Nuclear Data Needs for Interpreting Reactor Antineutrino Signals

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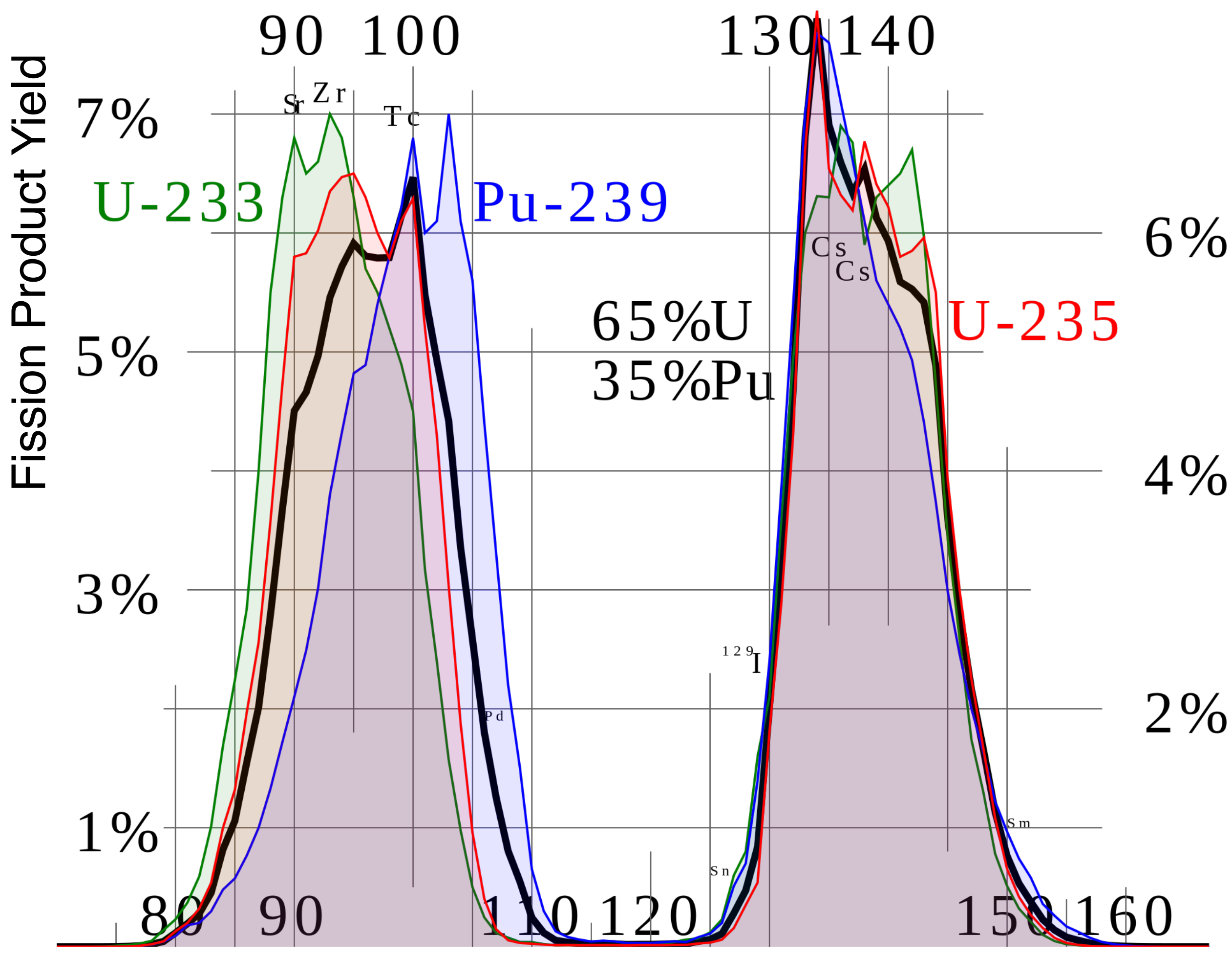
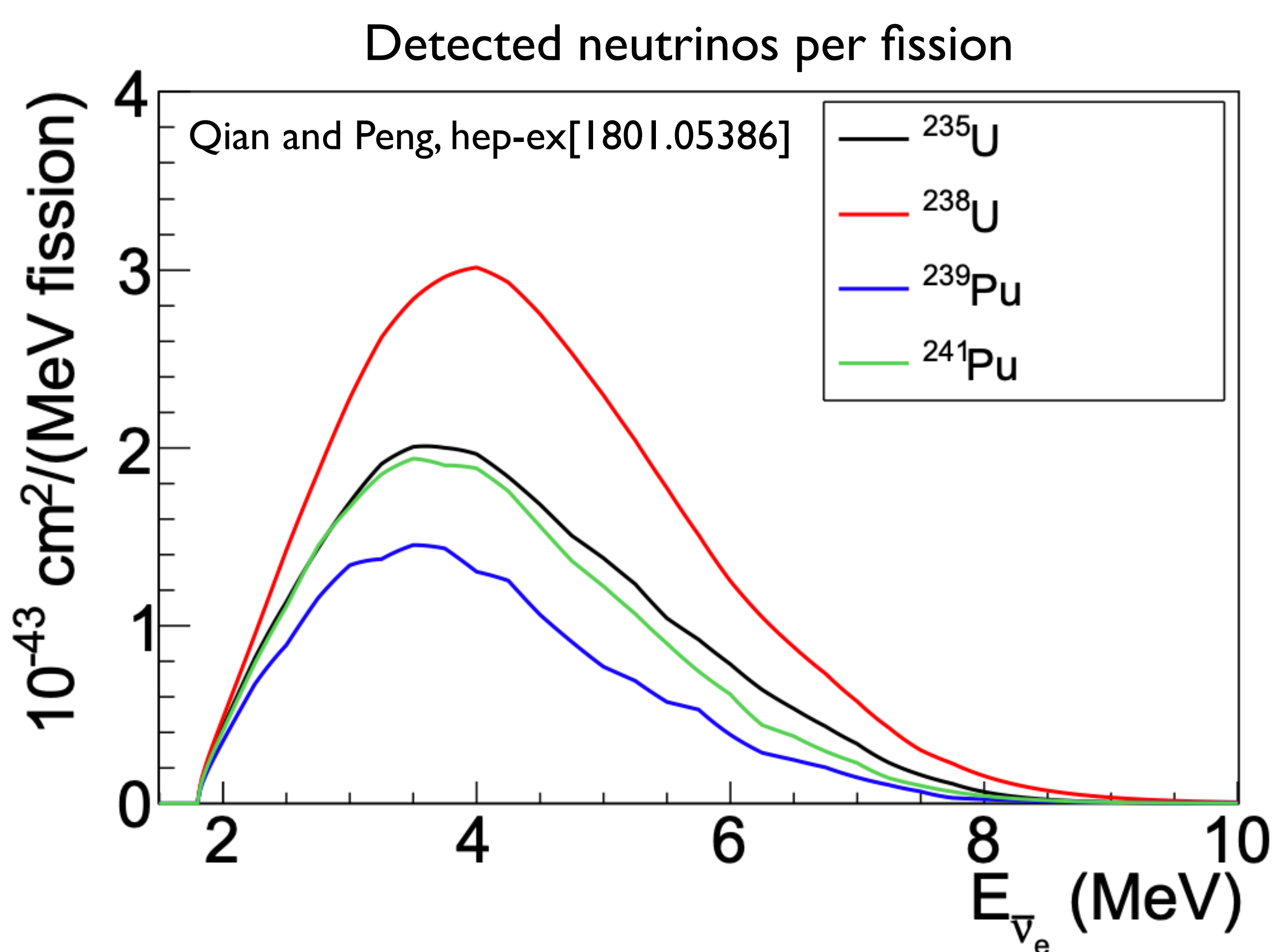
Differing Yields = Differing Neutrinos

- Semi-unique fission yields generate distinct neutrino fluxes and energy profiles for each fission isotope.
- Neutrinos easily escape the reactor vessel and present a promising target for remote monitoring.
    - Reactor fission rates (i.e: thermal power)
    - Reactor core content (i.e: how much plutonium)

