Short-Baseline Reactor Neutrinos and Anomalies

A brief review of theoretical and experimental effort to predict and measure reactor antineutrino flux

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6/22/2026

Neutrino 2026: XXXII International Conference on Neutrino Physics and Astrophysics, UC Irvine, U.S.A

The First SBL Reactor Neutrino Measurement

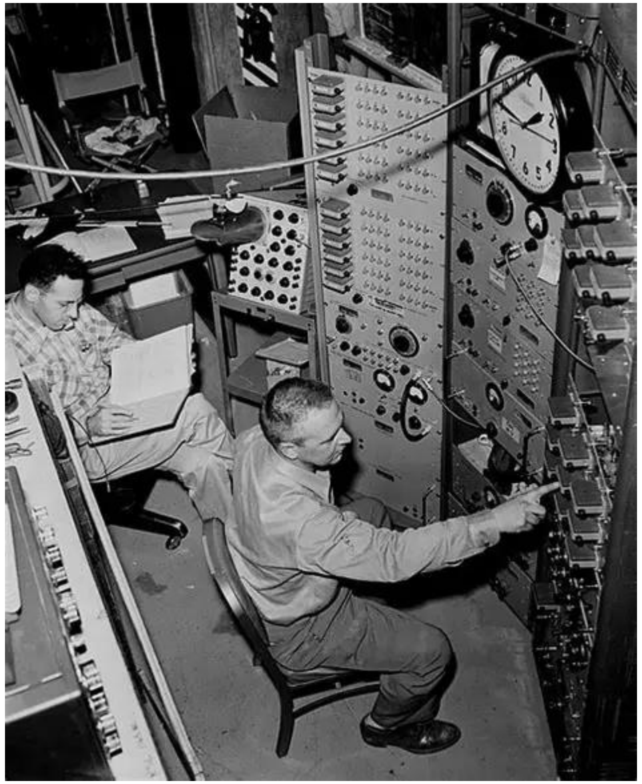
20 July 1956, Volume 124, Number 3212 **SCIENCE**

Detection of the Free Neutrino: a Confirmation

C. L. Cowan, Jr., F. Reines, F. B. Harrison, H. W. Kruse, A. D. McGuire

A two-page paper on Science

1) A reactor-power-dependent signal was observed which was (within 5 percent) in agreement with a cross section for reaction 1 of 6.3×10^{-44} cm². The predicted cross section (8) for the reaction, however, is uncertain by ± 25 percent. In one set of runs, the neutrino



Reines and Cowan @Savannah River Plant, neutrino discovery

- 1956: measured Inverse-Beta-Decay (IBD) cross section 6.3 x 10^{-44} cm^2 (with no uncertainty), in agreement with prediction (with 25% uncertainty): Lucky?

The First SBL Reactor Neutrino **Anomaly?**

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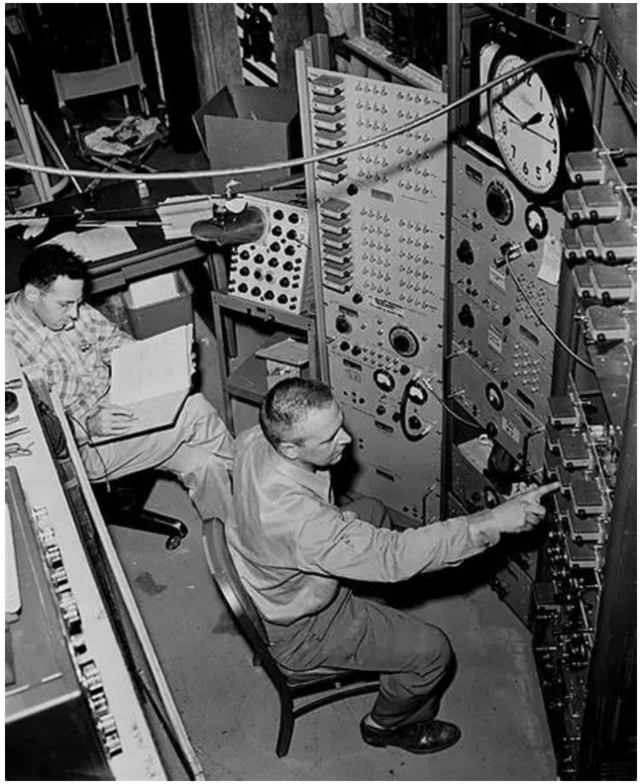
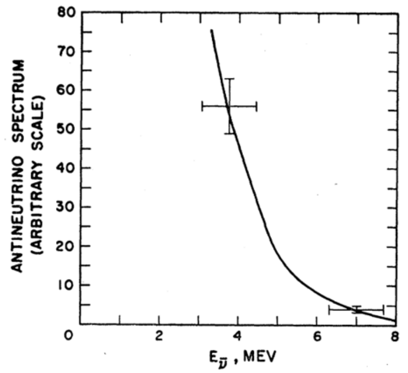


Reines and Cowan @Savannah River Plant, neutrino discovery

- ❑ 1956: measured Inverse-Beta-Decay (IBD) cross section 6.3 x 10^{-44} cm^2 (with no uncertainty), in agreement with prediction (with 25% uncertainty): Lucky?
- ❑ 1956-1957: parity violation was established, leading to the V-A theory of weak interaction that increased IBD cross section by a factor of 2

The Second SBL Reactor Neutrino Measurement, 1958



A 7-page paper on Physical Review

Free Antineutrino Absorption Cross Section. I. Measurement of the Free Antineutrino Absorption Cross Section by Protons*

FREDERICK REINES AND CLYDE L. COWAN, JR.†
Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico
(Received September 8, 1958)

$$\bar{\sigma}=\frac{36\pm4}{3600\times1.3\times10^{13}\times8.3\times10^{28}\times(0.85\pm0.05)\times(0.10\pm0.02)}=11\pm2.6\times10^{-44}\ \mathrm{cm}^2/\bar{\nu},$$

- ❑ Both theory and experiments are hard!
- ❑ Both theory and experiments evolve as scientific understanding improves.
- ❑ Anomaly happens when they don't agree with each other within their uncertainty estimations.

	1956 (discovery)	1958 (new measurement)
Theory		
Weak interaction	Fermi, parity-conserving (4 states)	V−A, parity-violating (2 states)
Predicted σ (cm²)	6 x 10^{-44} (±25%)	**1 x 10^{-43} (±17%)**
Experiment		
Efficiency / Background	analytical approx.; on/off subtraction	Monte Carlo simulation (IBM 704)
Measured σ (cm²)	*6.3 x 10^{-44}	**1.1 x 10^{-43} (±24%)**

**1959 reanalysis: 1.2 x 10^{-43} (-30%+58%)*

Timeline: Experiments vs. Flux Predictions

EXPERIMENTS

First generation reactor exp.
ILL · Bugey3 · Gösgen · Krasnoyarsk · Rovno · Savannah River · Bugey4

km-baseline reactor exp.
CHOOZ · Palo Verde

θ_{13} discovery era
Daya Bay · RENO · Double Chooz

VSBL sterile searches
NEOS · DANSS · STEREO · PROSPECT · Neutrino-4 · SOLID

Reactor Antineutrino Anomaly

1980-90s | 2000s | 2010s | 2020–2026

eV-mass-scale Sterile Neutrino Global Fits

Conversion Methods

ILL β-spectra data (1981 -1989)
Schreckenbach fit
Vogel refit (2007)
Huber-Mueller (2011)
Hayes (effective Z, forbidden β)
Haag ^{238}U data
Kurchatov (KI) β-ratio

Summation Methods

Early Models (Davis, Vogel, Shenter)
Greenwood TAGS (1997)
Tengblad β-data (111 nuclides, 1989)
Mueller (2011)
ENDF summation (Dwyer-Langford, Sonzogni)
TAGS Campaign (Jyväskylä, ORNL, 2010 - 2023)
SM2012 – 2018 (EF model)
BESTIOLE-2023 (CEA model)

Summation method

ENDF, JEFF, JENDL, CENDL, ROSFOND …

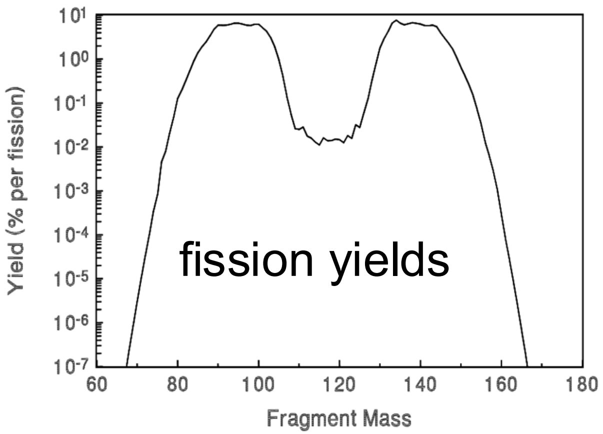
- Build the spectrum bottom-up: fission yields × decay schemes for every β branch using nuclear databases:

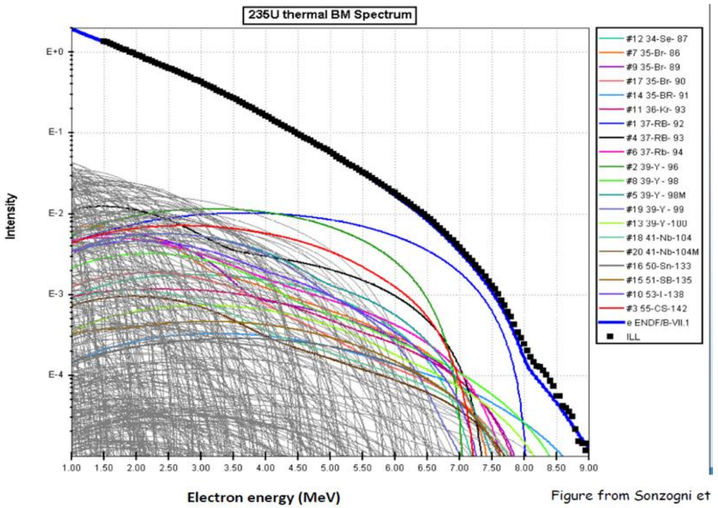
$$\frac{d\phi_i}{dE_\nu} = \sum_n Y_n\,(Z, A, t)\cdot\left(\sum_m b_{n,m}\cdot P\,(E_\nu, E_0, Z)\right),$$

