Impact of isomeric yield ratios on reactor antineutrino spectra

A. Mattera, A.A. Sonzogni, E.A. McCutchan, R.J. Lorek, C. Sears, C. Billings

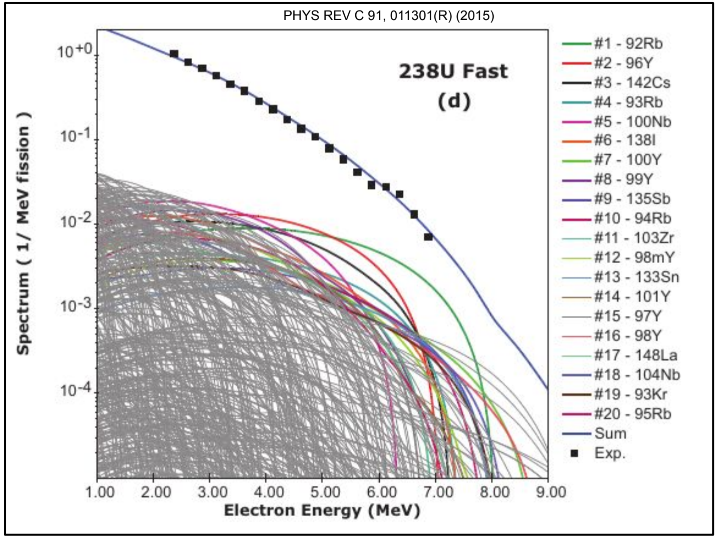
National Nuclear Data Center, Brookhaven National Laboratory

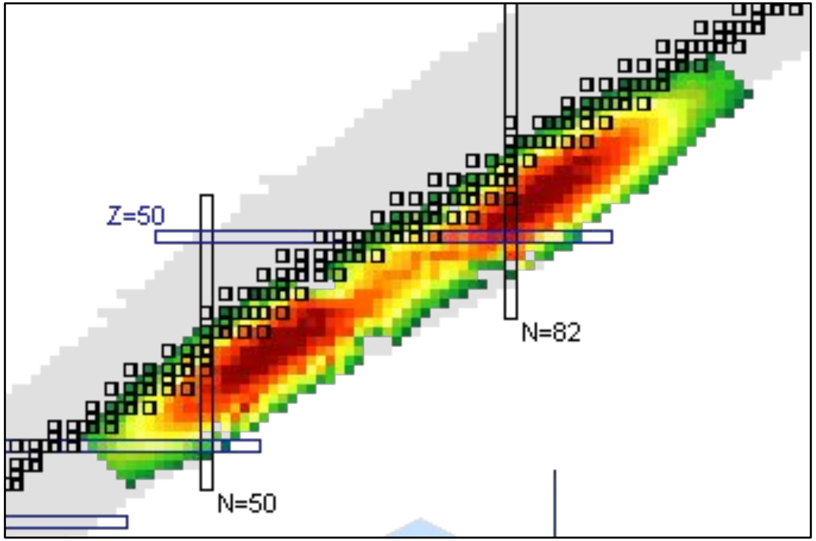
Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

