Reactor Experiment for Neutrino Oscillation

"Measurements of the Neutrino Mixing Angle θ_{13}"

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(On behalf of RENO collaboration)

KNRC Korea Neutrino Research Center

RENO

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Physics in Collision 2019 @NTU, Taipei

Outline

- Brief introduction of neutrino mixing angles
- RENO introduction and data taking status
- Latest results from RENO
  - θ_{13} & spectral analysis for Δm_{ee}^2
  - Reactor antineutrino flux and spectrum, 5 MeV access
  - Fuel-composition dependent reactor neutrino yield
  - Measurement of absolute reactor neutrino flux and spectrum
  - Results from n-H IBD analysis
- Summary

[Note] RENO results mainly will be reviewed

(even if Daya Bay, Double Chooz may attend here)

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

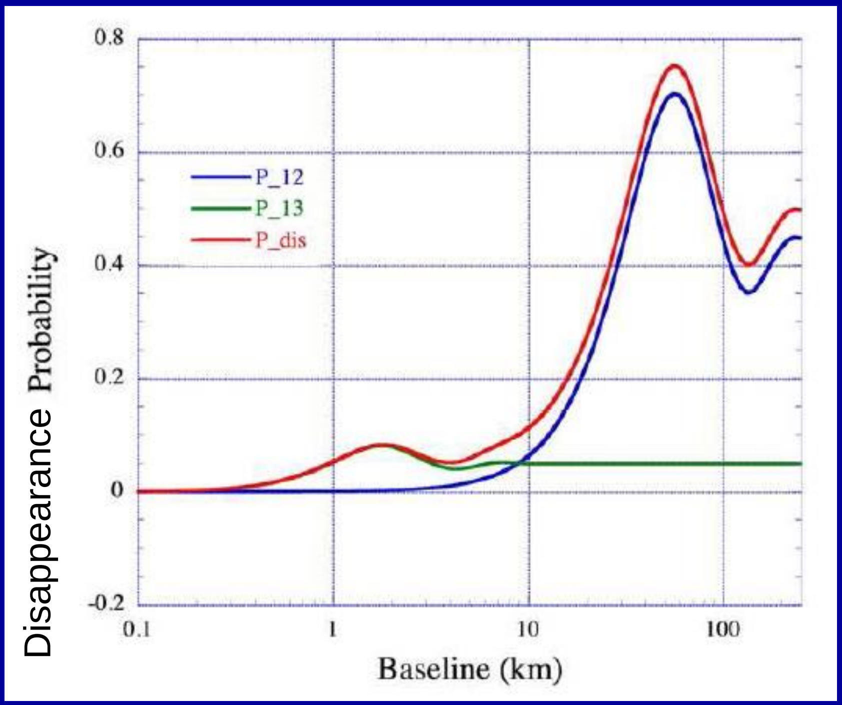
2015 Nobel Prize

All these imply that "Neutrino has mass".
"Established three-flavor mixing framework"

Reduction of reactor neutrinos due to oscillations

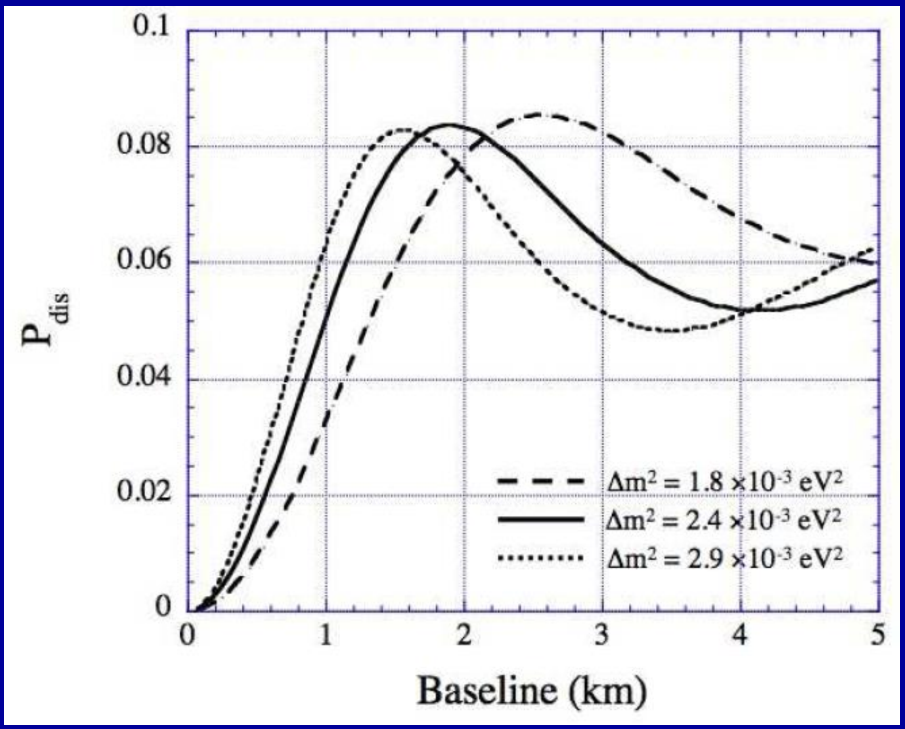
Survival probability

$$P(\bar{\nu}_e \to \bar{\nu}_e) \simeq 1 - \sin^2(2\theta_{13})\sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) - \cos^4\theta_{13}\sin^2(2\theta_{12})\sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$$



$$\sin^2 2\theta_{13} = 0.10$$

$$\theta_{12} = 34^\circ, \quad \Delta m^2_{21} = 7.9 \times 10^{-5}\mathrm{eV}^2, \quad \Delta m^2_{31} = 2.5 \times 10^{-3}\mathrm{eV}^2$$

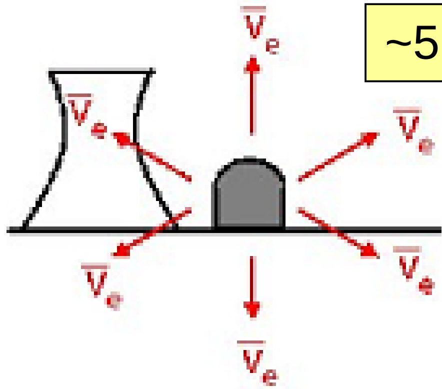


Reactor neutrino disappearance Prob. due to θ_{13} with the allowed 2σ range in Δm_{23}^2

- ❑ $\sin^2 2\theta_{13} > 0.01$ with 10 t •14GW •3yr ~ 400 t•GW•yr
  (400 t•GW•yr: a 10(40) ton far detector and a 14(3.5) GW reactor in 3 years)

Reactor Neutrinos

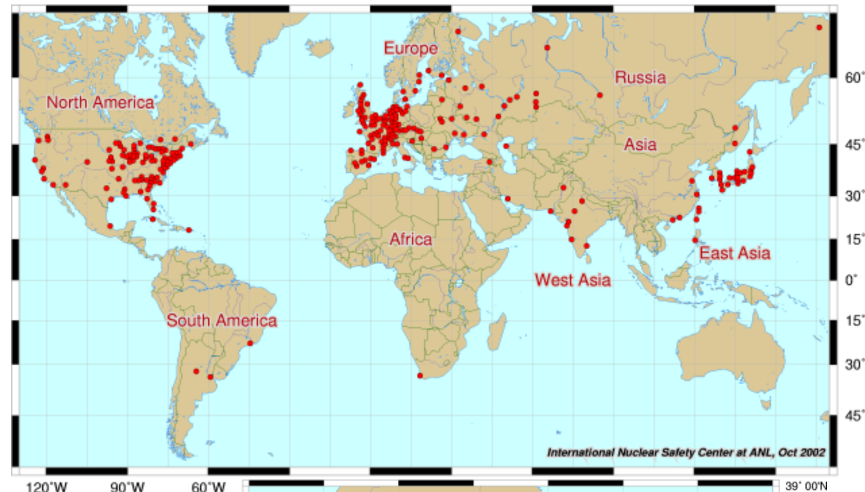
Reactor Neutrinos

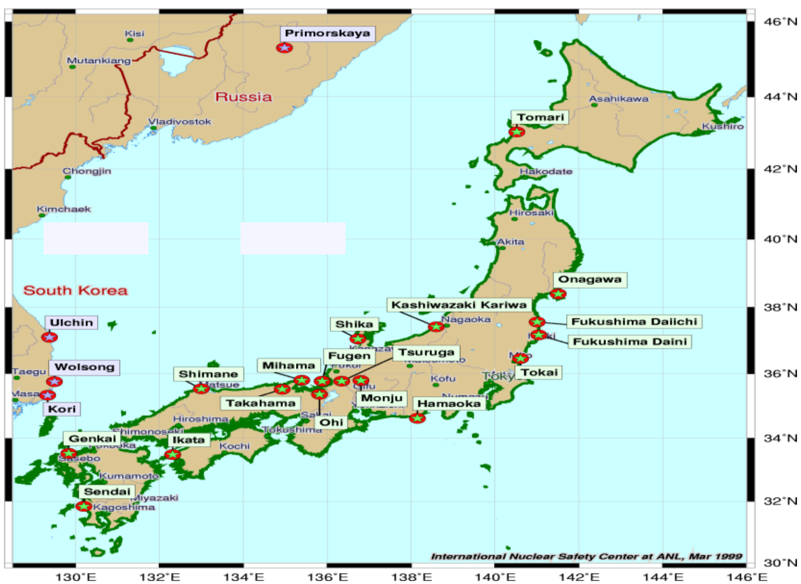


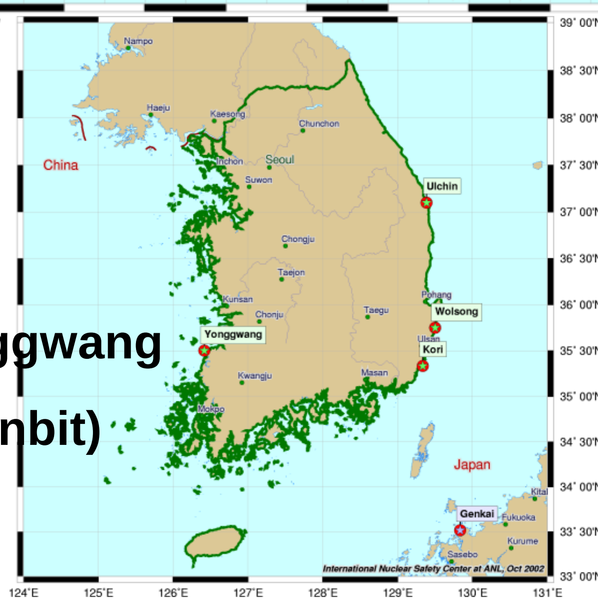
$\sim 5 \times 10^{21}$ ν/sec

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

Nuclear Power Plants







Yonggwang

(Hanbit)

Reactor Neutrino Experiments

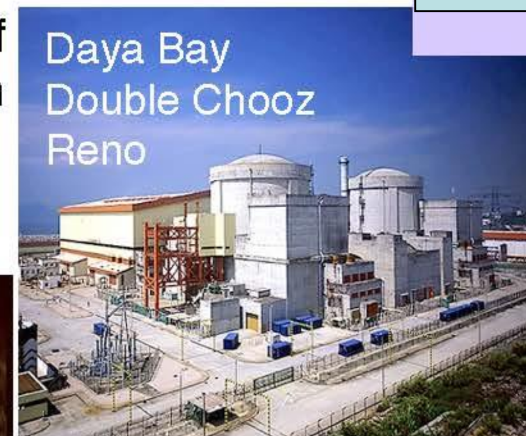
~2020

JUNO

China

Past → **Present** → **Future**

2011/2012 - The year of θ_{13}



2008 - Precision measurement of Δm_{12}^2. Evidence for oscillation

2003 - First observation of reactor antineutrino disappearance

1995 - Nobel Prize to Fred Reines

1980s & 1990s - Reactor neutrino flux measurements in U.S. and Europe

1956 - First observation of (anti)neutrinos

Japan

China
France
Korea
} complementary

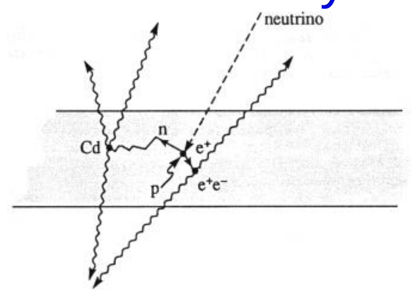
(Gd-loaded) Liquid Scintillator

Karsten M. Heeger

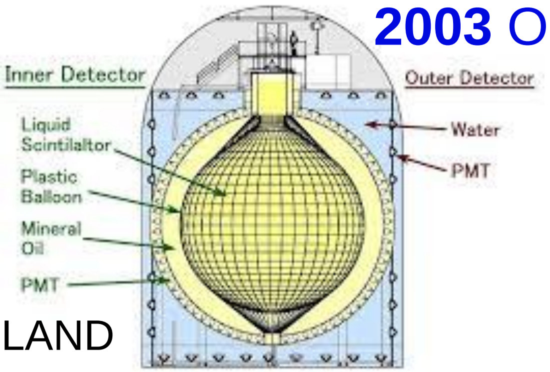
University of Wisconsin

Neutrino Physics with Reactor

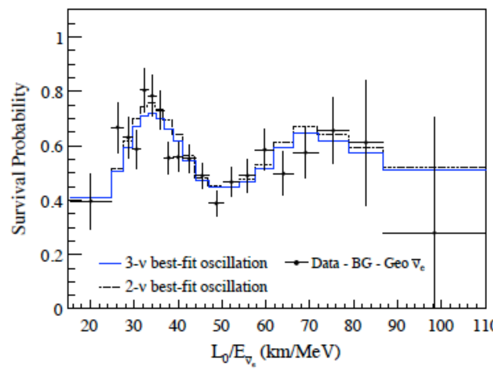
1956 Discovery of (anti)neutrino

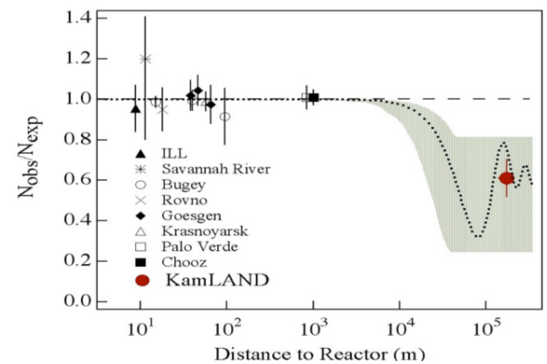


2003 Observation of reactor neutrino oscillation (θ_{12} & Δm_{21}^2)

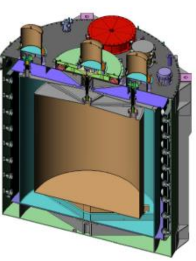


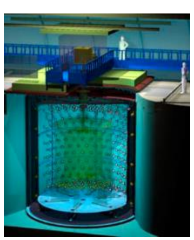
KamLAND

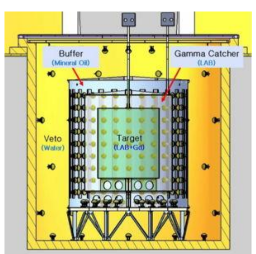


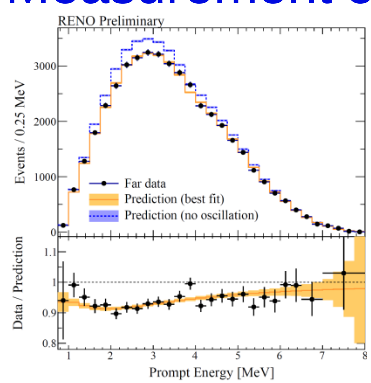


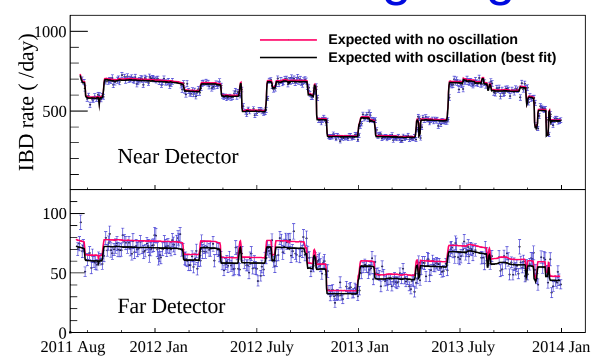
2012 Measurement of the smallest mixing angle θ_{13}





