Nuclear Data Needs:
The Problem of Reaction Antineutrinos

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Nuclear Data Needs for Capabilities and Applications

Berkeley, CA

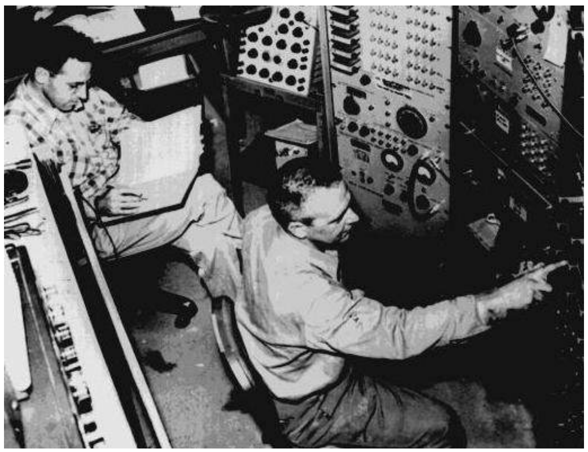
May 29, 2015

Reactor Antineutrinos: A Tool for Fundamental Science

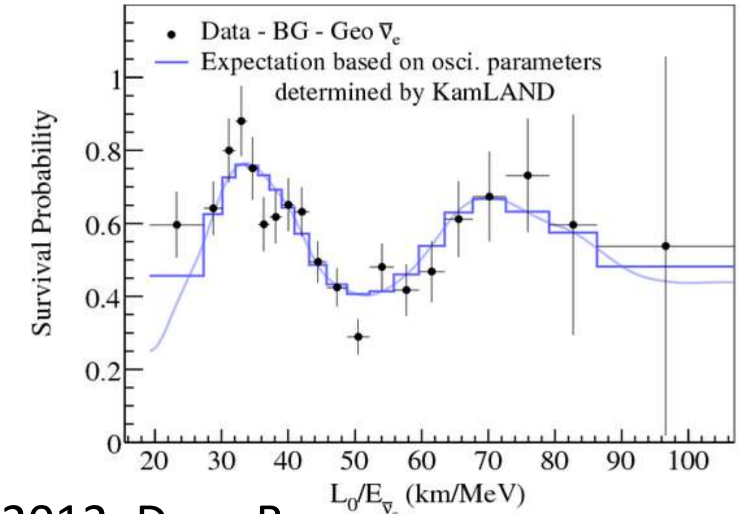
Reactors have resulted in great successes in neutrino physics.

