The PROSPECT Short Baseline Reactor Experiment

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For the PROSPECT collaboration

Crete '19

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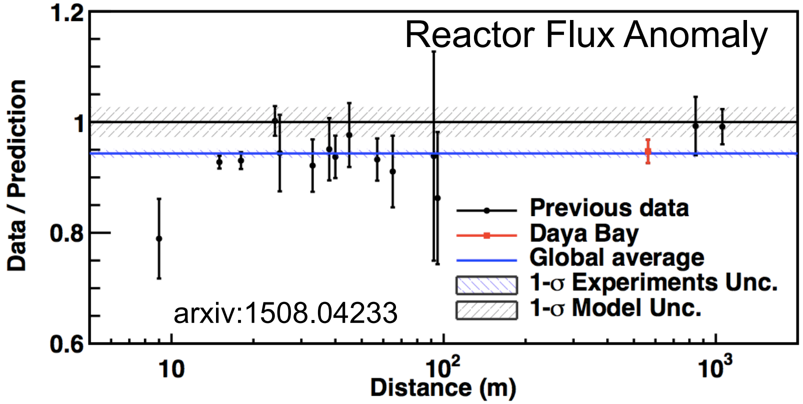
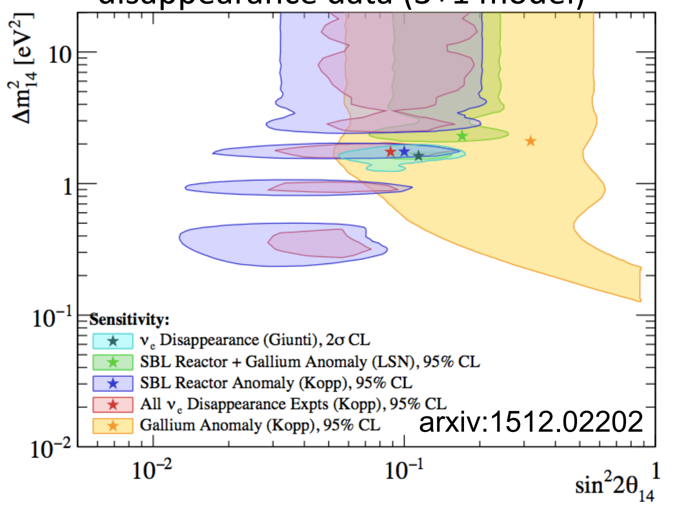
Lawrence Livermore National Laboratory

Motivation

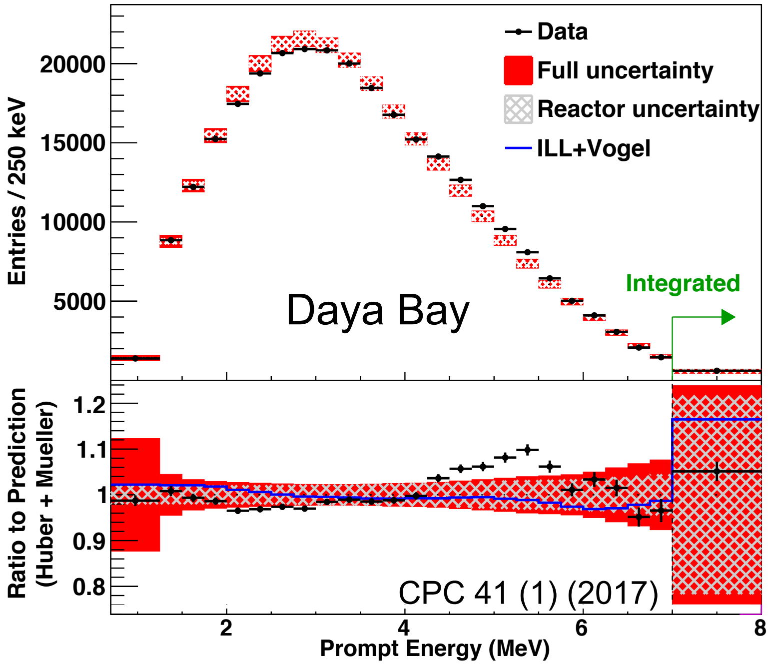
Directly test the hypothesis of a new oscillation with $\Delta m^2 \sim 1$ eV^2,
i.e. oscillation length of few meters



Allowed regions for ν_e disappearance data (3+1 model)

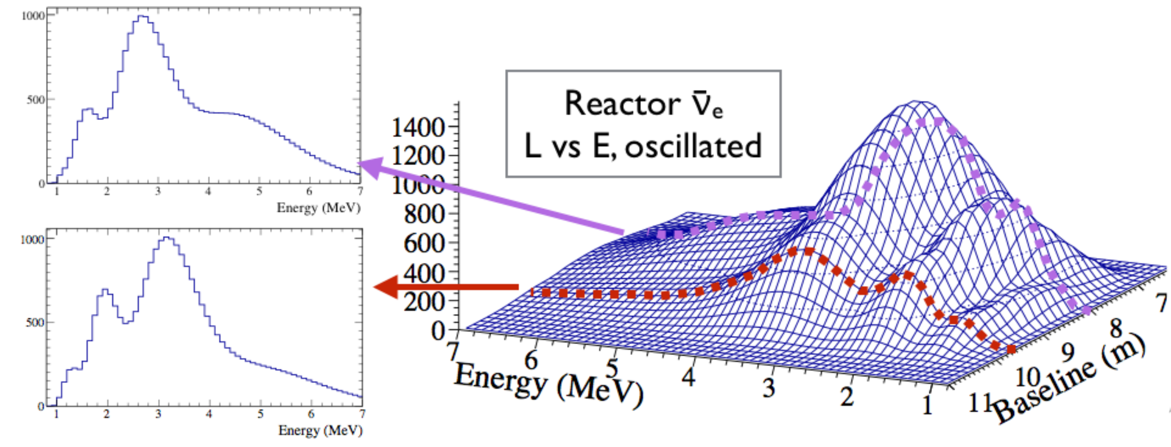


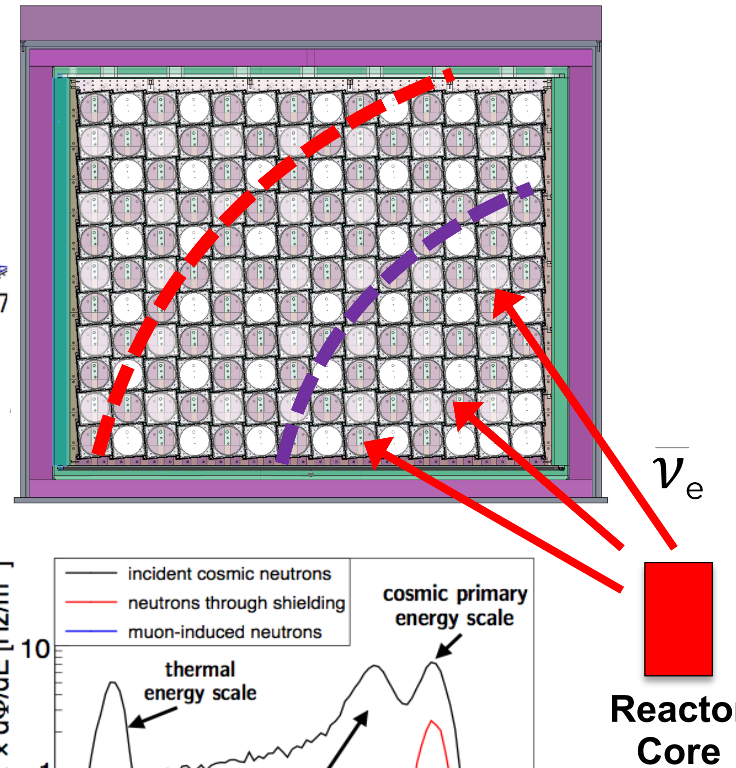
Provide new tests of reactor models by making precision measurements of novel reactor spectra, esp. ^{235}U fuel



Approach to Short Baseline Reactor Measurements

Search for relative shape distortion in identical detector segments at different baselines
→ eliminate reactor model dependence



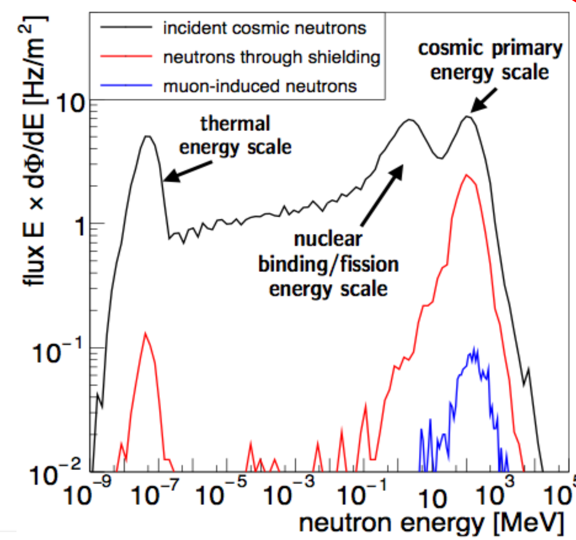


Research reactors generally preferable:

- Access to shortest baselines
- Often use ^{235}U fuel → static fissile inventory
- Compact core dimensions provide greatest sensitivity at Δm2 ~ 1 eV^2

But:

- Limited overburden – cosmogenic neutrons from atmosphere dominant correlated background source
- Possibility of reactor generated accidental background

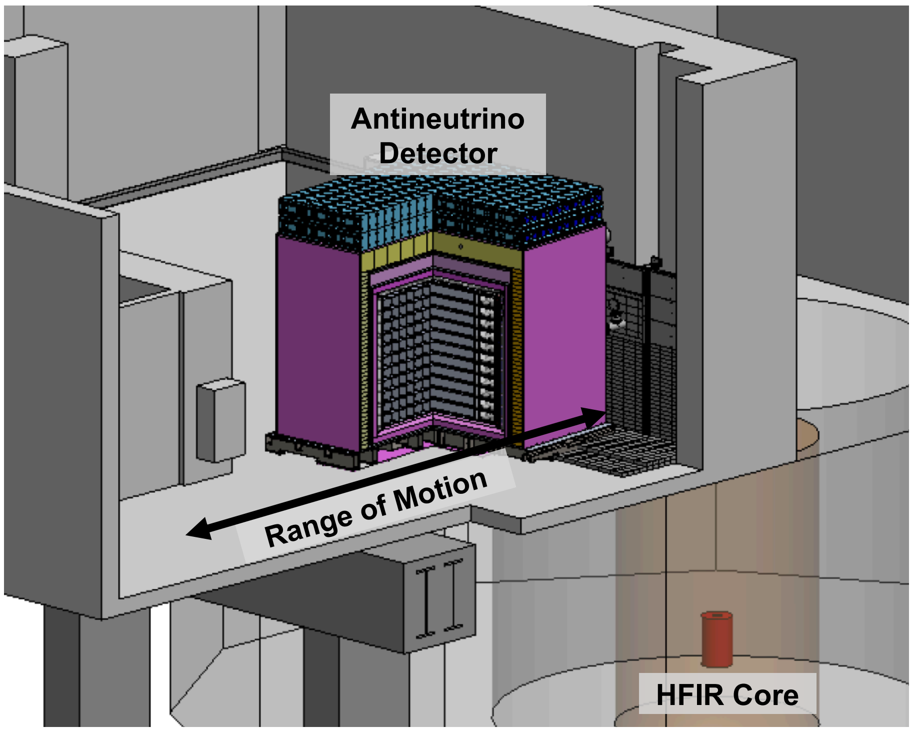


PROSPECT Experiment Overview

Physics Objectives

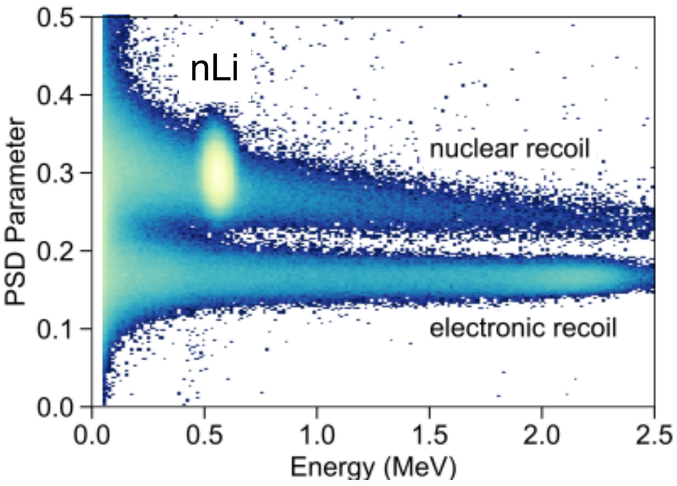
1. Model Independent search for short-baseline oscillation at distances <12m
2. Precision measurement of ^{235}U reactor $\overline{\nu}_e$ spectrum