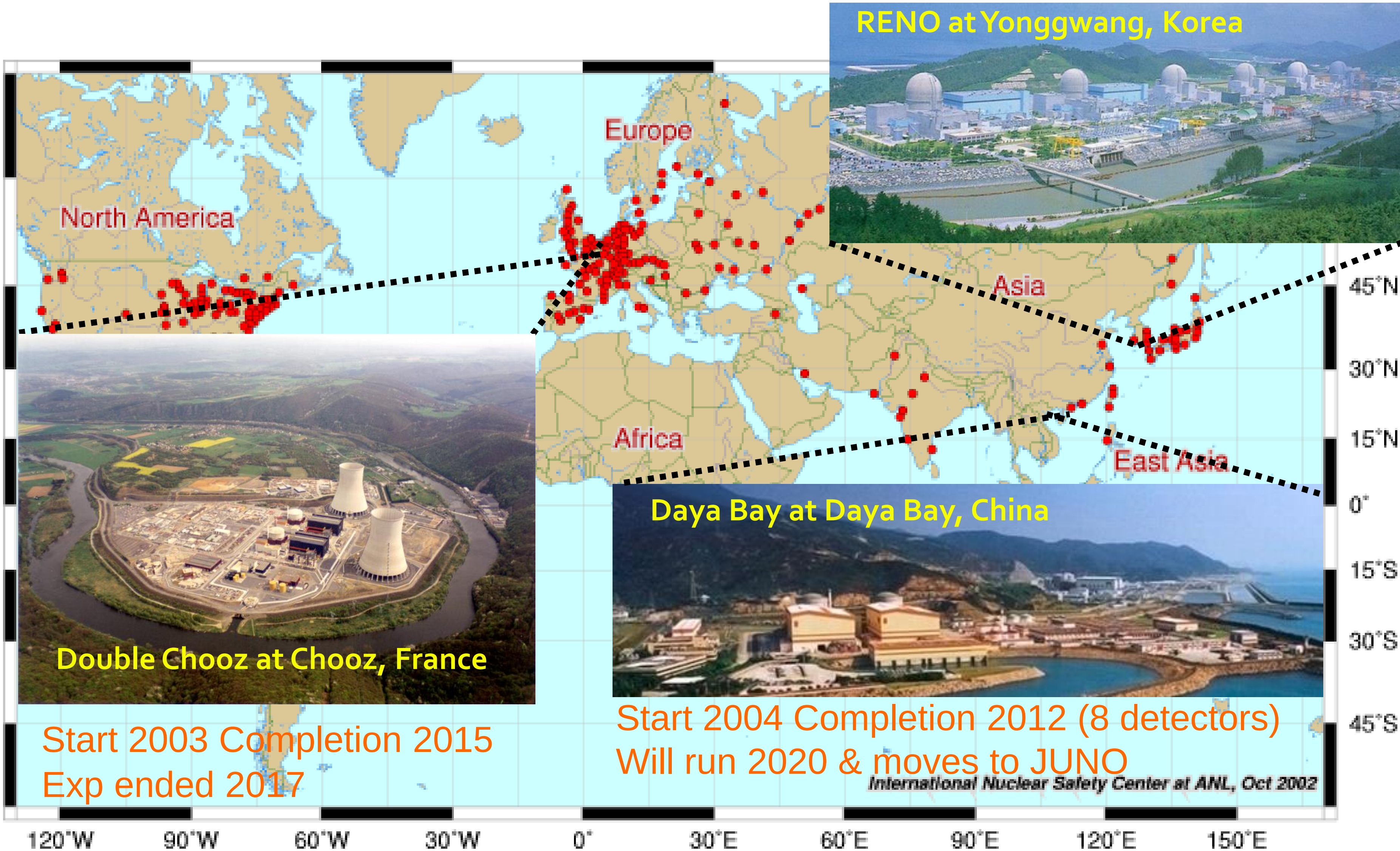






Reactor θ_{13} Experiments

Start 2006, Completion 2011



Start 2003 Completion 2015
Exp ended 2017

Start 2004 Completion 2012 (8 detectors)
Will run 2020 & moves to JUNO

RENO Collaboration

RENO ν θ_{13}

8 institutions and 35 physicists in Korea

- Chonnam National University
- Dongshin University
- GIST
- KAIST
- Kyungpook National 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**

YongGwang (靈光) :

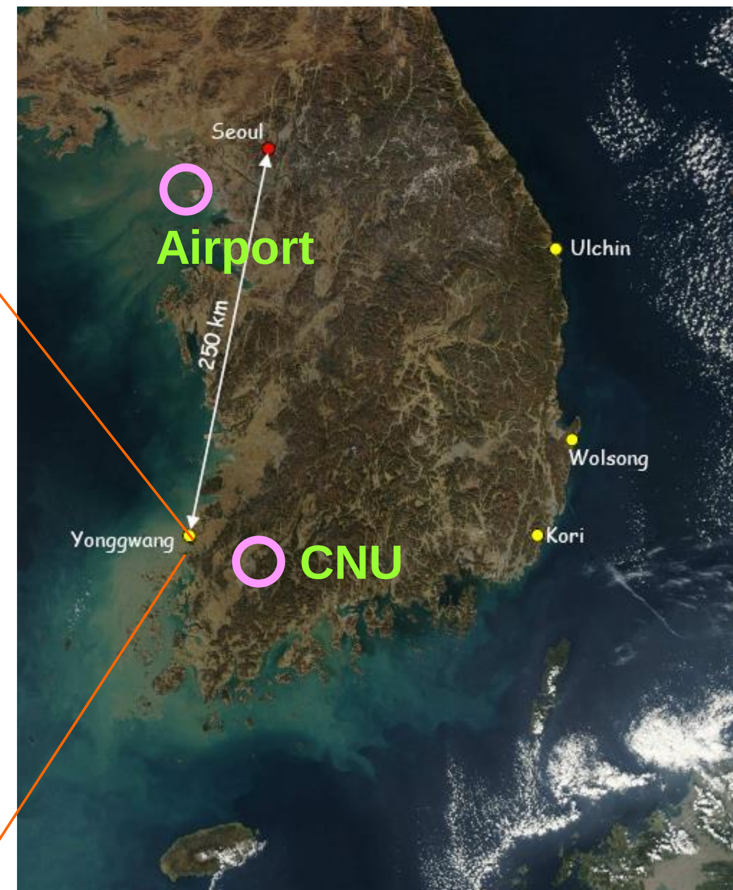
New name: Hanbit

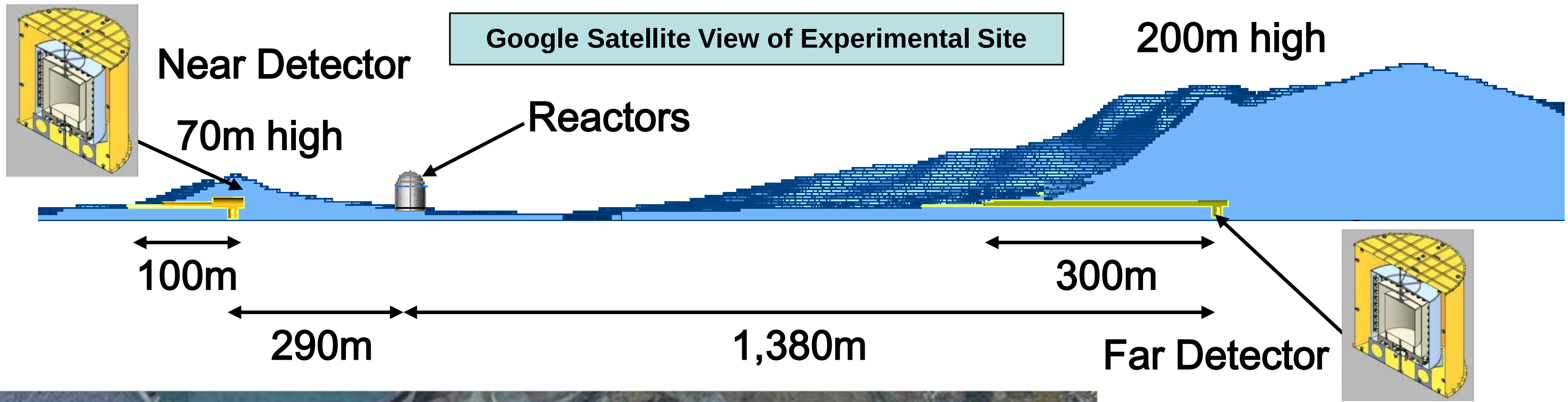
Reactor Experiment for Neutrino Oscillation

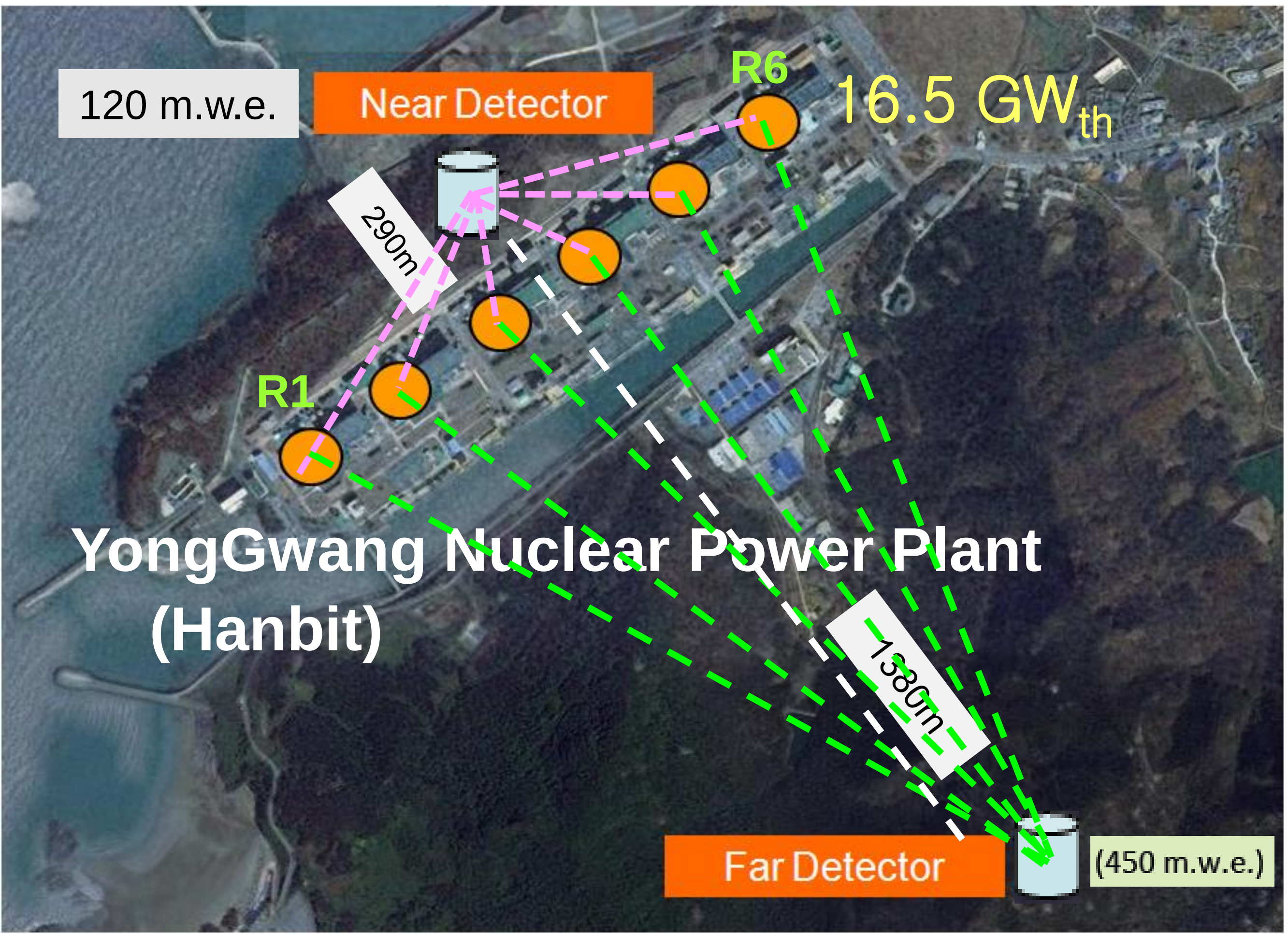
YongGwang Nuclear Power Plant

- Located in the west coast of southern part of Korea
- ~300 km from Incheon international airport (~2 hrs from Taoyuan airport, Taipei)
- 6 reactors are lined up in roughly equal distances and span ~1.3 km
- Total average thermal output ~16.7GW_{th}

YongGwang(靈光):
= glorious[splendid] light (~spirited)
New name: Hanbit



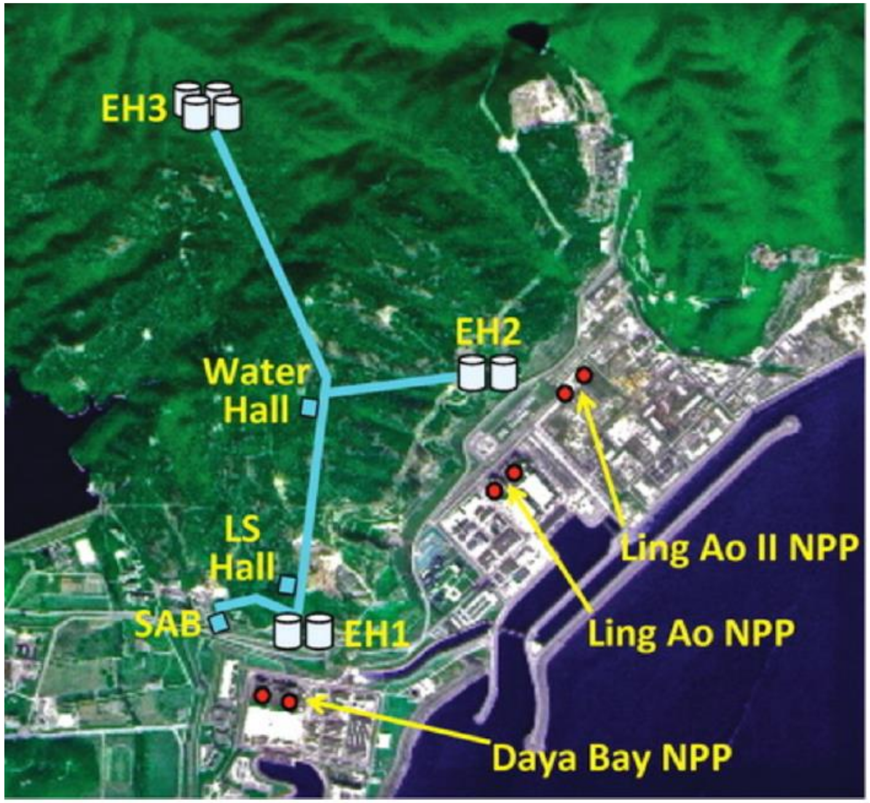




- ❒ Thermal output ~2.8GW_{th} x 6
- ❒ Two identical detectors
- ❒ Near detector ~300m
- ❒ Far detector ~1.4km

Experimental Layout

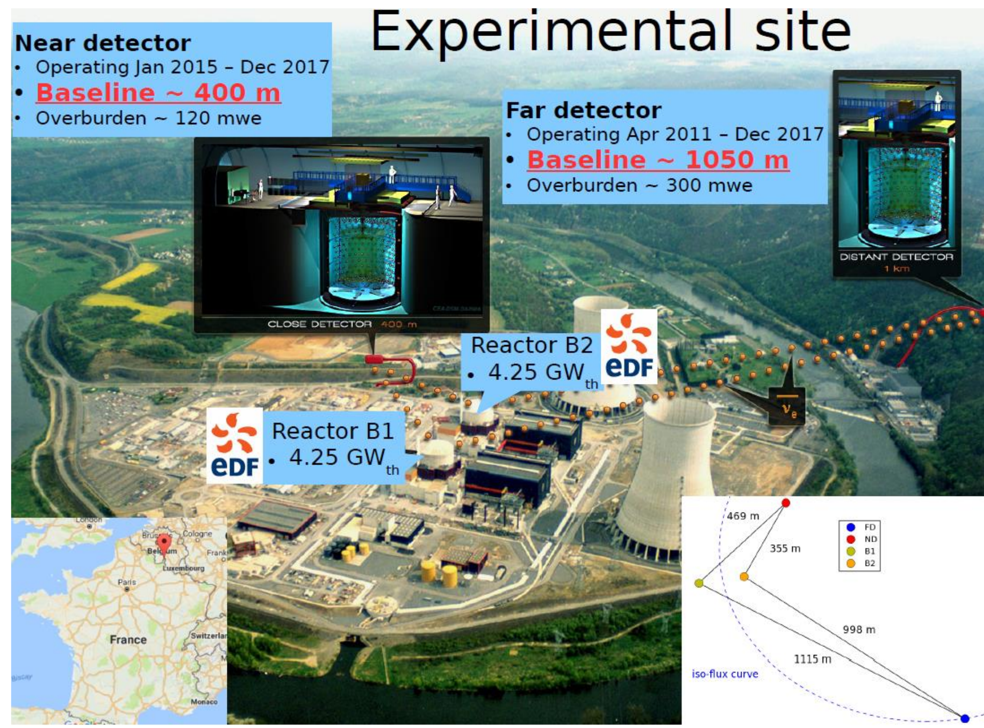
Daya Bay



8 detectors + 3 power plants

Most powerful nuclear power complexes in the world!

