RENO

Reactor Experiment for Neutrino Oscillation

Jonghee Yoo

Seoul National University

2023-01-16

The 2nd IAEA Technical Meeting

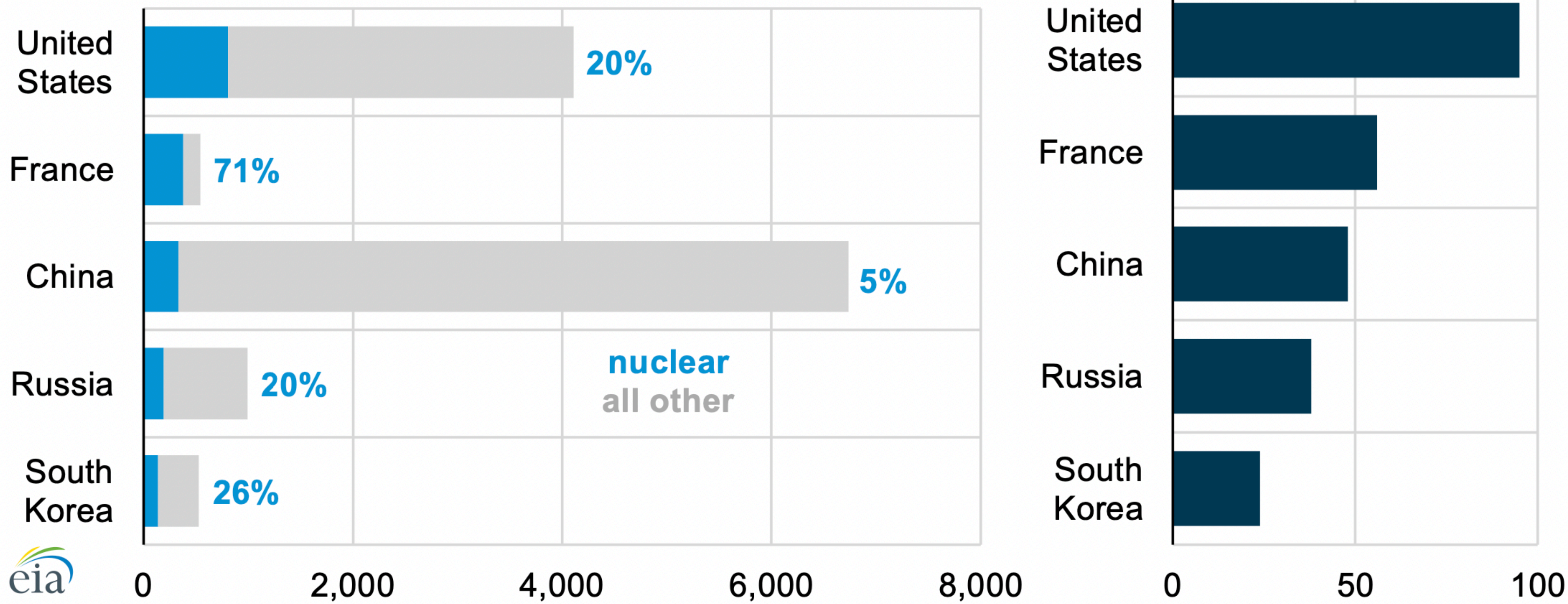
on nuclear data for antineutrino spectra and their applications

AUGUST 27, 2020 https://www.eia.gov

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

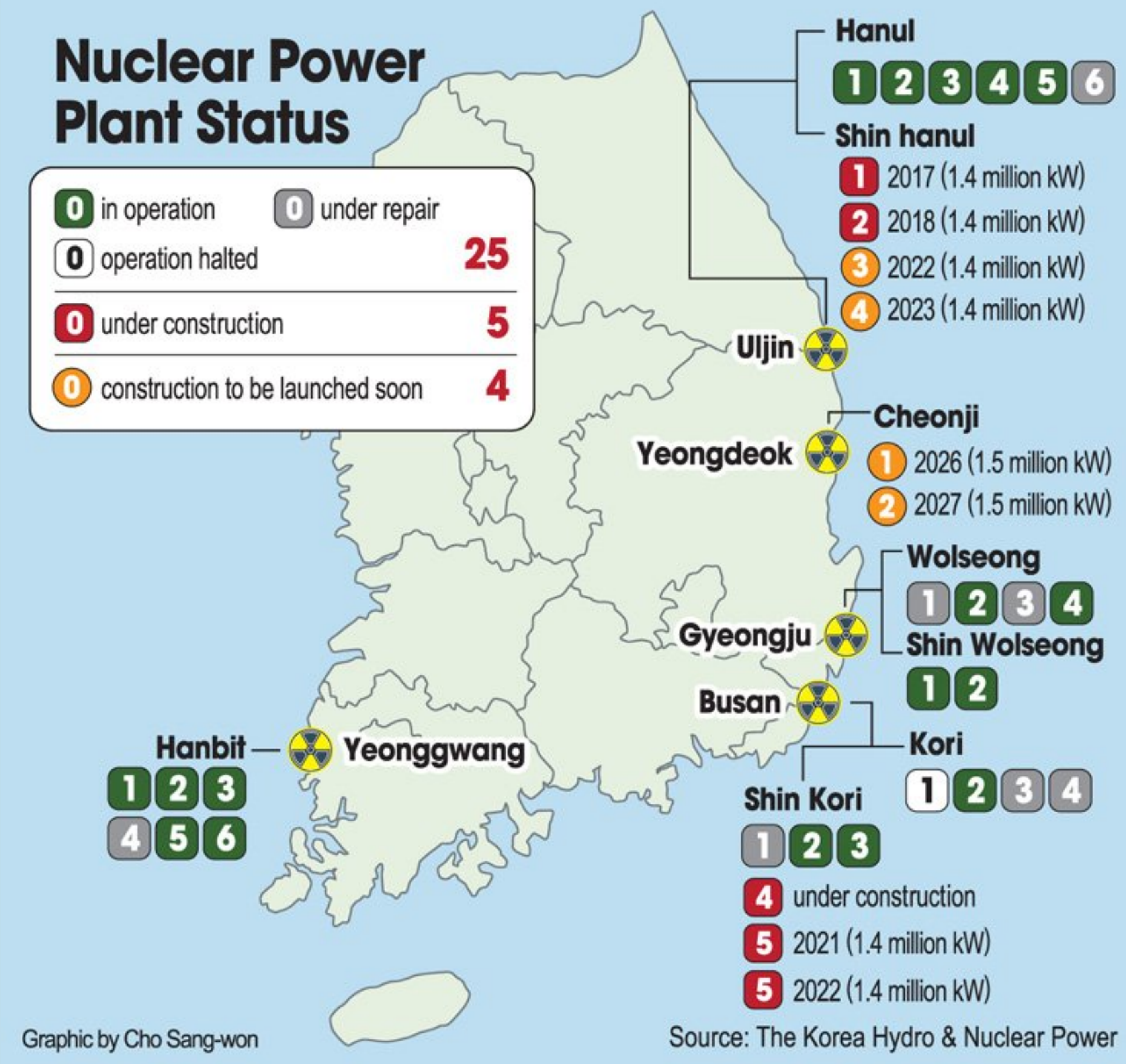
Share of total annual electricity generation from nuclear, top five nuclear power producers (2019)
terawatthours

Number of operational nuclear reactors (2020)



Source: International Atomic Energy Agency, Power Reactor Information System (IAEA-PRIS)

Nuclear Power Plants in South Korea



Reactor Experiment for Neutrino Oscillation

8 Institutions 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

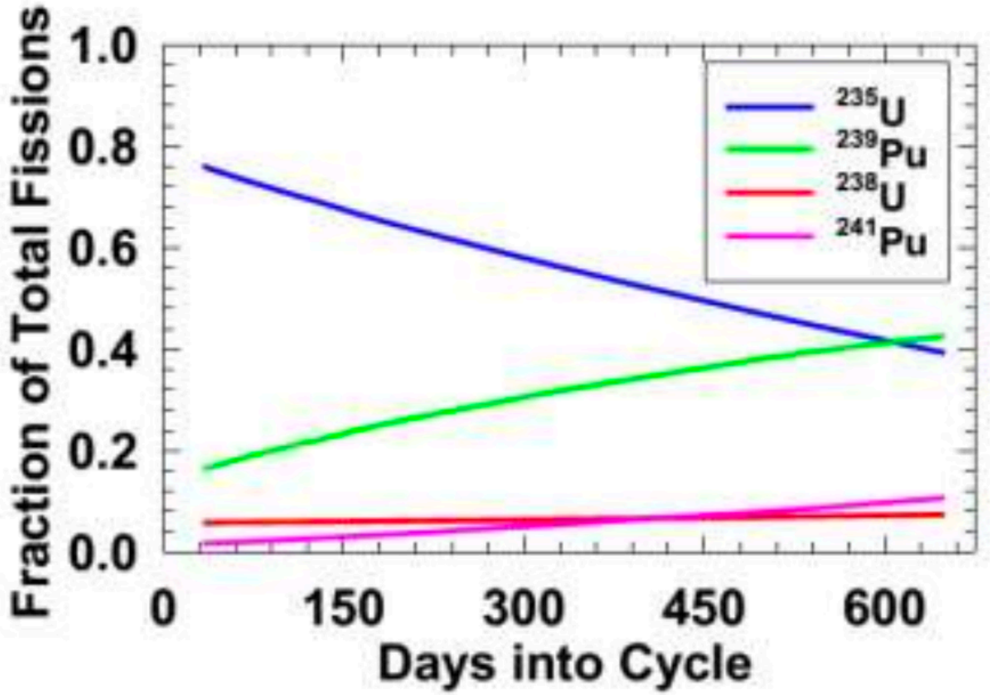
Sungkyunkwan University

- Start of project: 2006
- The first reactor experiment running with both near and far detectors
- Observation non-zero θ_{13} (2012)

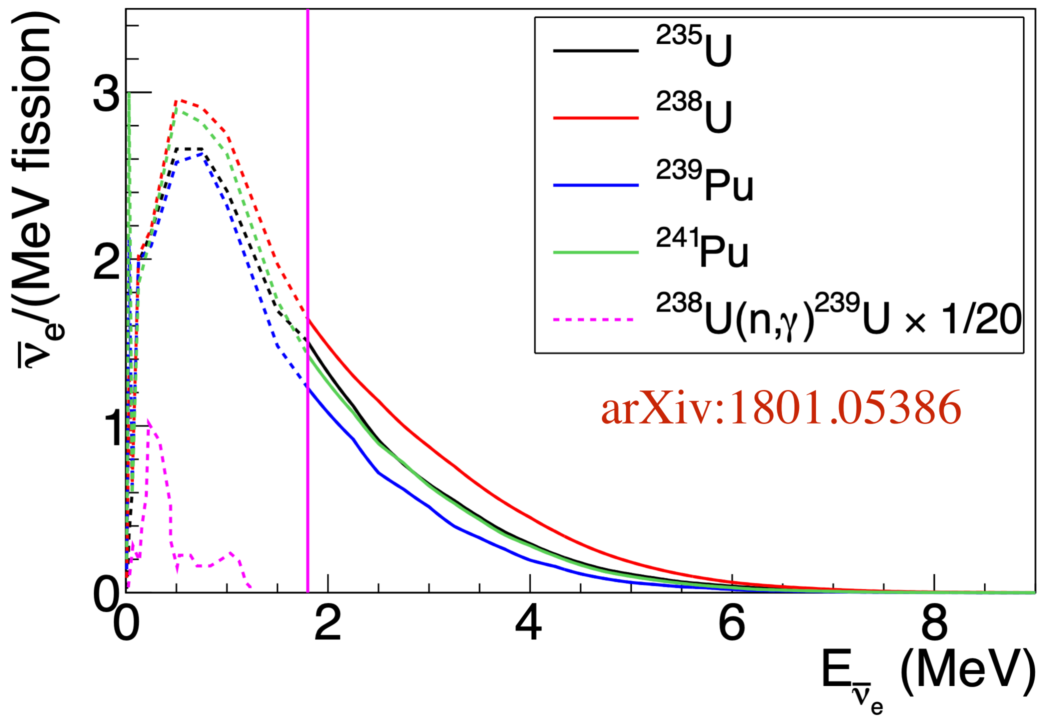
Hanbit Nuclear Power Plant & Neutrino Production

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

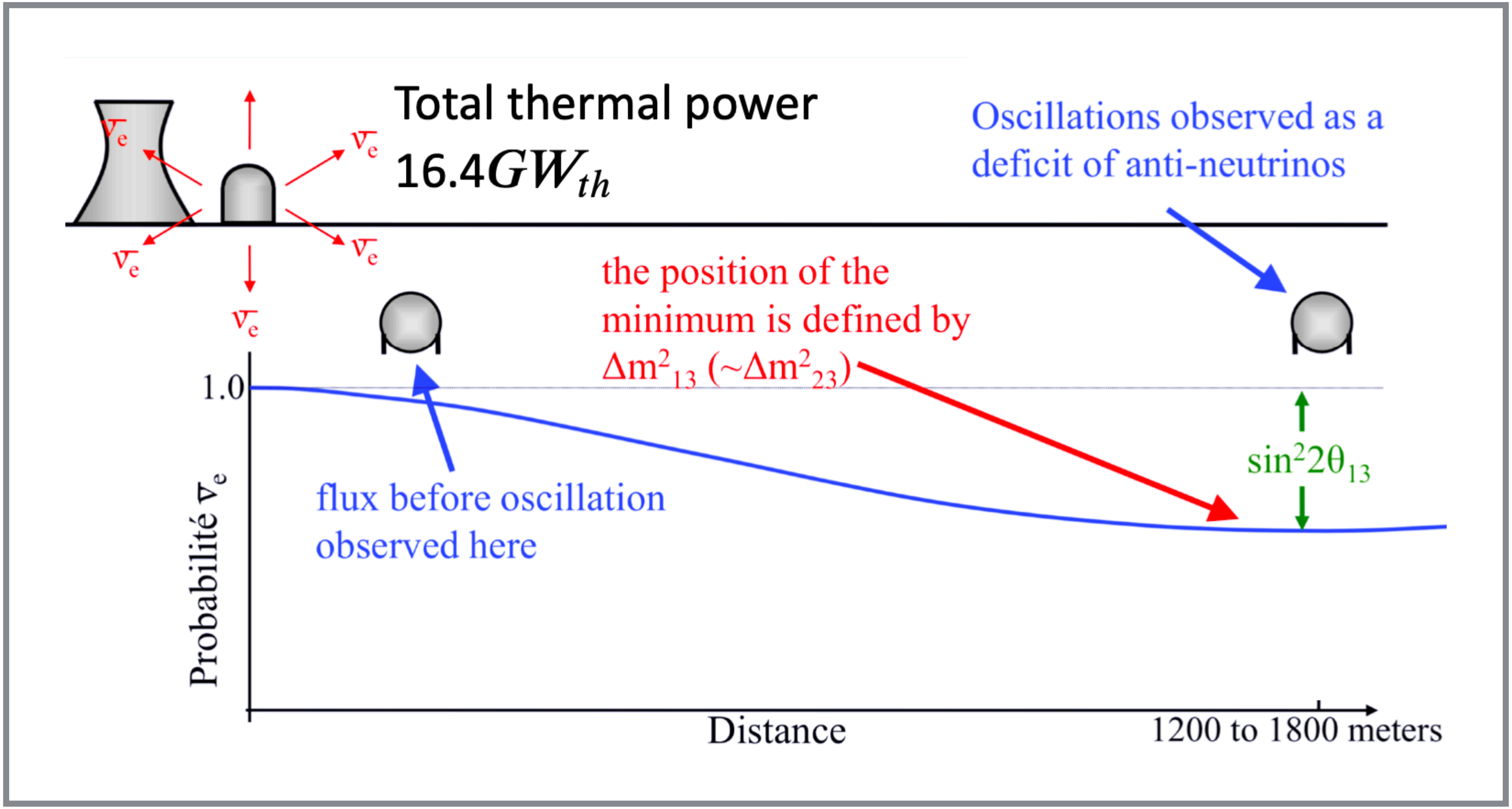


Anti-electron neutrinos for each GW_{th}
~2 x 10^{20} neutrinos / GW_{th}

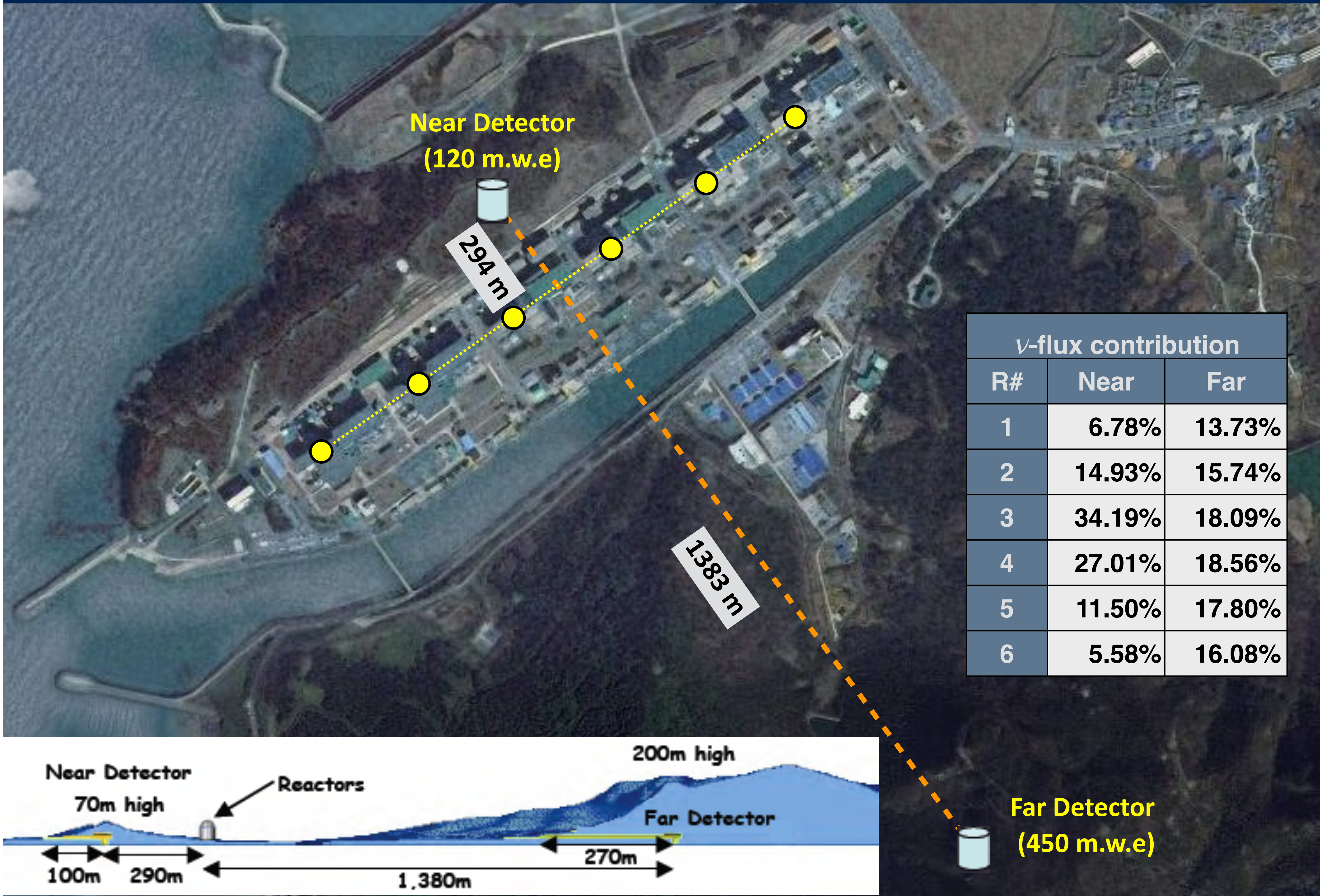


Reactor Experiment for Neutrino Oscillation

$$P(\nu_e \to \nu_e) \simeq 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\frac{1.27\Delta m^2_{12}L}{E_\nu}\right) - \sin^2 2\theta_{13}\sin^2\left(\frac{1.27\Delta m^2_{13}L}{E_\nu}\right)$$

