Recent Results and Future Outlook

3rd IAEA Technical Meeting Nuclear Data for Antineutrino Spectra Applications

4/8/2025

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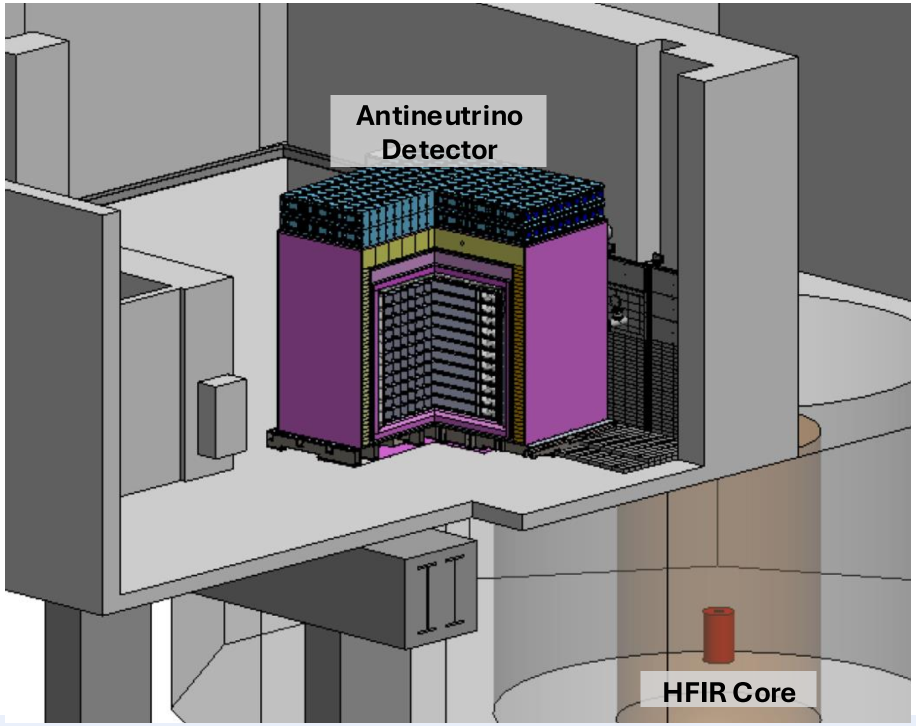
on behalf of the PROSPECT Collaboration

Prepared by LLNL under Contract DE-AC52-07NA27344.

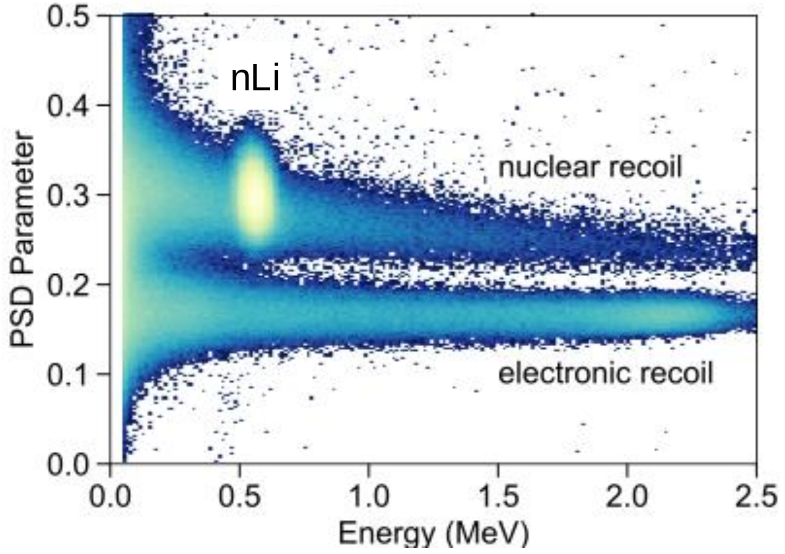
PROSPECT Overview

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**



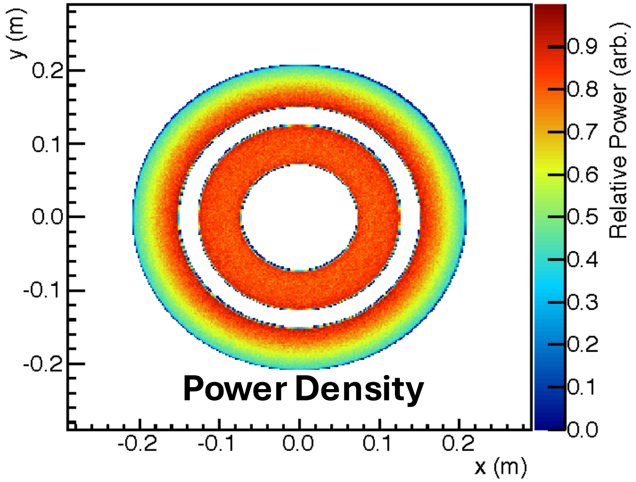
Neutron capture on ^{6}Li (nLi) provides:
- localized, distinct signal
- uniform efficiency in compact detector



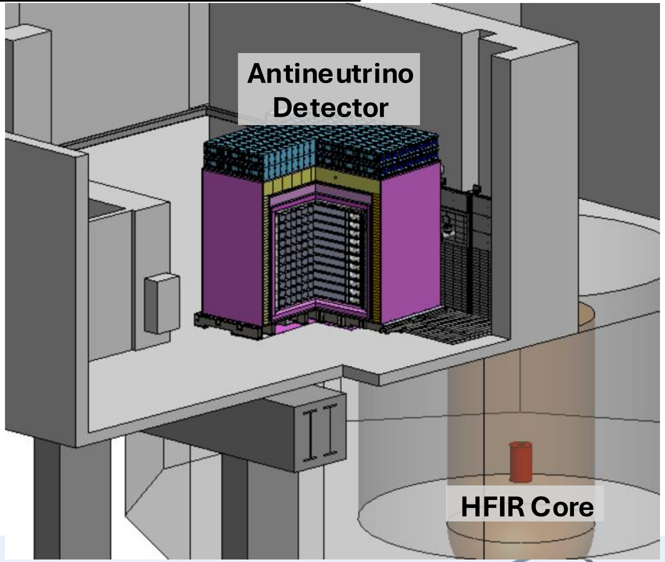
Experimental site: High Flux Isotope Reactor @ORNL

Compact Reactor Core

44cm



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

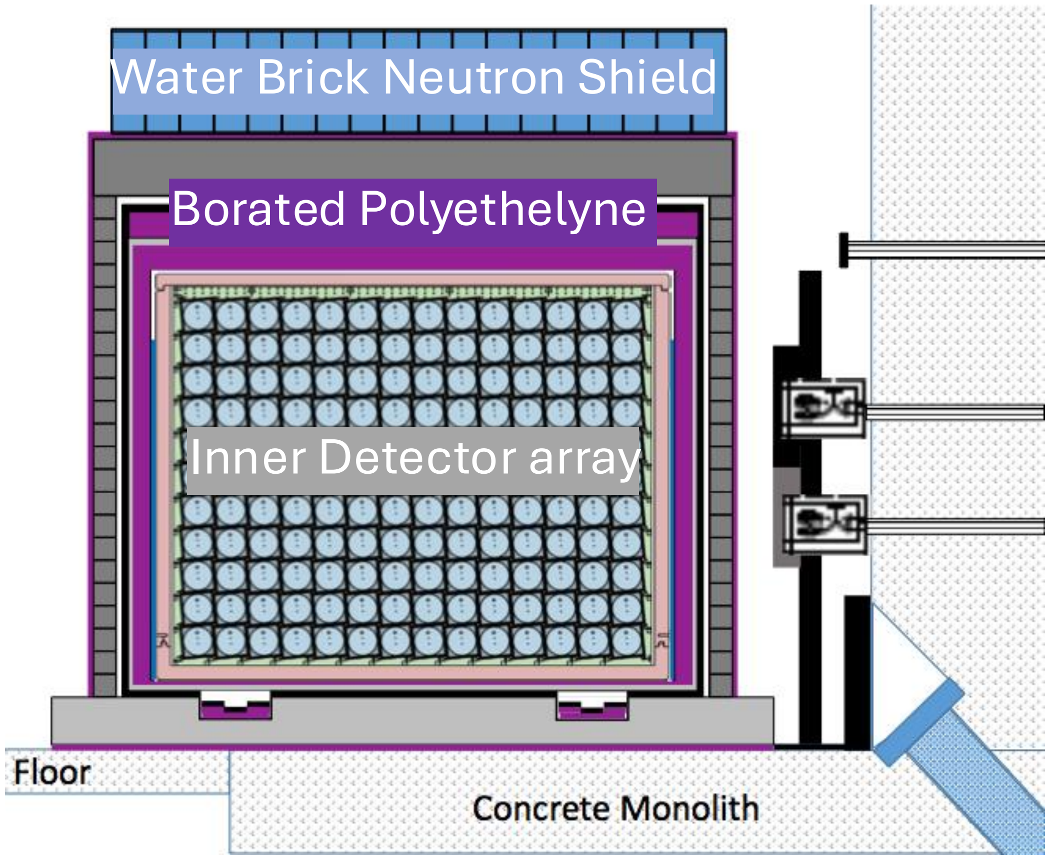


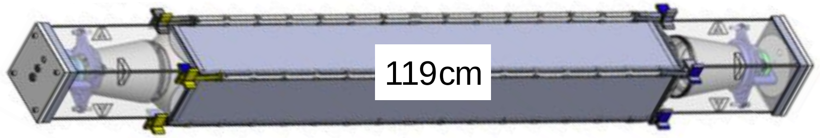
PROSPECT Overview

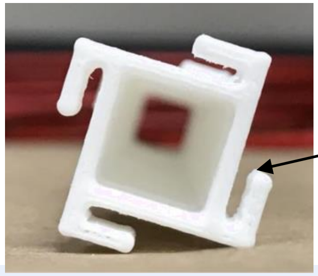
- 154 segments, 119cm x 15cm x 15cm
  - — ~25liters of LiLS per segment, total mass: 4ton
- Thin (1.5mm) reflector panels held in place by 3D-printed support rods

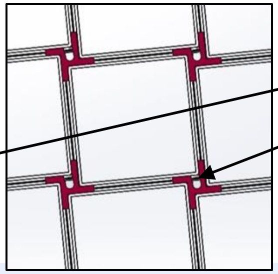
- **Segmentation enables:**
  - — Calibration access throughout volume
  - — Position reconstruction (X,Y)
  - — Event topology ID
  - — Fiducialization
- Double ended PMT readout for full (X,Y,Z) position reconstruction

- Optimized shielding to reduce reactor and cosmogenic backgrounds









Tilted Array for calibration access

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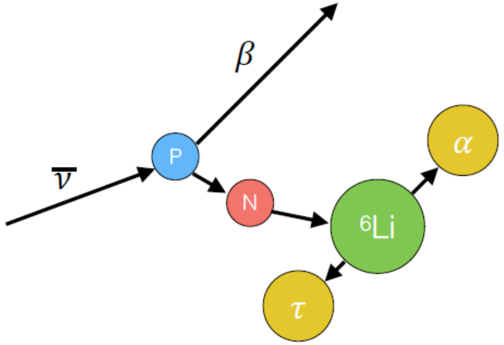
Event Detection in PROSPECT

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

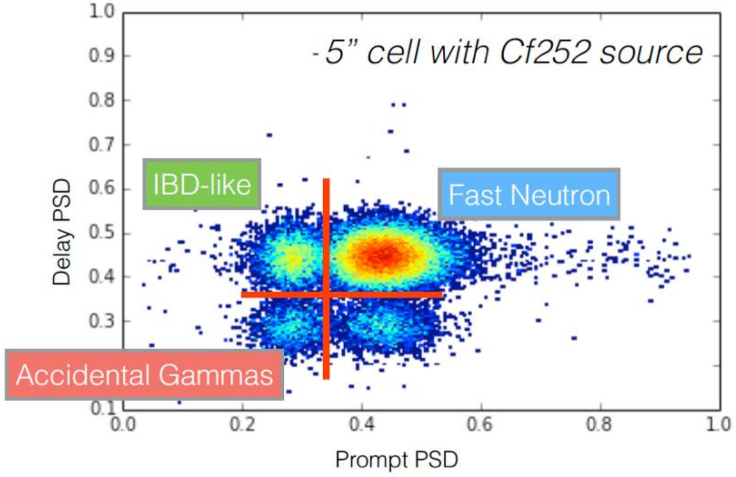
inverse beta decay (IBD)
γ-like prompt, n-like delay

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

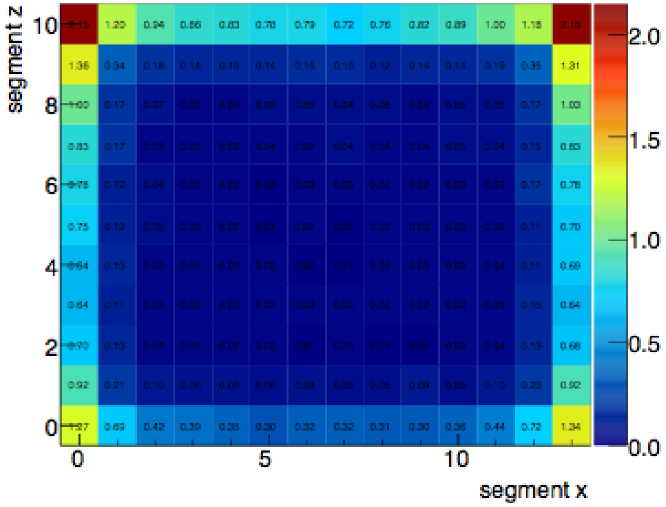
accidental gamma background
γ-like prompt, γ-like delay

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

Pulse Shape Discrimination



Simulation



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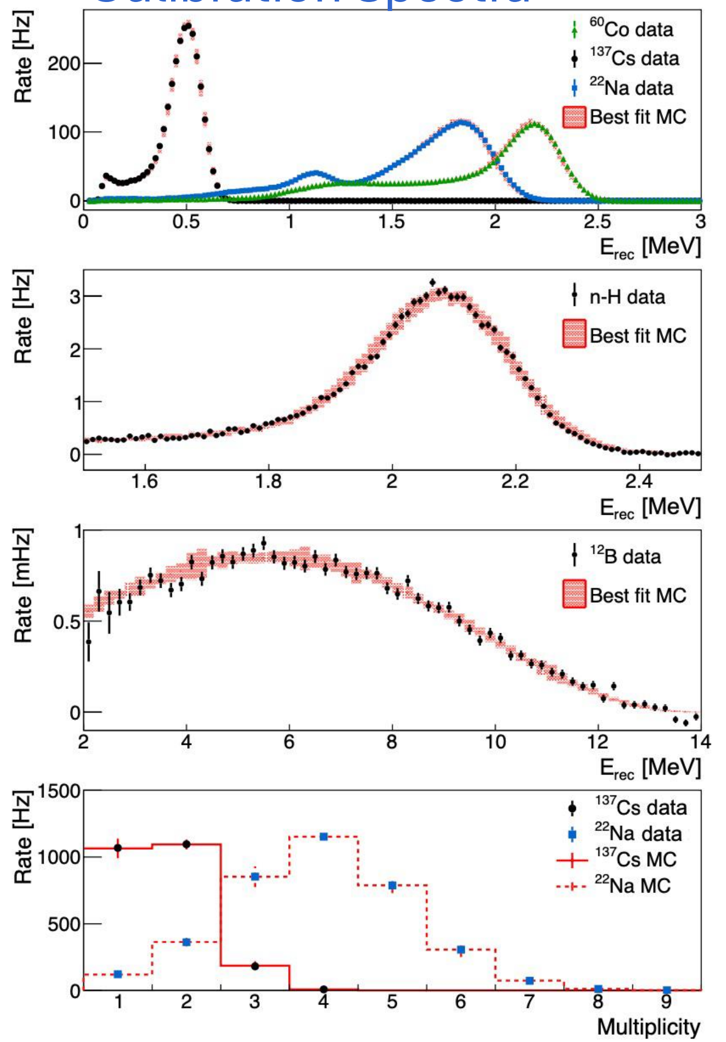
Background reduction is key challenge

