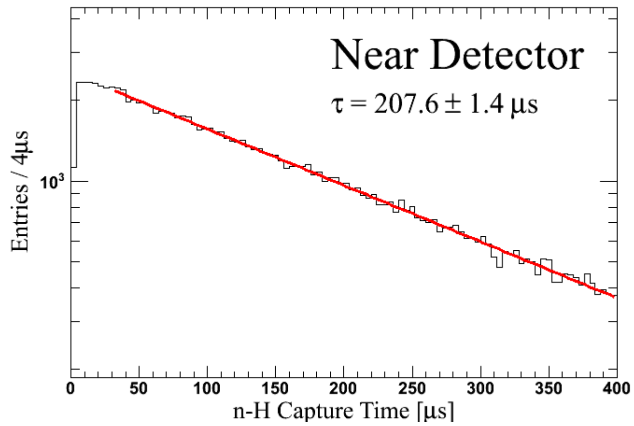
-- low radioactivity PMT

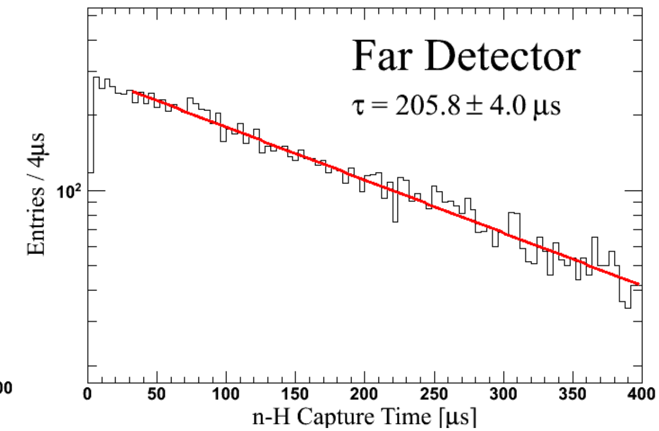
-- successful purification of LS and detector materials.

IBD Sample with n-H

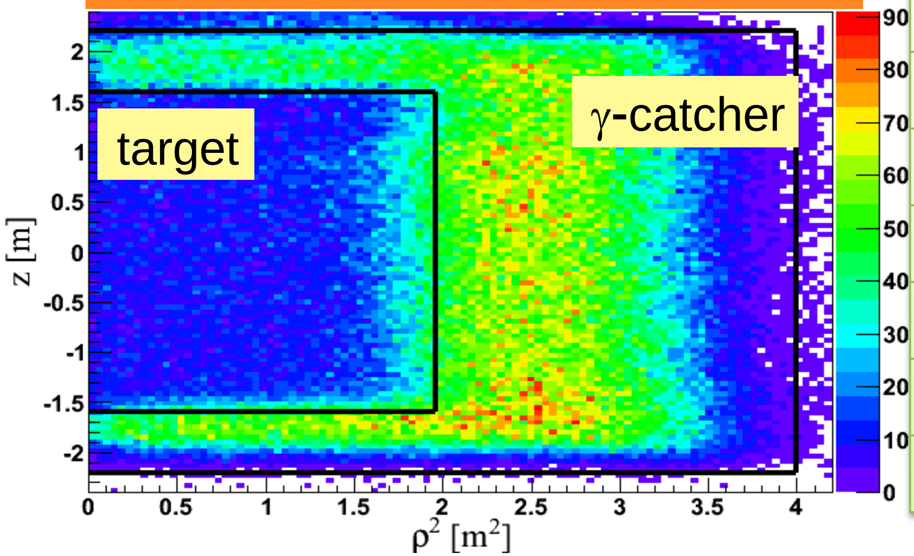
preliminary







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

Results from n-H IBD sample

Very preliminary
Rate-only result

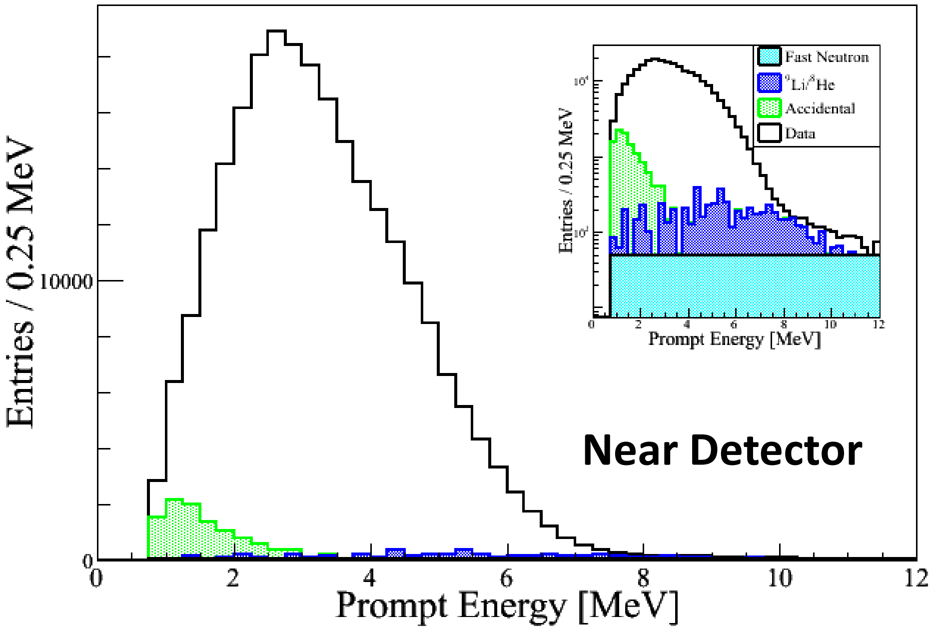
(B data set, ~400 days)

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

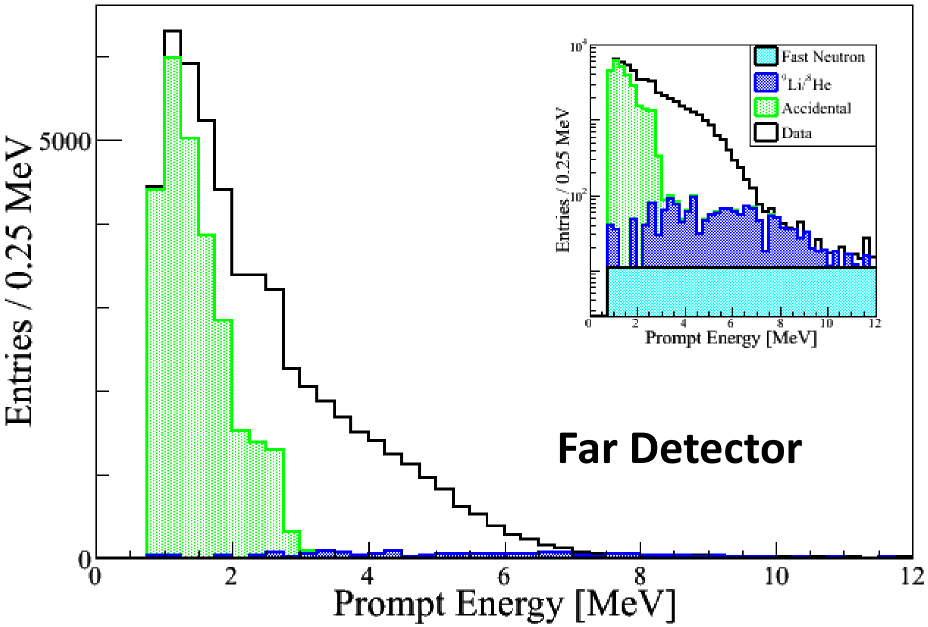
(Neutrino 2014) $\sin^2 2\theta_{13} = 0.095 \pm 0.015(\text{stat.}) \pm 0.025(\text{syst.})$

← Significant reduction in the uncertainty of the accidental background and new results coming soon.

