Reactor Antineutrino Anomaly
after 13 Years

Chao Zhang
Brookhaven National Lab
5/21/2024

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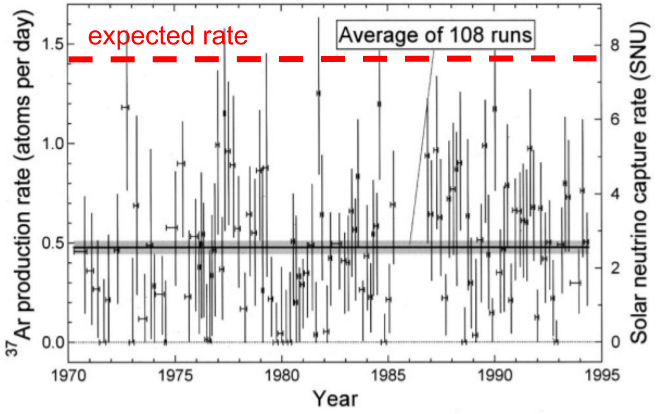
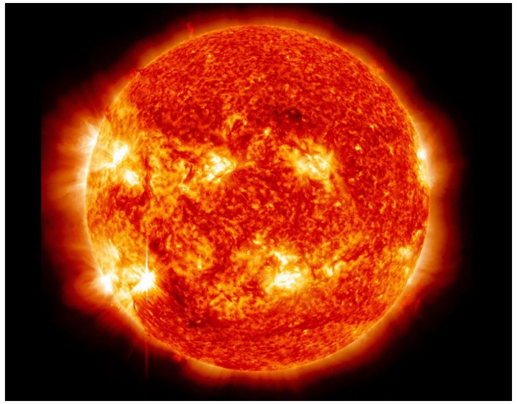
Over the past decades neutrino oscillation searches at length/distance scales of 1 MeV/m have found a number of anomalous results: The liquid scintillator neutrino detector (LSND) anomaly, the reactor antineutrino anomaly, the MiniBooNE low-energy excess and the gallium anomaly. These anomalies have not been confirmed, and the reactor antineutrino anomaly has been recently resolved. The remaining phase space will be conclusively tested by the current short-baseline neutrino (SBN) program at Fermilab. The SBN program is also crucial in maturing the liquid argon (LAr) technology and analysis. SBN, T2K, NOvA, and other ongoing experiments also make measurements of neutrino interactions, which underpin our understanding of neutrino oscillation mixing (Recommendation 1c).

How to Resolve an Anomalies in Physics

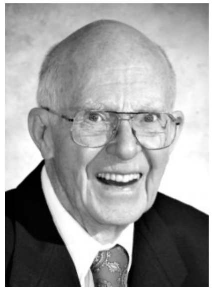


Error in experiments?



Mistake in theoretical models?

New Physics?



Raymond Davis Jr.

Outline

- ❑ History of reactors and reactor neutrinos @BNL
- ❑ What is the Reactor Antineutrino Anomaly (RAA)
- ❑ Possible explanations
- ❑ New experimental evidences
- ❑ New theoretical calculations
- ❑ Conclusion

Nuclear Reactors @BNL

GRAPHITE RESEARCH REACTOR

Operated: 1950 to 1969
World's first peacetime research reactor. Fuel placed in 700-ton graphite "pile" that moderated fission. Scientists exposed experiments to neutrons by inserting them into slots on top and three sides of the core.

Initially ran on natural uranium, but in 1958 fuel was switched to enriched uranium, with reactor operating at 20 megawatts.

Scientific advances

- The radioactive isotope Technetium-99m, used as a medical tracer and similar to X-rays for diagnostic imaging, first detected here.
- Multi-grade motor oils developed as a result of studying engine piston rings in the reactor.
- Irradiated seeds used to produce the Star Ruby grapefruit, a sweet and nearly seedless variety with deep red flesh.

Cost to close: $114 million, with **$92 million** already spent. Stimulus money will pay about 60 percent of remaining **$22 million** cost.

HIGH-FLUX BEAM REACTOR

Operated: 1965 to 1996
Permanently shut in 1999
Provided neutrons for research in material science, chemistry, biology and physics. Scientists conducted experiments with external neutron beams delivered through ports placed around reactor core.

Enriched uranium fueled the reactor. "Heavy" water — in which deuterium replaces the two hydrogen atoms — moderated fission and served as main coolant. Operated at 30, 40 or 60 megawatts.

Scientific advances

- Structure of cell's "protein factory" — the 16-part ribosome — first discerned here.
- New uses of radioactive isotopes developed for treating illnesses such as cancer, heart disease and arthritis.
- Advanced understanding of life span and decays of isotopes such as zinc-80, which astrophysicists use to study supernovas.
- Magnet experiments led to Nobel Prize-winning theories of cooperative ordering in large collections of atoms.
- Scientists using the high-flux beam reactor determined structures of the 23 amino acids, which make up every protein in every cell in living things.

Cost to close: $64 million, with **$32 million** already spent. Stimulus money will pay about 90 percent of the remaining cost, which excludes taking it apart after 65 years.

NEWSDAY, MONDAY, MAY 4, 2009 **www.newsday.com**

MEDICAL RESEARCH REACTOR

Operated: 1959 to 2000
The smallest of the lab's reactors, it was the first in the nation built just for medical research. Large objects were irradiated at one of the reactor's four faces; holes in another face permitted irradiation of samples and production of short-lived radioisotopes. Neutron streams traveled from two remaining ports to treatment rooms for animal and clinical studies.

Reactor operated at 3 megawatts but could generate 5 megawatts for short periods of time. Core was water cooled.

Scientific advances

- Boron neutron capture therapy, developed to treat a deadly form of brain cancer, was pioneered here.

Cost to close: Decommissioning plan and budget **not yet developed**.

Source: Brookhaven National Laboratory

- BNL's past 3 research reactors: BGRR, HFBR, BMRR

https://www.bnl.gov/about/history/reactors.php

Nuclear Reactors @BNL

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Initially ran on natural uran… was switched to enriched ura… operating at 20 megawatts.

Scientific advances
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- Multi-grade motor oils deve… studying engine piston ring…
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- Structure of cell's "protein factory" — the 16-part ribosome — first disc…
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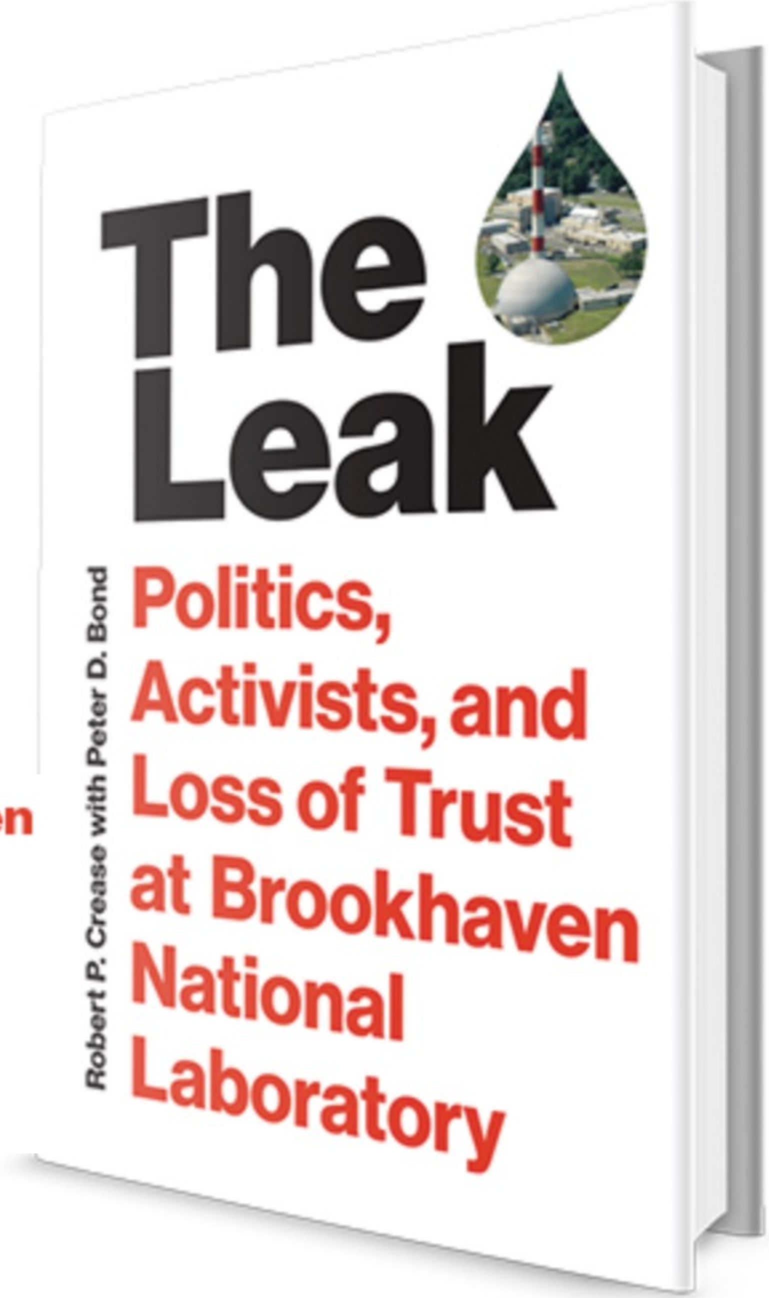
- Magnet experiments led to Nobel Prize-winning theories of cooperative… collections of atoms.
- Scientists using the high-flux beam reactor determined structures of the… which make up every protein in every cell in living things.

"Dramatically describes a titanic clash between world-class science, dishonest activists and celebrities, amoral politicians, and the federal bureaucracy."

—Robert Birgeneau, former Chancellor, University of California, Berkeley



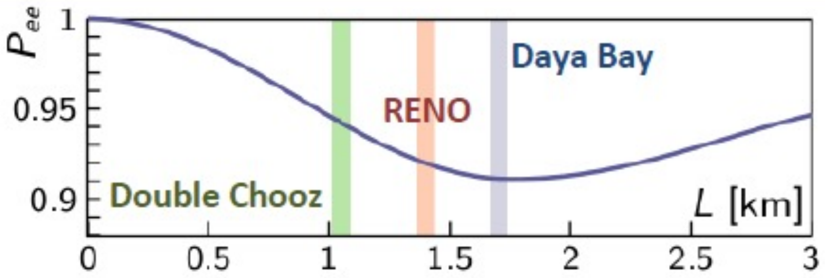
https://www.bnl.gov/about/history/reactor

Daya Bay Reactor Neutrino Experiment

- ❑ Designed to discover $\sin^2(2\theta_{13}) < 0.01$ @90% C.L.
- ❑ Started data taking on Dec 24, 2011
- ❑ Made the first 5σ discovery after 55 days

Baseline Optimization

- Detector locations optimized to known parameter space of $|\Delta m^2_{ee}|$
- Far site maximizes term dependent on $\sin^2 2\theta_{13}$



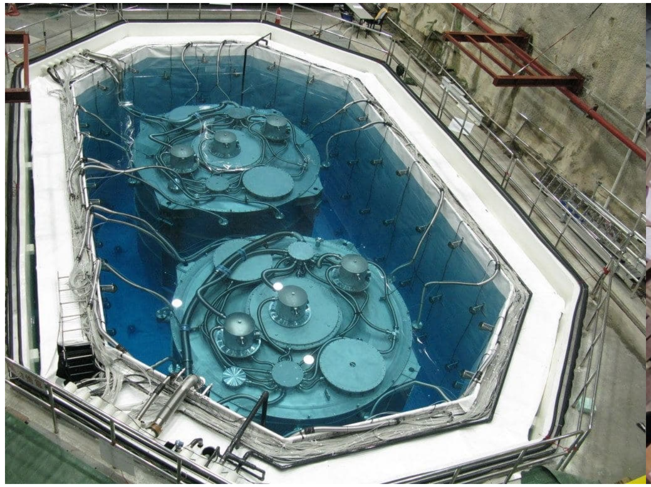
Go strong, big and deep!

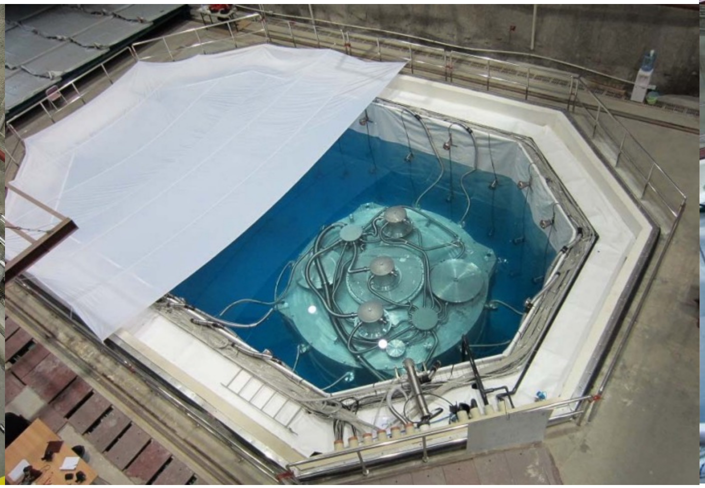
	Reactor [GW_{th}]	Target [tons]	Depth [m.w.e]
Double Chooz	8.6	16 (2 × 8)	300, 120 (far, near)
RENO	16.5	32 (2 × 16)	450, 120
Daya Bay	17.4	160 (8 × 20)	860, 250
	Large Signal		Low Background

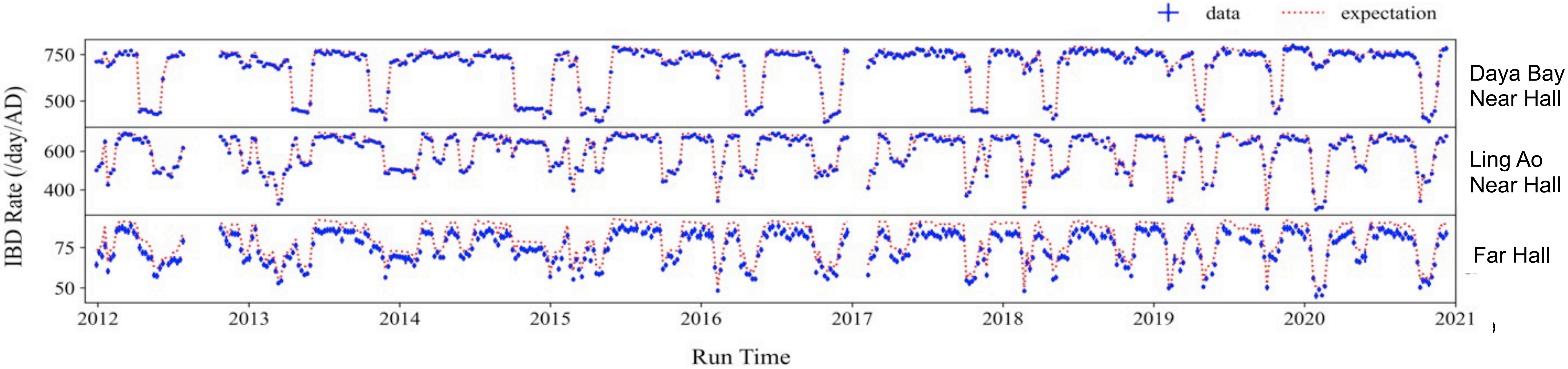
BNL Daya Bay Group, 2011

❑ Data taking (12/24/2011 – 12/12/2020)

