RENO

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Seoul National University

2022-12-13

Light Dark World 2022

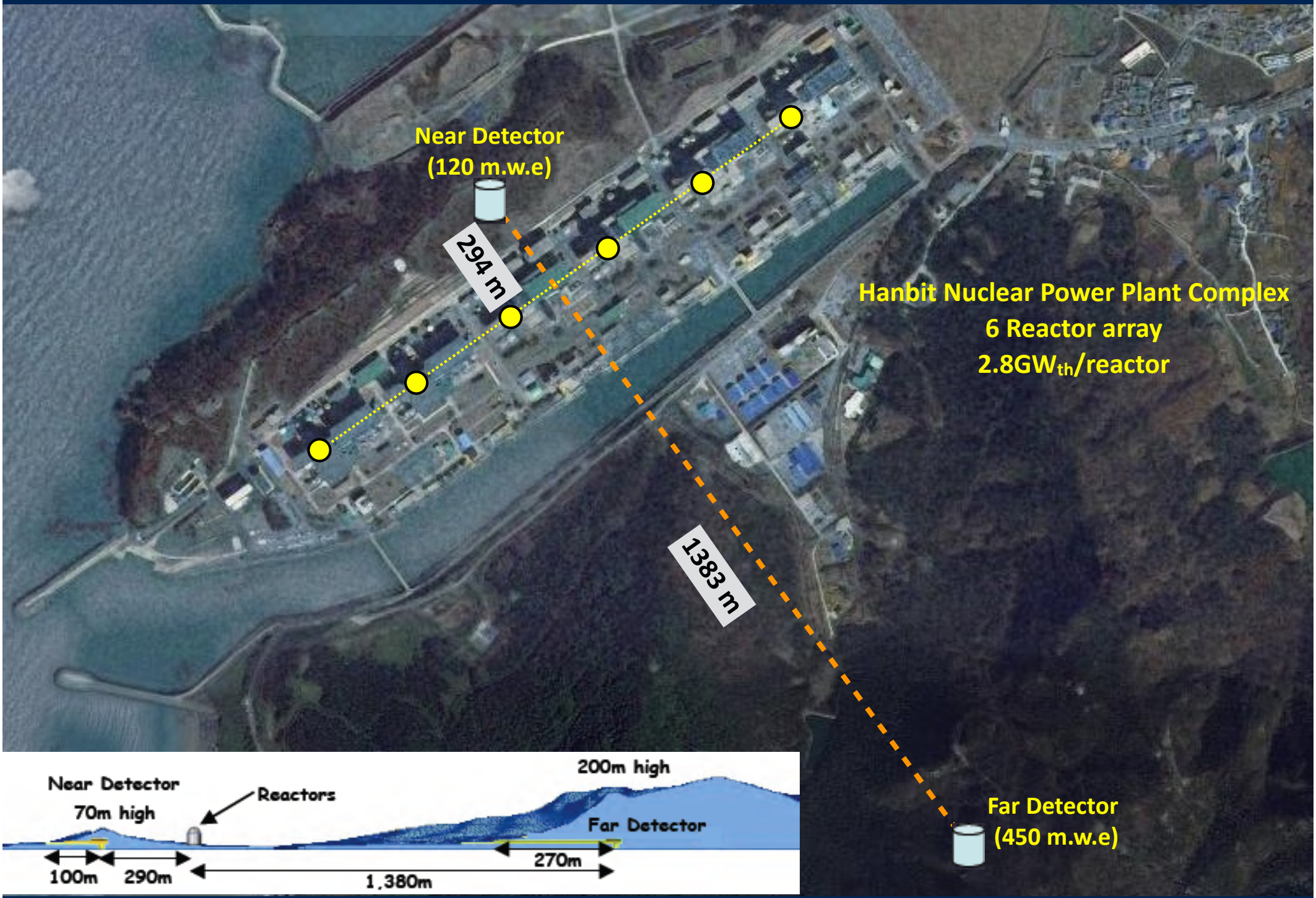
Reactor Experiment for Neutrino Oscillation

9 Institutions and 30 Physicists

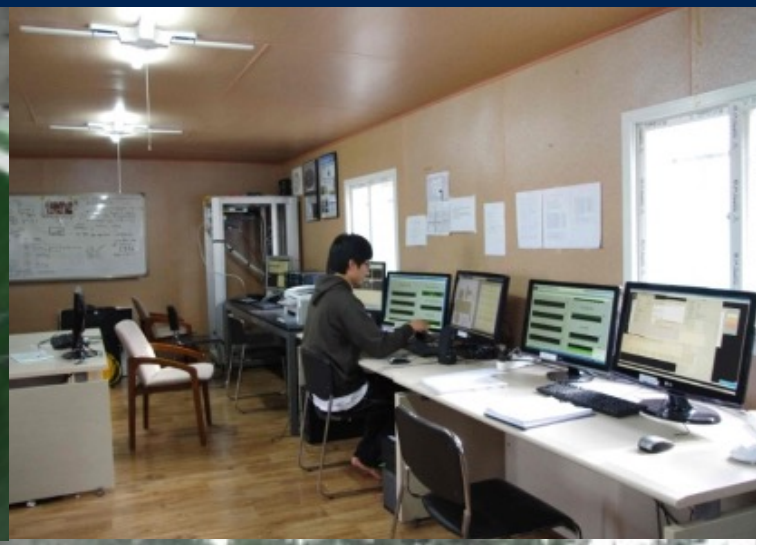
- Chonnam National University
- Dongshin University
- Gwangju Institute of Science and Technology
- Gyeongsang National University
- Korea Advanced Institute of Science and Technology
- Kyungpook National University
- Seoul National University
- Seoyeong University
- Sungkyunkwan University

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

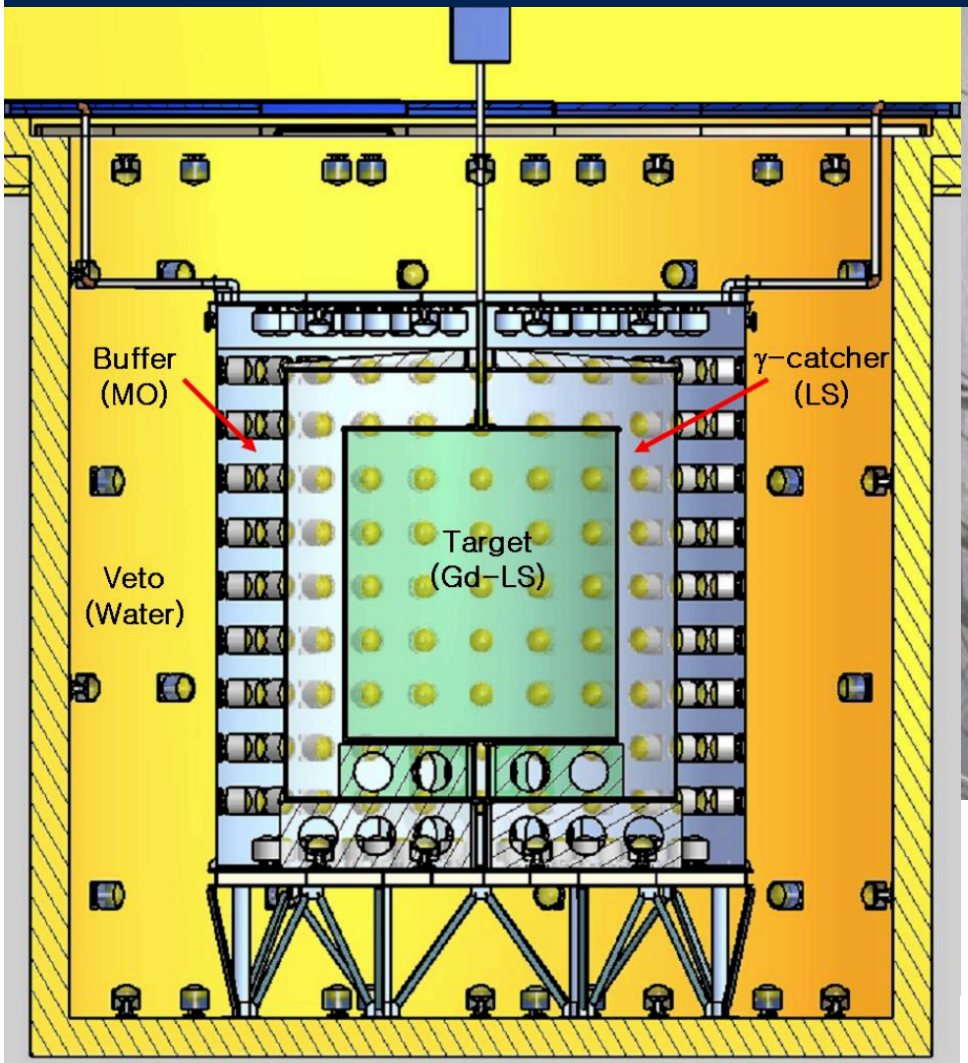
RENO Experimental Setup



RENO Experimental Setup



RENO Detectors

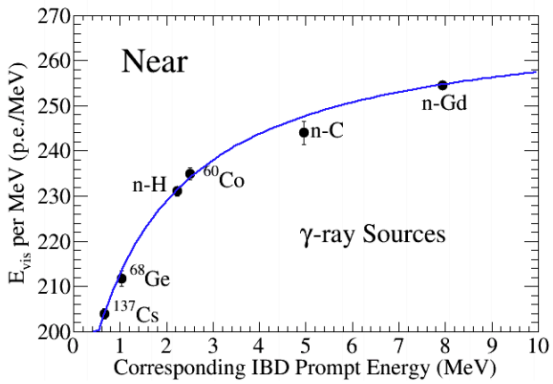


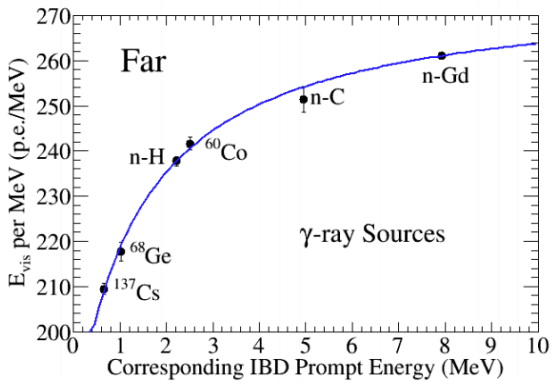
Two identical (near and far) detectors

354 (Buffer) + 67 (Veto) 10” PMTs

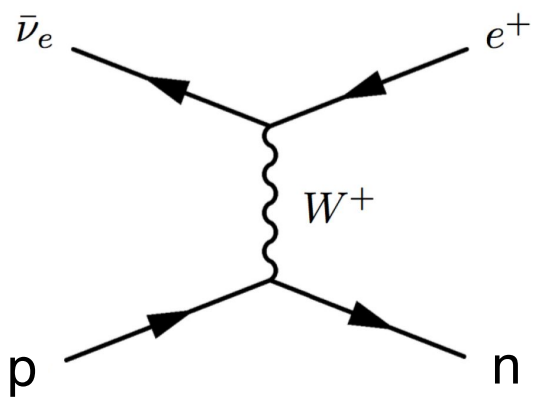
- Target (Gd-loaded LS) 16 tons
- Gamma catcher (LS) 29 tons
- Buffer (Mineral oil) 64 tons
- Veto (Water) 353 tons

Detector Calibration



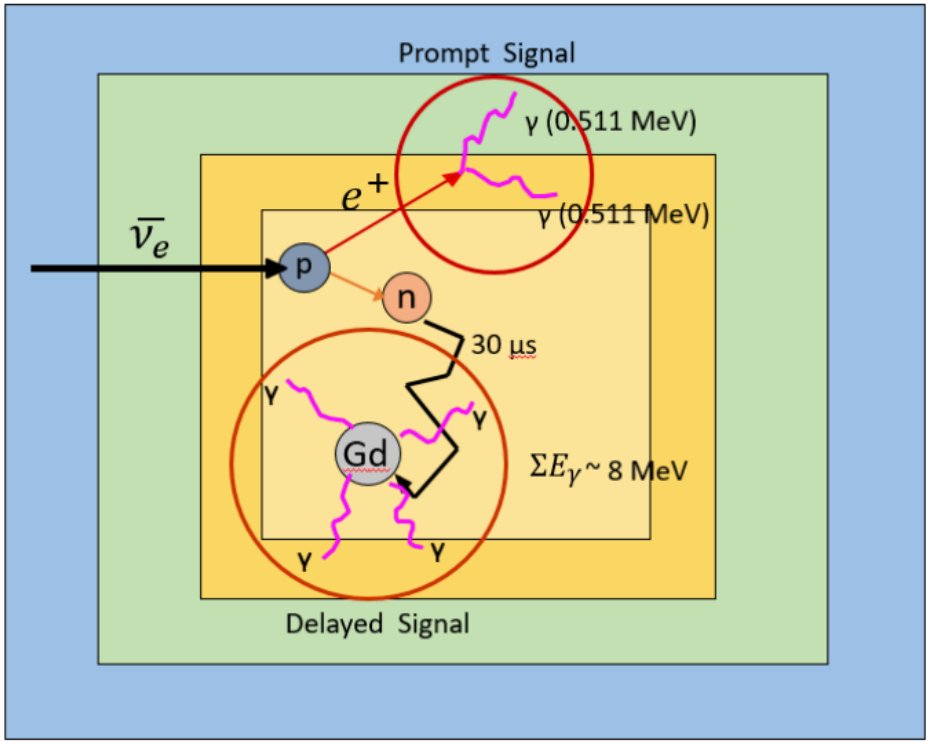


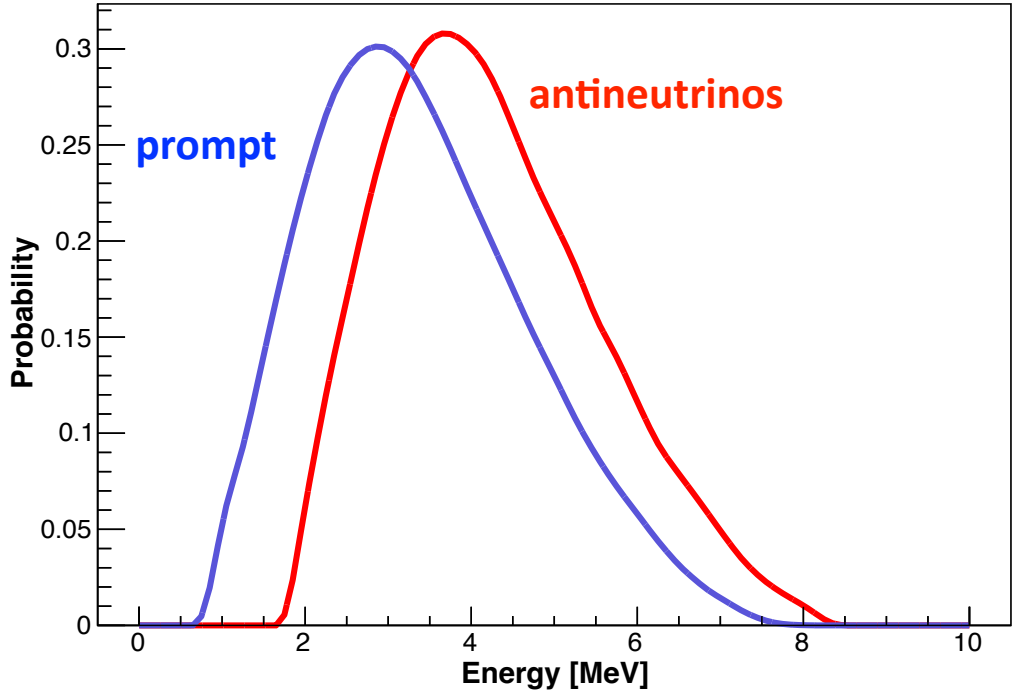
Inverse Beta Decay



$e^+e^- \to 2\gamma$
(prompt)

$\text{n-Gd} \to \gamma\ldots$
(delayed ~30μs)





