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Reactor Antineutrino Anomaly in Light of Recent Flux Model Refinements

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1. Introduction

- **HM model:** Huber's conversion model based on ILL measurements and Mueller's summation model for ^{238}U.
- **EF model:** Estienne-Fallot summation model with TAGs data (Pandemonium-free data).
- **HKSS model:** HM model including **forbidden transition,** improves the **shape anomaly (bump)** partially.
- **KI model:** Improved HM model with the KI measurement for ^{235}U, also with improved ^{238}U converted spectrum based on FRM II.
- **HKSS-KI model:** Improved HKSS model with the KI measurement for ^{235}U, also with improved ^{238}U converted spectrum based on FRM II.

2. Updated Model Prediction

- The official IBD yields from different references (the unit of σ_i is $10^{-43}\ cm^2/fission$)

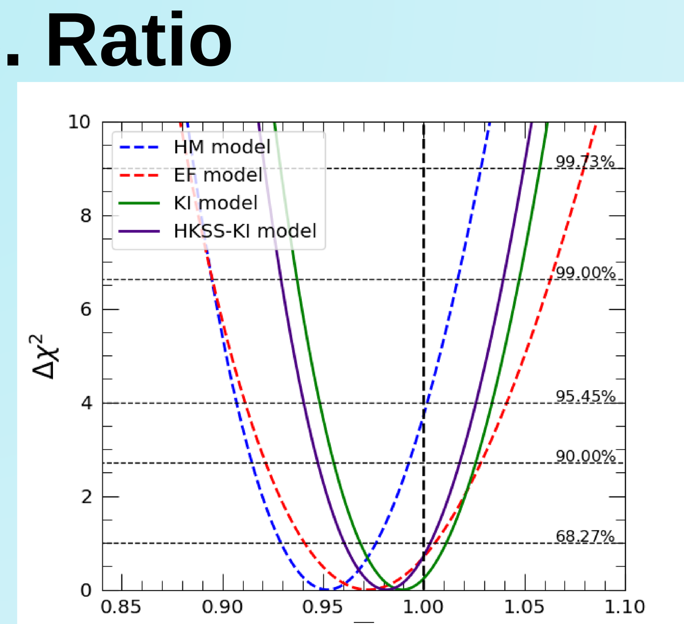
Models	σ_{235}	σ_{238}	σ_{239}	σ_{241}
HM [1][2]	6.69 ± 0.16	10.10 ± 0.82	4.40 ± 0.13	6.03 ± 0.16
EF [3]	6.28 ± 0.31	10.14 ± 1.01	4.42 ± 0.22	6.23 ± 0.31
KI [4]	6.27 ± 0.13	9.34 ± 0.47	4.33 ± 0.11	6.01 ± 0.13
HKSS [5]	6.74 ± 0.17	10.33 ± 0.85	4.43 ± 0.13	6.07 ± 0.16
HKSS-KI	6.32 ± 0.13	9.56 ± 0.49	4.36 ± 0.11	6.05 ± 0.14

- Updated IBD yields w/ Vogel-Beacom IBD cross section [6] & PDG 2020 [7]

Models	σ_{235}	σ_{238}	σ_{239}	σ_{241}
HM	6.62 ± 0.16	10.09 ± 0.82	4.34 ± 0.12	6.02 ± 0.16
EF	6.23 ± 0.31	10.07 ± 1.00	4.37 ± 0.22	6.17 ± 0.31
KI	6.31 ± 0.13	9.43 ± 0.47	4.34 ± 0.12	6.02 ± 0.16
HKSS	6.72 ± 0.16	10.19 ± 0.83	4.40 ± 0.13	6.10 ± 0.16
HKSS-KI	6.37 ± 0.13	9.52 ± 0.47	4.40 ± 0.13	6.10 ± 0.16

Our global fitting work is based on the updated IBD yields of models.