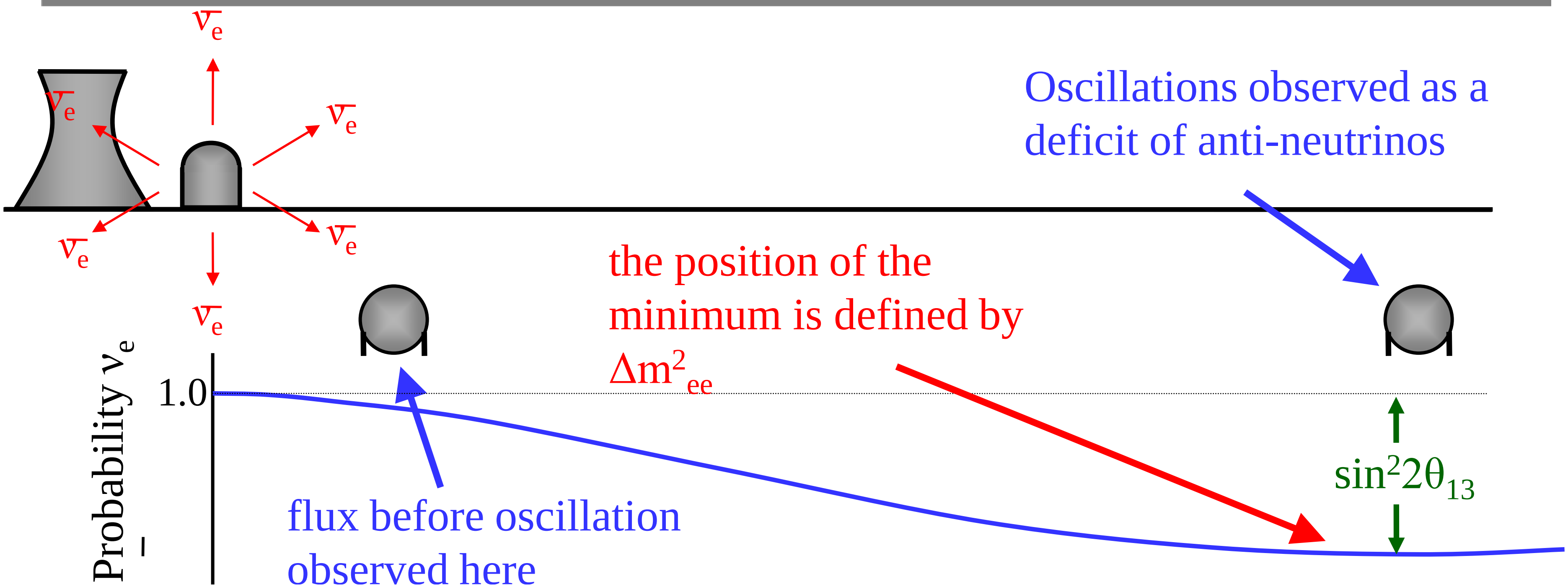
preliminary



preliminary



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

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

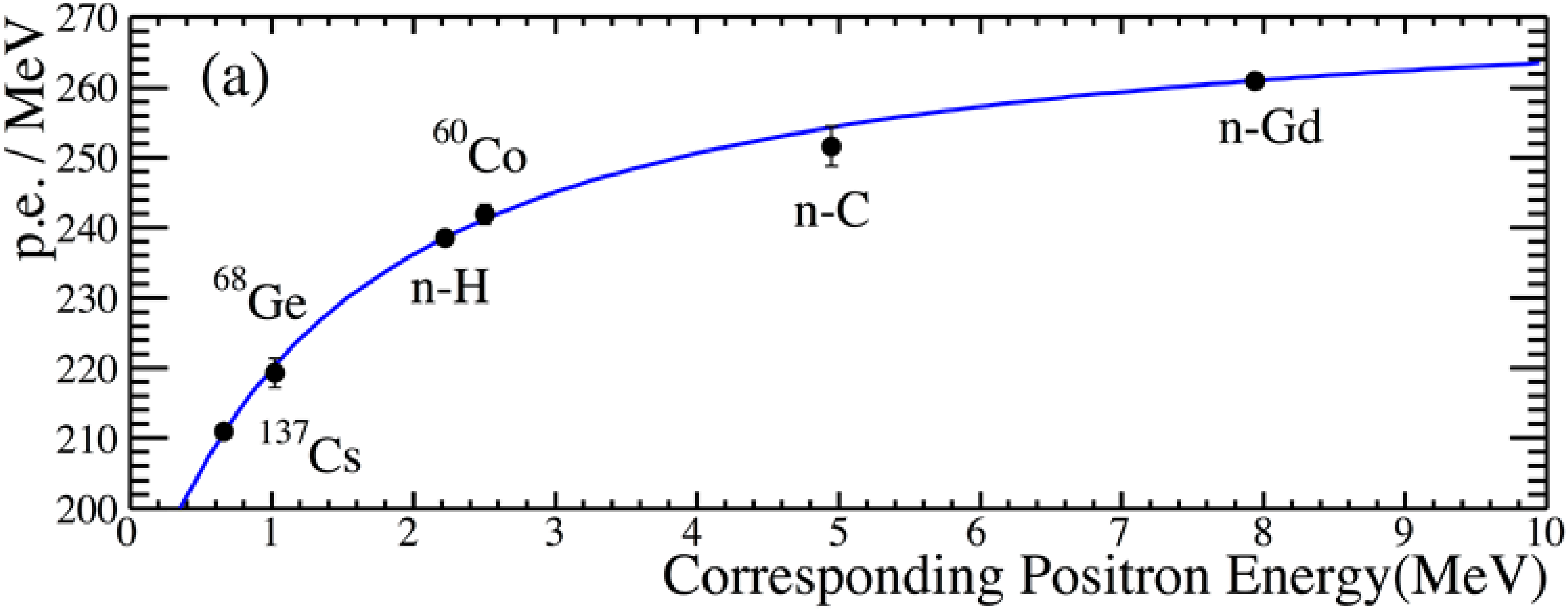
$$|\Delta m^2_{ee}| \simeq |\Delta m^2_{32}| \pm 5.21 \times 10^{-5}\mathrm{eV}^2$$

