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

Diego Venegas Vargas

The University of Tennessee Knoxville

On behalf of the PROSPECT collaboration

August 30th – TAUP Conference 2023

U.S. DEPARTMENT OF ENERGY

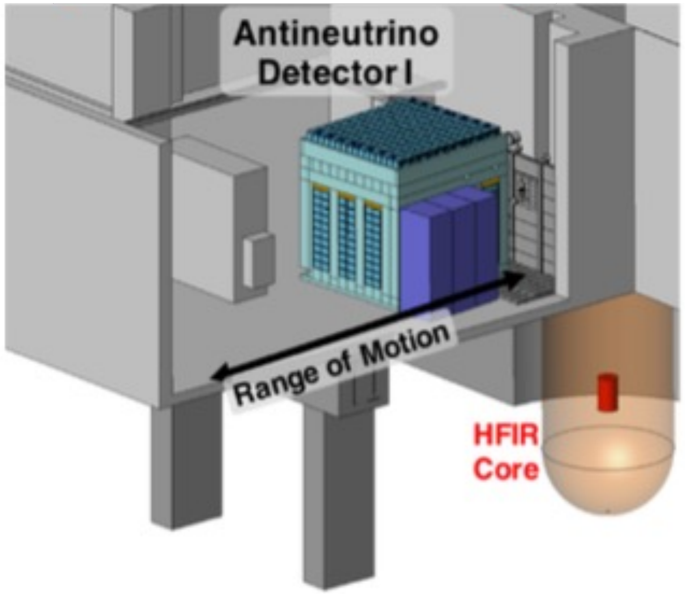
Physics Division

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

PROSPECT Detector at HFIR

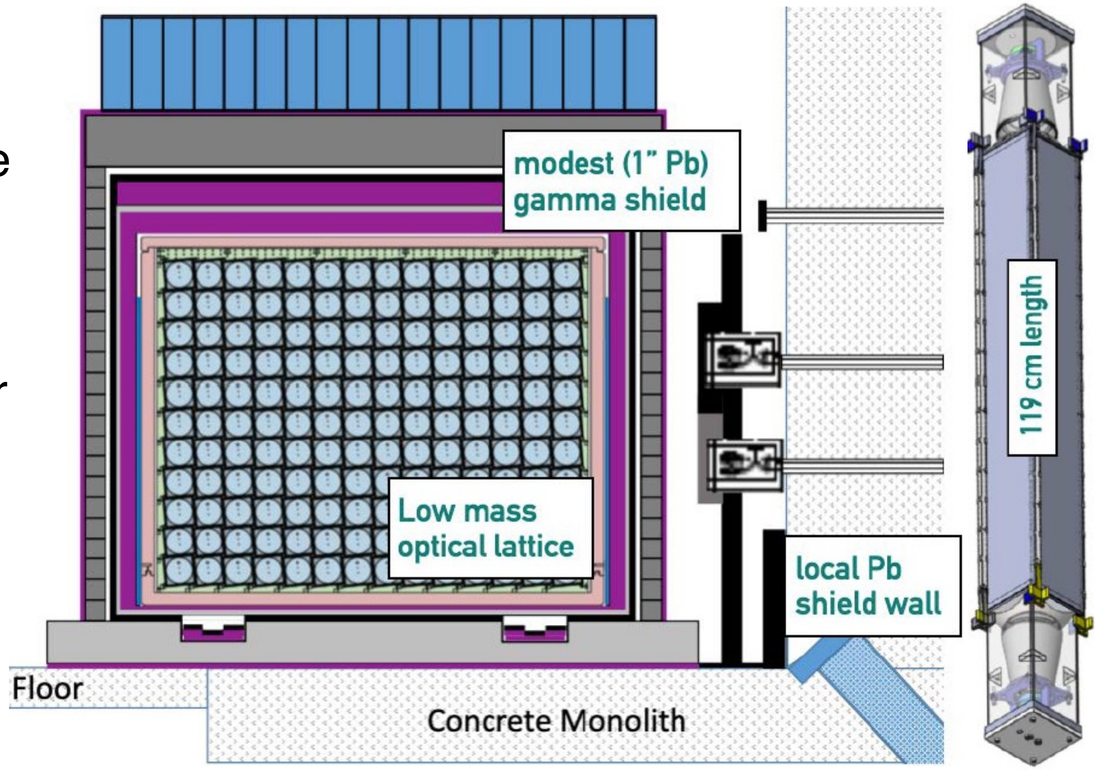
PROSPECT

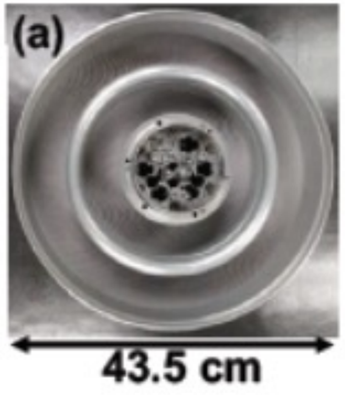
Layout of the PROSPECT experiment

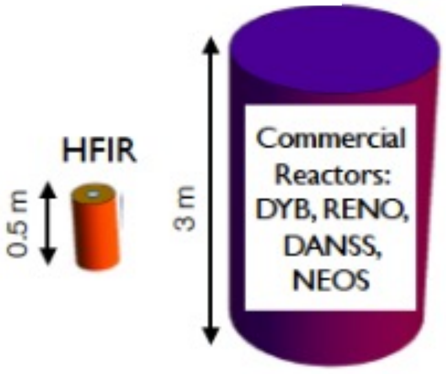


- 93% 235U Fuel
- 85 MW thermal powe
- Compact core
- Huge flux in the few MeV range
- ~50% duty cycle for BG measurements

Schematic of the active detector volume





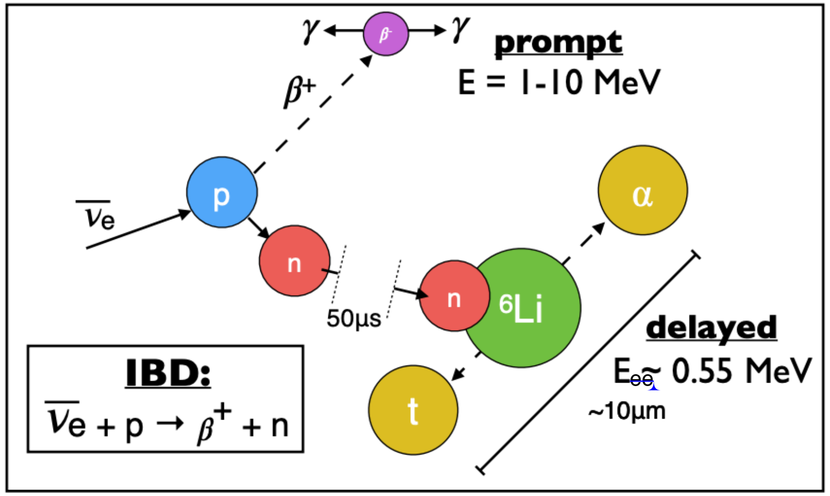


14 x 11 array of 6Li doped liquid scintillator for detecting reactor antineutrinos (6.7-9.2 m from compact highly enriched uranium reactor core)

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

Antineutrino Detection

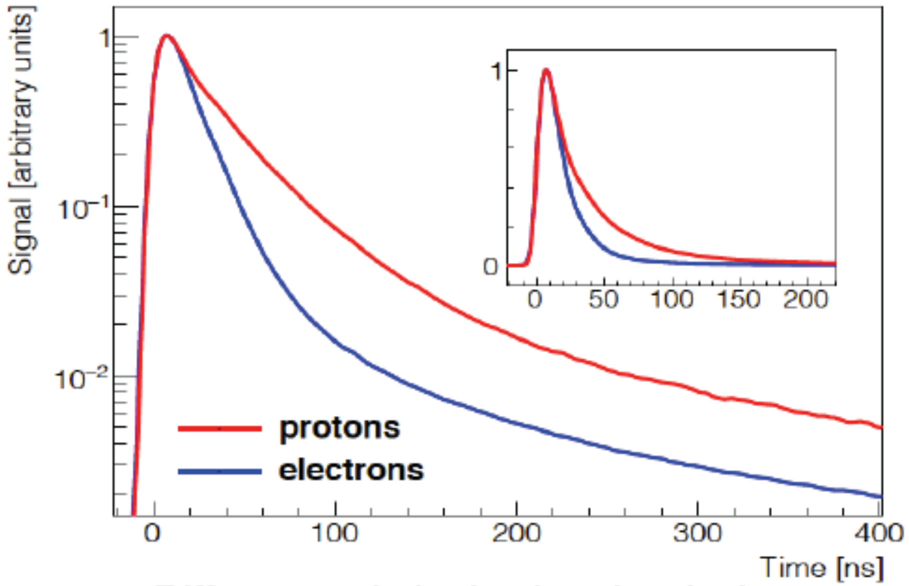
Schematic of the IBD process



- 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)

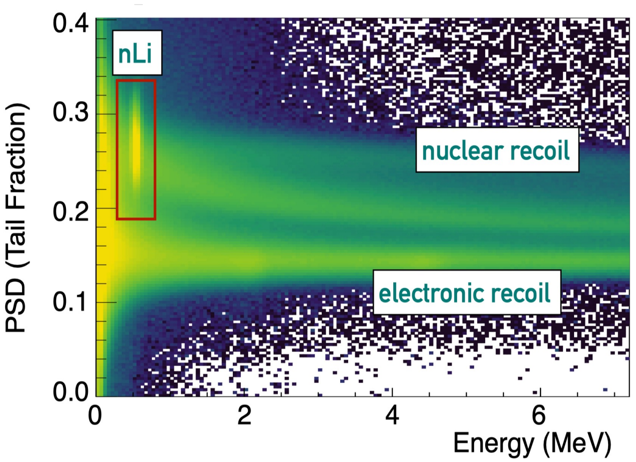
M. Andriamirado et al. (PROSPECT Collaboration), Phys. Rev. D 103, 032001 (2021).

