Anomaly of Dancing Reactor Antineutrino

Sep. 18th, 2018

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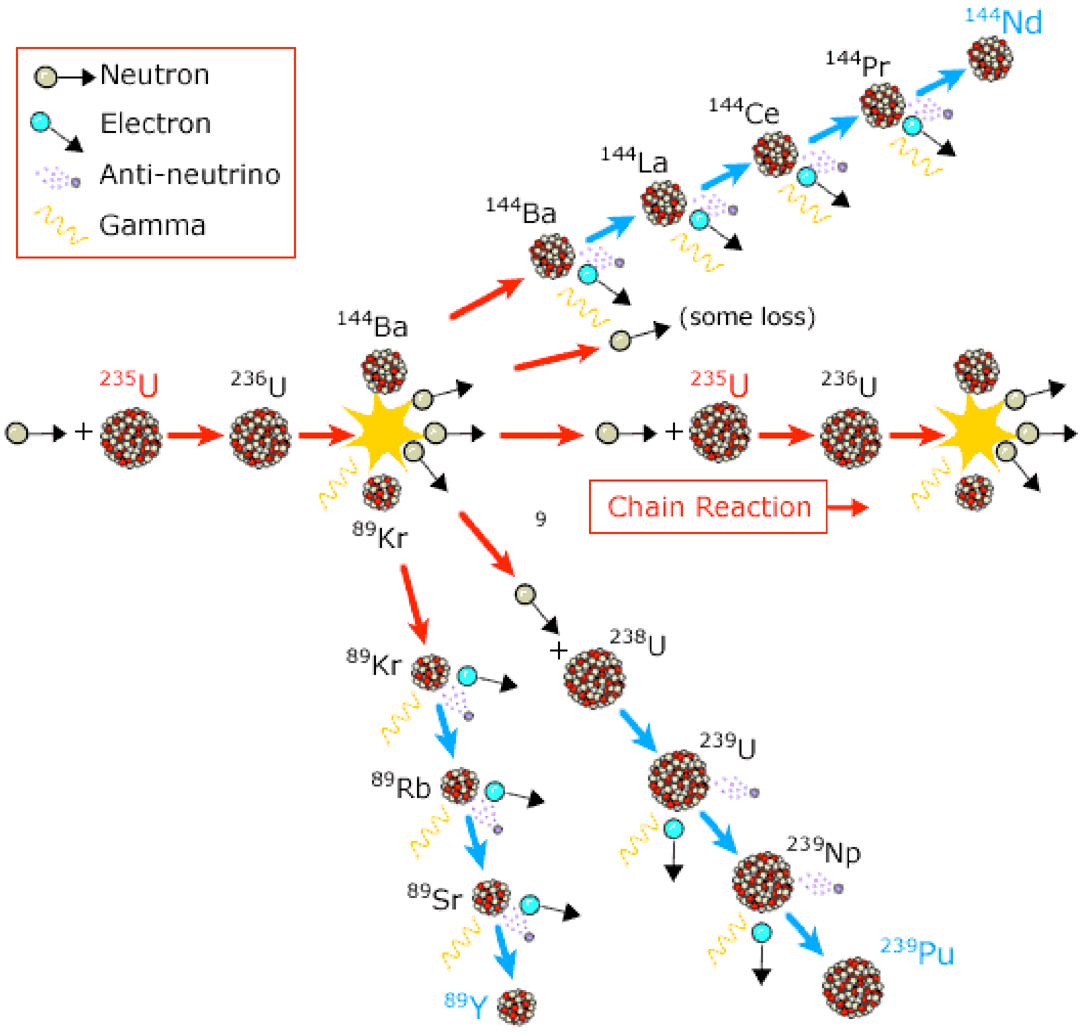
Nuclear Fission Products

Electron Antineutrino are produced from β-decay of reactor fuels;
Mainly ^{235}U, ^{238}U, ^{239}Pu and ^{241}Pu



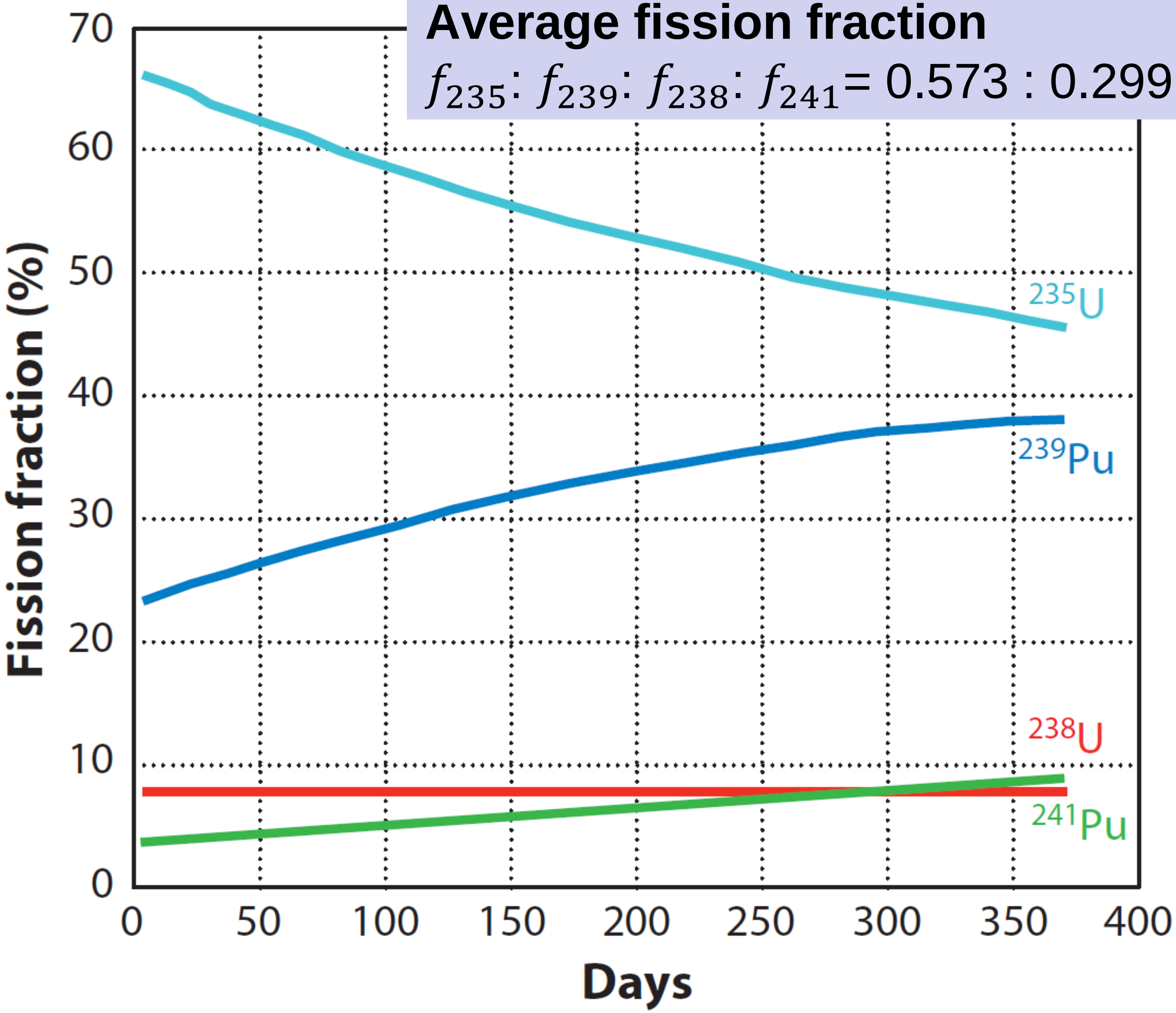
~ 200 MeV/fission
~ 6 $\bar{\nu}_e$/fission

1 GW$_{th}$ reactor
→ ~2x10^{20} $\bar{\nu}_e$/sec

Reactor Fuel Isotope Fraction

Average fission fraction

$f_{235}: f_{239}: f_{238}: f_{241}$= 0.573 : 0.299 : 0.073 : 0.055

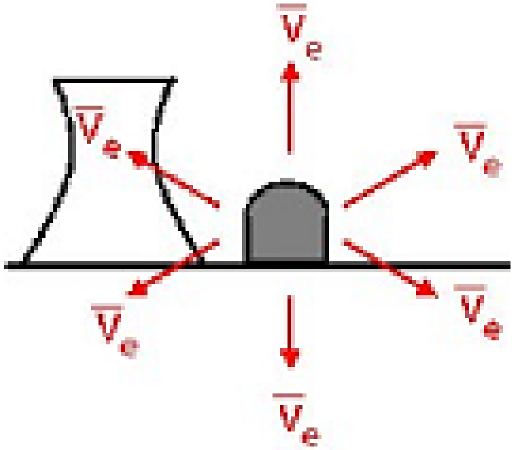


The **Fission fraction** of an isotope varies with **fuel-burning**

Reactor for Antineutrino Source

Reactor: A copious and isotropic source of electron antineutrinos

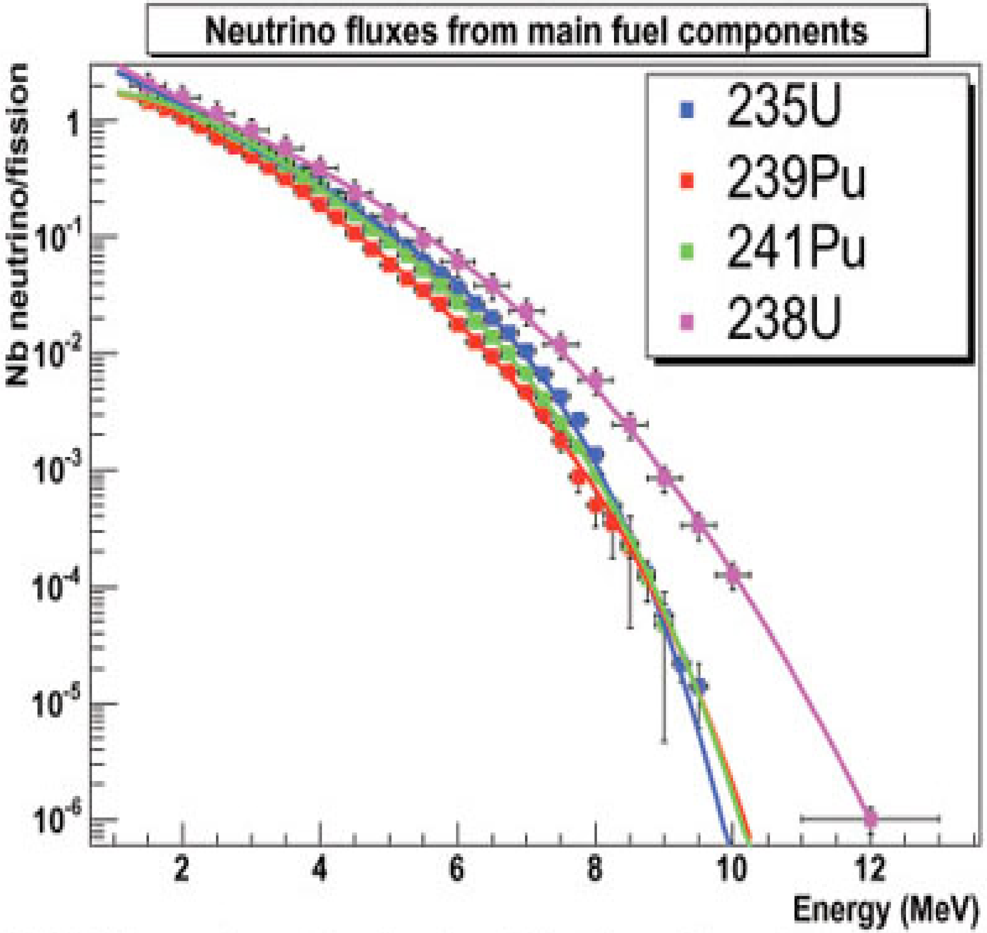
~3 GW_{th} or ~1 GW_{elec} per reactor



3 GW_{th} reactor

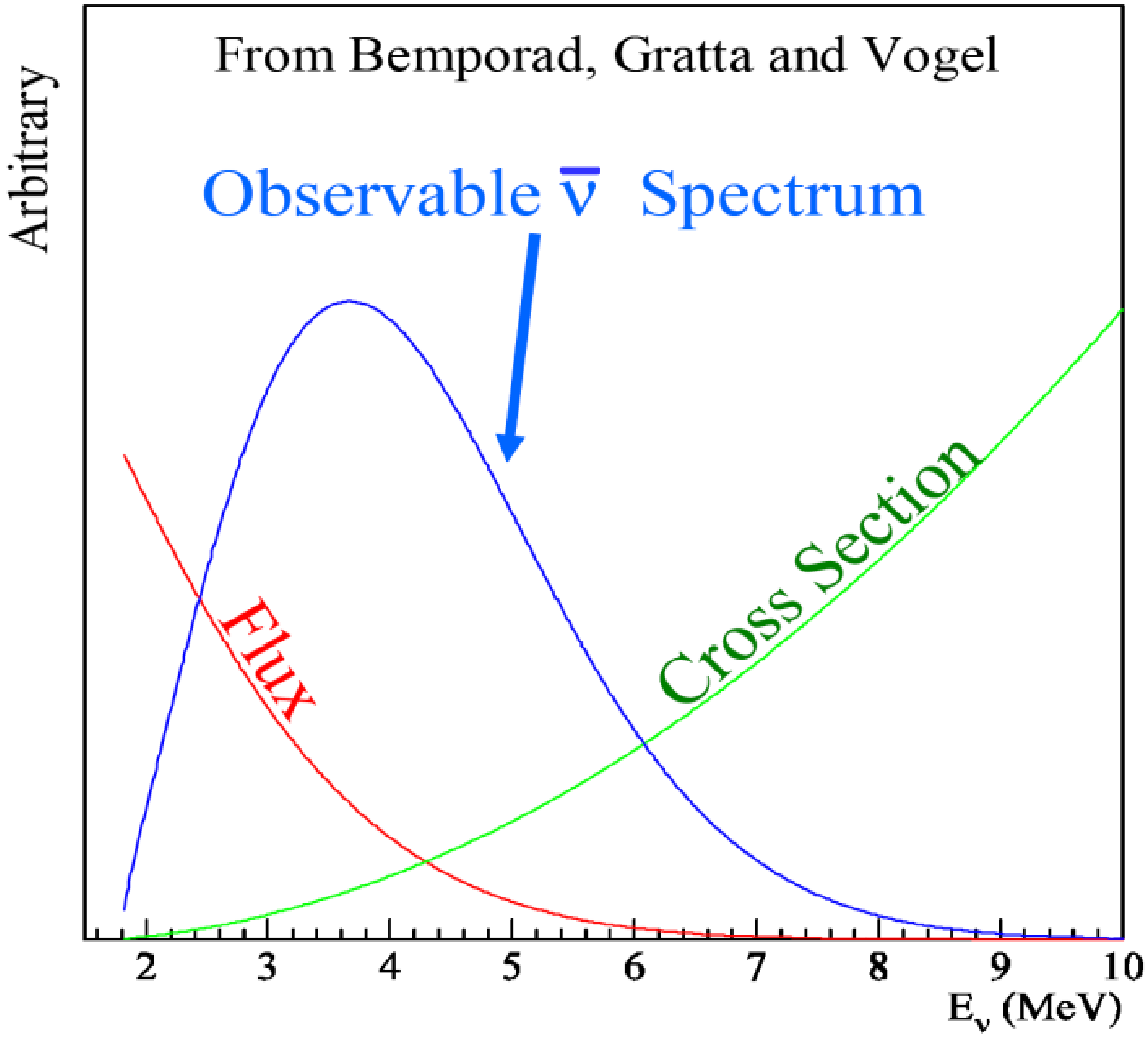
→ ~$6x10^{20}$ $\bar{\nu}_e$/sec

- 3-4% accurate neutrino source
- 0.13% uncertainty of IBD cross section



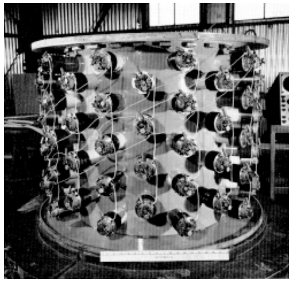
[* P. Huber, Phys. Rev. C84, 024617 (2011)
T. Mueller *et al*., Phys. Rev. C83, 054615 (2011)]

