# WONDRAM-2021

# **STATE OF THE ART** EXPERIMENTAL PROBES OF REACTOR FLUX AND SPECTRA

T.J. Langford Yale University



### **DIVERSE SUITE OF CURRENT ANTINEUTRINO EXPERIMENTS**

#### $heta_{13}$

Daya Bay, Double Chooz, RENO

Multiple large-volume detectors

significant overburden

**LEU Power Reactors** 

#### vSBL

DANSS, PROSPECT, STEREO, SoLiD

> Compact, segmented detectors

surface-deployment

**HEU Research Reactors** 

#### REACTOR MONITORING

miniChandler, ISMRAN, Panda

varied overburden

~25m baselines

**LEU Power Reactors** 

Only a selection of experiments...



# **ISOTOPIC ANTINEUTRINO YIELD IN 2021**

- LEU: time evolution extracts yield from <sup>235</sup>U and <sup>239</sup>Pu
- HEU: measure <sup>235</sup>U directly, but lower power and higher backgrounds
- 2021 Status: evidence points to a deficit in <sup>235</sup>U, good agreement between <sup>239</sup>Pu data and prediction
- Recent beta-decay measurements from Kopeikin et al. consistent with a problem in <sup>235</sup>U not <sup>239</sup>Pu

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### **ISOTOPIC ANTINEUTRINO SPECTRUM SHAPE IN 2021**



- ▶ LEU: time evolution extracts <sup>235</sup>U and <sup>239</sup>Pu, complications from <sup>238</sup>U/<sup>241</sup>Pu
- HEU: measure <sup>235</sup>U directly, high backgrounds and complicated detector response
- New results remove detector response via unfolding (Prompt => Antineutrino)
- 2021 Status: evidence points to disagreements in spectral shape in both <sup>235</sup>U and <sup>239</sup>Pu when compared to either beta-conversion or summation



# **EXPERIMENTAL UNCERTAINTIES AND "UNIVERSAL" RESULTS**

Experimental uncertainties are complicated and often only fully understood by the collaboration

#### Detector:

 escaping energy, nonlinearity, calibration, resolution, thresholds, ...

#### • Experimental:

exposure, reactor power/fuel, distance, ...

#### Analysis:

- statistics, modeling, assumptions, ...
- More than can fit in a letter-length publication
- Final results should be as free from these experiment-specific things as possible
- Shift from reporting experiment-specific to universal quantities:

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- Prompt Energy => Antineutrino Energy
- Detected Rate => Isotopic Neutrino Yield



## **UNFOLDING REACTOR NEUTRINO SPECTRA**

- Standard approach: compare theoretical models to data in the "experimental" space
  - Adjust model to account for detector effects
  - Perform any high-level analyses in "Prompt" or "Visible" energy space
- Since each experiment is unique, these spaces don't line up, and often have different treatments of detector effects
  - Can't directly compare measurements
- To remove these detector effects the response matrix needs to be inverted (which it can't be)
- Apply regularization while inverting balancing noise and bias, produce a true energy spectrum
  - Comparisons between measurements and theory happen in the "true" neutrino space

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#### Data Unfolding with Wiener-SVD Method

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## **UNFOLDING UNCERTAINTIES AND SUBTLETIES**



- Unfolding comes at a cost of decreased resolution and increased binto-bin correlation
  - Regularization smooths the spectrum, severity depends on the uncertainties
- Increased uncertainties from the unfolding process need to be accounted for
- Comparisons between theory and measurements need to use a smearing filter matrix to account for reduced resolution



### JOINT ANALYSES BETWEEN EXPERIMENTS

- Combining reactor spectral measurements is nontrivial at the moment
- PROSPECT/Daya Bay and PROSPECT/STEREO are working on jointly unfolding their <sup>235</sup>U measurements
- Analysis Goals:
  - 1. Demonstrate consistency between independent results
  - 2. Increase statistical power, decrease systematic uncertainties, and produce unfolded spectra for community use
- Discovered many subtle differences between analyses and experiments that stumped even the insiders!
- Potential for a combination of all three experiments to produce real "community" spectra for <sup>235</sup>U and <sup>239</sup>Pu