IBD Event Selection

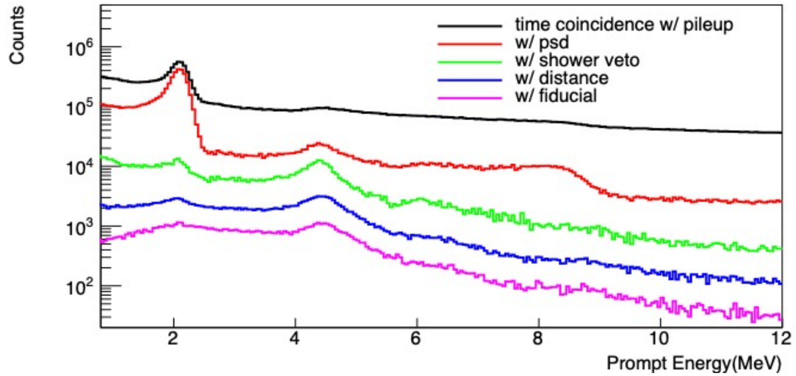
- **IBD Topology-based cuts**
  - Neutron Capture Region
  - Prompt PSD
  - Prompt-Delayed signal distance
  - Prompt-Delayed Timing
  - Fiducial z cut

- **Veto cuts**
  - Muon Veto Time
  - Neutron Veto Time
  - Recoil Veto time

Prompt PSD Cut

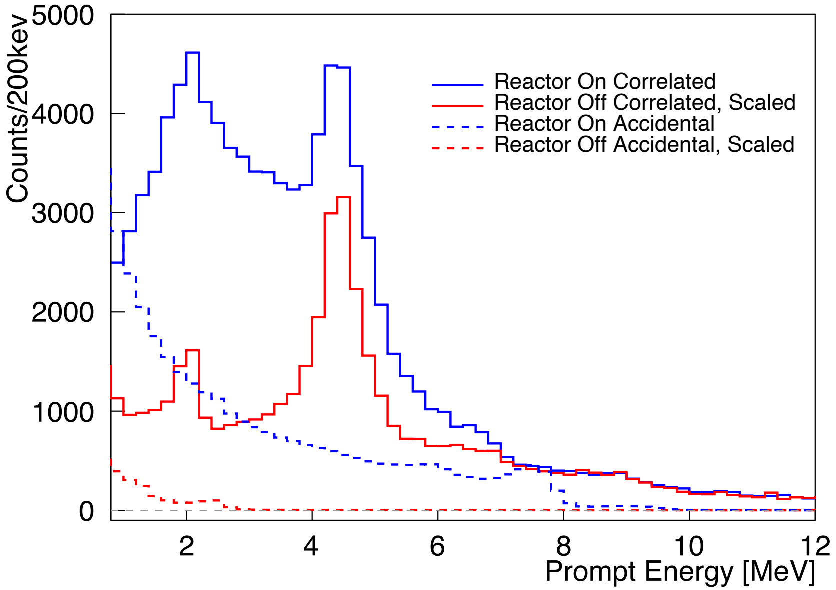


Prompt Energy Distributions Under Different Cuts



- 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

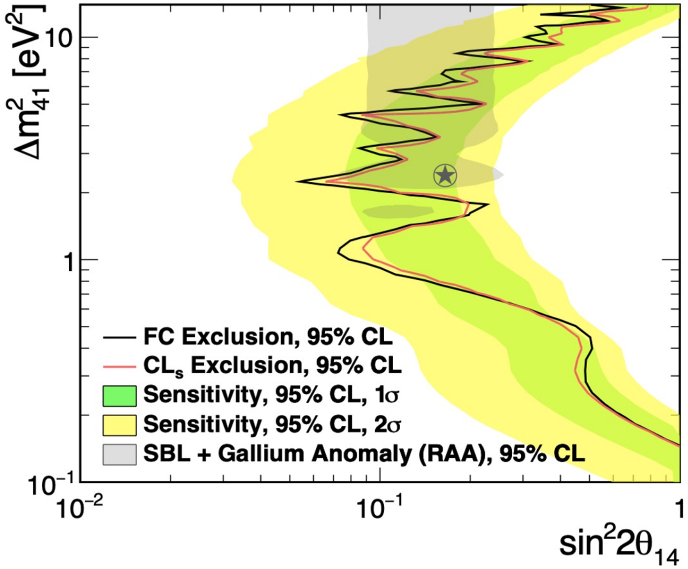


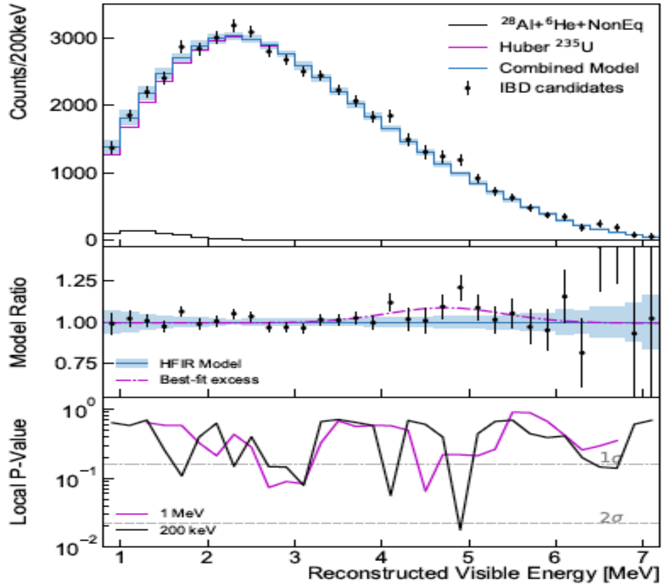
- 95.65 reactor-on calendar days, 73.09 reactor-off
- >50,000 IBD events
- Signal to background ratio > 1

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
- Performed 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

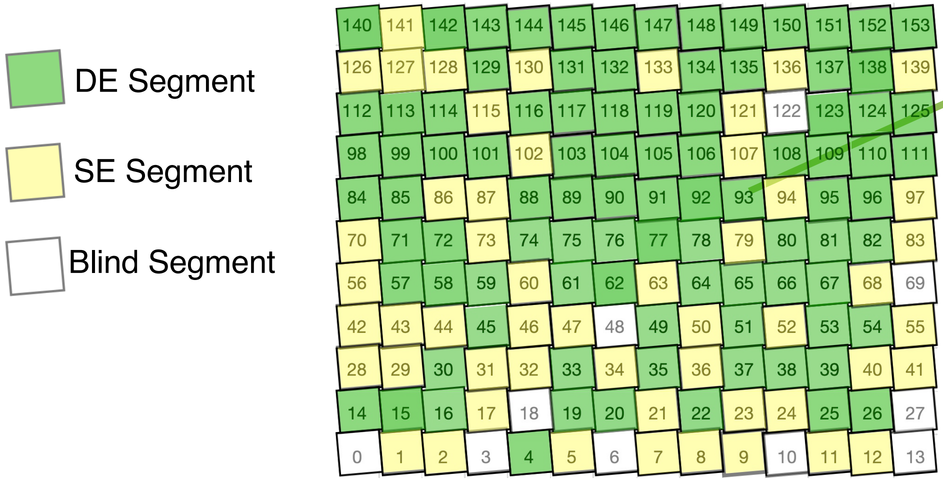
Correlated Background Study

Antineutrino Directionality

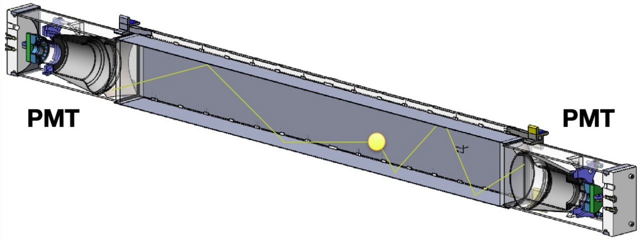
Motivation for a final PROSPECT-I Analysis

- 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

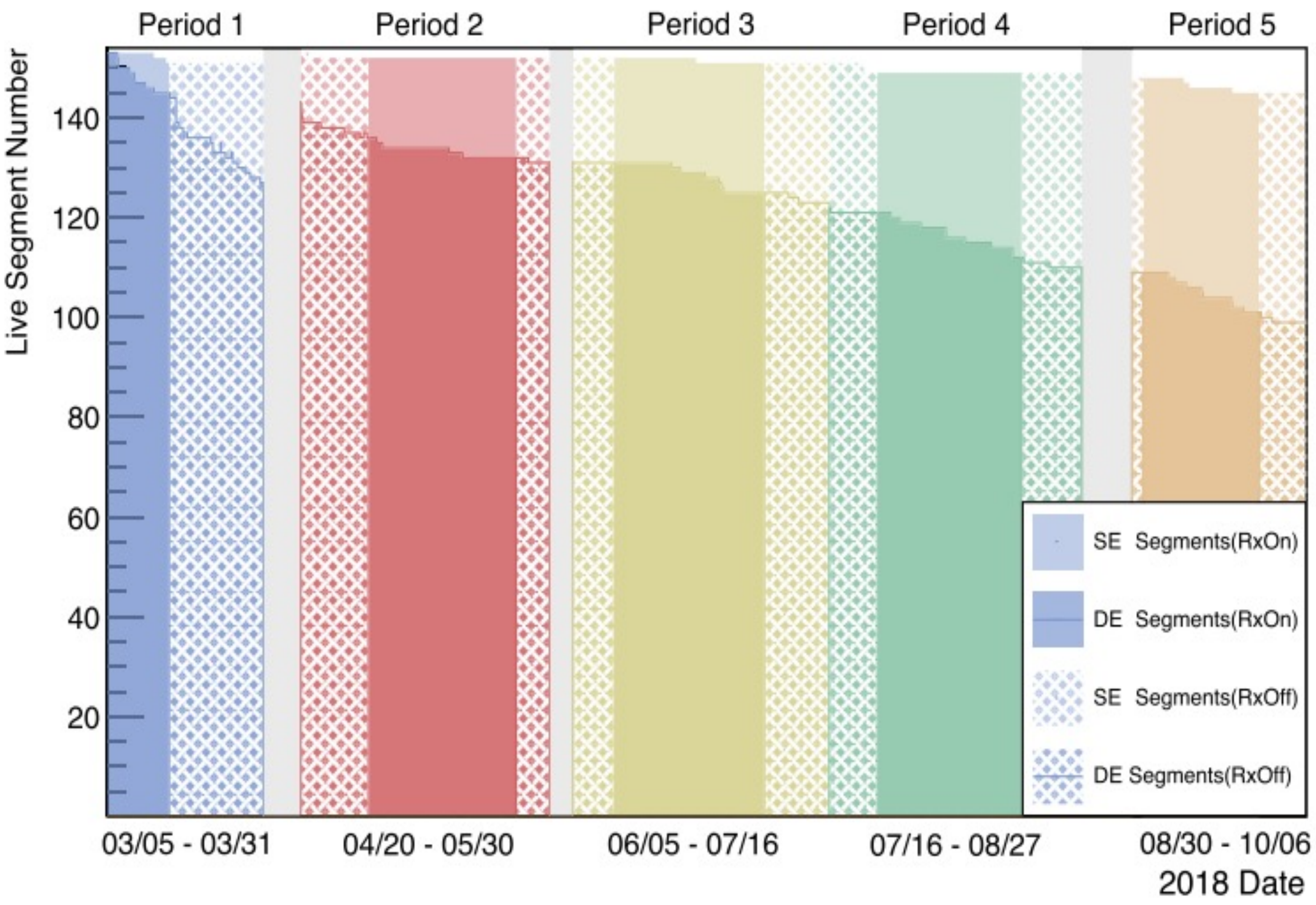


Some segments coupled to one PMT or both switched off due to scintillator leakage into PMT housing.