First detection of neutrinos

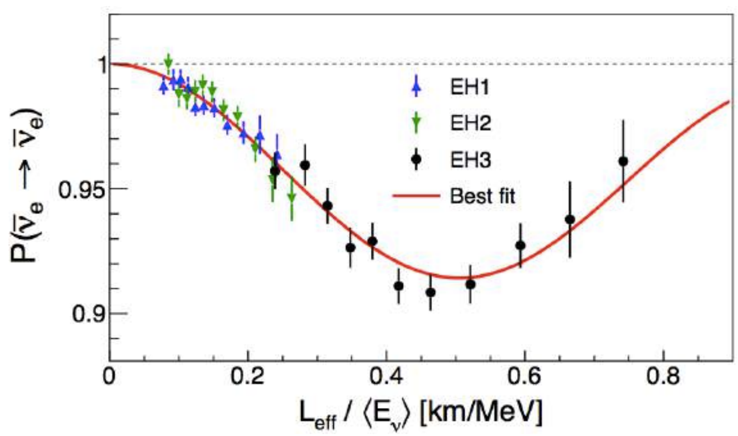
1950s: Hanford, Savannah River



Distinct signal of neutrino oscillation: -> massive neutrinos 2000s: KamLAND

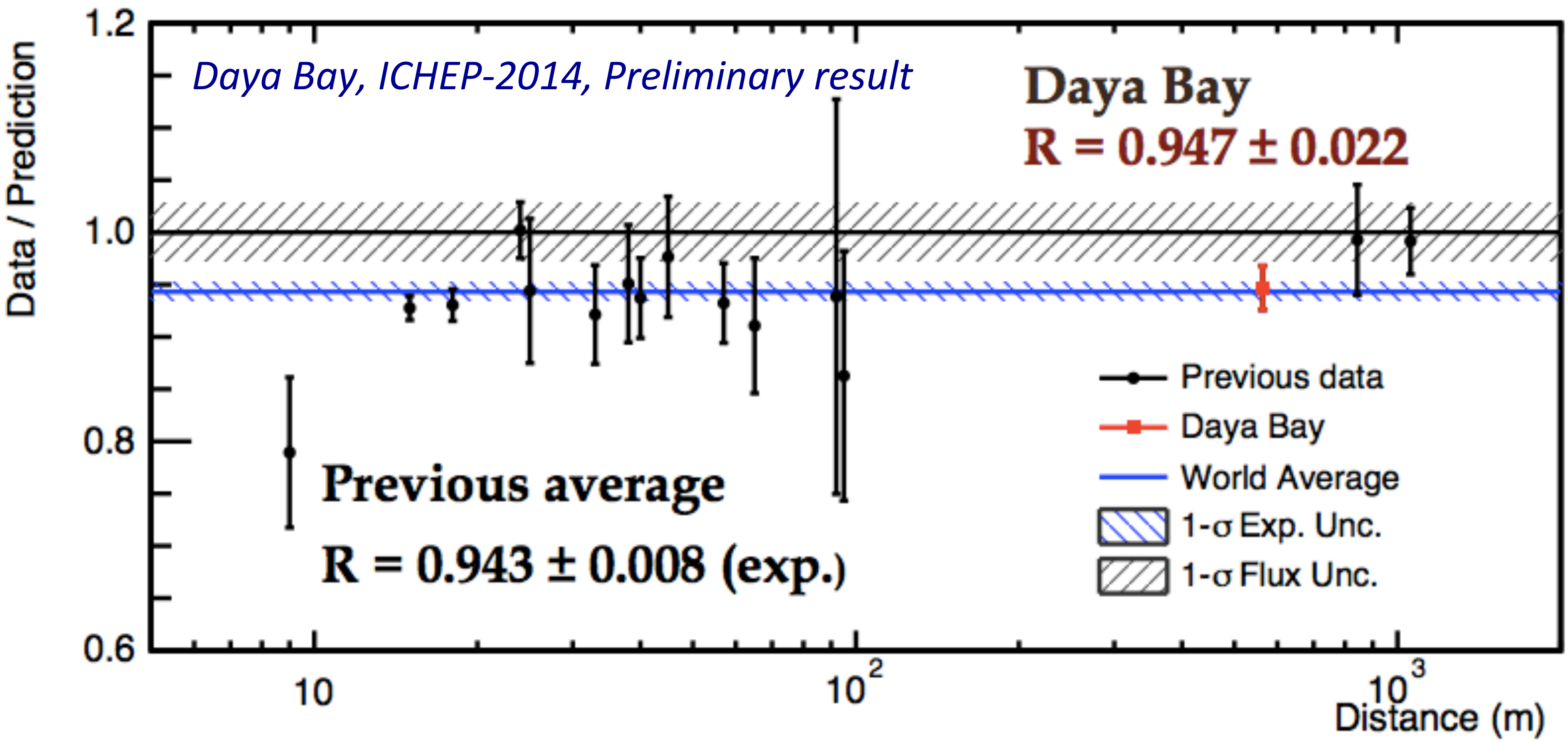


Oscillation at L/E at ~km/MeV: 2012: Daya Bay



Problems with Reactor $\overline{\nu}_e$

Measurement of total antineutrino flux disagrees with models

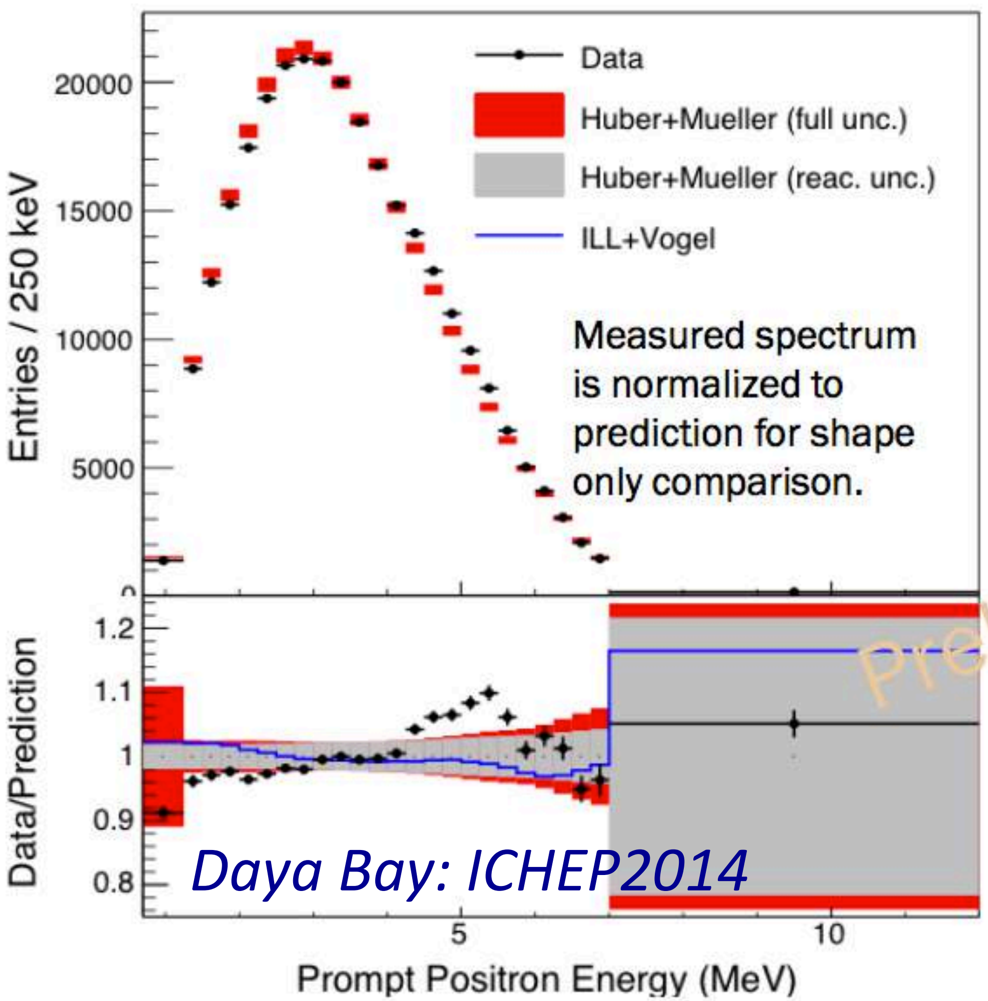


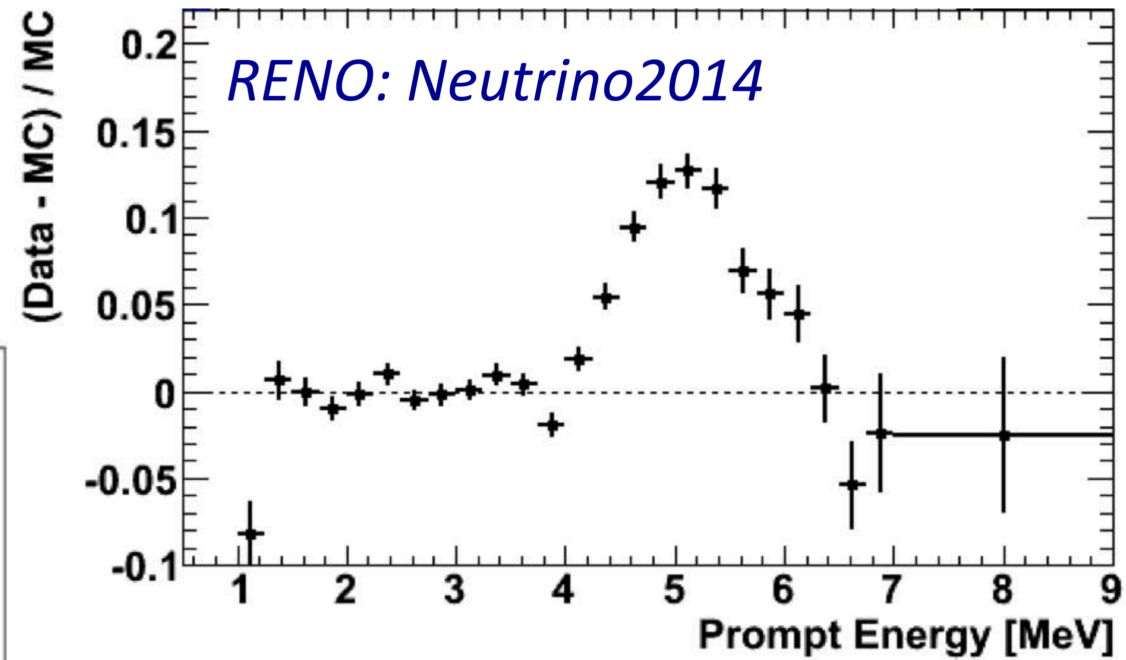
a.k.a. The Reactor Anomaly: *Phys. Rev. D83, 073006 (2011)*

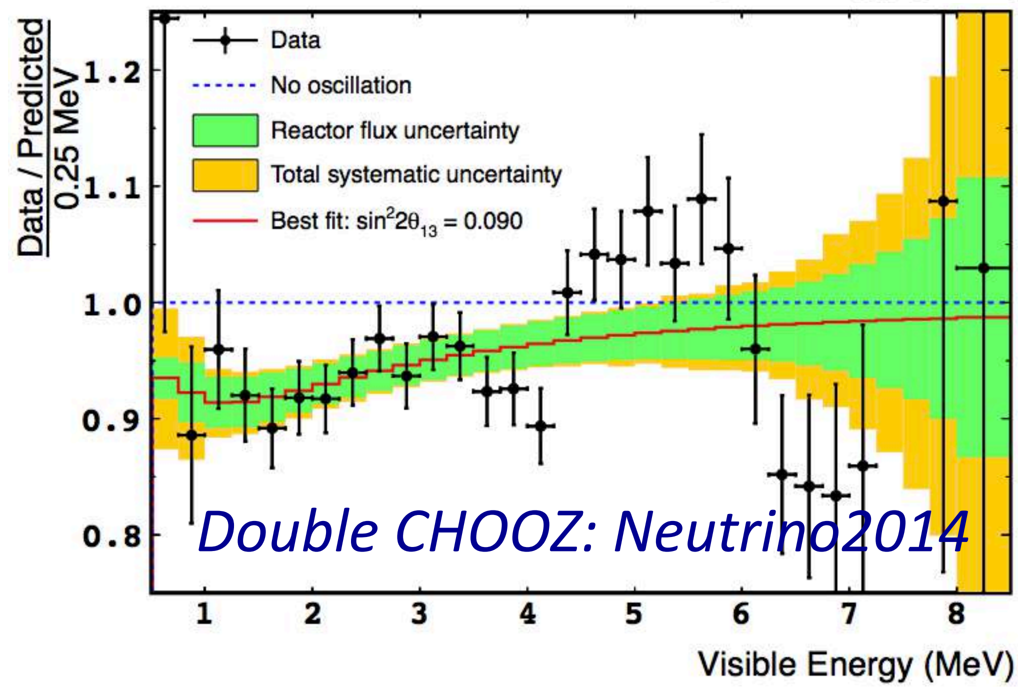
Considered possible evidence of non-interacting (*sterile*) neutrino states.

$\overline{\nu}_e$ Spectrum Disagreement

Recent $\overline{\nu}_e$ measurements also disagree with existing models.





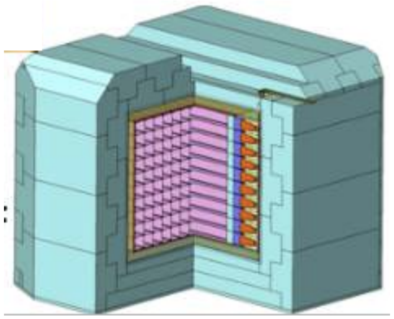


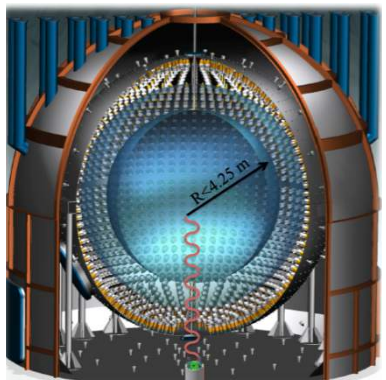
Two Paths Forward

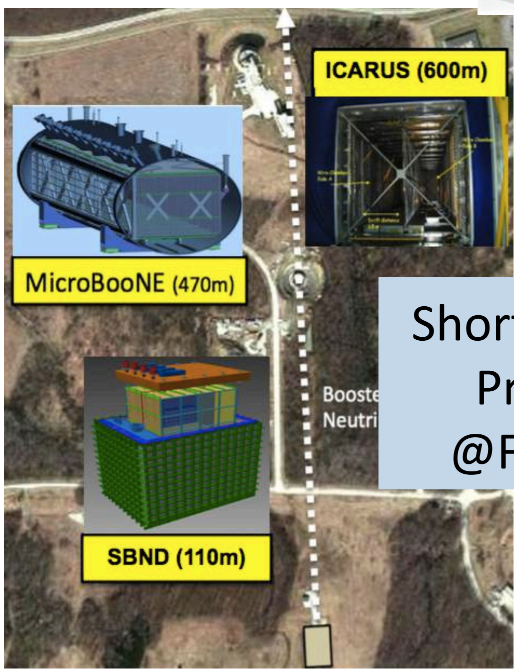
Direct Searches for Sterile ν's

Short-baseline reactor msmts

O(1M$)







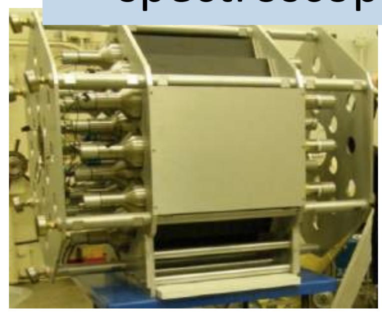
Radioactive ν_e Sources @Gran Sasso

Short-baseline Program @Fermilab

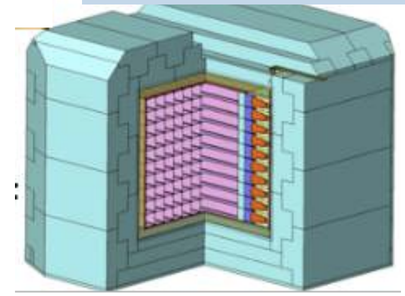
O(100M$)

