Current Results from Reactor Neutrino Experiments

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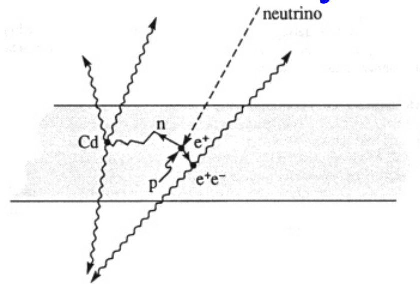
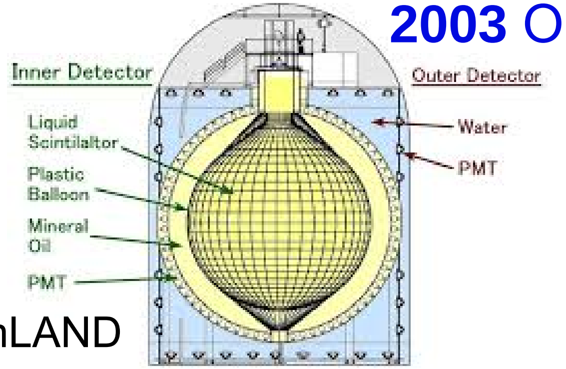
KNRC
Korea Neutrino Research Center

Neutrino Physics with Reactor

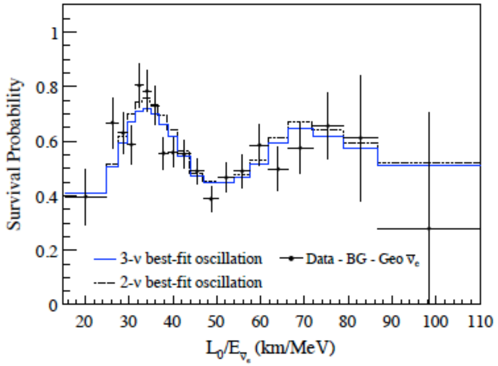
1956 Discovery of (anti)neutrino

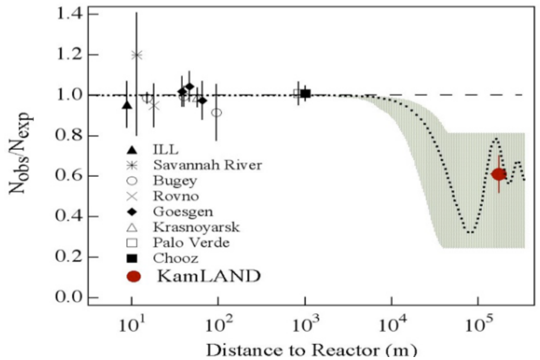


2003 Observation of reactor neutrino oscillation (θ_{12} & Δm_{21}^2)

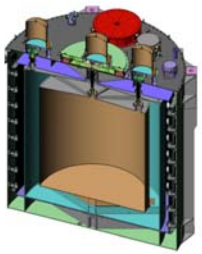


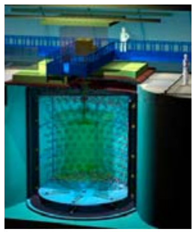
KamLAND

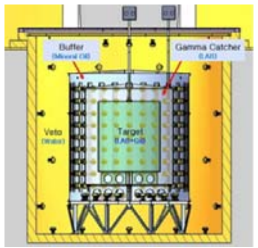


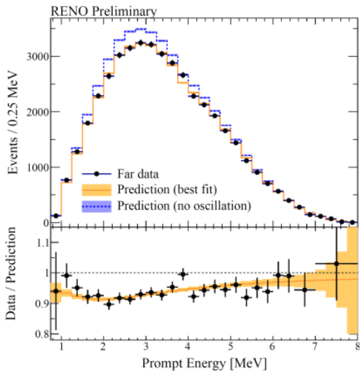


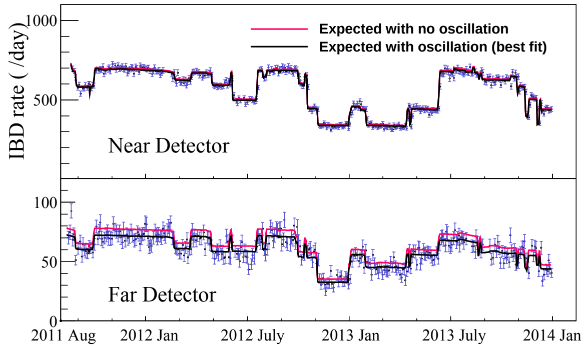
2012 Measurement of the smallest mixing angle θ_{13}





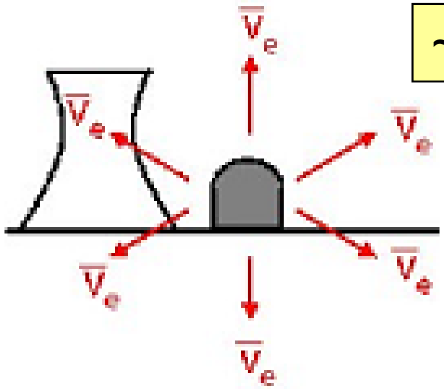






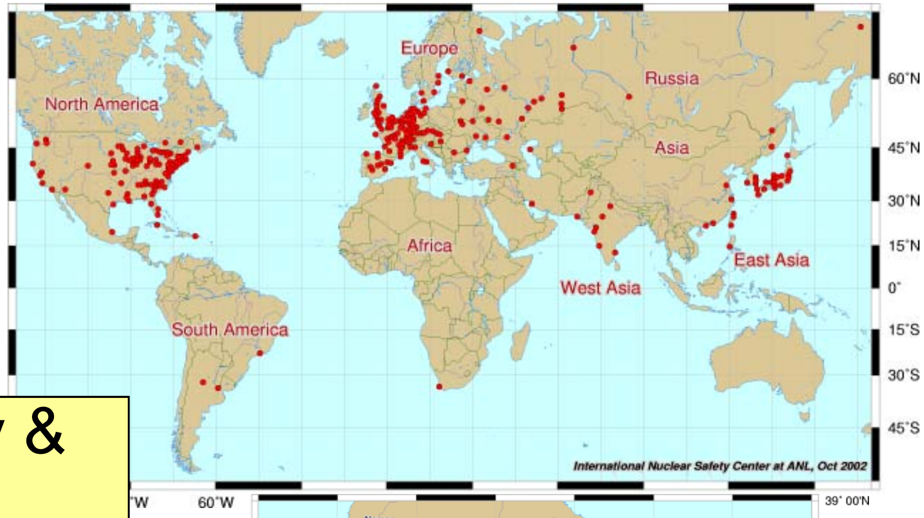
Reactor Neutrinos

Reactor Neutrinos

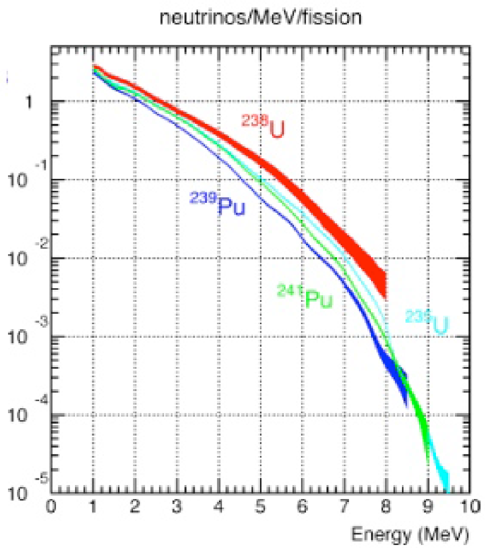


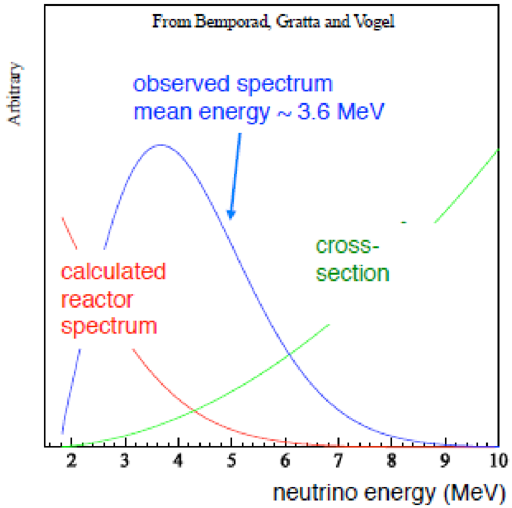
$\sim 5 \times 10^{20}$ ν/sec

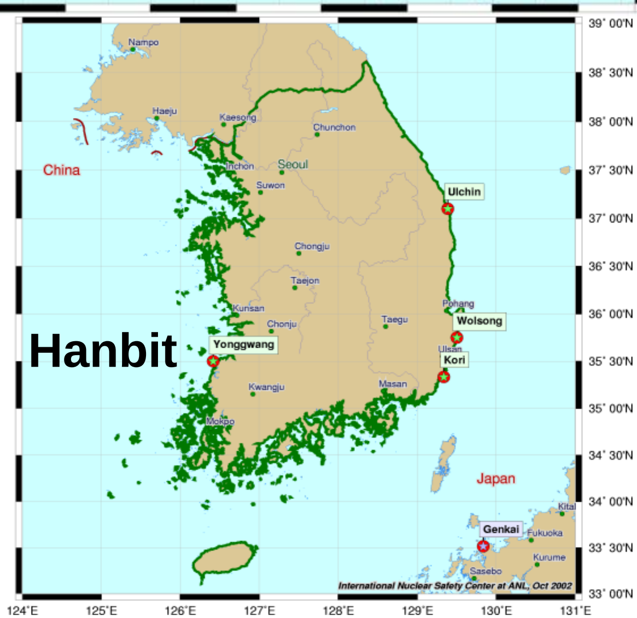
Nuclear Power Plants



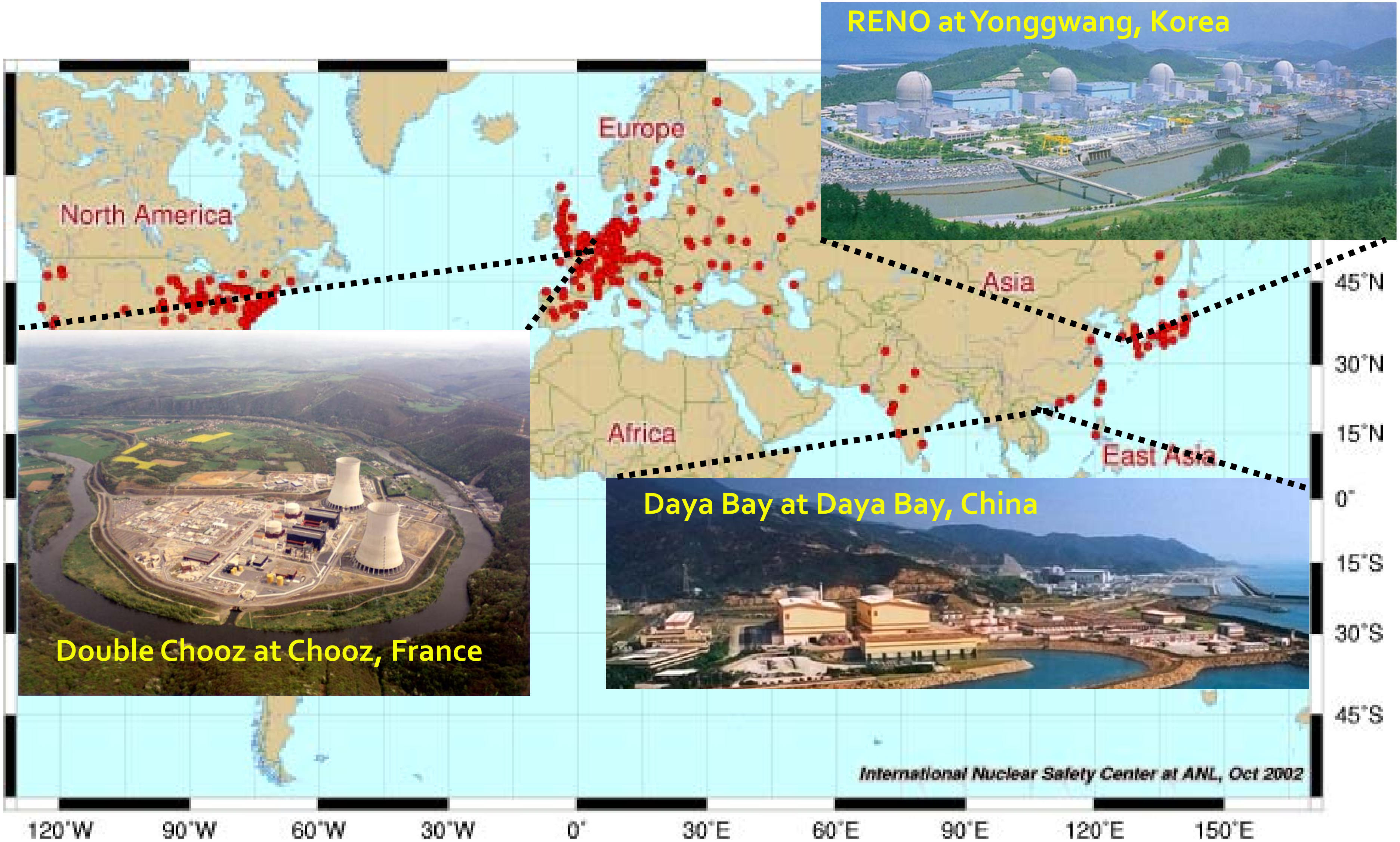
- Cost-free, intense, low-energy & well-known neutrino source !