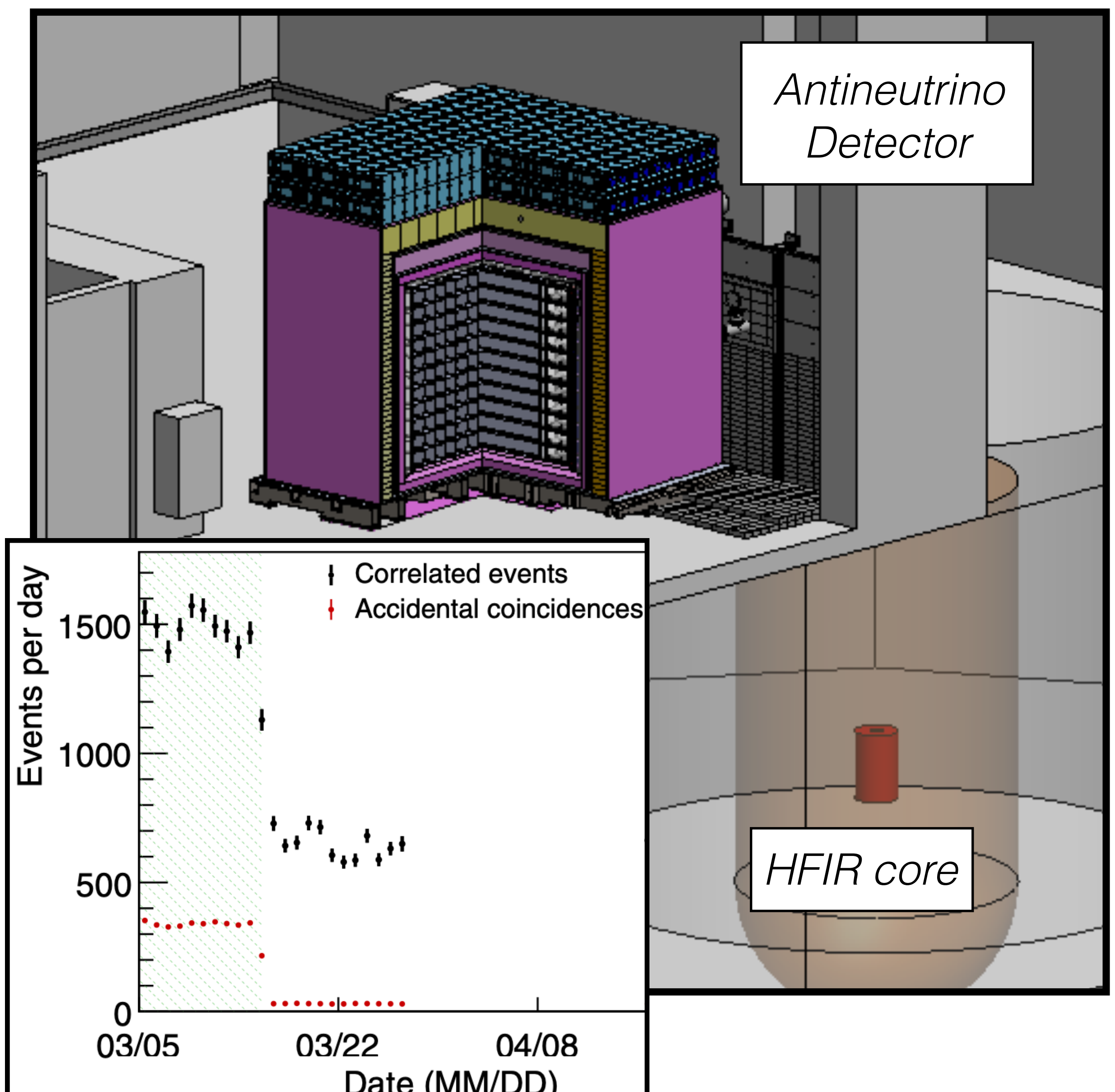


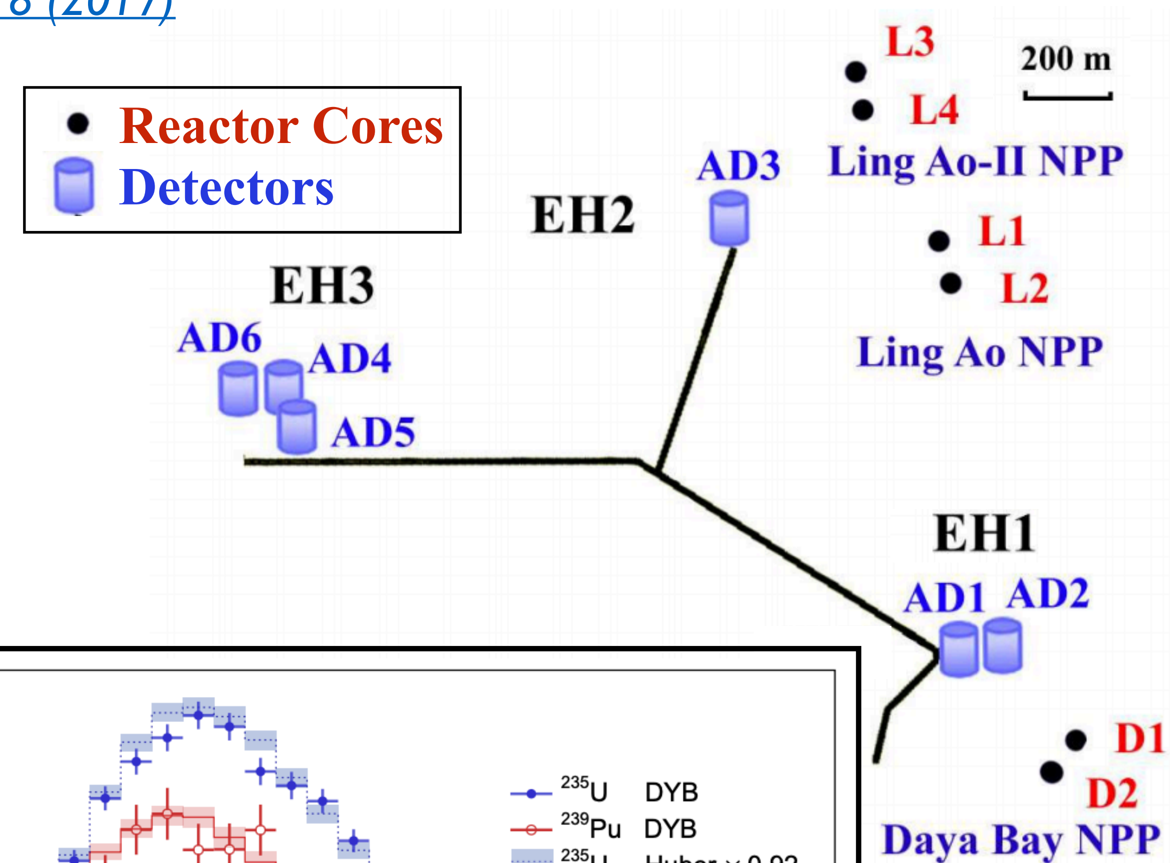
Wikipedia

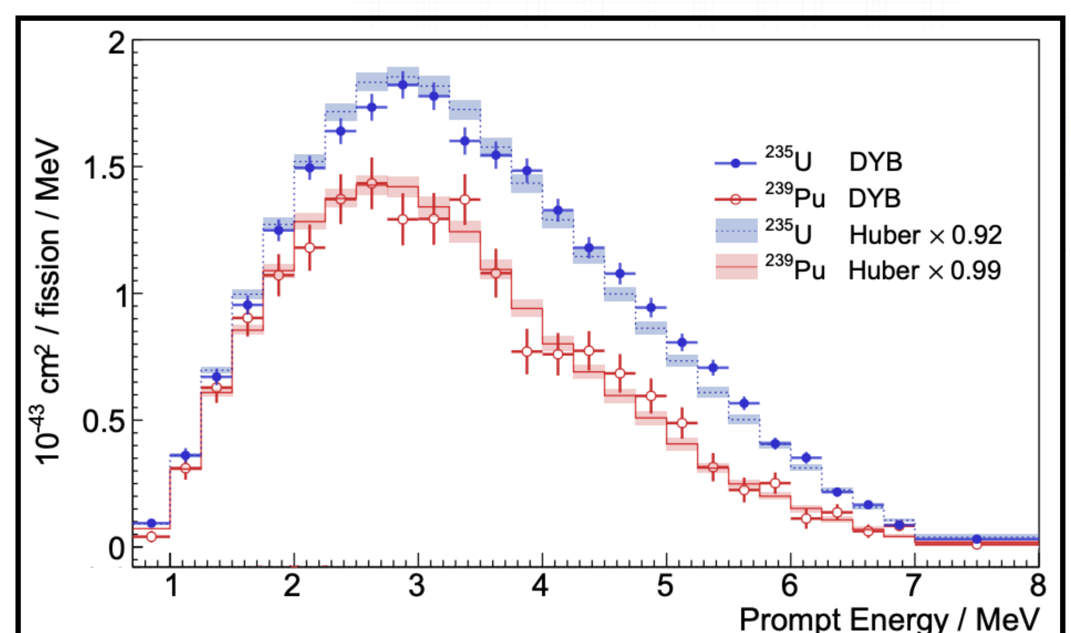


Neutrino-Based Monitoring Validations

- Existing experiments have validated feasibility of this approach.
  - PROSPECT: demonstrated percent-level daily reactor power load following with an on-surface 4 ton scintillator detector PROSPECT, PRL 121 (2018)
  - Daya Bay: directly measured changes in neutrino flux/energy associated with fuel burn-up Daya Bay, PRL 123 (2019); PRL 118 (2017)



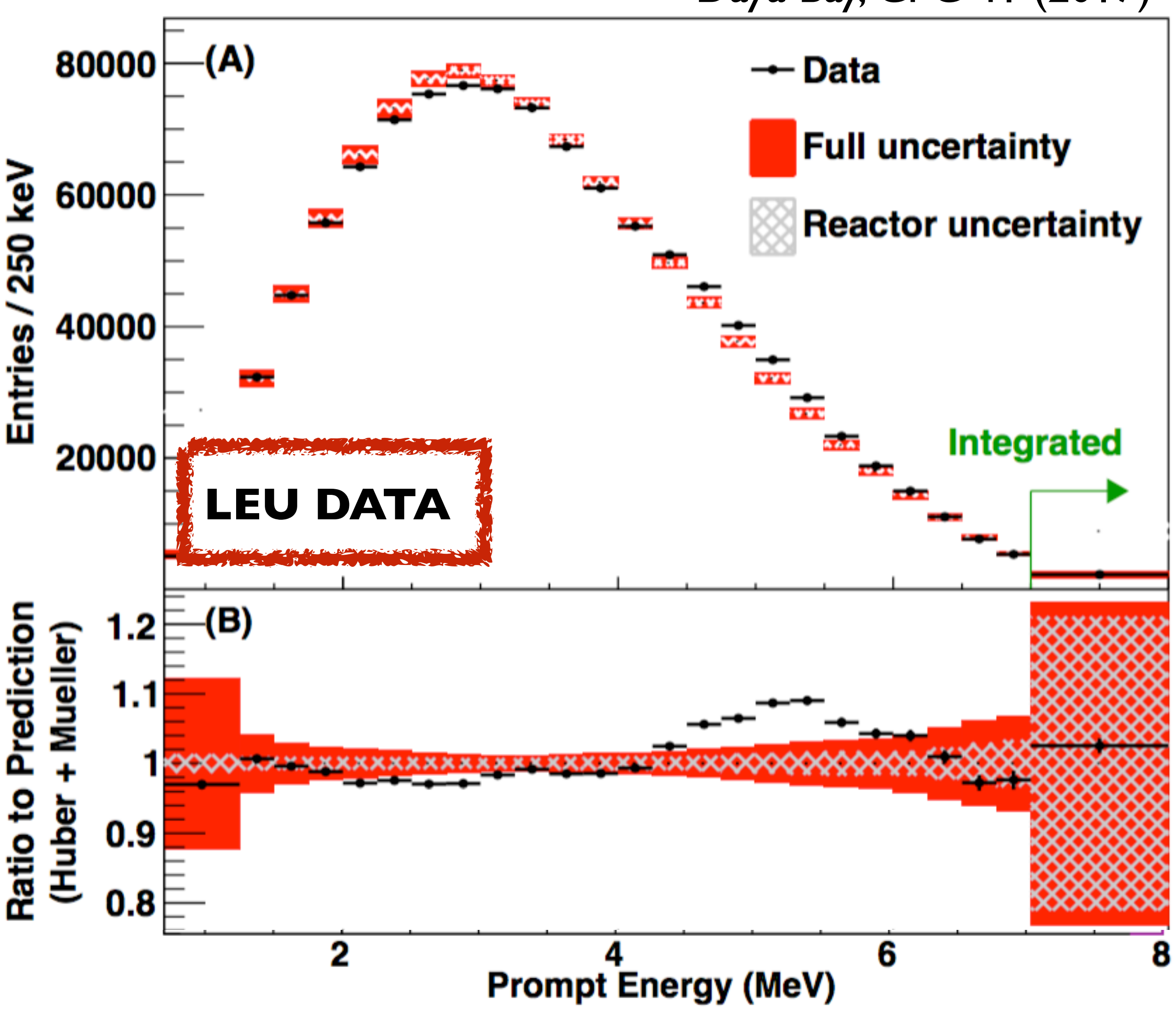




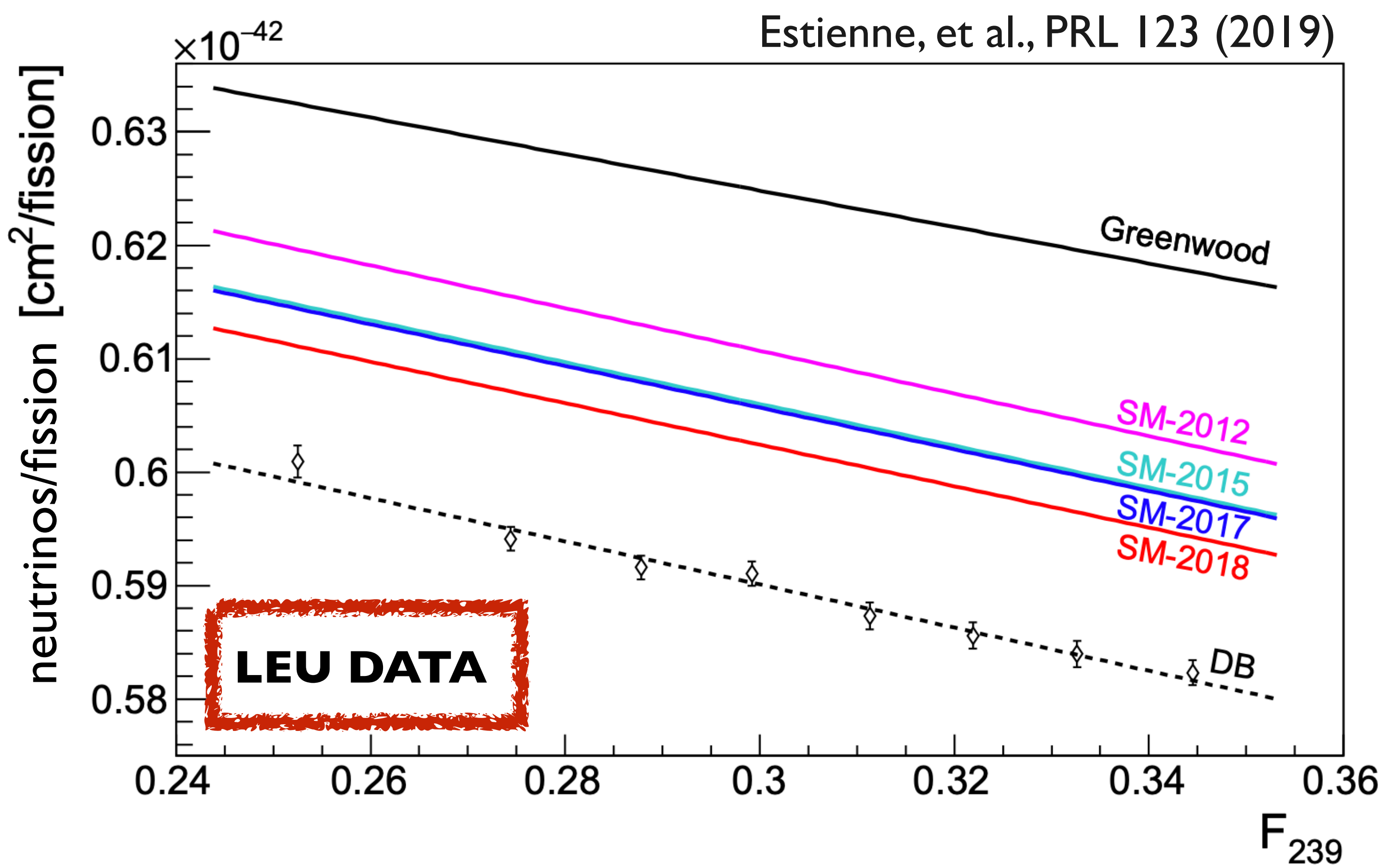
Interpreting Data: Current Limitations

- Better understanding of isotopic neutrino yields/spectra is required to achieve useful, reliable monitoring capabilities.
    - Models of antineutrino production — based on standard nuclear databases — fail to reproduce measured neutrino rates and energy spectra
    - Direct neutrino-based calibration of per-isotope fluxes and spectra is limited in precision by the lack of diversity in existing high-stats neutrino datasets

