# Reactor flux and spectrum overview

Leendert Hayen

Applied Antineutrino Physics, York, 18 September 2023

LPC Caen, France

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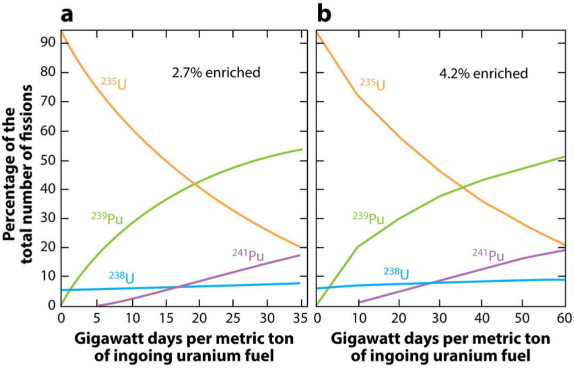
# Introduction

# Antineutrino origin

Typical Pressurized Water Reactor (PWR) starts with pure $^{235,238}$U



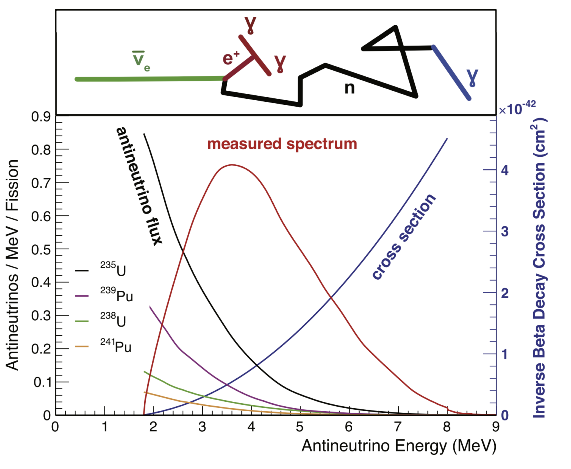

Hayes AC, Vogel P. 2016.
Annu. Rev. Nucl. Part. Sci. 66:219–44

Fission creates many neutron-rich final states

$\rightarrow 10^{21}\ \bar{\nu}_e$/s per GW$_e$ (Most powerful man-made $\bar{\nu}_e$ source)

# Inverse beta decay

Recover part of neutrino spectrum using IBD




Effective threshold at 1.8 MeV

J Phys G 43 (2016) 030401

# Antineutrino origin

Knowledge of energetic final state spectrum desirable for

- Fundamental physics
- Decay heat, reactor safeguards
- Reactor monitoring
- Non-proliferation

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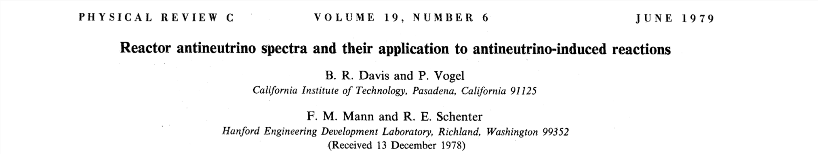
Long history of modeling for applications



PHYSICAL REVIEW C VOLUME 19, NUMBER 6 JUNE 1979

**Reactor antineutrino spectra and their application to antineutrino-induced reactions**

B. R. Davis and P. Vogel
*California Institute of Technology, Pasadena, California 91125*

F. M. Mann and R. E. Schenter
*Hanford Engineering Development Laboratory, Richland, Washington 99352*

(Received 13 December 1978)

See also Kwon et al., PRD 24 (1981); Achkar et al., PLB 374 (1996); . . .

# 2011: Annus mirabilis/horribilis?

Quite suddenly, improved calculations cause disruption

PHYSICAL REVIEW C **83**, 054615 (2011)

**Improved predictions of reactor antineutrino spectra**

Th. A. Mueller,[1] D. Lhuillier,[1,*] M. Fallot,[2] A. Letourneau,[1] S. Cormon,[2] M. Fechner,[3] L. Giot,[2] T. Lasserre,[3] J. Martino,[2]
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birthing the...

PHYSICAL REVIEW D **83,** 073006 (2011)

**Reactor antineutrino anomaly**

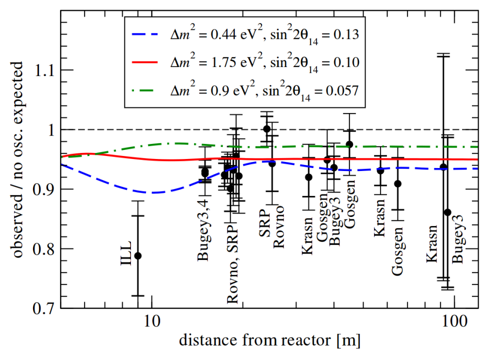
G. Mention,[1] M. Fechner,[1] Th. Lasserre,[1,2,*] Th. A. Mueller,[3] D. Lhuillier,[3] M. Cribier,[1,2] and A. Letourneau[3]

Deficiency in neutrino count rate at 94% (2-3$\sigma$)

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

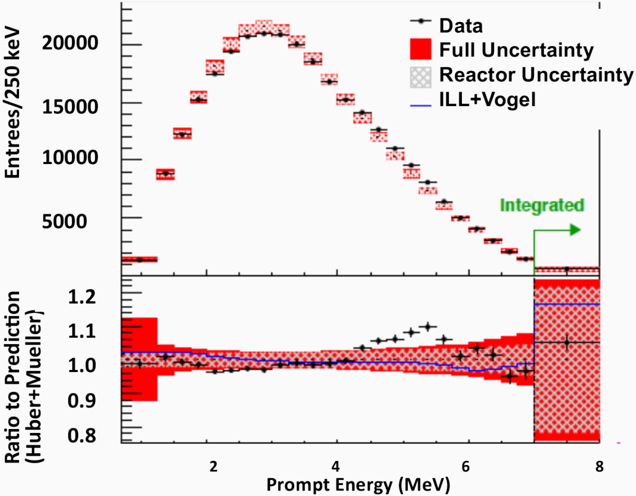
Very complicated nuclear physics problem

- Branching ratio's
- Fission Yields
- Nuclear structure
- ...




