New Results from RENO & Future RENO-50 Project

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Neutrino Seminar
Fermilab
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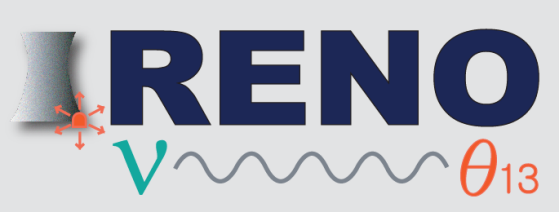
KNRC
Korea Neutrino Research Center

Outline

Reactor Experiment for Neutrino Oscillation



- Introduction
- Experimental setup & detector
- Data-taking & data set
- Data analysis
- New results
- Summary & Prospect

- Future Plan: RENO-50 project

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Recent & New Results from RENO

- Recent measurements of Δm_{ee}^2 and θ_{13} from rate+shape

using ~500 days of data (Aug. 2011 ~ Jan. 2013)

→ PRL 116, 211801, 2016; PRD paper will be submitted soon

- Updated the 5 MeV excess in reactor neutrino spectrum using 1400 days of data → paper in preparation

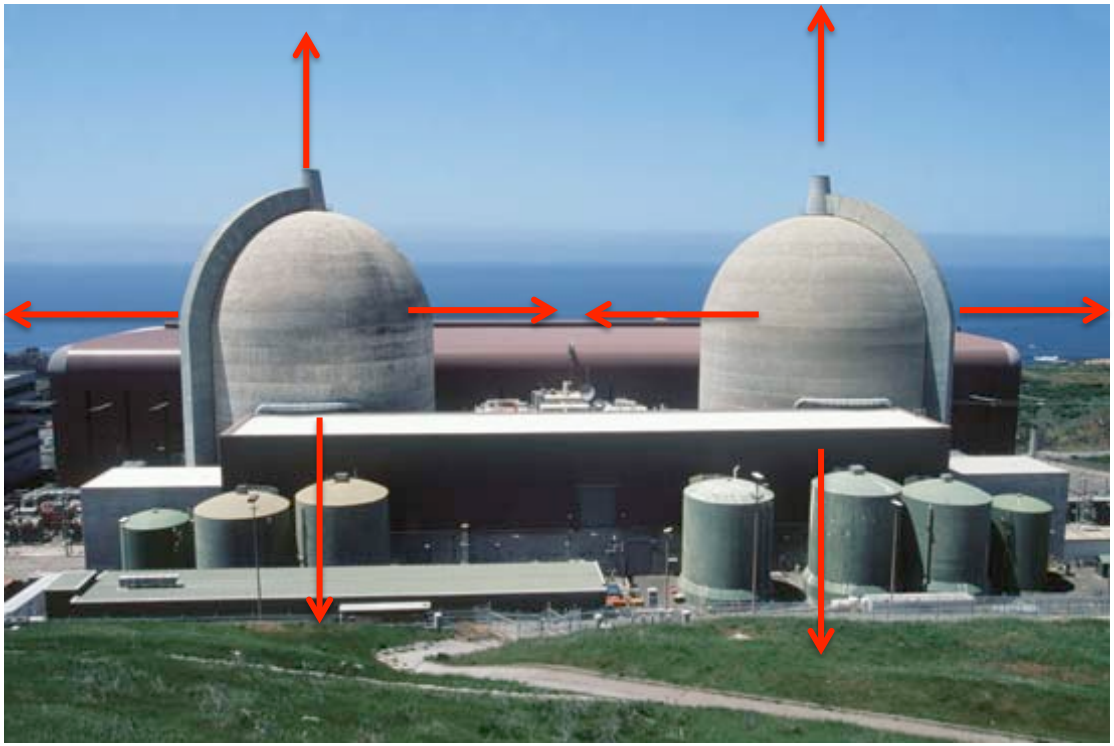
- Independent measurement of θ_{13} with n-H for a delayed signal w/ 500 d (additional background reduction in progress)

- Preliminary result on sterile neutrino search w/ 500 days data

- Preliminary result on absolute flux measurement w/ 500 days data

Nuclear Reactors: source of $\bar{\nu}_e$

Nuclear reactors are copious & isotropic sources of $\bar{\nu}_e$.



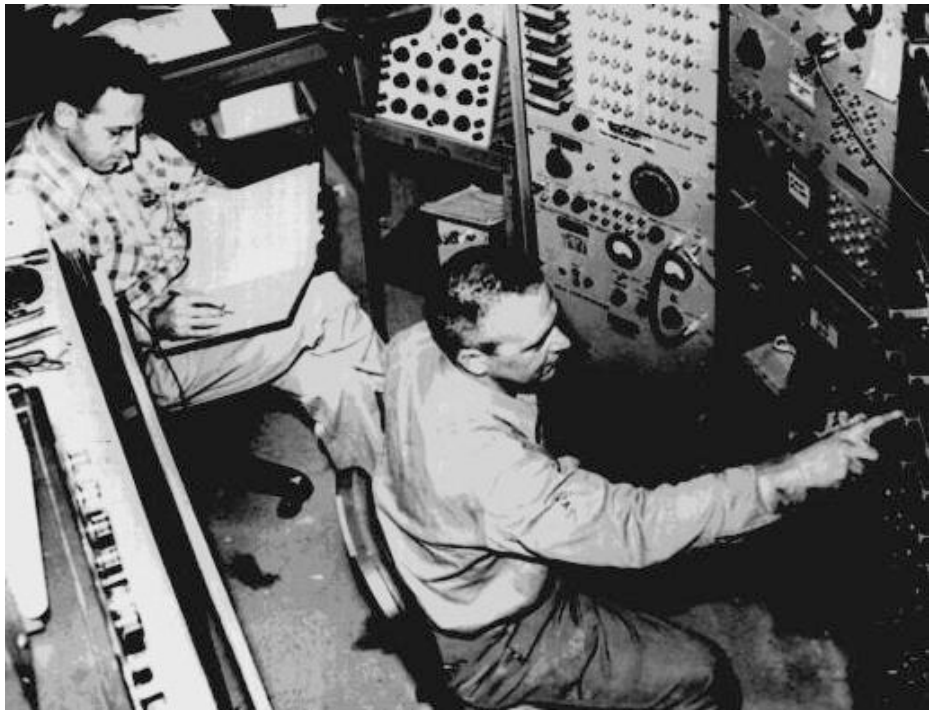
The Diablo Canyon nuclear power plant (~2.2 GW_{th}) in San Luis Obispo county, California.

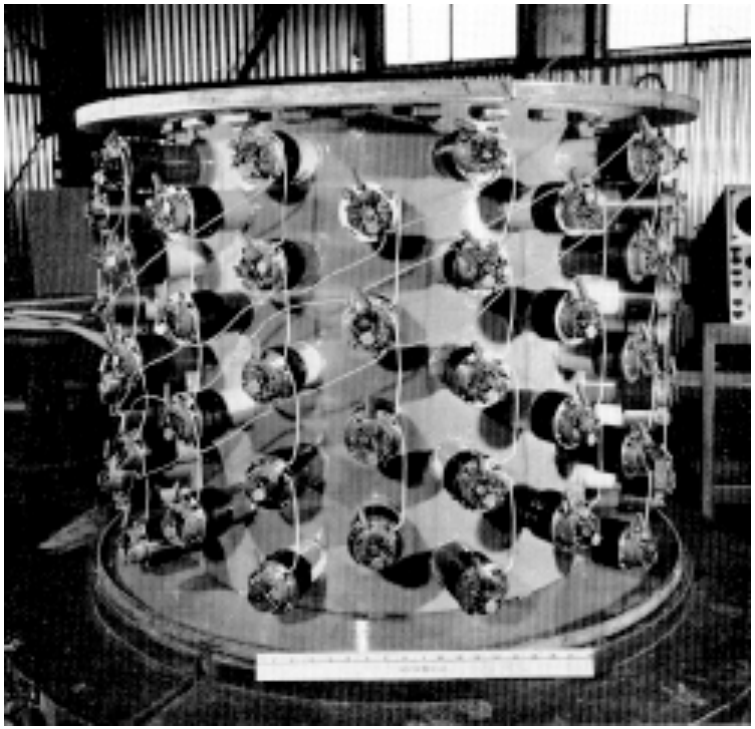
1 GW_{th} reactor
→ ~2×10^{20} ν_e/sec

First discovery of neutrino is from reactor neutrinos !

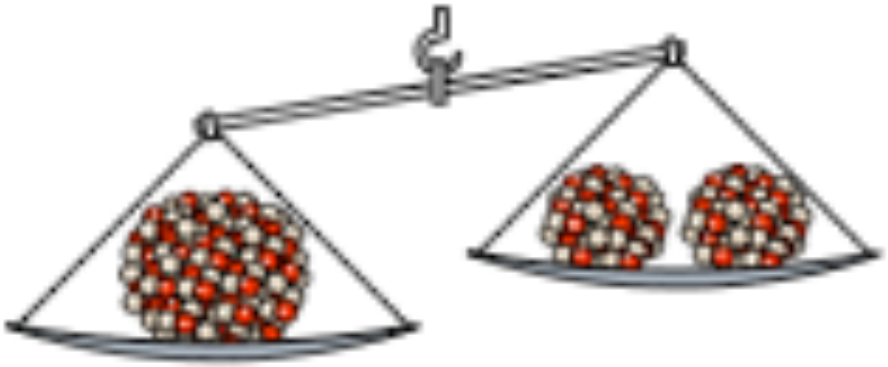
Nobel Prize in 1995

In **1956** @Savannah river, S. Carolina
By Reines and Cowan





What is Nuclear Fission ?



A heavy nucleus like uranium split in two parts: the heavy nucleus has a larger mass than the two splits.

The difference in masses, using the Einstein equation, corresponds to an energy of about 200 MeV.

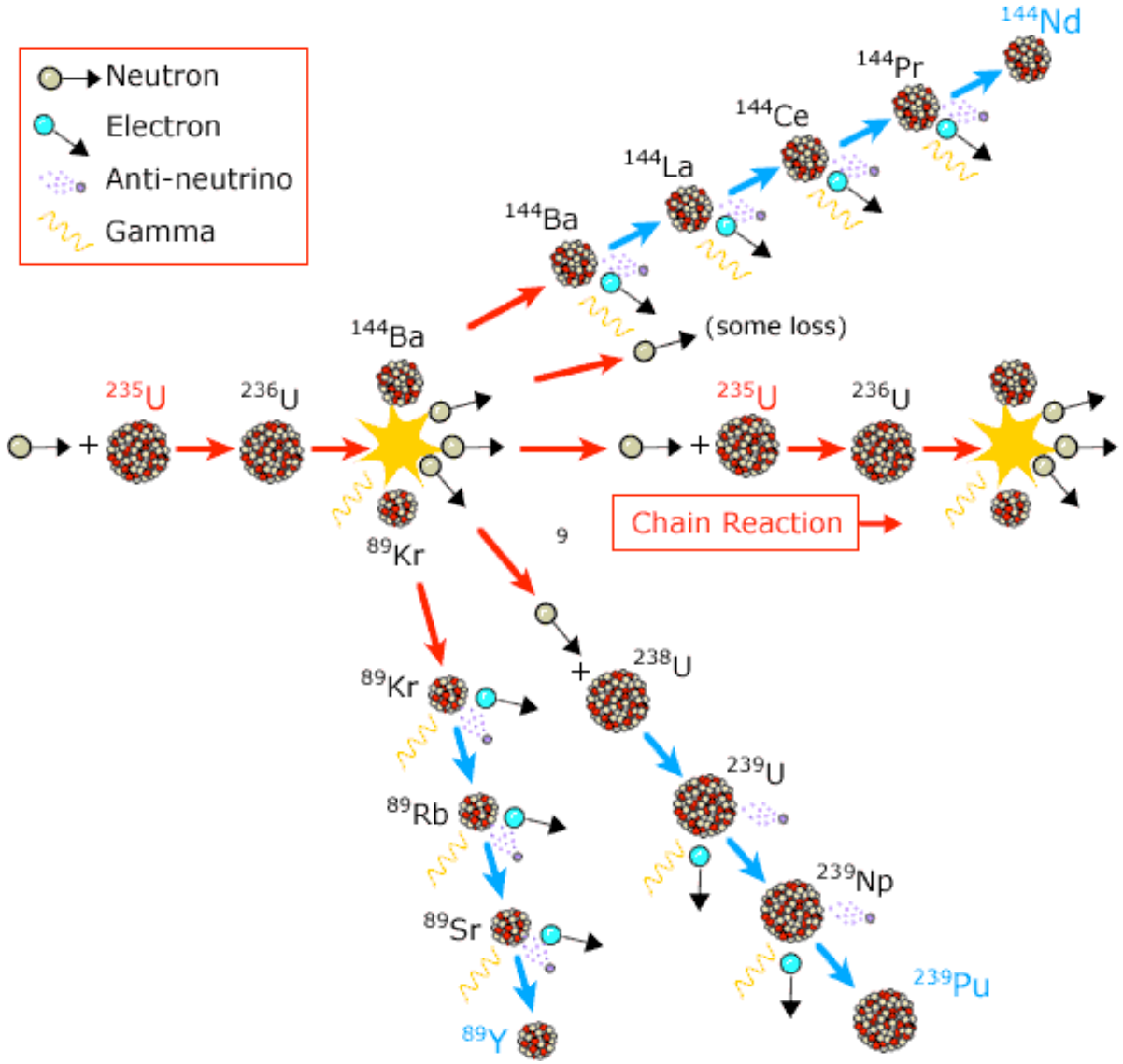
Discovery of Nuclear Fission

In 1938 by team of L. Meitner, O. Hahn, & F. Strassmann

Nobel Chemistry Prize in 1944

The Experimental Apparatus with which **the team of Otto Hahn, and Fritz Strassmann discovered Nuclear Fission in 1938**. The arrangement was originally in 3 separate rooms: irradiation, measurement, and chemistry at the Kaiser Wilhelm Institute for Chemistry in Berlin.

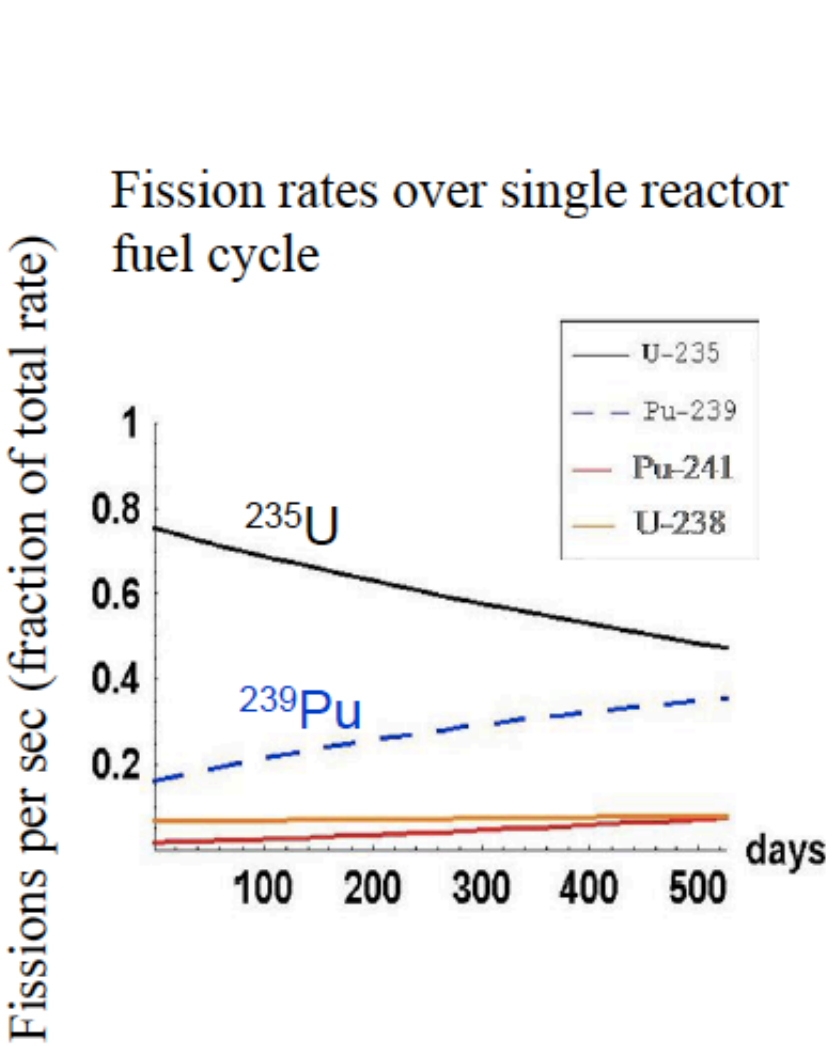
Nuclear Fission Process



~ 200 MeV/fission
~ 6 ν_e/fission

1 GW_{th} reactor
→ ~2×10^{20} ν_e/sec

> 99.9 % $\overline{\nu}_e$ are produced by ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu



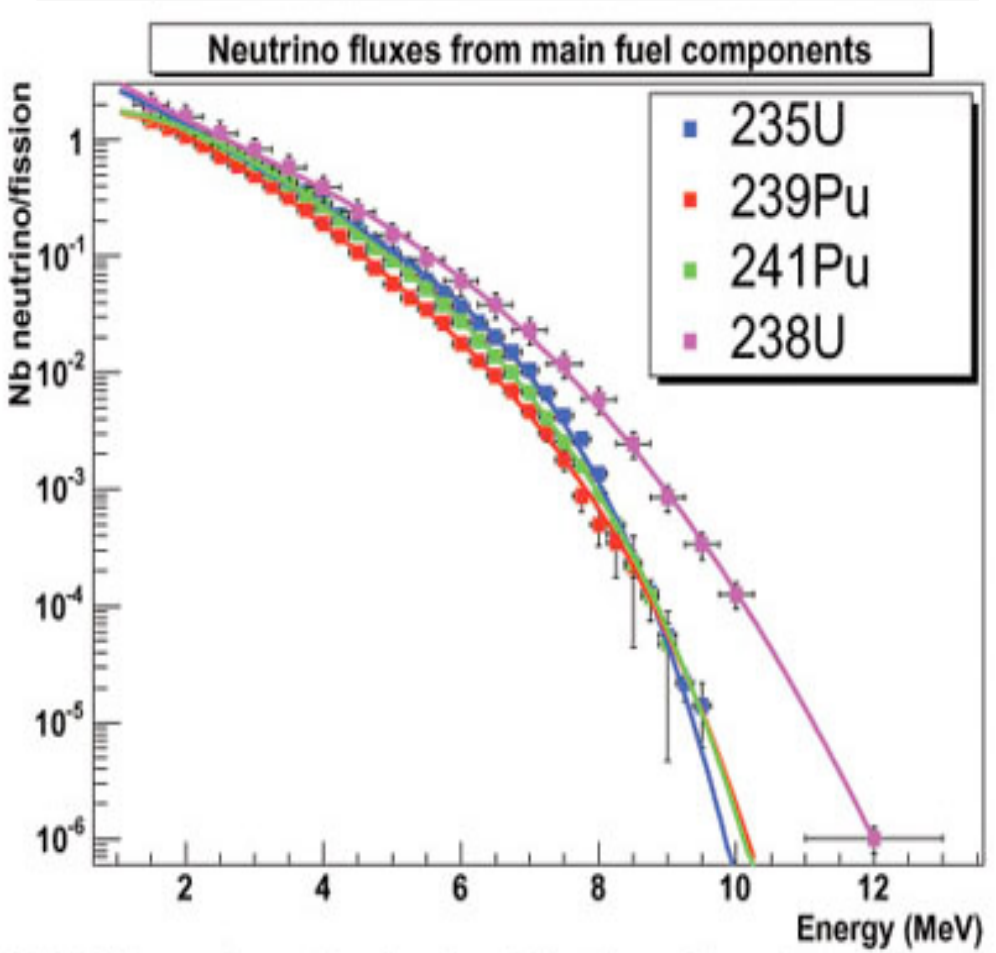
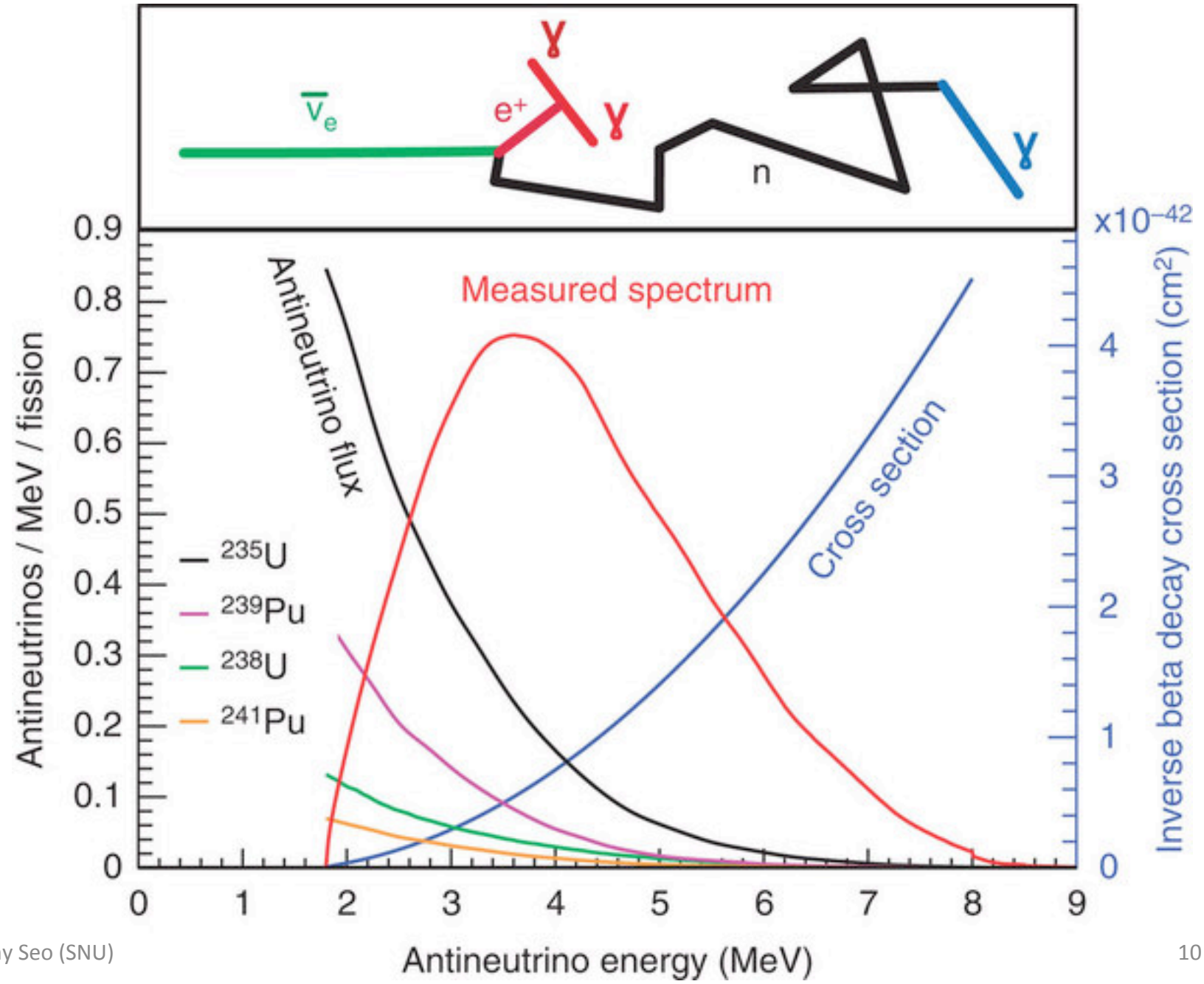


FIG. 7: Measured spectra of antineutrinos from the main components of the nuclear fuel. Taken from Ref. [20].

Plutonium breeding over fission cycle changes $\overline{\nu}_e$ rate by 5 ~ 10% and energy spectrum.


$\overline{\nu}_e$
e+
γ
γ
γ
n
Antineutrino flux
Measured spectrum
Cross section
235U
239Pu
238U
241Pu
Antineutrinos / MeV / fission
Inverse beta decay cross section (cm²)
x10⁻⁴²
Antineutrino energy (MeV)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
2
3
4
5
6
7
8
9

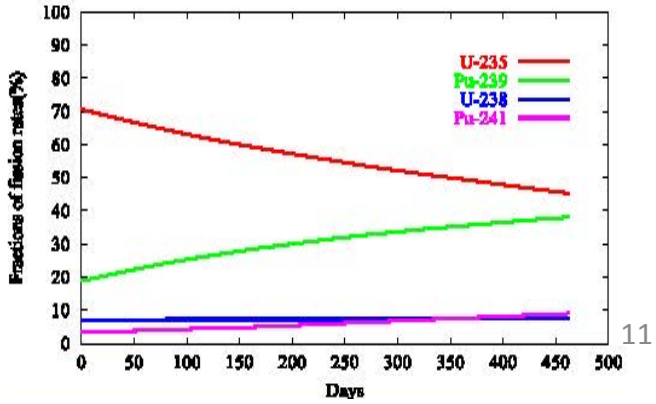
Expected Reactor Antineutrino Fluxes

- Reactor neutrino flux

$$\Phi(E_\nu) = \frac{P_{th}}{\sum_{i}^{isotopes} f_i \cdot E_i} \sum_{i}^{isotopes} f_i \cdot \phi_i(E_\nu)$$

- P_{th} : Reactor thermal power provided by the YG nuclear power plant
- f_i : Fission fraction of each isotope determined by reactor core simulation of Westinghouse ANC
- $\phi_i(E_\nu)$: Neutrino spectrum of each fission isotope
  [* P. Huber, Phys. Rev. C84, 024617 (2011)
  T. Mueller *et al.*, Phys. Rev. C83, 054615 (2011)]
- E_i : Energy released per fission
  [* V. Kopeikin *et al.*, Phys. Atom. Nucl. 67, 1982 (2004)]

Isotopes	James	Kopeikin
^{235}U	201.7±0.6	201.92±0.46
^{238}U	205.0±0.9	205.52±0.96
^{239}Pu	210.0±0.9	209.99±0.60
^{241}Pu	212.4±1.0	213.60±0.65



With Reactor Neutrinos

- To measure θ_{13} (finally measured in 2012 !)
- CP violation phase angle ?
  (when combined with accelerator data)
- 4^{th} family of neutrinos ?

