



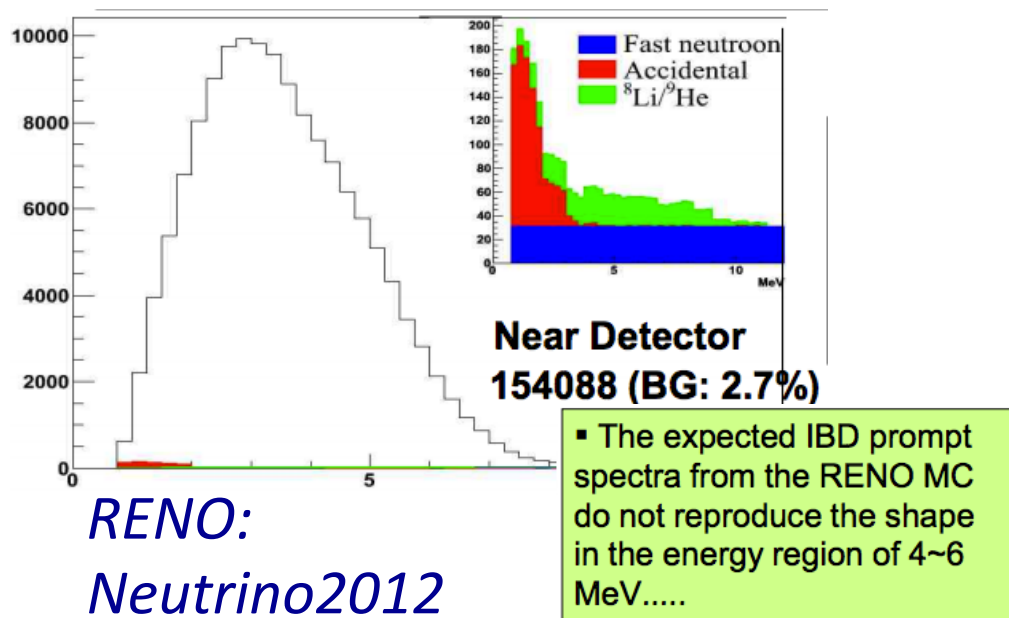
Spectral Structure of Antineutrinos from Nuclear Reactors

D. Dwyer, T. Langford

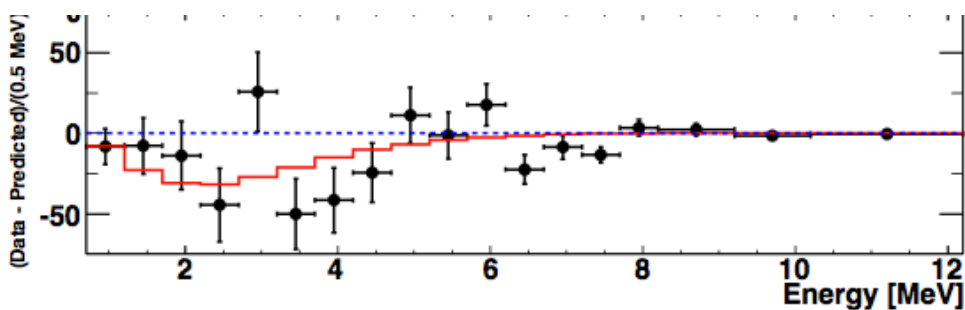
Jan. 22, 2015

A Spectral Problem?

Hints of deviation between data and models in Summer 2012

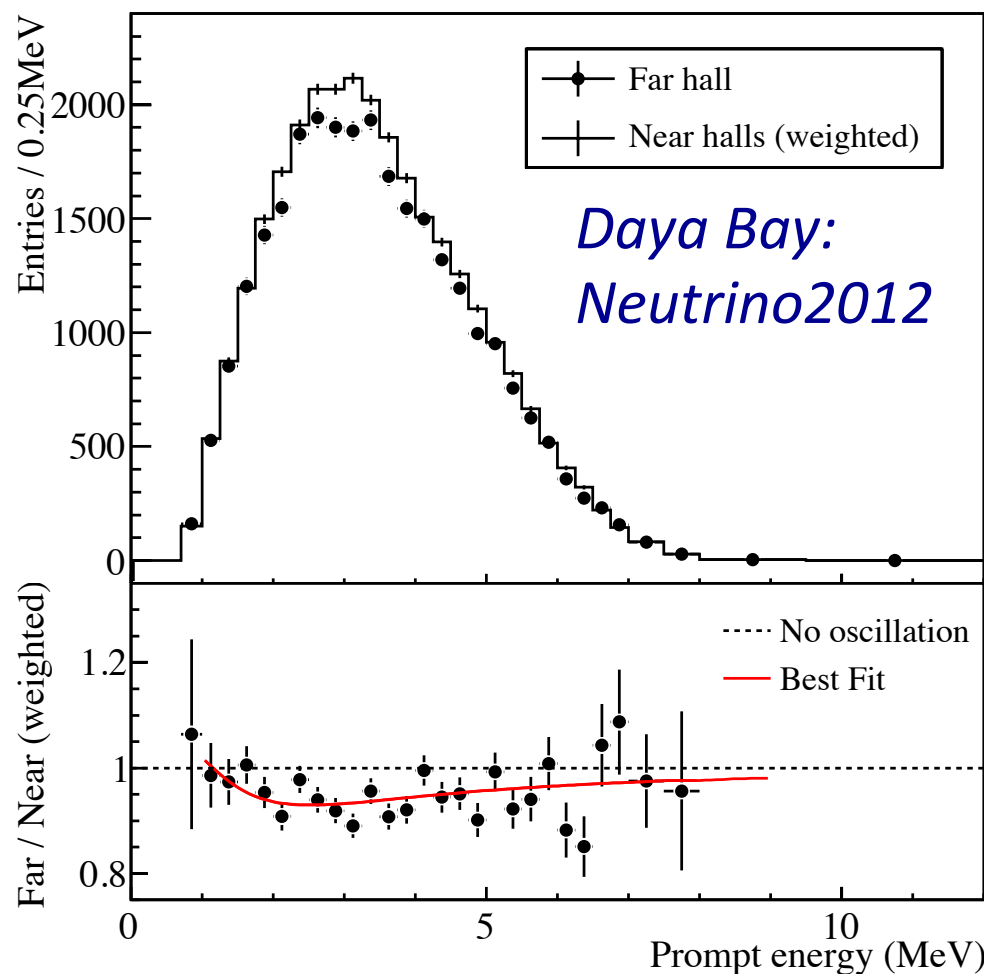


*RENO:
Neutrino2012*



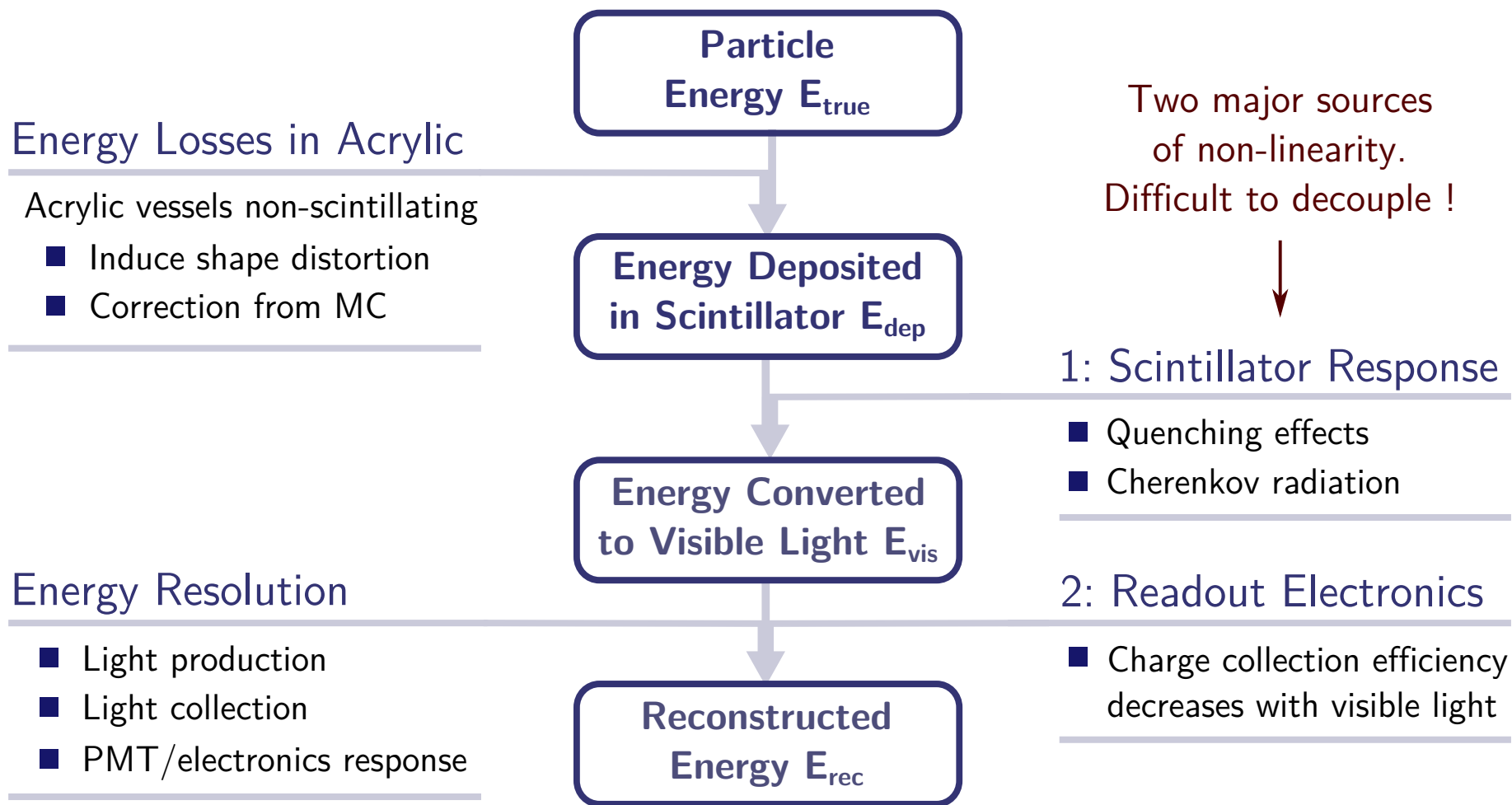
*Possible sign in Double CHOOZ data?
Phys. Rev. Lett. 108, 131801 (2012)*