- 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

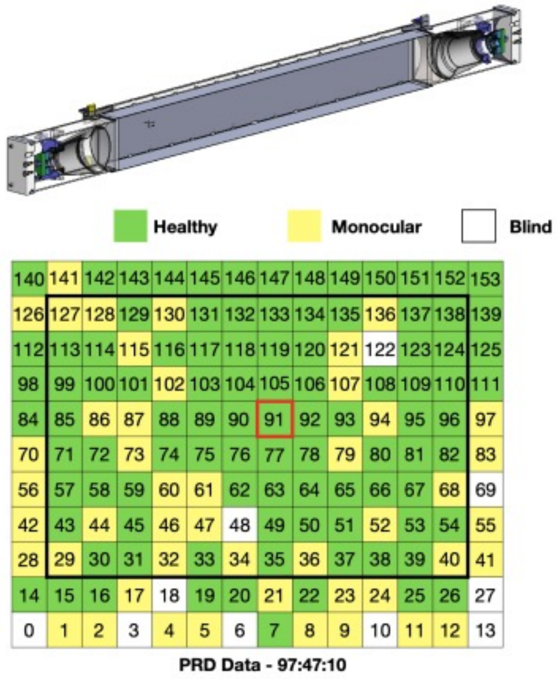
- Split PROSPECT-I data into distinct periods in order to recover statistics.
- Maximize number of live segments in each period

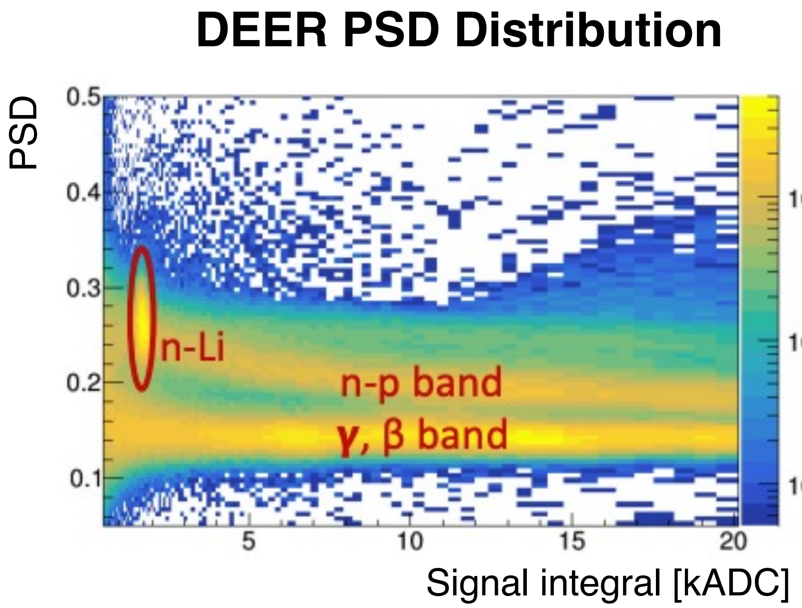
Splitting Criteria

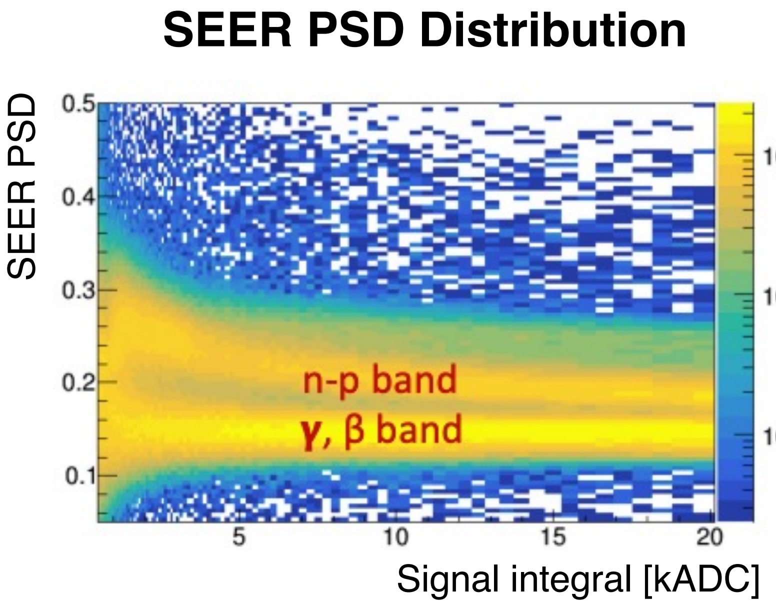
- Each period should start immediately after a new calibration campaign
- Each period must contain one full RxOn cycle
- All periods should have RxOff data before and after each corresponding RxOn cycle
  - Period 1 is an exception since there is no prior RxOff data available.
- Keep ratio of RxOff/RxOn 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) PROSPECT

- 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)

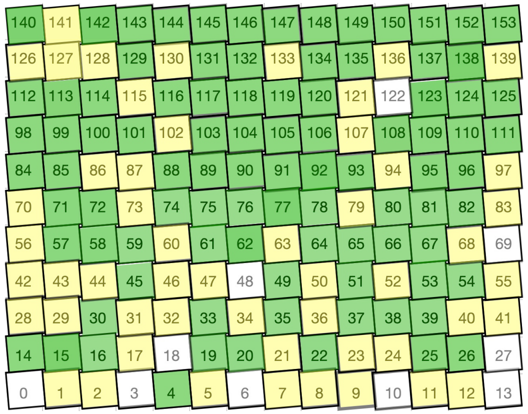






Detector Configuration for Each Period

Detector Configuration Used for Previous Analysis

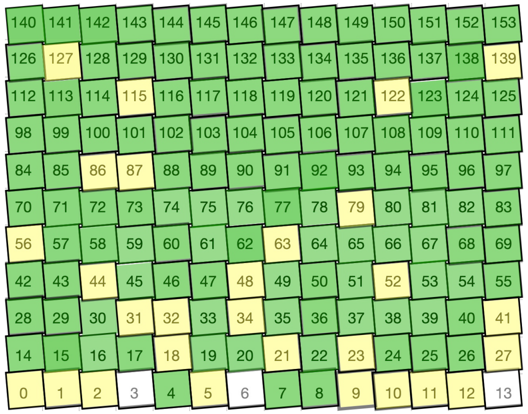


- Previous analysis did not make use of single ended segments.
- This new method takes full advantage of all the data collected by the PROSPECT detector