3. Ratio



The average ratio for each model.

$$\chi^2 = \sum_{a,b}\left(\sigma_{f,a}^{\rm exp} - R\cdot\sigma_{f,a}^{\rm fit}\right)\left(V^{\rm exp}\right)^{-1}_{ab}\left(\sigma_{f,a}^{\rm exp} - R\cdot\sigma_{f,a}^{\rm fit}\right) + \sum_{i,j}\left(r_i\sigma_i - \sigma_i\right)\left(V^{\rm mod}\right)^{-1}_{ij}\left(r_j\sigma_j - \sigma_j\right).$$

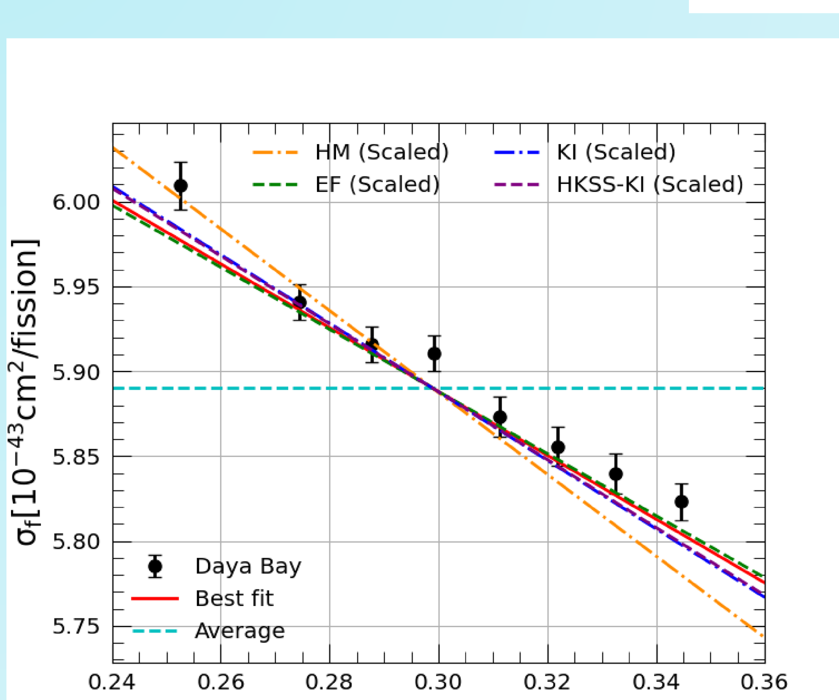
- This figure shows global fitting results of rate data of 27 reactor experiments.
- The ratio is defined as $R = \frac{N_{\rm exp}}{N_{\rm model}}$
- HM model: 0.952 ± 0.024
- EF model: 0.972 ± 0.032
- KI model: 0.989 ± 0.022
- HKSS-KI model: 0.982 ± 0.021

w/ KI measurements

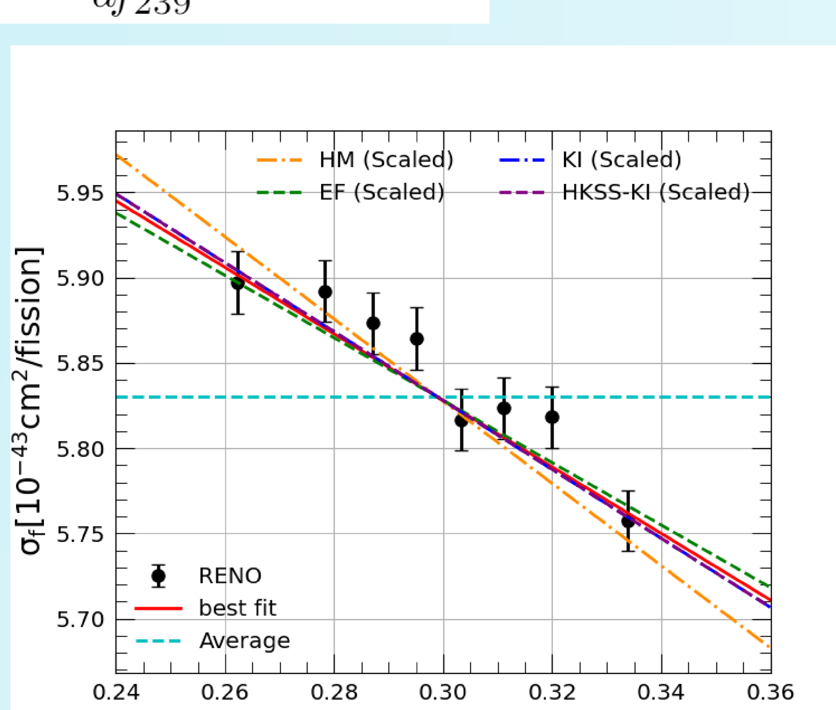
For **Huber-Mueller model**, a deficit about **5%** is the well-known **reactor antineutrino anomaly**.

