PROSPECT: a Precision Oscillation and Spectrum Experiment

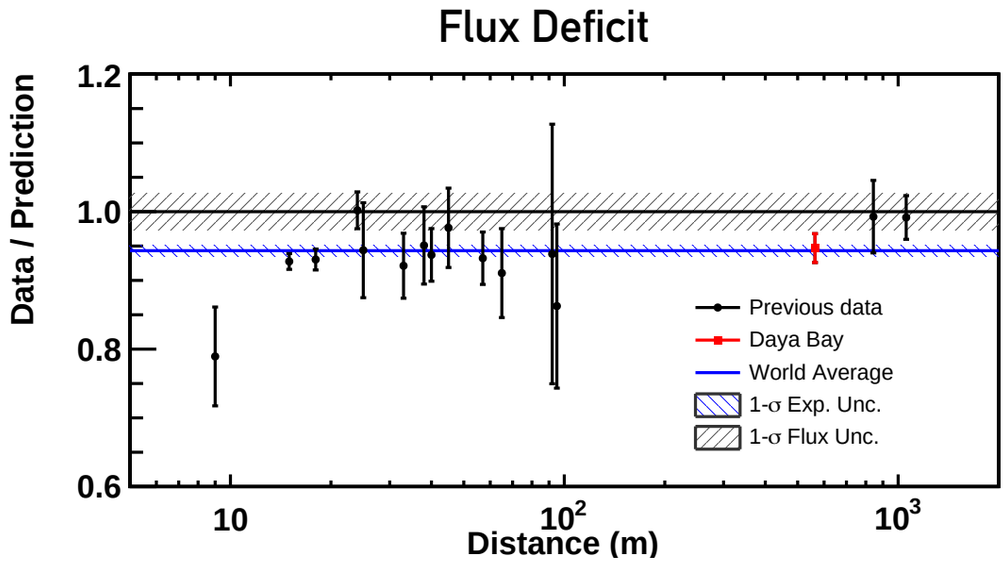
Pieter Mumm
National Institute of Standards and Technology

For the PROSPECT Collaboration

PROSPECT: Motivation

Spectral Shape as a Function of Energy and Baseline

Possibility of sterile neutrino oscillation as an explanation of observed electron antineutrino deficits

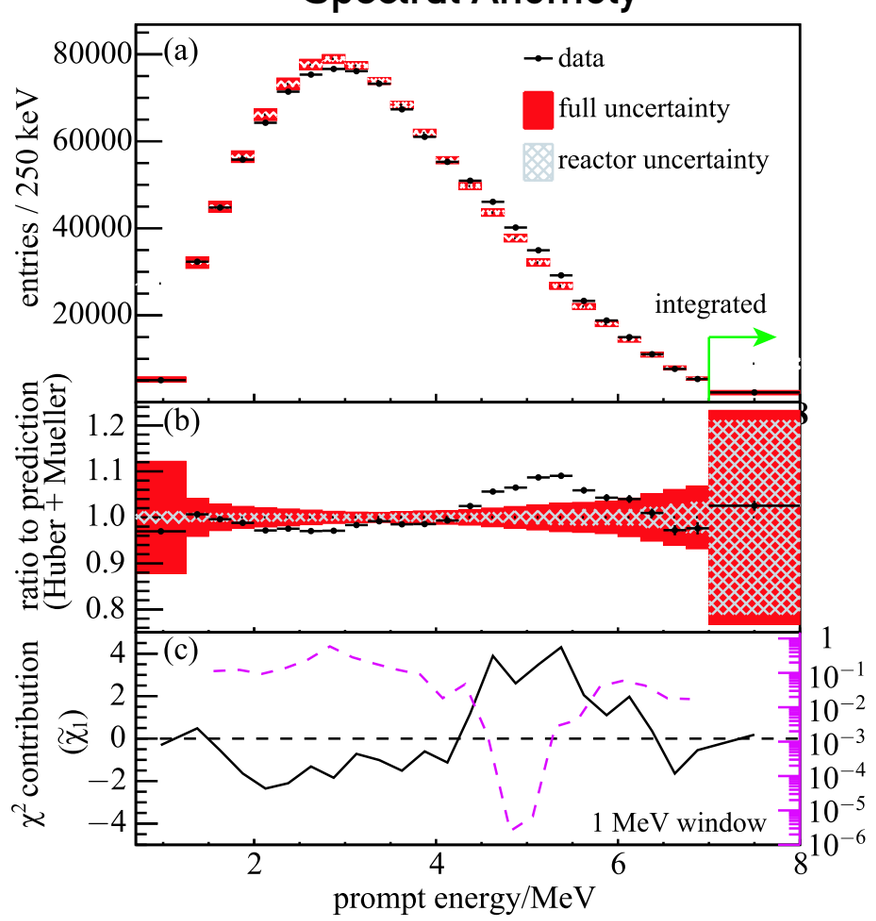


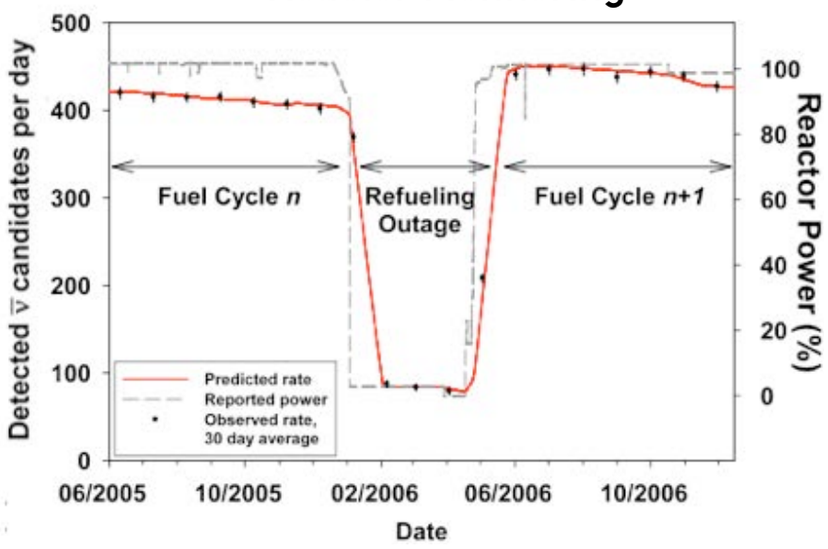
Precision Measurement of Reactor Spectrum

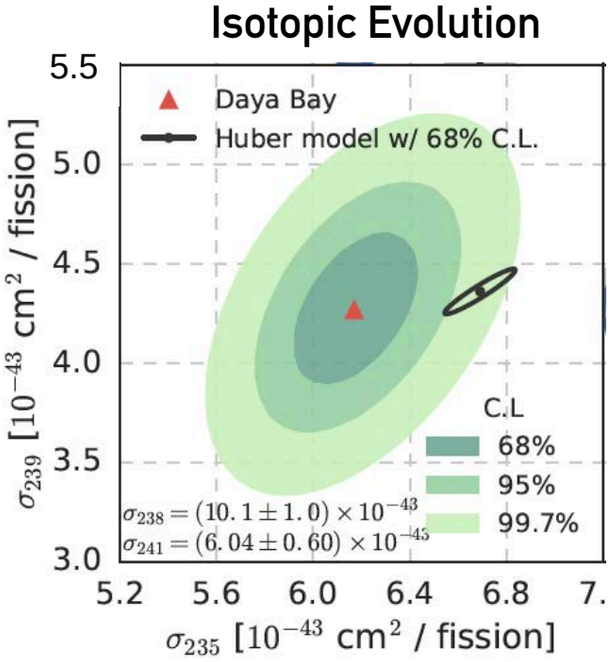
Anomalies in spectral shape at ~ 5-6 MeV
Provide complementary measurement of ^{235}U (fuel evolution)