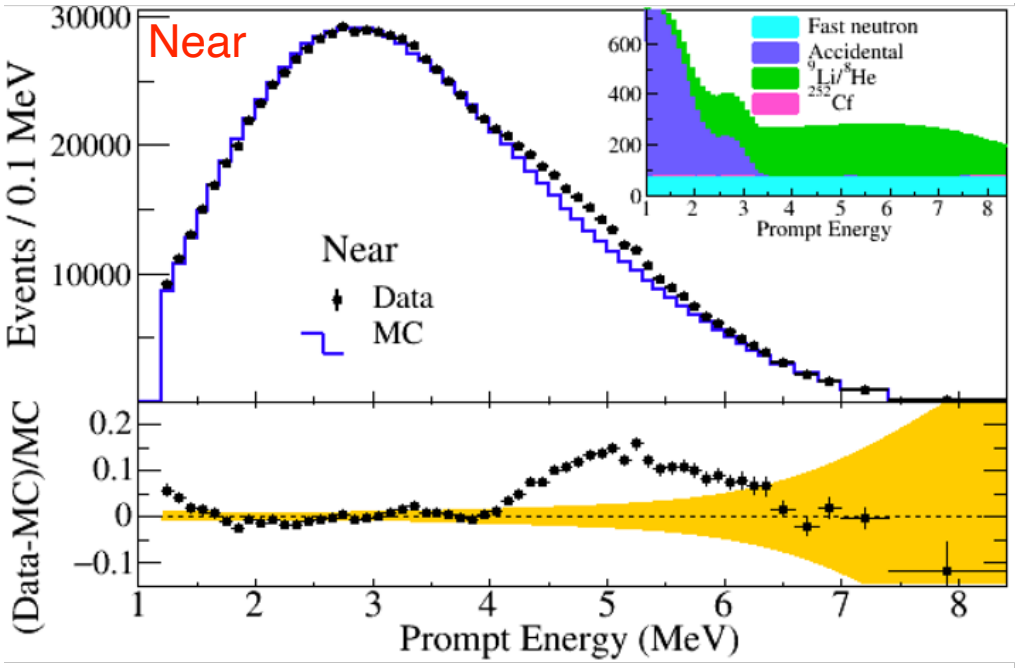
$$E_\nu^{thr} = \frac{(m_n + m_p)^2 - m_p^2}{2m_p} = 1.806\,\text{MeV}$$

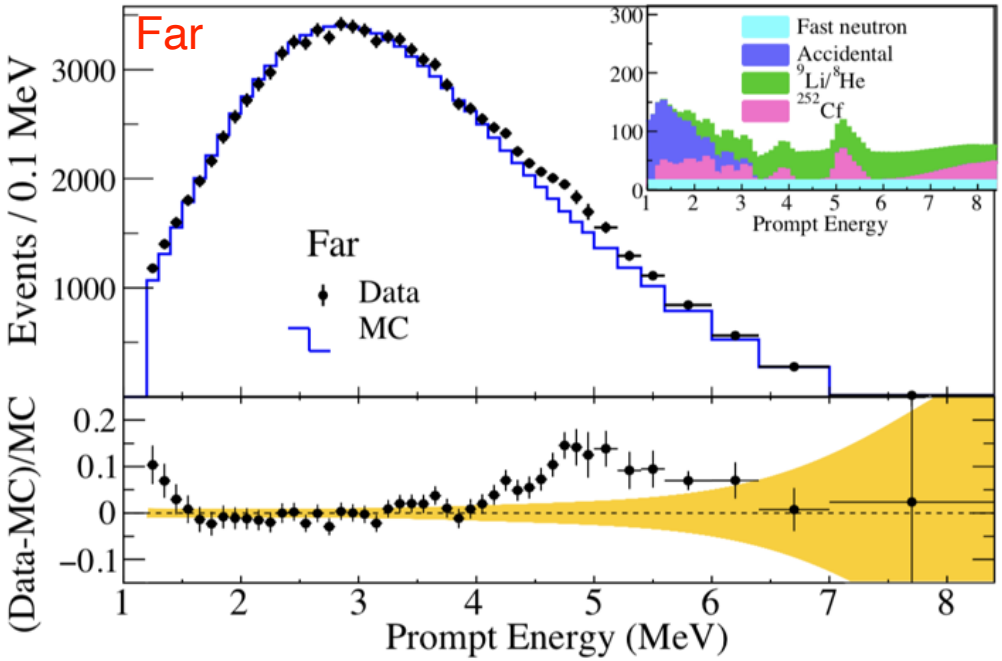
$$E_{\text{prompt}} = K.E.(e^+) + 2 \times (0.511)\,\text{MeV}$$

$$\simeq E_\nu - 0.78\,\text{MeV}$$

Measured Spectra of IBD Prompt Signal

RENO 2200 days results: PRL 121, 201801 (2018)
RENO 2900 days (2200 + 700 days) : Aug. 2011 — Feb. 2020
- Clear excess at 5MeV compared to the Huber-Mueller prediction

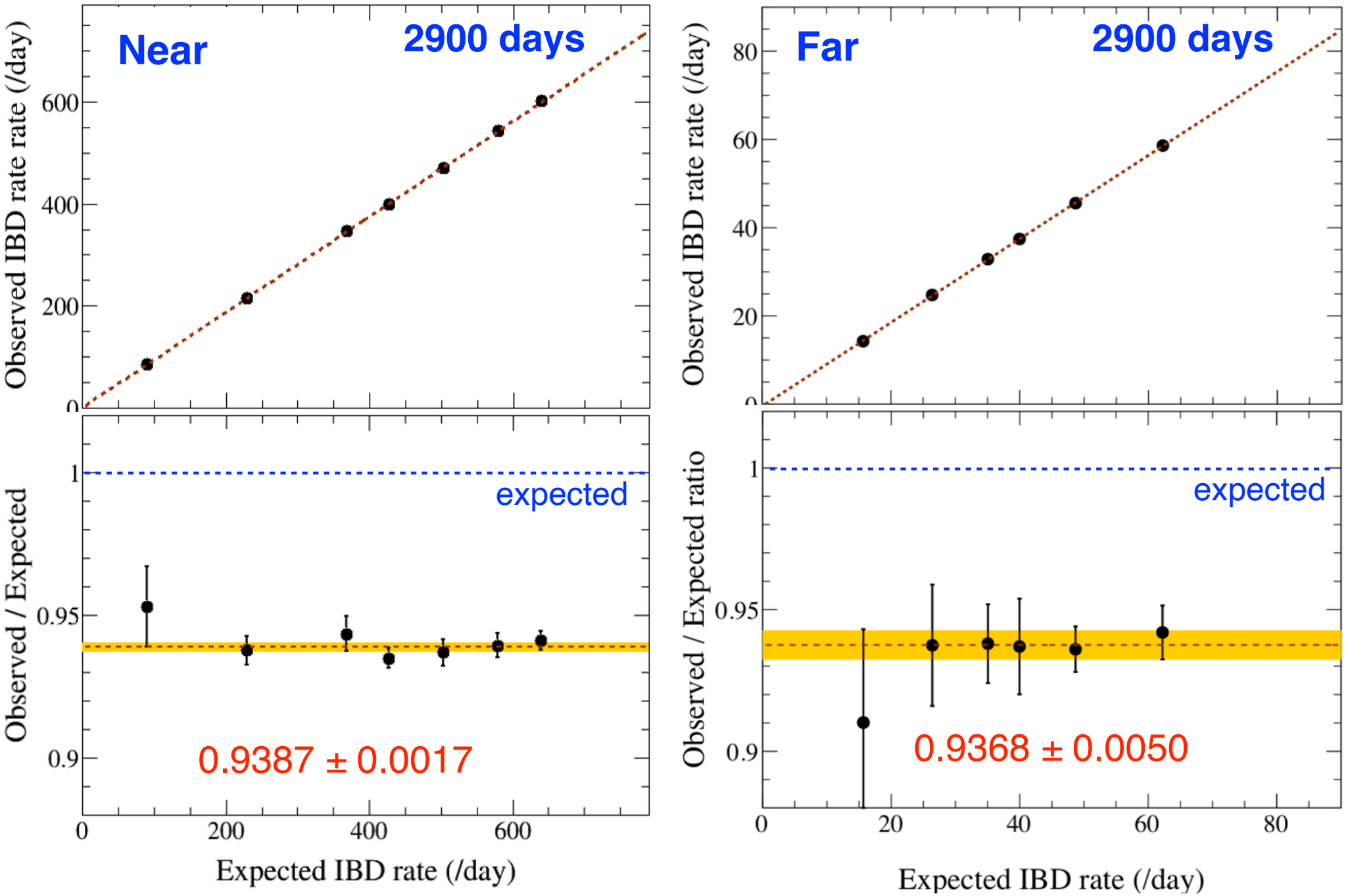




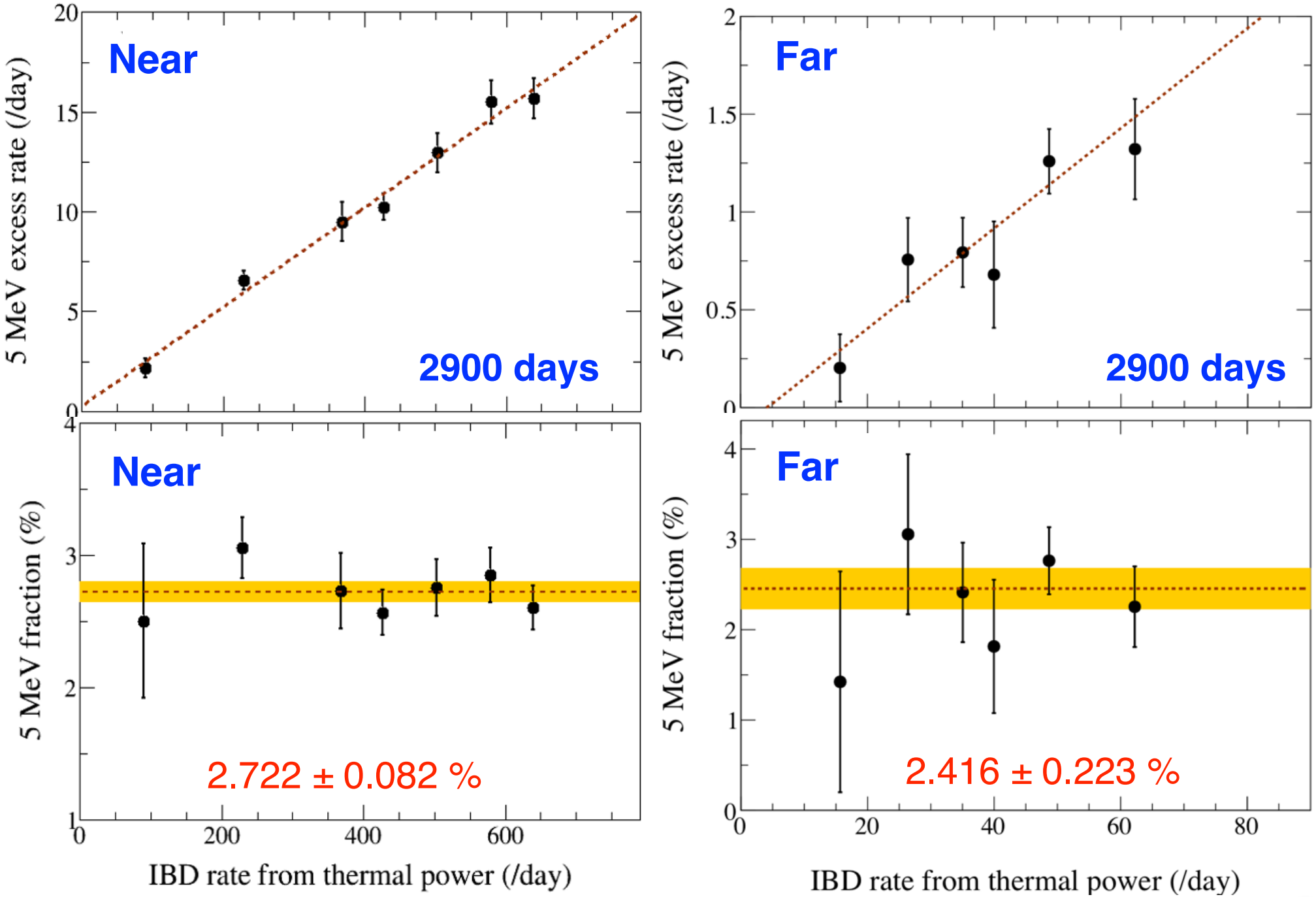
Near detector live time: 2509 days
#IBD candidates: 989,736
Background rate: 2.26 ± 0.05 %
5 MeV excess rate: 2.50 ± 0.06 %

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

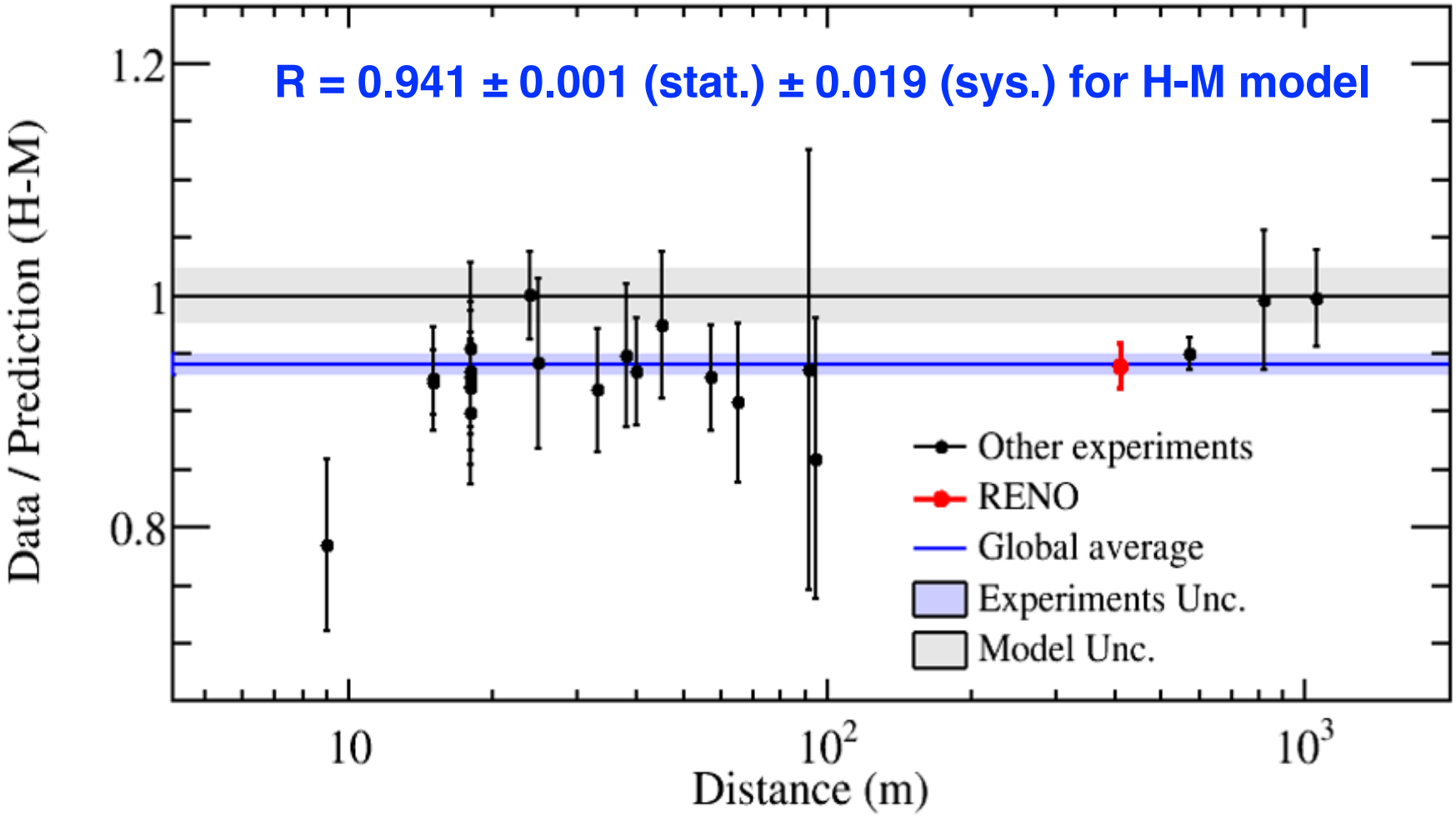
Reactor Antineutrino Anomaly (RAA)



5 MeV Excess VS Expected IBD Rate



Reactor Antineutrino Anomaly (RAA)