Current

Short Baseline: O(1km)

- To determine ν mass ordering (very challenging !)
- Very precise measurements on ν mixing parameters
- Super Nova ν, Solar ν, Geo ν
- Multi-purpose detector

Future

Medium Baseline: ~50 km

PMNS matrix

- Pontecorvo
- Maki
- Nakagawa
- Sakaga

in 1962

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

θ_{23} θ_{13} θ_{12}

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmos. (ν_μ, $\overline{\nu}_\mu$ deficit)
Long baseline (ν_μ deficit)

Reactor ($\overline{\nu}_e$ deficit)
Long baseline ($\nu_\mu \rightarrow \nu_e$)

Solar (ν_e deficit)
Reactor ($\overline{\nu}_e$ deficit)

Neutrino Oscillation Milestones

Atmos. Neutrino Oscillation → θ_{23}

~45° (1998)
Super-K; K2K

Solar Neutrino Oscillation → θ_{12}

34° (2001)
SNO, Super-K;
KamLAND

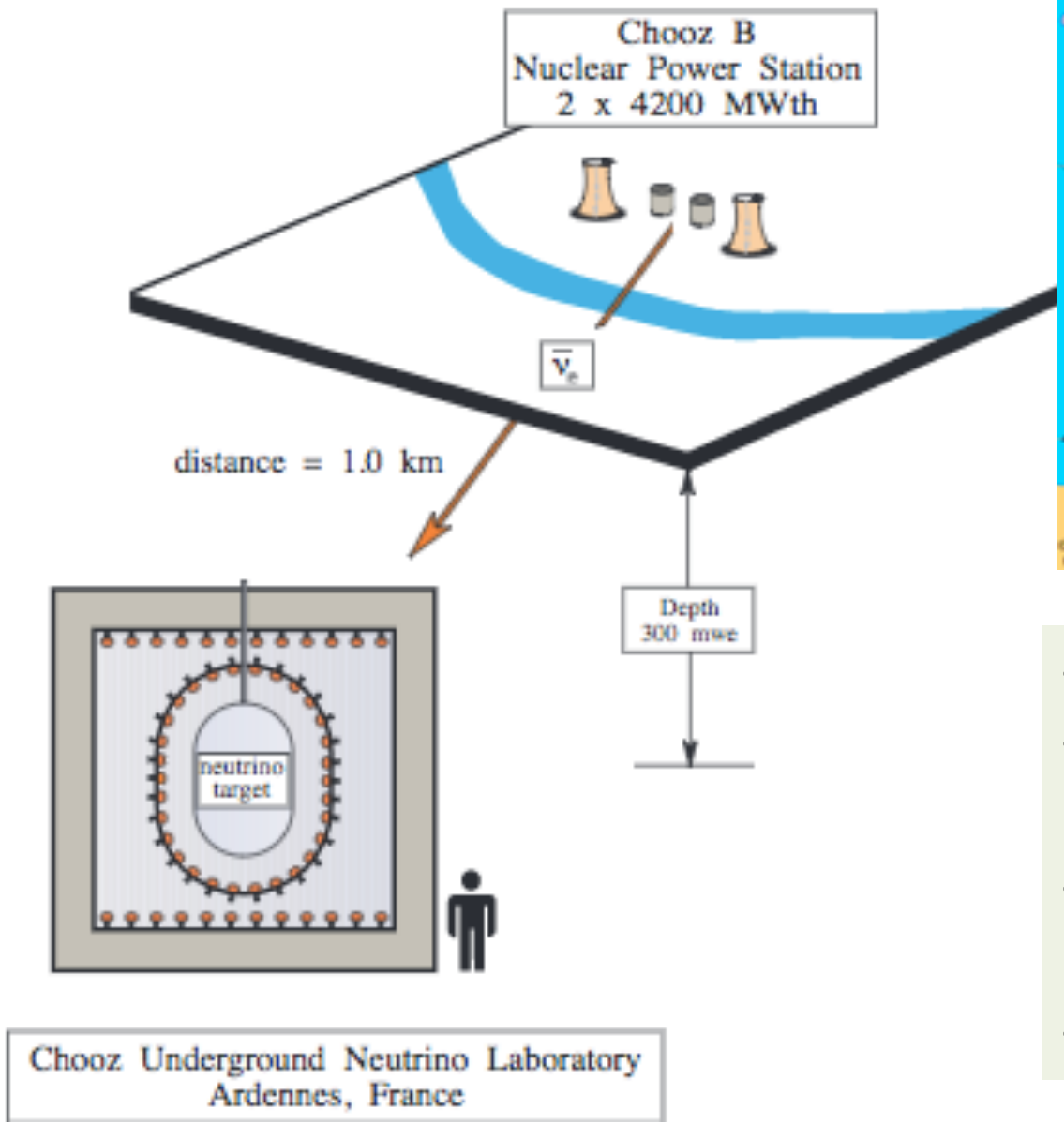
Reactor Neutrino Oscillation → θ_{13}

9° (2012)
Daya Bay, RENO
Double Chooz

2015 Nobel Prize

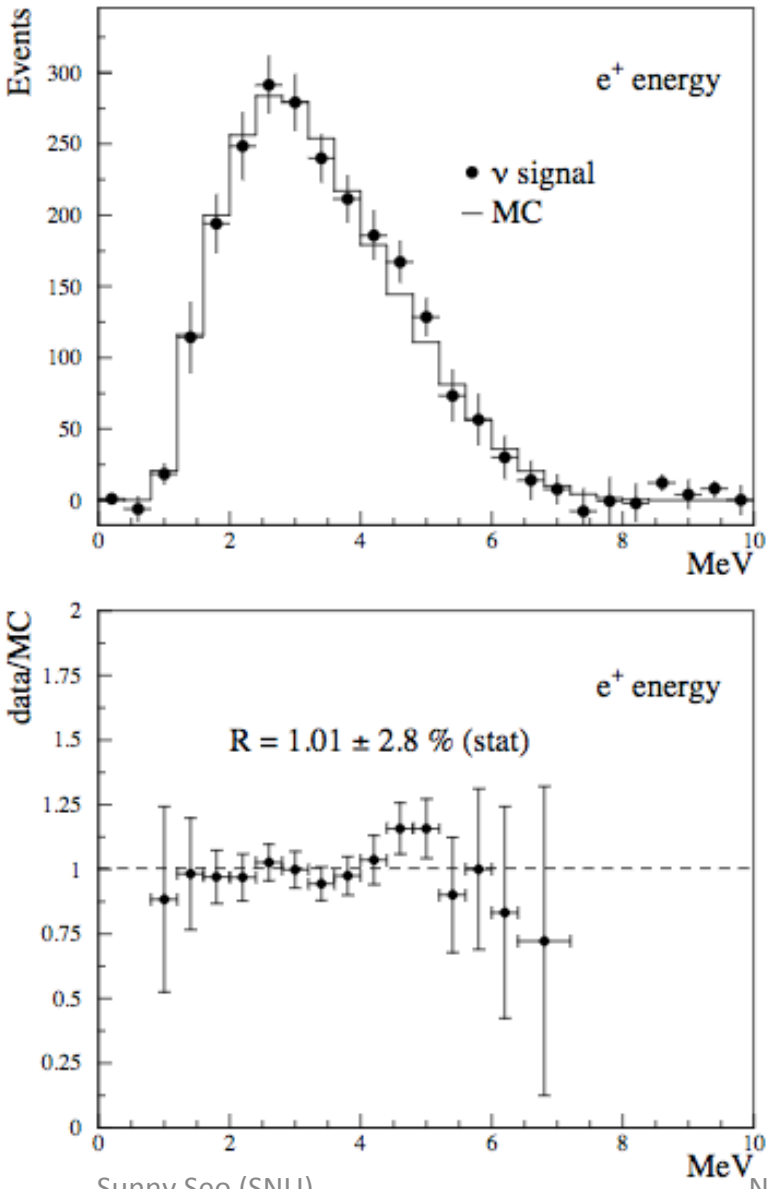
Nature was very kind to us !

Chooz Experiment

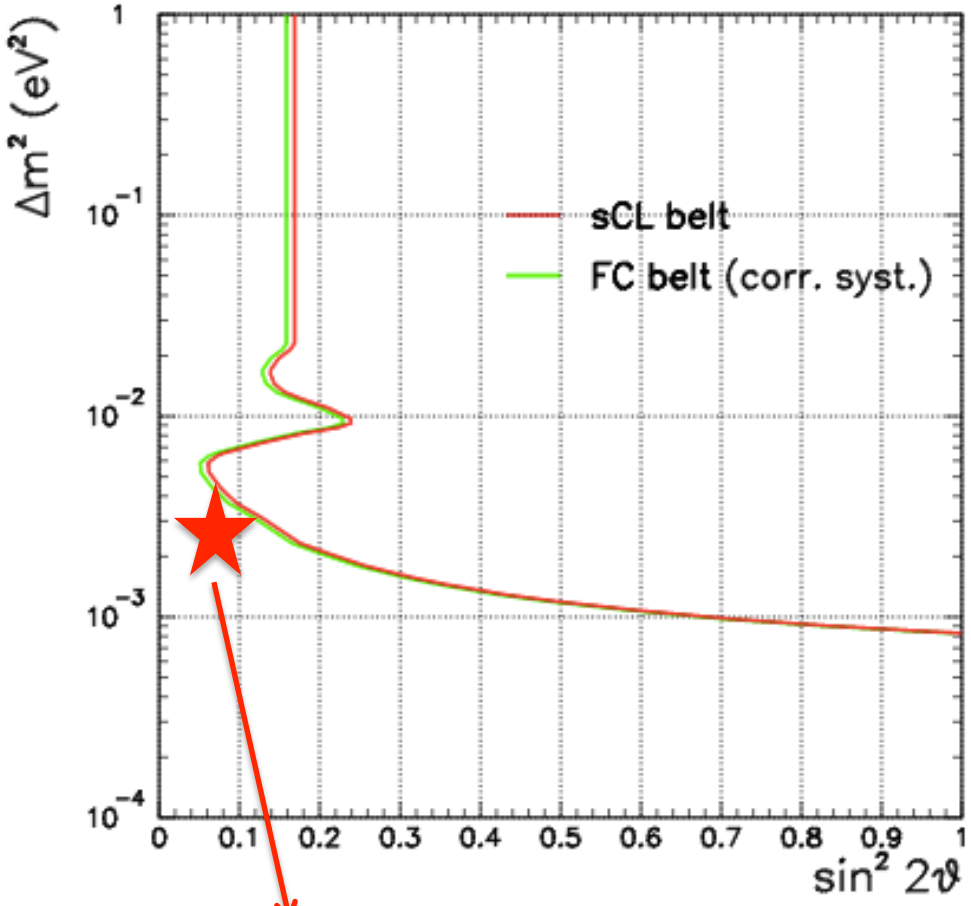


- 5 ton LS (0.09% Gd)
- took > 1 year data
  (until July 1998)
- No oscillation observed
  → set limit
- Detector degradation

Chooz Results in 2003

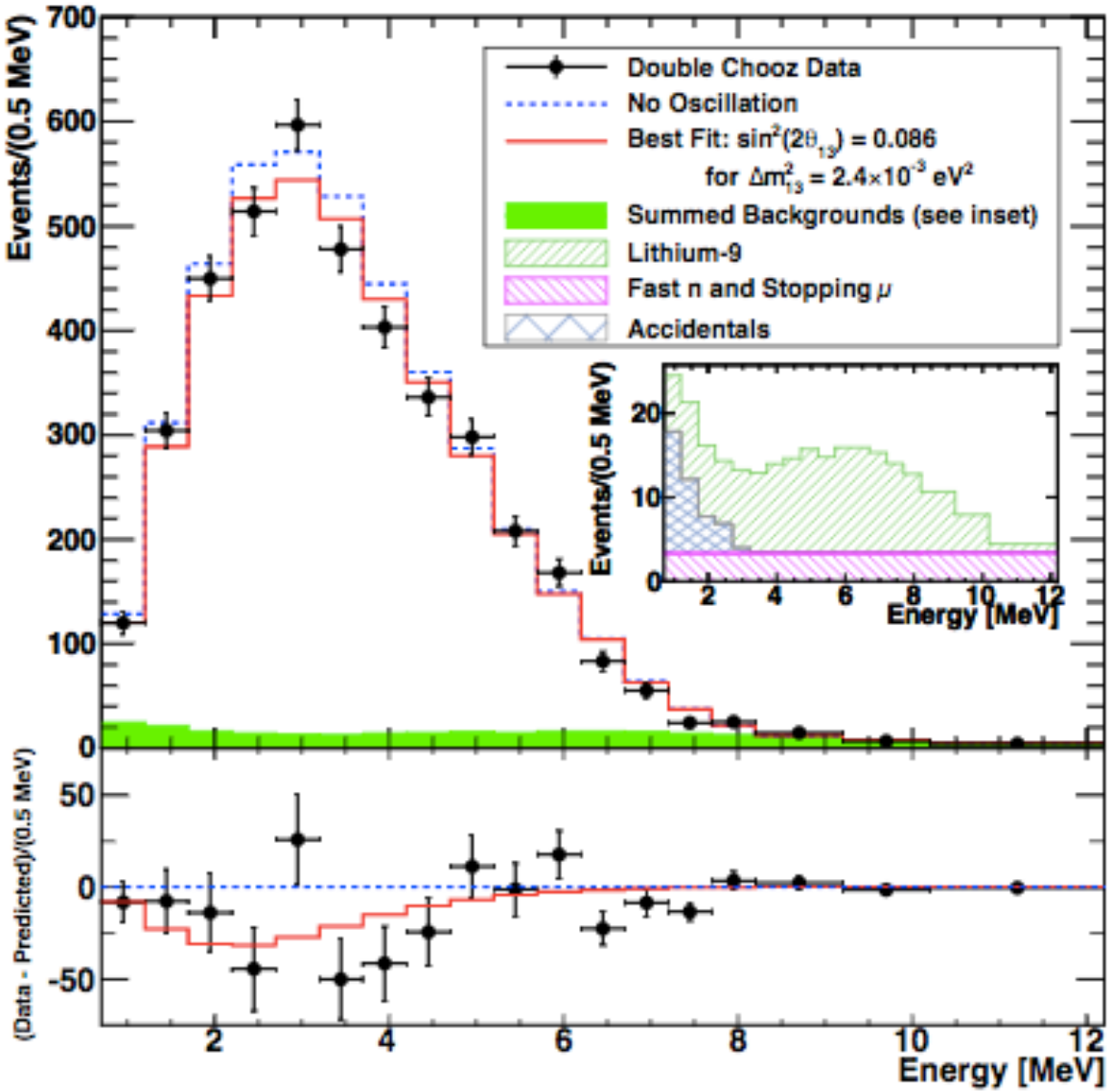


Eur.Phys.J.C27:331-374,2003



2016 best fit

Double Chooz Results in 2012



PRL 108, 131801

Result using only Far detector

First θ_{13} measurements in 2012

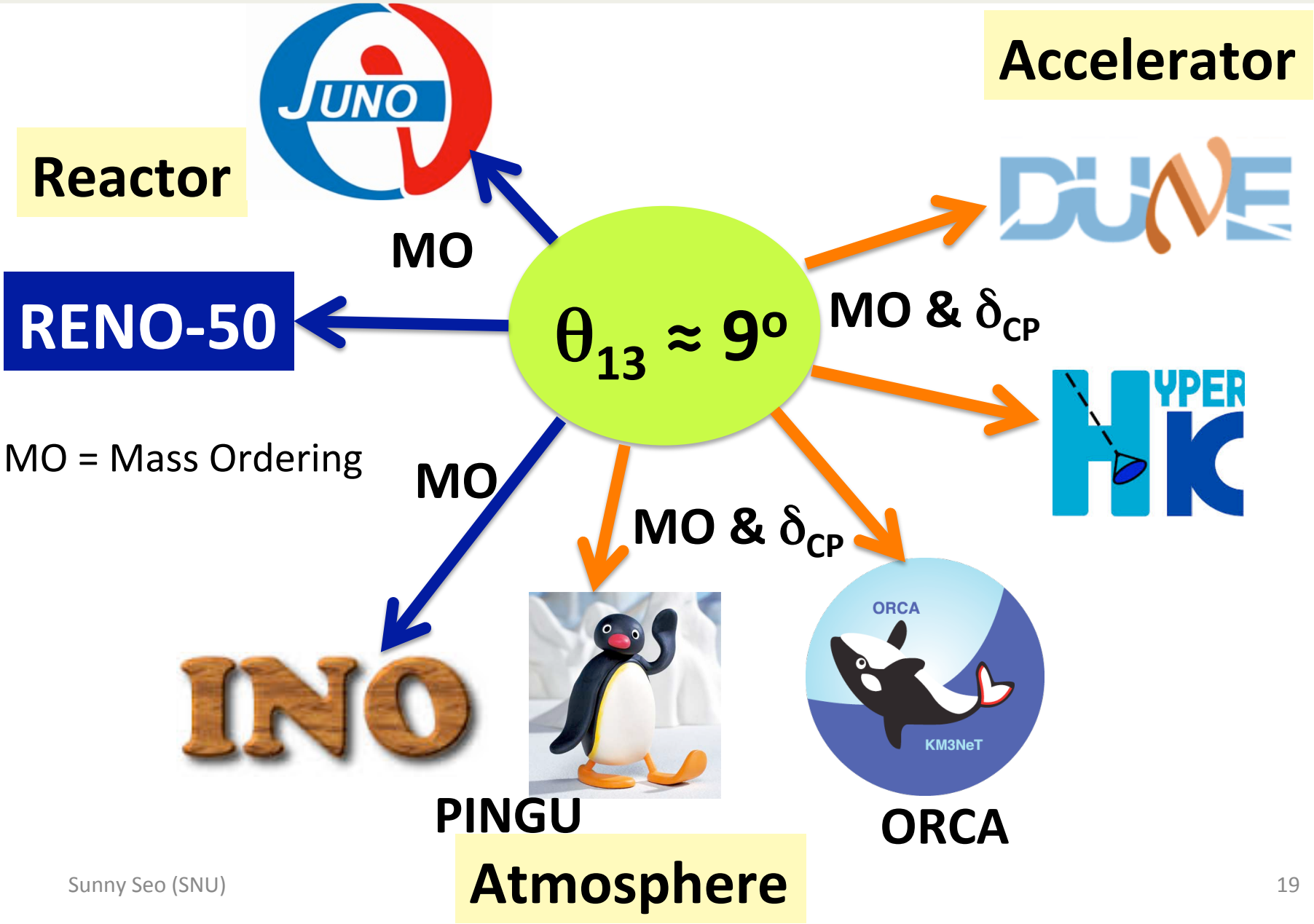
~ 4 years ago

	Double Chooz	Daya Bay	RENO
Publication	PRL 108, 131801 (Mar. 30, 2012)	PRL 108, 171803 (Apr.27, 2012)	PRL 108, 191802 (May 11, 2012)
$\sin^2(2\theta_{13})$	0.086	0.092	0.113
Stat. error	0.041 (101 days)	0.016 (49 days)	0.013 (220 days)
Syst. error	0.030 (flux uncert.)	0.005 (MC driven)	0.019 (data driven)
Significance	1.7 σ	5.2 σ	4.9 σ

1 month

2 weeks

θ_{13} and Future Experiments



Why Precise θ_{13} ?

1. θ_{13} affects θ_{12} (θ_{23}) and δ_{CP} measurements.

2. θ_{13} is best measured in short (1~2 km) baseline reactor ν experiments. → legacy measurement

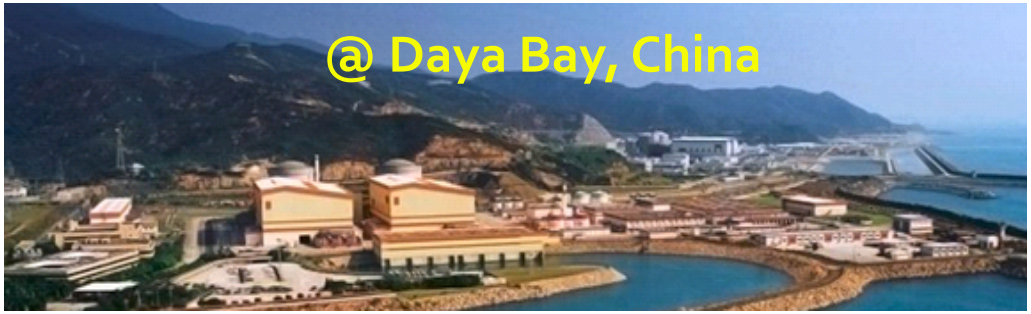
Thus, we need to measure it
as precise as possible
with the currently operating detectors.

Reactor θ_{13} Experiments

Double Chooz

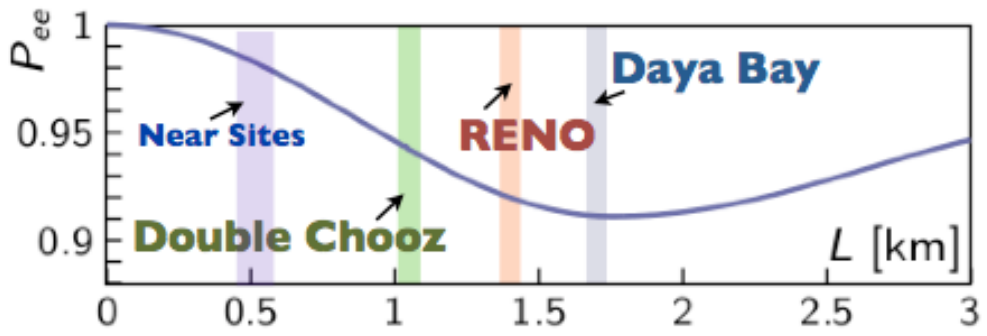
RENO

Daya Bay

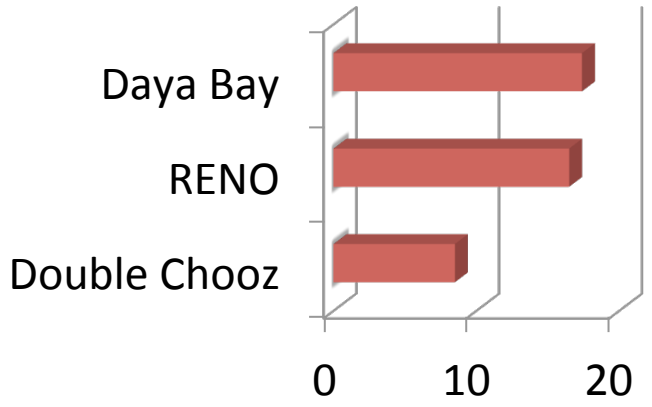


Comparisons

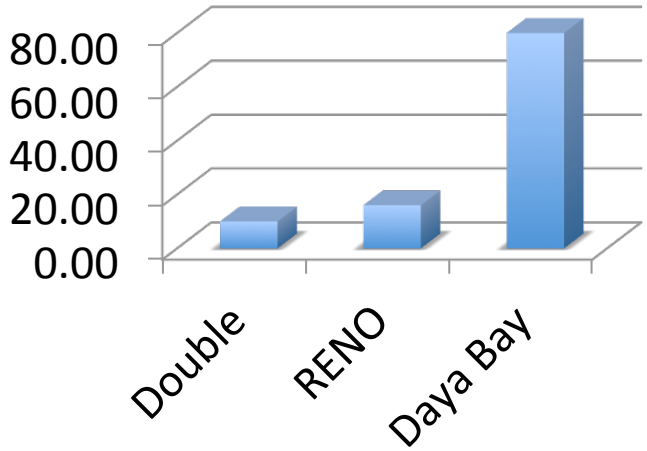
Baselines



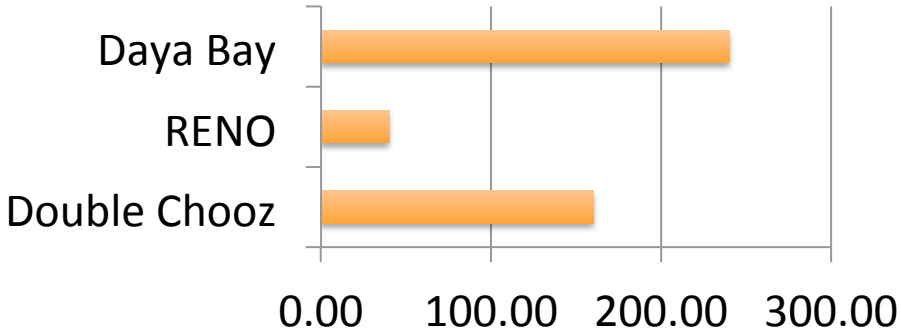
Reactor Thermal Power (GW_{th})



Target (ton)