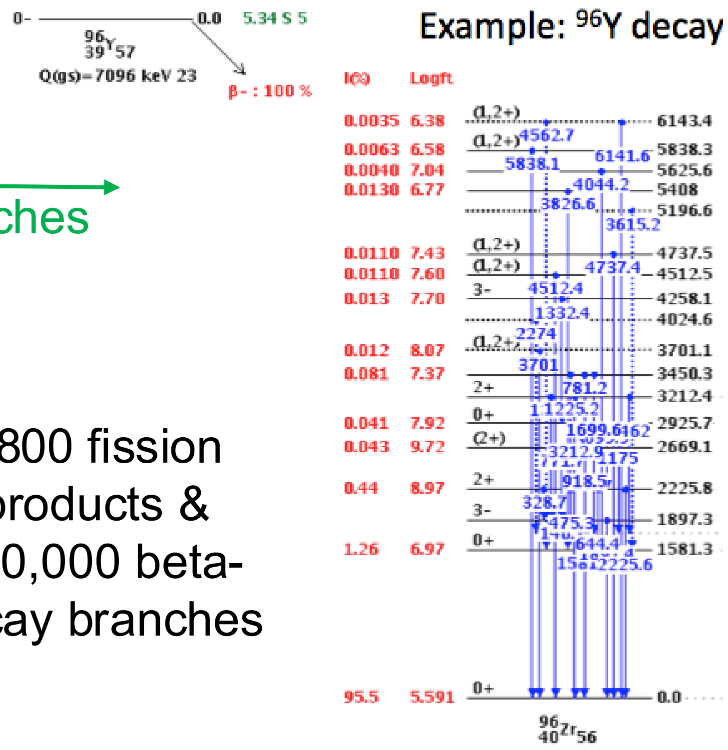
beta-decay branches

fission products

antineutrino spectra ($E_\nu = E_0 - E_e$)







~800 fission products & >10,000 beta-decay branches

Historically only used to predict ^{238}U flux (~8% fissions in LEU reactors)

Incomplete Database
(Decays: ~10% missing nuclides/branches;
Yields: tensions among db, isomeric ratios)

Forbidden decays non-unique shapes
(~30% decays)

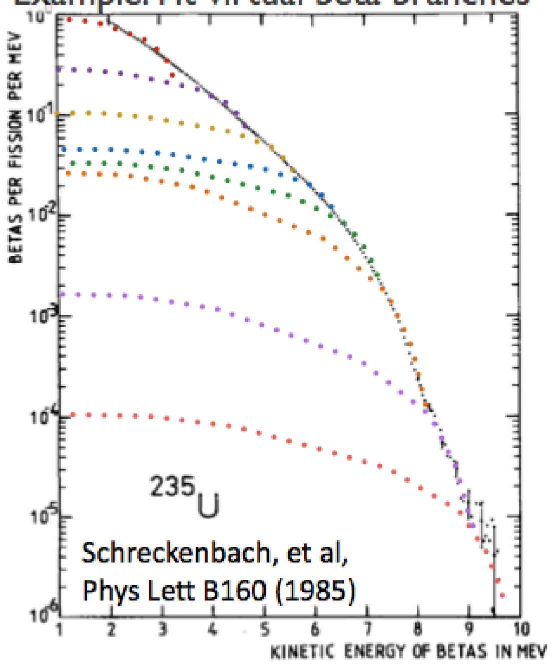
Pandemonium-biased beta-decay data
(over-predict high-energy spectra)

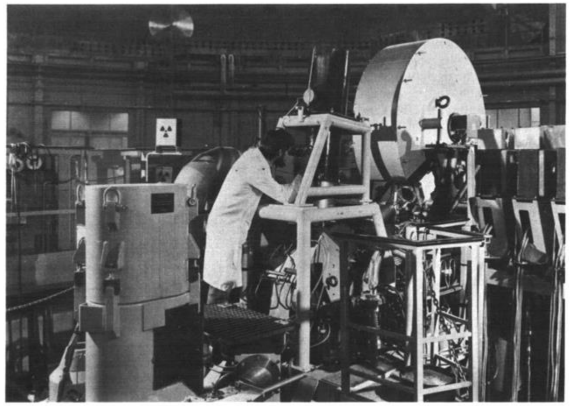
Difficult to estimate uncertainty budget
(often assigned a flat ~10% error)

Conversion method

- Anchor: aggregate β-spectra measured at ILL in 1981–89 (^{235}U, ^{239}Pu, ^{241}Pu)
  - Eradiated fission isotope target (e.g. thin foil of $^{235}UO_2$) in a high flux of thermal neutrons for tens of hours
- ^{238}U was not measured (only fission with fast neutrons) until 2014 at FRM-II in Garching, Germany (using the same BILL spectrometer)
- Convert total electron spectrum to total antineutrino spectra with fit to ~30 virtual beta-decay branches
  - equidistant end-point energy
  - assume allowed beta-decay shape $P(E_\nu, E_0, Z)$
  - empirical function of Z vs Q-value
- ILL-Vogel model
  - ILL conversion for ^{235}U, ^{239}Pu, ^{241}Pu
  - Vogel's summation for ^{238}U
  - agree with ~20 reactor flux measurements from 1980 -1990s

Example: Fit virtual beta branches





BILL spectrometer, ~1.8% normalization
NIMA 154, 127 (1978)

prompted two new evaluations in 2011

Very precise measurement and methodology: ~2.7% error

One and the only measurement (only @ILL using BILL)

Non-equilibrium effect (long-half-life (>10 h) fission products)

Virtual branches treatment (corrections from nuclear effects)

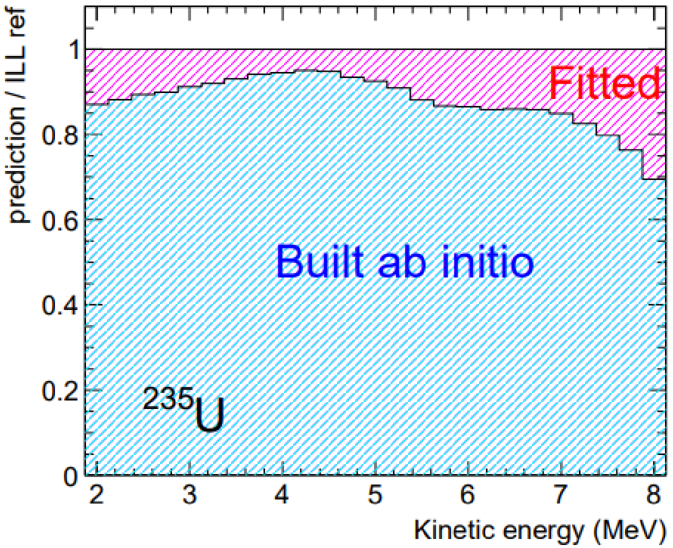
Re-evaluation: Huber-Mueller Model

"Improved Predictions of Reactor Antineutrino Spectra"

Mueller et al., Phys. Rev. C 83, 054615 (2011)

Hybrid method: +3%

- Updated summation calculation from the ENSDF database (for ^{235}U, ^{239}Pu, ^{241}Pu, ^{238}U)
- Conversion method for the missing 10% contribution (for ^{235}U, ^{239}Pu, ^{241}Pu)
- Correct for non-equilibrium effect

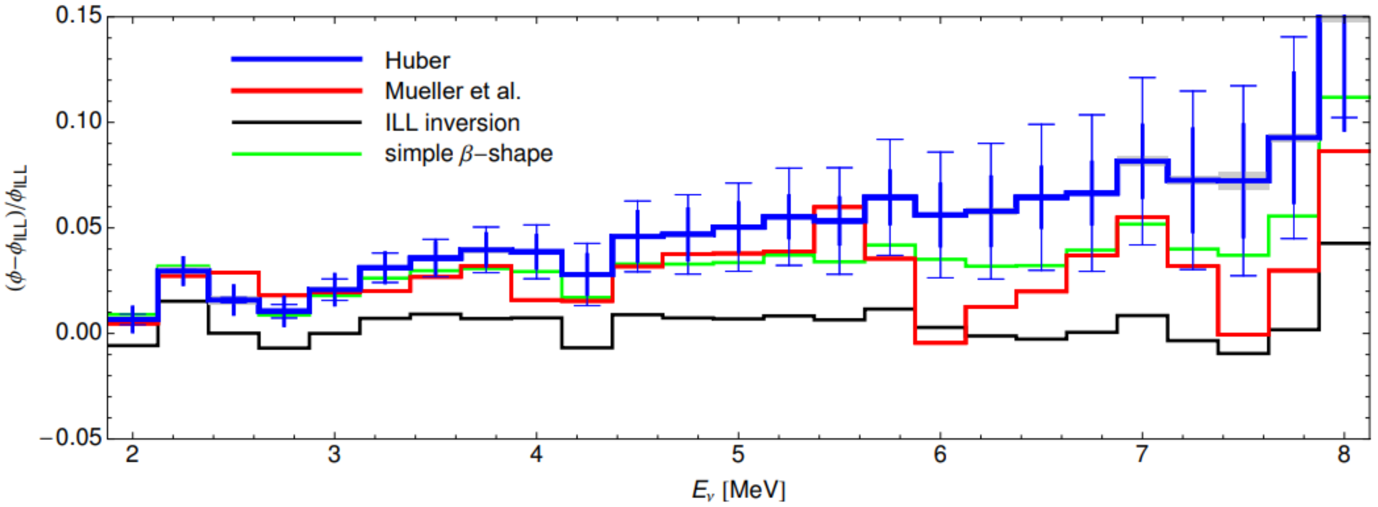


"On the determination of anti-neutrino spectra from nuclear reactors"

Huber, Phys. Rev. C 84, 024617 (2011)

Improved conversion method using ILL data (for ^{235}U, ^{239}Pu, ^{241}Pu)

- Reevaluated nuclear effects in correcting the beta-decay spectral shape +3%
  - effective Z as a function of Q-value for virtual branches
  - finite-size, radiative correction, weak magnetism
- Non-equilibrium effect +1-2%
- New neutron lifetime measurement +1%



