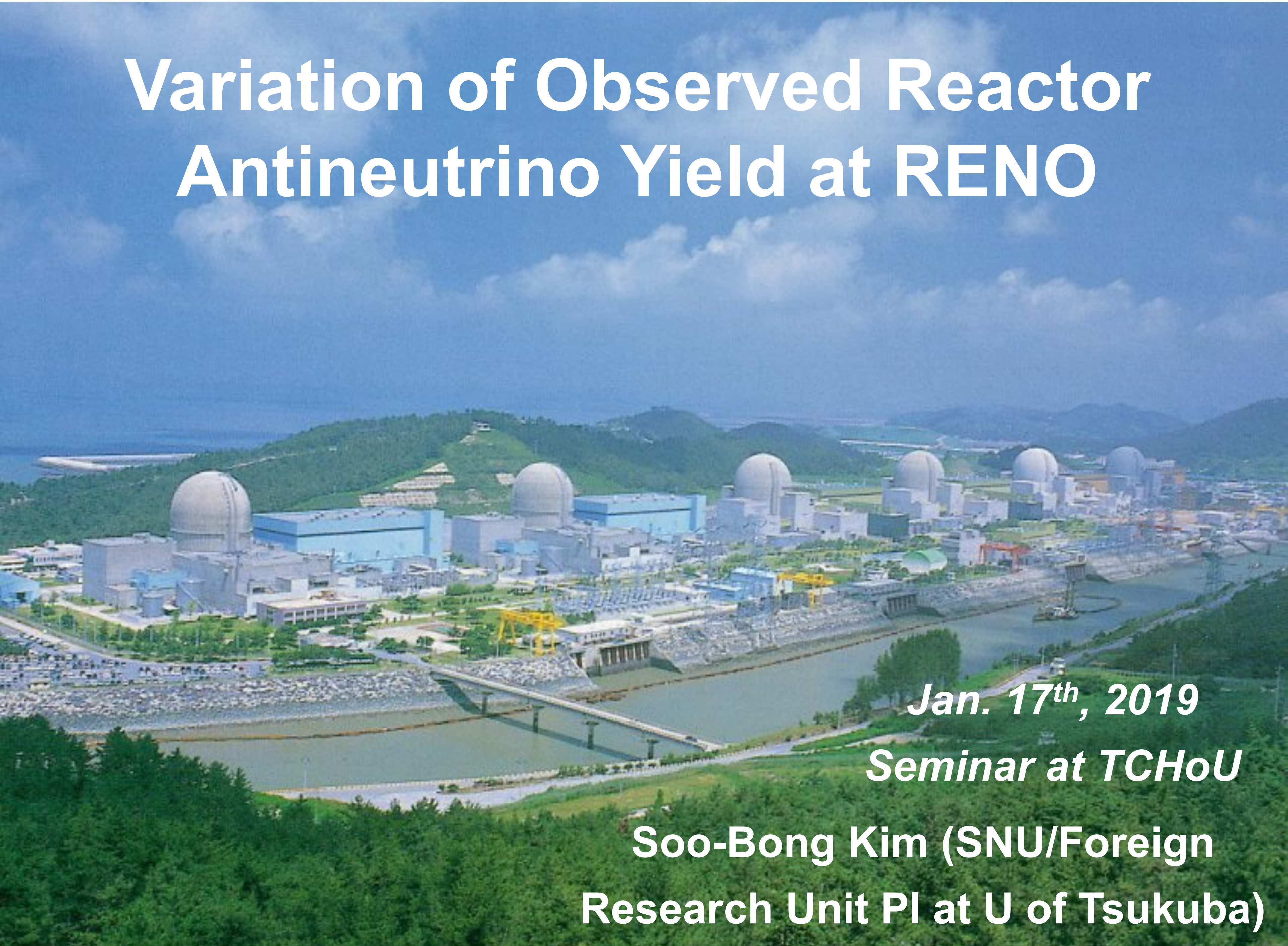


Variation of Observed Reactor Antineutrino Yield at RENO

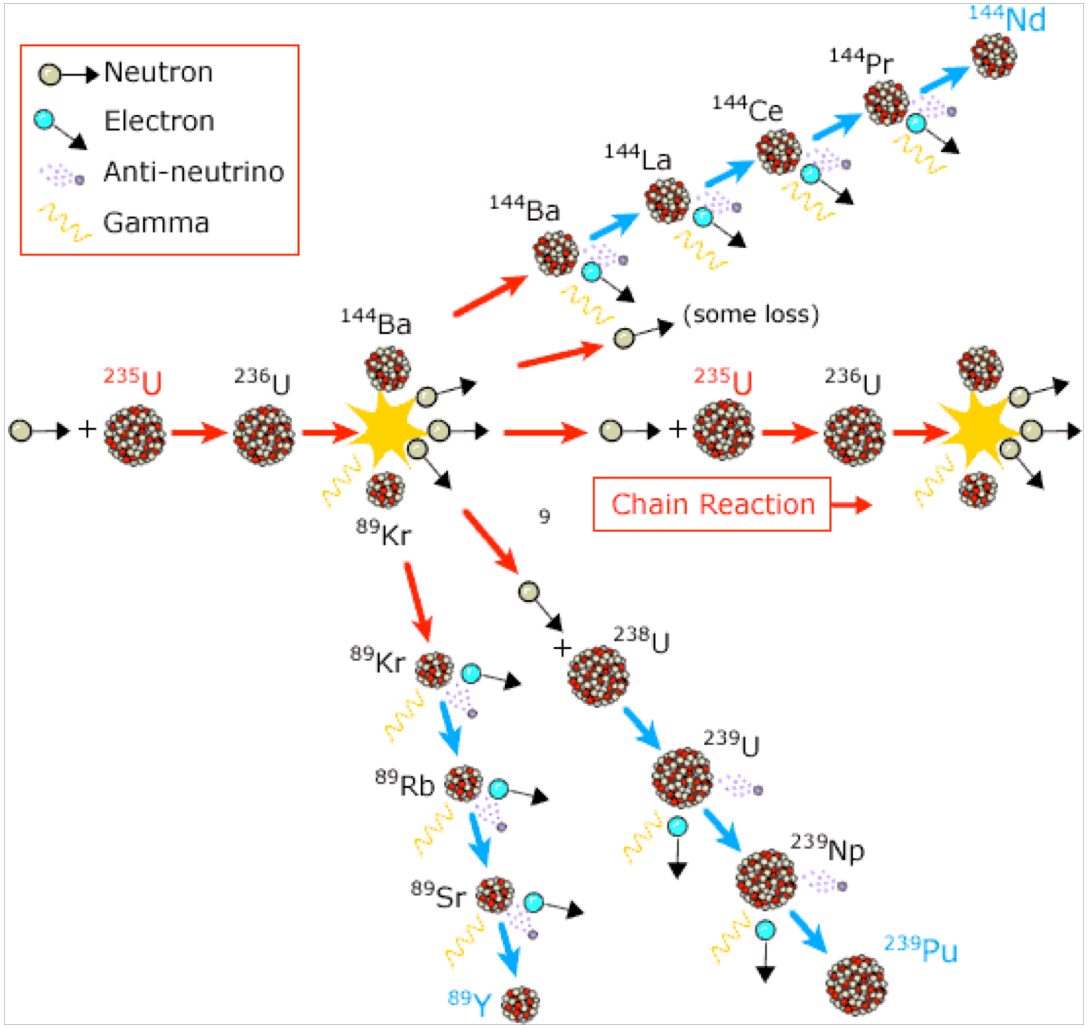
Jan. 17th, 2019

Seminar at TCHoU

Soo-Bong Kim (SNU/Foreign Research Unit PI at U of Tsukuba)

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

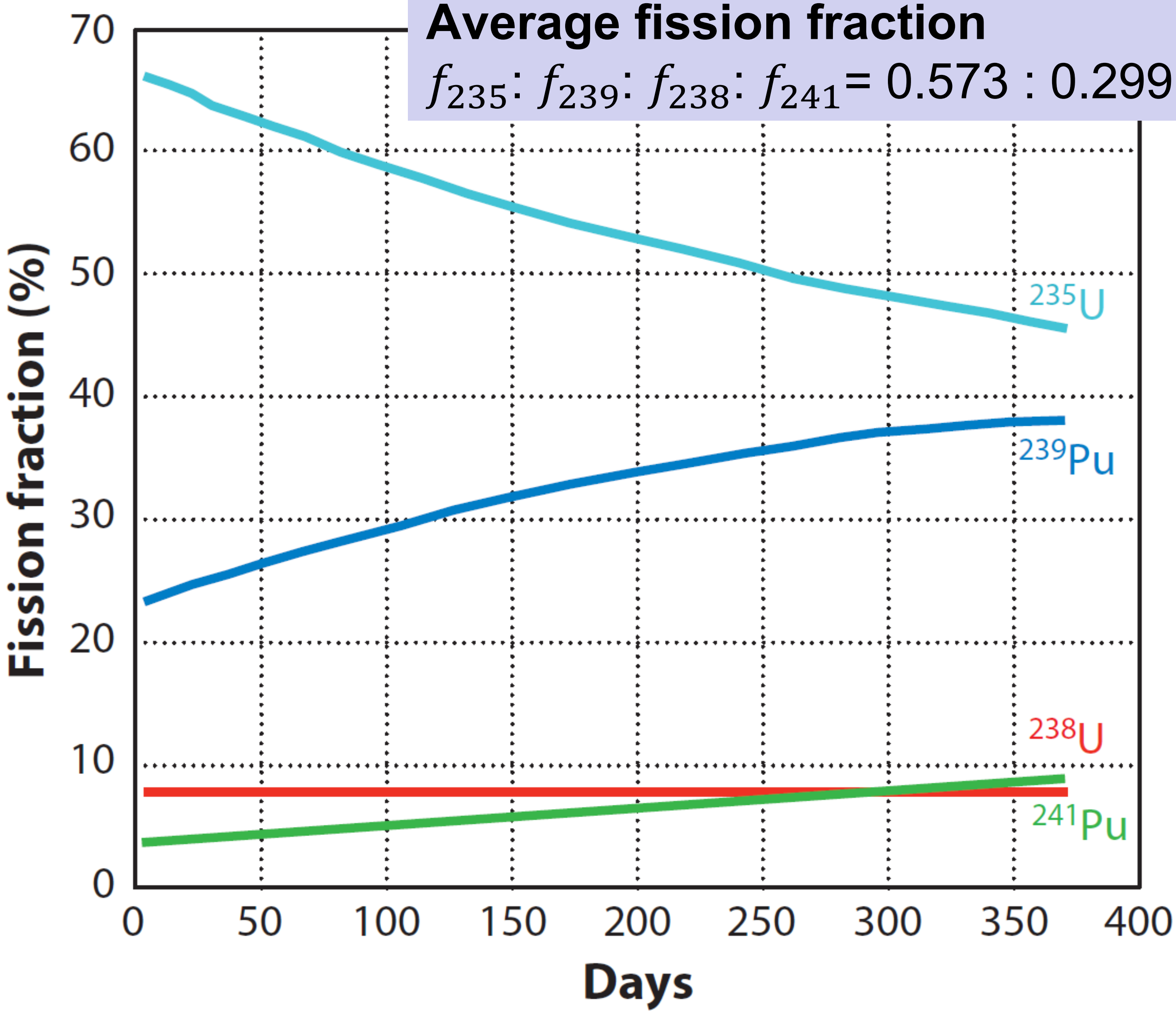
1 GW_{th} reactor

→ ~$2\text{x}10^{20}$ $\bar{\nu}_e$/sec

Reactor Fuel Isotope Fraction

Average fission fraction

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

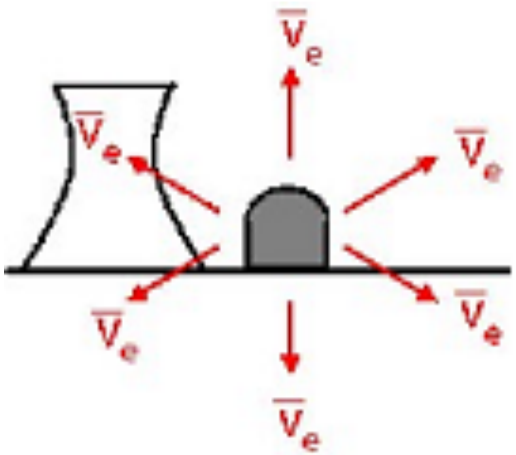


The **Fission fraction** of an isotope varies with **fuel-burning**

Reactor for Antineutrino Source

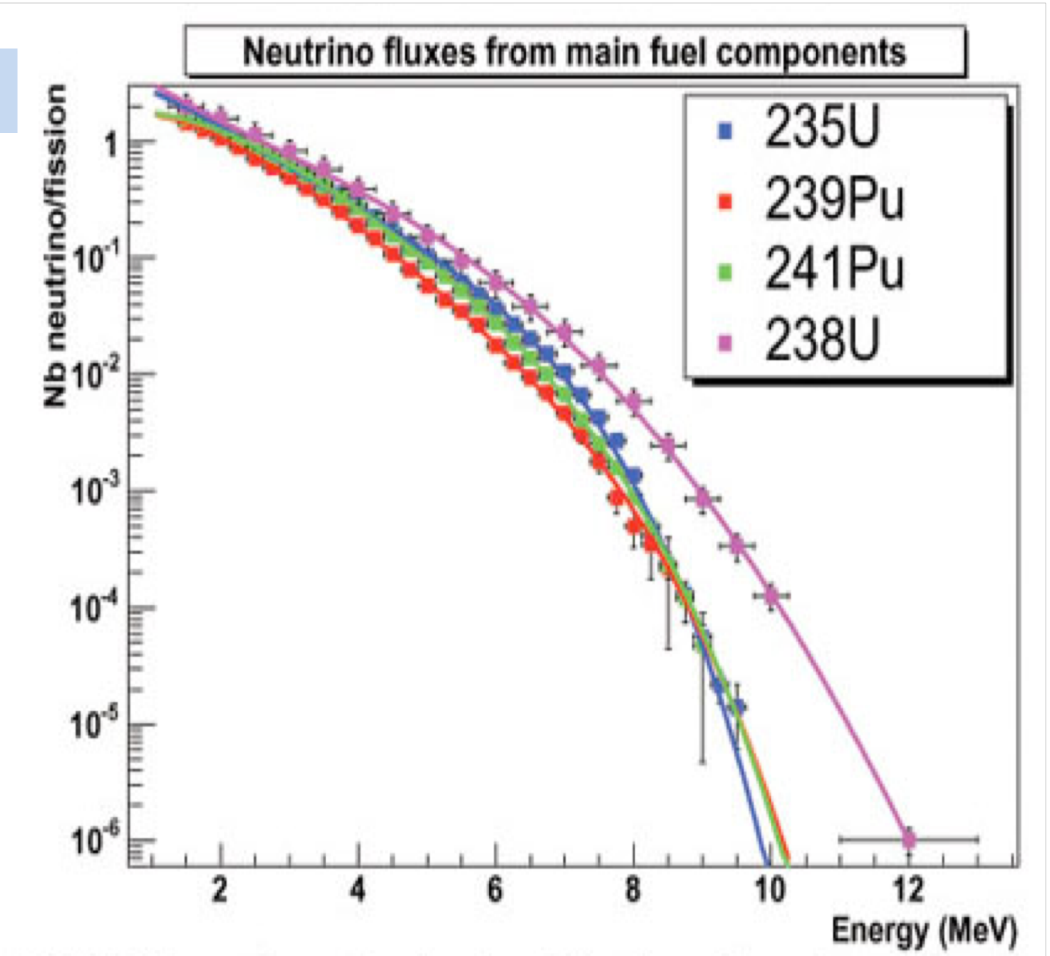
Reactor: A copious and isotropic source of electron antineutrinos