An *et al.* (Daya Bay Collab.), PRL 118 (2017) 251801 & J. Kopp et al., JHEP 05 (2013) 050

# 2014: Reactor bump




Something not understood, most likely **nuclear physics** problem

Hayes & Vogel, ARNPS **66** (2016) 219

## Very short baseline experiments

Since 2011, $\sim$ 10 experiments started setting up

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Very short (<10m) baseline experiments: measure oscillation directly

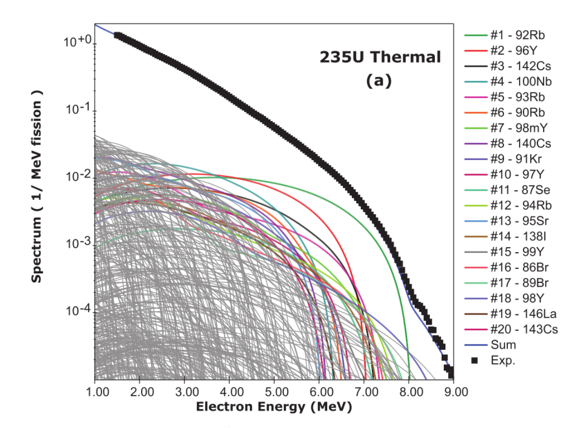
Several experiments came online late 2017/2018!

- NEOS (Korea)
- DANSS (Russia)
- STEREO (France)
- PROSPECT (USA)

and more, many now have final data!

# Antineutrino origin

Fission fragments from $^{235}$U, $^{238}$U, $^{239}$Pu and $^{241}$Pu have many $\beta^-$ branches, but can only measure cumulative spectrum.




Conversion of all $\beta$ branches is **tremendous** theory challenge

A. A. Sonzogni *et al.*, PRC **91** (2015) 011301(R)

# Spectral prediction progress

# Analysis procedure

Experimental benchmark are ILL (Schreckenbach) cumulative electron spectra

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Approaches split up in 2:

1. **Conversion** method: virtual $\beta$ branch fits

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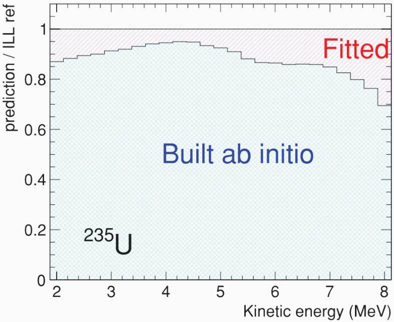
Approaches split up in 2:

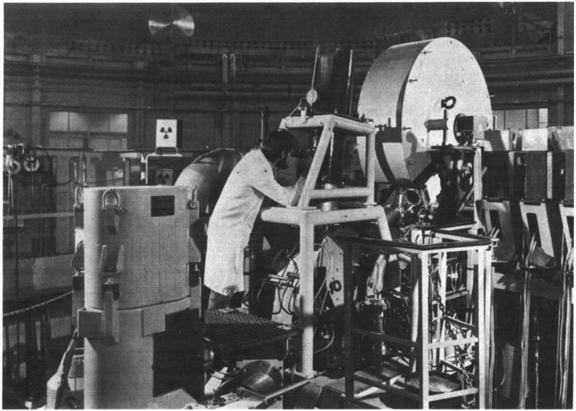
1. **Conversion** method: virtual $\beta$ branch fits
2. **Summation** method: Build from databases




Much of *summation* is based on same spectral assumptions Huber, PRC **84** (2011) 024617; Mueller *et al.*, PRC **83** (2011) 054615

# Conversion approach

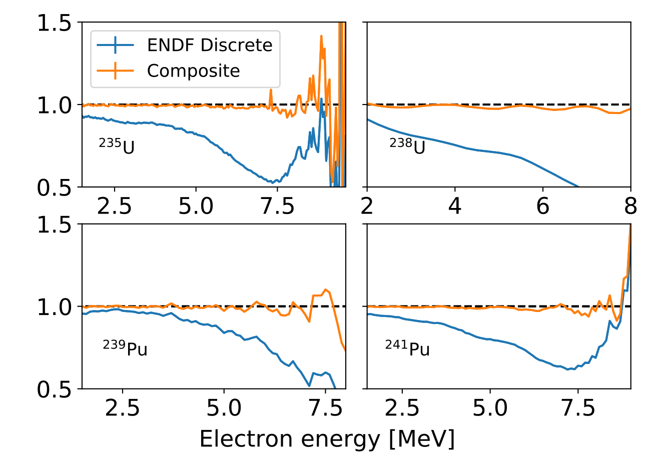
Correspondence with experimental cumulative $\beta$ spectrum



Mampe+ NIM 154 (1978); Schreckenbach+ PLB 99 (1981); Von Feilitzsch+, PLB 118 (1982); Schreckenbach+ PLB 160 (1985); Hahn+ PLB 218 (1989); ...