Safeguards - a Passive Standoff Capability

Provides a remote, non-intrusive reactor power and Pu production monitoring

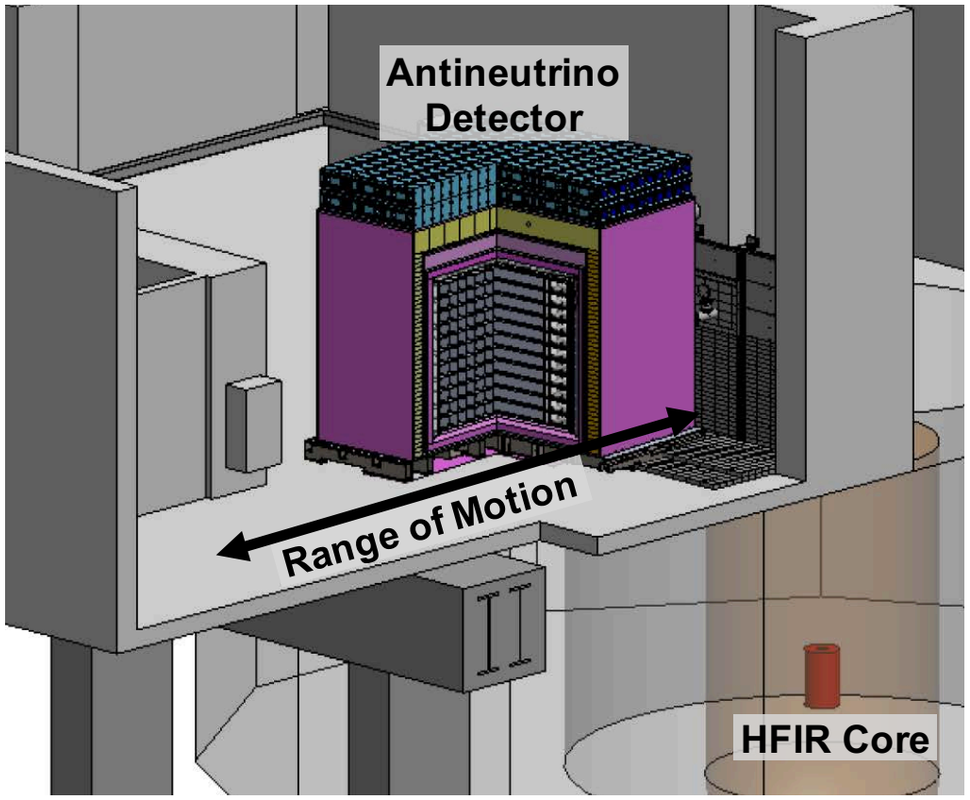


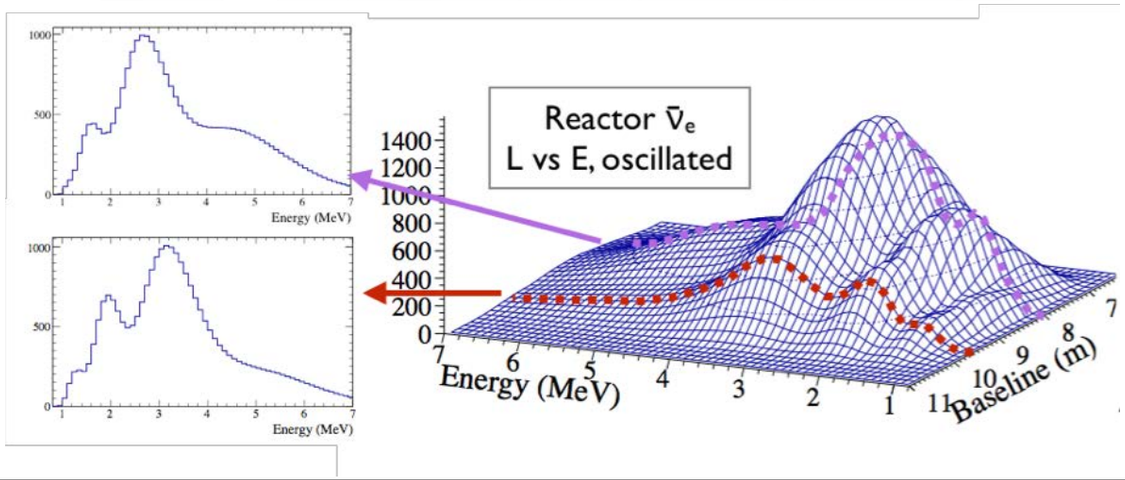




Experimental Strategy

1. Search for short-baseline sterile-neutrino oscillations independent of reactor models
2. Measure antineutrino spectrum due to ^{235}U
3. Demonstrate near-field surface operation



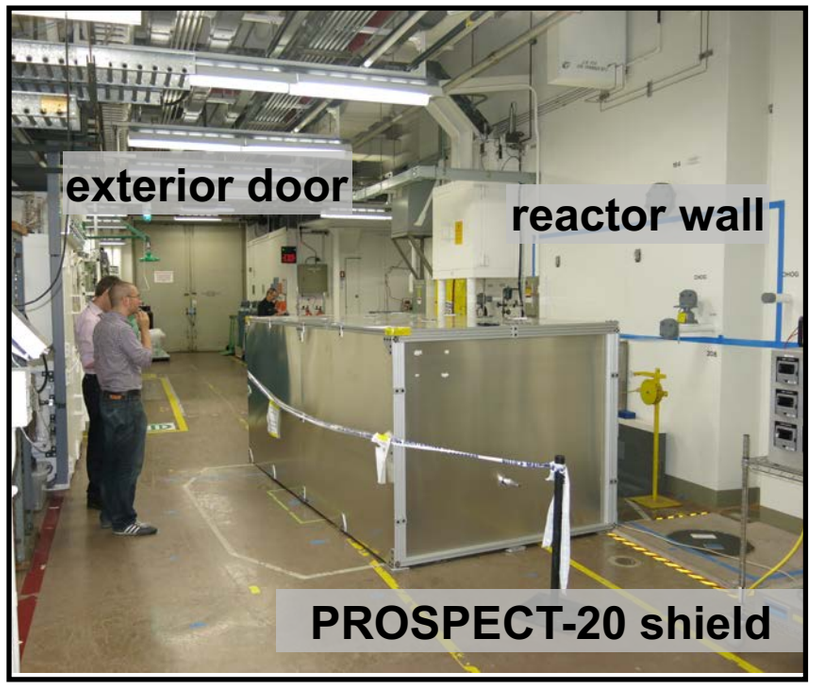


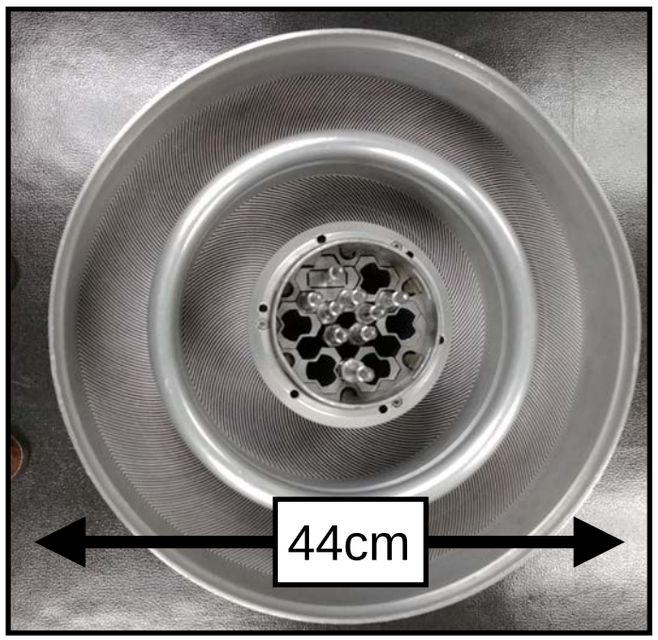
Experimental Strategy:

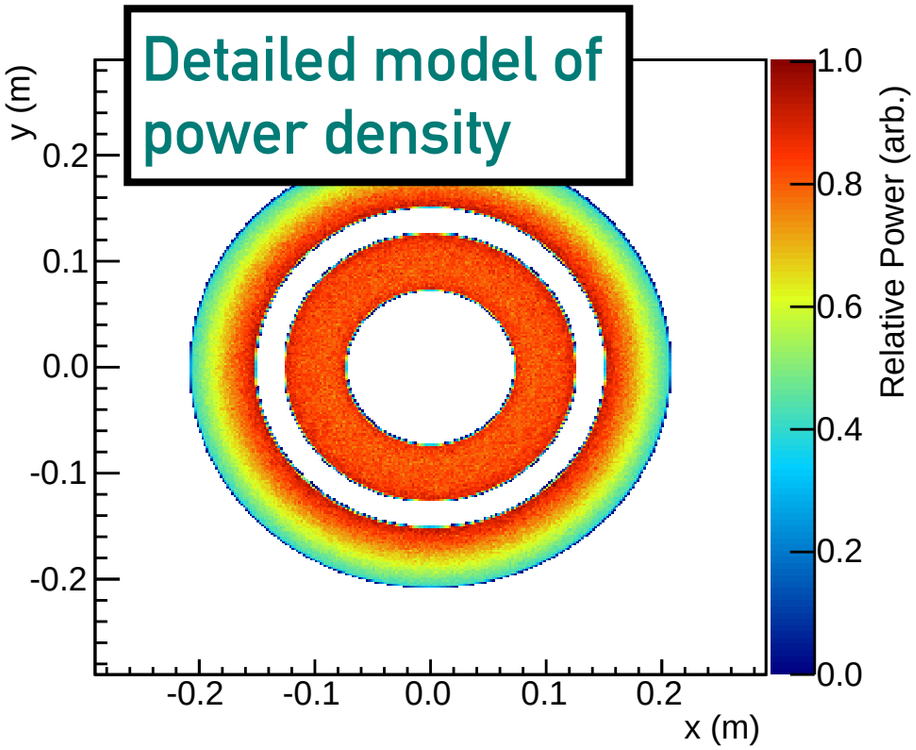
- Compact HEU research reactor
- ^{6}Li-doped liquid scintillator provides unique compact tag and light yield
- Segmented detector localizes events and supports background rejection
- Measure high-resolution spectrum at a range of baselines (7-9m in current position)
- Search for characteristic relative spectral distortions within detector volume

