The recent results of RENO experiment

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Chonnam National University

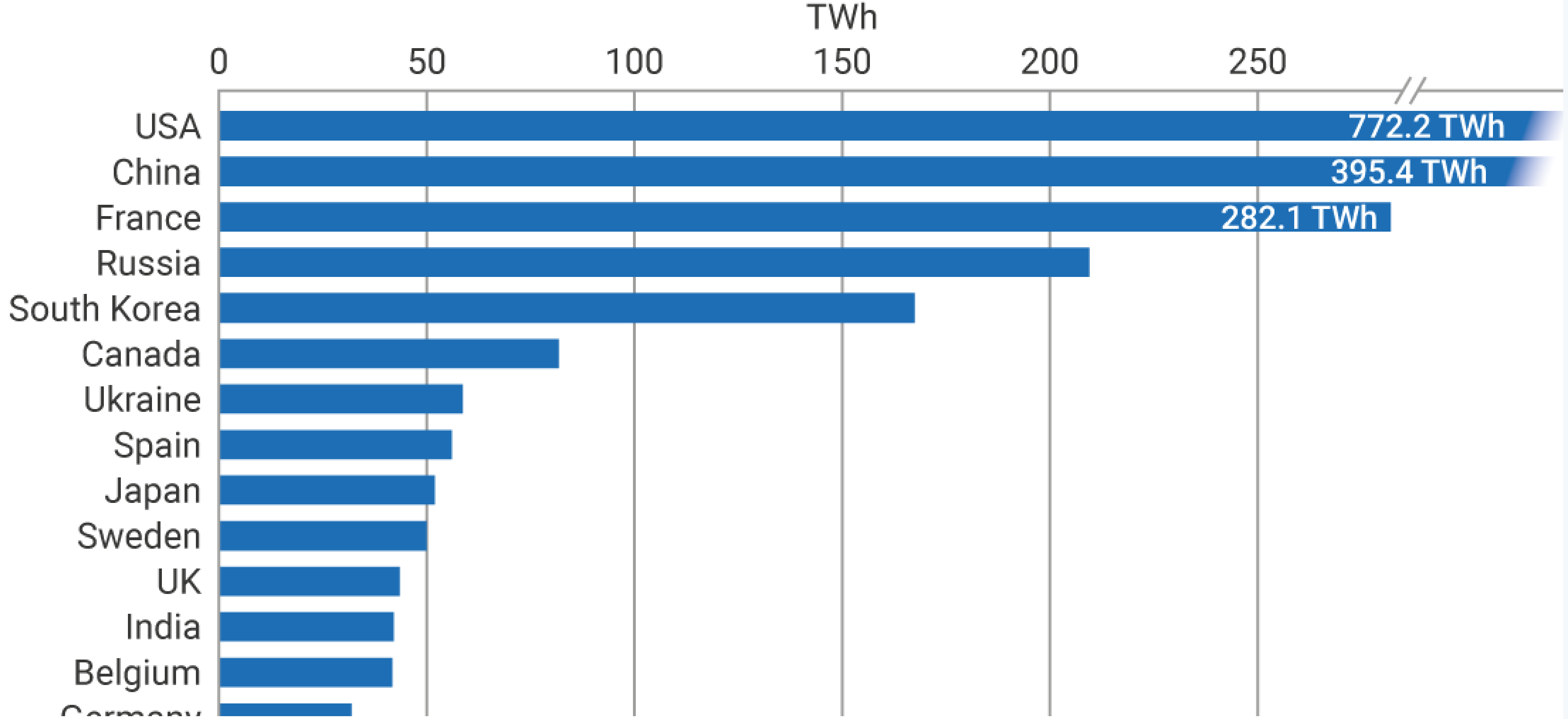
April 7, 2025

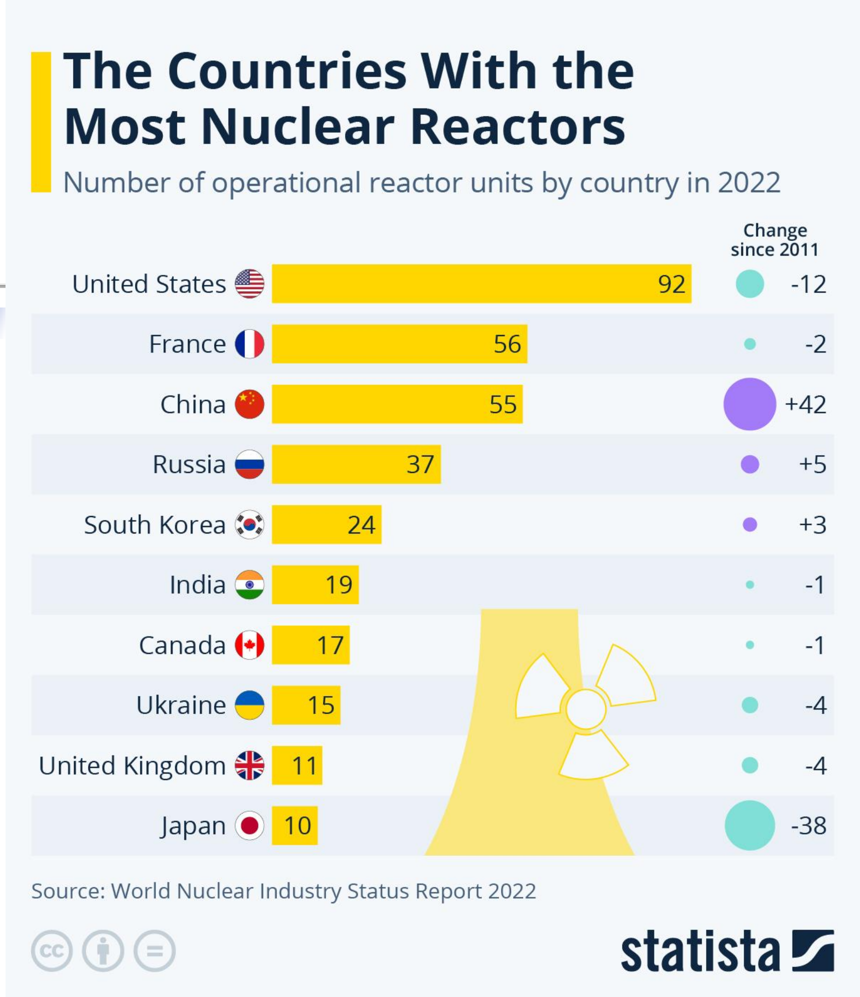
The 3rd IAEA Technical Meeting
on Nuclear data for antineutrino spectra applications

Nuclear Power producers

South Korea is one of the world's largest nuclear power producers.

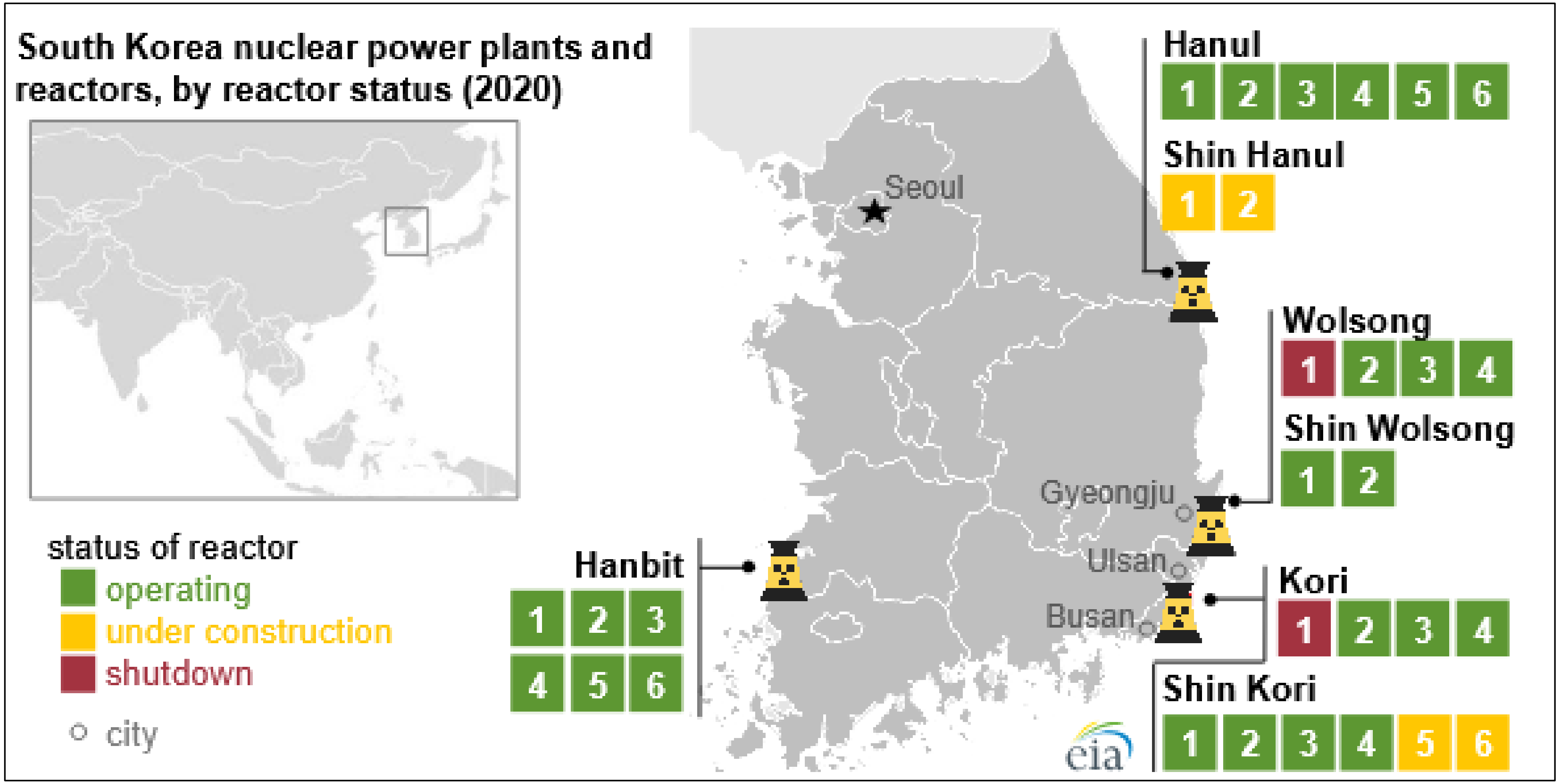
Nuclear generation by country 2023
source: World Nuclear Association, IAEA PRIS





Nuclear power plants in South Korea

Now, 26 operating reactors.



2024
Shin Hanul

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Reactor Experiment for Neutrino Oscillation

8 Institutes and 30 Physicists

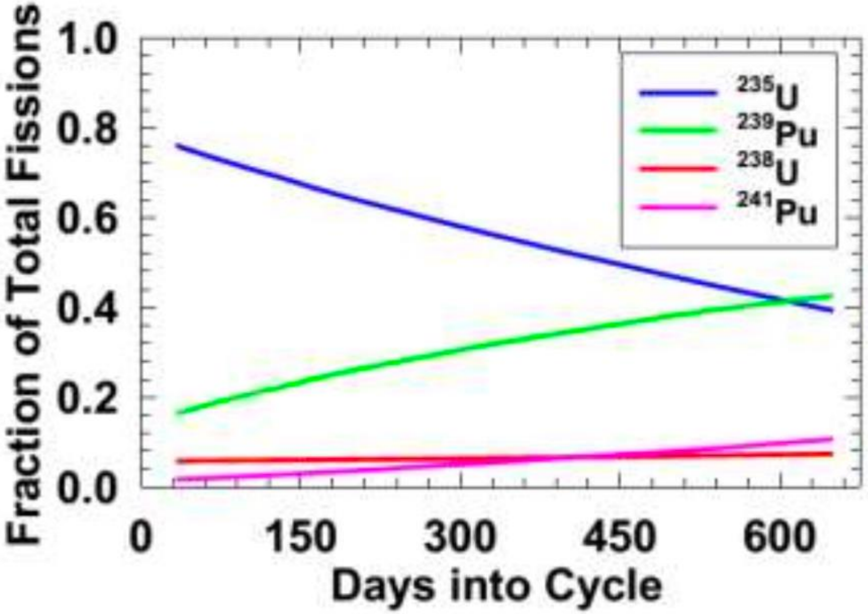
Chonnam National University
Dongshin University
Gwangju Institute of Science and Technology
Gyeongsang National University
Kyungpook National University
Seoul National University
Seoyeong University
Sungkyunkwan university

- Start of project: 2006
- The first reactor experiment running with both near and far detectors
- Observation non-zero θ_{13}

Hanbit Nuclear Power Plant & Neutrino Production

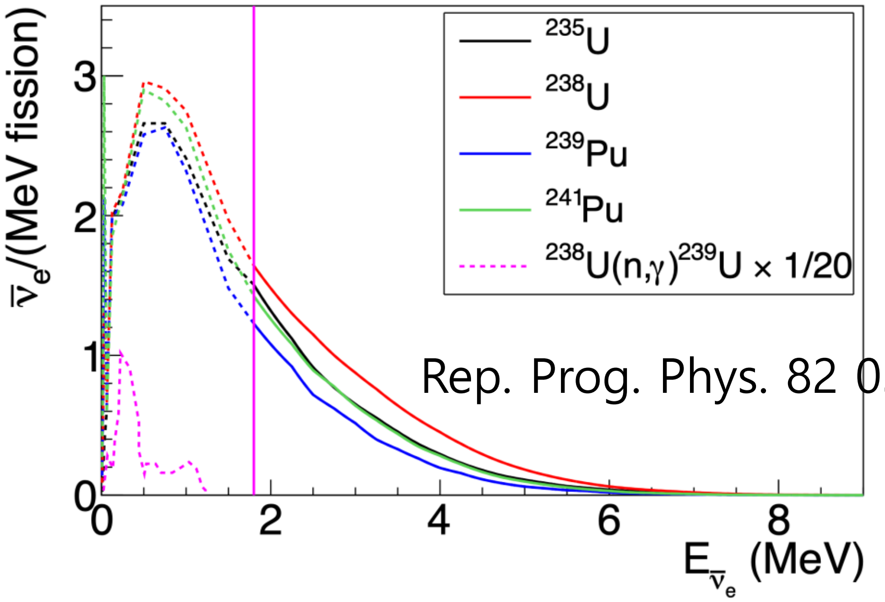
Reactor #	Net Capacity	Thermal Power	Model	Commissioning
1	903 MW	2787 MWt	WH F	1986
2	903 MW	2787 MWt	WH F	1987
3	950 MW	2825 MWt	OPR-1000	1995
4	950 MW	2825 MWt	OPR-1000	1996
5	992 MW	2825 MWt	OPR-1000	2002
6	993 MW	2825 MWt	OPR-1000	2002

Fuel consumption evolution



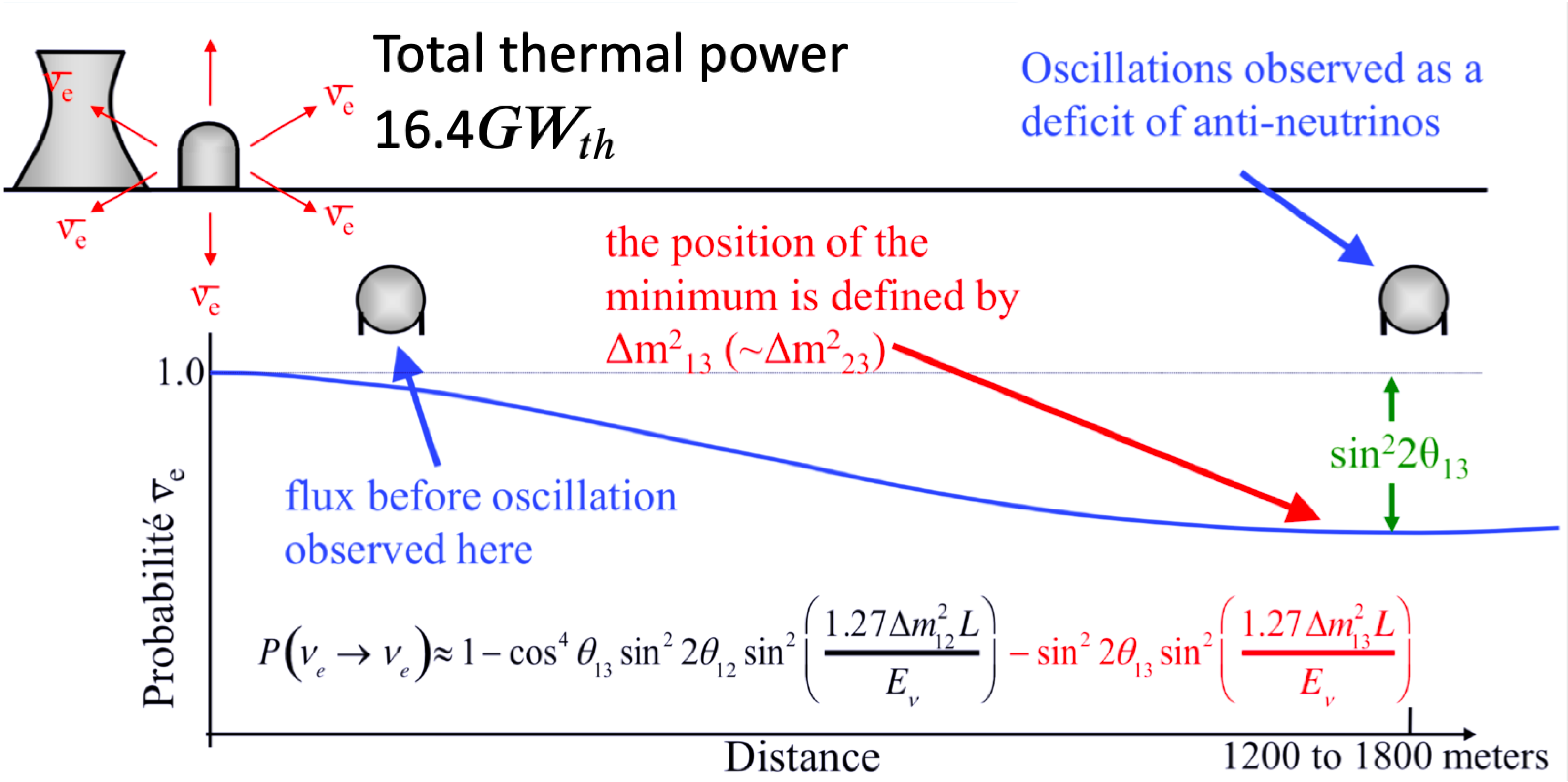
Anti-electron neutrinos for each GW_{th}