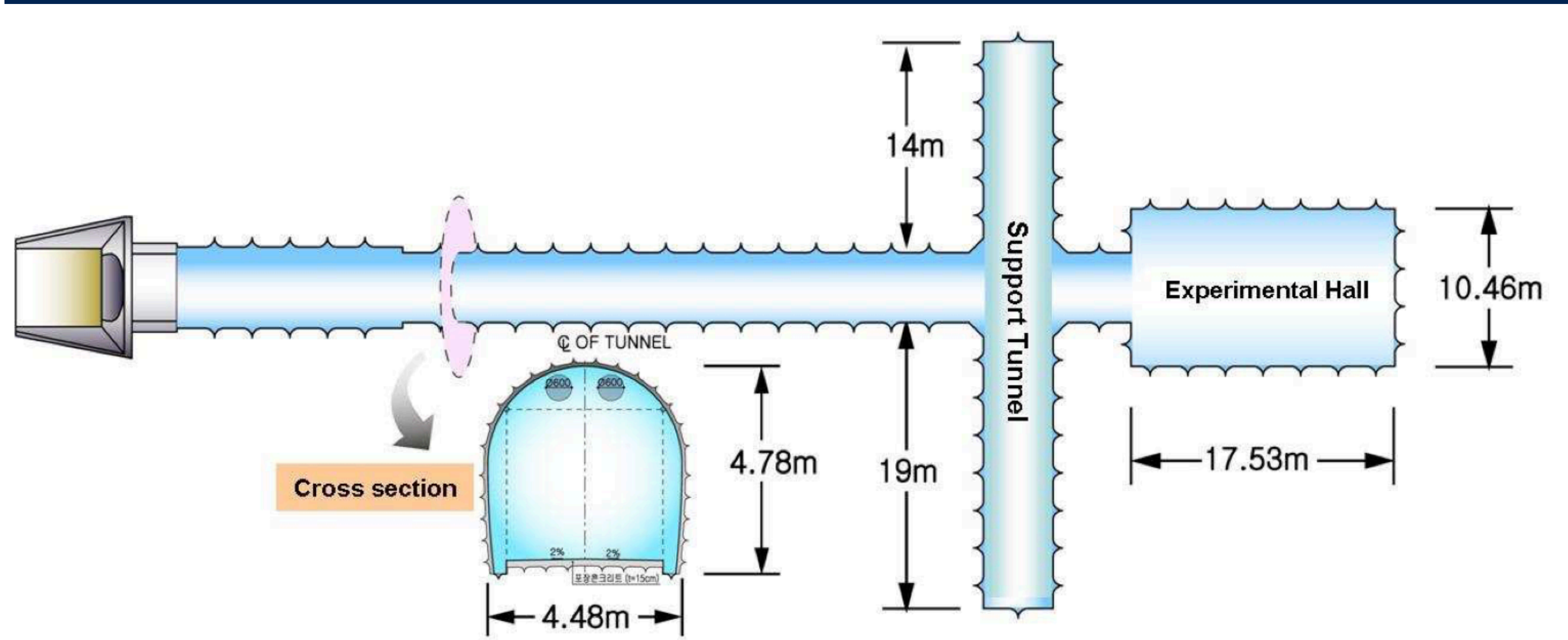


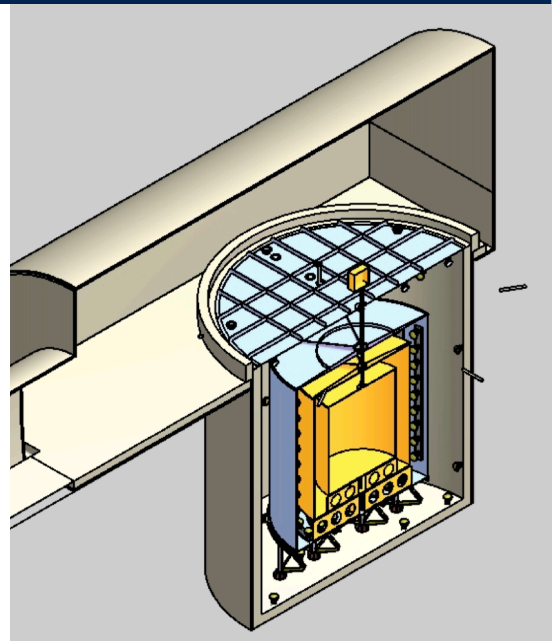
RENO Experimental Setup



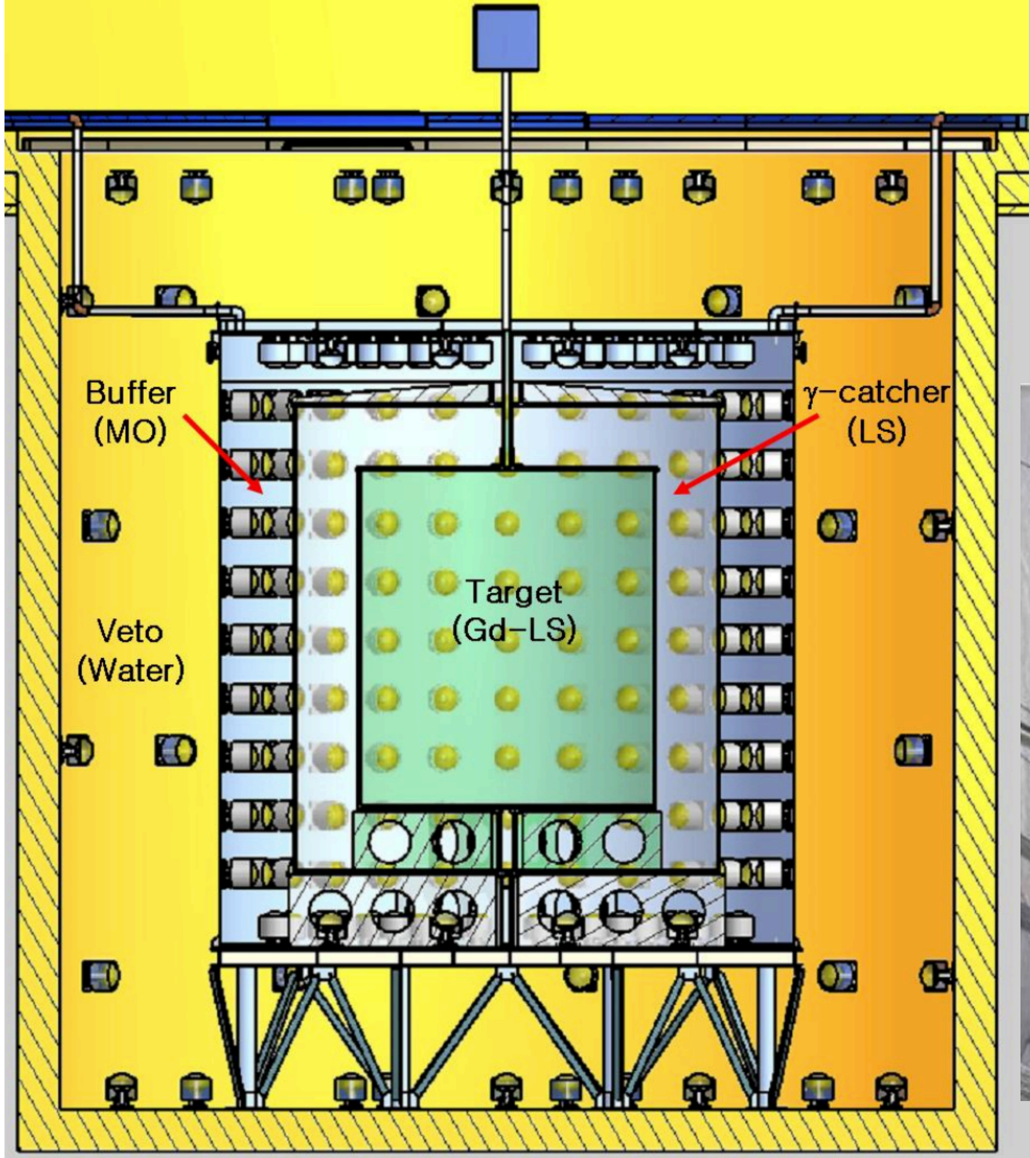
ν-flux contribution		
R#	Near	Far
1	6.78%	13.73%
2	14.93%	15.74%
3	34.19%	18.09%
4	27.01%	18.56%
5	11.50%	17.80%
6	5.58%	16.08%

RENO Experimental Setup



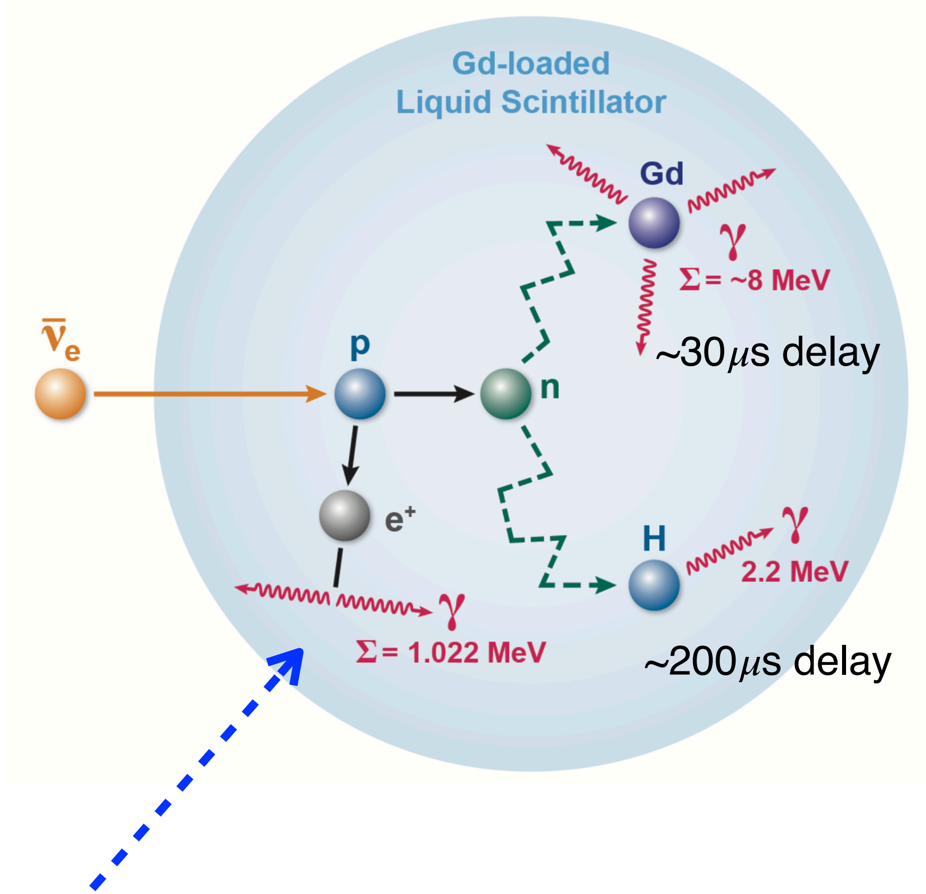


Identical detectors
at near and far sites



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

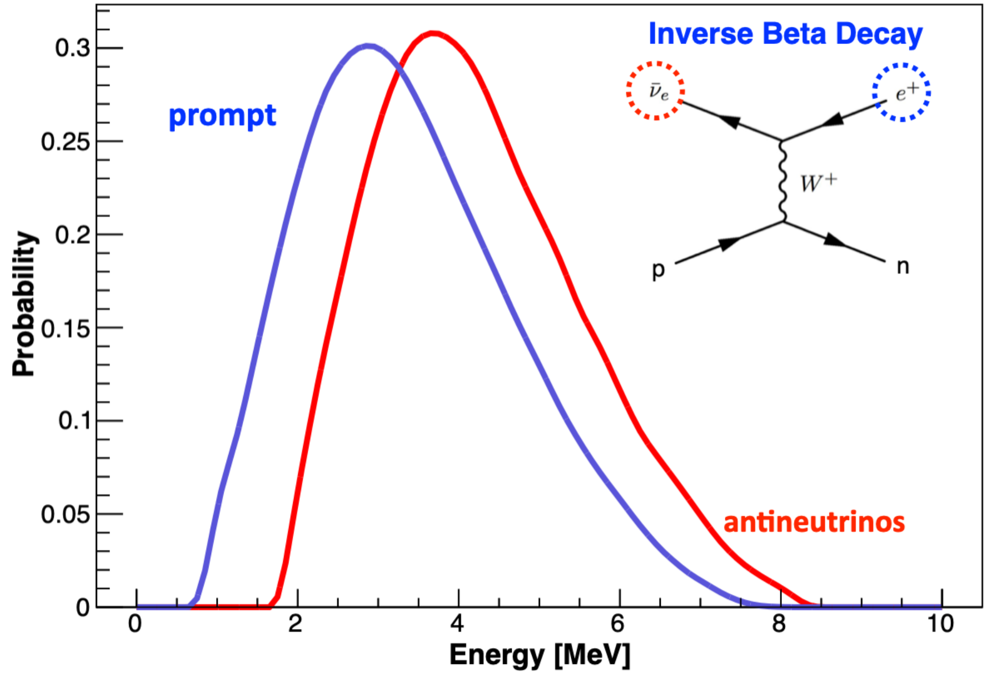
354 ID PMTs and 67 OD PMTs
(10” HAMAMATSU R7081)

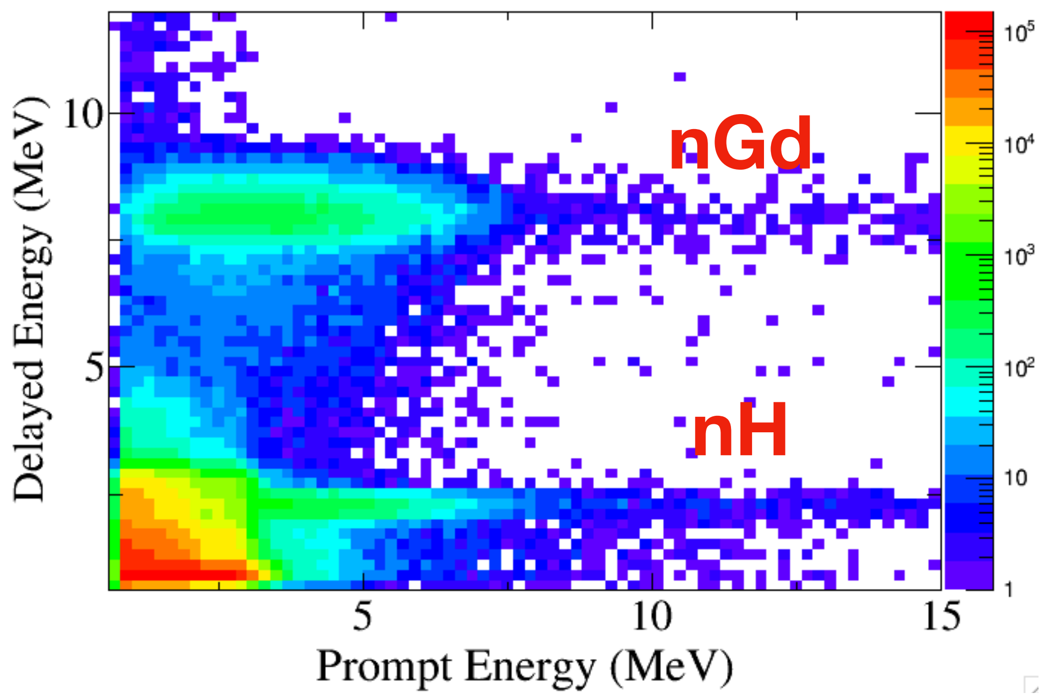


$$E_p \simeq E_\nu - 0.78\mathrm{MeV}$$

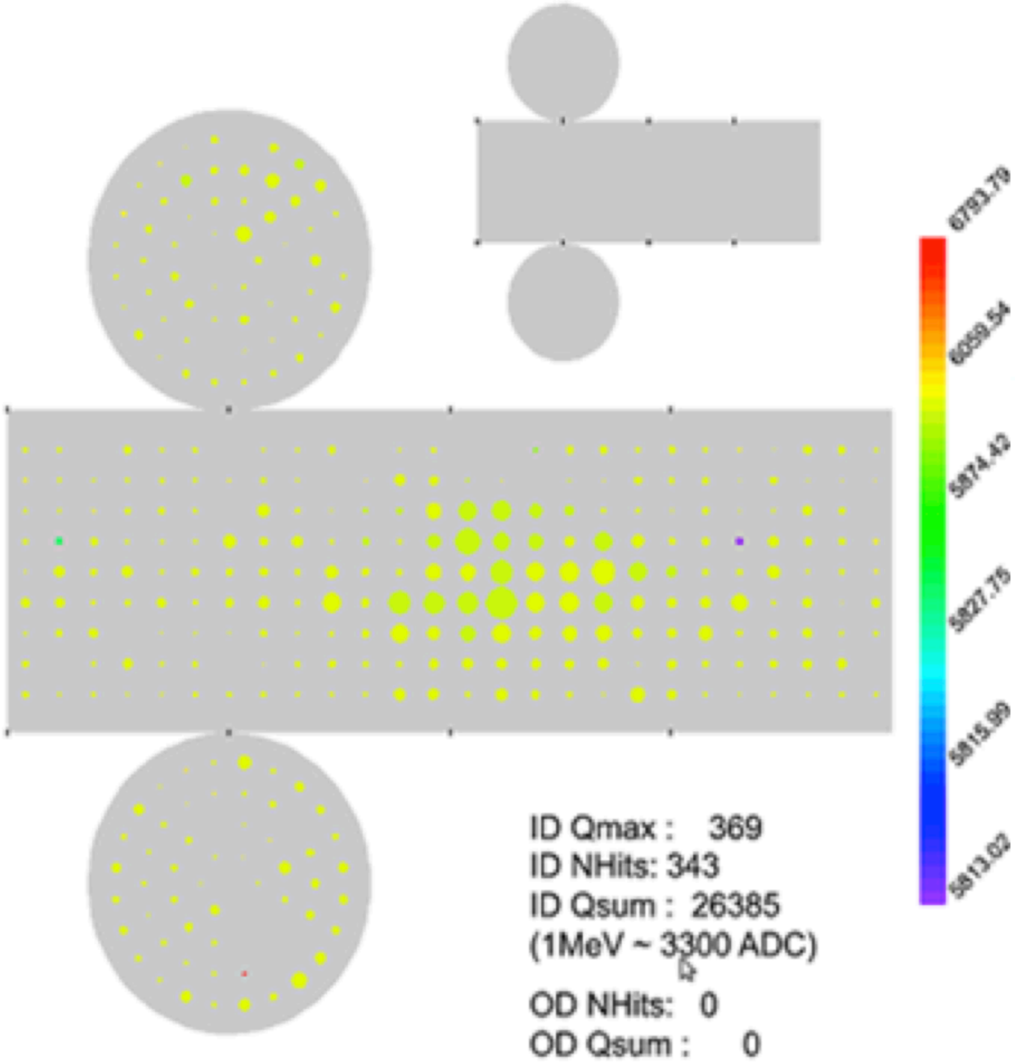
$$E_\nu^{thr} = \frac{(m_n + m_p)^2 - m_p^2}{2m_p}$$