Improve models of reactor ν's

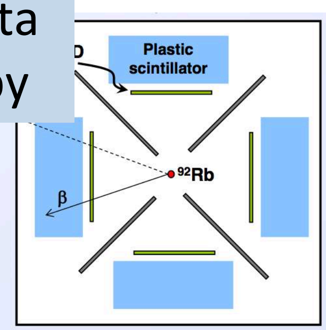
Total-absorption spectroscopy



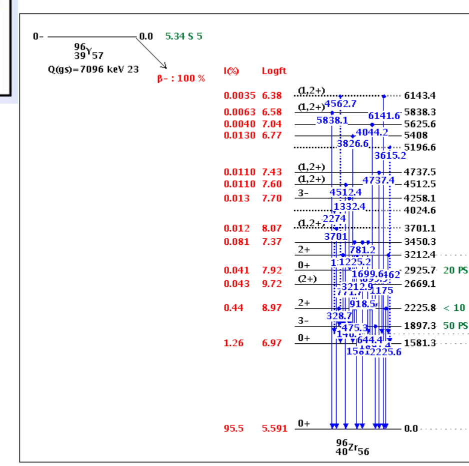
Short-baseline reactor msmts

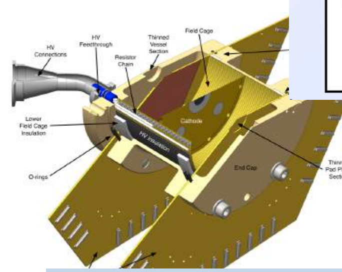


Precision beta spectroscopy



Improved Nuclear Data Evaluation





Fission yield msmts

β^- Conversion

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

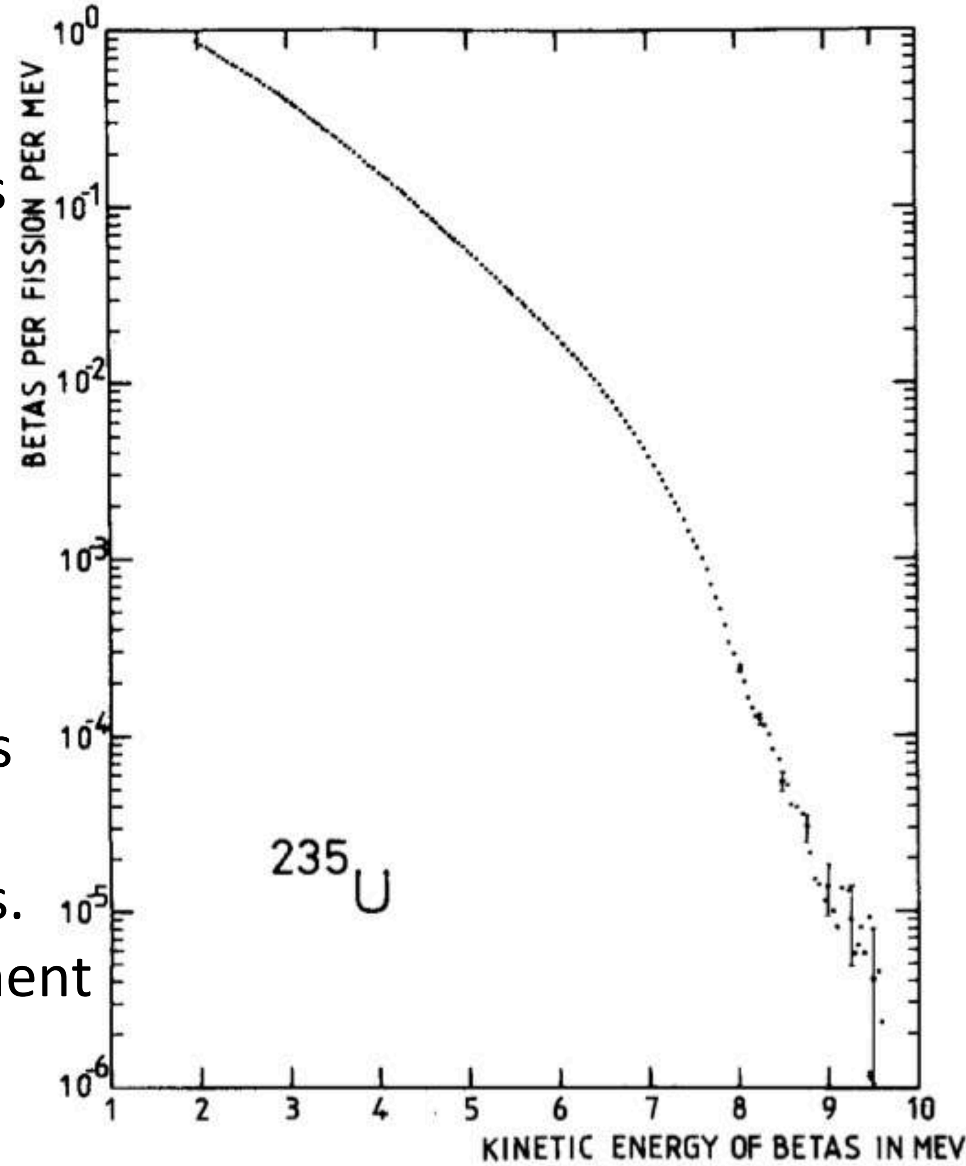
Method:

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 nuclear data predictions

Standard approach for ~30 years

Predicts 6% higher flux than reactor msmts.

Spectrum disagrees with recent measurement

Reactor Anomaly, Sterile Neutrinos?

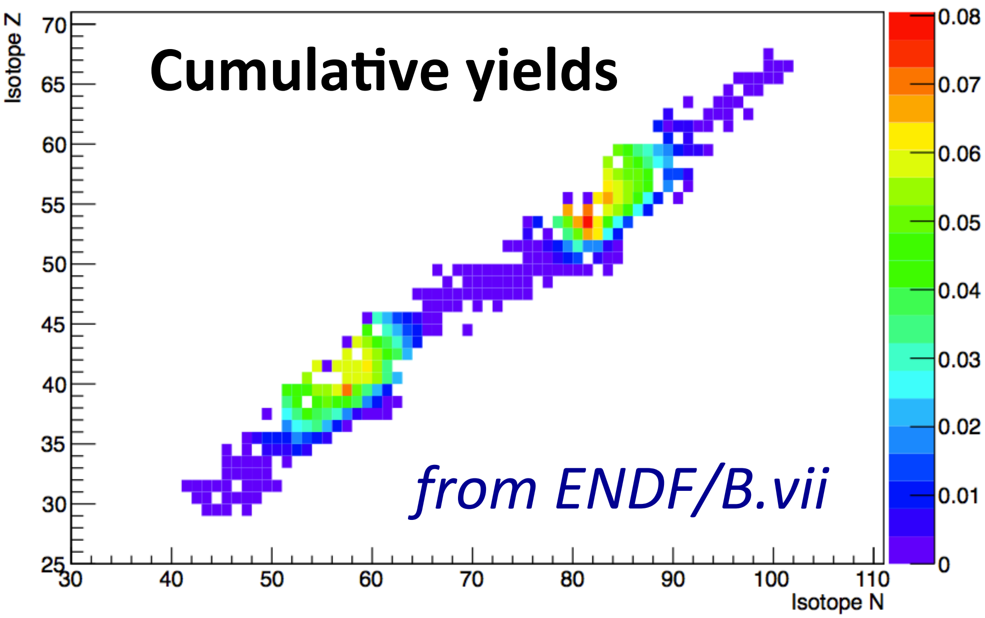
Phys. Rev. D83, 073006 (2011)

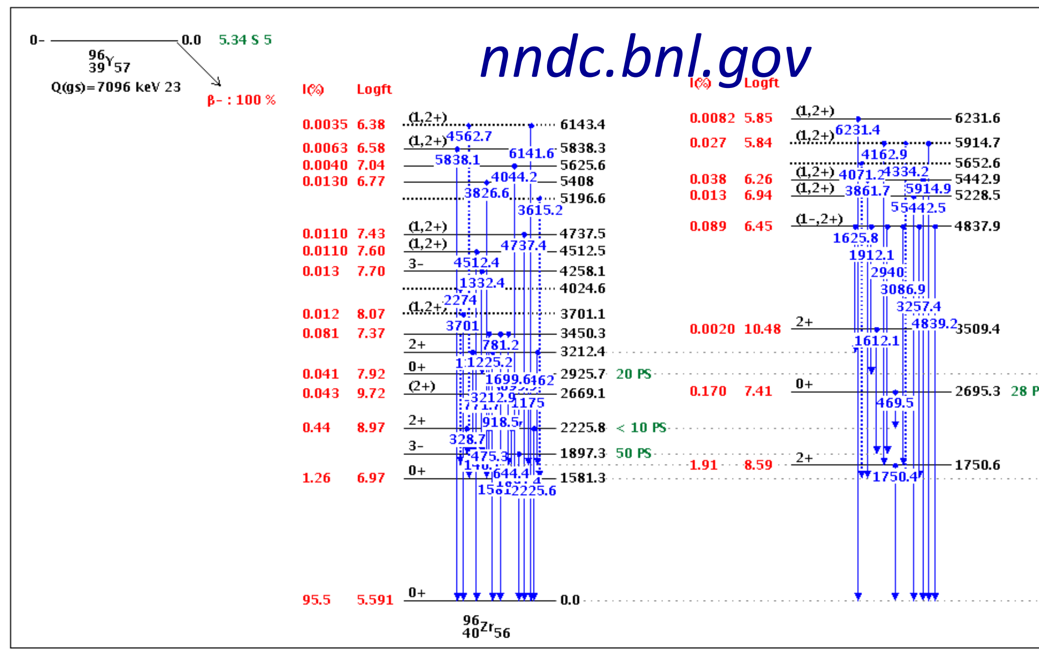
Guidance from Nuclear Data?

Does evaluated nuclear data suggest an explanation for anomalies?

To estimate antineutrino emission from a reactor:

Decay Rates (of beta emitters) + **Antineutrino Spectra** (from beta decay)





Estimated using:

- Fission parent rates
- Cumulative fission yields per parent

Estimated using:

- Evaluated nuclear data (levels, feeding)
- Estimated beta decay spectrum

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:

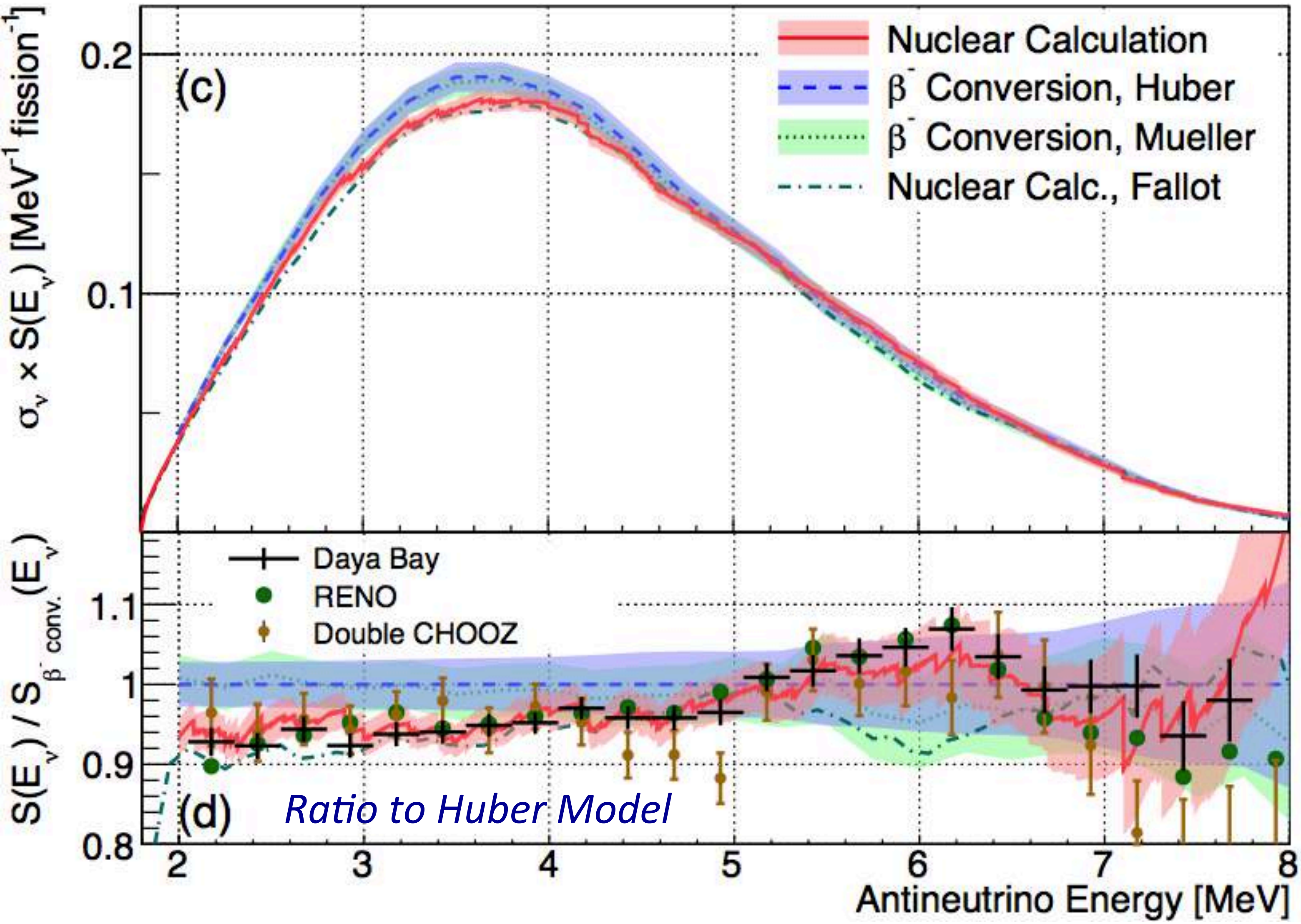
How do forbidden decay corrections impact spectrum?