~2 x 10^{20} neutrinos / GW_{th}



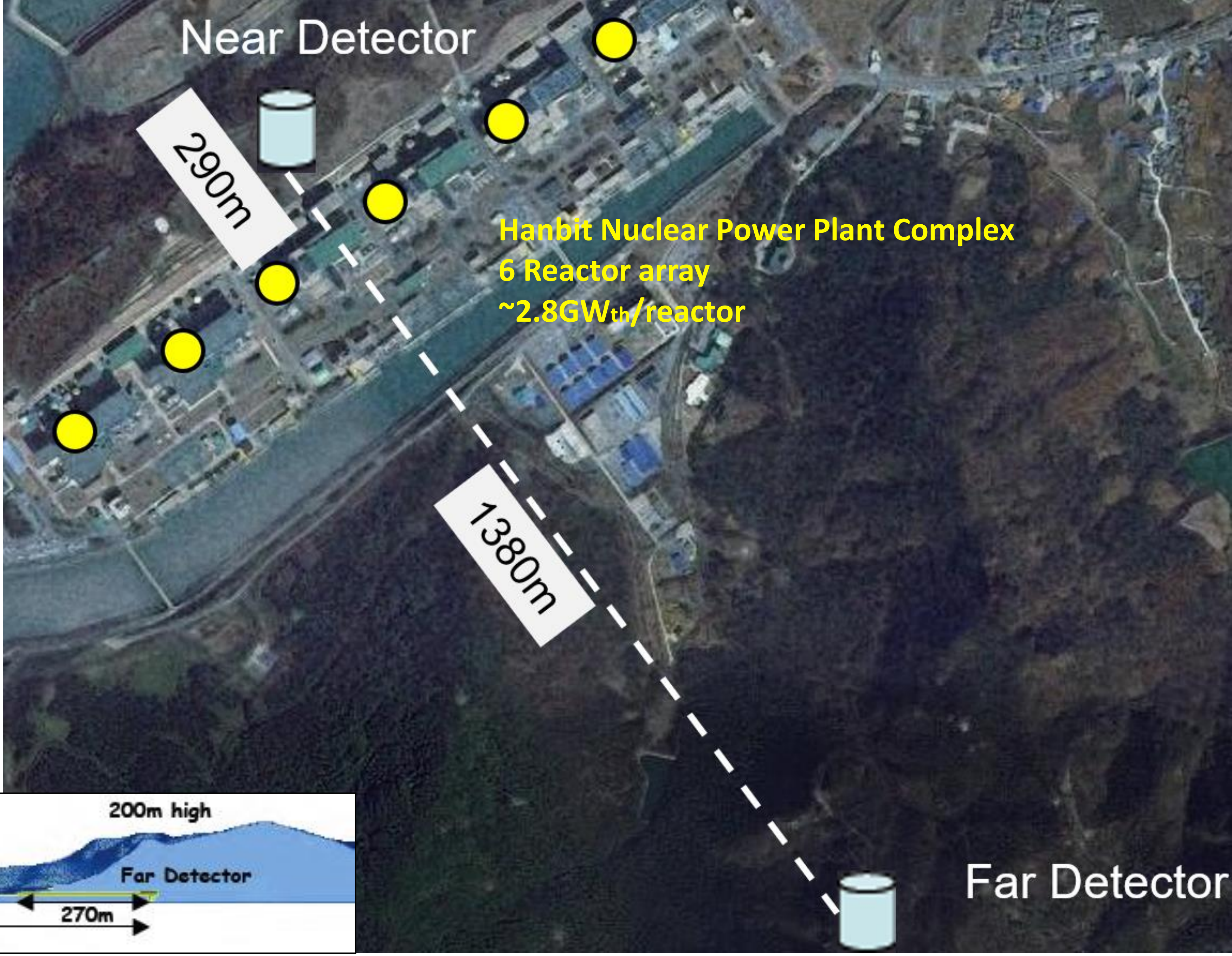
Rep. Prog. Phys. 82 036201 (2019)

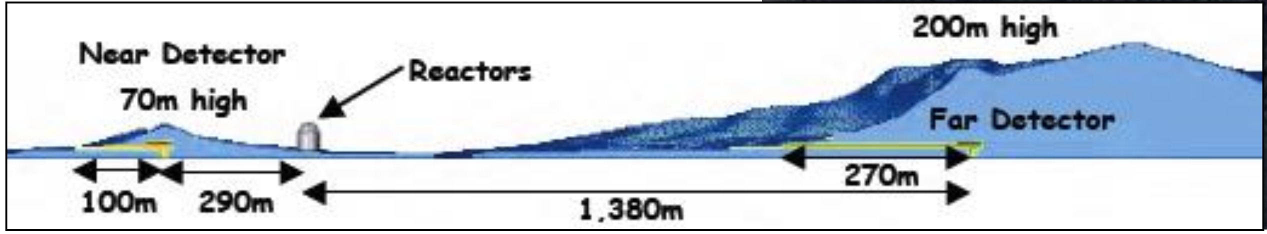
Reactor Experiment for Neutrino Oscillation



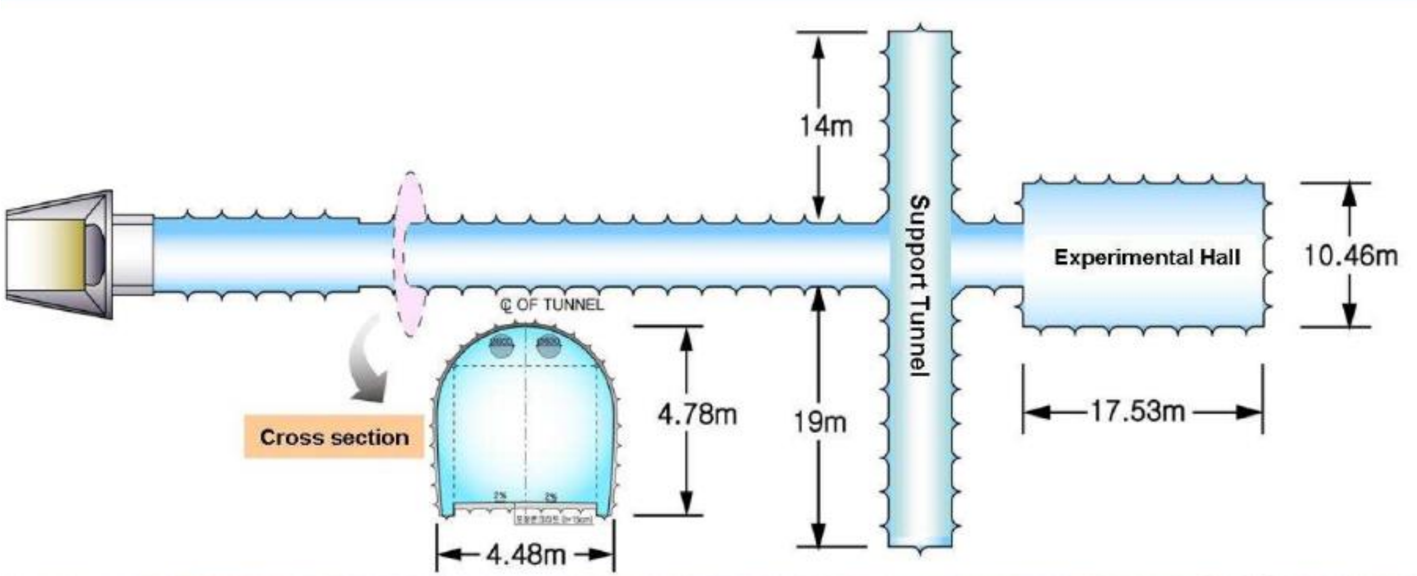
RENO Experimental Setup

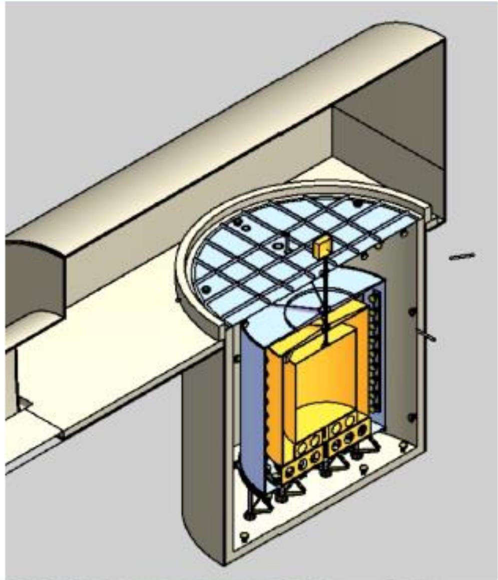
ν-flux contribution		
R#	Near	Far
1	6.78%	13.73%
2	14.93%	15.74%
3	34.19%	18.09%
4	27.01%	18.56%
5	11.50%	17.80%
6	5.58%	16.08%





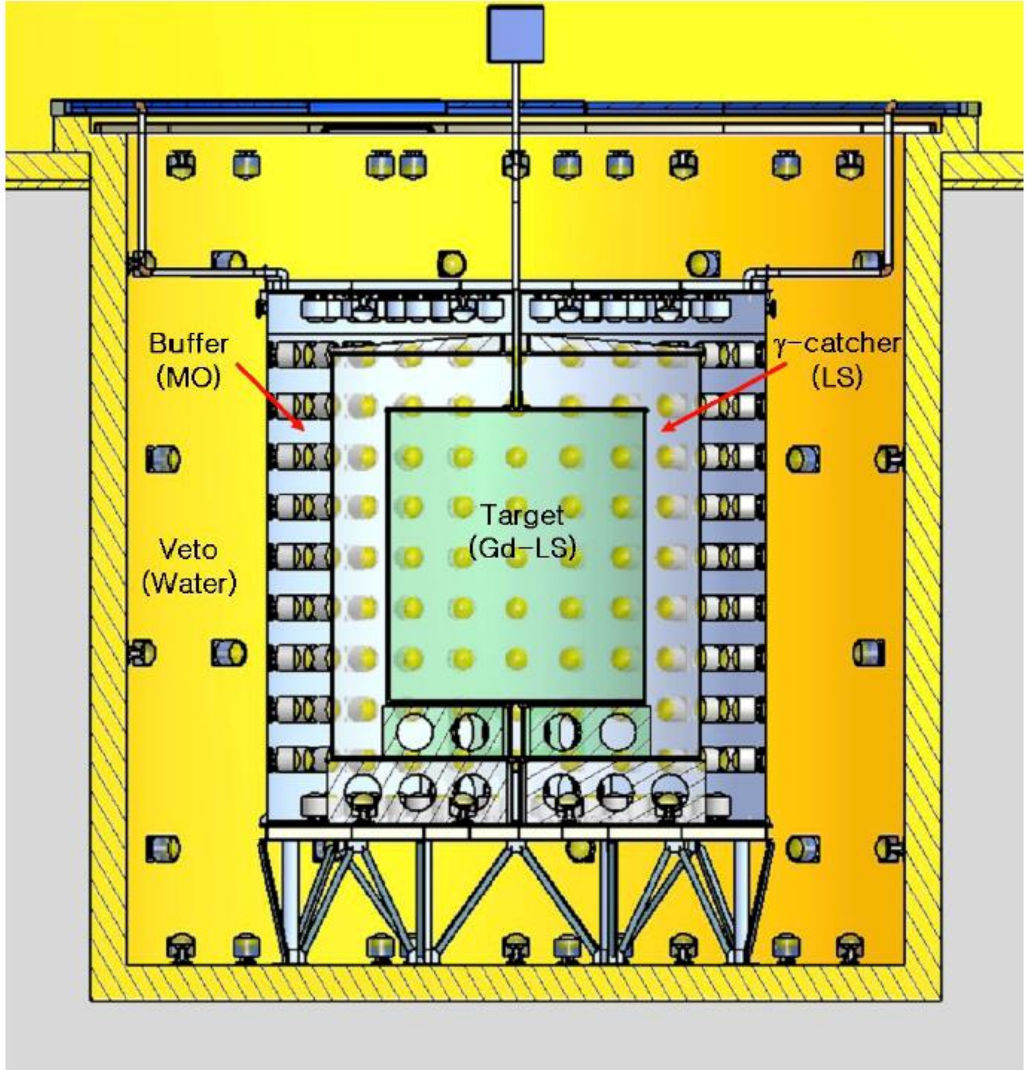
RENO Experimental Setup





RENO Detectors

Identical detectors at near and far sites

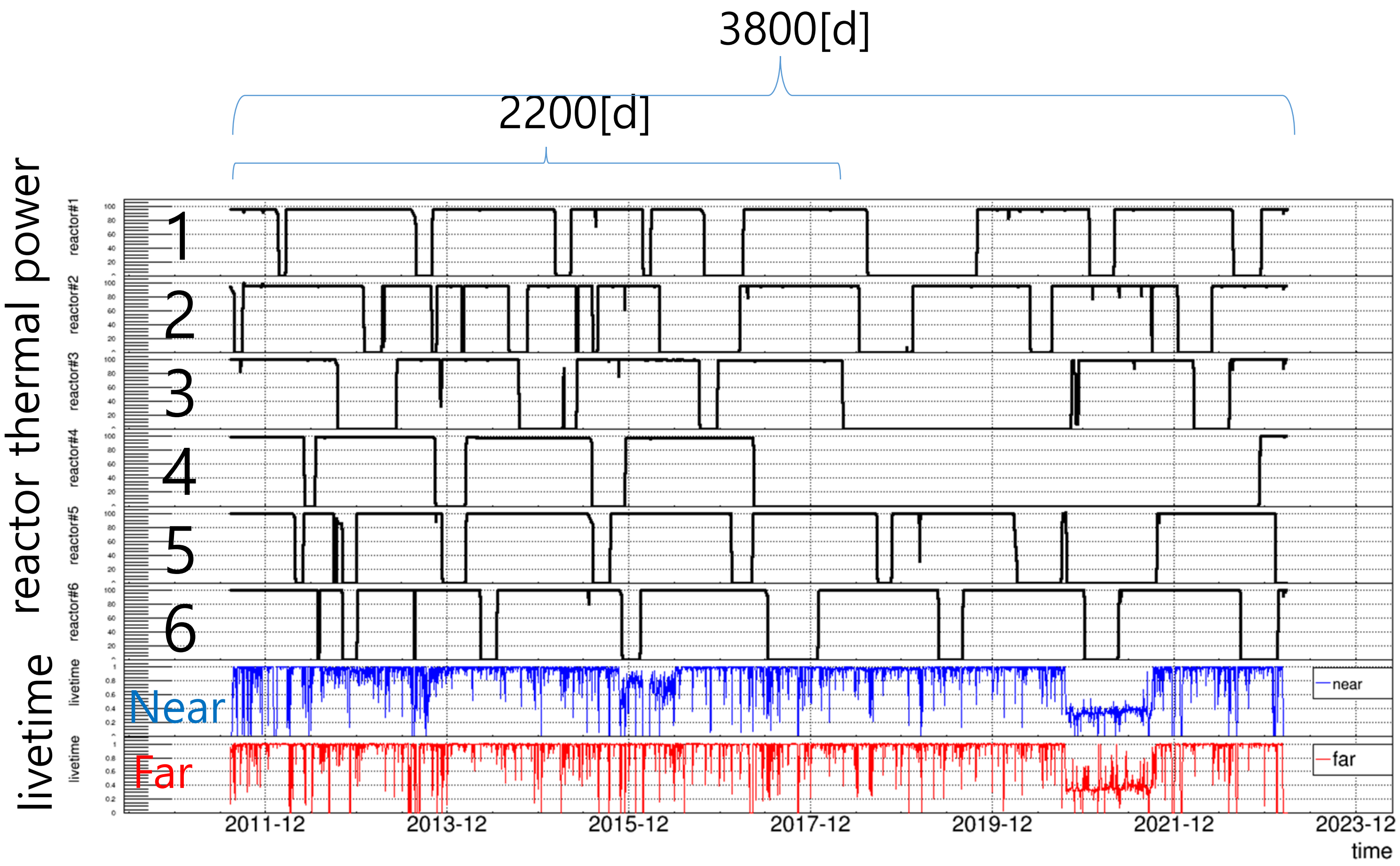


Detector	Material	Mass
IBD Target	Gd (0.1%)+LS	16.5 ton
Gamma Catcher	LS	30.0 ton
Buffer	Mineral oil	64.6 ton
Veto	Water	352.6 ton

354 ID PMTs and 67 OD PMTs
(10" HAMAMATSU R7081)

Data taking

- RENO DAQ running
  - Aug. 2011 ~ Mar. 2023.
- 3800[days] livetime
- The other systems maintaining quality of the hardware are under operation.
- Recently, started re-operating DAQ of the near detector.
  →RENE experiment
  (sterile neutrino search.
  See the next talk).



Period	Live time	Result
Aug. 2011 ~ Feb. 2018	2200 [days]	2018 PRL
Aug. 2011 ~ Mar. 2023	3800 [days]	New result

Major Results from RENO

- Precise measurement of $|\Delta m^2_{ee}|$ and θ_{13}
  - Phys. Rev. Lett. 108, 191802 (2012) - 229[d]
  - Phys. Rev. Lett. 116, 211801 (2016) - 500[d]
  - Phys. Rev. D 98, 012002(2018) - 500[d]
  - Phys. Rev. Lett. 121, 201801 (2018) - 2200[d]
  - arXiv:2412.18711 - 3800[d] days of data -> new result
- Measurement of θ_{13} with nH capture
  - JHEP 04 029 (2020) - 1500[d]
  - 2800[d] days of data

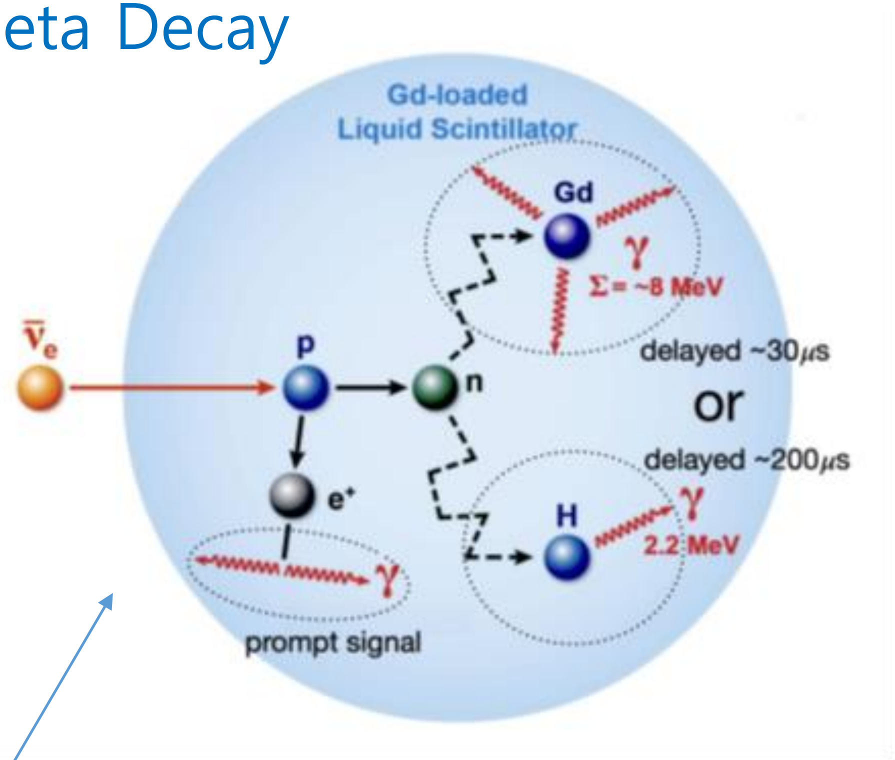
will be finished with 3800[d] analyses.

- Reactor neutrino yield & spectrum
  - Phys. Rev. Lett. 122, 232501 (2019) - 1800[d]
  - Phys. Rev. D 104, L111301 (2021) - 2900[d]
- Results from sterile neutrino search
  - Phys. Rev. Lett. 125, 191801 (2020) - 2200[d]
  - Phys. Rev. D 105, L111101 (2022) - 2500[d] x NEOS 180[d]

will be continued beyond 3800[d] analyses according to re-operation of the near detector.

