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PROSPECT

# Improved Inverse Beta Decay event selection and its impact on the PROSPECT oscillation analysis

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The University of Tennessee Knoxville

On behalf of the PROSPECT collaboration

December 30th – 6th ComHEP Meeting

ORNL is managed by UT-Battelle, LLC for the US Department of Energy

U.S. DEPARTMENT OF ENERGY

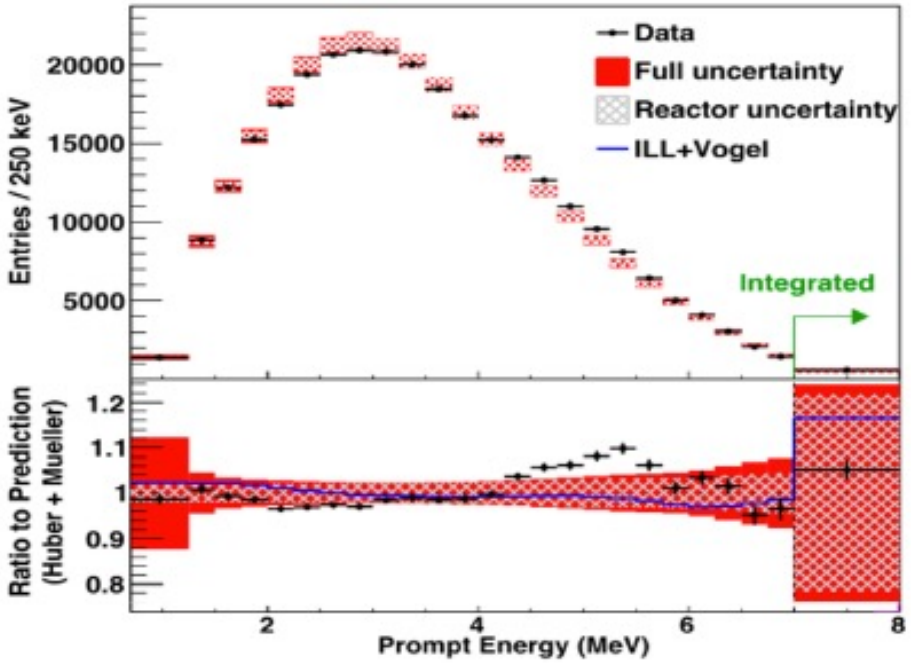
ComHEP

Physics Division

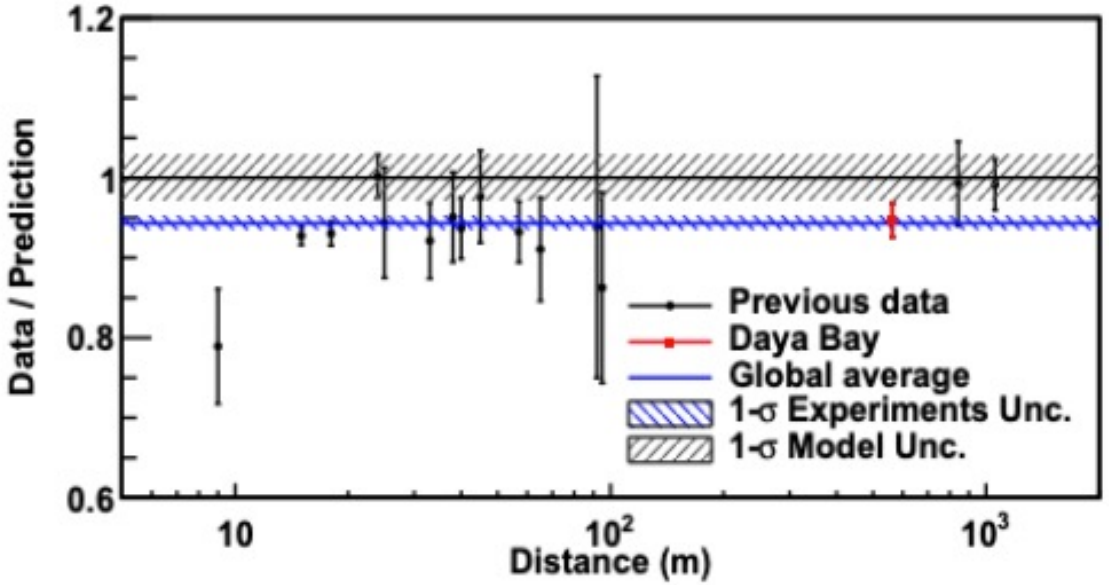
# Reactor Antineutrino Anomaly, a motivation for PROSPECT

- Short-baseline reactor experiments have reported a deficit of the measured antineutrino rate when compared to theoretical predictions

**Antineutrino anomaly bump in 4-6 MeV**




**Observed flux deficit of about 6%**




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.



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

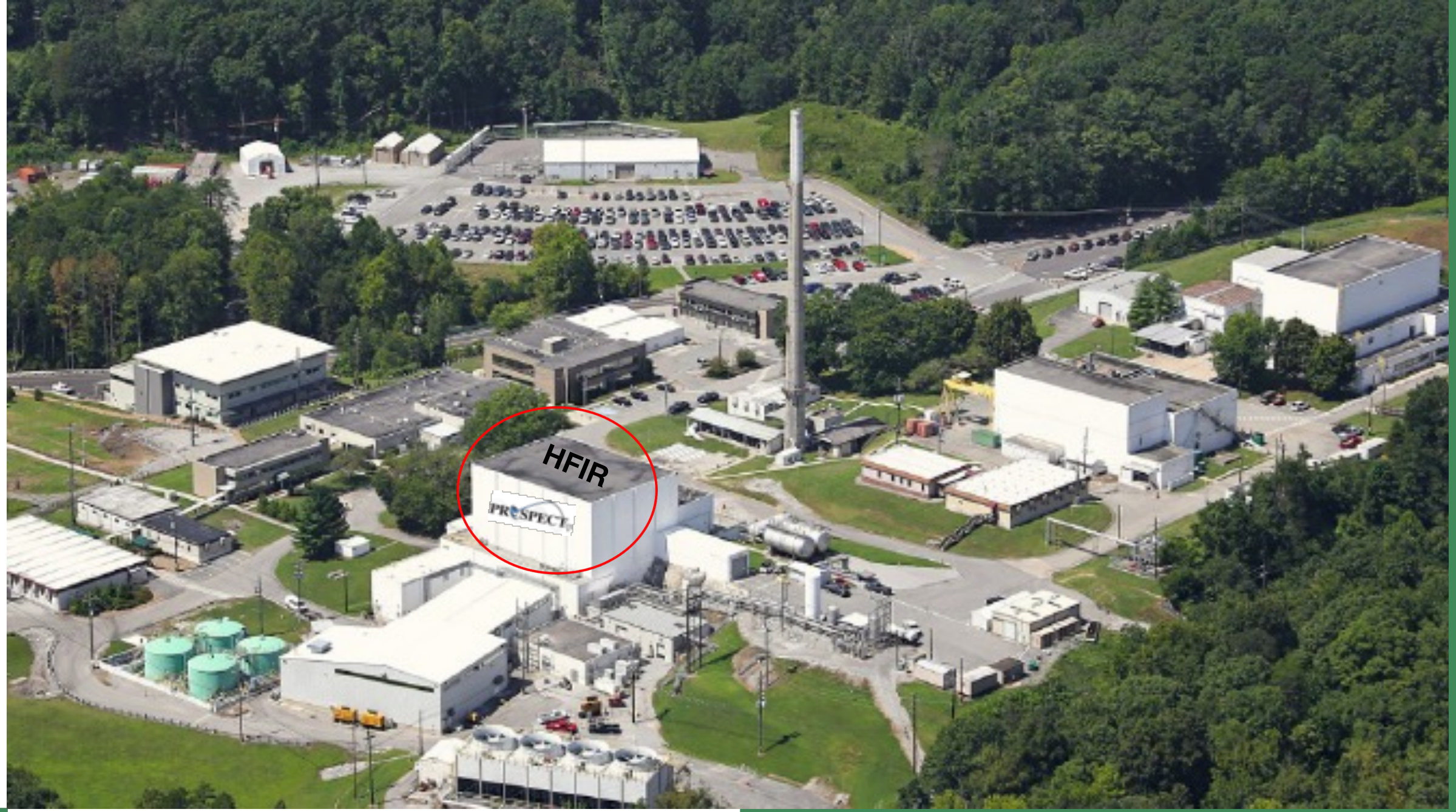
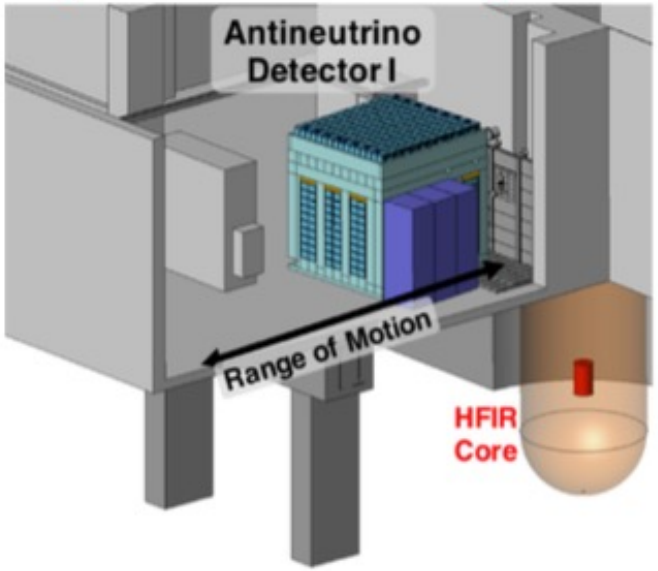