Not obvious in Daya Bay figure, since comparison with model not shown.



Major Question

Could deviation be due to experiment systematic effects?

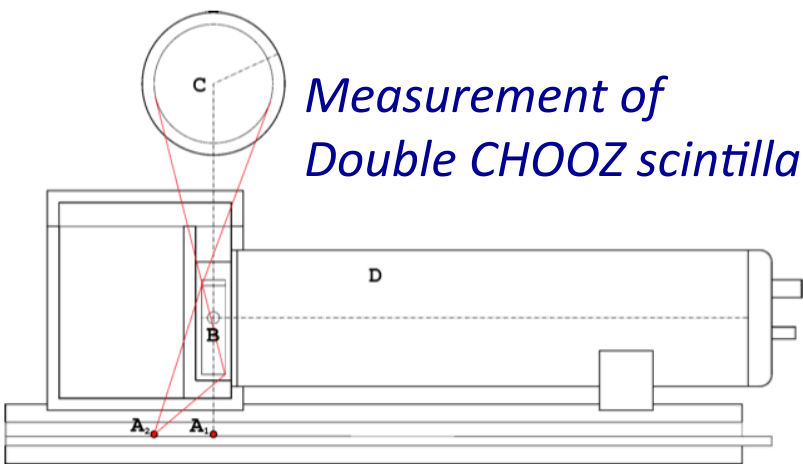


Example of detector response modeling (from Daya Bay)

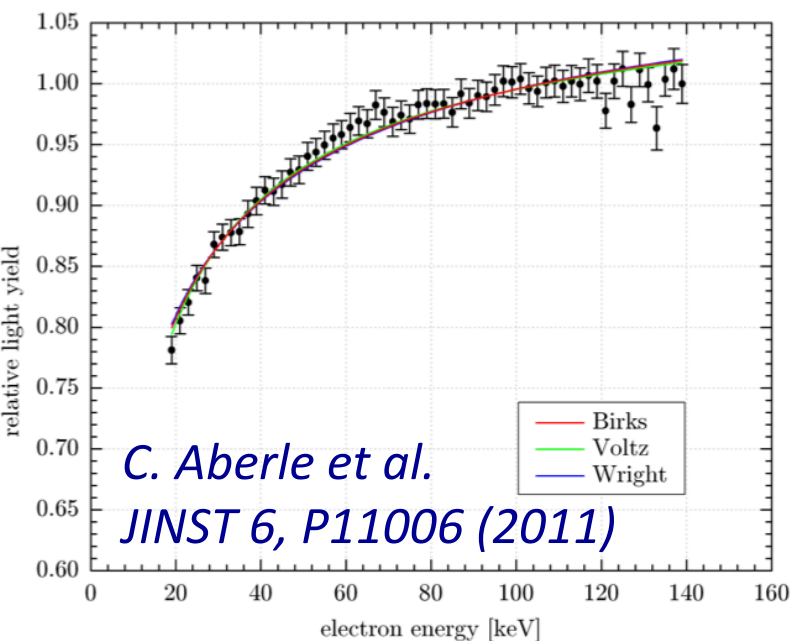
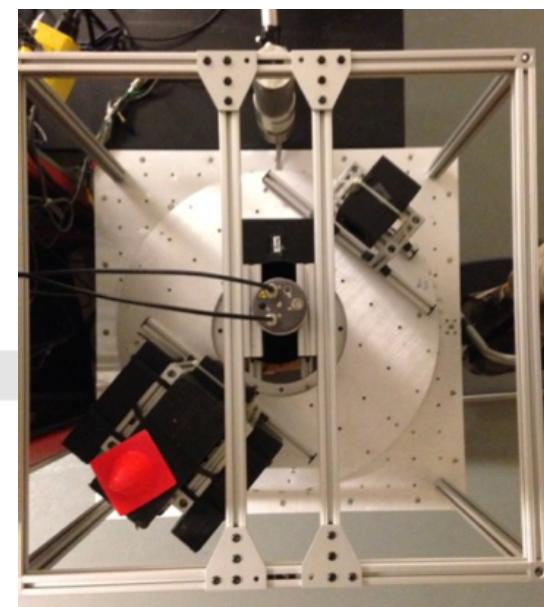
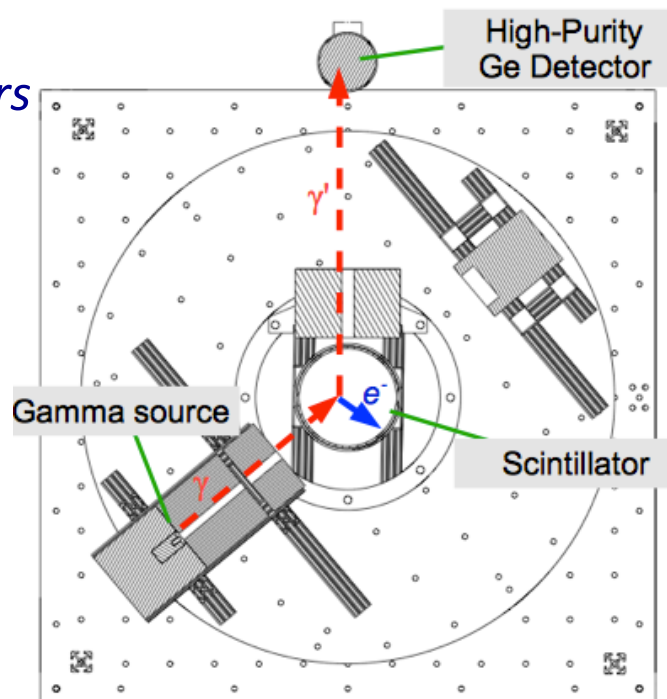
Scintillator Nonlinearity

Dedicated studies of nonlinear light emission by scintillators

Measurement of Double CHOOZ scintillators



Measurements in progress at LBNL



Other examples:

O. Perevozchikov Ph.D. Thesis (2009)

H.W.C. Tseung et al. NIM A654 318 (2011)

