Reactor Neutrino Flux and Spectrum Measurements

The XXX International Conference on Neutrino Physics and Astrophysics (Neutrino 2022)

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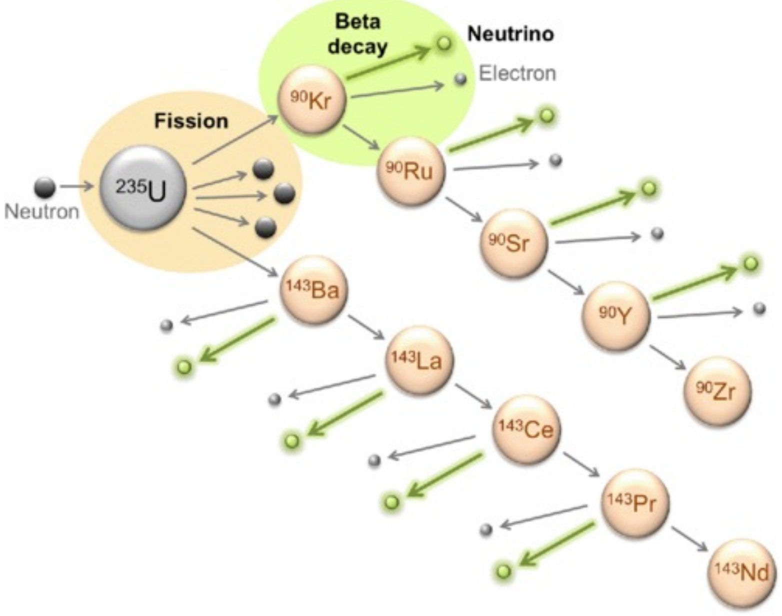
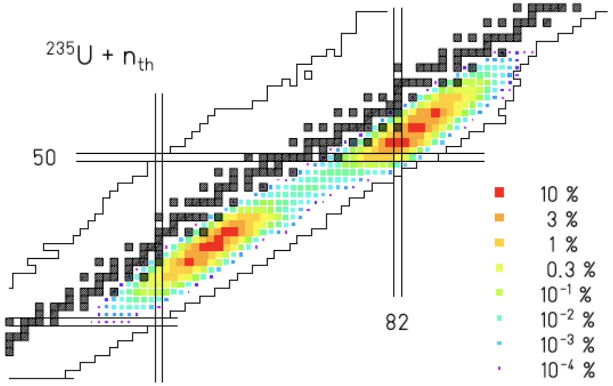
Reactor Neutrino Production & Prediction

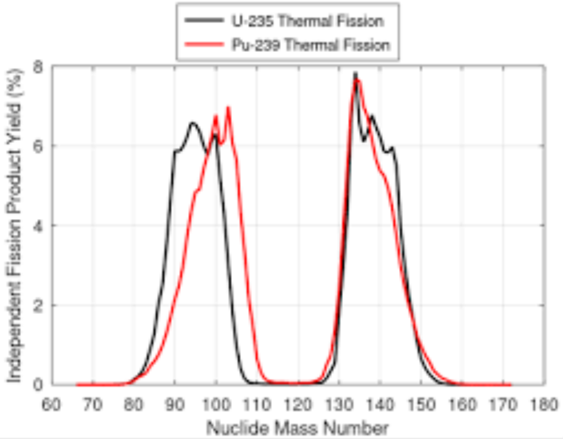
Reactors produce electron (anti)neutrinos via the β-decay of neutron rich fission daughter products



Courtesy of R. Carr; [RMP 92, 011003 (2020)](#)

Fission isotopes populate different fission product distributions → the neutrino flux and spectrum differs between isotopes

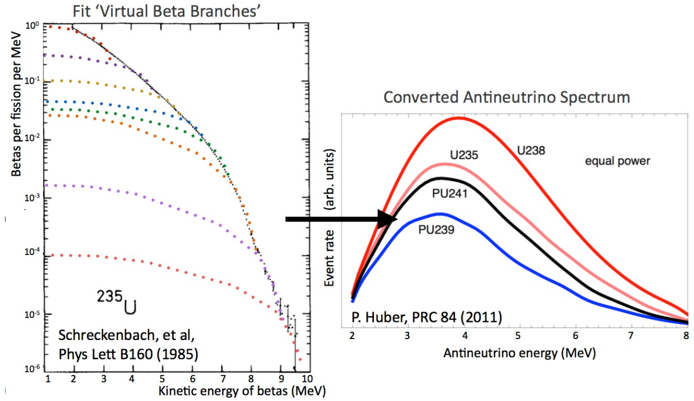




<u>Conversion Prediction Method</u>

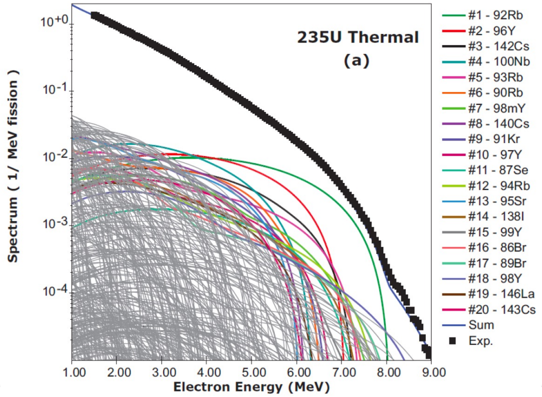
Use fitting & correction procedure to convert measured integral β-electron spectra measured at ILL in 1980s to neutrino spectra.

Commonly referred to as Huber-Muller (HM) model



<u>Summation or Ab Initio Method</u>

Build spectrum from FPY and β-decay nuclear data

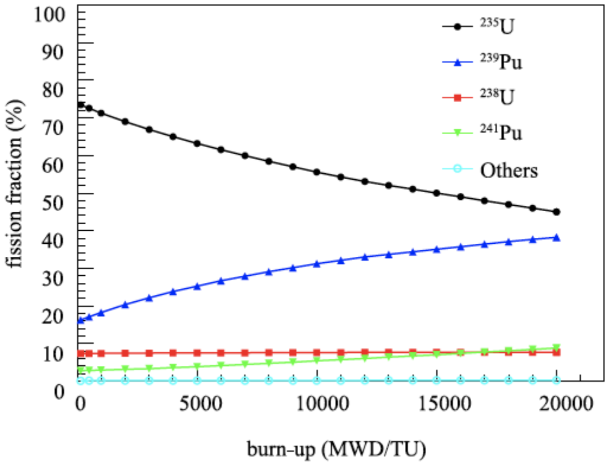


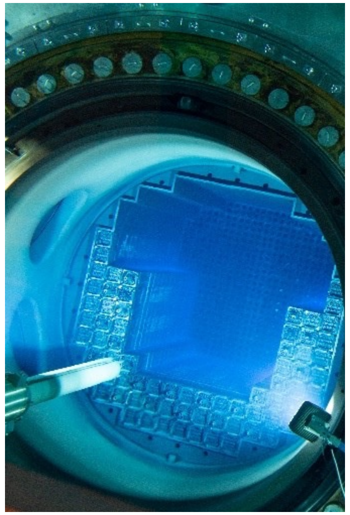
A. Sonzogni, [AAP 2019](#)

Nuclear Reactor Types

Low Enriched Uranium (LEU)-fueled Power Reactors

- 3-4 GW thermal power
- ~1.5-2 years between refueling
- Fuel mix evolves as ^{235}U is consumed and $^{239,241}Pu$ is produced

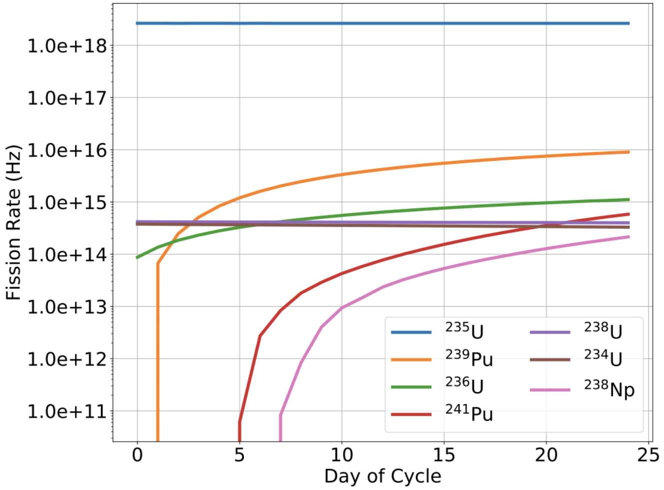


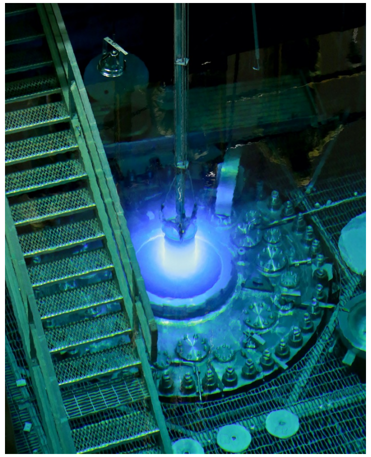


Daya Bay, [CPC, 2017, 41(1): 13002]

^{235}U-fueled (HEU) Research Reactors

- 50-100 MW thermal power
- ~1-3 months between refueling
- Highly Enriched Uranium (HEU) fuel and short cycles mean that almost all fissions are ^{235}U

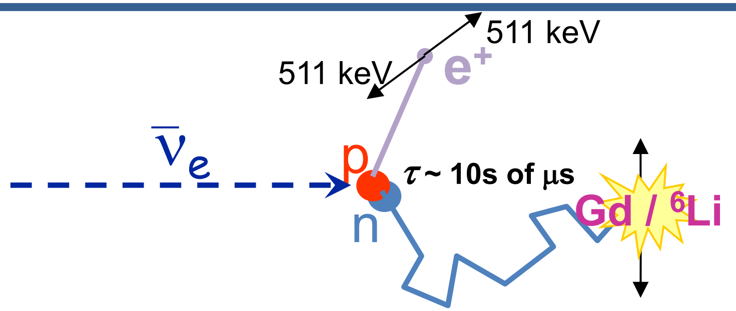




[A. Conant/PROSPECT]

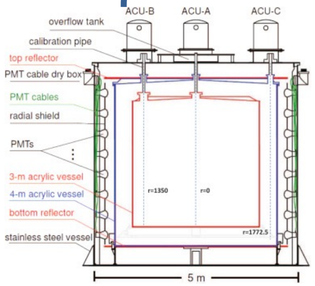
Recent Reactor Experiments with Flux and/or Spectrum Measurements

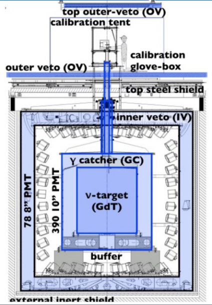
- Prompt Inverse Beta Decay (IBD) e^{+} signal proportional to incident E_{ν}
- Organic (liquid) scintillator used as target and detection medium

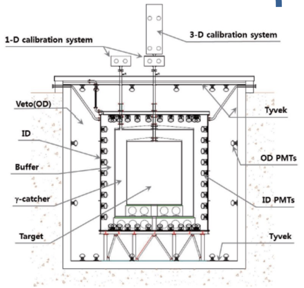


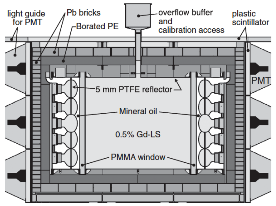
θ_{13} near detectors

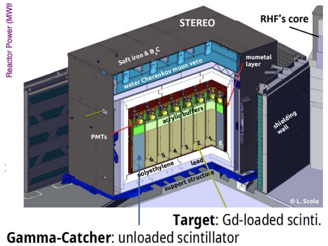
SBL reactor experiments (*)

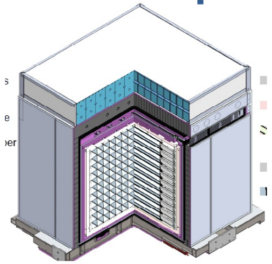












Experiment	Daya Bay	Double Chooz	RENO	NEOS (-II)	STEREO	PROSPECT
Target, Mass	~ 80 ton GdLS	~ 10 ton GdLS	~17 ton GdLS	~1 ton GdLS w/PSD	~1.5 ton GdLS, segmented w/PSD	~4 ton ^{6}LiLS, segmented w/PSD
Reactor Fuel & Power	LEU, ~17 GW_{th}	LEU, ~8.5 GW_{th}	LEU, ~17 GW_{th}	LEU, ~2.8 GW_{th}	HEU, 58 MW_{th}	HEU, 85 MW_{th}
Baseline	~500 m	~400 m	~400 m	24 m	9-11 m	7-9 m
Overburden, S/B	~300 mwe	~100 mwe	~100 mwe	~20 mwe, 29	~10 mwe, 1.1	~1 mwe, 1.4–3.7

(*) there are many other SBL reactor experiments using a range of detection media and approaches

Reactor Neutrino Detectors: *Precision Instruments*
Percent-level control of detection efficiencies

- By design, θ_{13} experiments excel in this respect
- Smaller SBL detectors at research reactors face challenges, but excellent systematic control also demonstrated

Source	Previous Value	Previous Rel err	This work Value	This work Rel err
Statistic	···	0.1%	···	0.1%
Oscillation	···	0.1%	···	0.1%
Target proton	···	0.92%	···	0.92%
Reactor				
Power	···	0.5%	···	0.5%
energy/fission	···	0.2%	···	0.2%
IBD cross section	···	0.12%	···	0.12%
Fission fraction	···	0.6%	···	0.6%
Spent fuel	···	0.3%	···	0.3%
Nonequilibrium	···	0.2%	···	0.2%
$\varepsilon_{\mathrm{IBD}}$				
ε_n	81.83%	1.69%	81.48%	0.74%
$\varepsilon_{\mathrm{other}}$	98.49%	0.16%	98.49%	0.16%
Total	···	2.1%	···	1.5%

Daya Bay, PRD 100, 052004 (2019)

Uncertainty (%)	ND
Proton Number	0.66
Thermal Power	0.47
TnC Selection	0.24
Background	0.18
Energy per Fission	0.16
θ_{13} Correction	0.16
Statistics	0.22
Total	0.97

Double Chooz, Nature Phys. 16 (2020) 558

IBD total cross section	±0.09%
Target protons	$(1.189 \pm 0.008) \times 10^{30}$
Detection efficiency (total)	$(74.87 \pm 1.06)\%$
Trigger efficiency	99.77 ± 0.05
Qmax/Qtot	100.00 ± 0.02
Gd capture fraction	84.95 ± 0.80
Spill-in	101.34 ± 0.69
Prompt energy requirement	97.95 ± 0.10
Delayed energy requirement	92.14 ± 0.70
Time coincidence	96.59 ± 0.26
Spatial correlation	100.00 ± 0.03

RENO, PRD 104, L111301 (2021)

TABLE I. Summary of all relevant quantities and their corresponding relative uncertainties on the IBD yield.