Fission Yields in anti-ν spectra summation calculations

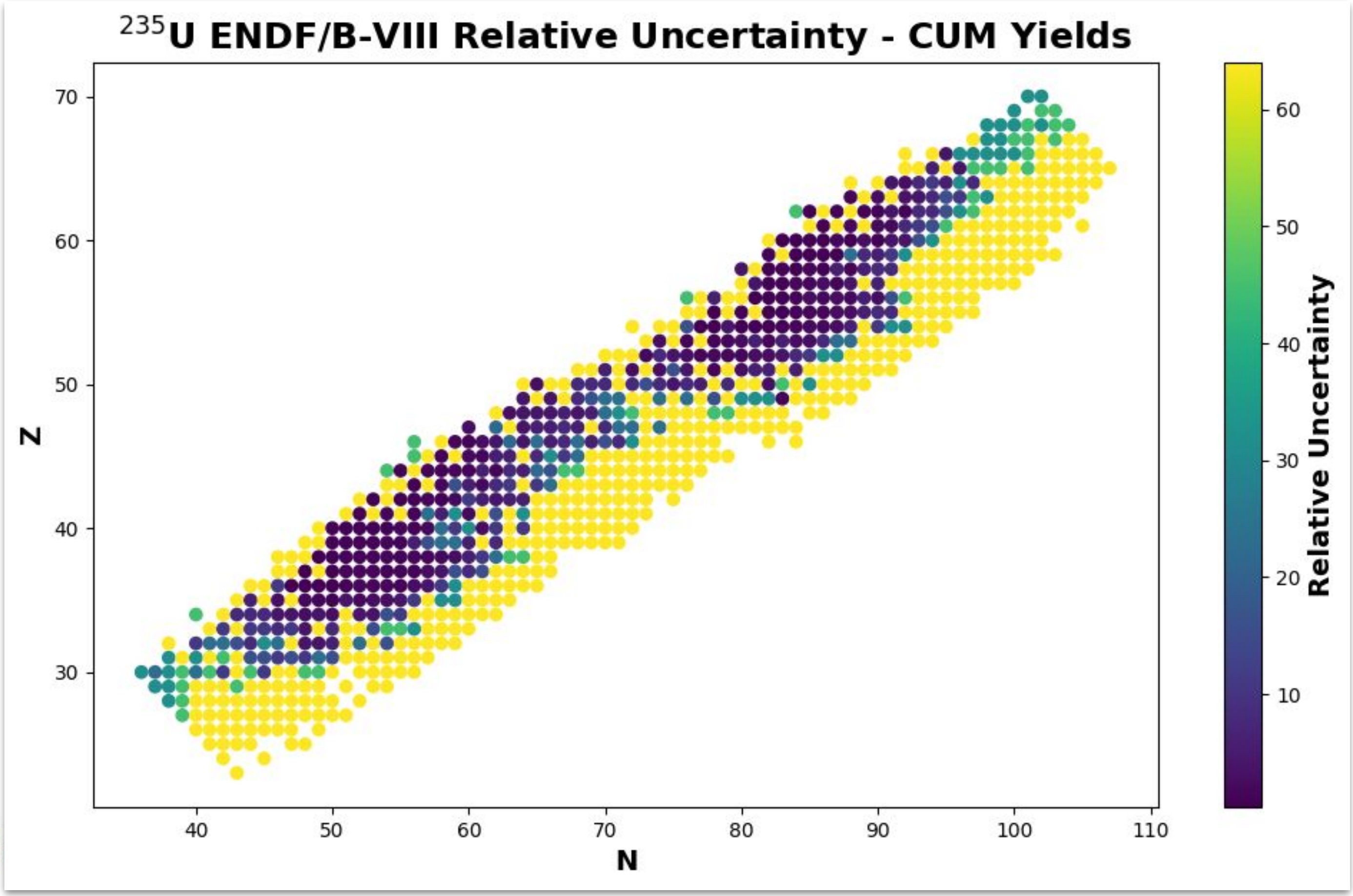
DECAY DATA + **FISSION YIELDS**



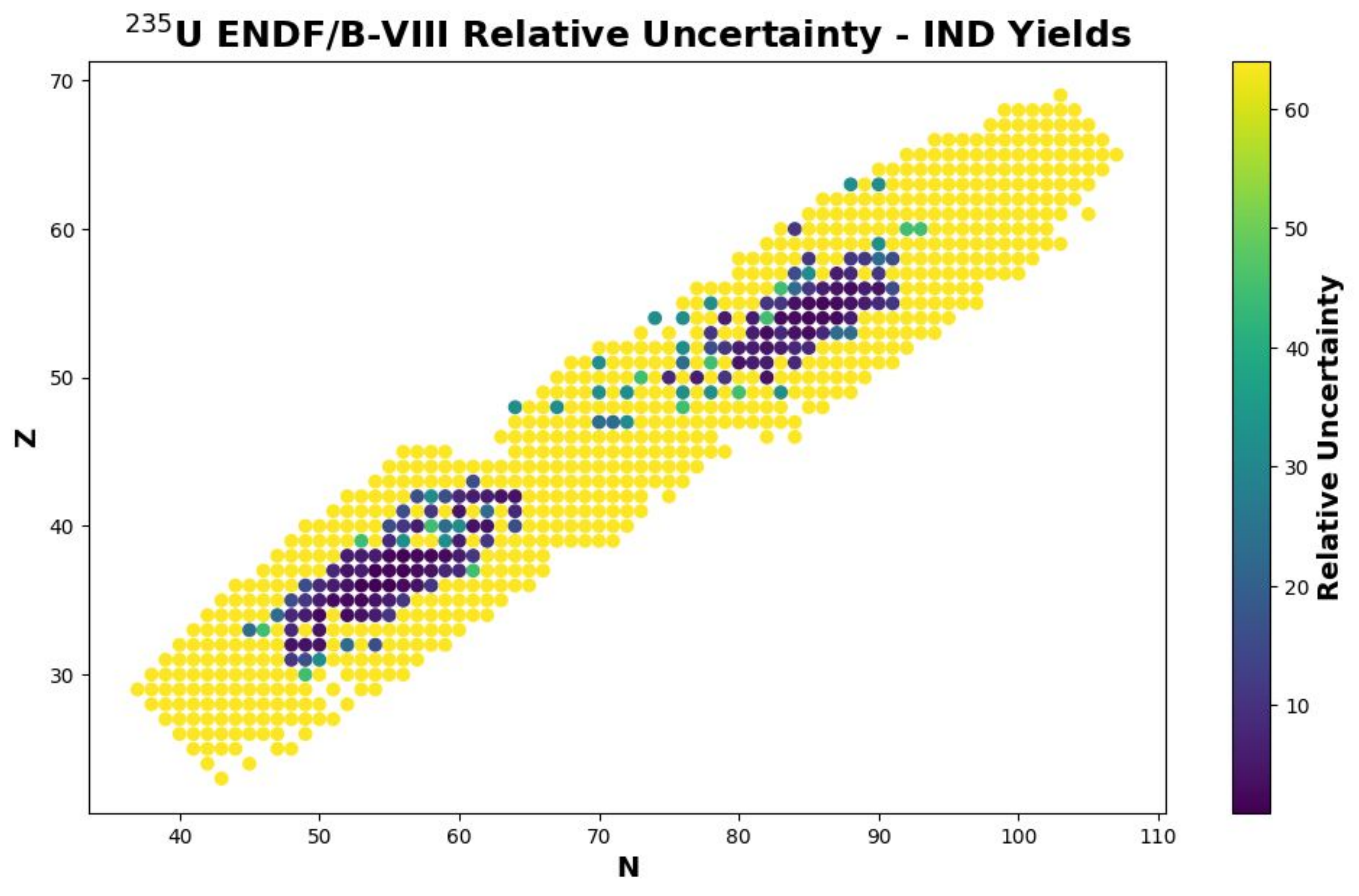


The contribution from the β-decay of each fission product is weighed with its fission yield

