Antineutrino Emission by Nuclear Reactors: Measurements and Models

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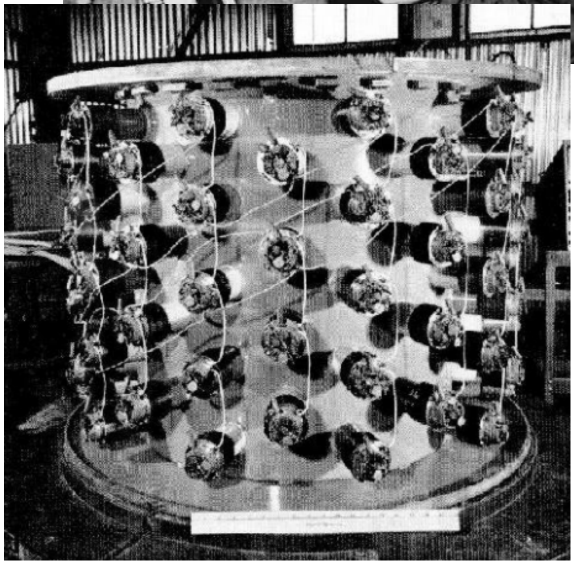
Erice, Sicily

Sep. 21, 2019

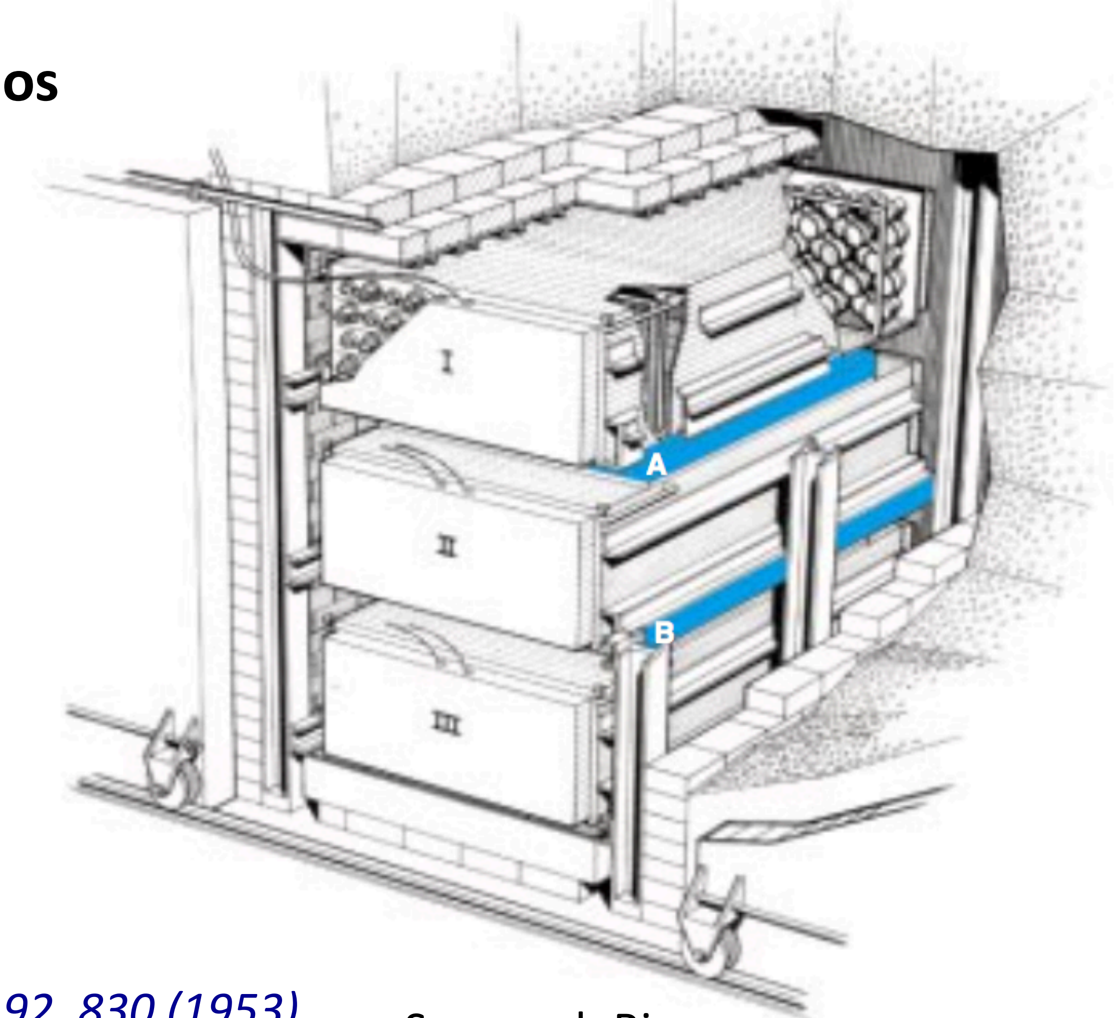
Neutrino Physics

Reactors have been a powerful tool in neutrino physics:

1950s: First detection of neutrinos



Hanford
Phys. Rev. 92, 830 (1953)

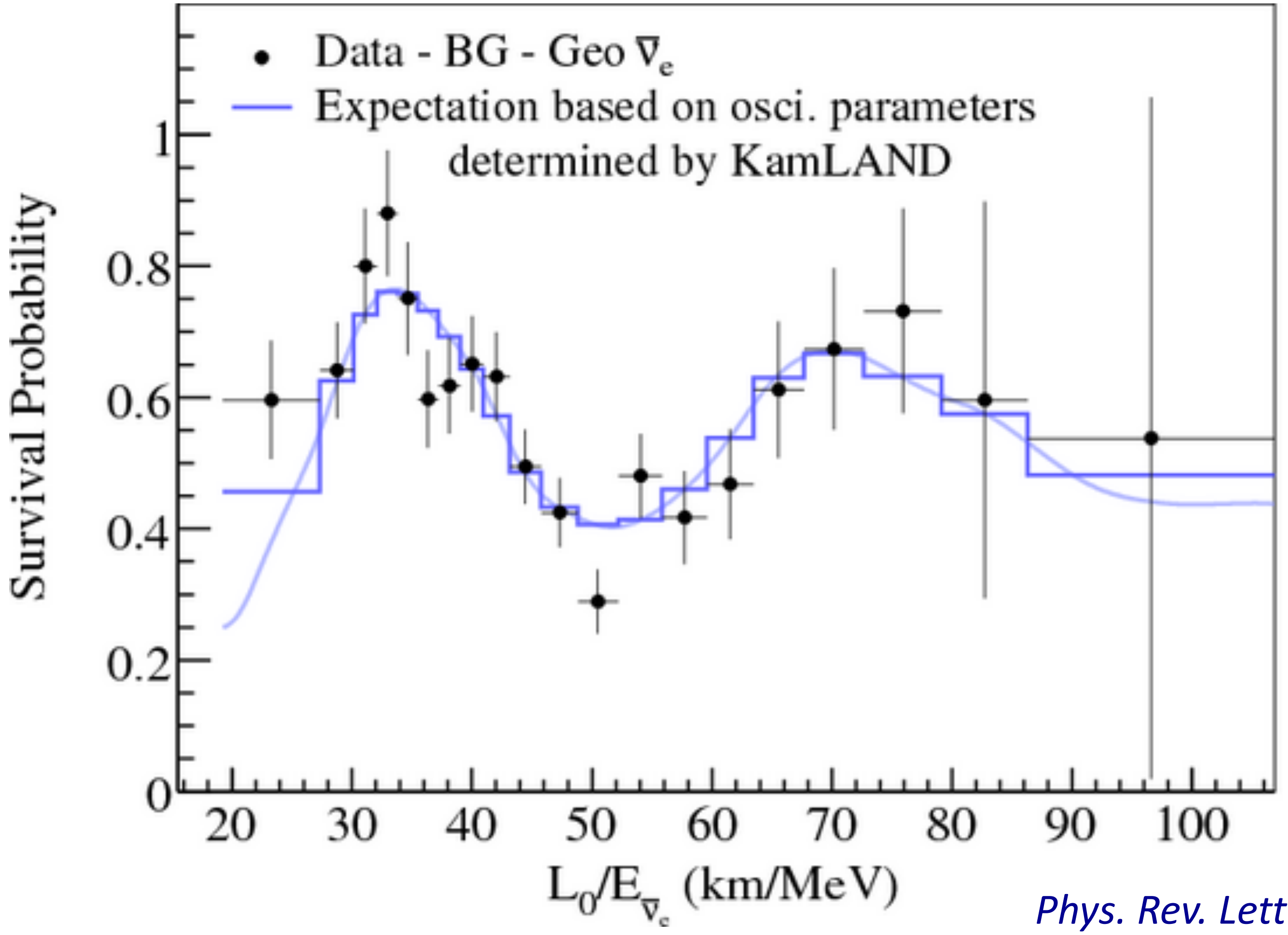


Savannah River
Science 124, 103 (1956)

Neutrino Physics

Reactors have been a powerful tool in neutrino physics:

2000s: Distinct signal of neutrino oscillation, Δm^2_{21}, θ_{12}



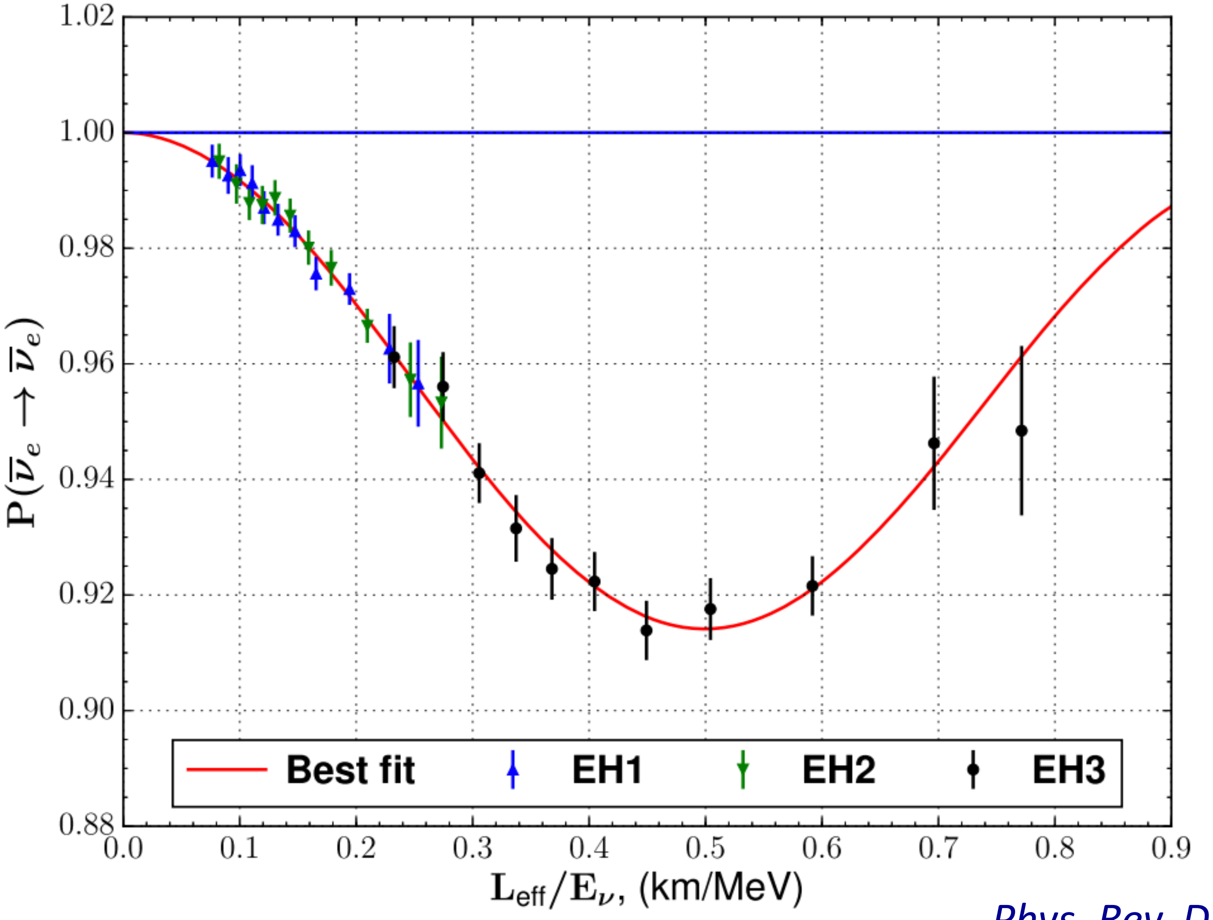
KamLAND

Phys. Rev. Lett. 90, 021802 (2003)
Phys. Rev. Lett. 94, 081801 (2005)
Phys. Rev. Lett. 100, 221803 (2008)

Neutrino Physics

Reactors have been a powerful tool in neutrino physics:

2012: Precision oscillation at ~0.5 km/MeV, Δm^2_{31}, θ_{13}



Phys. Rev. D95, 072006 (2017)

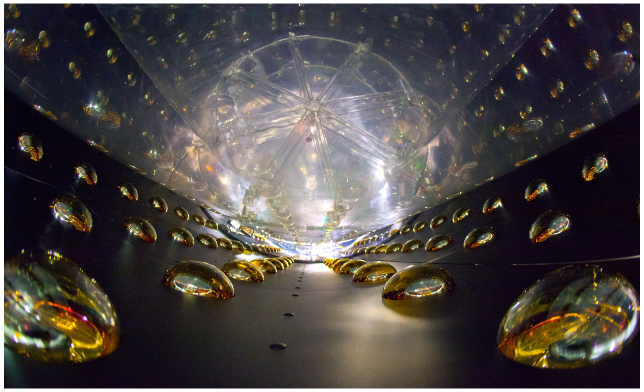
Recent Developments

Recent interest in models of reactor $\overline{\nu}_e$ driven on two fronts:

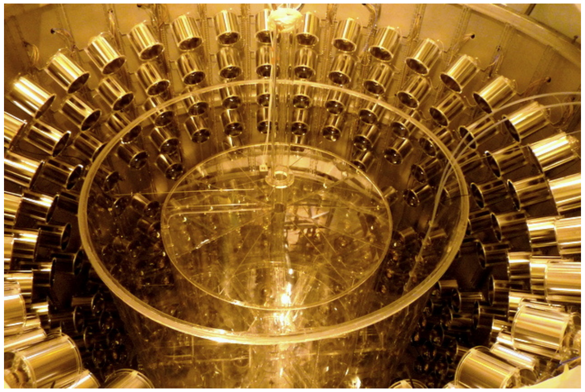
Oscillation Experiments in search of θ_{13}:

- Models of reactor $\overline{\nu}_e$ emission used as input to oscillation measurements
- High-statistics $\overline{\nu}_e$ rate and spectrum measurements reach %-level precision

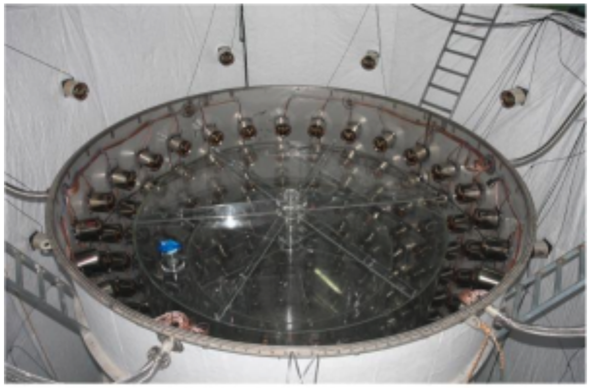
Daya Bay



Double Chooz



RENO



Reevaluated emission models inconsistent with past data:

- 2011 state-of-the-art reassessment predicts rate 6% higher than measurements

  Phys. Rev. C83, 054615 (2011), Phys. Rev. C84, 024617 (2012)
- Considered possible evidence for ~eV-scale sterile neutrino

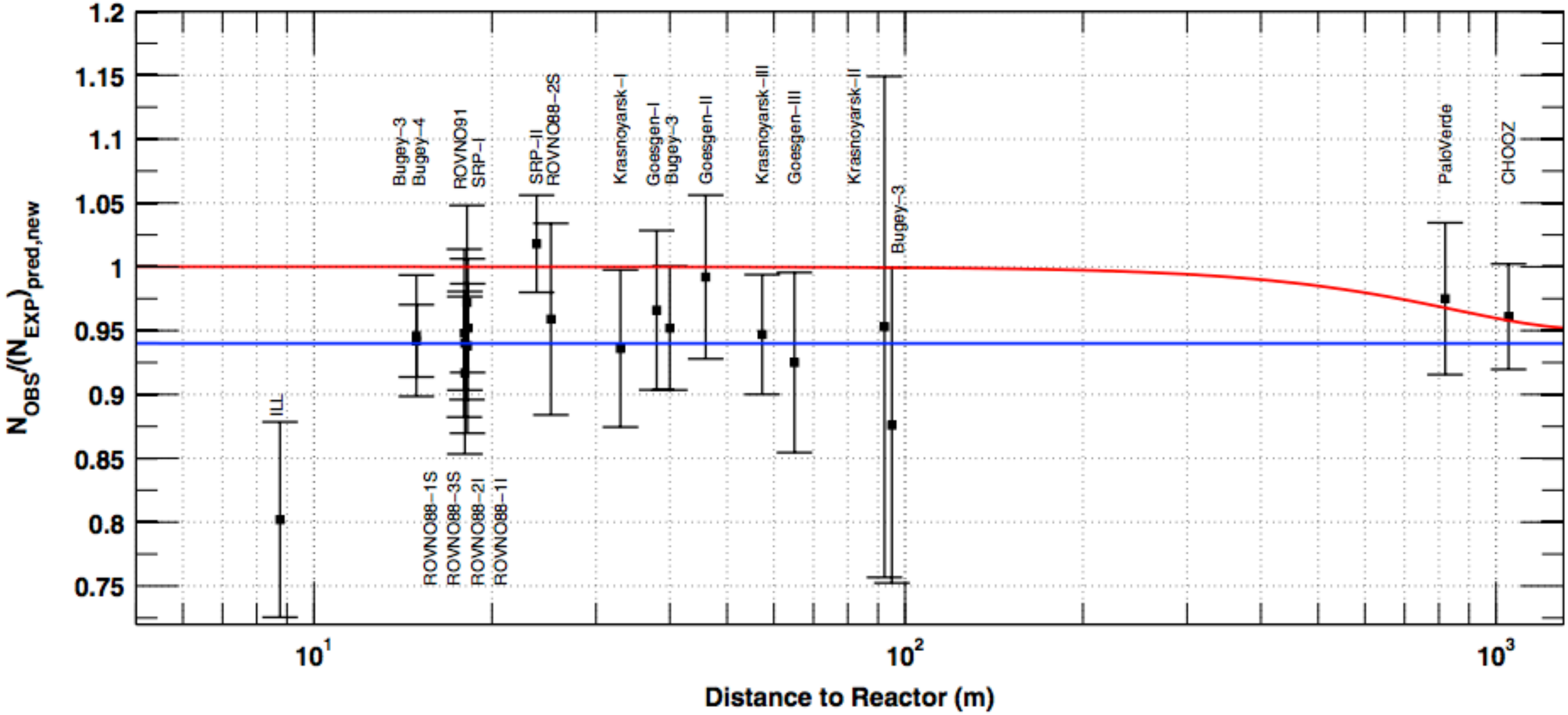
  Phys. Rev. D83, 073006 (2011)

Rate Discrepancy

Average $\overline{\nu}_e$ rate of past experiments less than model expectation

Observed / Expected = 0.927 ± 0.023 (2.9σ)

Phys. Rev. D83, 073006 (2011)



More recently:

Data vs. model comparisons of energy spectrum, and variations with reactor fuel

Today's Talk

Contents of this lecture:

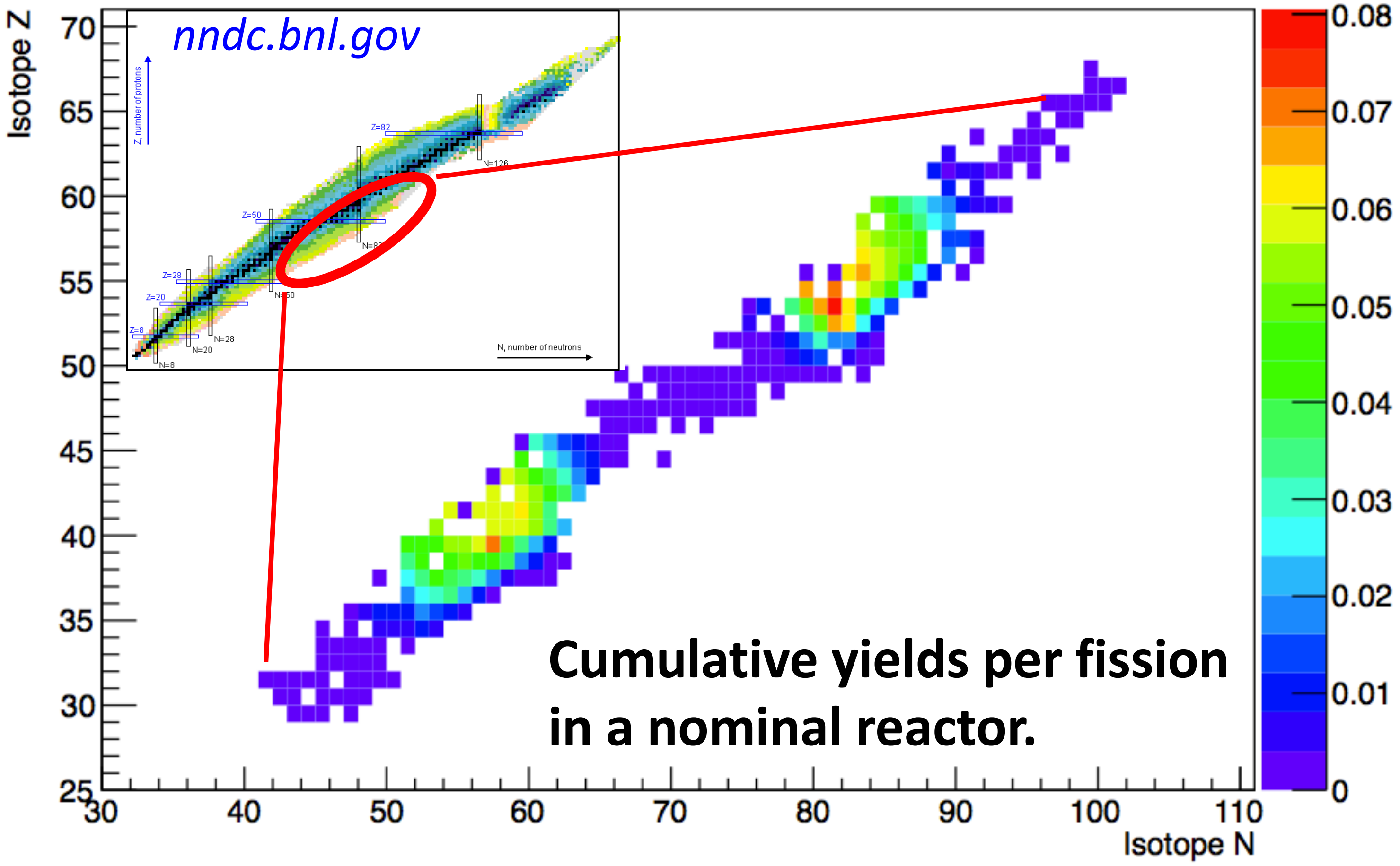
- Discuss the production and measurement of reactor antineutrinos
- Take a closer look at models of reactor antineutrino emission, and summarize recent progress
- Examine the consequences and potential future developments

Part 1:
Reactor antineutrino production and measurement

Reactor Antineutrinos

Antineutrino Production:

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



Cumulative yields per fission in a nominal reactor.