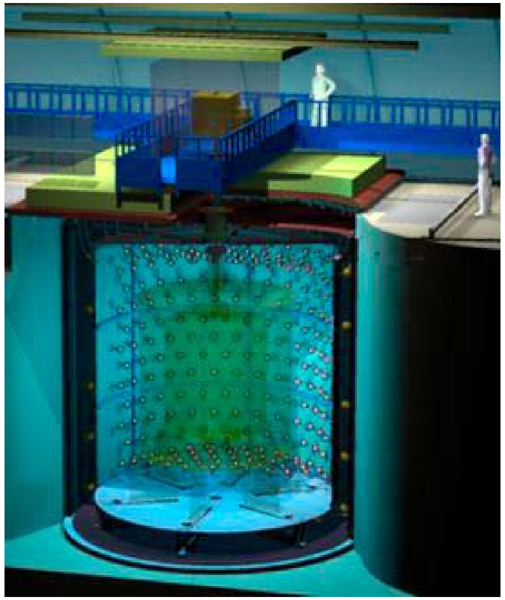


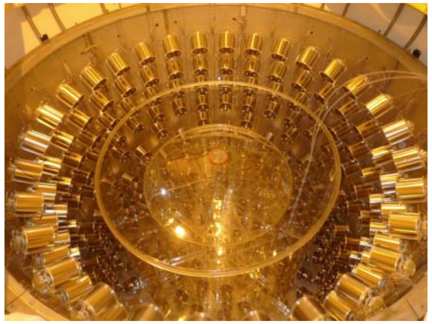


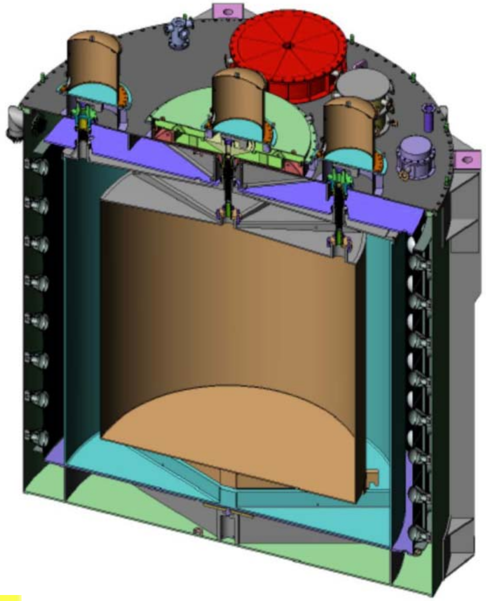
Reactor θ_{13} Experiments

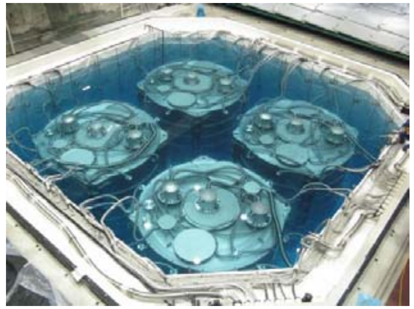


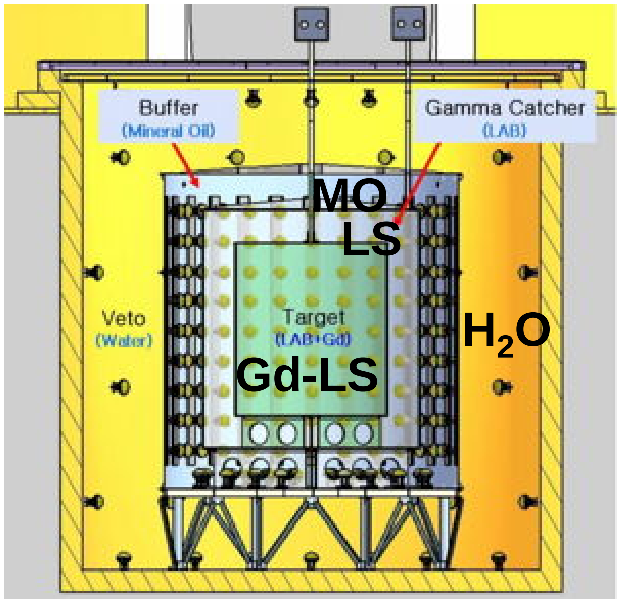
θ_{13} Reactor Neutrino Detectors











RENO Collaboration

Reactor Experiment for Neutrino Oscillation

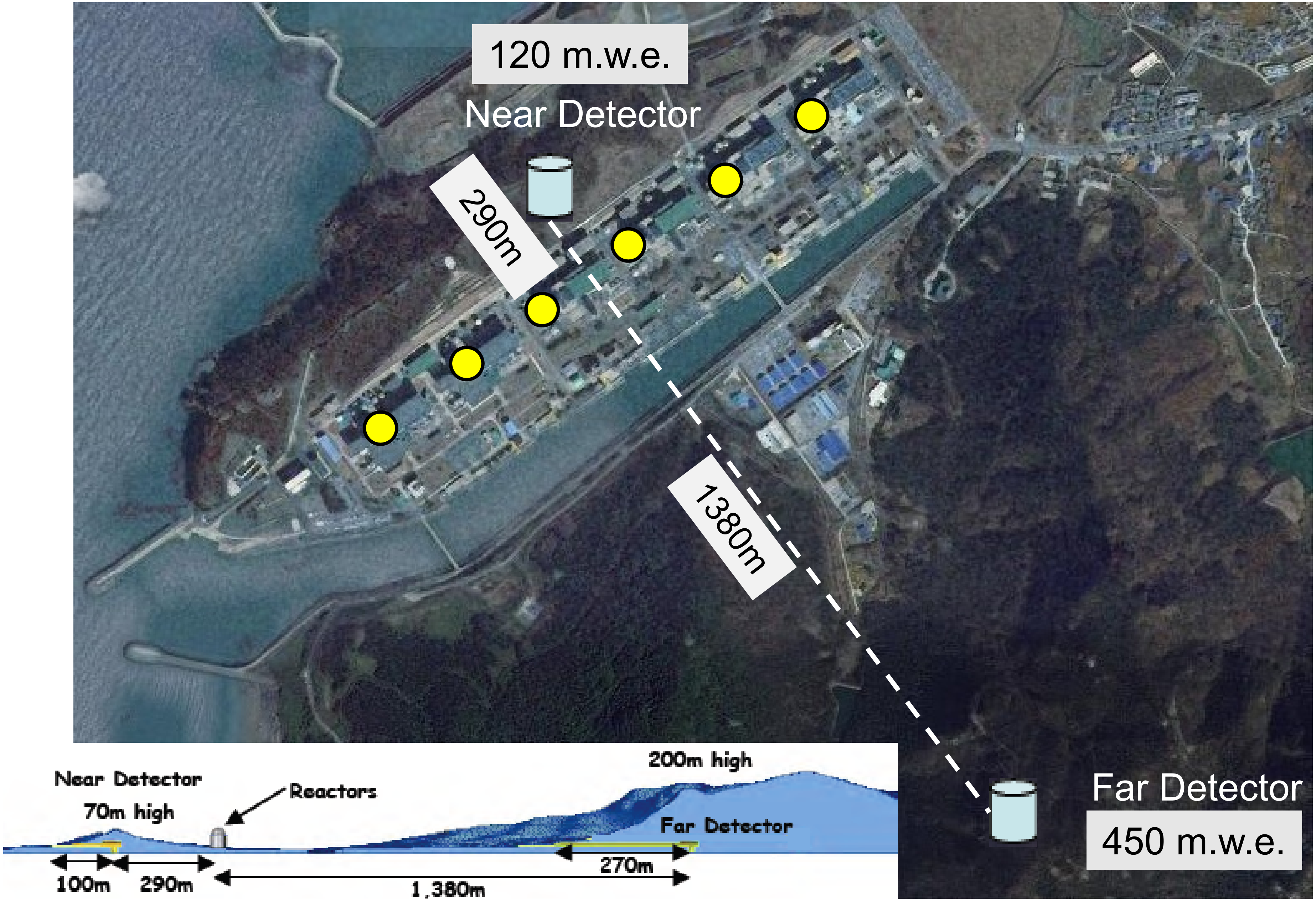
(11 institutions and 40 physicists)

- Chonbuk National University
- 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 Status

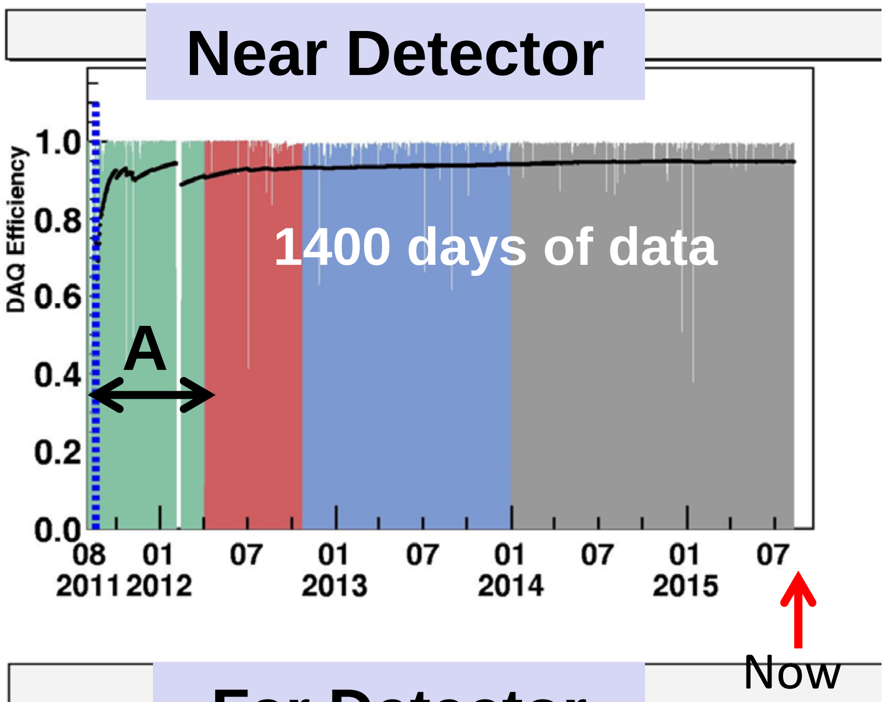
- Data taking began on Aug. 1, 2011 with both near and far detectors. (DAQ efficiency : ~95%)

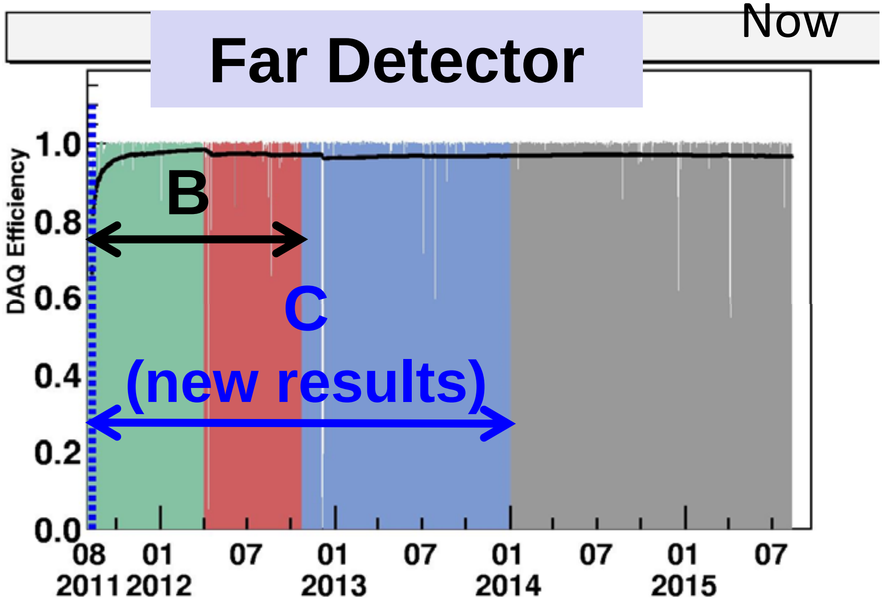
- **A** (220 days) : **First θ_{13} result**
  [11 Aug, 2011~26 Mar, 2012]
  PRL 108, 191802 (2012)

- **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]

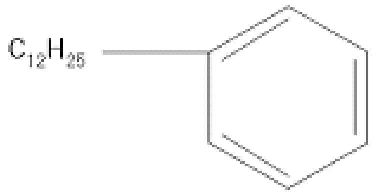
- Total observed reactor neutrino events as of today : **~ 1.5M** (Near), **~ 0.15M** (Far)
  → Absolute reactor neutrino flux measurement in progress
  [reactor anomaly & sterile neutrinos]





Detection of Reactor Antineutrinos

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



Linear Alkyl Benzene (LAB)

(prompt signal)

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

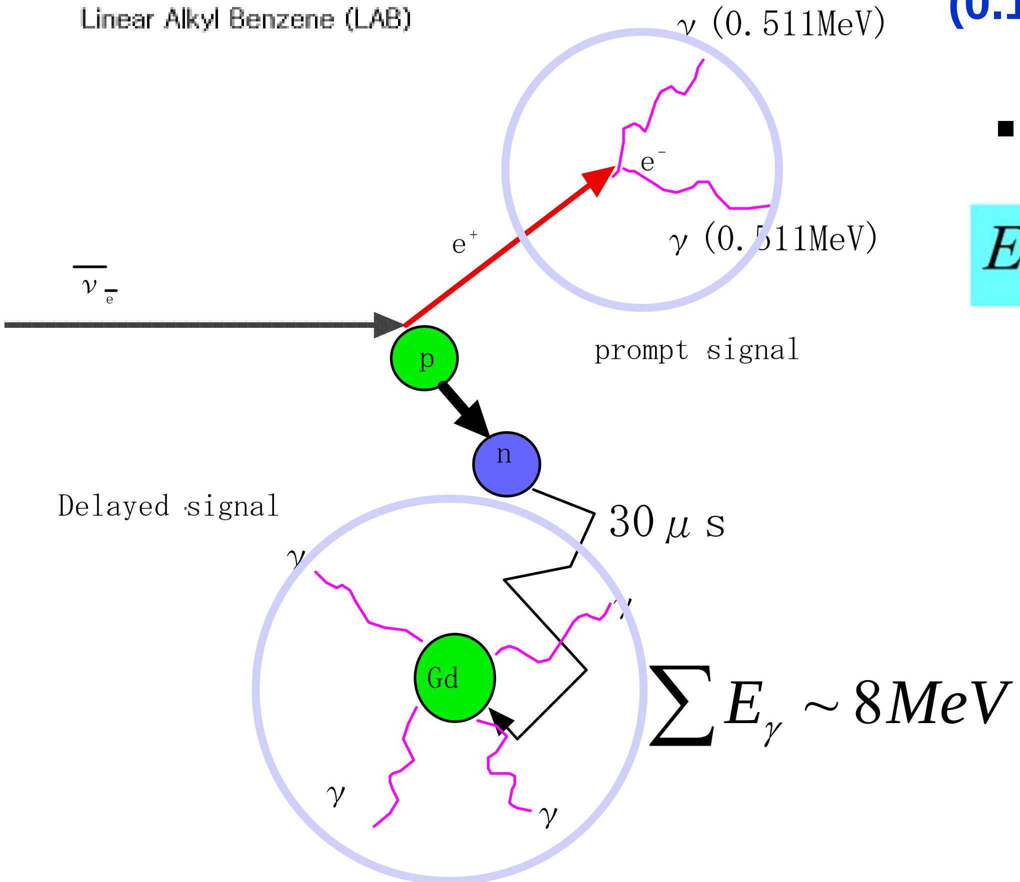
(delayed signal)