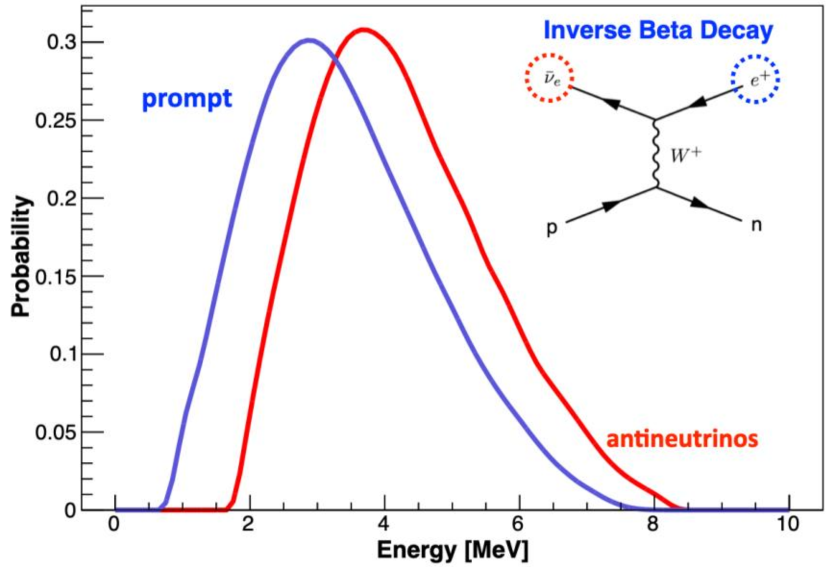
RENO Antineutrino Detection Principle

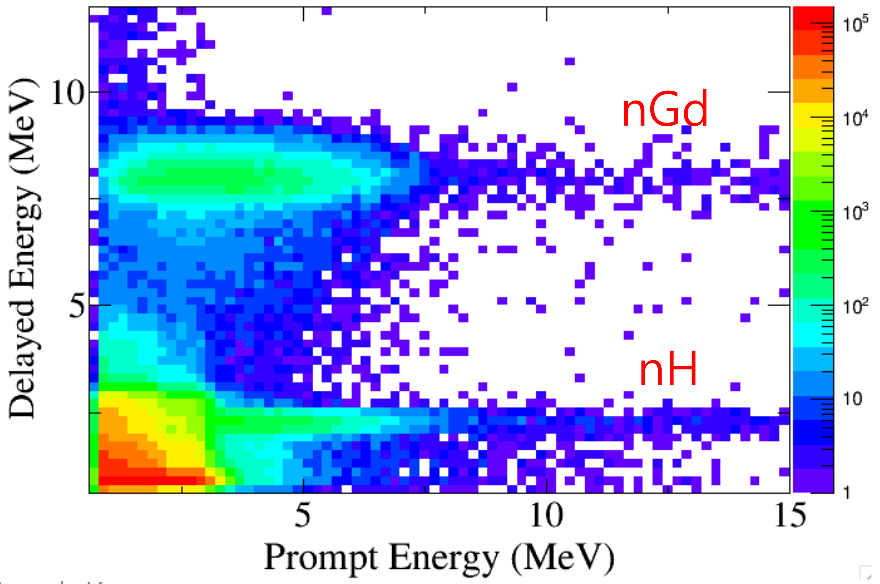
Inverse Beta Decay (IBD)



$$E_p \simeq E_\nu - 0.78\mathrm{MeV}$$

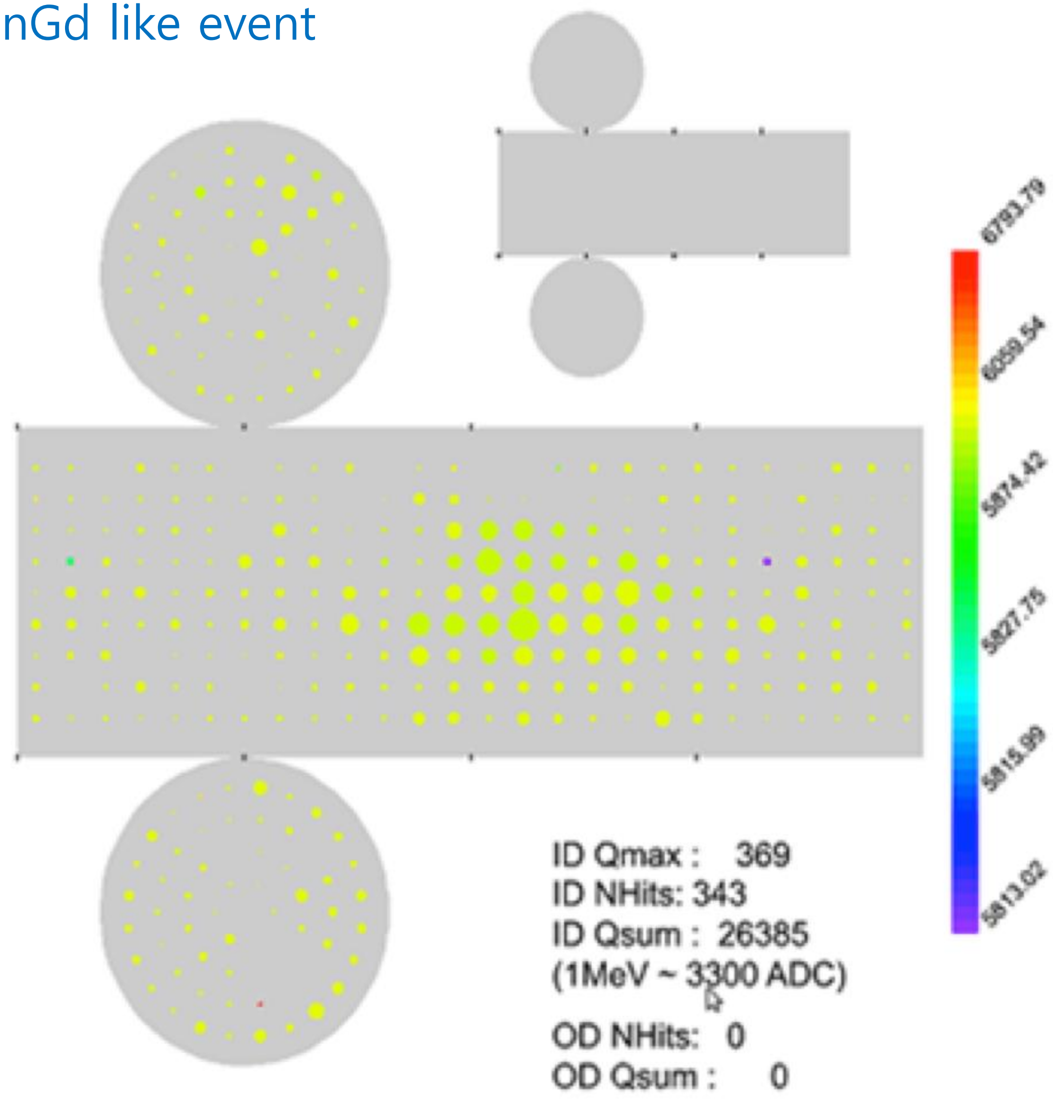
$$E_\nu^{thr} = \frac{(m_n + m_p)^2 - m_p^2}{2m_p} = 1.806\,\mathrm{MeV}$$



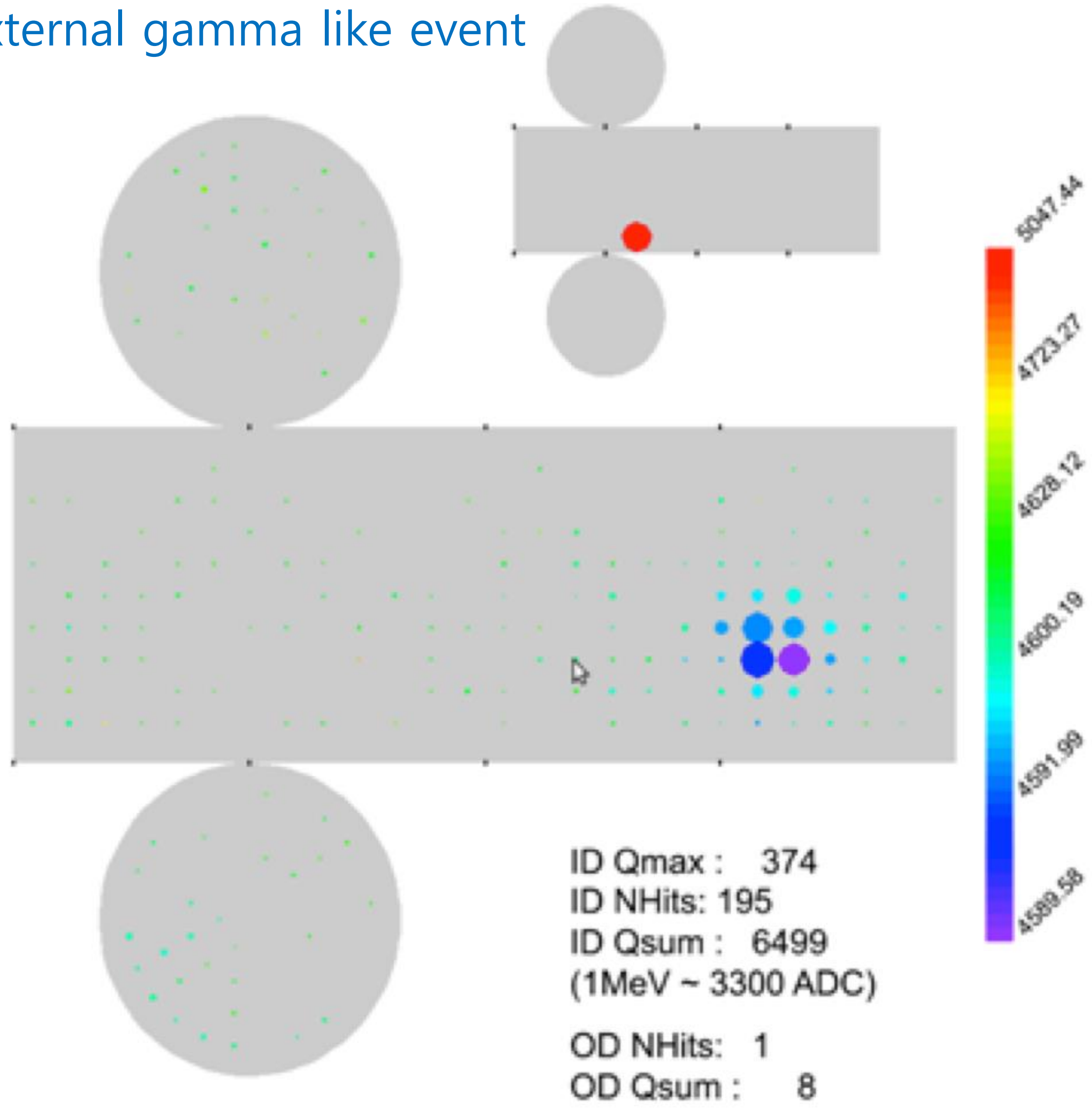


RENO Event Display

nGd like event

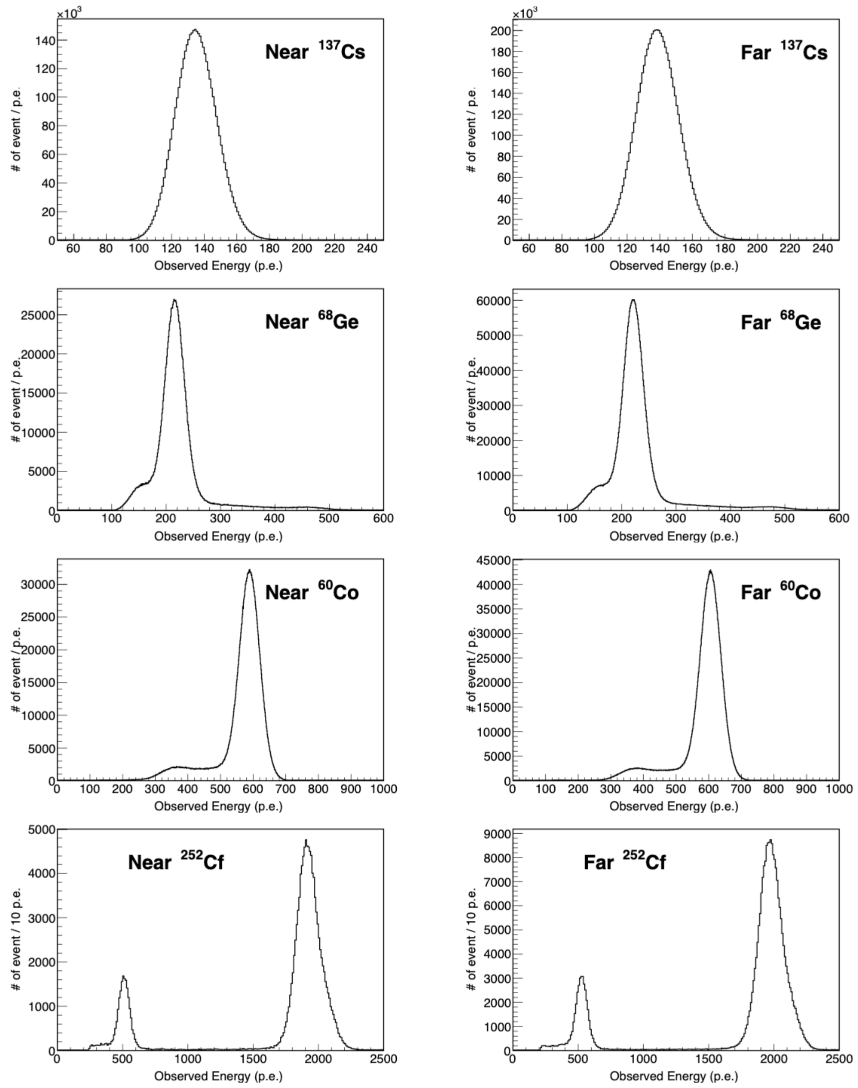


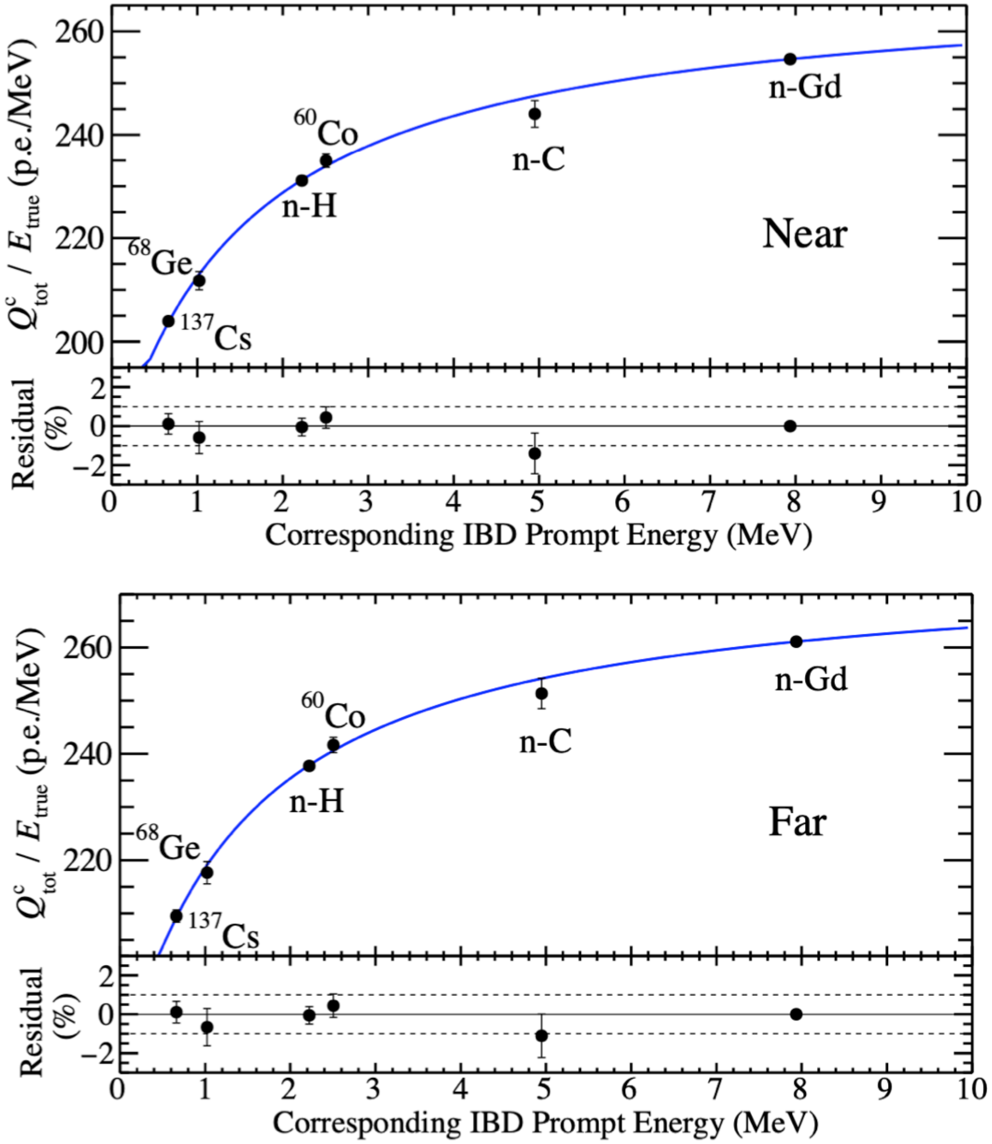
External gamma like event



RENO Detector Calibration

Radioactive sorce calibration

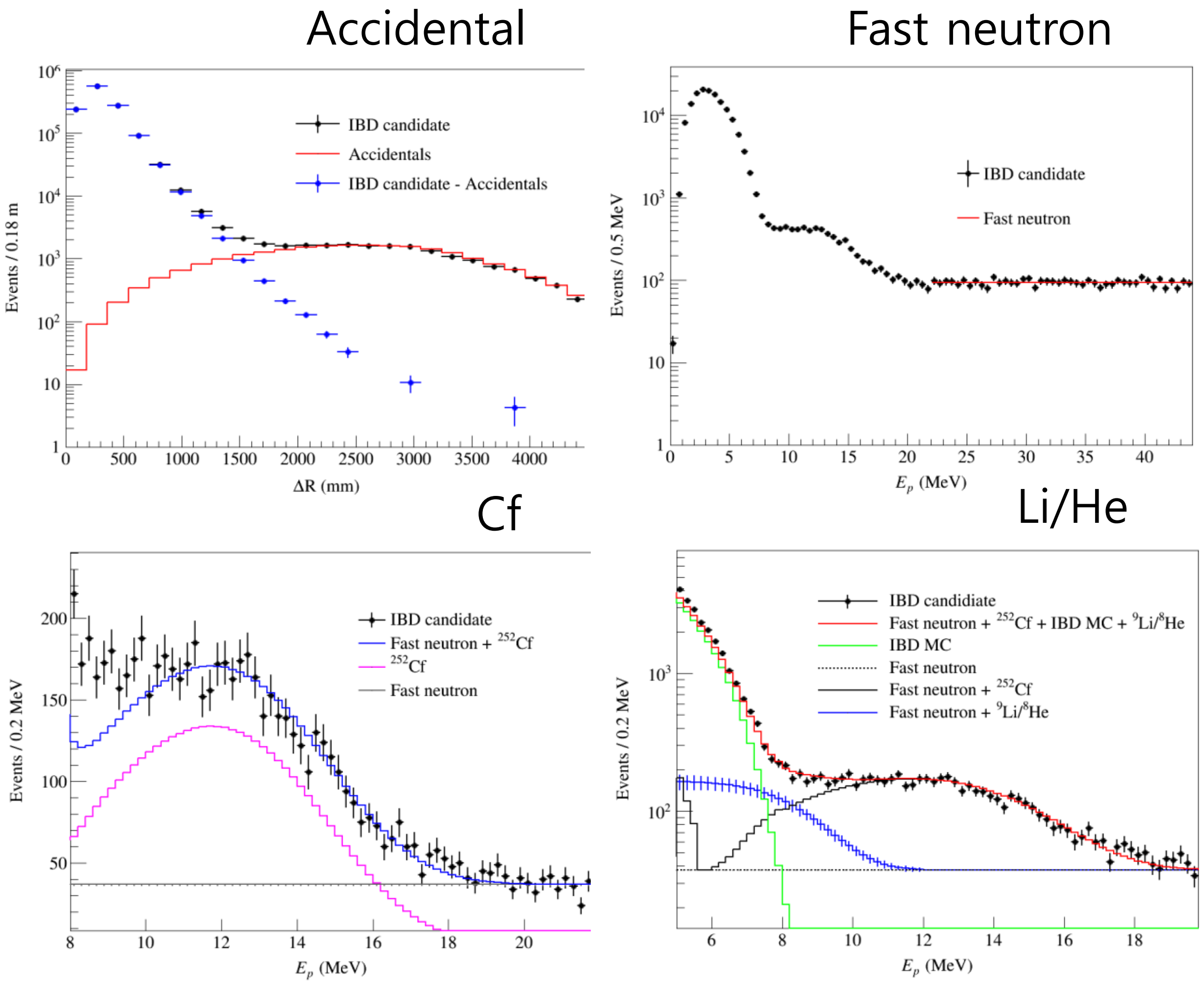




IBD Candidate Sample &Background Estimation

- 1,211,995(144,667) $\bar{\nu}_e$ candidate events observed for near(far).
- The total background rates
  - Near: 9.08±0.18 events/day (2.5%)
  - Far: 2.06±0.13 events/day (5.3%)

3800d: arXiv:2412.18711



Detector	Near	Far
IBD rate	366.47 ± 0.33	38.70 ± 0.10
after background subtraction	357.39 ± 0.38	36.64 ± 0.16
total background rate	9.08 ± 0.18	2.06 ± 0.13
live time [days]	3307.25	3737.85