Reactor Flux Expectation

Standard approach to antineutrino flux prediction

Total Antineutrino Spectrum:

$$S(E_\nu) = \frac{W_{th}}{\sum_i (f_i/F) e_i} \sum_i^{istopes} (f_i/F) S_i(E_\nu)$$

Reactor-specific:

- Reactor thermal power: W_{th}
- Relative isotope fission fractions: f_i

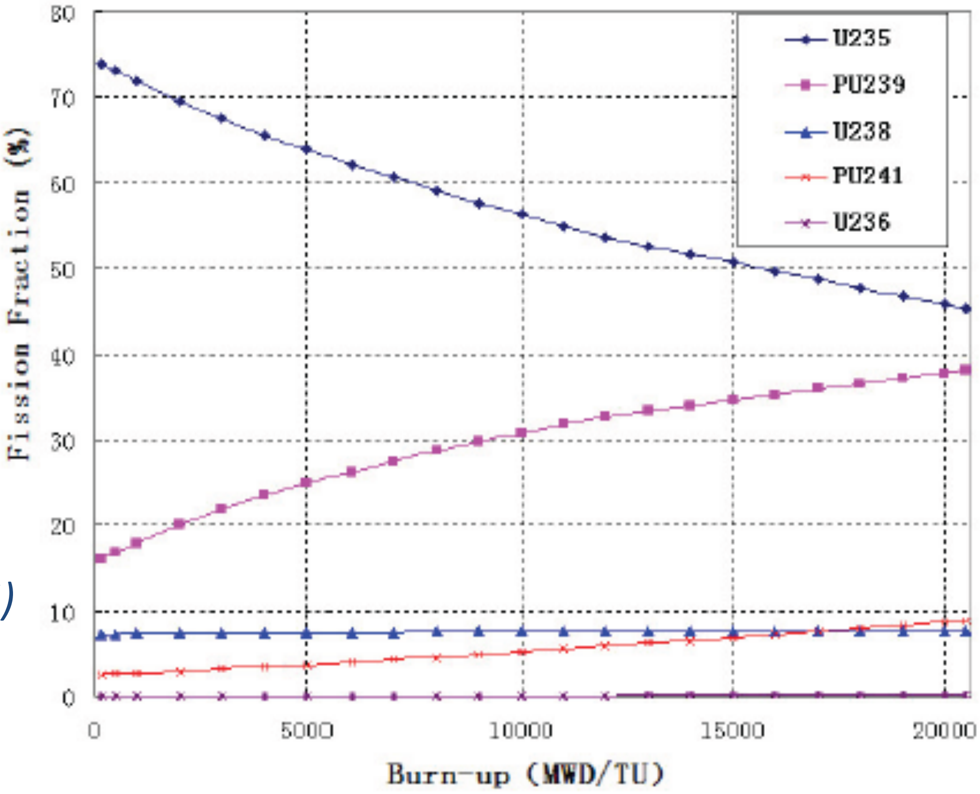
Energy released per fission: $e_{i.}$

V. Kopekin et al., Phys. Atom. Nucl. 67, 1892 (2004)

Antineutrino spectra per fission: $S_i(E_\nu)$

K. Schreckenbach et al., Phys. Lett. B160, 325 (1985)
A. A. Hahn et al., Phys. Lett. B218, 365 (1989)
P. Vogel et al., Phys. Rev. C24, 1543 (1981)
T. Mueller et al., Phys. Rev. C83, 054615 (2011)
P. Huber, Phys. Rev. C84, 024617 (2011)

Typical parent fission rates vs. burnup in power reactor



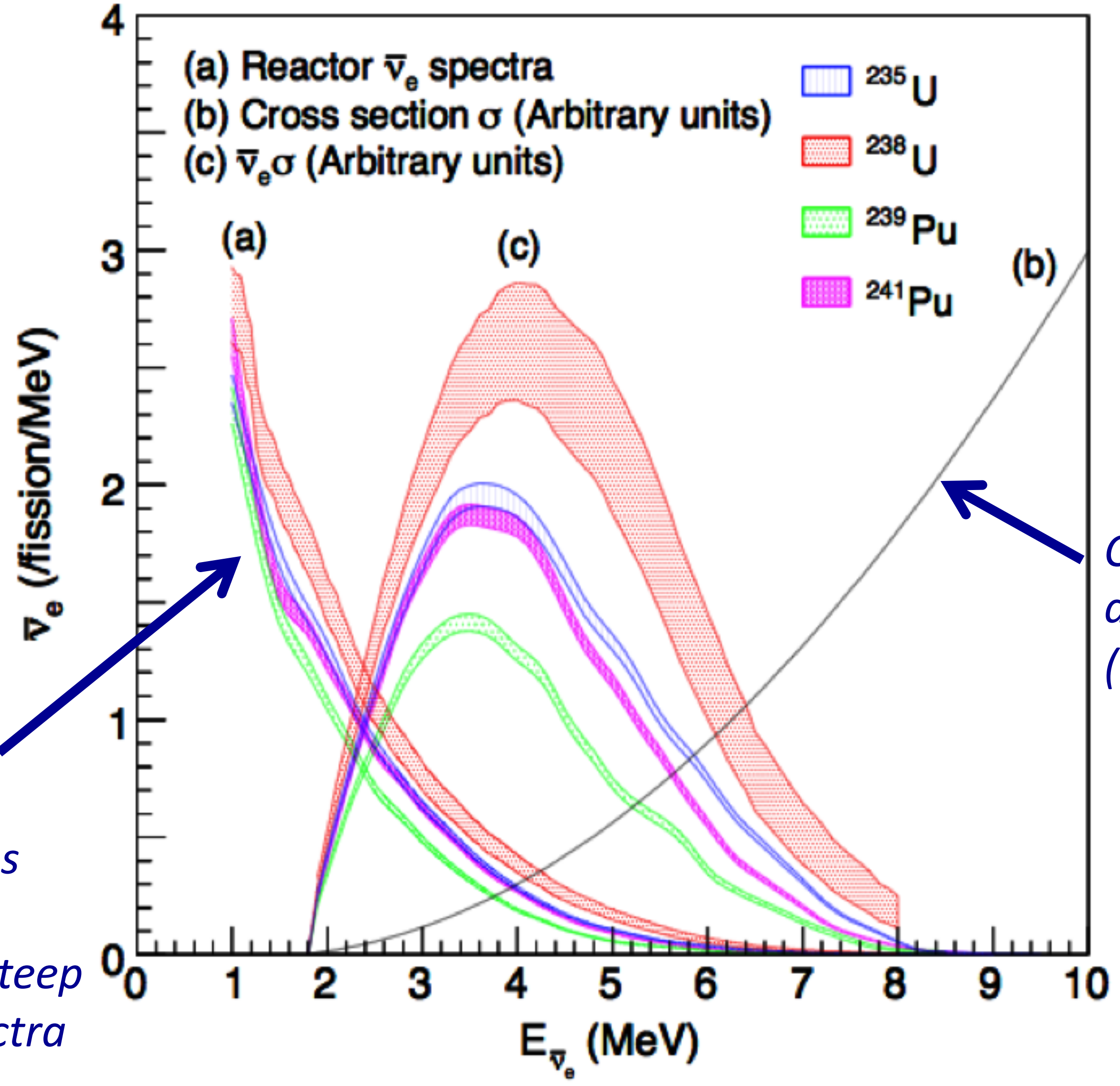
Chin. Phys. C41, 13002 (2017)

Minor corrections: Non-equilibrium fuel, neutron capture on reactor materials, non-linear isotopes

Cogswell, Huber 2016, Conant, Mumm, Erickson 2018, Jaffke, Huber 2015

Reactor Antineutrinos

Antineutrino spectra per fission of parent actinide



Beta-decays of O(1000) unique daughter isotopes from each fission parent produce steep antineutrino spectra

Cross-section for antineutrino detection (Inverse beta decay)

Detection Method

Inverse β-decay (IBD):

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

$$\downarrow$$

$$n + {}^{x}Gd \rightarrow {}^{x+1}Gd + \gamma$$

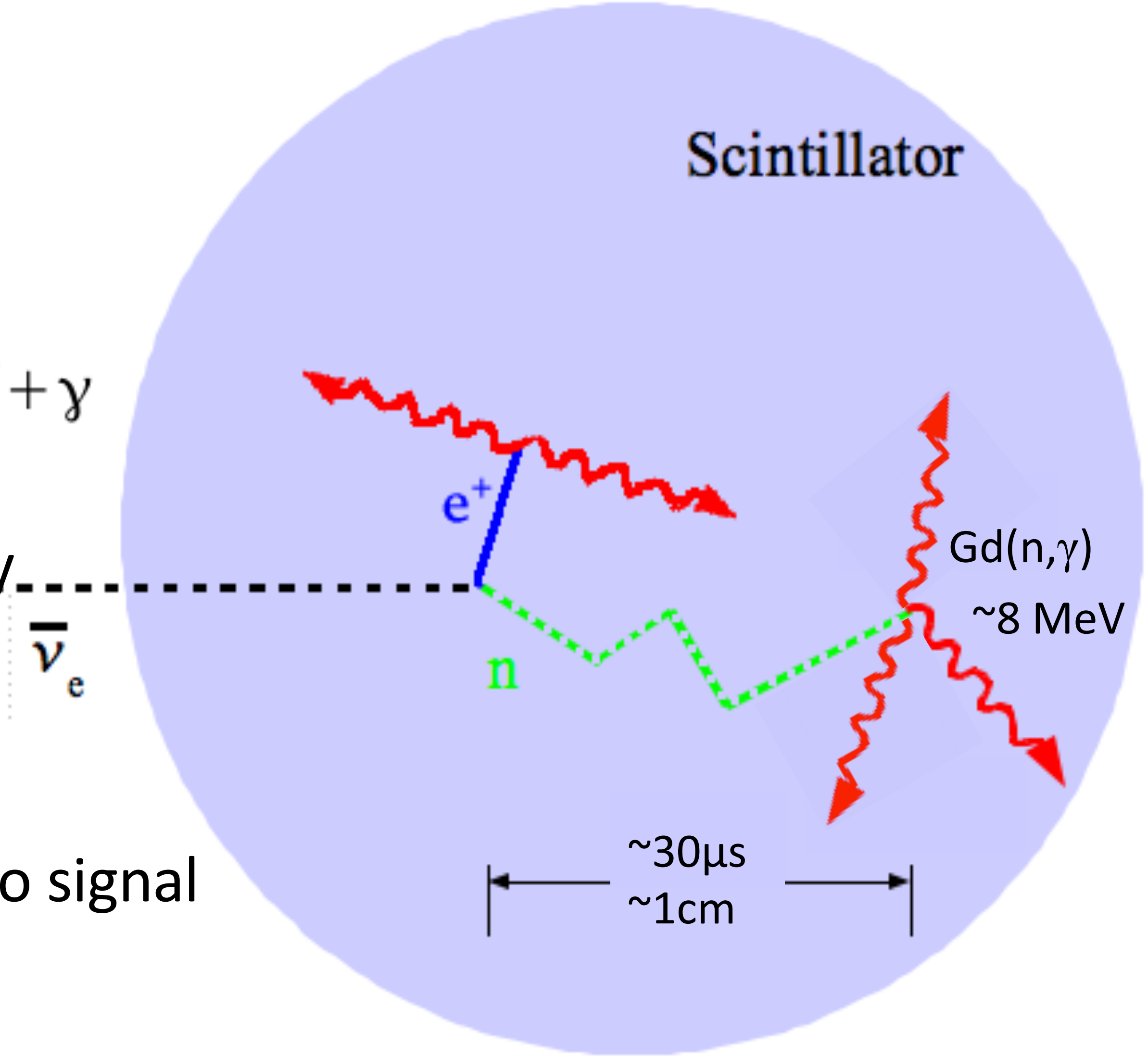
Prompt positron:

Carries antineutrino energy

$E_{e+} \approx E_\nu - 0.8\ \mathrm{MeV}$

Delayed neutron capture:

Efficiently tags antineutrino signal



Combination of prompt + delayed signals provides distinct signature

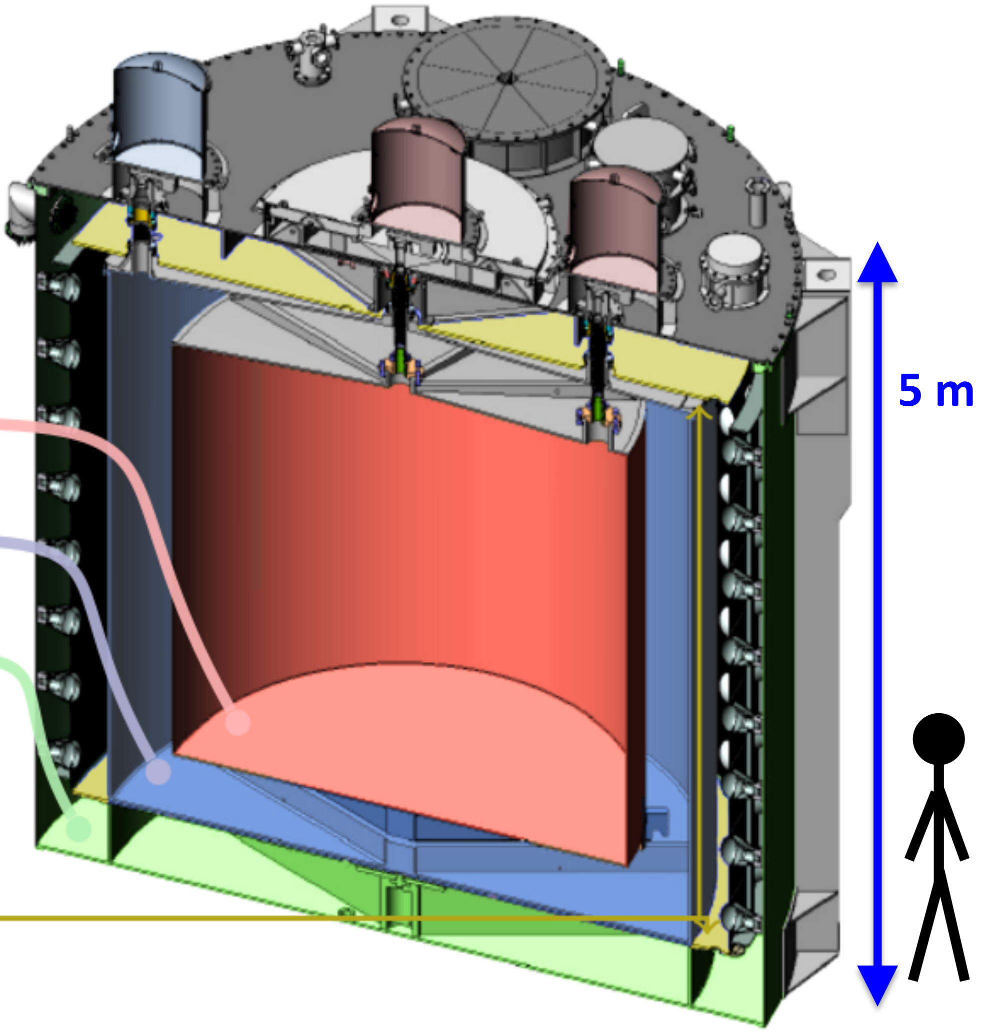
Example: Daya Bay Antineutrino Detectors

8 functionally identical detectors
reduce systematic uncertainties

	3 zone cylindrical vessels		
	Liquid	**Mass**	**Function**
Inner acrylic	Gd-doped liquid scint.	20 t	Antineutrino target
Outer acrylic	Liquid scintillator	20 t	Gamma catcher
Stainless steel	Mineral oil	40 t	Radiation shielding

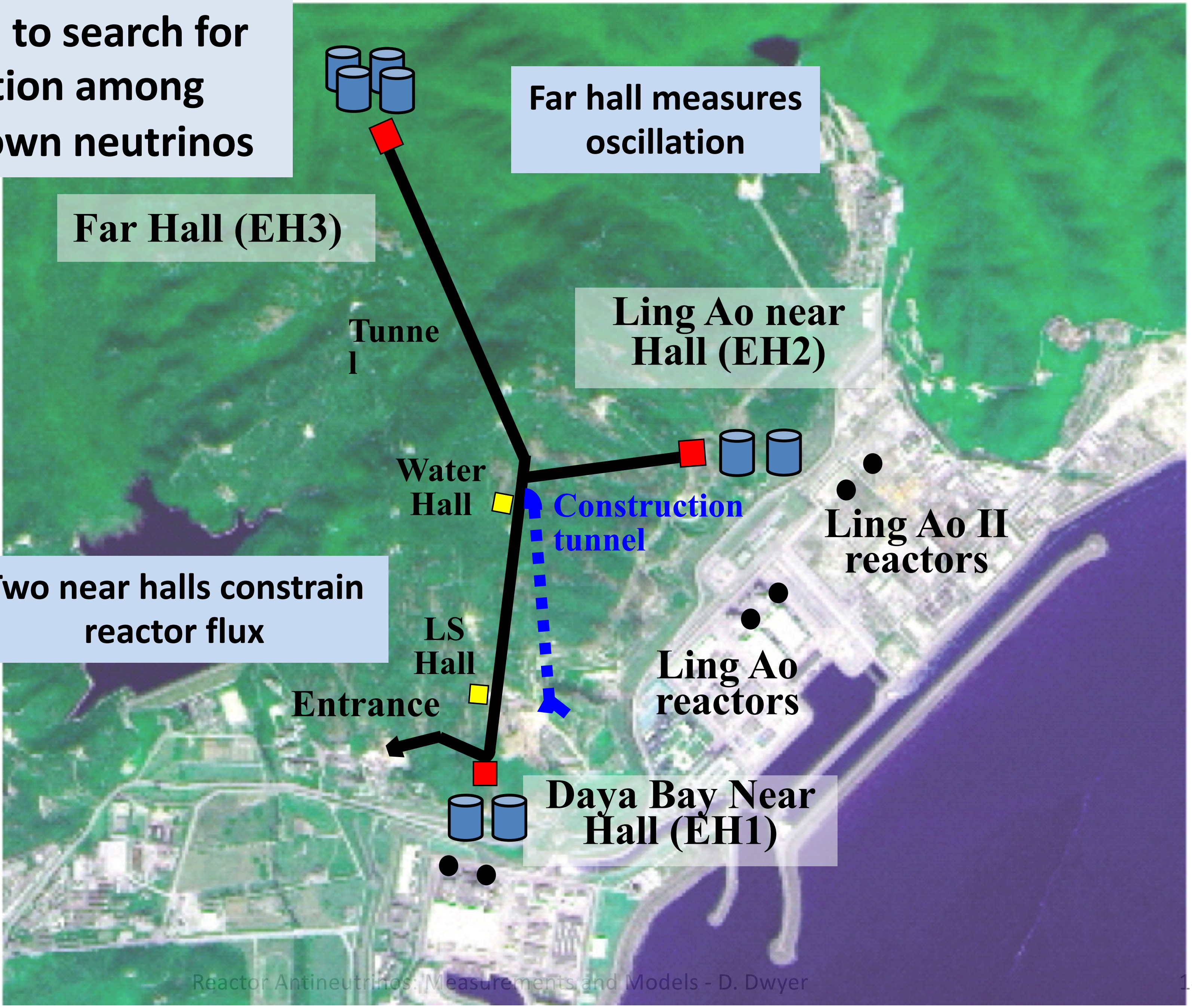
192 8 inch PMTs in each detector

Top and bottom reflectors increase light yield
and flatten detector response



Example: Daya Bay Experiment

Designed to search for oscillation among three known neutrinos

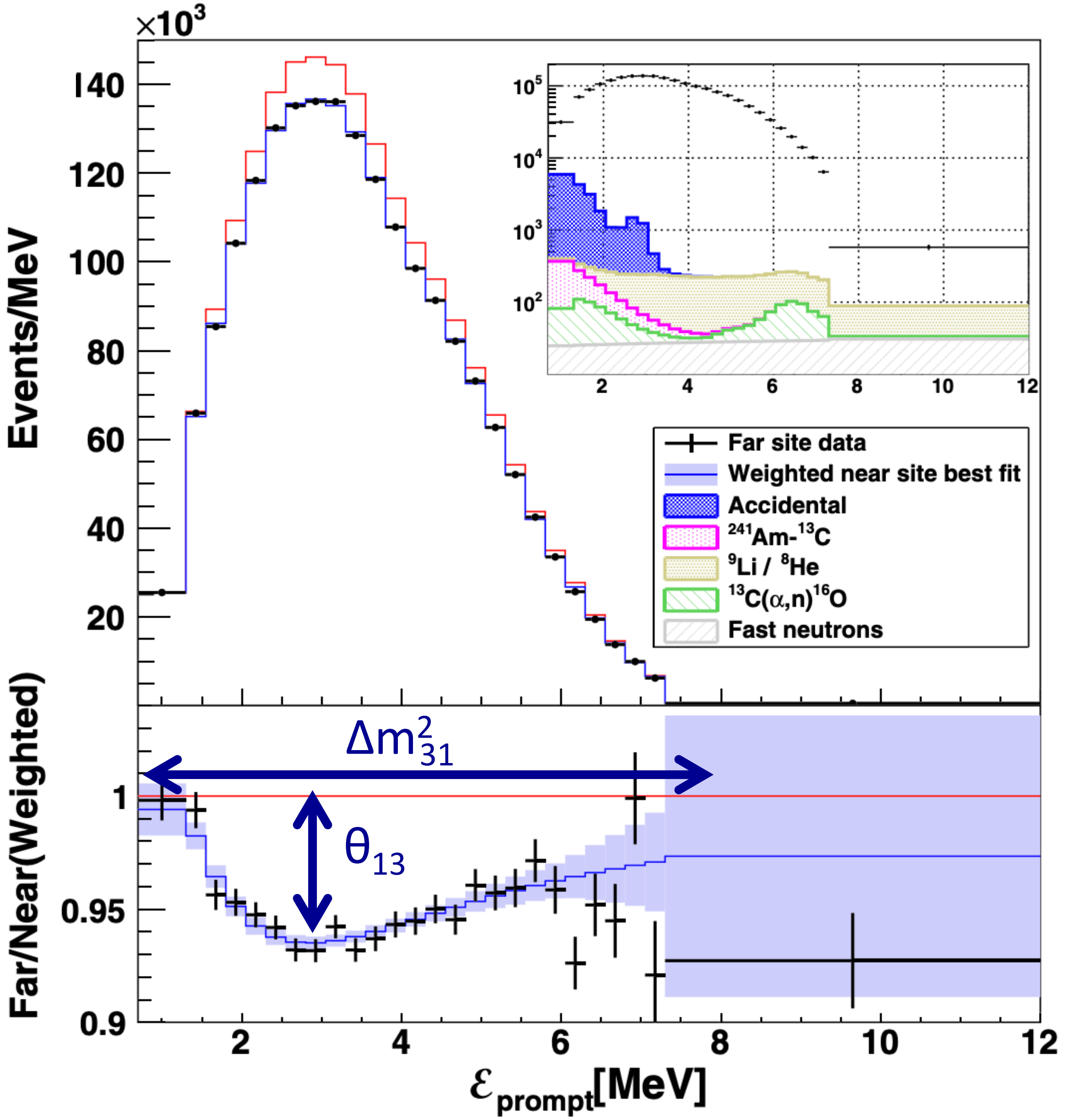


Far hall measures oscillation

Two near halls constrain reactor flux

θ_{13} Oscillation

Discovered oscillation driven by θ_{13} mixing.



