The Energy Spectrum of Antineutrinos from Nuclear Reactors

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Overview

What:

- Explore models of antineutrino emission from nuclear reactors

How:

- Examine *summation* predictions based on tabulated nuclear data

Why:

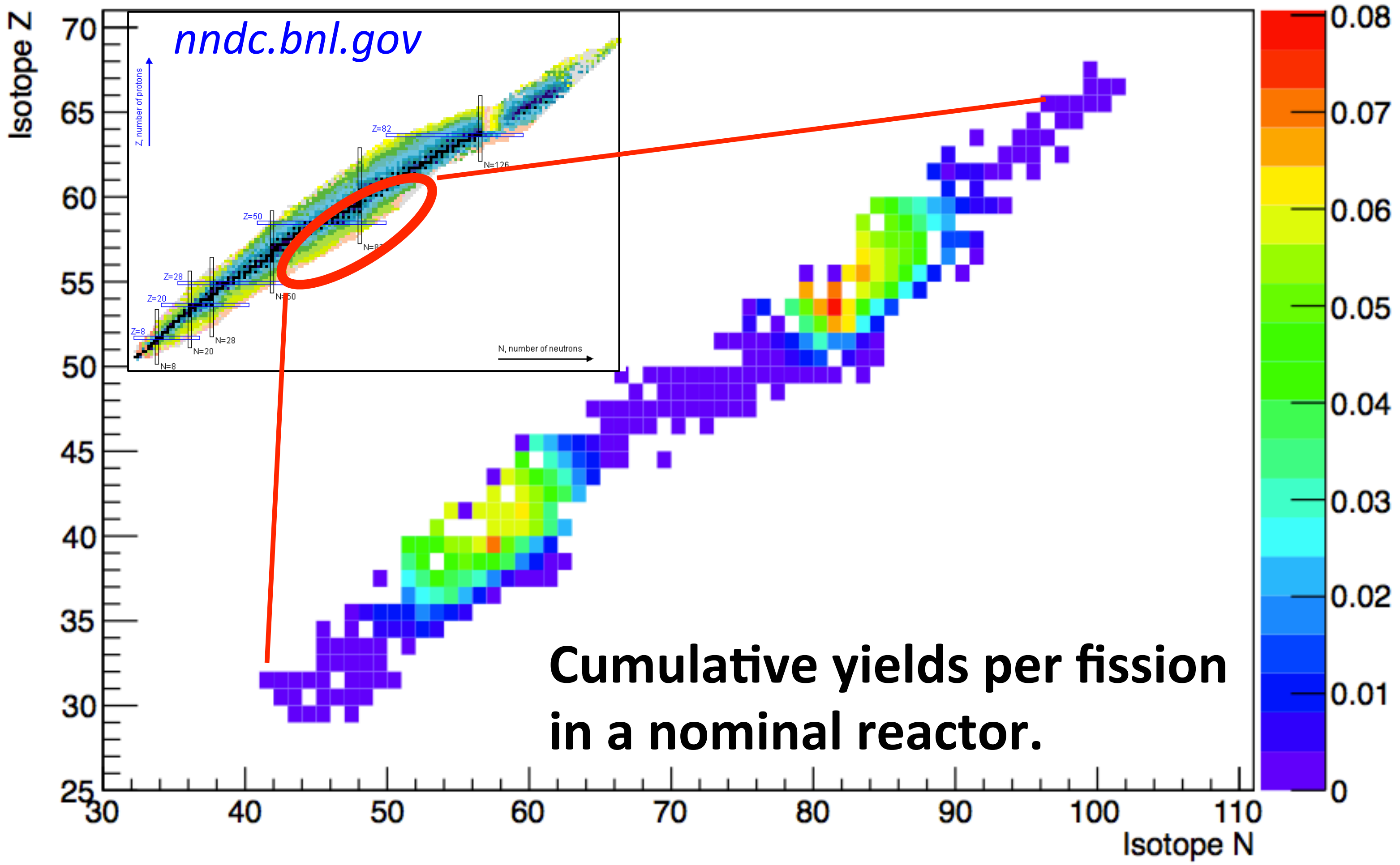
- Existing models predict $\overline{\nu}_e$ flux ~6% greater than measurement.
- Recently measured energy spectra disagree with existing models.

D.Dwyer, T.Langford
PRL 114, 012502 (2015)

Reactor Antineutrinos

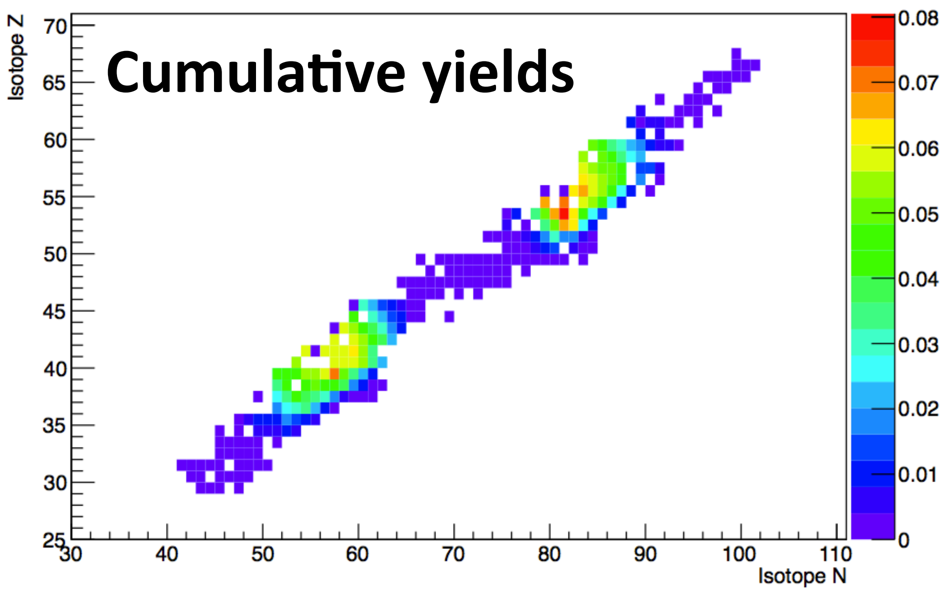
Antineutrino Production:

- Fission of heavy nuclei produce unstable neutron-rich daughters
- Two daughter fragments average ~6 beta decays until stable



Reactor Antineutrinos

Fission yields of daughter isotopes:



Daughter decay rate

$$R_i \simeq \sum_p R_p^f Y_{pi}^c$$

Parent fission rate

Cumulative yield

Instantaneous Yield:

Probability of daughter isotope *i* direct production from fission of parent isotope *p*.

Cumulative Yield Y_{pi}^{c}:

Probability of daughter isotope *i* indirect production, either from initial fission, or via decay.

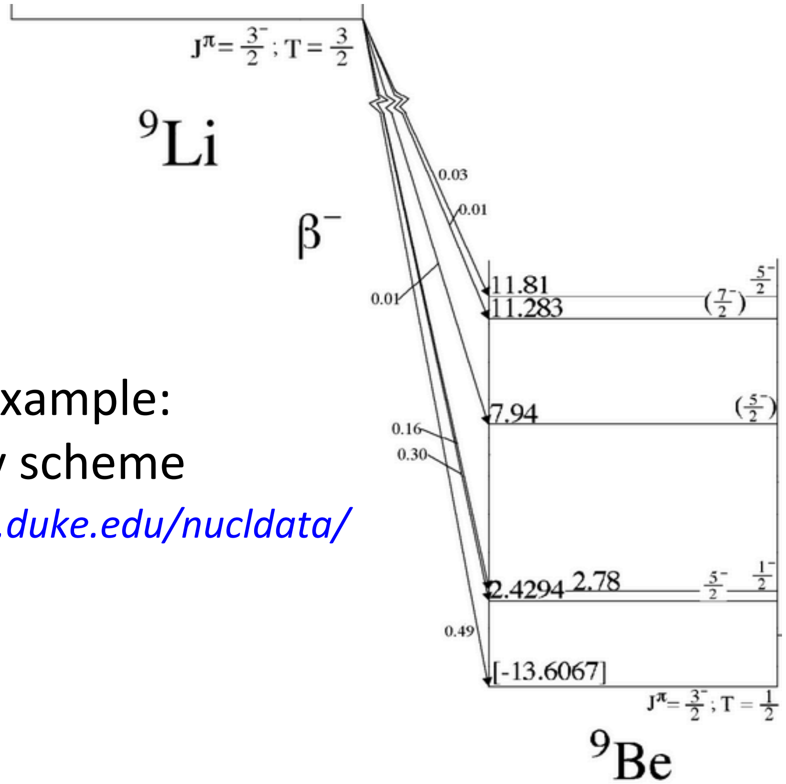
At Equilibrium:

Decay rate equals production rate.

ENDF/B.VII.1 database provides cumulative yields for >1300 fission daughter isotopes.

Beta Decay

Calculation of beta decay energy spectrum:



Simple Example:
^{9}Li decay scheme
www.tunl.duke.edu/nucldata/

Decay Branches:
Isotope decays to one
of multiple states, probability f_{ij}

Branch Spectra:
Spectra calculated including:
Coulomb, radiative, finite size,
weak magnetism corrections.

