Oak Ridge National Laboratory

Final Results from the PROSPECT-I Data Set:
Measurement of the U-235 Antineutrino Energy Spectrum at HFIR

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The University of Tennessee Knoxville

On behalf of the PROSPECT collaboration

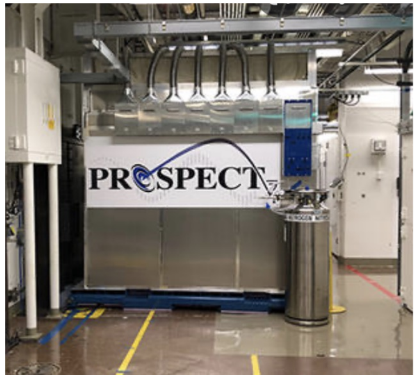
July 12th – MAYORANA Workshop

U.S. DEPARTMENT OF ENERGY

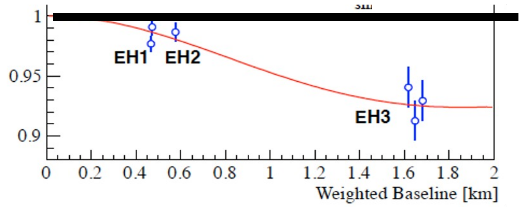
Physics Division

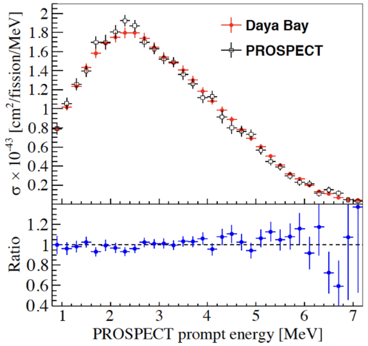
Reactor Neutrinos

A Tool for Discovery

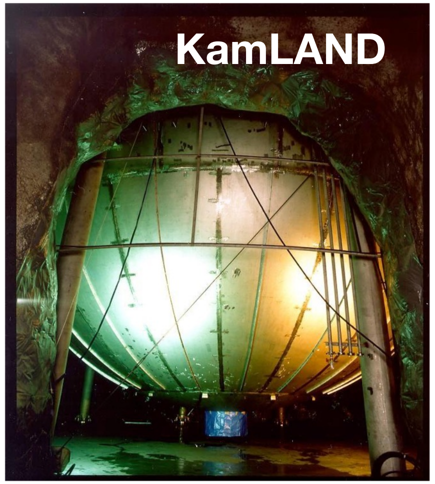


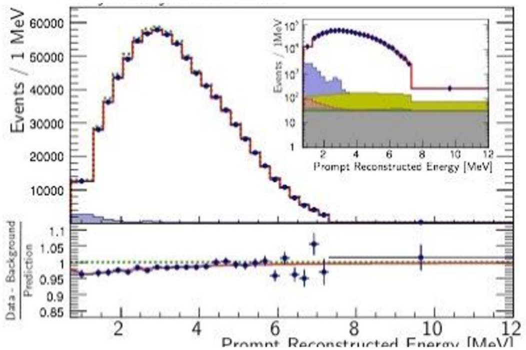
2012 - Measurement of θ_{13} with Reactor Neutrinos





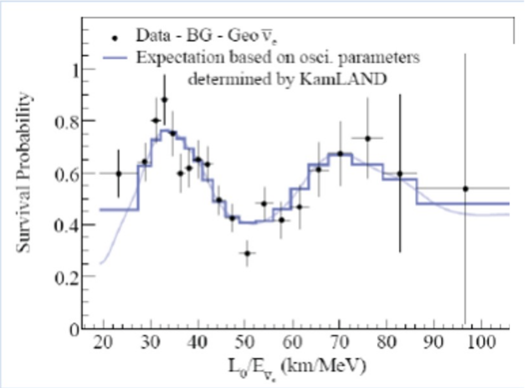
2003 - First observation of reactor antineutrino disappearance

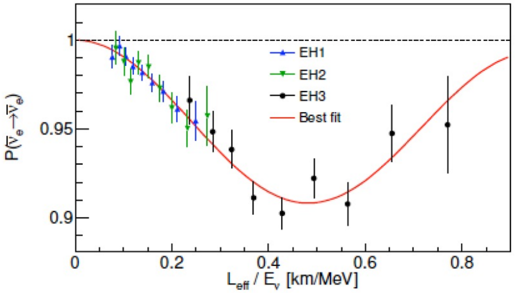




1995 - Nobel Prize to Fred Reines at UC Irvine

1956 - First observation of (anti)neutrinos





PROSPECT Motivations and Goals

The Flux Deficit
Previous reactor experiments observed a 6% flux deficit when compared to reactor models.

Questions:
- Can this deficit be explained by neutrinos oscillating into an active-sterile state?
- How would one look for such oscillations?

Physics Goal 1:
- Search for short-baseline oscillations and conclusively address the sterile neutrino hypothesis as an answer to the Reactor Antineutrino Anomaly (RAA)

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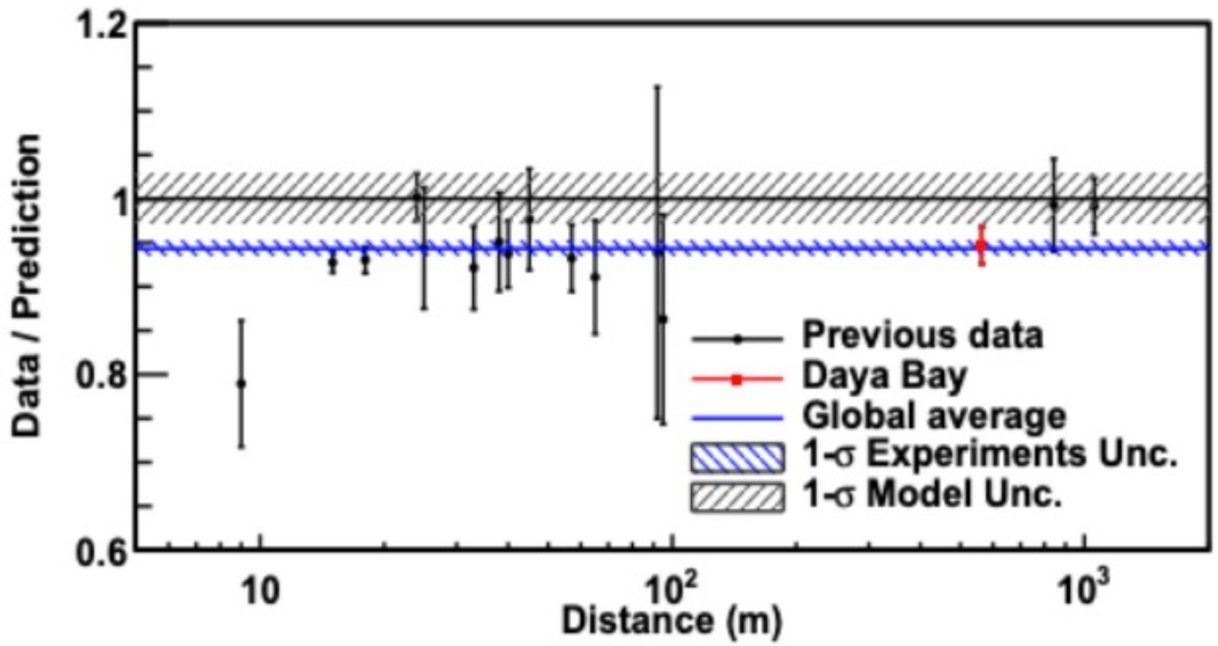


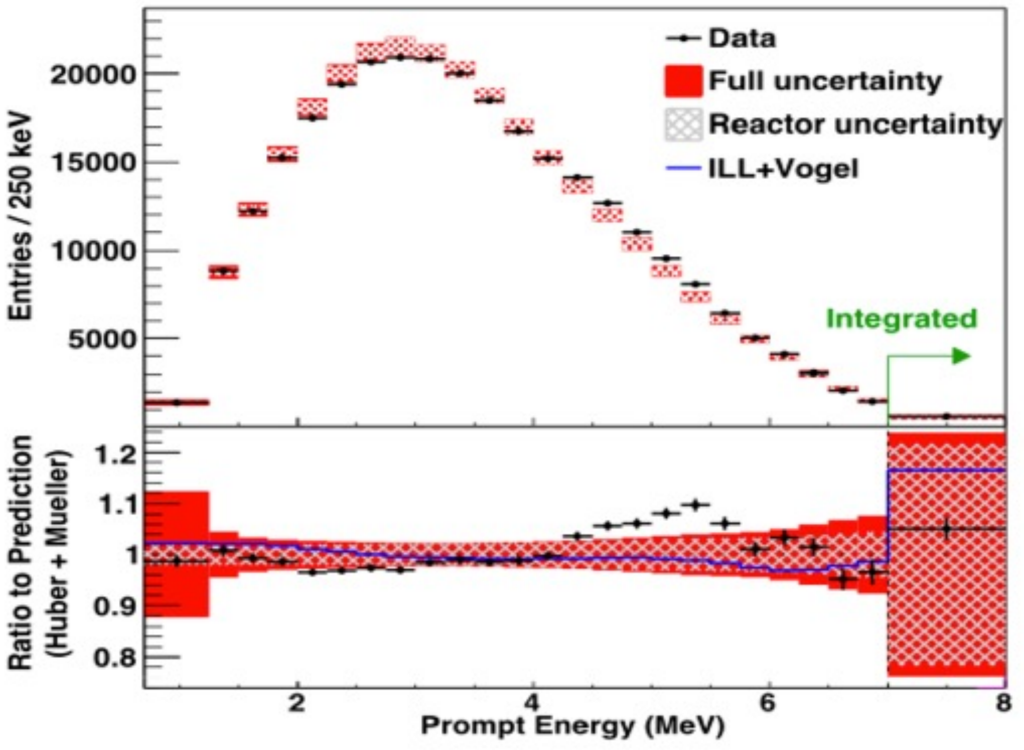
Feng Peng An et al. Measurement of the Reactor Antineutrino Flux and Spectrum at Daya Bay. Phys. Rev. Lett., 116(6):061801, 2016, 1508.04233.

PROSPECT Motivations and Goals

The Spectral Deviation
Daya Bay and other θ_{13} experiments observed bump in 4-6 MeV region, a deviation of ~10%.

Questions:
- What is the nature of this bump?
- Is it a modeling issue?
- Are the all the models wrong? Or does the problem lie with the prediction for one of the fissioning isotopes

Physics Goal 2:
- To make a precise measurement of the antineutrino spectrum from a HEU reactor (mainly ^{235}U).

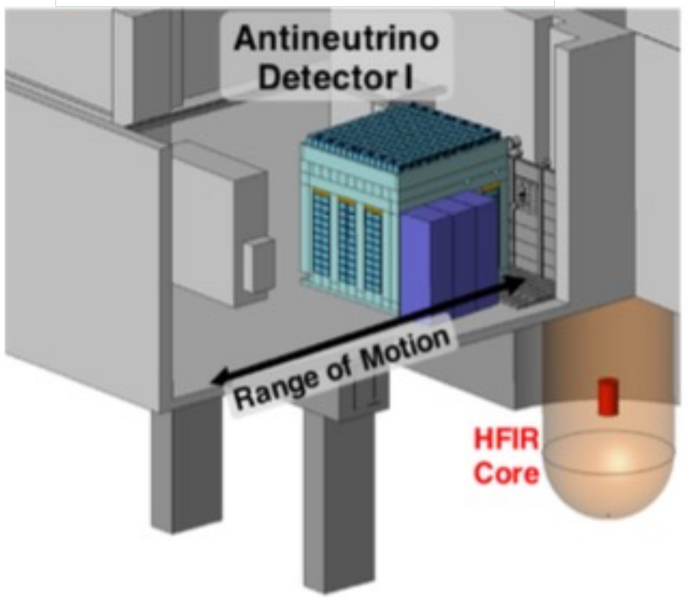


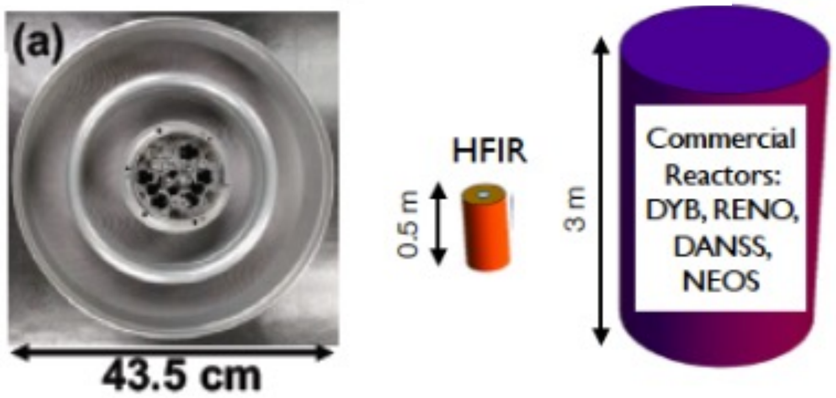
Feng Peng An et al. Measurement of the Reactor Antineutrino Flux and Spectrum at Daya Bay. Phys. Rev. Lett., 116(6):061801, 2016, 1508.04233.

Image source: https://neutrons.ornl.gov/hfir

PROSPECT Detector at HFIR

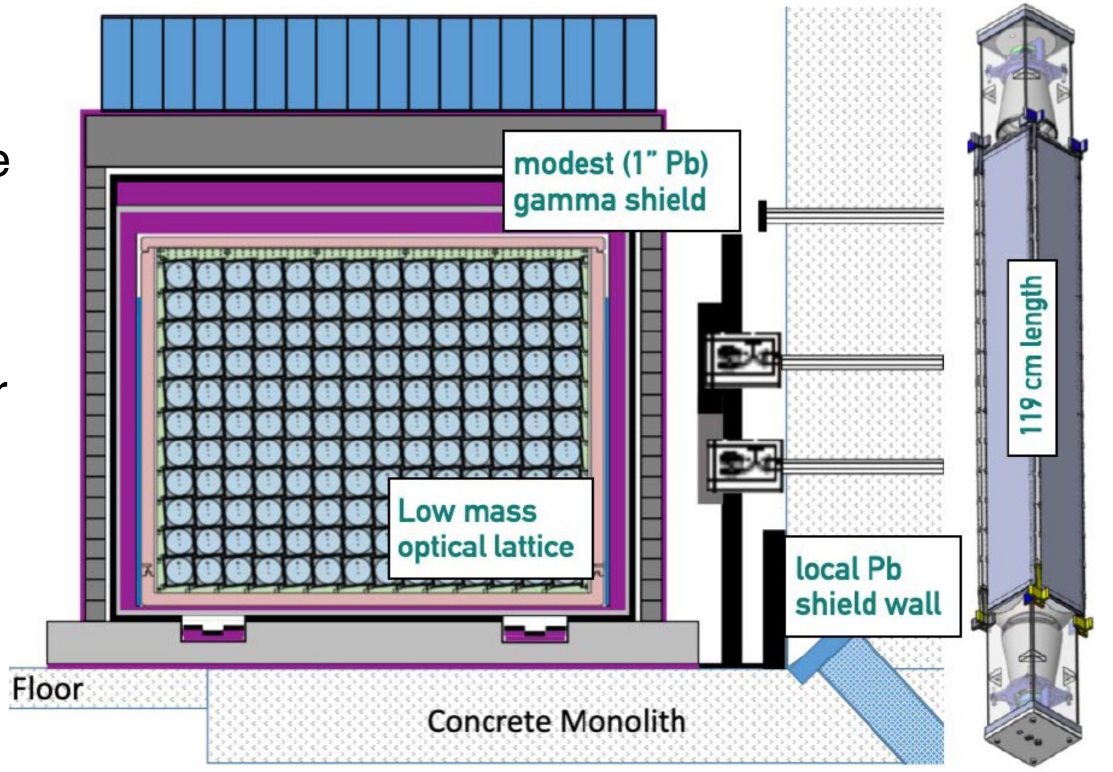
Layout of the PROSPECT experiment





- 93% 235U Fuel
- 85 MW thermal powe
- Compact core
- Huge flux in the few MeV range
- ~50% duty cycle for BG measurements

Schematic of the active detector volume

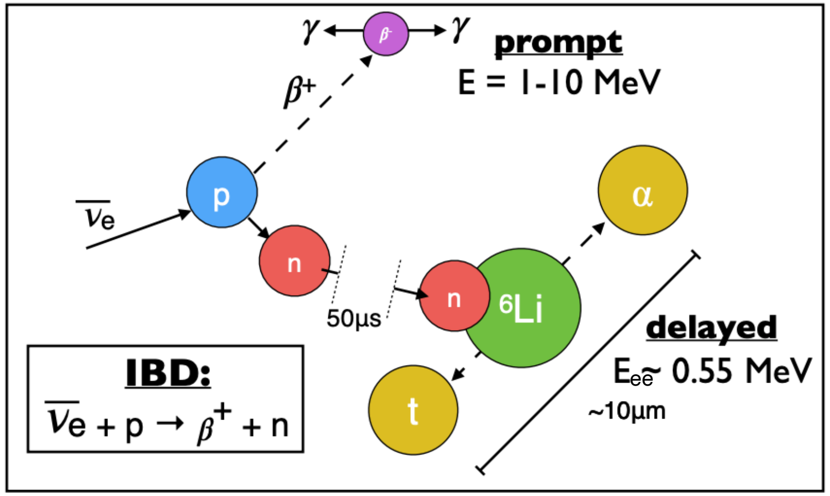


14 x 11 array of 6Li doped liquid scintillator for detecting reactor antineutrinos (6.7-9.2 m from compact highly enriched uranium reactor core)

J. Ashenfelter et al. (PROSPECT), Nucl. Inst. Meth. A 922, 287(2019)

Antineutrino Detection

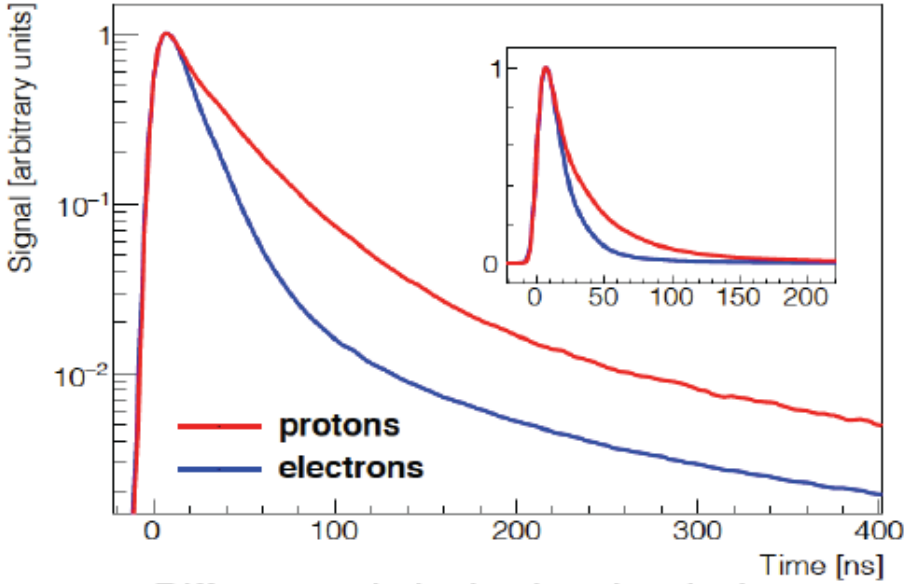
Schematic of the IBD process



- PROSPECT detects antineutrinos via the Inverse Beta Decay (IBD) process
- Prompt signal (e^+) provides a good energy estimate of incoming ν
- Localized delayed (n - ^6Li) signal

