Reactor antineutrino anomaly in light of recent flux model refinements

Z. Xin (IHEP, Beijing)

July 08, 2022

Based on C. Giunti, Y. F. Li, C. A. Ternes, ***ZX***, Phys.Lett.B 829 (2022) 137054

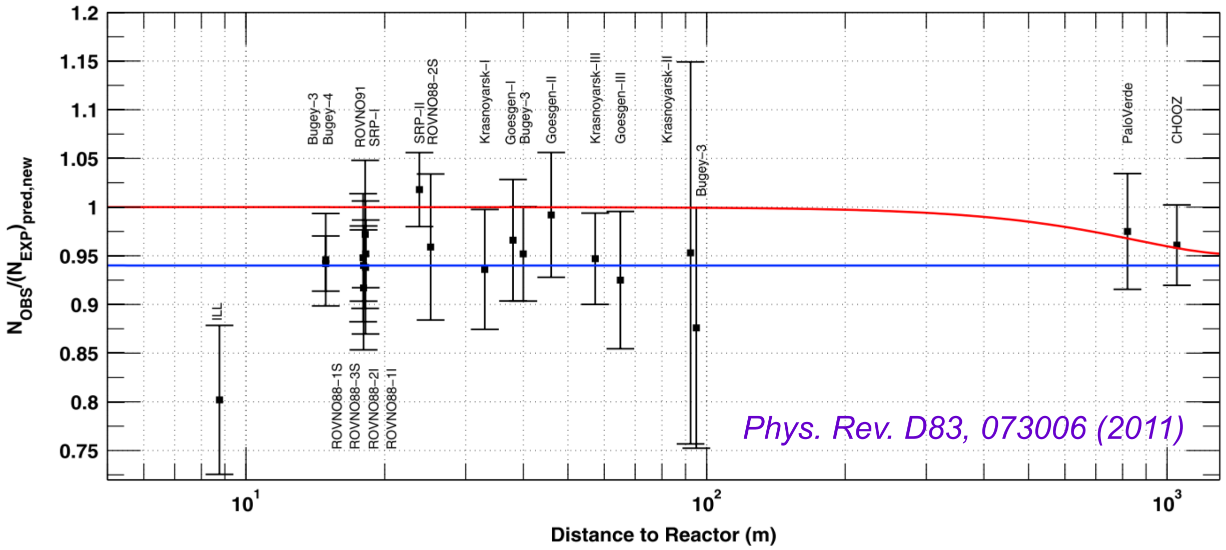
And Y. F. Li, ***ZX***, Phys.Rev.D 105 (2022) 7, 073003

International Conference on High Energy Physic (ICHEP 2022)

Parallel Talk

Reactor antineutrino anomaly

- **Reactor antineutrino anomaly**



mean averaged ratio:

$$\bar{R} = 0.943 \pm 0.024 \quad (2.4\,\sigma)$$

The possible flaw of HM (and other models)

The possible existence of light sterile neutrinos

- **Reactor data to test RAA for different models**

Models → **Best one ?**

C. Giunti, Y. F. Li, C. A. Ternes, ZX, Phys.Lett.B 829 (2022) 137054

- Huber-Mueller model
- Hayen-Kostensalo-Severijns-Suhonen model
- Recent Kurchatov Institute measurements
  - HM → KI model
  - HKSS → HKSS-KI model
- Estienne-Fallot summation model

Y. F. Li, ZX, Phys.Rev.D 105 (2022) 7, 073003

Data-driven Flux model ?

↑

Reactor data

- Reactor rates data (27)
  - 80s-90s, 2000s, 2010s
  - Recent Prospect & STEREO
- Fuel evolution data (8+8)
  - Daya Bay
  - RENO

Reactor flux models: Huber-Mueller model

- How to predict reactor antineutrino spectra
  - Conversion method

    Measured β spectra → neutrino spectra
  - Summation method

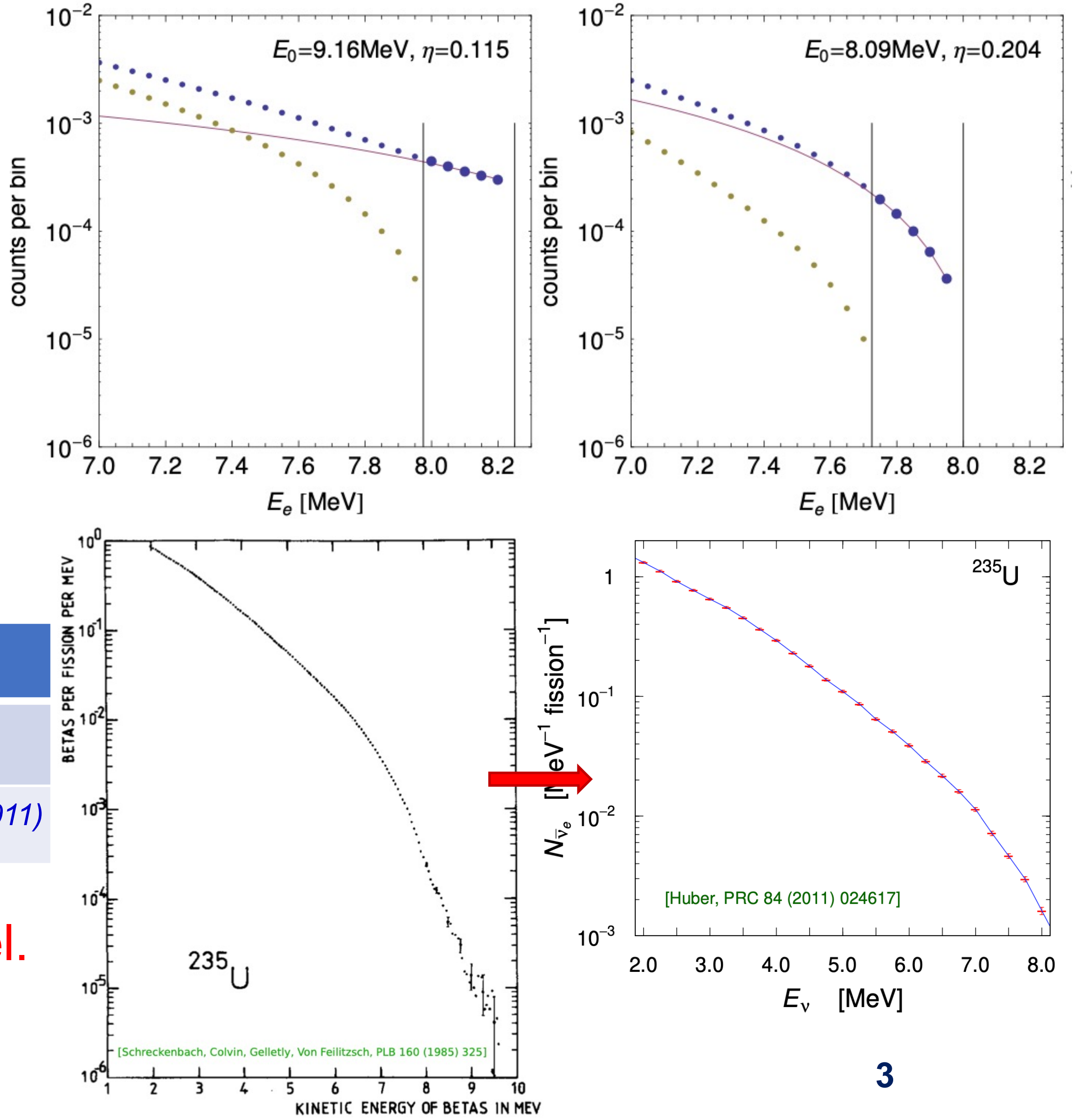
    Sum of all the decay branches ← database

- Huber-Mueller model

^{235}U	^{239}Pu	^{241}Pu	^{238}U
ILL measurement → neutrino spectra			Summation method
Phys. Rev. C 85, 029901 (2012)			*Phys. Rev. C 83, 054615 (2011)*

Only allowed transitions are considered in HM model.

How to convert ILL into neutrino spectra

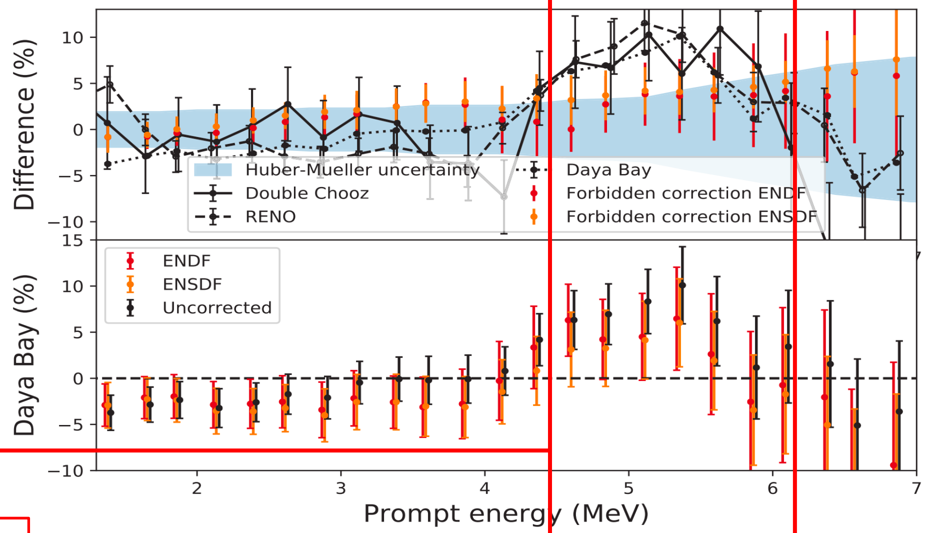


Corrections to HM model

- HKSS model **Shape correction**

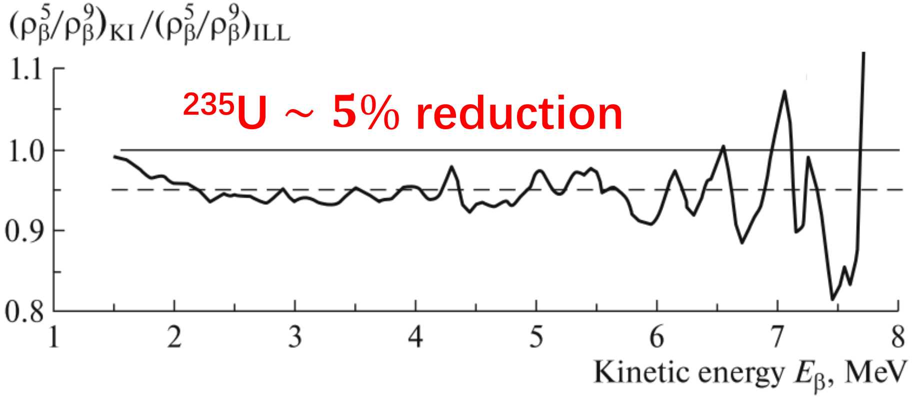
HM model + Forbidden transitions (some branches)

^{235}U	^{239}Pu	^{241}Pu	^{238}U
ILL measurement → neutrino spectra			Summation method
Phys. Rev. C 100, no.5, 054323 (2019)			



Partially explain the '5 MeV Bump'

- Kurchatov Institute measurement **Rate correction**
  - Ratio of beta spectra: $\left(S_\beta^5/S_\beta^9\right)_{ILL} > \left(S_\beta^5/S_\beta^9\right)_{KI}$
  - HM model → KI model *Phys. Rev. D 104 (2021) L071301*
  - HKSS model → HKSS-KI model

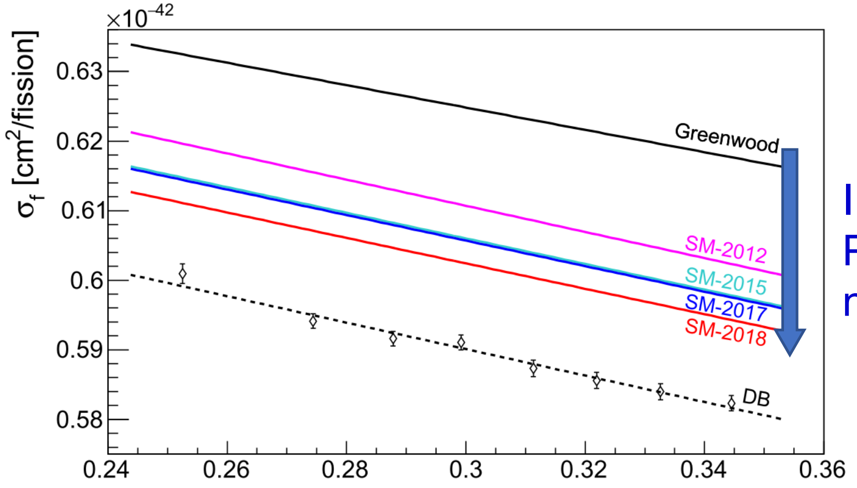


	^{235}U	^{238}U	$^{239,\ 241}Pu$
KI	KI measurement	Garching measurement	ILL measurement
HKSS-KI	KI measurement	Summation method	ILL measurement