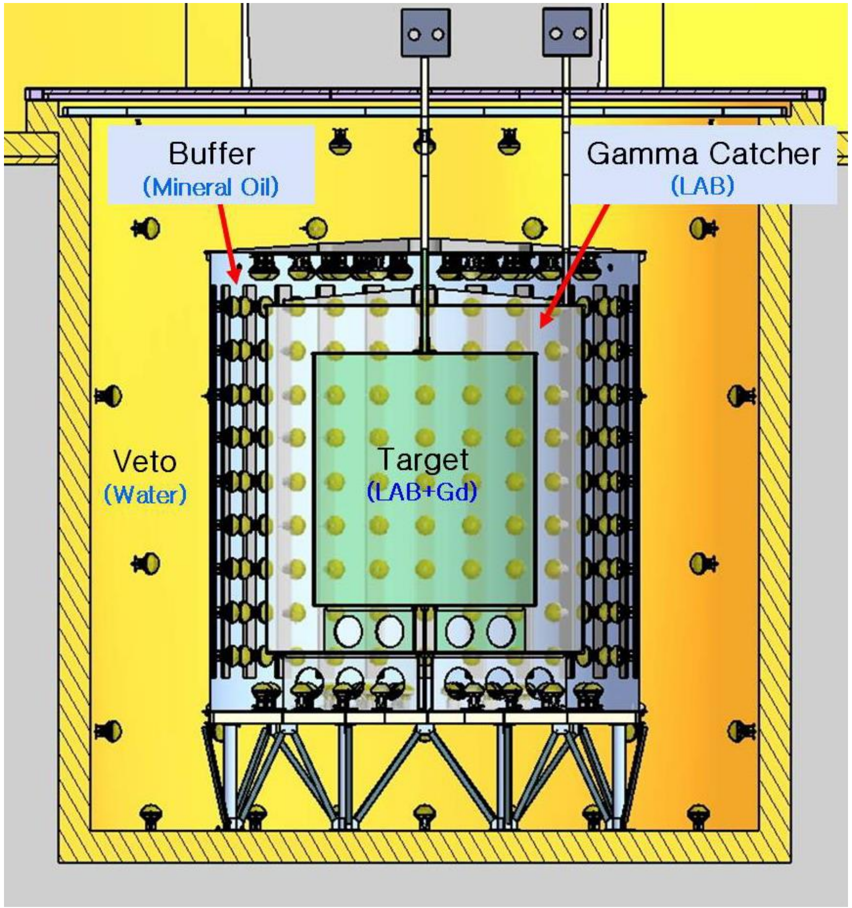
Double Chooz



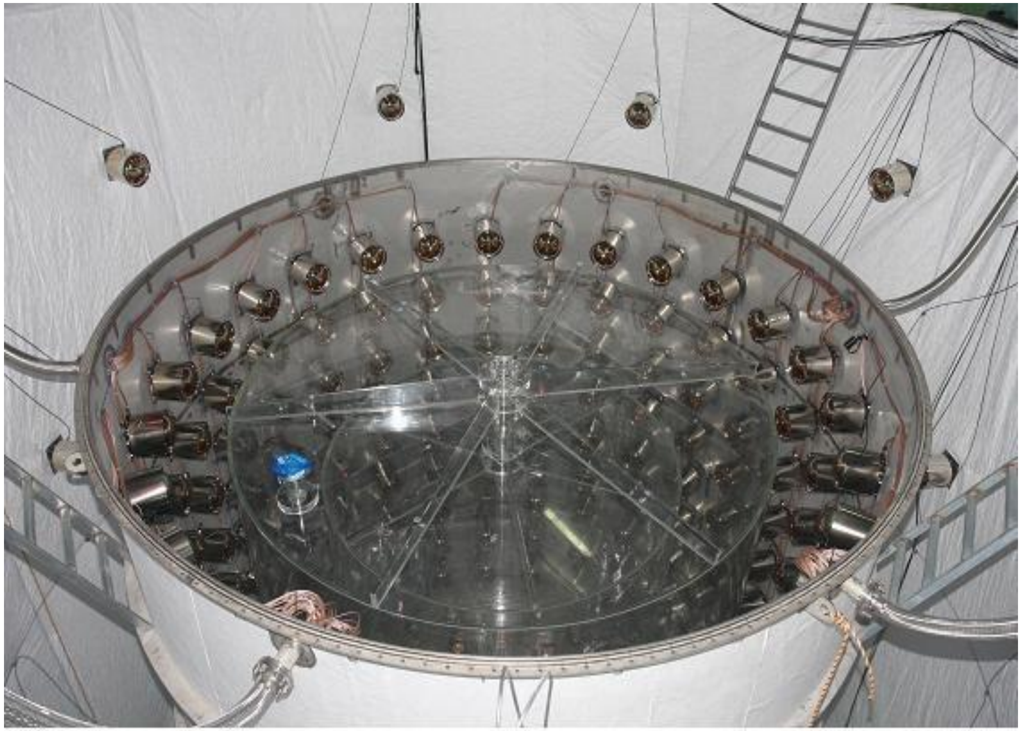
2 detectors + 2 reactors

RENO Detector

4 cylindrical layers



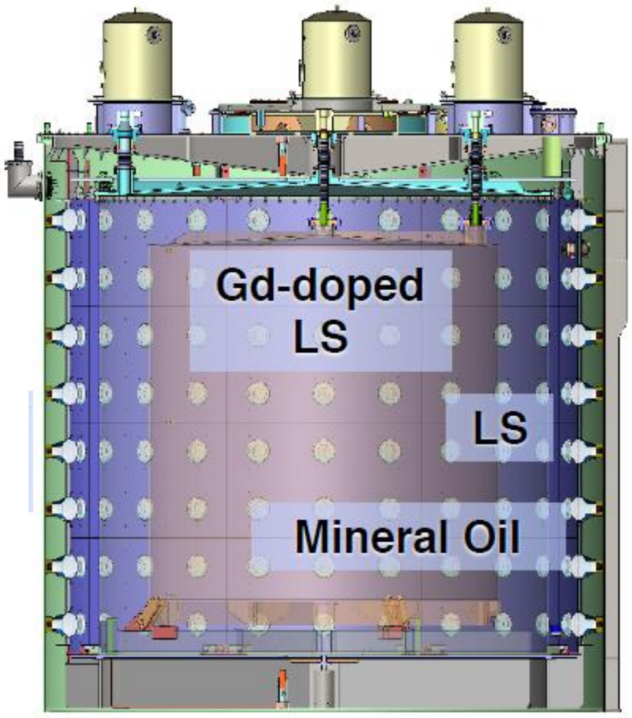
- **Inner PMTs: 354 10” PMTs**
  - solid angle coverage = ~14%
- **Outer PMTs: ~ 67 10” PMTs**

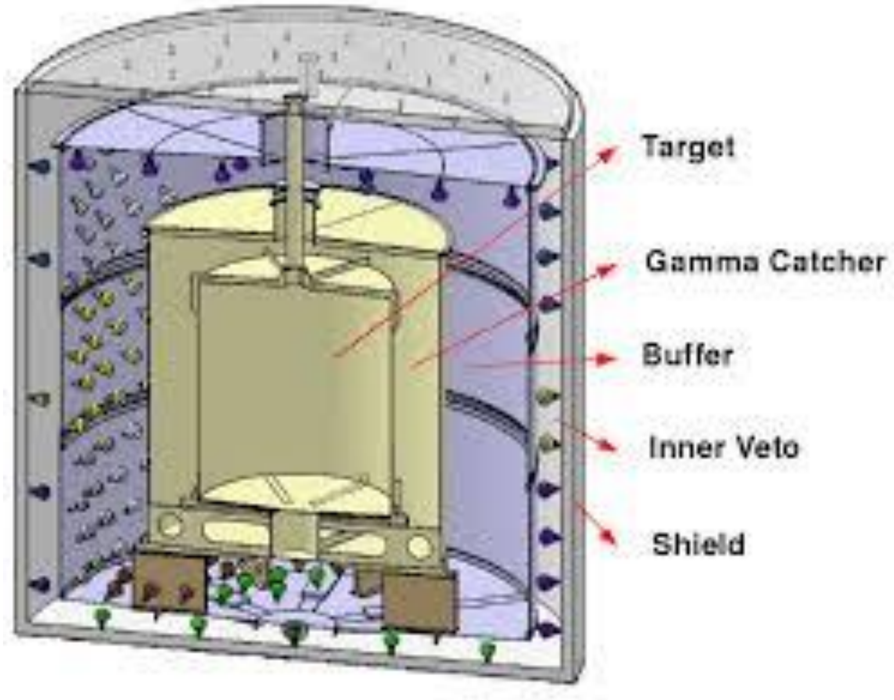


- Target : **16.5 ton** Gd-LS (R=1.4m, H=3.2m)
- Gamma Catcher : 30 ton LS (R=2.0m, H=4.4m)
- Buffer : 65 ton mineral oil (MO) (R=2.7m, H=5.8m)
- Veto : 350 ton water (R=4.2m, H=8.8m)

total ~460 tons

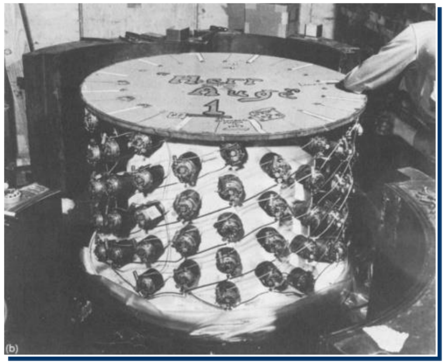
Daya Bay	Double Chooz

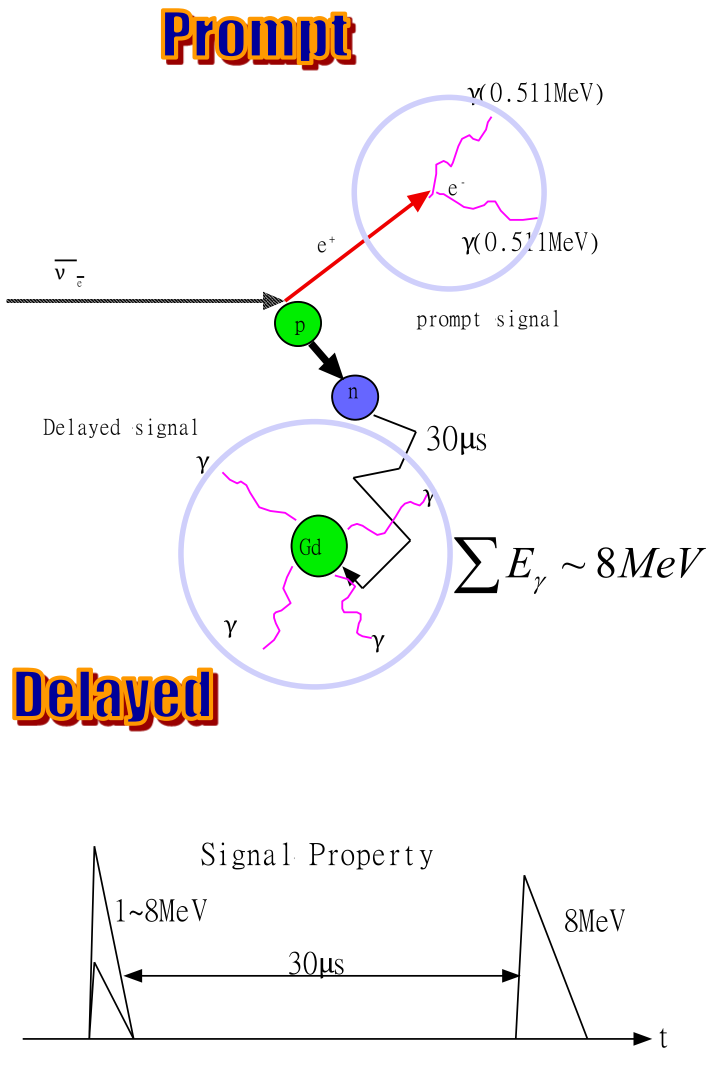




- Conceptually the same detector design & layout are used for all 3 experiments (DB, DC, RENO)

Detection of Reactor Antineutrinos





- Use inverse beta decay ($\bar{\nu}_e + p \rightarrow e^+ + n$) reaction process
- Prompt part:
  subsequent annihilation of the positron to two 0.511MeV γ
- Delayed part:
  neutron is captured
  ~200μs w/o Gd
  ~ 30μs w Gd
  Gd has largest n absorption cross section & emits high energy γ
- Signal from neutron capture
  ~2.2MeV w/o Gd
  ~ 8MeV w Gd
- Measure prompt signal & delayed signal
- “Delayed coincidence” reduces backgrounds drastically

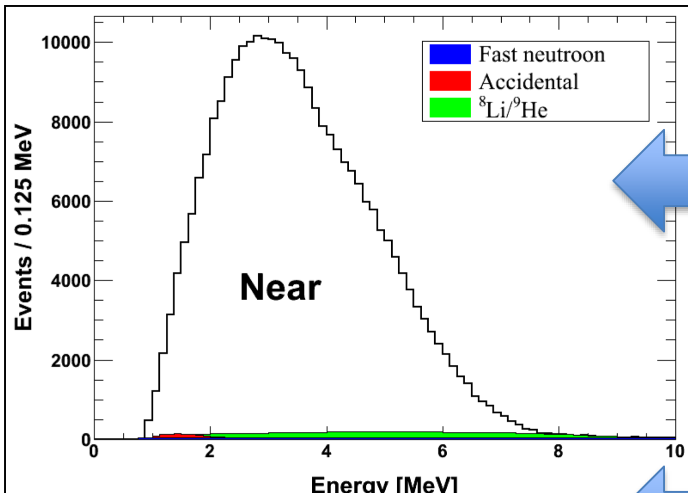
Coincidence of Prompt and Delayed Signals

(prompt signal)

$$\bar{\nu}_e + p \rightarrow e^+ + n$$ (delayed signal)

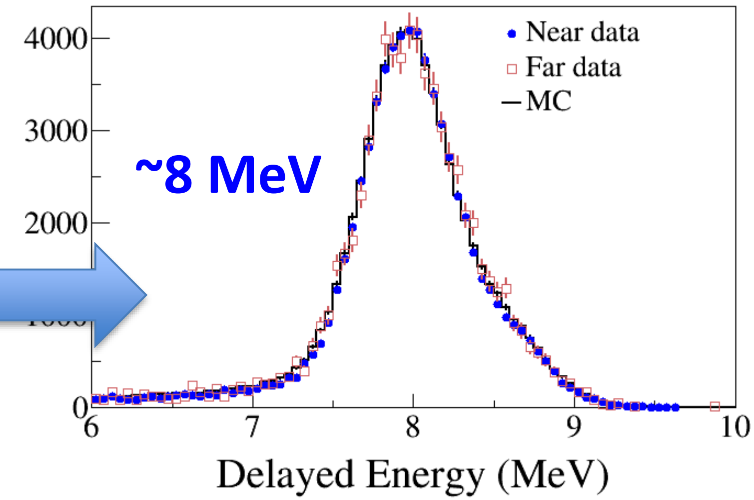
Delayed signal (S2)

Prompt signal (S1)



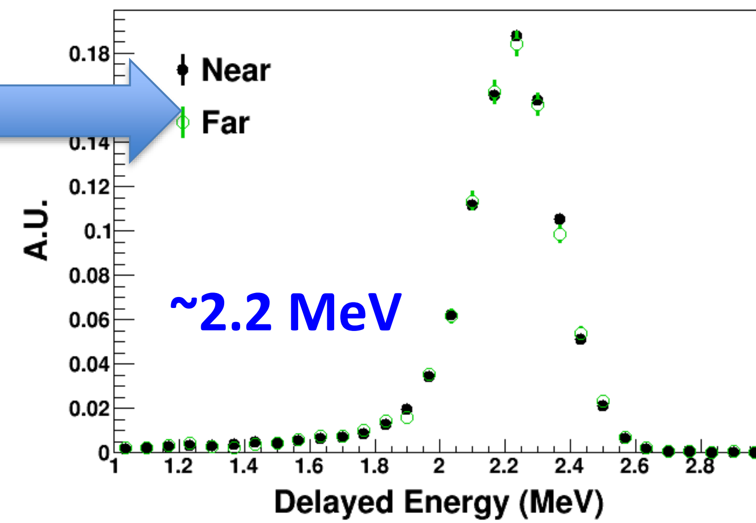
n-Gd IBD

~30 μs



~200 μs

n-H IBD



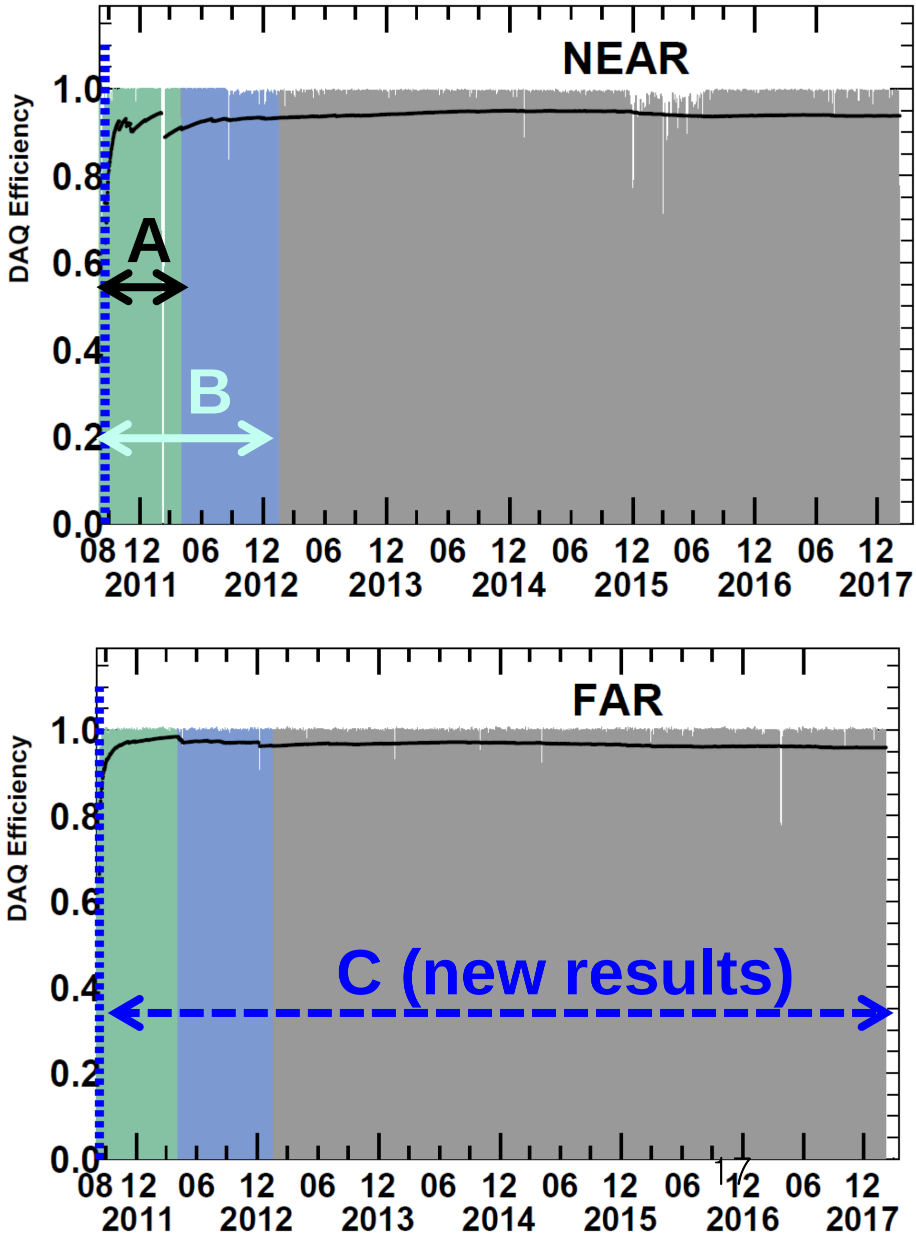
RENO Data-taking Status

- 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 (~500 days)** : **Updated results**
  Rate+shape analysis (**θ_{13} and $|\Delta m_{ee}^2|$**)
  [11 Aug, 2011~21 Jan, 2013]
  → PRL 116, 211801 (2016)
  PRD 98, no.1, 012002 (2018)