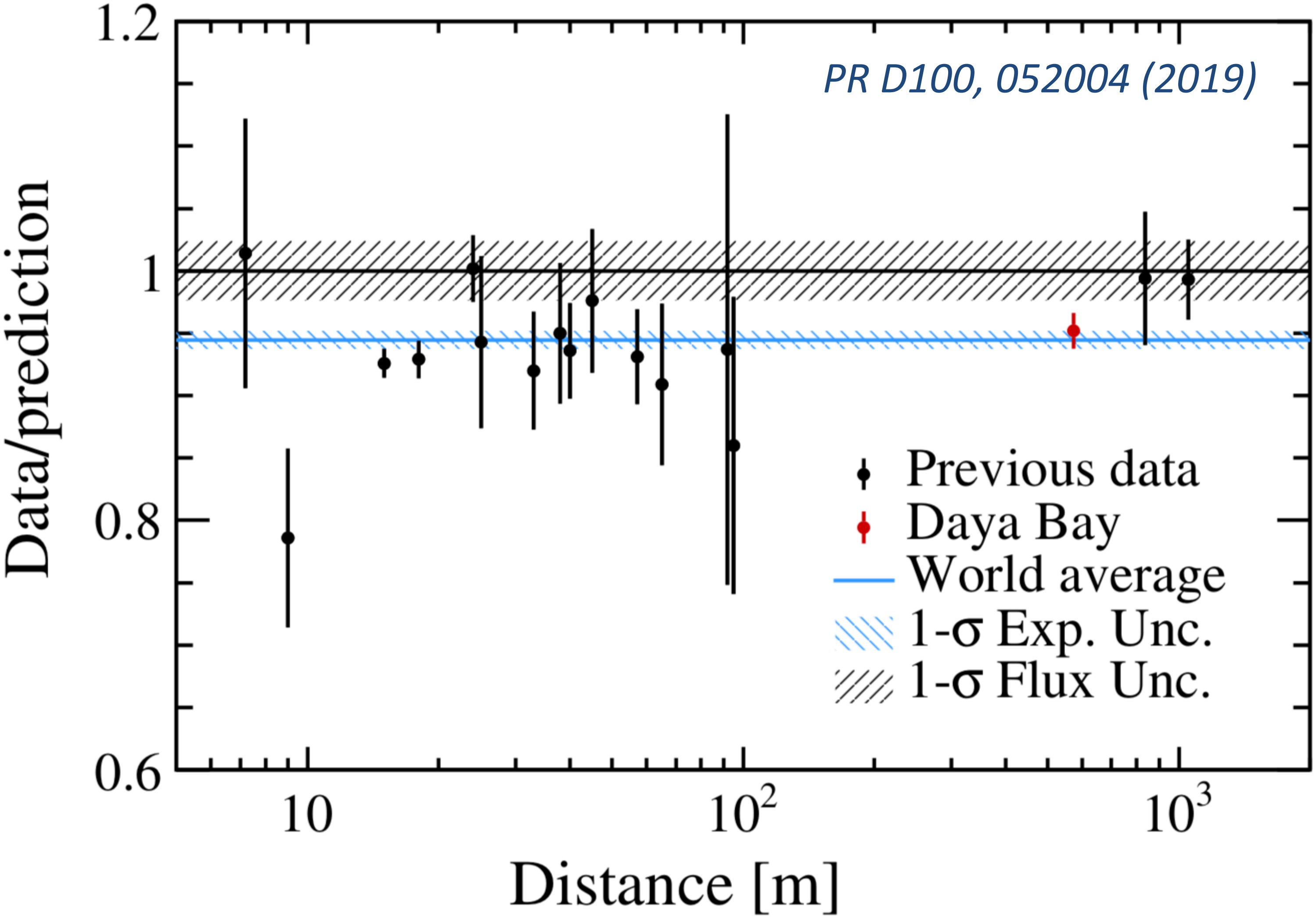
Latest Result:

$4 \times 10^6\ \overline{\nu}_e$

PRL 141, 2041805 (2018)

Absolute Reactor Flux

Daya Bay provides precise measurement of reactor flux



Consistent with average of past measurements. Inconsistent with model.

Spectral Discrepancy

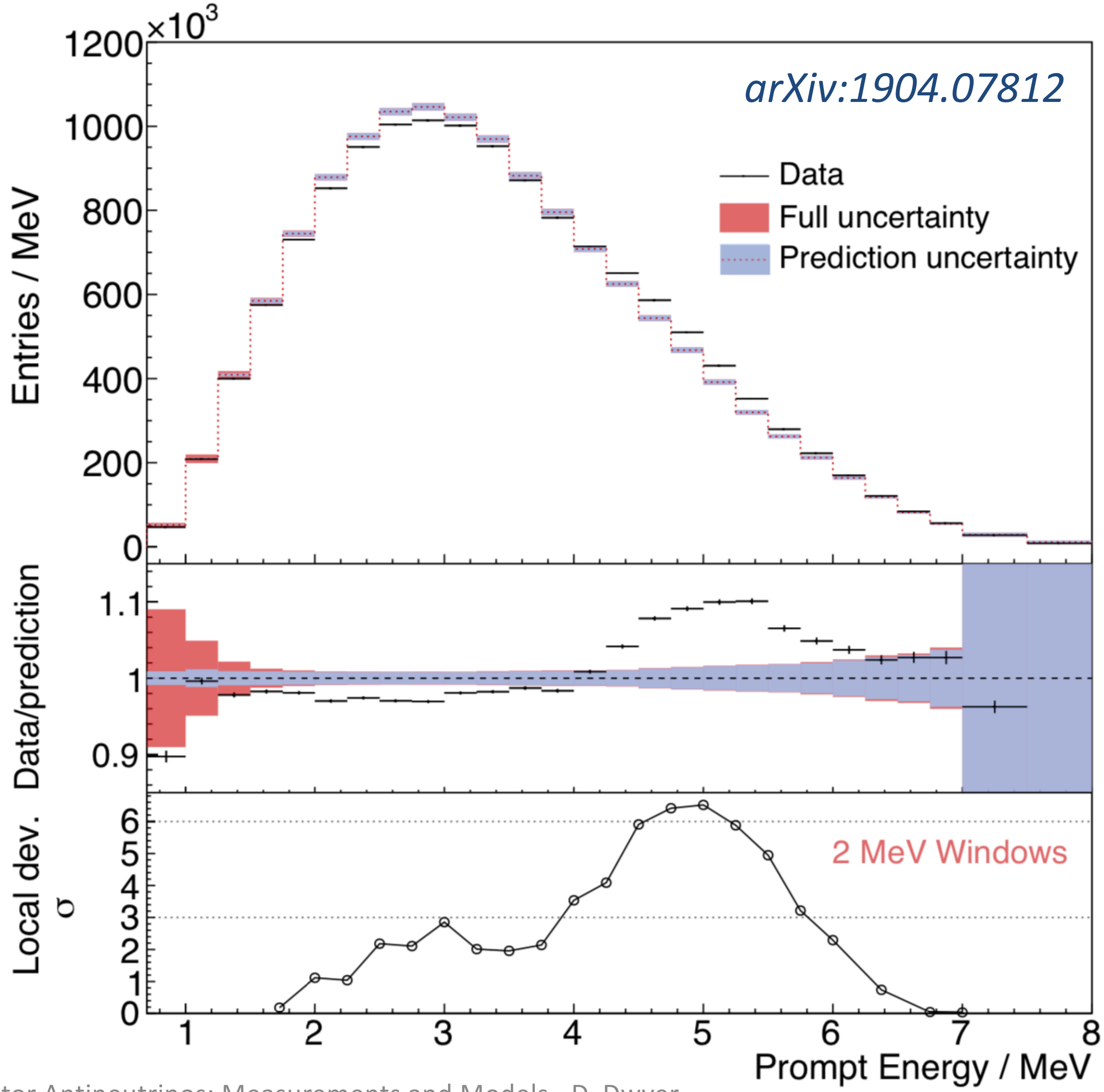
Daya Bay spectrum inconsistent with standard reactor models

Spectrum containing 3.5 million antineutrino interactions.

Particularly strong deviation 5-7 MeV

a.k.a. 'The 5 MeV Bump'
→ More accurately,
it is a shoulder.

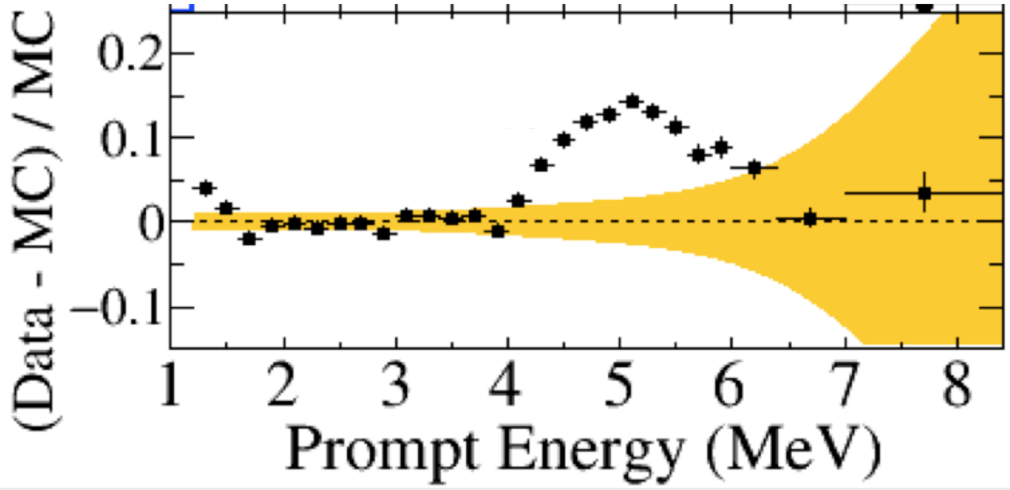
Inconsistent with eV sterile neutrino.

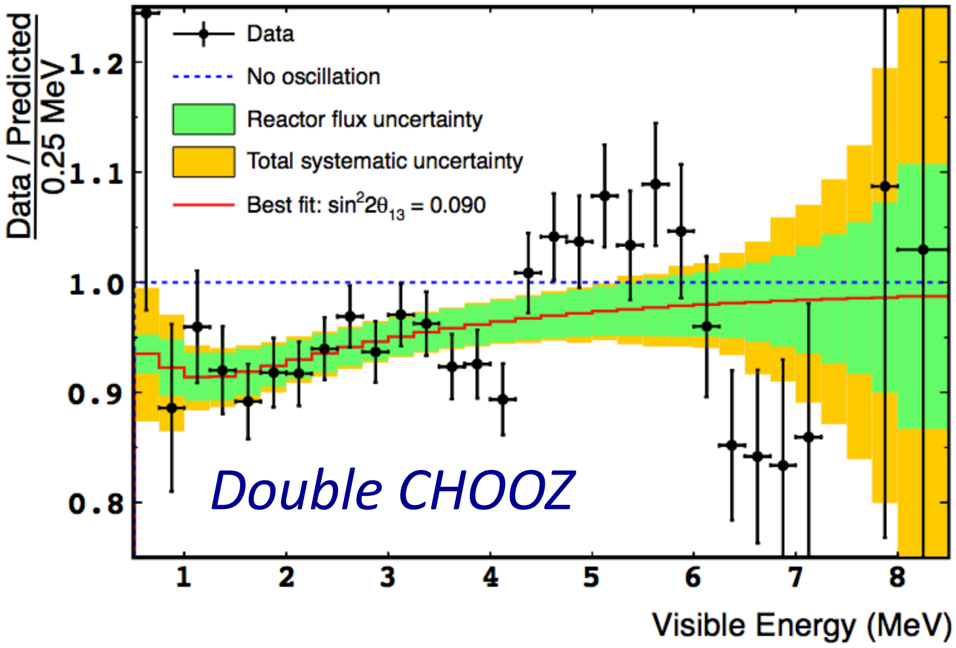


Spectrum Discrepancy

Similar discrepancies observed by RENO and Double CHOOZ Experiments

RENO



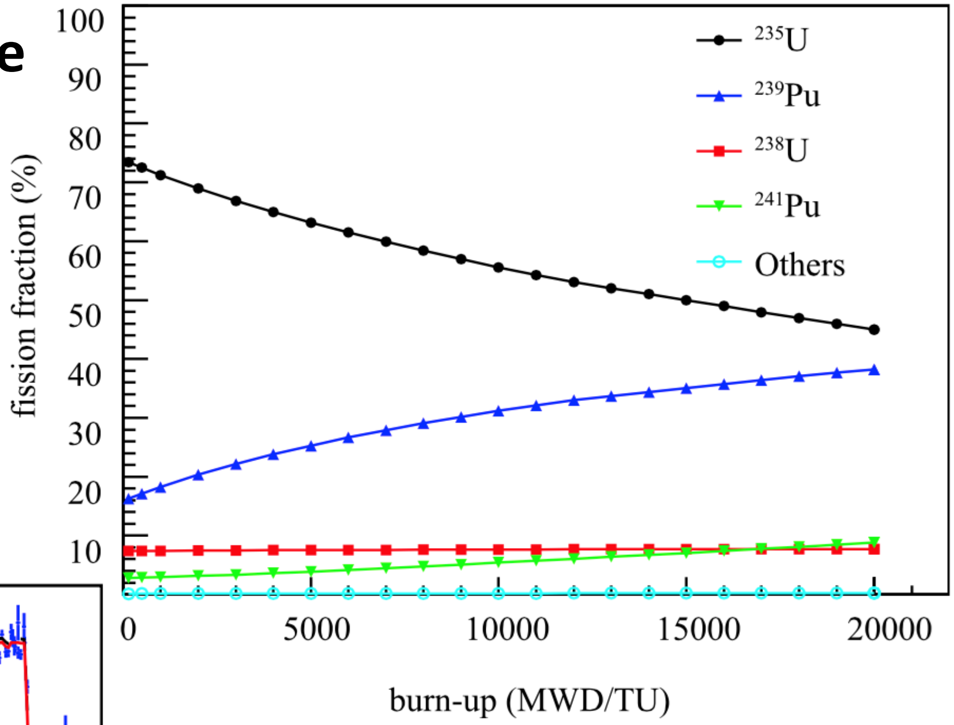


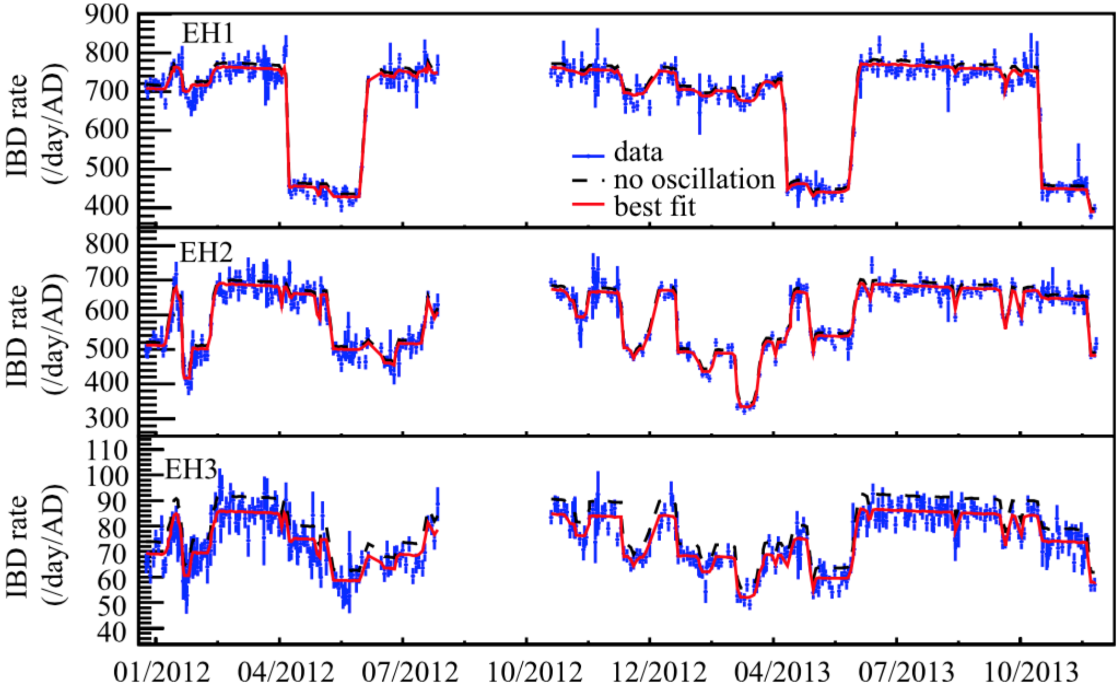
Fuel Variation at Daya Bay

Reactor fuel and fission varies over time

Reactor cores refueled on either 12 month or 18 month cycle.

1/3 of fuel rods replaced, changing ratios of fission parents.





Refueling periods clearly visible in observed antineutrino rates in each experimental hall.

Chin. Phys. C41, 13002 (2017)

→ *Can variation of reactor fuel test antineutrino models?*

Fuel Variation at Daya Bay

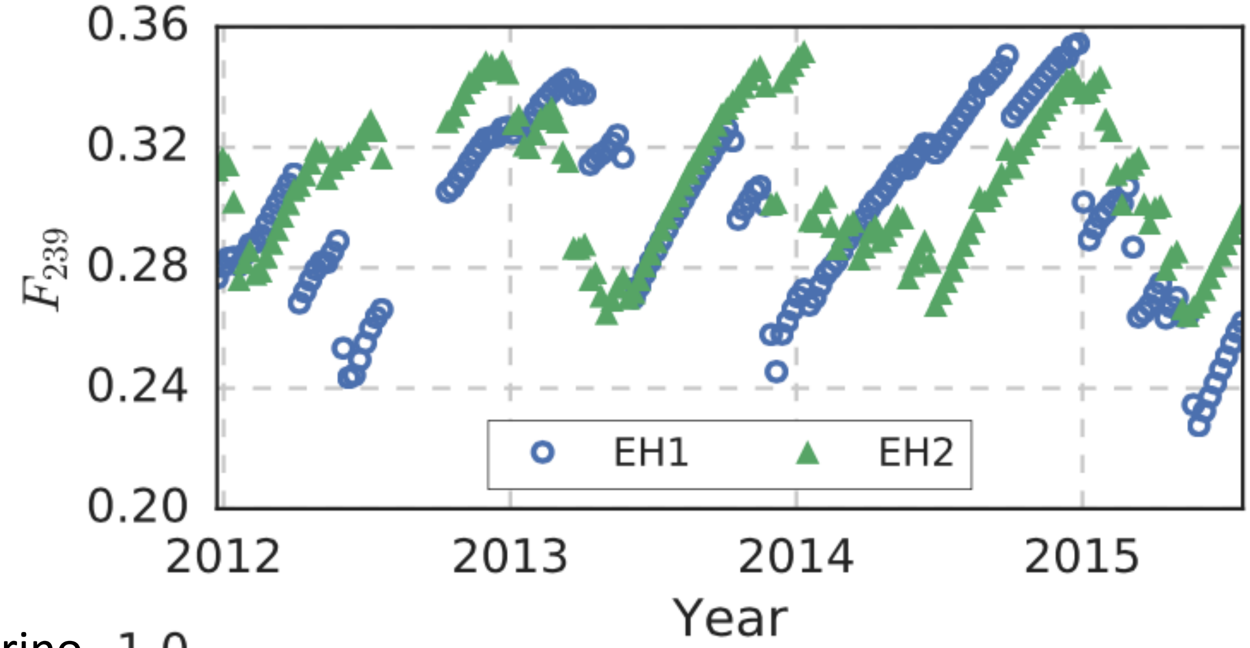
Primary effect:

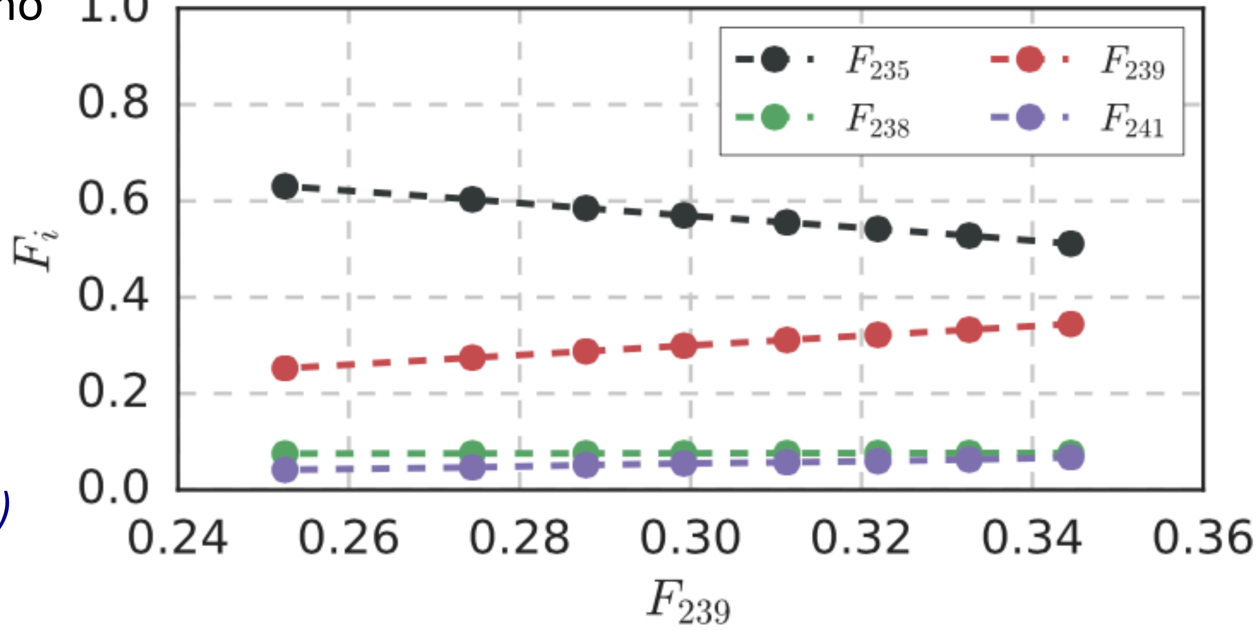
Refueling decreases ^{239}Pu fission rate relative to ^{235}U

Latest analysis:

Bin data in common bins of F_{239} (^{239}Pu fission fraction).

Measure variation in antineutrino rate and spectrum versus fuel composition.



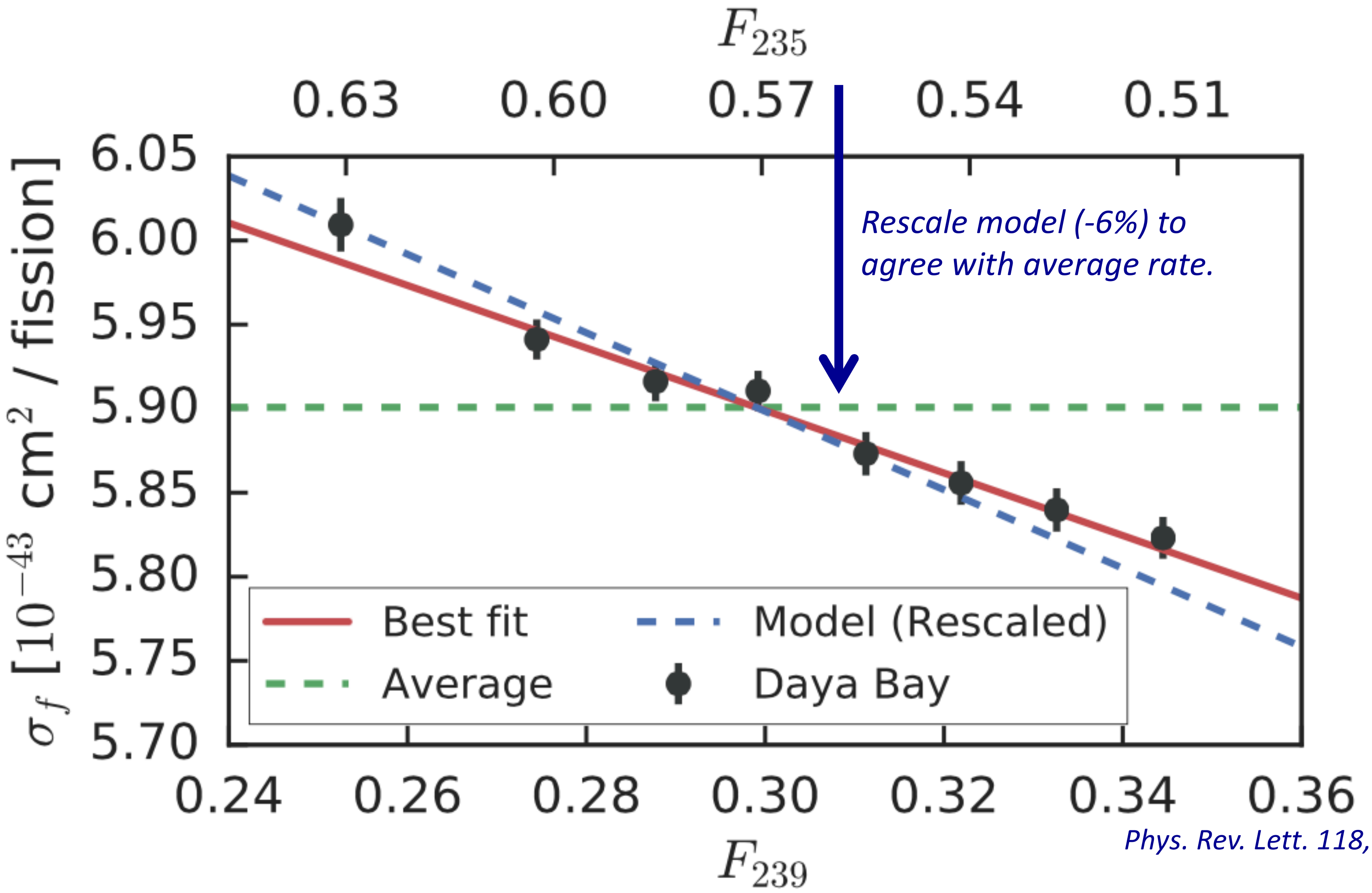


Phys. Rev. Lett. 118, 251801 (2017)