$$= 1.806\,\mathrm{MeV}$$

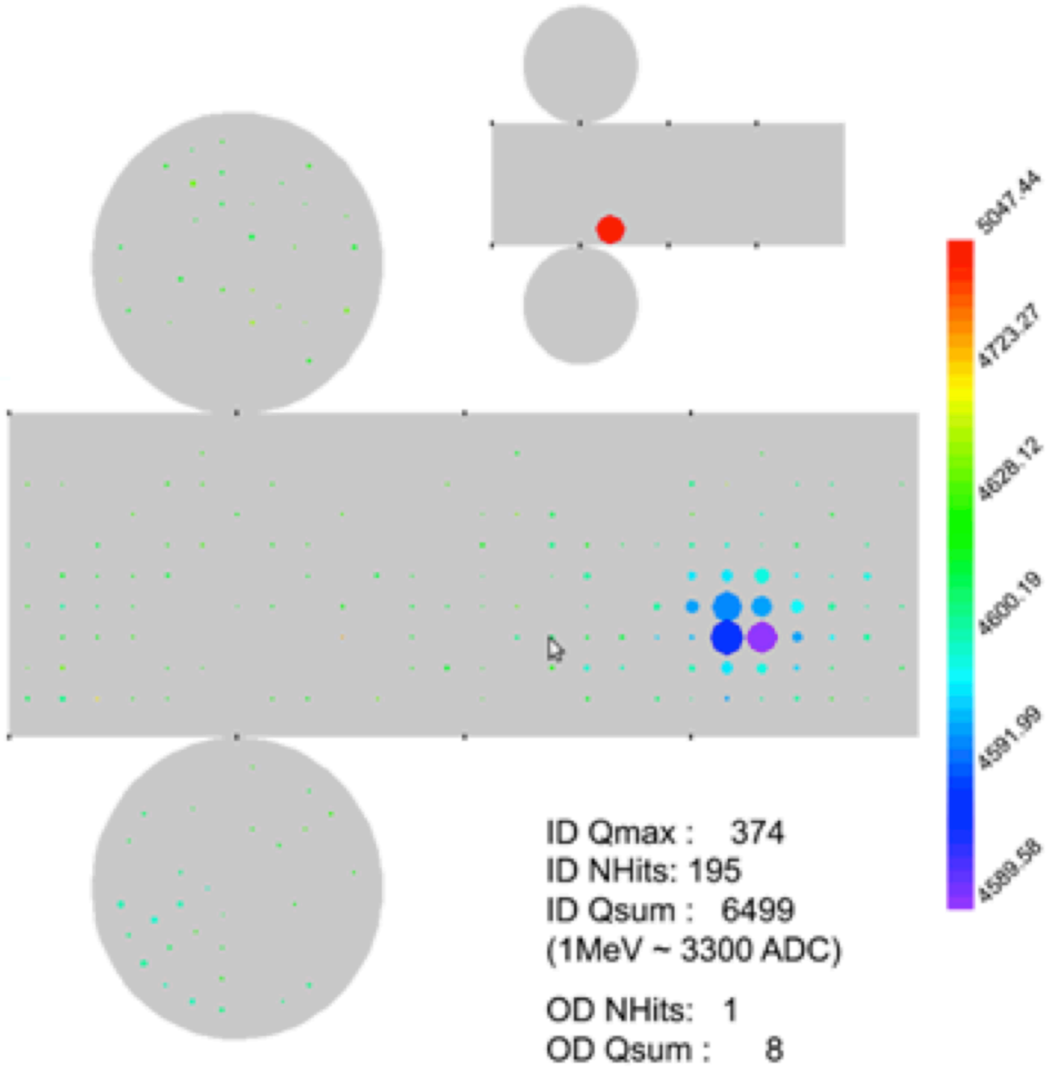




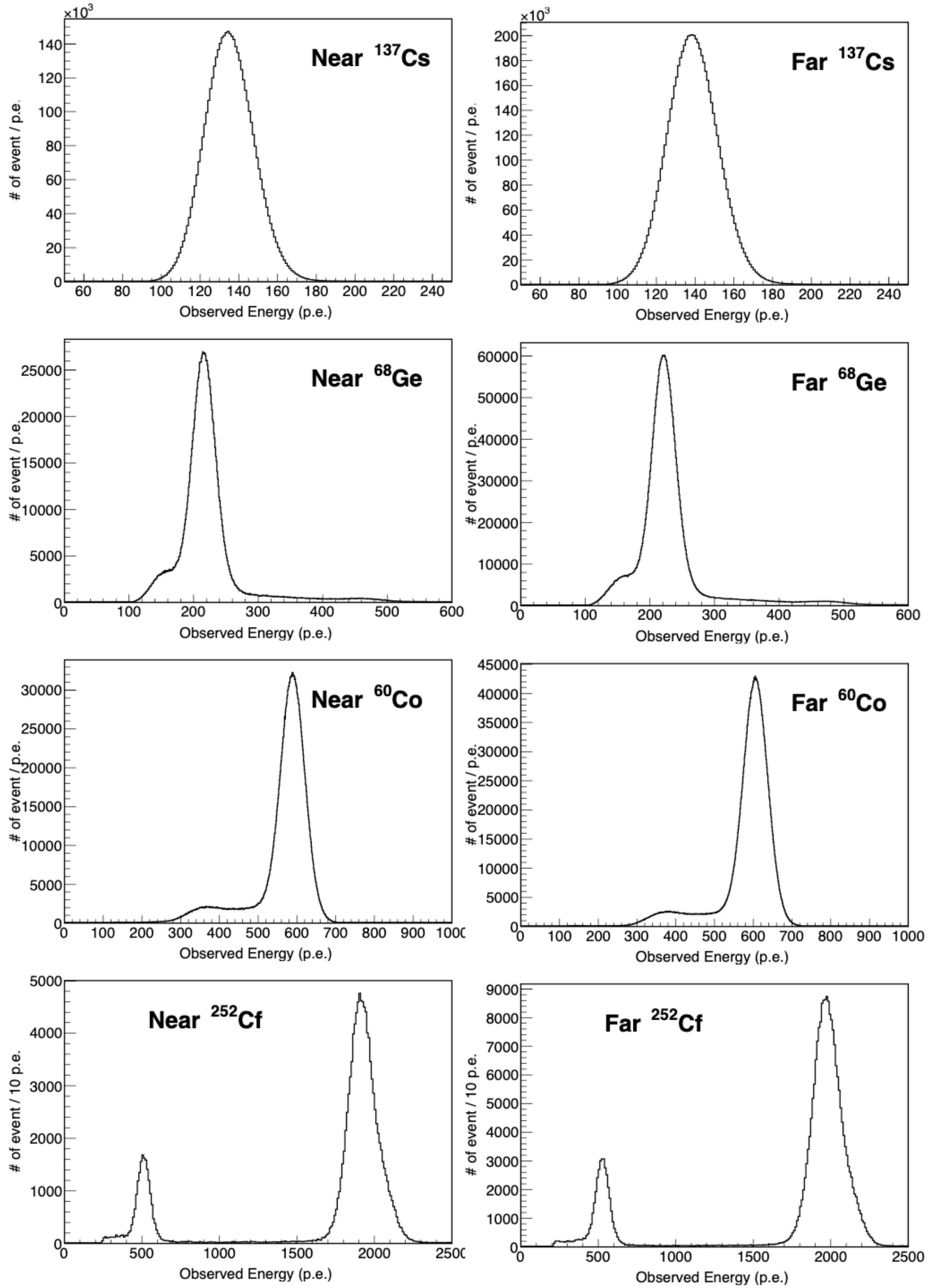
nGd like event

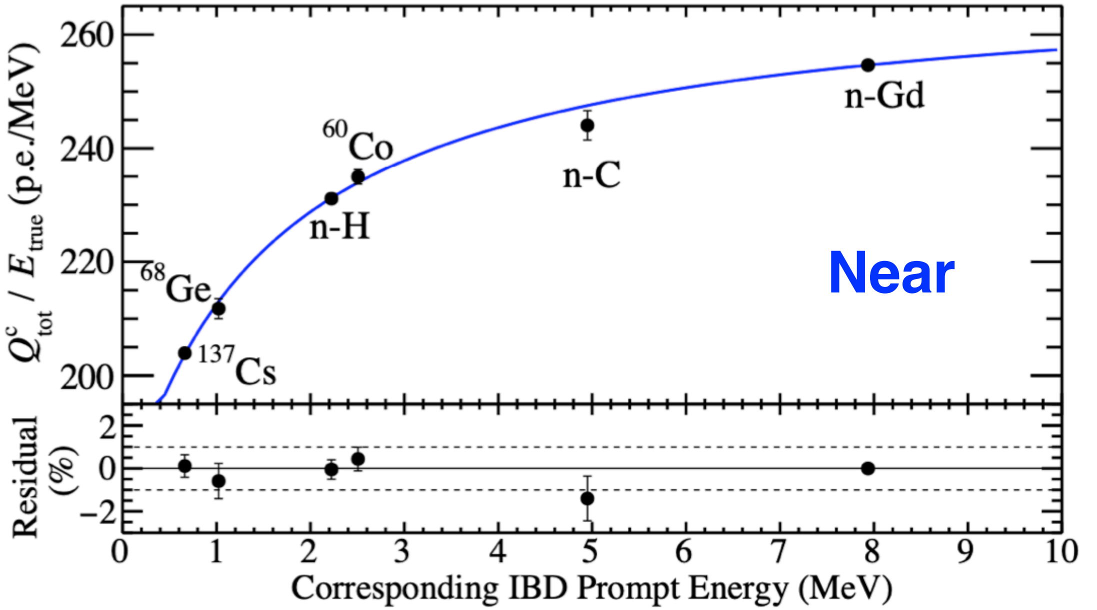


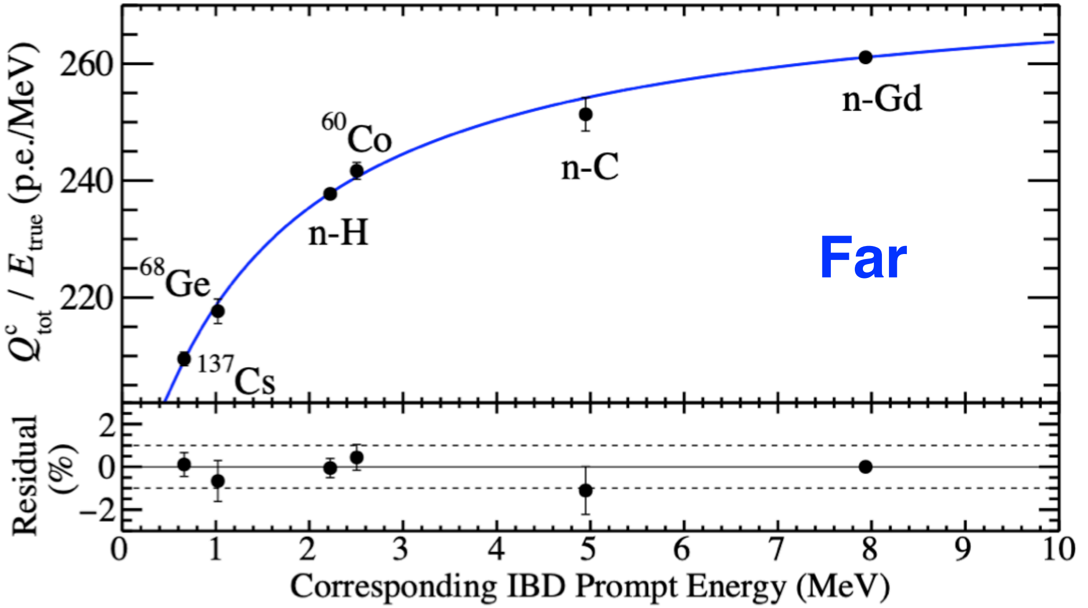
External gamma like event



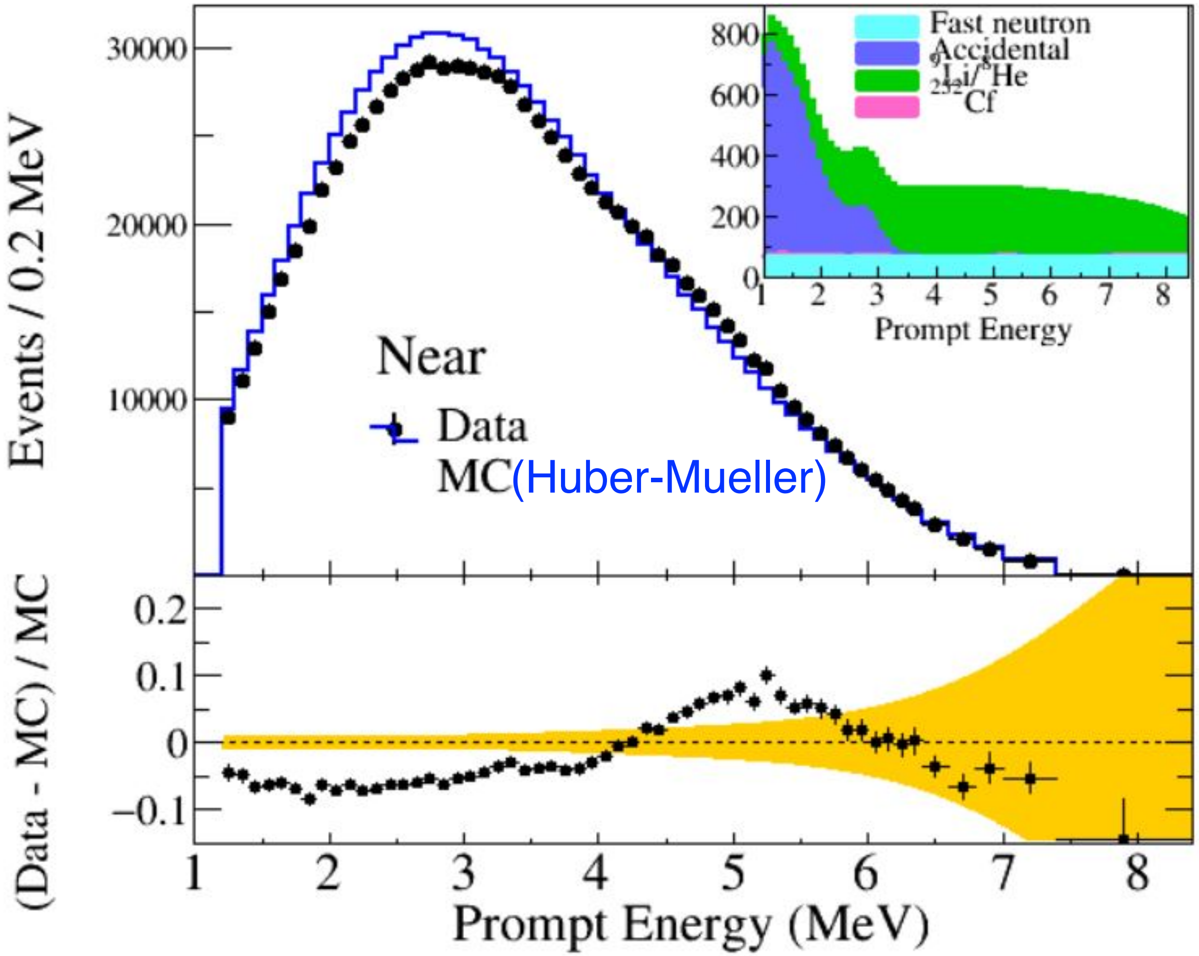
Radioactive sorce calibration



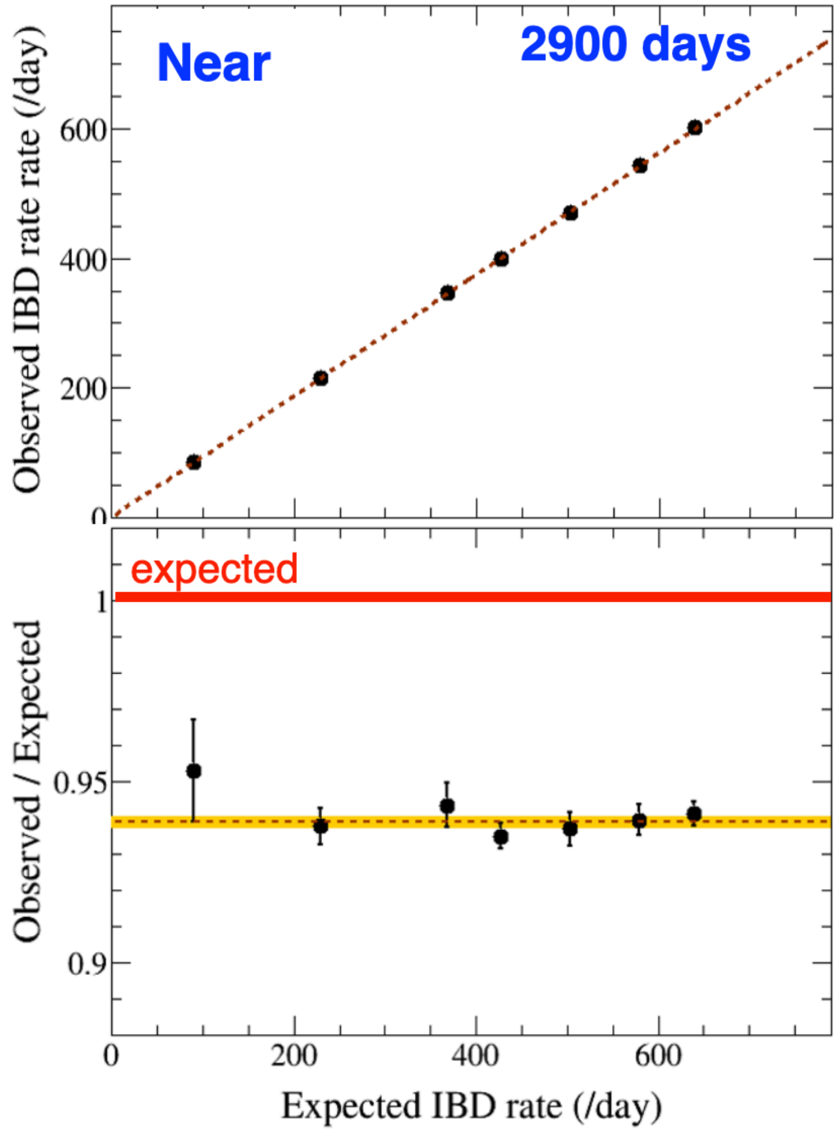




- Measured reactor antineutrino flux & spectrum disagree with the expected value!

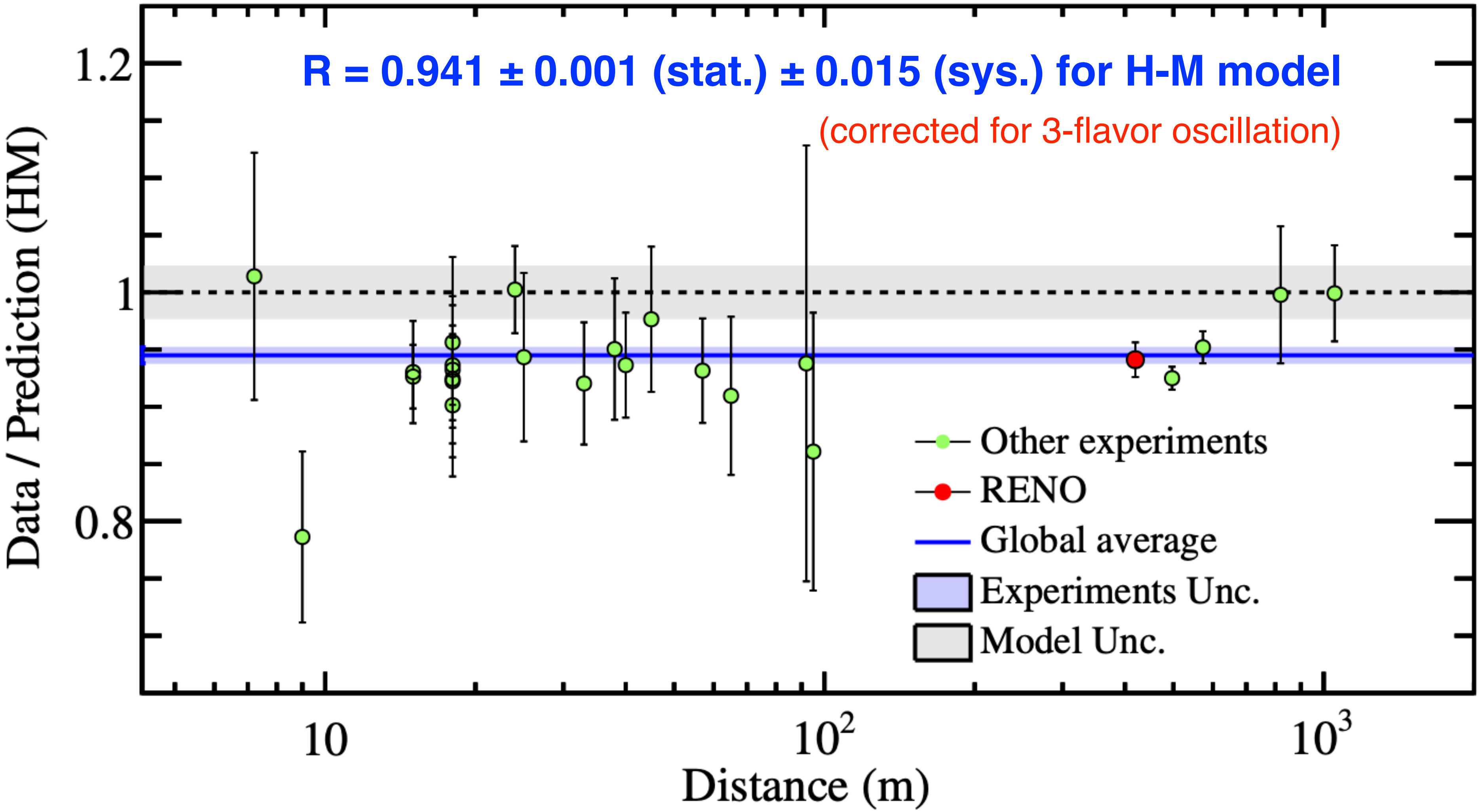


Observed IBD rate vs. Thermal Power



Reactor Antineutrino Anomaly: RAA

PRD 104, L111301 (2021)



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

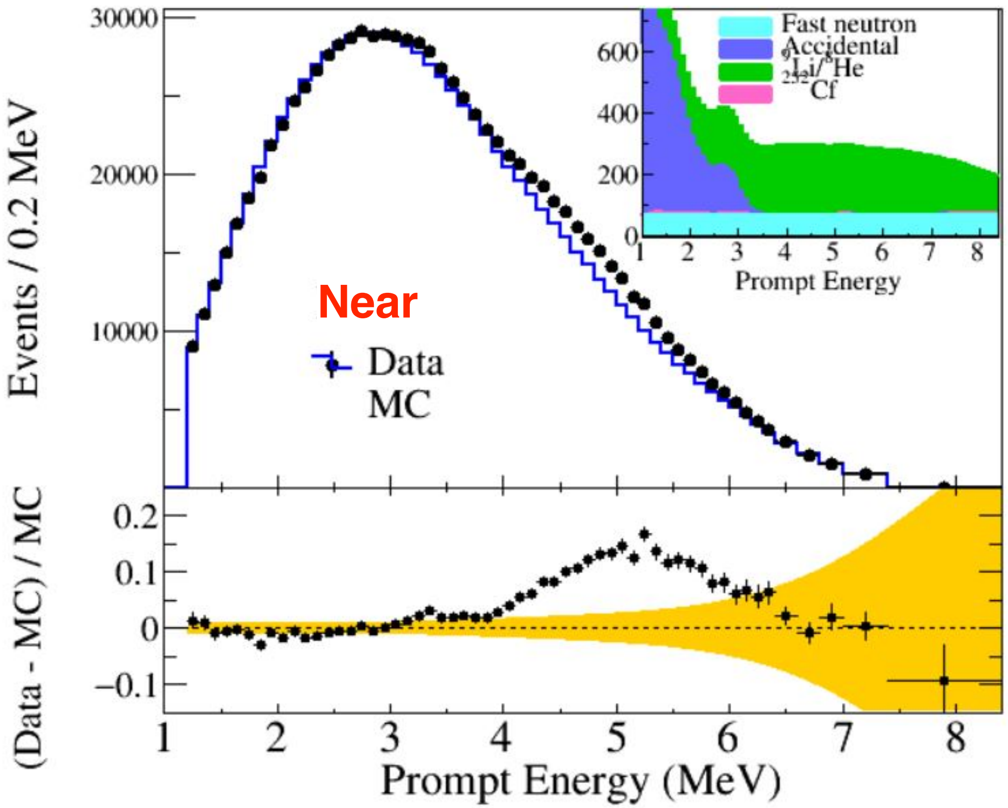
Average fission fraction: $\overline{F}_{235} : \overline{F}_{238} : \overline{F}_{239} : \overline{F}_{241} = 0.571 : 0.073 : 0.300 : 0.056$

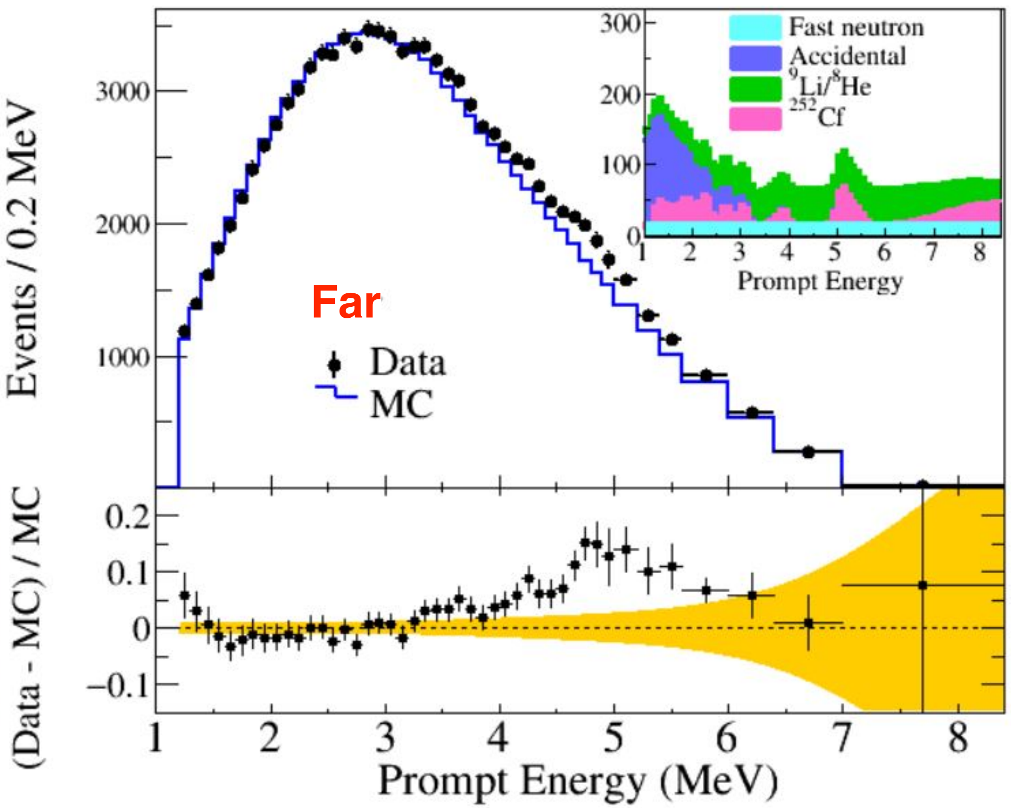
Observed IBD Prompt Signal

RENO 2200 days results: PRL 121, 201801 (2018)

RENO 2900 days: Aug. 2011 — Feb. 2020 (This results)

- Clear excess at 5MeV compared to the *scaled* Huber-Mueller prediction



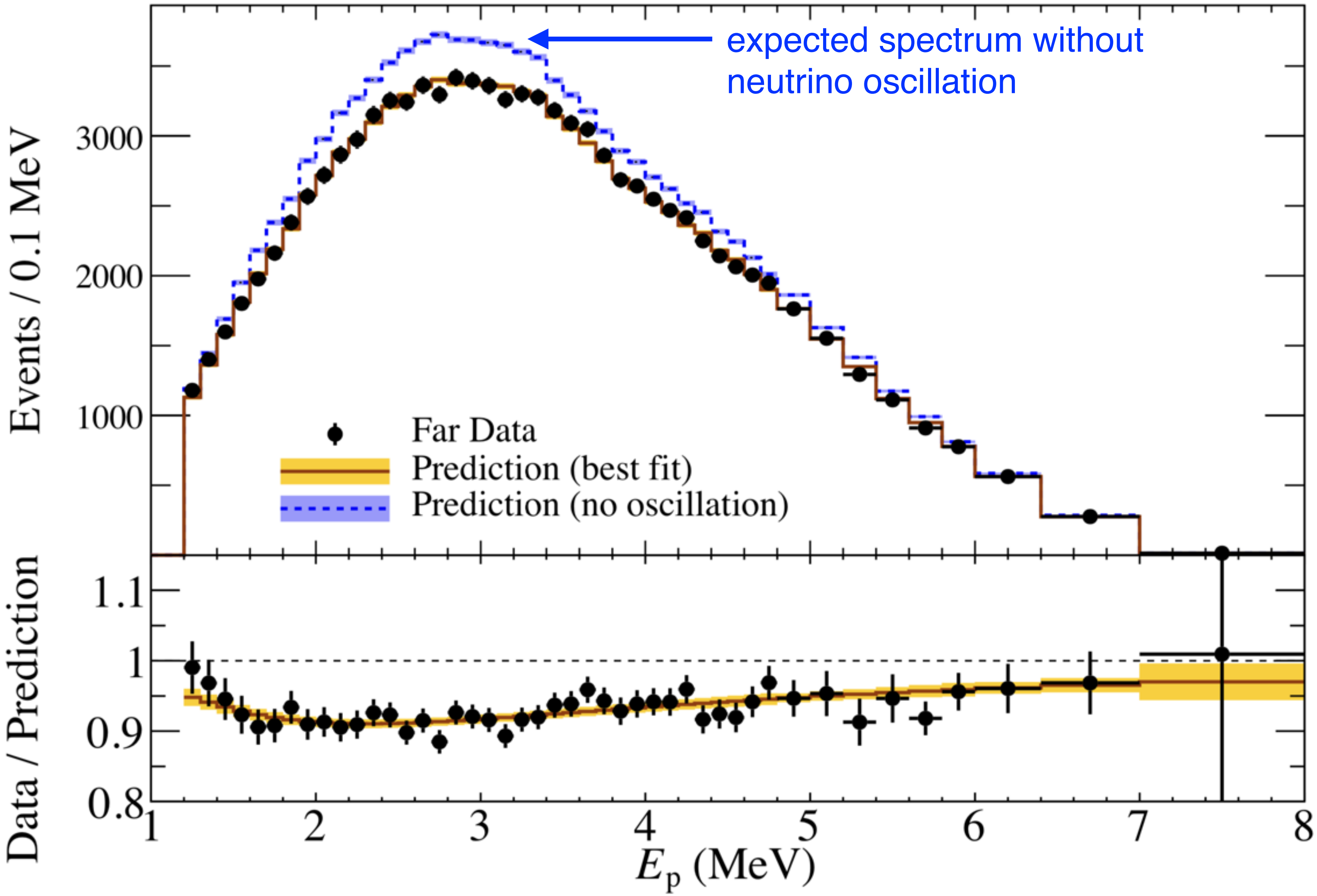


Near detector live time: 2509 days
#IBD candidates: 989,736
Background rate: 2.26 ± 0.05 %
5 MeV excess rate: 2.50 ± 0.06 %