High Flux Isotope Reactor (HFIR) and ORNL

- 85MW highly enriched uranium reactor
  - >99% ^{235}U fissions, effectively no isotopic evolution
- Compact core (44cm diameter, 51cm tall)
- Short baselines of order meters
- 24 day cycles, 46% reactor up time
  - Allows equal stats for detailed study of cosmogenic backgrounds
- User facility 24/7 access

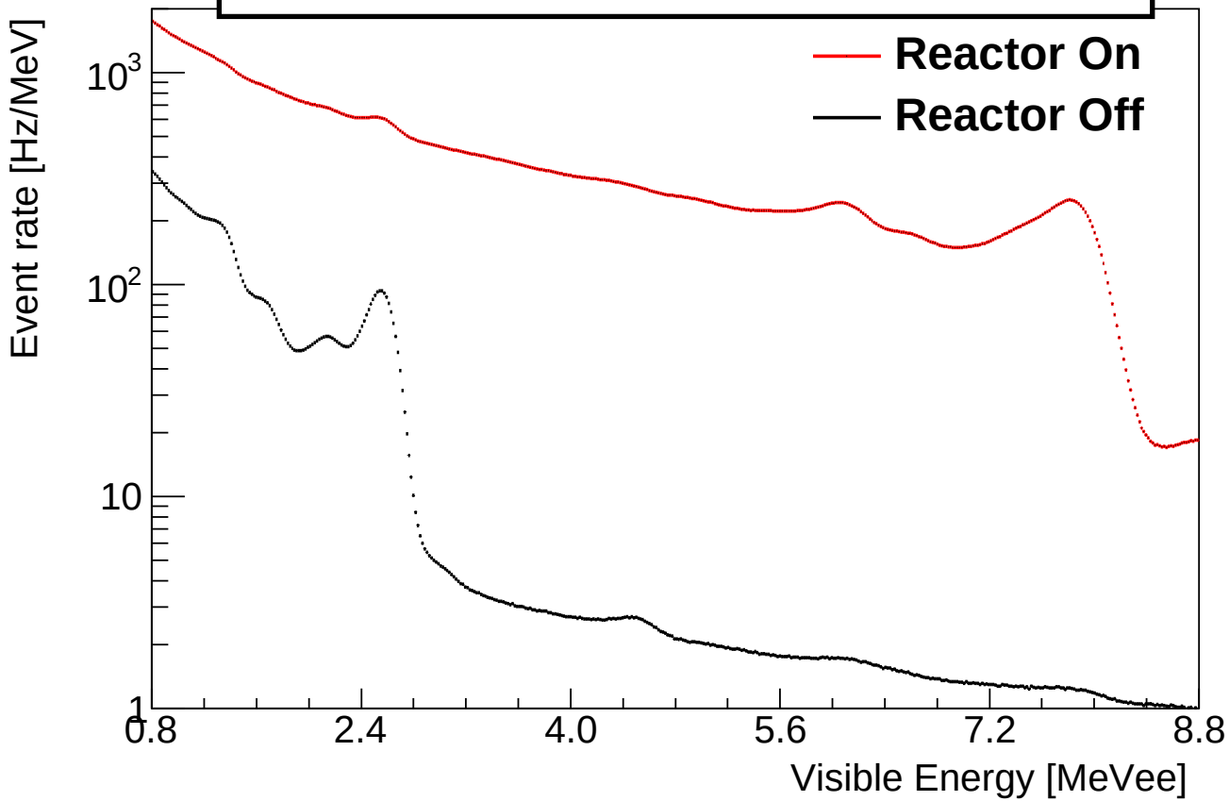




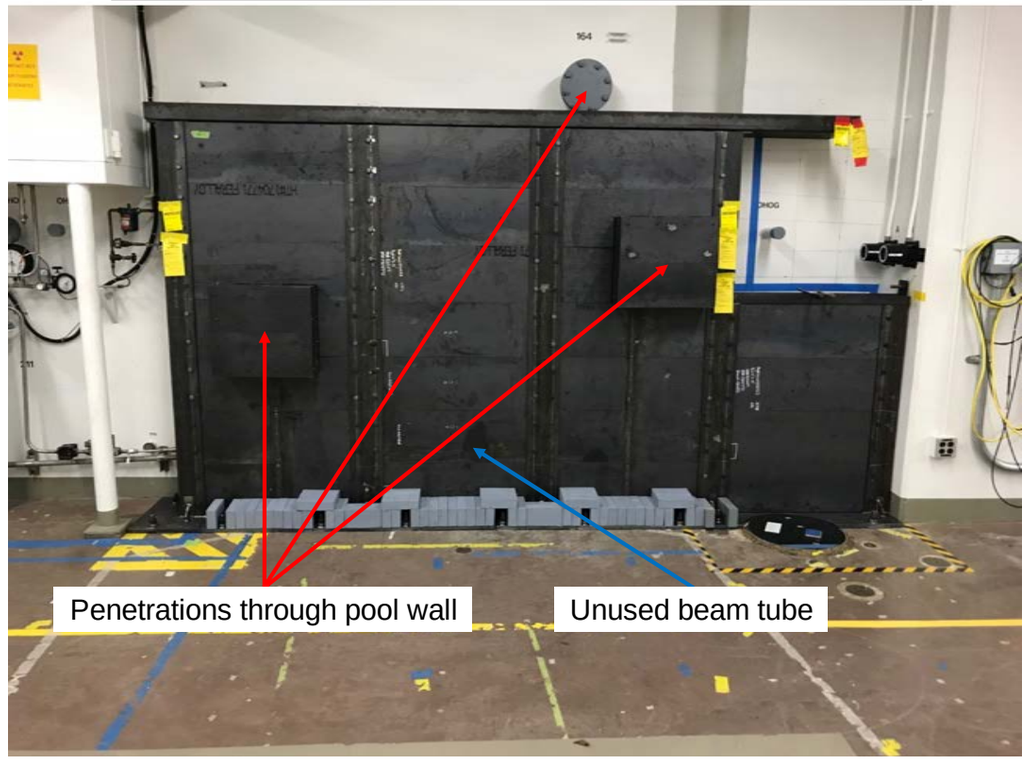


Ambient Backgrounds

Electron-like event rate in detector



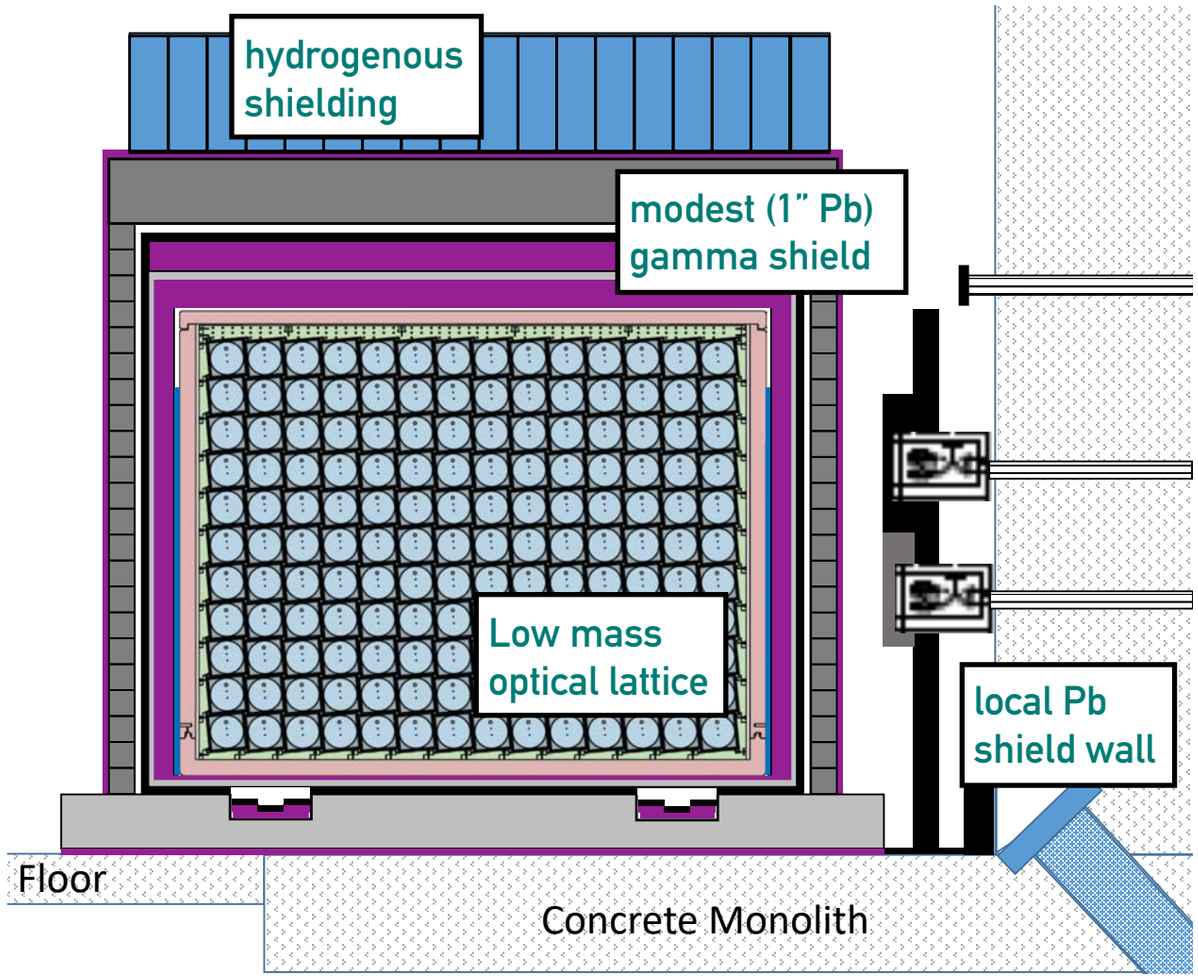
Local shield against pool wall

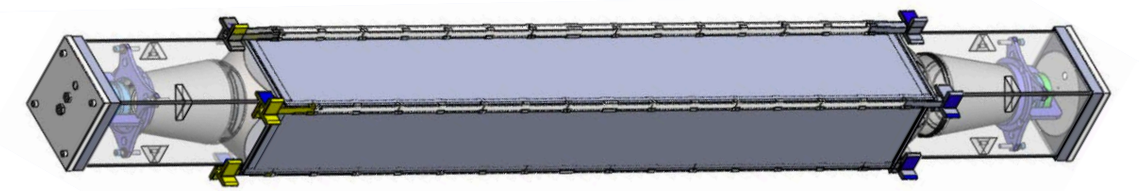


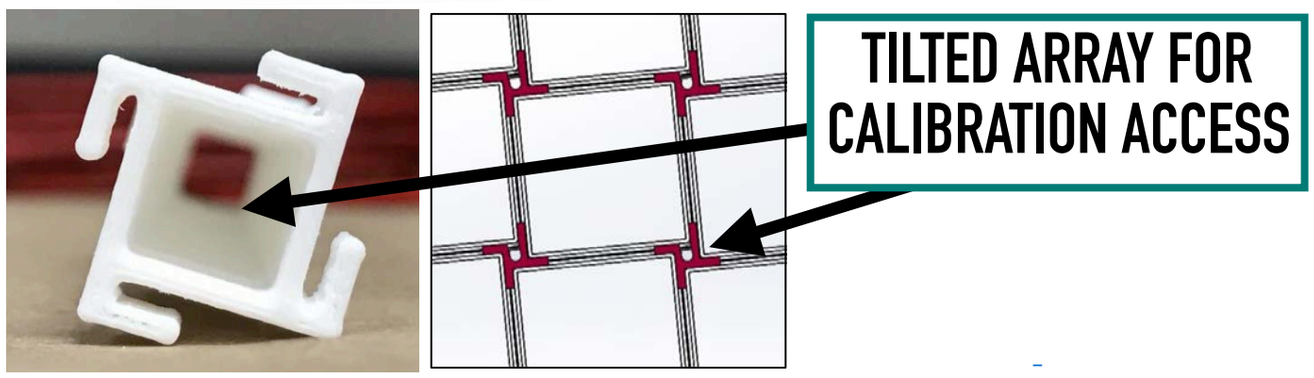
- Shortest baselines at HFIR imply in-building operation
  - high time-dependent gamma rates (in some locations approaching 5 mrem/hr)
  - time and spatially varying thermal neutron fields