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



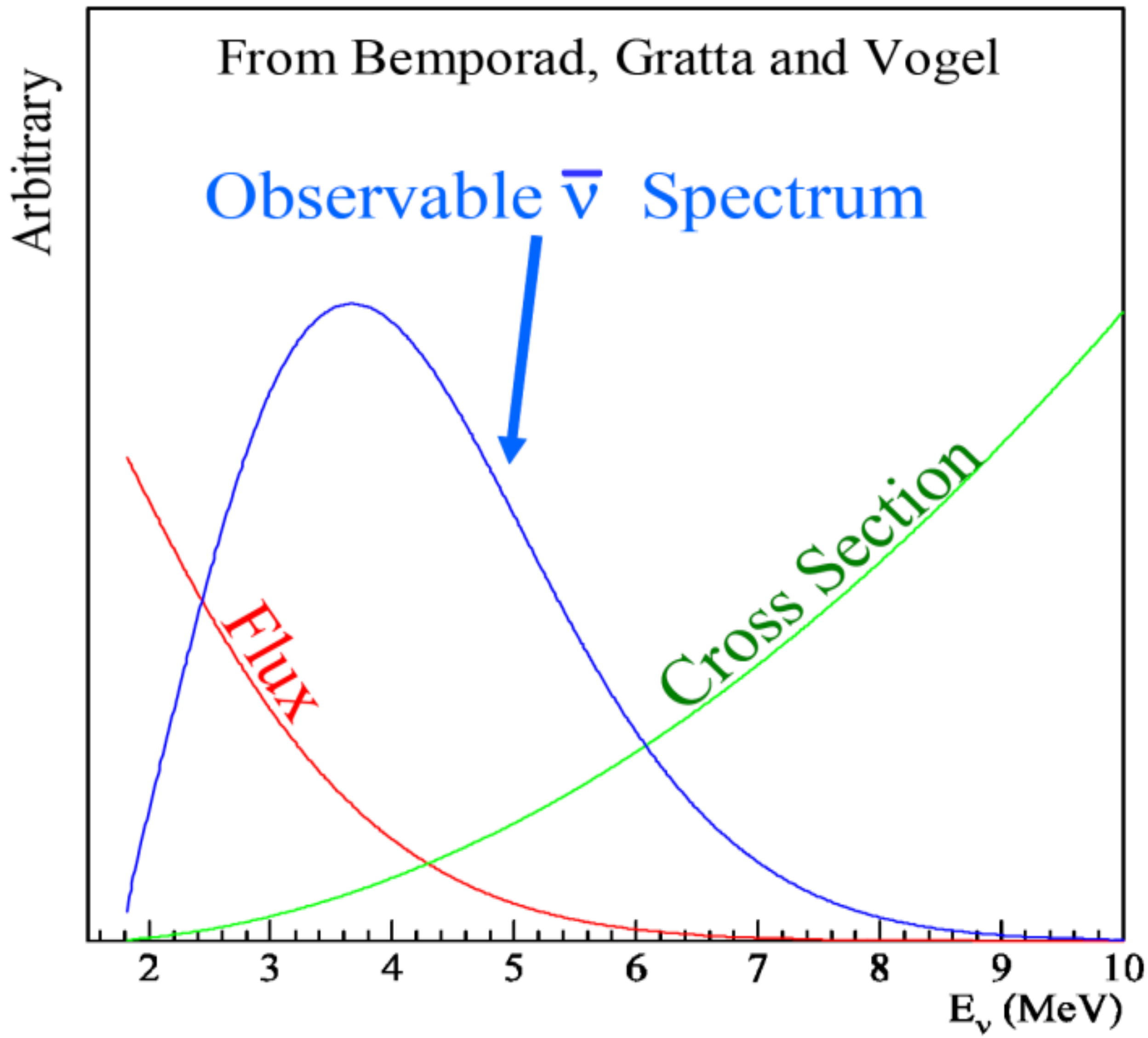
3 GW_{th} reactor
→ ~6×10^{20} $\bar{\nu}_e$/sec

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



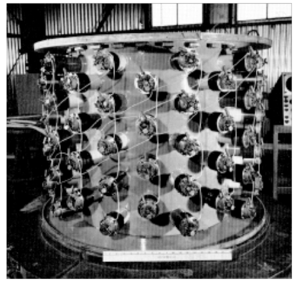
[* P. Huber, Phys. Rev. C84, 024617 (2011)
T. Mueller *et al.*, Phys. Rev. C83, 054615 (2011)]

Observable Reactor Neutrino Spectrum



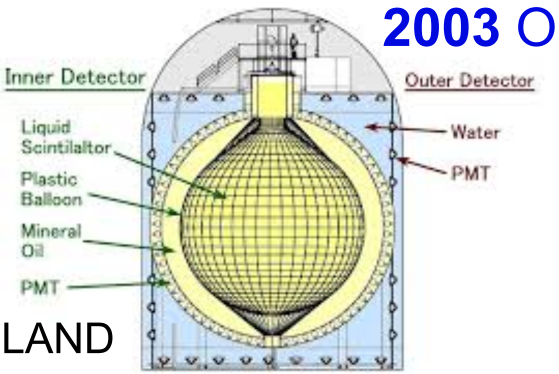
Neutrino Physics with Reactor

1956 Discovery of (anti)neutrino

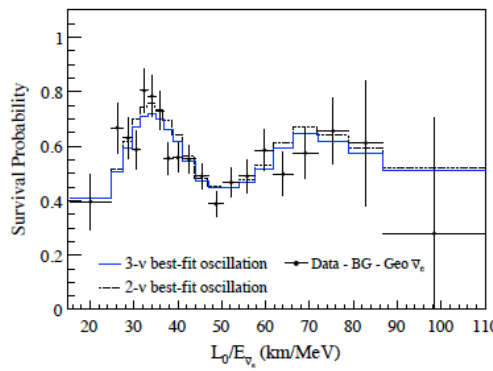


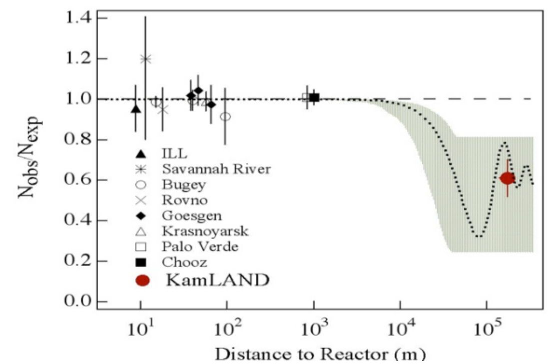
Nobel Prize in 1995

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



KamLAND



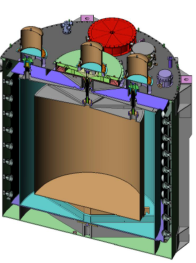


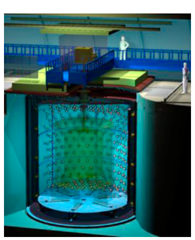
Daya Bay θ_{13}

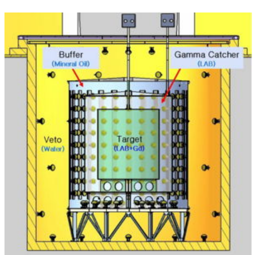
DOUBLE CHOOZ

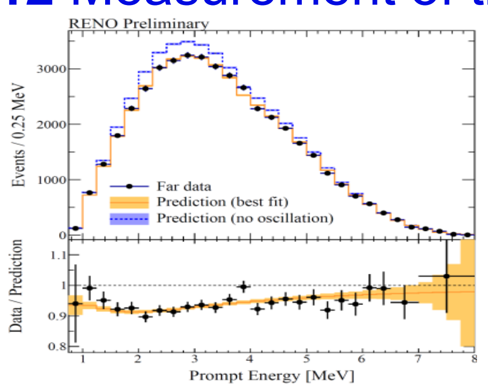
RENO ν θ_{13}

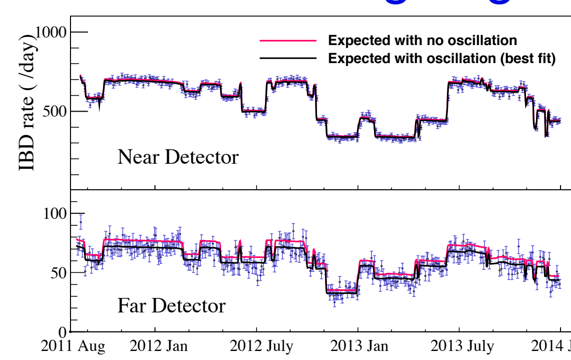
2012 Measurement of the smallest mixing angle θ_{13}









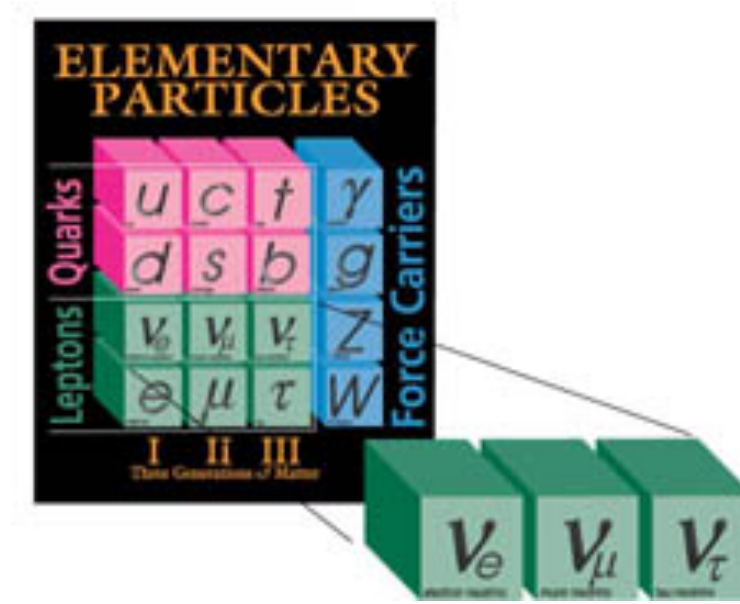


Neutrino Oscillation

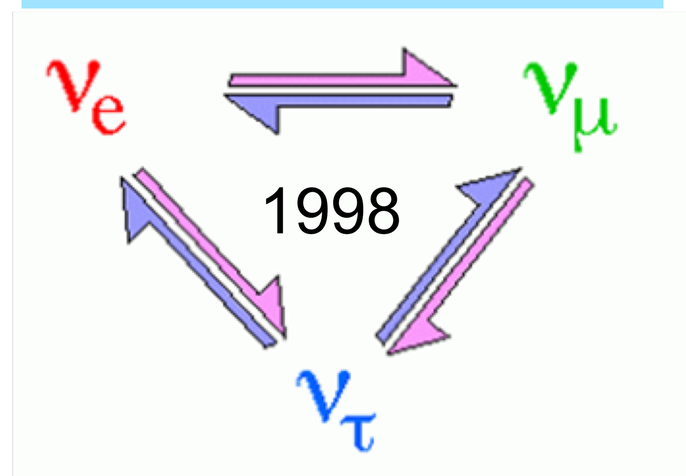
Wolfgang Pauli
(1900 - 1958)
Invention of neutrino

Frederick Reines
(1918 - 1998)
Detection of neutrino

Bruno Pontecorvo
(1913 - 1993)
Invention of neutrino oscillation



Neutrino oscillation



Neutrino Mixing Angles

Atmospheric Neutrino Oscillation	θ_{23}		**~45°** (1998) **Super-K;** K2K	2015 Nobel Prize
↓			↓	
Solar Neutrino Oscillation	θ_{12}		**34°** (2001) **SNO, Super-K;** KamLAND	
↓			↓	
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"

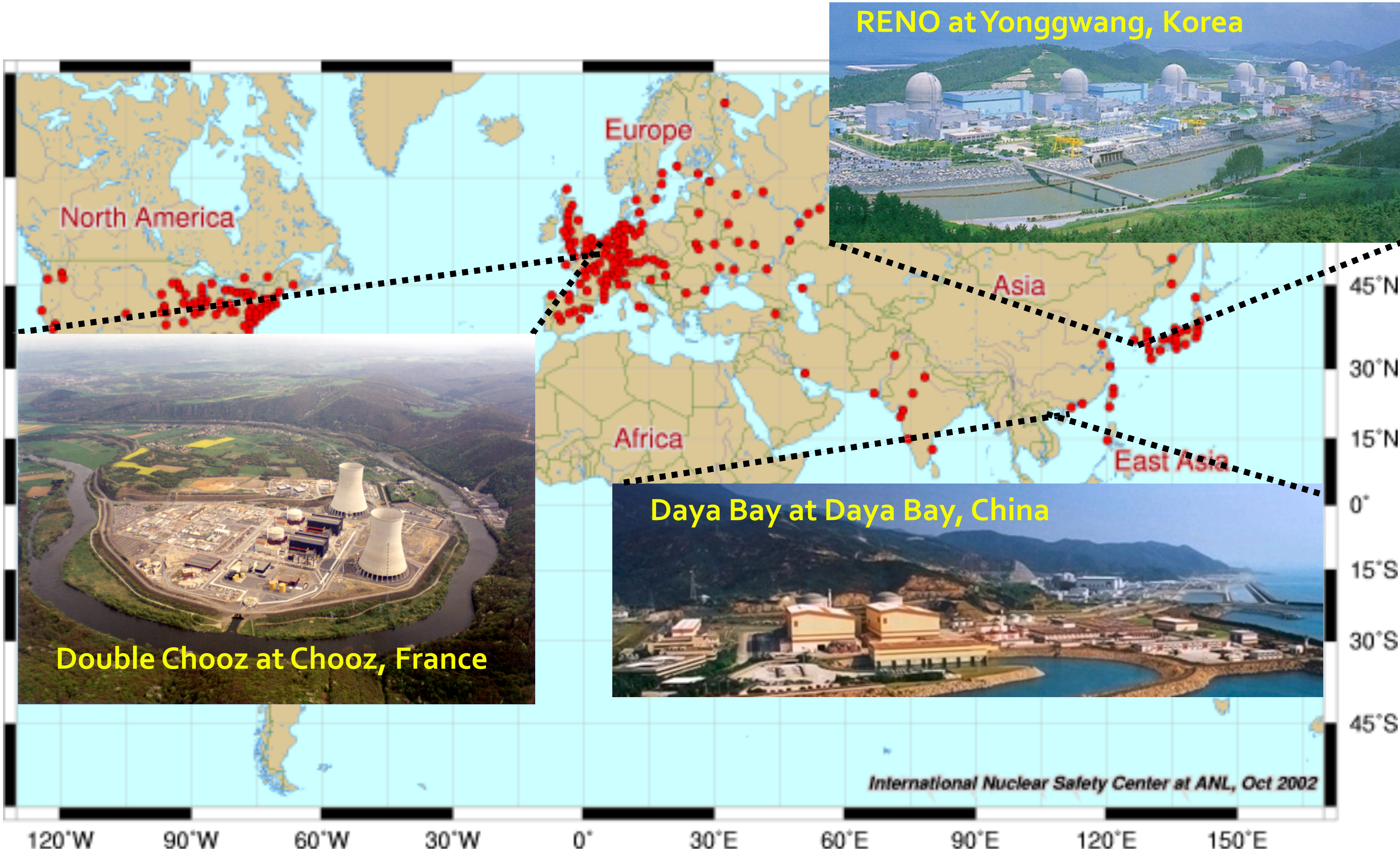
Impact of θ_{13} Measurement

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

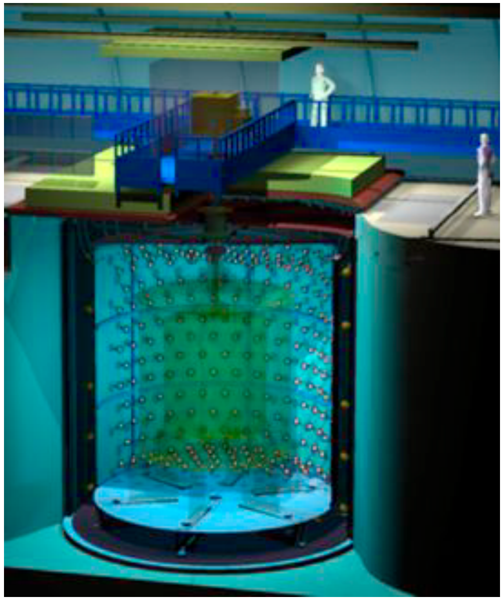
→ Open a new window for determining
(1) CP violating phase, and
(2) neutrino mass ordering
without a neutrino factory