F.H. Zhang et al. arXiv:1403.3257

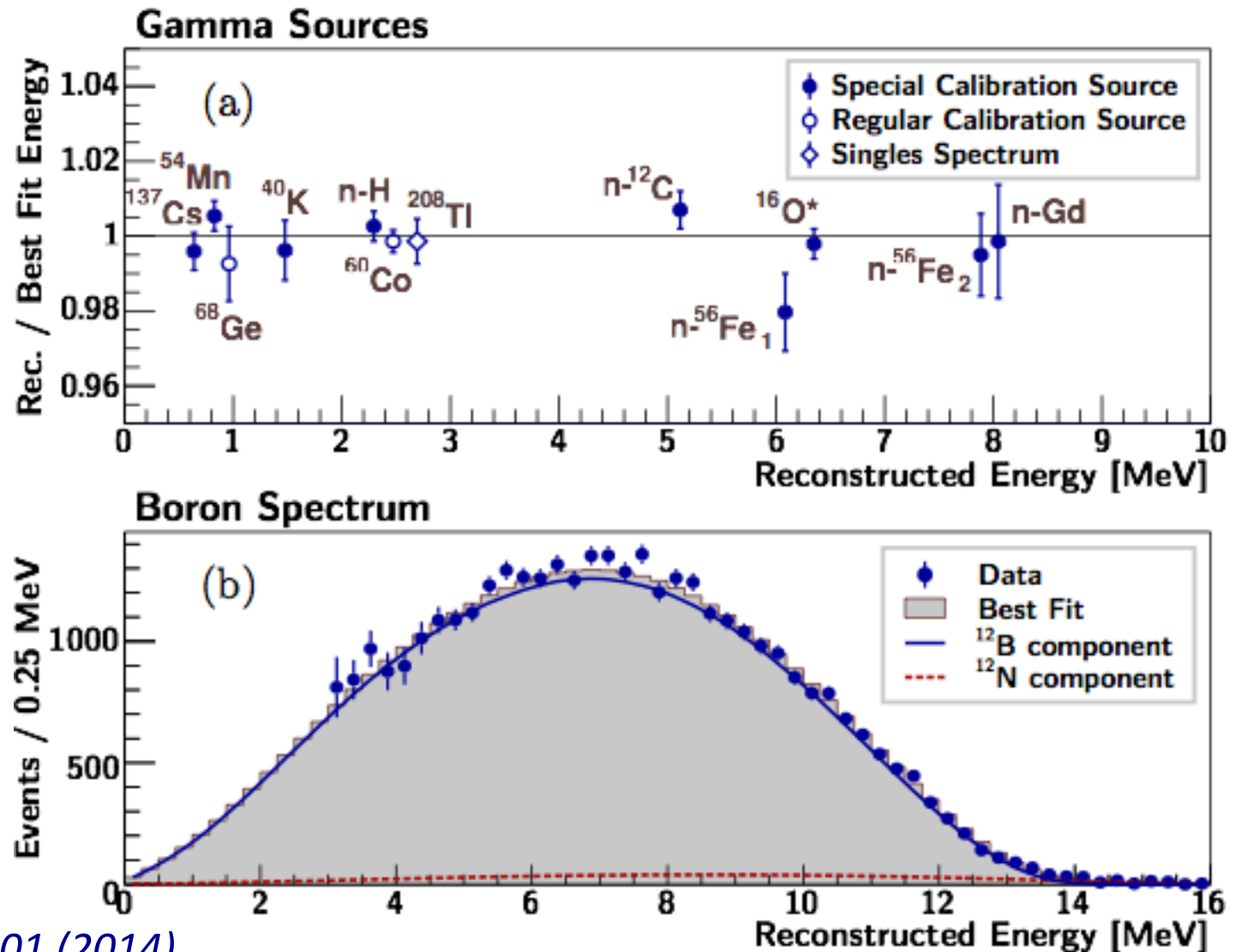
W.S. Choong et al. IEEE Trans. Nucl. Sci. 55 1073 (2008)

Detector Nonlinearity

Challenging to precisely constrain nonlinear detector response

Competing effects from scintillator and electronics.

Impact positrons (from antineutrinos) differently than gamma rays (from calibration)

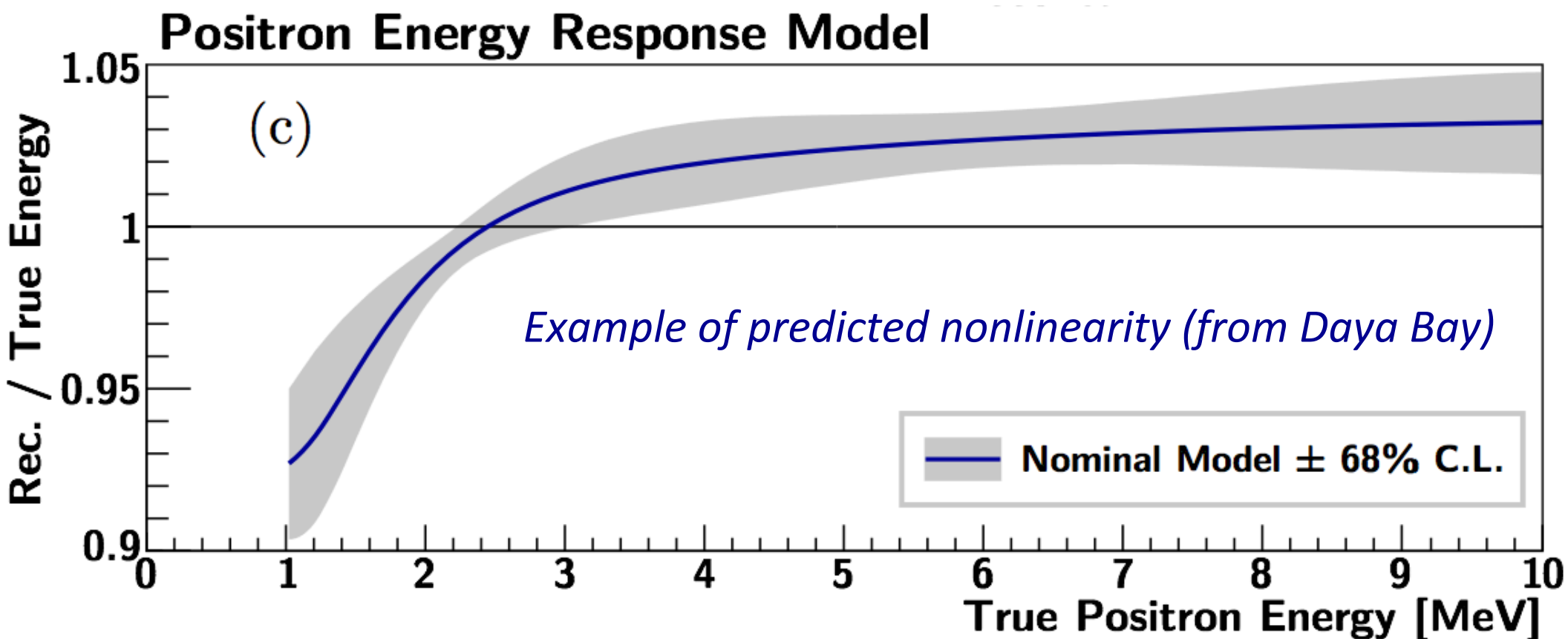


Phys. Rev. Lett. 112, 061801 (2014)