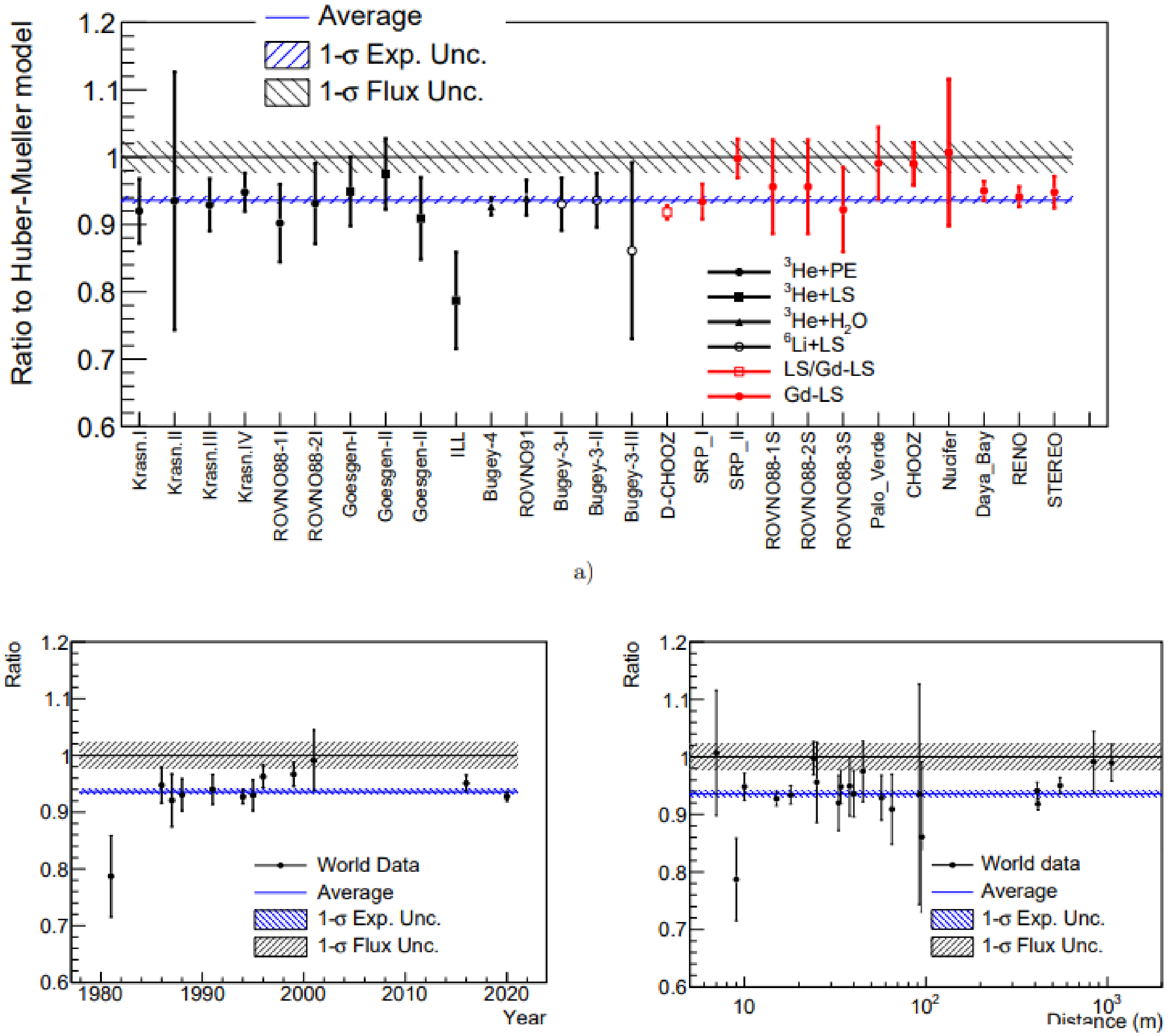
Flux Measurements

27 SBL reactor antineutrino flux measurements

- ❑ Span over 40 years from 1980s – 2020s
- ❑ Different detector types
  - Water/LS + ^{3}He counters
  - Gd- or ^{6}Li-loaded LS
- ❑ Different reactor types
  - Low-enriched Uranium (LEU)
  - Highly-enriched Uranium(HEU)
- ❑ Different baselines
- ❑ Different efficiency and background challenges

Consistent results with <0.5% combined experimental uncertainty

Zhang, Qian, Fallot, Prog. Part. Nucl. Phys. (2024)



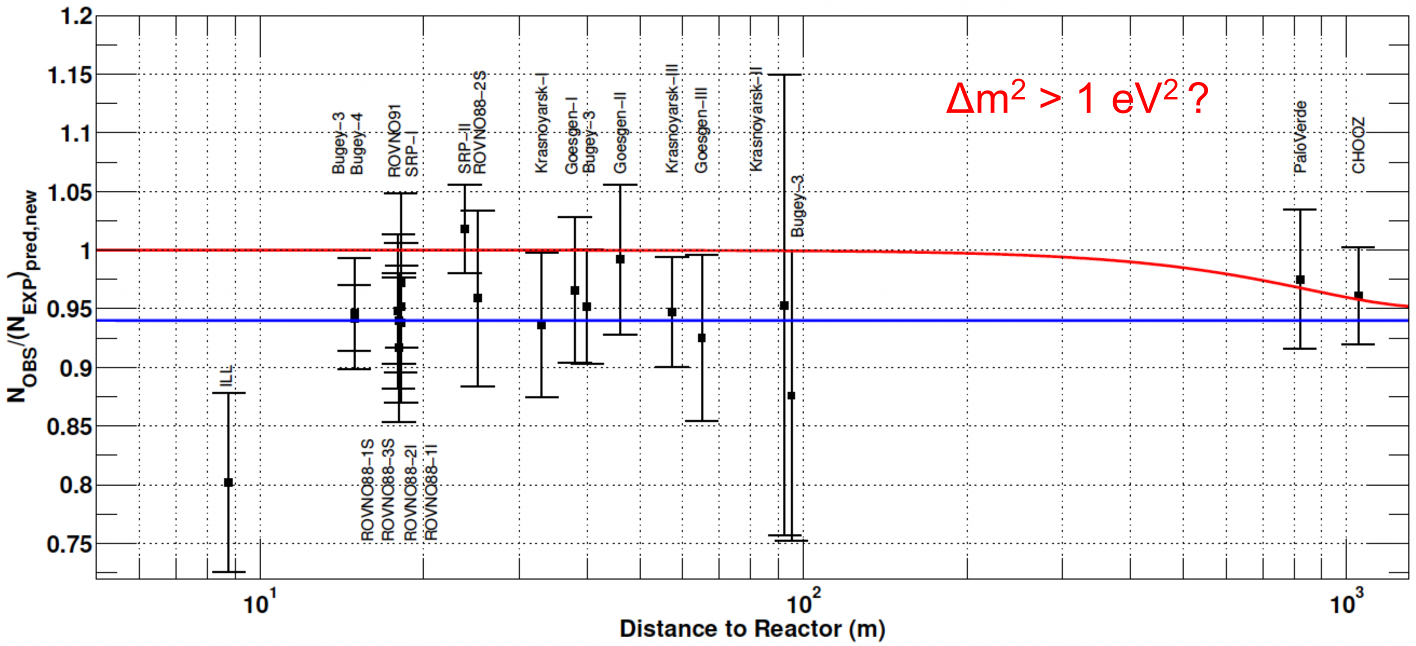
$$\bar{R} = 0.936^{+0.024}_{-0.023} \approx 0.936 \pm 0.005\ (\text{exp.}) \pm 0.023\ (\text{model}),$$

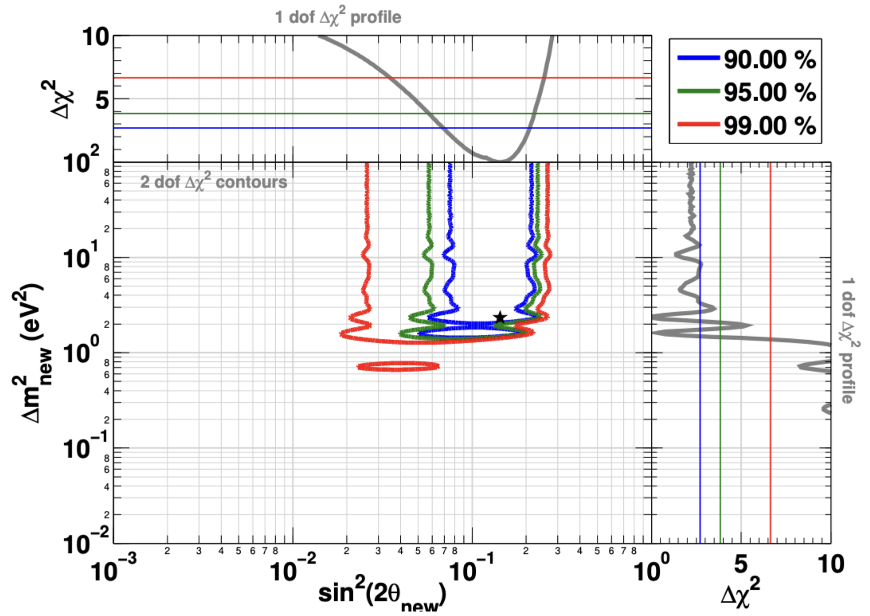
6.4% deficit, 2.6 σ dominated by model uncertainties

Sterile Neutrino Explanation

“The Reactor Antineutrino Anomaly” (RAA)

Mention et al., Phys. Rev. D 83, 073006 (2011)