# Conversion approach

Optional: build up $\beta$ spectrum with databases




Make up difference with fitted *virtual* (fictitious) $\beta$ branches

LH+, PRC 100 (2019) 054323

# $\beta$ spectrum shape

Central element in analysis is knowledge of $\beta$ spectrum shape

$$\frac{dN}{dW} \propto pW(W_0 - W)^2 F(Z, W) C(Z, W) \ldots$$

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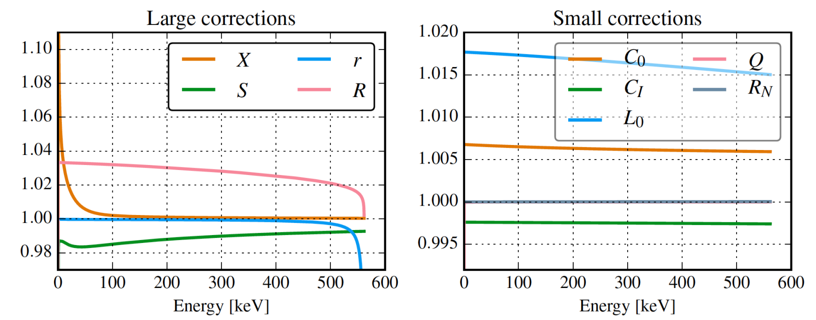


LH, Severijns, Comp. Phys. Comm. 240 (2019) 152; github.com/leenderthayen/BSG

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- allowed ($C \approx 1$)
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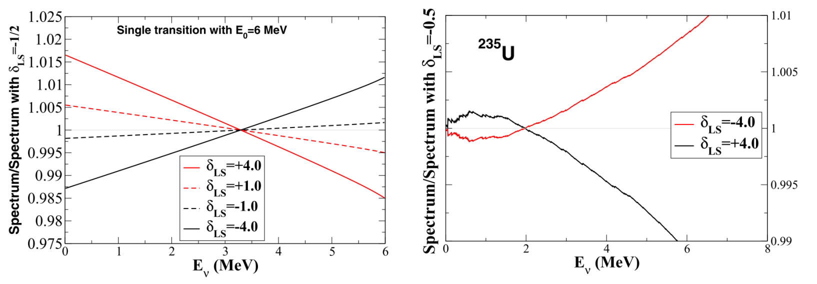
unlikely to be correct, hard to quantify uncertainty

# Conversion approach

Dependence on 'weak magnetism'

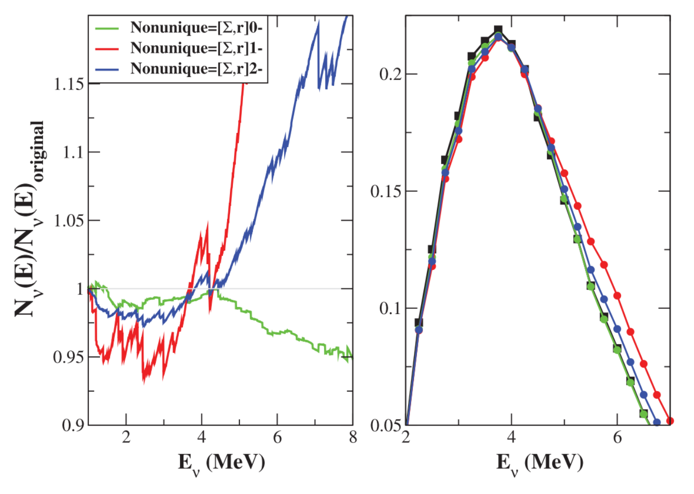



Despite 'simplicity', many nuclei make calculations very hard

Wang+, PRC 95 (2017)

# Conversion approach

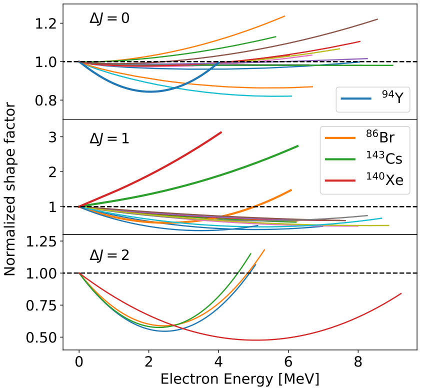
Strong model dependencies from forbidden transitions




Hayes et al., PRL 112 (2014) 202501

# Forbidden shape factors

Picked 36 dominant forbidden transitions, calculated shape factor in nuclear shell model



# Forbidden shape factors

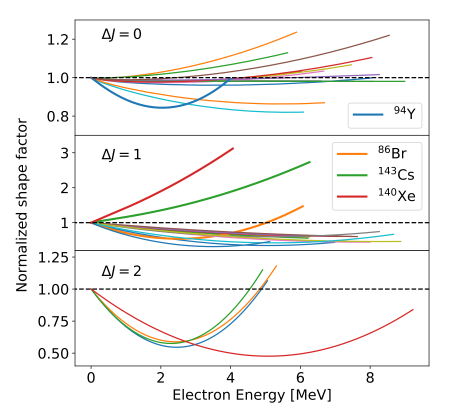
Picked 36 dominant forbidden transitions, calculated shape factor in nuclear shell model