ENSDF:
Evaluated Nuclear Structure Data File

Total Reactor Spectrum:

$$S(E_{\overline{\nu}}) = \sum_{i=0}^{n} R_i \sum_{j=0}^{m} f_{ij} S_{ij}(E_{\overline{\nu}})$$

Branching fraction

Daughter decay rate

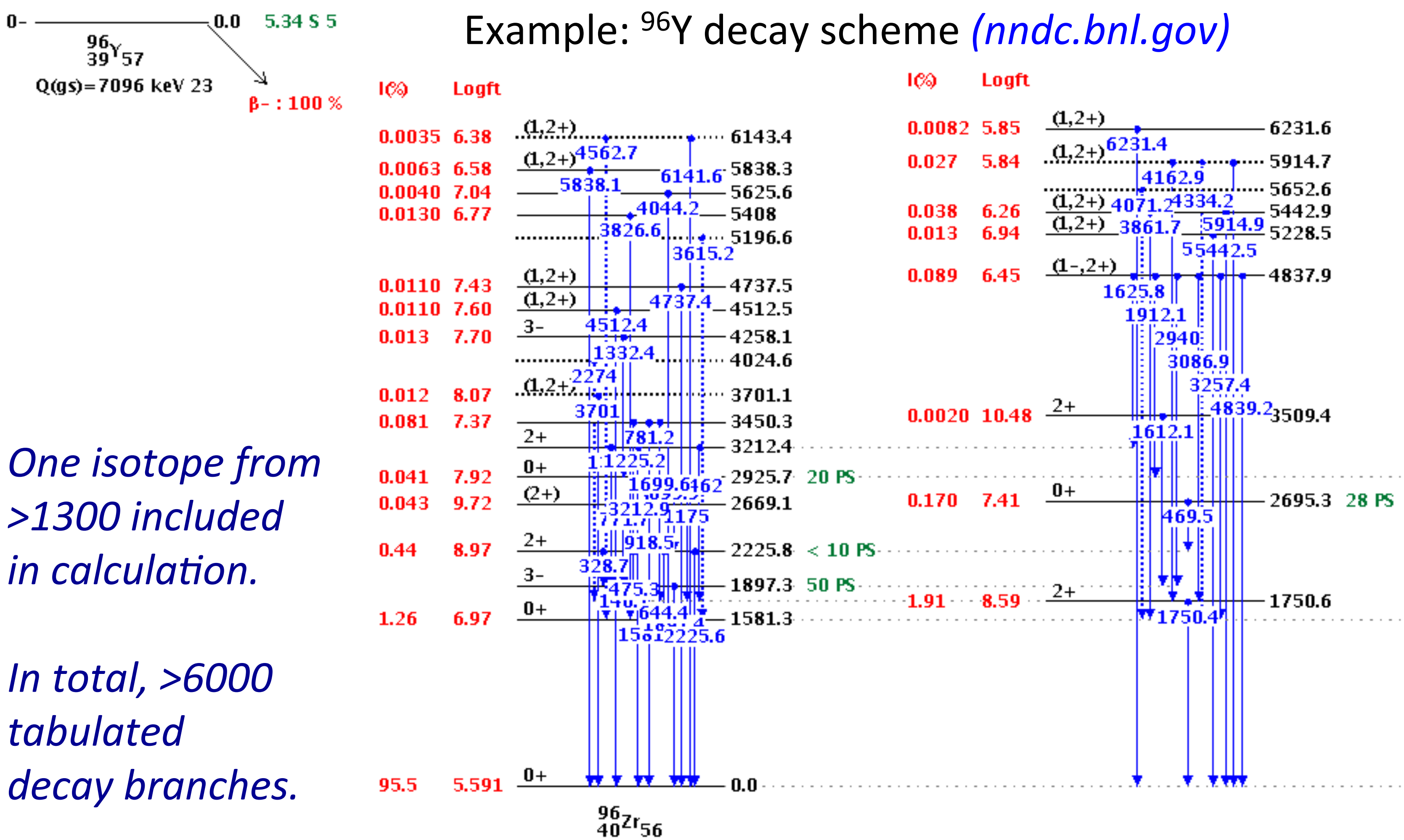
Branch spectrum

A. Hayes:
Provided tabulated ENSDF decay data for fission daughters

Nuclear Structure

Complex decays of neutron rich fission daughters.

Example: ^{96}Y decay scheme *(nndc.bnl.gov)*



One isotope from >1300 included in calculation.

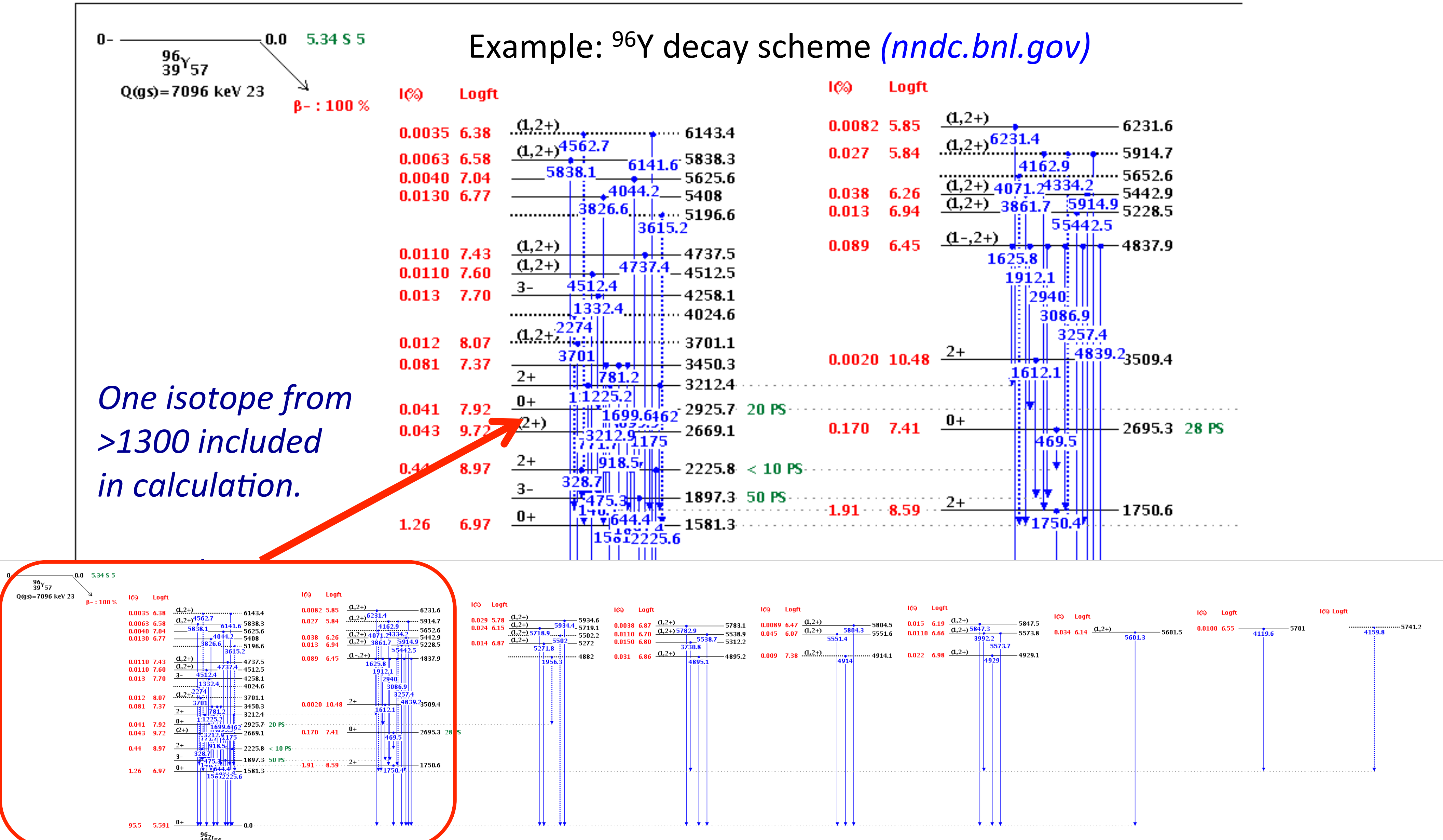
In total, >6000 tabulated decay branches.

Fission yield and decay branch uncertainties can be considerable.

Nuclear Structure

Complex decays of neutron rich fission daughters.

Example: ^{96}Y decay scheme *(nndc.bnl.gov)*



One isotope from >1300 included in calculation.

Here Be Dragons…

Significant uncertainty when directly calculating energy spectrum.

Missing Details:

Are tabulated fission and decay data comprehensive?

- Fission: What about possible very short-lived unstable daughters?
- Decay: 6% of yield has no corresponding ENDF decay information

eg. Phys. Rev. C24, 1543 (1981)

Biased Data:

Are there systematic biases in the yield or beta decay data?

- Uncertainty from assumption of reactor equilibrium, parent fission rates.
- Pandemonium Effect: Tabulated branches biased toward high-endpoints.

eg. Phys. Rev. Lett. 109, 202504 (2012)

Beta Decay Shape Corrections:

How do forbidden decay corrections impact spectrum?

- Mismatch of decay initial-final spin and parity can distort spectrum

eg. Phys. Rev. Lett. 112, 202501 (2014)

Approach: Choose simplest assumption at each step (all allowed shapes, etc.)