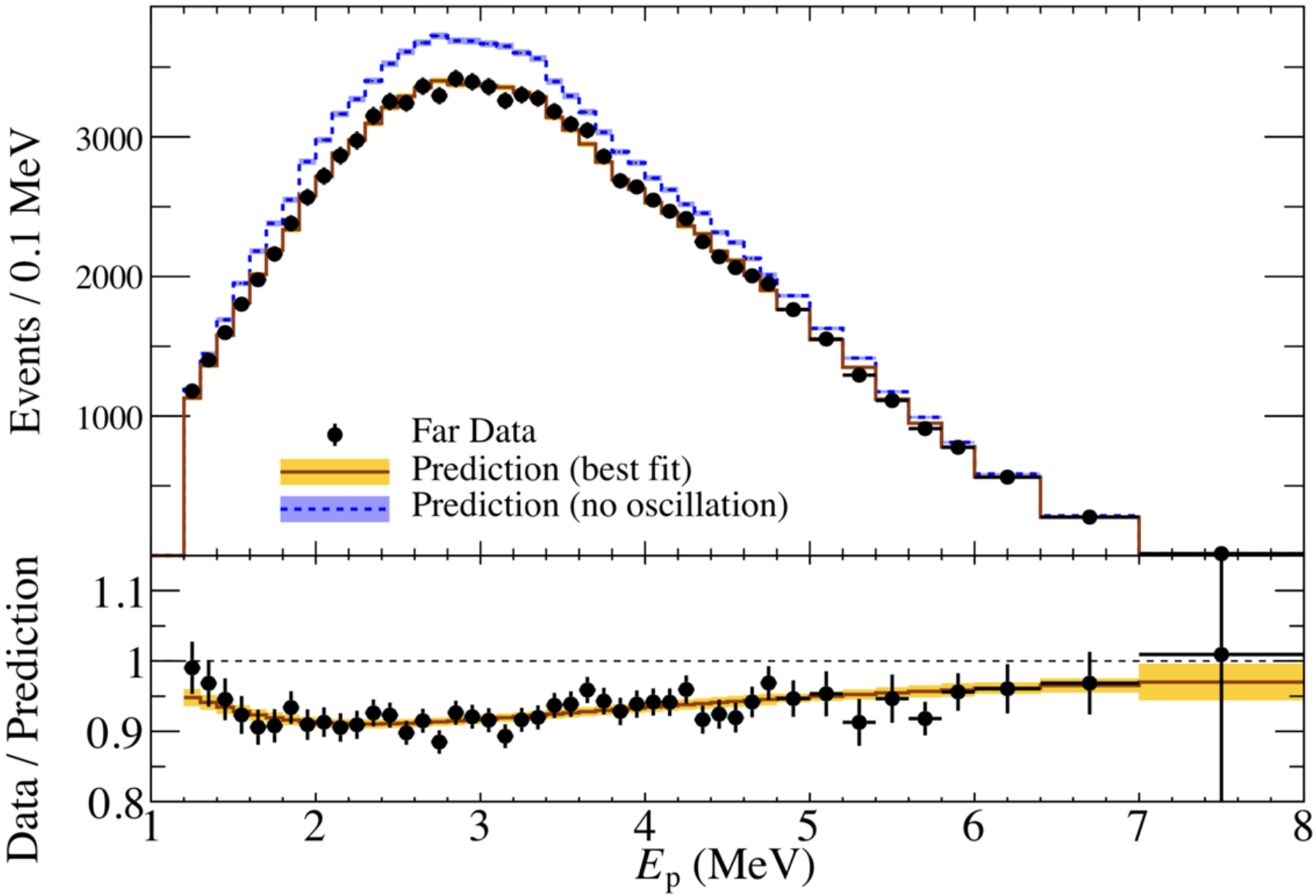
IBD yield: $\overline{y}_f = 5.852 \pm 0.124 (\times 10^{-43} \mathrm{cm}^2/\mathrm{fission})$

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

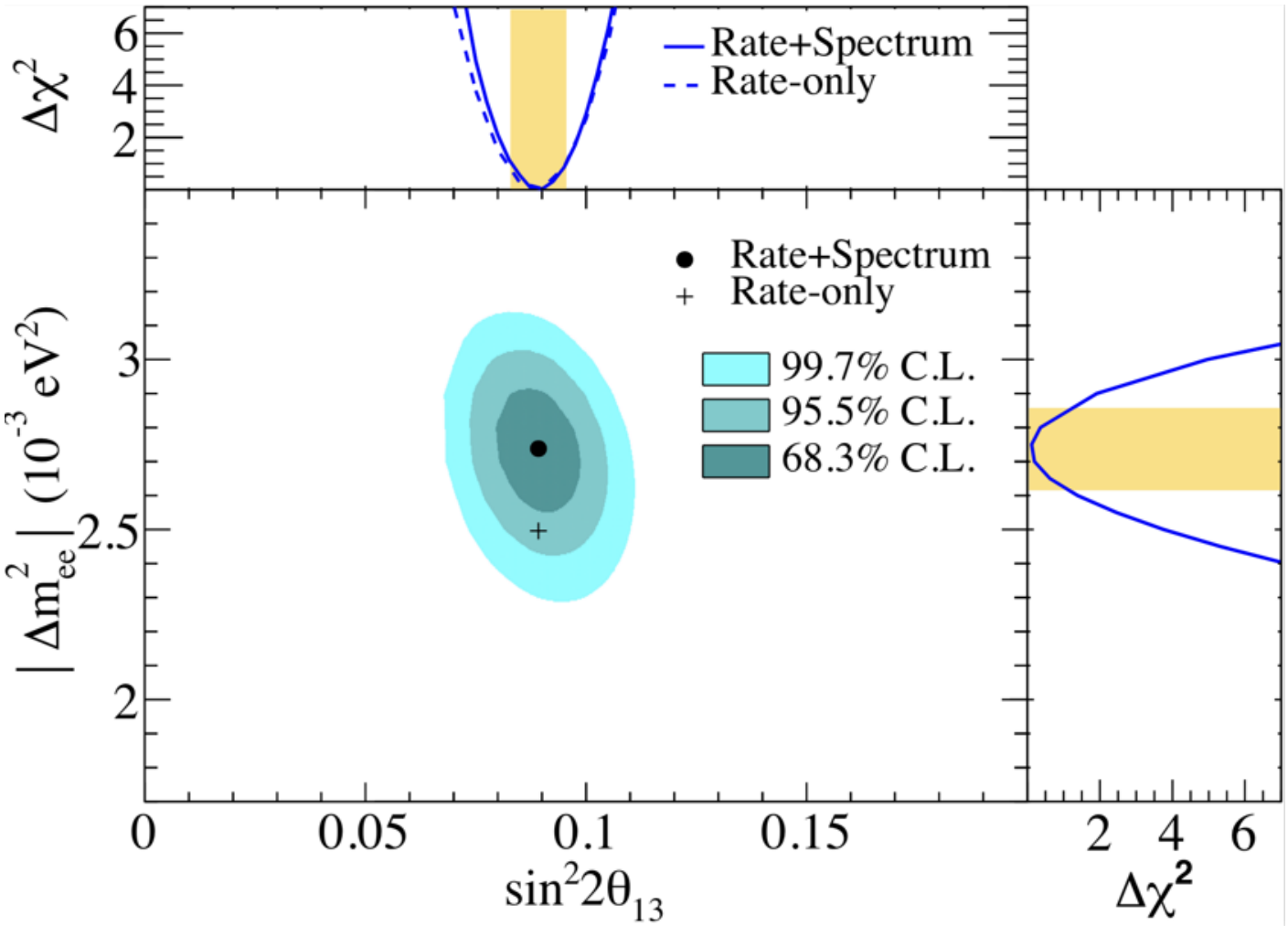
Far to Near Prompt Spectra Shape Comparison

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

- Energy dependent disappearance of reactor antineutrinos



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

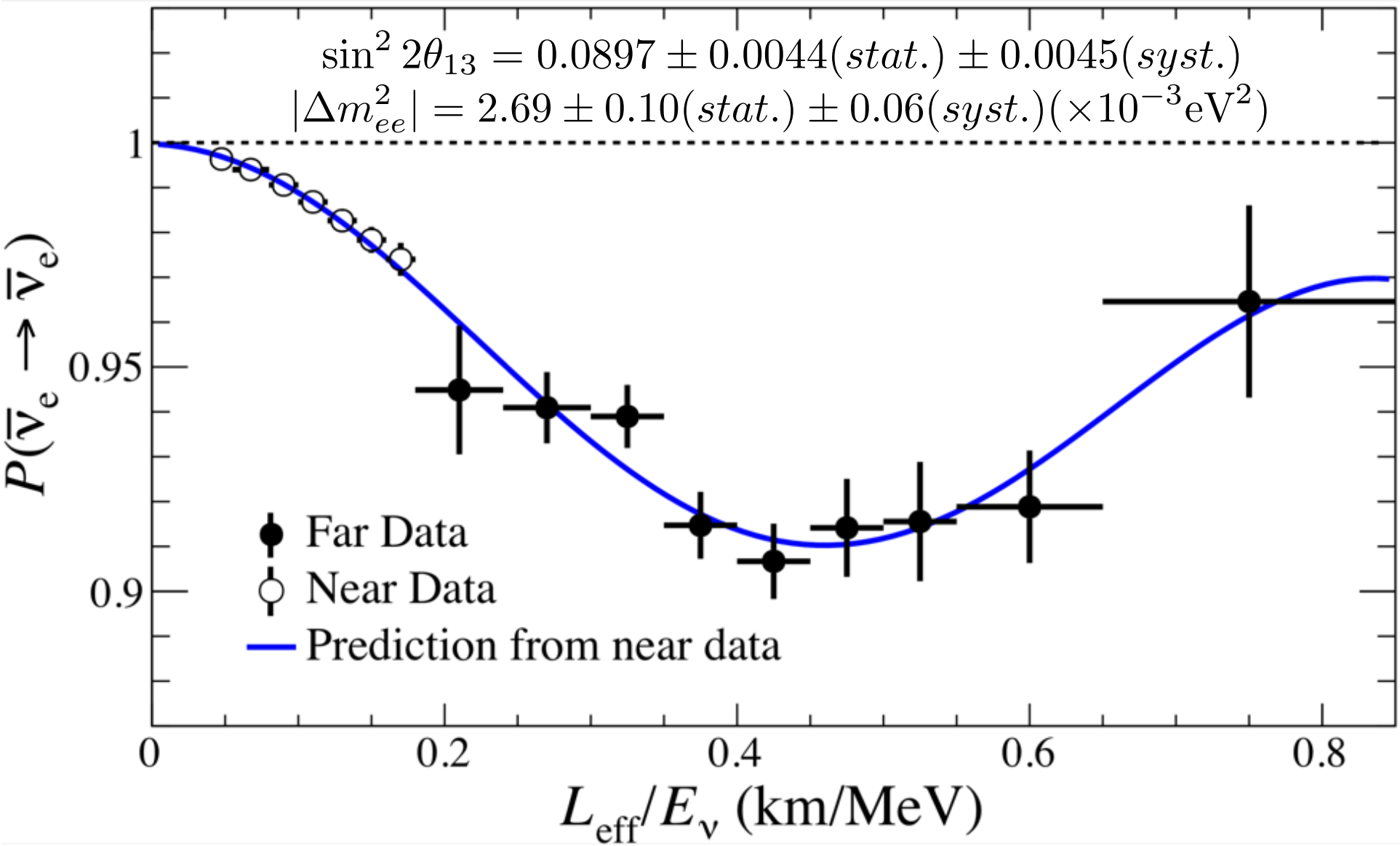


$$\sin^2 2\theta_{13} = 0.0892 \pm 0.0044(stat.) \pm 0.0045(sys.)$$ **± 7.0%**

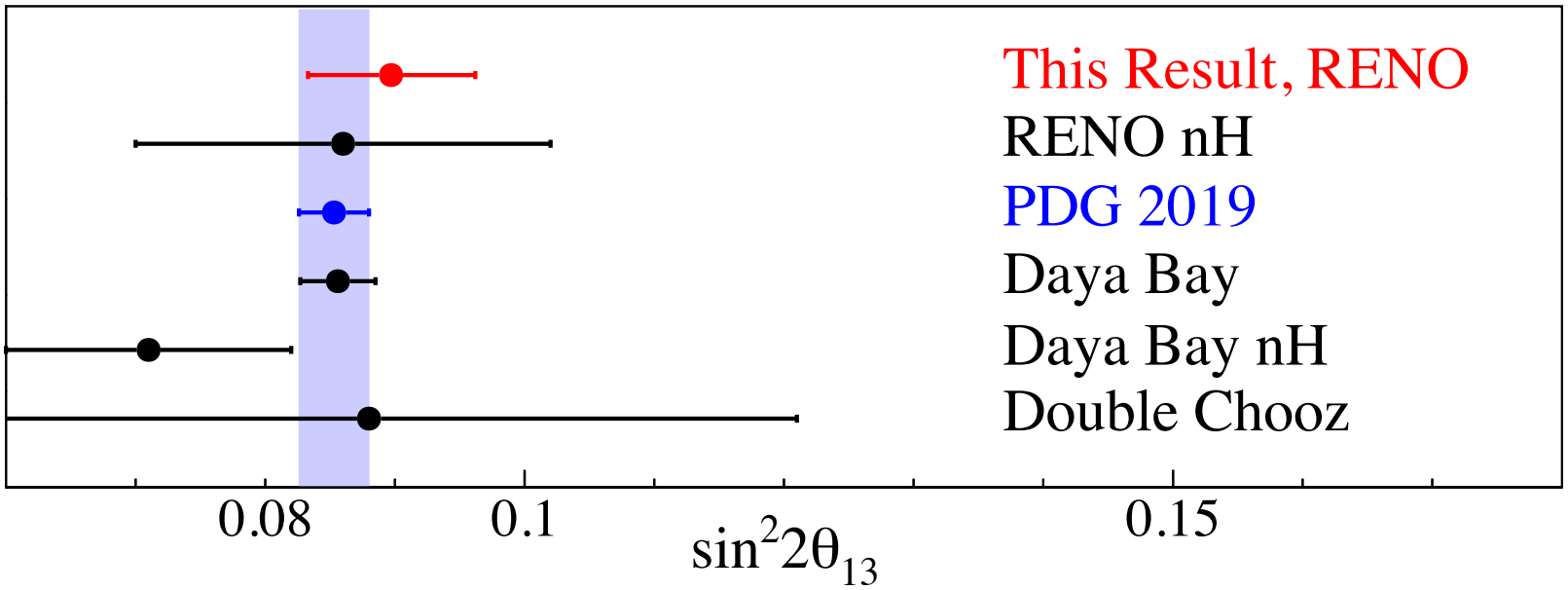
$$|\Delta m^2_{ee}| = 2.74 \pm 0.10(stat.) \pm 0.06(sys.)(\times 10^{-3}\mathrm{eV}^2)$$ **± 4.4%**