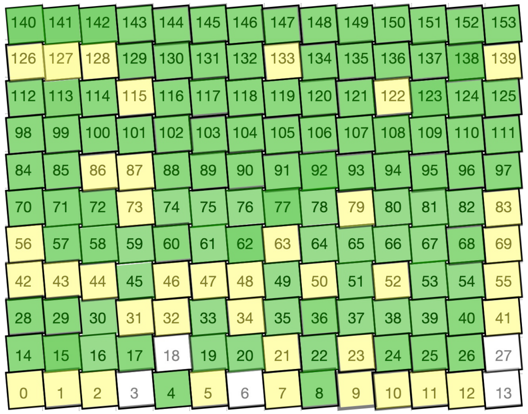
Period 1

Period 2

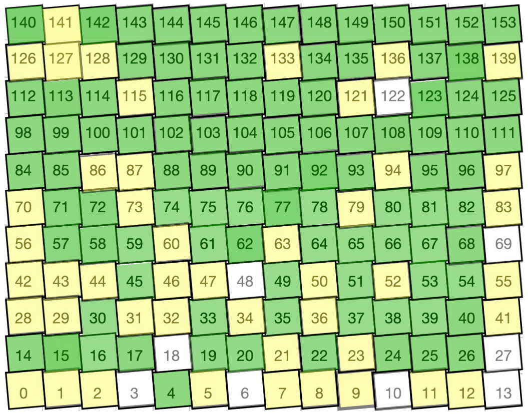
Period 3



Period 4



Period 5



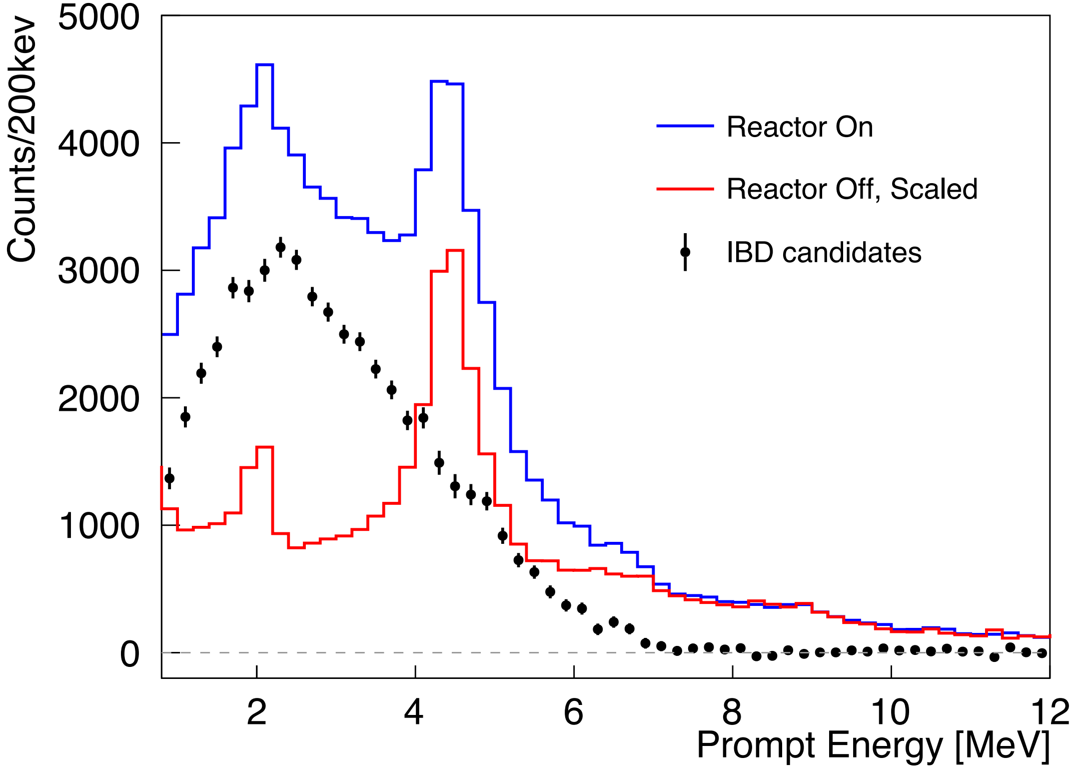
DE Segment

SE Segment

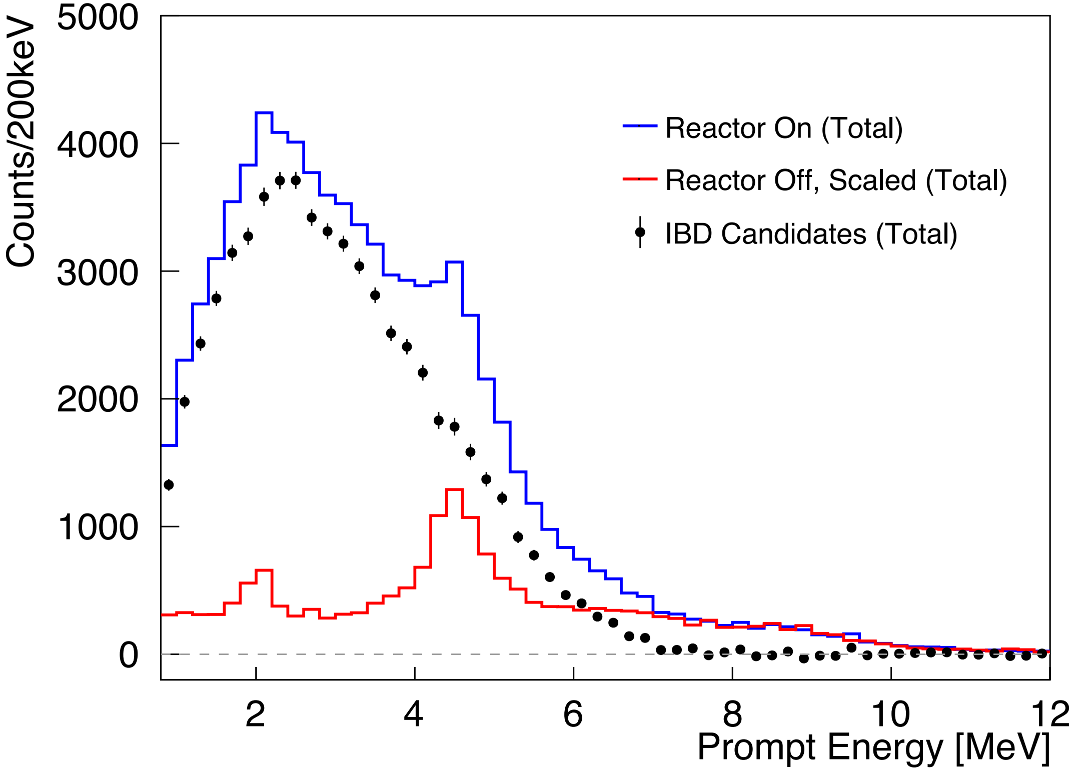
Blind Segment

Multi-Period Spectrum Analysis

Previous PROSPECT Analysis



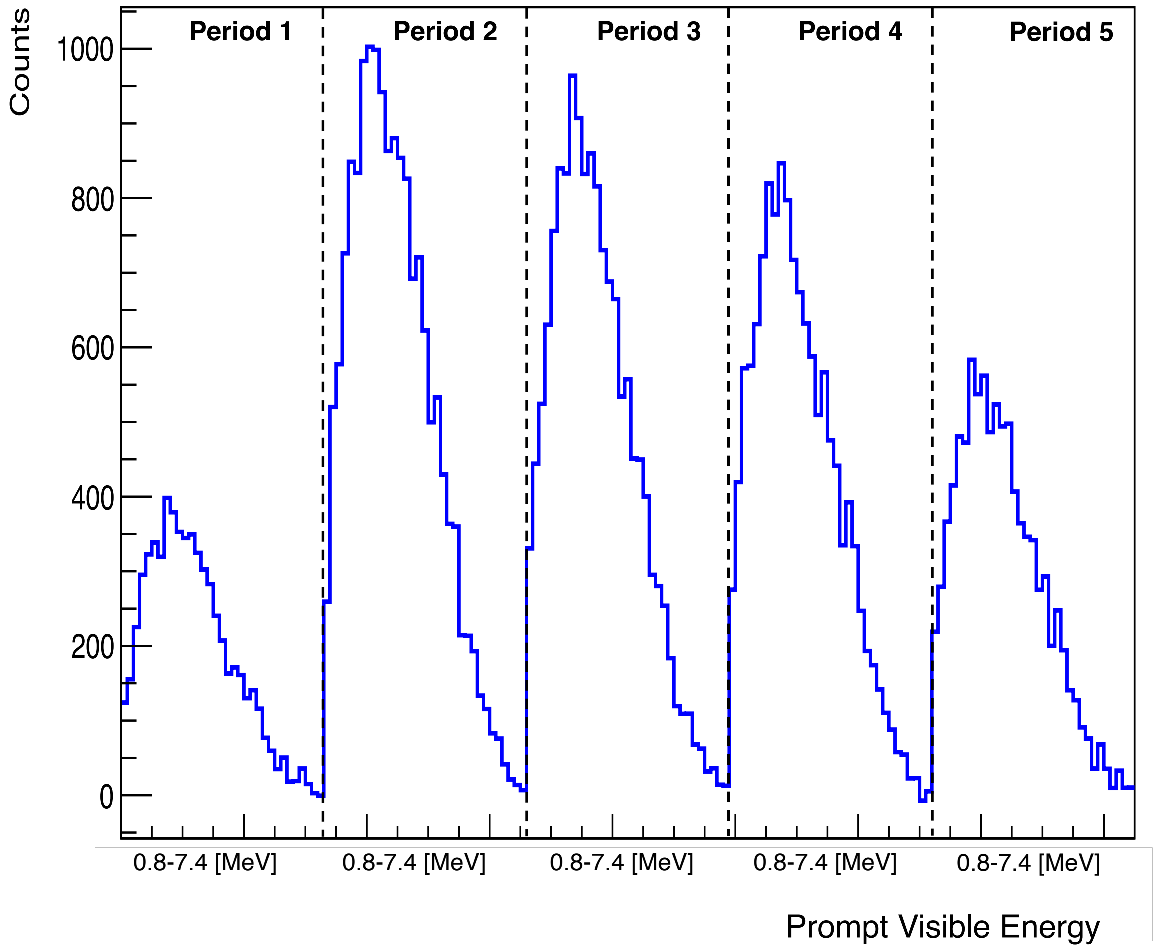
New DS+SEER Multi-Period Analysis



Great background reduction provided by new analysis

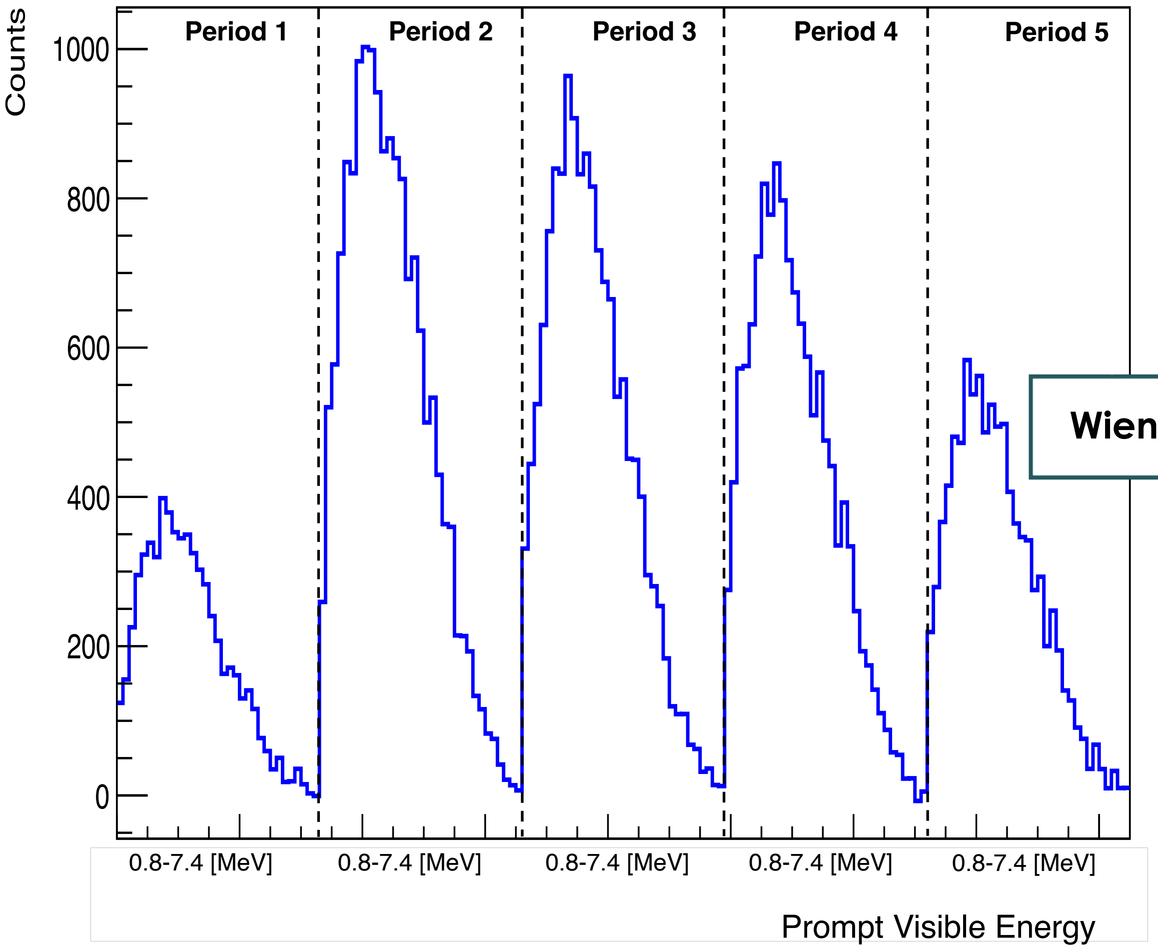
- Implementation of new DS+SEER optimized provided the following improvements:
  - IBD counts ~**(x1.2)**
  - IBD effective counts ~**(x2)**
  - Signal to cosmogenic background (S/CB) ~**(x2.8)**
  - Signal to accidental background (S/AB) ~**(x2.4)**

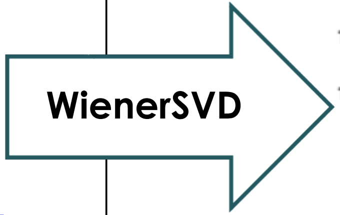
Multi-Period Spectrum Analysis: Unfolded Spectrum