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

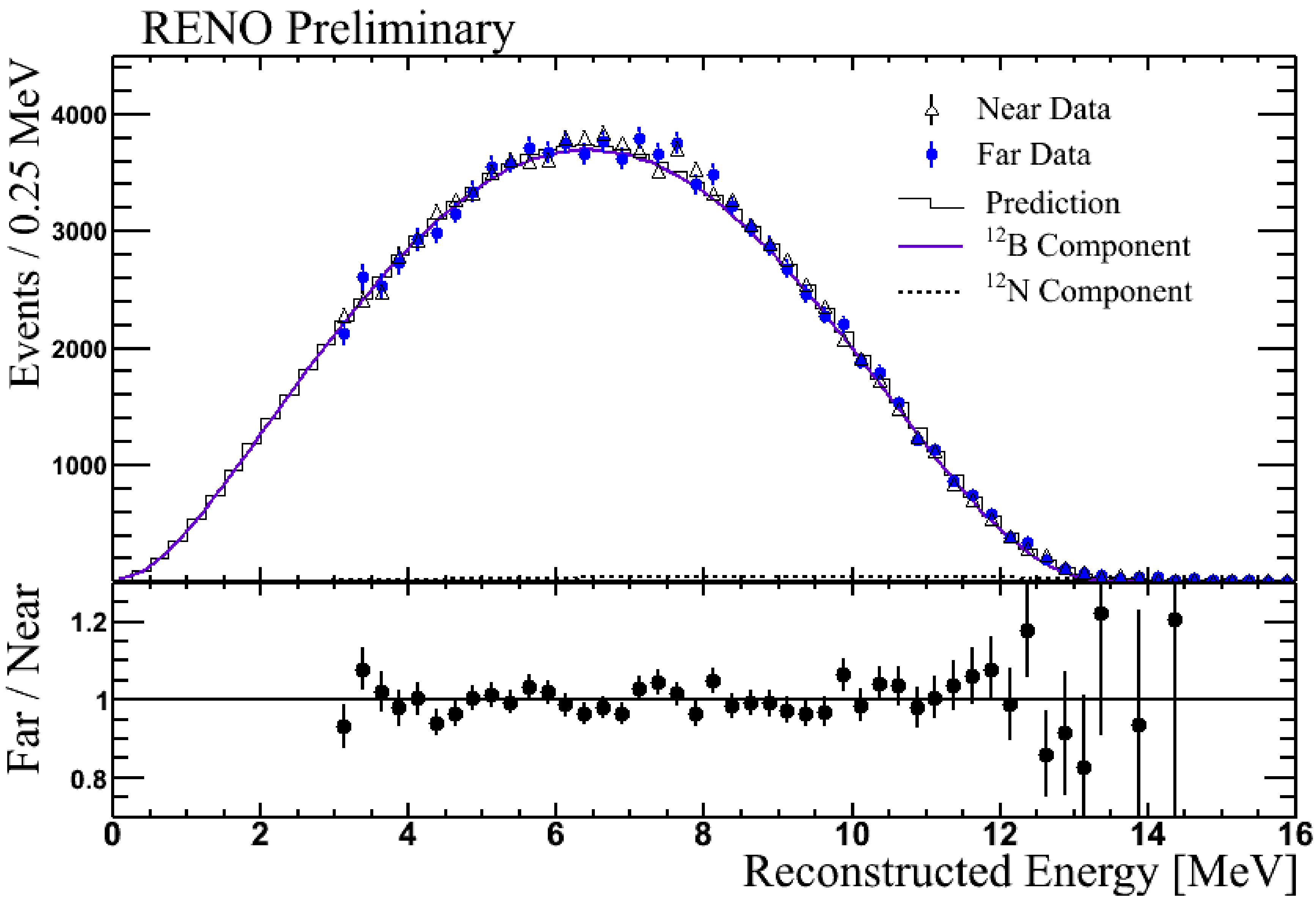
+: Normal Hierarchy

−: Inverted Hierarchy

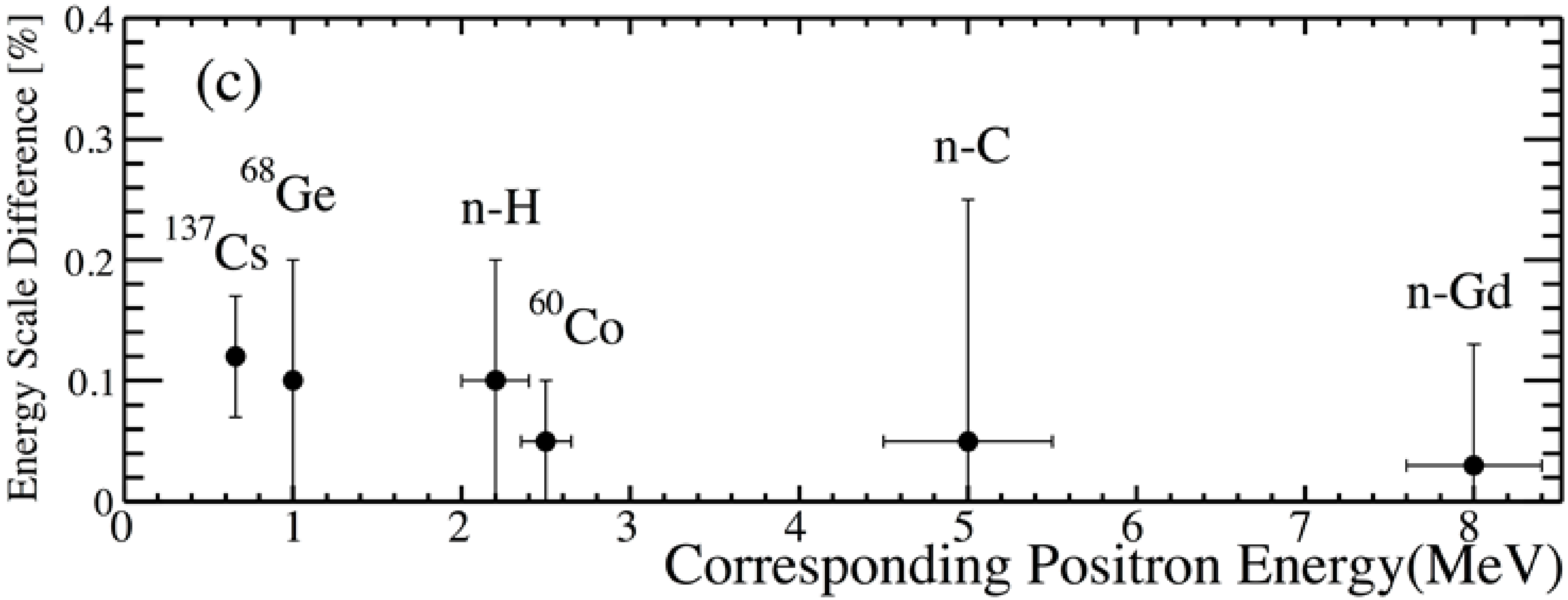
Energy Calibration from γ-ray Sources



B12 Energy Spectrum (Near & Far)