6-LiLS with PSD Capabilities

- Average waveforms for electronic/nuclear type events



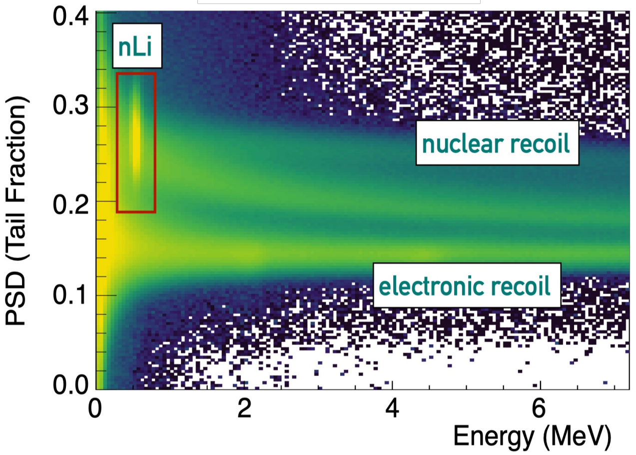
- Differences in ionization density between electronic/nuclear recoil type events result in distinct pulse shapes for each event
- Prompt and delayed signal posses unique pulse shapes (different from background events)

M. Andriamirado et al. (PROSPECT Collaboration), Phys. Rev. D 103, 032001 (2021).

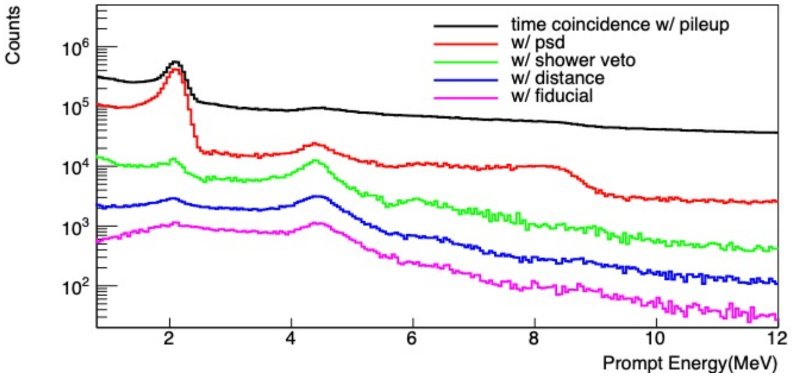
IBD Event Selection

- **IBD Topology-based cuts**
  - Neutron Capture Region
  - Prompt PSD
  - Prompt-Delayed signal distance
  - Prompt-Delayed Timing
  - Fiducial z cut
- **Veto cuts**
  - Muon Veto Time
  - Neutron Veto Time
  - Recoil Veto time

Prompt PSD Cut

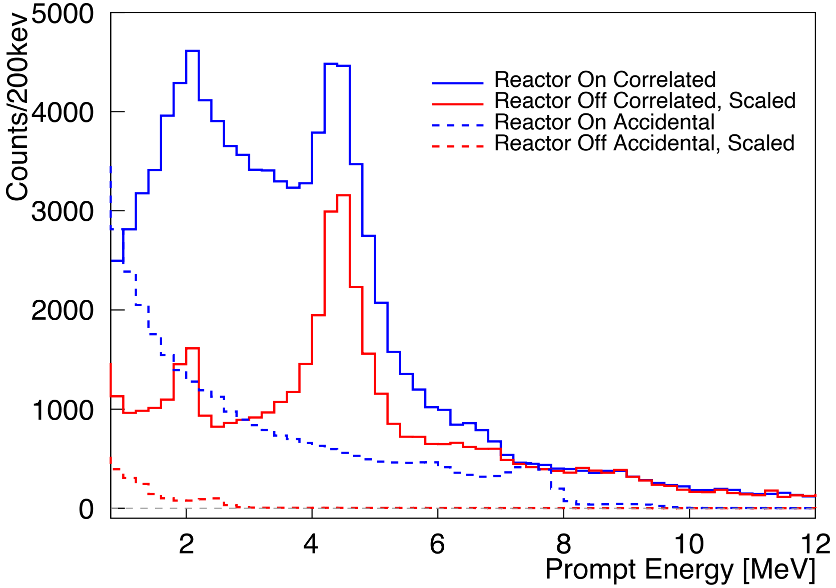


Prompt Energy Distributions Under Different Cuts



- Sequential application of selection cuts results in a significant reduction of background events
- These selection criteria was used for most recent results

Measured prompt energy spectrum of correlated IBD-like candidates

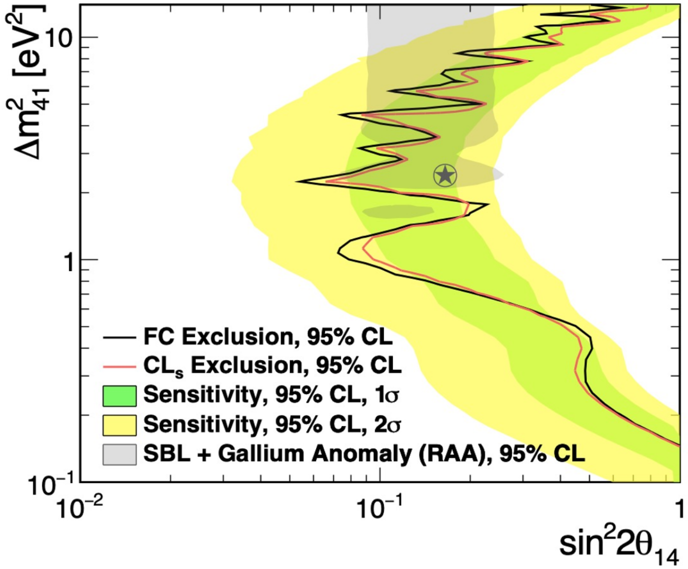


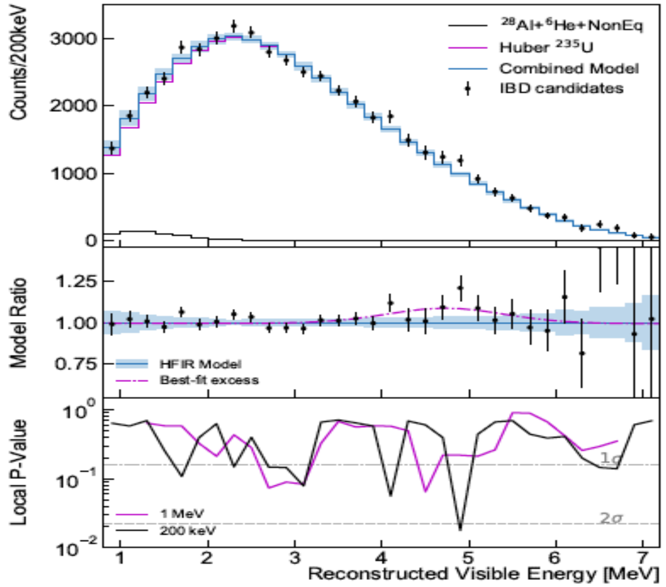
- 95.65 reactor-on calendar days, 73.09 reactor-off
- >50,000 IBD events
- Signal to background ratio > 1

M. Andriamirado et al. (PROSPECT Collaboration), Phys. Rev. D 103, 032001 (2021).

Results and plans from PROSPECT-I

2011 RAA paper & SNAC workshop,
2012 white paper motivated search for eV-scale sterile neutrinos,
2018 first physics limits from PROSPECT





- Performed direct test of the Reactor Antineutrino Anomaly,
  - RAA best-fit excluded: 98.5% CL
  - Data is compatible with null oscillation hypothesis (p=0.57)
- Helped establish new constraints on the origin of the data-model disagreement observed between 5-7 MeV
  - Likely due to an equal mismodeling of all fissile isotopes
- Led joint analyses with other experiments: STEREO and Daya Bay

First Oscillation Search
Phys. Rev. Lett. **121**, 251802 (2018)

First Spectrum Result
Phys. Rev. Lett. **122**, 251801 (2019)

Non-fuel reactor neutrinos
Phys. Rev. C **101**, 054605 (2021)

Improved Osc. + Spectrum
Phys. Rev. D **103**, 032001 (2021)

Boosted Dark Matter Search
Phys. Rev. D **104**, 012009 (2021)

Daya Bay/PROSPECT Joint Spectrum Analysis
Phys. Rev. Lett. **128**, 081801 (2022)

PROSPECT/STEREO Joint Spectrum Analysis
Phy. Rev. Lett **128**, 081802 (2022)

New Analysis Techniques

Final PROSPECT-I Spectrum
Phys. Rev. Lett. 131, 021802 (2023)

'Final' PROSPECT-I Oscillation

Absolute Flux Analysis

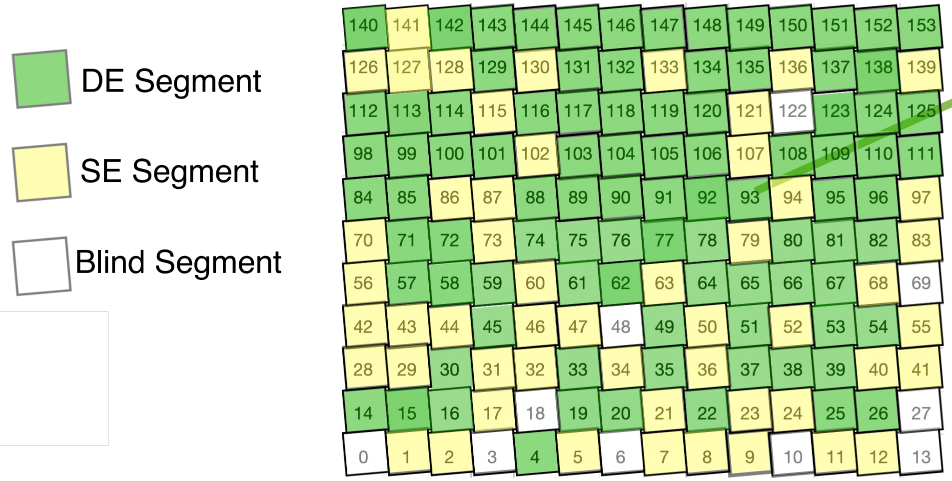
Correlated Background Study

Antineutrino Directionality

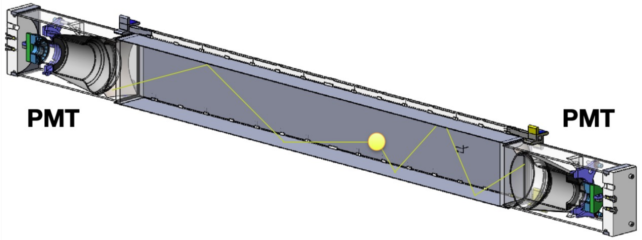
Motivation for a final PROSPECT-I Analysis

- Previous results were impacted by the periodic loss of photo-multiplier tube bases throughout data collection.

Detector configuration used for PRD analysis



154 segments with two PMTs

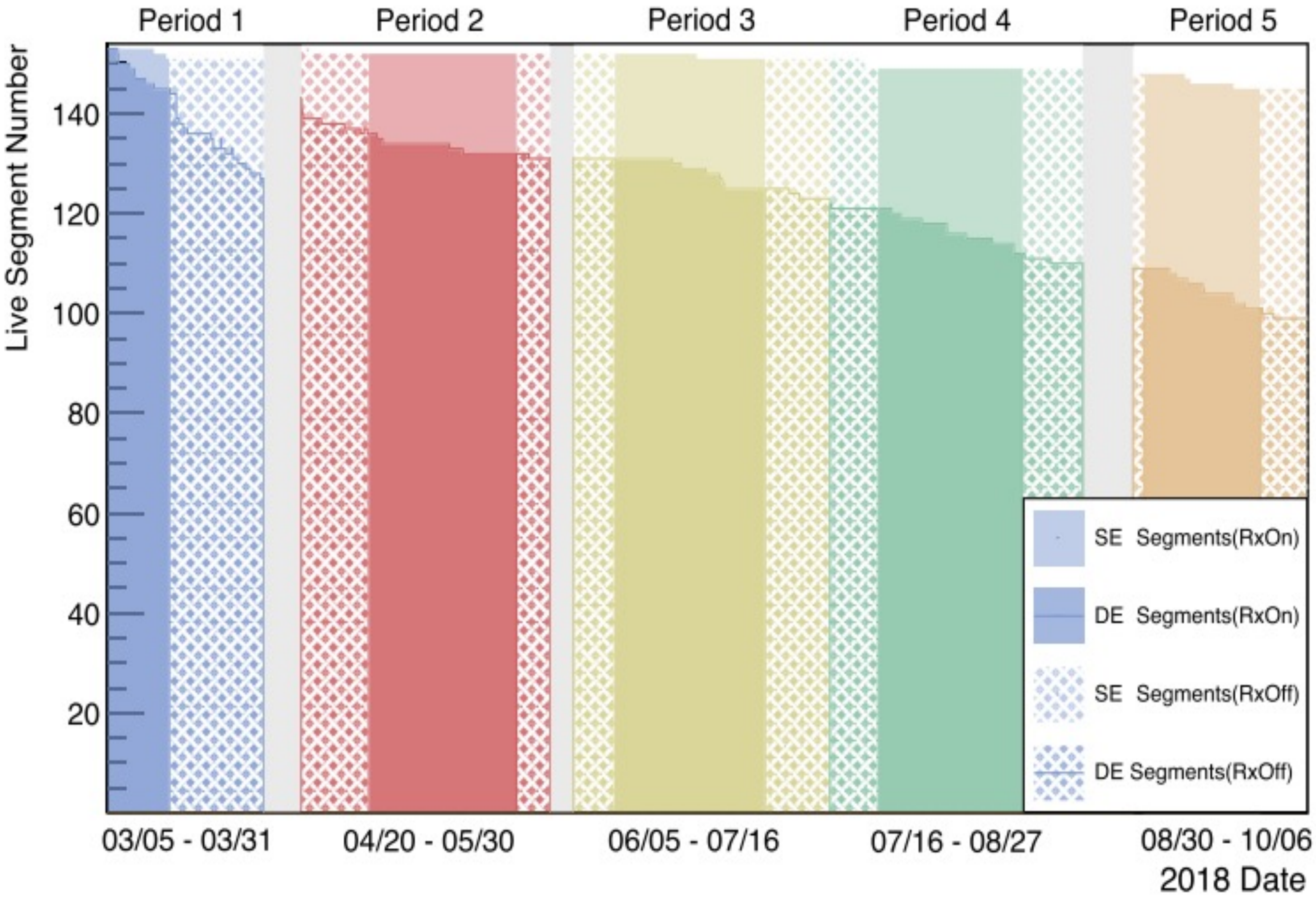


Some segments coupled to one PMT or both switched off due to scintillator leakage into PMT housing.

- In order to improve upon previous results, two new data recovery approaches have been proposed:

Data Splitting (DS)
&
Single Ended Event Reconstruction (SEER)

First Approach: Data Splitting (DS)



[Phys. Rev. Lett. 131, 021802 (2023)]

Goals

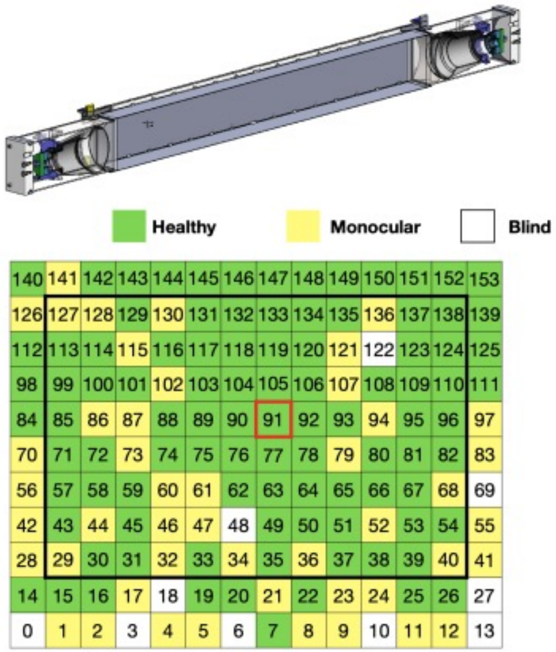
- Split PROSPECT-I data into distinct periods in order to recover statistics.
- Maximize number of live segments in each period

Splitting Criteria

- Each period should start immediately after a new calibration campaign
- Each period must contain one full RxOn cycle
- All periods should have RxOff data before and after each corresponding RxOn cycle
  - Period 1 is an exception since there is no prior RxOff data available.
- Keep ratio of RxOff/RxOn data between 50%-70%.
  - Since there is no calibration campaign between periods 3 and 4, we used the ratio of RxOff/RxOn files to define these two (70%).

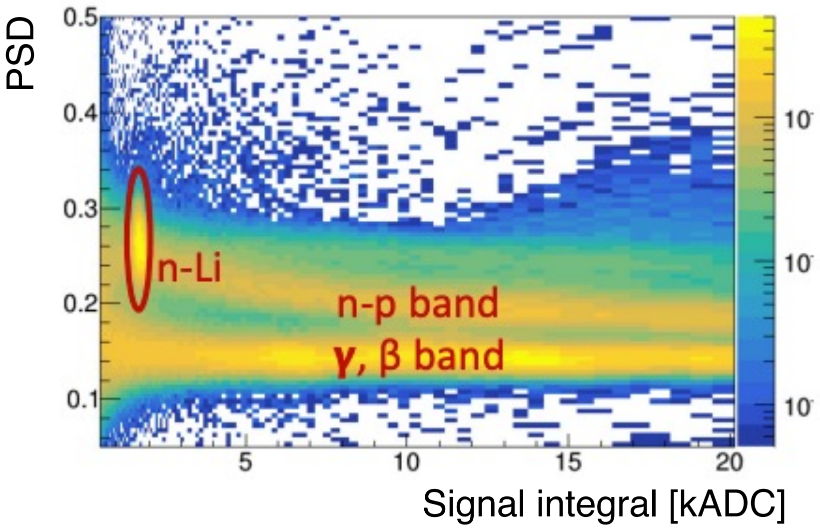
Second Approach: Single Ended Event Reconstruction (SEER)

- The implementation of SEER into the existing analysis presents a great opportunity to improve our current results (statistics and S:B).
- Lacks energy and position reconstruction capabilities
- Provides a good handle on particle identification (great background suppression)