Far detector live time: 2908 days
IBD candidates: 120,383
Background rate: 4.77 ± 0.19 %
5 MeV excess rate: 2.26 ± 0.18 %

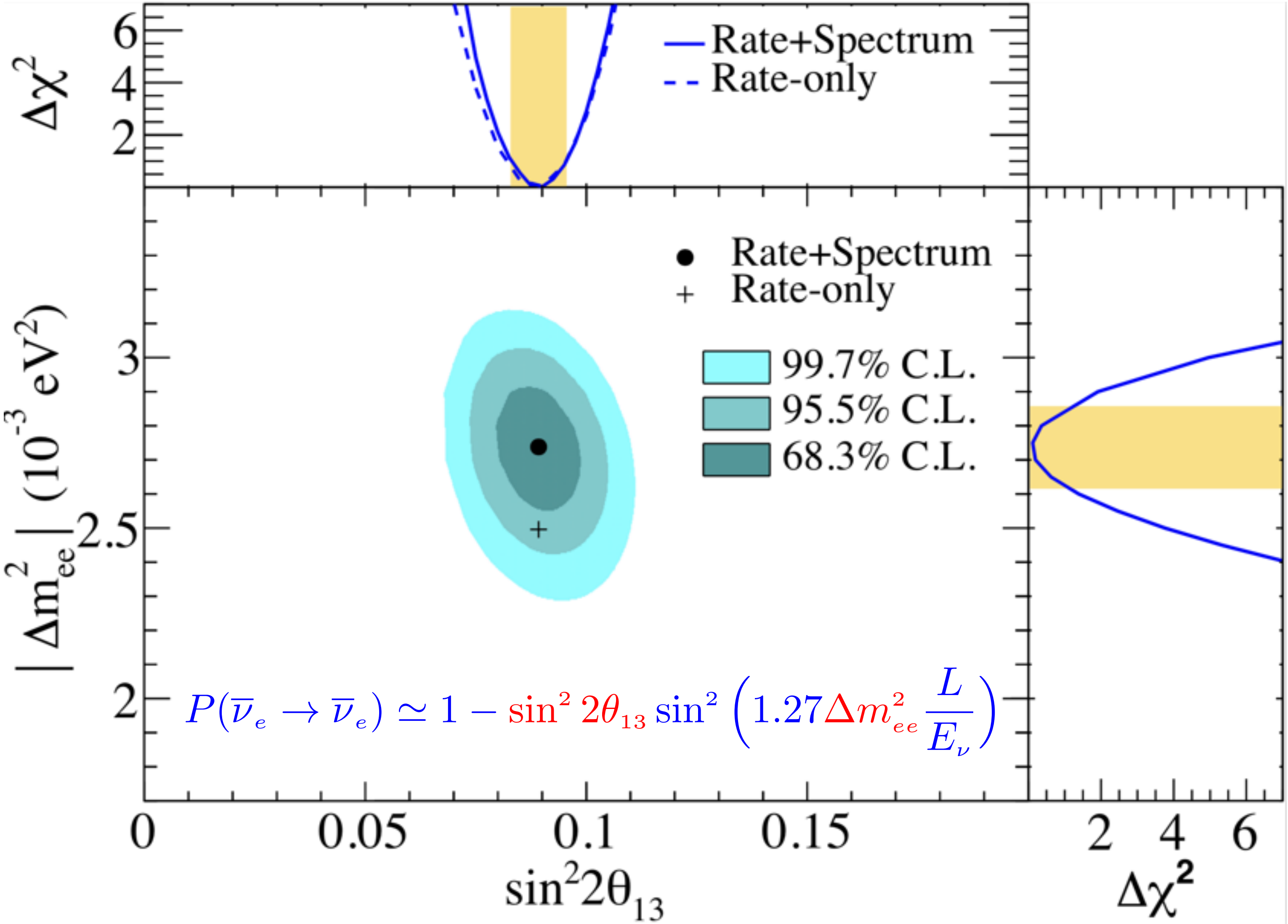
RENO 2900 days (Aug. 2011 — Feb. 2020)

- Energy dependent disappearance of reactor antineutrinos



Neutrino Oscillation: $\sin^2\theta_{13}$ and Δm^2_{ee}

RENO 2900 days (Aug. 2011 — Feb. 2020)

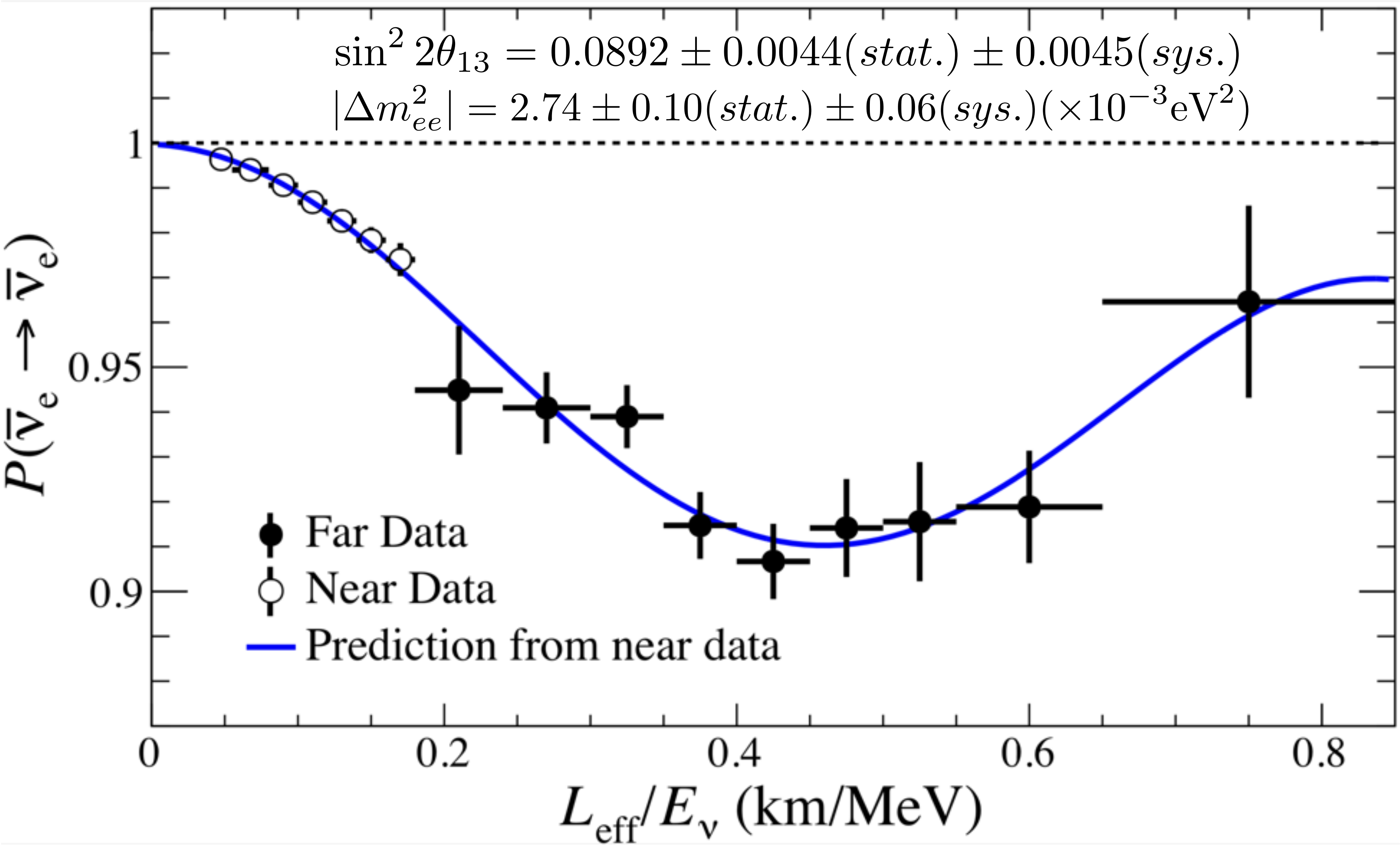


$$\sin^2 2\theta_{13} = 0.0892 \pm 0.0044(stat.) \pm 0.0045(sys.)$$ **± 7.0%**

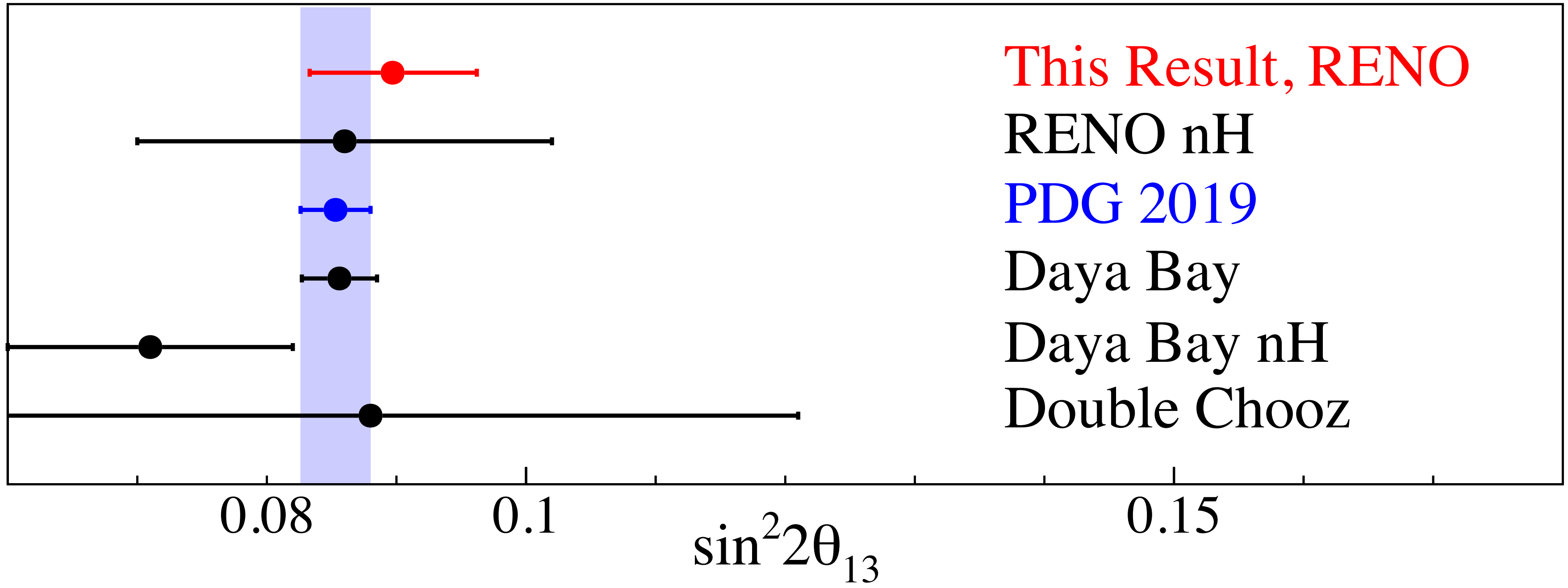
$$|\Delta m^2_{ee}| = 2.74 \pm 0.10(stat.) \pm 0.06(sys.)(\times 10^{-3}\mathrm{eV}^2)$$ **± 4.4%**

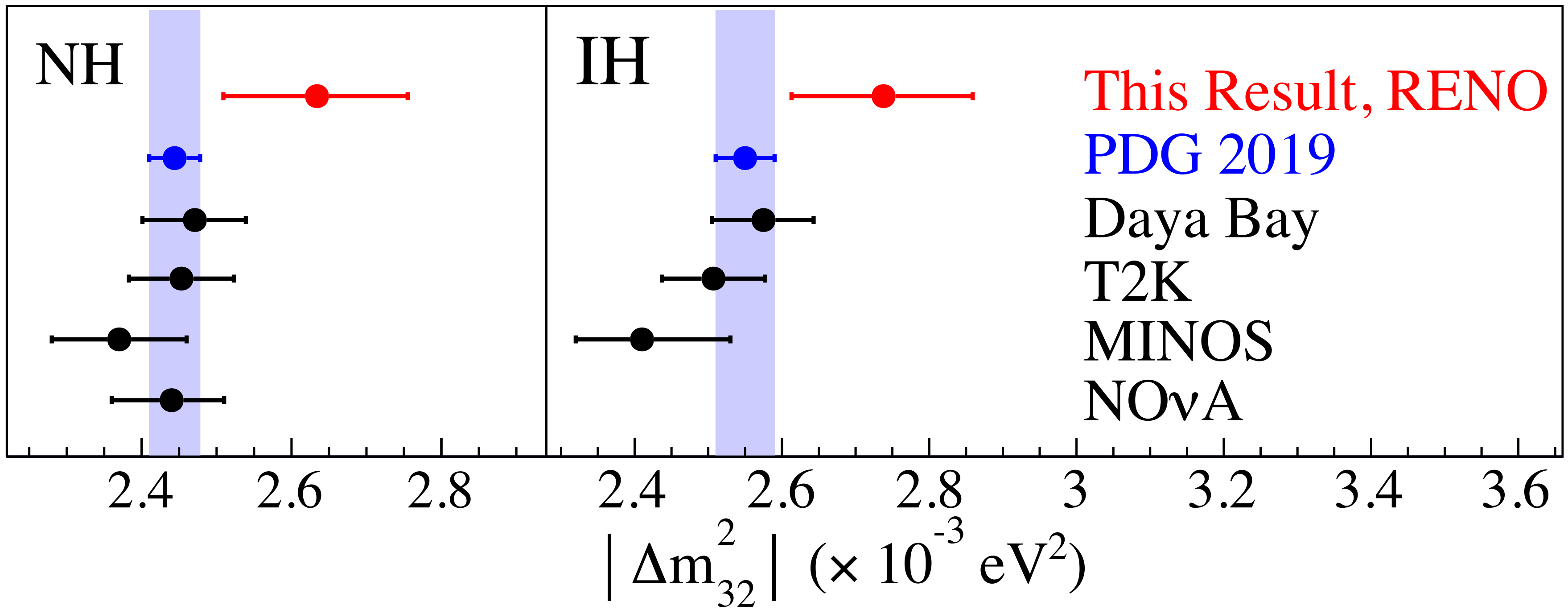
Neutrino Oscillation: L/E Dependence

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

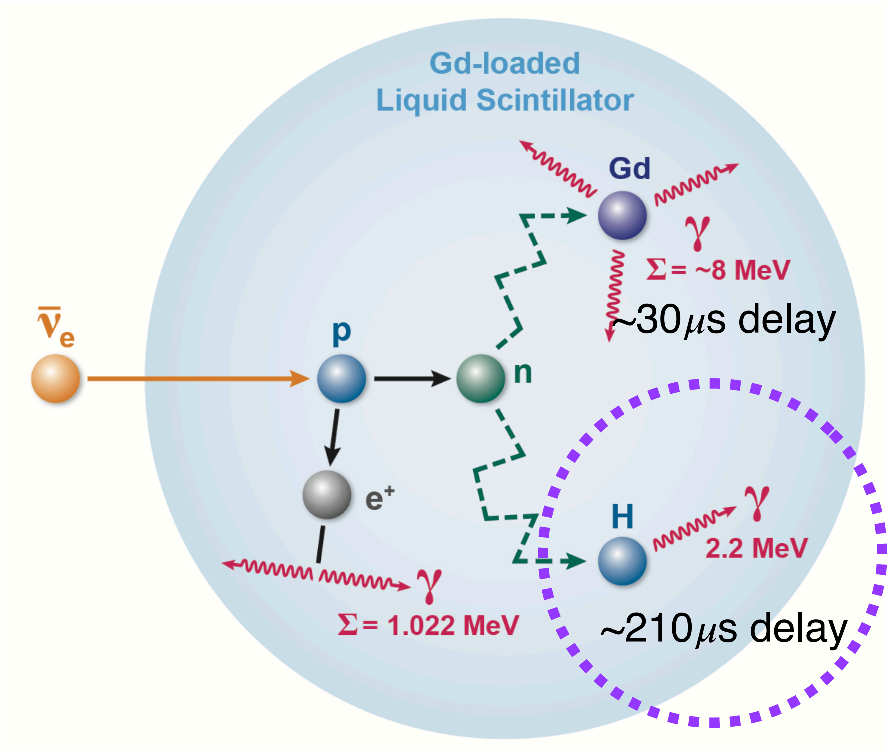


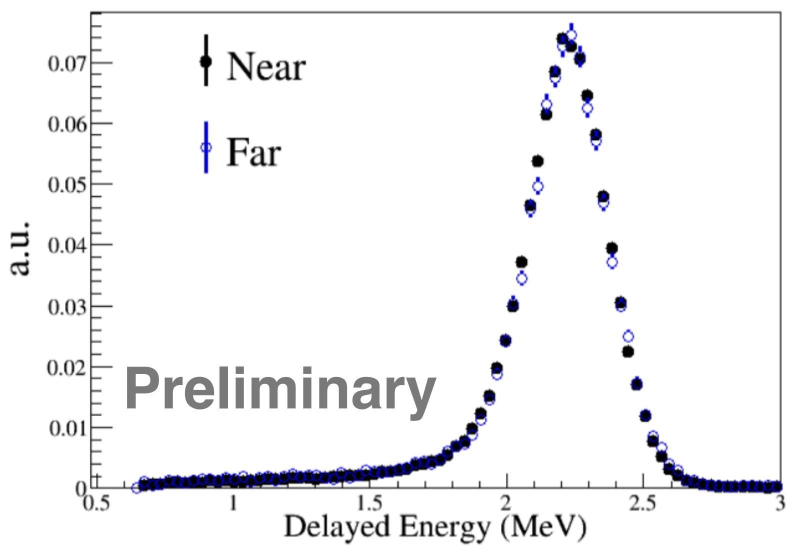
Neutrino Oscillation: $\sin^2\theta_{13}$ and Δm^2_{32}

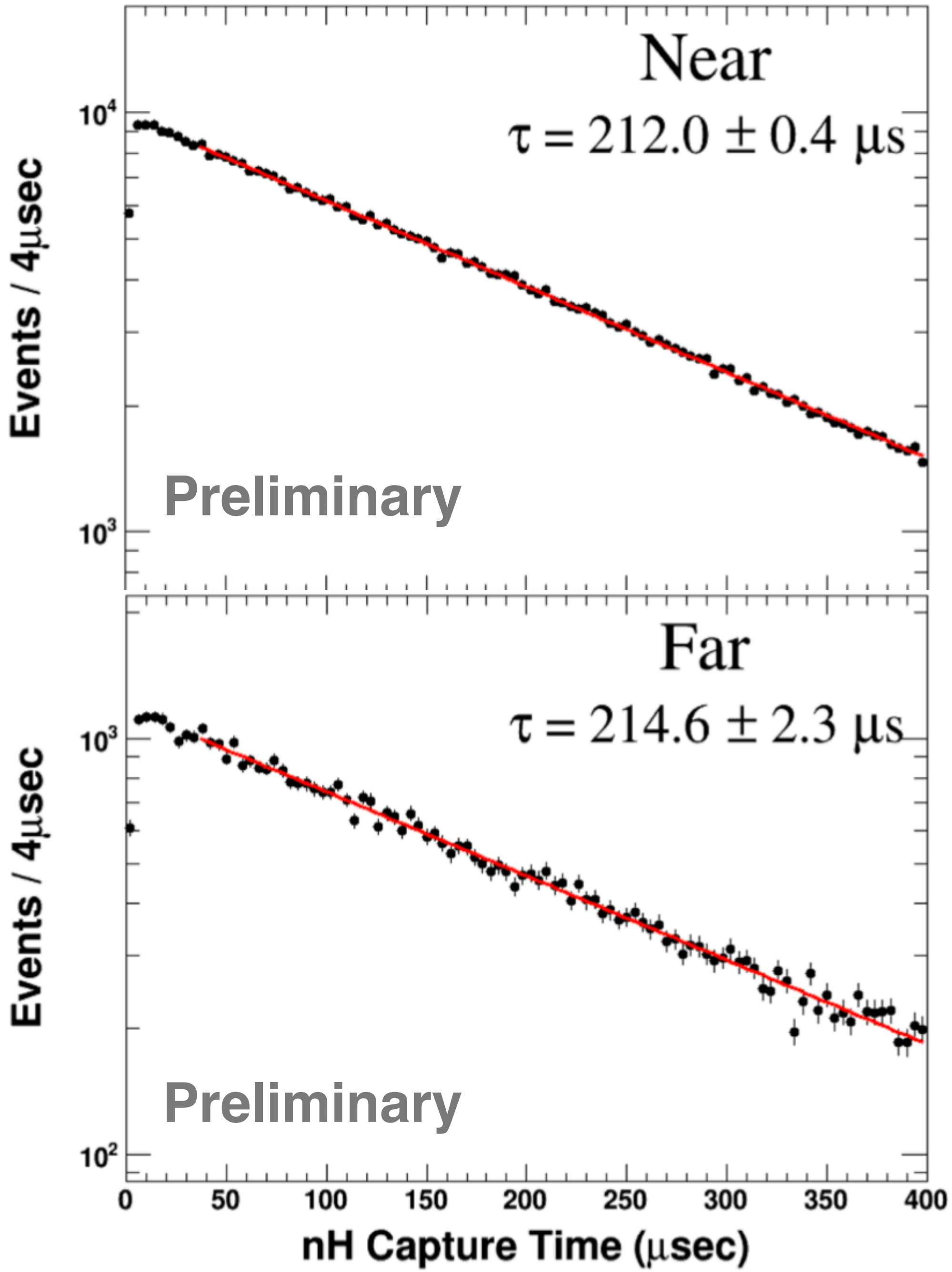




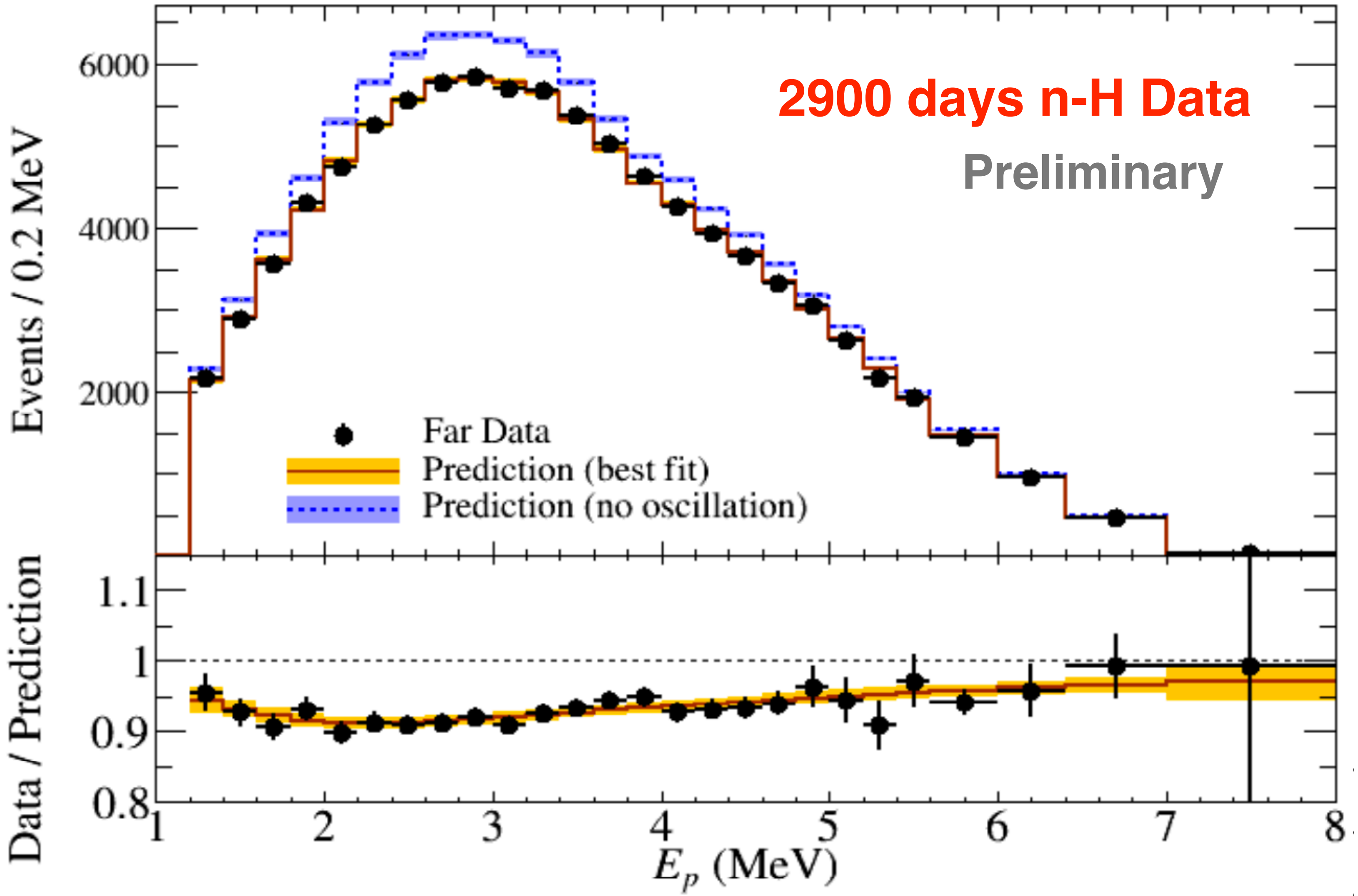
RENO 2900-Days Data n-H Analysis Results