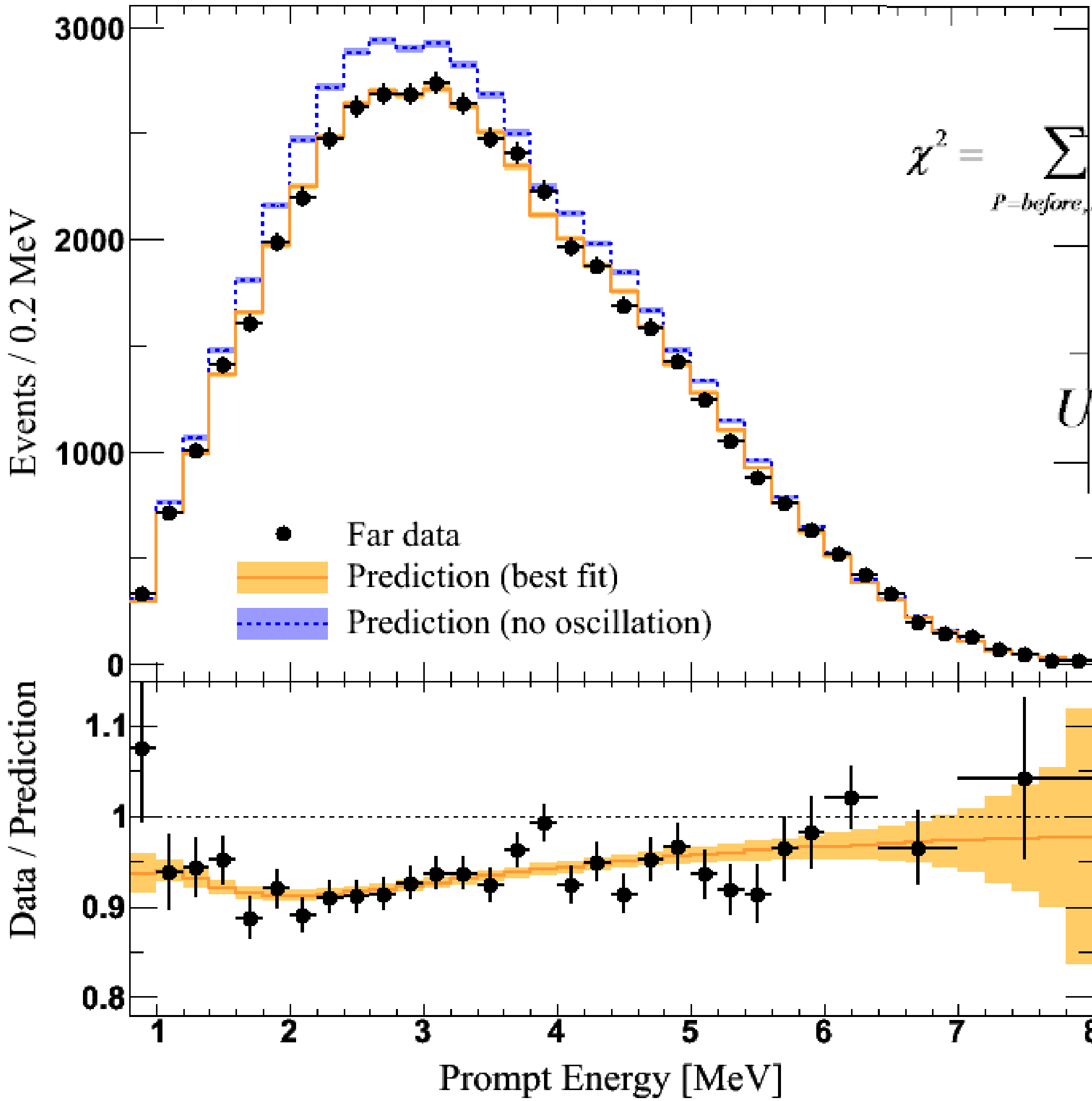
Energy Scale Difference between Near & Far



Energy scale difference < 0.15%

Far/Near Shape Analysis for Δm_{ee}^2

(work in progress)



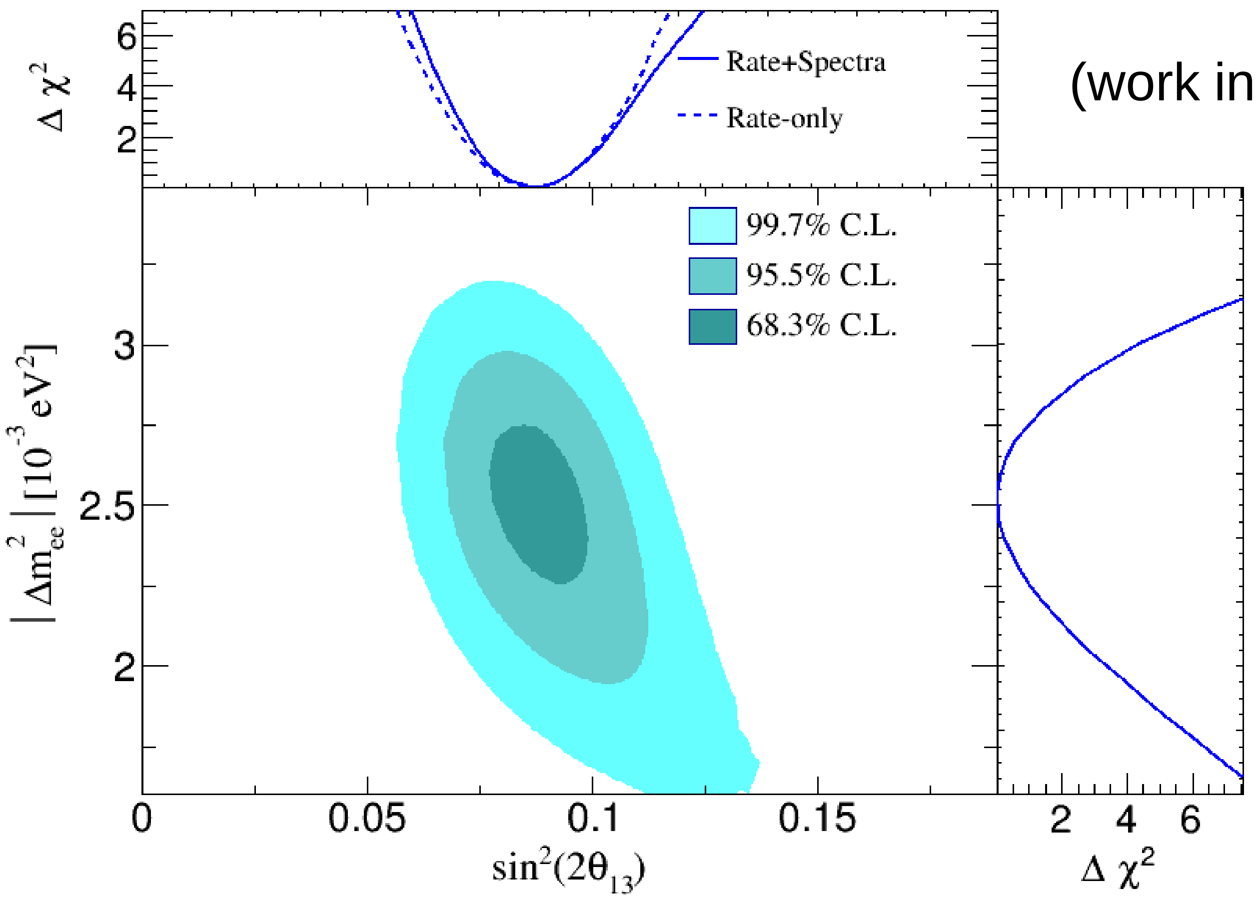
Minimize X² Function

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

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

Results from Spectral Fit

(work in progress)



$$\Delta m_{ee}^{2} = [2.52 \pm 0.19(\text{stat}) \pm 0.17(\text{syst})]\, x10^{-3}\ \text{eV}^2$$