$$\frac{dN}{dE} \propto pE(E_0 - E)^2 F(Z, E)$$

$$\boldsymbol{C(Z, E)}$$

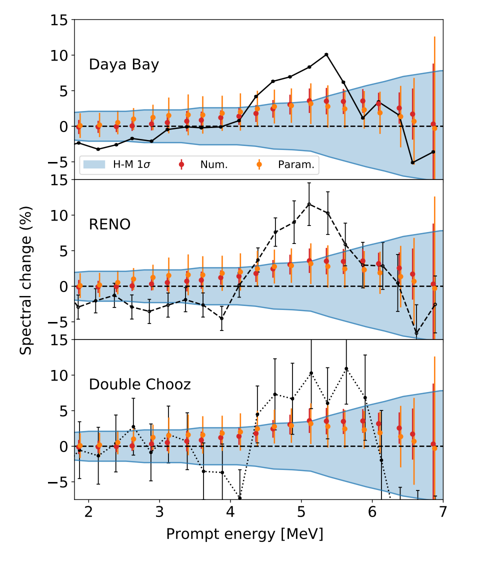
Allowed: $C \approx 1$

large spectral changes



# Forbidden transitions & the bump

Large scale
shell model calculations
of dominant forbidden
transitions change
spectra at few-% level



# Forbidden transitions & the bump

Large scale
shell model calculations
of dominant forbidden
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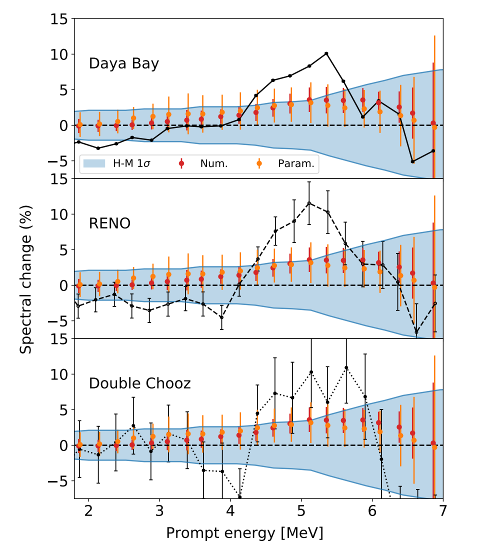
spectra at few-% level

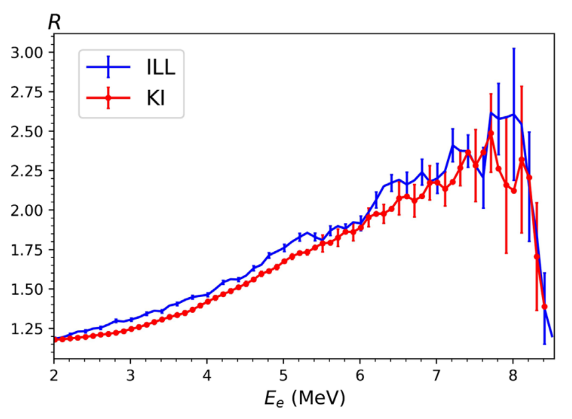
Bump
mitigated + increased
theoretical uncertainties,
but not solved




LH *et al.*, PRC 99 (2019) 031301(R), LH *et al.*, PRC 100(2019) 054323

# New $e^-$ spectral measurements

Daya Bay & others point towards normalization issues with $^{235}U$




Kurchatov Institute measured ${}^eS_5/{}^eS_9$ and found 5%! ~~Anomaly~~?

PRD 104 (2021) L071301

# Summation approach

Build both $\beta$ and $\bar{\nu}_e$ *ab initio*

$$S(E_\nu) = \sum_i f_i \sum_n Y_n(Z, A, t) \sum_{n,i} b_{n,i}(E_0^i) P_\nu(E_\nu, E_0^i, Z)$$

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Needs full database information on

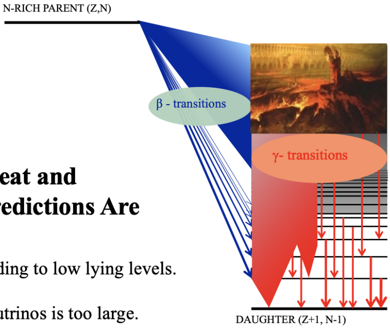
- Fission yields
- Branching ratios
- Spin-parities

Extremely challenging, but only method with **predictive power**

# Pandemonium, Decay heat (Courtesy of Charlie Rasco)

## The Pandemonium Effect

If low efficiency detectors are used to measure γ rays in complex β decays, this can lead to an overestimate of feeding to low lying levels in the daughter nucleus.
J.C. Hardy, *et al.*, PLB 71 (1977)




## Underestimated Reactor Decay Heat and Overestimated Reactor Antineutrino Predictions Are Intimately Connected

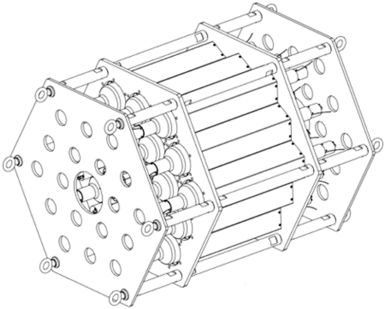
There are two important consequences of overestimating β feeding to low lying levels.

The predicted energy of electrons (β particles) and antineutrinos is too large. Overpredicting the antineutrino energy results in an overestimate of the number of detected antineutrinos when using the summation method to calculate either β or antineutrino reactor fluxes.

The predicted amount of γ-ray energy released from a reactor (Decay Heat) is underestimated.

Oak Ridge National Laboratory

# Pandemonium, Decay heat (Courtesy of Charlie Rasco)



The Modular Total Absorption Spectrometer (MTAS) detector, the world's largest TAS contains 1 ton of NaI.