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

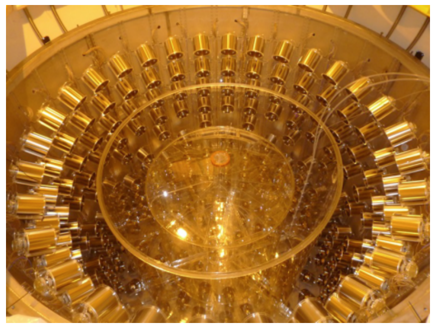
Reactor θ_{13} Experiments

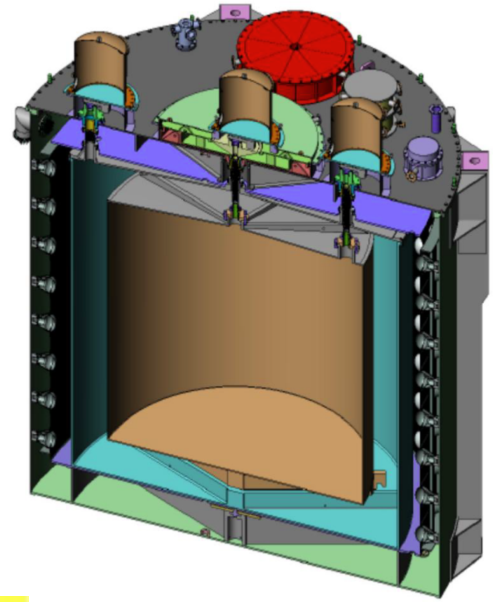


θ_{13} Reactor Neutrino Detectors

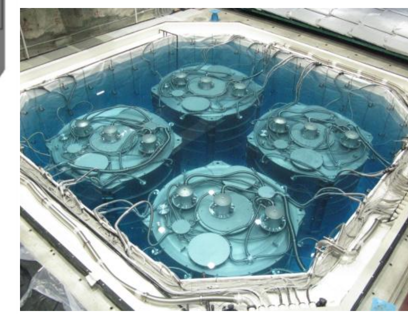


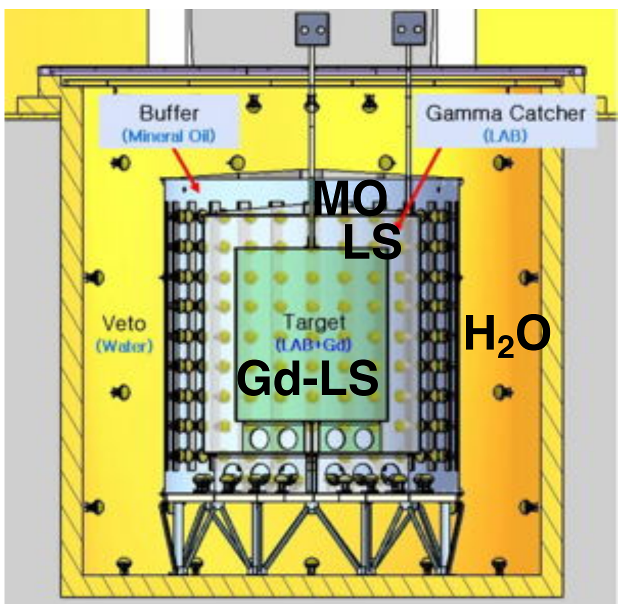
DOUBLE CHOOZ





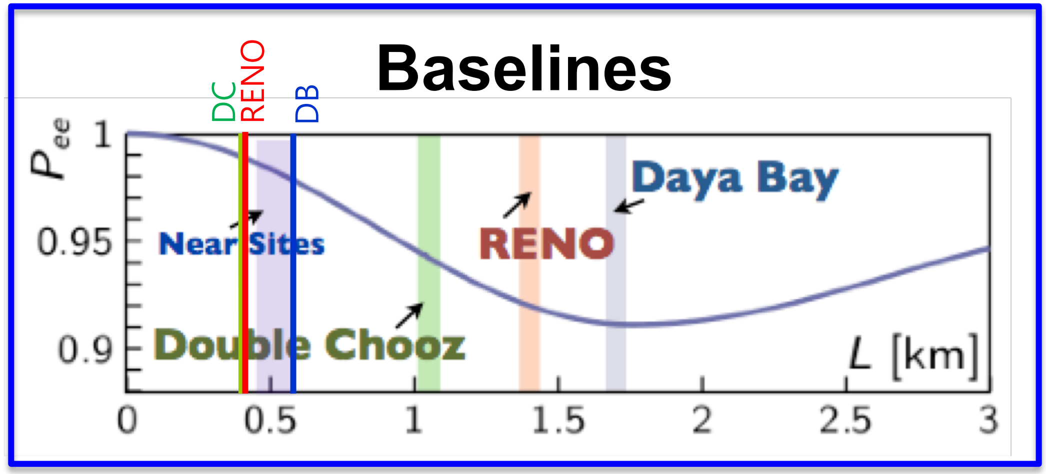
Daya Bay θ_{13}

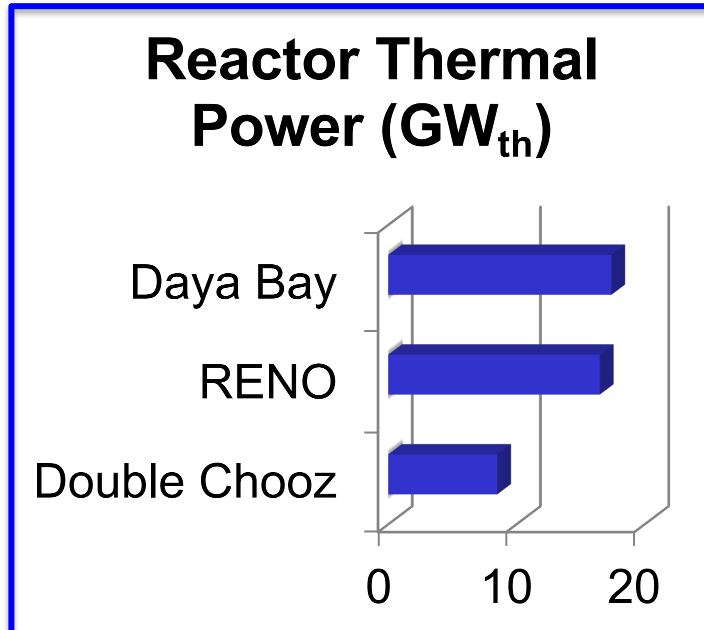


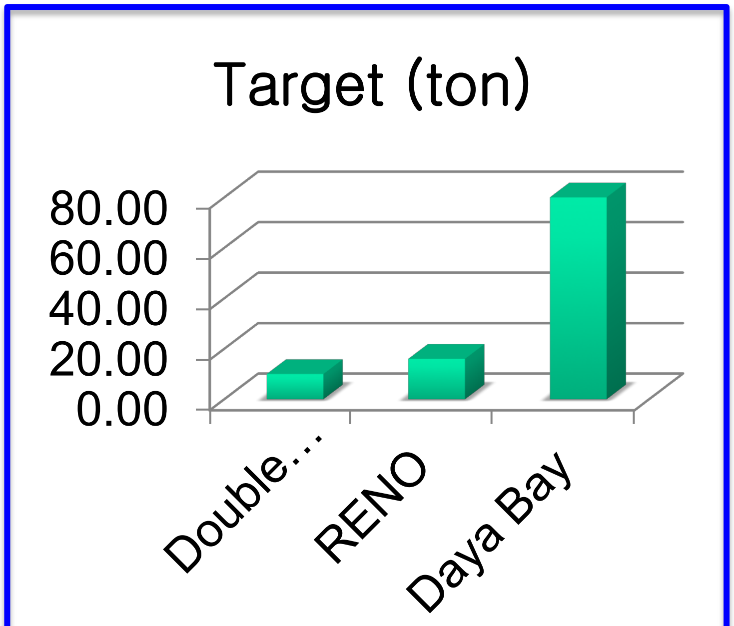


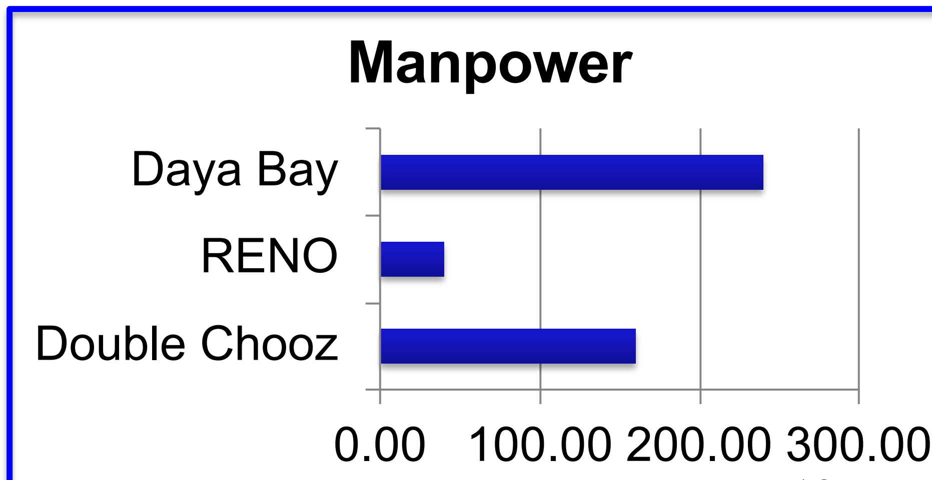
RENO ν θ_{13}

Comparisons of Reactor θ_{13} Experiments









RENO Collaboration

Reactor Experiment for Neutrino Oscillation

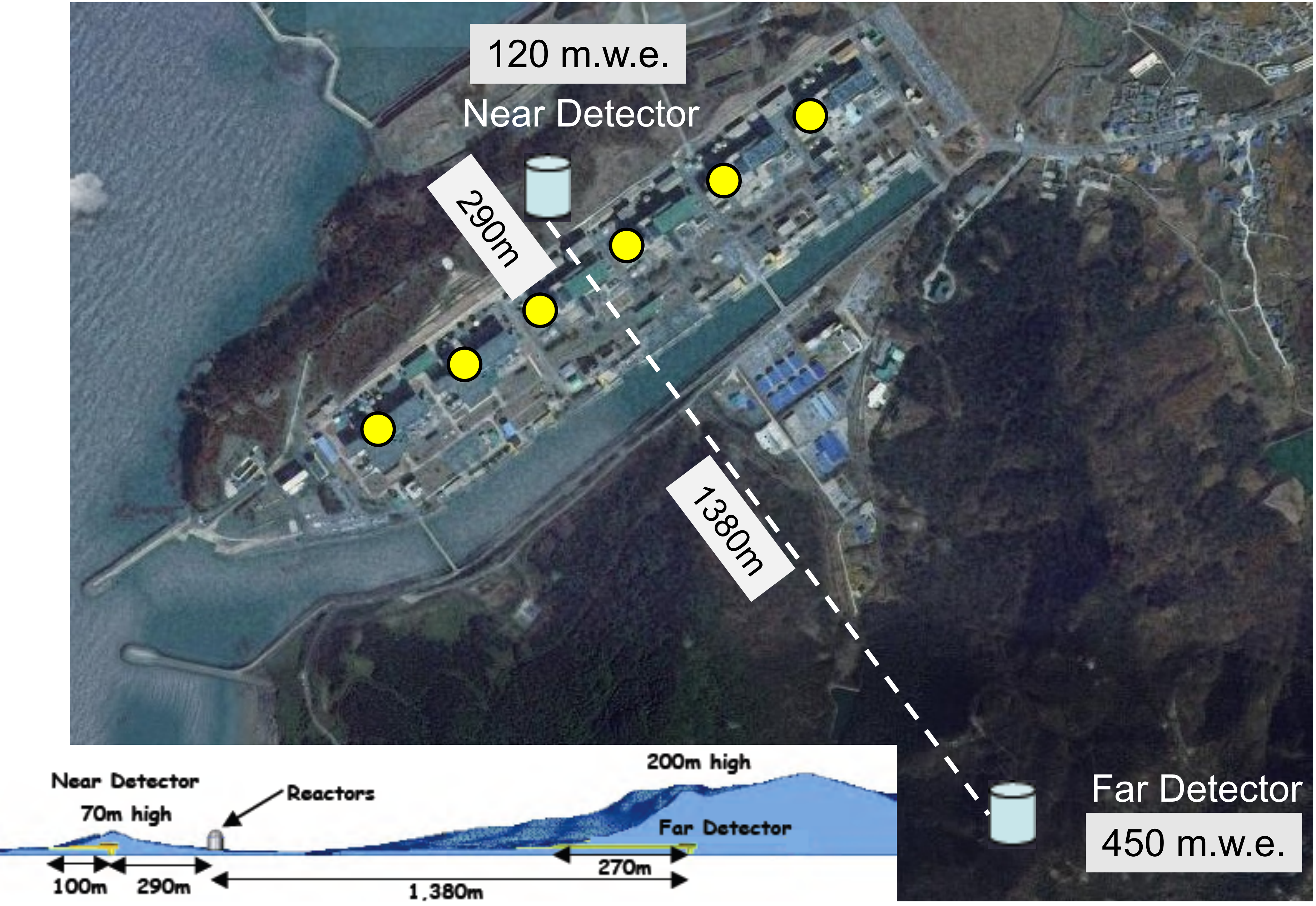
(7 institutions and 40 physicists)

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

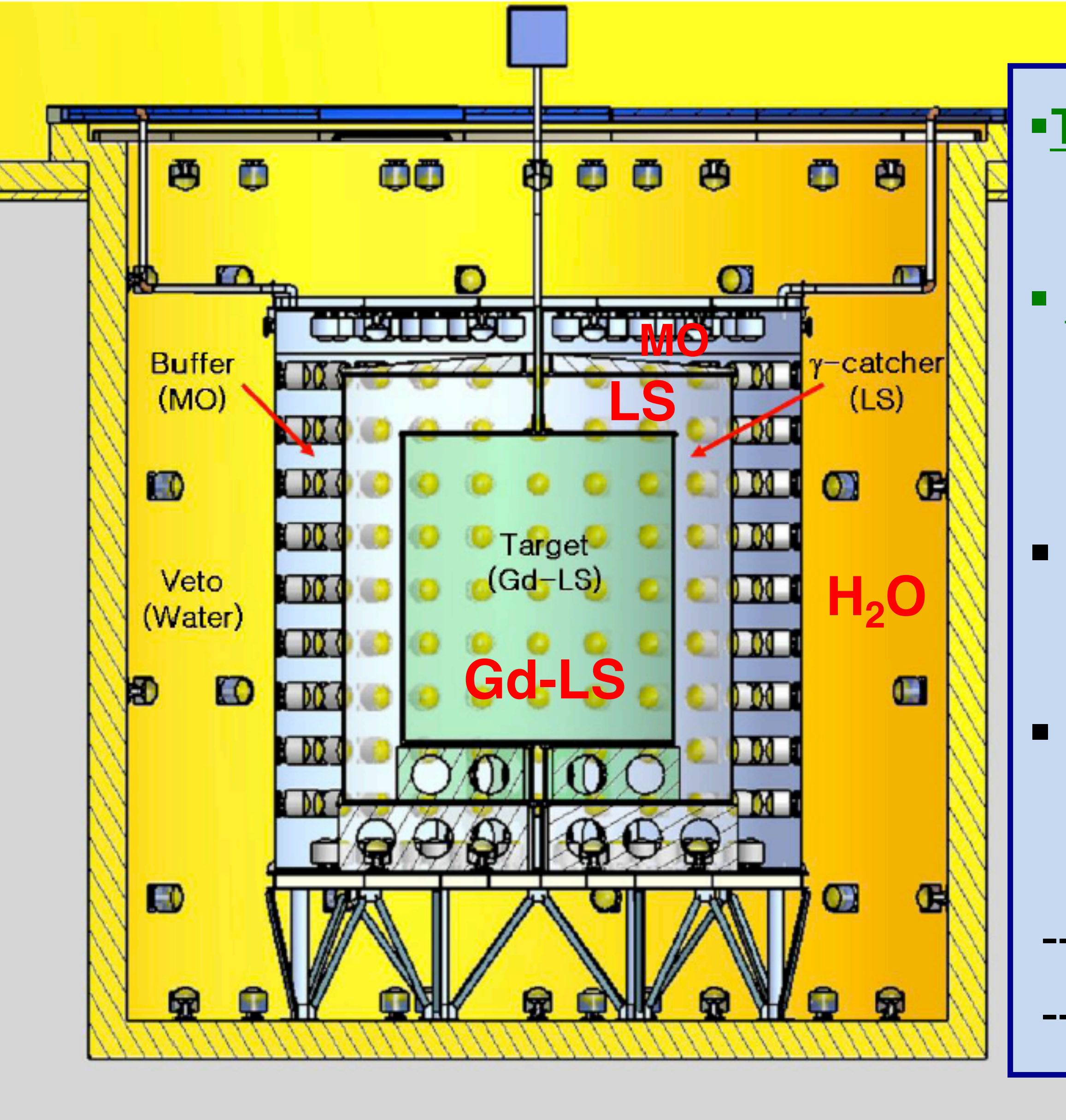
- Total cost : $10M
- Start of project : 2006
- The first experiment running with both near & far detectors from Aug. 2011

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

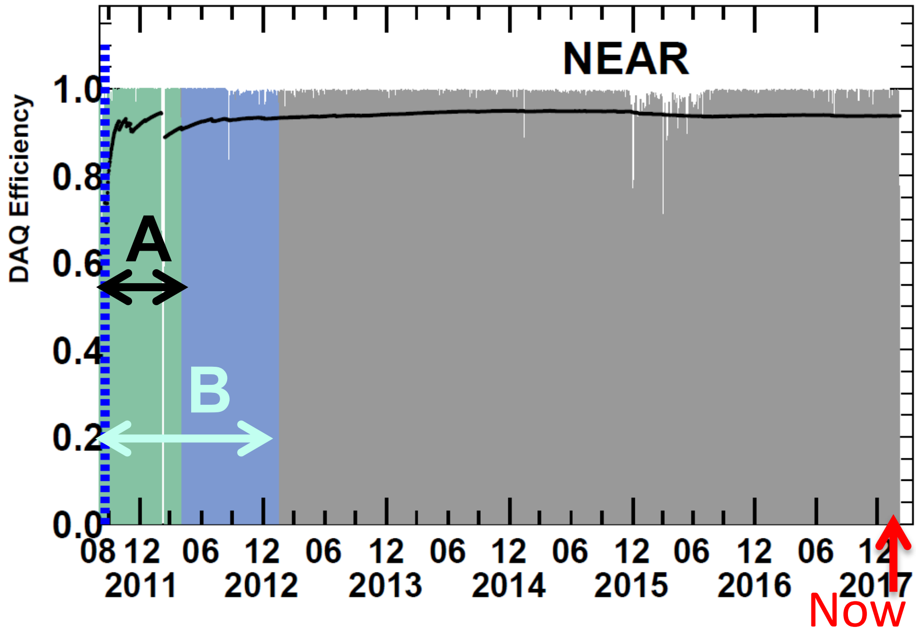
RENO Data-taking Status

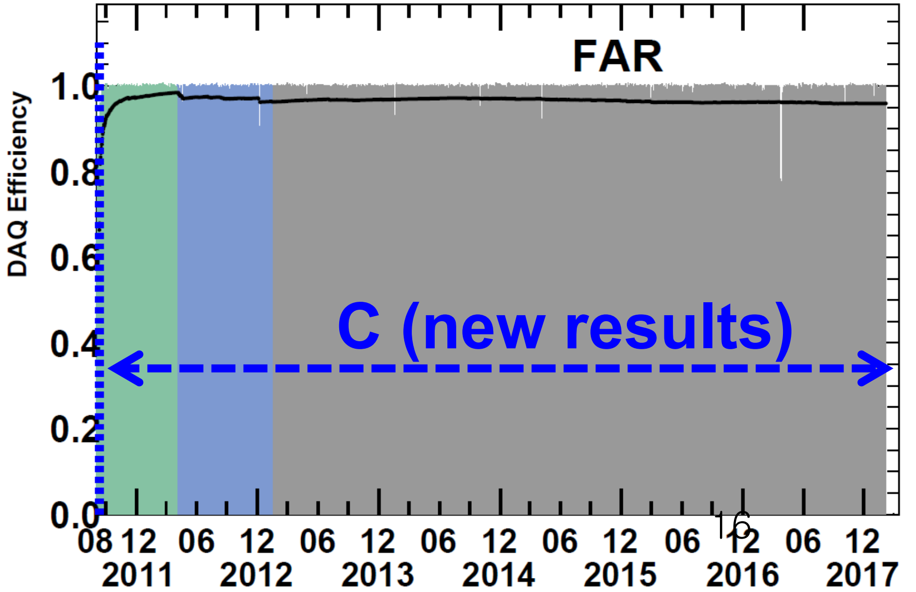
- Data taking began on Aug. 1, 2011 with both near and far detectors.
  (DAQ efficiency : ~95%)