Detector Nonlinearity

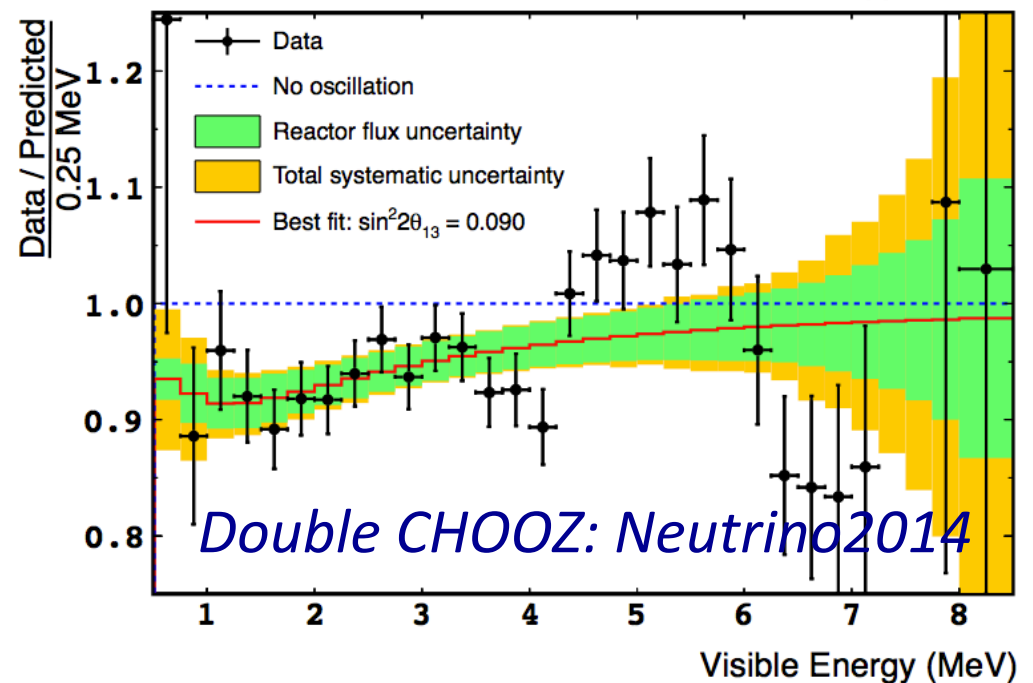
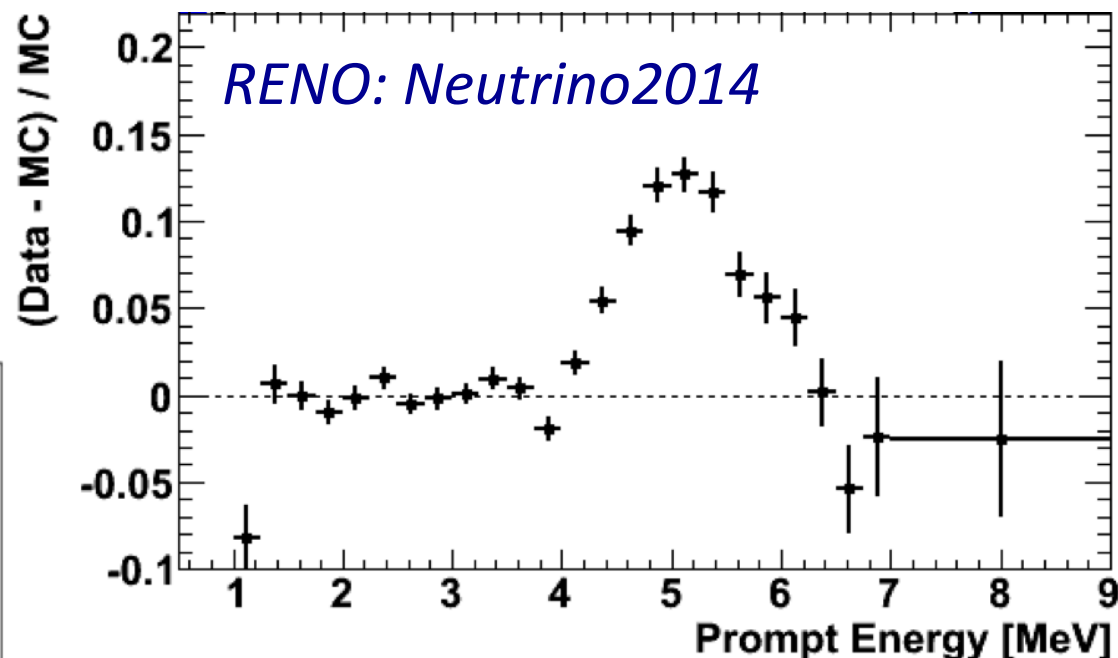
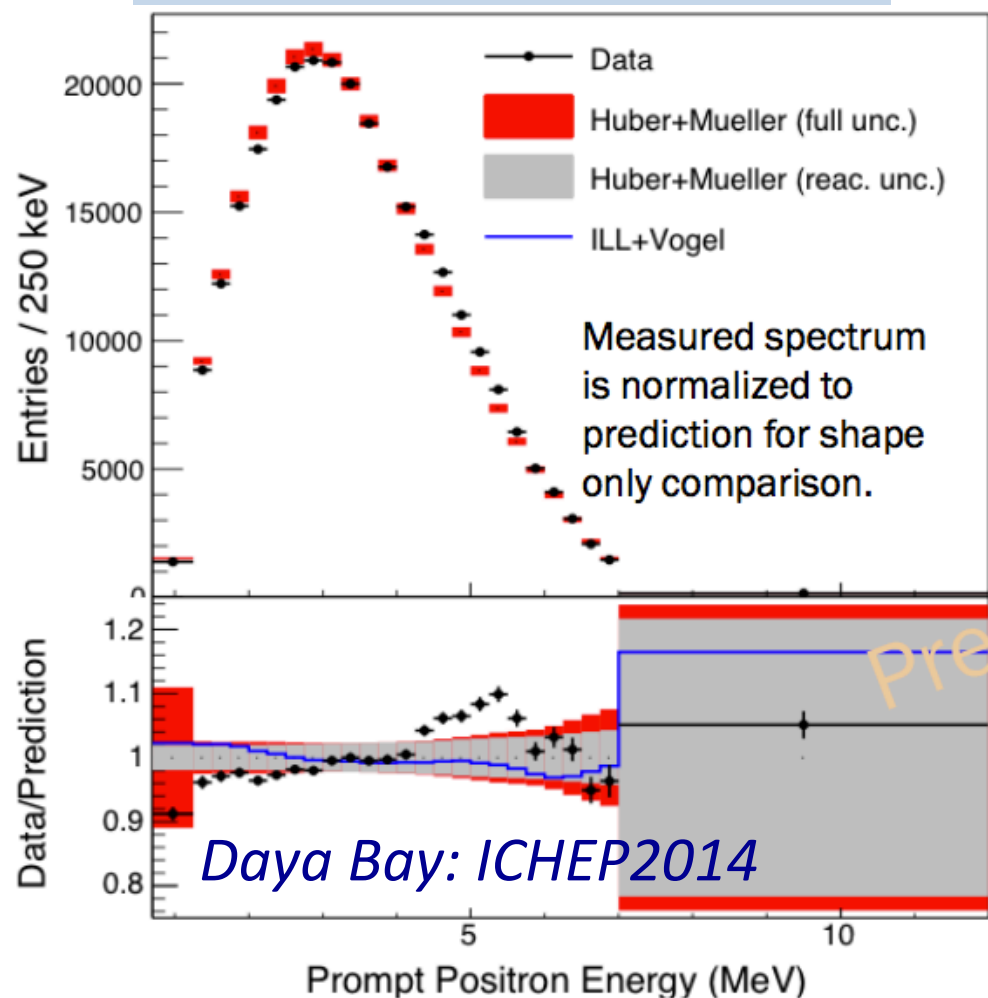
Model uncertainties initially leave room to account for deviation.



By Summer 2014, precision in models improved.

$\bar{\nu}_e$ Spectrum Disagreement

All three recent $\bar{\nu}_e$ measurements show a consistent deviation from β^- conversion spectra.





β^- Conversion

Standard: Use cumulative β^- spectrum to predict $\bar{\nu}_e$ spectrum

Method:

- Expose fission parents to thermal neutrons
- Measure total outgoing β^- energy spectra
- Predict corresponding $\bar{\nu}_e$ 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)

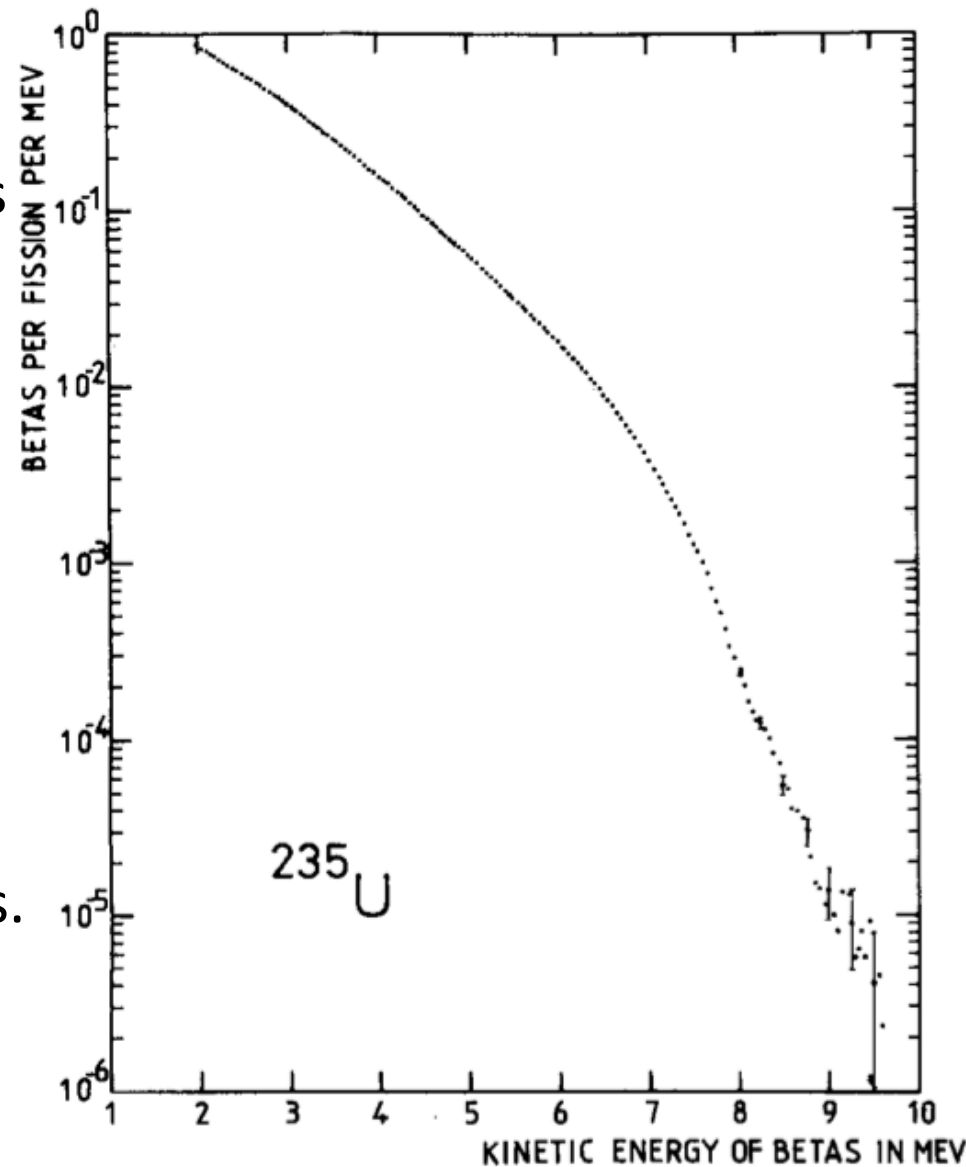
Phys. Rev. C84, 024617 (2011)

Results:

- More precise than *ab initio* predictions
- Standard approach for ~ 30 years
- Predicts 6% higher flux than reactor msmts.