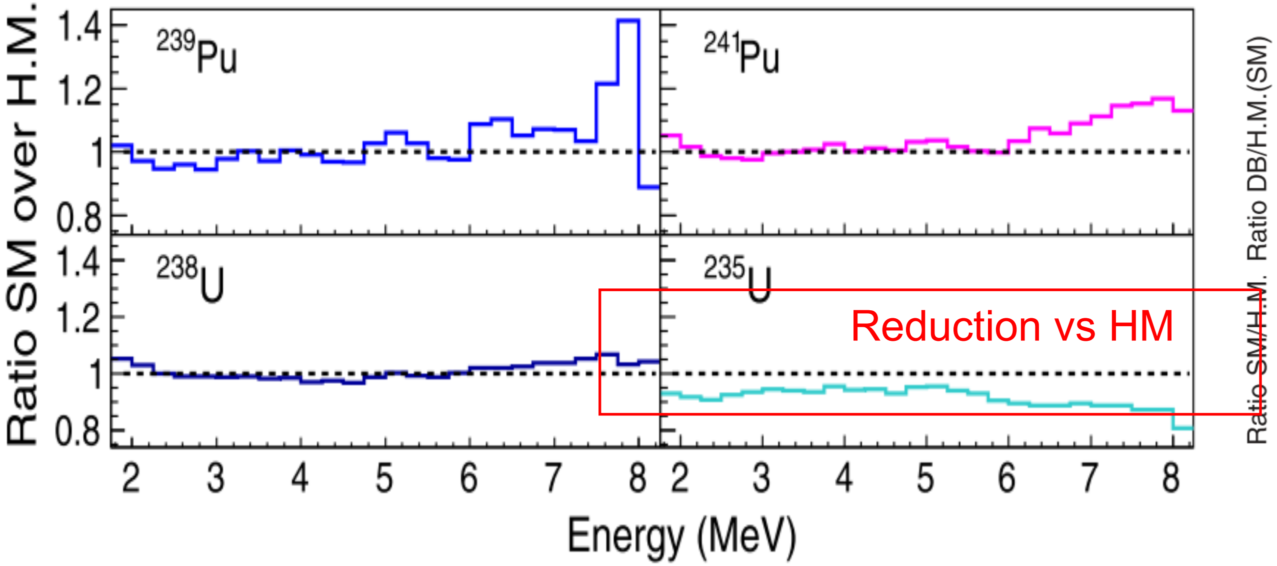
Phys. Atom. Nucl. 84, no.1, 1-10 (2021)

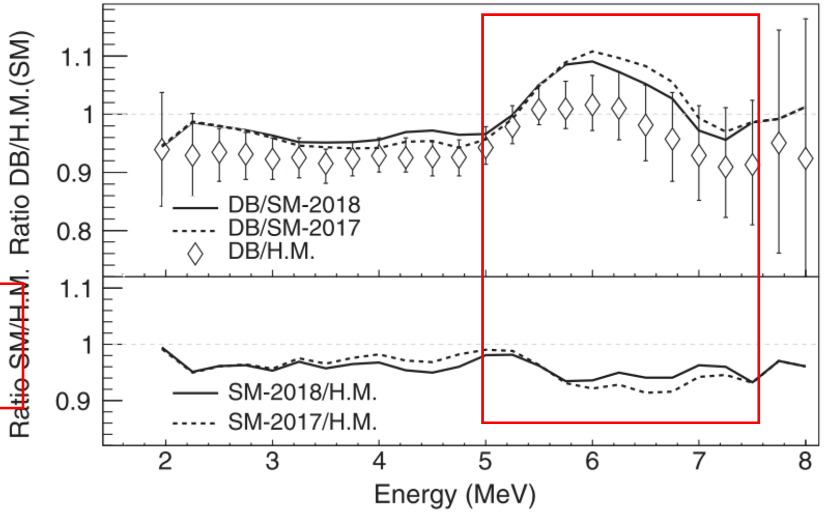
Reactor flux models: summation model

- **Estienne-Fallot summation model** *Phys. Rev. Lett. 123, no. 2, 022502 (2019)*
  - Summation method
  - Nuclear data
    - Pandemonium-free data
    - ENSDF nuclear database
    - JEFF and ENDF database
  - Reduction in ^{235}U versus HM
  - Bump anomaly still exists



Including more Pandemonium-free nuclear data





Bump anomaly

Reactor flux models: a brief summary

Models considered in this work

Phys.Lett.B 829 (2022) 137054

Conversion model

ILL measurement (Beta spectra) → HM model (RAA) → Forbidden transition → HKSS model (Partially explain "5 MeV bump")

KI measurement (Beta spectra) → KI model, HKSS-KI model

KI measurement: Reduction of ^{235}U

Summation model

EF model

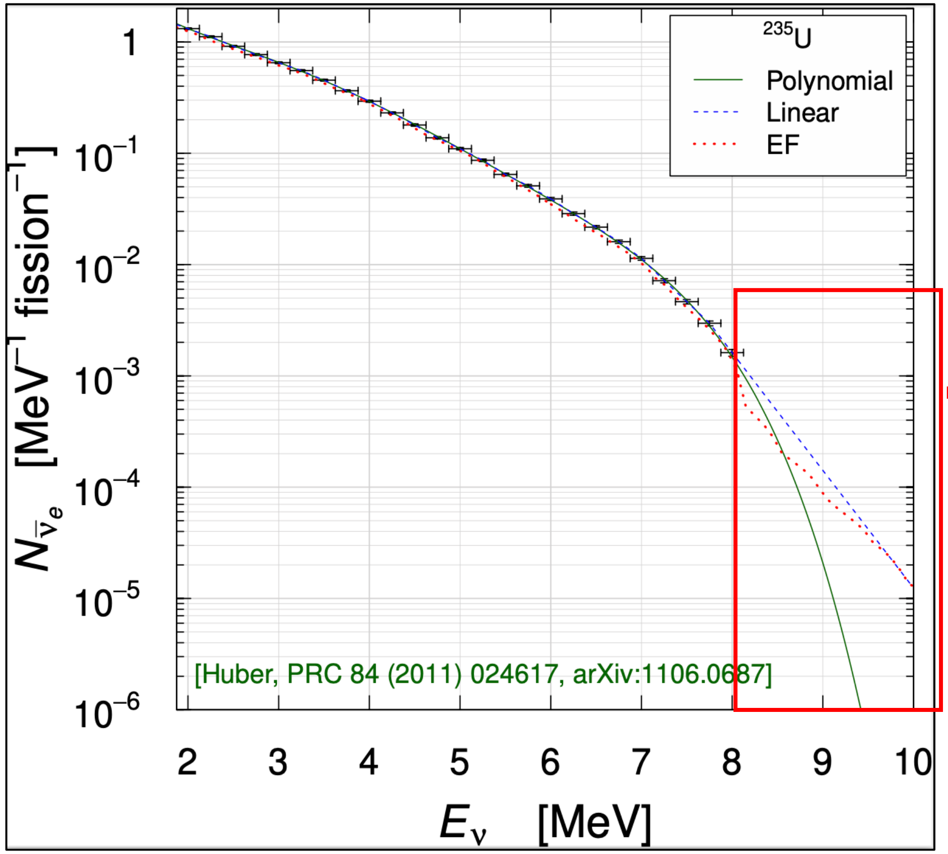
only 1.9% deviation from Daya Bay

Conversion models: HM, HKSS, KI, HKSS-KI

Summation models: EF

	^{235}U	^{238}U	^{239,241}Pu
HM	ILL measurement	Summation method	ILL measurement
HKSS	ILL measurement	Summation method	ILL measurement
KI	KI measurement	Garching measurement	ILL measurement
HKSS-KI	KI measurement	Summation method	ILL measurement
EF	Summation method	Summation method	Summation method

IBD yields



Small contribution above 8 MeV:
0.3% for ^{235}U, 0.9% for ^{238}U,
0.2% for ^{239}Pu, 0.3% for ^{241}Pu.

IBD yield → Reactor event rates

$$\sigma_i = \int_{E_{\min}}^{E_{\max}} dE\, \Phi_i(E)\, \sigma_{\mathrm{IBD}}(E),$$

1. IBD cross section
2. The high energy region

More details can be found in
C. Giunti, Y. F. Li, C. A. Ternes, ZX, Phys.Lett.B 829 (2022) 137054

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
HKSS	6.82 ± 0.18	10.28 ± 0.84	4.42 ± 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	4.42 ± 0.13	6.17 ± 0.16
EF	6.29 ± 0.31	10.16 ± 1.02	4.42 ± 0.22	6.23 ± 0.31

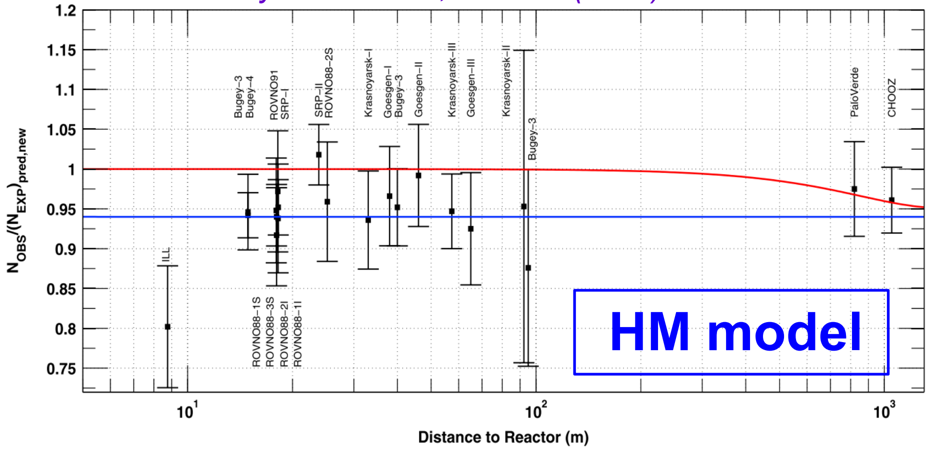
Shape correction
σ_i's ⬆

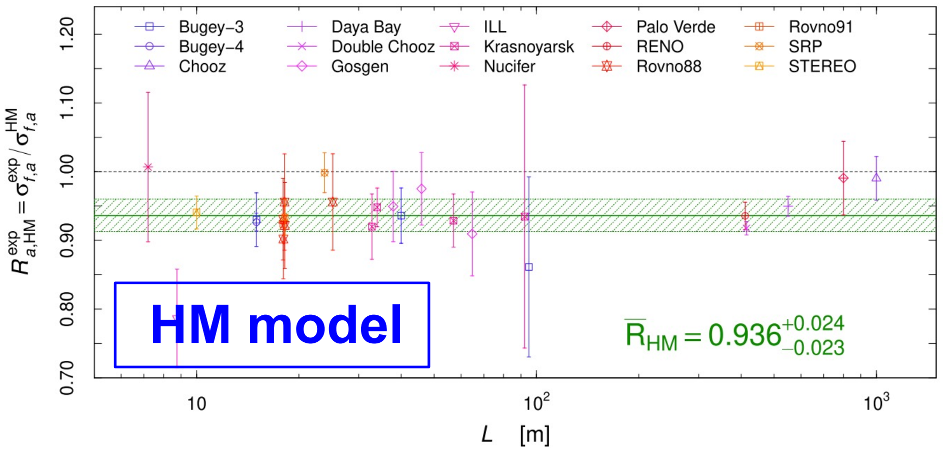
σ_{235} ⬇
Rate correction

Fit of reactor rates

C. Giunti, Y. F. Li, C. A. Ternes, ZX,
Phys.Lett.B 829 (2022) 137054

Phys. Rev. D83, 073006 (2011)