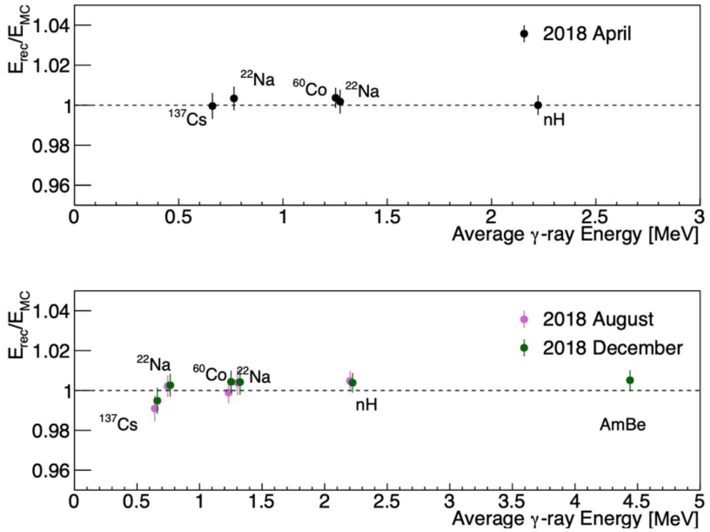
Energy Reconstruction

Calibration Spectra

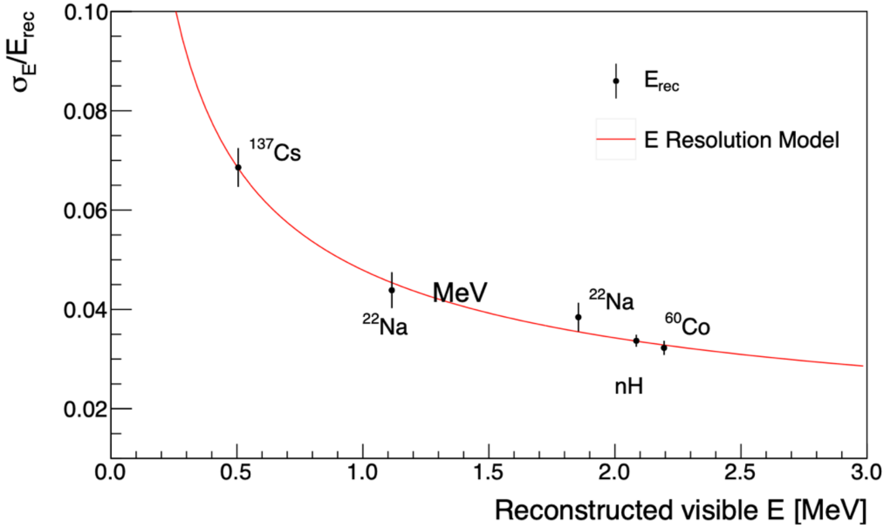


- Sources deployed throughout detector, measure single segment respons
- Proton PSD tagged ^{12}B production - high-energy beta spectrum calibratio
- Full-detector E_{rec} within 1% of E_{true}

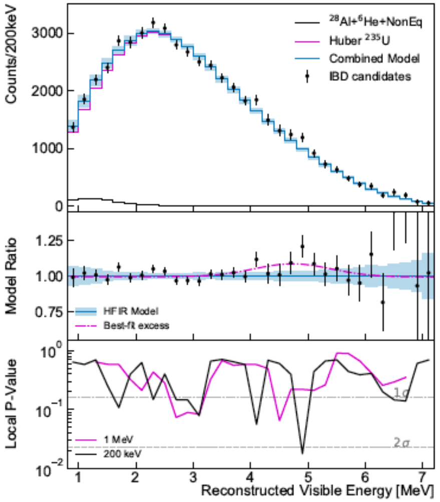
Data vs MC

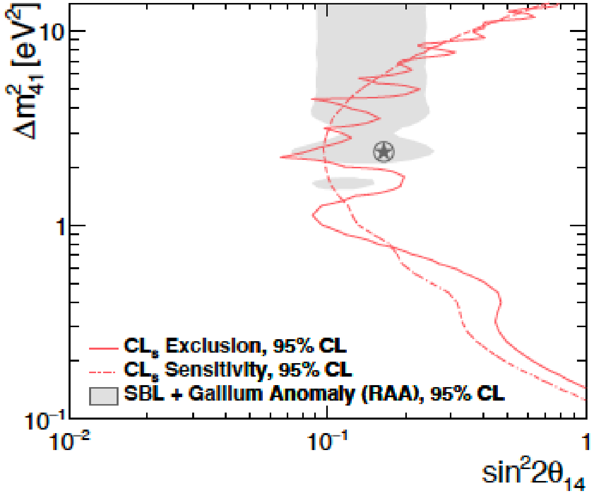


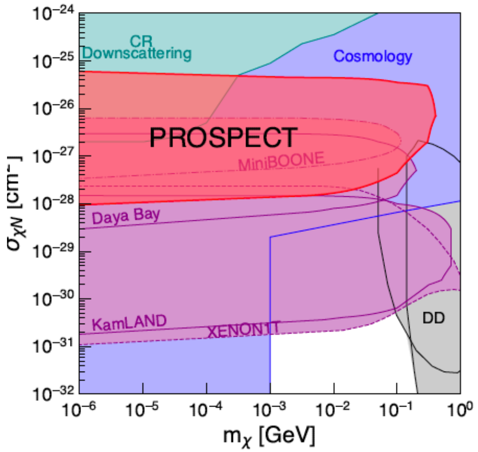
Stochastic resolution

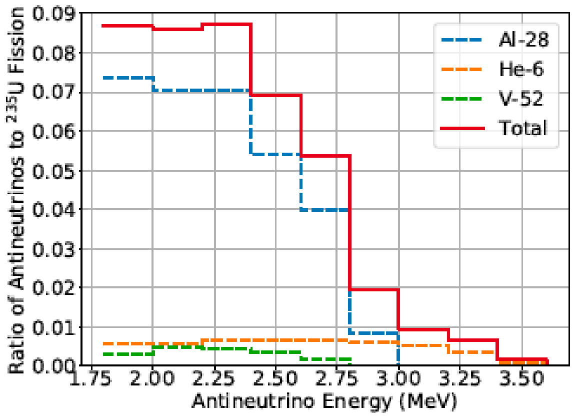


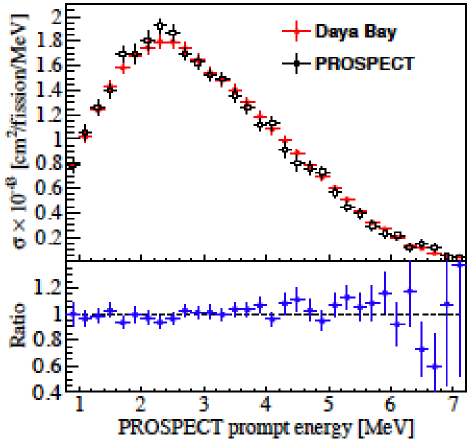
Physics Results & Plans

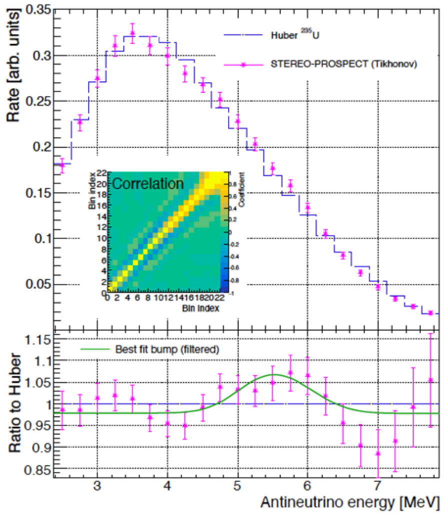












First Oscillation Search
Phys.Rev.Lett. 121 (2018) 251802

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

Non-fuel reactor neutrinos
Phys.Rev. C 101 (2020) 5, 054605

Improved Osc. + Spectrum
Phys.Rev.D 103 (2021) 3, 032001

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
Phys. Rev Lett 128, 081802 (2022)

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

Antineutrino Directionality
Phys.Rev.D 111, 032014 (2025)

'Final' PROSPECT-I Oscillation
arxiv:2406.10408, accepted PRL

Daya Bay/PROSPECT/STEREO Joint Analysis

Correlated Background Study

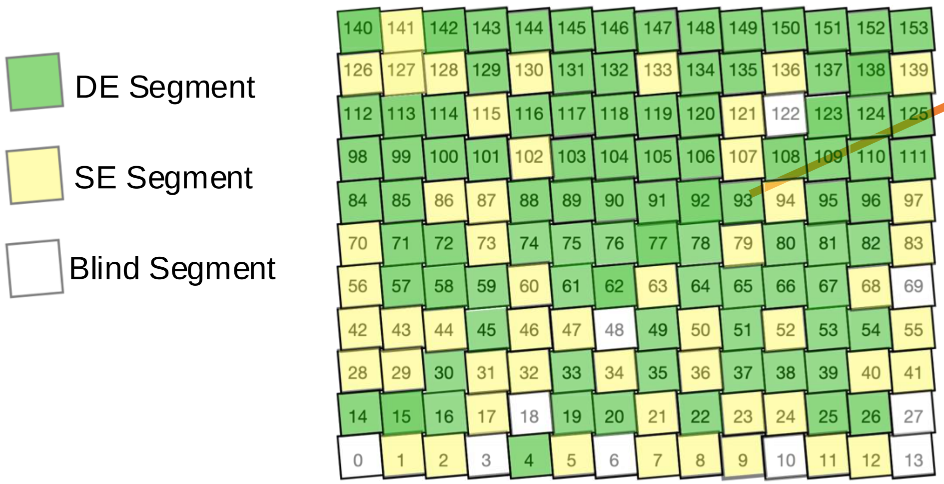
Absolute Flux Analysis

Further BSM studies?

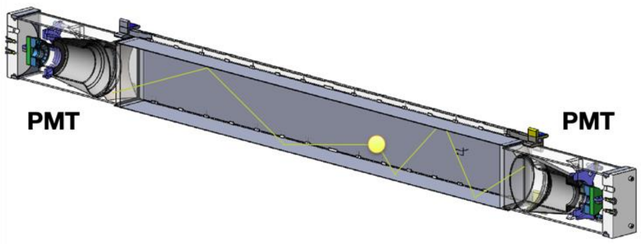
Reconstruction and Analysis Improvements

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

Detector configuration used for 2021 PRD analysis



154 segments with two PMTs

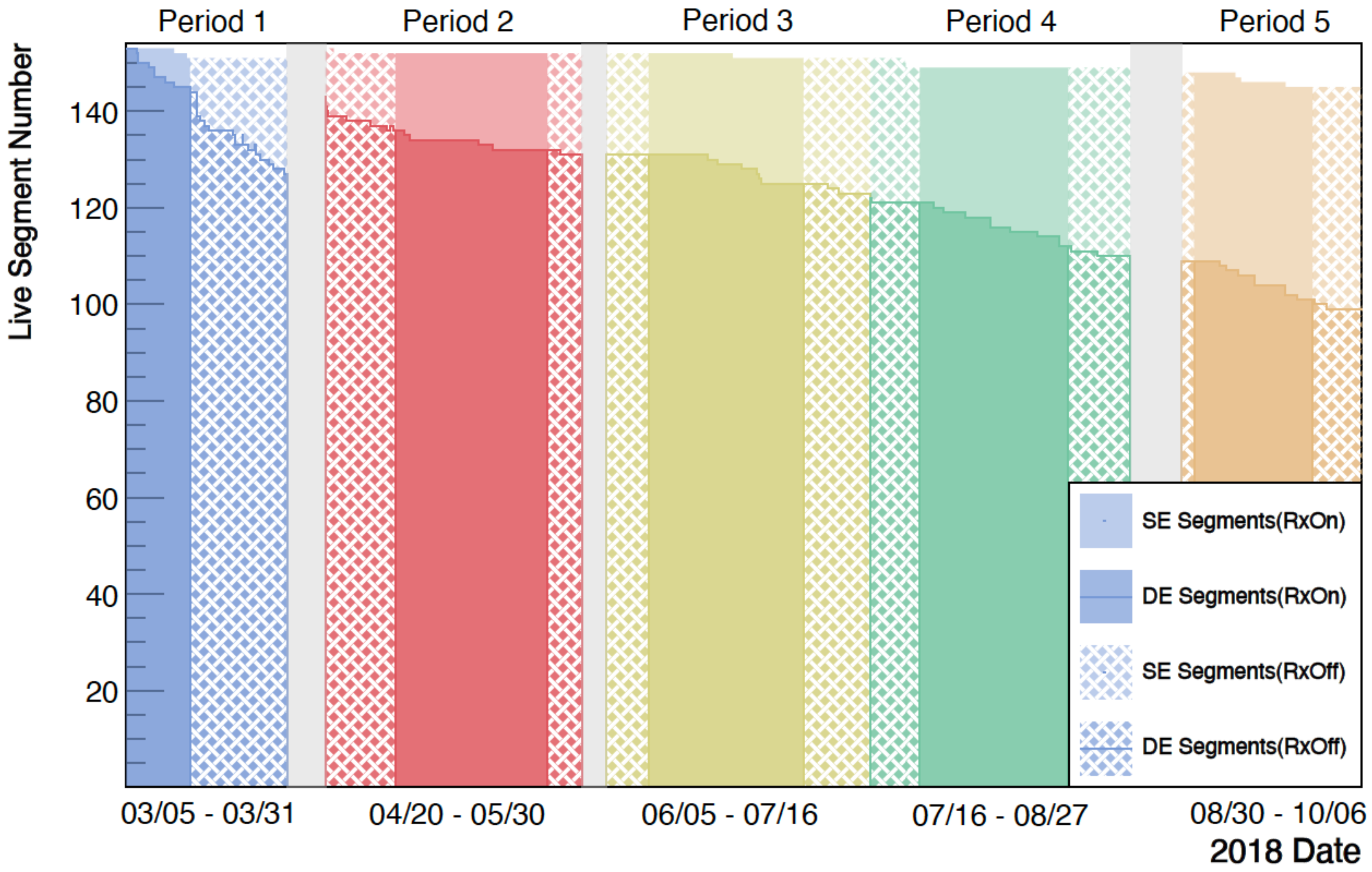


Some segments coupled to one PMT or both switched off due to scintillator leakage into PMT housing.

