

Results of reactor antineutrinos at RENO

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On behalf of the RENO collaboration

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NEUTRINO 2022

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<https://neutrino2022.org/>

■ Brief introduction of RENO

Latest results from RENO	Poster	
■ Analysis for θ_{13} & Δm_{ee}^2		
■ Measurement of the smallest neutrino mixing angle using reactor antineutrino events with neutron capture on hydrogen at RENO	Sang-Yong Kim	#704
■ Measurement of cosmogenic Li/He production rate	Hyun-Ki Lee	#036
■ Reactor antineutrino flux and spectrum at RENO	Seok-Gyeong Yoon	#599
■ Sterile neutrino search		

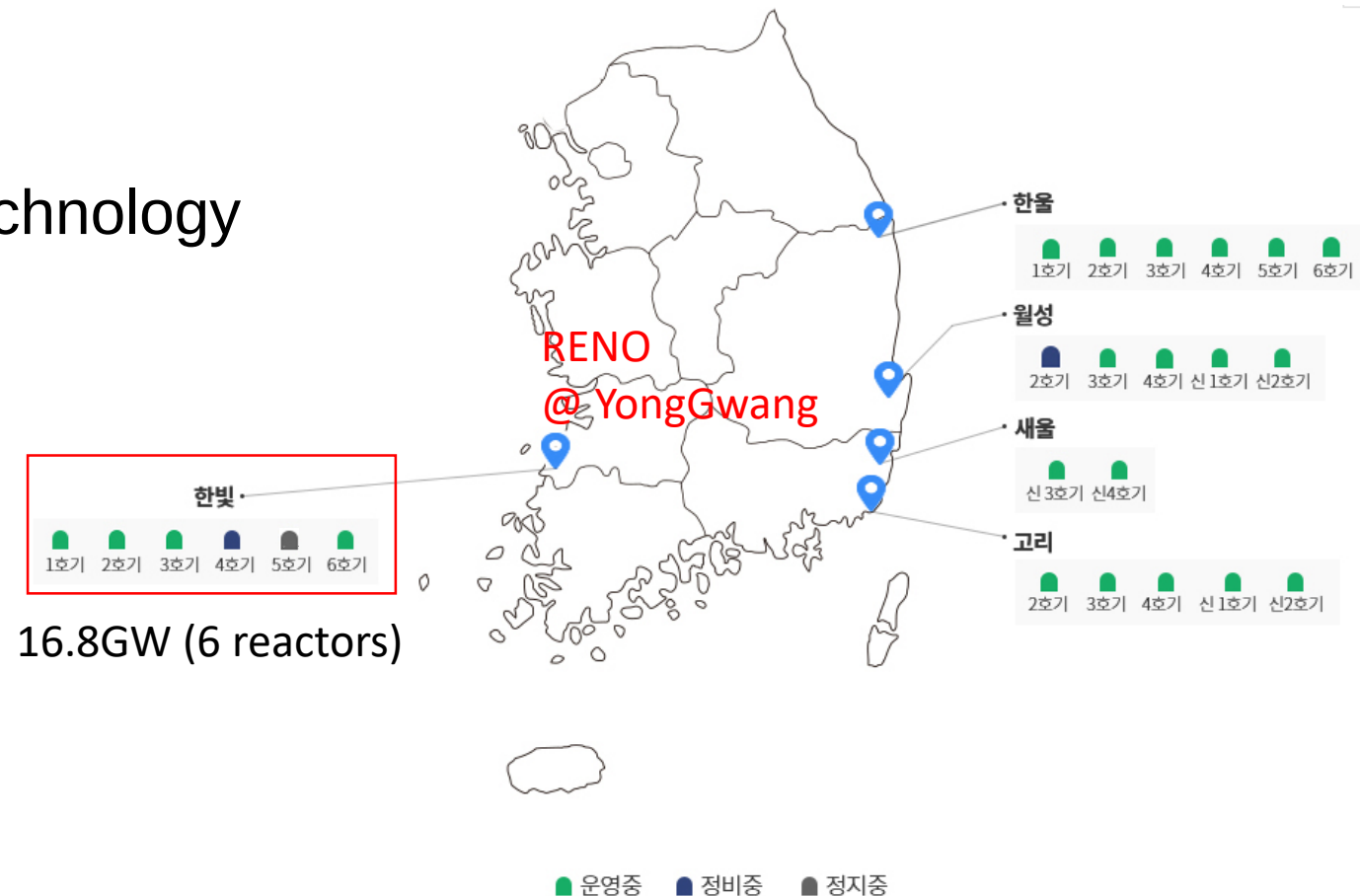
■ Summary

(7 institutions and 30 physicists)

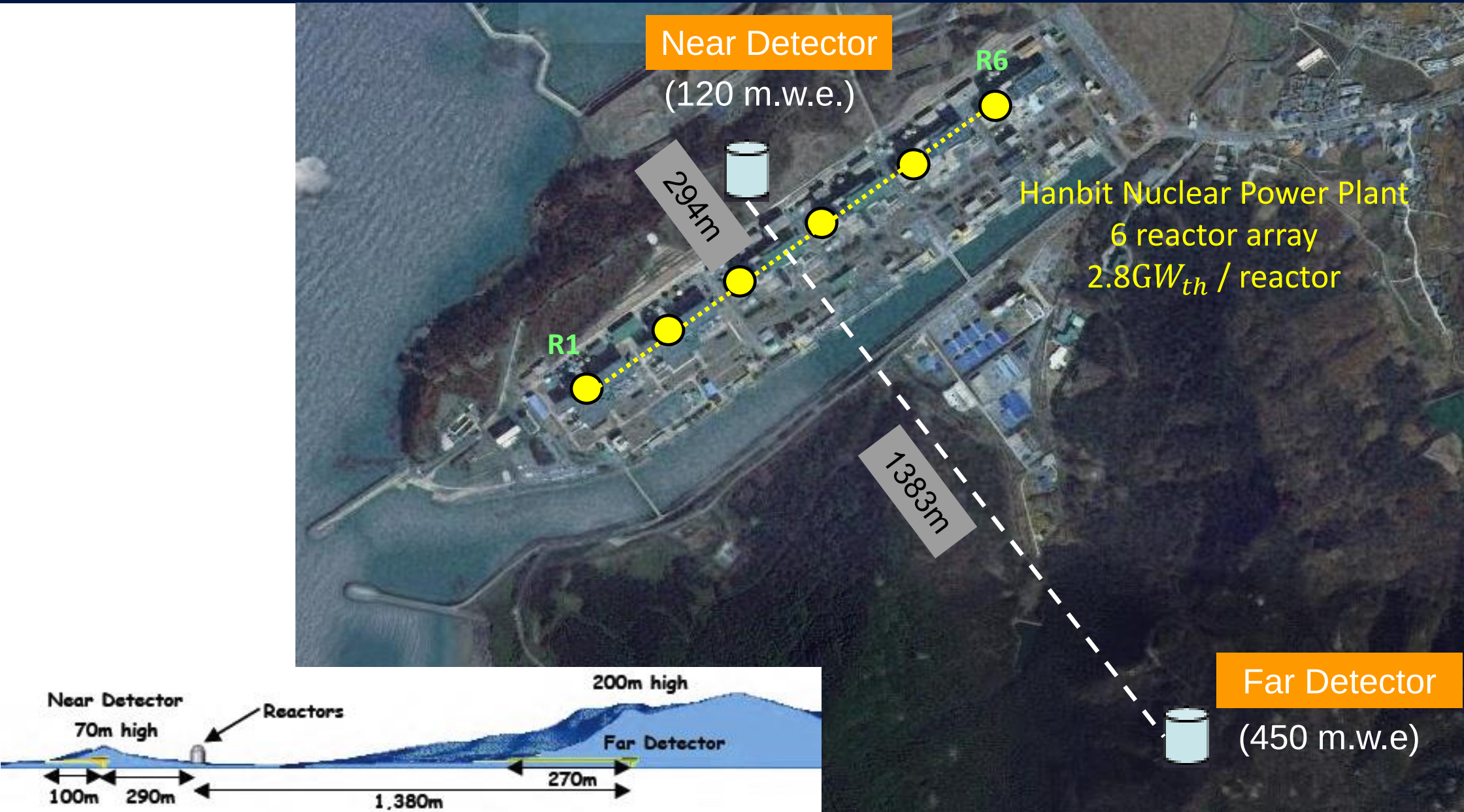
- Chonnam National University
- Dongshin University
- Gwangju Institute of Science and Technology
- Gyeongsang National University
- Kyungpook National University
- Seoul National University
- Seoyeong University
- Sungkyunkwan University



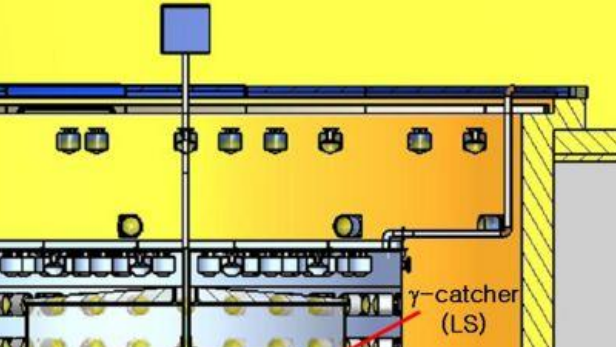
- Start of project : 2006
- Data-taking with both near & far detectors has been on progress since Aug. 2011



RENO Experimental Set-up



RENO Detector



~400 10" PMTs

Target (Gd-loaded LS) - 16.5 tons
 γ -catcher (LS) - 29 tons
Buffer (Mineral oil) - 64 tons
Veto (Water) - 353 tons

(Prompt signal)

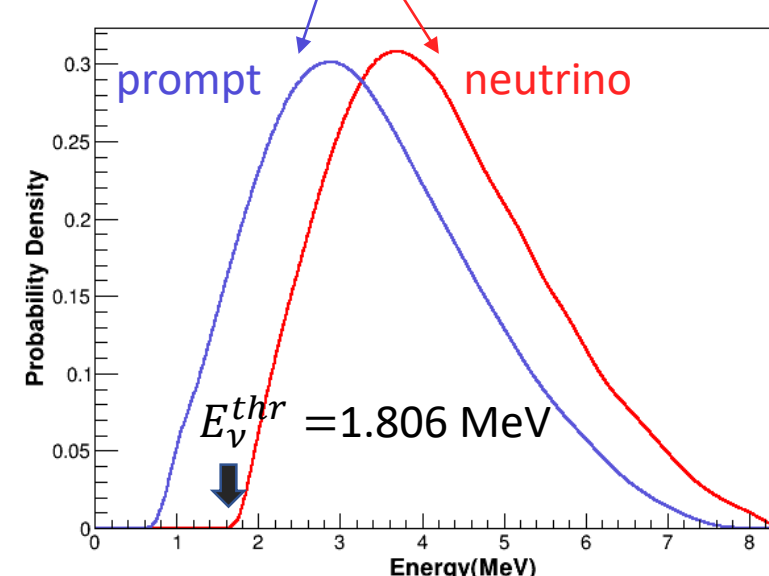
$$\bar{\nu}_e + p \rightarrow e^+ + n \quad \sim 200 \mu\text{s}$$

Inverse Beta Decay (IBD)

(Delayed signal)

$$+ p \rightarrow D + \gamma \quad (2.2 \text{ MeV})$$
$$+ \text{Gd} \rightarrow \text{Gd} + \gamma\text{'s} \quad (8 \text{ MeV})$$

$\sim 26 \mu\text{s}$
(0.1% Gd)

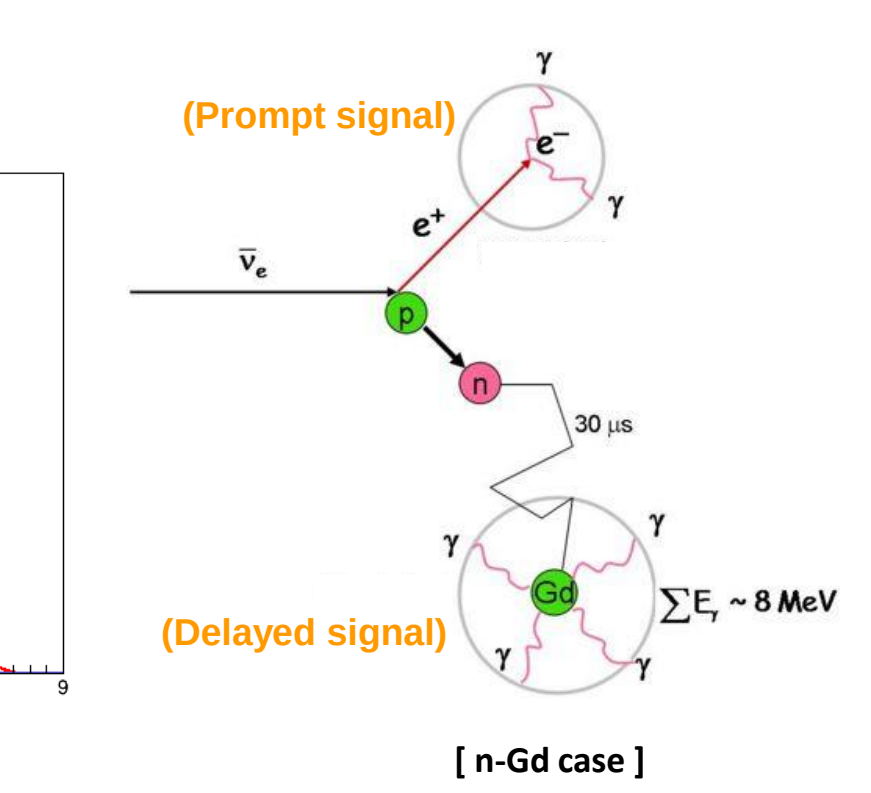


prompt neutrino

$E_v^{thr} = 1.806 \text{ MeV}$

Probability Density

Energy (MeV)



(Prompt signal)

(Delayed signal)