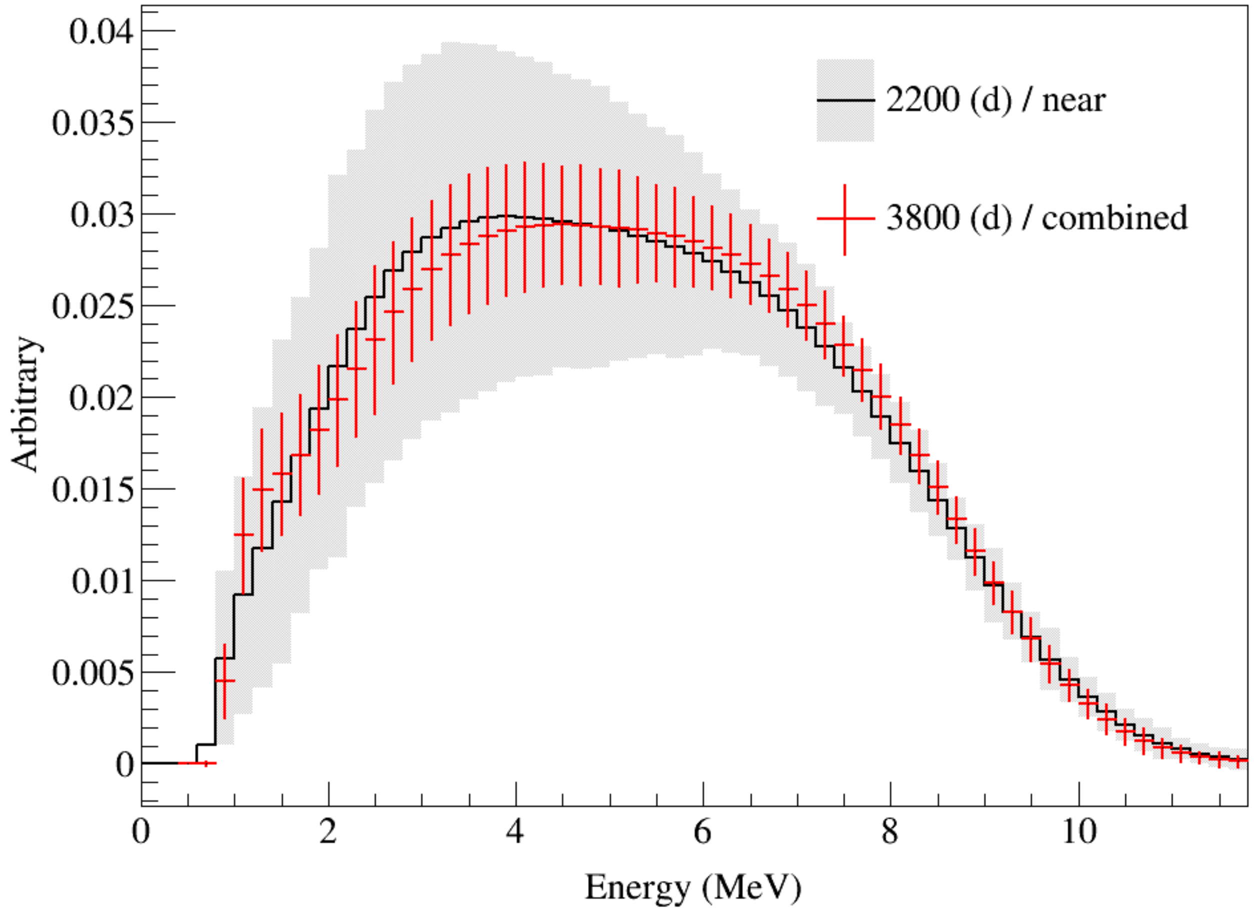
measured IBD and estimated background rates with 1.2 < E_p < 8.0 [MeV], given per day

Improvement

- Li/He Background Spectrum
  - extension of dataset
  - combined far & near spectrum

- reactor-related uncertainties
  - decomposition of detector-correlated & detector-uncorrelated components
  - only detector-uncorrelated component can be considered for far-to-near ratio analysis.

comparison of the Li/He spectrums



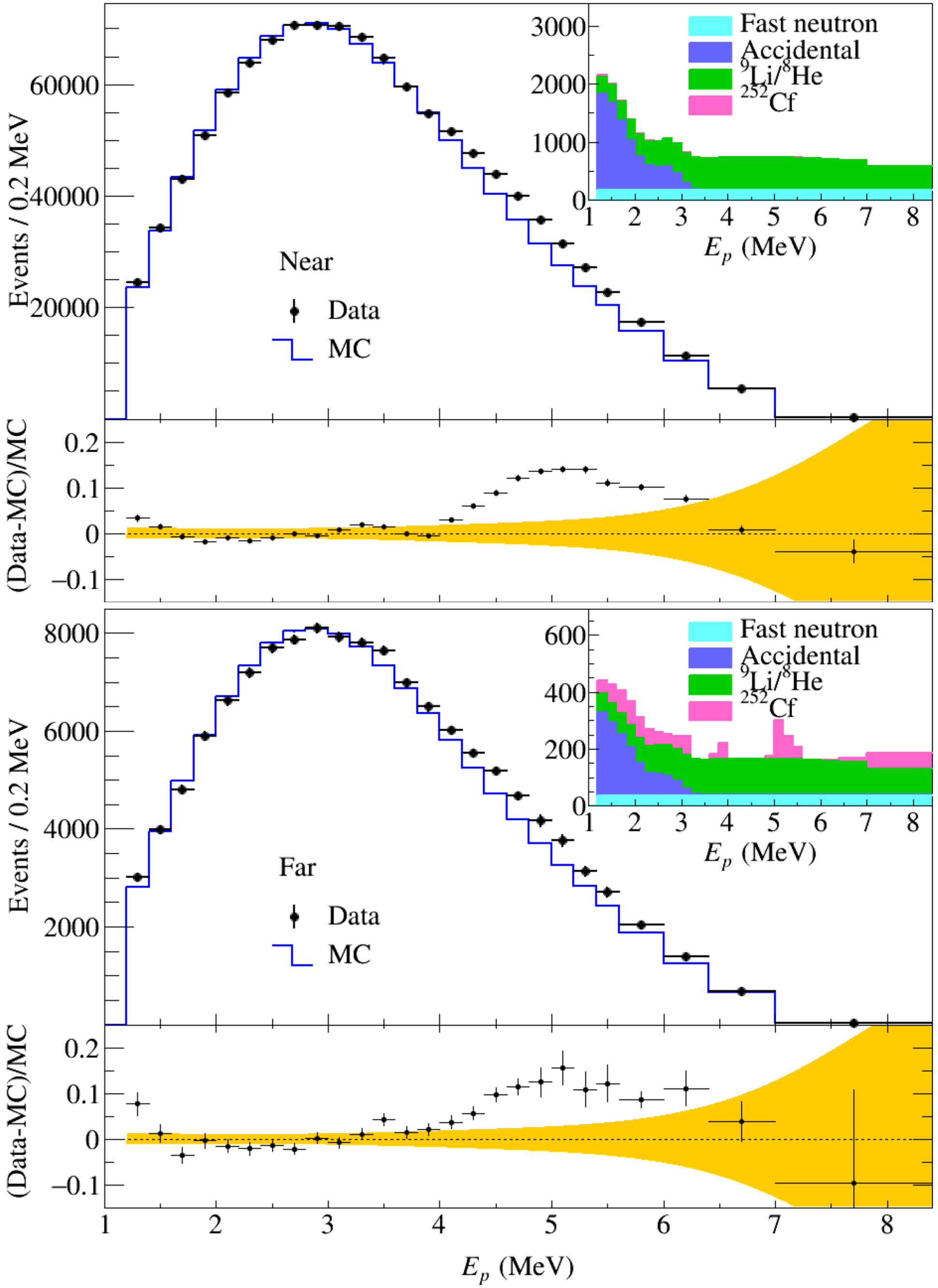
3800d: arXiv:2412.18711

IBD prompt spectrum

- A shape comparison between the observed IBD prompt spectrum and the prediction from a reactor $\bar{\nu}_e$ model
  - Data : observed IBD prompt spectrum after background subtraction
  - MC : prediction with best-fit oscillation

- The fractional difference between data and prediction in the lower panel

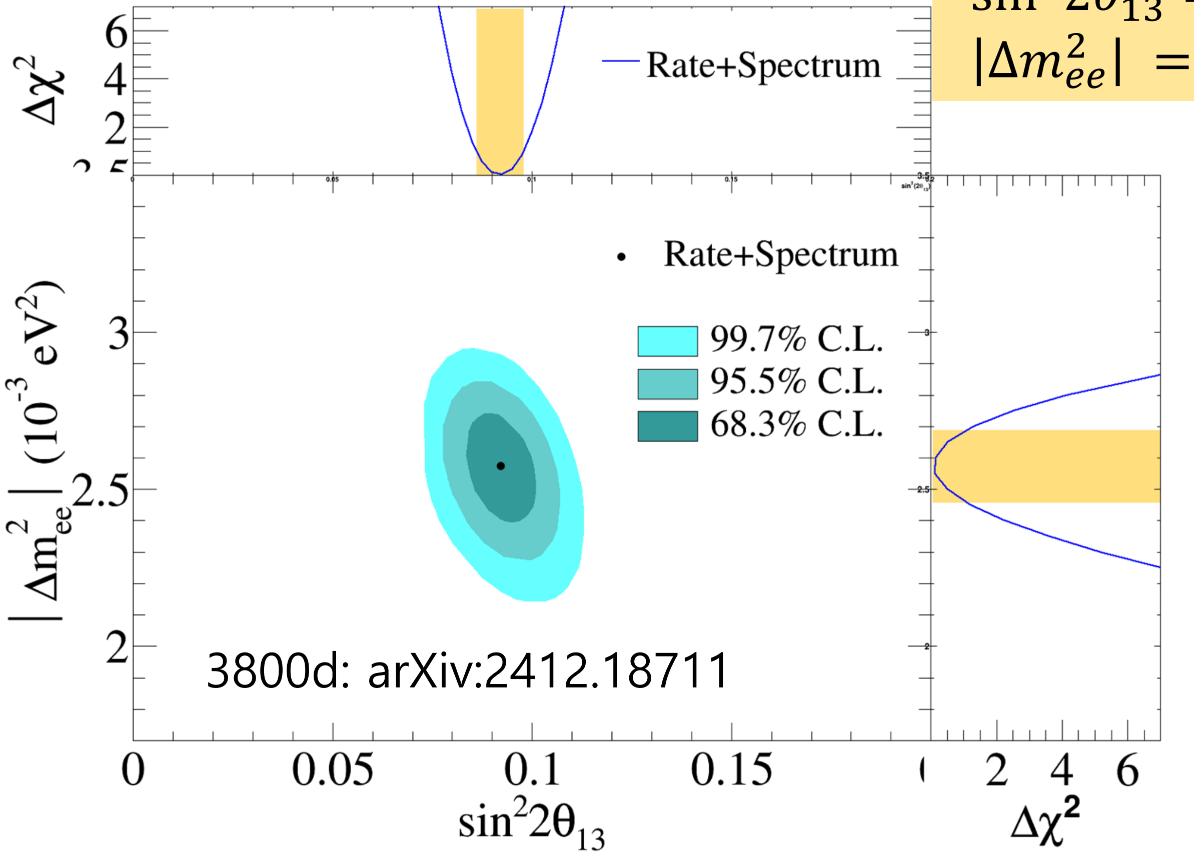
- A clear discrepancy between the observed and the predicted spectral shapes in the region of 5 [MeV]



3800d: arXiv:2412.18711

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

Based on the measured far-to-near ratio of prompt spectra from RENO 3800 days (Aug. 2011 – Mar. 2023)



$\sin^2 2\theta_{13} = 0.0920^{+0.0044}_{-0.0042}\,(stat.)^{+0.0041}_{-0.0041}(syst.)$ (6.4% precision)

$|\Delta m^2_{ee}| = 2.57^{+0.10}_{-0.11}(stat.)^{+0.05}_{-0.05}(syst.)\ (\times 10^{-3}\ \mathrm{eV}^2)$ (4.5% precision)

source of the systematic uncertainty

	Δm^2_{ee} $[10^{-3} eV^2]$	$sin^2 2\theta_{13}$ []
reactor	-	± 0.0013
detection efficiency	-	± 0.0032
energy scale	± 0.05	± 0.0016
backgrounds	± 0.02	± 0.0020

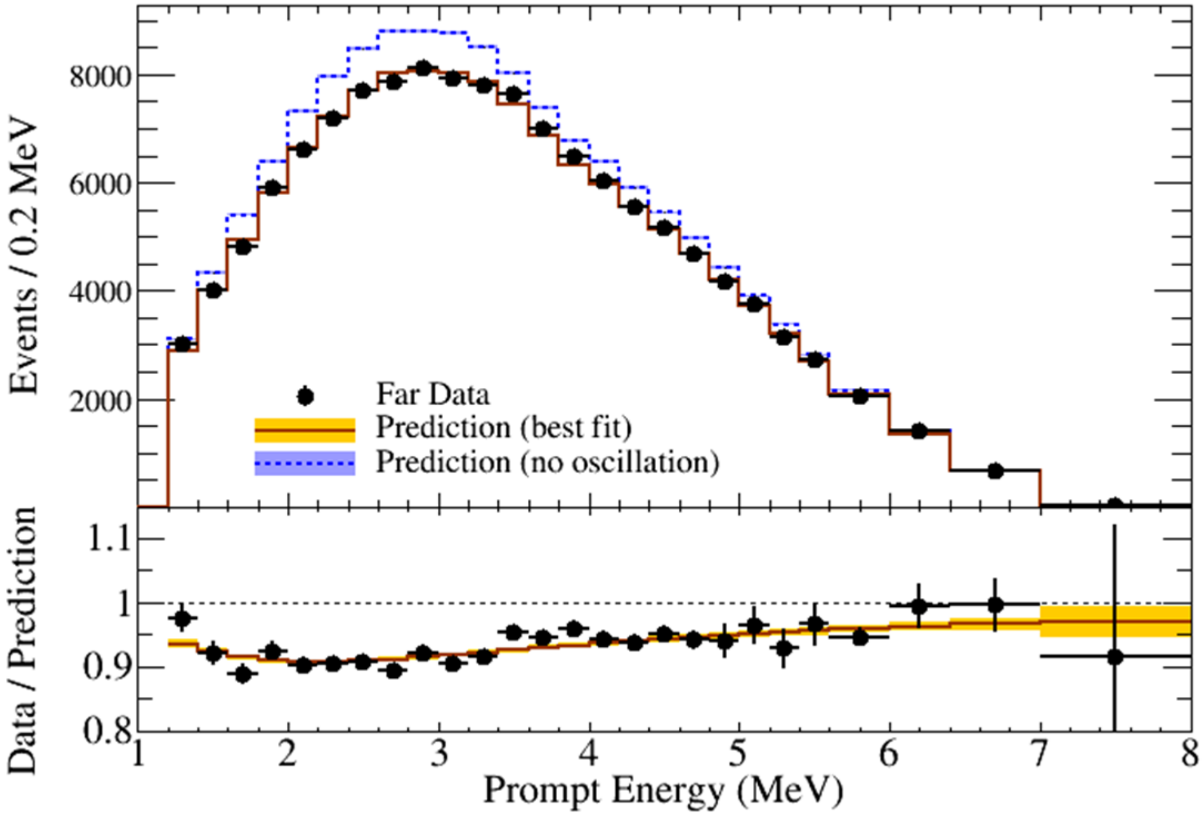
(reference) 2018 PRL

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

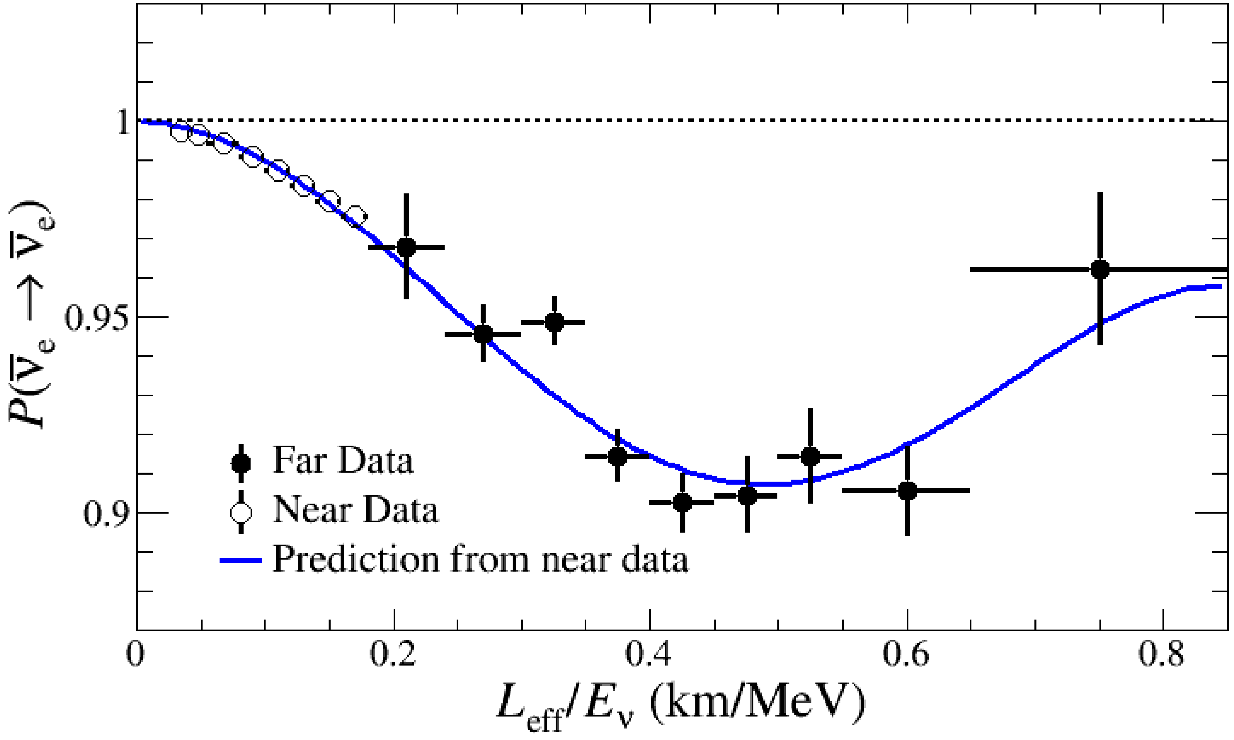
$|\Delta m^2_{ee}|$ = 2.68±0.12(stat.)±0.07(syst.) (x10^{-3} eV^2)

Energy & L/E Dependent $\bar{\nu}_e$ Oscillation

Energy-dependent
disappearance of reactor $\bar{\nu}_e$



observed L/E dependent oscillation

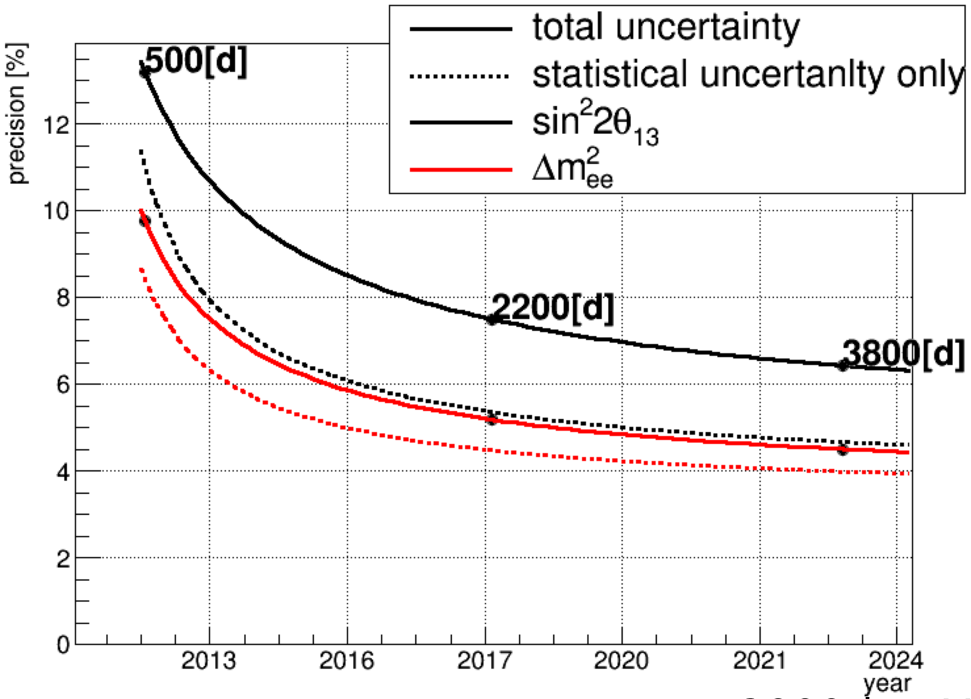


$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - sin^2 2\theta_{13} sin^2\left(\Delta m^2_{ee}\frac{L}{4E_\nu}\right)$$

