Results from Reactor Neutrino Experiments

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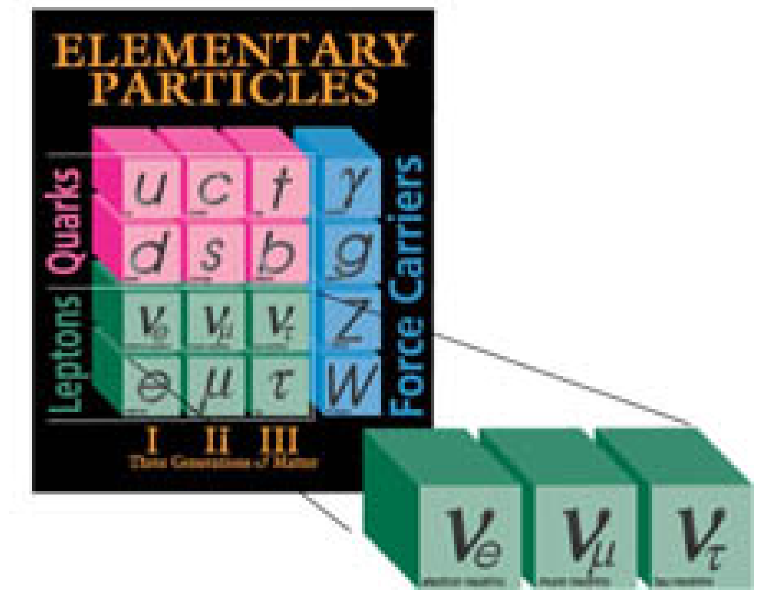
"Tsukuba Global Science Week (TGSW2017), Tsukuba, Sep. 25-27, 2017"

KNRC
Korea Neutrino Research Center

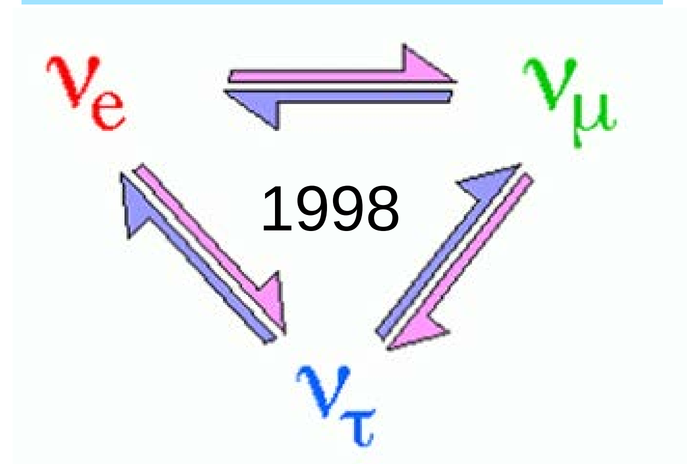
Neutirno Oscillation

Bruno Pontecorvo
(1913 - 1993)

1946: Proposal of neutrino detection using ^{37}Cl
1957: Proposal of neutrino transformation
(neutrino ↔ antineutrino)
1967/69: Proposal of neutrino flavor 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, …..

θ_{13} Impacts for Future Experiments

$\theta_{13} \approx 9^o$

Reactor

JUNO — MO

RENO-50

Accelerator

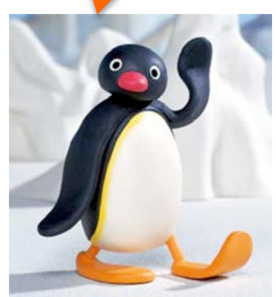
DUNE — MO & δ_{CP}

Hyper-K

Atmosphere

INO — MO

PINGU — MO & δ_{CP}

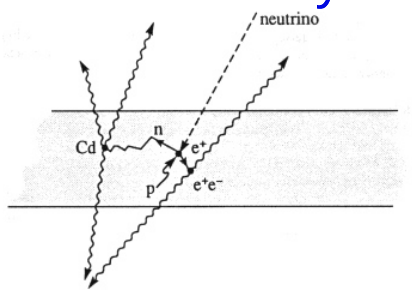


ORCA

MO = Mass Ordering

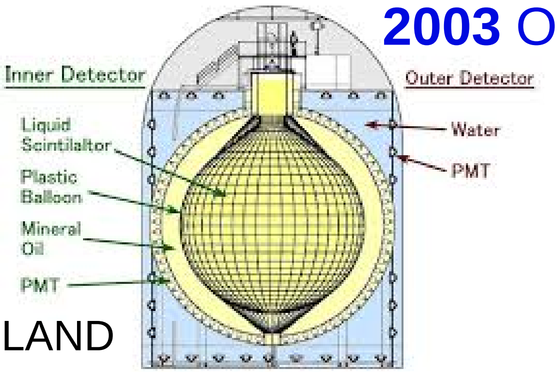
Neutrino Physics with Reactor

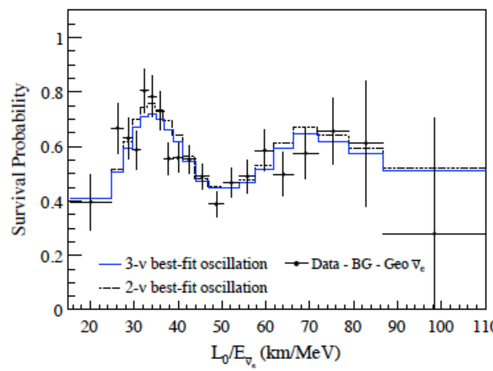
1956 Discovery of (anti)neutrino

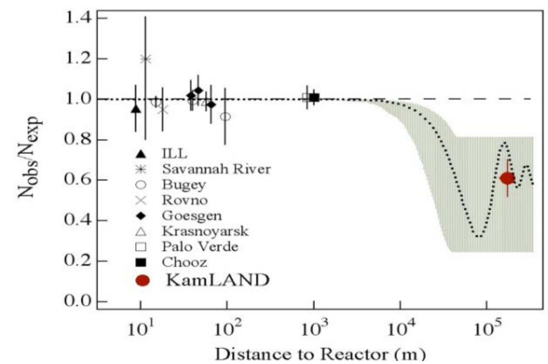


2003 Observation of reactor neutrino oscillation (θ_{12} & Δm_{21}^2)

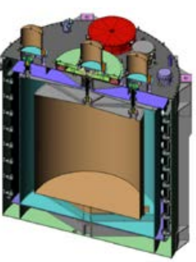
KamLAND

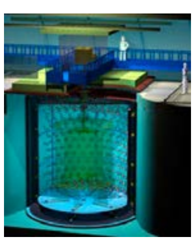


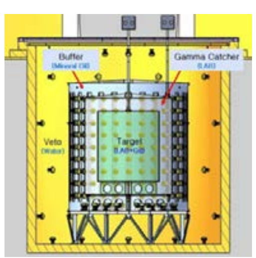


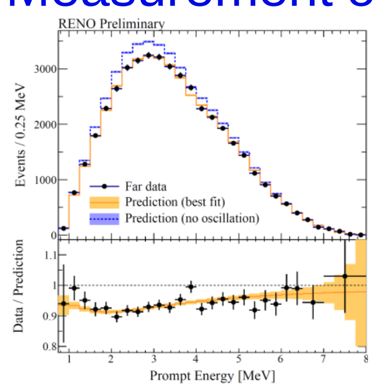


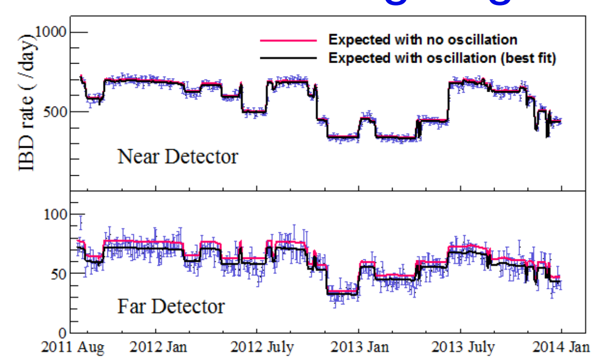
2012 Measurement of the smallest mixing angle θ_{13}





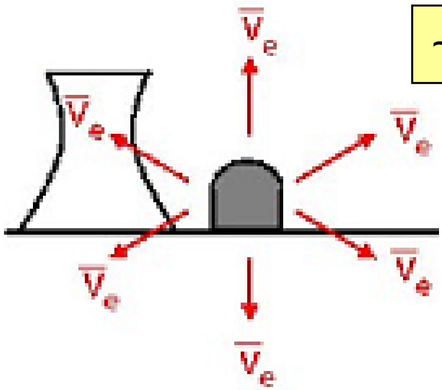






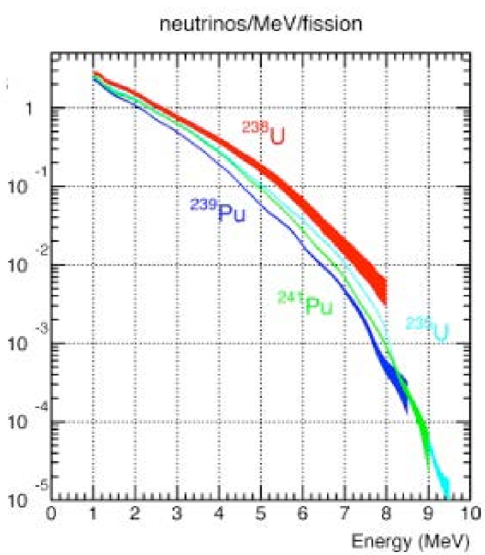
Reactor Neutrinos

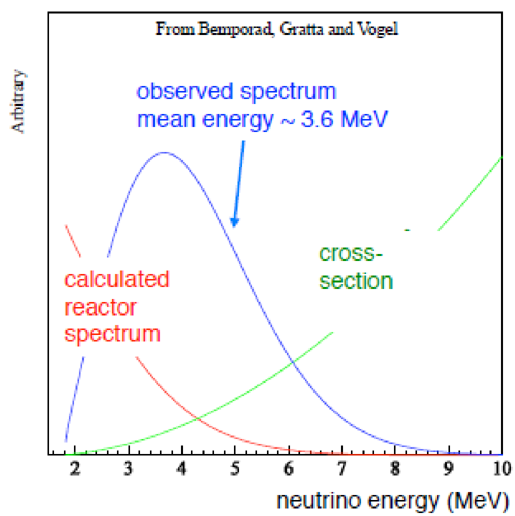
Reactor Neutrinos



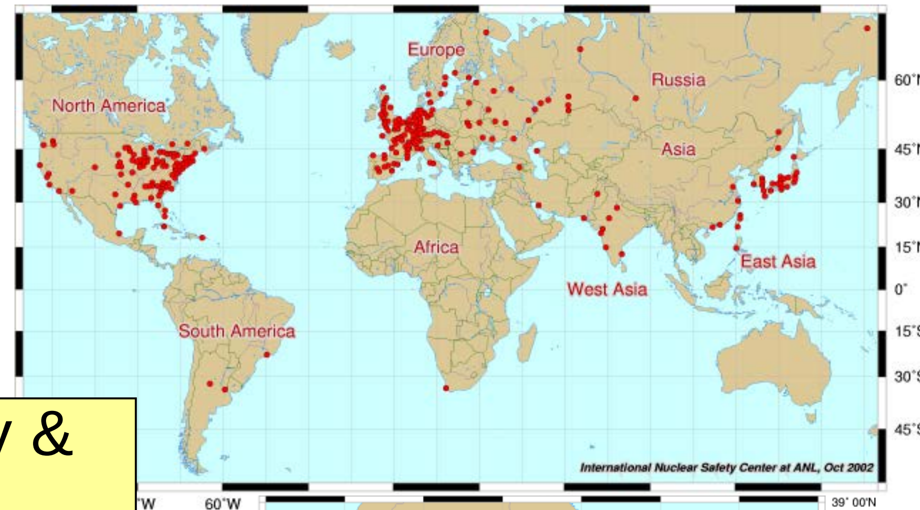
$\sim 5 \times 10^{20}$ ν/sec

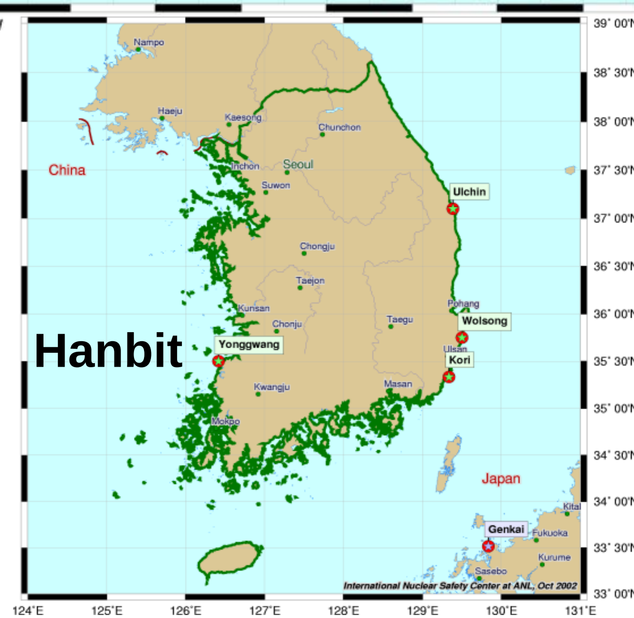
- Cost-free, intense, low-energy & well-known neutrino source !