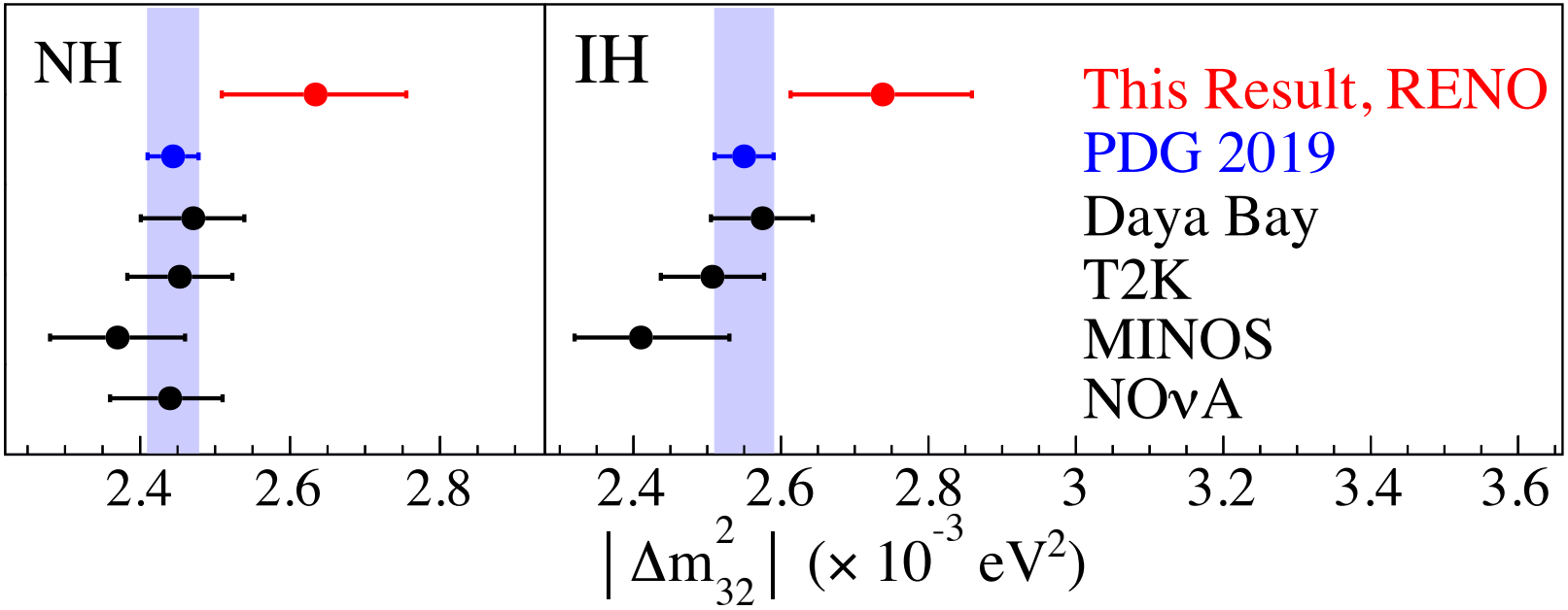
Neutrino Oscillation: L/E Dependence

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

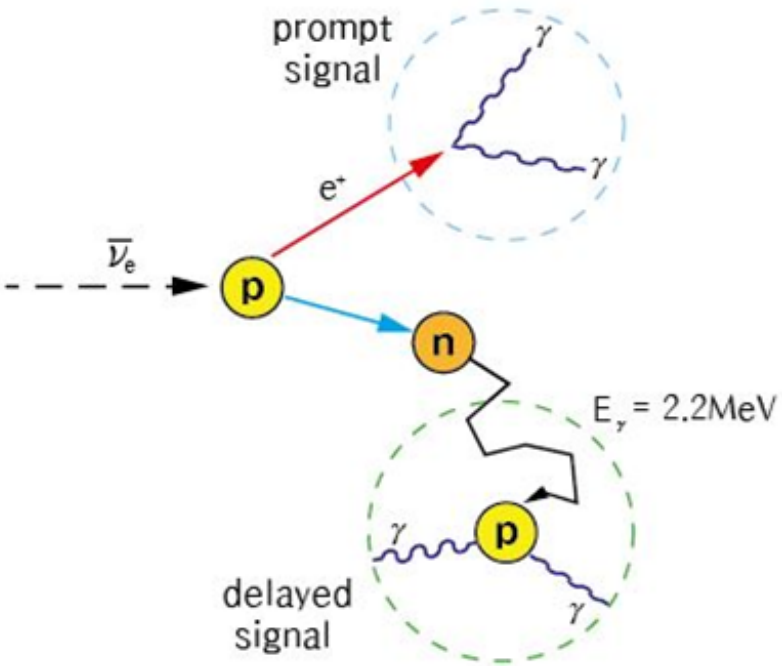


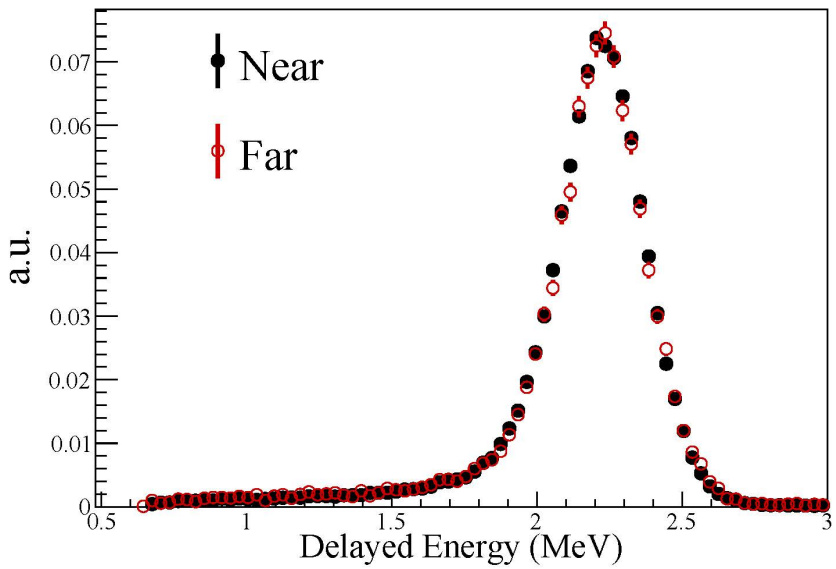
Neutrino Oscillation: θ_{13} and Δm^2_{32}

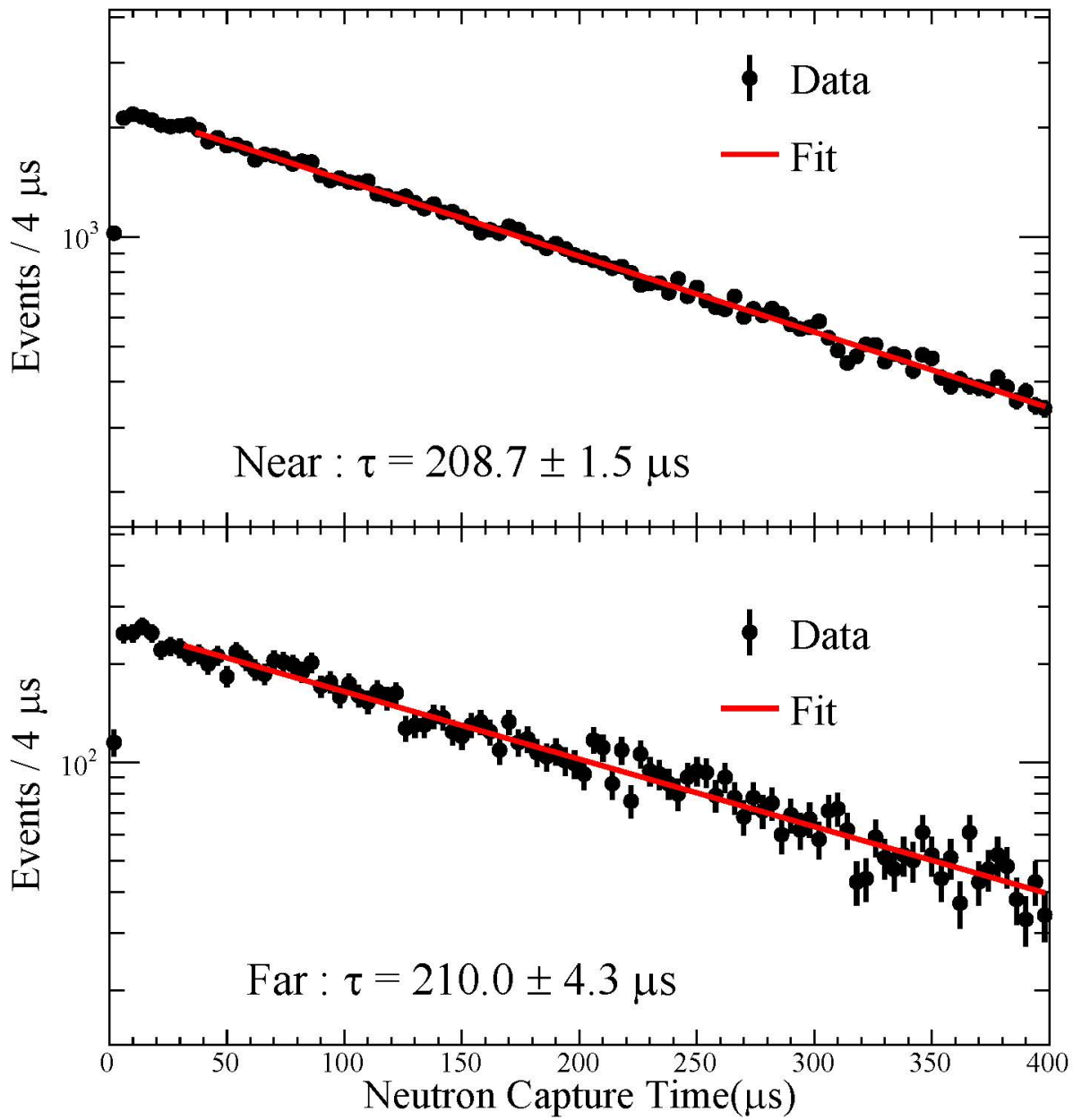




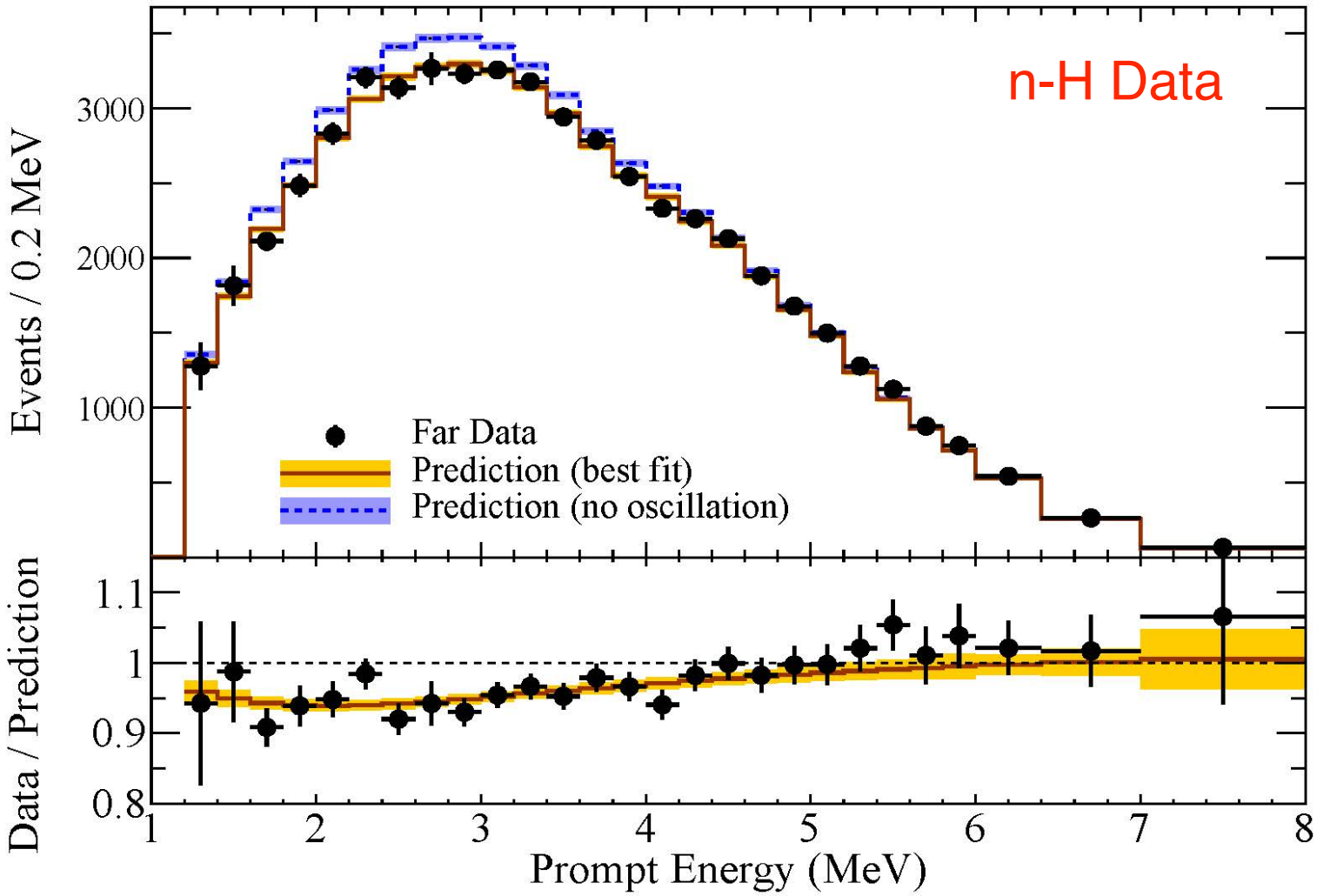
RENO 1500-Days Data n-H Analysis Results







Independent measurement of $\sin^2 2\theta_{13}$ using 1500 live days n-H data



$$\sin^2 2\theta_{13} = 0.086 \pm 0.008(stat.) \pm 0.014(sys.)$$

$$\left(\text{using PDG input: } |\Delta m^2_{ee}| = 2.562 \times 10^{-3}\,\text{eV}^2\right)$$

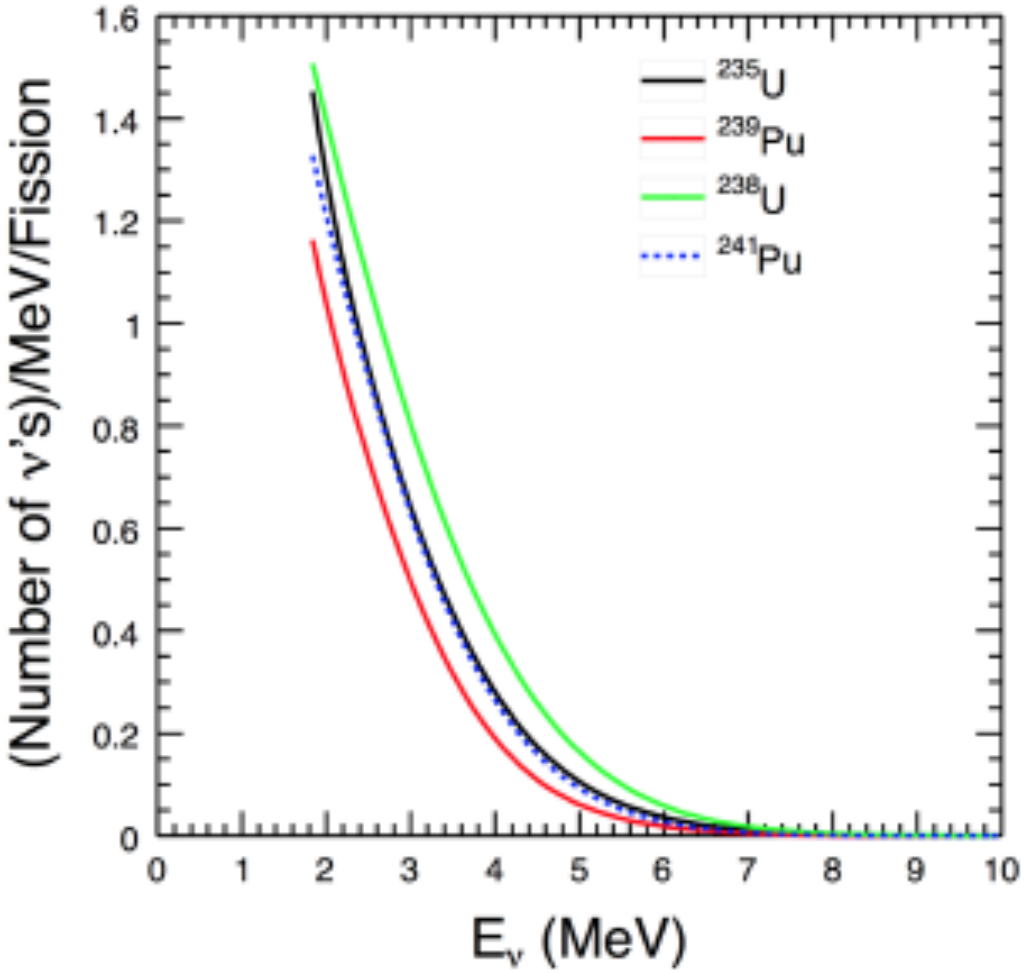
RENO Fuel Fraction in the Reactor Core

IBD yield per fission for each isotope
(total # of produced IBD events)

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

Averaged IBD yield per fission
(for each 8 group, j)

