# Continuing Physics Results from PROSPECT-I

## The 2nd IAEA Technical Meeting on Nuclear Data Needs for Antineutrino Spectra Applications

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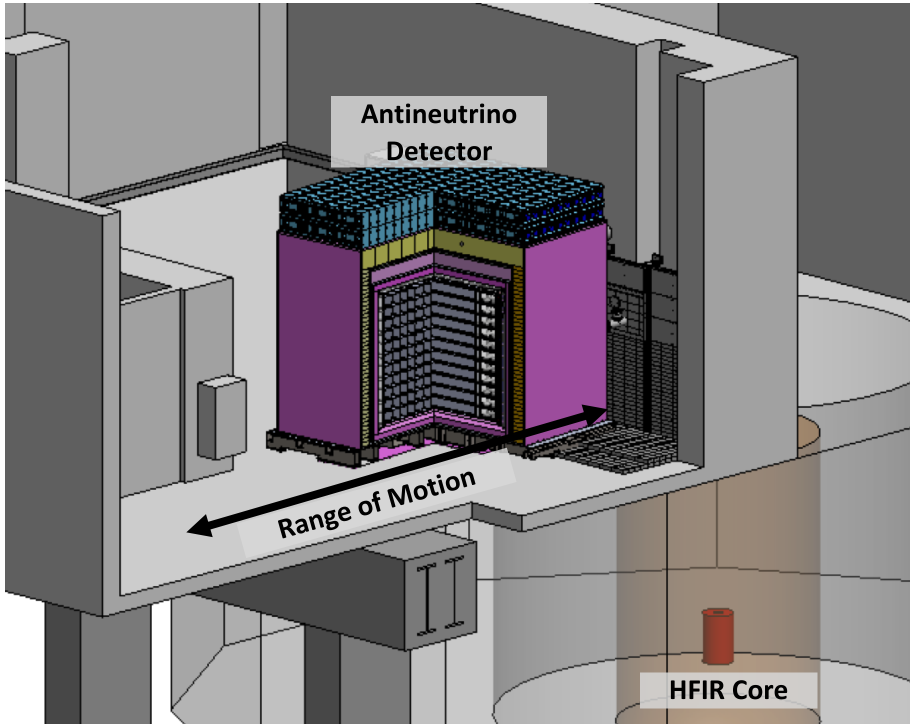
# PROSPECT Experiment Overview

Physics Objectives

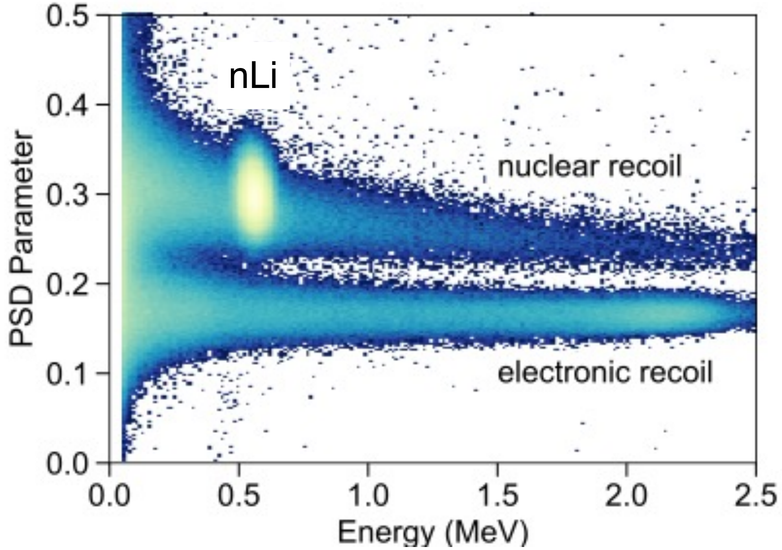
1. Model Independent search for short-baseline oscillation at distances <12m
2. Precision measurement of $^{235}$U reactor $\overline{\nu}_e$ spectrum

**Segmented detector** design using PSD capable **$^{6}$Li-doped liquid scintillator** (LiLS) provides powerful **aboveground background rejection**




Neutron capture on $^{6}$Li (nLi) provides:

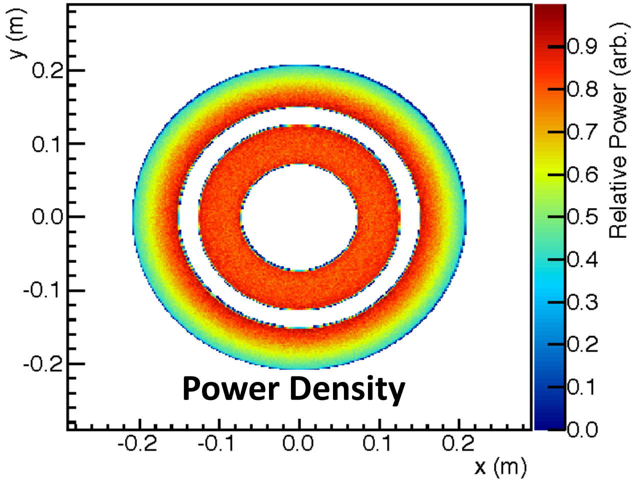
- localized, distinct signal
- uniform efficiency in compact detector



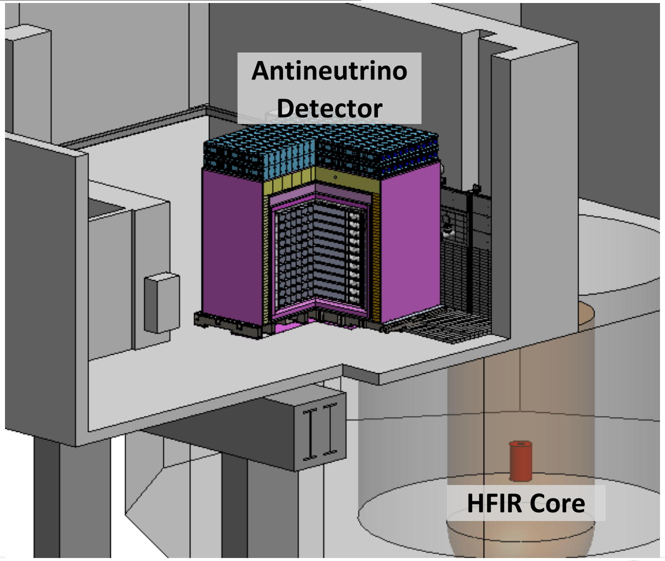
# Experimental site: High Flux Isotope Reactor @ORNL

## Compact Reactor Core


**Power:** 85 MW
**$^{235}$U Fission Frac.:** >99%
**Size:** h=51cm d=44cm
**Duty-cycle: 46%**





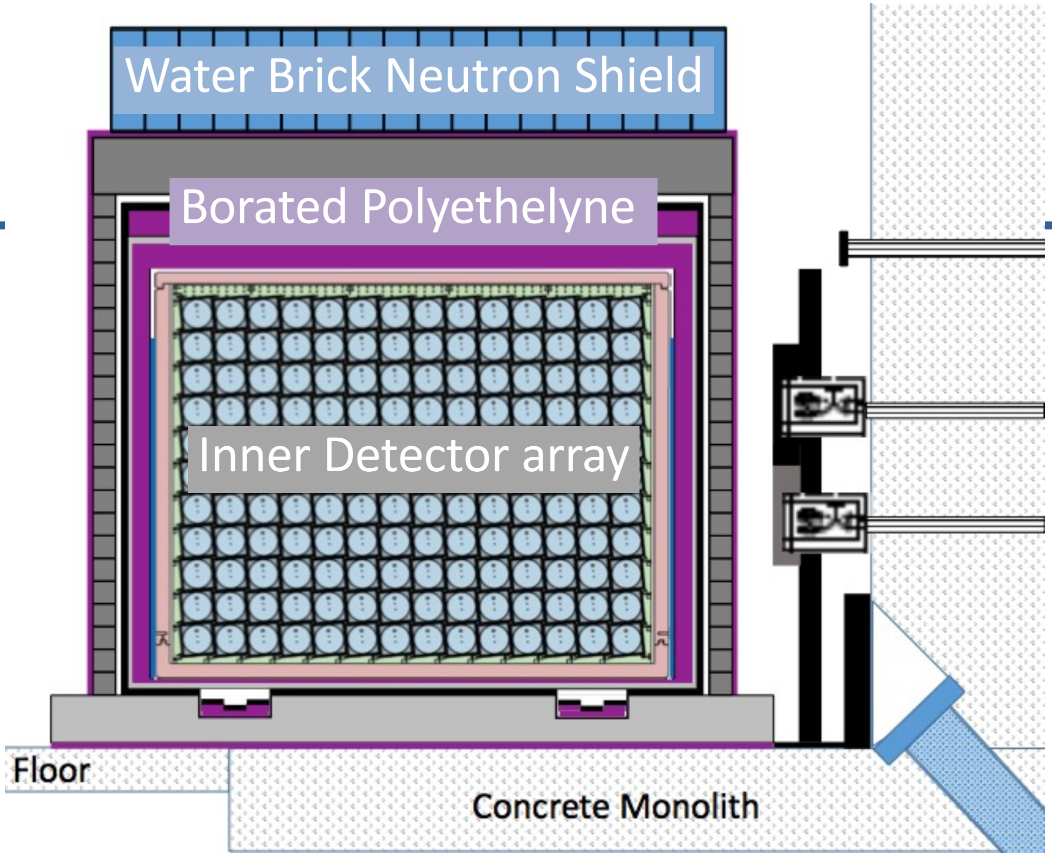


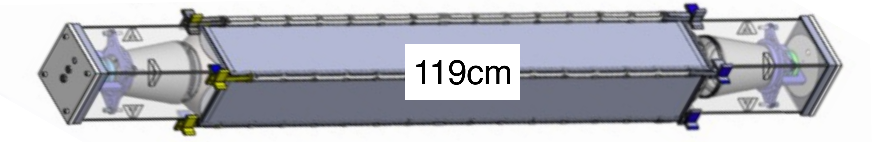
# PROSPECT Detector Design

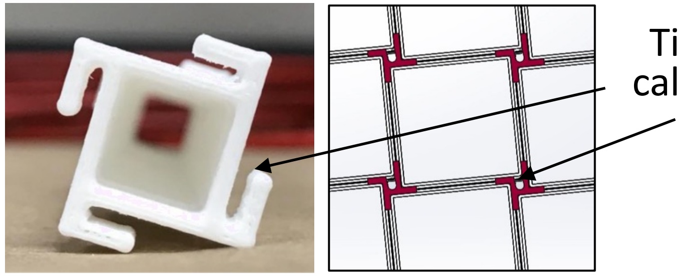
- 154 segments, 119cm x 15cm x 15cm
  - ~25liters of LiLS per segment, total mass: 4ton
- Thin (1.5mm) reflector panels held in place by 3D-printed support rods

- **Segmentation enables:**
  - Calibration access throughout volume
  - Position reconstruction (X,Y)
  - Event topology ID
  - Fiducialization
- Double ended PMT readout for full (X,Y,Z) position reconstruction

- Optimized shielding to reduce reactor and cosmogenic backgrounds




PROSPECT - NIMA 922 (2019) 286

# Comprehensive R&D Program

**PROSPECT Whitepaper**
arXiv:1309.7647

**Reactor Background**
NIMA A806 (2016) 401
arXiv:1506.03547

**Long Segment Energy & PSD**
JINST 10 P11004 (2015)
arXiv:1508.06575

**Physics Program**
J. Phys. G, 43 113001
arXiv:1512.02202

**Production Prototype**
JINST 13 P06023 (2018)
arXiv:1805.09245

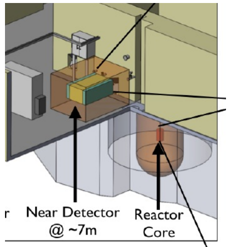
**PROSPECT Experiment**
NIMA 922 (2019) 286
arXiv:1808.00097

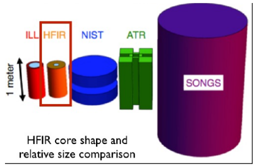
**LiLS Production**
JINST 14 P03026 (2019)
arXiv:1901.05569

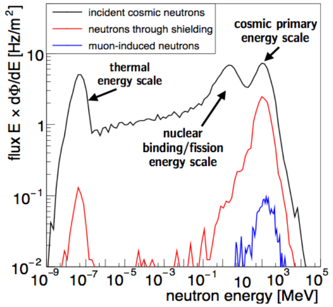
**Optical Grid**
JINST 14 P04014 (2019)
arXiv:1902.06430

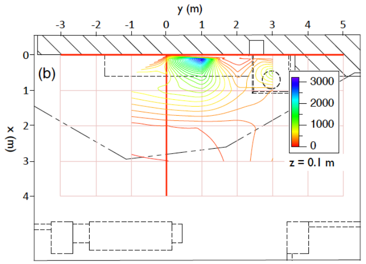
**Calibration System**
NIMA 944 (2019) 162465
arXiv:1906.07244

- **Conceptual design for physics & bkg requirements**
- **Reactor site assessment**



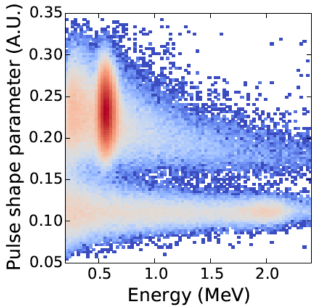



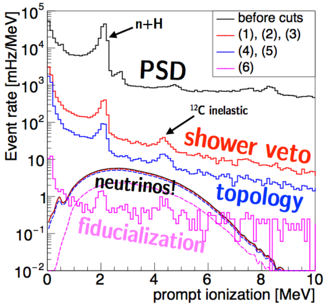



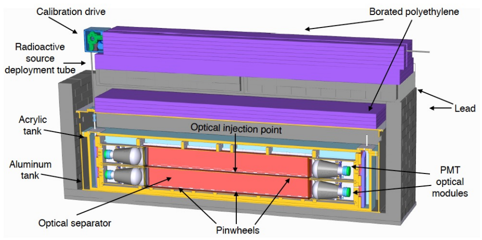



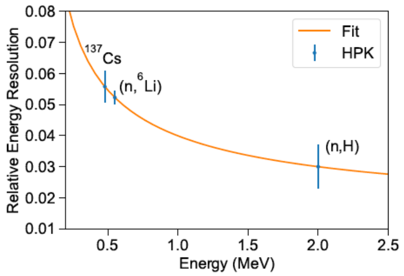

- **Characterize reactor & cosmogenic background**
- **Validate shielding & detector MC with onsite prototypes**

- **Develop detector design and analysis that achieves required S:B**
- **Demonstrate required segment and LiLS performance**

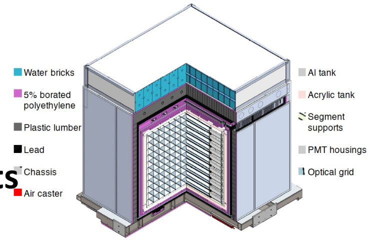


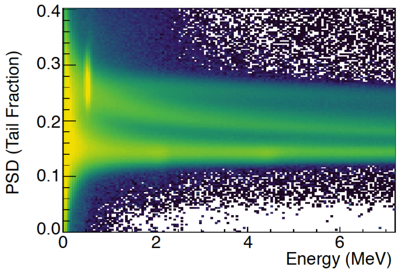



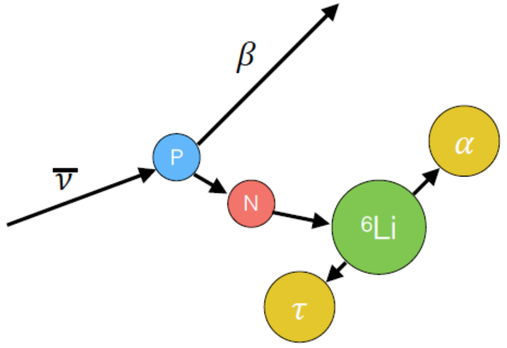

- **Demonstrate required performance with production components**
- **Full scale detector meets performance requirements**