4. Flux Evolution

$$\sigma_{f,a}^{\rm fit} = \bar{\sigma}_f + \frac{d\sigma_f}{df_{239}}\left(f_{239}^a - \bar{f}_{239}\right)$$



(a) Daya Bay



(b) RENO

	$\bar{\sigma}_f$	$d\sigma/df_{239}$
Daya Bay	5.89 ± 0.12	-1.88 ± 0.18
RENO	5.83 ± 0.12	-1.95 ± 0.30
HM Model	6.16 ± 0.15	-2.41 ± 0.06
EF Model	5.95 ± 0.20	-1.83 ± 0.06
KI Model	5.93 ± 0.12	-2.02 ± 0.05
HKSS-KI Model	6.00 ± 0.13	-2.01 ± 0.05

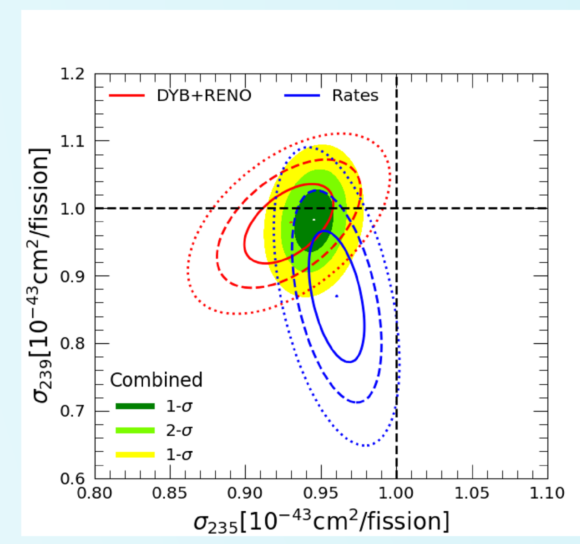
w/ KI measurements

(c) Results of the fit of flux evolution

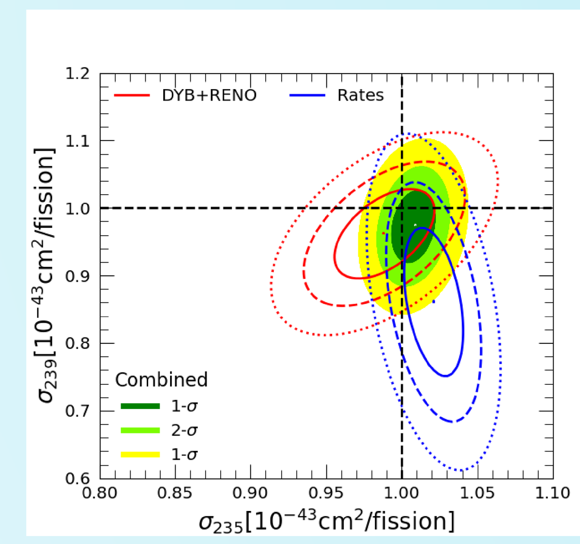
The unit of $\bar{\sigma}_f$ is 10^{-43} cm^2/fission

- These figures shows the **flux evolution** data for (a) **Daya Bay** and (b) **RENO**.
- The slope of HM model prediction has the most deviation.
- KI measurement also improves the prediction of the slope.