- 3275 days, 5.5M $\bar{\nu}_e$ events
  largest reactor neutrino data sample in the world







Oscillation results with the full data set

Phys. Rev. Lett. 130, 161802 (2023)

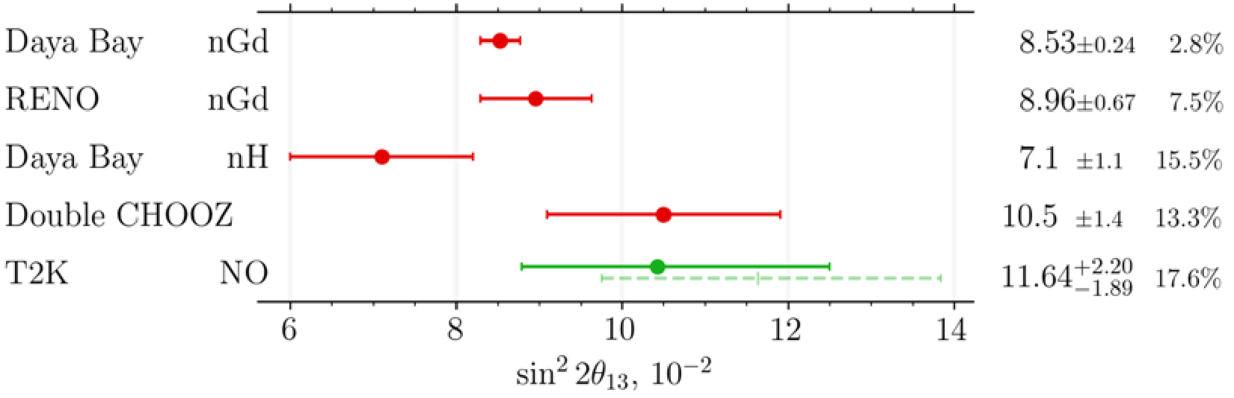
$$\sin^2 2\theta_{13} = 0.0853^{+0.0024}_{-0.0024}$$

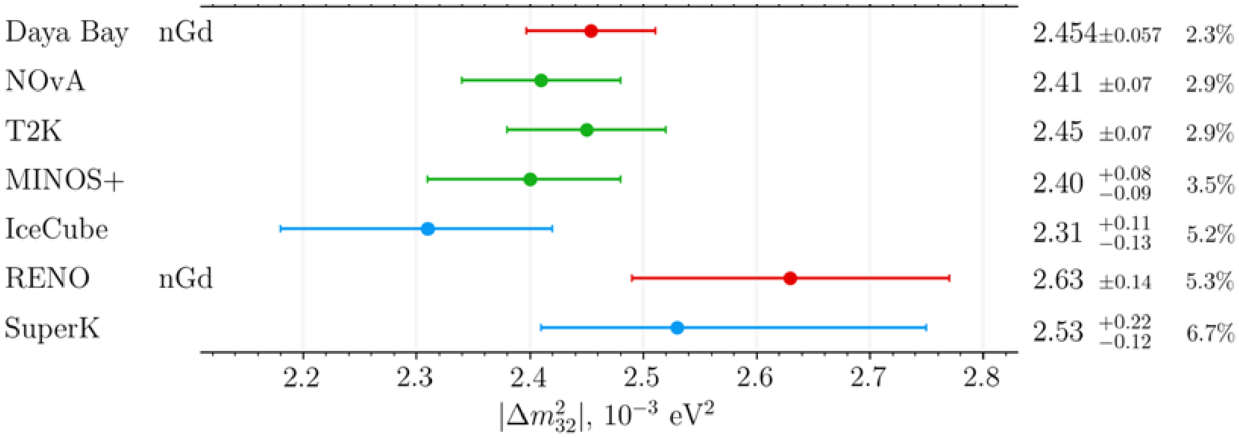
(2.8% precision)

NMO: $\Delta m^2_{32} = +\left(2.454^{+0.057}_{-0.057}\right) \times 10^{-3}\ \mathrm{eV}^2$

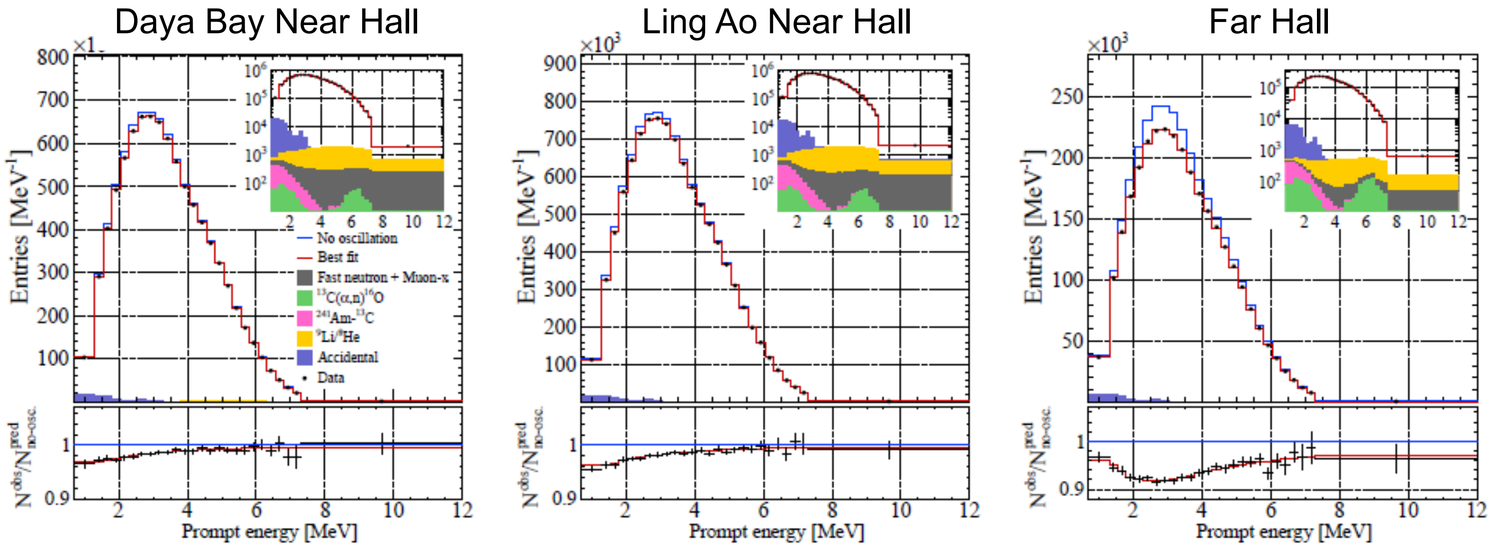
IMO: $\Delta m^2_{32} = -\left(2.559^{+0.057}_{-0.057}\right) \times 10^{-3}\ \mathrm{eV}^2$

(2.3% precision)





- ❑ Likely to be the best measurement in the foreseeable future
- ❑ Critical input to the current and future long-baseline experiments (DUNE)



First Appearance of the Reactor Antineutrino Anomaly

[Submitted on 13 Jan 2011 (v1), last revised 11 Mar 2011 (this version, v3)]

Improved Predictions of Reactor Antineutrino Spectra

Th. A. Mueller, D. Lhuillier, M. Fallot, A. Letourneau, S. Cormon, M. Fechner, L. Giot, T. Lasserre, J. Martino, G. Mention, A. Porta, F. Yermia

>1200 citations

[Submitted on 14 Jan 2011 (v1), last revised 23 Mar 2011 (this version, v4)]

The Reactor Antineutrino Anomaly

G. Mention, M. Fechner, Th. Lasserre, Th. A. Mueller, D. Lhuillier, M. Cribier, A. Letourneau

>1600 citations

Two back-to-back papers on 13/14 Jan 2011 from 3 French groups (CEA Saclay, APC, U. Nantes)

- Part of a theoretical effort in preparing for the Double Chooz θ_{13} reactor neutrino experiment
- *Mueller paper* re-evaluated the reactor antineutrino flux prediction
- *Mention paper* *Using the new model, found* a 2.4σ deficit in data/model and named it the RAA

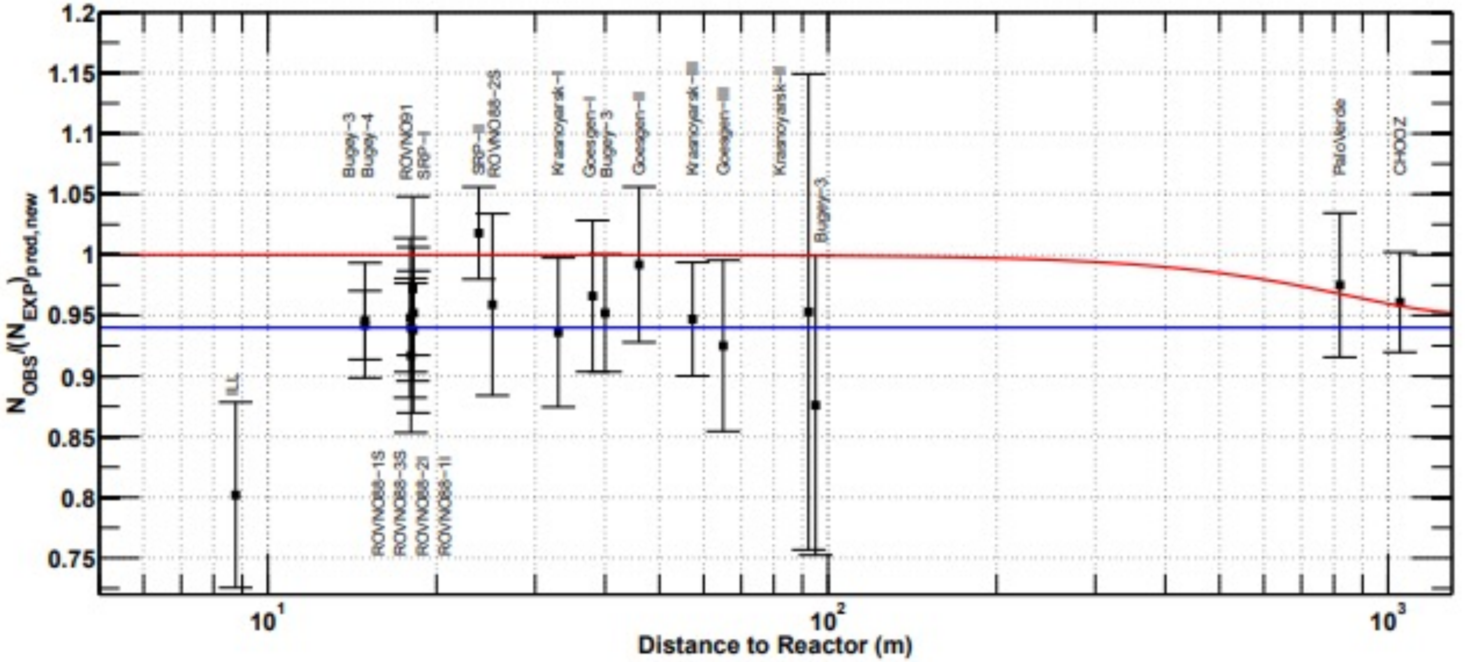
The RAA

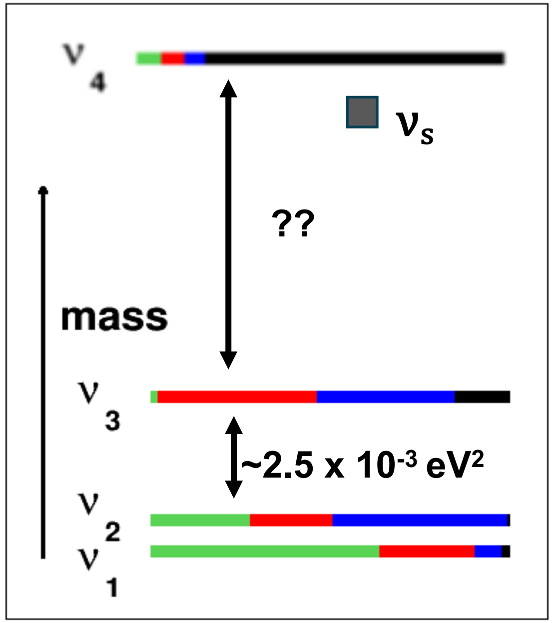
- The new Mueller model increased reactor antineutrino flux prediction by ~3%
- Global fit of 19 reactor flux measurements from 1980-1990s including their correlated uncertainties

#	result	Det. type	τ_n (s)	^{235}U	^{239}Pu	^{238}U	^{241}Pu	old	new	err(%)	corr(%)	L(m)
1	Bugey-4	^{3}He+H$_2$O	888.7	0.538	0.328	0.078	0.056	0.987	0.942	3.0	3.0	15
2	ROVNO91	^{3}He+H$_2$O	888.6	0.614	0.274	0.074	0.038	0.985	0.940	3.9	3.0	18
3	Bugey-3-I	^{6}Li-LS	889	0.538	0.328	0.078	0.056	0.988	0.946	4.8	4.8	15
4	Bugey-3-II	^{6}Li-LS	889	0.538	0.328	0.078	0.056	0.994	0.952	4.9	4.8	40
5	Bugey-3-III	^{6}Li-LS	889	0.538	0.328	0.078	0.056	0.915	0.876	14.1	4.8	95
6	Goesgen-I	^{3}He+LS	897	0.620	0.274	0.074	0.042	1.018	0.966	6.5	6.0	38
7	Goesgen-II	^{3}He+LS	897	0.584	0.298	0.068	0.050	1.045	0.992	6.5	6.0	45
8	Goesgen-II	^{3}He+LS	897	0.543	0.329	0.070	0.058	0.975	0.925	7.6	6.0	65
9	ILL	^{3}He+LS	889	$\simeq 1$	—	—	—	0.832	0.802	9.5	6.0	9
10	Krasn. I	^{3}He+PE	899	$\simeq 1$	—	—	—	1.013	0.936	5.8	4.9	33
11	Krasn. II	^{3}He+PE	899	$\simeq 1$	—	—	—	1.031	0.953	20.3	4.9	92
12	Krasn. III	^{3}He+PE	899	$\simeq 1$	—	—	—	0.989	0.947	4.9	4.9	57
13	SRP I	Gd-LS	887	$\simeq 1$	—	—	—	0.987	0.952	3.7	3.7	18
14	SRP II	Gd-LS	887	$\simeq 1$	—	—	—	1.055	1.018	3.8	3.7	24
15	ROVNO88-1I	^{3}He+PE	898.8	0.607	0.277	0.074	0.042	0.969	0.917	6.9	6.9	18
16	ROVNO88-2I	^{3}He+PE	898.8	0.603	0.276	0.076	0.045	1.001	0.948	6.9	6.9	18
17	ROVNO88-1S	Gd-LS	898.8	0.606	0.277	0.074	0.043	1.026	0.972	7.8	7.2	18
18	ROVNO88-2S	Gd-LS	898.8	0.557	0.313	0.076	0.054	1.013	0.959	7.8	7.2	25
19	ROVNO88-3S	Gd-LS	898.8	0.606	0.274	0.074	0.046	0.990	0.938	7.2	7.2	18