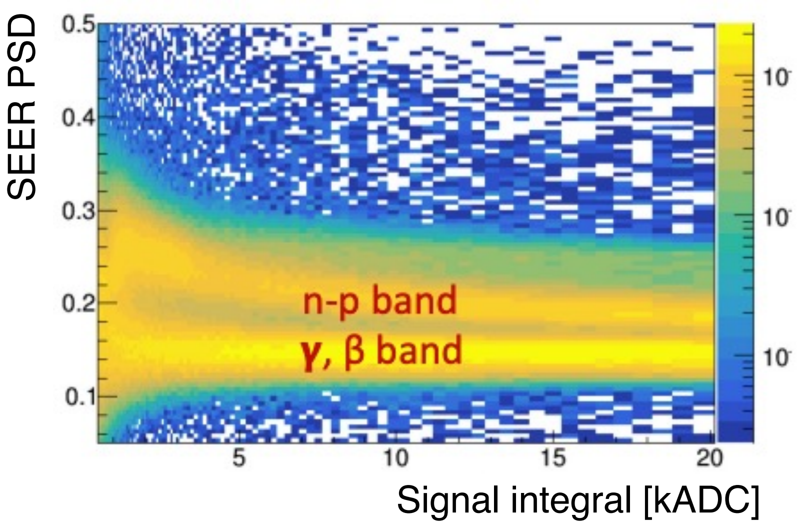


PRD Data - 97:47:10

DEER PSD Distribution

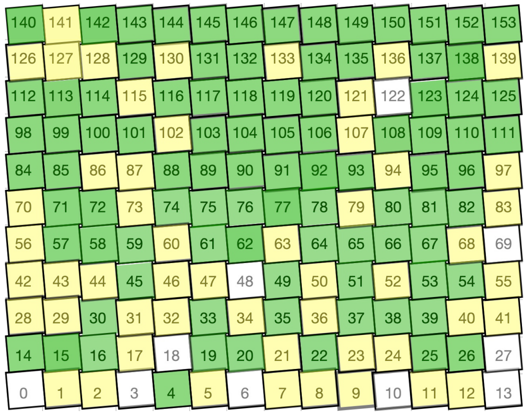


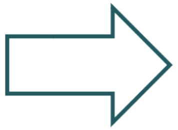
SEER PSD Distribution



Detector Configuration for Each Period

Detector Configuration Used for Previous Analysis

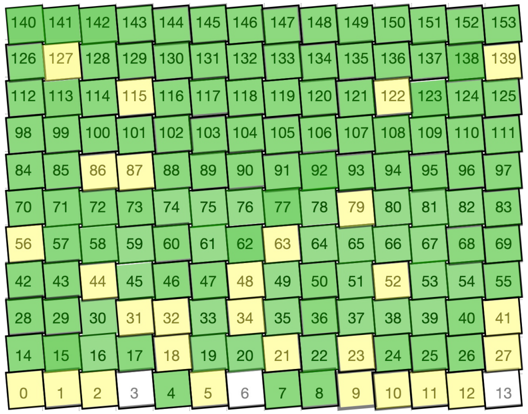




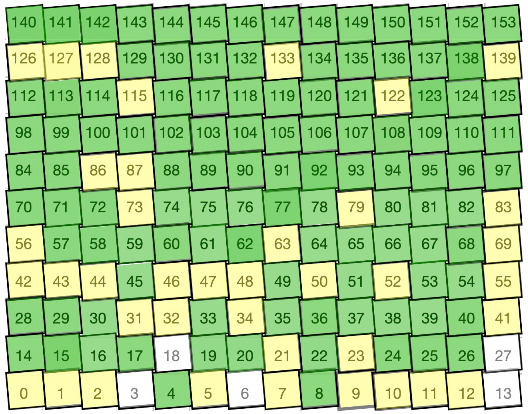
Period 1

Period 2

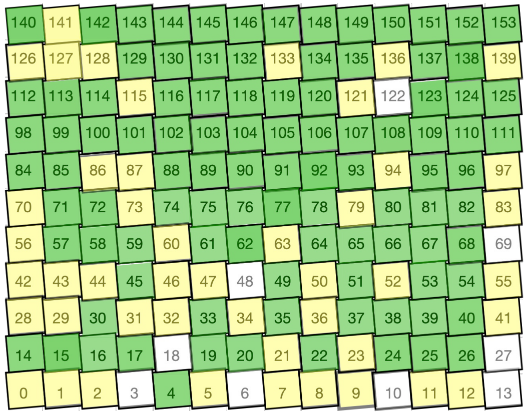
Period 3



Period 4



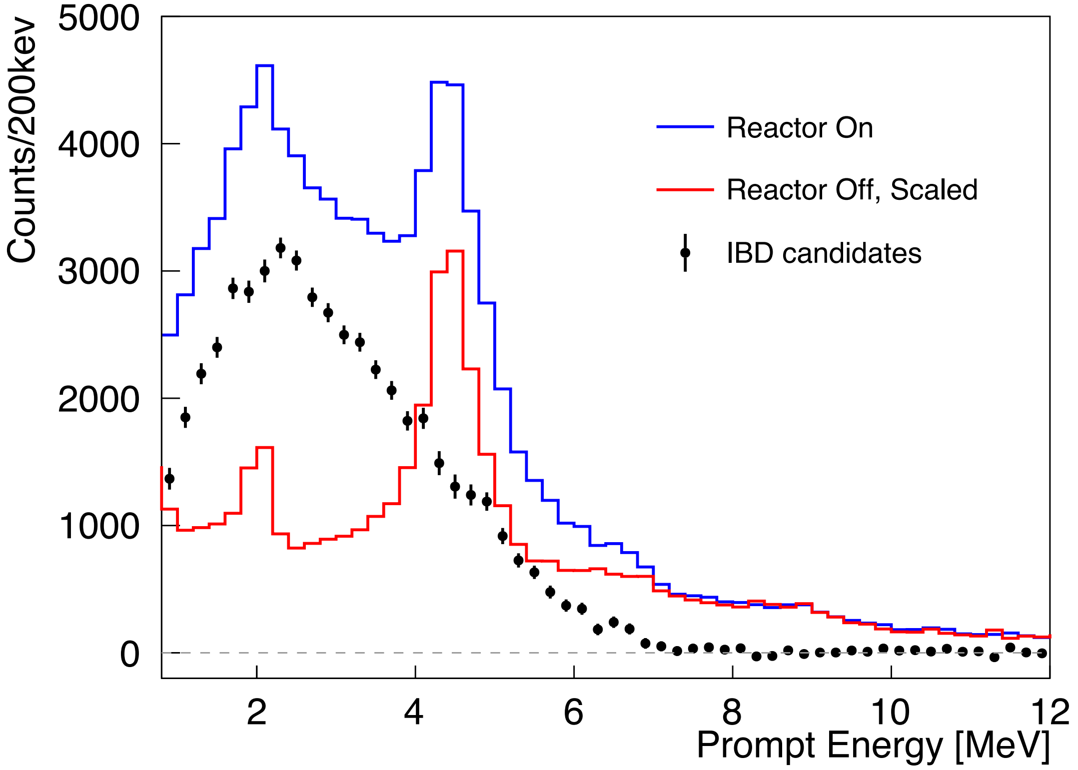
Period 5



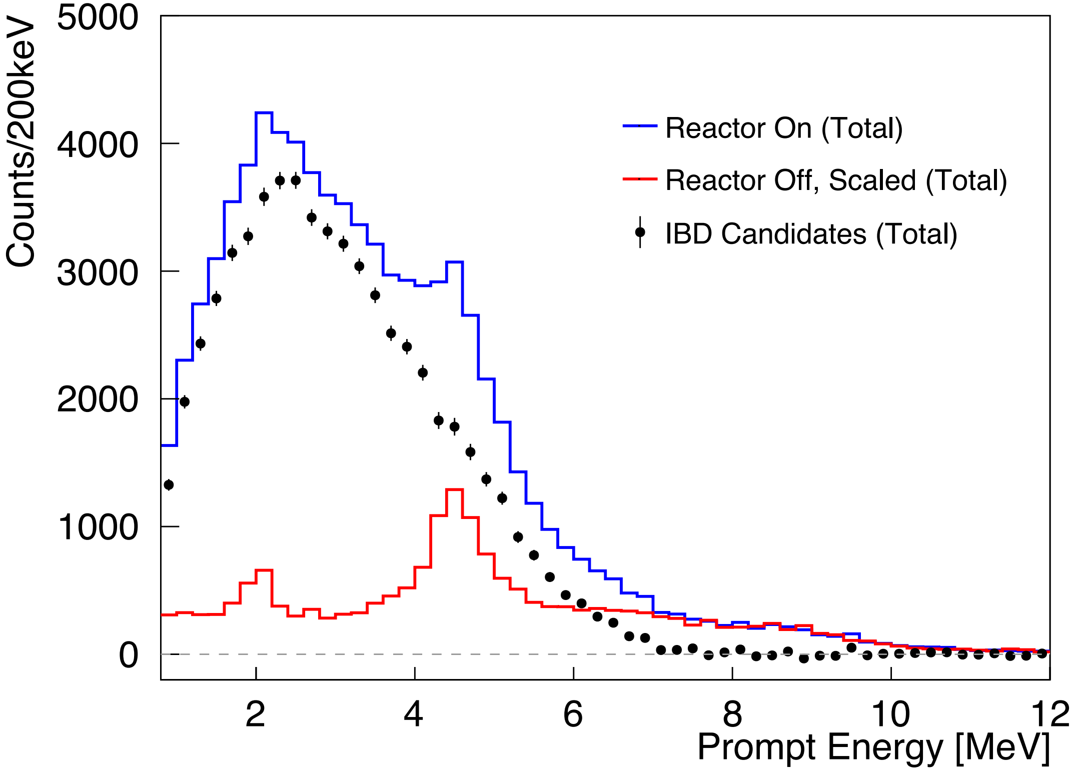
- Previous analysis did not make use of single ended segments.
- This new method takes full advantage of all the data collected by the PROSPECT detector

Multi-Period Spectrum Analysis

Previous PROSPECT Analysis



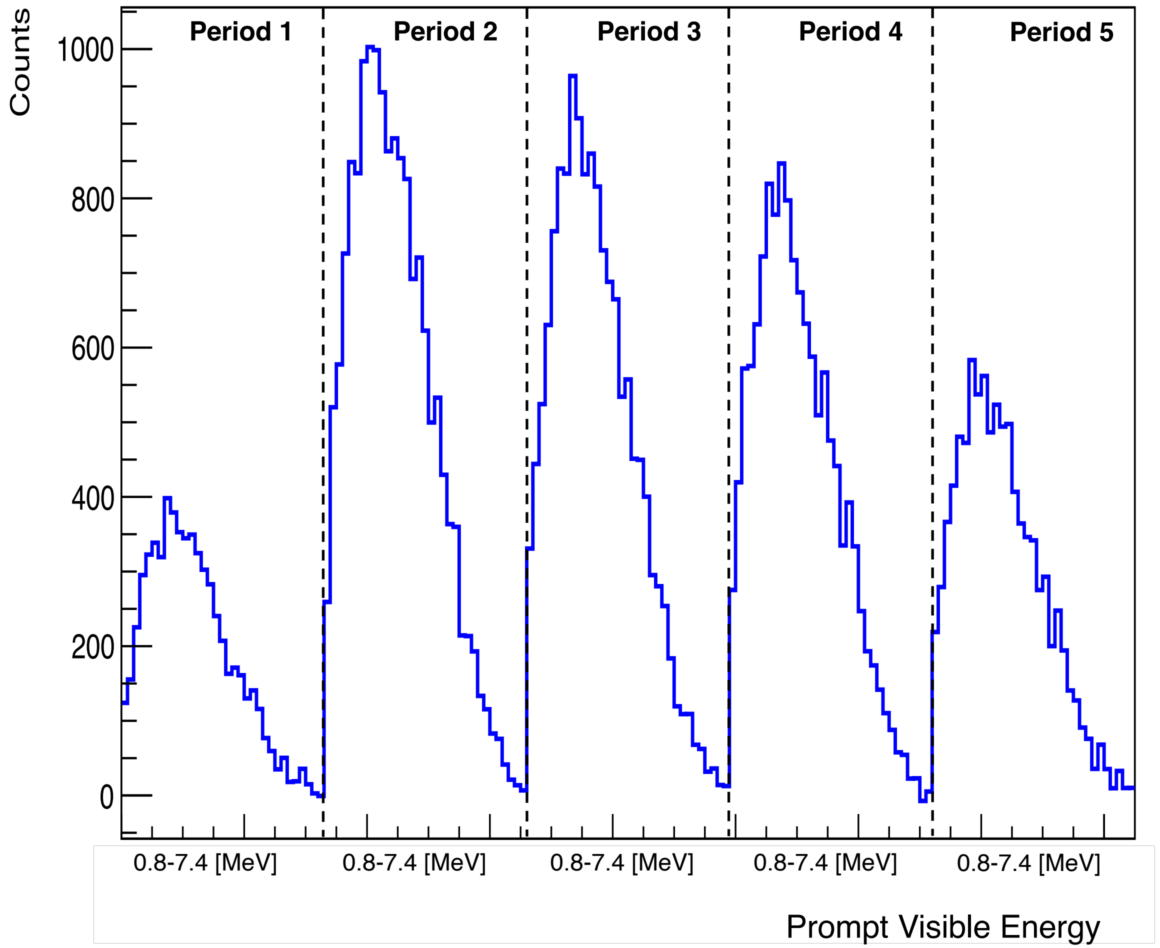
New DS+SEER Multi-Period Analysis



Great background reduction provided by new analysis

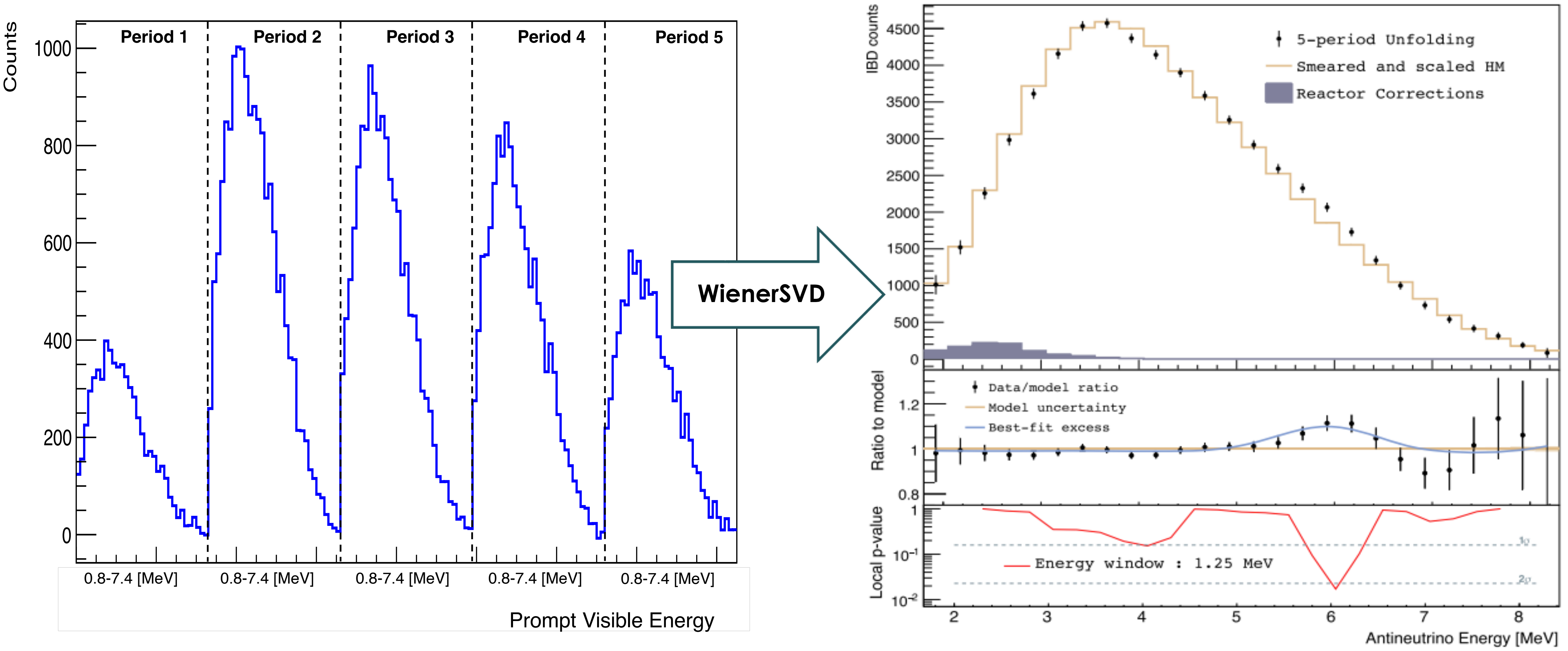
- Implementation of new DS+SEER optimized provided the following improvements:
  - IBD counts ~**(x1.2)**
  - IBD effective counts ~**(x2)**
  - Signal to cosmogenic background (S/CB) ~**(x2.8)**
  - Signal to accidental background (S/AB) ~**(x2.4)**

Multi-Period Spectrum Analysis: Unfolded Spectrum



- The implementation of a period-by-period analysis allows for the treatment of each period as an independent experiment.
- Following the work done during the joint spectrum analysis, a new unfolding framework has been developed to jointly unfold the prompt spectrum from each period into one final antineutrino energy spectrum

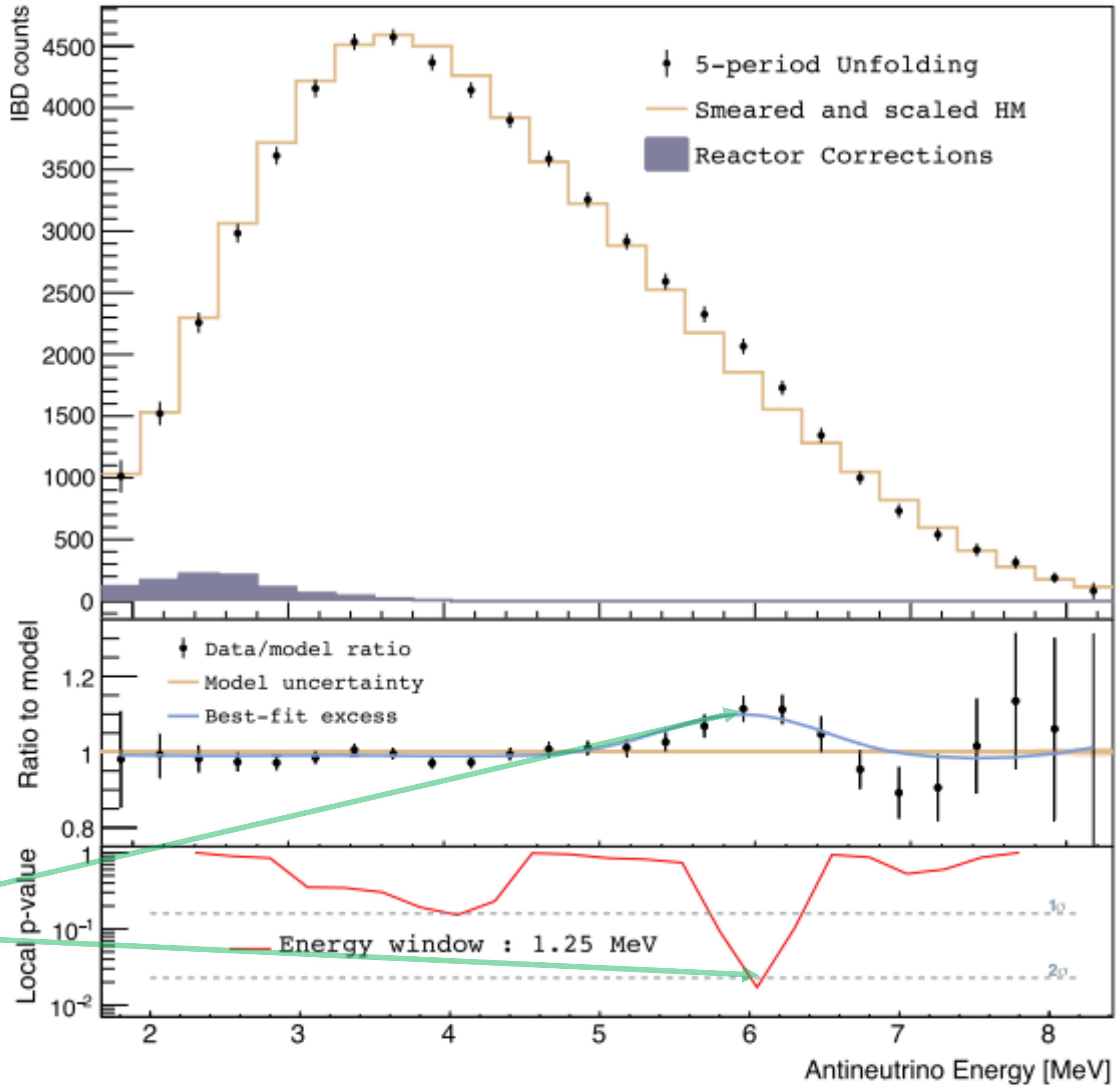
Multi-Period Spectrum Analysis: Results



[Phys. Rev. Lett. 131, 021802 (2023)](#)

Multi-Period Spectrum Analysis: Unfolded Spectrum

- Obtain antineutrino energy spectrum by inverting detector response over all five periods with the Wiener-SVD method
- Systematics are treated as period-correlated (e.g energy response) or period-uncorrelated (e.g background subtraction).
- Same technique can be used for combining different experiments.
- Most precise measurement of the antineutrino spectrum of Uranium-235