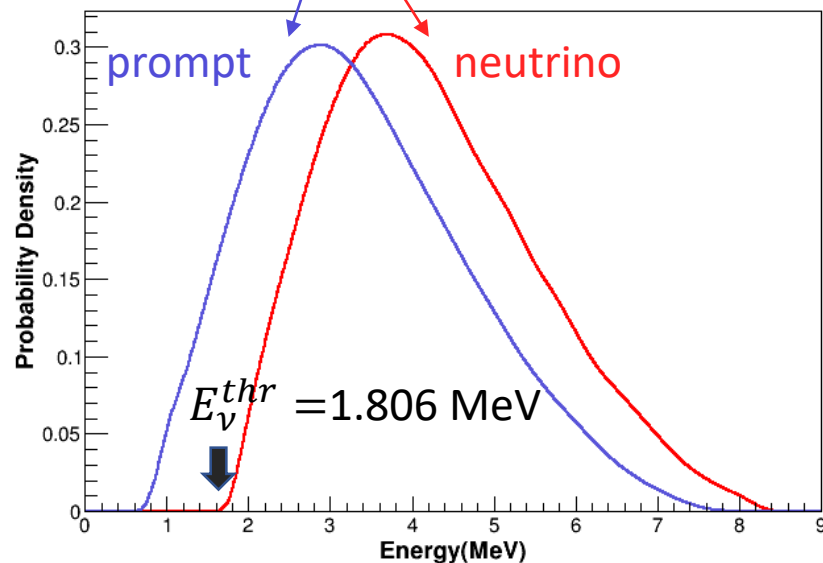
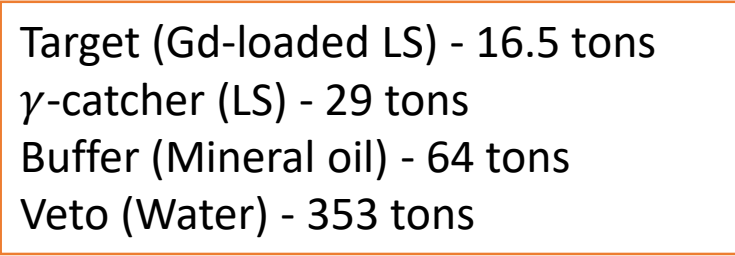
$\Sigma E_\gamma \sim 8 \text{ MeV}$

[n-Gd case]

2022-06-01

NEUTRINO 2022 (K.K. Joo)

5



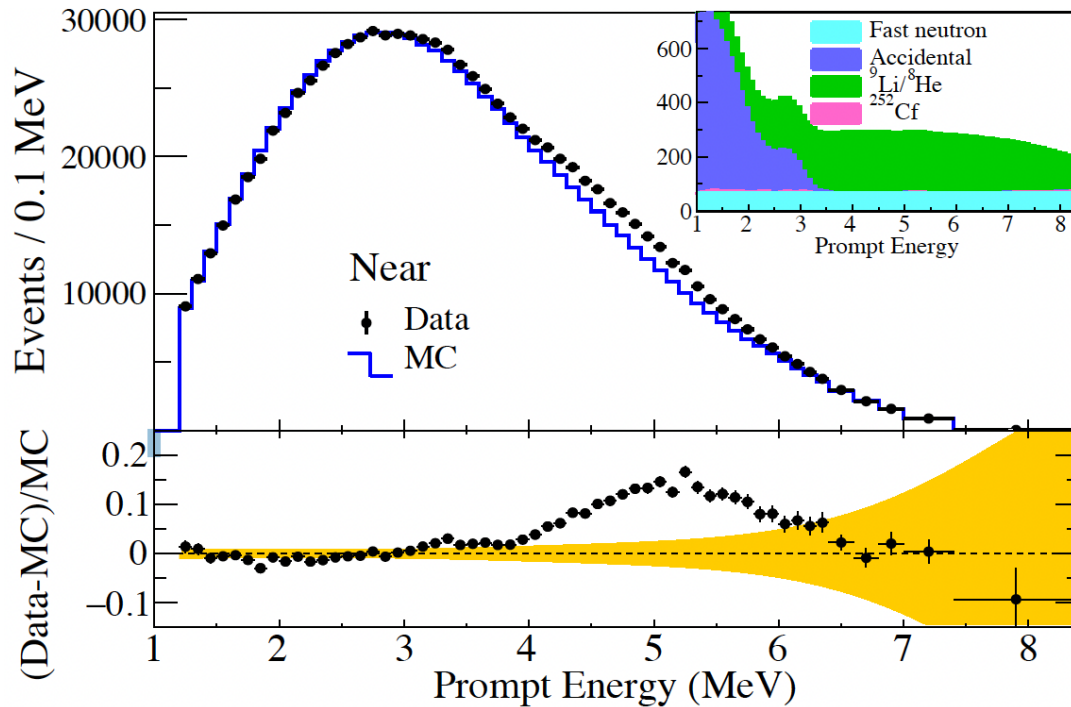
Recent Results from RENO

- Updated analysis of 2900 days of **n-Gd** data to measure $|\Delta m_{ee}^2|$ and θ_{13}
 - ✓ 2200 days result is published at PRL “**Measurement of Reactor Antineutrino Oscillation Amplitude and Frequency at RENO**” (Phys. Rev. Lett. 121 (2018), 201801)
- Updated analysis of 2800 days of **n-H** channel to measure θ_{13}
 - ✓ “**Observation of Reactor Antineutrino Disappearance Using Delayed Neutron Capture on Hydrogen at RENO**” (JHEP 04 (2020) 029, 1500 days)
- “**Measurement of cosmogenic ^9Li and ^8He production rates at RENO**” (arXiv:2204.09215)
- “**Fuel-Composition Dependent Reactor Antineutrino Yield at RENO**” (Phys. Rev. Lett. **122** (2019), 232501)
- “**Measurement of Reactor Antineutrino Flux and Spectrum at RENO**” (Phys. Rev. D **104** (2021), L111301)
- Sterile neutrino search program at RENO
 - ✓ “**Search for Sub-eV Sterile Neutrinos at RENO**” (Phys. Rev. Lett. 125 (2020), 191801)
 - ✓ “**Search for sterile neutrino oscillation using RENO and NEOS data**” (arXiv:2010.14989, accepted by PRD)

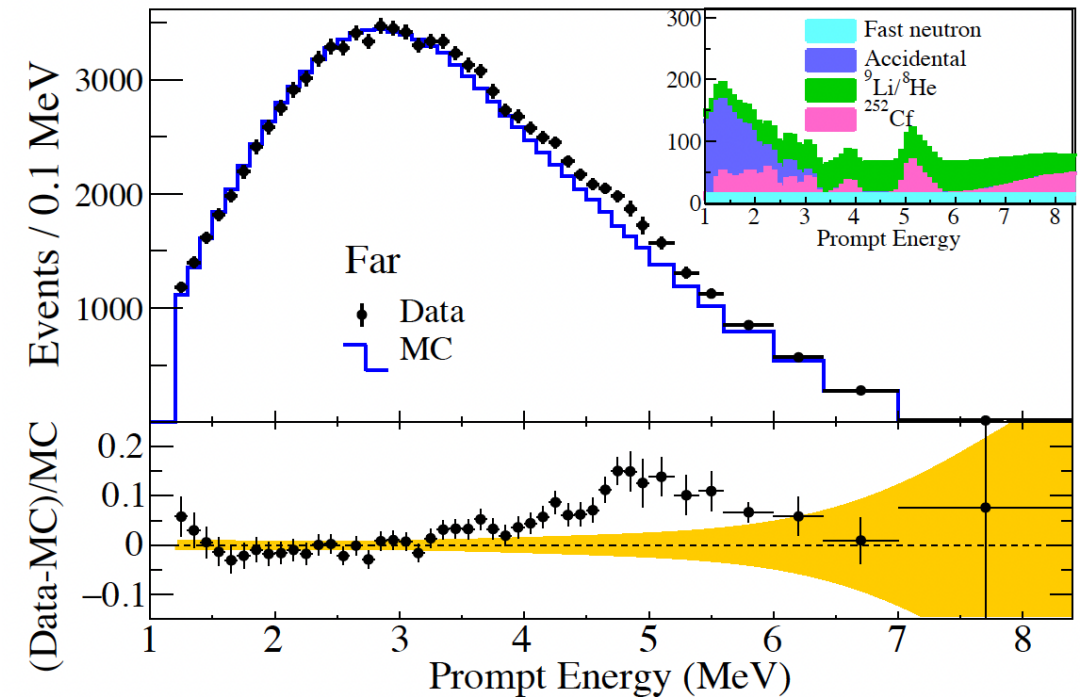
Measured Spectra of IBD prompt signal (n-Gd)

RENO 2900 days (2200 + 700 days) : Aug. 2011 – Dec. 2019

- Clear excess at 5 MeV compared to the Huber-Mueller (HM) prediction

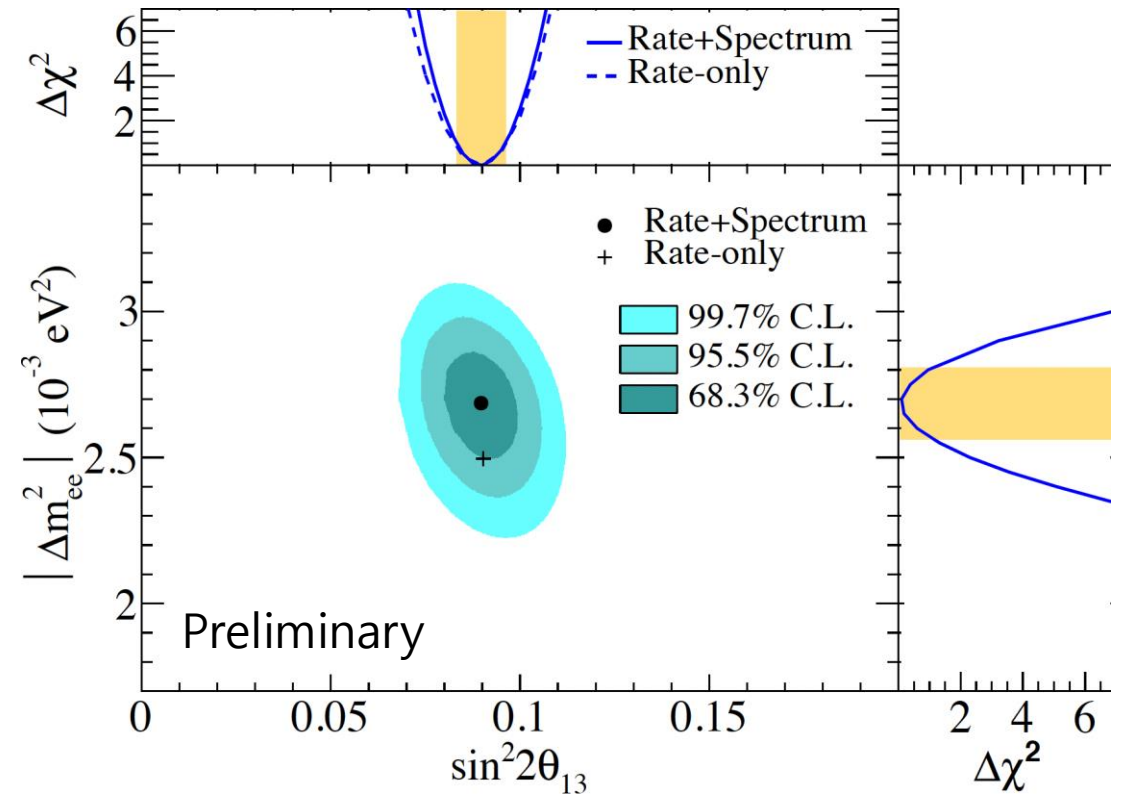
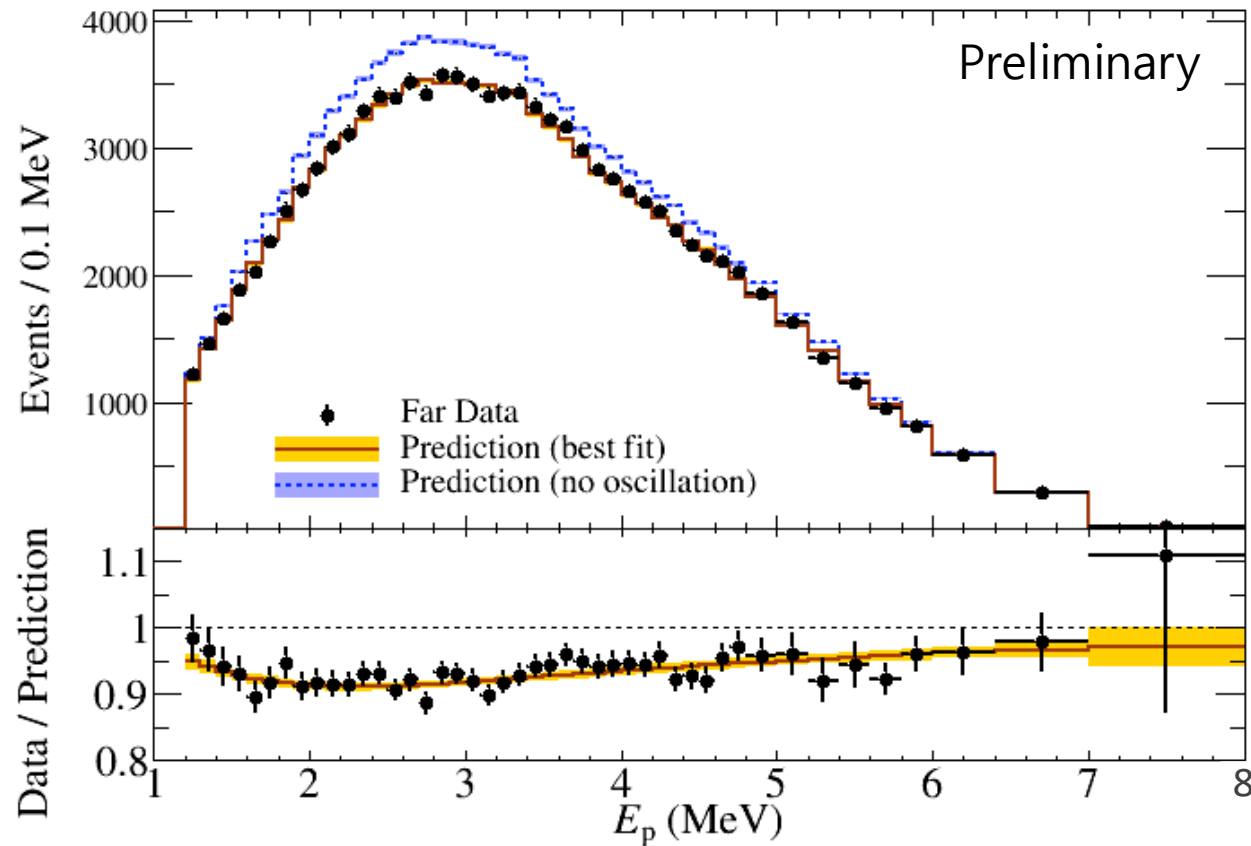


Near Live time = 2509 days
of IBD candidate = 989,736
Background : $2.26 \pm 0.05\%$
5 MeV excess rate : $2.50 \pm 0.06\%$



Far Live time = 2908 days
of IBD candidate = 120,383
Background : $4.77 \pm 0.19\%$
5 MeV excess rate : $2.26 \pm 0.18\%$

Measurement of $|\Delta m_{ee}^2|$ and $\sin^2 2\theta_{13}$ (n-Gd)