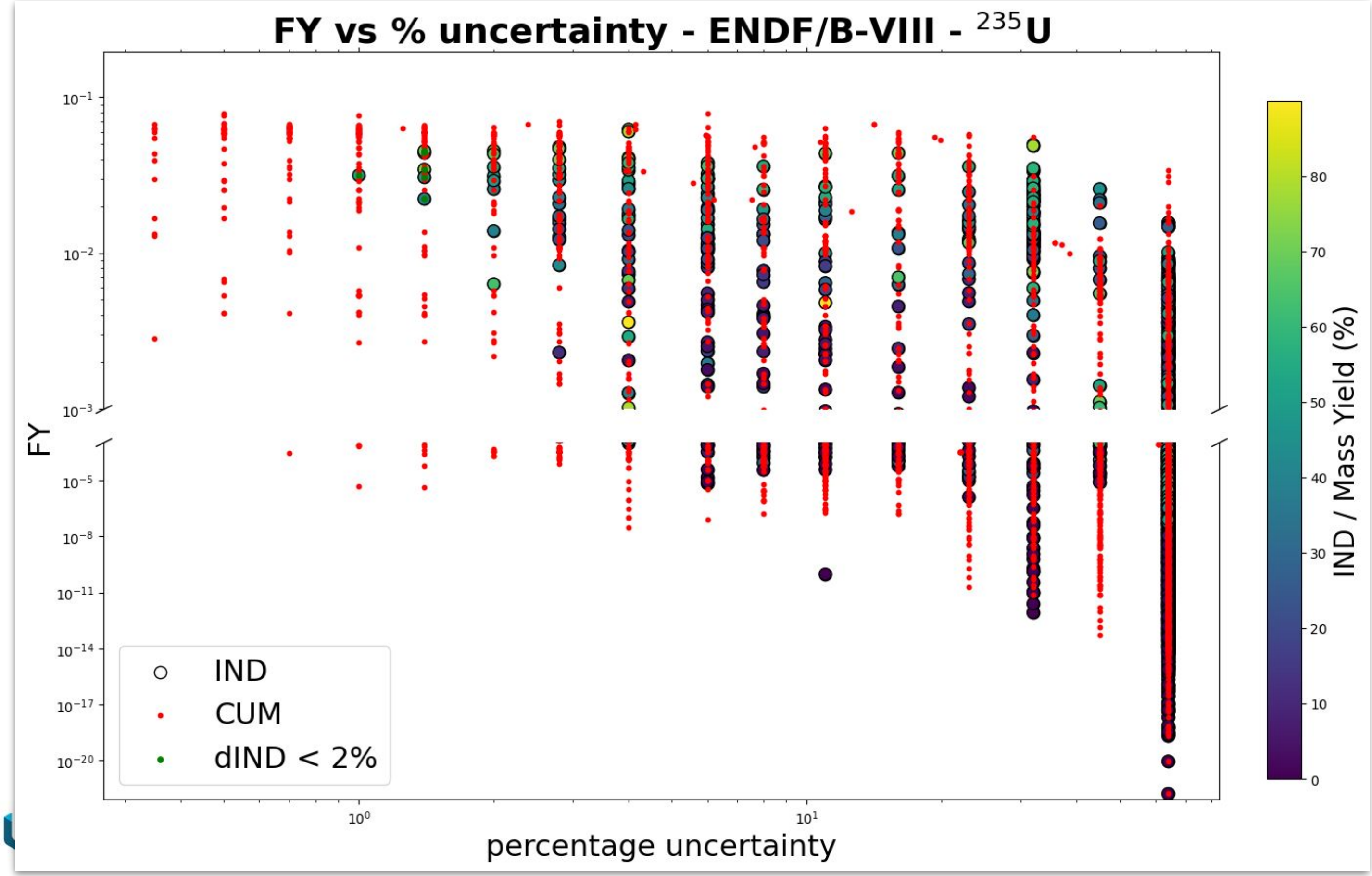
FY evaluations -- uncertainties



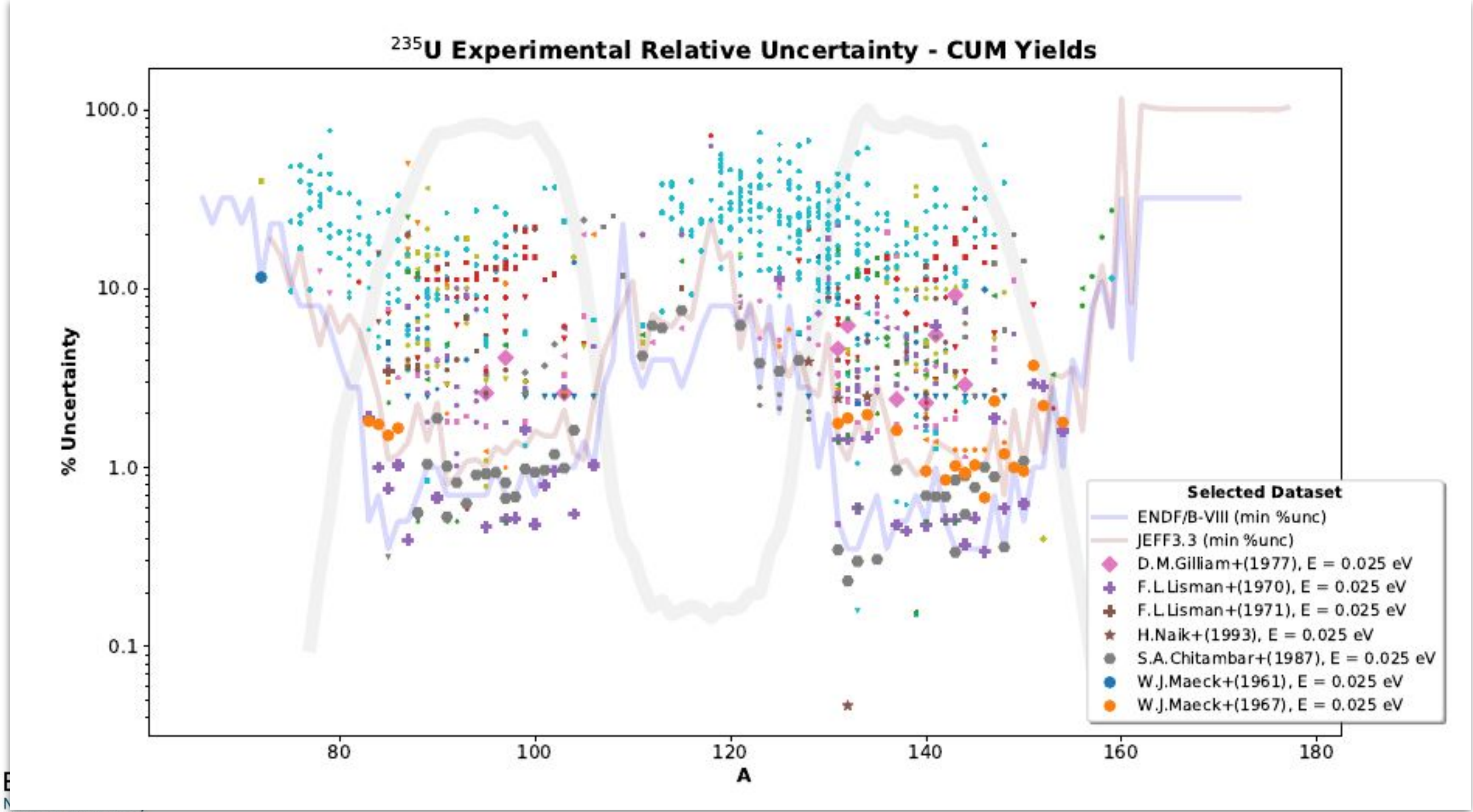
FY evaluations -- uncertainties



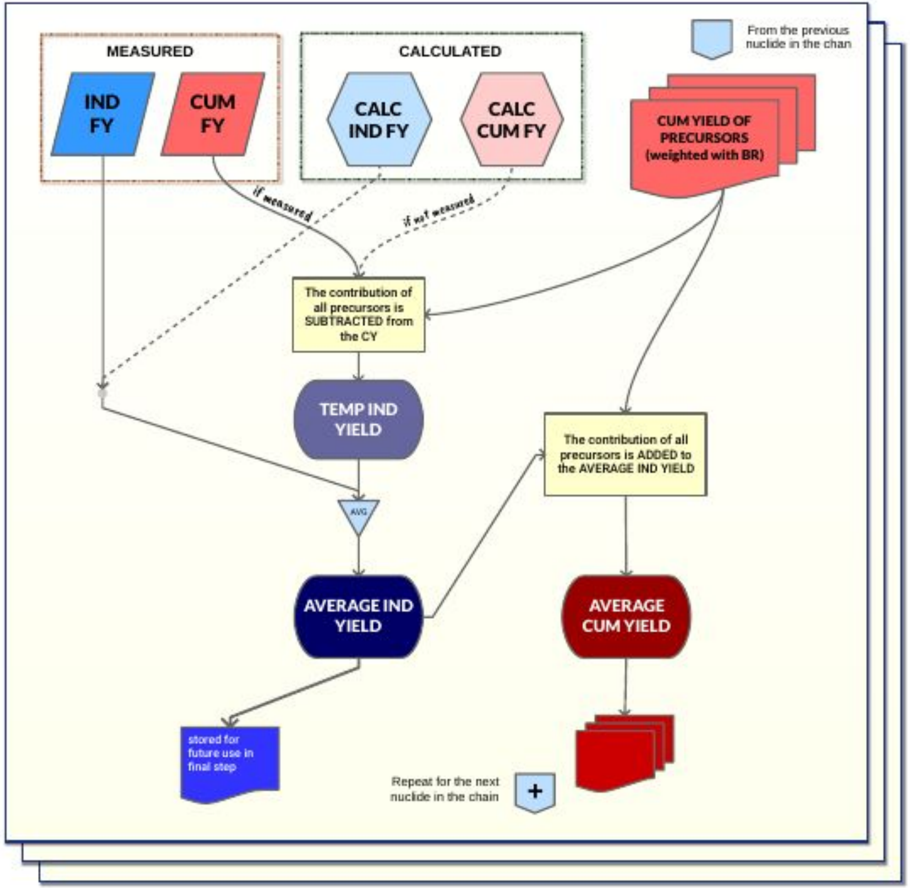
FY evaluations -- uncertainties



FY evaluations -- what's in there?



FY evaluations -- what's in there?

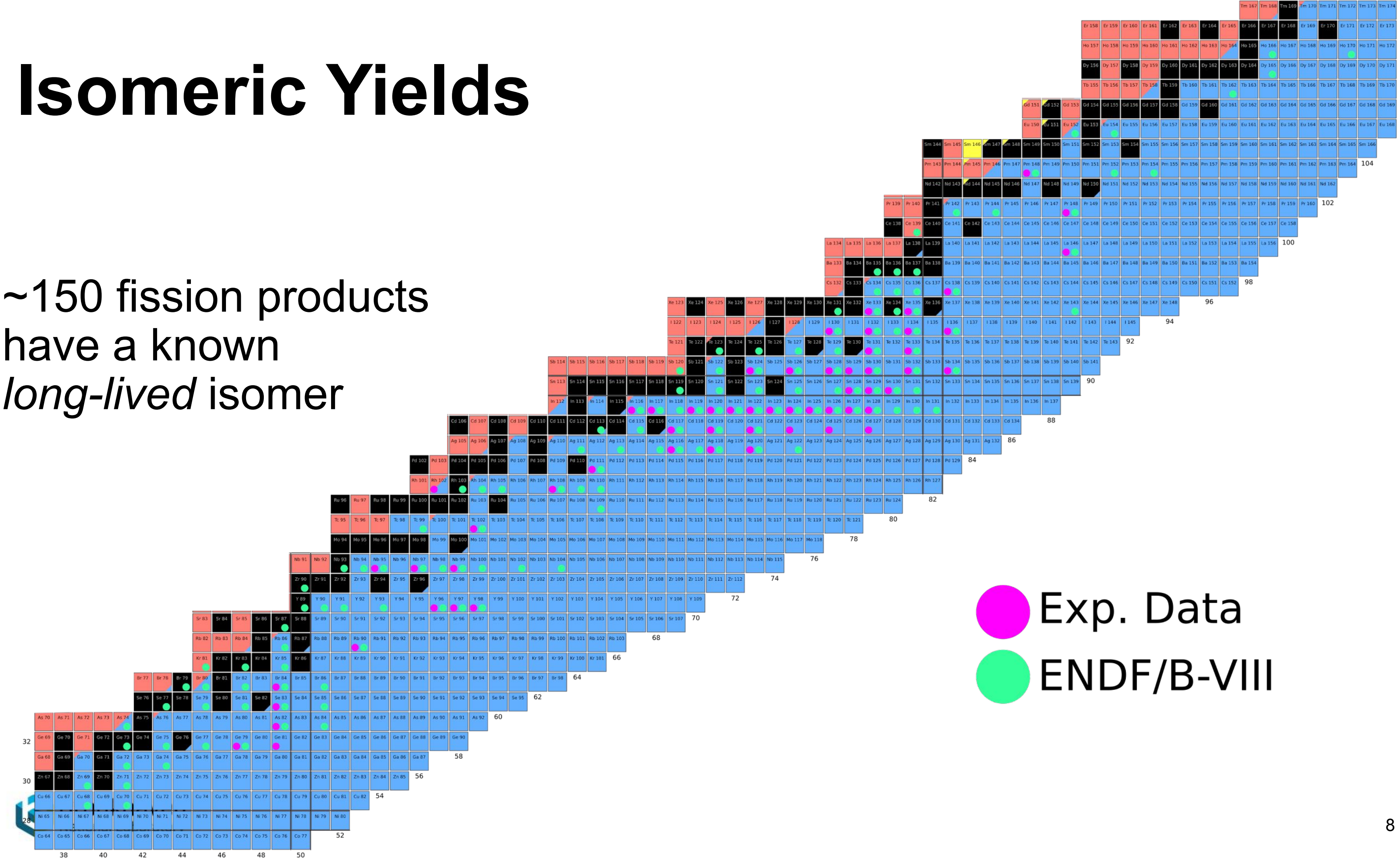


when no measurement is available, independent yields are obtained from Wahl charge-distribution model (errors ~ 32-100%, depending on the yield).

Evaluated yields are obtained normalizing the model prediction to the closest available data points → a large error was assumed in these cases.

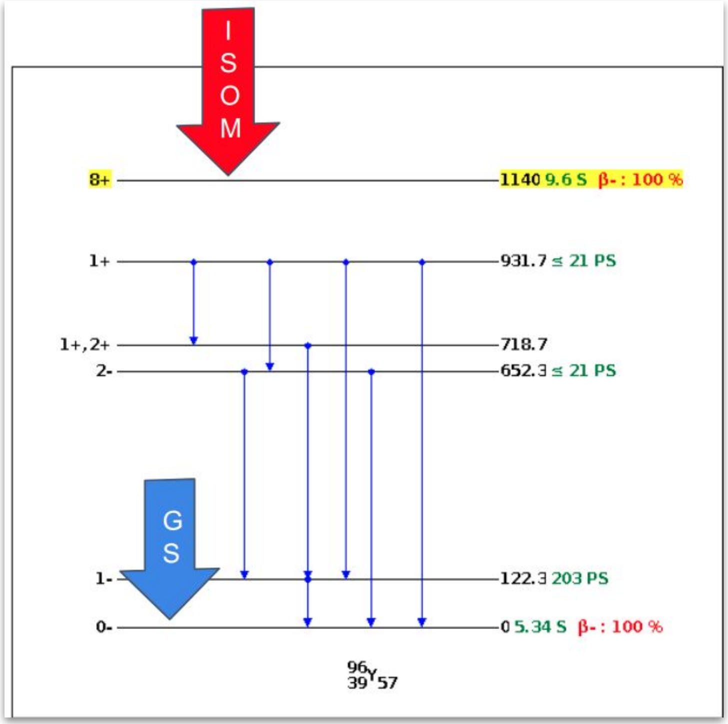
Isomeric Yields

~150 fission products have a known *long-lived* isomer



Isomeric Yield Ratios

- Fission Yields are a key component of the Summation Method
- **Isomeric Yield Ratios** represent another key component that is difficult to accurately predict, and must be based on experimental data.