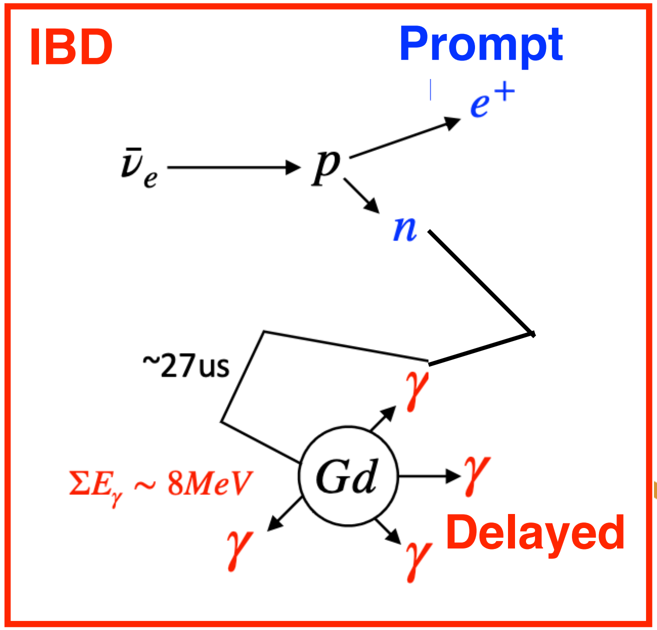
Independent measurement of $\sin^2 2\theta_{13}$ using 2900 days n-H data

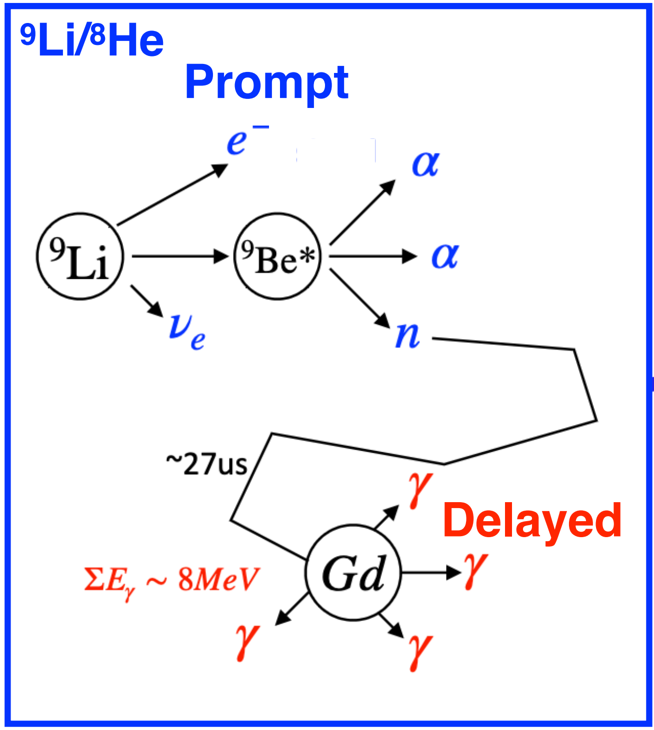


$$\sin^2 2\theta_{13} = 0.086 \pm 0.006(\mathrm{stat.}) \pm 0.010(\mathrm{syst.})$$ (Preliminary)

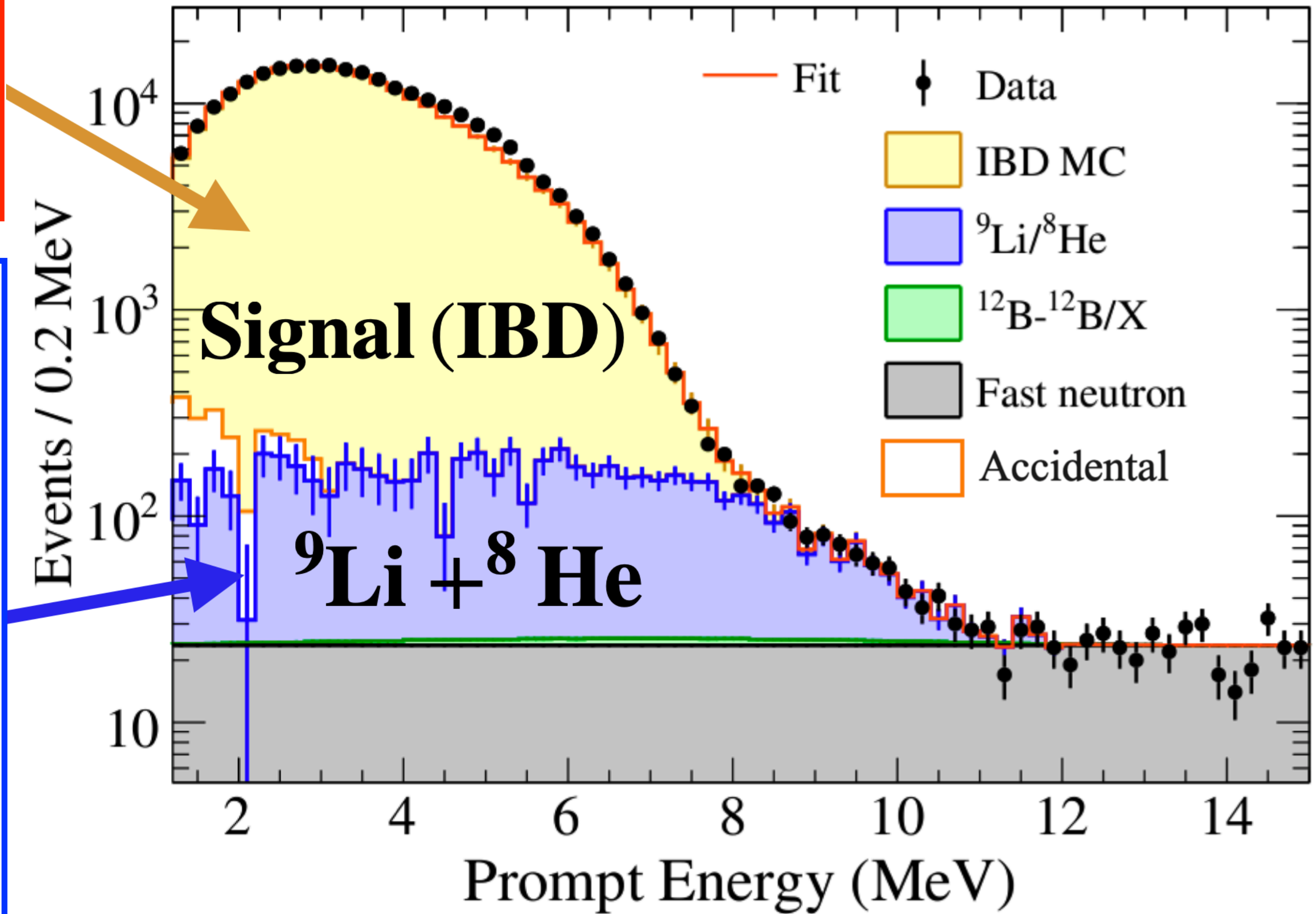
using world average value of $|\Delta m^2_{ee}| = 2.50 \pm 0.06 \times 10^{-3}\mathrm{eV}^2$

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

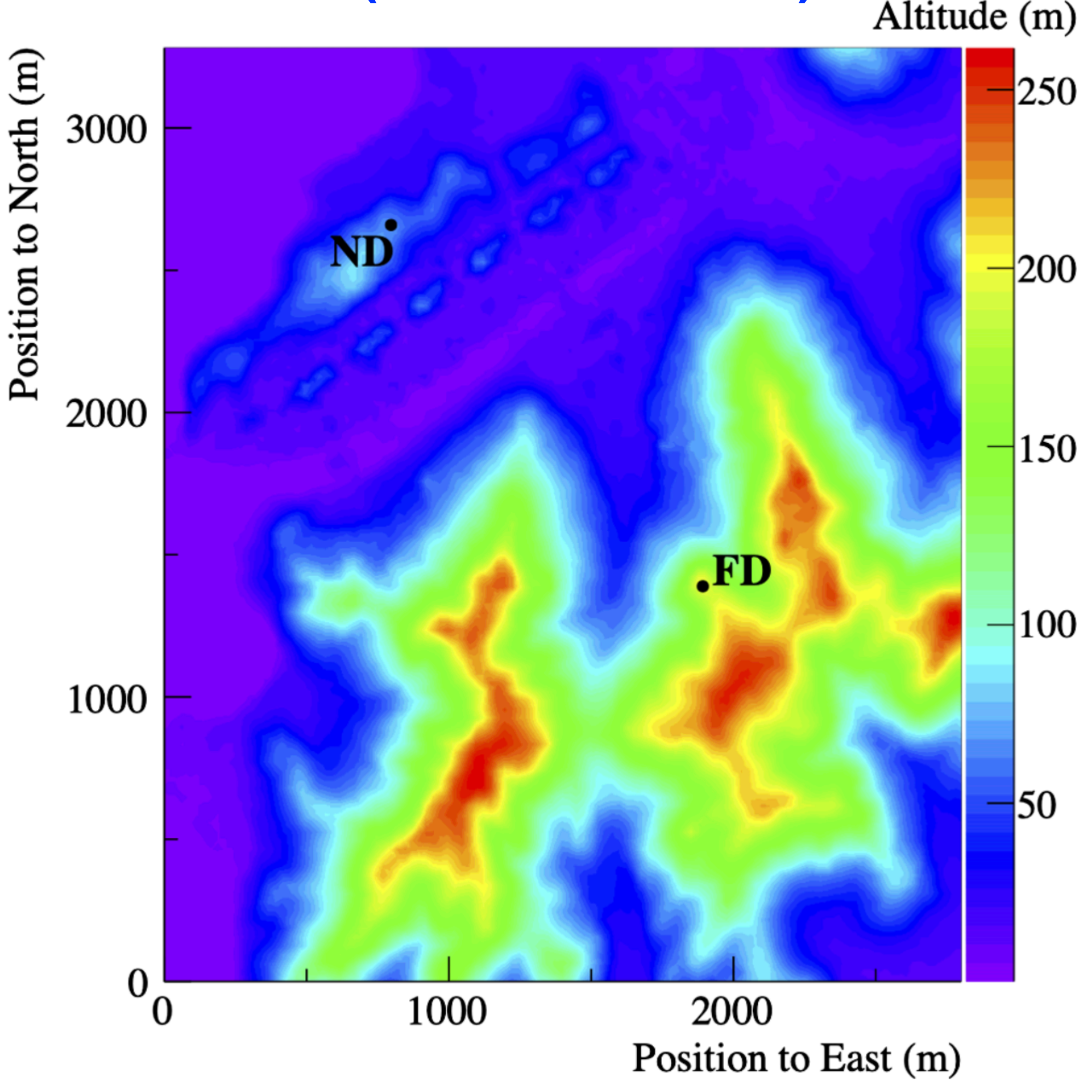




- Cosmic muon spallate ^{12}C ➔ (n, ^{12}B, ^{9}Li, ^{8}He,…)
- Long lived ^{9}Li and ^{8}He β-n decays are the major backgrounds of the IBD events

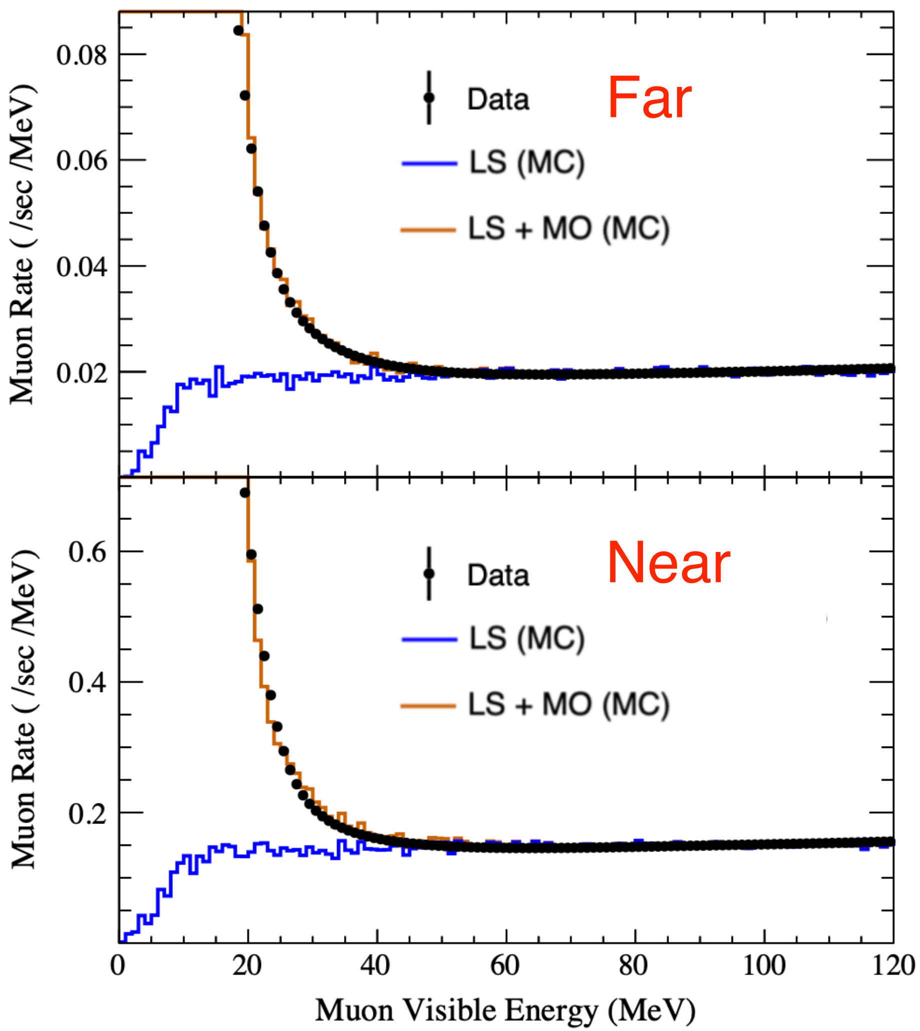


Topological profile of RENO site (ALOS world 3D)