# Event Detection in PROSPECT

## Event Identification




Prompt signal: 1-10 MeV positron from inverse beta decay (IBD)

Delay signal: ~0.5 MeV signal from neutron capture on $^6$Li

40µs delayed n capture

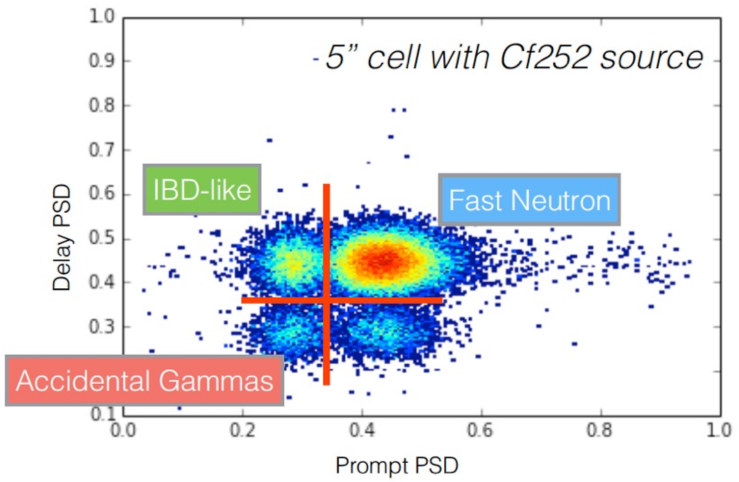
inverse beta decay (IBD)
γ-like prompt, n-like delay

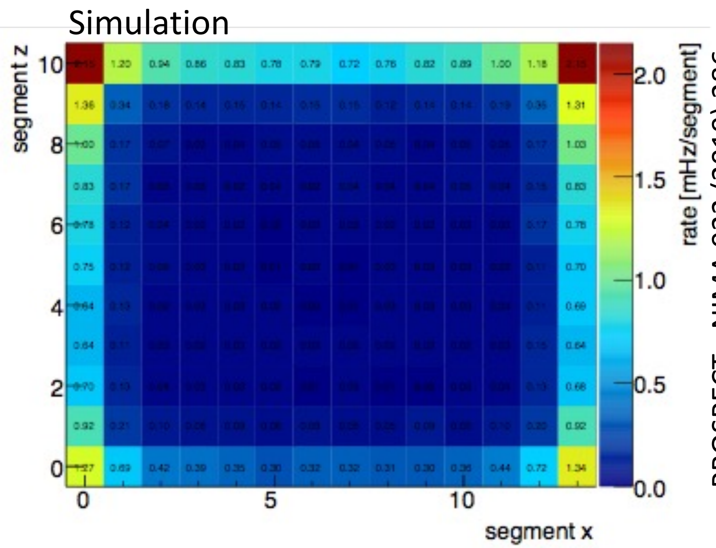
fast neutron background
recoil-like prompt, capture-like delay
capture-like prompt, capture-like delay

accidental gamma background
γ-like prompt, γ-like delay

Background reduction through **detector design** & **fiducialization**

**Pulse Shape Discrimination**



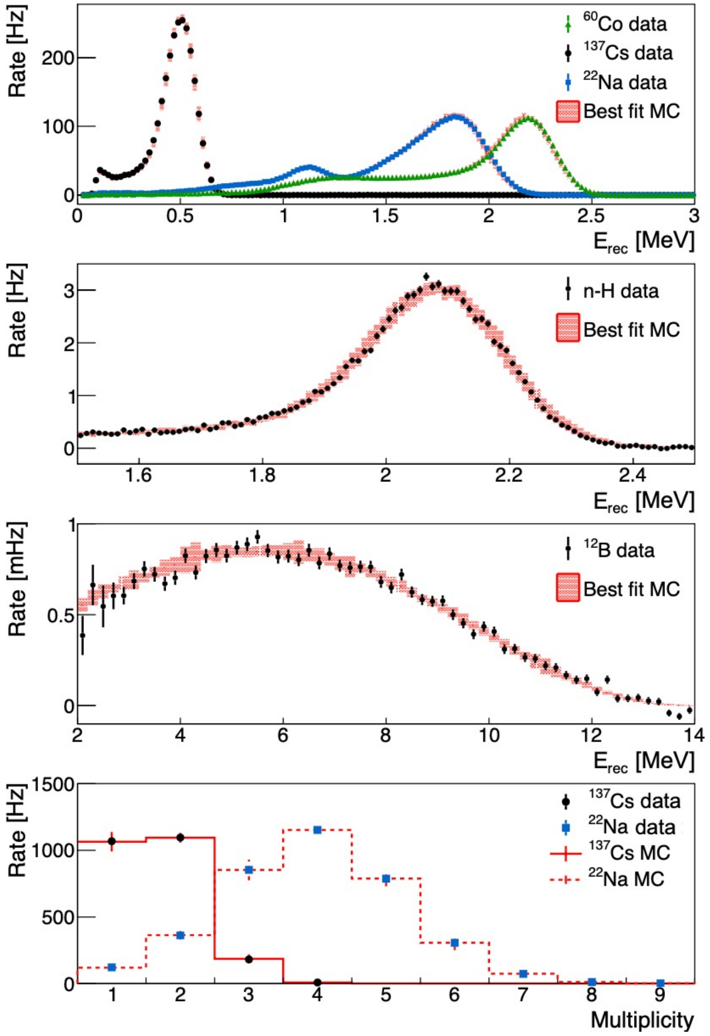




PROSPECT - NIMA 922 (2019) 286

Background reduction is key challenge

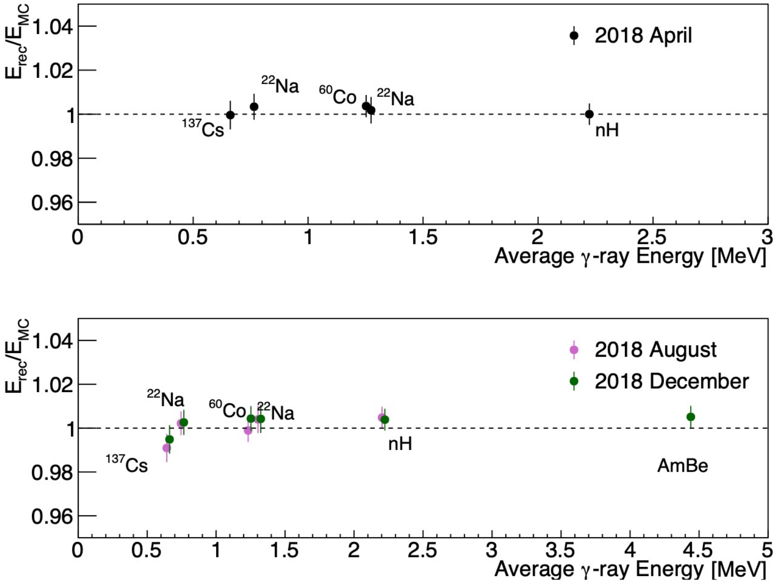
# Energy Reconstruction

## Calibration Spectra

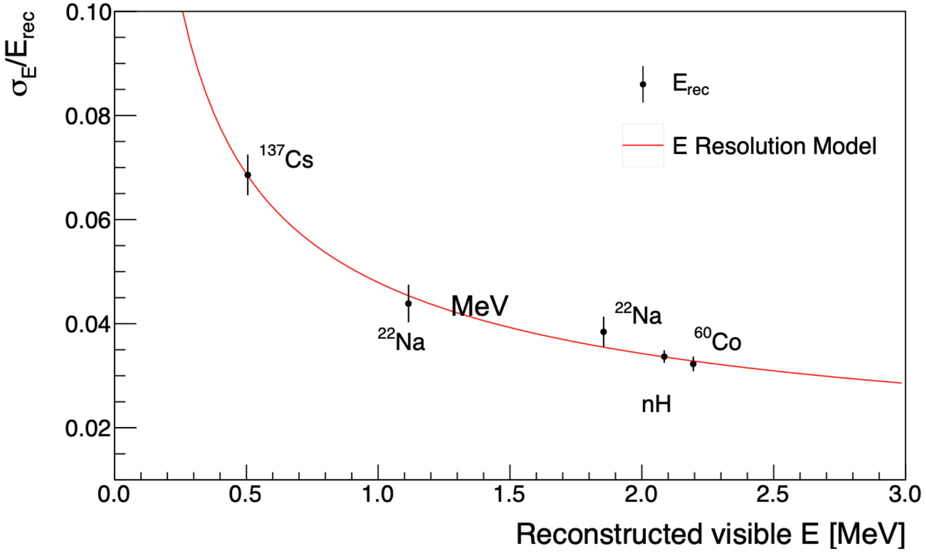



- Sources deployed throughout detector, measure single segment response
- Proton PSD tagged $^{12}$B production - high-energy beta spectrum calibration
- Full-detector $E_{rec}$ within 1% of $E_{true}$

## Data vs MC



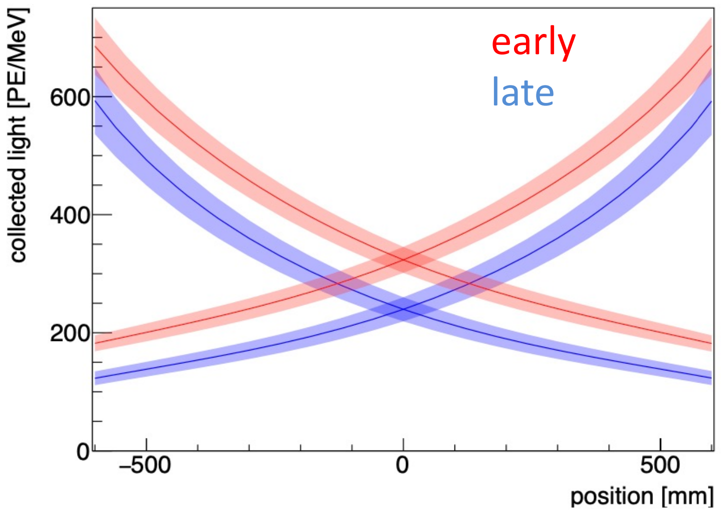

## Stochastic resolution vs Energy



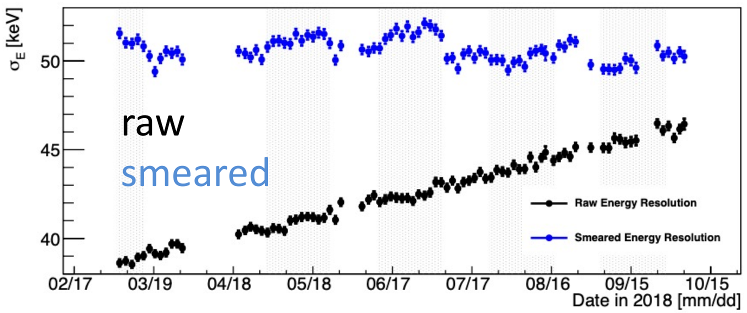
# Event Reconstruction Stability

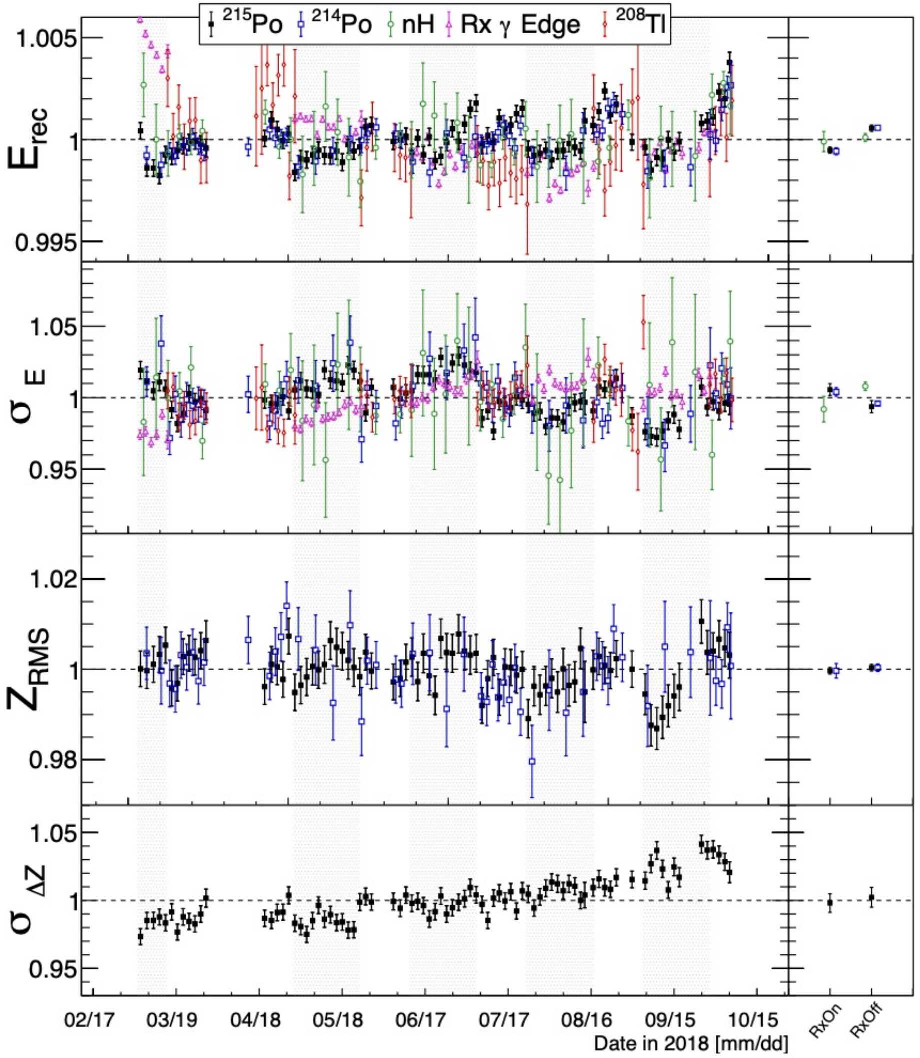
- Scintillator light yield decreased over the PROSPECT-I run
  — Energy smearing applied to normalize response
- Track uniformity of reconstructed quantities over time with distributed internal single-segment sources:
  — Alpha lines from $^{212}Bi \rightarrow {}^{212}Po \rightarrow {}^{208}Pb$ decays, nH capture peak, gamma backgrounds
- Reconstructed energy stability over time < 1%