Daya Bay, CPC 41 (2017)



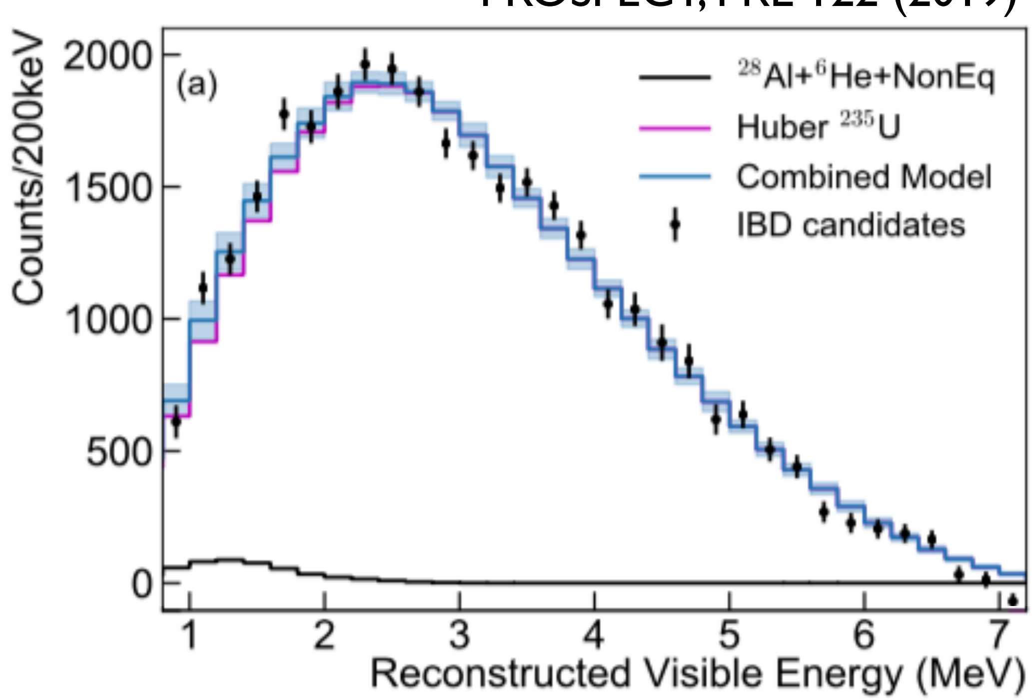
Estienne, et al., PRL 123 (2019)



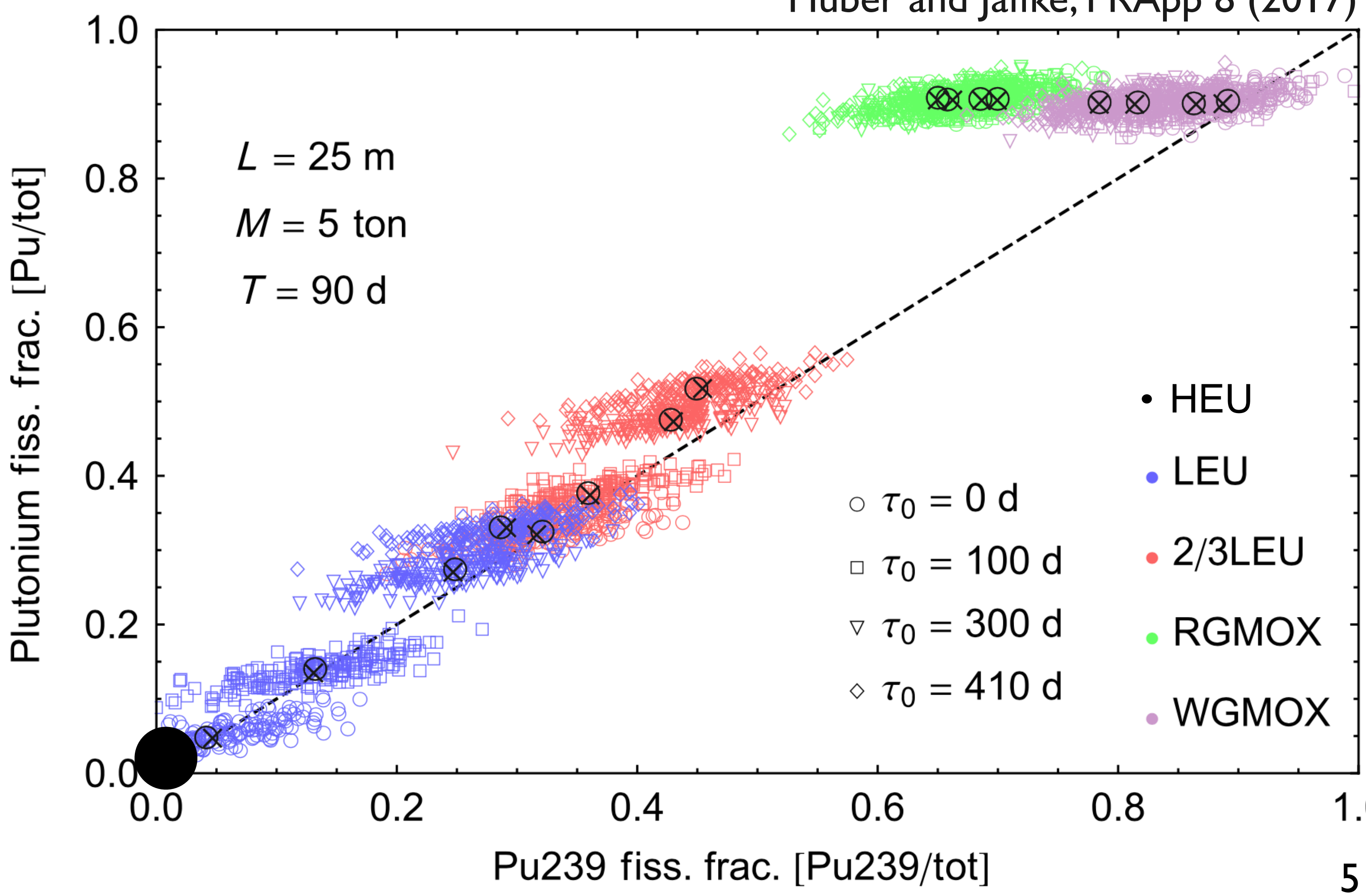
Future Measurements: Neutrinos

- A broad range of measurements can help address these issues.
- Neutrino side:
  - Higher-statistics datasets from reactors of more widely varying fuel content
    - **HEU** and single-core full-cycle **LEU** measurements with existing, future detectors
    - Detailed study of hypothetical future measurements at **MOX** reactors
  - Self-consistent comparisons between existing **HEU** and **LEU** datasets

PROSPECT, PRL 122 (2019)



Huber and Jaffke, PRApp 8 (2017)

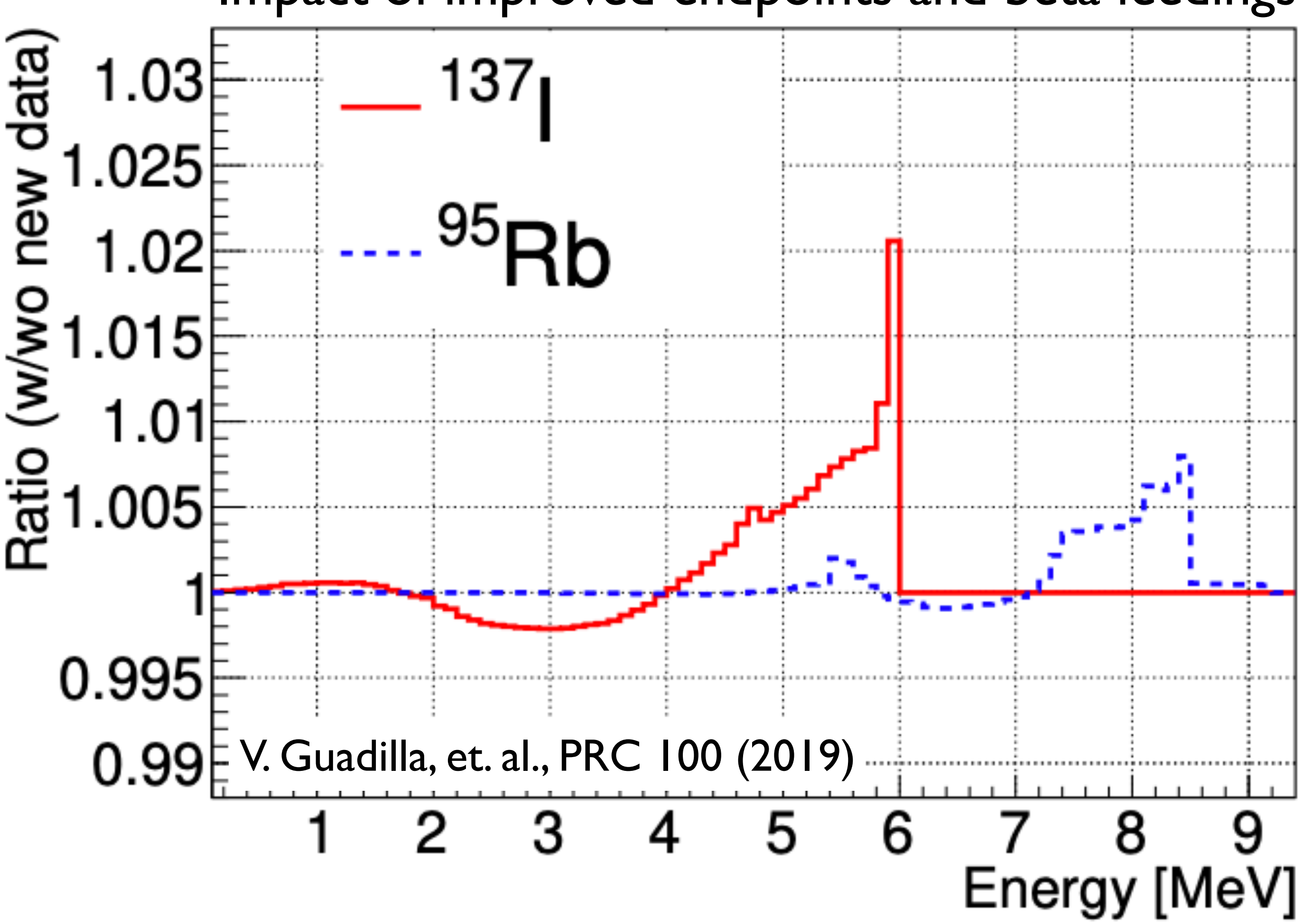


Future Measurements: Nuclear Physics

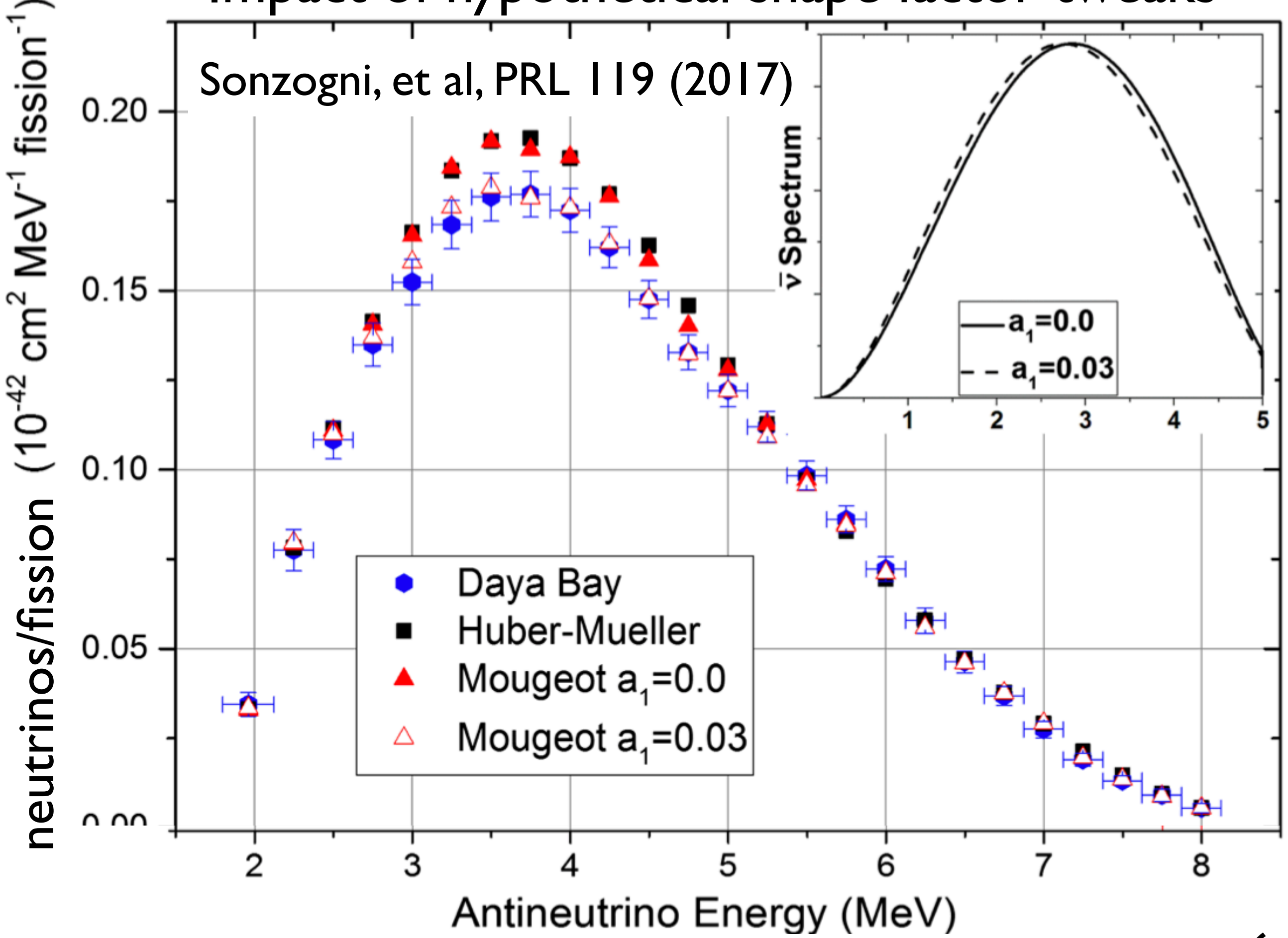
- **A broad range of measurements can help address these issues.**
- Nuclear physics measurements side:
  - Improved fission yield, beta feeding, and beta shape factor measurements
  - Fission delayed gamma spectrum measurements
  - Improved description of nuclear data uncertainties

Previous FOAs have focused on some of these items; more data is needed though!