Observable Reactor Neutrino Spectrum



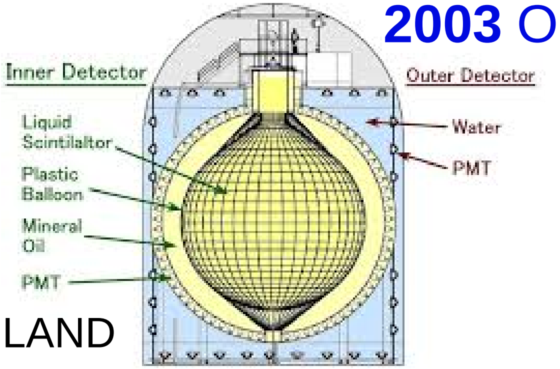
Neutrino Physics with Reactor

1956 Discovery of (anti)neutrino

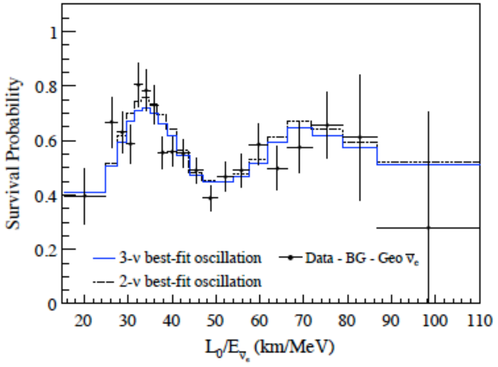


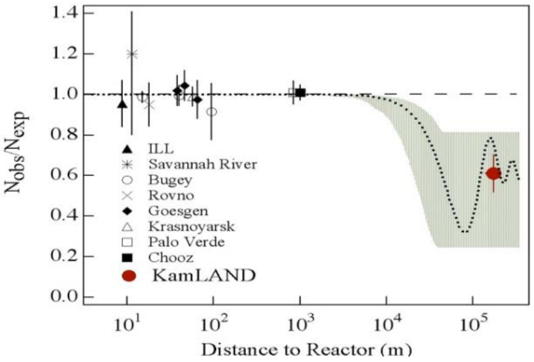
Nobel Prize in 1995

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

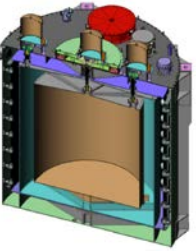


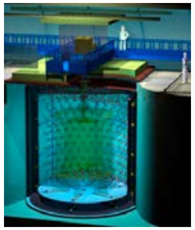
KamLAND

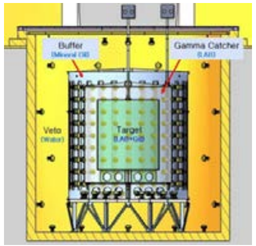


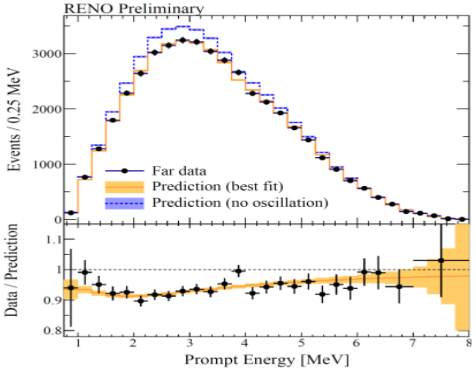


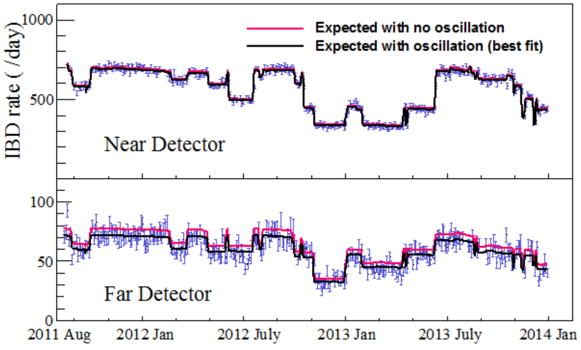
2012 Measurement of the smallest mixing angle θ_{13}











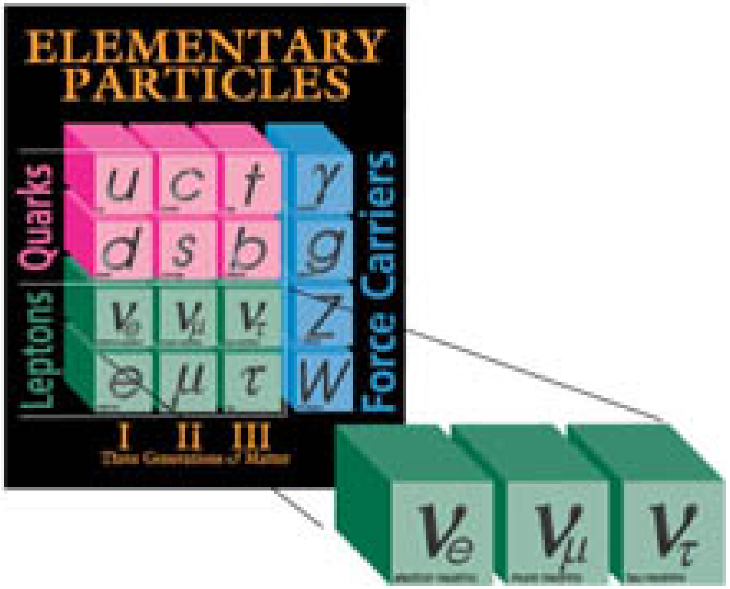
Neutrino Oscillation

Wolfgang Pauli
(1900 - 1958)
Invention of neutrino

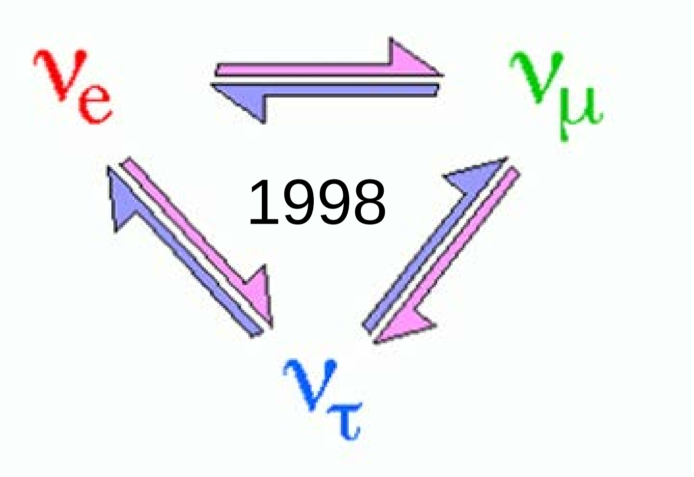
Frederick Reines
(1918 - 1998)
Detection of neutrino

Бруно Понтекорво

Bruno Pontecorvo
(1913 - 1993)
Invention of neutrino oscillation



Neutrino oscillation



Neutrino Mixing Angles

Atmospheric Neutrino Oscillation

θ_{23}

~45° (1998)

Super-K; K2K

Solar Neutrino Oscillation

θ_{12}

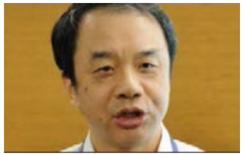
34° (2001)

SNO, Super-K;
KamLAND

2015
Nobel
Prize

Reactor Neutrino Oscillation

θ_{13}



9° (2012)

Daya Bay, RENO
Double Chooz
+ **T2K (2011)**

2017
Pontecorvo
Prize

"Neutrino has mass"

"Established three-flavor mixing framework"

Impact of θ_{13} Measurement

- Definitive measurement of the last, smallest neutrino mixing angle θ_{13} based on the disappearance of reactor electron antineutrinos

→ Open a new window for determining

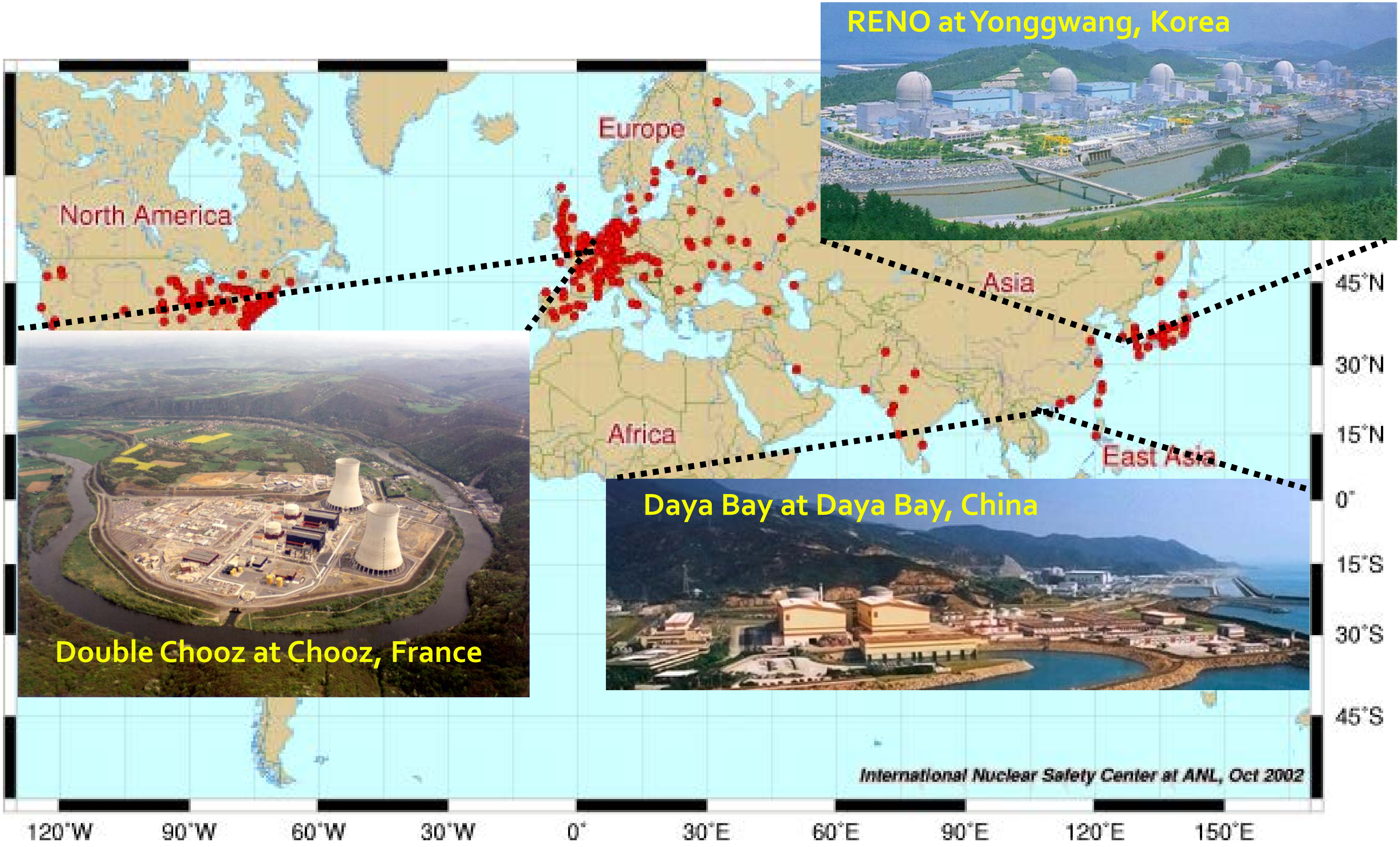
(1) CP violating phase, and

(2) neutrino mass ordering

without a neutrino factory

For example, Hyper-Kamiokande(+ KNO), DUNE, JUNO, PINGU, INO, …..

Reactor θ_{13} Experiments



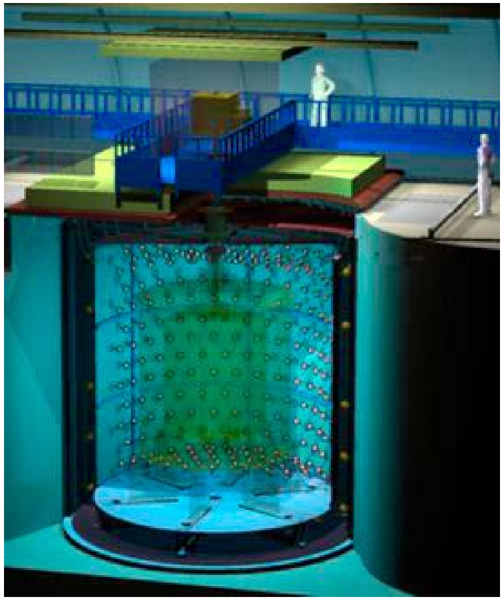
RENO at Yonggwang, Korea

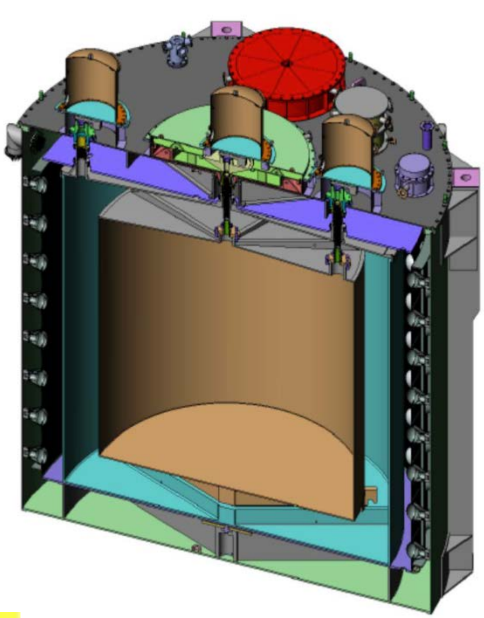
Double Chooz at Chooz, France

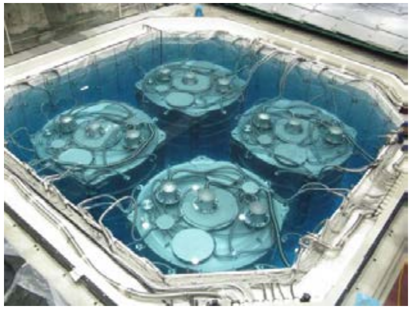
Daya Bay at Daya Bay, China

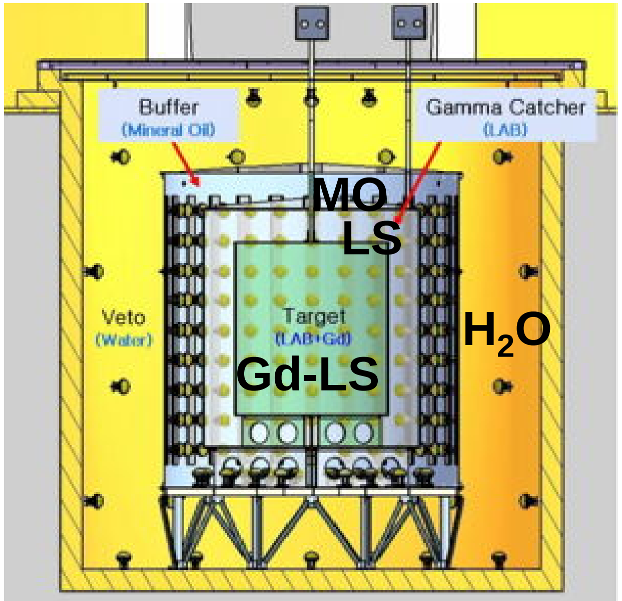
International Nuclear Safety Center at ANL, Oct 2002