Manpower



RENO Collaboration

RENO
ν θ_{13}

9 institutions and 35 physicists in Korea

- 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 since **Aug. 2011**

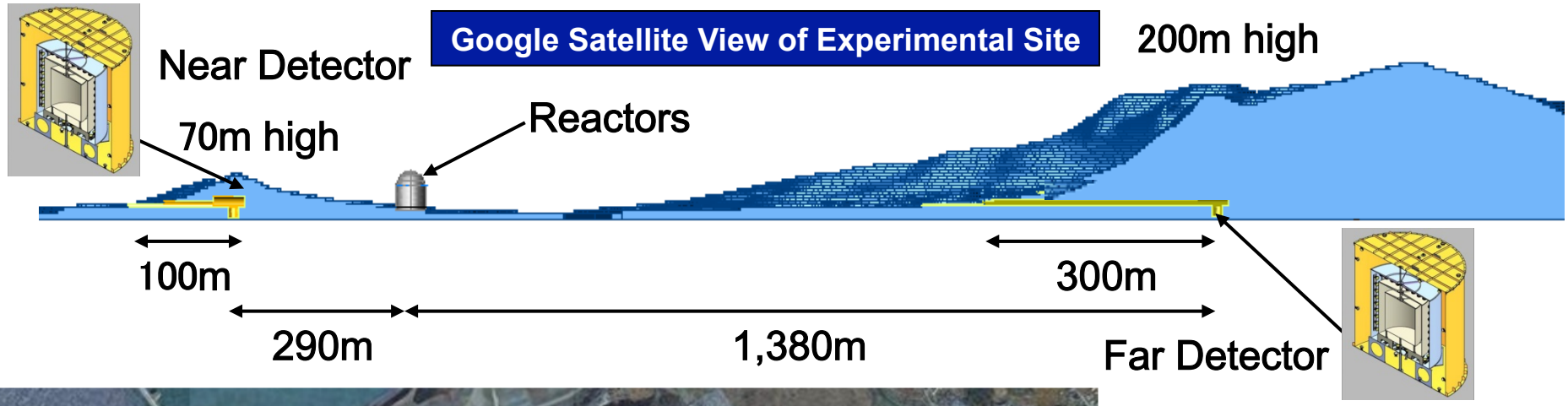
Reactor Experiment for Neutrino Oscillation

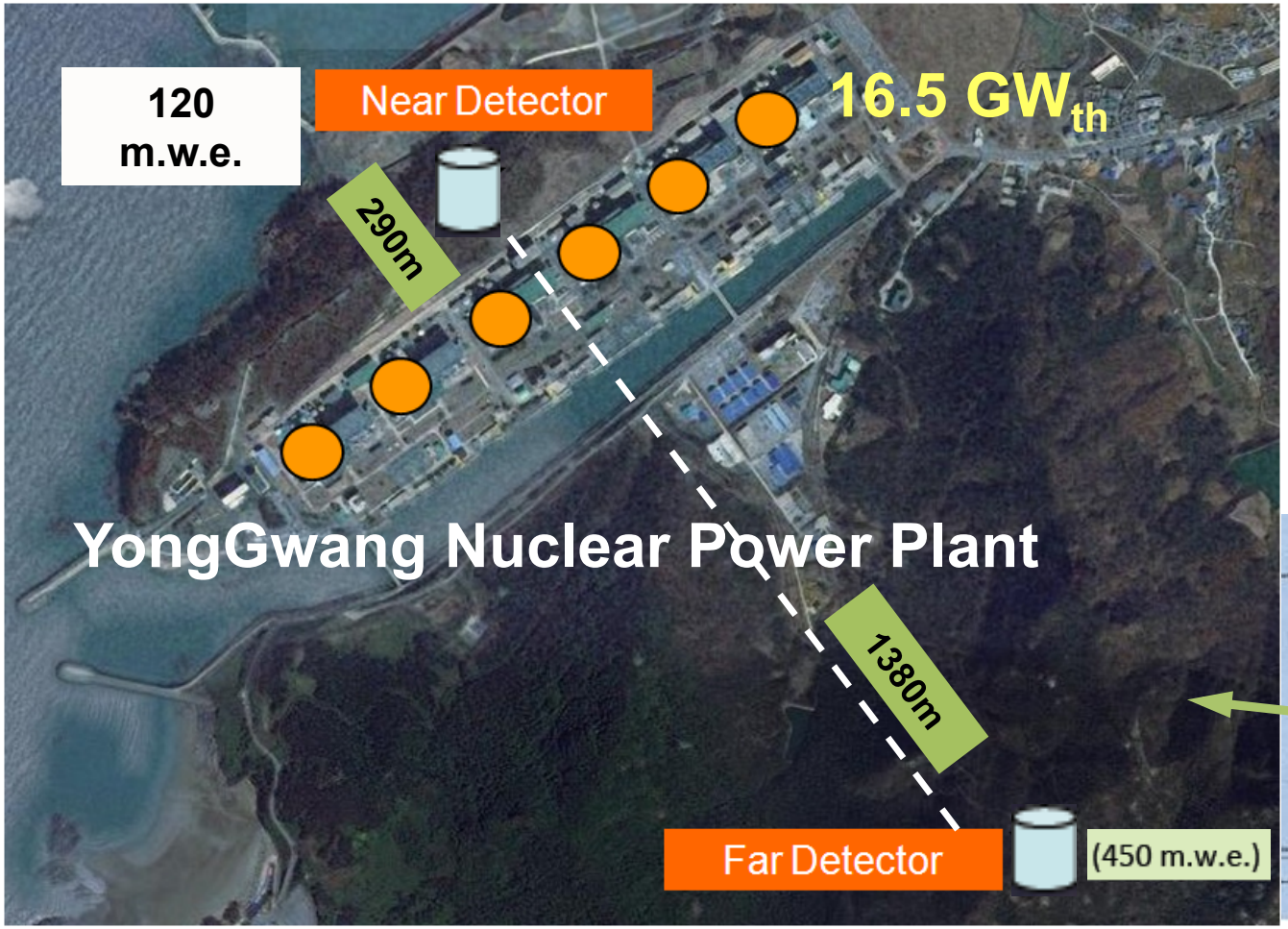
RENO Location: YongGwang S. Korea

YongGwang (靈光) :

means "Glorious light"

~ 4 hours driving distance from Seoul





RENO

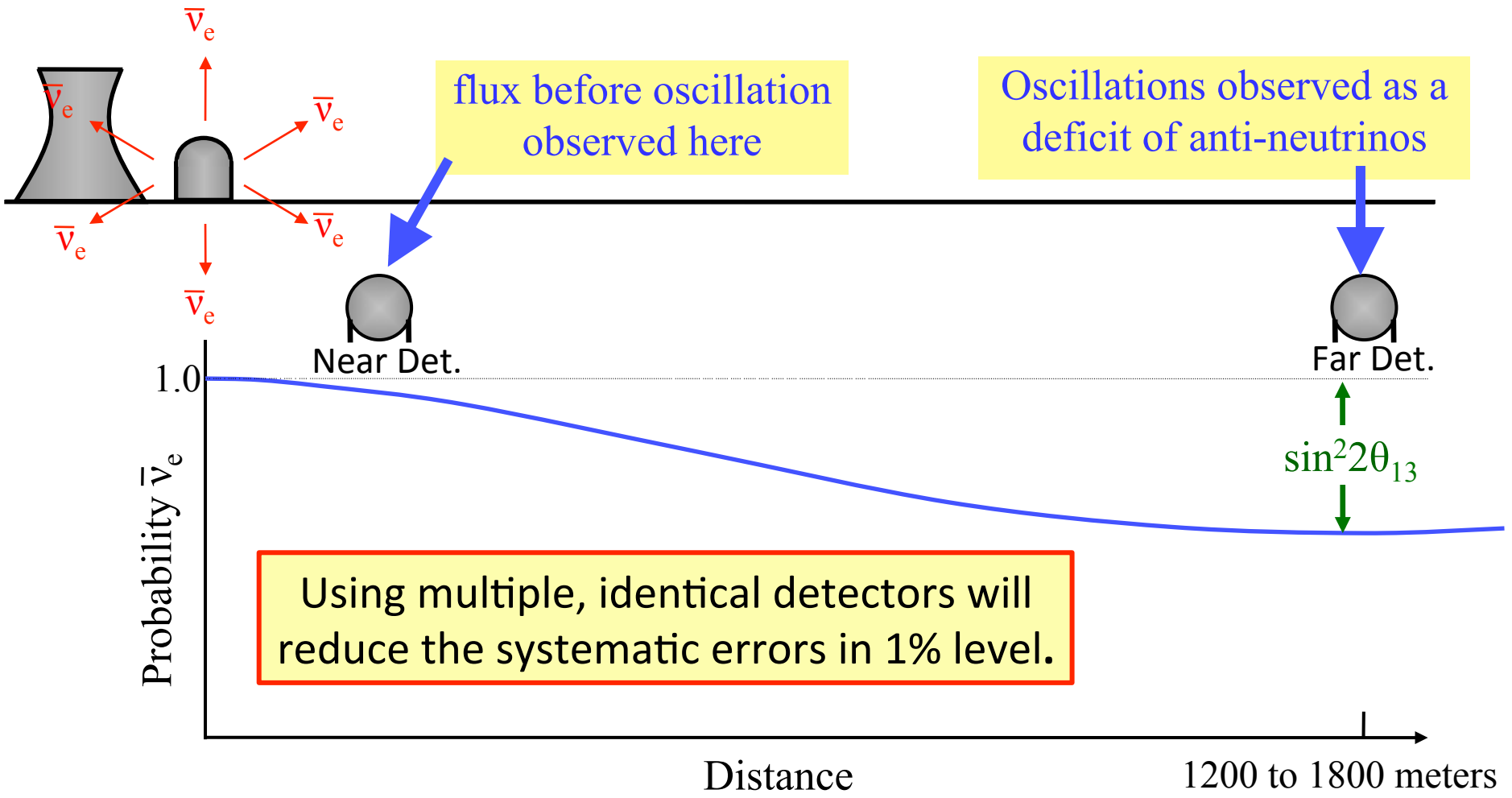
ν θ_{13}

ν_e ν_μ ν_τ

KNRC

Korea Neutrino Research Center

Reactor Neutrino Oscillations



$$1 - P = \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}) + \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} \approx \sin^2 2\theta_{13}\sin^2\Delta_{ee} + \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}, \quad (1)$$

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

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

Nunokawa, Parke, Funchal, PRD 72, 013009 (2015)

What is Δm_{ee}^2 ?

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

Parke
arXiv:1601.07464

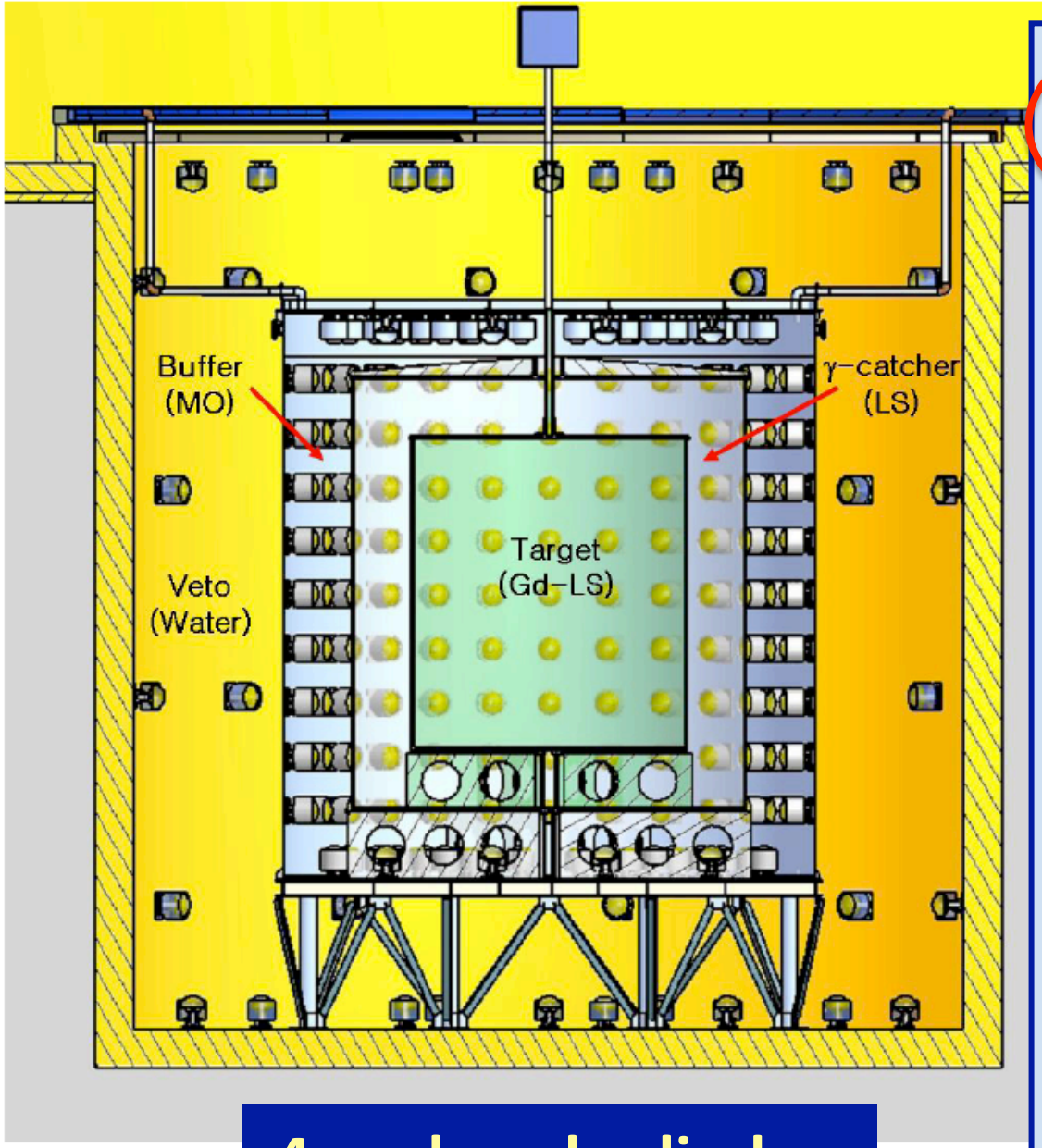
Nunokawa, Parke, Funchal, PRD 72, 013009 (2015)

- ν_e weighted average of Δm_{31}^2 and Δm_{31}^2
- L/E independent
- Mass ordering independent
- Weakly dependent on solar parameters

$$|\Delta m^2_{31}| = |\Delta m^2_{ee}| \pm \sin^2\theta_{12}\Delta m^2_{21}$$
$$|\Delta m^2_{32}| = |\Delta m^2_{ee}| \mp \cos^2\theta_{12}\Delta m^2_{21}$$

→ More dependent on Solar parameters

The RENO Detector



4 enclosed cylinders

- **Target : 16 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

Tunnel Construction

(2008.6~2008.12)

by Daewoo Eng. Co. Korea

Near & far tunnels are completed

(2008.6~2009.3)

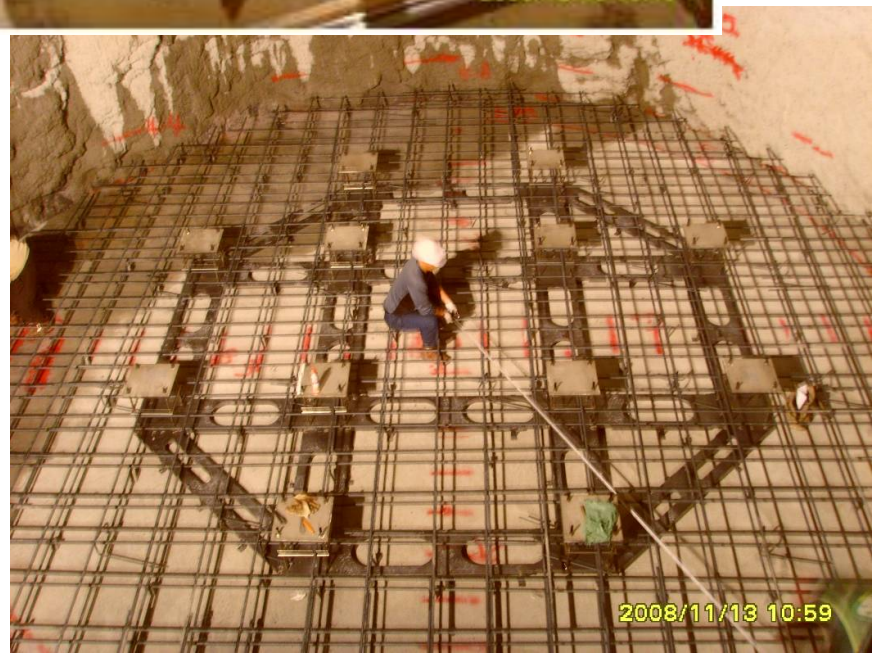
by Daewoo Eng. Co. Korea

Far site

Near site

Detector vertical halls are ready

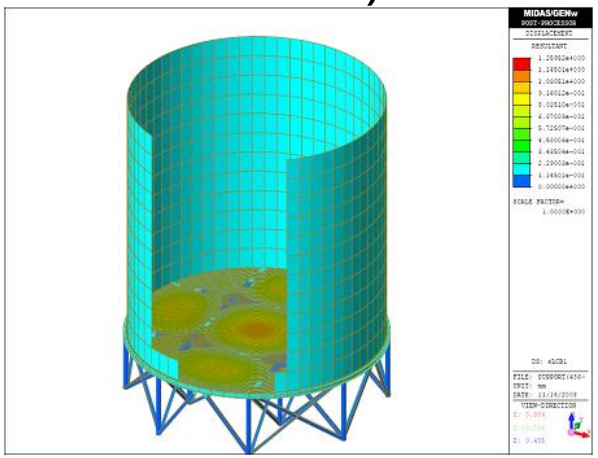
(2008.12~2009.2)

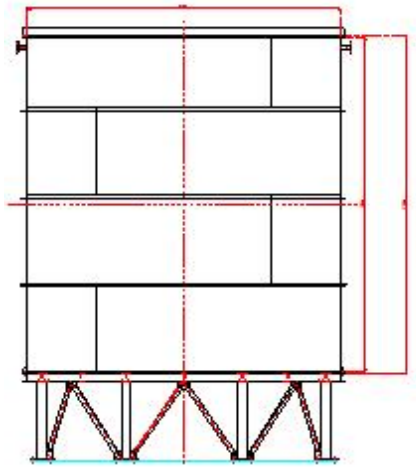


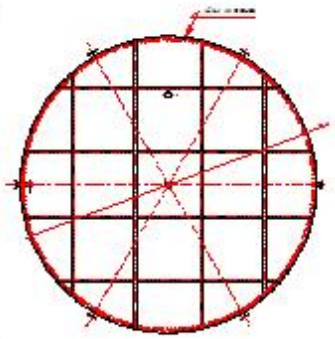
Buffer steel tanks are installed

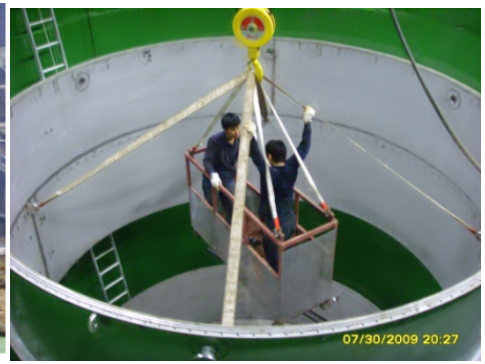
(2009.6~2009.11)

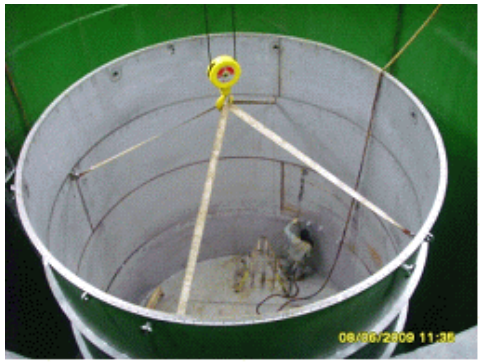
by NIVAK Co. Korea

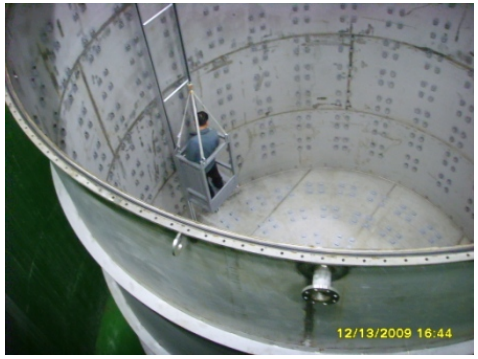


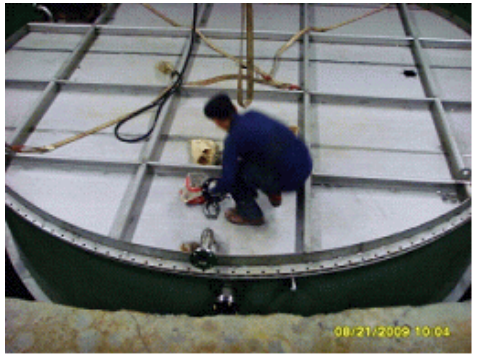




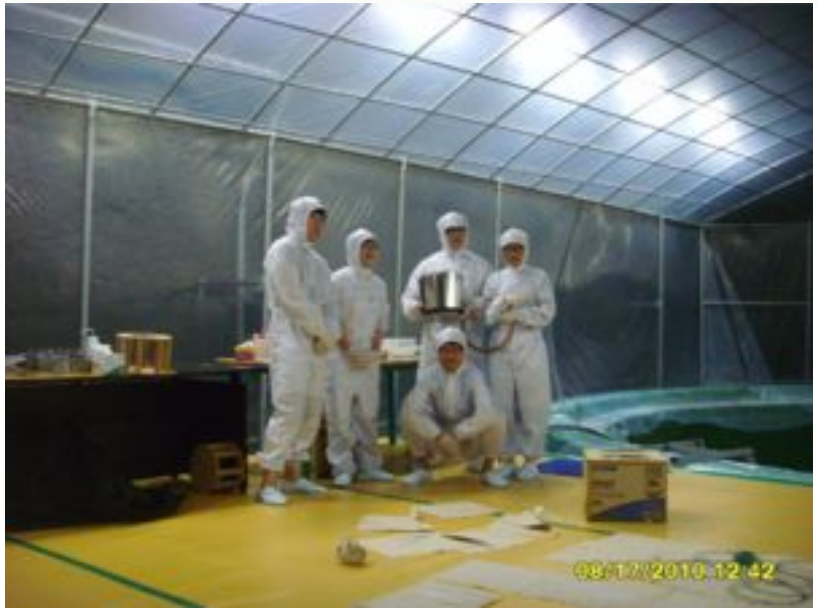




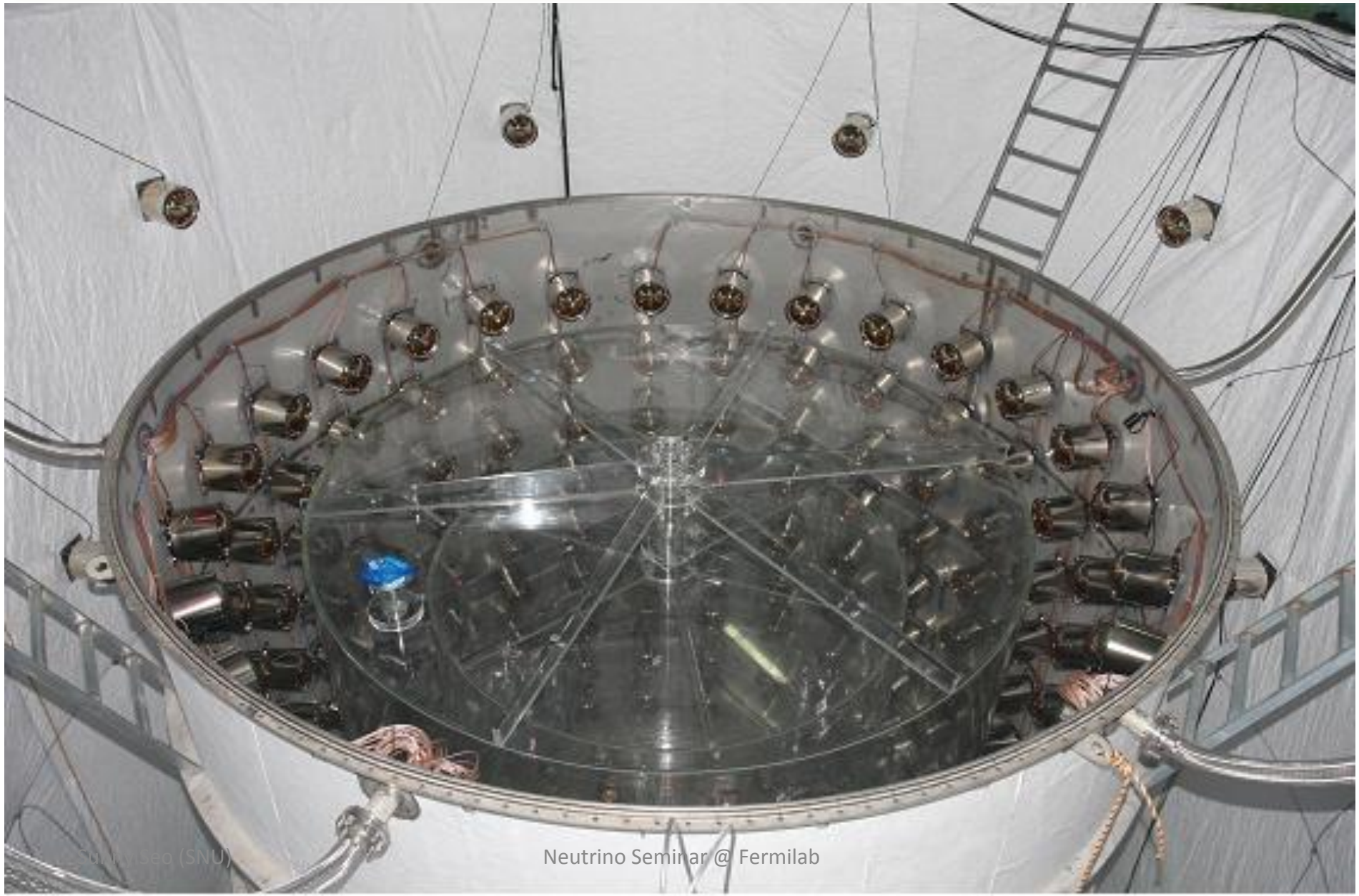




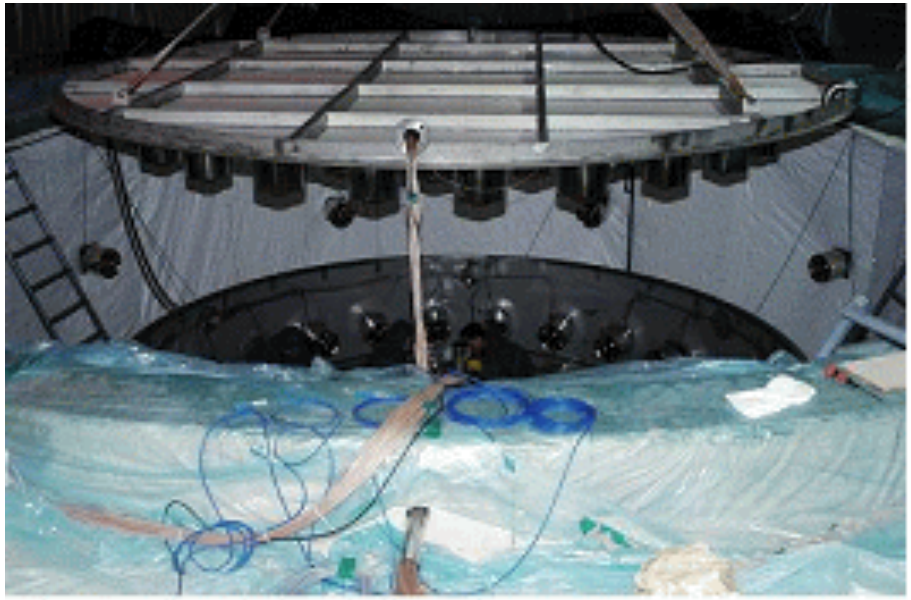
PMT Mounting (Aug. – Oct. 2010)