- **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 $|\Delta m^2_{ee}|$)
  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 $|\Delta m^2_{ee}|$)
  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" (*Phys. Rev. Lett. 121, 201801* (2018. 11. 15))

- Fuel-composition dependent reactor antineutrino yield and spectrum

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

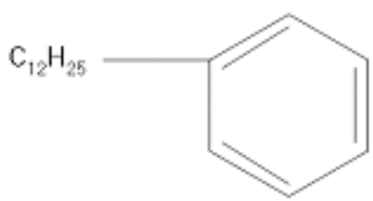
- Independent measurement of θ_{13} with delayed n-H IBD analysis

Detection of Reactor Antineutrinos

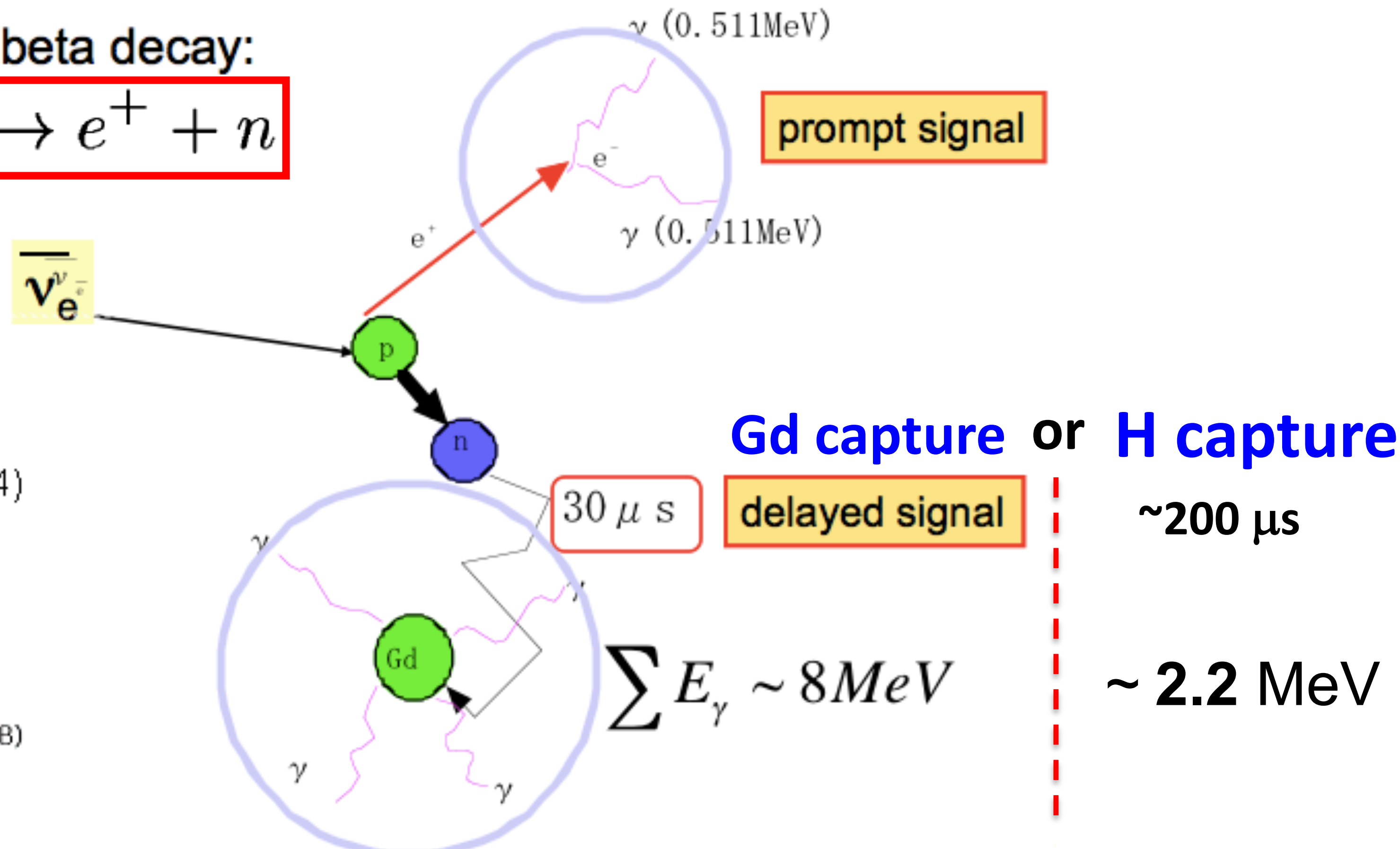
Inverse beta decay:

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

$C_nH_{2n+1}\text{-}C_6H_5$ (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**

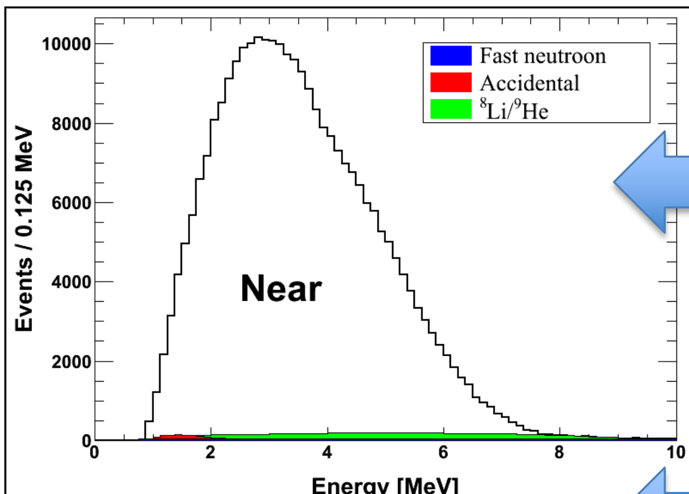
  ~30 μs or ~200 μs

Coincidence of prompt and delayed signals

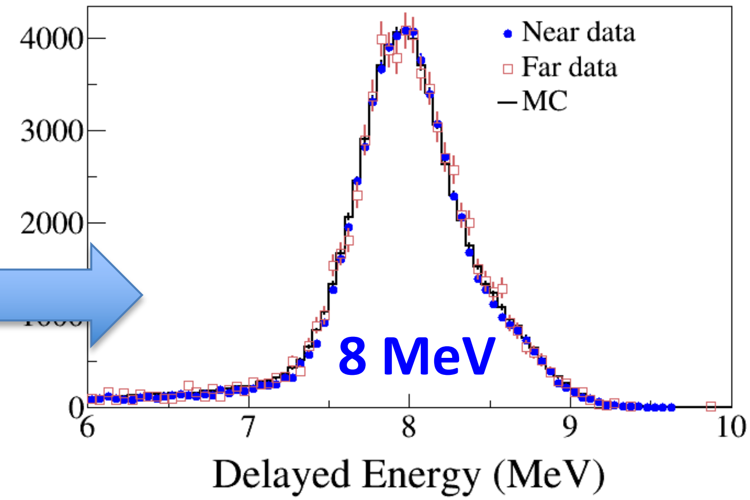
(prompt signal)