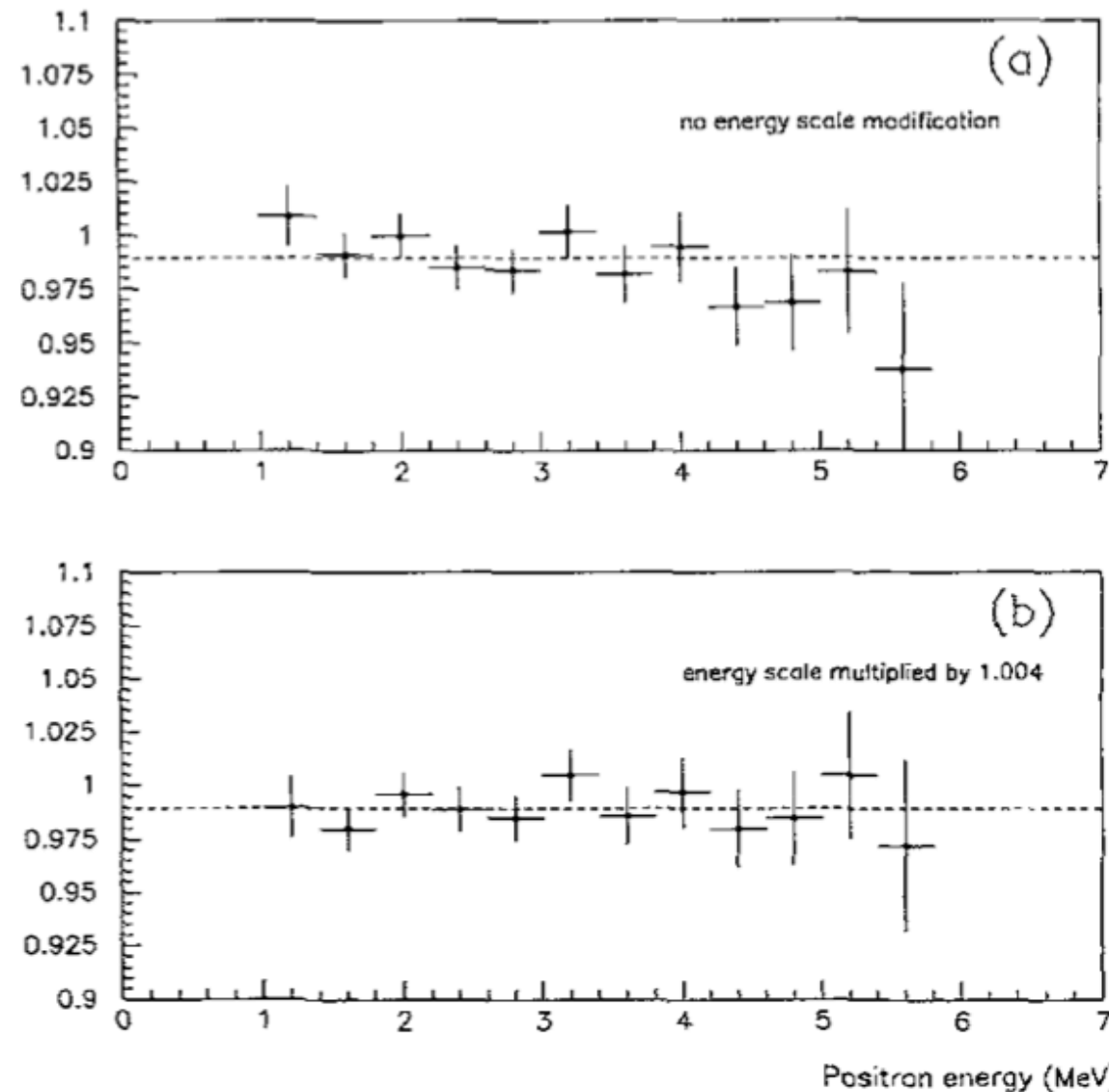
Reactor Anomaly, Sterile Neutrinos?

Phys. Rev. D83, 073006 (2011)



Bugey Measurement

Bugey spectral measurement agreed with β^- conversion model.



Comparison of Bugey 3 spectrum relative to conversion model.
Phys. Lett. B 374, 243 (1996)

No evidence of significant deviation.
Measured from 1 to 6 MeV.

Measured spectrum has slightly steeper slope with energy.

A minor (0.4%) shift in detector energy scale improves agreement.



Guidance

Do *ab initio* models suggest an origin for the 5-7 MeV deviation?

Approach:

Examine tabulated nuclear data to determine antineutrino spectrum composition from 5 to 7 MeV.

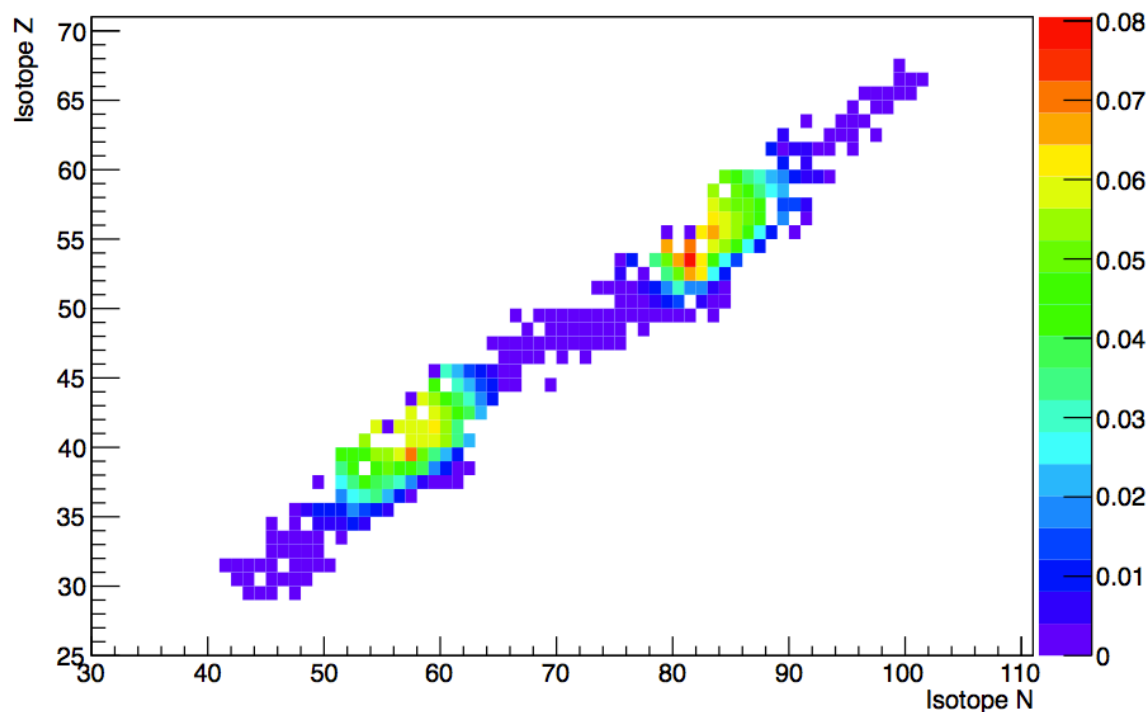
Method:

Cumulative fission yields for >1300 fission daughters provided by ENDF/B.VII.1 database.

Decay endpoints and branching fractions provided by ENSDF (kindly tabulated by A. Hayes).

Assume allowed beta decay shapes (including coulomb, radiative, weak magnetism corrections).

Cumulative fission daughter isotope yields for a nominal reactor





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?