## Light Production & Collection

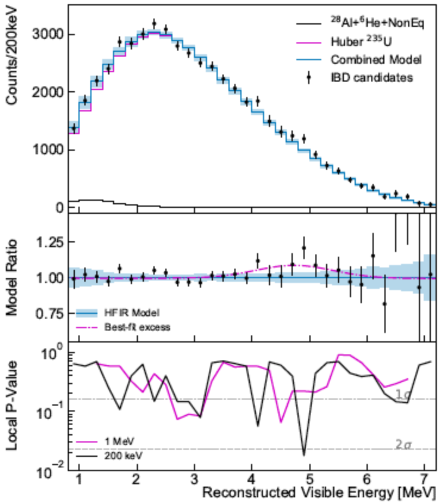


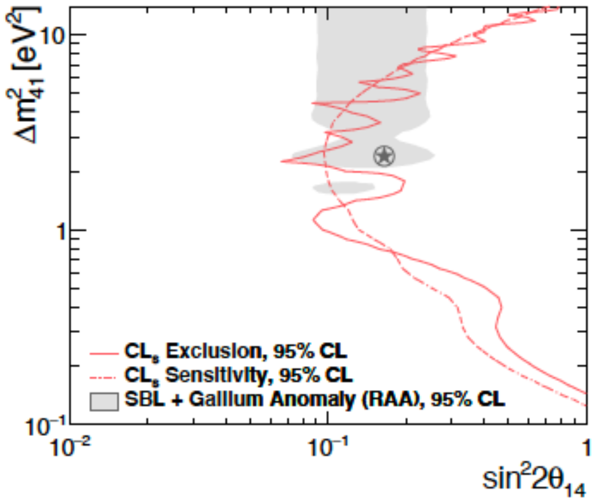

## Resolution vs Time ($^{215}$Po)

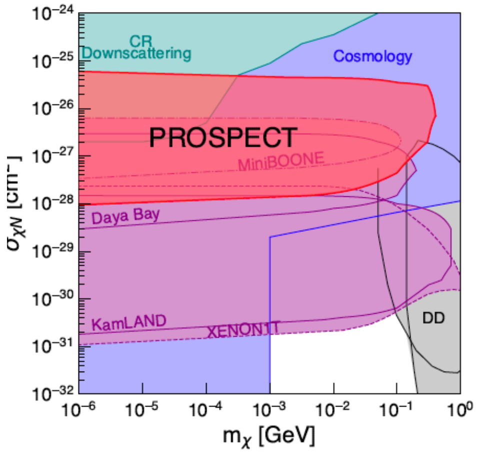


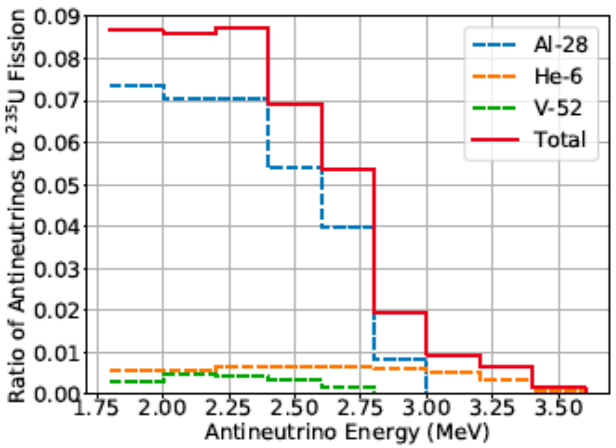



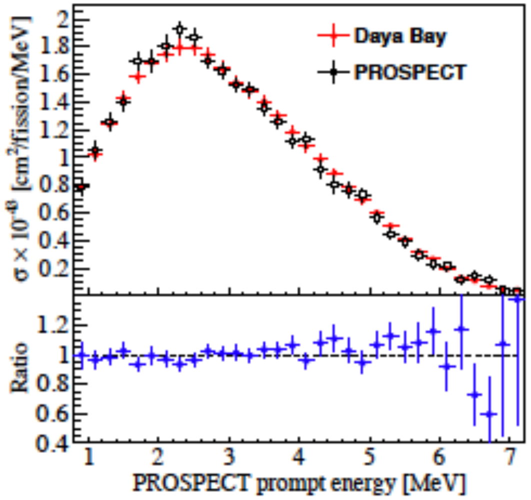
# Physics Results & Plans

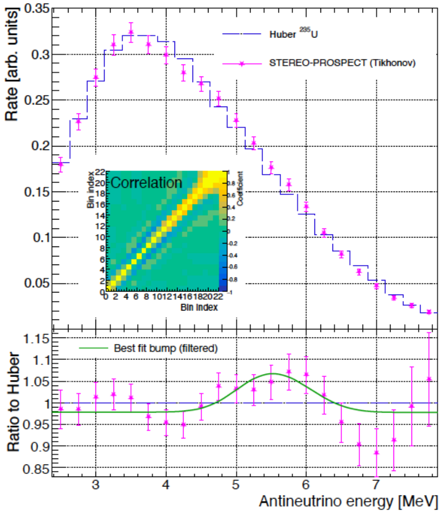



**First Oscillation Search**
Phys.Rev.Lett. 121 (2018) 251802

**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)

**Final PROSPECT-I Spectrum**
arXiv:2212.10669v1

**Final PROSPECT-I Oscillation**

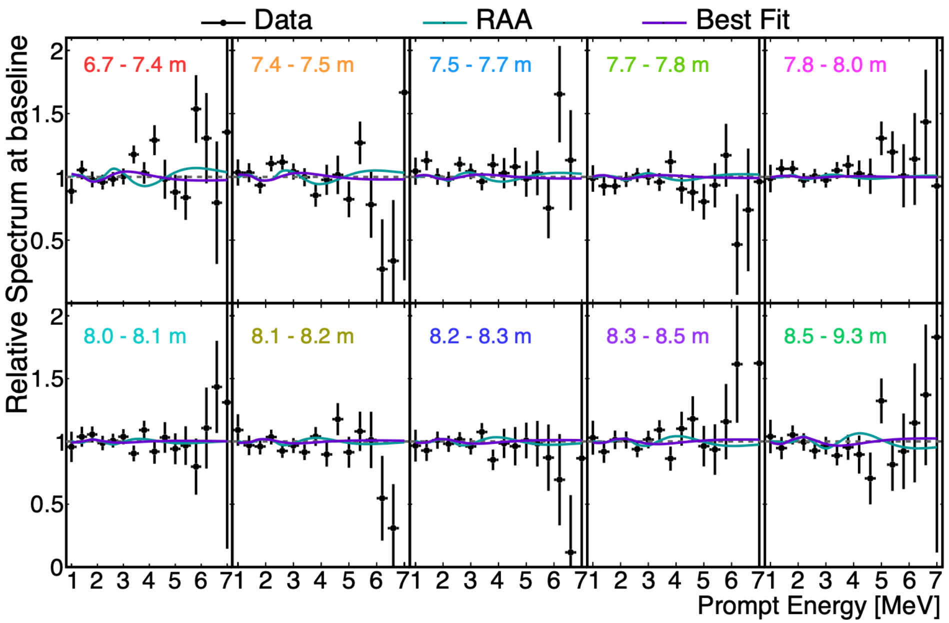
**Absolute Flux Analysis**

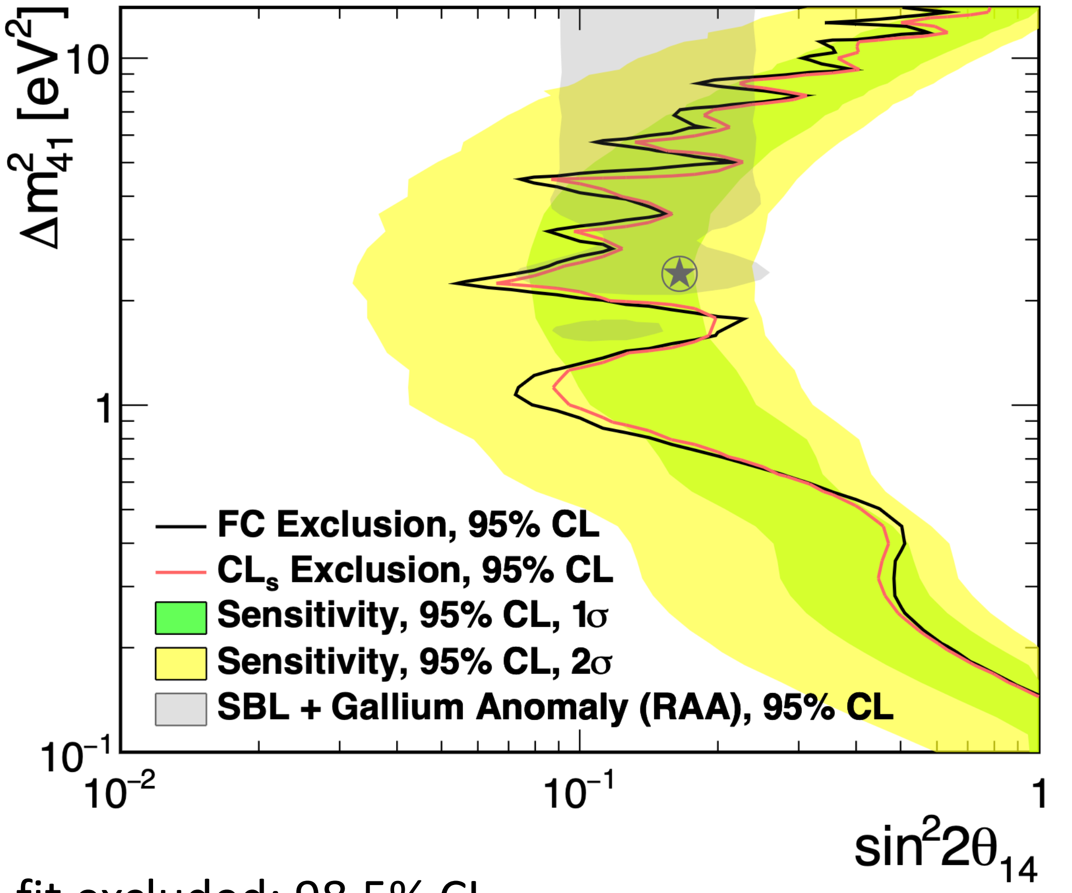
**Correlated Background Study**

**Antineutrino Directionality**

# Short Baseline Oscillation Search

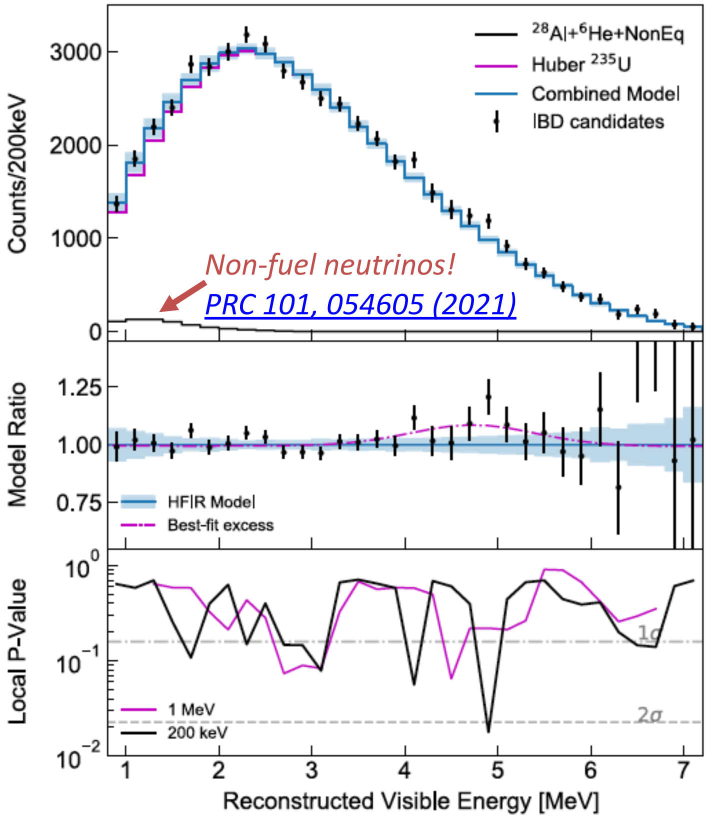
- Build $\chi^2$ by comparing measured spectra to average at multiple baselines
- Covariance matrices capture all uncertainties and energy/baseline correlations
- Use both Feldman-Cousins and CLs to convert $\Delta\chi^2$ values to statistically valid excluded regions of oscillation phase space




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

# Pure $^{235}$U Spectra from PROSPECT-I

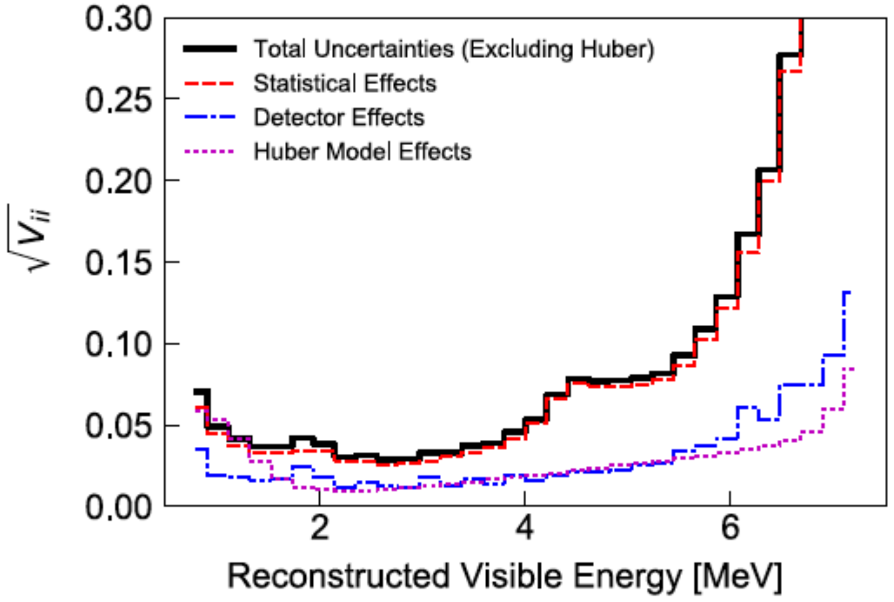



*PROSPECT, [PRD 103, 032001 (2021)]*

PROSPECT 'bump' amplitude
(1= Daya Bay)

- A = 0.84 ± 0.39
- 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
~18k "effective counts"