Energy-dependent
disappearance of reactor
antineutrinos

<2900 days>

$$\sin^2 2\theta_{13} = 0.0892 \pm 0.0044(\text{stat.}) \pm 0.0045(\text{sys.})$$

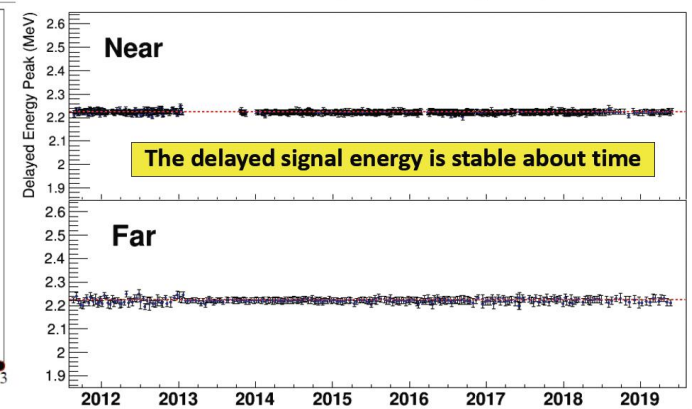
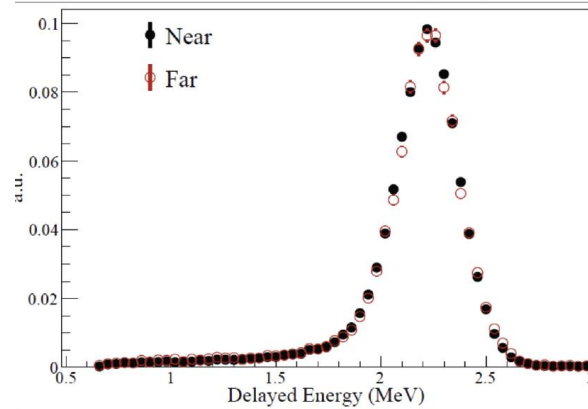
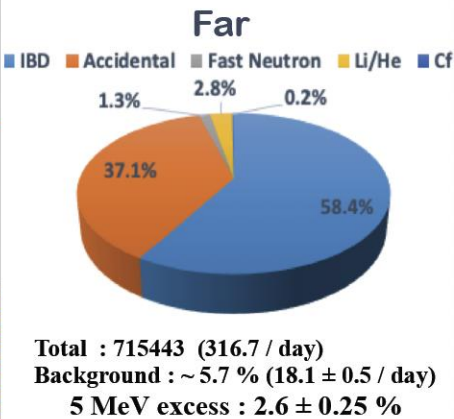
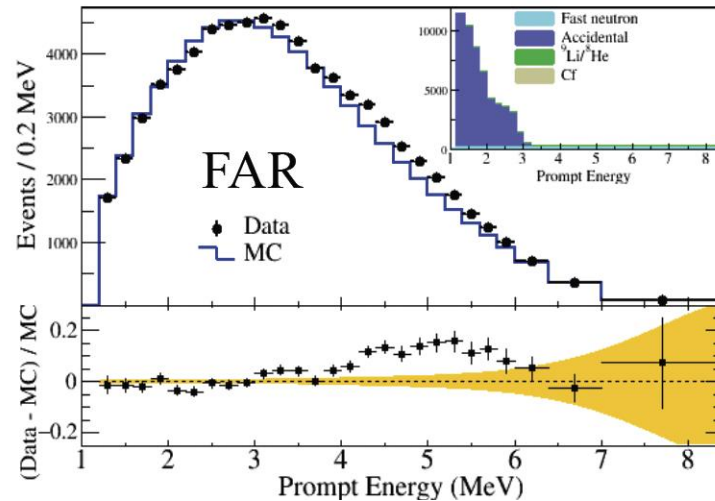
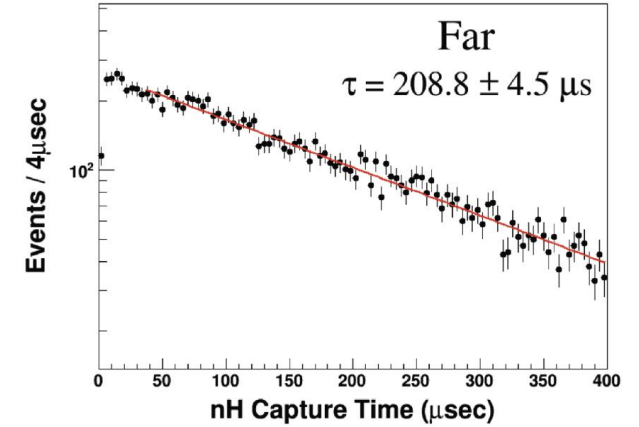
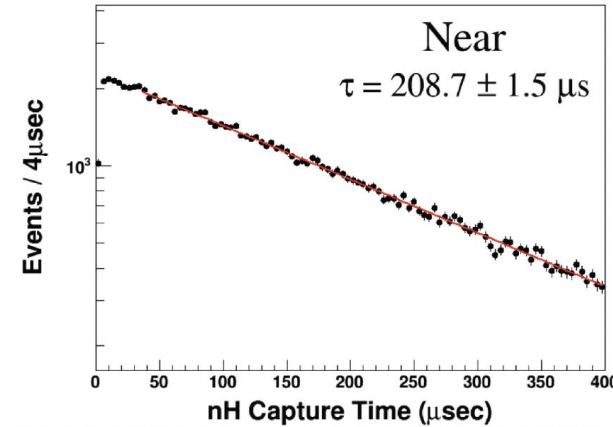
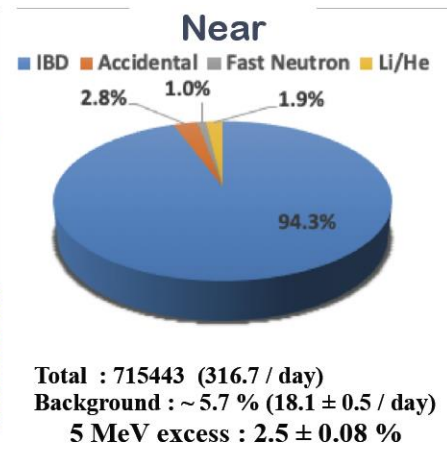
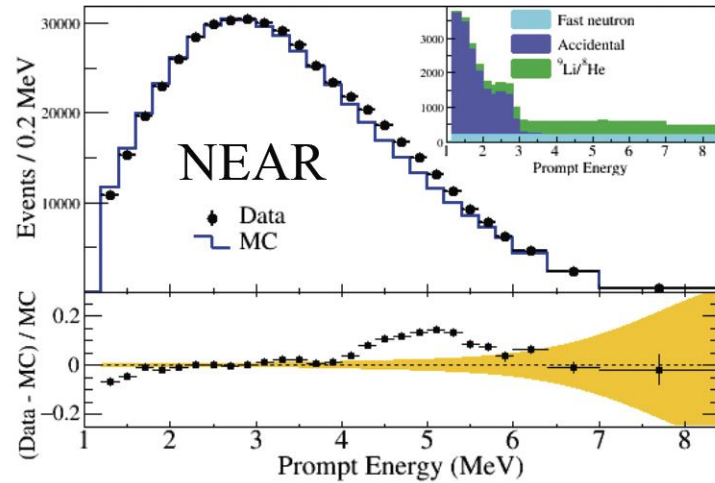
($\pm 7.0\%$)

$$|\Delta m_{ee}^2| = 2.74 \pm 0.10(\text{stat.}) \pm 0.06(\text{sys.}) (\times 10^{-3} \text{ eV}^2)$$

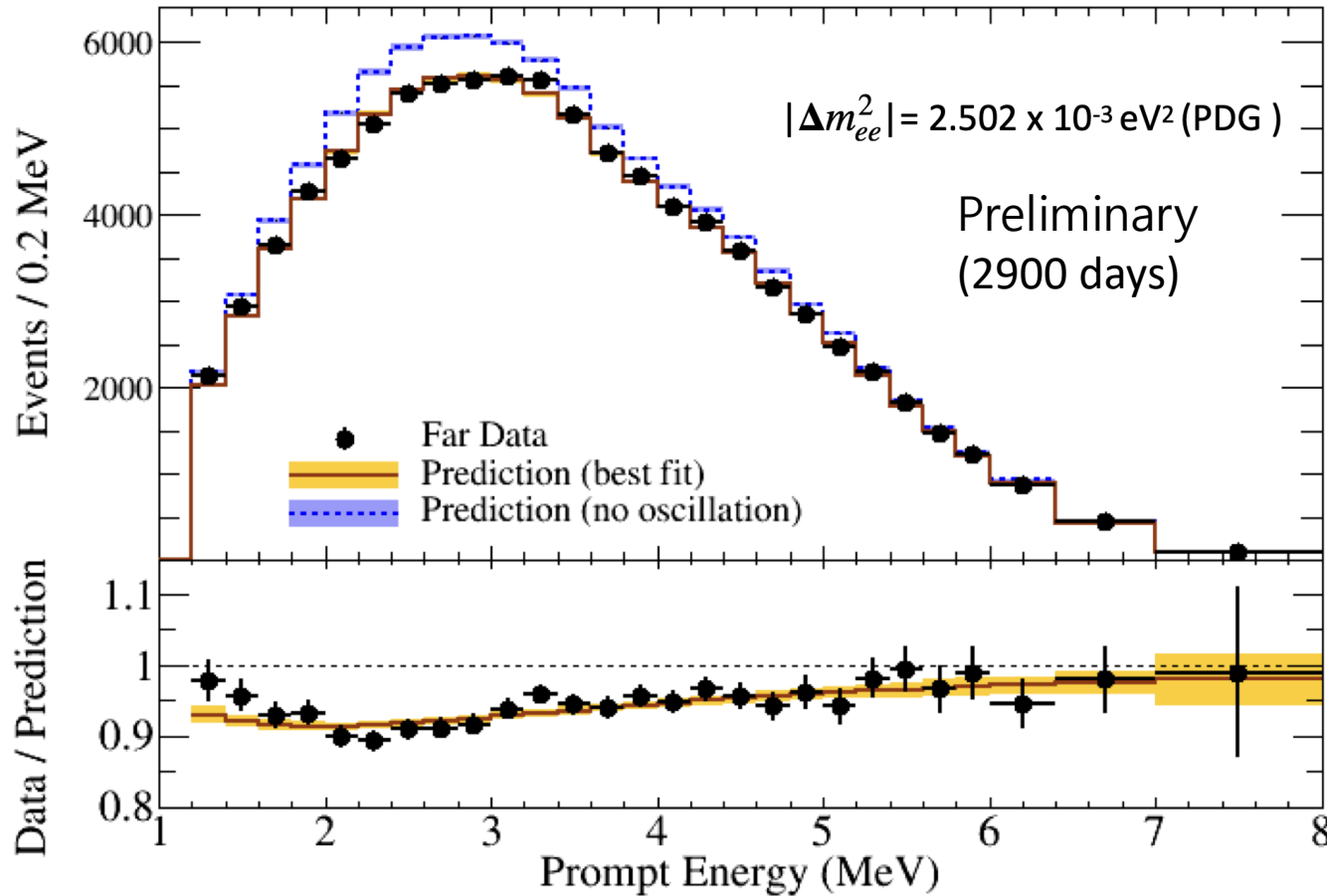
($\pm 4.4\%$)

Independent measurement of IBD using n-H channel

- Neutron capture with Hydrogen $\bar{\nu}_e + p \rightarrow e^+ + \textcircled{n} \longrightarrow + \text{H}^+ \rightarrow \text{D} + \gamma \text{ (2.2 MeV)}$
~200 μs



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



- Improved statistics and PMT flasher events removal
- Energy-dependent disappearance of reactor antineutrinos in n-H case
- Obtained a consistent result with n-Gd measurement