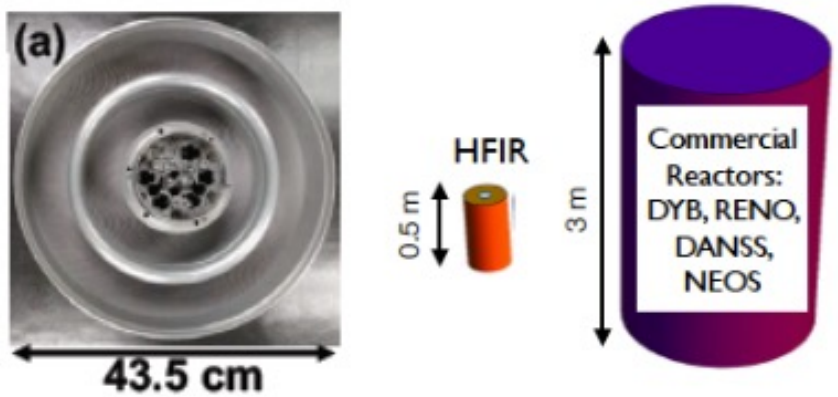

Image source: https://neutrons.ornl.gov/hfir

# PROSPECT Detector at HFIR

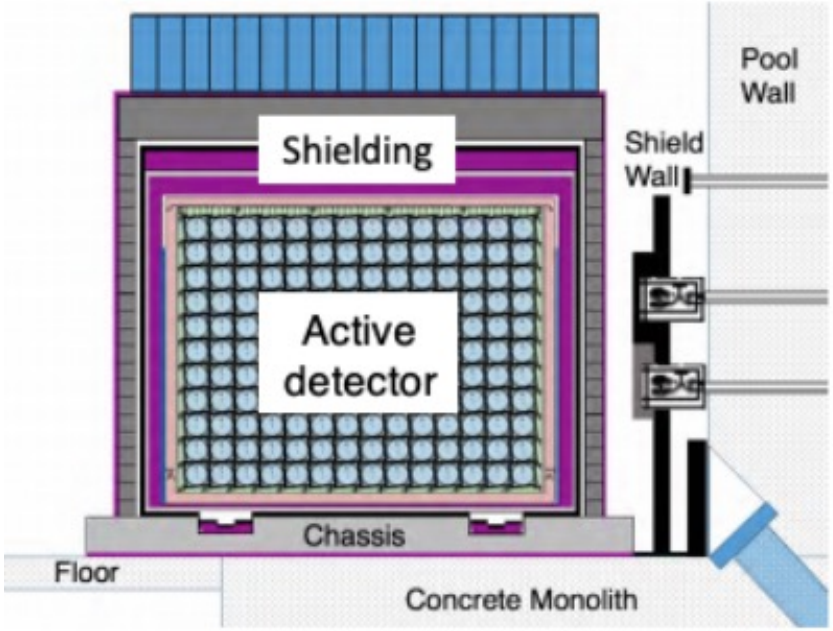
Layout of the PROSPECT experiment




- 93% 235U Fuel
- 85 MW thermal power
- 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)



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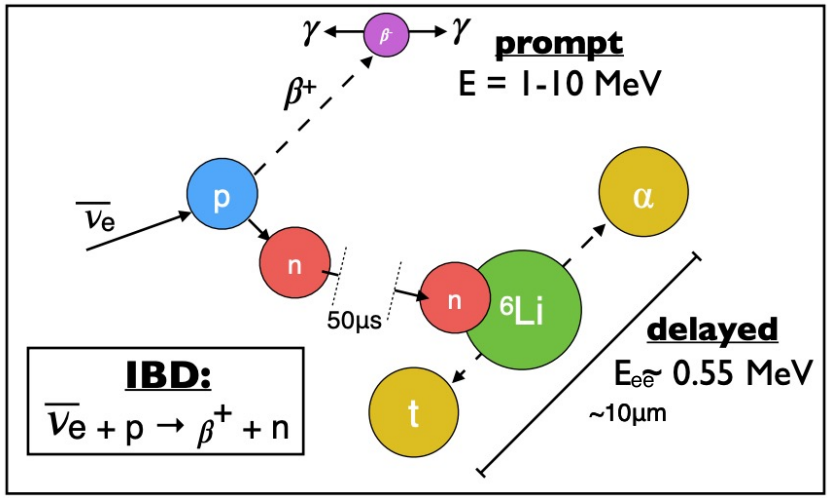
# Antineutrino Detection

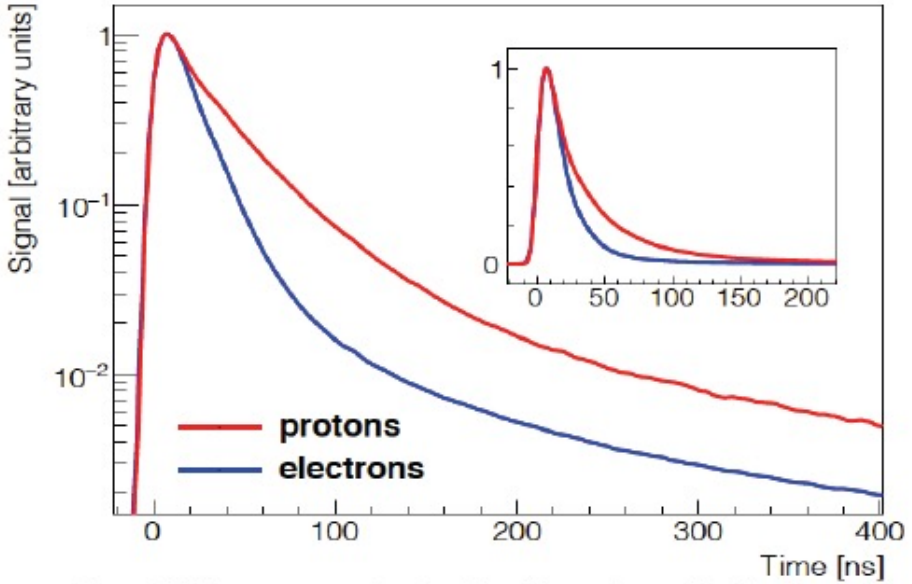
**Use of the IBD process**




- PROSPECT detects antineutrinos via the Inverse Beta Decay (IBD) process
- Prompt signal ($e^+$) provides a good energy estimate of incoming $\nu$
- 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).



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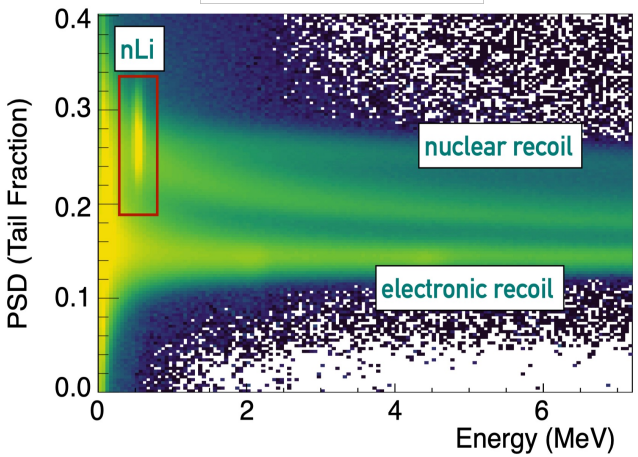
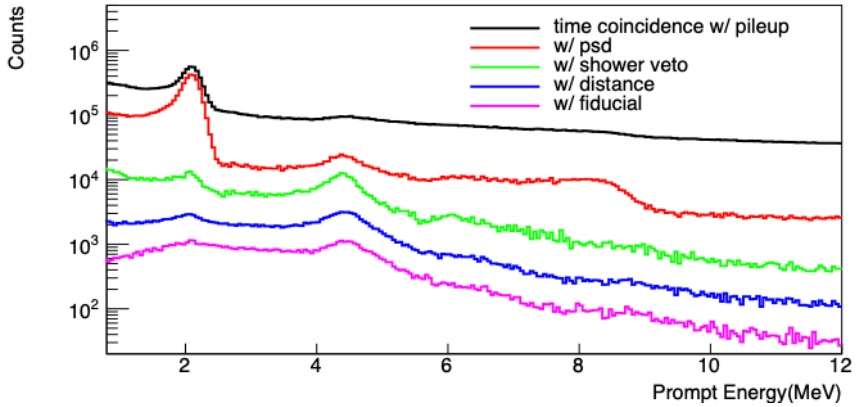
# IBD Event Selection

- **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

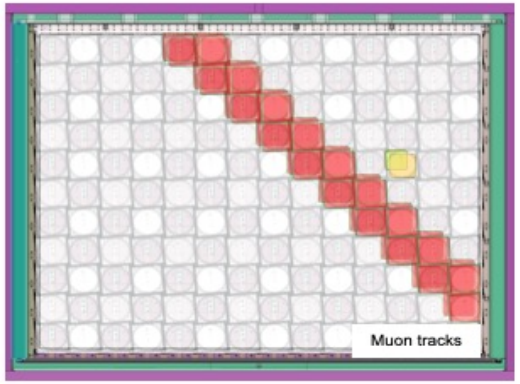
**Prompt PSD Cut**




**Prompt Energy Distributions Under Different Cuts**




**Muon tracks in the PROSPECT detector**




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

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



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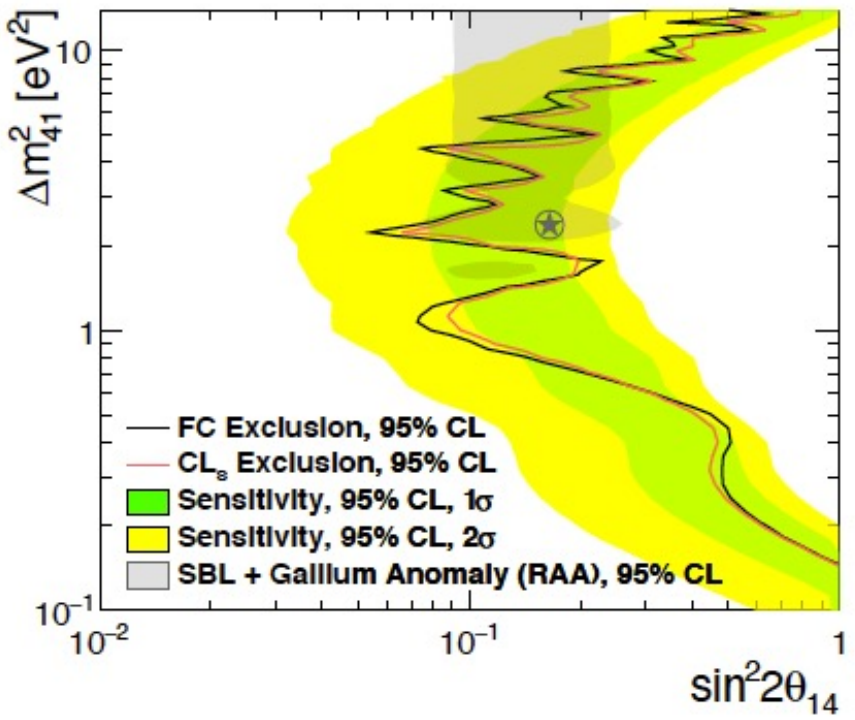
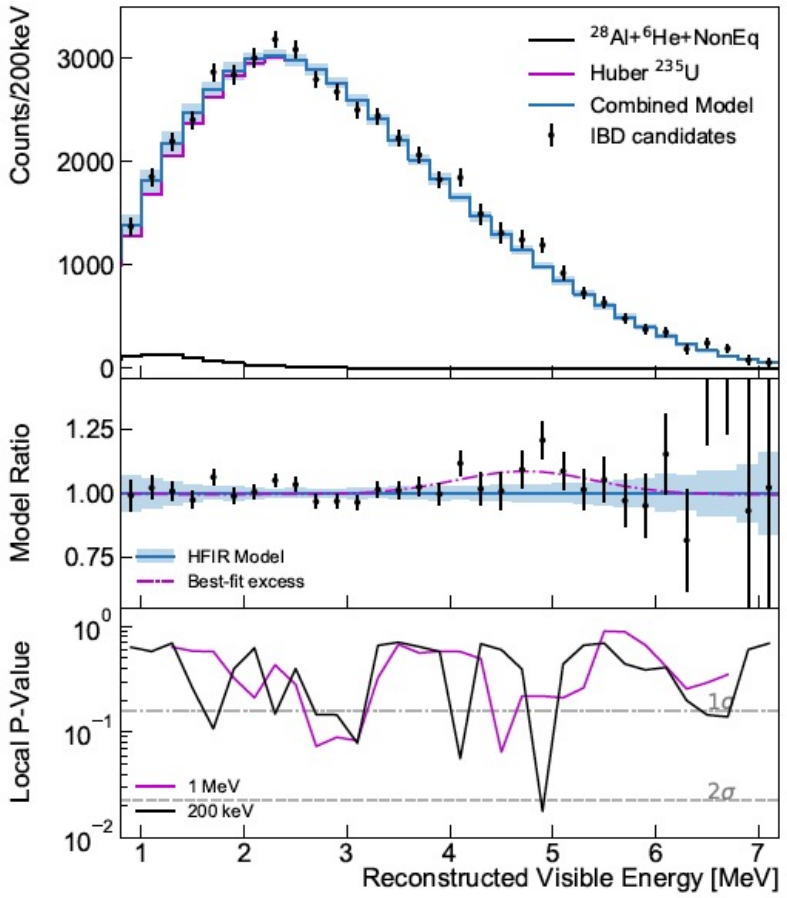
# Latest PROSPECT Results