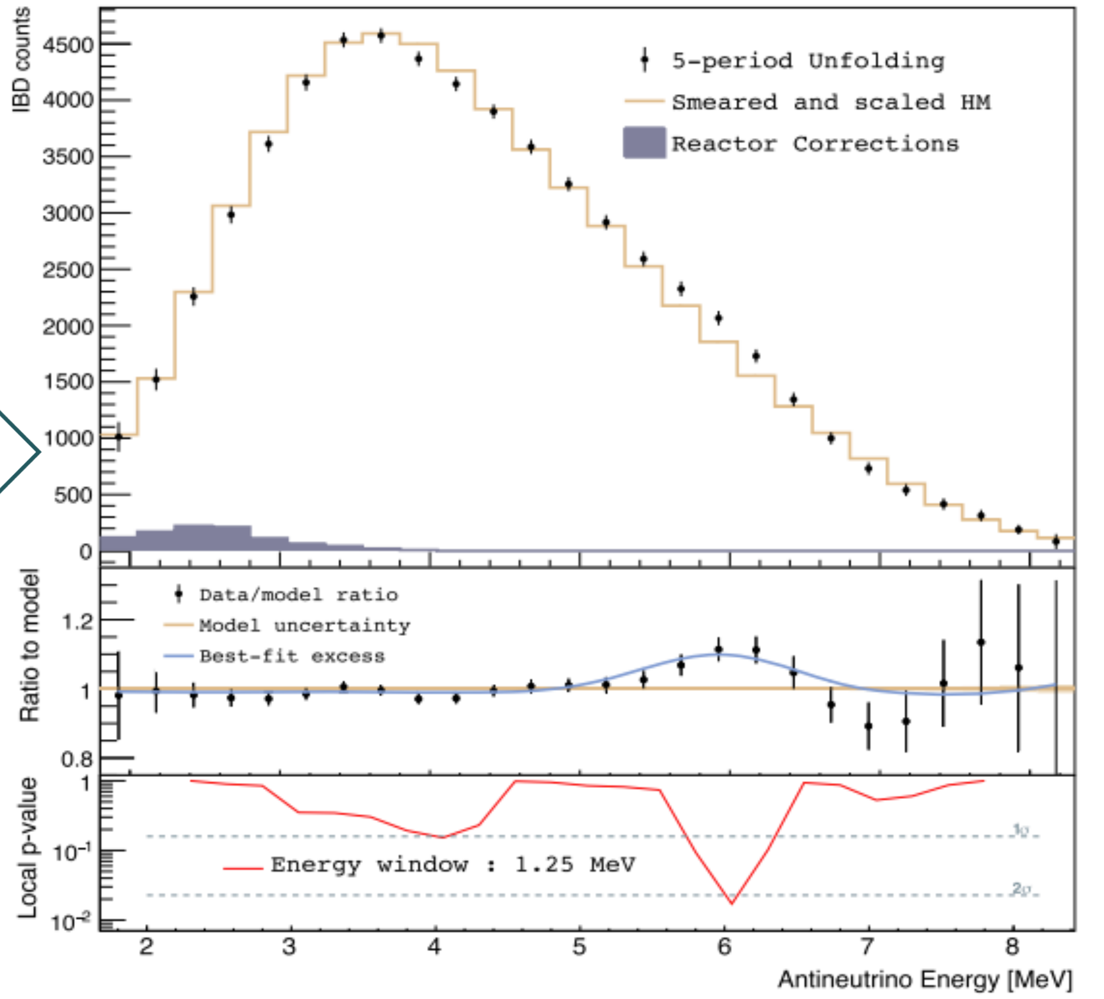


- The implementation of a period-by-period analysis allows for the treatment of each period as an independent experiment.
- Following the work done during the joint spectrum analysis, a new unfolding framework has been developed to jointly unfold the prompt spectrum from each period into one final antineutrino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

Multi-Period Spectrum Analysis: Results





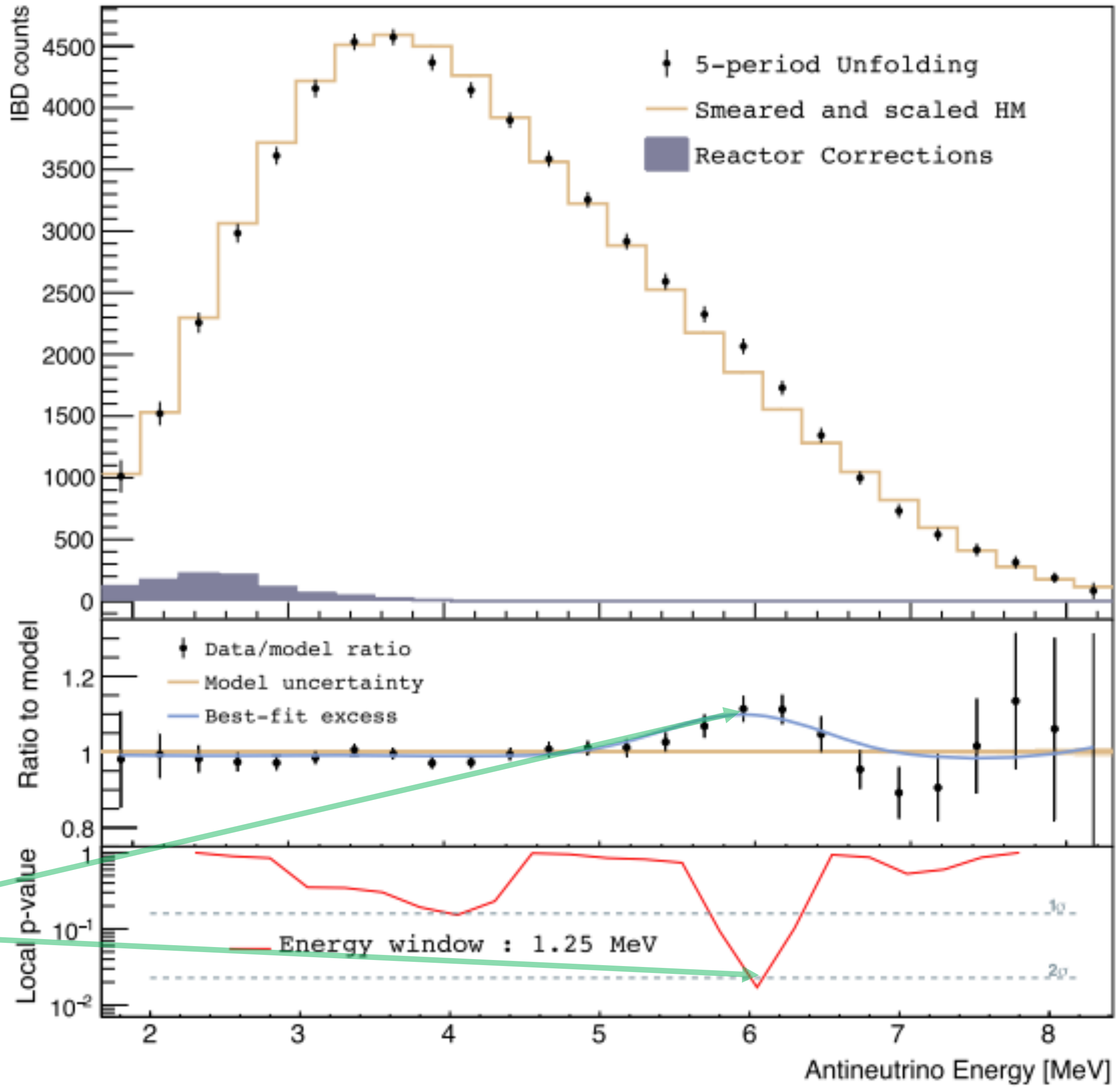


[Phys. Rev. Lett. 131, 021802 (2023)]

Oak Ridge National Laboratory

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.
- One of the most precise measurement of the antineutrino spectrum of Uranium-235



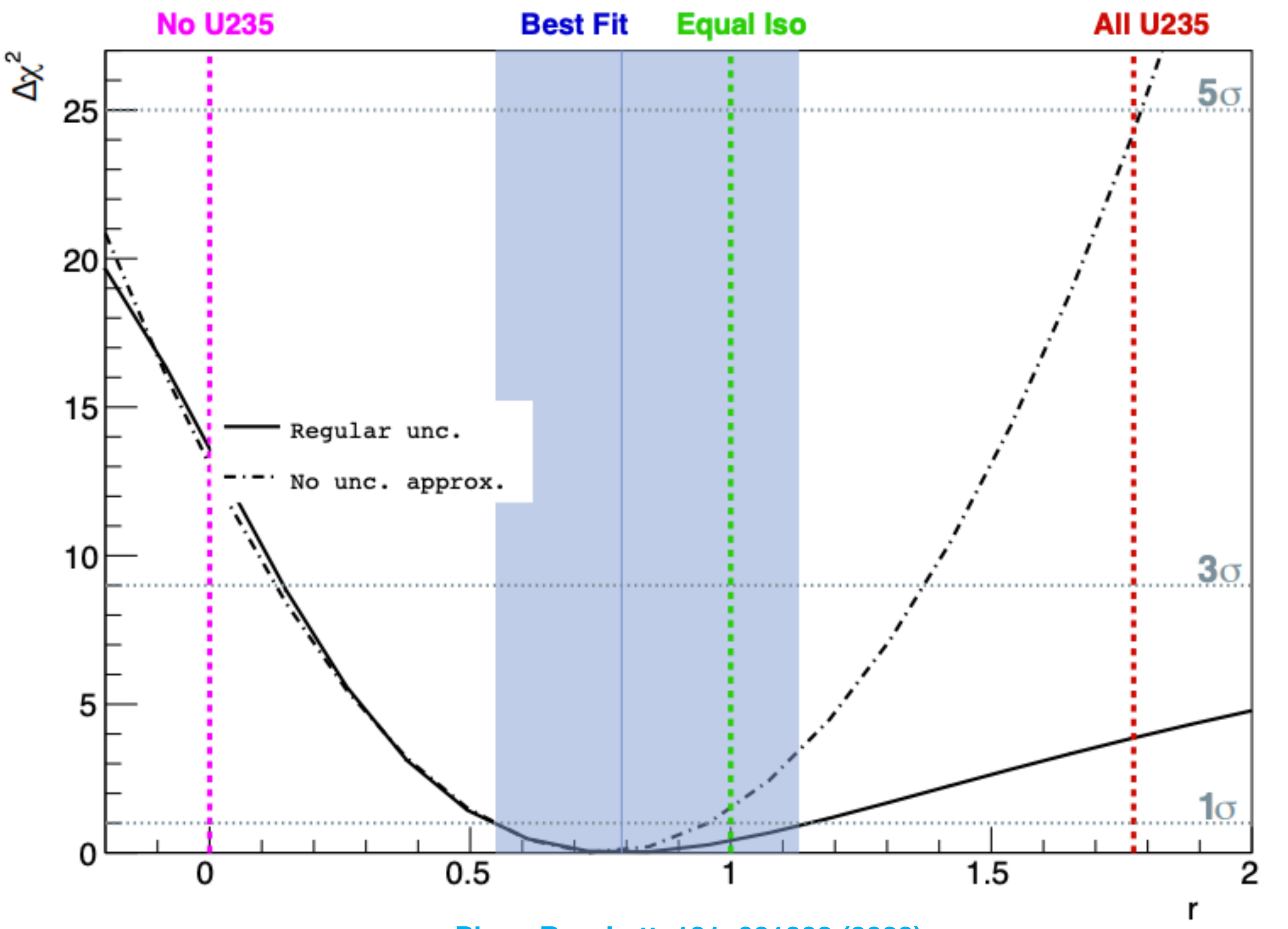
Excess wrt model observed at ~ 6 MeV

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)