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



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

- localized, distinct signal
- uniform efficiency in compact detector

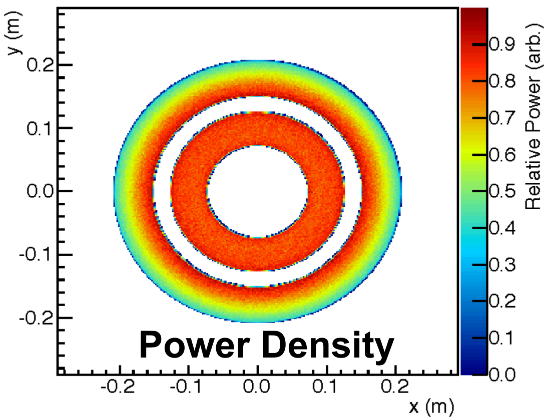


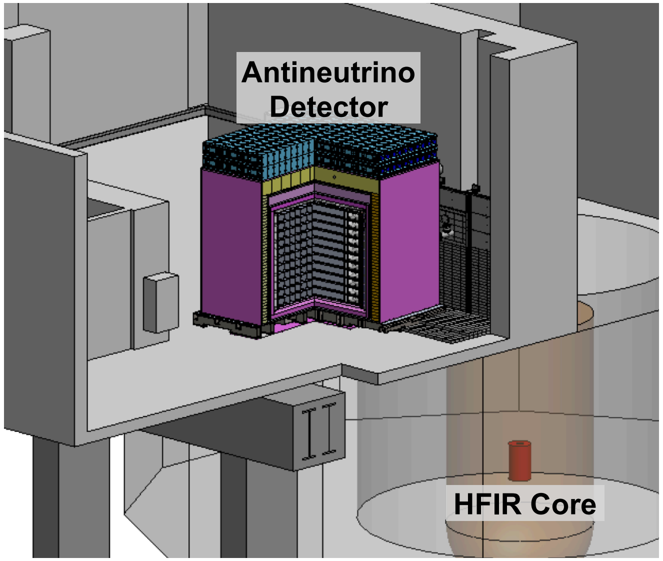
Experimental site: High Flux Isotope Reactor @ORNL

Compact Reactor Core

44cm

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

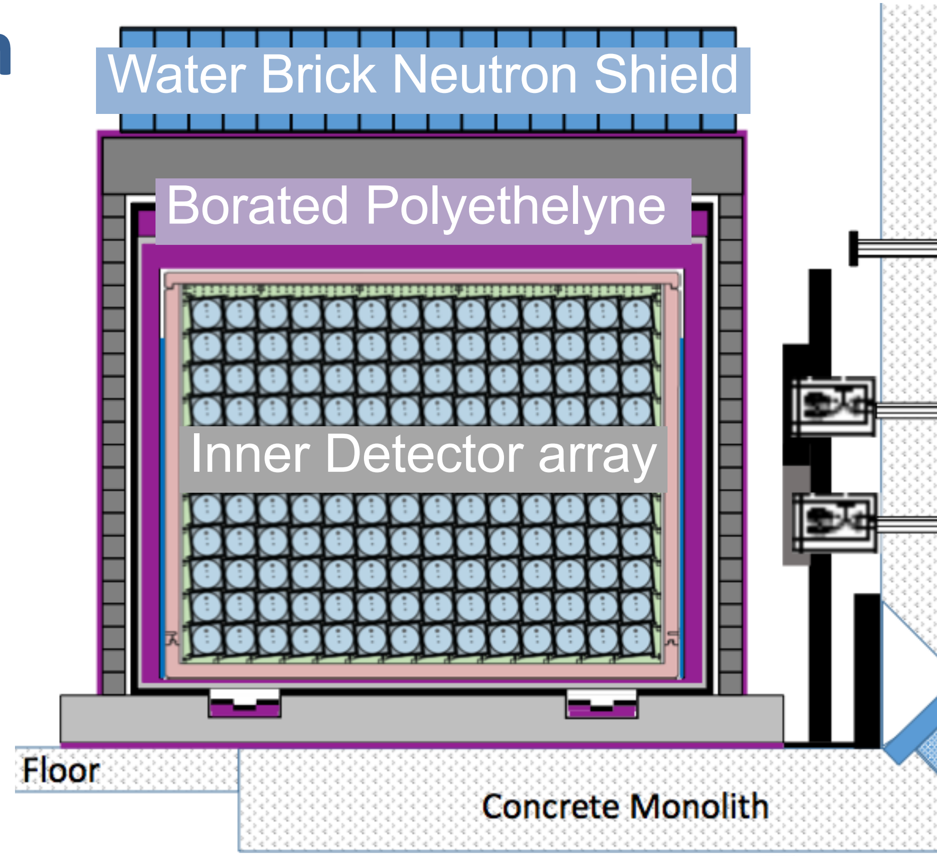


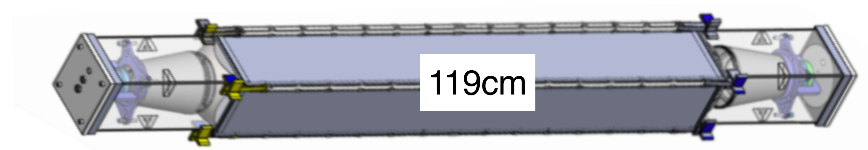


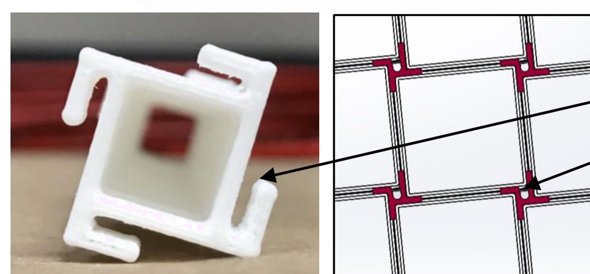
User facility with 24/7 access; Exterior access at grade

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





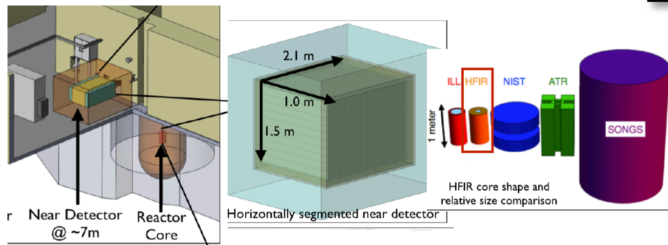


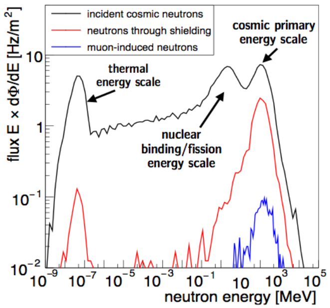
Tilted Array for calibration access

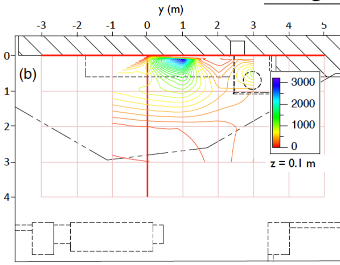
PROSPECT - arXiv:1808.00097

Comprehensive R&D Program

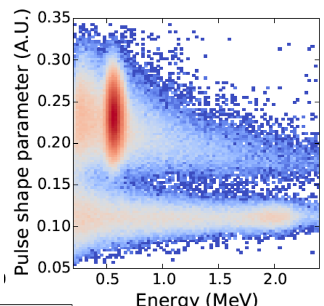
- **Conceptual design for physics and background requirements**
- **Reactor site assessment**

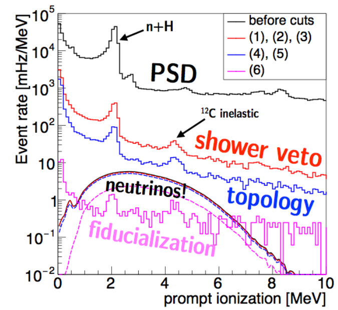




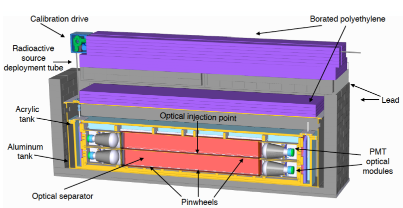


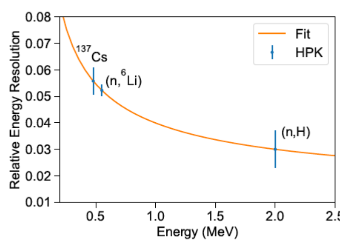
- **Characterize reactor & cosmogenic background**
- **Validate shielding & detector MC with onsite prototypes**





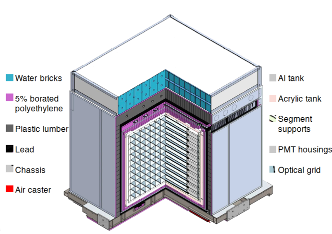
- **Develop detector design and analysis that achieves required S:B**
- **Demonstrate required segment and LiLS performance**

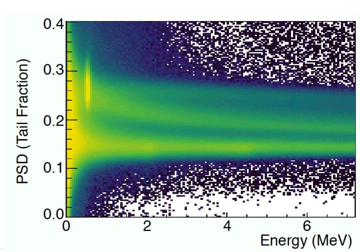




- **Demonstrate required performance with production components**

- **Full scale detector meets all performance requirements**





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

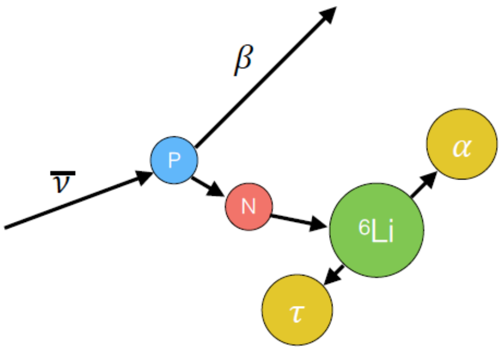
PROSPECT Experiment
NIMA 922 (2019) 286
arXiv:1808.00097

LiLS Production
JINST 14 P03026 (2019)
arXiv:1901.05569

Optical Grid
JINST 14 P04014 (2019)
arXiv:1902.06430

Event Detection in PROSPECT AD

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

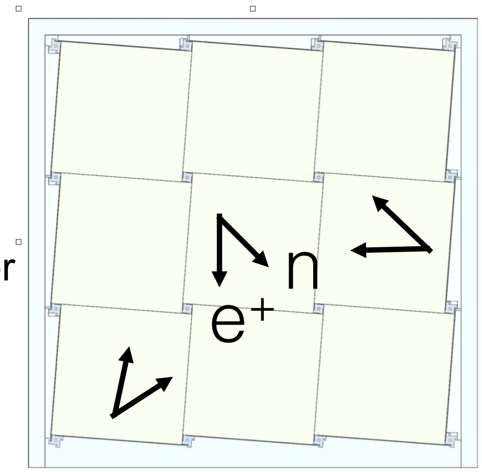
fast neutron background
recoil-like prompt, capture-like delay
capture-like prompt, capture-like delay