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

Prompt signal



Delayed signal

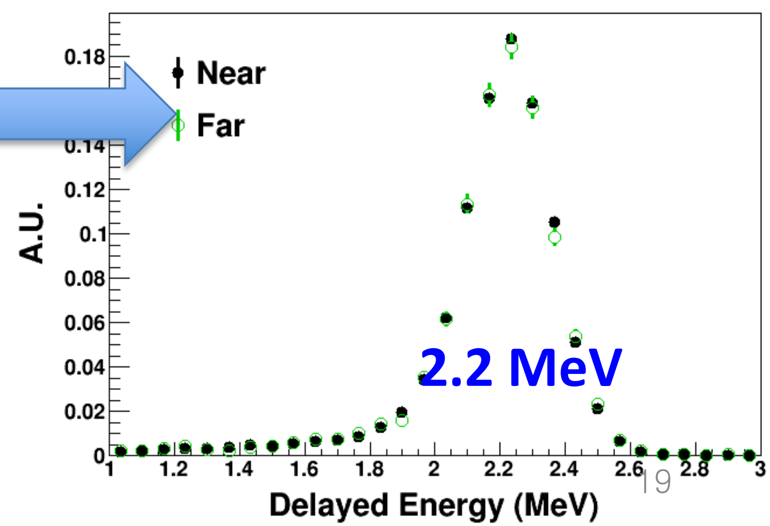


n-Gd IBD

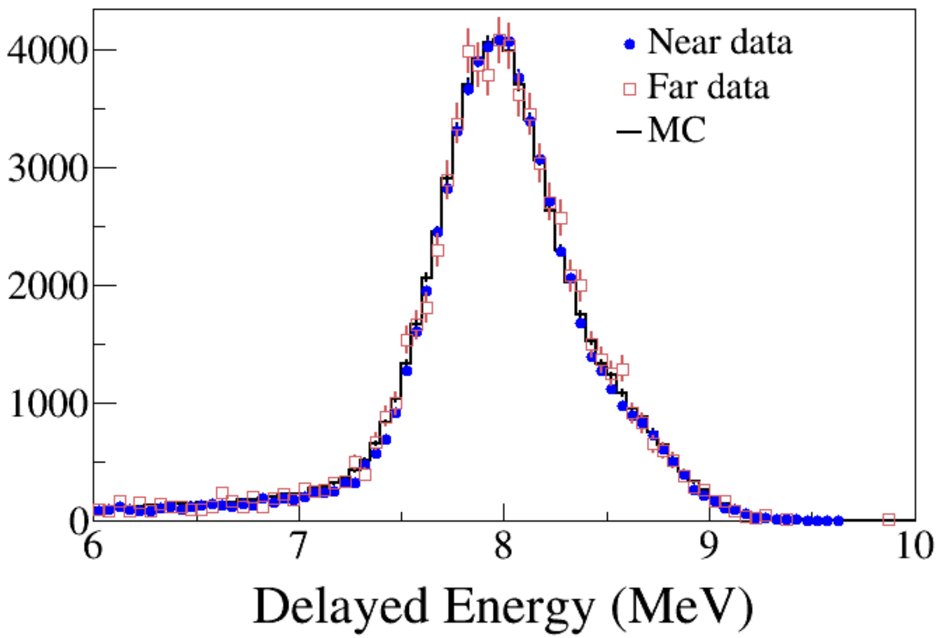
~30 μs

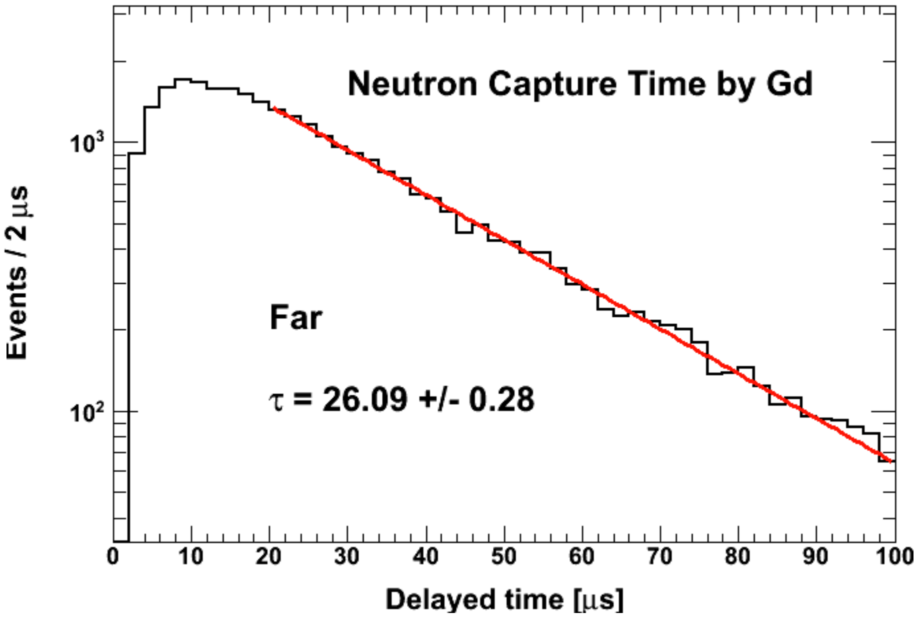
~200 μs

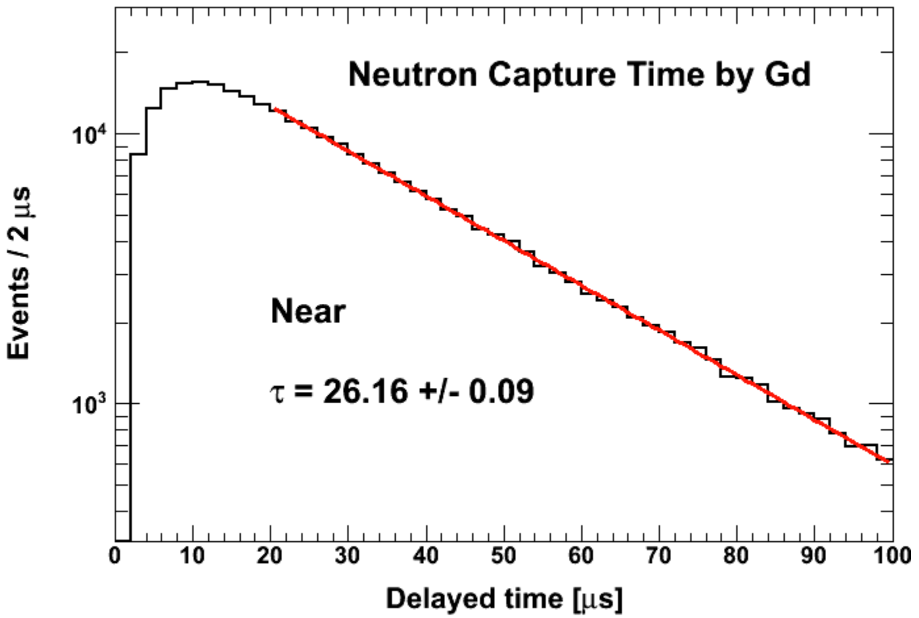
n-H IBD



Delayed Signals from Neutron Capture by Gd

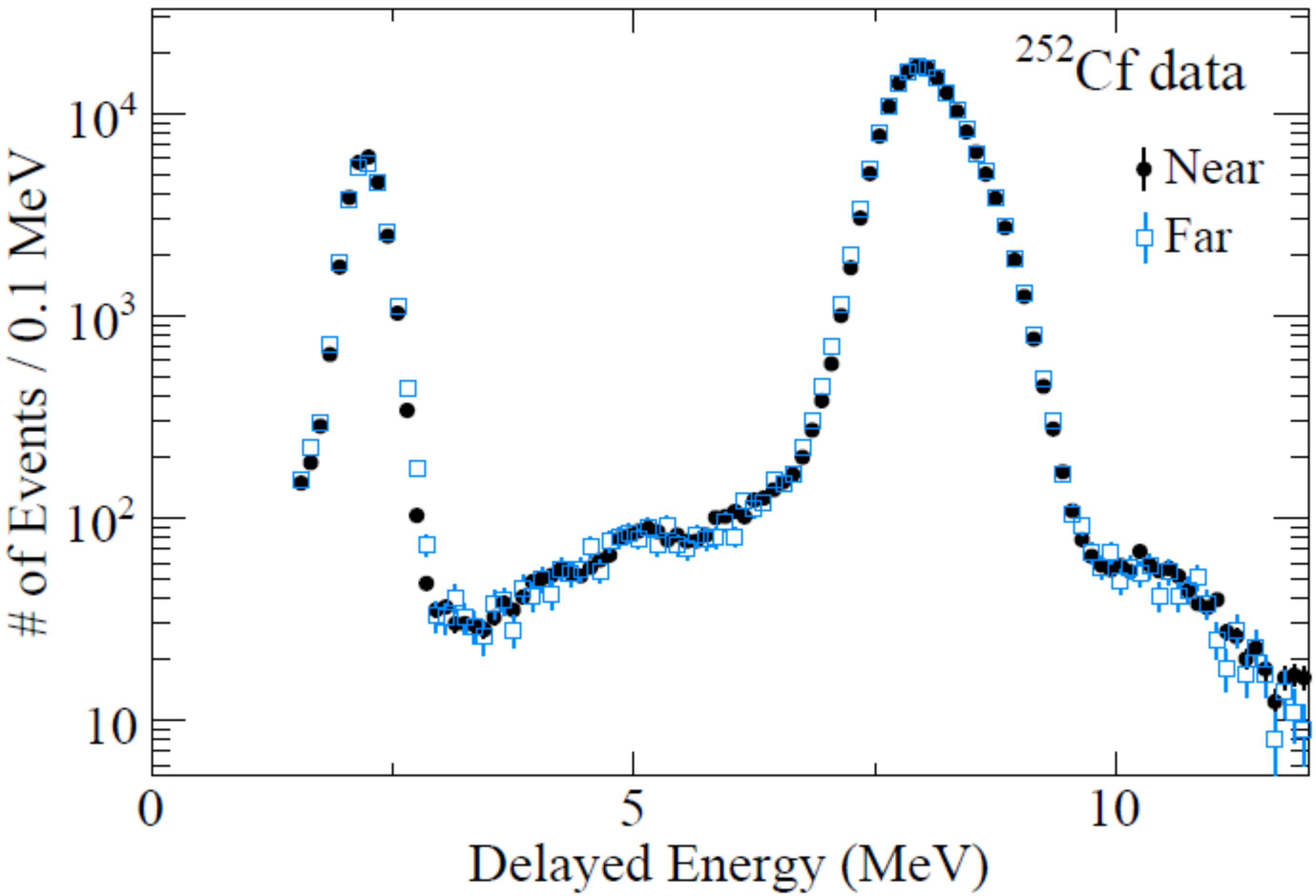






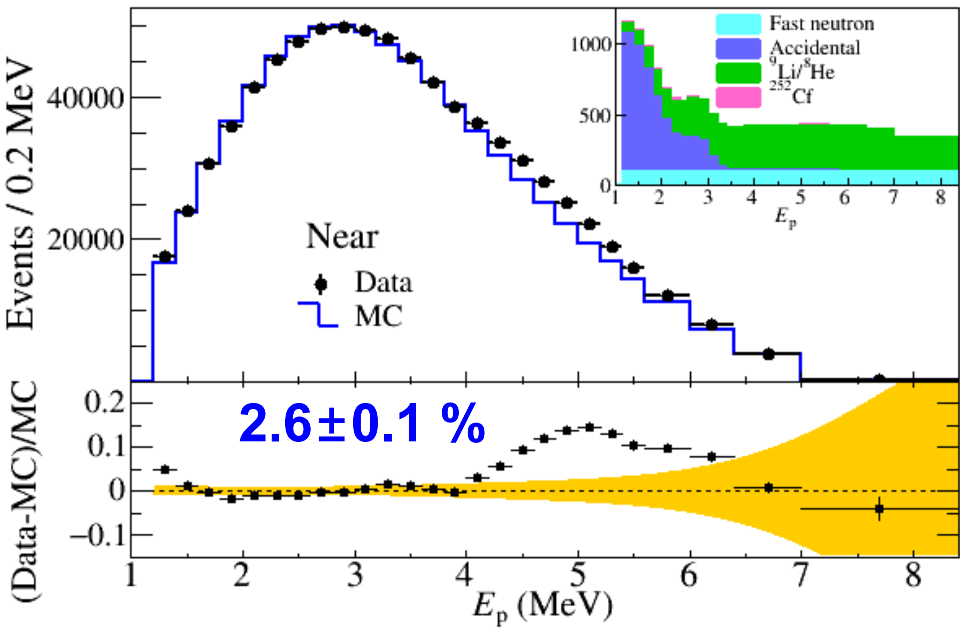
Identical Performance of Near and Far Detectors

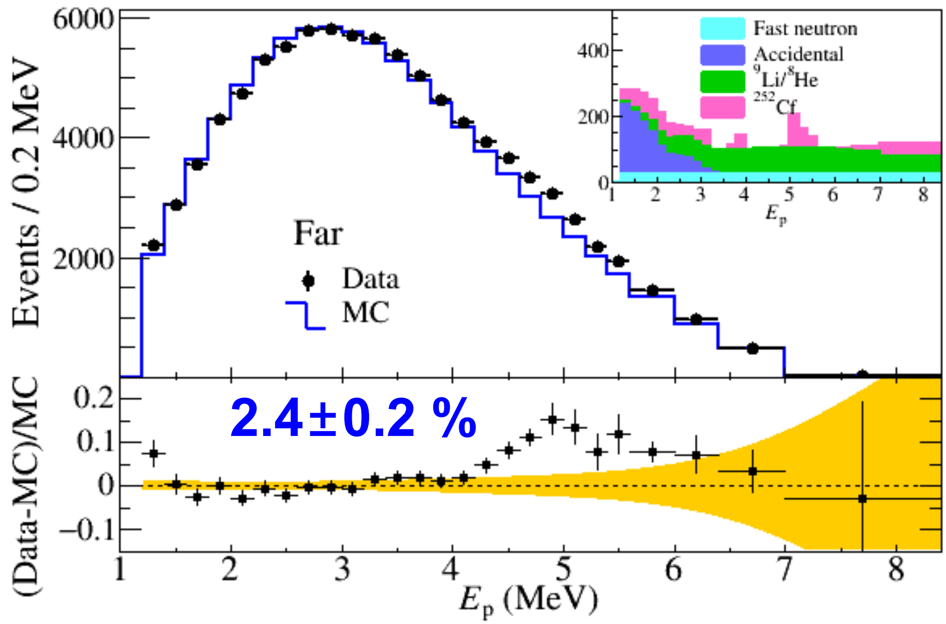
Spectra of Delayed Signals Using ^{252}Cf Source



Measured Spectra of IBD Prompt Signal

Clear excess at 5 MeV

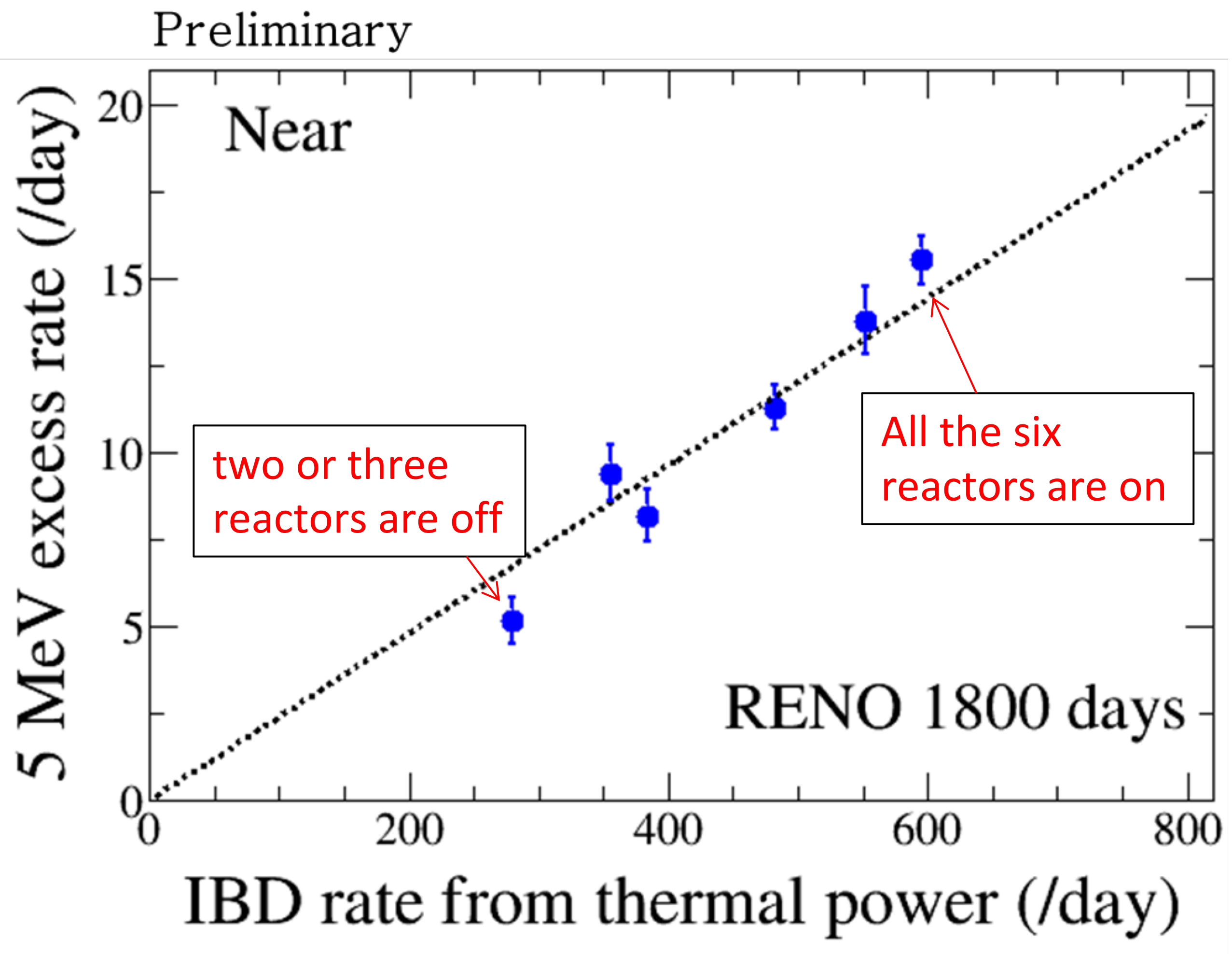




Near Live time = 1807.88 days
# of IBD candidate = 850,666
Background : 2.03±0.06%

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

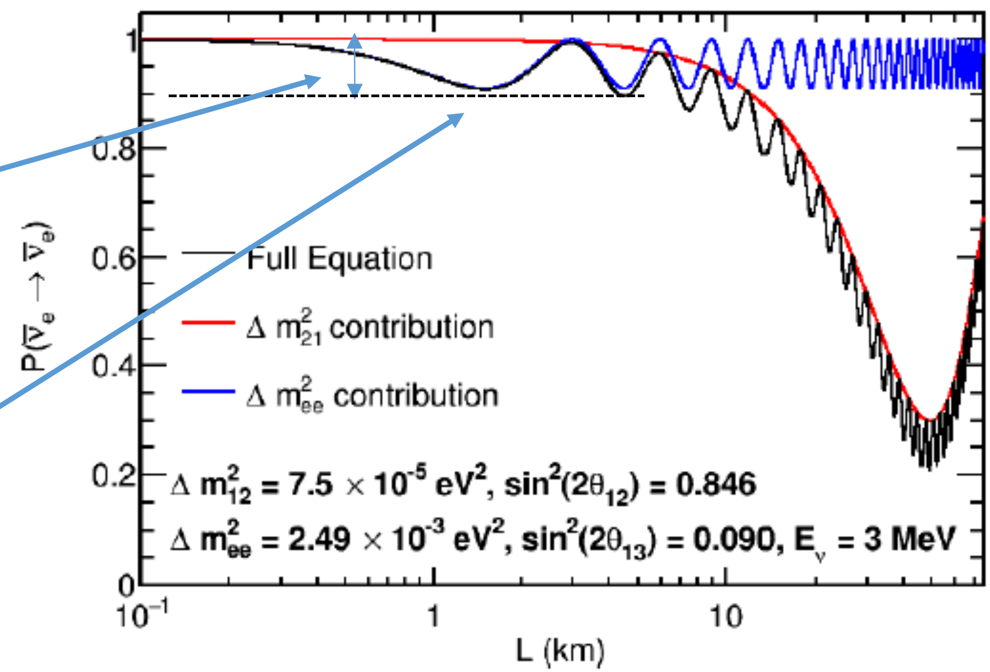
$$P(\bar{\nu}_e \to \bar{\nu}_e) \simeq 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\frac{\Delta m^2_{21}L}{4E}\right) - \sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{ee}L}{4E}\right)$$

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

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

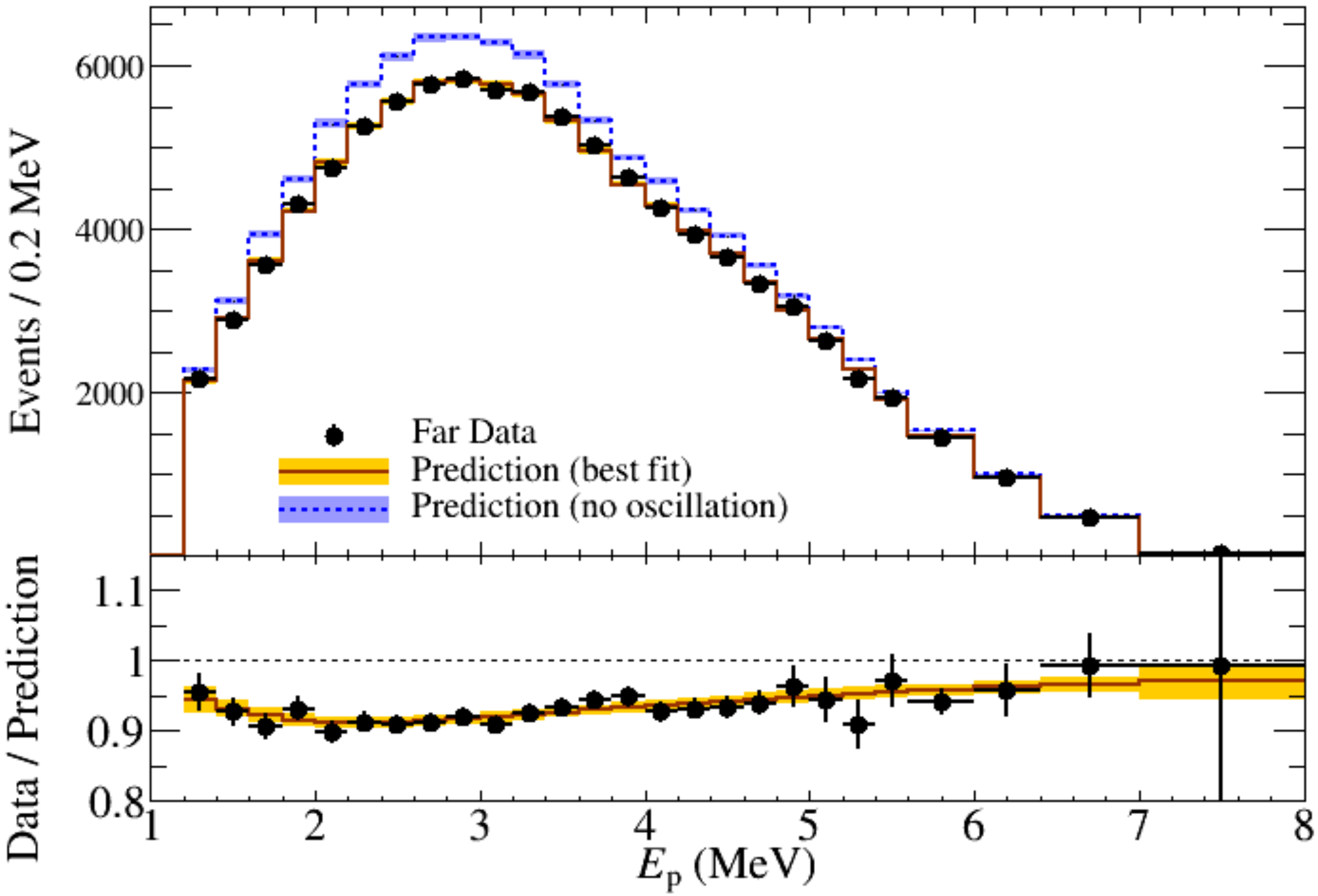
$\sin^2(2\theta_{13})$ is determined by **oscillation amplitude.**