Impact of improved endpoints and beta feedings



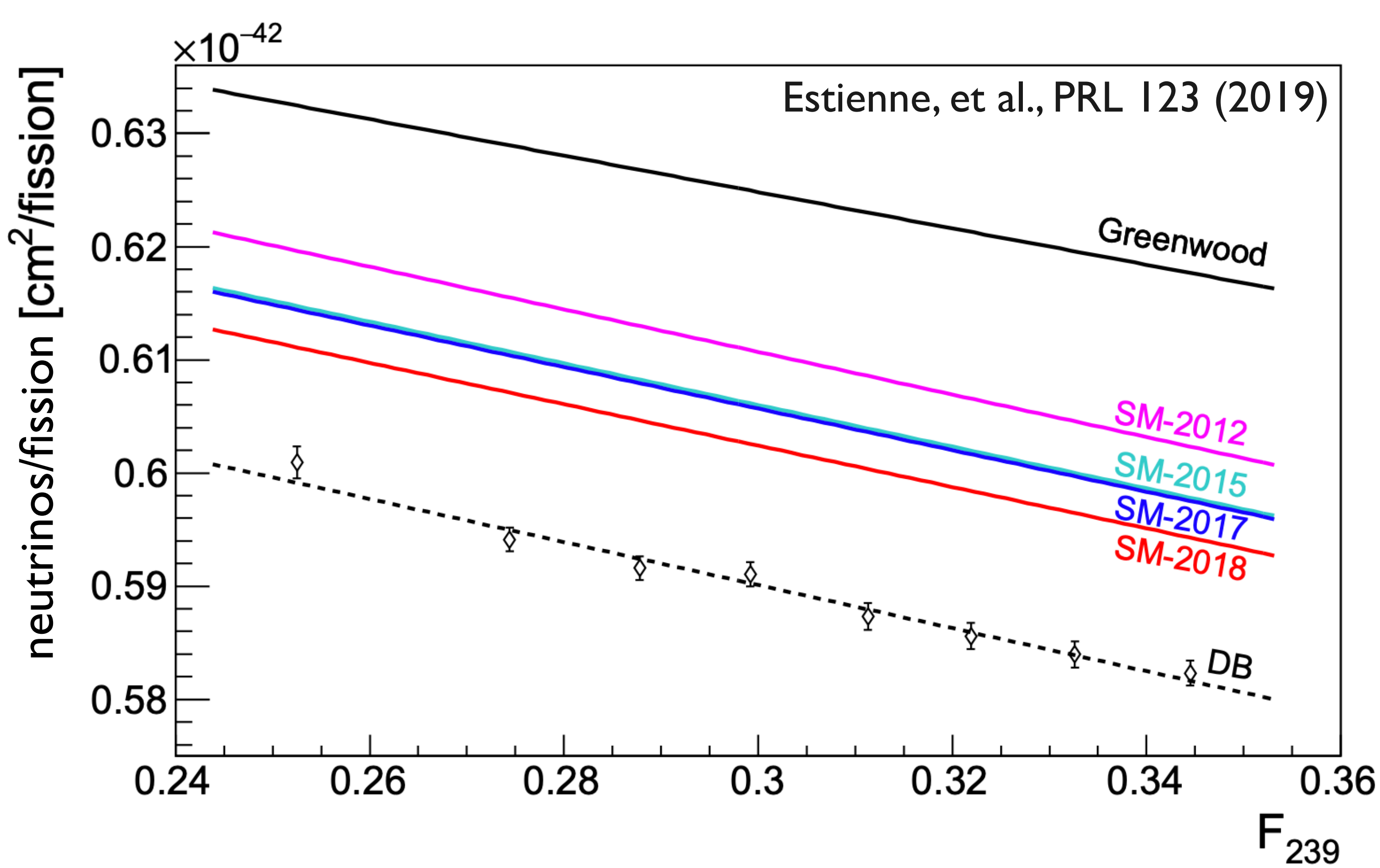
Impact of hypothetical shape factor tweaks



Synergies With Nuclear Data

- Matching increasingly precise neutrino data to improved reactor models can be an iterative, mutually beneficial process
    - **Better modeling and nuclear data** enables precise neutrino monitoring, better understanding of reactor neutrino properties
    - **Better neutrino data** enables new probes of weak points in existing nuclear datasets, robust assessment of new nuclear data measurements.

THANKS!



Backups

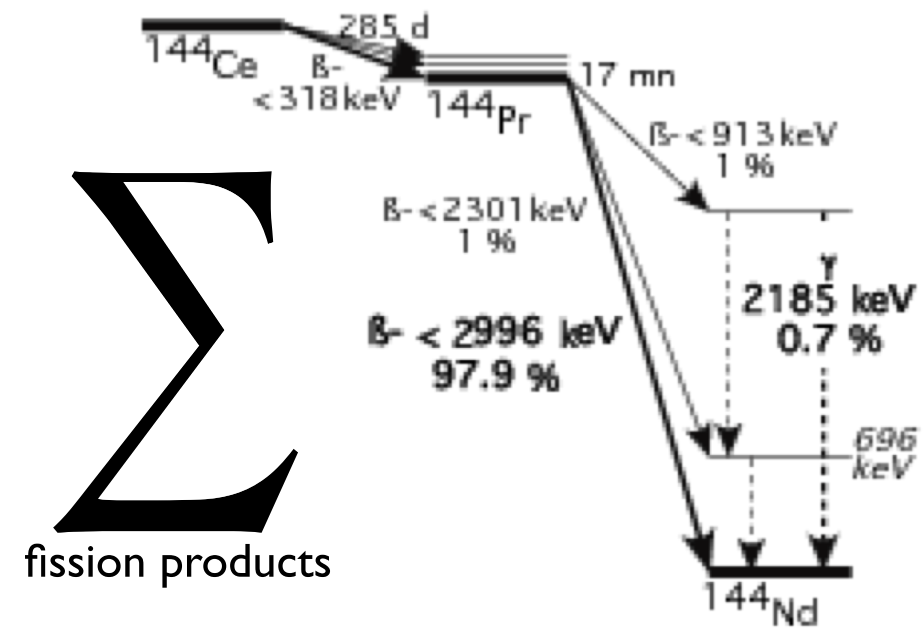
Predicting $S_i(E)$, Neutrinos Per Fission

- Two main methods:

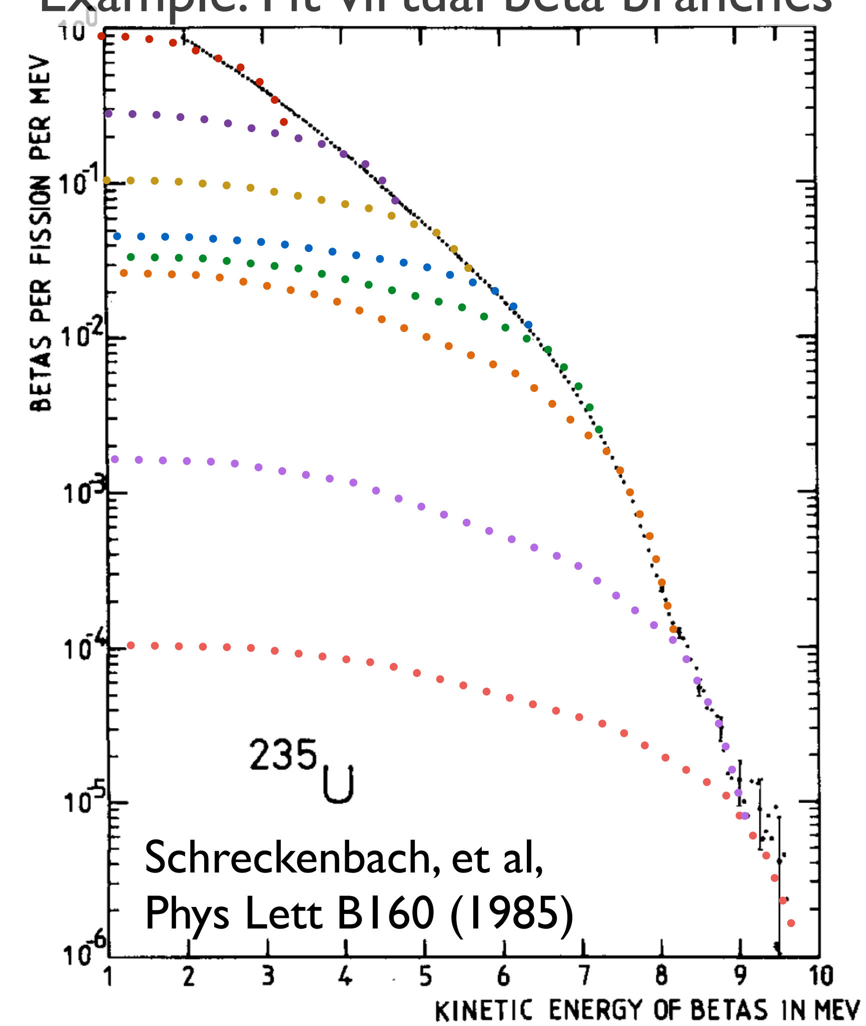
- *Ab Initio* approach:
  - Calculate spectrum branch-by-branch w/ databases: fission yields, decay schemes, …
  - **Problem:** rare isotopes / beta branches: missing, possibly incorrect info…

- Conversion approach
  - Measure beta spectra directly
  - Convert to $\overline{\nu}_e$ using 'virtual beta branches'
  - **Problem:** 'Virtual' spectra not well-defined: what forbiddenness, charge, etc. should they have?
  - 'Preferred' method: smaller error bars