  - only facility overburden concrete roof (<1 mwe), atmospheric neutron interactions highly significant
- Design for background rejection

Design Overview

- Single 4,000 L ^{6}Li-loaded liquid scintillator (3,000 L fiducial volume)
- 11 x 14 (154) array of optically separated segments
- Very low mass separators (1.5 mm thick)
  - Corner support rods allow for full in situ calibration access
- Double ended PMT readout, with light concentrators
  - good light collection and energy response ~4.5-5%$\sqrt{E}$ energy resolution
  - full X,Y,Z event reconstruction
- Optimized shielding to reduce cosmogenic and local backgrounds

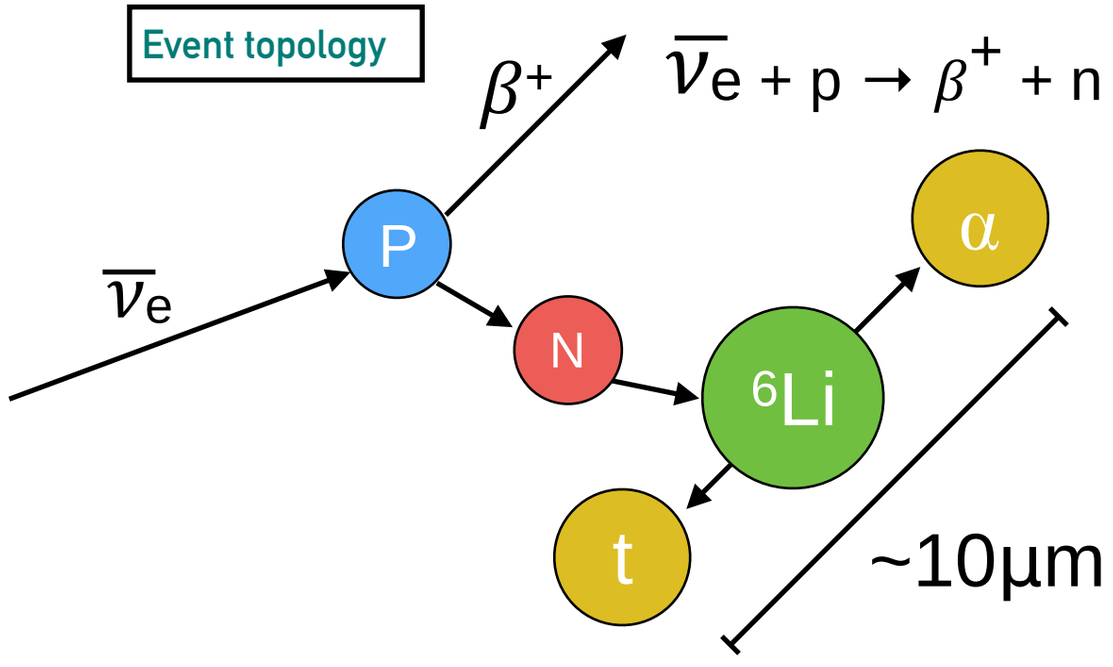




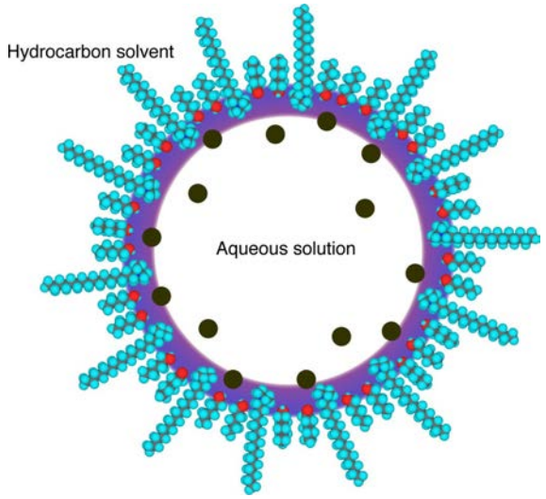


6Li Loaded Liquid Scintillator

- Compact, segmented detector needs a capture signal that is highly localized
  - Minimize position dependent efficiency variation
  - Distance between prompt/delay to reject accidental backgrounds