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

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

(work in progress)

$$\sin^2 2\theta_{13} = 0.088 \pm 0.008(\text{stat}) \pm 0.007(\text{syst})$$ ($\pm$ 11 %)

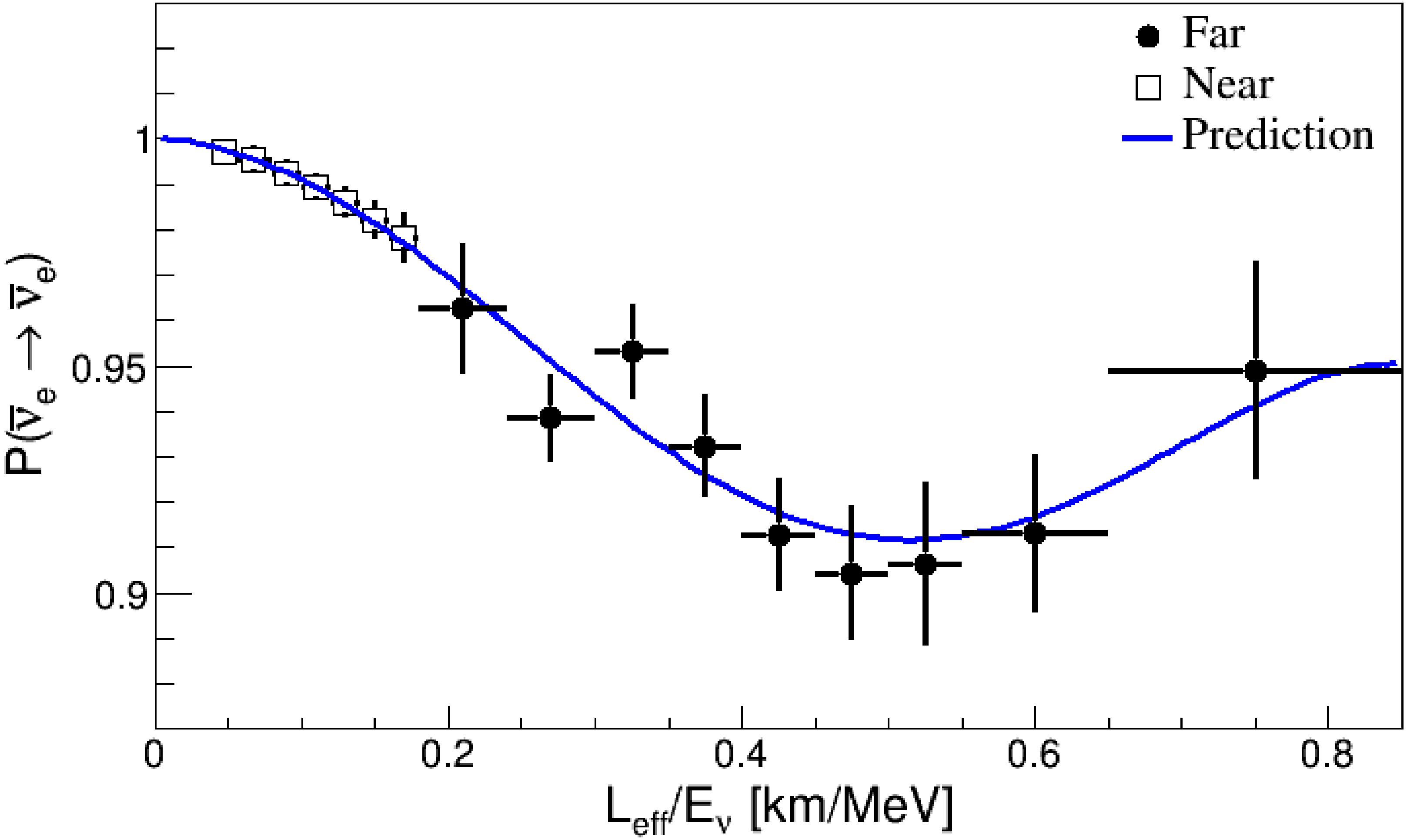
$$\Delta m_{ee}^2 = [2.52 \pm 0.19(\text{stat}) \pm 0.17(\text{syst})] \text{x}10^{-3}\ \text{eV}^2$$ ($\pm$ 10 %)

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)

Observed L/E Dependent Oscillation

(work in progress)



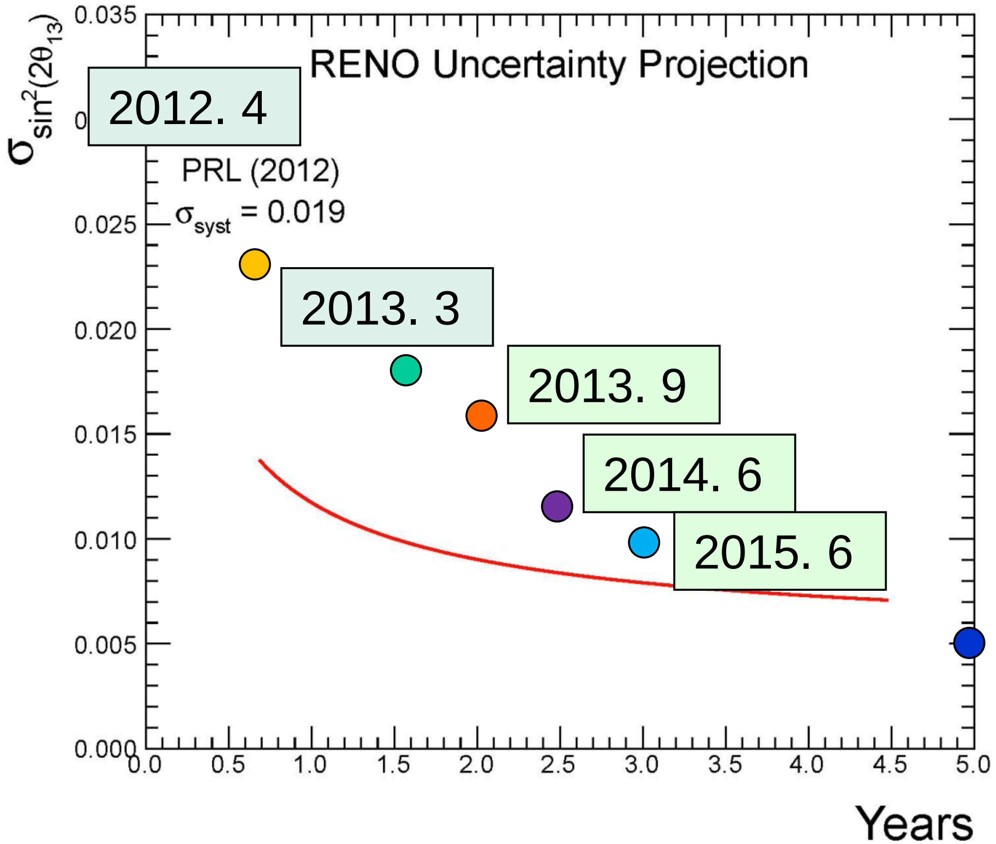
Projected Sensitivity of θ_{13} & Δm_{ee}^2