- Two new analysis approaches implemented:

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

Data Splitting



Goals

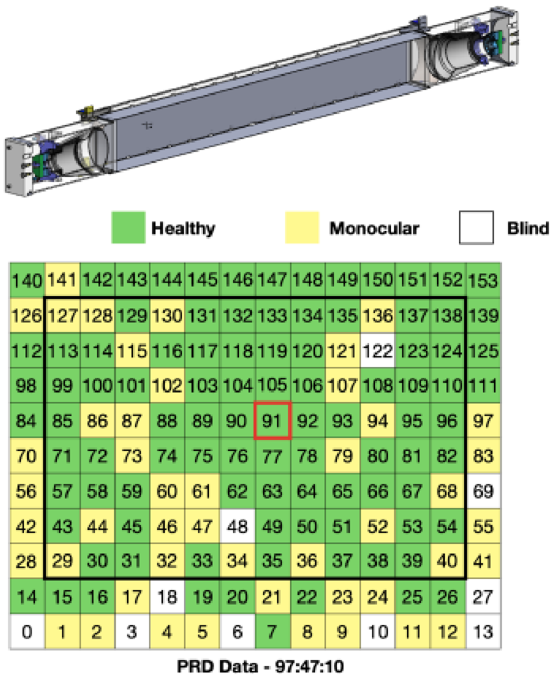
- Split PROSPECT-I data into distinct periods to increase active volume
- Maximize number of live segments in each period

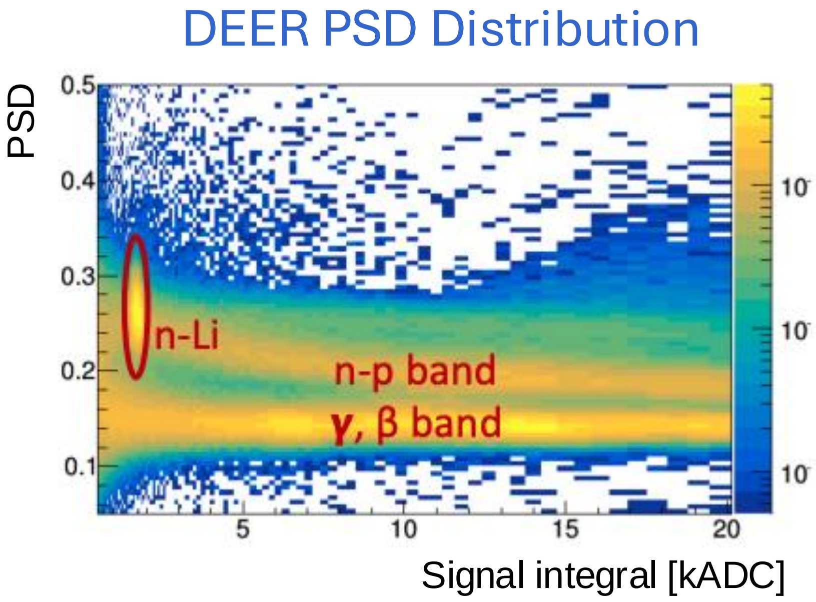
Splitting Criteria

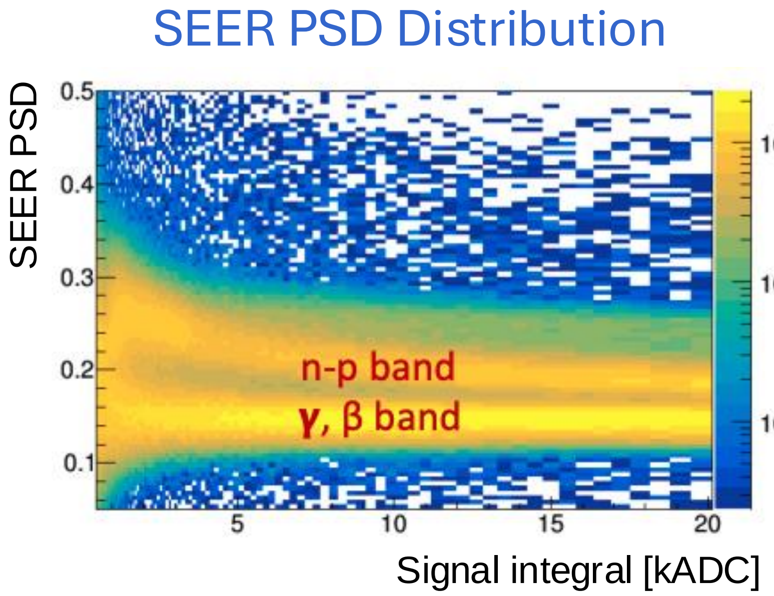
- Each period should start immediately after a new calibration campaign
- Each period must contain one full RxOn cycle
- All periods should have RxOff data before and after each corresponding RxOn cycle
  - Exception: Period 1 since no prior RxOff
- Keep ratio of RxOff/RxOn between 50%-70%

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

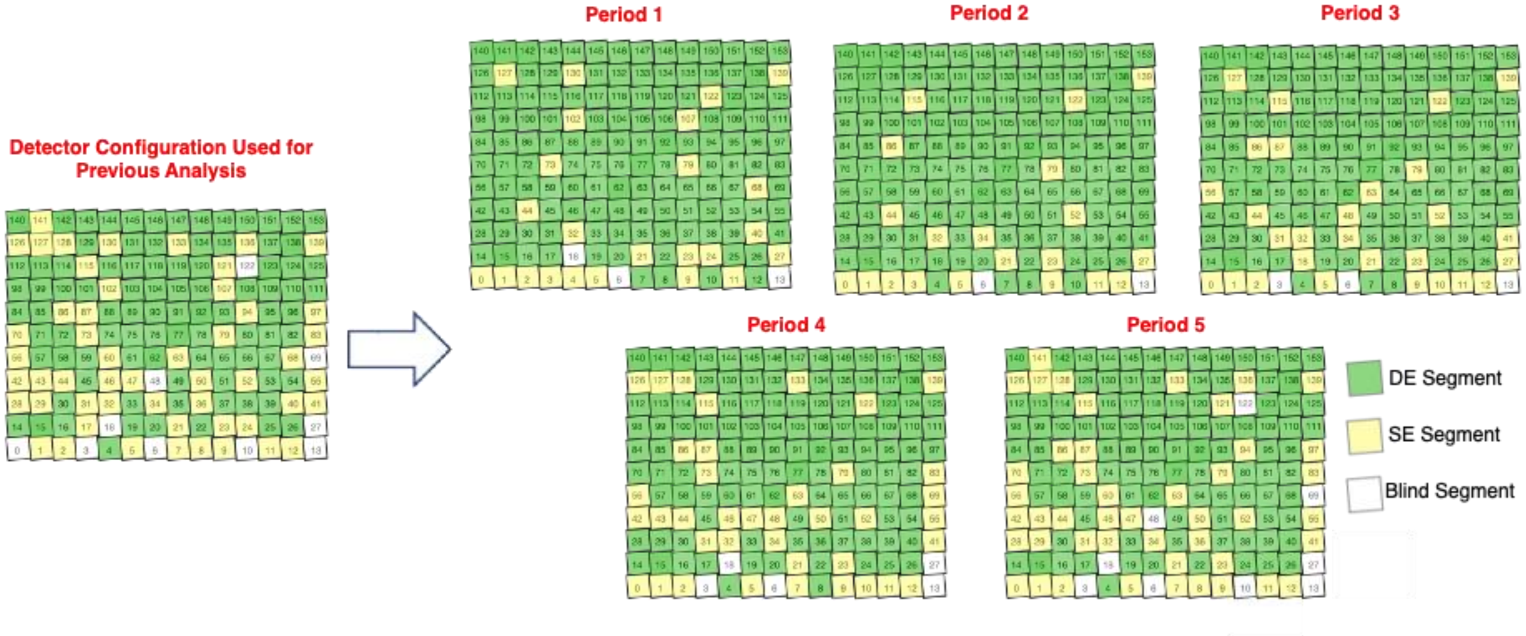




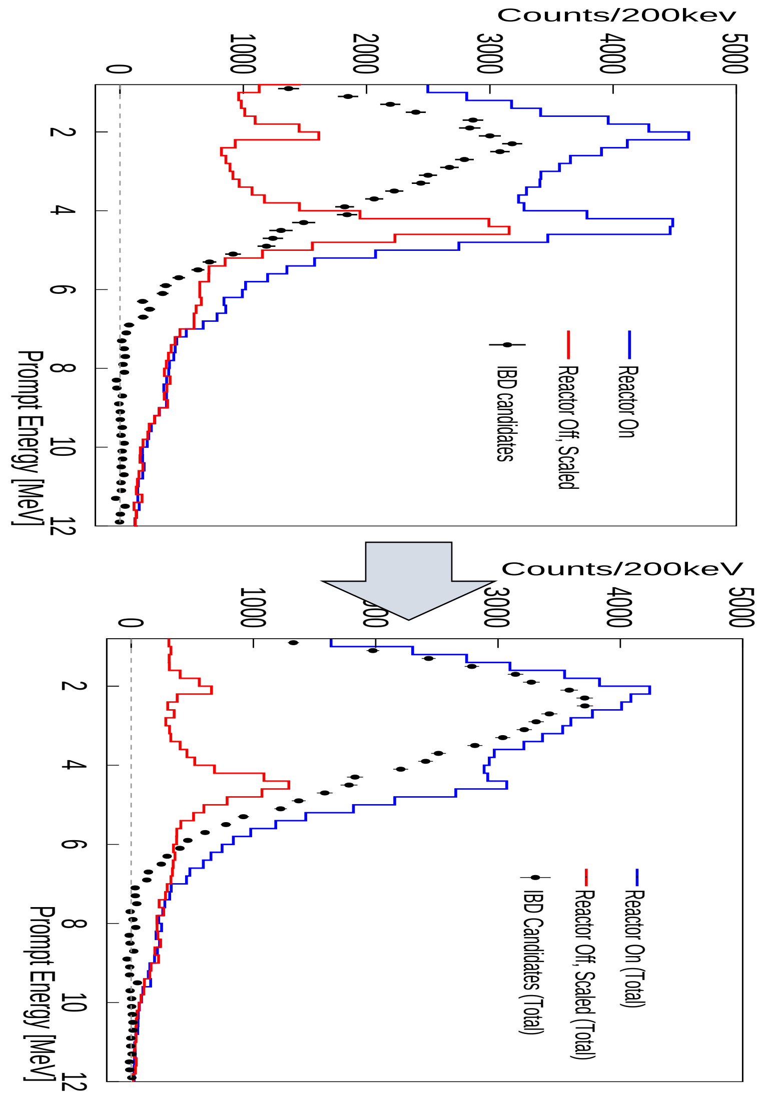


DS + SEER Improvements

Segment configuration



Prompt Spectra

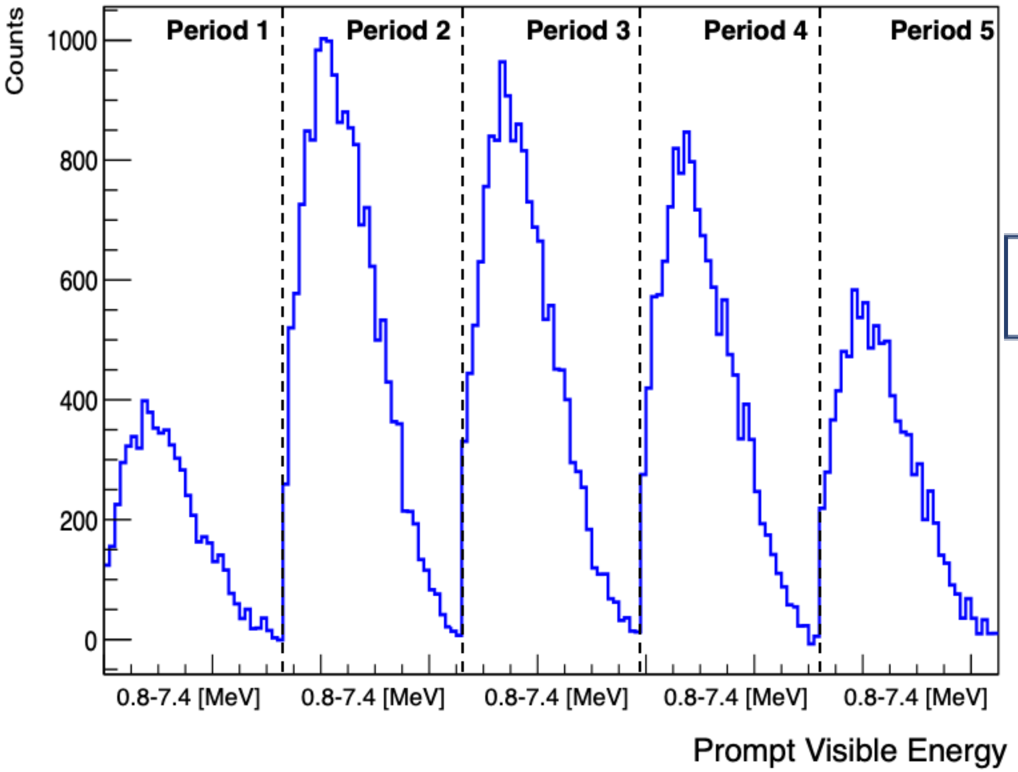


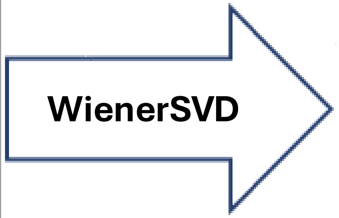
- IBD counts ~**(x1.2)**
- IBD effective counts ~**(x2)**
- Signal to cosmogenic background (S/CB) ~**(x2.8)**
- Signal to accidental background (S/AB) ~**(x2.4)**

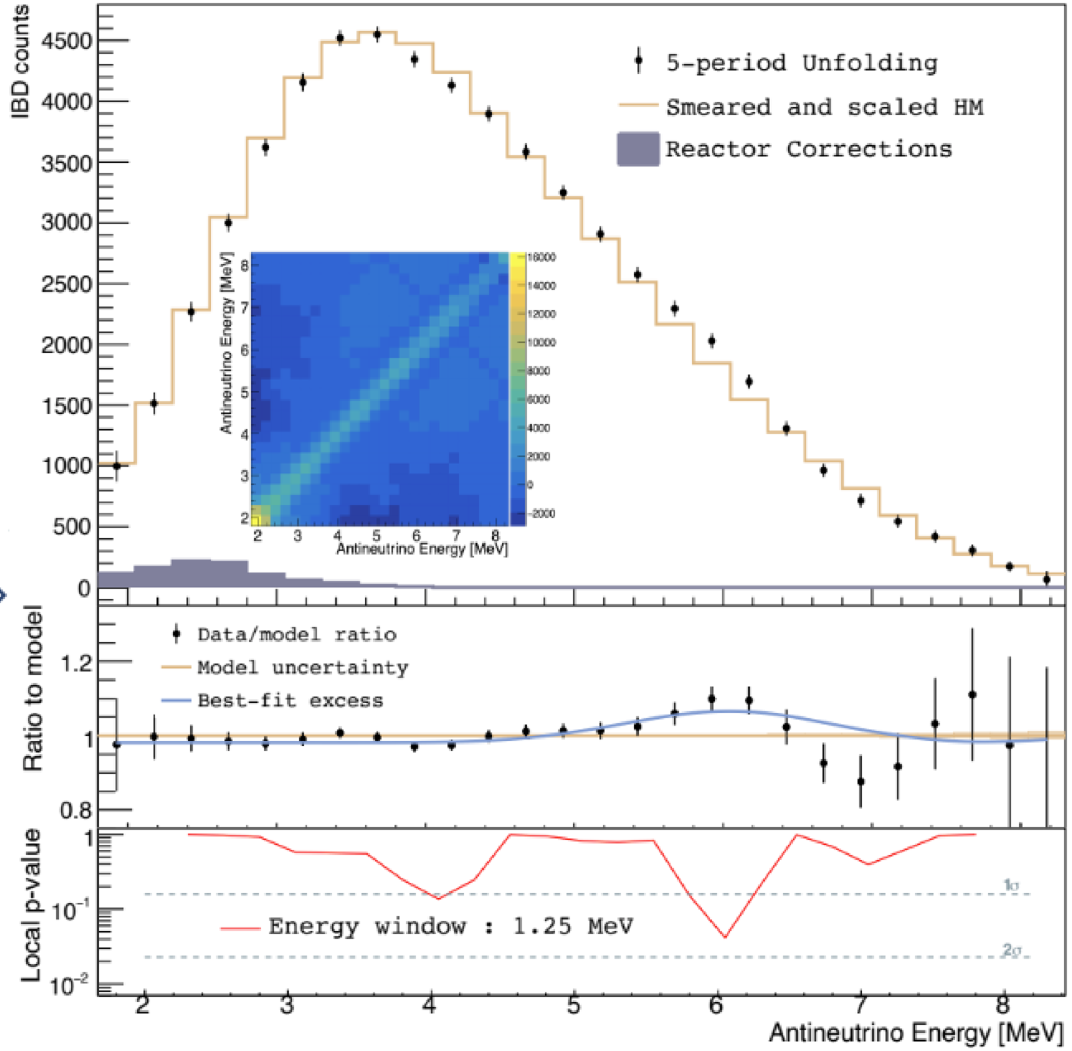
Multi-Period Spectrum Analysis

[PRL 131, 021802 (2023)](PRL 131, 021802 (2023))