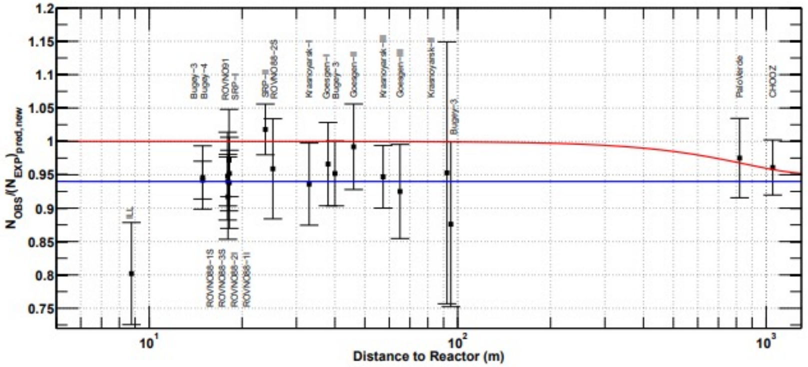
$$\frac{\text{Experiments' average}}{\text{Mueller model}} = 0.943 \pm 0.023$$

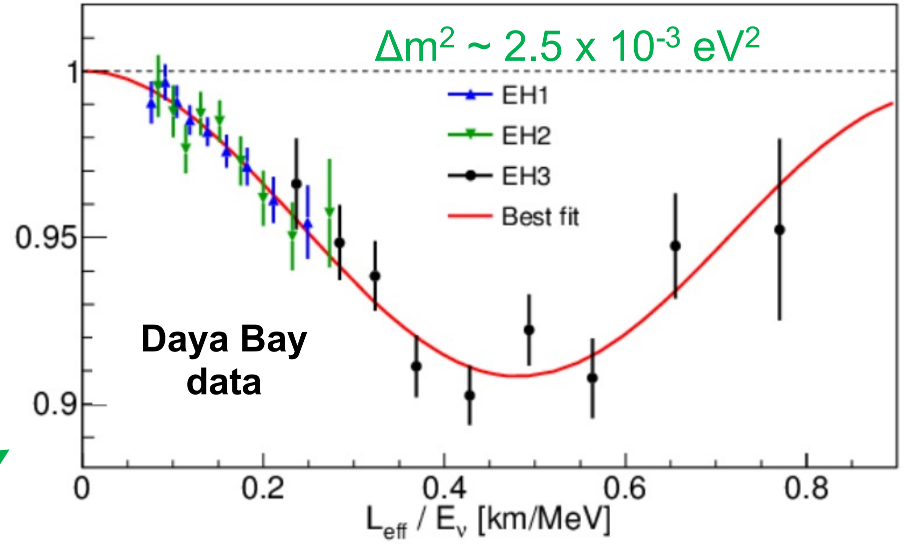
- Compatible with a 4th (sterile) neutrino with mass > 1 eV
  - baselines all < 100 m
  - no oscillation disfavored at 99.8% C.L.

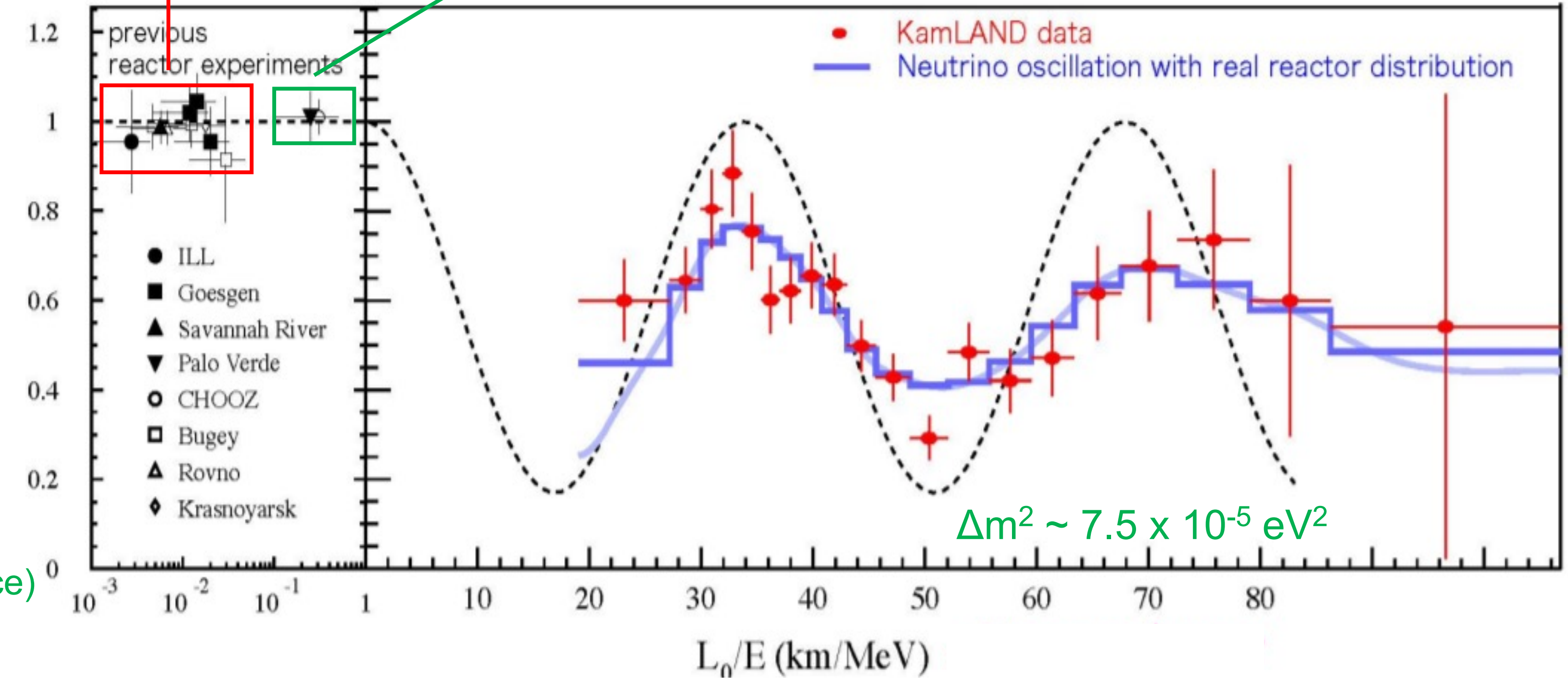




Δm² > 1 eV² ?







$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) =$$

$$1 - \sin^2 2\theta \cdot \sin^2(1.27|\Delta m^2| \cdot \frac{L}{E})$$

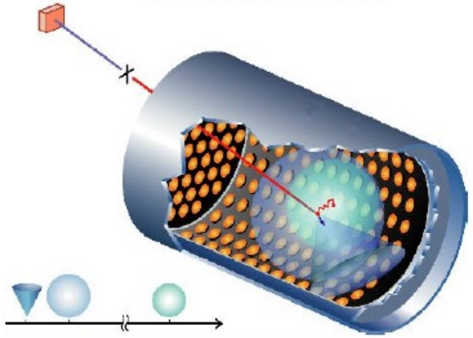
amplitude
(mixing angle)

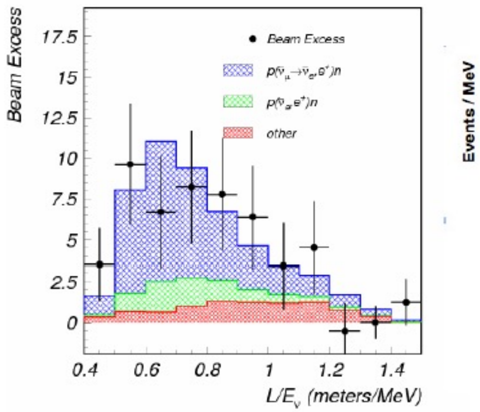
frequency
(mass² difference)

Hints of eV-scale Sterile Neutrinos before the RAA

2001

LSND
decay at rest

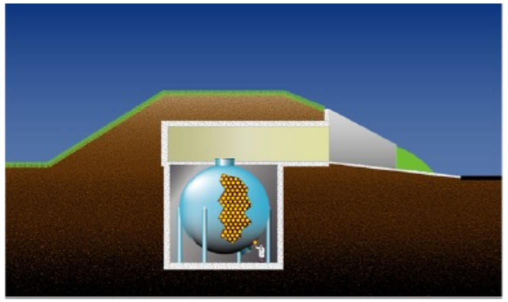


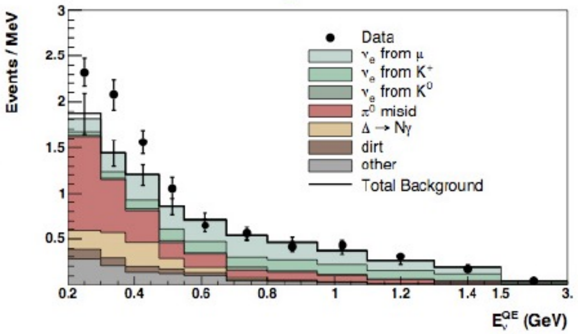


anti-ν_e appearance

2008

MiniBooNE
short baseline accelerator

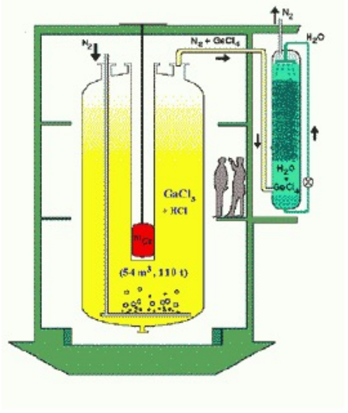


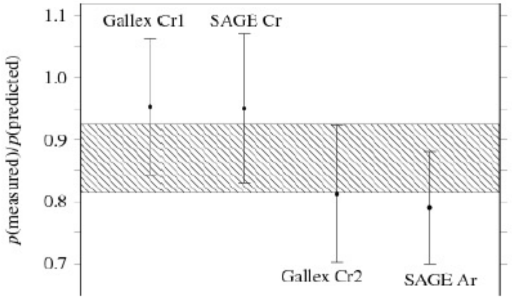


low energy ν_e appearance

SAGE 1999 - 2006
GALLEX reanalysis ~2010

GALLEX/SAGE
Ga source calibration





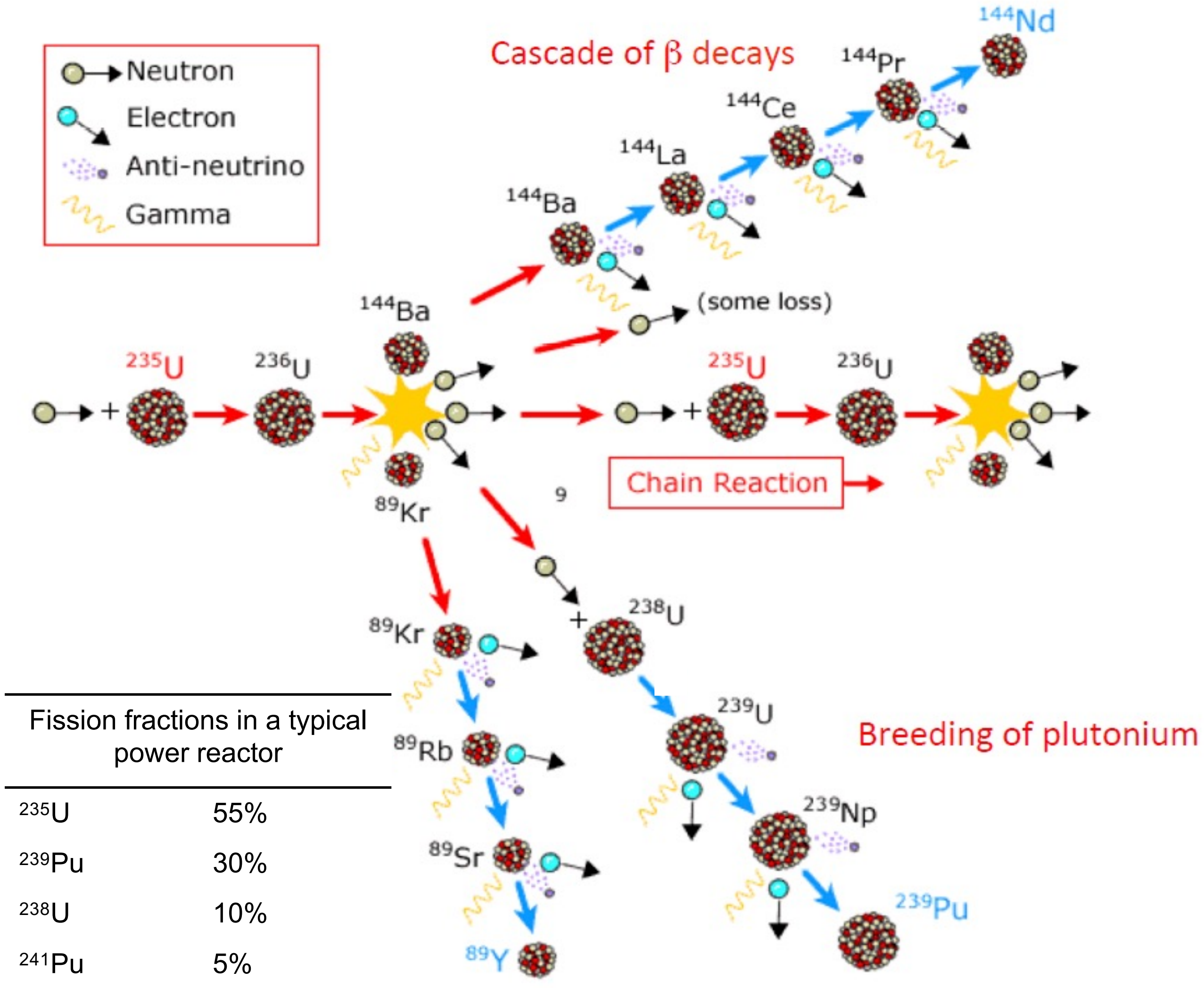
ν_e disappearance

These anomalies + RAA has triggered many new experiments searching for eV-scale sterile neutrinos

- ❑ Short-baseline reactor
  - PROSPECT, STEREO, DANSS, SOLID, Neutrio-4, …
- ❑ Short-baseline accelerator
  - FNAL SBN program: MicroBooNE, ICARUS, SBND
  - JSNS2
- ❑ New Gallium experiment
  - BEST

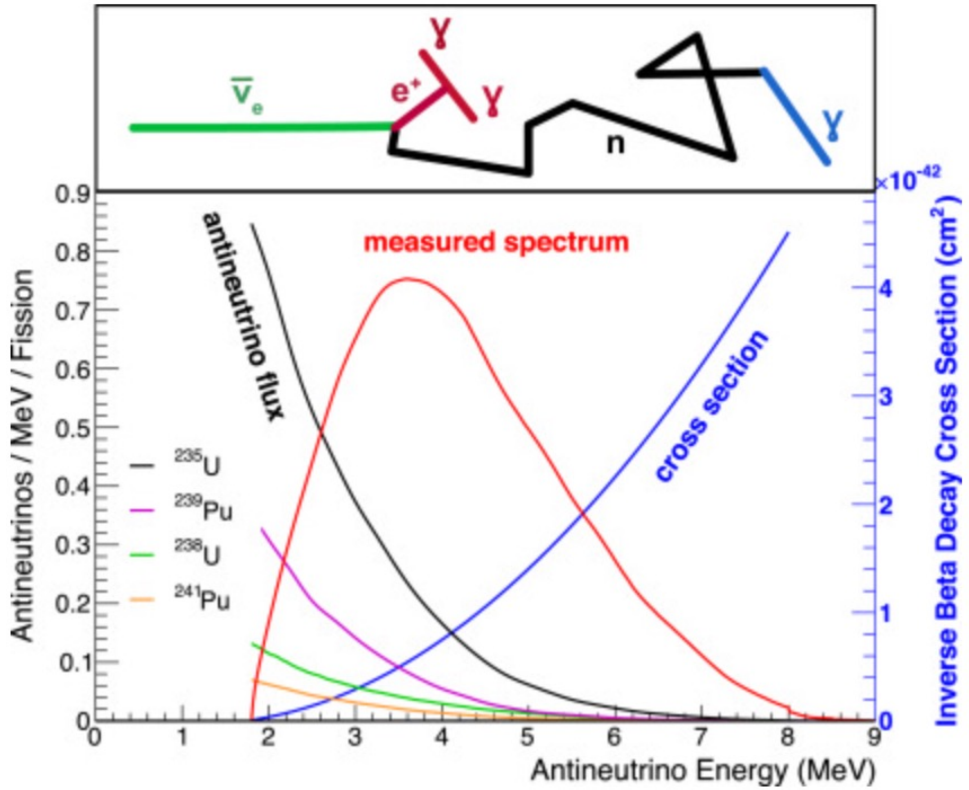
Why did the flux prediction change?