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

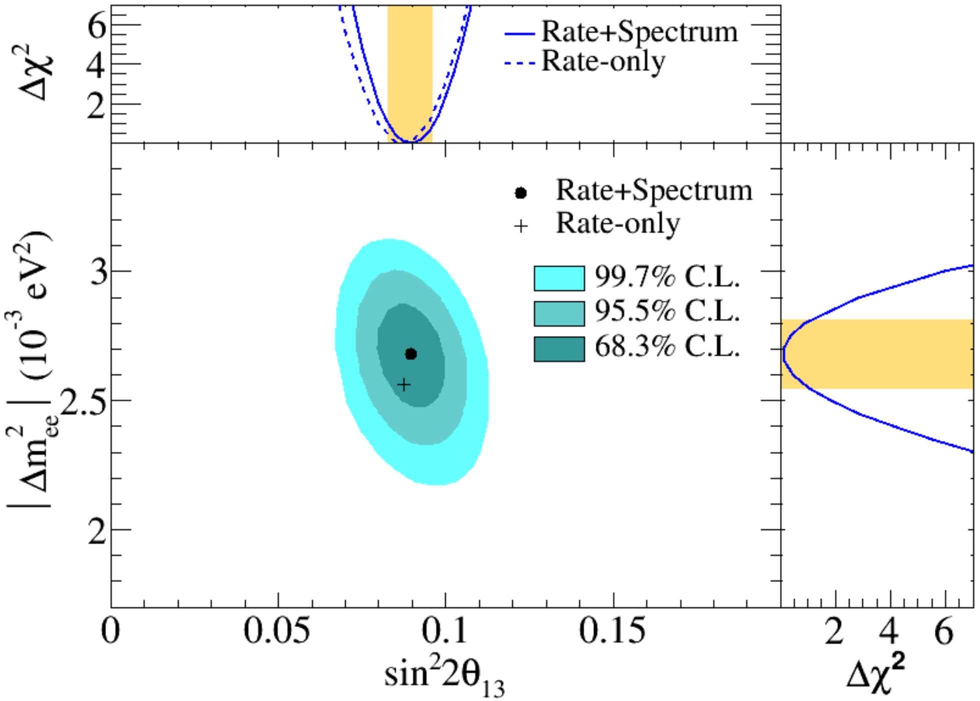


Measurement of $|\Delta m_{ee}^2|$ and θ_{13}

Energy-dependent disappearance of reactor antineutrinos



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



<500 days>

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

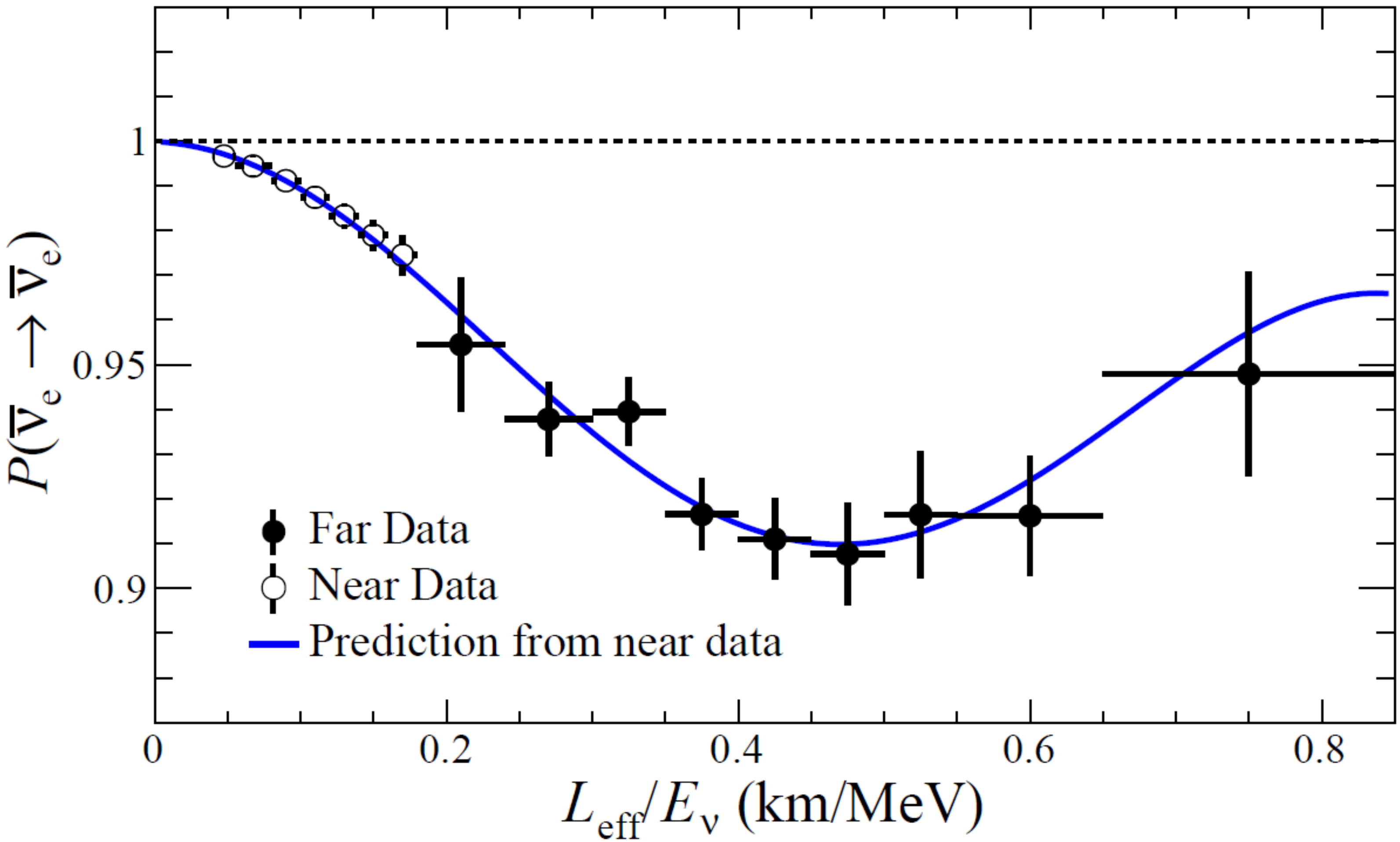
$$|\Delta m^2_{ee}| = [2.62^{+0.21}_{-0.23}(\text{stat.})^{+0.12}_{-0.13}(\text{syst.})] \times 10^{-3}\ \text{eV}^2$$

<2200 days>

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

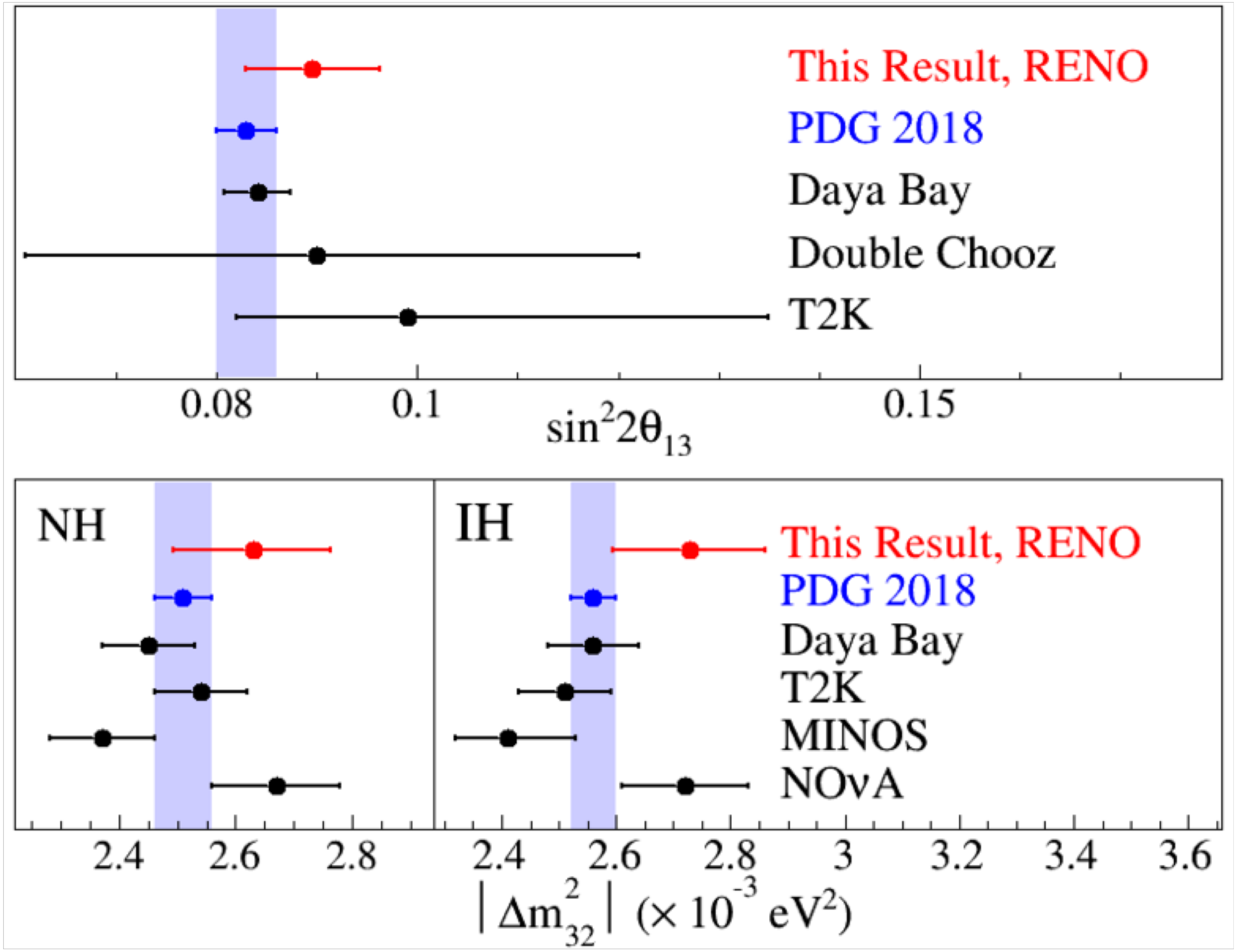
$$|\Delta m^2_{ee}| = 2.68 \pm 0.12(\text{stat.}) \pm 0.07(\text{syst.})(\times 10^{-3}\text{eV}^2)$$ (± 5.2 %)

Observed L/E Dependent Oscillation

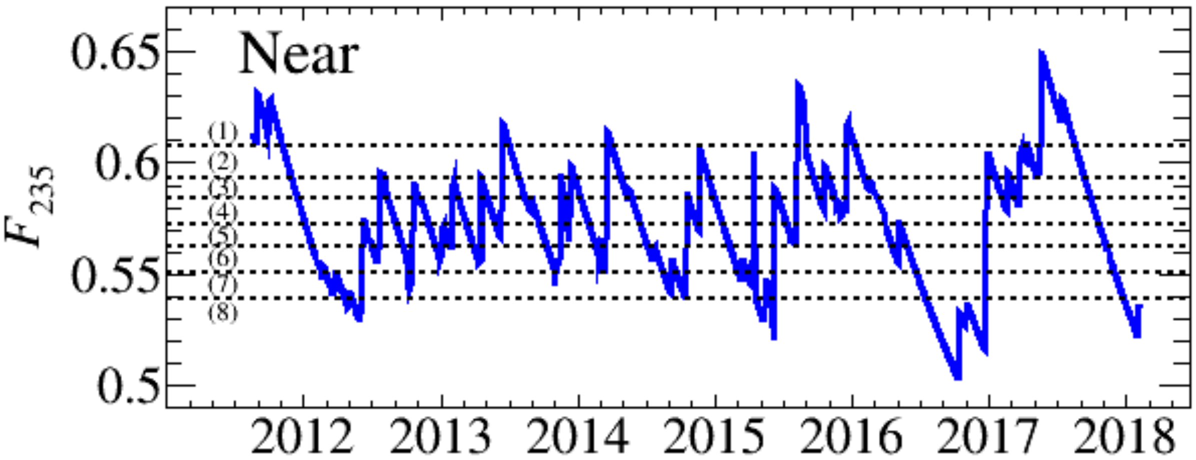


$$P(\overline{\nu}_e \rightarrow \overline{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\Delta m^2_{ee} \frac{L}{4E_\nu}\right)$$

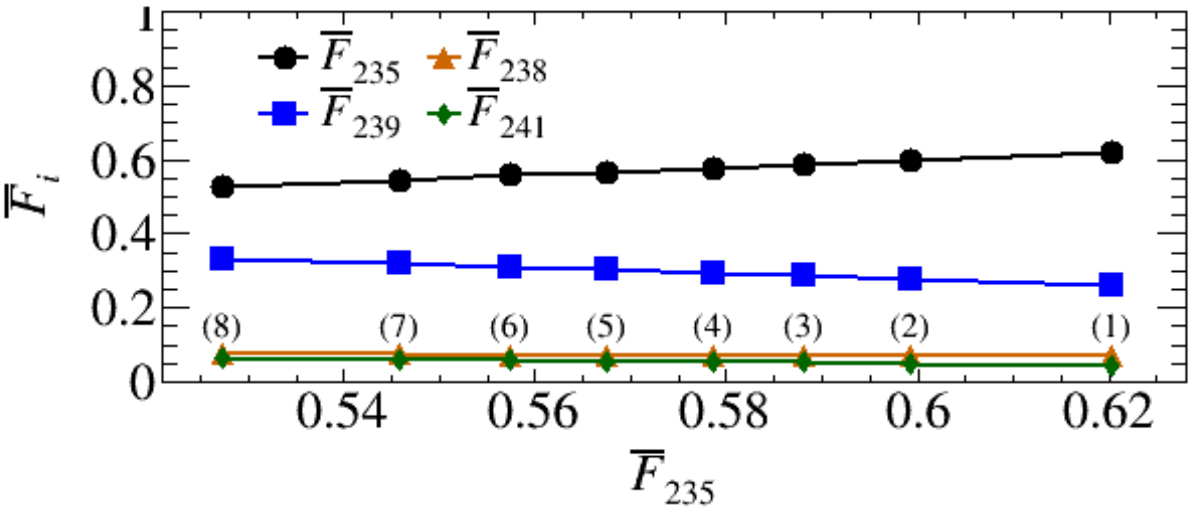
Comparison of θ_{13} and $|\Delta m_{ee}^2|$ Results



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

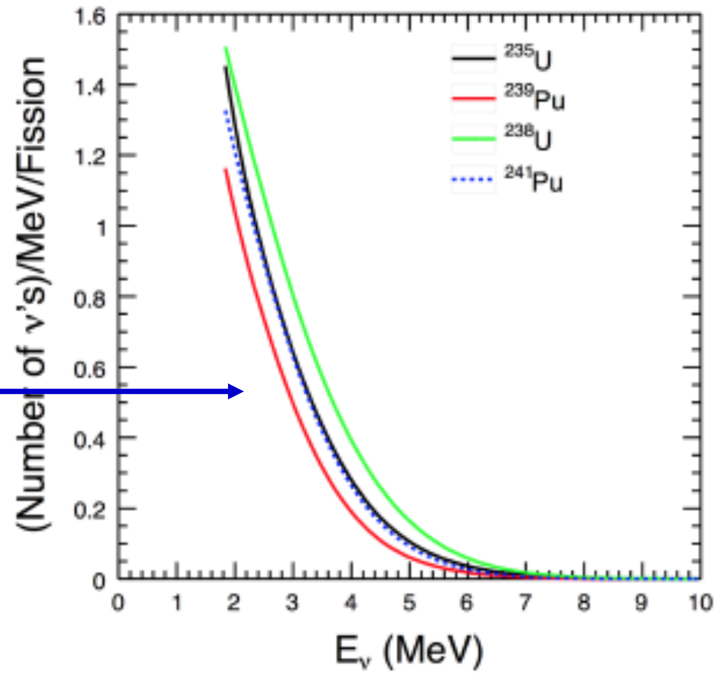
IBD yield per fission for each isotpoe

(Total # of produced IBD events)

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

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 +- 0.14
y_{239}	4.38 +- 0.11
y_{238}	10.07 +- 0.82
y_{241}	6.07 +- 0.13

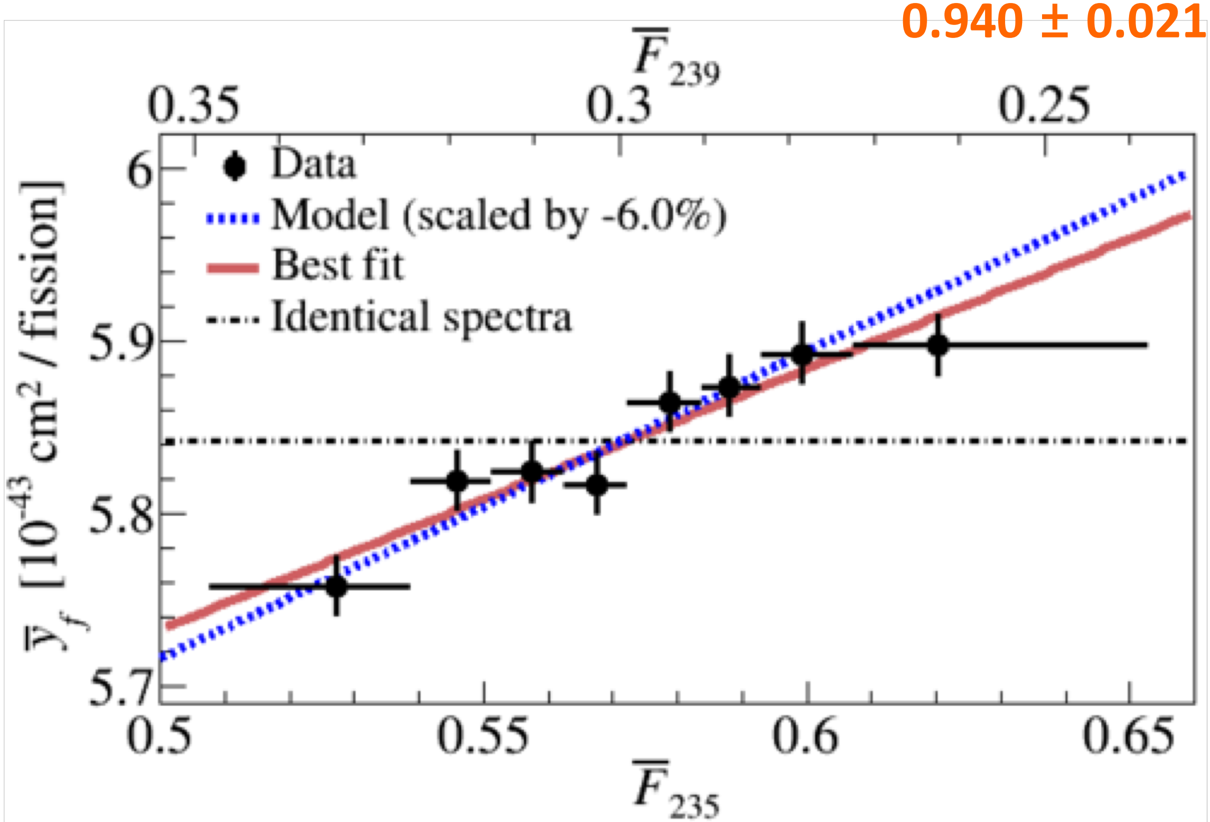
Fuel-Composition Dependent Reactor Neutrino Yield