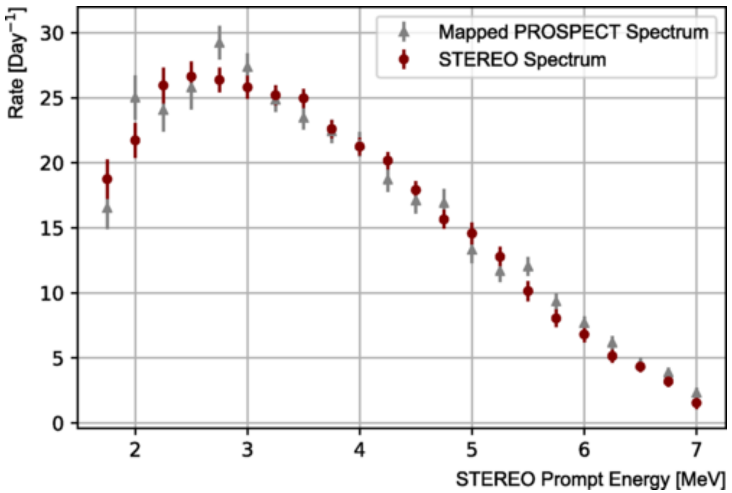



Suggests Spectrum Anomaly not due to $^{235}$U alone

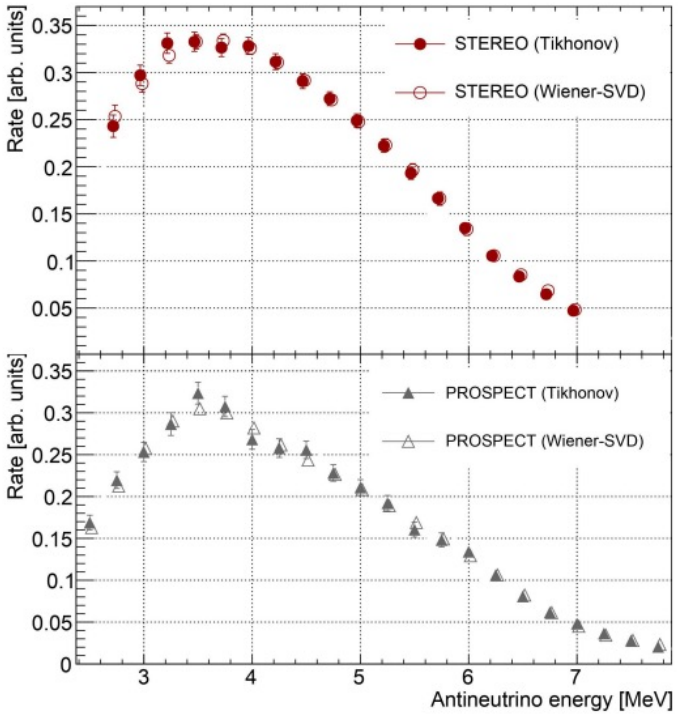
# PROSPECT and STEREO Joint Spectrum Analysis

## 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

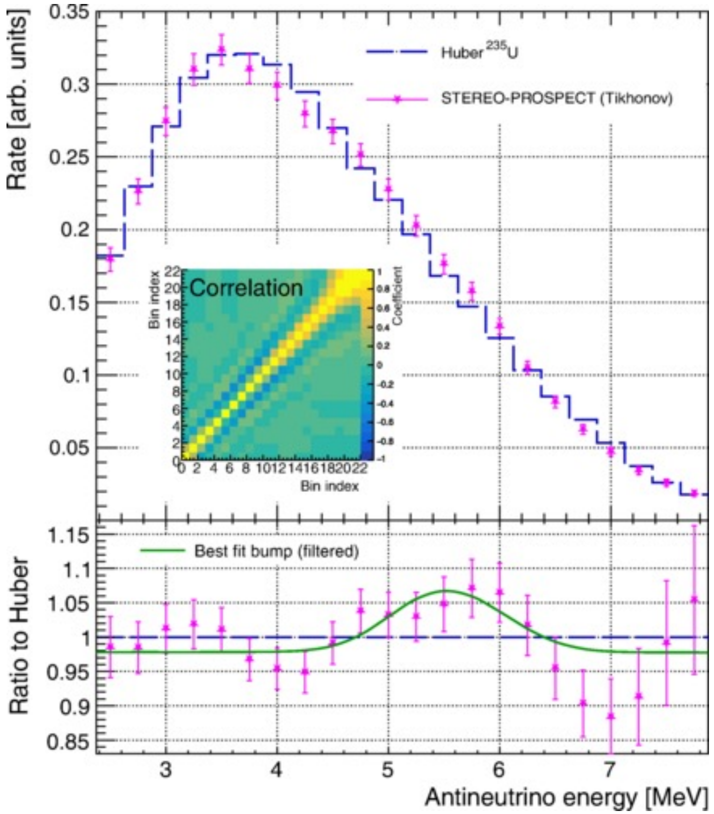



Two unfolding methods used, with compatibility between the two being established




Joint unfolding provides an improved reference for the community

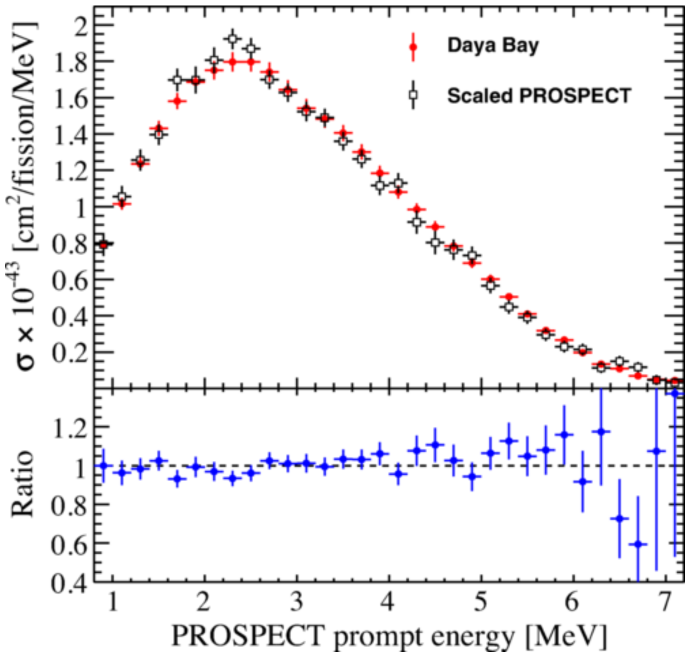
Bump excess has 2.4$\sigma$ significance



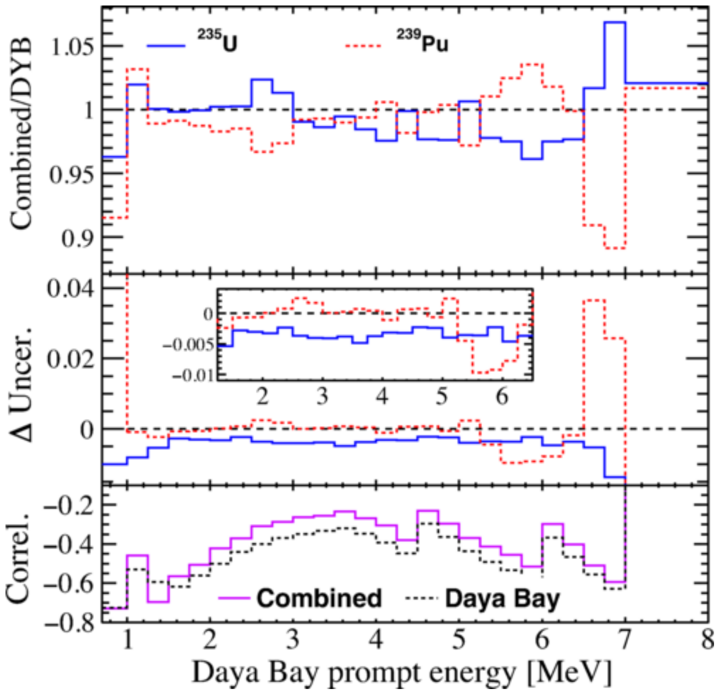

*PROSPECT & STEREO , [PRL 128, 081802 (2022)]*

# 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

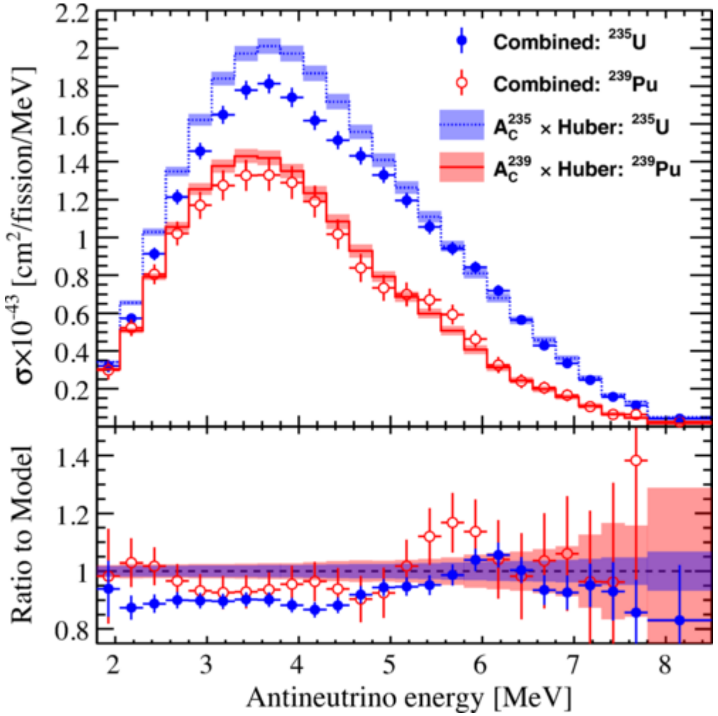



Combined analysis reduces degeneracy between dominant $^{235}U$ and $^{239}Pu$ isotopes in evolution analysis by ~ 20%




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

$^{235}U$ bump significance also improved

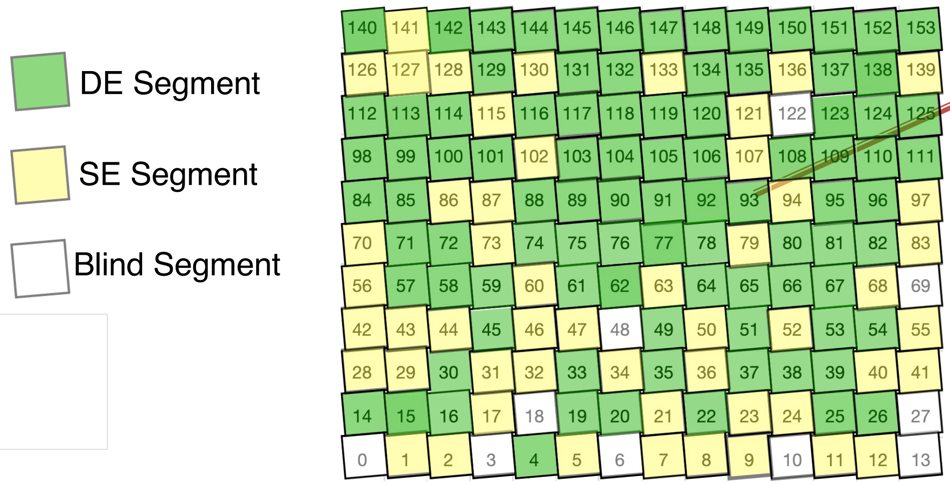



*Daya Bay & PROSPECT* , [PRL 128, 081801 (2022)]

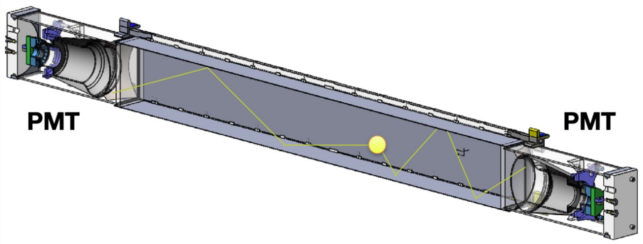
# Motivation for additional PROSPECT-I Analyses

- Previous results were limited by degradation of photo-multiplier tube bases throughout data collection.

**Detector configuration used for PRD analysis**




154 segments with two PMTs

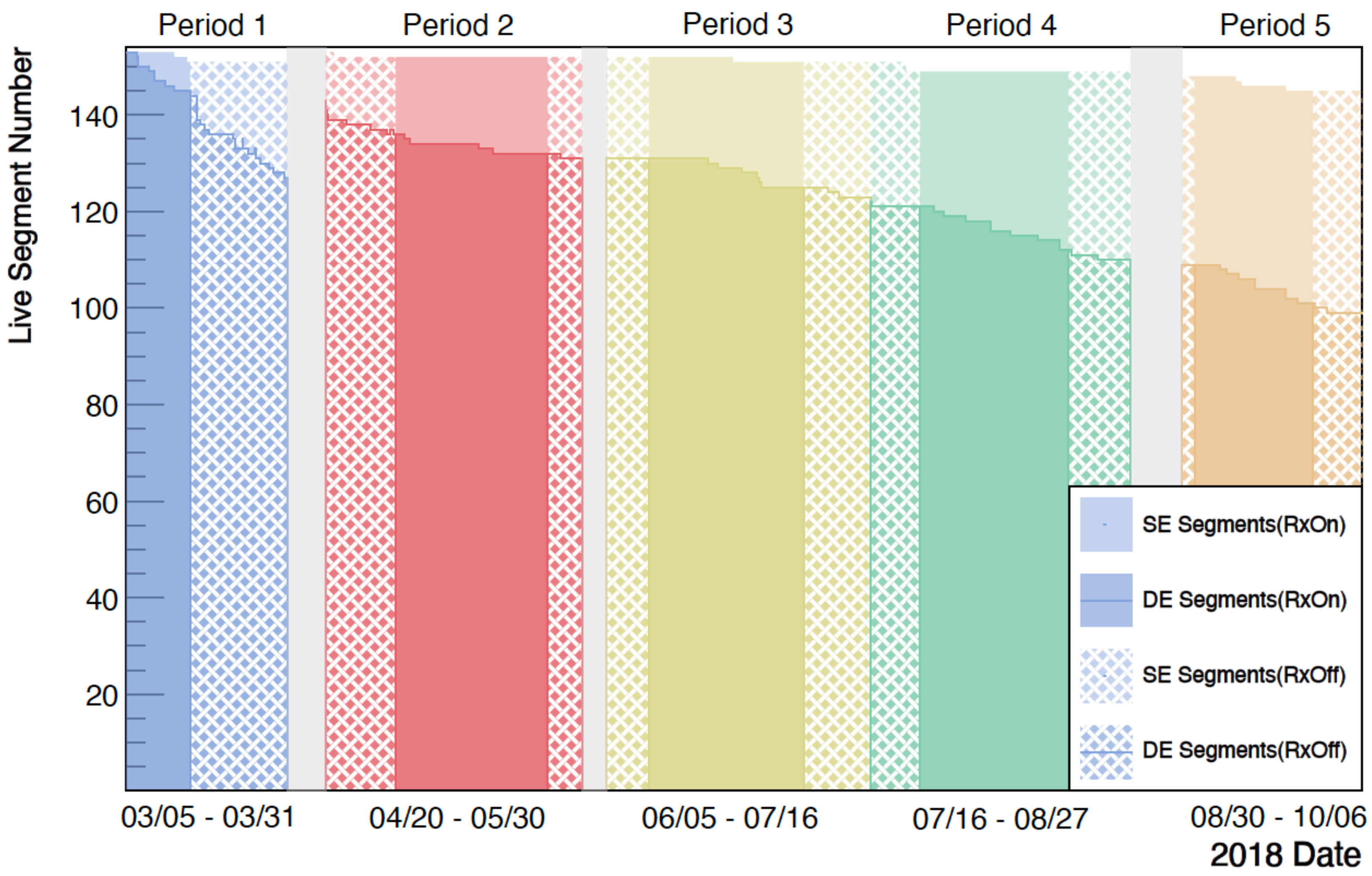



Some segments coupled to one PMT or both switched off due to scintillator leakage into PMT housing.