Nuclear Reactor as Antineutrino Source



Fission fractions in a typical power reactor	
^{235}U	55%
^{239}Pu	30%
^{238}U	10%
^{241}Pu	5%

- Pure $\bar{\nu}_e$ from beta decays of fission products
- 6 x 10^{20} ν / sec / 3-GW_{th}
- Detect using inverse beta decay



Reactor $\bar{\nu}_e$ Flux Prediction: Summation method

- Calculate each beta-decay spectrum using nuclear databases:

National Nuclear Data Center — Brookhaven National Laboratory

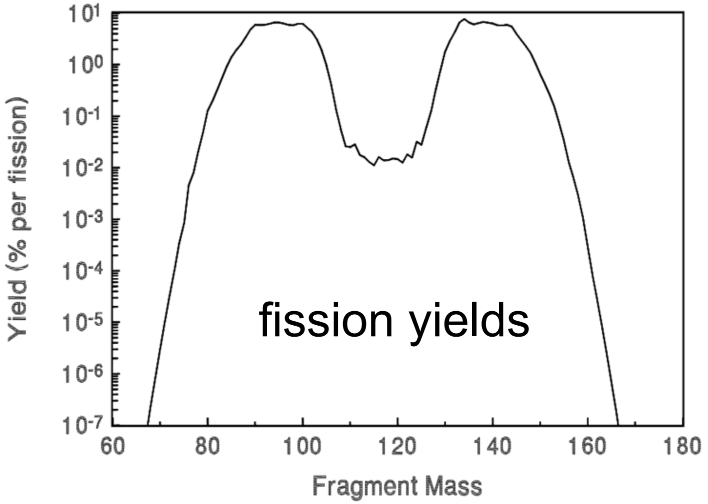
ENDF, JEFF, JENDL, CENDL, ROSFOND …

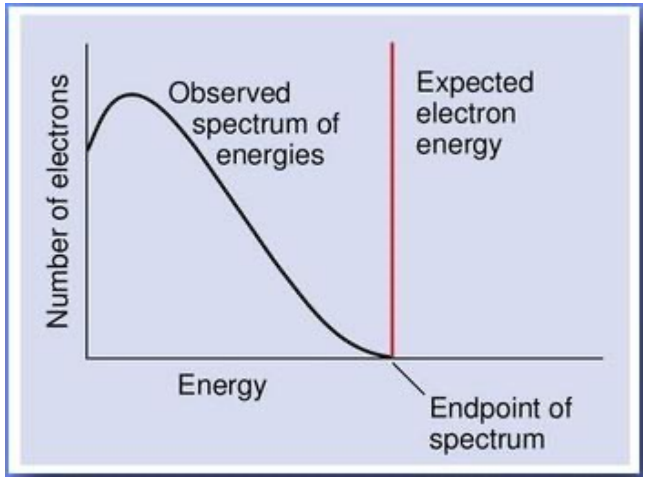
beta-decay branches

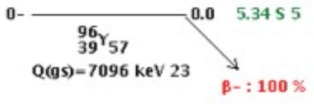
$$\frac{d\phi_i}{dE_\nu} = \sum_n Y_n(Z, A, t) \cdot \left(\sum_m b_{n,m} \cdot P(E_\nu, E_0, Z)\right),$$

fission products

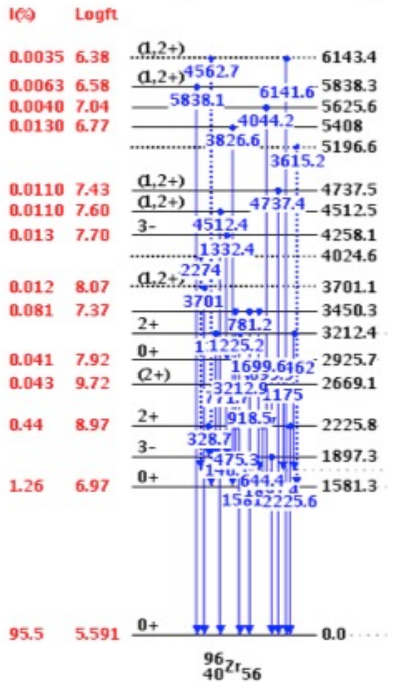
beta spectra
($E_\nu = E_0 - E_e$)







Example: ^{96}Y decay



One isotope from >1300 included in calculation.

In total, >6000 tabulated decay branches.

Reactor $\bar{\nu}_e$ Flux Prediction: Summation method

- Challenges
  - Incomplete databases for beta-decay branches (~10% missing)
  - Known systematic bias in some beta decay data with large Q-values (pandemonium effect)
  - ~30% of beta decays are forbidden decays where shape corrections are necessary but not easy to calculate theoretically
- Large uncertainty (~10%)
  - Historically only used to predict ^{238}U flux (~10% fissions in a commercial reactor)
    - *Vogel et.al, PRC 24, 1543 (1981)*

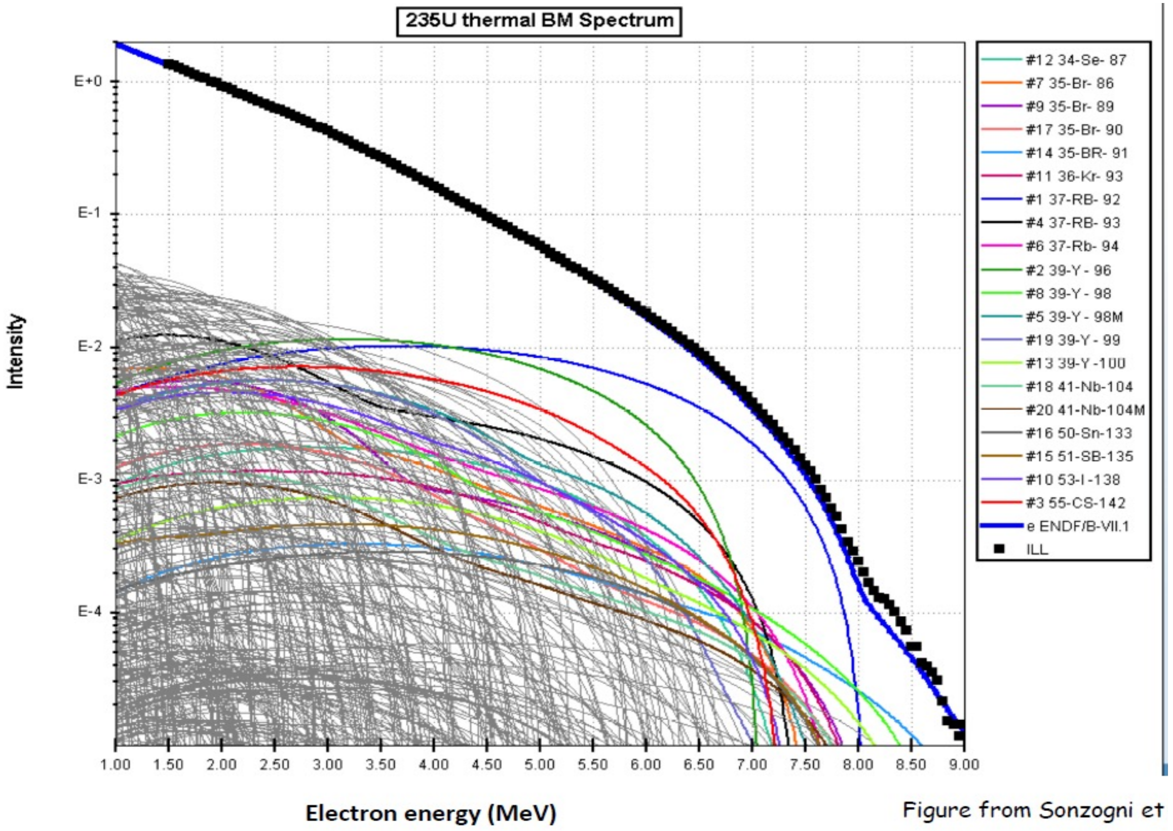
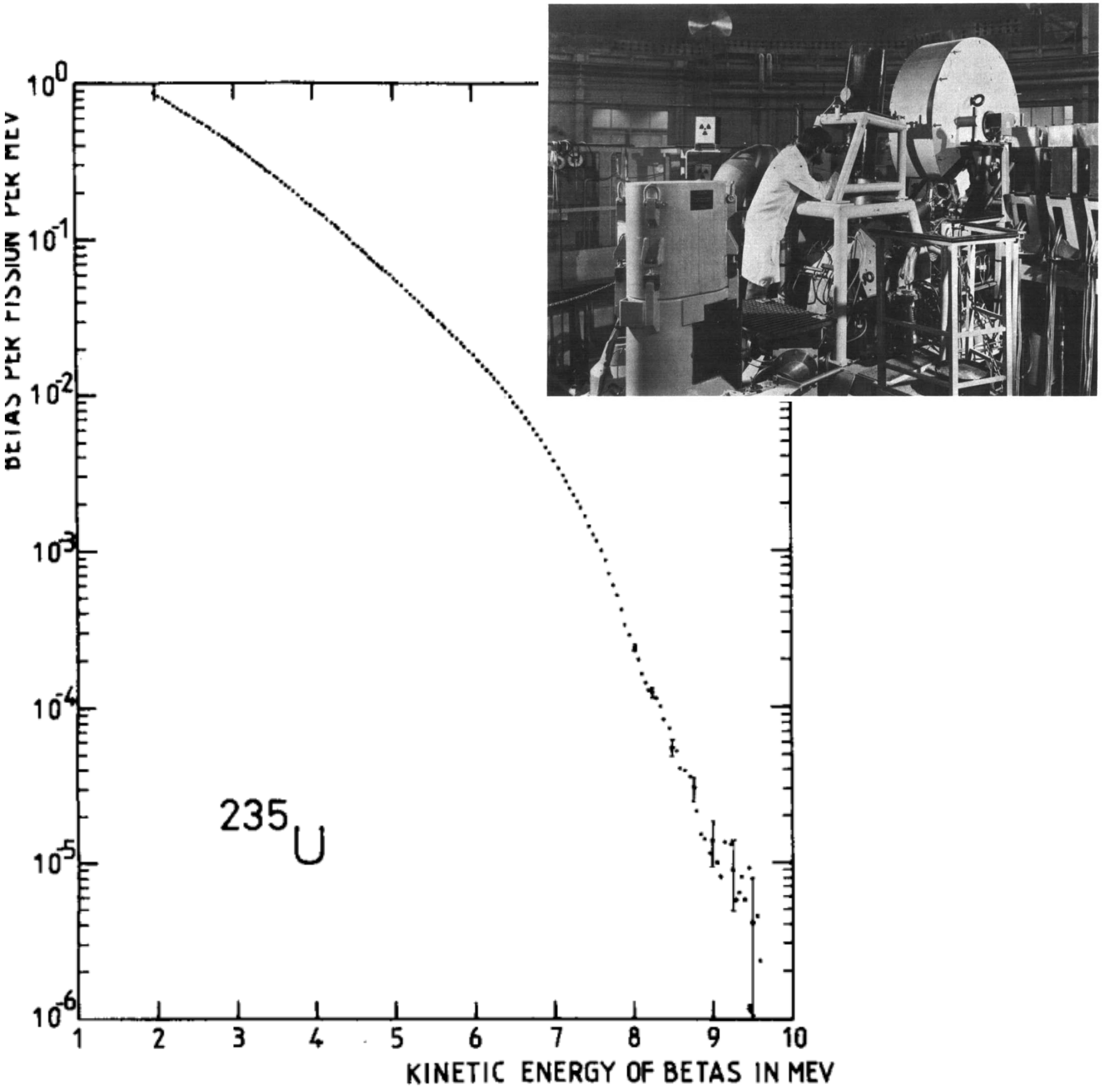


Figure from Sonzogni et

Reactor $\bar{\nu}_e$ Flux Prediction: Conversion method

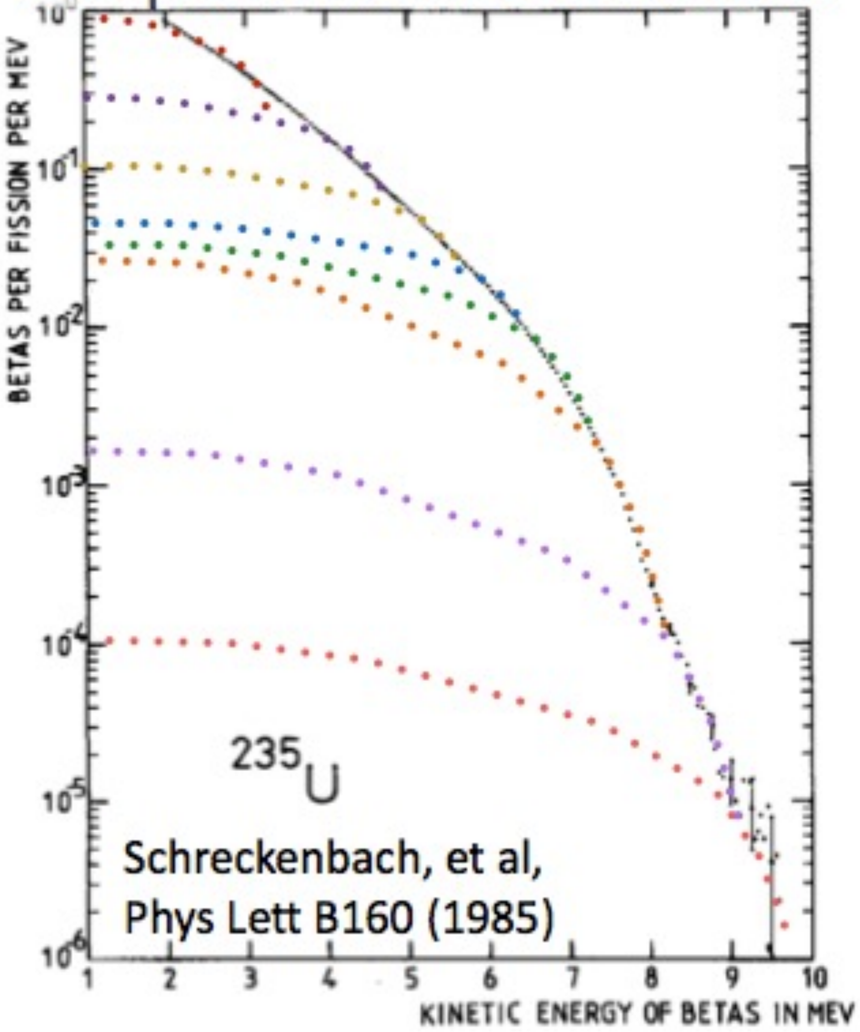
- Experiments at ILL in Grenoble, France in the 1980s for ^{235}U, ^{239}Pu, ^{241}Pu
  - Eradiate fission isotope target (e.g. thin foil of $^{235}UO_2$) in a high flux of thermal neutrons for tens of hours.
  - Measure total outgoing beta-decay electron energy spectrum.
  - Used a high resolution, double focusing e-spectrometer “BILL”: *NIMA 154, 127 (1978)*
    - Calibration with conversion electron sources (^{207}Pb, ^{197}Au, ^{113}Cd, ^{115}In)
  - High statistics in bins of 50 keV.
- ^{238}U was not measured (only fission with fast neutrons) until 2014 at FRM-II in Garching, Germany