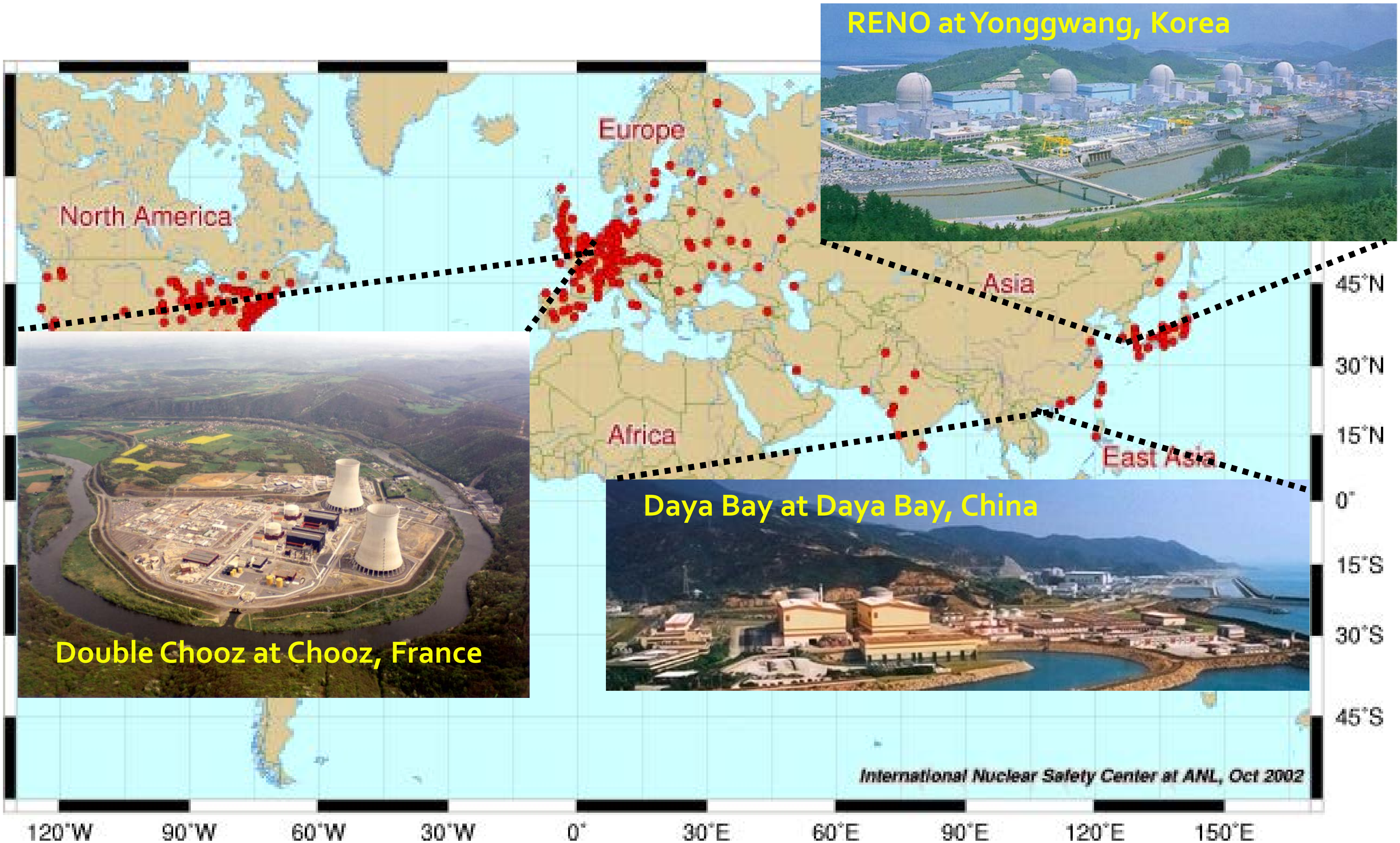


Nuclear Power Plants

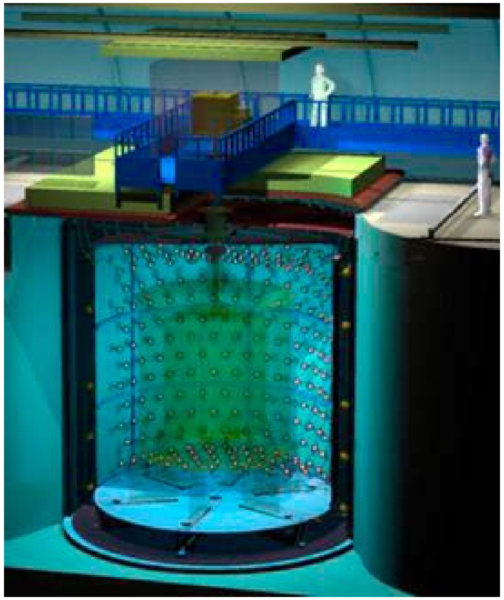


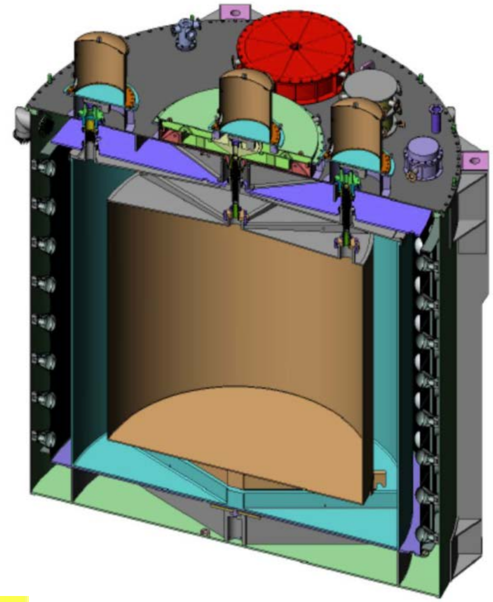


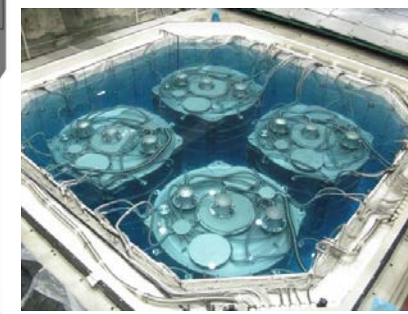
Reactor θ_{13} Experiments

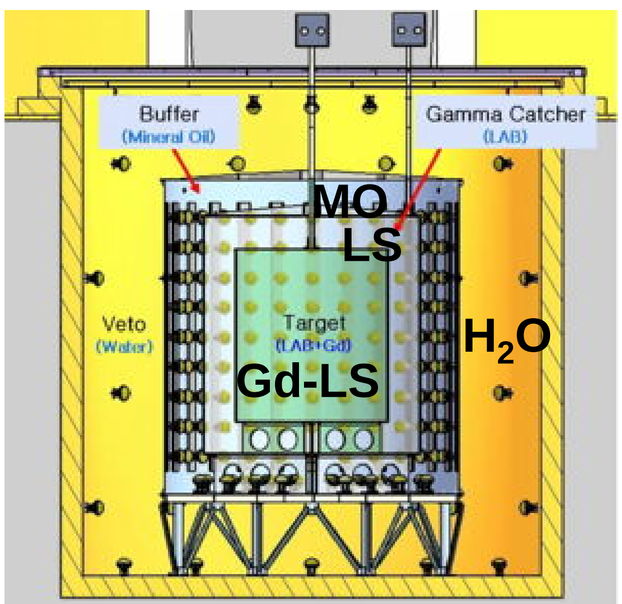


θ_{13} Reactor Neutrino Detectors

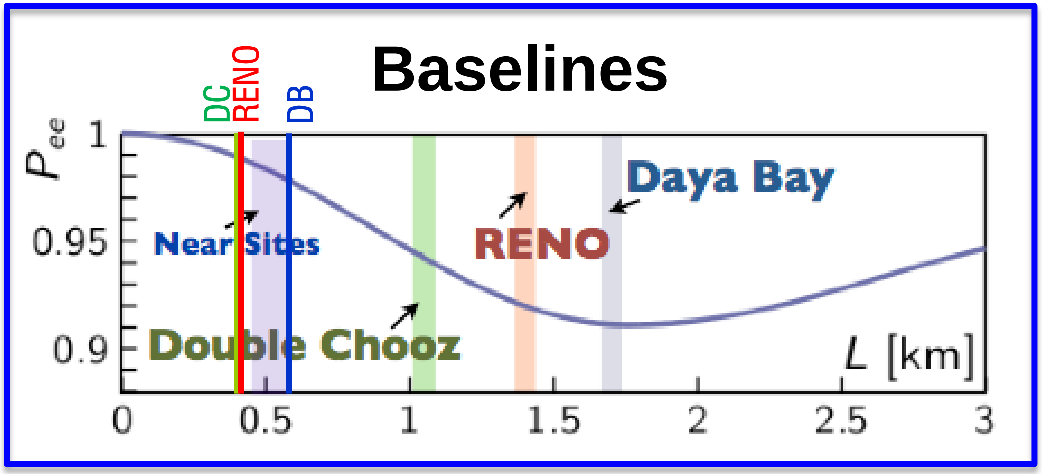


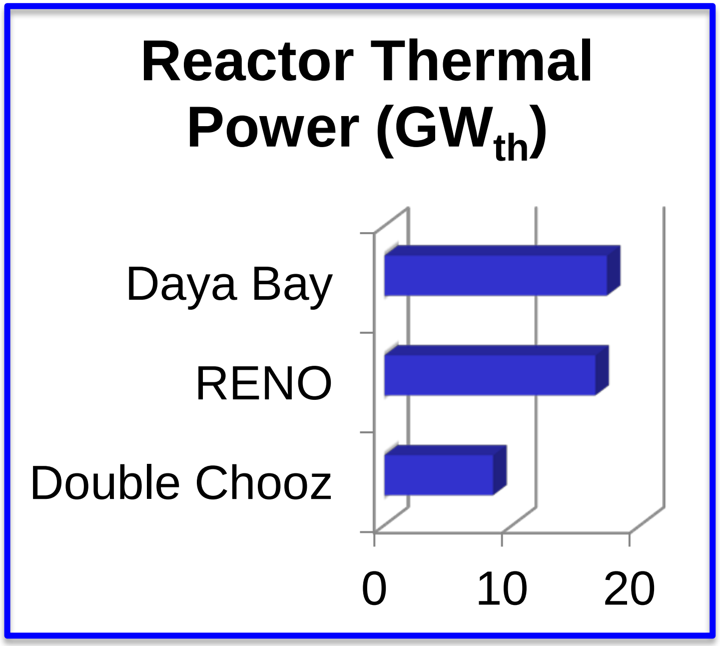


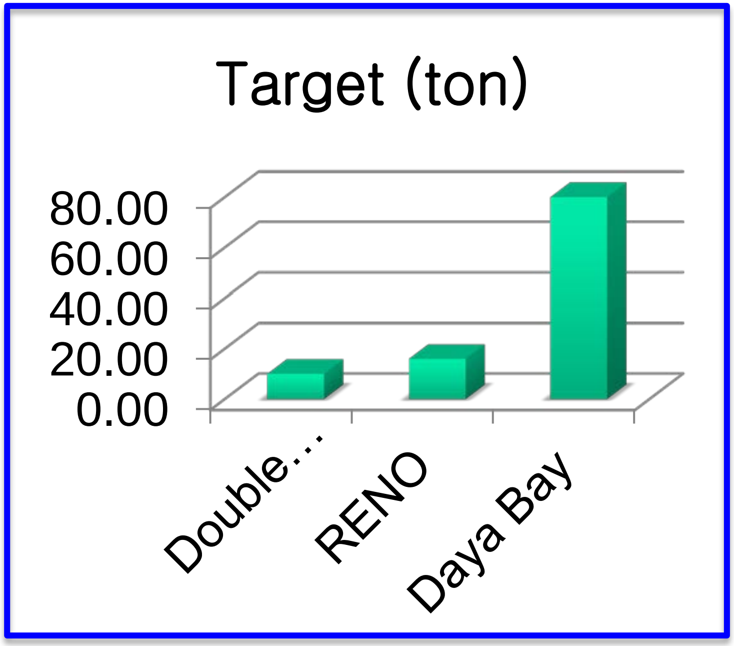


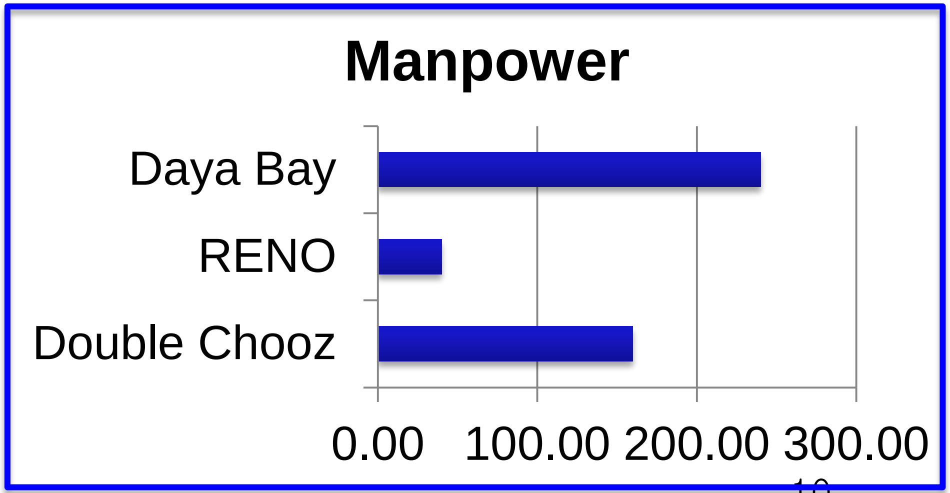


Comparisons of Reactor θ_{13} Experiments









First θ_{13} measurements in 2012

~ 5 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

RENO Collaboration

Reactor Experiment for Neutrino Oscillation

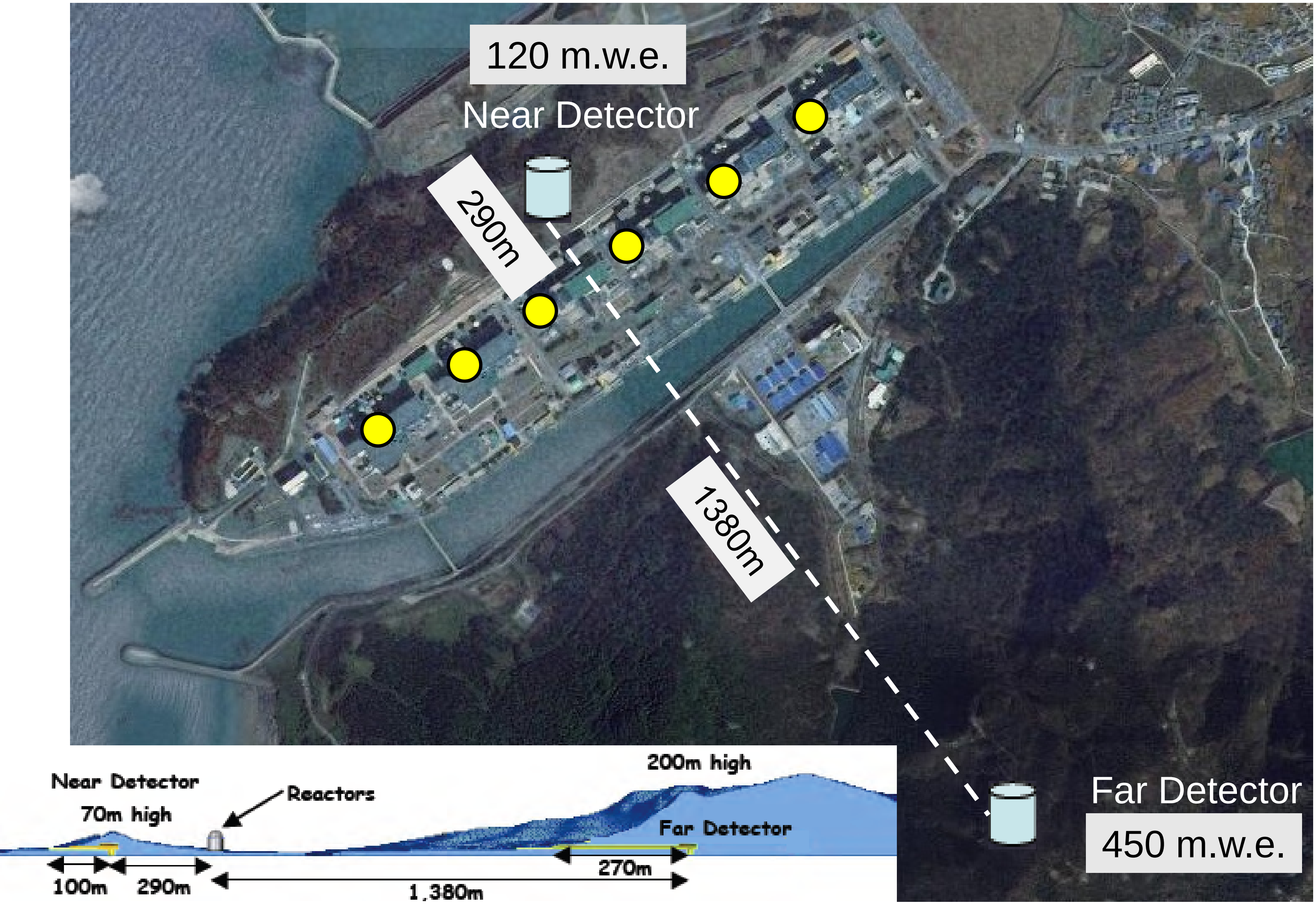
(7 institutions and 40 physicists)