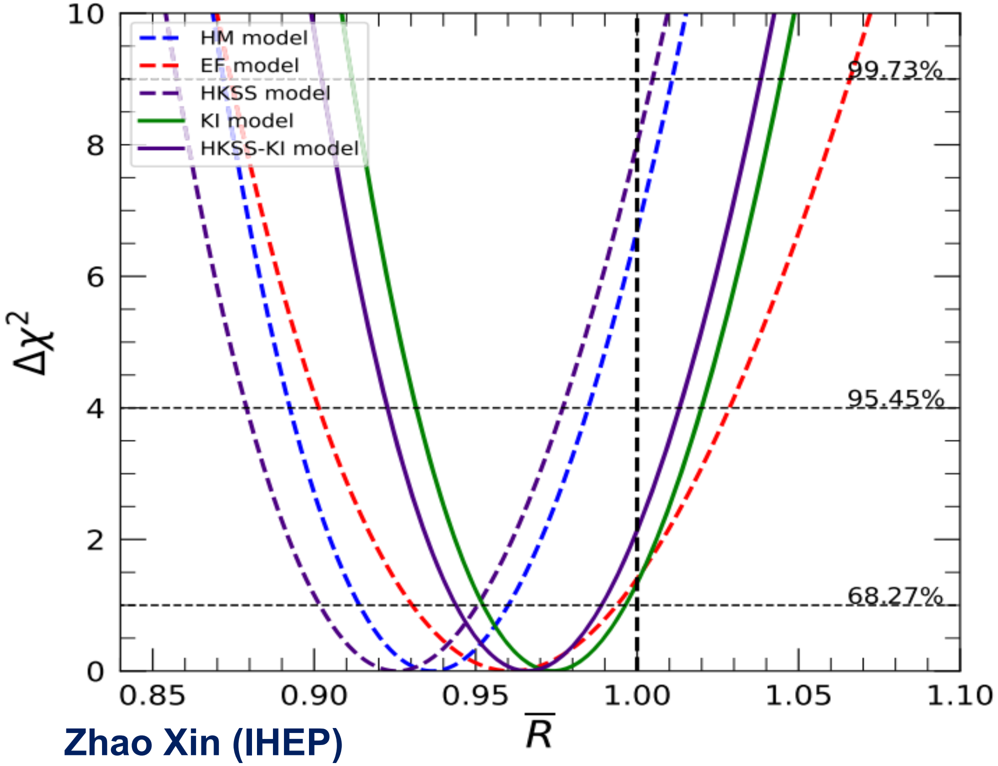


RAA: 2.4 σ

0.943 ± 0.024

$0.936^{+0.024}_{-0.023}$

RAA: 2.5 σ



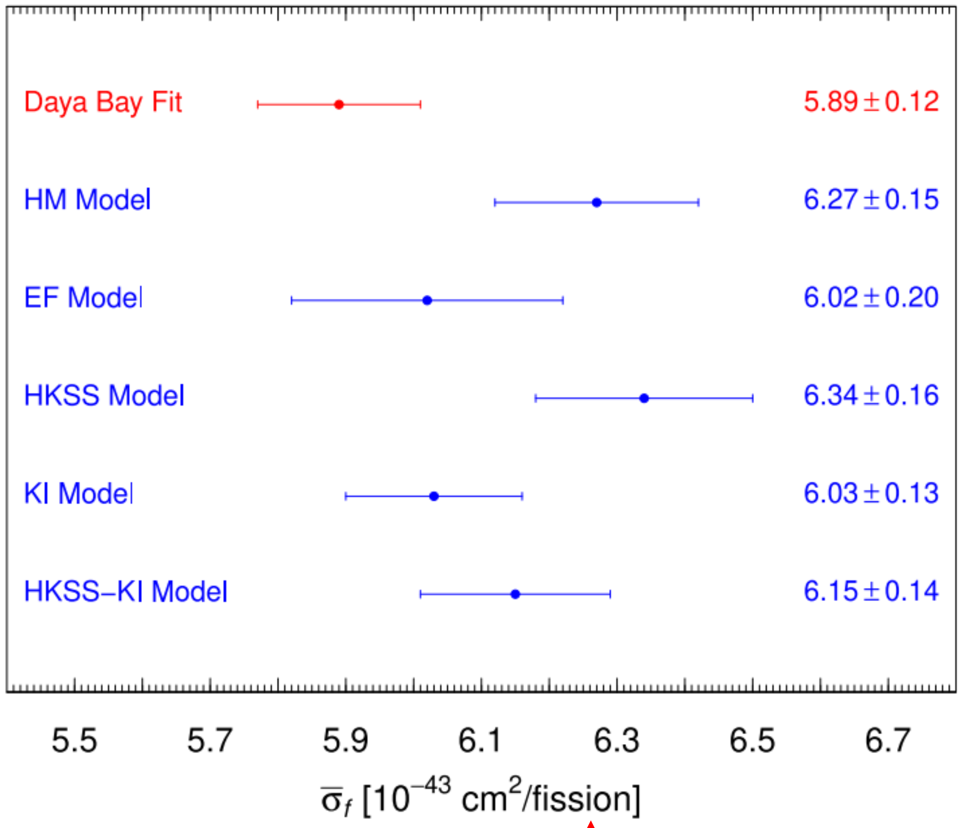
Model	$\overline{R}$	RAA
HM	$0.936^{+0.024}_{-0.023}$	2.5σ
HKSS	$0.925^{+0.025}_{-0.023}$	2.9σ
KI	$0.975^{+0.022}_{-0.021}$	1.1σ
HKSS-KI	$0.964^{+0.023}_{-0.022}$	1.5σ
EF	$0.960^{+0.033}_{-0.031}$	1.2σ

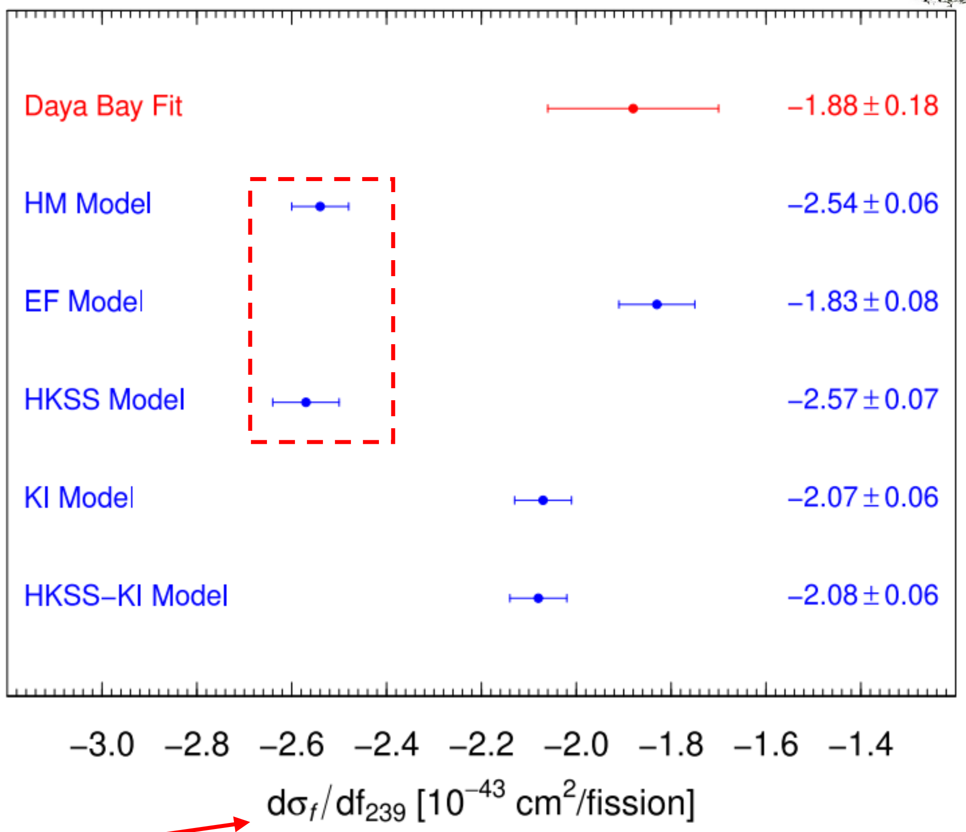
Increase in σ_i's enlarges RAA

No RAA

Reduction in σ_{235} helps to decrease RAA

Fit of reactor fuel evolution data





A linear function $\sigma_{f,a}^{\text{lin}} = \bar{\sigma}_f + \frac{d\sigma_f}{df_{239}}(f_{239}^a - \bar{f}_{239})$

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- EF, KI and HKSS-KI agree with evolution data
- 3.5 σ for HM model
- 3.6 σ for HKSS model

HM and HKSS are disfavored.

RENO evolution data ⟶ similar results

Statistic test

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Statistic test

which model provides the best fit of reactor rates and the evolution data.

A normalized deviation of data and model

$$x_a^{\text{mod}} = \sum_b \left(V^{\text{tot}}\right)_{ab}^{-1/2} \left(\sigma_{f,b}^{\text{exp}} - \sigma_{f,b}^{\text{mod}}\right)$$

Shapiro-Wilk test →

χ^2 test

size of deviation

↓

Sign test

'+' or '-' deviation

↓

Kolmogorov-Smirnov test

Cramer-von Mises test

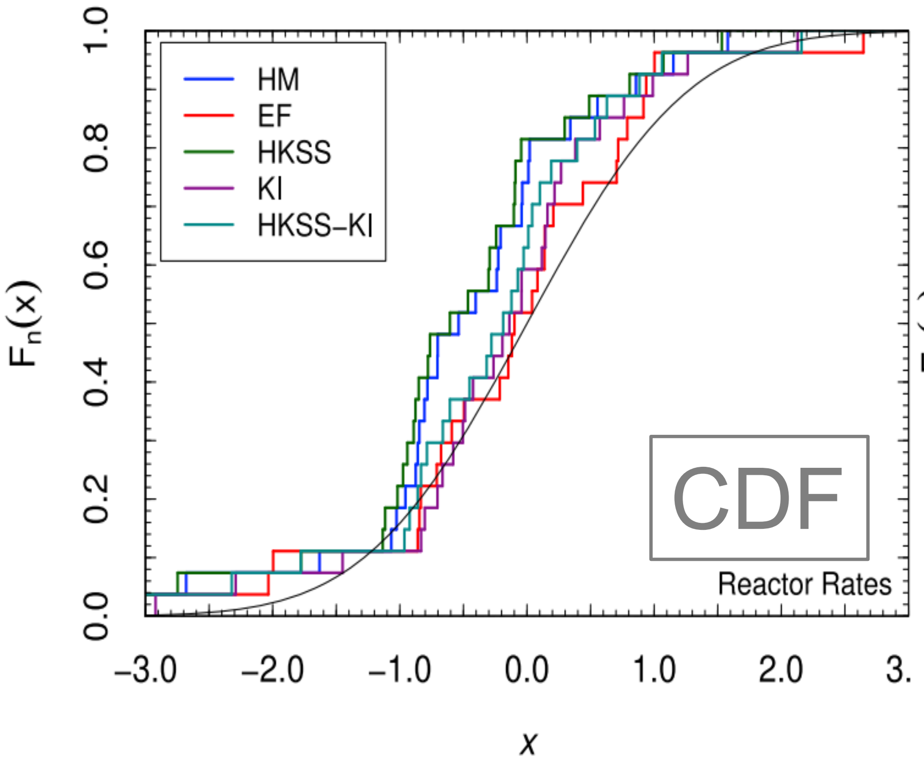
Anderson-Darling test

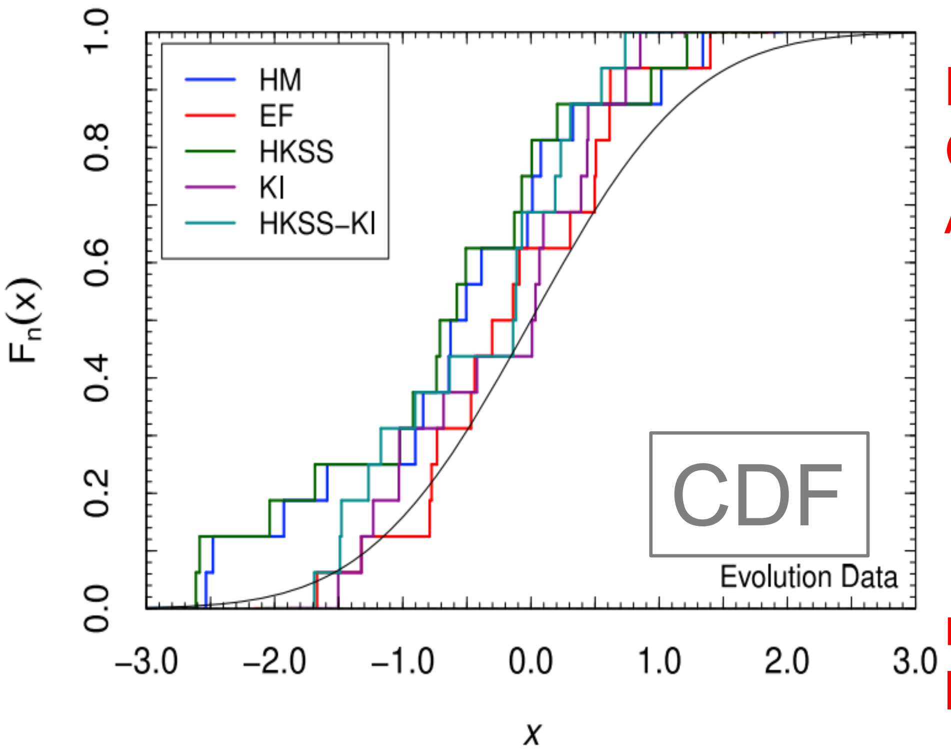
↓

Z_K, Z_C, Z_A test

Journal of the Royal Statistical Society Series B 64, 281 (2002).