β^- Conversion

Alternative: Use cumulative β^- spectrum to predict $\overline{\nu}_e$ spectrum

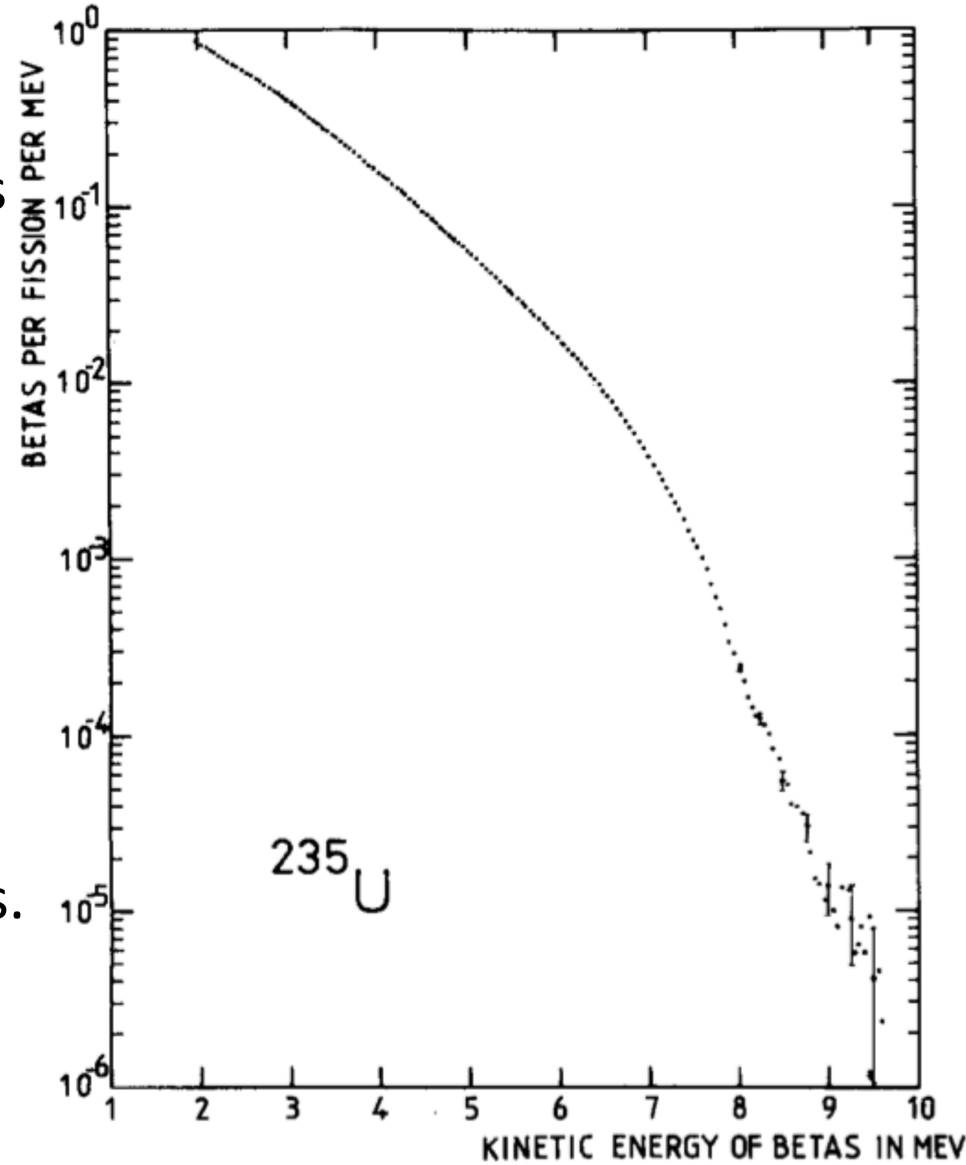
Method:

Expose fission parents to thermal neutrons

Measure total outgoing β- energy spectra

Predict corresponding $\overline{\nu}_e$ spectra

Phys. Lett. B160, 325 (1985), Phys. Lett. B118, 162 (1982)
Phys. Lett. B218, 365 (1989), Phys. Rev. Lett. 112, 122501 (2014)
Phys. Rev. C83, 054615 (2011)
Phys. Rev. C84, 024617 (2011)



Results:

More precise than *ab initio* predictions

Standard approach for ~30 years

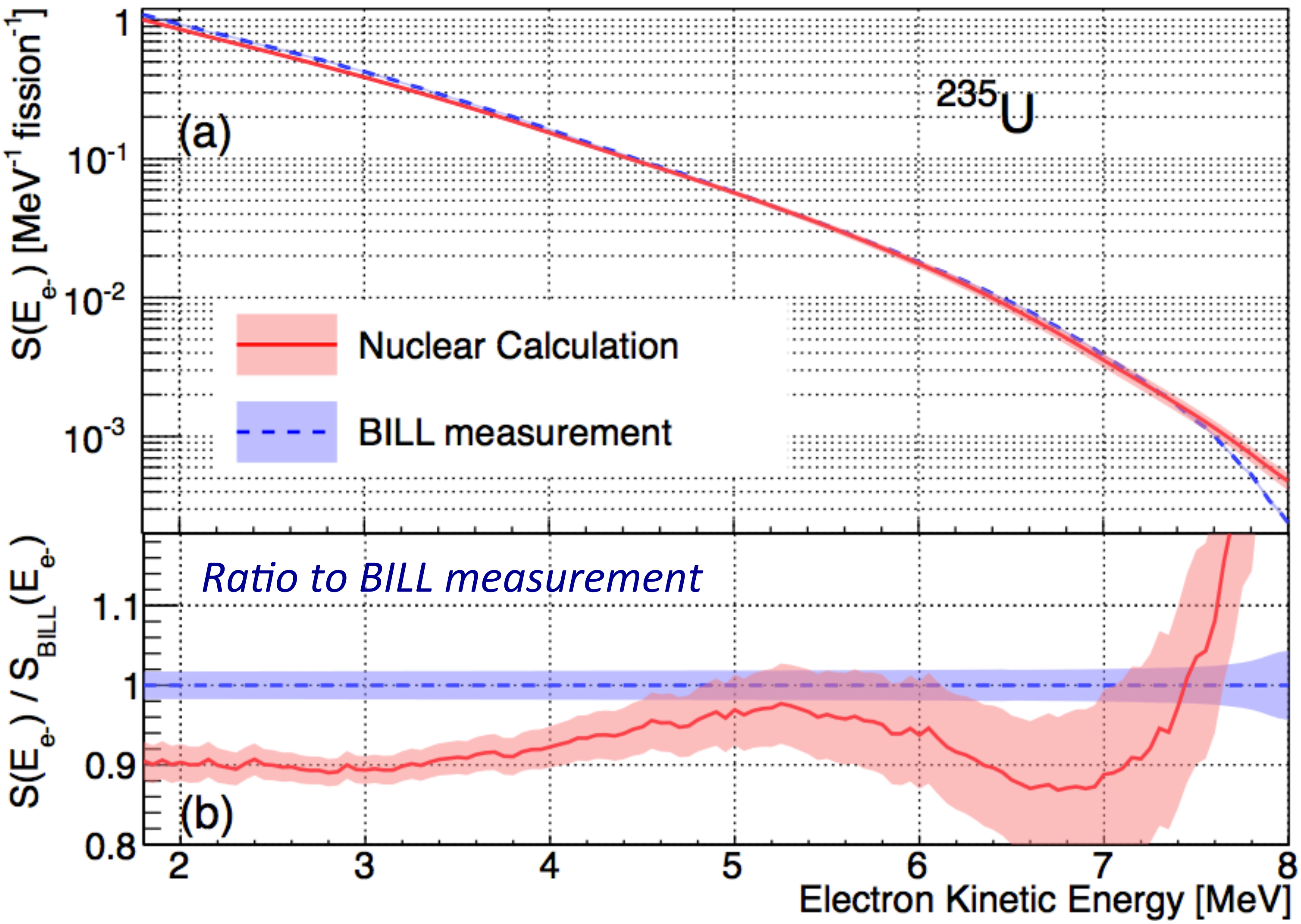
Predicts 6% higher flux than reactor msmts.

Reactor Anomaly, Sterile Neutrinos?

Phys. Rev. D83, 073006 (2011)

β^- Spectrum Disagreement

Direct calculation of ^{235}U β^- spectrum disagrees with BILL msmt.



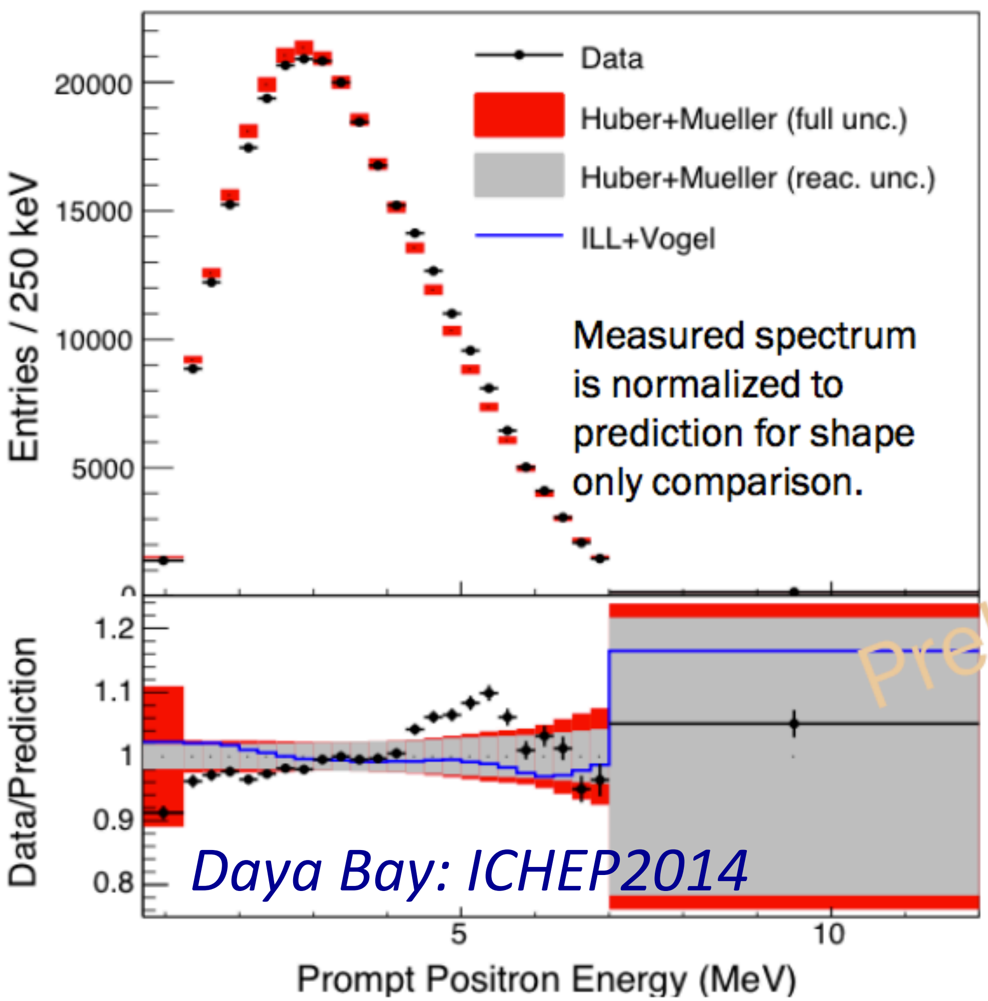
Note:
Uncertainty band for calc. is a lower bound.