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

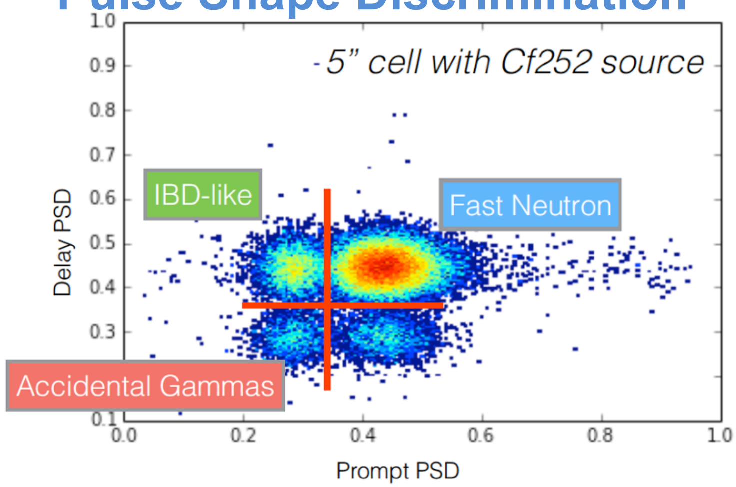
Background reduction is key challenge

Background reduction through **detector design & fiducialization**

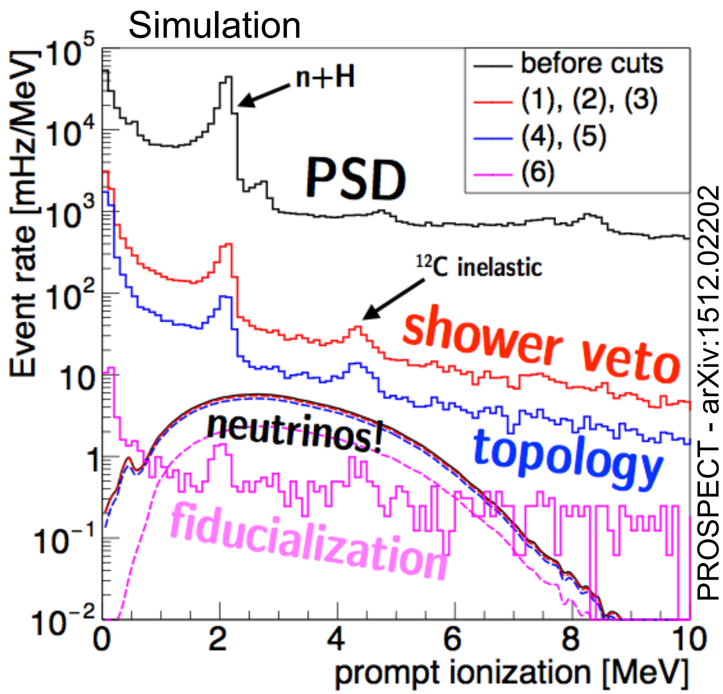
IBD event in segmented ^{6}LiLS detector

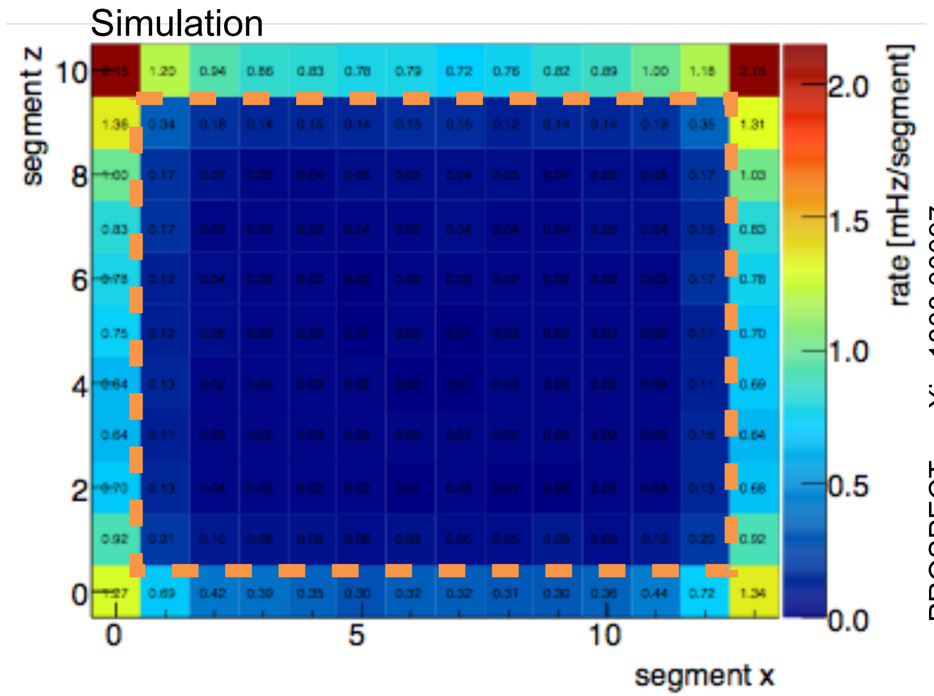


Pulse Shape Discrimination



Active Background Suppression





- Detector design features provide background rejection via
  - Efficient recoil & neutron capture identification
  - Multi-interaction & multi-particle identification
  - Fiducialization

PSD & ^{6}Li

Position Reconstruction

- Signal:Background > 1:1 predicted using prototype validated MC; > 10^4 background rejection

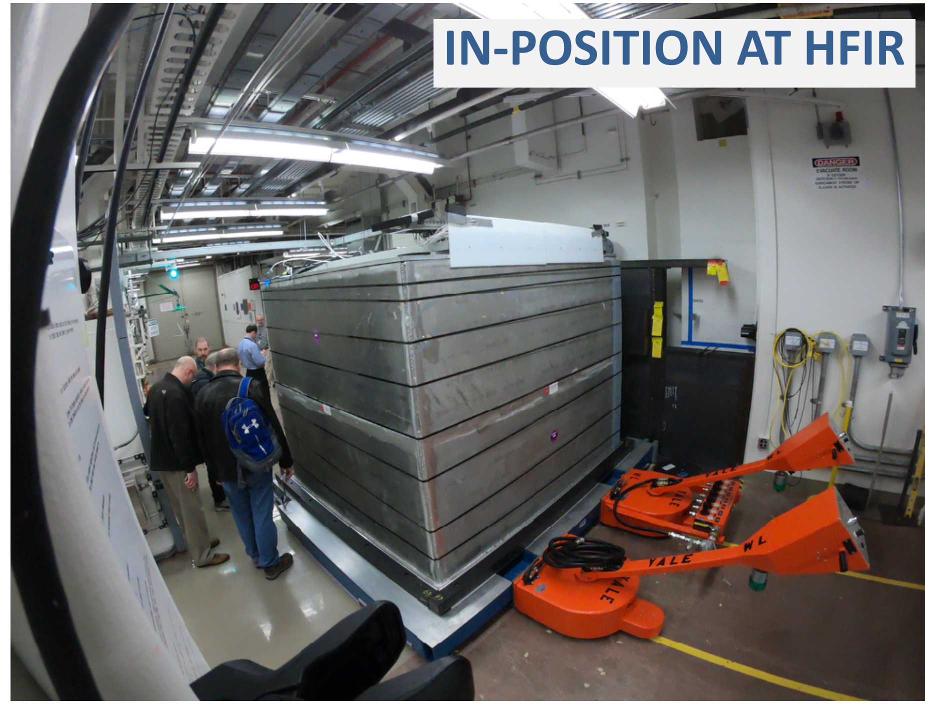
ASSEMBLY OF FIRST ROW

NOVEMBER 1, 2017

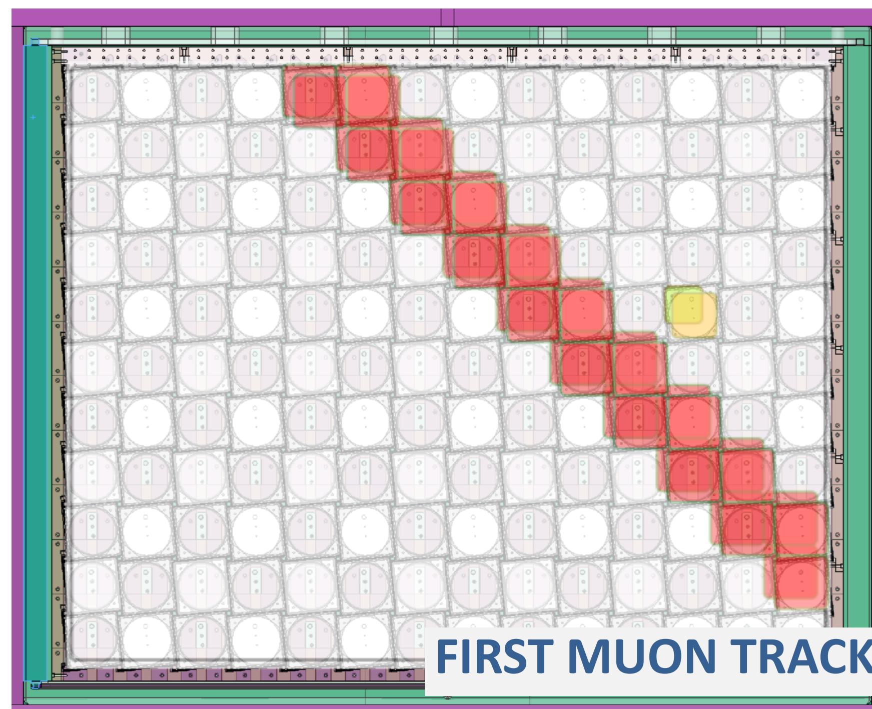
NOVEMBER 17, 2017
FINAL ROW INSTALLATION