more powerful, based on likelihood ratio





Statistic test

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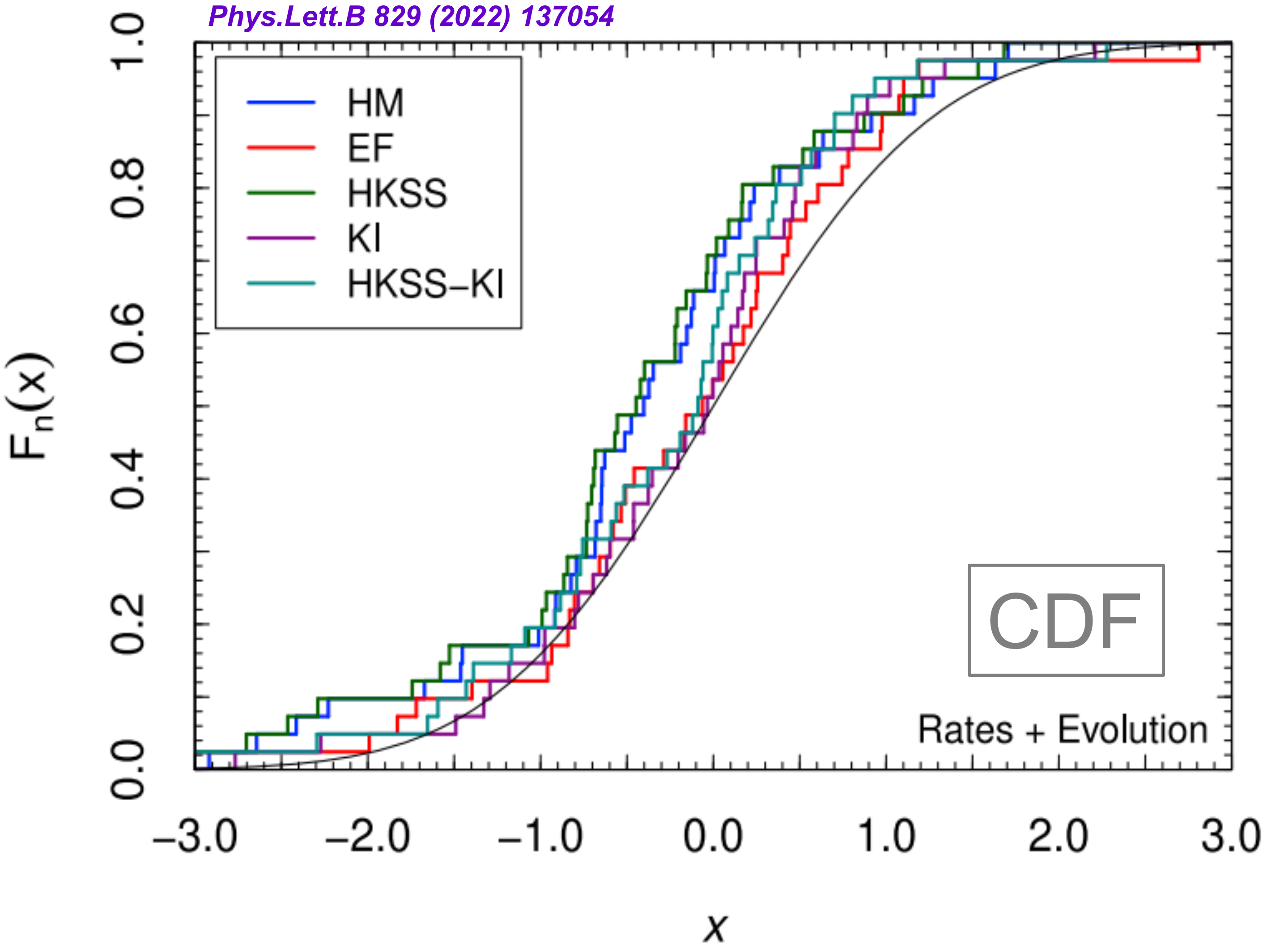
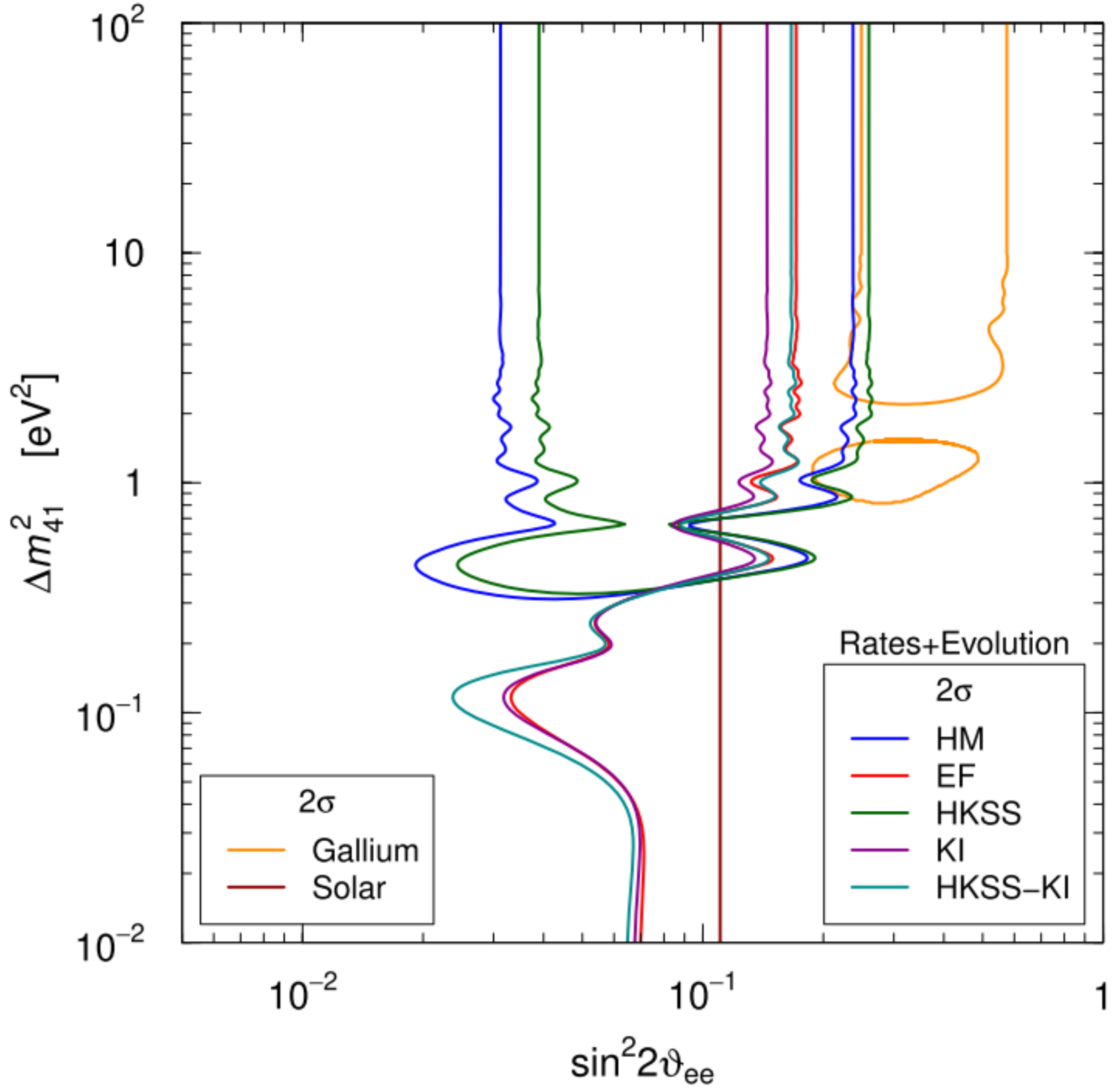


Rates + Evolution data

Test	HM	EF	HKSS	KI	HKSS-KI
χ^2	0.13	0.22	0.08	0.68	0.44
SW	0.32	0.13	0.35	0.59	0.41
sign	0.03	0.38	0.006	0.38	0.11
KS	0.04	0.84	0.02	0.39	0.20
CVM	0.02	0.67	0.006	0.38	0.14
AD	0.02	0.57	0.006	0.40	0.13
Z_K	$< 10^{-3}$	0.05	$< 10^{-3}$	0.05	0.008
Z_C	0.02	0.11	0.005	0.55	0.15
Z_A	0.03	0.20	0.01	0.41	0.12
weighted average	0.05	0.35	0.03	0.42	0.16