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

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

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

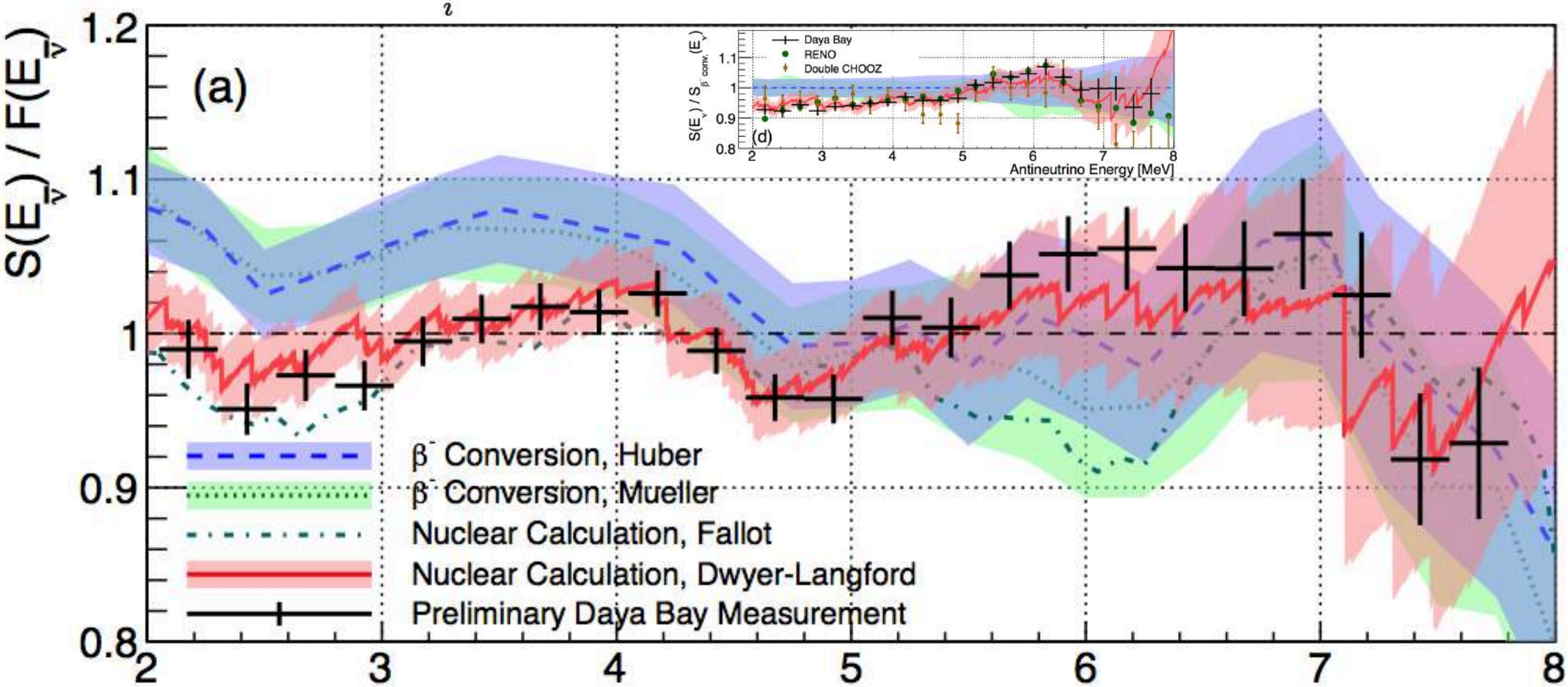
Data normalization adjusted to accurately compare shape.

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)*

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



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

Dominant Branches

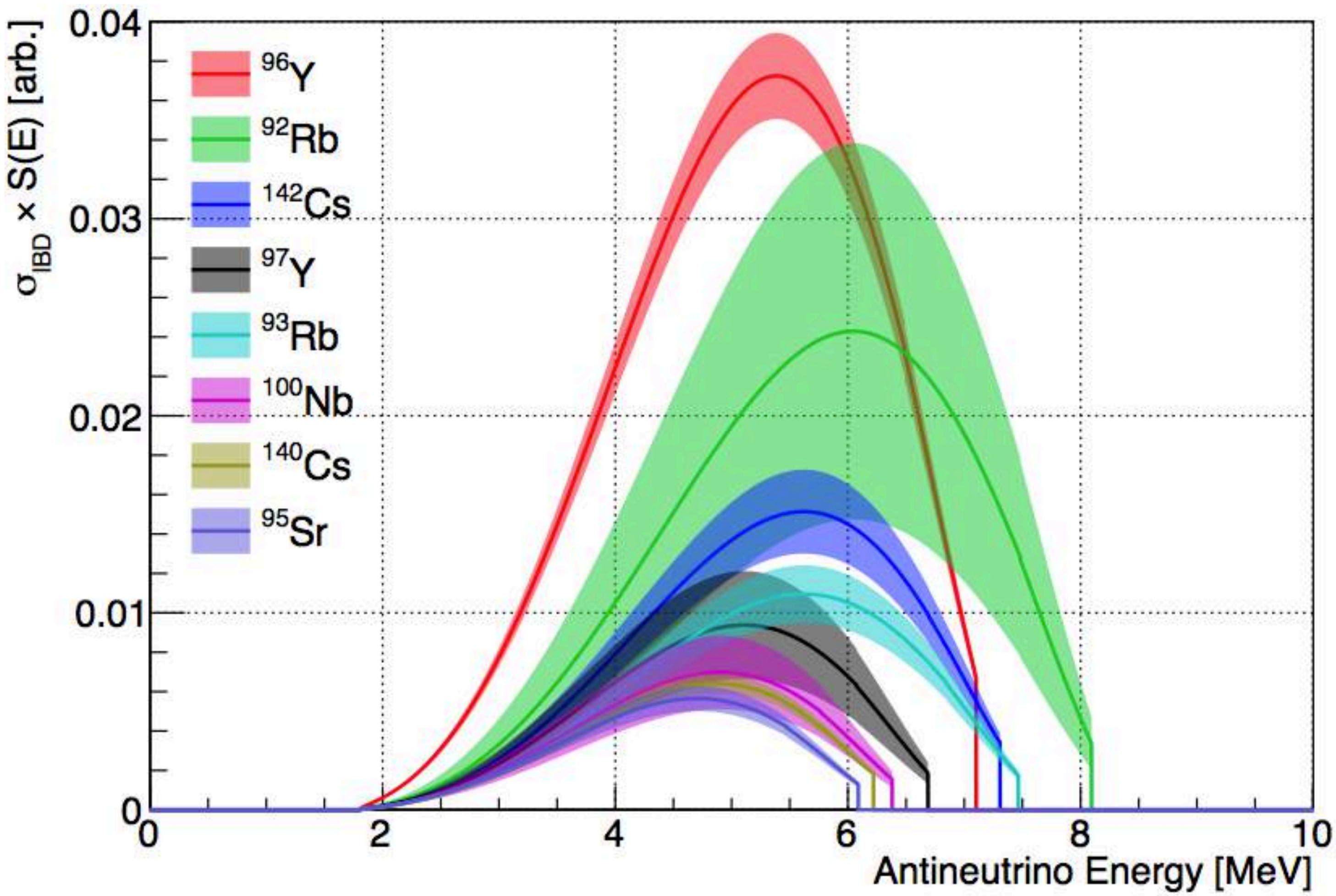
Eight dominant branches cause 5-7 MeV excess in the calculation.

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

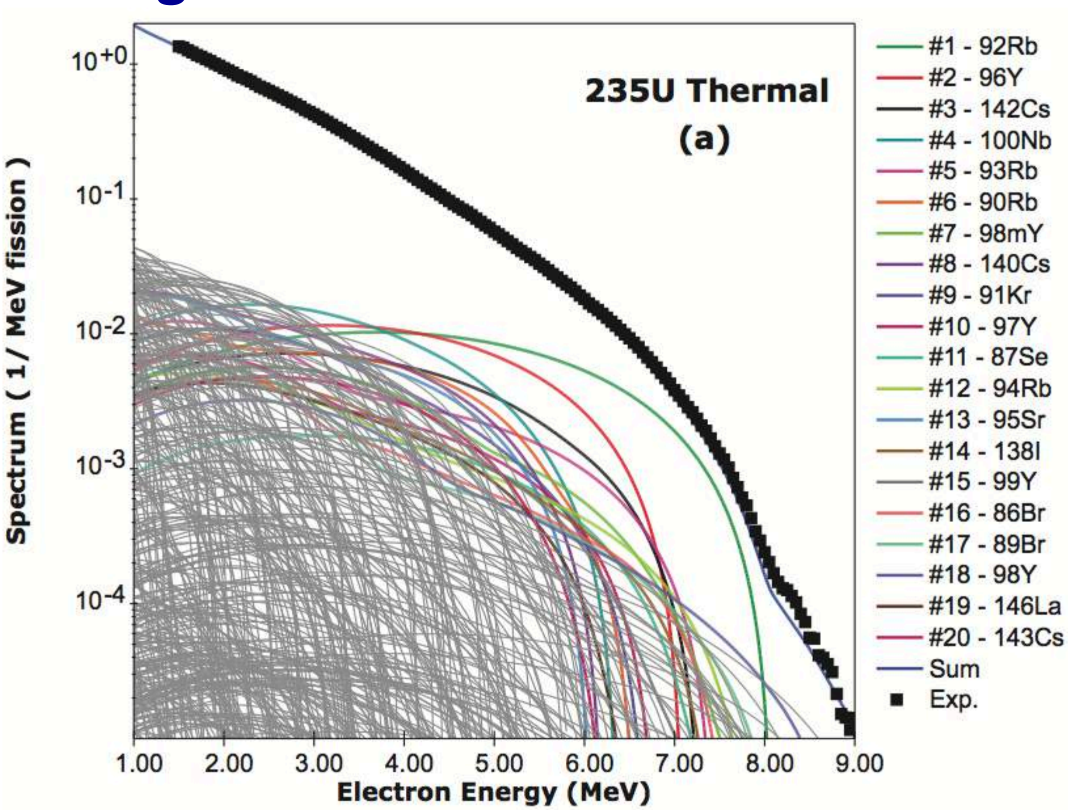
If nuclear data accurate, calculated 5-7 MeV shoulder seems robust.