**Oscillation Exclusion Contours**




**Antineutrino Spectrum**




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



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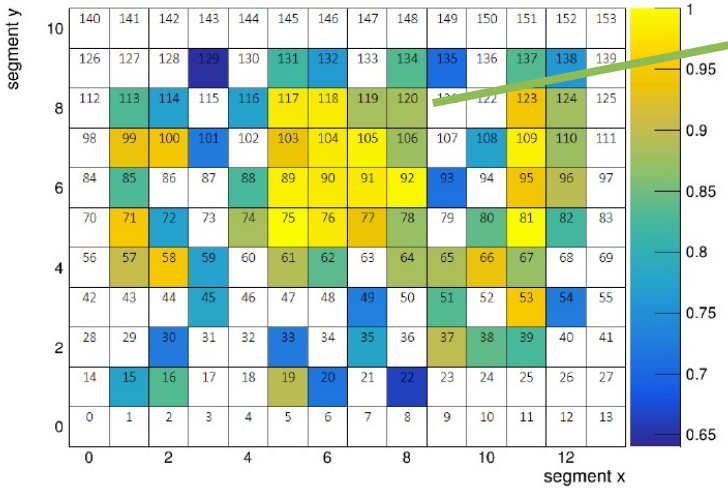
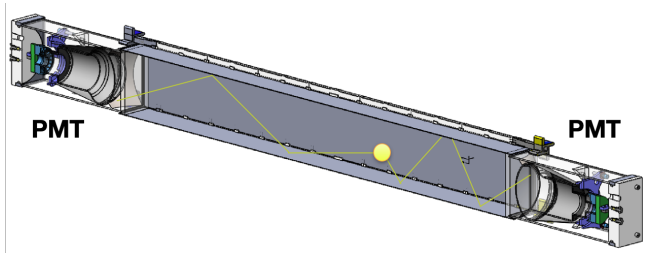
# Motivation for a final PROSPECT-I Analysis

- 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.

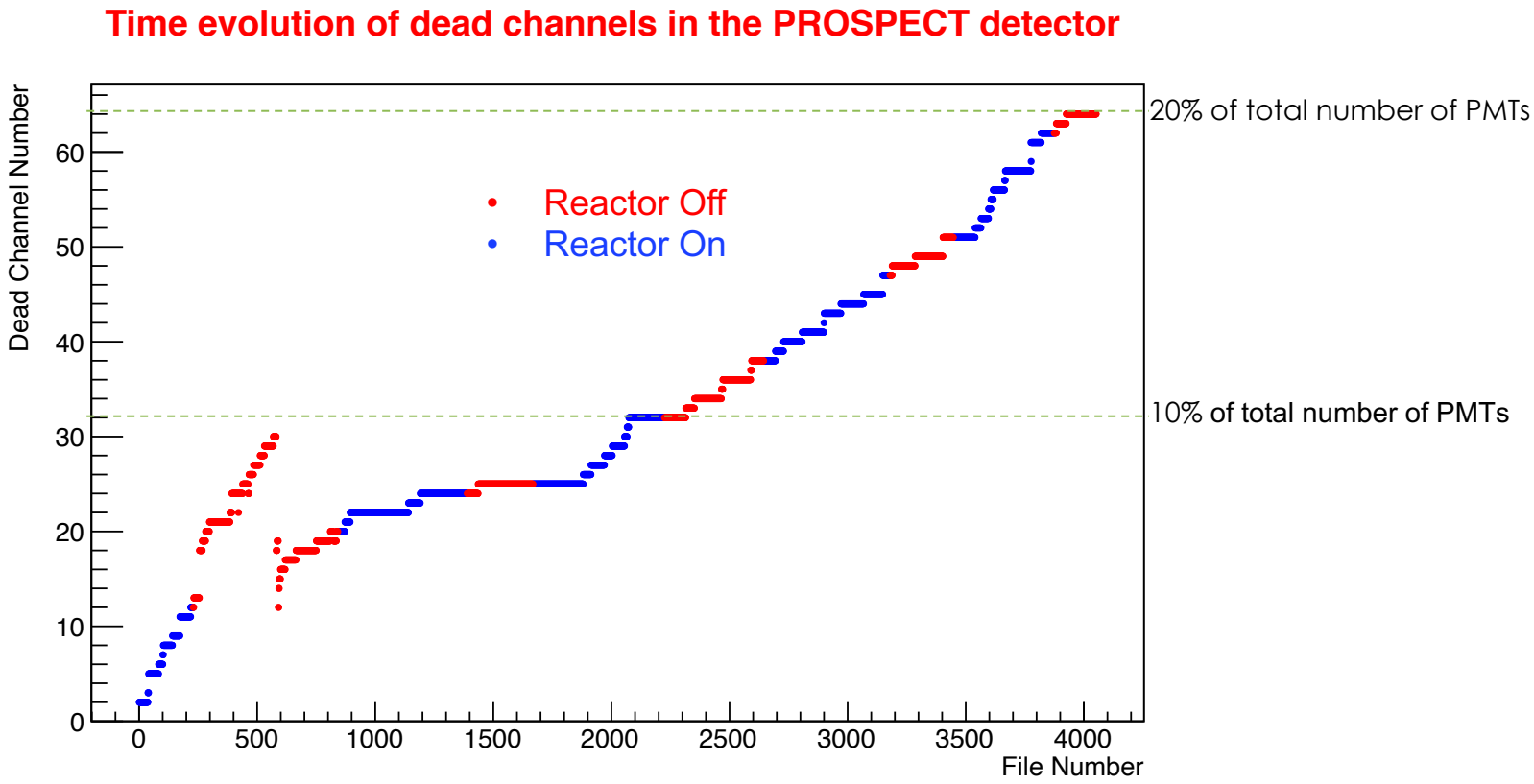
- In order to improve upon previous results, two new data recovery approaches have been proposed:

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

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

# **First Approach:** Data Splitting

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



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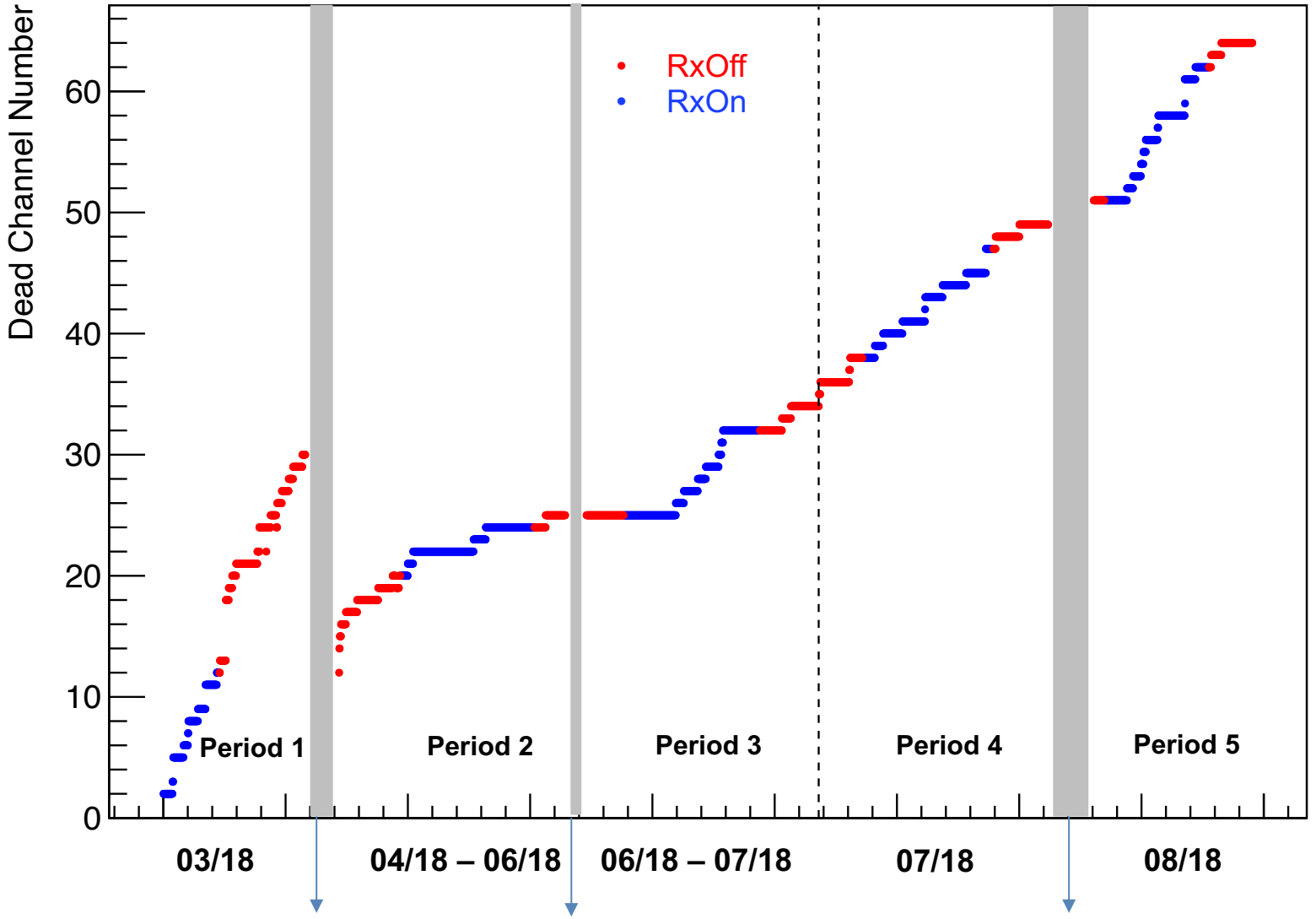
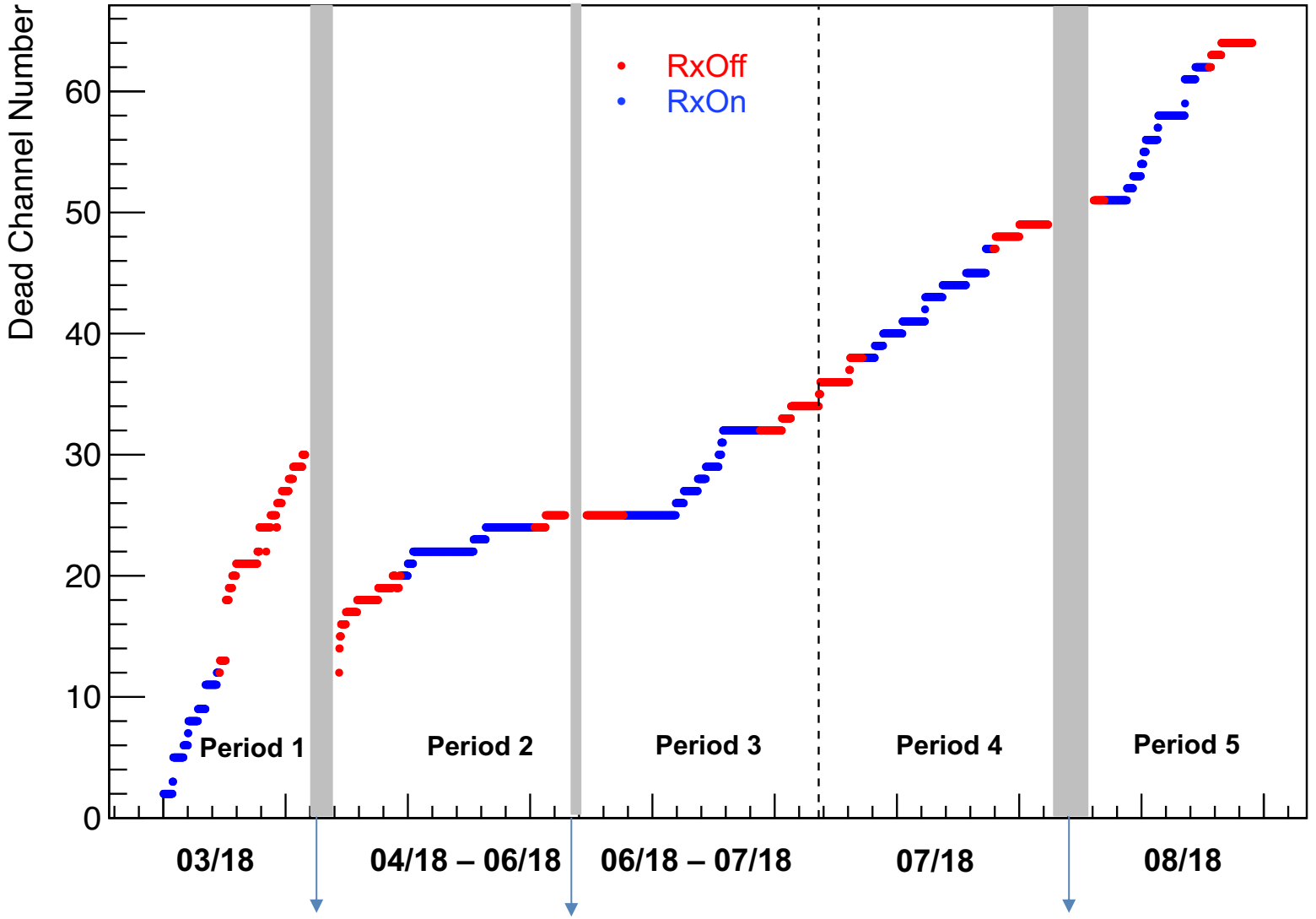
# Criteria for Calibration-Based Splitting




- 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%).

# Criteria for Calibration-Based Splitting




| | Double Ended Segment | Single Ended Segment | Blind Segments |
|---|---|---|---|
| **PROSPECT Latest Results** | 97 | 47(not-used) | 10 |
| **Period 1** | 127 | 24 | 3 |
| **Period 2** | 131 | 21 | 2 |
| **Period 3** | 123 | 28 | 3 |
| **Period 4** | 110 | 39 | 5 |
| **Period 5** | 97 | 47 | 10 |



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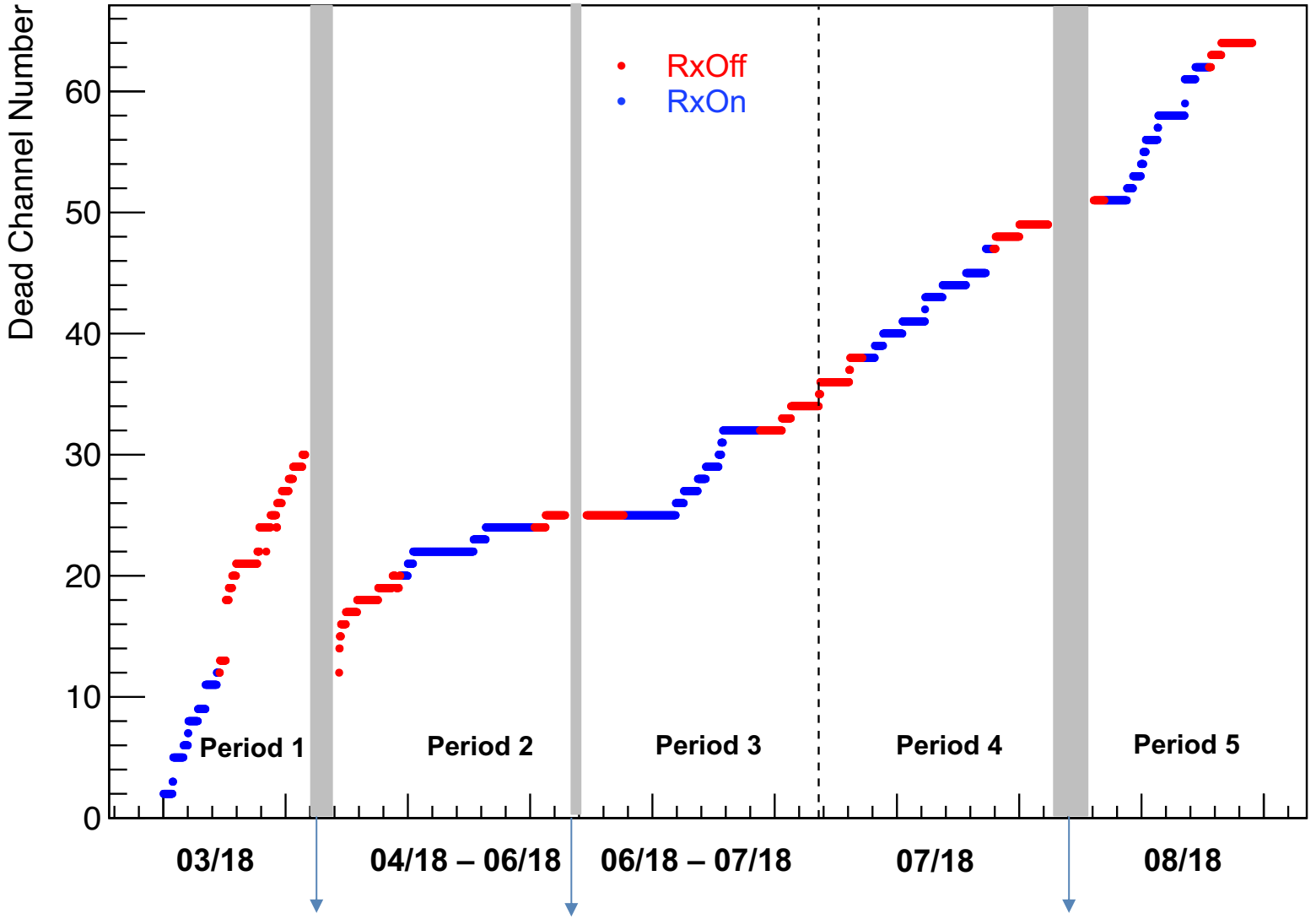
# Criteria for Calibration-Based Splitting

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Next Method



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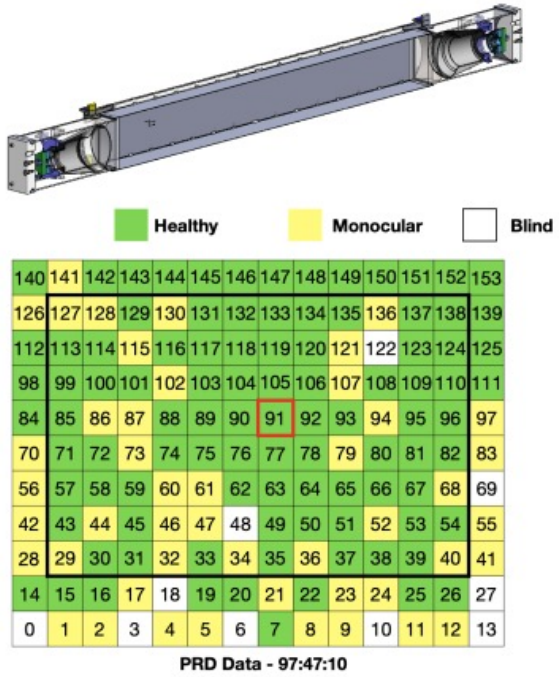
# Second Approach: SEER

- 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)



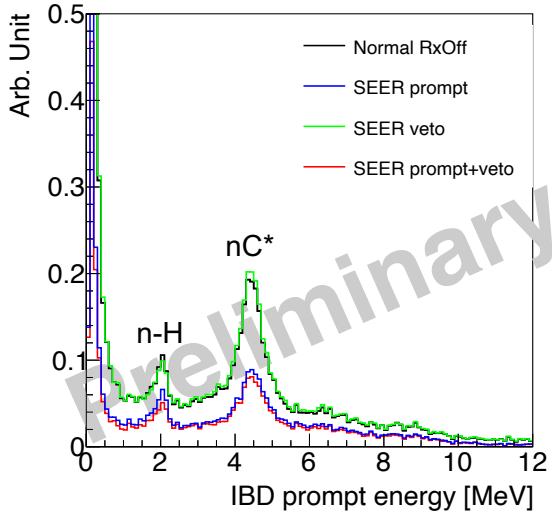

Prompt and delayed signal time coincidence

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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# 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