Poster presentation #704

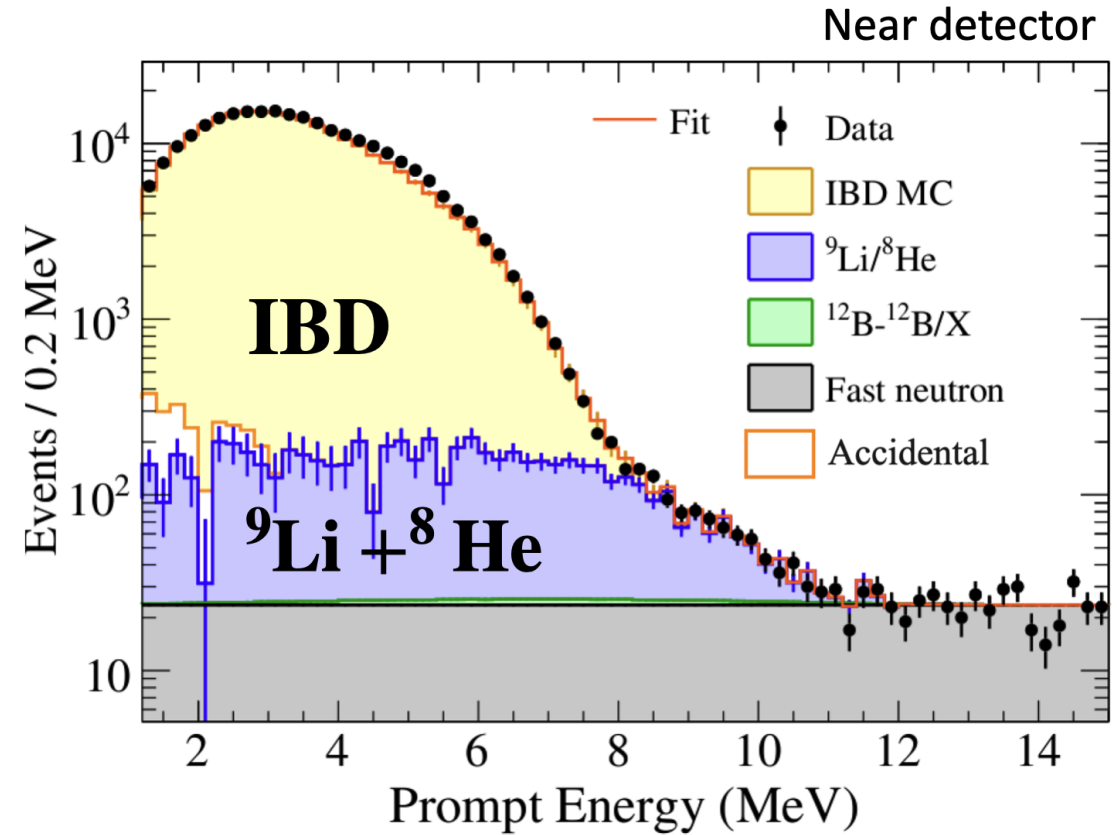
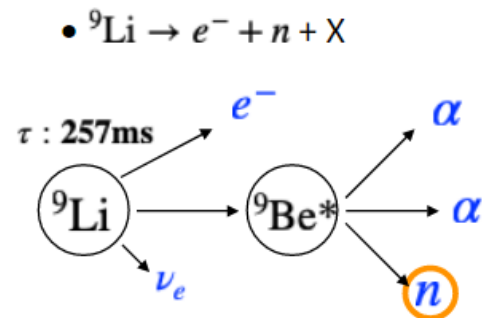
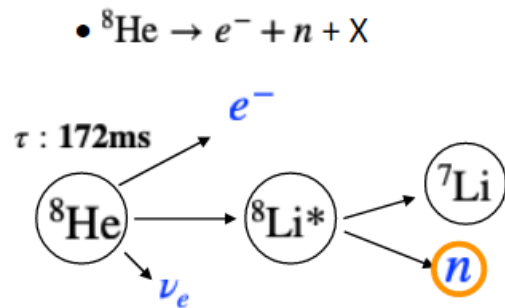
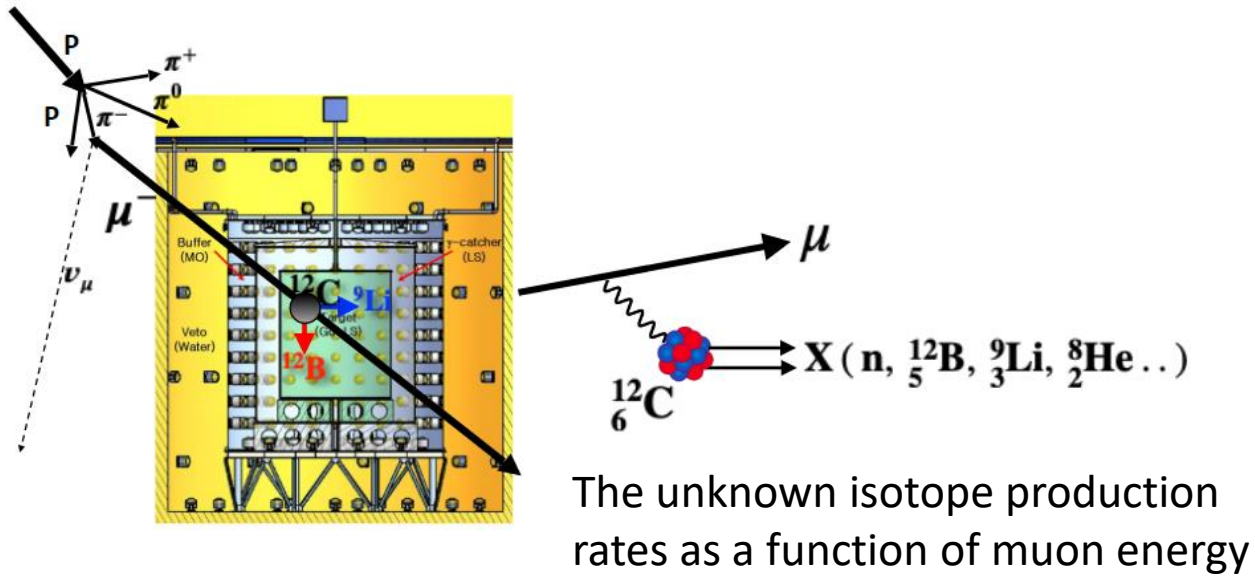
Sang-Yong Kim, "Measurement of the smallest neutrino mixing angle using reactor antineutrino events with neutron capture on hydrogen at RENO"

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

JHEP(2019) : 1500days n-H result $\rightarrow \sin^2(2\theta_{13}) = 0.0858 \pm 0.008(\text{stat.}) \pm 0.014(\text{syst.})$

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

Cosmogenic ^9Li and ^8He $\beta - n$ Decays

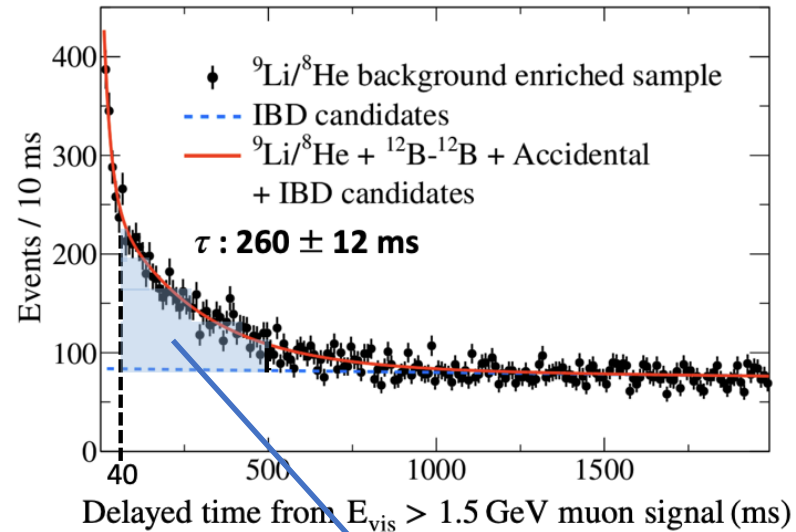


arXiv:2204.09215

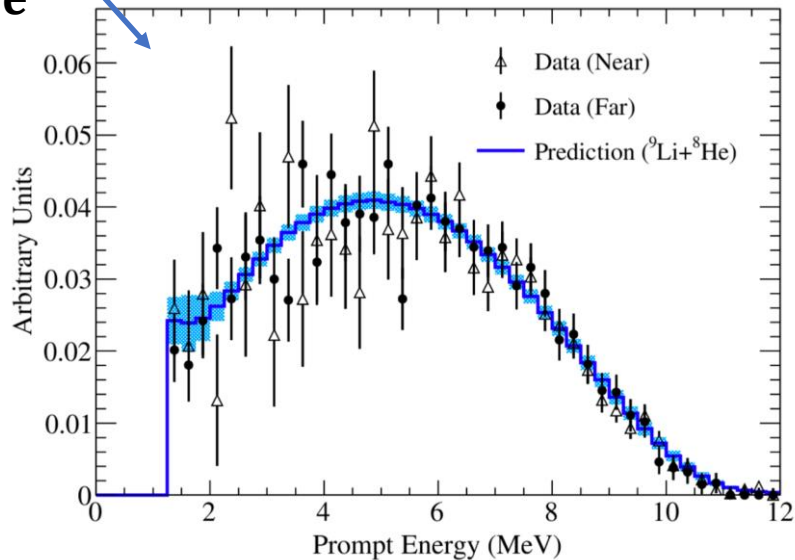
Poster presentation #036
Hyun-Ki Lee, "Measurement of cosmogenic Li/He production rate"

Measured yields of cosmogenic ^9Li and ^8He

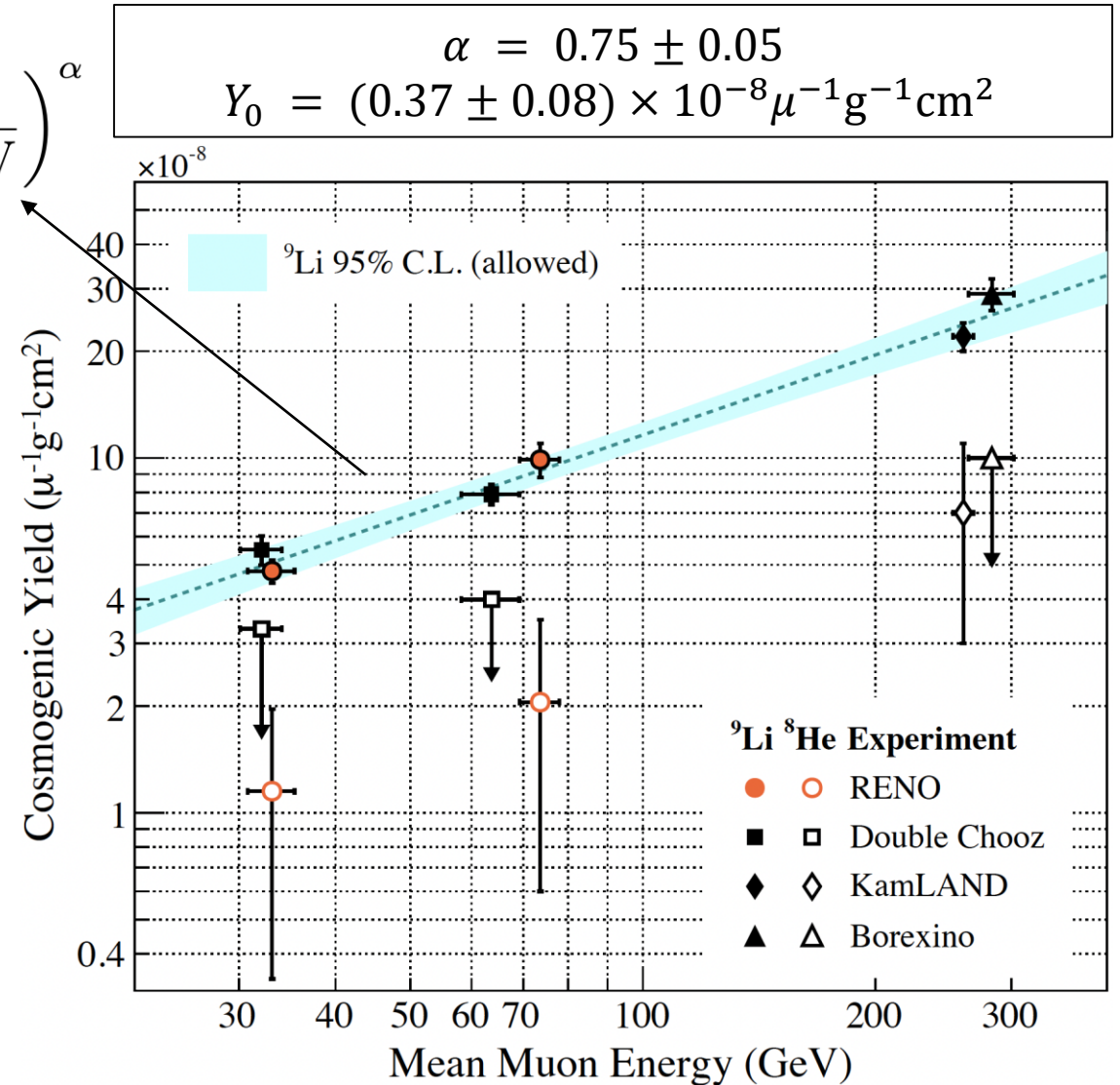
Direct measurement of ^9Li and ^8He products from their β -decay spectra



^9Li and ^8He
 β spectrum

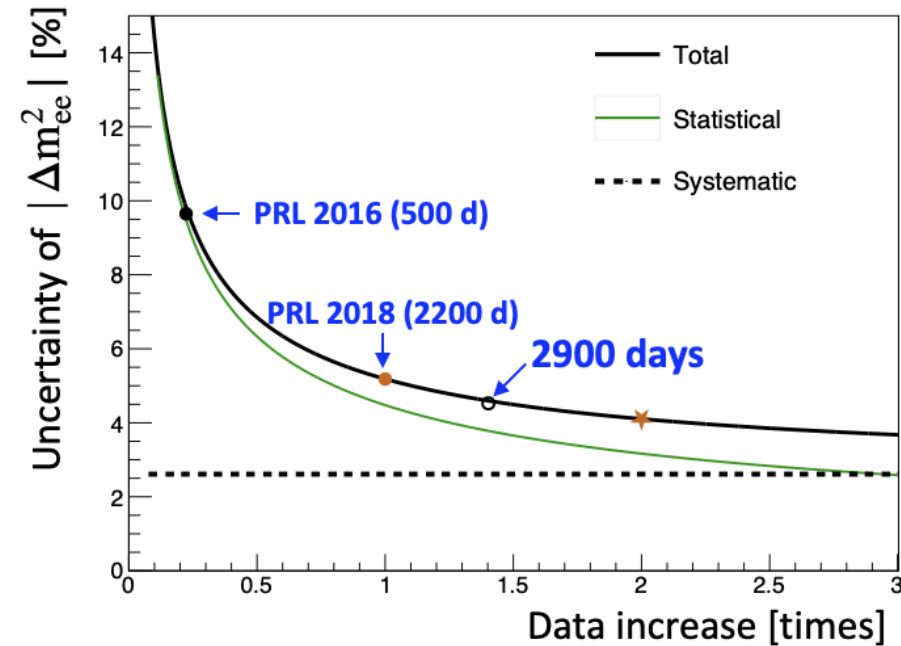
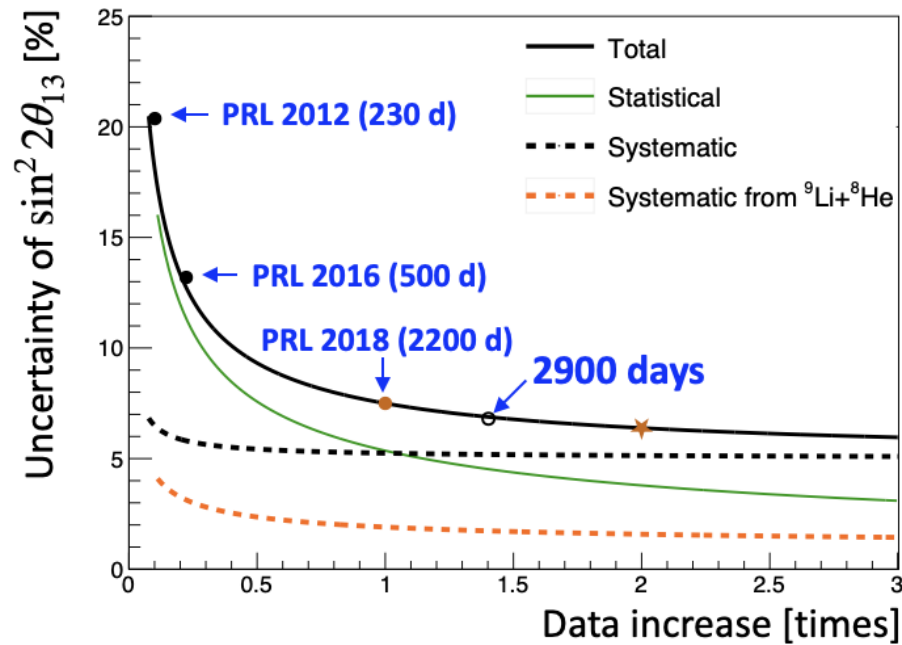