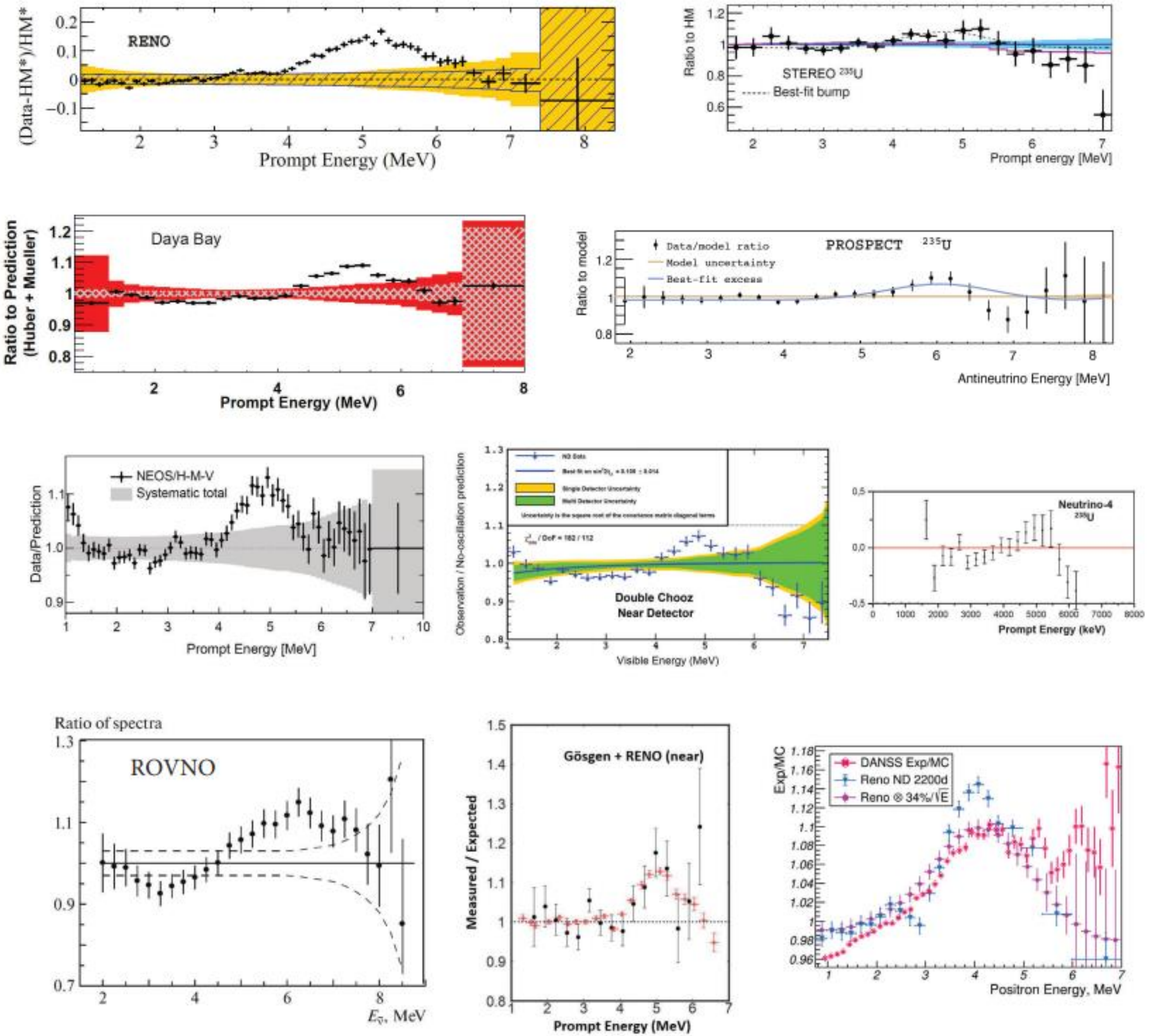


- ❑ RAA came from a theory update: Is theory and its uncertainty reliable?
- ❑ RAA is a rate-only analysis: is there spectral distortion in L/E?

- ❑ **Is theory and its uncertainty reliable?**
- ❑ **Is there a spectral distortion in L/E?**

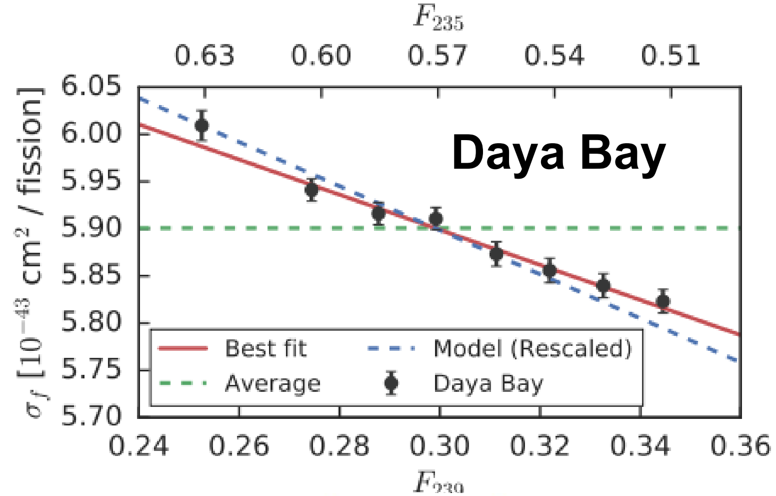
5-MeV Bump

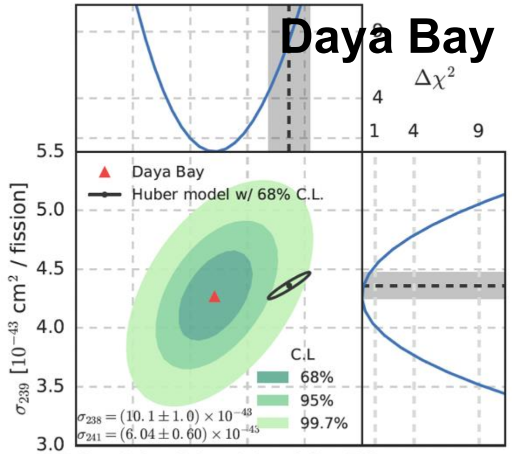
- First presented by Double CHOOZ and RENO at Neutrino 2014, then by Daya Bay within 2 months
- By now, has been observed in >10 experiments
  - reanalysis found evidence dated back to Gosgen / ROVNO in 1980s
- Bump is after normalization, shape discrepancy in other energy regions as well
- Cannot be explained by sterile neutrino oscillations
- Indicating issues inside the Huber-Mueller model

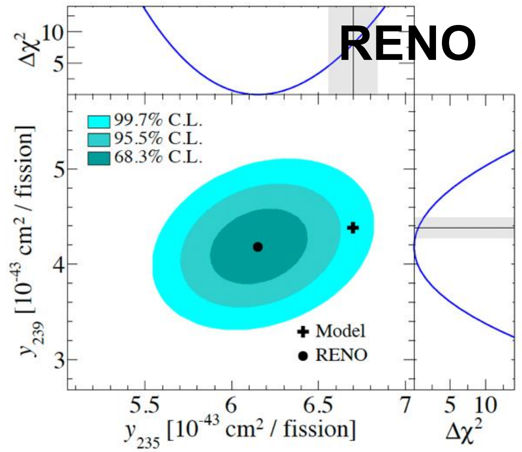


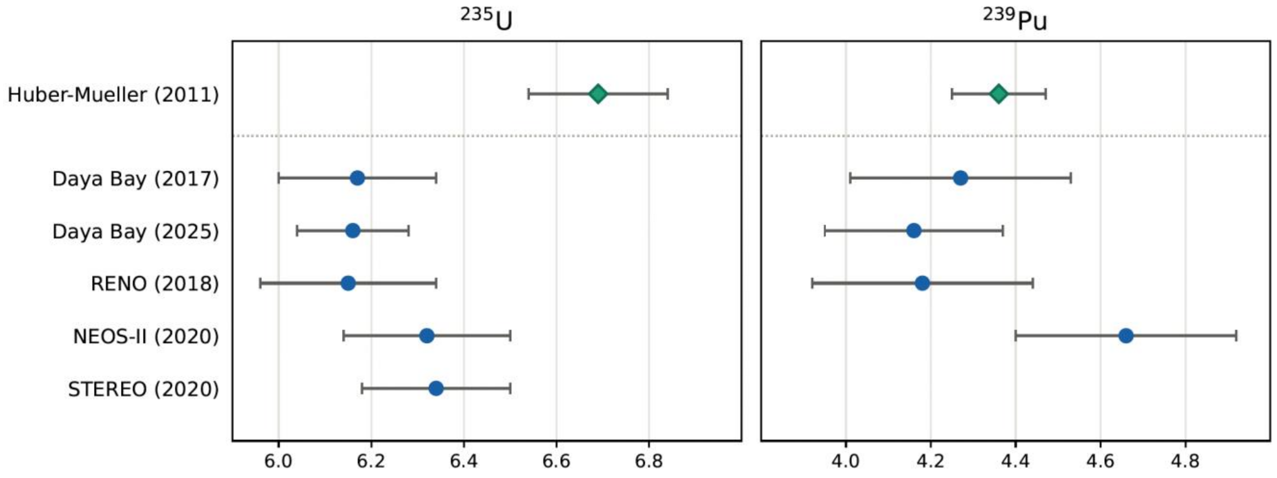
Individual ^{235}U and ^{239}Pu flux

- In 2017, Daya Bay used fuel evolution (changing fuel composition over reactor cycles) to separate ^{235}U and ^{239}Pu contributions, and measured a larger deficit in ^{235}U than ^{239}Pu. Confirmed by RENO in 2018 and NEOS-II in 2020.
  - ^{235}U flux also measured by STEREO in 2020 (HEU reactor)
  - ^{235}U flux ~8% below prediction, while ^{239}Pu is consistent (with larger exp. uncertainty)
- Isotope dependence cannot be explained by sterile neutrino oscillations, indicating issues in the Huber-Mueller model.









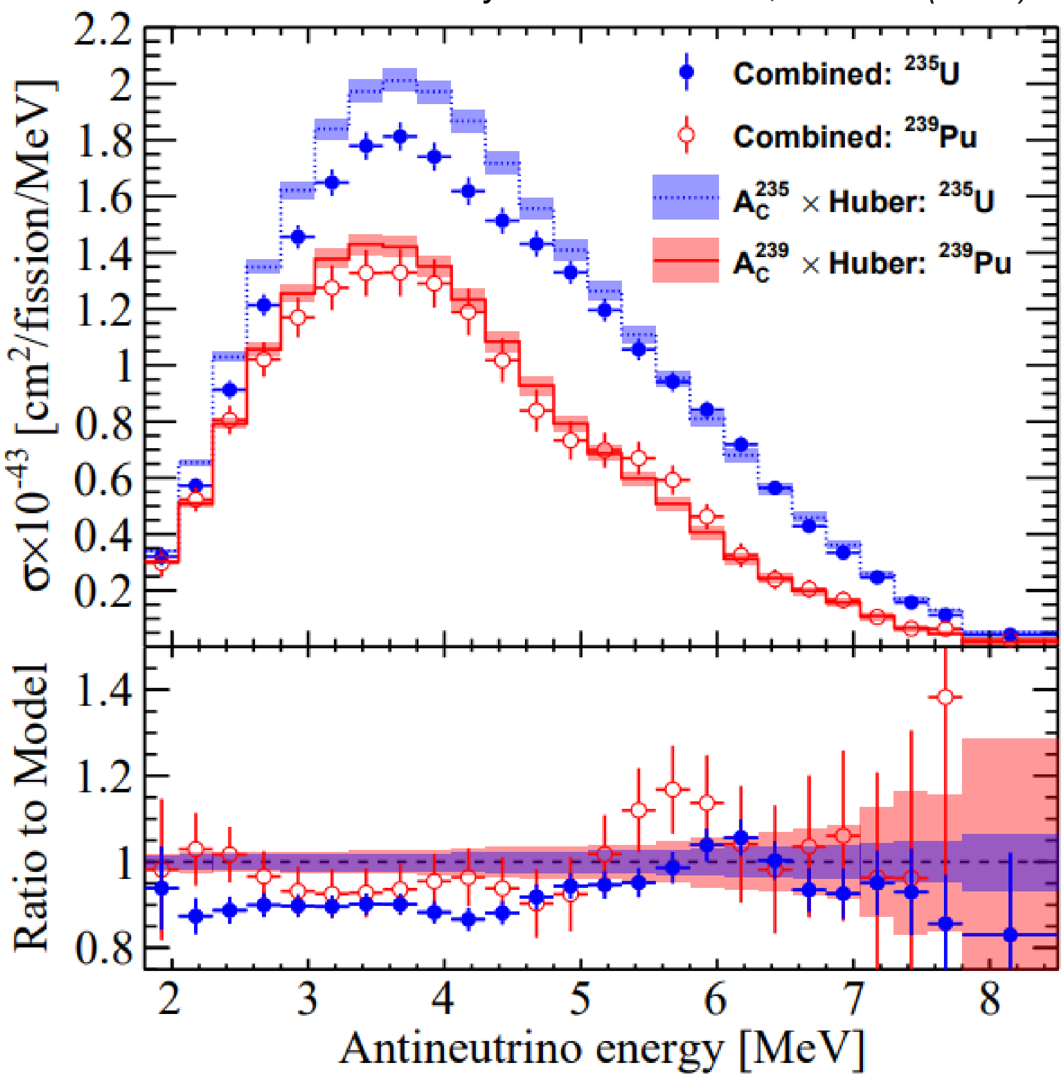
** DANSS also measured ^{235}U / ^{239}Pu ratio in Phys. Rev. D 112, 112005 (2025)*