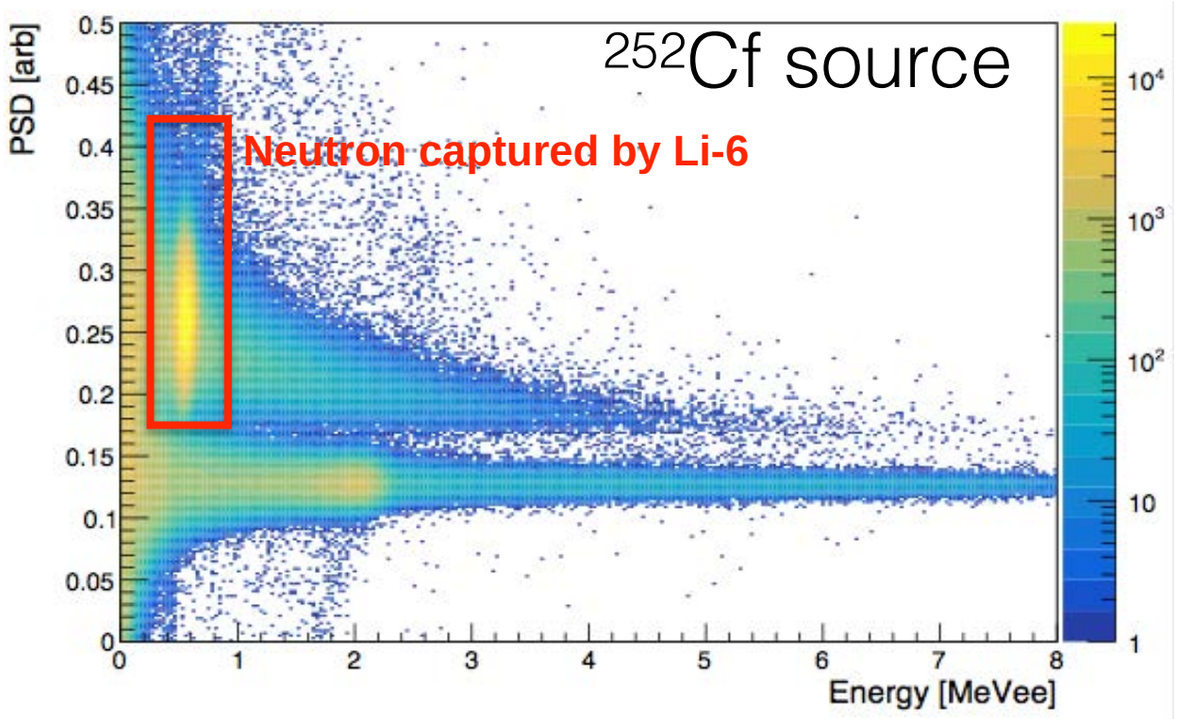


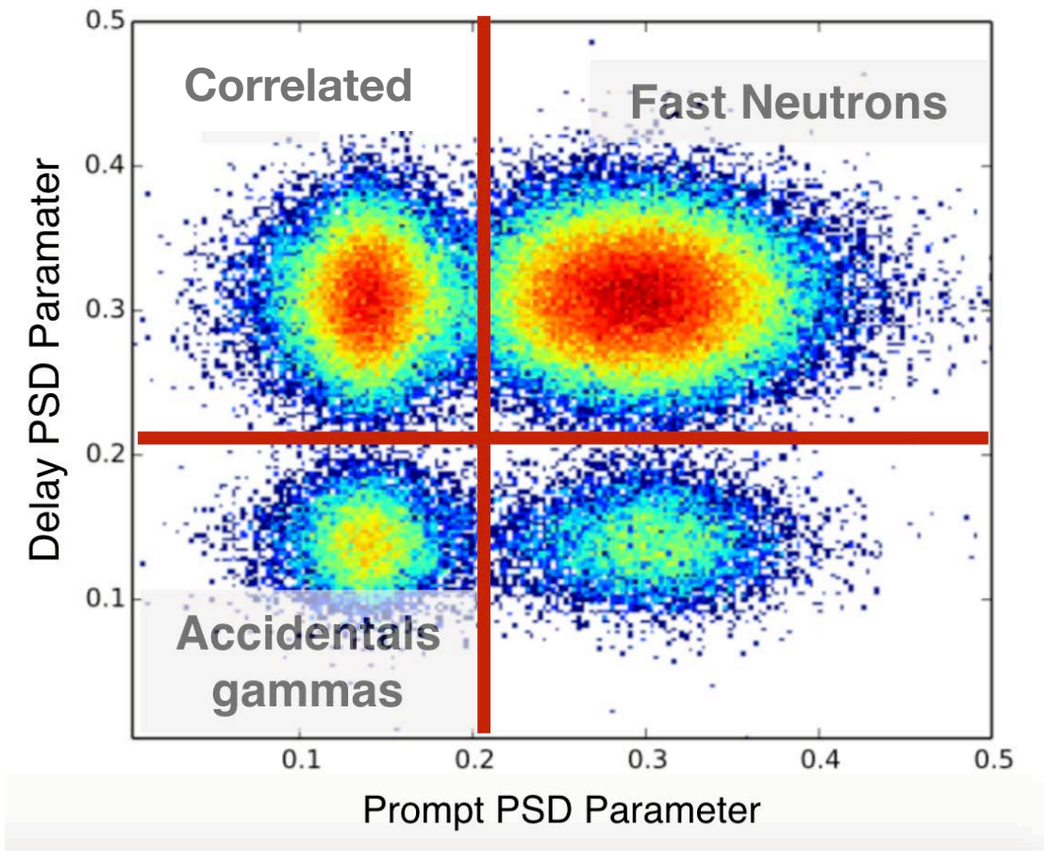
- R&D program led to 0.07% ^{6}LiLS loaded liquid scintillator based on EJ-309, meets all requirements.
  - capture time long compared to scattering physics, short compared to accidental rate.
  - High light yield (8200ph/MeV) for energy resolution
  - Particle ID through pulse-shape discrimination (PSD)
  - Long term stability, material compatibility, nonflammable



^{6}Li loading via Reverse micelles:
- Surfactants added to base liquid scintillator
- Dynamically stable
- relatively high loading possible > 0.1%
- minimal reduction in light yield
- minimal reduction of PSD performance

Unique IBD Signature





- Coincidence + PSD to reject backgrounds

Event Coincidence Signature:
e-like prompt signal, followed by a ~40-50μs delayed neutron capture

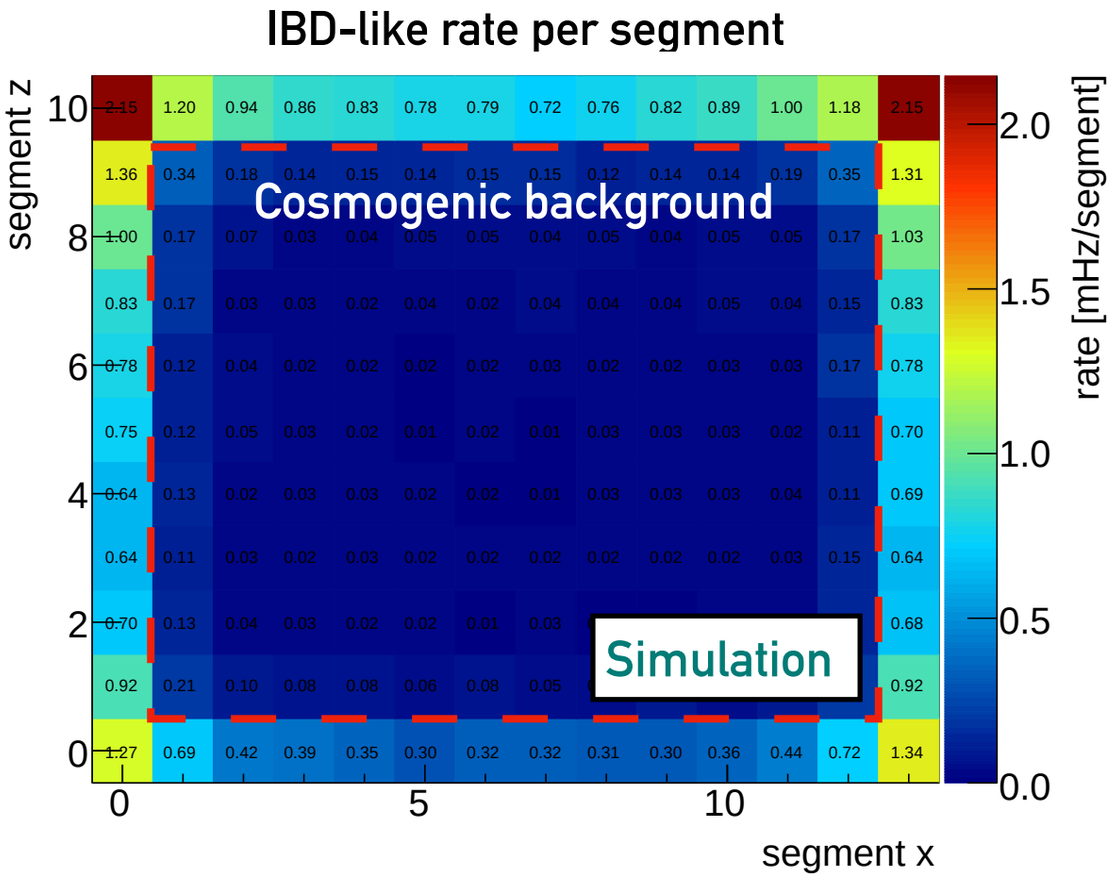
Pulse-shape Discrimination (PSD) Signatures