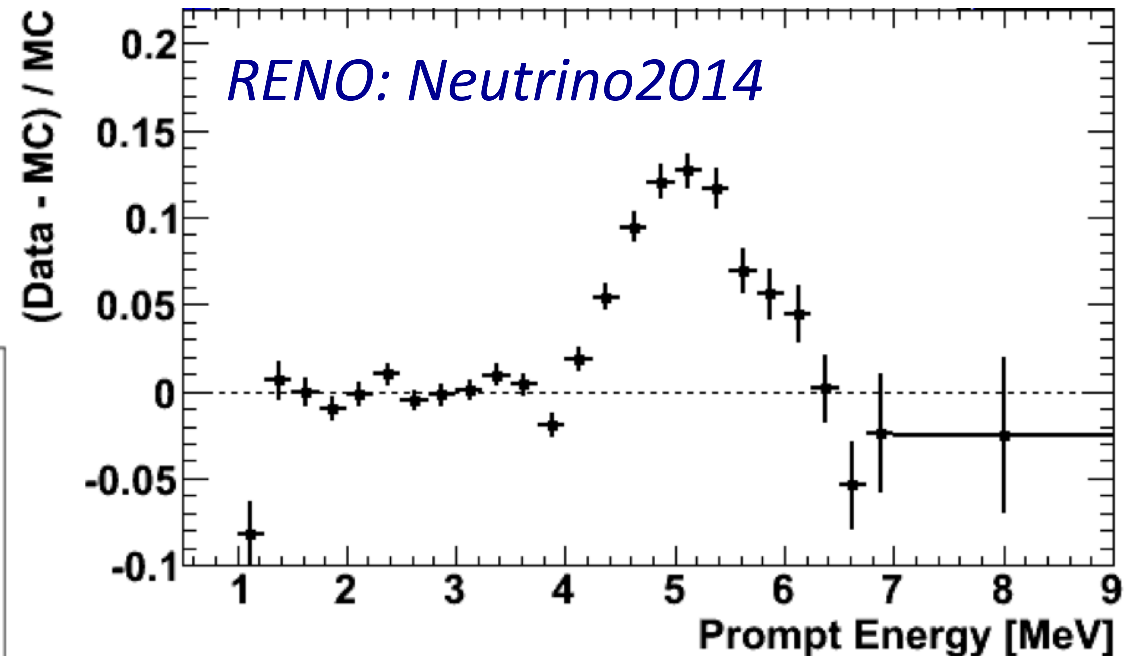
Only includes tabulated yield+branch uncertainties.

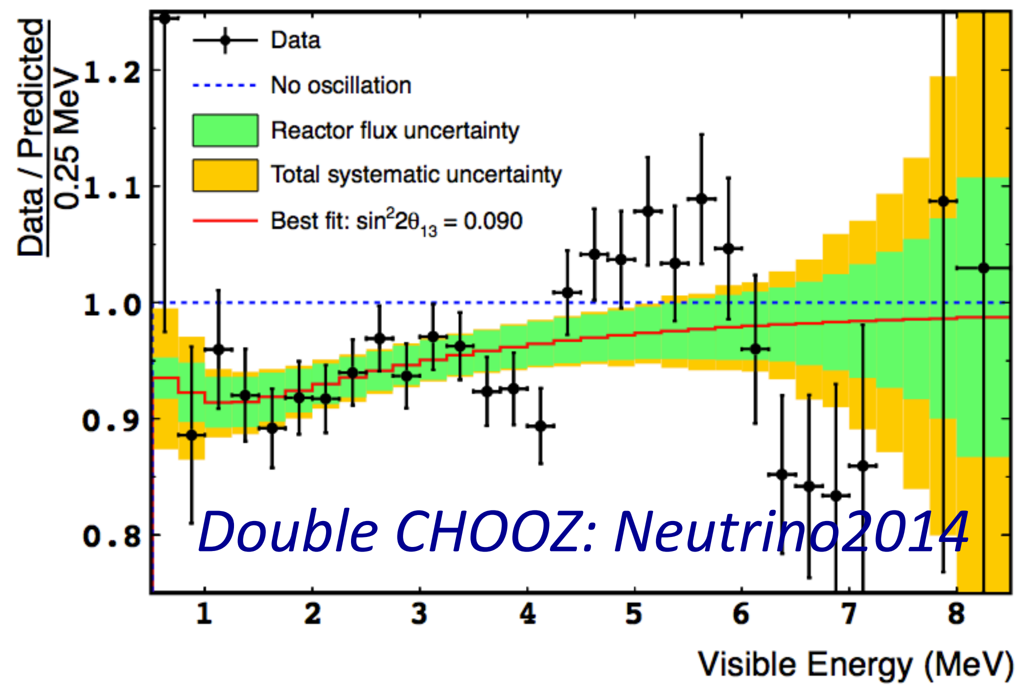
Occam's razor:
Something wrong with calculation?

$\overline{\nu}_e$ Spectrum Disagreement

Recent $\overline{\nu}_e$ measurements also disagree with BILL-derived spectra.

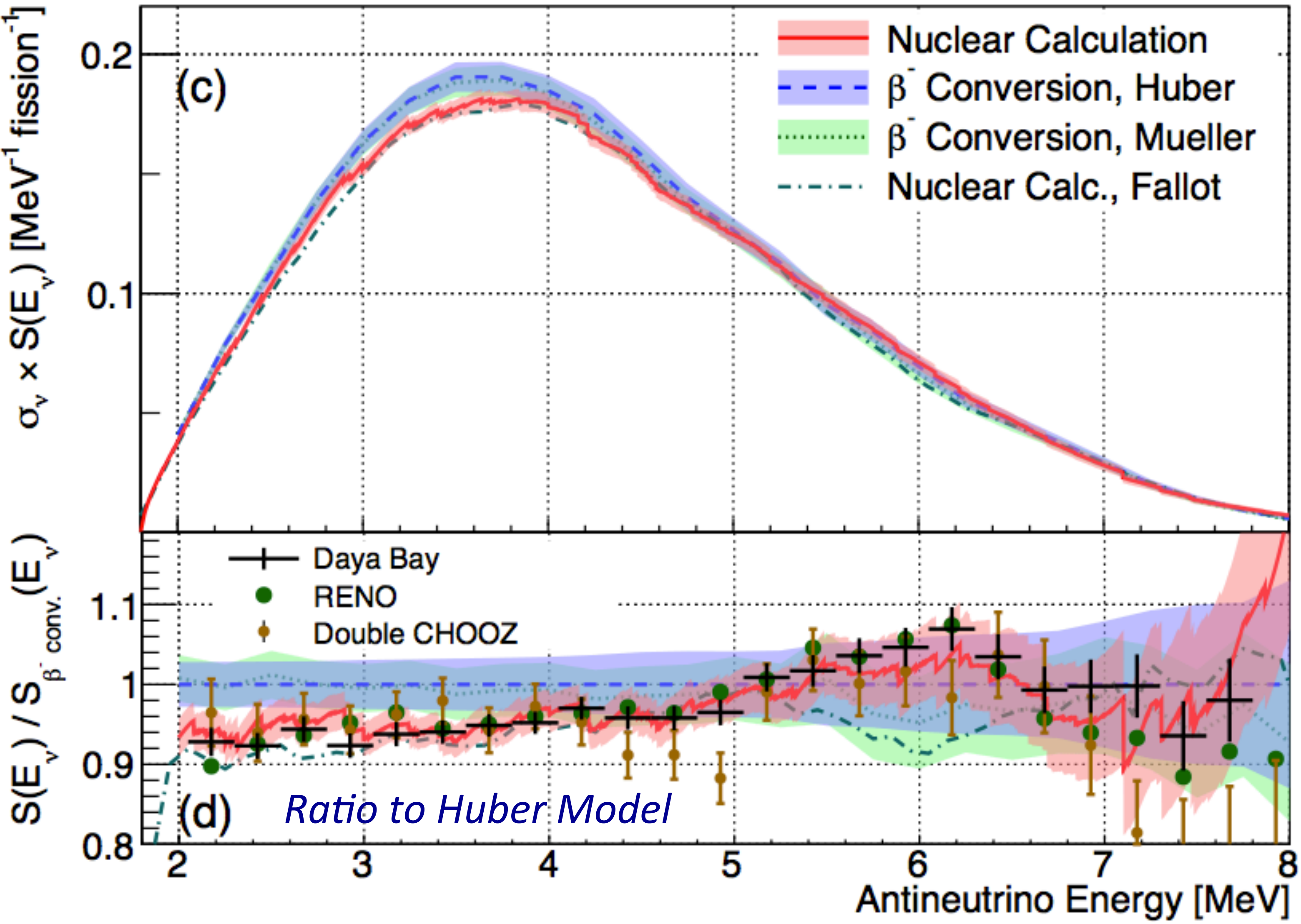






Reactor $\overline{\nu}_e$ Spectrum

Direct calculation unexpectedly agrees with preliminary msmts.



