New Results from RENO and Future RENO-50 Project

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"XXX Rencontres de Physique de la Vallee d'Aoste."

La Thuile, Aosta Valley, Italy, Mar. 6-12, 2016"

VERI TAS LUX MEA

ν_e ν_μ ν_τ

KNRC

Korea Neutrino Research Center

Neutrino Mixing Angles

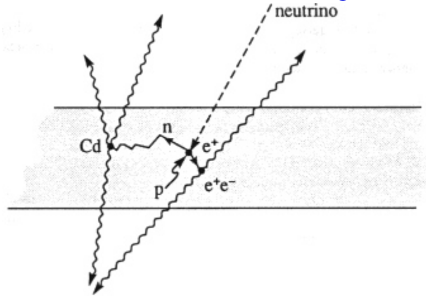
Atmospheric Neutrino Oscillation	θ_{23}		**~45°** (1998) Super-K; K2K	
Solar Neutrino Oscillation	θ_{12}		**34°** (2001) SNO, Super-K; KamLAND	
Reactor Neutrino Oscillation	θ_{13}		**9°** (2012) Daya Bay, RENO Double Chooz	

2015 Nobel Prize

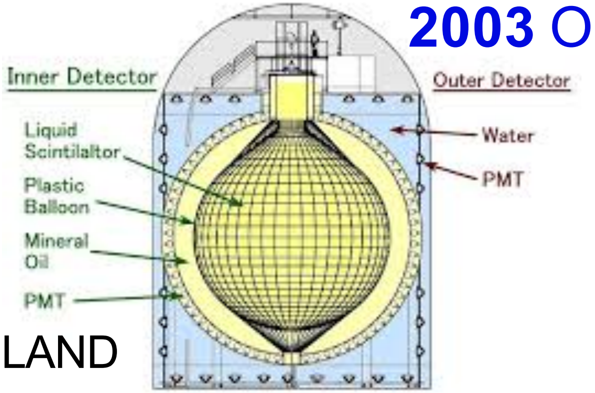
"Neutrino has mass"
"Established three-flavor mixing framework"

Neutrino Physics with Reactor

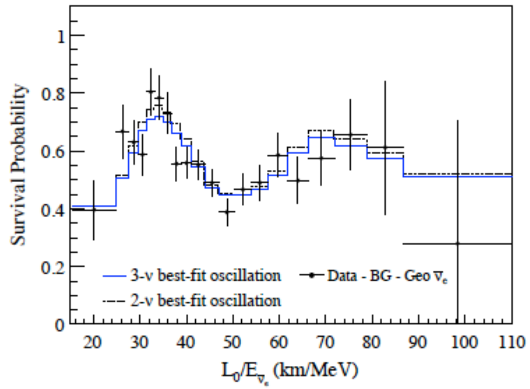
1956 Discovery of (anti)neutrino

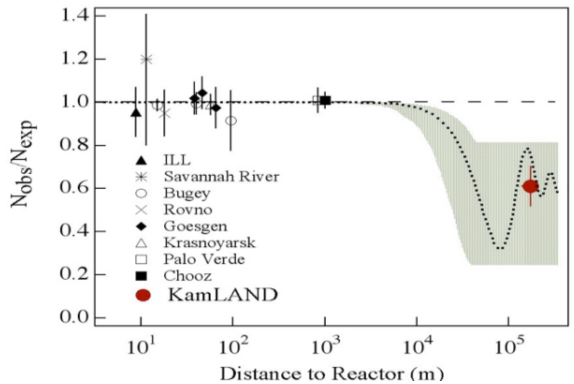


2003 Observation of reactor neutrino oscillation (θ_{12} & Δm_{21}^2)

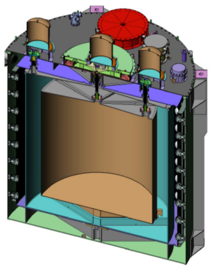


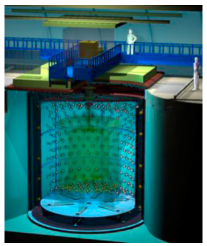
KamLAND

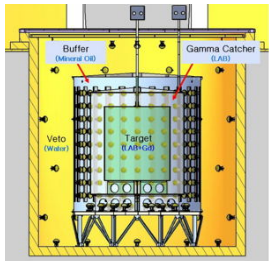


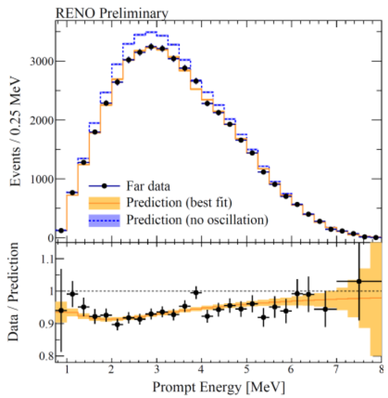


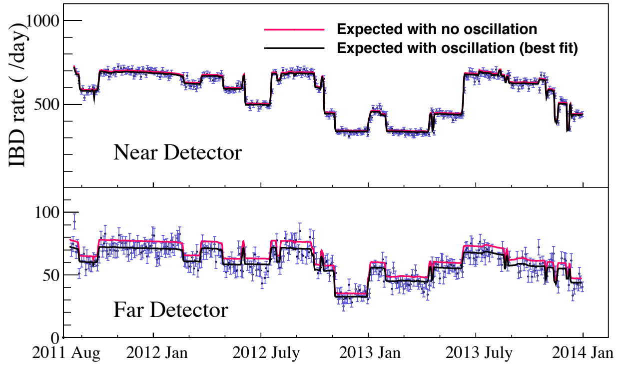
2012 Measurement of the smallest mixing angle θ_{13}



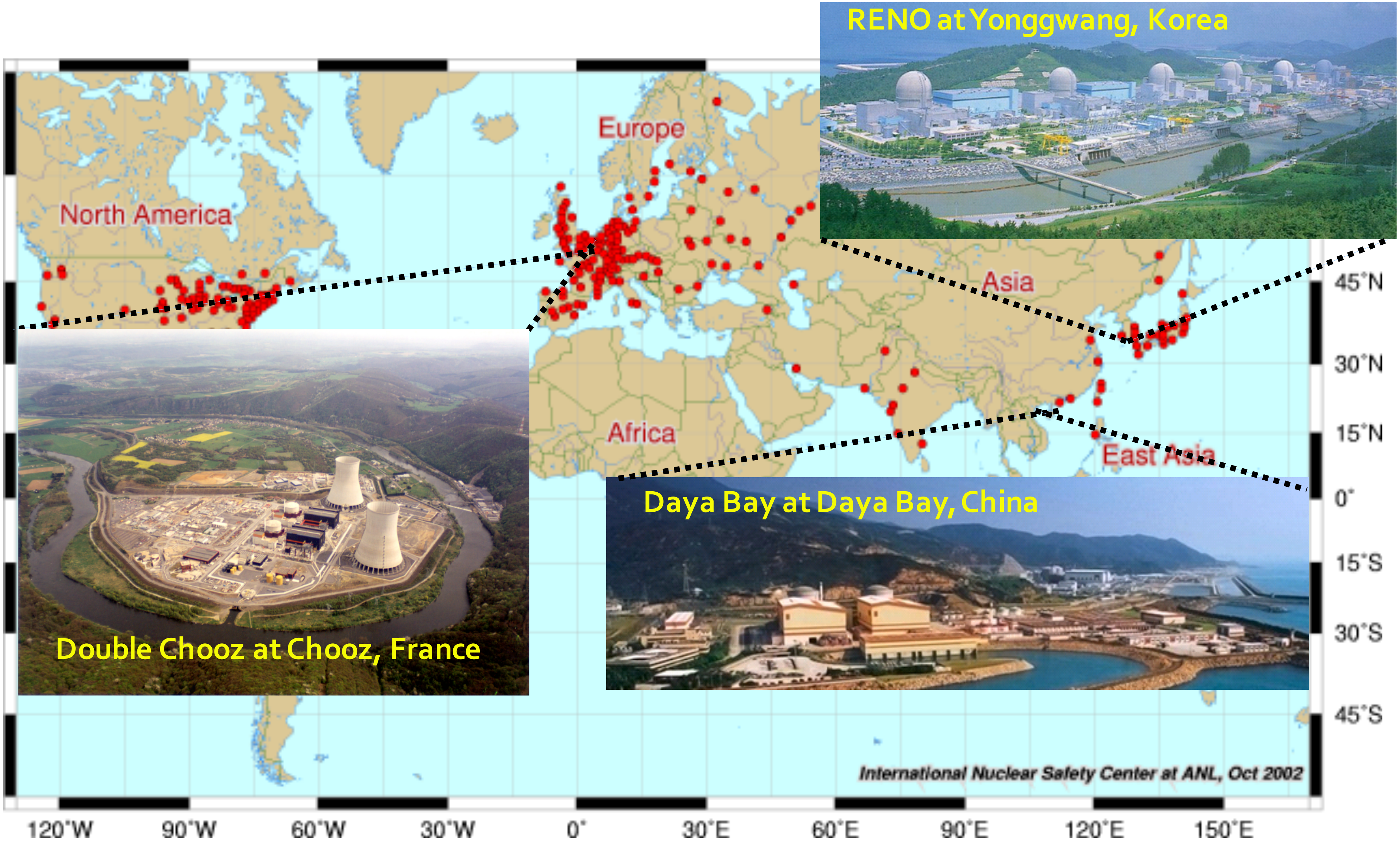






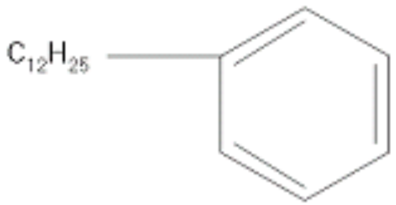


Reactor θ_{13} Experiments



Detection of Reactor Antineutrinos

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



Linear Alkyl Benzene (LAB)

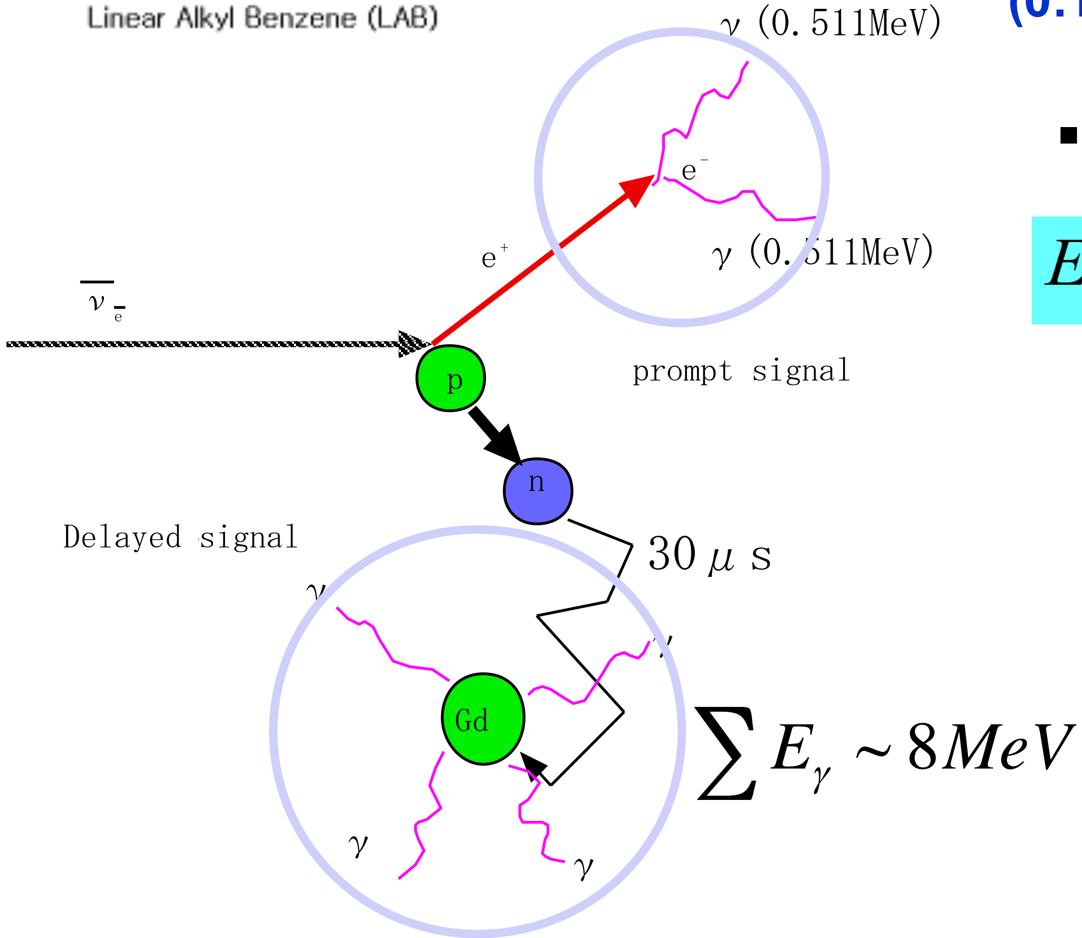
(prompt signal)