- Varying configuration yields a different detector response for each period
- Implemented framework to jointly unfold prompt spectra from each period into a final antineutrino energy spectrum



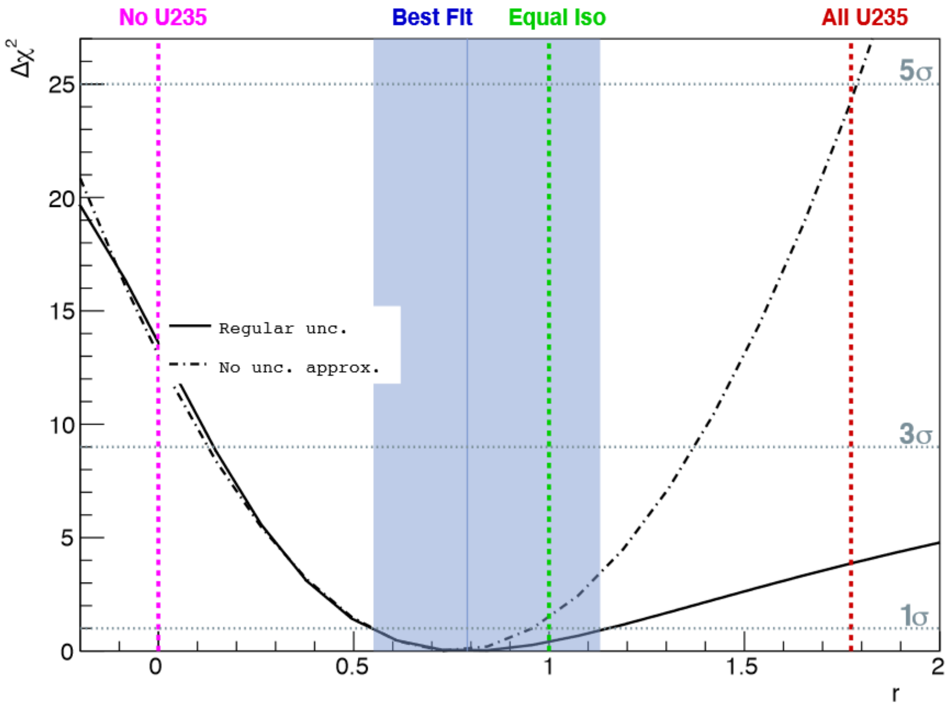


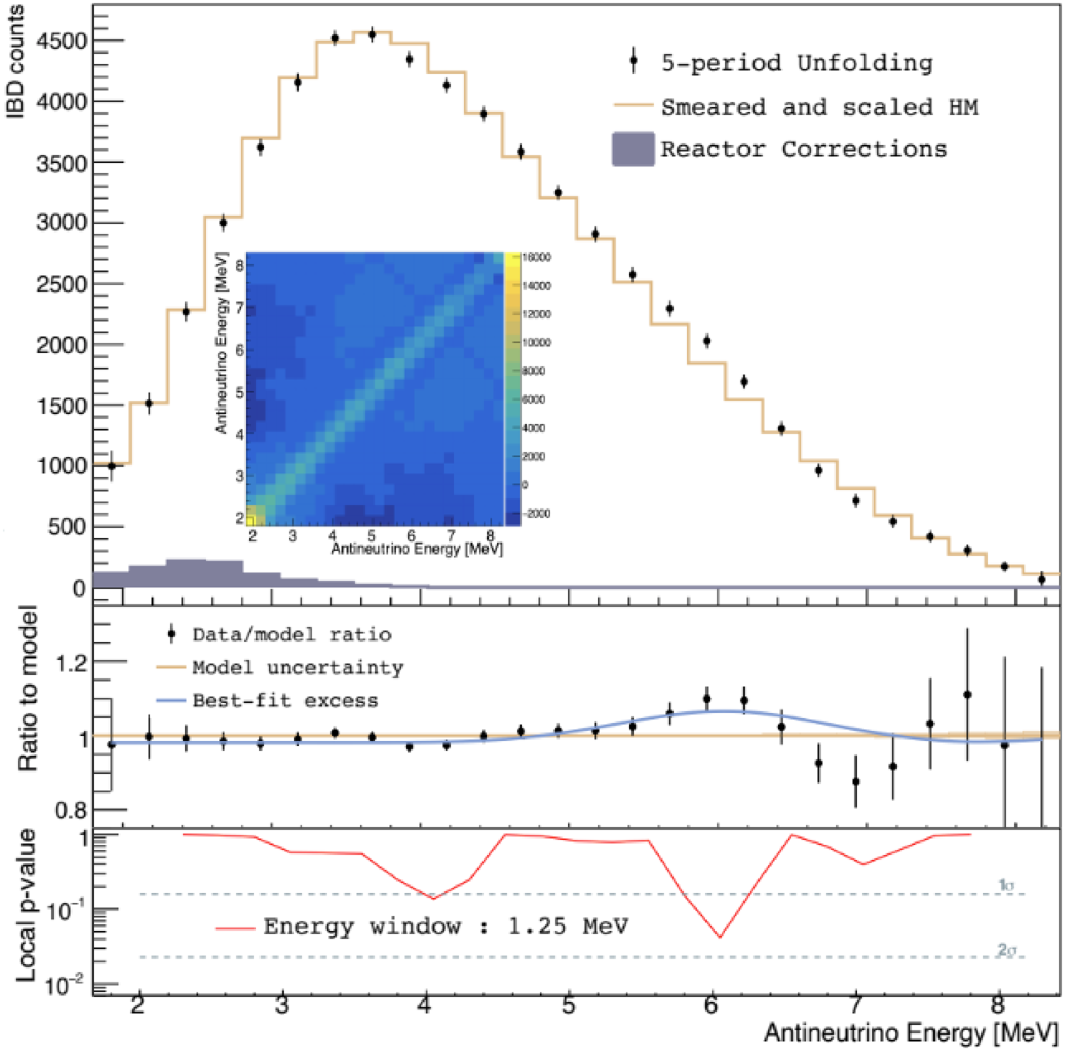


Improved ^{235}U Spectrum Measurement

[PRL 131, 021802 (2023)](#)

- Stronger constraints on the isotopic contributions of data-model disagreement ('bump')
  - 235U as sole contributor to bump disfavored at 2.2σ
  - No contribution from 235U disfavored at 3.2σ

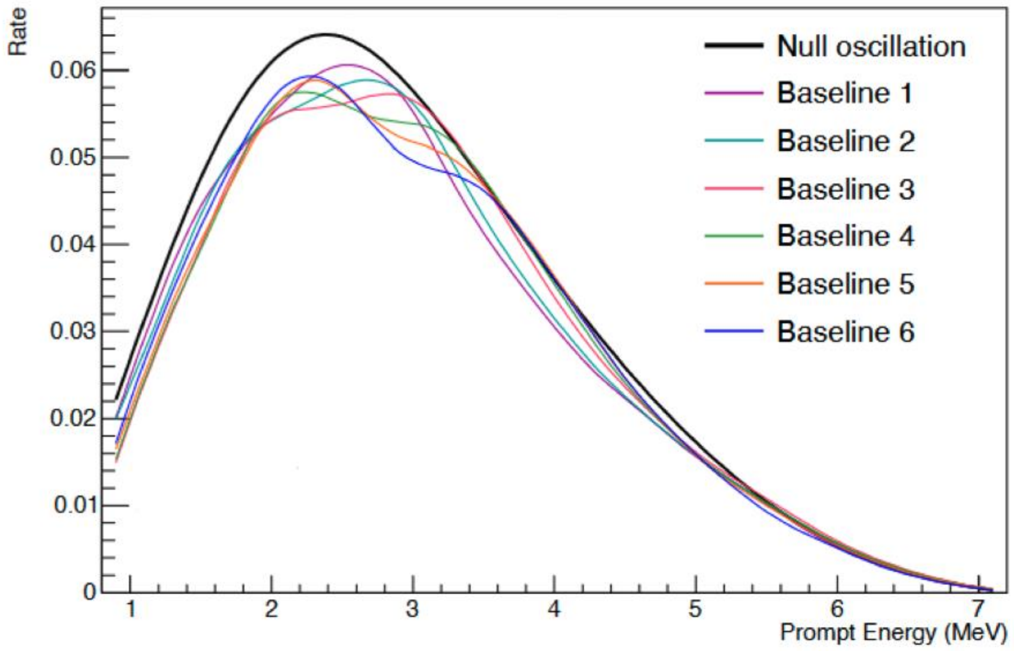


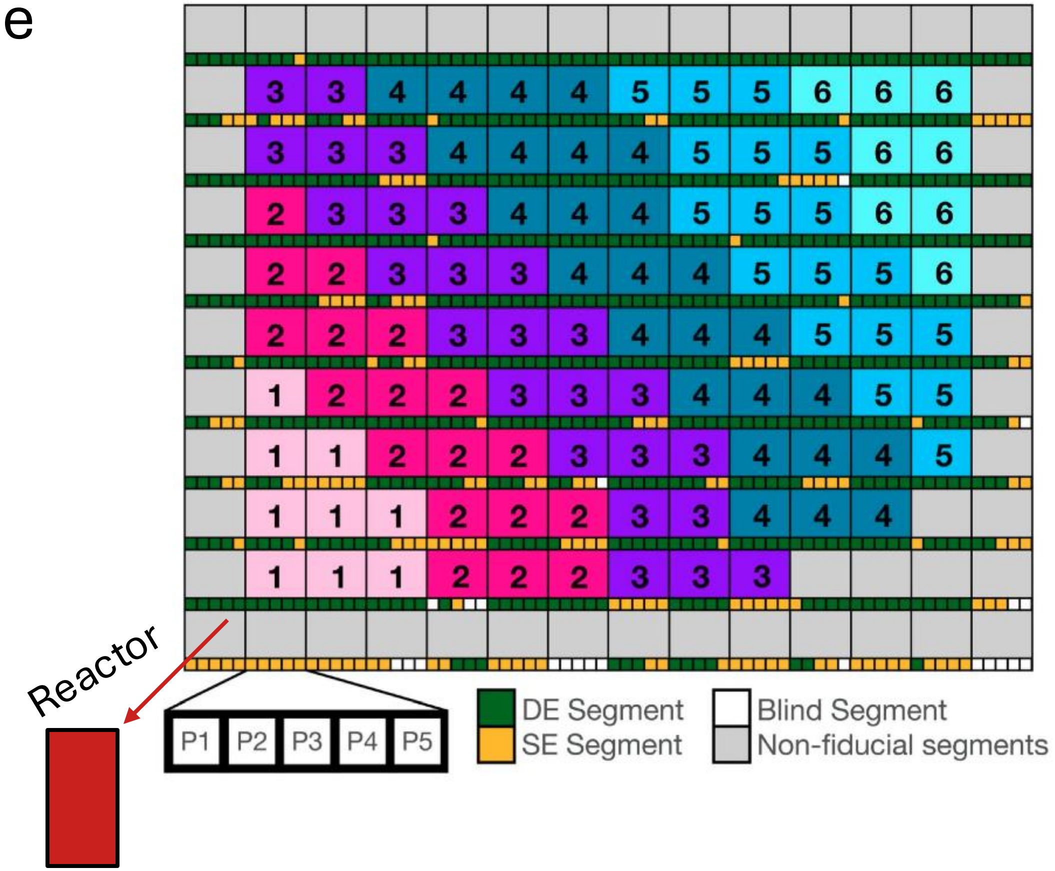


Oscillation Analysis: Strategy

- Build spectra from segments at similar baseline
  - 6 baseline bins x 33 energy bins x 5 periods
- Search for spectral distortion at each baseline induced by neutrino oscillation

$$P_{ee} = 1 - \sin^2(2\theta_{ee})\sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$





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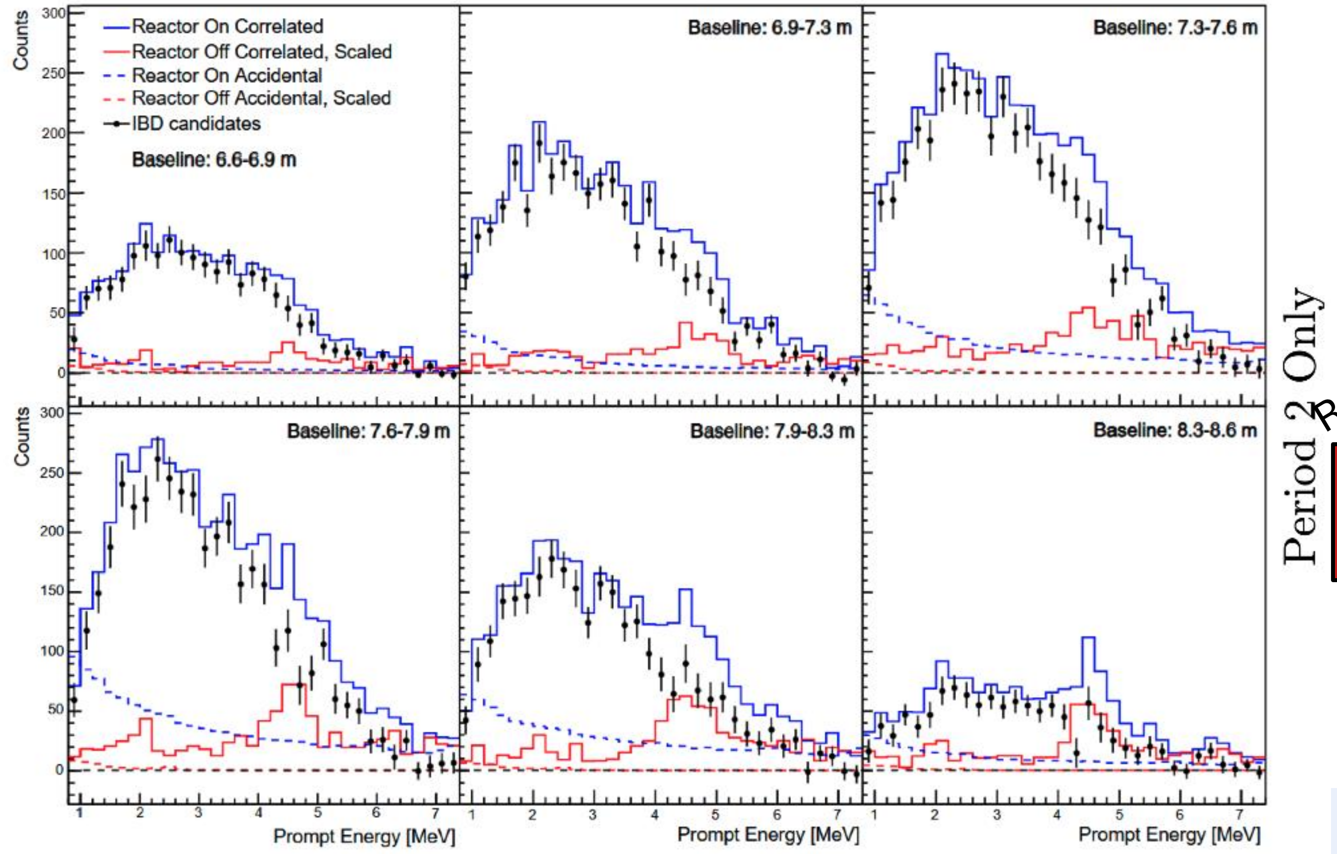