Reactor $\bar{\nu}_e$ Flux Prediction: Conversion method

- 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
- Does not rely on fission yields or beta decay data. Considered much more precise and can reach ~2% uncertainty
- Standard reactor $\bar{\nu}_e$ flux model (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



Reactor $\bar{\nu}_e$ Flux Prediction: Conversion method

- Issues in the conversion method
  - No independent measurements beside ILL
  - Non-equilibrium effect: ILL irradiation is only tens of hours, while 10% of fission products have lifetime of more than a few days
  - Virtual branches
    - Assume allowed beta decay shape but corrections for various nuclear effects were not considered
    - The 30% forbidden decays introduce additional shape uncertainty
    - Z as a function of Q-value is a simple fit to the summation calculation
- These issues prompted two new evaluations of reactor antineutrino flux in 2011

Re-evaluation: Huber-Mueller Model

[Submitted on 13 Jan 2011 (v1), last revised 11 Mar 2011 (this version, v3)]

Improved Predictions of Reactor Antineutrino Spectra

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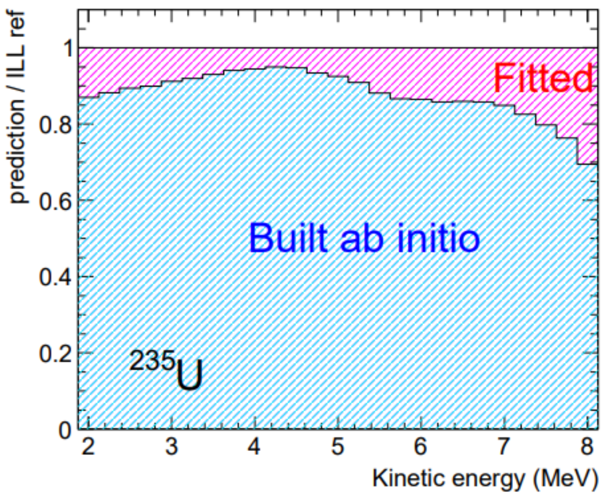
- Hybrid method: +3%
  - Updated summation calculation from the ENSDF database (for ^{235}U, ^{239}Pu, ^{241}Pu, ^{238}U)
  - Conversion method for the missing 10% contribution (for ^{235}U, ^{239}Pu, ^{241}Pu)
  - Correct for non-equilibrium effect

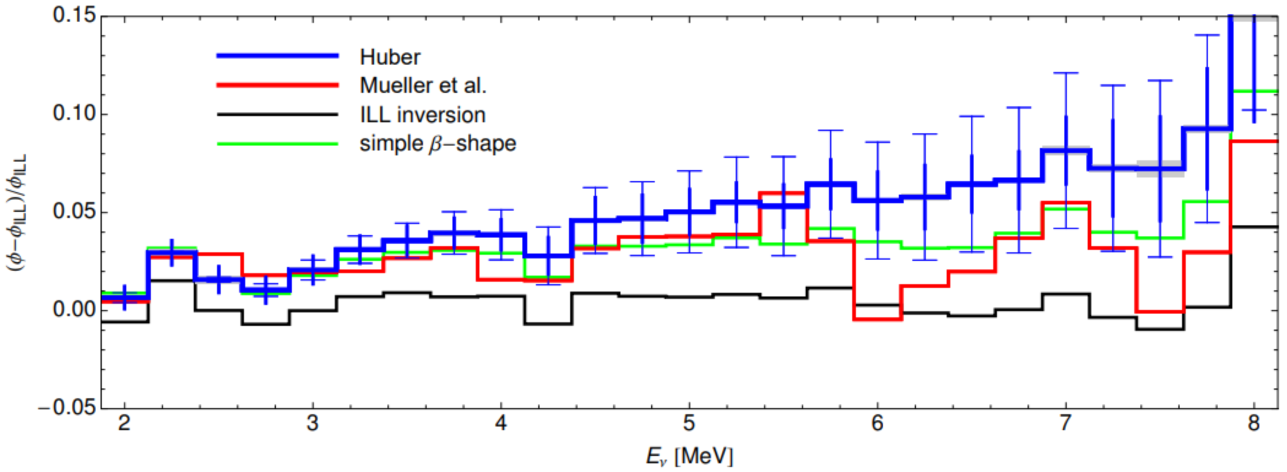


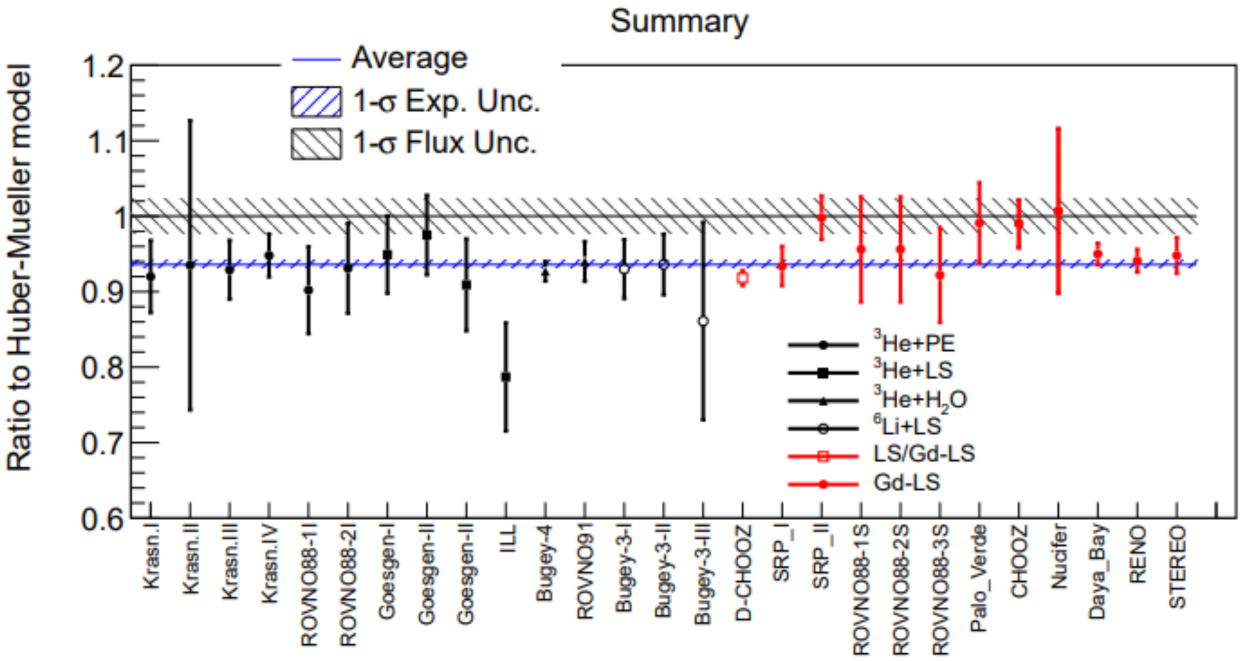
[Submitted on 3 Jun 2011 (v1), last revised 17 Jan 2012 (this version, v4)]

On the determination of anti-neutrino spectra from nuclear reactors

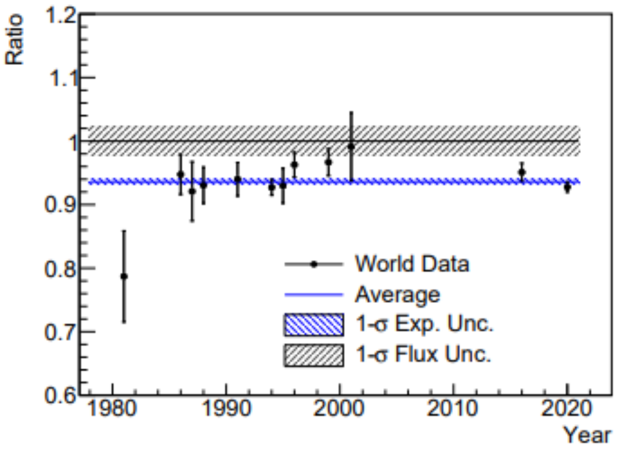
Patrick Huber

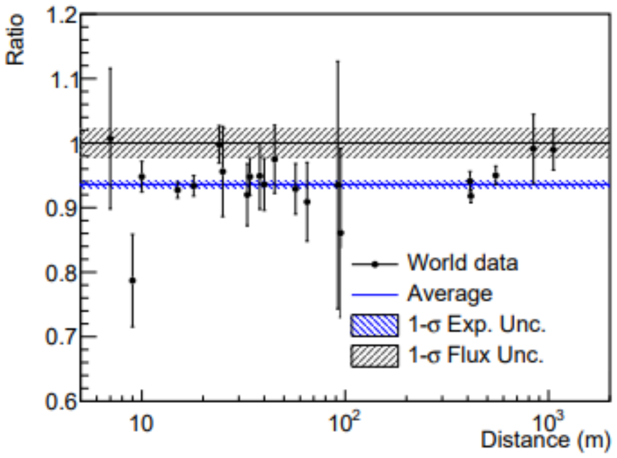
- Improved conversion method using ILL data (for ^{235}U, ^{239}Pu, ^{241}Pu):
  - Reevaluated nuclear effects in correcting the beta-spectrum shape +3%
    - effective Z as a function of Q-value for virtual branches
    - finite-size, radiative correction, weak magnetism
  - Non-equilibrium effect +1-2%
  - New neutron lifetime measurement +1%





a)





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

Comparison of 27 measurements to the Huber-Mueller model
(extension of the original RAA paper)

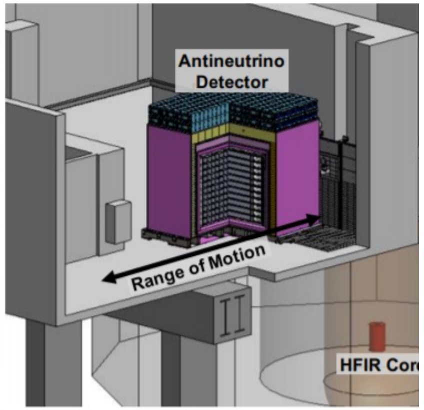
- ❑ Span over 40 years from 1980s – 2020s
- ❑ Different detector types
  - Water/LS + ^{3}He counters
  - Gd- or ^{6}Li-loaded LS
- ❑ Different reactor types
  - Low-enriched Uranium (LEU)
  - Highly-enriched Uranium(HEU)
- ❑ Different baselines
- ❑ Different challenges in determining efficiency and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

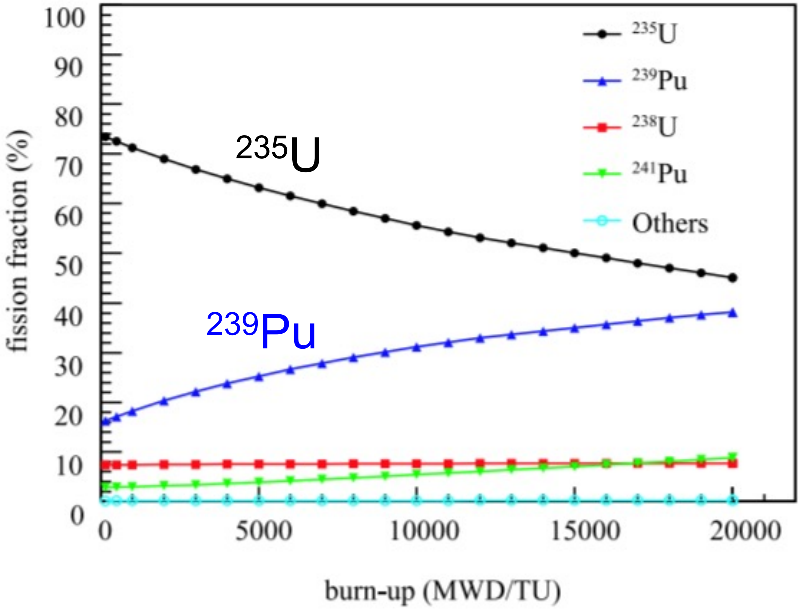
Consistent results with <0.5% combined experimental uncertainty

Is the RAA related to Sterile Neutrino Oscillations?

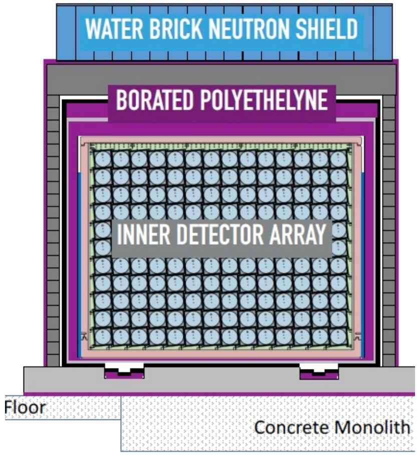
Two other reactor measurements that can shed light onto the origin of RAA

- ❑ Reactor antineutrino energy spectrum
  - at < a few meters, an eV-scale sterile neutrino will alter the spectrum in an oscillatory pattern, with an L/E dependence
  - at > 10 meters, an eV-scale sterile neutrino will not cause spectral distortion (oscillation is too fast compared to the resolution of the detector)
- ❑ Isotopic reactor antineutrino flux
  - Highly-enriched uranium (HEU) reactors: 99% ^{235}U fission
  - fuel evolution in commercial reactors: fission fractions change with time
  - Sterile neutrino oscillation does not care about the origin of the neutrino (e.g. produced by ^{235}U or ^{239}Pu).