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

Dominant Branches

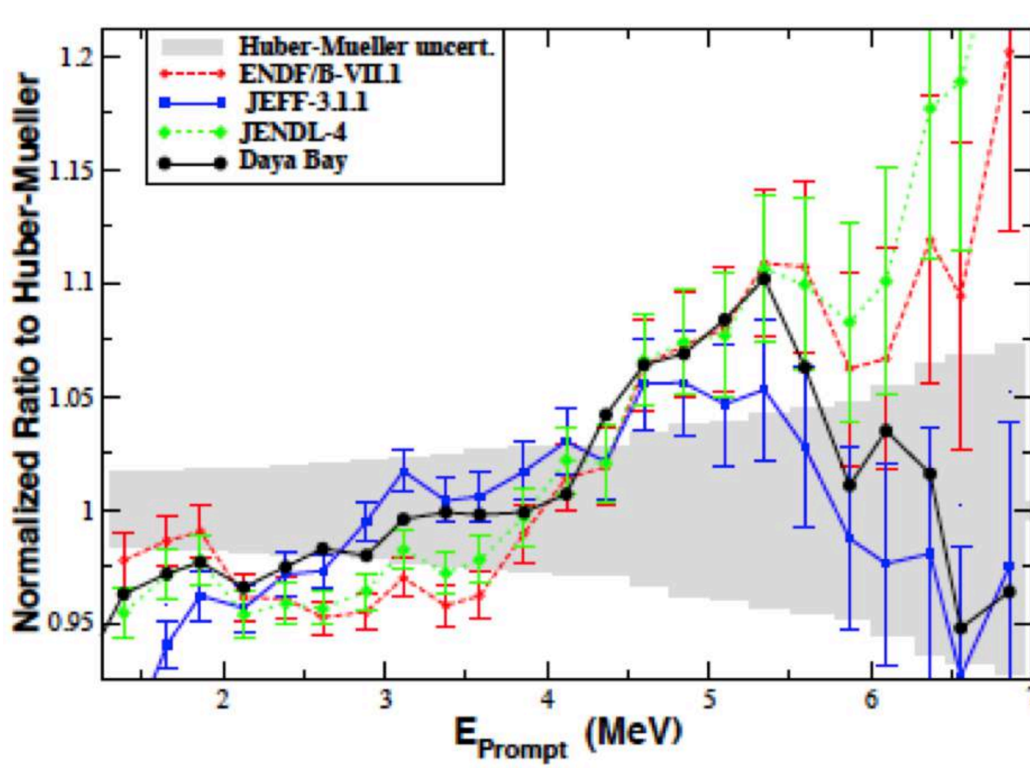
Recent calculations also identify similar aspects of spectrum

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



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

Spectra predicted by various nuclear databases



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

A Path Forward

These observations suggest a method to elucidate reactor $\overline{\nu}_e$'s.

Improve characterization of prominent isotopes:

- Priority given by contribution to detected rate:

$$R_{det} \propto R_{decay} \int S(E_\nu)\, \sigma_{IBD}$$

- R_{decay}: Requires improved fission yields
- $S(E_\nu)$: Requires precision beta spectra and/or total absorption spectrometry

Normalization:
Now: 5-10%
Potential: 2-3%?

Hardness/Slope:
Now: ~2% / MeV
Potential: 0.2-0.5%?

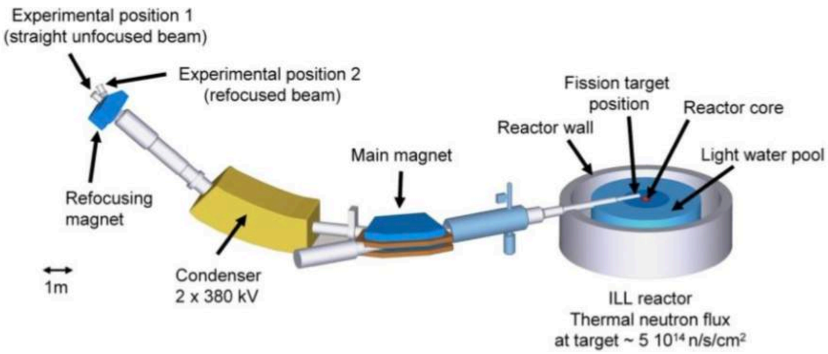
Non-smooth Shape:
Now: ~<1% bin-to-bin
Potential: ?

Precision reactor antineutrino measurements:

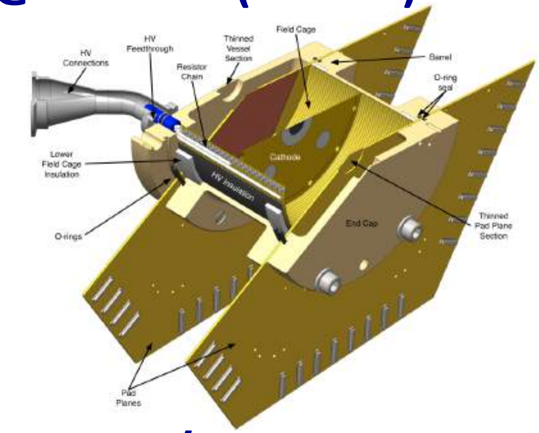
- Daya Bay, RENO, Double CHOOZ will provide high-statistics ($>10^6$) spectra from commercial power reactors (low-enriched uranium), with ~2% absolute rate uncertainty.
- Potential measurement of HFIR reactor (high-enriched uranium) spectrum by the PROSPECT experiment (~2016-2017).

Upcoming Measurements

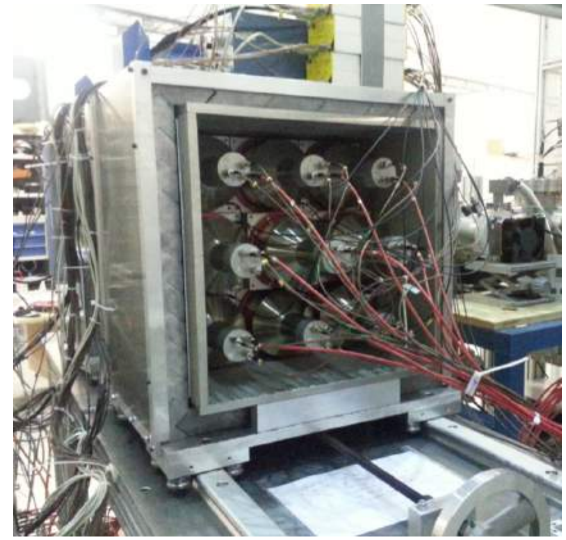
Fission Yields @ ILL (Lohengrin)



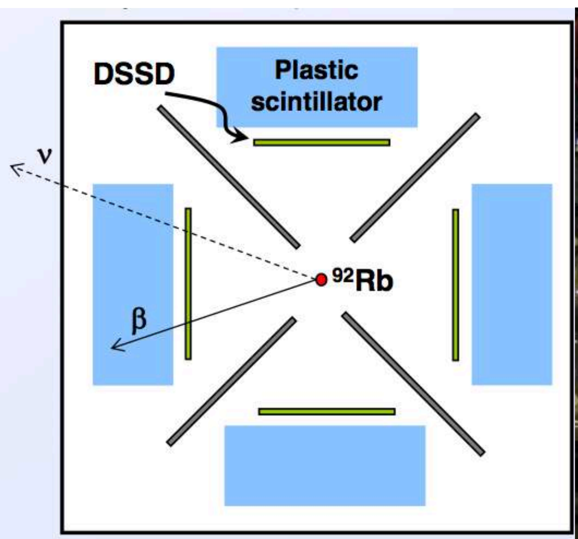
Fission Yields @ LANSCE (NIFFTE)

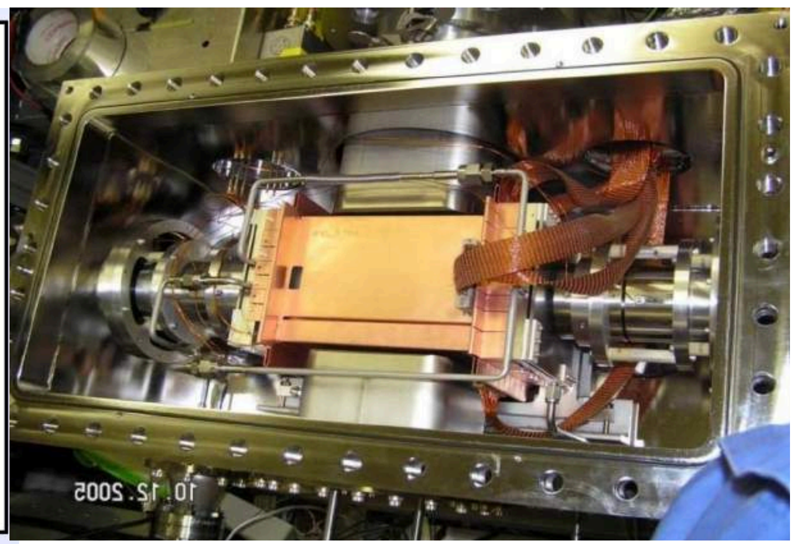


Total Absorp. Spec. @ IGISOL (DTAS)



Precision β^- Spec. with Trapped Ions @ ANL/CARIBU





Total Absorp. Spec. @ ORNL (MTAS)