- In order to improve upon previous results, two new analysis approaches have been implemented:

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

# Data Splitting




## Goals

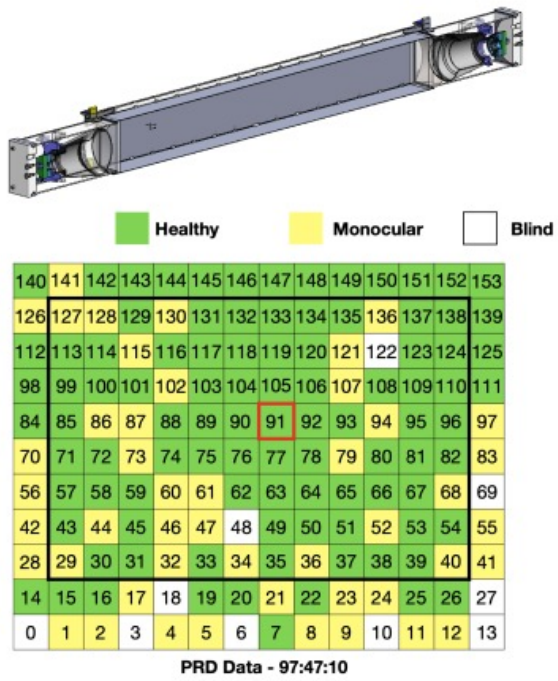
- Split PROSPECT-I data into distinct periods to increase average active volume
- Maximize number of live segments in each period

## Splitting Criteria

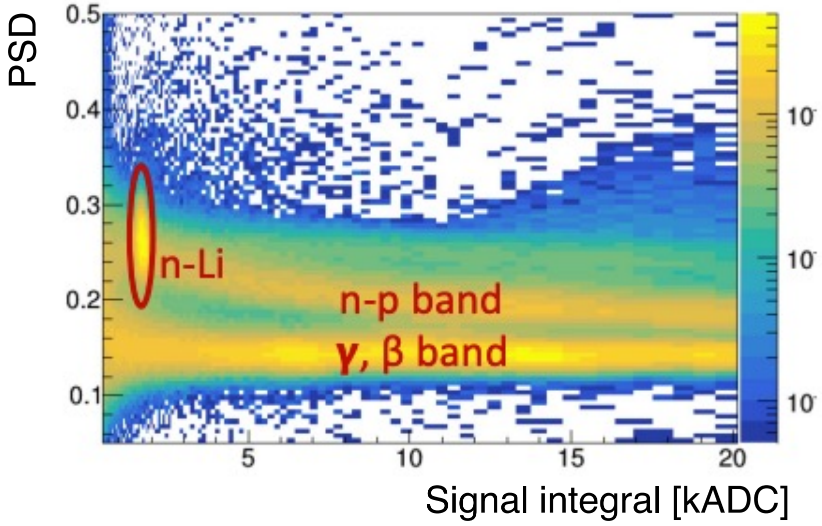
- Each period should start immediately after a new calibration campaign
- Each period must contain one full RxOn cycle
- All periods should have RxOff data before and after each corresponding RxOn cycle
  - Exception: Period 1 since no prior RxOff
- Keep ratio of RxOff/RxOn between 50%-70%

# Single Ended Event Reconstruction (SEER)

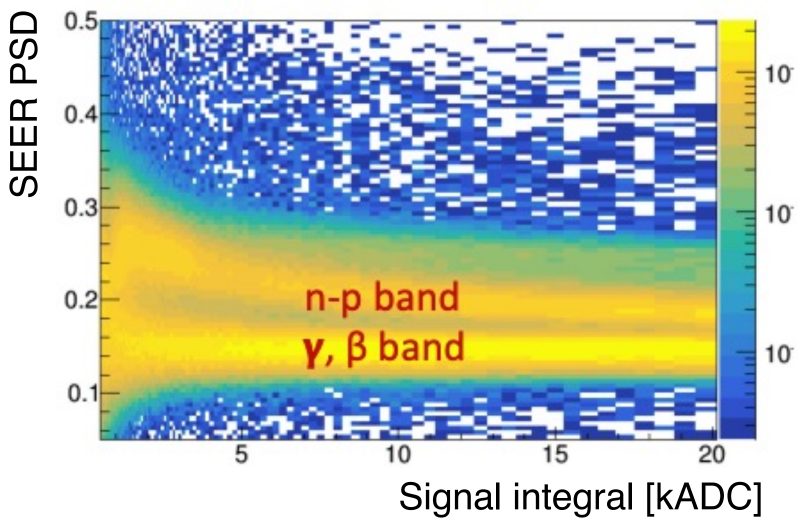
- Poor energy and position reconstruction capabilities since event position unknown
- Provides a good handle on particle identification → additional background suppression




**DEER PSD Distribution**

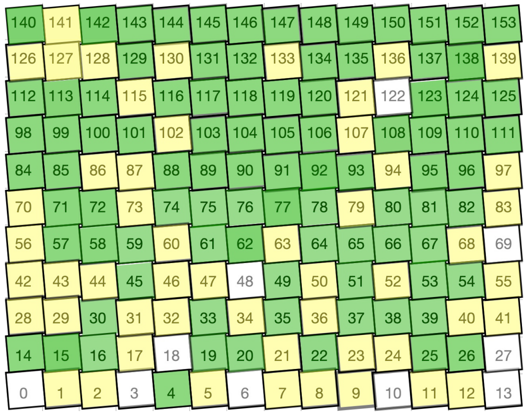



**SEER PSD Distribution**



# Detector Configuration for Each Period

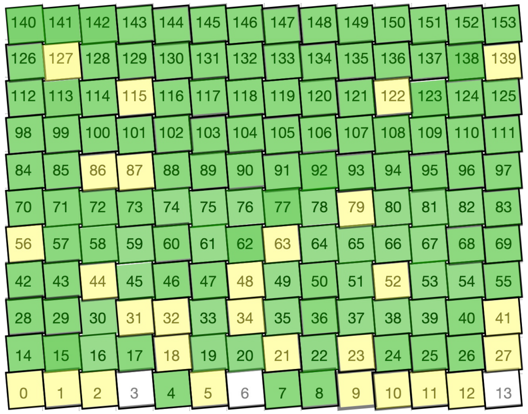
**Detector Configuration Used for Previous Analysis**