θ_{13} Reactor Neutrino Detectors



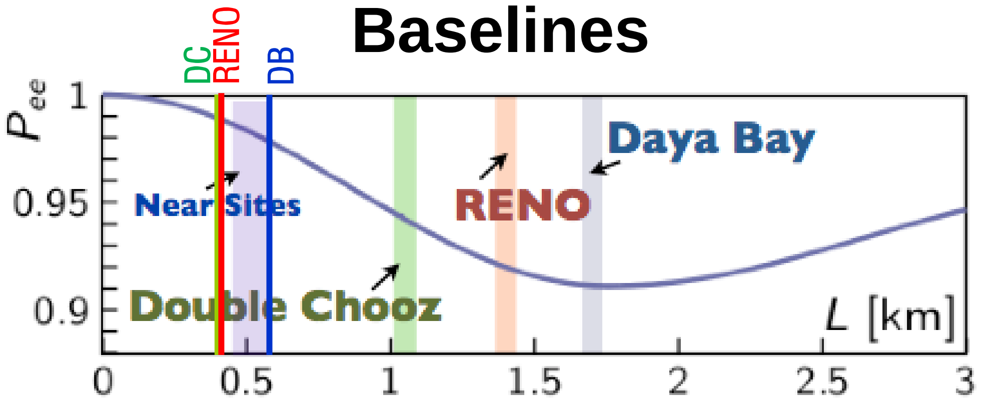




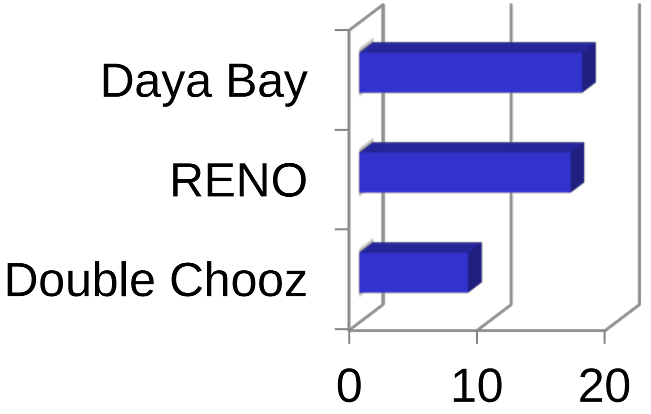


Comparisons of Reactor θ_{13} Experiments

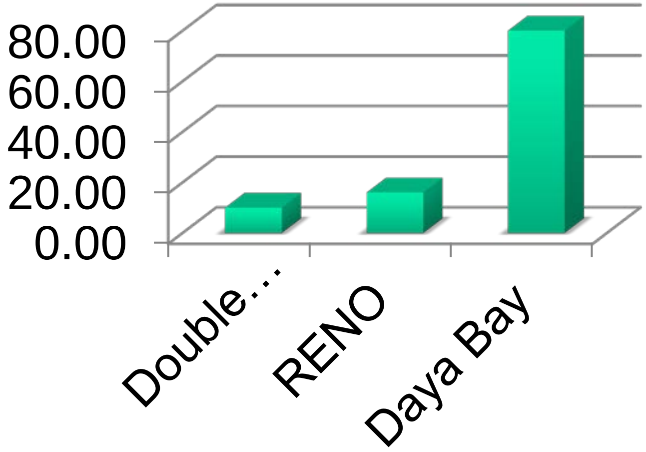
Baselines



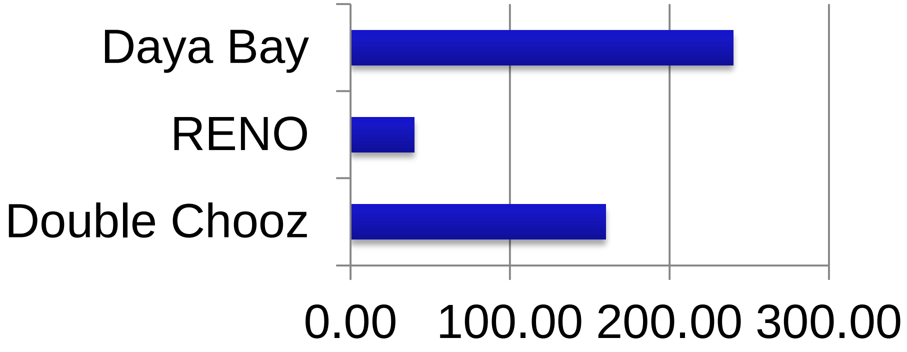
Reactor Thermal Power (GW$_{th}$)



Target (ton)



Manpower



RENO Collaboration

Reactor Experiment for Neutrino Oscillation

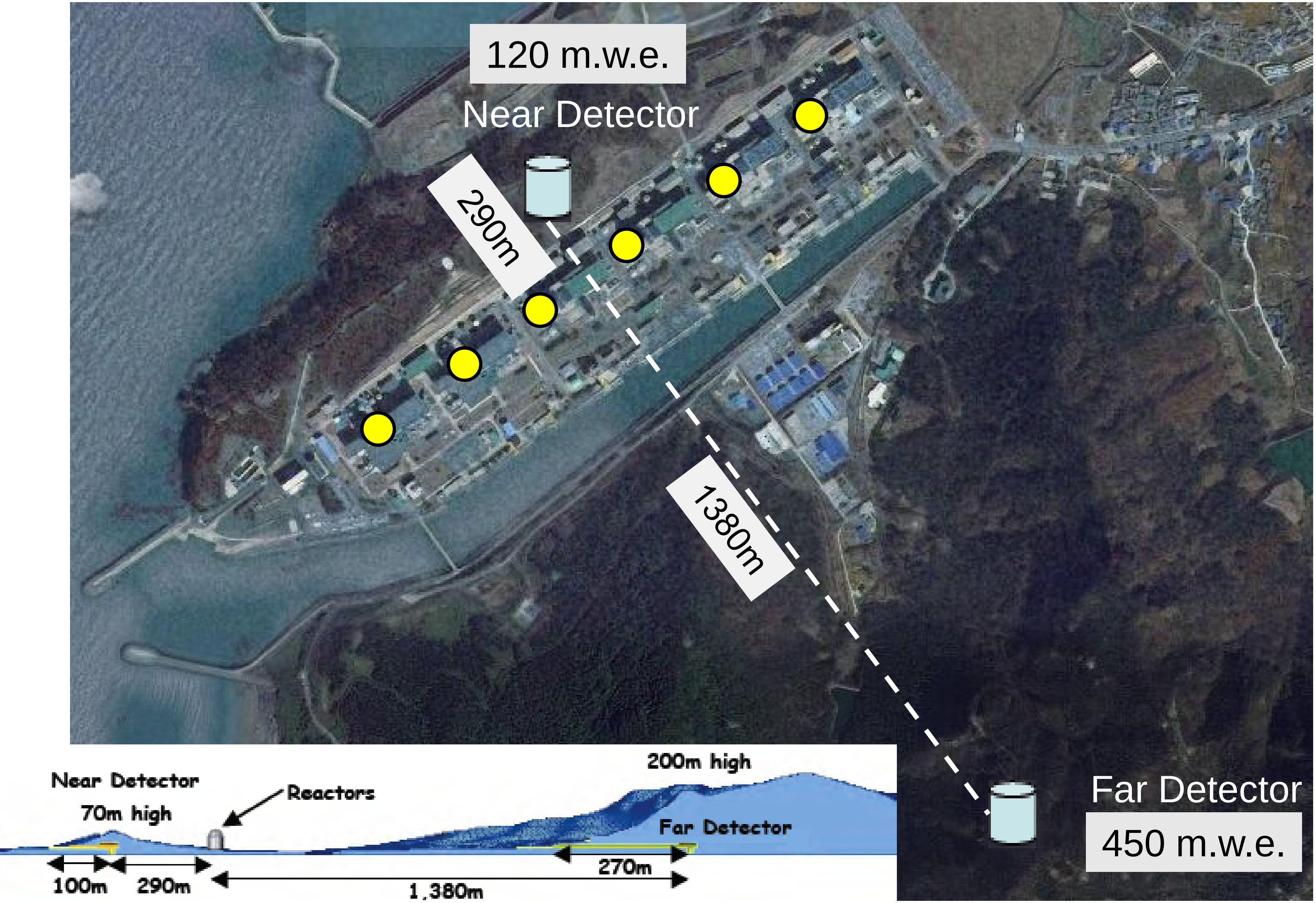
(7 institutions and 40 physicists)

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

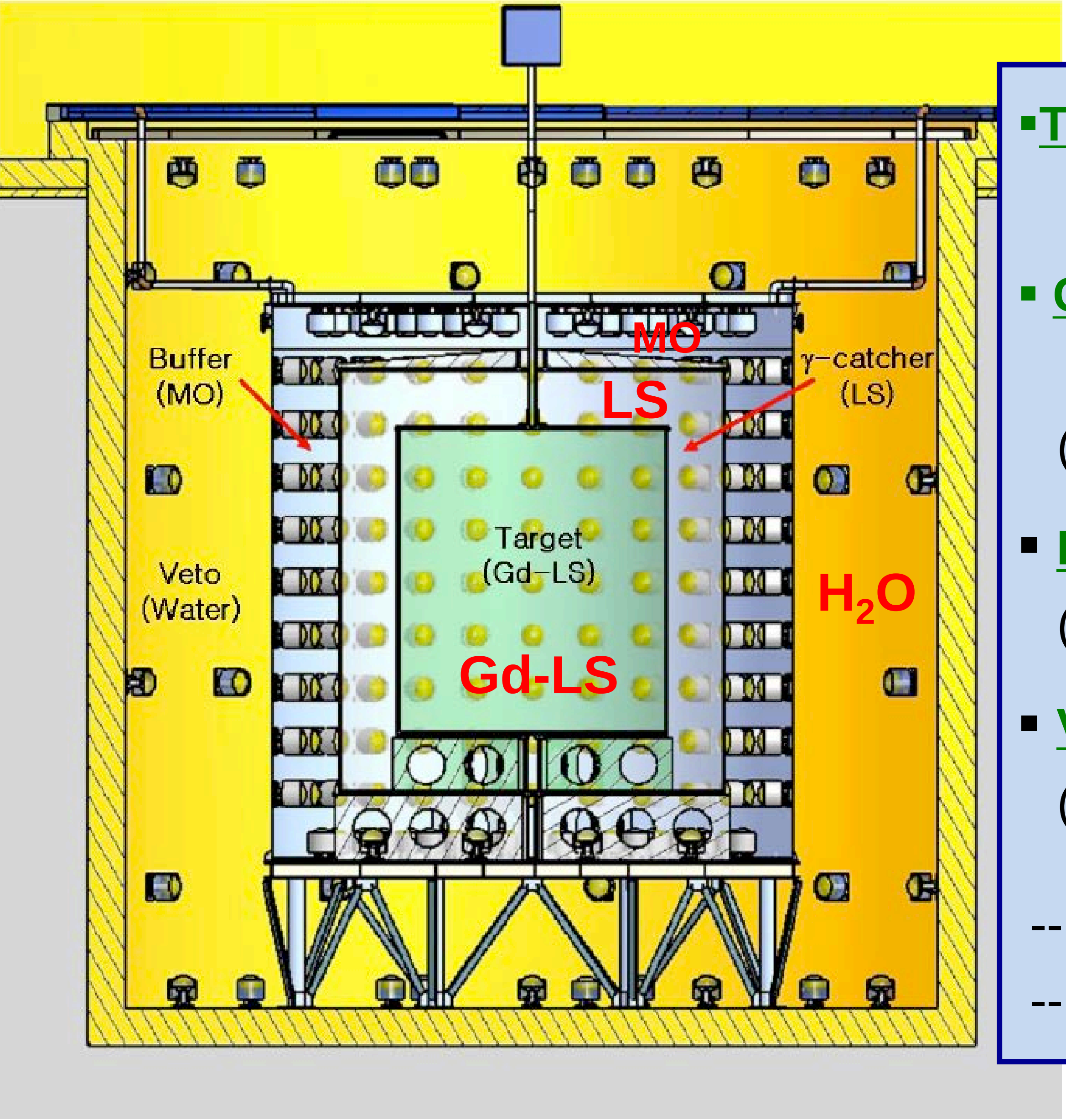
- Total cost : $10M
- Start of project : 2006
- The first experiment running with both near & far detectors from Aug. 2011

YongGwang (靈光) :

RENO Experimental Set-up



The RENO Detector



- **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)

-- 354 ID 10 “ PMTs

-- 67 OD 10” PMTs

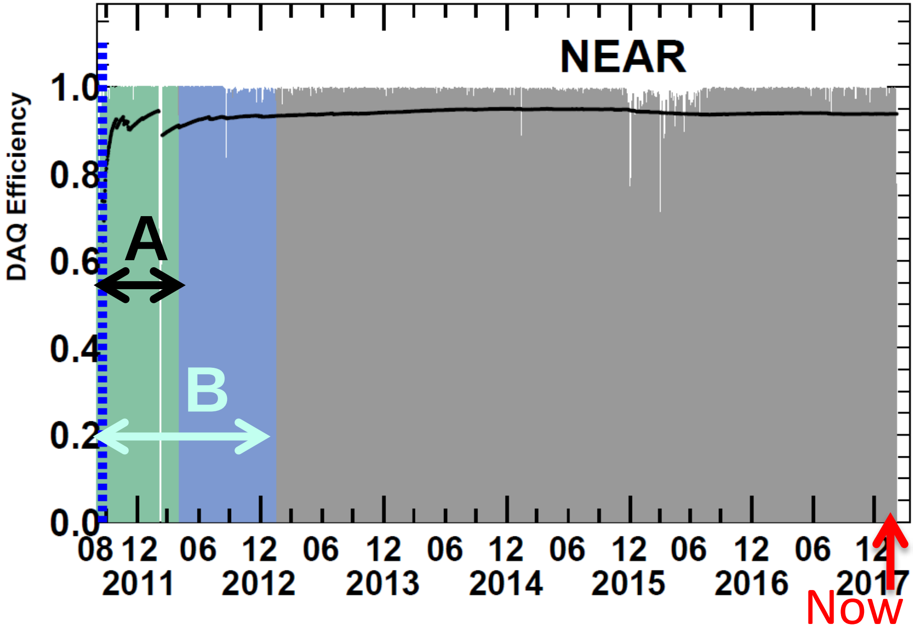
RENO Data-taking Status

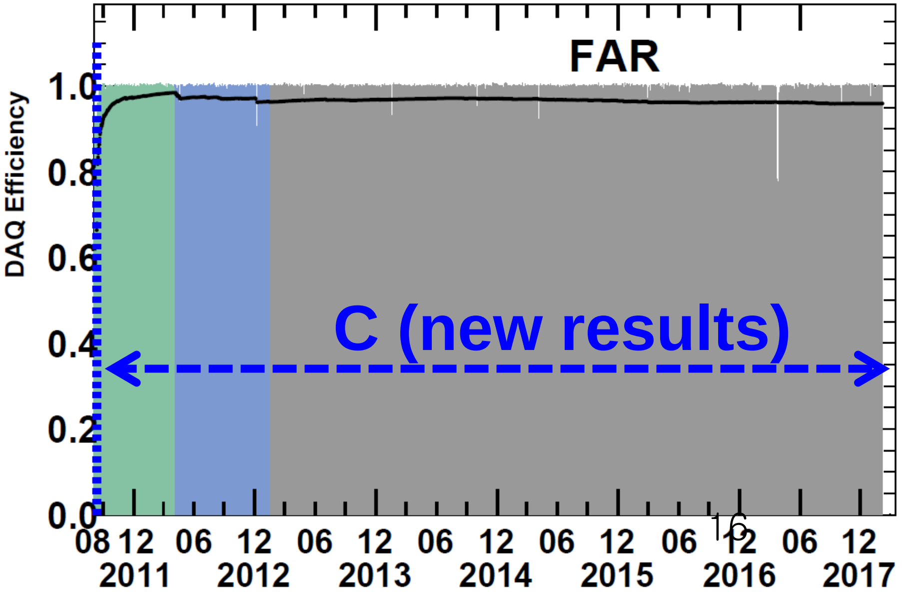
- Data taking began on Aug. 1, 2011 with both near and far detectors.
  (DAQ efficiency : ~95%)

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

- **B (~500 days)** : **Recent results**
  Rate+shape analysis (θ_{13} and $|\Delta m_{ee}^2|$)
  5 MeV excess
  [11 Aug, 2011~21 Jan, 2013]
  → PRL 116, 211801 (2016)
  PRD 98, 012002 (2018)

- **C (~2200 days)** : **New results**
  Rate+shape analysis (θ_{13} and $|\Delta m_{ee}^2|$)
  Variation of reactor neutrino yield
  5 MeV excess from ^{235}U
  [11 Aug, 2011~7 Feb, 2018]
  → (arXiv:1806.00248 & arXiv:1806.00574)