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

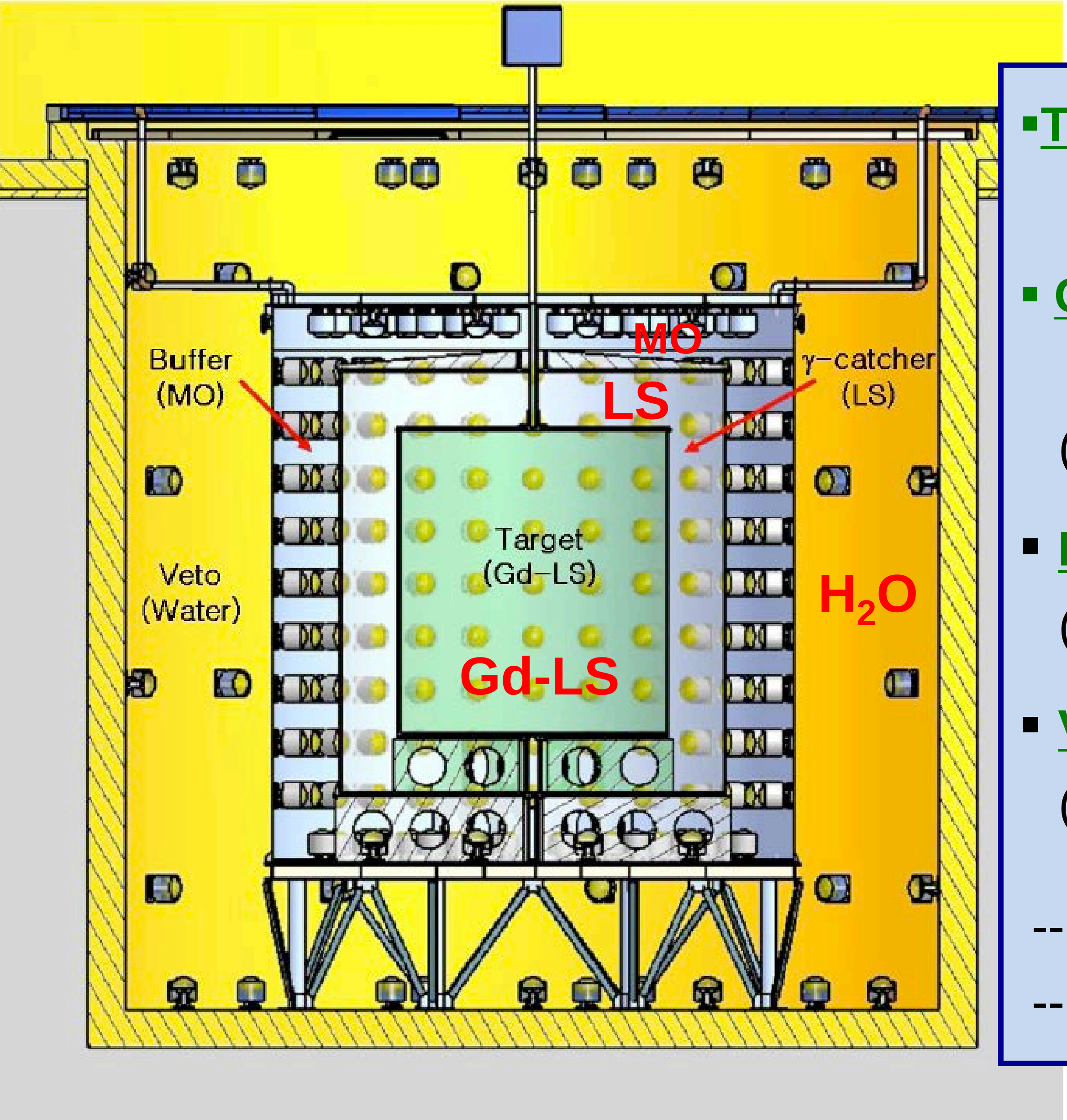
- Total cost : $10M
- Start of project : 2006
- The first experiment running with both near & far detectors from Aug. 2011

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)

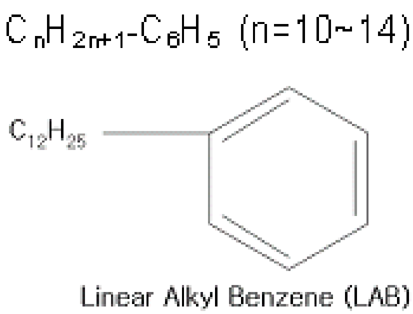
-- 354 ID 10 " PMTs

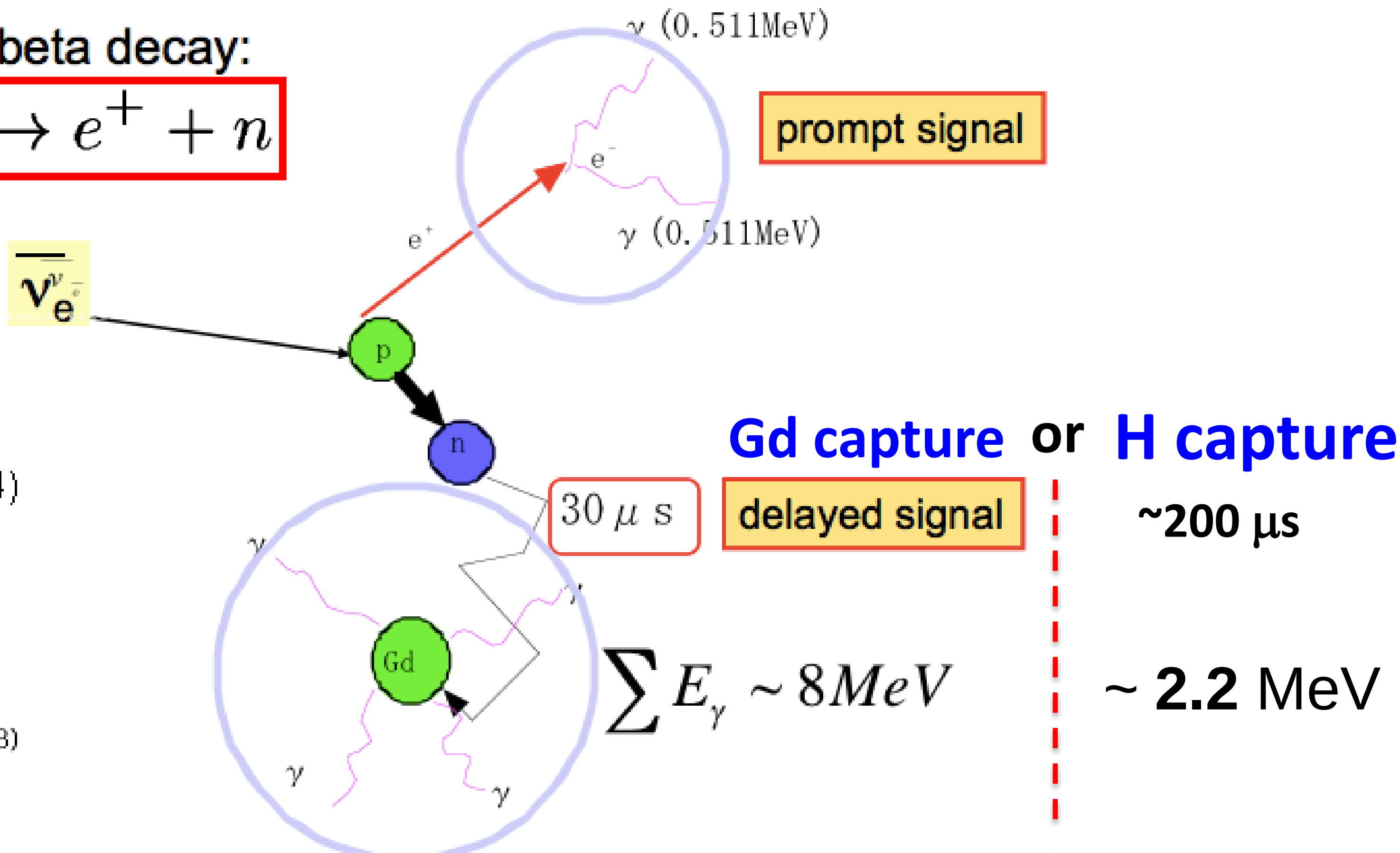
-- 67 OD 10" PMTs

Detection of Reactor Antineutrinos

Inverse beta decay:

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





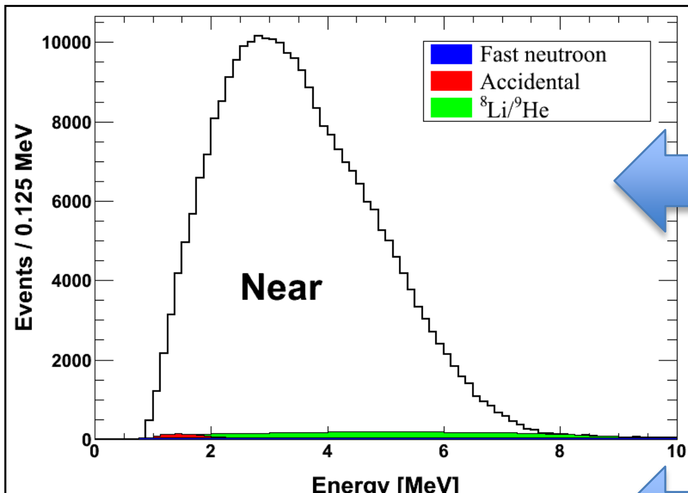
- Prompt signal (e^+) : 1 MeV 2γ's + e^+ kinetic energy (E = 1~10 MeV)
- Delayed signal (n) : 8 MeV γ's from neutron's capture by **Gd** or **H**
  ~30 μs or ~200 μs

Coincidence of prompt and delayed signals

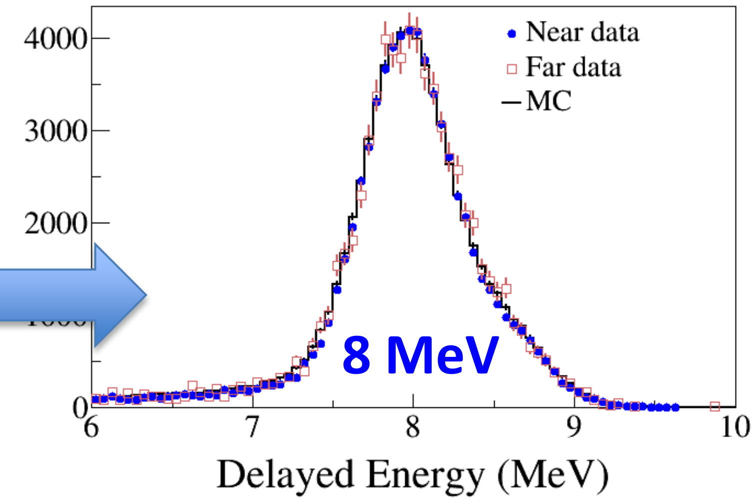
(prompt signal)