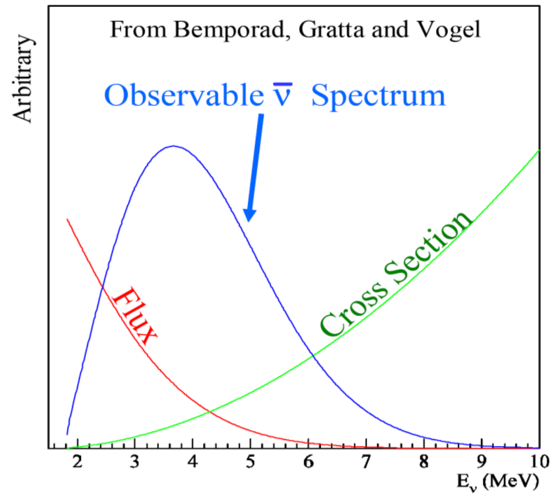
~180 μs: + p → D + γ (2.2 MeV)

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

- **Neutrino energy measurement**

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





New RENO Results

- ~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} (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 Li/He background

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

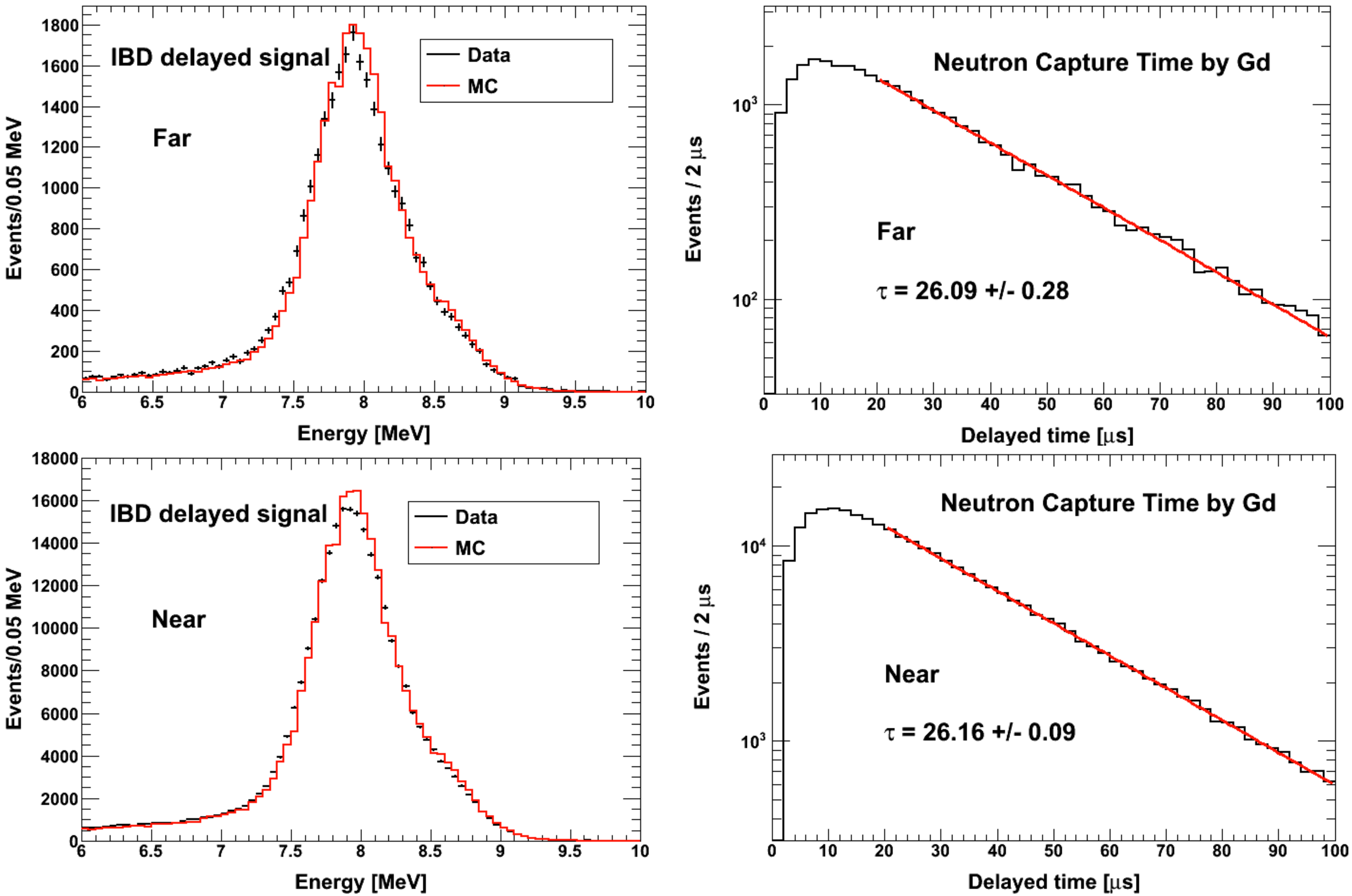
- More accurate energy calibration

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

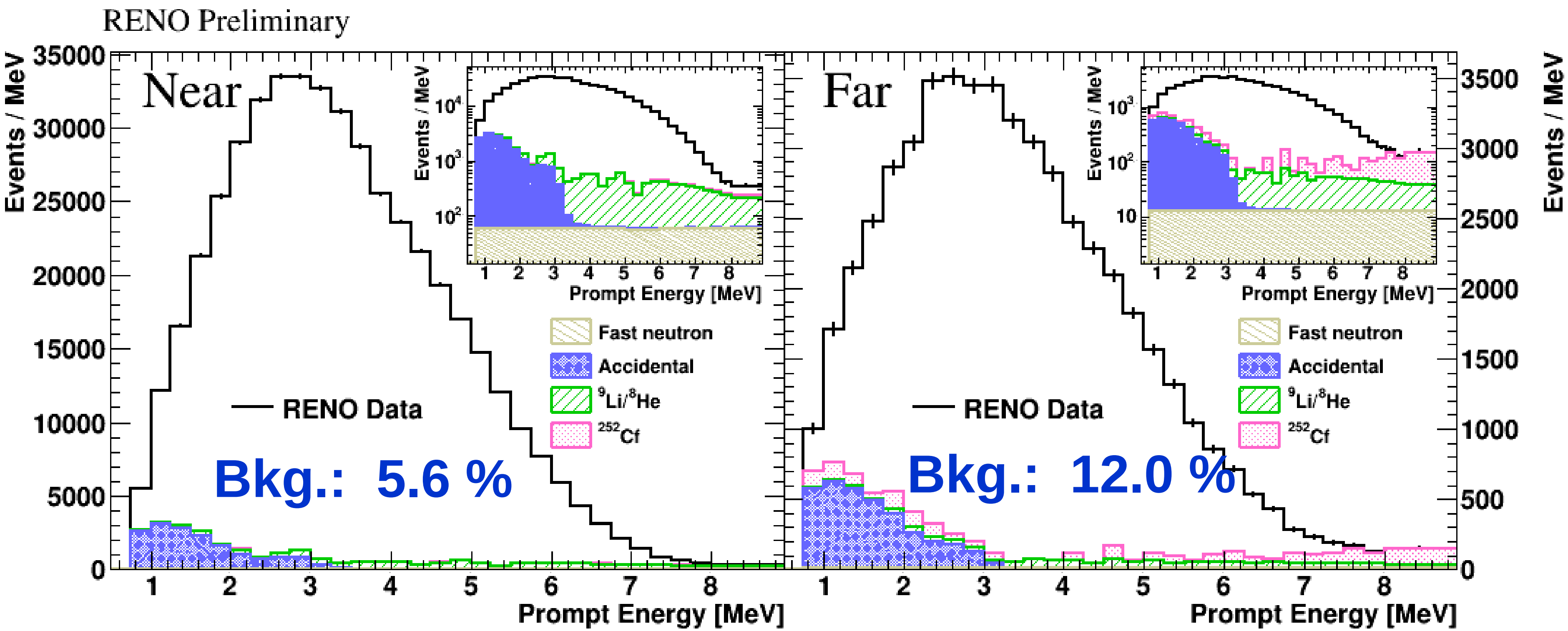
- Elaborate study of systematic uncertainties on a spectral fitter

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

Neutron Capture by Gd



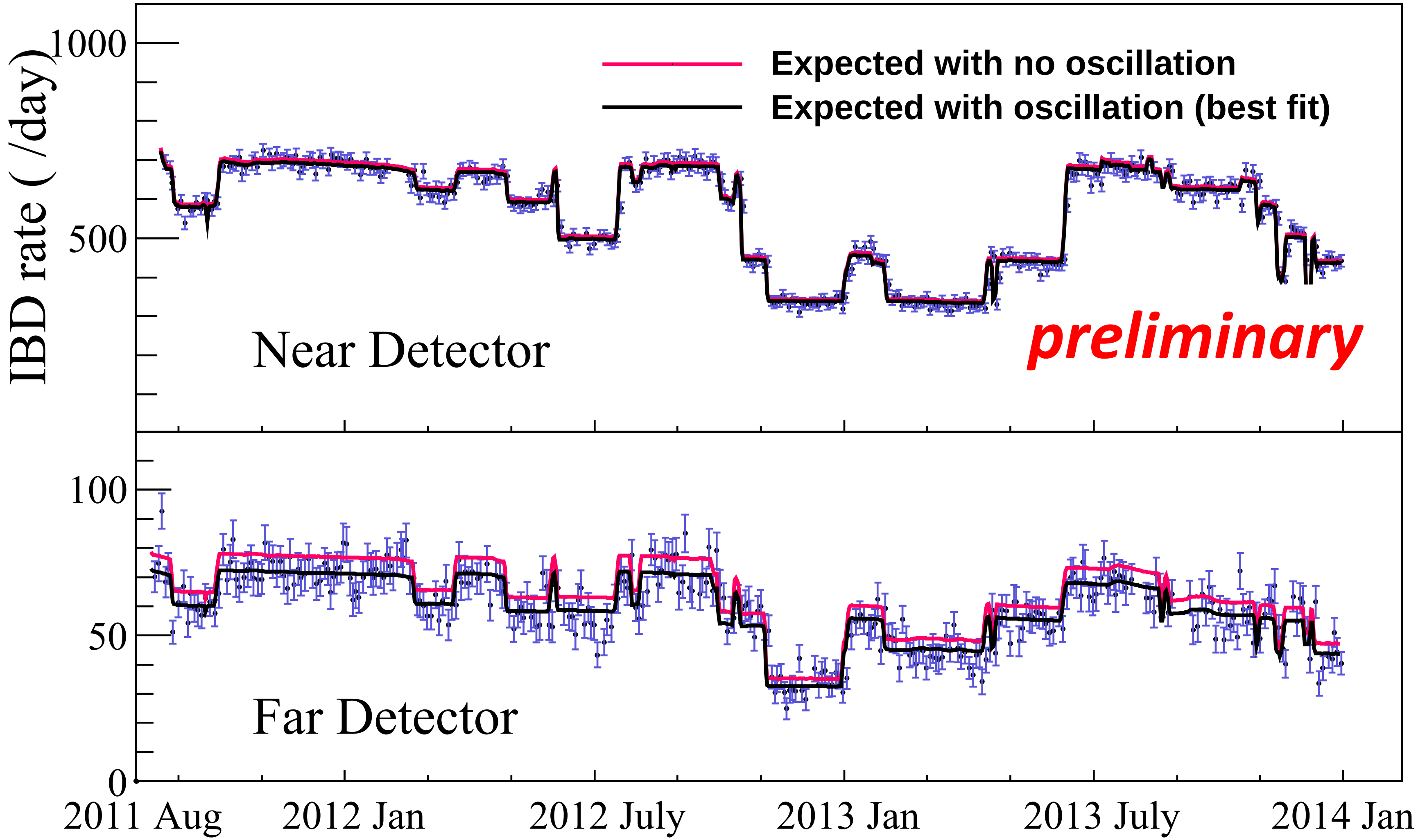
Measured Spectra of IBD Prompt Signal



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

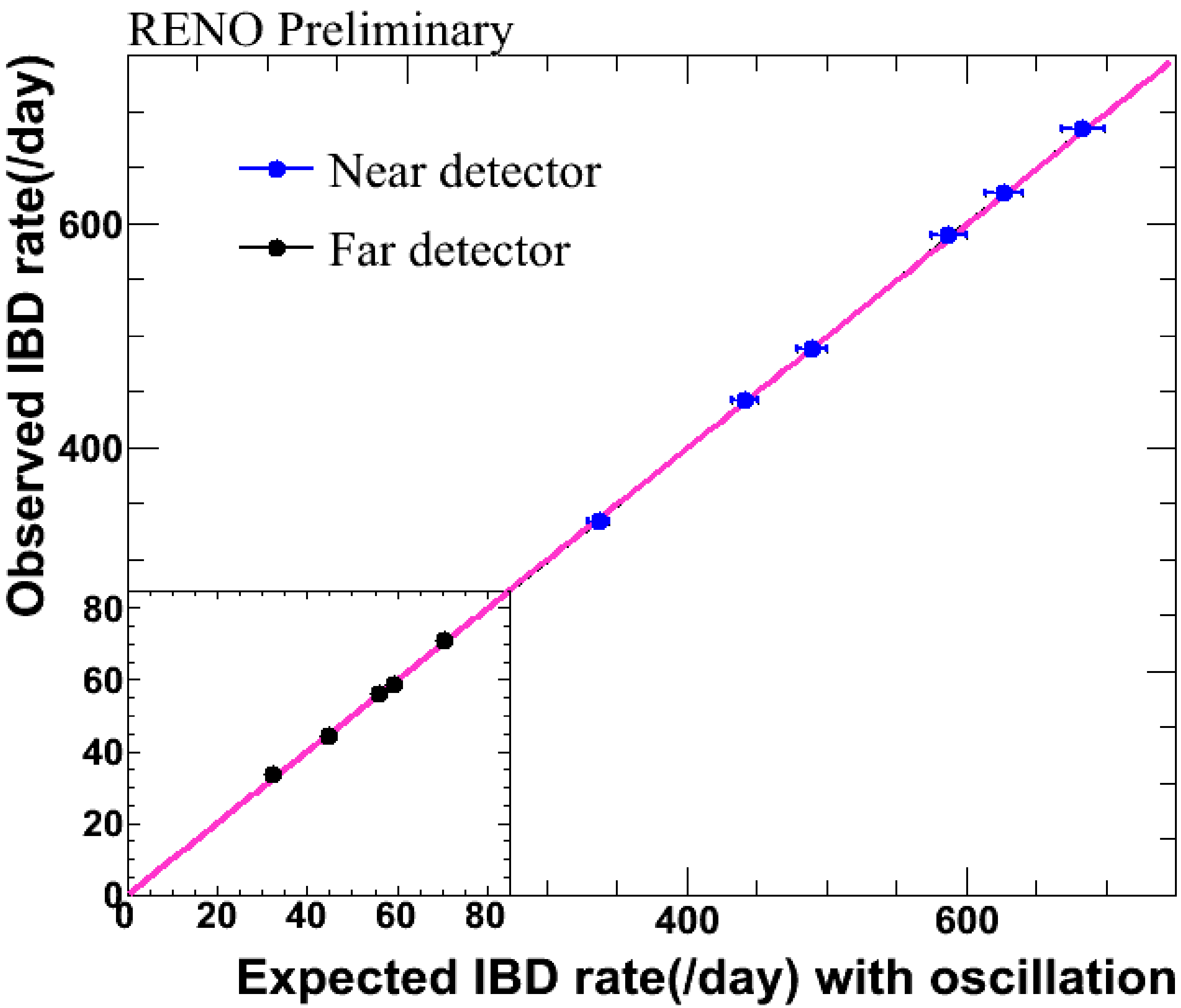
Far Live time = 794.72 days
# of IBD candidate = 52,250
# of background = 6,292 (12.0 %)