$$IYR = \frac{Y_{isom}}{(Y_{isom} + Y_{gs})}$$

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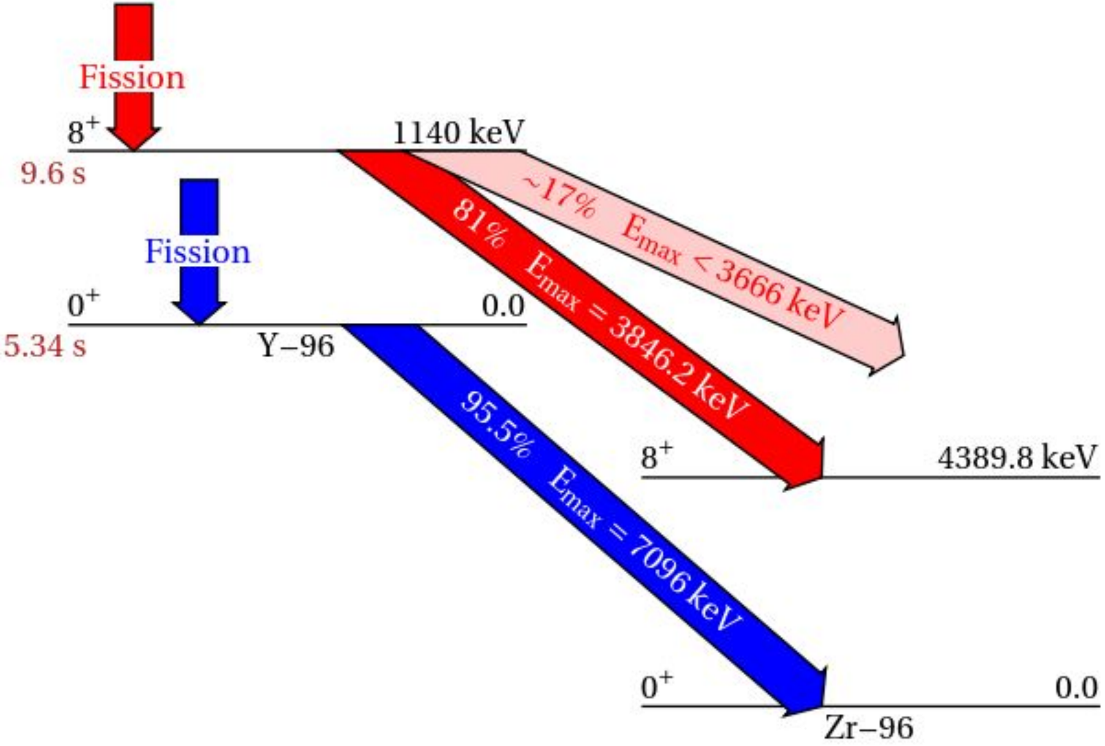
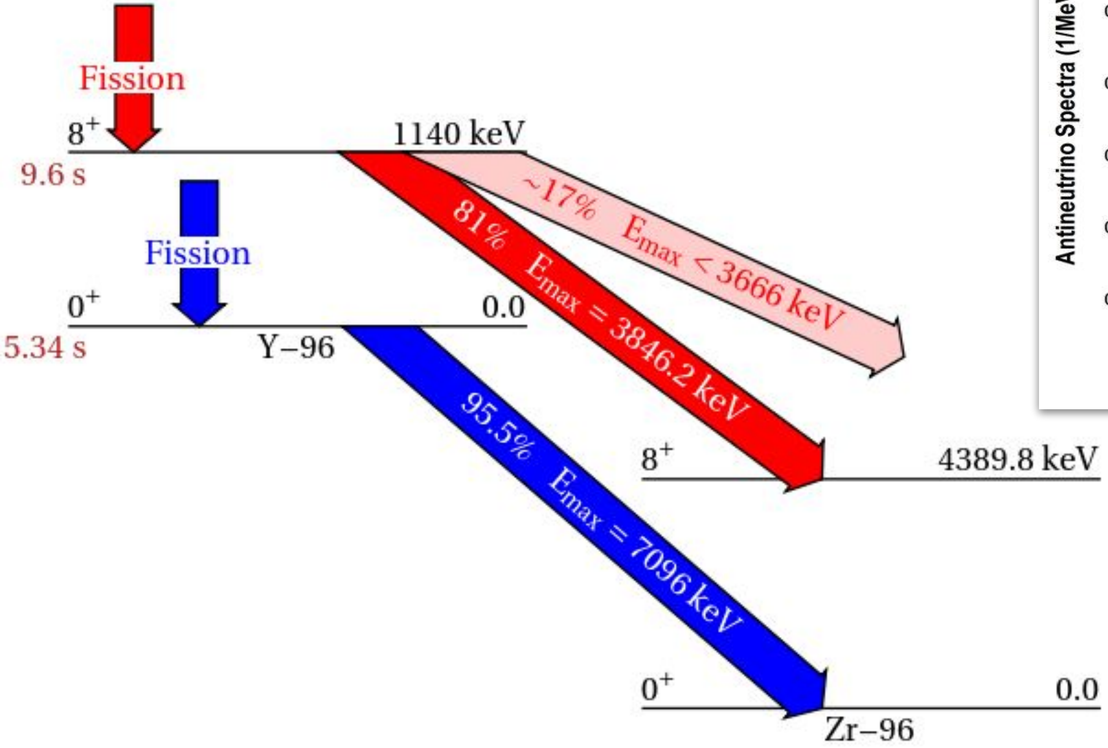
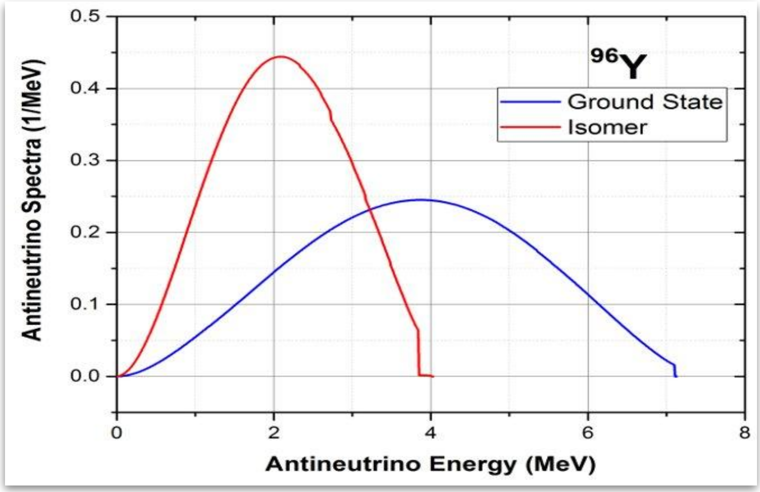
Isomers and antineutrino spectra



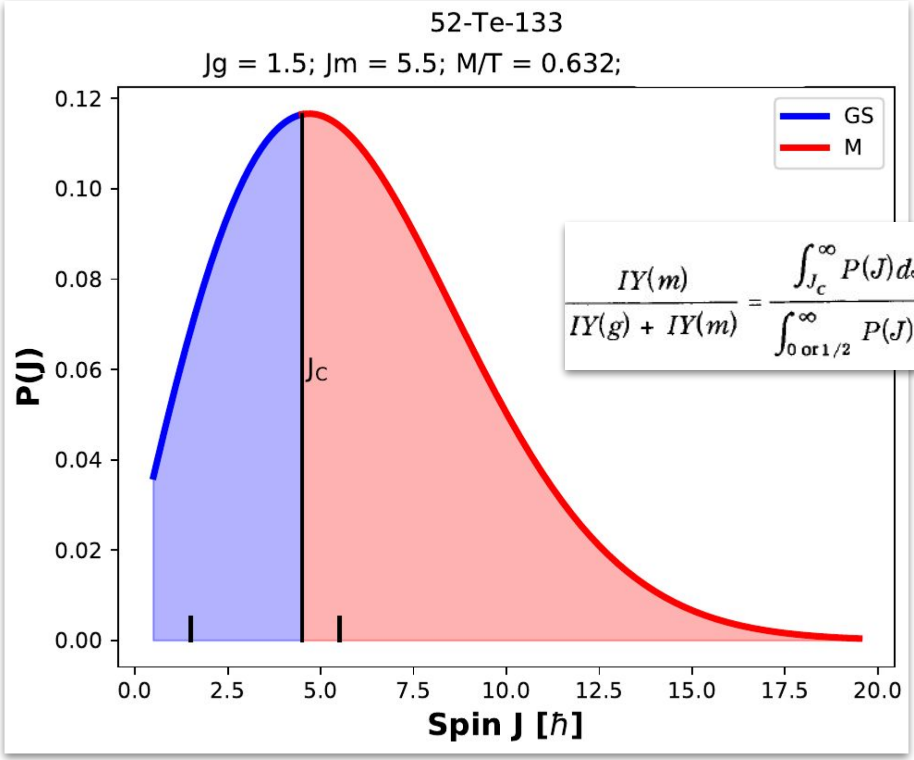
Isomers and antineutrino spectra





The importance of each curve is weighted by the yield that populates the G.S. or the isomer