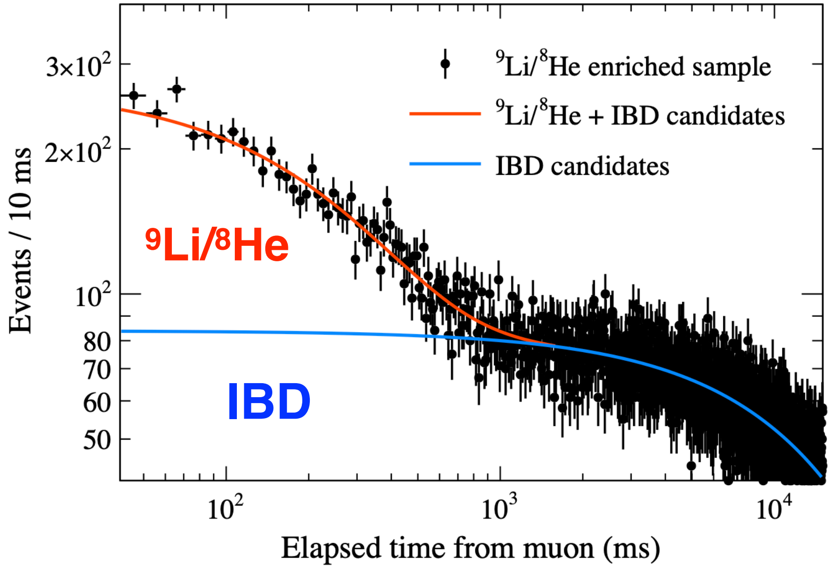


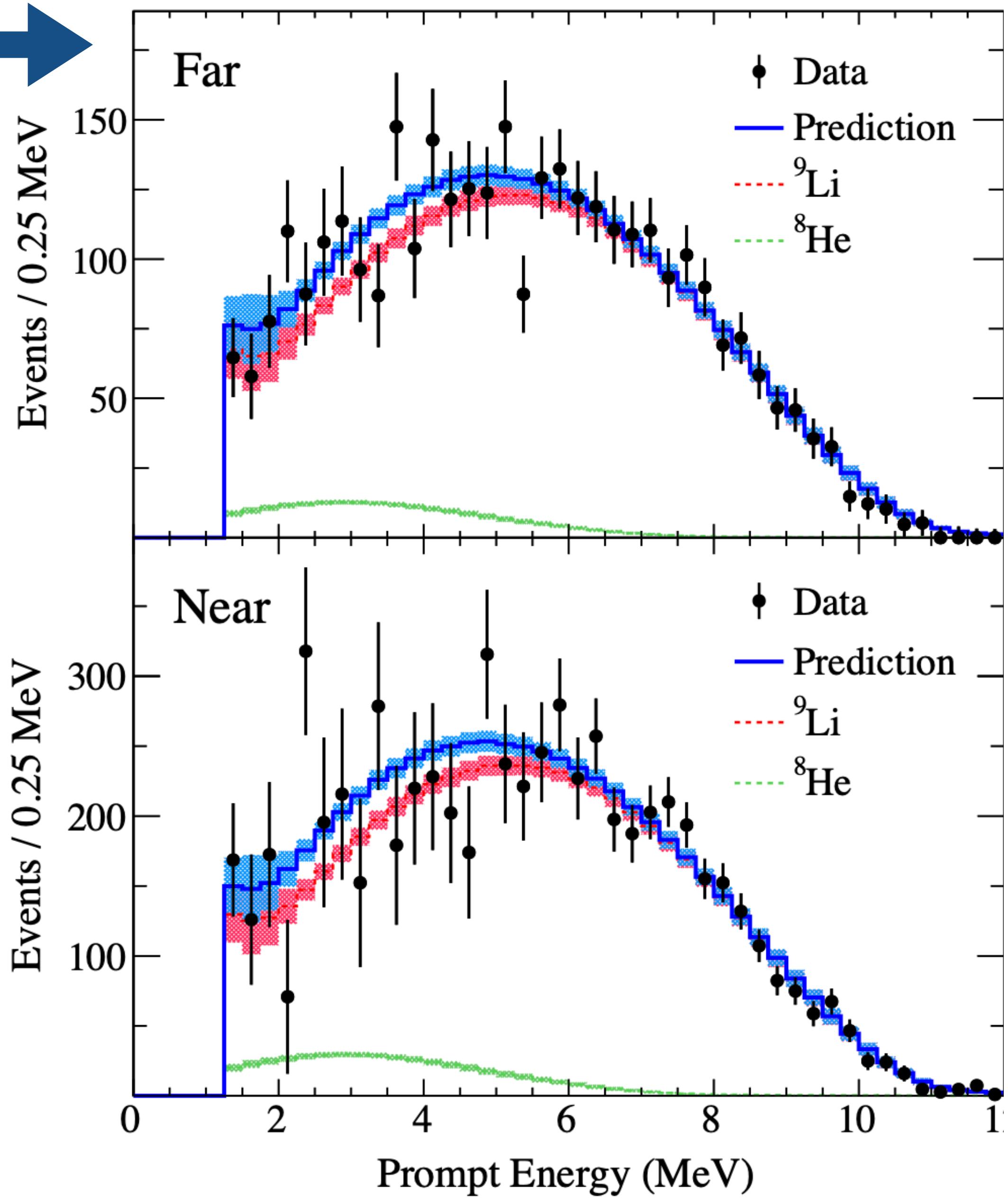
Visible Energy of Cosmic Muons

Cosmic Muon MC: MUSIC



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

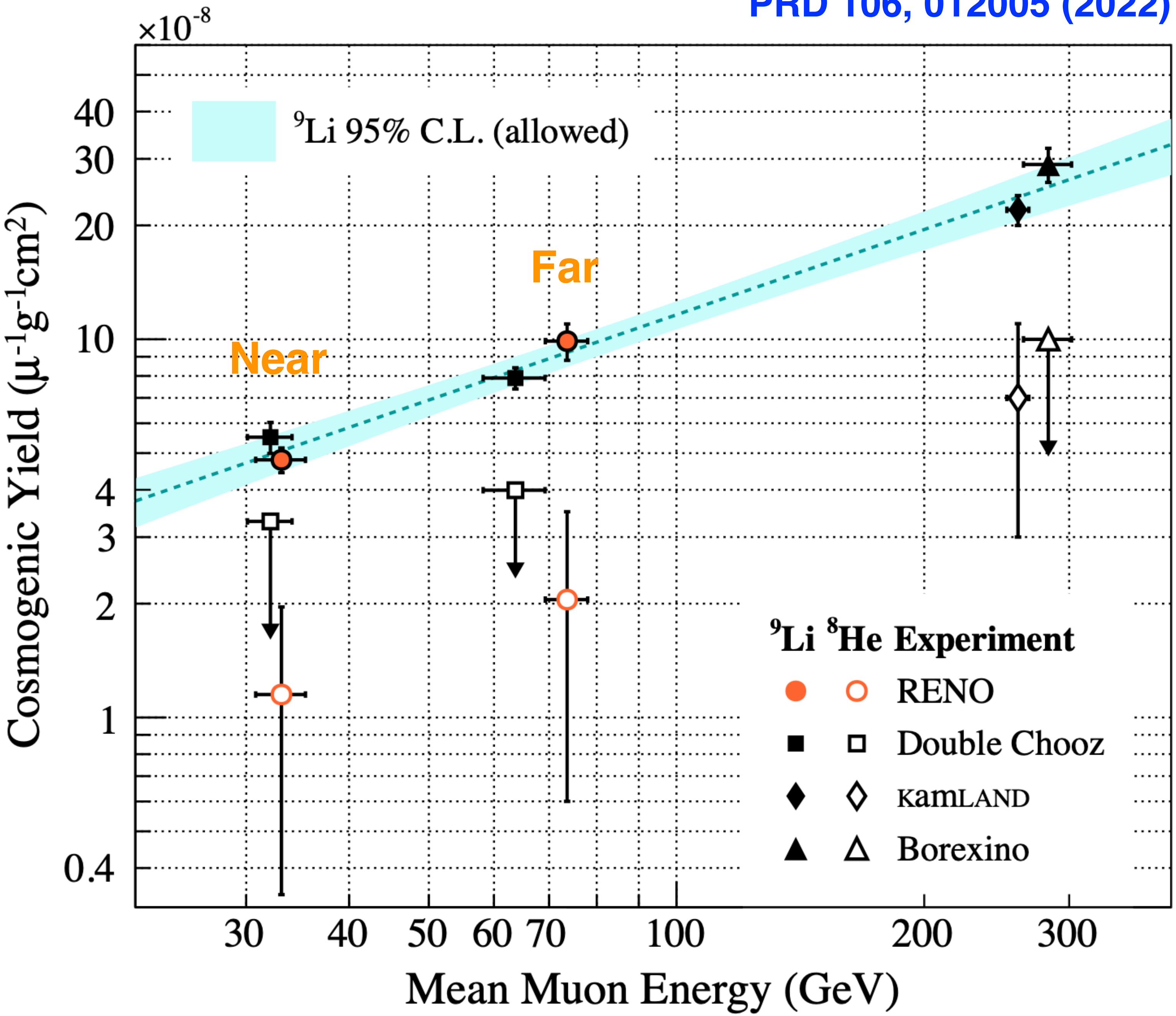




		ND	FD
$R_{\beta-n}$(/day)	…	11.92 ± 0.45	3.04 ± 0.28
R_μ (/ sec)	…	61.84 ± 0.71	6.94 ± 0.08
$\bar{L}_\mu$ (cm)	…	201.1 ± 3.9	197.4 ± 3.9
ρ (g/cm^3)	…	0.856 ± 0.001	
ϵ (%)	^{9}Li	49.6 ± 1.5	56.2 ± 1.6
	^{8}He	46.8 ± 1.5	53.0 ± 1.7
f (%)	^{9}Li	93.3 ± 4.6	94.2 ± 4.1
	^{8}He	6.7 ± 4.6	5.8 ± 4.1
$Br_{\beta-n}$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

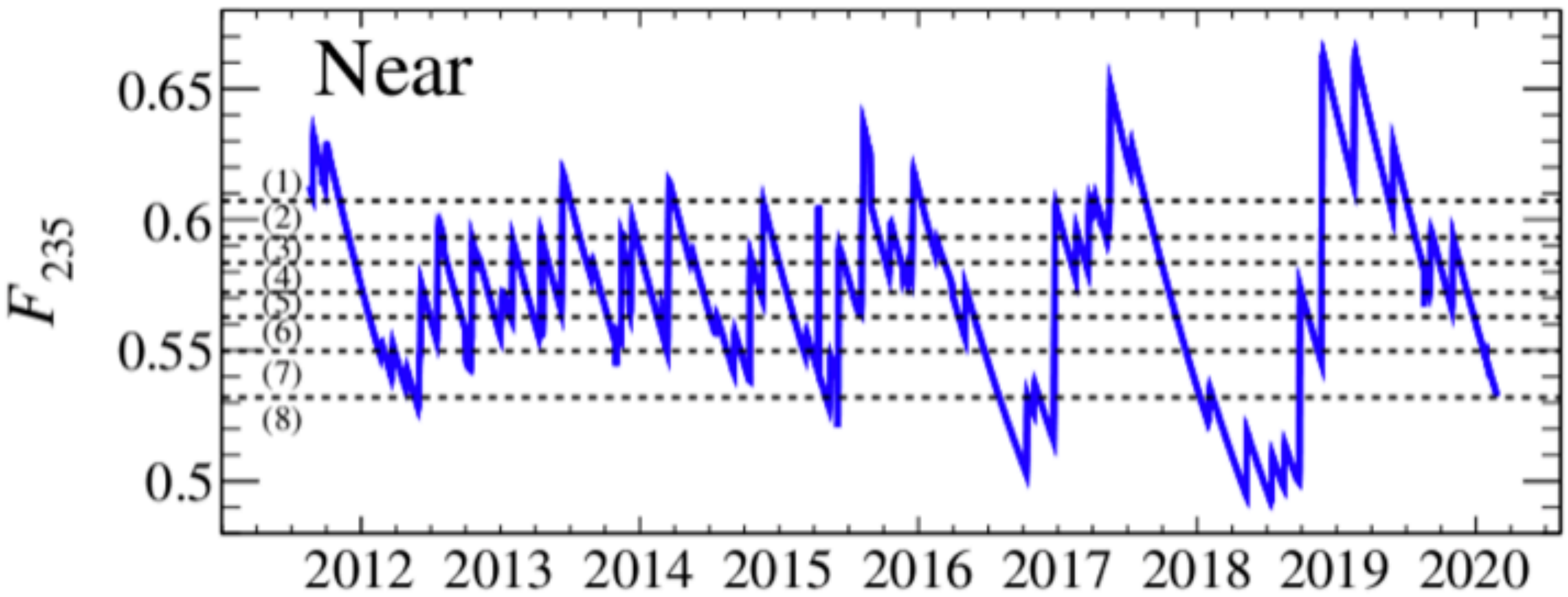
Yields of Cosmogenic ^9Li and ^8He

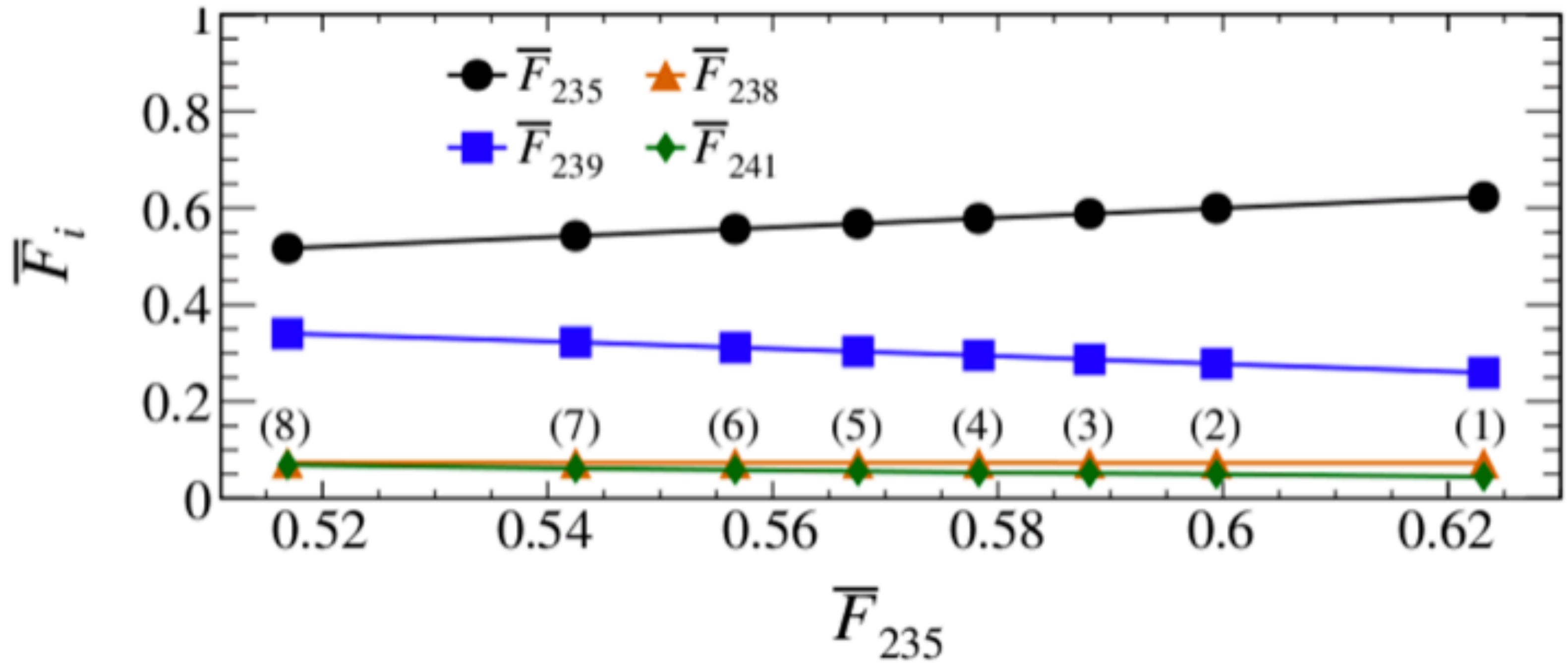
PRD 106, 012005 (2022)



RENO Fuel Fraction in the Reactor Core

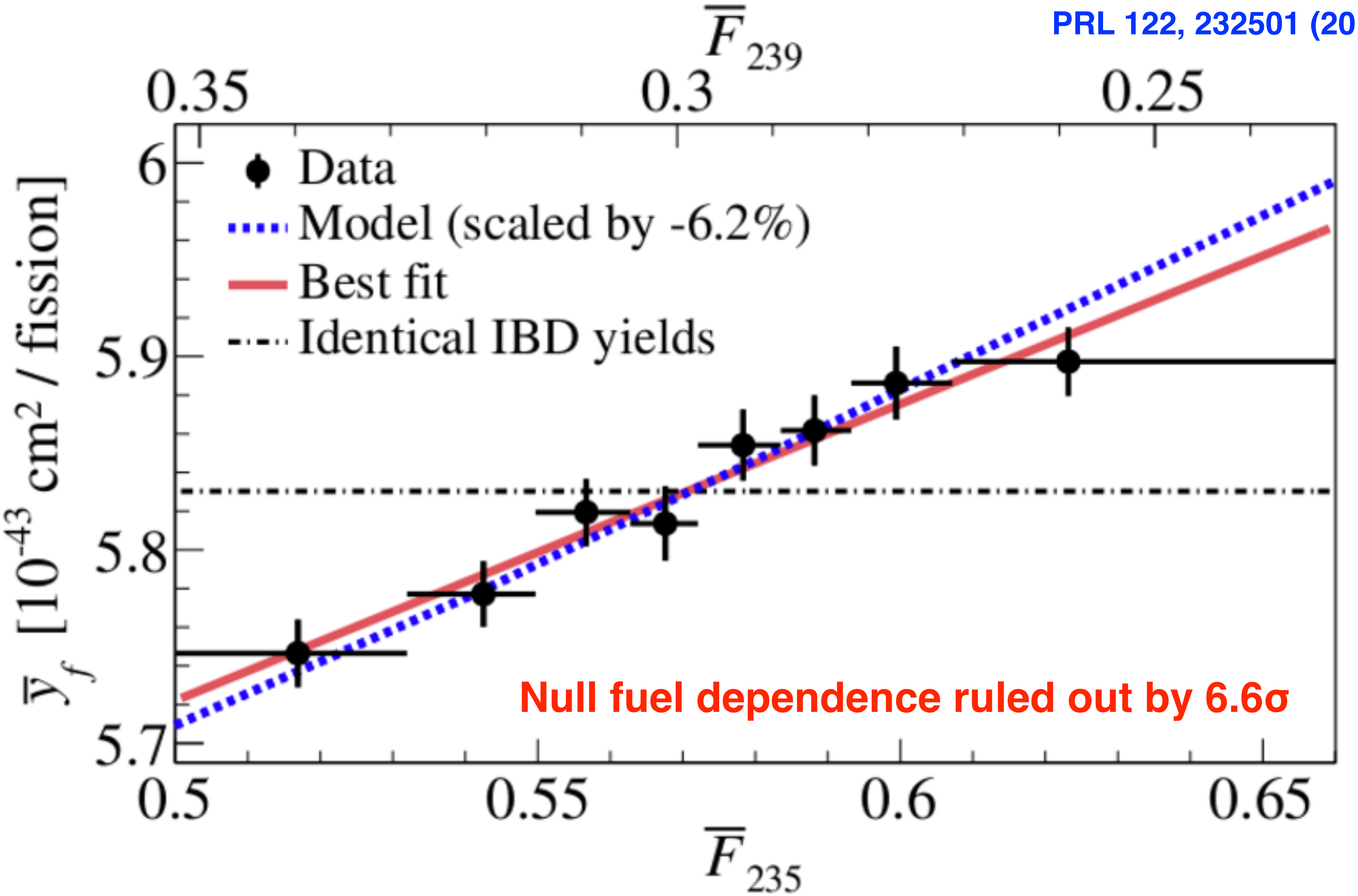
Average fission fraction: f_235: f_239: f_238: f_241= 0.573 : 0.299 : 0.073 : 0.055





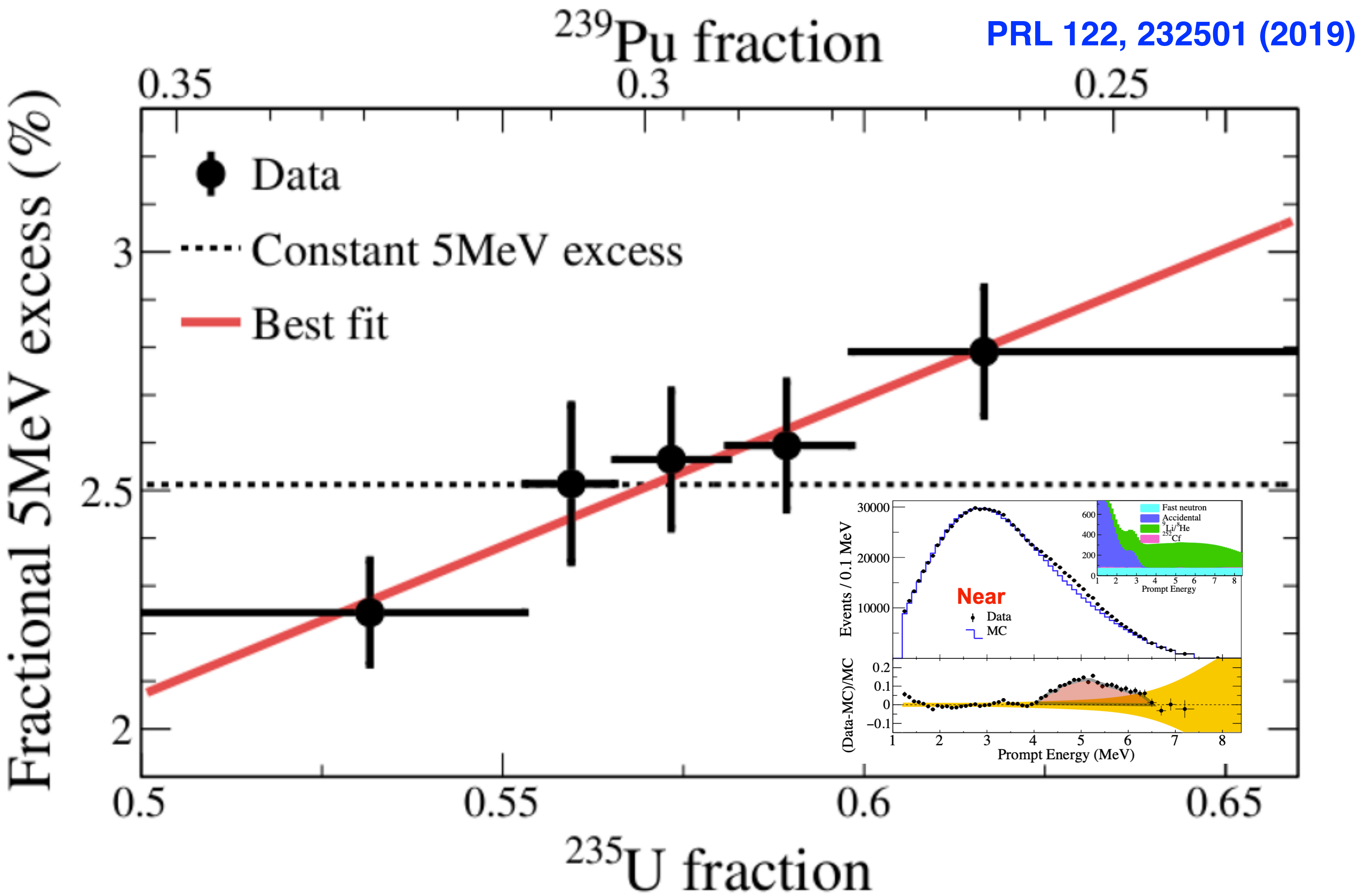
Fuel Dependence of IBD Yield

PRL 122, 232501 (2019)



Fuel dependence study of IBD spectrum is underway

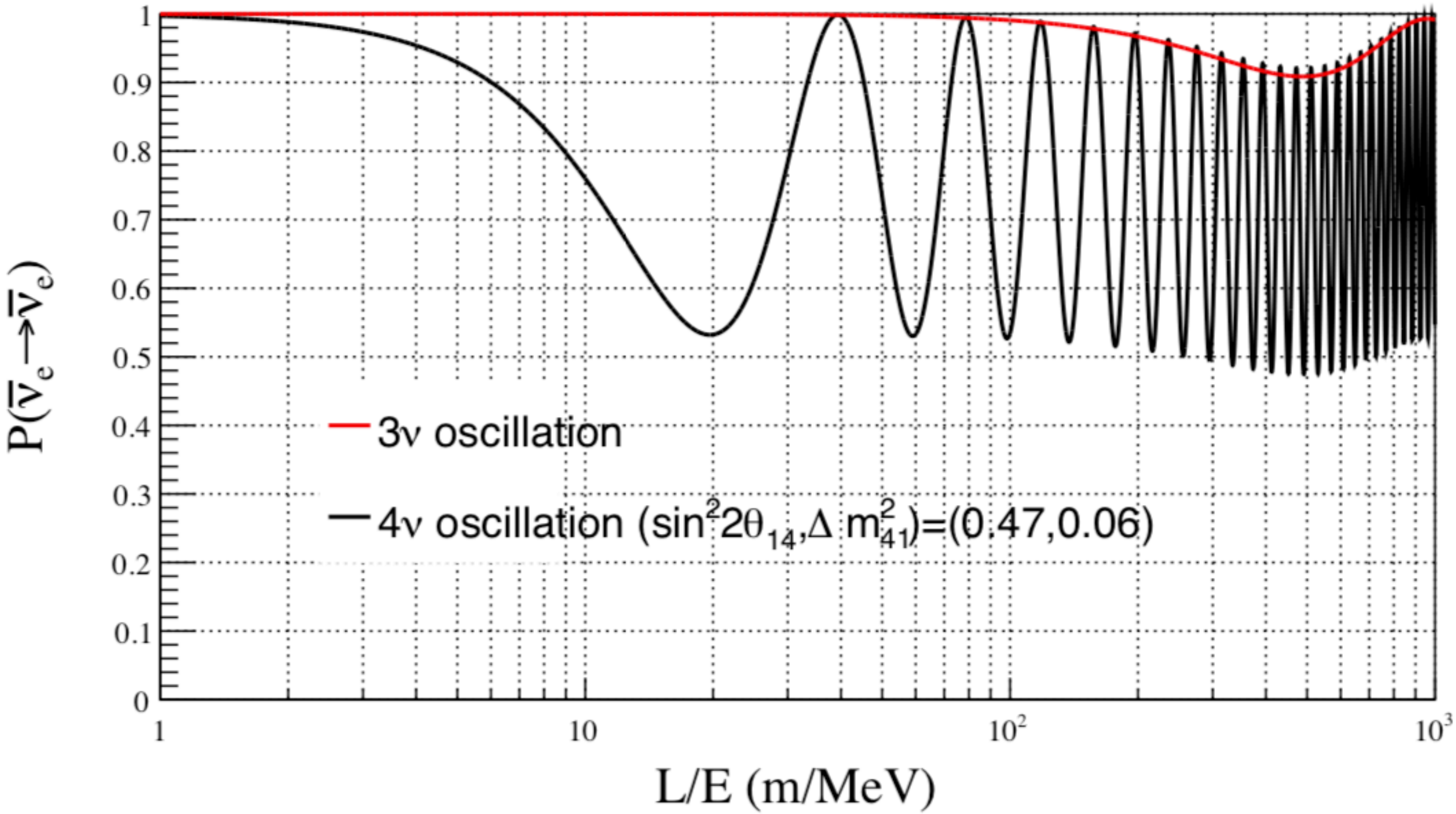
Fuel Dependence of the 5 MeV Excess



Null fuel dependence is disfavored by 2.9σ

(3 active +1 sterile) Neutrino Model

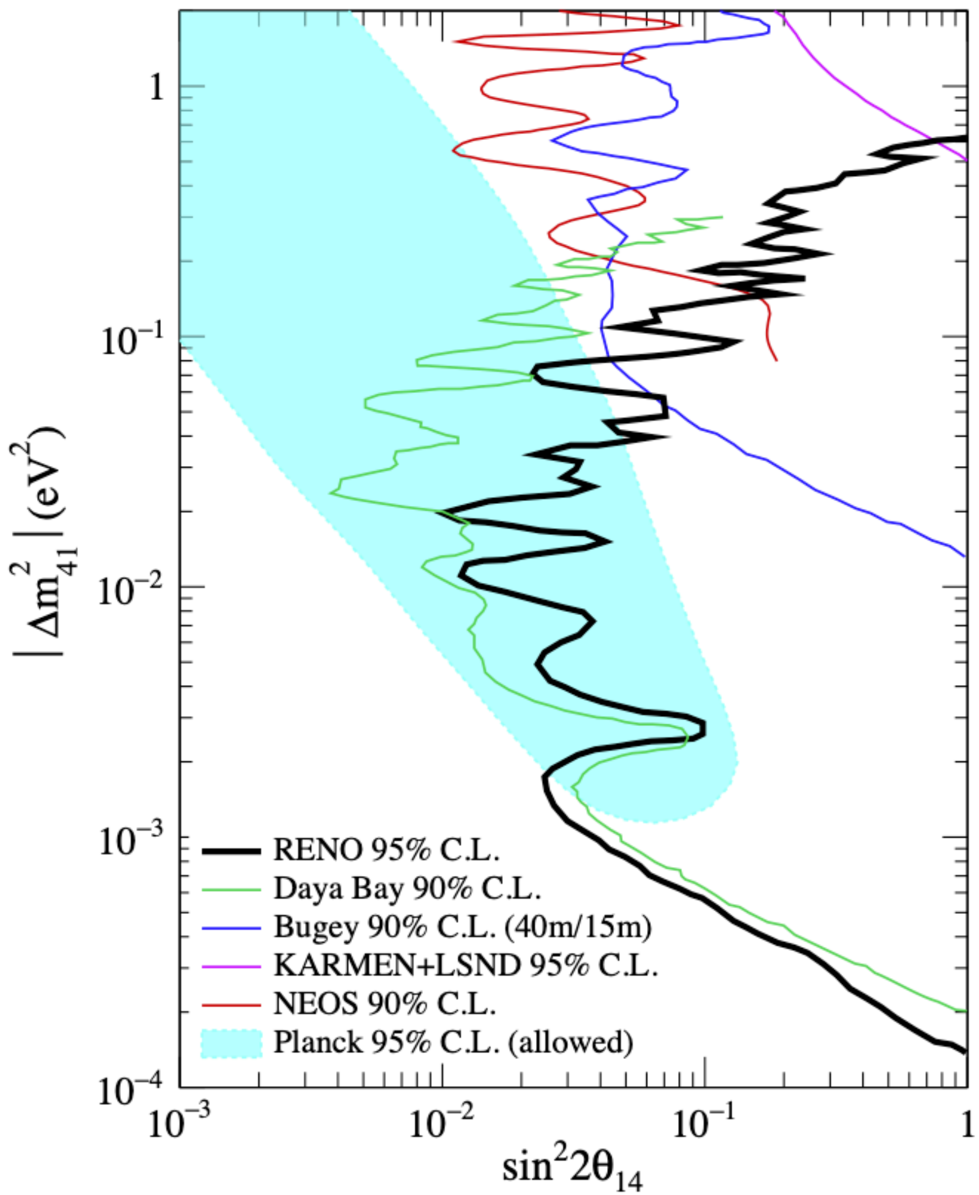
$$P(\overline{\nu}_e \to \overline{\nu}_e) \simeq 1 - \sin^2 2\theta_{13} \sin^2 \left(1.27\Delta m^2_{31} \frac{L}{E_\nu}\right) - \sin^2 2\theta_{14} \sin^2 \left(1.27\Delta m^2_{41} \frac{L}{E_\nu}\right)$$