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

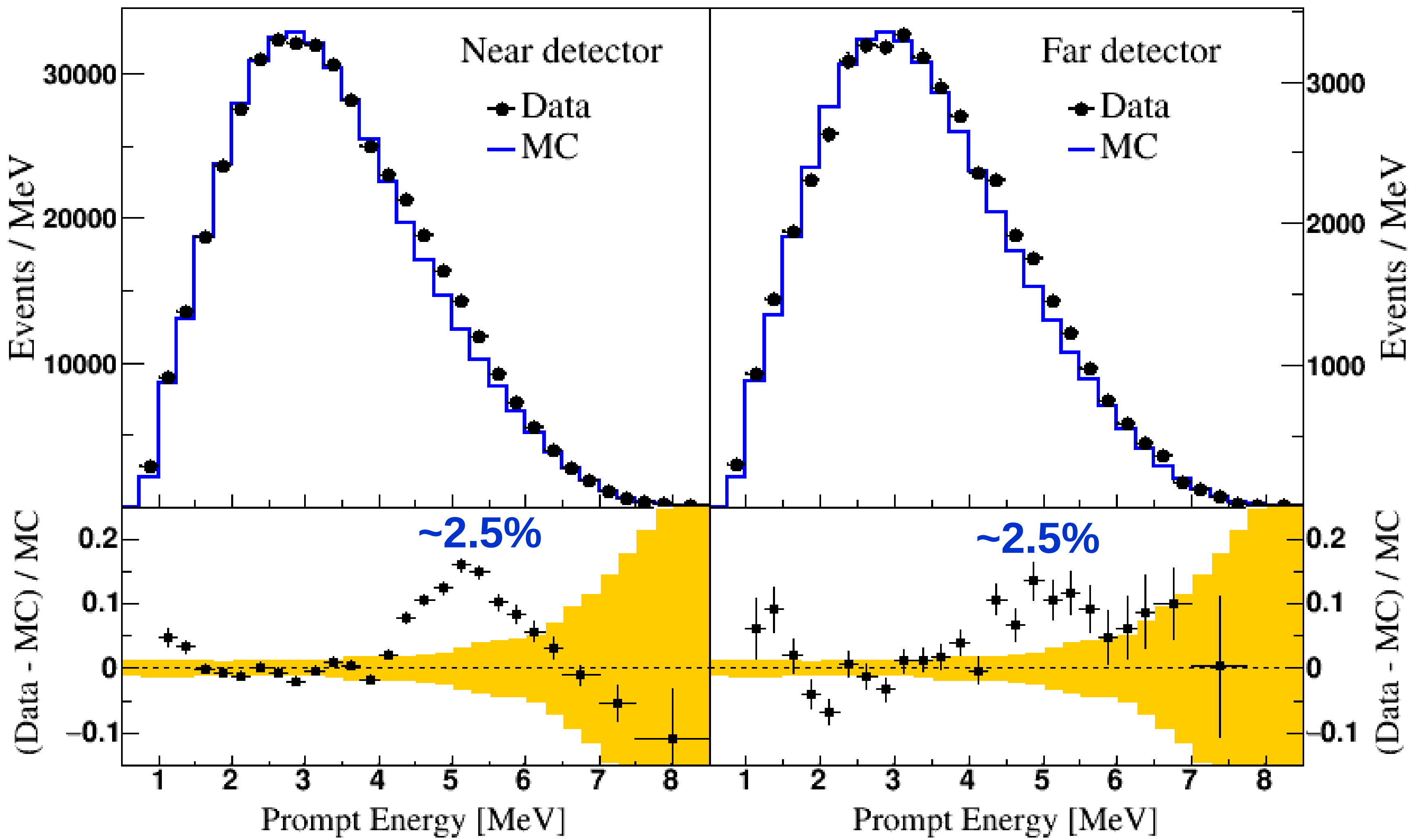
New θ_{13} Measurement by Rate-only Analysis

(Preliminary)

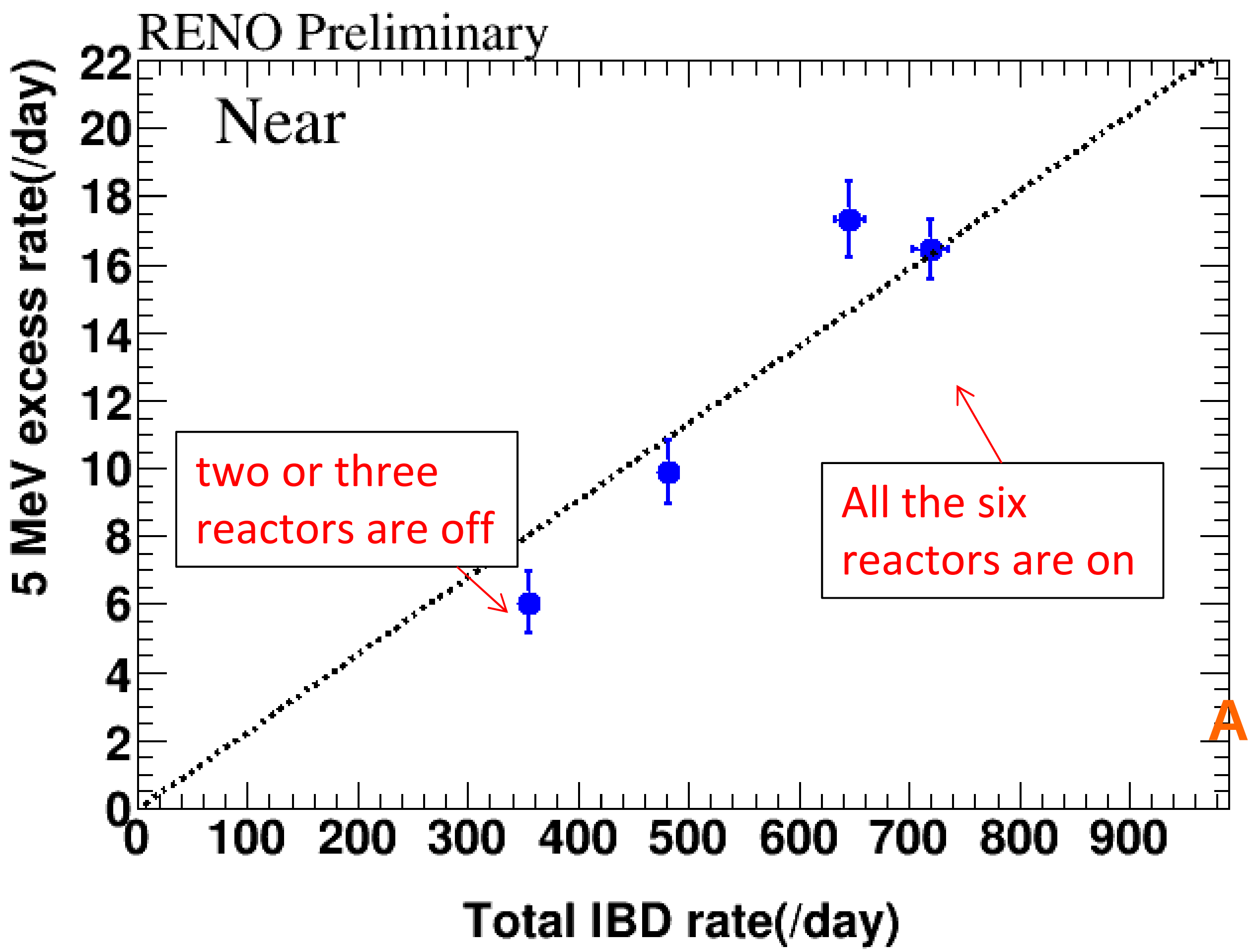
$$\sin^2 2\theta_{13} = 0.087 \pm 0.008(\text{stat.}) \pm 0.008(\text{syst.})$$

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



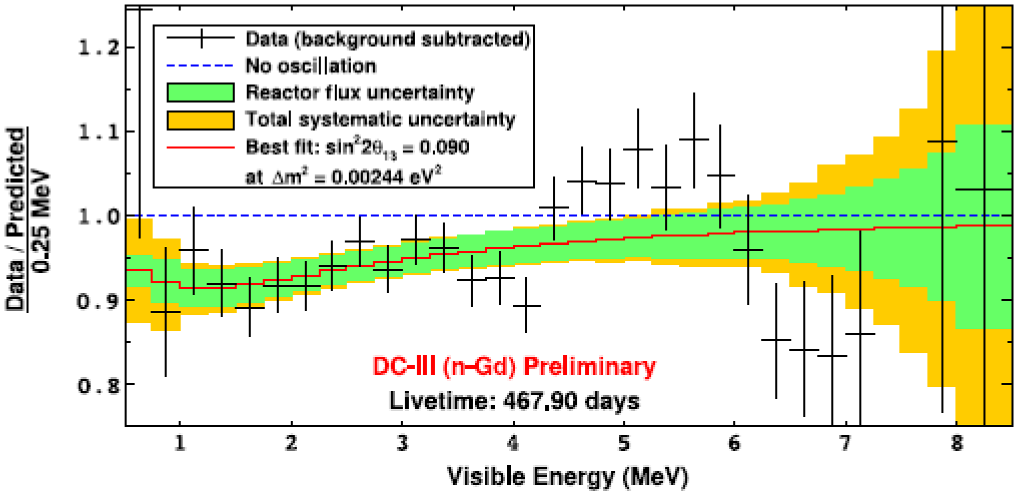
5 MeV excess has a clear correlation with reactor thermal power !

A new reactor neutrino component !!

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

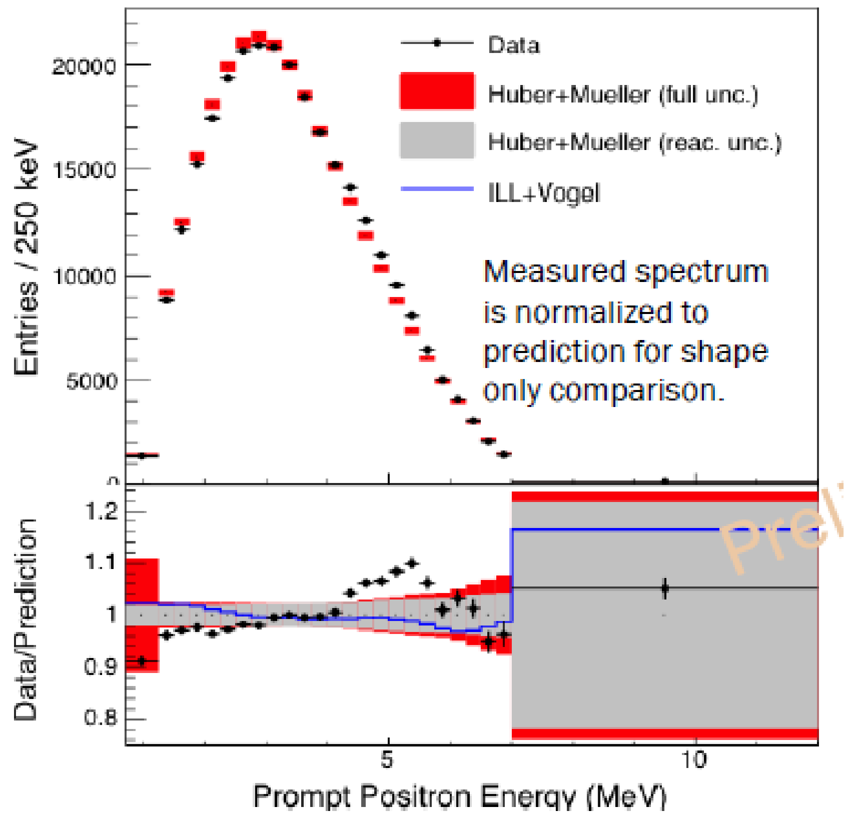
- The excess may be explained by addition of eight isotopes, such as ^{96}Y and ^{92}Rb

The 5 MeV Excess Seen at Double-Chooz and Daya Bay



Double-Chooz, Neutrino 2014

Daya Bay, ICHEP 2014



Why n-H IBD Analysis?

Motivation:

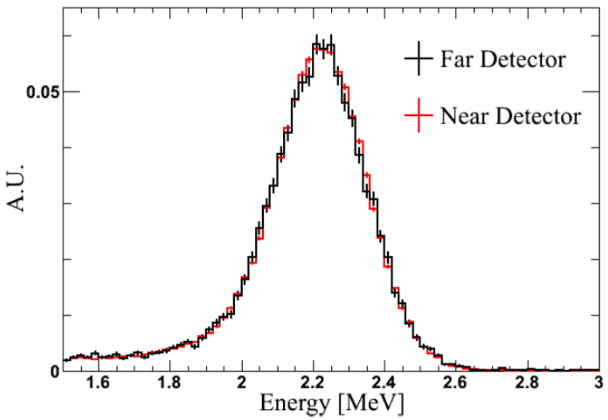
1. Independent measurement of θ_{13} value.
2. Consistency and systematic check on reactor neutrinos.

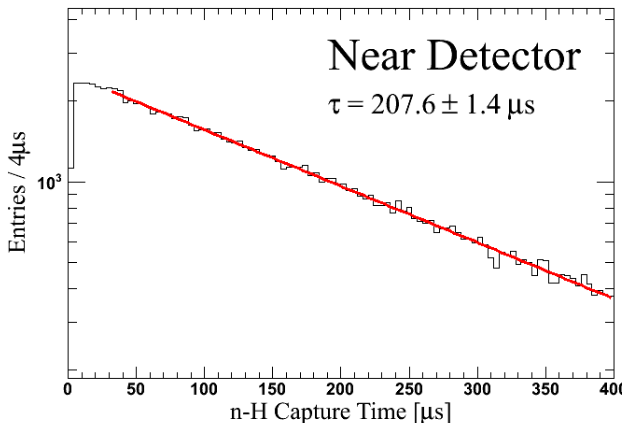
* RENO's low accidental background makes it possible to perform n-H analysis.