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

(delayed signal)

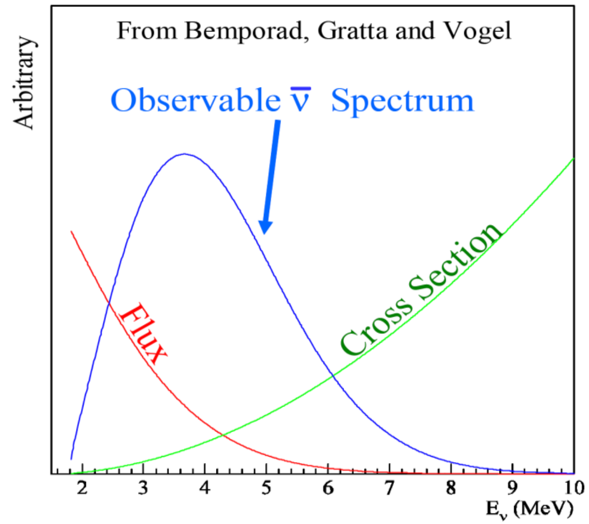
~180 μs: + p → D + γ (2.2 MeV)

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



- 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

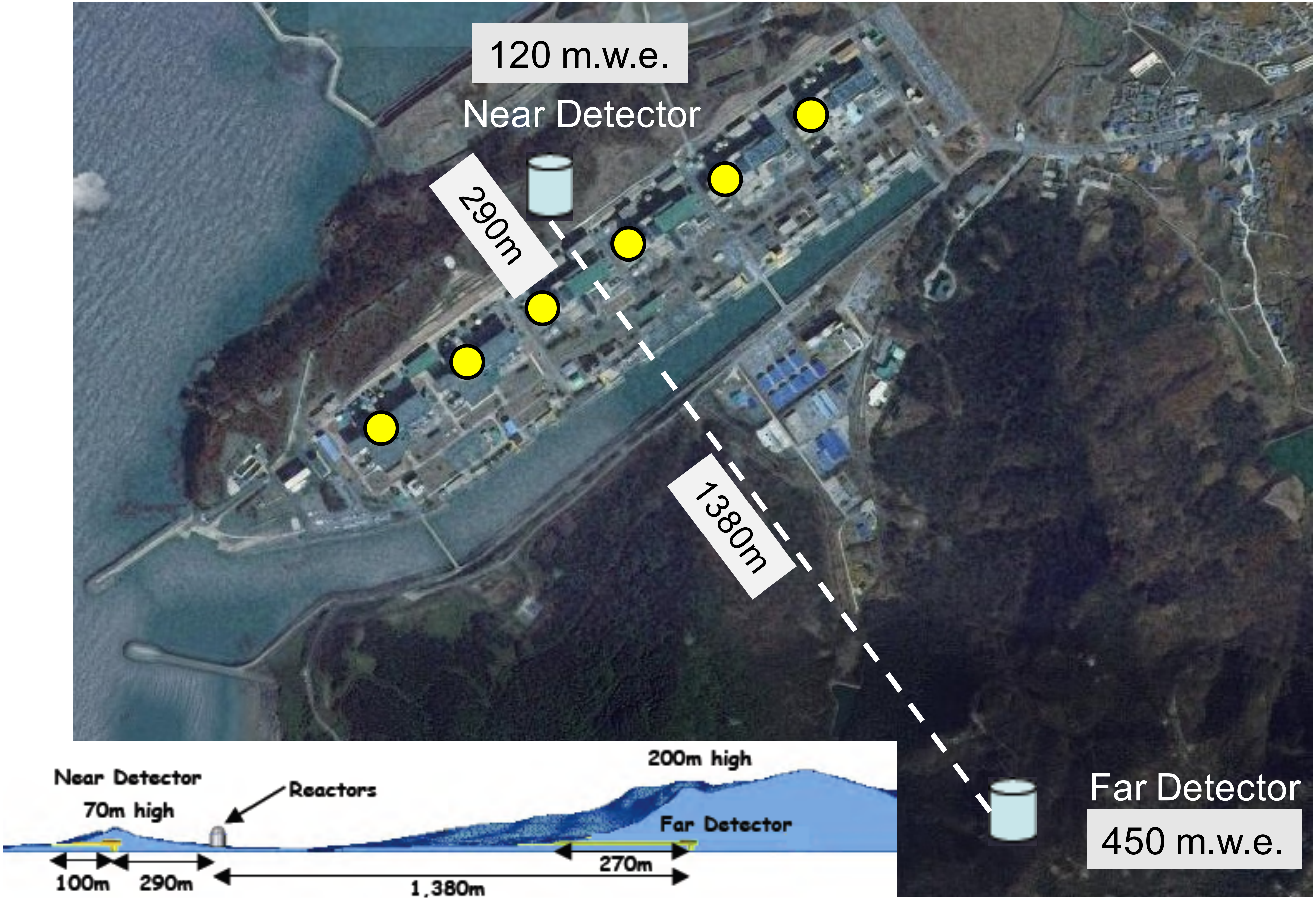
(9 institutions and 40 physicists)

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

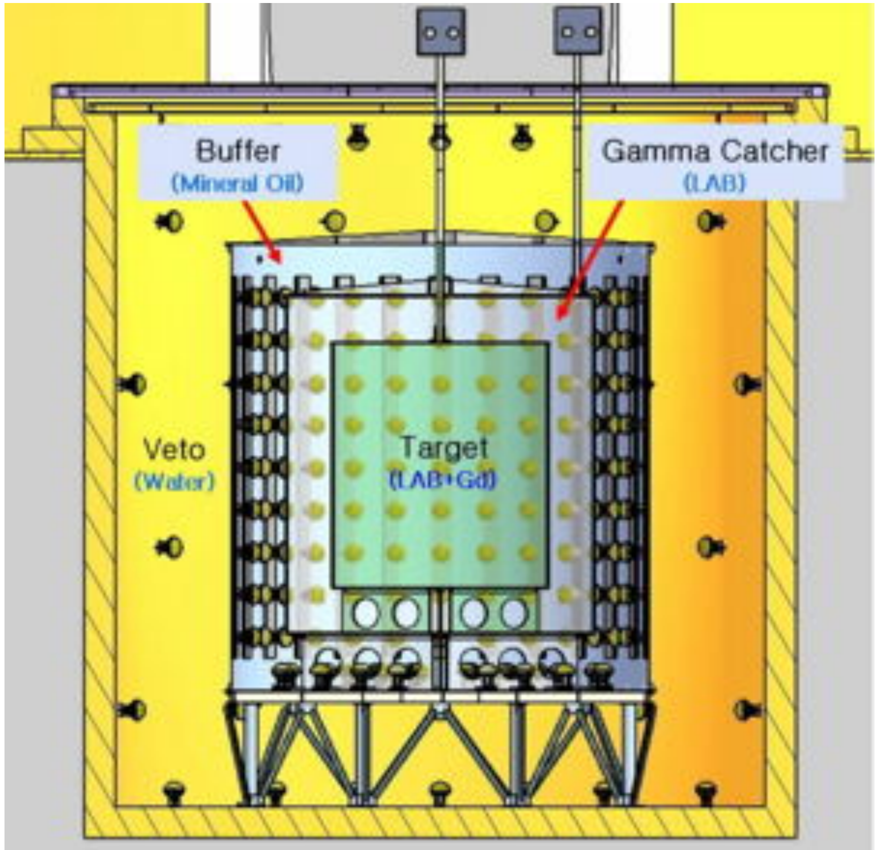
- Total cost : $10M
- Start of project : 2006
- The first experiment running with both near & far detectors from Aug. 2011

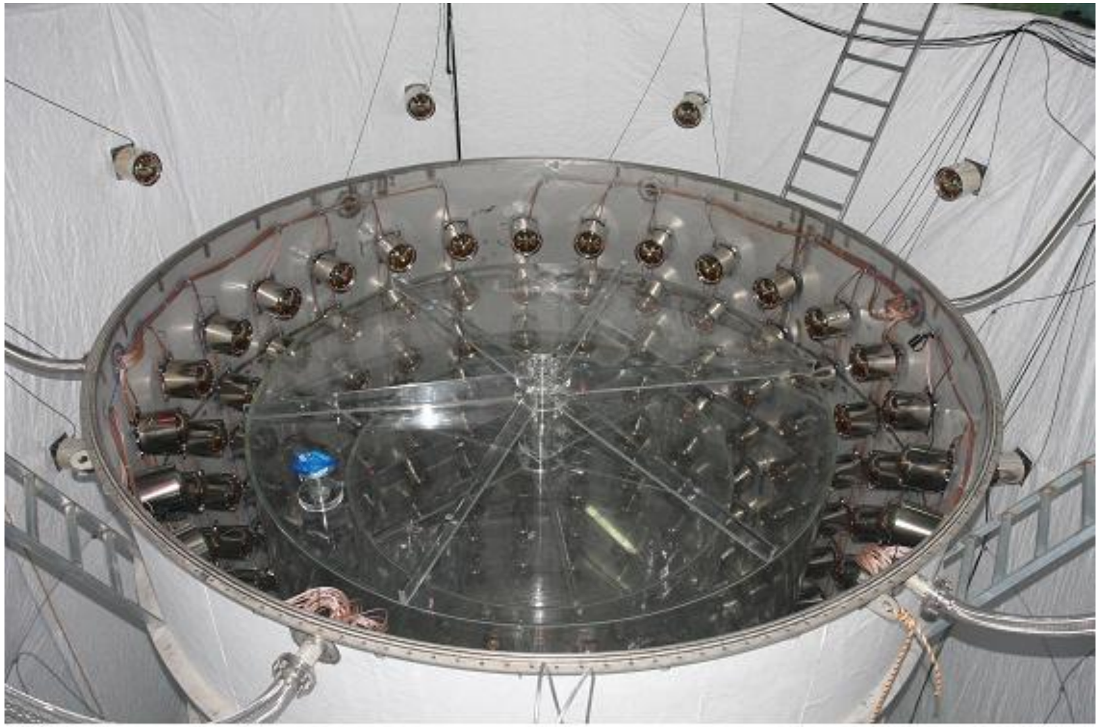
YongGwang (靈光) :

RENO Experimental Set-up



RENO Detector





- 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

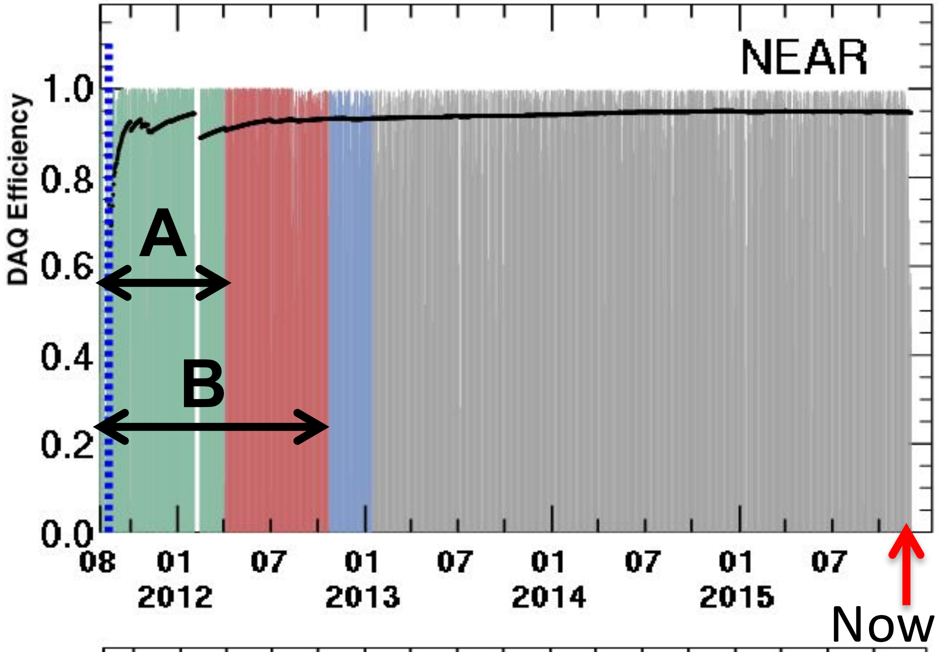
- Data taking began on Aug. 1, 2011 with both near and far detectors. (DAQ efficiency : ~95%)