# IBD Event Selection + SEER - New Cuts Needed

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




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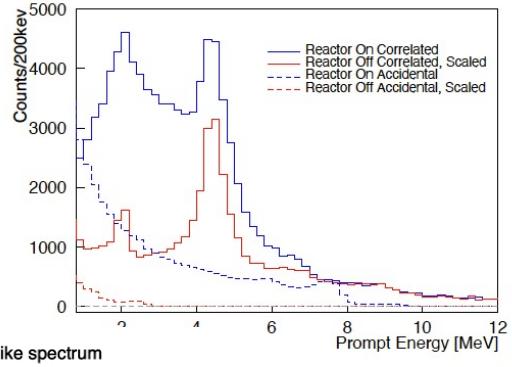
# Cut optimization including new SEER cuts - metrics

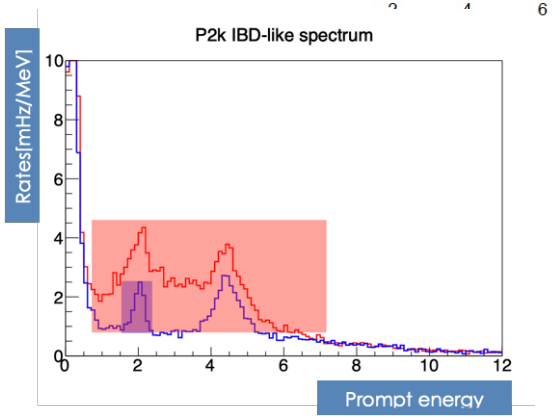
- In order to optimize the IBD selection cuts with the new SEER analysis the following data and metrics were considered:
  - 20% of the data used for the PRD
  - Effective IBD counts

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

  - Signal to cosmogenic background ratio (S:CB)
  - Signal to accidental background ratio (S:AB)




  - nH peak signal to background ratio
  - nC peak signal to background ratio





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# Summary of Results with DS and SEER

| Cut/Veto Name |
|---|
| Muon Veto Time |
| Neutron Veto Time |
| Recoil Veto Time |
| SE Recoil Veto Time |
| IBD Neutron Capture: PSD |
| IBD Neutron Capture: Energy |
| IBD PSD |
| IBD SE PSD |
| IBD SE PSD: Energy Threshold |
| IBD Distance |
| IBD Fiducial |

Improved

Unchanged

New

| | IBD Effective | IBD Effective/ calendar day | Total IBD counts | Total IBD counts/ calendar day |
|---|---|---|---|---|
| **Latest PROSPECT Results** | 15312 | 160 | 50560 | 529 |
| **Period 1** | 3124 | 327 | 6446 | 676 |
| **Period 2** | 7054 | 306 | 17321 | 759 |
| **Period 3** | 6004 | 261 | 16027 | 691 |
| **Period 4** | 4345 | 197 | 13862 | 622 |
| **Period 5** | 2796 | 155 | 10473 | 589 |
| **DS Total** | 23325 | 244 | 64130 | 670 |

- An increase of **~50%** in effective statistics is expected when including SEER cuts into our IBD selection re-optimization

- Increase of ~**27**% in total IBD counts using DS
- Increase of ~**50%** in effective statistics sing DS



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- An increase of **~50%** in effective
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  selection re-optimization

f **~27**% in total IBD counts using DS

f **~50%** in effective statistics sing DS

Stay tuned for DS+SEER Analysis!



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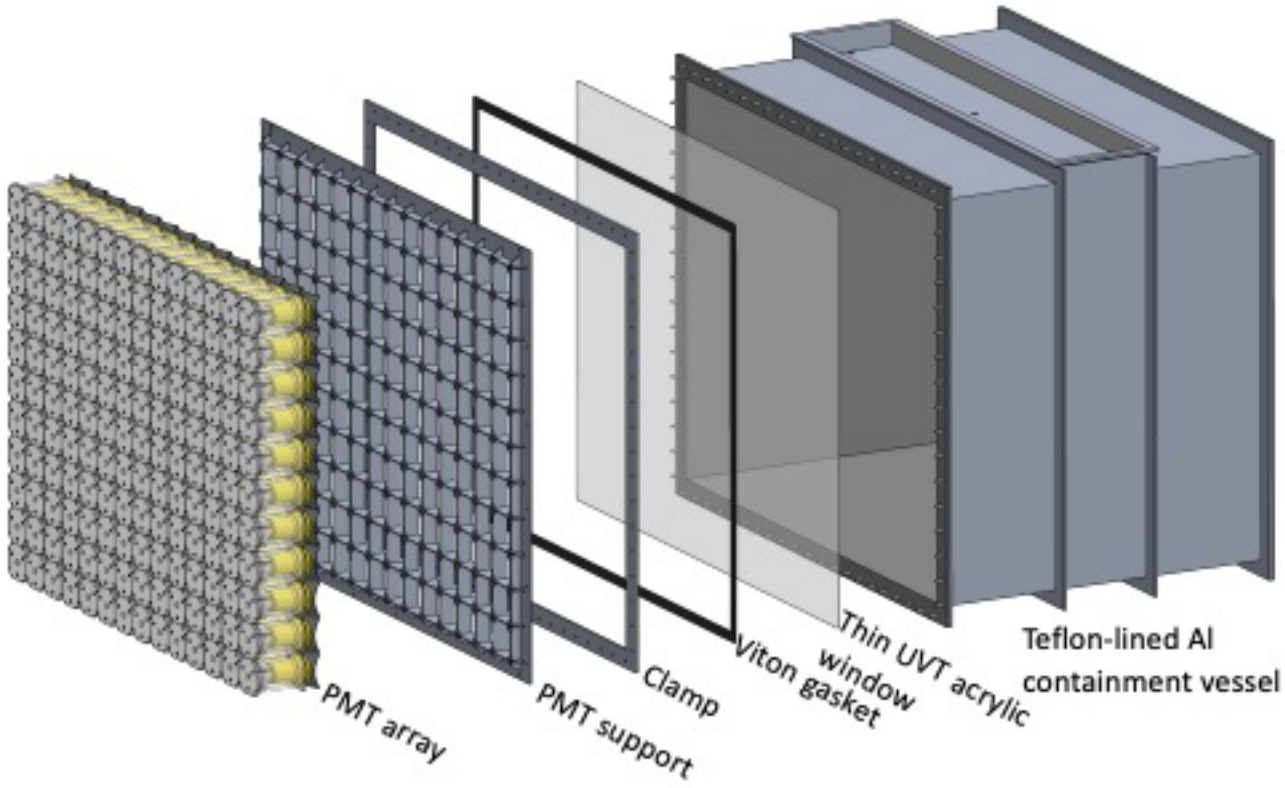
# Next Phase of Prospect

- Retains successful elements of PROSPECT-I: **segmented $^{6}$Li-doped liquid scintillator with minimal shielding, located 7-9m from HEU core of HFIR**
- **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

PROSPECT-II

*Inner detector*



# June 2021 Collaboration Meeting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HEISING-SIMONS FOUNDATION

U.S. DEPARTMENT OF ENERGY

GRFP NSF GRADUATE RESEARCH FELLOWSHIP PROGRAM

BROOKHAVEN NATIONAL LABORATORY

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Drexel UNIVERSITY

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UNIVERSITY OF HAWAI'I UA MAU KE EA O KA 'ĀINA I KA PONO

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Lawrence Livermore National Laboratory

NIST

Yale

prospect.yale.edu



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# Back Up Slides

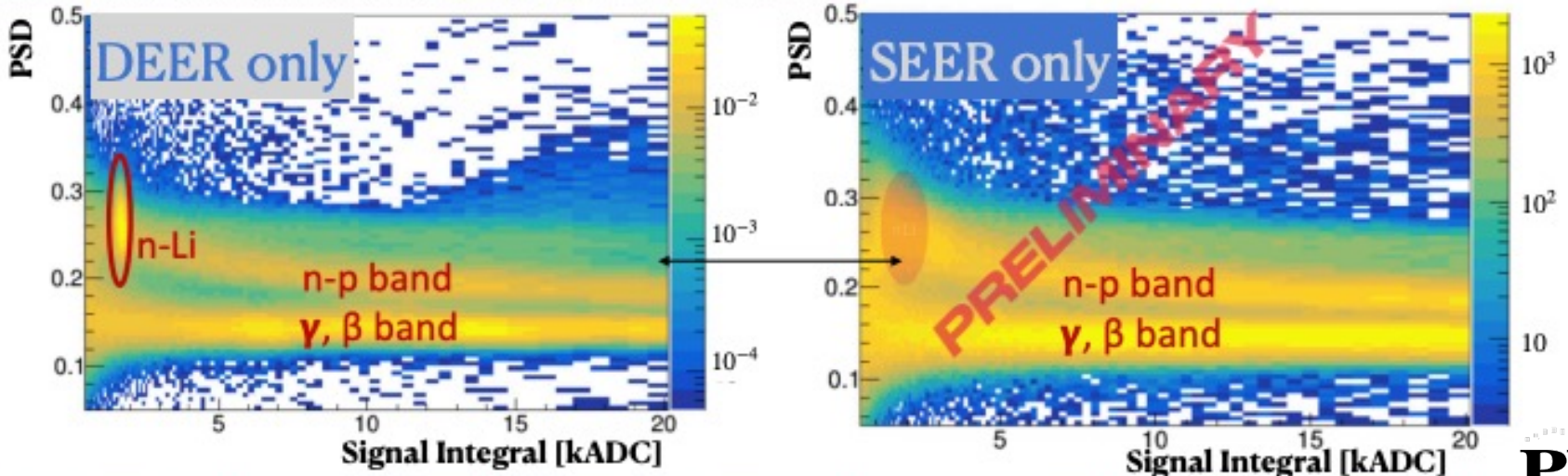
# Single Ended Event Reconstruction


## Position and energy reconstruction

- **SEER lacks** the ability to reconstruct **position** because of no counter part pulse comparison (**1 PMT** available).
- **Energy reconstruction** depends on position, therefore **not applicable** as IBD selection cut.

## Particle Identification (PID)

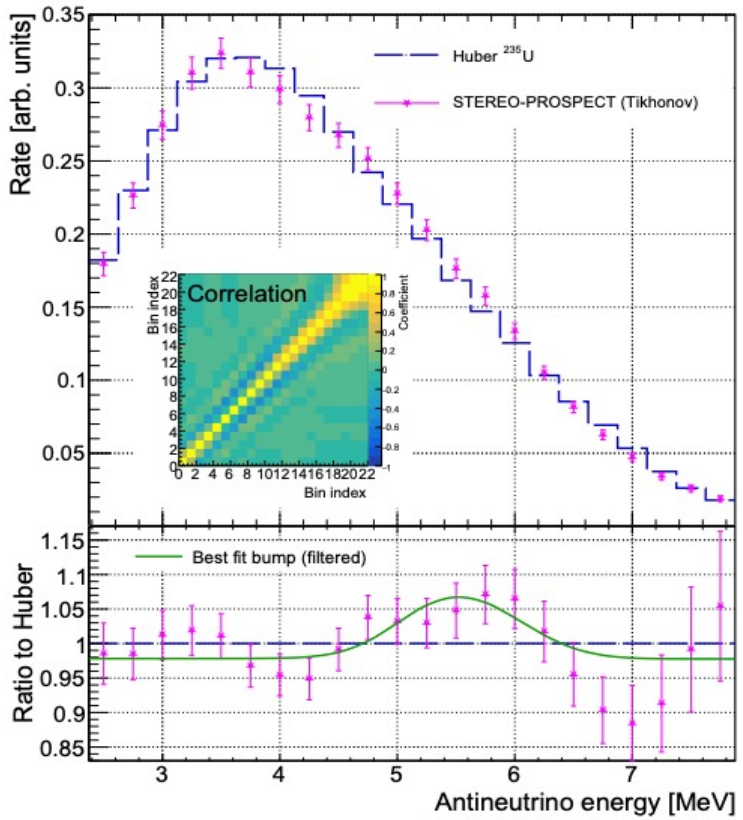
- **PSD** capability with **single PMT** readout is applicable for **PID**
- **SEER** PSD **lacks** the ability to **distinguish n-Li capture** from n-p recoil events.
- **More** active **segments** from SEER+DEER allow for **better IBD selection** and bkg rejection.