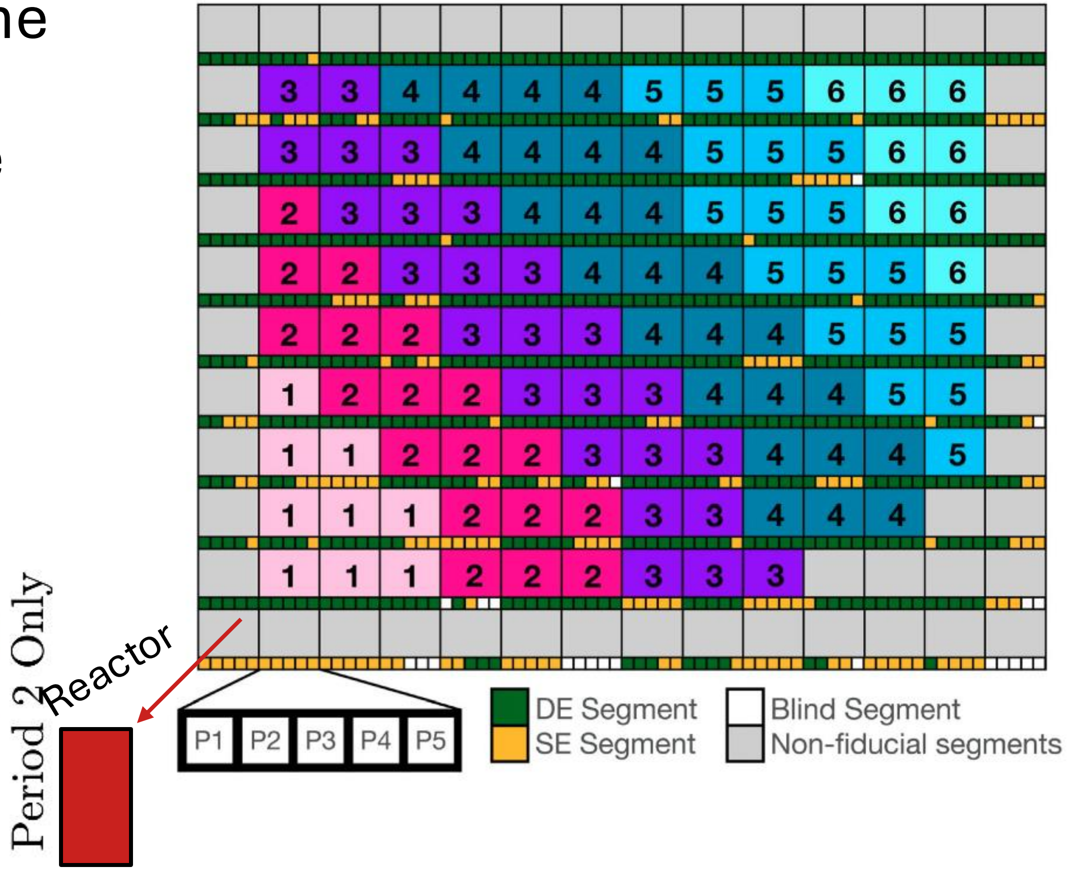

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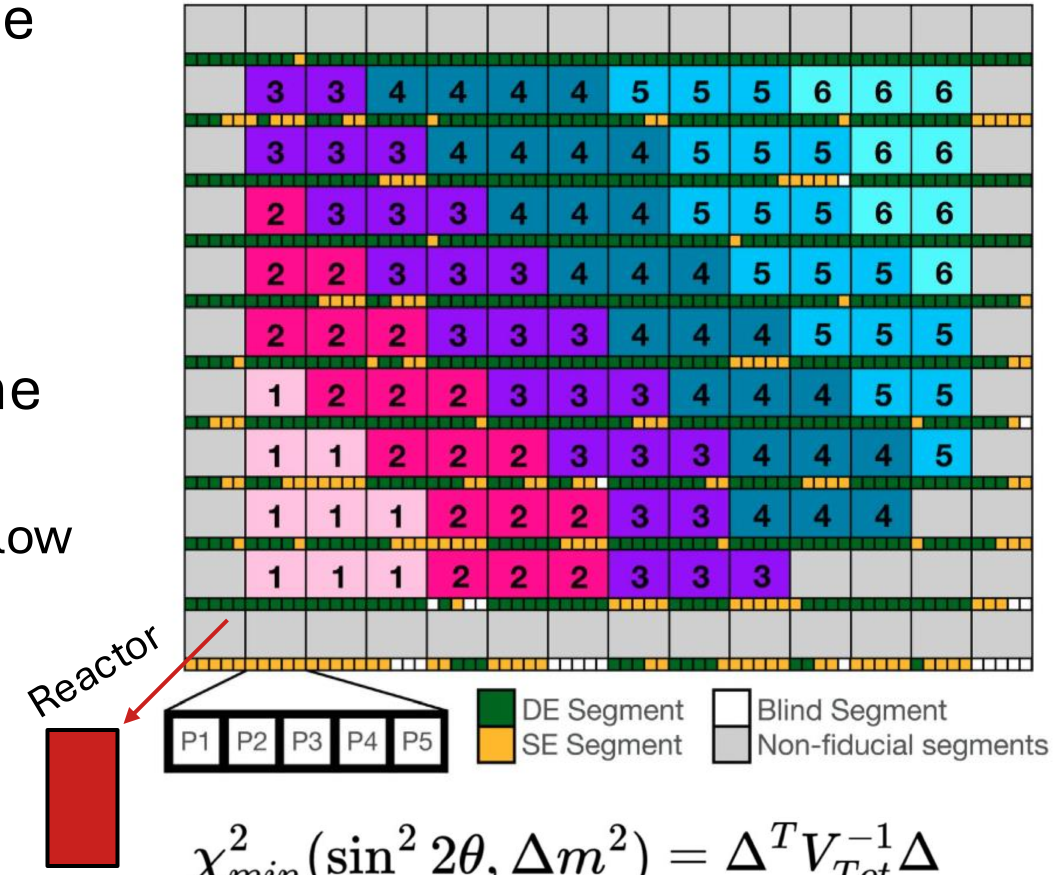
- Use Chi-square test to quantitatively assess the parameter fitting the dataset:
  - Combined Neyman-Pearson to minimize bias from low statistics bins, NIMA 961, P163677 (2020).

- Remove reactor model dependency with 'relative spectral ratio' analysis approach:
  - Correlated statistical uncertainty.



$$\chi^2_{min}(\sin^2 2\theta, \Delta m^2) = \Delta^T V_{Tot}^{-1} \Delta$$

V: Stat + Sys uncertainty

$$\Delta_{l,e} = O_{l,e} - O_e \frac{P_{l,e}}{P_e}$$

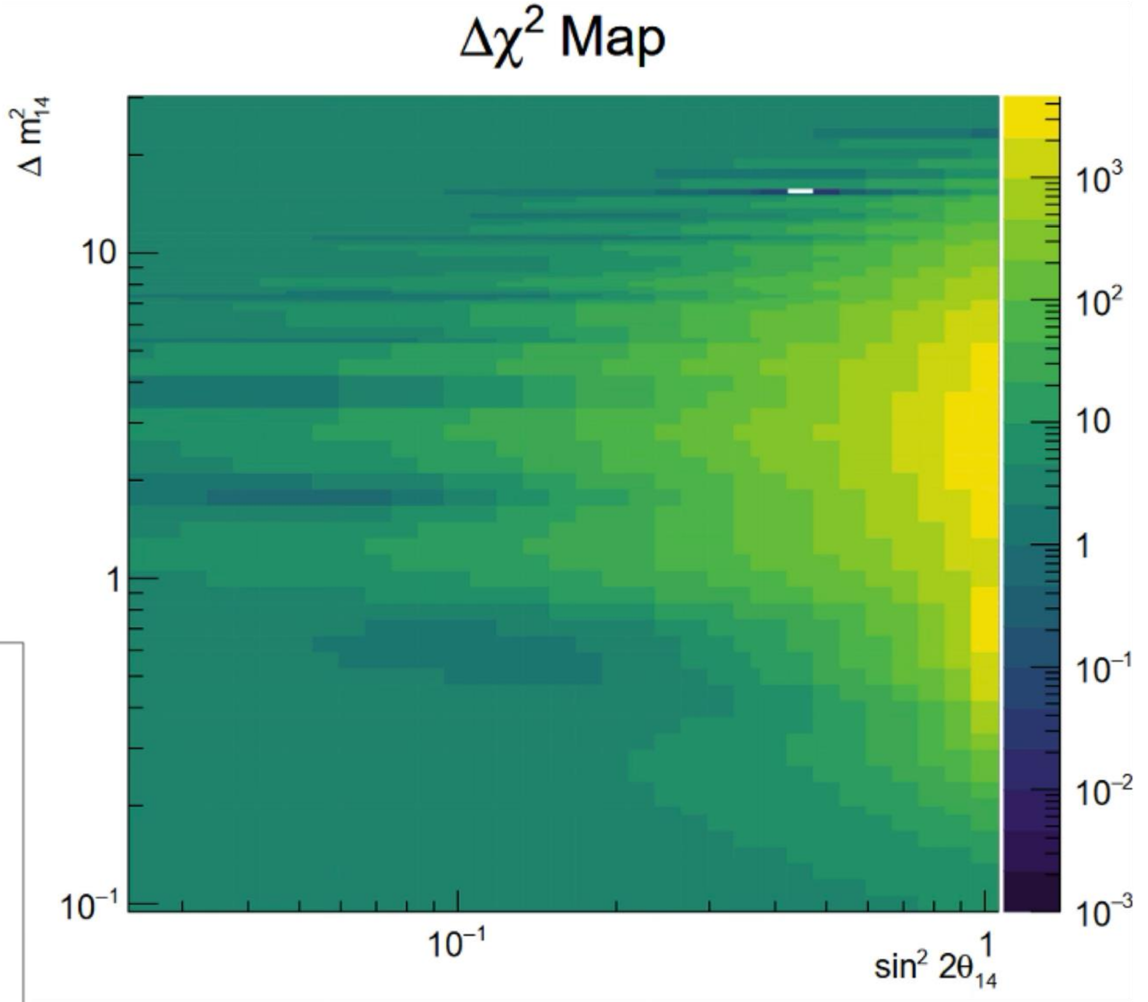
$O_{l,e}$: Observed

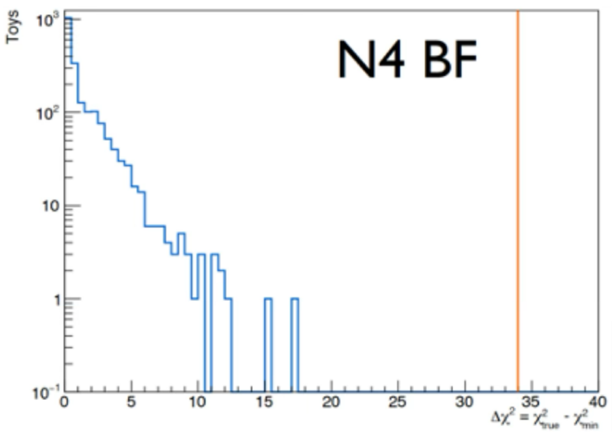
$P_{l,e}$: Prediction

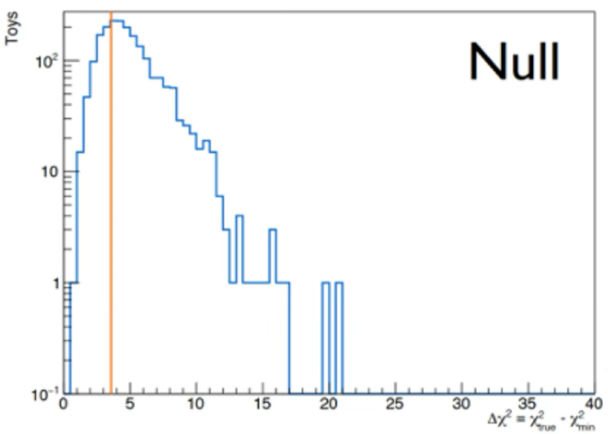
Oscillation Analysis: Results

- Best-fit point $(\sin^2 2\theta_{14}, \Delta m_{14}^2) = (0.42, 15.2)$
  - $\Delta\chi^2$ of 3.56 w.r.t to null hypothesis

- Frequentist tests at specific grid points:
  - Data consistent with null-oscillation toys (p=0.73)
  - Toys at Neutrino-4 best-fit point provide $\Delta\chi^2$ far below data