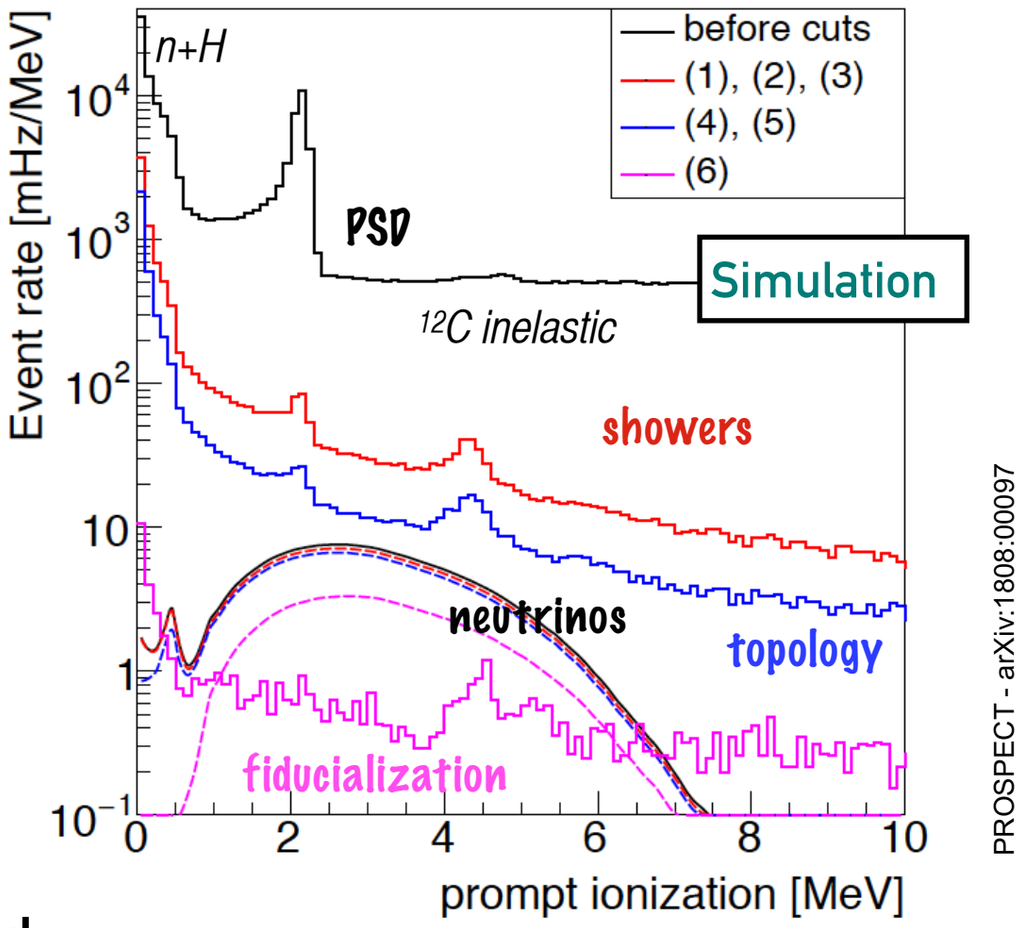
Inverse Beta Decay
γ-like prompt, n-like delay

Fast Neutron
~~n-like prompt, n-like delay~~

Accidental Gammas
~~γ-like prompt, γ-like delay~~

Background Rejection



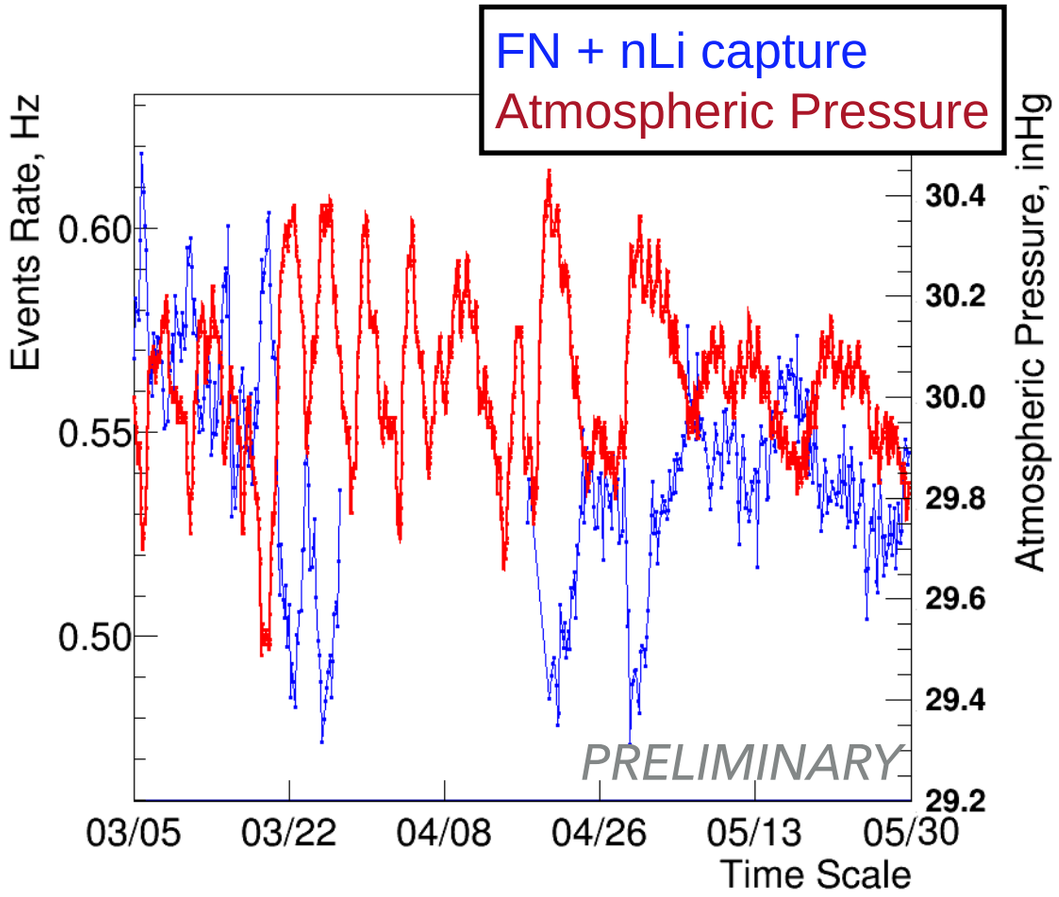


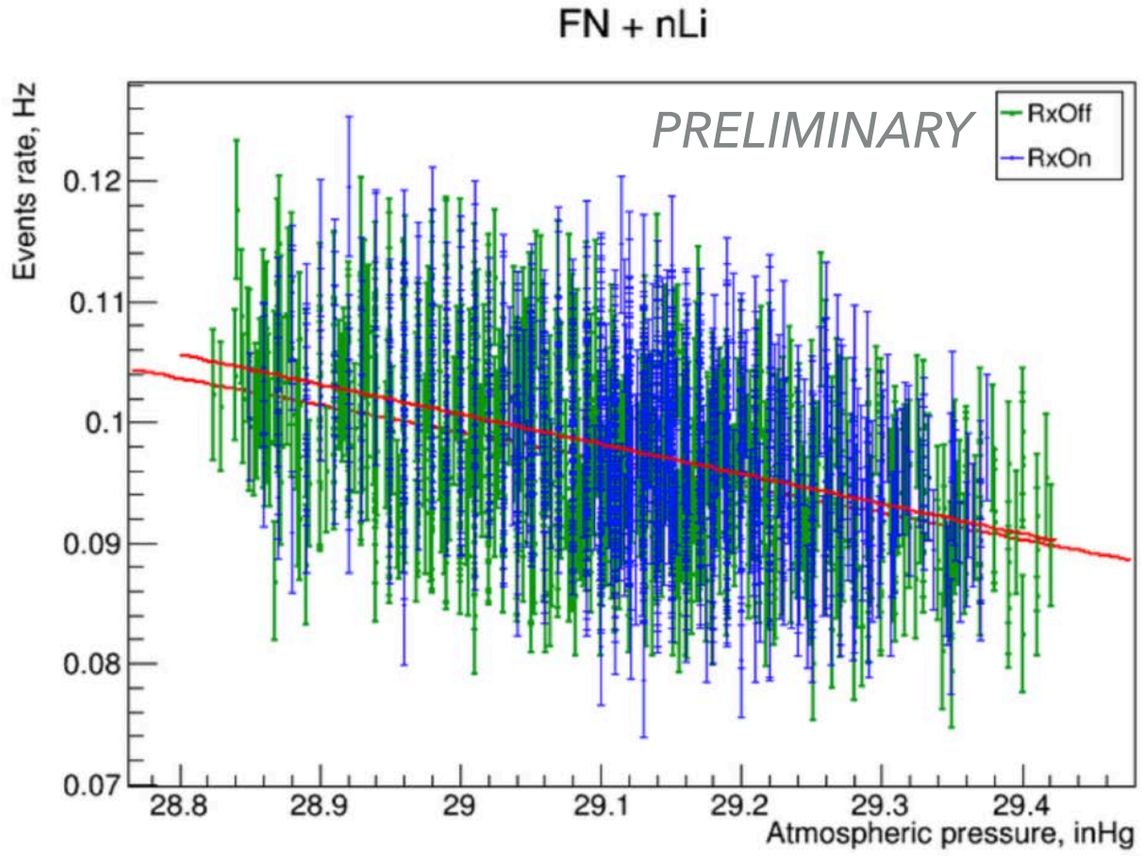
- Detector design further optimized for background rejection
- A sequence of cuts leveraging spatial and timing characteristics of an IBD yields > 10^4 background suppression and signal to background of > 1:1.
- Rate and shape of residual IBD-like background can be measured during multiple interlaced reactor-off periods.