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(from M. Licciardi's talk at Moriond 2021)

## **PRESERVING DATA FOR FUTURE SCIENTISTS**

- Too often data are scattered and incomplete, leaving results impossible to reproduce without "insider knowledge"
  - Combining different experiments is nearly impossible by outsiders
  - Example: aggregation of <sup>235</sup>U neutrino yield by the 2011 Mention et al. paper
- It should be a priority of each experiment to produce data in a format that future generations can use
  - Common format that includes detector info, data, uncertainties, experimental conditions, and example code
  - Publicly accessible and citable (via DOI or similar)
- Community-developed "standard" flux and spectrum data that can be used directly



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Repository for publication-related High-Energy Physics data

#### **HEPDATA EXAMPLE: STEREO SPECTRUM MEASUREMENT**

Q Revised all definitions on engregy spectrum from any first data states on the STEREO detector at the STE	HEPData QSearch HEPData	a Search				🚯 About 🛛 Submission Help 🖷 Sign in						
	Q Browse all 🖉 Almazán, H. et al.			Last updated on 2020-12-03 08:49 [III] Accessed 263 times 59 Cite JSON								
In the construction of the constructio	<ul> <li>Hide Publication Information</li> <li>First antineutrino energy spectrum fro</li> <li><sup>235</sup>U fissions with the STEREO detecto</li> </ul>	► Download All - m r at Filter 7 data tables	Measured spectrum and normalized prediction for Phase-II 10.17182/hepdata.99805.v1/t1 JSON									
10.1172/hpdta.99005.1/2         Austract (data bastract)         Nine dia support the measurement of the <sup>235</sup> U-induced antineutricino support method support the measurement of the <sup>235</sup> U-induced antineutricino support method. A significant support the measurement of the <sup>235</sup> U-induced antineutricino support method. A significant support the measurement of the <sup>235</sup> U-induced antineutricino support method. A significant support the measurement of the <sup>235</sup> U-induced antineutricino support the measurement of the <sup>236</sup> U-induced antineutricino support the induced and induced measurement of the <sup>236</sup> U-induced antineutricino support the induced antineutricino support the induced and induced antineutricino support the induced andifice andifice and induced antineutricino support the	The STEREO collaboration Almazán, H. , Bernard, L. , Blanchet, A. , Bonhomme, A. , Buck, C. , del Amo Sanchez, P. , El Atmani, I. , Labit, L. , Lamblin, J. , Letourneau, A. J.Phys.G 48 (2021) 075107, 2021. https://doi.org/10.17182/hepdata.99805 Journal INSPIRE Resources	Measured spectrum and > normalized prediction for Phase-II 10.17182/hepdata.99805.v1/t1 Data from Figure 13 - Measured IBD yield spectrum and area-normalized HM-based prediction. Here, error bars inlude only uncorrelated uncertainties, Experimental covariance > matrix	Data from Figur bars inlude only background sys provided in and <b>phrases</b> Measured sp	Data from Figure 13 – Measured IBD yield spectrum and area-normalized HM-based prediction. Here, error bars inlude only uncorrelated uncertainties, namely statistics, time-evolution systematic, reactor background systematic. This uncorrelated uncertainty is σ <sub>j</sub> in eqn.(14). The full covariance matrix is provided in another entry.  phrases  Measured spectrum Normalized prediction								
These data support the measurement of the $\frac{329}{1100}$ the determines the $\frac{329}{100}$ the $\frac{329}{100}$ the $\frac{329}{100}$ the method $\frac{329}{100}$ the $\frac{329}{100}$ the method $\frac{329}{100}$ the met	Abstract (data abstract)	10.17182/hepdata.99805.v1/t2 Total covariance matrix of the measured	$E_{ m pr}$ [MeV]	Event rate [nu/day]	Normalized prediction [nu/day]	Visualize						