Rate versus Fuel

Average antineutrino rate: $\bar{\sigma}_f = (5.90 \pm 0.13) \times 10^{-43}\ \mathrm{cm}^2/\mathrm{fission}$

First precise measurement of rate variation: $d\sigma_f/dF_{239} = (-1.86 \pm 0.18) \times 10^{-43}\ \mathrm{cm}^2/\mathrm{fission}$



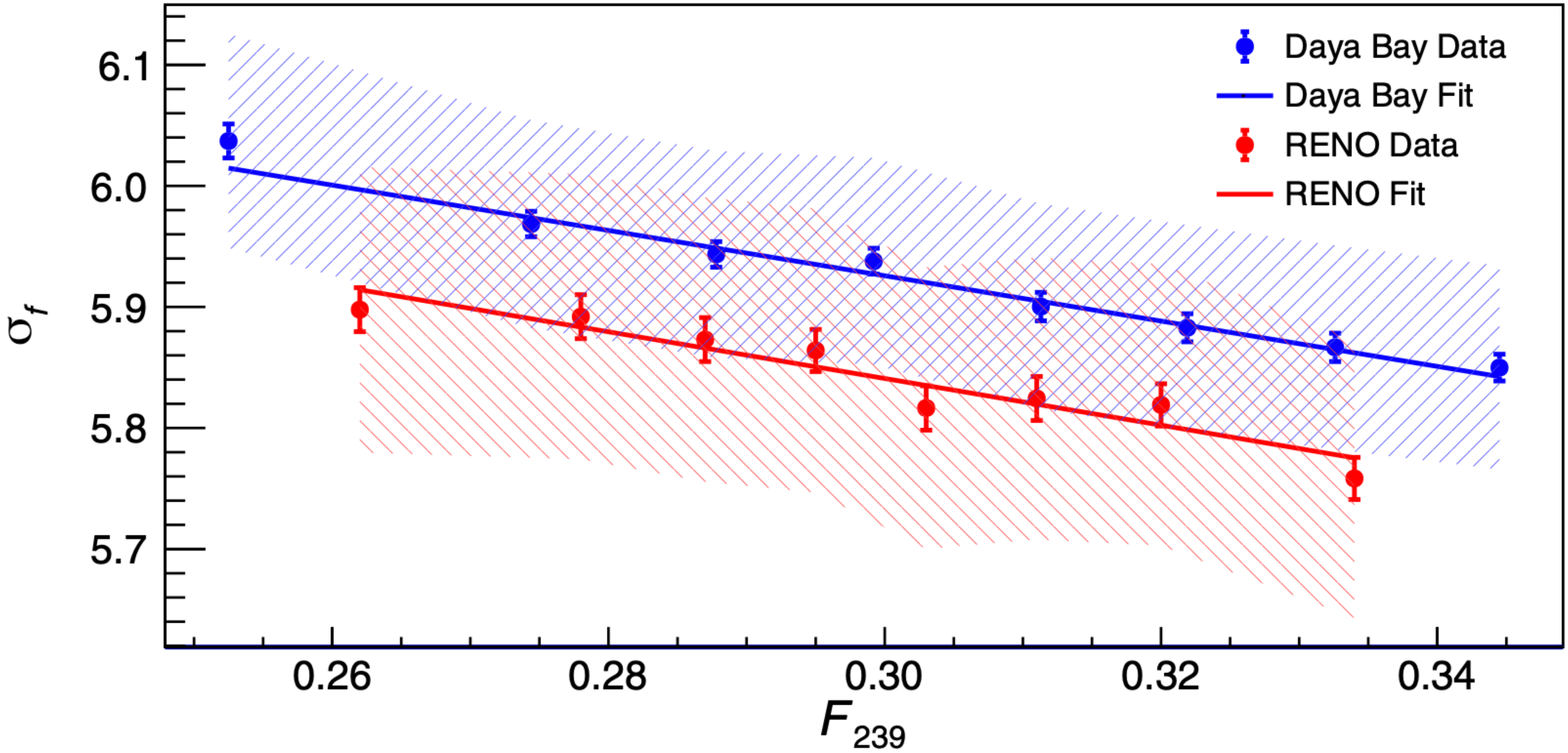
Rescale model (-6%) to agree with average rate.

Phys. Rev. Lett. 118, 251801 (2017)

Not only is rate inconsistent, but slope also disagrees with model.

Rate versus Fuel

RENO observes similar dependence of rate versus fuel



PRL 122, 232501 (2019)
PRD 99 073005 (2019)

Rate By Fission Parent

Use rate vs. fuel to extract antineutrino rate versus fission parent.

Include conservative 10% uncertainties on rates for minor fission parents (i.e. ^{238}U, ^{241}Pu)

Conclusion:

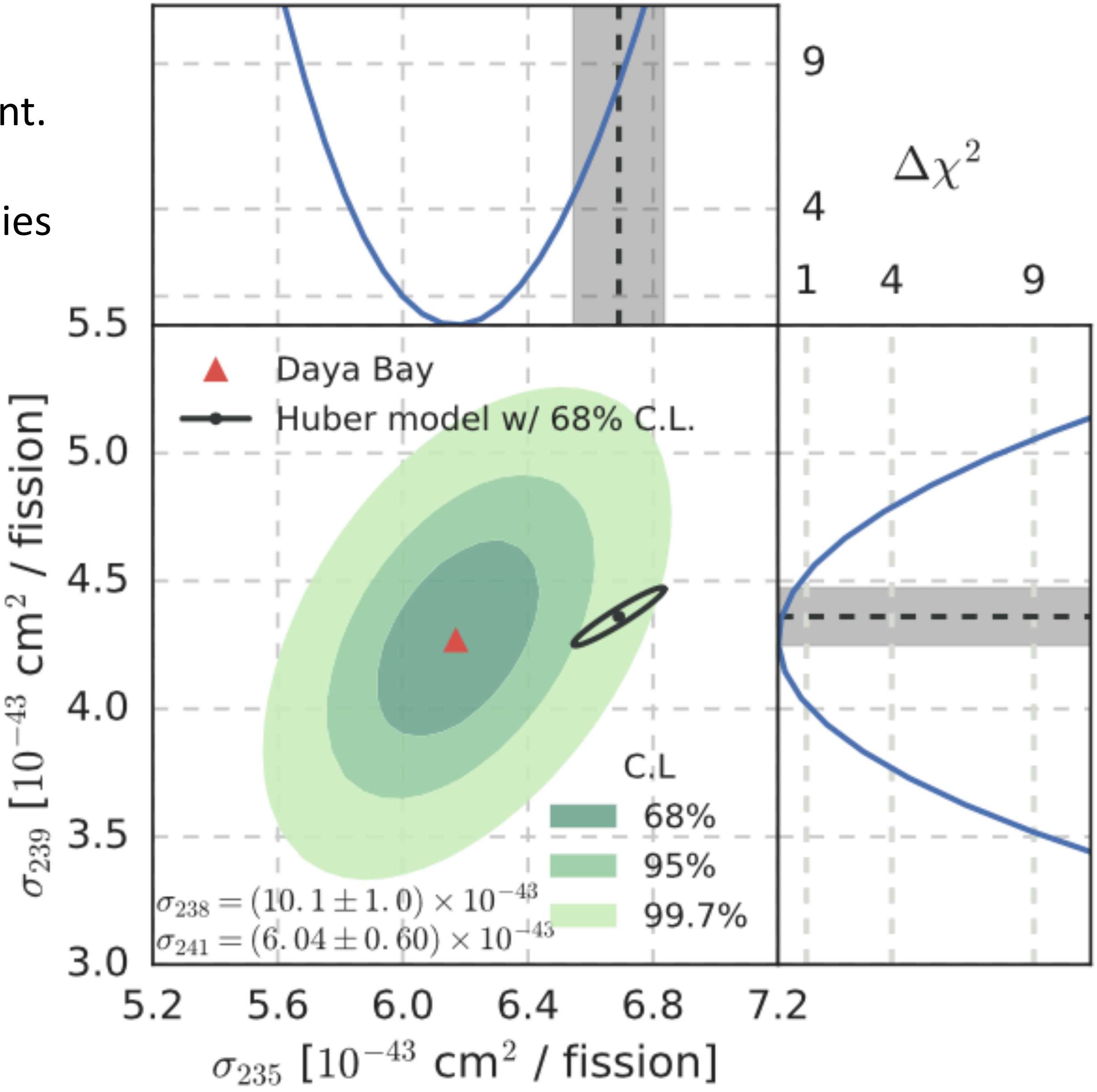
^{239}Pu rate is consistent with model
^{235}U rate is inconsistent (-7.8%)

eV sterile hypothesis:

Would predict equal deficit for each fission parent.

→ Not consistent with Daya Bay observation (2.8σ).

Phys. Rev. Lett. 118, 251801 (2017)



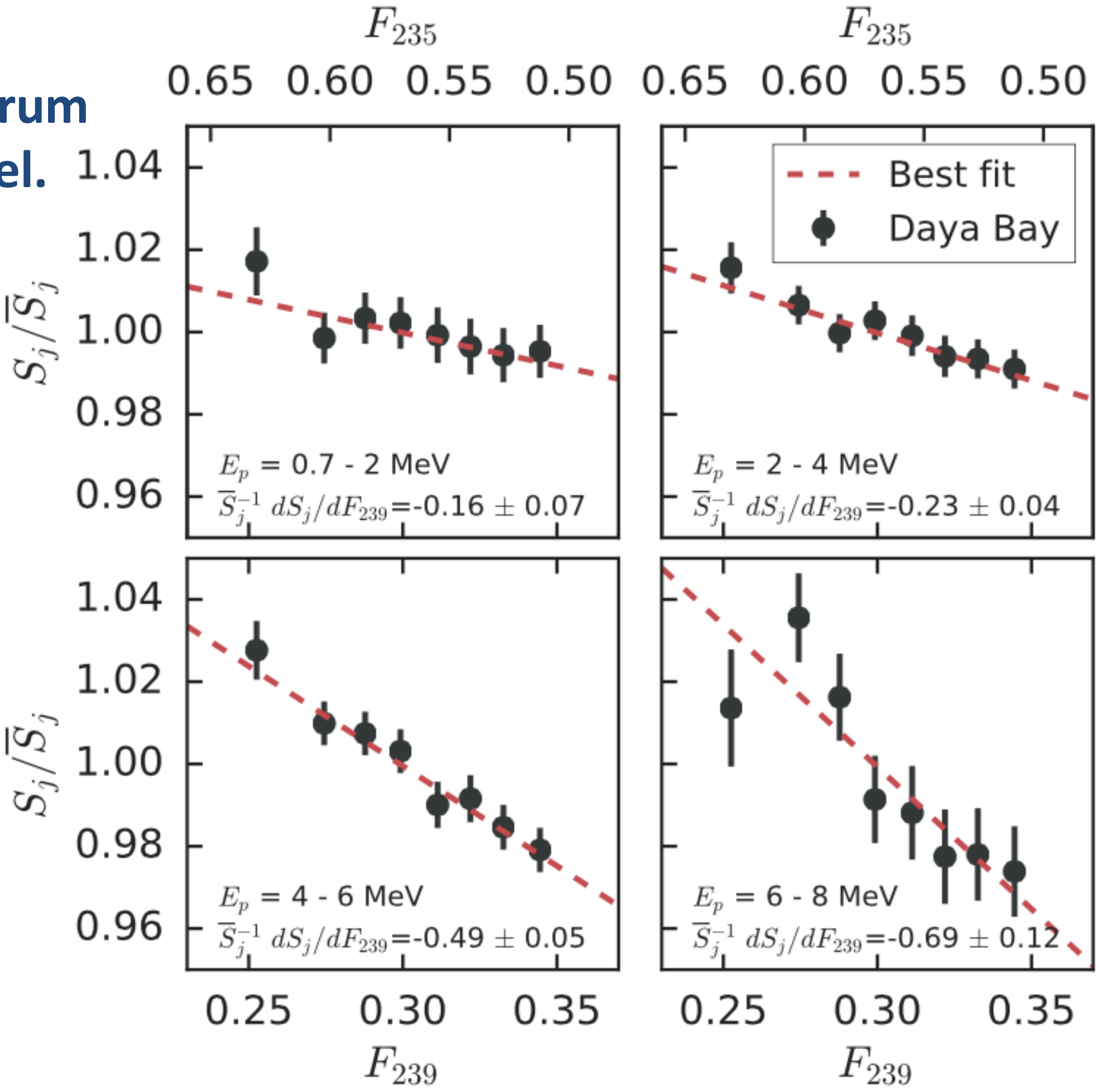
Spectrum vs. Fuel

Antineutrino energy spectrum also varies with reactor fuel.

First clear measurement of change of energy spectrum versus fuel composition.

Not yet sufficiently precise for relevant tests of models.

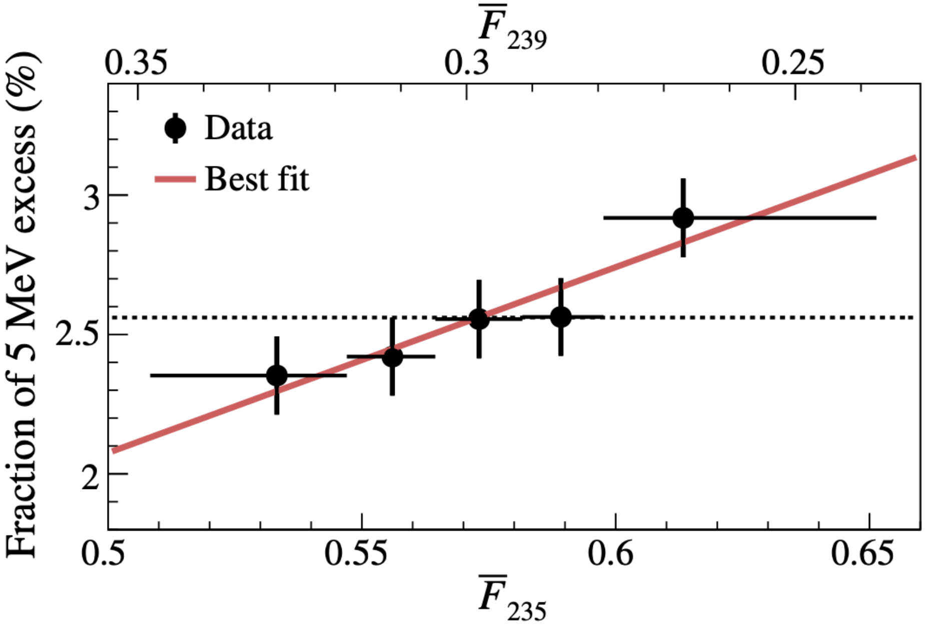
Also of interest to nuclear non-proliferation community.



Phys. Rev. Lett. 118, 251801 (2017)

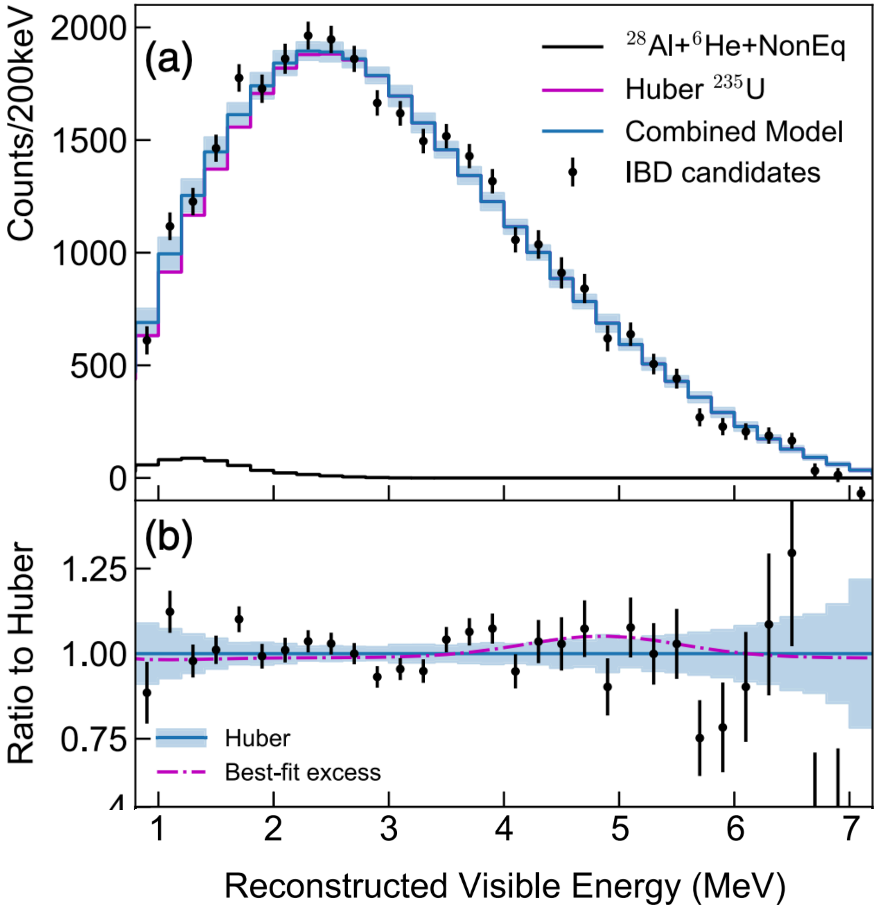
Spectrum vs. Fuel

RENO reports spectral variation



PRL 122, 232501 (2019)

PROSPECT: measures ^{235}U spectrum at high-enriched uranium reactor



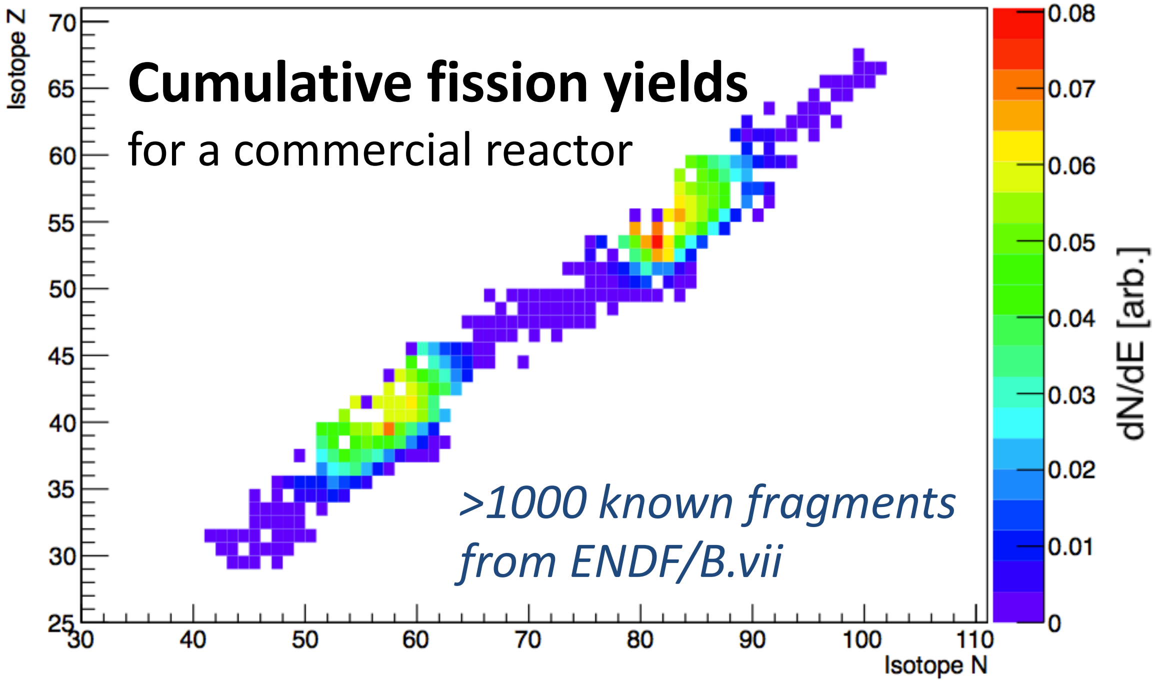
Spectrum shows slight tension with β^- conversion model

PRL 121, 251801 (2018)

Part 2:
Details of Models of Reactor Antineutrino Emission

Method 1: Nuclear Summation

Fission of actinides (^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu) produce neutron-rich daughter fragments.



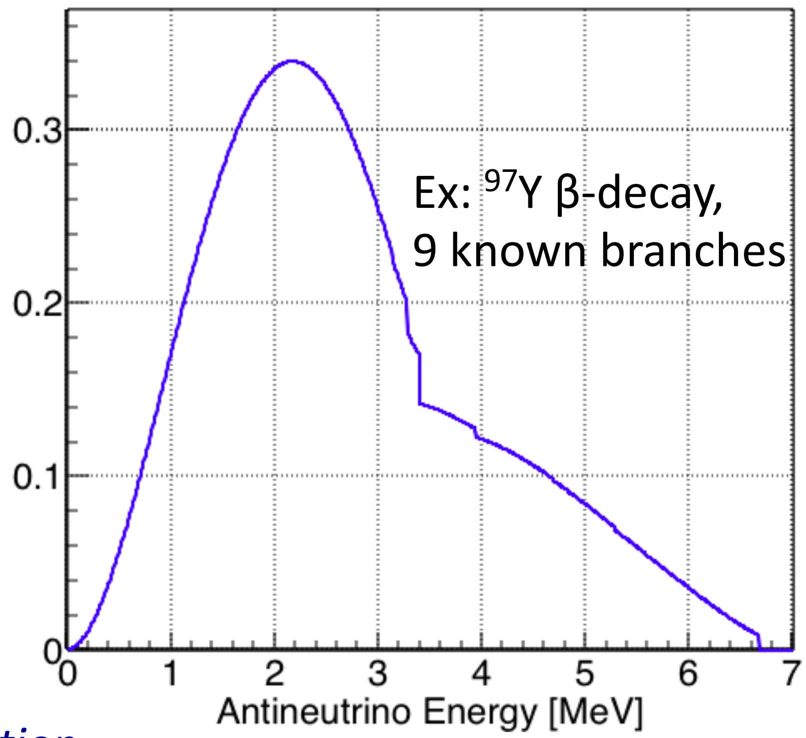
Cumulative fission yields

for a commercial reactor

>1000 known fragments from ENDF/B.vii

β-decays of daughters emit electrons and antineutrinos.

O(10k) known β-decays



Ex: ^{97}Y β-decay, 9 known branches

Total Reactor $\bar{\nu}_e$ Spectrum:

Branching fraction

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

Daughter decay rate

Branch spectrum

Unfortunately, nuclear data have been insufficiently precise to achieve desired accuracy.