**Total Absorption Spectroscopy (TAS)!**
**TAS detectors can be ~99% efficient to detect γ rays and over 80% efficient to detect all γ-ray energy.**

There are several total absorption spectrometers around the world
Example total absorption detectors include the SuN detector, the DTAS detector, and the MTAS detector.

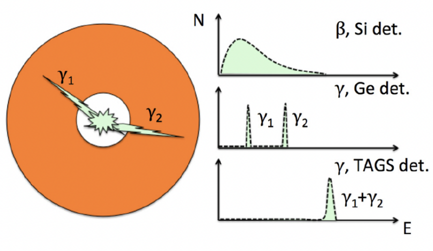
There are many TAS papers publishing corrected β-feeding patterns which impact predicted reactor antineutrino fluxes and reactor decay heat.

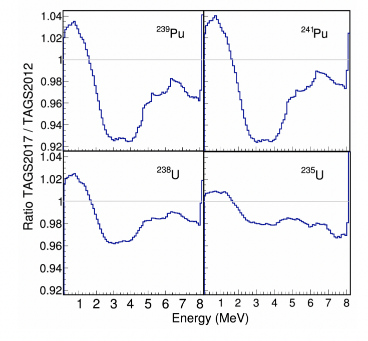
A. Algora, *et al.*, PRL 105, 202501 (2010)
A.-A. Zakari-Issoufou, *et al.*, PRL 115, 102503 (2015)
B.C. Rasco, *et al.*, PRL 117, 092501 (2016)
A. Fijałkowska, *et al.*, PRL 119, 052503 (2017)
...
(+Many more...)

OAK RIDGE National Laboratory

# TAGS

Large changes in branching ratio from Pandemonium isotopes



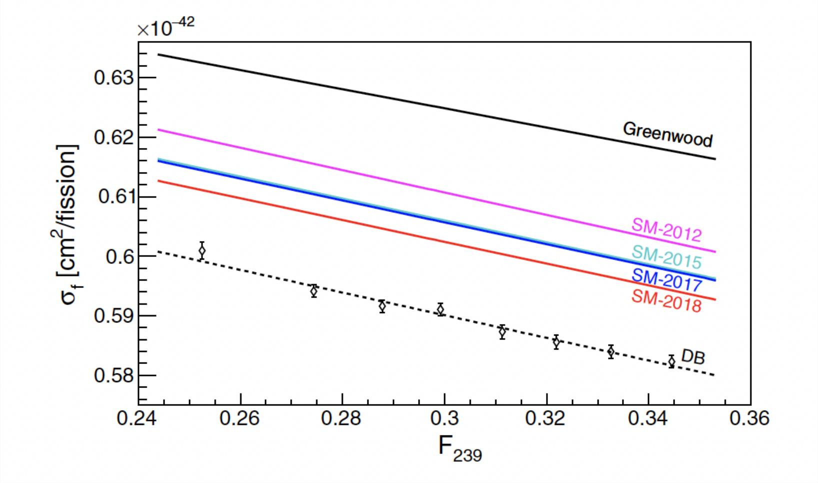




Several percent-level shifts in $\bar{\nu}$ spectra

Algora+, EPJA (2021) 57

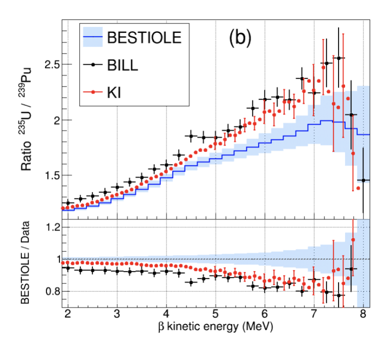
# Summation results

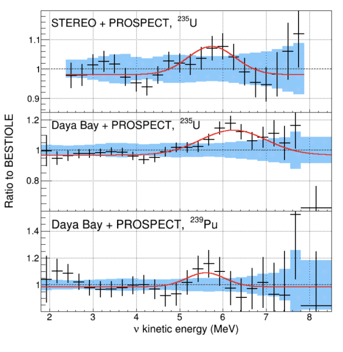
TAGS measurements have improved situation dramatically




Estienne+, PRL 2019

Others are joining summation efforts, uncertainty quantification




No progress on bump, however.

2304.14992

# Reactor $\nu$ detection progress

## Overview of reactor $\bar{\nu}_e$ decade

Faced with some interesting developments:

1. 2011: Emergence of flux anomaly, sterile neutrinos?
2. 2014: Appearance of 5 MeV bump
3. 2017-: Very short baseline expts come online, RAA best fit value excluded

## Overview of reactor $\bar{\nu}_e$ decade

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4. Also 2017: fuel dependencies in spectra

# Overview of reactor $\bar{\nu}_e$ decade

Faced with some interesting developments:

1. 2011: Emergence of flux anomaly, sterile neutrinos?
2. 2014: Appearance of 5 MeV bump
3. 2017-: Very short baseline expts come online, RAA best fit value excluded
4. Also 2017: fuel dependencies in spectra
5. 2021: New $e^-$ spectral measurements!
6. Also 2021: BEST confirms Gallium anomaly
7. 2022-2023: VSBL experiments publish final results

In parallel: **15+ years of TAGS progress**!