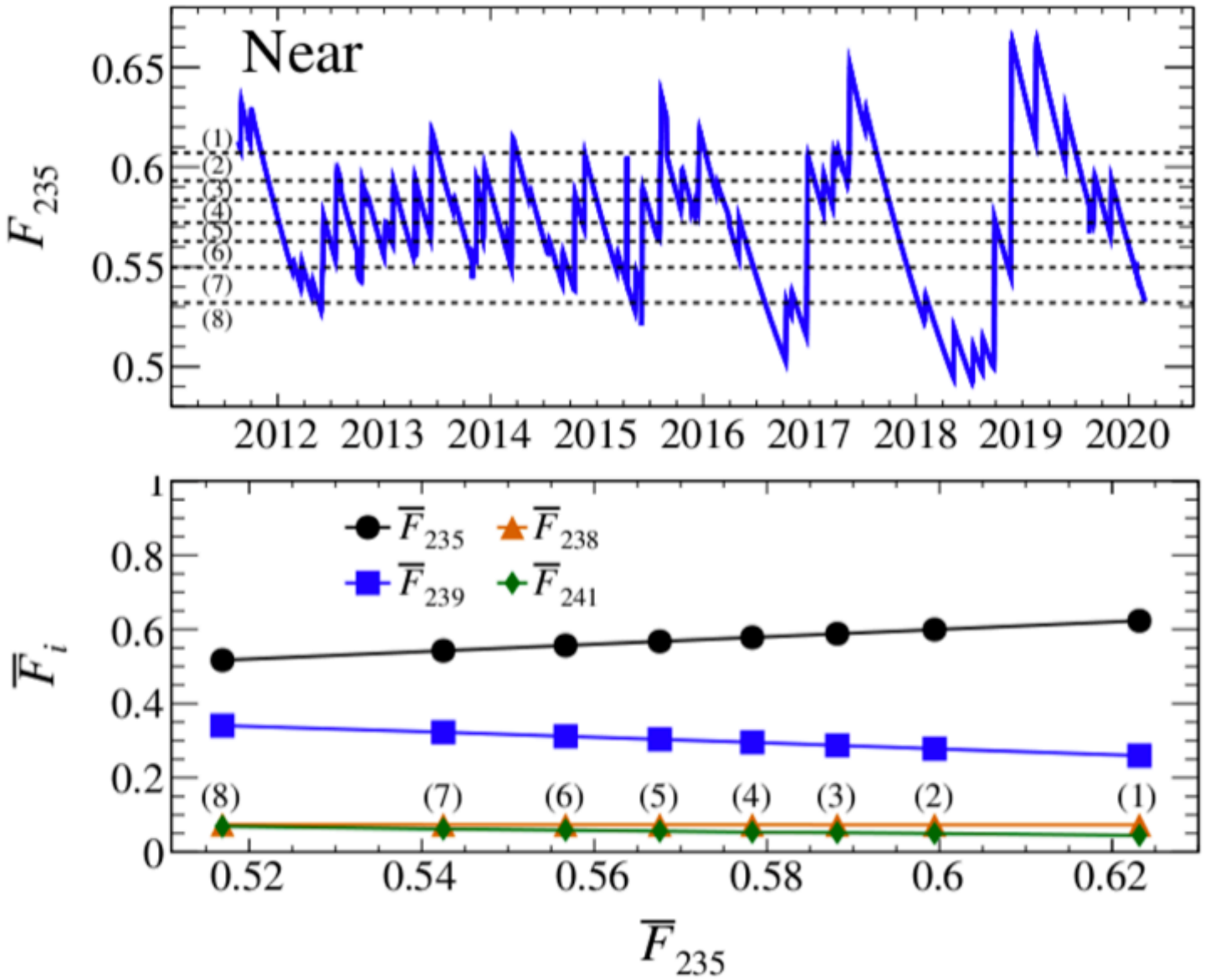
$$\overline{y}_{f,j} = \sum_{i=1}^{4} \overline{F}_{i,j} y_i$$



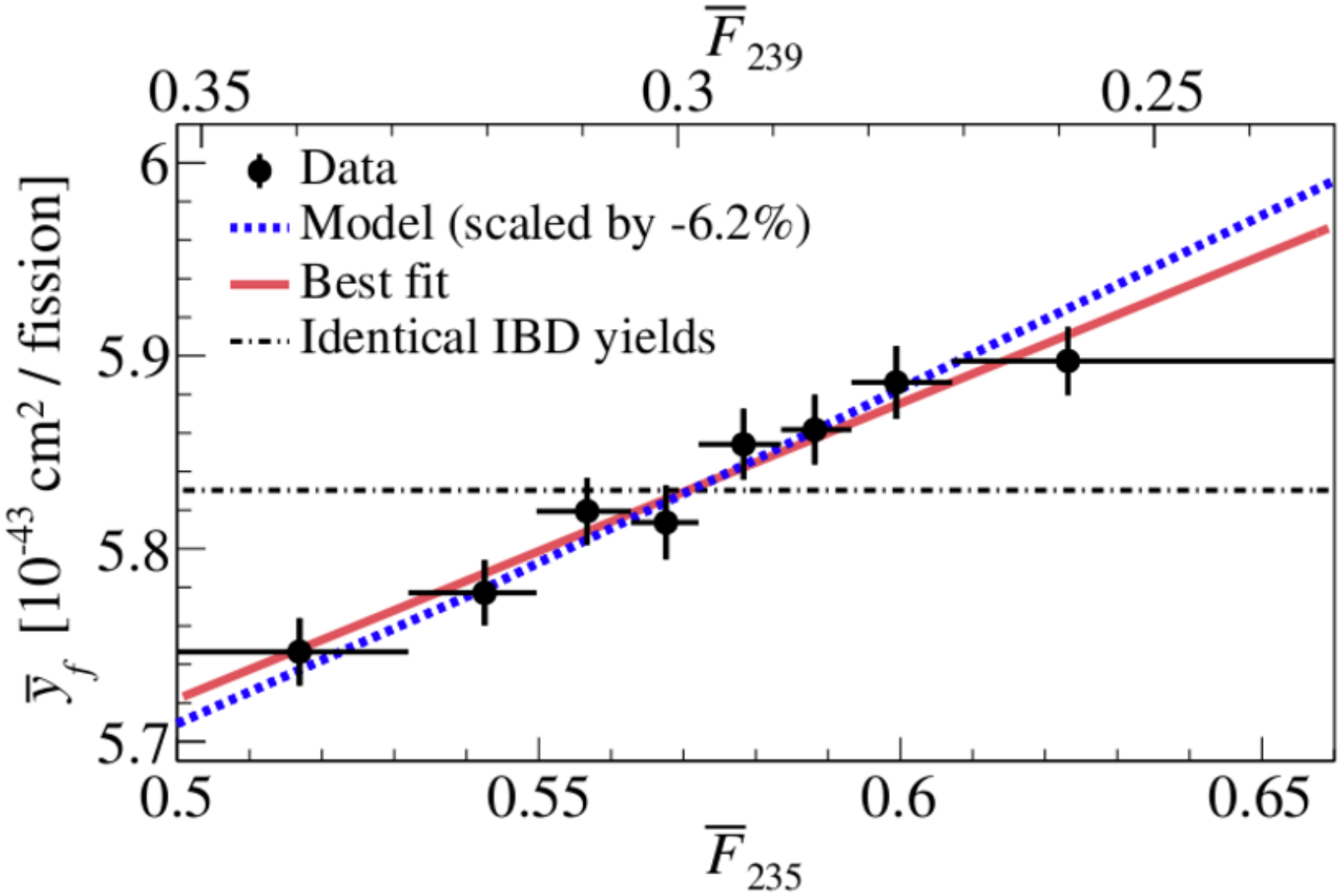
	H-M model (10^{-43} cm²/fission)
y_{235}	6.70 +- 0.14
y_{239}	4.38 +- 0.11
y_{238}	10.07 +- 0.82
y_{241}	6.07 +- 0.13

RENO Fuel Fraction in the Reactor Core: PRL 122, 232501 (2019)

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



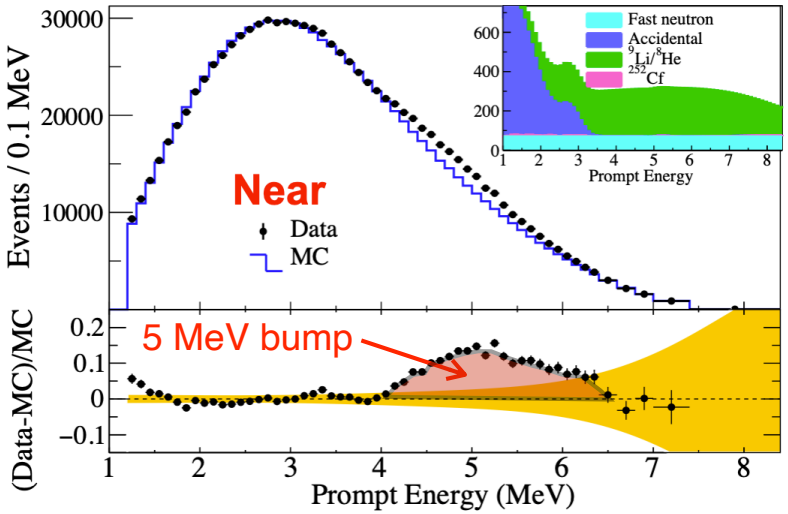
Fuel Dependence of IBD Yield: PRL 122, 232501 (2019)



Identical yield $\overline{y}_f = 5.8303 \pm 0.0063 \times 10^{-43}\,\mathrm{cm}^2/\mathrm{fission}$

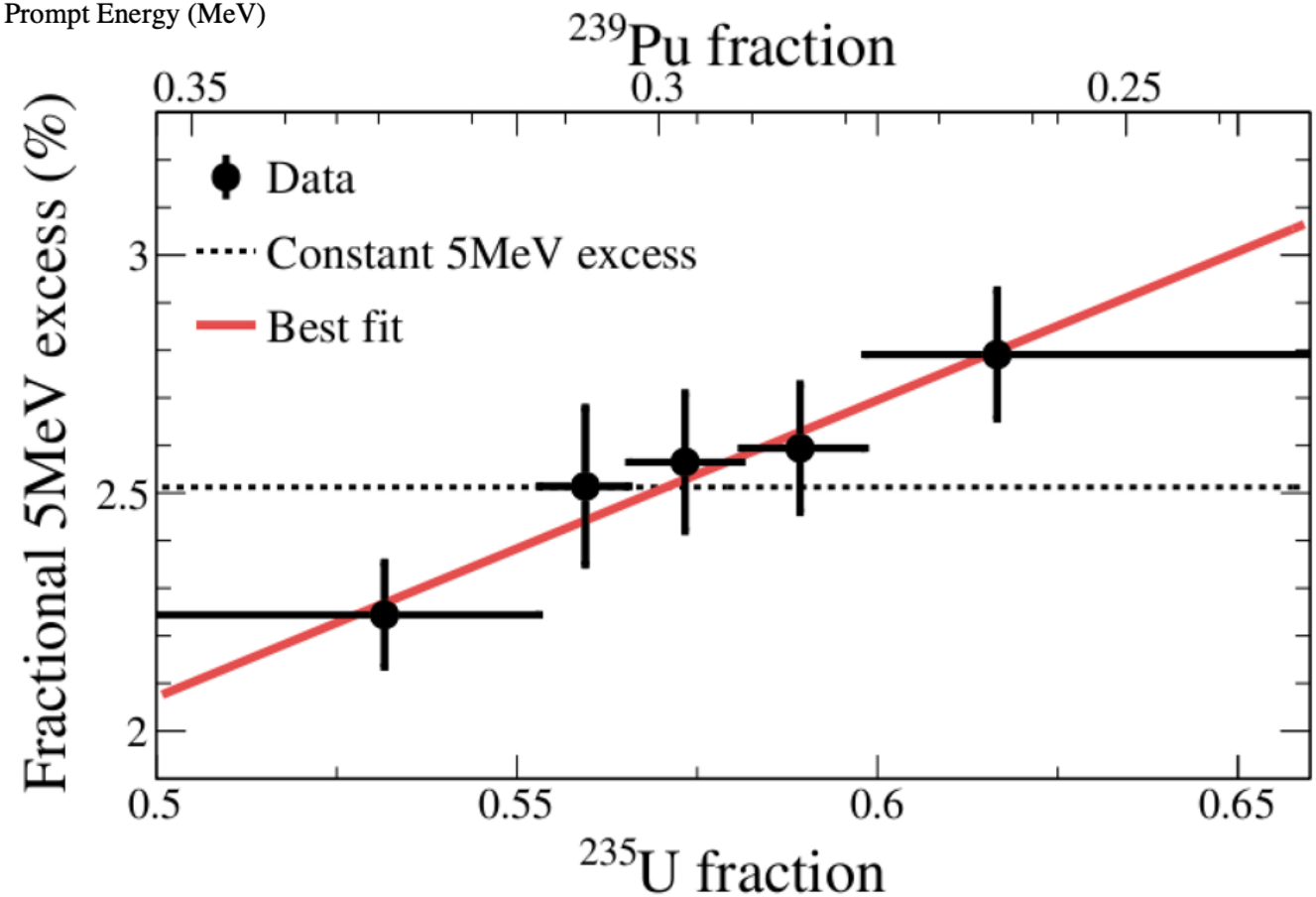
Null fuel dependence ruled out by 7.7σ

Fuel Dependence of the 5 MeV Excess: PRL 122, 232501 (2019)



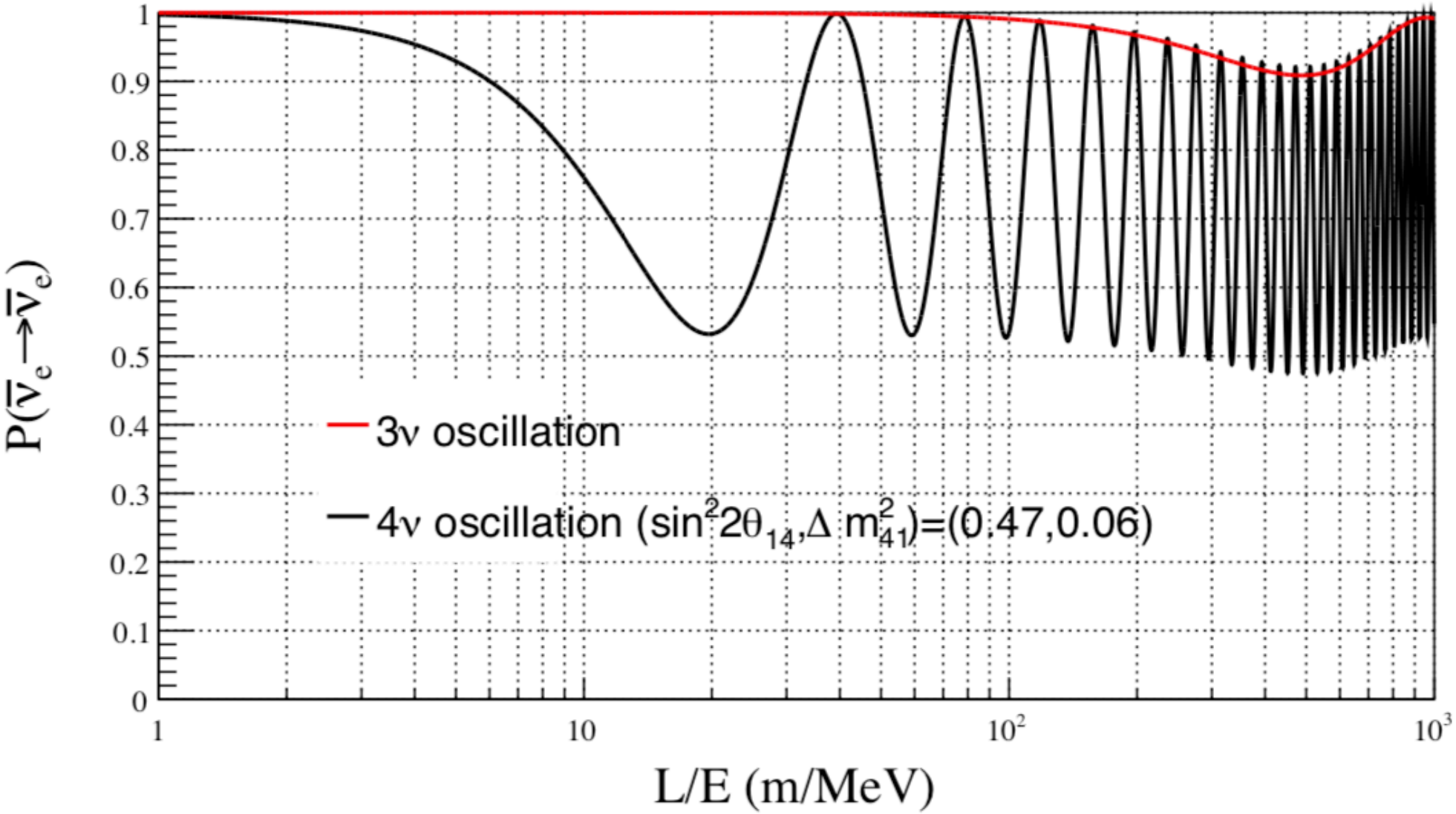
It appears the 5MeV excess is from the ^{235}U (2.9σ), while the ^{239}Pu contribution can not be completely ruled out.

➔ Need precision measurements!