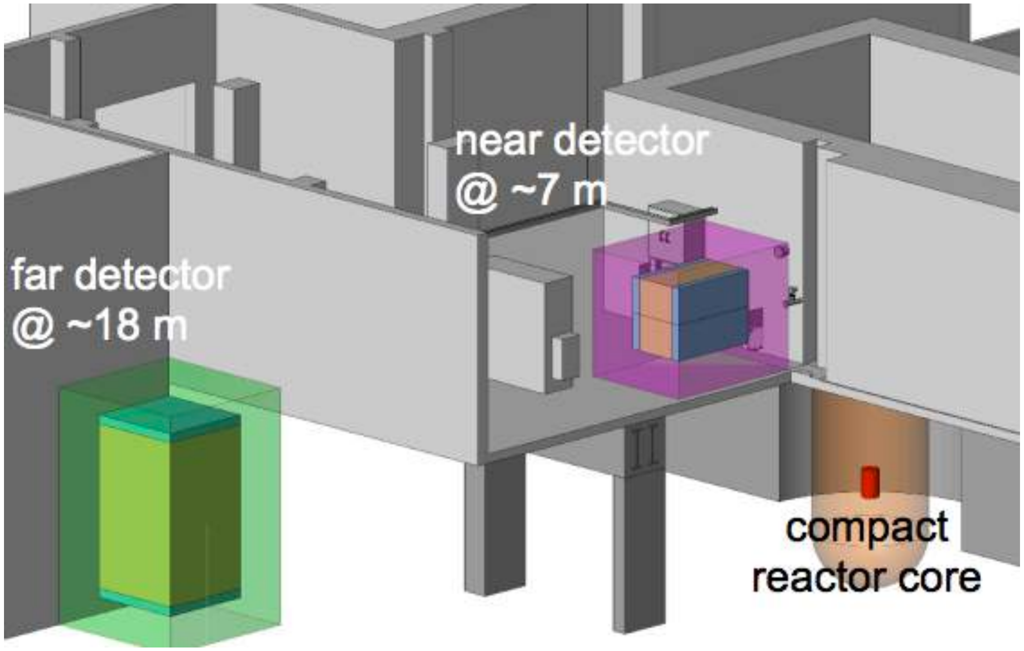
Some examples of planned measurements of these decays:

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

Proposed $\overline{\nu}_e$ Measurement

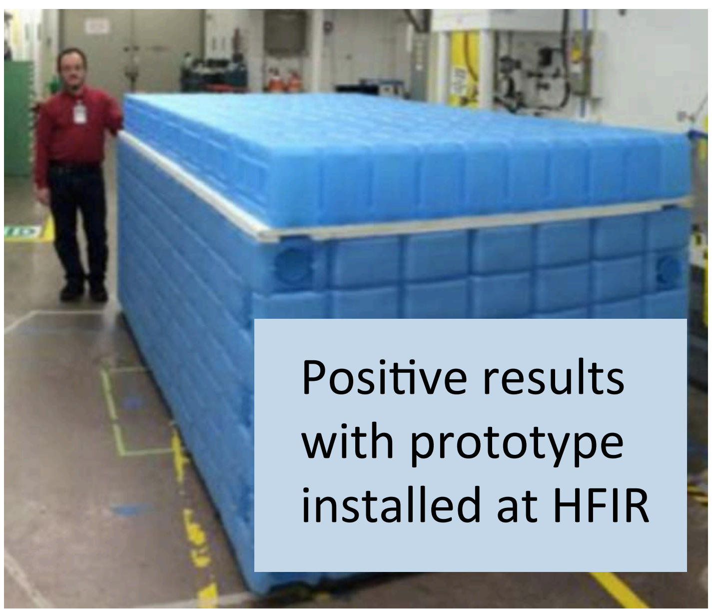


PROSPECT:

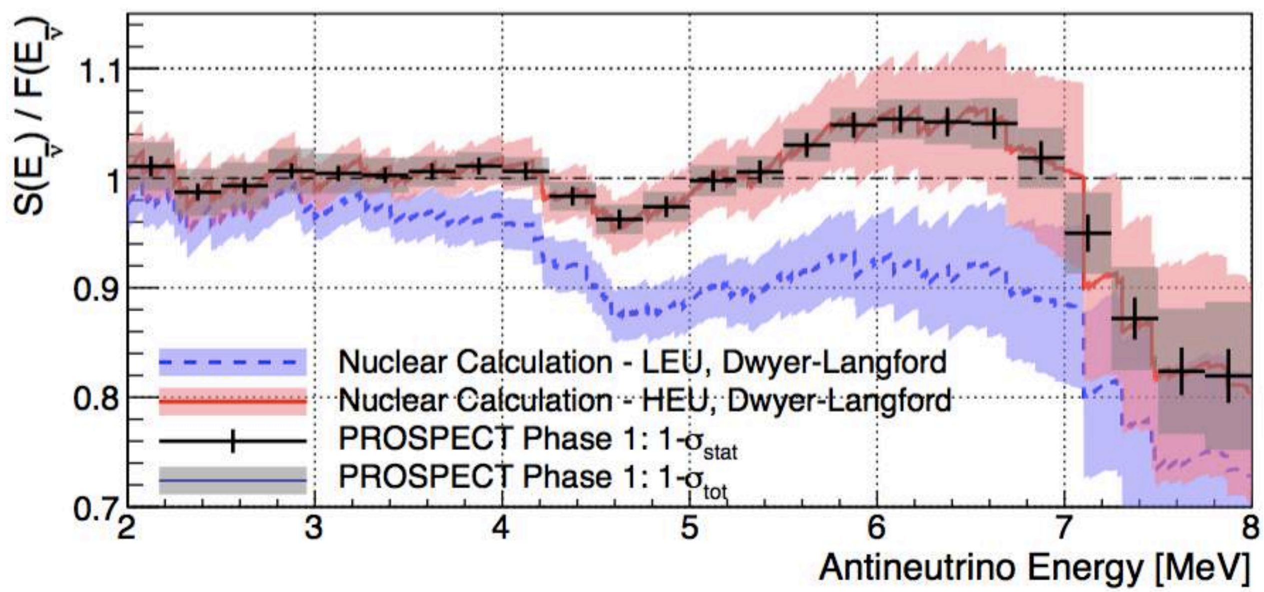
Precision Reactor Oscillation and Spectrum Experiment

- Directly test for sterile oscillation across detector
- Potentially measure precise spectrum

Aiming for measurements: ~2017



Positive results with prototype installed at HFIR



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

Calculation predicts significant discontinuities in spectrum.

Reactor Spectroscopy?

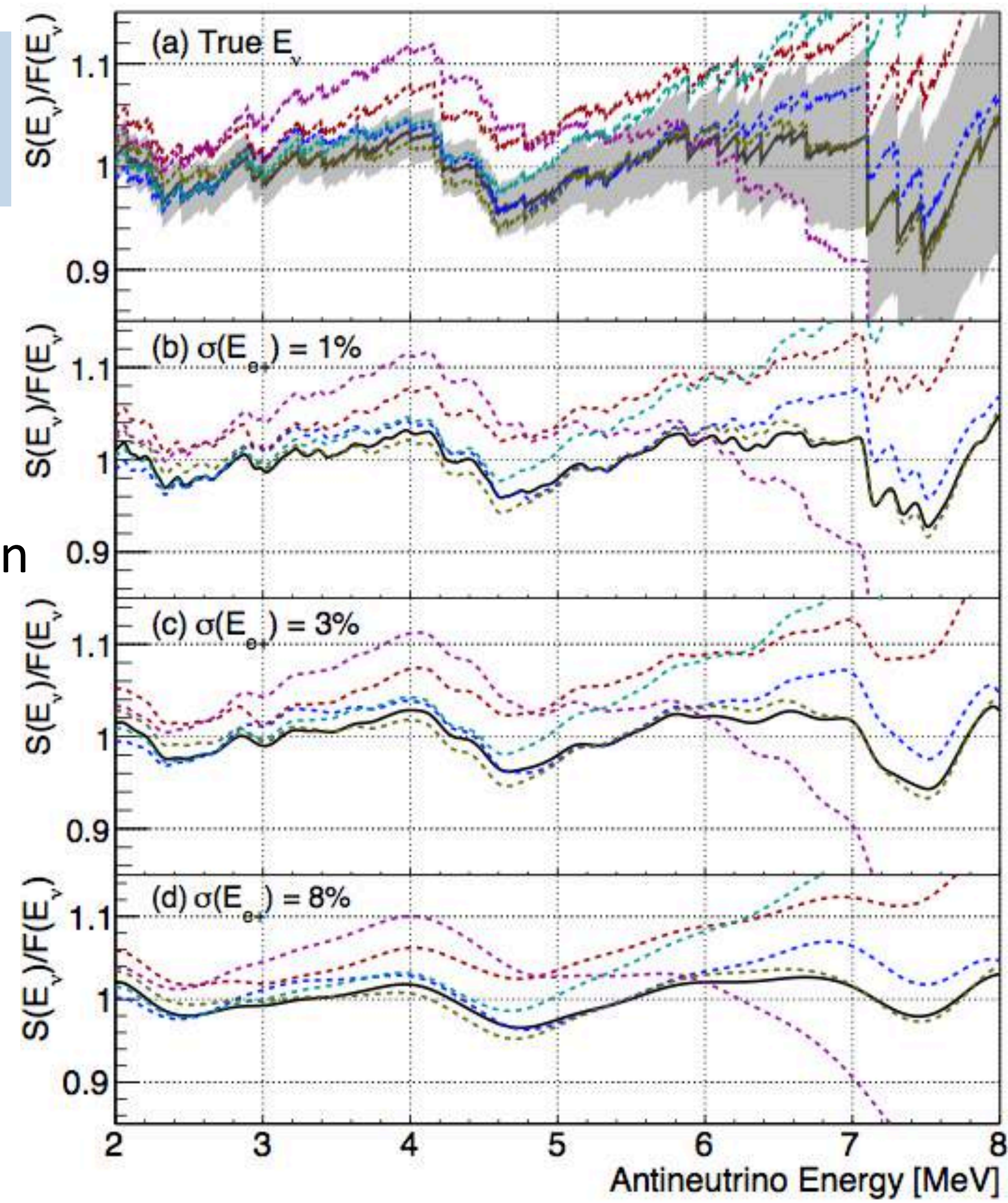
Each edge identifies one significant decay branch.

Current detectors: 6-8%/√E resolution unlikely to see details.

PROSPECT: ~4-5%/√E resolution.
JUNO: targeting ~3%/√E resolution.

Innovation required to reach <1%.
Value beyond fundamental science?

Solid: Nominal calc.   *Dashed: Varying uncertainties*



Reactor $\overline{\nu}_e$ as Benchmark

Can $\overline{\nu}_e$ spectra serve as precision benchmark for reactor physics?