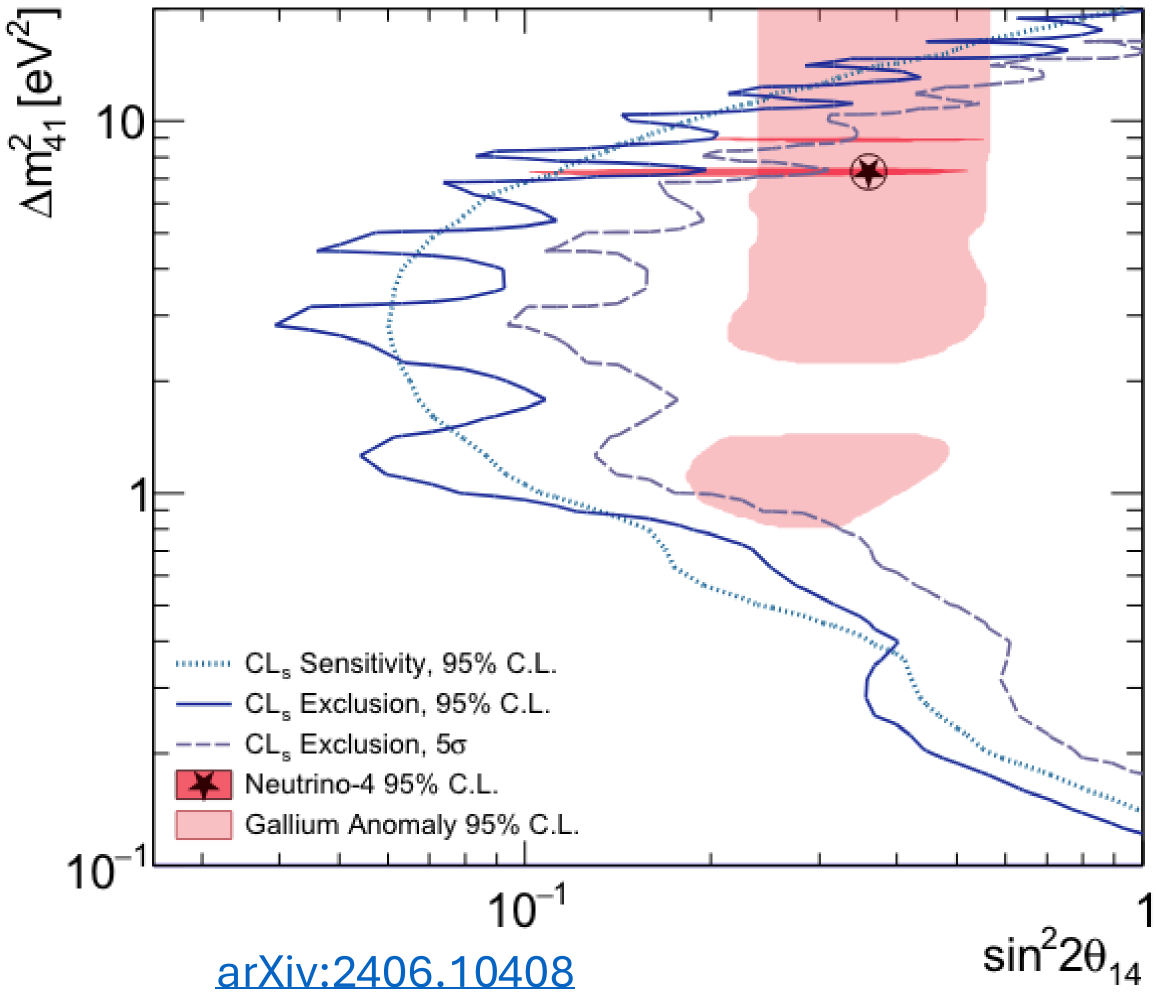






Oscillation Analysis: Exclusion

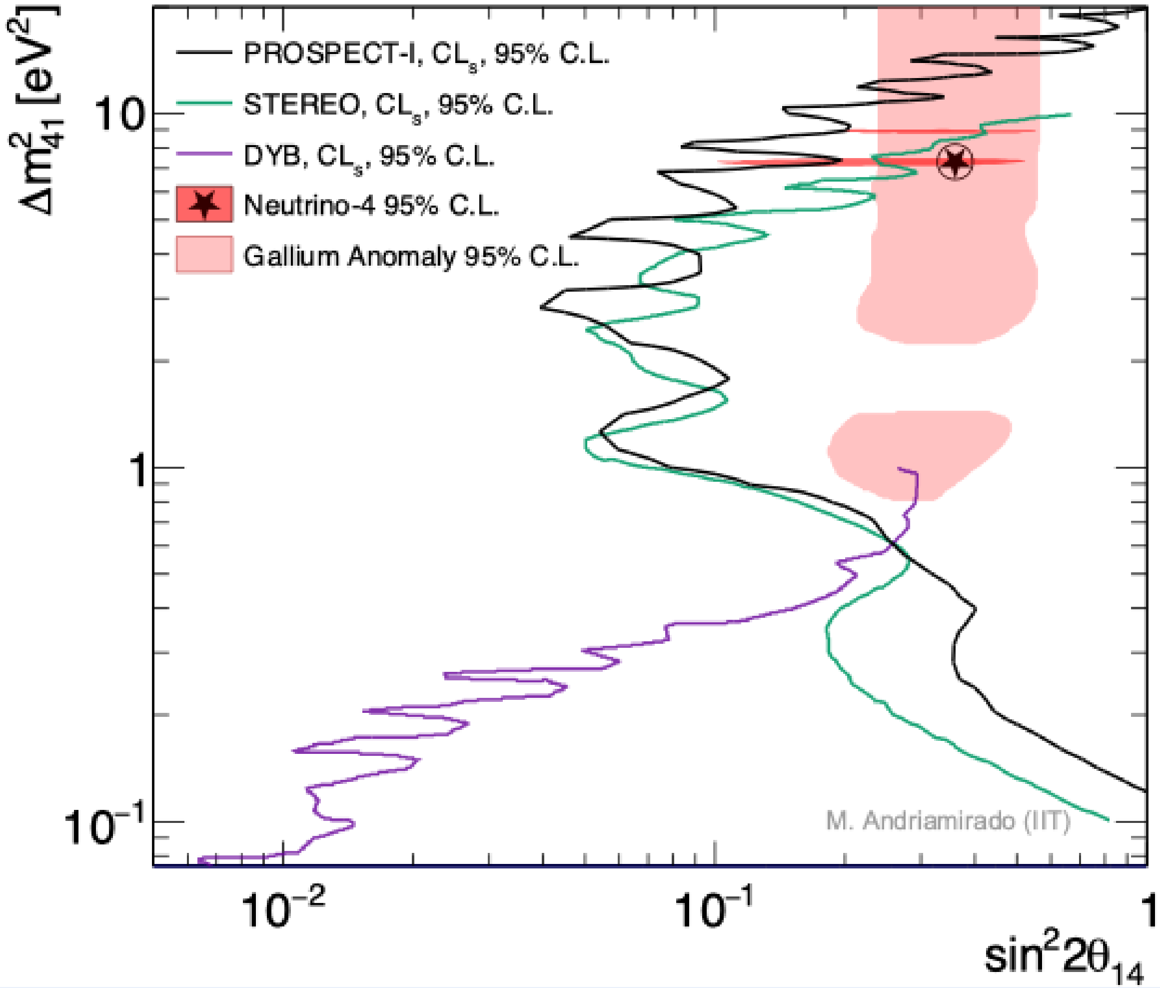
- Given compatibility of data with null hypothesis, Gaussian CLs method used to draw an exclusion contour
- Parameters for Neutrino-4 oscillation claim is ruled out at more than 5σ
- Exclude oscillation hypothesis for Δm^2 below 10 eV^2 of recently strengthened Gallium Anomaly at 95% CL.



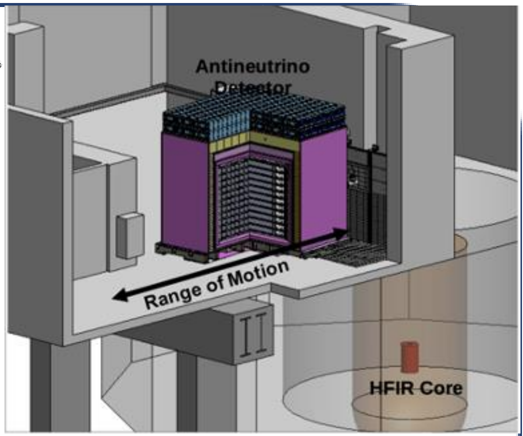
arXiv:2406.10408
Accepted to PRL

Joint Analysis: Motivation

- Daya Bay, PROSPECT and STEREO have performed model-independent searches for sterile neutrino oscillations
  - all consistent with null hypothesis
- Improved sensitivity at high-Δm^2_{14} from combination PROSPECT+STEREO, as well as from introducing Daya Bay ^{235}U unfolded spectrum as reference model
- Introducing an absolute ^{235}U spectrum measurement from Daya Bay into the fit will improve sensitivity at low-Δm^2_{14}



Joint Analysis: Experiments



Experimental Site (HFIR, USA):

- 85 MW$_{th}$ HEU reactor
- Compact core Ø 40cm, h=50cm
- >99% of flux from ^{235}U fissions

Detector design:

- Segmented detector, 154 segments
- Baseline coverage [6.9,8.9] m
- Li-doped LS, PSD

Physics Results Highlights:

- 60k IBD counts
- Spectral shape analysis
- Oscillation analysis
- S:B ~ 4

Experimental Site (ILL, France):

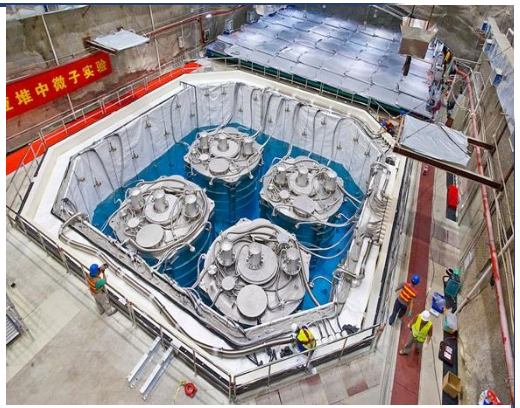
- 58 MW$_{th}$ HEU reactor
- Compact core Ø 40cm, h=80cm
- >99% of flux from ^{235}U fissions

Detector design:

- Segmented detector, 6 cells
- Baseline coverage [9.4,11.2] m
- Gd-doped LS, PSD

Physics Results Highlights:

- 107k IBD counts
- Absolute flux measurement
- Spectral shape analysis
- Oscillation analysis
- S:B ~ 1



Experimental Site (Daya Bay, China):

- 6-2.9 GW$_{th}$ LEU reactors
- Flux from evolving fuel mixture

Detector design:

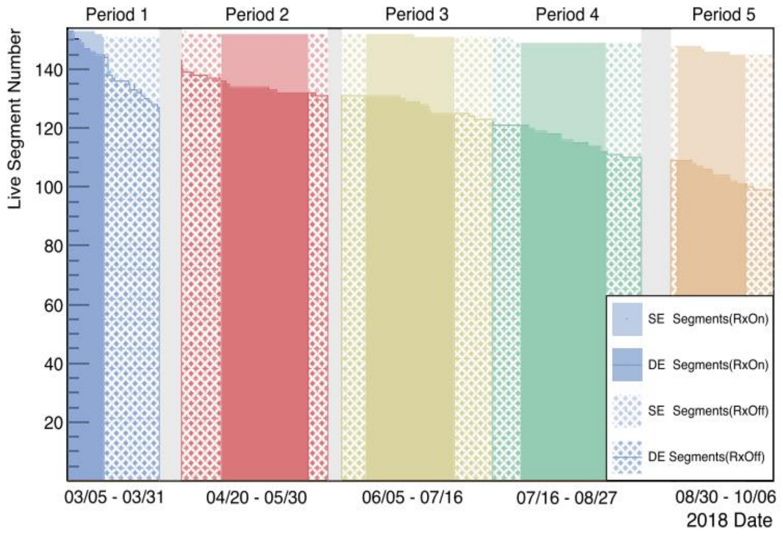
- 8 antineutrino detectors (20kL of fiducial volume)
- Baseline coverage: [360,1900] m
- Gd-doped LS

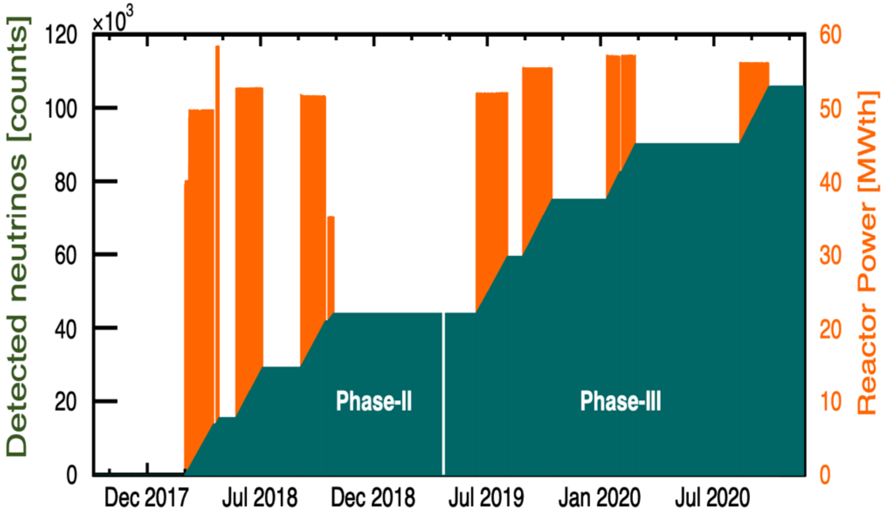
Physics Results Highlights:

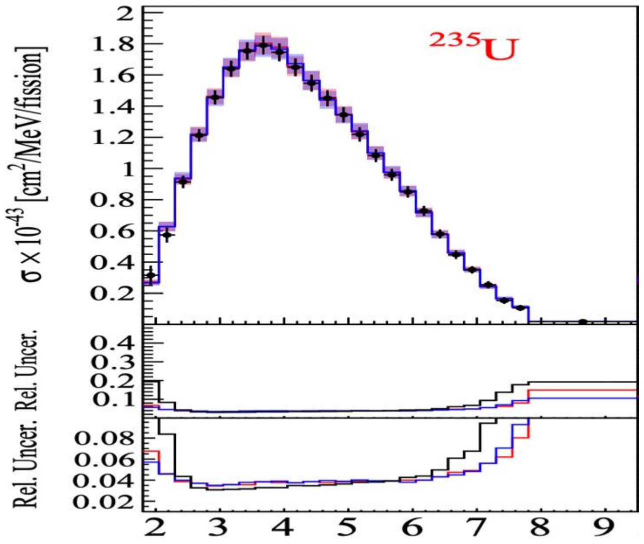
- 5.55 x 10^6 IBD counts
- Absolute flux measurement
- Oscillation analysis
- Spectral shape analysis
- background/signal <2%

Joint Analysis: Approaches & Example

- Multiple analysis approaches being pursued to check for consistency and with goal of providing complete range of physics outputs:
  - Unfolded ^{235}U and Pu spectra
  - θ_{14} and Δm^2_{14}
- <u>Example</u>: using PROSPECT CNP multi-period oscillation framework, perform joint-oscillation analysis incorporating inputs from all expts