(3+1) Neutrino Model

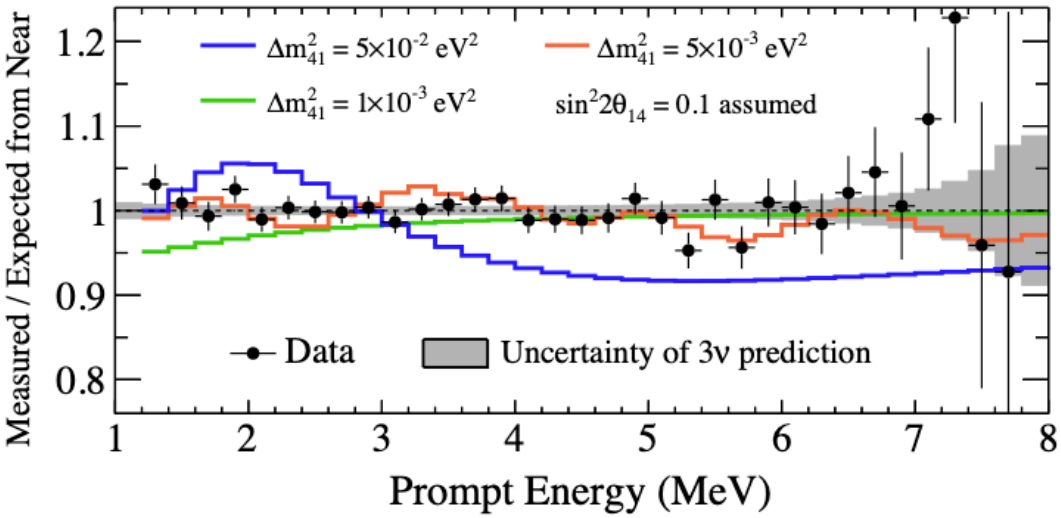
$$P(\overline{\nu}_e \to \overline{\nu}_e) \simeq 1 - \sin^2 2\theta_{13} \sin^2\left(1.27\Delta m^2_{31}\frac{L}{E_\nu}\right) - \sin^2 2\theta_{14} \sin^2\left(1.27\Delta m^2_{41}\frac{L}{E_\nu}\right)$$



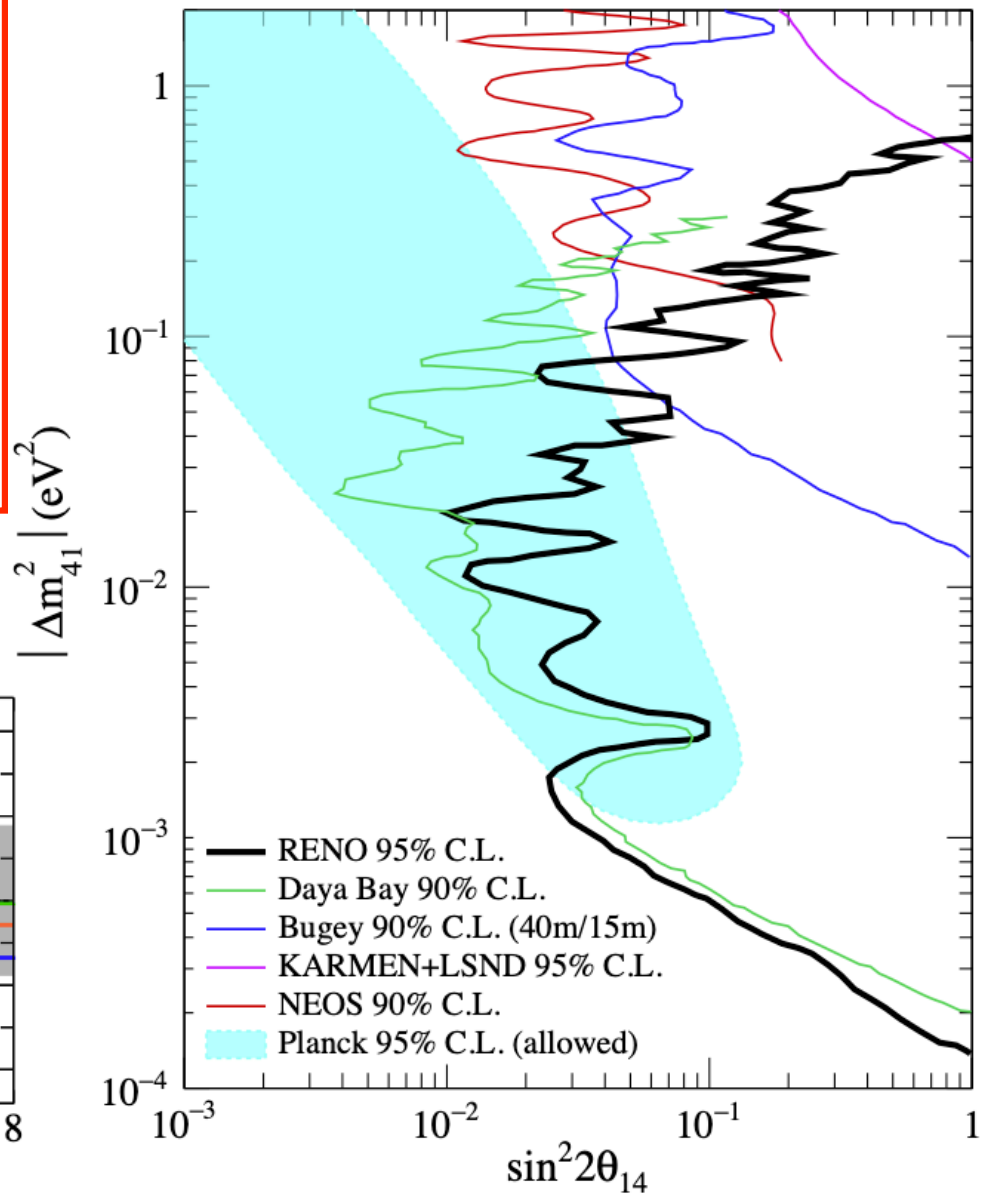
Search Sterile Neutrinos (RENO Near/Far) : Sub-eV Scale

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

Using RENO Far to Near spectral ratio

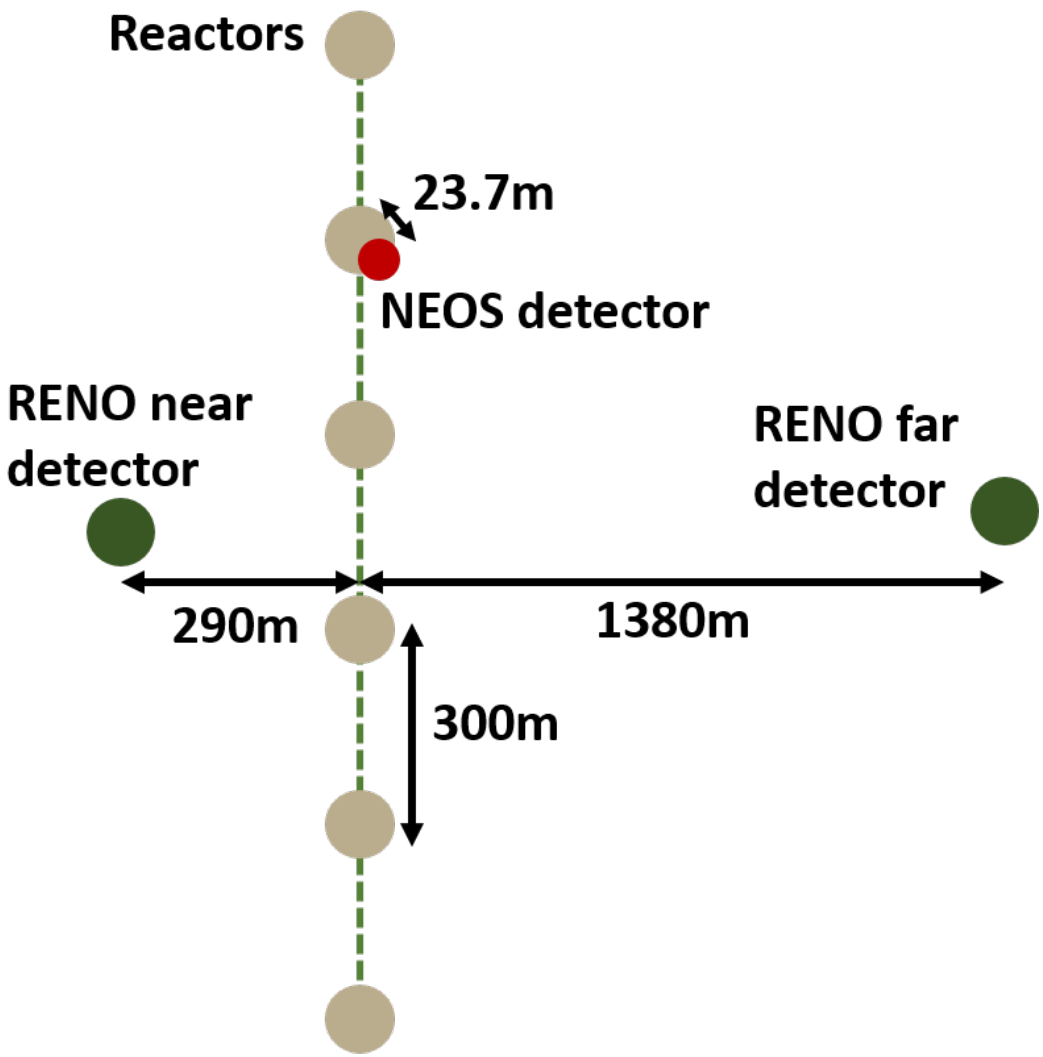


Phys. Rev. Lett. 125, 191801 (2020-11-06)

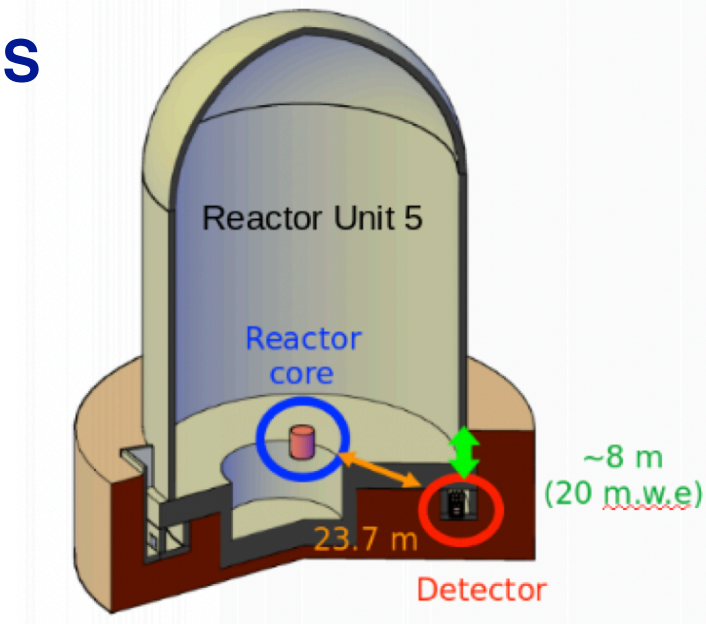


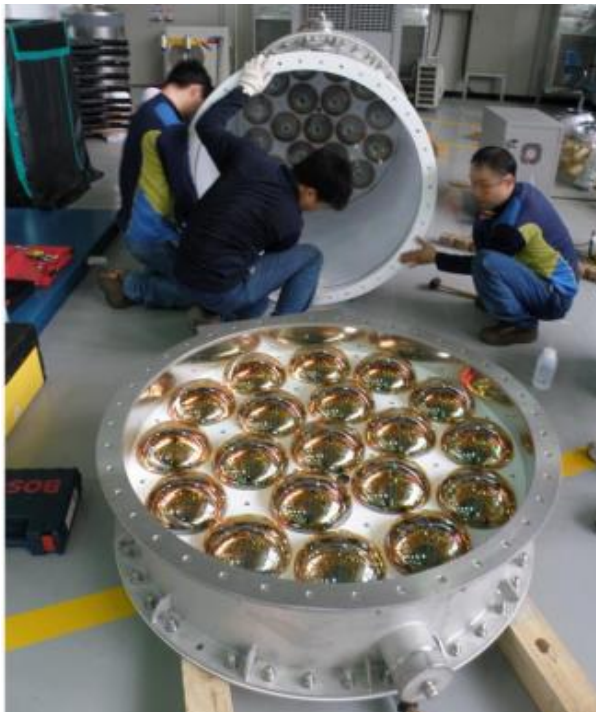
Sterile Neutrino Search (RENO + NEOS) : eV Scale