# More Results from PROSPECT

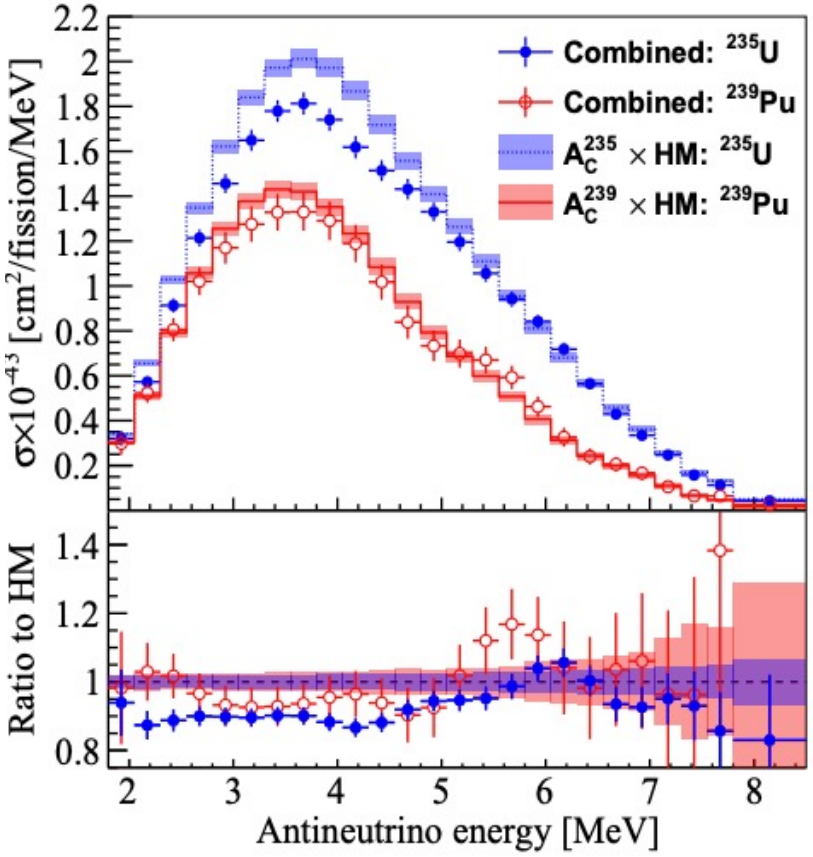
## Joint Spectrum Analyses

### STEREO & PROSPECT



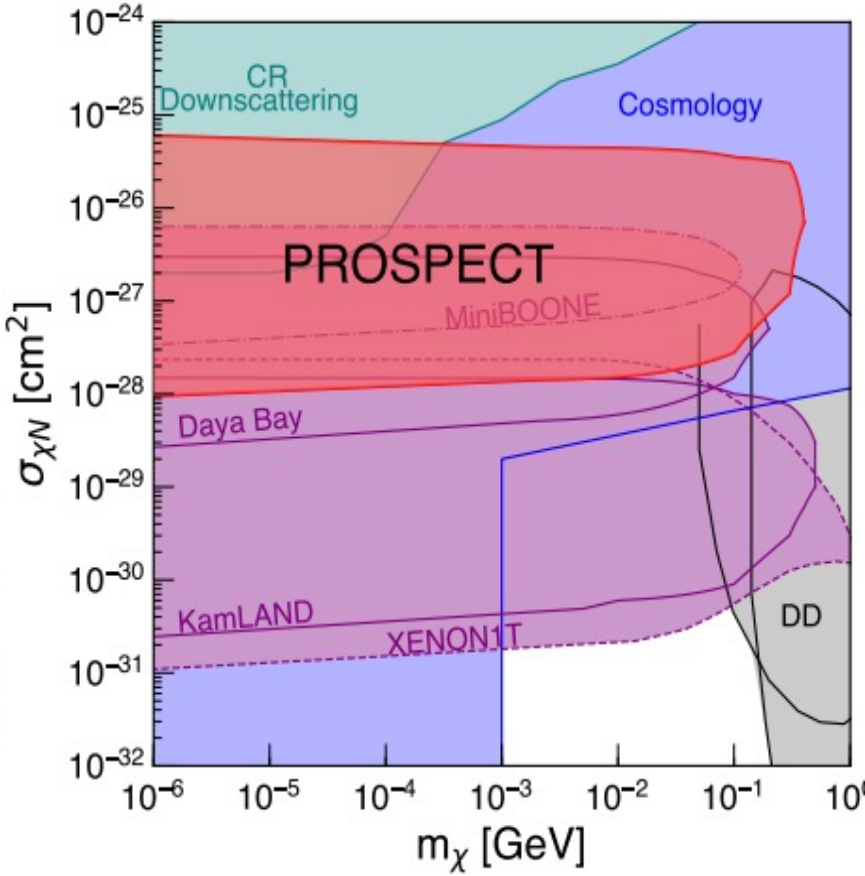

arxiv:2107.03371

### Daya Bay & PROSPECT




arXiv:2106.12251

### Boosted Dark Matter Search




PhysRevD 104 (2021) 012009



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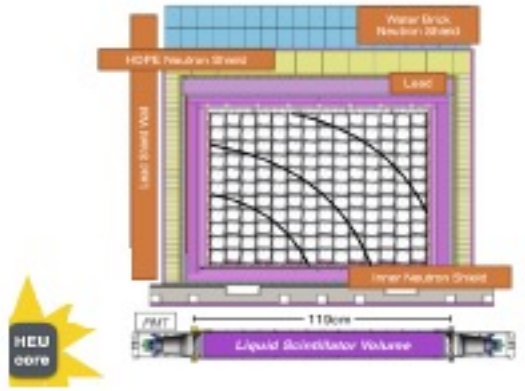
# Sterile Neutrino Oscillation

## Relative Spectrum Measurement

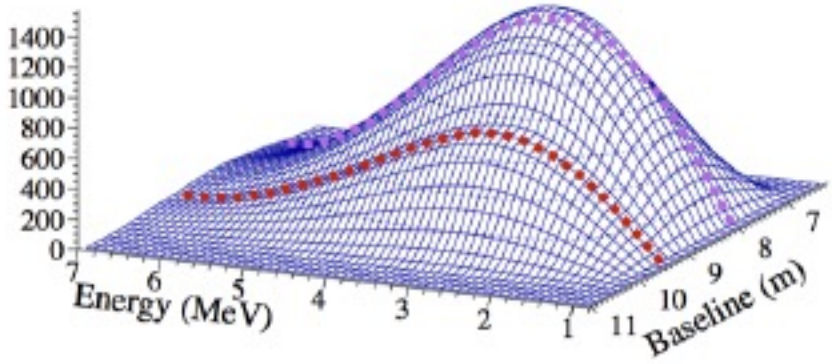
relative measurement of L/E and spectral shape distortions