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

Prompt signal



Delayed signal

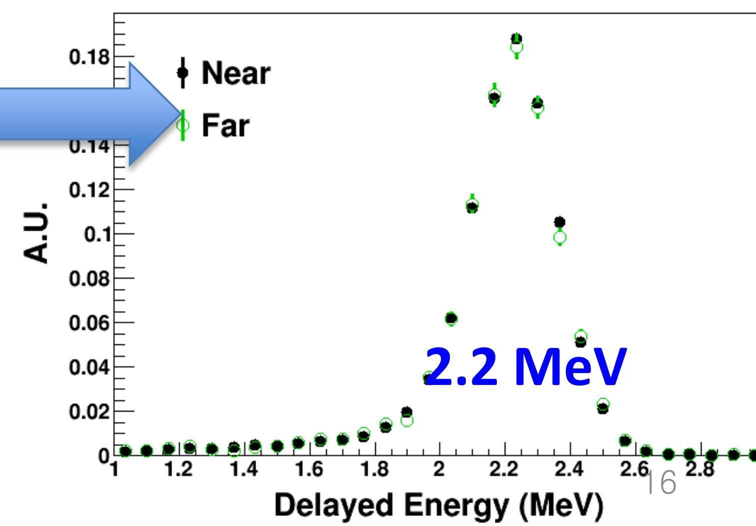


n-Gd IBD

~30 μs

~200 μs

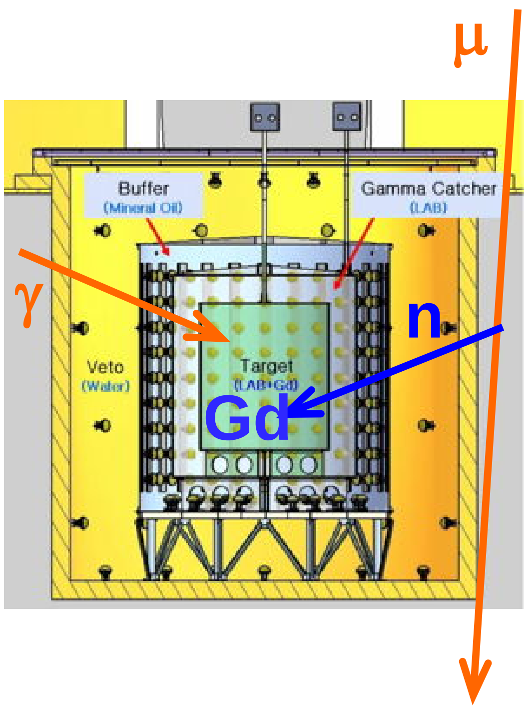
n-H IBD



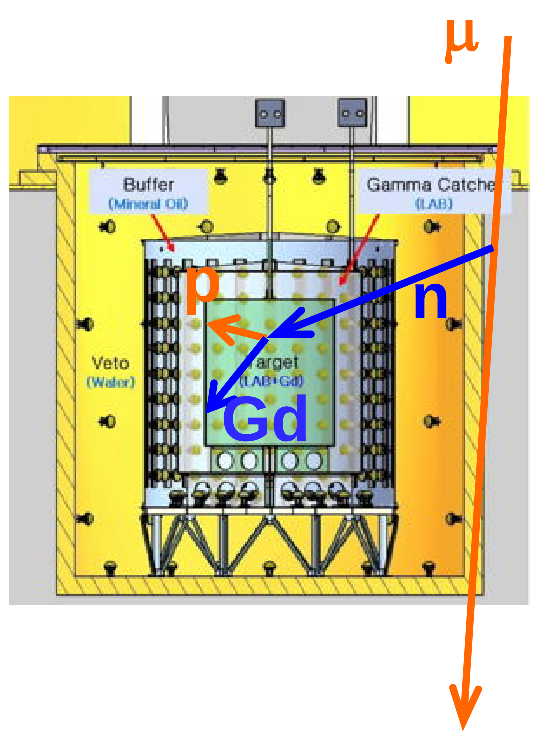
Backgrounds

- 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

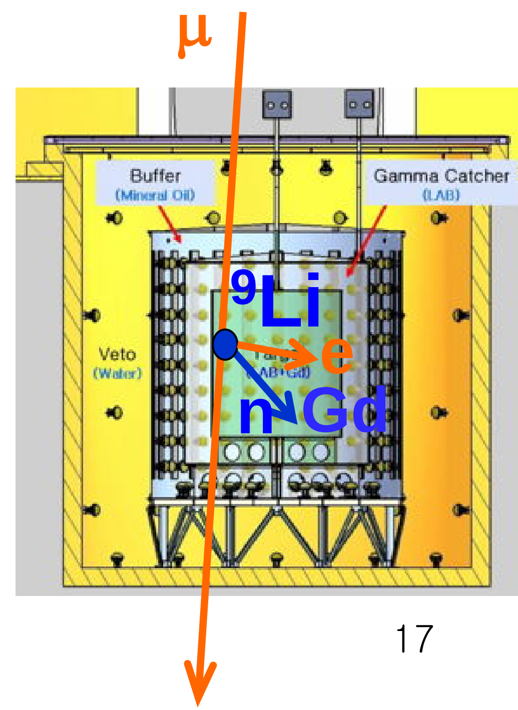
Accidentals



Fast neutrons



$^{9}Li/^{8}He$ β-n followers



New Results from RENO

- Observation of energy dependent disappearance of reactor neutrinos to measure Δm_{ee}^2 and θ_{13} using ~1500 days of data (Aug. 2011 ~ Sep. 2015)

- Measurement of absolute reactor neutrino flux using 1500 days

- Observation of an excess at ~5 MeV in reactor neutrino spectrum using ~1500 days of data

RENO Data-taking Status

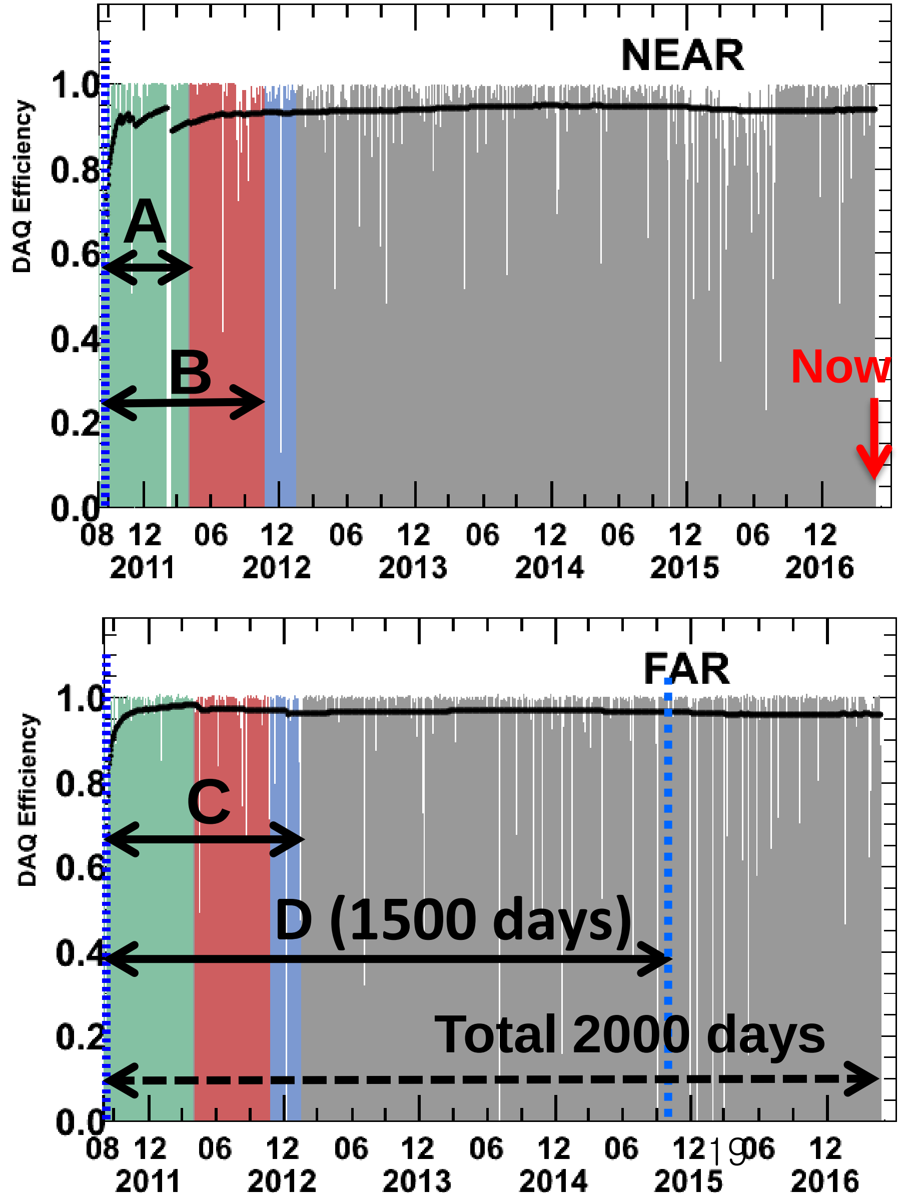
- Data taking began on Aug. 1, 2011 with both near and far detectors.
  (DAQ efficiency : ~95%)

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

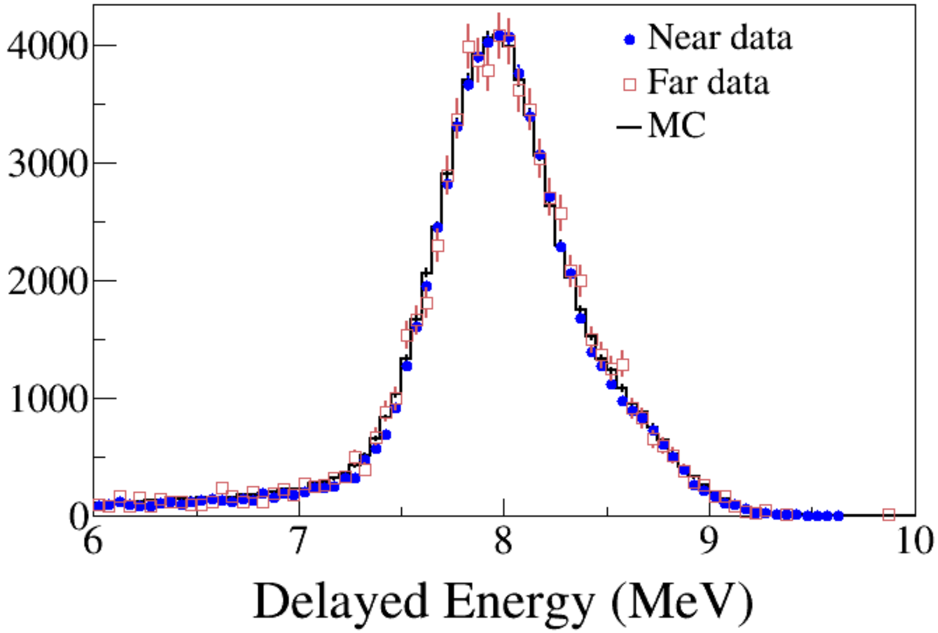
- **B (403 days)** : **Improved θ_{13} result**
  [11 Aug, 2011~13 Oct, 2012]
  NuTel 2013, TAUP 2013, WIN 2013

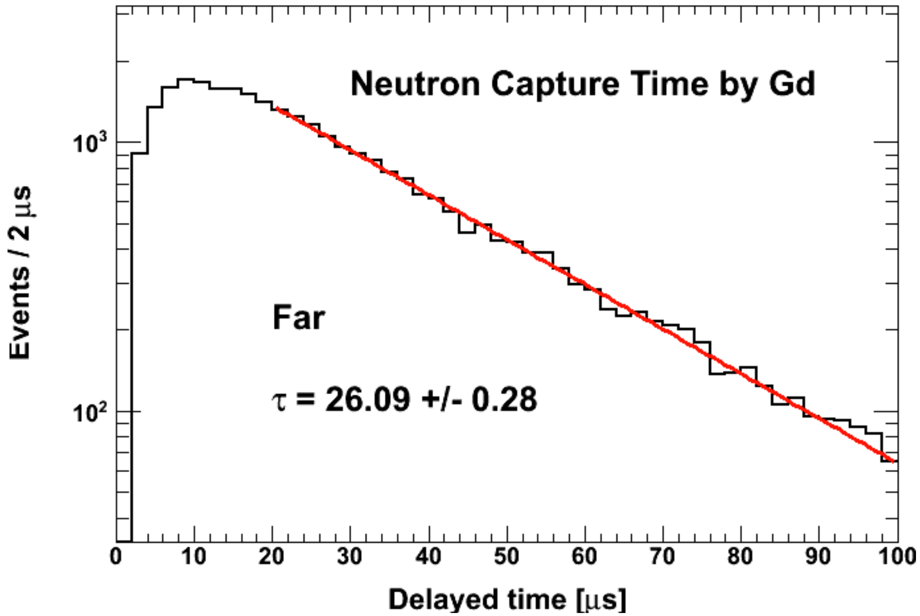
- **C (500 days)** : **First $|\Delta m_{ee}^2|$ result**
  Rate+shape analysis (θ_{13} and $|\Delta m_{ee}^2|$)
  [11 Aug, 2011 ~ 21 Jan,2013]
  PRL 116, 211801 (2016)
  submitted to PRD (arXiv:1610.04326)

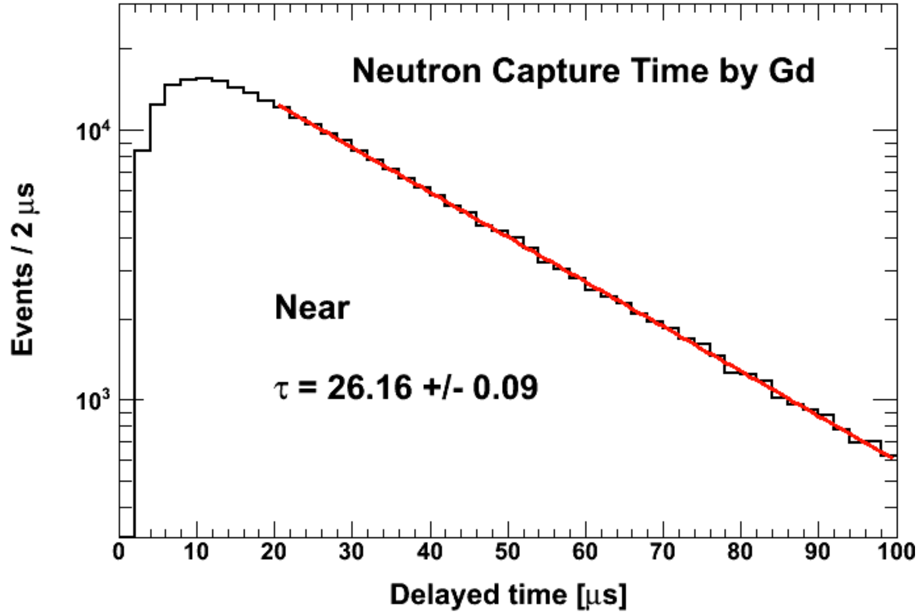
- **D (1500 days)** : **New results**
  [11 Aug, 2011 ~ Sep, 2015]