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 Δm_{ee} : ~ 0.1×10^{-3} eV^2

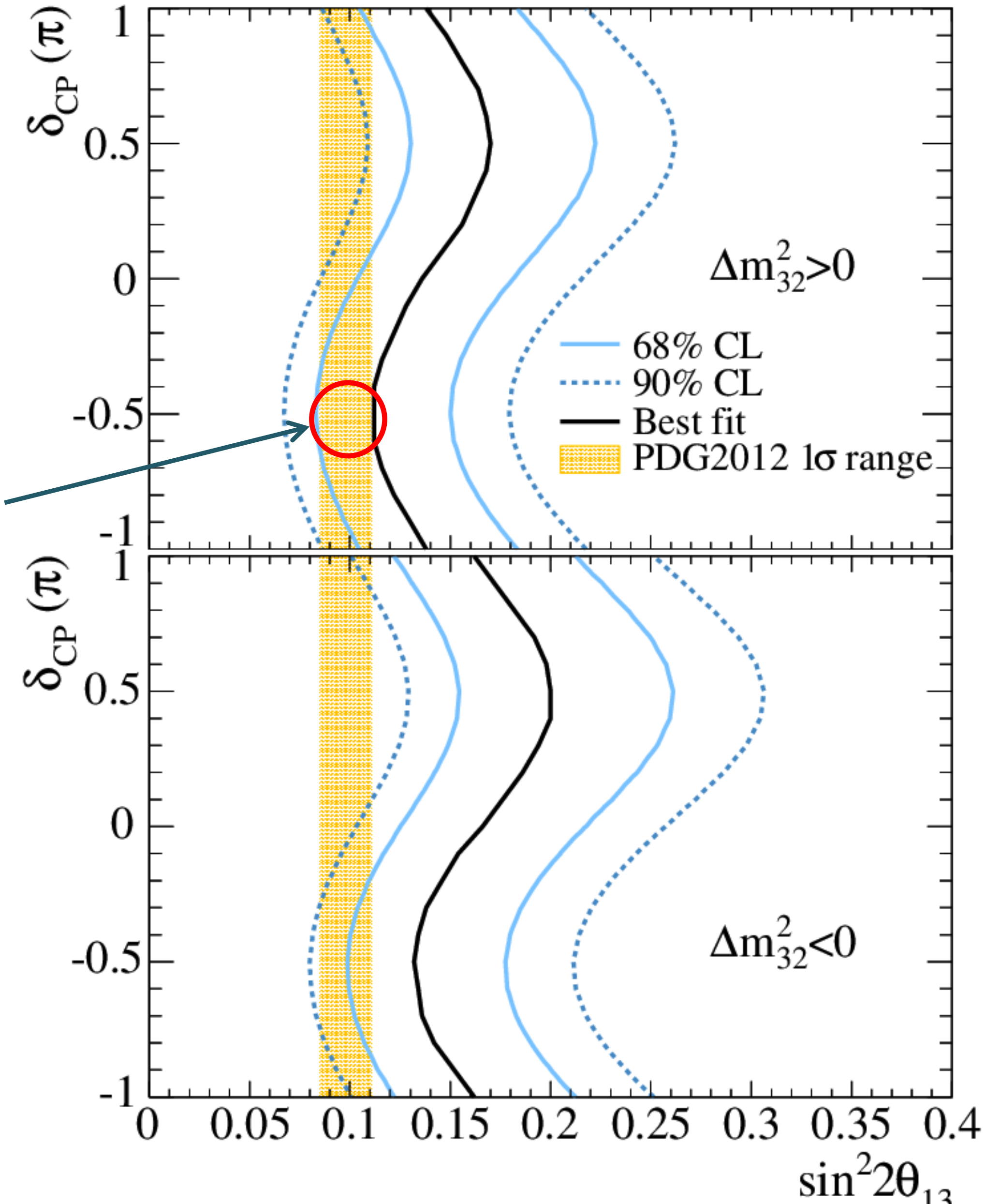
(~ 4% precision)



(5 % precision)

(sensitivity goal of θ_{13})

θ_{13} from Reactor and Accelerator Experiments



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

Best overlap is for Normal hierarchy & δ_{CP} = - π/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)

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 on 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
  Δm_{ee}^2 to 0.1×10^{-3} eV^2 (4%) accuracy within 3 years

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}
  - 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

Determination of Neutrino Mass Ordering

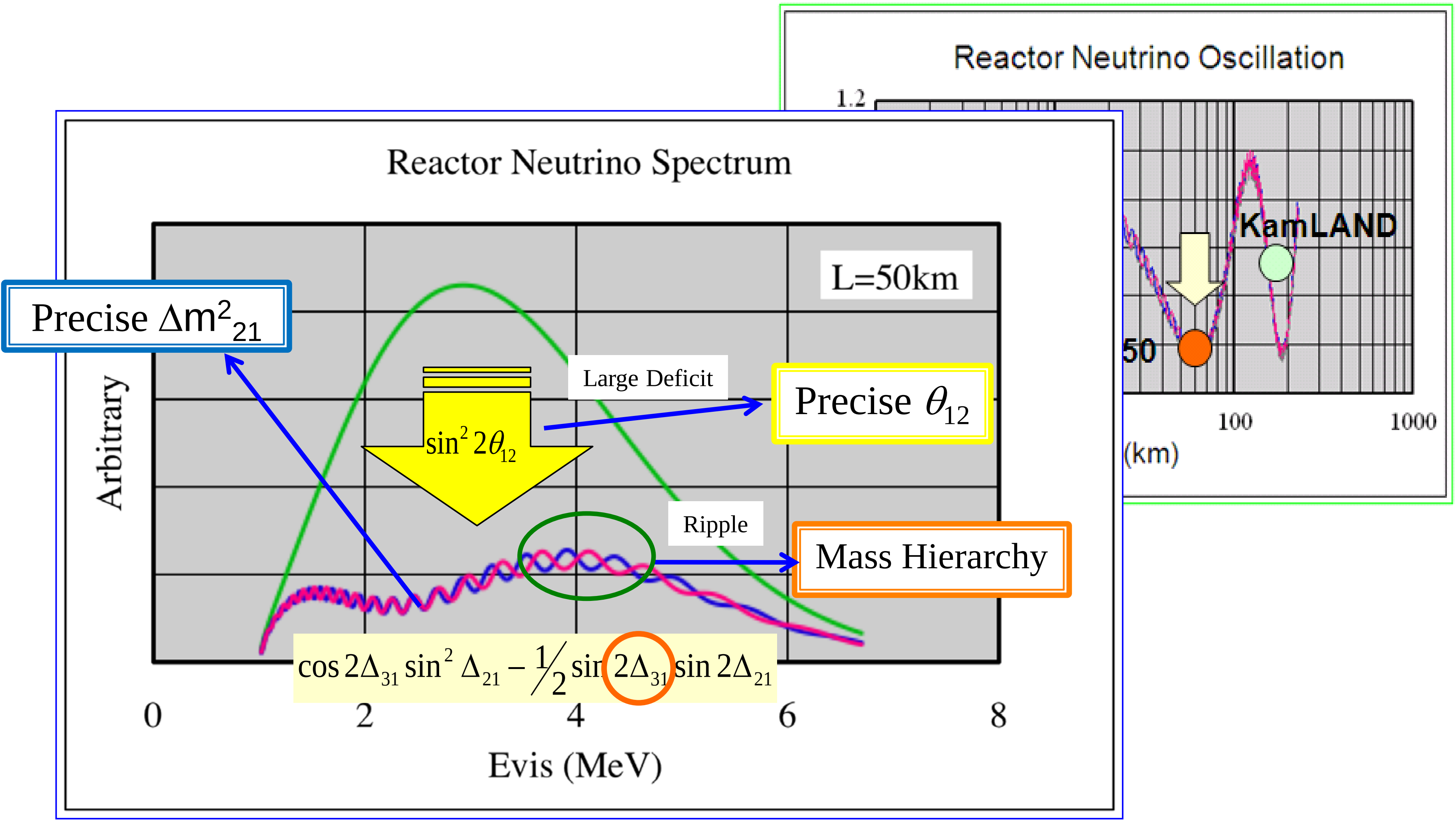
- Reactor experiments: JUNO and RENO-50
  - Subdominant oscillation pattern of Δm_{31}^2
  - Large liquid scintillator detector with a baseline of ~50 km
  - Extraordinary energy resolution (<3% at 1 MeV)