Quantity	Symbol	Value	Uncertainty (%)
Number of ν/fission	$N_\nu^{[2,8]\ \mathrm{MeV}}$	1.846	2.40
Huber prediction		1.722	2.40
Correction factors		1.072	0.10
Number of fissions/day		1.30×10^{23}	1.44
Thermal power	$\langle P_{\mathrm{th}} \rangle$	49.2 MW	1.44
Energy per fission	$\langle E_f \rangle$	203.4 MeV	0.13
Fraction of interacting ν	τ_{int}	8.10×10^{-21}	0.56
Solid angle			0.50
IBD cross section	σ_{IBD}		0.22
MC statistics			0.12
Correction of p number	$c_p^{\mathrm{Data/MC}}$	0.983	1.00
Detection efficiency	ϵ_d	0.2049	0.54
Selection cuts			0.41
Energy scale			0.30
MC statistics			0.19
Correction of delayed efficiency	$c_n^{\mathrm{Data/MC}}$	0.9774	0.86
Predicted IBD yield		383.7 d^{-1}	$2.10 \oplus 2.40$
Observed IBD yield		363.8 d^{-1}	$0.88 \oplus 1.06$
Statistics			0.88
ν extraction method			0.65
Reactor-induced background			0.83
Off-time method			0.14

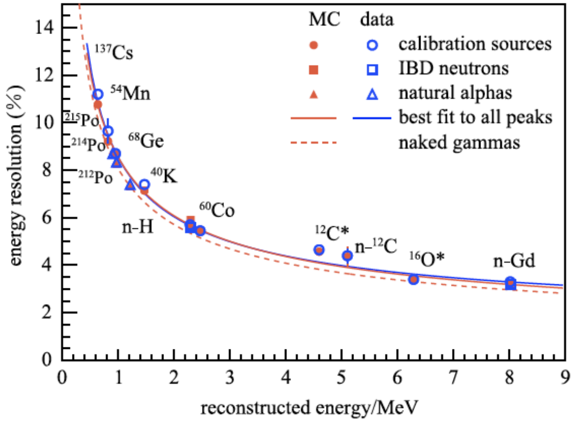
STEREO, PRL 125, 201801 (2020)

Reactor Neutrino Detectors: *Precision Instruments*

Energy-scale and response well understood

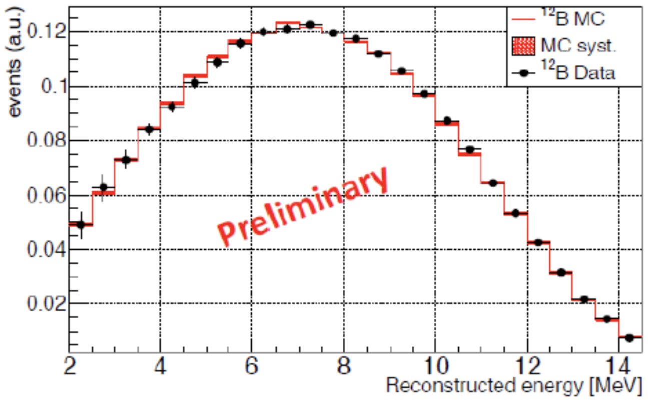
Joint fits to multiple calibration sources control energy scale at 1% level & enable accurate response generation

Resolution & Source Response



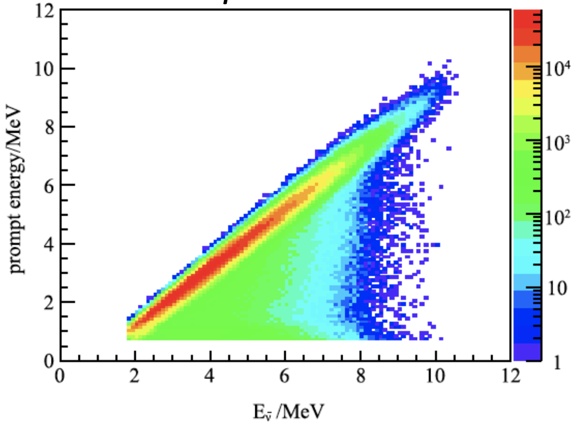
Daya Bay, CPC, 2017, 41(1): 13002

Cosmogenic ^{12}B Spectrum

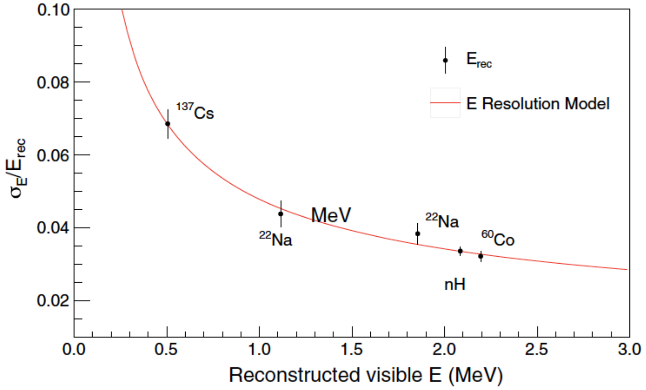


STEREO: J.Phys.G 48 (2021) 075107 & P0195

IBD Response Matrices

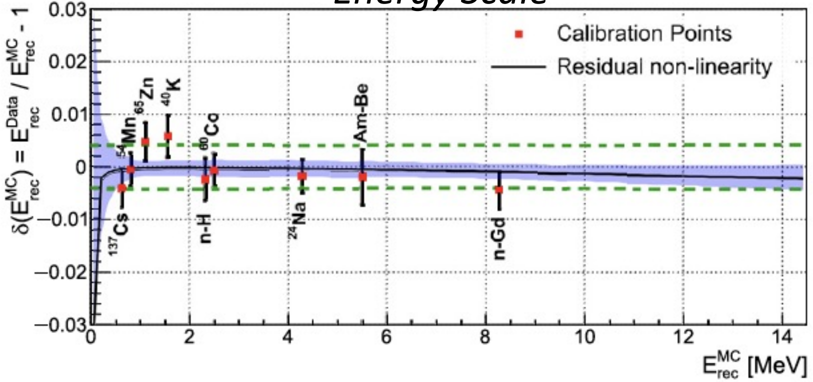


Daya Bay, CPC, 2017, 41(1): 13002

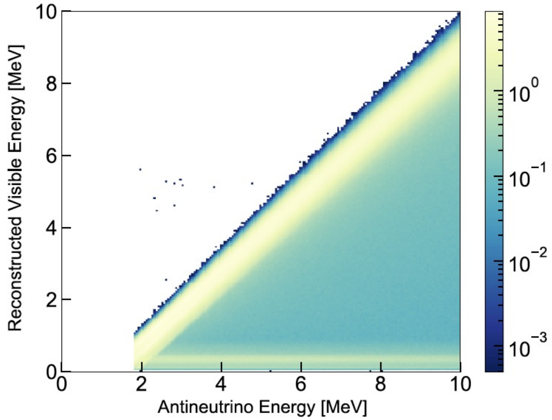


PROSPECT, PRD 103, 032001 (2021)

Energy Scale



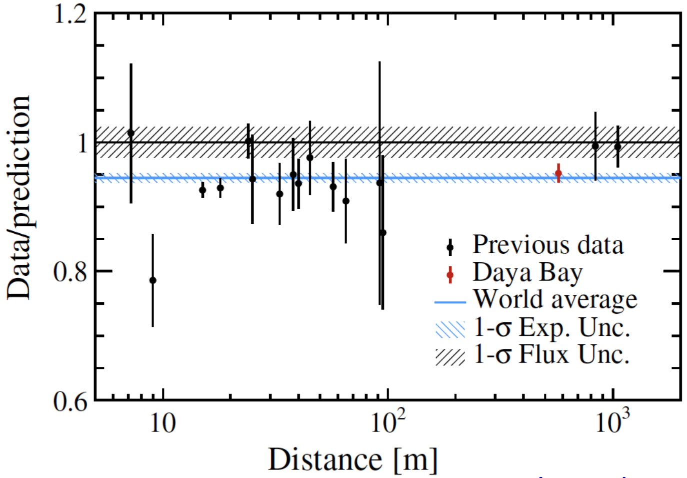
STEREO: J.Phys.G 48 (2021) 075107 & P0195



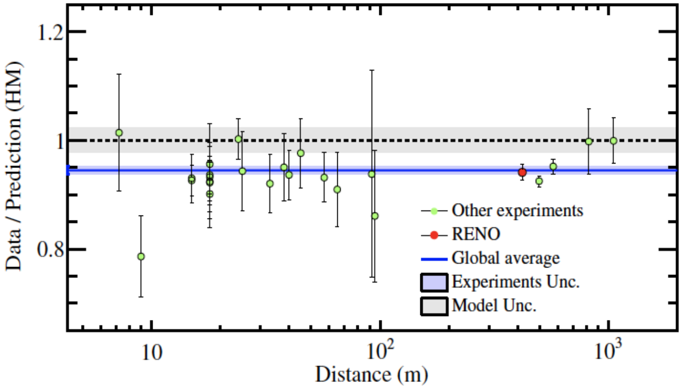
PROSPECT, PRD 103, 032001 (2021)

Total neutrino yield measurements have achieved great precision

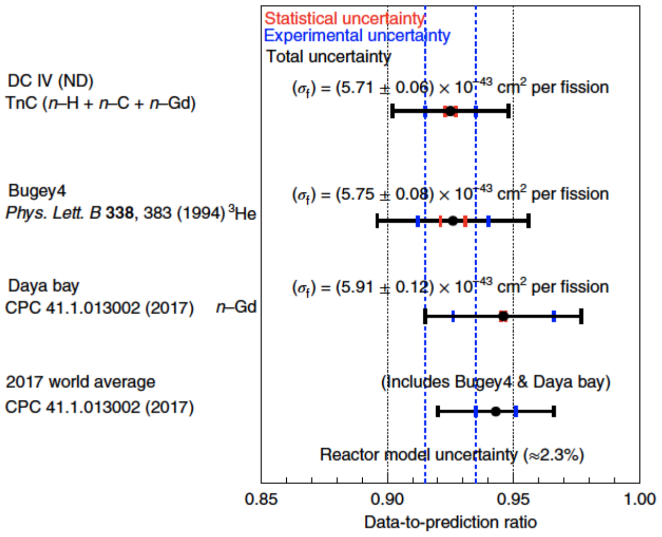
LEU Power Reactors: Multi-isotope source



Daya Bay, PRD 100, 052004 (2019)

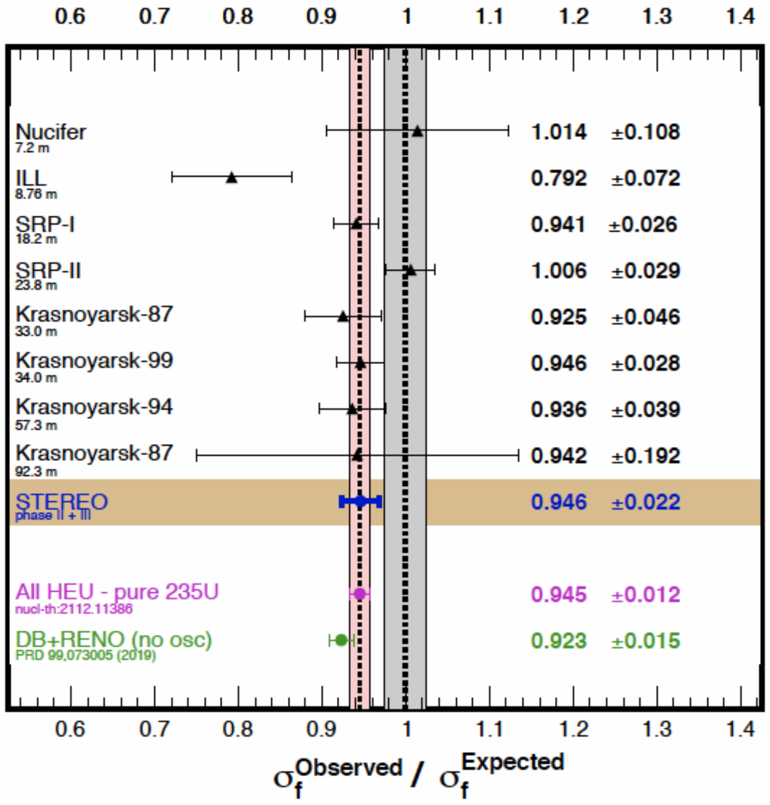


RENO, PRD 104, L111301 (2021)