Example: Ce-144 Decay Scheme

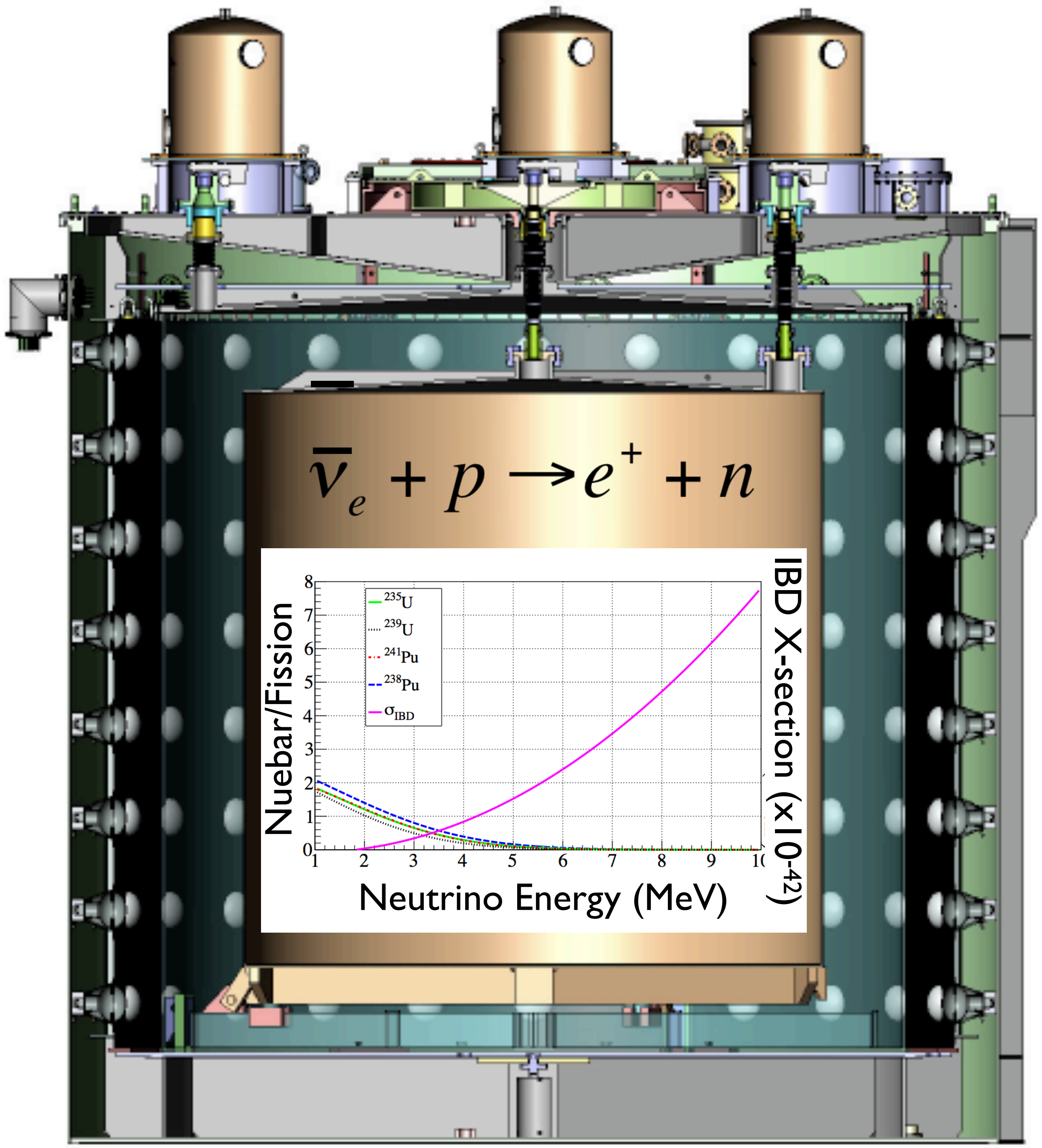


Example: Fit virtual beta branches

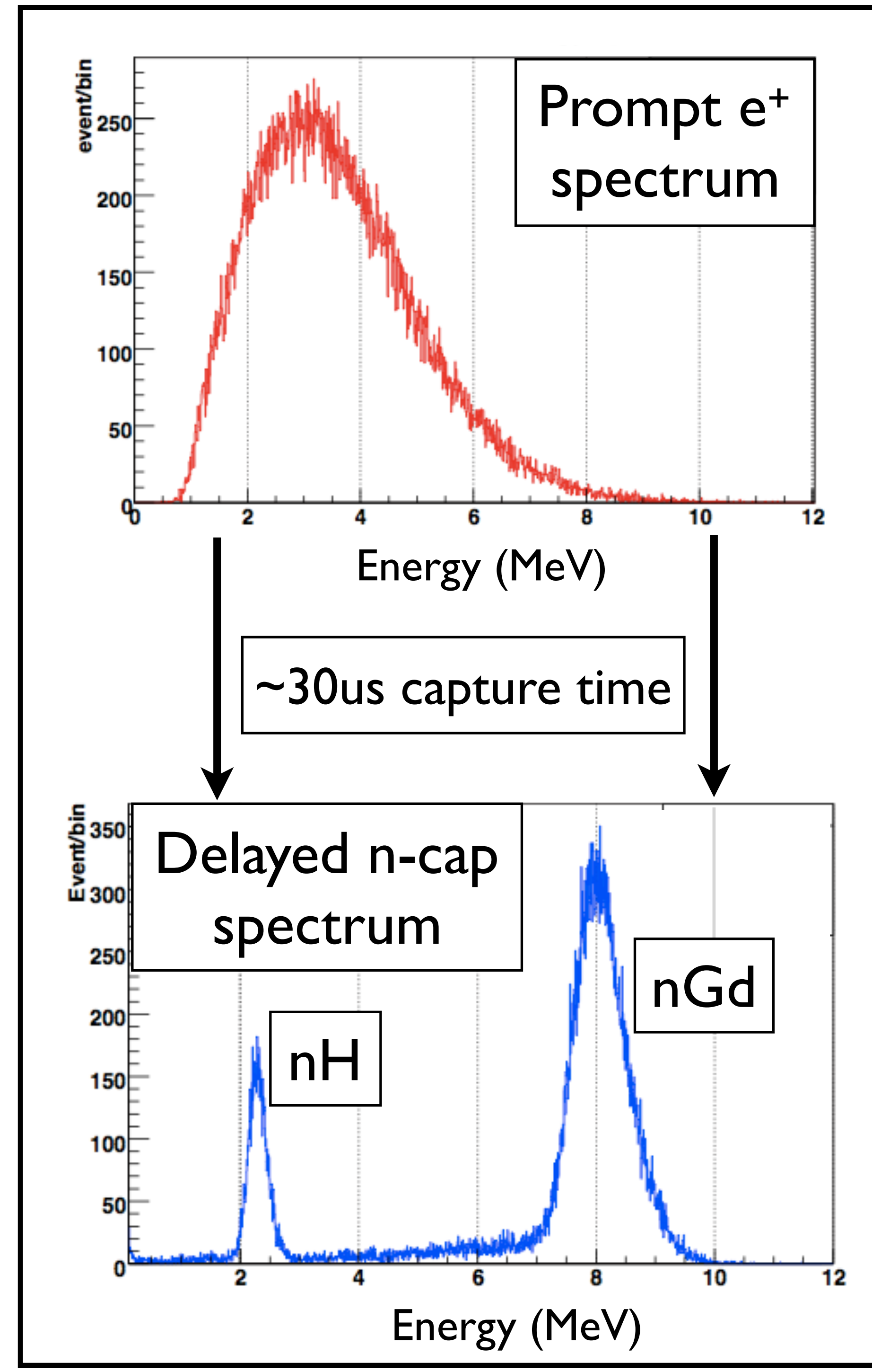


Reactor Antineutrino Detection

- Detect inverse beta decay with liquid or solid scintillator, PMTs
  - IBD e+ is direct proxy for antineutrino energy



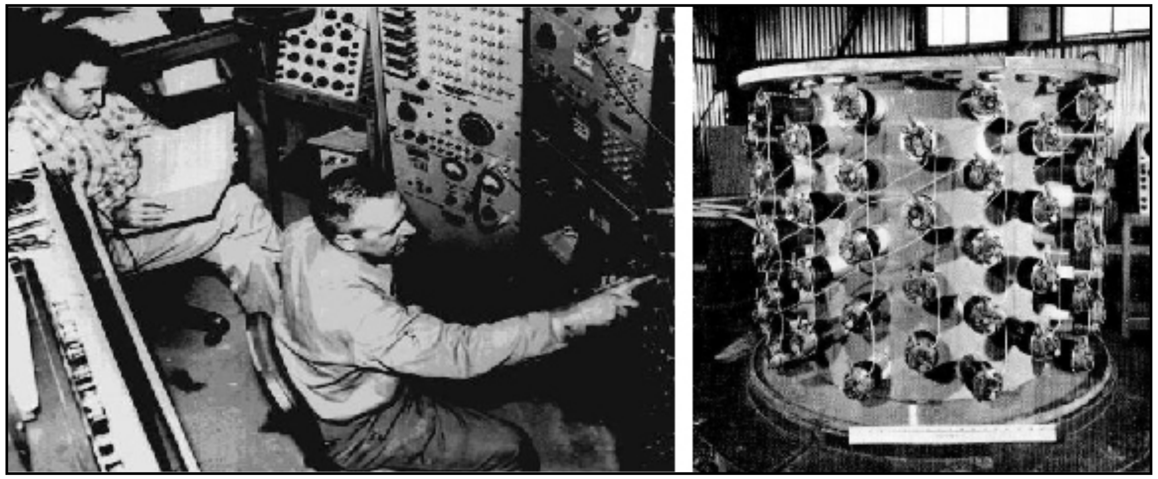
Example: Daya Bay Detector



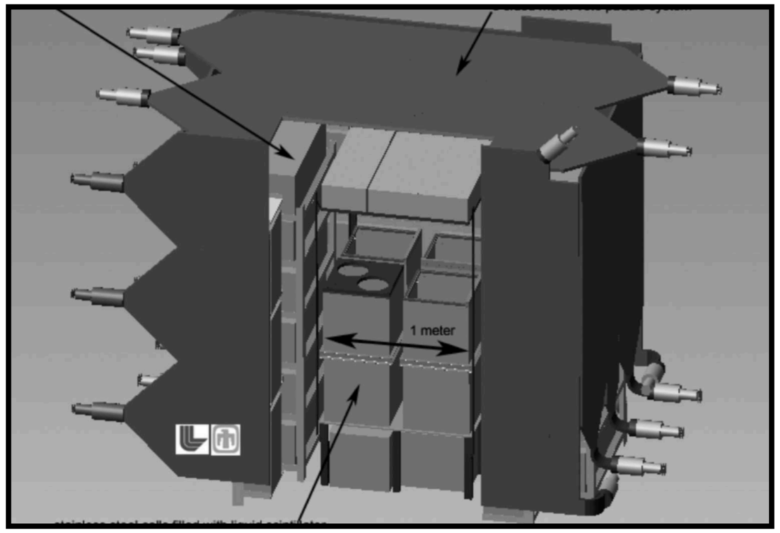
Daya Bay Monte Carlo Data

Reactor Neutrino Monitoring Advances

- Last few decades have brought major advances in realized tech:

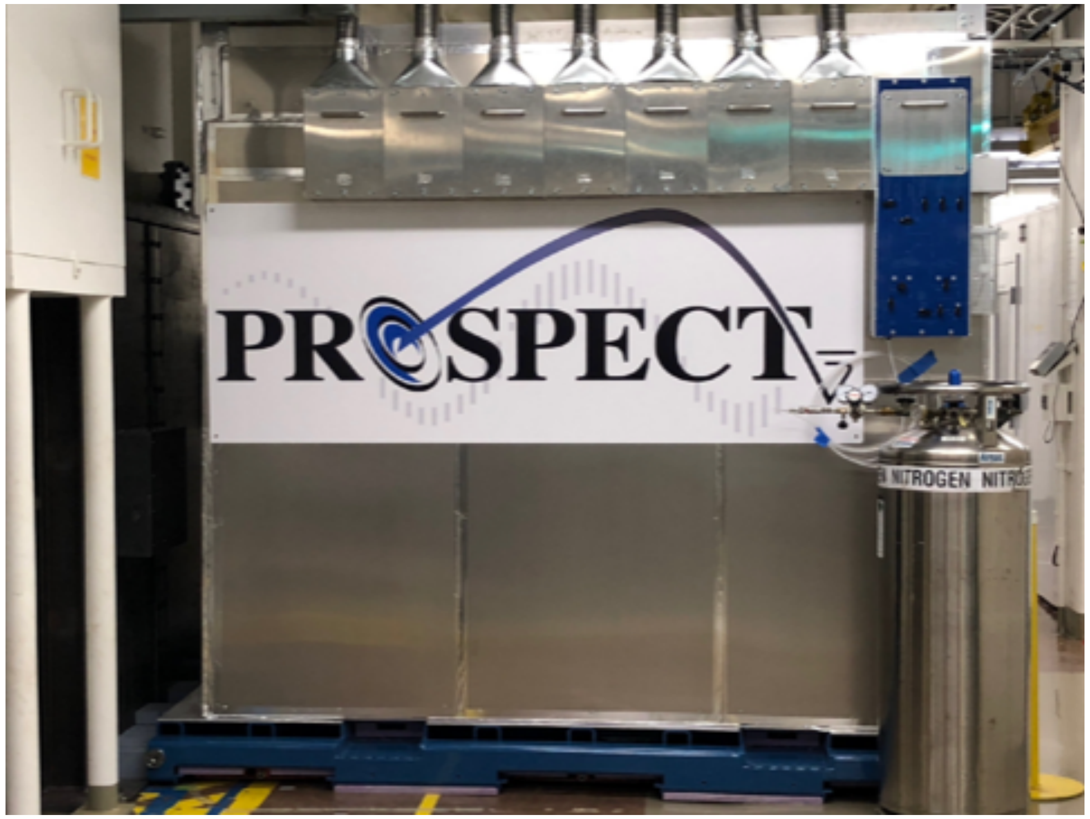


1950s: First Detection; ~1000 counts in 1 month;
5 background counts per 1 antineutrino count (S:B 1:5)