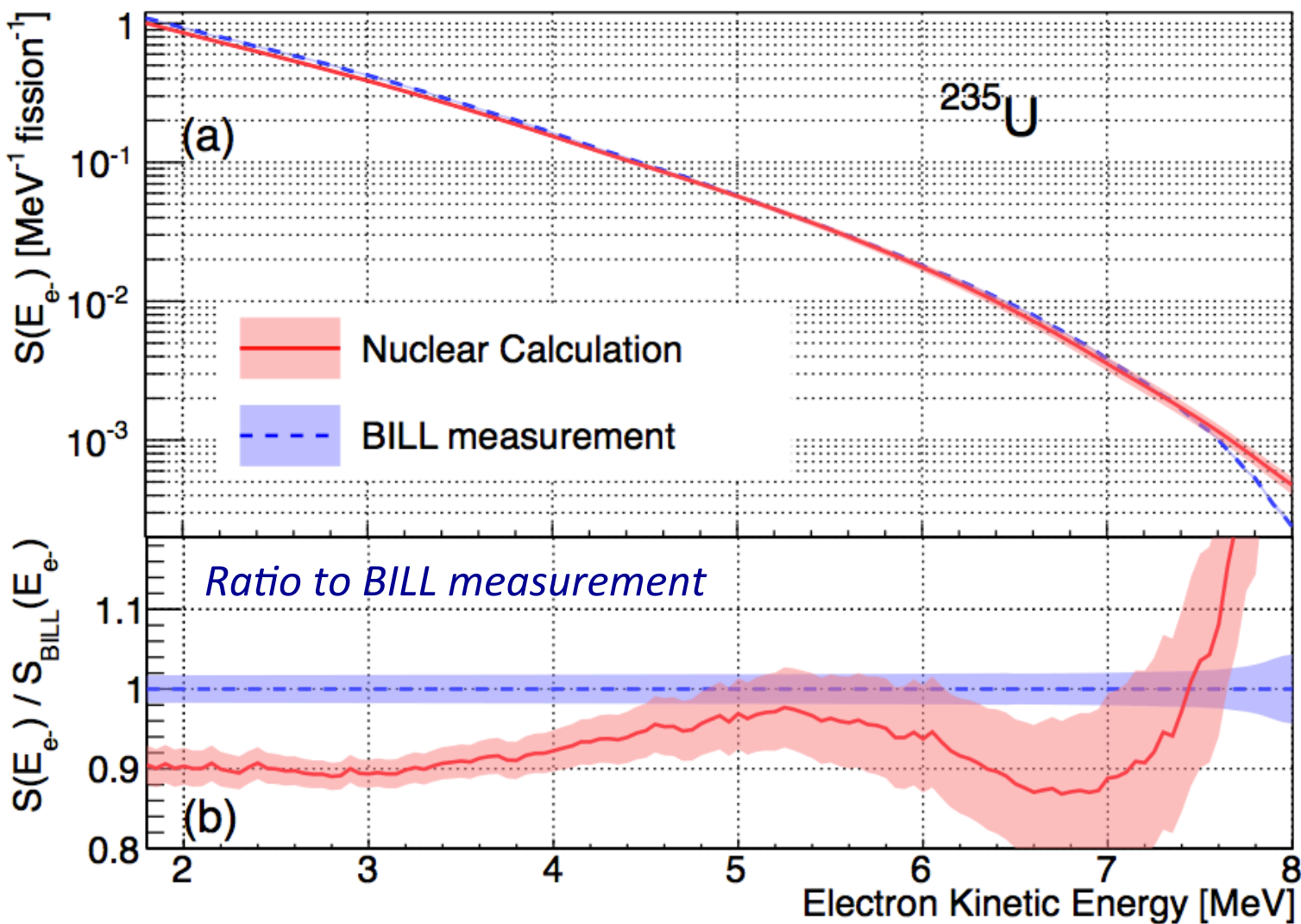
- Mismatch of decay initial-final spin and parity can distort spectrum

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

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

β^- Spectrum Disagreement

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



Note:

Uncertainty band for calc. is a lower bound.

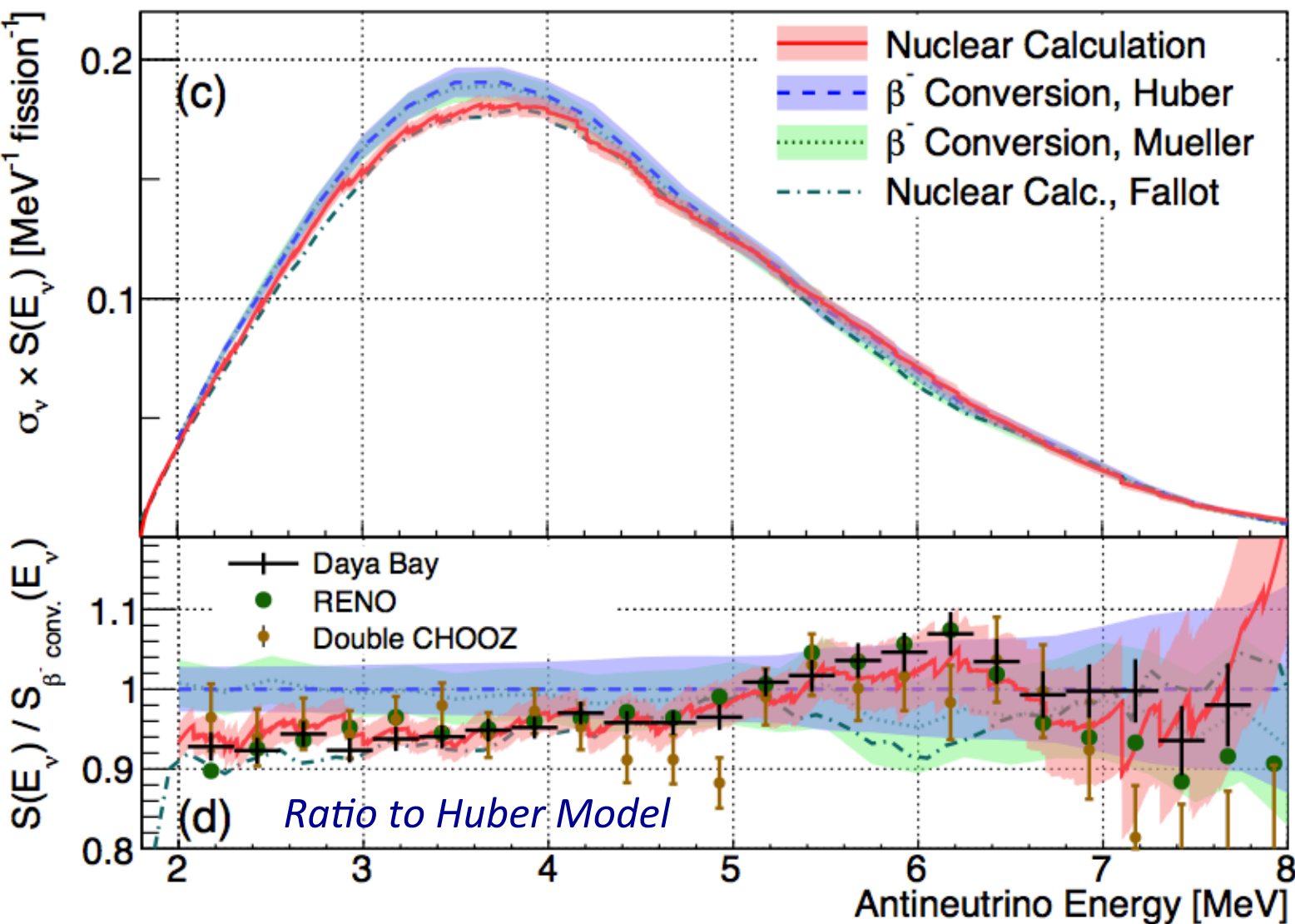
Only includes tabulated yield+branch uncertainties.

Occam's razor:
 Something wrong with calculation?

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

Reactor $\bar{\nu}_e$ Spectrum

Direct calculation unexpectedly agrees with preliminary msmts.



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

Data normalization adjusted to accurately compare shape.

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

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



Dominant Branches

Eight decay branches dominate 5-7 MeV shape in the calculation.