- **C (~2200 days)** : **New results**
  Rate+shape analysis (**θ_{13} and $|\Delta m_{ee}^2|$**)
  [11 Aug, 2011~7 Feb, 2018]
  → (arXiv:1806.00248)
  PRL 121, 201801 (2018)



New Results from RENO

■ Precise measurement of $|\Delta m_{ee}^2|$ and θ_{13} using ~2200 days of data (Aug. 2011 – Feb 2018)

"Measurement of Reactor Antineutrino Oscillation Amplitude and Frequency at RENO" " → Published in PRL (Phys. Rev. Lett. 121, 201801 (2018))

■ Fuel-composition dependent reactor antineutrino yield →
"Fuel-composition dependent reactor antineutrino yield and spectrum at RENO" → Published in PRL (Phys. Rev. Lett. 122, no.23, 232501 (2019))

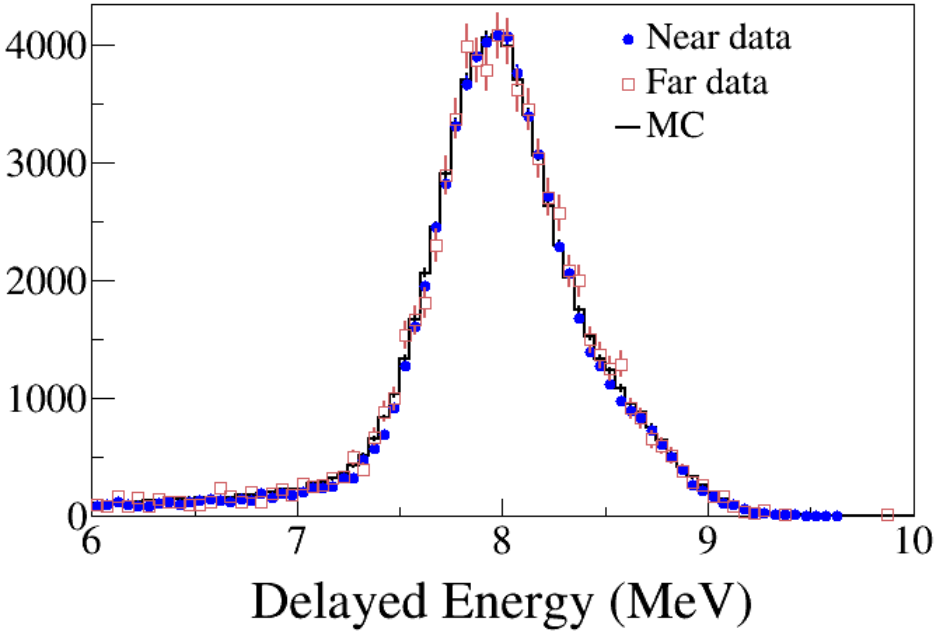
■ Independent measurement of θ_{13} and $|\Delta m_{ee}^2|$ with delayed n-H signals (using ~500 days of data)

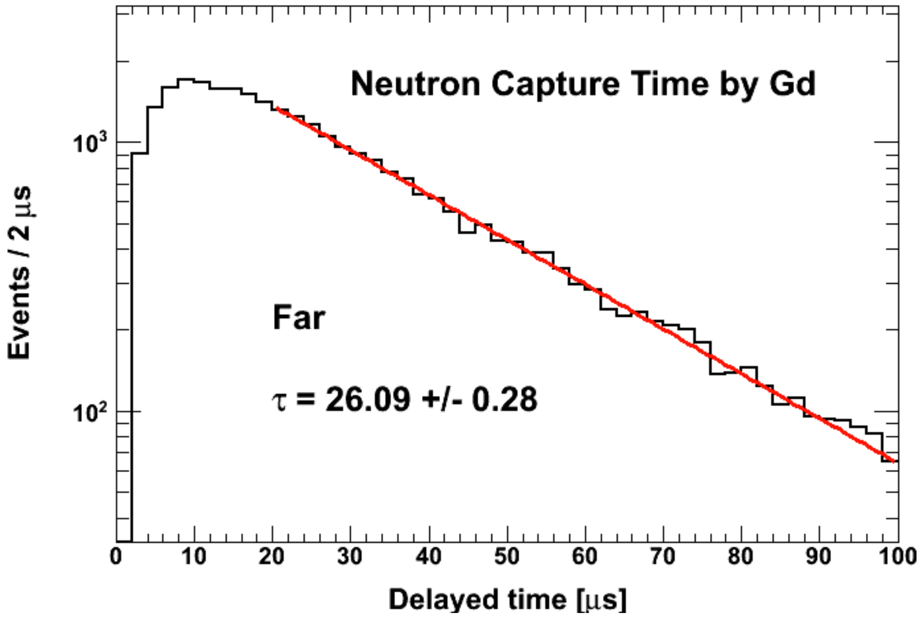
→ Prepared for paper & will be submitted soon

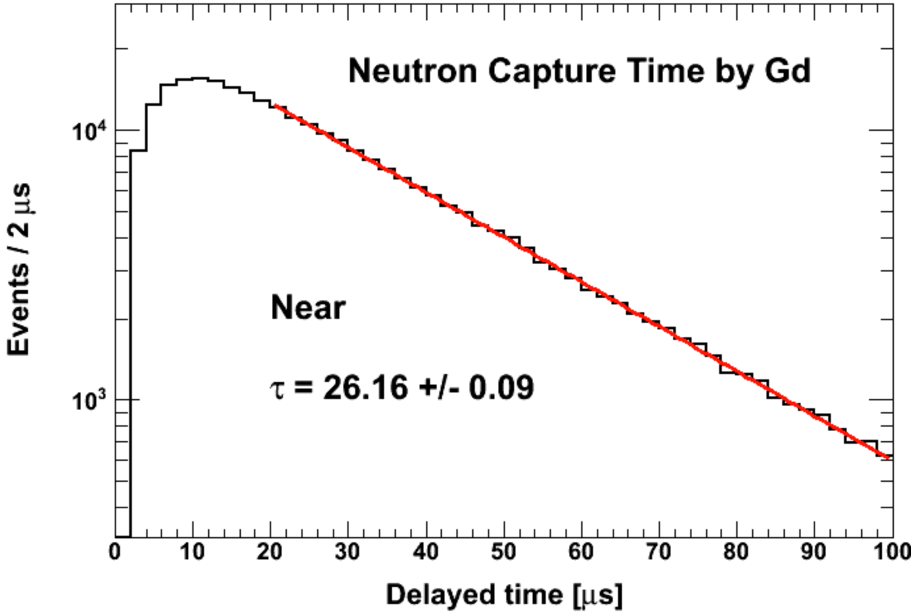
Observed Delayed Signal (n-Gd)

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

Delayed energy distribution (S2)



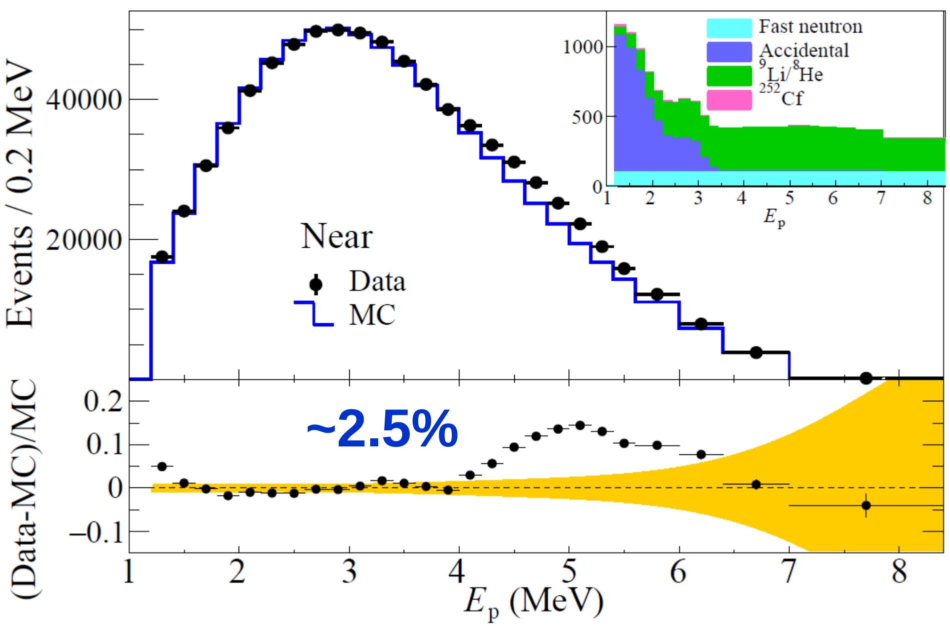


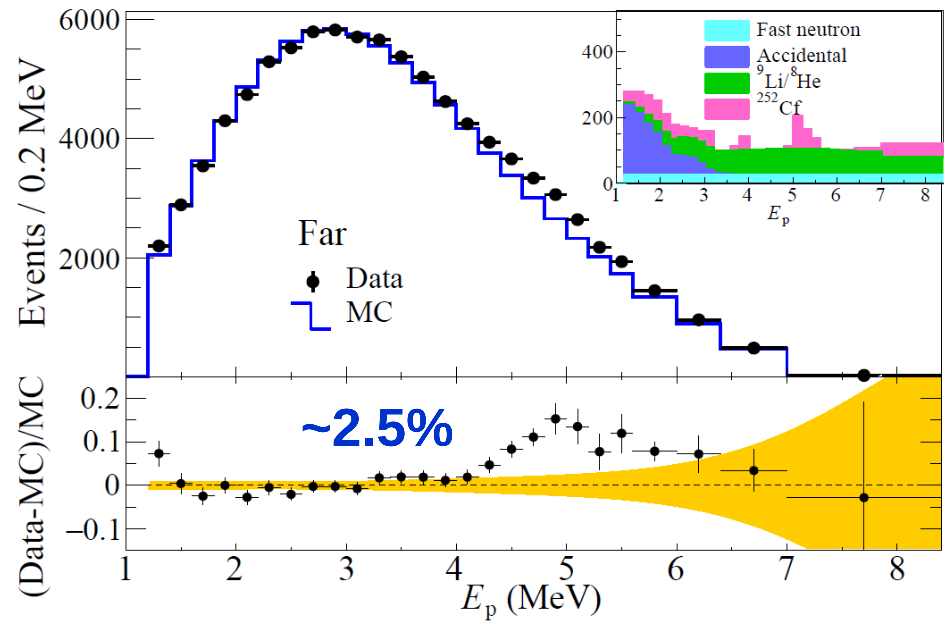


- Agree well each other

Measured Spectra of IBD Prompt Signal

Clear excess at 5 MeV (persistent from the first result)





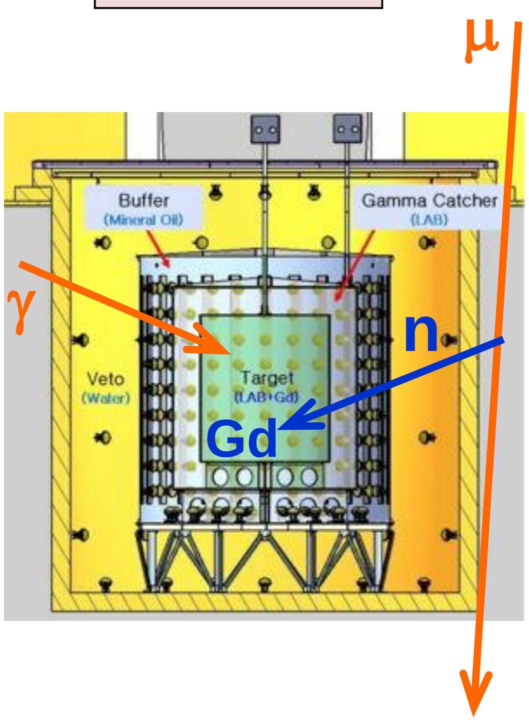
Near Live time = 1807.88 days
# of IBD candidate = 850,666
# of background = 17,233 (2.0 %)

Far Live time = 2193.04 days
# of IBD candidate = 103,212
# of background = 4,879 (4.8 %)