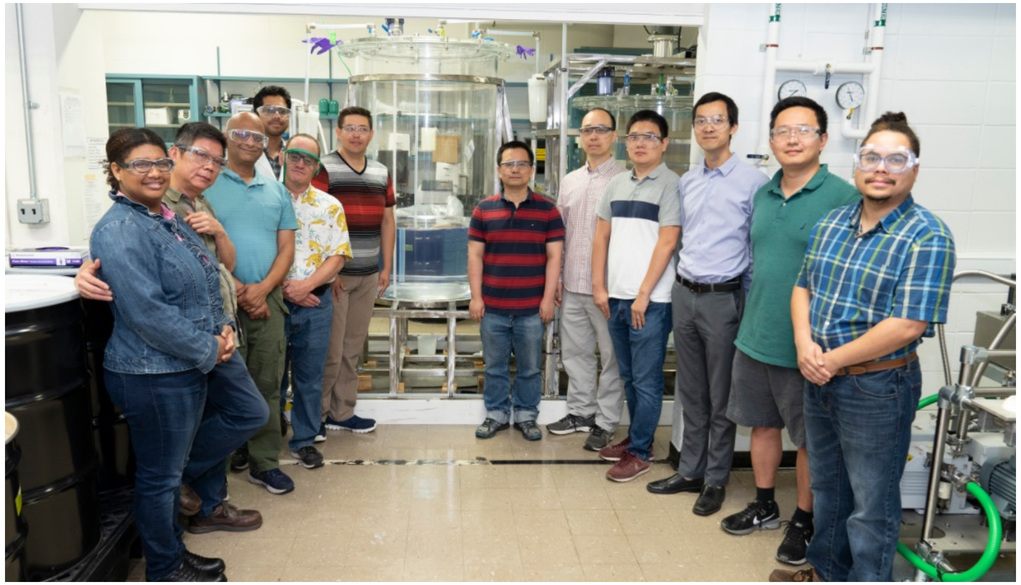




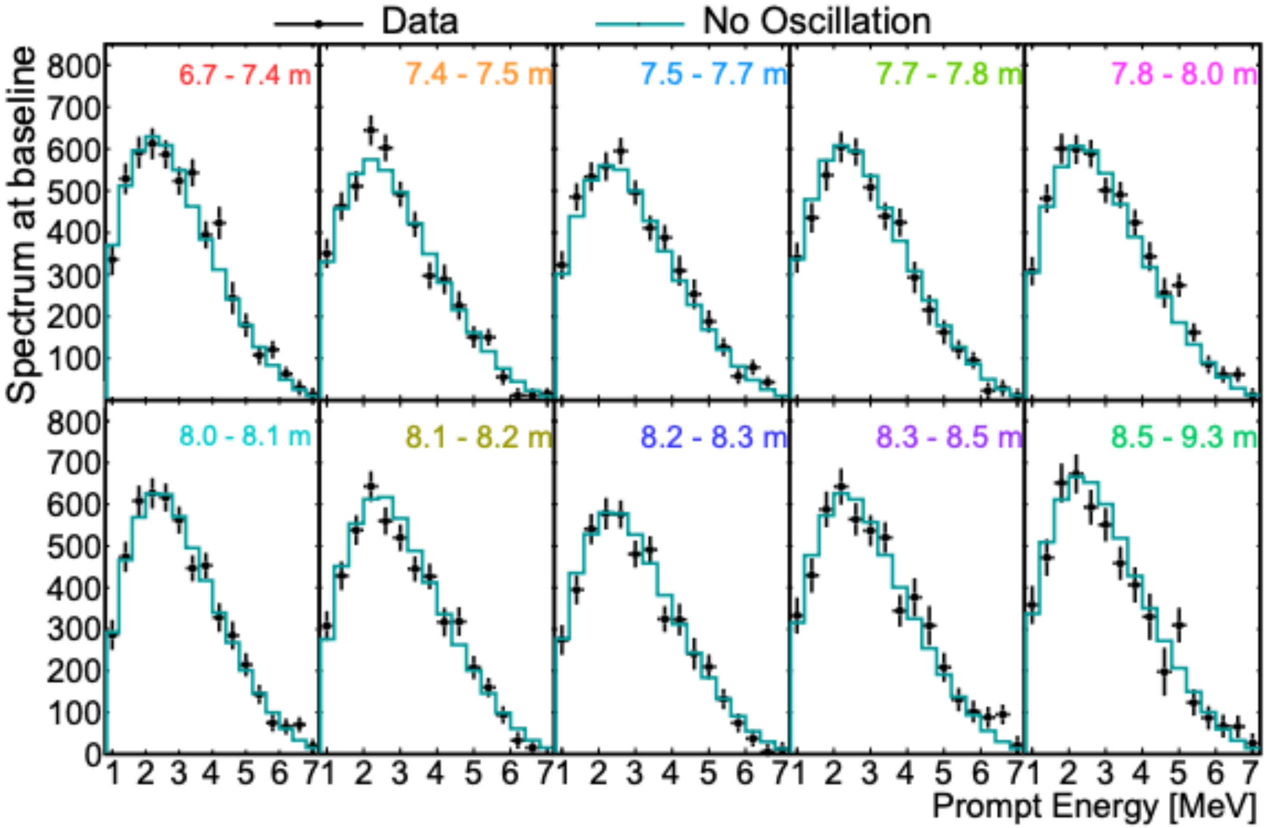
PROSPECT: No "Oscillations" Found



BNL PROSPECT Group, 2019



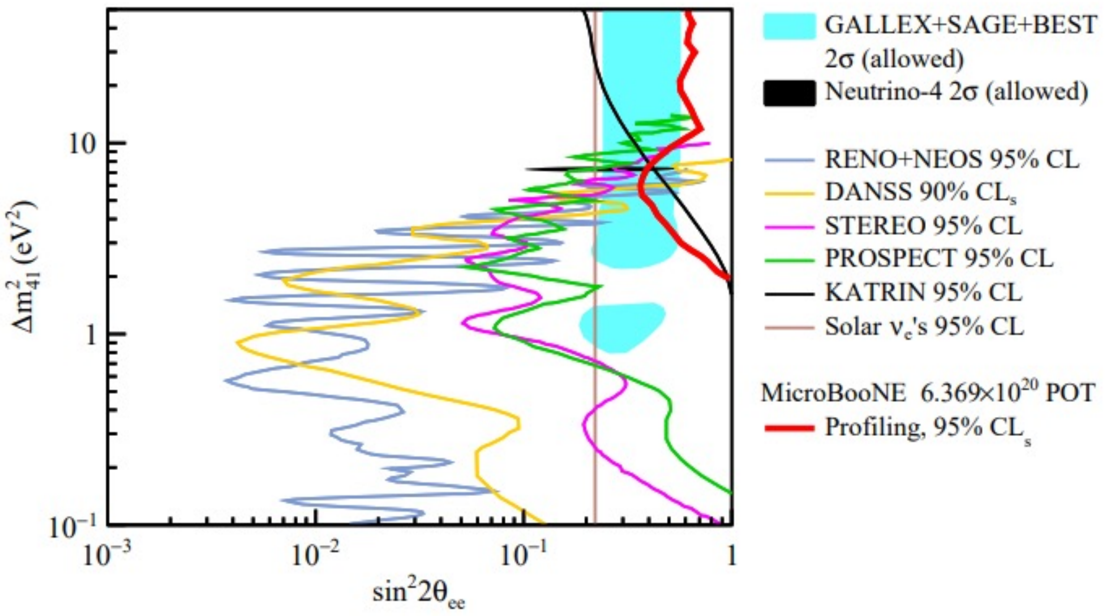
> 50,000 antineutrinos from pure ^{235}U fissions collected in 2018



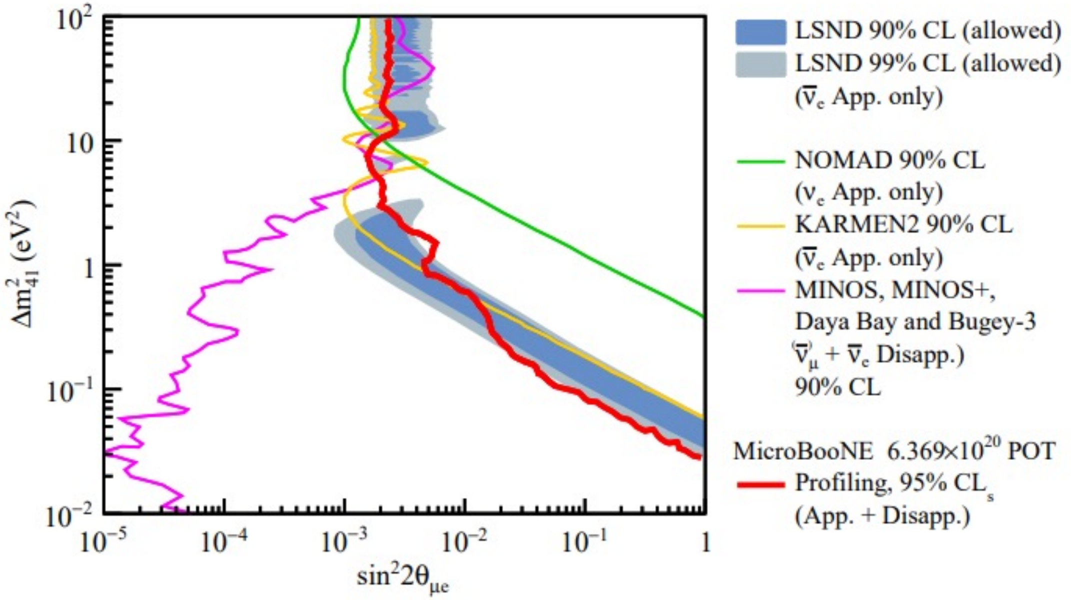
Phys. Rev. Lett. 121, 251802 (2018)

Phys. Rev. D 103, 032001 (2021)

Recent experimental exclusions

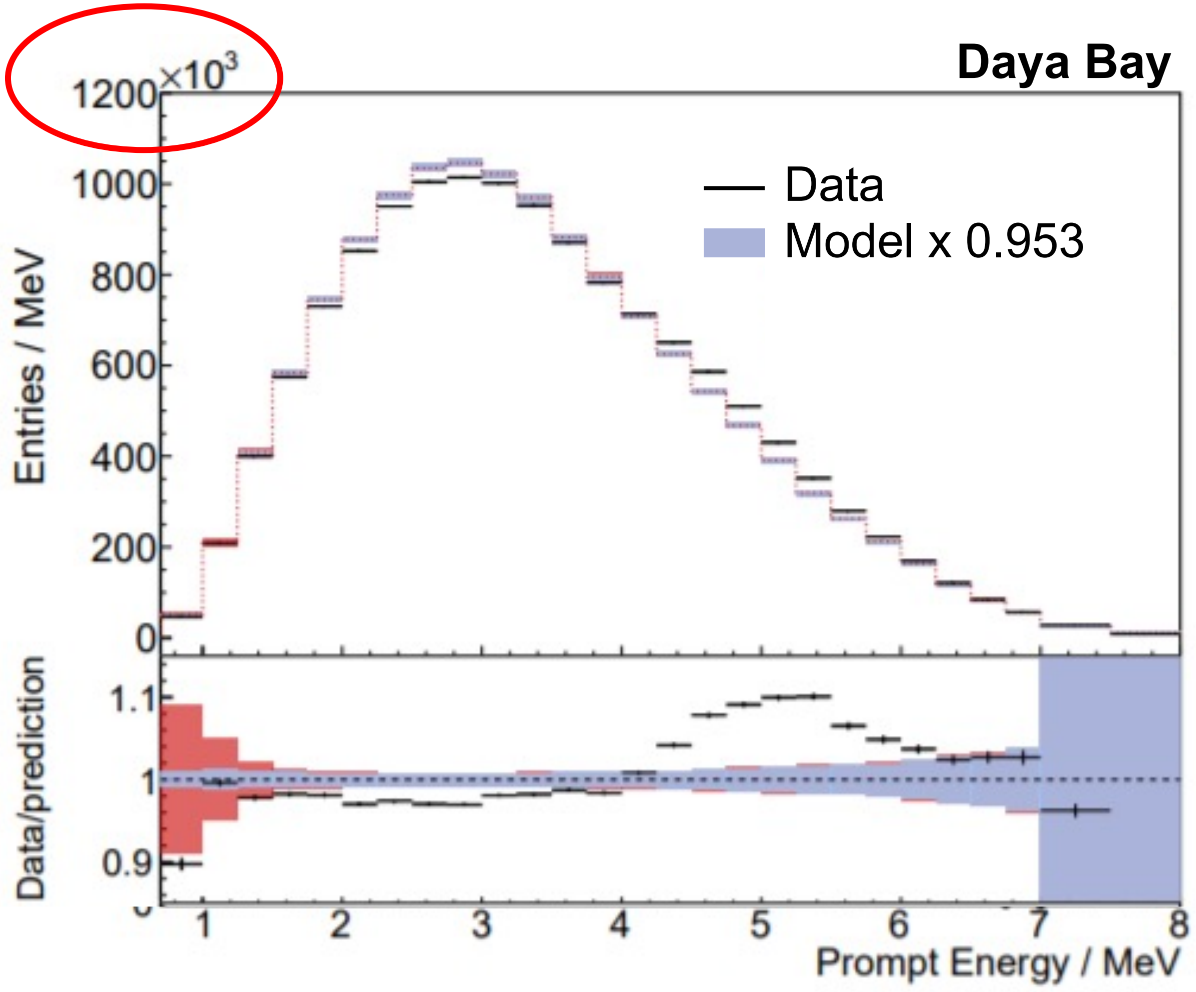


Phys. Rev. Lett. 130, 011801 (2022), MicroBooNE



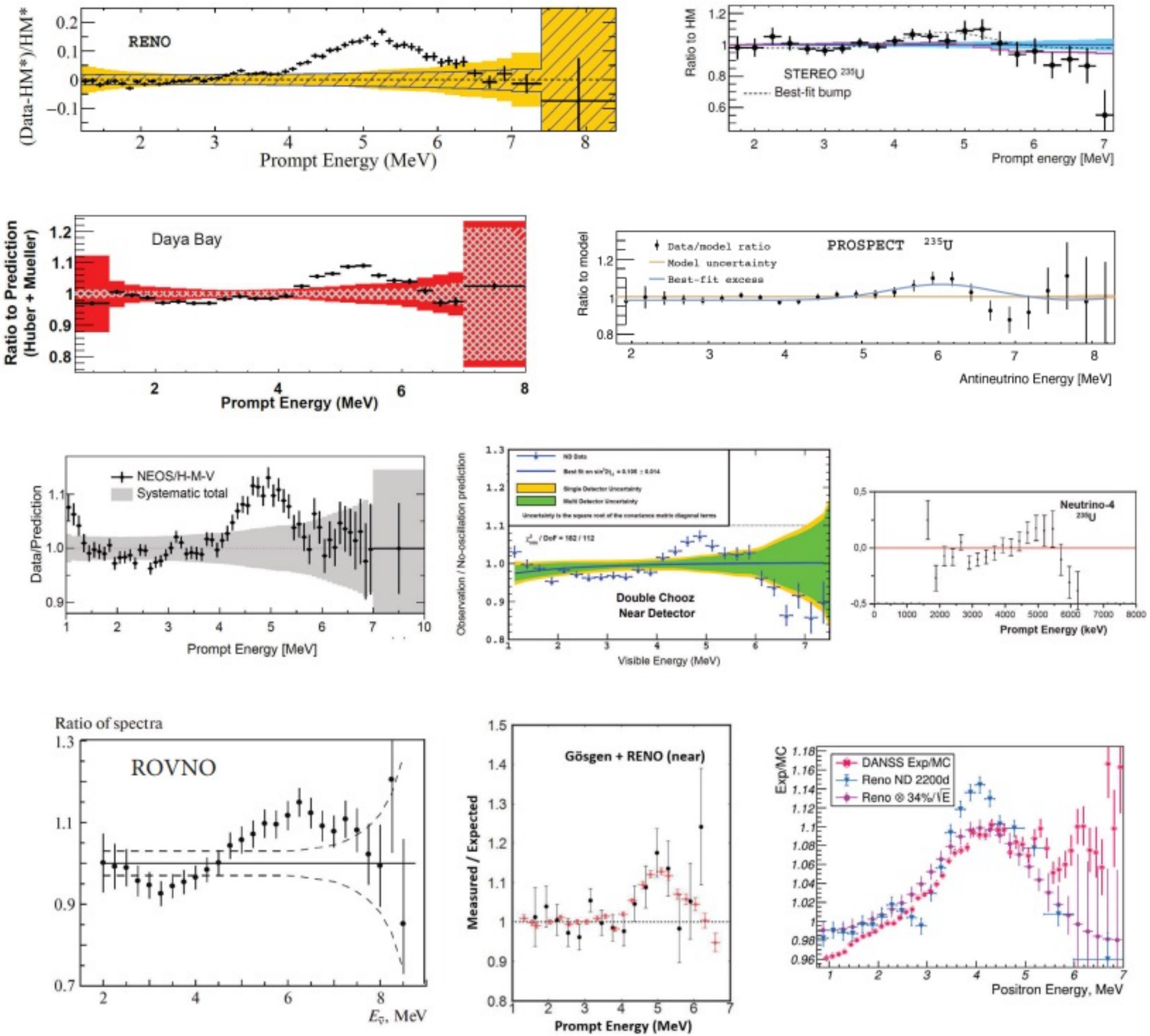
- ❑ $\bar{\nu}_e$ disappearance: recent SBL reactors (e.g. PROSPECT) didn't observe shape distortion (except Neutrino-4)
- ❑ ν_e appearance: MicroBooNE disfavors MiniBooNE with the LArTPC technology (expect updated results coming this summer)
- ❑ The simple 3 active +1 sterile neutrino oscillation is not compatible with global data
  - Need more exotic models (e.g. oscillation + decay)