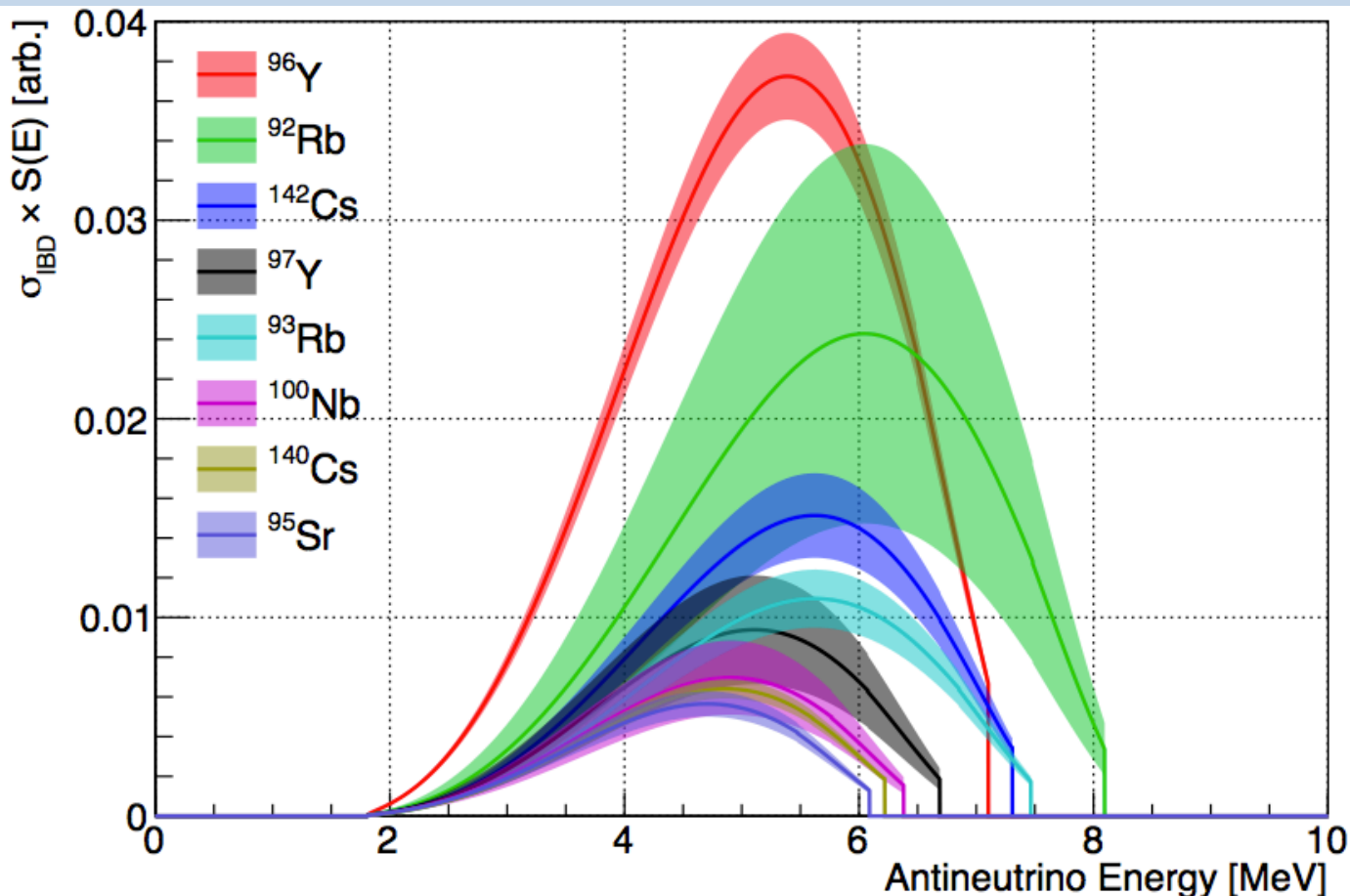
Isotope	Q[MeV]	$t_{1/2}$ [s]	$\log(ft)$	Decay Type	N [%]	σ_N [%]
^{96}Y	7.103	5.34	5.59	$0^- \rightarrow 0^+$	13.6	0.8
^{92}Rb	8.095	4.48	5.75	$0^- \rightarrow 0^+$	7.4	2.9
^{142}Cs	7.308	1.68	5.59	$0^- \rightarrow 0^+$	5.0	0.7
^{97}Y	6.689	3.75	5.70	$1/2^- \rightarrow 1/2^+$	3.8	1.1
^{93}Rb	7.466	5.84	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.

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

Dominant Branches

Eight decay branches dominate 5-7 MeV shape in the calculation.



Energy Spectra:
Allowed shape
+ IBD cross-section

Uncertainties:
Fission Yield
Branch fraction
⁹²Rb most significant

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

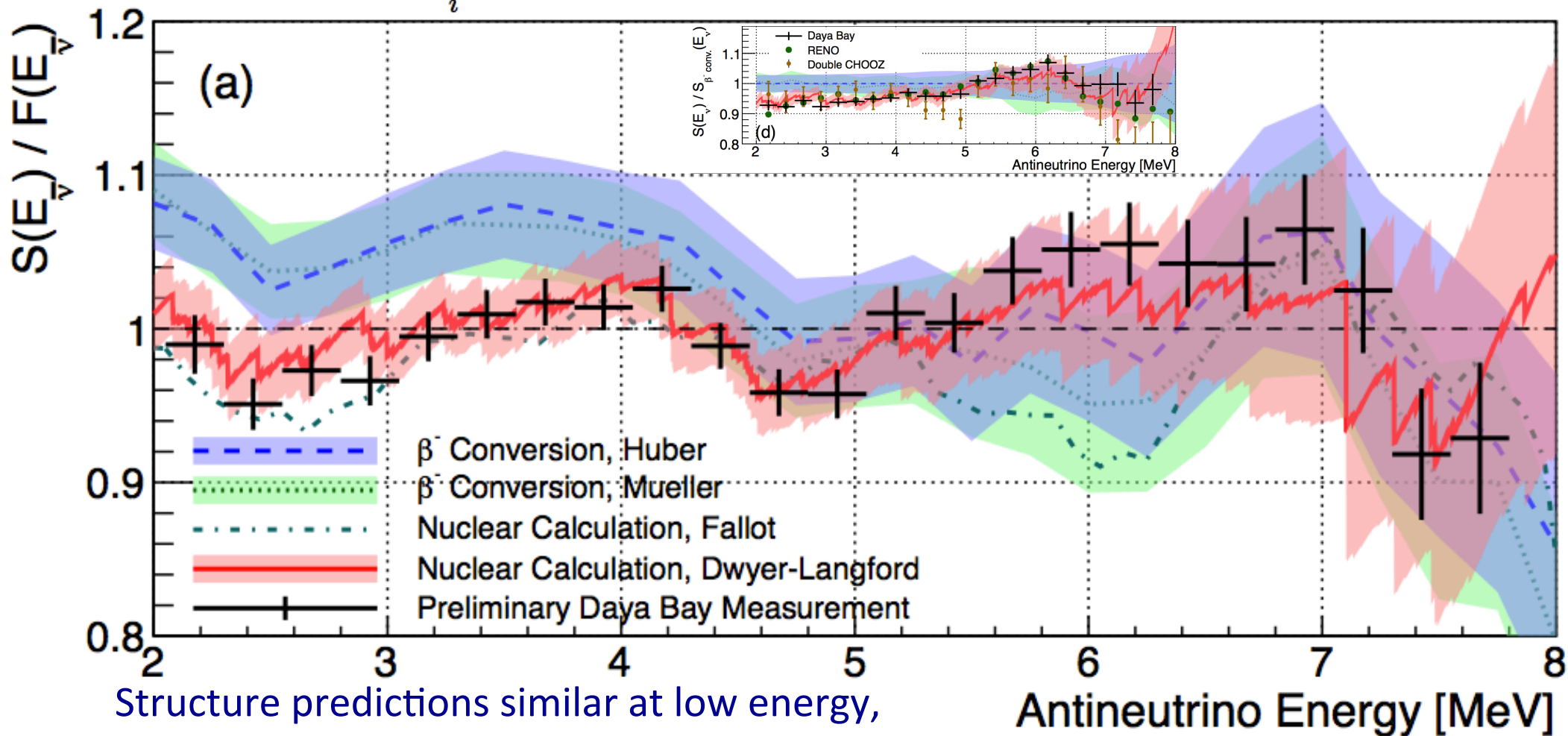
Recent plans for direct measurements of these decays:

- N.D. Scielzo, private communication [G.Li et al., PRL 110, 092502 (2013), R.M. Yee et al., PRL 110, 092501 (2013)]*
- A.-A. Zakari-Issoufou et al., EPJ Web of Conferences 66, 10019 (2014)*
- M. Heffner et al. (NIFTE Collaboration), arXiv:1403.6771*