$$Y = Y_0 \left(\frac{\bar{E}_\mu}{1 \text{ GeV}} \right)^\alpha$$



Prospect of measurement of $\sin^2 2\theta_{13}$ and $|\Delta m_{ee}^2|$ at RENO

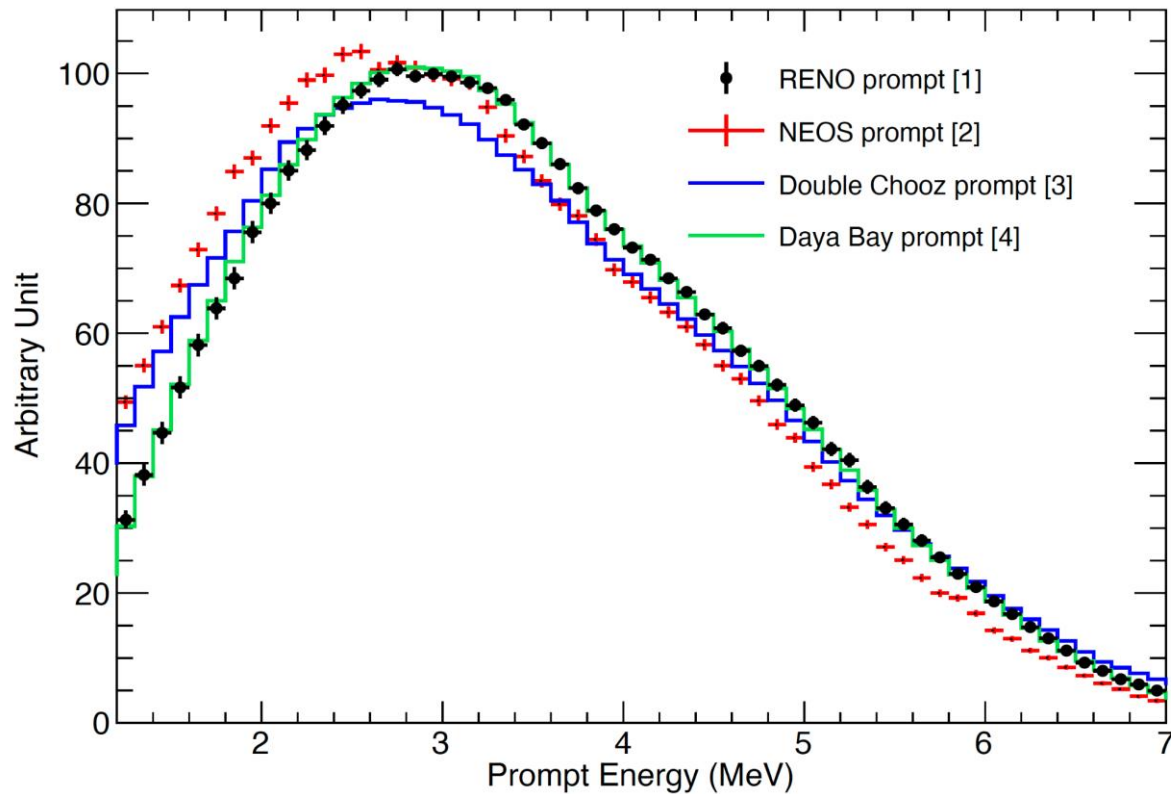
- $\times 2$ more data (★) from 2200 days publication
Error $\rightarrow \sin^2 2\theta_{13} : 7.6 \% \rightarrow 6.4 \%, |\Delta m_{ee}^2| : 5.2 \% \rightarrow 4.1 \%$
- There is also room to reduce systematic uncertainties.



Data increase 1 refer to "2200 days".

Reactor “Neutrino” spectrum from unfolding

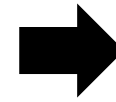
Prompt energy spectrum
(e^+ kinetic energy + pair annihilation, smeared)



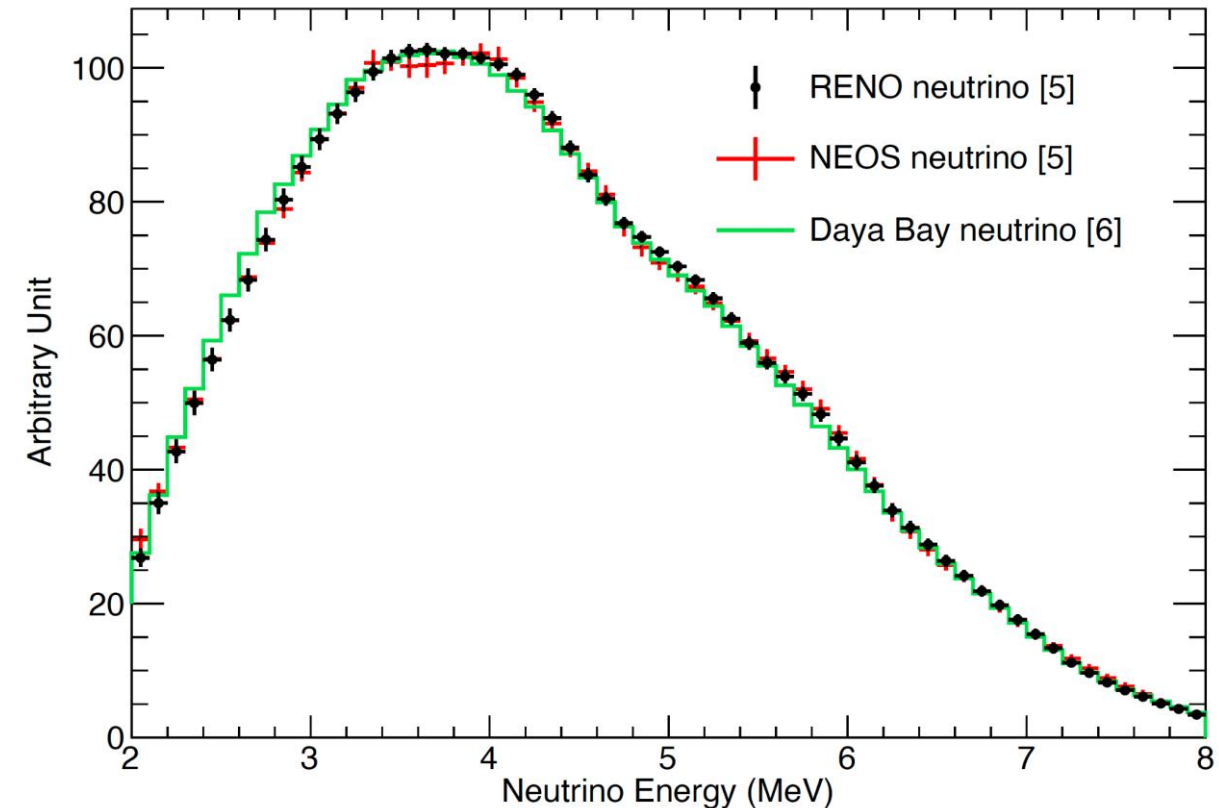
[1] Z. Atif *et al.* (RENO), (2020), arXiv:2010.14989

[3] H. de Kerret *et al.* (Double Chooz), Nature Phys.16, 558(2020), arXiv:1901.09445

[5] Z. Atif *et al.* (RENO), (2020), arXiv:2011.00896.



Reactor neutrino energy spectrum



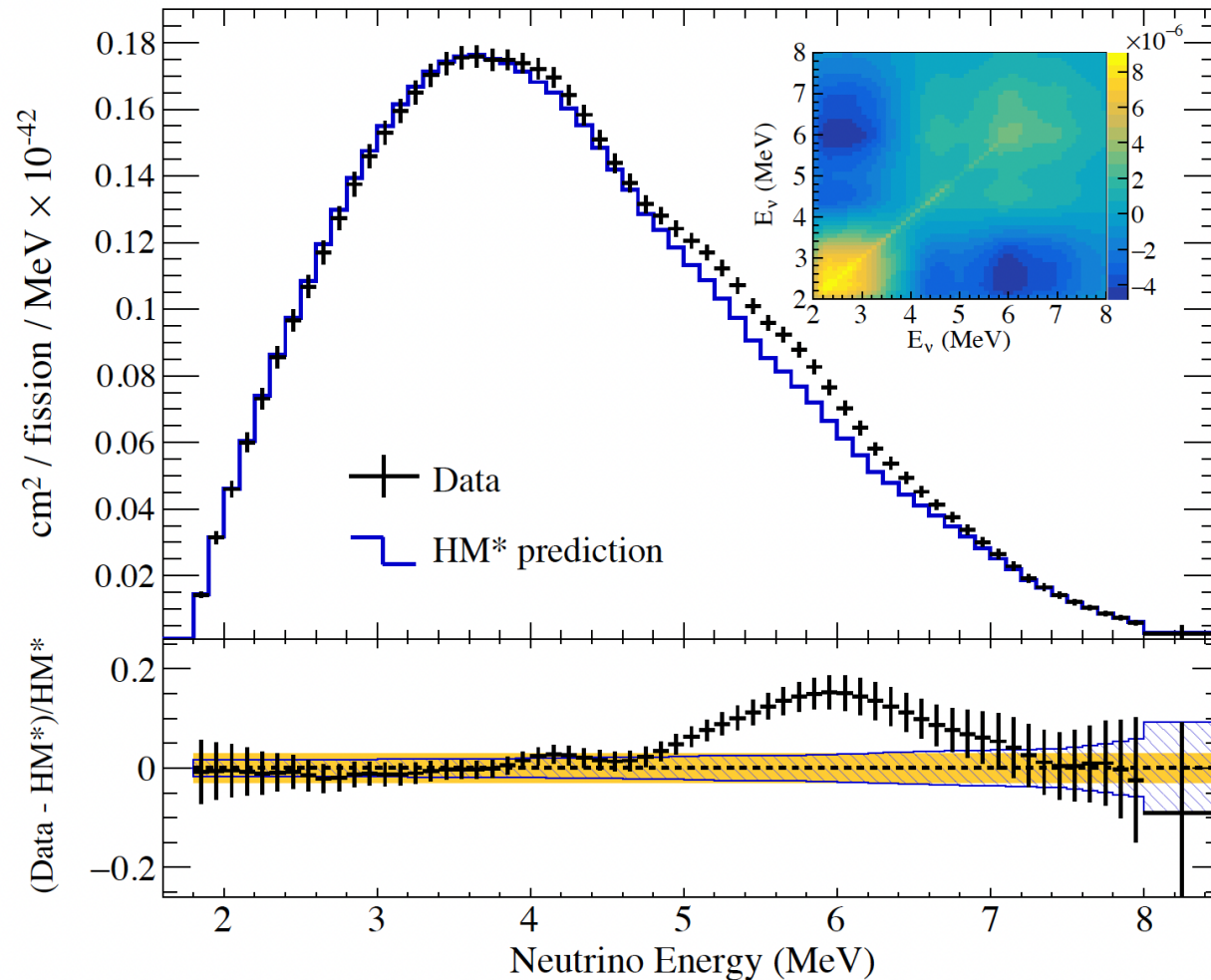
[2] Y. Ko *et al.* (NEOS), Phys. Rev. Lett.118, 121802(2017), arXiv:1610.05134

[4] Adey, D *et al.* (Daya Bay), Phys. Rev. Lett.123, 111801(2019), arXiv:1904.07812

[6] F. P. An *et al.* (Daya Bay), Chin. Phys. C41, 013002(2017), arXiv:1607.05378

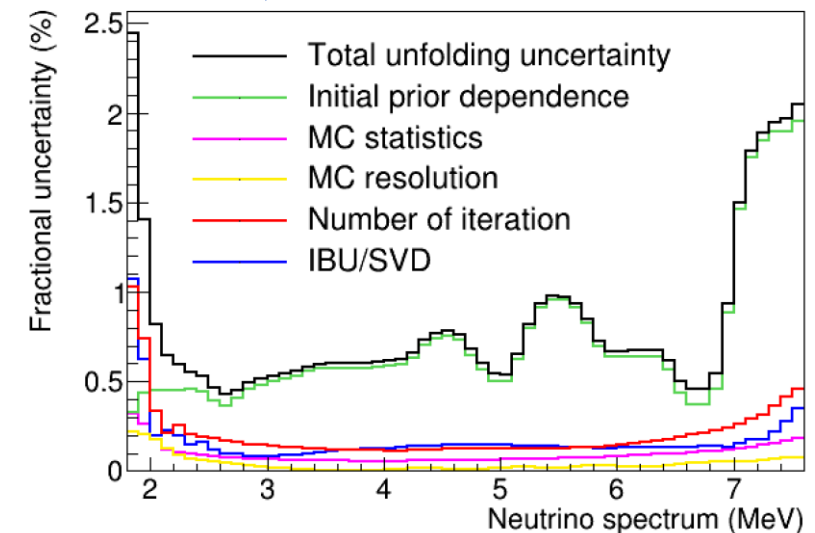
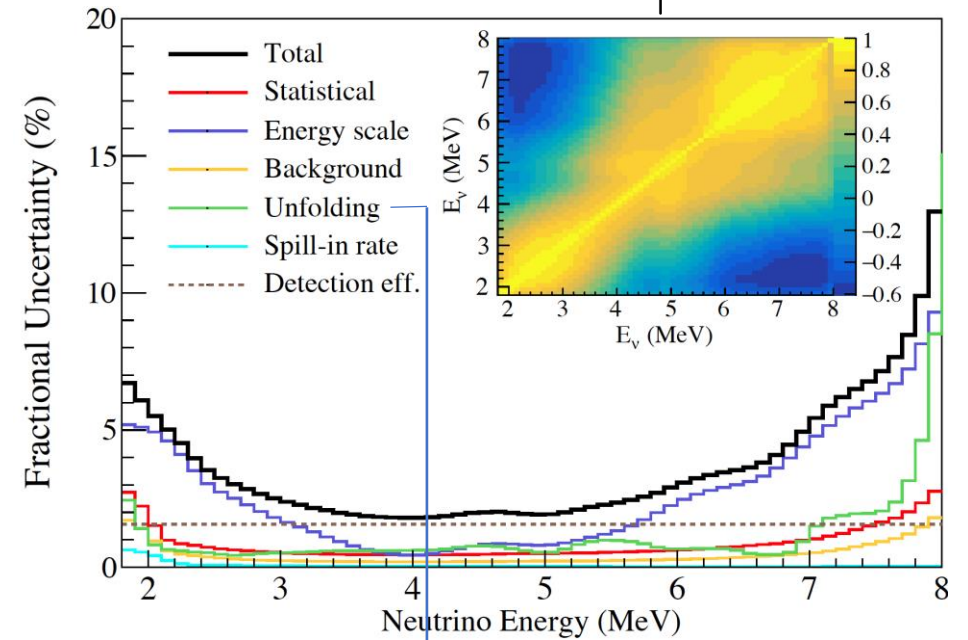
Measured reactor neutrino flux and spectrum