Method 2: β^- Conversion

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

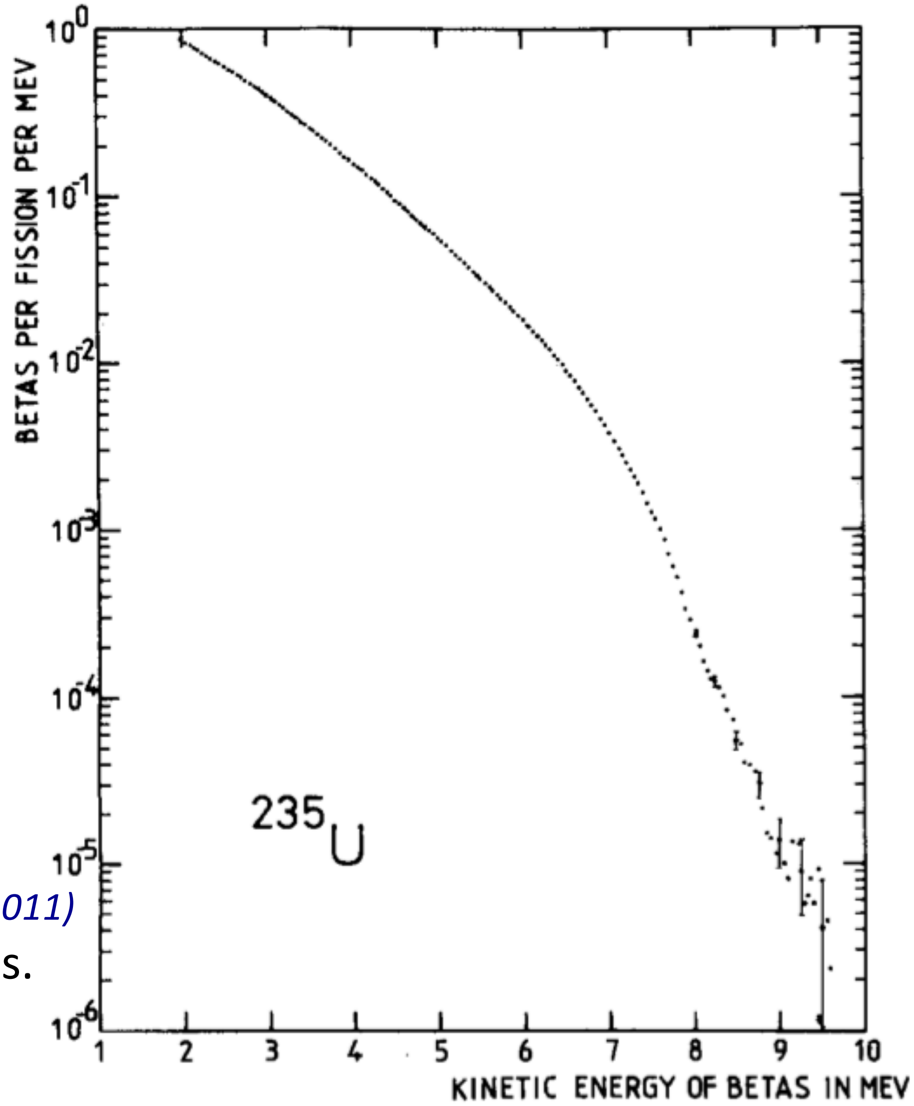
Method:

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:

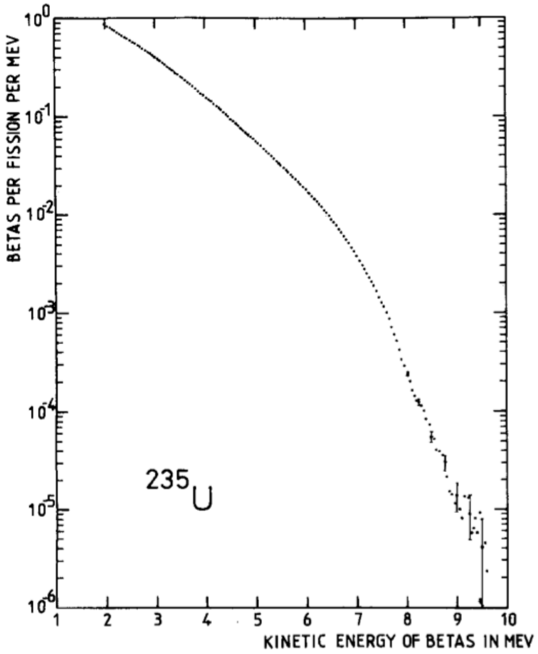
More precise than *summation* method

Standard approach for ~30 years

Predicts:

- 6% higher flux than reactor msmts.
  Reactor Anomaly, Sterile Neutrinos? Phys. Rev. D83, 073006 (2011)
- Stronger variation of rate vs. fuel relative to msmts.
- No shoulder at 5-7 MeV, unlike msmts.

β^- Conversion



Conversion Method:

- Assume fission electron spectrum is composed of many 'virtual' beta decay branches of different Q-values.
- Iteratively fit electron spectrum with 'virtual' beta spectra, until spectrum is completely described.
- Calculate corresponding 'virtual' $\overline{\nu}_e$ spectra, including expected corrections.

Phys. Rev. C76, 025504 (2007)
Phys. Rev. C84, 024617 (2011)

- Use known decay data (90%) with virtual branches (10%) to reduce uncertainty of nuclear corrections.

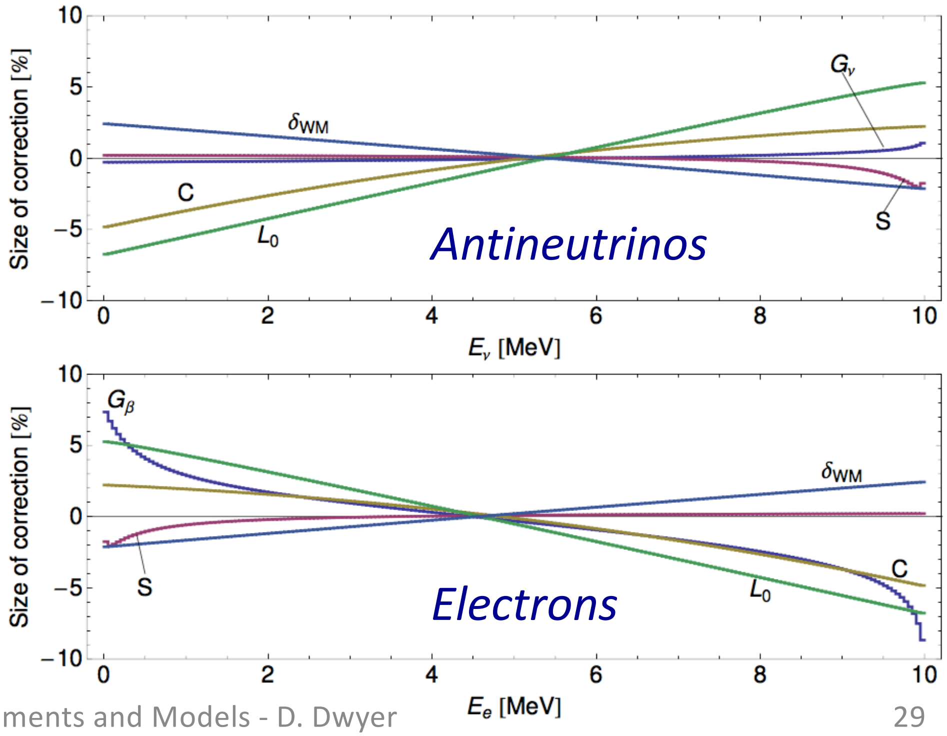
Phys. Rev. C83, 054615 (2011)

Nuclear corrections:

Differ for e^- and $\overline{\nu}_e$.

- Coulomb
- Finite nuclear size
- Weak magnetism
- Screening
- Radiative
- Forbiddeness

Example: $^{117}_{46}$X with E_0=10 MeV



Possible Origins?

What might cause the difference between the e^- and $\bar{\nu}_e$ spectra?

Phys. Rev. D92, 033015 (2015)

1) Non-fission sources of antineutrinos

2) The forbidden nature of some beta decay transitions

3) ^{238}U fission as a source of the shoulder

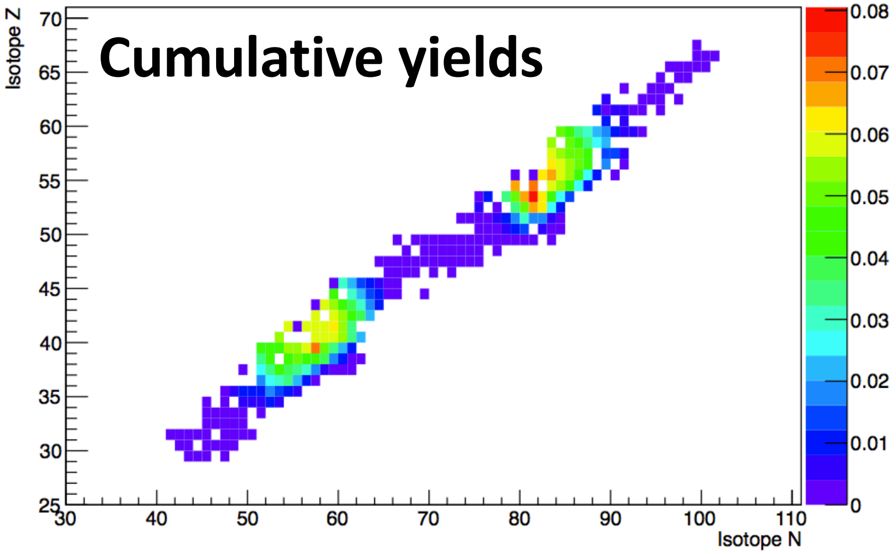
4) The relatively harder PWR neutron spectrum

5) A possible error in the in the ILL beta-decay measurements

Summation Revisited

Phys. Rev. 109, 202504 (2012)

Fission yields of daughter isotopes:



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.

Daughter decay rate

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

Parent fission rate

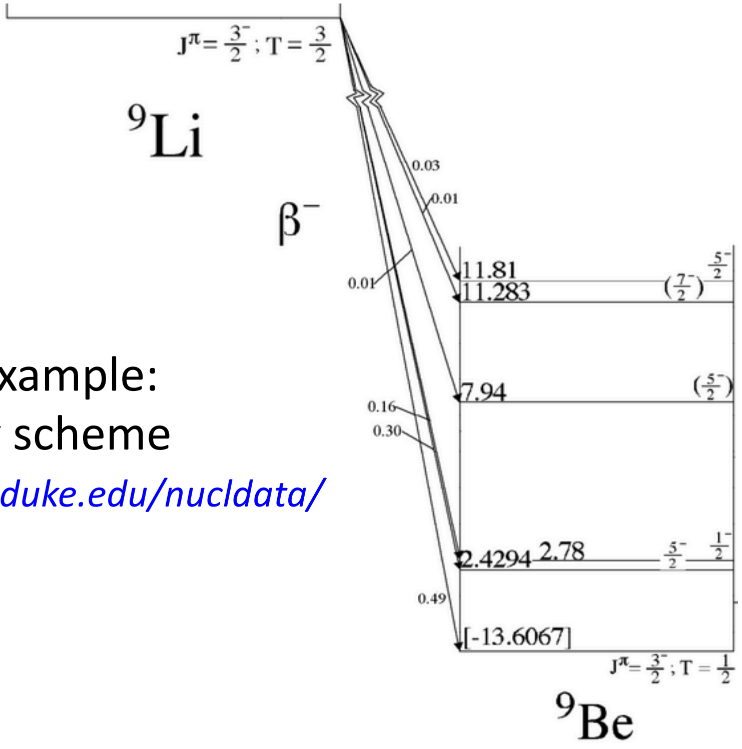
Cumulative yield

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

Summation: Beta Decays

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.

Rely on nuclear databases
e.g. ENSDF:
Evaluated Nuclear
Structure Data File

Total Reactor Spectrum:

Branching fraction

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

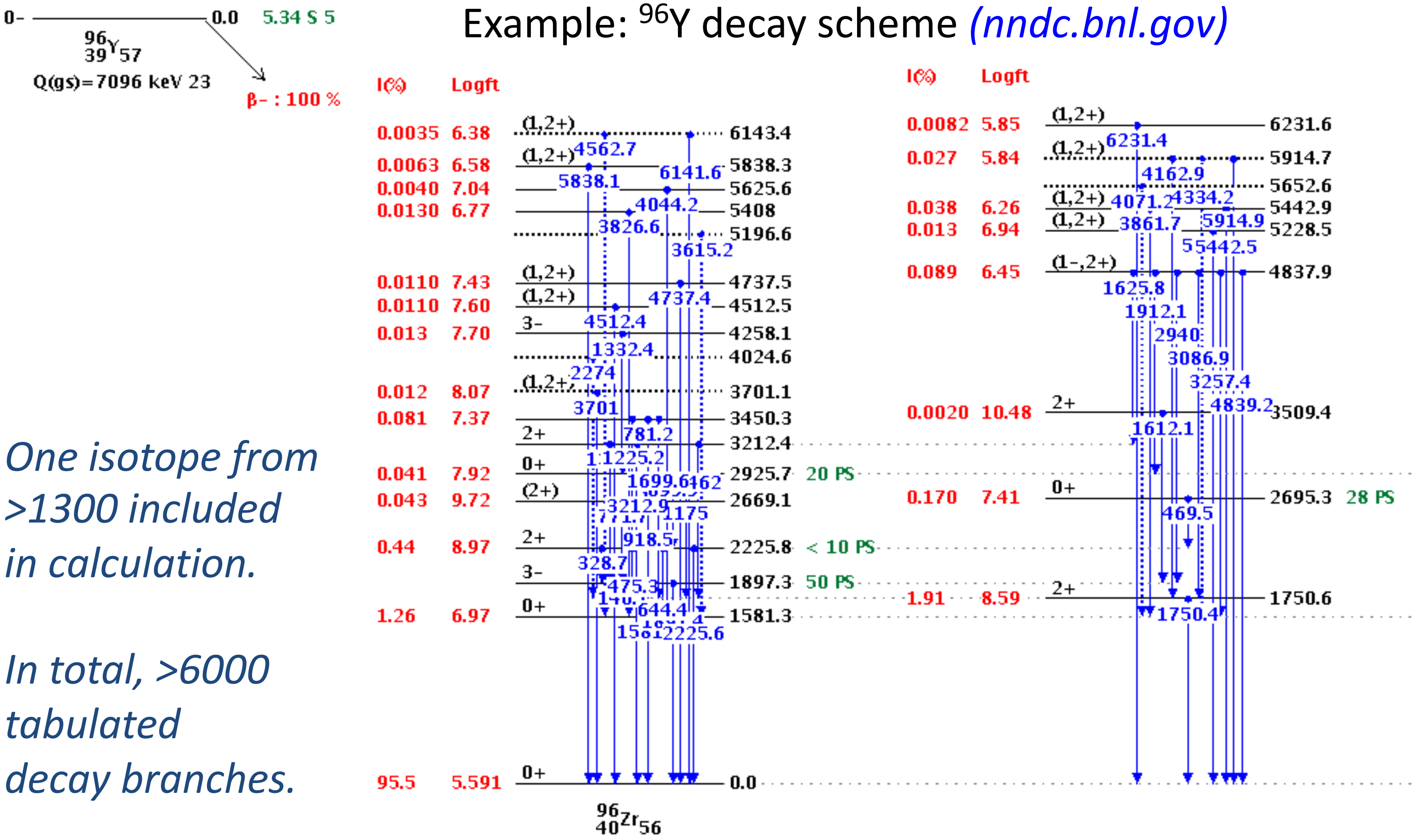
Daughter decay rate

Branch spectrum

Nuclear Structure

Complex decays of neutron rich fission daughters.

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



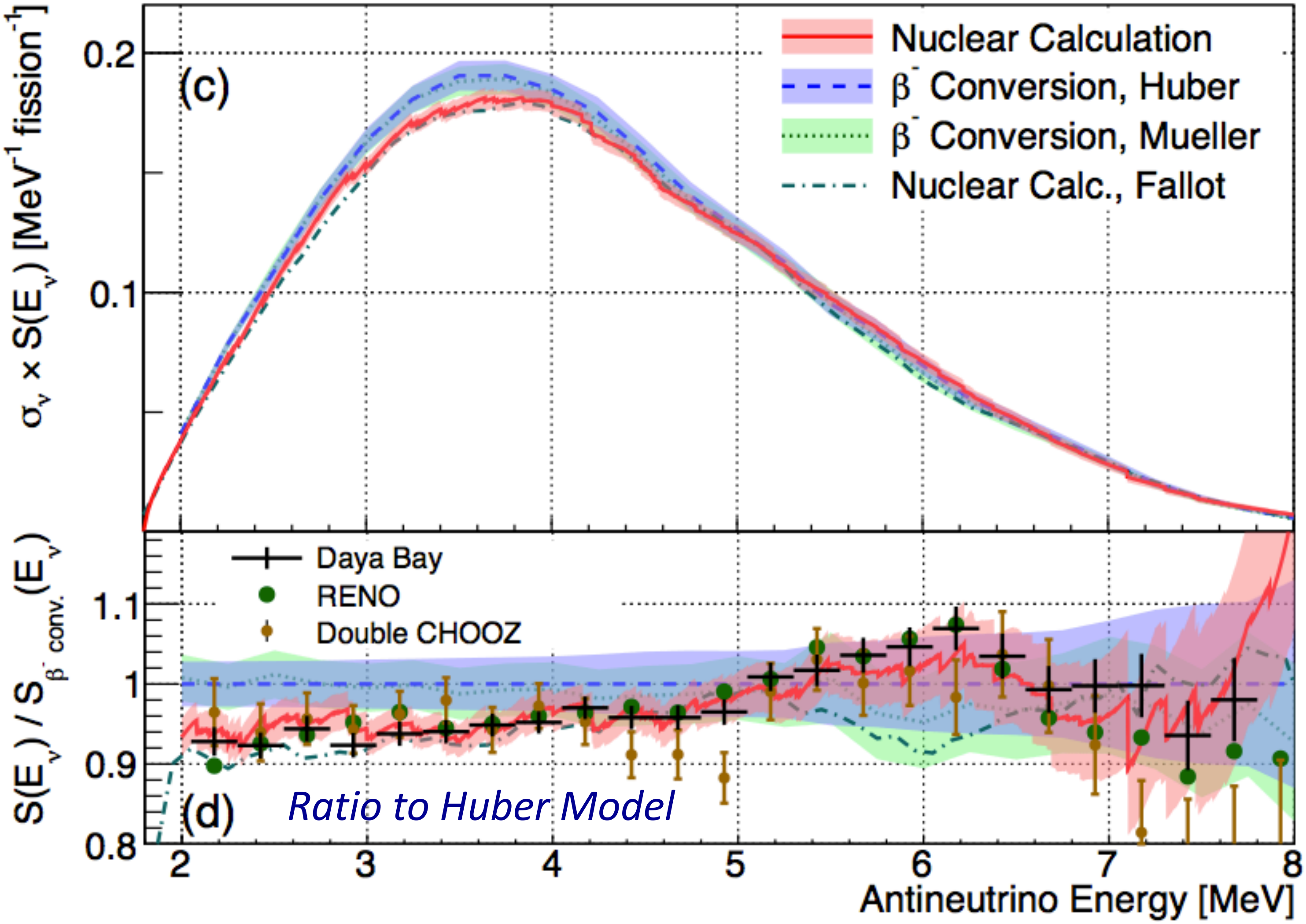
One isotope from >1300 included in calculation.

In total, >6000 tabulated decay branches.

Fission yield and decay branch uncertainties can be considerable.

Summation Revisited

Summation calculation unexpectedly agrees with reactor msmts.



Ratio to Huber Model

PRL 114, 012502 (2015)

Only includes tabulated uncertainties.

But summation suffers from large unquantified uncertainties.

How do missing uncertainties not cause more tension with measurements?

→ Shape dominated by small number of prominent fission daughters.

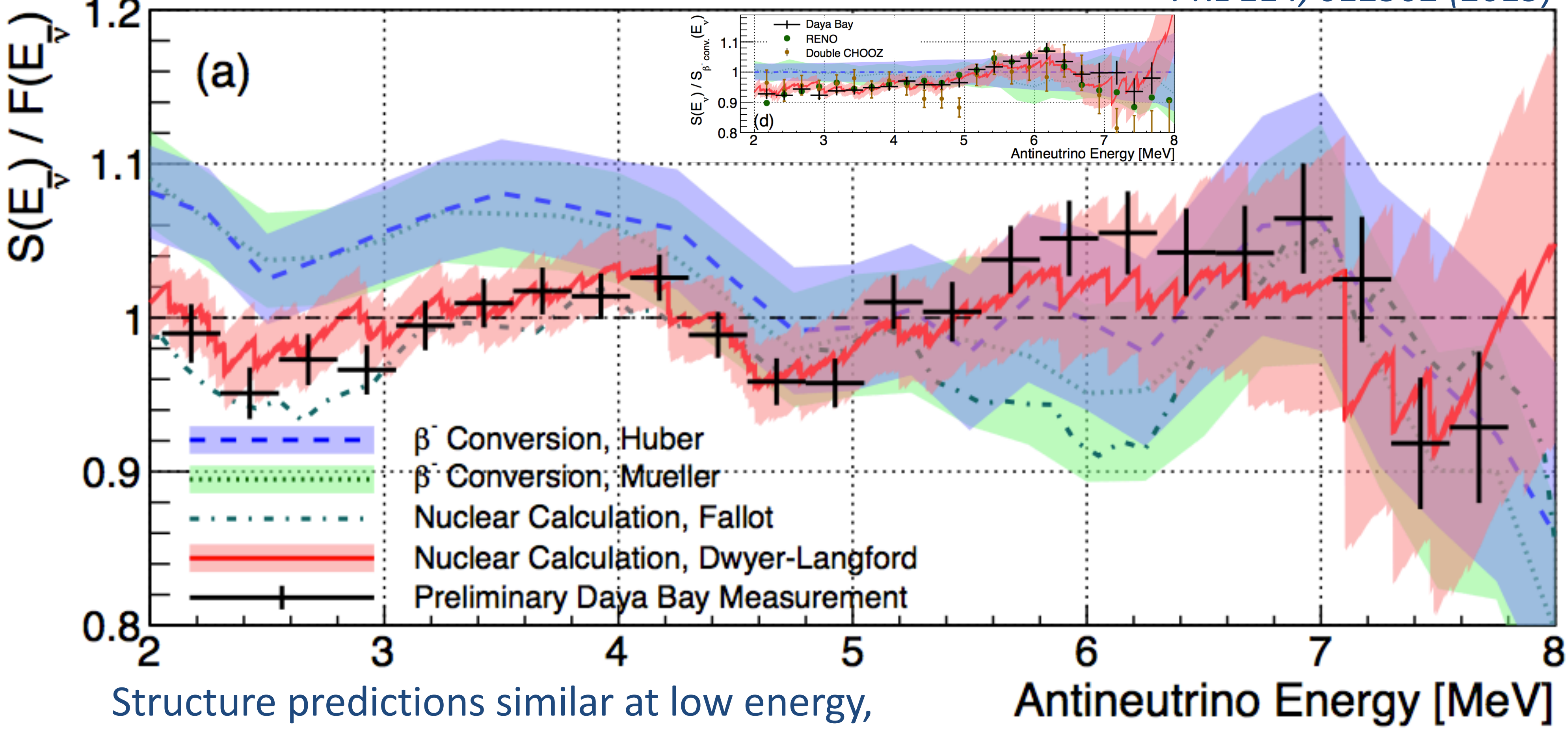
Detailed $\overline{\nu}_e$ Spectrum Shape

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

$$F(E_{\overline{\nu}}) = \exp\left(\sum_i \alpha_i E_{\overline{\nu}}^{i-1}\right)$$

α = {0.4739, 0.3877, −0.3619, 0.04972, −0.002991}

PRL 114, 012502 (2015)

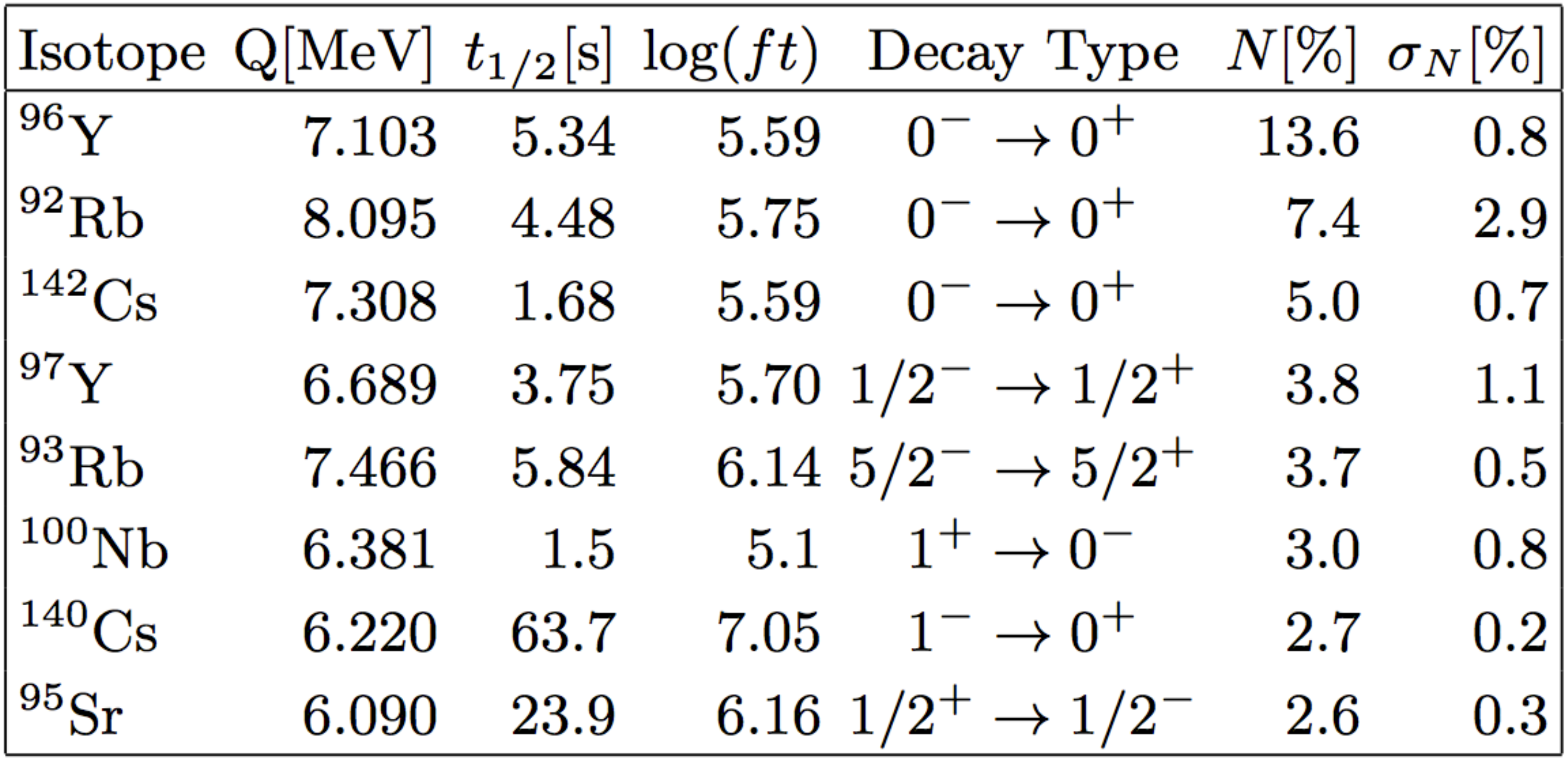


Structure predictions similar at low energy, but differ above 4.5 MeV

Dominant Branches

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

PRL 114, 012502 (2015)