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

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

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



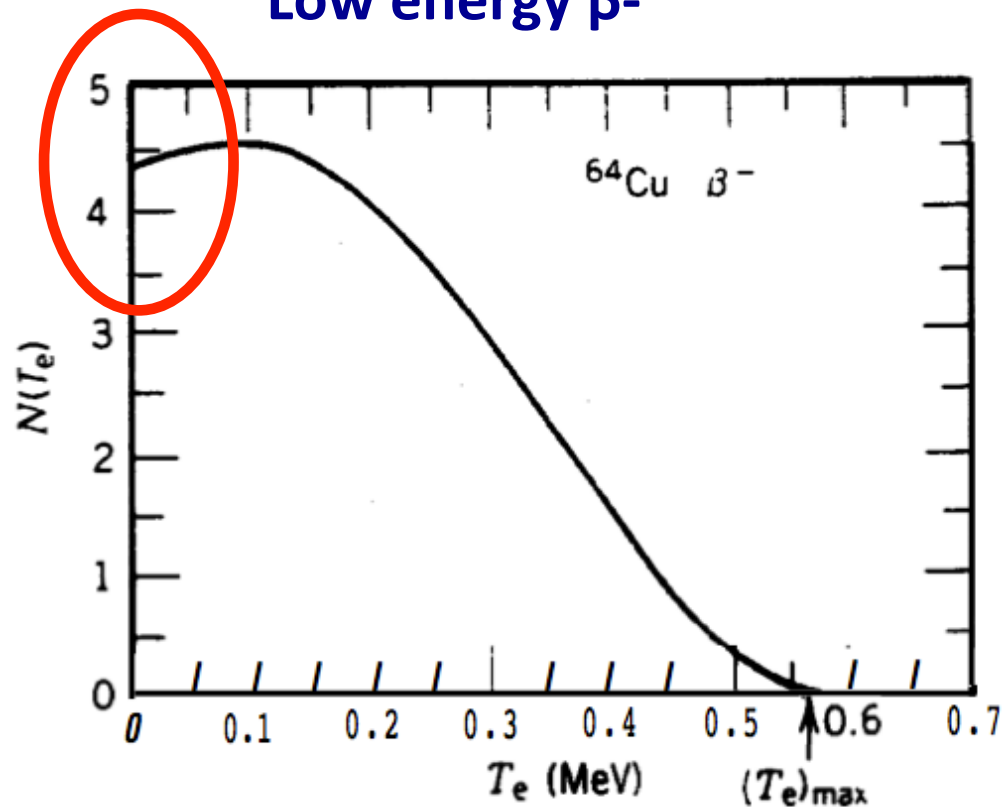
Detailed $\bar{\nu}_e$ Spectrum Shape

Calculation predicts significant discontinuities in spectrum.

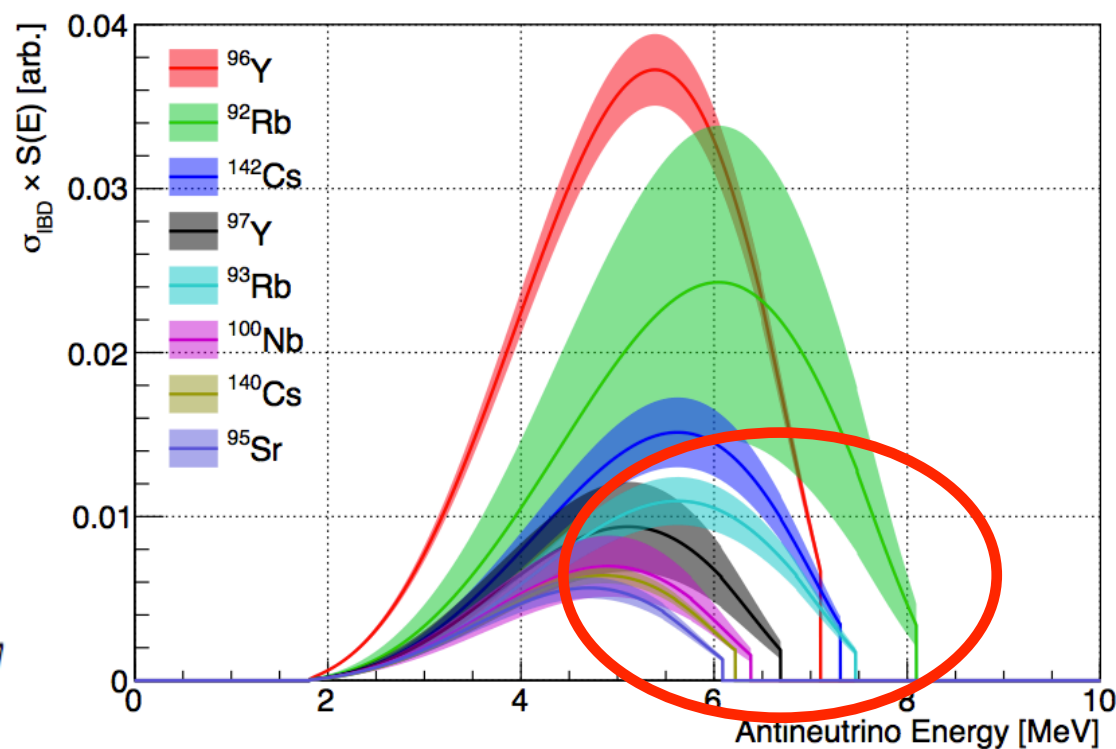
Coulomb correction:

Nuclear charge enhances production of:

Low energy β^-



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



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



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

Calculation predicts significant discontinuities in spectrum.

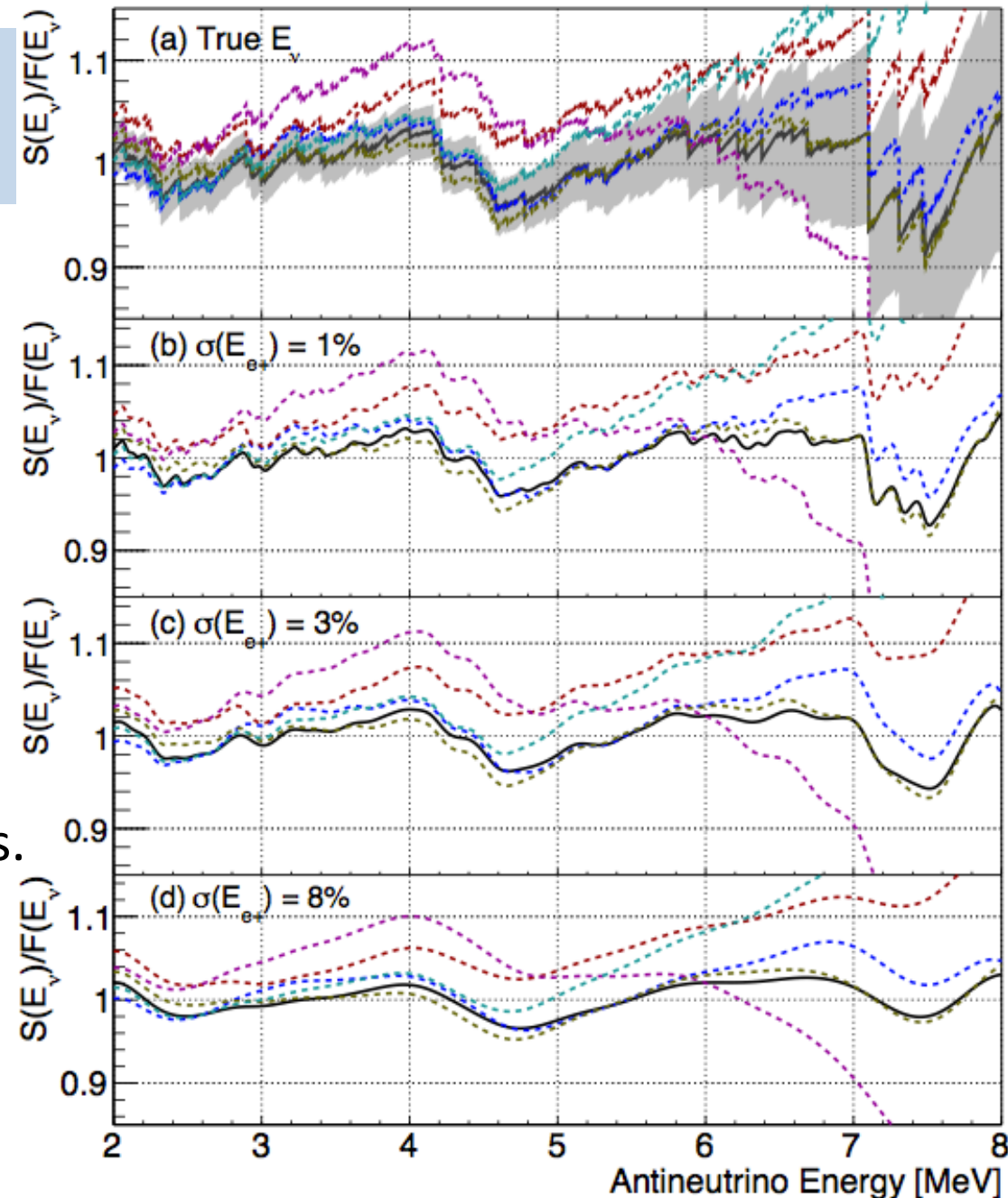
Reactor Spectroscopy?

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





Prospects and Questions

Some discussion topics for this workshop.

Prospects:

- Antineutrino measurements now more precise than models
- Ab initio calculations may help explain spectrum structure, although normalization and large-scale systematic biases difficult to constrain.
- Direct measurement of prominent isotope beta-decays may constrain

Questions:

- How to make $\bar{\nu}_e$ spectral measurements more useful for model testing?
- Impact of a precision measurement of HEU reactor spectrum?
- Any hope for 'spectroscopic' decomposition of reactor spectrum?
- How to quantify impact of spectral structure on future measurements?
- Systematic approach for accounting for forbidden spectral shapes?
- Origin of deviation of β^- conversion spectrum models from measurements?