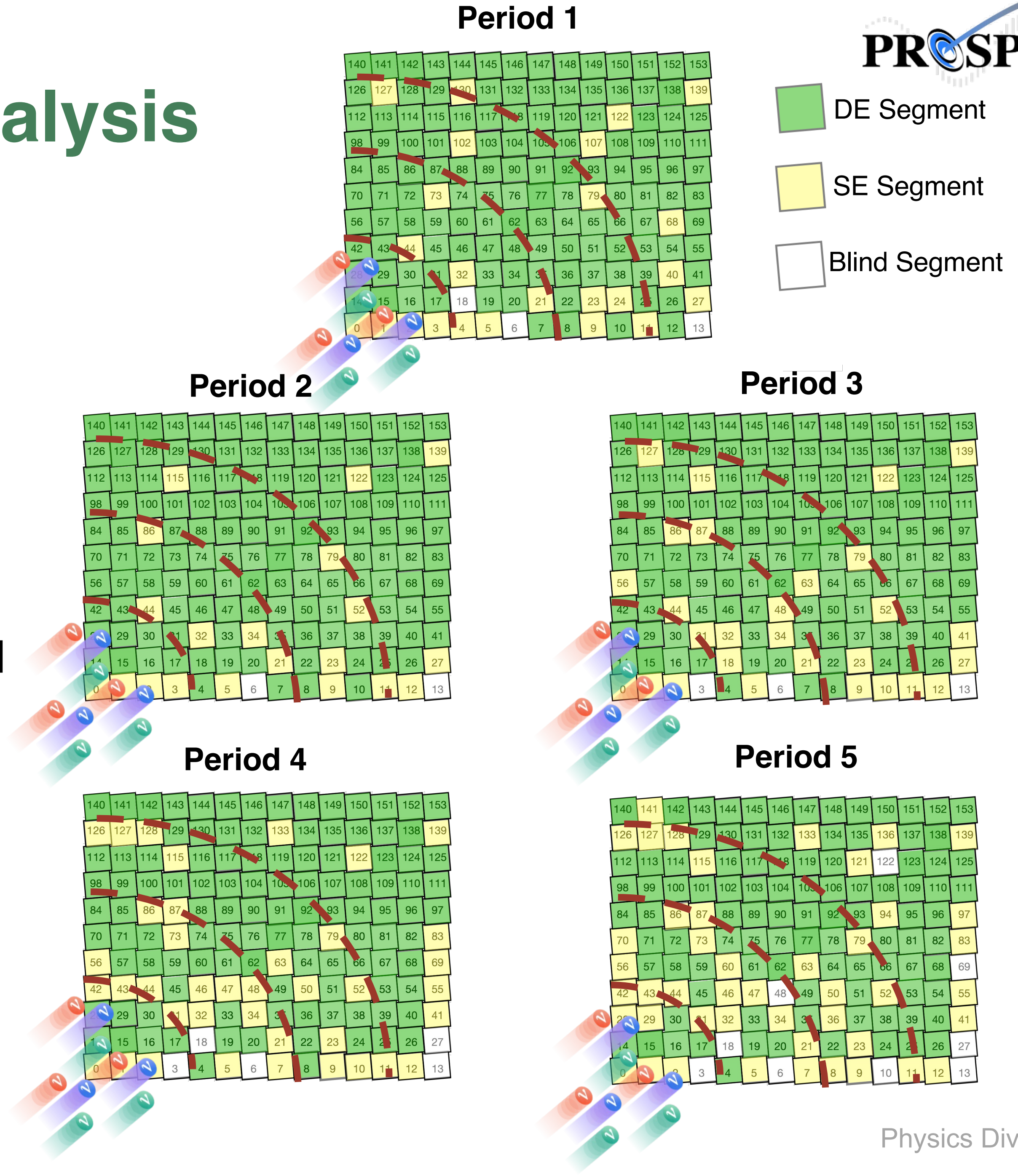
Summary and Conclusions

- PROSPECT-I data 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.yale.edu

Multi-Period Oscillation Analysis

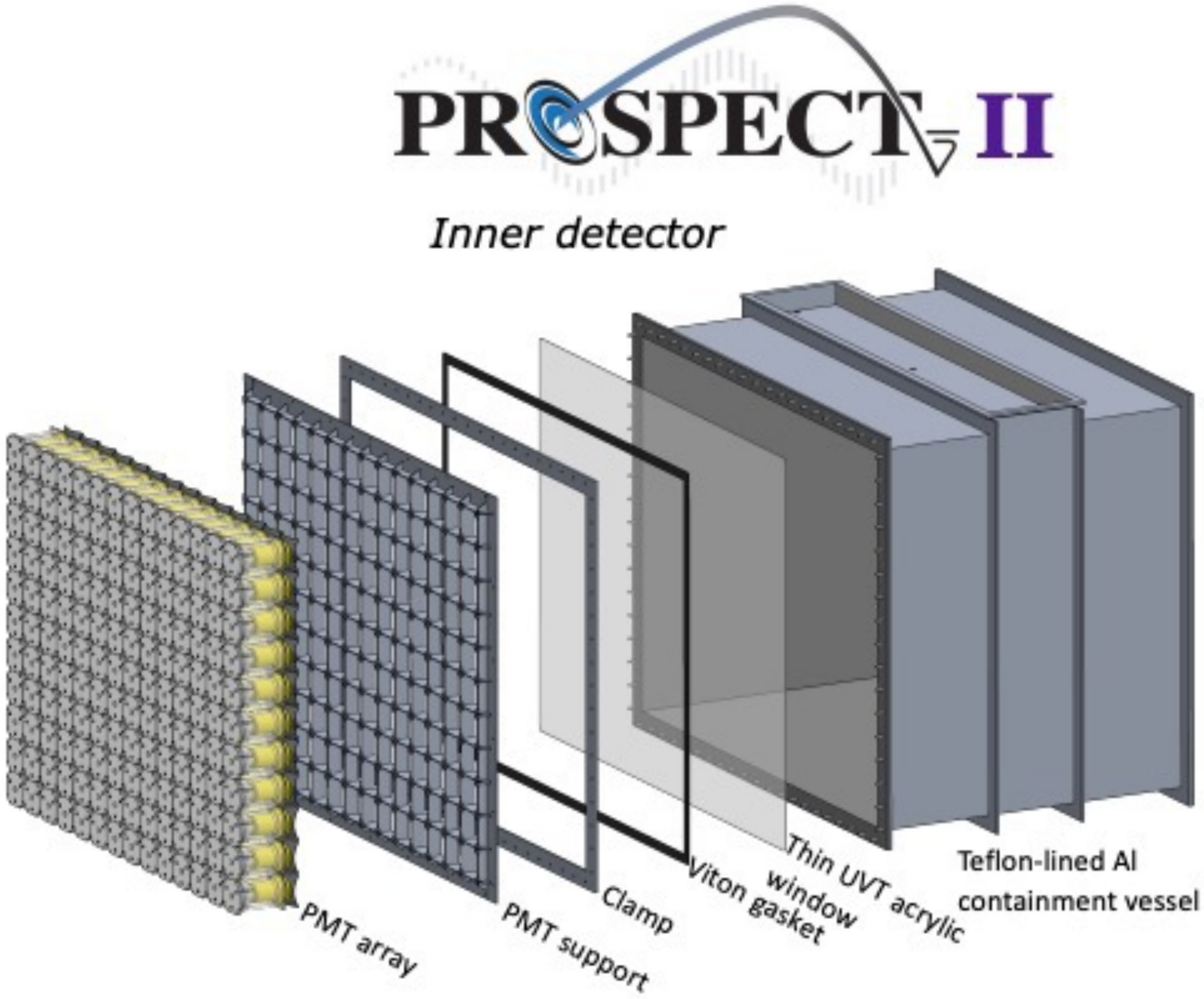
- Previous oscillation measurement was statistics-limited. Increase in effective statistics (x2) will improve current sensitivity
- Multi-period analysis allows for the use of additional baseline bins which result in a sensitivity gain.
- A new framework capable of producing a joint oscillation analysis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



PROSPECT

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

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

- 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)**

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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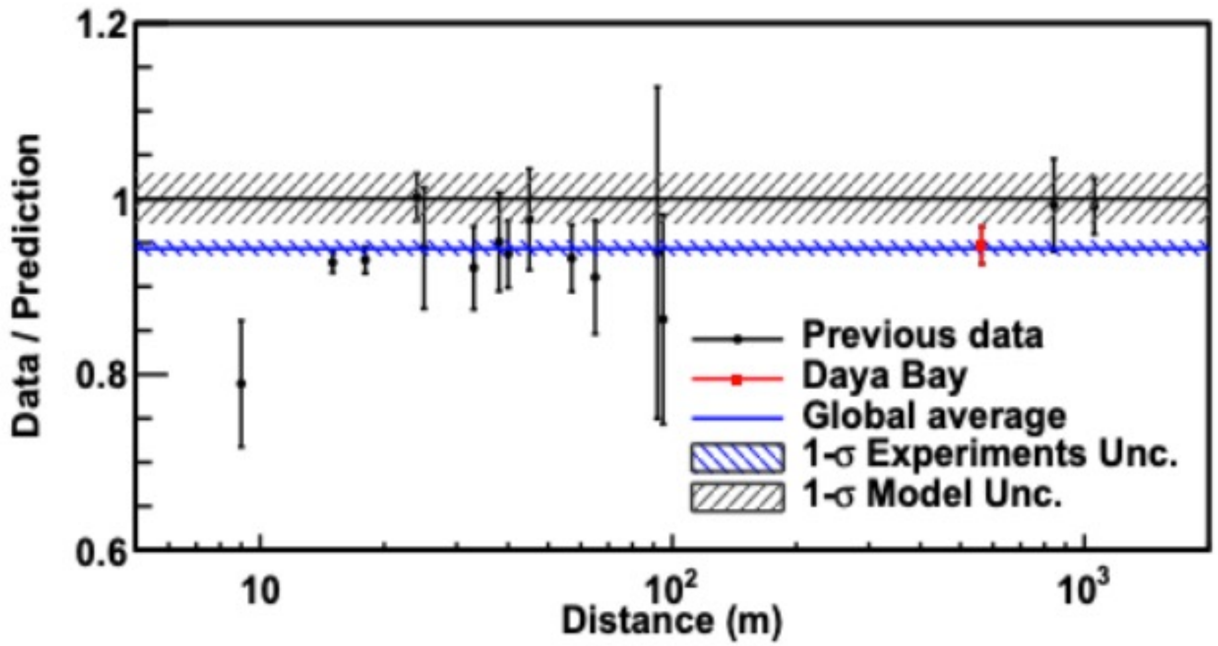