Individual ^{235}U and ^{239}Pu Energy Spectra

In 2022, Daya Bay applied the same fuel evolution trick to each energy bin to extract ^{235}U and ^{239}Pu energy spectra, in combination with PROSPECT (HEU, shape-only ^{235}U spectrum)

- The normalization and the shape discrepancy with model prediction are different between ^{235}U and ^{239}Pu
- The "bump" structure is visible in both extracted spectra
  - Hinted at a common origin, such as inaccurate shape factors from forbidden decays

Phys. Rev. Lett. **128**, *081801 (2022)*

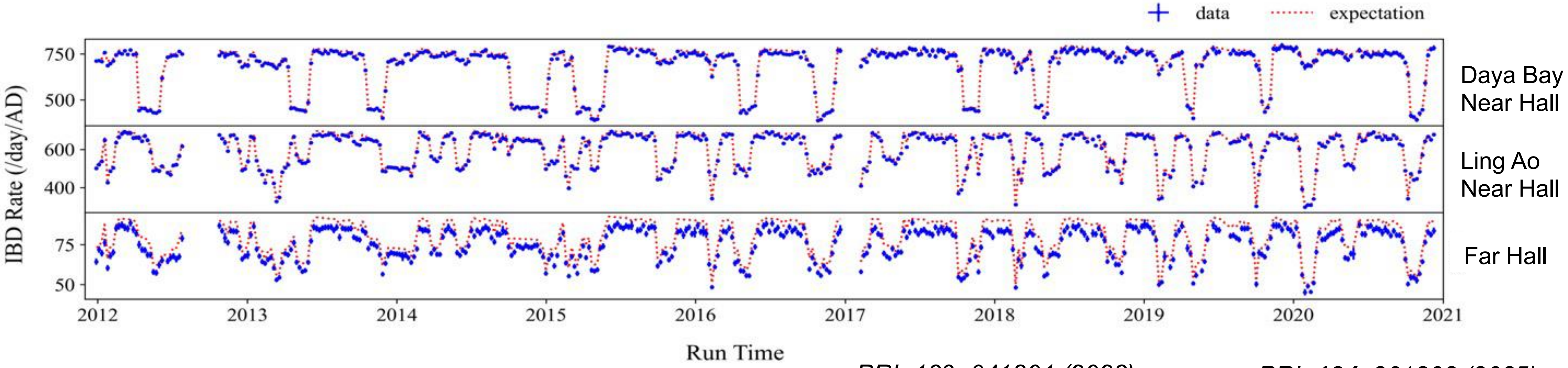


Daya Bay Full Dataset

Full Data Release of the Daya Bay Reactor Neutrino Experiment (2025)

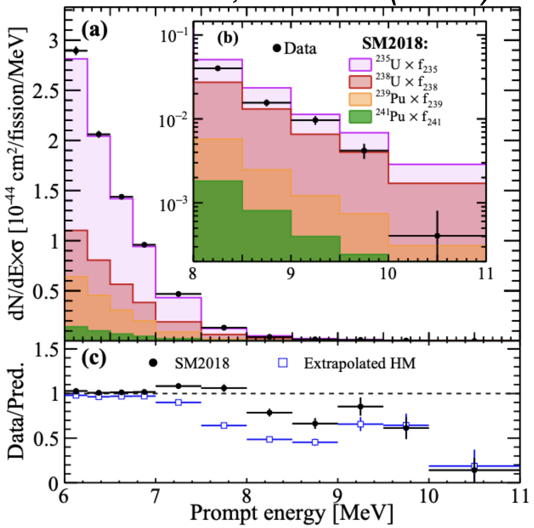
https://zenodo.org/records/17587229

- ❑ 9-year data taking, 5.5M $\bar{\nu}_e$ events

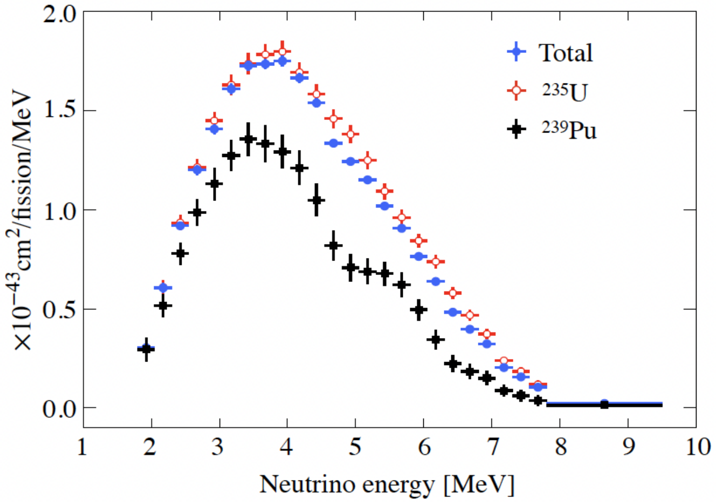


- ❑ Clean: S:B > 20
- ❑ High-statistics IBD prompt energy spectrum
- ❑ High-energy reactor antineutrino > 8 MeV
- ❑ Extraction of ^{235}U and ^{239}Pu spectra
- ❑ Unfolded antineutrino spectrum: reference spectrum for other reactor experiments

PRL 129, 041801 (2022)



*PRL **134**, 201802 (2025)*

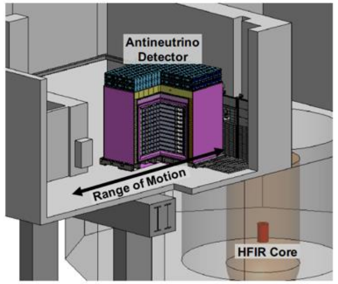


- ❑ Is theory and its uncertainty reliable? No
- ❑ Is there a spectral distortion in L/E?

Very-Short-Baseline Reactor Neutrino Experiments, 2015–2025

PROSPECT · HFIR (HEU)

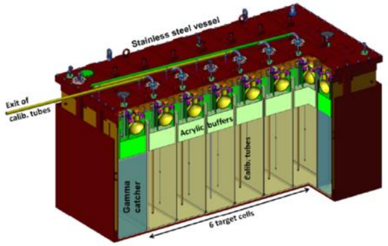
85 MW
7–12 m
segmented ^{6}Li-LS



Phys. Rev. Lett. 134, 151802 (2025)

STEREO · ILL (HEU)

58 MW
9–11 m
6-cell Gd-LS



Nature 613, 257 (2023)

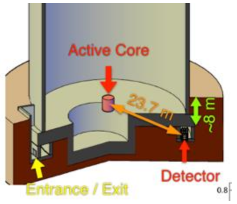
DANSS · Kalinin (LEU)

3 GW
10.7–12.9 m
movable plastic scint.

PoS ICHEP2022, 616 (2022)

NEOS / NEOS-II · Hanbit (LEU)

2.8 GW
24 m
Gd-LS
RENO+NEOS fit



Phys. Rev. D 105, L111101 (2022)

Neutrino-4 · SM-3 (HEU)

90 MW
6–12 m
movable Gd-LS

Phys. Rev. D 104, 032003 (2021)

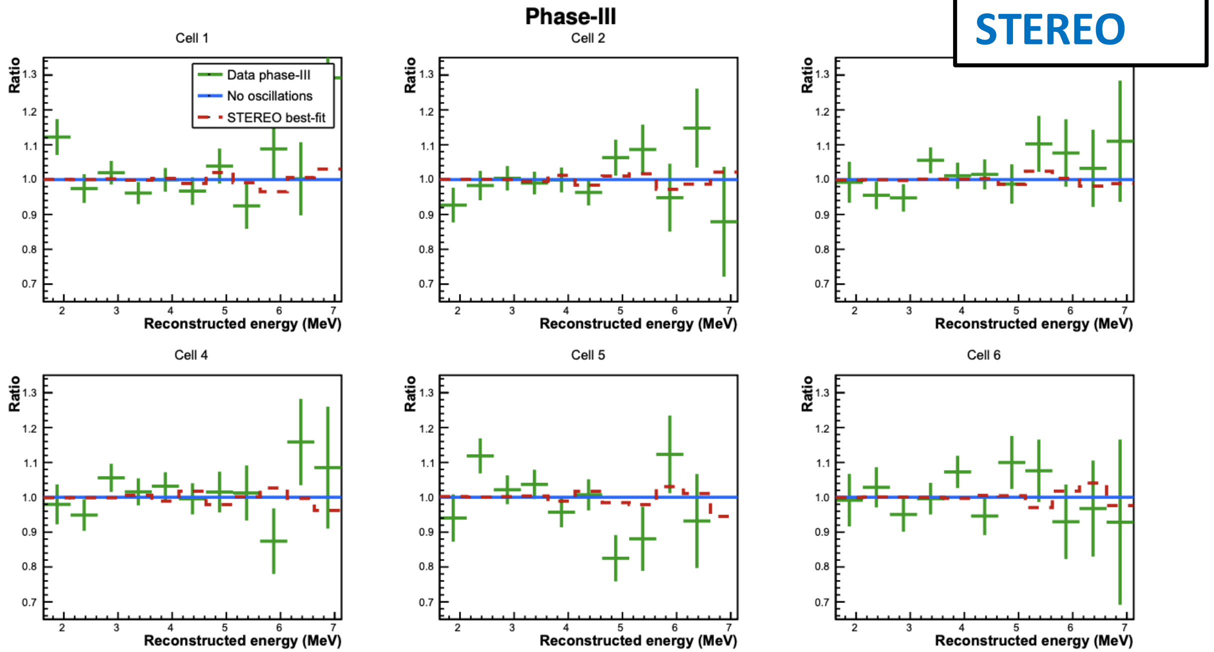
SoLid · BR2 (HEU)