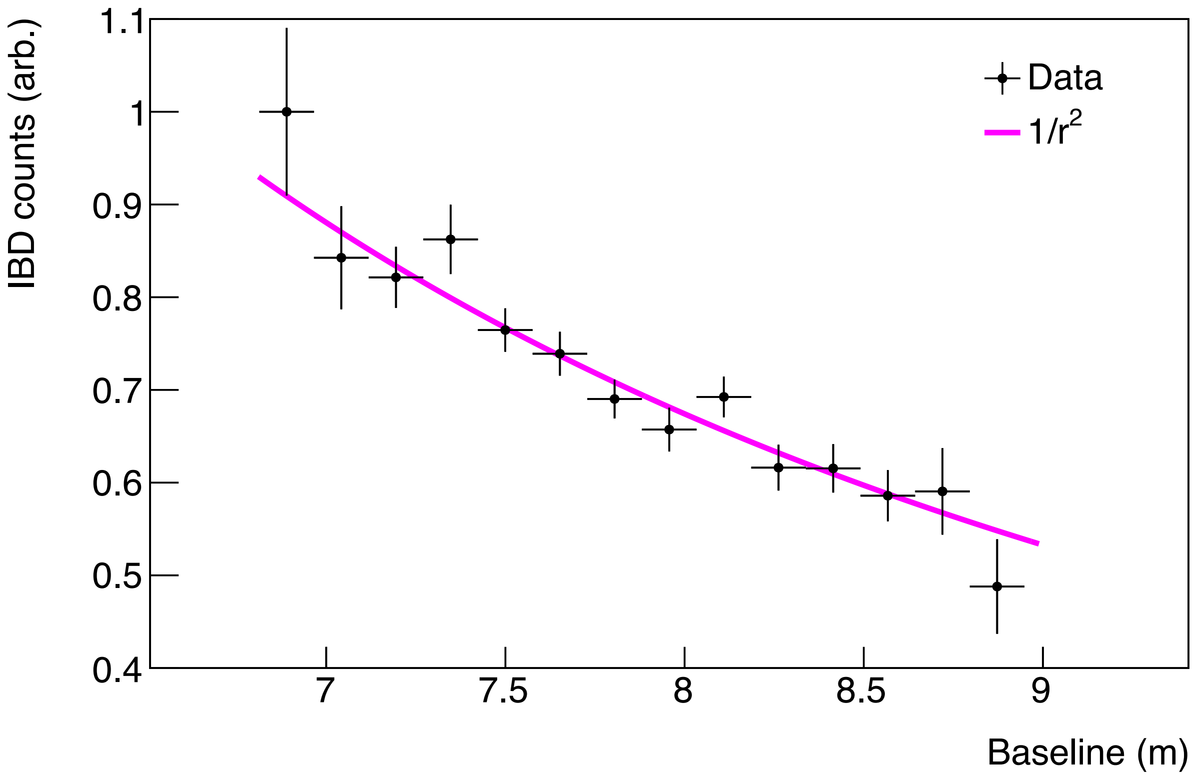
2000s: SONGS: ~230 counts per day, 25:1 S:B, but must be underground. 'semi-safe' detector liquid

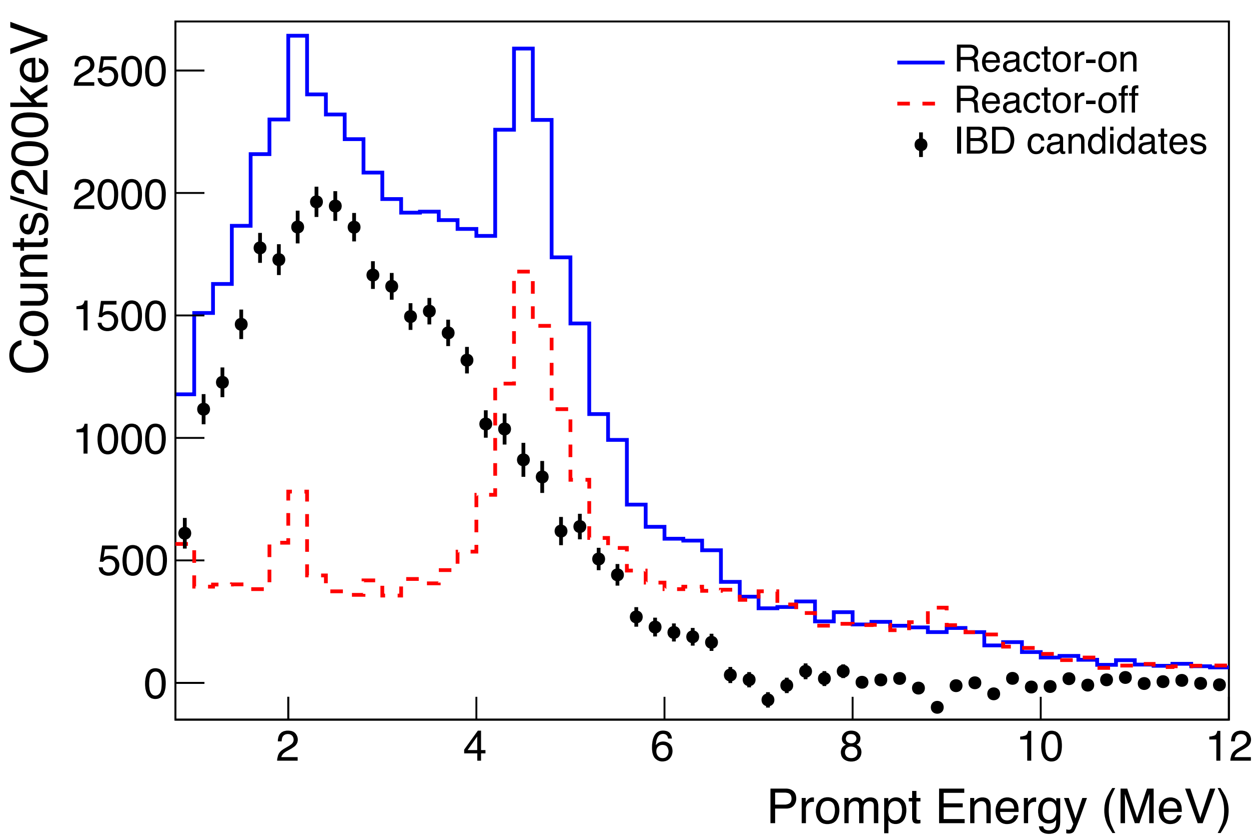
1980s: Bugey: ~1000 counts per day, S:B 10:1, but only underground. flammable/corrosive solvent detector liquids

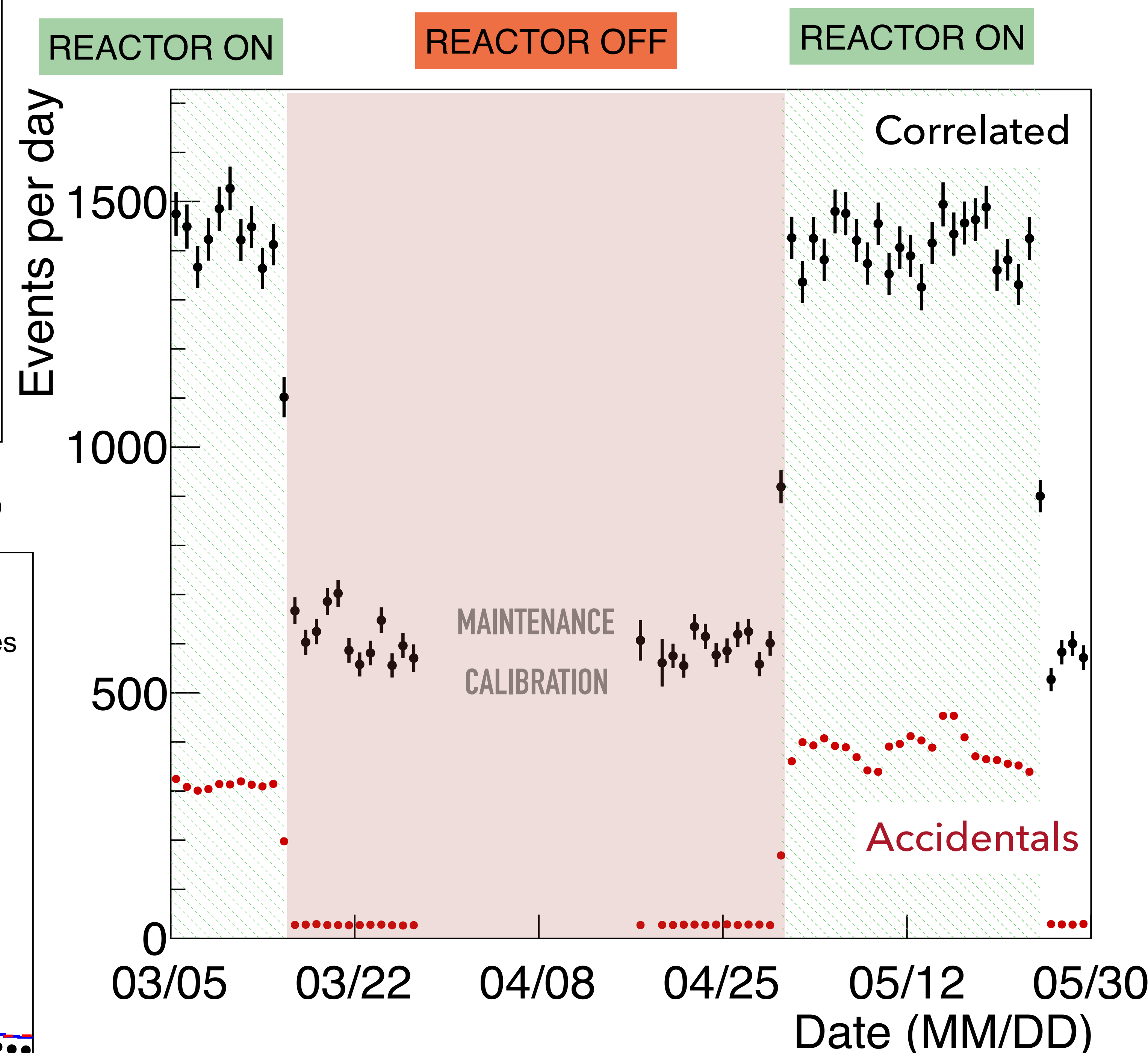


NOW: PROSPECT detector: ~750/day from only 80MW reactor, S:B 1:1 on surface, 'safe' plug-n-play detector