# Status of understanding

We may consider status on three items

1. Total reactor flux
2. Spectral agreement
3. Fuel evolution

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1. Total reactor flux
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Much progress since 2011, but community has **not reached consensus** on all points, nor have predictions converged

# Total reactor flux

Several experiments (near-)final results, but no uniform picture

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Several experiments (near-)final results, but no uniform picture

Some see no oscillation

- STEREO (Nature 613 (2023))
- PROSPECT (PRD 103 (2021))
- DANSS (Phys At Nucl 86 (2023))

# Total reactor flux

Several experiments (near-)final results, but no uniform picture

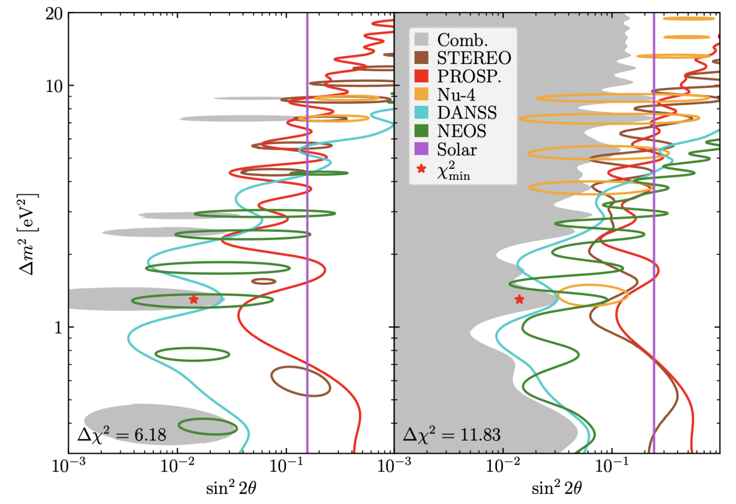
Some see no oscillation

- STEREO (Nature 613 (2023))
- PROSPECT (PRD 103 (2021))
- DANSS (Phys At Nucl 86 (2023))

. . .while others do

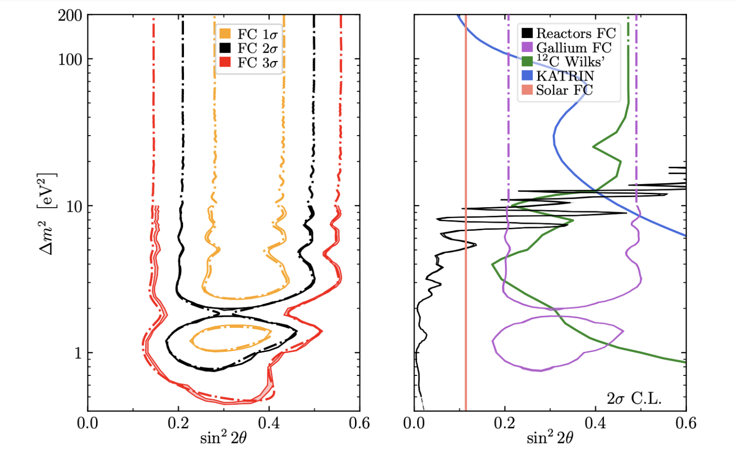
- NEOS/RENO (PRD 105 (2022))
- Neutrino-4 (PRD 104 (2021))

# Current reactor status




2111.12530

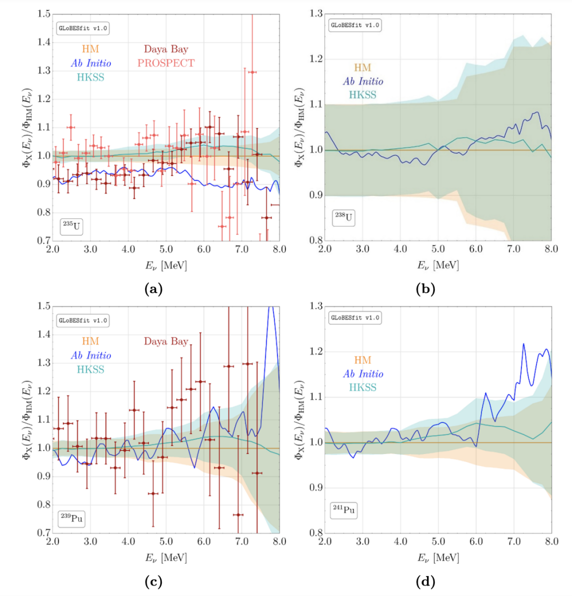
# Global fits




Clear tension between strong BEST result & solar, $\Delta m^2 \gtrsim 10$ eV$^2$?