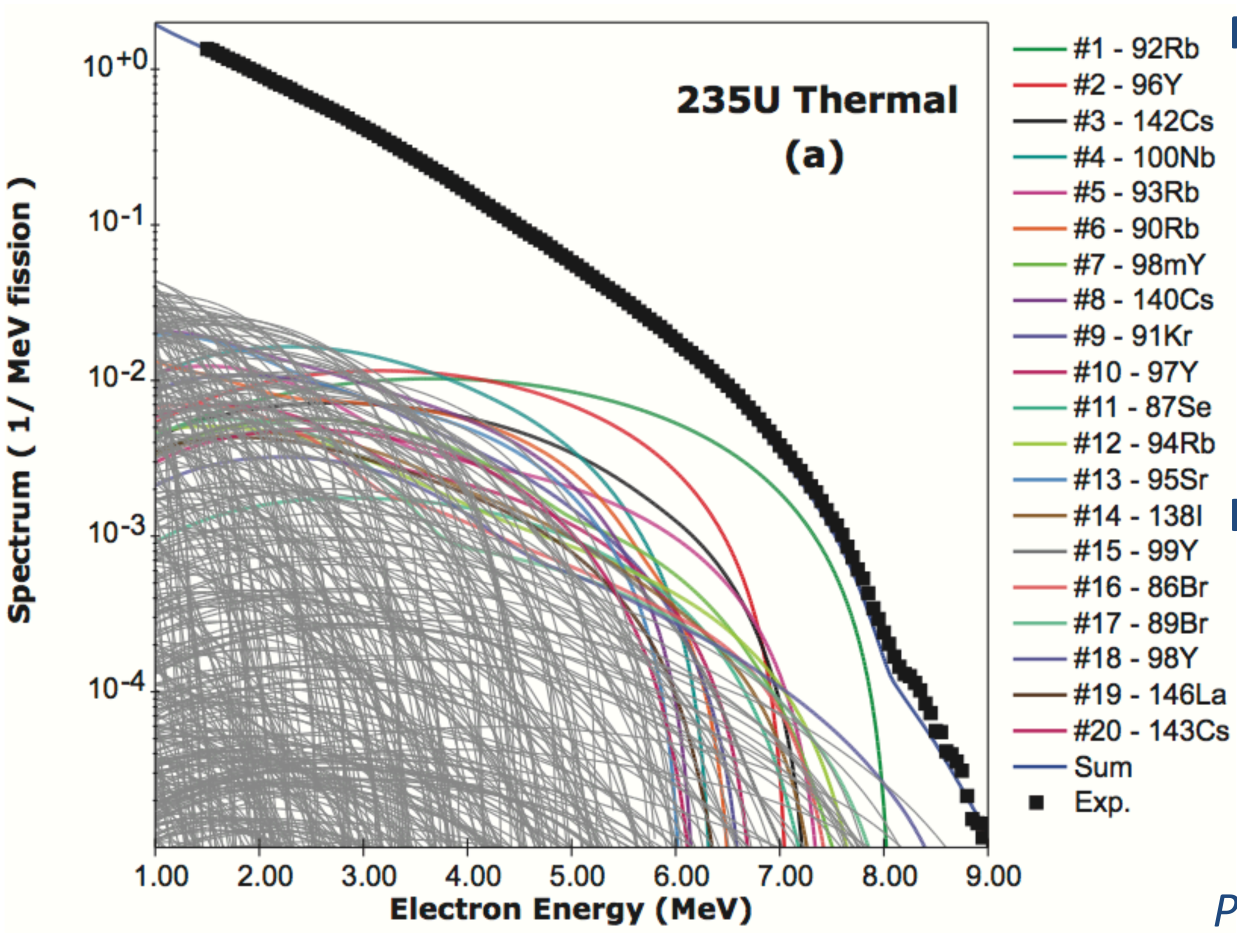
Isotope	Q[MeV]	$t_{1/2}$[s]	$\log(ft)$	Decay Type	N[%]	σ_N[%]
^{96}Y	7.103	5.34	5.59	$0^- \to 0^+$	13.6	0.8
^{92}Rb	8.095	4.48	5.75	$0^- \to 0^+$	7.4	2.9
^{142}Cs	7.308	1.68	5.59	$0^- \to 0^+$	5.0	0.7
^{97}Y	6.689	3.75	5.70	$1/2^- \to 1/2^+$	3.8	1.1
^{93}Rb	7.466	5.84	6.14	$5/2^- \to 5/2^+$	3.7	0.5
^{100}Nb	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.

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

Dominant Branches

Recent calculations also identify similar prominent branches.



National Nuclear Data Center Group

'Optimized' data sources
- ENDF/B.VII.1 decay library
  & latest TAGS measurements
  & direct β-spectrum msmts.
  & theoretical calc. for missing data
- JEFF 3.1 fission library (OECD-NEA)

Interesting observations

Reactor antineutrino spectra dominated by:
- Light fission fragments (~70%)
- Odd-Z, odd-N nuclides (~50%)

PRC 91, 011301(R) (2015)

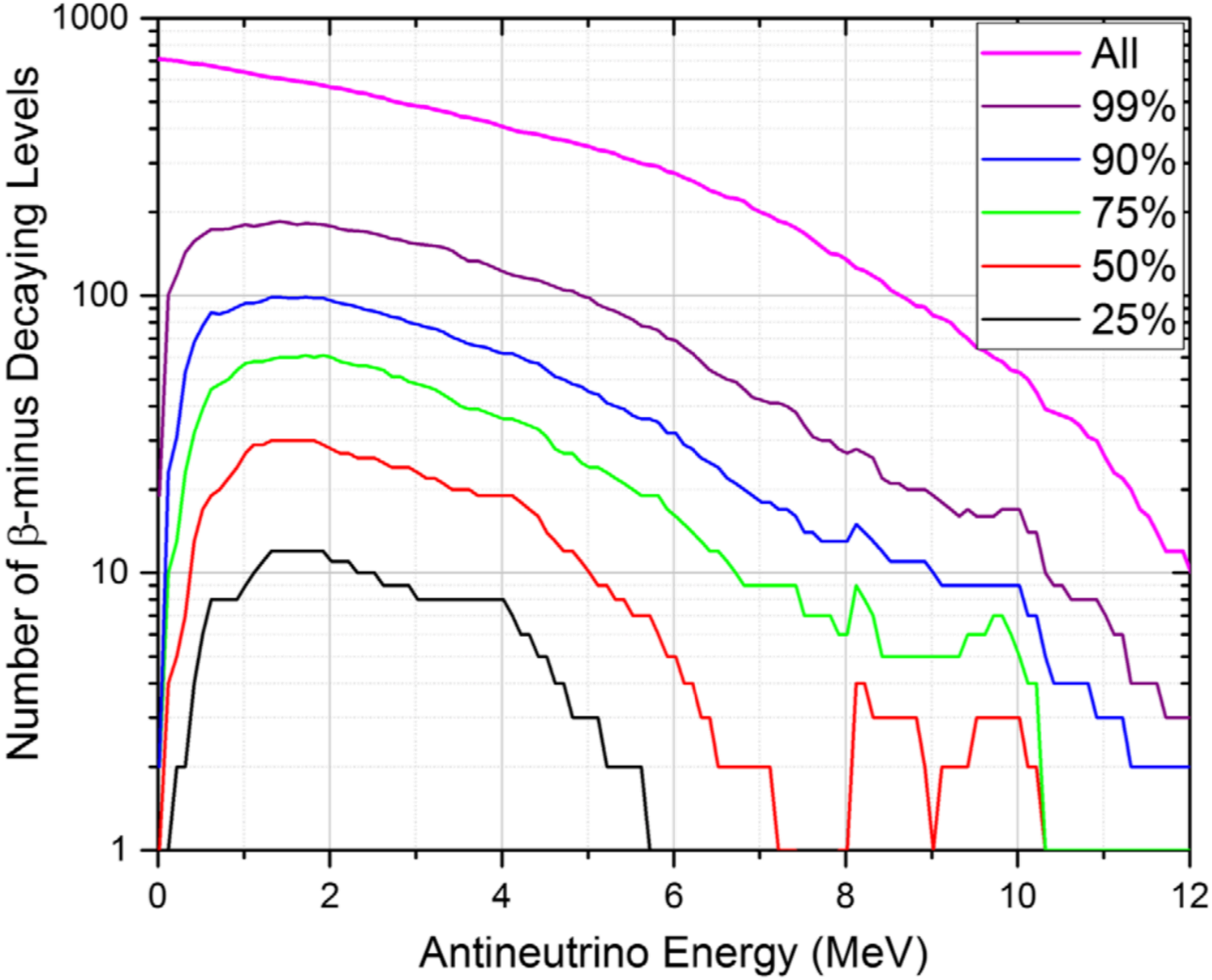
Dominant Branches

Summation:

Databases suggest limited number of decays contribute the bulk of the emission

Addressing uncertainties for these prominent decays should improve confidence in summation model.

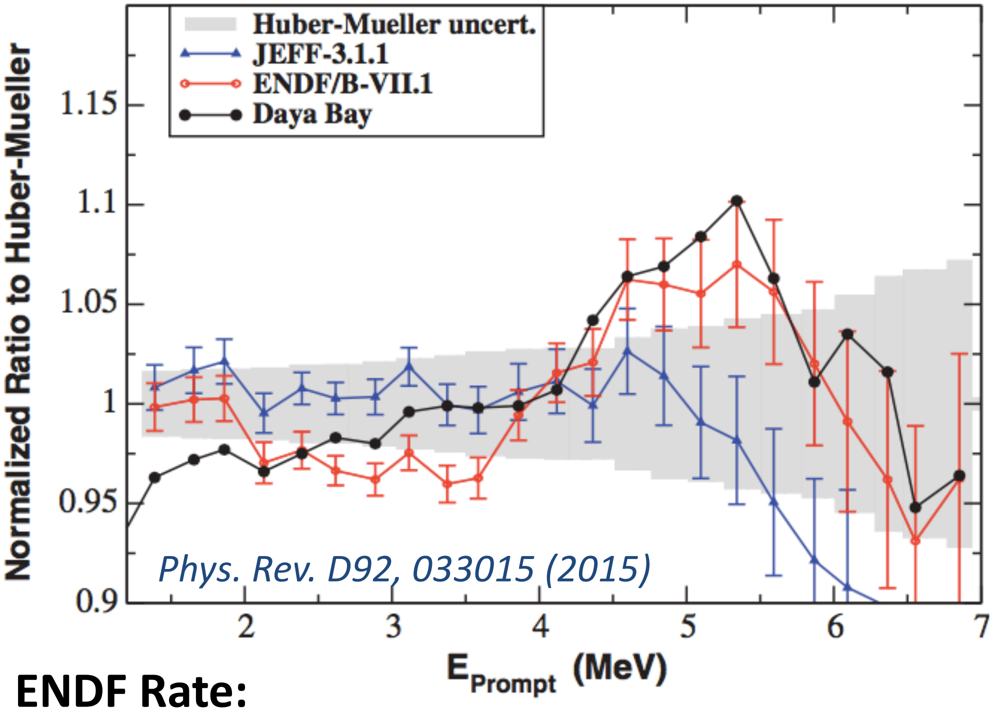
PRL 119, 112501 (2017)



Inconsistent Databases

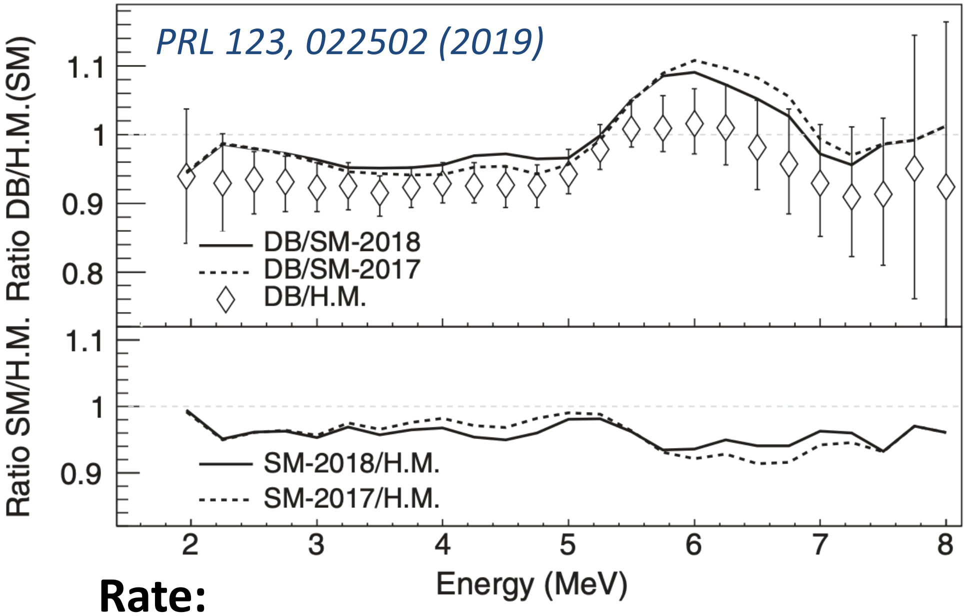
Calculated spectrum depends on which nuclear database is used.

ENDF vs. JEFF database



Phys. Rev. D92, 033015 (2015)

JEFF database, corrected with recent TAS beta decay measurements



PRL 123, 022502 (2019)

ENDF Rate:

Potentially consistent with data, imprecise (~10%)

ENDF Spectrum:

Inconsistent with beta conversion method

Potentially consistent with measurements

Rate:

~4% lower than beta conversion method

~2% higher than measurements

Spectrum:

Consistent with beta conversion method

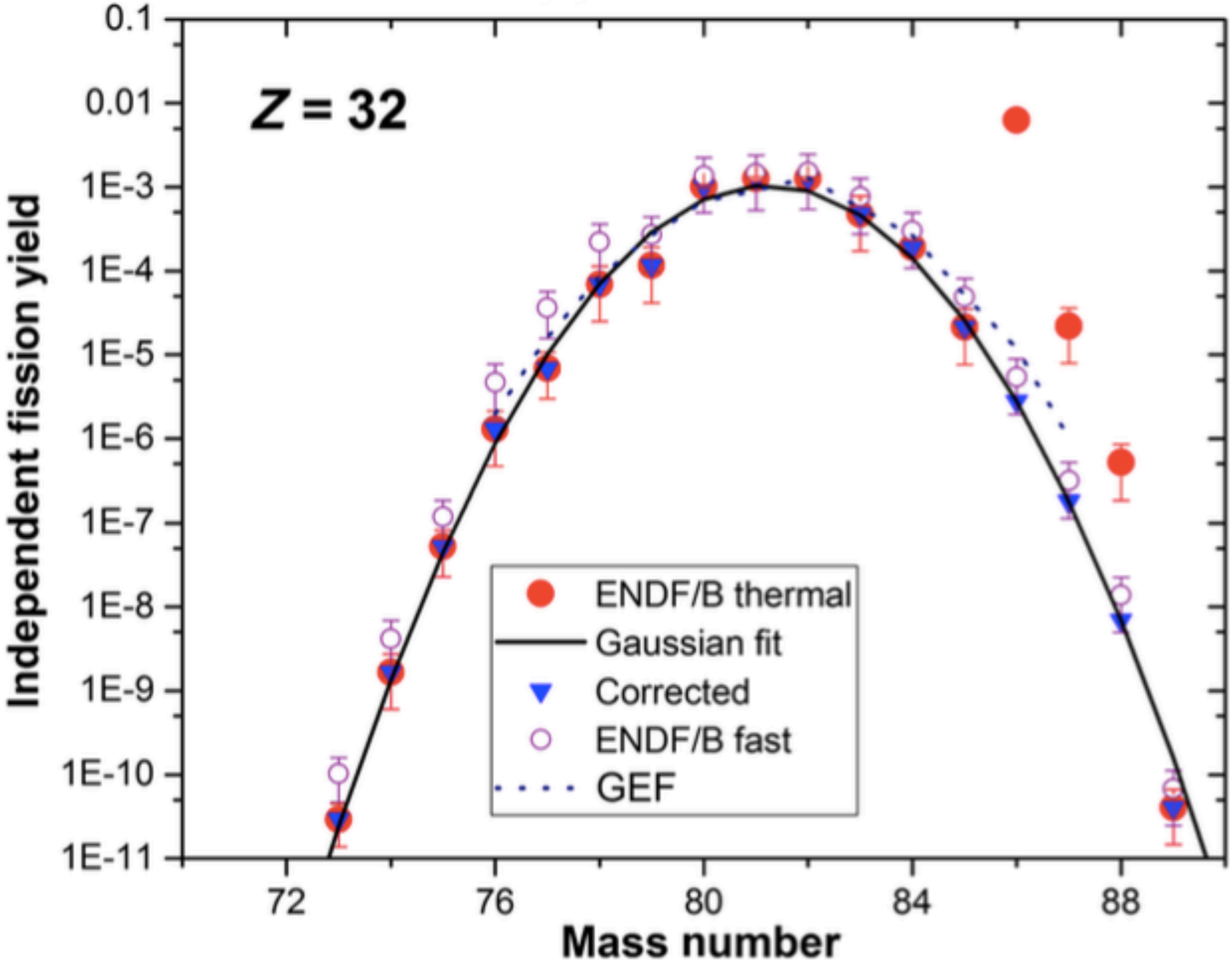
Inconsistent with measurements

See also: *arXiv:1807.09265*

But model uncertainties are difficult to quantify!

Nuclear Data Woes

Recent errors found in ENDF/B.vii thermal fission yield tables.

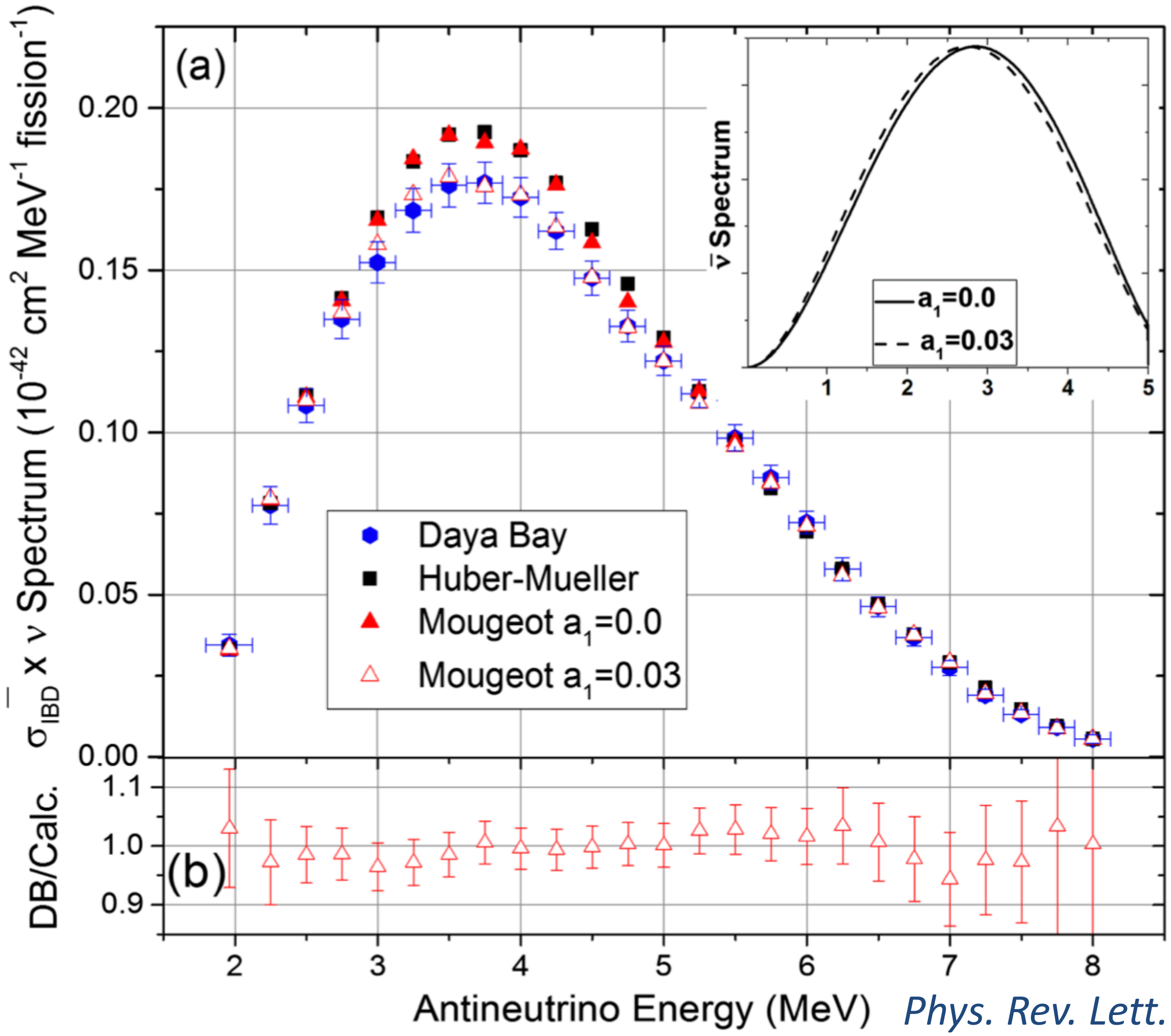


Phys. Rev. Lett. 116, 132502 (2016)

Forbidden Decays

Decay spectra may require correction for forbidden transitions

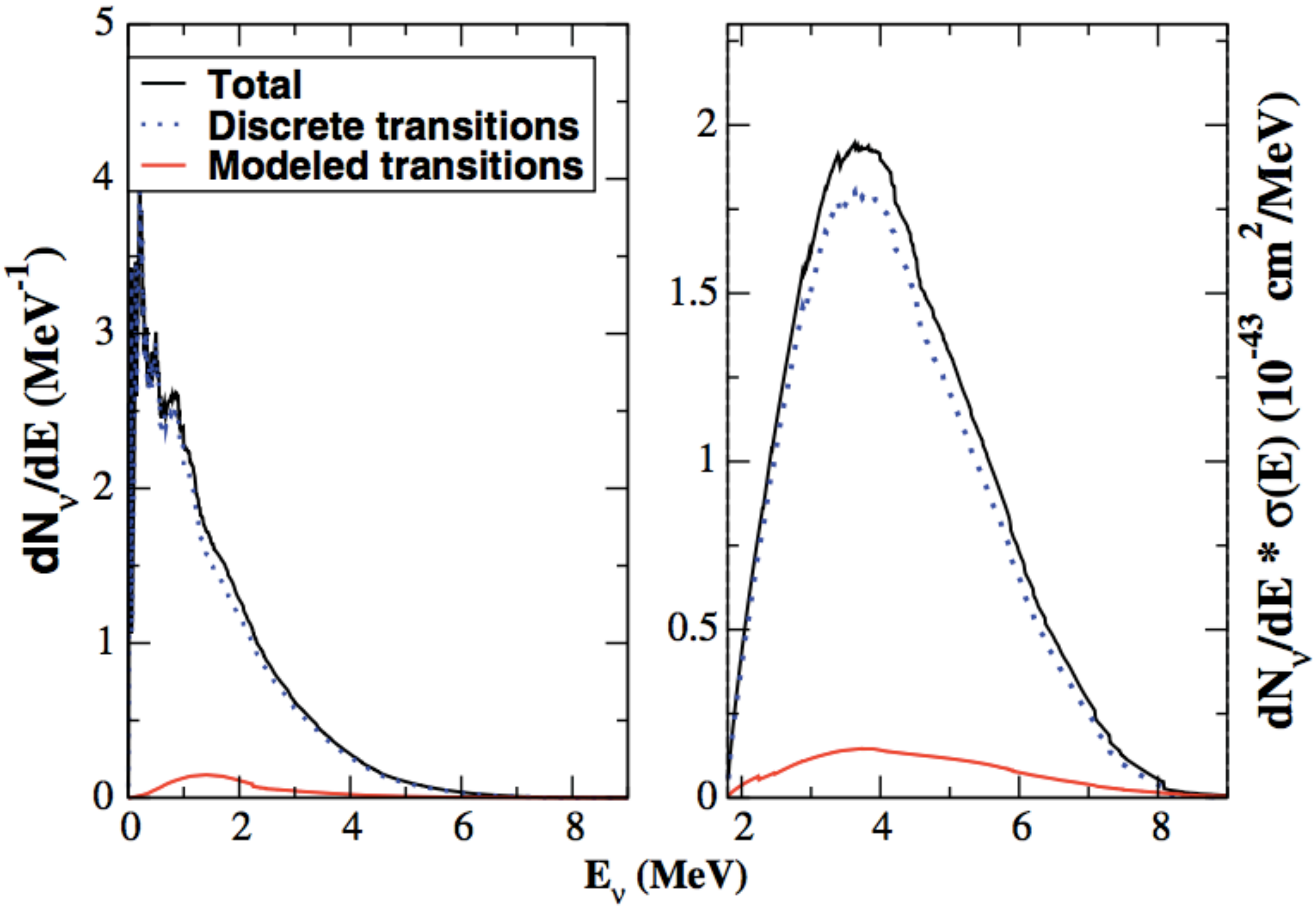
Phys. Rev. Lett. 112, 202501



Phys. Rev. Lett. 119, 112501 (2017)

Missing Decays

Fission daughter nuclei with unknown decays must be modeled.