PROSPECT

5 Data Periods:

- 6 Baseline bins: [6.94, 8.94] m
- 33 Prompt energy bins [0.8, 7.4] MeV

STEREO

2 Data Periods:

- 6 Baseline bins: [9.4, 11.2] m
- 11 Prompt energy bins: [1.625, 7.125] MeV

Daya Bay

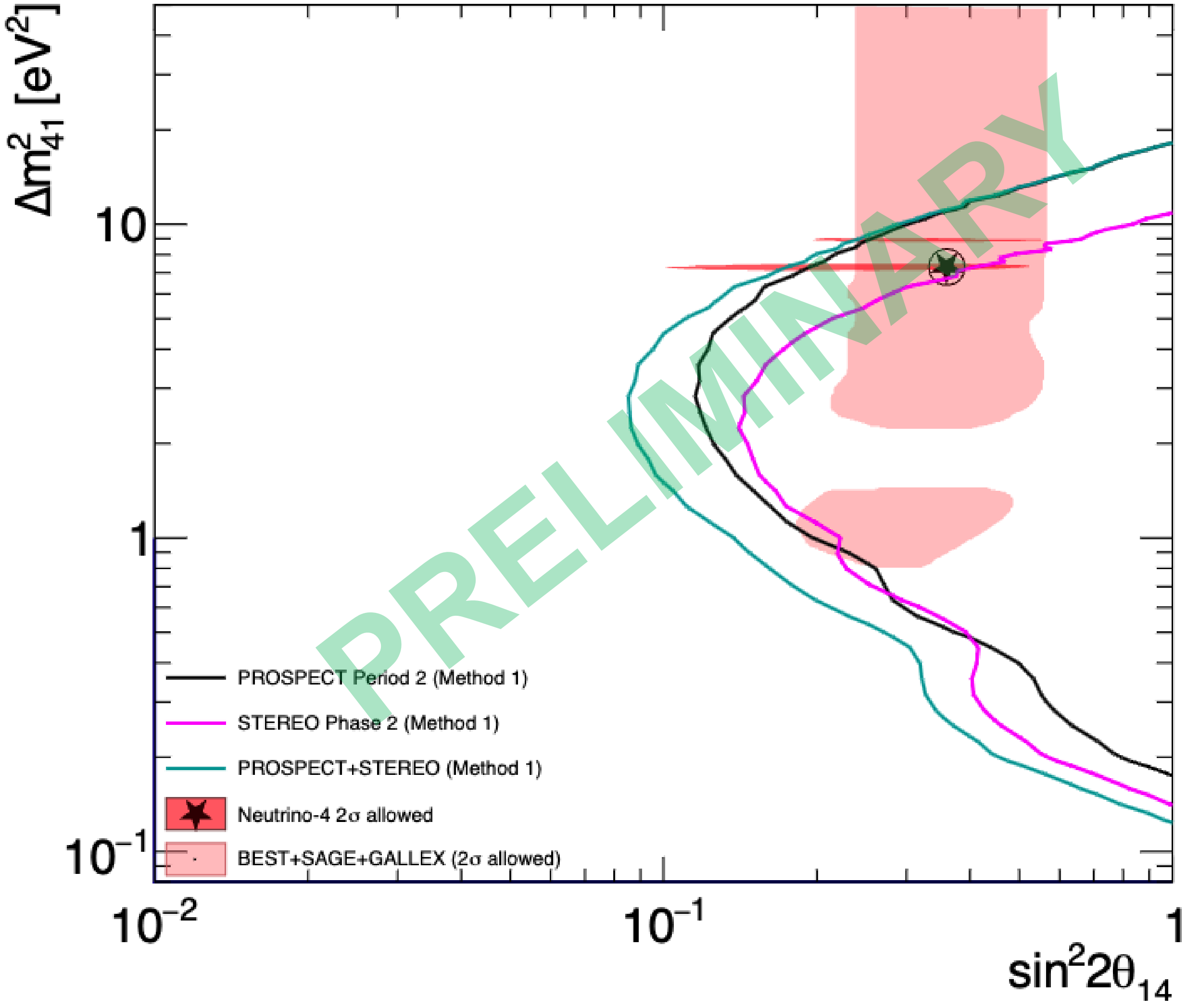
- reference ^{235}U energy spectrum
- used to constrain the fit for sterile neutrino oscillations

Example: Improved Sensitivity Projections

- Sensitivity contour making use of PROSPECT and STEREO data **for one data period/phase**
  - Method1:

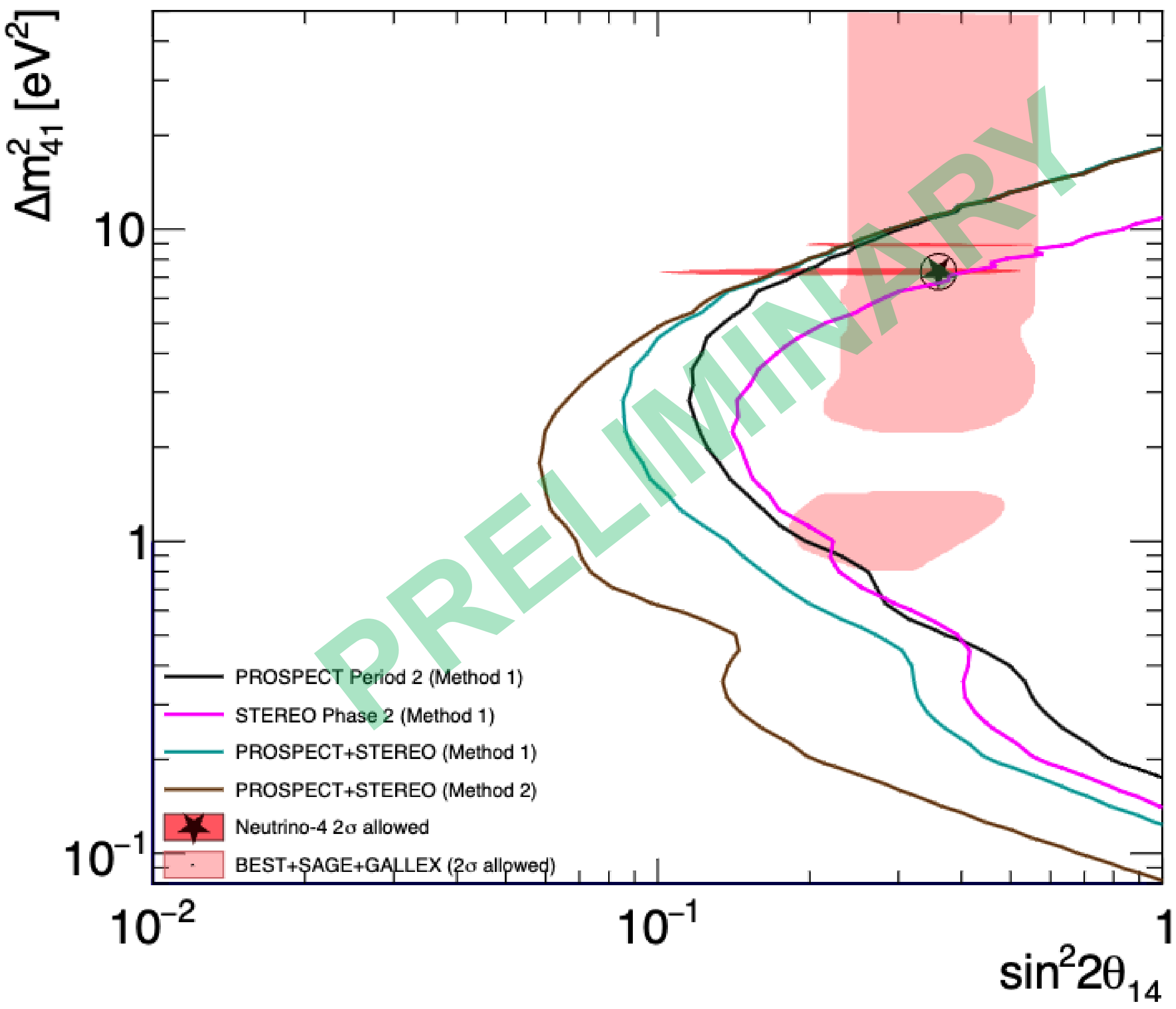
$$\chi^2_{rel} = \Delta^T V^{-1}_{rel}\, \Delta$$

$$\Delta_{l,e} = M_{l,e} - P_{l,e}\frac{M_e}{P_e}$$



Example: Improved Sensitivity Projections

- Sensitivity contour making use of PROSPECT and STEREO data **<u>for one data period/phase</u>**
  - Method1:
    $$\chi^2_{rel} = \Delta^T V_{rel}^{-1} \Delta$$
    $$\Delta_{l,e} = M_{l,e} - P_{l,e}\frac{M_e}{P_e}$$
  - Method2:
    $$\chi^2_{abs} = \delta^T V_{abs}^{-1} \delta$$
    $$\delta_{l,e} = M_{l,e} - \boxed{P_{l,e}}$$
    Using DYB unfolded spectra
- A clear increase in sensitivity when using DYB's unfolded spectrum to constrain fit



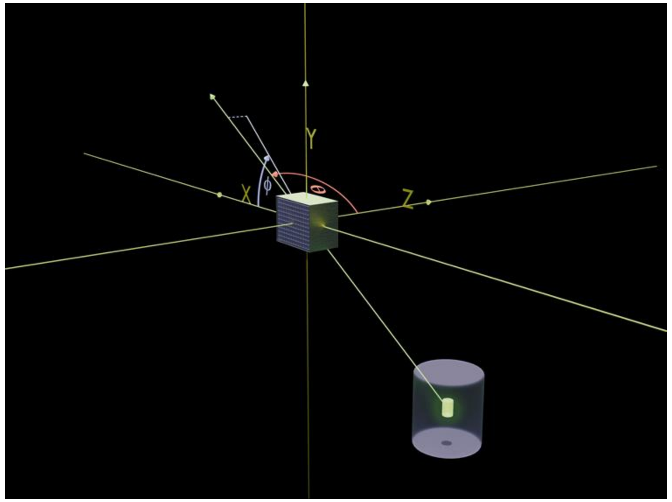
Antineutrino Directionality: Method

- In IBD, final state neutron carries off most momentum → prompt-delayed displacement, averaged over many events, gives some directionality information

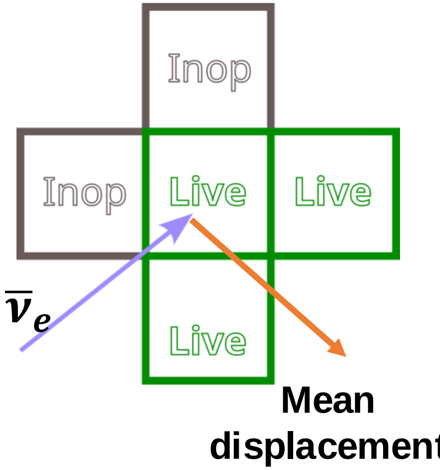
p_i → Mean value $(s_d - s_p)$ of IBD signal along principle axes

$$\tan\phi = \frac{p_y}{p_x}$$

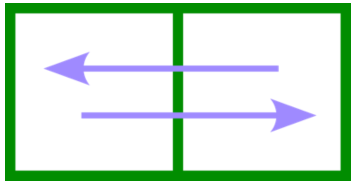
$$\tan\theta = \frac{p_z}{\sqrt{p_x^2 + p_y^2}}$$



- Event selections, edge effects, and inoperative segments can introduce directional bias

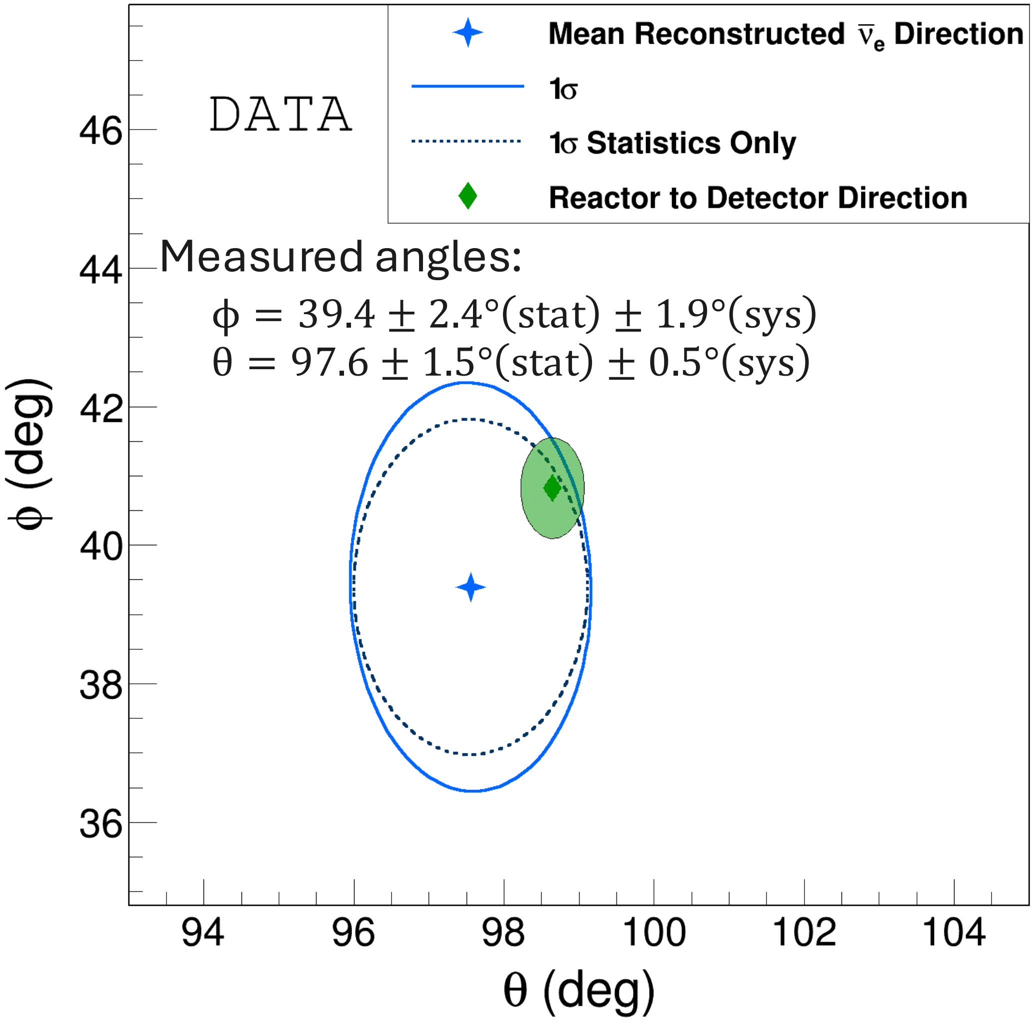


- Consider only neighboring live segment pairs, calculating ratio of events that move between



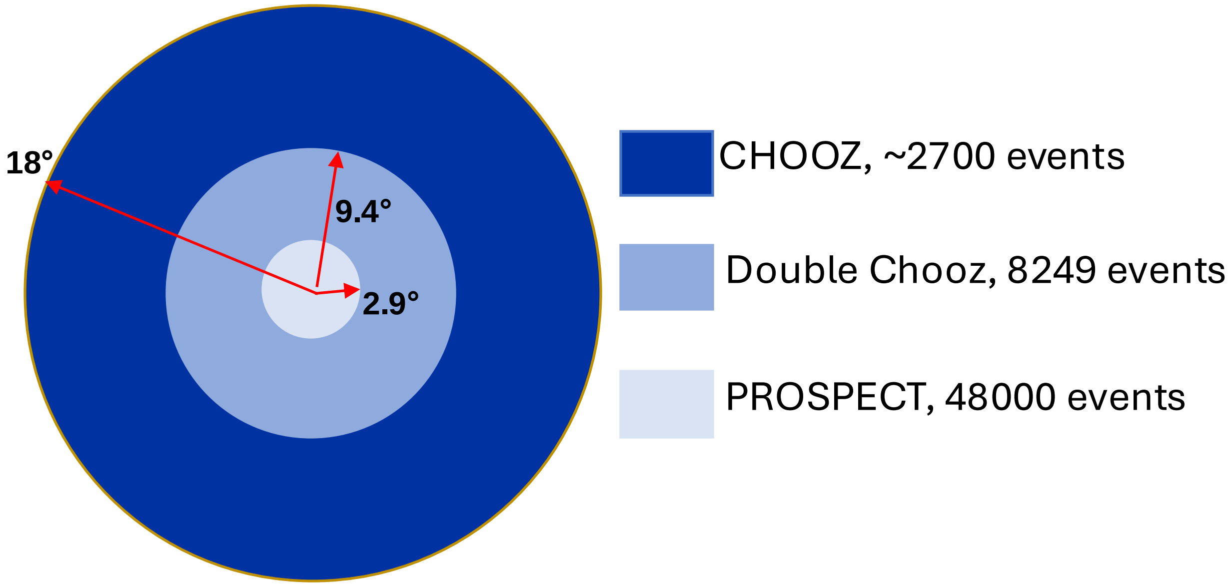
- Averaged over live pairs, this gives average neutron displacement in each axis