Combine:
- PSD
- Shower veto
- Event topology
- Fiducialization

See M. Mendenhall's talk later this workshop

Time Dependent Cosmogenics





- Correlation between cosmogenic backgrounds and atmospheric pressure:
  - Fast Neutron
  - Fast Neutron + nLi,
  - Inelastic recoil + nLi,
  - Correlated captures
  - IBD-like (passes all cuts)
- Measure correlation during reactor off time, use it to correct average background subtraction during reactor on (typical scaling < 0.5%)
- Opportunity to study surface background in detail

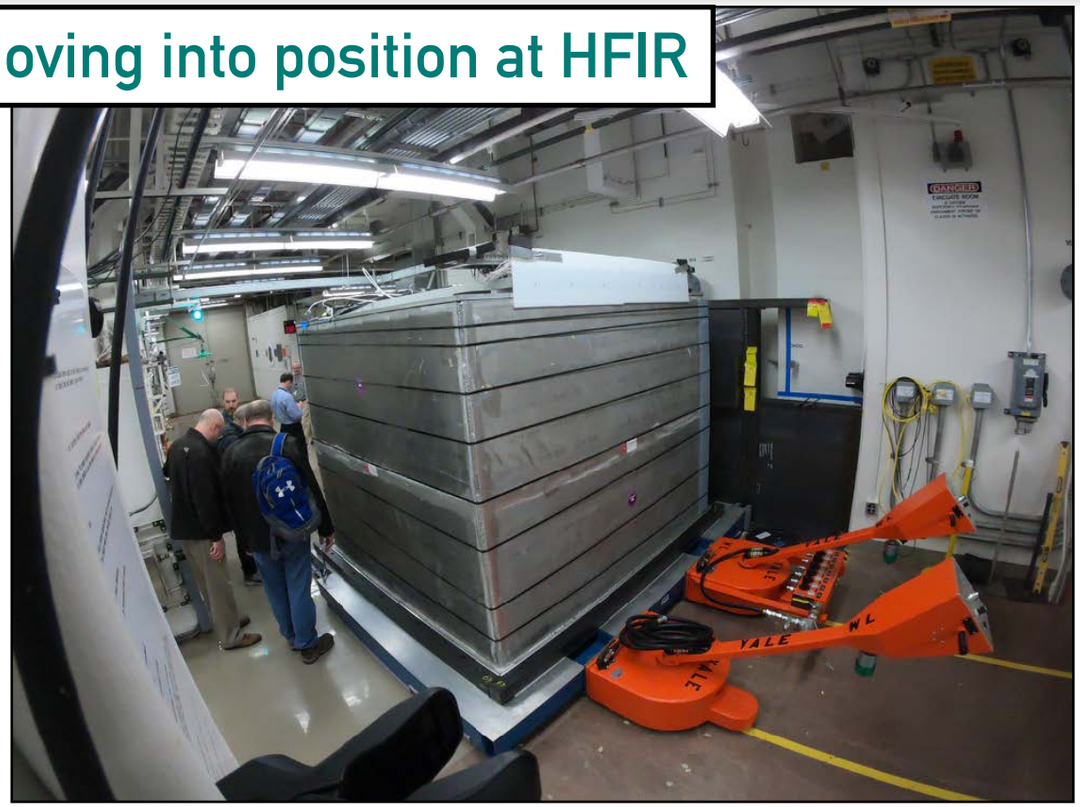
PROSPECT: a Precision Oscillation and Spectrum Experiment


November 17th, 2017

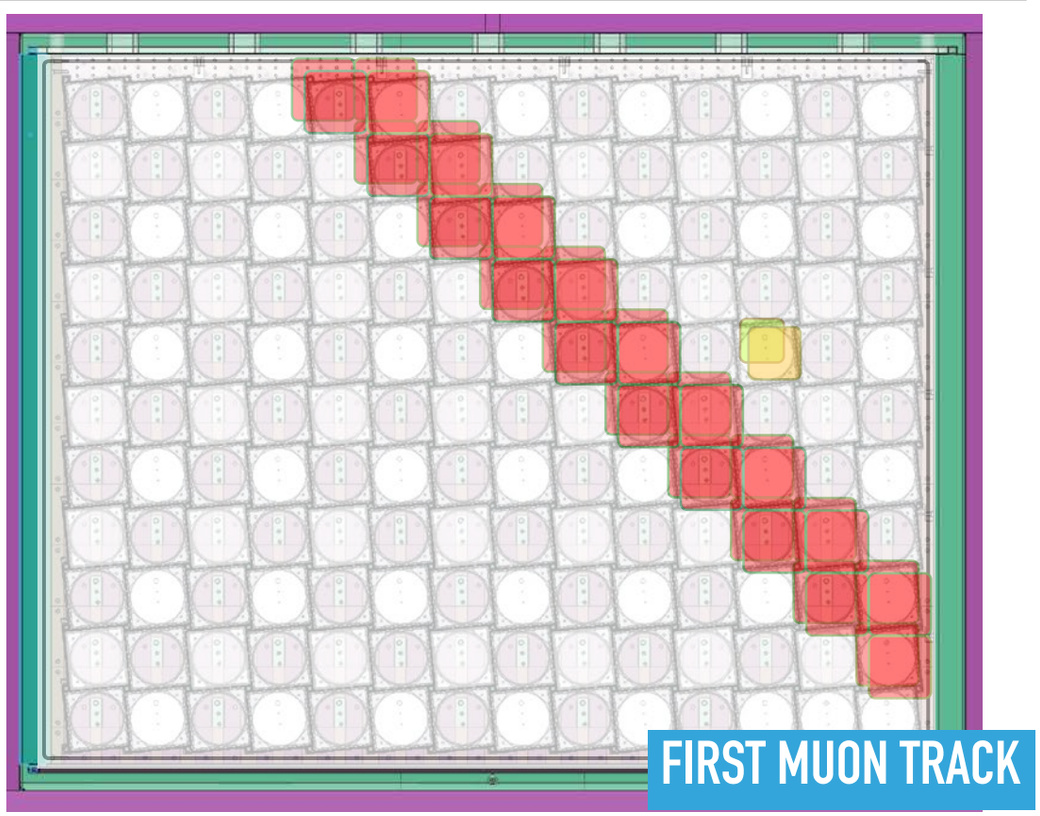
December 2017 – January 2018, Dry commissioning at Yale