anticutions have been detected at about 10 m from the higher       Response matrix       22.2125       22.7154       22.011       22.011         automical power. The messure diverses bead ocary spectrum is unfolded to provide a puer <sup>253</sup> U spectrum is unfolded to provide a puer <sup>253</sup> U spectrum is unfolded to provide a puer <sup>253</sup> U spectrum amplet ubs of 12.1 ± 3.4% (3.5 or).       10.1712/hepdata.39805.V/12       12.52-2.375       26.5307       26.5307       10.0000         26.55.2       26.7857       21.525       25.705       26.5307       10.0000	These data support the measurement of the <sup>235</sup> U-induced antineutrino spectrum shape by the STEREO experiment. 4	systematic uncertainties. It is denoted $V_{\rm pr}$ in eqn.(18).	1.625 - 1.875	20.4965 ±1.49953 uncorr	20.8851							
at nomial power. The measured inverses beta decay spectrum in nutineutrino energy. A careful study of the unfolding procedure, including a cross-validation using nutrinos with energy distributed according to HYSI BD yield prediction. The       2.125 - 2.375       26.273 = 1.1387 are energy       2.4359 1       1111         Section efficiency       >       2.175 - 2.625       26.5047 # sources       26.5007       1111         Section efficiency       >       2.425 - 2.875       26.5047 # sources       26.5007       1111         Data form figure e- sole cont efficiency was a function of E <sub>n</sub> .       Section efficiency as a function of E <sub>n</sub> .       2.5099 # sources       25.0295       1111         Spectrum prediction on E <sub>n</sub> .       Spectrum prediction on the sole was detained for the sole source was a function of E <sub>n</sub> .       2.125 - 4.375       2.203 - 2.30139       Sum errors @ Fill bars       Log Scale (X)         10.17182/hepdata_99805.vt/M       3.675 - 4.125       1.3075 # source = 15.3339       10.5313       Sum errors @ Fill bars       Log Scale (X)         10.17182/hepdata_99805.vt/M       4.625 - 4.875       15.6916 # source = 15.3339       13.4072       Sum errors @ Fill bars       Log Scale (X)	antineutrinos have been detected at about 10 m from the h enriched core of the ILL reactor during 118 full days equiva	nighly lent Response matrix >	1.875 - 2.125	22.7754 ±1.32684 uncorr	23.2011	22-						
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no major biases are introduced by the method. A significant local distortions around ing to HFR's IBD yield prediction.       according to HFR's IBD yield prediction.       2.625 - 2.875       26.5047 ±3.48524 • eorr       27.227         be a from Figure 6 - 5.3 MeV. A gaussian fit of this local excess leads to an amplitude of 12.1 ± 3.4% (3.5 or).       Selection efficiency * 3.375 - 3.625       25.5089 ±8.878811 • eorr       26.9077       8-	energy. A careful study of the unfolding procedure, includir cross-validation by an independent framework, has shown	sampled using STEREO's simulation using neutrinos with energy distributed	2.375 - 2.625	26.7857 ±1.1536 uncorr	26.5307	14-						
E_p = 5.3 MeV. A gaussian fit of this local excess leads to an amplitude of 12.1 ± 3.4% (3.5\sigma).       Selection efficiency > 10.17182/hepdata.59805.v1/t4       2875 - 3.125       25.9089 ±8.871811 ever       26.9077       4-       4-       2-       <	no major biases are introduced by the method. A significan local distortion is found with respect to predictions around	<pre>ht according to HFR's IBD yield prediction. The</pre>	2.625 - 2.875	26.5047 ±0.943214 uncorr	27.227							
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3.375 - 3.625       25.0364 ±0.727643 uncerr       24.7281       2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0 6.5 7.0 E Vectori IMeVI         Spectrum prediction in neutrino energy       3.625 - 3.875       22.6644 ±0.583567 uncerr       23.0139       Sum errors © Fill bars _ Log Scale (X) _ E Vectori IMeVI         10.17182/hepdata_99805.x1/15       Spectrum prediction for IL'S High Filx Reactor; given night from 1.8 to 10 MeV). Huber's       10.262 - 4.375       20.2163 ±0.647976 uncerr       18.9694       Log Scale (Y)		10.17182/hepdata.99805.v1/t4	3.125 - 3.375	25.2816 ±0.774756 uncorr	25.9295	2-						