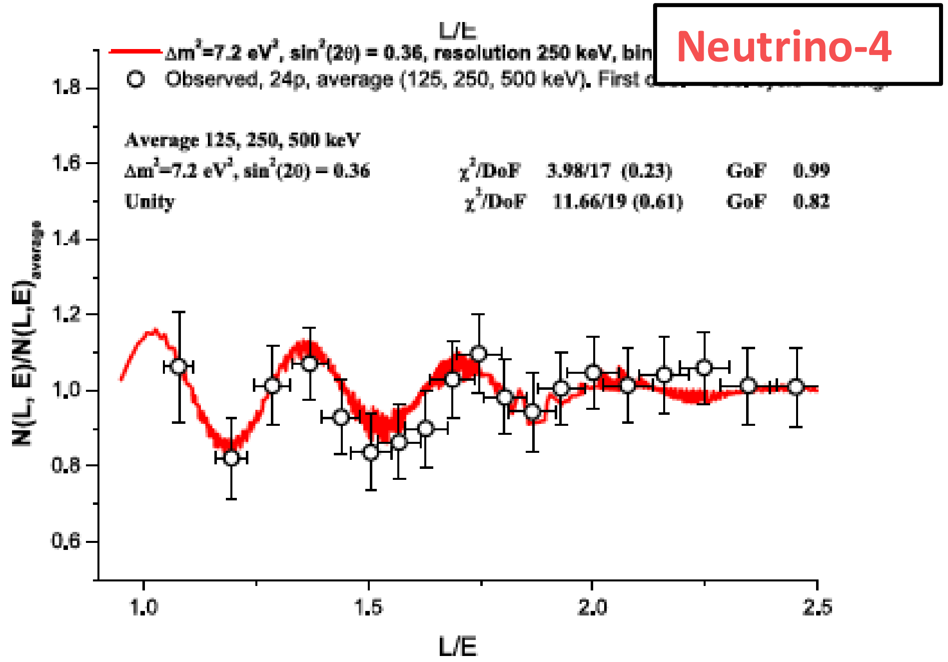
50-80 MW
6–9 m
^{6}LiF:ZnS + PVT cubes

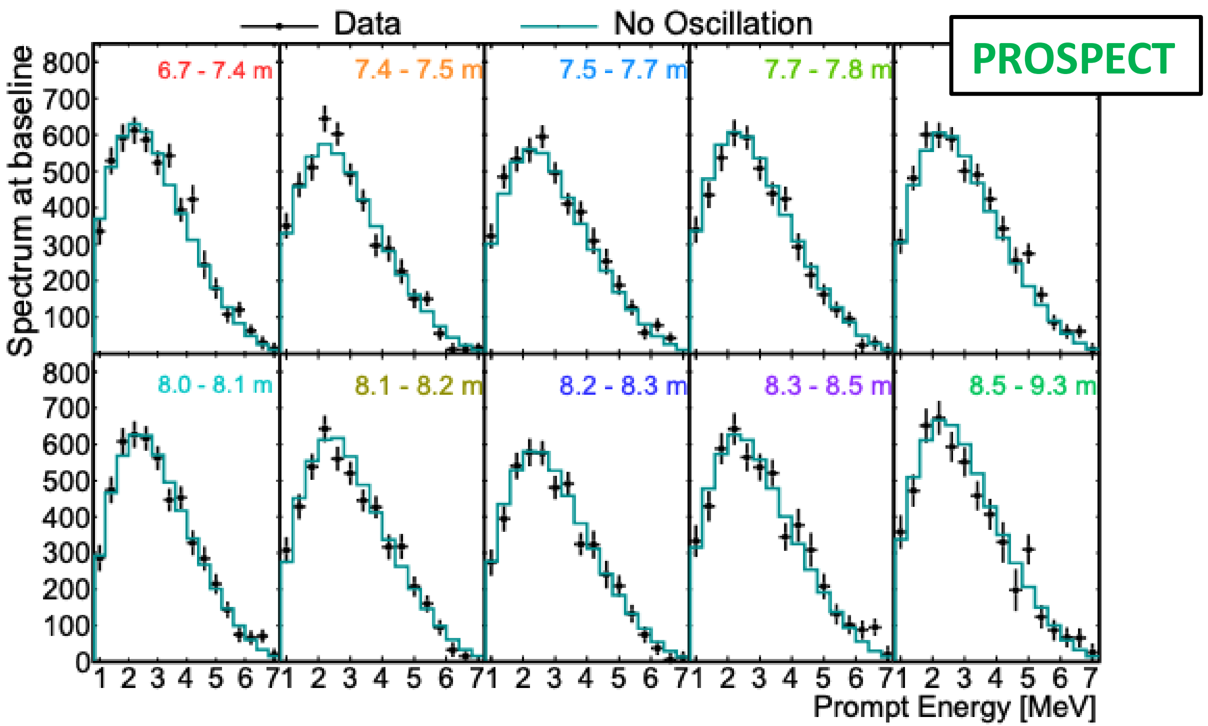
Phys. Rev. D 111, 072005 (2025)

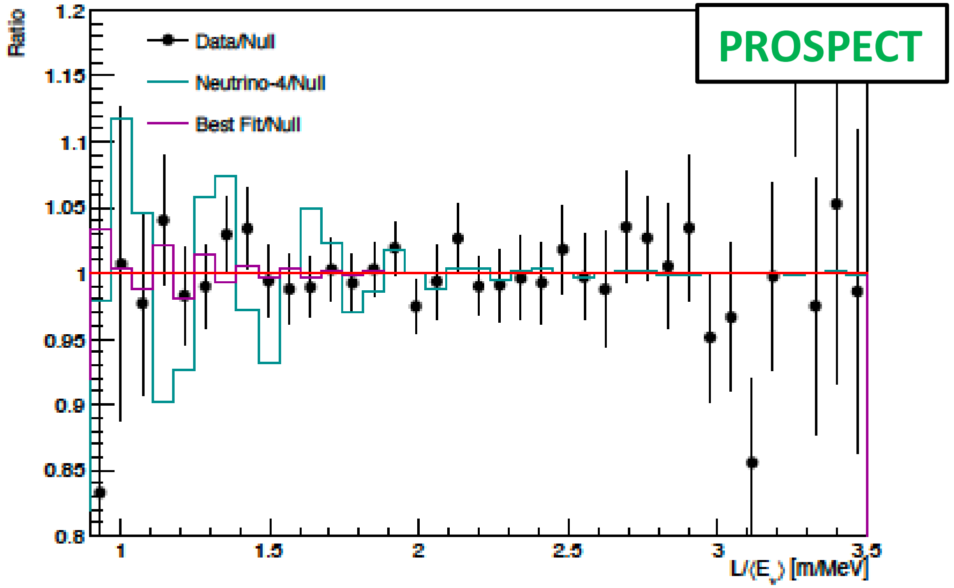
Reactor-model-independent search for sterile neutrinos

- ❑ Measure relative spectrum distortion at different baselines
- ❑ Use experimental spectrum as a reference (e.g. RENO), rather than from a theoretical model
- ❑ Look for multiple "wiggles" in the L/E space
- ❑ Target toward 0.3-10 eV^2 region

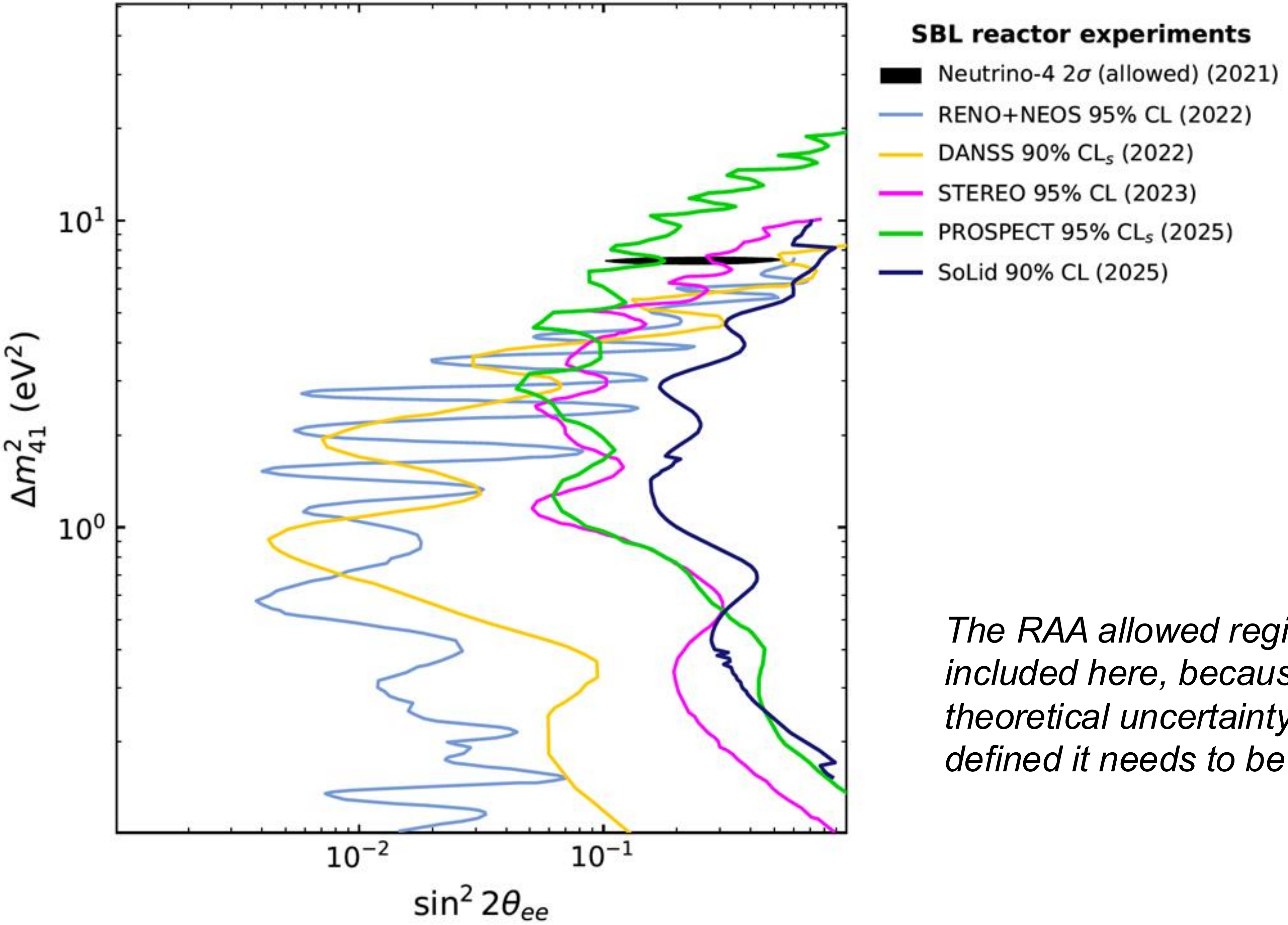








Neutrino-4's L/E distortion NOT confirmed by other SBL reactor experiments



The RAA allowed region is not included here, because the theoretical uncertainty that defined it needs to be revisited