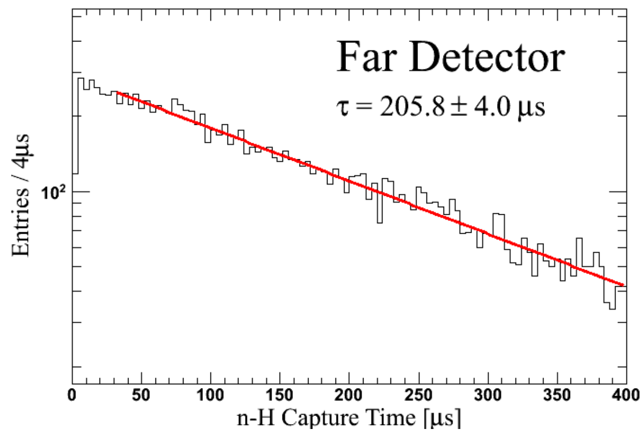
-- low radio-activity PMT
-- successful purification of LS and detector materials.

IBD Sample with n-H

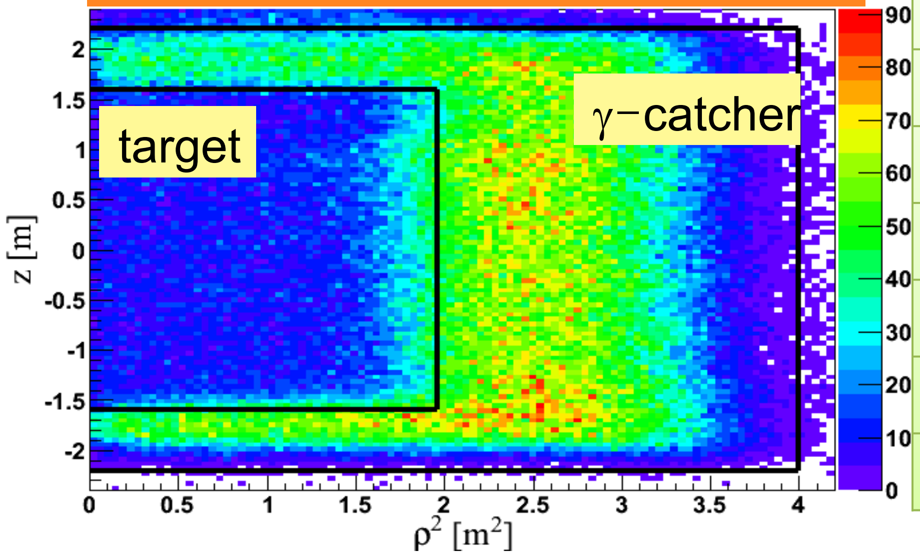
preliminary







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

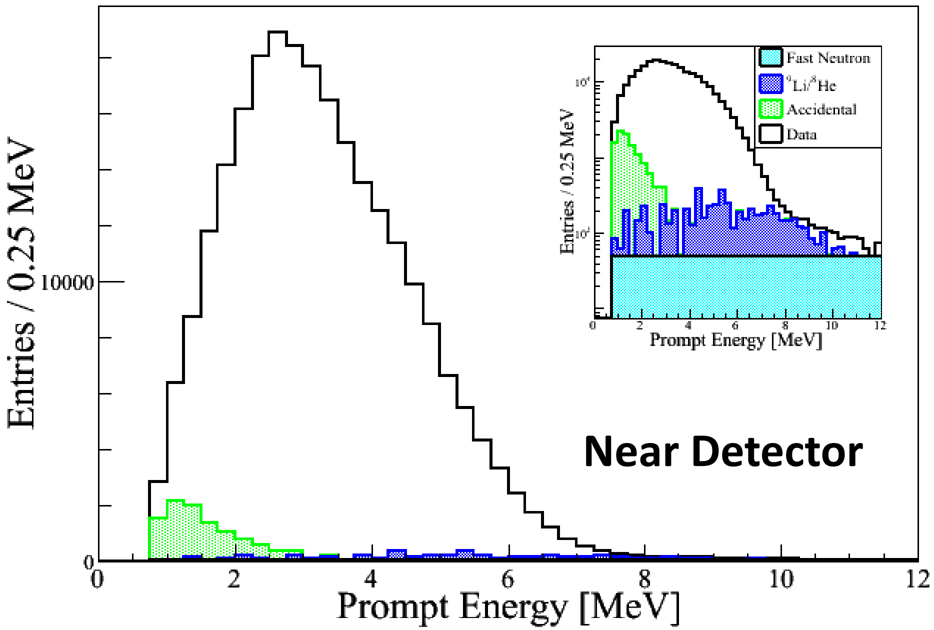
(B data set, ~400 days)

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

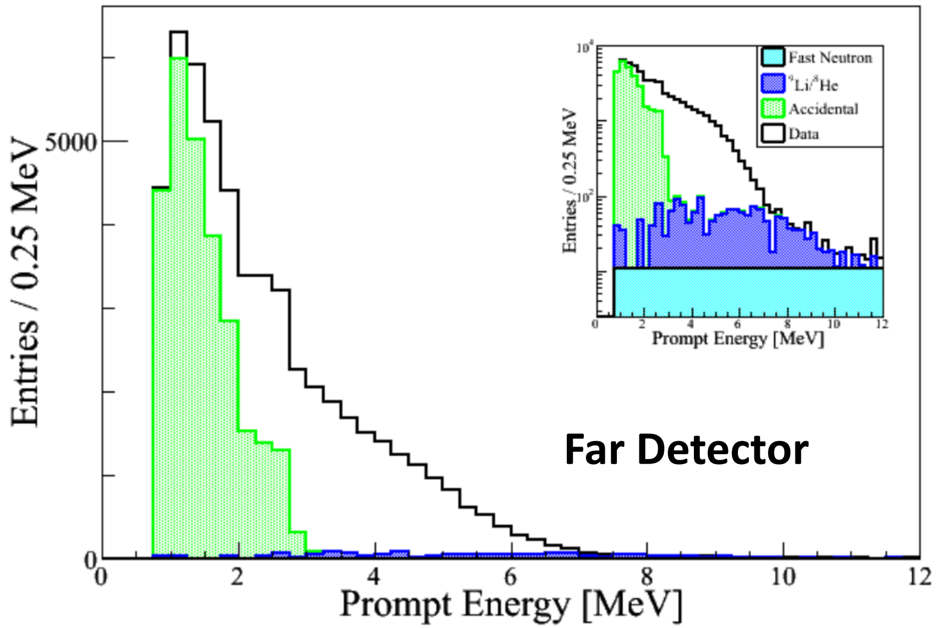
(Neutrino 2014) $\sin^2 2\theta_{13} = 0.095 \pm 0.015(\text{stat.}) \pm 0.025(\text{syst.})$

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

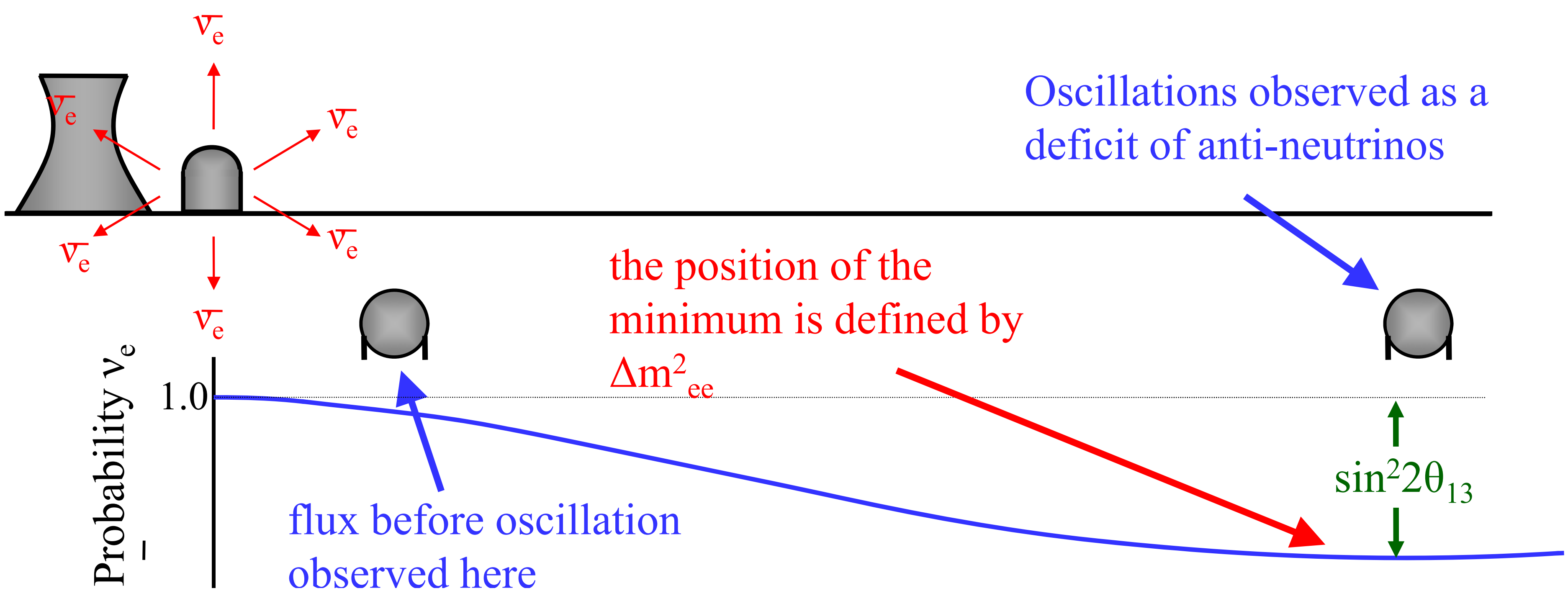
preliminary



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

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

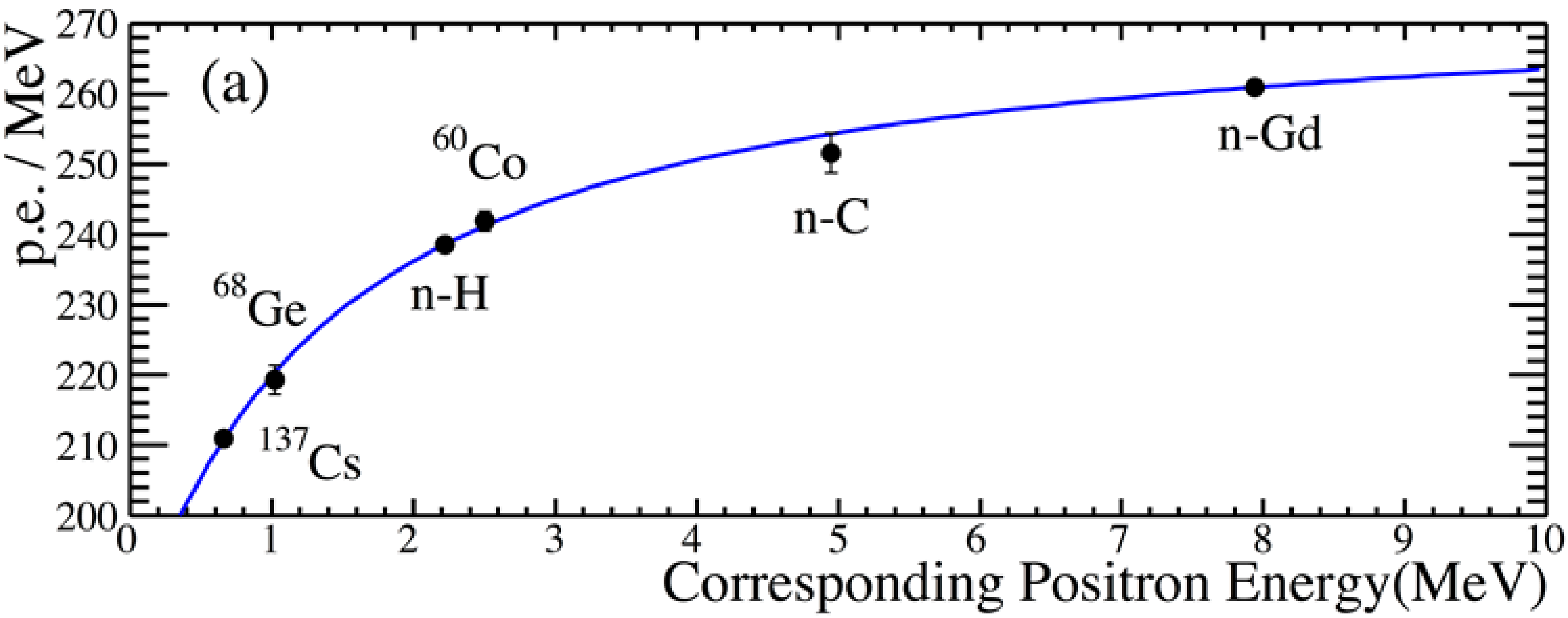
$$|\Delta m^2_{ee}| \simeq |\Delta m^2_{32}| \pm 5.21 \times 10^{-5}\mathrm{eV}^2$$