3800d: arXiv:2412.18711

New Result(3800[d]) vs 2018 PRL(2200[d])

Precision of oscillation measurement in the RENO's analyses

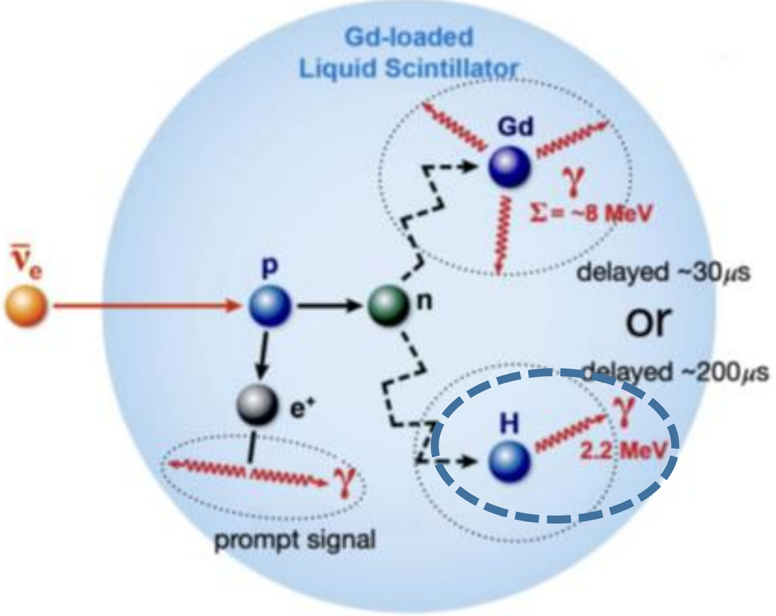


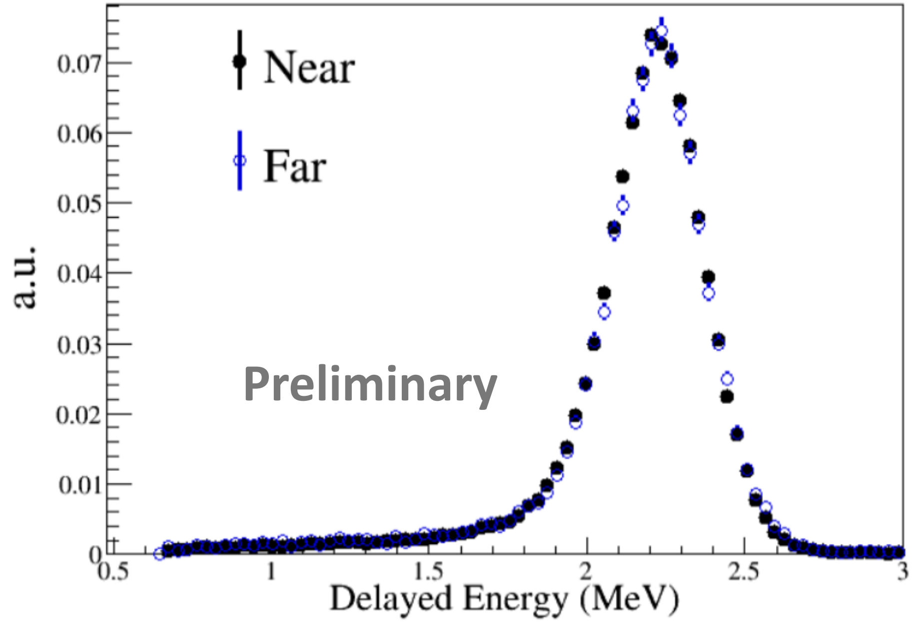
	live time	precision	
		$sin^2 2\theta_{13}$	Δm^2_{ee}
2018 PRL	2200 [d]	7.5%	5.2%
new result	3800 [d]	6.4%	4.5%

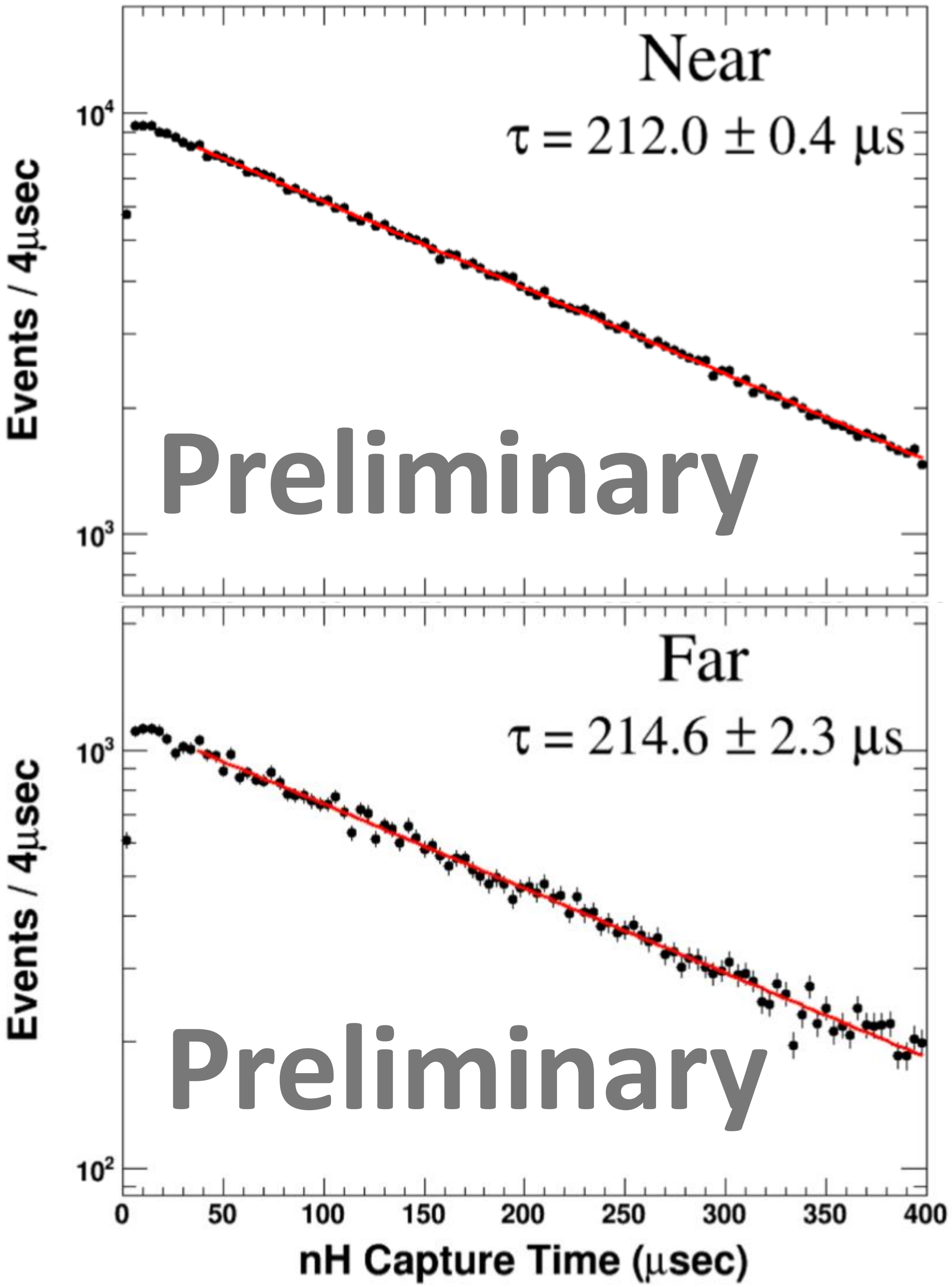
Comparing with the 2018 PRL result, the new result gives 14% and 13% improved precision for $\sin^2 2\theta_{13}$ and Δm^2_{ee} each.

3800d: arXiv:2412.18711

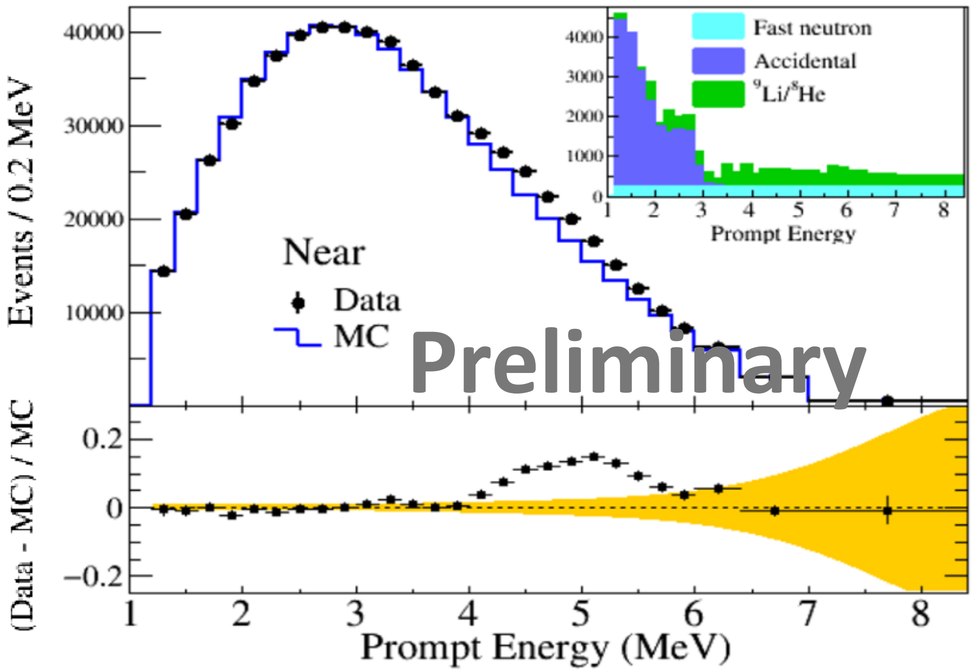
RENO 2800 Days Data n-H Analysis Results







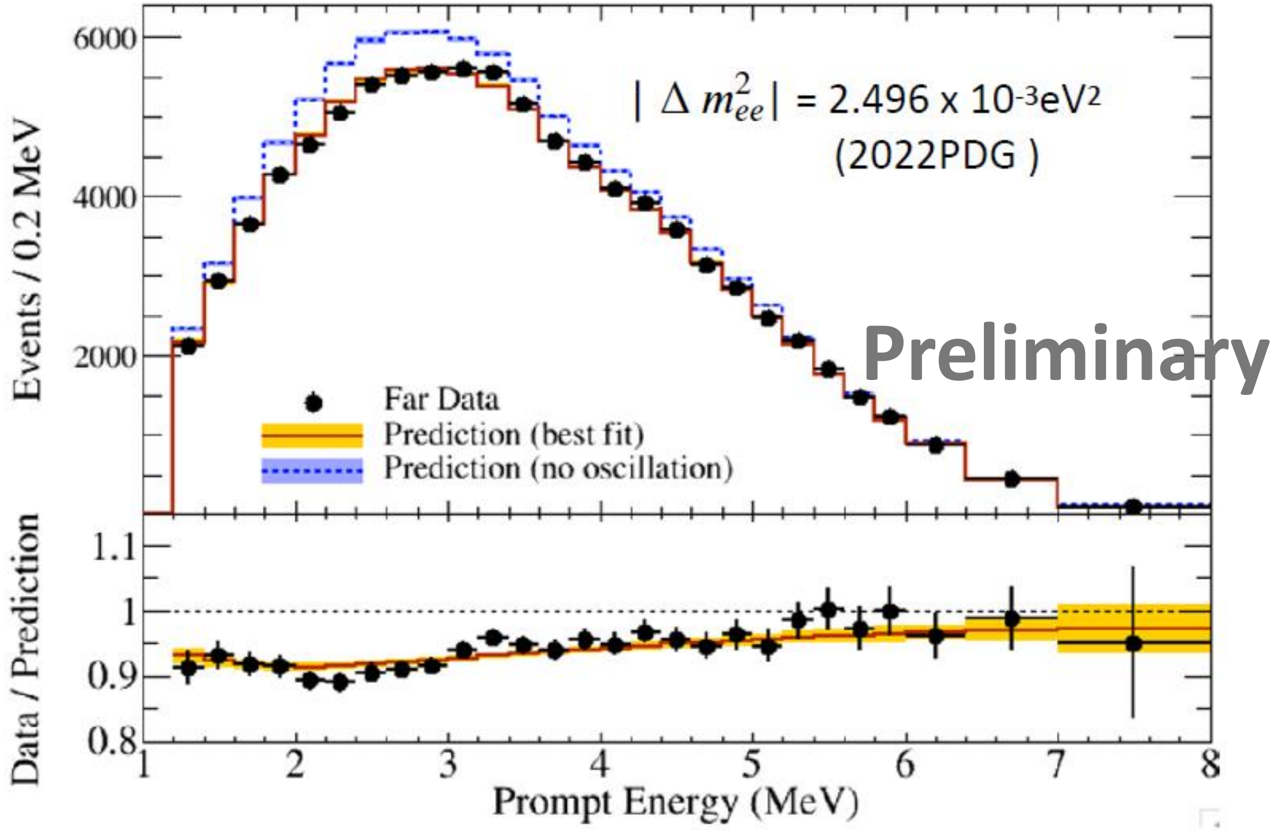
θ_{13} Measurement with 2800 Days n-H data



$$\sin^2(2\theta_{13}) = 0.082 \pm 0.007(\text{stat.}) \pm 0.011(\text{syst.})$$

JHEP(2019) : 1500days n-H result → $\sin^2(2\theta_{13}) = 0.086 \pm 0.008(\text{stat.}) \pm 0.014(\text{syst.})$

PRL(2018) : 2200days n-Gd result → $\sin^2(2\theta_{13}) = 0.0896 \pm 0.0048(\text{stat.}) \pm 0.0047(\text{syst.})$



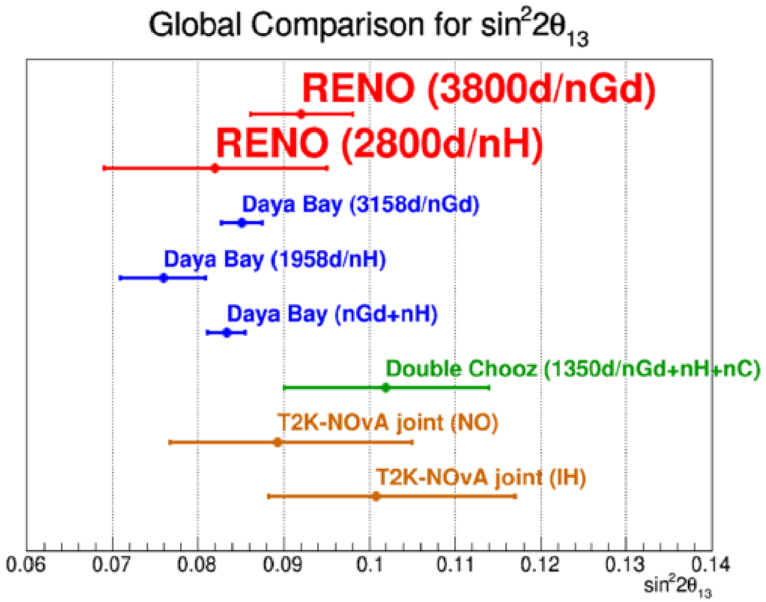
	Near	Far
DAQ live time (days)	2259.298	2653.297
IBD candidates & backgrounds rate	316.67 ± 0.37	61.10 ± 0.15
After background subtraction	298.60 ± 0.62	35.67 ± 0.28
Total background rate	18.06 ± 0.50	25.43 ± 0.24

Study using 3800d data is underway.

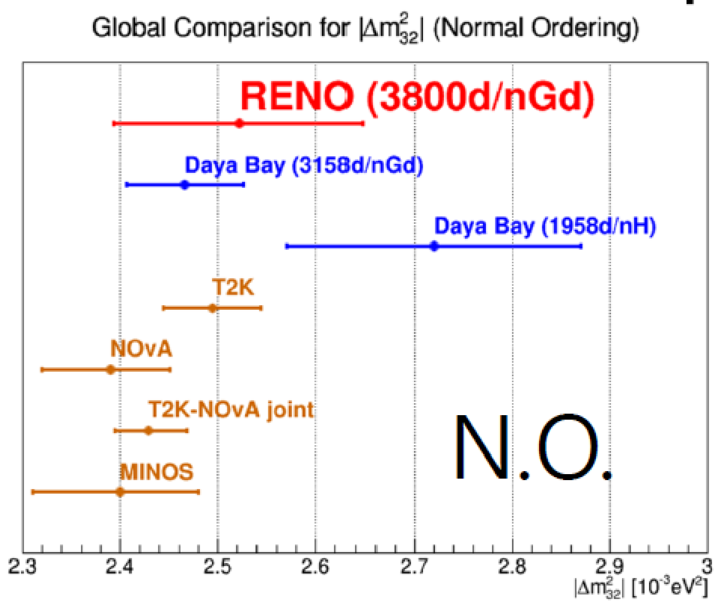
Global Comparison

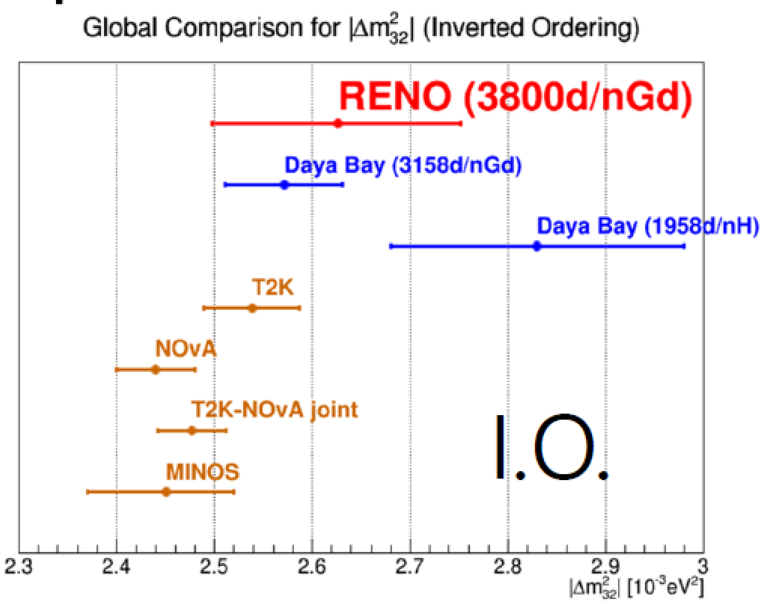
The new result shows good agreement with the global results.