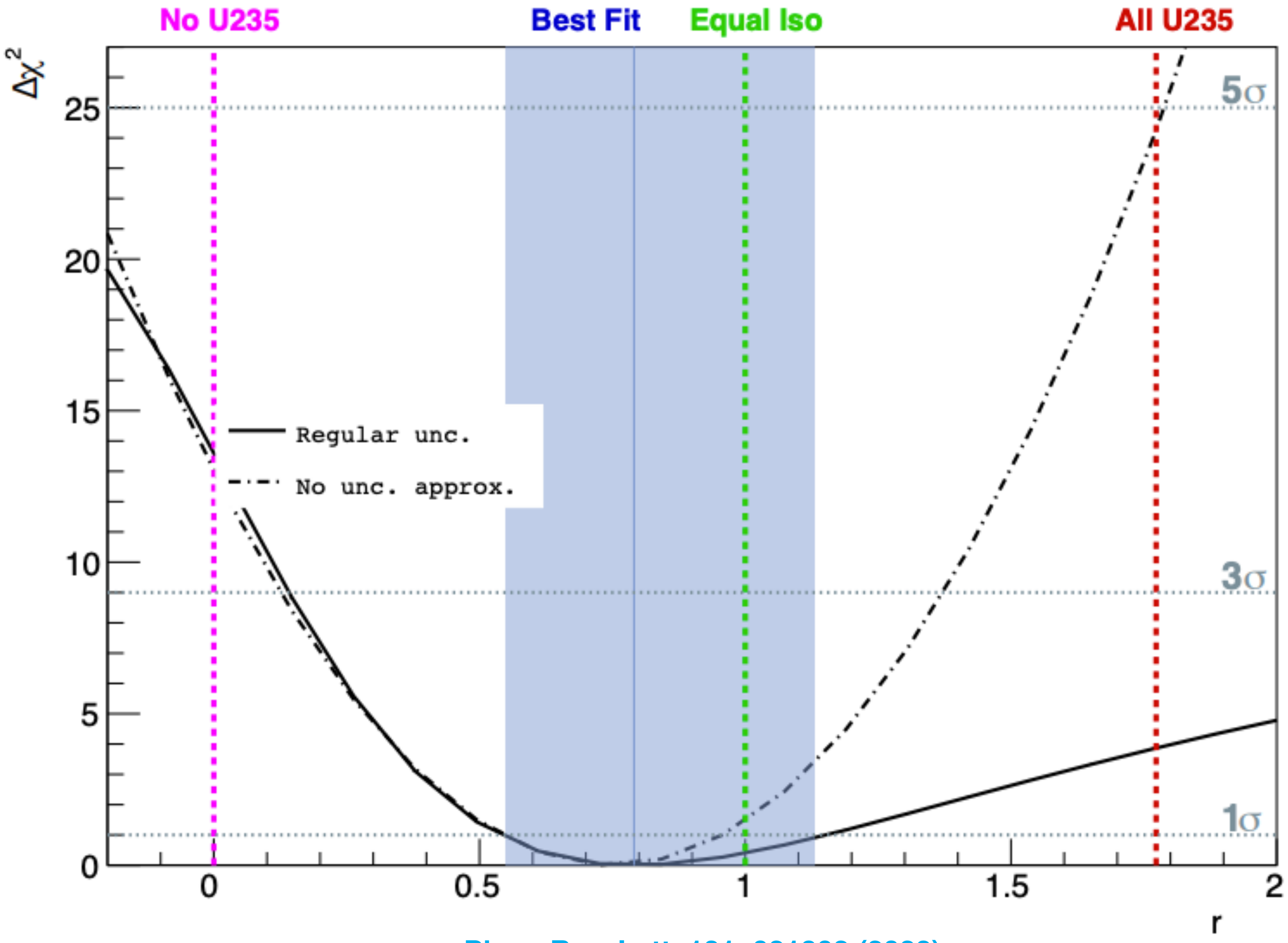


[Phys. Rev. Lett. 131, 021802 (2023)]

Multi-Period Spectrum Analysis: Isotopic Nature of the Bump

- Equal Isotope hypothesis preferred.
- Ratio = 0 (no U-235 bump) disfavored at 3.7σ.
- Ratio = 1.78 (all U-235 bump) disfavored at 2.0σ.
- Detector systematics limited. Multi-reactor measurement with correlated detector systematics (same detector) would strengthen the result

Ratio of PROSPECT bump amplitude to Daya-Bay bump



Phys. Rev. Lett. 131, 021802 (2023)

Summary and Conclusions

- PROSPECT-I data still presents a fantastic opportunity to obtain world-class physics results.
- New DS+SEER analysis provided significant statistical improvements:
  - **IBD effective counts ~(x2)**
  - **Signal to cosmogenic background~(x2.8)**
- New multi-period spectrum analysis produced the final P-I antineutrino spectrum from the HFIR HEU reactor:
  - **Observation of an excess in the region between 5-7 MeV**
  - **New constraints on the origin of the data-model disagreement suggesting that all fissioning isotopes might be equal contributors.**

PROSPECT HEISING-SIMONS FOUNDATION U.S. DEPARTMENT OF ENERGY GRFP

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Lawrence Livermore National Laboratory NIST Yale

prospect.yale.edu

Summary and Conclusions

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- New DS+SEER analysis provided significant statistical improvements:
  - **IBD effective counts ~(x2)**

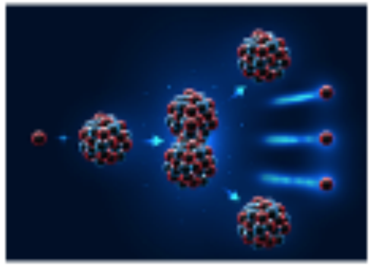
Editors' Suggestion

PDF HTML

Final Measurement of the ^{235}U Antineutrino Energy Spectrum with the PROSPECT-I Detector at HFIR

M. Andriamirado *et al.* (PROSPECT Collaboration)

Phys. Rev. Lett. **131**, 021802 (2023) – Published 11 July 2023

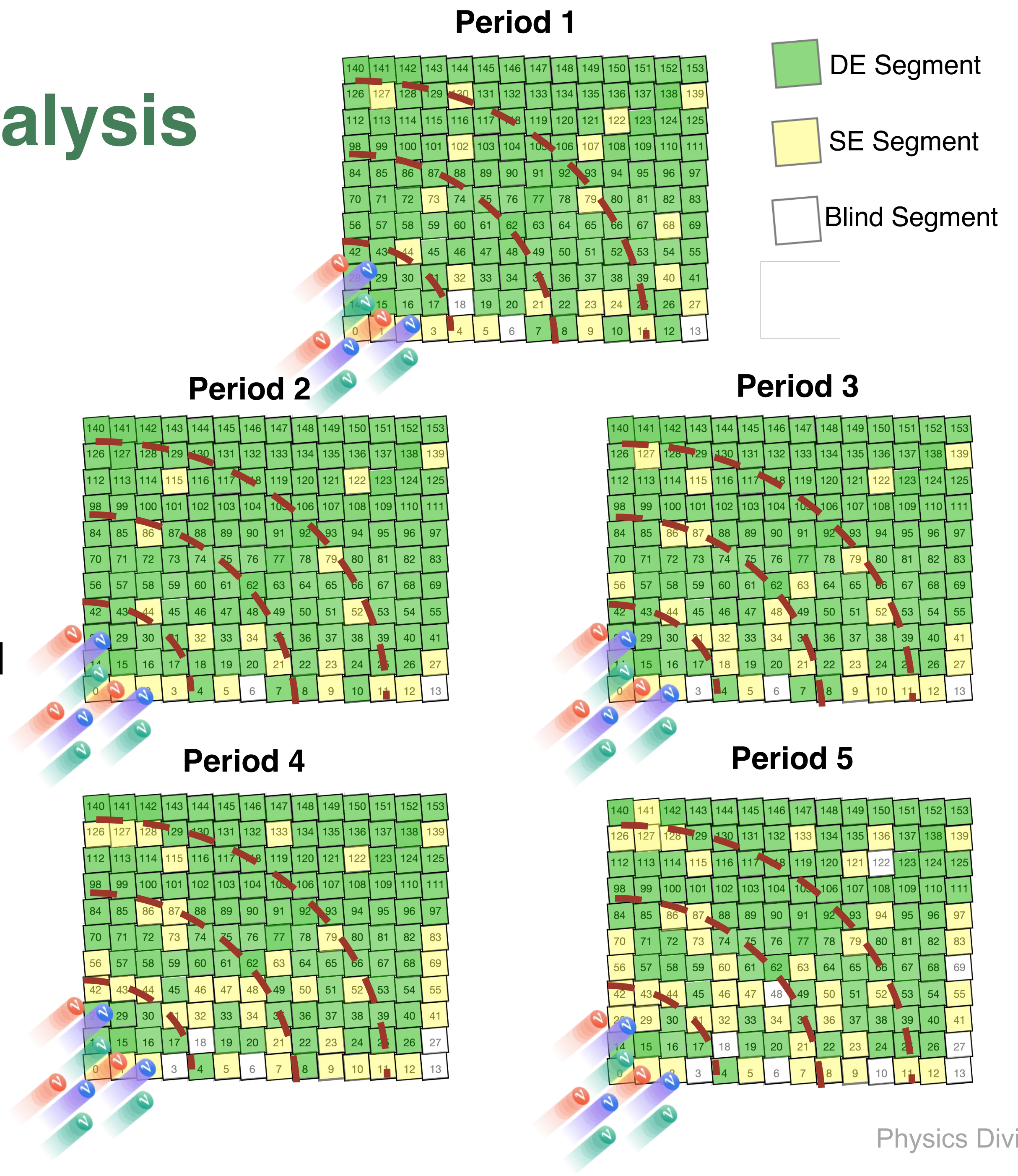


The most precise measurement of the antineutrino spectrum of Uranium-235 using the PROSPECT-I detector at the High Flux Isotope Reactor.

Show Abstract +

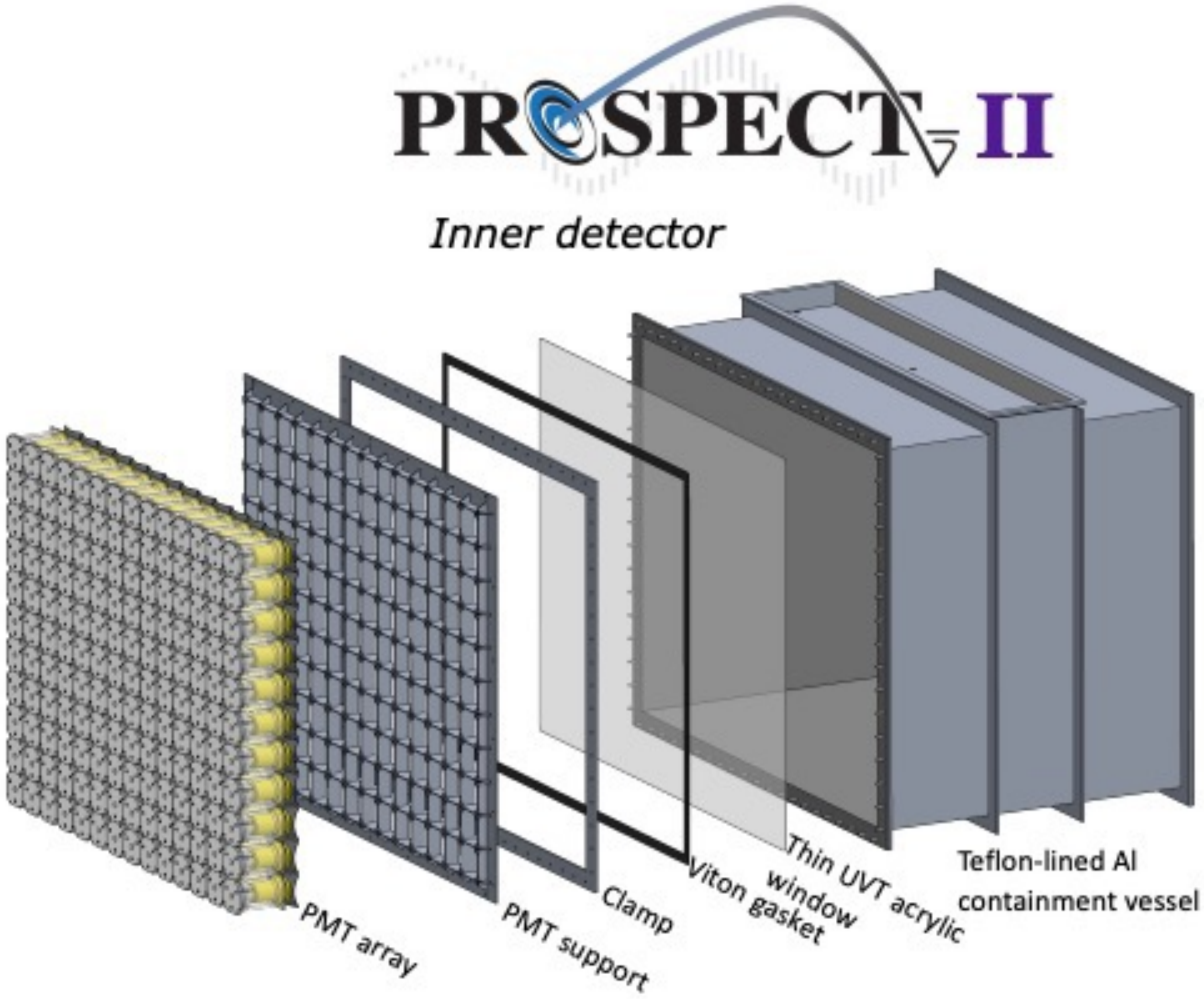
Multi-Period Oscillation Analysis

- Previous oscillation measurement was statistics-limited. Increase in effective statistics (x2) will improve current sensitivity
- Multi-period analysis allows for the use of additional baseline bins which result in a sensitivity gain.
- A new framework capable of producing a joint oscillation analysis for each data period is being developed
  - Future joint-oscillation analysis with other reactor experiments



Next Phase of PROSPECT

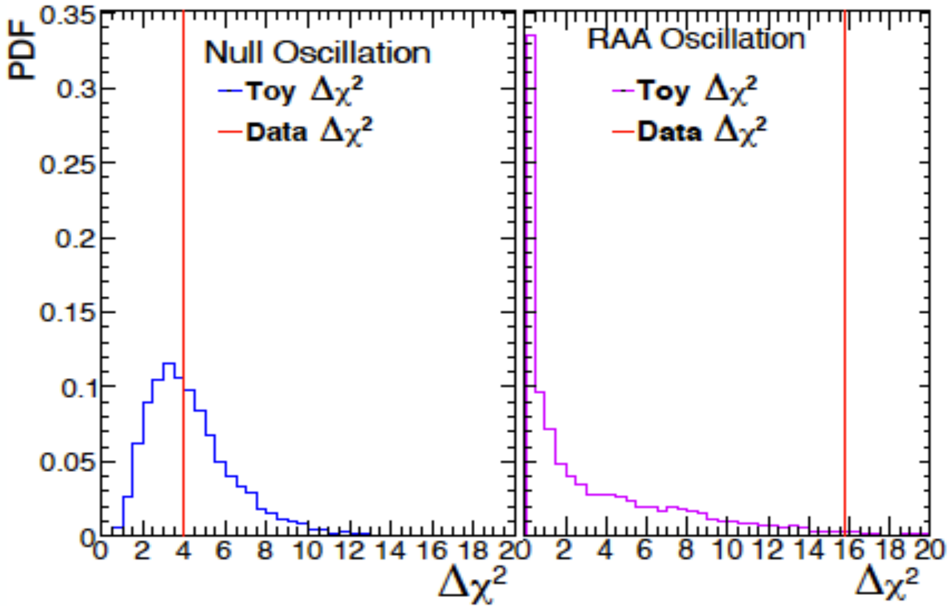
- Retains successful elements of PROSPECT-I: **segmented ^{6}Li-doped liquid scintillator with minimal shielding, located 7-9m from HEU core of HFIR** (+ possible LEU site)
- **Moves PMTs out of liquid scintillator volume**
- **Uses external calibration system** instead of calibration tubes inside active volume
- **Increases signal collection capacity** with 25% longer segments, 20% increased ^{6}Li fraction, longer data-taking period

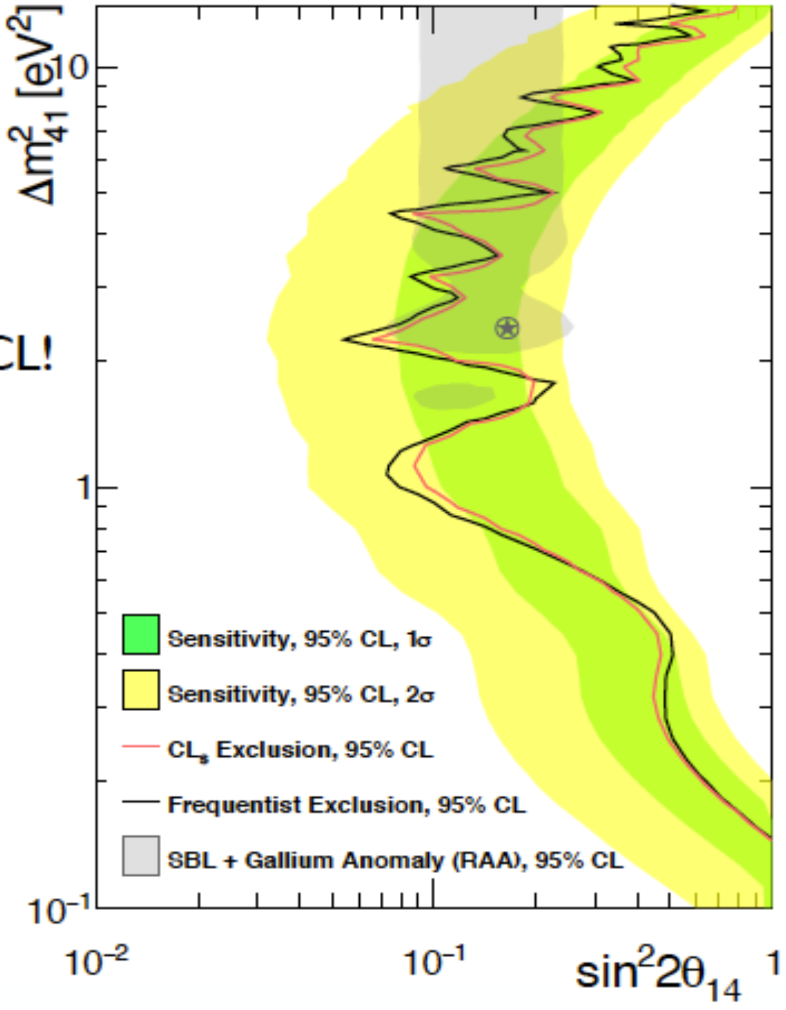


Back Up Slides

Previous Oscillations Results

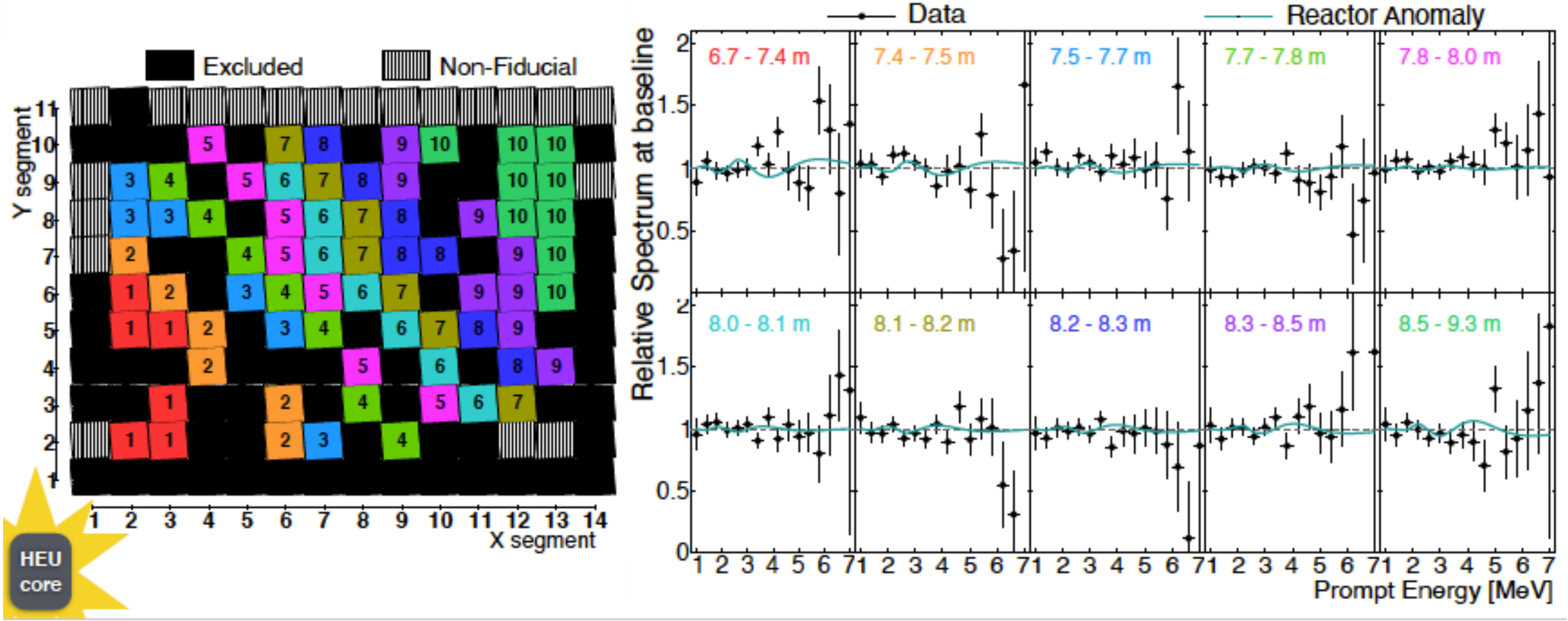
- Use both Feldman-Cousins and CL_s to convert $\Delta\chi^2$ values to statistically valid excluded regions of oscillation phase space
  - RAA best-fit excluded: 98.5% CL
  - Data is compatible with null oscillation hypothesis (p=0.57)
- $\Delta\chi^2$ doesn't follow χ^2 distribution
  - Wilk's incorrectly 'excludes' RAA at 99.96% CL!