Delayed Signals from Neutron Capture by Gd

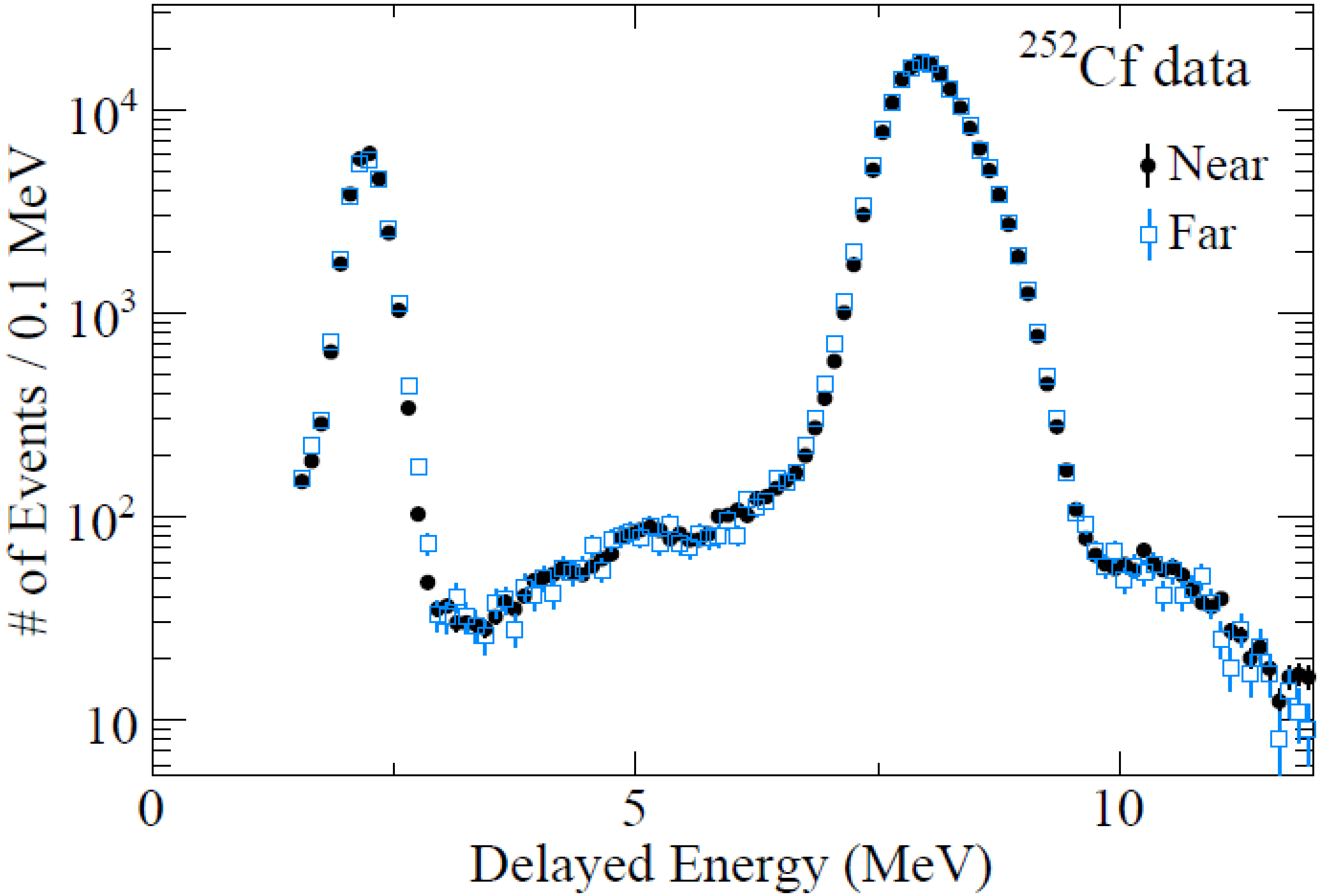






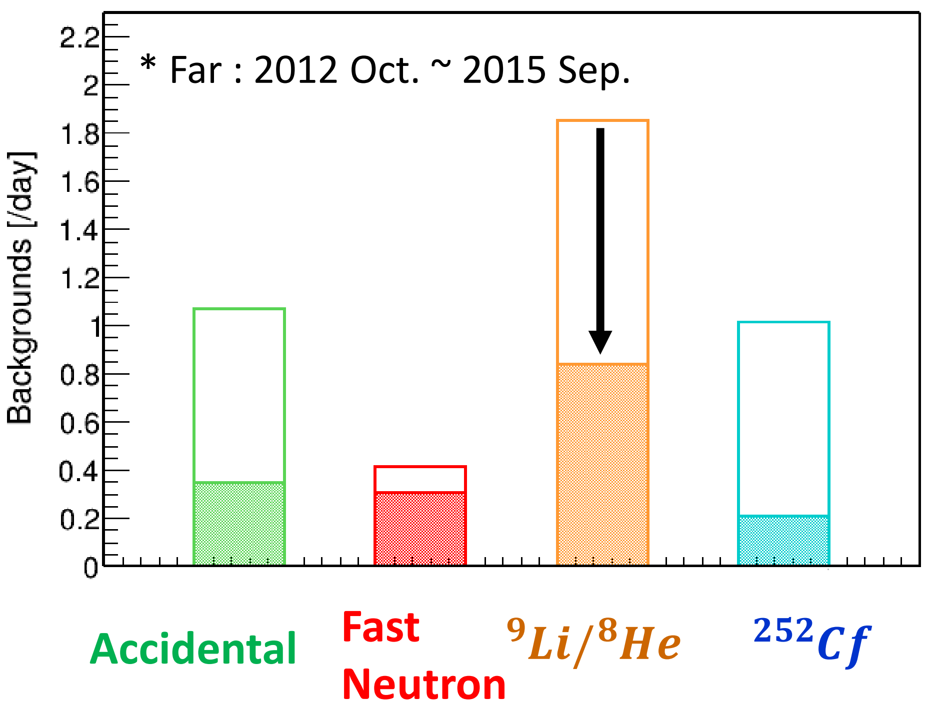
Identical Performance of Near and Far Detectors

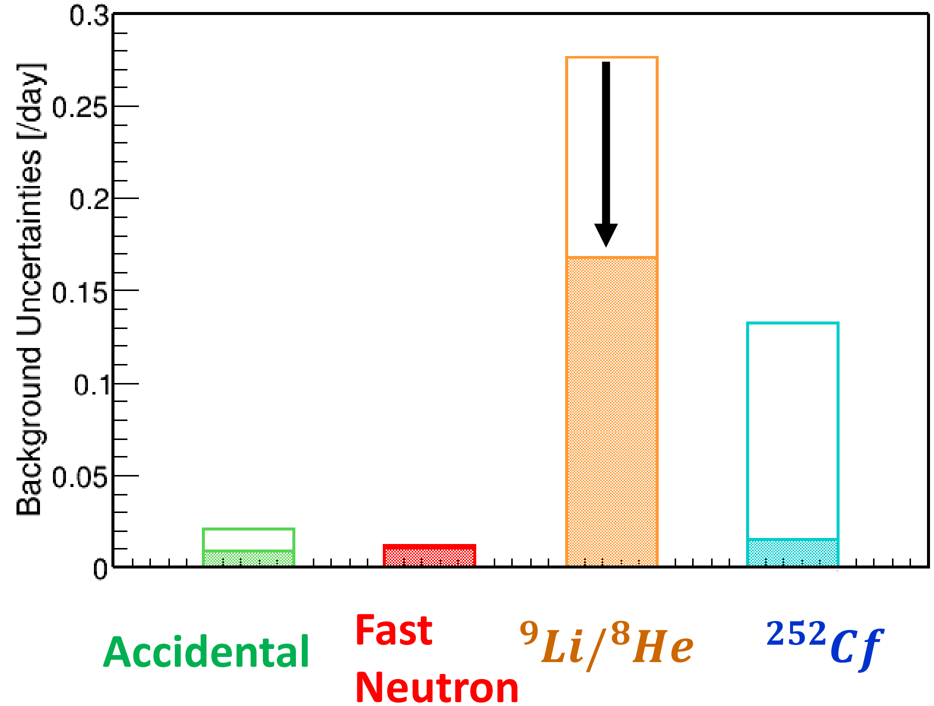
Spectra of Delayed Signals Using ^{252}Cf Source



Reduction of background rates & uncertainties

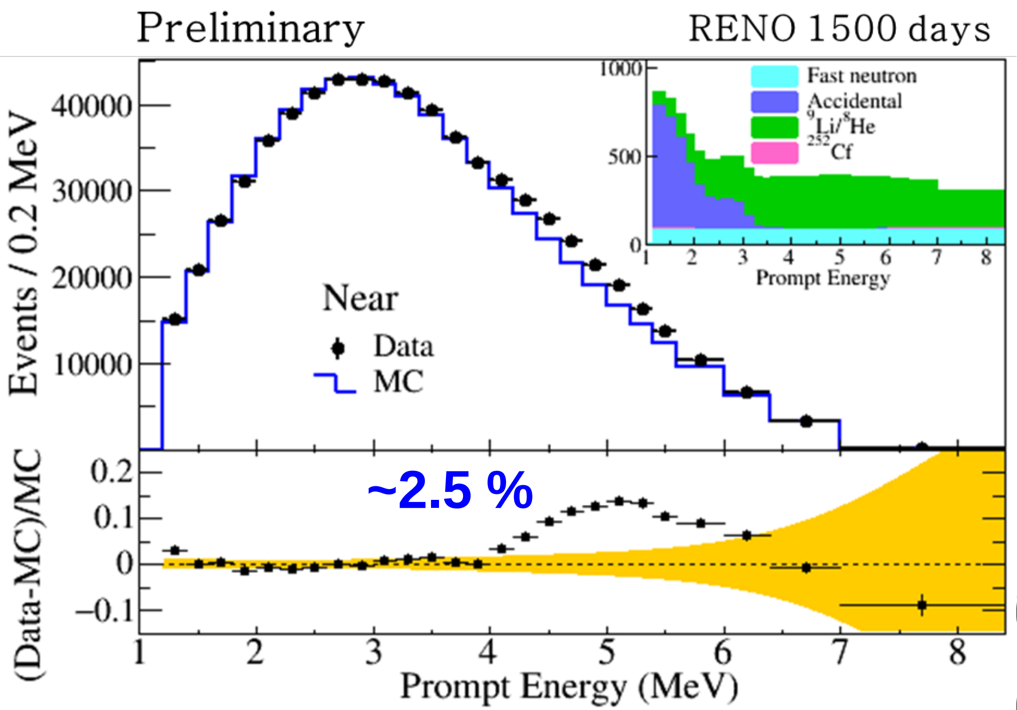
Allows precise measurements of $sin^2 2\theta_{13}$ and Δm^2_{ee}





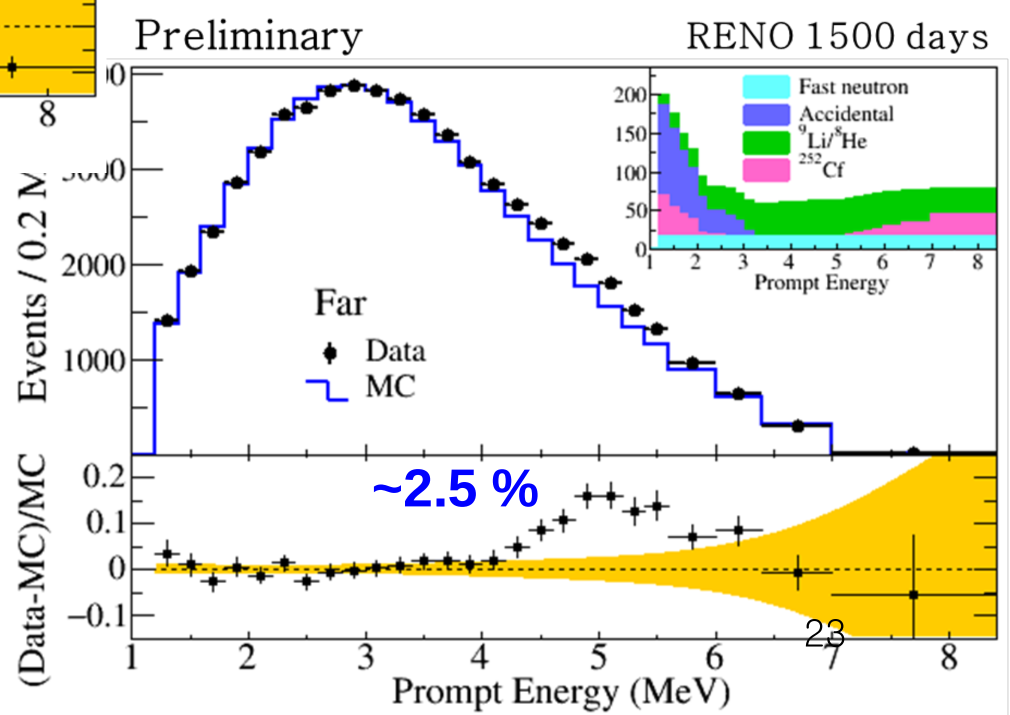
- Accidentals : Additional cuts and improved flashing-PMT removal algorithms
- Cosmogenic $^9Li/^8He$: Optimized muon veto criteria
- ^{252}Cf contamination : Improved multiple-neutron removal algorithms