Phys. Rev. D 104 (2021), L11130

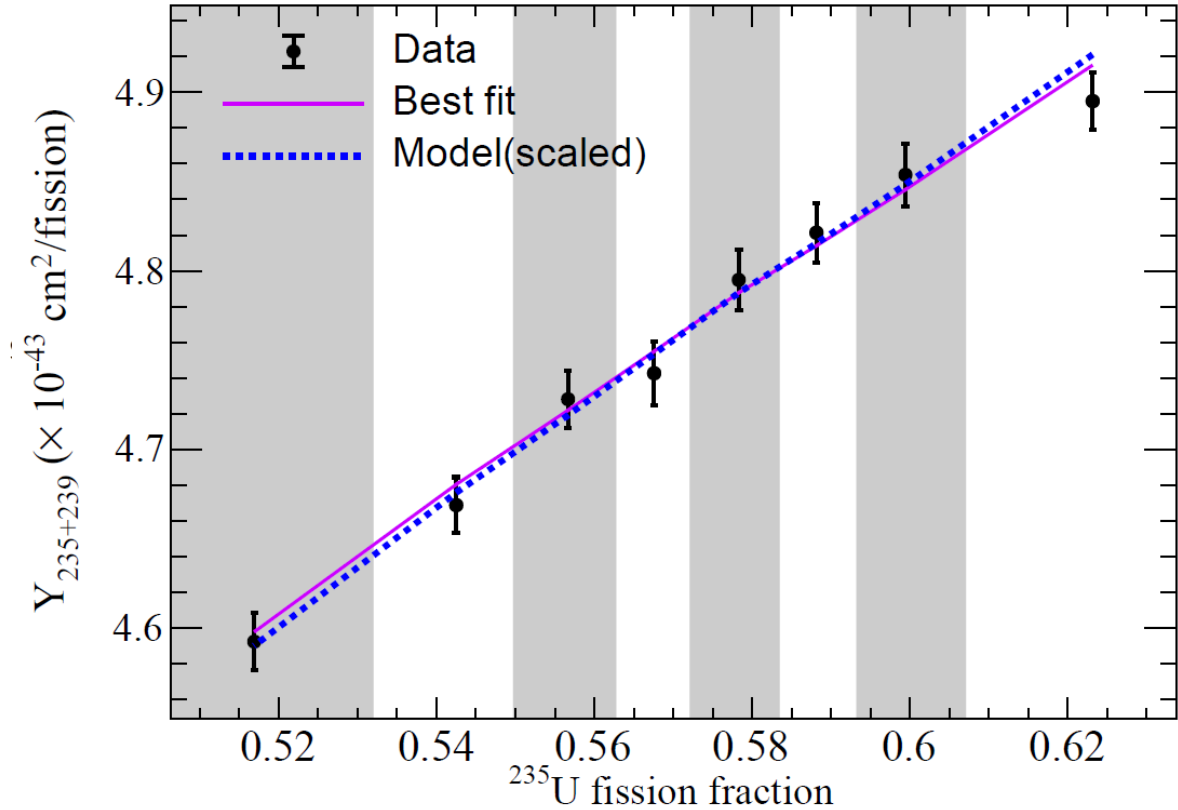
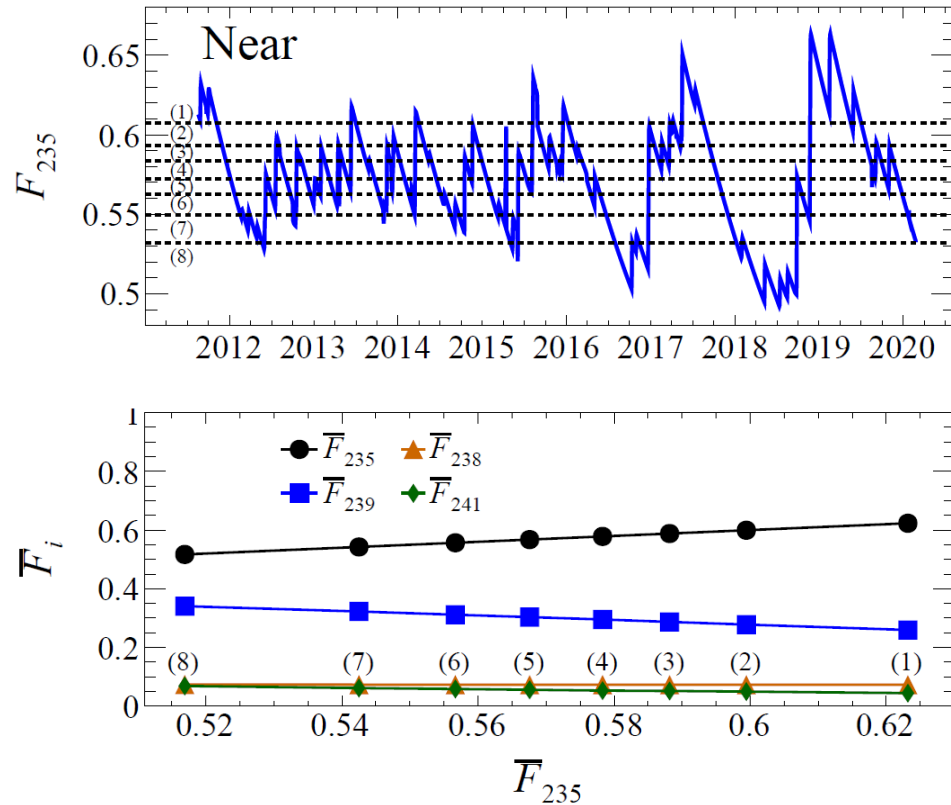


**IBD yield measurement : $(5.852 \pm 0.094) \times 10^{-43} \text{cm}^2 / \text{fission}$
(0.941 $\pm$ 0.015) of HM prediction -> RAA confirmed**

(RAA: reactor antineutrino anomaly)



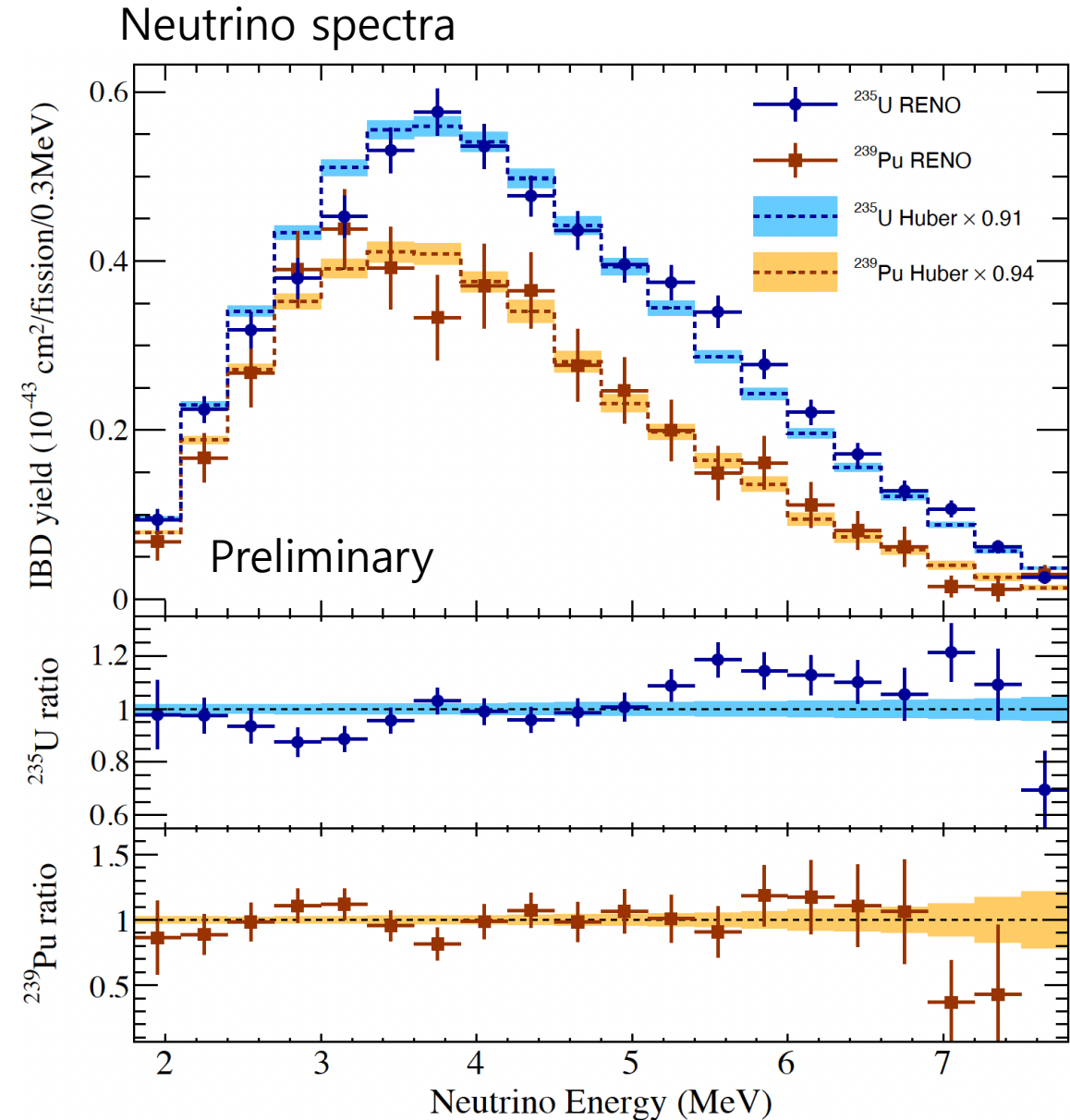
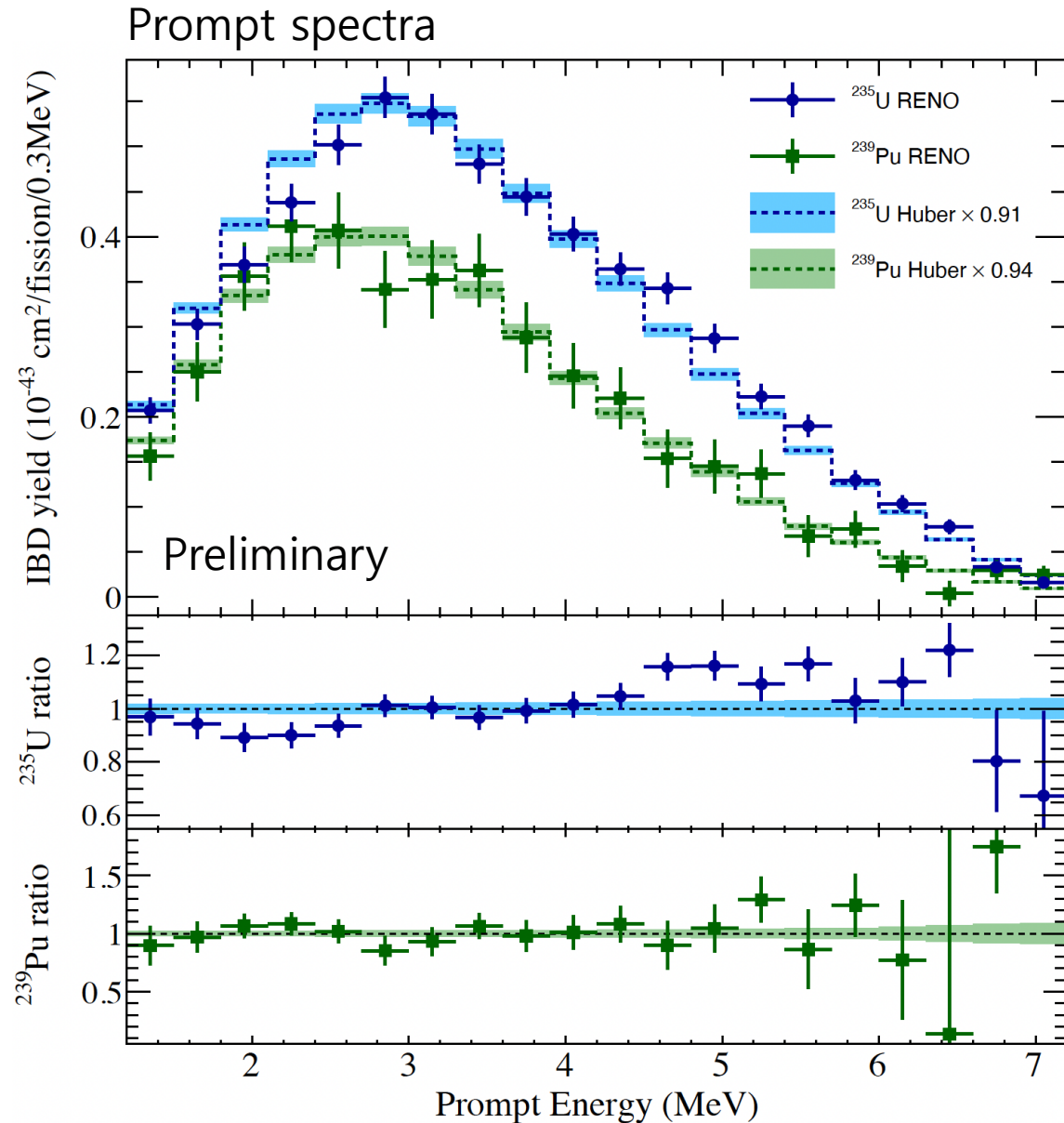
Fuel-composition dependent reactor antineutrino yield