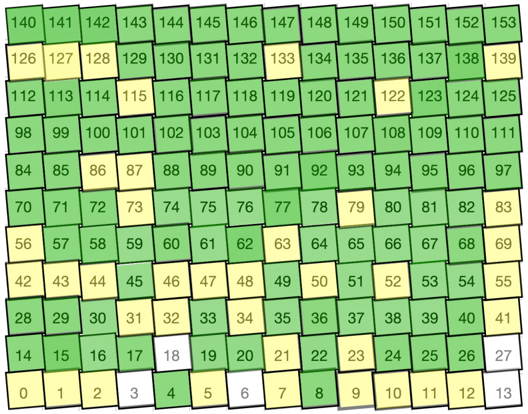

**Period 1**


**Period 2**

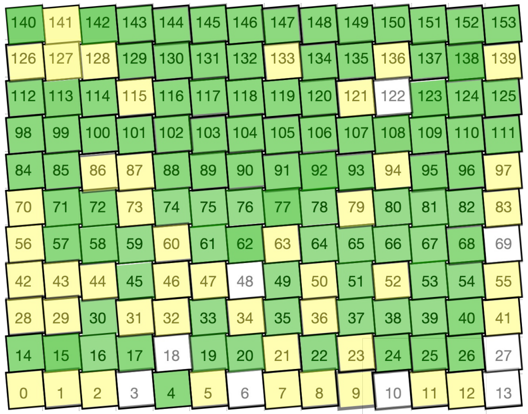

**Period 3**




**Period 4**

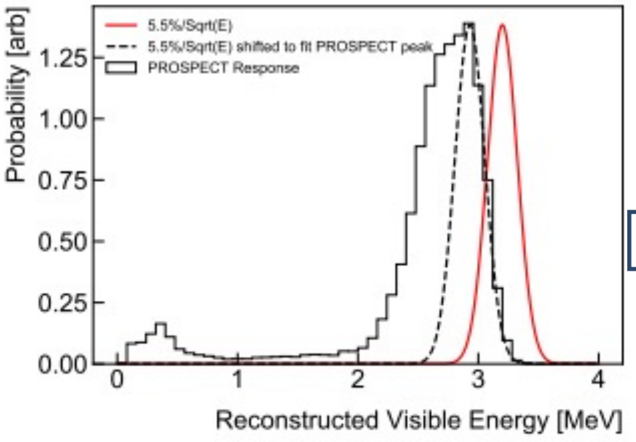



**Period 5**



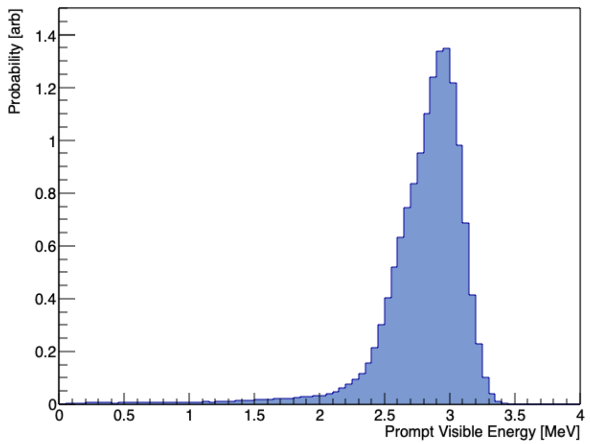

# Detector Response for Each Period

**Detector Configuration Used for Previous Analysis**

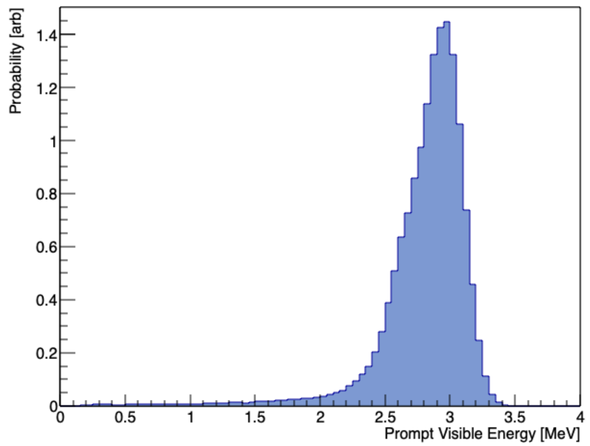



4 MeV antineutrino detector response

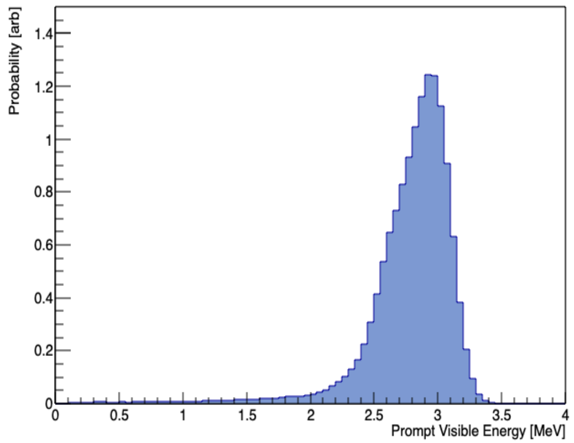
**Period 1**



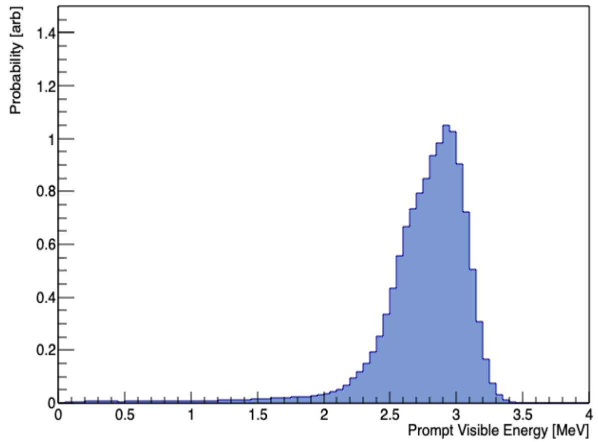

**Period 2**



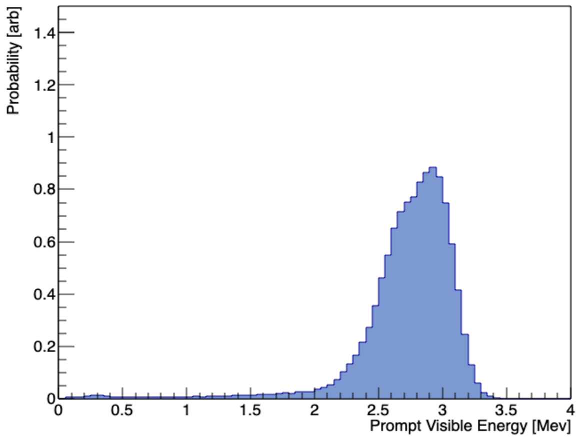

**Period 3**




**Period 4**

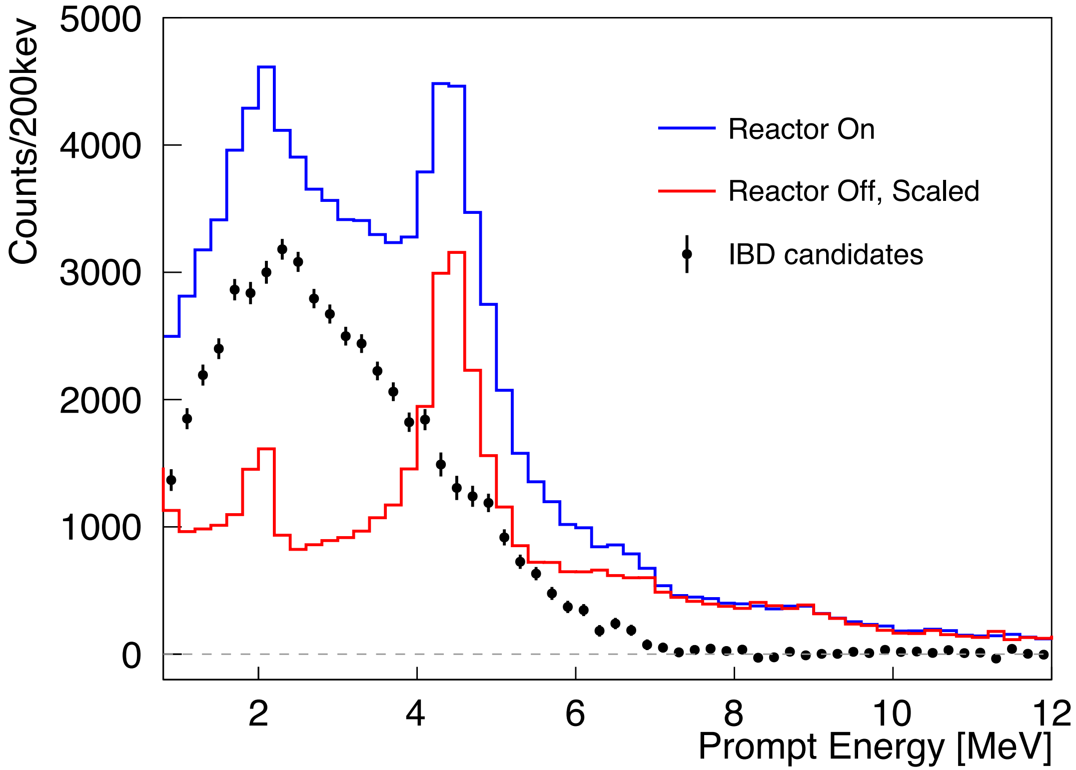



**Period 5**

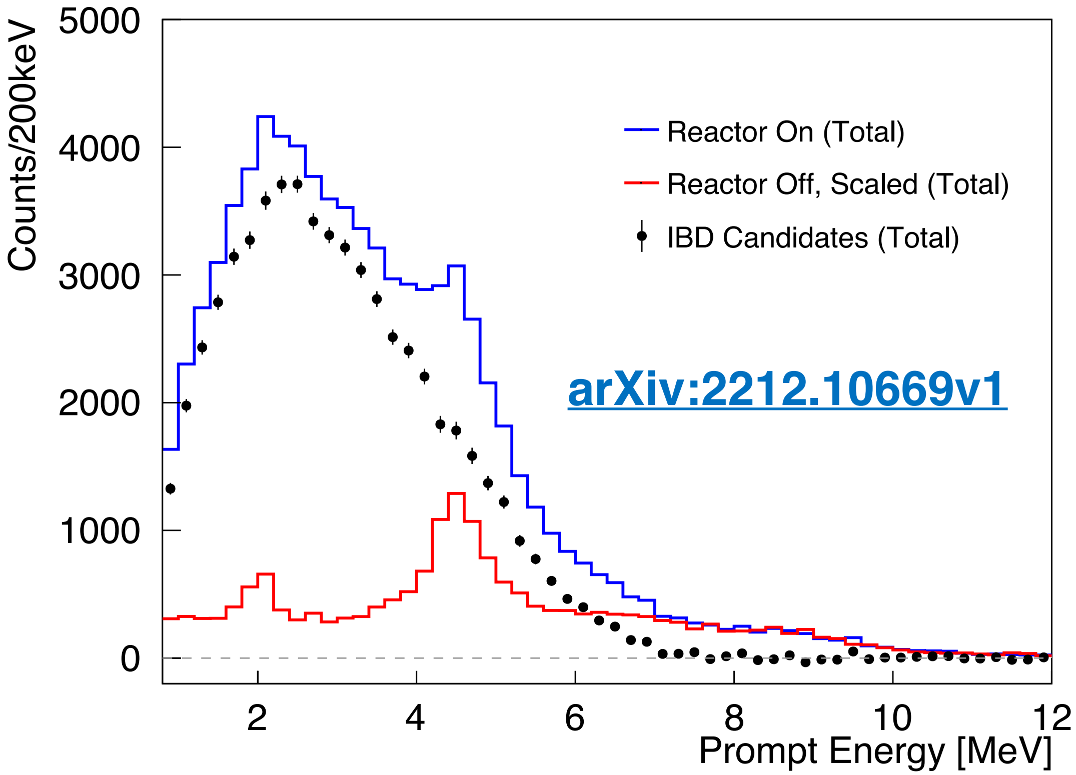


# DS + SEER Improvement in Statistical Power

## Previous PROSPECT Analysis




## New DS+SEER Multi-Period Analysis




arXiv:2212.10669v1

- Implementation of DS+SEER yields improved:
  - IBD counts ~**(x1.2)**
  - IBD effective counts ~**(x2)**
  - Signal to cosmogenic background (S/CB) ~**(x2.8)**
  - Signal to accidental background (S/AB) ~**(x2.4)**

# DS + SEER Improvement in Statistical Power

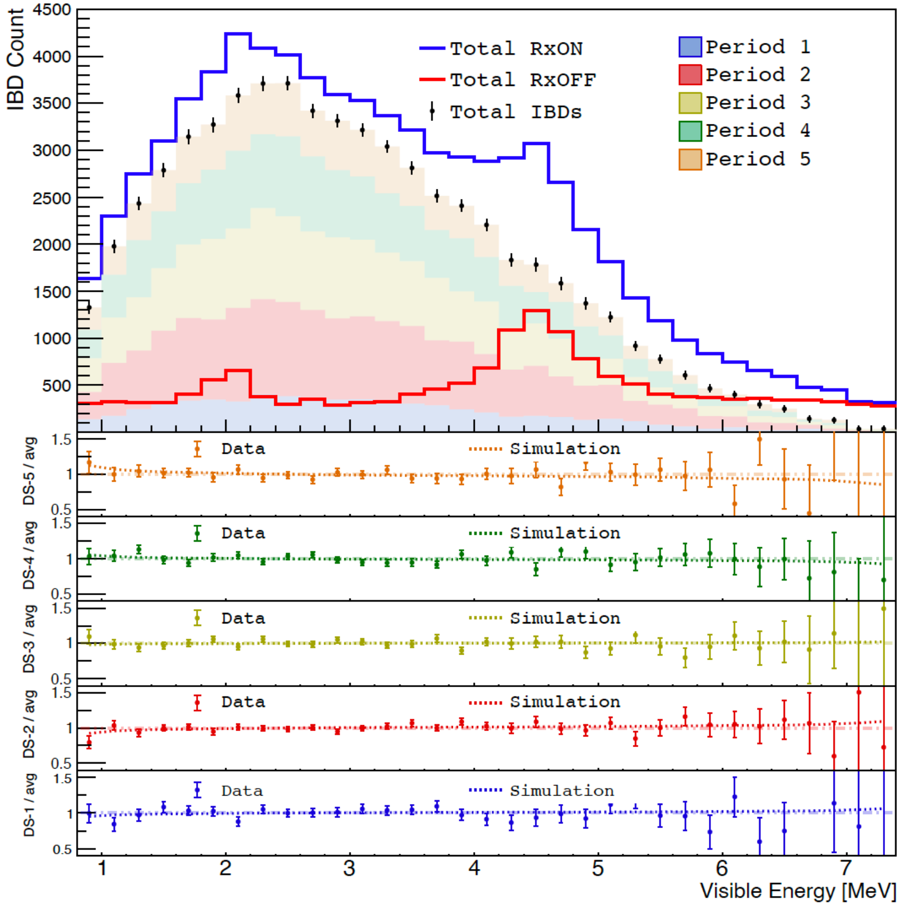
| | IBD Effective | IBD Effective/ calendar day | Total IBD counts | Total IBD counts/ calendar day | S/CB (Total) | S/AB (Total) |
|---|---|---|---|---|---|---|
| **Previously Published PROSPECT Results** | 18100 | 189 | 50560 | 529 | 1.37 | 1.78 |
| **Data Splitting** | 28464 | 302 | 64323 | 670 |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

Equivalent statistical 'effective counts' = $\frac{S^2}{S + 2(AB + CB)}$ (for equal signal and background integration times)

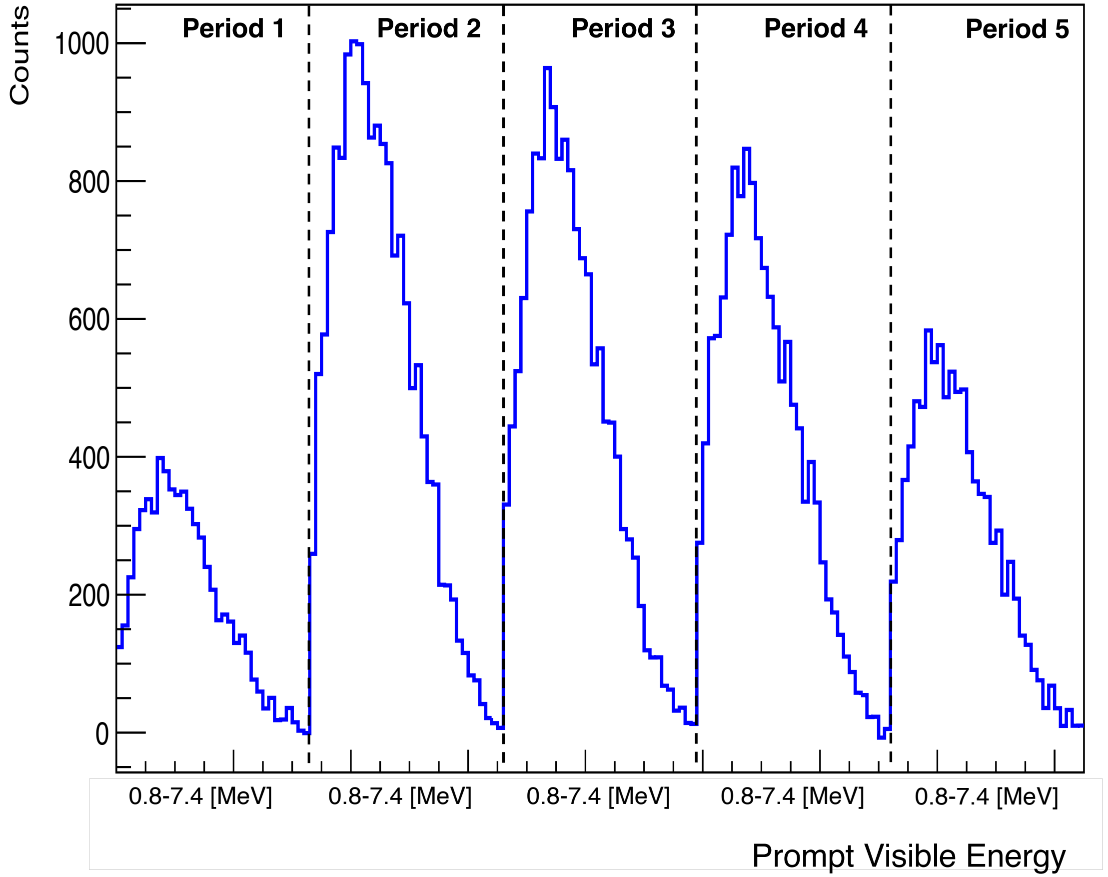
- Implementation of DS+SEER yields improved:
  - IBD counts ~**(x1.2)**
  - IBD effective counts ~**(x2)**
  - Signal to cosmogenic background (S/CB) ~**(x2.8)**
  - Signal to accidental background (S/AB) ~**(x2.4)**

# Multi-Period Spectrum Contributions & Unfolding

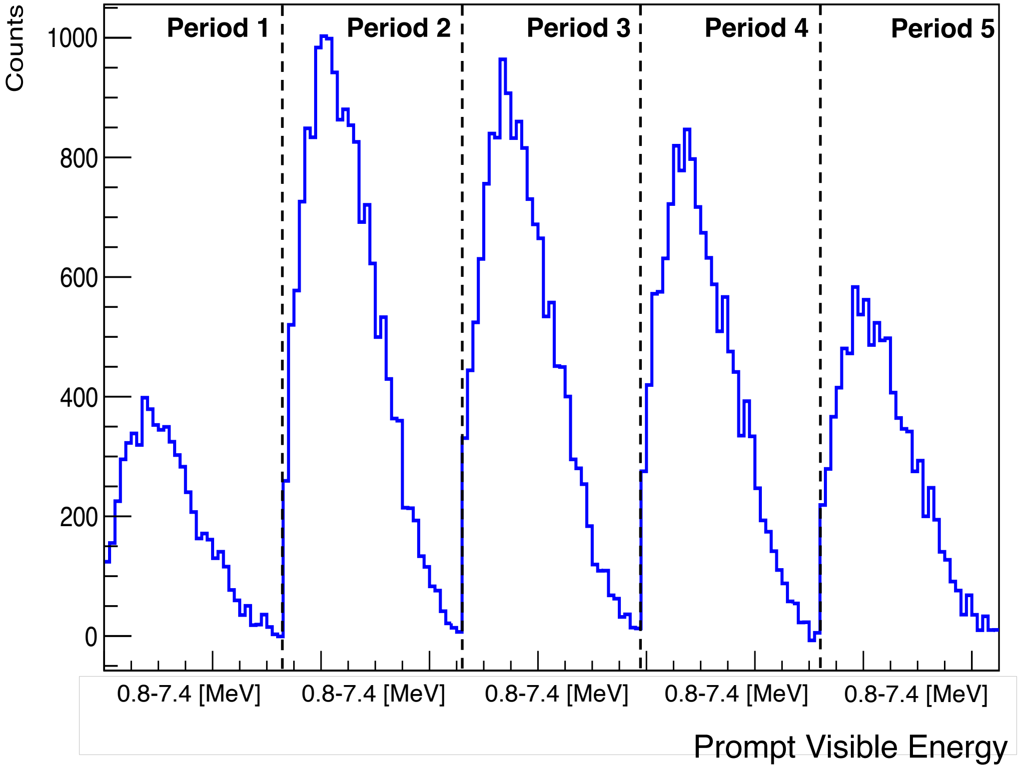
- Comparison of each prompt spectrum to simulated response indicates inter-period compatibility

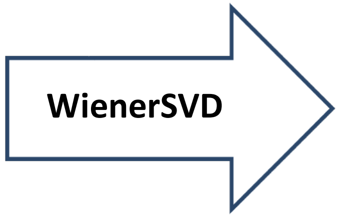



- Building from joint-experiment spectrum analyses, perform joint multi-period of prompt spectra
- Example of how these techniques could be extended to multi-experiment / multi-reactor experiments