D.Dwyer, T.Langford
PRL 114, 012502 (2015)

Note:
Preliminary data compared using approx. $E_\nu \approx E_{e+} + 0.8$ MeV

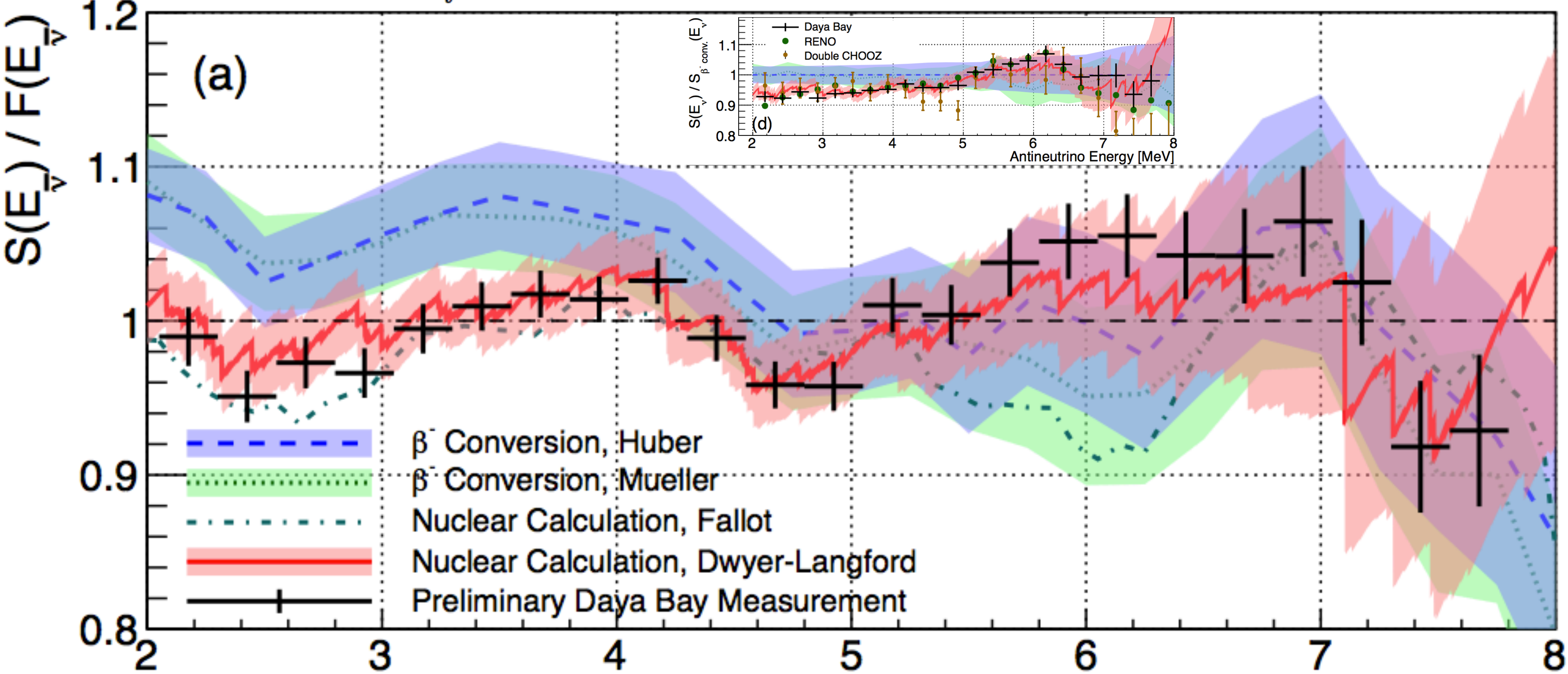
Data normalization adjusted to accurately compare shape.

How do large calc. uncertainties not cause more tension with measurements?

Detailed $\overline{\nu}_e$ Spectrum Shape

Structure clearer when compared with smooth approximation *F(E)*

$$F(E_{\overline{\nu}}) = \exp(\sum_i \alpha_i E_{\overline{\nu}}^{i-1}) \qquad \alpha = \{0.4739, 0.3877, -0.3619, 0.04972, -0.002991\}$$



Structure predictions similar at low energy, but differ above 4.5 MeV

Dominant Branches

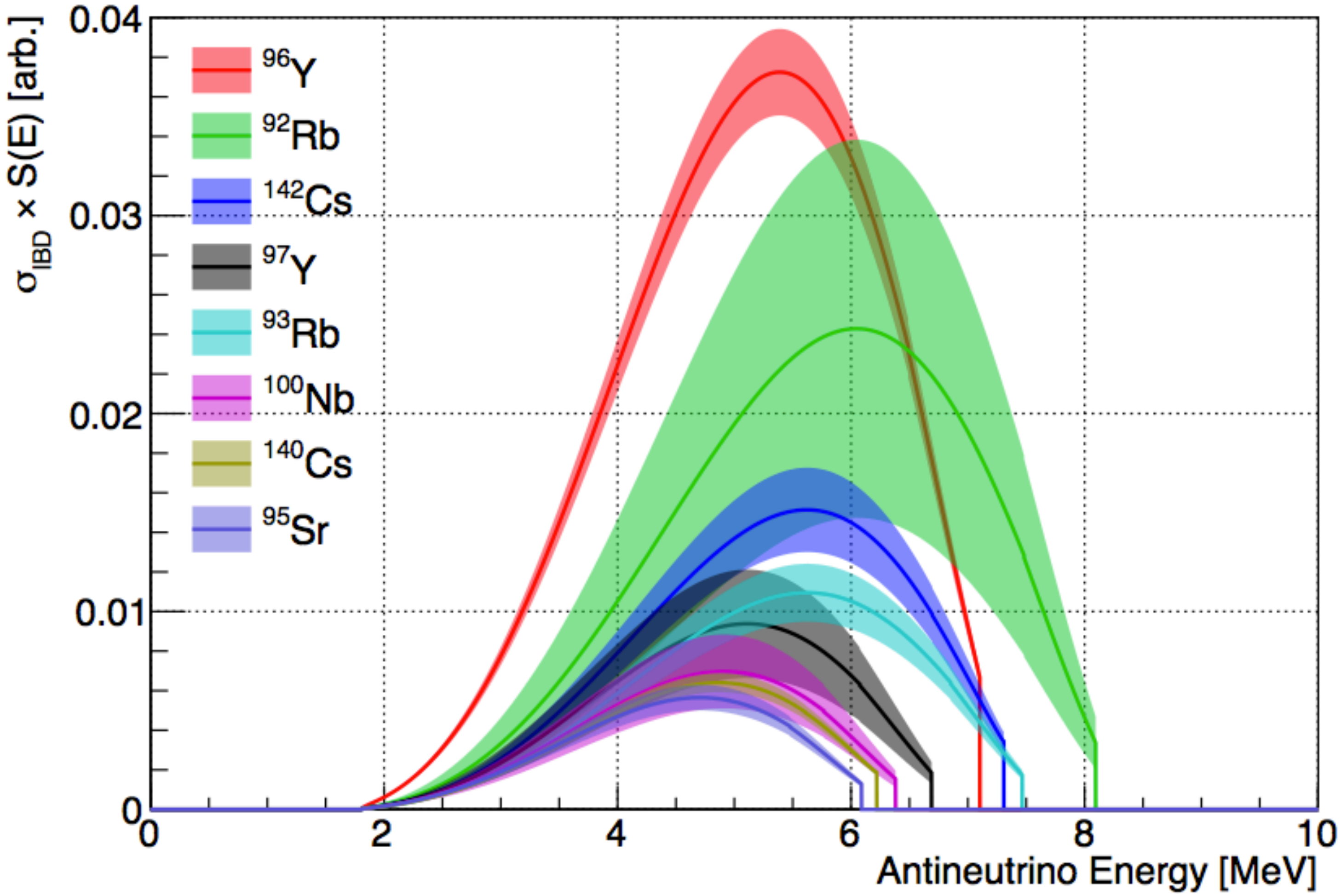
Eight dominant branches cause 5-7 MeV excess in the calculation.

Isotope	Q[MeV]	$t_{1/2}$[s]	log(ft)	Decay Type	N[%]	σ_N[%]
^{96}Y	7.103	5.34	5.59	$0^- \rightarrow 0^+$	13.6	0.8
^{92}Rb	8.095	4.48	5.75	$0^- \rightarrow 0^+$	7.4	2.9
^{142}Cs	7.308	1.68	5.59	$0^- \rightarrow 0^+$	5.0	0.7
^{97}Y	6.689	3.75	5.70	$1/2^- \rightarrow 1/2^+$	3.8	1.1
^{93}Rb	7.466	5.84	6.14	$5/2^- \rightarrow 5/2^+$	3.7	0.5
^{100}Nb	6.381	1.5	5.1	$1^+ \rightarrow 0^-$	3.0	0.8
^{140}Cs	6.220	63.7	7.05	$1^- \rightarrow 0^+$	2.7	0.2
^{95}Sr	6.090	23.9	6.16	$1/2^+ \rightarrow 1/2^-$	2.6	0.3

Calculation predicts ~42% of rate in 5-7 MeV caused by these 8 beta decay branches.

Dominant Branches

Eight prominent branches cause 5-7 MeV excess in the calculation.



Energy Spectra:
Allowed shape
+ IBD cross-section

Uncertainties:
Fission Yield
Branch fraction
^{92}Rb most significant

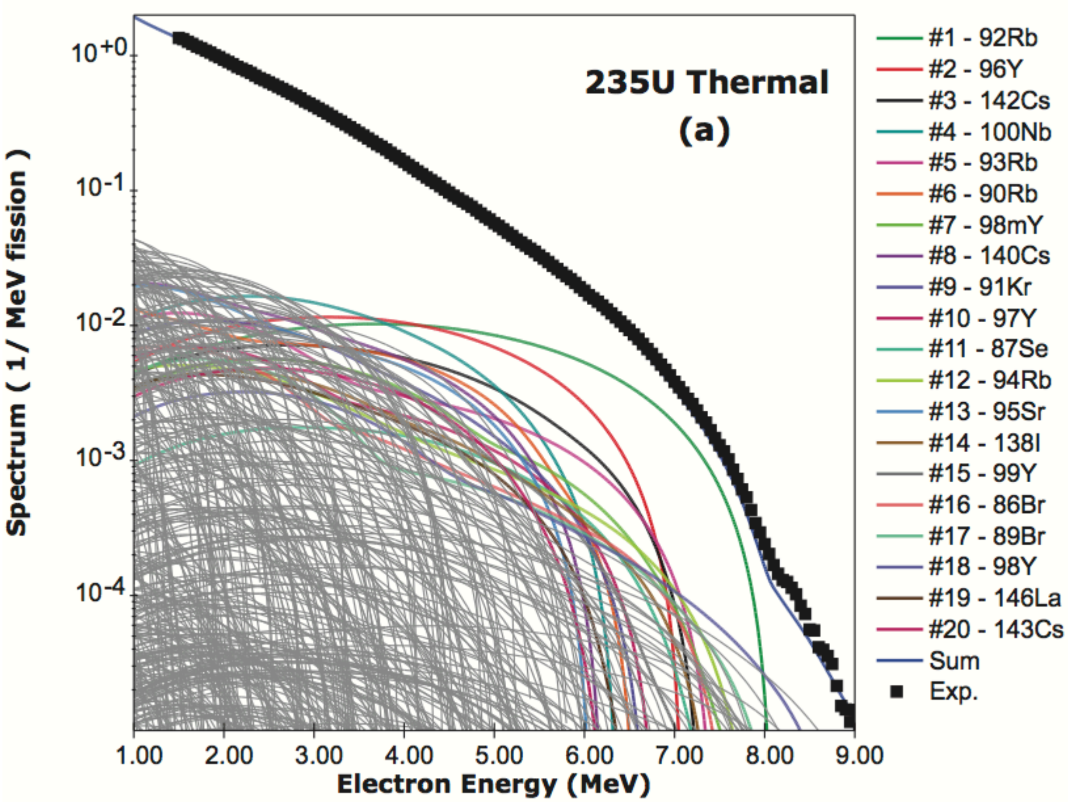
If nuclear data accurate, calculated 5-7 MeV shoulder seems robust.