Reactor $\overline{\nu}_e$ Energy Spectrum @Daya Bay



Phys. Rev. Lett. 123, 111801 (2019)

- ❑ High precision reactor antineutrino energy spectrum measured with 4 million events
- ❑ Expect no shape distortion if RAA is caused by “eV-scale” sterile neutrinos (Daya Bay is too far and can only see overall rate deficit)
- ❑ However, saw a significant disagreement in the “shape” of the spectrum compared with reactor neutrino model prediction
  - ❑ often referred to as the “5-MeV” bump in prompt energy after the re-normalization to remove the overall flux deficit



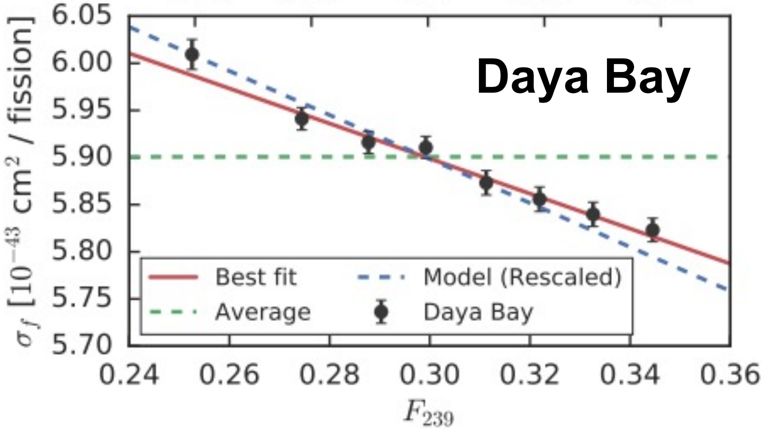
- ❑ The “5-MeV” bump has been observed in >10 experiments
- ❑ This shape discrepancy cannot be explained by sterile neutrino oscillations, indicating issues in the Huber-Mueller model

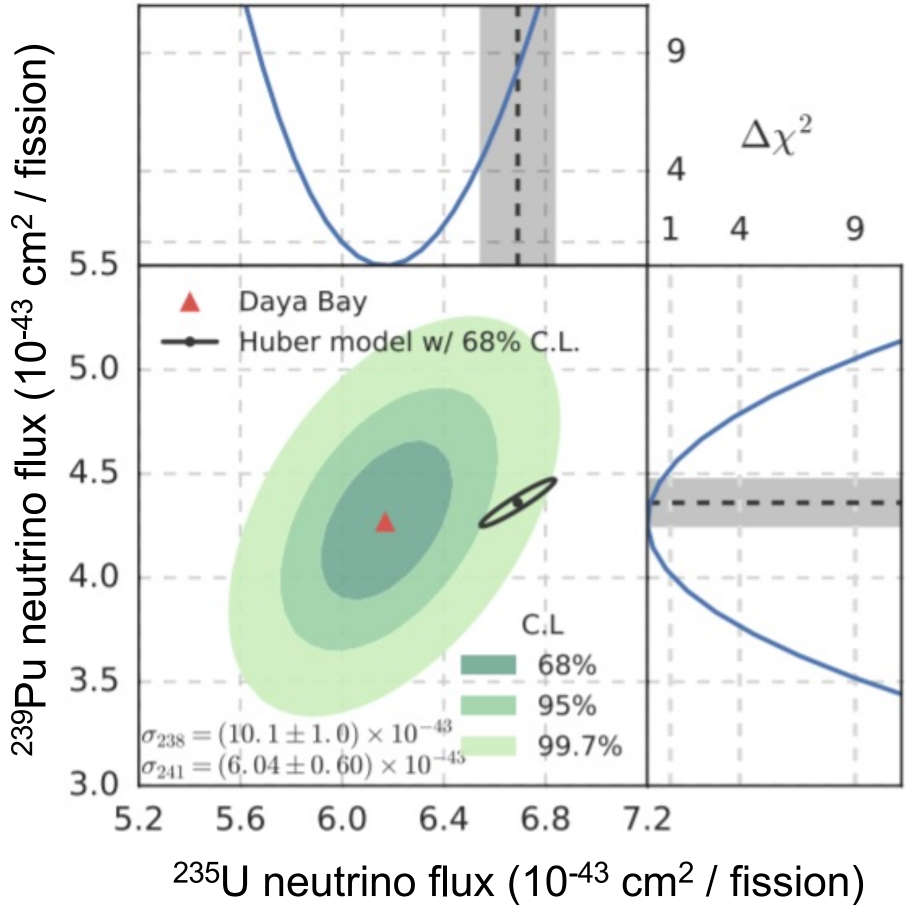
Isotopic Reactor $\overline{\nu}_e$ flux

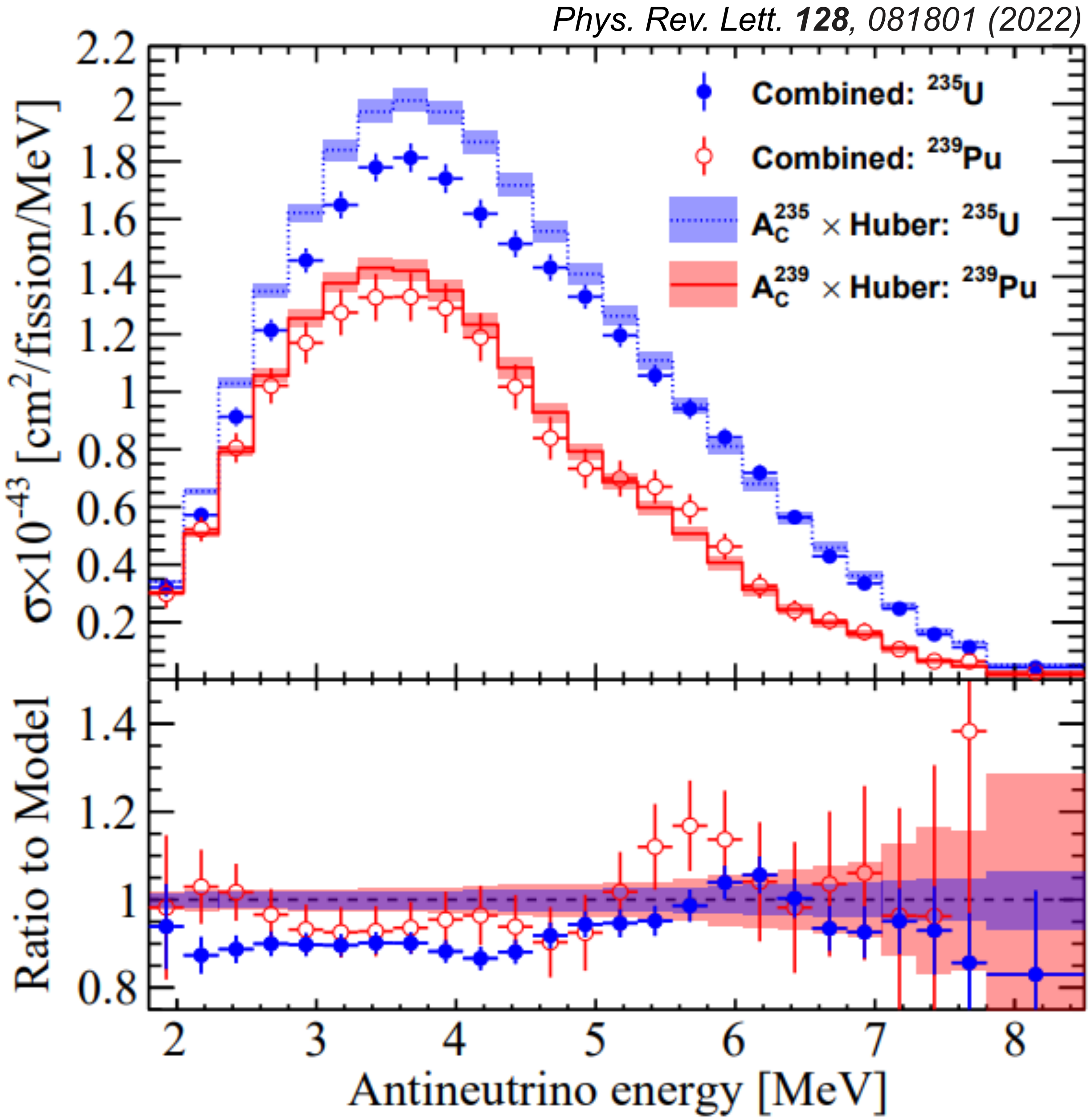
Year	(10^{-43} cm^2/fission)	^{235}U	^{239}Pu
2011	Huber–Mueller [11], [12]	6.69 ± 0.15	4.36 ± 0.11
2017	Daya Bay [161]	6.17 ± 0.17	4.27 ± 0.26
2018	RENO [162]	6.15 ± 0.19	4.18 ± 0.26
2019	Daya Bay [164]	6.10 ± 0.15	4.32 ± 0.25
2020	NEOS-II [163]	6.32 ± 0.18	4.66 ± 0.26
2020	STEREO [87]	6.34 ± 0.16	–

- Expect equal flux deficit for ^{235}U and ^{239}Pu if RAA is caused by sterile neutrinos
- Instead, fuel evolution analyses show a much larger deficit in ^{235}U
  - RAA can be resolved by only adjusting ^{235}U flux prediction by 8%
  - ^{239}Pu uncertainty is still very large

Phys. Rev. Lett. 118, 251801 (2017)







Combined measurement of ^{235}U and ^{239}Pu spectra from Daya Bay and PROSPECT

- Both the normalization and the shape do not agree with the model prediction for either isotope
- The “bump” structure is visible in both the extracted ^{235}U and ^{239}Pu spectra
  - Hinted at similar origins, such as inaccurate shape factors from forbidden decays

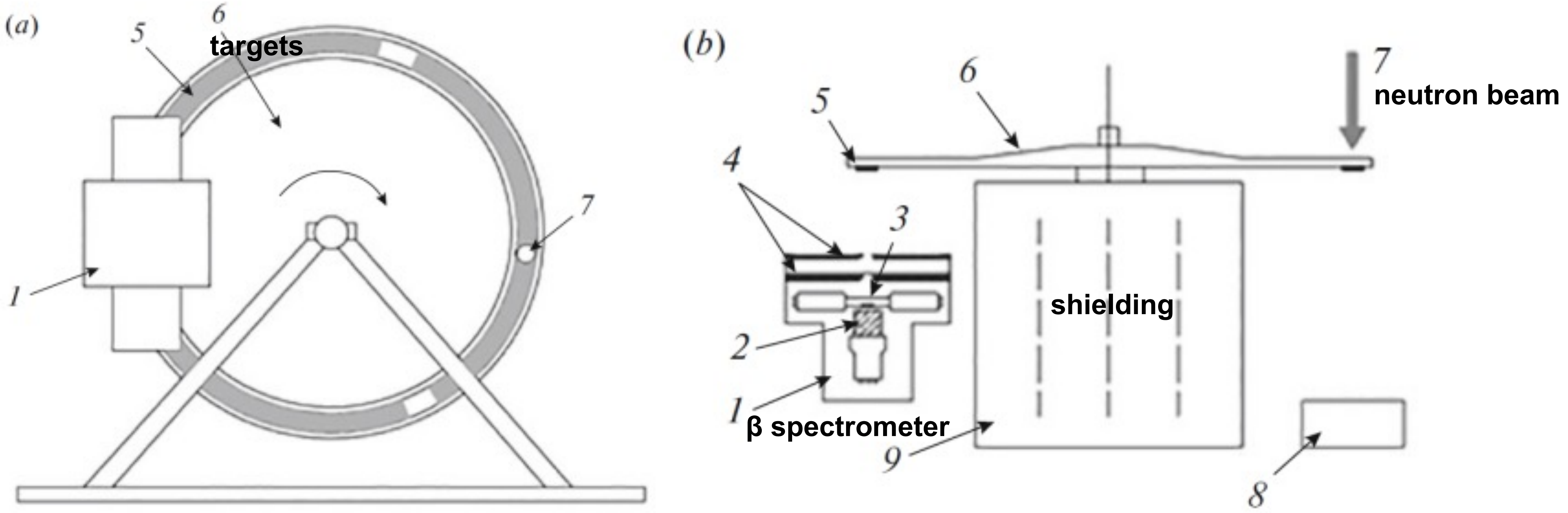
RAA: What have we learned so far?