IYRs in current FY evaluation



$$\frac{IY(m)}{IY(g) + IY(m)} = \frac{\int_{J_c}^{\infty} P(J)dJ}{\int_{0 \text{ or } 1/2}^{\infty} P(J)dJ}$$

NUCLEAR SCIENCE AND ENGINEERING: **64**, 859-865 (1977)

The Influence of Isomeric States on Independent Fission Product Yields

David G. Madland and Talmadge R. England

University of California, Los Alamos Scientific Laboratory, Theoretical Division
P. O. Box 1663, Los Alamos, New Mexico 87545

It predicts IYR with minimal information on the fission products:

- Isomeric ratio is split based on the J_g / J_m assuming a statistical P(J):

$$P(J) = P_0(2J + 1)\ \exp[-(J + \tfrac{1}{2})^2/\langle J^2\rangle]$$

- 1-parameter (J_{rms}) that fixes the P(J) distribution for **all** FFs

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Experimental Recommended IYRs

ELSEVIER

Available online at www.sciencedirect.com

ScienceDirect

Nuclear Data Sheets 173 (2021) 118–143

Nuclear Data Sheets

www.elsevier.com/locate/nds

Compilation and Evaluation of Isomeric Fission Yield Ratios

C.J. Sears,[1,2] A. Mattera,[1,*] E.A. McCutchan,[1] A.A. Sonzogni,[1] D.A. Brown,[1] and D. Potemkin[1,3,4]

[1] *National Nuclear Data Center, Brookhaven National Laboratory, Bldg. 817, P.O. Box 5000, Upton, NY 11973-5000*

[2] *Smith College, 10 Elm Street, Northampton, MA 01063*

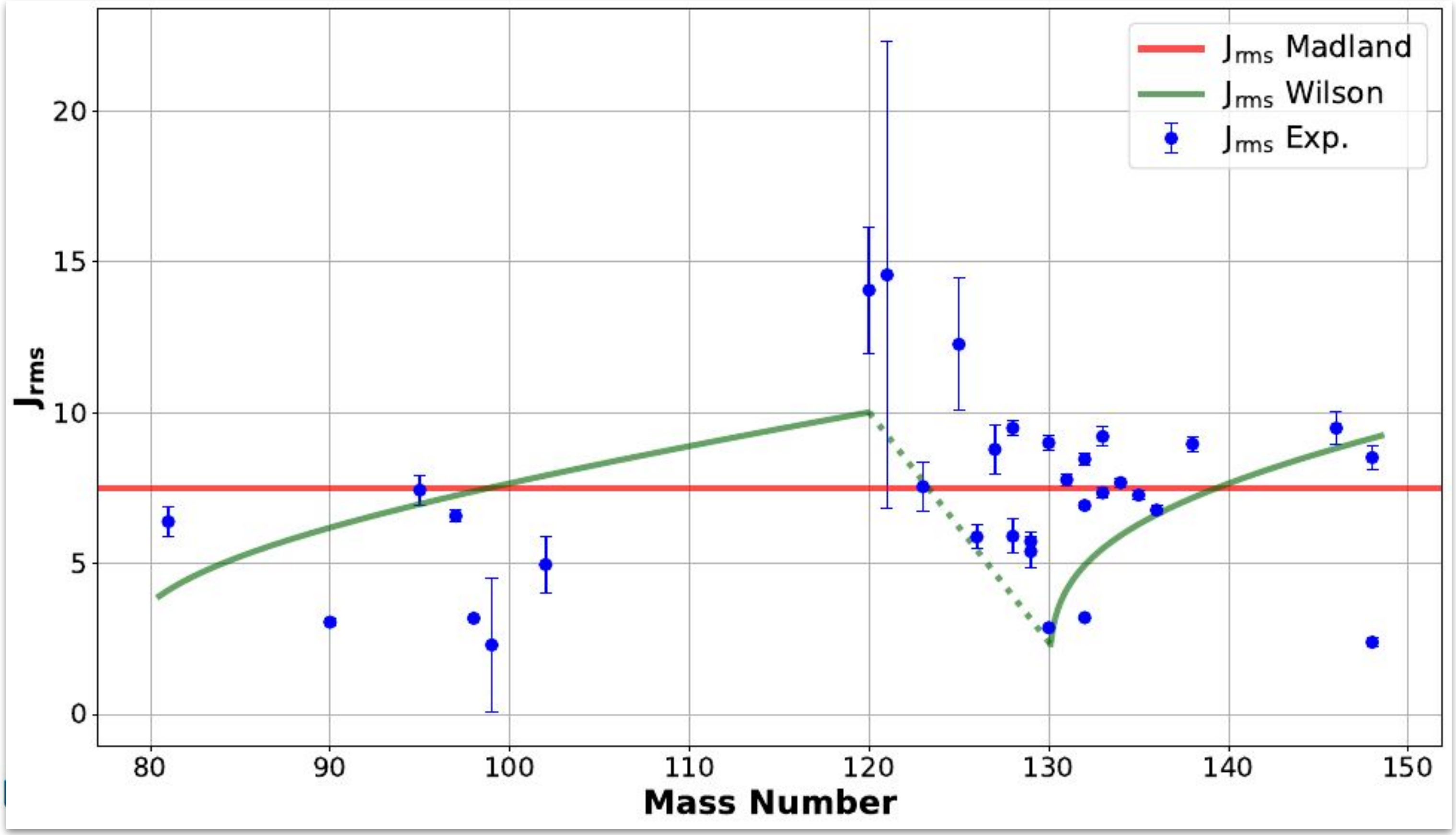
Id	Tgt Name	Proj Name	E_{inc} (MeV)	Fission Product Name	J_g	J_m	IYR (org)	Form	IYR (M/T)	EXFOR	Ref.	Notes
0	U-235	n	2.5×10^{-8}	32-Ge-79	1/2	7/2	0.8(10)	M/T	$[0 \cdots 1]$	22161	[31]	O
1	U-233	n	2.5×10^{-8}	32-Ge-81	9/2	1/2	0.24(7)	M/T	0.24(7)	22798	[34]	
2	U-235	n	2.5×10^{-8}	32-Ge-81	9/2	1/2	0.30(6)	M/T	0.30(6)	22161	[31]	
3	U-238	n	1	32-Ge-81	9/2	1/2	0.46(8)	M/T	0.46(8)	22334	[32]	
4	Th-232	p	25	32-Ge-81	9/2	1/2	0.920(20)	M/T	0.920(20)	O2429	[27]	
5	U-238	p	25	32-Ge-81	9/2	1/2	0.970(10)	M/T	0.970(10)	O2429	[27]	
6	U-238	p	25	32-Ge-81	9/2	1/2	0.975(7)	M/T	0.975(7)	O2395	[28]	
7	U-233	n	2.5×10^{-8}	33-As-82	2	5	0.13(8)	M/T	0.13(8)	22798	[34]	D
8	U-235	n	2.5×10^{-8}	33-As-82	2	5	0.17(7)	M/T	0.17(7)	22161	[31]	D
9	U-238	n	1	33-As-82	2	5	0.08(4)	M/T	0.08(4)	22334	[32]	D
10	U-238	p	24	33-As-82	2	5	0.270(30)	M/G	0.213(19)	E1855	[30]	
11	U-235	n	2.5×10^{-8}	34-Se-83	9/2	1/2	0.11(7)	M/T	0.11(7)	22161	[31]	
12	U-238	p	24	34-Se-83	9/2	1/2	8(4)	G/M	0.11(6)	E1855	[30]	
13	Th-232	γ	8.5	35-Br-84	2	6	0.28(4)	M/G	0.219(24)	G4028	[41]	
14	U-238	γ	8.5	35-Br-84	2	6	0.80(20)	M/G	0.44(6)	G4028	[41]	

TABLE II: Recommended IYR values for all low-energy (thermal to 2 MeV) n-induced fission reactions on any fissionable target. The recommended yield ratios are expressed in the M/T form. The number of data points in brackets represents the number of values excluded from the average because considered statistical outliers.