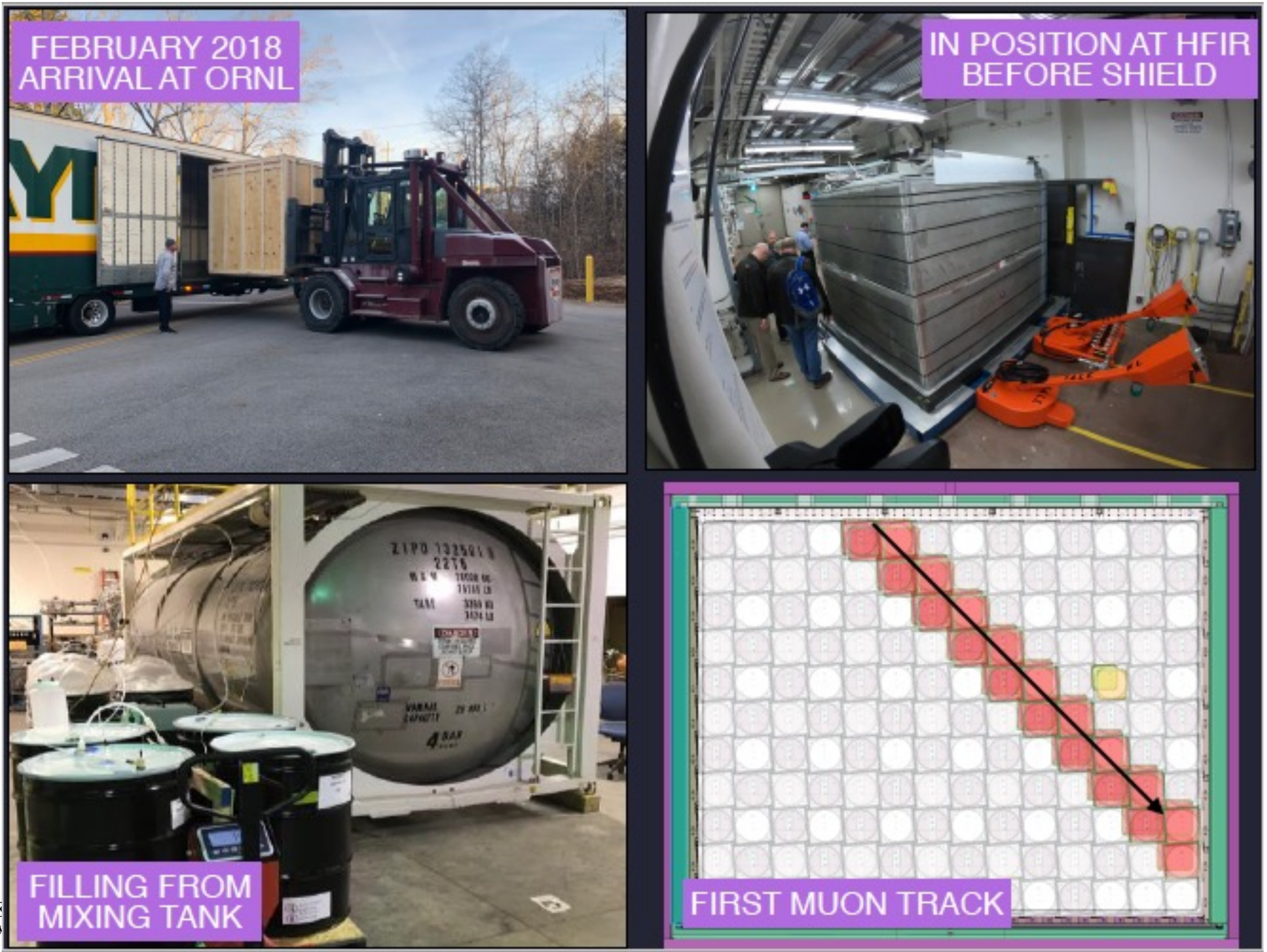




Previous Oscillations Results

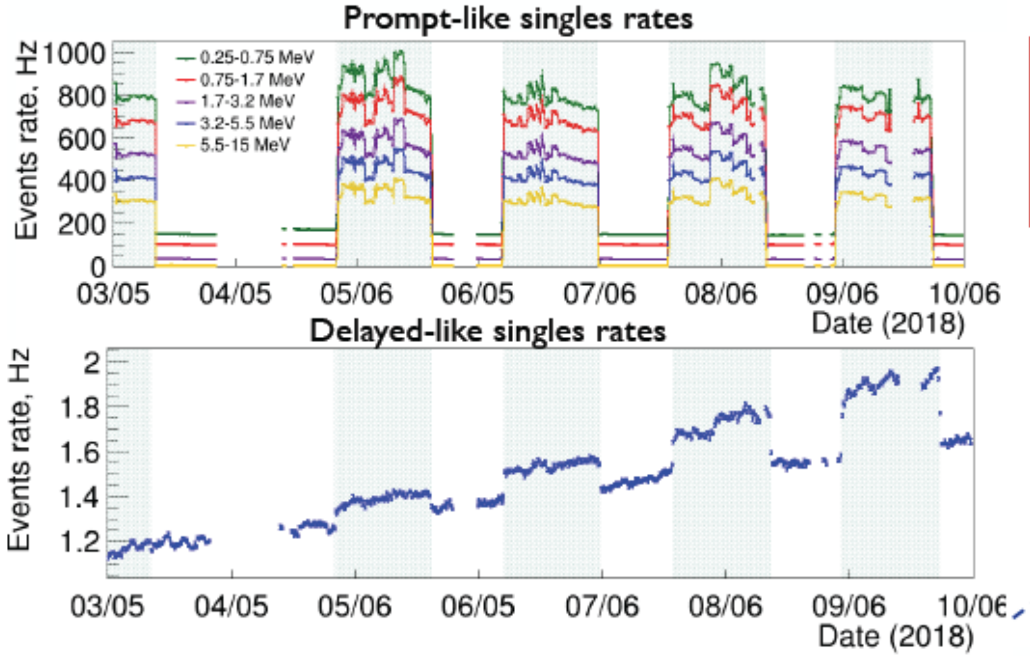
- Combine data into 16 energy, 10 baseline bins
- Remove reactor model dependence by dividing each baseline's measured energy spectrum by the full-detector spectrum
  - Also correct for MC-predicted difference in response between baseline bins
- No obvious deviations from flat no-oscillation scenario

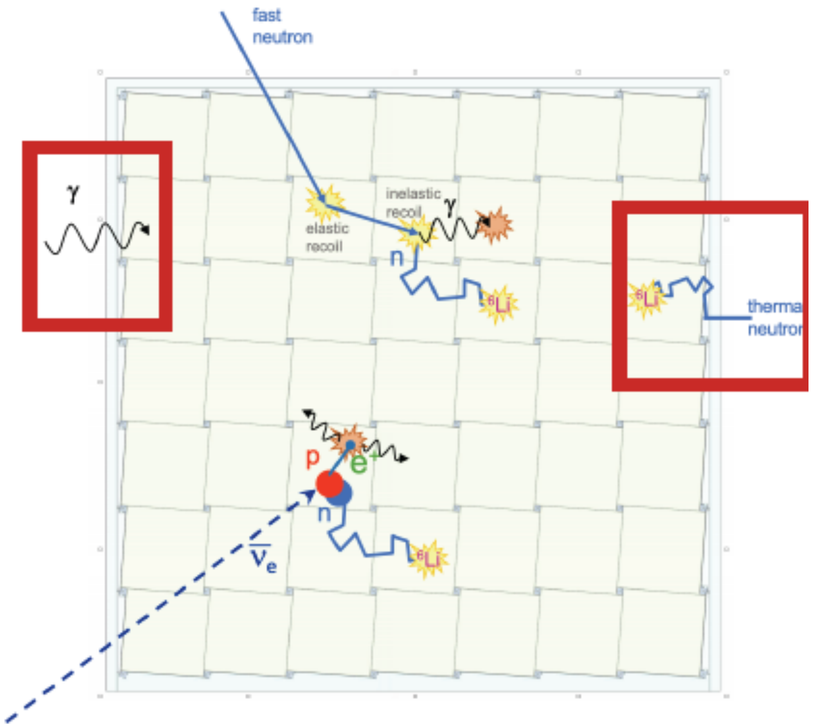



FEBRUARY 2018
ARRIVAL AT ORNL
IN POSITION AT HFIR
BEFORE SHIELD
FILLING FROM
MIXING TANK
FIRST MUON TRACK

Accidental Backgrounds

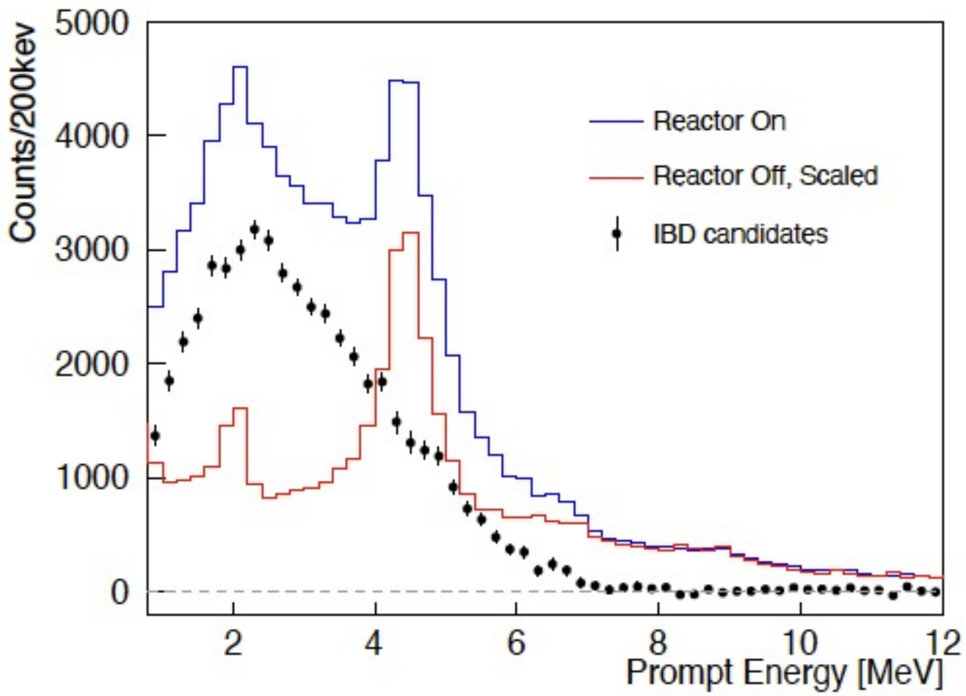
- Random coincidence of gamma and nLi-like signal
  - Variation in delayed signals from gammas bleeding into nLi PSD region
- Estimate precisely using off-window method
  - IBD offset by few hundred <u>us</u>, accidentals offset by 1-2 <u>seconds</u>

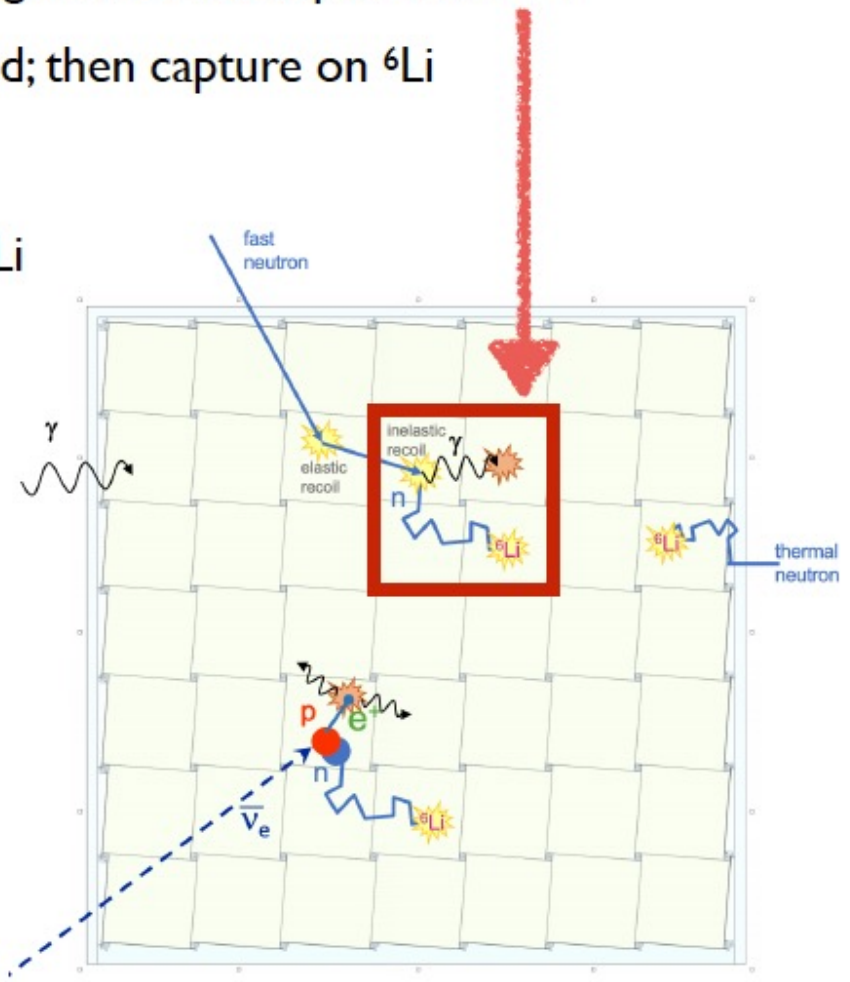




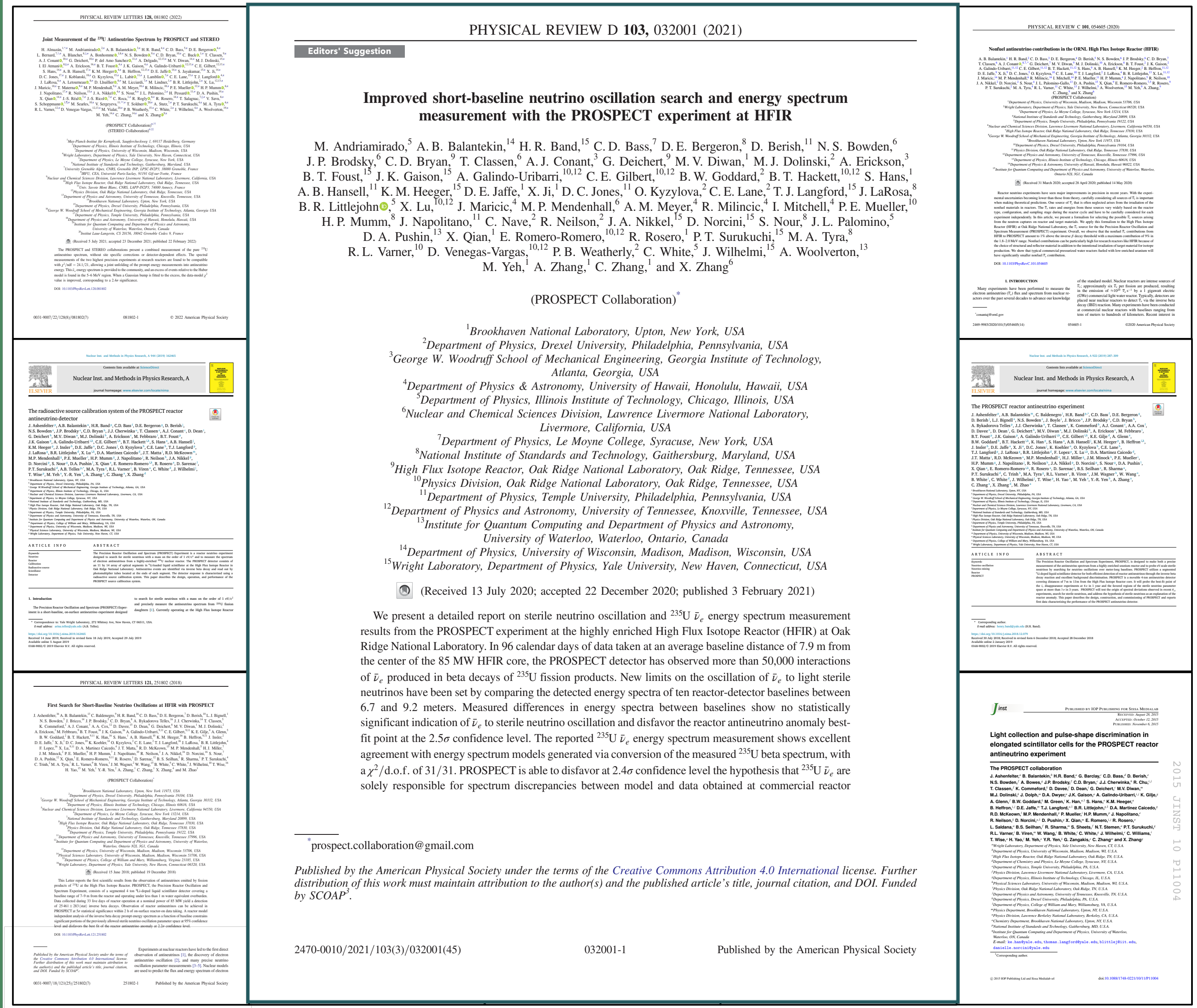
Correlated Backgrounds

- Fast neutron produced background:
  - Inelastic scatter off C-12 gives 4.5MeV gamma; then captures on ^{6}Li
  - n-p scatter in low side of high PSD band; then capture on ^{6}Li
- Multi-neutron background:
  - First neutron captures on H, next on ^{6}Li





PROSPECT-I Results and Highlights - Oscillation and Spectrum


PHYSICAL REVIEW D **103**, 032001 (2021)

Editors' Suggestion

Improved short-baseline neutrino oscillation search and energy spectrum measurement with the PROSPECT experiment at HFIR

M. Andriamirado,[5] A. B. Balantekin,[14] H. R. Band,[15] C. D. Bass,[7] D. E. Bergeron,[8] D. Berish,[11] N. S. Bowden,[6] J. P. Brodsky,[6] C. D. Bryan,[9] T. Classen,[6] A. J. Conant,[3] G. Deichert,[9] M. V. Diwan,[1] M. J. Dolinski,[2] A. Erickson,[3] B. T. Foust,[15] J. K. Gaison,[15] A. Galindo-Uribarri,[10,12] C. E. Gilbert,[10,12] B. W. Goddard,[2] B. T. Hackett,[10,12] S. Hans,[1] A. B. Hansell,[11] K. M. Heeger,[15] D. E. Jaffe,[1] X. Ji,[1] D. C. Jones,[11] O. Kyzylova,[2] C. E. Lane,[2] T. J. Langford,[15] J. LaRosa,[8] B. R. Littlejohn,[5] X. Lu,[10,12] J. Maricic,[4] M. P. Mendenhall,[6] A. M. Meyer,[4] R. Milincic,[4] I. Mitchell,[4] P. E. Mueller,[10] H. P. Mumm,[8] J. Napolitano,[11] C. Nave,[2] R. Neilson,[2] J. A. Nikkel,[15] D. Norcini,[15] S. Nour,[8] J. L. Palomino,[5] D. A. Pushin,[13] X. Qian,[1] E. Romero-Romero,[10,12] R. Rosero,[1] P. T. Surukuchi,[15] M. A. Tyra,[8] R. L. Varner,[10] D. Venegas-Vargas,[10,12] P. B. Weatherly,[2] C. White,[5] J. Wilhelmi,[15] A. Woolverton,[13] M. Yeh,[1] A. Zhang,[1] C. Zhang,[1] and X. Zhang[6]