Measured Spectra of IBD Prompt Signal

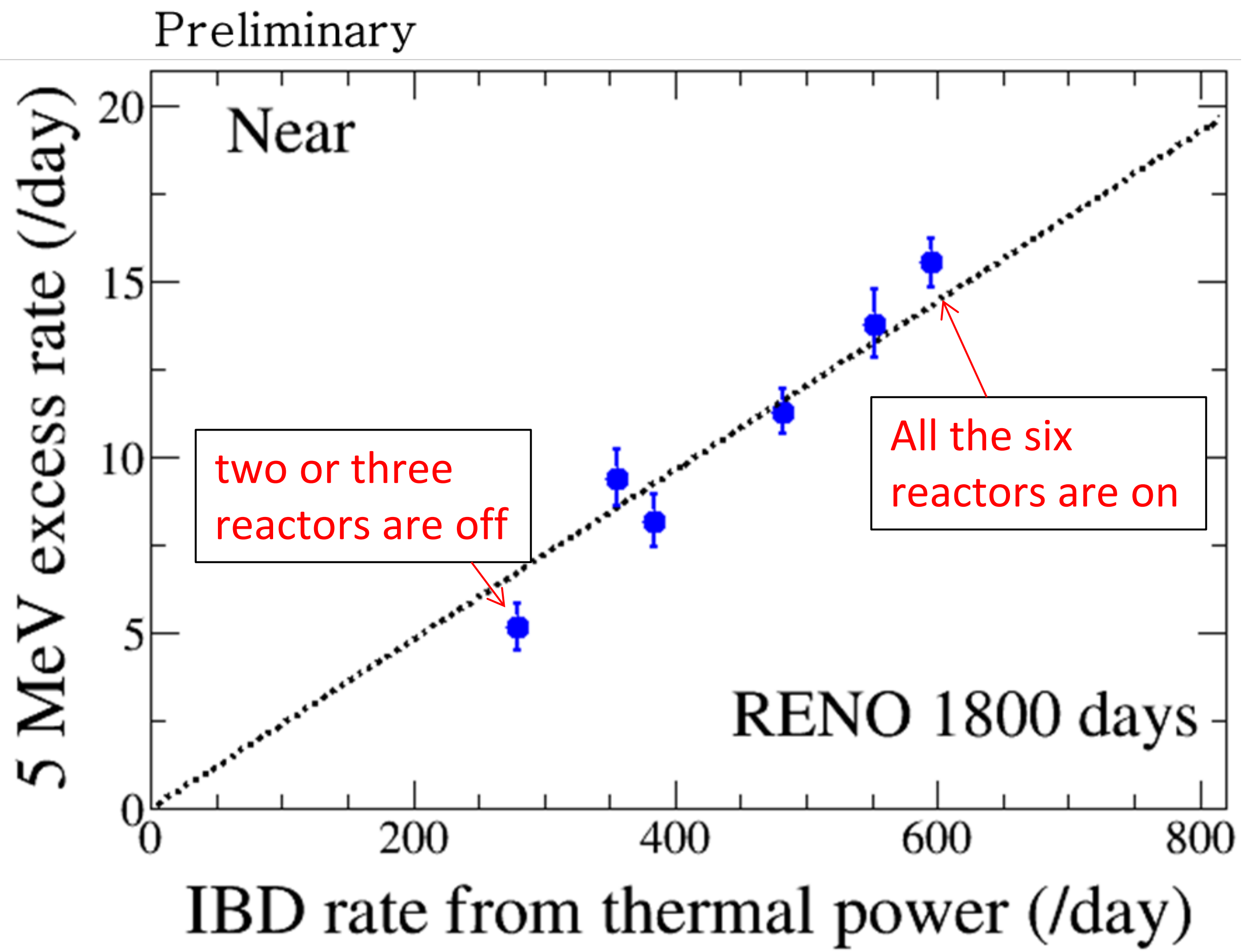


RENO's observation of 5 MeV excess

Clear excess at 5 MeV



Correlation of 5 MeV Excess with Reactor Power

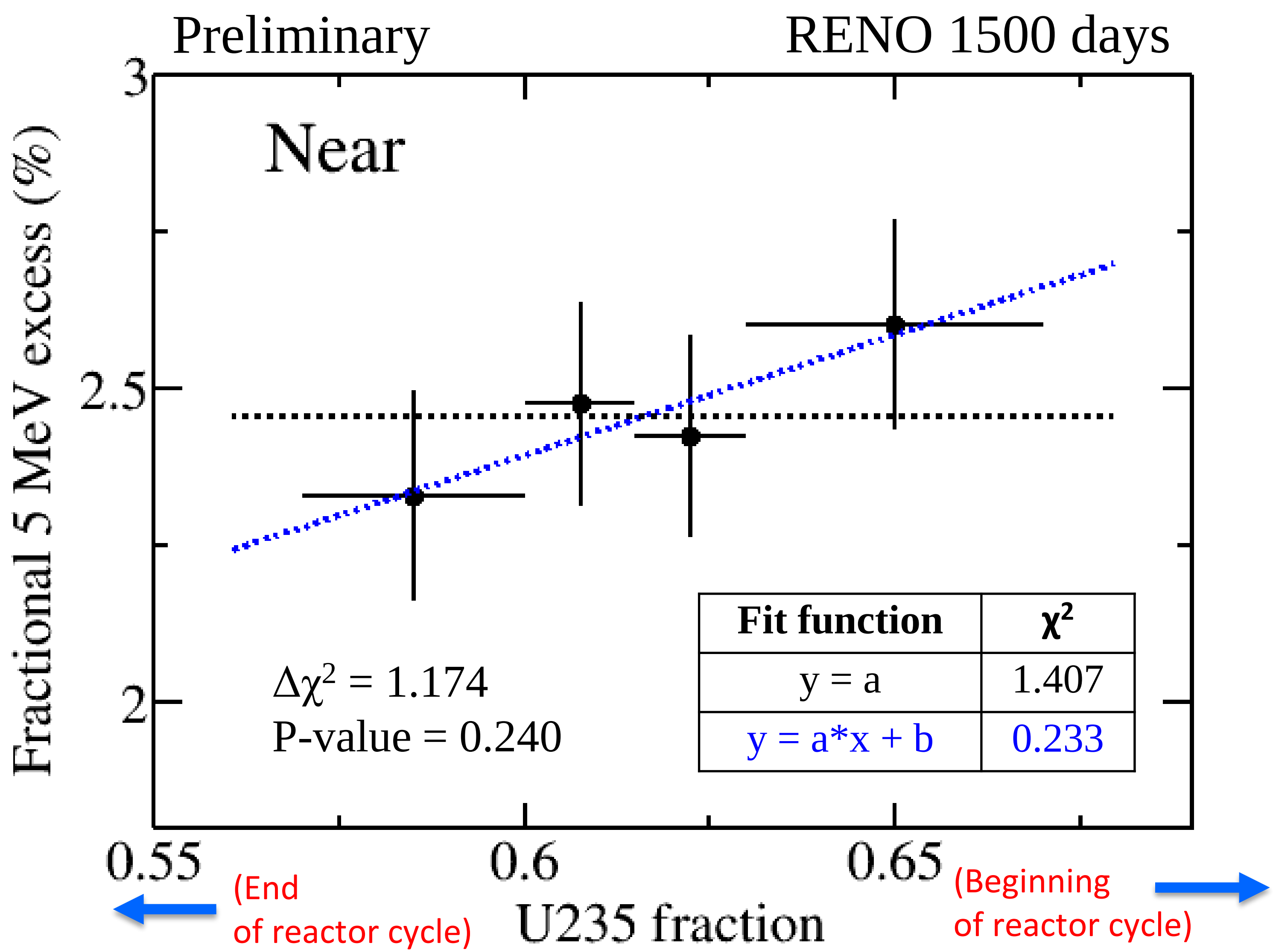


5 MeV excess has a clear correlation with reactor thermal power !

The 5 MeV excess comes from reactors!

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

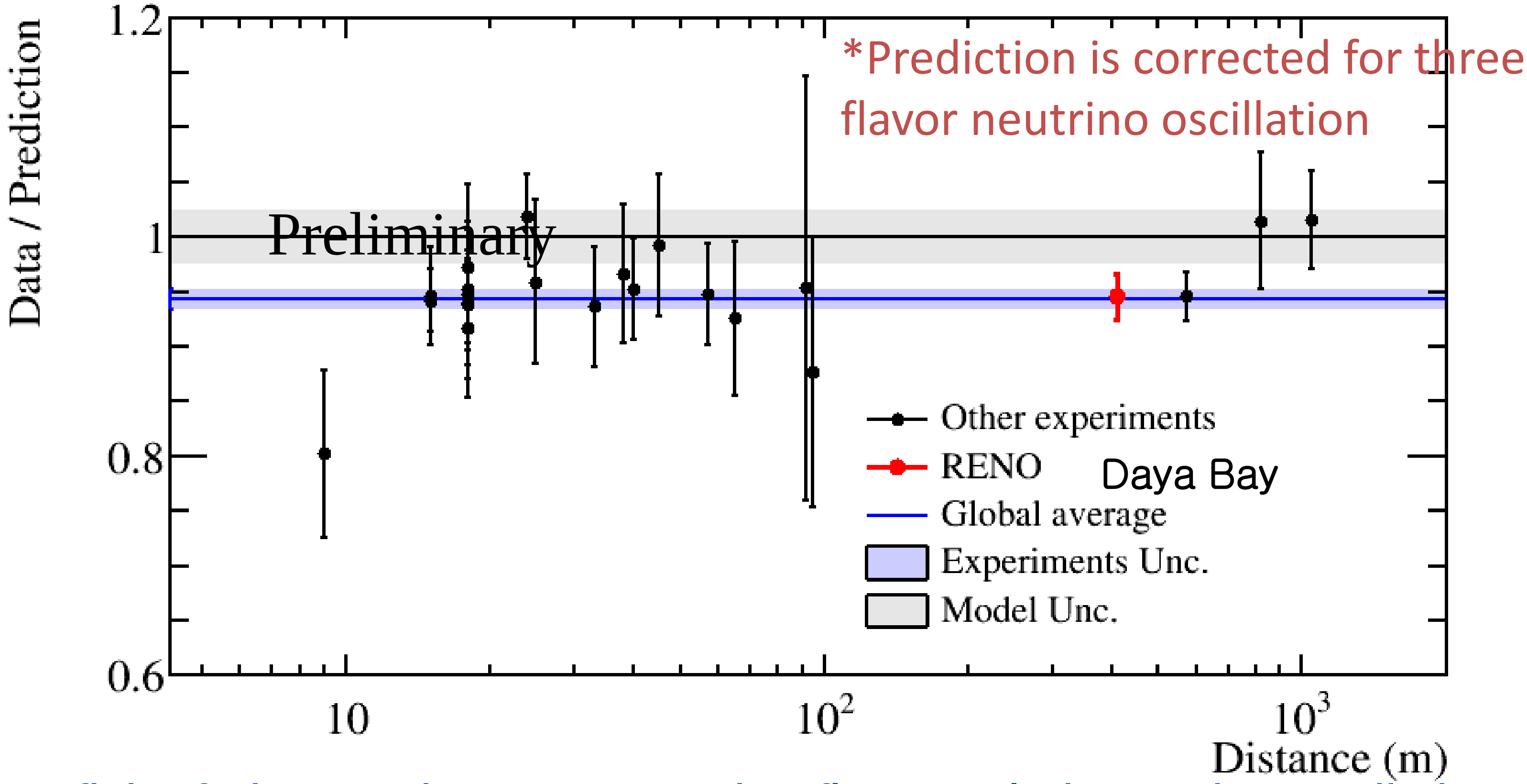
^{235}U fraction corresponds to freshness of reactor fuel



Measurement of Absolute Reactor Neutrino Flux

R (data/prediction) = 0.946 ± 0.021 (1500 days)

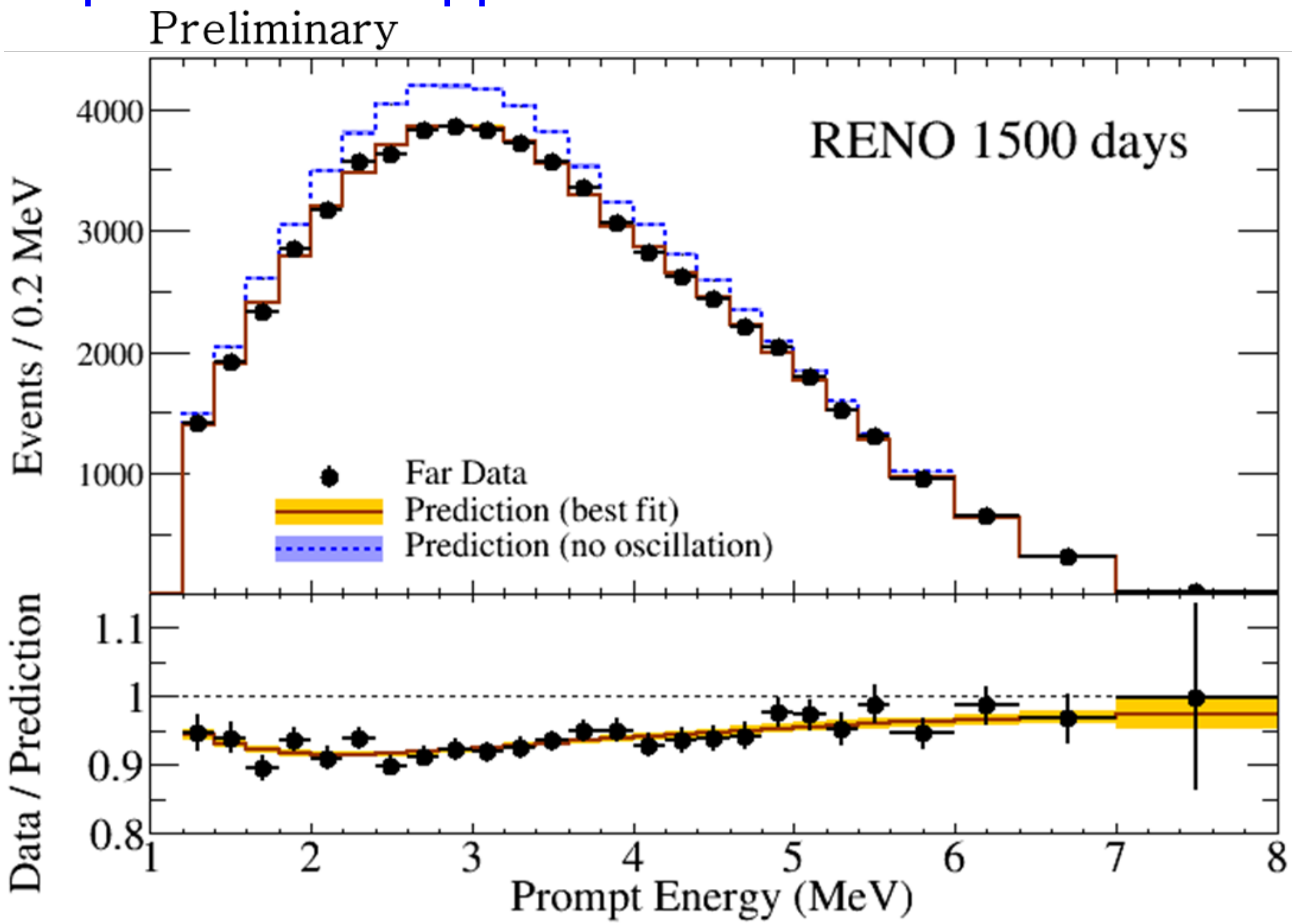
- The flux prediction is with Huber + Mueller model
- Flux weighted baseline at near : 411 m



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

Far/Near Shape Analysis

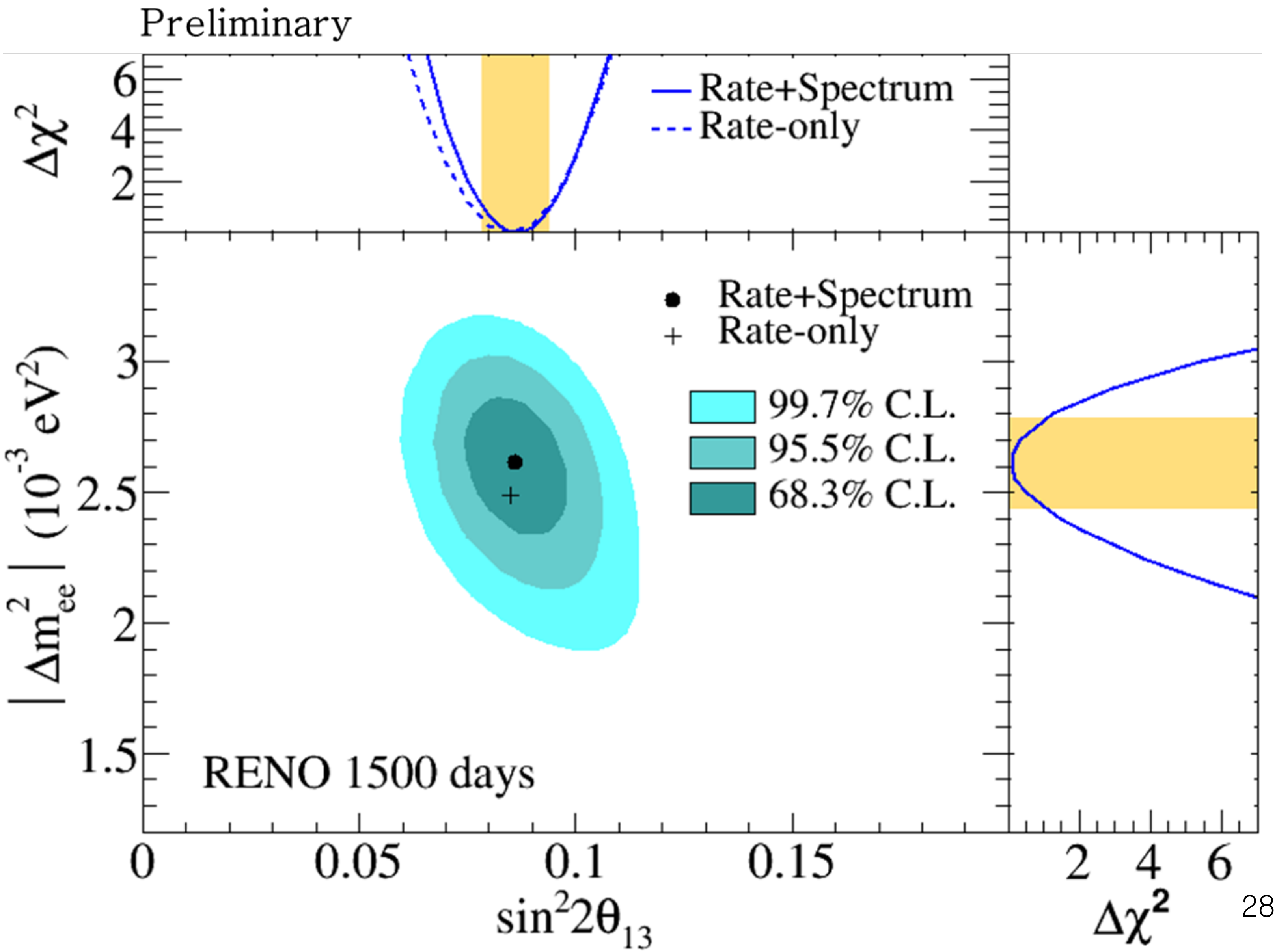
Energy-dependent disappearance of reactor antineutrinos