Fission Product	Recomm. IYR (M/T)	Nr. of data points
32-Ge-81	0.32(4)	3
34-Se-83	0.11(7)	1
37-Rb-90	0.526(30)	3 *(1)*
41-Nb-95	0.248(29)	1
39-Y-97	0.695(14)†	1
39-Y-98	0.139(6)	2
41-Nb-99	0.83(17)	1 *(1)*
45-Rh-102	0.44(14)	1
47-Ag-120	0.86(4)	2 *(1)*
49-In-120	0.21(20)	1
49-In-120 M2	0.27(25)	1
48-Cd-121	0.89(11)	1
49-In-122	0.24(10)	1
49-In-122 M2	0.48(20)	1
48-Cd-123	0.65(6)	2
49-In-123	0.07(7)	1
48-Cd-125	0.85(5)	2
49-In-126	0.30(5)	3
49-In-127	0.185(31)	3
49-In-128	0.30(7)	1
51-Sb-128	0.463(16)†	14
49-In-129	0.42(6)	2
50-Sn-129	0.47(4)	3
49-In-130	0.25(5)	1
49-In-130 M2	0.41(7)	1
50-Sn-130	0.089(7)	4
51-Sb-130	0.499(17)†	18

†: uncertainty recalculated from statistical value to reflect possible systematic sources (see text for details).

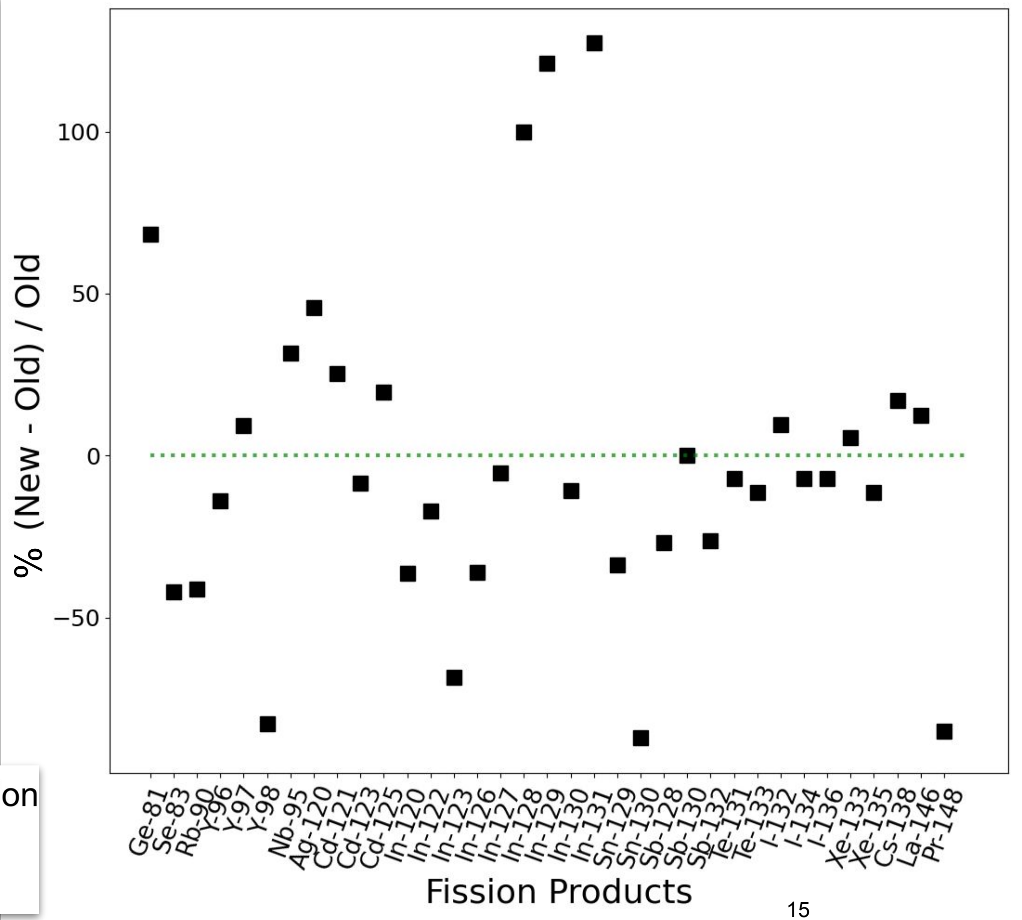
J_{rms} is not constant - M&E model is too simplistic



Evaluated IYRs

- of the ~150 isomeric yields that are included in the ND libraries, 42 have exp. data at low energy.

- In about half the cases where data is available, the libraries contain a value that doesn't agree with the measurements



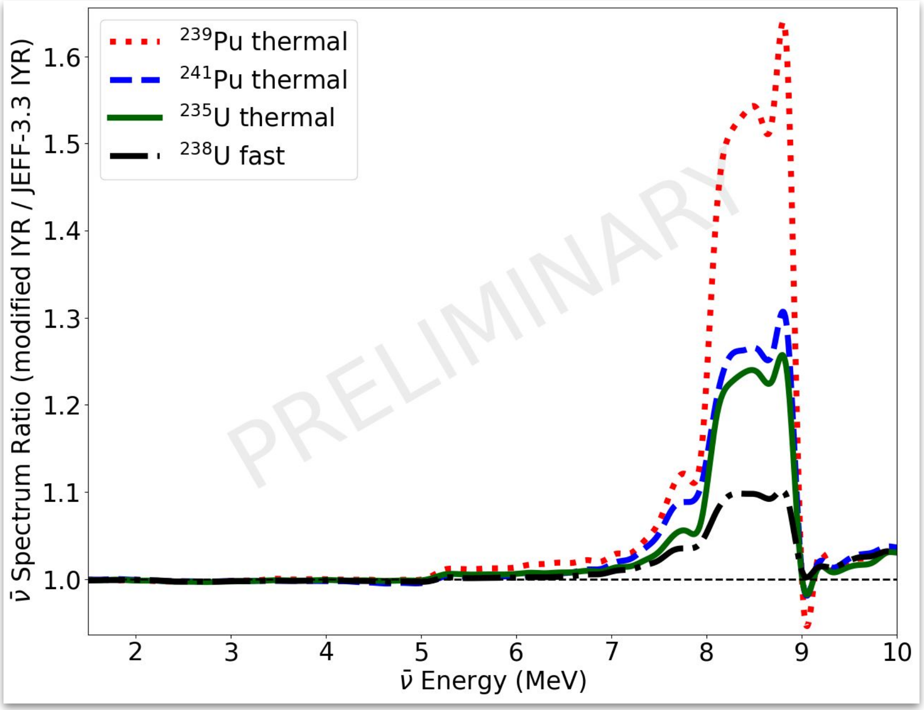
Sears, C.J., et al. "Compilation and Evaluation of Isomeric Fission Yield Ratios." Nuclear Data Sheets 173 (2021): 118-143.

Impact of experimental values on anti-ν spectra

- Spectrum shown as a ratio of the benchmark (JEFF-3.3 yields and IYRs)
- Virtually no difference below 5 MeV
- Overall increase elsewhere:

  up to + 5% at 6 MeV

  up to +60% at 8 MeV



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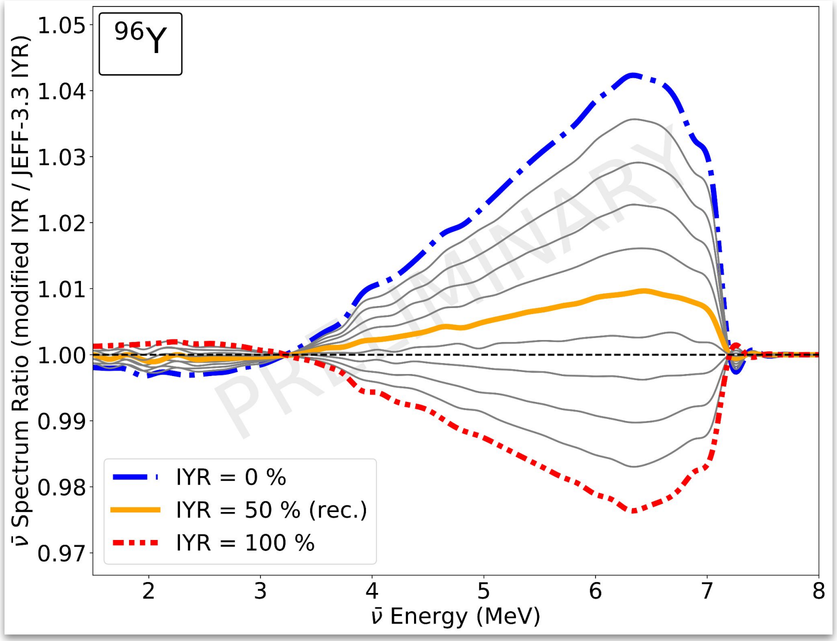
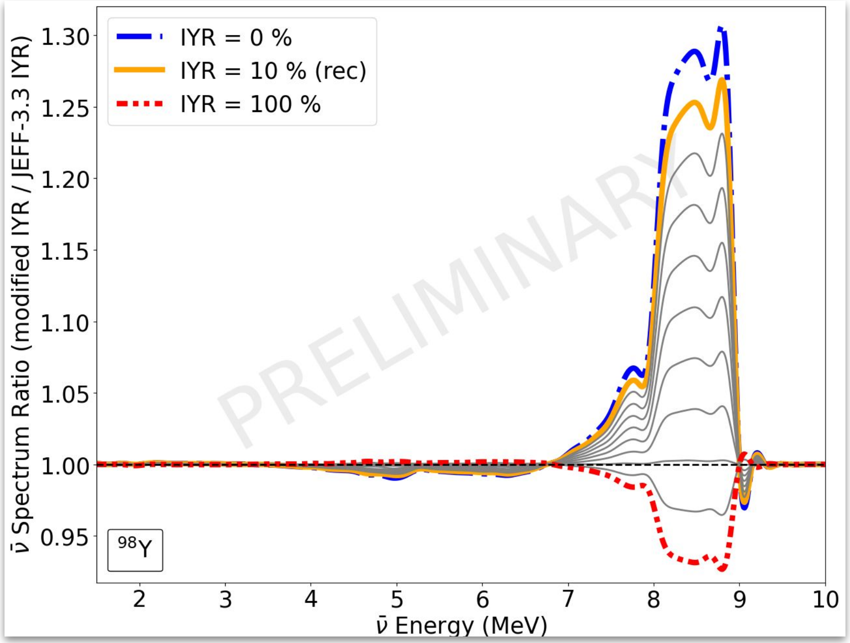
Some isomers are more equal than others...