(PROSPECT Collaboration)*

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[12] *Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee, USA*
[13] *Institute for Quantum Computing and Department of Physics and Astronomy, University of Waterloo, Waterloo, Ontario, Canada*
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[15] *Wright Laboratory, Department of Physics, Yale University, New Haven, Connecticut, USA*

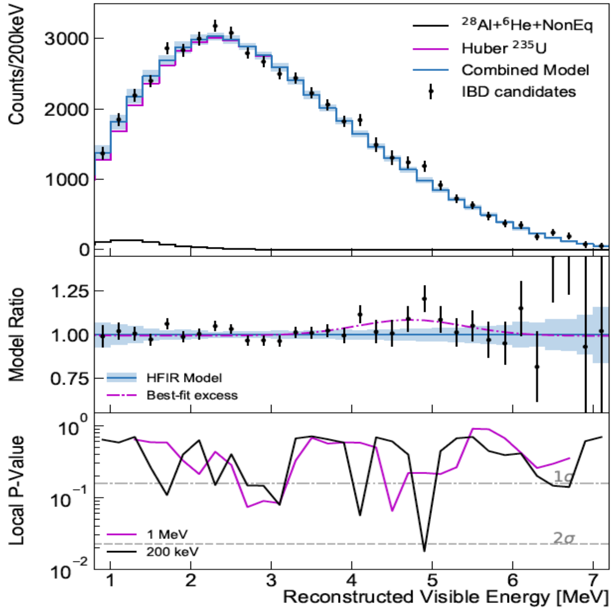
(Received 13 July 2020; accepted 22 December 2020; published 3 February 2021)

We present a detailed report on sterile neutrino oscillation and ^{235}U $\bar{\nu}_e$ energy spectrum measurement results from the PROSPECT experiment at the highly enriched High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory. In 96 calendar days of data taken at an average baseline distance of 7.9 m from the center of the 85 MW HFIR core, the PROSPECT detector has observed more than 50,000 interactions of $\bar{\nu}_e$ produced in beta decays of ^{235}U fission products. New limits on the oscillation of $\bar{\nu}_e$ to light sterile neutrinos have been set by comparing the detected energy spectra of ten reactor-detector baselines between 6.7 and 9.2 meters. Measured differences in energy spectra between baselines show no statistically significant indication of $\bar{\nu}_e$ to sterile neutrino oscillation and disfavor the reactor antineutrino anomaly best-fit point at the 2.5σ confidence level. The reported ^{235}U $\bar{\nu}_e$ energy spectrum measurement shows excellent agreement with energy spectrum models generated via conversion of the measured ^{235}U beta spectrum, with a χ^2/d.o.f. of 31/31. PROSPECT is able to disfavor at 2.4σ confidence level the hypothesis that ^{235}U $\bar{\nu}_e$ are solely responsible for spectrum discrepancies between model and data obtained at commercial reactor

*prospect.collaboration@gmail.com

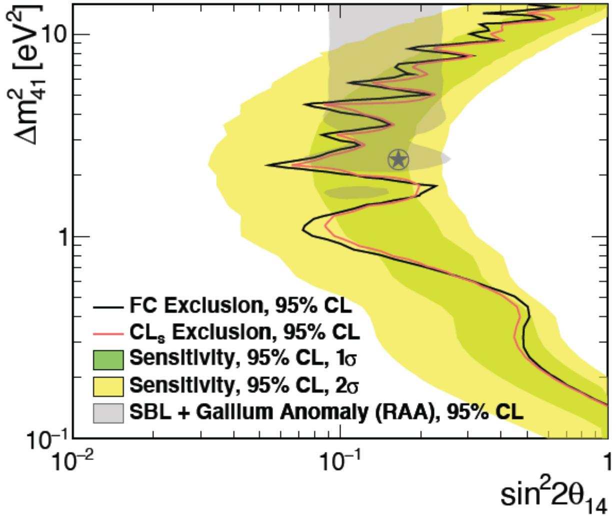
2470-0010/2021/103(3)/032001(45) 032001-1 Published by the American Physical Society

Prompt Energy Antineutrino Spectrum



- χ^2/ndf =30.79/31 for shape-only comparison with model
- No ^{235}U bump disfavored at 2.2σ CL
- All ^{235}U is disfavored at 2.4σ CL

Oscillation Exclusion Contours



- RAA best-fit excluded: 98.5% CL
- Data is compatible with null oscillation hypothesis (p=0.57)

M. Andriamirado et al. (PROSPECT Collaboration), Phys. Rev. D 103, 032001 (2021).

PROSPECT-I Results and Highlights
- Joint Spectrum Analyses


PHYSICAL REVIEW LETTERS **128,** 081802 (2022)

Joint Measurement of the ^{235}U Antineutrino Spectrum by PROSPECT and STEREO

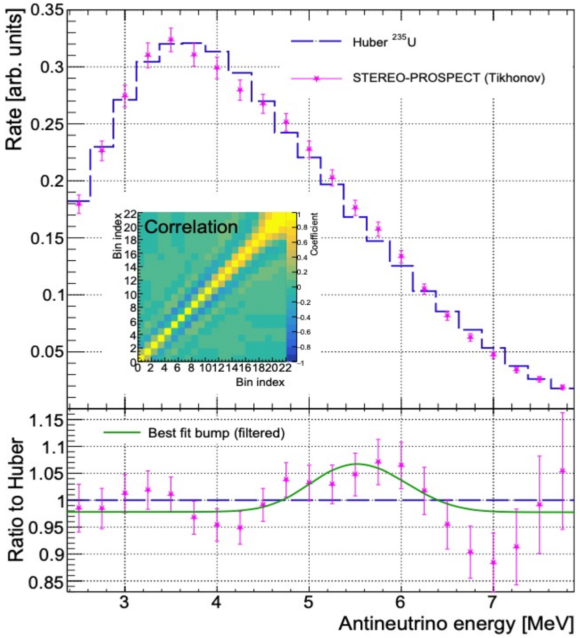
(PROSPECT Collaboration)
(STEREO Collaboration)

PHYSICAL REVIEW LETTERS **128,** 081801 (2022)

Joint Determination of Reactor Antineutrino Spectra from ^{235}U and ^{239}Pu Fission by Daya Bay and PROSPECT

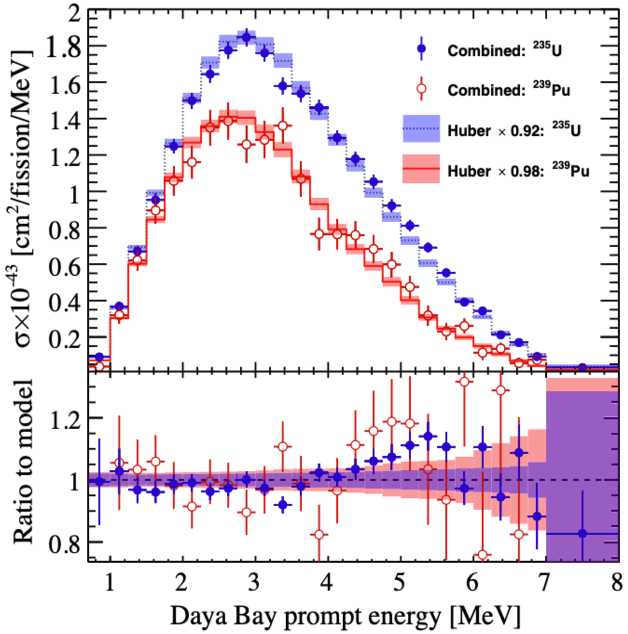
(Daya Bay Collaboration)
(PROSPECT Collaboration)

PROSPECT + STEREO



- Improved ^{235}U reference
- Bump excess at 2.4σ

PROSPECT + Daya Bay



- 3% improvement to ^{235}U relative shape uncertainty
- ~20% Reduced degeneracy between dominant ^{235}U and ^{239}Pu isotopes in evolution analysis

PROSPECT-I Results and Highlights
- Joint Spectrum Analyses


PHYSICAL REVIEW LETTERS 128, 081802 (2022)

Joint Measurement of the ^{235}U Antineutrino Spectrum by PROSPECT and STEREO

(PROSPECT Collaboration)
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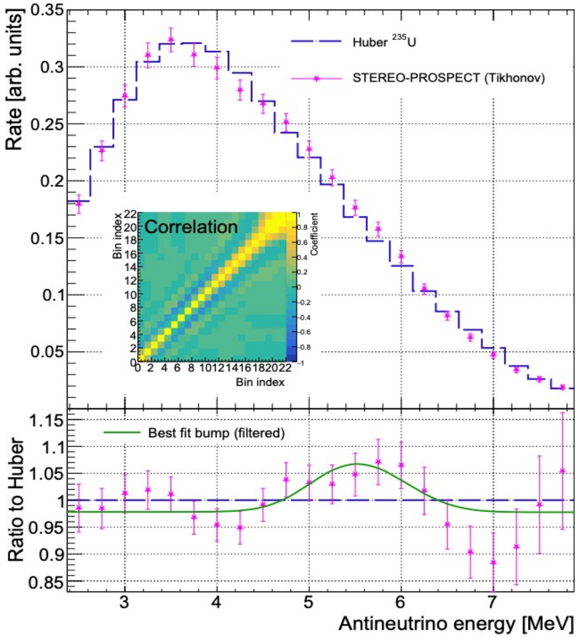
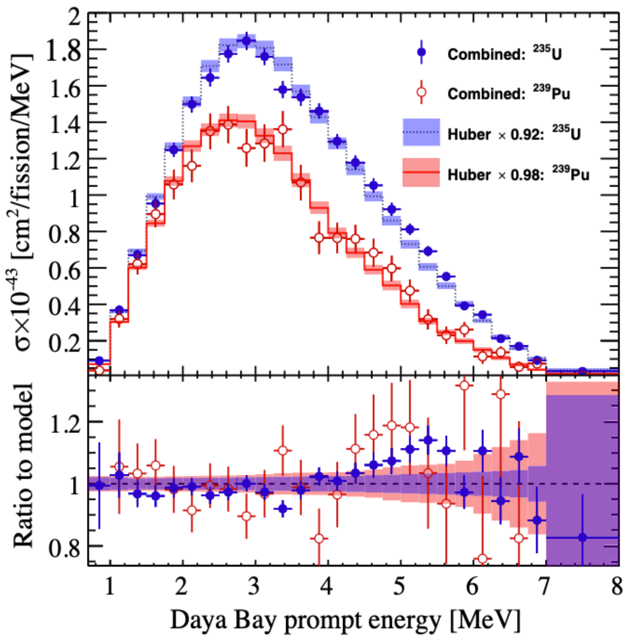
PROSPECT + STEREO

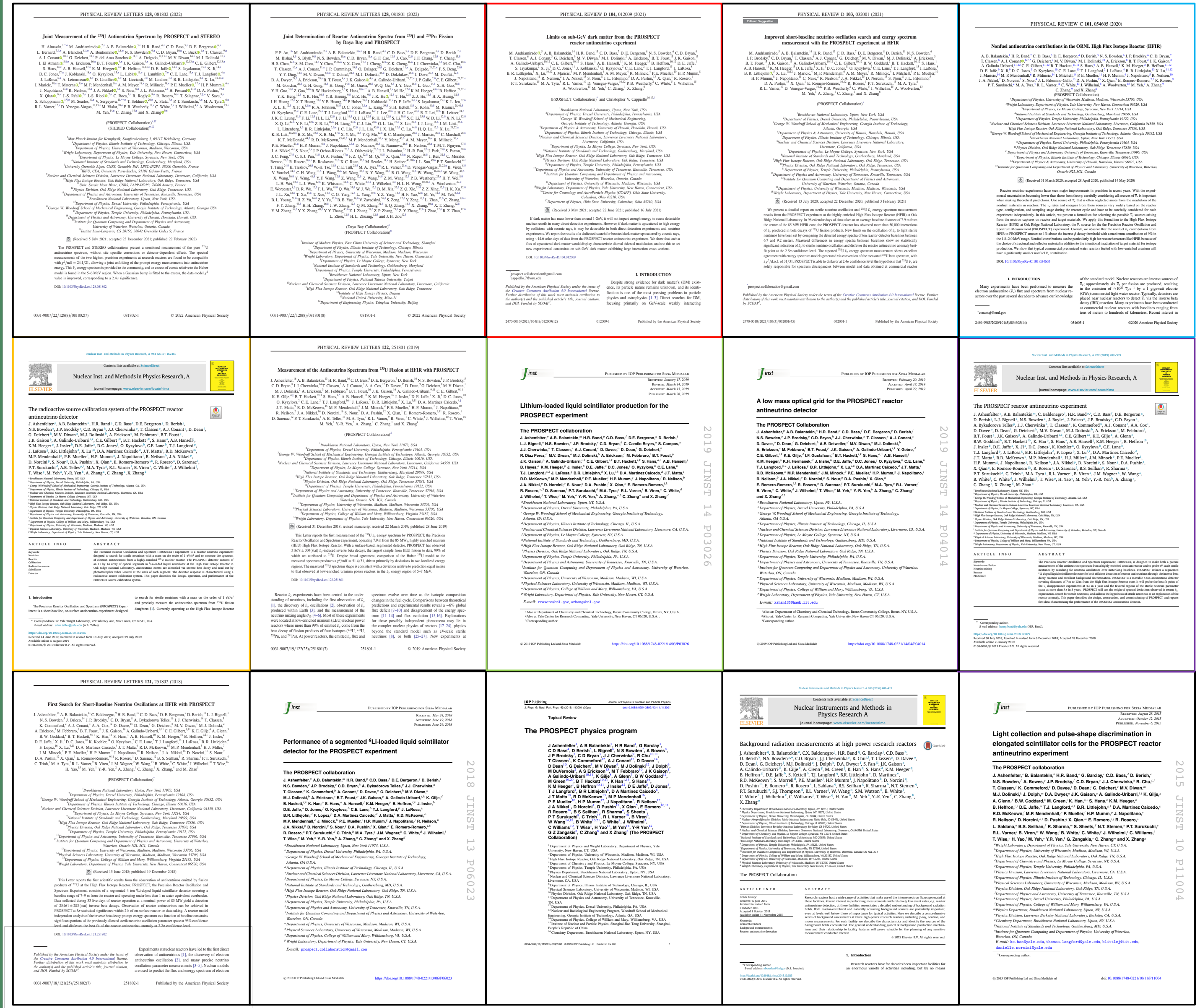


PROSPECT + Daya Bay



- **Stronger confirmation of excess between 4-6 MeV area**
- **Successful combination of results between HEU/HEU and HEU/LEU experiments**

PROSPECT-I Results and Highlights:
- Publications

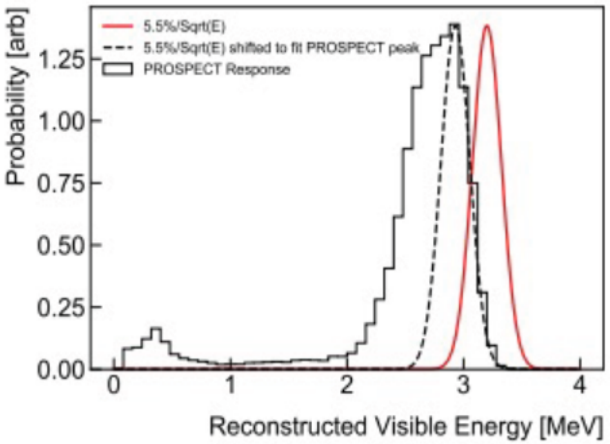


Additional results include:

- **Search for Boosted Dark Matter**
  - PhysRevD 104 (2021) 012009
- **Non-fuel reactor contributions**
  - PhysRevC 101 (2020) 054605
- **Liquid Scintillator production and characterization**
  - JINST 14 (2019) P03026
- **Calibration Method**
  - NIMA 944 (2019) 162465
- **Instrumentation**
  - NIMA 922 (2018) 287