DEC, 2017 - JAN 2018
DRY COMMISSIONING AT YALE

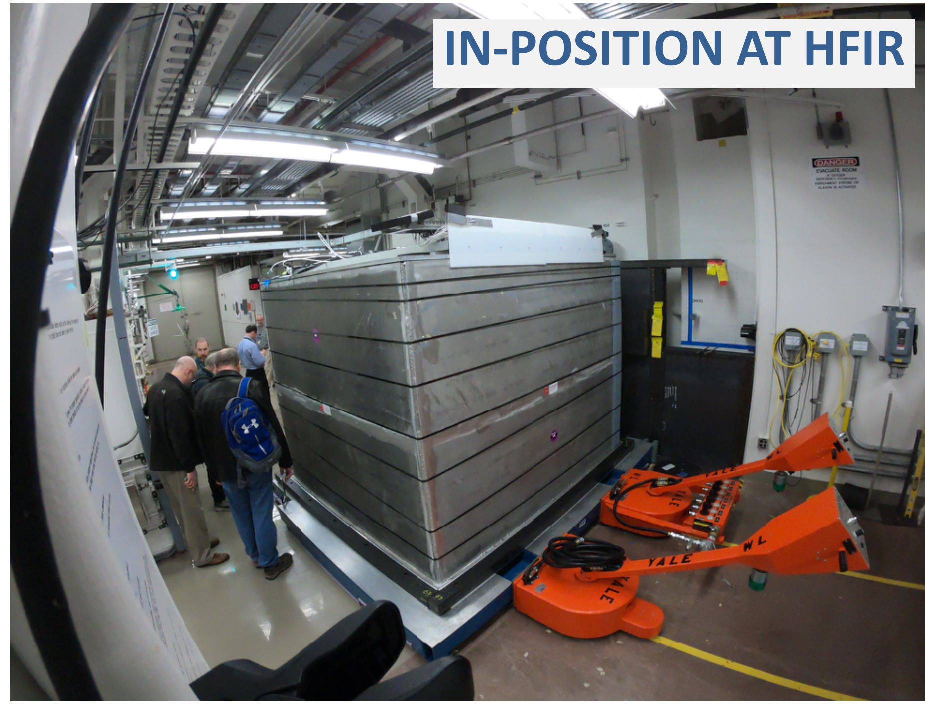

FEBRUARY 2018
ARRIVAL AT ORNL


IN-POSITION AT HFIR


FILLING FROM MIXING TANK


FIRST MUON TRACK


FEBRUARY 2018
ARRIVAL AT ORNL


IN-POSITION AT HFIR
YALE


FILLING FROM MIXING TANK
TARE
NOMINAL CAPACITY
4 BAR

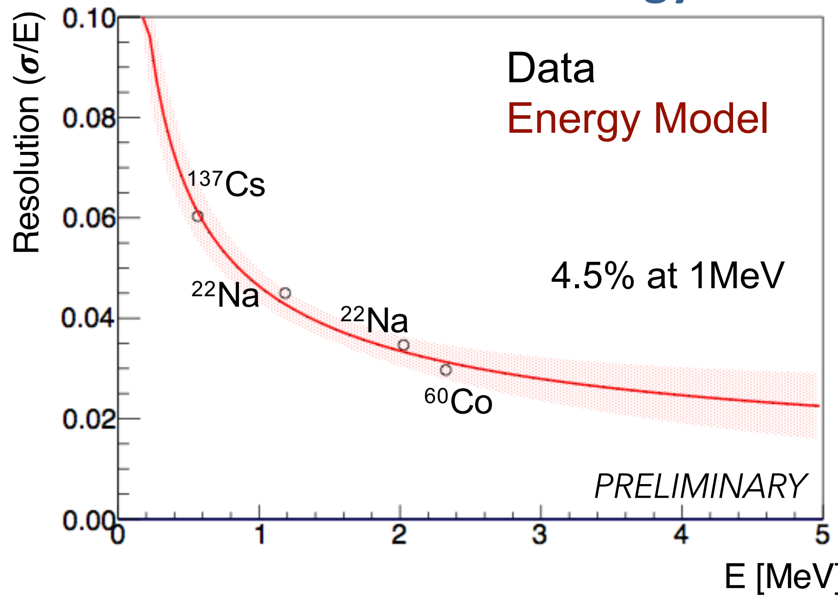

HADRONIC SHOWER


FEBRUARY 2018
ARRIVAL AT ORNL
IN-POSITION AT HFIR
FILLING FROM MIXING TANK
IBD CANDIDATE

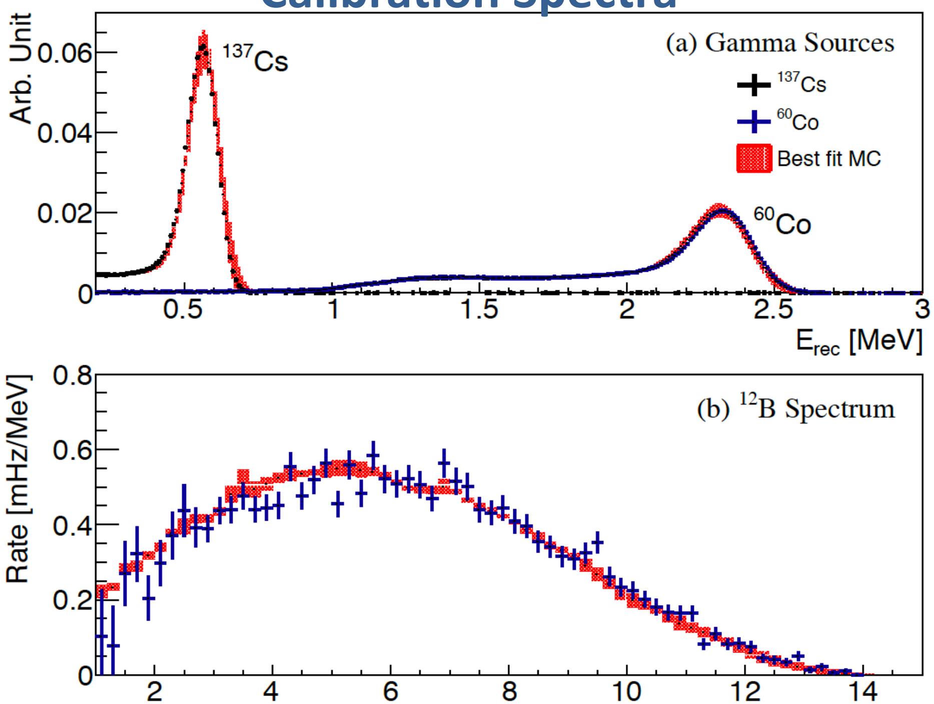
Energy Reconstruction

- 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}
- **High light collection: 795±15 PE/MeV**

Resolution vs Energy



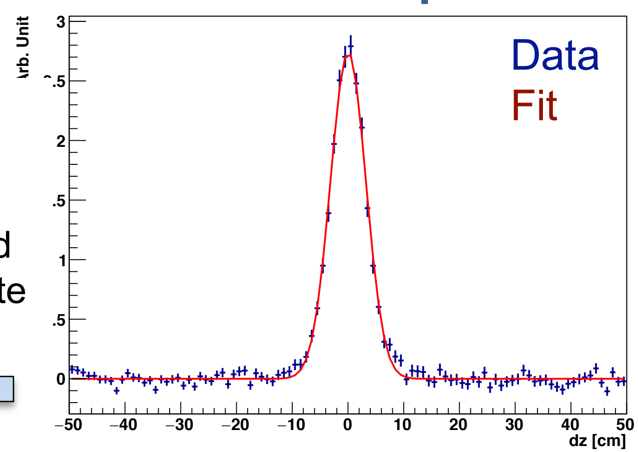
Calibration Spectra



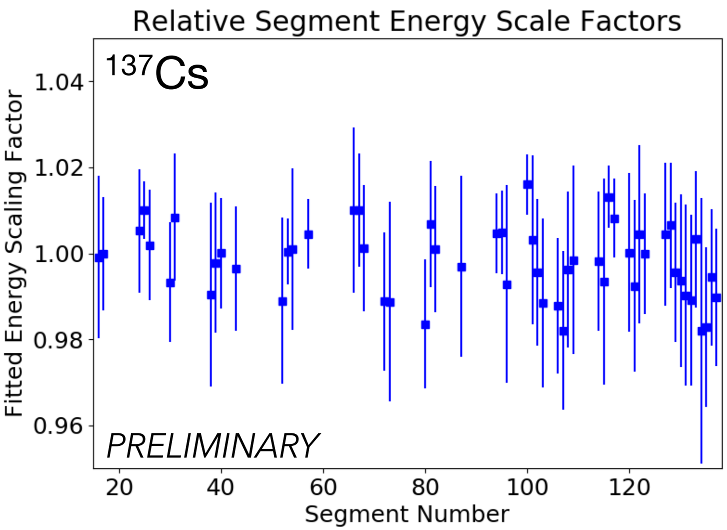
Phys.Rev.Lett. 121 (2018) 251802

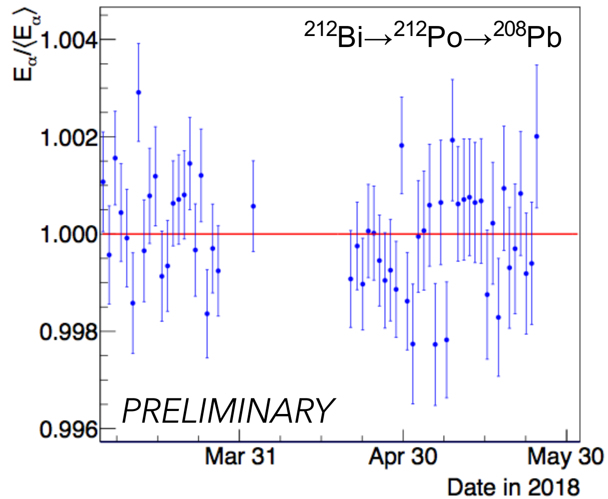
$^{12}C(n,p)^{12}B$
Proton – ^{12}B separation

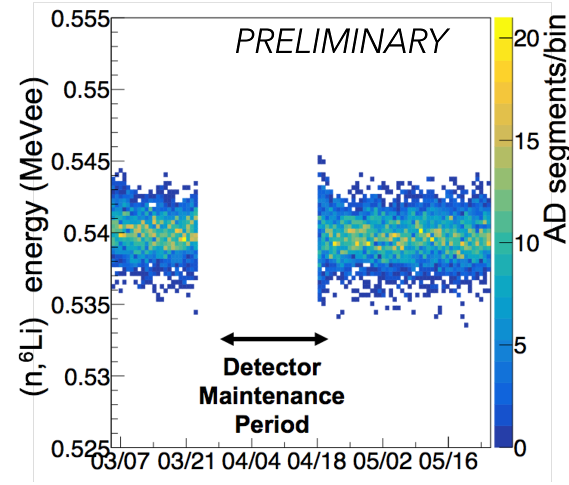
High-purity ^{12}B sample position & time tagged by final state proton



Energy Stability and Uniformity



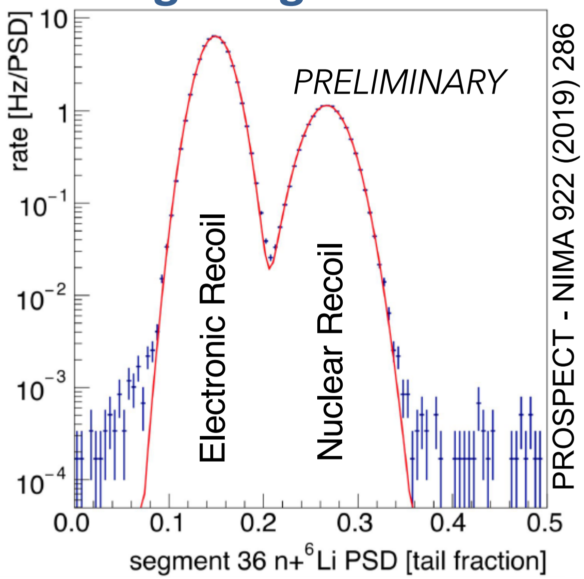




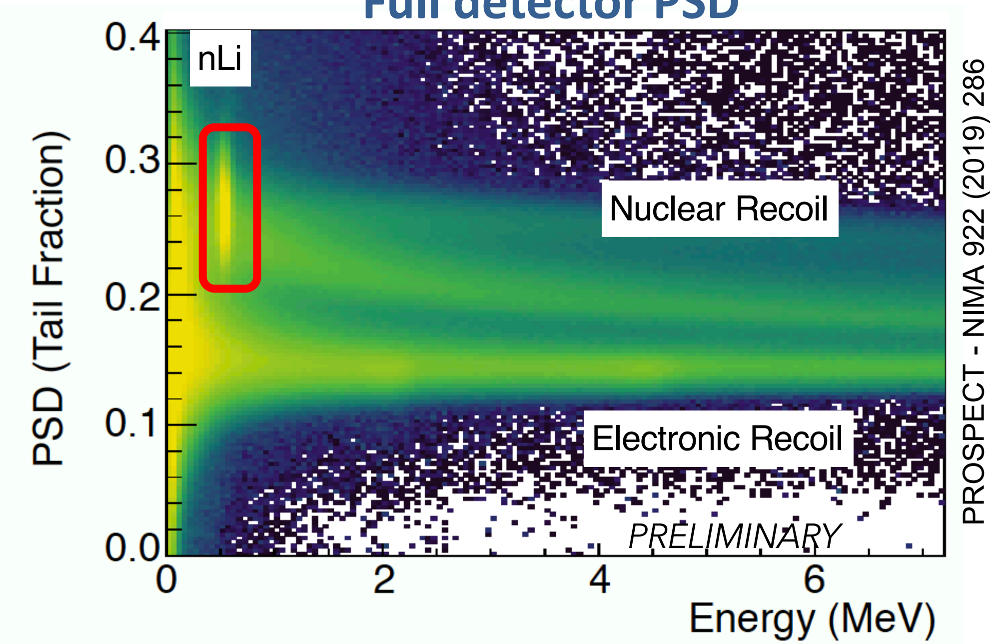
- **Calibration Source Deployment:**
  - 35 calibration source tubes throughout detector to map energy response
  - Segment to segment uniformity ~1%
  - ^{252}Cf source to study neutron capture efficiency
- **Intrinsic radioactive sources**
  - Track uniformity over time with distributed internal single-segment sources:
  - Alpha lines from ^{212}Bi→ ^{212}Po→^{208}Pb decays, nLi capture peak
  - Reconstructed energy stability over time < 1%