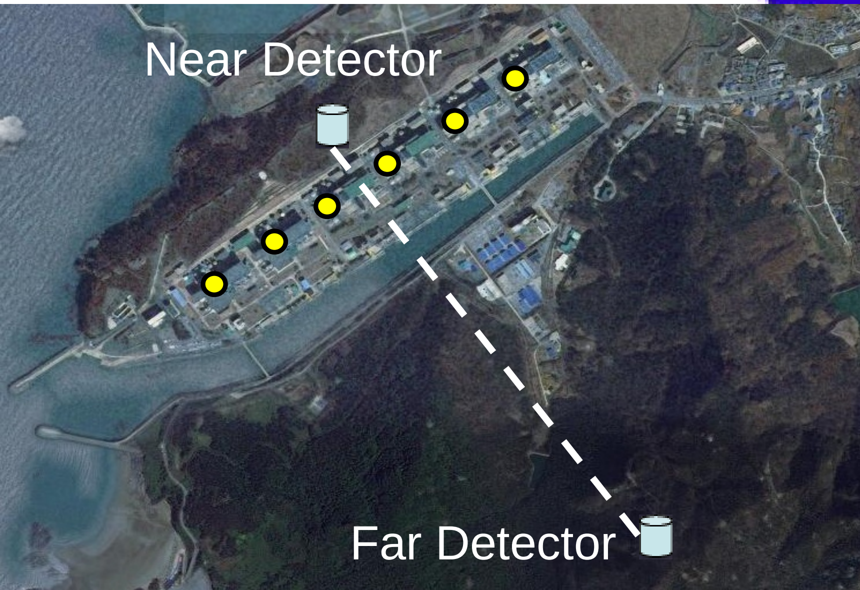
- Long baseline beam experiments: T2K, NOvA, T2HK and LBNE
  - Matter effects of neutrino oscillation
  - Small value of $|\Delta m_{32}^2|/E$ & long baseline L

- Atmospheric neutrino experiments with Mton scale : HK, LBNE, MEMPHIS, PINGU and INO
  - Matter effects of neutrino oscillation
  - Small value of $|\Delta m_{32}^2|/E$ & long baseline L

Reactor Neutrino Oscillations at 50 km

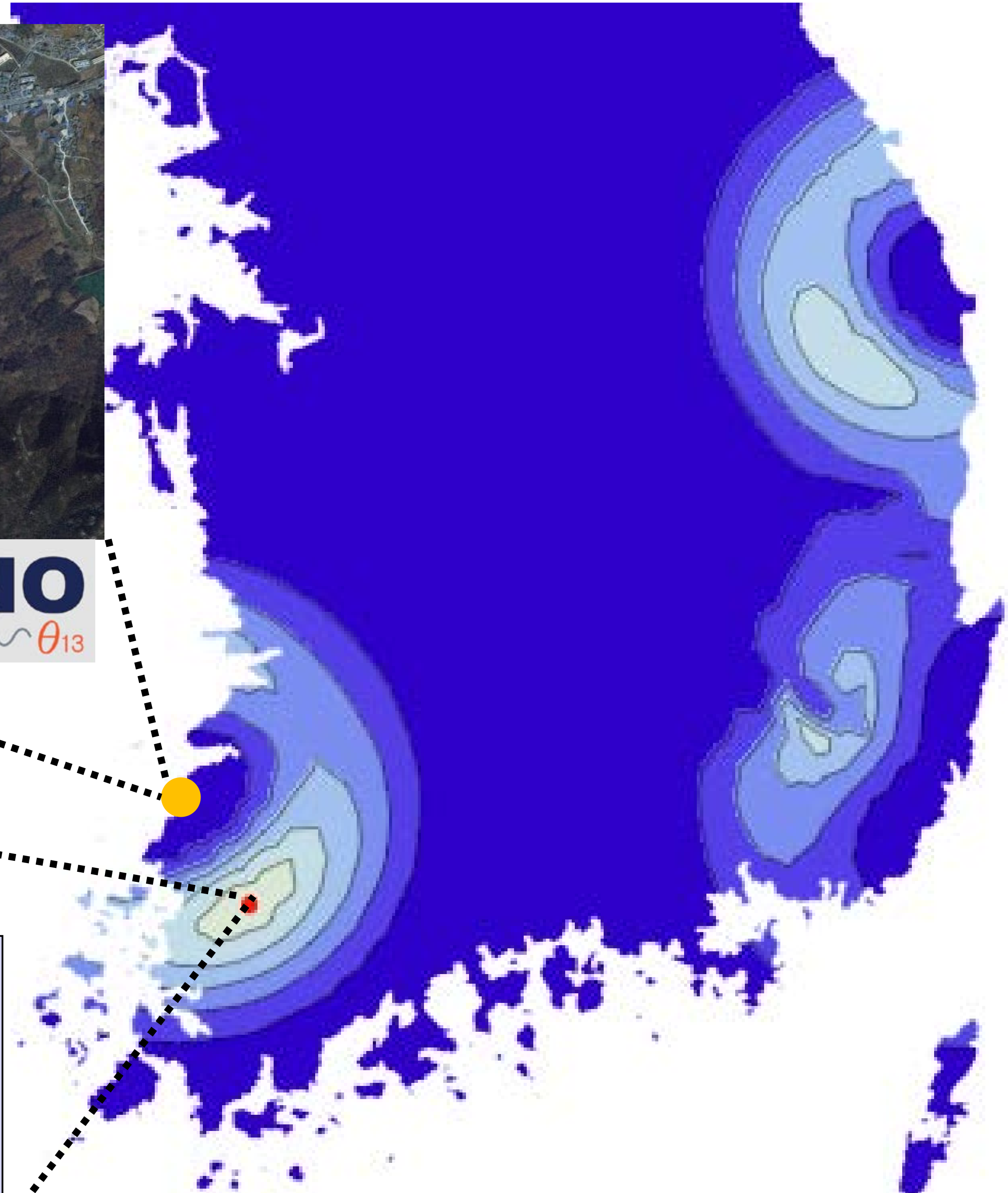
Neutrino mass ordering (sign of Δm^2_{31})+precise values of θ_{12}, Δm^2_{21} & Δm^2_{ee}