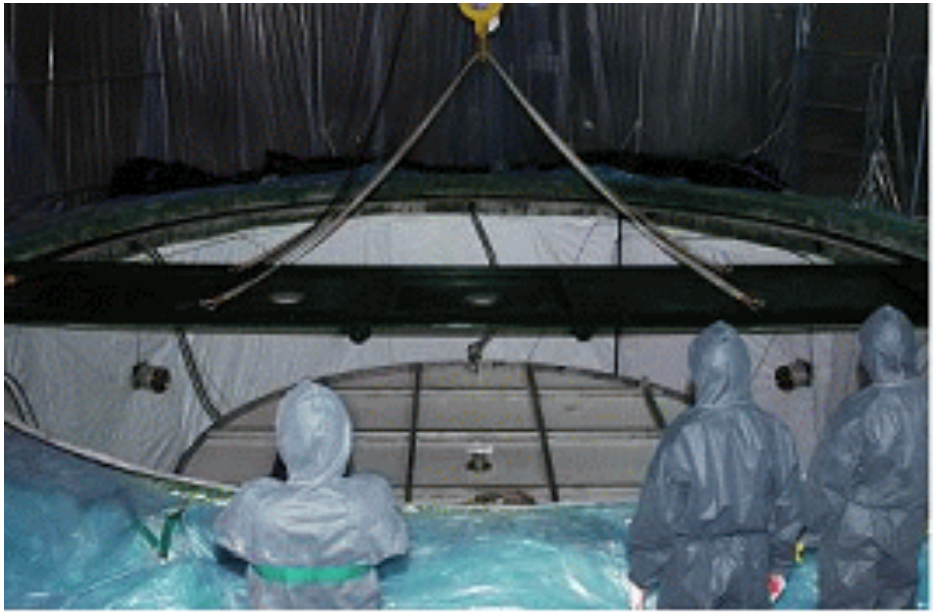


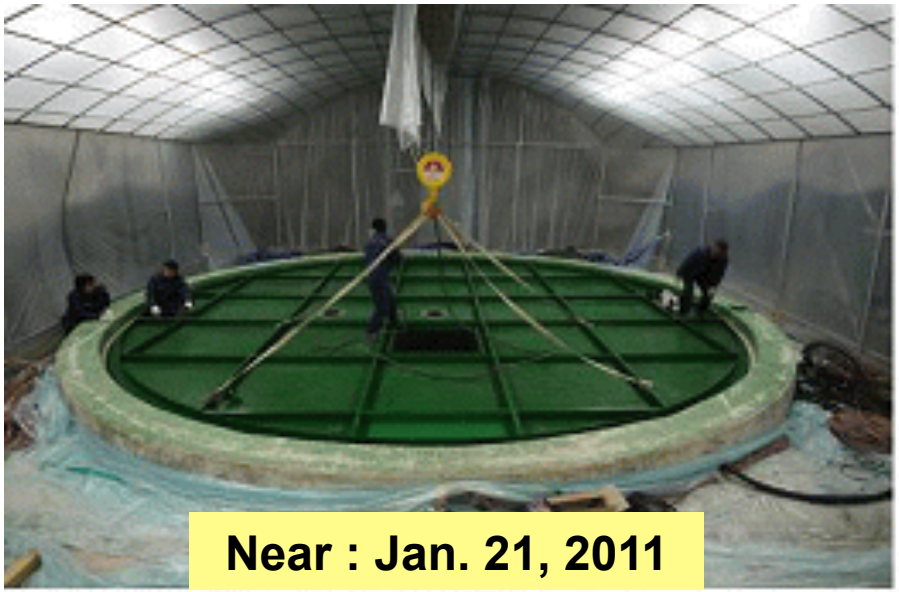
Mounted PMTs



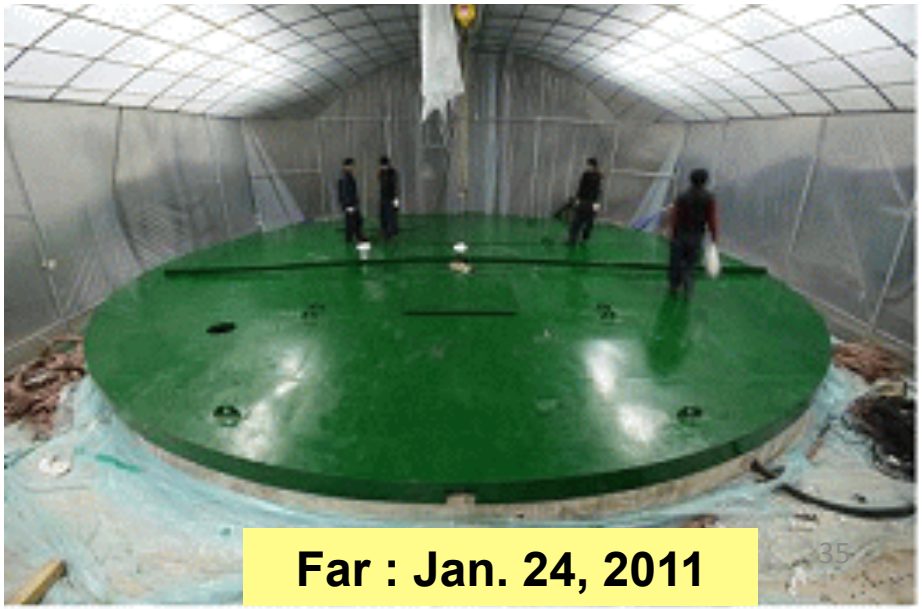
Closing Detector (Jan. 2011)







Near : Jan. 21, 2011



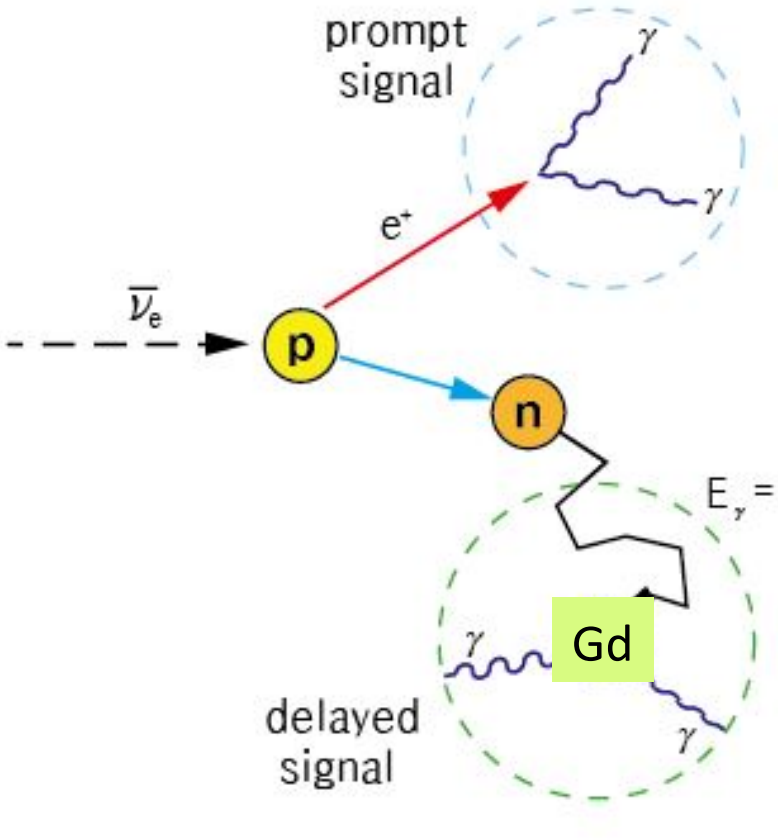
Far : Jan. 24, 2011

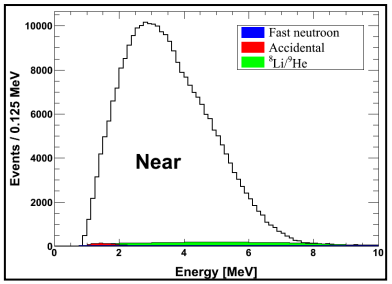
Production of Liquid Scintillator (Feb.-July 2011)

Yonggwang Neutrino Detector Facility

- 3-6 permanent residents: taking shifts and operation of the detectors

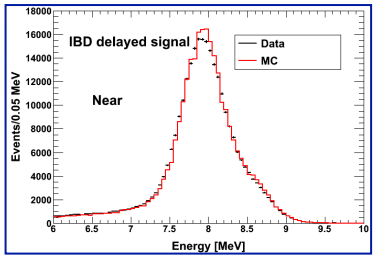
Detection Principle of Reactor Neutrinos





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

IBD process



or

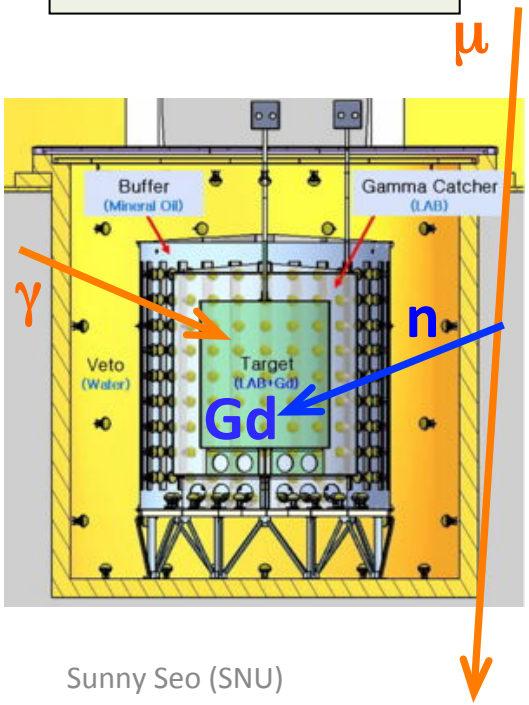
Gd capture	**H capture**
Delayed signal	**Delayed signal**
~30 μs	**~200 μs**
~8 MeV	**~2.2** MeV

- Prompt signal (e^+) : 1 MeV 2γ's + e^+ kinetic energy (E = 1~10 MeV)
- Delayed signal (n) : 8 MeV γ's from neutron's capture by **Gd** in ~30 μs
  or 2.2 MeV '' by H in ~200 μs

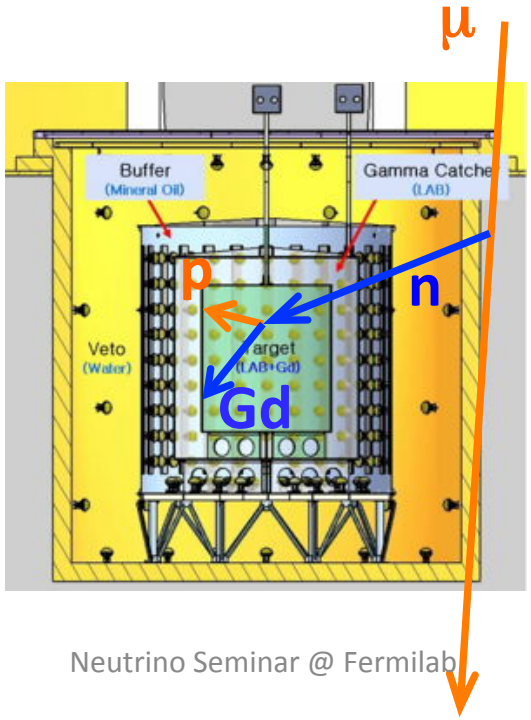
Backgrounds

- Accidental coincidence between prompt and delayed signals
- Fast neutrons produced by muons, from surrounding rocks and inside detector (n scattering : prompt, n capture : delayed)
- **^{9}Li/^{8}He** β-n followers produced by cosmic muon spallation

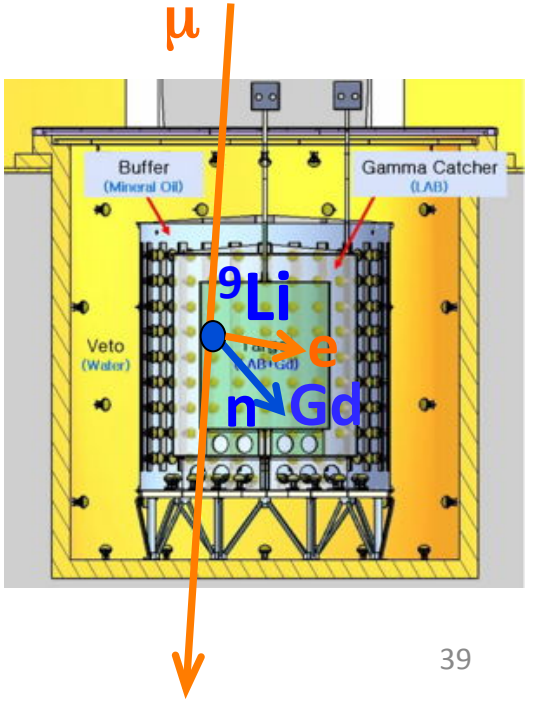
Accidentals



Fast neutrons



^{9}Li/^{8}He β-n followers



RENO Data-taking Status

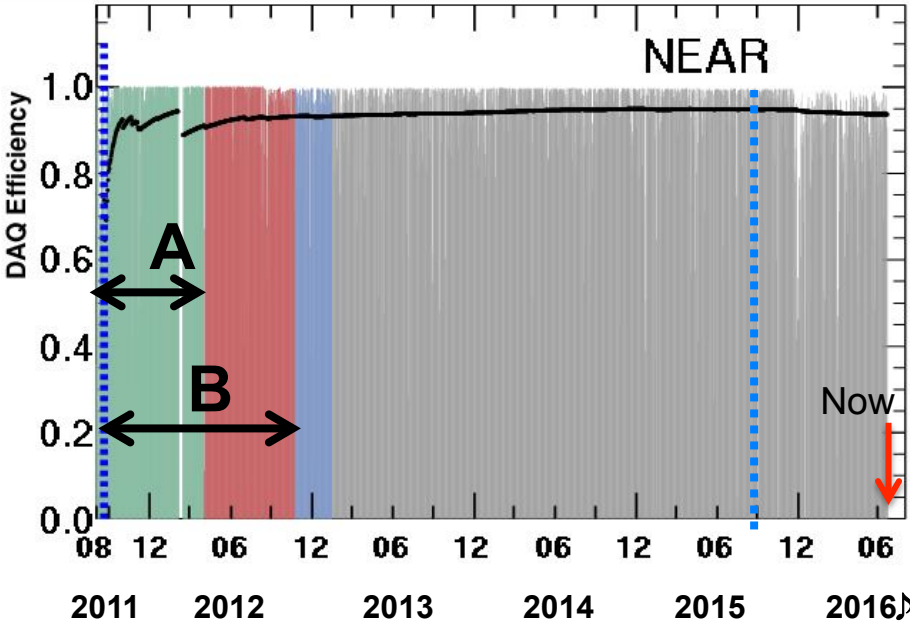
- Data taking began on Aug. 1, 2011 with both near and far detectors.
  (DAQ efficiency : ~95%)

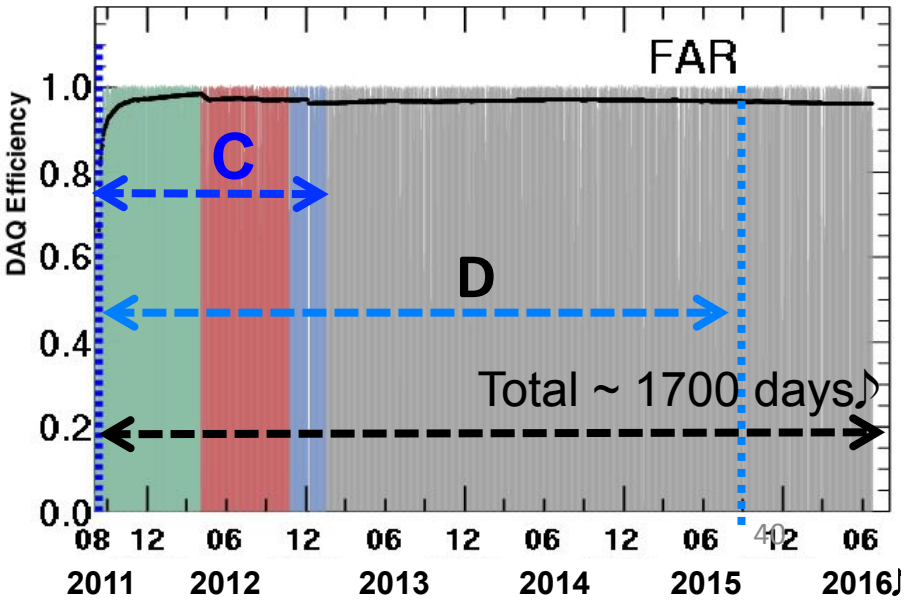
- **A (220 days)** : **First θ_{13} result**
  [11 Aug, 2011~26 Mar, 2012]
  PRL 108, 191802 (2012)

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

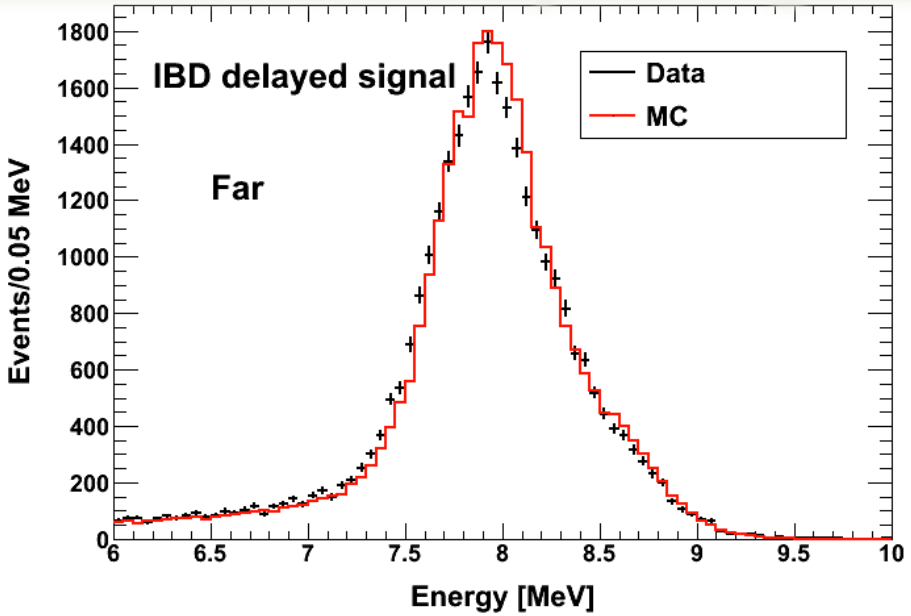
- **C (~500 days)** : New **result**
  Shape+rate analysis (θ_{13} **and** $|\Delta m^2_{ee}|$)
  [11 Aug, 2011~21 Jan, 2013]
  PRL 116, 211801 (2016)♪

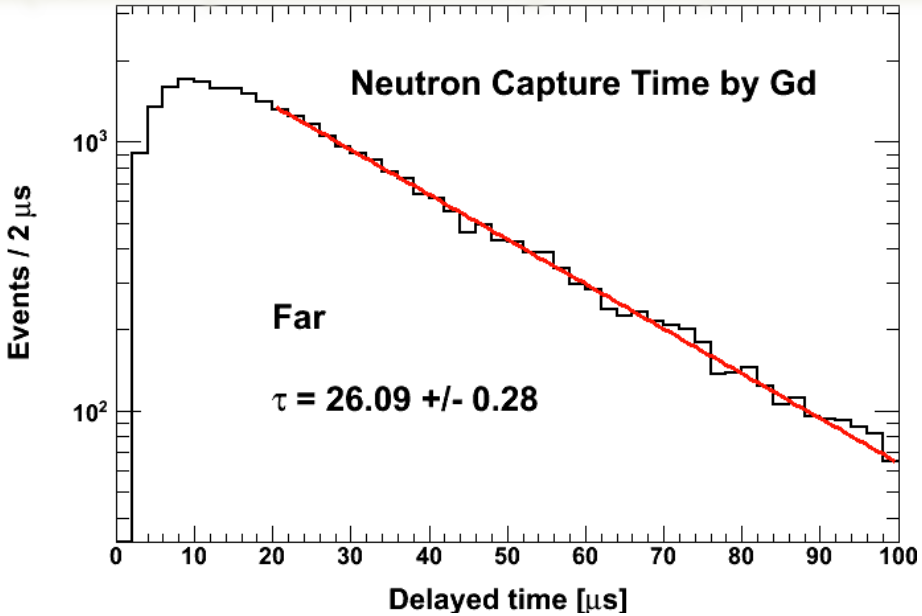
- **D (~1400 days)** : **5MeV excess result**
- Absolute reactor flux and spectrum
  [11 Aug. 2011~ 30 Sep, 2015]

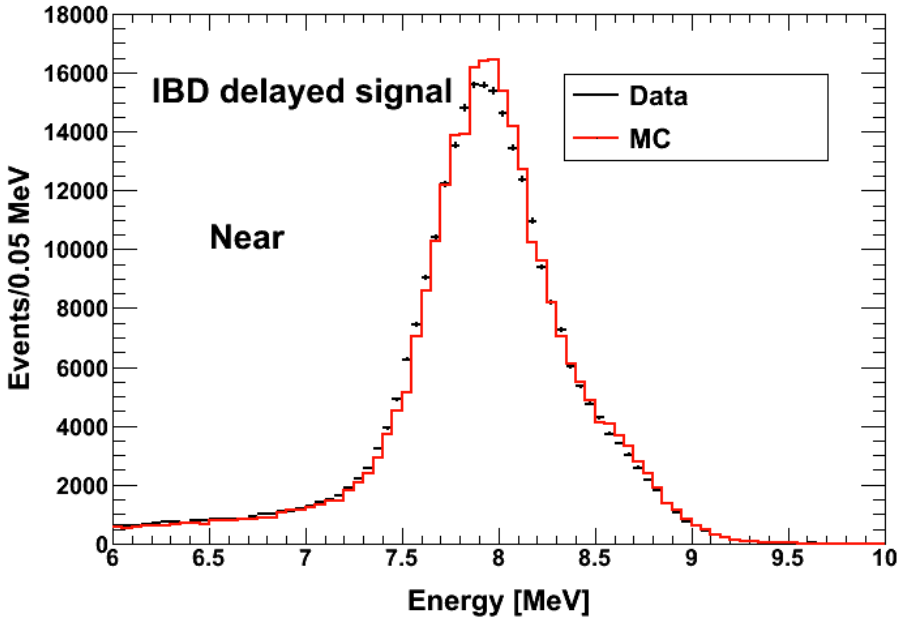


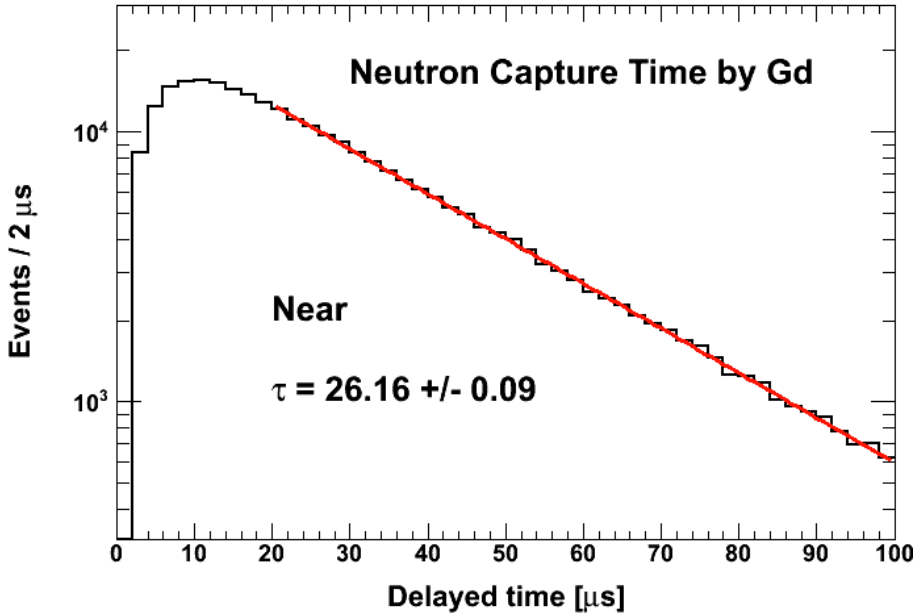


Observed Spectra for Delayed Signal (n captured by Gd)