~70% of daughters lack decay data, but only amount to ~5% of reactor yield.

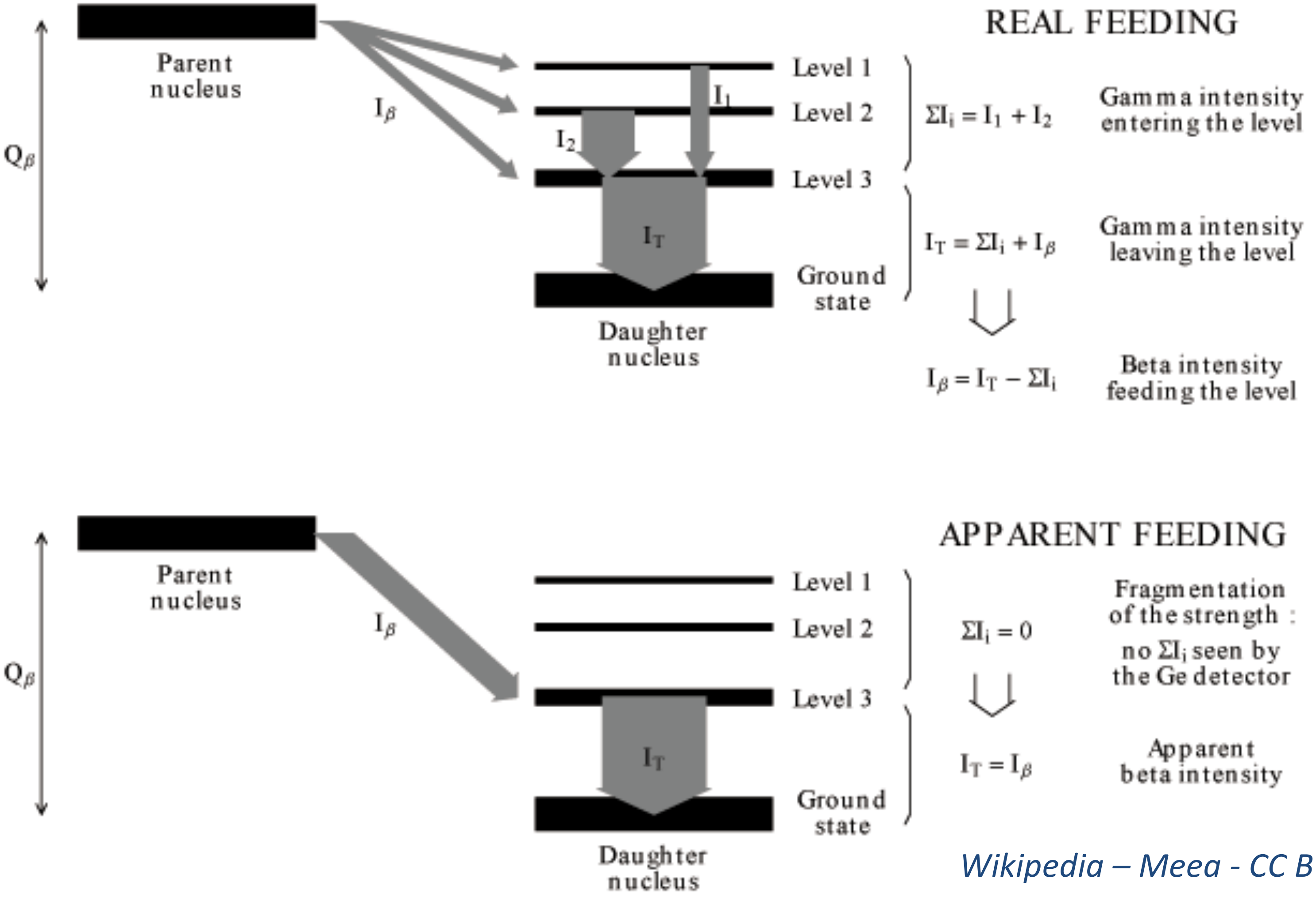
Phys. Rev. D92, 033015 (2015)

Pandemonium Effect

Existing nuclear data overestimates high-energy β^- feeding

Measurements missed gammas associated with low-Q decays

PL B71, 307 (1977)



Wikipedia – Meea - CC BY.SA 3.0

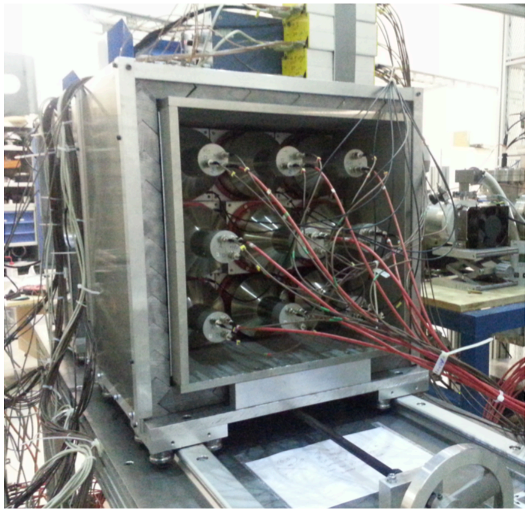
Improving Nuclear Data

TAS: Total absorption spectroscopy

Full calorimetery of gammas emitted during beta decay provides more accurate beta branching fractions.

Specifically overcomes the Pandemonium effect.

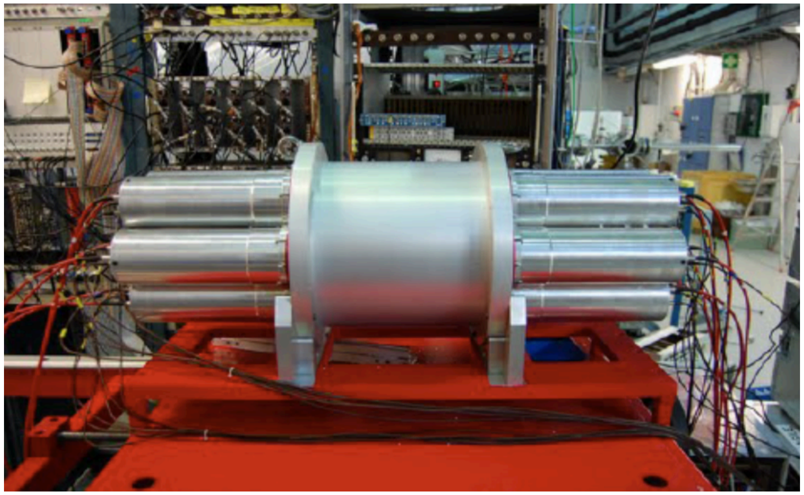
IGISOL (DTAS)



Strong program of TAS measurements:

PRL 105, 202501 (2010),
PR C87, 044318 (2013),
PRL 115, 102503 (2015),
PRL 117, 092501 (2016),
PR C95, 024320 (2017),
PR C95, 054328 (2017),
PR C96, 014320 (2017),
PRL 119, 052503 (2017)

IFIC (ROCINANTE)



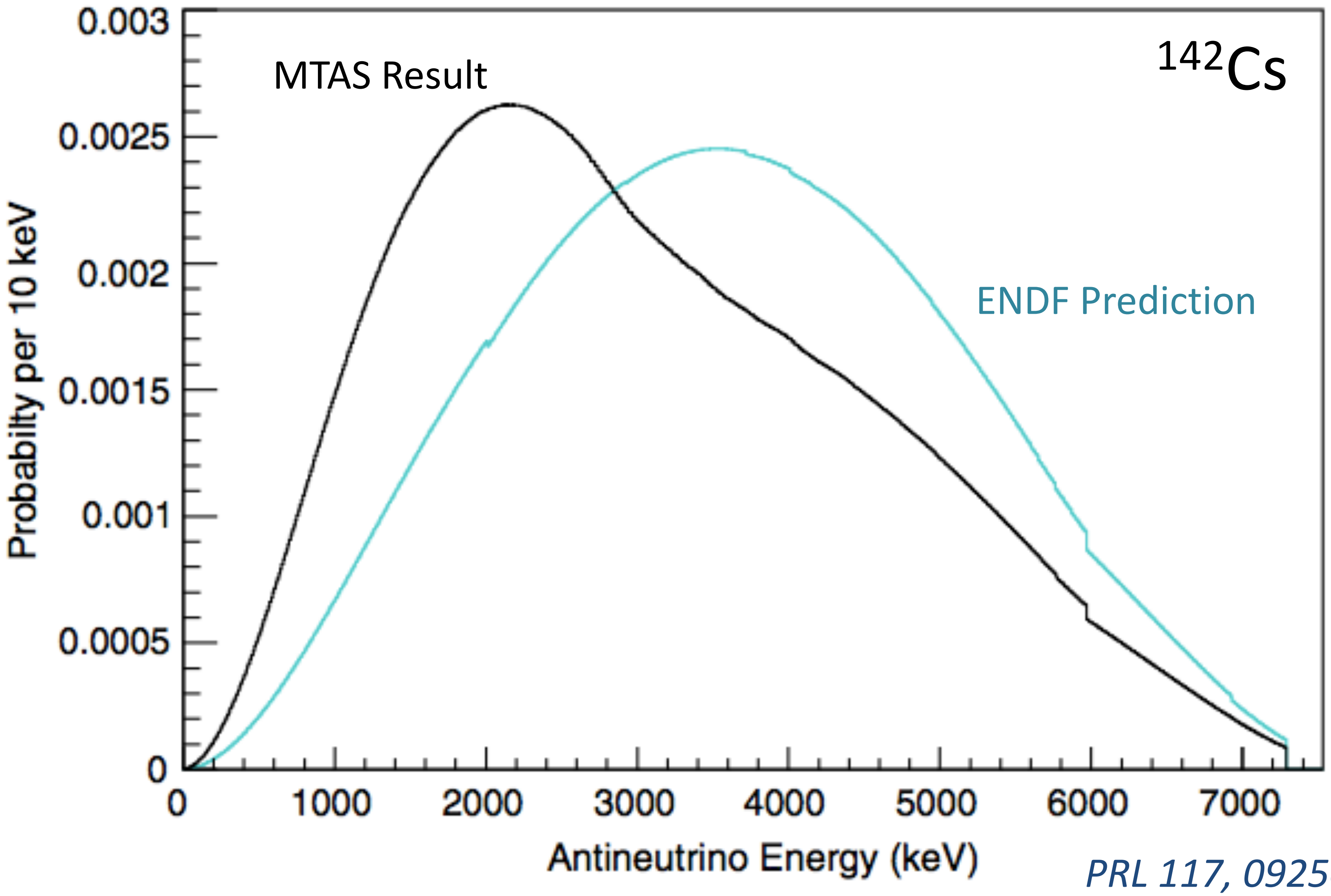
ORNL (MTAS)

January 2011

Total Absorption Spectroscopy

Example: TAS Measurement of ^{142}Cs

Results in significant changes in β-decay spectra of ^{142}Cs.

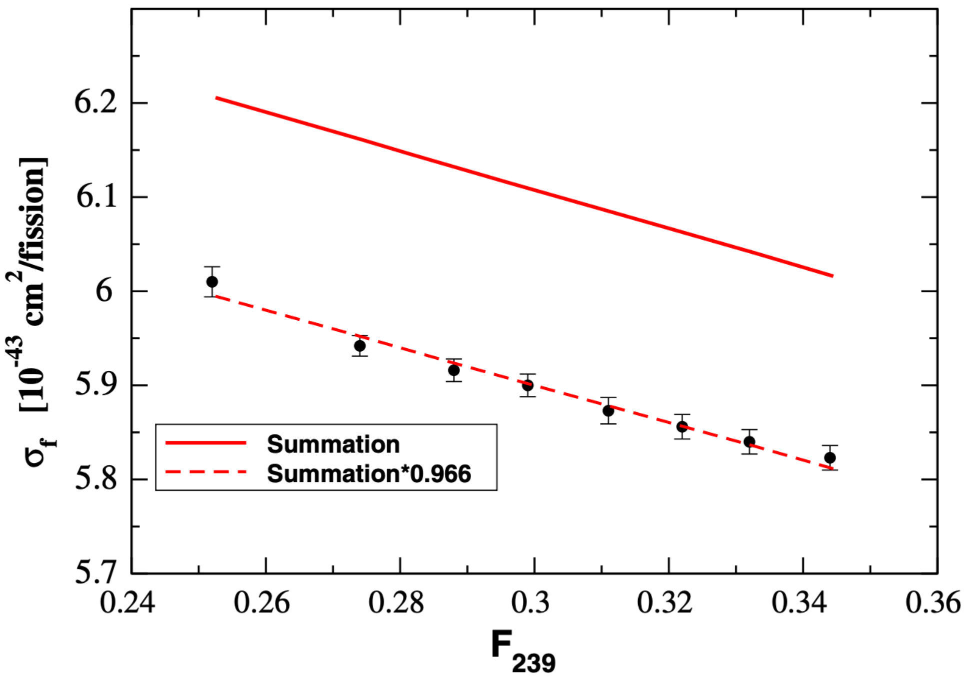


PRL 117, 092501 (2016)

Summation: Fuel Dependence

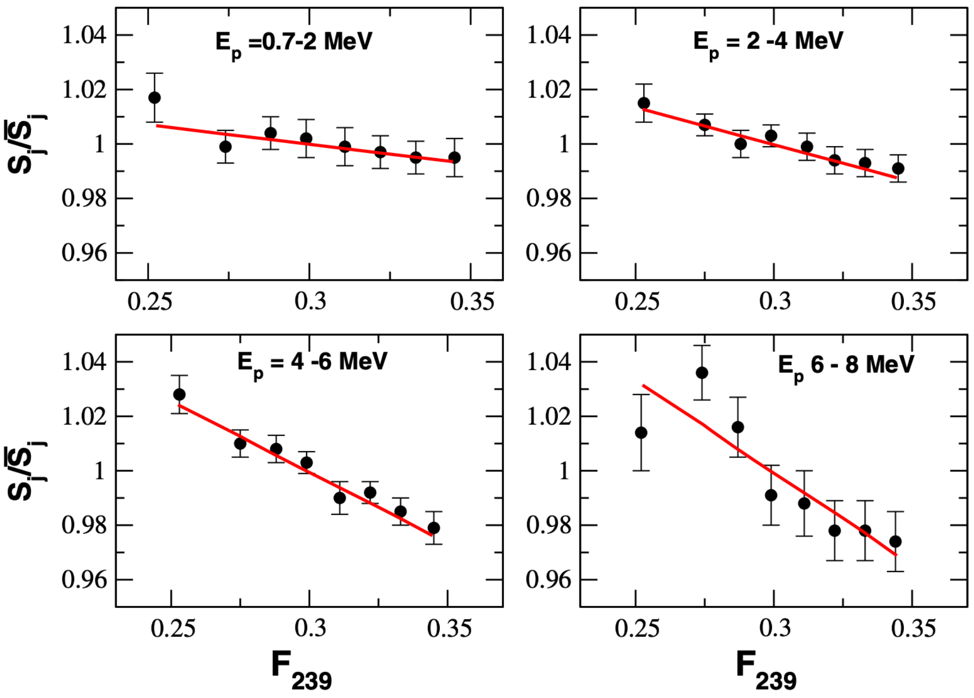
Summation predicts a fuel dependence consistent with measurement

Total Rate



After correcting for 3.4% excess rate, slope consistent with Daya Bay measurement

Spectrum variation



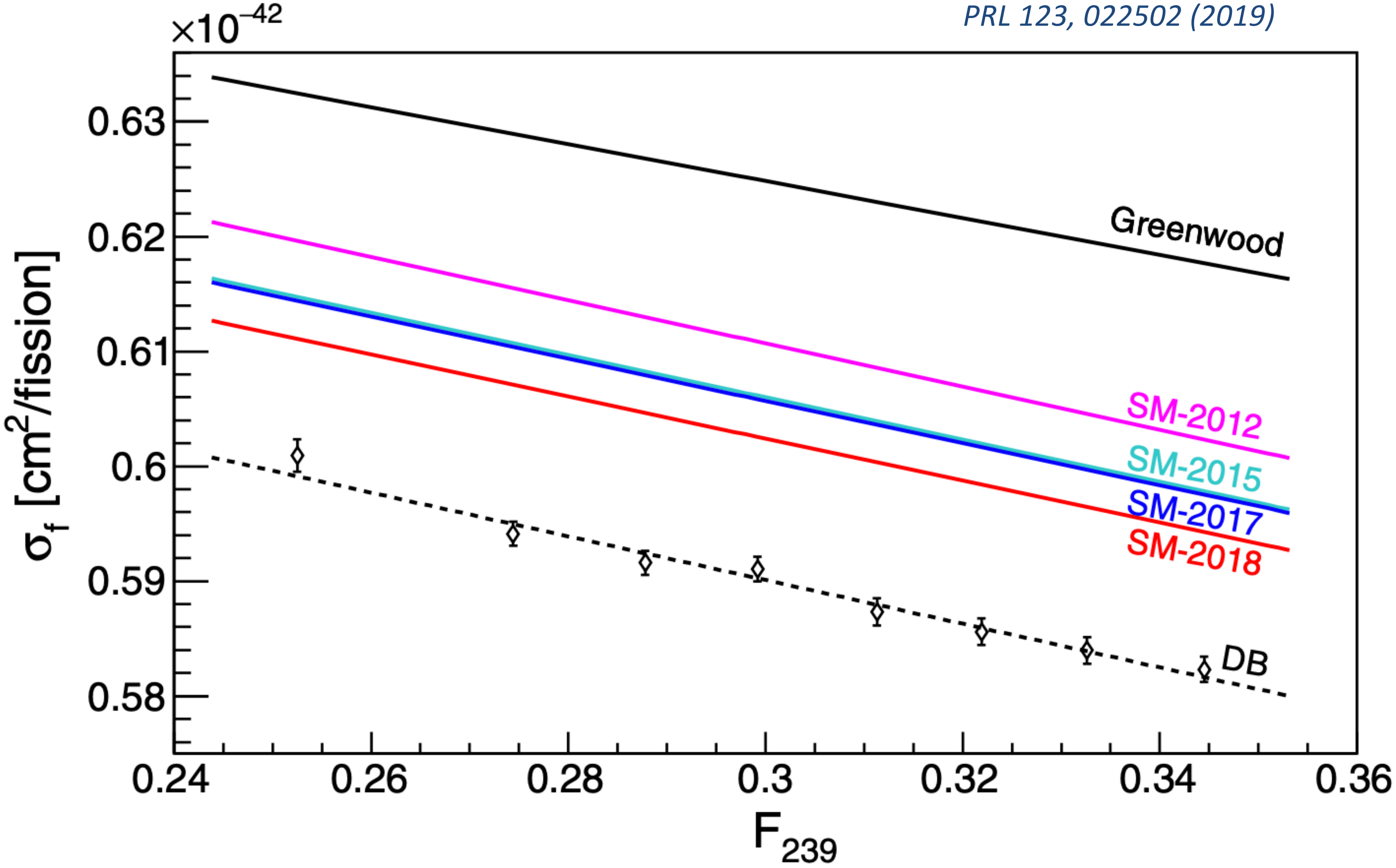
Spectrum variation consistent, but measurement has limited precision

PRL 120 022503 (2018)

Summation: Fuel Dependence

Summation (JEFF- and TAS-based) converging toward measured data, but uncertainties difficult to quantify

PRL 123, 022502 (2019)



Fission Neutron Energy

Blame the fission neutron energy spectrum?

Fission e^- measurements:

Thermal neutrons on foils of ^{235}U, ^{239}Pu, ^{241}Pu

Fission $\overline{\nu}_e$ measurements:

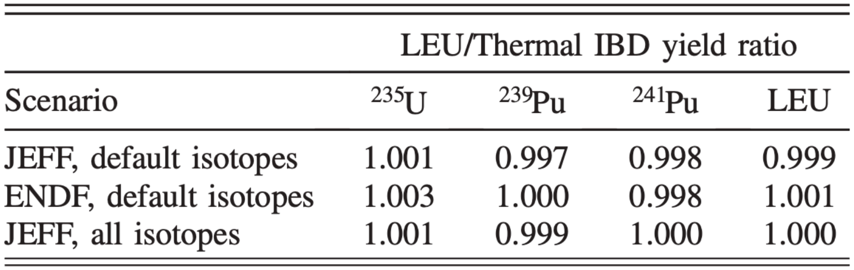
Mix of thermal, epithermal, fast neutron fission in commercial power reactor.

Could the differences in the fission neutron energy explain the e^- to $\overline{\nu}_e$ tension?

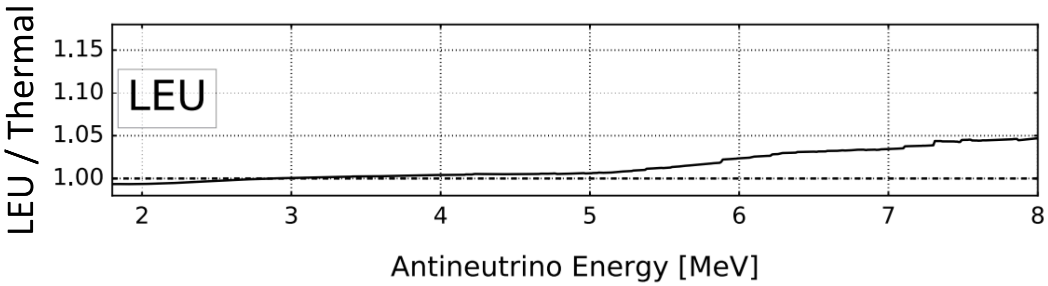
Method:

Use summation model to examine relative rate and spectrum change versus neutron energy

Conservative assumption: use fast fission yields for epithermal neutron fission.