Spectrum prediction in neutrino energy       3.625 - 3.875       22.6644 ±0.688367 uncorr       23.0139       Sum errors © Fill bars □ Log Scale (X) □         10.17182/hepdata.99805.v1/t5       3.875 - 4.125       21.3075 ±0.6595 uncorr       20.8214       Log Scale (Y) □         10.17182/hepdata.99805.v1/t5       4.125 - 4.375       20.2163 ±0.647976 uncorr       18.9694       Log Scale (Y) □         10.17182/hepdata.99805.v1/t5       4.125 - 4.375       17.9515 ±0.673652 uncorr       17.0313       Deselect variables or hide different error bars by clicking on them.         10.17182/hepdata.99805.v1/t6       4.875 - 5.125       14.6039 ±0.89959 uncorr       13.4072       Variables		a function of $E_{\nu}$ .	3.375 - 3.625	25.0364 ±0.727643 uncorr	24.7281	2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0 6.5 7.0 E \textfor\ [MeV]						
10.17182/hepdata.99805.v1/t5       3.875 - 4.125       21.3075 ±0.6596 uncorr       20.8214       Log Scale (Y)         Spectrum prediction for ILL's High Flux Reactor, given in 50keV-wide E <sub>w</sub> bins (centers ranging from 1.8 to 10 MeV). Huber's       4.125 - 4.375       20.2163 ±0.647976 uncorr       18.9694       Log Scale (Y)         0.17182/hepdata.99805.v1/t6       4.375 - 4.625       17.9515 ±0.673652 uncorr       17.0313       Deselect variables or hide different error bars by clicking on them.         10.17182/hepdata.99805.v1/t6       4.875 - 5.125       14.6039 ±0.80955 uncorr       13.4072       Yariables		Spectrum prediction in >	3.625 - 3.875	22.6644 ±0.688367 uncorr	23.0139	Sum errors 🕢 Fill bars 🗌 Log Scale (X) 🗌						
Spectrum prediction for ILL's High Flux Reactor, given in 50keV-wide E <sub>v</sub> bins (centers ranging from 1.8 to 10 MeV). Huber's       4.125 - 4.375       20.2163 ±0.647976 uncorr       18.9694       Deselect variables or hide different error bars by clicking on them.         Unfolded <sup>235</sup> U spectrum v       4.625 - 4.875       15.6916 ±0.705883 uncorr       15.3339       Deselect variables or hide different error bars by clicking on them.         10.17182/hepdata.99805.v1/t6       4.875 - 5.125       14.6039 ±0.809659 uncorr       13.4072       Variables		10.17182/hepdata.99805.v1/t5	3.875 - 4.125	21.3075 ±0.6596 uncorr	20.8214	Log Scale (Y)						
Huber's       4.375 - 4.625       17.9515 ±0.673652 uncorr       17.0313       Deselect variables or hide different error bars by clicking on them.         Unfolded <sup>235</sup> U spectrum > 10.17182/hepdata.99805.v1/t6       4.875 - 5.125       14.6039 ±0.809659 uncorr       13.4072       Deselect variables or hide different error bars by clicking on them.		Spectrum prediction for ILL's High Flux Reactor, given in 50keV-wide $E_{\nu}$ bins	4.125 - 4.375	20.2163 ±0.647976 uncorr	18.9694							
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#### **PROPOSAL: INTEGRATION INTO NNDC SIGMA**

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Database Manager: Dave Brown, NNDC, Brookhaven National Laboratory Web and Programming: B. Pritychenko, A.A. Sonzogni, NNDC, Brookhaven National Laboratory Data Source: CSEWG and NEA-WPEC



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- There continue to be new results from a diverse set of reactor antineutrino experiments
- Leveraging these data we are gaining a clearer picture of the antineutrino yield and energy spectrum
  - Yield: Indications of a data/model mismatch for <sup>235</sup>U
  - **Spectrum:** data/model mismatch for (at least) <sup>235</sup>U and <sup>239</sup>Pu
- Enhanced sensitivity can be enabled by combining data across experiments
- We need to prioritize preserving our data for future analyses, including all the details that don't fit in a five page letter
- Should develop a "community standard" for data archival and build an accessible repository of these data