Double Chooz, Nature Phys. 16 (2020) 558

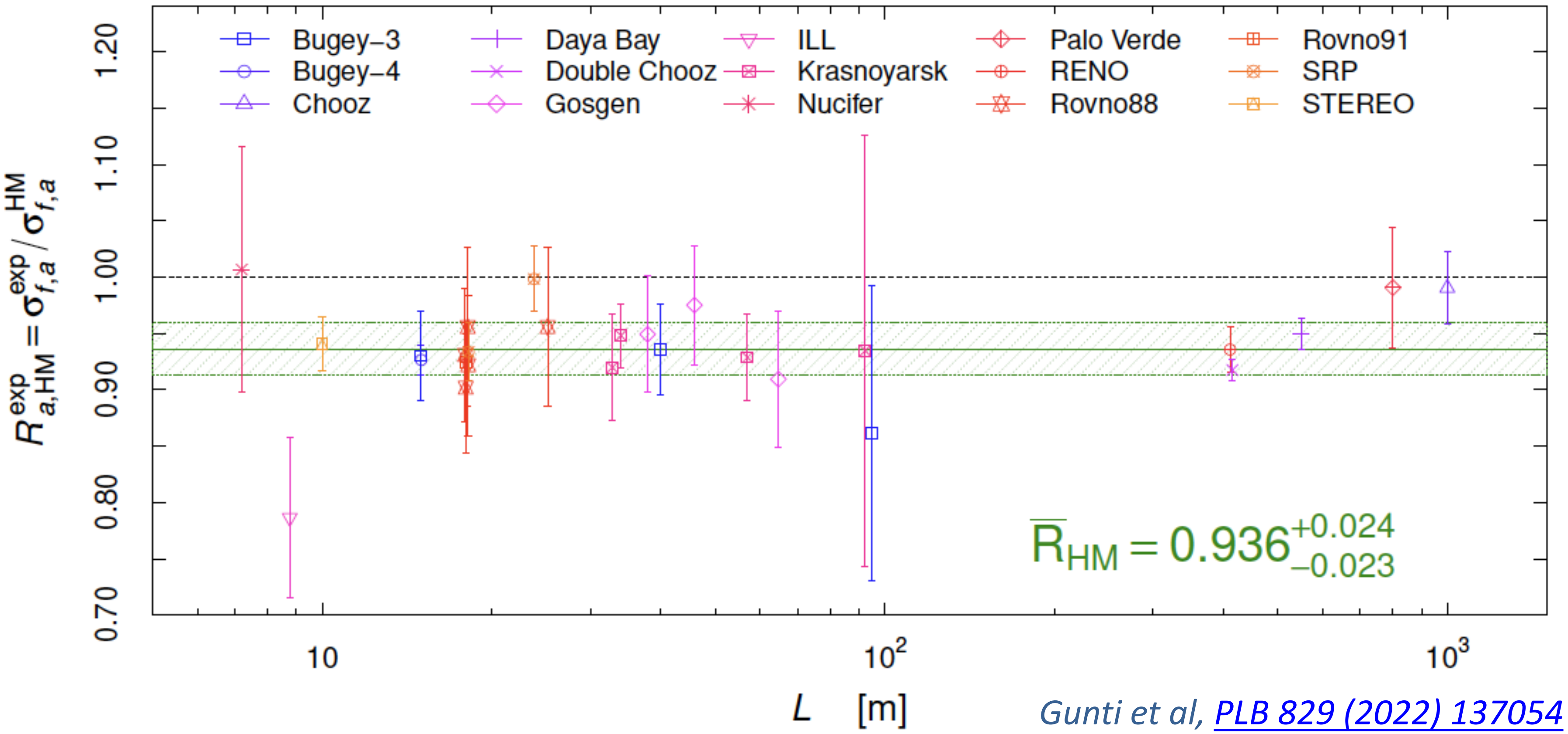
^{235}U Research Reactors: Pure isotopic source



STEREO (R. Rogly), Moriond-EW 2022
& PRL 125, 201801 (2020)

In ratio to H-M conversion prediction, Reactor Flux Anomaly is consistent at LEU and ^{235}U sources

Total neutrino yield measurements have achieved great precision



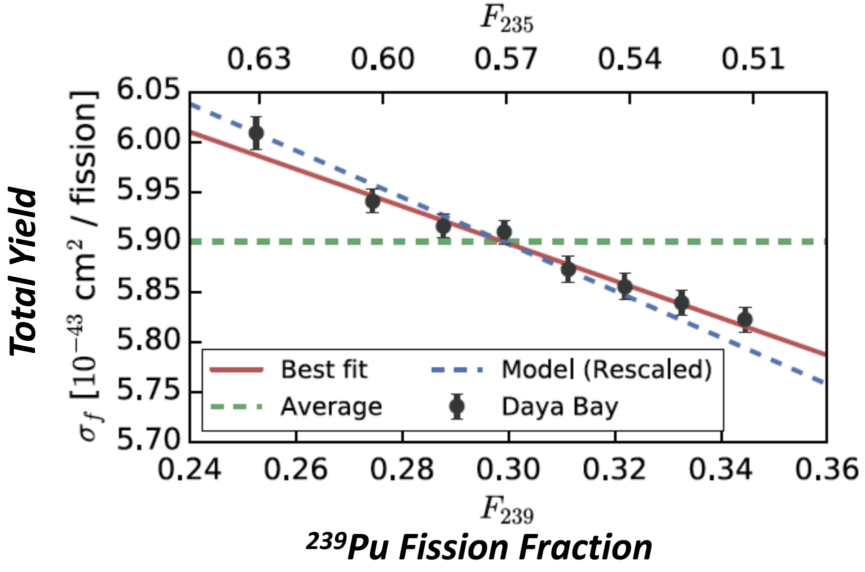
Gunti et al, PLB 829 (2022) 137054

In ratio to H-M conversion prediction, Reactor Flux Anomaly is consistent at LEU and ^{235}U sources

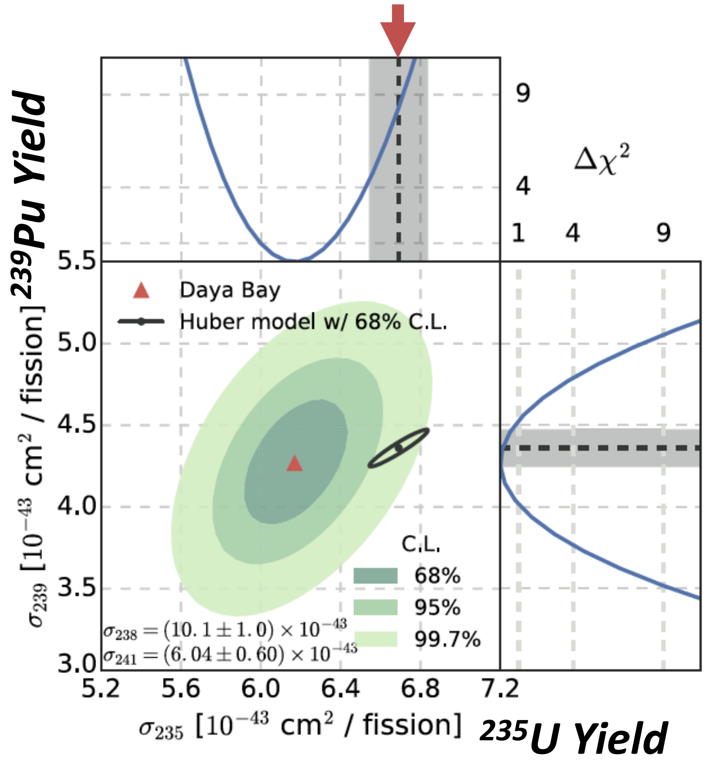
Recent Flux updates to RAA : P0121

Separating ^{235}U and ^{239}Pu Isotopic Yields at LEU Reactors:
Fuel Evolution Measurements

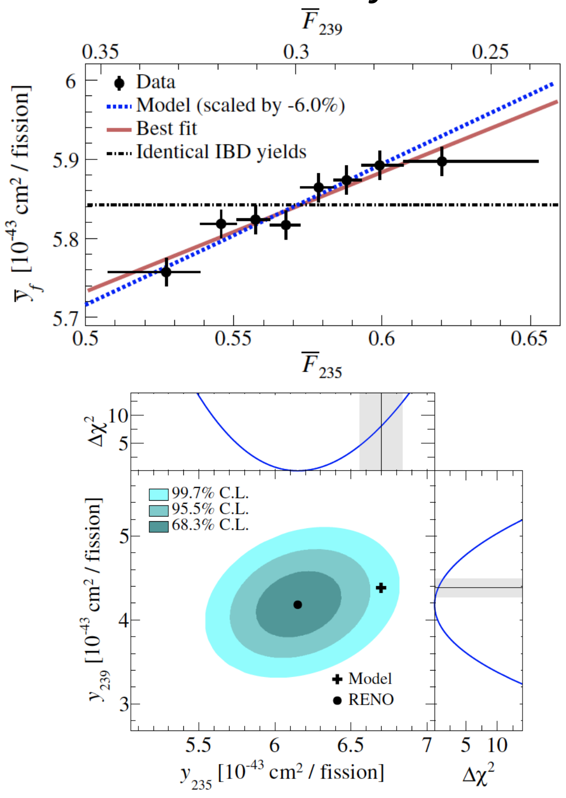
- θ_{13} experiments have collected large data sets that span a wide range of reactor fission fractions
- Can disentangle ^{235}U and ^{239}Pu contributions using yield variation with fission fraction



^{235}U yield ~ 8% less than H-M prediction



Consistent results from RENO



Daya Bay, PRL 118, 251801 (2017)

RENO, PRL 122, 232501 (2019)

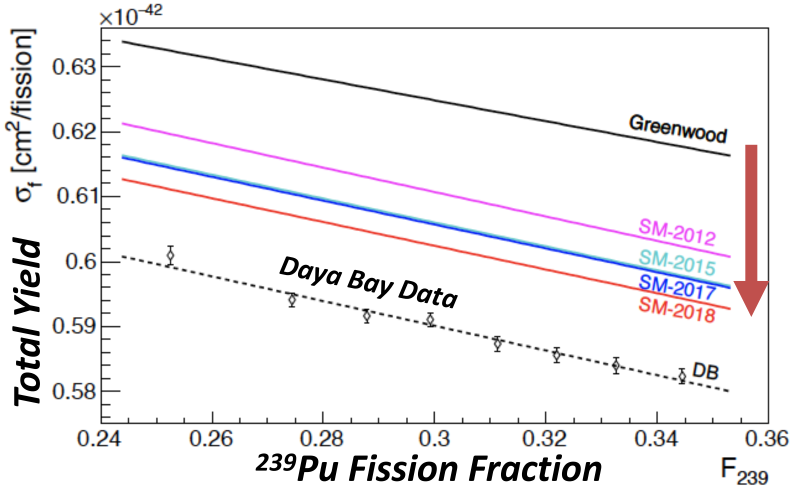
Evolution of total yield suggests ^{235}U conversion prediction is major contribution to Flux Anomaly

Daya Bay Fuel Evolution: P0387

RENO Yield & Spectrum Evolution: P0599

New measurements test and improve data underlying predictions
Further insight on isotopic yield differences

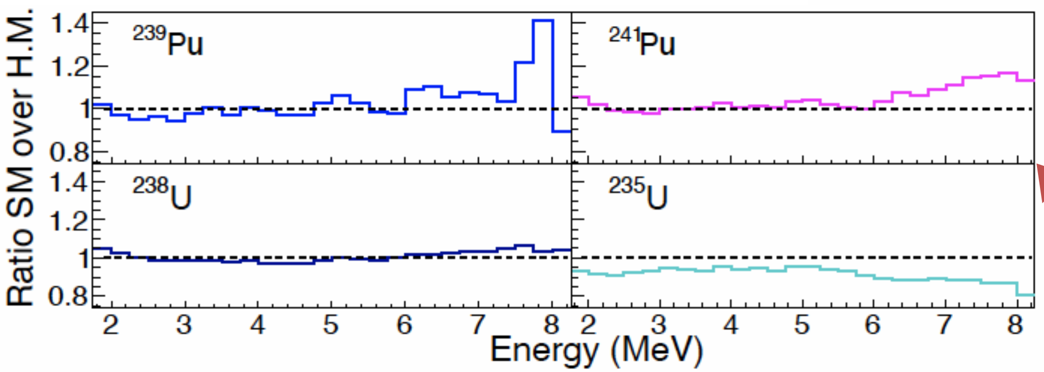
- Huge effort to improve nuclear data for summation predictions via TAGS measurements



Summation models reproduce fuel evolution slope

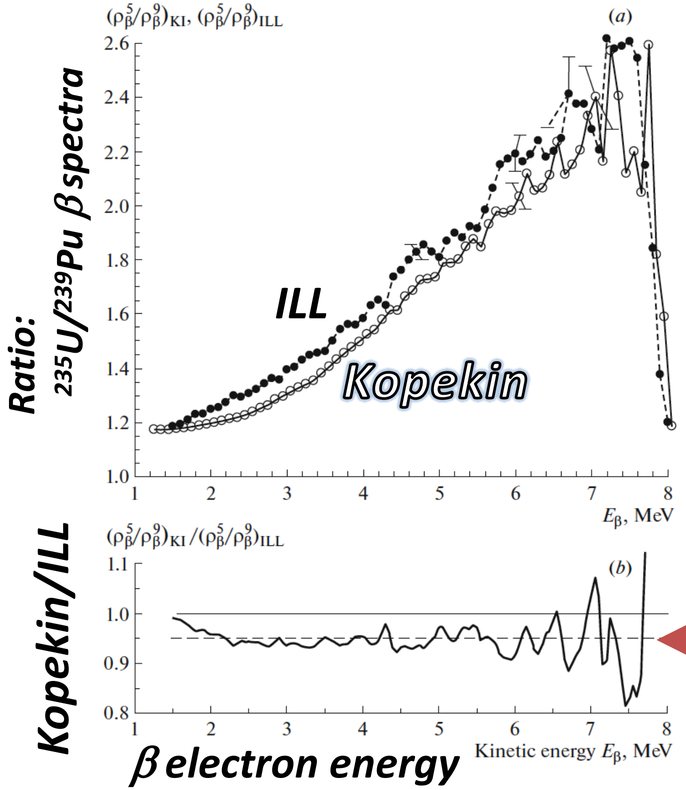
Flux anomaly shrinking as nuclear data inputs improved

In ratio summation/conversion ^{235}U stands out



Estienne, et al , , PRL 123, 022502 (2019)

- Recent $^{235}U/^{239}Pu$ fission beta ratio measurement tests ILL ('Schreckenbach') integral beta spectra that underly all conversion predictions