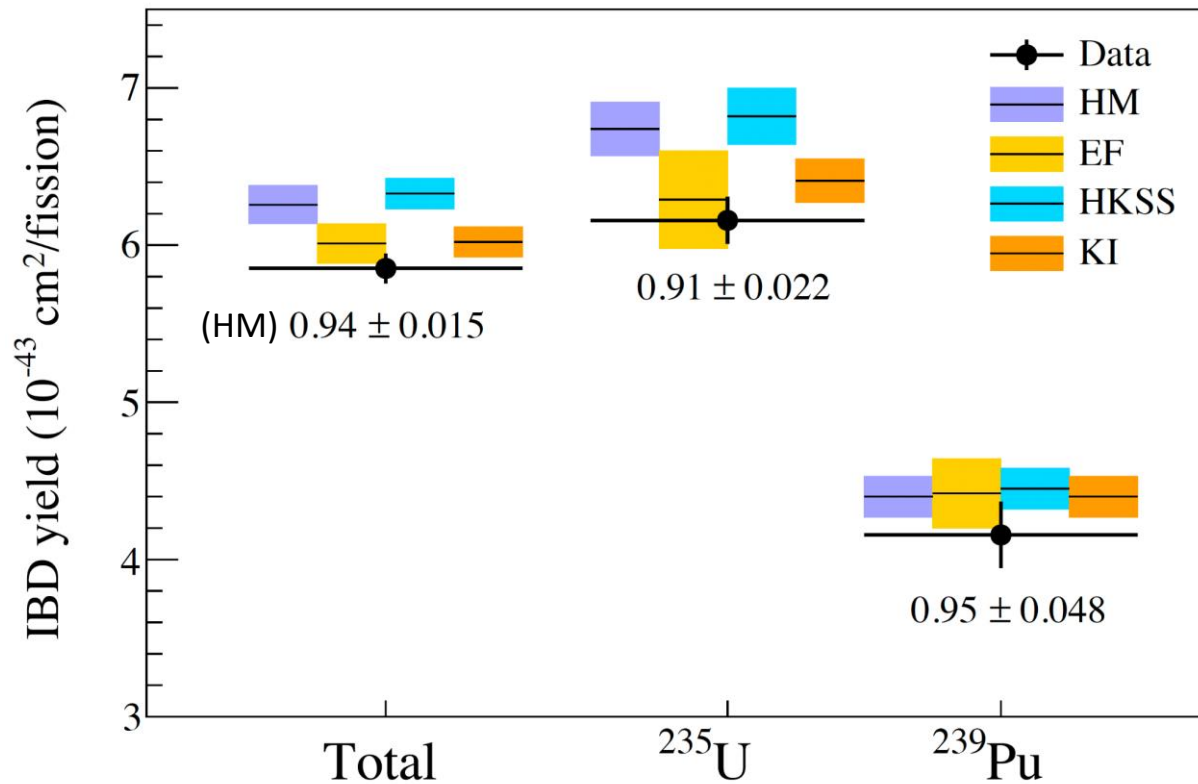
- 8 groups of data with different fission fractions
- Individual isotope contribution to the IBD yield can be separated

$$\chi^2 = \sum_{gr}^{NG} \sum_i^{NE} \left(\frac{Y_{gr,i}^{meas} - Y_{gr,i}^{expect}}{\sigma_{gr,i}^{stat}} \right)^2 + \left(\frac{\epsilon}{\sigma_{escape}} \right)^2 + \left(\frac{\xi}{\sigma_{det}} \right)^2 + \sum_{gr}^{NG} (b_{gr}^{mag})^2 + \sum_i^{NE} (b_i^{shape})^2 + \sum_i^{NE} (m_{238_i}^{shape})^2 + \sum_i^{NE} (m_{241_i}^{shape})^2 + (m_{238}^{norm})^2 + (m_{239}^{norm})^2 + \eta^2$$

Reactor antineutrino spectra from ^{235}U and ^{239}Pu



Measured IBD yields of ^{235}U and ^{239}Pu



- $Y_{235} = (6.16 \pm 0.15) \times 10^{-43} \text{ cm}^2/\text{fission}$
 -> **0.91** of Huber model prediction (**4.1σ**)
- $Y_{239} = (4.16 \pm 0.21) \times 10^{-43} \text{ cm}^2/\text{fission}$
 -> **0.94** of Huber model prediction (**1.6σ**)
- **Similar flux deficit from**
 ^{235}U ($8.6 \pm 2.1\%$) and ^{239}Pu ($5.5 \pm 4.7\%$)

- Recent reevaluation of HM model and presentation of other models (Giunti et al. *Phys.Lett.B* 829 (2022))

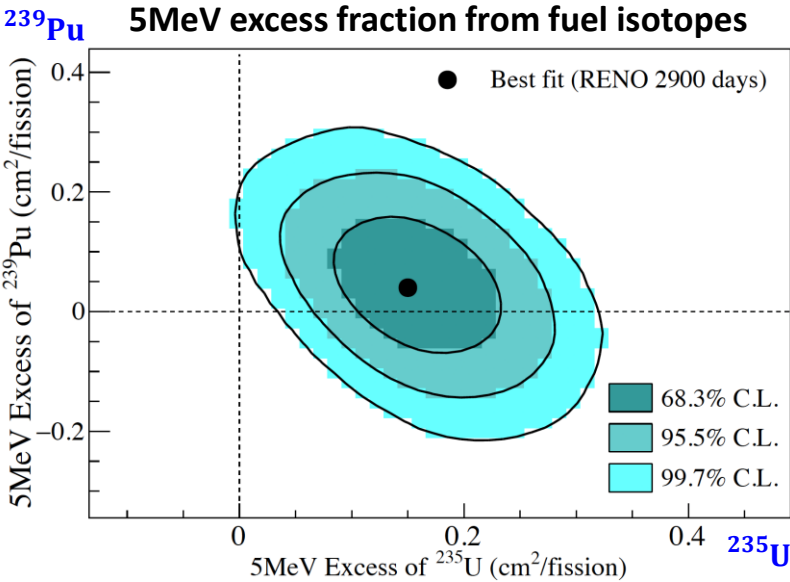
($10^{-43} \text{ cm}^2/\text{fission}$)

Model	σ_{235}	σ_{238}	σ_{239}	σ_{241}
HM	6.74 ± 0.17	10.19 ± 0.83	4.40 ± 0.13	6.10 ± 0.16
EF	6.29 ± 0.31	10.16 ± 1.02	4.42 ± 0.22	6.23 ± 0.31
HKSS	6.82 ± 0.18	10.28 ± 0.84	4.45 ± 0.13	6.17 ± 0.16
KI	6.41 ± 0.14	9.53 ± 0.48	4.40 ± 0.13	6.10 ± 0.16
HKSS-KI	6.48 ± 0.14	10.28 ± 0.84	4.45 ± 0.13	6.17 ± 0.16

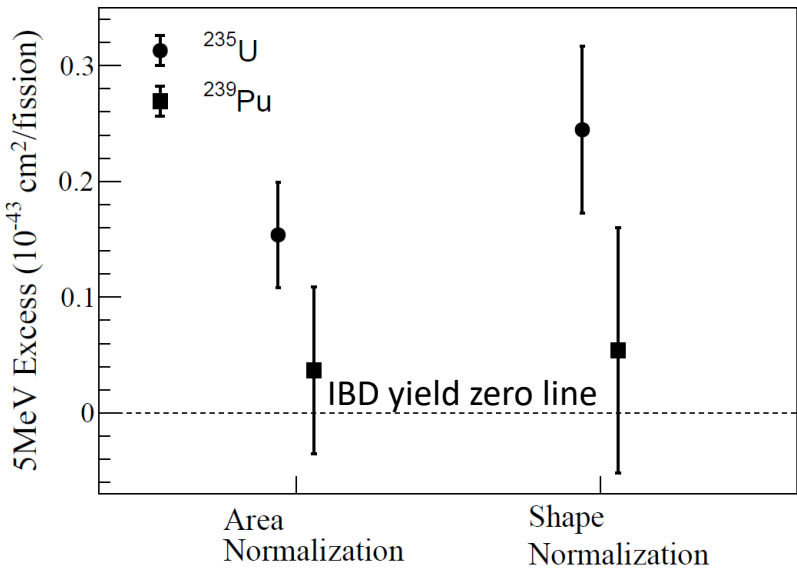
- Ratio to the RENO measurement

Model	R_{235}	R_{238}	Reactor average
HM	0.91 ± 0.022	0.95 ± 0.048	0.94 ± 0.015
EF	0.98 ± 0.024	0.94 ± 0.048	0.97 ± 0.016
HKSS	0.90 ± 0.022	0.93 ± 0.047	0.92 ± 0.015
KI	0.96 ± 0.023	0.95 ± 0.048	0.97 ± 0.016
HKSS-KI	0.95 ± 0.023	0.93 ± 0.047	0.95 ± 0.015
RENO data ($\text{cm}^2/\text{fission}$)	6.16 ± 0.15	4.16 ± 0.21	5.85 ± 0.12

5 MeV excess of ^{235}U and ^{239}Pu



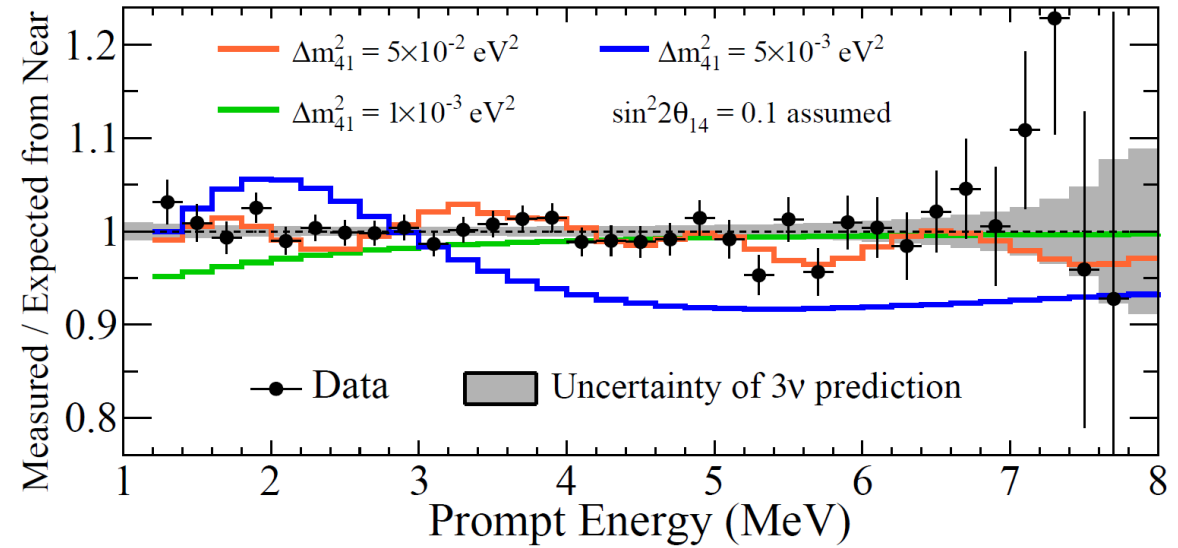
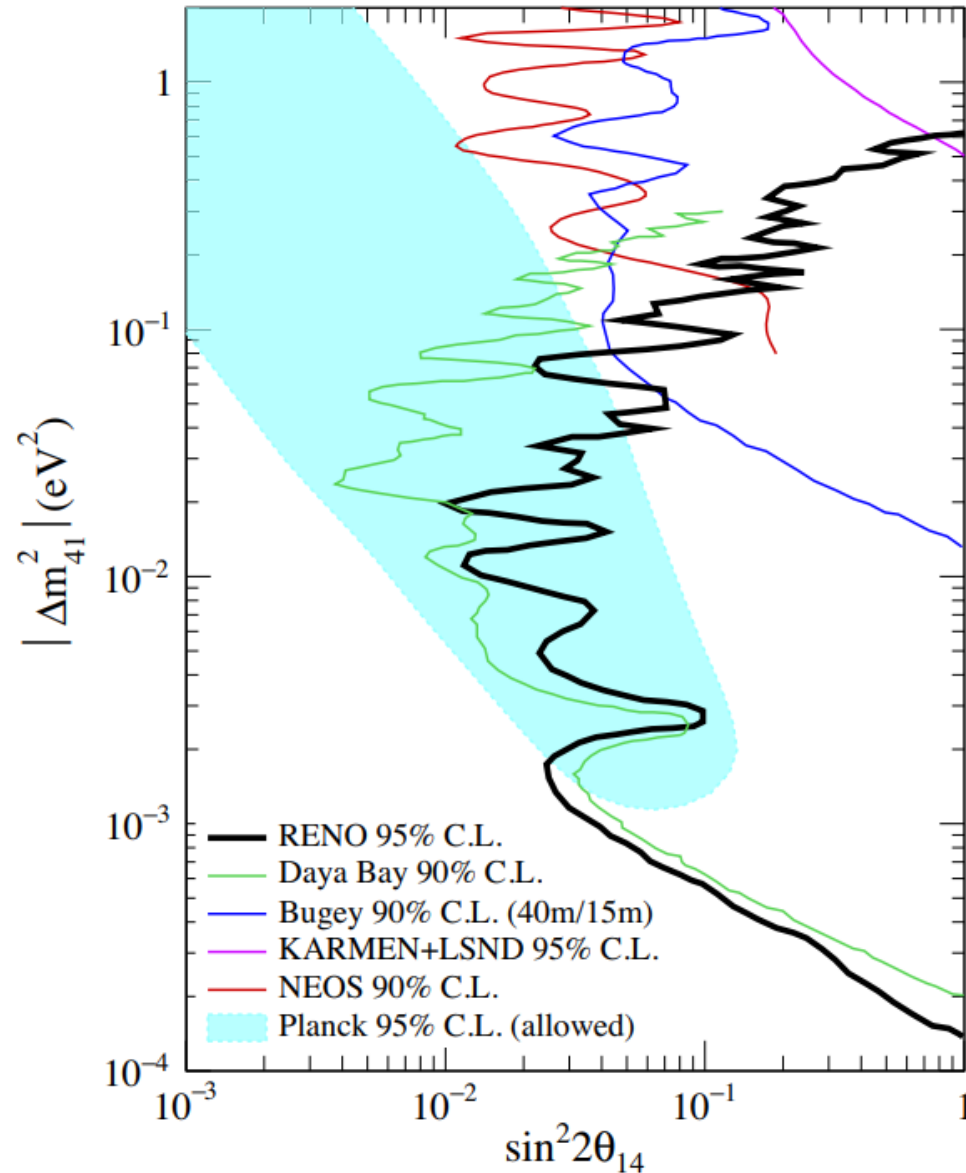
- 5 MeV excess :
 - ^{235}U = (2.5 ± 0.7) % of the observed total flux (3.9σ)
 - ^{239}Pu = (0.9 ± 1.7) % to the observed total flux (0.6σ)



	Area normalization	Shape normalization (outside the excess)
5MeV excess of ^{235}U (cm ² /fission)	0.15 ± 0.05 (2.5 ± 0.7 %)	0.24 ± 0.07 (4.0 ± 1.2 %)
5MeV excess of ^{239}Pu (cm ² /fission)	0.04 ± 0.07 (0.9 ± 1.7 %)	0.05 ± 0.11 (1.3 ± 2.5 %)

Poster presentation #599
Seok-Gyeong Yoon, "Reactor Antineutrino Flux and Spectrum at RENO"

Search for Sub-eV Sterile Neutrino at RENO



- 2200 days of RENO far / near data
- Excluded $10^{-4} \lesssim |\Delta m_{41}^2| \lesssim 0.5 \text{ eV}^2$
- No significant evidence for a sterile neutrino oscillation