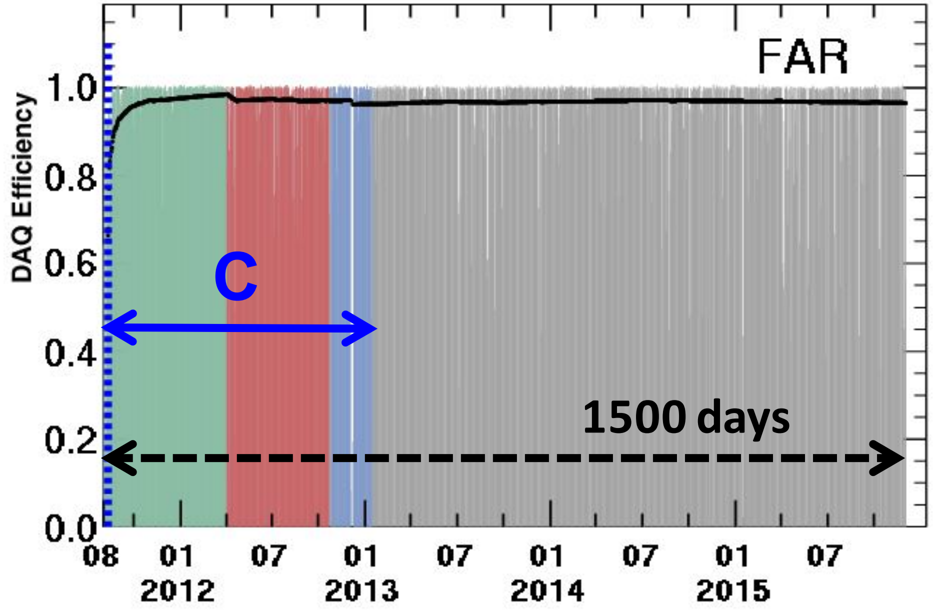
- **A (220 days)** : **First θ_{13} result**
  [11 Aug, 2011~26 Mar, 2012]
  PRL 108, 191802 (2012)

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

- **C (~500 days)** : New **result**
  Shape+rate analysis (**θ_{13} and $|\Delta m_{ee}^2|$**)
  [11 Aug, 2011~21 Jan, 2013]
  → Sterile neutrino search and updated n-H analysis in progress

- Total observed reactor neutrino events as of today (1500 days)
  ~ 1.5M (Near), ~ **0.15M** (Far)





Recent RENO Results and Status

- ~500 days of data (Aug. 2011 – Jan 2013)
- 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} (submitted to PRL)
  arXiv:1511.05849
- 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

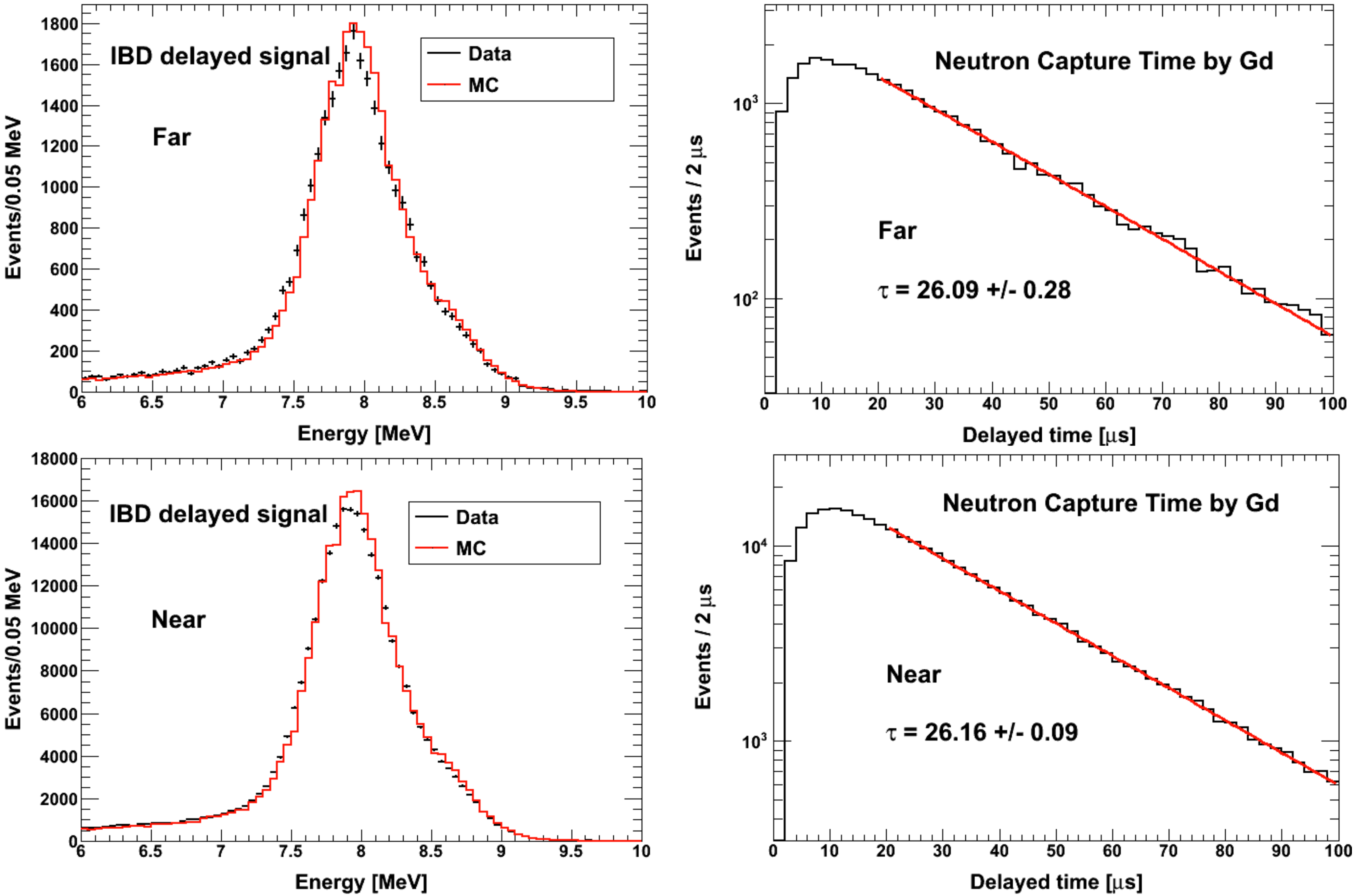
- More accurate energy calibration

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

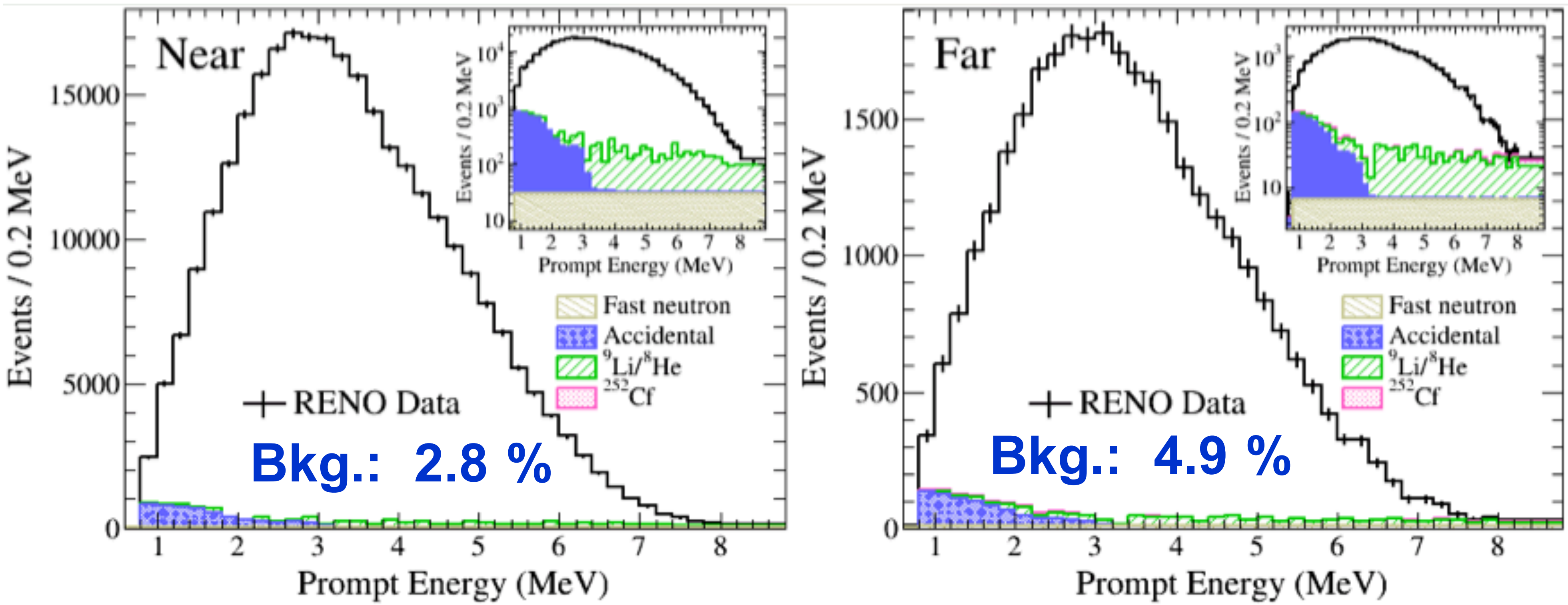
- Elaborate study of systematic uncertainties on a spectral fitter

  - 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

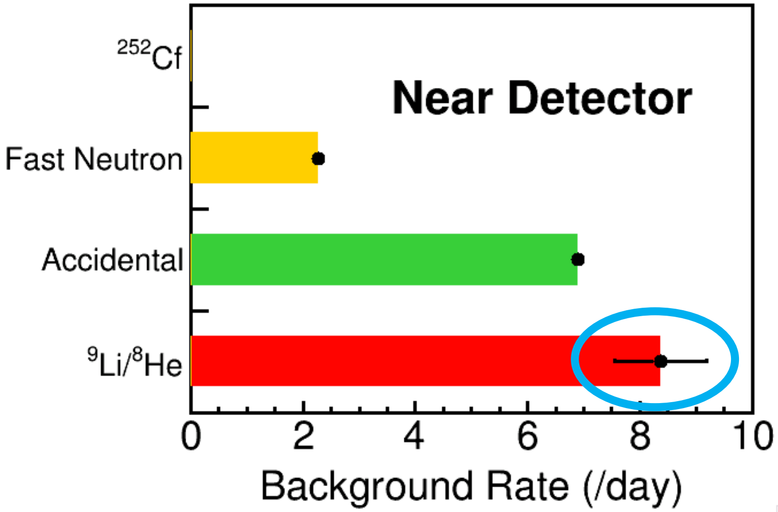


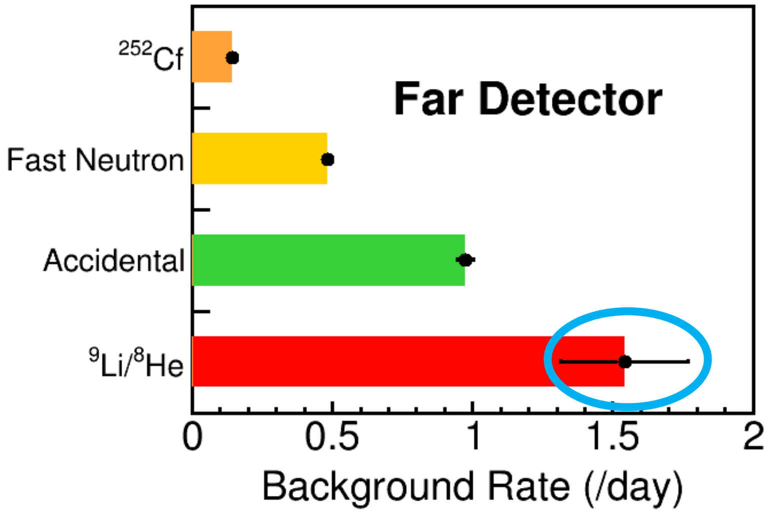
Near Live time = 458.49 days
# of IBD candidate = 290,775
# of background = 8,041 (2.8 %)