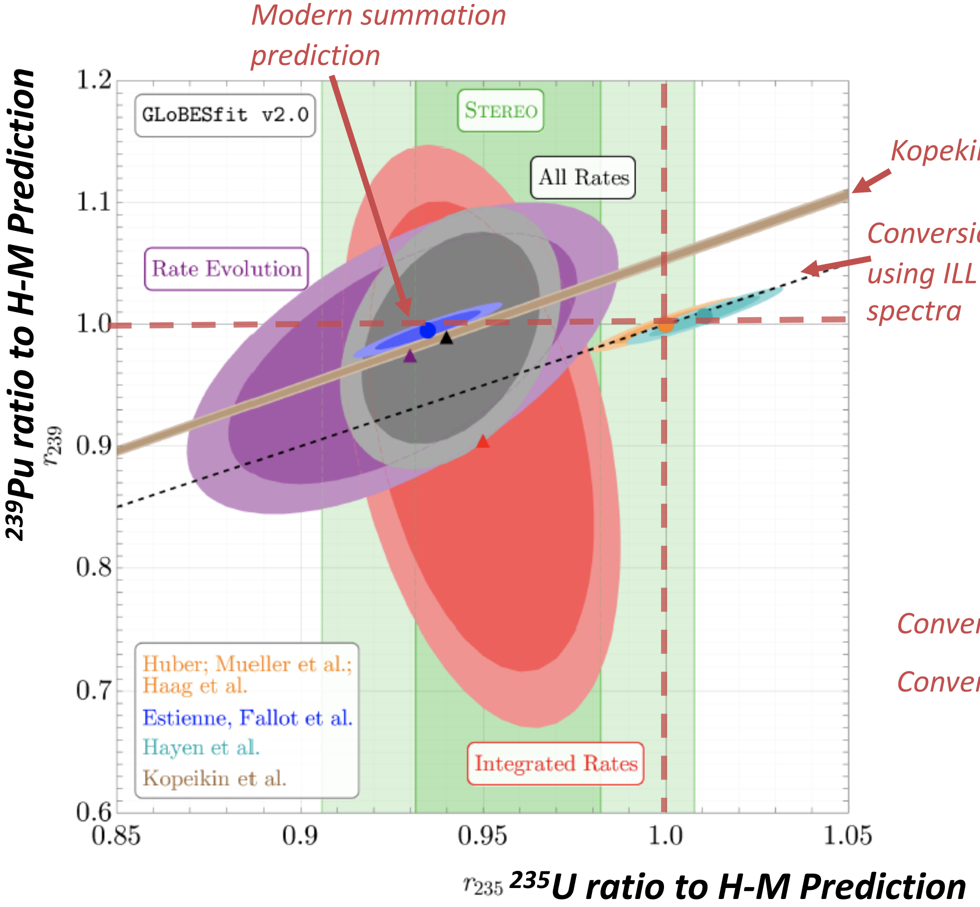


~ 5% difference

Kopekin, et al., Phys. Atom. Nucl. 84 1–10, Phys. Rev. D 104, L071301 (2021)

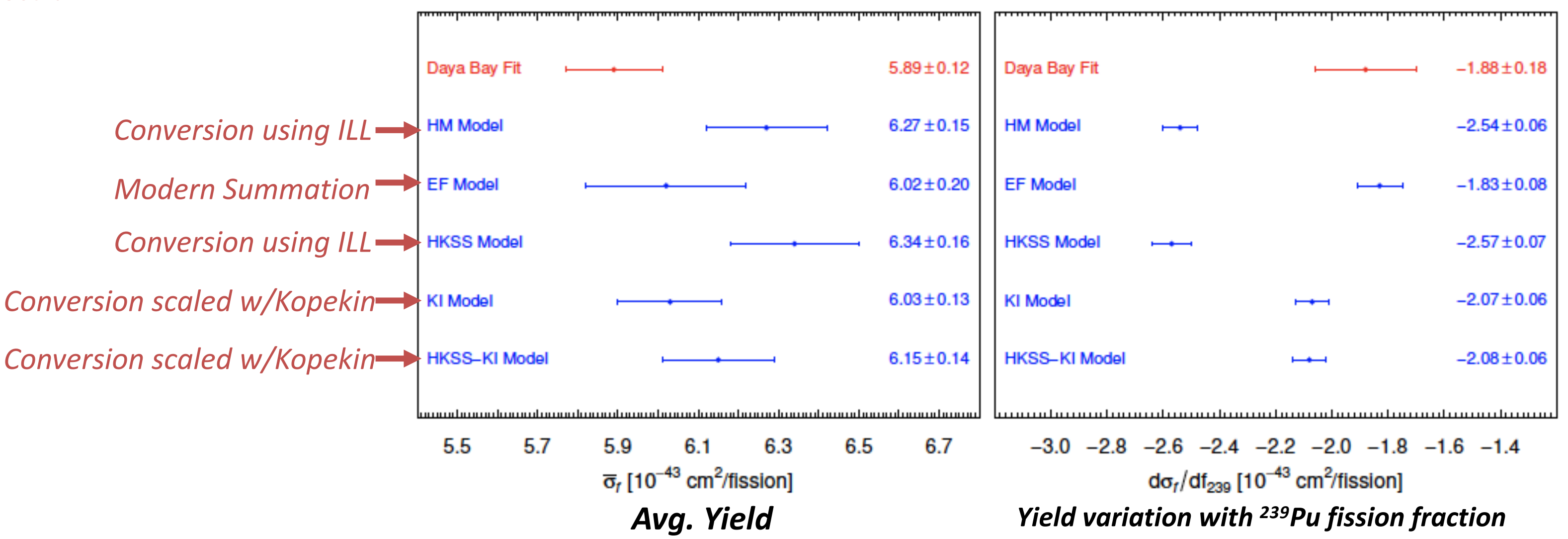
Further indications of a problem with data underlying conversion predictions

Comparison of Neutrino Yield and Beta Ratio Measurements to Conversion and Summation Predictions



[arxiv:2203.07214](), adapted from
Berryman & Huber, [JHEP 2021, 167 (2021)]()

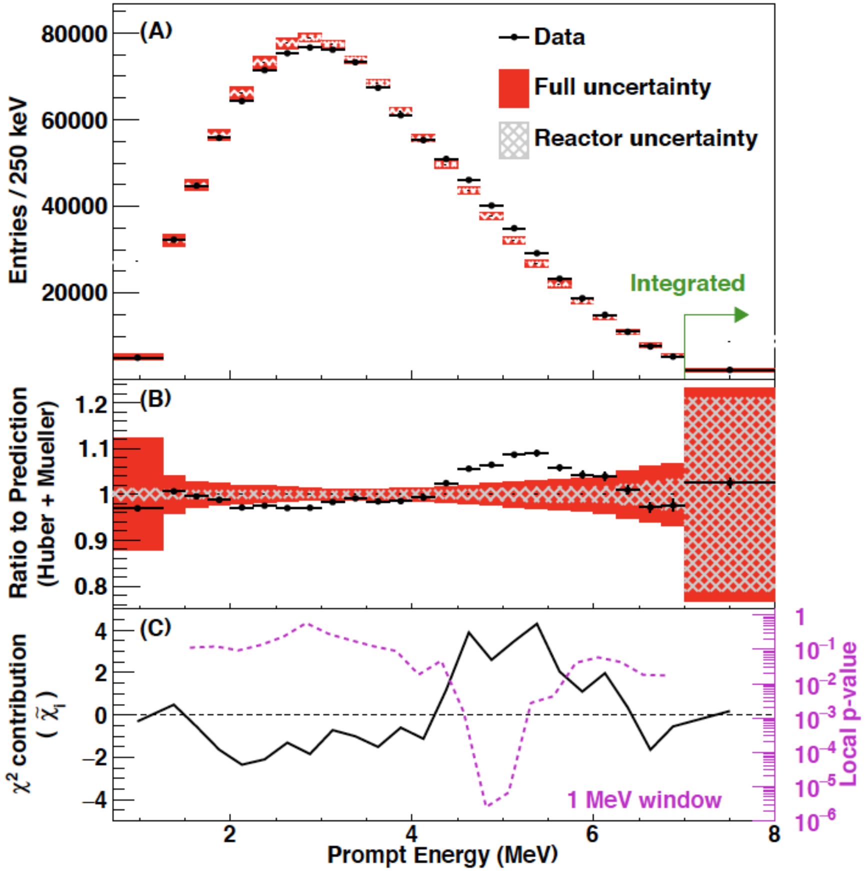
e.g. models compared to Daya Bay evolution analysis



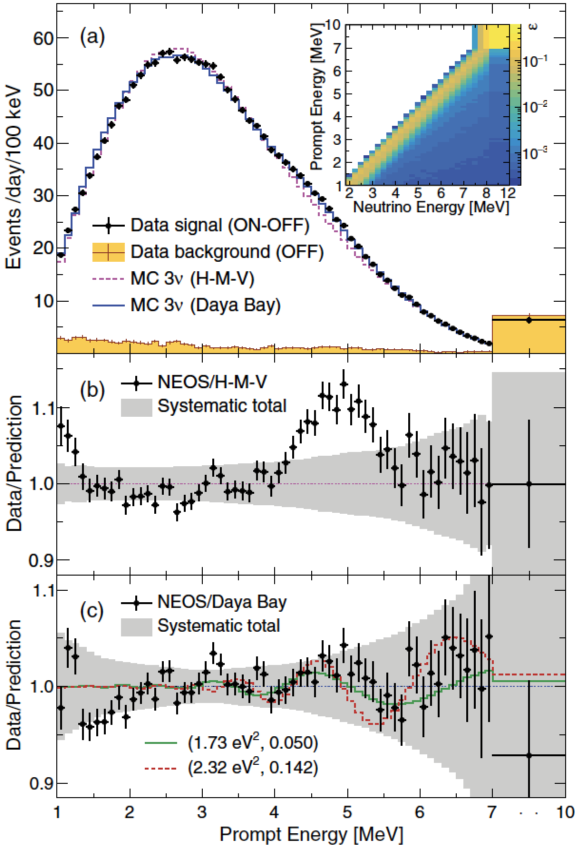
Gunti et al, [PLB 829 (2022) 137054]()

Multiple lines of evidence in concordance: ILL ^{235}U integral beta spectrum largely responsible for Flux Anomaly

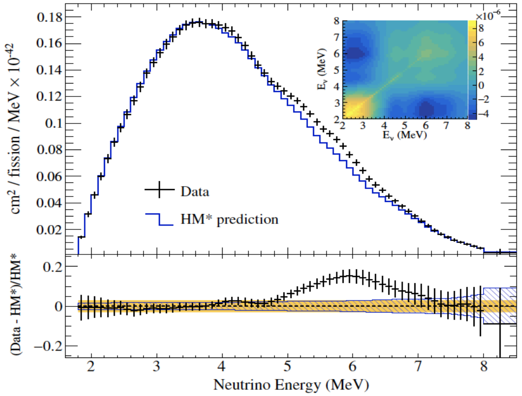
Spectrum Anomaly consistent across LEU reactor experiments



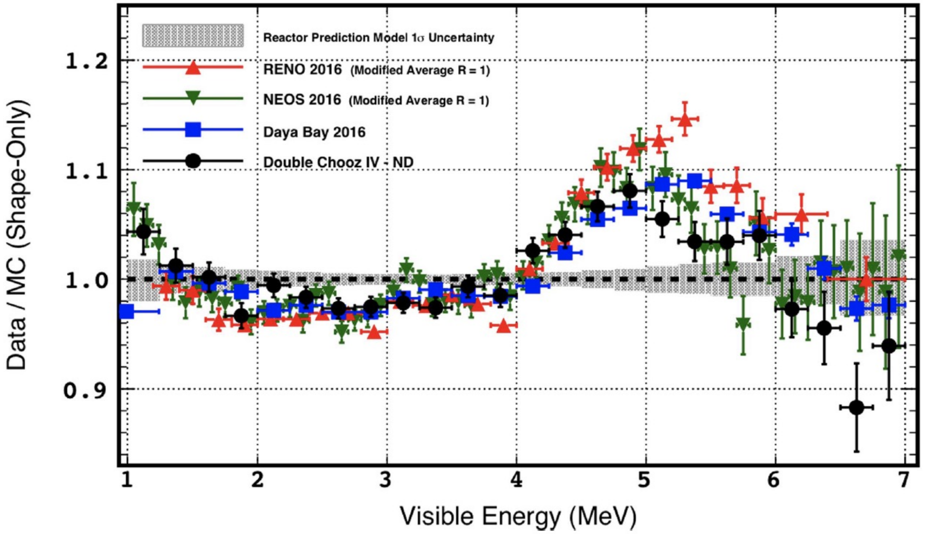
Daya Bay, CPC, 2017, 41(1): 13002



NEOS, PRL 118, 121802 (2017)

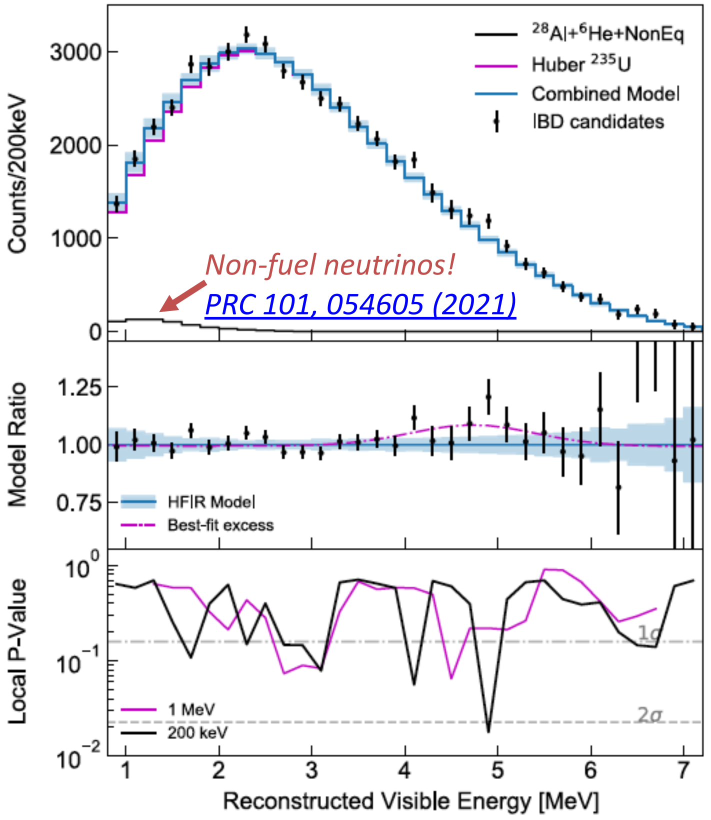


RENO, PRD 104, L111301 (2021)