Are the fission yields and branching fractions accurate for these prominent branches?

Dominant Branches

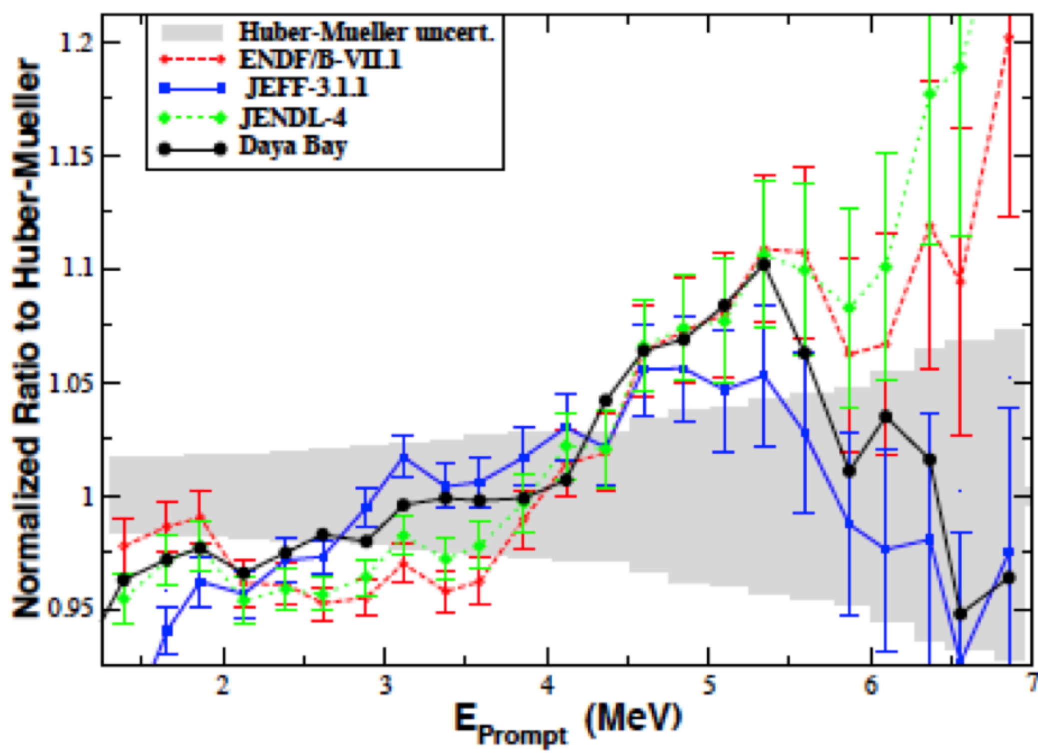
Recent calculations also identify similar aspects of spectrum

Light, odd-N, odd-Z fission fragments dominate emission



A.A.Sonzogni, T.D.Johnson,E.A.McCutchan PRC 91, 011301(R) (2015)

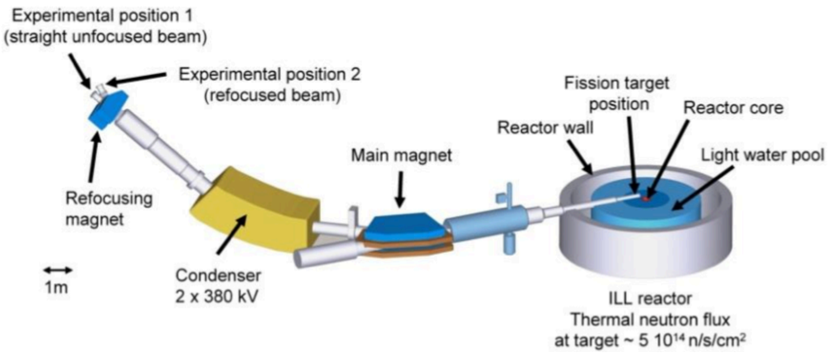
Similar spectra predicted by various nuclear databases



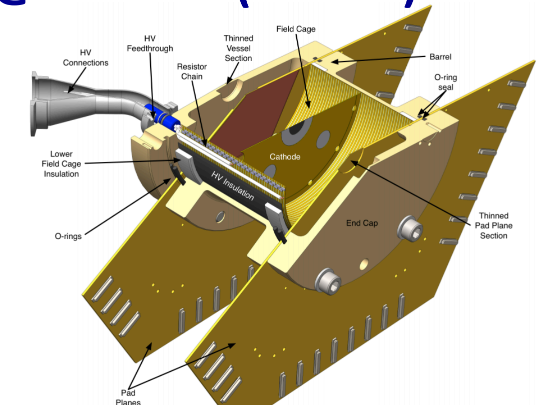
A.Hayes, Presented at the Workshop on the Intermediate Neutrino Program (BNL, Feb. 4-6, 2015)

Upcoming Measurements

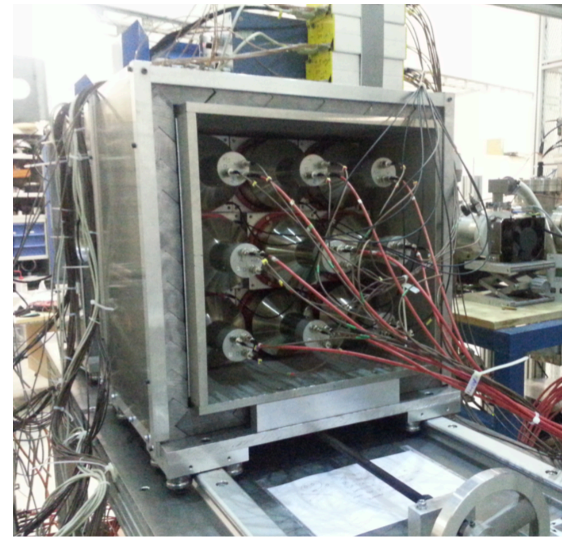
Fission Yields @ ILL (Lohengrin)



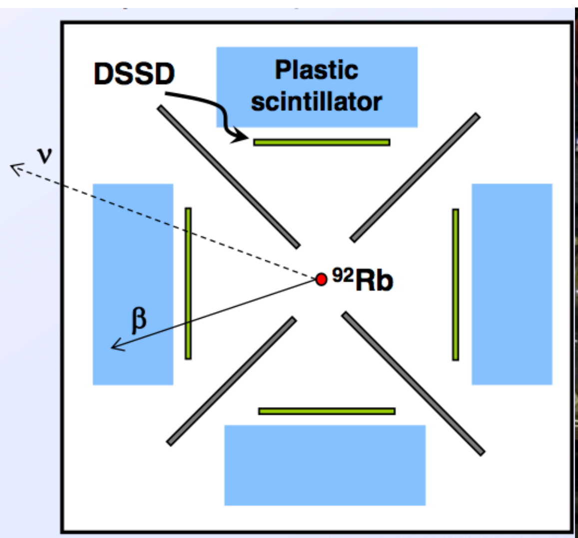
Fission Yields
@ LANSCE (NIFFTE)

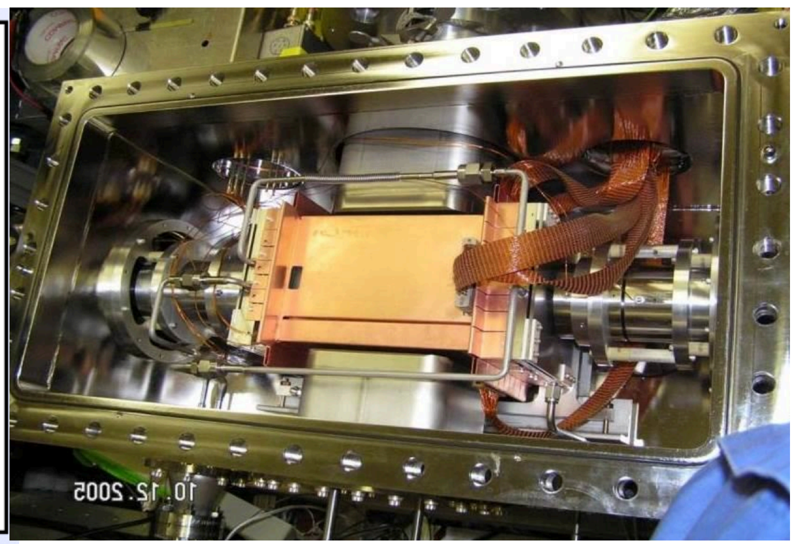


Total Absorp. Spec.
@ IGISOL (DTAS)



Precision β⁻ Spec. with Trapped Ions @ ANL/CARIBU





Total Absorp. Spec.
@ ORNL (MTAS)

Some examples of planned measurements of these decays:

N.D. Scielzo, private comm. [G.Li et al., PRL 110, 092502 (2013)]
A.-A. Zakari-Issoufou et al., EPJ Web of Conferences 66, 10019 (2014)
M. Heffner et al. (NIFFTE Collaboration), arXiv:1403.6771