Antineutrinos as 'unbiased' estimator:

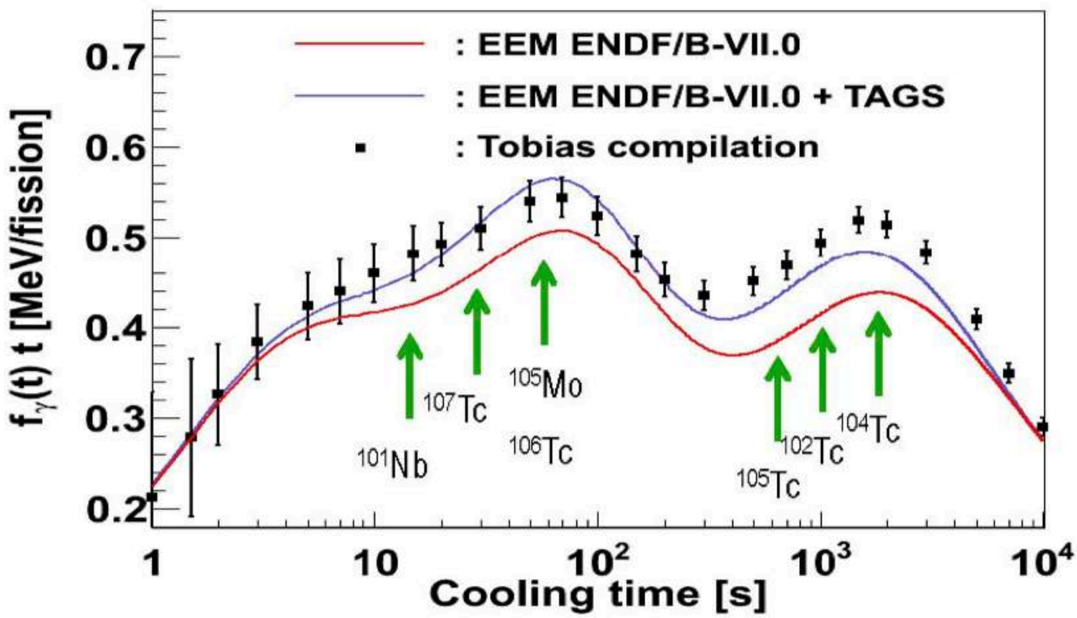
- Negligible interaction with environment
- Integral measurement of beta decays occurring in reactor

Questions:

How to best report and archive these measurements?

What peripheral data is needed to make these measurements useful?

Analogy: Decay Heat



P.Dimitriou, Report on the IAEA TAGS meeting (Vienna, Dec. 15-17, 2014), INDC(NDS)-0676

Summary

Reactor Antineutrinos:

- Successful tool for fundamental physics
- Anomalies: New physics or overlooked nuclear physics?

Path forward:

- Measurements of yields and decays of prominent fission daughters
- Precision reactor antineutrino measurements

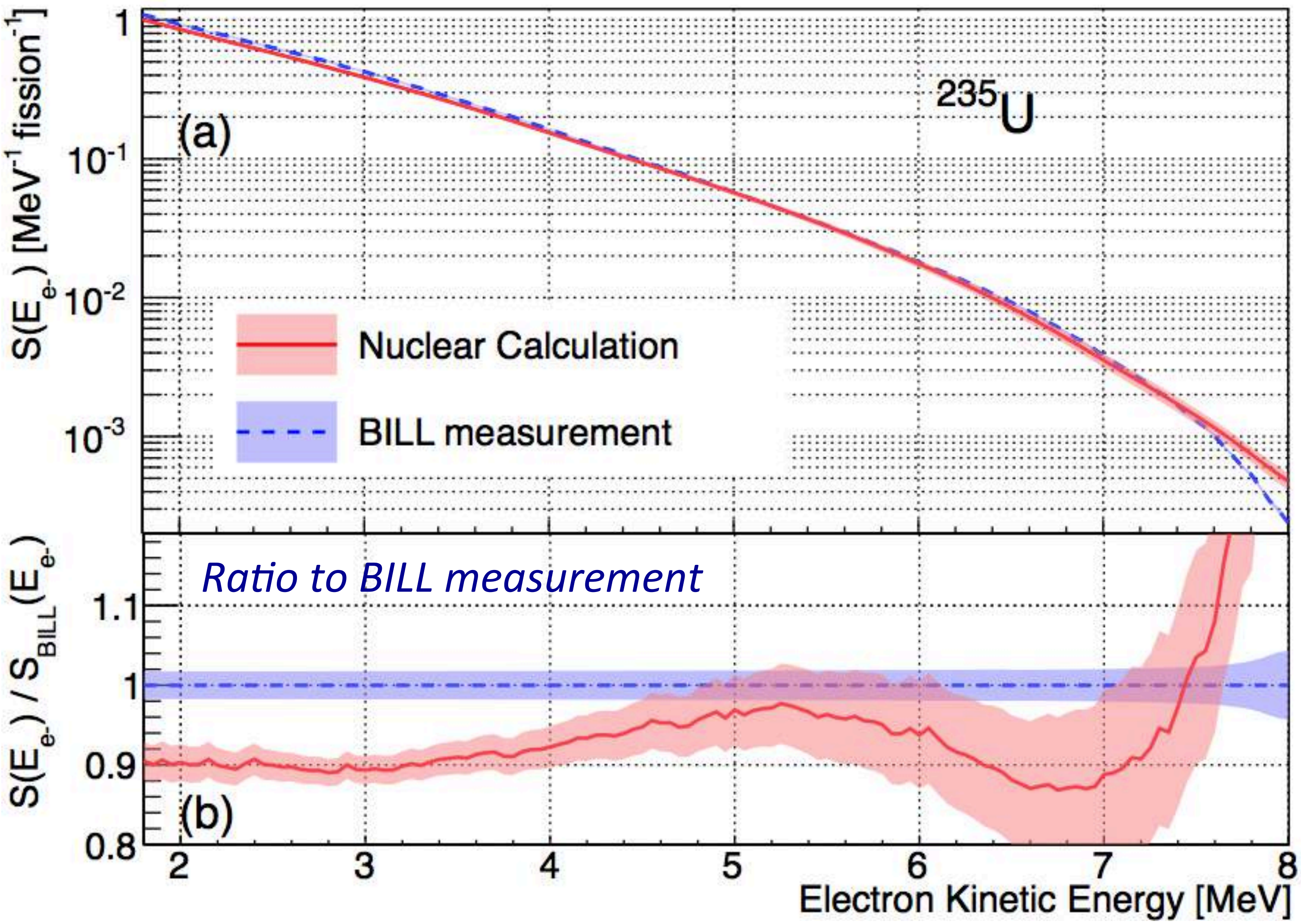
Questions:

- What precision can be reasonably achieved for summation calculation?
  Consider factorizing: normalization, spectral slope, spectral shape
- What is the potential value of a HEU reactor spectra measurement?
  …and what it the necessary precision and energy resolution?
  …and what peripheral data should be archived?
- Do antineutrino measurements have potential as reactor benchmarks?
  …and is a measurement with 1% energy resolution worth pursuing?

Additional Material

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.

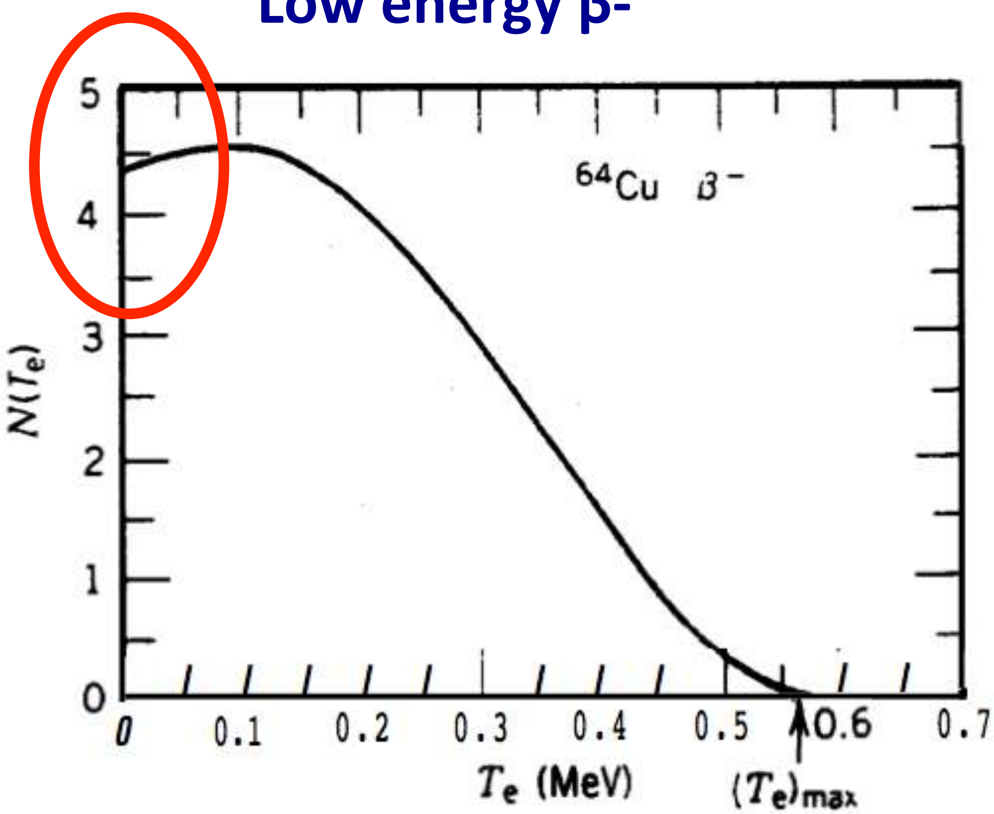
Detailed $\overline{\nu}_e$ Spectrum Shape

Calculation predicts significant discontinuities in spectrum.