From Double Chooz, Nature Phys. 16 (2020) 558

Pure ^{235}U Spectra from PROSPECT & STEREO also exhibit 'bump'



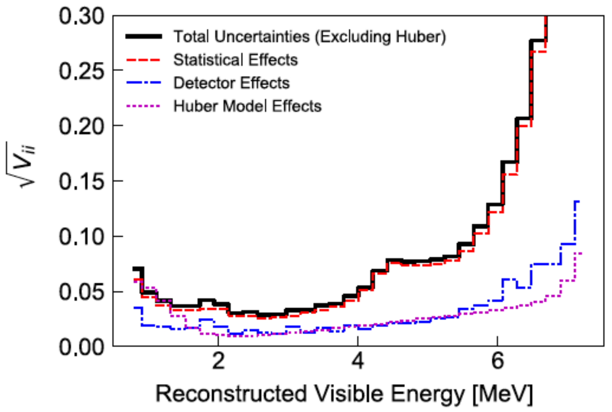
Non-fuel neutrinos! [PRC 101, 054605 (2021)](#)

PROSPECT, [*PRL 122, 251801 (2019)*](#) *&* [*PRD 103, 032001 (2021)*](#)

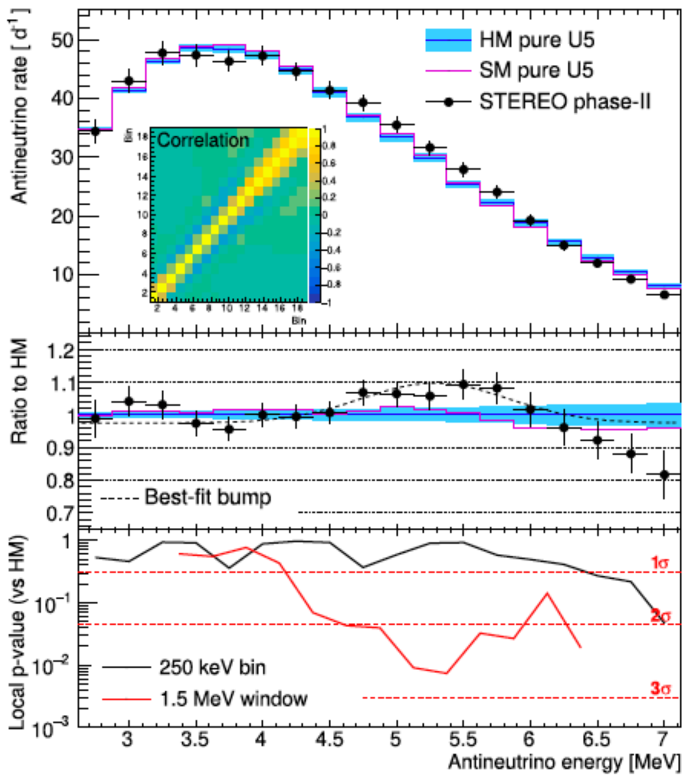
PROSPECT 'bump' amplitude
(1= Daya Bay)

- A = 0.84 ± 0.34
- A = 0 (no bump)
  → disfavored at 2.2σ
- A = 1.78 (LEU bump all ^{235}U)
  → disfavored at 2.4σ

Statistics limited with ~50k IBD events



Consistent observation by STEREO with ~50k IBD events in prompt *and* unfolded neutrino energy space



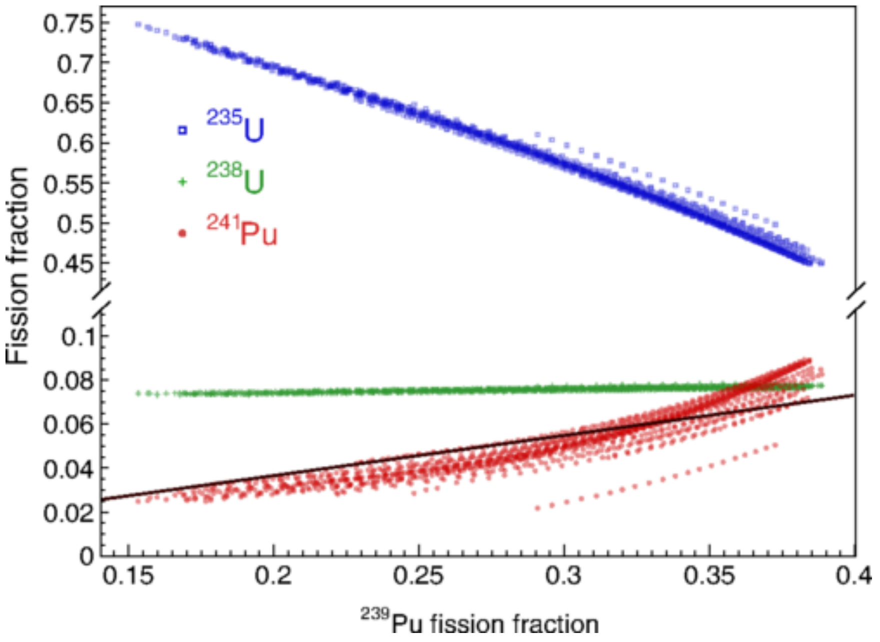
STEREO: [*J.Phys.G 48 (2021) 075107*](#)

First modern ^{235}U reference spectra!

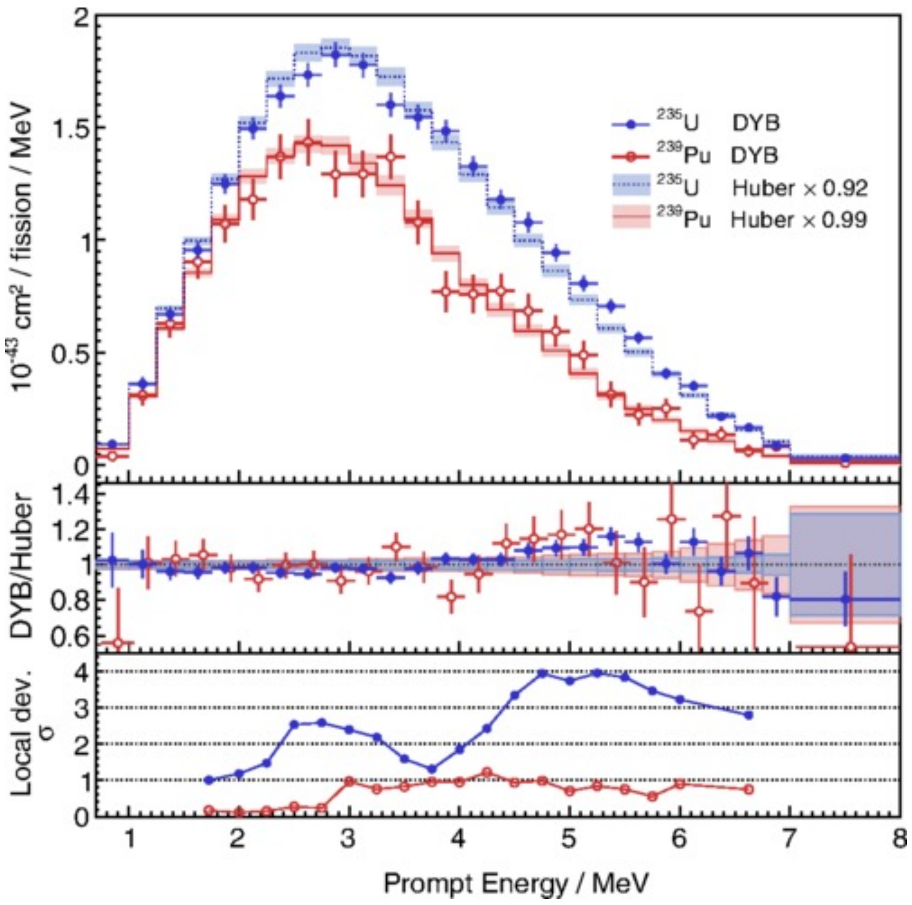
Suggests Spectrum Anomaly not due to ^{235}U alone

Extraction of ^{235}U and ^{239}Pu Isotropic Spectra from LEU data

^{235}U and ^{239}Pu spectra are extracted using prompt spectrum evolution as a function of isotope fission fractions.



Daya Bay, [PRL 123, 111801 (2019)]



'Bump' Significance:

- ^{235}U: 4.0σ
- ^{239}Pu: 1.2σ

Major uncertainties:

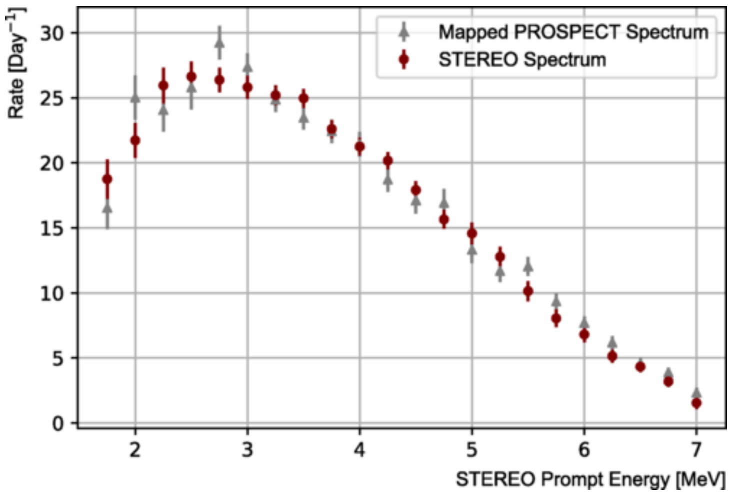
- Statistics (55-60%)
- ^{238}U & ^{241}Pu input models (35%)

First ^{239}Pu reference spectra!

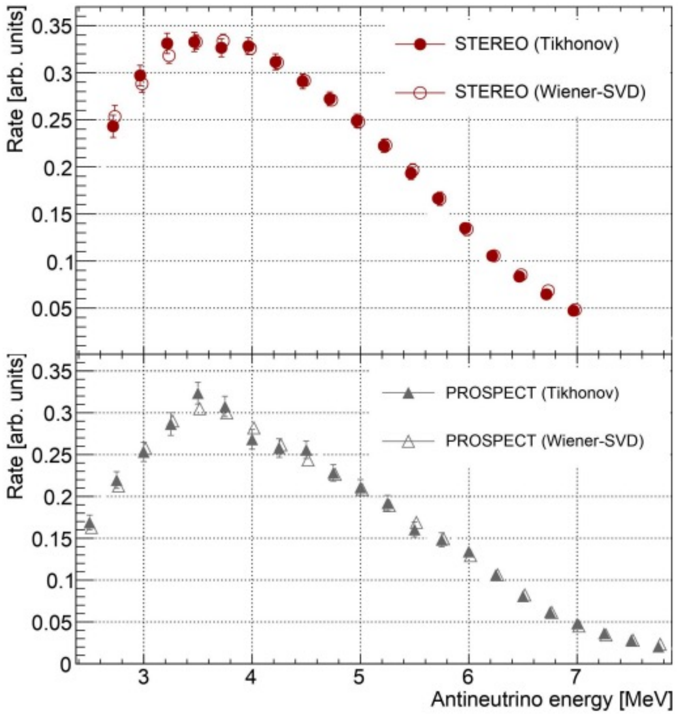
Suggests Spectrum Anomaly not due to ^{235}U alone

PROSPECT and STEREO Joint Spectrum Analysis
Increasing the power of statistics limited ^{235}U data sets

Compatibility of data sets collected with different detectors and reactors verified in prompt energy space of STEREO