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” (arXiv:1806.00248)

- Fuel-composition dependent reactor antineutrino yield and spectrum

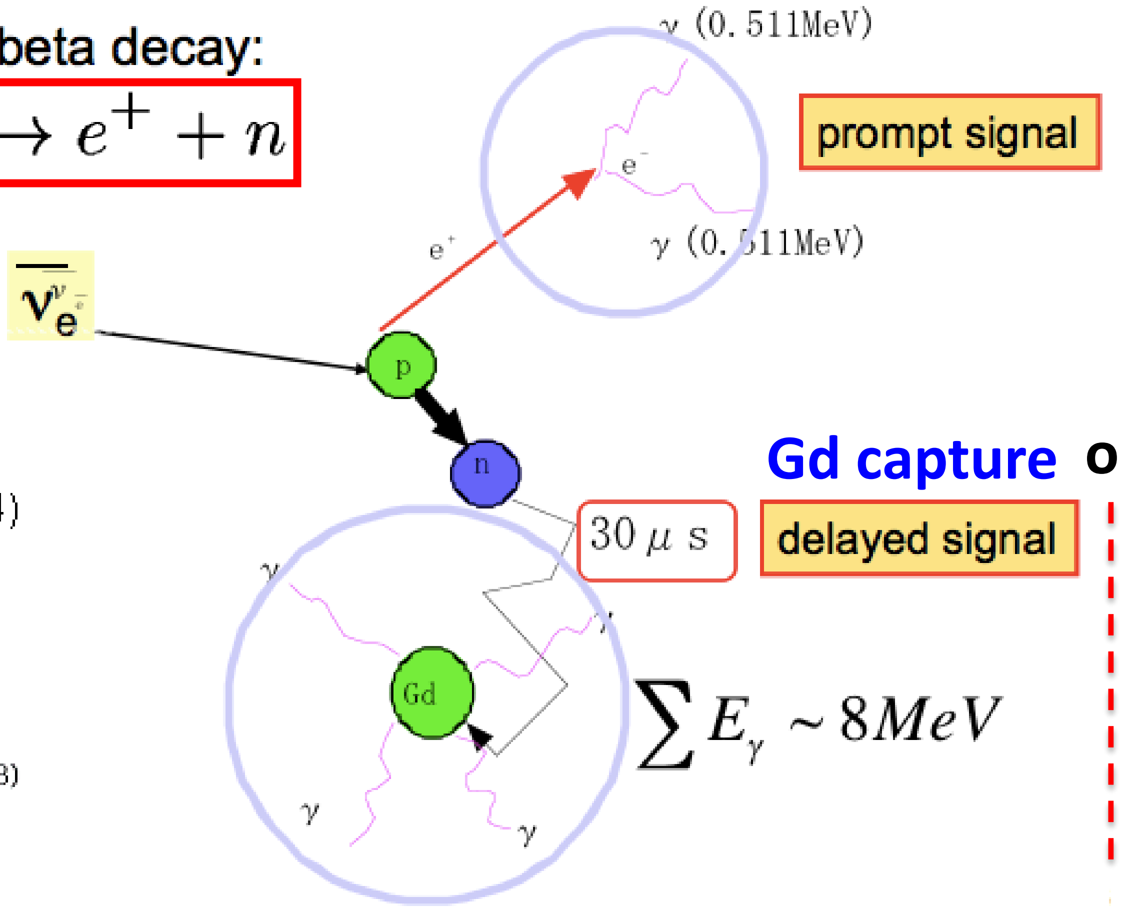
“Fuel-composition dependent reactor antineutrino yield and spectrum at RENO” (arXiv:1896.00574)

- Independent measurement of $|\Delta m_{ee}^2|$ and θ_{13} with delayed n-H IBD analysis

Detection of Reactor Antineutrinos

Inverse beta decay:

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



prompt signal

30 μ s

delayed signal

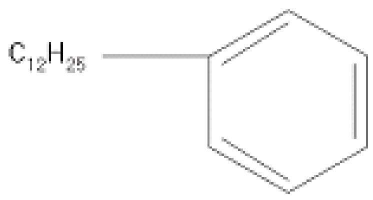
$$\sum E_\gamma \sim 8MeV$$

Gd capture or **H capture**

~200 μs

~ **2.2** MeV

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



Linear Alkyl Benzene (LAB)

- 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 or ~200 μs

Coincidence of prompt and delayed signals

(prompt signal)