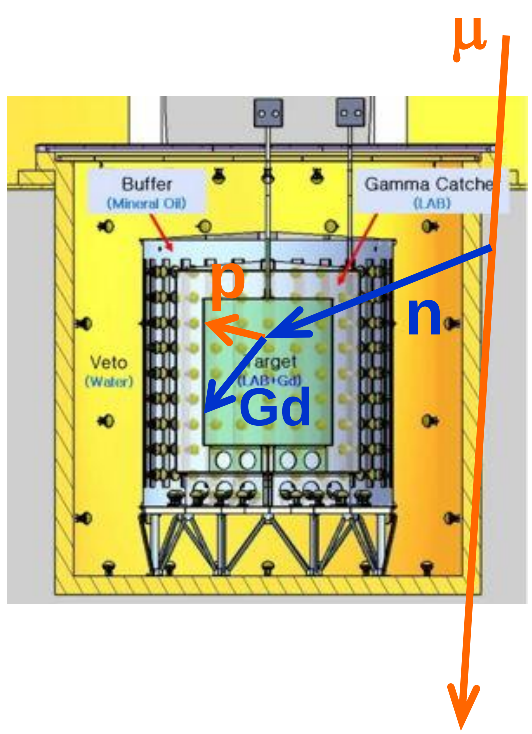
Backgrounds

- 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

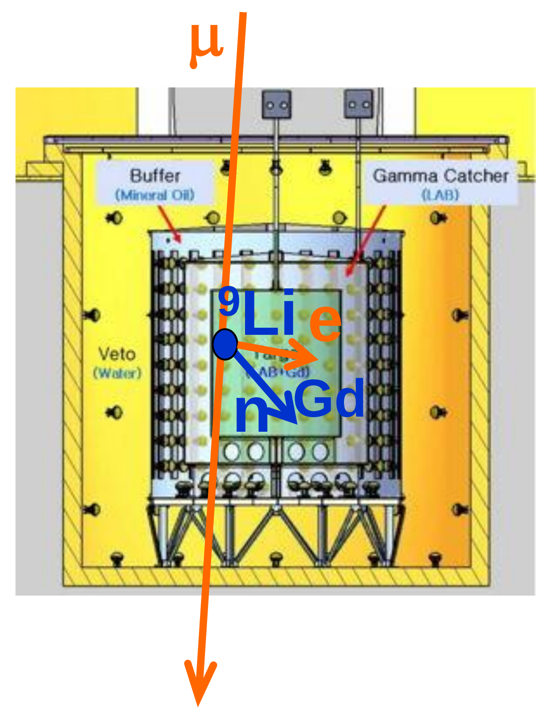
Accidentals



Fast neutrons

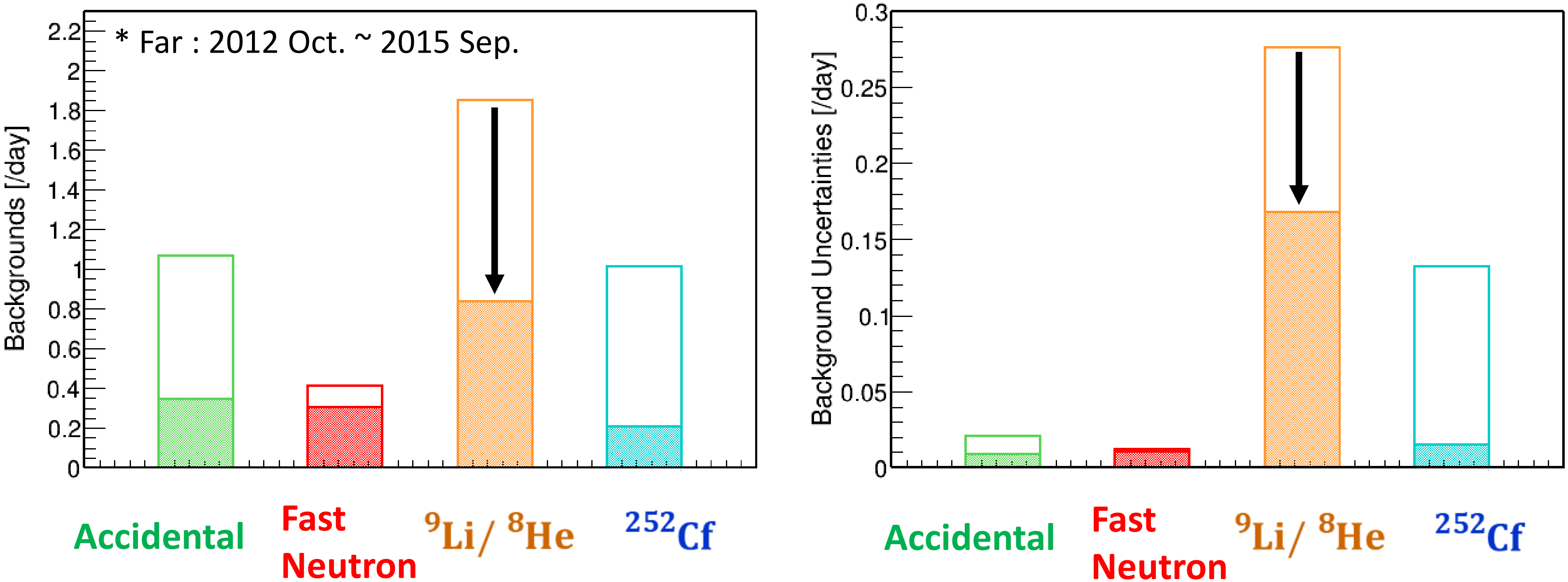


^{9}Li/^{8}He β-n followers



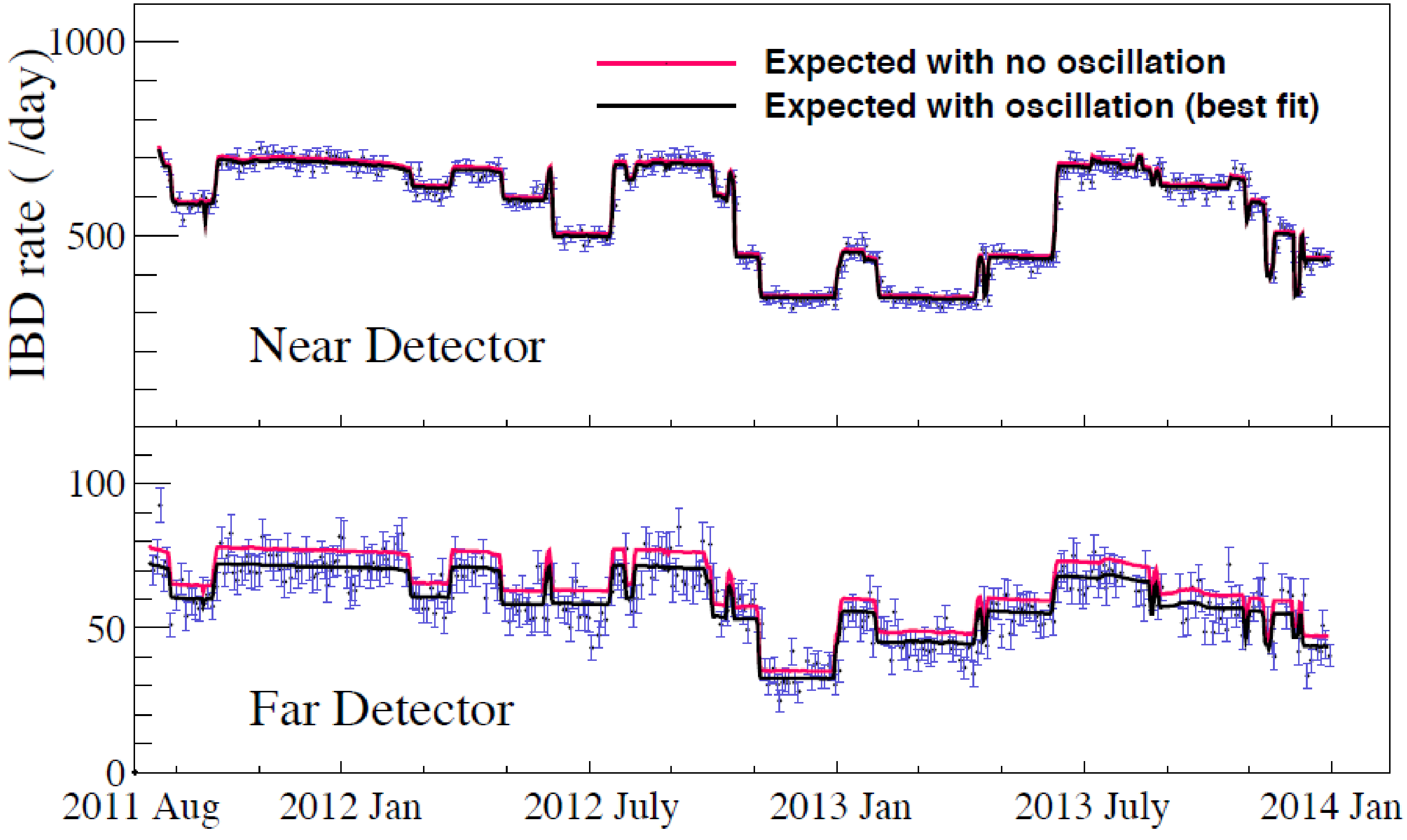
Reduction of Background Rates & Uncertainties

Allows precise measurements of $\sin^2 2\theta_{13}$ and Δm^2_{ee}



- Accidentals : additional cuts and improved flashing-PMT removal algorithms
- Cosmogenic $^{9}Li/\ ^{8}He$: optimized muon veto criteria
- ^{252}Cf contamination : improved multiple-neutron removal algorithms

Observed Daily Averaged IBD Rate

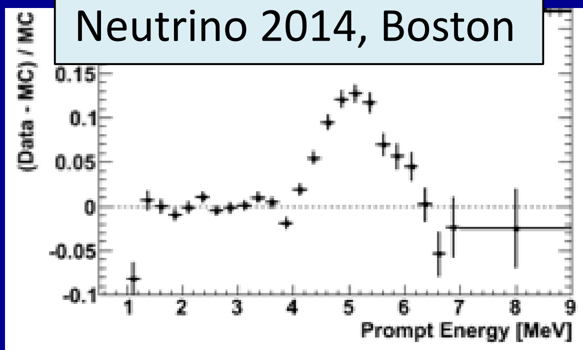


- Good agreement with observed rate and prediction
- Accurate measurement of thermal power by reactor neutrinos
- Any change of reactor condition can be monitored

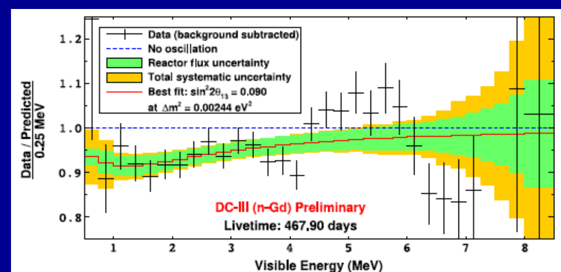
The 5 MeV Excess is there !

RENO

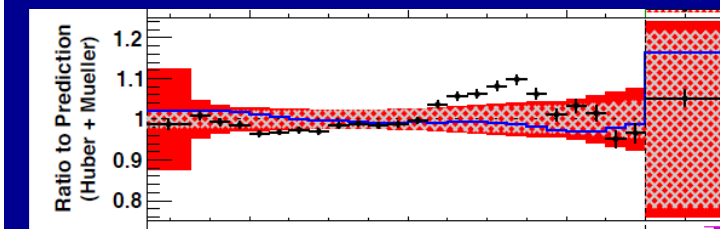
Neutrino 2014, Boston



Double Chooz



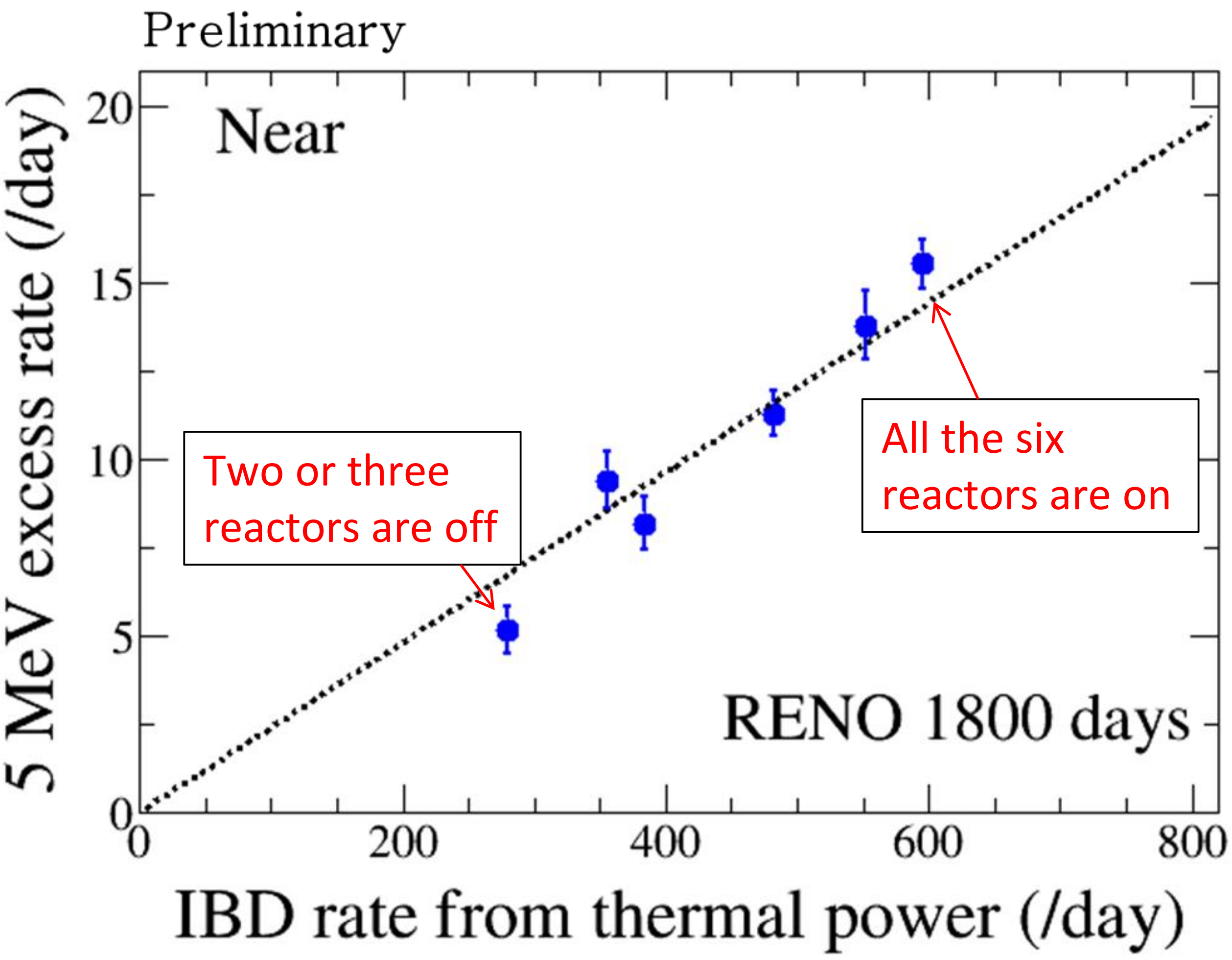
Daya Bay



In 2014, RENO showed that the 5 MeV excess is from reactor neutrinos @Boston

DC & DB also observed the same 5 MeV excess

Correlation of 5 MeV Excess with Reactor Power

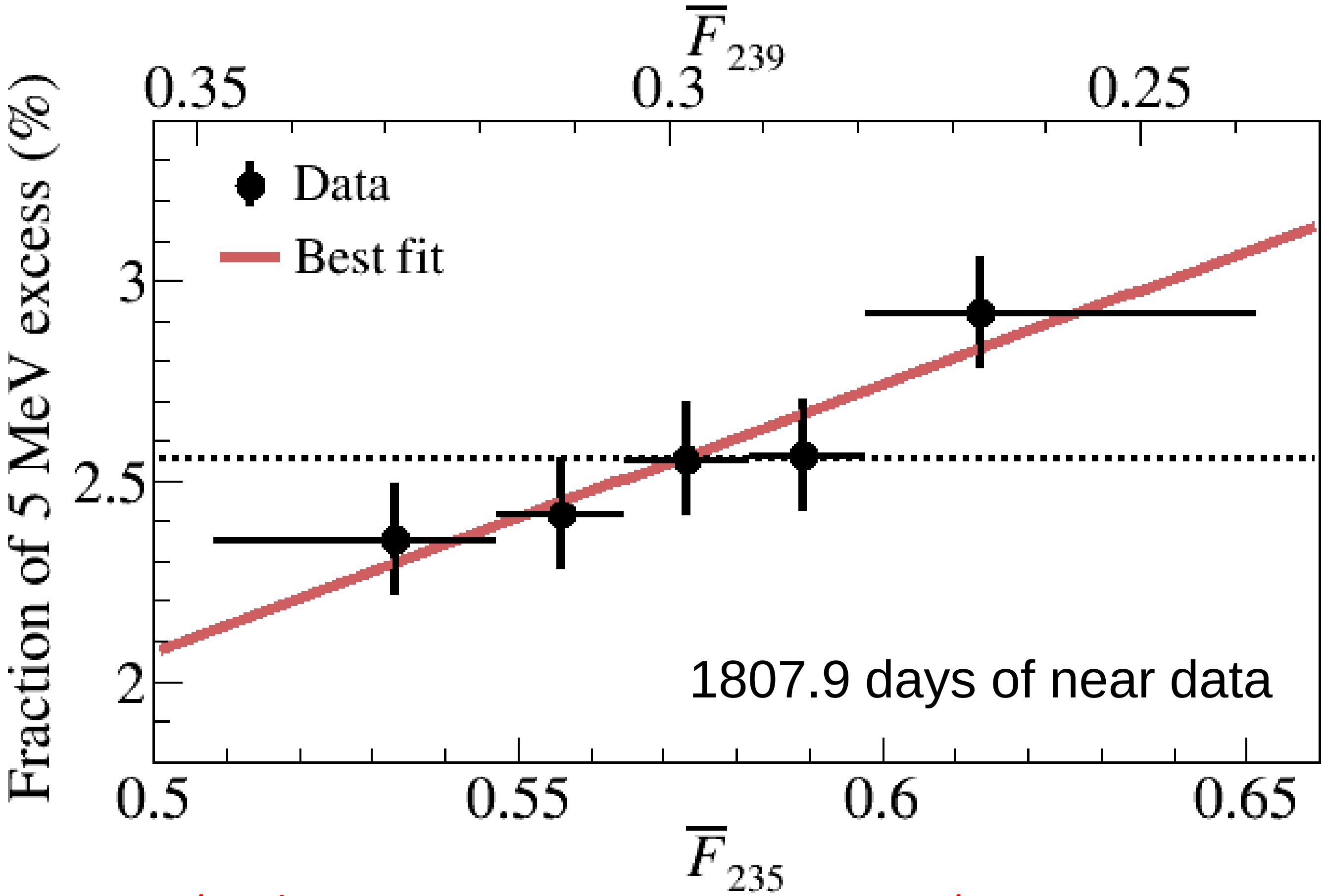


5 MeV excess has a clear correlation with reactor thermal power !

The 5 MeV excess comes from reactors!

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

- ^{235}U fraction corresponds to freshness of reactor fuel
- 2.9σ indication of 5 MeV excess coming from ^{235}U fuel isotope fission



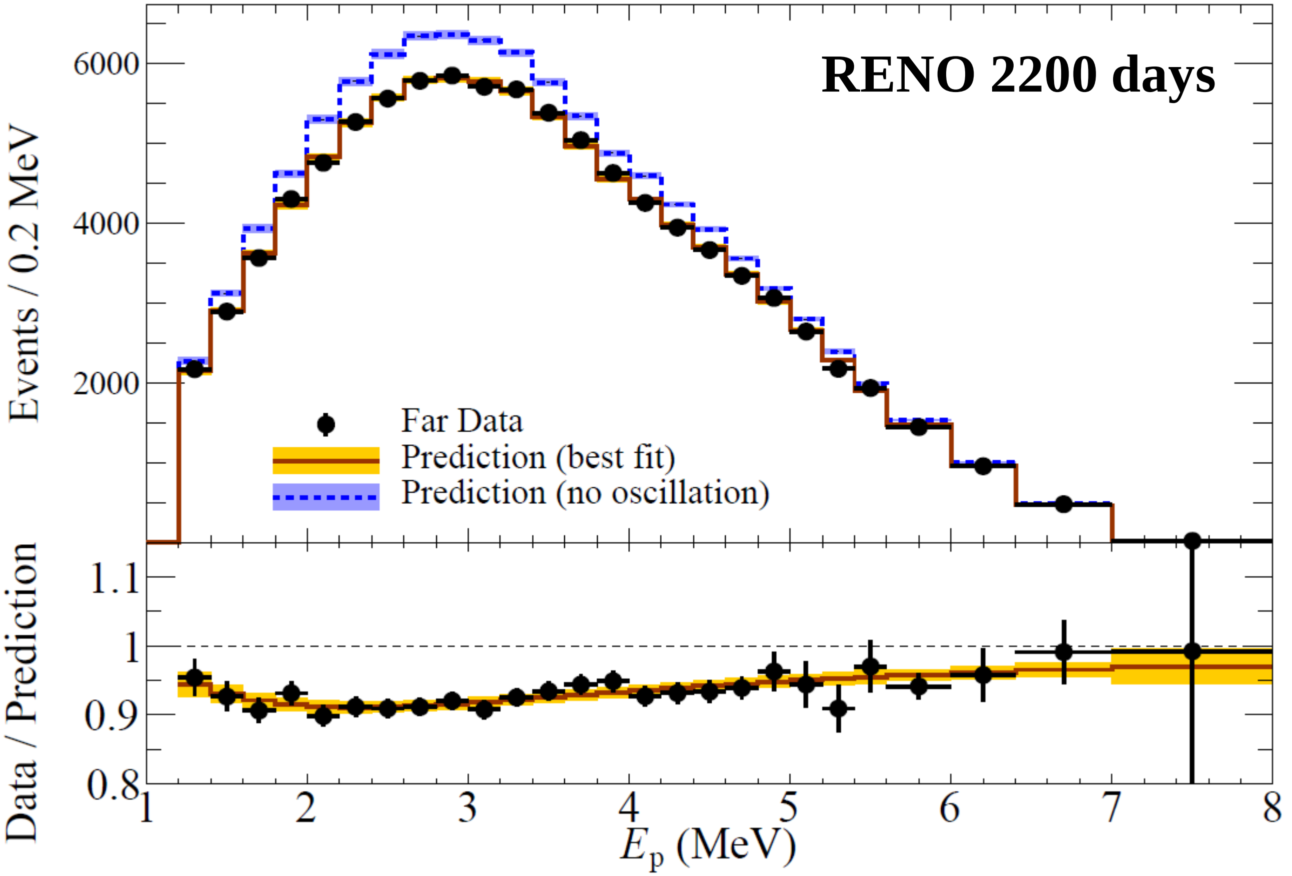
(2.56±0.06) %

(End of reactor cycle)

(Beginning of reactor cycle)