Pulse Shape Discrimination Performance

Single segment PSD



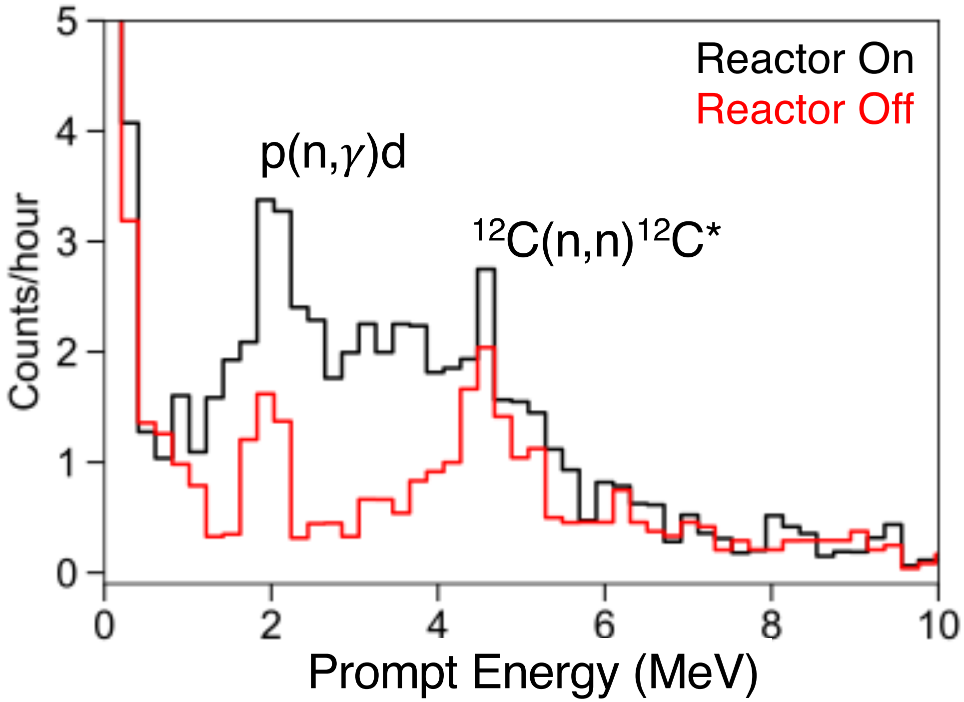
Full detector PSD



- Excellent particle ID of gamma interactions, neutron captures, and nuclear recoils
- Dominant backgrounds: Cosmogenic fast neutrons, reactor-related gamma rays, reactor thermal neutrons
  – Vast majority identified and rejected by PSD for Prompt and Delayed signals
- **Tag IBDs with high efficiency and high purity**

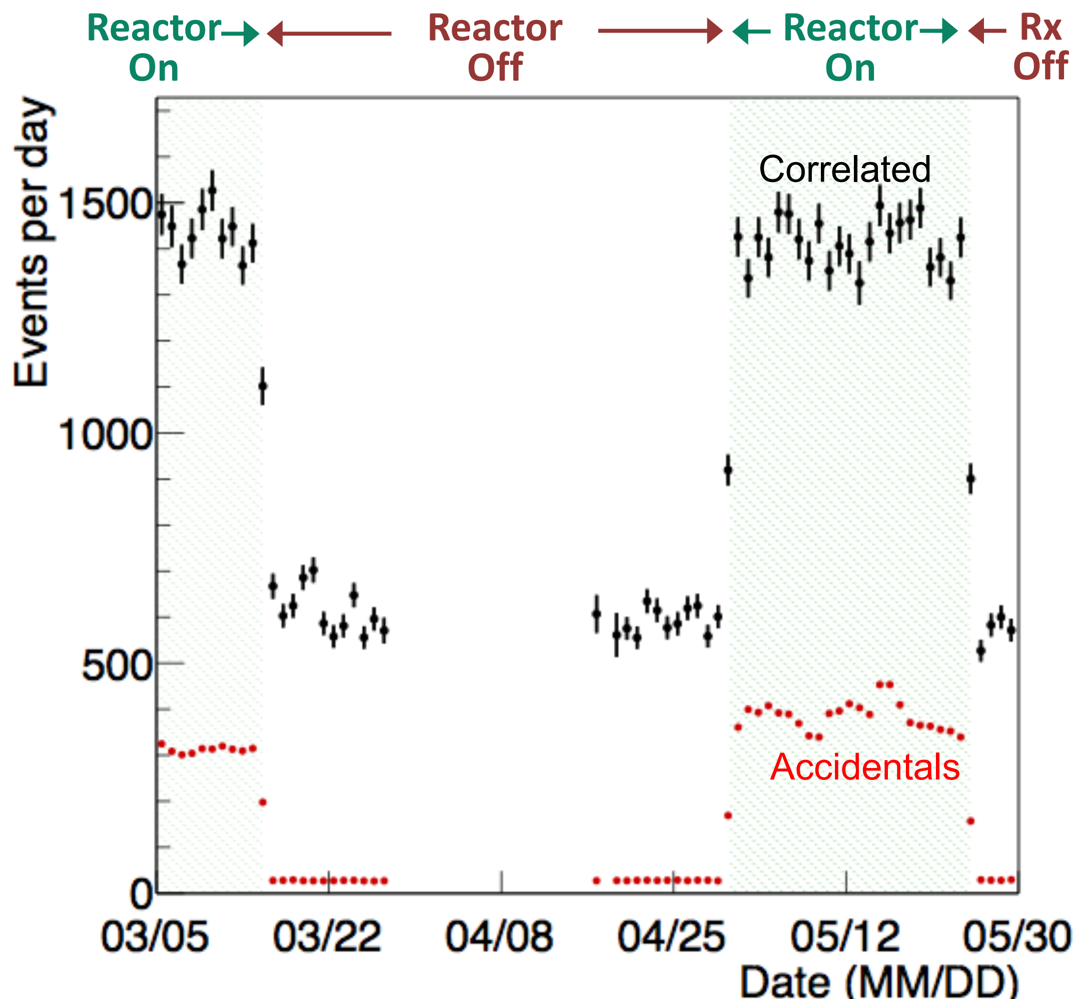
First 24hr of Detector Operation

- **March 5, 2018:** Fully assembled detector began operation
- **Reactor On:** 1254±30 correlated events between [.8, 7.2MeV]
- **Reactor Off**: 614±20 correlated events (first off day March 16)
  – Distinct peaks in background from neutron interactions with H and ^{12}C
- Time to 5σ reactor antineutrino detection at earth's surface: < 2hrs



First Analysis Data Set - arXiv:1806.02784

- 33 days of Reactor On
- 28 days of Reactor Off
- Correlated S:B = 1.36
- Accidental S:B = 2.25
- 24,608 IBD interactions
- Average of ~750 IBDs/day
- IBD event selection defined and froz
on 3 days of data



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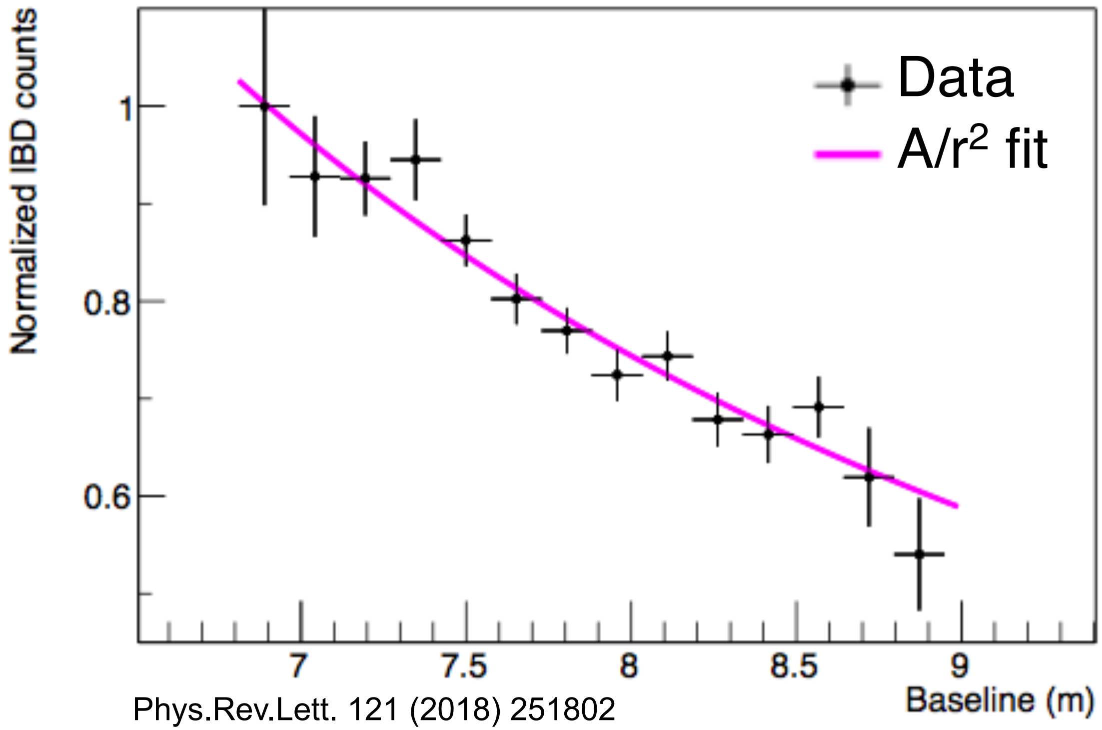
Best Signal-to-Background achieved On-Surface (< 1 mwe overburden)

IBD Rate vs Baseline



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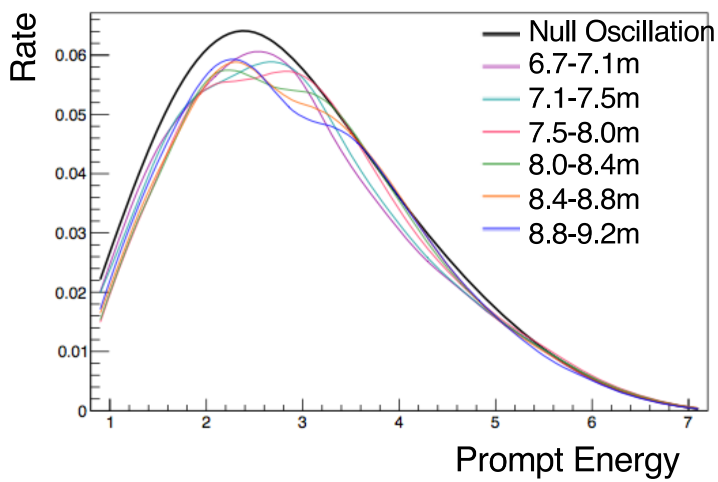
- Observation of $1/r^2$ behaviour within the detector itself
- Cover a wide relative baseline range, even in one detector position

IBD Spectrum vs Baseline

Illustration of Baseline Dependent Oscillation



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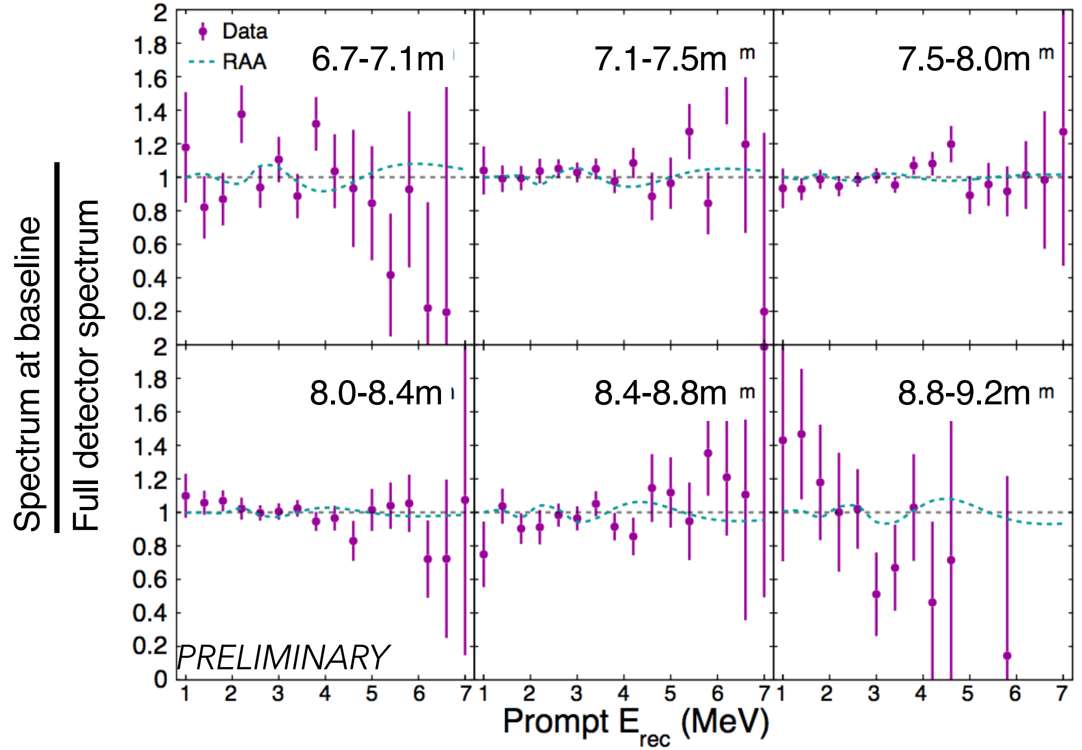