EF model is the best summation model
KI model is the best conversion model

Implications for neutrino oscillations



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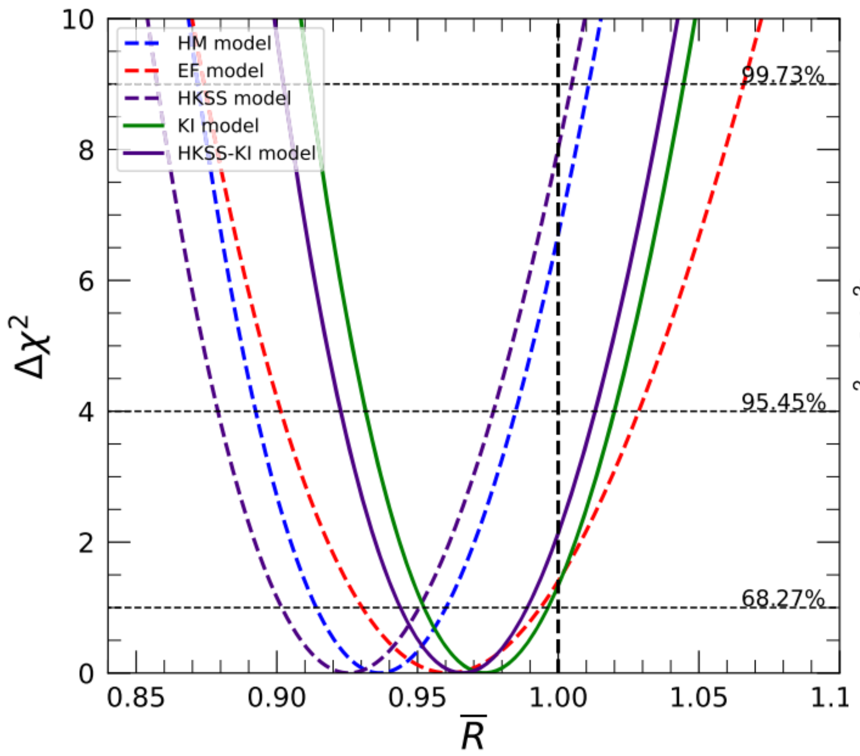
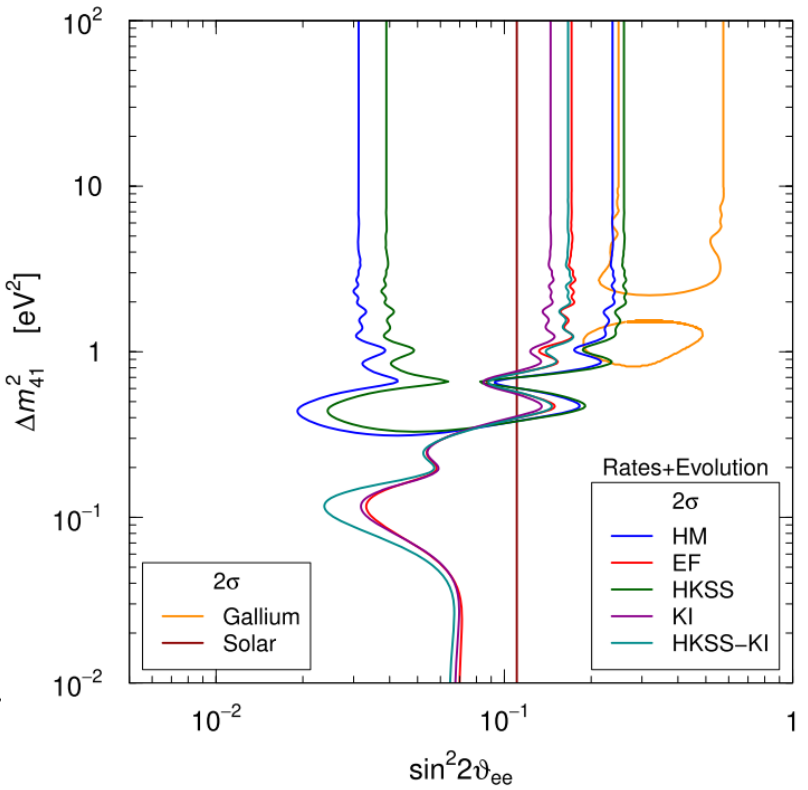
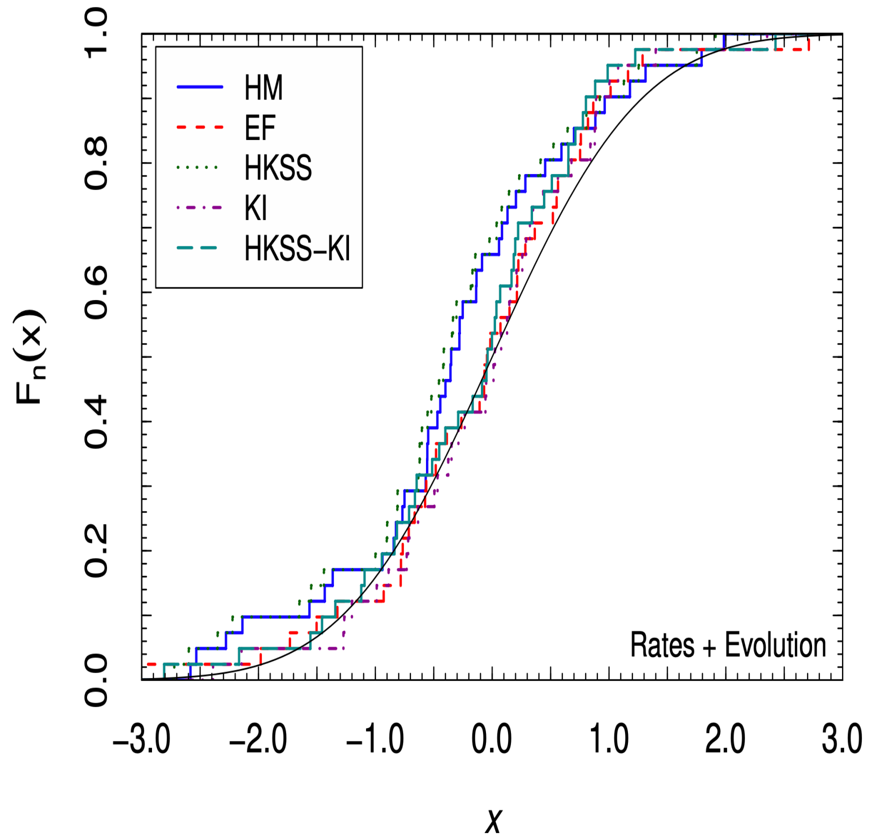
$$P_{ee} \simeq 1 - \sin^2 2\theta_{ee} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

- EF and KI models → No short-baseline oscillations
- Reactor data upper limits
  - $\sin^2 2\theta_{ee} \lesssim 0.14 \sim 0.25$ at 2σ
  - disfavor Gallium anomaly allowed region
- Gallium anomaly allowed region is also in tension with solar upper bound.

What more can reactor data provide ?







- Flux models still have a (small) deviation compared with reactor data.
- **Can reactor data offer a data-driven flux model?**

Model independent fluxes

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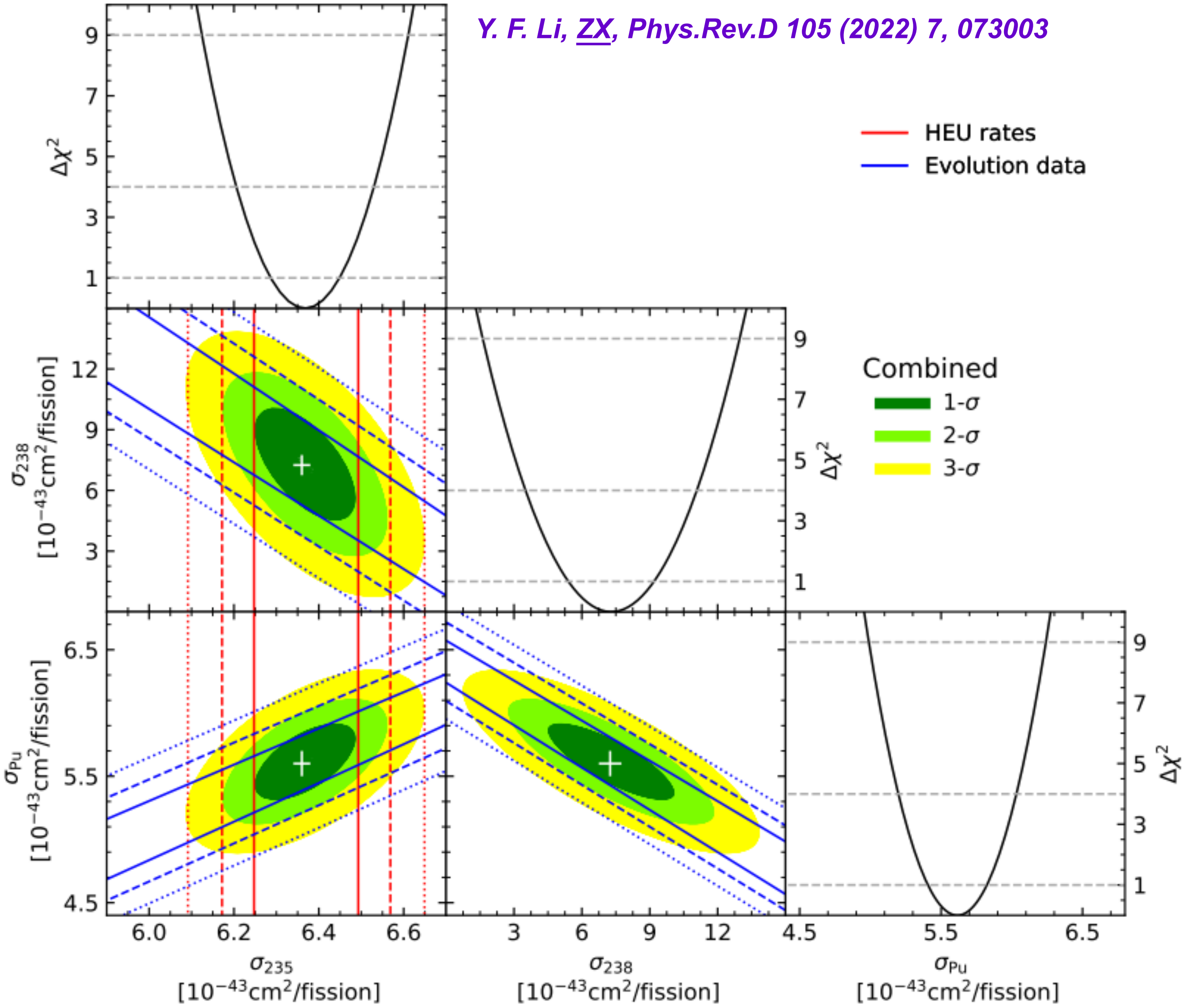
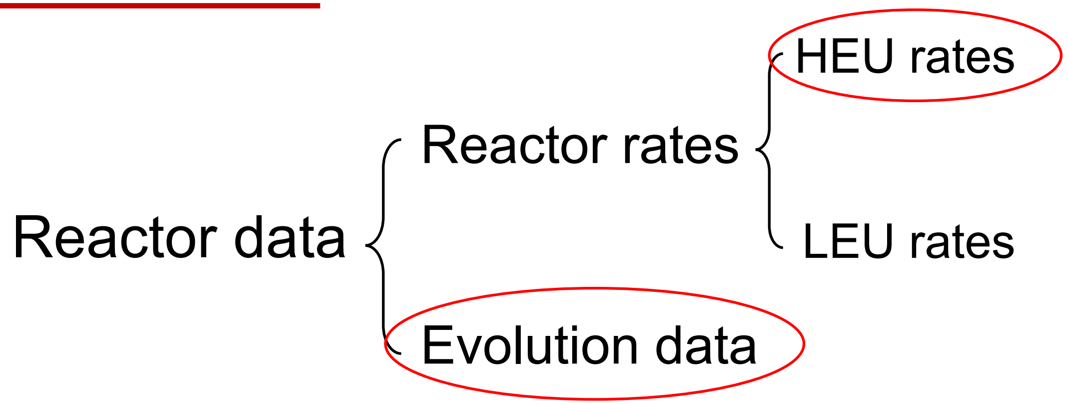
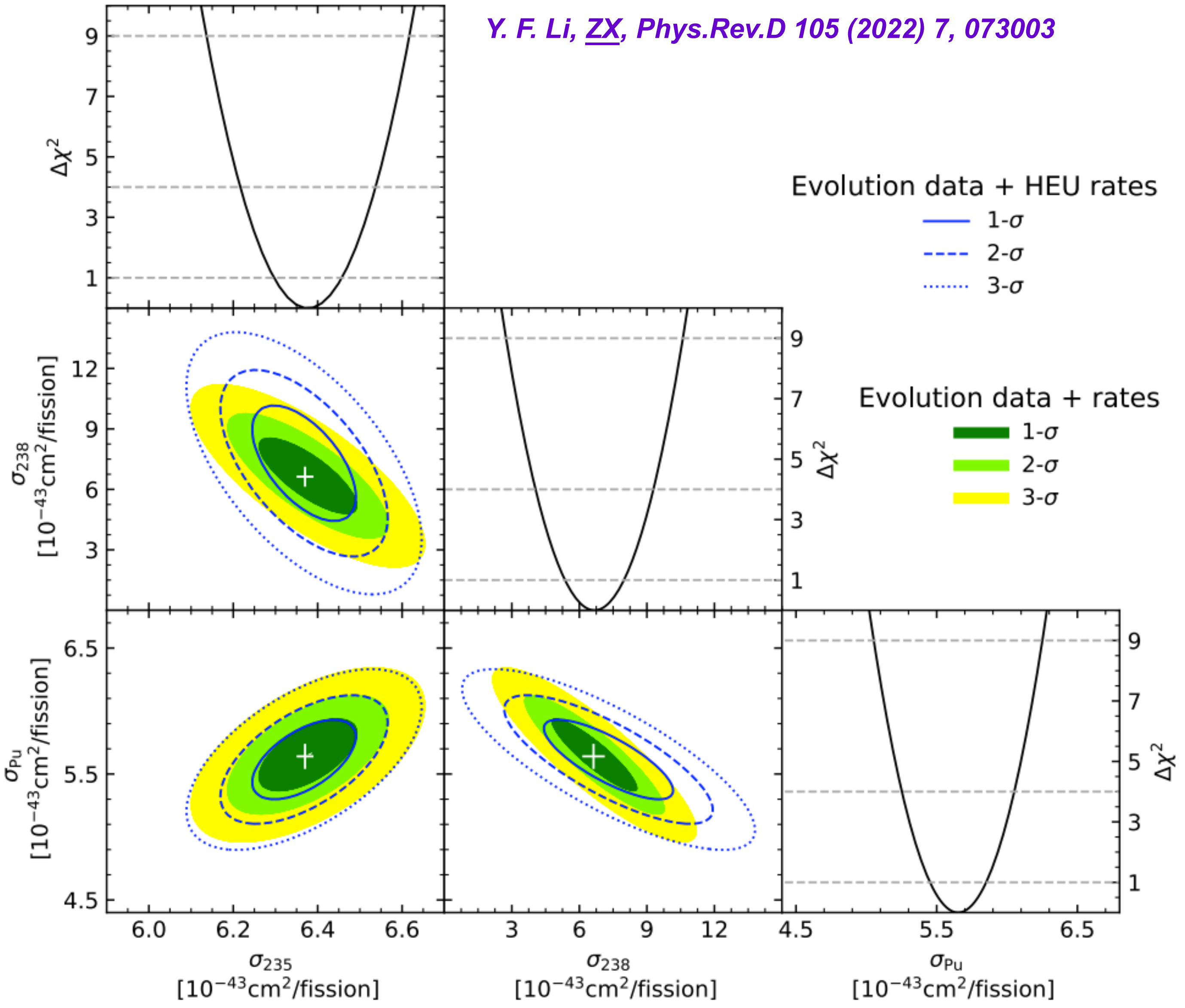