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

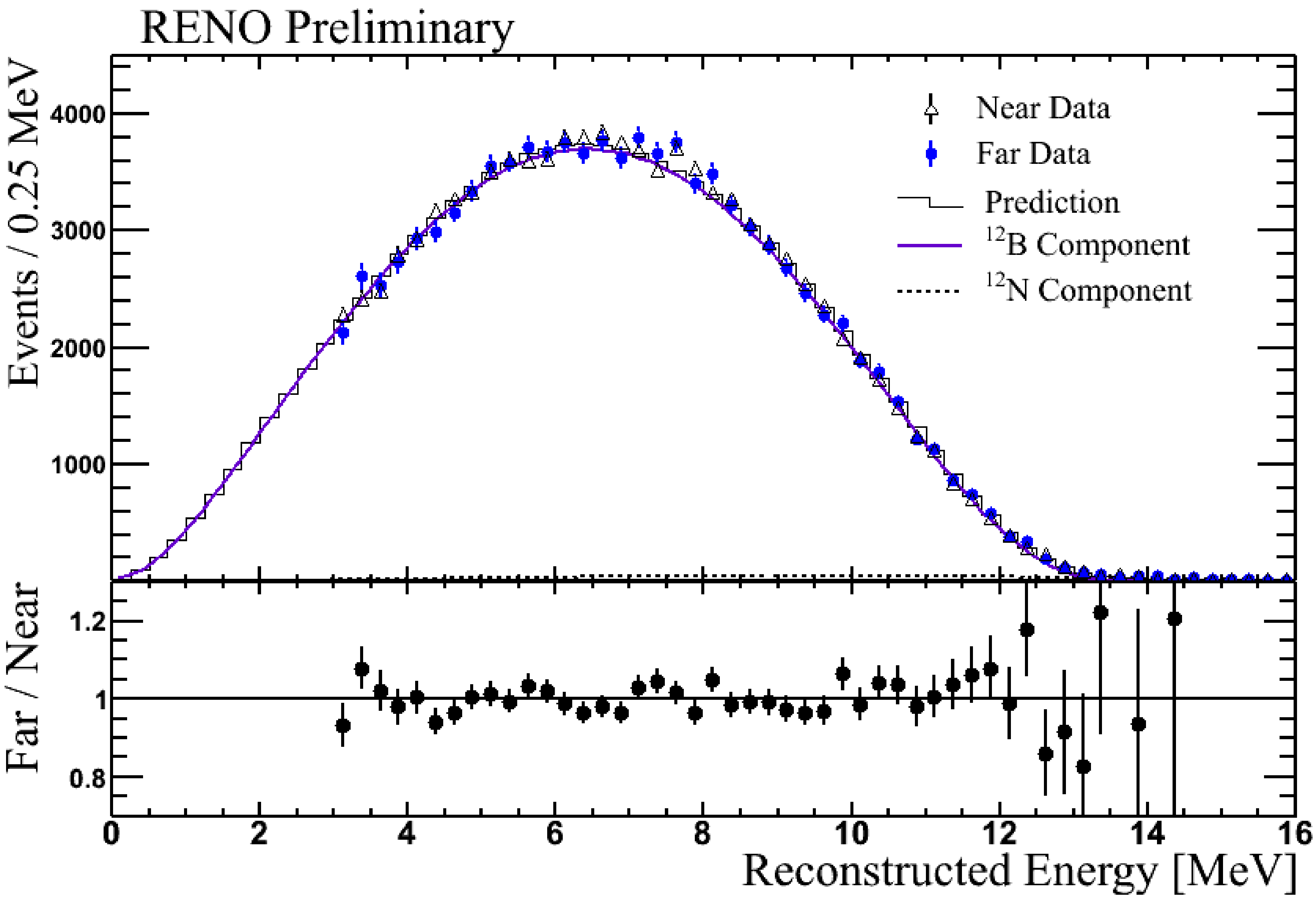
+: Normal Hierarchy

−: Inverted Hierarchy

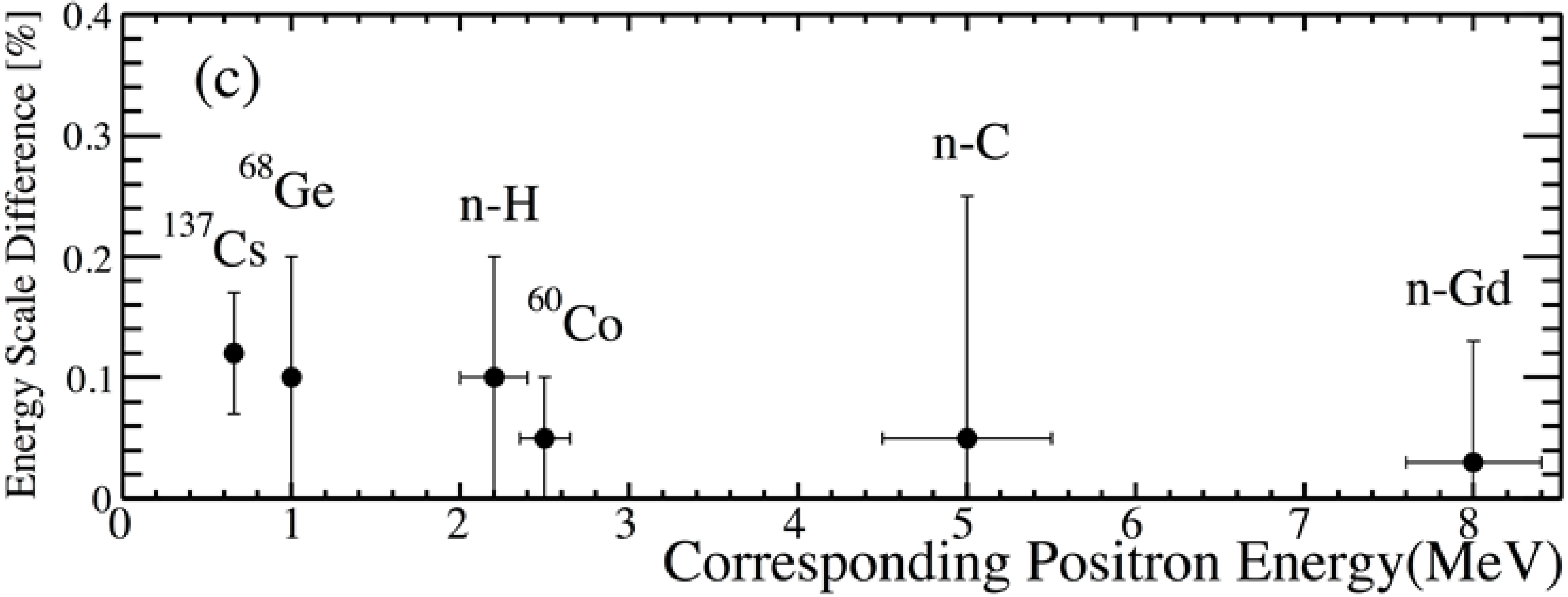
Energy Calibration from γ-ray Sources



B12 Energy Spectrum (Near & Far)



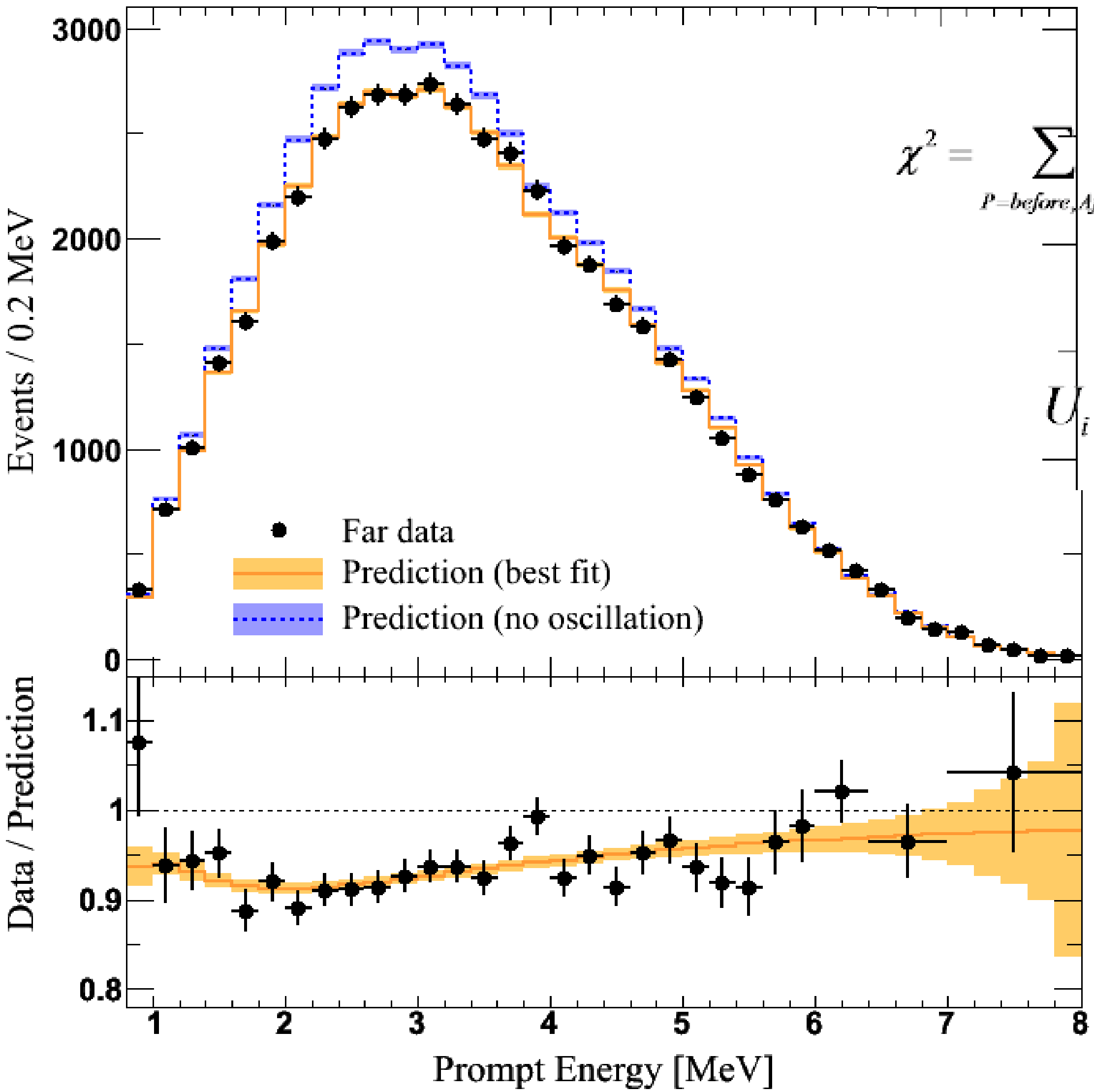
Energy Scale Difference between Near & Far



Energy scale difference < 0.15%

Far/Near Shape Analysis for Δm_{ee}^2

(work in progress)

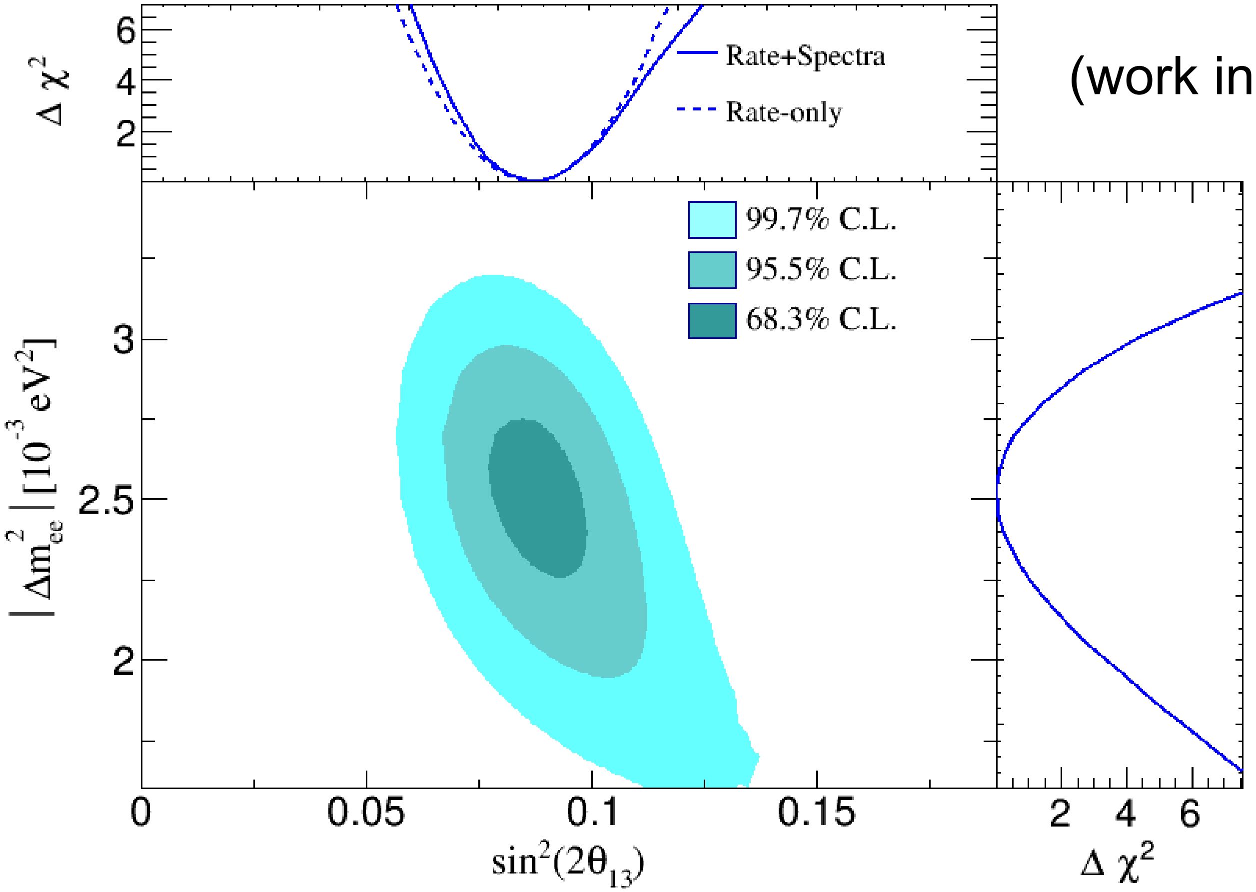


Minimize X^2 Function

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

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

Results from Spectral Fit



(work in progress)

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

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

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

(work in progress)