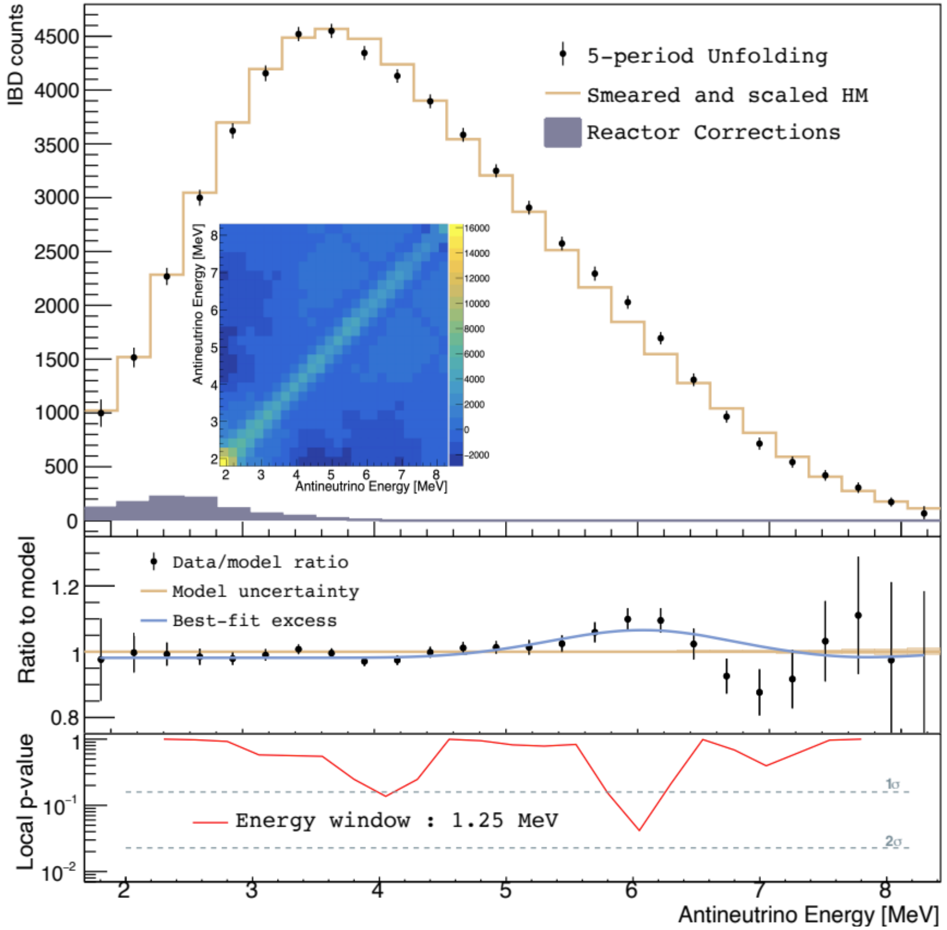


# Multi-Period Unfolded Spectrum



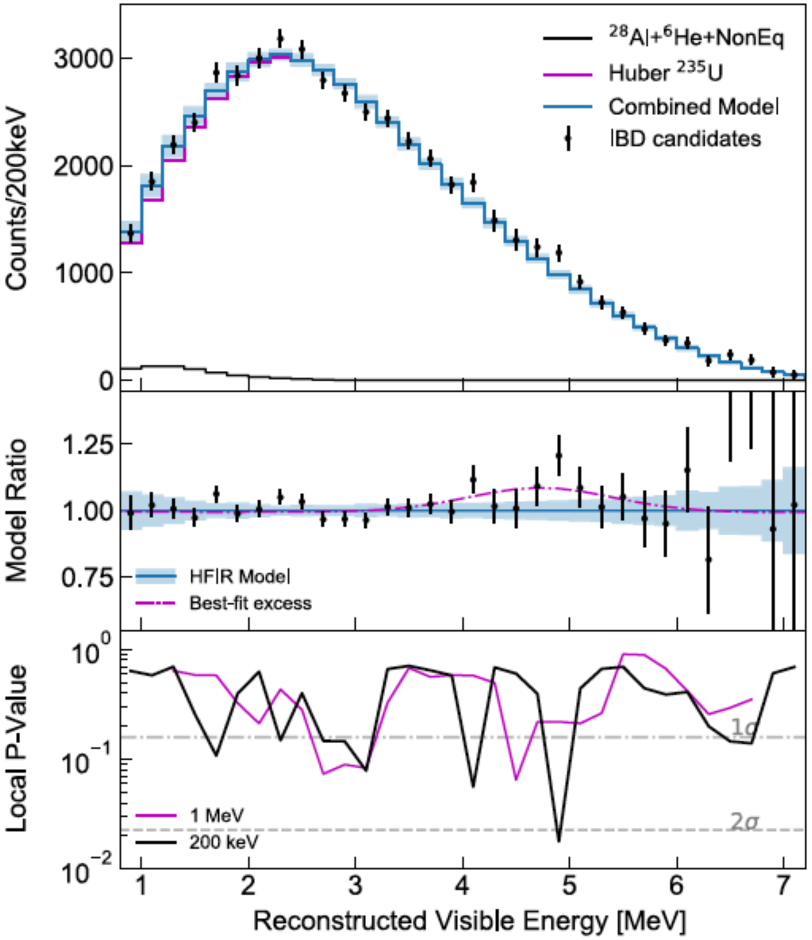

PROSPECT, [arXiv:2212.10669v1](arXiv:2212.10669v1)




- Period correlated systematics:
  *energy response, resolution smearing, reflector thickness, z-fiducialization, acquisition thresholds*
- Uncorrelated systematic:
  *background variation, background subtraction*

# Improved spectrum uncertainties

*PROSPECT, [PRD 103, 032001 (2021)]*



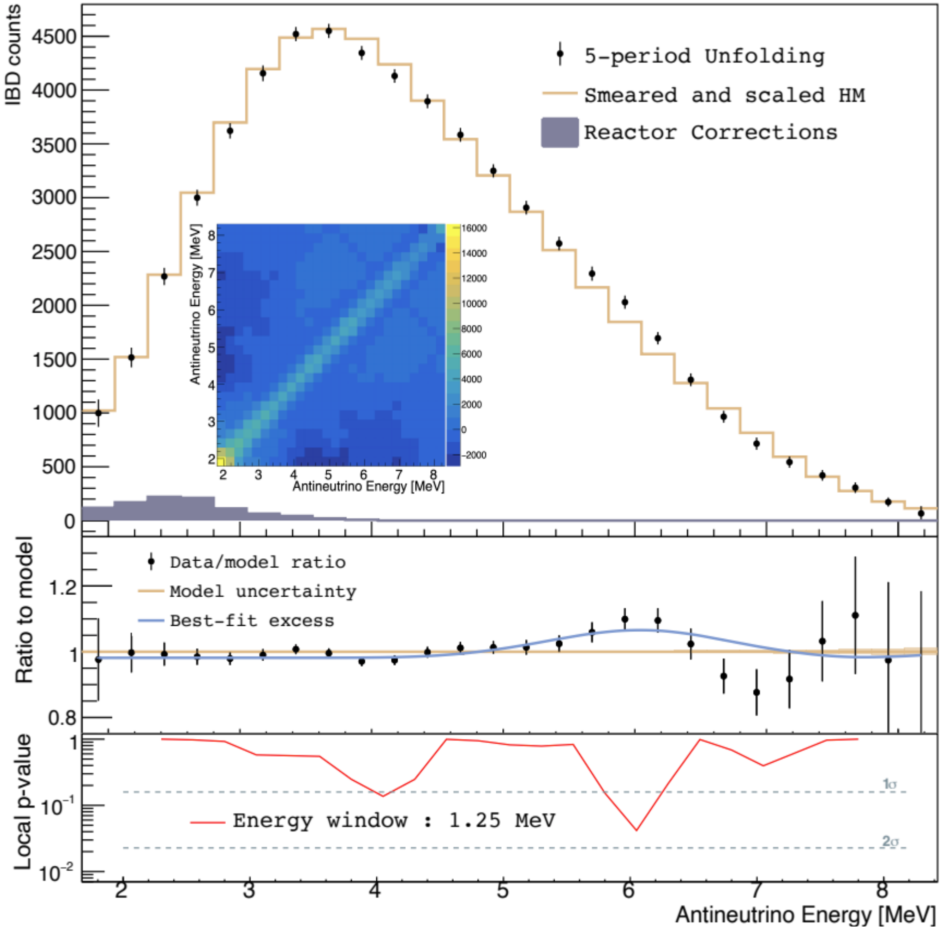

PROSPECT PRD 'bump' amplitude (1= Daya Bay)

- A = 0.84 ± 0.39

Improved PROSPECT amplitude (1= Daya Bay)

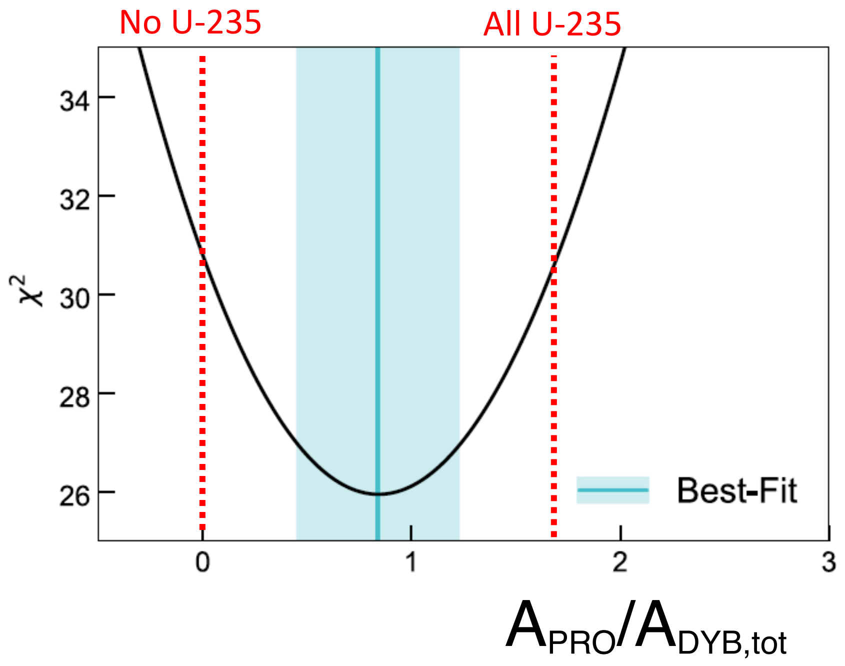
- A = 0.64 ± 0.21

*PROSPECT, [arXiv:2212.10669v1]*



# Improved spectrum uncertainties strengthen 'equal isotope' interpretation

*PROSPECT, PRD 103, 032001 (2021)*

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- A = 0.84 ± 0.39
- A = 0 (no bump)
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- A = 1.78 (LEU bump all $^{235}U$)
  → disfavored at 2.4σ

Improved PROSPECT amplitude (1= Daya Bay)

- A = 0.64 ± 0.21
- A = 0 (no bump)
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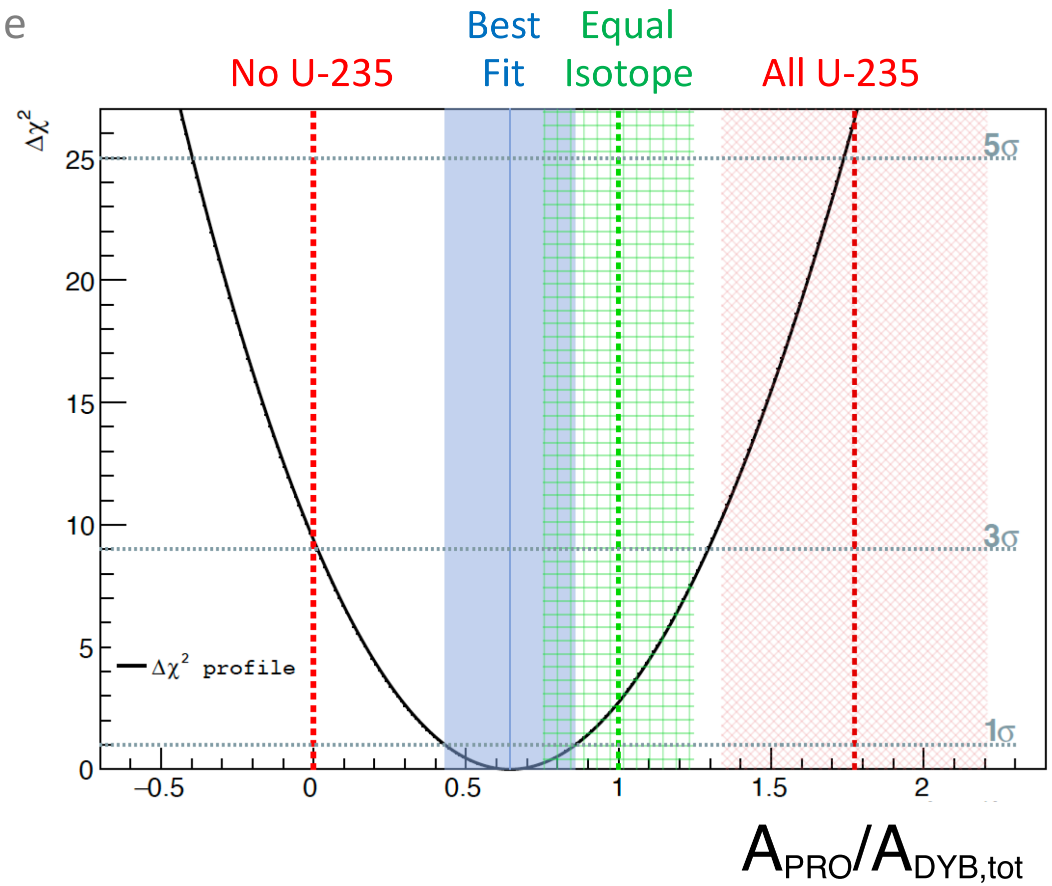
- A = 1.78 (LEU bump all $^{235}U$)
  → disfavored at 5.2σ

*PROSPECT, arXiv:2212.10669v1*



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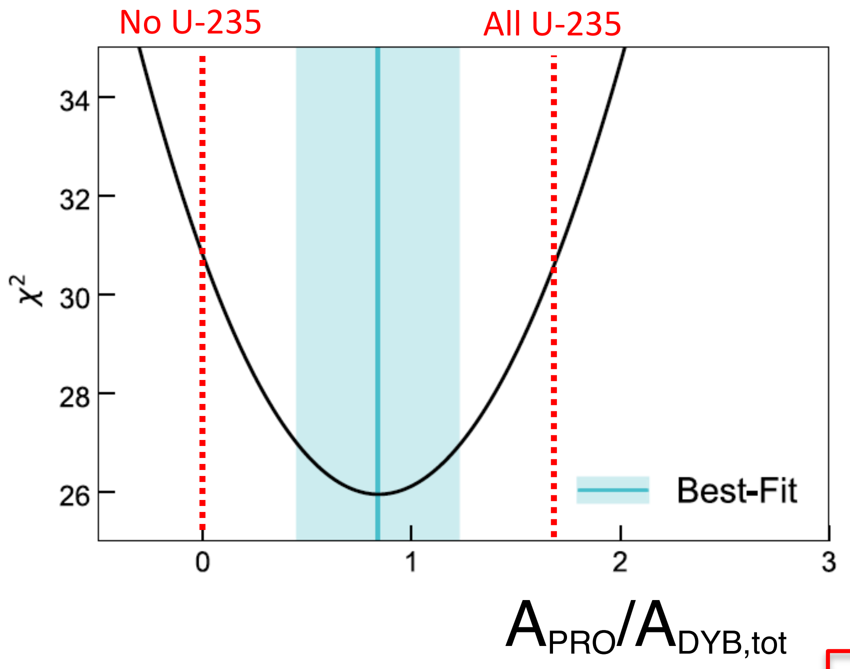
PROSPECT, PRD 103, 032001 (2021)