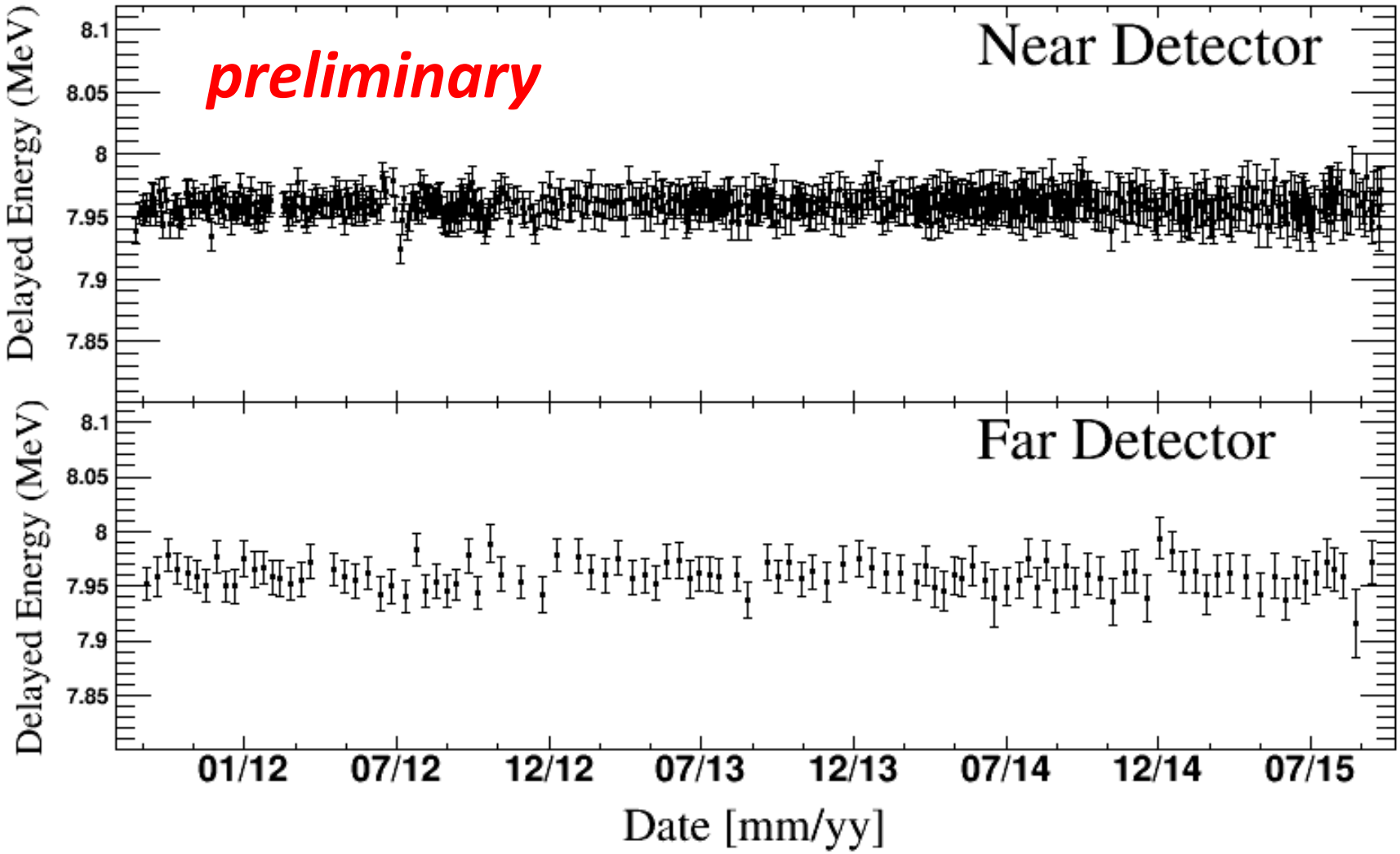




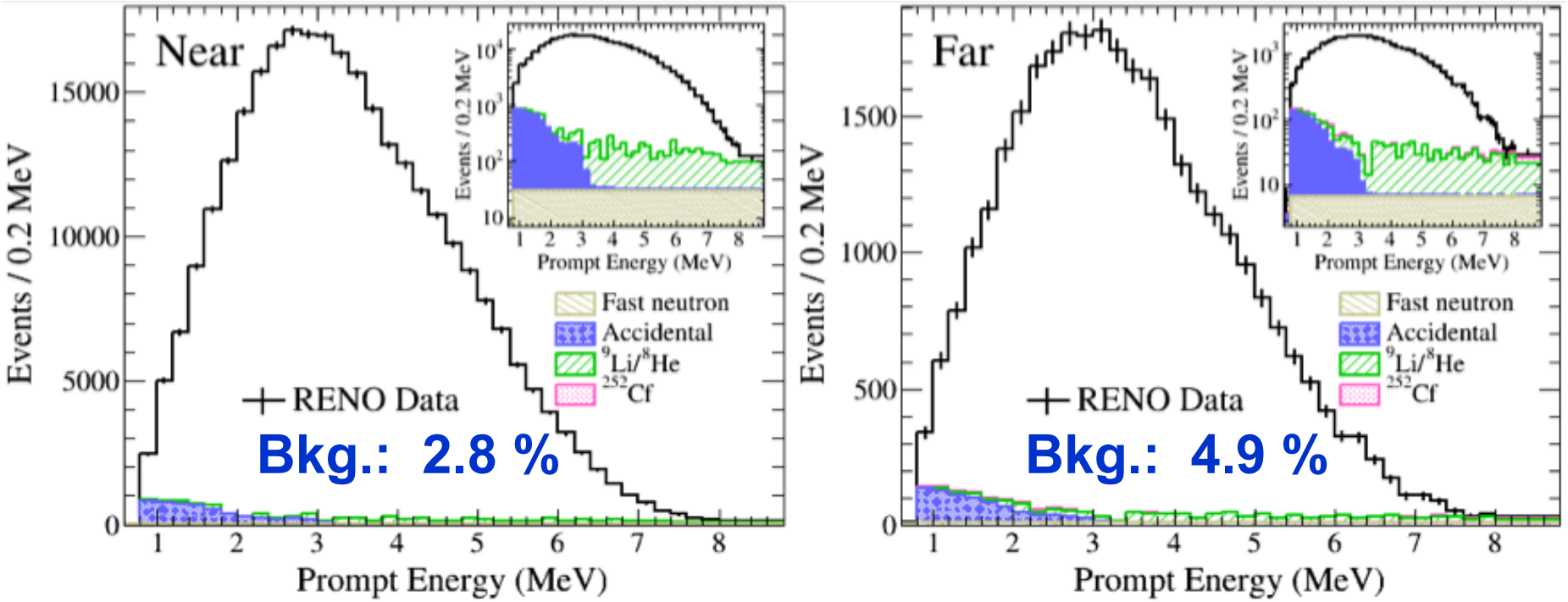


Detector Stability

- IBD candidate's delayed signals (capture on Gd)



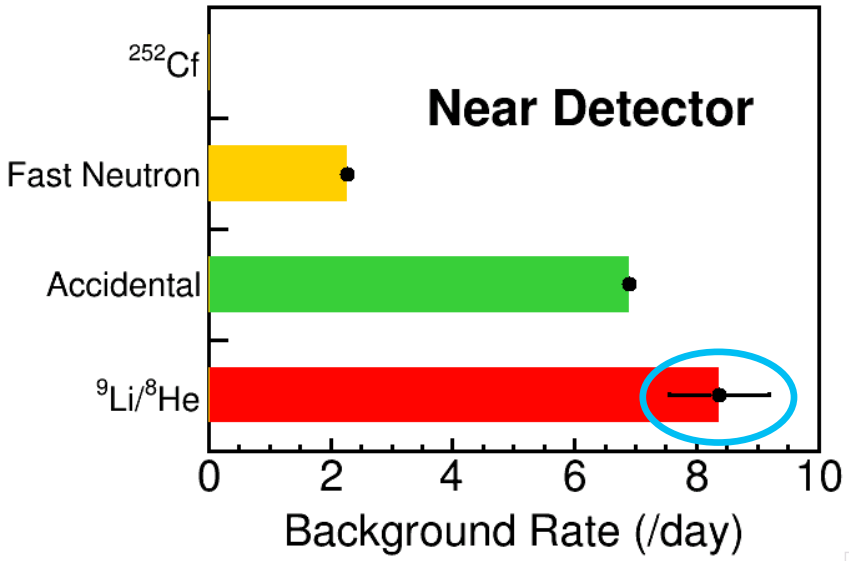
Measured Spectra of IBD Prompt Signal

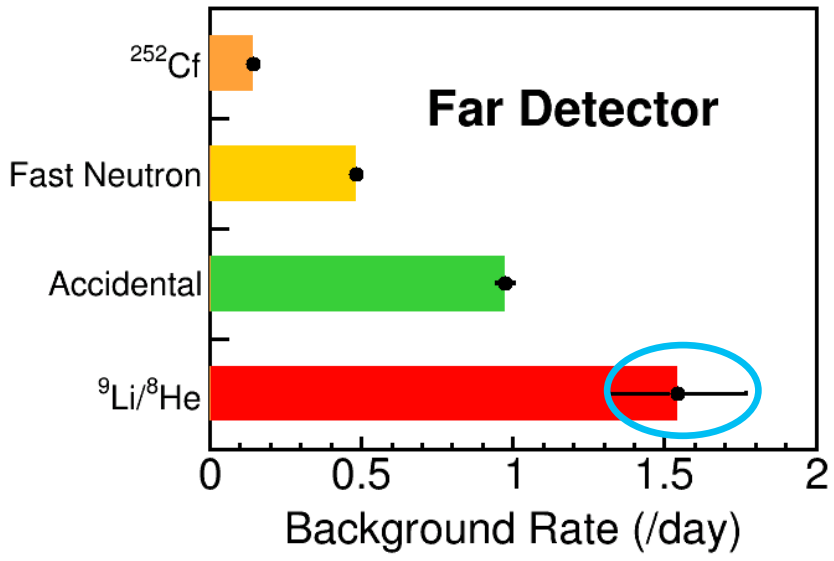


Near Live time = 458.49 days
# of IBD candidate = 290,775
# of background = 8,041 (2.8 %)

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

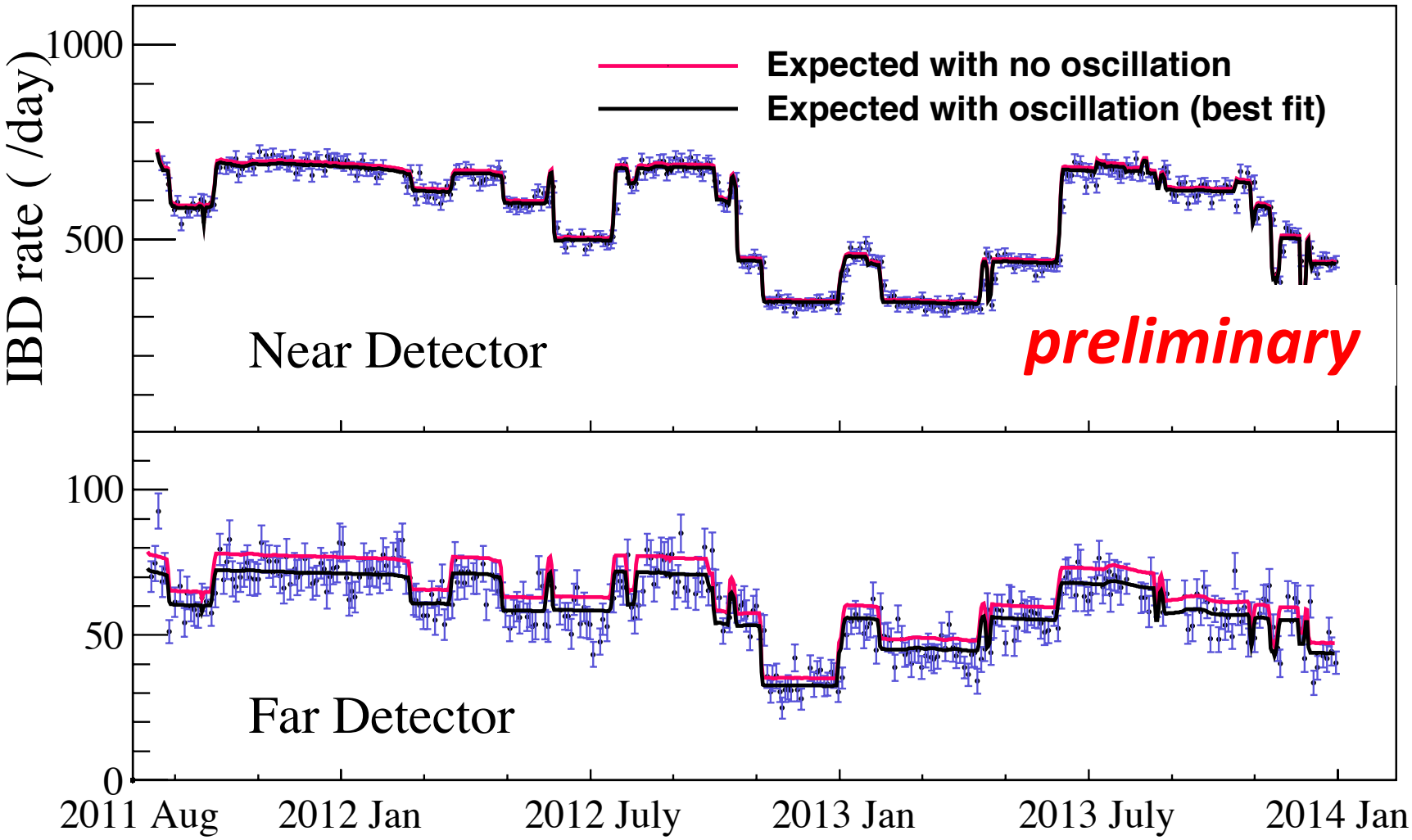
IBD Candidates & Background





	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

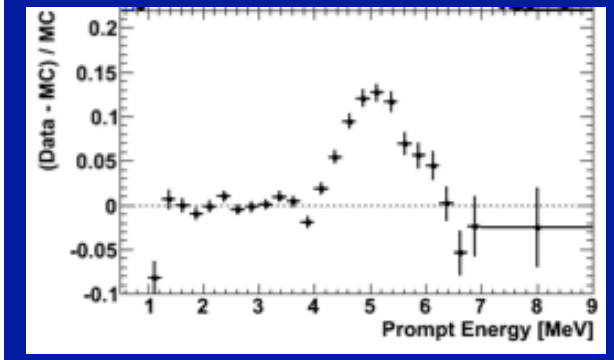
Observed Daily Averaged IBD Rate



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

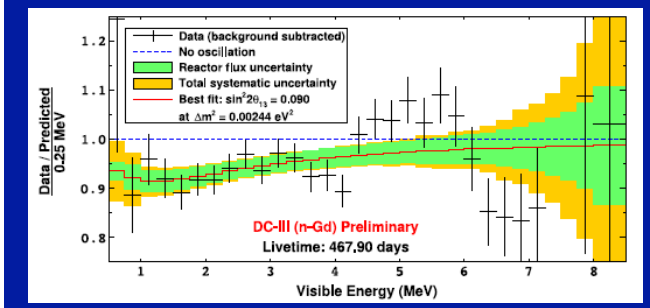
The 5 MeV Excess in 2014

RENO



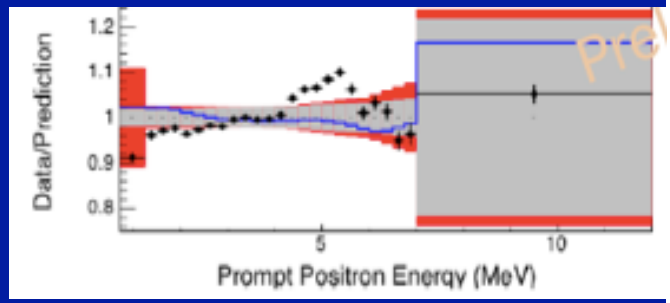
(In Neutrino 2014)

Double Chooz



(In Neutrino 2014)

Daya Bay



(In ICHEP 2014)

In 2012

-- **RENO**: excess (? σ)
in [3, 8] MeV region

(1) new background ?
(2) energy scale issue ?
(3) reactor ν model issue ?

(In Neutrino 2012)

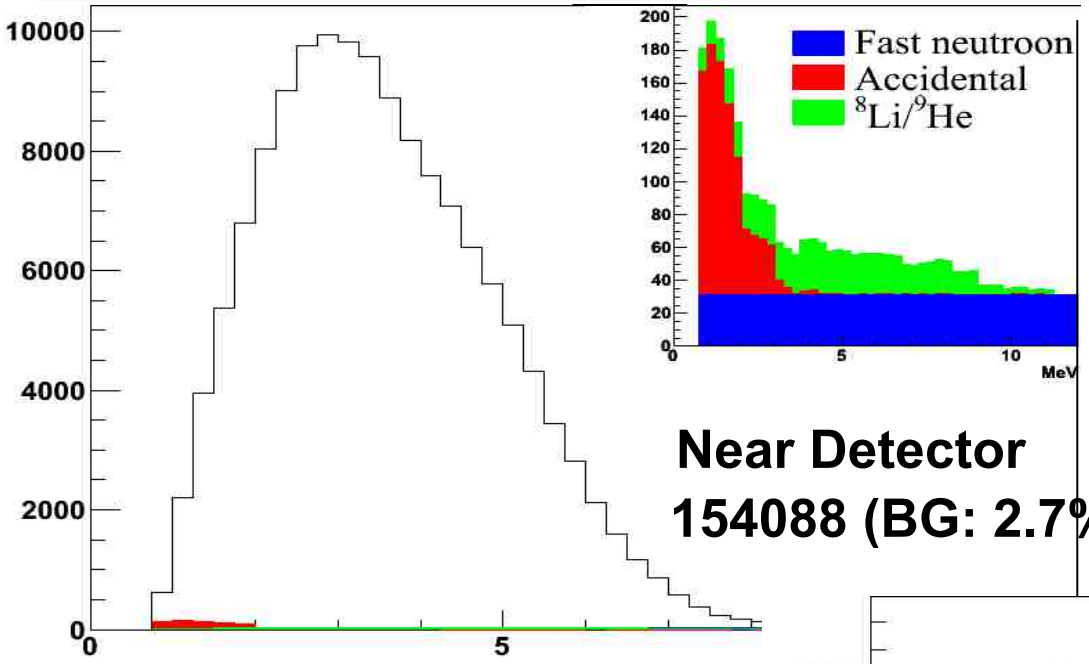
In 2014

-- **RENO**: 5 MeV excess (**3.5 σ**)
correlation w/ reactor P_{th}.

-- **DC**: 5 MeV excess (? σ)
correlation w/ reactor P_{th}.

-- **DB**: 5 MeV excess (? σ) → 4 σ in 2016

Observed Spectra of IBD Prompt Signal

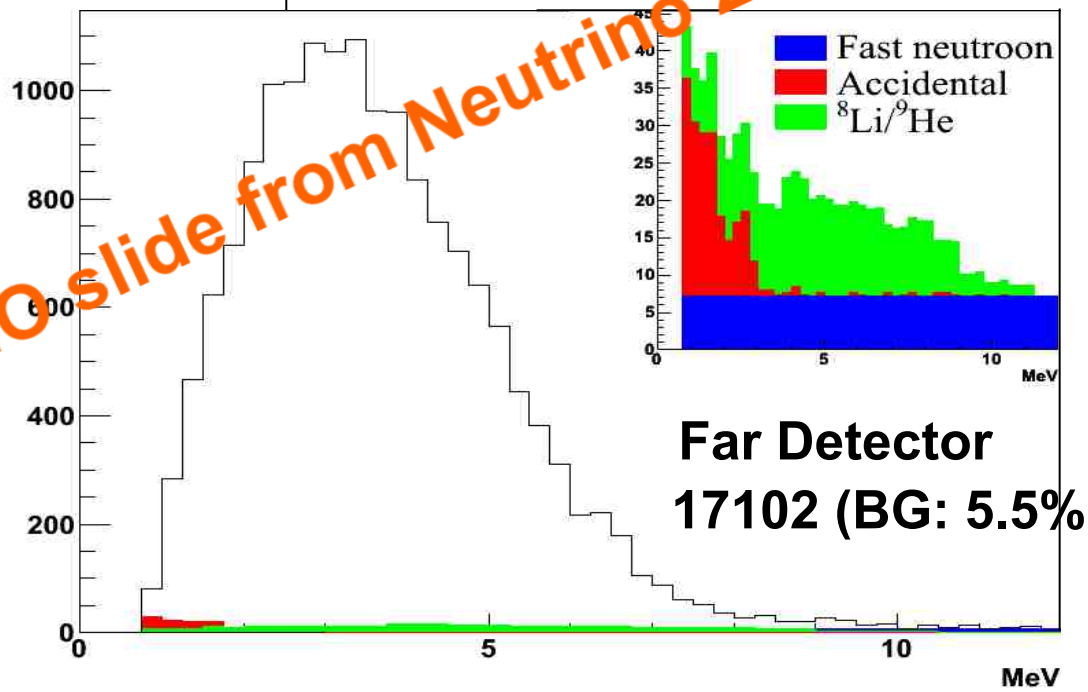


Near Detector
154088 (BG: 2.7%)

- The expected IBD prompt spectra from the RENO MC do not reproduce the shape in the energy region of 4~6 MeV.....

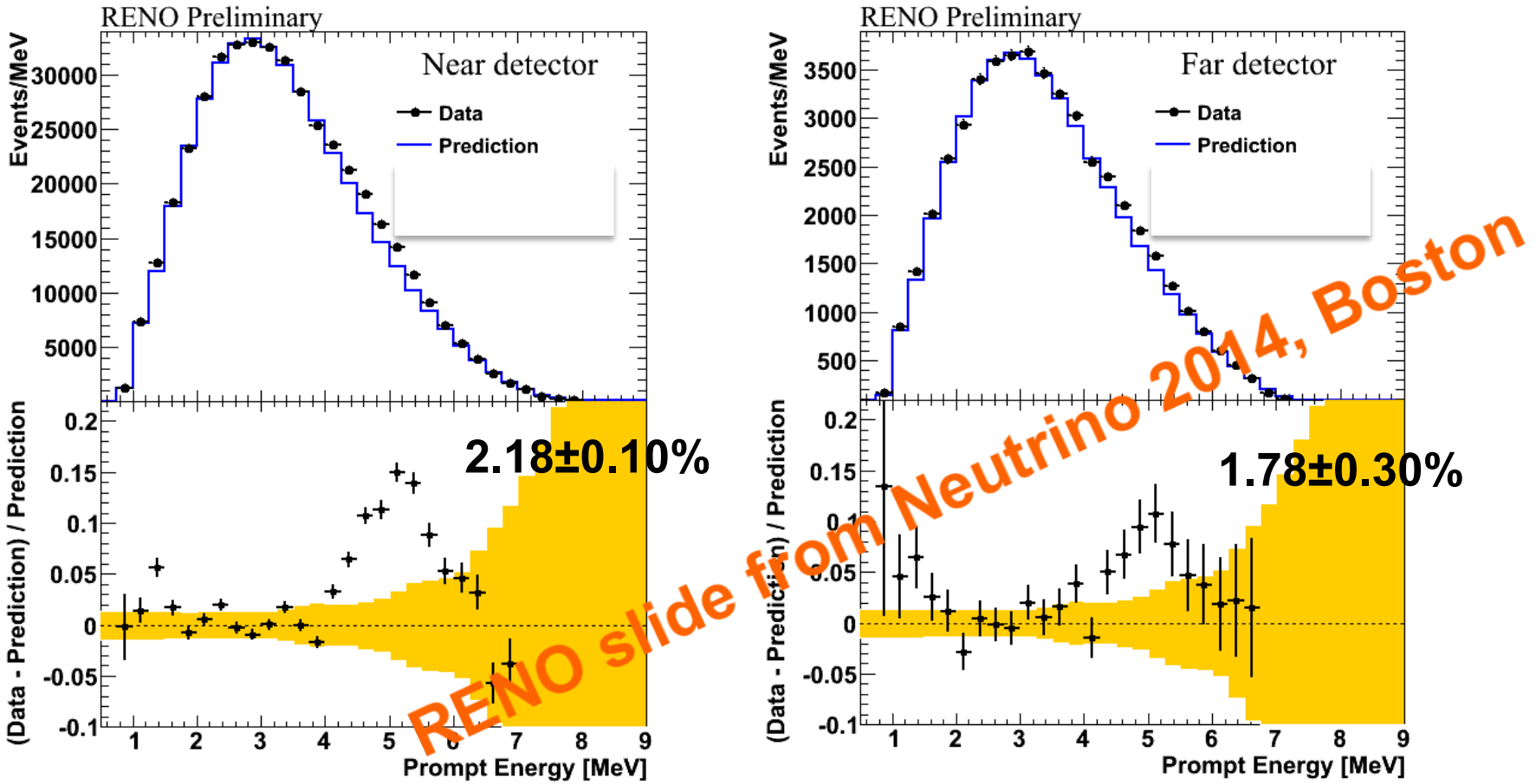
- Need more detailed energy calibration between 3 and 8 MeV using new radioactive sources.
- Any new components of background sources?
- Is the prediction of reactor neutrino spectra correct??