- Combined Pu component (LEU data)
  $f_{241} = k \cdot f_{239}$
  $\sigma_{\mathrm{Pu}} = \sigma_{239} + k \cdot \sigma_{241}$
- The HEU rates constrain σ_{235}
- The evolution data constrain the linear combination of σ_i's
- The LEU rates data constrain σ_{238} and σ_{Pu}

Model independent fluxes



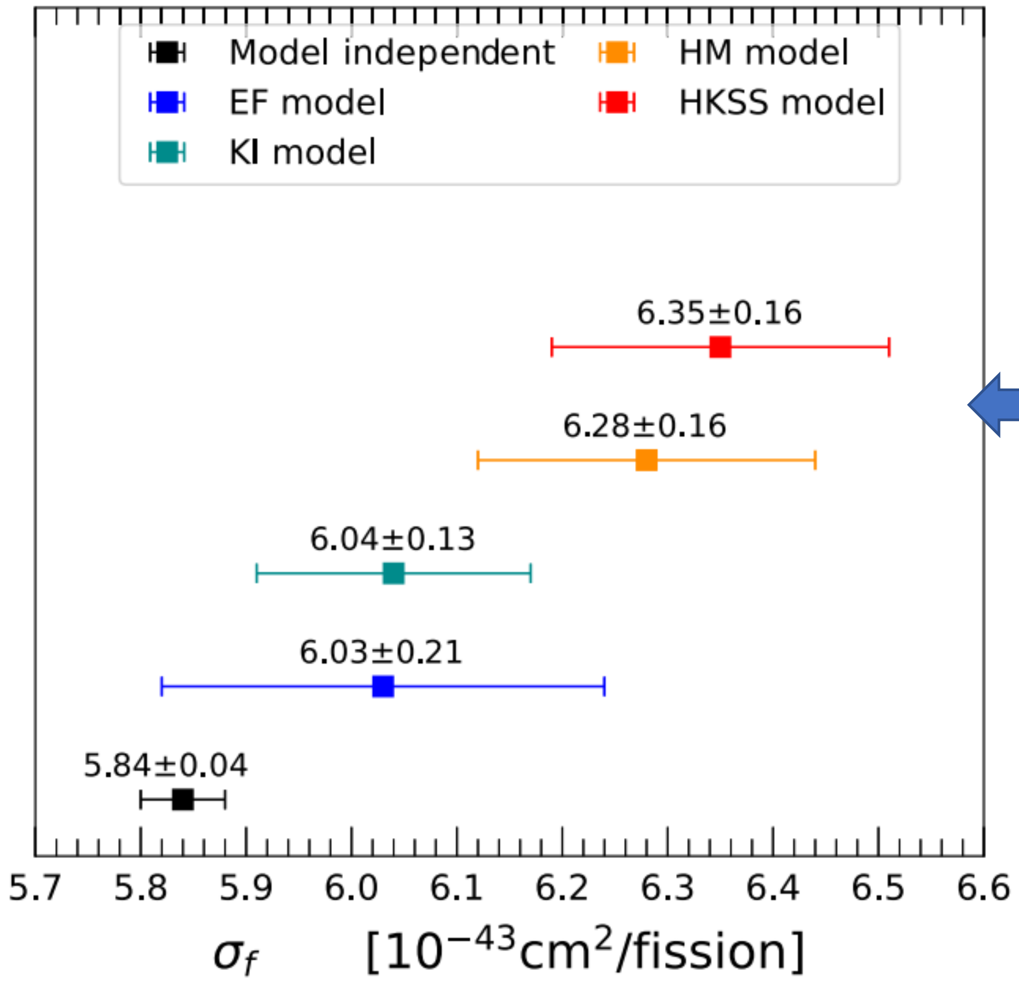
Reactor data
- Reactor rates
  - HEU rates
  - LEU rates
- Evolution data

- Combined Pu component (LEU data)
  $f_{241} = k \cdot f_{239}$
  $\sigma_{Pu} = \sigma_{239} + k \cdot \sigma_{241}$
- The LEU rates constrain σ_{238} and σ_{Pu} further
- Model independent fluxes

$$\begin{cases} \sigma_{235} = (6.37 \pm 0.08) \times 10^{-43}\ \mathrm{cm}^2/\mathrm{fission}, \\ \sigma_{238} = (6.63 \pm 1.30) \times 10^{-43}\ \mathrm{cm}^2/\mathrm{fission}, \\ \sigma_{Pu} = (5.64 \pm 0.20) \times 10^{-43}\ \mathrm{cm}^2/\mathrm{fission}, \end{cases}$$

Prediction of a future experiment

$f_{241} = k \cdot f_{239}$ (LEU data)



- How to predict the IBD yield for a certain experiment:

$$\sigma_A = f_{235}^A \sigma_{235} + f_{238}^A \sigma_{238} + f_{239}^A \sigma_{Pu} + \Delta f^A \sigma_{241}^{\mathrm{HM}}$$

- A LEU reactor with typical fission fractions

(0.577: 0.076: 0.295:0.052)

$$\sigma^{\mathrm{pre}} = 5.84 \pm (0.04)_{\mathrm{MI}} \pm (0.0004)_{\mathrm{HM}} \quad (0.7\%)$$

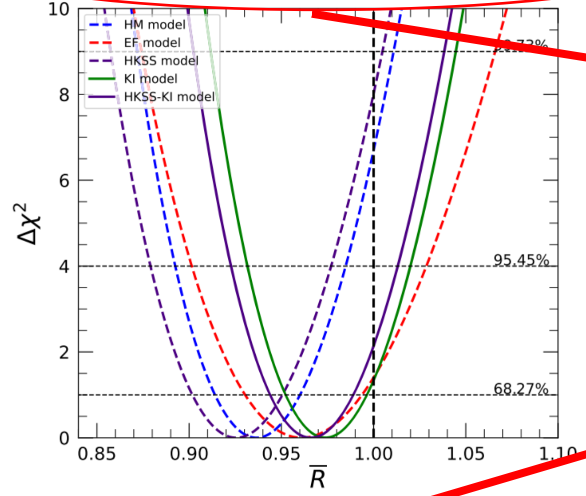
- Another European reactors with mixed oxide technology with typical fission fractions

(0.000: 0.080: 0.708: 0.212)

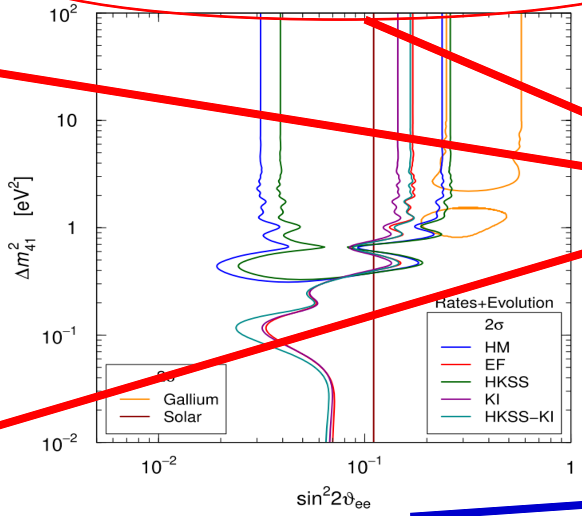
$$\sigma^{\mathrm{pre}} = 5.05 \pm (0.07)_{\mathrm{MI}} \pm (0.01)_{\mathrm{HM}} \quad (1.4\%)$$

Conclusion

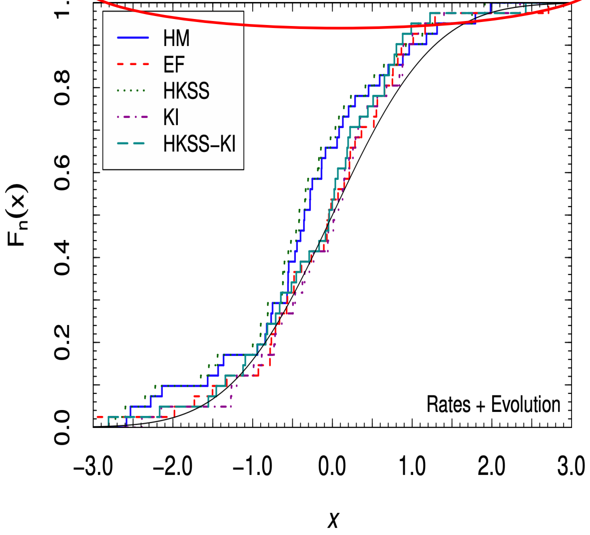
Reactor Antineutrino Anomaly



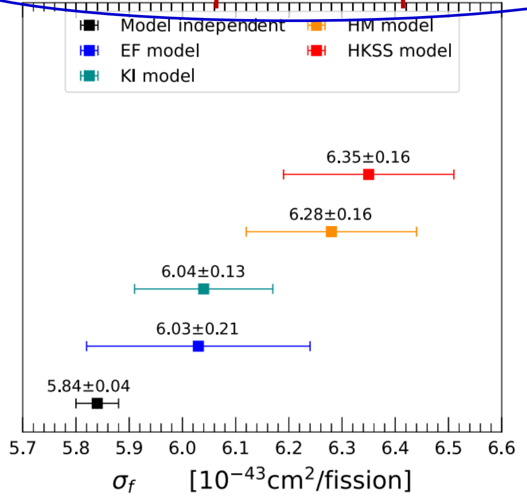
Short-baseline oscillation



Best-fit model



Model-independent prediction



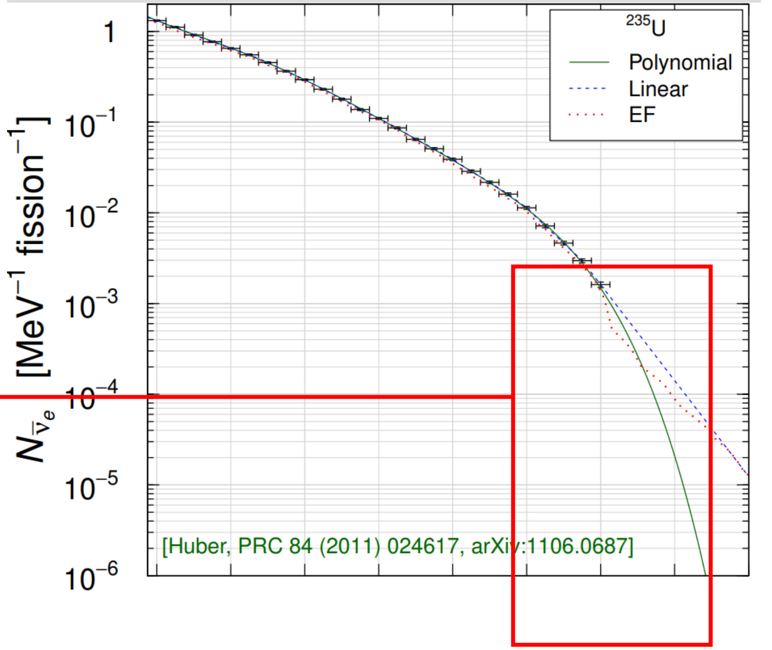
- RAA ➡ recent flux model refinements
- Best-fit models: EF and KI
  - No RAA
  - No short-baseline oscillations
- Global fits of reactor data
  - Model independent isotopic fluxes
  - High precision IBD yields
- The bump anomaly needs more investigation.