- Compare spectra from 6 baselines to measured full-detector spectrum
- Null-oscillation would yield a flat ratio for all baselines

Direct ratio search for oscillations, independent of reactor models

Oscillation Search Results

- Build a χ^2 by comparing measured spectra to predicted spectra at each baseline
- Covariance matrices capture all uncertainties and energy/baseline correlations
- Feldman-Cousins based confidence intervals for oscillation search
- Critical χ^2 map generated from toy MC using full signal and background covariance matrices
- 95% exclusion curve based on 33 days Reactor On operation

Phys.Rev.Lett. 121 (2018) 251802
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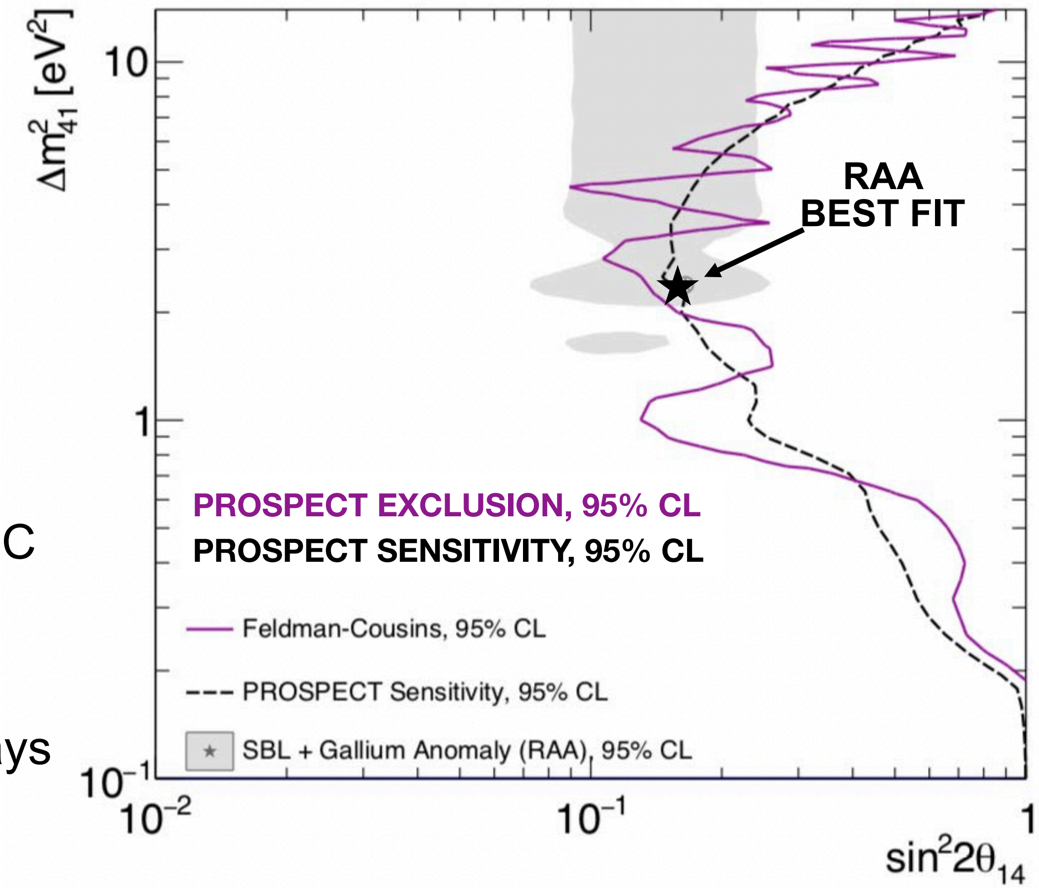


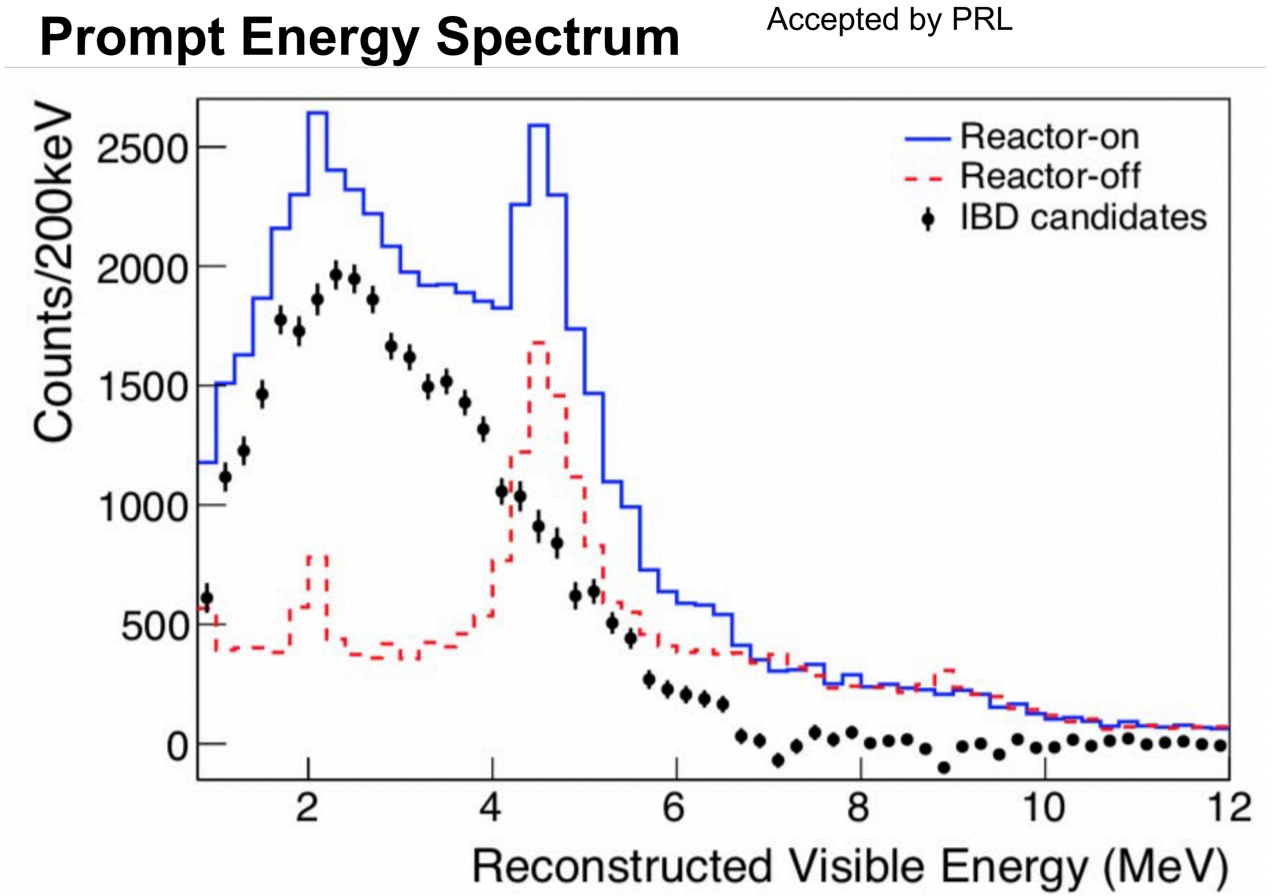
Direct test of the Reactor Antineutrino Anomaly

Disfavors RAA best-fit point at >95% (2.3σ)

Measurement of ^{235}U Spectrum

- 40.2 days of reactor-on exposure
- 37.8 days of reactor-off exposure
- ~ 31,000 IBD candidate events (reactor-off candidate events scaled to match exposure)

PROSPECT arxiv:1812.10877
Accepted by PRL



Measured spectrum with good S/B at surface 1.7/1 (0.8-7.2 MeV)

~ 6x greater statistics than ILL (1981)

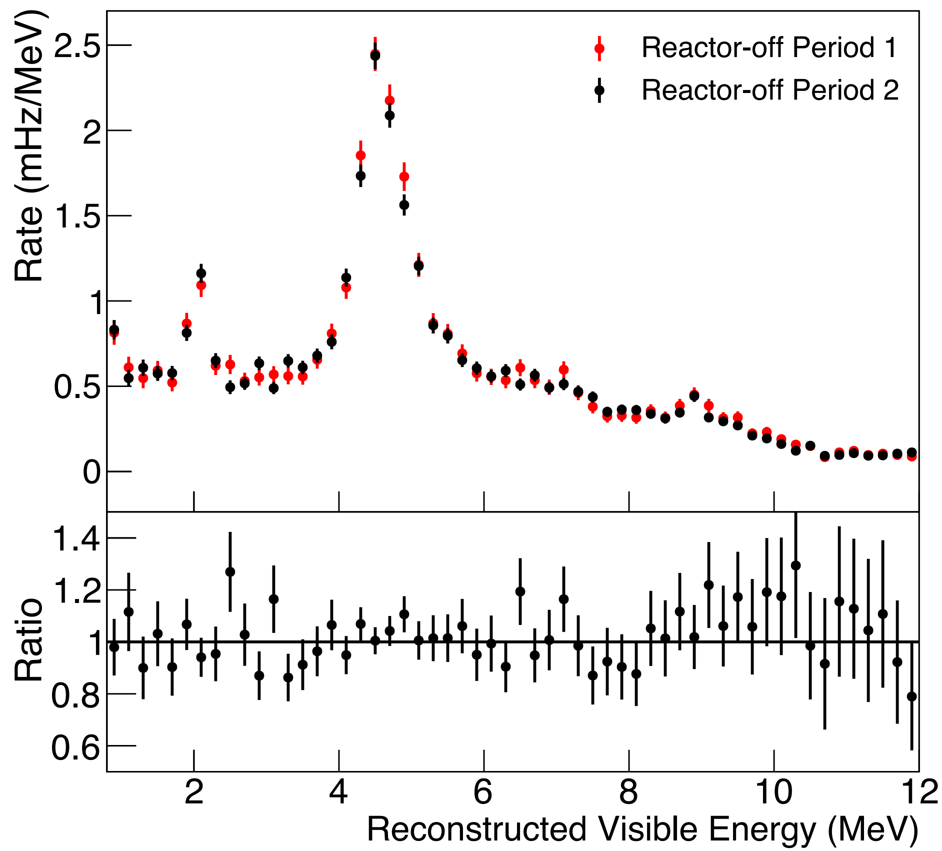
Measurement of ^{235}U Spectrum

Reconstruction & Background Subtraction Cross Checks

PROSPECT arxiv:1812.10877
Accepted by PRL

Compare:

- Different reactor on/off periods, accounting for variation of cosmogenic background
- Different detector halves & quadrants
- Inner and outer detector volumes



Consistency is found for many selection variations, testing energy reconstruction and background subtraction across segmented PROSPECT detector