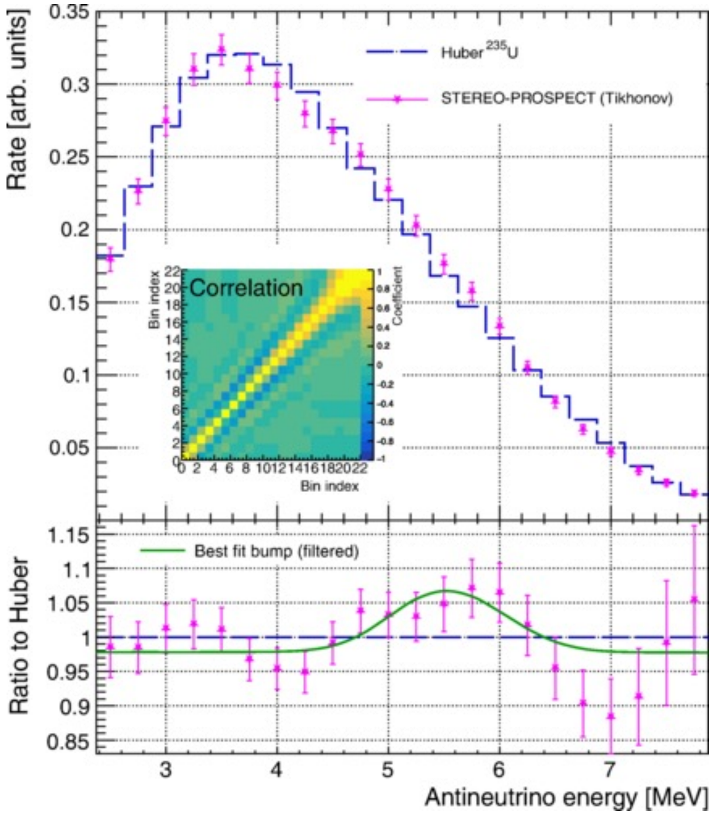


Two unfolding methods used, with compatibility between the two being established



Joint unfolding provides an improved reference for the community

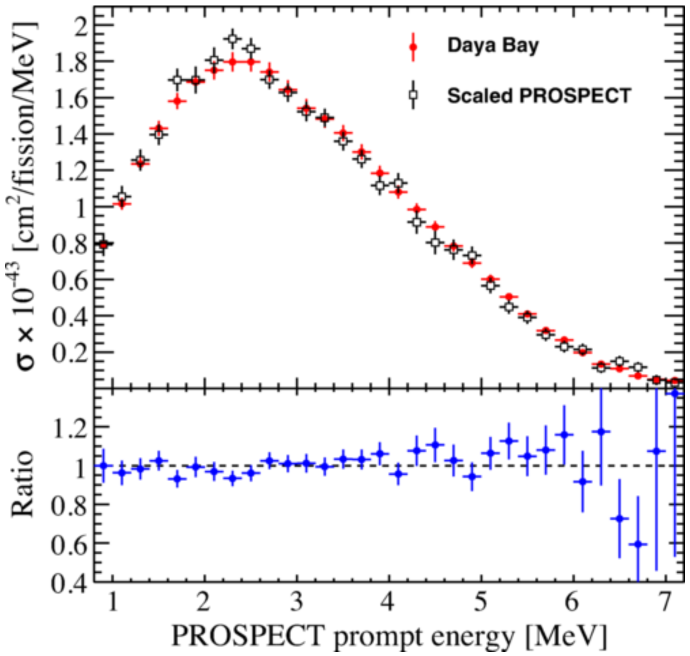
Bump excess has 2.4σ significance



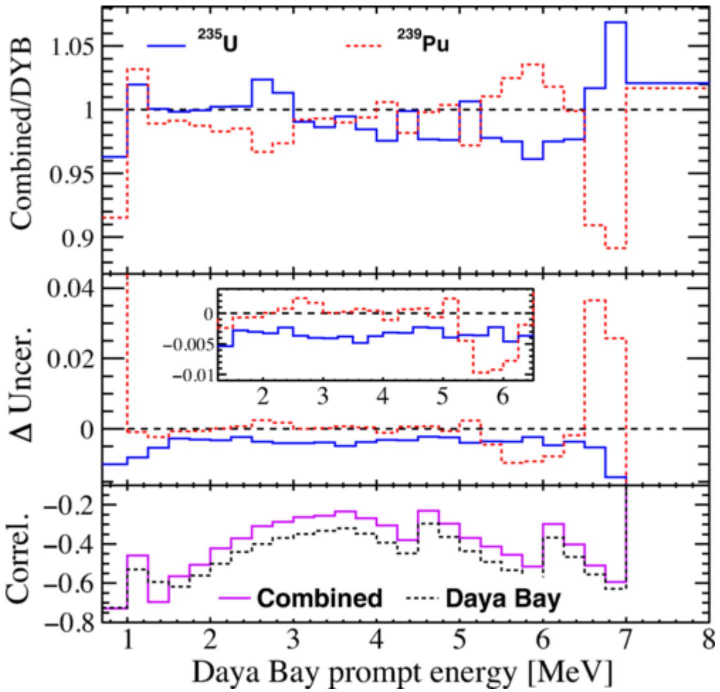
PROSPECT & STEREO , [PRL 128, 081802 (2022)](#) *STEREO/PROSPECT Joint Spectrum: [P0359](#)*

Daya Bay and PROSPECT Joint Spectrum Analysis
Pure ^{235}U data provides additional constraint on evolution analysis

Compatibility of data sets collected with different detectors and reactors verified in prompt energy space of PROSPECT

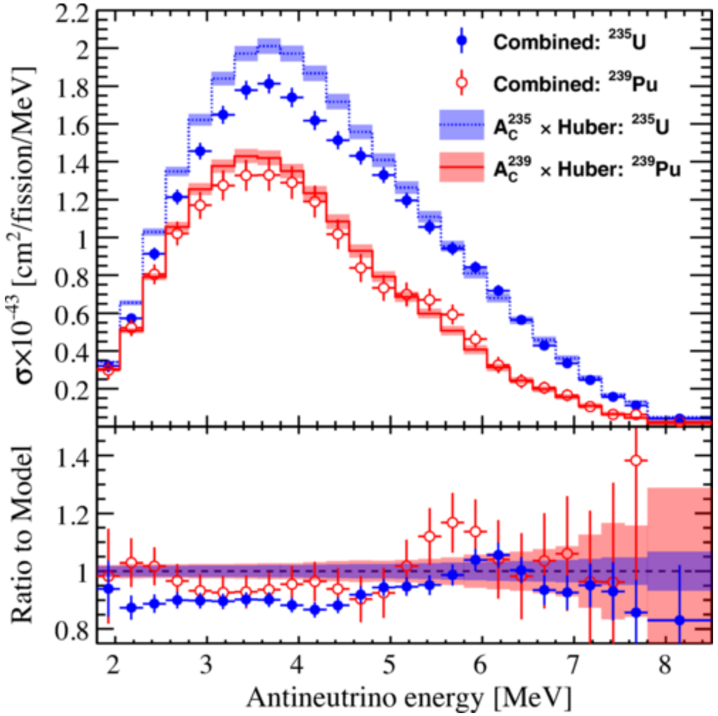


Combined analysis reduces degeneracy between dominant ^{235}U and ^{239}Pu isotopes in evolution analysis by ~ 20%



Relative shape uncertainty of ^{235}U improved to 3%

^{235}U bump significance also improved



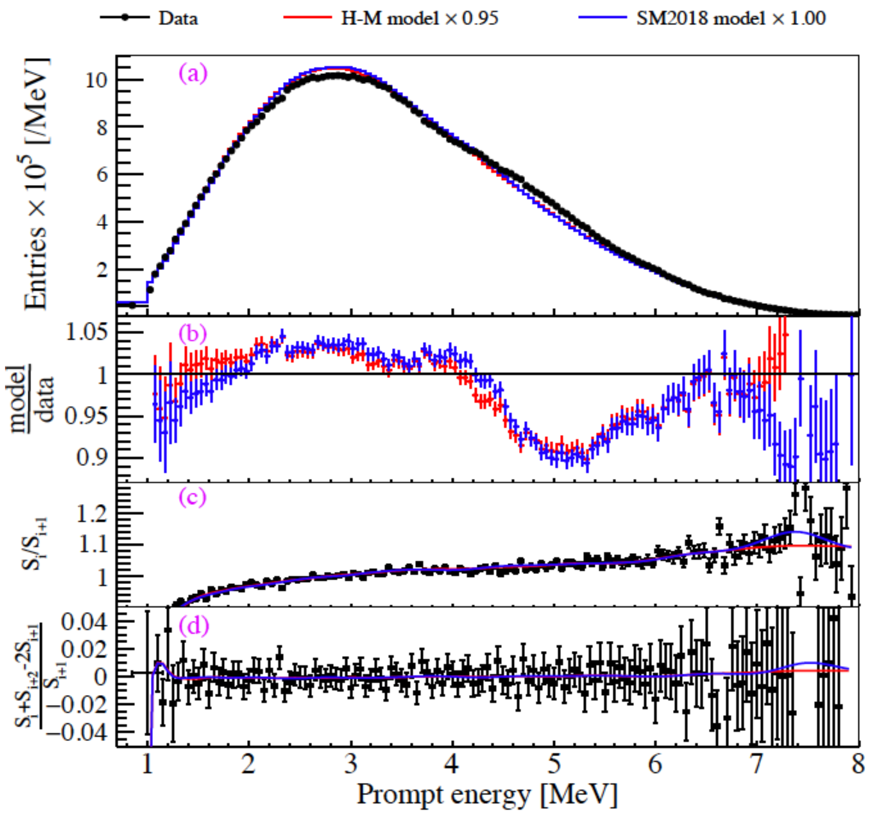
Daya Bay & PROSPECT , *[PRL 128, 081801 (2022)]*   *Daya Bay/PROSPECT Joint Spectrum : [P0067]*

Comparison of Spectrum Measurements to Conversion and Summation Predictions

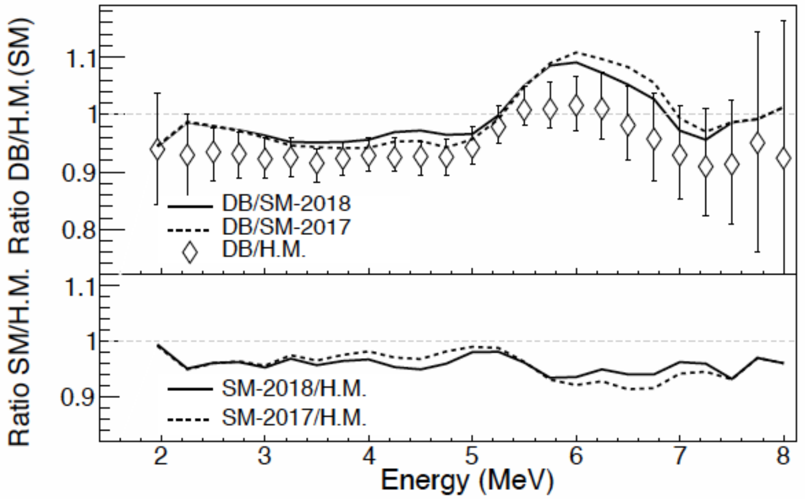
Spectrum anomaly is present in both ^{235}U and ^{239}Pu when compared to either Conversion or Summation Predictions

Even as summation models have incorporated improved nuclear data, giving better flux agreement, spectrum anomaly remains

Similarity between conversion and summation comparisons suggests common origin / underlying assumption



Daya Bay, [CPC, 2021, 45(7): 073001]()

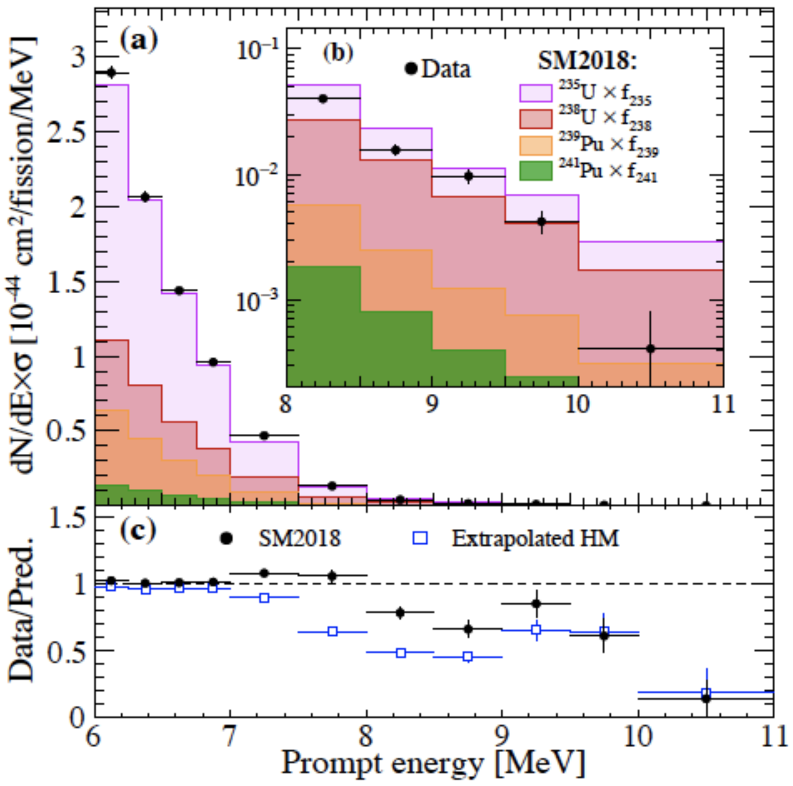


Estienne, et al, , [PRL 123, 022502 (2019)]()

Cause of Spectrum Anomaly still not understood

High Energy Reactor Neutrino Measurement by Daya Bay

- Test of summation predictions in new regime
- Provides the first direct observation of neutrinos from several high-Q isotopes in LEU reactors



Daya Bay, [arxiv:2203.06686]

First high energy reference!