RENO slide from Neutrino 2012, Kyoto



Far Detector
17102 (BG: 5.5%)

Observation of a New Reactor Neutrino Component at 5 MeV

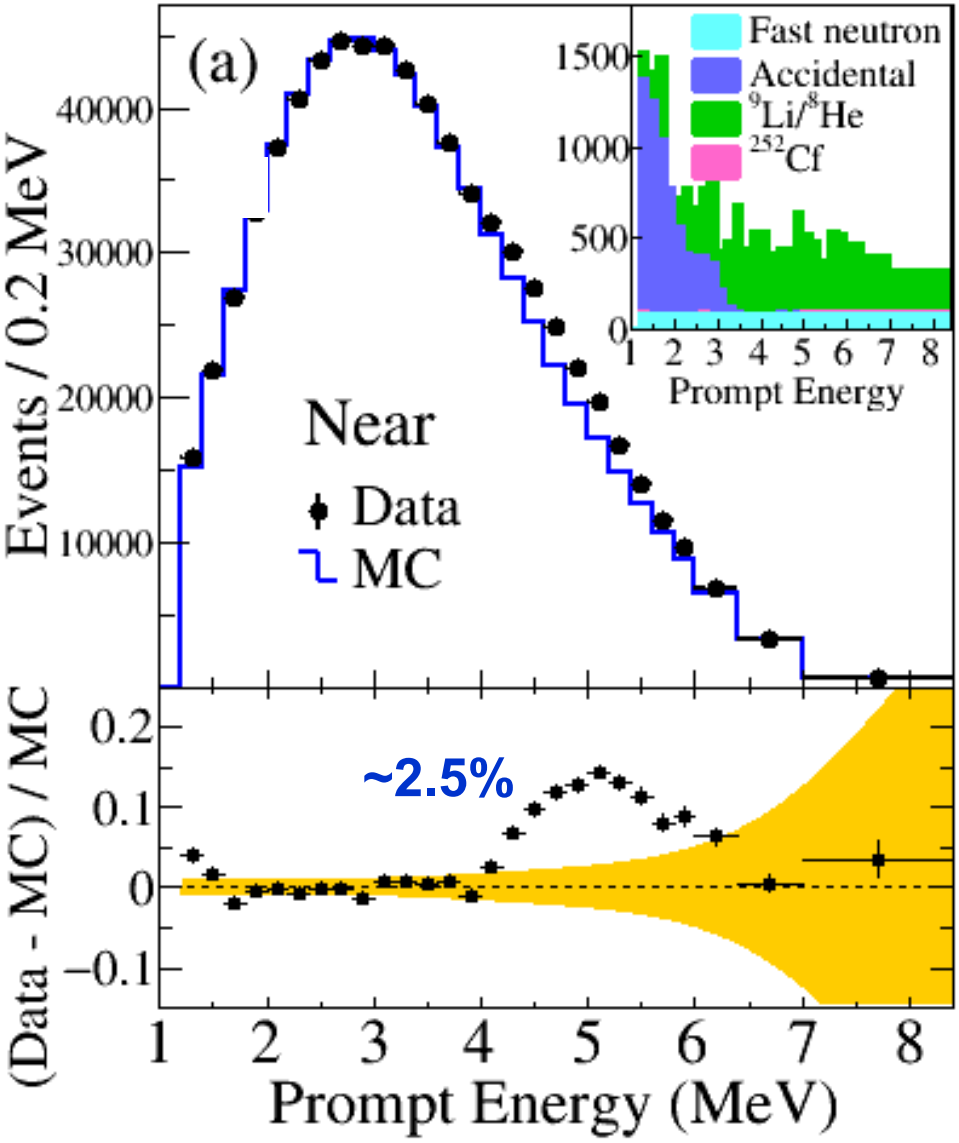


Fraction of 5 MeV excess (%) to expected flux [2011 Huber+Mueller]

- Near : 2.18 ± 0.40 (experimental) ± 0.49 (expected shape error)
- Far : 1.78 ± 0.71 (experimental) ± 0.49 (expected shape error)

Observation of an excess at 5 MeV

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



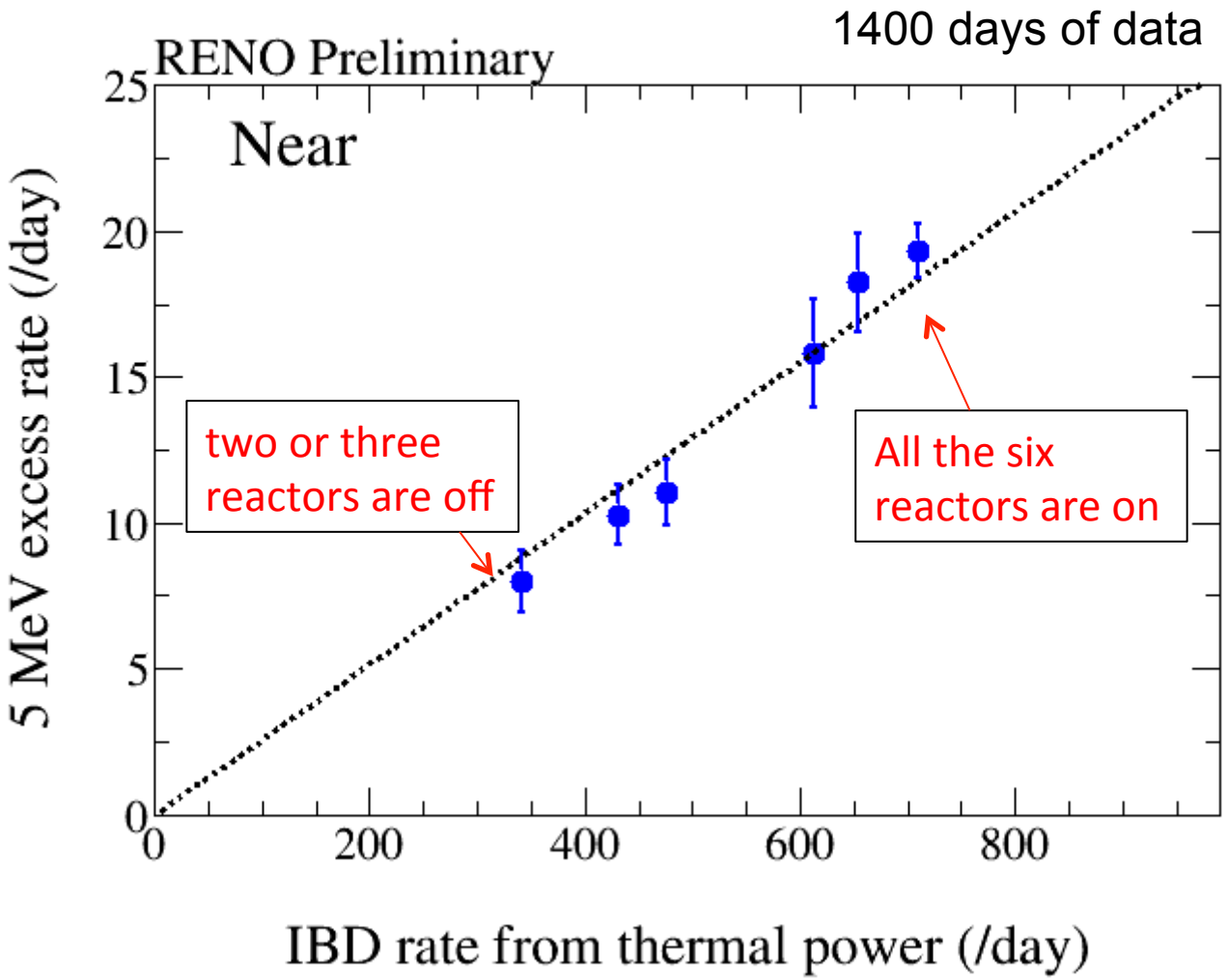
The measured near spectrum is compared with prediction using χ^2 method.

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

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

First announced in Neutrino 2016

Correlation of 5 MeV Excess with Reactor Power



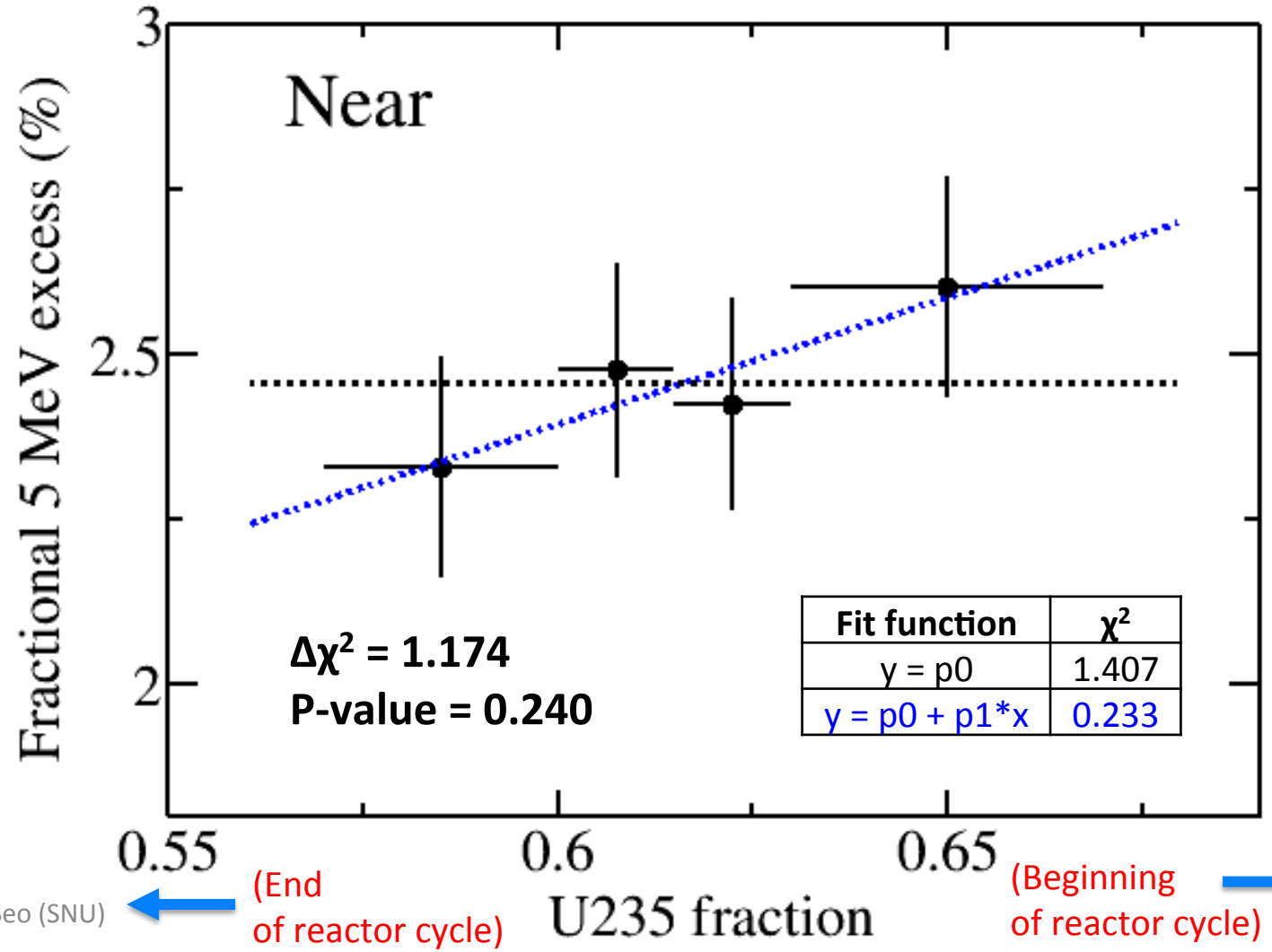
5 MeV excess has a clear correlation with reactor thermal power !

The 5 MeV excess comes from reactors!

Correlation of 5 MeV excess with ^{235}U isotope fraction

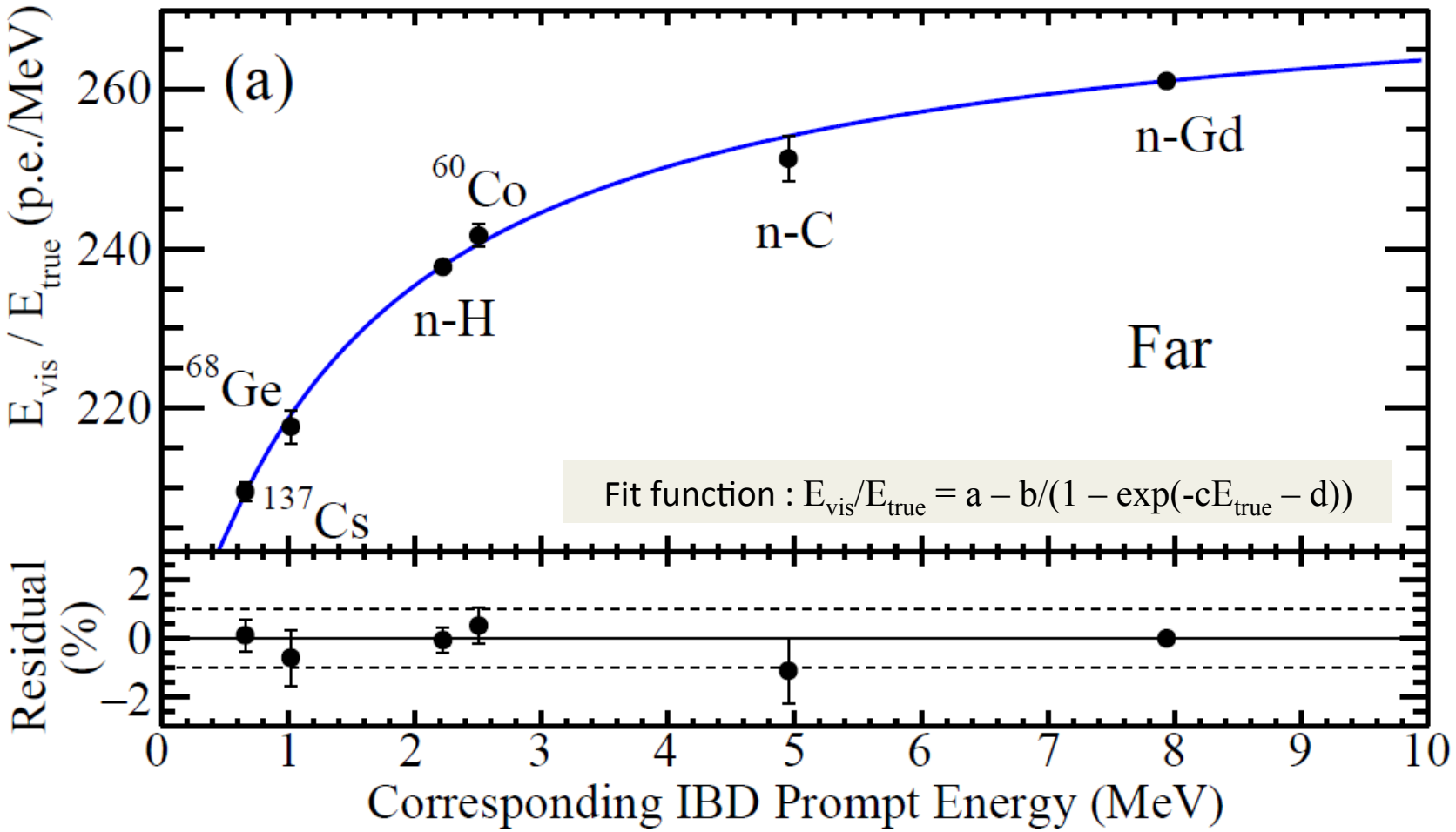
(Preliminary)

^{235}U fraction corresponds to freshness of reactor fuel



Energy Calibration from γ-ray Sources

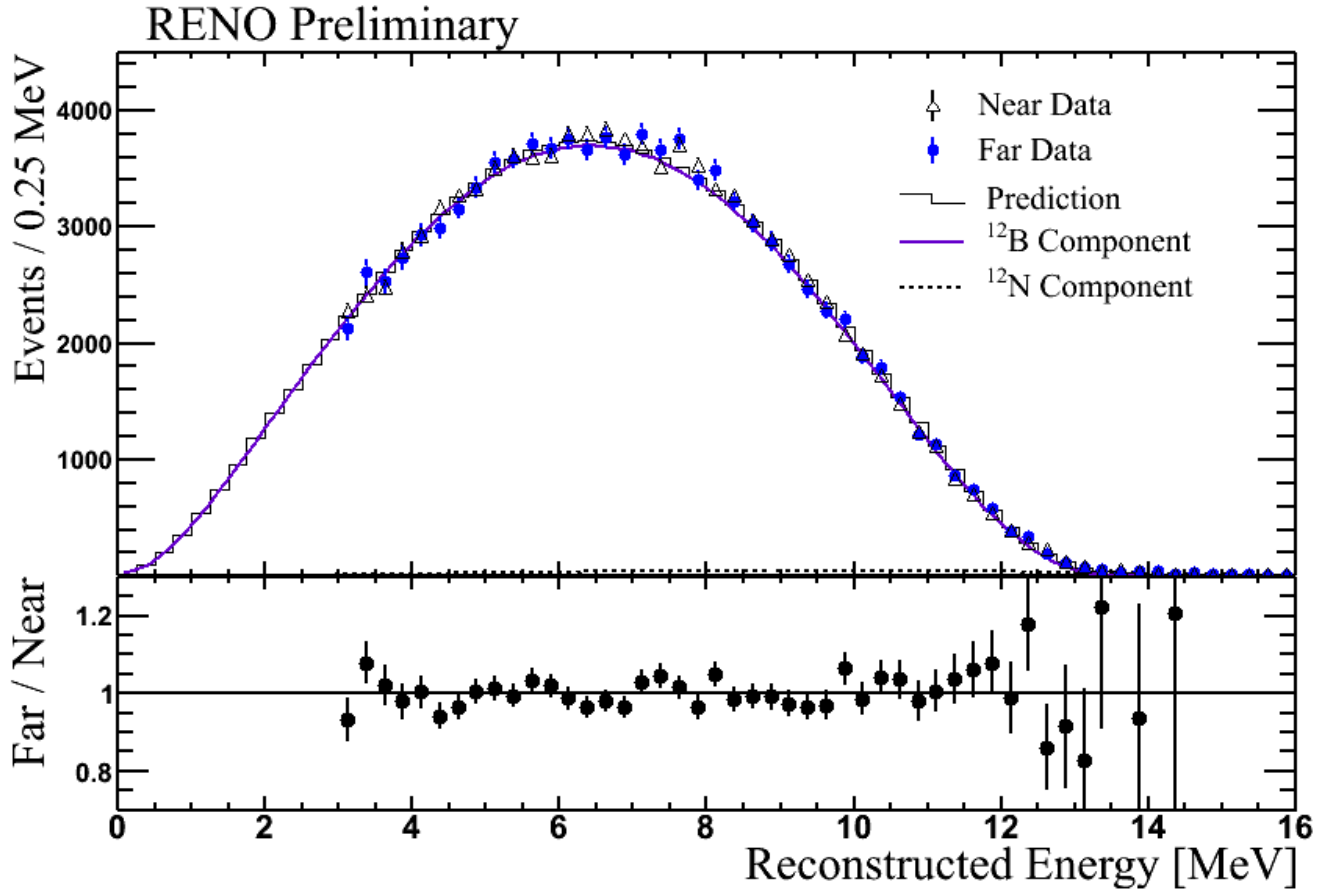
Non-linear response of the scintillation energy is calibrated with γ-ray source



Deviation of all calibration data points with respect to the best-fit is within ~1%.

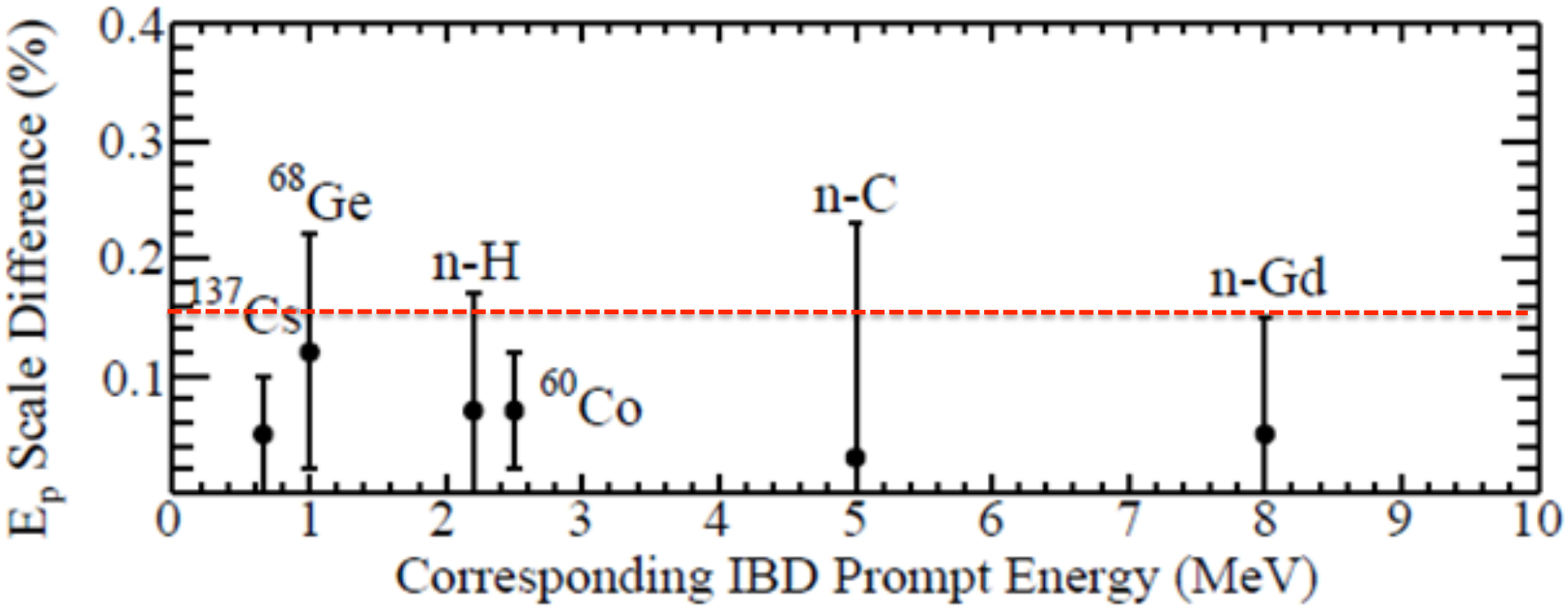
^{12}B Energy Spectrum (Near & Far)

- Electron energy spectrum from β-decays from ^{12}B and ^{12}N, which are produced by cosmic-muon interactions



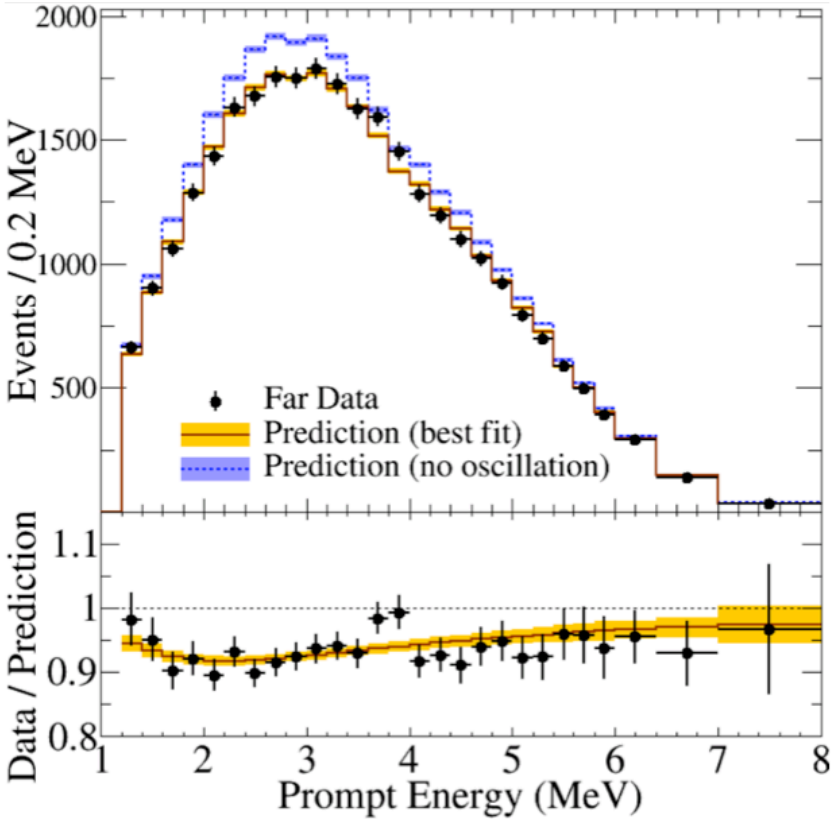
Good agreement between data and MC spectrum!