(NEAR Detector)

(FAR Detector)



RENO-50

10 kton LS Detector
~47 km from YG reactors

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

Various Physics with RENO-50

- Precise (<1%) measurement of θ_{12}, Δm^2_{21} and Δm^2_{ee}
  - Provide an interesting test for unitarity
  - Essential for the future discoveries

- Neutrino burst from a Supernova in our Galaxy
  - ~5,600 events (@8 kpc) (* NC tag from 15 MeV deexcitation γ)
  - Study the core collapsing mechanism with neutrino cooling

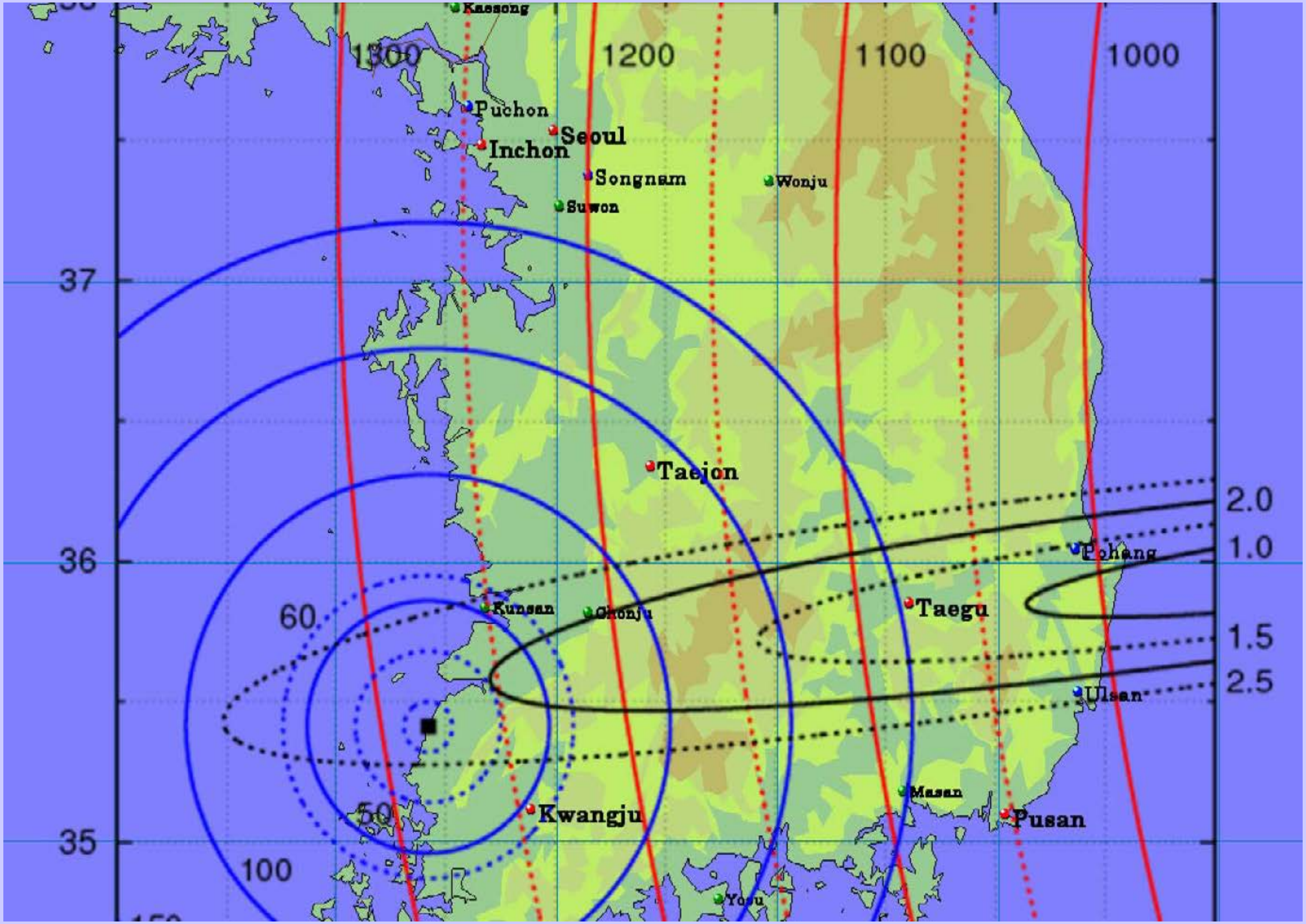
- Geo-neutrinos : ~ 1,000 geo-neutrinos for 5 years
  - Study the heat generation mechanism inside the Earth

- Solar neutrinos : with ultra low radioacitivity
  - MSW effect on neutrino oscillation
  - Probe the center of the Sun to study the metallicity problem

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

J-PARC neutrino beam

Dr. Okamura & Prof. Hagiwara



Essential R&D

(1) Obtain energy resolution of 3%

- Light yield of LS: > 1,000 pe/MeV (← 500 pe/MeV)
- Attenuation length of LS: ~25 m (← ~15 m)
- Surface coverage of PMT: ~60% using 15,000 HQE 20” PMTs (← ~30%)
- Quantum efficiency of PMT: 35% (← ~20%)
- Gain of PMT: ~10^7

(2) Develop techniques of LS mass production & purification

- Reduction of LS radioactivity to 10^{-16} g/g of U and Th
- Removal of LS impurities for attenuation length of ~25 m
- Mass production of LS with light yield of >1,000 pe/MeV

Current Status

- A longer baseline (~50 km) reactor experiment, RENO-50 is proposed to determine the mass ordering in 3-4σ for 10 years of data-taking, and to perform high-precision (<1%) measurements of θ_{12}, Δm^2_{21}, & Δm^2_{ee} .

- Domestic and international workshops held in 2013 to discuss the feasibility and physics opportunities

- An R&D funding (US $2M for 3 years of 2015-2017) is obtained from the Samsung Science & Technology Foundation. R&D is in progress to produce TDR.

- A proposal has been submitted to obtain full funding.

- An international collaboration needs to be formed.
  You are welcome to join this effort!

Thanks for your attention!