Far Live time = 489.93 days
# of IBD candidate = 31,541
# of background = 1,540 (4.9 %)

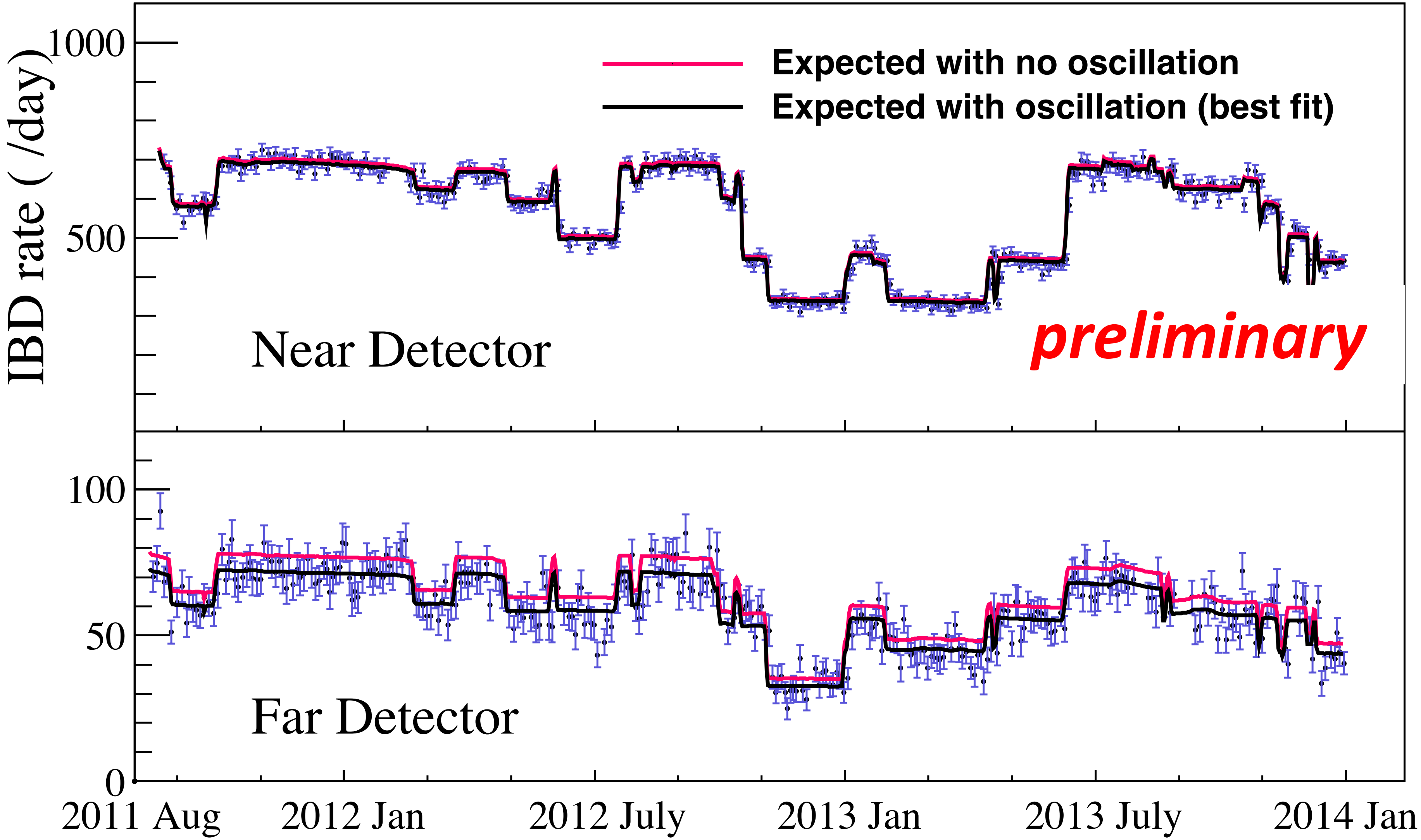
IBD Candidates & Backgrounds

	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



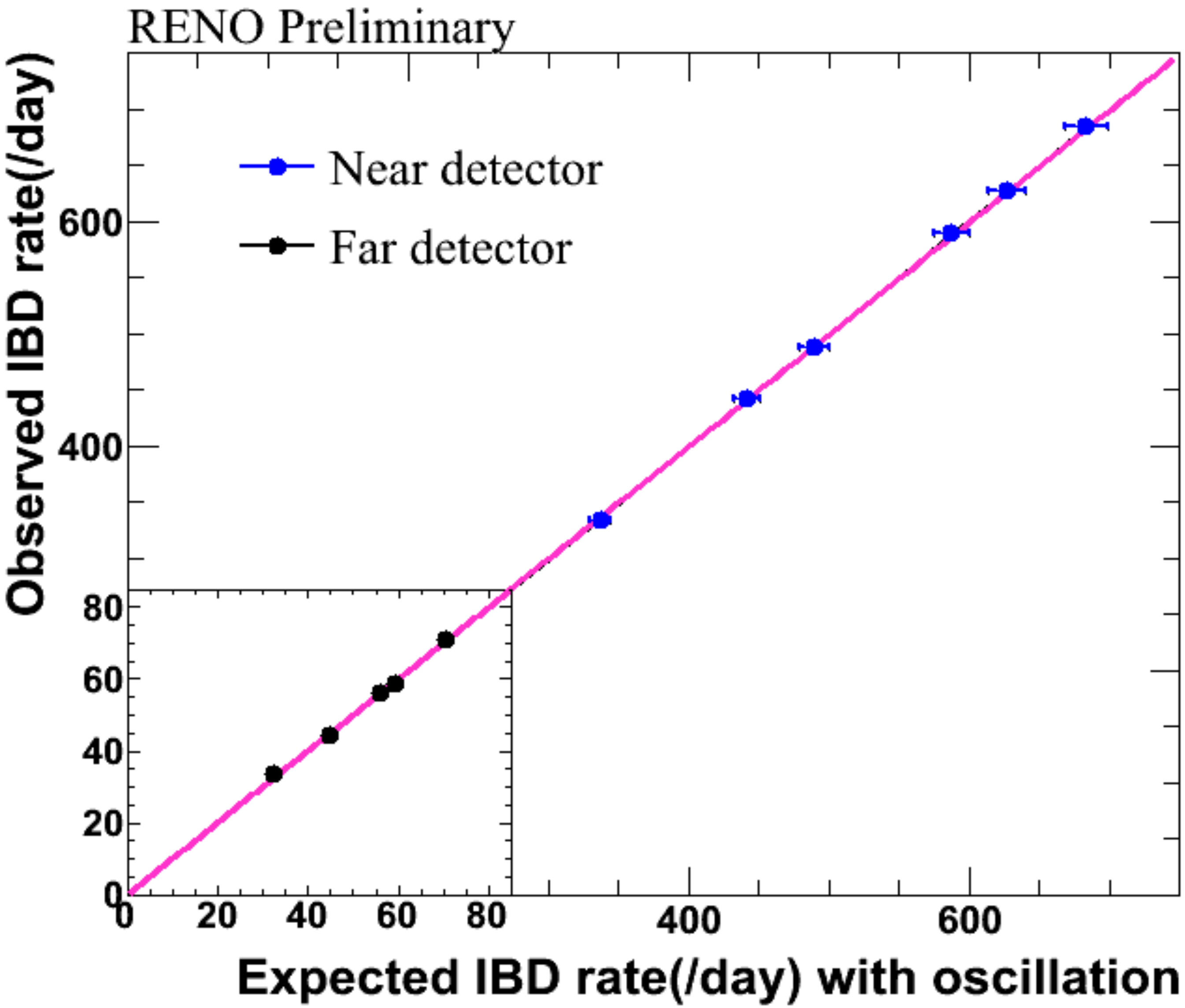


Observed Daily Averaged IBD Rate



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

Observed vs. Expected IBD Rates



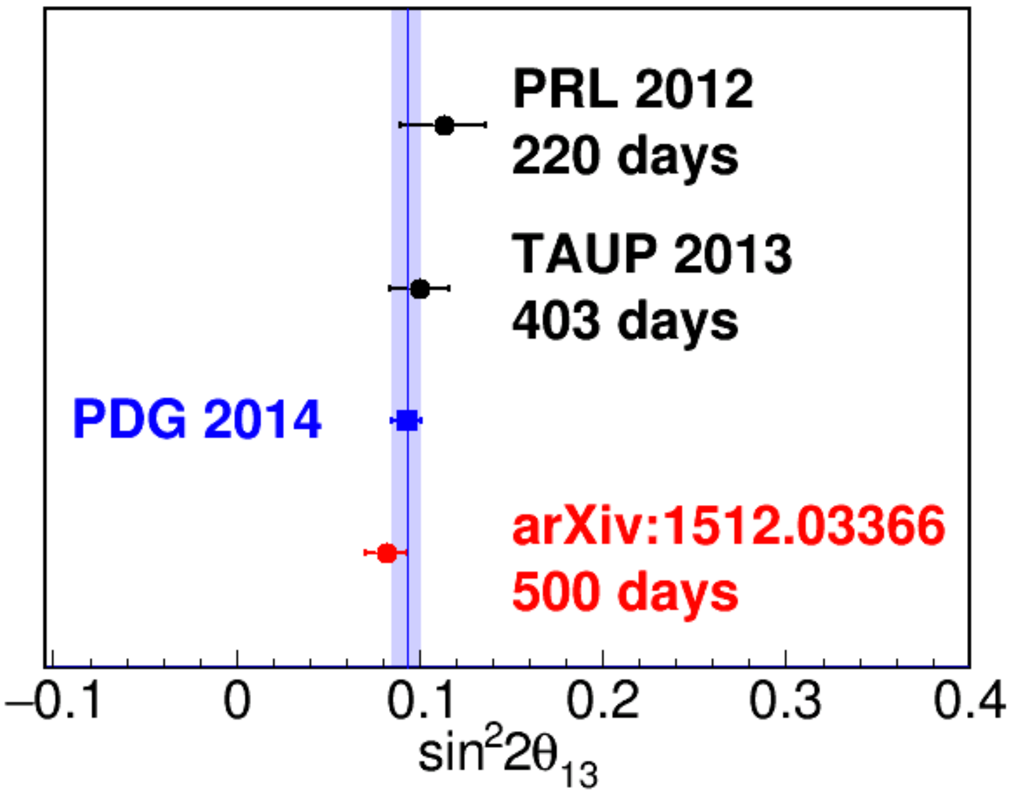
- Good agreement between observed rate & prediction
- Indication of correct background subtraction

New θ_{13} Measurement by Rate-only Analysis

Rate-only new result

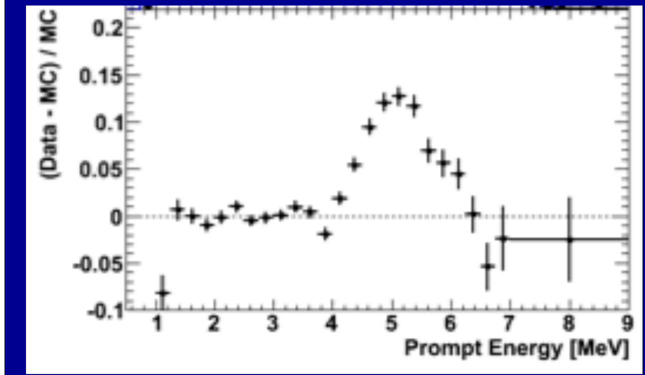
$$\sin^2 2\theta_{13} = 0.087 \pm 0.009(\text{stat.}) \pm 0.007(\text{syst.})$$

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

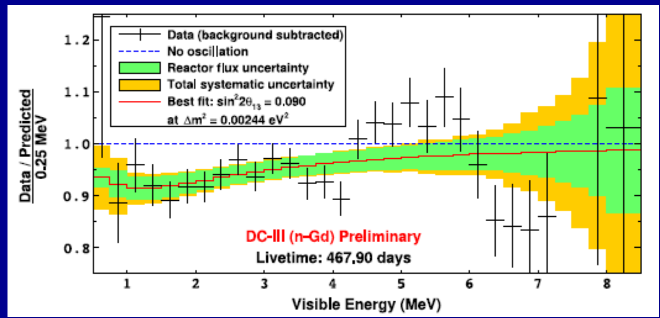


The 5 MeV Excess is there !