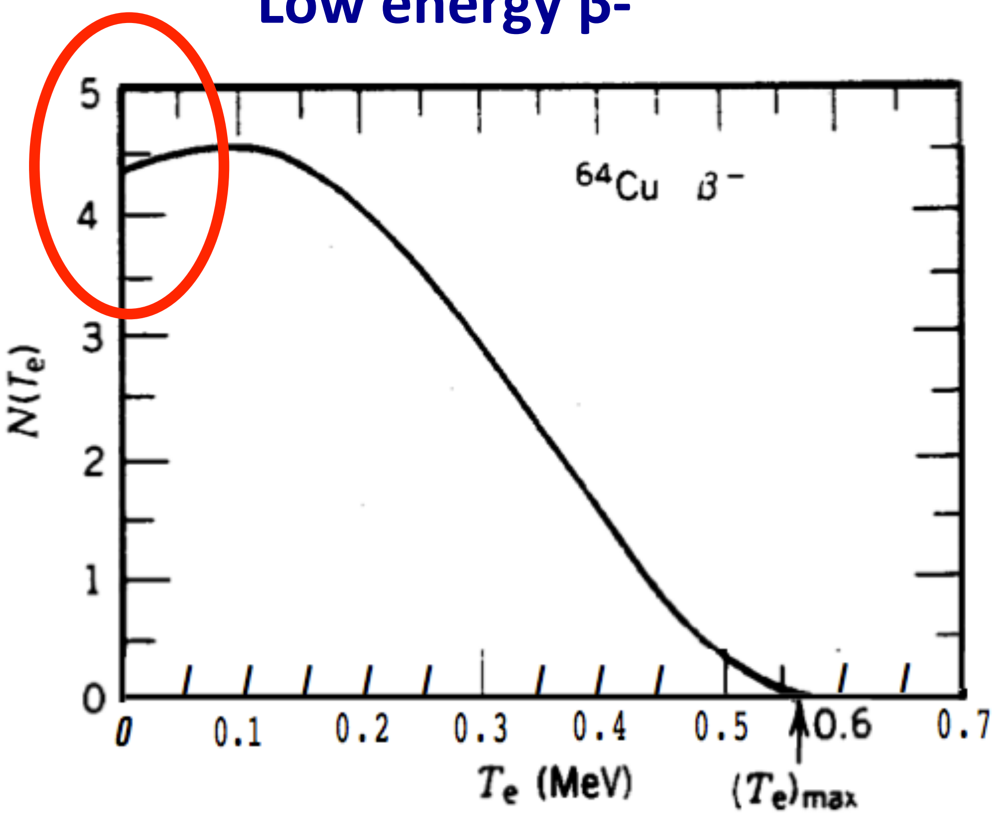
Detailed $\overline{\nu}_e$ Spectrum Shape

Calculation predicts significant discontinuities in spectrum.

Coulomb correction:

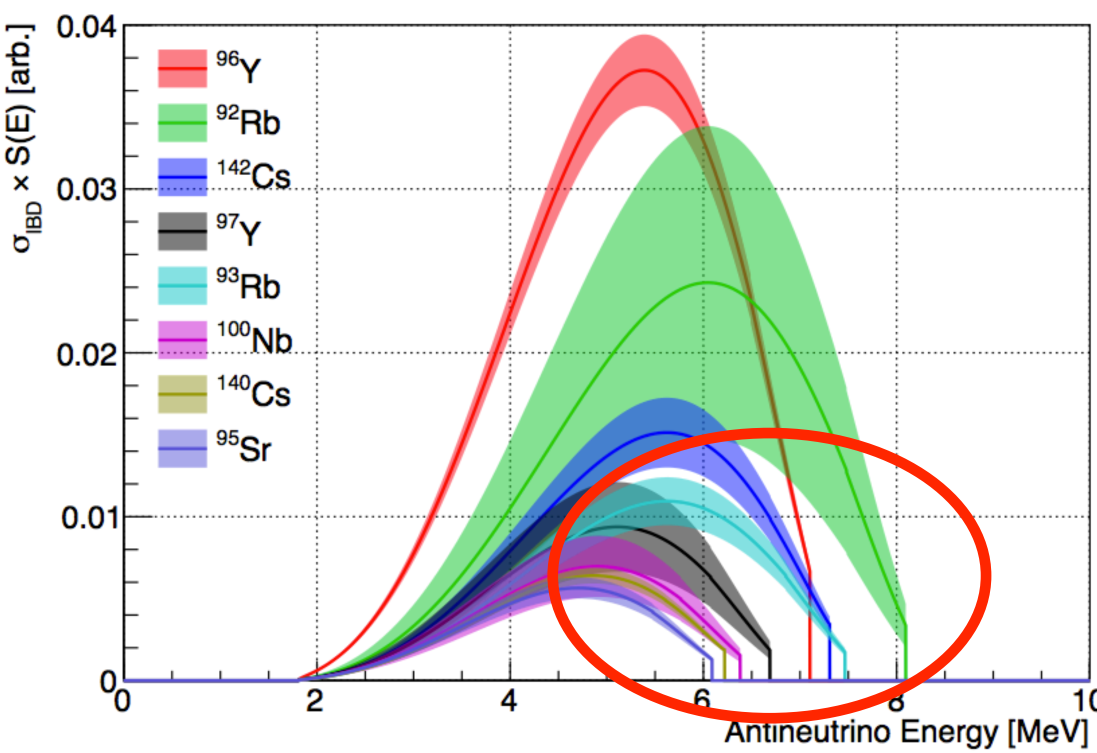
Nuclear charge enhances production of:

Low energy β-



Pronounced example from
R. D. Evans, The Atomic Nucleus

High-energy $\overline{\nu}_e$



Detailed $\overline{\nu}_e$ Spectrum Shape

Calculation predicts significant discontinuities in spectrum.

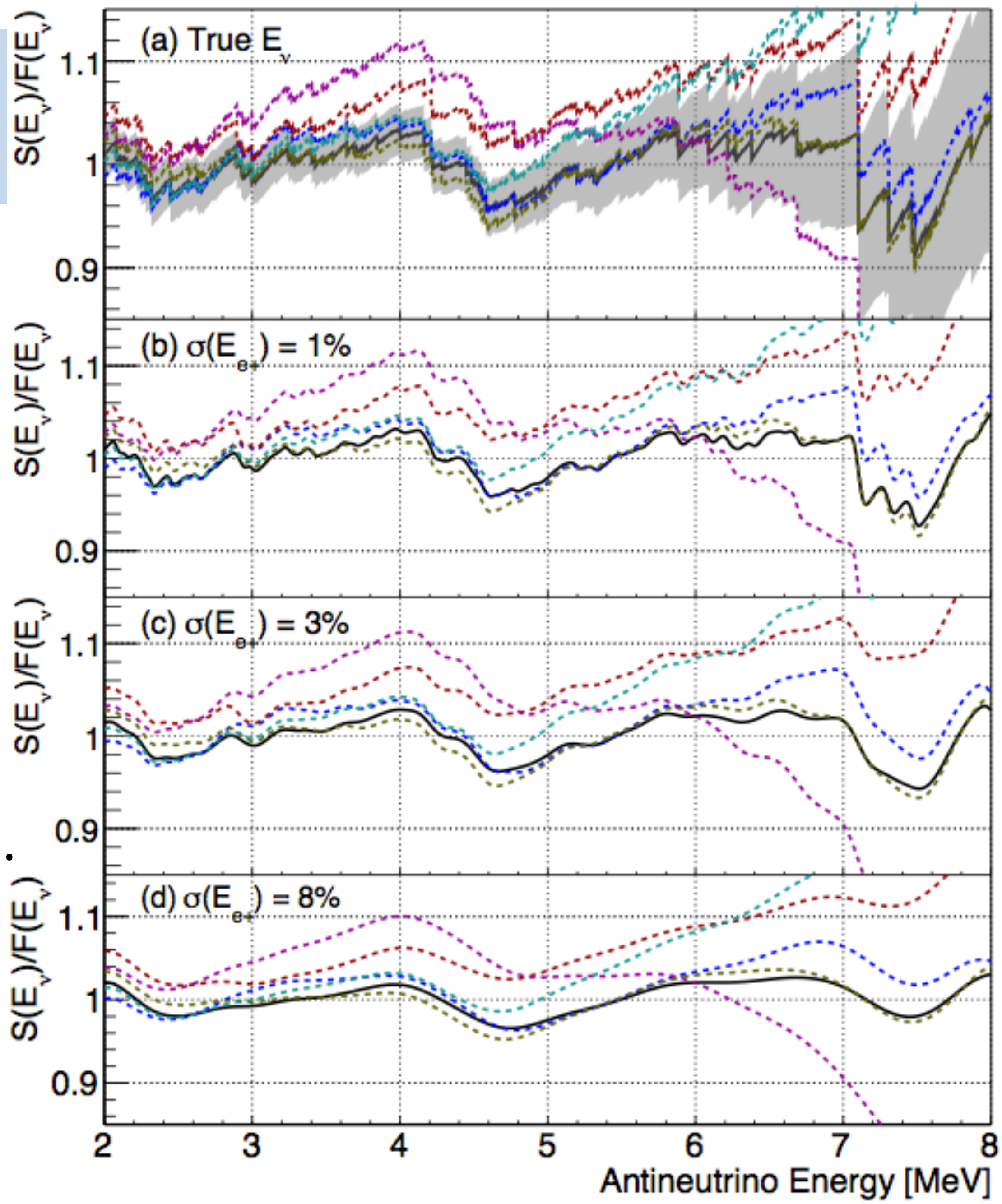
Reactor Spectroscopy?

Each edge identifies one significant decay branch.

Current detectors (6-8% resolution) unlikely to see details.