	LEU/Thermal IBD yield ratio			
Scenario	^{235}U	^{239}Pu	^{241}Pu	LEU
JEFF, default isotopes	1.001	0.997	0.998	0.999
ENDF, default isotopes	1.003	1.000	0.998	1.001
JEFF, all isotopes	1.001	0.999	1.000	1.000

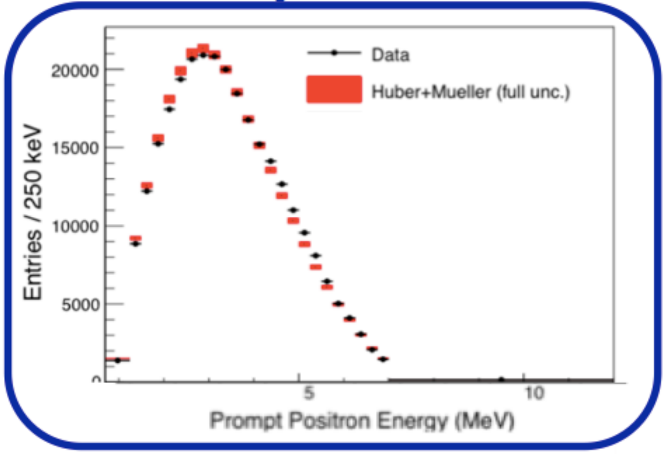


Conclusion: Summation displays insufficient variation to resolve e^- to $\overline{\nu}_e$ tension

Phys. Rev. D97, 073007 (2018)

Summary

Reactor $\overline{\nu}_e$ Measurements



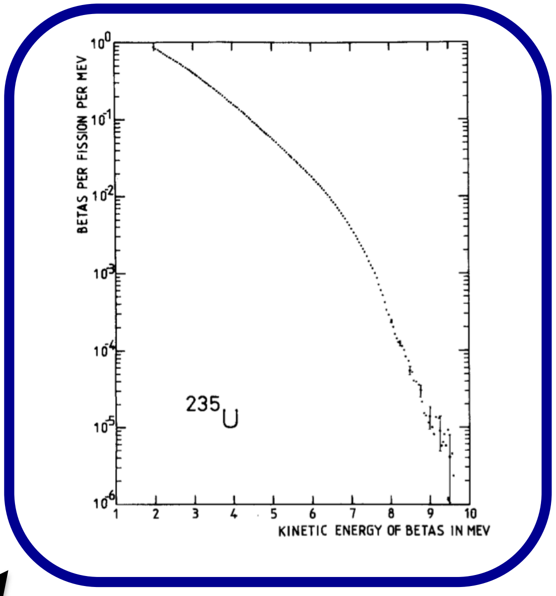
β^- Conversion

~~Rate~~

~~Rate vs. Fuel~~

~~Spectrum~~

Fission e^- Measurements



Origin?

~~Different fission neutron energy~~?

~~eV sterile neutrino~~?

Problem with e^- measurements?

Overlooked systematic?

$\overline{\nu}_e$ Summation

Rate? → *Difficult*

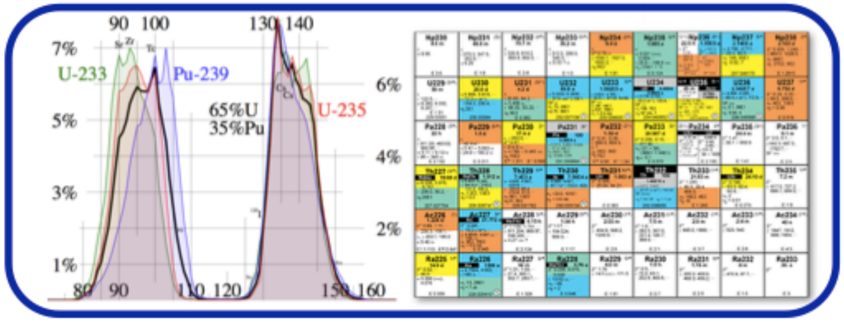
Rate vs. Fuel? → *Promising*

Spectrum? → *Maybe*

β^- Summation

Rate? → *Difficult*

Spectrum? → *Maybe*



Differences in ENDF/JEFF fission yields impact compatibility with either β^- or $\overline{\nu}_e$ spectra.

Fission and Nuclear Decay Measurements

Part 3:
Implications and Looking Ahead

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

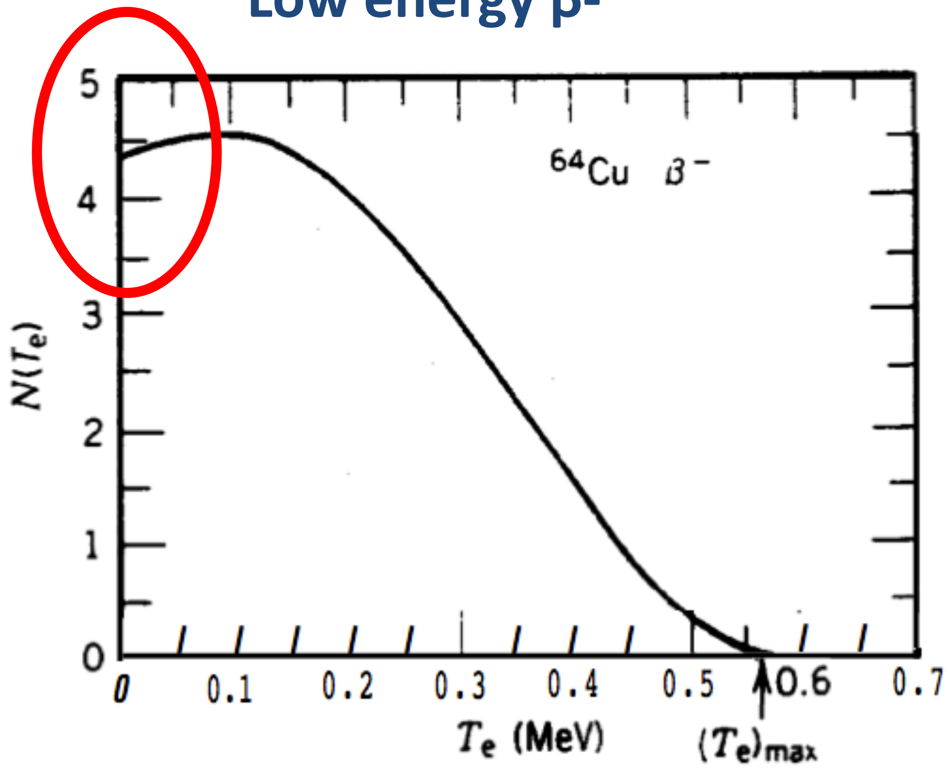
Calculation predicts significant discontinuities in spectrum.

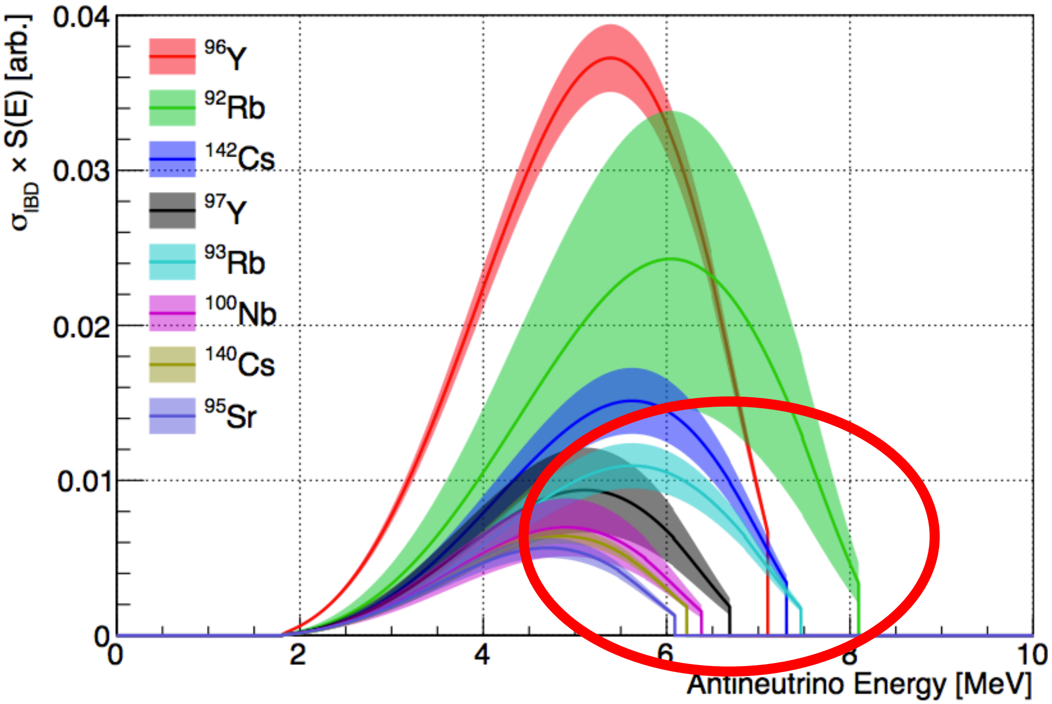
Coulomb correction:

Nuclear charge enhances production of:

Low energy β-

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





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

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

Calculation predicts significant discontinuities in spectrum.

Reactor Spectroscopy?

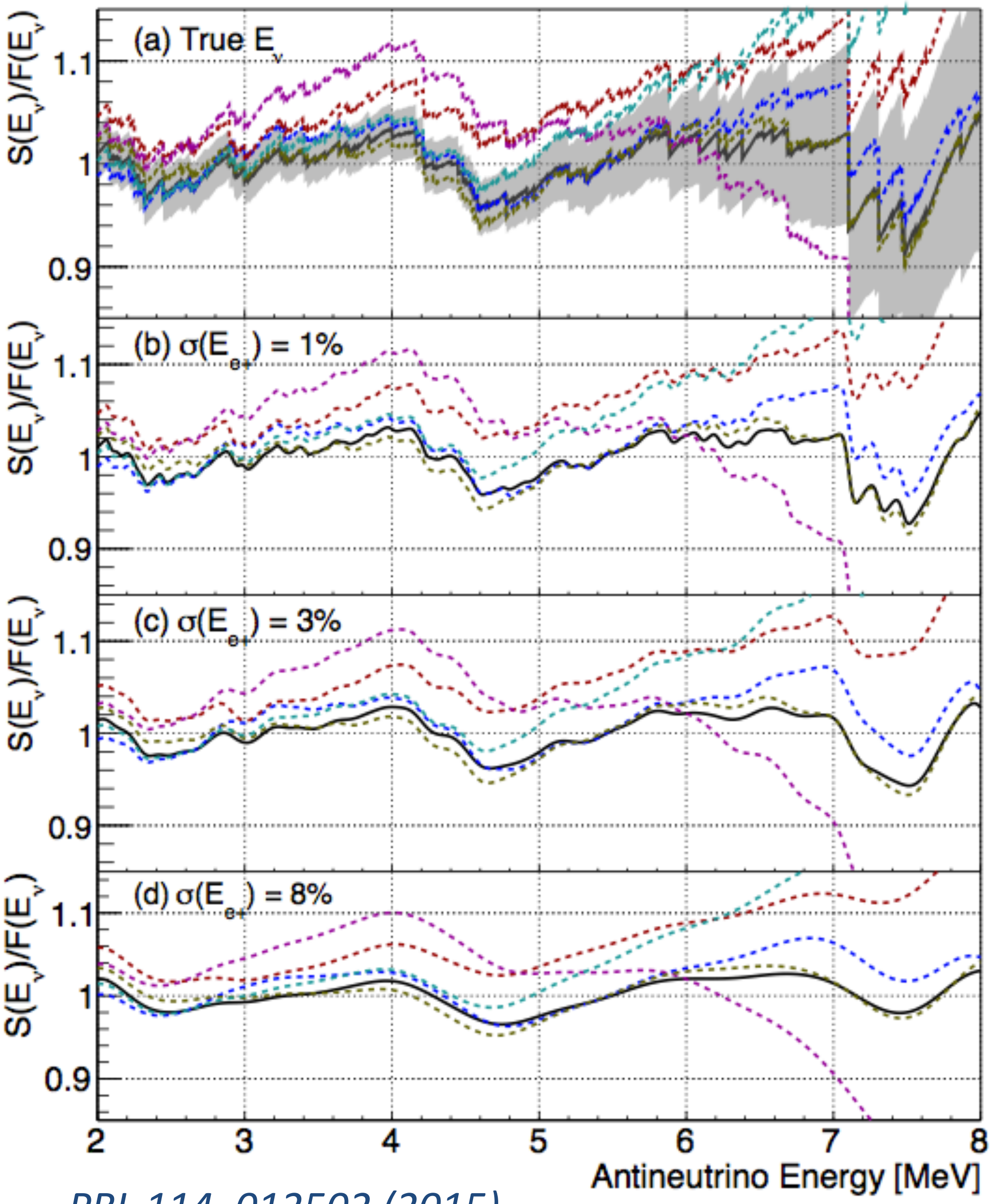
Each edge identifies one significant decay branch.

Current detectors:

Energy resolution: 6-8%/√E

Unlikely to detect fine details

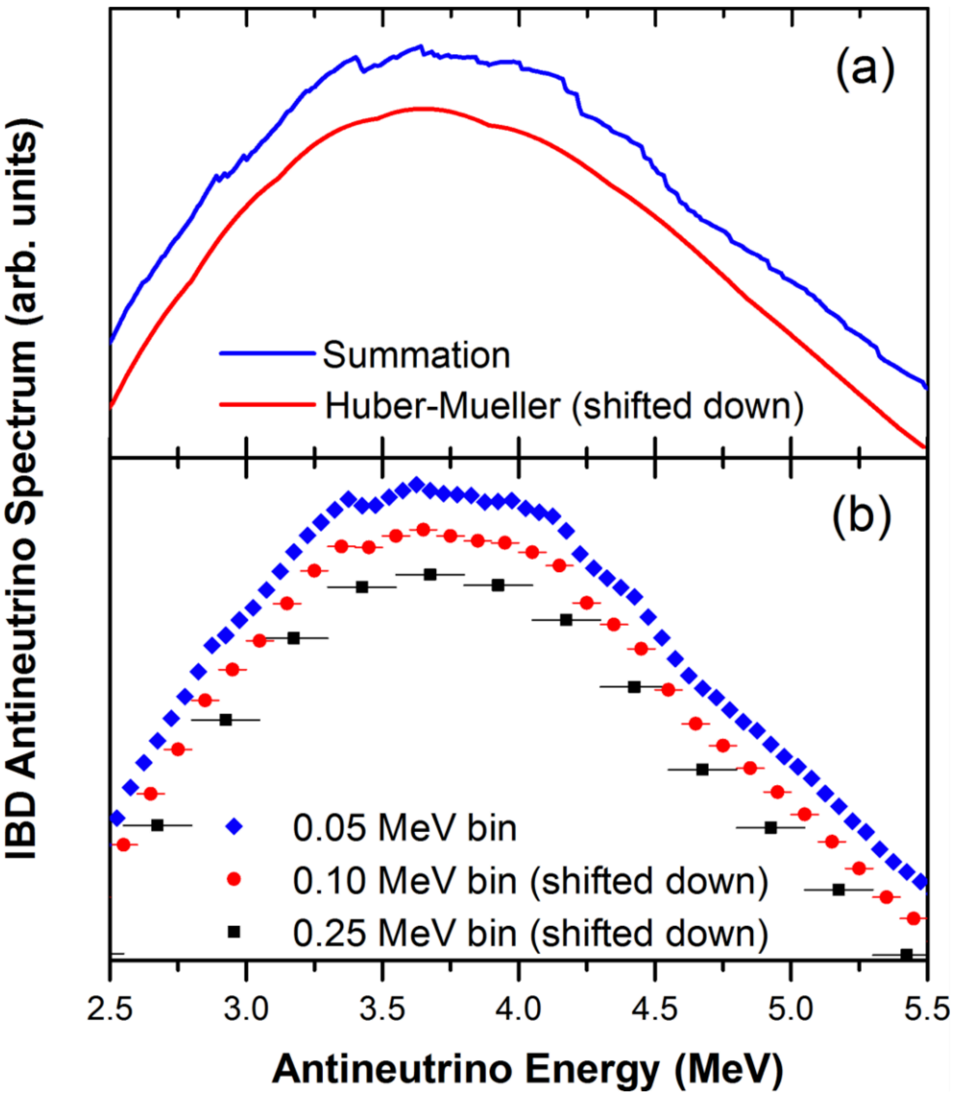
Solid: Nominal calc. *Dashed: Varying uncertainties*



PRL 114, 012502 (2015)

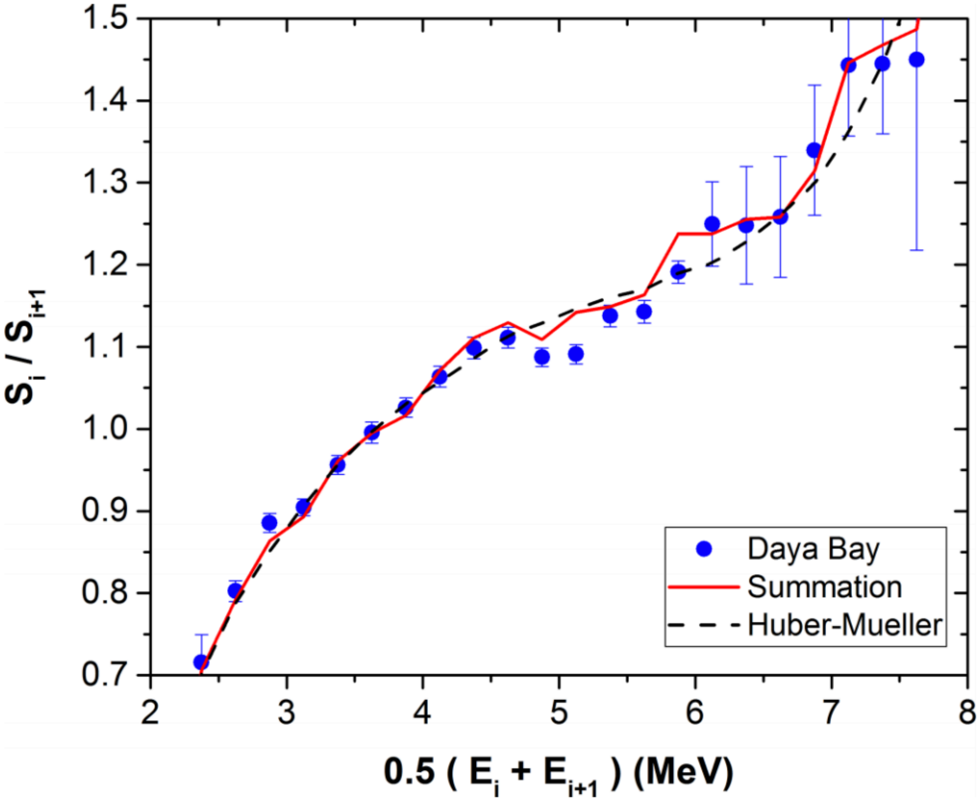
Detailed $\overline{\nu}_e$ Spectrum Shape

Attempt to quantify structure in spectral measurements



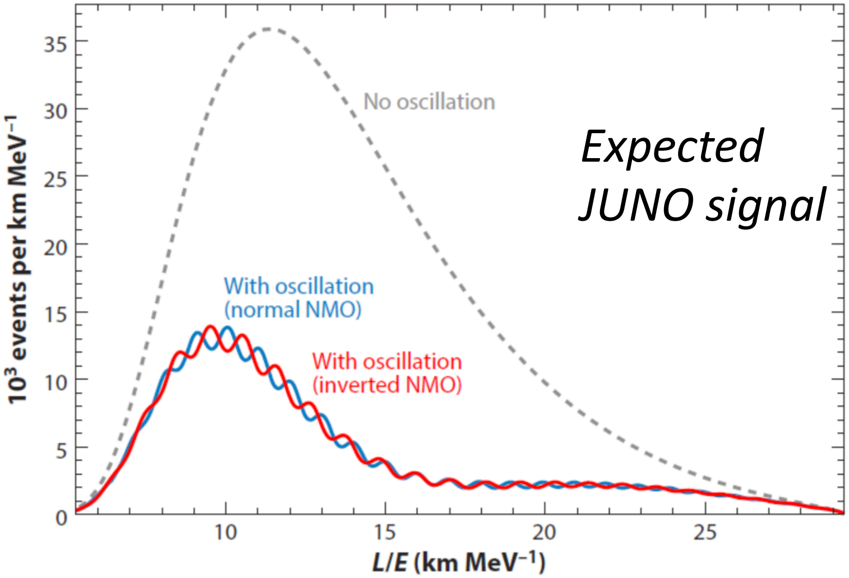
Examine spectral variations between adjacent spectrum bins, and compare with model predictions.

PRL 114, 012502 (2015)



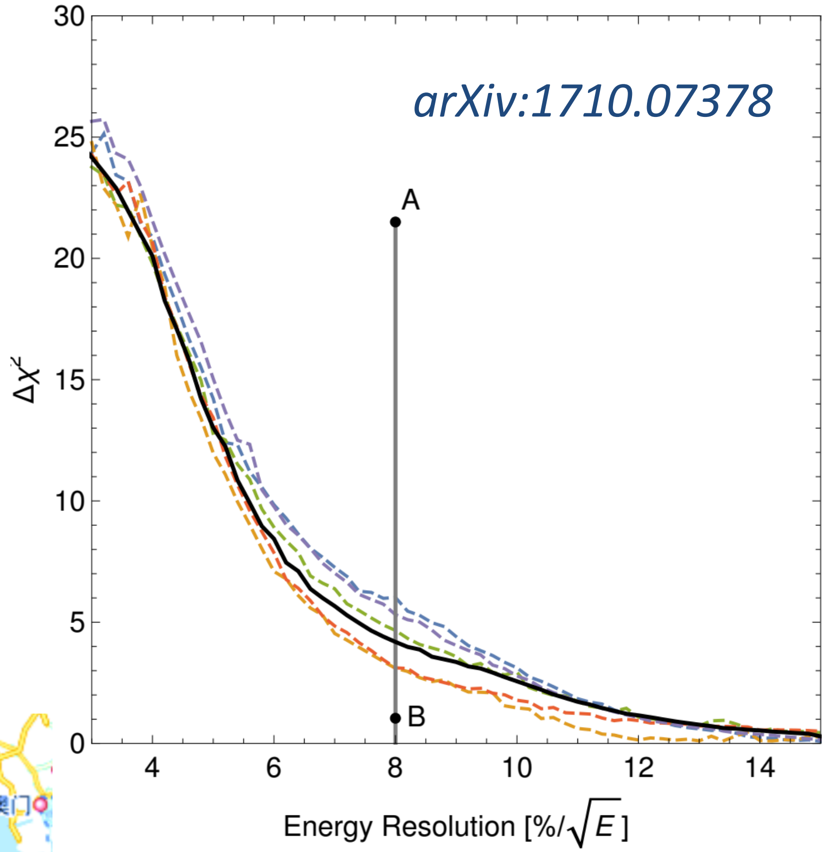
Detailed $\overline{\nu}_e$ Spectrum Shape

Structure introduces model dependency to JUNO mass hierarchy

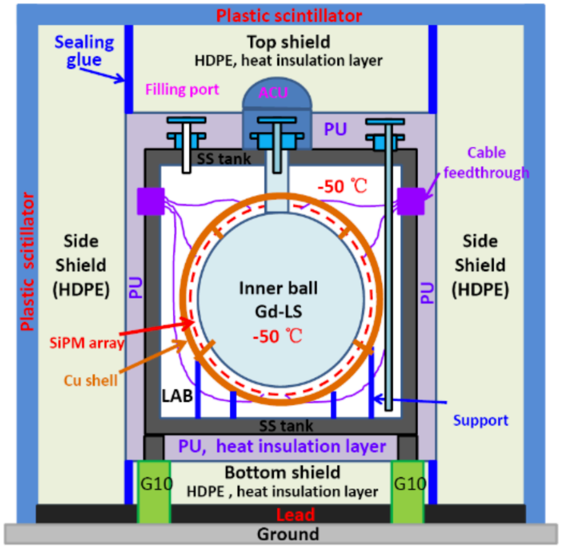


Expected JUNO signal

J. Phys. G43, 030401 (2016)



arXiv:1710.07378



TAO:

High-energy-resolution near detector for JUNO

Summary

Particle physics successes using reactor antineutrinos:

- First ν detection, distinct evidence for ν oscillation, Δm^2_{21}, θ_{12}, Δm^2_{31}, θ_{13}

But discrepancies between measurements and models:

β^- conversion models:

- Provide the most precise estimates of rate and spectra (~3%)
- Predicts ~6% higher flux than measurements (*i.e. the rate anomaly*)
- Energy spectrum inconsistent with measurements (*i.e. the 'bump'*)
- Predicts stronger rate variation versus reactor fuel burnup
- Tension between e^- and $\overline{\nu}_e$ measurements seems unavoidable

Summation models:

- Rely on fission yields and decay data of >1000 isotopes
- Suffer from significant unquantified uncertainties (~10%?), inconsistent databases
- Potential consistency with measured $\overline{\nu}_e$ rate, rate vs. fuel, and spectra

Looking forward:

- Improved fission and decay data has potential to reduce summation uncertainties
- Reactor spectroscopy via high-energy resolution $\overline{\nu}_e$ spectrum measurement