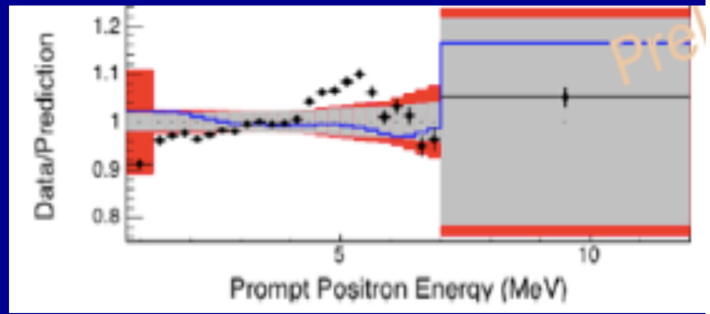
RENO



Double Chooz

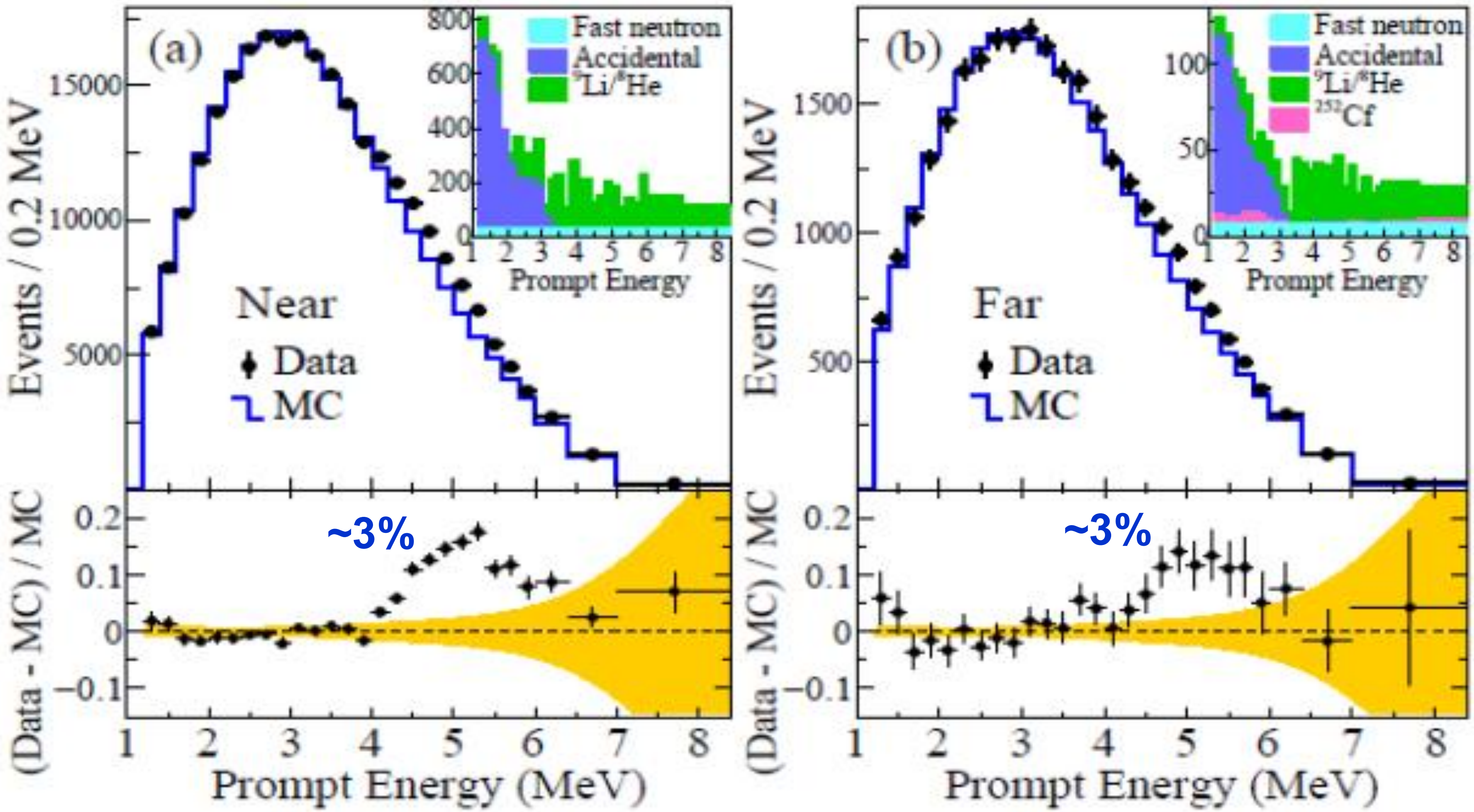


Daya Bay

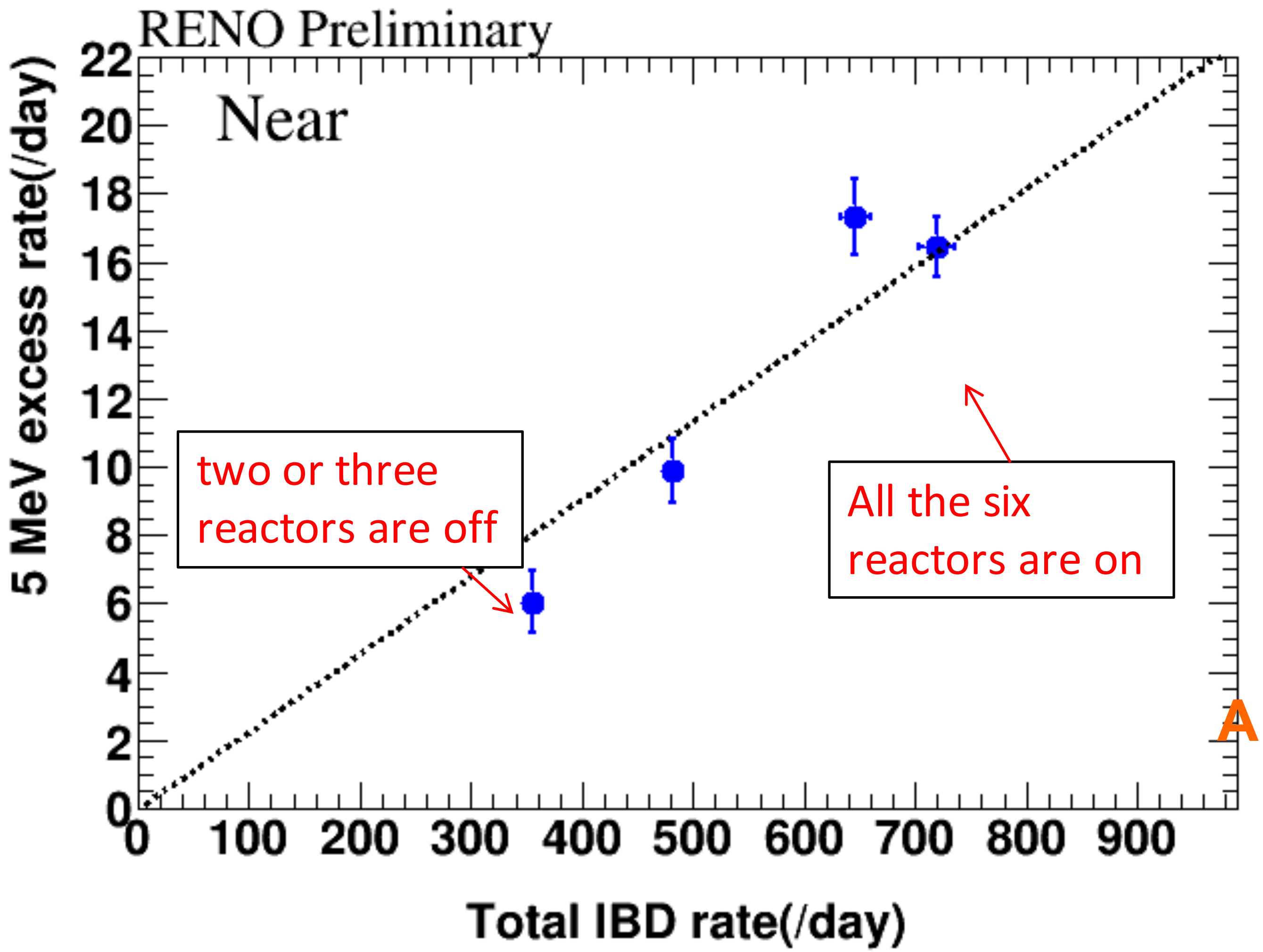


In 2014, RENO showed the 5 MeV excess is from reactor neutrinos.

Observation of an excess at 5 MeV



Correlation of 5 MeV Excess with Reactor Power



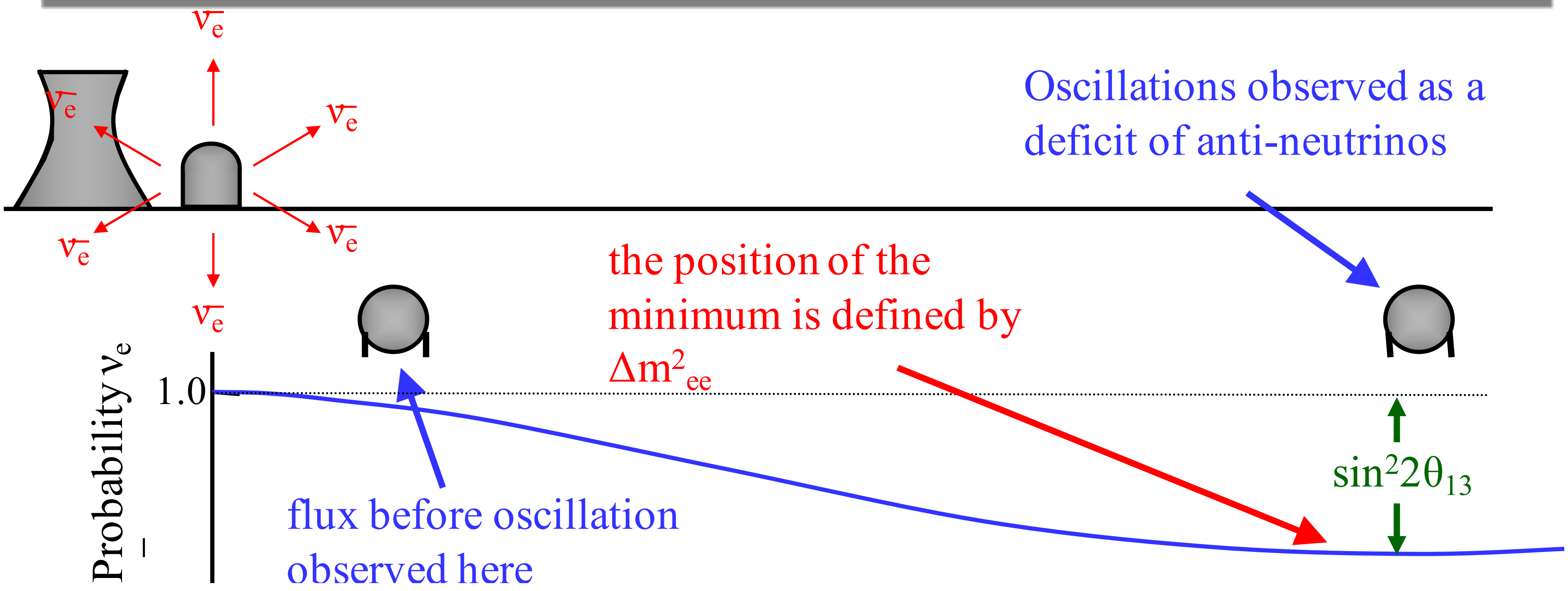
5 MeV excess has a clear correlation with reactor thermal power !