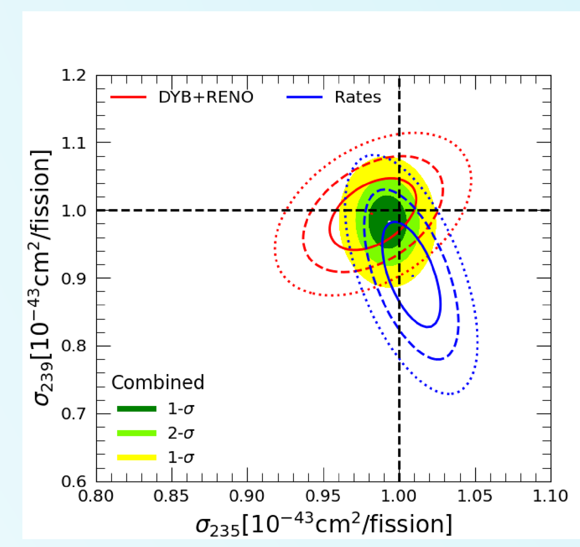
5. Combined measurement of σ_{235} and σ_{239}



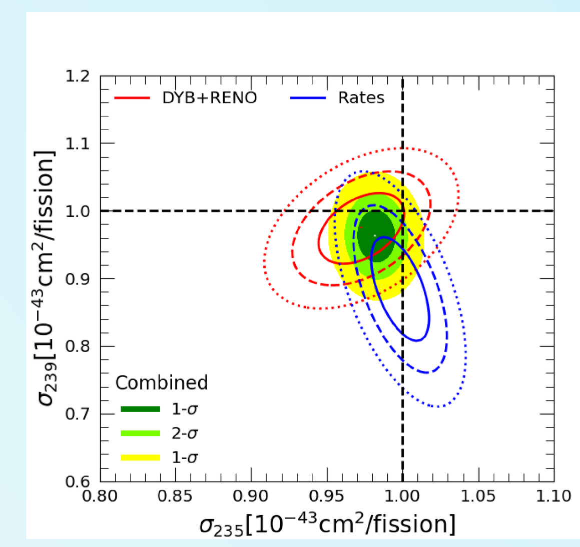
(a) HM model



(b) EF model



(c) KI model



(d) HKSS-KI model

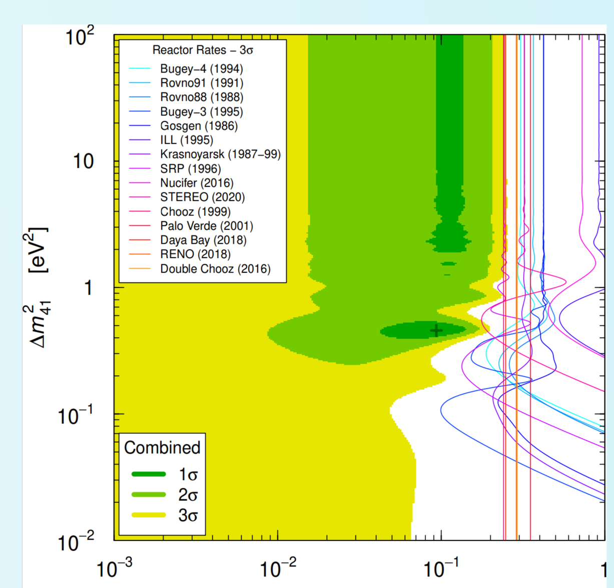
$$\chi^2 = \sum_{a,b}\left(\sigma_{f,a}^{\rm exp} - \sigma_{f,a}^{\rm fit}\right)\left(V^{\rm exp}\right)^{-1}_{ab}\left(\sigma_{f,b}^{\rm exp} - \sigma_{f,b}^{\rm fit}\right) + \left(\frac{r_{238}-1}{\delta_{238}}\right)^2 + \left(\frac{r_{241}-1}{\delta_{241}}\right)^2$$

- These figures show the combined measurement of ^{235}U and ^{239}Pu for different models.
- For each model, the rate data and flux evolution data (Daya Bay and RENO) are both used.