Thanks for your attention!

Backup

Updated IBD yields

- The individual IBD yield σ_i
  1. **IBD cross section**
  2. **Integral energy regions** (1.8→10.0 MeV)
     - Low energy region (1.8 → 8.0 MeV)
       extrapolate and interpolate with the original spectra.
     - High energy region approximation (8.0 → 10.0 MeV)
       EF summation model spectra with a very conservative 100% uncertainty.



original IBD yields

Model	σ_{235}	σ_{238}	σ_{239}	σ_{241}
HM	6.69 ± 0.14	10.10 ± 0.82	4.40 ± 0.11	6.03 ± 0.13
EF	6.28 ± 0.31	10.14 ± 1.01	4.42 ± 0.22	6.07 ± 0.31
HKSS	6.74 ± 0.17	10.33 ± 0.85	4.43 ± 0.13	6.07 ± 0.16
KI	6.27 ± 0.13	9.34 ± 0.47	4.33 ± 0.11	6.01 ± 0.13

our updated results

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	4.42 ± 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

Small contribution above 8 MeV:
0.3% for ^{235}U, 0.9% for ^{238}U,
0.2% for ^{239}Pu, 0.3% for ^{241}Pu.

Data Sets: reactor rates

- The data sets in our work are separated into three categories:
  - High-enriched uranium (HEU) reactor rates (8 rates)
    - As known as the research reactors, where ^{235}U is the main contributor to the neutrino spectra.
  - Low-enriched uranium (LEU) reactor rates (18 rates)
    - As known as the commercial reactors, where the fission fraction of ^{235}U is only $0.5 \sim 0.6$
  - Fuel evolution data LEU-like evolution data
    - Daya Bay (8 data points)
    - RENO (8 data points)

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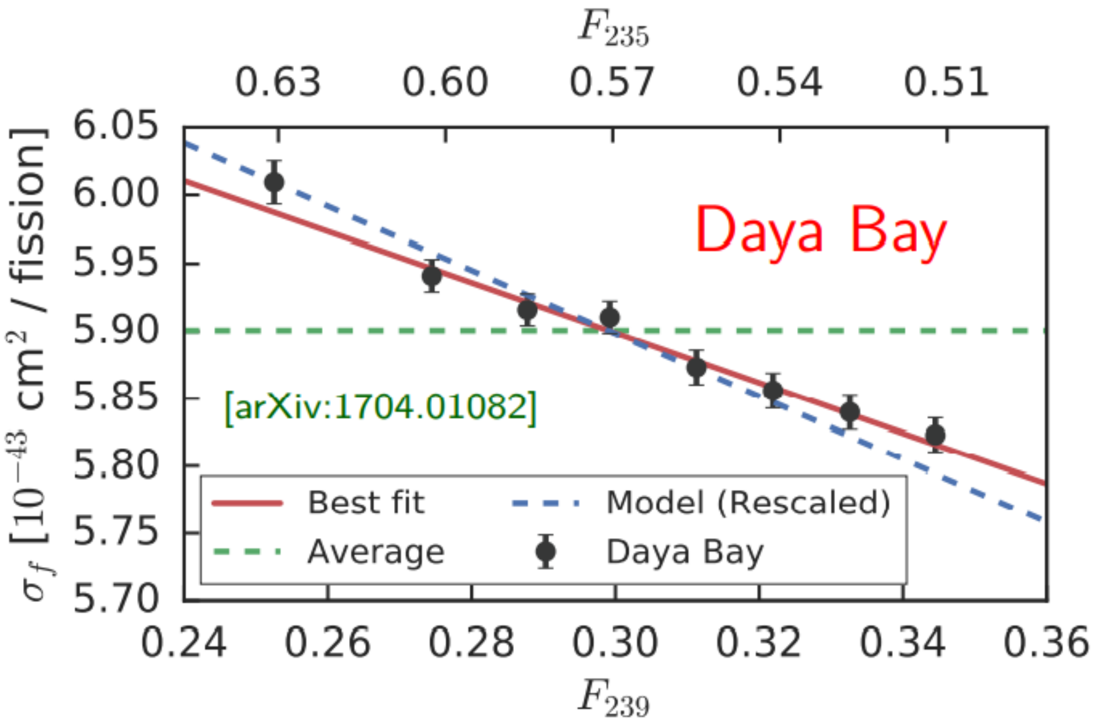
HEU rates

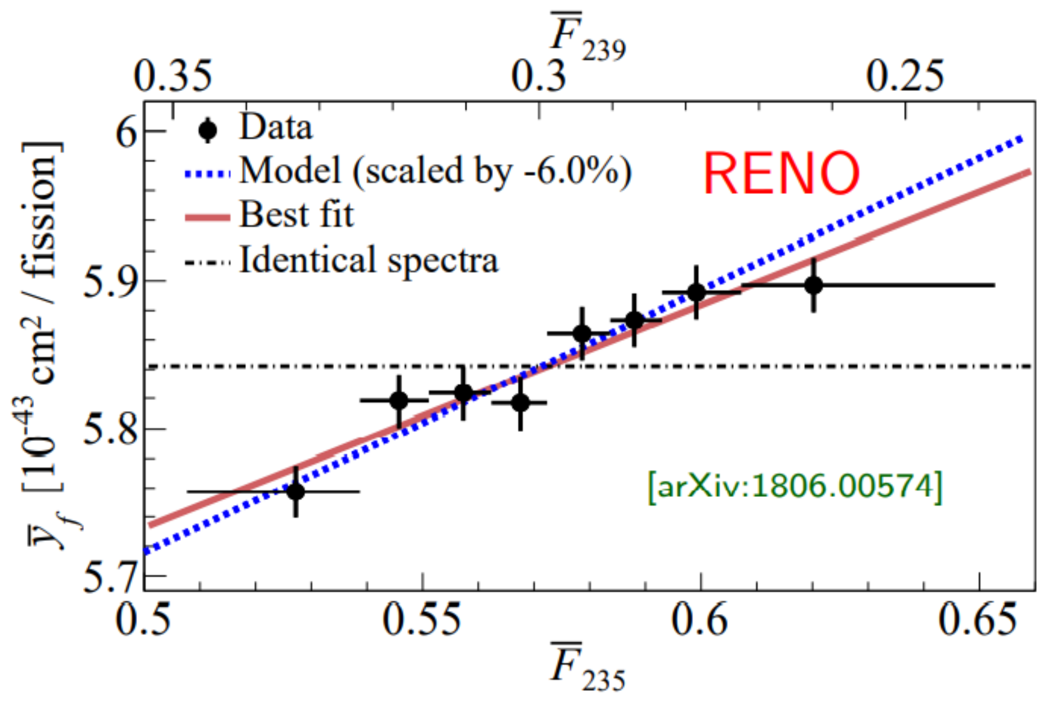
Experiment	f^a_{235}	f^a_{238}	f^a_{239}	f^a_{241}	$\sigma^{exp}_{f,a}$	δ^{exp}_a [%]
ILL	1	0	0	0	5.30	9.1
Krasnoyarsk87-33	1	0	0	0	6.20	5.2
Krasnoyarsk87-92	1	0	0	0	6.30	20.5
Krasnoyarsk94-57	1	0	0	0	6.26	4.2
Krasnoyarsk99-34	1	0	0	0	6.39	3.0
SRP-18	1	0	0	0	6.29	2.8
SRP-24	1	0	0	0	6.73	2.9
STEREO	1	0	0	0	6.34	2.5

LEU rates

Experiment	f^a_{235}	f^a_{238}	f^a_{239}	f^a_{241}	$\sigma^{exp}_{f,a}$	δ^{exp}_a [%]
Chooz	0.496	0.087	0.351	0.066	6.12	3.2
Palo Verde	0.600	0.070	0.270	0.060	6.25	5.4
Daya Bay	0.564	0.076	0.304	0.056	5.94	1.5
RENO	0.571	0.073	0.300	0.056	5.85	2.1
Double Chooz	0.520	0.087	0.333	0.060	5.71	1.1
Bugey-4	0.538	0.078	0.328	0.056	5.75	1.4
Rovno91	0.614	0.074	0.274	0.038	5.85	2.8
Rovno88-1I	0.607	0.074	0.277	0.042	5.70	6.4
Rovno88-2I	0.603	0.076	0.276	0.045	5.89	6.4
Rovno88-1S	0.606	0.074	0.277	0.043	6.04	7.3
Rovno88-2S	0.557	0.076	0.313	0.054	5.96	7.3
Rovno88-3S	0.606	0.074	0.274	0.046	5.83	6.8
Bugey-3-15	0.538	0.078	0.328	0.056	5.77	4.2
Bugey-3-40	0.538	0.078	0.328	0.056	5.81	4.3
Bugey-3-95	0.538	0.078	0.328	0.056	5.35	15.2
Gosgen-38	0.619	0.067	0.272	0.042	5.99	5.4
Gosgen-46	0.584	0.068	0.298	0.050	6.09	5.4
Gosgen-65	0.543	0.070	0.329	0.058	5.62	6.7

Data Sets: evolution data





LSM with Wilks' theorem

How to treat the systematic theoretical uncertainties in the least-squares function.

Method A

Phys. Rev. D83, 073006 (2011)
JHEP 1706, 135 (2017)

A covariance matrix with experimental and theoretical uncertainties added in quadrature.

$$\chi^2 = \sum_{a,b} \left(\sigma^{\rm exp}_{f,a} - R^a_{\rm NP}\sigma^{\rm th}_{f,a}\right) \left(V^{\rm tot}\right)^{-1}_{ab} \left(\sigma^{\rm exp}_{f,b} - R^b_{\rm NP}\sigma^{\rm th}_{f,b}\right)$$

$$V^{\rm tot} = V^{\rm exp} + \underline{V^{\rm th}} \qquad \sigma^{\rm th}_{f,a} = \sum_i f^a_i \sigma^{\rm mod}_i.$$

A strongly-correlated theoretical matrix derived from the covariance matrix V^{mod}_{ij} among ^{235}U, ^{238}U, ^{239}Pu, and ^{241}Pu

The method A will suffer the PPP!

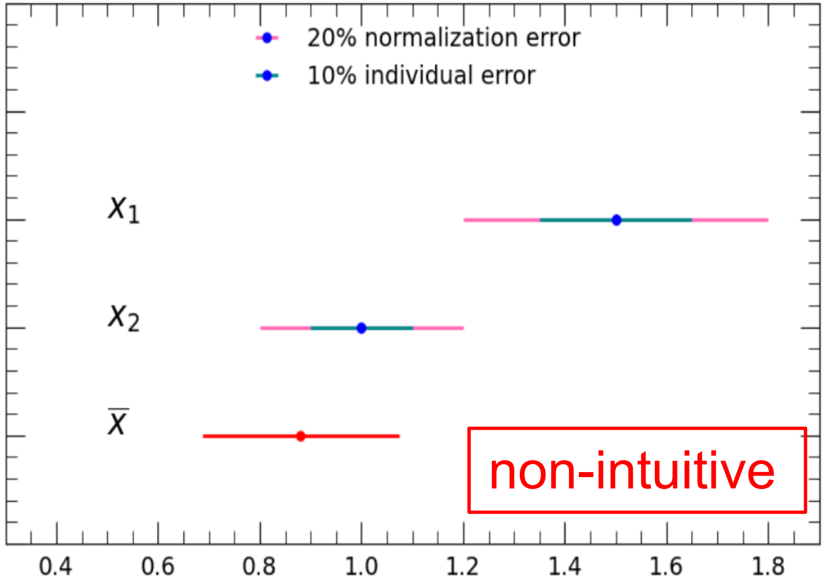
Journal of Nuclear Science and Technology 31, 770 (1994).

Peelle's Pertinent Puzzle

strongly correlated data

↓

the best-fit average can be lower than most of the data



- improper combination of experimental and theoretical matrices
- truncation of data space.