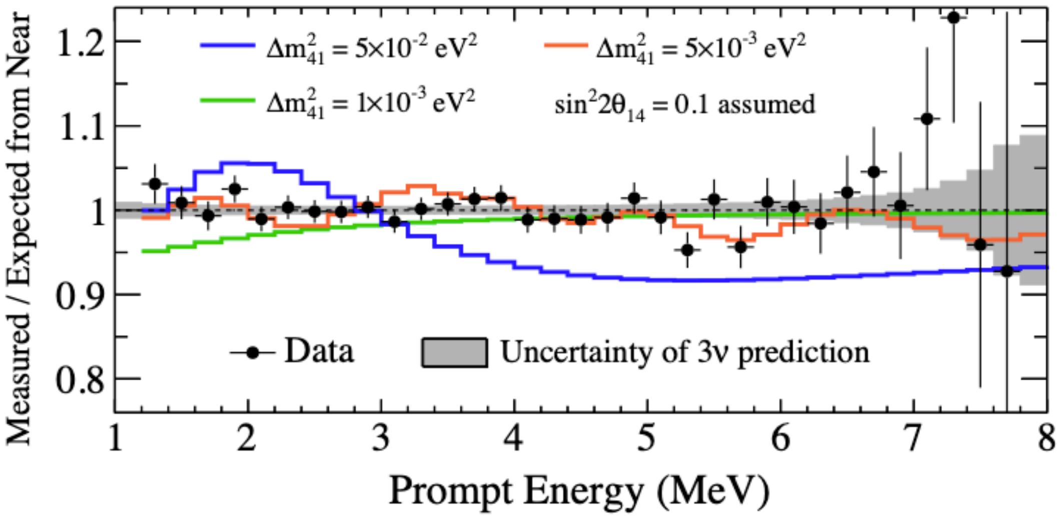
Search Sterile Neutrinos (RENO Near/Far) : Sub-eV Scale

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

Phys. Rev. Lett. 125, 191801 (2020)

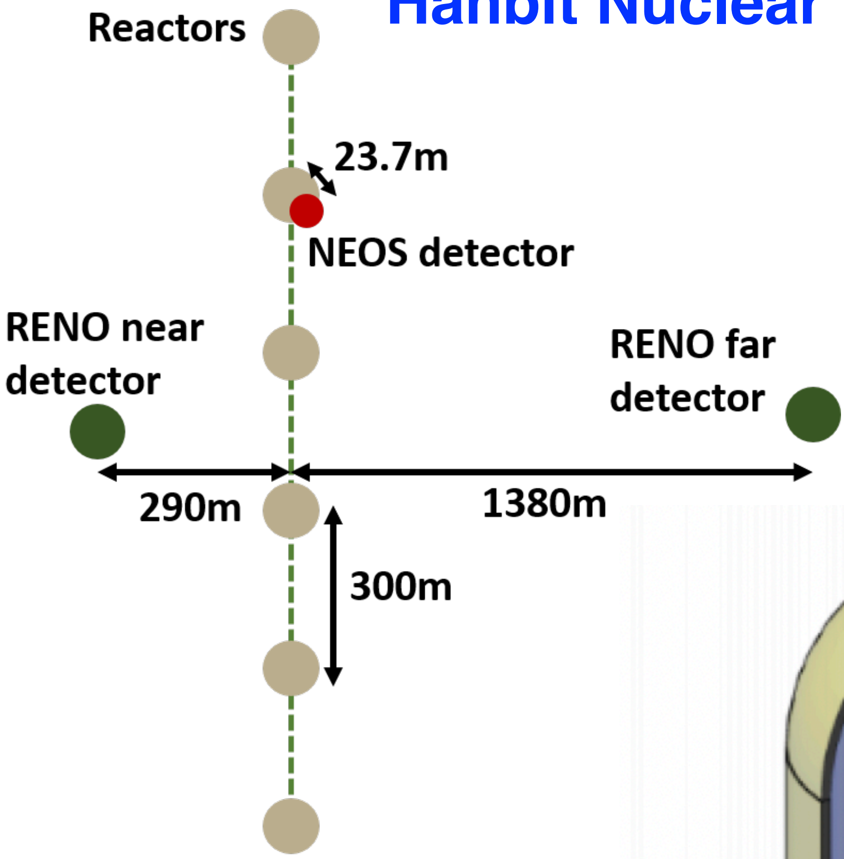


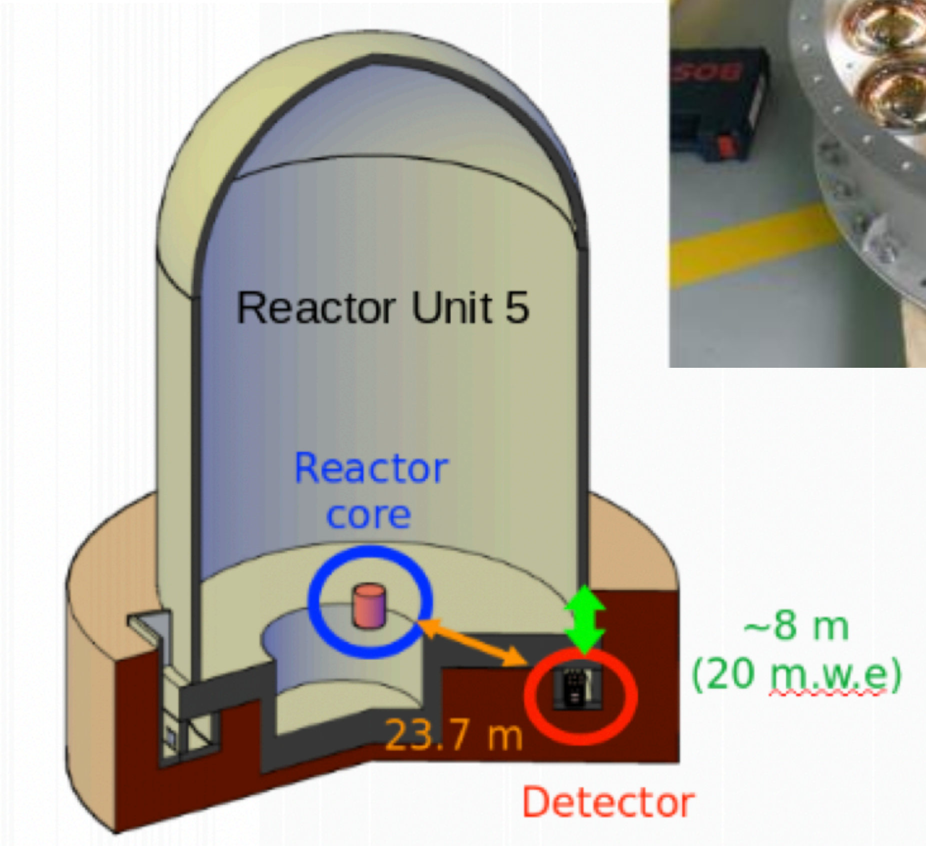
RENO Far to Near spectral ratio

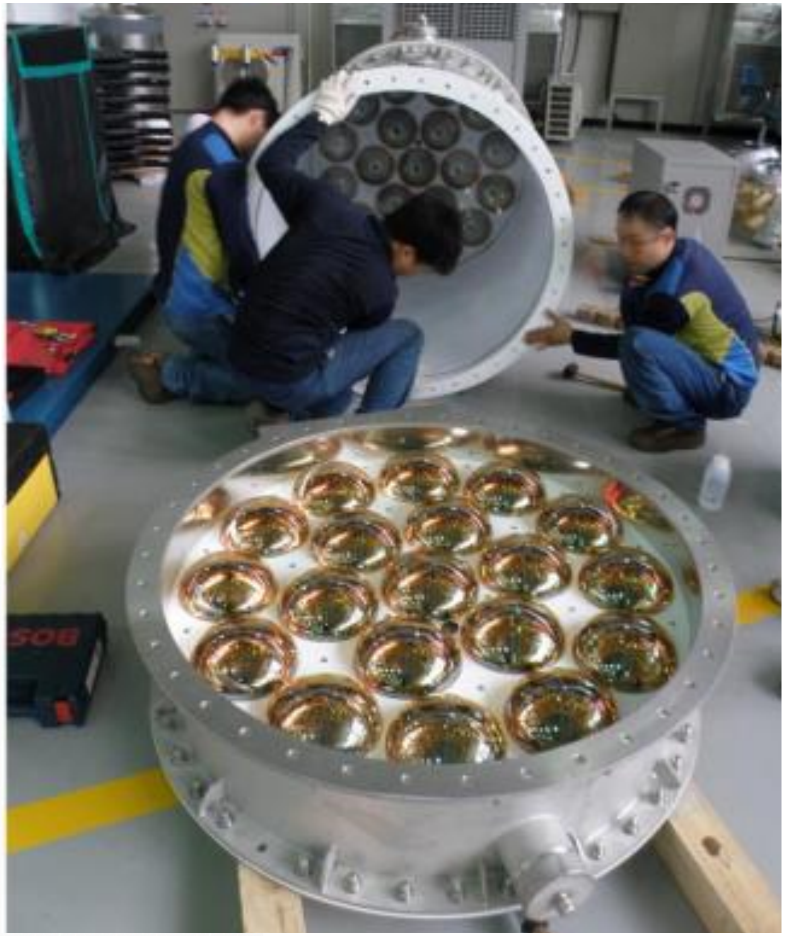


Sterile Neutrino Search (RENO + NEOS) : ~eV Scale

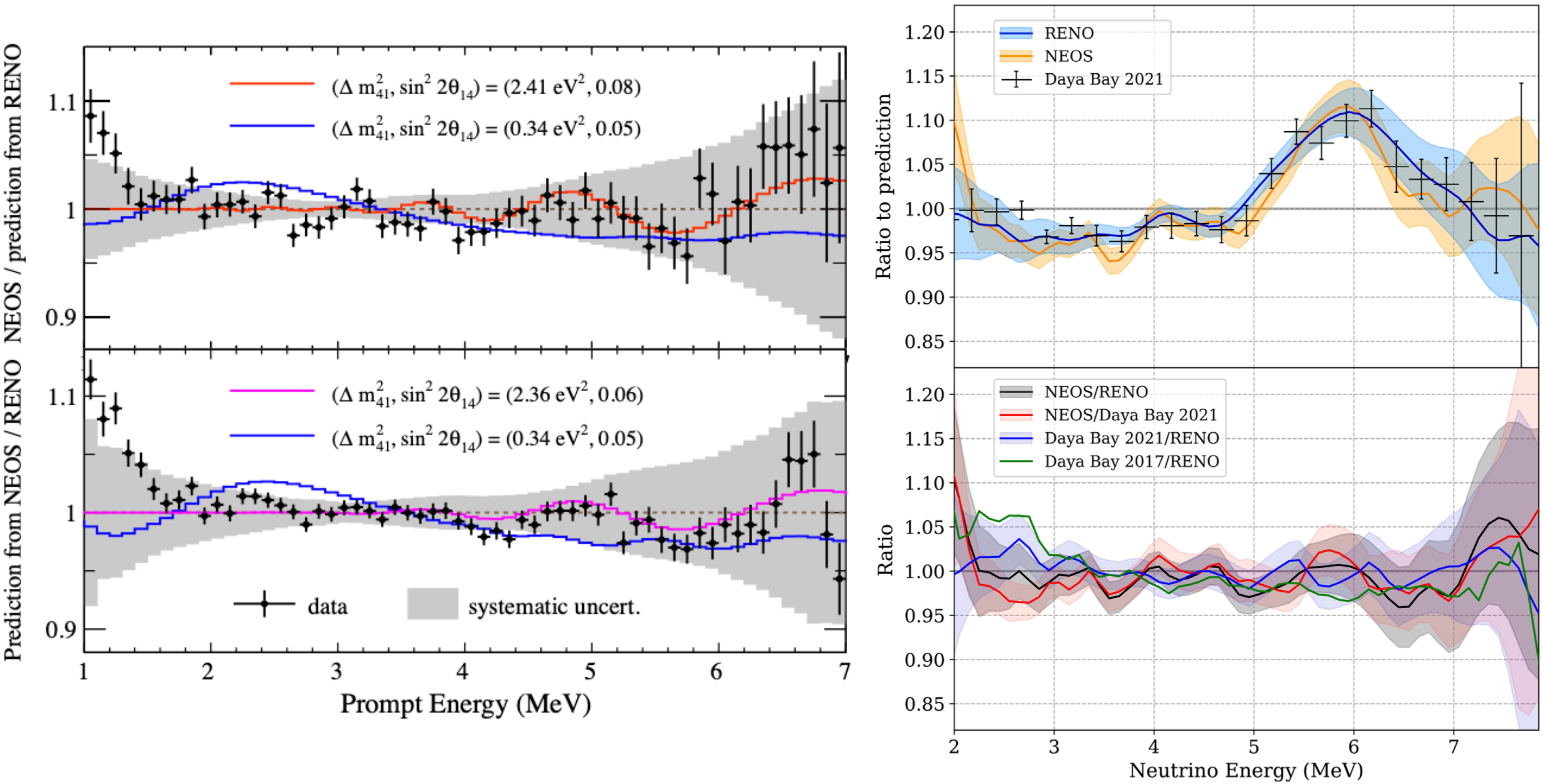
Hanbit Nuclear Power Plant







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

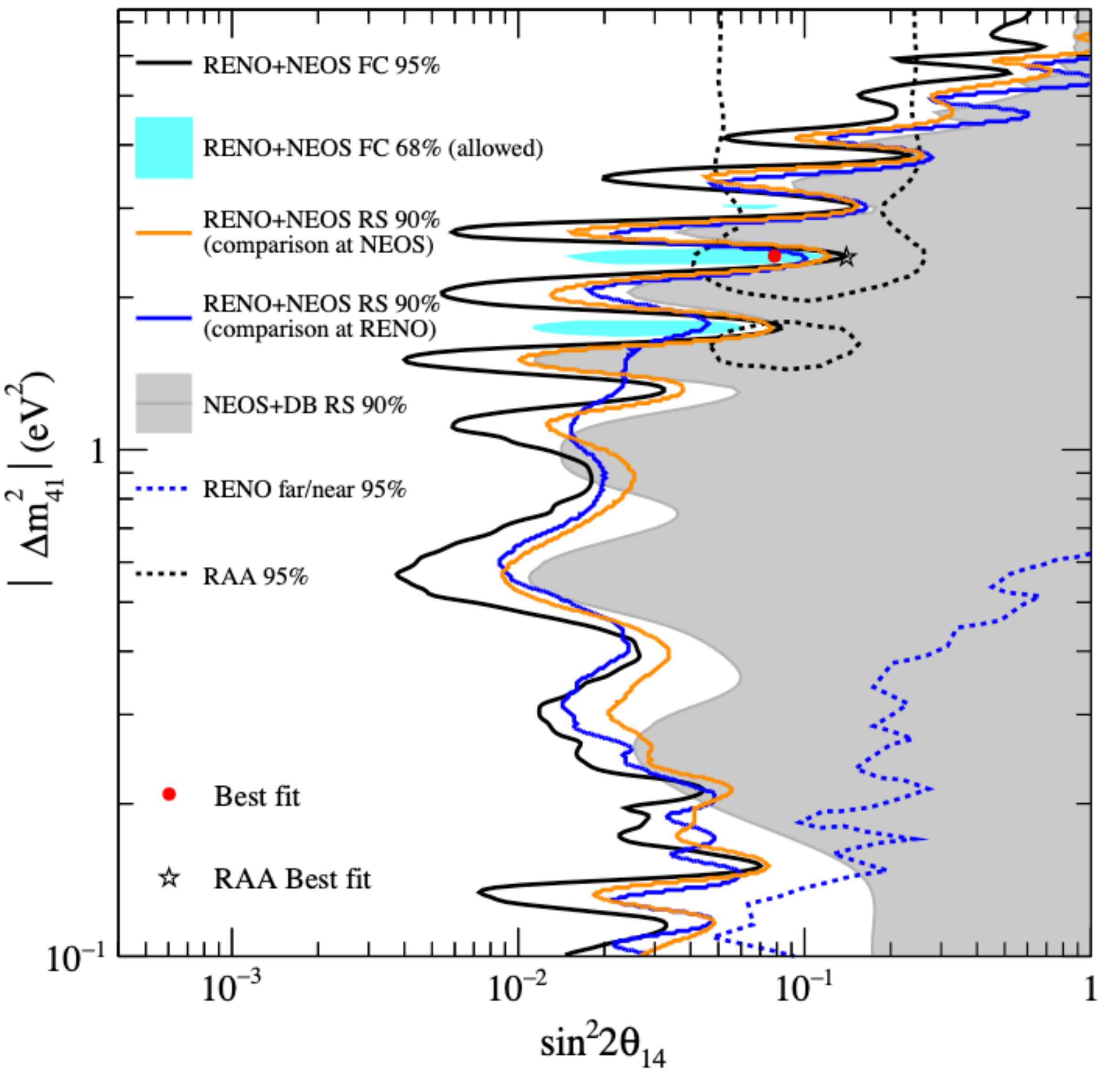


Data release of prompt and neutrino spectrum (with error matrices)

PRD 104, L111301 (2021) RENO
PRD 105, L111101 (2022) RENO+NEOS

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

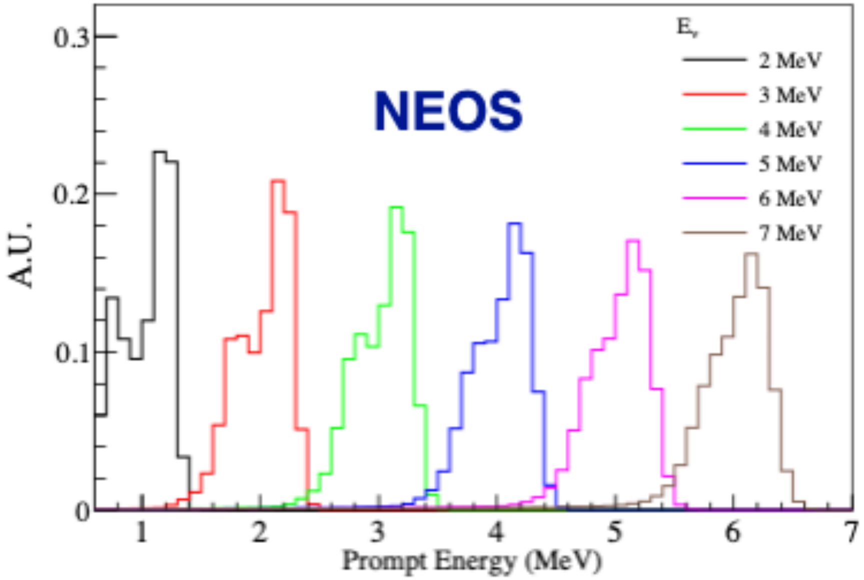
PRD 105, L111101 (2022)

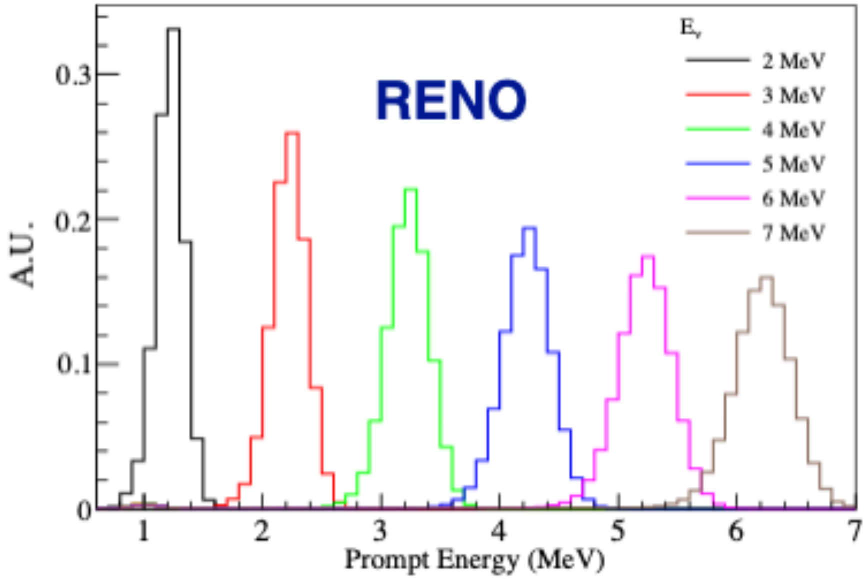


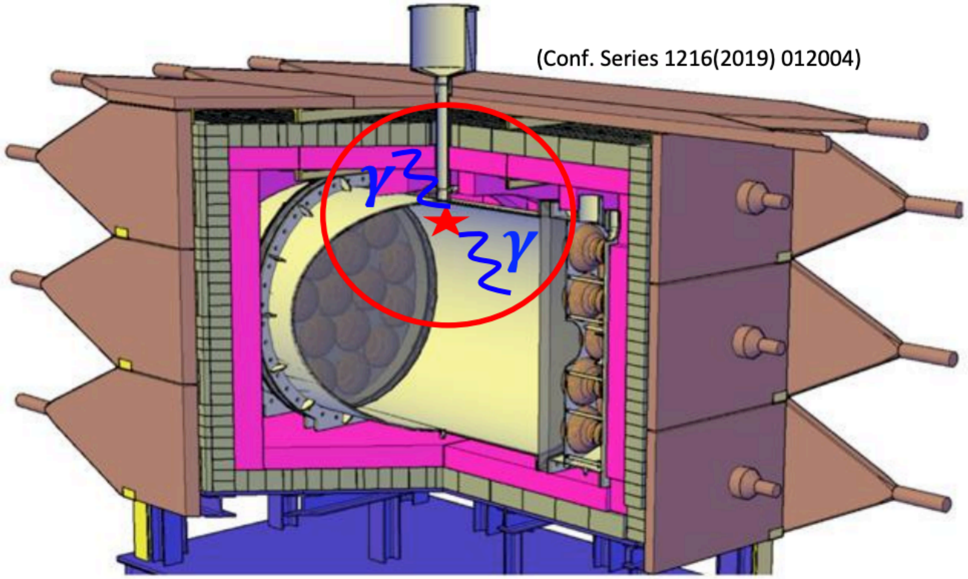
RENO+NEOS best fit at (0.08, 2.4 eV²)