Hanbit Power Plant

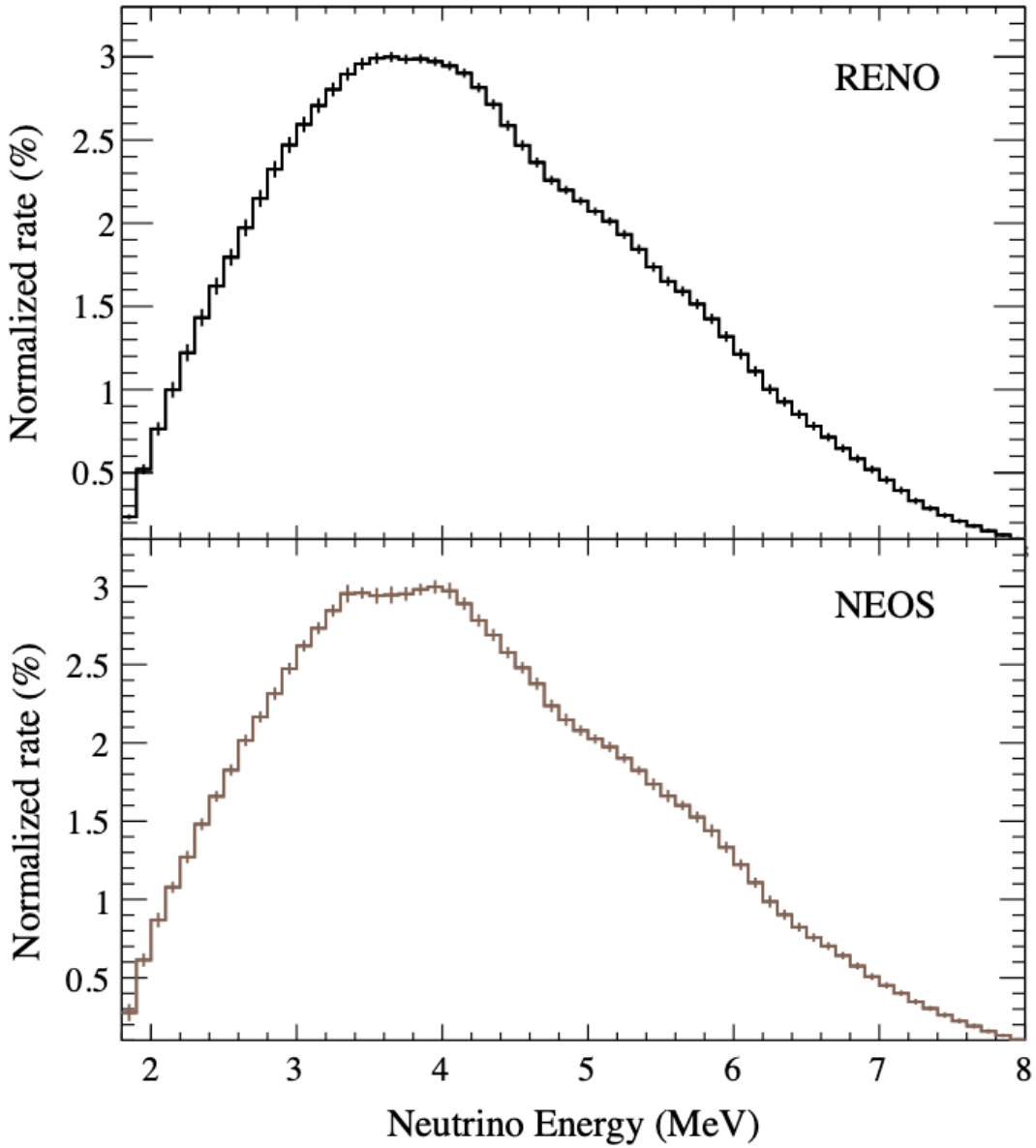


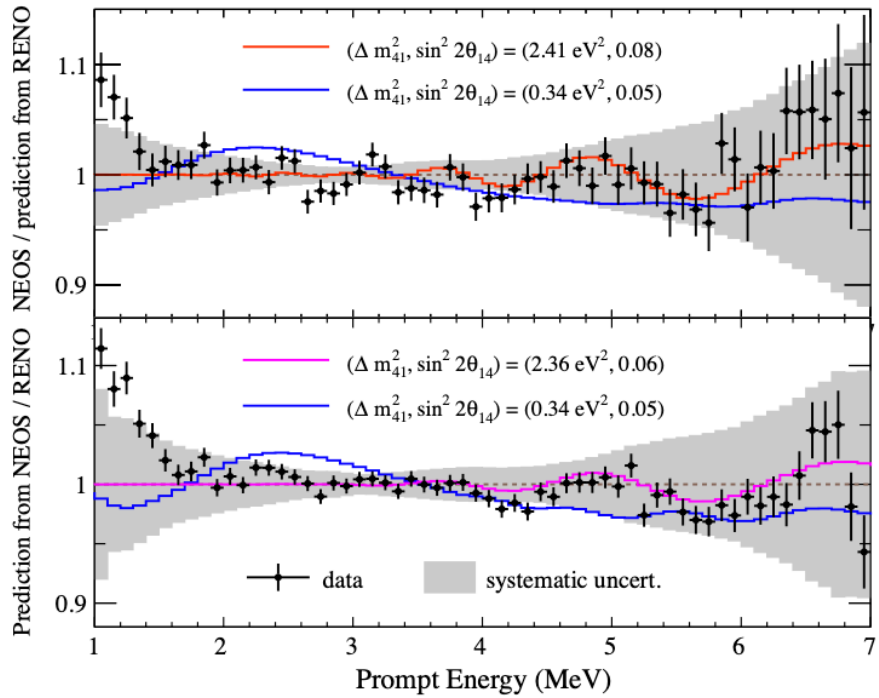
NEOS

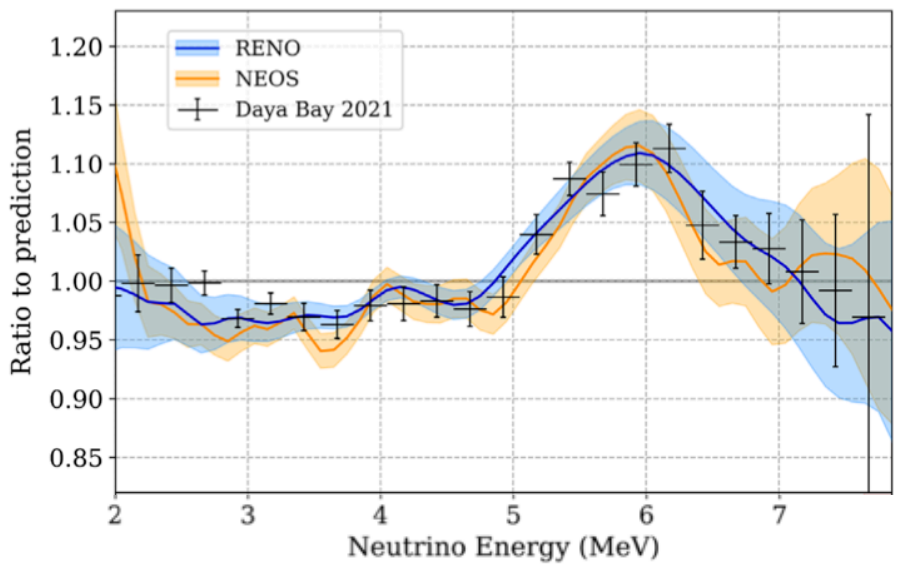




Sterile Neutrino Search (RENO + NEOS) : eV Scale

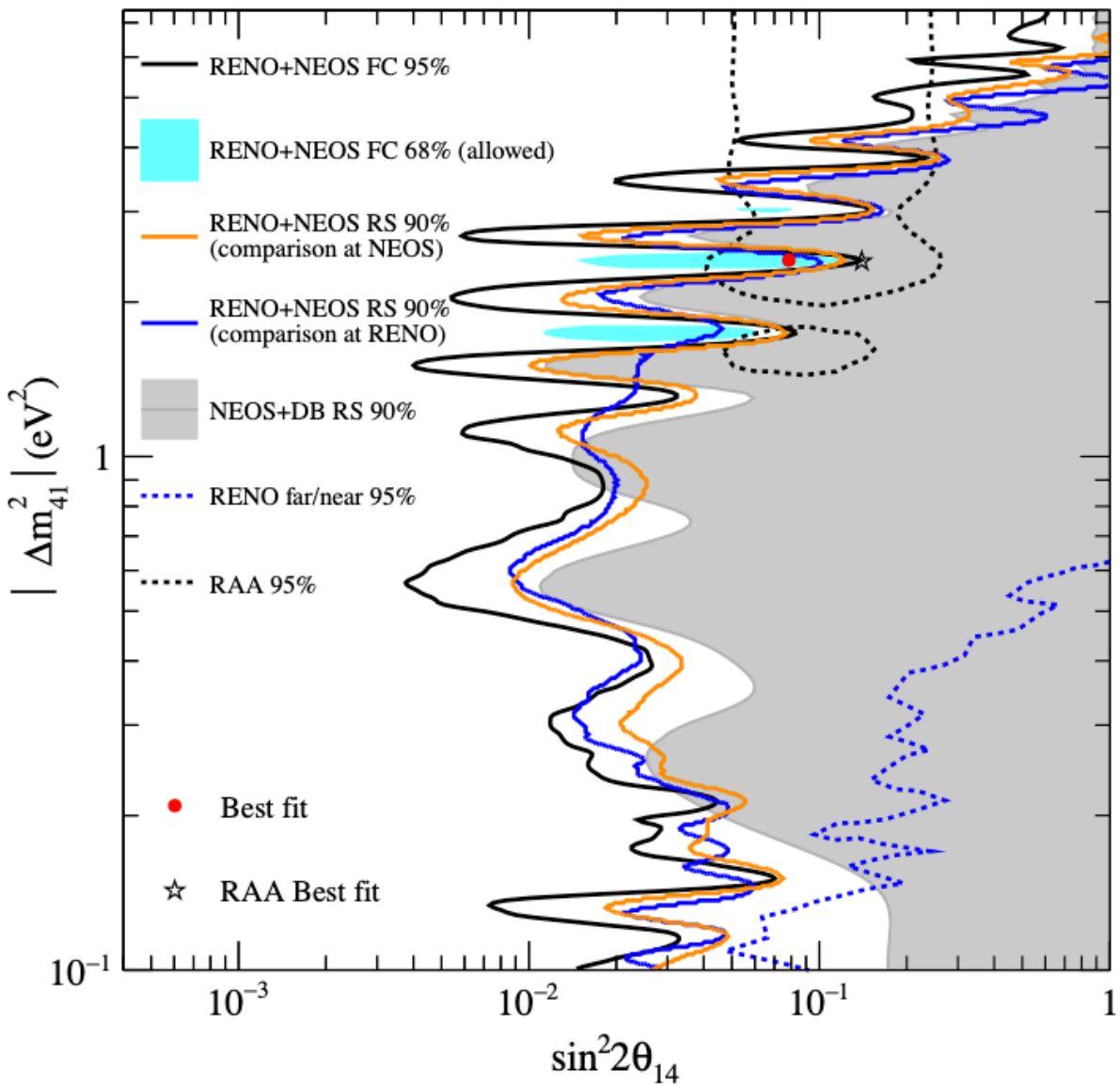






Sterile Neutrino Search (RENO + NEOS) : eV Scale

PRD 105, L111101 (2022)

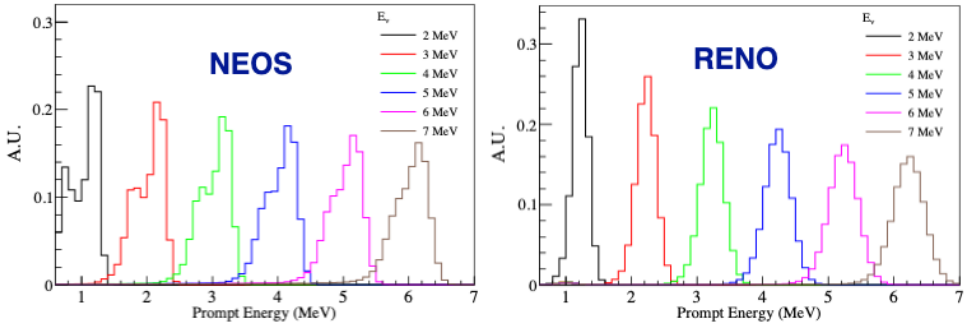


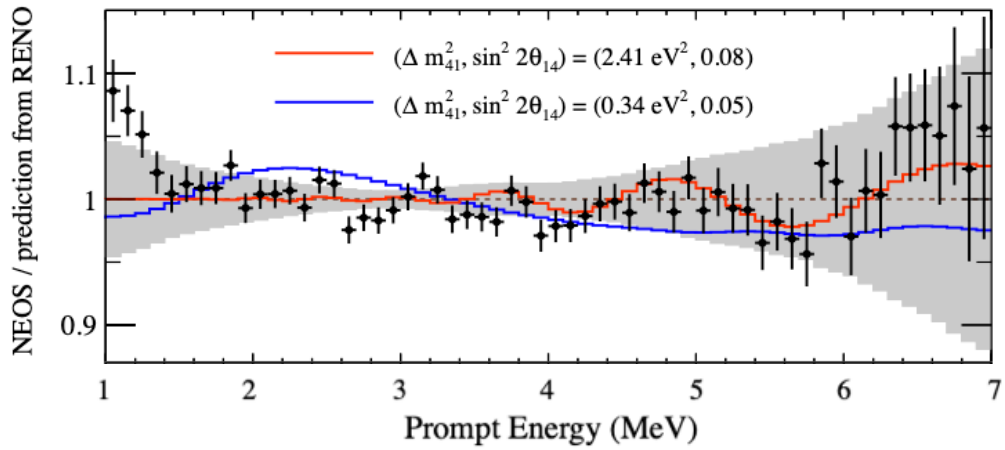
RENO+NEOS best fit at (0.08, 2.4 eV^2)

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

RENE: Reactor Experiment for Neutrinos and Exotics

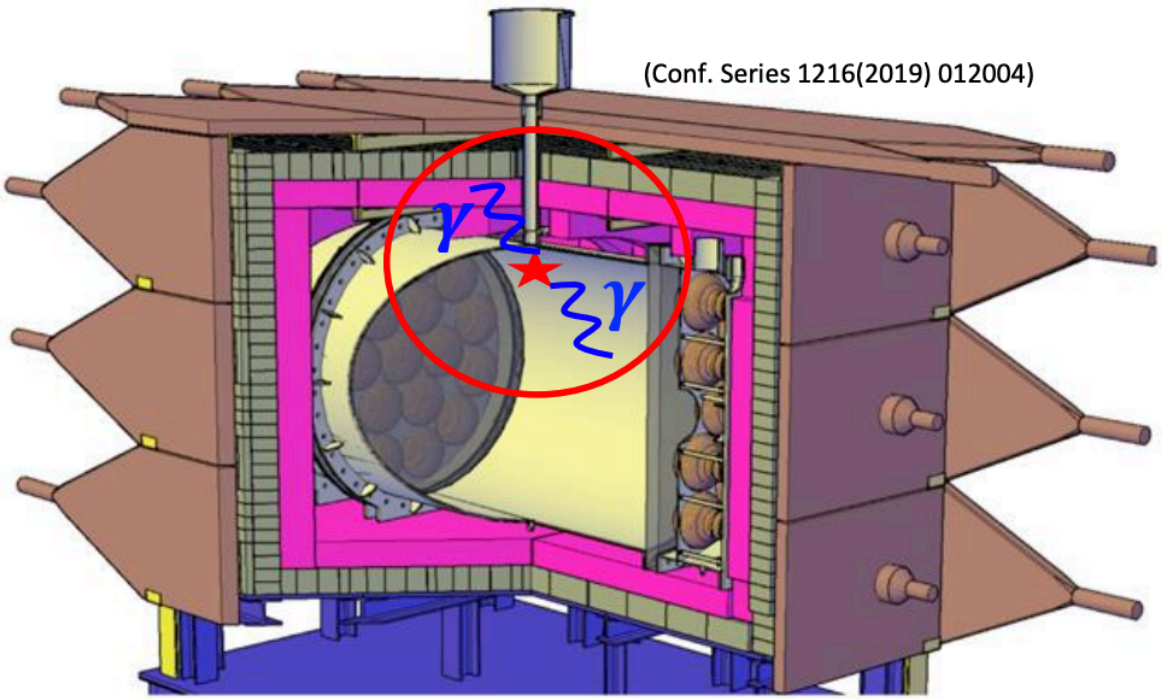
Detector Response of NEOS vs. RENO



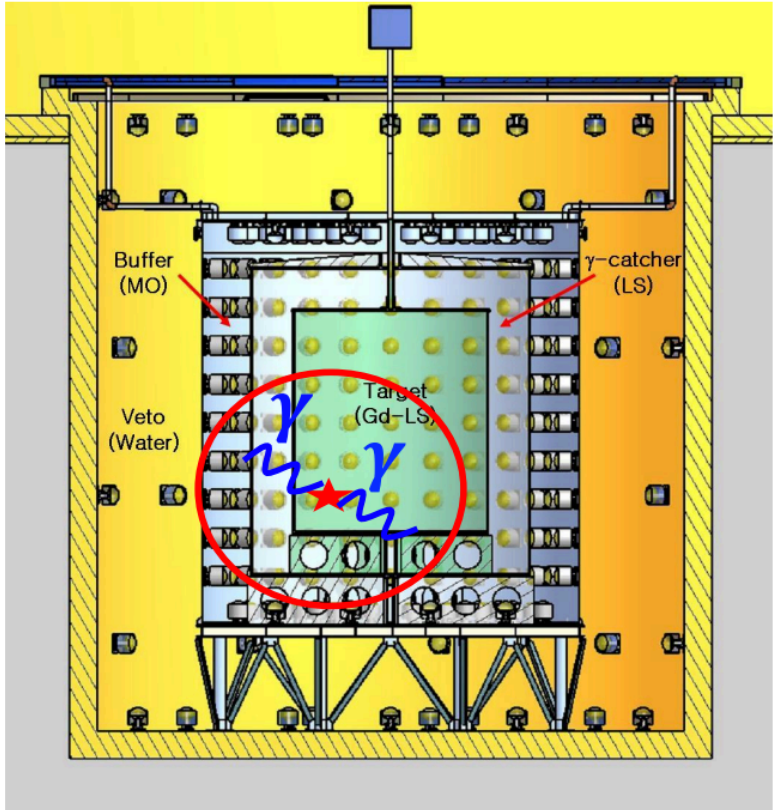


NEOS

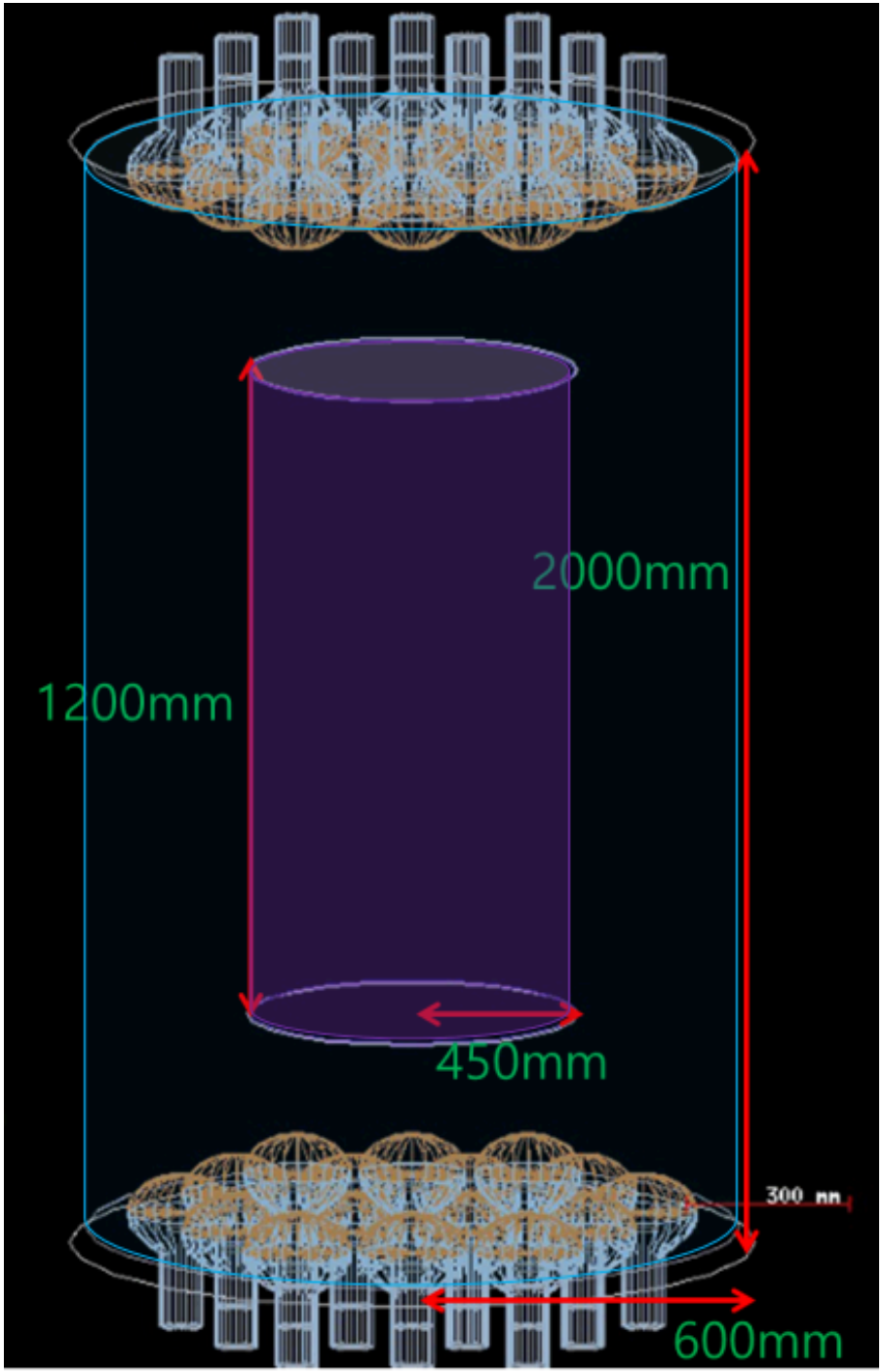
(Conf. Series 1216(2019) 012004)