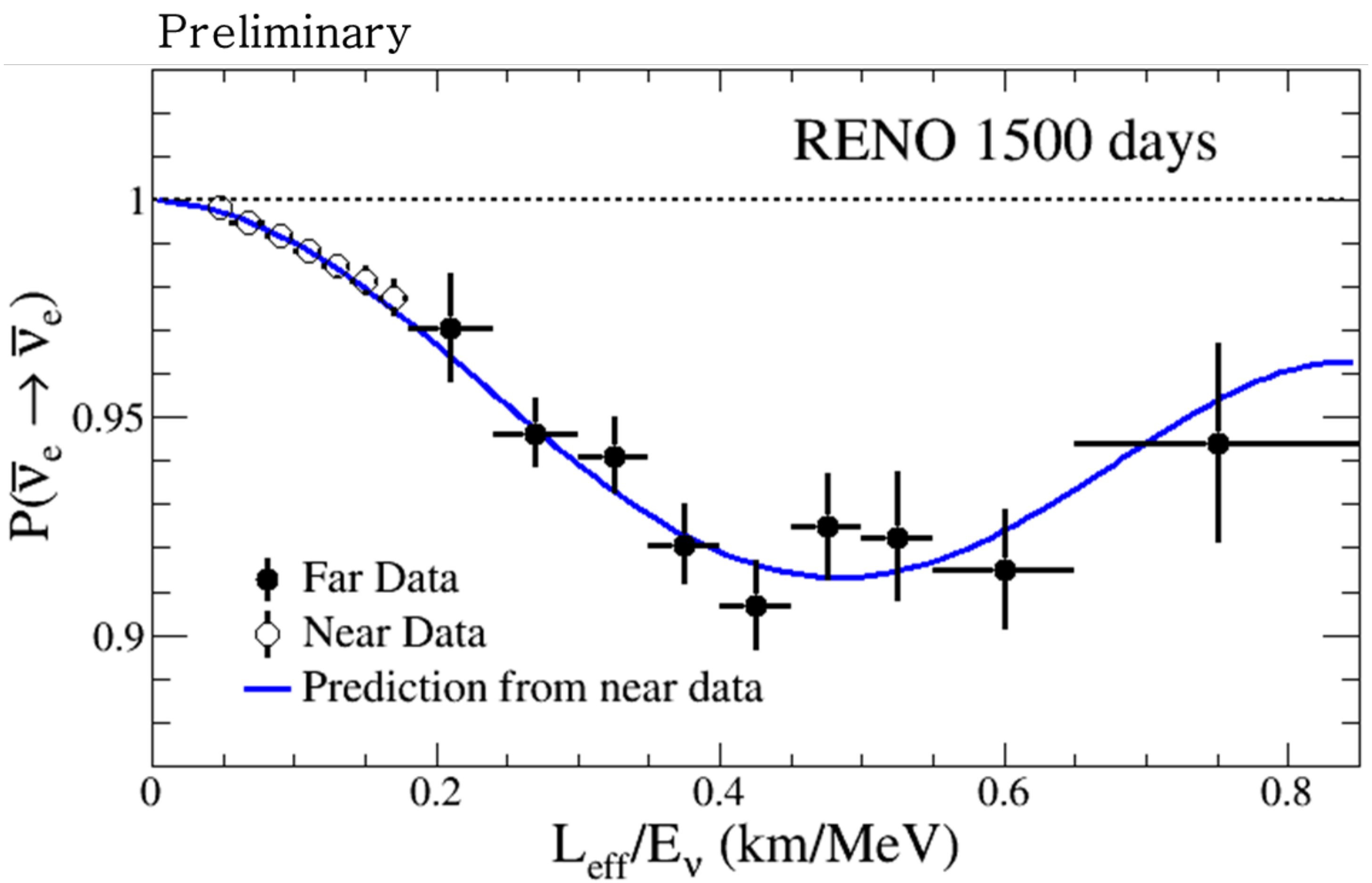
$$\sin^2 2\theta_{13} = 0.086 \pm 0.006(\text{stat.}) \pm 0.005(\text{syst.})$$ (± 9 %)

$$\left|\Delta m^2_{ee}\right| = 2.61^{+0.15}_{-0.16}(\text{stat.})^{+0.09}_{-0.09}(\text{syst.}) \ (\times 10^{-3}\text{eV}^2)$$ (± 7 %)

Allowed regions in $|\Delta m_{ee}^2|$ and $\sin^2 2\theta_{13}$



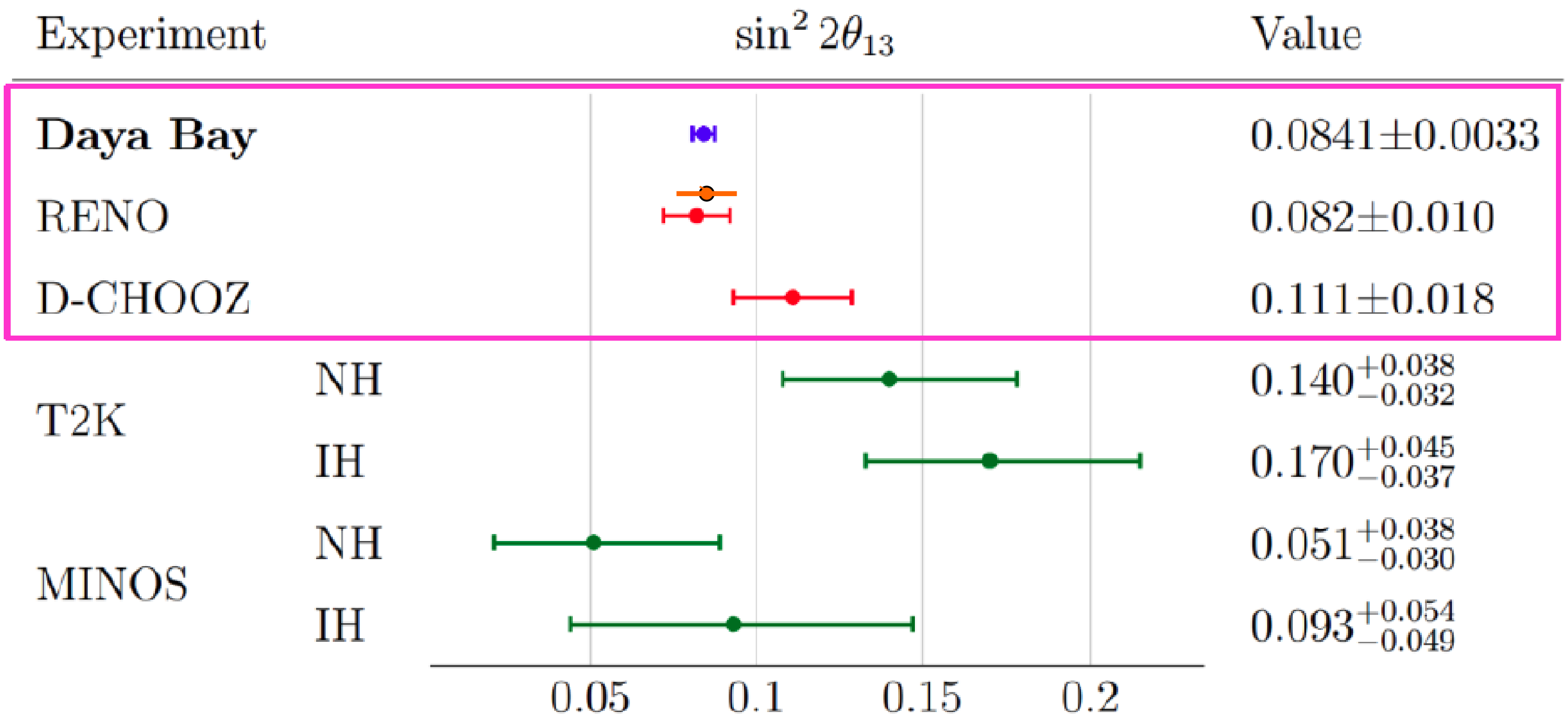
Observed L/E Dependent Oscillation



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

Summary of θ_{13} Results

Summary of θ_{13} results from reactors compared to accelerator experiments



More precise measurement of θ_{13} and $|\Delta m_{ee}^2|$

PRL 116, 211801 (2016), Submitted to PRD (arXiv:1610.04326)

500 days	Mean	Stat.	Sys.	Precision
$\sin^2 2\theta_{13}$	0.082	+0.009 -0.009	+0.006 -0.006	12 %
$\|\Delta m_{ee}^2\|$ ($\times 10^{-3}$ eV^2)	2.62	+0.21 -0.23	+0.12 -0.13	10 %

New results (preliminary)

1500 days	Mean	Stat.	Sys.	Precision
$\sin^2 2\theta_{13}$	0.086	+0.006 -0.006	+0.005 -0.005	**9 %**
$\|\Delta m_{ee}^2\|$ ($\times 10^{-3}$ eV^2)	2.61	+0.15 -0.16	+0.09 -0.09	**7 %**

Systematic errors are reduced due to background reduction and larger statistics of control samples

RENO : Plan and Prospects

Plan for RENO data taking

2017	2018	2019	2020	2021

RENO data will be taken for 2 more years from now and it will take 3 additional years 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.

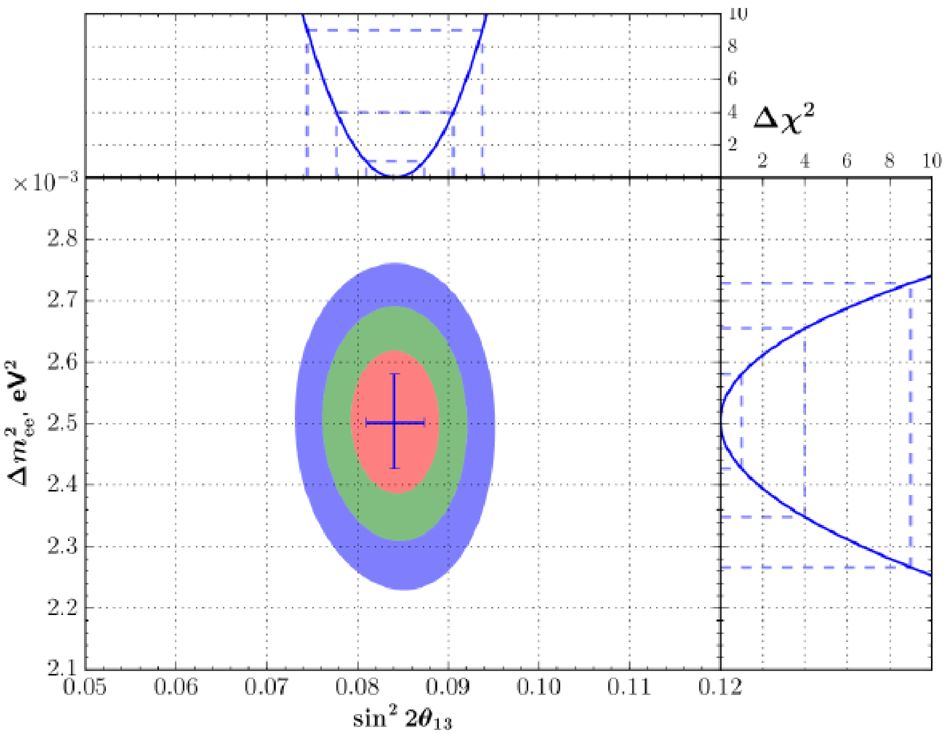
$\sin^2 2\theta_{13}$ and $|\Delta m_{ee}^2|$ will approach to **~6% precision** (our design goal).

	500 days Measured	1500 days Measured (preliminary)	~3000 days Expected
$\sin^2 2\theta_{13}$	12 %	9 %	~ 5 %
$\|\Delta m_{ee}^2\|$	10 %	7 %	4 ~ 5 %

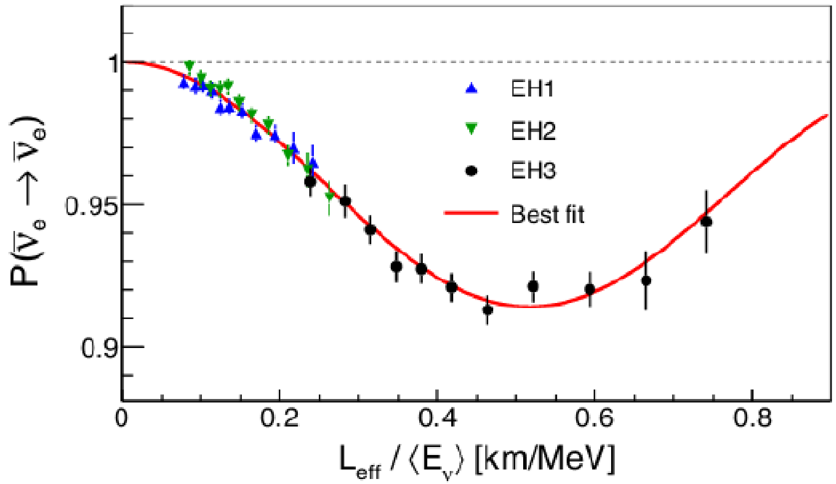
θ_{13} & $|\Delta m^2_{ee}|$ in Daya Bay

Neutrino 2016

1230 days data



$$P = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\frac{1.267\Delta m^2_{21}L}{E} - \sin^2 2\theta_{13}\sin^2\frac{1.267\Delta m^2_{ee}L}{E}.$$



$\sin^2 2\theta_{13} = [8.41 \pm 0.27(\text{stat.}) \pm 0.19(\text{syst.})] \times 10^{-2}$
$|\Delta m^2_{ee}| = [2.50 \pm 0.06(\text{stat.}) \pm 0.06(\text{syst.})] \times 10^{-3}\text{eV}^2$
$\chi^2/\text{NDF} = 232.6/263$

Last publication: $\sin^2 2\theta_{13} = [8.4 \pm 0.5] \times 10^{-2}$
P. R. L. 115, 111802 (2015) $|\Delta m^2_{ee}| =]2.42 \pm 0.11] \times 10^{-3}\text{eV}^2$