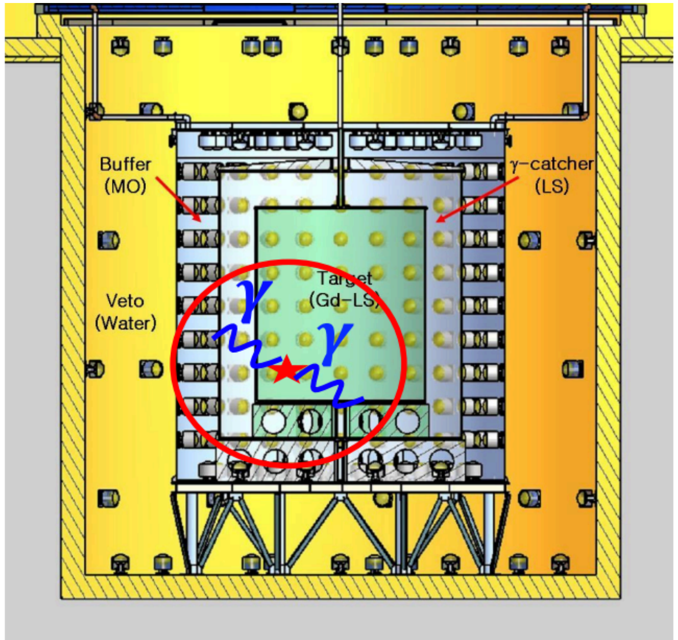
4ν min χ^2/DOF = 47.45/58 (3ν χ^2/DOF = 56.24/60) $\Delta\chi^2$ = 8.8, p=8.5%

Detector Response



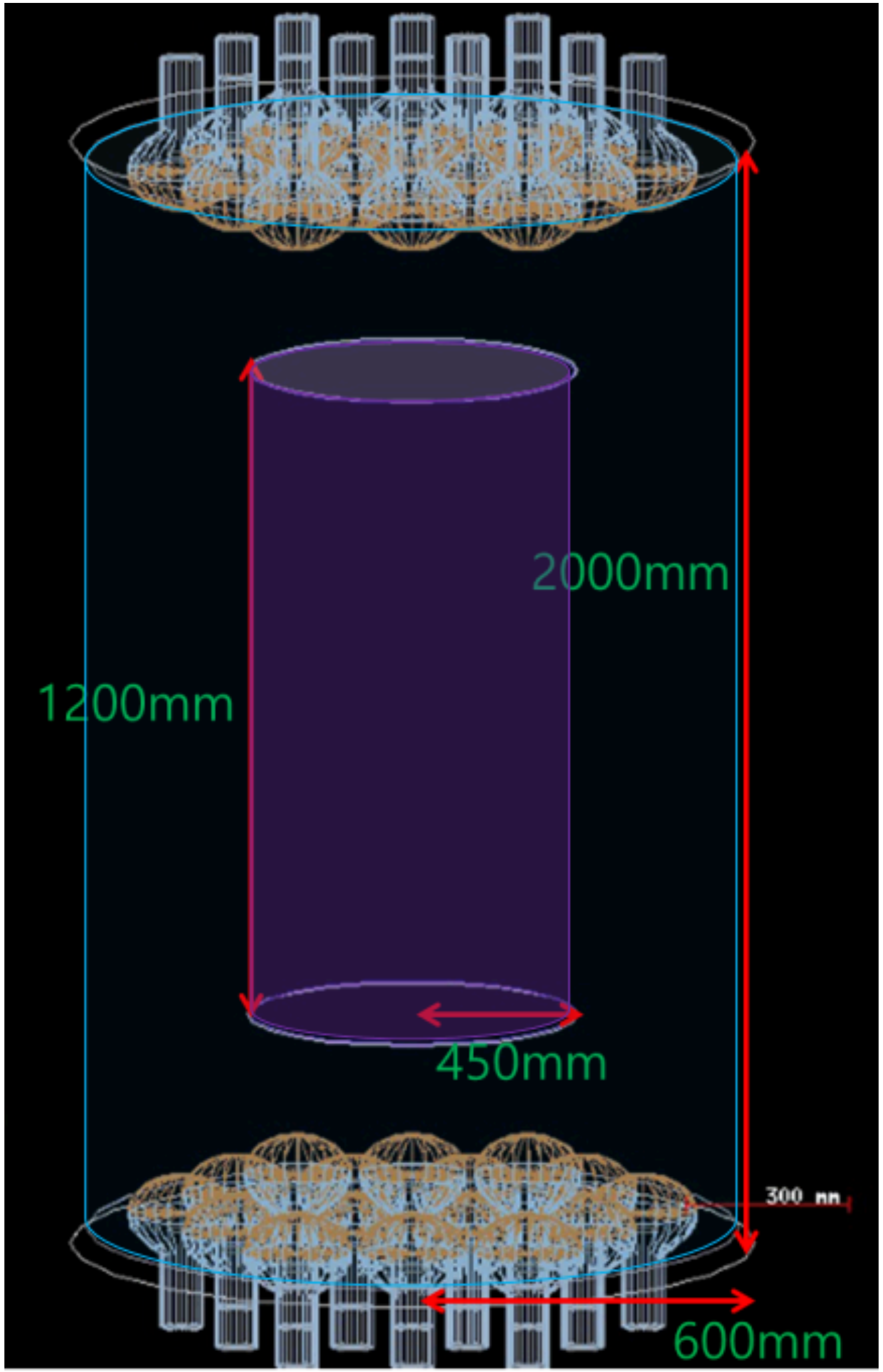


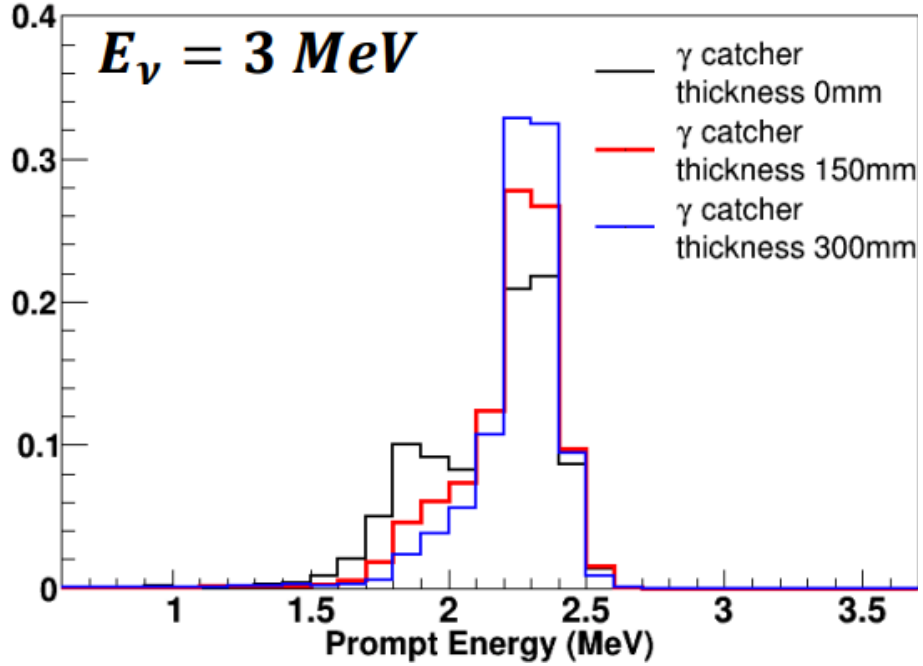


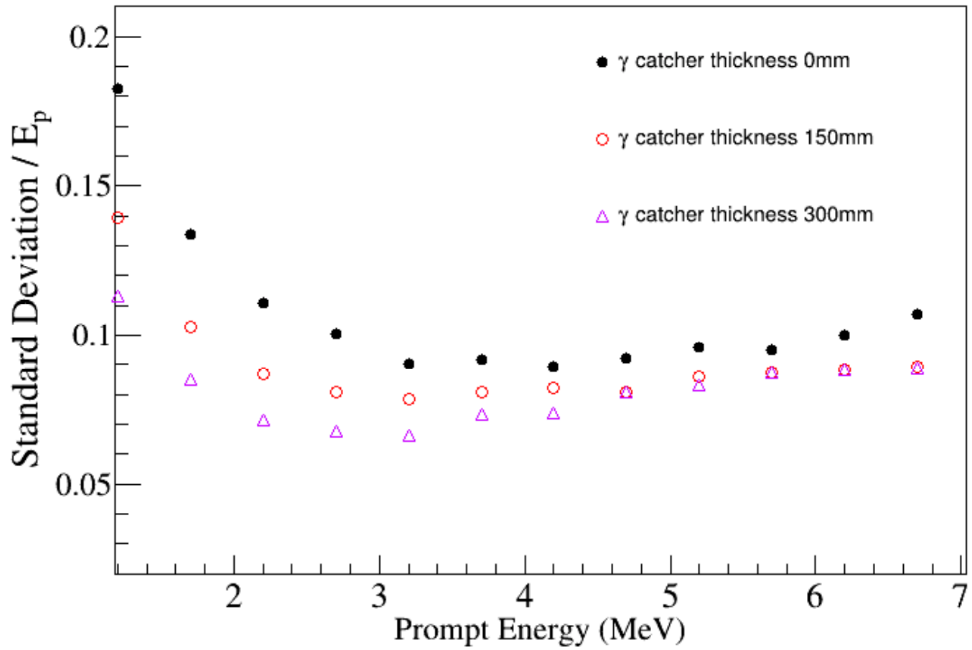


NEOS detector does **not** have a **gamma catcher** (limited space at the tendon gallery)

Reactor Experiment for Neutrinos and Exotics (RENE Phase-1)

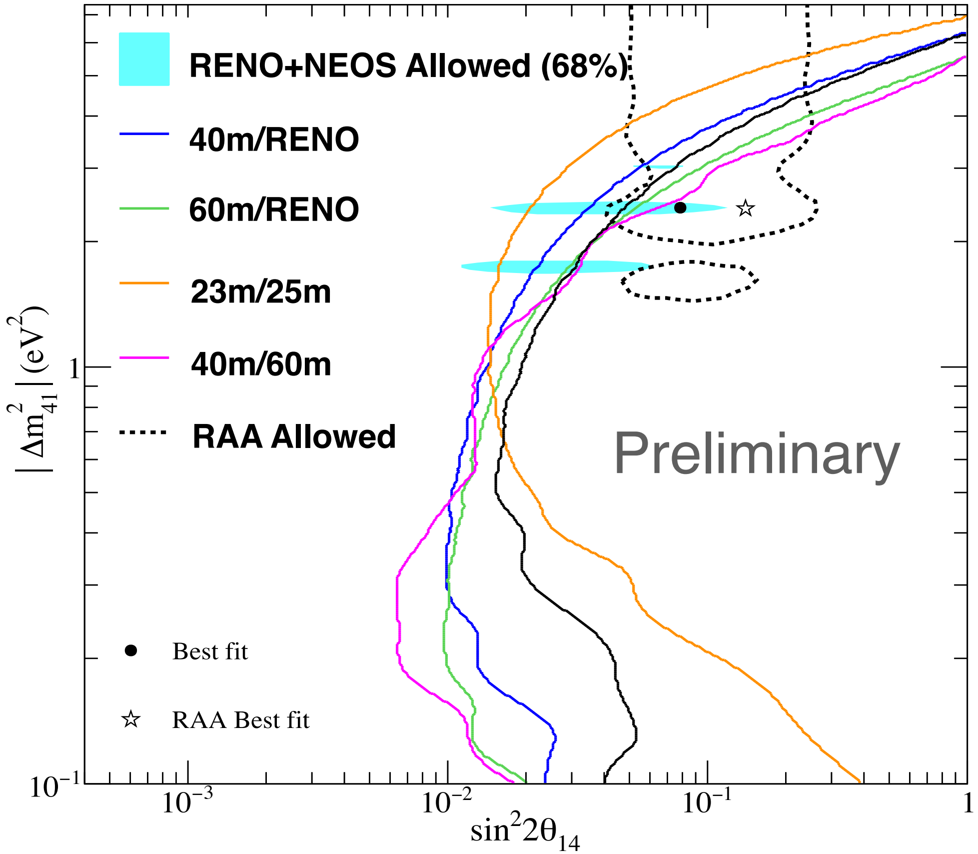


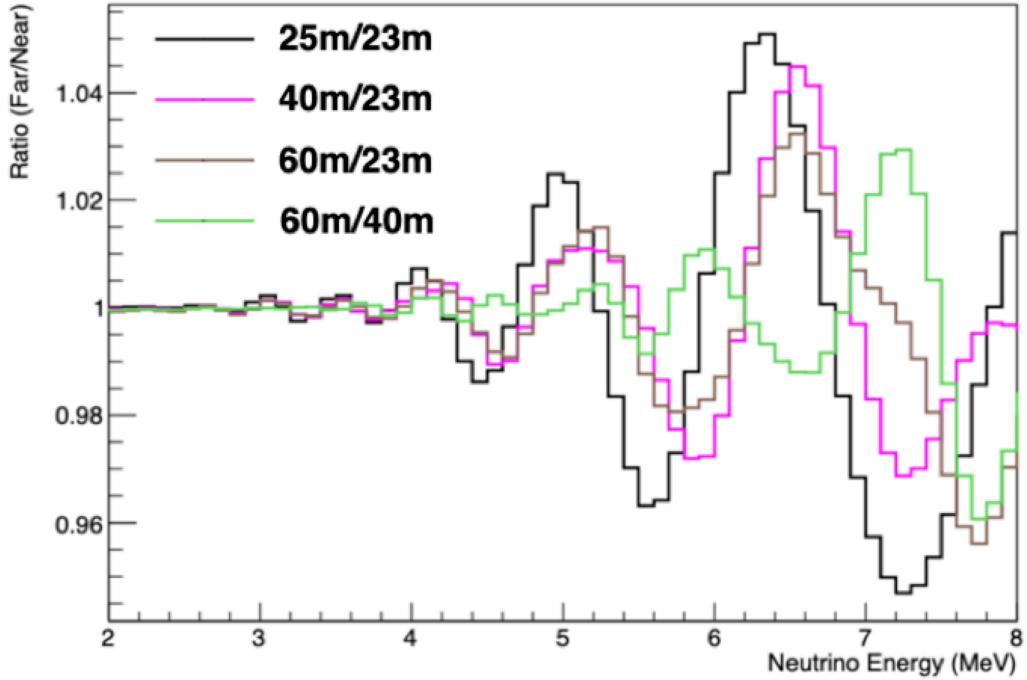


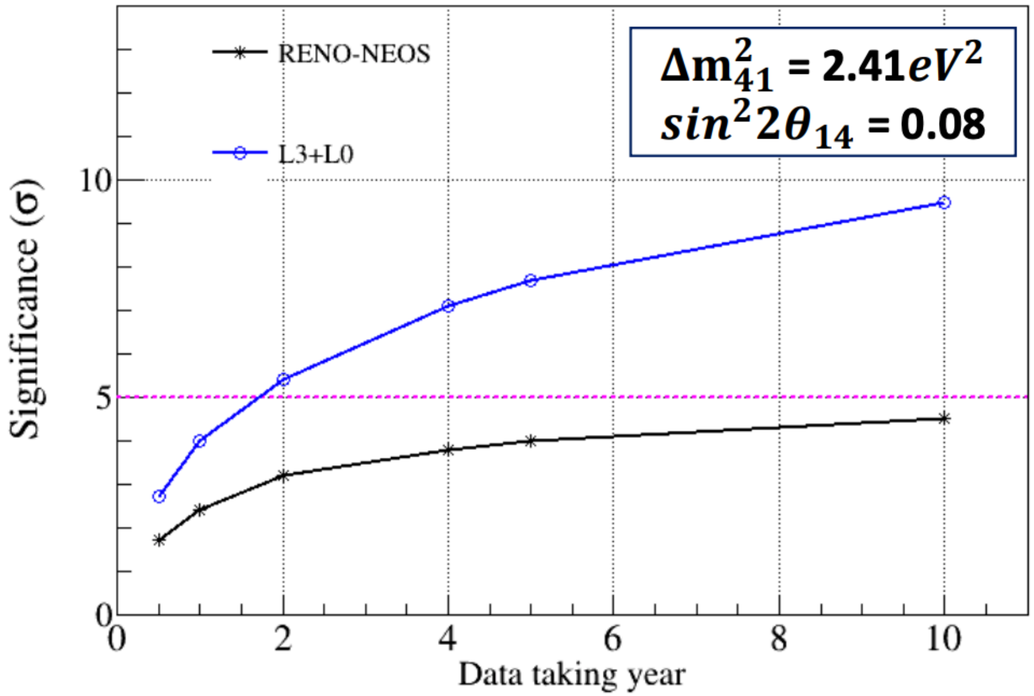


RENE Phase-1: Expected Sensitivity

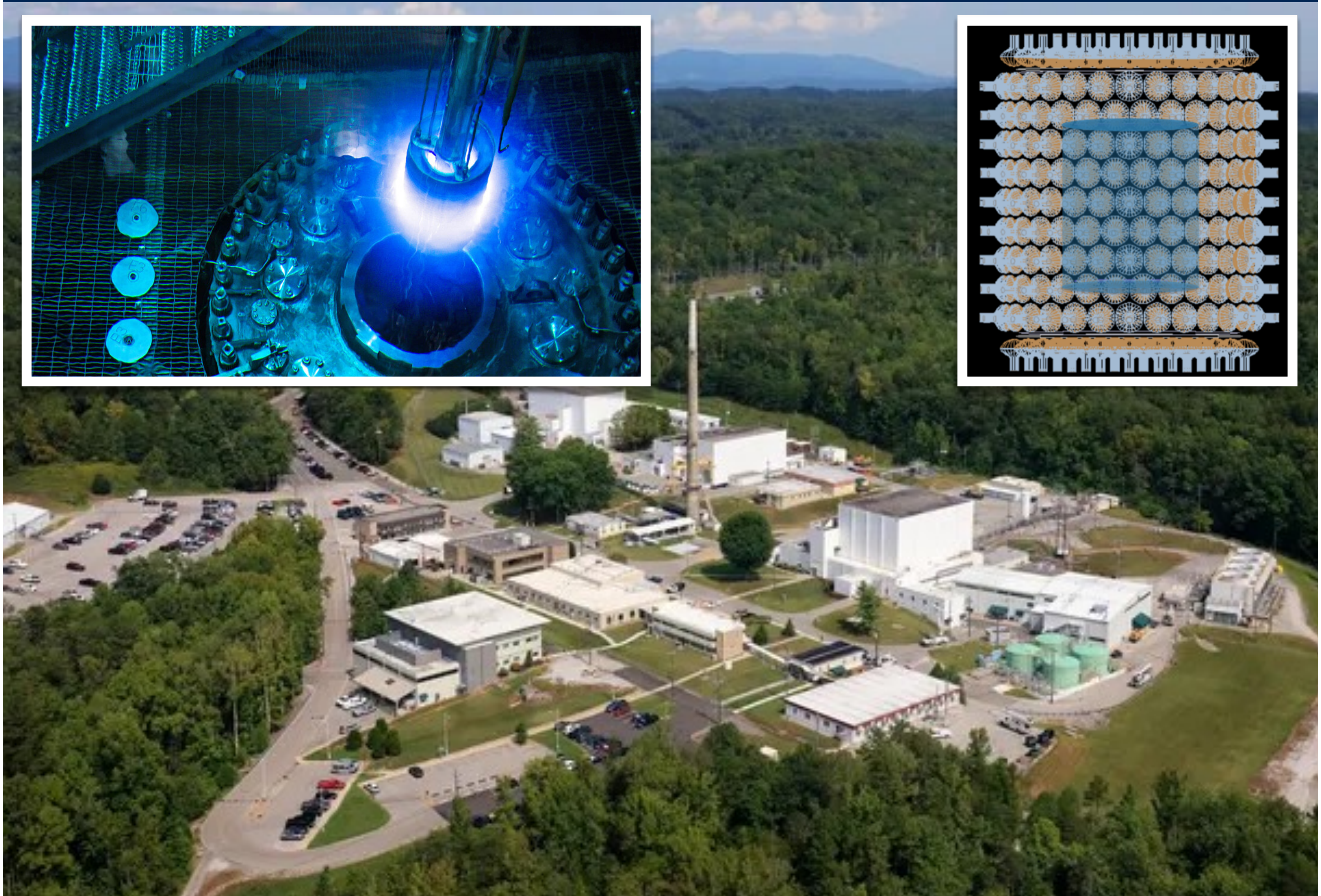
- RENE Collaboration is formed (Nov. 2022)
  - About 30 members ~10 institutions
- Detector design is progressing
  - A uniform unsegmented detector concept with improved energy resolution
  - Mobile or multiple detectors
  - Anticipate data taking in 2023~







RENE Phase-2: Precision Measurement (Provisonal)



Summary

- Report **RENO 2900 days data**
- Precision measurement of θ_{13} and $|\Delta m_{ee}^2|$
- Absolute reactor neutrino flux: **R = 94.1 % ± 1.9 % (of HM)**
- Correlation btw 5 MeV excess and ^{235}U fission **(2.9σ C.L.)** **PRL 122, 232501 (2019)**
- The first RENO sterile neutrino search: **PRL 125, 191801 (2020)**
- RENO antineutrino spectrum: **PRD 104, L111301 (2021)**
- Sterile neutrino search (RENO + NEOS): **PRD 105, L111101 (2022)**
- Cosmogenic ^{9}Li and ^{8}He rate at RENO: **PRD 105, L111101 (2022)**
- RENO nH data analysis (**in preparation**)
- Reactor fuel dependence of neutrino spectrum (**in preparation**)
- **RENE** experiment
  for precision measurements, sterile neutrino search, and exotics search


NuFACT 2023
Seoul, Korea
21~26 Aug. 2023
http://nufact2023.snu.ac.kr

Thank you