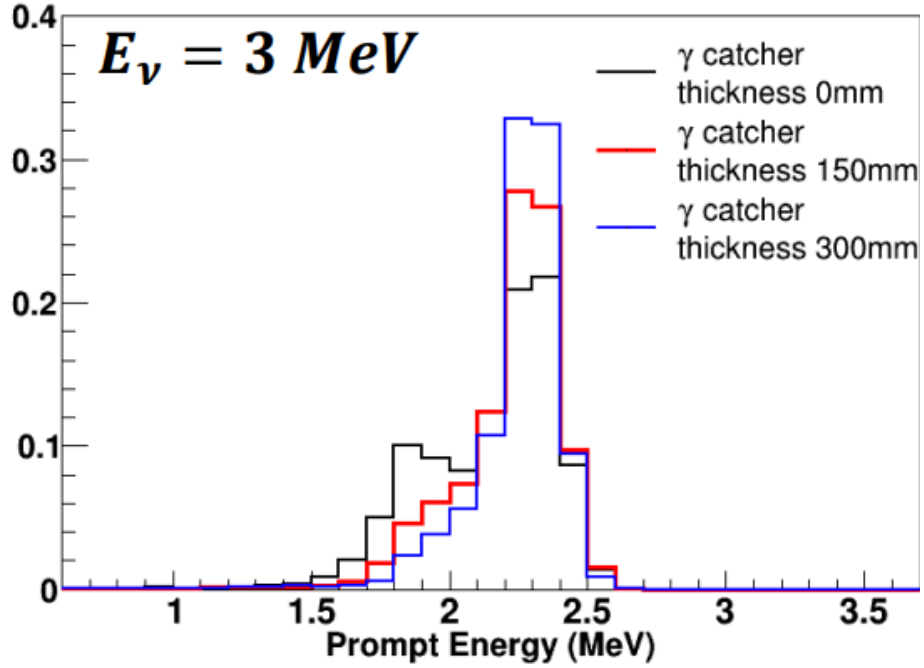


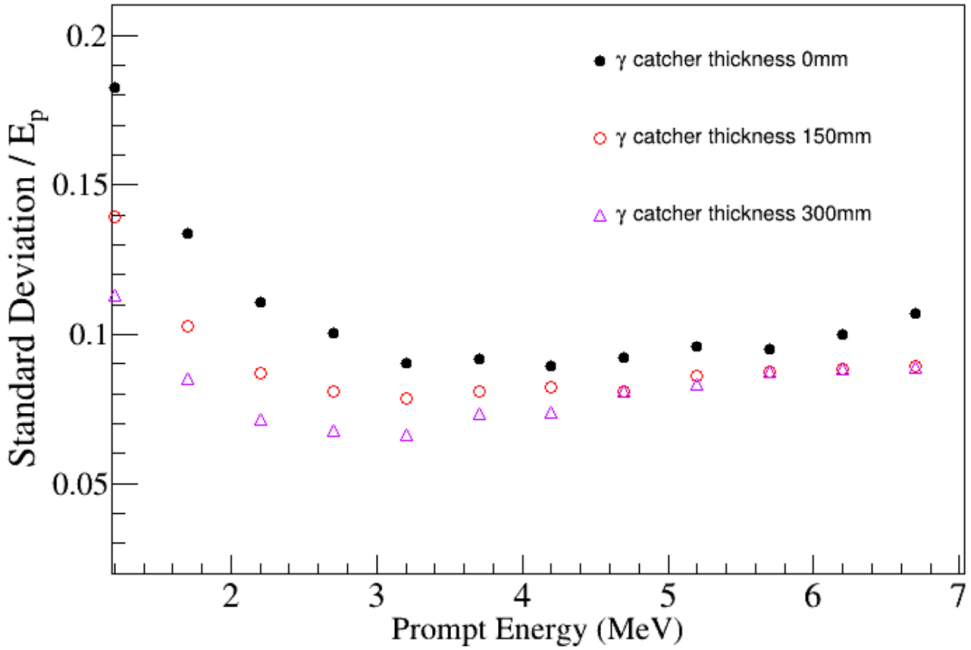
RENO



RENE Phase-1: Reactor Experiment for Neutrinos and Exotics

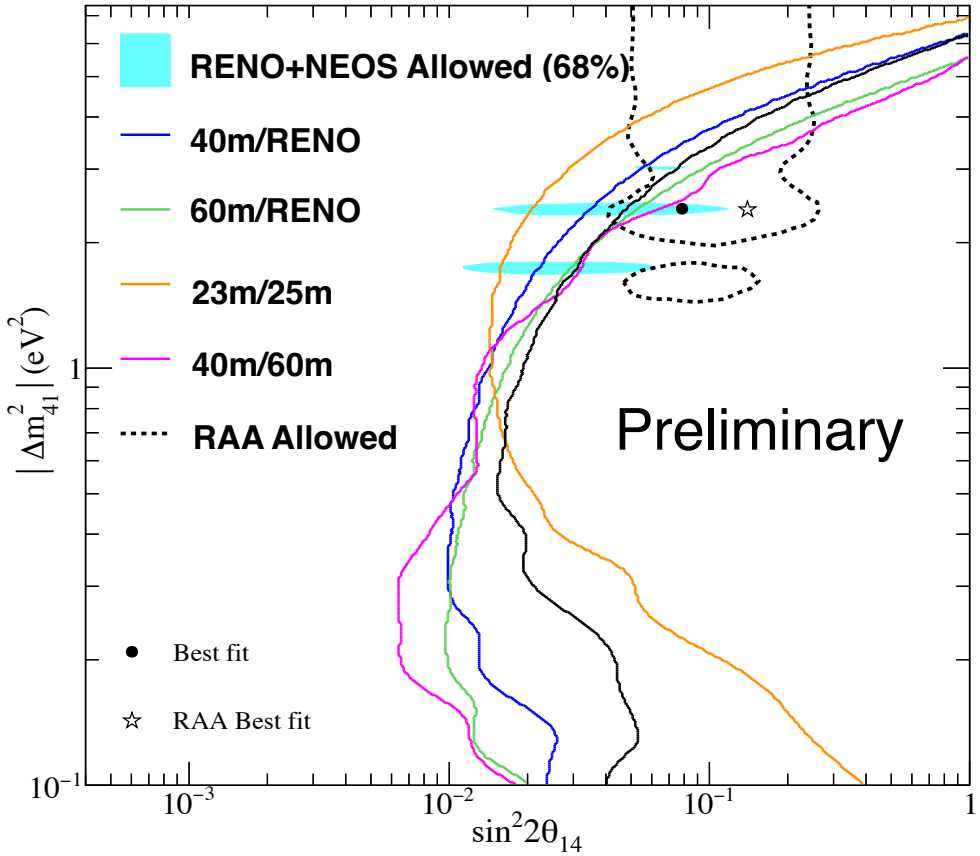


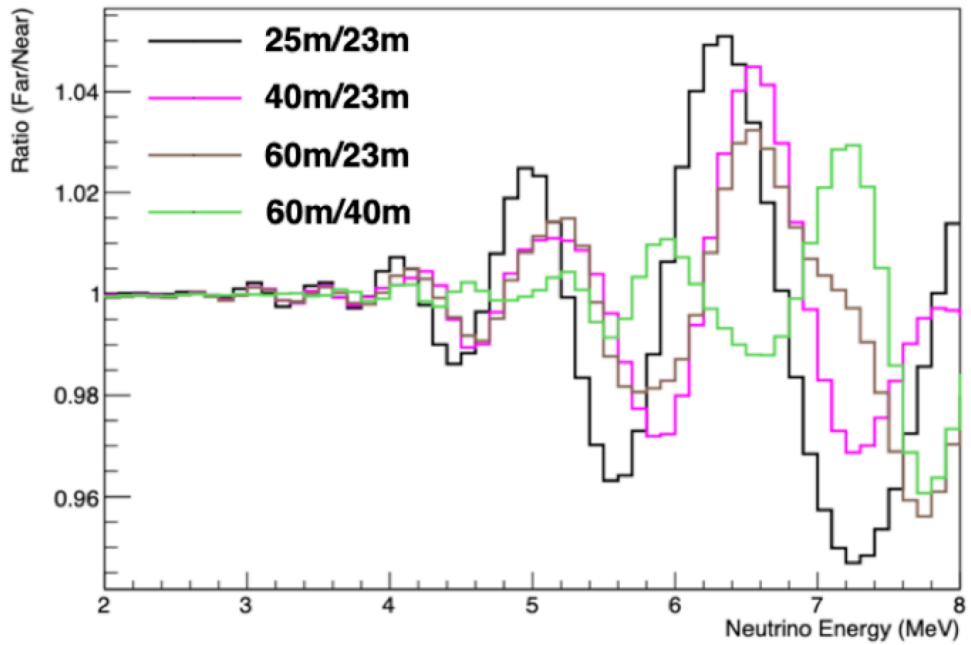


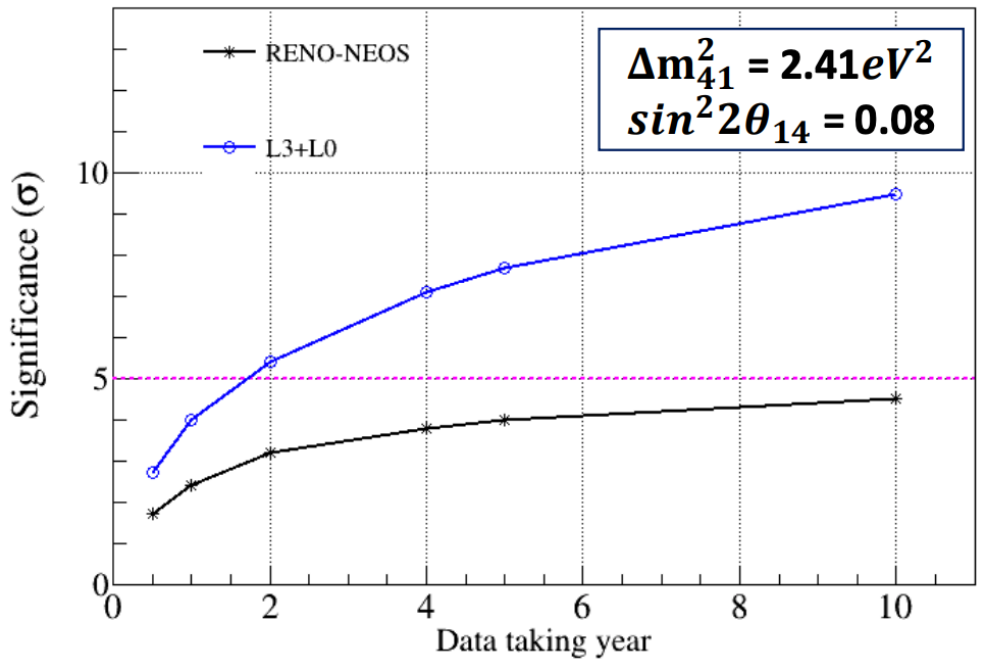


RENE Phase-1: Reactor Experiment for Neutrinos and Exotics

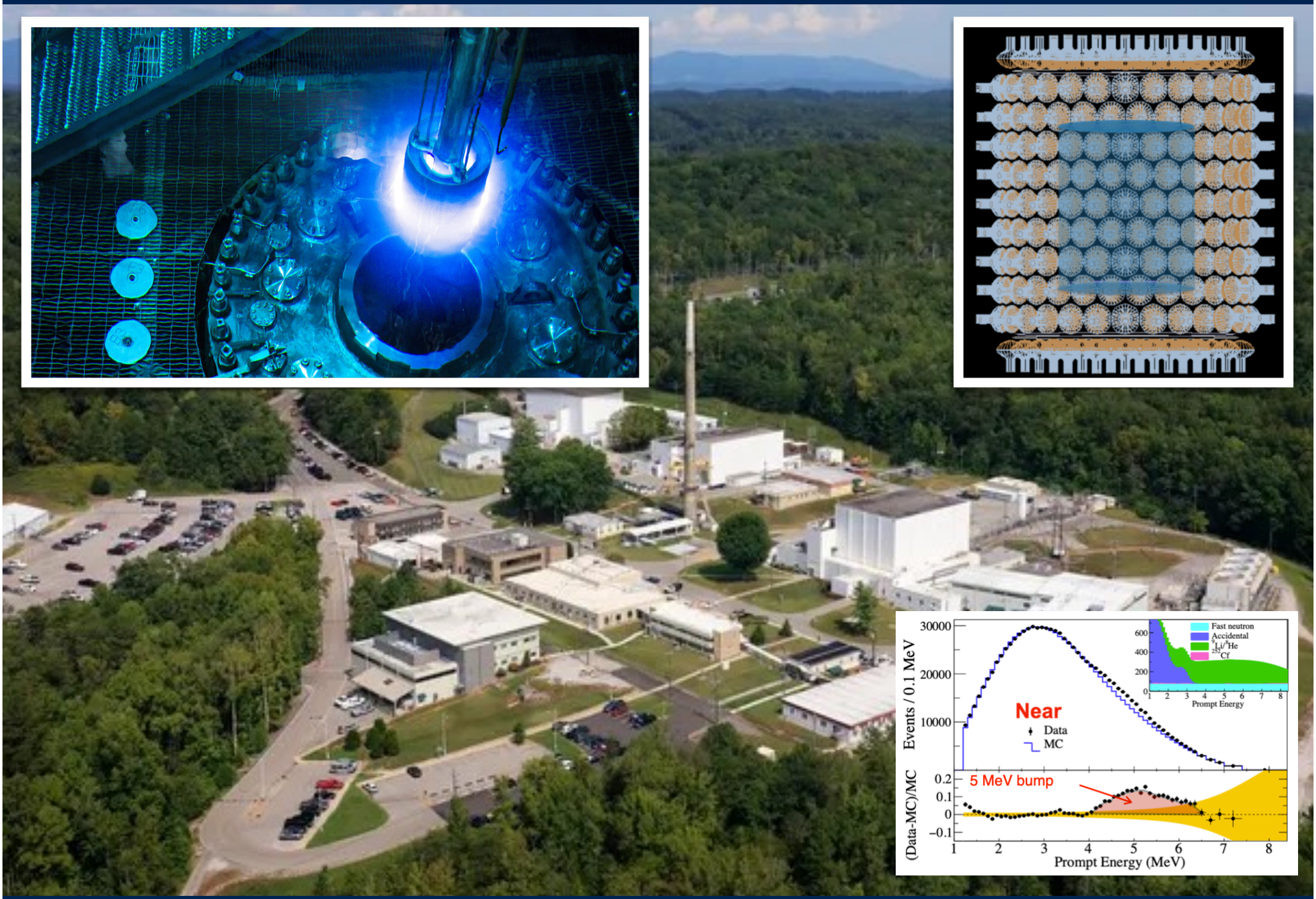
- RENE Collaboration is formed (Nov. 2022)
  - About 30 members ~10 institutions
- Detector design is progressing
  - A uniform unsegmented volume detector with improved energy resolution
  - Mobile or multiple detectors
  - Expect data taking in 2023~







RENE Phase-2 (provisonal)



Summary

- Report updated results using **RENO 2900 days data**
- Precision measurement of θ_{13} and $|\Delta m_{ee}^2|$
- Absolute reactor neutrino flux : **R = 94.1 ± 1.9 % (for HM)**
- Correlation between 5 MeV excess and ^{235}U fission **(3.2σ C.L.)**
- 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 ^{8}Li and ^{8}He rate at RENO: **PRD 105, L111101 (2022)**
- RENE experiment (@nearest location) will proceed
  for sterile neutrino search, exotics search, and precision measurements