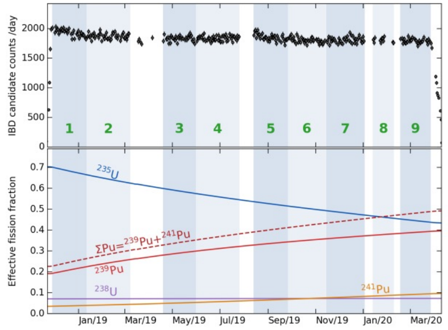
New Results from NEOS-II & RENO

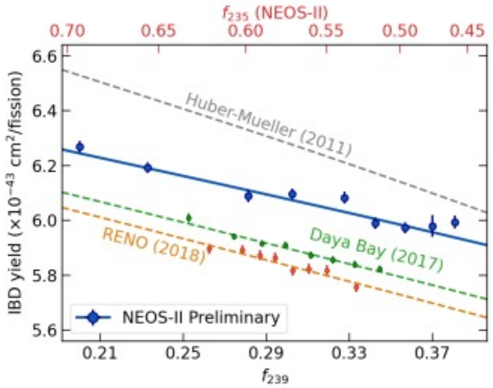
Extraction of ^{235}U and ^{239}Pu Isotopic Yields and Spectra from LEU data

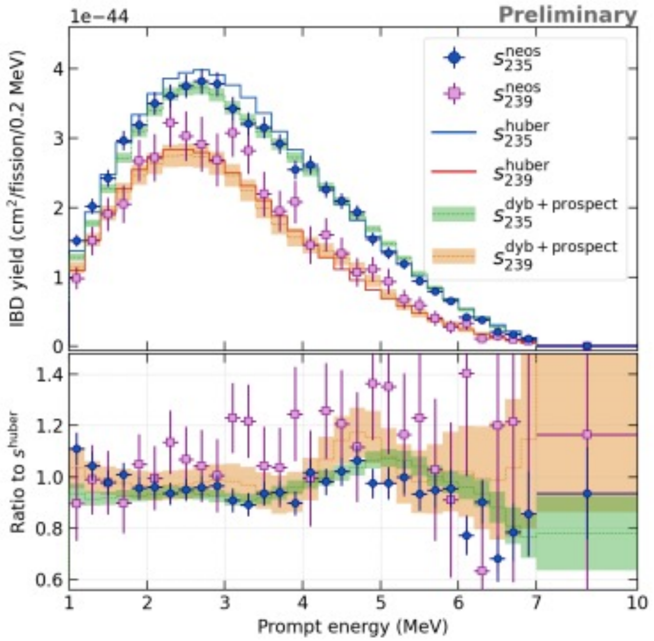
NEOS-II

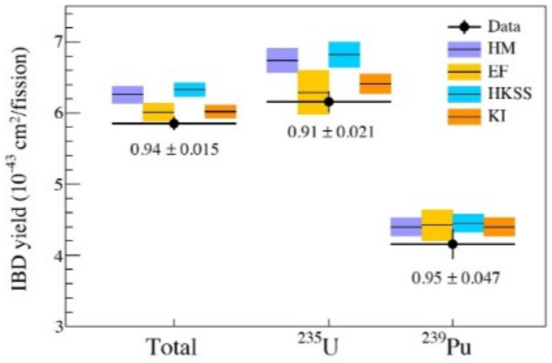
RENO

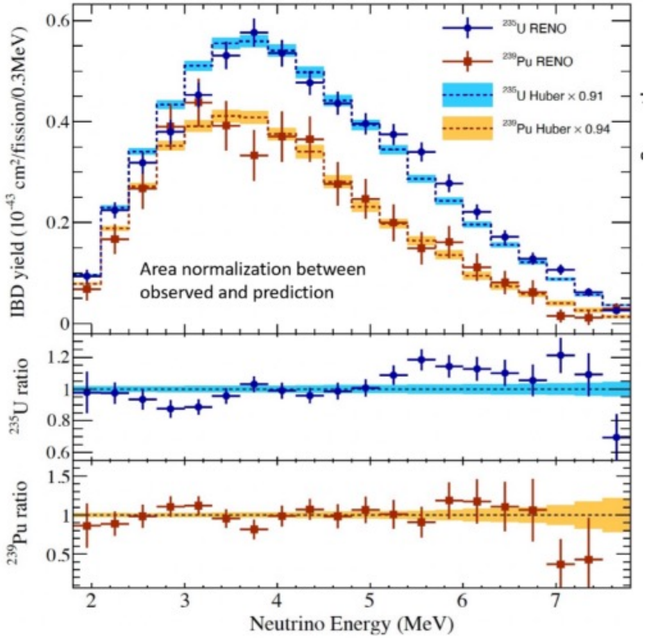
Data set spans full reactor cycle











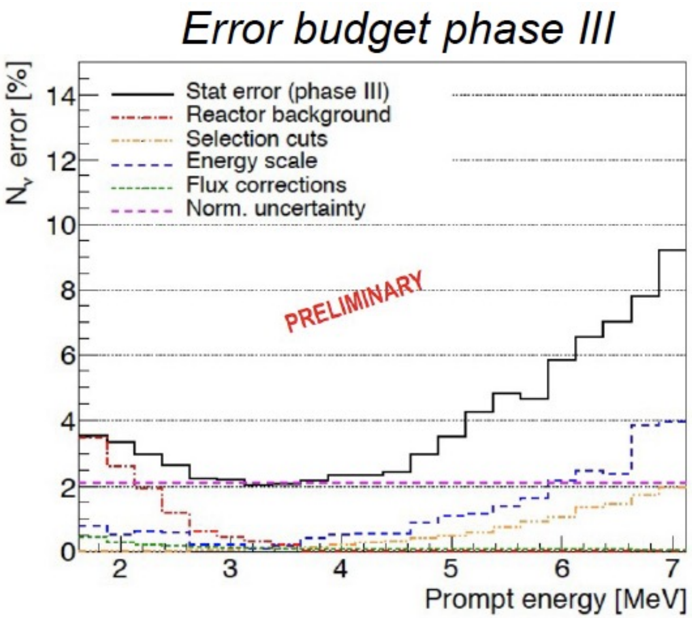
NEOS-II Presentation

RENO Presentation

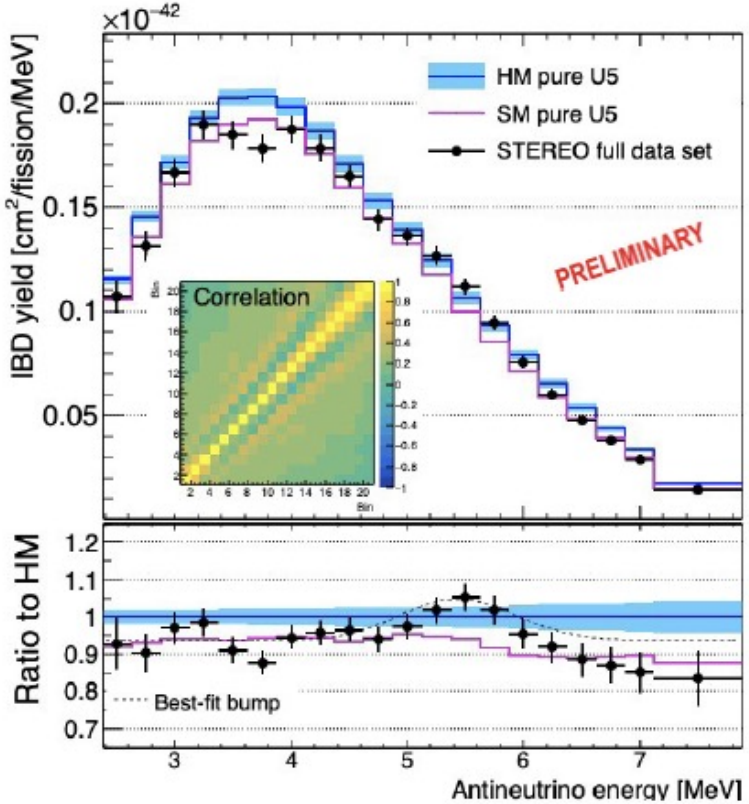
RENO Yield & Spectrum Evolution: P0599

New Result: ^{235}U Spectrum from Full STEREO Data Set

- Full data set of STEREO adds Phase II (43k IBD) & Phase III (64k IBD)

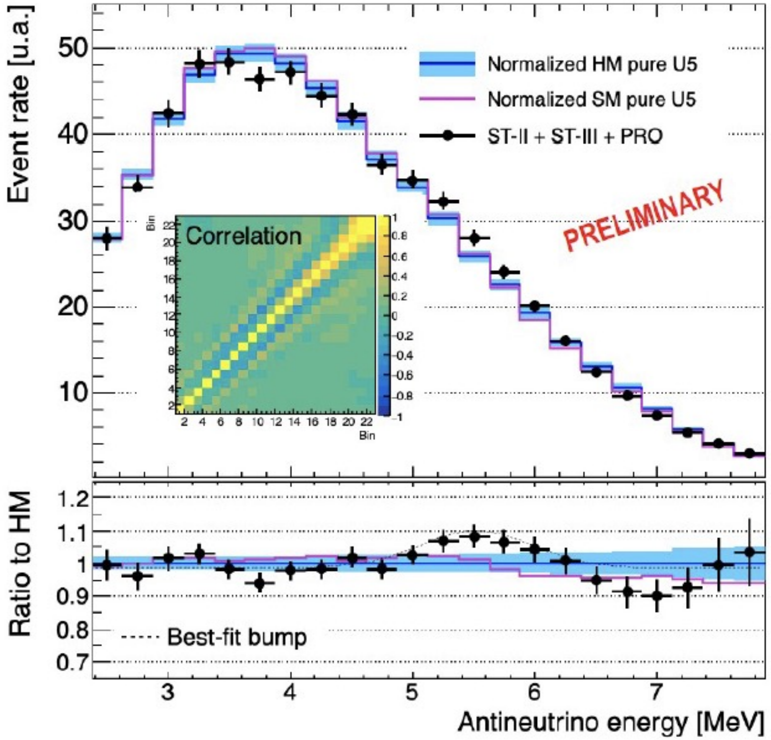


STEREO full data
≈ 107k ^{235}U neutrinos



Spectral anomaly with 4.6σ significance

STEREO full data + PROSPECT
≈ 107k + 51k neutrinos

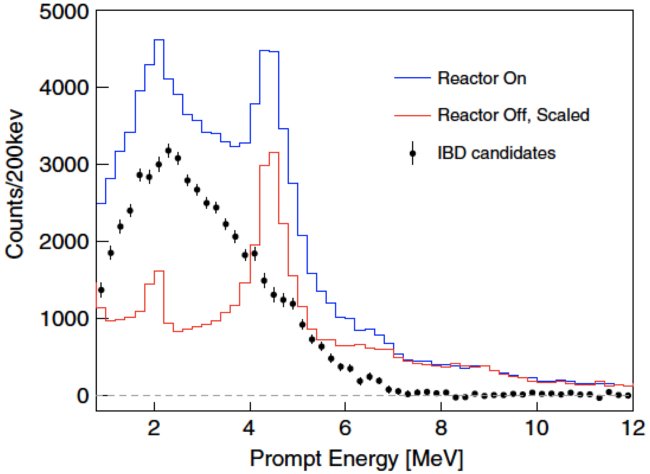


Spectral anomaly with 4.7σ significance

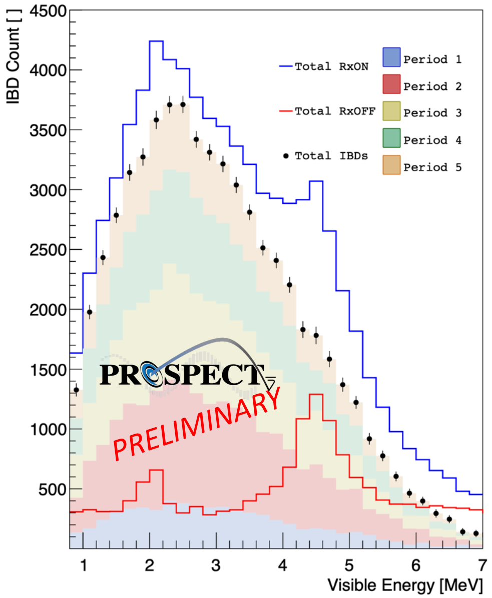
Largest ^{235}U sample to date!

STEREO Spectrum Analysis: P0177

Forthcoming Improvements from PROSPECT:
More efficient use of fully & partially operating detector segments

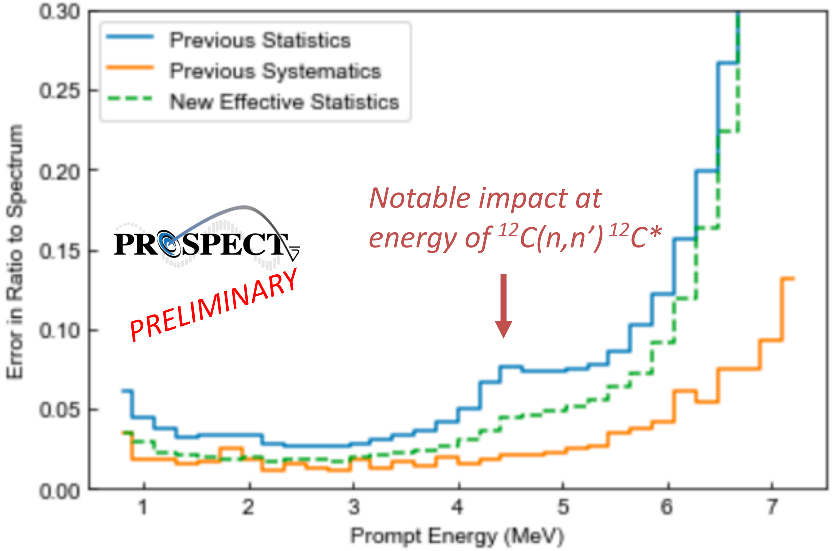


PROSPECT, [PRD 103, 032001 (2021)]

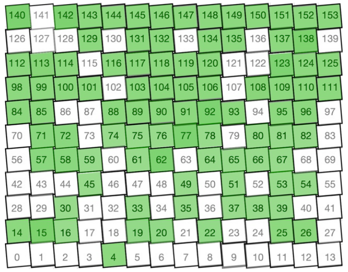


Performance Gain:

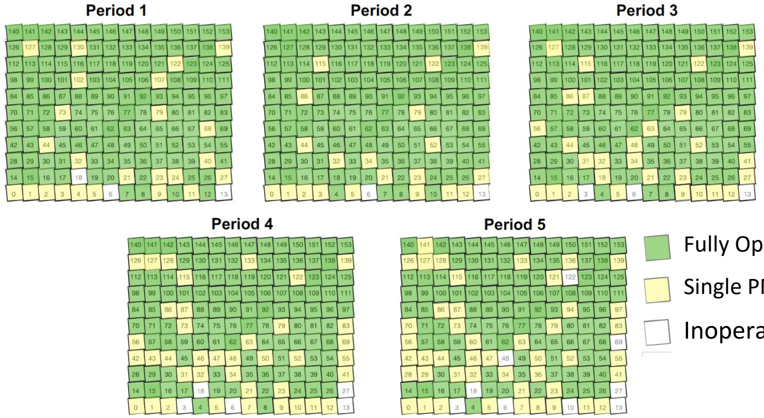
- Signal : Background : 1.4 → 3.8 (x2.7)
- IBD count : ~50,000 → ~60,000 (x1.2)
- 'Effective Statistics': ~15,000 → ~30,000 (x2.0)