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

Prompt signal

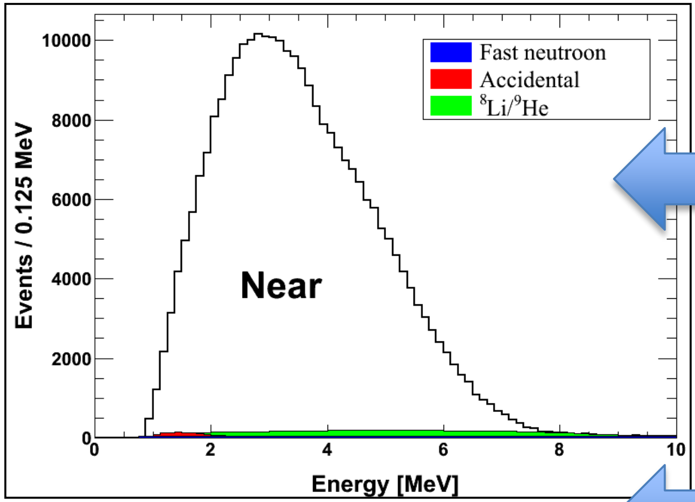
Delayed signal

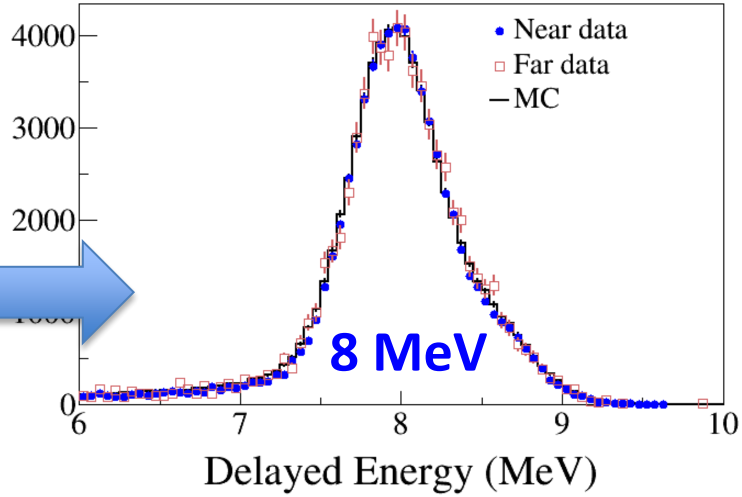
n-Gd IBD

~30 μs

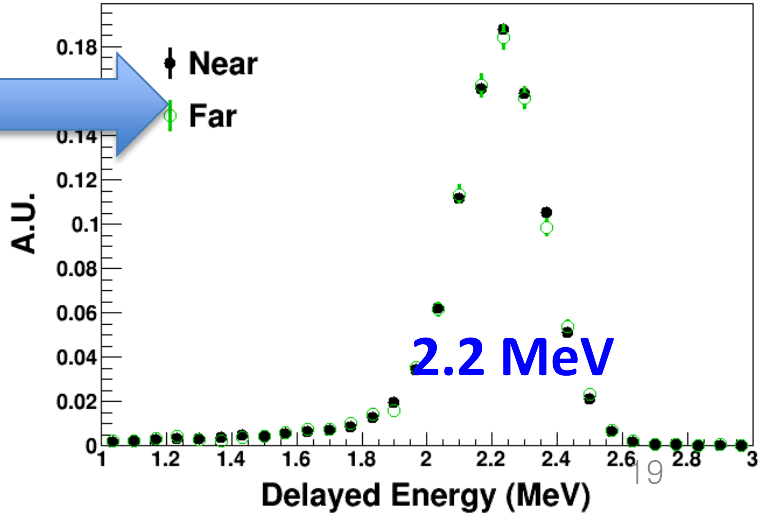
n-H IBD

~200 μs



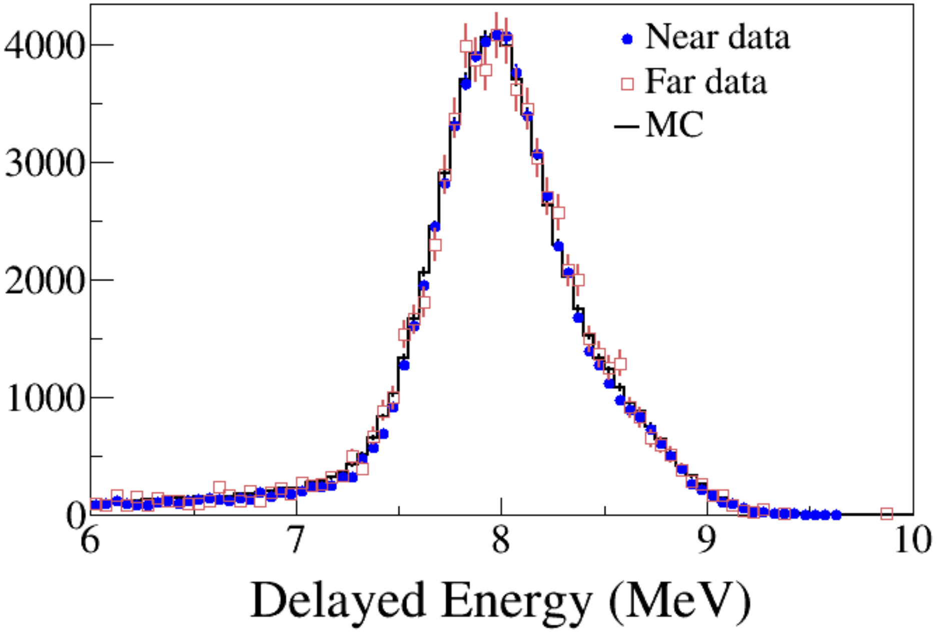


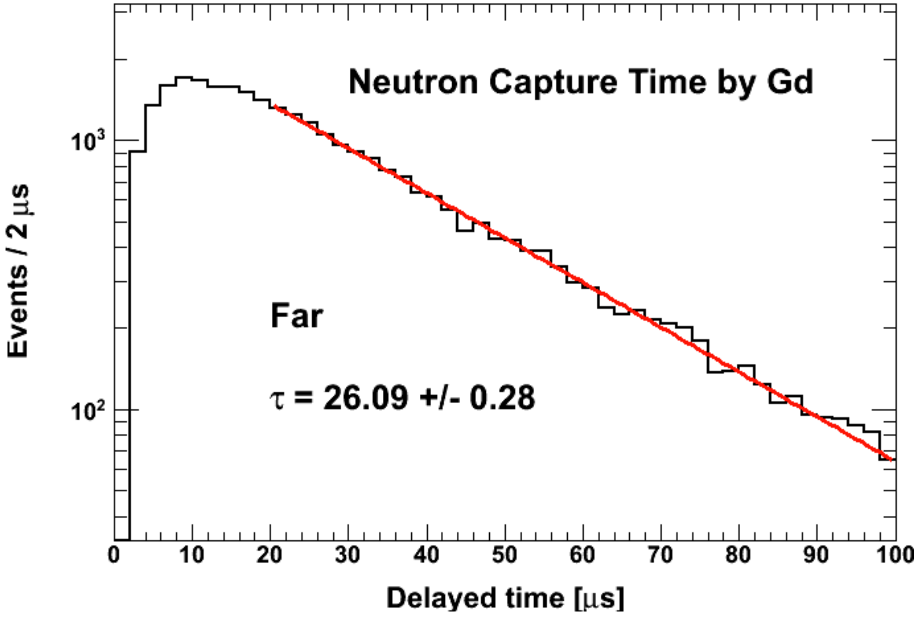
8 MeV

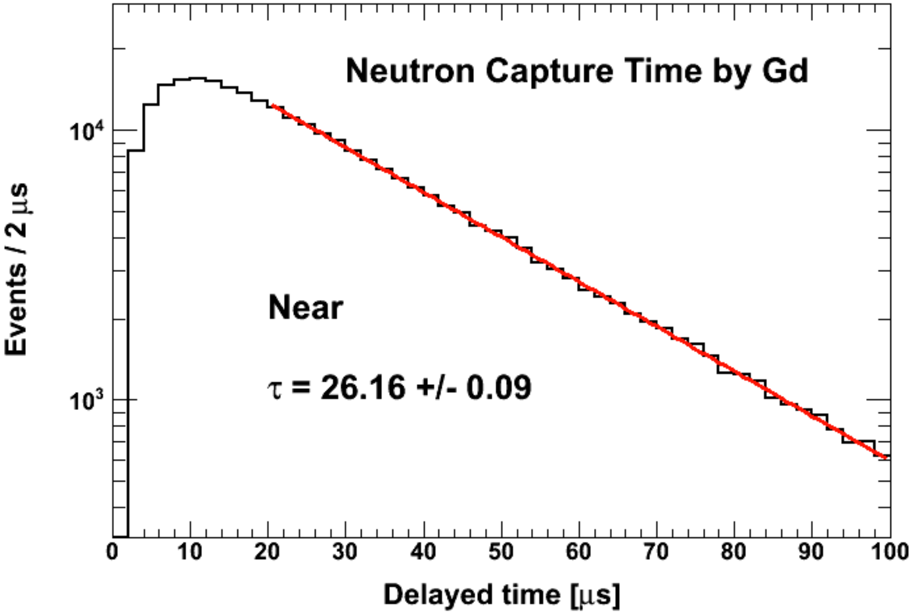


2.2 MeV

Delayed Signals from Neutron Capture by Gd

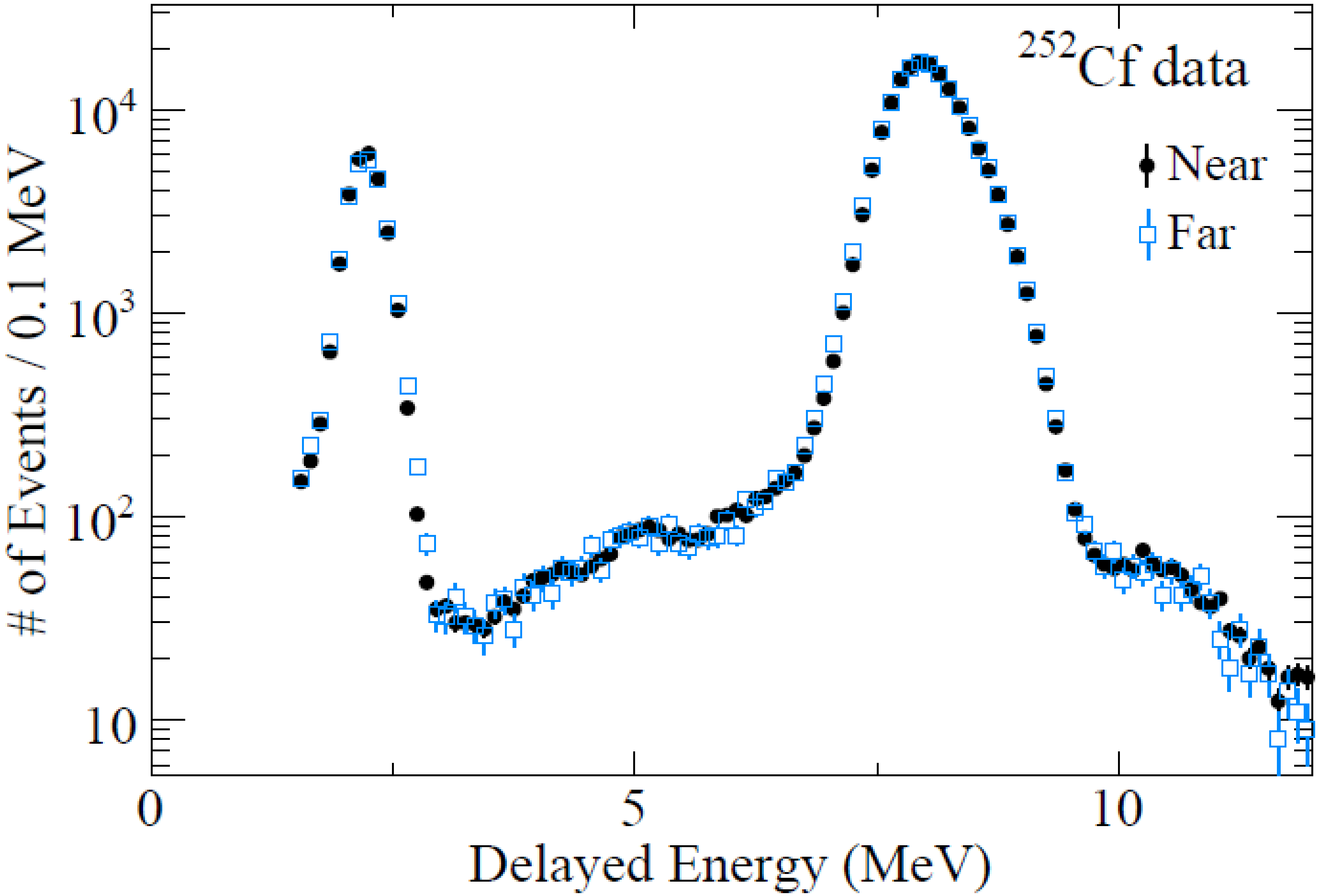






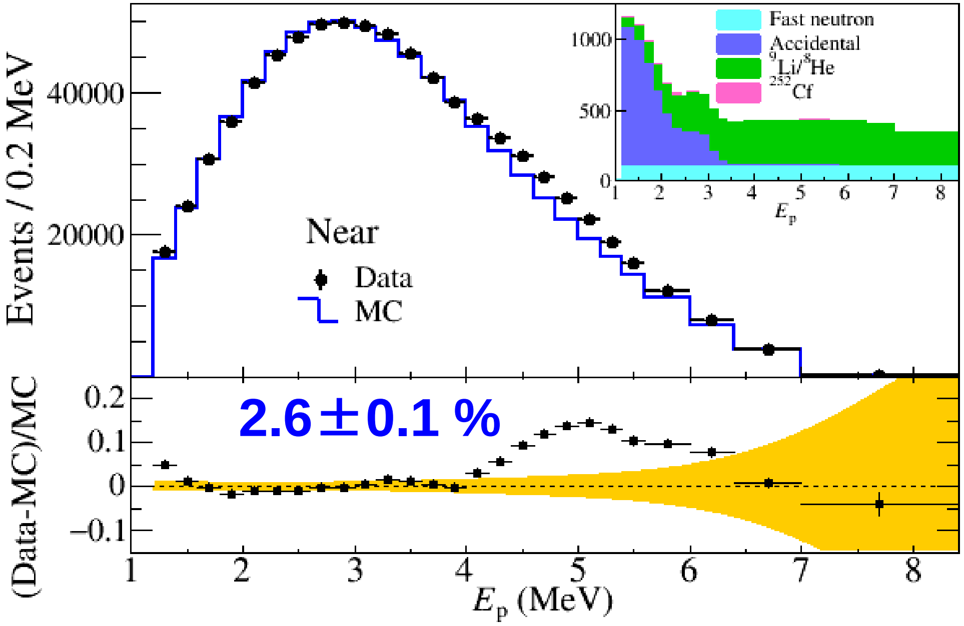
Identical Performance of Near and Far Detectors

Spectra of Delayed Signals Using ^{252}Cf Source

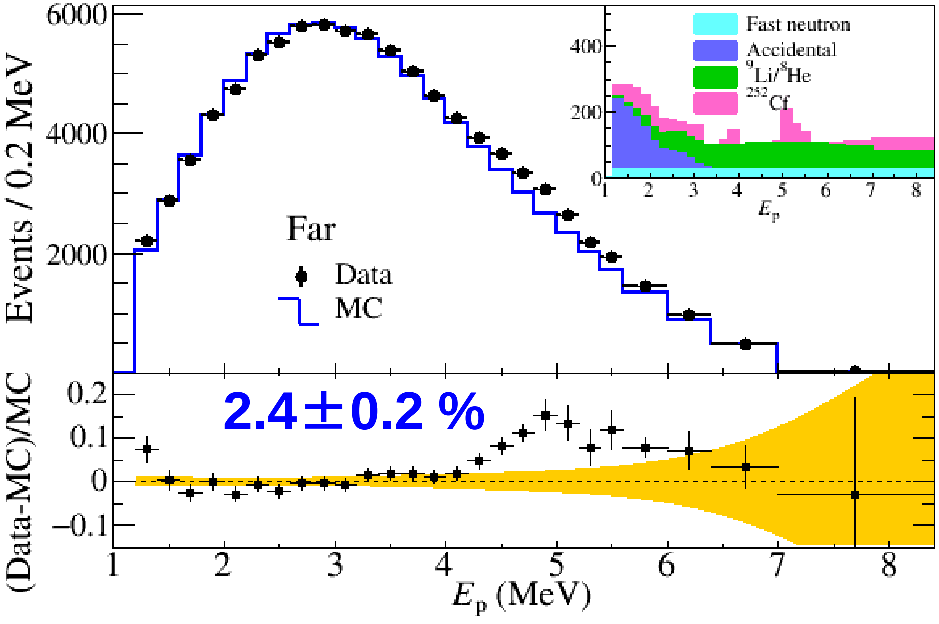


Measured Spectra of IBD Prompt Signal

Clear excess at 5 MeV



2.6±0.1 %

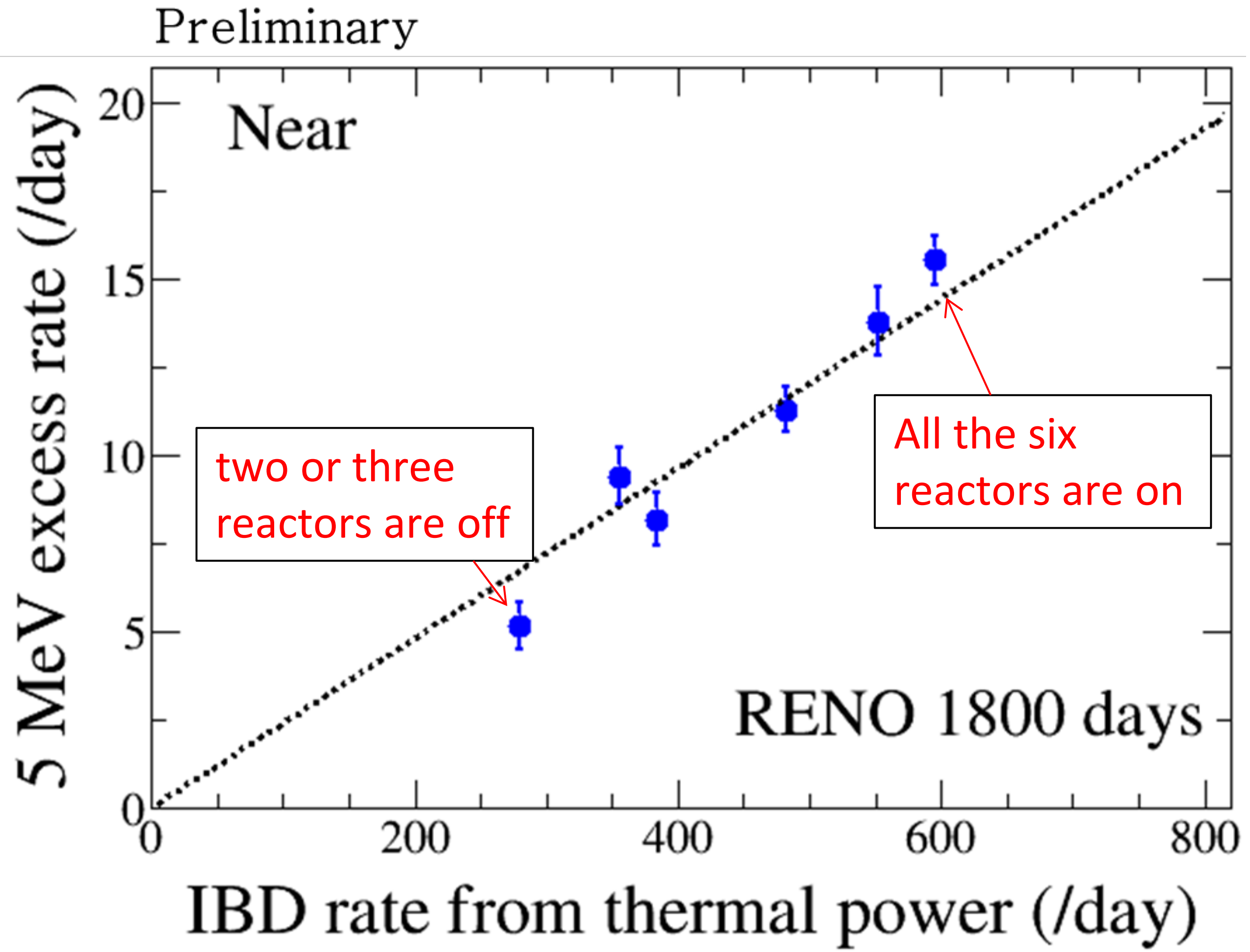


2.4±0.2 %

Near Live time = 1807.88 days
# of IBD candidate = 850,666
Background : 2.03±0.06%

Far Live time = 2193.04 days
# of IBD candidate = 103,212
Background : 4.76±0.20%

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!

Reactor Neutrino Oscillations

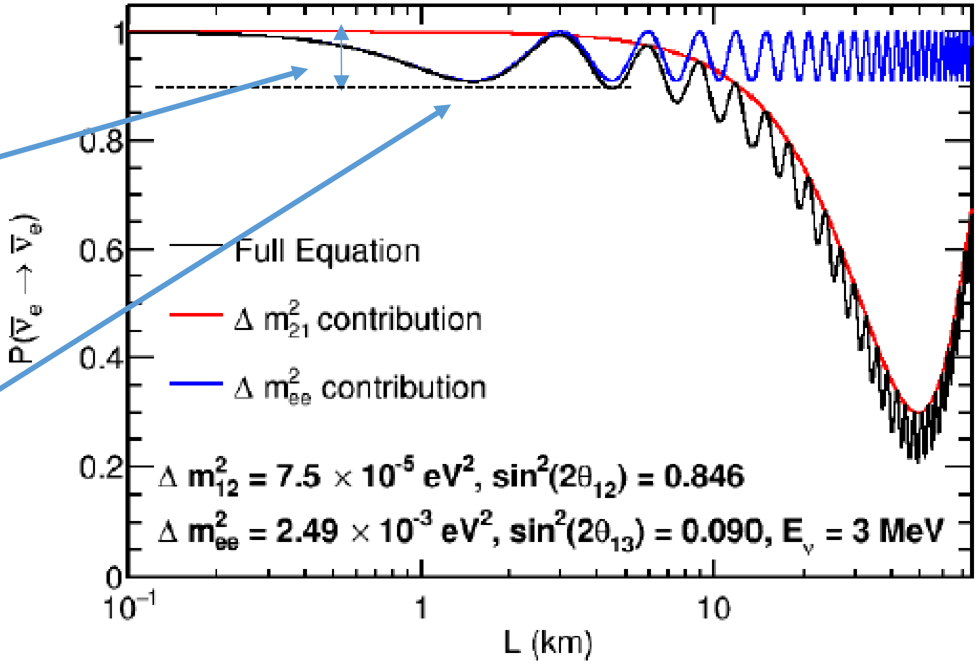
$$P(\bar{\nu}_e \to \bar{\nu}_e) \simeq 1 - \boxed{\cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\frac{\Delta m^2_{21}L}{4E}\right)} - \boxed{\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{ee}L}{4E}\right)}$$

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

${\Delta m_{21}}^2$ term is negligible compared to ${\Delta m_{ee}}^2$ term for ~1km baseline.
$({\Delta m_{21}}^2 \sim 7.5\ \times 10^{-5} eV^2,\quad {\Delta m_{ee}}^2 \sim 2.5\ \times 10^{-3} eV^2)$

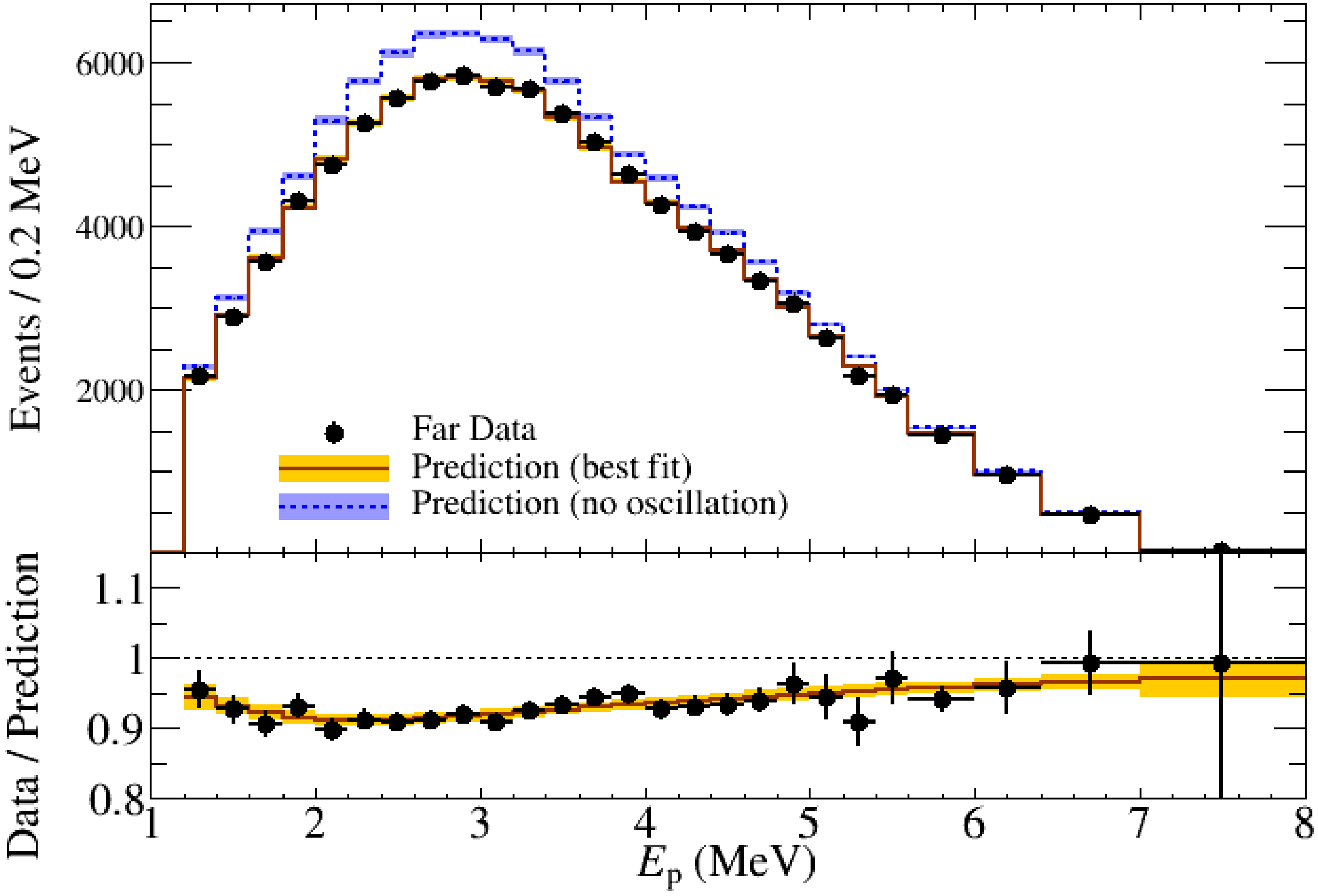
$\sin^2(2\theta_{13})$ is determined by **oscillation amplitude.**