IYR_{th} = 65% → IYR_{exp} = 50 %
CFY ≈ 5 %

IYR_{th} = 81% → IYR_{exp} = 14 %
CFY ≈ 3 %

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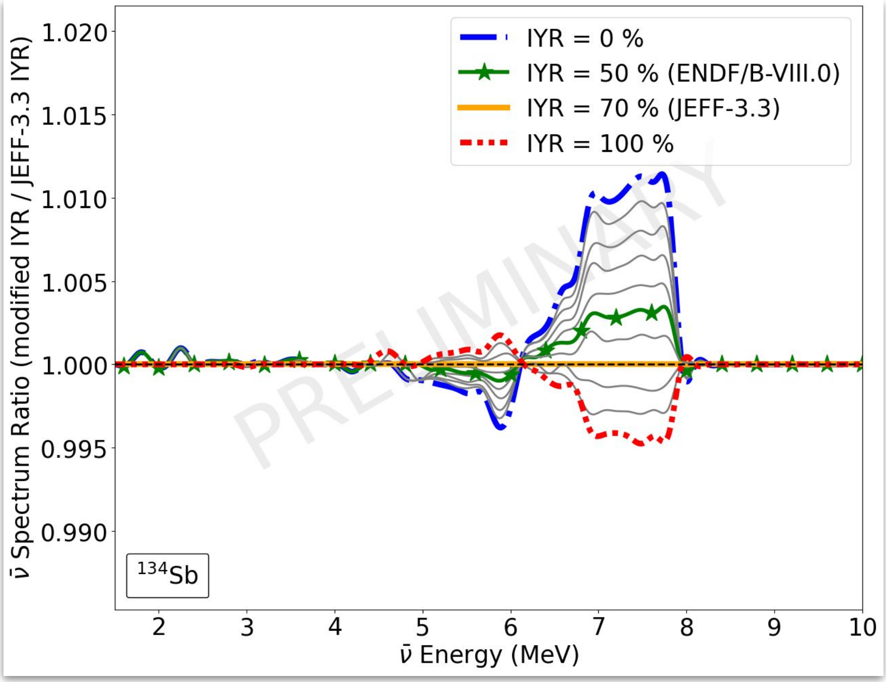
A broader sensitivity study

- Analysis of all fission products with a known isomer included in ENDF (many without published IYR data)
- Varied the value within physical boundaries
- Identified a fission products whose IYR affects the antineutrino spectra (e.g., Sb-134, Nb-100, La-146, Rb-90)



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Summary and Outlook

- New evaluated isomeric ratios result in an **increased antineutrino flux** compared to the current FY libraries **up to 60%** for specific energies and fissile targets.
- Experimental data on IYRs exist only for a fraction of the fission products
- A sensitivity study shows that **a number of other isomers could** considerably **affect the antineutrino spectrum**, especially at high energies

Impact of isomeric yield ratios on reactor antineutrino spectra

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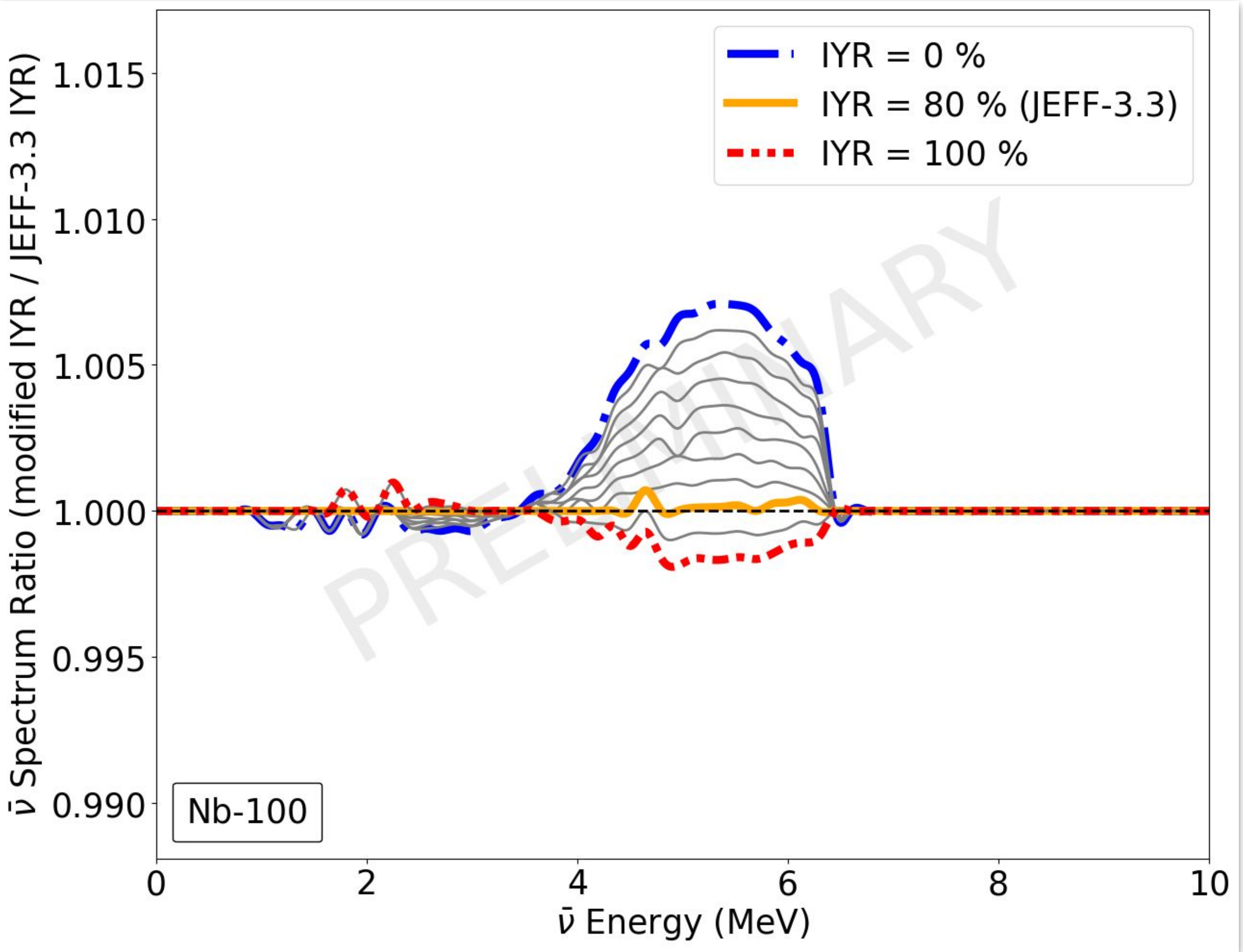