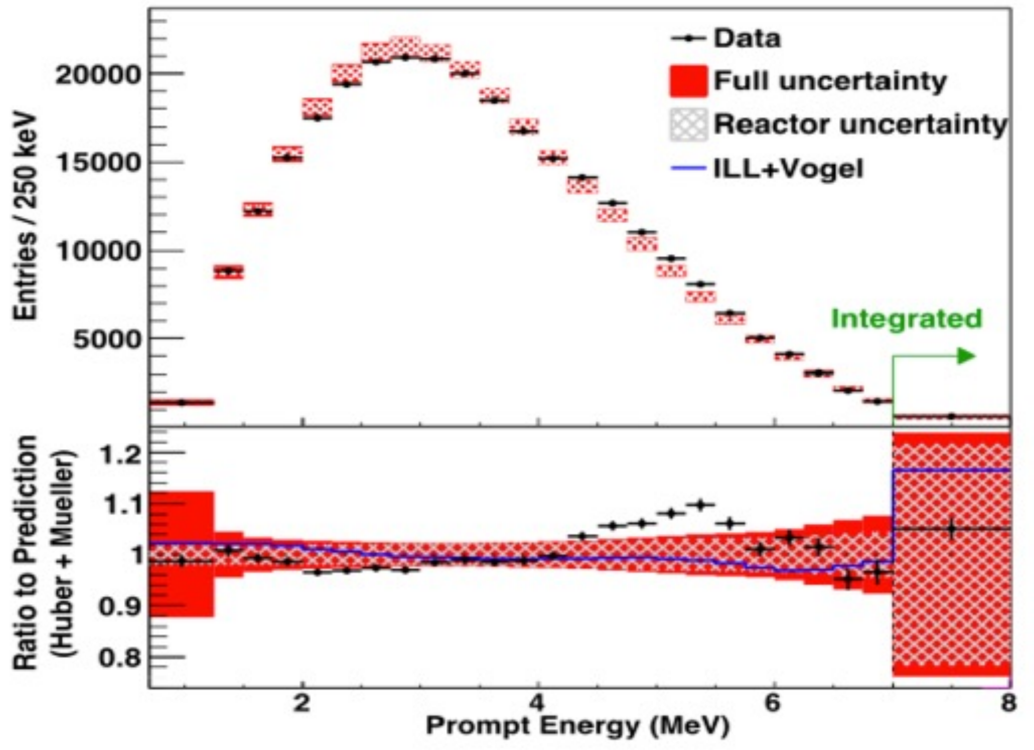
Feng Peng An et al. Measurement of the Reactor Antineutrino Flux and Spectrum at Daya Bay. Phys. Rev. Lett., 116(6):061801, 2016, 1508.04233.

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

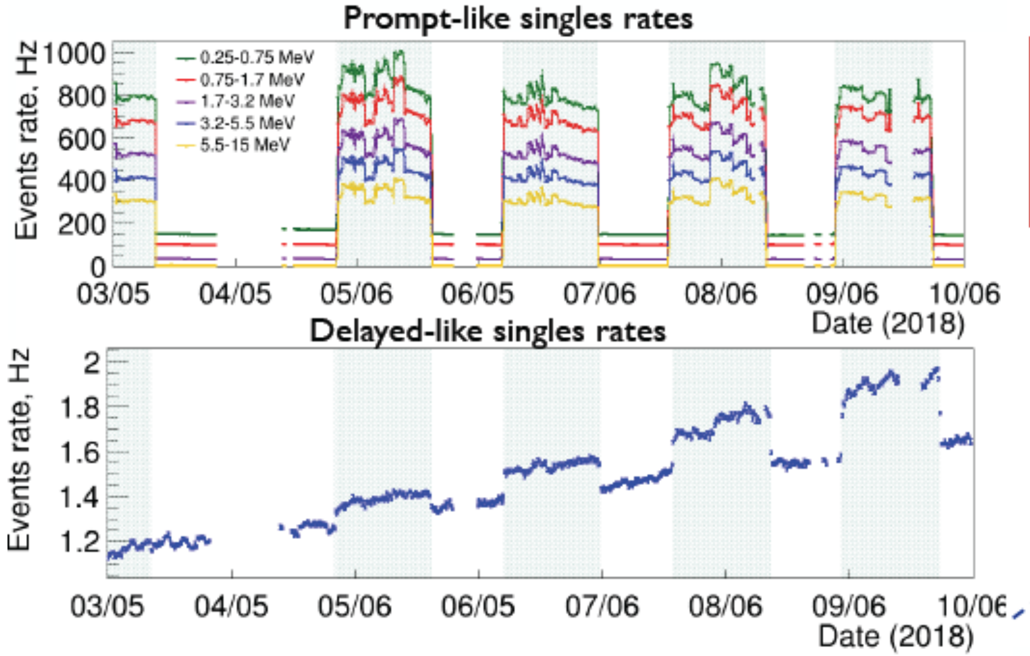
Physics Goal 2:
- To make a precise measurement of the antineutrino spectrum from a HEU reactor (mainly ^{235}U).

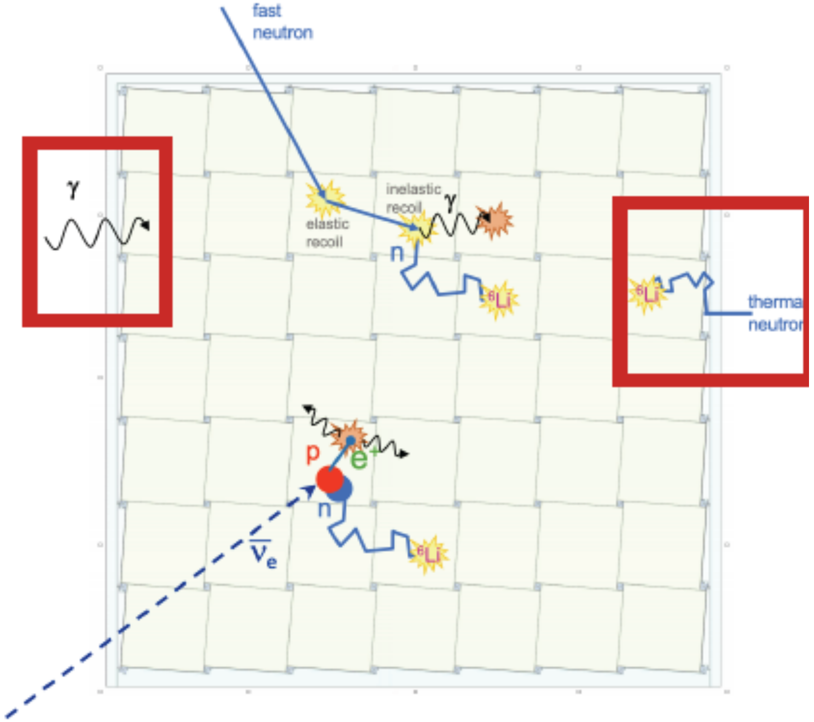


Feng Peng An et al. Measurement of the Reactor Antineutrino Flux and Spectrum at Daya Bay. Phys. Rev. Lett., 116(6):061801, 2016, 1508.04233.

Accidental Backgrounds

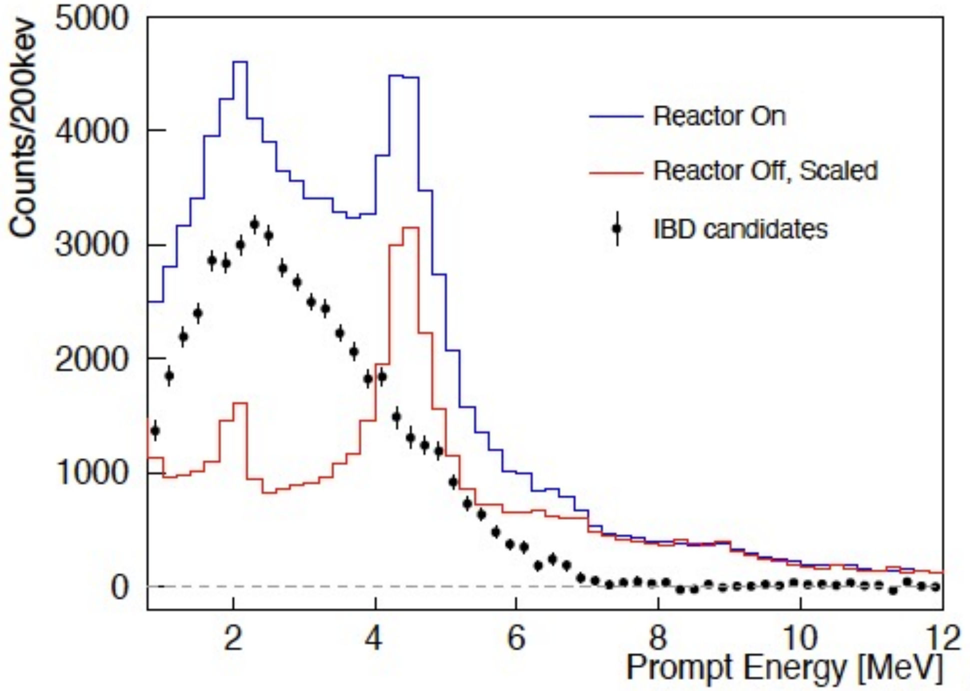
- Random coincidence of gamma and nLi-like signal
  - Variation in delayed signals from gammas bleeding into nLi PSD region
- Estimate precisely using off-window method
  - IBD offset by few hundred <u>us</u>, accidentals offset by 1-2 <u>seconds</u>