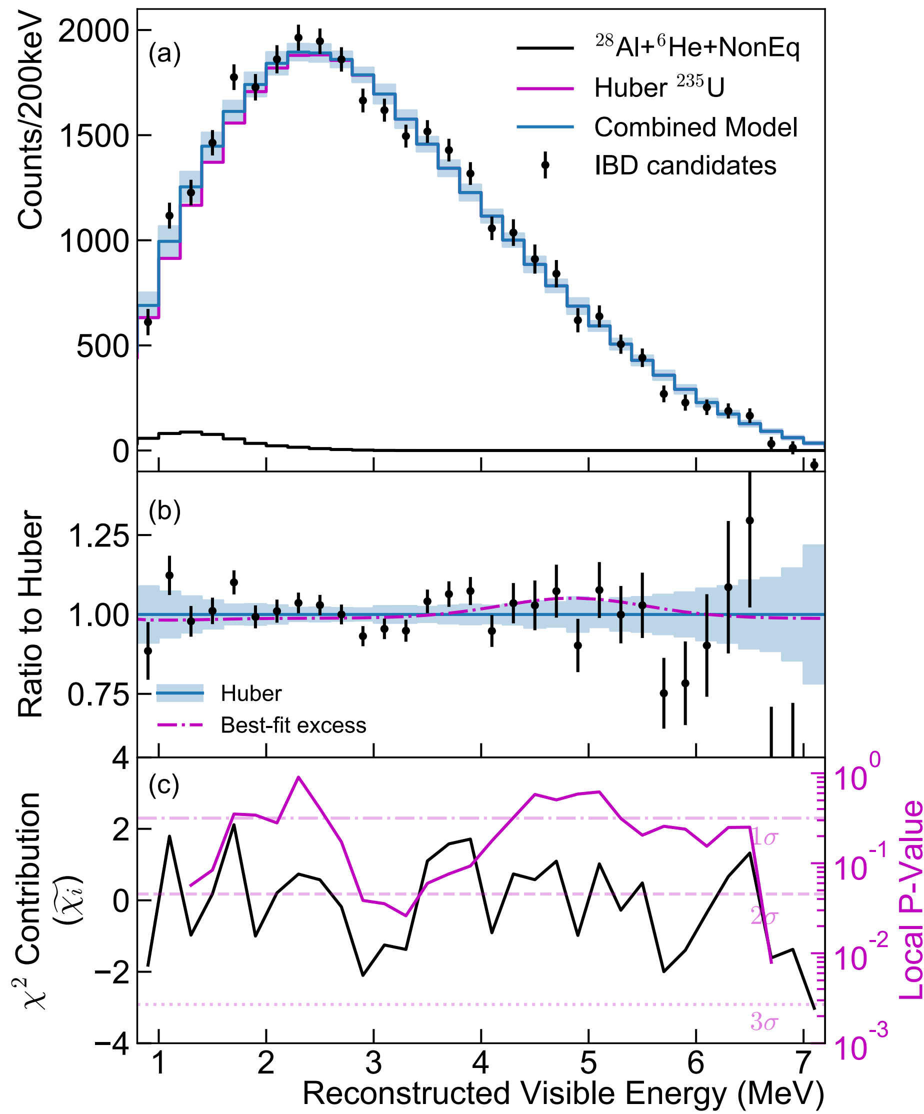
Interpretation of Prompt Energy Spectrum

Is PROSPECT consistent with Huber ^{235}U model for HFIR HEU reactor?

- χ^2/ndf = 52.1/31, p-value = 0.01
- Huber model broadly agrees with spectrum but exhibits large χ^2/ndf with respect to measured spectrum, not a good fit.
- Deviations mostly in two energy regions.

Current PROSPECT measurement is statistically limited

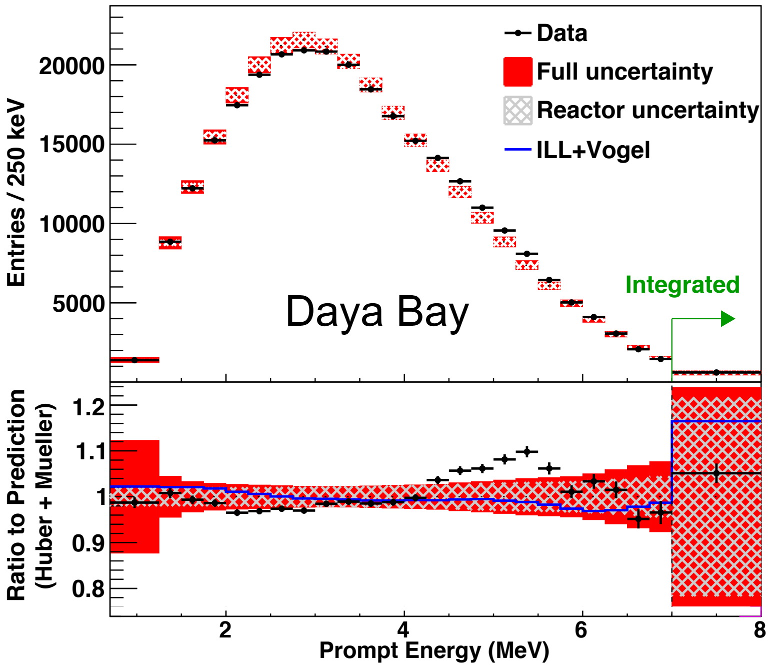
PROSPECT arxiv:1812.10877
Accepted by PRL

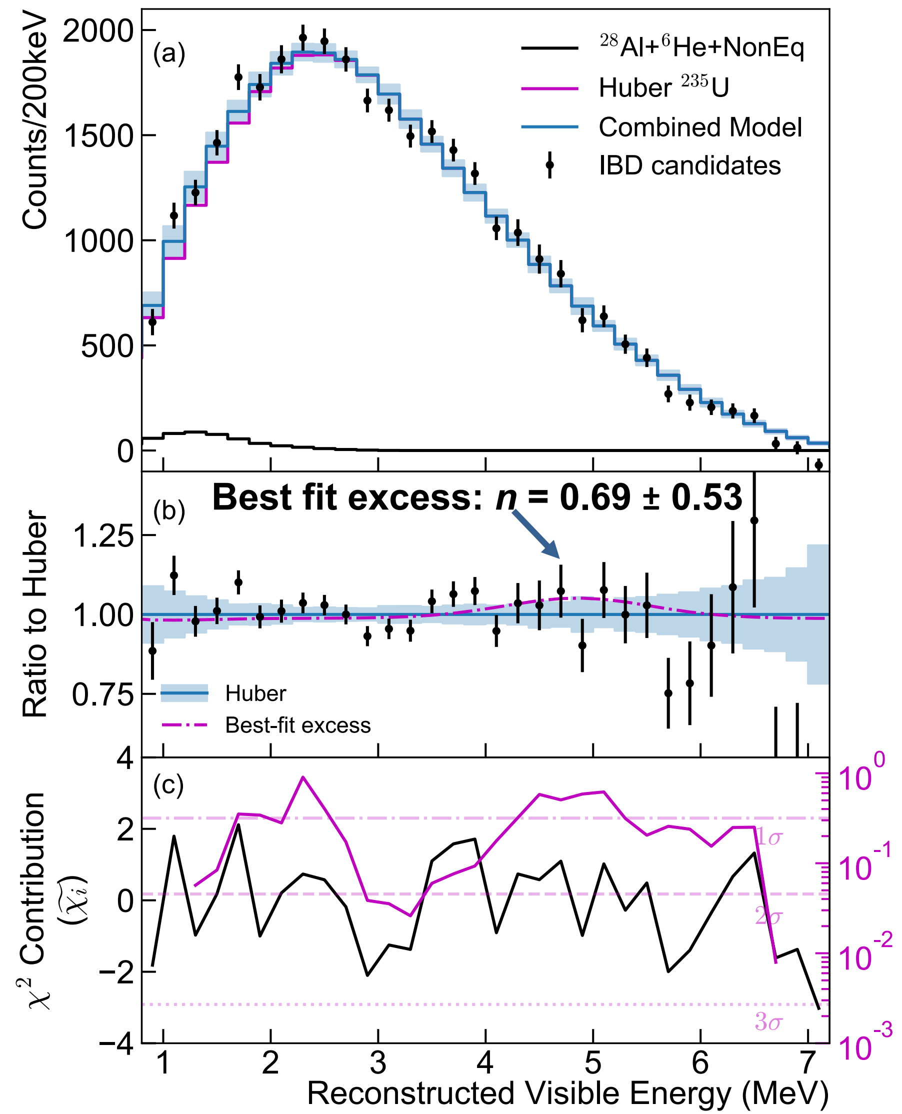


Interpretation of Prompt Energy Spectrum

PROSPECT arxiv:1812.10877
Accepted by PRL

How does PROSPECT compare to 'bump' in θ_{13} experiments?





Shape of measured ^{235}U spectrum is consistent with deviation relative to prediction observed at LEU reactors

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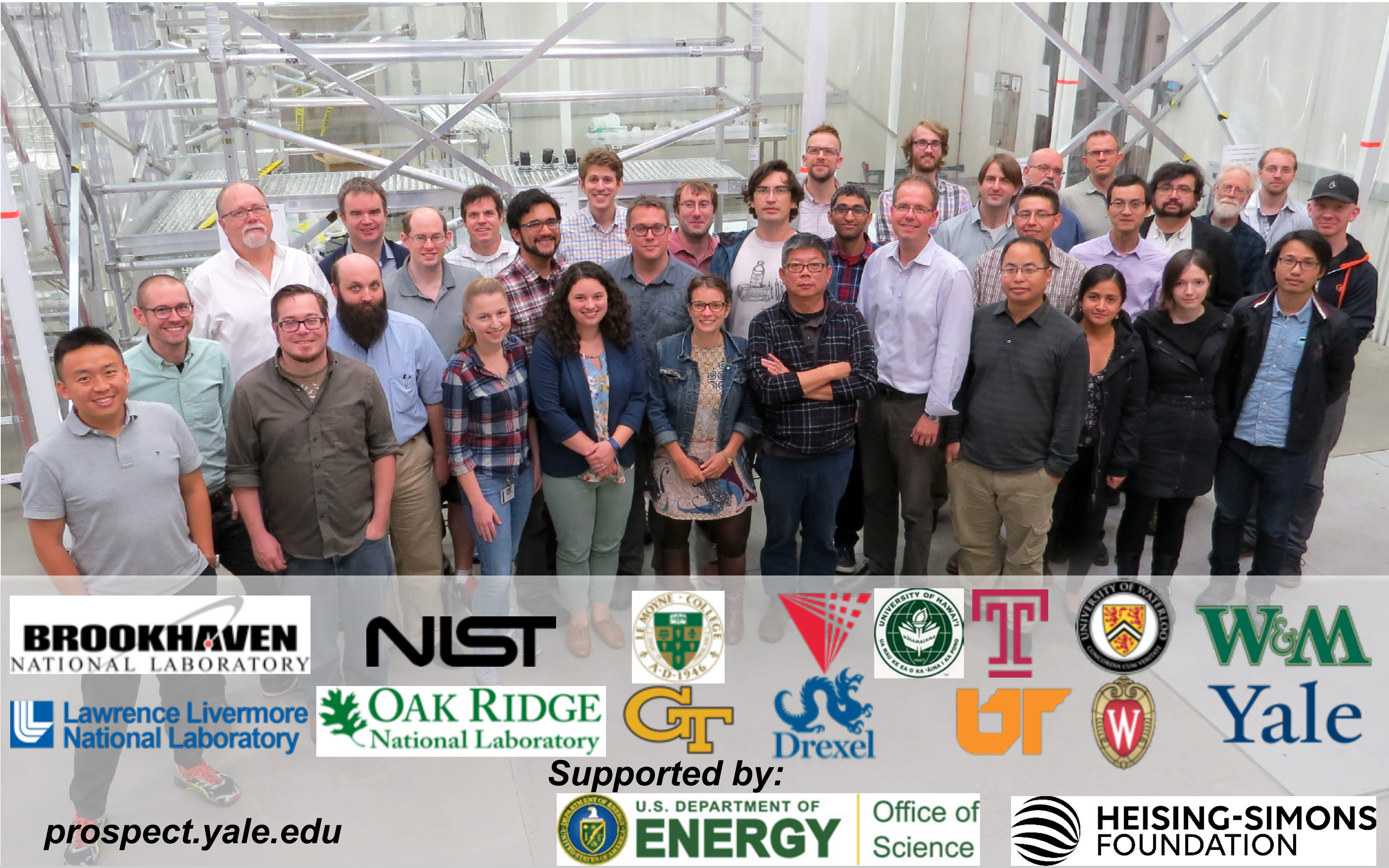