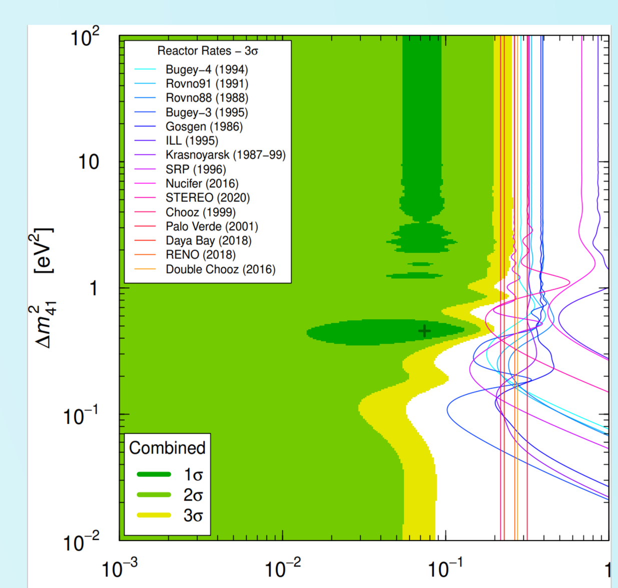
	σ_{235}	σ_{239}
HM	6.25 ± 0.06	4.25 ± 0.14
EF	6.27 ± 0.06	4.24 ± 0.16
KI	6.25 ± 0.06	4.25 ± 0.12
HKSS-KI	6.25 ± 0.06	4.22 ± 0.12