$sin^2 2\theta_{13}$

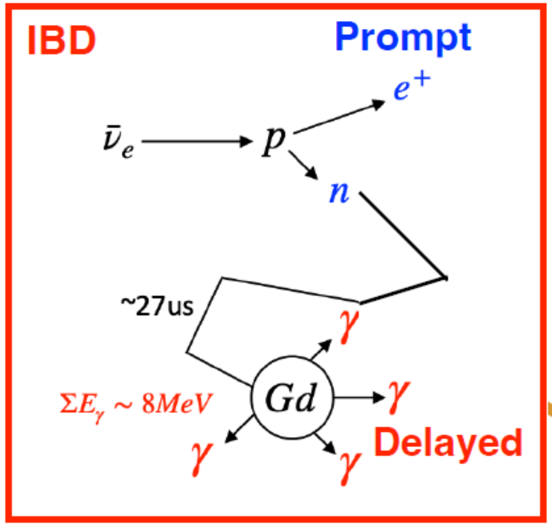


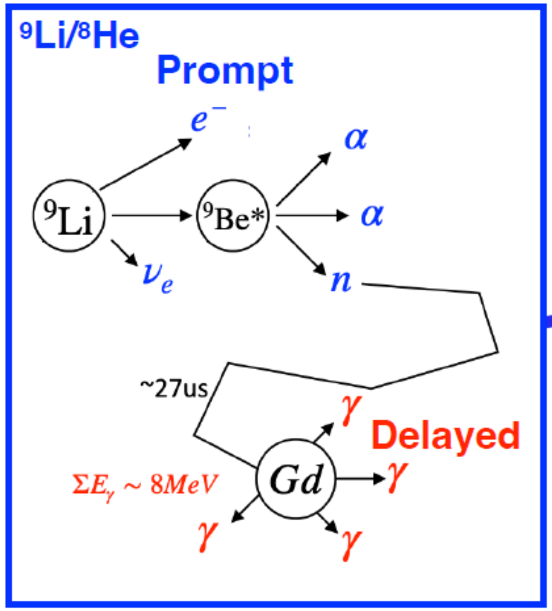
$|\Delta m^2_{32}|$



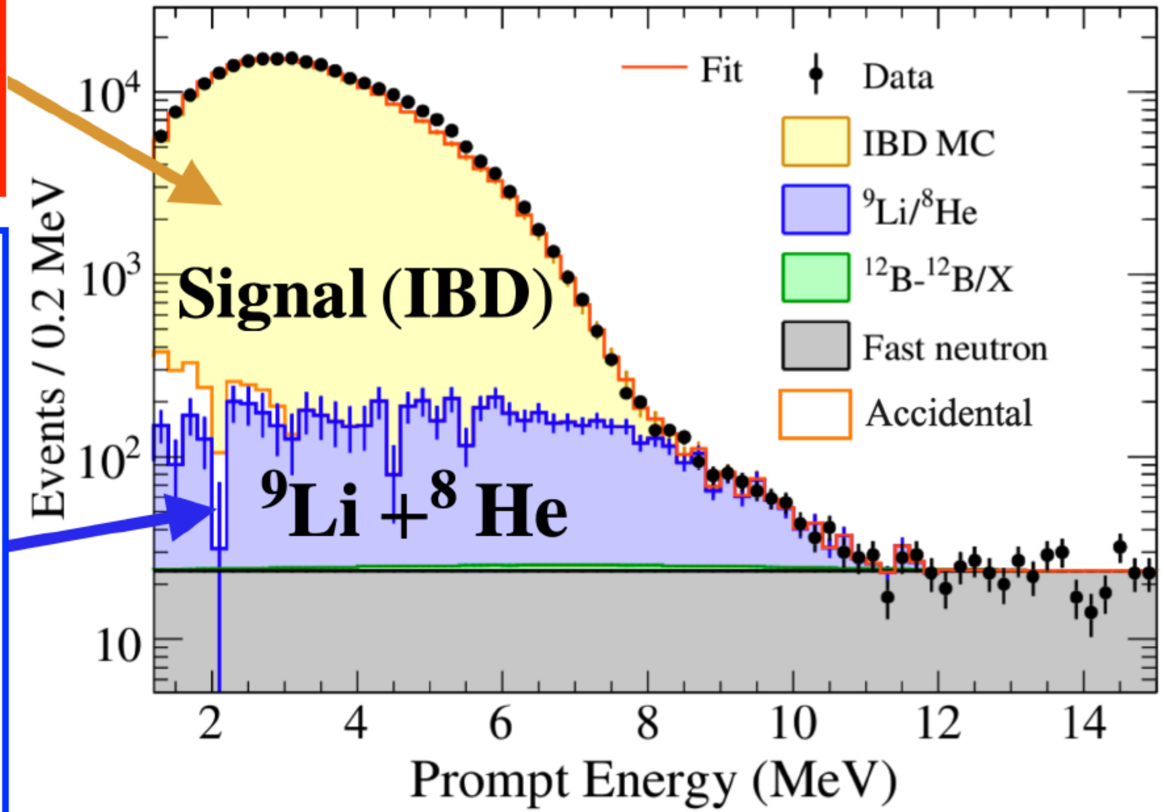


Cosmogenic ^{9}Li and ^{8}He: β-n Decays





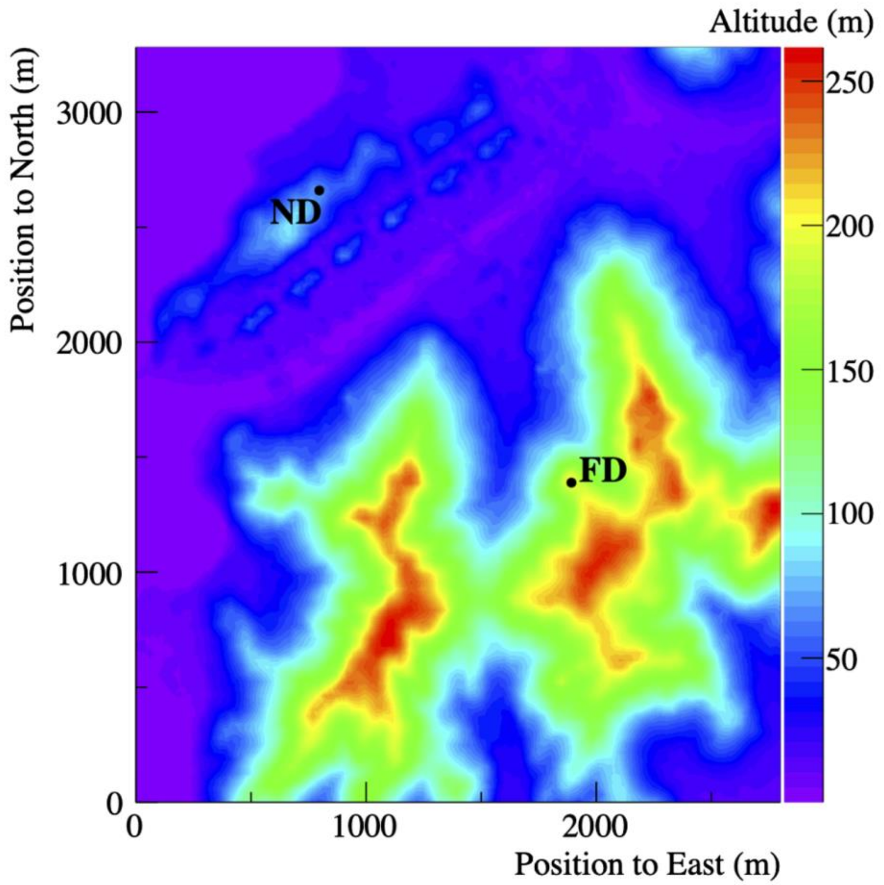
- Cosmic muon spallate ^{12}C → (n, ^{12}B, ^{9}Li, ^{8}He,…)
- Long lived ^{9}Li and ^{8}He β-n decays are the major backgrounds of the IBD events



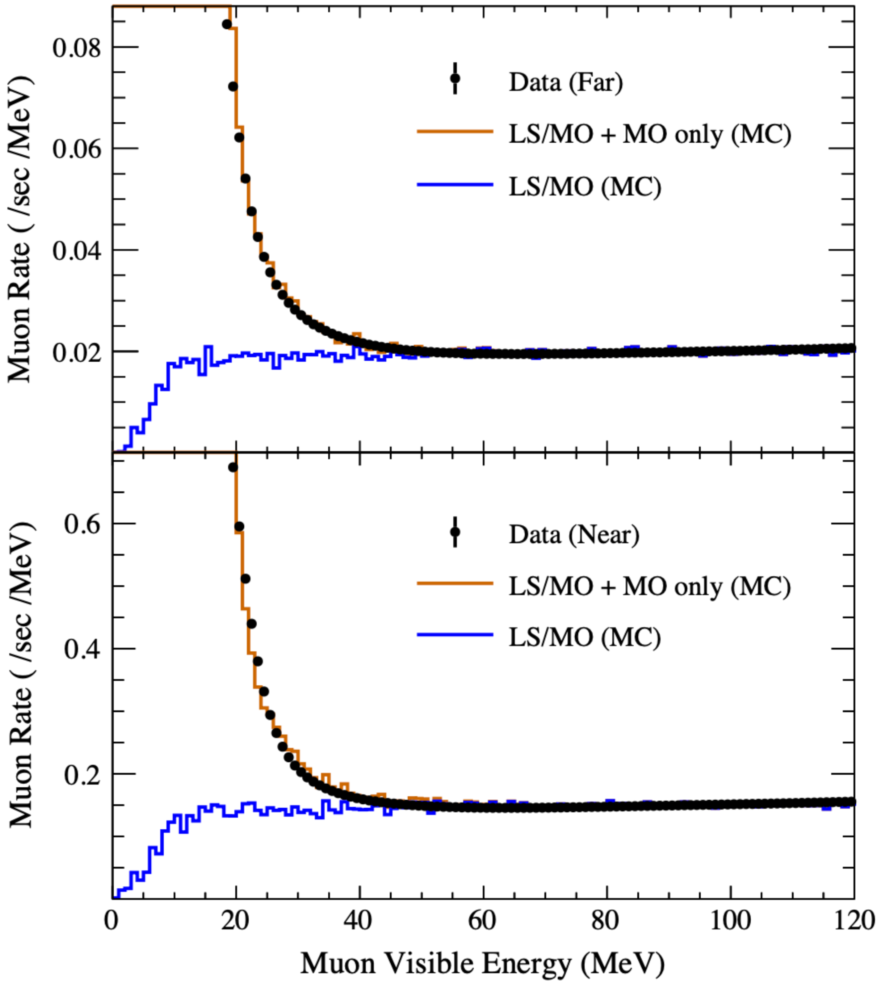
Cosmogenic Muons at RENO

PRD 106, 012005 (2022)

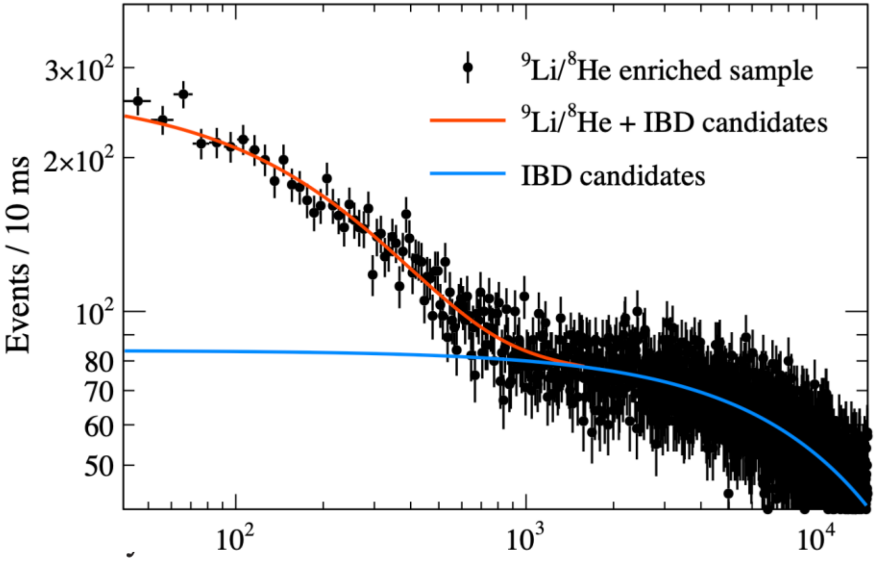
Topological profile of RENO site
(ALOS world 3D)



Visible Energy of Cosmic Muons
Cosmic Muon MC: MUSIC

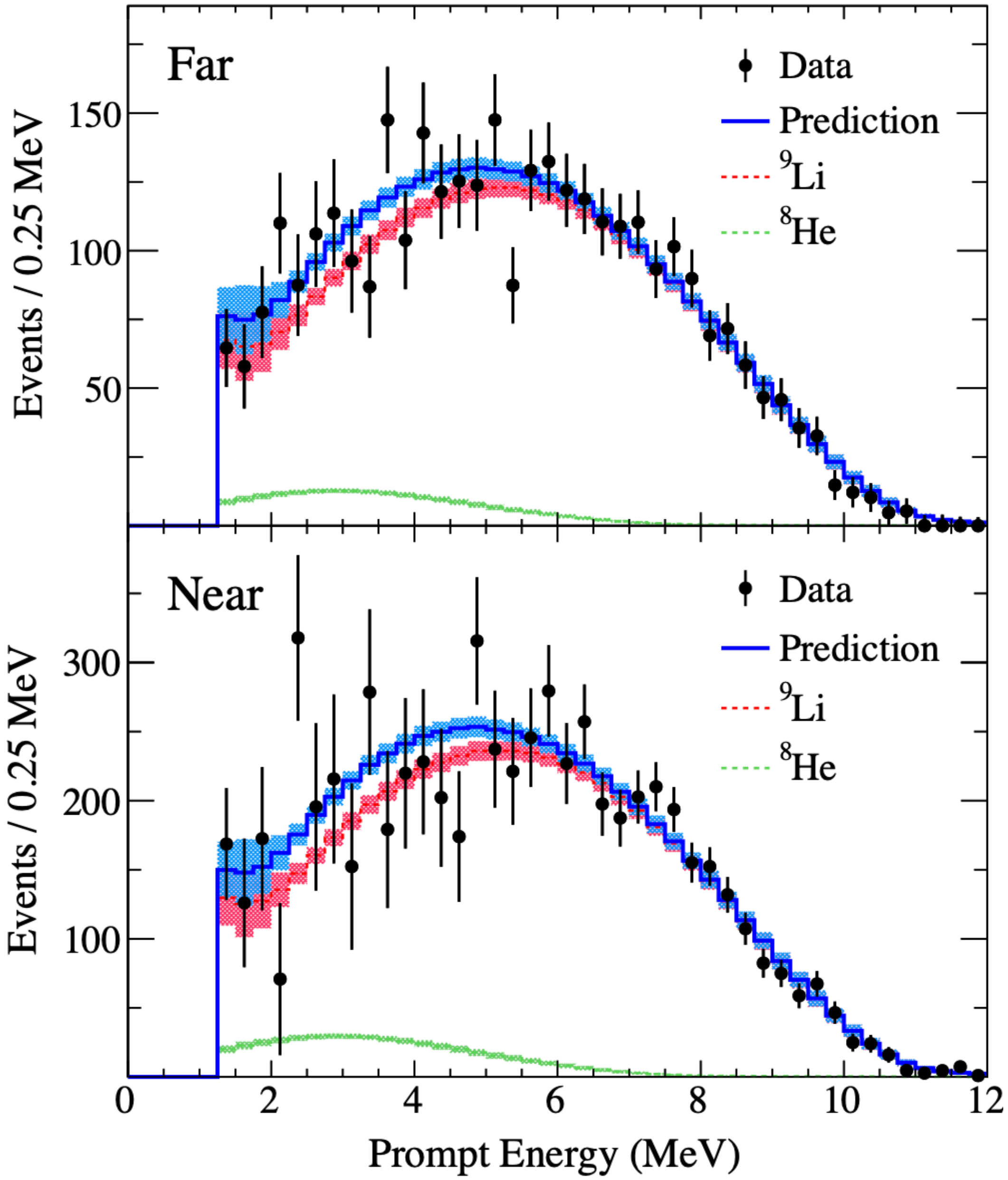


Cosmogenic ^{9}Li and ^{8}He:

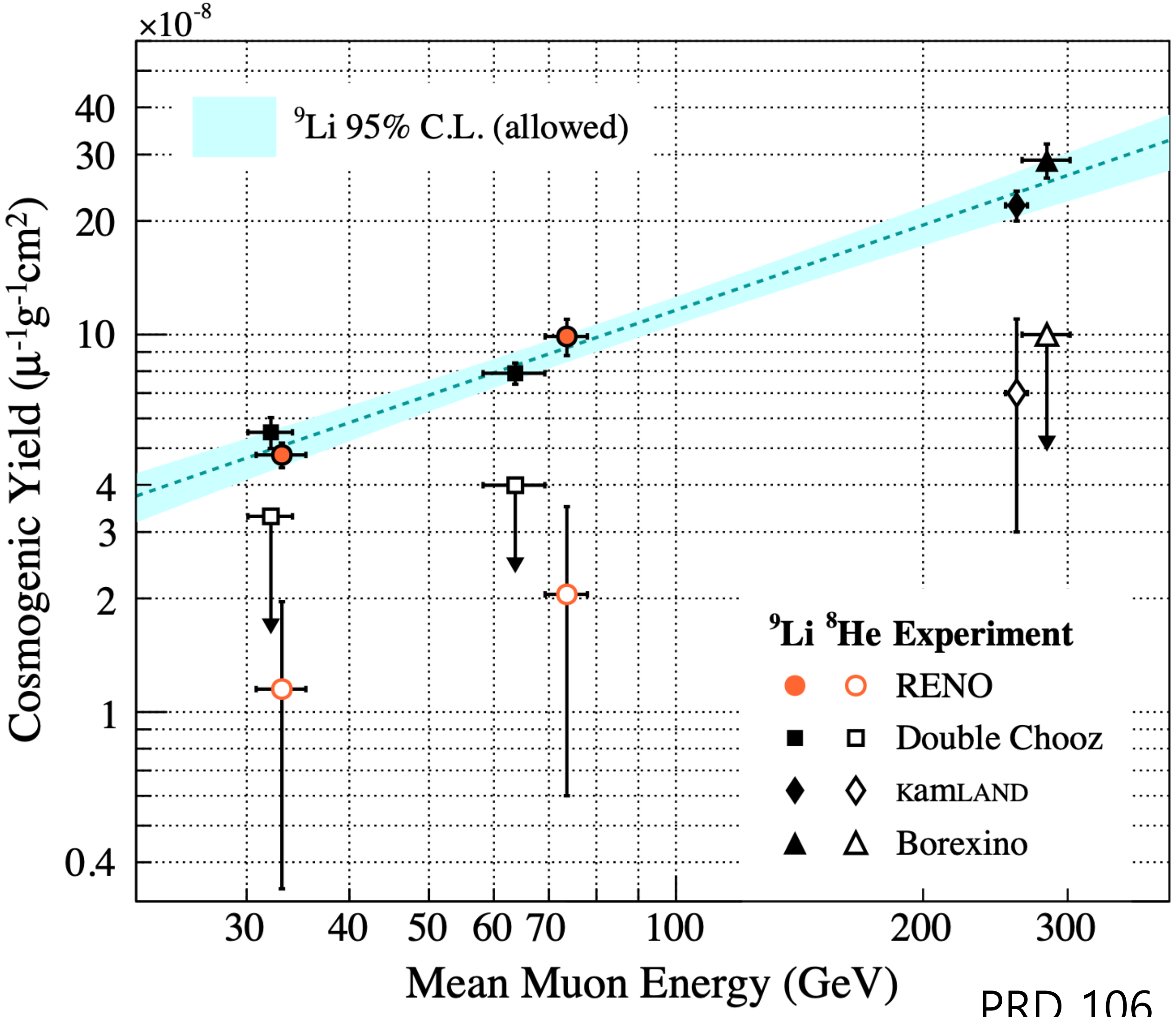


		ND	FD
$R_{\beta-n}$(/day)	…	11.92 ± 0.45	3.04 ± 0.28
R_μ (/ sec)	…	61.84 ± 0.71	6.94 ± 0.08
$\bar{L}_\mu$ (cm)	…	201.1 ± 3.9	197.4 ± 3.9
ρ (g/cm^3)	…	0.856 ± 0.001	
ϵ (%)	^{9}Li	49.6 ± 1.5	56.2 ± 1.6
	^{8}He	46.8 ± 1.5	53.0 ± 1.7
f (%)	^{9}Li	93.3 ± 4.6	94.2 ± 4.1
	^{8}He	6.7 ± 4.6	5.8 ± 4.1
$Br_{\beta-n}$ (%)	^{9}Li	50.8 ± 0.9	
	^{8}He	16 ± 1	

PRD 106, 012005 (2022)