LSM with Wilks' theorem

Method B *Phys. Rev. D87, 073018 (2013)*

Calculate the fit results considering only the experimental uncertainties and add by hand a global theoretical uncertainty to the final result.

hard to calculate

$$\chi^2 = \sum_{a,b} \left(\sigma_{f,a}^{\text{exp}} - R_{\text{NP}}^{a}\sigma_{f,a}^{\text{th}}\right) (V^{\text{exp}})_{ab}^{-1} \left(\sigma_{f,b}^{\text{exp}} - R_{\text{NP}}^{b}\sigma_{f,b}^{\text{th}}\right)$$

Method C **Method C is adopted in this work!**

Phys.Rev.Lett. 120, 022503 (2018), Phys.Rev. D99, 073005 (2019)

Consider the theoretical uncertainties with appropriate pull terms

$$\chi^2 = \sum_{a,b} \left(\sigma_{f,a}^{\text{exp}} - R_{\text{NP}}^{a}\sigma_{f,a}^{\text{th}}\right) (V^{\text{exp}})_{ab}^{-1} \left(\sigma_{f,b}^{\text{exp}} - R_{\text{NP}}^{b}\sigma_{f,b}^{\text{th}}\right)$$

$$+ \sum_{i,j\in\Omega} (r_i - 1) \left(\widetilde{V}^{\text{mod}}\right)_{ij}^{-1} (r_j - 1),$$

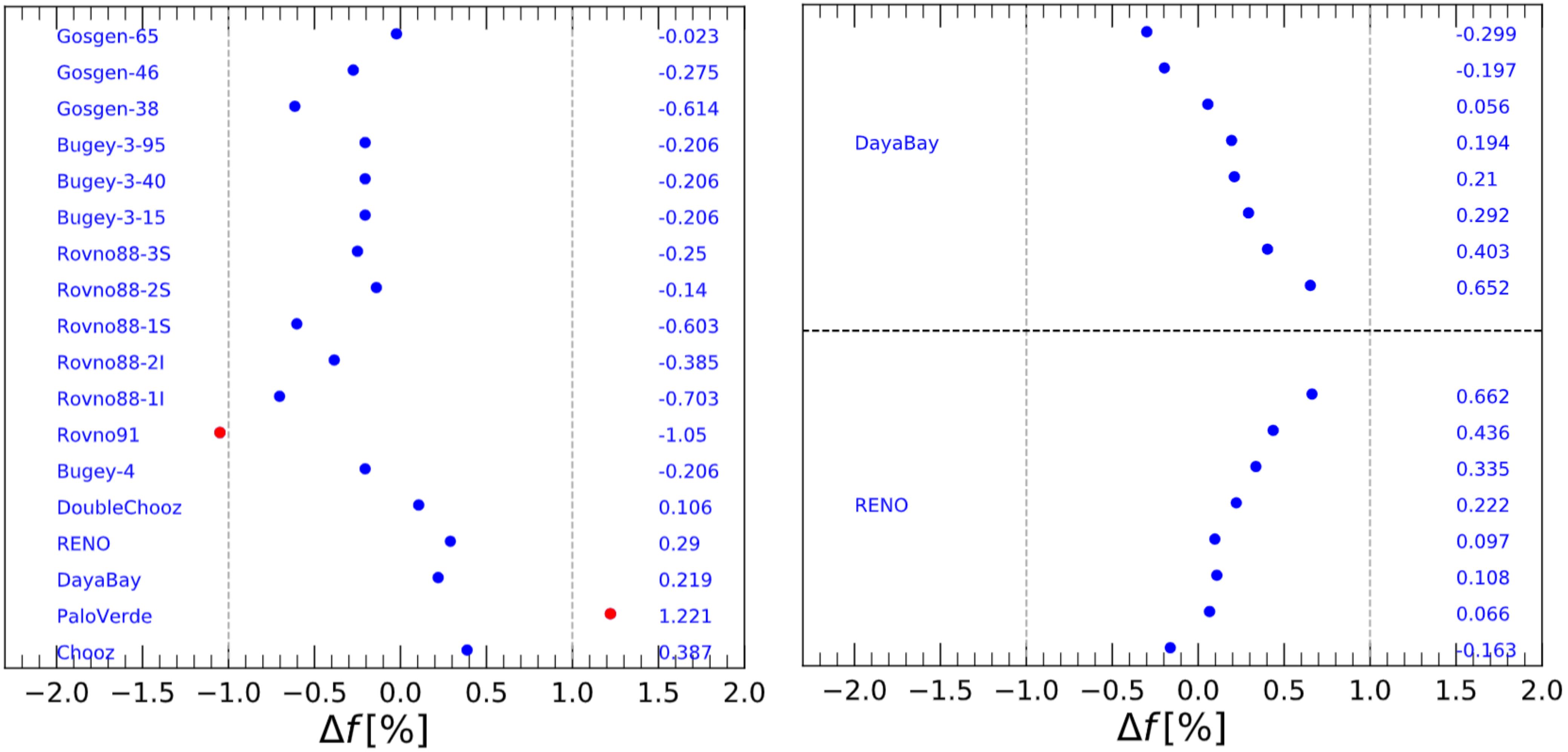
$$\sigma_{f,a}^{\text{th}} = \sum_i r_i f_i^a \sigma_i^{\text{mod}}. \qquad \widetilde{V}_{ij}^{\text{mod}} = V_{ij}^{\text{mod}} / (\sigma_i^{\text{mod}} \sigma_j^{\text{mod}})$$

V_{ij}^{mod} covariance matrix for these four isotopes

PPP is avoided by decoupling the minimization of physical parameters from the minimization of pull coefficients!

Pu's linearity

$\Delta f = f_{241} - k \cdot f_{239}$ for LEU-like data sets



(a) LEU reactor data

(b) Reactor evolution data

The linearity between Pu's is well described, for most data points $\Delta f < 1\%$

χ^2 function in model-independent fit

- The χ^2 fuction

$$\chi^2 = \sum_{a,b} \left(\sigma_{f,a}^{\exp} - \sigma_{f,a}^{\text{fit}}\right) \left(V^{\exp}\right)_{ab}^{-1} \left(\sigma_{f,b}^{\exp} - \sigma_{f,b}^{\text{fit}}\right),$$

The direct extraction

$$\sigma_{f,a}^{\text{fit}} = f_{235}^{a} \cdot \sigma_{235}^{\text{fit}} + f_{238}^{a} \cdot \sigma_{238}^{\text{fit}} + f_{239}^{a} \cdot \sigma_{239}^{\text{fit}} + f_{241}^{a} \cdot \sigma_{241}^{\text{fit}}$$

all data →

$$\sigma_{235} = 6.37 \pm 0.08$$
$$\sigma_{238} = 8.97 \pm 2.62$$
$$\sigma_{239} = 2.98 \pm 1.54$$
$$\sigma_{241} = 11.62 \pm 5.33$$

Used in this work

The improved extraction

$$\sigma_{f,a}^{\text{fit}} = f_{235}^{a} \cdot \sigma_{235}^{\text{fit}} + f_{238}^{a} \cdot \sigma_{238}^{\text{fit}} + f_{239}^{a} \cdot \sigma_{\text{Pu}}^{\text{fit}} + \Delta f^{a} \cdot \sigma_{241}^{\text{HM}},$$

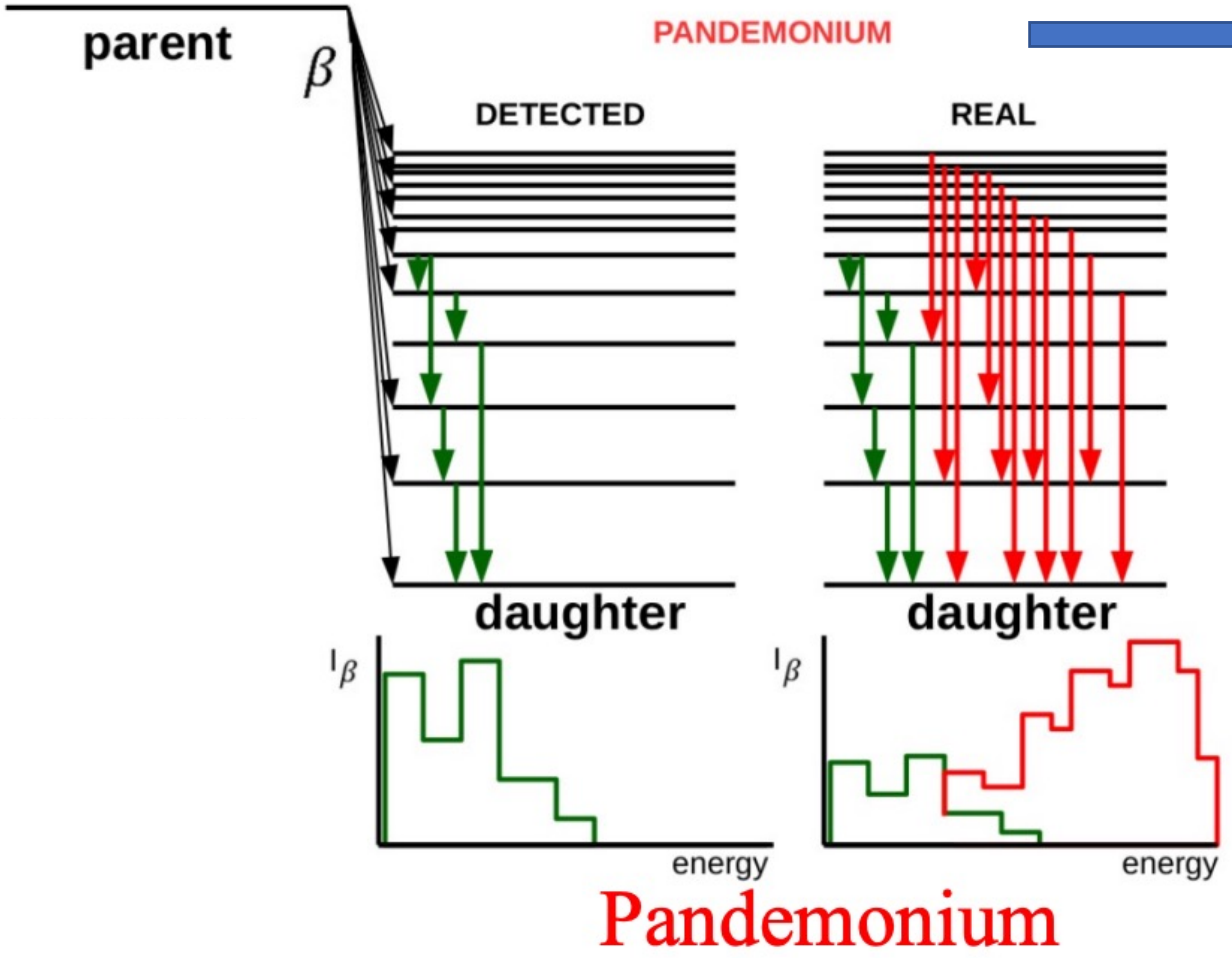
all data →

$$\sigma_{235} = 6.37 \pm 0.08$$
$$\sigma_{238} = 6.63 \pm 1.30$$
$$\sigma_{\text{Pu}} = 5.64 \pm 0.20$$

- Reactor neutrino spectra models can offer referenced Pu's IBD yields
- The improved extraction can obtain more precise IBD yields

Model	σ_{235}	σ_{238}	σ_{239}	σ_{241}	$\sigma_{239} + 0.177\sigma_{241}$
HM	6.74 ± 0.17	10.19 ± 0.83	4.40 ± 0.13	6.10 ± 0.16	5.48 ± 0.13
EF	6.29 ± 0.31	10.16 ± 1.02	4.42 ± 0.22	6.23 ± 0.31	5.52 ± 0.23
HKSS	6.82 ± 0.18	10.28 ± 0.84	4.45 ± 0.13	6.17 ± 0.16	5.54 ± 0.13
KI	6.41 ± 0.14	9.53 ± 0.48	4.40 ± 0.13	6.10 ± 0.16	5.48 ± 0.13
HKSS-KI	6.48 ± 0.14	10.28 ± 0.84	4.45 ± 0.13	6.17 ± 0.16	5.54 ± 0.13

Pandemonium effect



Ge detector

high-energy gamma ↓

high-energy beta decay branch ↑

Pandemonium effect will enlarge the RAA