Segments used in previous analysis



- Fully Operational
- Ignored/ Inoperative



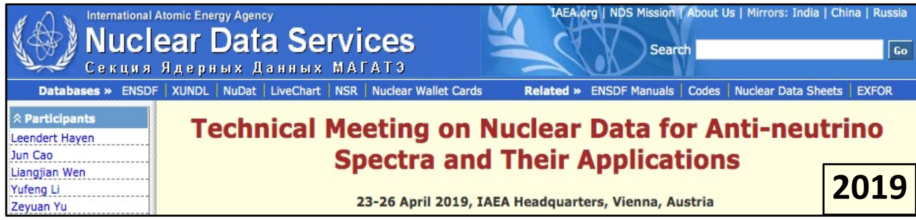
- Fully Operational
- Single PMT (bkg veto)
- Inoperative

Multi-period unfolding under development to account for response variation
→ Generalized framework for multi-experiment and multi-reactor joint analyses

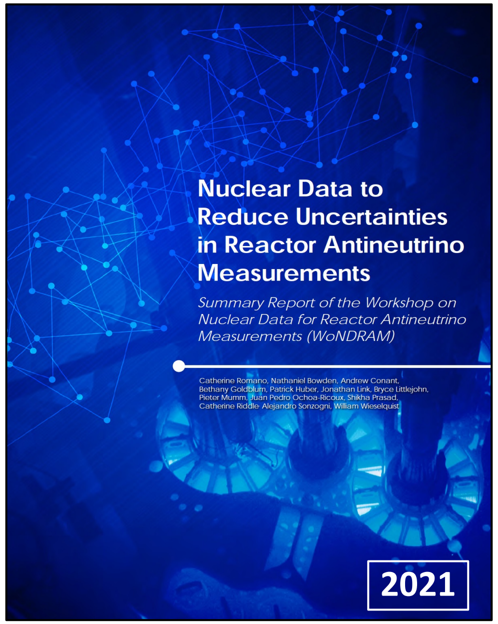
Improved statistics and S:B to be used in forthcoming Oscillation, Absolute Flux, and Spectrum analyses

Reactor Neutrinos as Nuclear Data

- Flux and Spectrum Anomalies have caught the attention of Nuclear Data community
- Reactor neutrino studies have helped motivate improvements in Nuclear Data used in other communities, e.g.
  - TAGS measurements improving Reactor Decay Heat calculations
  - Improved Fission Product Yield data, evaluations, and uncertainties
  - …
- High precision reactor neutrino measurements could naturally be considered for an ‘evaluated’ nuclear data product
  - Emphasis on ‘universal’ quantities: Isotopic Yield and Neutrino Energy space
  - Detailed documentation & standardization will be essential, e.g.
    - Detector effects, experimental configuration, systematic uncertainties, analysis methods



IAEA NDS Report & Presentations



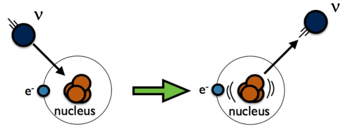
WonDRAM Report & Presentations

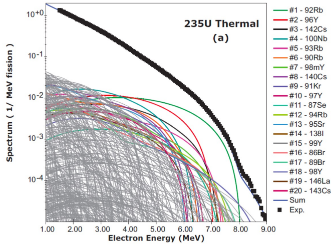
Where to from here?

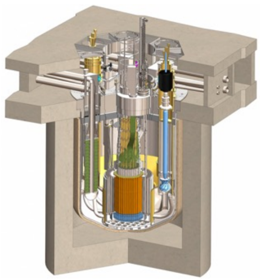
- That reactors are a uniquely powerful, flavor-pure source of antineutrinos provides abundant motivation for strong resolution of the Flux and Spectrum Anomalies

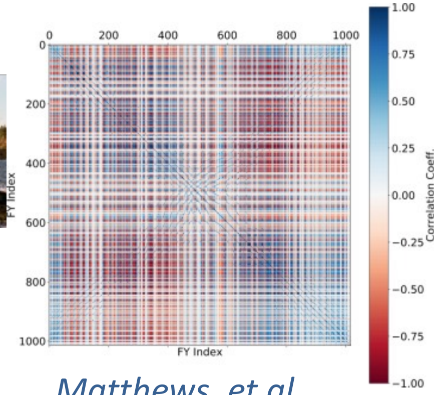
- Improved Reference Measurements and Validated Predictions are important for:
  - Fundamental Physics: e.g. reactor CEvNS detection, future BSM searches using reactors
  - Nonproliferation Applications: e.g. predicting neutrino emissions from advanced reactors
  - As a stringent test of many nuclear data inputs

- Workshop Recommendations include (in no particular order):
  - Continued improvement to LEU and HEU data and analysis
  - Establishing standards for Data and Predictions (*peer reviewed*)
  - Continued emphasis on Joint Analyses
  - Multi-reactor measurements with correlated detector systematics
  - Exploring CEvNS as a tool to probe below IBD threshold
  - Modern integral fission beta measurements (detailed concepts exist)
  - Continued improvement of FPY and TAGS nuclear data
  - Continued development of prediction methods & uncertainty quantification
  - Targeted measurement of high-Q beta shapes
  - …







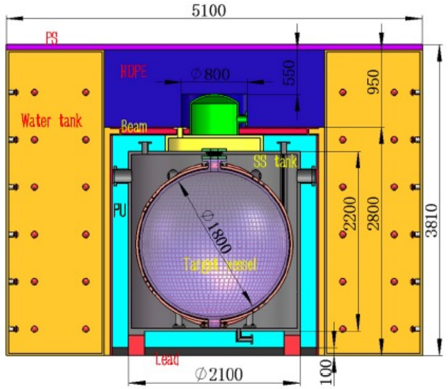


Matthews, et al., NDT 140 (2021) 101441

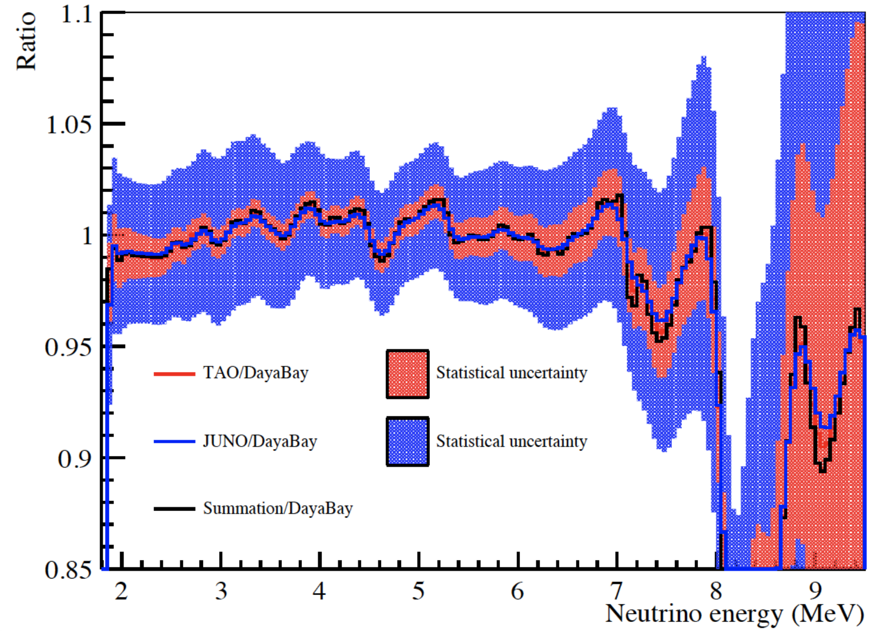
Future Efforts: JUNO-TAO

JUNO-TAO will provide the JUNO reference spectrum

- 1 ton fiducial Gd-LS volume
- SiPM readout and Gd-LS at -50°C
- **~1.7% @ 1 MeV energy resolution**

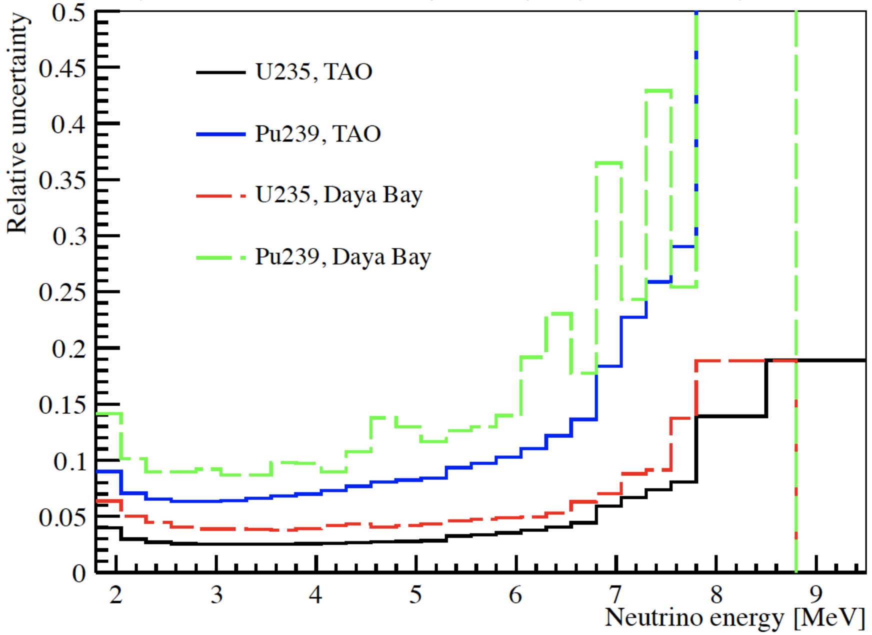


Exceptional resolution and high statistics will allow measurement of spectrum fine structure



JUNO-TAO CDR
[*arxiv:2005.08745*]

High resolution and statistics, plus wide range of fission fractions at single reactor source will allow improved extraction of isotopic yield and spectra

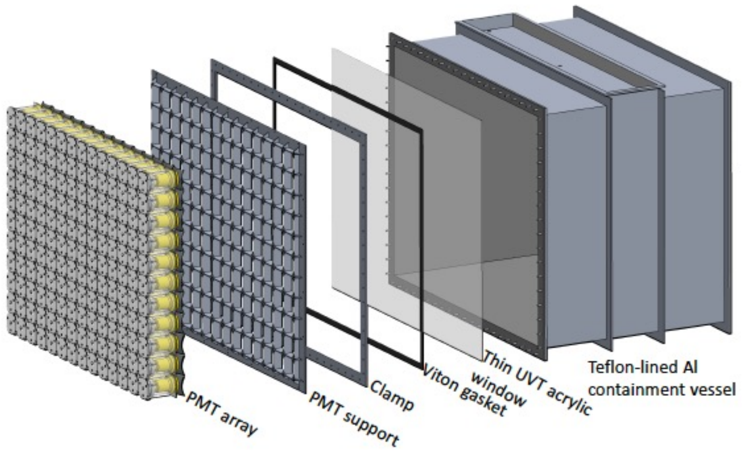


Future Efforts: The PROSPECT-II Upgrade

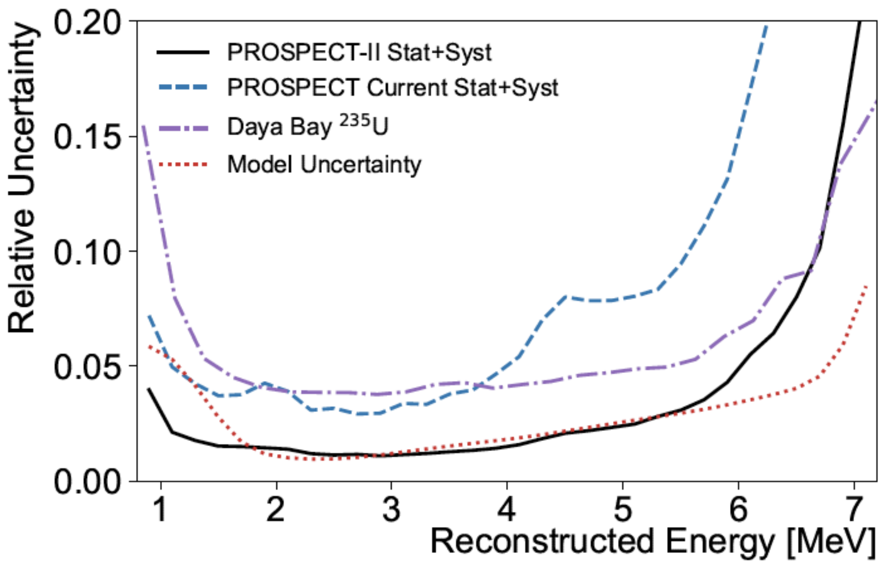
PROSPECT-II is a proposed detector upgrade:

- Address technical challenges of PROSPECT-I, increase robustness
- Option for modest target volume increase
- Relocatable between ^{235}U and LEU reactors (correlated detector systematics)

Data taking at HFIR could begin after a 1 year construction period



^{235}U spectrum uncertainty (stat+syst) would reach model precision after ~ 2 years of data collection



High statistics ^{235}U data set gives opportunity to significantly improve isotopic yields, especially with multi-reactor measurement

Case	Description	Precision on σ_i (%)		
		^{235}U	^{239}Pu	^{238}U
1	Daya Bay LEU	3.7	8.2	30
2	Daya Bay LEU + P-II HEU	2.4	6.3	21.3
3	P-II LEU + P-II HEU+	1.4	3.4	15.9
4	P-II LEU + P-II HEU+, Correlated	1.4	3.0	8.7
-	Model Uncertainty [66]	2.1	2.5	11.2

PROSPECT-II Physics Opportunities - arxiv:2107.03934 & arXiv:2202.12343

Conclusions

- Tremendous progress has been made improving the precision of reactor neutrino measurements and predictions
- Higher precision revealed discrepancies between measurement & prediction: Flux & Spectrum Anomalies
- Through intense effort from multiple directions, the Flux Anomaly can be largely attributed to normalization of ILL ^{235}U integral beta spectrum measurement underlying all conversion predictions
- Spectrum anomaly persists across all measurement types and prediction methods. The cause is not well understood
- Neutrino measurements, underlying nuclear data, and predictions continue to improve, with many pathways to continue this momentum
- Strong, synergistic motivations from multiple communities to resolve the anomalies and establish reactors as a well understood neutrino source
- Community moving towards standardized quantities → Reactor Neutrinos as reference Nuclear Data