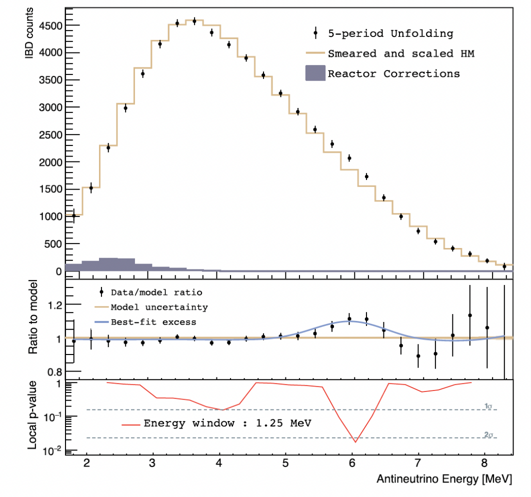
2111.12530

# Role in global analysis (Berryman & Huber JHEP01(2021)167)



# Status on the bump

All experiments see the bump relative to Huber-Mueller




PRL 131 (2023) 021802

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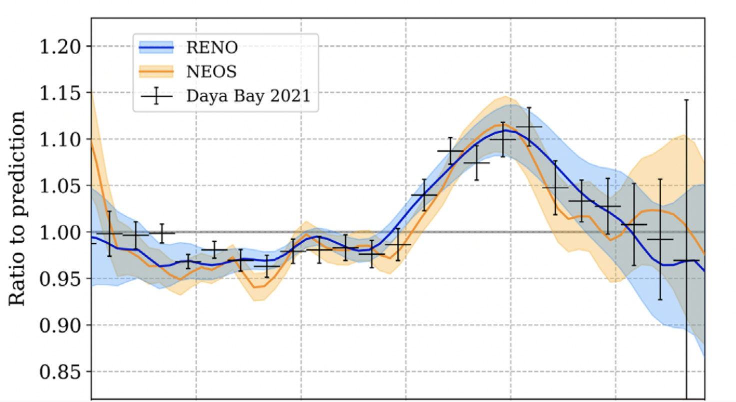
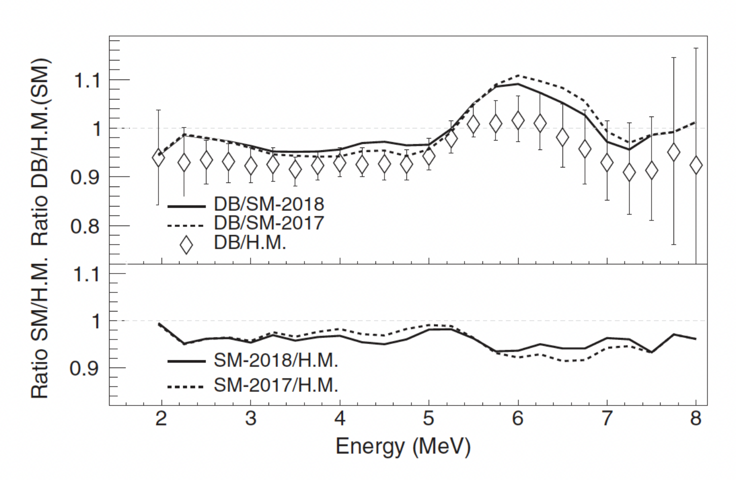



PRD 105 (2022) L111101

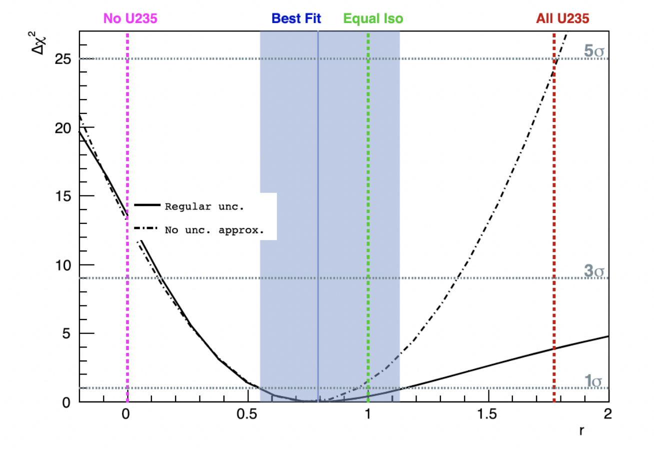
But also state of the art summation models cannot explain it




PRL 123 (2019) 022502

# Status on the bump

Interesting development, bump is unlikely from 1 isotope

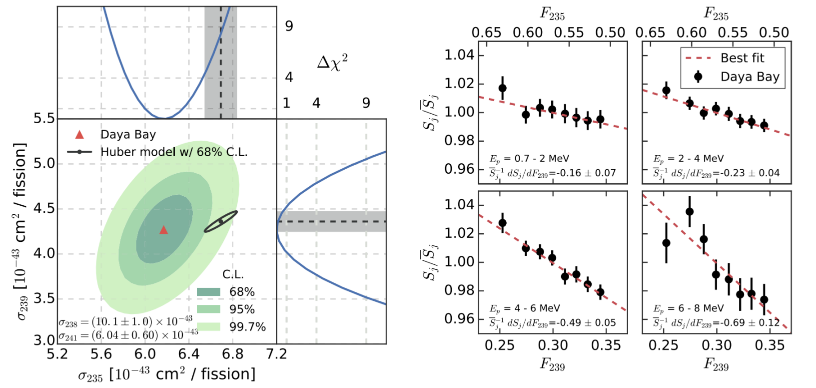



Compatible with forbidden corrections for individual $\beta$ spectra

PRL 131 (2023) 021802

# Fuel evolution in 2017

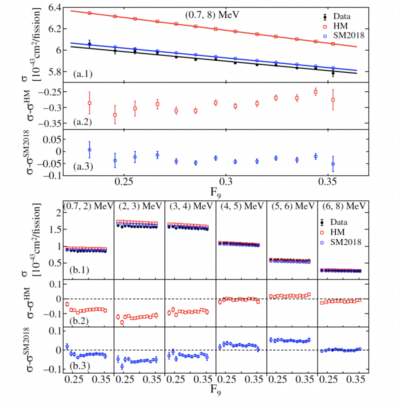
Fuel evolution studies showed potential normalization offset, but also good fuel evolution correspondence