Far/Near Shape Analysis

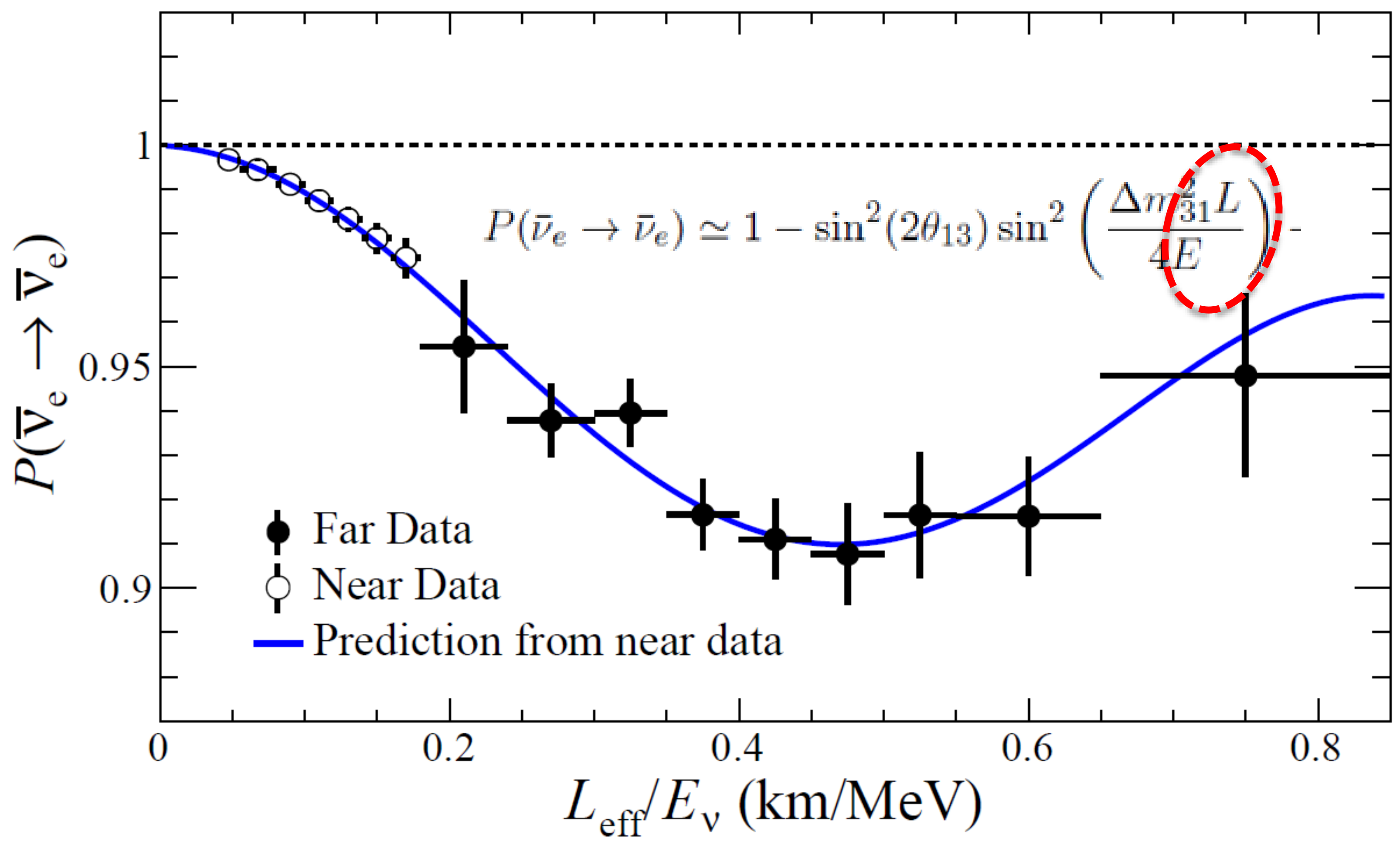
Energy-dependent disappearance of reactor antineutrinos



$\sin^2 2\theta_{13} = 0.0896 \pm 0.0048(\text{stat.}) \pm 0.0047(\text{syst.})$ (± 7.6%)

$|\Delta m_{ee}^2| = 2.68 \pm 0.12(\text{stat.}) \pm 0.07(\text{syst.})\ (\times 10^{-3}\ \text{eV}^2)$ (± 5.2 %)

Observed L/E Dependent Oscillation



- Data follows exactly curve
- Clear energy-dependent disappearance of reactor antineutrinos

RENO : Plan and Prospects

Plan for RENO data taking

2018	2019	2020	2021

RENO data has taken for almost 9 for the analysis

Possible extension of additional 2~3 years

According to our recent study, the systematic error of $|\Delta m_{ee}^2|$ is smaller than the statistical error

$\sin^2 2\theta_{13}$ and $|\Delta m_{ee}^2|$ will approach to **~6% precision** (our design goal)

	500 days Measured	1500 days Measured (preliminary)	~3500 days Expected
$\sin^2 2\theta_{13}$	12 %	9 %	6 ~ 7 %
$\|\Delta m_{ee}^2\|$	10 %	7 %	4 ~ 5 %

Daya Bay : Outlook & News

(@NUFACT2019)

JUNO (Jiangmen Underground Neutrino Observatory)

Main goal: Mass Hierarchy (MH)

- Have recently updated many results and released some new ones:

Latest oscillation results →

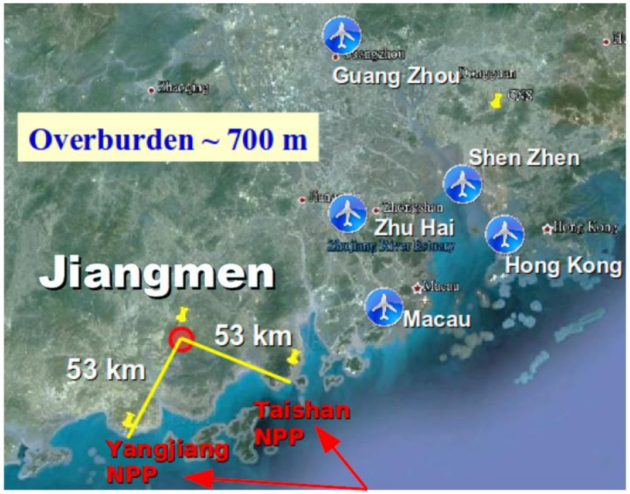
$$\sin^2 2\theta_{13} = 0.0856 \pm 0.0029$$

$$|\Delta m^2_{ee}| = (2.522^{+0.068}_{-0.070}) \times 10^{-3}\ \text{eV}^2$$

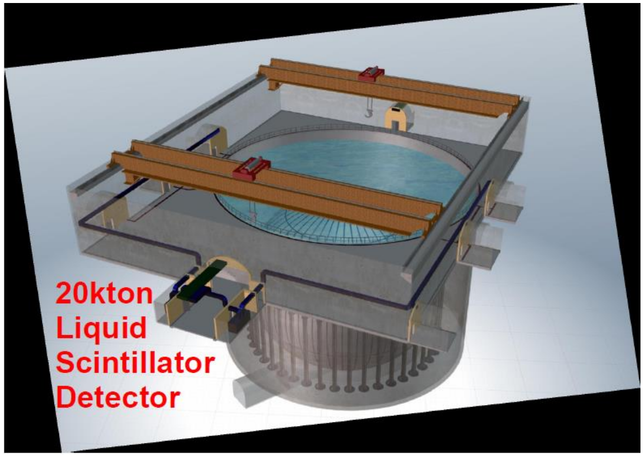
3.4%
2.8%

+ high-statistics absolute reactor antineutrino flux and shape measurements and evolution with fuel composition, searches for new physics, … etc.

- Daya Bay will run until 2020 and produce many other important results:
  - New oscillation measurement with **$\sin^2 2\theta_{13}$ uncertainty below 3%**
  - Results from campaign to study liquid scintillator recipes and purification methods with EH1-AD1, which was dedicated permanently to this purpose
  - Other measurements in preparation including:
    - New unfolded reactor antineutrino spectrum
    - Improved measurement of θ_{13} and Δm^2_{ee} via neutron capture on H
    - Search for ν signals coincident with gravitational wave events



High power nuclear power plants (26.6 GW total power)



Double Chooz : Summary

(@NUFACT2019)

- Three years of Double Chooz data with two detectors: 2015 – 2017
- Novel IBD selection : Total Neutron Capture (H+Gd+C)
  - Improved statistics
- Good background control (S/B > 10)
  - Background model confirmed with reactor off data
  - ~25 days reactor off data in the final dataset
- New result based on 15 month of data:

  $\sin^2 2\theta_{13} = 0.105 \pm 0.014$

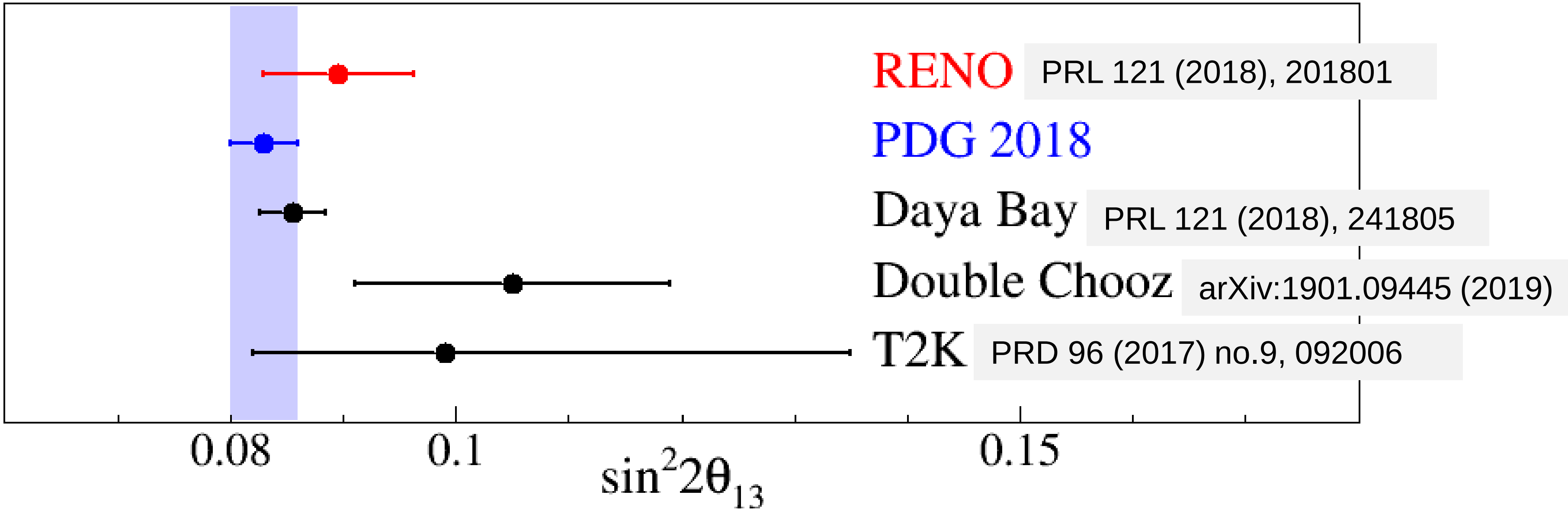
- Spectral distortion investigation
- Most precise mean cross section per fission results to date:

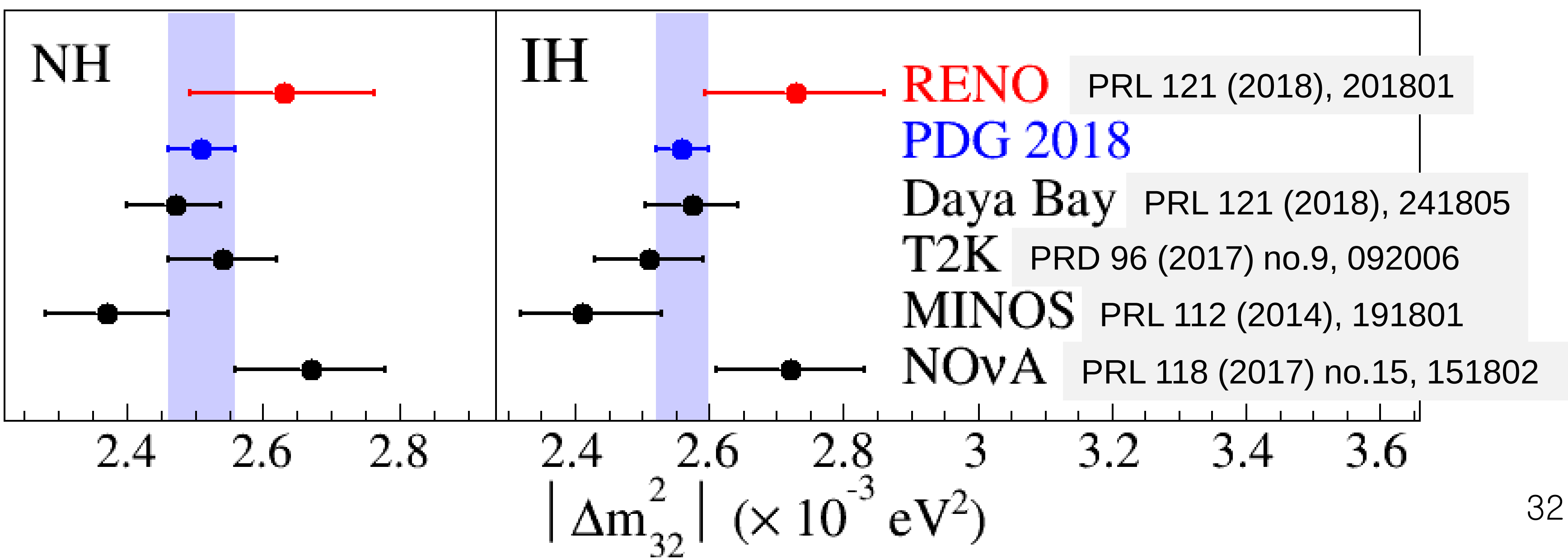
$$\langle \sigma_f \rangle = 5.71 \pm 0.06 \cdot 10^{-43}\, cm^2/\mathrm{fission}$$

- Double Chooz is unfortunately decommissioned
- Analyze the remaining data → increase statistics
- Improve systematics by proton number calibration during dismantling

See also:
arXiv:1901.09445 [hep-ex]

Comparison of θ_{13} and $|\Delta m^2_{ee}|$





Motivation for the study of fuel composition dependent reactor antineutrino yield

Reactor Antineutrino Anomaly

- ~6% deficit of measured reactor neutrino flux compared to the prediction with new predicted flux evaluation in 2011 by Huber and Mueller.
- Deficit of observed reactor neutrino fluxes relative to the prediction (Huber + Mueller model) indicates an overestimated flux or possible oscillation to sterile neutrinos.

The possibility that reactor anomaly is due to miscalculation of one or more of the ^{235}U, ^{239}Pu, ^{238}U and ^{241}Pu antineutrino fluxes is investigated by observing **fuel-composition dependent variation of reactor antineutrino yield and spectrum.**

C. Giunti, Phys. Lett. B 764, 145 (2017)

F. P. An et al. (Daya Bay Collaboration), PRL 118, 251801 (2017)

- **RENO Collaboration, Phys. Rev. Lett. 122, no.23, 232501 (2019)**

Evolution of Fuel Isotope Composition Fraction

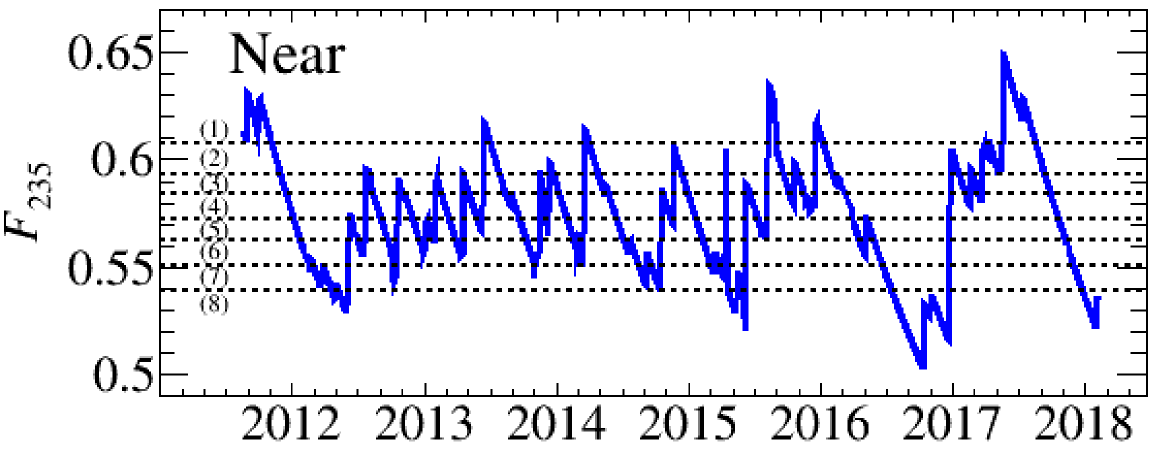
Average fission fraction f_{235}: f_{239}: f_{238}: f_{241}= 0.573 : 0.299 : 0.073 : 0.055

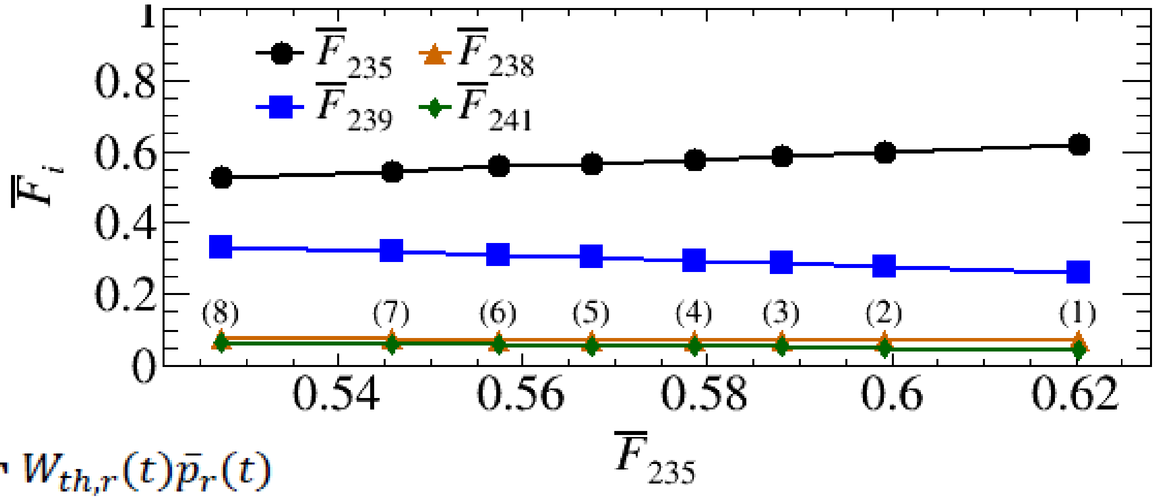
- Study on fuel dependent variation of reactor antineutrino yield and spectrum