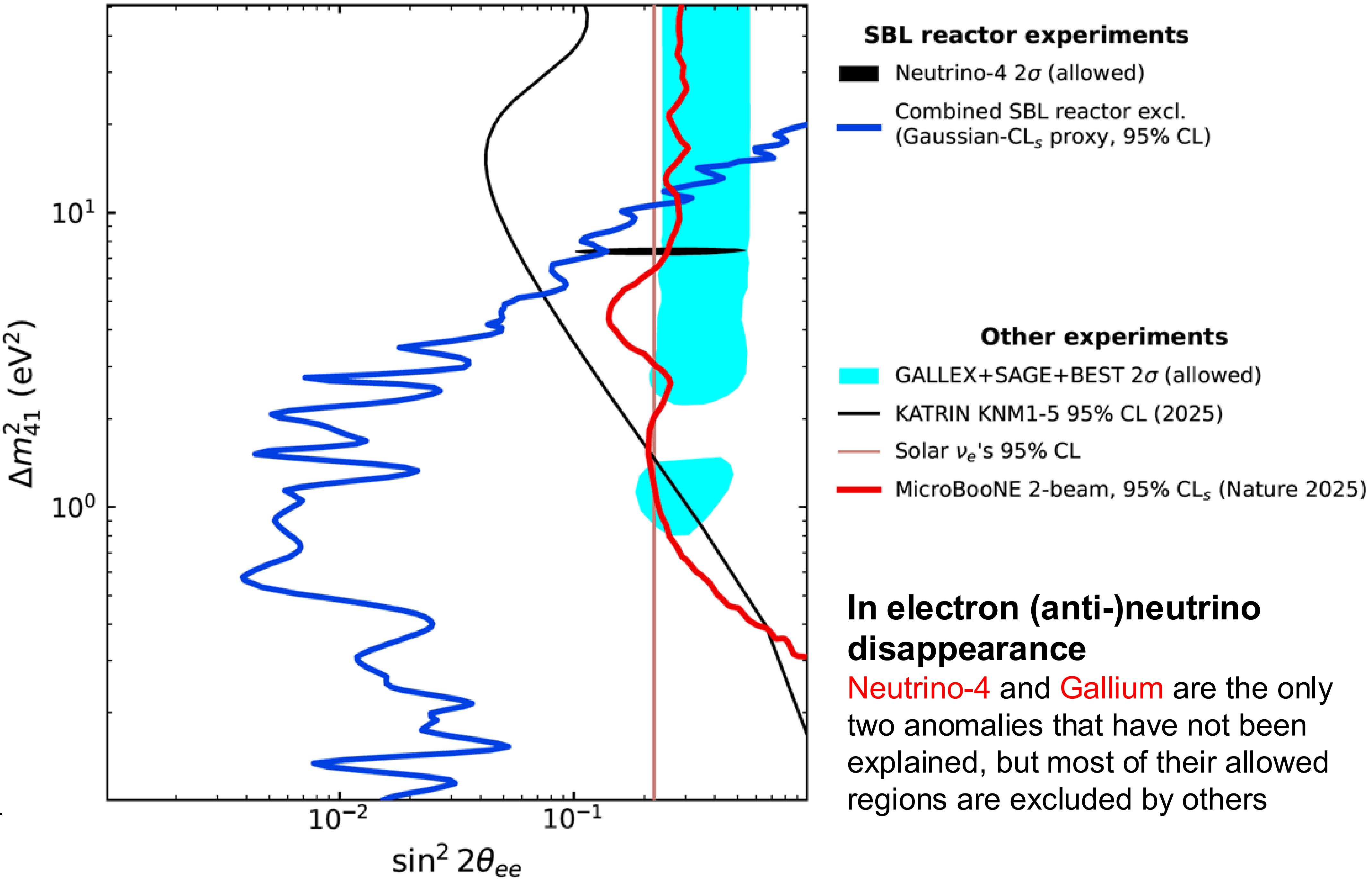
Recent reviews on light sterile neutrino global fit status:

Giunti & Lasserre, Annu. Rev. Nucl. Part. Sci. 69, 163 (2019)

Böser et al., Prog. Part. Nucl. Phys. 111, 103736 (2020)

Dasgupta & Kopp, Phys. Rep. 928, 1 (2021)

Giunti, Li, Xin PLB 829, 137054 (2022)



In electron (anti-)neutrino disappearance

Neutrino-4 and Gallium are the only two anomalies that have not been explained, but most of their allowed regions are excluded by others

- ❑Is theory and its uncertainty reliable? No
- ❑Is there spectral distortion in L/E? No
- ❑**Where does the theory fall short?**

Challenges to the Huber-Mueller Model

ILL β data
1981–89, BILL

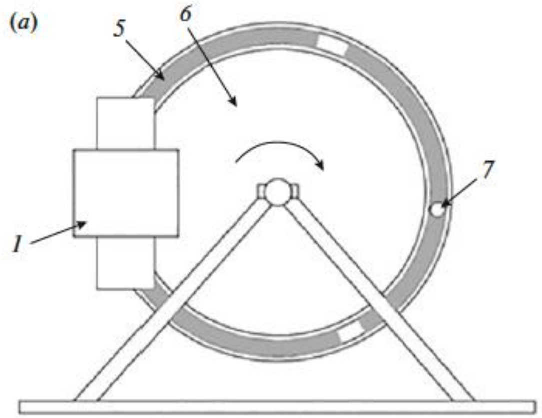
→ **Virtual-branch fit**
~30 allowed branches

→ **Fermi corrections**
WM, finite size

→ **$\bar{\nu}$ spectrum**
2–3% claimed

Possible bias
KI 2021:
$^{235}U/^{239}Pu$ ratio ~5% lower

Forbidden β-decay Shape
Hayes 2014, Fang-Brown, HKSS
Effective Z, WM also reevaluated ~1% effect

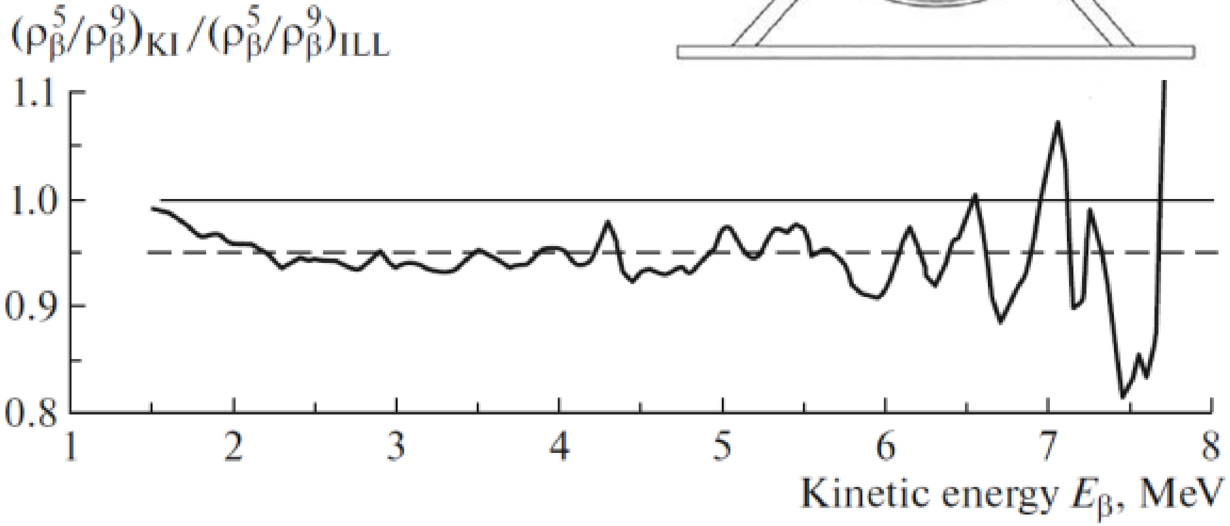


Conversion method should have >5% uncertainty

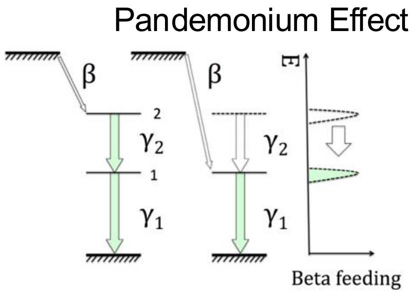
Hayes et al., PRL 112, 202501 (2014)
Hayes et al., PRD 92, 033015 (2015)
Fang-Brown: PRC 91, 025503 (2015)
HKSS: PRC 99, 031301 (2019)

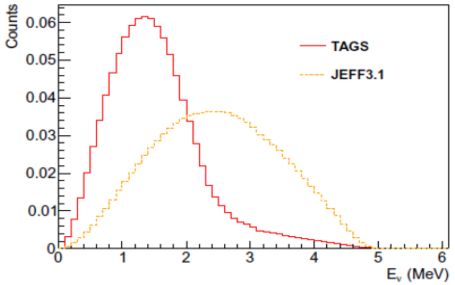
$^{235}U/^{239}Pu$ ratio is ~5% lower than ILL