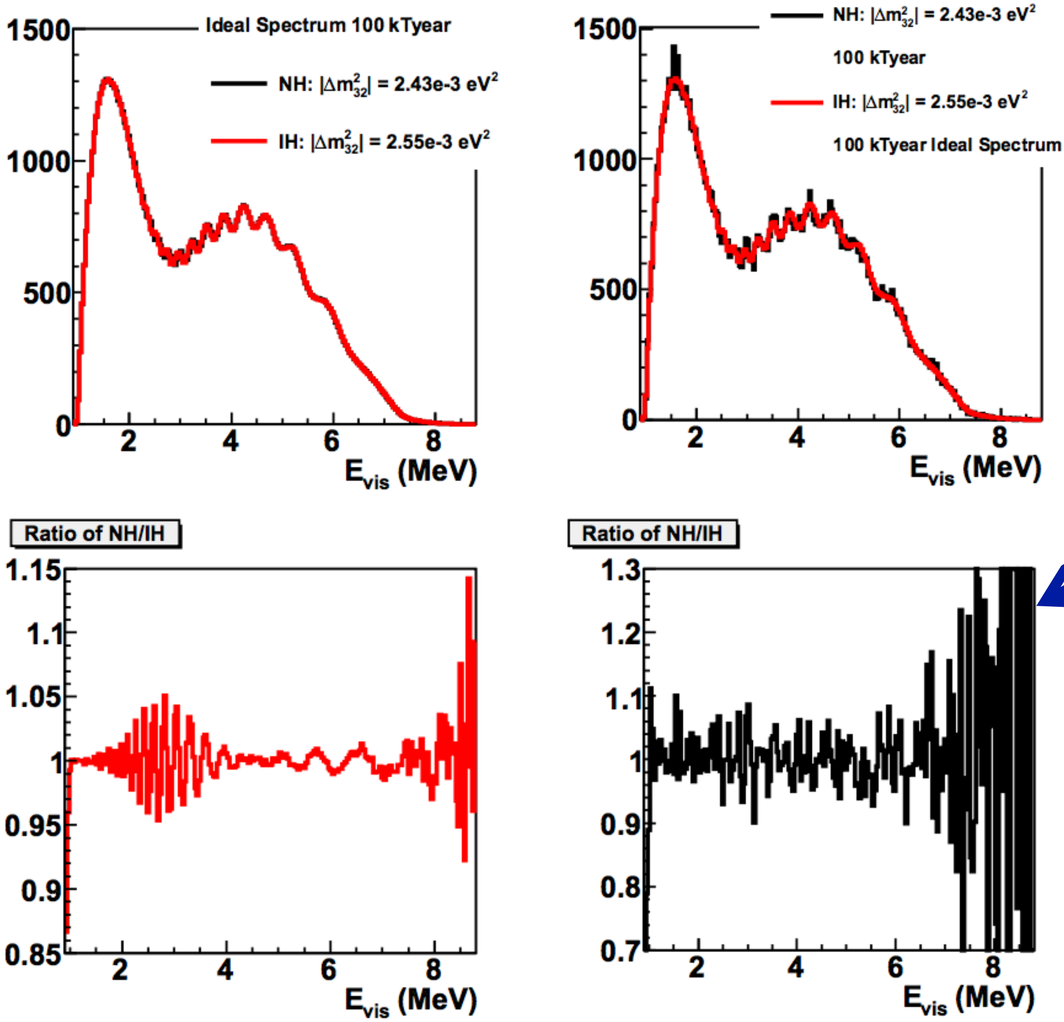
Could pose systematic issue for future high-resolution measurements.

Solid: Nominal calc. *Dashed: Varying uncertainties*



Neutrino Mass Ordering

Spectral structure complicates determination of the mass ordering



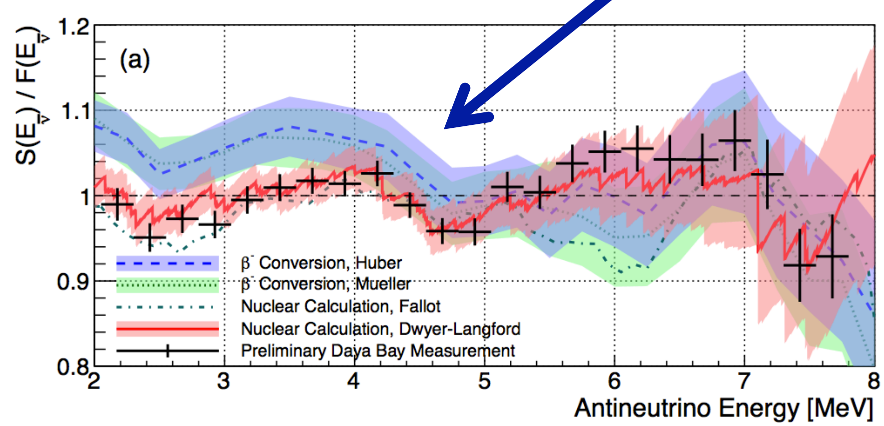
X.Qian, D.Dwyer, et al. PRD 87, 033005 (2013)

Detailed structure in spectrum:

In principle, not a show-stopper for measurement, but it adds difficult to quantify systematic uncertainty

Example measurement assuming true spectrum is smooth

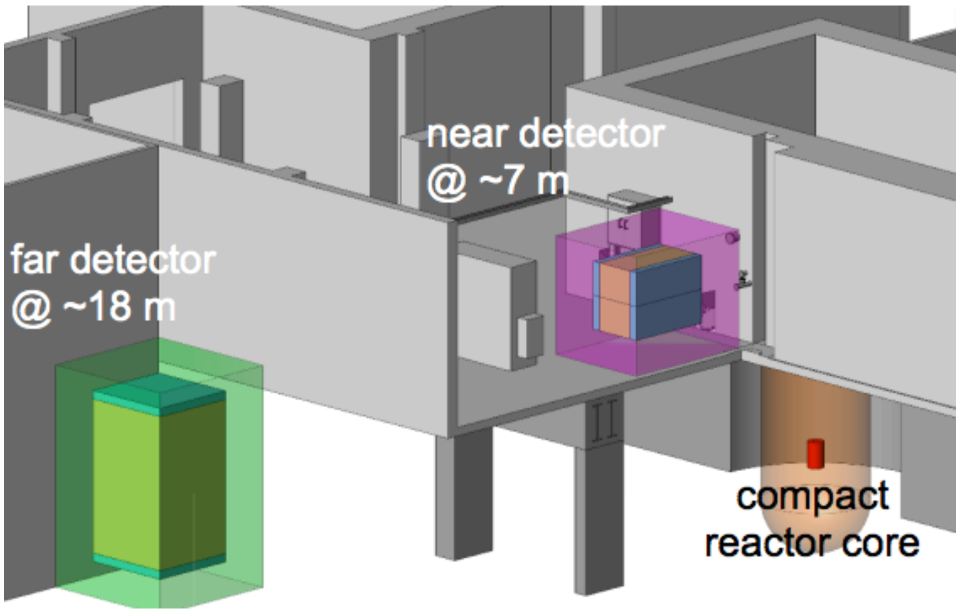
Example measured and calculated structure relative to smooth shape



Precision $\overline{\nu}_e$ Spectra?

Precision reactor $\overline{\nu}_e$ measurements as accurate benchmarks

Short-baseline reactor experiments

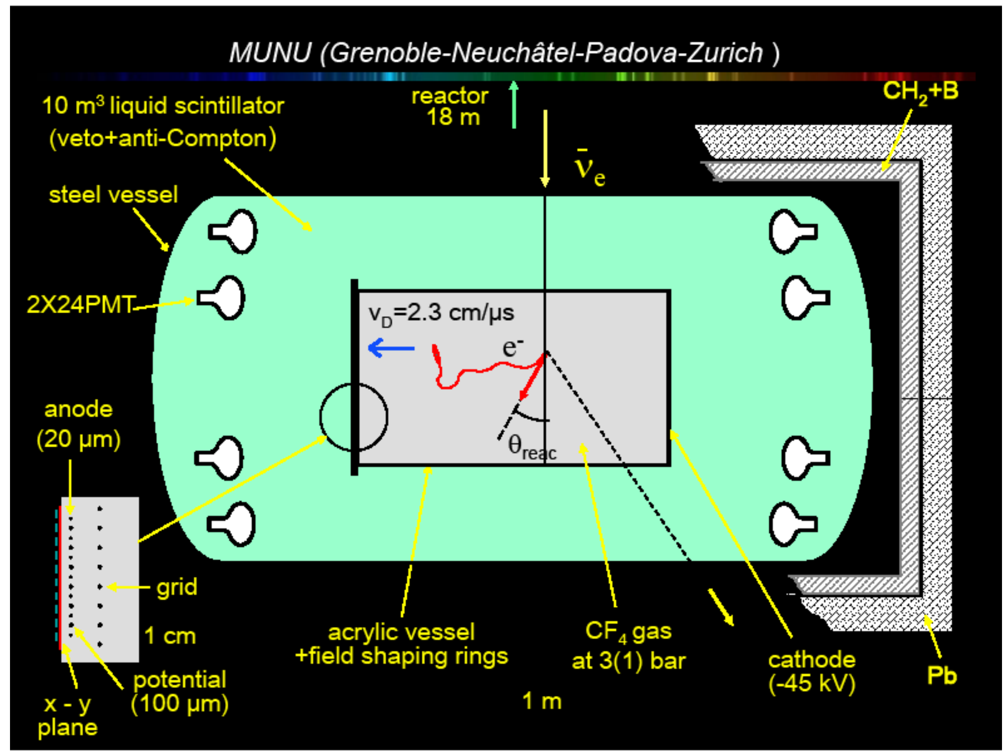


Example: PROSPECT @ ORNL, $\sigma_E \approx 4.5\%$

Precision measurement of $^{235}U\ \overline{\nu}_e$
- Strong constraint of models

Challenges: controlling backgrounds.

High-pressure gas TPC (IHEP-Beijing)



Similar to MUNU Gas TPC design

Potent for higher energy resolution

Conclusions

Modeling nuclear reactor antineutrino emission is a messy business.

Existing β^- conversion models:

- Based on measurements of post-fission cumulative β^- emission
- Predict a flux ~6% higher than reactor measurements
- Spectral shape inconsistent with recent reactor measurements

Nuclear *summation* models:

- Based on direct calculation from tabulated nuclear data
- Depend on fission yields and decay data of >1000 isotopes
- Suffer from significant unquantified uncertainties
- Spectrum shows surprising agreement with recent $\overline{\nu}_e$ measurements

Detailed spectral structure:

- Provides a unique signature of nuclear processes in reactor
- Could be a systematic issue for future ν-physics measurements

Future measurements have significant potential to improve our understanding.