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

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

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

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

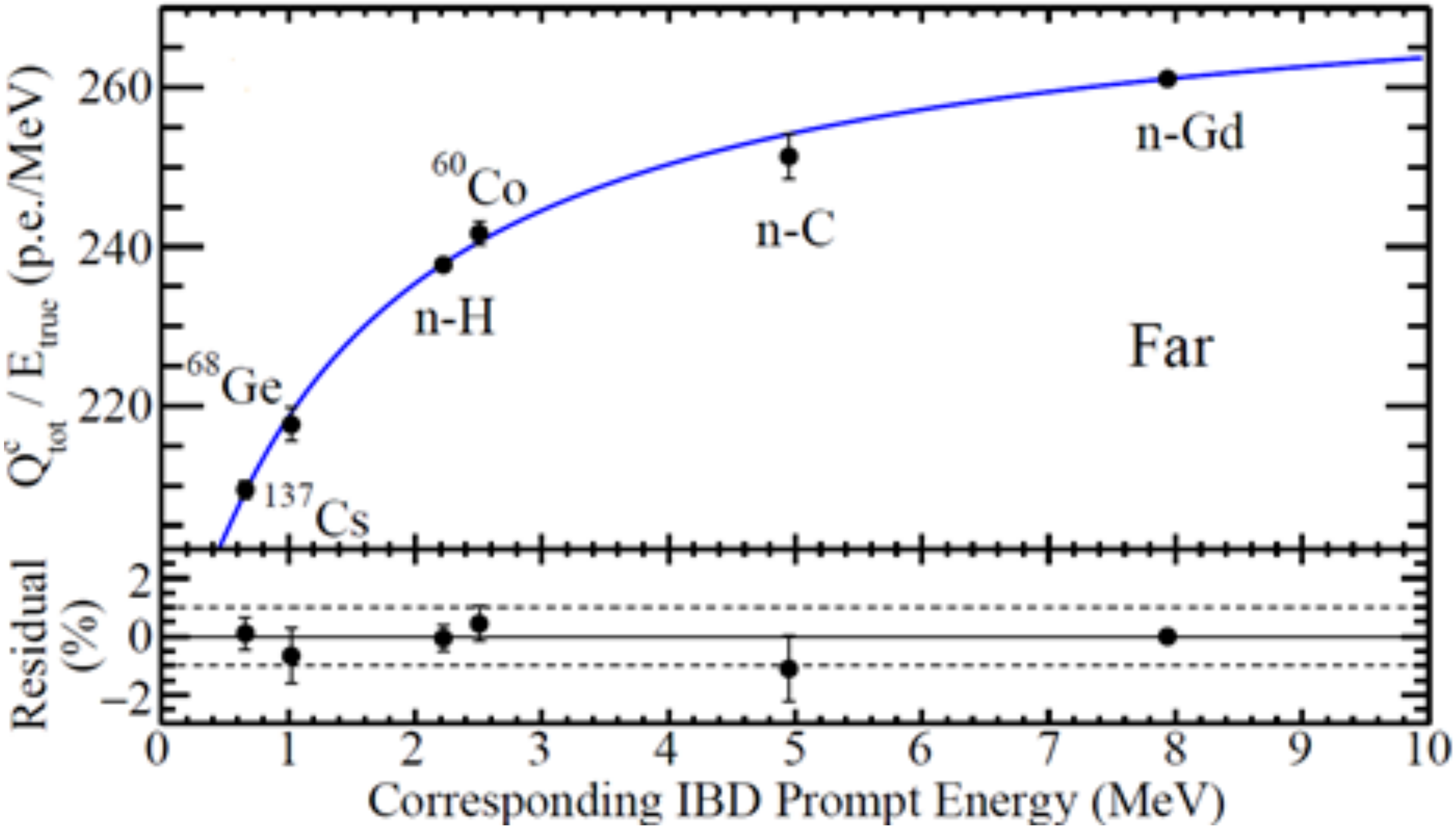
$\cos^2\theta_{12}|\Delta m^2{}_{21}|$

+: Normal Hierarchy

−: Inverted Hierarchy

Energy Calibration from γ-ray Sources

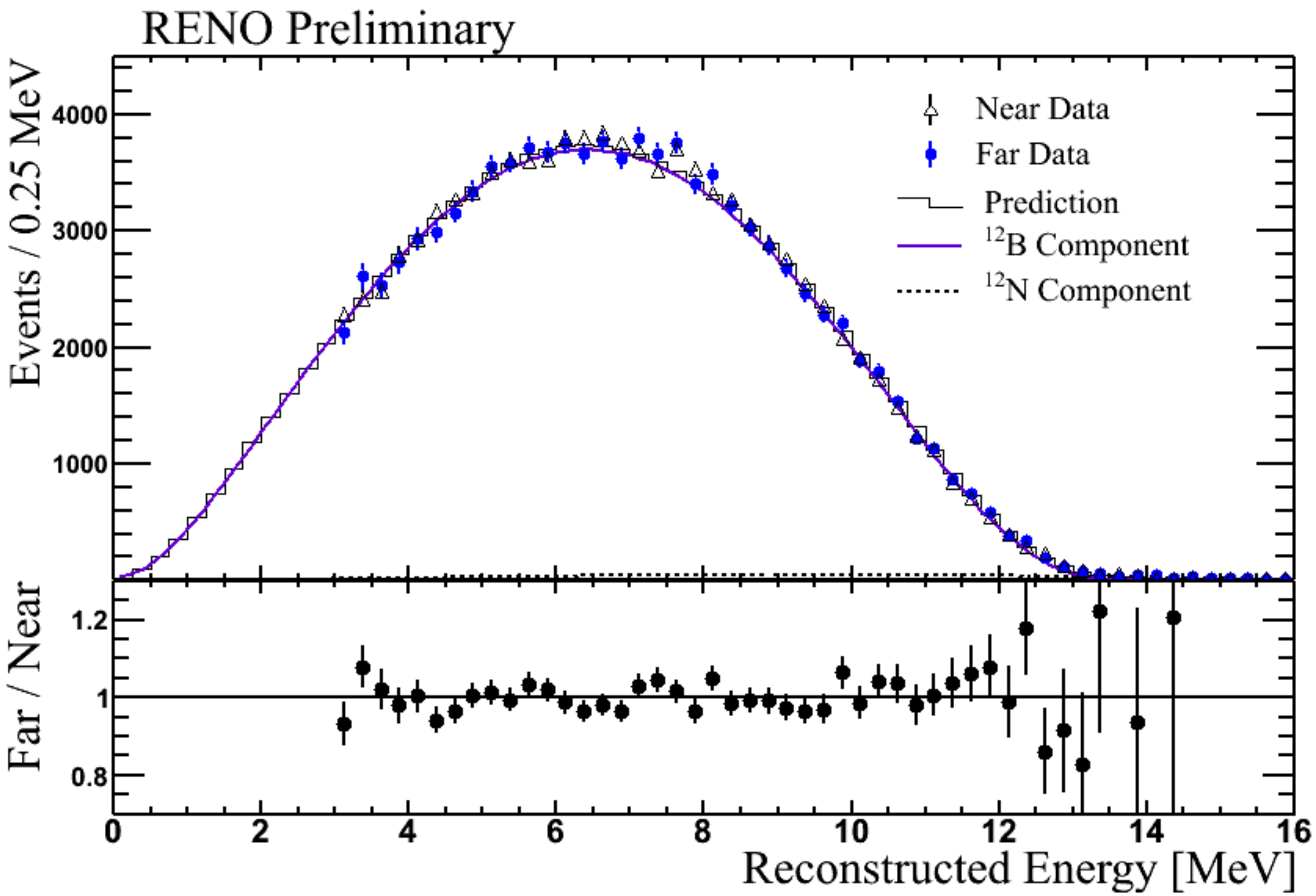
- Non-linear resonse of the scintillation energy is calibrated using γ-ray sources.
- The visible energy from γ-ray is corrected to its corresponding positron energy.



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

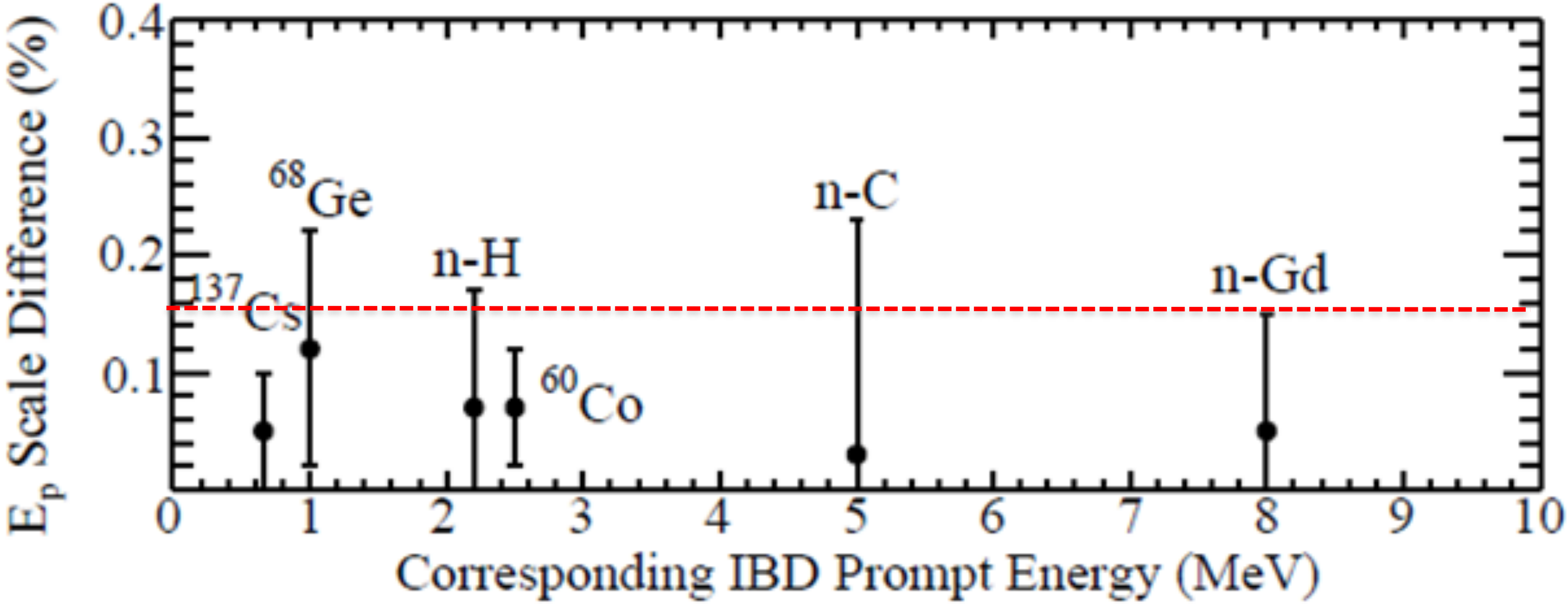
B12 Energy Spectrum (Near & Far)

- 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!