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

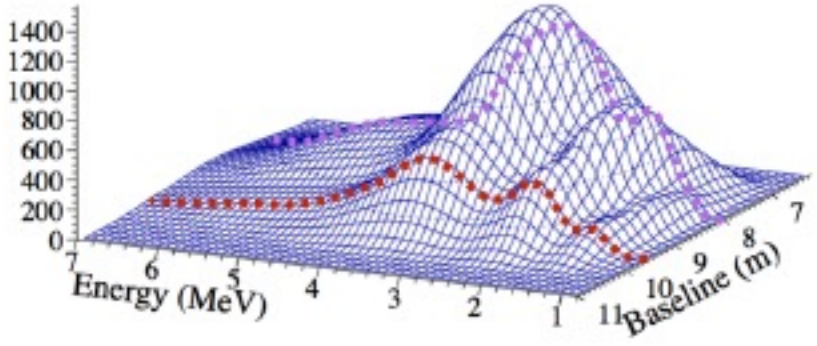



**Simulations**

**unoscIllated spectrum**




**oscIllated spectrum**



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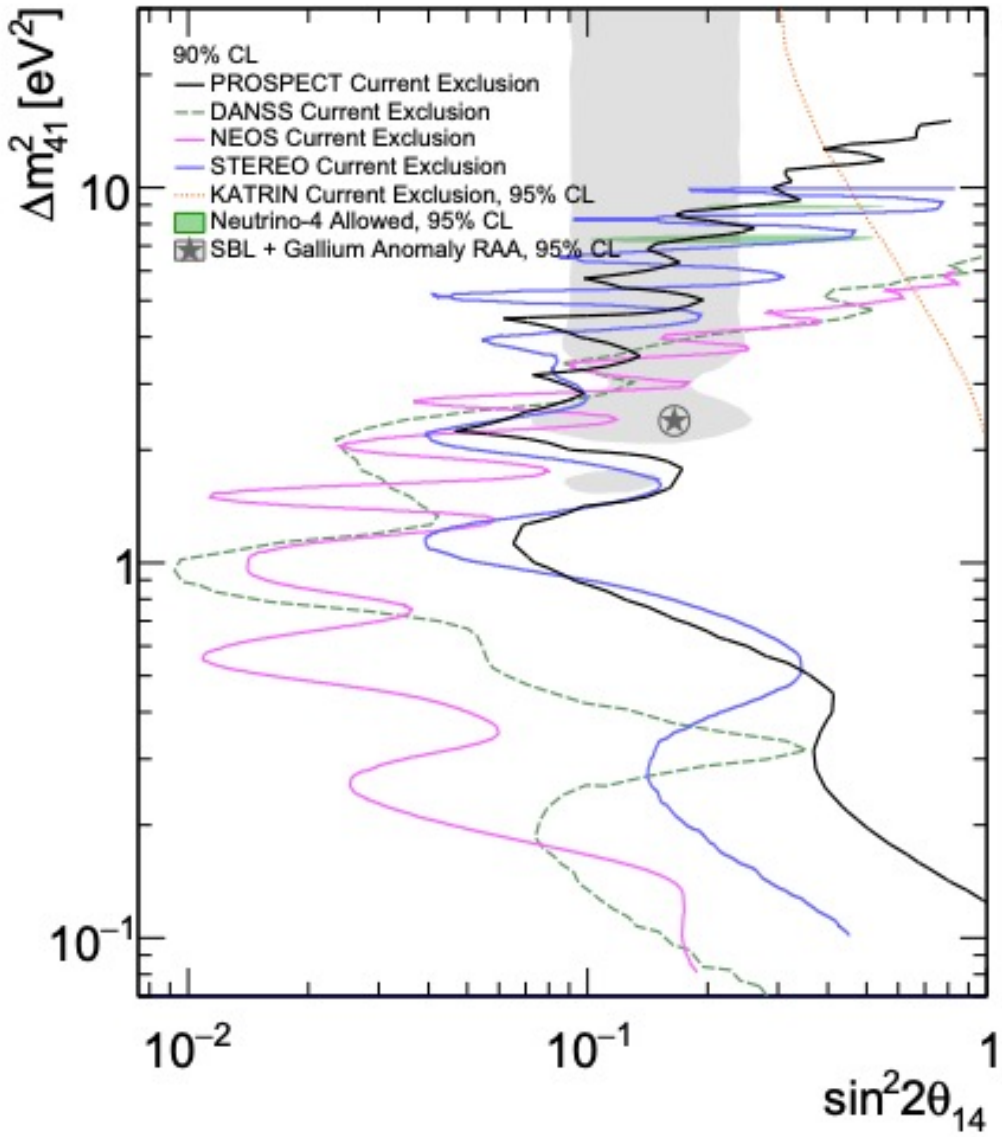
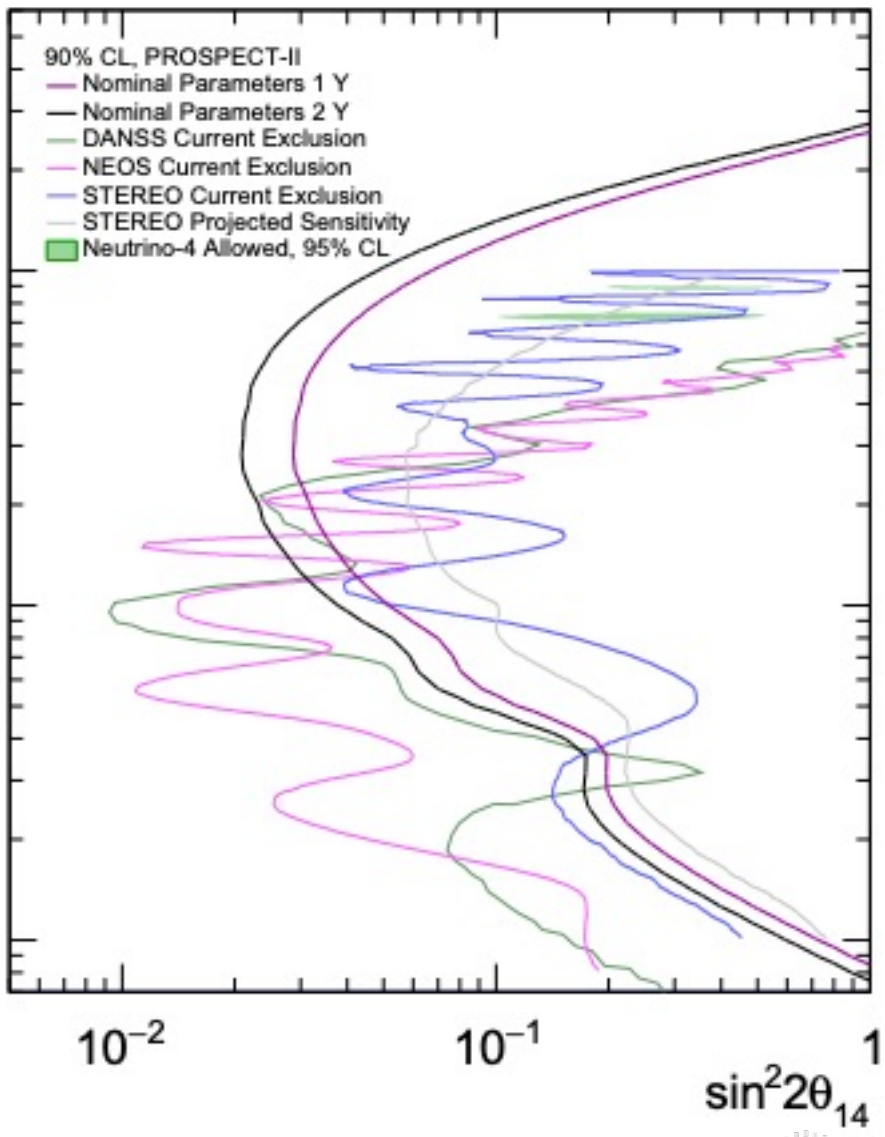
# Sterile Neutrino Oscillation: Global Picture




arxiv:2107.03934



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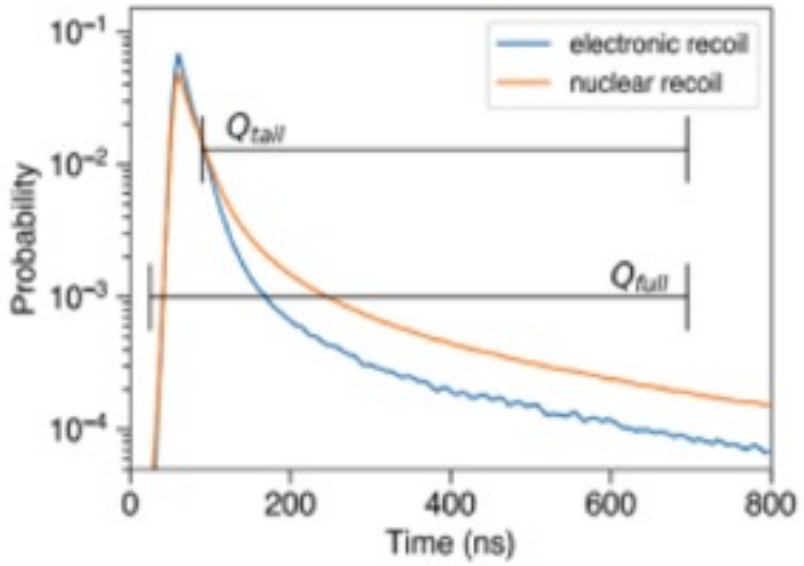
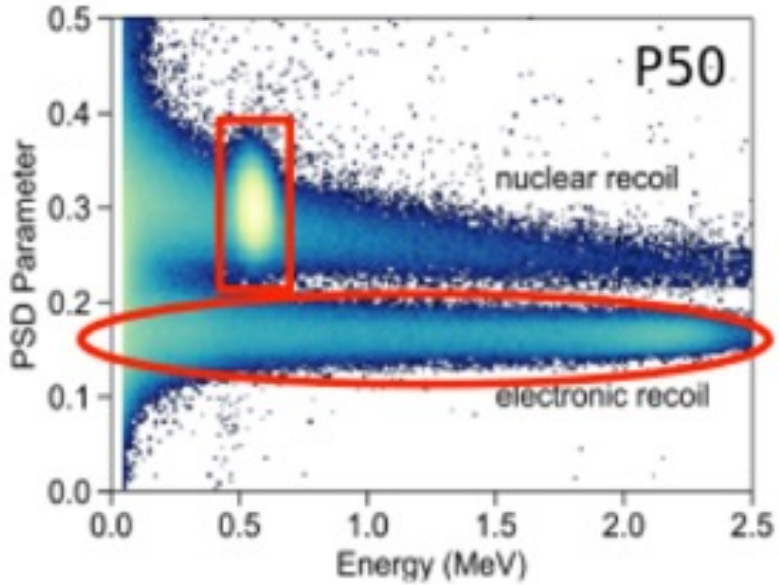
# Reactor Antineutrino Anomaly

- What is the nature of the bump?
  - Is it an incorrect modeling of the fission products?
  - Are all of them responsible or only one?
  - A. Hayes, J. Friar, G. Garvey, D. Ibeling, G. Jungman,T. Kawano, and R. Mills, Phys. Rev. D 92, 033015 (2015).
  - Y. Gebre, B. Littlejohn, and P. Surukuchi, Phys. Rev. D 97, 013003 (2018).
- Total absorption spectrometry has been used in order to investigate both the flux deficit and the bump.
  - M. Wolińska-Cichocka,K.Rykaczewski,A.Fijałkowska,M.Karny,R.Grzywacz,C.Gross,J. Johnson, B. Rasco, E. Zganjar, Nuclear Data Sheets 120 (2013) 22, ISSN 0090-3752,URL(http://www.sciencedirect.com/science/article/pii/S0090375214004487)

# PSD Parameter




- $Q_{Tail}$ = integrated charge from 40 ns to 120 ns after the leading-edge half-height
- $Q_{Full}$ = *integrated charge 12 ns before to 120 ns after of* the leading-edge half-height
- $PSD = \frac{Q_{Tail}}{Q_{Full}}$



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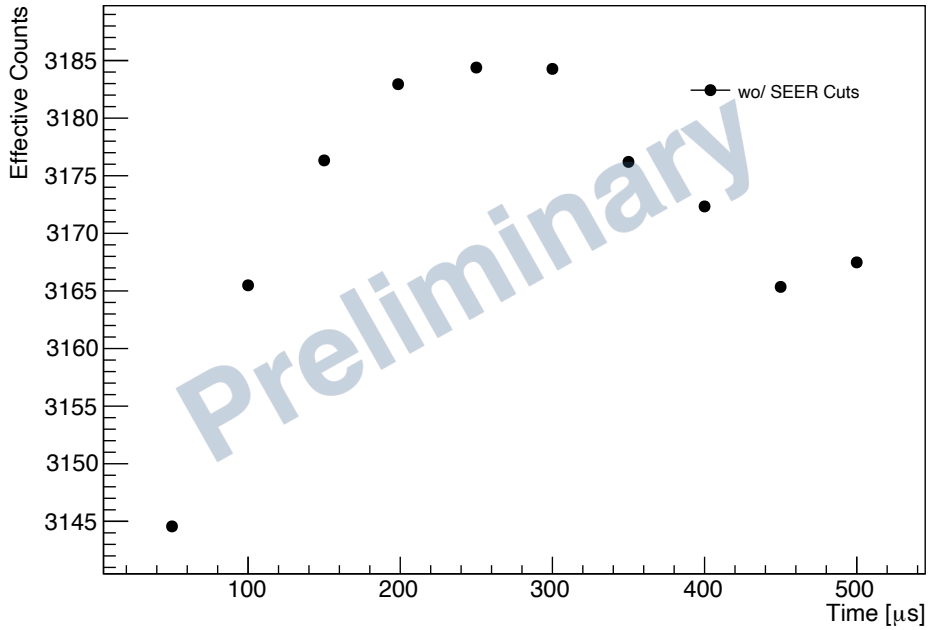
PROSPECT