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

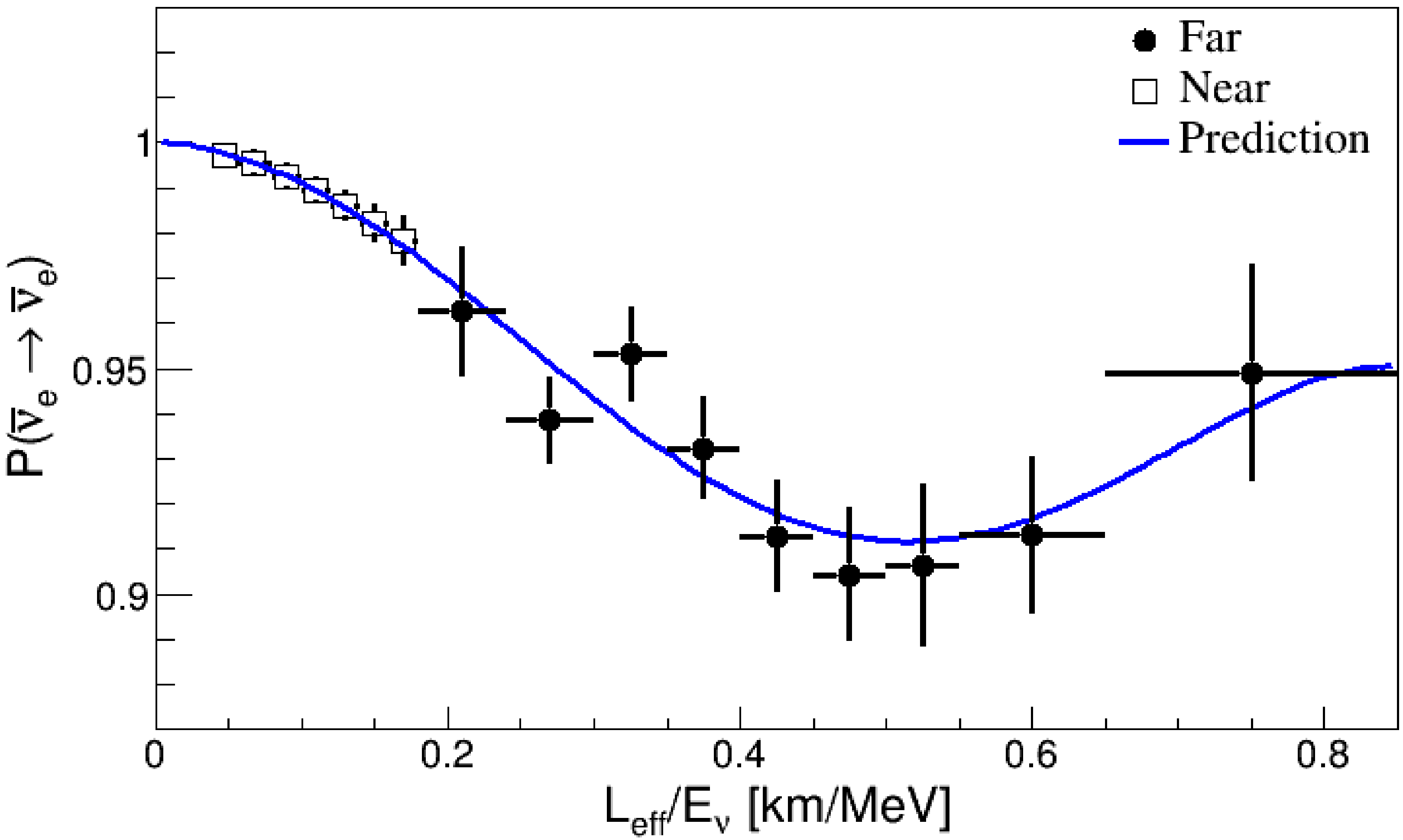
$$\Delta m_{ee}^2 = [2.52 \pm 0.19(\mathrm{stat}) \pm 0.17(\mathrm{syst})] \times 10^{-3}\ \mathrm{eV}^2$$ (± 10 %)

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)

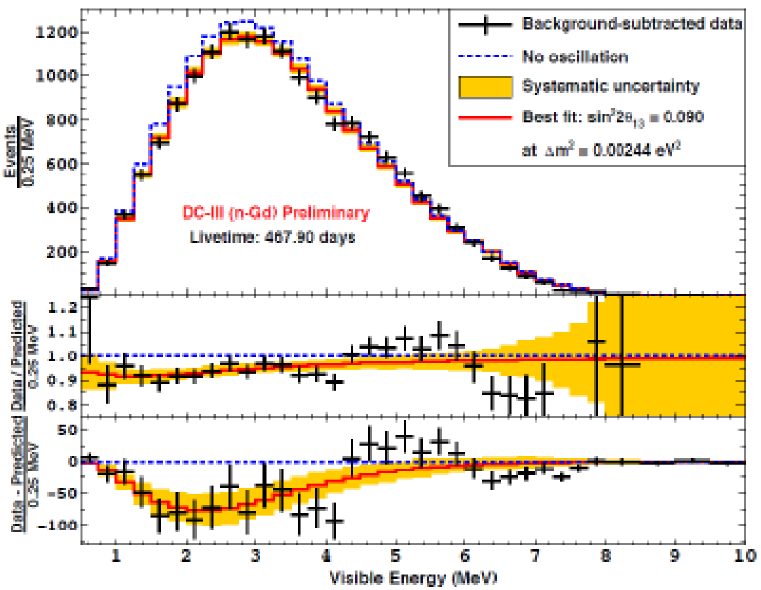
Observed L/E Dependent Oscillation

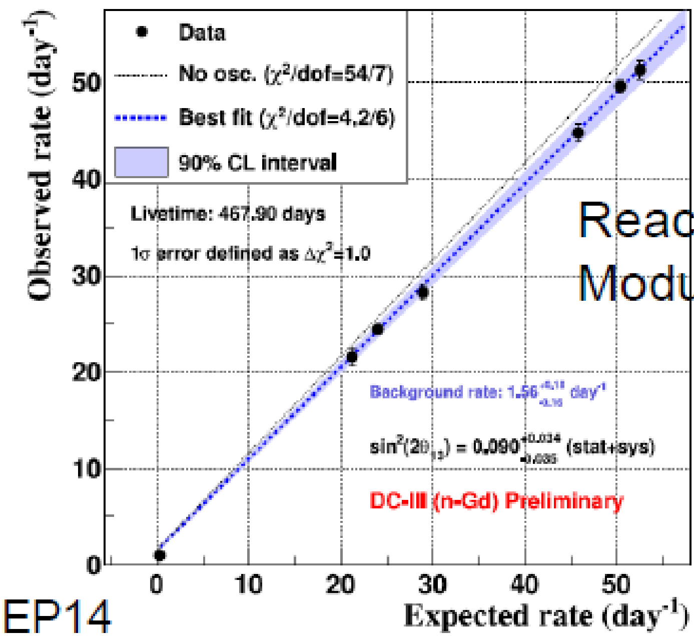
(work in progress)



Double Chooz Results

- 2011.4 – 2013.1 (460 days) : No near site detector until 2014.11
- Spectral analysis for n-Gd & n-H samples
- Reactor-off data for direct measurement of backgrounds





Reactor Rate Modulation

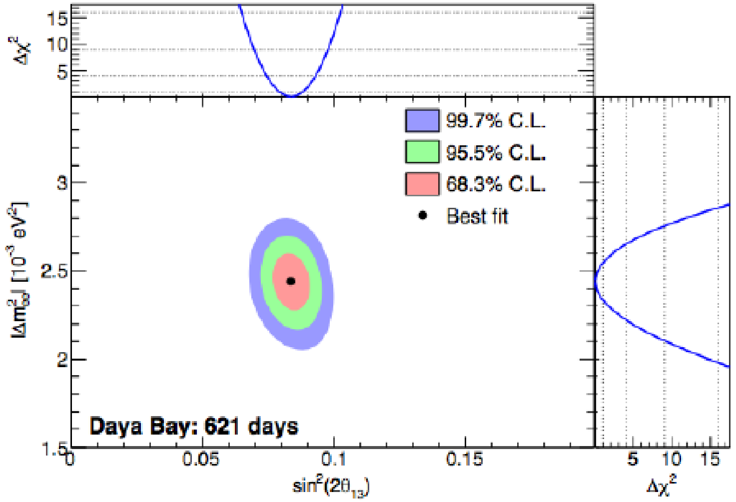
Haser, ICHEP14

- R+S : $\sin^2 2\theta_{13} = 0.090^{+0.032}_{-0.029}$

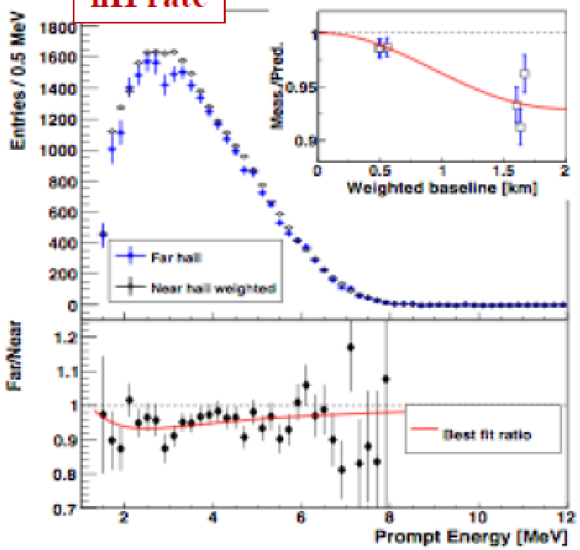
Daya Bay Results

- 2011.12 – 2013.11 (621 days)
- Rate+Spectral analysis for n-Gd sample
- Rate analysis for n-H sample

nGd rate+shape



nH rate



$$\sin^2 2\theta_{13} = 0.084^{+0.005}_{-0.005}$$

$$|\Delta m^2_{ee}| = 2.44^{+0.10}_{-0.11} \times 10^{-3}\mathrm{eV}^2$$

$$\chi^2/NDF = 134.7/146$$

$\sin^2 2\theta_{13} = 0.083$ +- 0.018

arXiv: 1505.03456

- $\Delta(\sin^2 2\theta_{13})/\sin^2 2\theta_{13} \sim 6\%$
  - ⇨ best among all mixing angles
- $\Delta(\Delta m^2_{ee})/\Delta m^2_{ee} \sim 5\%$
  - ⇨ similar to that of MINOS

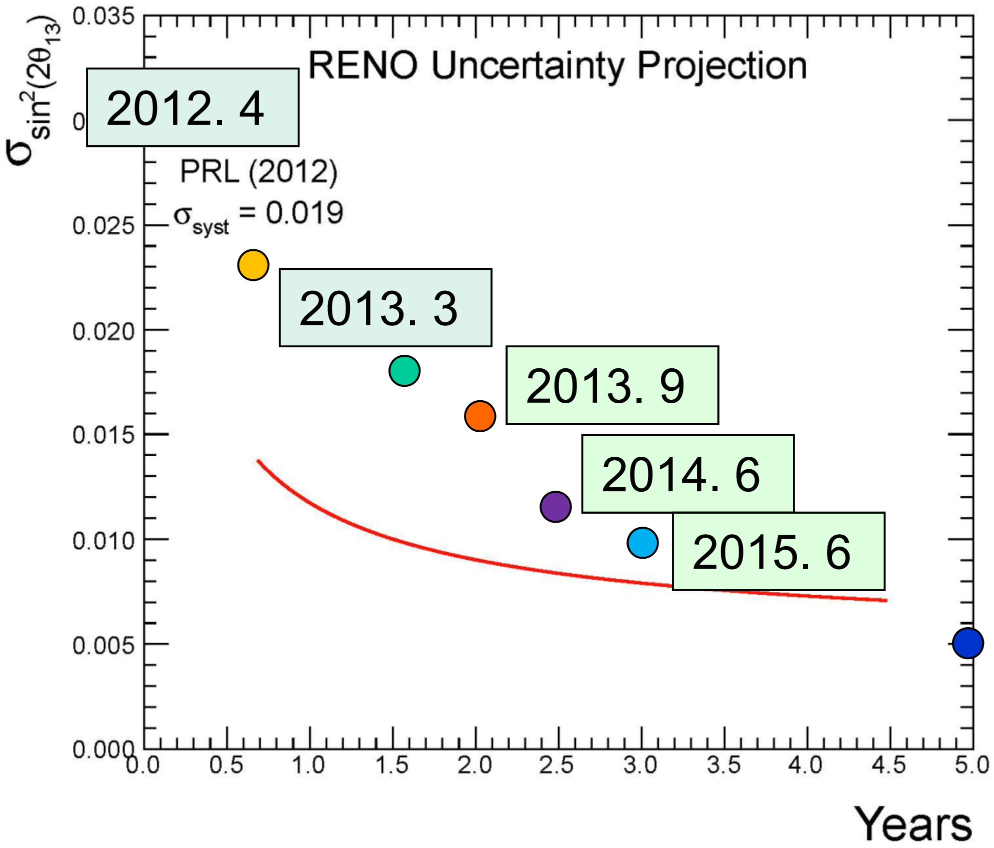
Projected Sensitivity of θ_{13} & Δm_{ee}^2

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

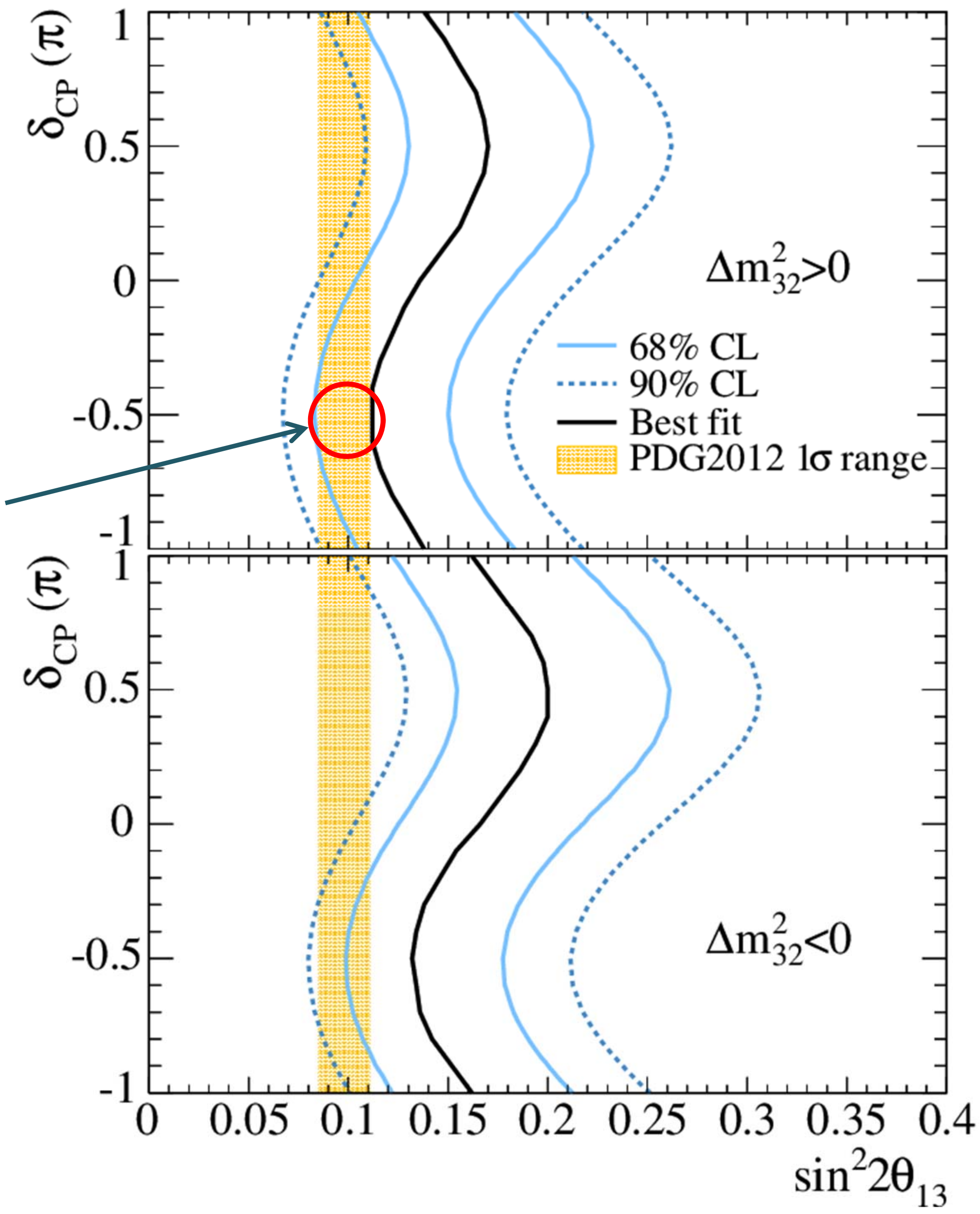
Future Prospects on θ_{13} & Δm_{ee}^2

- Precision dominated by statistics
- Continued efforts on improving systematics

- Expected ultimate precision :