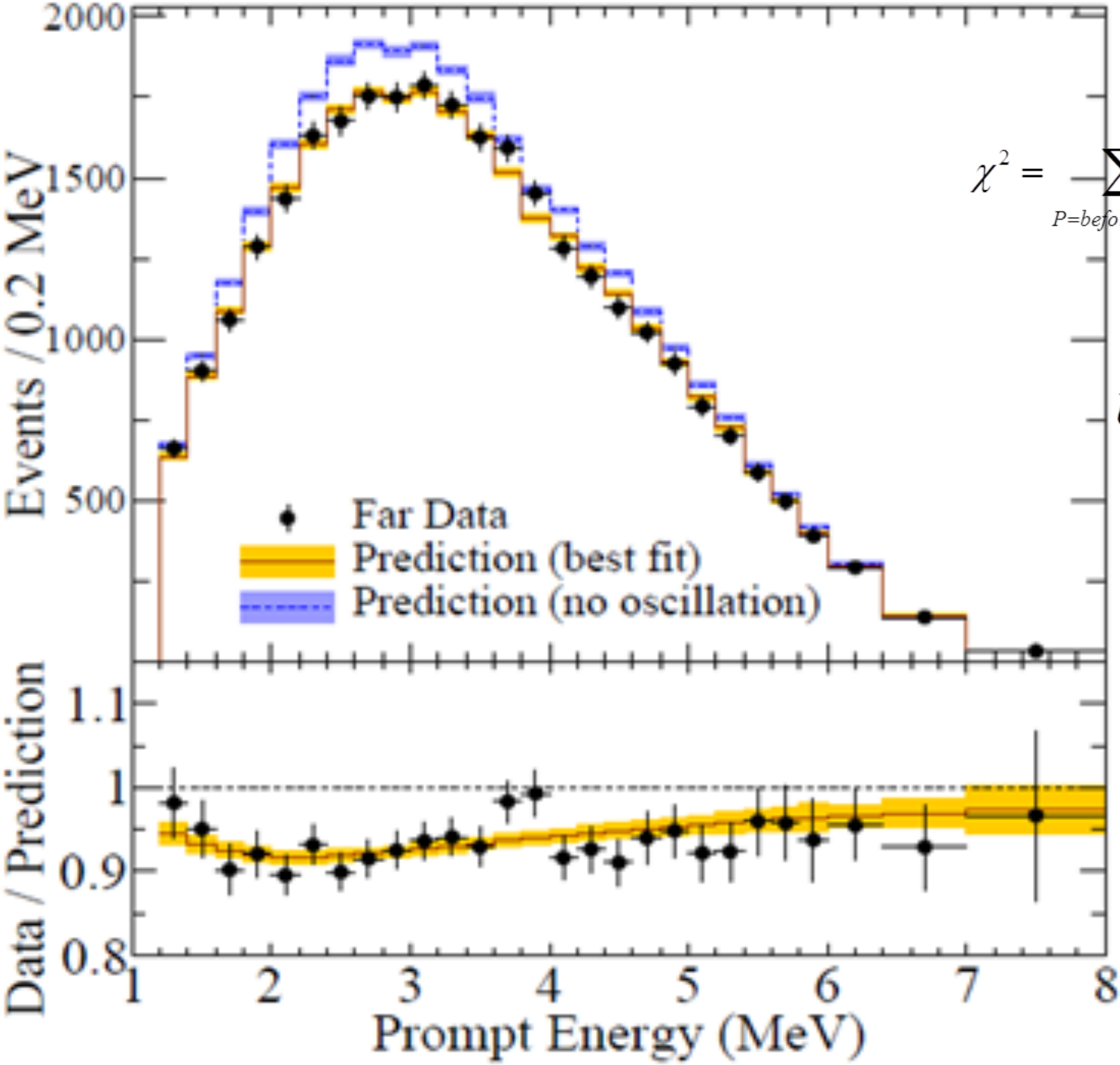
Energy Scale Difference between Near & Far



Energy scale difference < 0.15%

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

arXiv:1511.05849.v2



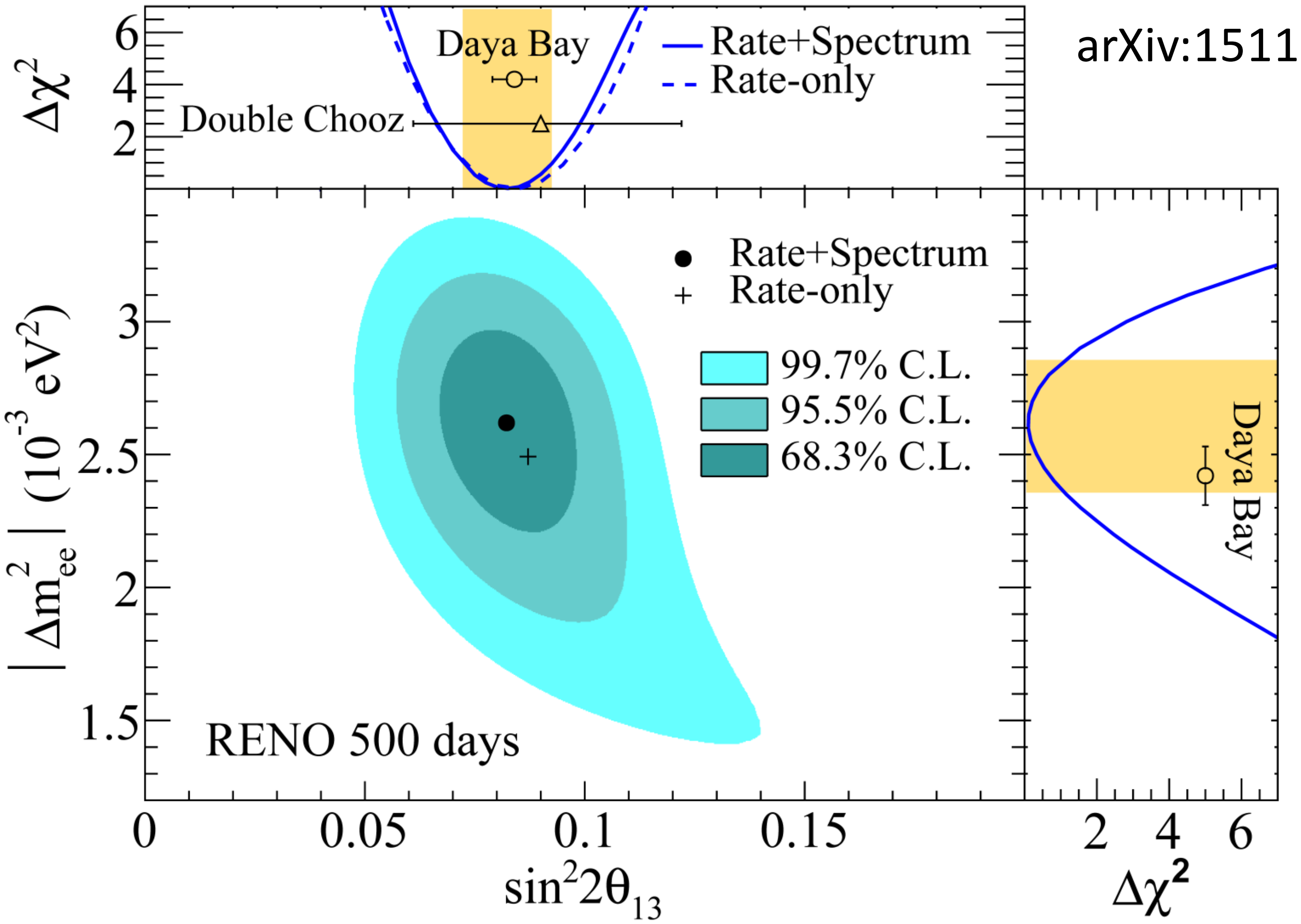
Minimize X^2 Function

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

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

Results from Spectral Fit

arXiv:1511.05849.v2



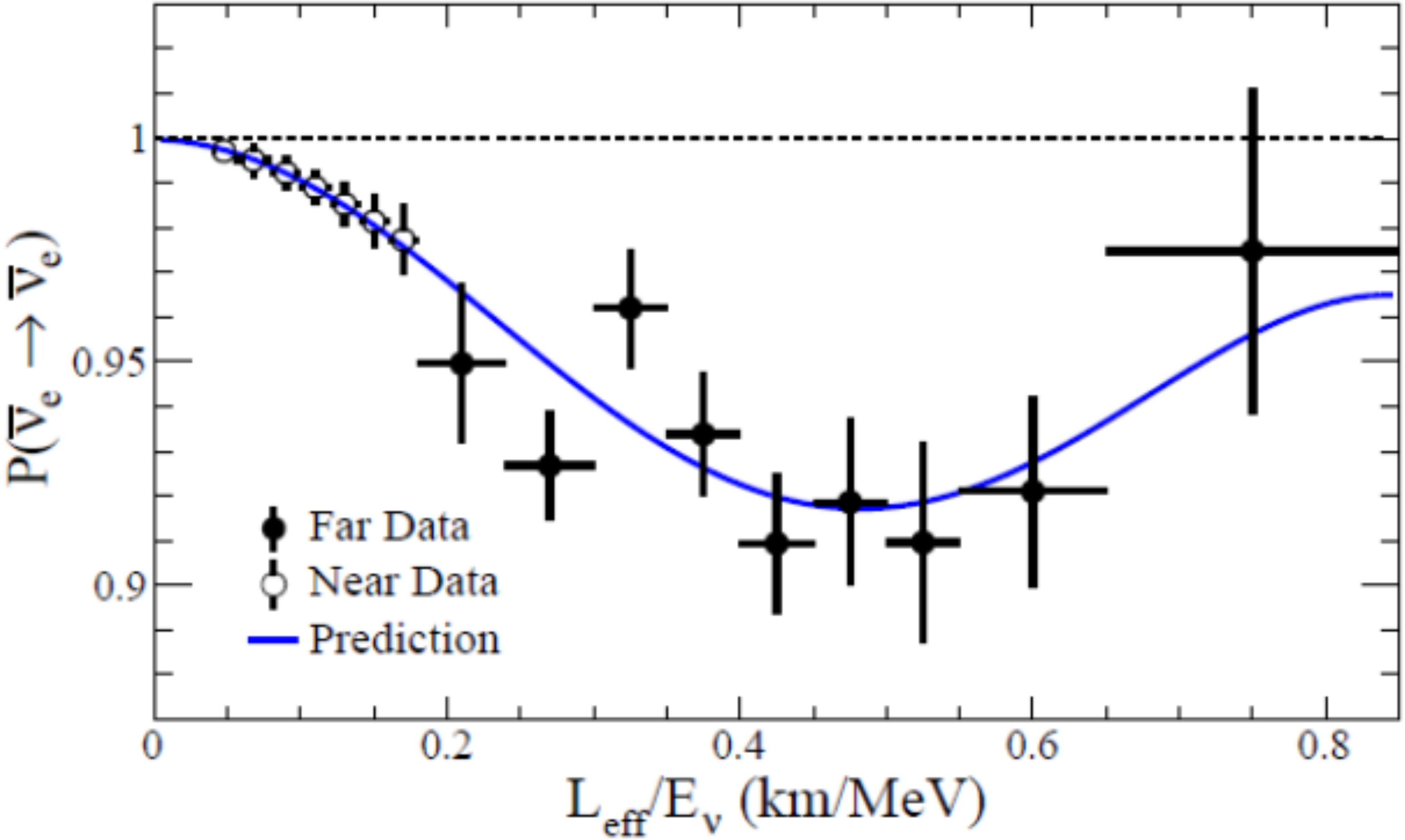
Rate+shape new results

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

arXiv:1511.05849.v2



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

RENO New Results

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

^{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)

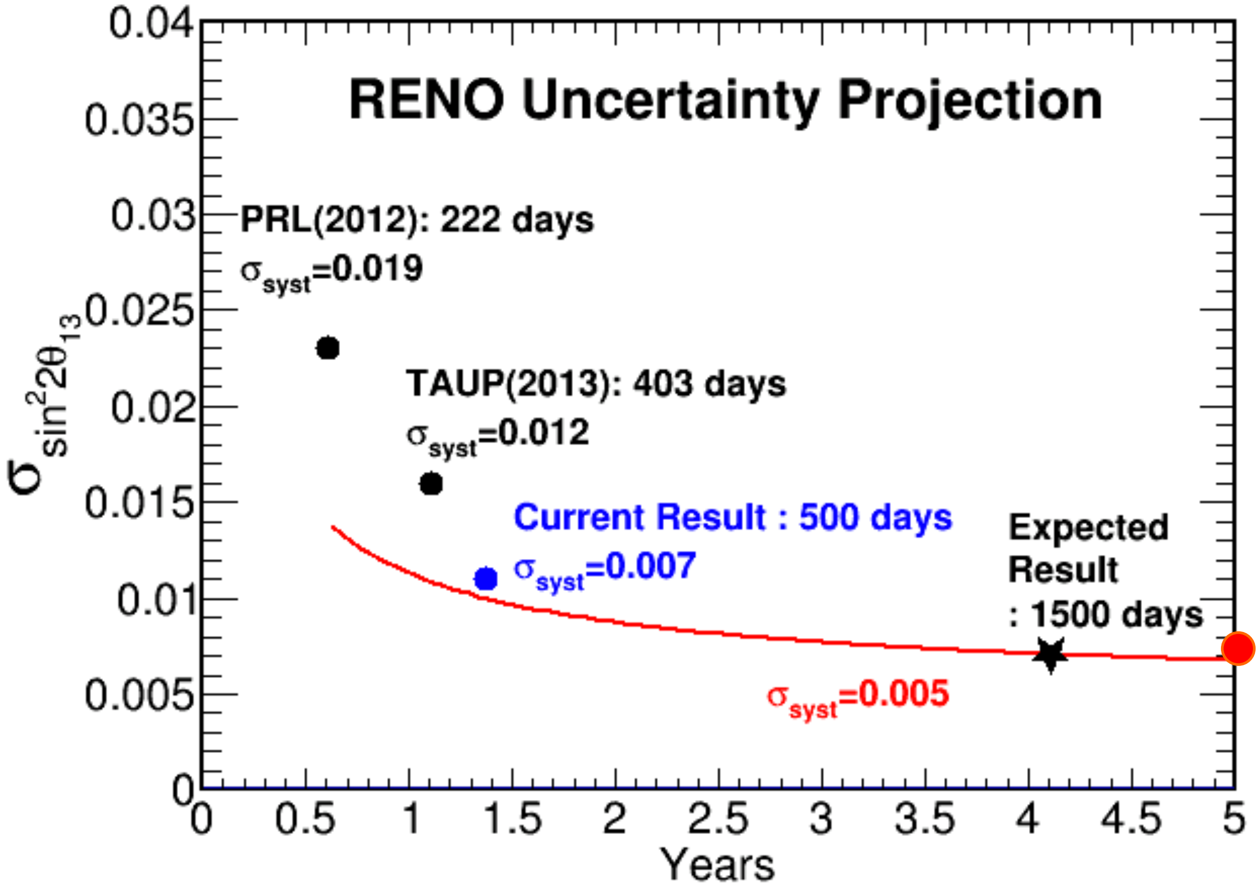
Projected Sensitivity of θ_{13} & $|\Delta m_{ee}^2|$