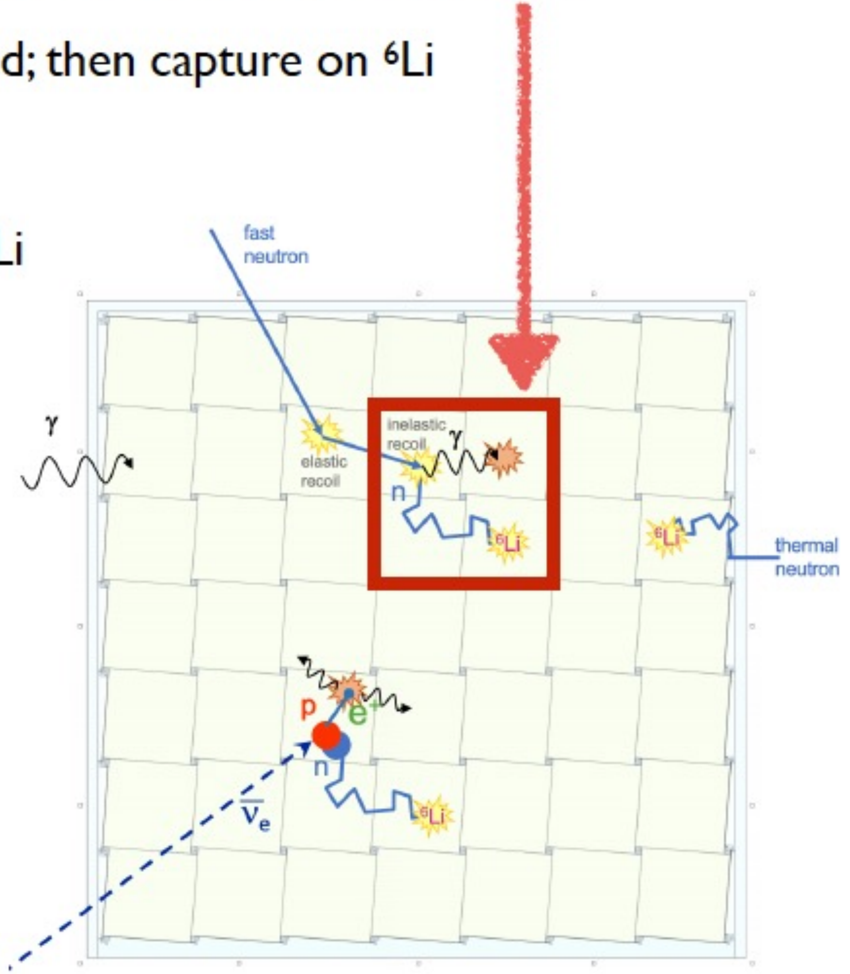




Correlated Backgrounds

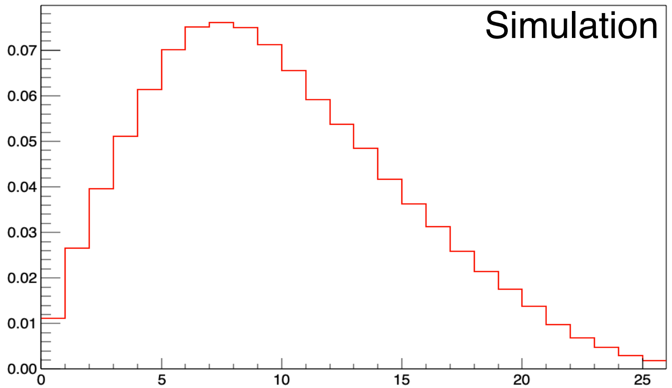
- Fast neutron produced background:
  - Inelastic scatter off C-12 gives 4.5MeV gamma; then captures on ^{6}Li
  - n-p scatter in low side of high PSD band; then capture on ^{6}Li
- Multi-neutron background:
  - First neutron captures on H, next on ^{6}Li



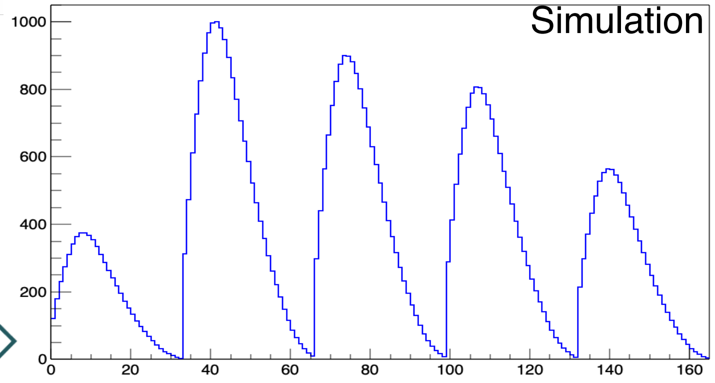


Multi-Period Spectrum Analysis: WienerSVD Unfolding Technique

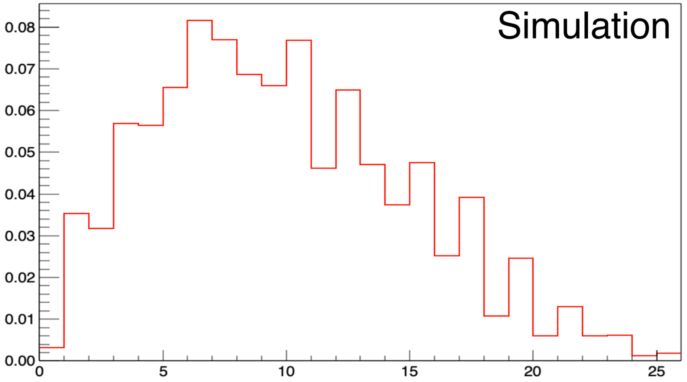
True Spectrum S



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

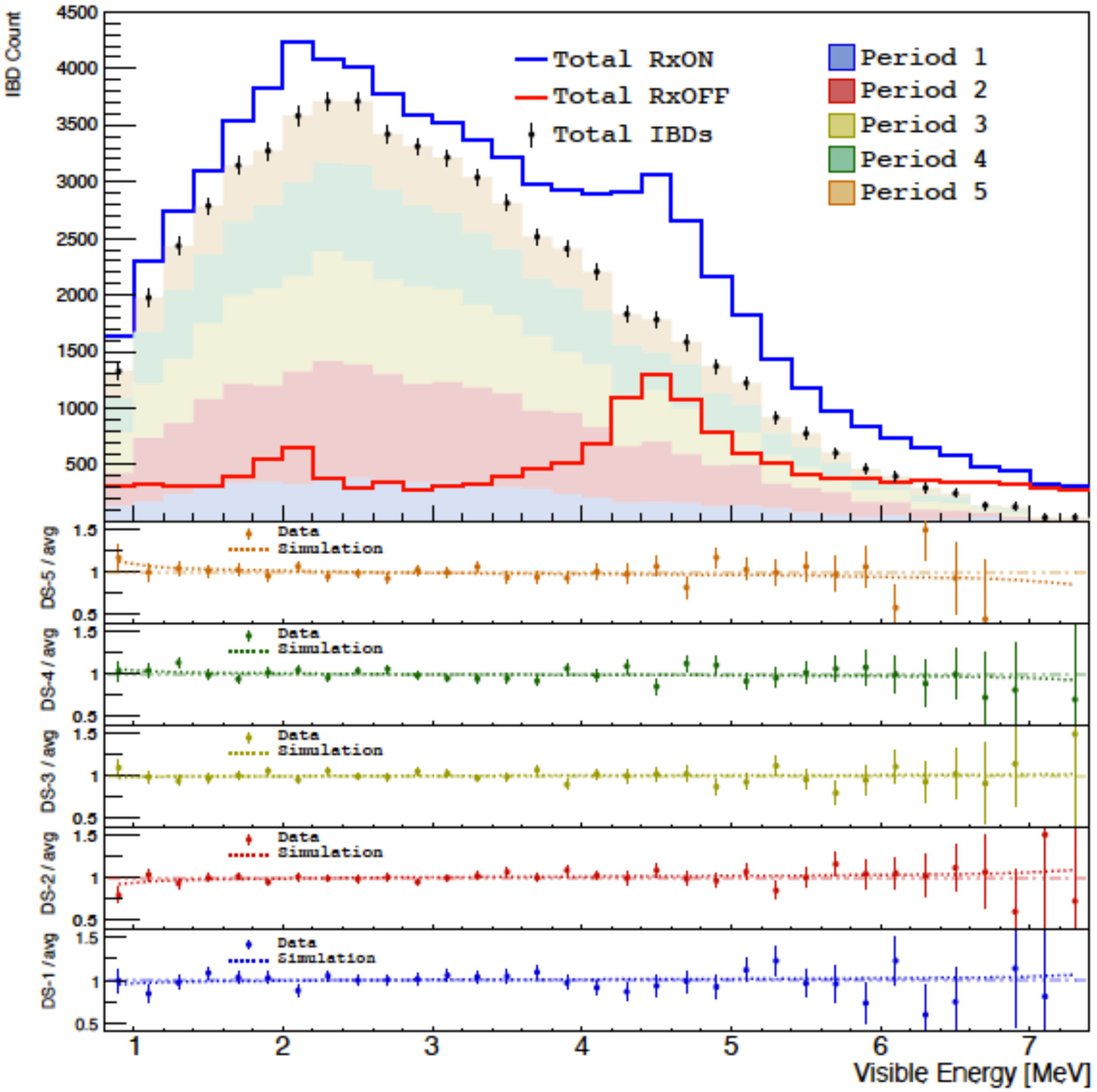
$$R^{-1} \cdot (R \cdot S + N) = S'$$

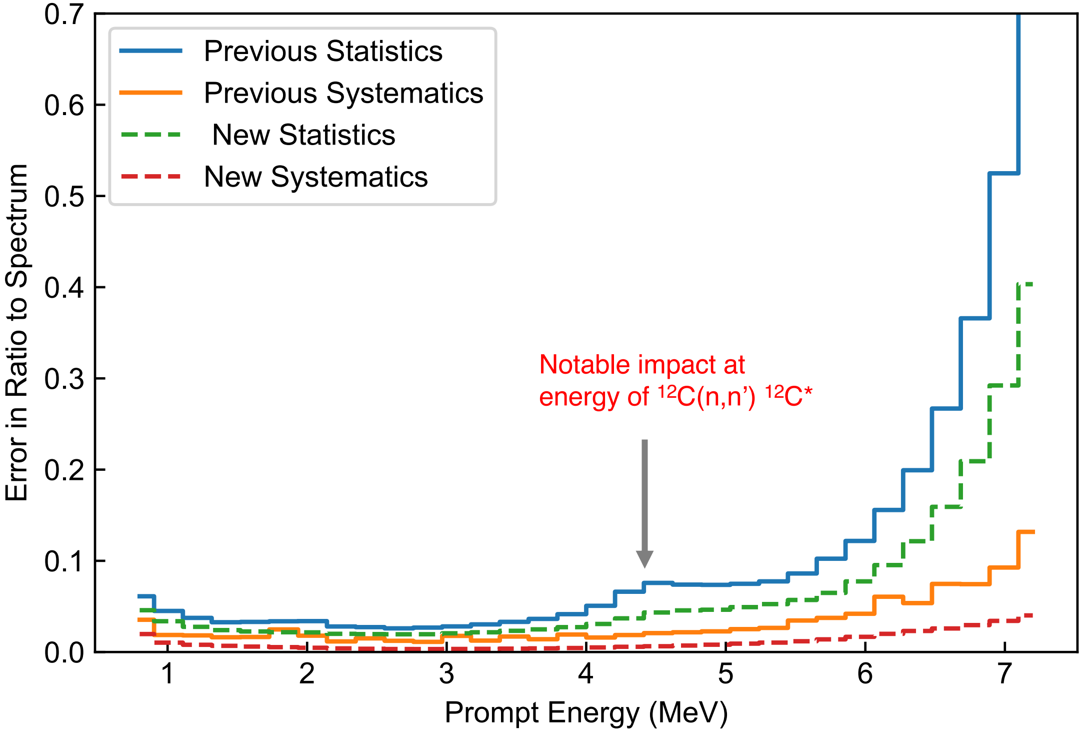
$$S' = S + R^{-1} \cdot N$$

Solution: Add Regularization Filter Function F

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

Multi-Period Spectrum Analysis





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)