Supported by:

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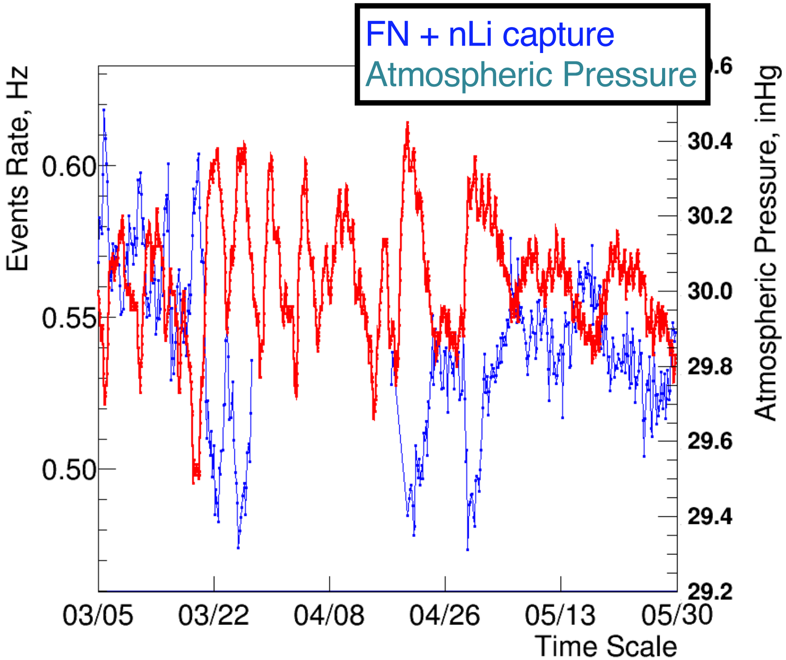
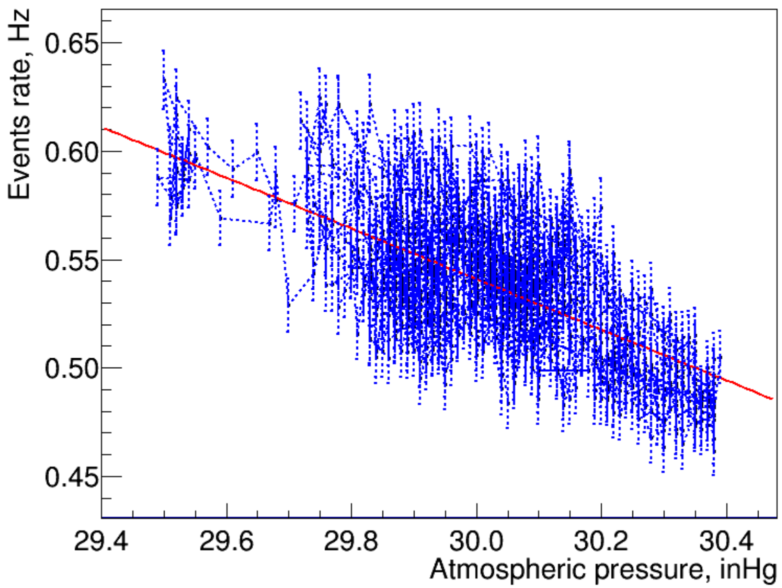
prospect.yale.edu

Conclusion

- PROSPECT started data collection in early March 2018
- Observed antineutrinos from HFIR on the surface with good signal/background
- Background rejection and energy resolution meet expectations based on comprehensive PROSPECT R&D program
- The PROSPECT Detector provides:
  - opportunity for detailed study of cosmogenic backgrounds
  - important capability demonstration for reactor safeguards applications
- First oscillation analysis using 33 days of reactor-on data disfavors the RAA best-fit at 2.3σ
- Performed a modern high-statistics ^{235}U spectrum measurement using a surface-based detector; currently statistics limited
- More data has been collected and analysis is ongoing

Time dependence of Cosmogenic backgrounds





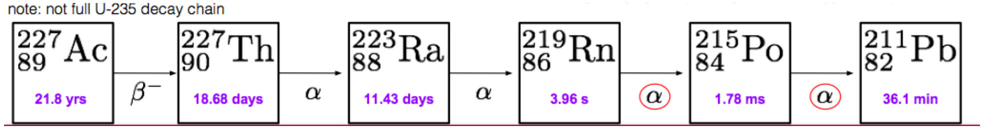
- Correlation between cosmogenic backgrounds and atmospheric pressure

- Measure correlation during reactor off time, and use it to correct background subtraction during reactor on

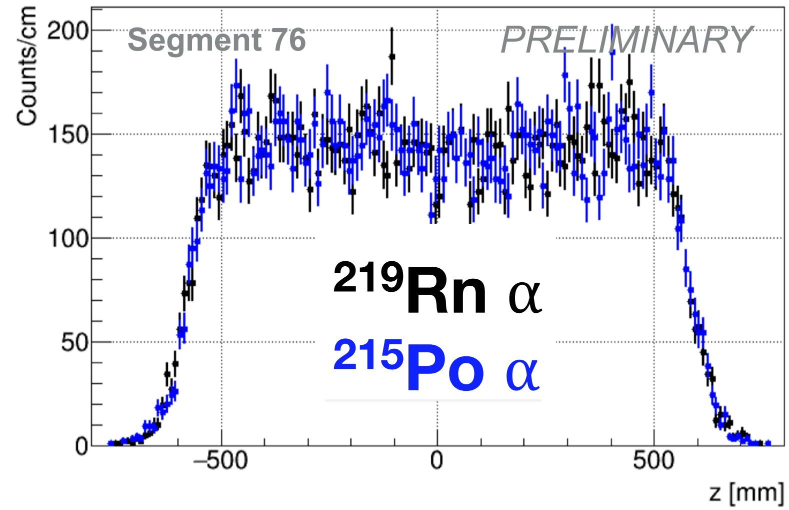
Relative Segment Volume Measurement

- Relative mass important for oscillation search
- Survey during assembly: < 1% variation

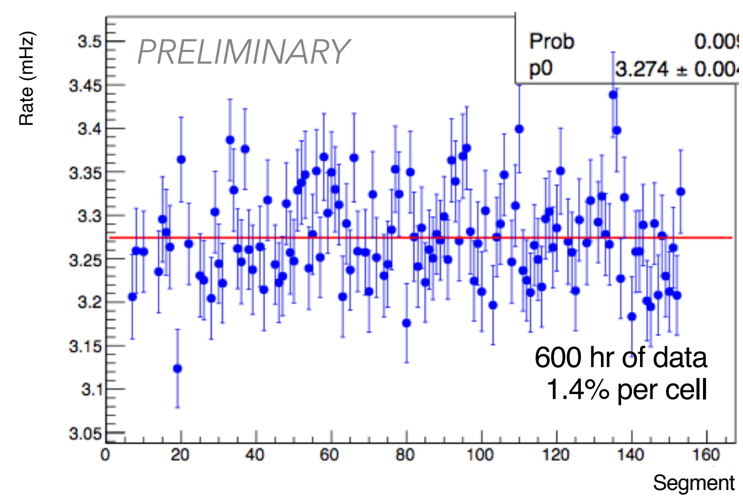
note: not full U-235 decay chain



- ^{227}Ac added to LS prior to filling
- Double alpha decay (^{219}Rn→^{215}Po→^{211}Pb), highly localized, 1.78ms half-life, efficient selection straightforward,
- Measured absolute z-position resolution of < 5cm
- Direct measurement of relative target mass in each segment



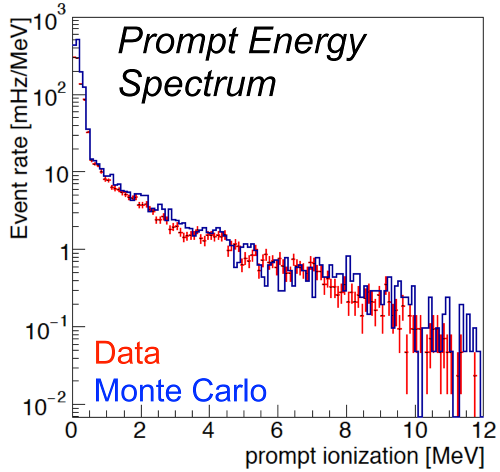
Uniformity in rates within segment

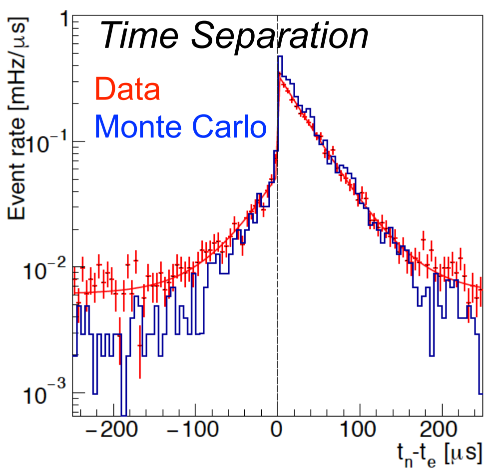


Uniformity in rates between segments

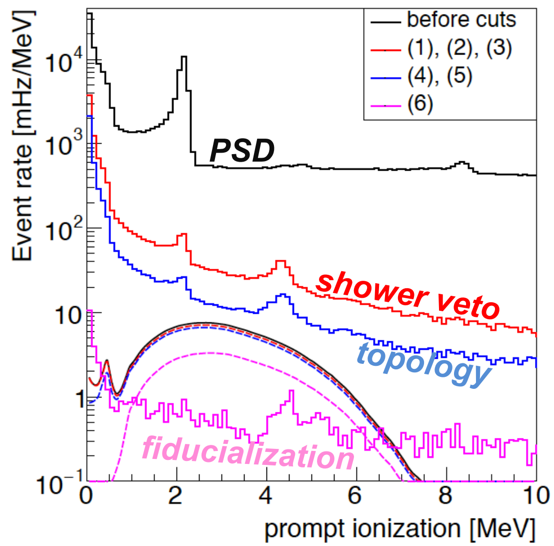
Signal to Background Prediction

Prototype systems provide benchmarking of AD Monte Carlo



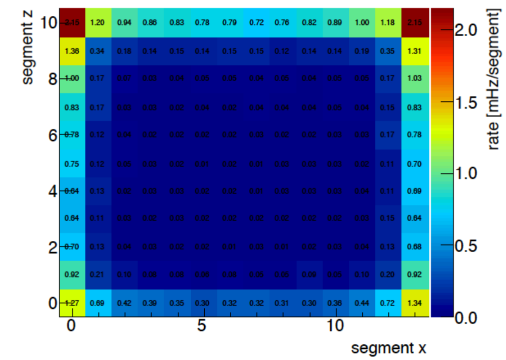


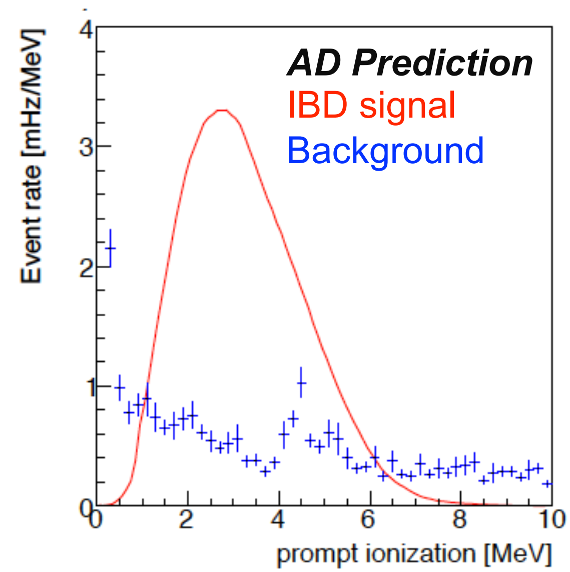
PROSPECT20 Correlated Background Measurements



Background rejection via:

- Efficient PSD & neutron identification
- Multi-interaction & multi-particle identification
- Fiducialization





S/B better than 1:1 is predicted for PROSPECT AD. Rate and shape of residual IBD-like background can be measured during numerous reactor off periods.