# Cut optimization including new SEER cuts - example

## Neutron Veto Time [$\mu s$]:

- IBD candidates are rejected if their delayed capture times are within μs of another n-6Li candidate



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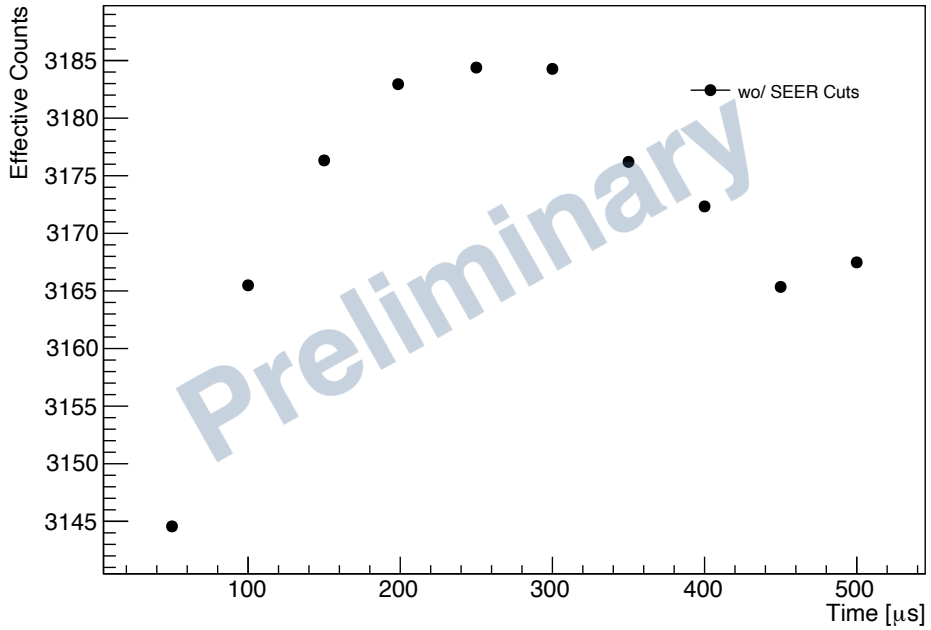
PROSPECT

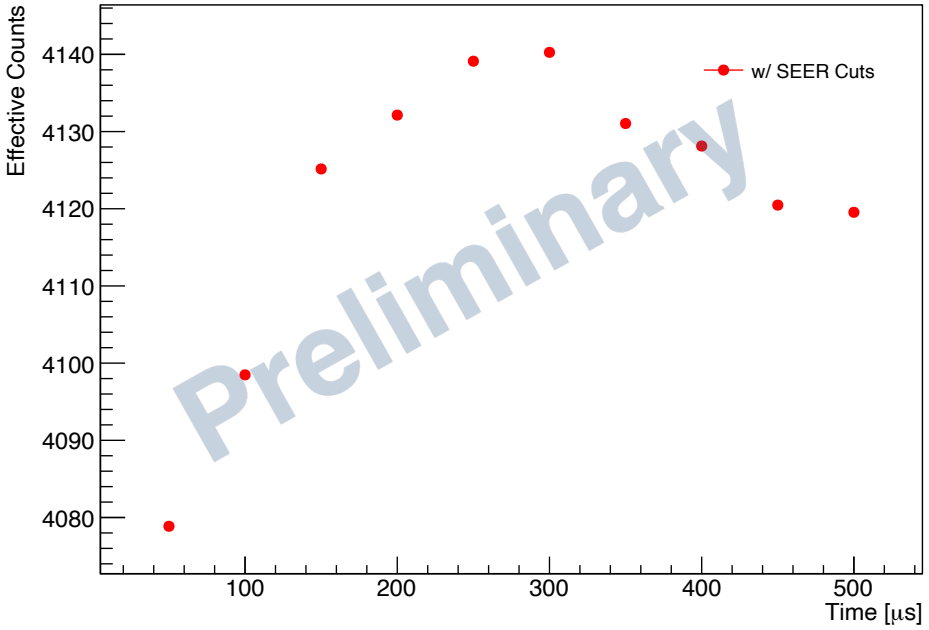
# Cut optimization including new SEER cuts - example

## Neutron Veto Time [$\mu s$]:

- IBD candidates are rejected if their delayed capture times are within μs of another n-6Li candidate




- Introduction of new SEER cuts into our optimization results in a ~30% increase in effective statistics
- Other metrics exhibit similar improvement



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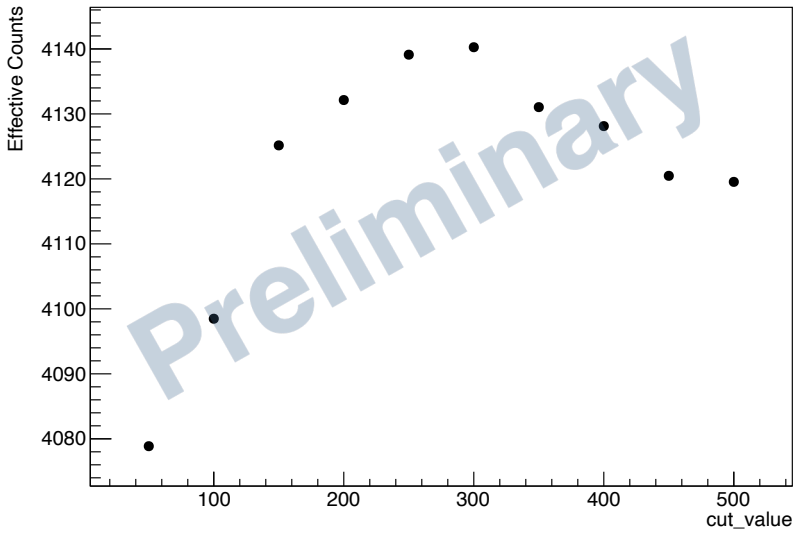
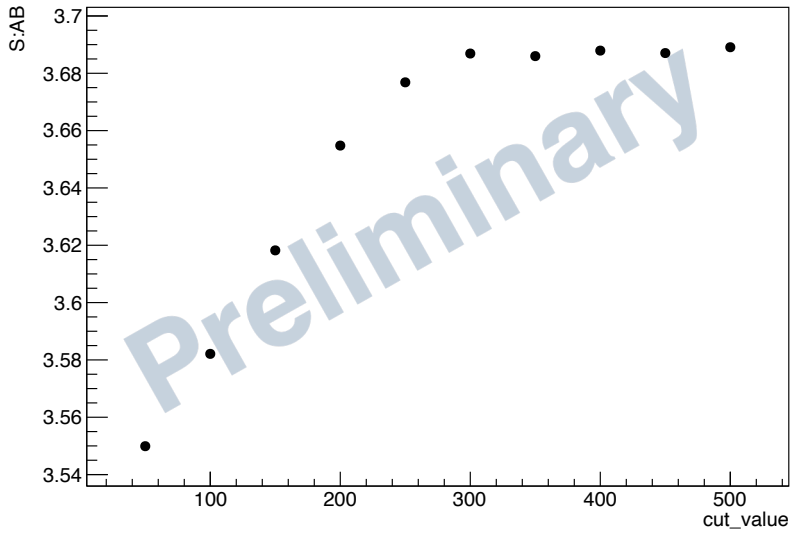
PROSPECT

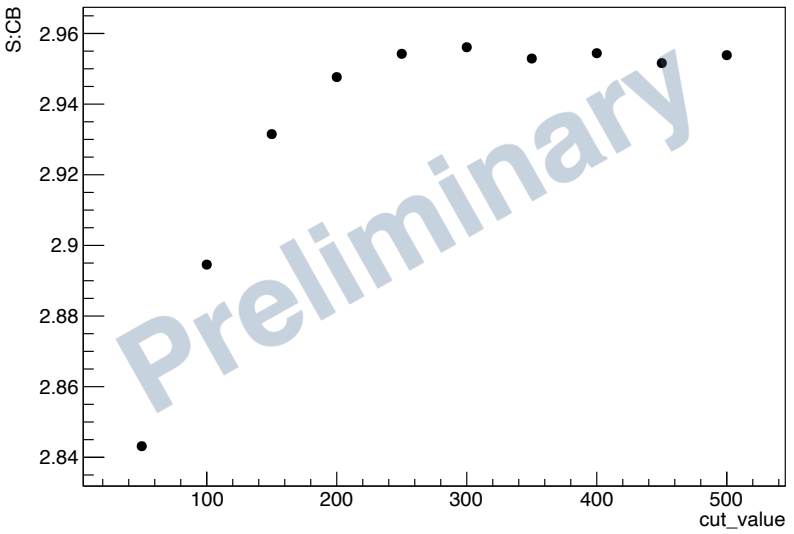
# Cut optimization including new SEER cuts - example

## Neutron Veto Time [$\mu s$]:

- IBD candidates are rejected if their delayed capture times are within μs of another n-6Li candidate



| CALIBRATION BASED | PERIOD_1 | PERIOD_2 | PERIOD_3 | PERIOD_4 | PERIOD_5 | Total |
|---|---|---|---|---|---|---|
| Good_files | 580 | 925 | 965 | 922 | 649 | 4041 |
| Missing_files | 0 | 0 | 0 | 1 | 0 | 1 |
| RxOn livetime (days) | 8.11461 | 19.1629 | 19.5476 | 18.7133 | 14.8146 | 80.35301 |
| RxOn runtime (days) | 9.54015 | 22.8299 | 23.2049 | 22.2884 | 17.789 | 95.65235 |
| RxOff livetime (days) | 12.8744 | 13.8421 | 14.9884 | 14.2507 | 8.17725 | 64.13285 |
| RxOff runtime (days) | 14.5798 | 15.706 | 16.9799 | 16.1203 | 9.24865 | 72.63465 |
| IBD Candidates (Rxon) | 11080 | 31423 | 30854 | 31028 | 24806 | 129191 |
| IBD Candidates (Rxoff) | 4206 | 4443 | 5303 | 5932 | 3675 | 23559 |
| Accidental Candidates (Rxon) (per day) | 2179.47 | 8486.87 | 8462.03 | 9888.75 | 8082.41 | 37099.53 |
| Accidental Candidates (Rxoff) (per day) | 314.197 | 388.197 | 423.721 | 391.233 | 225.741 | 1743.089 |
| Correlated Candidates (Rxon) | 8900.53 | 22936.1 | 22392 | 21139.2 | 16723.6 | 92091.43 |
| Correlated Candidates (Rxoff) | 3891.8 | 4054.8 | 4879.28 | 5540.77 | 3449.26 | 21815.91 |
| Cosmogenic Background | 2453.59 | 5614.89 | 6365.12 | 7277.71 | 6250.56 | 27961.87 |
| Total IBD Signal | 6446.94 | 17321.2 | 16026.9 | 13861.5 | 10473 | 64129.54 |
| eff_IBD | 3124.3 | 7054.18 | 6004.9 | 4345.04 | 2796.13 | 23324.55 |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