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

- N_j: # of Observed IBD
- $\bar{y}_{f,j}$: Measured IBD yield per fission
- N_p: # of Target proton
- $\sum_i f_{i,r}(t)E_i$: # of fission
- $\epsilon_d(t)$: Detection Efficiency

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)% deficit

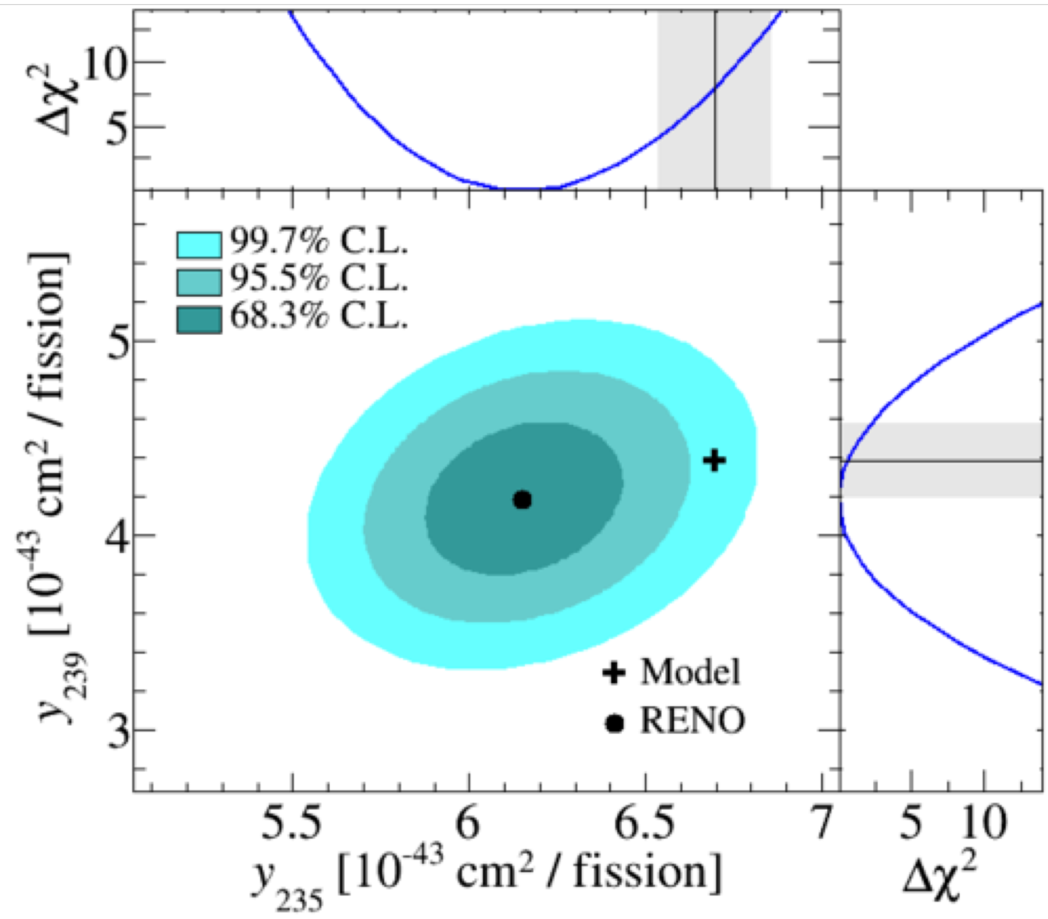


Averaged IBD yield per fission ($\bar{y}_f$) vs $\bar{F}_{i,j}$
→ slope means **different neutrino spectrum** for each isotope
→ rules out the no fuel-dependent variation at **6.6σ**

The scaled model indicates the **reactor 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} :

2.8 σ deficit

6.15 ± 0.19/6.70 ± 0.14

The best-fit value of y_{239} :

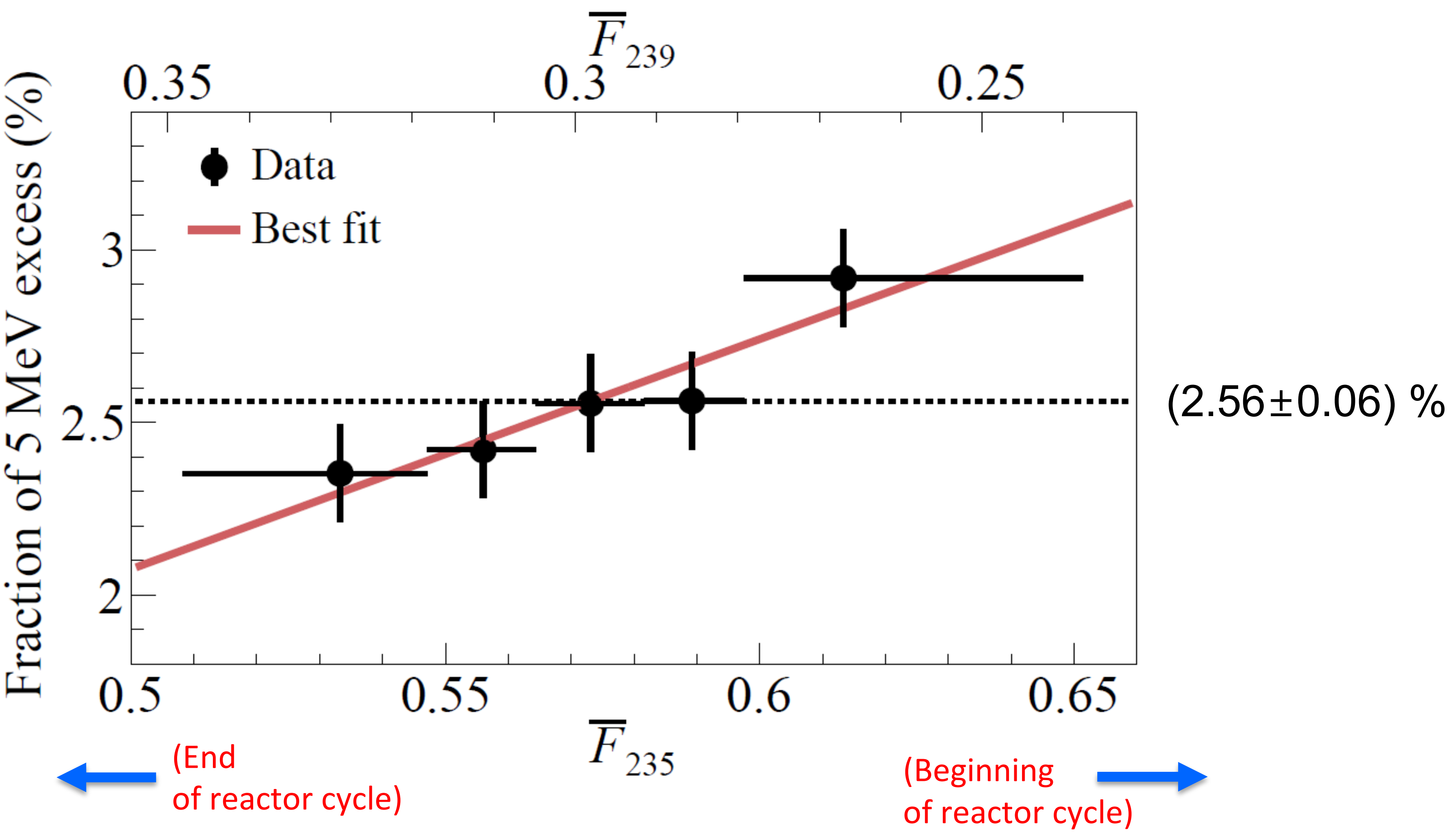
0.8 σ deficit

4.18 ± 0.26/4.38 ± 0.11

Reevaluation of the y_{235} may **mostly solve** the 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

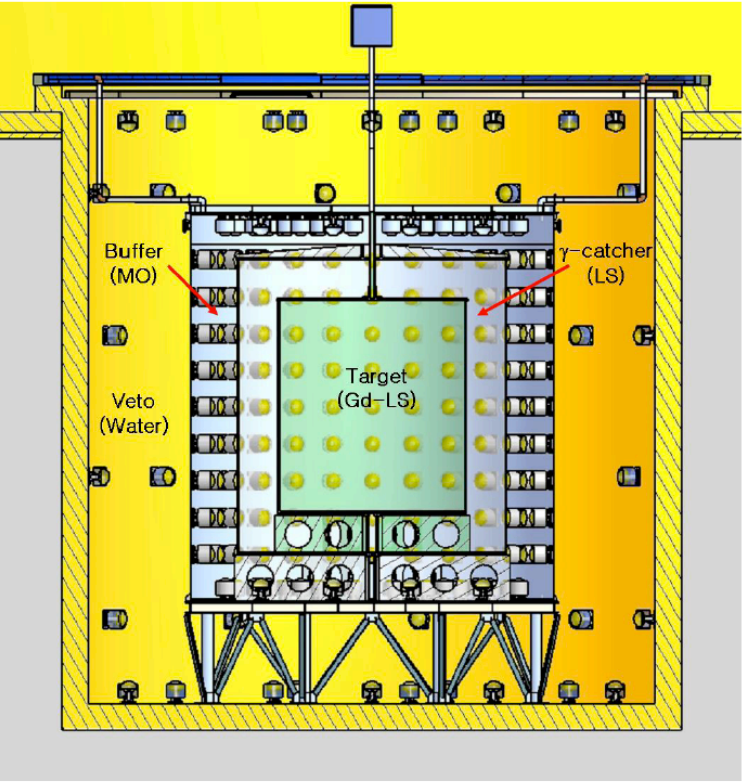
2.9σ indication of 5 MeV excess coming from ^{235}U fuel isotope fission !!



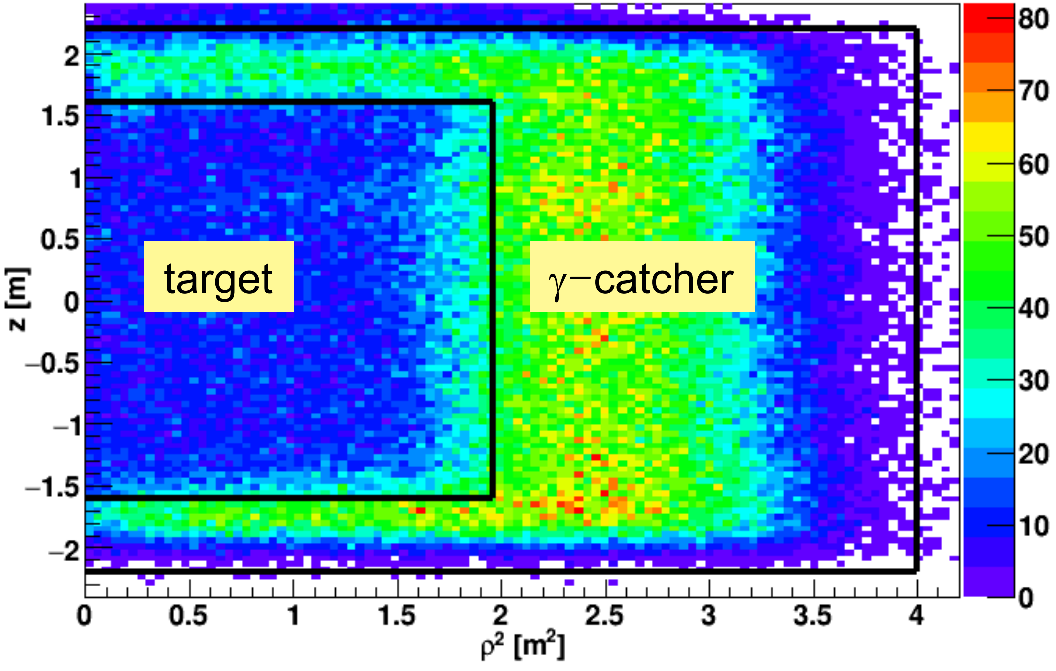
n-H IBD Analysis

Motivation:

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

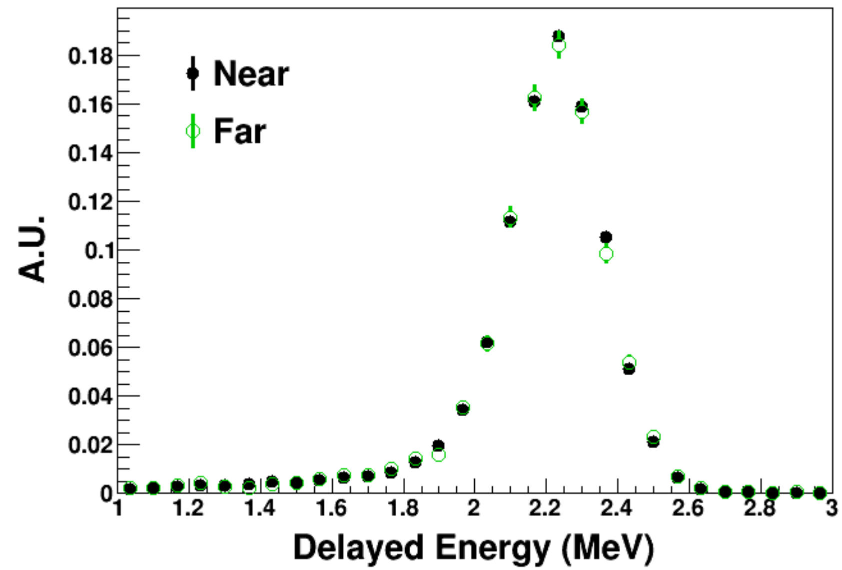


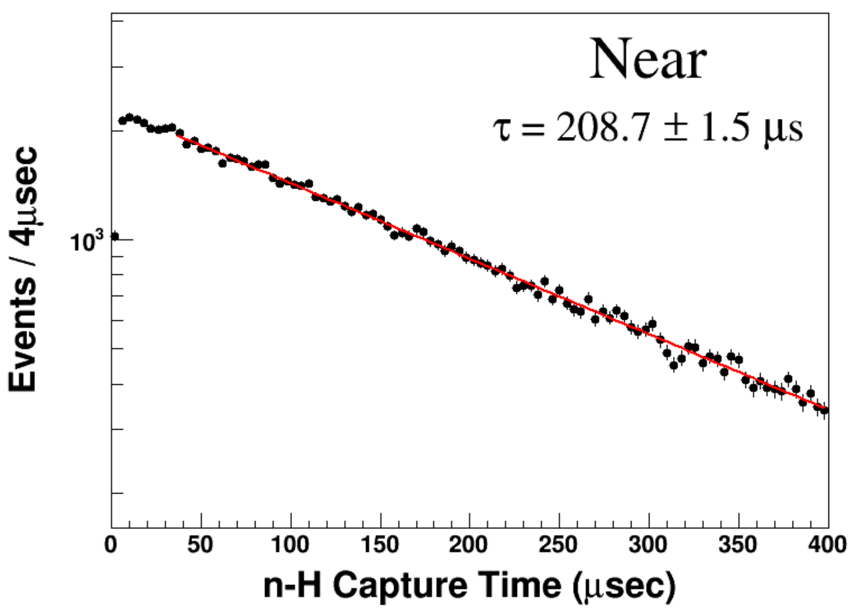
n-H IBD Event Vertex Distribution

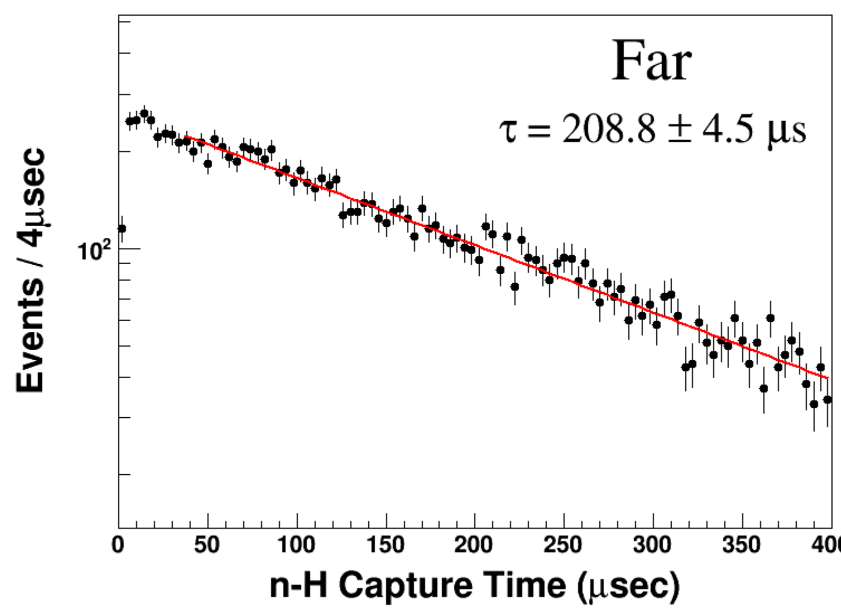


Delayed Spectrum and Capture Time

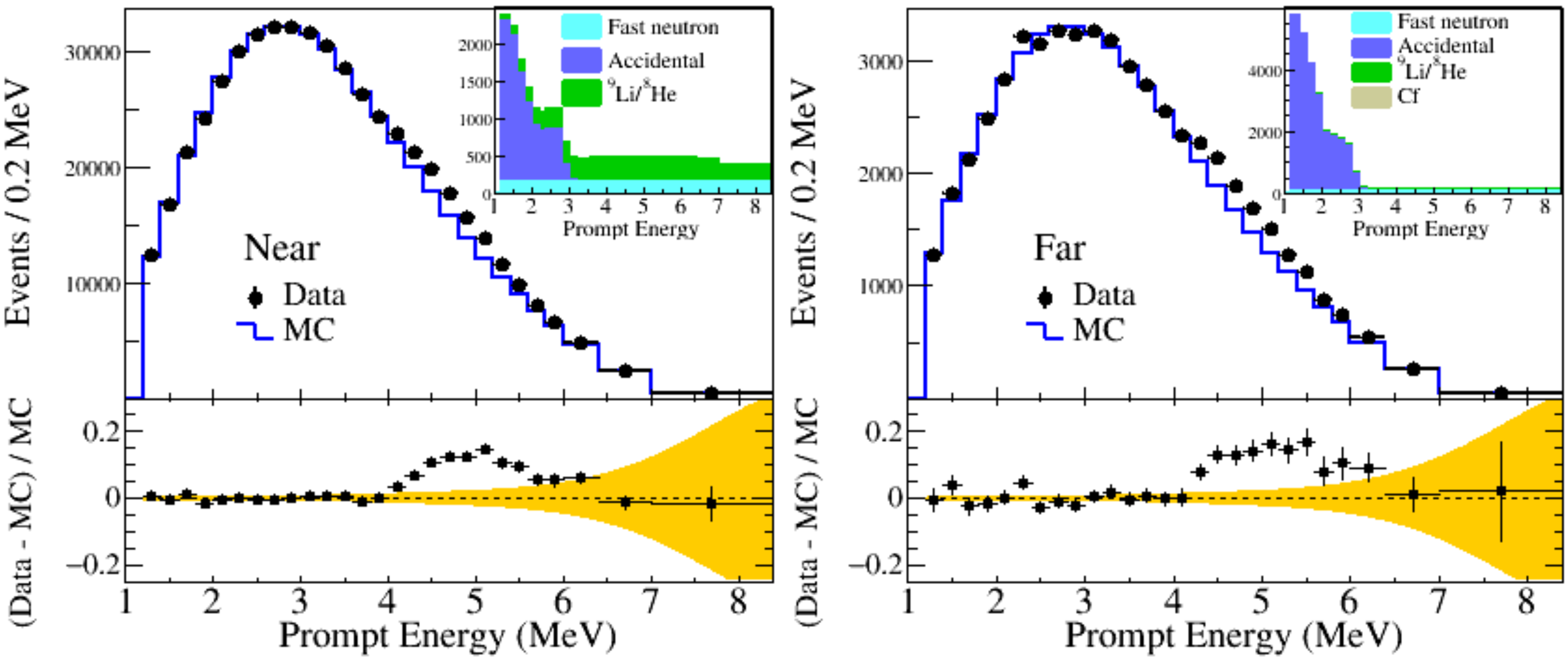
- Delayed signal peak:
  ~2.2 MeV
- Mean coincidence time:
  ~ 200 μs







θ_{13} Measurement with n-H



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

Reactor Neutrino Detector for Denuclearization

Rachel Carr et al., "Neutrino physics for Korean diplomacy", Science 362, 649 (Nov. 2018)

PHOTO: SEONGJOON CHO/BLOOMBERG/GETTY IMAGES

Edited by **Jennifer Sills**

Denuclearizing North Korea requires trust

In their Policy Forum "Denuclearizing North Korea: A verified, phased approach" (7 September, p. 981) A. Glaser and Z. Mian describe a pathway for verified denuclearization of North Korea. I agree that such an approach is necessary and, equally importantly, technically feasible. However, Glaser and Mian only highlight the disarmament side of the denuclearization agreement, without a plan to develop the mutual trust and the assurances on which such a deal depends. Incentivizing North Korea to reduce nuclear weapons and fissile materials will require confidence-building measures, ease of sanctions, and security guarantees. These elements are strongly related to the disarmament questions and must be regulated with similar precision.

Coordinating with the proposed phased approach, the involved parties could pair North Korea's freeze on weapon-related activities with a freeze of new nuclear-related sanctions or military exercises in the region. Such commitments would lay the foundation for an interim agreement, paving the way for long-term denuclearization. In a final step, the facilitation of humanitarian trade in areas such as health and nutrition would initiate the ease of sanctions and the establishment of credible security guarantees.

These measures need control and verification mechanisms, too. In case of nonfulfillment of such an agreement, it must be possible to swiftly reinstate the United Nations Security Council's sanctions. The structure of this contingency could be similar to the snapback mechanism in Article 37 of the Joint Comprehensive Plan of Action with Iran (*1*). Likewise, North Korea will insist on similar guarantees if it dismantles its nuclear weapons. It is always a challenge to create mechanisms that can credibly assure such guarantees for both parties, and this has become even more difficult after the U.S. withdrawal from the Iran nuclear agreement.

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REFERENCE

1. United Nations Security Council Resolution 2231 (2015); https://undocs.org/S/RES/2231(2015).

10.1126/science.aav4636

Neutrino physics for Korean diplomacy

Continued diplomatic progress with North Korea will be a journey of many steps, as A. Glaser and Z. Mian describe in their Policy Forum "Denuclearizing North Korea: A verified, phased approach" (7 September, p. 981). Leaders in North Korea, South Korea, and the United States agree that one step could be dismantlement or civilian repurposing of the nuclear reactors at Yongbyon. We propose a cooperative method for verifying reactor shutdown or conversion. The key tools are meter-scale, field-deployable detectors that track neutrino emissions from reactor cores.

Neutrino detectors can track power levels and fuel evolution in nuclear reactors, as experiments in South Korea, China, Russia, the United States, and Europe have demonstrated (*1–7*). At Yongbyon, neutrino detectors could be deployed to verify reactor shutdown or civilian operations without the need for operational records or access inside reactor buildings. Shutdown of North Korea's main plutonium production reactor could be verified with a detector in a standard freight container parked outside the reactor building.

Existing neutrino technology may be attractive to all parties in the ongoing talks. North Korea may value a tool for demonstrating treaty compliance while maintaining custody of the reactor buildings. Other parties may value the tamper resistance of the neutrino signal and resilience of neutrino detectors, which require minimal on-site access and can reconstruct reactor operational history even after a data-taking pause. Neutrino projects are also a natural opportunity to strengthen relations between North and South Korea and to build international scientific ties. South Korea has an active neutrino community and could choose to deploy a counterpart to a Yongbyon-based detector at one of its own reactors. Resulting scientific collaboration could benefit Korea and the world. We encourage policy-makers to consider neutrino detectors as one step toward stability and security on the Korean Peninsula.

Rachel Carr,[1]* Jonathon Coleman,[2] Giorgio Gratta,[3] Karsten Heeger,[4] Patrick Huber,[5] YuenKeung Hor,[6] Takeo Kawasaki,[7] Soo-Bong Kim,[8] Yeongduk Kim,[9] John

A freeze in military exercises could help to establish trust during nuclear negotiations with North Korea.

Published by AAAS

Neutrino physics for Korean diplomacy

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Neutrino detectors can track power

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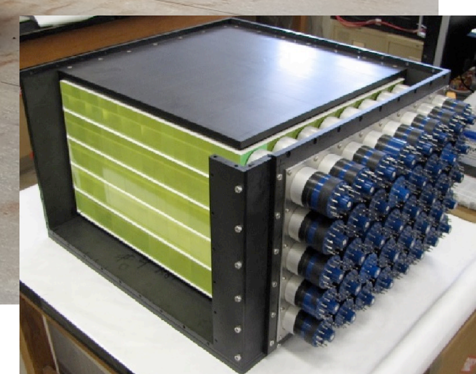
Mobile Antineutrino Detector

MiniCHANDLER, *Jonatnan Link*



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

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

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

- First hint for 2.9σ correlation between 5 MeV excess and ^{235}U fission fraction

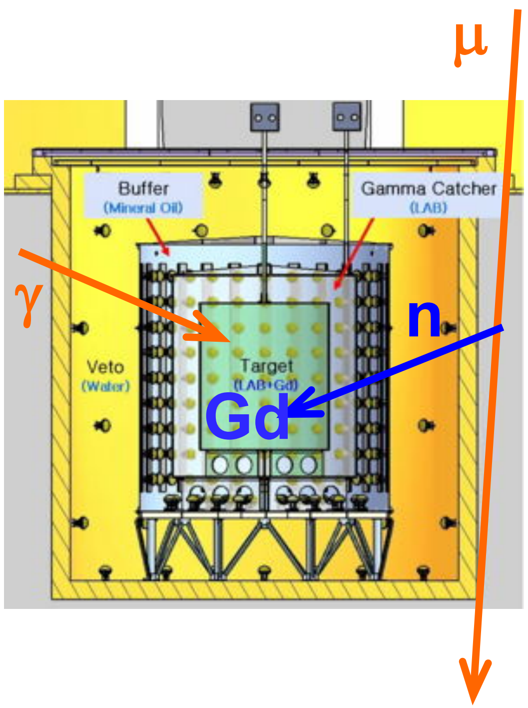
- Measurement of θ_{13} using n-H IBD analysis

Thanks for your attention!

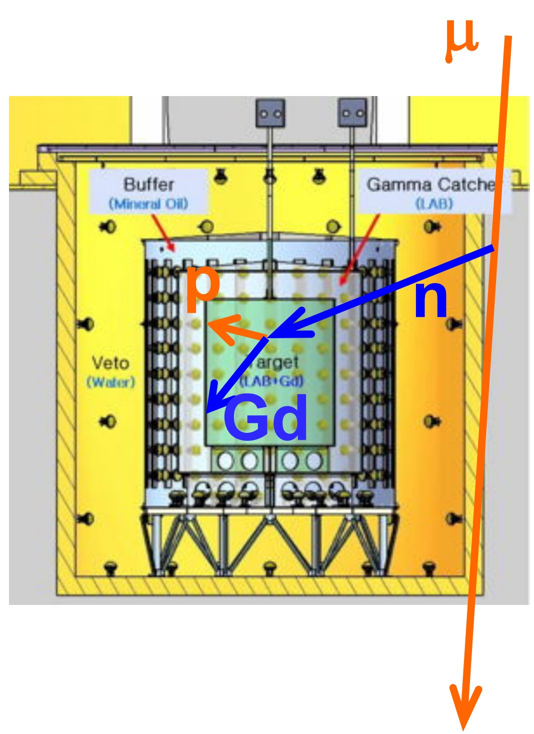
Backgrounds

- 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

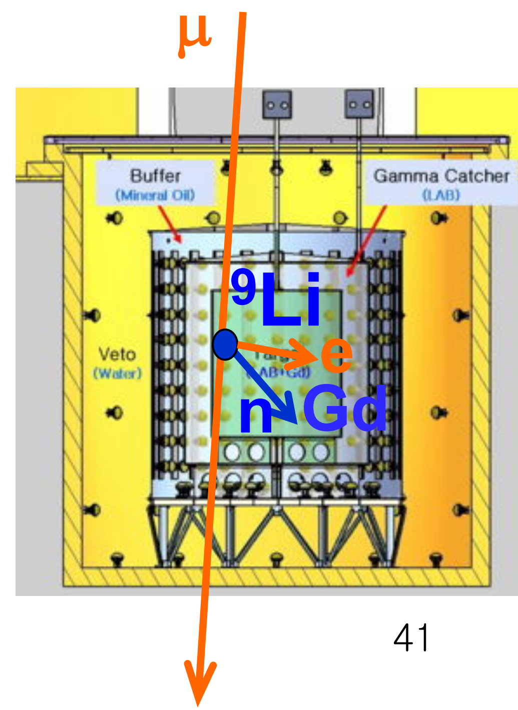
Accidentals



Fast neutrons

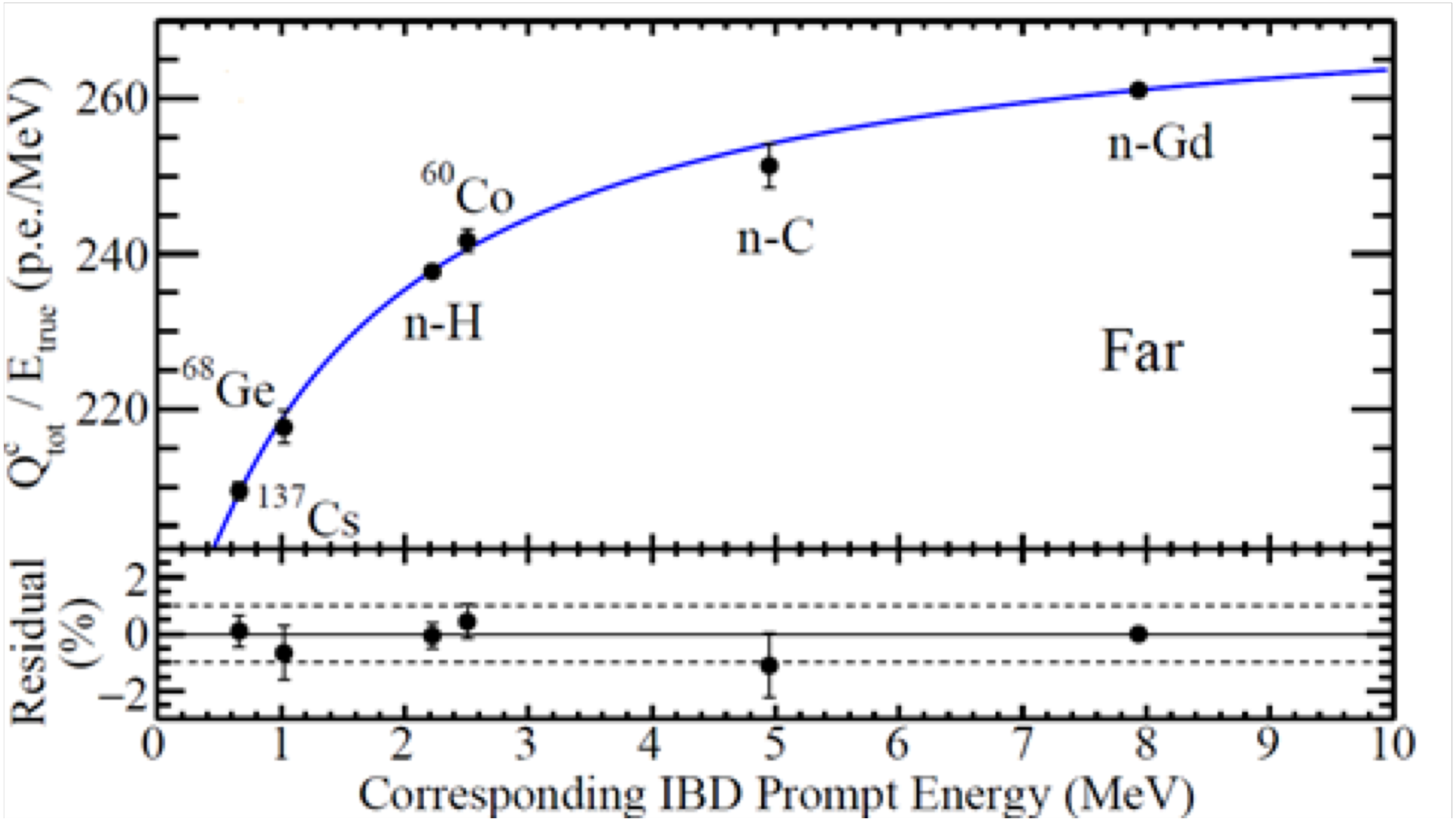


^{9}Li/^{8}He β-n followers



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