Coulomb correction:

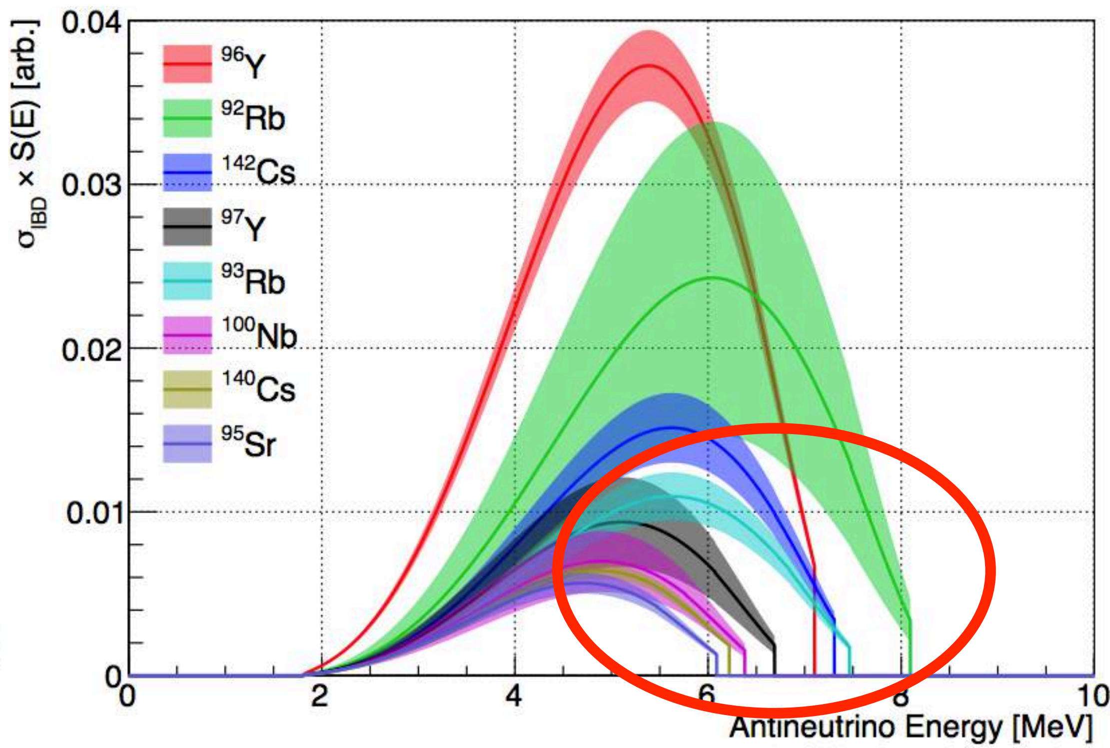
Nuclear charge enhances production of:

Low energy β-



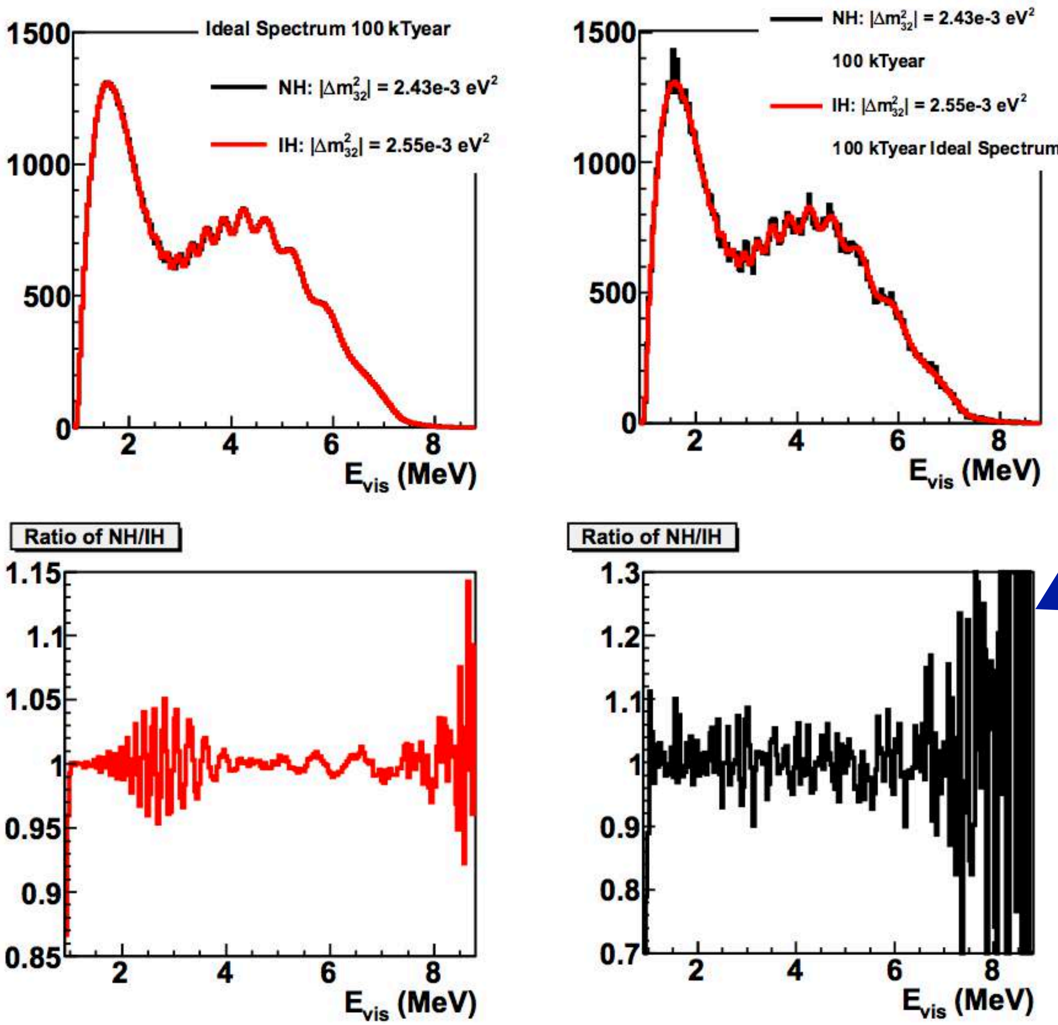
Pronounced example from
R. D. Evans, The Atomic Nucleus

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



Neutrino Mass Ordering

Spectral structure complicates determination of the mass ordering



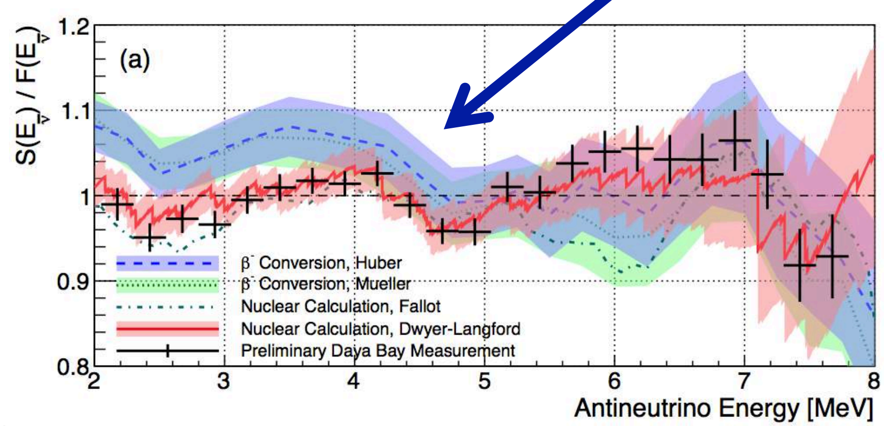
X.Qian, D.Dwyer, et al. PRD 87, 033005 (2013)

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

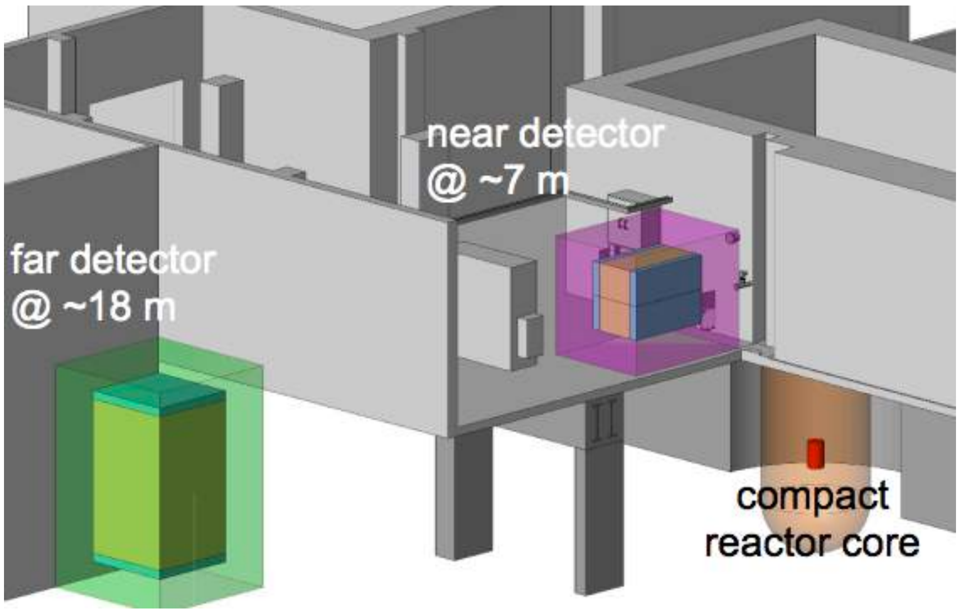
Example measured and calculated structure relative to smooth shape



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

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

Short-baseline reactor experiments

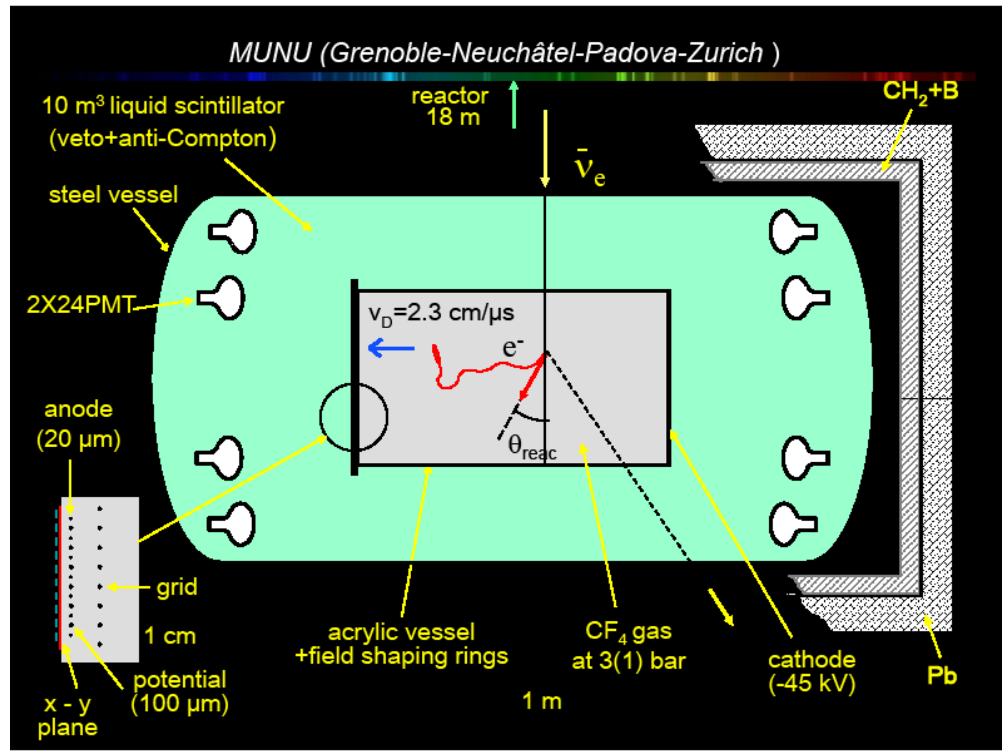


Example: PROSPECT @ ORNL, $\sigma_E \approx 4.5\%$

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

Potential for higher energy resolution