- 8 groups of near IBD samples with different ^{235}U isotope fraction

Effective fission fraction for each isotope

Effective fission fraction of ^{235}U





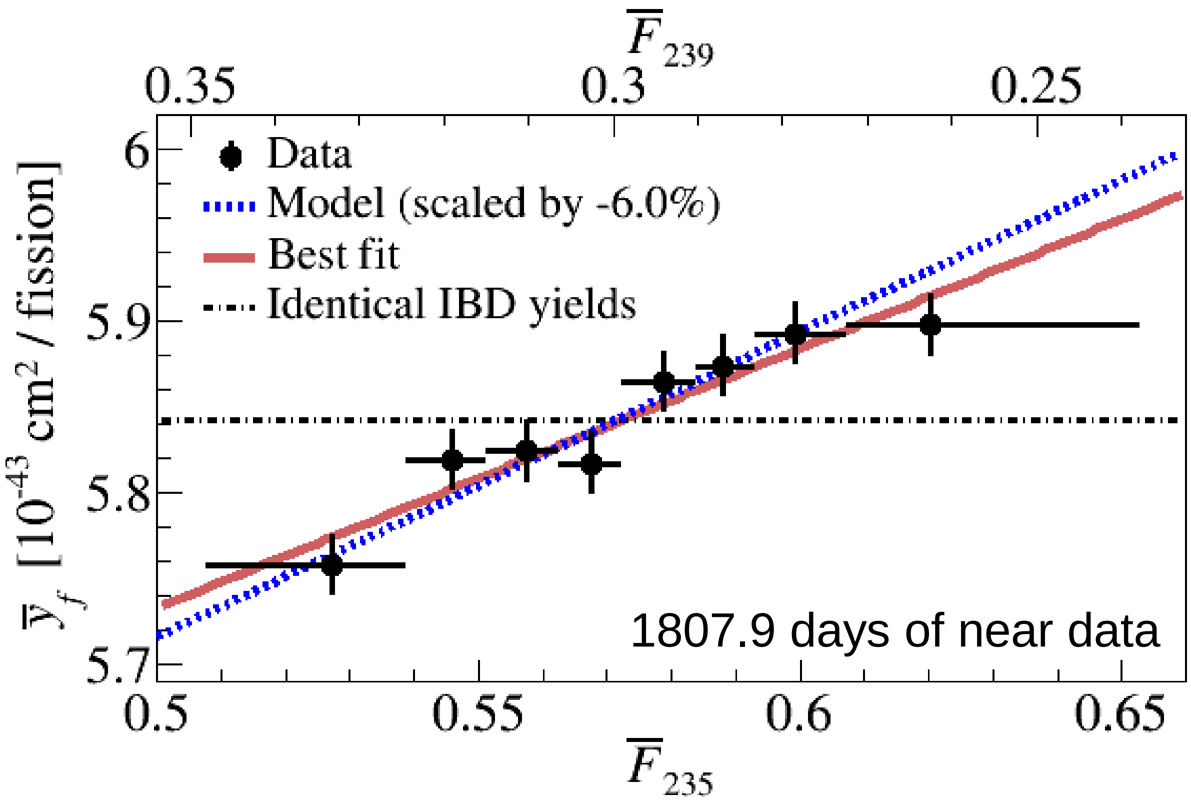
$$F_i(t) = \sum_{r=1}^{6} \frac{W_{th,r}(t)\bar{p}_r(t) f_{i,r}(t)}{L_r^2 \bar{E}_r(t)} \Bigg/ \sum_{r=1}^{6} \frac{W_{th,r}(t)\bar{p}_r(t)}{L_r^2 \bar{E}_r(t)}$$

Fuel-Composition Dependent Reactor Neutrino Yield

→ Dependence of IBD yield per fission on the isotope fraction of ^{235}U

Measured total averaged IBD yield per fission ($\bar{y}_f$)
= $(5.84 \pm 0.13) \times 10^{-43}$ cm²/fission

Ratio (Data /H-M model) for the total average IBD yield
= 0.940 ± 0.021 → (6.0 ± 2.1)% deficit



Averaged IBD yield per fission ($\bar{y}_f$) vs $\bar{F}_{i,j}$
→ slope means **different neutrino yield** for each isotope
→ rules out the no fuel-dependent variation at **6.6σ**

The scaled model indicates the **reactor antineutrino anomaly**

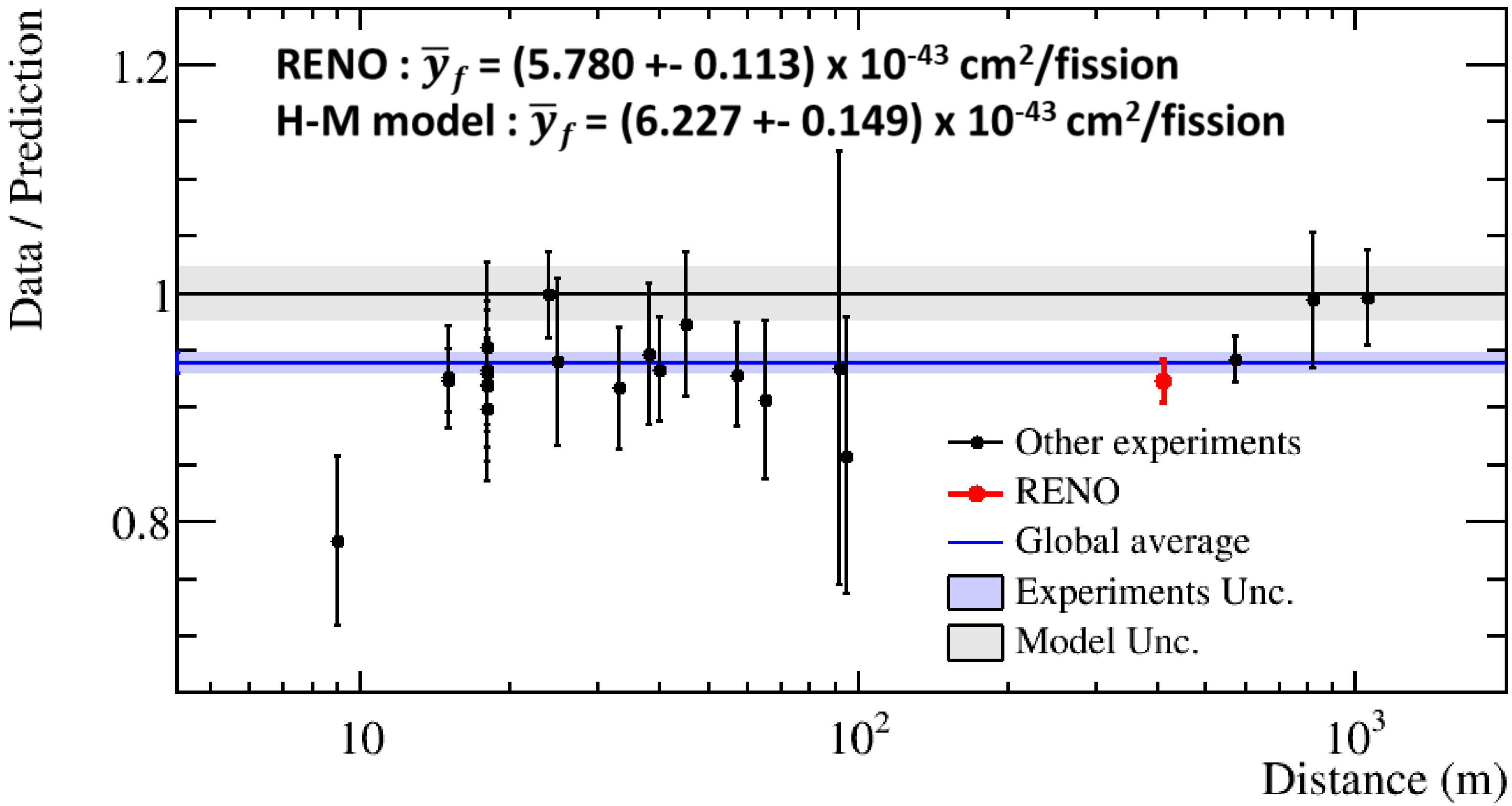
→ Observed data ruled out no fuel-dependent variation of IBD yield/fission

Measurement of Absolute Reactor Neutrino Flux

Cross section calculation

- Vogel 84 formalism
- $\tau_n = 880.2s$ (PDG2017)

Data / Prediction, RENO 2200 days at near detector
0.924 +- 0.018 (for Huber + Mueller model) 0.966 +- 0.019 (for ILL + Vogel model)

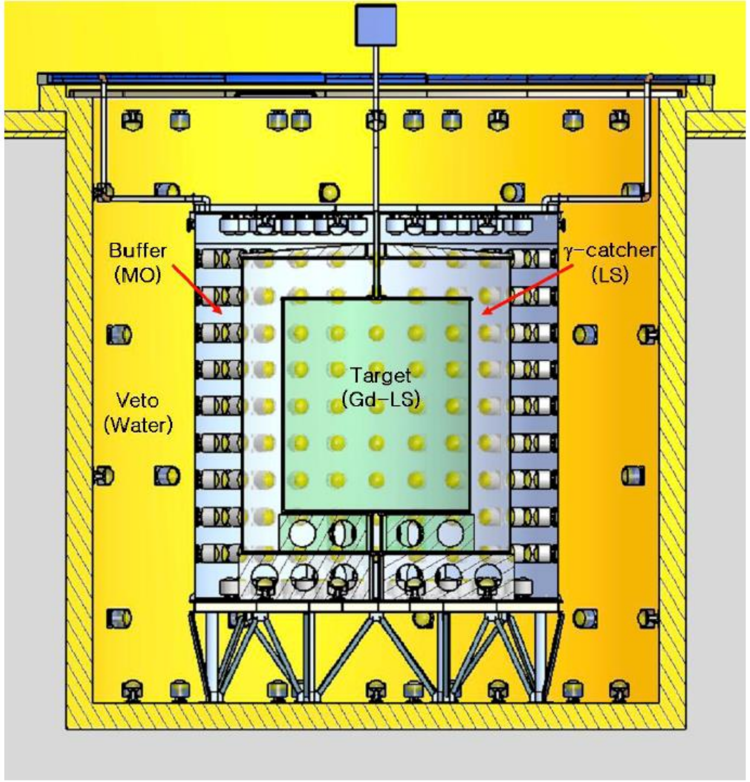


Deficit of observed reactor neutrino fluxes relative to the prediction (Huber + Mueller model) indicates an overestimated flux or possible oscillation to sterile neutrinos

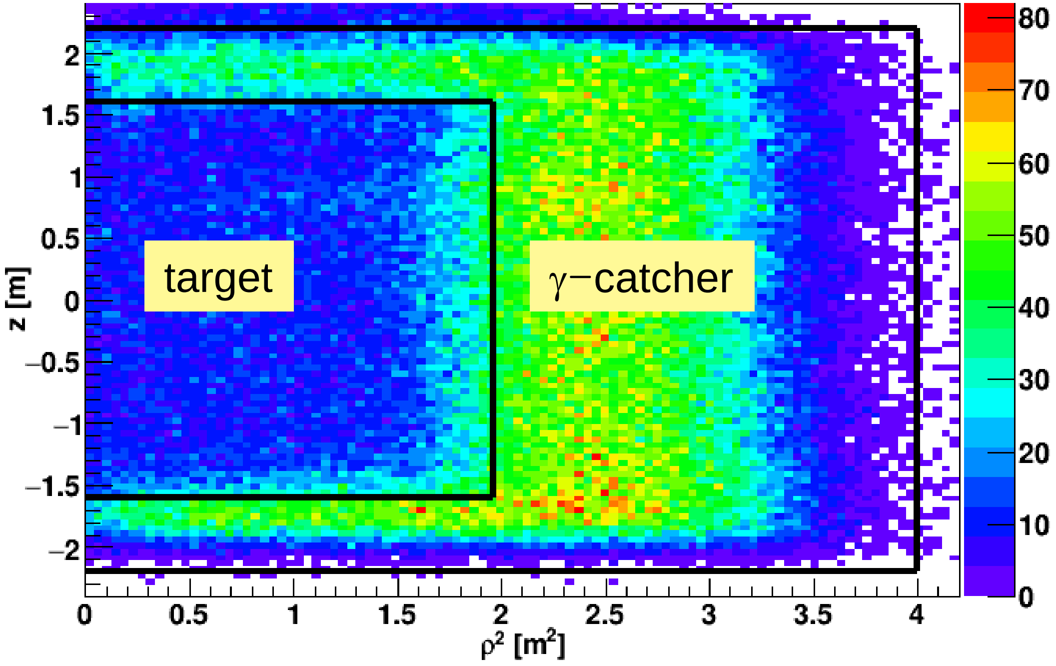
n-H IBD Analysis

Motivation:

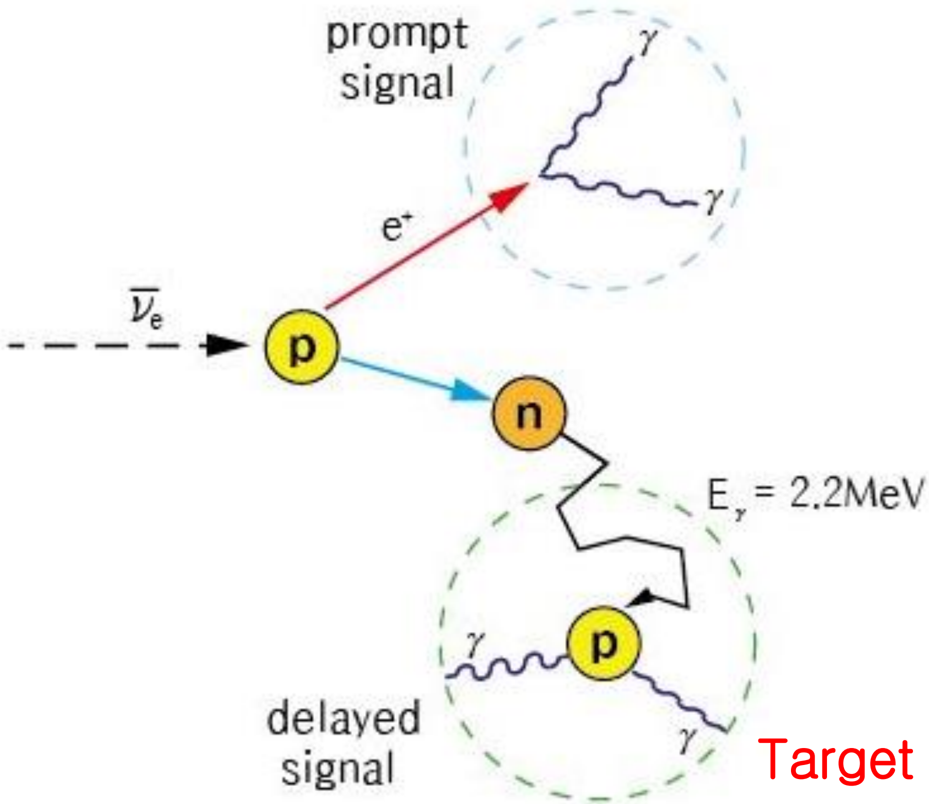
1. Independent measurement of θ_{13} and $|\Delta m_{ee}^2|$ value
2. Consistent check on θ_{13} result from with n-Gd
3. Consistency and systematic check on reactor neutrinos



n-H IBD Event Vertex Distribution



Detection Principle of Reactor Neutrinos (n-H)



Inverse Beta Decay

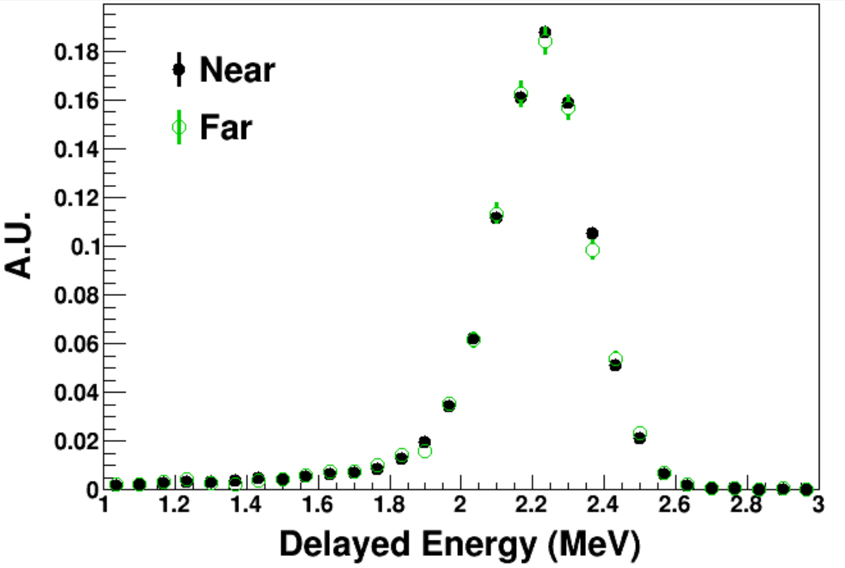
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

H capture	or	Gd capture
Delayed signal		Delayed signal
~200 μs		~30 μs
~ 2.2 MeV		~ 8 MeV
Target + Gamma catcher		Target only

- 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** or **H**
  ~30 μs for n-Gd , ~200 μs for n-H