Yields of Cosmogenic ^{9}Li and ^{8}He

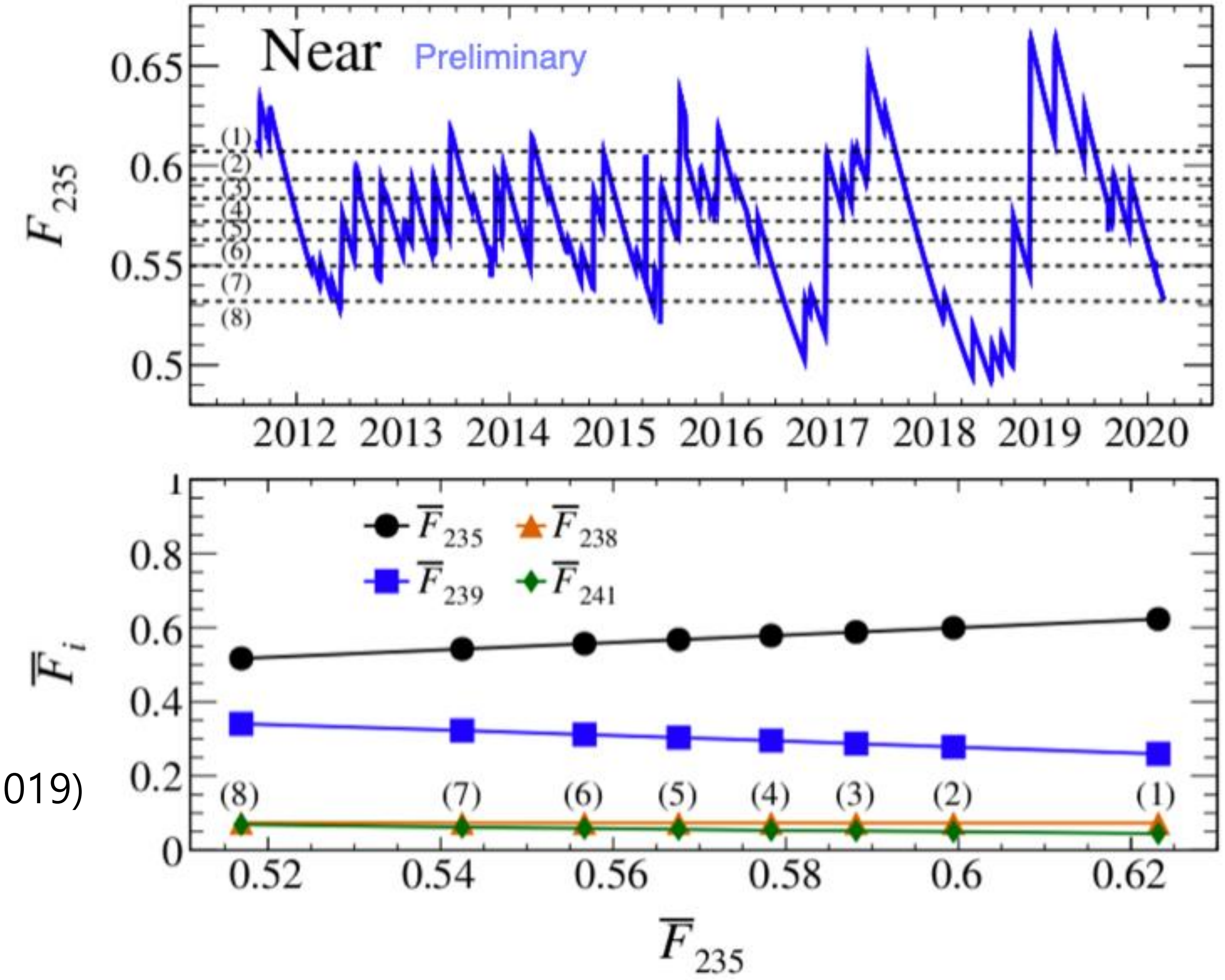


PRD 106, 012005 (2022)

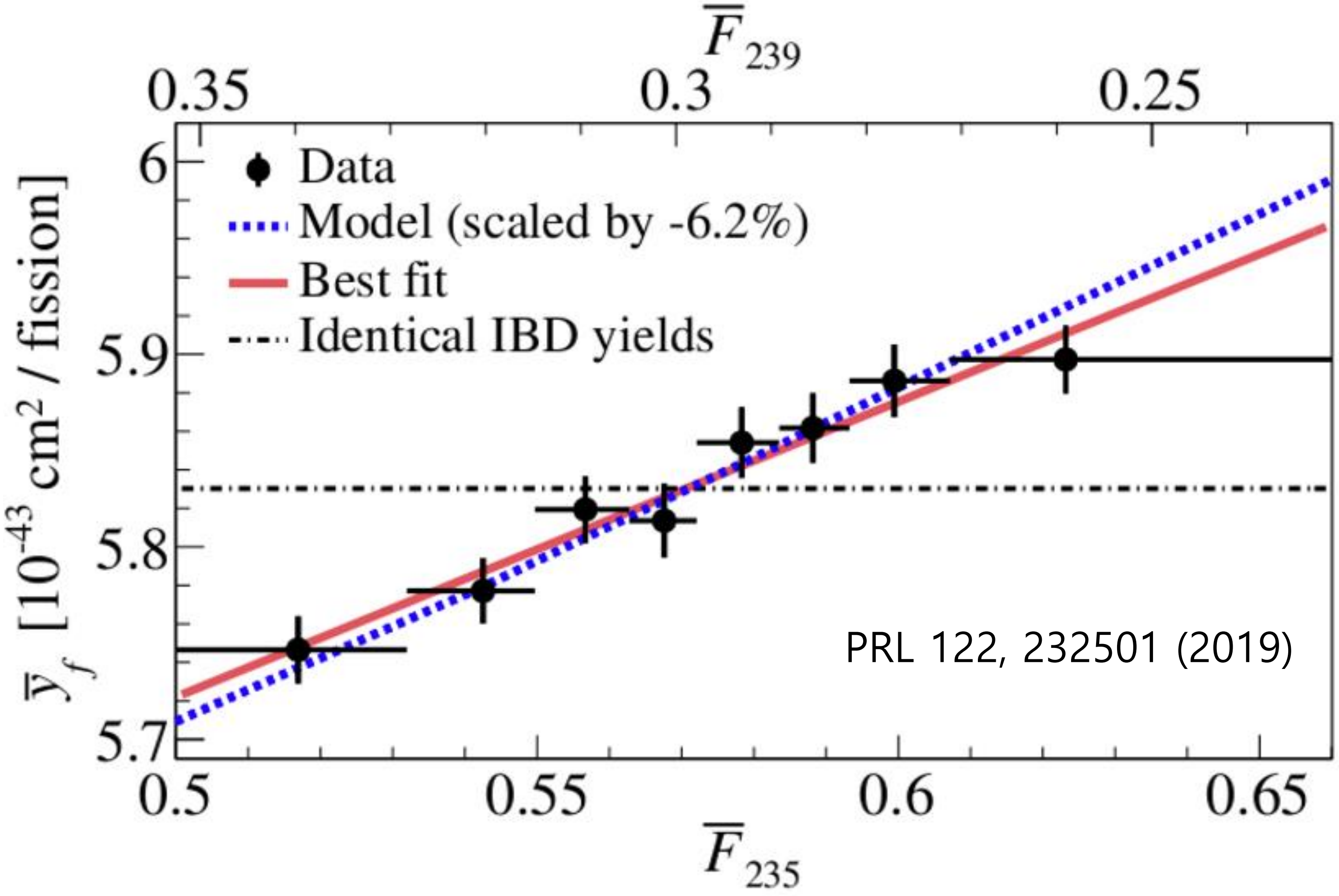
RENO Fuel Fraction in the Reactor Core

- Average fission fraction: f_235: f_239: f_238: f_241= 0.573 : 0.299 : 0.073 : 0.055

PRL 122, 232501 (2019)



Fuel Dependence of IBD Yield

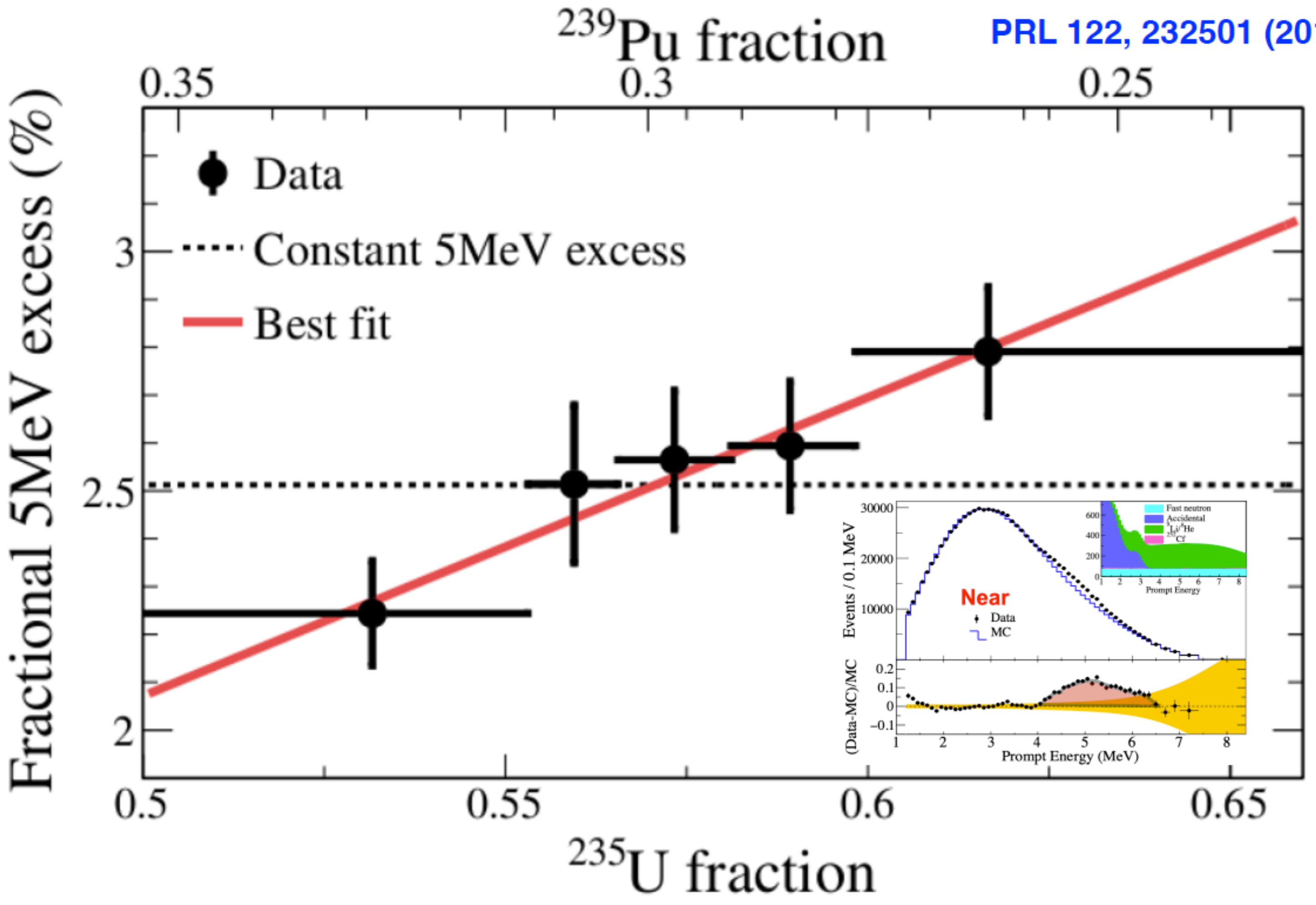


PRL 122, 232501 (2019)

- Fuel dependence study of IBD spectrum is underway

Fuel Dependence of the 5 MeV Excess

PRL 122, 232501 (2019)



Null fuel dependence is disfavored by 2.9σ

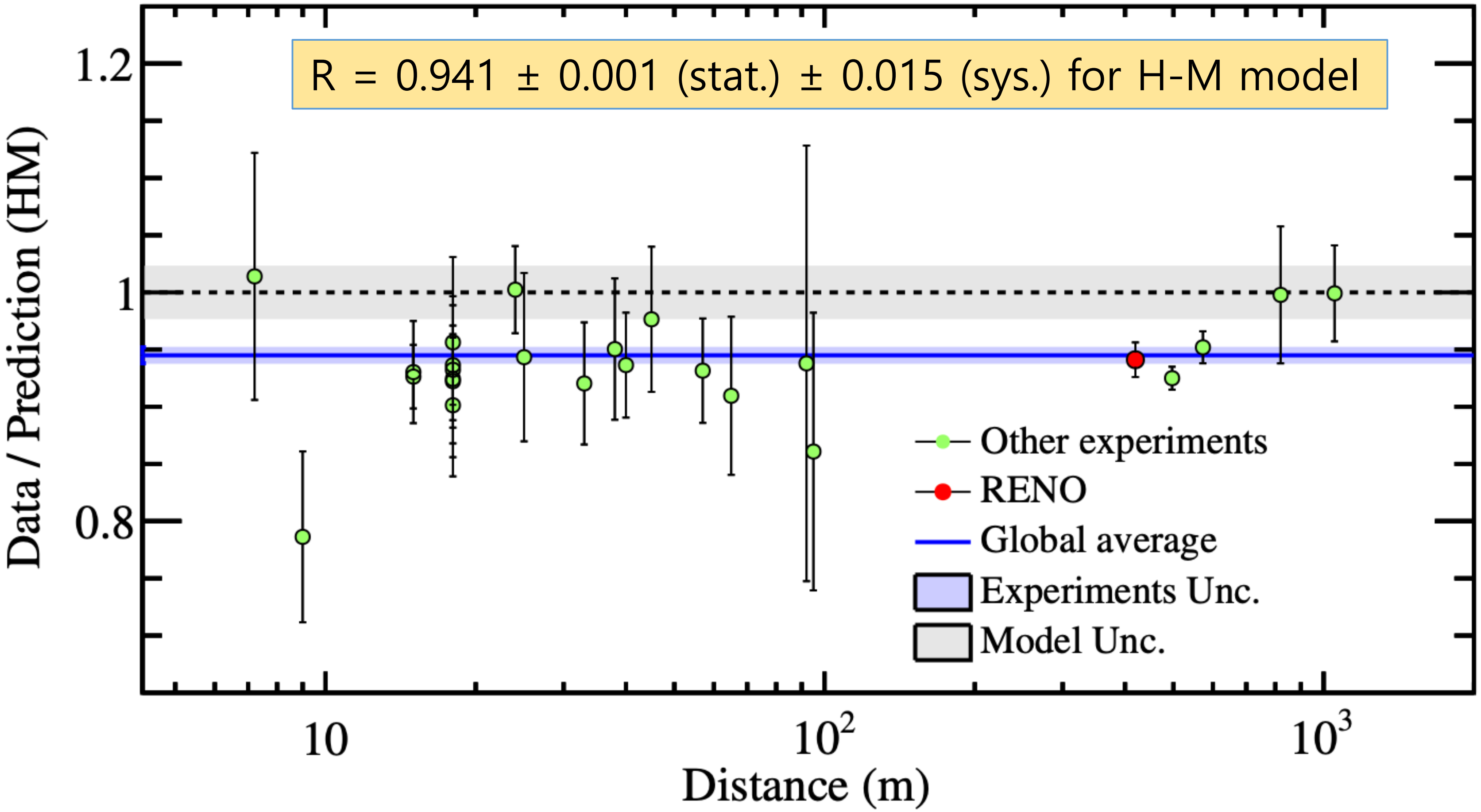
- Fuel dependence study is underway

Reactor Antineutrino Anomaly: RAA

IBD yield: $\bar{y}_f = 5.852 \pm 0.124(\times 10^{-43}\mathrm{cm}^2/\mathrm{fission})$

PRD 104, L111301 (2021)

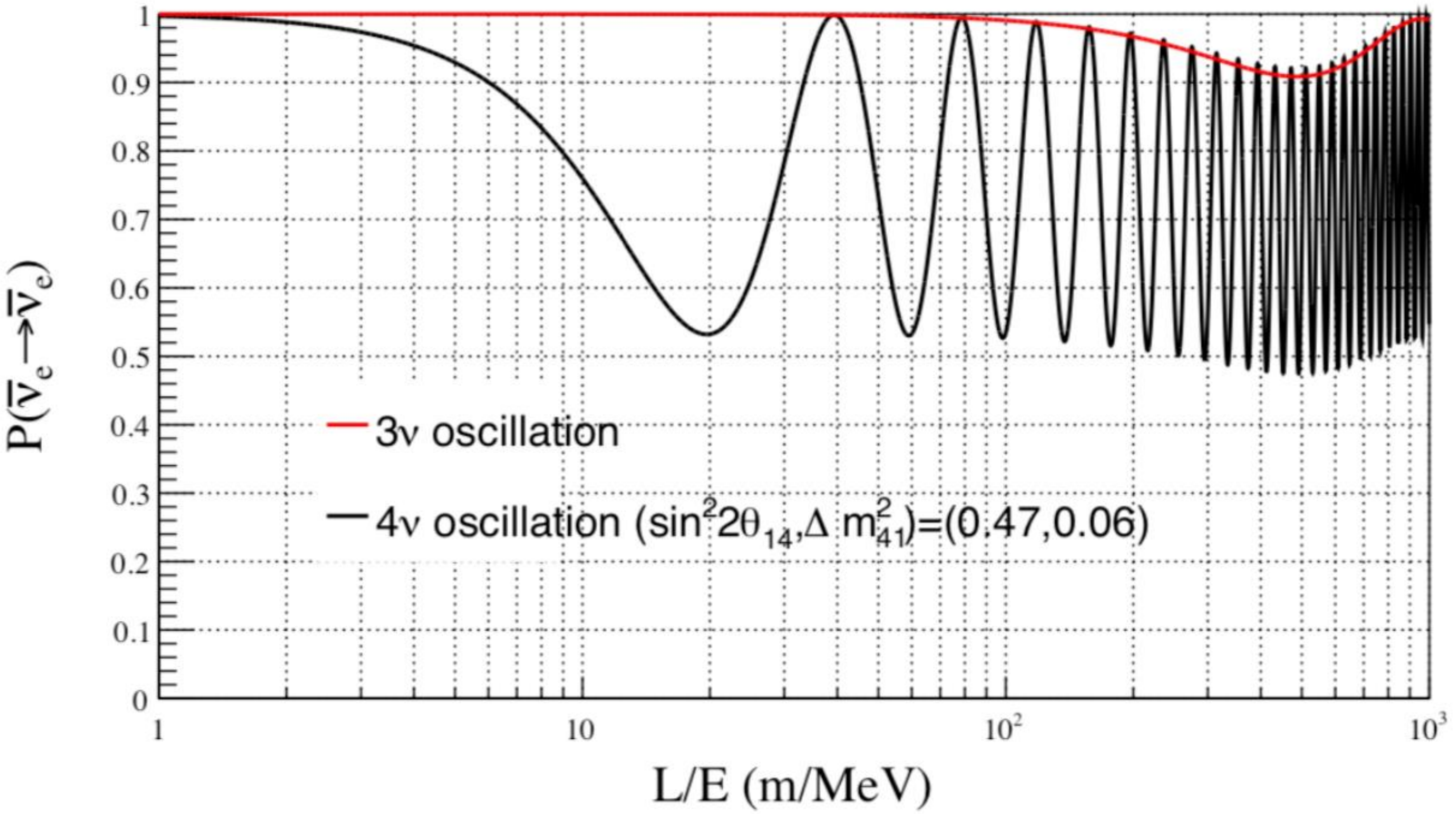
Average fission fraction:
f_235: f_239: f_238: f_241
= 0.571 : 0.073 : 0.300 : 0.056



RENO Sterile Neutrino Search

(3 active +1 sterile) Neutrino Model

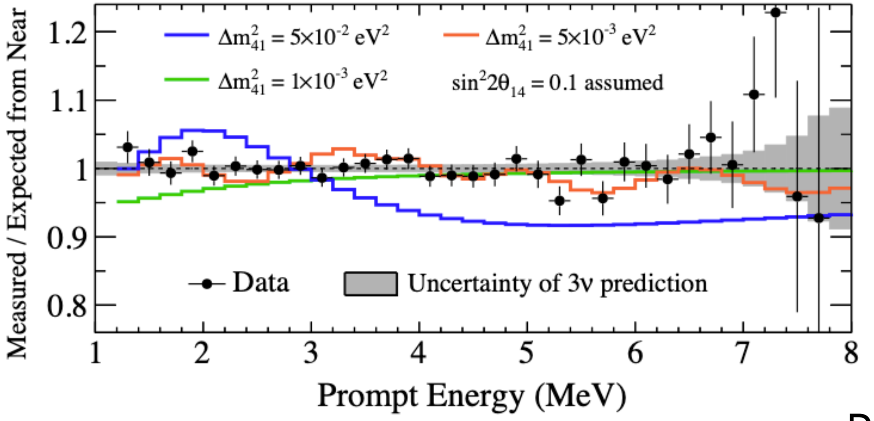
$$P(\overline{\nu}_e \to \overline{\nu}_e) \simeq 1 - \sin^2 2\theta_{13} \sin^2\left(1.27\Delta m^2_{31}\frac{L}{E_\nu}\right) - \sin^2 2\theta_{14} \sin^2\left(1.27\Delta m^2_{41}\frac{L}{E_\nu}\right)$$