- Sterile neutrino is unlikely to be relevant in resolving RAA
  - Didn’t observe L/E dependence in <10 m reactor experiments
  - Saw the “5-MeV” bump in the energy spectrum
  - Saw possible isotopic dependence of the flux deficit

- The observations suggest issues in the Huber-Mueller Model
  - Issues in the original ILL beta-spectra measurements
  - Impact of forbidden decays on the shape of the spectra

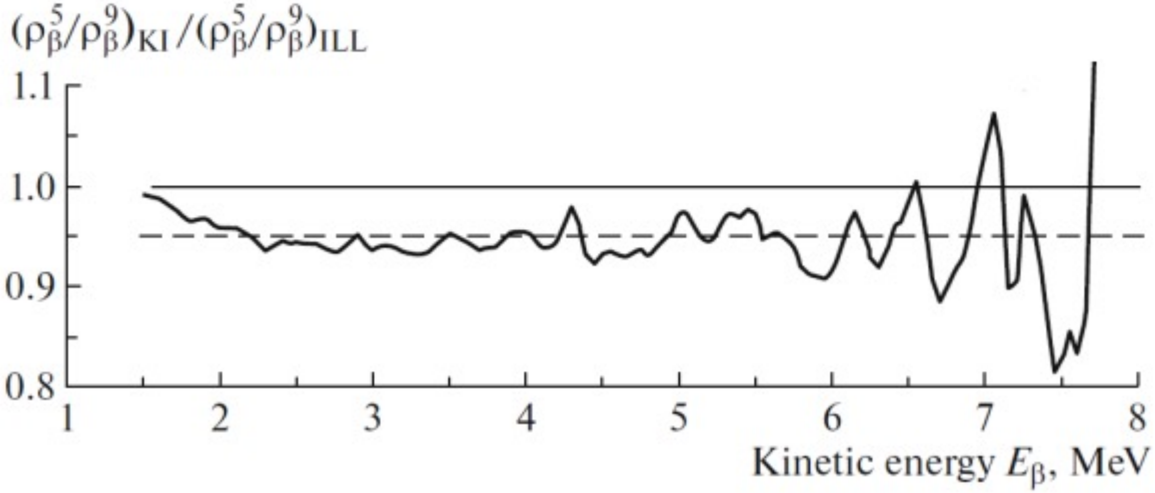
New β-spectrum ratio measurement at Kurchatov Institute (KI) in 2021

Back view　　　　　　　　　　　　Top view



- ^{235}U, ^{239}Pu targets (metallic foils) each covering 1/3 of the rim of a rotating disk, remaining 1/3 for background measurement
- Neutron beam (to activate targets) and beta spectrometer on two sides with passive shielding in between

New β-spectrum ratio measurement at Kurchatov Institute (KI) in 2021



Year	$(10^{-43}\ cm^2/fission)$	^{235}U	^{239}Pu	^{238}U	^{241}Pu
2011	Huber-Mueller [11, 12]	6.69 ± 0.15	4.36 ± 0.11	10.10 ± 1.00	6.04 ± 0.13
2018	SM-2018 [152]	6.28	4.42	10.14	6.23
2021	KI [162]	6.27 ± 0.13	4.33 ± 0.11	9.34 ± 0.47	6.01 ± 0.13
2017	Daya Bay [157]	6.17 ± 0.17	4.27 ± 0.26	–	–
2018	RENO [158]	6.15 ± 0.19	4.18 ± 0.26	–	–
2019	Daya Bay [160]	6.10 ± 0.15	4.32 ± 0.25	–	–
2020	NEOS-II [159]	6.32 ± 0.18	4.66 ± 0.26	–	–
2020	STEREO [84]	6.34 ± 0.16	–	–	–

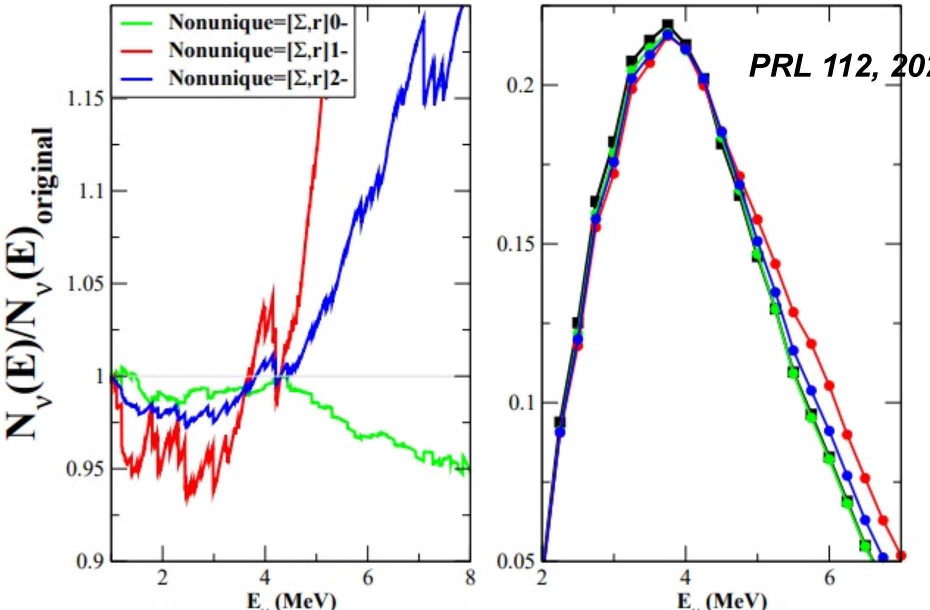
- ^{235}U/^{239}Pu ratio is ~5% lower than that from ILL
- Assuming issues in the original ILL ^{235}U measurement (e.g. normalization), a rescaling of ^{235}U flux by 5% would agree with Daya Bay/RENO's measurements and resolve the RAA
- Desire a new ILL-like experiment to remeasure the cumulative β-spectra

Shape impact from forbidden transition

- Allowed decay
  - Well-known β-spectrum shape with several nuclear-effect corrections: *Coulomb correction, finite-size, radiative correction, weak magnetism etc.*
  - Assumed in the Conversion methods' fit to virtual branches
- Forbidden decay:
  - ~30% of decays in fission products
  - Shape factor depends on transition type, difficult to represent in the conversion methods with virtual branches
    - Different treatment results in >4% difference: uncertainty in H-M model is underestimated

→ Time to take another look at the summation methods

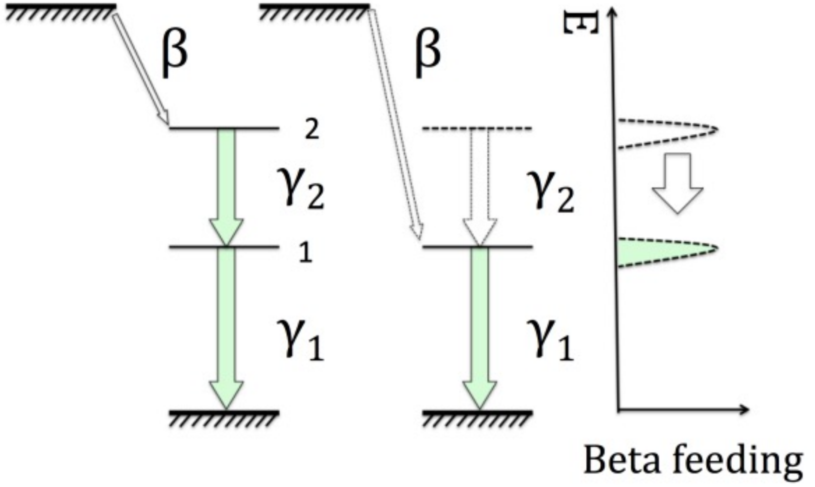
Classification	ΔJ	Δπ	logft
Allowed	0,±1 (0+ ↛ 0+)	No	4-6
1st forbidden non-unique	0, ± 1	Yes	6-10
1st forbidden unique	± 2	Yes	7-10
2nd forbidden non-unique	± 2	No	11-14
2nd forbidden unique	± 3	No	14
3rd forbidden non-unique	± 3	Yes	17-19
3rd forbidden unique	± 4	Yes	18



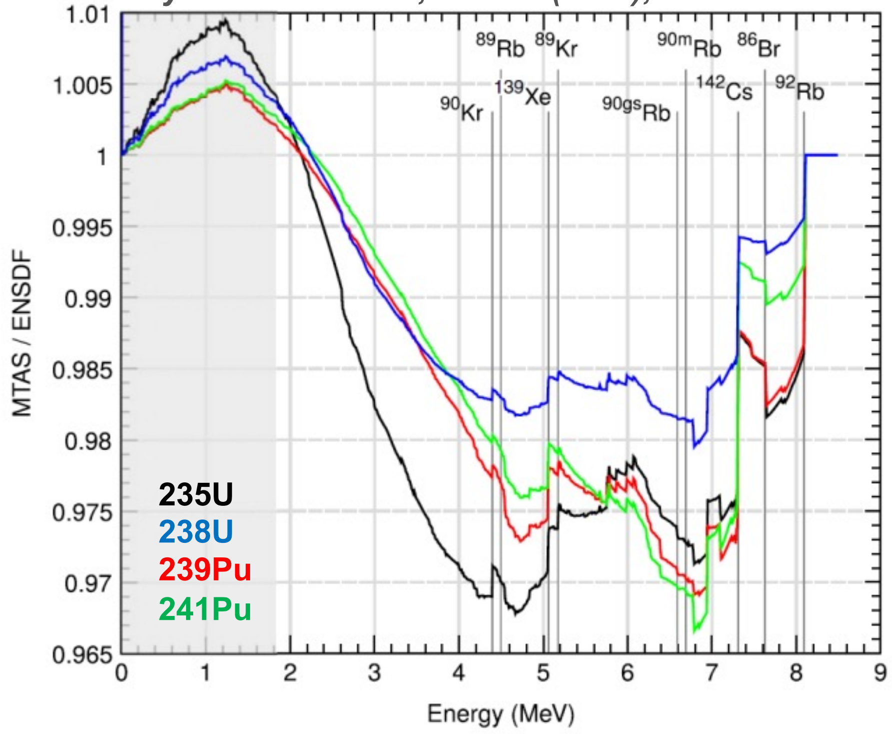
PRL 112, 202501 (2014)

Improve the Summation Method

- Pandemonium Effect
  - Many beta-decay data are measured with Hi-resolution Ge detector (low efficiency for high energy gamma rays)
  - Missing gamma rays would overpopulate low energy levels of the daughter → overestimate beta energy
- Solution: Total Absorption Gamma-ray Spectroscopy (TAGS)
  - High efficiency γ–ray detectors with lower resolution (e.g. NaI, BaF_2)
  - TAGS campaigns since 2009 in both Europe (IGISOL @U. Jyvaskyla, Finland) and US (HRIBF @ORNL)
    - Prioritize nuclides that impact most to reactor antineutrino spectrum (identified by IAEA)

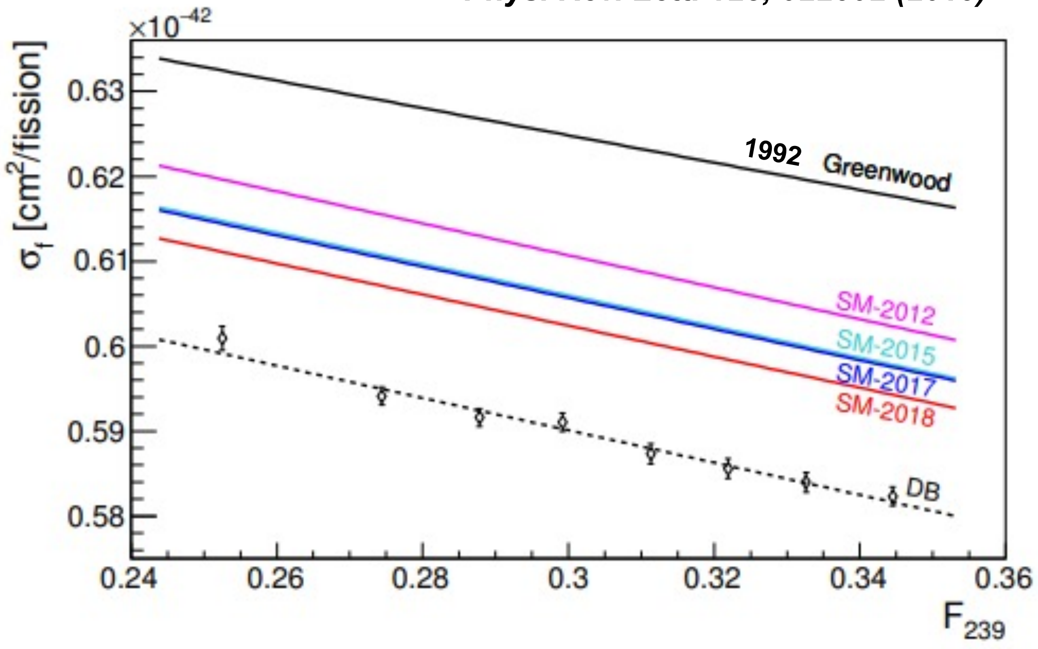


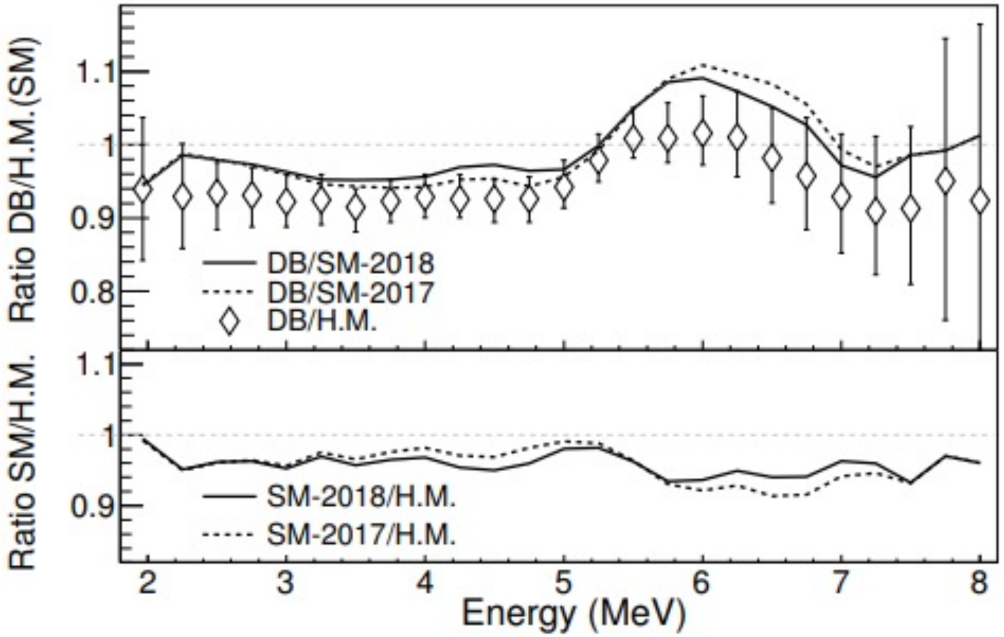
Phys. Rev. Lett. 119, 052503 (2017), ORNL



New Summation Models vs. Daya Bay

Phys. Rev. Lett. 123, 022502 (2019)





- Systematically better agreement after more TAGS data sets are included. Newest model (SM-2018) only differs by 1.9%
- “5-MeV” bump still exists (DB data/SM-2018) and to be understood
  - Possible from forbidden transitions:
  - Shape factor calculation for forbidden transitions has large uncertainties: shell model, QRPA, etc
  - New experiments to measure electron shape of first-forbidden transitions + new microscopic calculations

Summary


Progress in Particle and Nuclear Physics
Volume 136, March 2024, 104106

Review

Reactor antineutrino flux and anomaly

Chao Zhang [a], Xin Qian [a], Muriel Fallot [b]

After 13 years, the Reactor Antineutrino Anomaly (RAA) is considered resolved

Error in experiments?
No, all experimental results were consistent

New Physics?
No, sterile neutrino is unlikely to be relevant to the RAA
- ❑ Didn't observe L/E dependence in <10 m reactor experiments
- ❑ Saw the "5-MeV" bump in the energy spectrum
- ❑ Saw possible isotopic dependence of the flux deficit

Issues in theoretical models?
Yes, Huber-Mueller model uncertainty is underestimated
- ❑ Old data from ILL could have systematic issues: KI's new ratio measurement
- ❑ Effects from forbidden decays could be large
- ❑ New summation models give much better agreement after including more Pandemonium-free data from the TAGS campaign.