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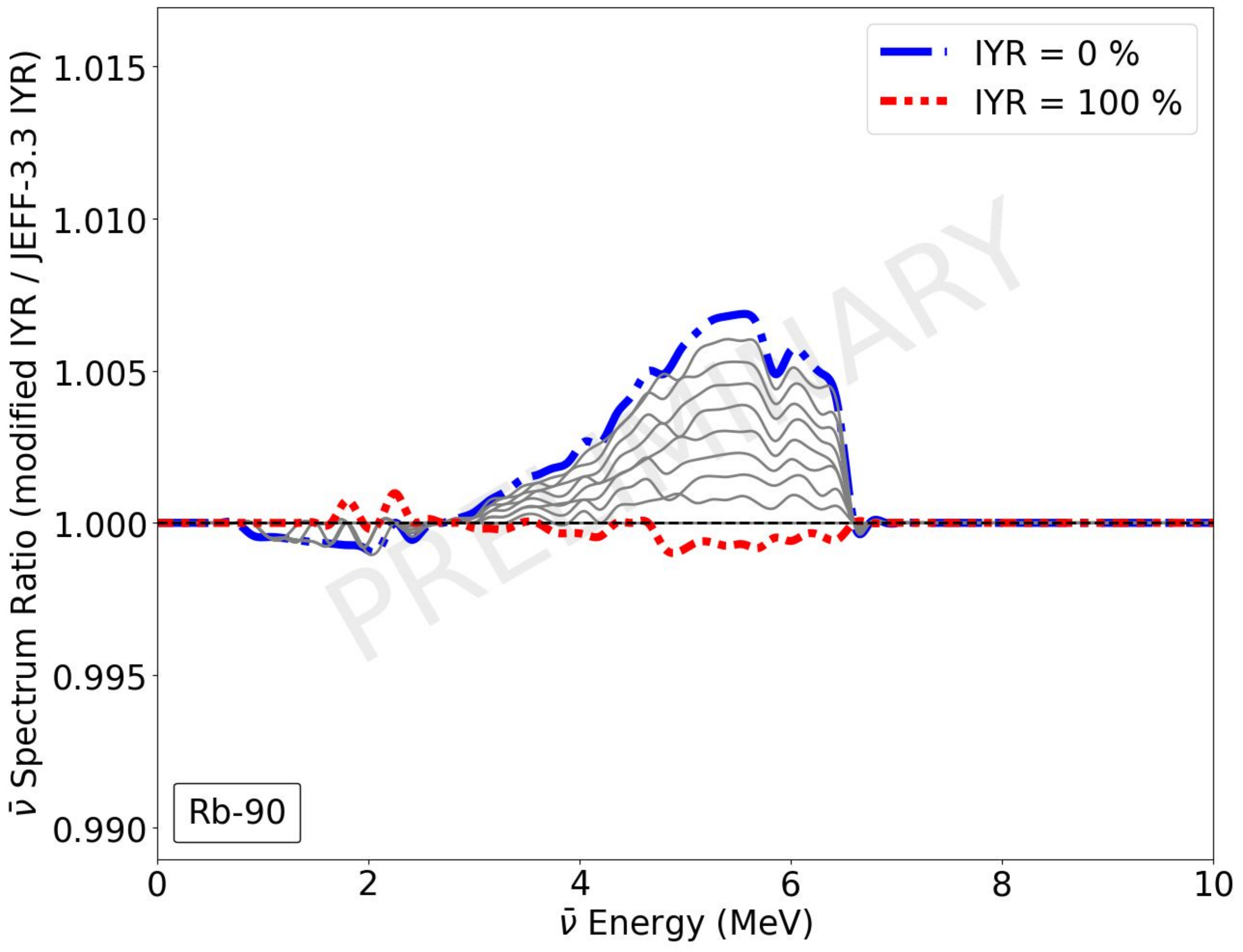
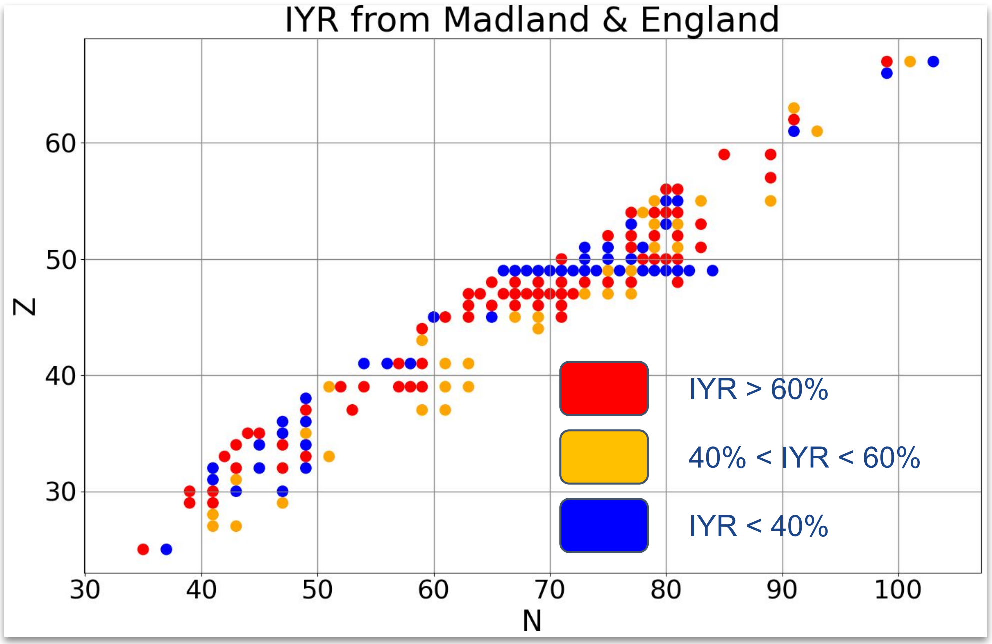

IYR = 0 %
IYR = 100 %
PRELIMINARY
Rb-90
$\bar{\nu}$ Spectrum Ratio (modified IYR / JEFF-3.3 IYR)
1.015
1.010
1.005
1.000
0.995
0.990
0
2
4
6
8
10
$\bar{\nu}$ Energy (MeV)

Evaluation of Isomeric Yield Ratios

- There are ~200 fission products with a known long-lived isomer

$$IYR = \frac{Y_{isom}}{(Y_{isom} + Y_{gs})}$$

- The Madland & England model, loosely based on data from 40 yrs ago, is **used in all evaluated data libraries** as the basis to split Independent FYs between the GS and the IS based on the levels J_{rms}



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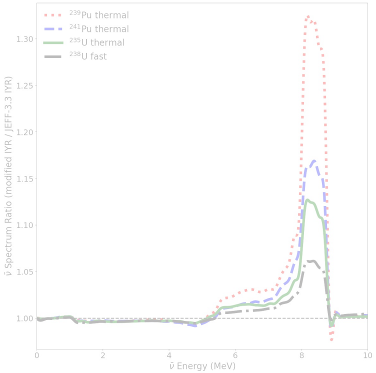
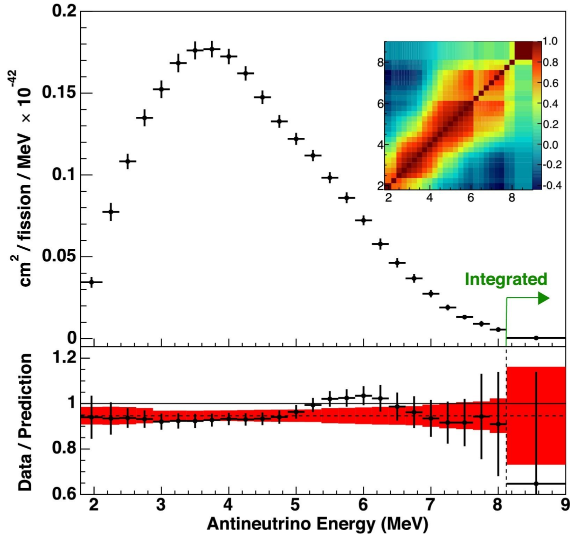
Outline

- The “bump” in antineutrino spectra
- Fission yields and isomers in antineutrino summation calculations
- Impact of newly evaluated recommended isomeric yields
- A broader sensitivity study
- Outlook



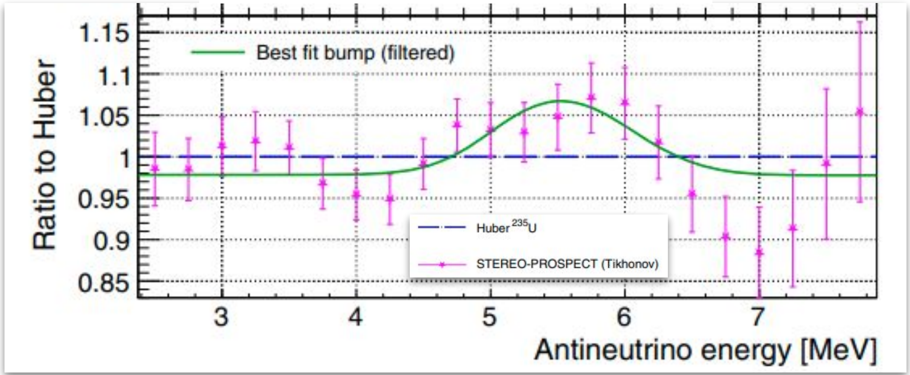
Reactor antineutrino spectra and "the bump"

- km-baseline experiments measured the antineutrinos from β⁻-decay of fission products
- 5% deficit of the total number of antineutrinos (RAA)
- Excess of antineutrinos between 5-6 MeV → "The Bump"



Cao, Jun, and Kam-Biu Luk. "An overview of the Daya Bay reactor neutrino experiment." *Nuclear Physics B* 908 (2016): 62-73.

PHYSICAL REVIEW LETTERS 128, 081802 (2022)



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