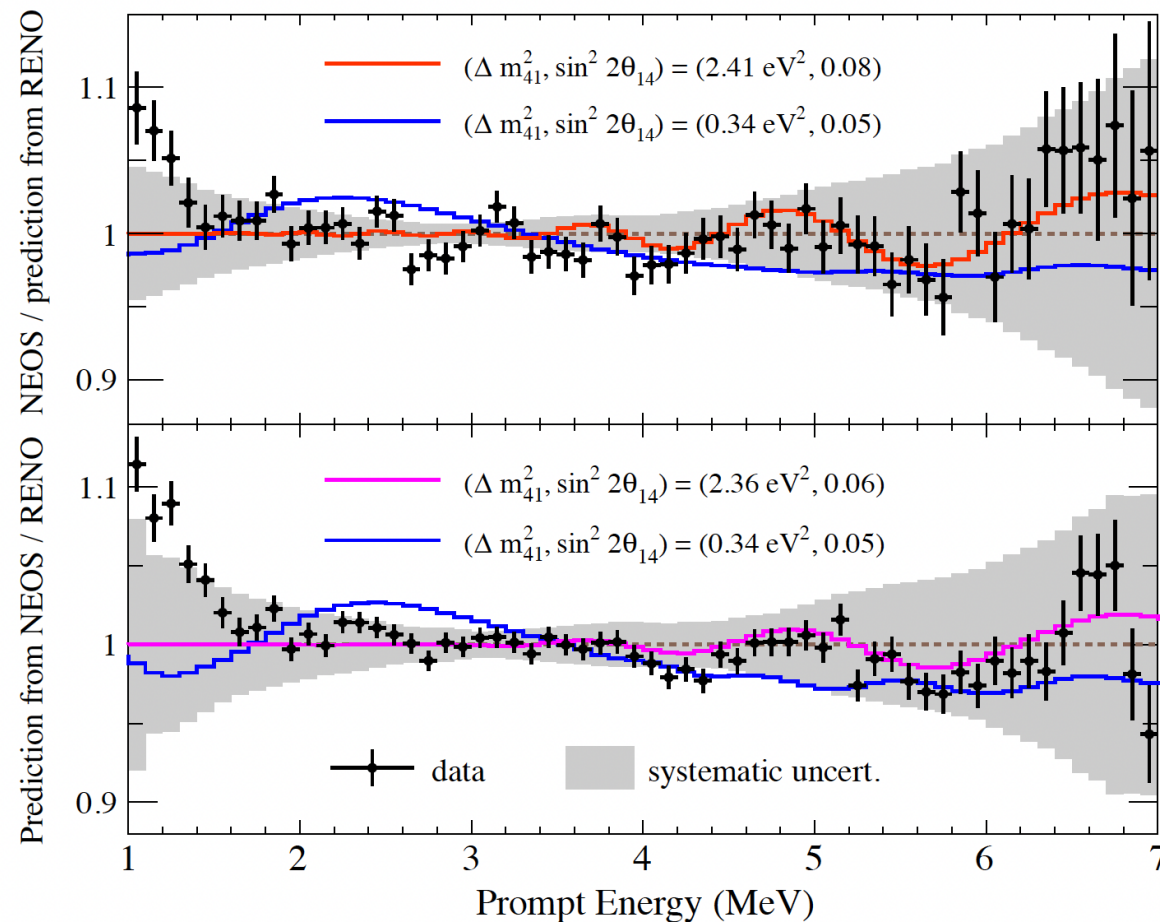
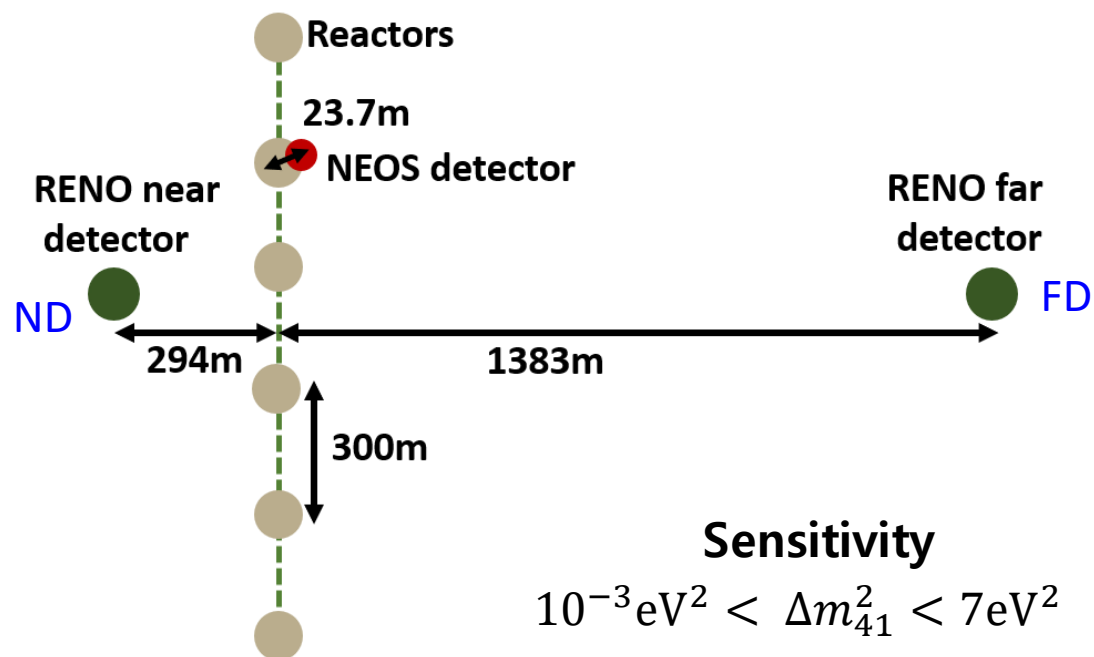
Phys. Rev. Lett. 125 (2020), 191801

RENO & NEOS joint sterile neutrino search

✓ **3+1 active - sterile neutrino mixing**

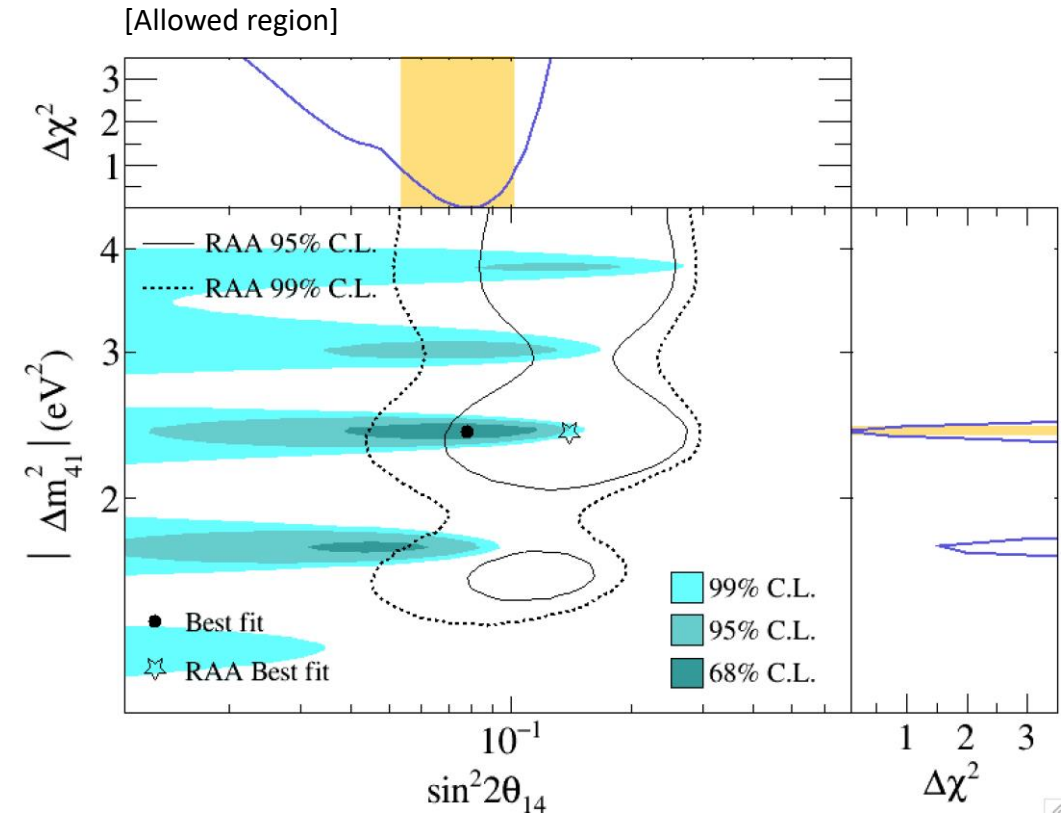
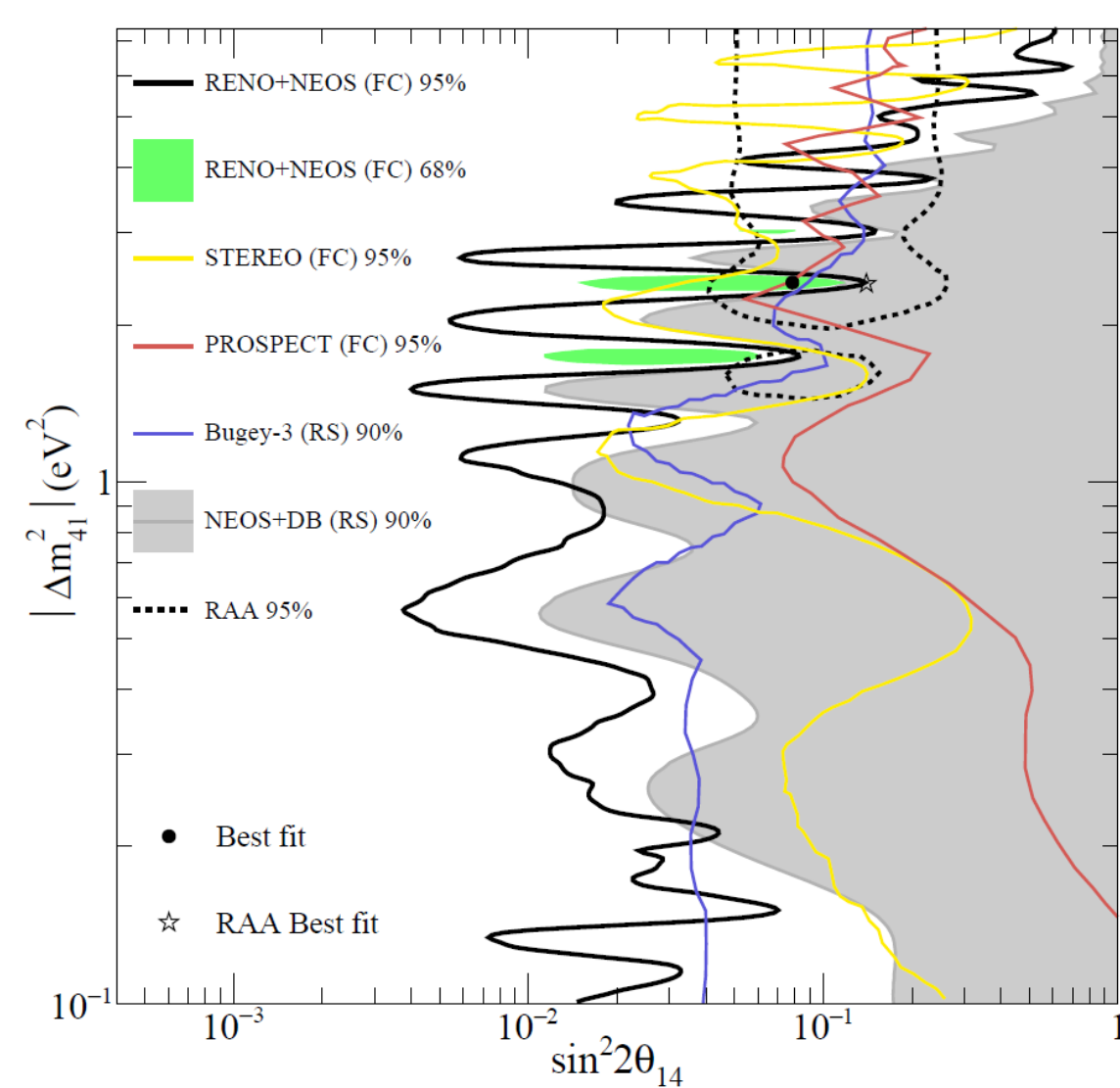
$$P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} \simeq 1 - \sin^2 2\theta_{13} \sin^2(1.27 \Delta m_{31}^2 \frac{L}{E}) \\ - \sin^2 2\theta_{14} \sin^2(1.27 \Delta m_{41}^2 \frac{L}{E})$$

✓ **L/E determines the sensitivity**



$$\chi^2 = \sum_{i,j}^N \left(N_{\text{R}}^i - \alpha \frac{M_{\text{R}}^i}{M_{\text{N}}^i} N_{\text{N}}^i \right) V_{ij}^{-1} \left(N_{\text{R}}^j - \alpha \frac{M_{\text{R}}^j}{M_{\text{N}}^j} N_{\text{N}}^j \right)$$

Excluded and allowed region of RENO-NEOS sterile ν search



Best fit : $\Delta m_{41}^2 = 2.41 \pm 0.03 \text{ eV}^2$, $\sin^2 2\theta_{14} = 0.08 \pm 0.03$

$$\chi_{4\nu, \min}^2 / NDF = 48.2 / 57 \quad \chi_{3\nu}^2 / NDF = 56.6 / 59$$

- P-value (assuming 3ν with MC) $\sim 8.2\%$
- Weak hint for the sterile neutrino oscillation
- The best fit is compatible with the RAA allowed region
- $\sin^2 2\theta_{14}$ fit is far more consistent with EF and HKSS-KI model.

Summary and Conclusion

- Updated measurement of $|\Delta m_{ee}^2|$ and θ_{13} using both n-Gd and n-H channel

➤ $\sin^2 2\theta_{13} = 0.0892$ (0.086, for n-H) , $|\Delta m_{ee}^2| = 2.74$

Phys. Rev. Lett. 121 (2018), 201801
JHEP 04 (2020) 029

- Direct measurement of ${}^9\text{Li}$ and ${}^8\text{He}$ products from their β -decay spectra

arXiv:2204.09215

- First report of the reactor antineutrino spectrum of RENO
- Reactor antineutrino yield & spectra from ${}^{235}\text{U}$ and ${}^{239}\text{Pu}$ are measured
- 5 MeV excess is seen in the ${}^{235}\text{U}$ spectrum (3.9σ)

Phys. Rev. Lett. 122(2019), 232501

Phys. Rev. D 104(2021), L111301

- Search for Sub-eV Sterile Neutrino at RENO
- Sterile neutrino search using RENO and NEOS spectra

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

arXiv:2011.00896

➤ 95% excluded limit : $10^{-1}\text{eV}^2 < \Delta m_{41}^2 < 7\text{eV}^2$ (p-value $\sim 8.2\%$)

➤ Best fit ($\Delta m_{41}^2 = 2.41\text{eV}^2$, $\sin^2 2\theta_{14} = 0.08$) is consistent with the RAA allowed region

Thank you!

For more technical details, please send e-mail
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