$\sin^2 2\theta_{13} = 0.082 \pm 0.011$ (±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})

Summary

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

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

$$\sin^2 2\theta_{13} = 0.082 \pm 0.011$$

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

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

- Observed an excess at 5 MeV in reactor neutrino spectrum

- $\sin(2\theta_{13})$ to 6% accuracy
  Δm_{ee}^2 to 0.15×10^{-3} eV^2 (6%) accuracy for final sensitivity

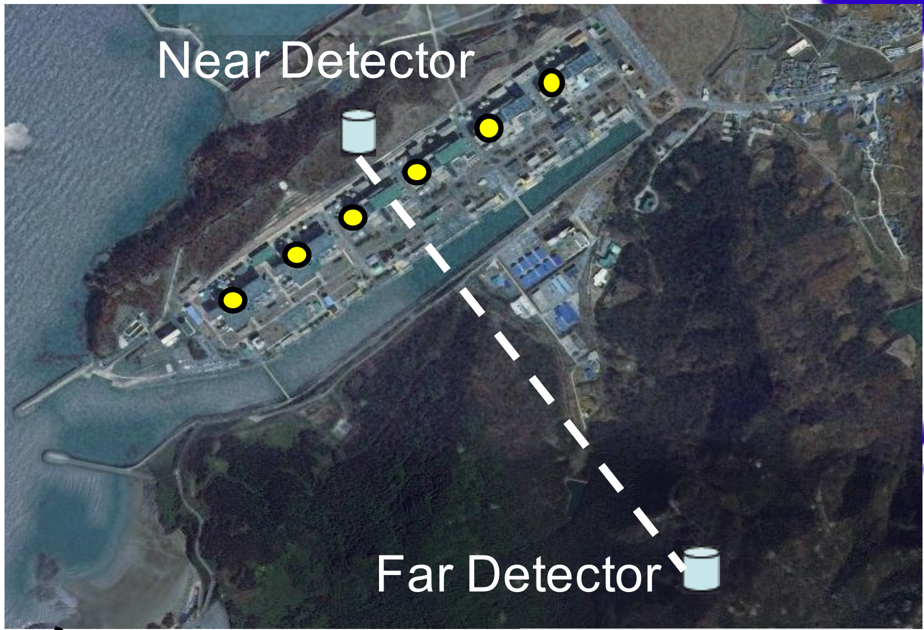
Overview of RENO-50

- **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)

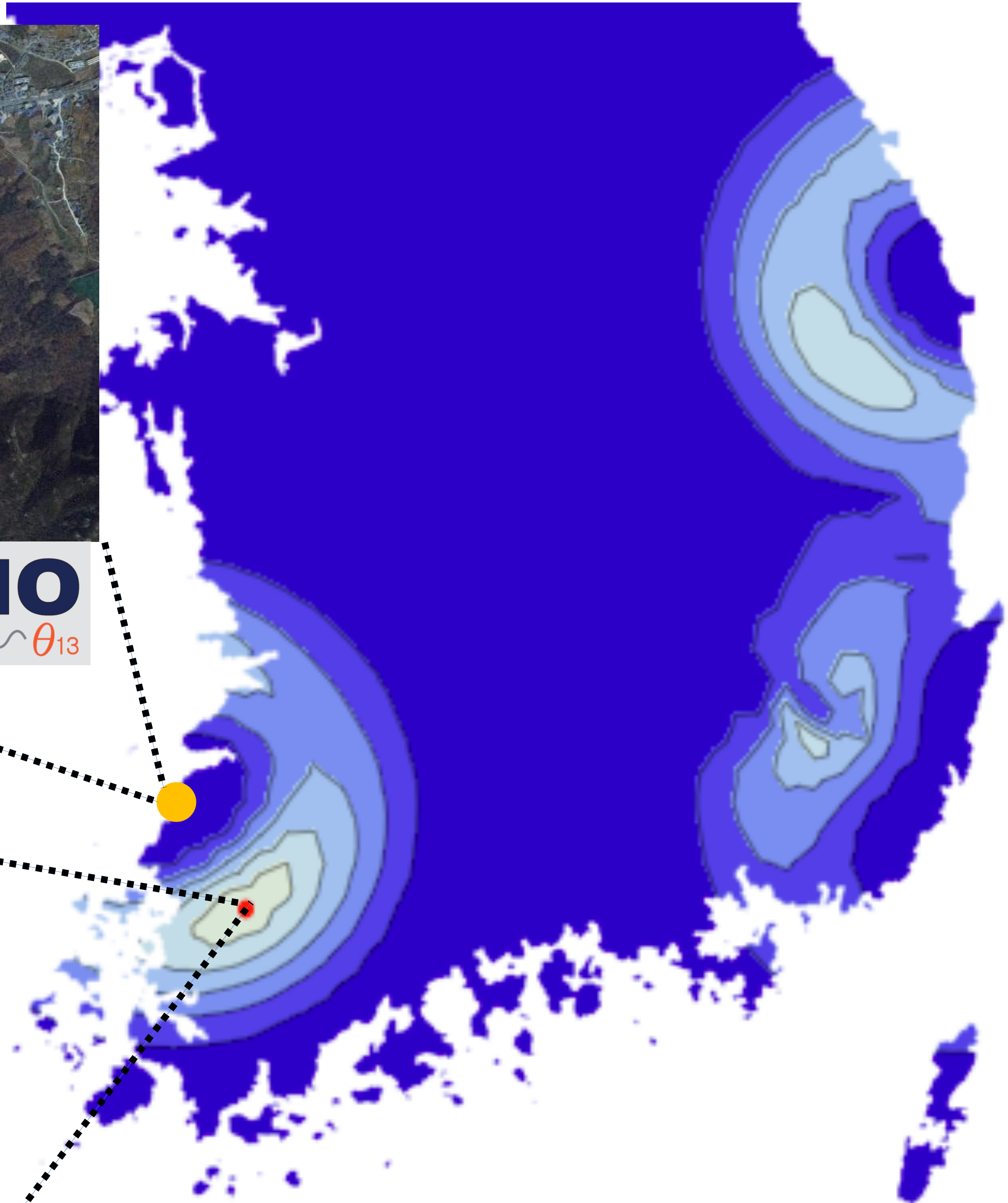
- **Schedule** : 2016 ~ 2021 : Facility and detector construction
  2022 ~ : Operation and experiment



RENO

(NEAR Detector)

(FAR Detector)



RENO-50

18 kton LS Detector
~47 km from YG reactors

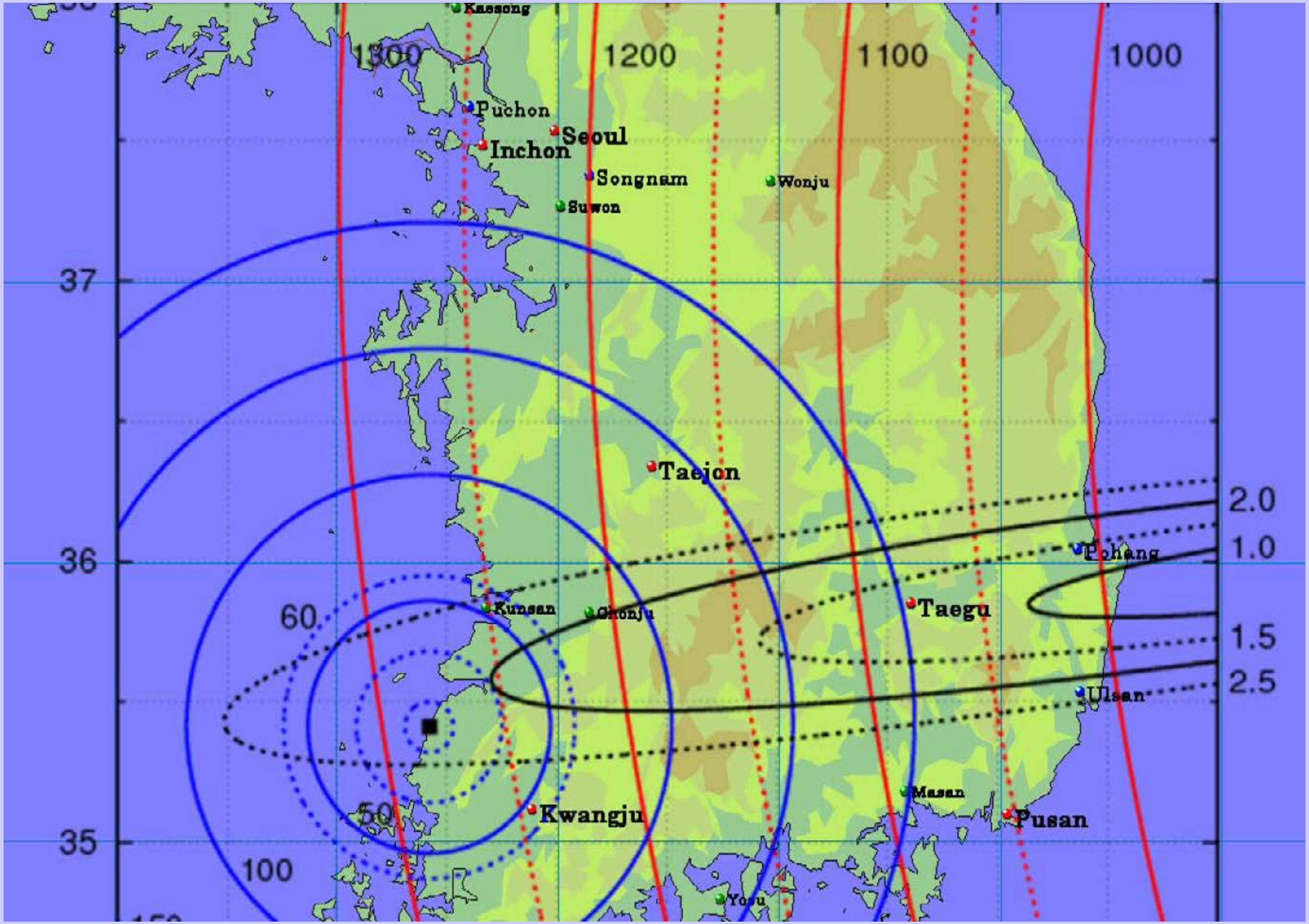
Mt. Guemseong (450 m)
~900 m.w.e. overburden

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

J-PARC neutrino beam

Dr. Okamura & Prof. Hagiwara



Current Status of Funding and R&D

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

- A proposal has been submitted to obtain construction funding.

→ **International Neutrino community's supports will greatly enhance our opportunities !**

- A domestic symposium and an international workshop held in 2013 to discuss the feasibility and physics opportunities

- A R&D in progress for LS. PMT, DAQ, MC and detector design to produce a TDR

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

Thanks for your attention!