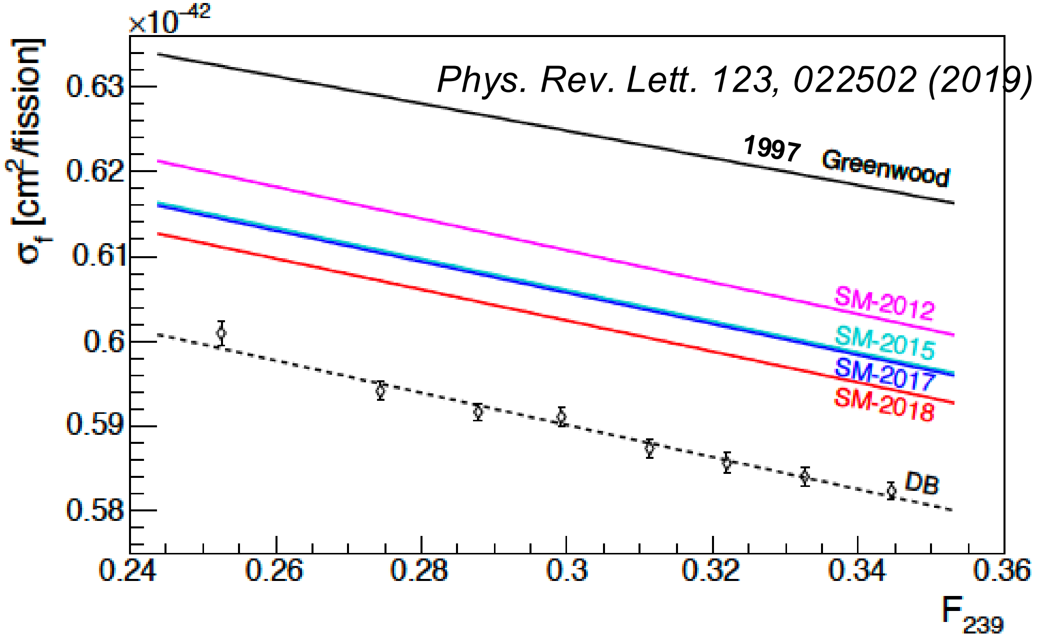
Kopeikin et al., Phys. At. Nucl. 84, 1,
Phys. Rev. D 104, L071301 (Kurchatov Institute , 2021)



Improve the Summation Method: TAGS campaigns, 2010–2023







Summation Model	New TAGS nuclei added	TAGS reference
SM-2012	Greenwood (49 nuclides) + 102,104,105,106,107Tc, 105Mo and 101Nb	PRL 105, 202501 (2010)
SM-2015	92,94Rb and 87,88Br	PRL 115, 102503 (2015), PRC 95, 024320 (2017)
SM-2017	91Rb, 86Br	PRC 96, 014320 (2017)
SM-2018 (EF)	100,100m,102,102mNb	PRL 122, 042502 (2019)
BESTIOLE-2023 (CEA)	28 new nuclides	ORNL+ post-2019 campaigns

Total Absorption Gamma-ray Spectroscopy (TAGS)

- ❑ High efficiency γ–ray detectors (e.g. NaI, BaF_2), free of Pandemonium Effect
- ❑ Two parallel TAGS campaigns in Europe (@Jyvaskyla, Nantes–Valencia group) and U.S. (@ORNL)

Early Summation Method Studies that motivated the TAGS campaigns

Dwyer & Langford, PRL 114, 012502 (2015)
Sonzogni et al., PRL 116, 132502 (2016)
Sonzogni, McCutchan, Hayes, PRL 119, 112501 (2017)

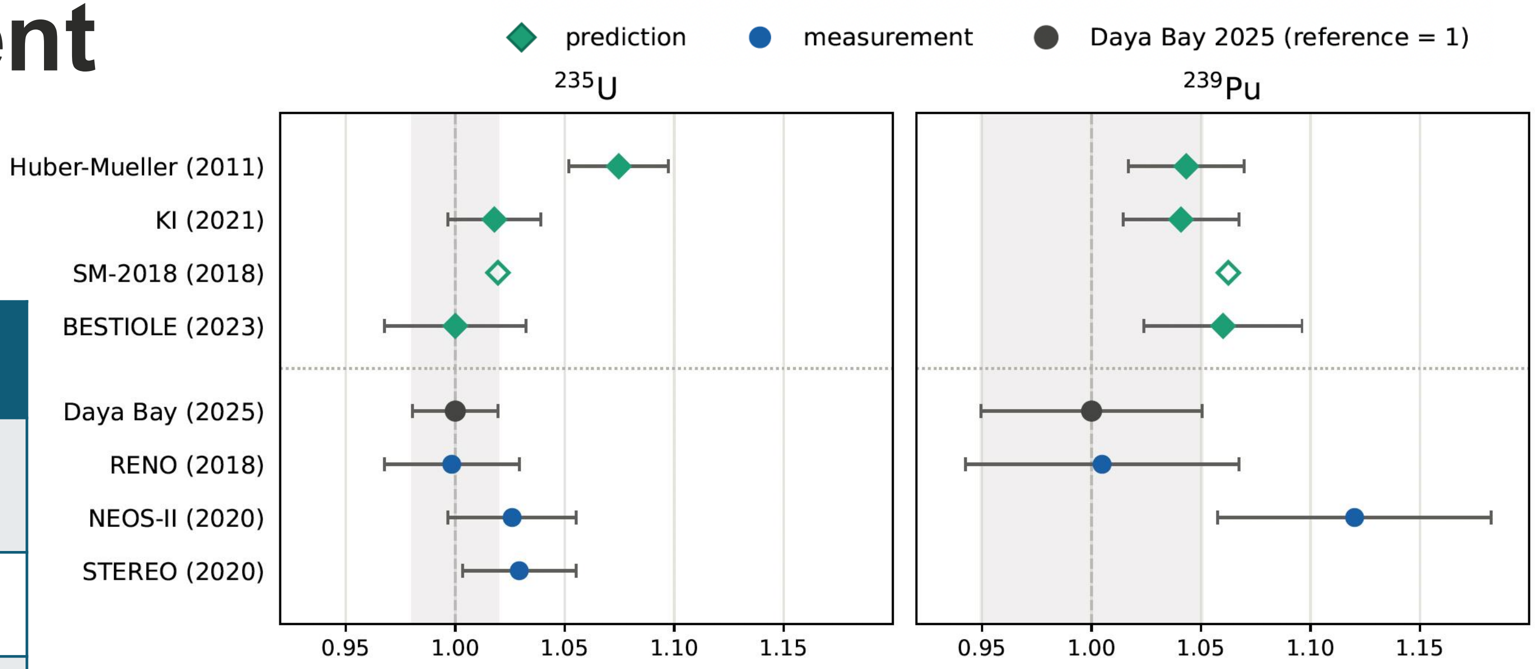
- ❑ Since 2012, Summation model (by the Nantes–Valencia group) systematically gets better agreement with Daya Bay after more TAGS data sets are included. SM-2018 (EF) only differs by 1.9%.
- ❑ Shape discrepancy still exists (DB data/SM-2018) and needs to be understood.

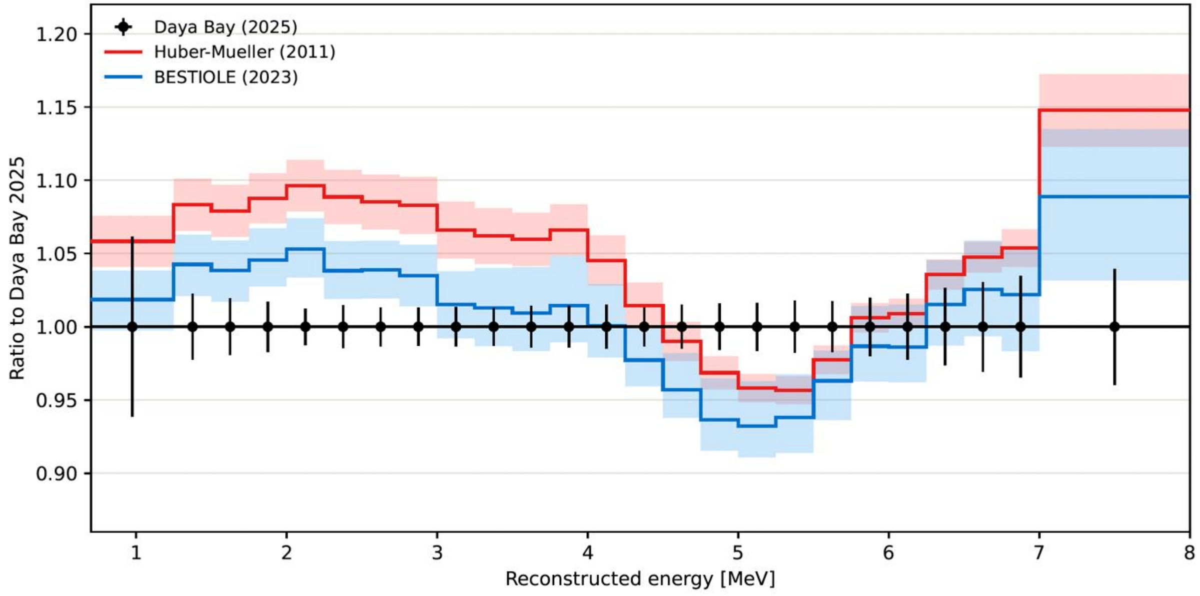
Improve the Summation Method: Uncertainty Treatment

BESTIOLE-2023 (CEA)

L. Perisse et al., Phys. Rev. C 108, 055501 (2023)

Source	Uncertainty (%)	Methods
Residual Pandemonium	2.1–2.6	Evaluated from 81 measured nuclides and applied to ~29 nuclides
Tengblad integral β conversion	1.4–1.7	Evaluated from 23 TAGS and apply to 44 nuclides;
Fission yield	1.1–1.3	Cumulative uncertainty (JEFF-3.3), kept uncorrelated
Nuclides with no data	0.6–1.3	Statistical “Pool method”
Model correction (ξ-approximation, WM, etc.)	0.4–0.6	estimated against a few transitions that can be calculated exactly
Branching ratio + β^- intensity	0.3–0.4	ENSDF BR/intensity uncertainties, Monte Carlo propagated





Summary

Both theory and short-baseline reactor neutrino experiments have come a long way to predict and measure the reactor antineutrino flux

Experiments

- ❑ Consistent measurements of integrated flux with <0.5% combined experimental uncertainty
- ❑ Consistent energy spectra measurements
- ❑ Consistent individual ^{235}U and ^{239}Pu flux
- ❑ No L/E oscillation observed by short-baseline reactor experiments
  - Neutrino-4 results to be understood
- ❑ Future (a watch list):
  - JUNO-TAO (high-resolution)
  - CEvNS (new channel)
  - New SBL experiments with better syst. / stat.

Theory

- ❑ Better understanding of the uncertainty and limitation of the conversion method
  - (>5% uncertainty + KI) likely explains the origin of RAA
- ❑ Greatly improved summation methods
  - Inclusion of TAGS data
  - Quantitative uncertainty estimation
- ❑ Future (a wish list):
  - ILL data independently validated
  - More TAGS measurements (IAEA priority list of nuclides)
  - Shape discrepancy explained
  - Refined estimation of model uncertainties

Selected reviews for further readings

Hayes & Vogel, Annu. Rev. Nucl. Part. Sci. 66, 219 (2016)
Hayen et al., Rev. Mod. Phys. 90, 015008 (2018)
Giunti & Lasserre, Annu. Rev. Nucl. Part. Sci. 69, 163 (2019)
Algora et al., Eur. Phys. J. A 57, 85 (2021)
Zhang, Qian, Fallot, Prog. Part. Nucl. Phys. (2024)