${\Delta m_{ee}}^2$ is determined by **maximum oscillation energy (frequency).**

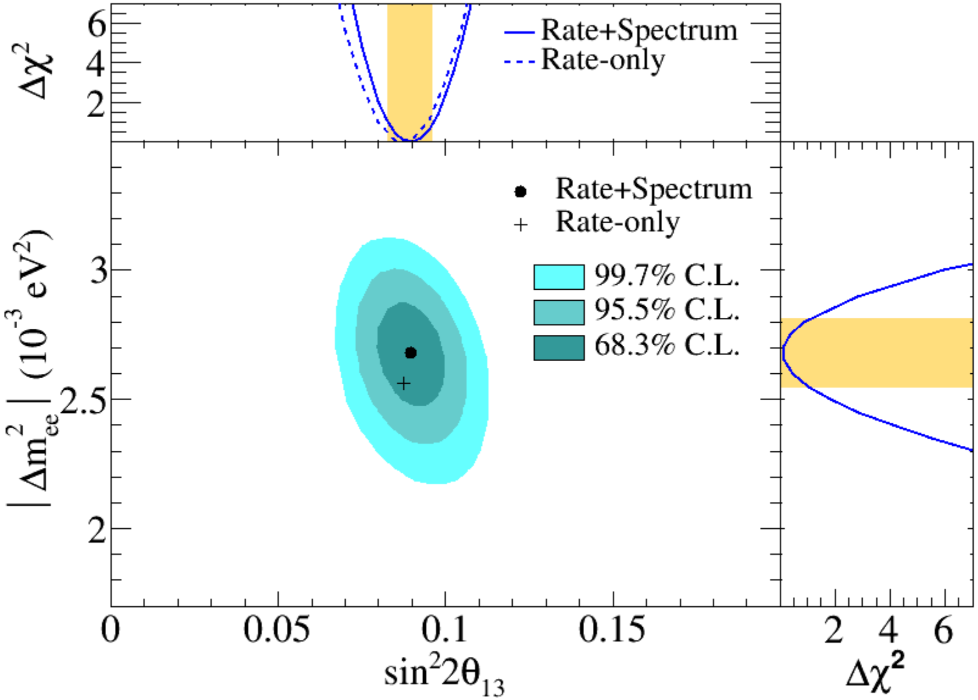


Measurement of $|\Delta m_{ee}^2|$ and θ_{13}

Energy-dependent disappearance of reactor antineutrinos



Measurement of $|\Delta m_{ee}^2|$ and θ_{13}



<500 days>

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

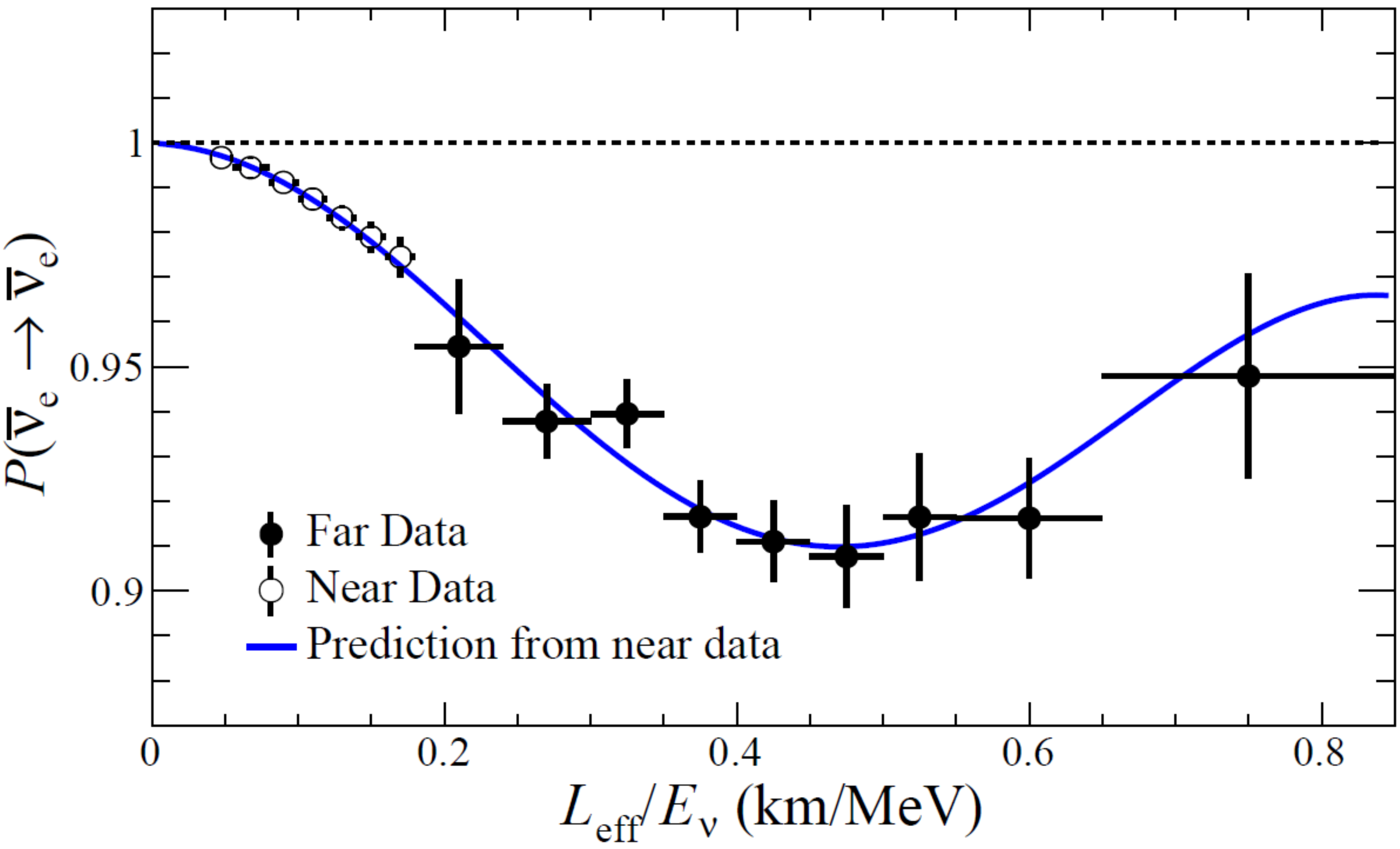
$$|\Delta m^2_{ee}| = [2.62^{+0.21}_{-0.23}(\text{stat.})^{+0.12}_{-0.13}(\text{syst.})] \times 10^{-3}\ \text{eV}^2$$

<2200 days>

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

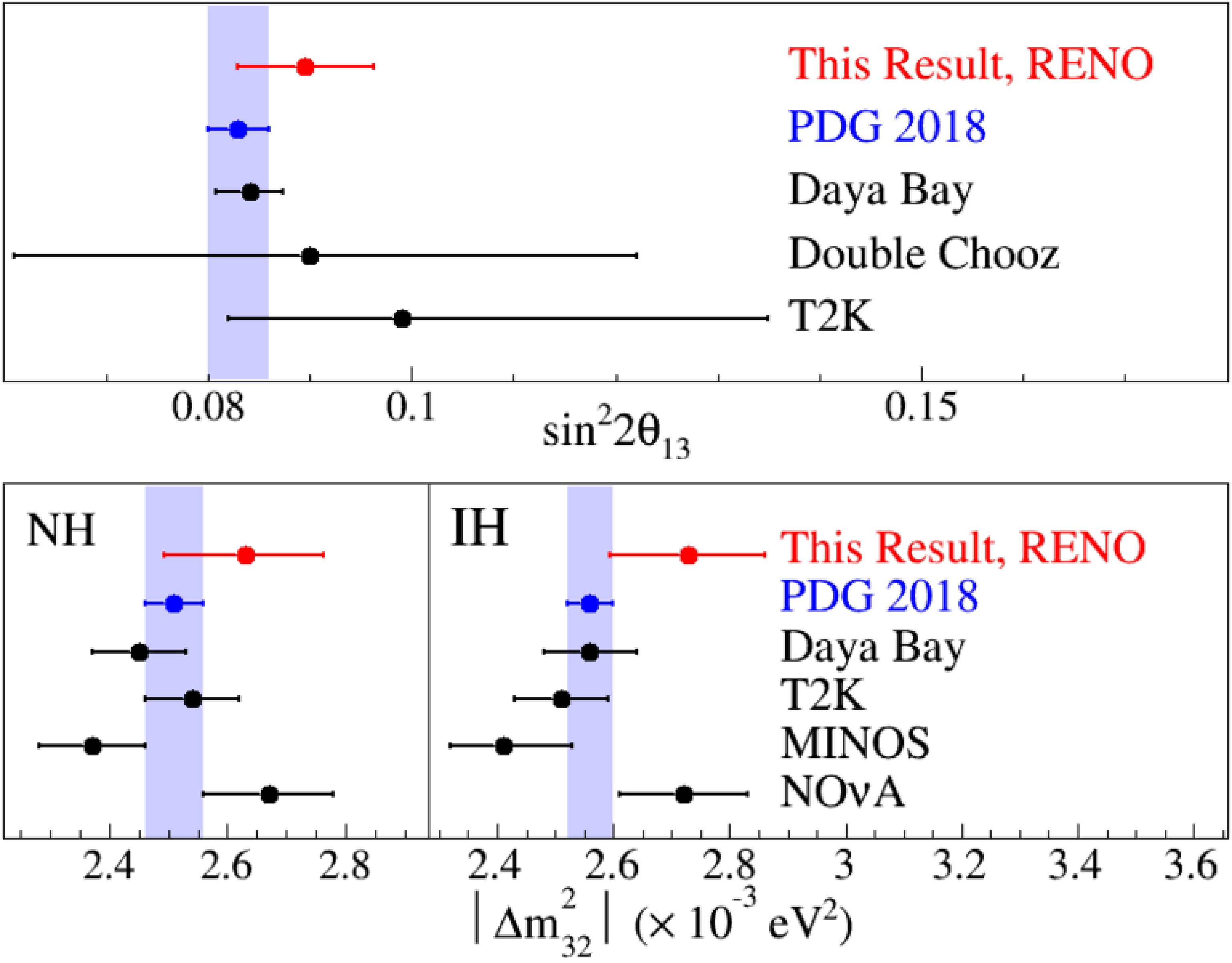
$$|\Delta m^2_{ee}| = 2.68 \pm 0.12(\text{stat.}) \pm 0.07(\text{syst.})(\times 10^{-3}\text{eV}^2)$$ (± 5.2 %)

Observed L/E Dependent Oscillation

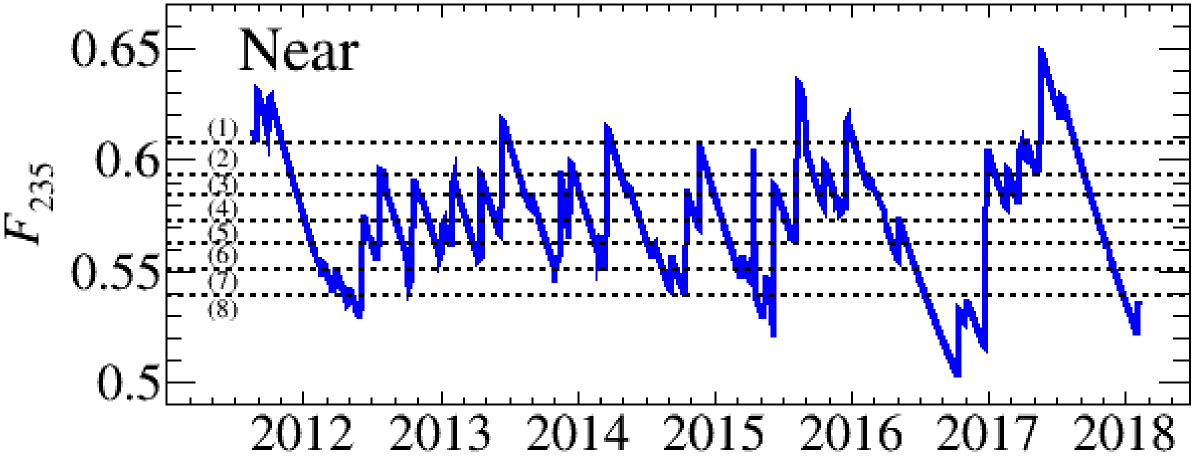


$$P(\overline{\nu}_e \rightarrow \overline{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\Delta m^2_{ee} \frac{L}{4E_\nu}\right)$$

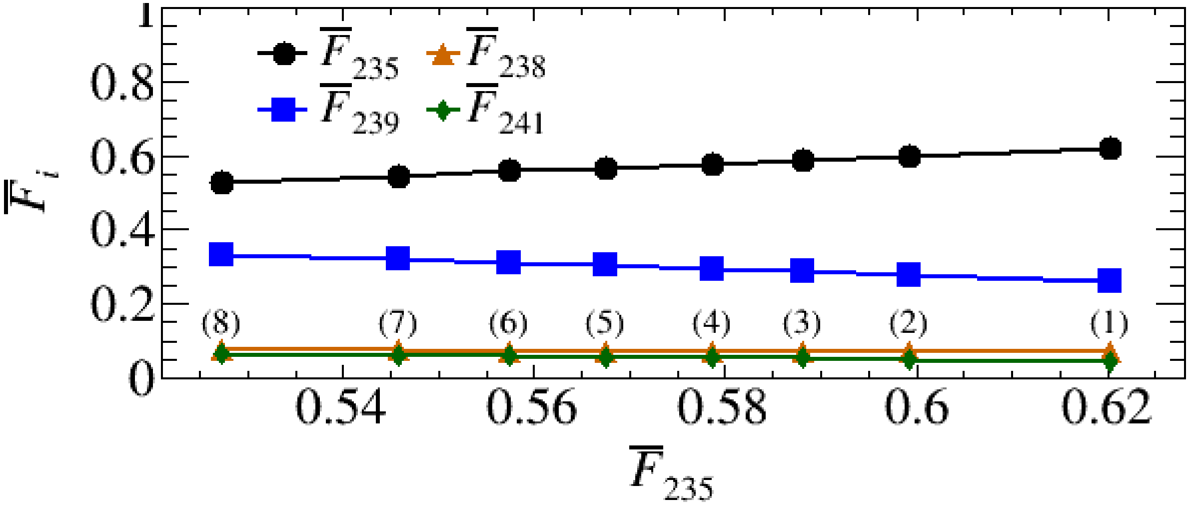
Comparison of θ_{13} and $|\Delta m_{ee}^2|$ Results



Evolution of Fuel Composition



Effective fission fraction of ^{235}U (weighted by each reactor's thermal power and fission fraction)



8 groups of near IBD samples with equal statistics according to ^{235}U isotope fraction

Effective Fission fraction for each isotope

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

Predicted IBD Yield per Fission

IBD yield per fission for each isotpoe

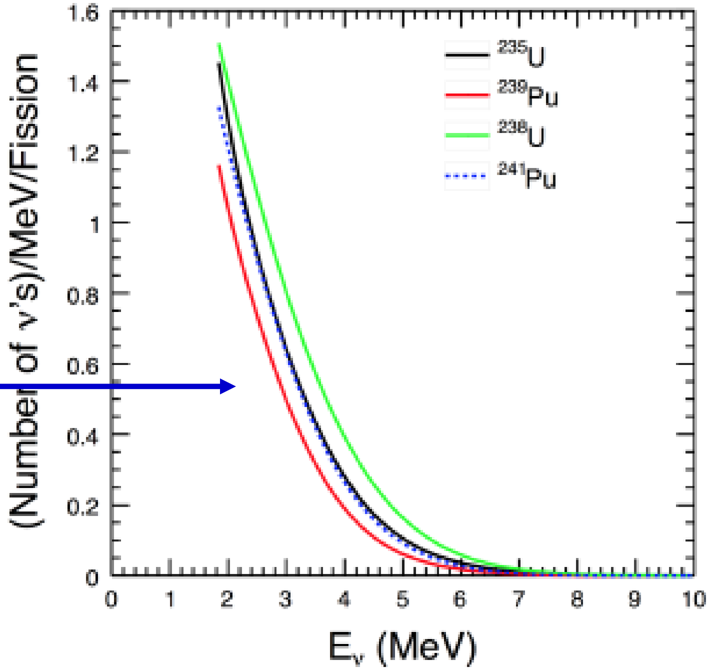
(Total # of produced IBD events)

$$y_i = \int \boxed{\sigma(E_\nu)}\boxed{\phi_i(E_\nu)}dE_\nu$$

IBD cross section

Antineutrino spectrum (H-M model)

(i : each isotope)



Average IBD yield per fission

(for each 8 group, j)

$$\bar{y}_{f,j} = \sum_{i=1}^{4} \bar{F}_{i,j} y_i$$

$\overline{F}_{i,j}$: Effective Fission fraction for each isotope

	H-M model (10^{-43}cm²/fission)
y_{235}	6.70 +- 0.16
y_{239}	4.38 +- 0.19
y_{238}	10.07 +- 1.22
y_{241}	6.07 +- 0.19