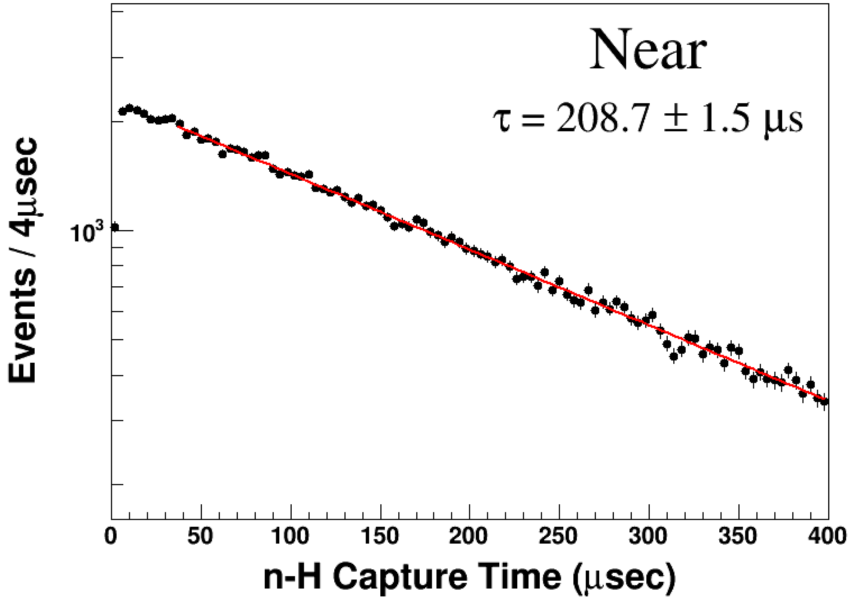
Delayed spectrum and capture time

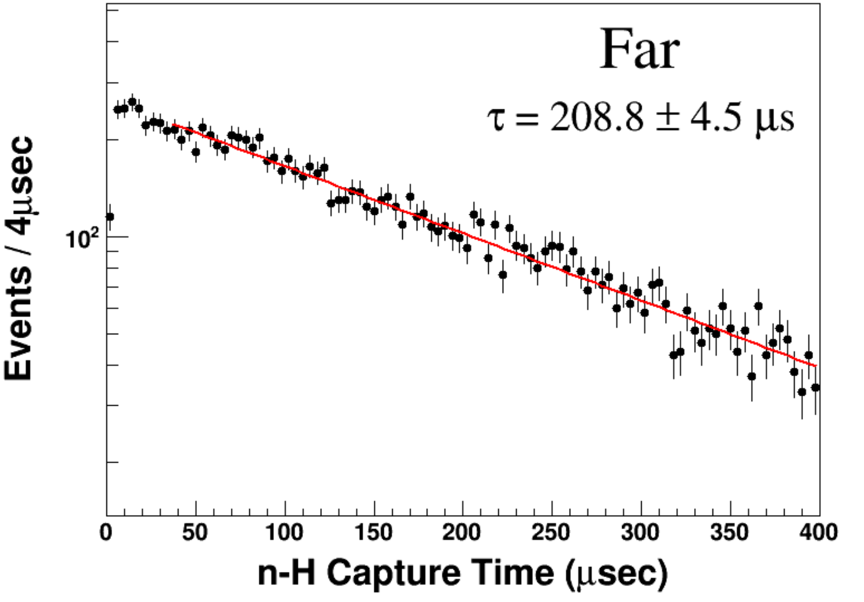
- Delayed signal peak:
  ~2.2 MeV
- Mean coincidence time:
  ~ 200 μs



Capture time (n-H)

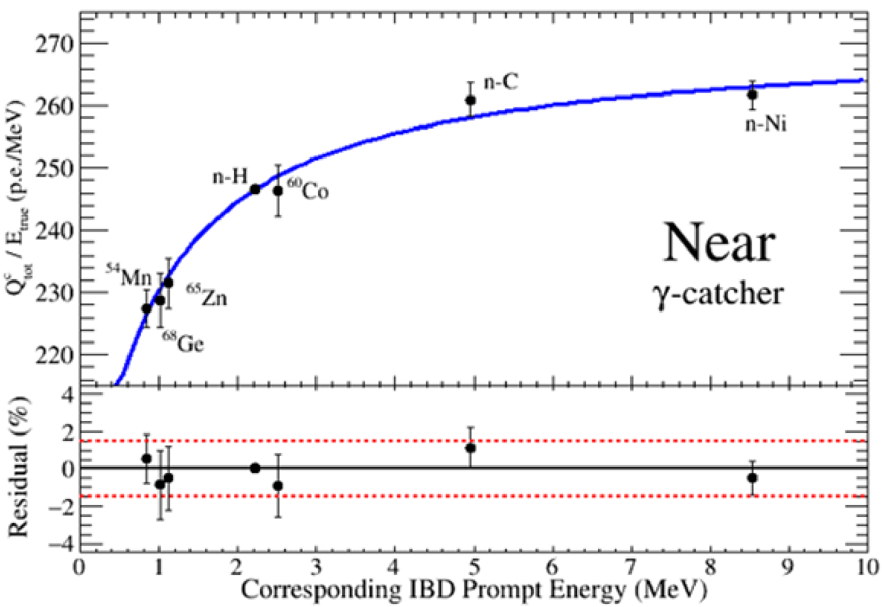
Far and near data match very well

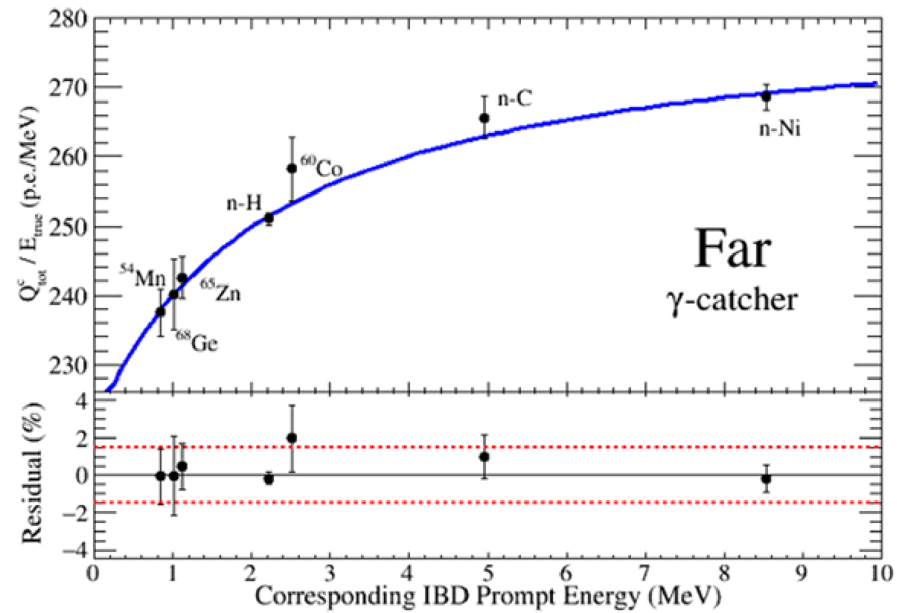




Energy Calibration from γ-ray Sources

- Non-linear resonse of the scintillation energy is calibrated using γ-ray source



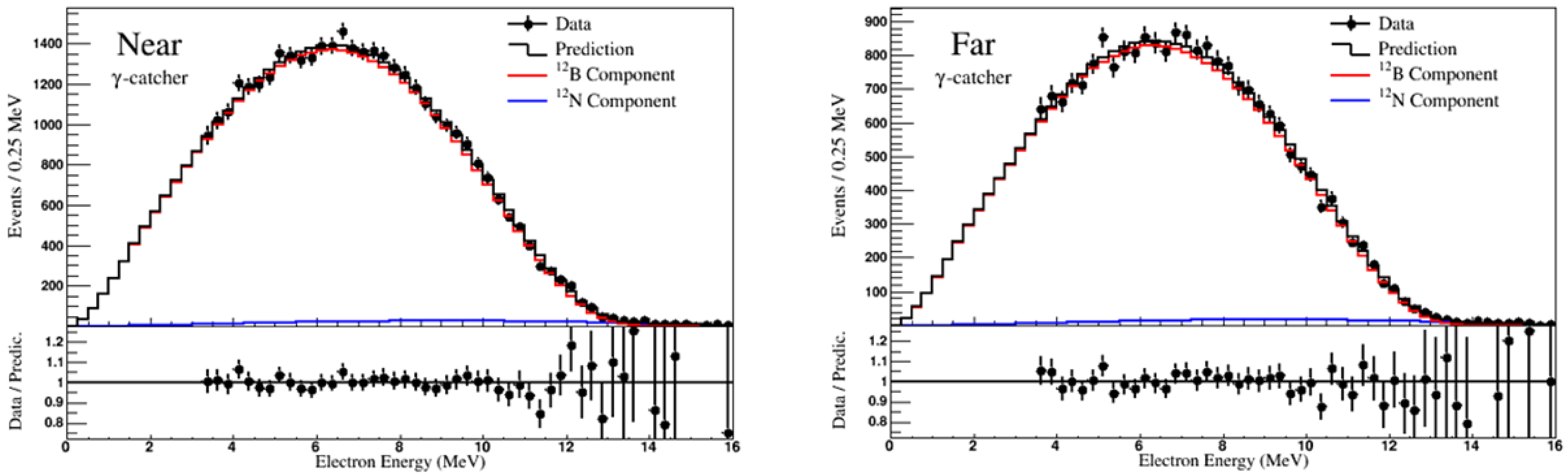


Fit function : $E_{vis}/E_{true} = a - b/(1 - \exp(-cE_{true} - d))$

- 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



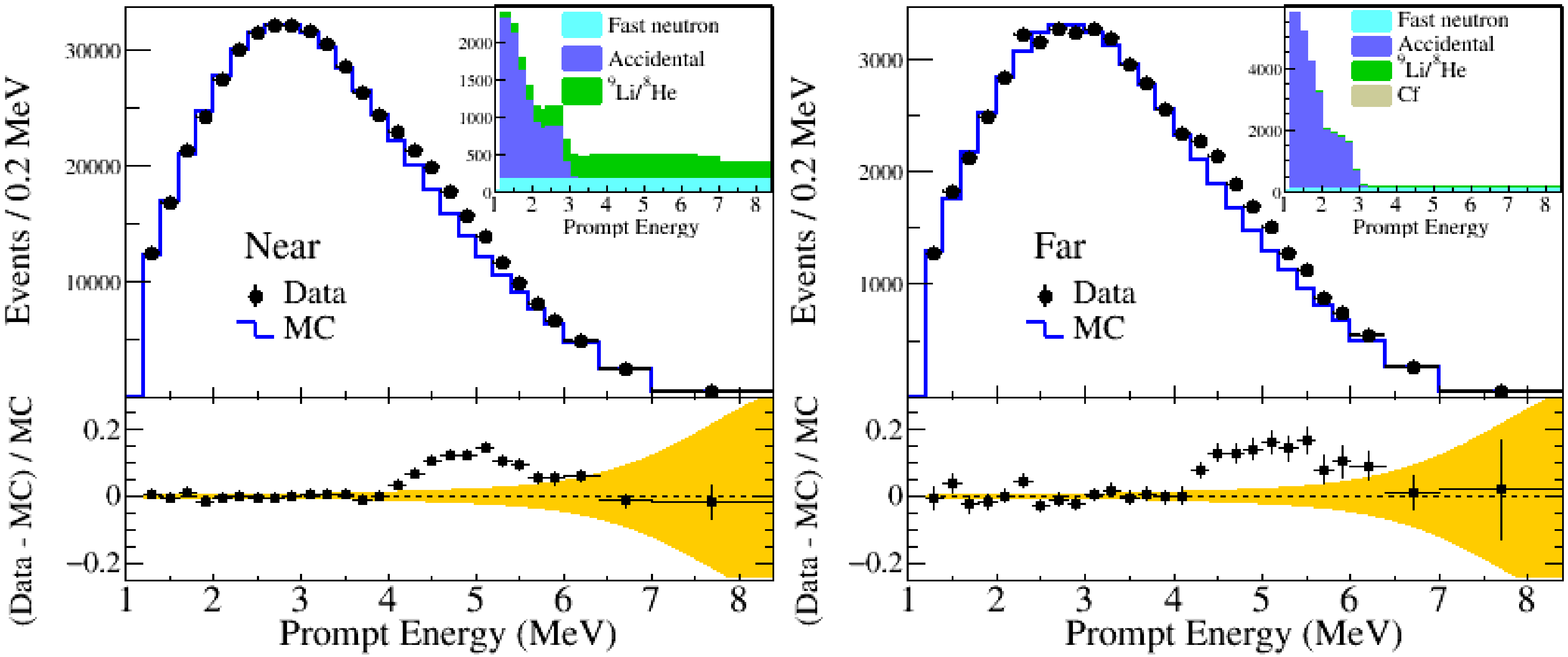
- Good agreement between data and MC spectrum!

- One of examples to show how RENO MC well tuned and works fine

θ_{13} Measurement with n-H

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

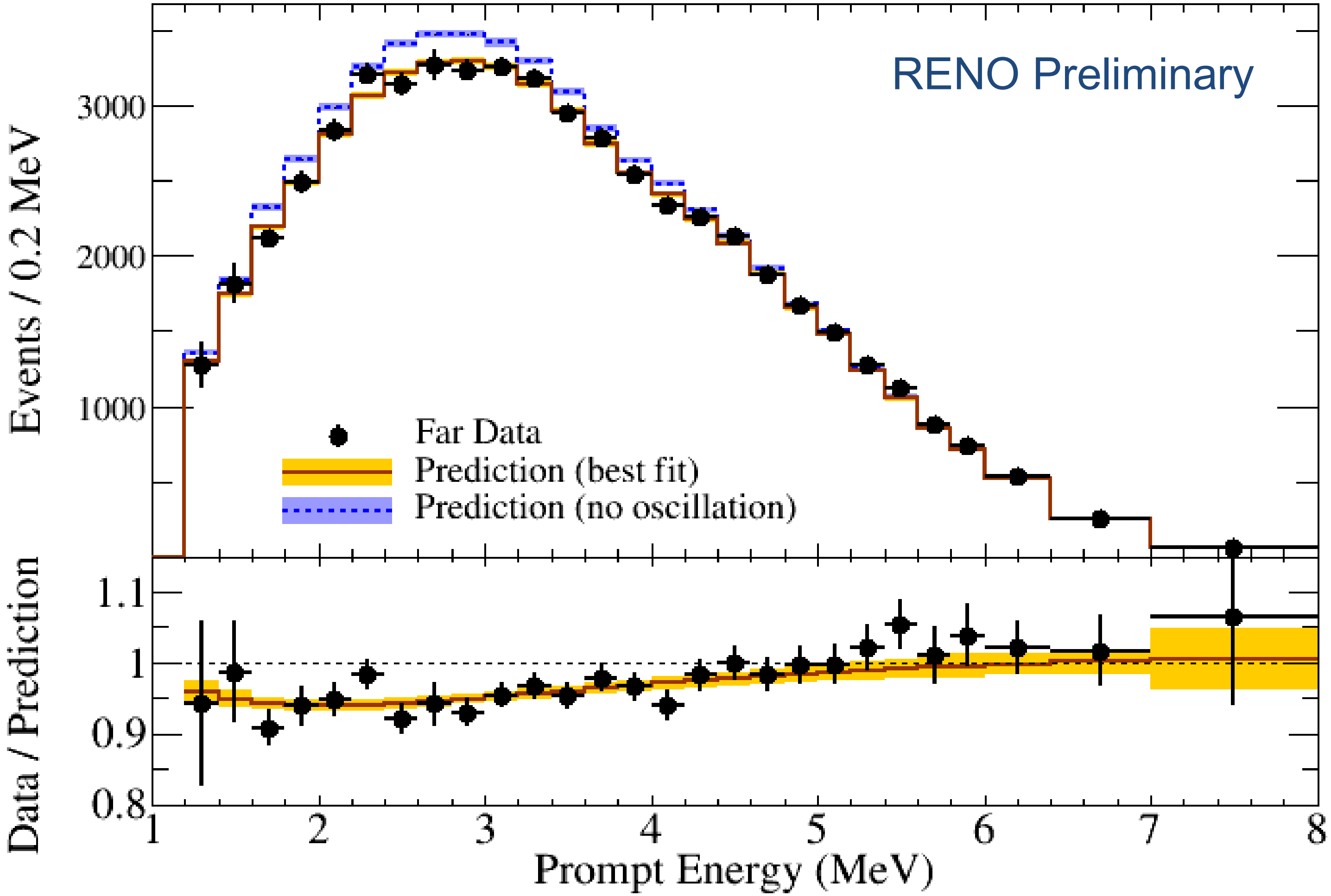
Preliminary rate only analysis results is



$$\sin^2 2\theta_{13} = 0.085 \pm 0.008(\text{stat.}) \pm 0.012(\text{syst.})$$

- Paper is preparing & will be submitted soon

θ_{13} and $|\Delta m^2_{ee}|$ Measurement with n-H



$$\sin^2 2\theta_{13} = 0.094^{+0.012}_{-0.010}(\text{stat}) \pm 0.009(\text{syst})$$

$$|\Delta m^2_{ee}| = 2.53^{+0.25}_{-0.28}(\text{stat.})^{+0.13}_{-0.16}(\text{syst.})\ (\times 10^{-3}\text{eV}^2)$$

Summary

- Observation of energy dependent disappearance of reactor neutrinos and improved measurement of and $|\Delta m_{ee}^2|$ and θ_{13}

$$\sin^2 2\theta_{13} = 0.0896 \pm 0.0048(\text{stat}) \pm 0.0048(\text{syst})$$ ± 0.0068 | 7.6 % precision

$$\left|\Delta m_{ee}^2\right| = 2.68 \pm 0.12(\text{stat}) \pm 0.07(\text{syst}) \ (\times 10^{-3}\,\text{eV}^2)$$ ± 0.14 | 5.2 % precision

- First hint for correlation between 5 MeV excess and ^{235}U fission fraction

- Measured absolute reactor neutrino flux : R= 0.918±0.018 (H-M)

- Measurement of $|\Delta m_{ee}^2|$ and θ_{13} using n-H IBD analysis

- Additional 2~3 years of data taking under consideration to improve Δm_{ee}^2 accuracy and the fuel dependent IBD yield.