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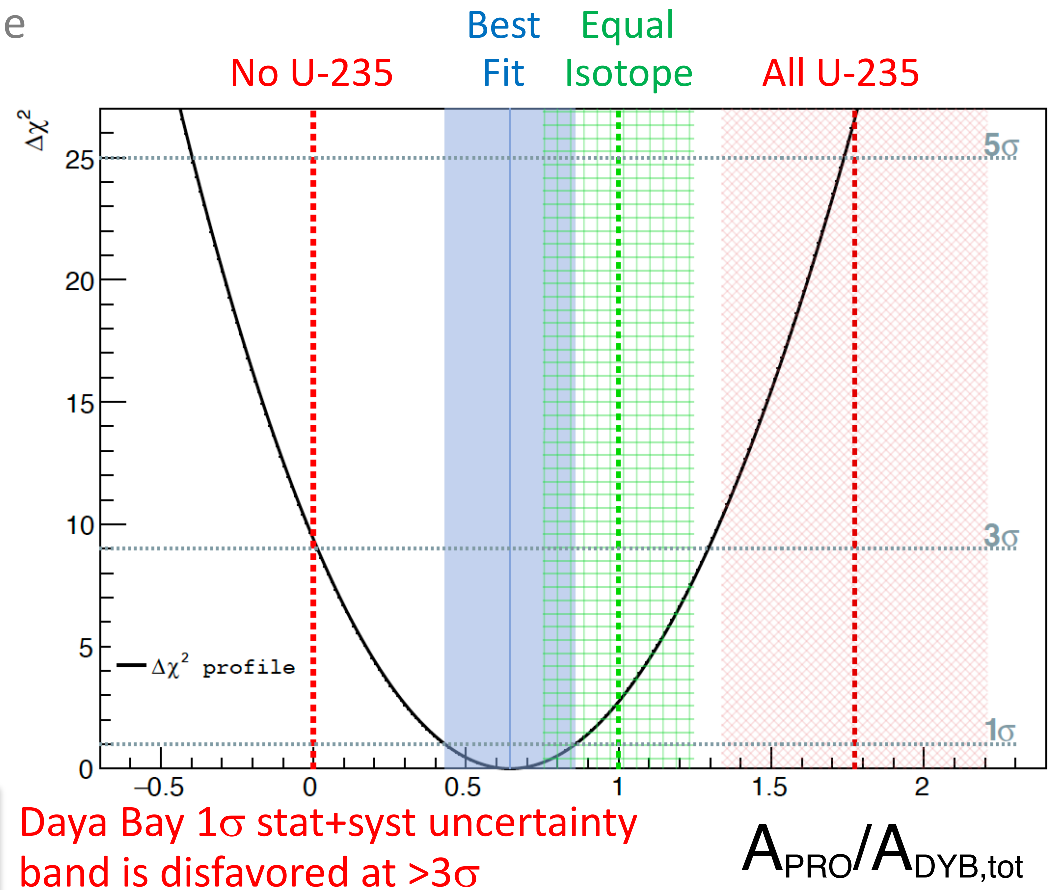
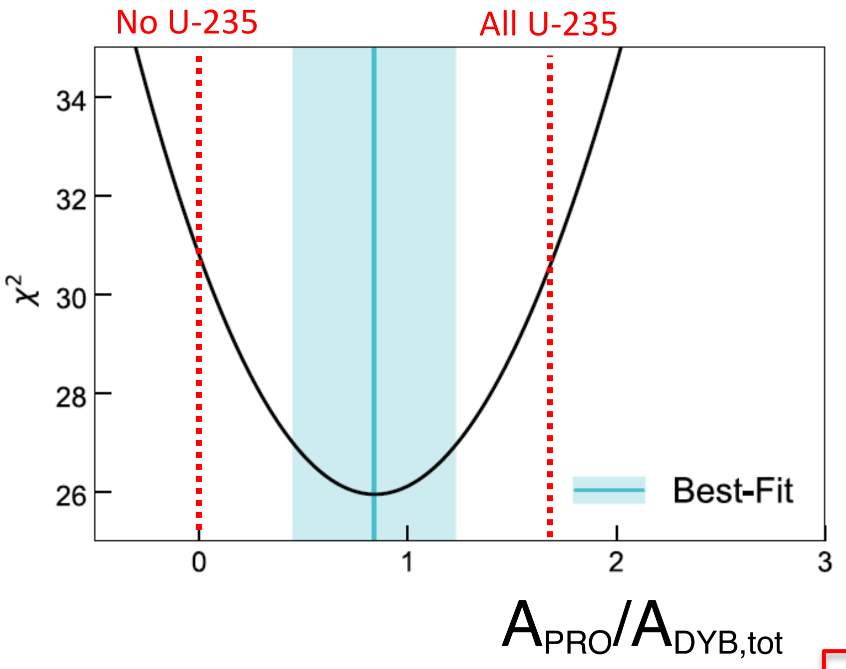
PROSPECT, arXiv:2212.10669v1




Daya Bay 1σ stat+syst uncertainty band is disfavored at >3σ

# Improved spectrum uncertainties strengthen ‘equal isotope’ interpretation

*PROSPECT, PRD 103, 032001 (2021)*

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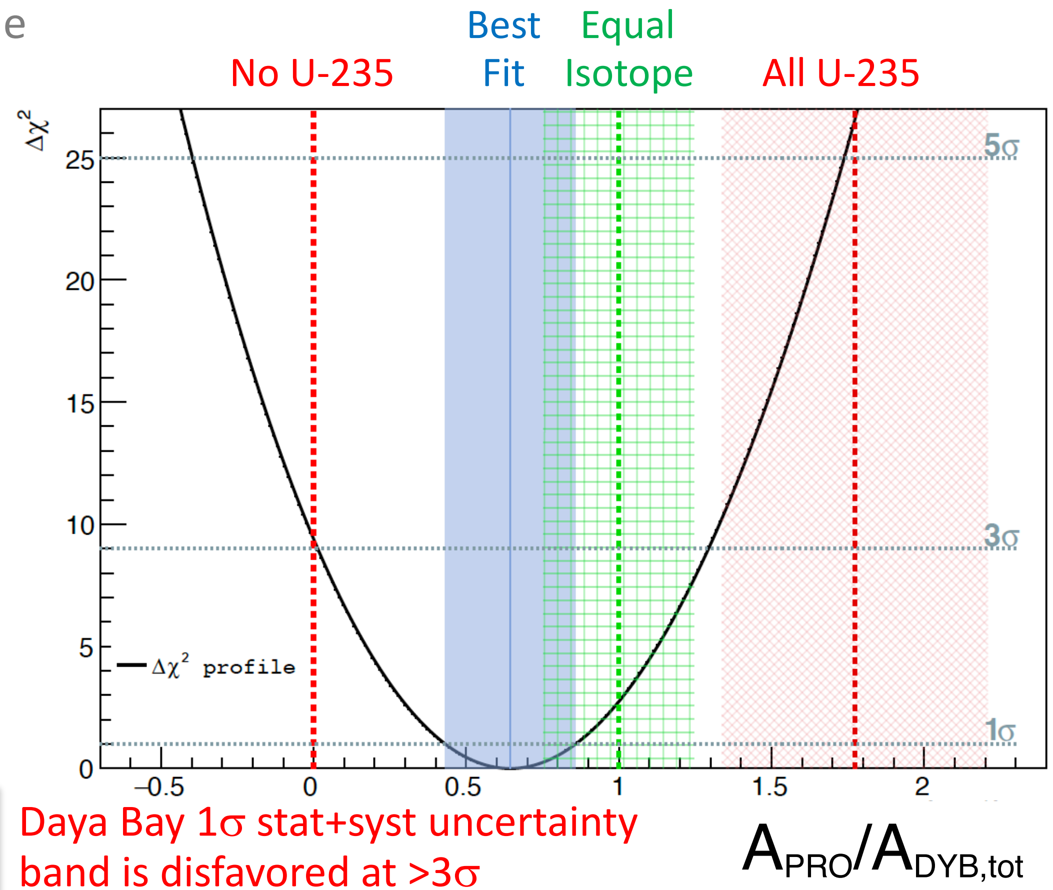
*PROSPECT, arXiv:2212.10669v1*




Daya Bay 1σ stat+syst uncertainty band is disfavored at >3σ

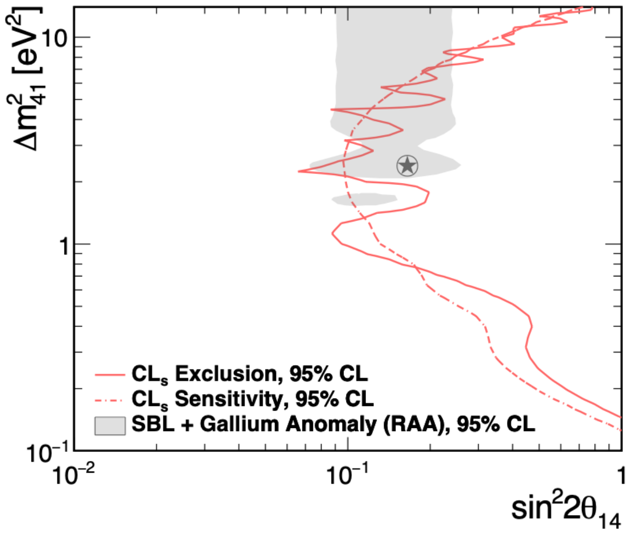
Work in progress to incorporate DB uncertainties via simultaneous fit

Uncorrelated detector systematics, not HEU statistics, are now limiting the ability to probe the all U-235 hypothesis

# Forthcoming Results from PROSPECT-I Data: Oscillation | Absolute Flux | IBD Backgrounds

## Oscillation

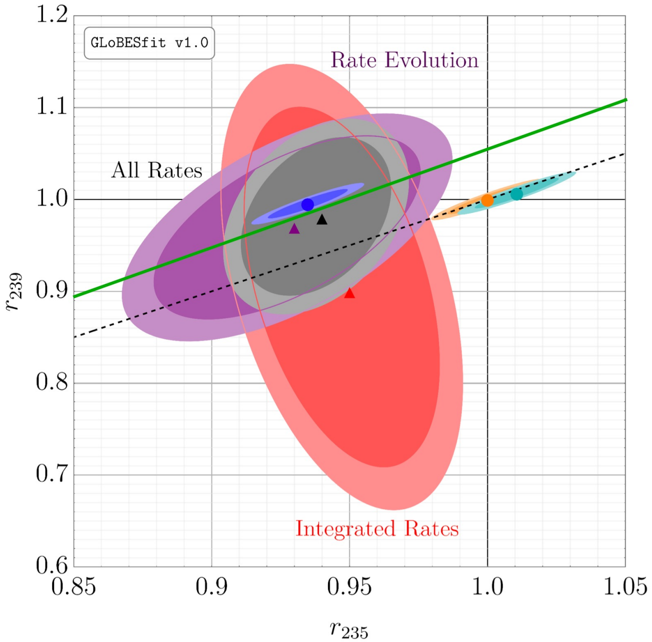
- Will perform 5-period oscillation analysis with PROSPECT-I IBD dataset
- Improved statistical power → improved oscillation sensitivity
- Finer baseline, multi-period, low-statistics binning requires CNP $\chi^2$ to avoid bias
- Expect result in mid-2023




*PROSPECT, PRD 103, 032001 (2021)*

## Absolute Flux

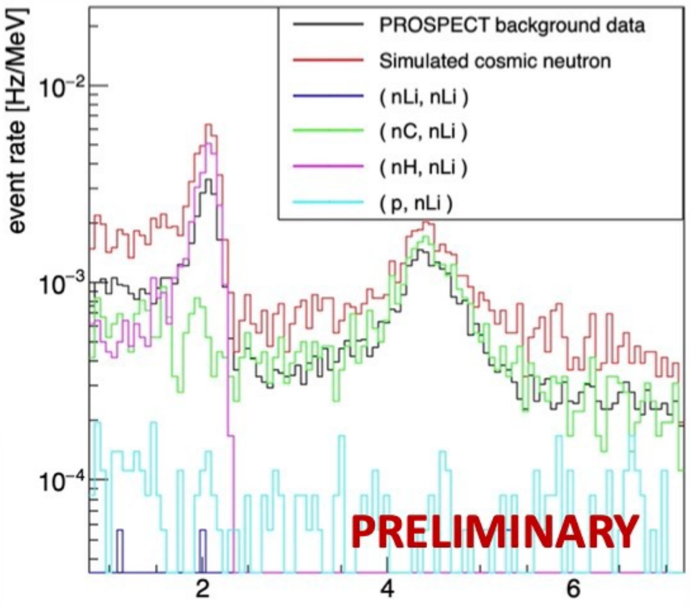
- New PROSEPCT-I measurement will further constrain $^{235}$U yield w/ < 3% uncertainty:
  - Statistics better than 1.5%
  - Expect systematics ~ 2% (mostly Rx power)
- Anticipated result later in 2023
- Guides ~1.5% PROSPECT-II measurement to improve $^{235}$U, $^{239}$Pu, & $^{238}$U yields




P. Kunkle, Neutrino 2022 poster

## IBD Backgrounds

- Use PROSPECT-I data to provide insights into background mitigation for aboveground IBD detection
- Have achieved reasonable data and simulation agreement & identified important background classes

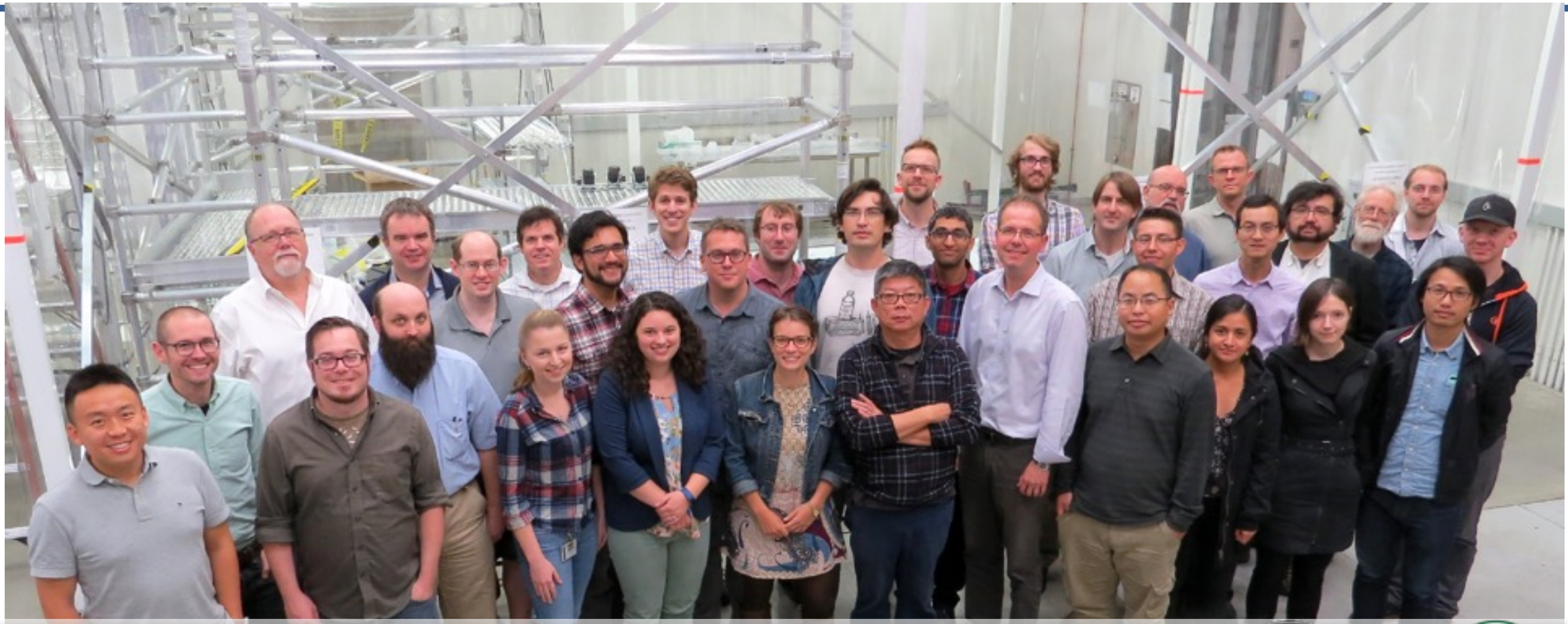



F. Sutanto, Neutrino 2022 poster

# Conclusions

- PROSPECT has supported a rich technical and scientific program
- Joint Spectrum Analyses with Daya Bay and STEREO have leveraged the unique features of each experiment to extract further information and represent a first step towards common data standards for neutrino data
- The statistical power of the PROSPECT-I dataset has been approximately doubled through new analysis techniques: Data Splitting and Single Ended Event Reconstruction
- A multi-period (-detector configuration) response unfolding strengthens our observation of a spectrum excess between 5-7 MeV and provides new constraints on the origin of the data-model disagreement
  - this approach could be further extended to multi-experiment/multi-reactor measurements
- The final PROSPECT-I spectrum measurement strengthens the 'equal isotope' hypothesis for the origin of the data/model discrepancy between 5-7 MeV
  - Multi-reactor measurements with correlated detection systematics would help to further test this
- The PROSPECT-I dataset will continue to produce scientific results as the new DS+SEER event selection is is applied to our SBL Oscillation Search, an Absolute Flux measurement, and studies of aboveground IBD backgrounds

# PROSPECT Collaboration



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