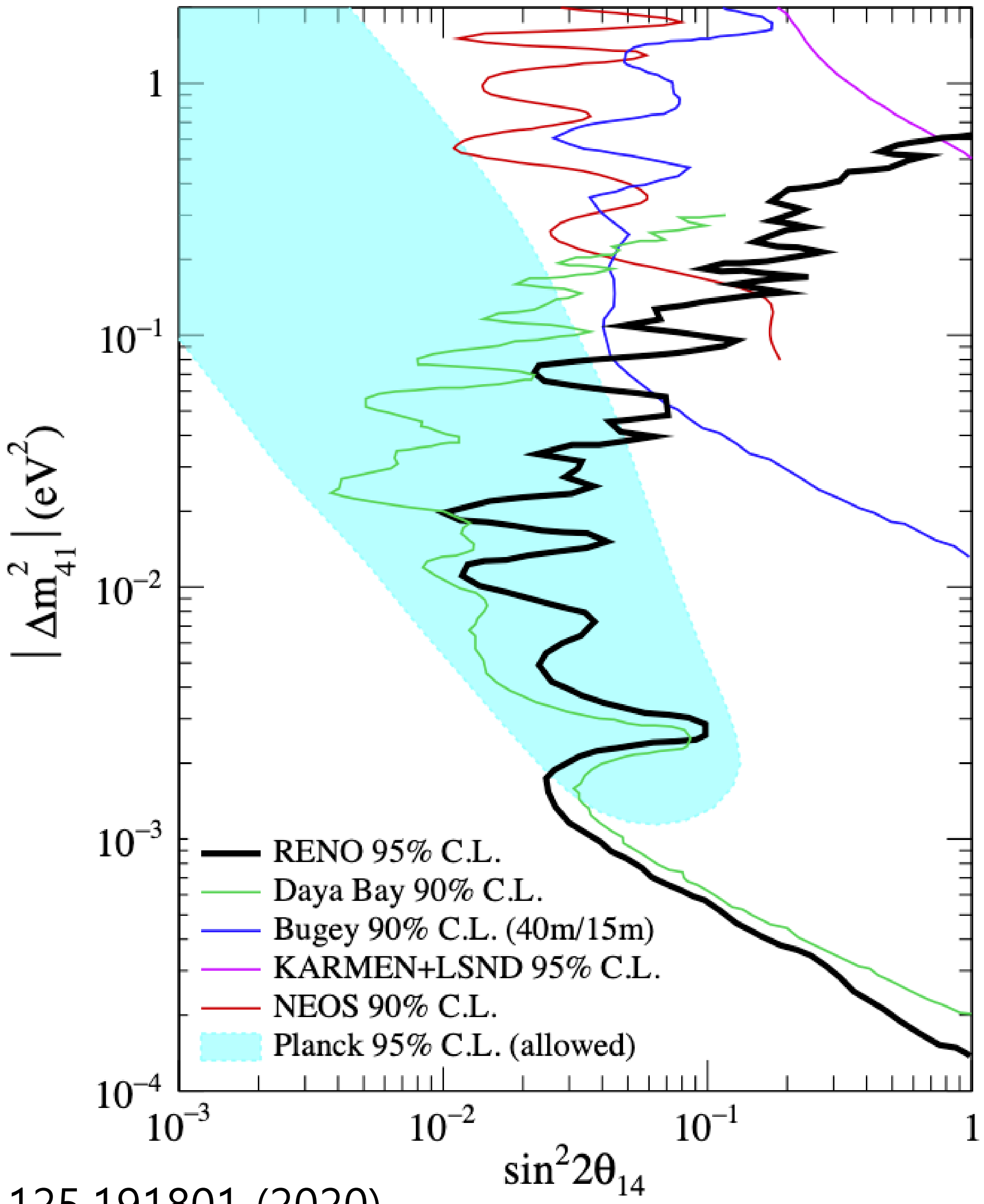


Search Sterile Neutrinos (RENO Near/Far) : Sub-eV Scale

Based on 2200 days nGd data

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

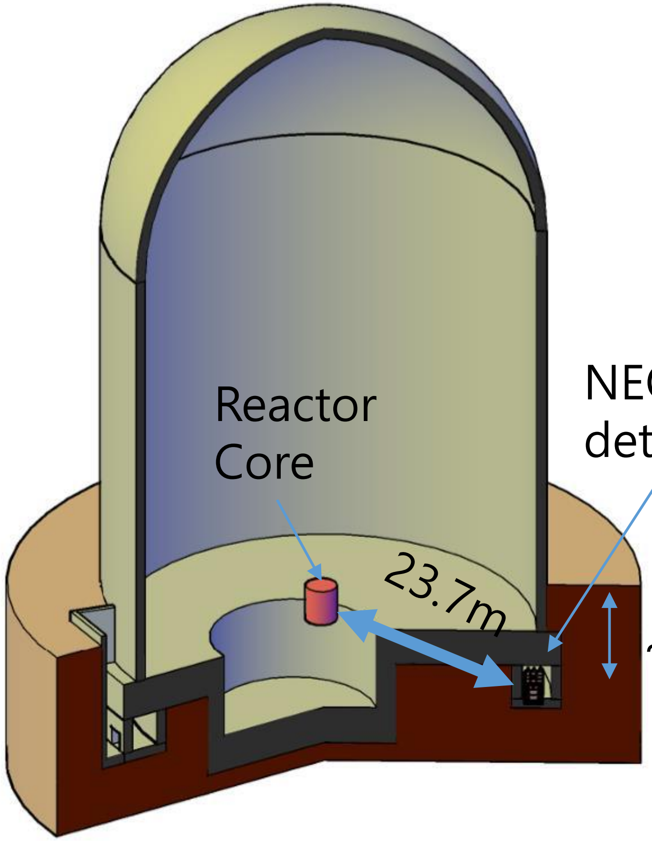


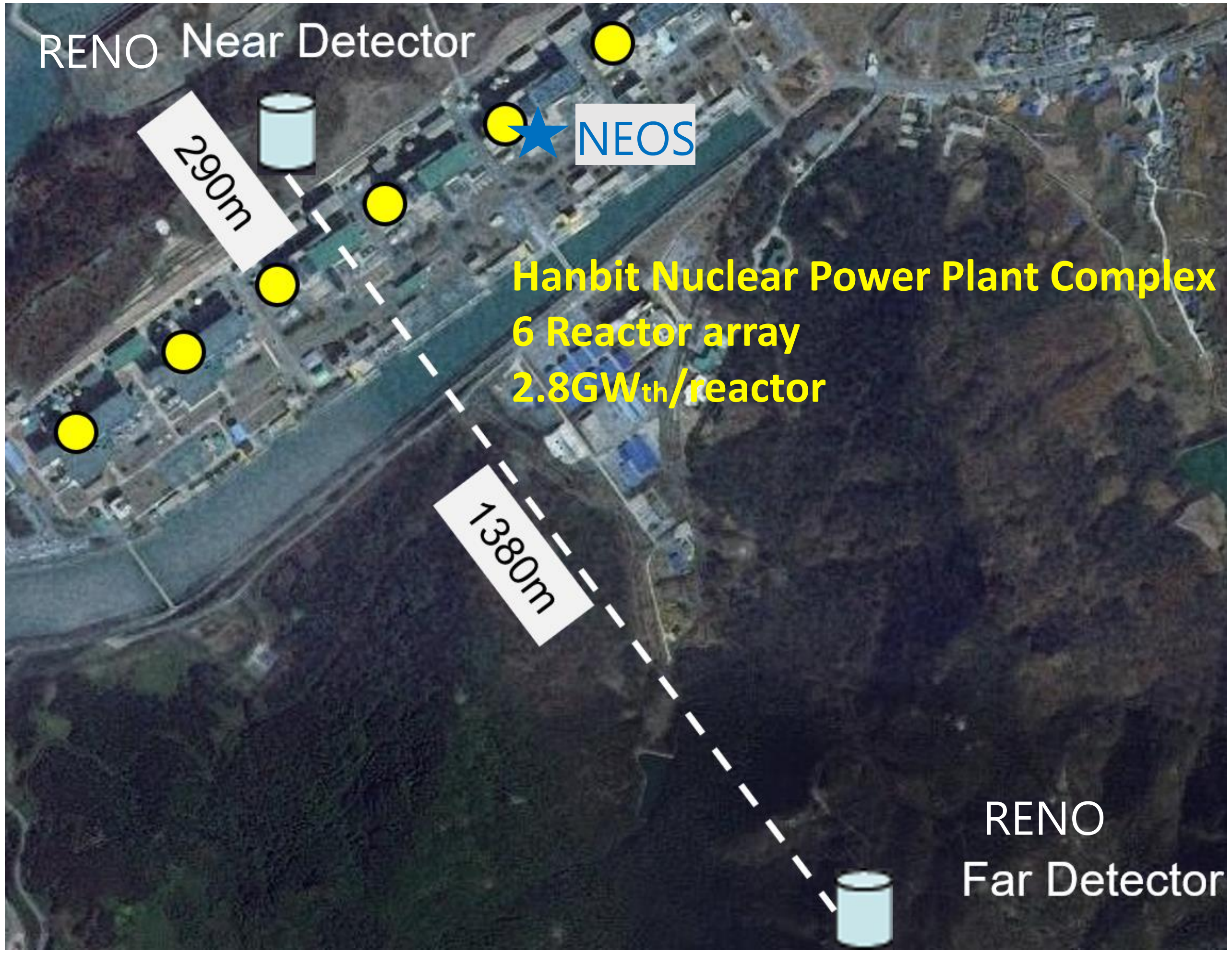


PRL 125,191801 (2020)

Sterile Neutrino Search (RENO + NEOS) : ~eV Scale

Neutrino Experiment for Oscillation at Short baseline

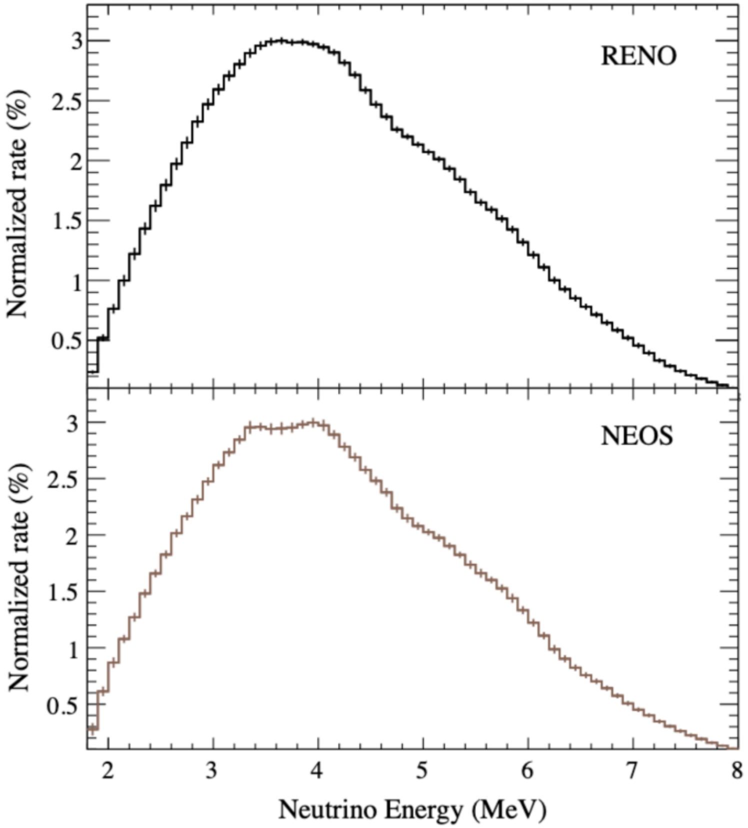




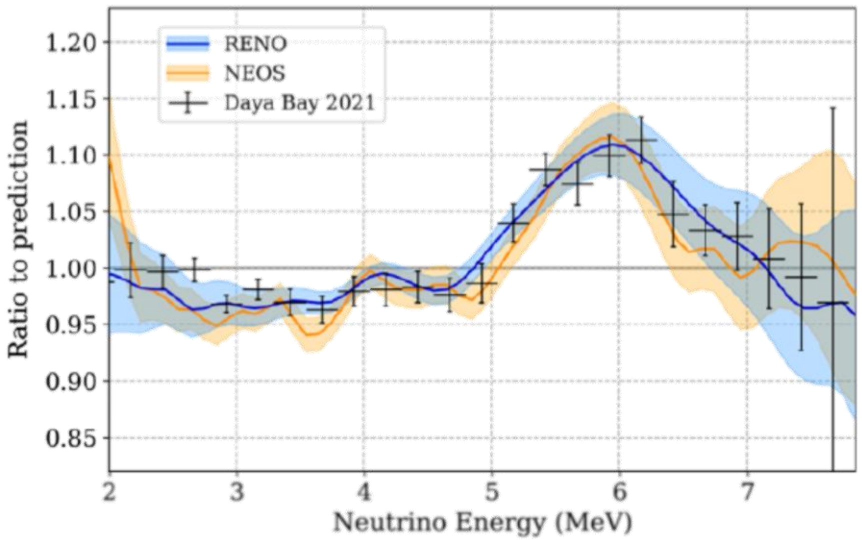
- Primary goal: search for eV scale sterile neutrino in the 4 ν framework.
- NEOS-1: Aug. 2015 - May 2016
- NEOS-2: Sep. 2018 ~ Oct. 2020

Sterile Neutrino Search (RENO + NEOS) : ~eV Scale

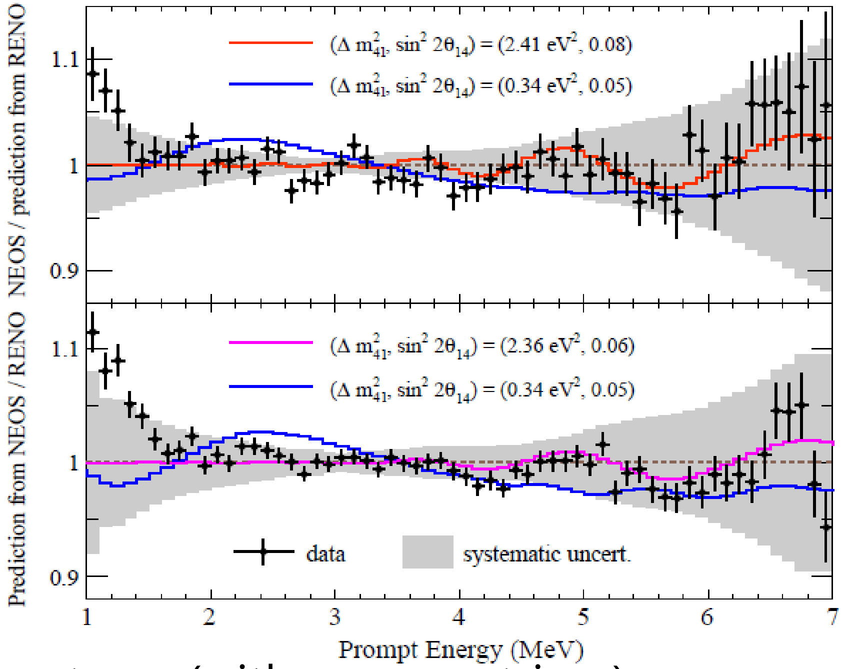
Reactor antineutrino spectra unfolded from RENO and NEOS data



Comparison of neutrino energy spectra among RENO, NEOS and Daya Bay



Comparison with spectra of 4 ν models



Data release of prompt and neutrino spectrum (with error matrices)

PRD 104, L111301 (2021) RENO

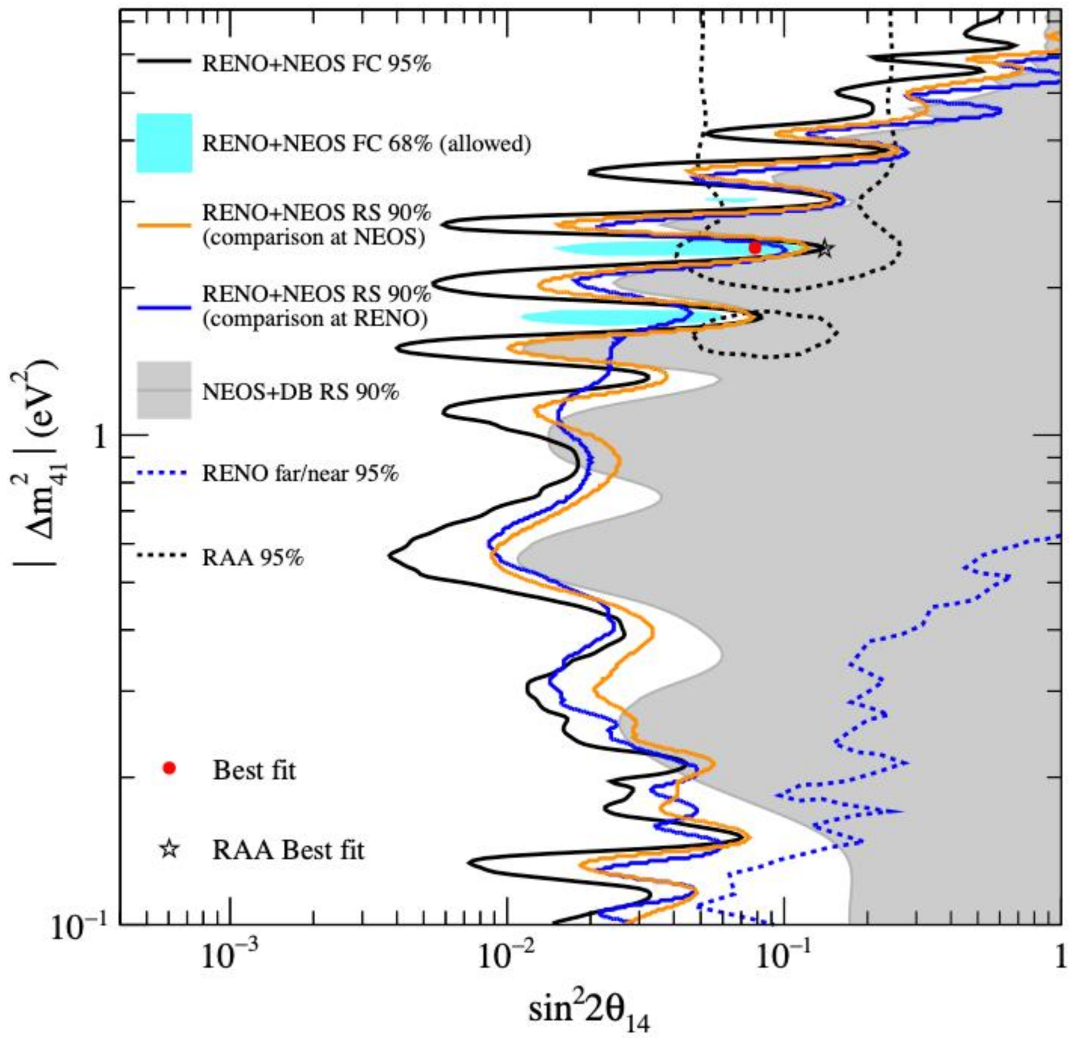
PRD 105, L111101 (2022) RENO+NEOS

Sterile Neutrino Search (RENO + NEOS) : ~eV Scale

PRD 105, L111101 (2022)

- RENO+NEOS best fit at (0.08, 2.4 eV^2) around the RAA best fit
- 4 ν min χ^2/DOF = 47.45/58
  3 ν min χ^2 /DOF = 56.24/60
- $\Delta\chi^2$ = 8.8, p=8.5%

- Motivate the RENE experiment
  (sterile neutrino search.
  See the next talk).



Summary

- Report Precision measurement of $|\Delta m_{ee}^2|$ and θ_{13} using RENO 3800 days nGd data
- Correlation btw 5 MeV excess and 235U fission (2.9$\boldsymbol{\sigma}$ C.L.) PRL 122, 232501 (2019)
- The first RENO sterile neutrino search: PRL 125, 191801 (2020)
- RENO antineutrino spectrum: PRD 104, L111301 (2021)
- Absolute reactor neutrino flux: R = 94.1 % ± 1.9 % (of HM) PRD 104, L111301 (2021)
- Sterile neutrino search (RENO + NEOS): PRD 105, L111101 (2022)
- Cosmogenic 9Li and 8He rate at RENO: PRD 105, L111101 (2022)
- RENO nH data analysis (in preparation)
- Reactor fuel dependence of neutrino spectrum (in preparation)