Experiments	$\delta(\sin^2 2\theta_{13})$	$\delta(\Delta m_{ee})$ [$\times 10^{-3}$ eV^2]
Daya Bay	± 0.003 ($\pm 3\%$)	± 0.07 ($\pm 3\%$)
RENO	± 0.005 ($\pm 5\%$)	± 0.1 ($\pm 4\%$)
Double Chooz	± 0.010 ($\pm 10\%$)	

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 Hierarchy

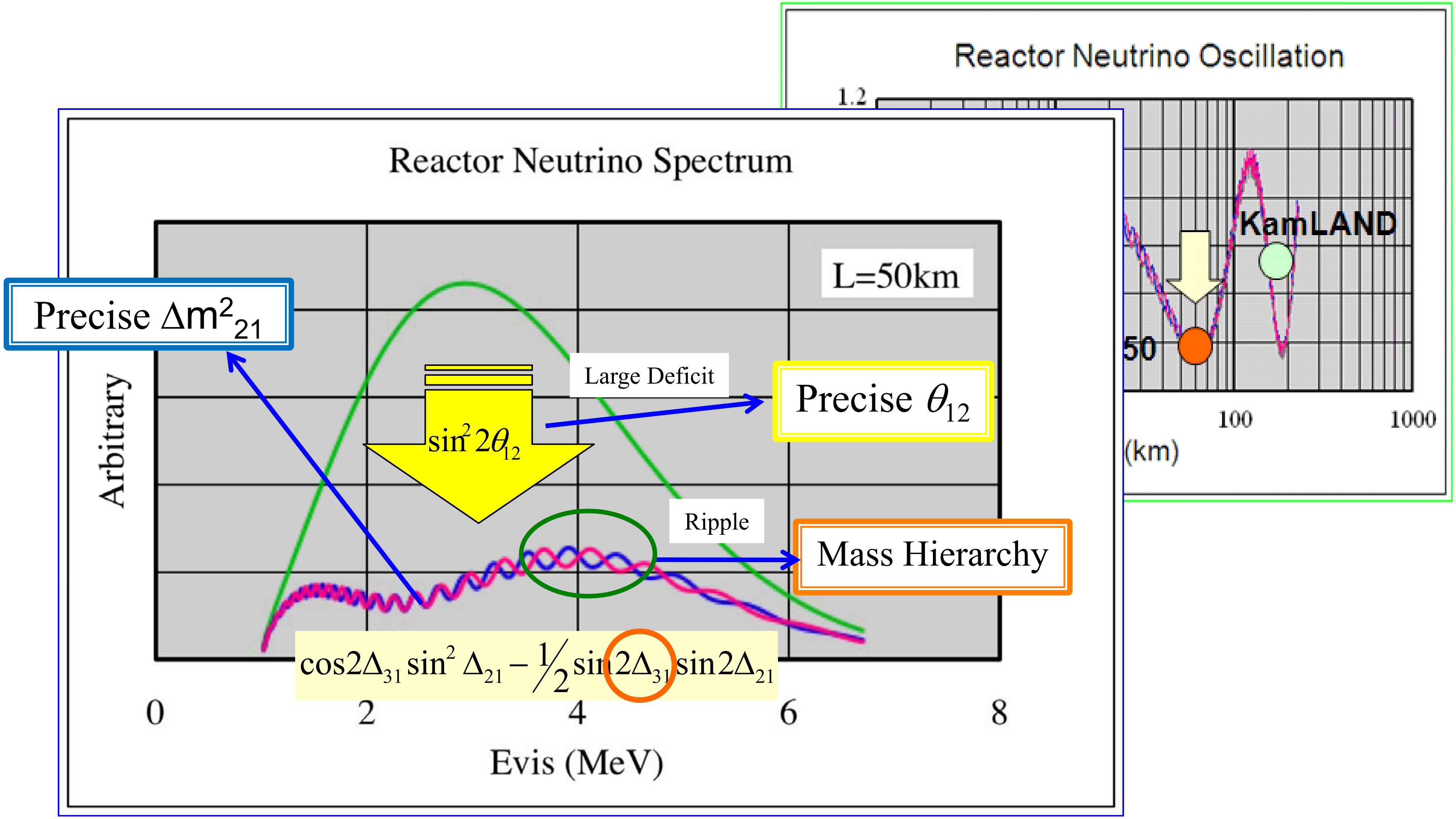
- Reactor experiments: JUNO and RENO-50
  - Subdominant oscillation pattern of Δm_{31}^2
  - Large liquid scintillator detector with a baseline of ~50 km
  - Extraordinary energy resolution (<3% at 1 MeV)

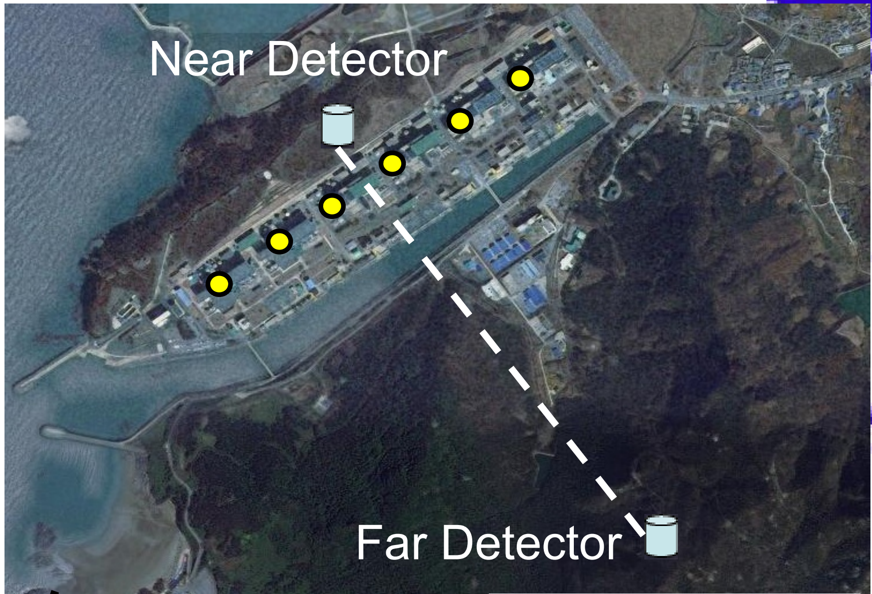
- Long baseline beam experiments: T2K, NOvA, T2HK and LBNE
  - Matter effects of neutrino oscillation
  - Small value of $|\Delta m_{32}^2|/E$ & long baseline L

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





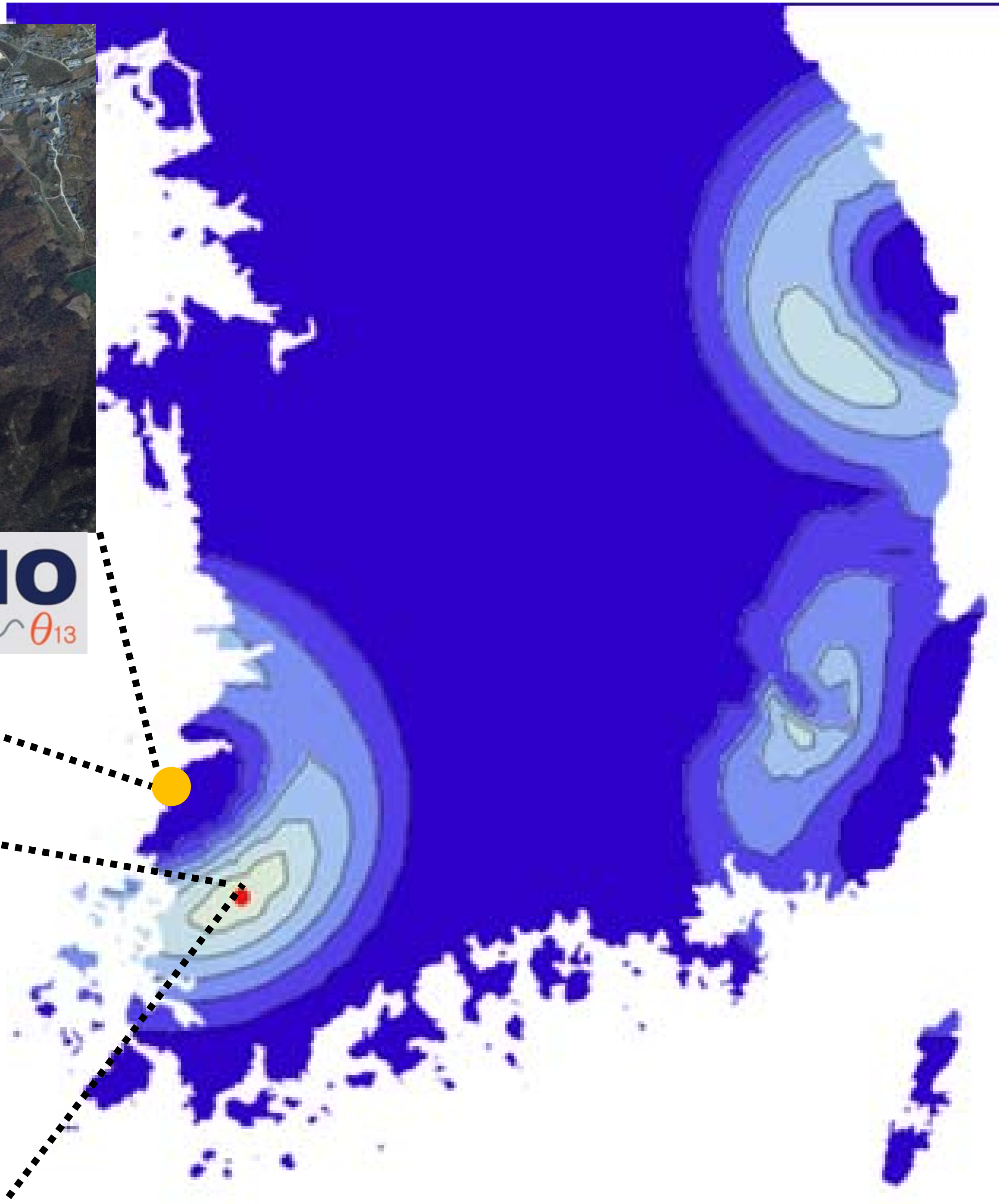
(NEAR Detector)

(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

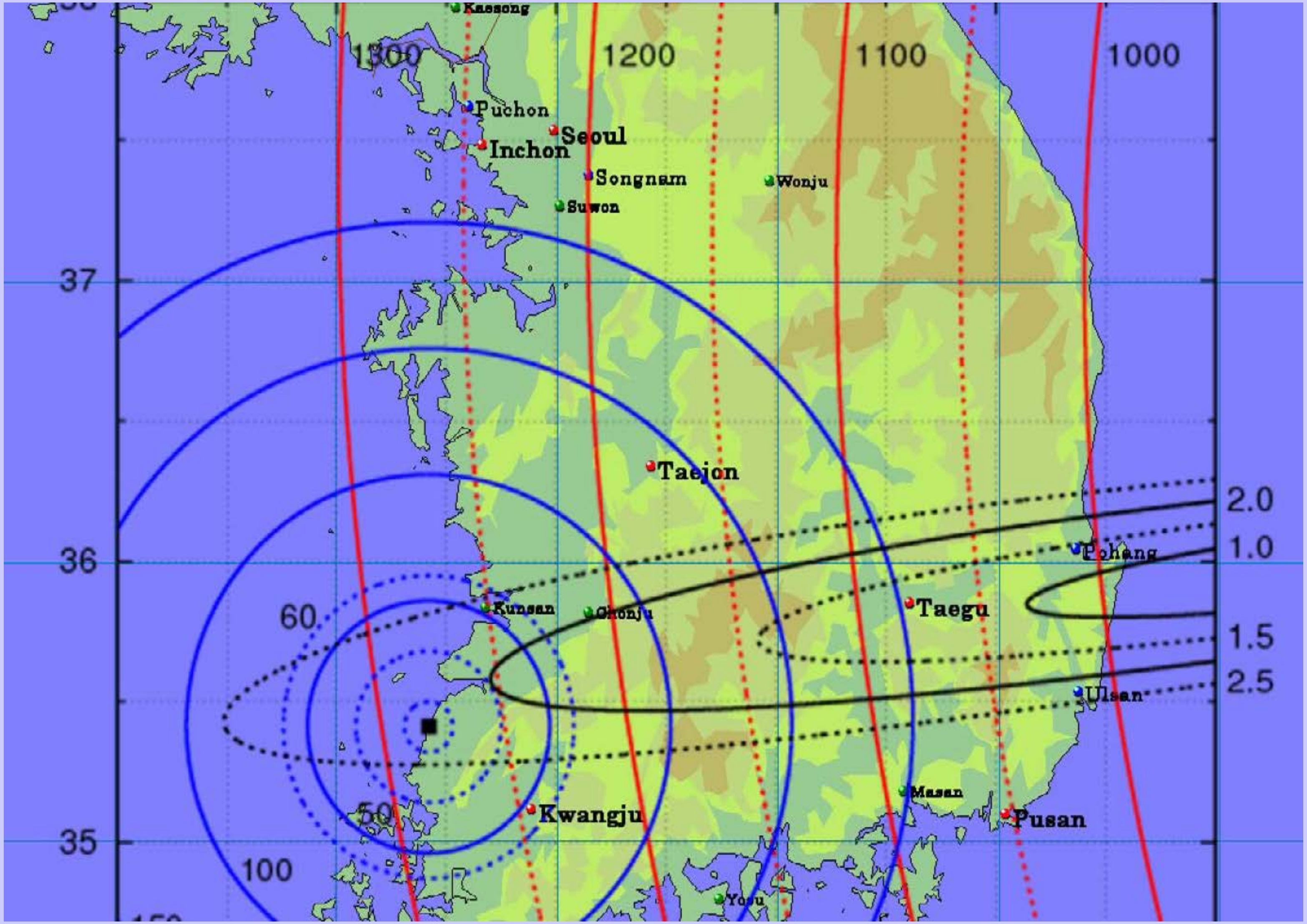
- Geo-neutrinos : ~ 1,000 geo-neutrinos for 5 years
  - Study the heat generation mechanism inside the Earth

- 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



Thanks for your attention!

Experimental site

NPP	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	Operational	Planned	Planned	Under construction	Under construction
Power	17.4 GW	17.4 GW	17.4 GW	17.4 GW	18.4 GW