Energy Scale Difference between Near & Far



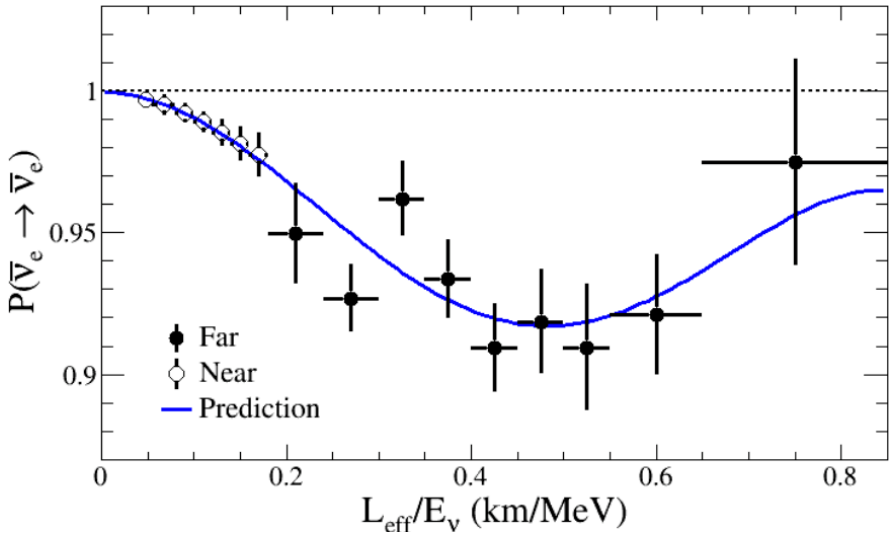
Energy scale difference < 0.15% for E_p = 1~8 MeV

Far to Prediction for Shape Analysis



Observed L/E Dependent Oscillation

PRL 116, 211801, 2016



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

Clear energy-dependent disappearance of reactor antineutrinos

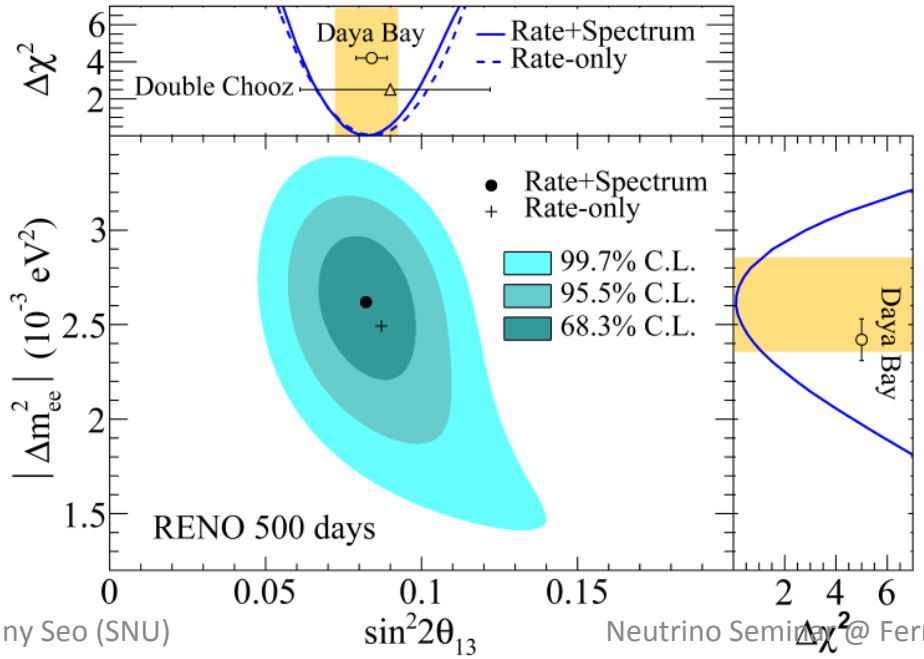
Analysis Results

Rate Only $\sin^2 2\theta_{13} = 0.087 \pm 0.009(\text{stat.}) \pm 0.007(\text{syst.})$ $\pm 0.011(\text{total})$

(Rate + Shape) new results

$\left|\Delta m^2_{ee}\right| = 2.62^{+0.21}_{-0.23}(\text{stat.})^{+0.12}_{-0.13}(\text{syst.})\ (\times 10^{-3} eV^2)$ ± 0.26 (total) 10 % precision

$\sin^2 2\theta_{13} = 0.082 \pm 0.009(\text{stat.}) \pm 0.006(\text{syst.})$ $\pm 0.010(\text{total})$ 12 % precision



- arXiv:1511.05849.v2
- PRL 116, 211801 (2016)

- PRD now in preparation and will be submitted soon

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

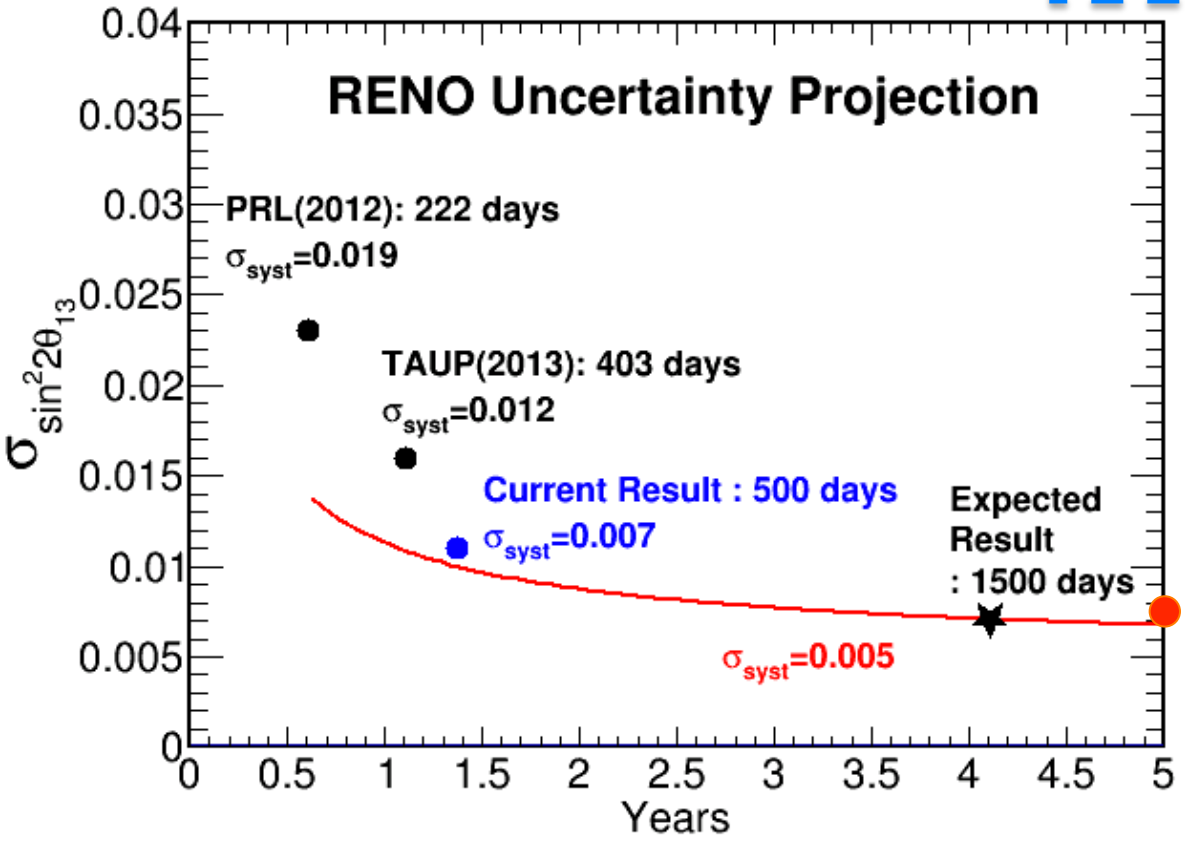
$\sin^2 2\theta_{13} = 0.082 \pm 0.011$ (±12%) (~500 days)

$\left|\Delta m^2_{ee}\right| = (2.62^{+0.24}_{-0.26}) \times 10^{-3}\,\mathrm{eV}^2$ (±10%) (~500 days)

± 0.005 (±6 %)

$\pm 0.15 \times 10^{-3}\,\mathrm{eV}^2$ (±6 %)

(5 years of data)



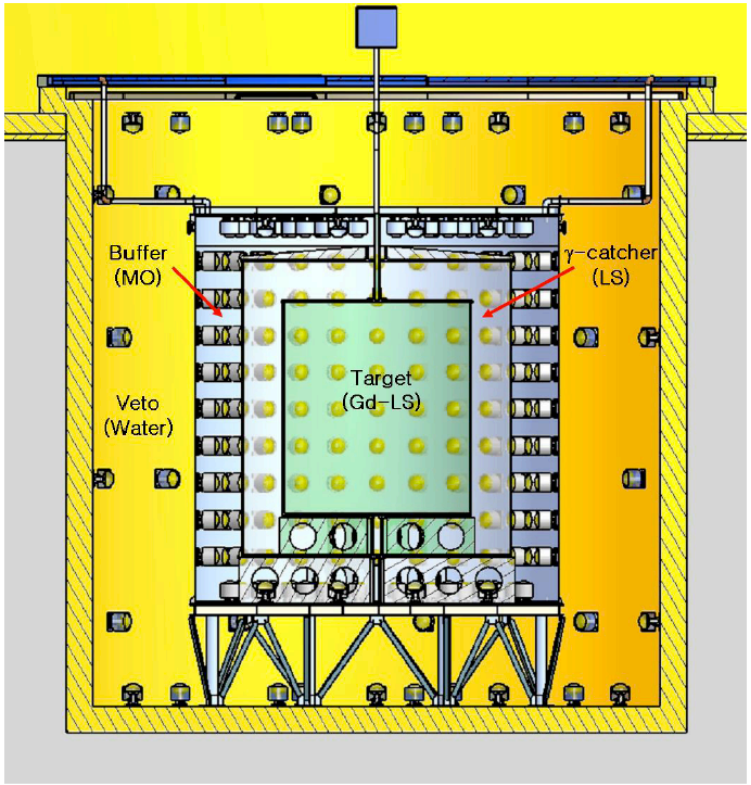
(6 % precision)

(sensitivity goal of θ_{13})

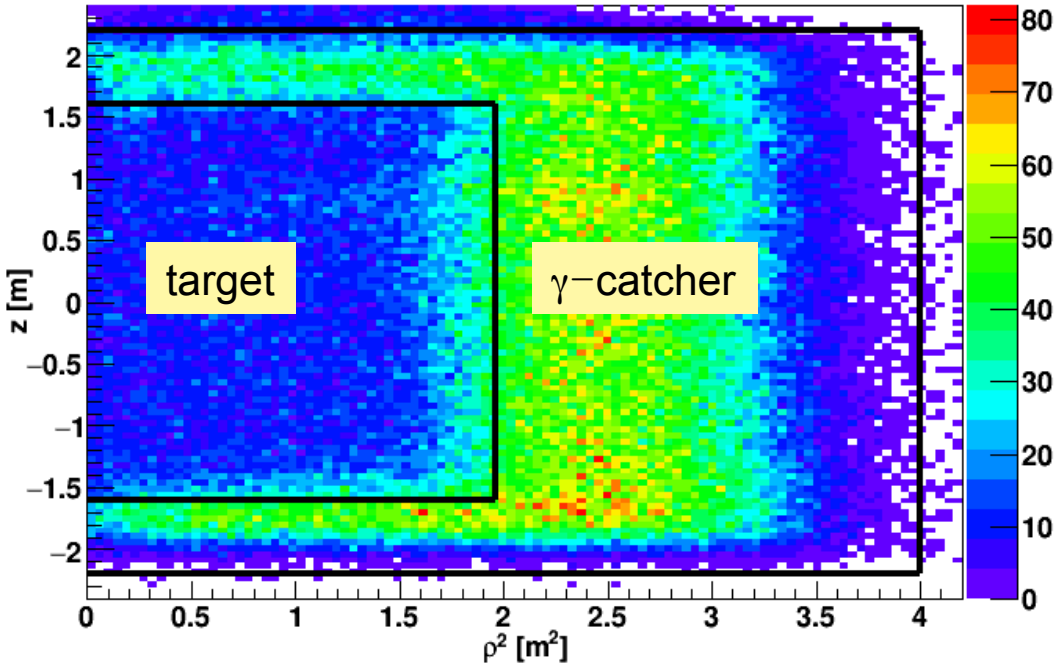
n-H IBD Analysis

Motivation:

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

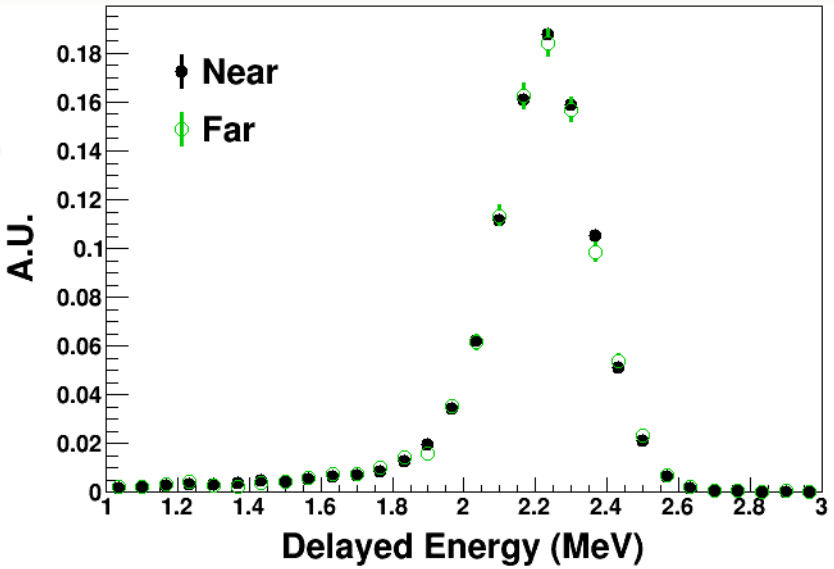


n-H IBD Event Vertex Distribution

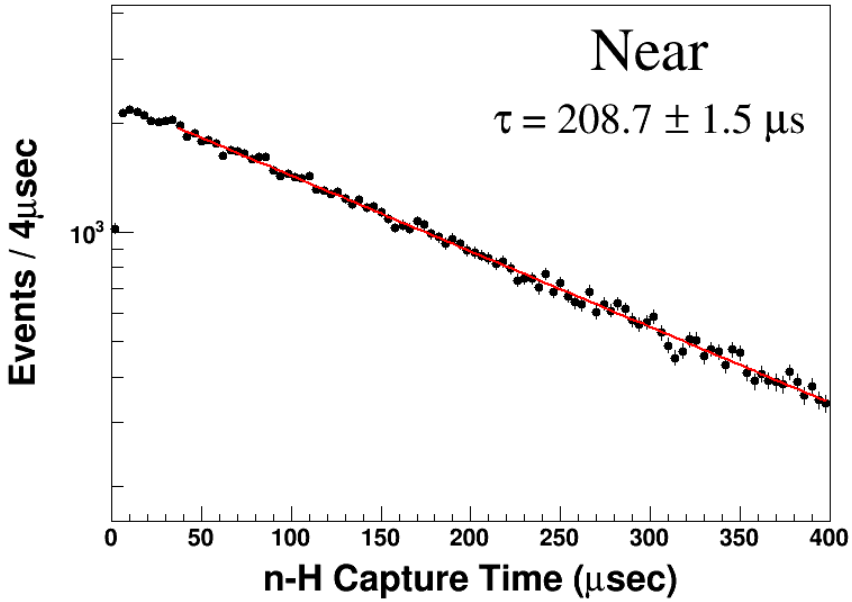


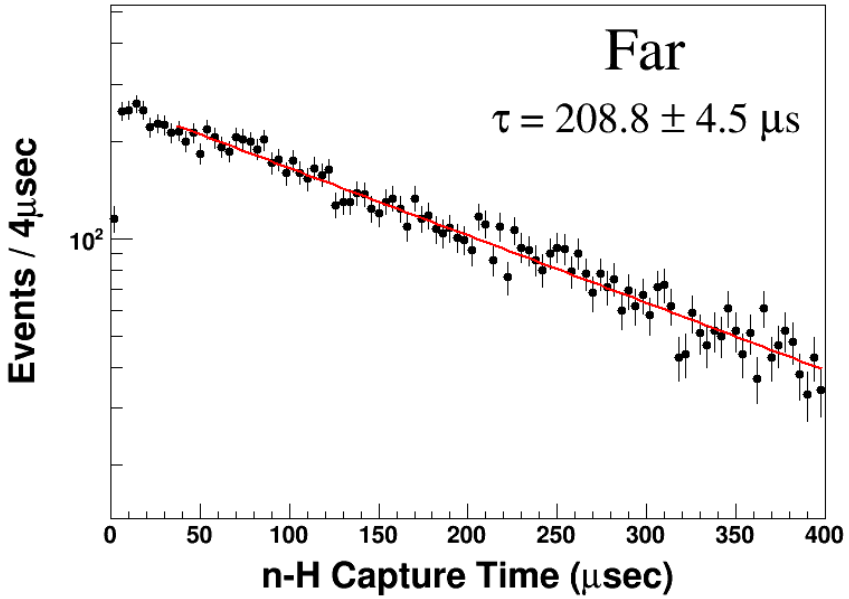
Features of n-H Events

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



Far and near data match very well♪





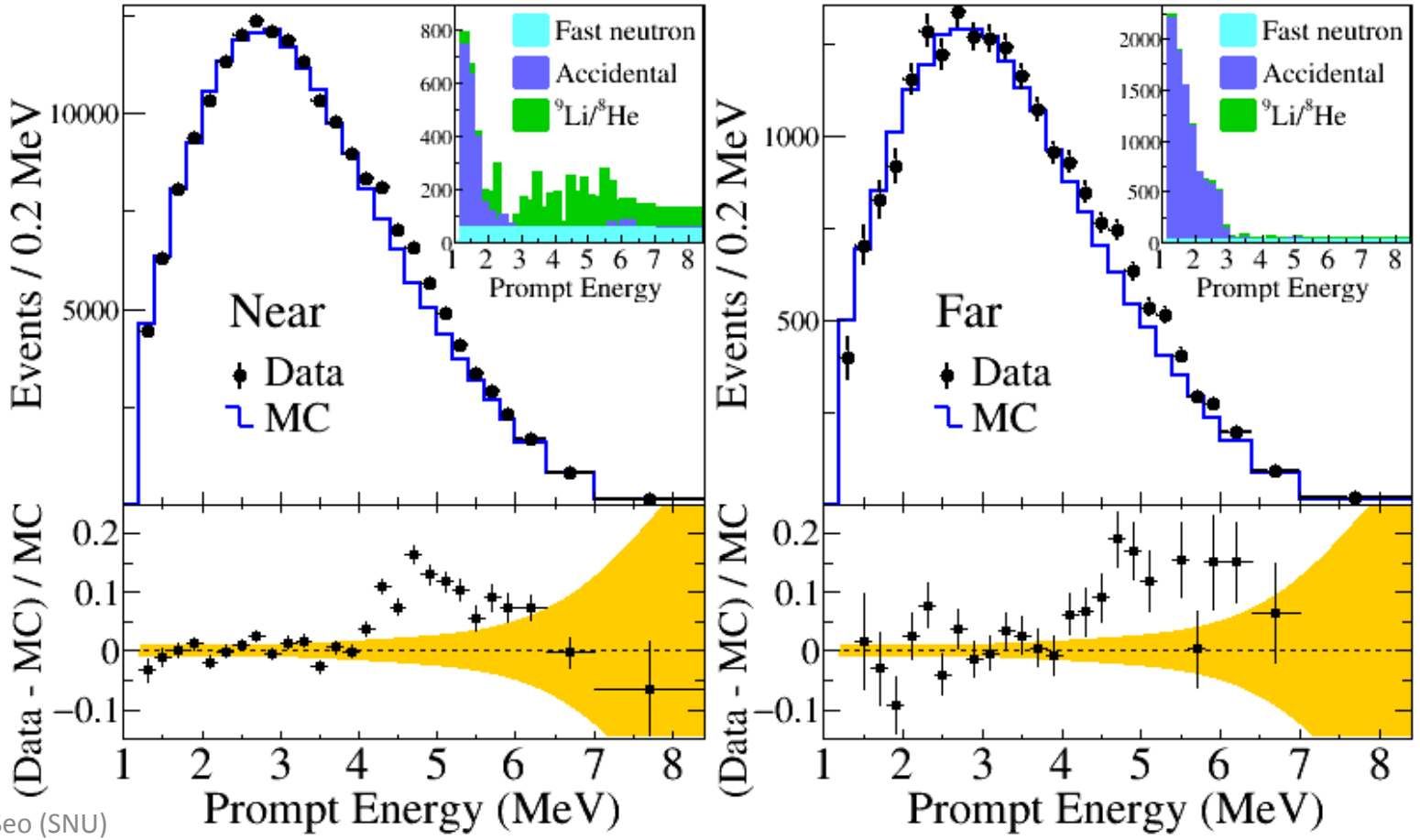
θ_{13} Measurement with n-H

	Uncertainty
Detection efficiency	**0.59%**
Thermal power	**0.5 %**
Isotope fraction	**0.7 %**
Background	**Near : 0.2%** **Far : 0.8%**

Data set: 2011/08 ~ 2013:01 (~500 days)

Preliminary rate only analysis results is

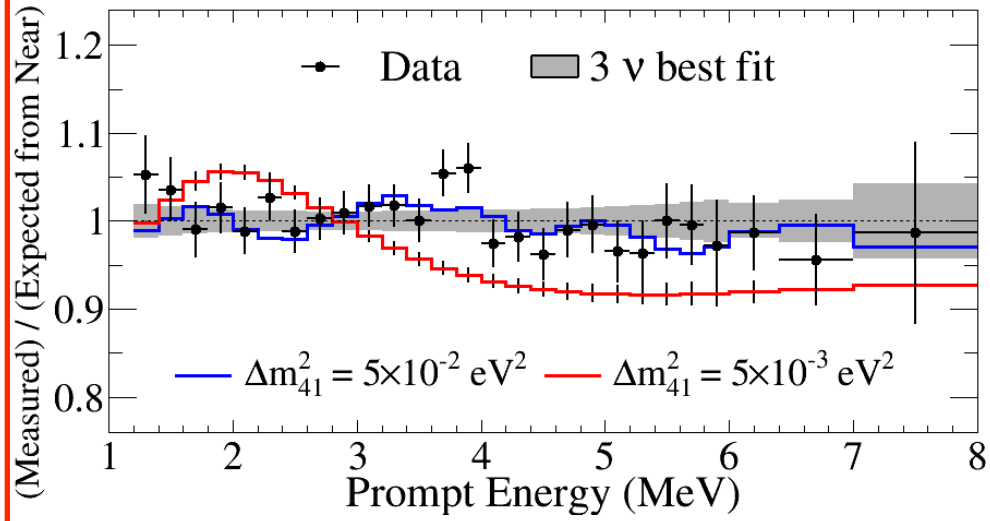
$$\sin^2 2\theta_{13} = 0.086 \pm 0.012(\text{stat.}) \pm 0.015(\text{syst.})$$