PROSPECT Money Plots



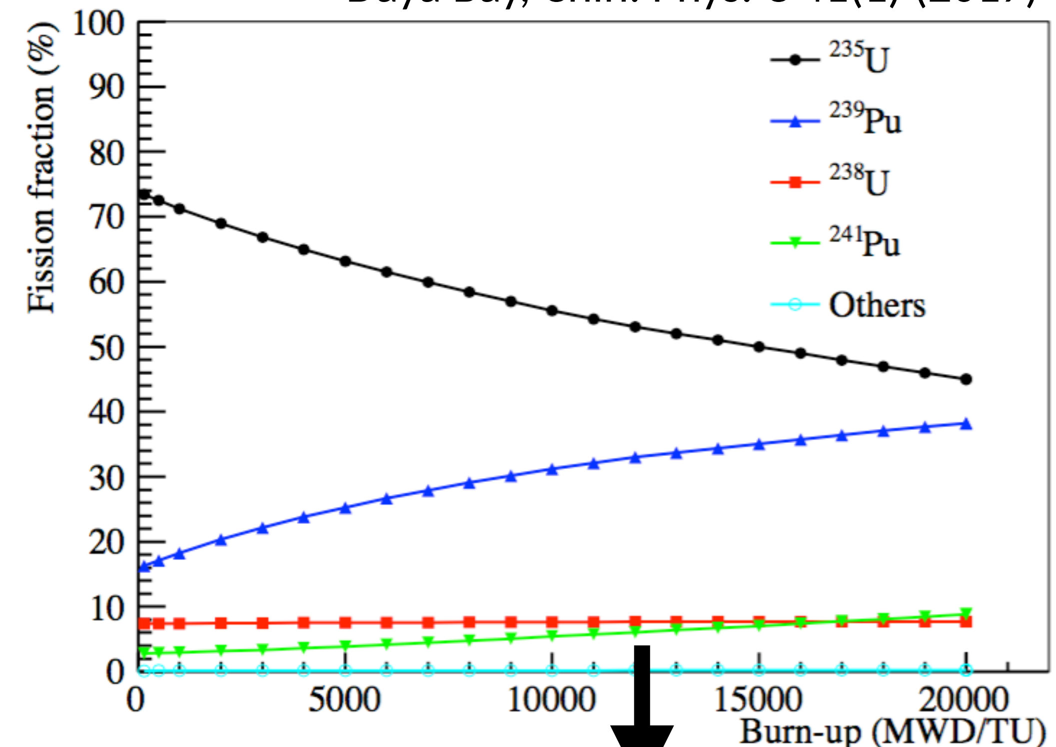




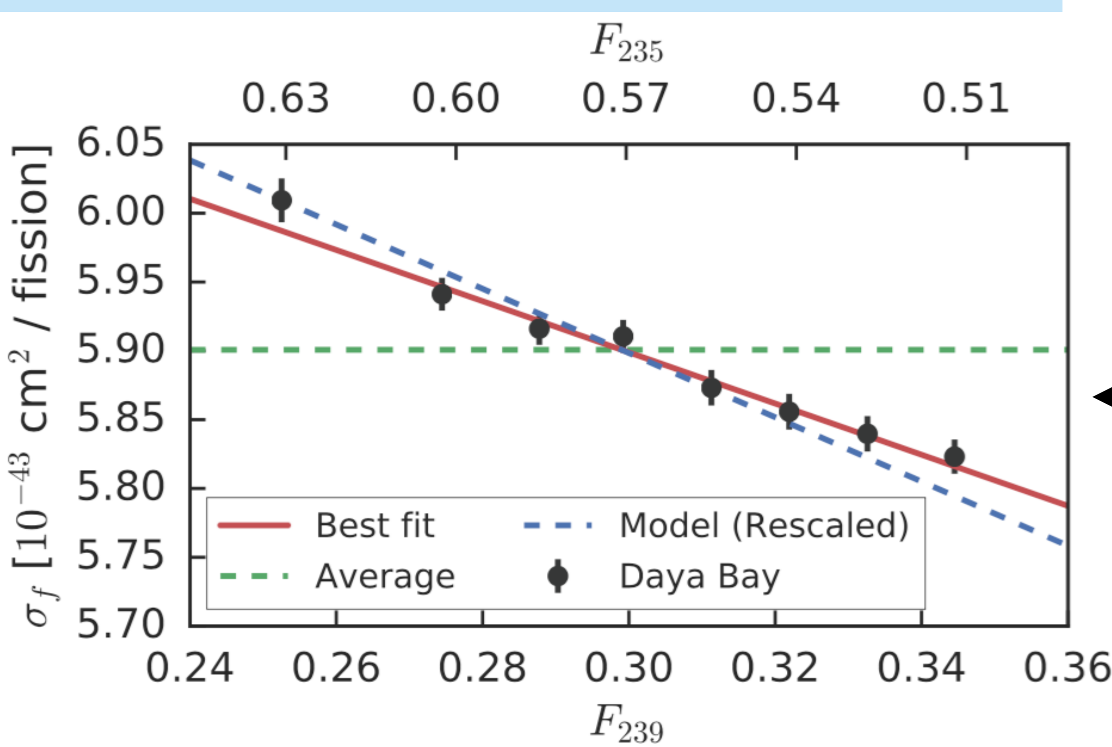
Daya Bay Evolution Measurements

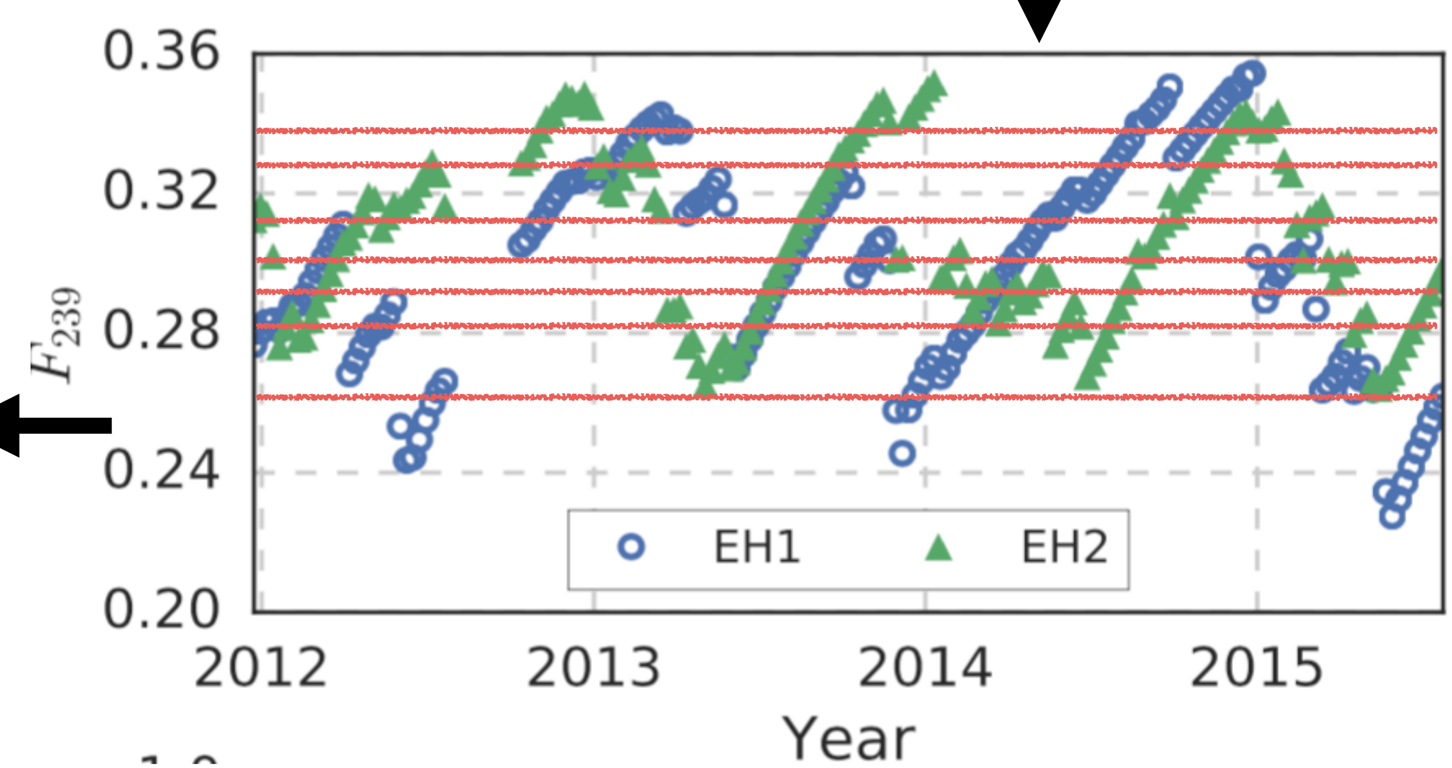
- Look at reactors' fission fractions
  - % of fissions from ^{235}U ^{239}Pu, ^{238}U, ^{241}Pu
- Calculate 'effective fission fraction,' observed by each detector:
  - Weight core fission fraction by power, baseline, oscillation, etc.
- Calculate IBD rate (per fission) for each bin in effective fission fraction.

Daya Bay, Chin. Phys. C 41(1) (2017)



weight; then repeat x6

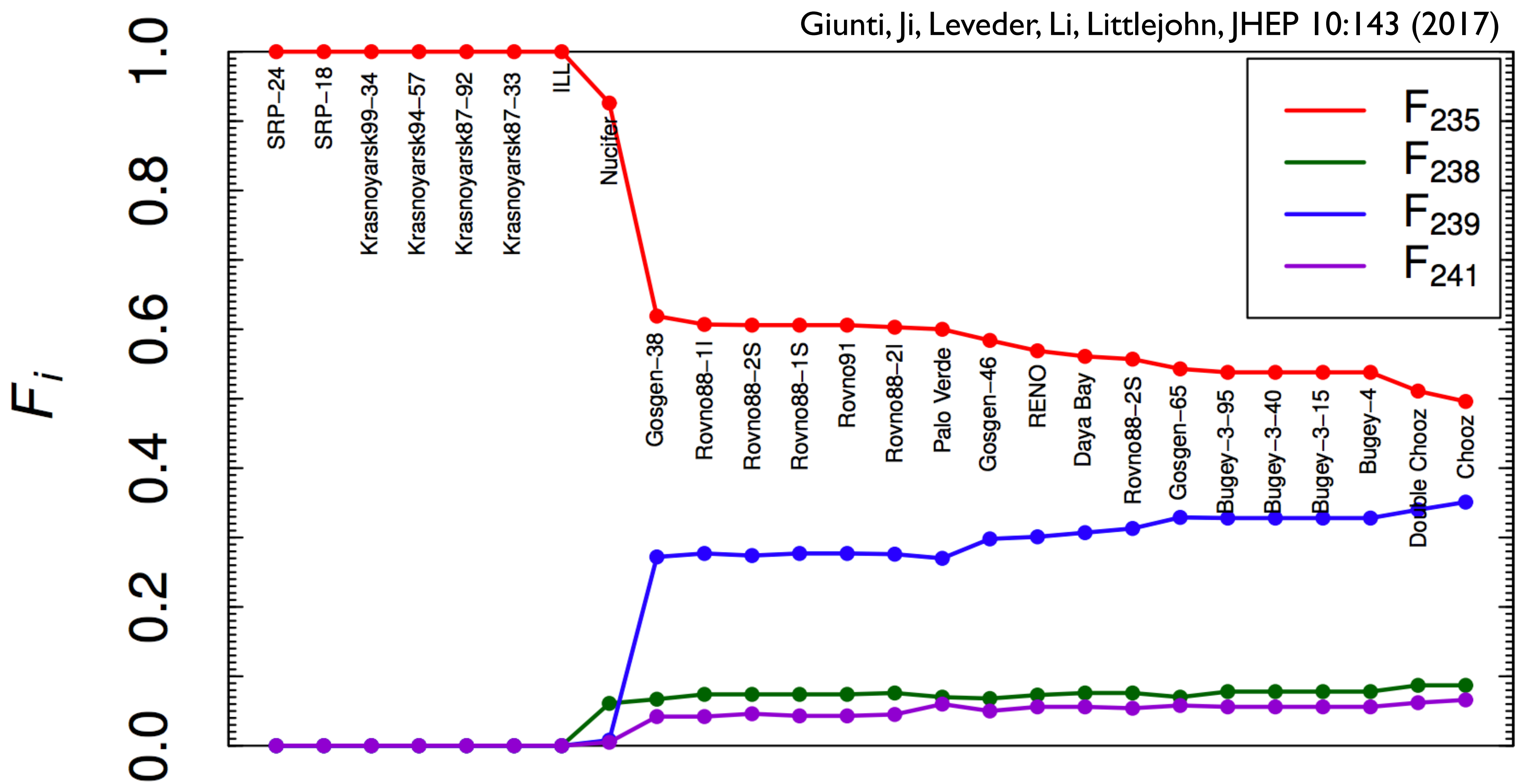




Other Neutrino Data Out There?

- Some old and ~unreliable HEU measurements
- Some old and precise and seemingly reliable LEU flux measurements
- New HEU: PROSPECT and STEREO (EU)
- New LEU, single-core: DANSS (Russia) and NEOS (Korea)
- New LEU multi-core: Daya Bay and RENO (Korea) and Double Chooz (EU)

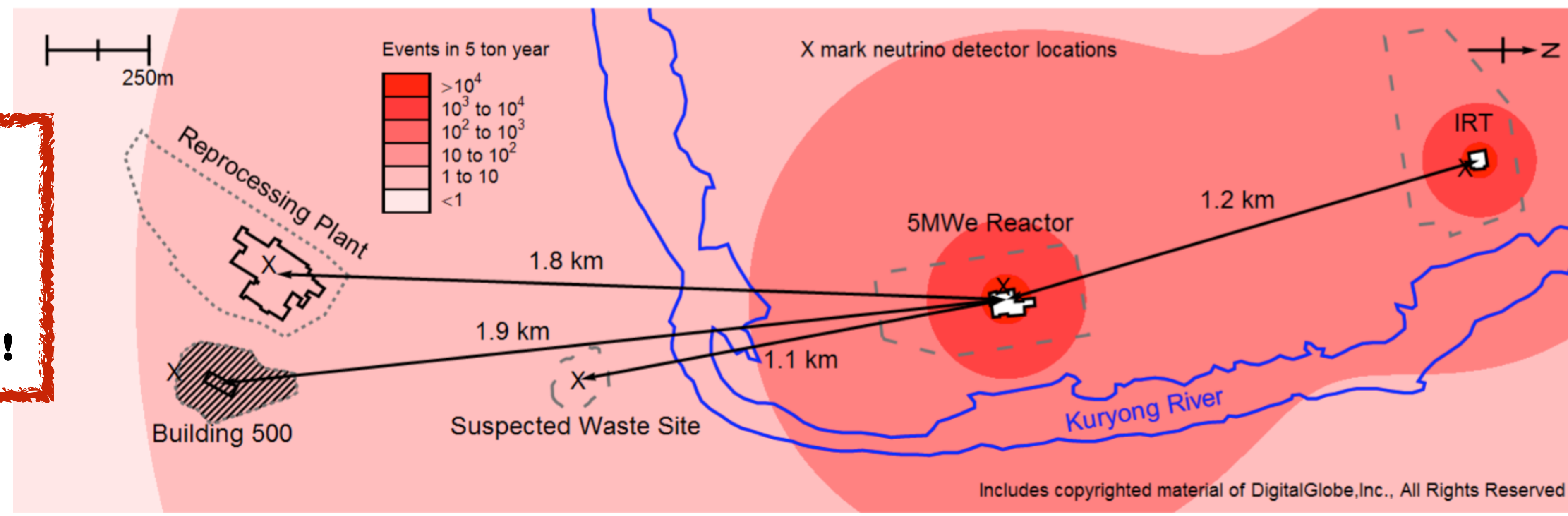
Giunti, Ji, Leveder, Li, Littlejohn, JHEP 10:143 (2017)