θ_{13}: Double Chooz

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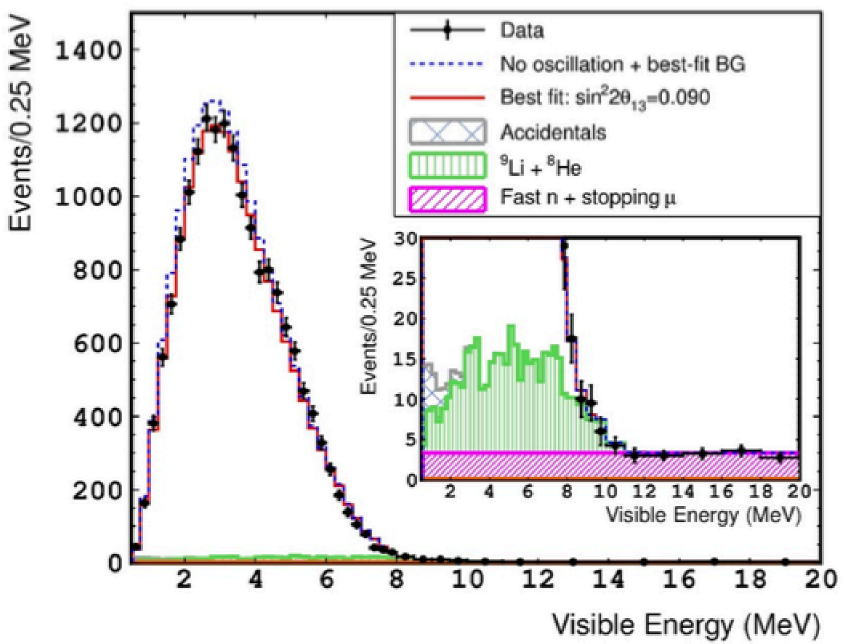
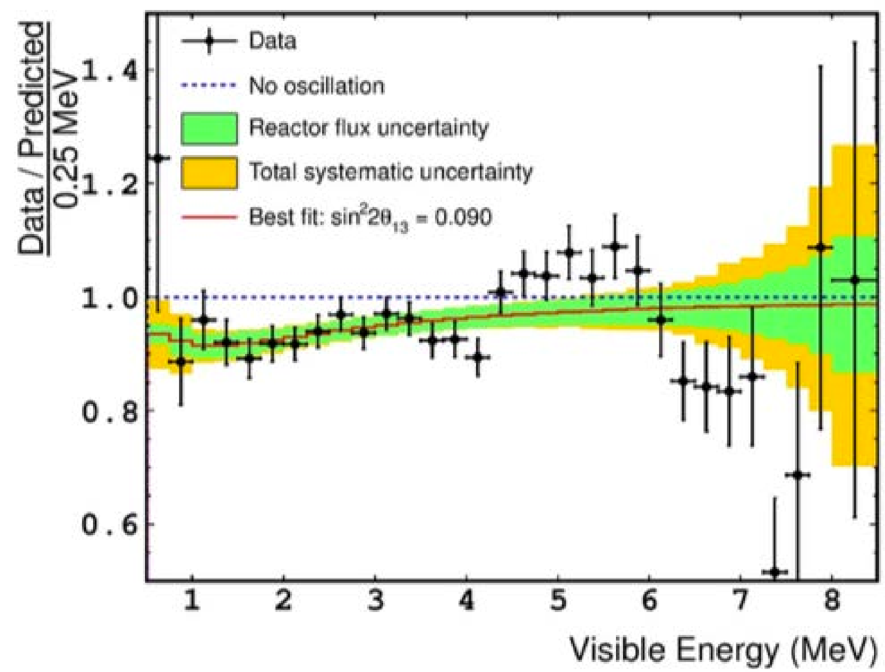


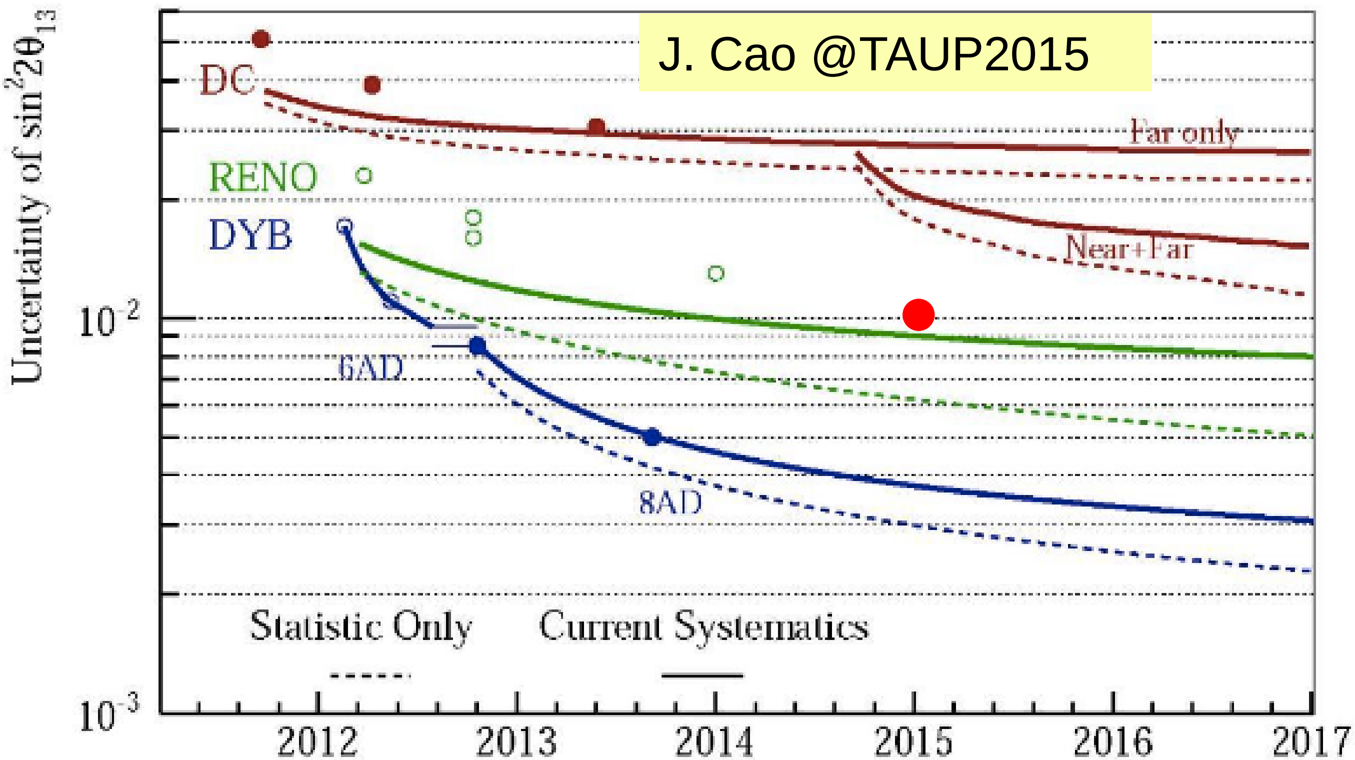


468 days $\sin^2 2\theta_{13} = 0.090^{+0.032}_{-0.029}$

Assuming Δm^2_{31} = $2.44^{+0.09}_{-0.10} \times 10^{-3}\text{eV}^2$ → MINOS result

Future Prospects on θ_{13}

	Double Chooz	RENO	Daya Bay
Data	3 yrs Near&Far	5 yrs	6 yrs
$\Delta(\sin^2(2\theta_{13}))$	~10 %	~5 %	~3 %
$\Delta(\lvert m^2_{ee}\rvert)$	-	~5 %	~3 %



Summary

- More precise measurements of θ_{13} and Δm_{ee}^2 using energy dependent disappearance of reactor neutrinos

$$\sin^2 2\theta_{13} = 0.086 \pm 0.006(\text{stat}) \pm 0.005(\text{syst})$$ ± 0.008 9 % precision

$$\left|\Delta m_{ee}^2\right| = 2.61^{+0.15}_{-0.16}(\text{stat.})^{+0.09}_{-0.09}(\text{syst.})\,(\times 10^{-3}\text{eV}^2)$$ ± 0.18 7 % precision

- Measured absolute reactor neutrino flux : R= 0.946±0.021

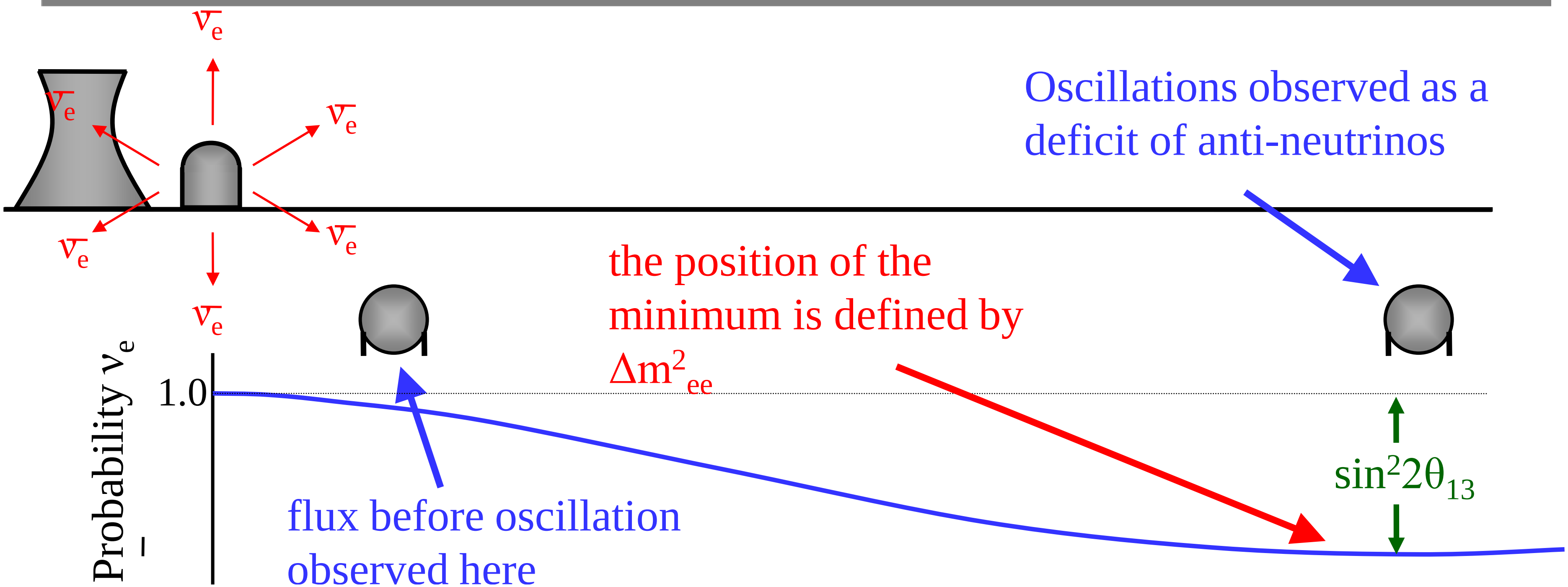
- Observed an excess at 5 MeV in reactor neutrino spectrum

- $\sin^2(2\theta_{13})$ and Δm_{ee}^2 to 6% accuracy after 2 more years data taking

- Additional 2~3 years of data taking under consideration to improve Δm_{ee}^2 accuracy

Thanks for your attention!

Reactor Neutrino Oscillations



$$P(\overline{\nu}_e \to \overline{\nu}_e) = 1 - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$

$$\simeq 1 - \sin^2 2\theta_{13}\sin^2\Delta_{ee} - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$

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

Distance

1200 to 1800 meters

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

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

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

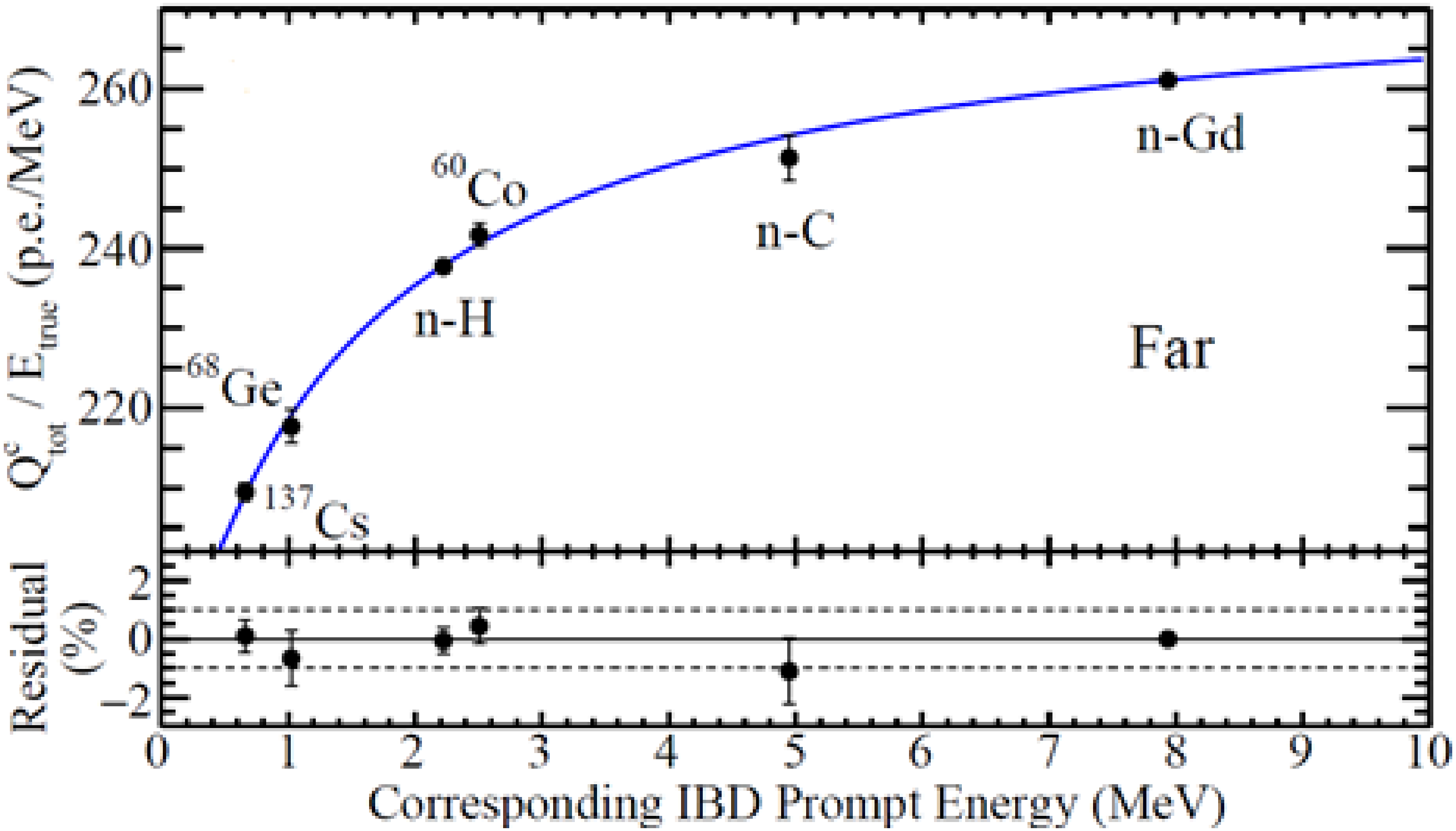
+: Normal Hierarchy

−: Inverted Hierarchy

H. Nunokawa et al, PRD72 013009(2005)

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