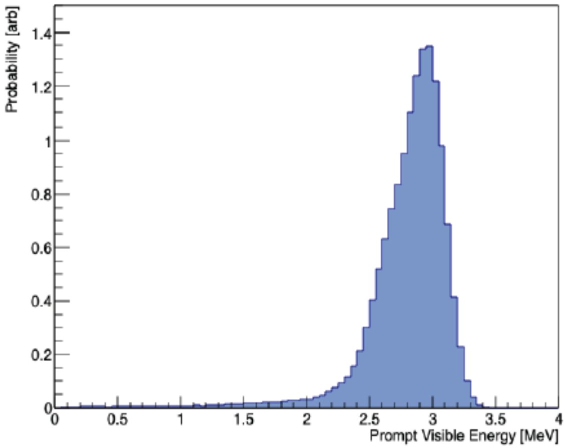
Detector Response for Each Period

Detector Configuration Used for Previous Analysis

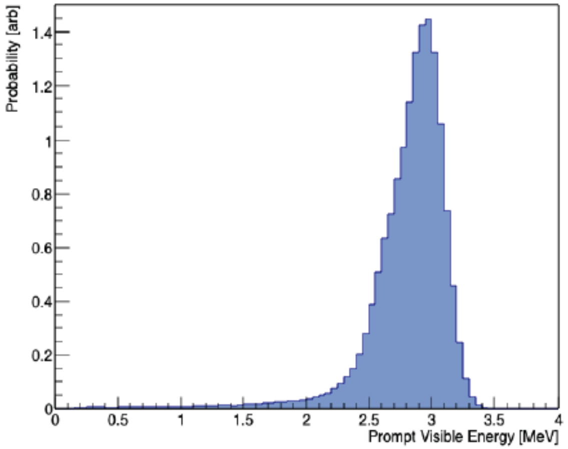


4 MeV antineutrino detector response

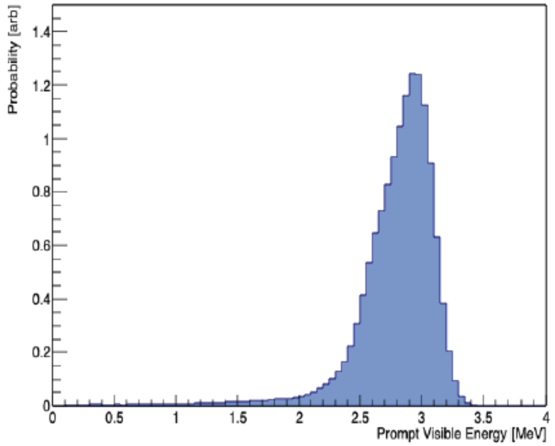
Period 1



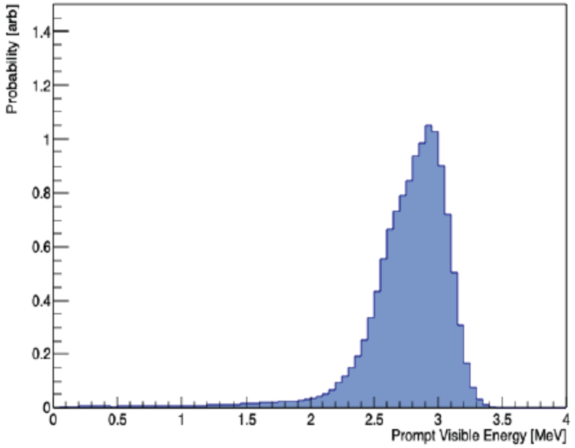
Period 2



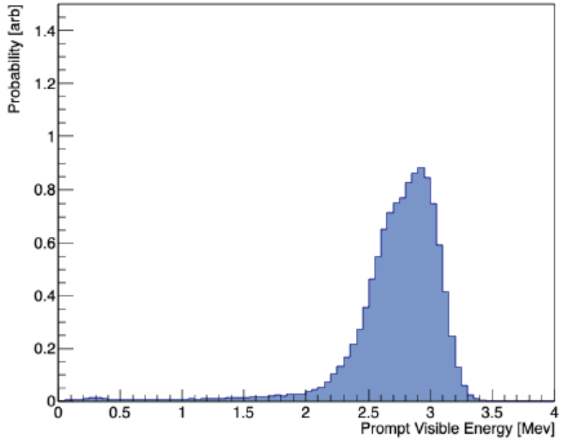
Period 3



Period 4

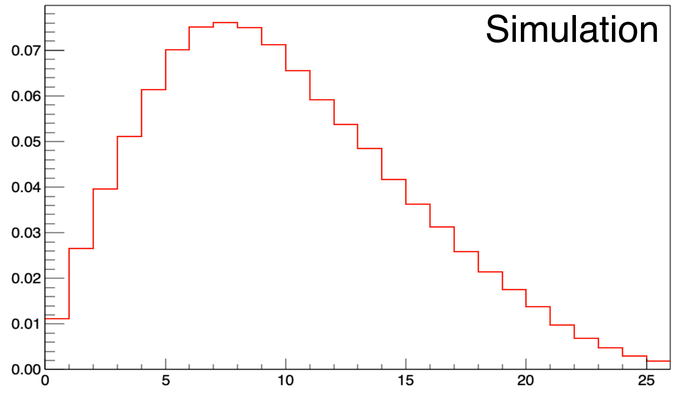


Period 5

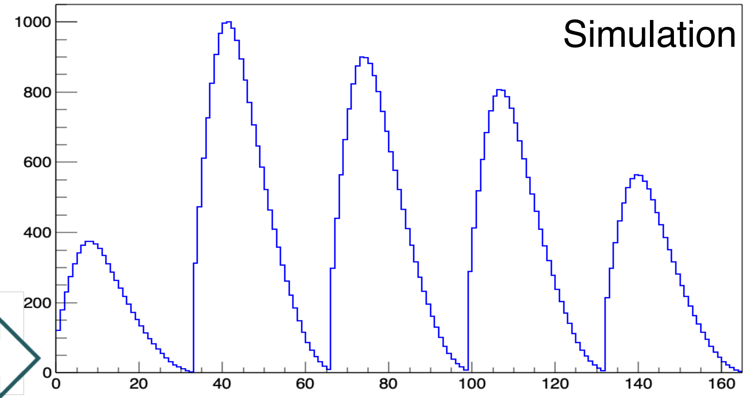


Multi-Period Spectrum Analysis: WienerSVD Unfolding Technique

True Spectrum S



Measured Spectrum M

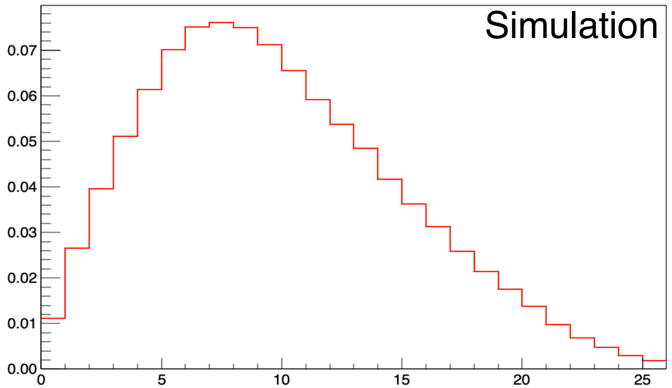


Detector Response R

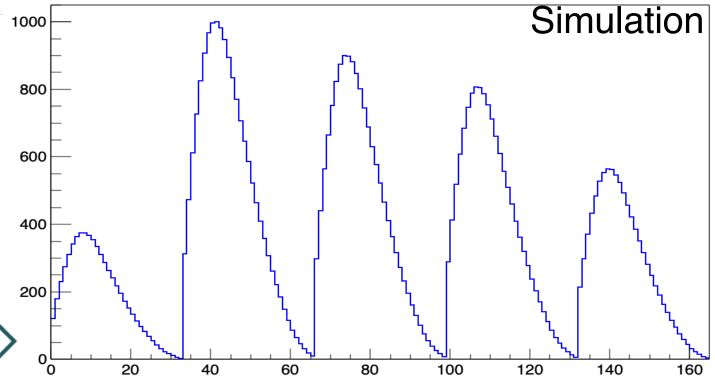
One could say that $R \cdot S = M$

Multi-Period Spectrum Analysis: WienerSVD Unfolding Technique

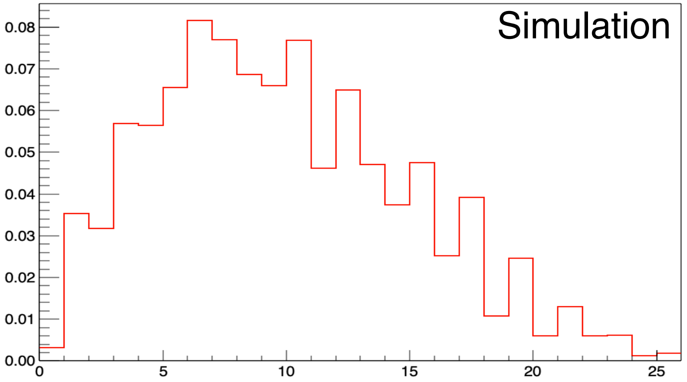
True Spectrum S



Measured Spectrum M



Rec. Spectrum S’



Detector Response R

Inverse Detector Response R^{-1}

~~One could say that $R \cdot S = M$~~

However... $R^{-1} \cdot M = S' \neq S$

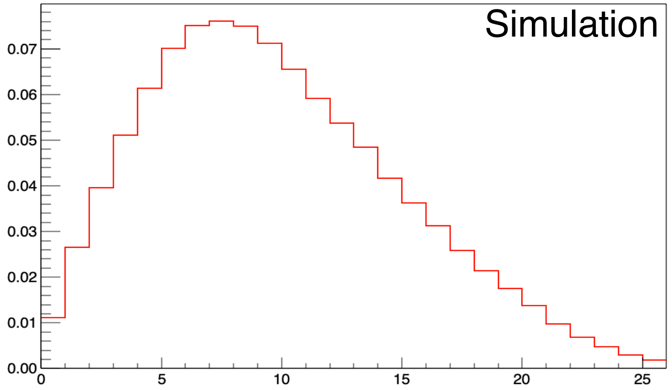
Complications:
- R is not necessarily an invertible matrix: pseudo-inverse using SVD
- Still, small elements in R can blow up in R^{-1}
- Measurements $M = R \cdot S + N$, containing experimental noise N

$$R^{-1} \cdot (R \cdot S + N) = S'$$

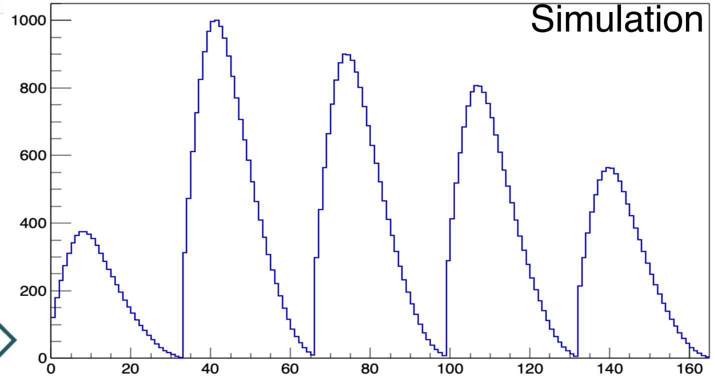
$$S' = S + R^{-1} \cdot N$$

Multi-Period Spectrum Analysis: WienerSVD Unfolding Technique

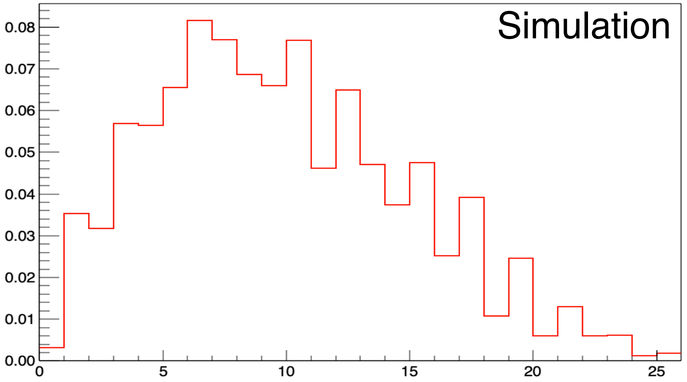
True Spectrum S



Measured Spectrum M



Rec. Spectrum S’



Detector Response R

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- Still, small elements in R can blow up in R^{-1}
- Measurements $M = R \cdot S + N$, containing experimental noise N

$$R^{-1} \cdot (R \cdot S + N) = S'$$

$$S' = S + R^{-1} \cdot N$$

Solution: Add Regularization Filter Function F

$$S'' = R^{-1} \cdot M \cdot F$$

PROSPECT-I Results and Highlights - Professional Training

1. Ben Foust

2. Jeremy Gaison

3. Adam Hansell

3. Olga Kyzylova

5. Xianyi Zhang

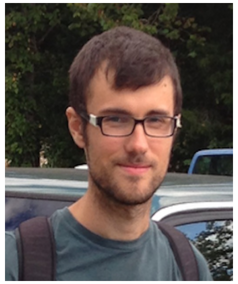
6. Danielle Norcini

7. Andrew Conant

8. Danielle Berish

9. Pranava Teja Surukuchi

10. Blaine Heffron



11. Brennan Hackett

- PROSPECT has served as a fantastic professional development and training program for young scientists.
  - 10 Ph.D. Theses
  - 2 M.S. Theses
  - Multiple Postdocs and undergraduates as well

1. **Precision Measurement of the U-235 Antineutrino Spectrum with PROSPECT and STEREO,** Ph.D. Thesis, Yale, 2022.
2. **Measurement of the Reactor Antineutrino Spectrum of U-235 by PROSPECT and Daya Bay,** Ph.D. Thesis, Yale, 2021.
3. **Characterization of Time-Varying Backgrounds in the PROSPECT Experiment,** Ph.D. Thesis, Drexel, 2021.
4. **A New Measurement of the Neutron Multiplicity Emitted in 252Cf Spontaneous Fission, Temple,** Ph.D. Thesis, Temple, 2020.
5. **Energy Scale Study for PROSPECT'S Measurement of the Antineutrino Spectrum of 235U,** Ph.D. Thesis, IIT, 2019.
6. **First Search for eV-Scale Sterile Neutrinos and Precision Measurement of the 235U Antineutrino Spectrum with the PROSPECT Experiment,** Ph.D. Thesis, Yale, 2019.
7. **Antineutrino Spectrum Characterization of the High Flux Isotope Reactor Using Neutronic Simulations,** Ph.D. Thesis, Georgia Tech, 2019.
8. **Short-Wavelength Reactor Neutrino Oscillations with the PROSPECT Experiment,** Ph.D. Thesis, Temple, 2019**.**
9. **Search for Sterile Neutrino Oscillations with The Prospect Experiment,** Ph.D. Thesis, IIT, 2019.
10. **- Characterization of Reactor Background Radiation at HFIR for the PROSPECT Experiment,** M.S. Thesis, UTK, 2017.
11. **DANG and the Background Characterization of HFIR for PROSPECT, Brennan Hackett,** M.S. Thesis, Surrey, 2017.

"Local" Students and Postdocs that worked in PROSPECT-I

+ more than 35 from collaboration institutions

Ran Chu UTK

Brennan Hackett UTK

Elisa Romero UTK

Rosa Luz Peinado Sonora

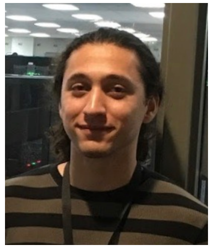
Andrea Delgado Texas A&M

Adriana Ghiozzi UC Berkeley

Sabrina Cheng MIT

Brandon White PD-ORNL 13

James Matta PD-ORNL 17



Alex Guirado Sonora

Alan Garcia UTEP

Diego Vargas Wesleylan

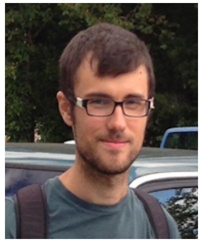
Ivan Corona UAEM

Corey Gilbert UTK

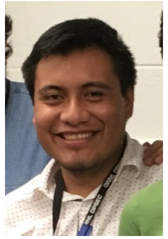
Xiaobin Lu UTK

Cristian Baldenegro Sonora

Omar Garcia CINVESTAV

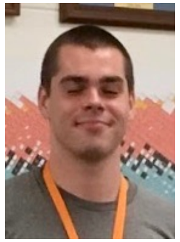


Blaine Heffron UTK



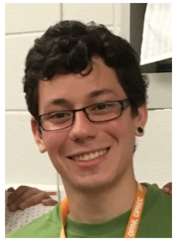
Noel Cruz UNAM

Jack Boyle Surrey



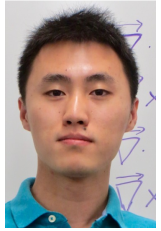
Travis Stockinger UTK

Biswas Sharma UTK



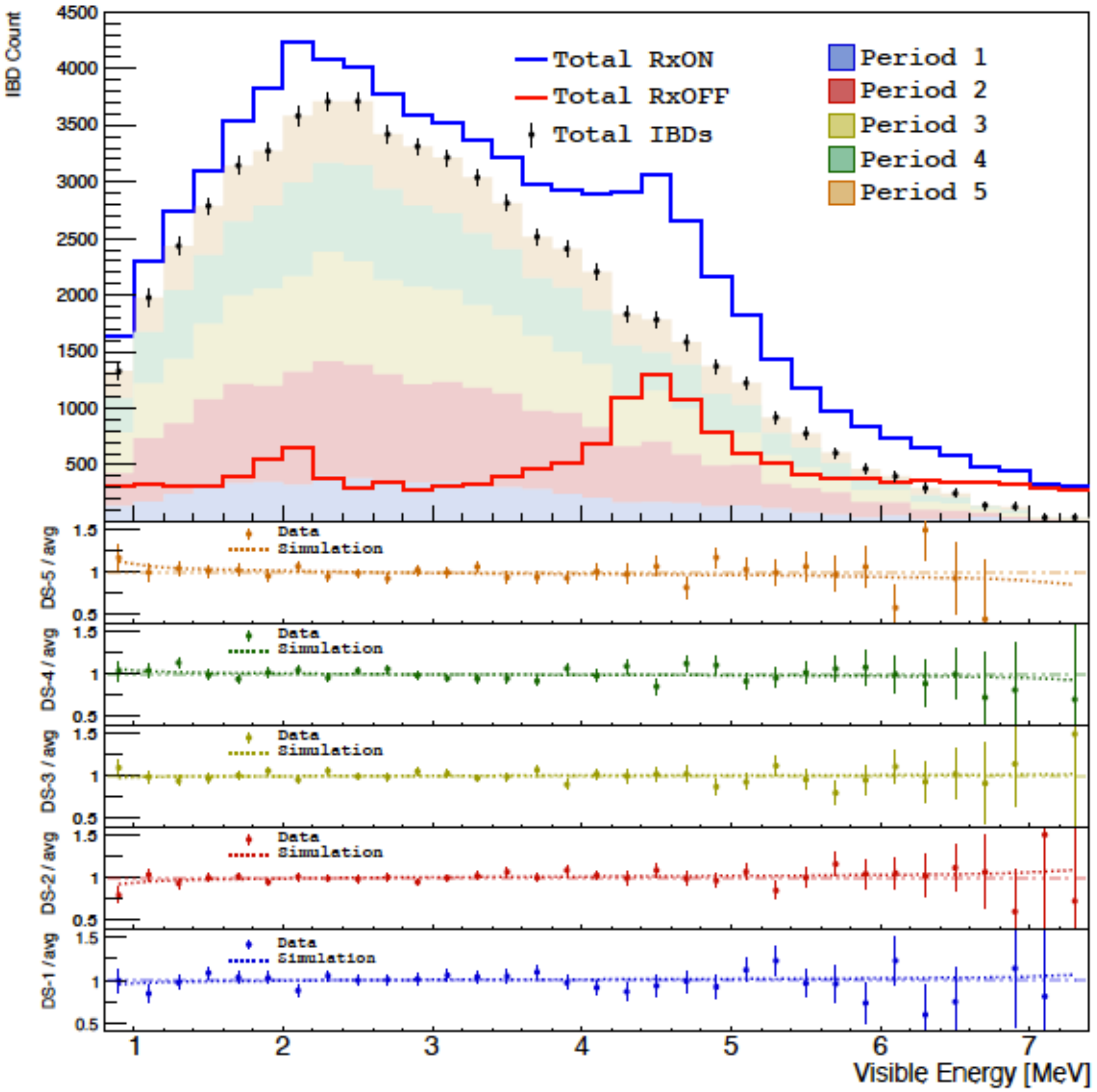
Felix Pastrana Colombia

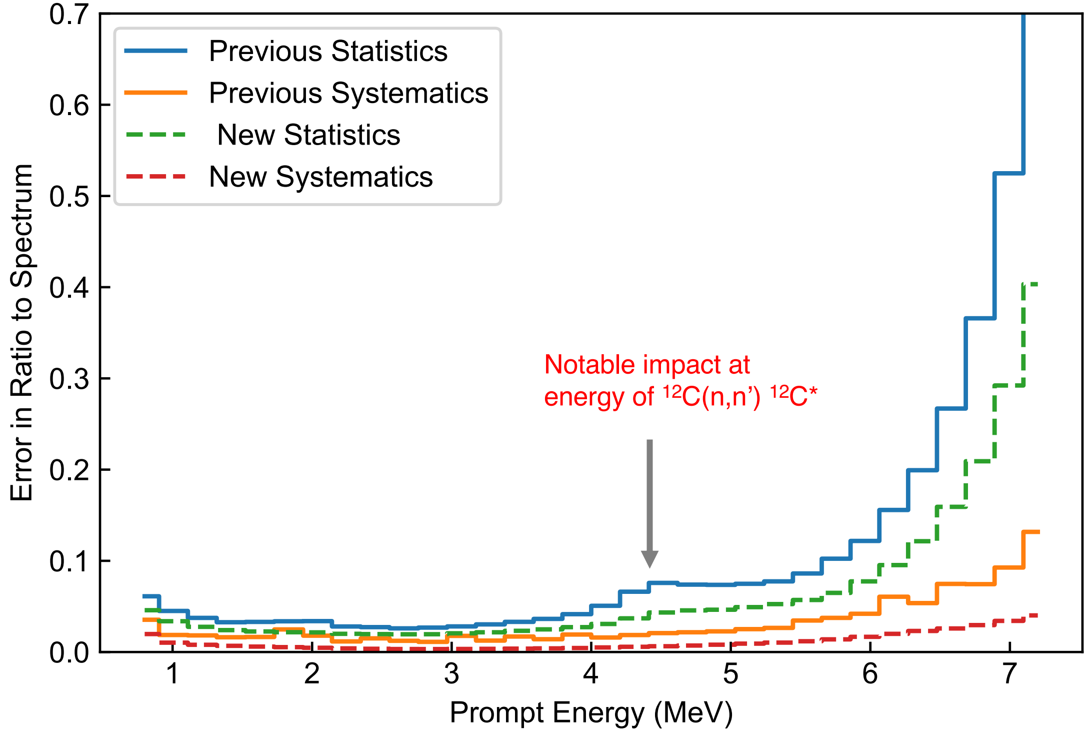
David Murphy UCD



Shiyu Fan UTK

Multi-Period Spectrum Analysis





OAK RIDGE National Laboratory

PROSPECT is a successful outcome of the last Snowmass / P5 cycle

Recommendation 4: Maintain a program of projects of all scales, from the largest international projects to mid- and small-scale projects.
Recommendation 6: In addition to reaping timely science from projects, the research program should provide the flexibility to support new ideas and developments.
Recommendation 15: Select and perform in the short term a set of small-scale short-baseline experiments that can conclusively address experimental hints of physics beyond the three-neutrino paradigm. Some of these experiments should use liquid argon to advance the technology and build the international community for LBNF at Fermilab.