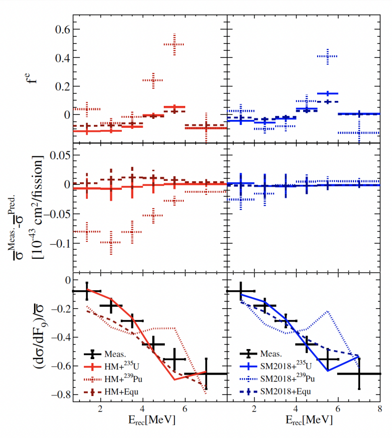



PRL 118 (2017) 251801

# Fuel evolution in 2023

Good average, but poor spectral agreement





Data shows good agreement with all isotopes being equally mis-predicted

PRL 130 (2023) 211801

# Looking forward

# IAEA: Delegates of major experiments & theorists

IAEA
International Atomic Energy Agency

INDC(NDS)-0786
Distr. G, EN, ND

**INDC International Nuclear Data Committee**

## Antineutrino spectra and their applications

Summary of the Technical Meeting

IAEA Headquarters, Vienna, Austria
23-26 April 2019

Targeted lists of forbidden non-unique transitions that contribute significantly to the antineutrino energy spectra based on the theoretical calculations of A. Sonzogni, A. Hayes and L. Hayen have been published [19, 22] and could serve as a guidance for measurements.

- We recommend estimating the impact of the largest shape factors predicted by theory by including these shape factors computed by Hayen et al. (see presentation in this report) in the summation calculations and in conversion calculations.

# TAGS spectral measurements (Courtesy of Charlie Rasco)

**Up next are integral and individual transition β-energy measurements.**

**Precision Reactor Antineutrino Spectra**
Summation Method
Summing anti-neutrinos from each individual fission product to get a reference reactor anti-neutrino spectrum, needs accuracy and precision better than about 5%, and ultimately at the 1% level of precision

Also needed for predicting individual detected antineutrino spectra. (See first measurement of long lived reactor antineutrinos from Double Chooz!)

**Precision Reactor Decay Heat**
β-energy spectrum allows for precision better than the few percent level
Also needed are improved precision of fission yields.

**Expected residual IBD$\bar{\nu}_e$ flux from a discharged assembly**

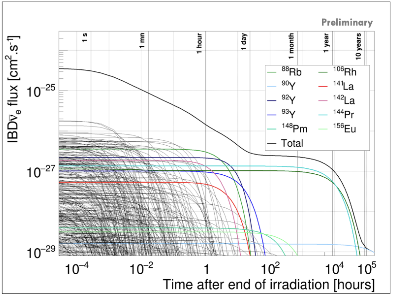



**Fig.** IBD$\bar{\nu}_e$ flux from a $UO_2$ (4%) spent fuel assembly irradiated for 45 GWd/t.

Onillion - IAEA Presentation Jan 2023

# Standardization of predictions

Work with theorists & experimentalists to facilitate goals

CONFLUX

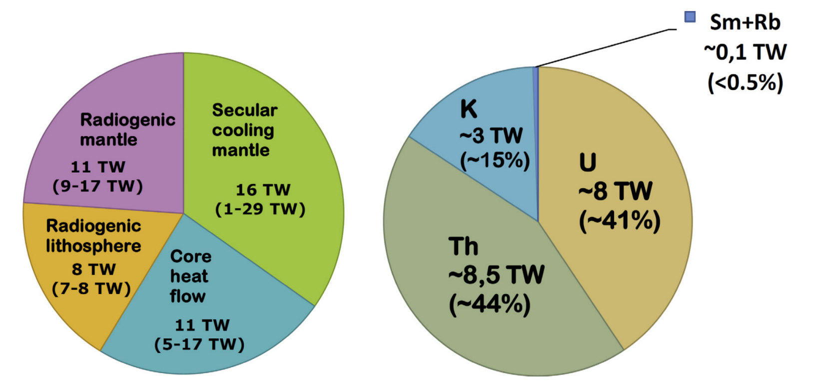
A Standard Framework for Reactor Neutrino Flux Calculation

Make precision beta spectra available to entire community

Talk by Xianyi Zhang

# Impact on geoneutrino's

Precise spectral measurements are essential for geoneutrino detection

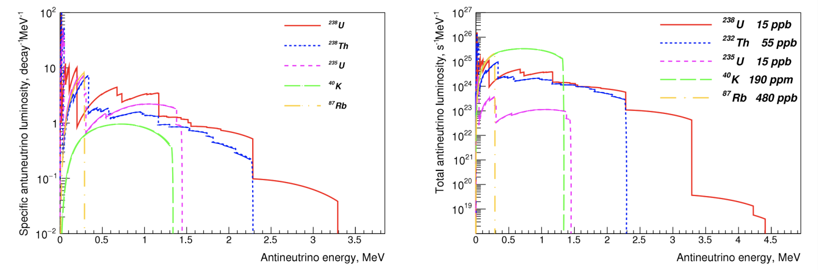



Measurements in Borexino & upcoming in JUNO

Smirnov PPNP 109 (2019)

# Impact on geoneutrino's

Precise spectral measurements are essential for geoneutrino detection




Several major contributors are forbidden decays, can significantly change over-threshold fraction

Smirnov PPNP 109 (2019)

# Coherent neutron scattering

High flux makes reactors interesting for coherent $\nu$ scattering

No 1.8 MeV threshold from IBD $\rightarrow$ need predictive power from *ab initio* approaches for the spectrum

Currently many experiments setting up and getting ready for initial results (CONNIE, NUCLEUS, Dresden-II, ...)

# Conclusion

# Conclusion

Decade+ of burst in research activity, despite much progress many problems still outstanding

Substantial *ab initio* improvements following many dedicated TAGS campaigns

Beta spectral shape measurements currently ongoing in several collaborations, results incoming

Increased spectral precision wanted for geoneutrino's, reactor monitoring, etc.

# Thank you!