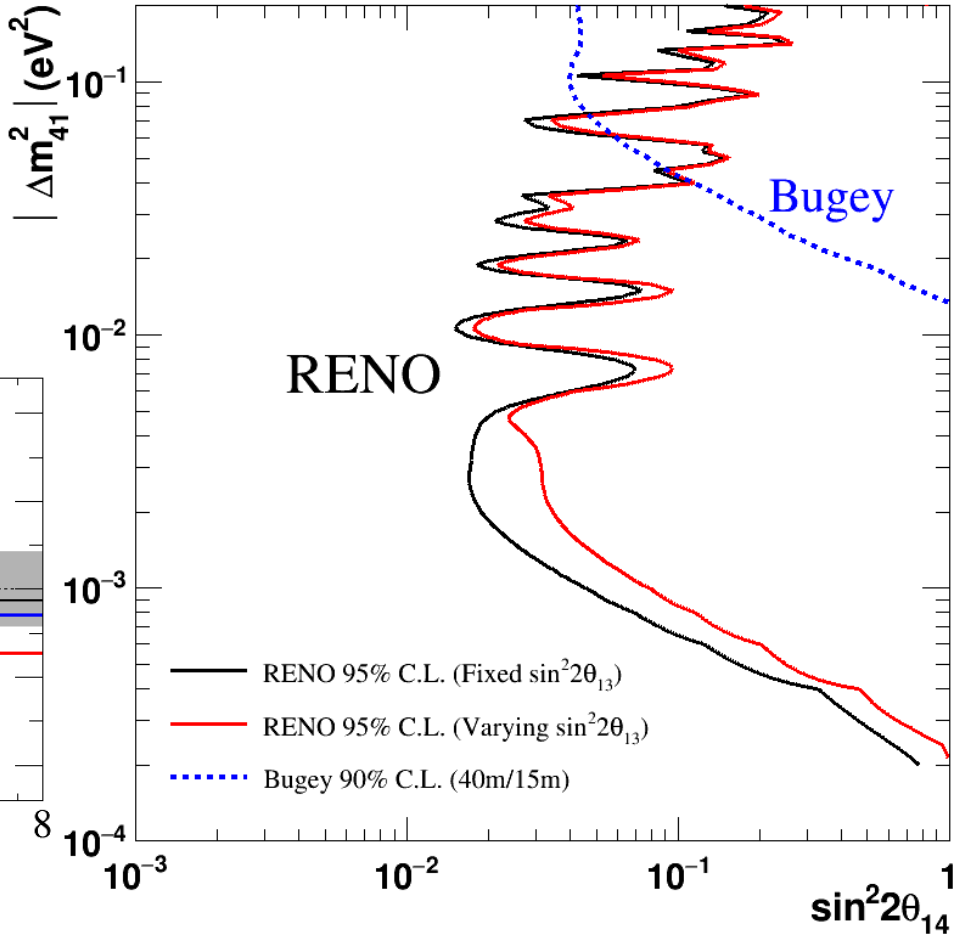


Light Sterile Neutrino Search Results

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

Paper in preparation





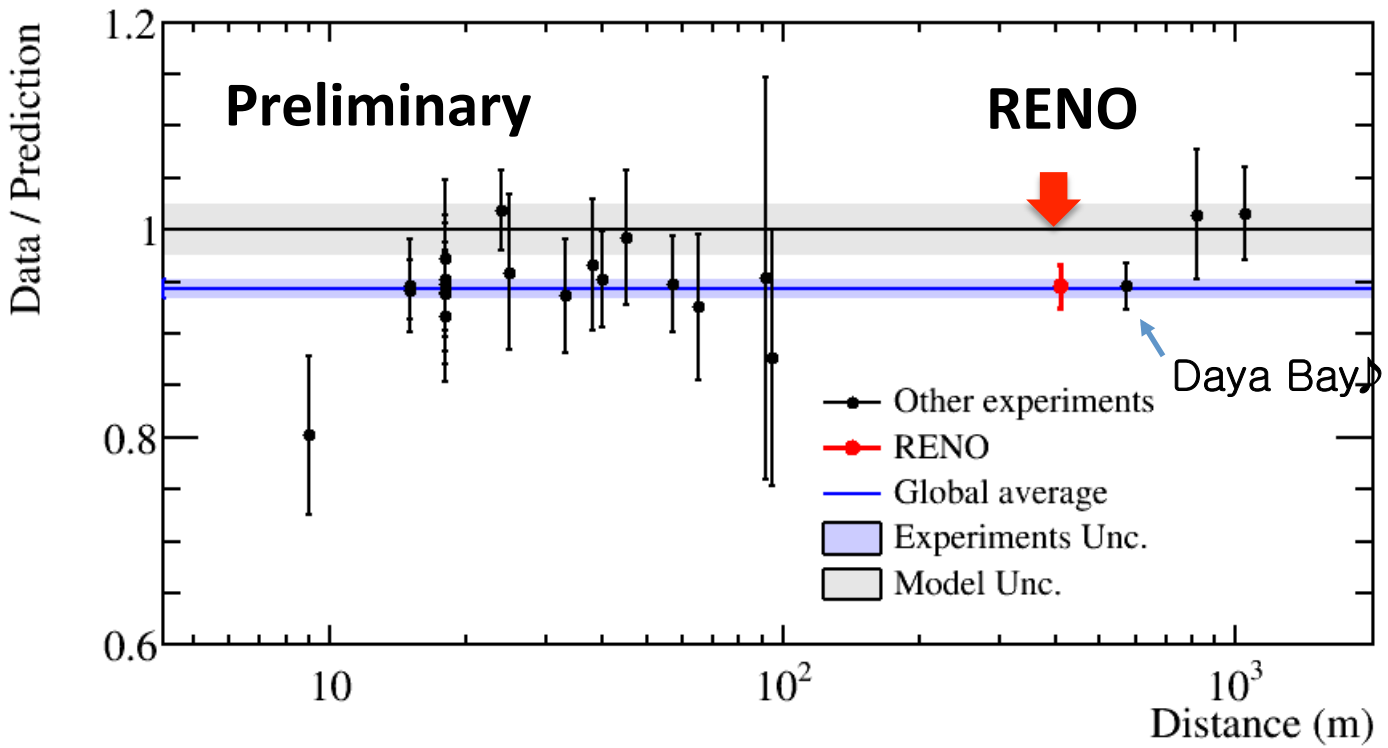
full curves assumes $\sin^2 2\theta_{14} = 0.1$

Determination of normalization factor, R

R (data/prediction) = 0.946 +- 0.021 (500 days)

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

Comparison with other experiments



*Prediction is corrected for three flavor neutrino oscillation

Summary

- New measurement of θ_{13} by rate-only analysis

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

- Observed an excess at 5 MeV in reactor neutrino spectrum

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

$$\left|\Delta m^2_{ee}\right| = 2.62^{+0.21}_{-0.23}(\text{stat.})^{+0.12}_{-0.13}(\text{syst.}) \ (\times 10^{-3} eV^2) \quad \pm 0.26(\text{total})$$ 10 % precision

$$\sin^2 2\theta_{13} = 0.082 \pm 0.009(\text{stat.}) \pm 0.006(\text{syst.}) \quad \pm 0.010(\text{total})$$ 12 % precision

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

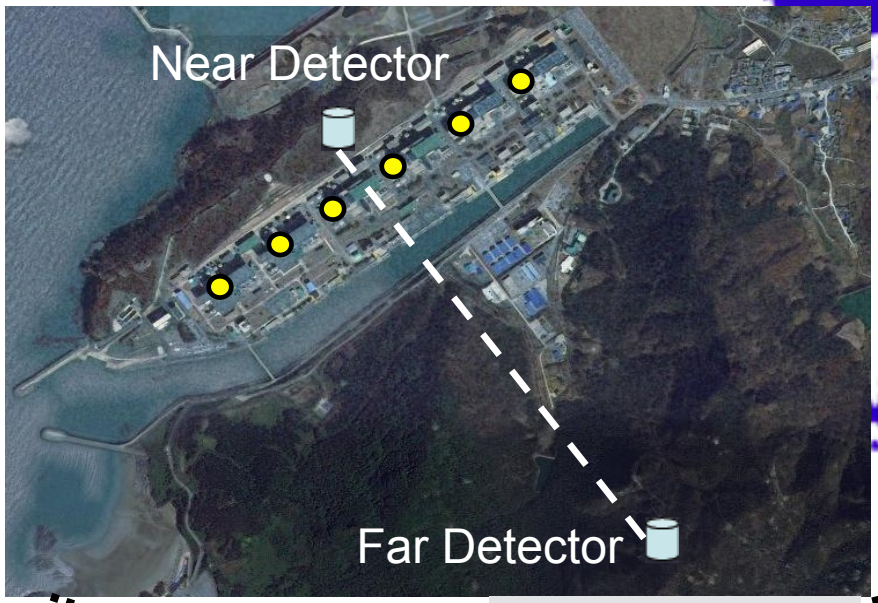
- **Goals** : - Determination of neutrino mass ordering
- High-precision measurement of θ_{12}, Δm^2_{21} and Δm^2_{ee} - Supernova neutrinos, Geo neutrinos, Sterile neutrino search, ….

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

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

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



Courtesy by Yoshitaro Takaesu
(Tokyo)

(NEAR Detector)

RENO

$\nu \sim\sim\sim \theta_{13}$

(FAR Detector)

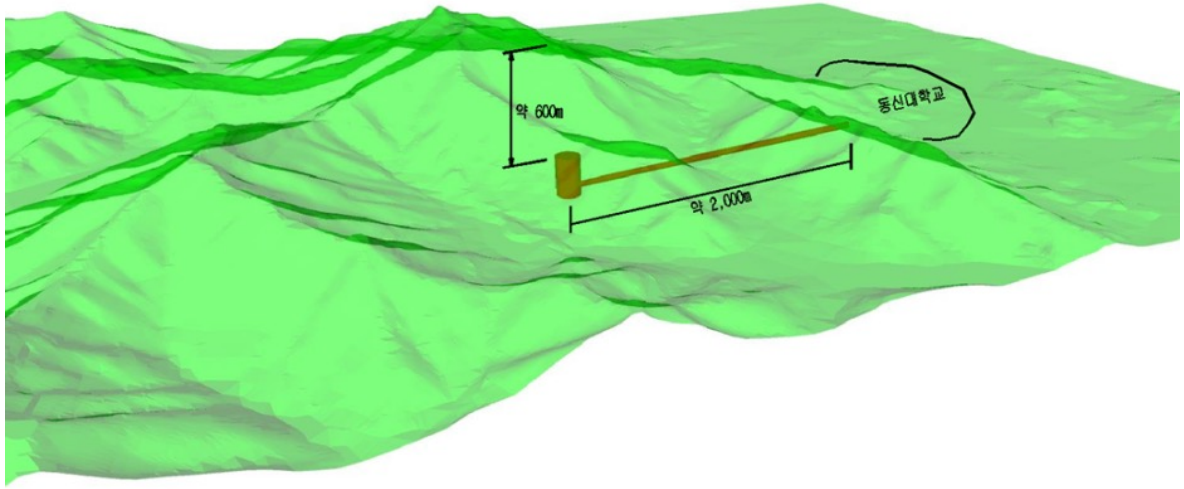
RENO-50

18 kton LS Detector
~47 km from YG reactors

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

RENO-50 Candidate Site

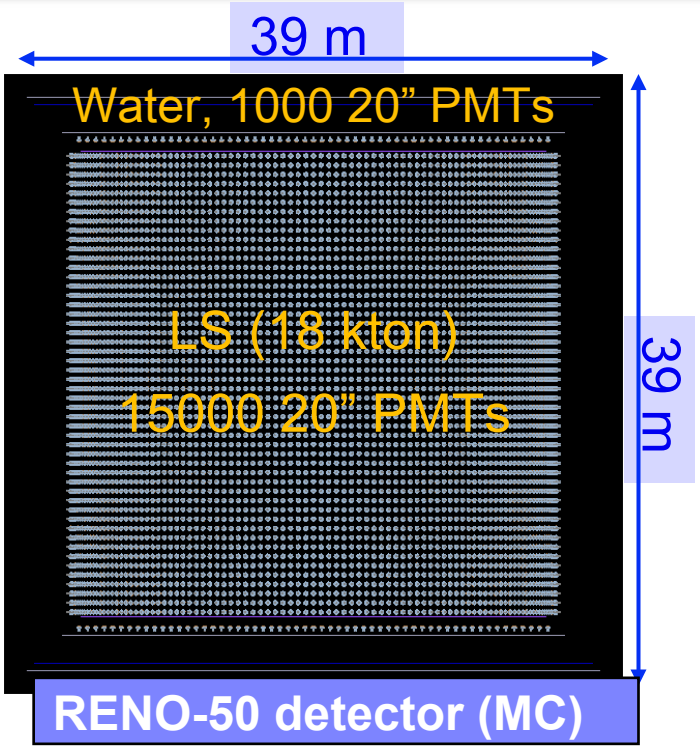
Geological Survey for Underground Facility



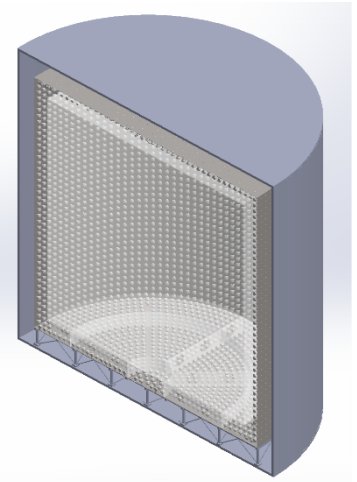
Cost estimation for RENO-50 underground facility (in progress)

- 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 in Progress

(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 detector material is on-going.

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

Current status

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 are on-going.

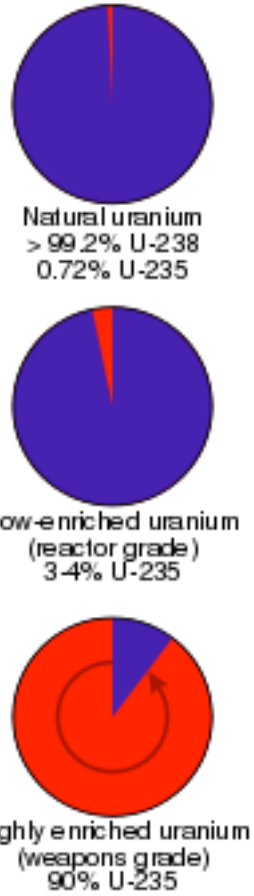
Summary of RENO/RENO-50

- Various measurements done
  - Update on θ_{13} value
  - 5 MeV excess with reactor thermal power
  - First measurement of Δm_{ee}^2
  - Absolute antineutrino flux measurement
  - Independent measurement of θ_{13} with n-H
  - Sterile neutrinos search
- RENO will continue data-taking for next 3 more years, reaching its sensitivity limit, in order to obtain a precise measurement of θ_{13}
- RENO-50: various R&D in progress

Backup slides

Uranium ore

- U-235: 0.72 %
  fissile;
  most widely used
  fuel in reactors
- U-238: 99.27 %
  fertile;
  breeding Pu-239



Fission isotopes	Critical mass	
U-233	16 kg	manufactured
U-235	54 kg	natural
Pu-239	10 kg	manufactured

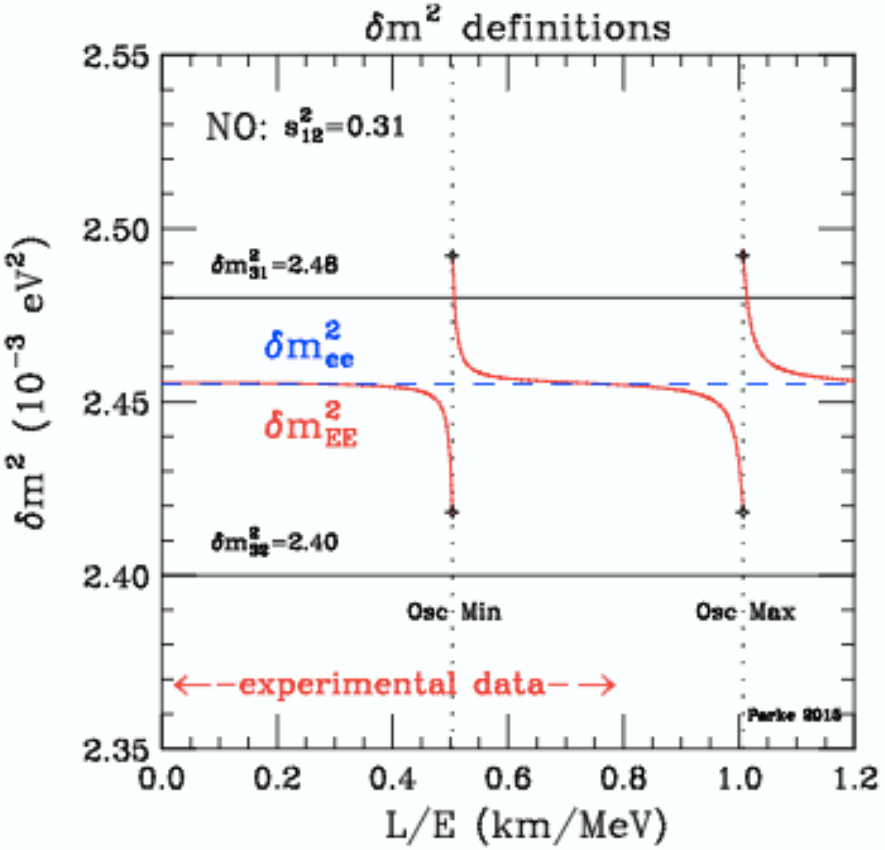
Breakdown of fission energy

	MeV
Kinetic energy of fission fragments	165 +/- 5
Instantaneous gamma rays	7 +/- 1
Kinetic energy of neutrons	5 +/- 0.5
Beta particles from product decay	7 +/- 1
Gamma rays from product decay	6 +/- 1
Neutrinos from product decay	10
TOTAL	200 +/- 6

How Does Daya Bay Define Δm^2_{EE} ?

$$\sin^2\Delta_{EE} \equiv c_{12}^2\sin^2\Delta_{31} + s_{12}^2\sin^2\Delta_{32}$$

$$\Rightarrow \quad \Delta m^2_{EE} = \left(\frac{4E}{L}\right)\arcsin\left[\sqrt{(c_{12}^2\sin^2\Delta_{31} + s_{12}^2\sin^2\Delta_{32})}\right]$$



Maladies:

- L/E dependent
- no simple physical meaning !
- Discontinuous at Osc. Max./Min. (L/E ≈ 0.5, 1.0, .. km/MeV) 3% jump

Why???

RHS (1) never gets exactly to 1, or back to 0 whereas LHS does !

eg $\sin^2(\frac{\pi}{2} \mp \epsilon) = 1 - \epsilon^2 + \mathcal{O}(\epsilon^4)$
with $\epsilon = s_{12}c_{12}\Delta_{21}$

RENO: X^2 fit

$$\chi^2 = \sum_{i=1}^{N_{bins}} \frac{(O_i^{F/N} - T_i^{F/N})^2}{U_i^{F/N}} + \sum_{d=N,F} \left(\frac{b^d}{\sigma_{bkg}^d} \right)^2$$

$$+ \sum_{r=1}^{6} \left(\frac{f_r}{\sigma_{flux}^r} \right)^2 + \left(\frac{\epsilon}{\sigma_{eff}} \right)^2 + \left(\frac{e}{\sigma_{scale}} \right)^2$$

PRL 116, 211801 (2016)

(Pull method)

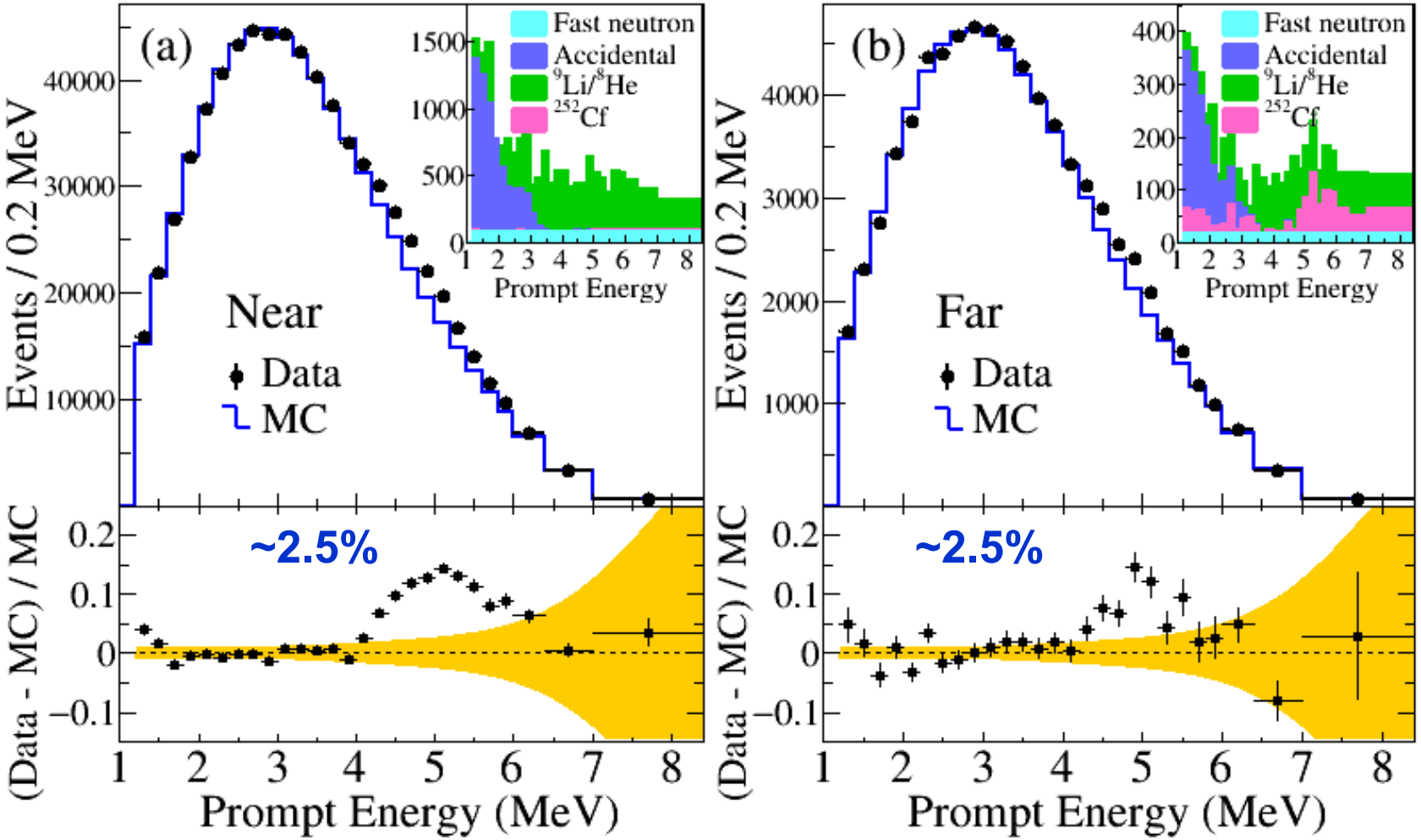
$$T_i^{F/N} = T_i^{F/N}(b^d, f_r, \epsilon, e; \theta_{13}, |\Delta m_{ee}^2|)$$

- Expected events term ($T_i^{F/N}$) contains energy dependent BKG uncertainties.

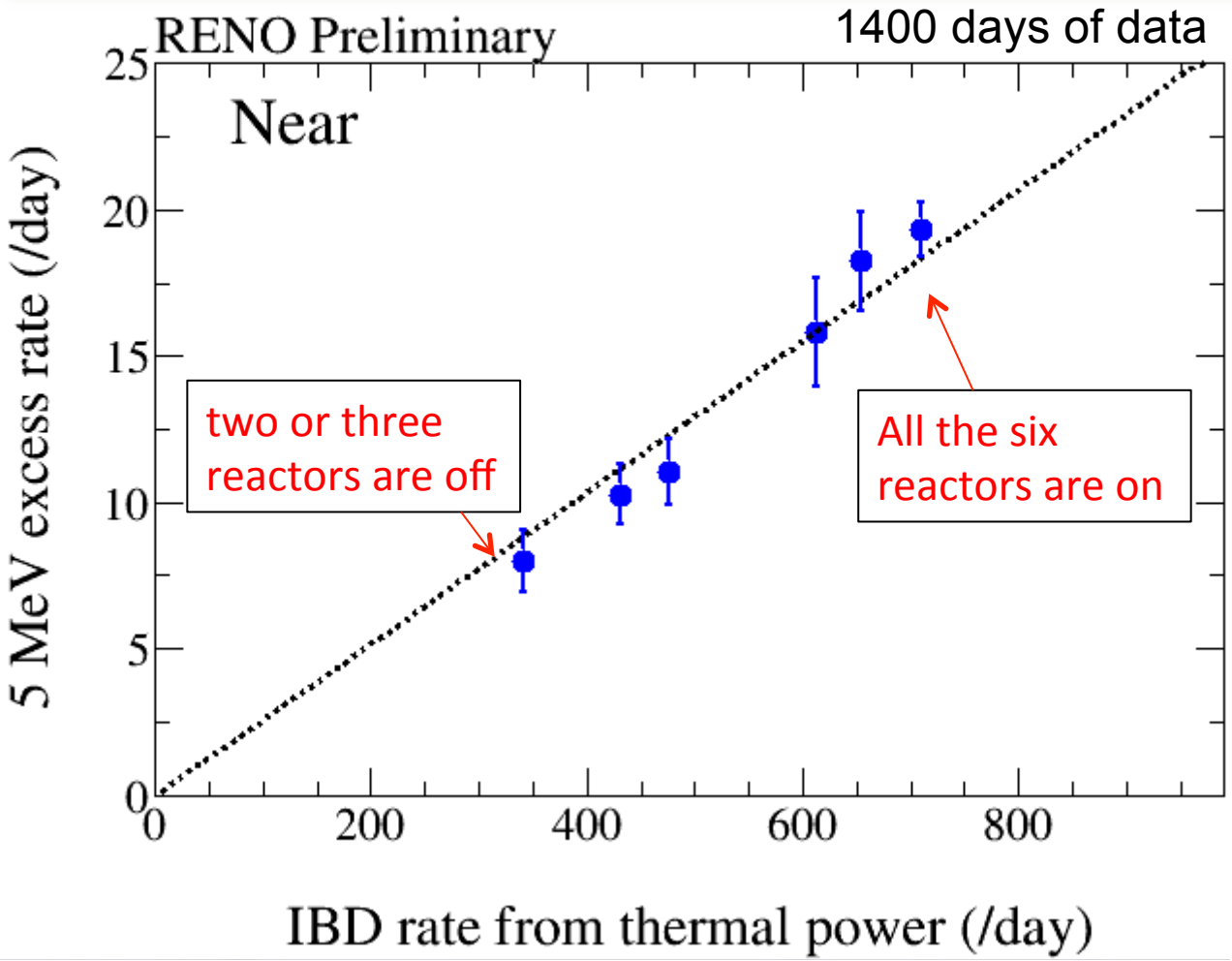
68 bins = **34** energy bins **x 2** periods

Observation of an excess at 5 MeV

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



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

What is Nuclear Fission ?