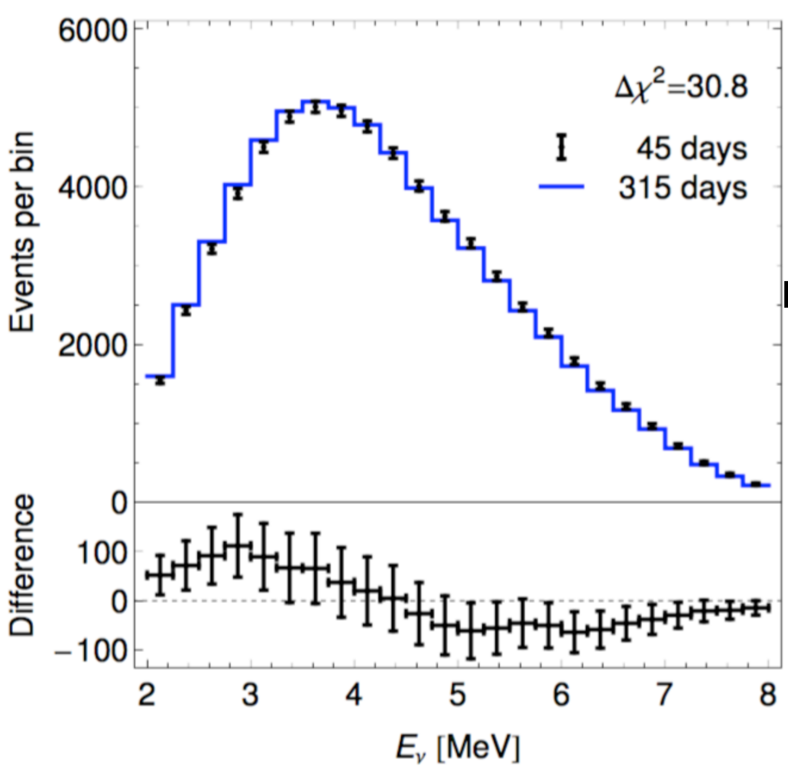


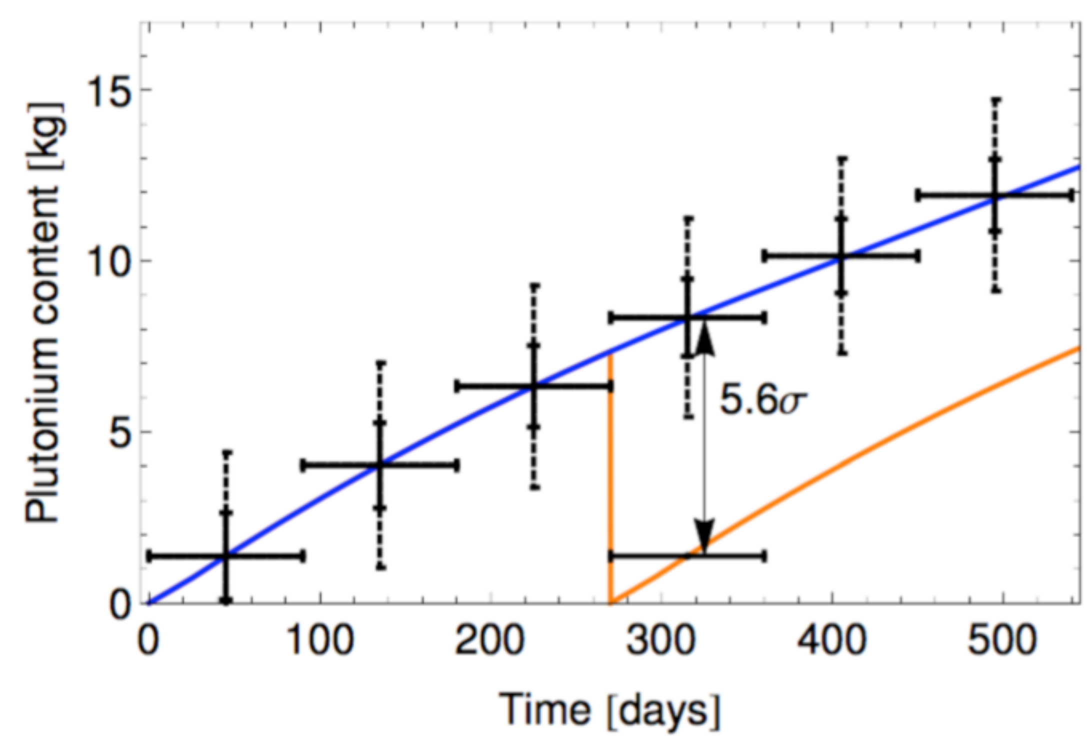
Nuclear Data For Neutrino Tools

- A case study demonstration of reactor monitoring
  - Theory-based case-studies of Iranian, North Korean nuclear reactors: arXiv[1403.7065], arXiv[1312.1959]
  - Unambiguous monitoring of reactor's ^{239}Pu content utilizing a reactor's antineutrino spectrum

This study relies *entirely* on the U235 and Pu239 neutrino *models*, for which nuclear data from databases is one of the essential inputs!







Neutrino-Driven Models: Hard Numbers

- If we make better neutrino measurements at HEU and LEU reactors, how well can we constrain neutrinos/fission without any nuclear data at all?
  - Note: nuclear data would benefit, not just neutrino modeling. Better neutrino data = better ability to validate nuclear data.

Parameter	Value	Precision on σ (%)					
		^{235}U		^{239}Pu		^{238}U	
		D3	D5	D3	D5	D3	D5
None	Default	1.26	1.50	4.80	3.84	8.91	6.68
Signal to Background	1:2	1.27	1.51	4.80	4.15	8.91	6.83
	10:1	1.25	1.49	4.80	3.40	8.91	6.53
HEU Reactor Power	1.0%	1.39	1.67	4.80	3.95	9.01	7.43
	2.0%	1.67	1.94	4.90	4.15	9.21	8.61
Detector Normalization	2.0%	1.82	2.27	5.10	4.45	9.41	6.73
	3.0%	2.46	3.1	5.65	5.30	9.60	6.78
Combined	Worst, Combined	2.51	3.51	5.78	5.90	9.68	8.71

TABLE IV. Impact of variations in experimental parameters on future achievable ^{235}U, ^{238}U, and ^{239}Pu IBD yield precisions. Measurement precisions are given as a percentage of the best fit IBD yields for Datasets 3 (D3) and 5 (D5) described above.

Important Isotopes

TABLE IV. Thermal fission yields Y_t^c and thermal-fast yield differences, $Y_t^c - Y_f^c$, for isotopes with the largest contribution to the ^{235}U and ^{239}Pu 5-7 MeV antineutrino flux. Values of $Y_t^c - Y_f^c$ are provided for the JEFF and ENDF fission yield databases, as well as Q-value and N, the relative flux contribution to the 5-7 MeV range of antineutrino energy, in percent. A '*' denotes a metastable state for that isotope, while a '^' indicates that JEFF fission yield values are used in place of ENDF fission yield values, for reasons described in the text.

Isotope	Y_t^c (JEFF)	$Y_t^c - Y_f^c$ (JEFF)	$Y_t^c - Y_f^c$ (ENDF)	N(5-7) (%)	Q-Value (MeV)
^{235}U					
Y-96	0.047	-0.0004	-0.0004^	10.66	7.10
Rb-92	0.048	-0.0032	+0.0064	9.63	8.10
Cs-142	0.029	-0.0025	-0.0012	5.77	7.32
Nb-100	0.056	- 0.0036	-0.0003	4.61	6.38
Rb-93	0.035	-0.0064	-0.0021	3.92	7.47
Cs-140	0.060	+0.0034	-0.0002	3.26	6.22
I-138	0.015	+0.0009	+0.0013	3.09	7.99
Y-99	0.019	-0.0103	-0.0038	3.05	6.97
Rb-90	0.044	+0.0051	+0.0023	3.03	6.58
Sr-95	0.053	-0.0004	+0.0003	3.01	6.09
^{239}Pu					
Y-96	0.029	-0.0015	-0.0015^	10.86	7.10
Nb-100	0.052	+1.6e-5	+1.6e-5^	7.16	6.38
Nb-102*	0.016	-0.0039	-0.0039^	6.85	7.26
Rb-92	0.020	-0.0035	-0.0009	6.73	8.10
Cs-142	0.016	+0.0043	+0.0019	5.35	7.32
Cs-140	0.044	+0.0026	-0.0047	4.02	6.22
Y-99	0.013	-0.0045	+0.0017	3.60	6.97
Rb-93	0.017	-0.0050	-0.0015	3.11	7.47
Y-98*	0.019	-0.0051	+0.0014	3.08	9.40
Sr-95	0.032	-0.0003	-0.0021	3.07	6.09

Littlejohn et al, PRD 97 (2018)

Table I. Summary of the calculated dominant forbidden transitions above 4 MeV. Here Q_β is the ground-state to ground-state Q-value, E_{ex} the excitation energy of the daughter level, BR the branching ratio of the transition normalized to one decay and FY the cumulative fission yield of ^{235}U taken from the ENDF database [42].

Nuclide	Q_β (MeV)	E_{ex} (MeV)	BR (%)	$J_i^\pi \to J_f^\pi$	FY (%)	ΔJ
^{89}Br	8.3	0	16	$3/2^- \to 3/2^+$	1.1	0
^{90}Rb	6.6	0	33	$0^- \to 0^+$	4.5	0
^{91}Kr	6.8	0.11	18	$5/2^+ \to 5/2^-$	3.5	0
^{92}Rb	8.1	0	95.2	$0^- \to 0^+$	4.8	0
^{93}Rb	7.5	0	35	$5/2^- \to 5/2^+$	3.5	0
^{94}Y	4.9	0.92	39.6	$2^- \to 2^+$	6.5	0
^{95}Sr	6.1	0	56	$1/2^+ \to 1/2^-$	5.3	0
^{96}Y	7.1	0	95.5	$0^- \to 0^+$	6.0	0
^{97}Y	6.8	0	40	$1/2^- \to 1/2^+$	4.9	0
^{98}Y	9.0	0	18	$0^- \to 0^+$	1.9	0
^{133}Sn	8.0	0	85	$7/2^- \to 7/2^+$	0.1	0
^{135}Te	5.9	0	62	$(7/2-) \to 7/2^+$	3.3	0
^{136m}I	7.5	1.89	71	$(6^-) \to 6^+$	1.3	0
^{136m}I	7.5	2.26	13.4	$(6^-) \to 6^+$	1.3	0
^{137}I	6.0	0	45.2	$7/2^+ \to 7/2^-$	3.1	0
^{138}I	8.0	0	26	$0^+ \to 0^-$	1.5	0
^{142}Cs	7.3	0	56	$0^- \to 0^+$	2.7	0
^{86}Br	7.3	0	15	$(1^-) \to 0^+$	1.6	1
^{86}Br	7.3	1.6	13	$(1^-) \to 2^+$	1.6	1
^{87}Se	7.5	0	32	$3/2^+ \to 5/2^-$	0.8	1
^{89}Br	8.3	0.03	16	$3/2^- \to 5/2^+$	1.1	1
^{91}Kr	6.8	0	9	$5/2^+ \to 3/2^-$	3.4	1
^{134m}Sb	8.5	1.69	42	$(7-) \to 6^+$	0.8	1
^{134m}Sb	8.5	2.40	54	$(7^-) \to (6^+)$	0.8	1
^{140}Cs	6.2	0	36	$1^- \to 0^+$	5.7	1
^{88}Rb	5.3	0	76.5	$2^- \to 0^+$	3.6	2
^{94}Y	4.9	0	41	$2^- \to 0^+$	6.5	2
^{95}Rb	9.2	0	0.1	$5/2^- \to 1/2^+$	0.8	2
^{139}Xe	5.1	0	15	$3/2^- \to 7/2^+$	5.0	2

Hayen et al, PRC 100 (2019)