FINANCIAL ASSISTANCE
FUNDING OPPORTUNITY ANNOUNCEMENT

U. S. Department of Energy
Office of Science
High Energy Physics

Intermediate Neutrino Research Program
Funding Opportunity Number: DE-FOA-0001381
Announcement Type: Initial
CFDA Number: 81.049

Issue Date: July 14, 2015

Letter of Intent Due Date: July 29, 2015, at 5 PM Eas
(A Letter of Intent is requ

Application Due Date: September 2, 2015, at 5 P

2015

High Energy Physics

Intermediate Neutrino Research Program Awards

JULY 26, 2016

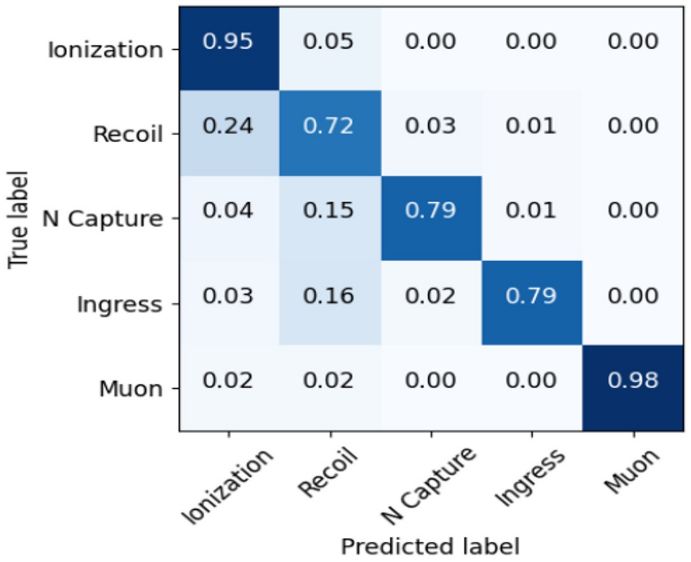
2016

High Energy Physics » Intermediate Neutrino Research Program Awards

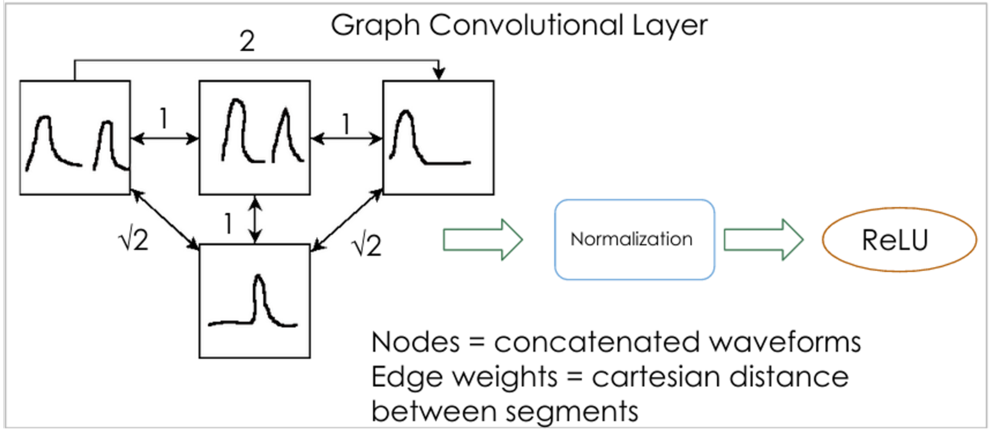
The DOE Office of High Energy Physics has made two awards in response to the Intermediate Neutrino Research Program Funding Opportunity .pdf file (443KB). We are pleased to announce that ANNIE and PROSPECT will investigate the properties and interactions of the known neutrinos and search for new types of neutrinos as part of our implementation of the strategic plan .pdf file (8.7MB) for the HEP program.

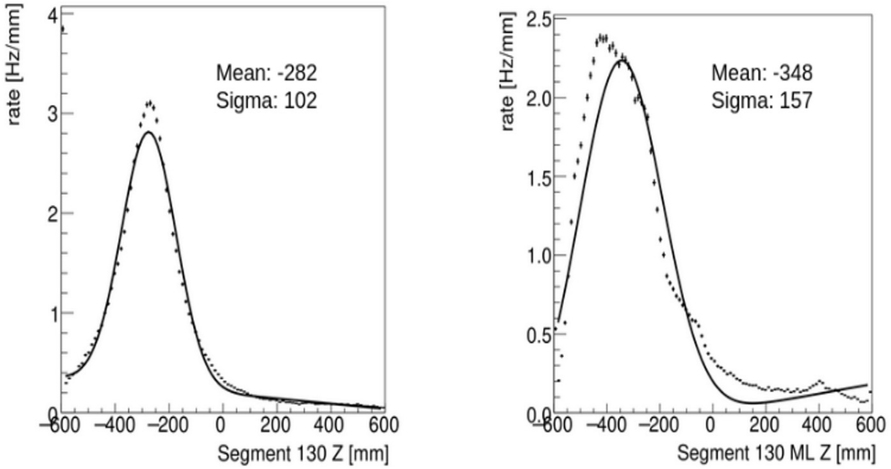
Machine Learning Efforts

- Neural networks have been used to improve single ended event reconstruction
- Truth table which shows the classifier performance, with most difficulty arising from misidentifying recoil events as ionizations
- Overall, the SE Z reconstruction error is on the order of 60 mm which is roughly three times larger than the dual ended error.



Classifier for event selection using graph neural networks





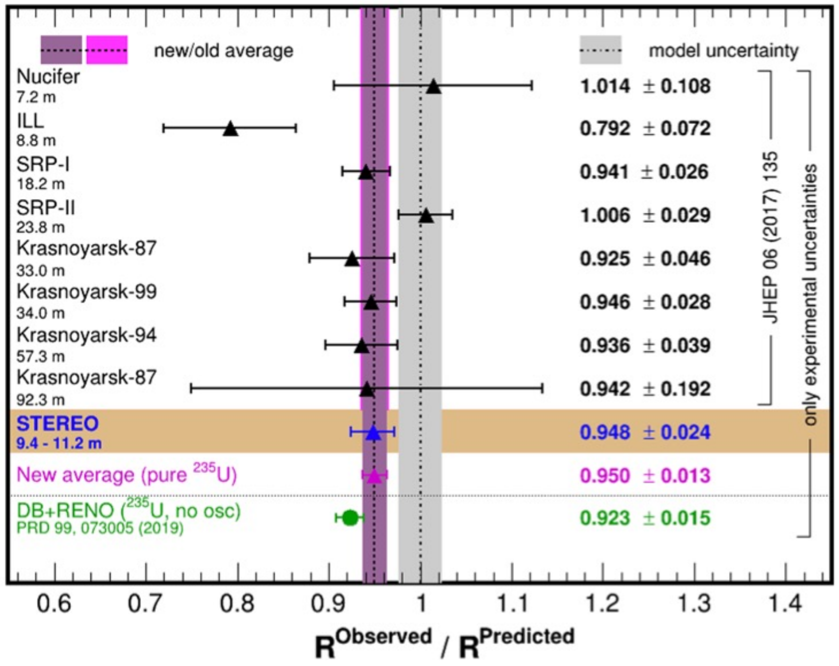
SE Z prediction model using sparse convolutional neural networks

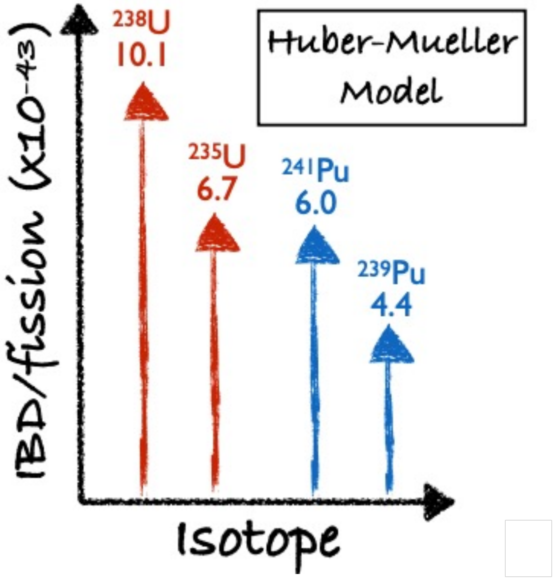
- Left: dual ended calibration source position reconstruction (fit + data)
- Right: ML SE reconstruction (fit + data)

Motivation for an Absolute Flux Analysis

- Previous results for measured and predicted do not agree: Observed flux deficit
  - Are reactor neutrinos oscillating to sterile neutrinos?
  - Are the flux predictions overestimated?
- A P-I absolute flux measurement with a target precision of about 2% would be dominated by systematic uncertainties.
  - Reactor power
  - Proton Density
  - IBD detection efficiency
- Applications:
  - Updated and more precise measurement relative to flux predictions
  - Reactor antineutrino anomaly and sterile neutrino oscillation
  - Reactor power monitoring for verification and safeguards

Phys. Rev. Lett. 125, 201801 (2020)

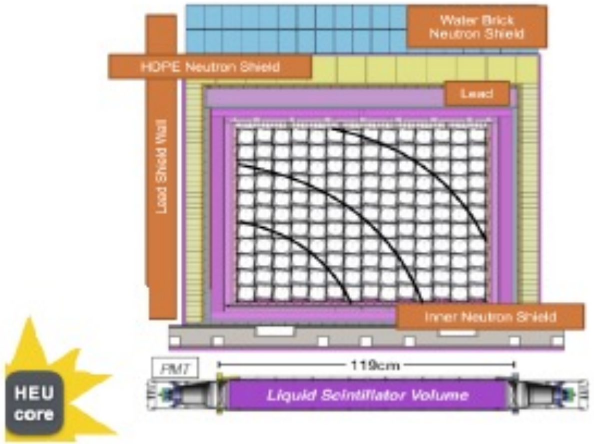




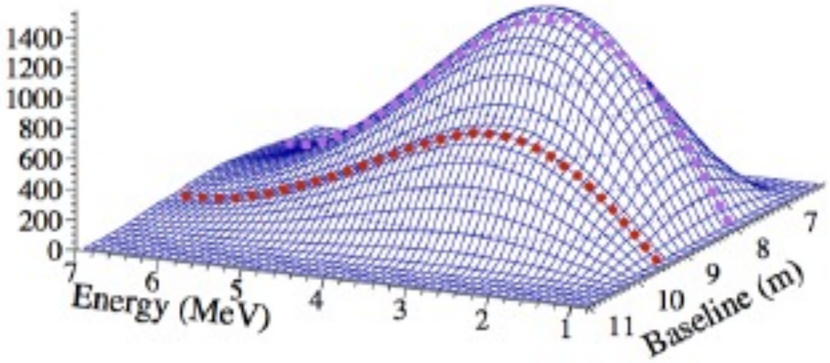
Sterile Neutrino Oscillation

Relative Spectrum Measurement
relative measurement of L/E and spectral shape distortions

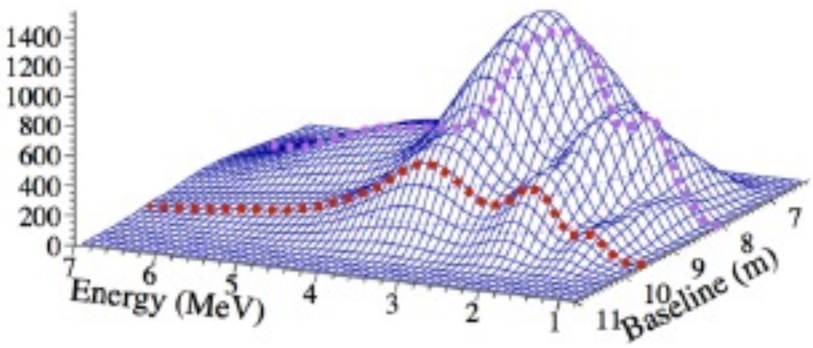
$$P_{\text{dis}} = \sin^2 2\theta \sin^2 \left(1.27 \Delta m^2 (\text{eV}^2) \frac{L(\text{m})}{E_\nu(\text{MeV})} \right)$$



unoscillated spectrum



oscillated spectrum



Simulations

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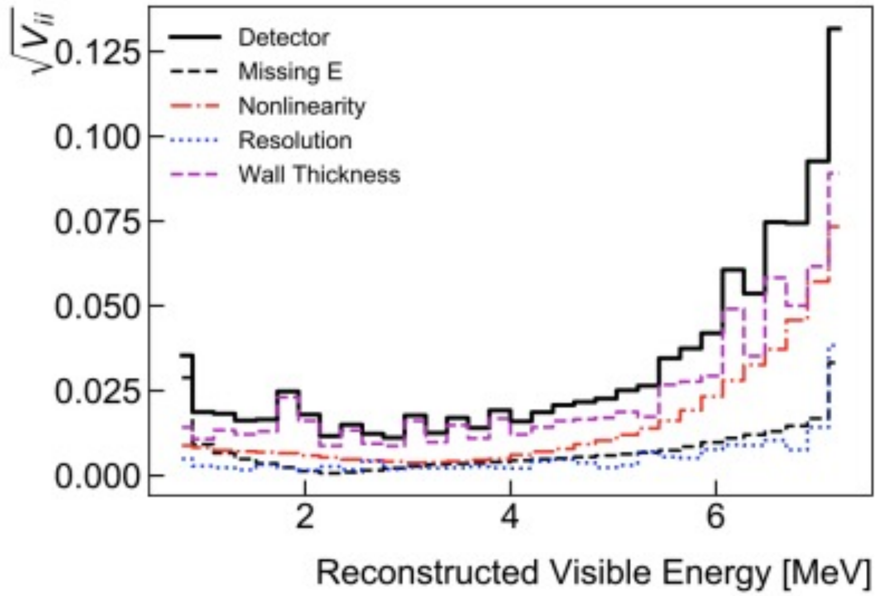
Spectrum Analysis Systematics

Previous Results

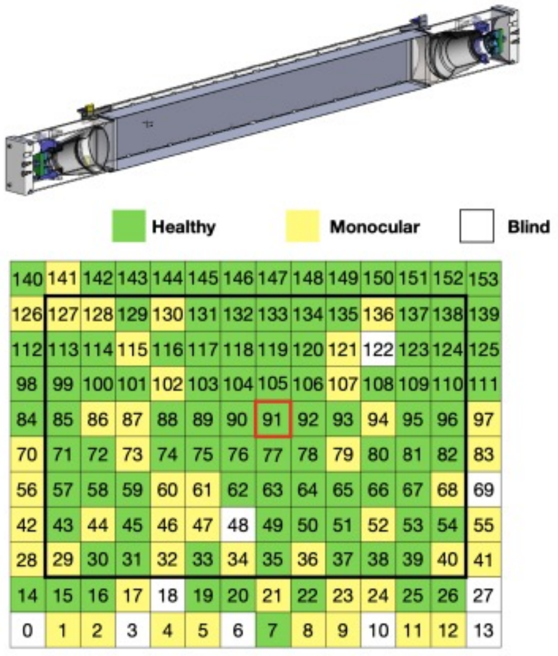


Spectrum Analysis Systematics

Parameter	Section	Uncertainty	Description
Background Normalization	VI B, VI D	1%	Accounts for variation between reactor-off periods
n-H Peak	VI D	3%	Accounts for uncertainty on background subtraction in the n-H peak region
Detector Non-linearity	IV B	0.002	Uncertainty for Birks non-linearity in energy deposition
Cherenkov Contribution	IV B	0.41	Uncertainty on Cherenkov contributions to collected photons
Energy Scale	IV B	0.004	Uncertainty on linear energy scale
Energy Resolution	IV C	5%	Uncertainty in photostatistics contribution to energy-dependent resolution
Energy Loss	IV D	8 keV	Uncertainty in energy lost by escaping 511 keV γ-rays
^{28}Al Activation	IX A	100%	Uncertainty in the amount of ^{28}Al contributing to the spectrum
Non-equilibrium Correction	IX A	100%	Uncertainty in extrapolating $\overline{\nu}_e$ contribution from long-lived fission daughters
Panel Thickness	IV B	0.03 mm	Uncertainty in mass of the panels separating segments
Z Fiducial Cut	V C	25 mm	Uncertainty in the position of events near the edge of the fiducial volume
Energy Threshold	IV B, III G	5 keV	Uncertainty in the segment-by-segment energy threshold cut

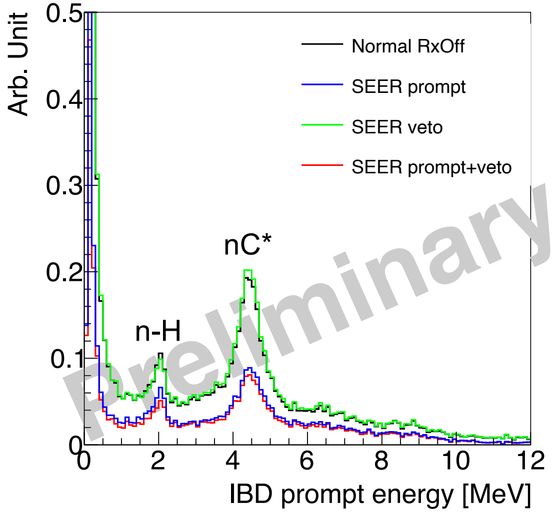
Second Approach: SEER

- The implementation of SEER into the existing analysis presents a great opportunity to improve our current results (statistics and S:B).
- Lacks energy and position reconstruction capabilities
- Provides a good handle on particle identification (great background suppression)



PRD Data - 97:47:10

- Prompt and delayed signal time coincidence
- Exclude prompt signals containing high PSD events
- Veto events coincident with cosmogenic muons and neutrons
- Require proximity between prompt and delayed signals
- Reject events outside of the fiducial volume



SEER prompt PSD reduces background by 2x

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PROSPECT

IBD Event Selection + SEER - New Cuts Needed

- The implementation of SEER into the existing analysis presents a great opportunity to improve our current results.

- Existing cuts:
  - n-Li capture
  - Prompt PSD cut
  - IBD prompt-delay distance
  - Prompt-delay timing difference
  - Fiducial volumes
- Existing Vetoes
  - Muon veto
  - n-Li capture veto
  - n-p recoil veto
  - Pileup veto

+

New:

- SEER cut:
  - Prompt SEER PSD cut
- SEER veto:
  - Neutron (capture/recoil) veto

Cut optimization including new SEER cuts - results

- In order to optimize the IBD selection cuts with the new SEER analysis the following data and metrics were considered:
  - 20% of the data used for previous results
  - Signal to cosmogenic background ratio (S:CB)
  - Signal to accidental background ratio (S:AB)
  - Effective IBD counts

$$\text{IBD}_{\text{Effective}} = \sum_{0.8MeV}^{7.2MeV} \frac{1}{(\sigma_{\text{IBD}}/\text{IBD})^2}$$

Cut/Veto Name	Status
Muon Veto Time	Unchanged
Neutron Veto Time	Improved
Recoil Veto Time	Improved
SE Recoil Veto Time	New
IBD Neutron Capture: PSD	Unchanged
IBD Neutron Capture: Energy	Improved
IBD PSD	Improved
IBD SE PSD	New
IBD Distance	Improved
IBD Fiducial	Improved

Improved

Unchanged

New

Combined DS+SEER Analysis Results and Summary

	IBD Effective	IBD Effective/ calendar day	Total IBD counts	Total IBD counts/ calendar day	S/CB (Total)	S/AB (Total)
Previously Published PROSPECT Results	18100	189	50560	529	1.37	1.78
Data Splitting	28464	302	64323	670	2.35	1.89
SEER	26779	280	47996	502	3.24	3.74
Data Splitting + SEER	35875	374	60650	632	3.81	4.25

- First implementation of new DS+SEER optimized provided the following improvements:
  - IBD counts ~**(x1.2)**
  - IBD effective counts ~**(x2)**
  - Signal to cosmogenic background (S/CB) ~**(x2.8)**
  - Signal to accidental background (S/AB) ~**(x2.4)**
- **This new analysis is expected to have a big impact on both spectrum and sterile neutrino oscillation results!**