Fuel-Composition Dependent Reactor Neutrino Yield

of Observed IBD

$$N_j = \bar{y}_{f,j} \sum_{r=1}^{6} \frac{N_p}{4\pi L_r^2} \int dt \left[\frac{W_{\mathrm{th},r}(t)\overline{P}_r(t)}{\sum_i f_{i,r}(t)E_i} \right] \epsilon_{\mathrm{d}}(t)$$

Detection Efficiency

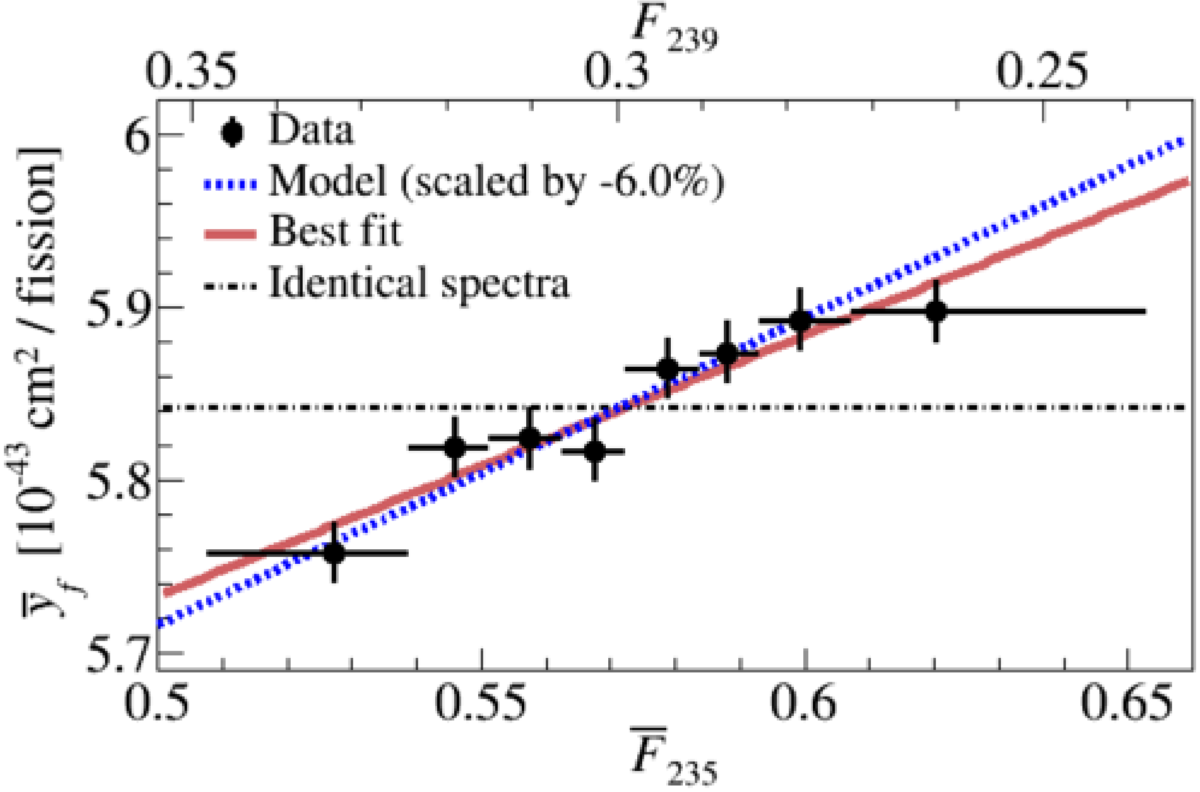
Measured IBD yield per fission

# of Target proton

# of fission

Total averaged IBD yield per fission ($\bar{y}_f$) = (5.84 ± 0.13)×10^{-43} cm^2/fission

0.940 ± 0.021 → (6.0 ± 2.1)%



Averaged IBD yield per fission ($\bar{y}_f$) vs $\bar{F}_{i,j}$

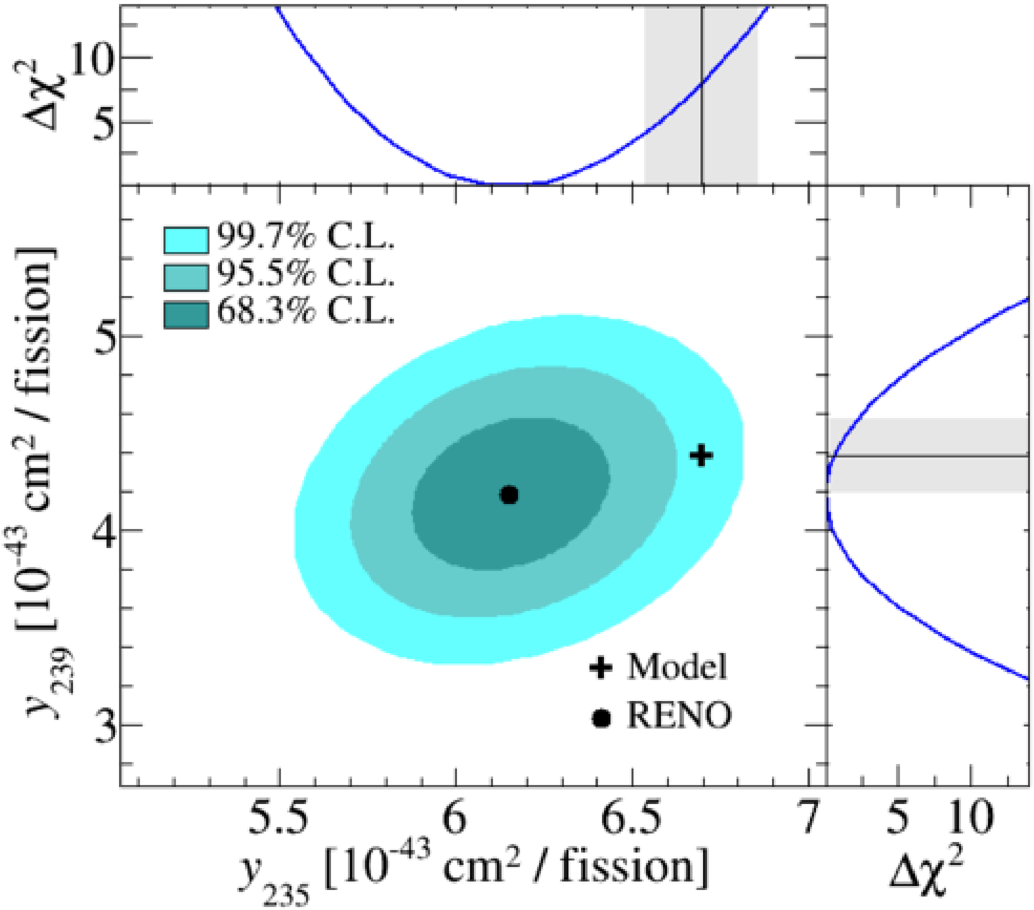
→ slope means **different neutrino spectrum** for each isotope

→ rules out the no fuel-dependent variation at **6.6σ**

Scaled Model and its slope indicates **antineutrino anomaly**

Measurement of y_{235} and y_{239}

The best-fit measured yields per fission of ^{235}U and ^{239}Pu



The best-fit value of y_{235} :

3.0 σ deficit

6.15 ± 0.19/6.70 ± 0.16

The best-fit value of y_{239} :

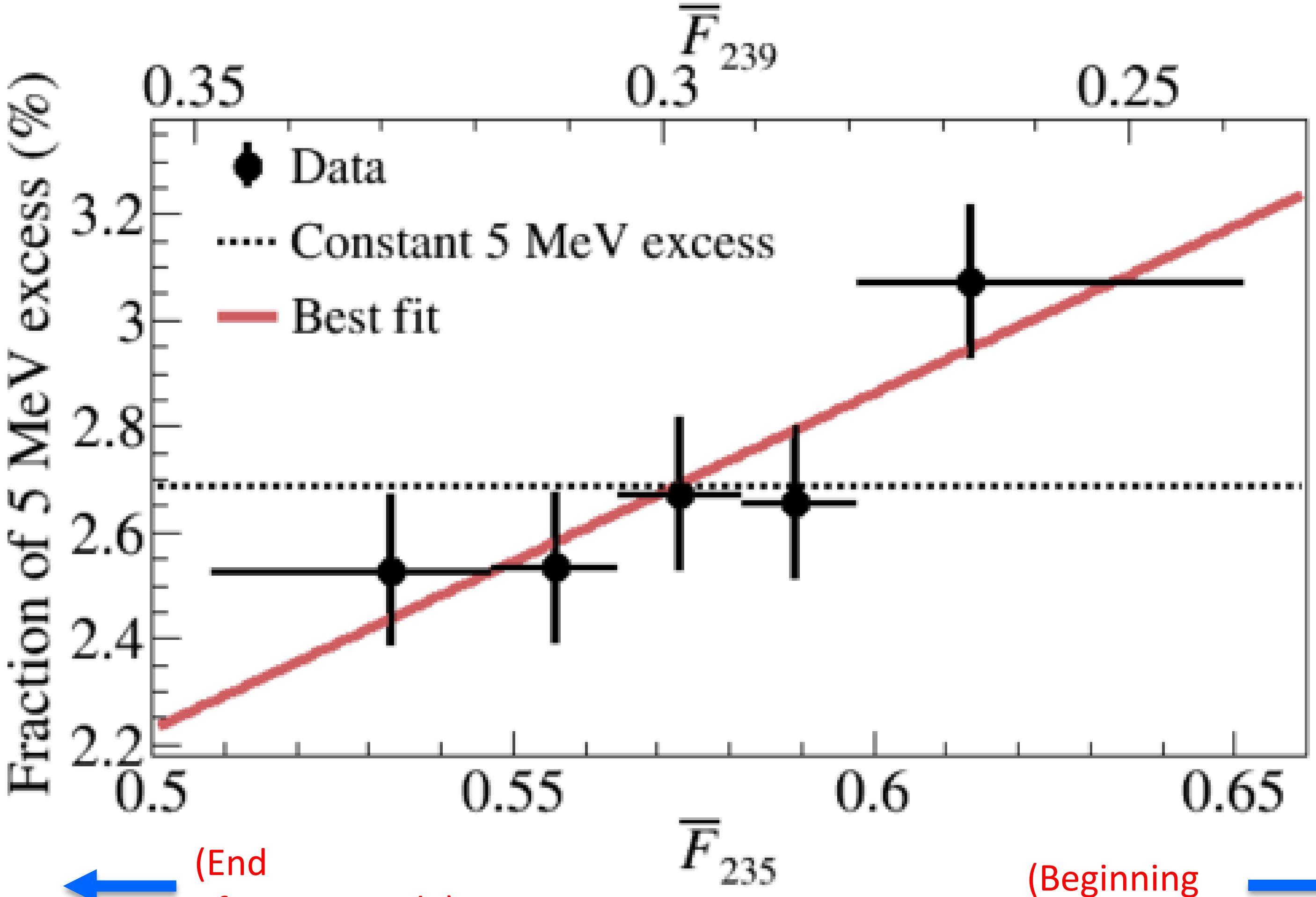
0.8 σ deficit

4.18 ± 0.26/4.38 ± 0.19

Reevaluation of the y_{235} may **mostly solve** reactor antineutrino **anomaly.**
But ^{239}Pu is **not entirely** ruled out as a possible source of the anomaly.

Correlation of 5 MeV excess with fuel ^{235}U

2.7σ indication of 5 MeV excess coming from ^{235}U fuel isotope fission !!



(2.69±0.07) %

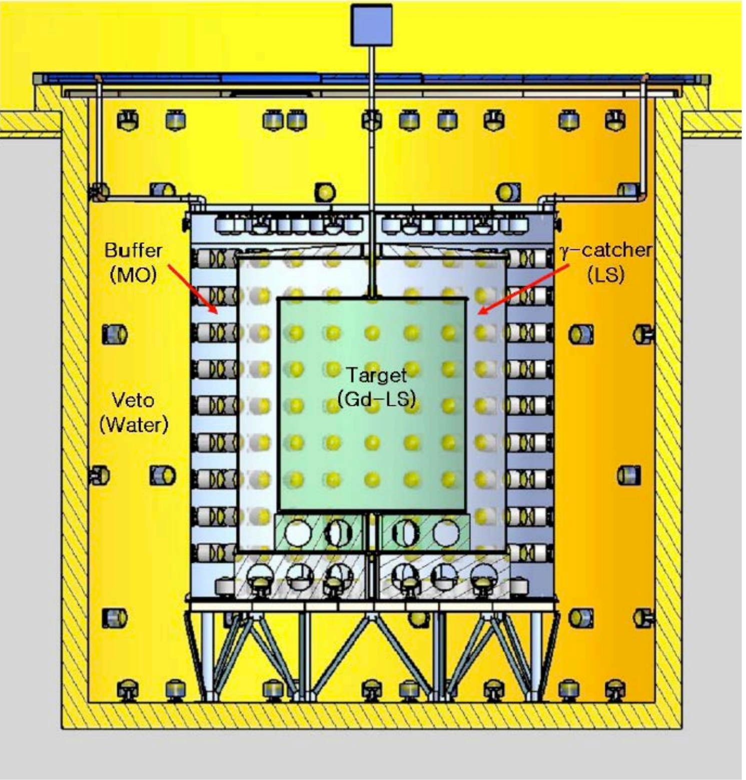
(End of reactor cycle)

(Beginning of reactor cycle)

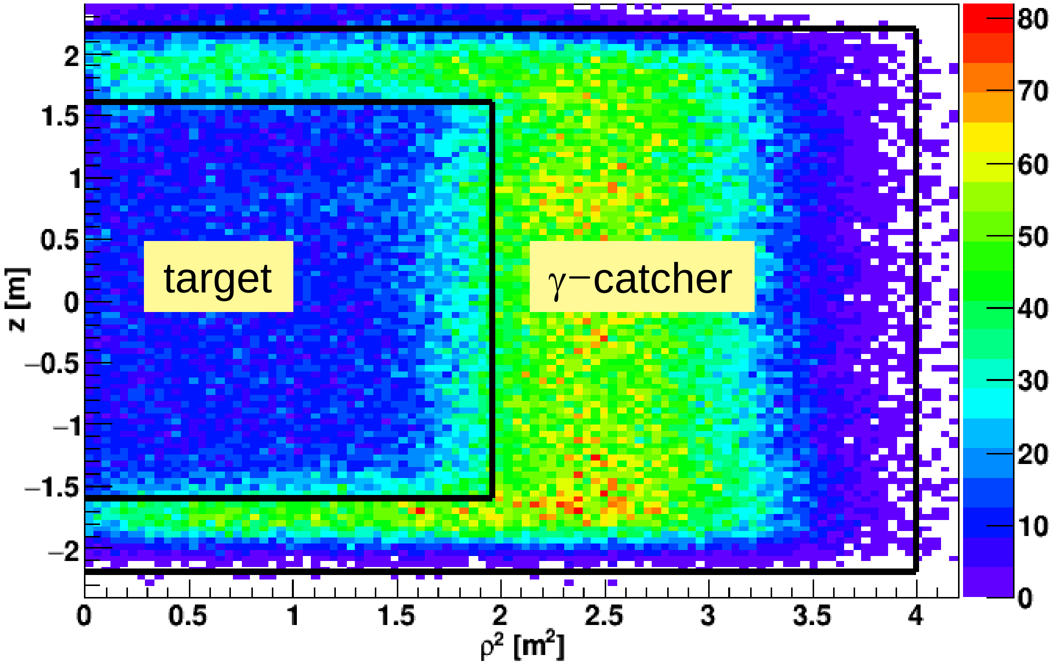
n-H IBD Analysis

Motivation:

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

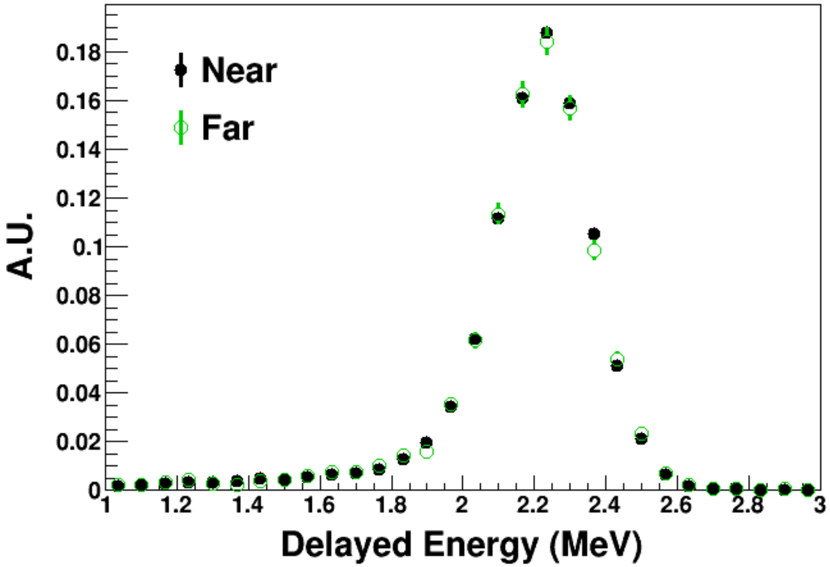


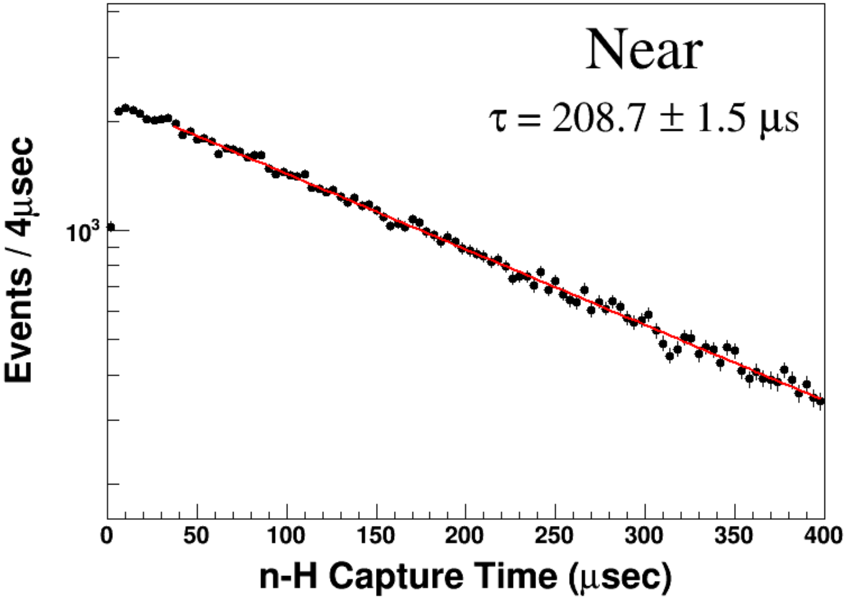
n-H IBD Event Vertex Distribution



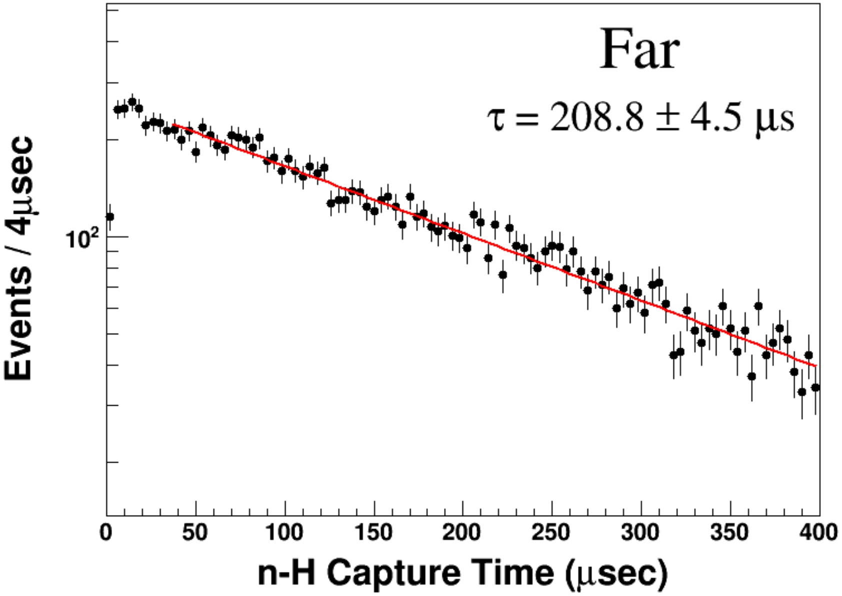
Delayed Spectrum and Capture Time

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



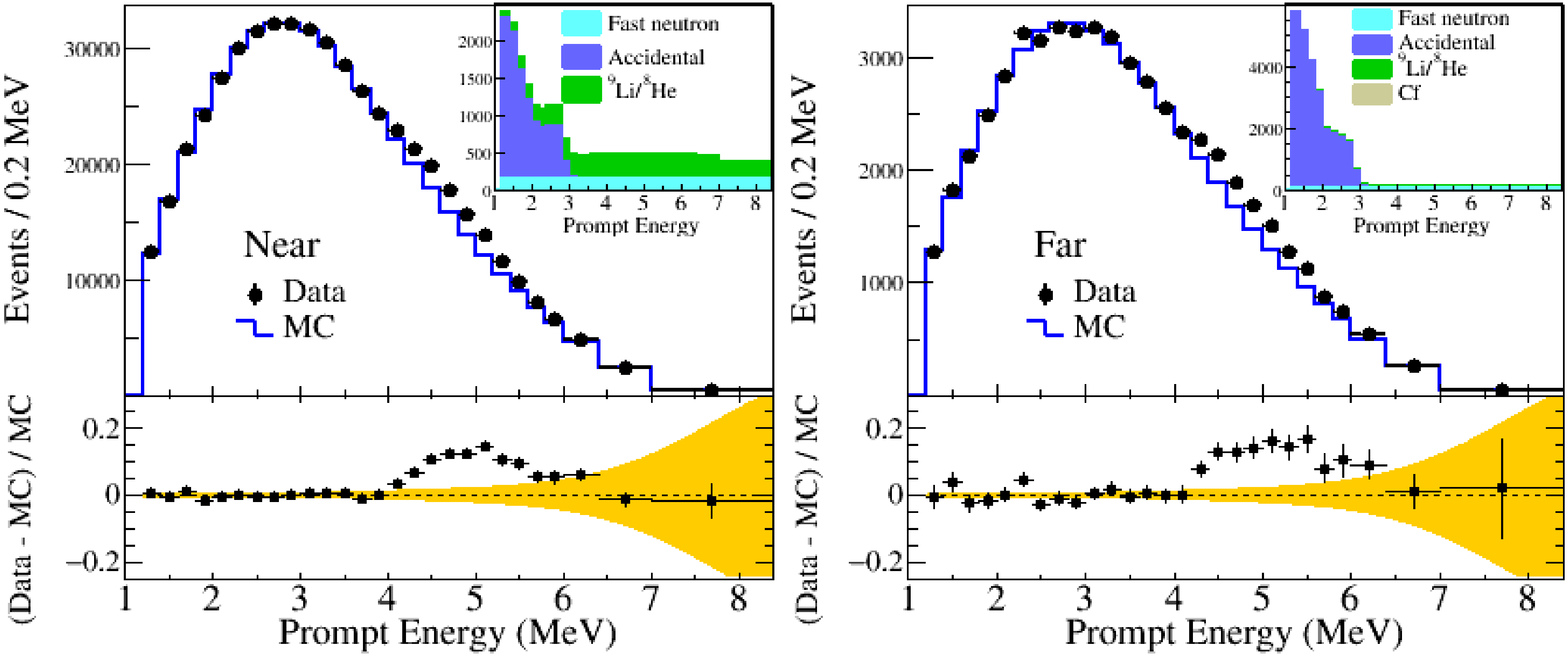

Near

τ = 208.7 ± 1.5 μs


Far

τ = 208.8 ± 4.5 μs

θ_{13} Measurement with n-H



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

Summary

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

$$\sin^2 2\theta_{13} = 0.0896 \pm 0.0048(\mathrm{stat}) \pm 0.0048(\mathrm{syst})$$

± 0.0068

7.6 % precision

$$\left|\Delta m_{ee}^2\right| = 2.68 \pm 0.12(\mathrm{stat}) \pm 0.07(\mathrm{syst})\ (\times 10^{-3}\,\mathrm{eV}^2)$$

± 0.14

5.2 % precision

- Observation of fuel-composition dependent variation of IBD yield at 6.6σ CL

- First hint for 2.7σ correlation between 5 MeV excess and ^{235}U fission fraction

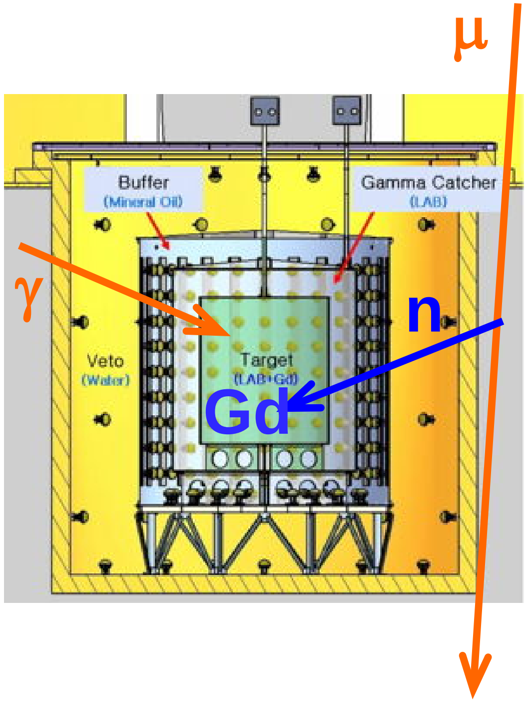
- Measurement of $|\Delta m_{ee}^2|$ and θ_{13} using n-H IBD analysis

Thanks for your attention!

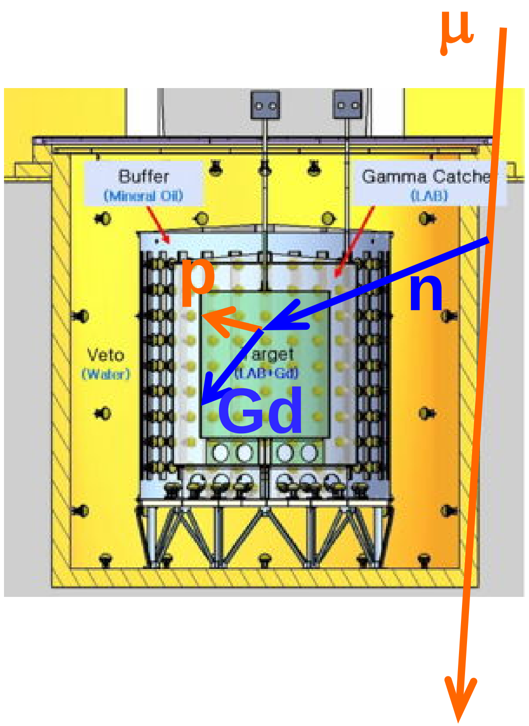
Backgrounds

- 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

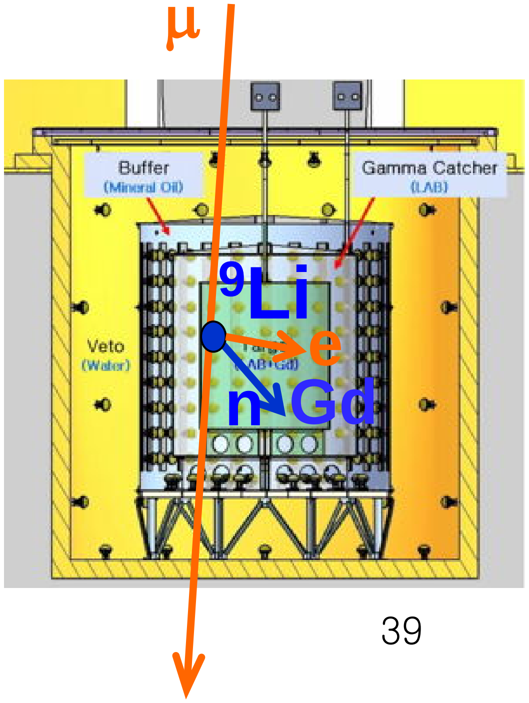
Accidentals



Fast neutrons

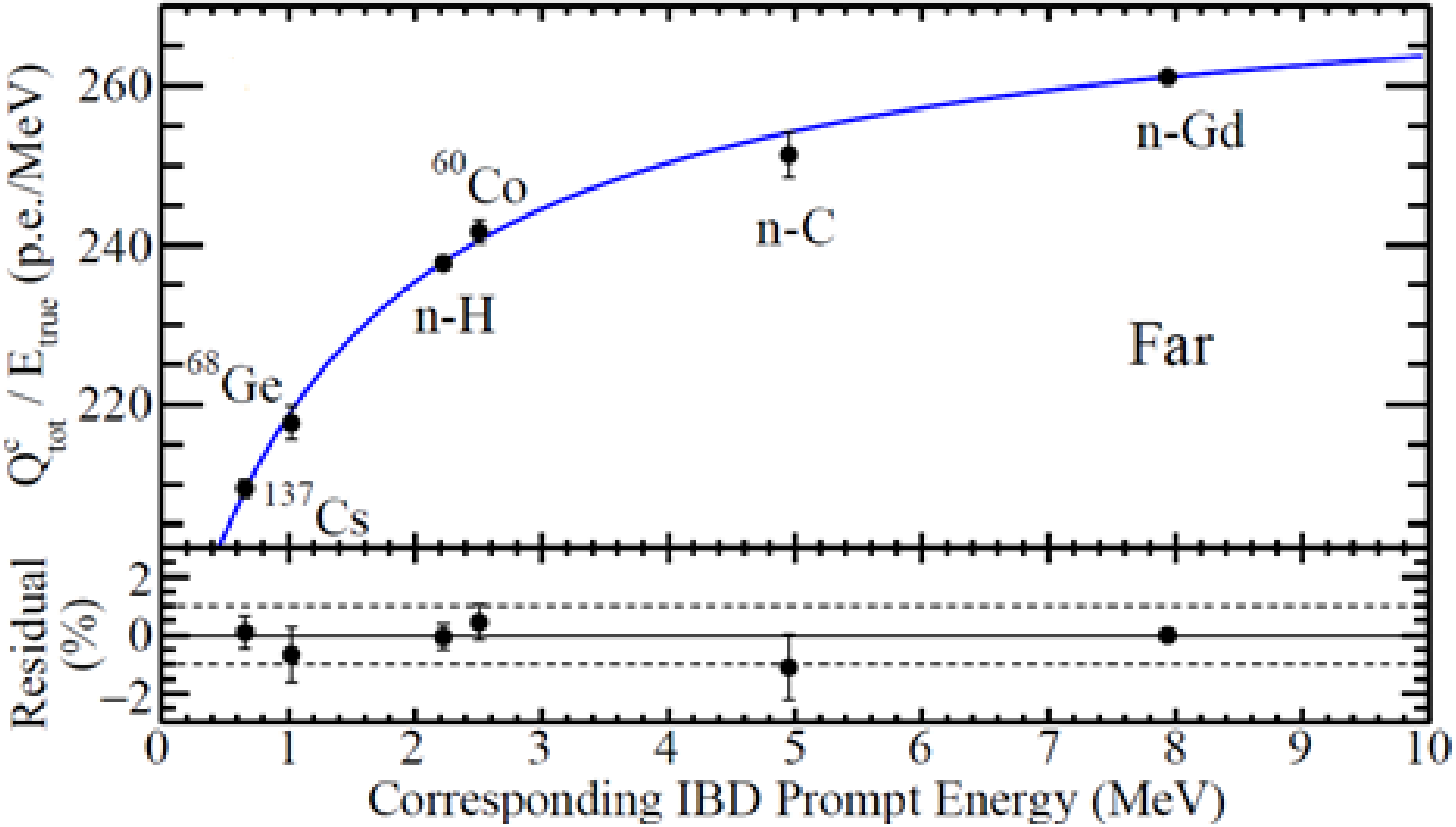


^{9}Li/^{8}He β-n followers



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