Antineutrino Directionality: Measurement



Comparison to past measurements

- CHOOZ and Double Chooz performed similar measurements with single volume Gd-doped LS



- Via segmentation and ^{6}Li neutron capture, PROSPECT improves event localization by factor of ~2 (11 cm vs 25cm for CHOOZ)

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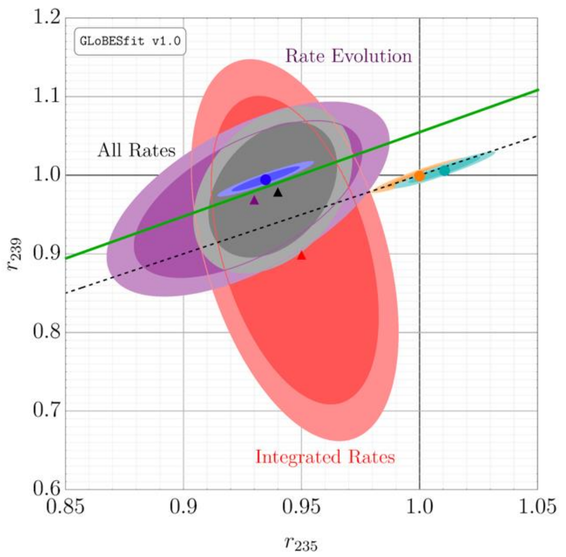
Forthcoming Result: Absolute Flux

- Global data strongly suggests conversion modeling of ^{235}U neutrino production is deficient and disfavors sterile neutrino explanation of RAA. Absolute flux data provides valuable test of reactor nuclear physics explanations.
- New measurement from PROSPECT-I will further constrain pure ^{235}U yield w/ < 3% uncertainty,
  - Statistics better than 1.5%
  - Expect systematic uncertainty dominated by reactor power at about 2.1%
- Detailed work evaluating detection efficiency is current focus, e.g. data derived MC correction factors



Cut	Sim Efficiency	Correction Factor	Uncertainty
Prompt PSD	0.969	1.0056	0.0002
Prompt Energy	0.973	0.9942	0.0005
Delayed PSD	0.990	1.0006	0.0002
Delayed Energy	0.995	0.9982	0.0001
Dt min	0.978	1.0001	0.0004
Dt max	0.920	1.0006	0.0005
Distance	0.929	1.0001	0.0001

(PRELIMINARY)

Applying lessons learned: PROSPECT-II Concept

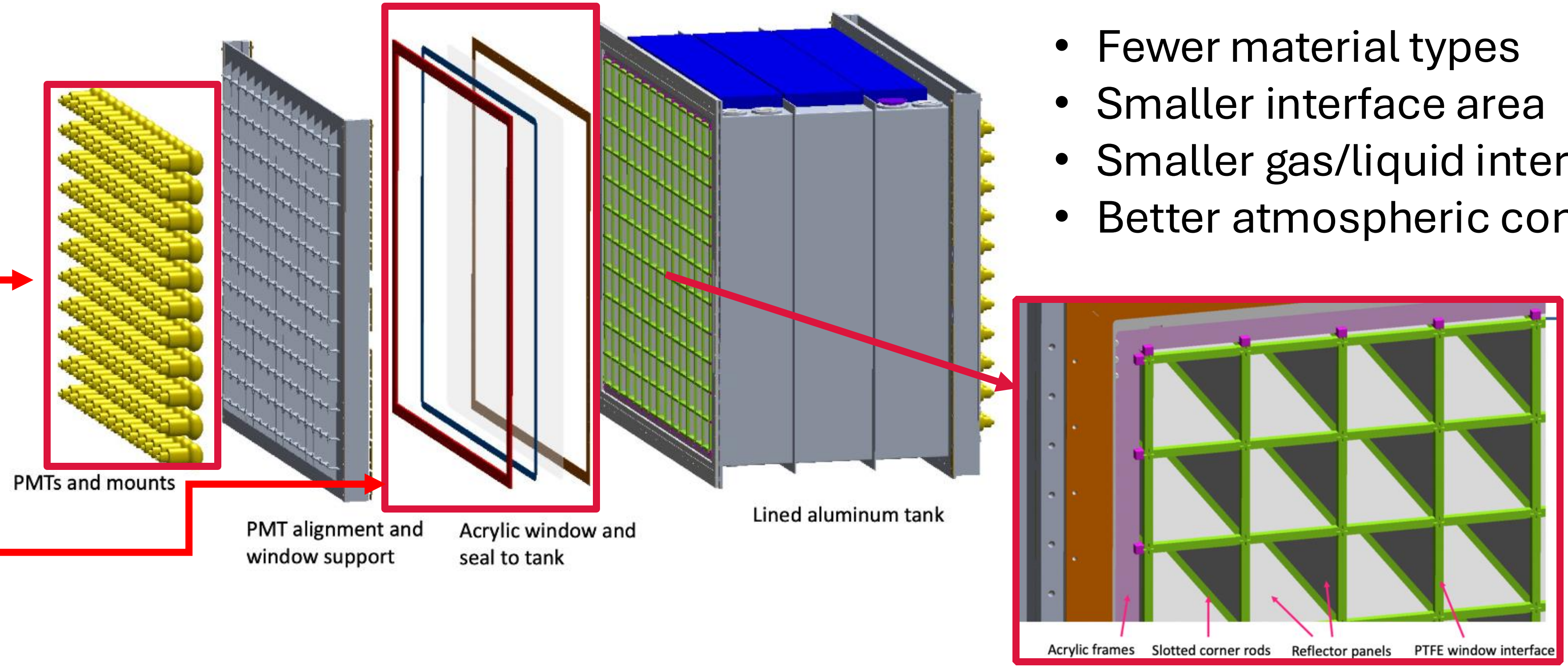
Pursue greater physics reach while improving stability and performance.

Avoid PMT exposure to the liquid scintillator:

- Separate PMTs from LiLS.

Minimize LiLS contact with other materials:

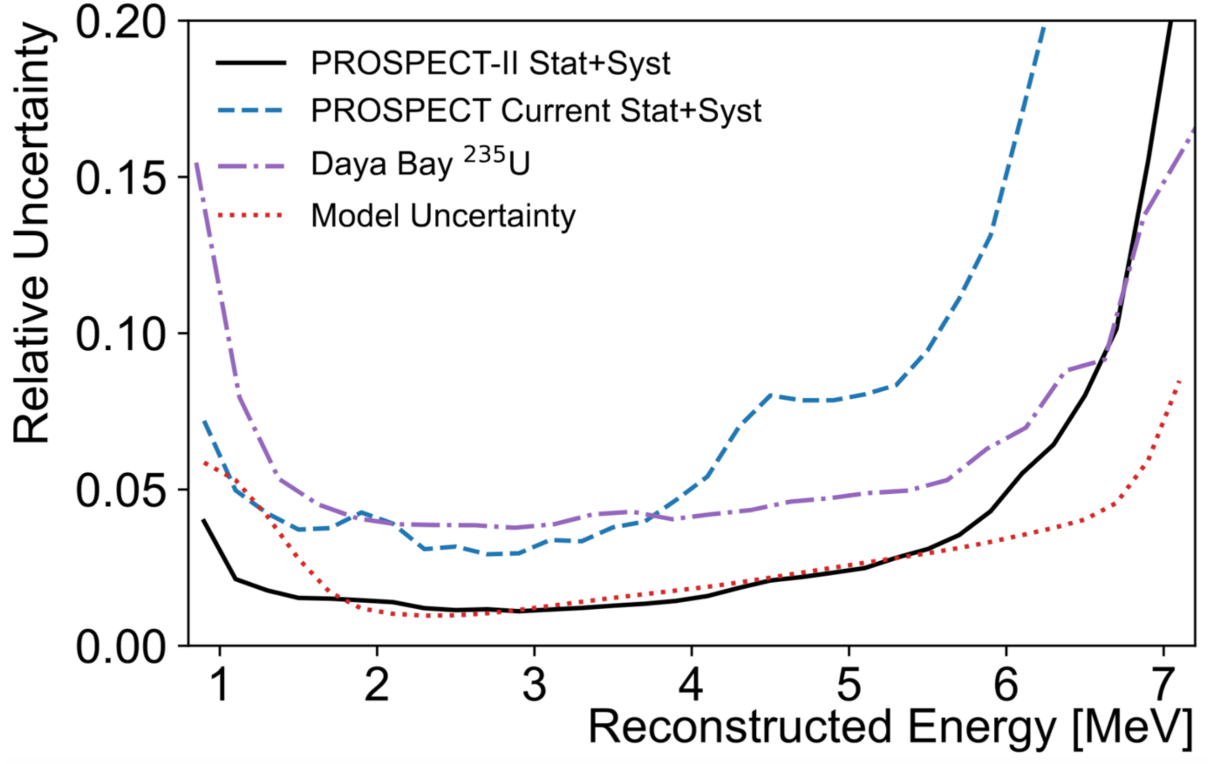
- Thin UVT acrylic windows serve as optical interface Double-layer seal design.

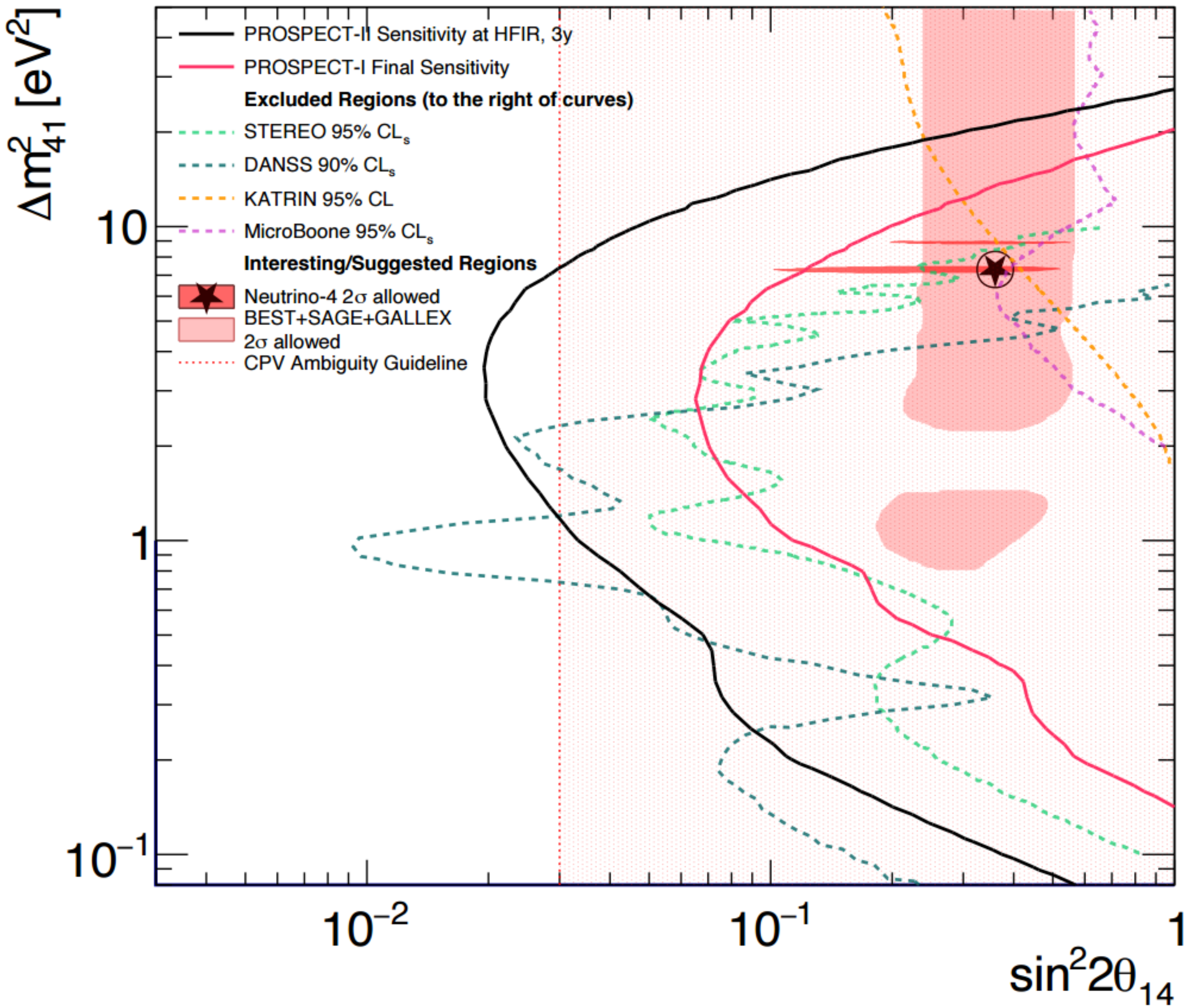


- Fewer material types
- Smaller interface area
- Smaller gas/liquid interface
- Better atmospheric control

Design work on new Inner Containment concept advancing - planning for fabrication and testing

PROSPECT-II Projected Sensitivity





- Increase precision of U-235 spectrum measurement and possibility for multi-reactor measurement with correlated detector systematics
- Extend sensitivity in unique range of higher Δm^2

Conclusions

- PROSPECT has supported a rich technical and scientific program
- 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 observation of spectrum excess between 5-7 MeV and provides further constraints on the origin of the data-model disagreement
  - strengthens 'equal isotope' hypothesis for origin of the data/model discrepancy between 5-7 MeV
- A new search for sterile-driven oscillations provides the strongest reactor-based limits at high Δm^2_{14}
- A Joint Analysis between Daya Bay, PROSPECT and STEREO is underway
  - By leveraging unique inputs from each experiment, the goal is to provide stronger oscillation limits and more precise unfolded 235U and Pu spectra
- PROSPECT has published the most precise IBD directionality measurement, and the first using ^{6}Li and segmentation
- Work is continuing on absolute flux measurement, other physics topics, and the PROSPECT-II upgrade

PROSPECT Collaboration

Supported by: U.S. DEPARTMENT OF ENERGY | Office of Science   HEISING-SIMONS FOUNDATION

All experiments contribute to solving the puzzle.

1 - Short-Baseline Neutrino

Direct MiniBooNE test.
Access to rich hidden sector in > GeV beam.
Two-beam osc capabilities.

2 - DUNE

Highest v/BSM flux.
High beam energy.
PRISM ND concept.
Ambiguity with sterile v

3 - IceCube

Probe BSM effects.
Very high energy v's also accessible

6 - JSNS

Direct LSND test.
Access to rich 'low mass' hidden sector.
Probe LFV models.

5 - Reactor

Pure e-flavor.
Low (MeV) v energies.
Pure probe of vacuum oscillations.

4 - Sources

Direct Gallium Anomaly Test.
Pure e-flavor.
Lowest v energy.