For σ_i $(i = 235, 239)$, the units are 10^{-43} cm^2/fission

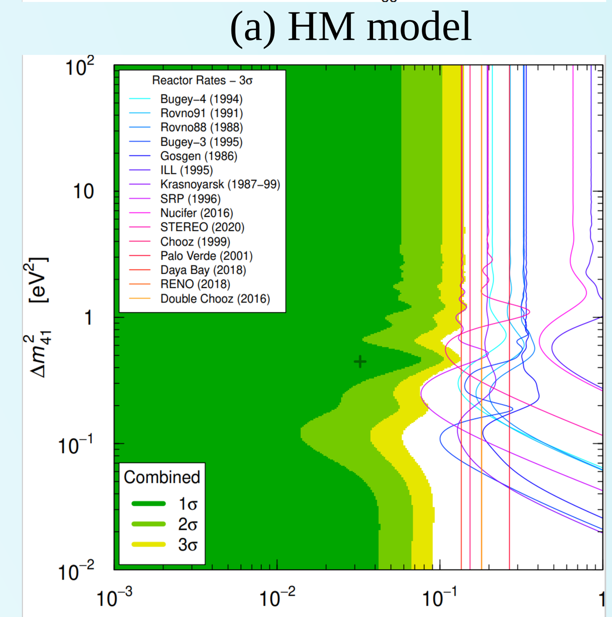
6. Oscillation



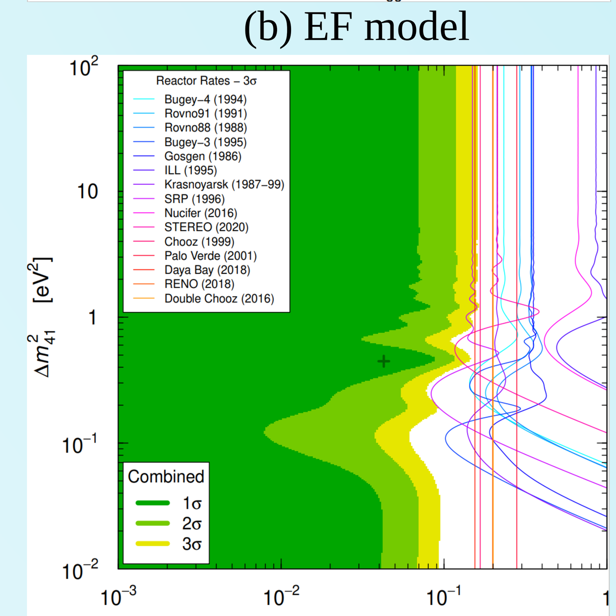
(a) HM model



(b) EF model



(c) KI model



(d) HKSS-KI model

No Osc.	χ^2	26.3
	NDF	27
	GoF	0.5
Osc.	$\chi^2_{\rm min}$	18.8
	NDF	25
	GoF	0.8
	$\sin^2 2\vartheta$	0.093
	Δm^2	0.46
No Osc. – Osc.	$\Delta\chi^2_{\rm NO}$	7.5
	$\rm NDF_{NO}$	2
	$n\sigma_{\rm NO}$	2.3σ

(e) Fitting results for HM model

No Osc.	χ^2	23.2
	NDF	27
	GoF	0.68
Osc.	$\chi^2_{\rm min}$	22.1
	NDF	25
	GoF	0.63
	$\sin^2 2\vartheta$	0.032
	Δm^2	0.45
No Osc. – Osc.	$\Delta\chi^2_{\rm NO}$	1.1
	$\rm NDF_{NO}$	2
	$n\sigma_{\rm NO}$	0.56σ

(f) Fitting results for KI model

$$\chi^2 = \sum_{a,b}\left(\sigma_{f,a}^{\rm exp} - P_{ee}^a\sum_i r_i f_i^a \sigma_i\right)\left(V^{\rm exp}\right)^{-1}_{ab} \times \left(\sigma_{f,b}^{\rm exp} - P_{ee}^b\sum_i r_i f_i^b \sigma_i\right) + \sum_{i,j}\left(r_i\sigma_i - \sigma_i\right)\left(V^{\rm mod}\right)^{-1}_{ij}\left(r_j\sigma_j - \sigma_j\right)$$

- These figures show the 3+1 mixing scheme of different models.
- For each model, the rate data (w/o Daya Bay nor RENO) and flux evolution data are both used.
- $\Delta\chi^2$ is defined as: $\chi^2_{\rm NoOsc} - \chi^2_{\rm Osc}$
- The confidence level of oscillation is getting down with the KI measurement inputs.

	$\Delta\chi^2$	$n\sigma$
HM	7.5	2.3σ
EF	3.4	1.3σ
KI	1.1	0.56σ
HKSS-KI	1.9	0.86σ

$\Delta\chi^2$ for different models

$\Delta\chi^2 = \chi^2_{\rm NoOsc} - \chi^2_{\rm Osc}$

7. Conclusion

- With PDG 2020 inputs, the IBD yield of model prediction is more close to experimental data ($\mathbf{3\sigma \to 2\sigma}$).
- The KI measurement can improve the **rate deficit**, which implies the reactor antineutrino anomaly might be caused by **mis-normalization** in ILL measurements.
- The KI measurement also improves the **model prediction of flux evolution** in Daya Bay and RENO.
- According KI model and HKSS-KI model, **rate anomaly** and **shape anomaly** should be complementary.
- With the KI measurement, the confidence level of active-sterile oscillation decreases.

Reference

[1] T. A. Mueller, *et al.* Phys. Rev. C 83, 054615 (2011)
[2] P. Huber, Phys. Rev. C 85, 029901 (2012)
[3] M. Estienne, M. Fallot, *et al.* Phys. Rev. Lett. 123, no. 2, 022502 (2019)
[4] V. Kopeikin, *et al.* arXiv:2103.01684 [nucl-ex]
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[6] P. Vogel and J. F. Beacom, Phys. Rev. D 60, 053003(1999)
[7]] P. A. Zyla *et al.*[Particle Data Group], PTEP 2020, no.8, 083C01 (2020)