February 2018, arrival at ORNL

Moving into position at HFIR

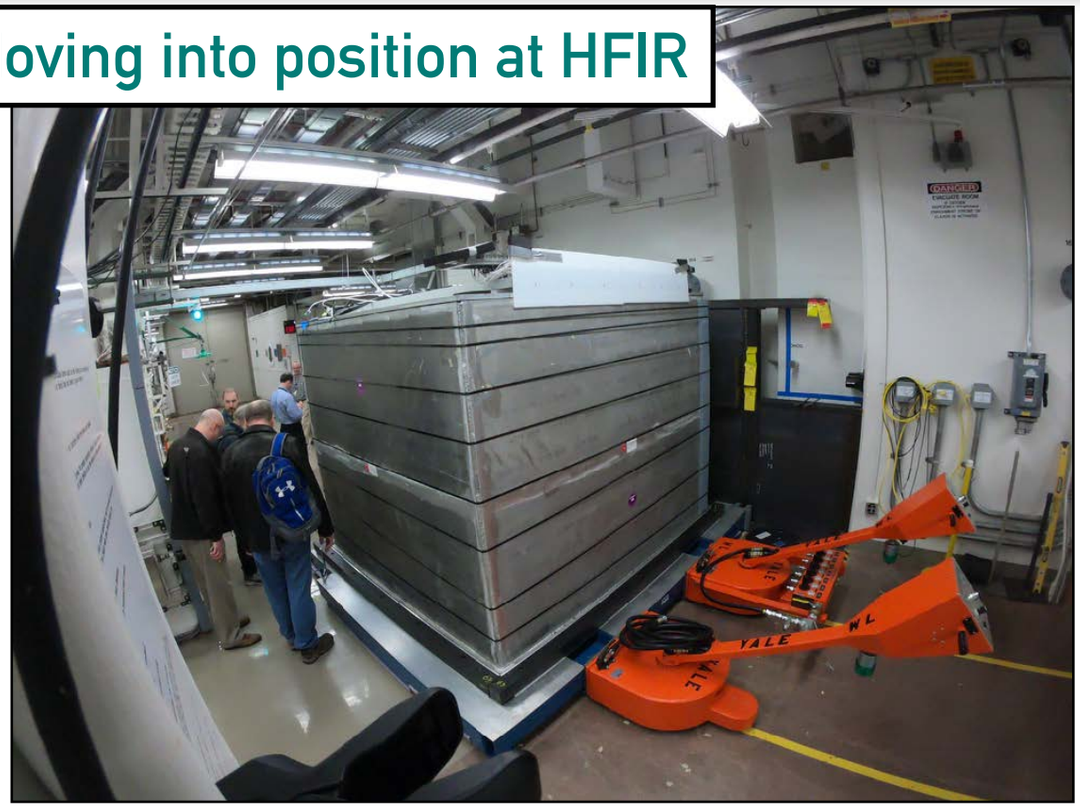


Batches mixes and sparged

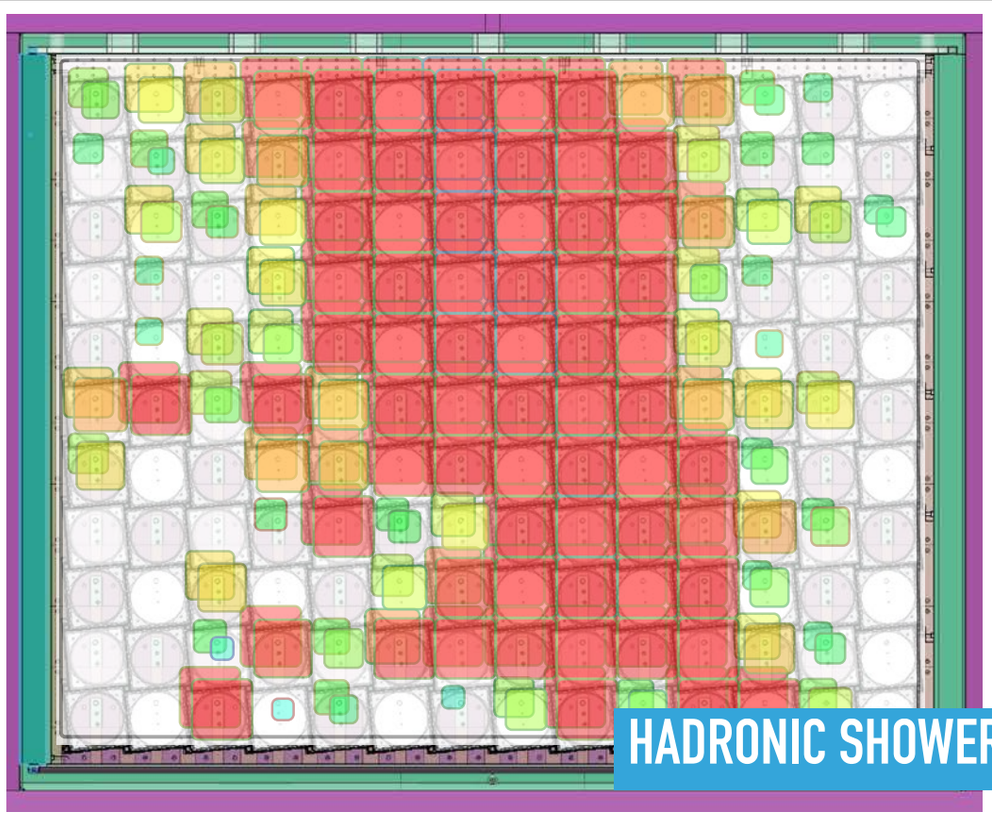


February 2018, arrival at ORNL

Moving into position at HFIR

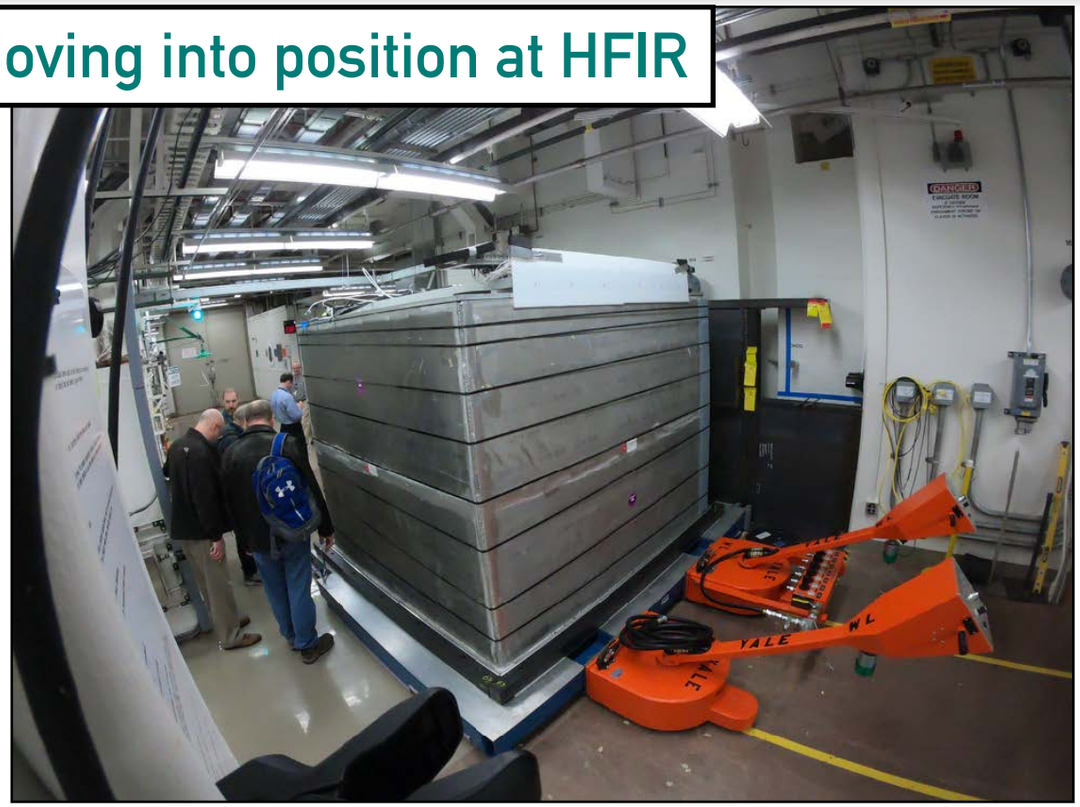


Batches mixes and sparged

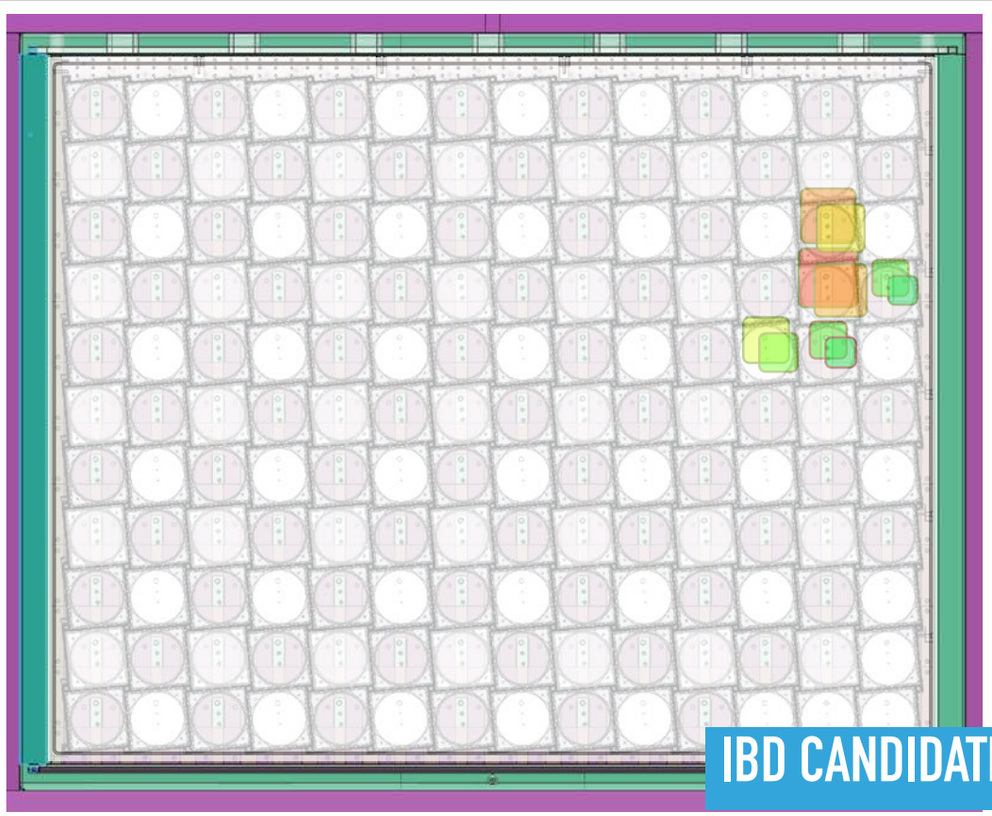


February 2018, arrival at ORNL

Moving into position at HFIR

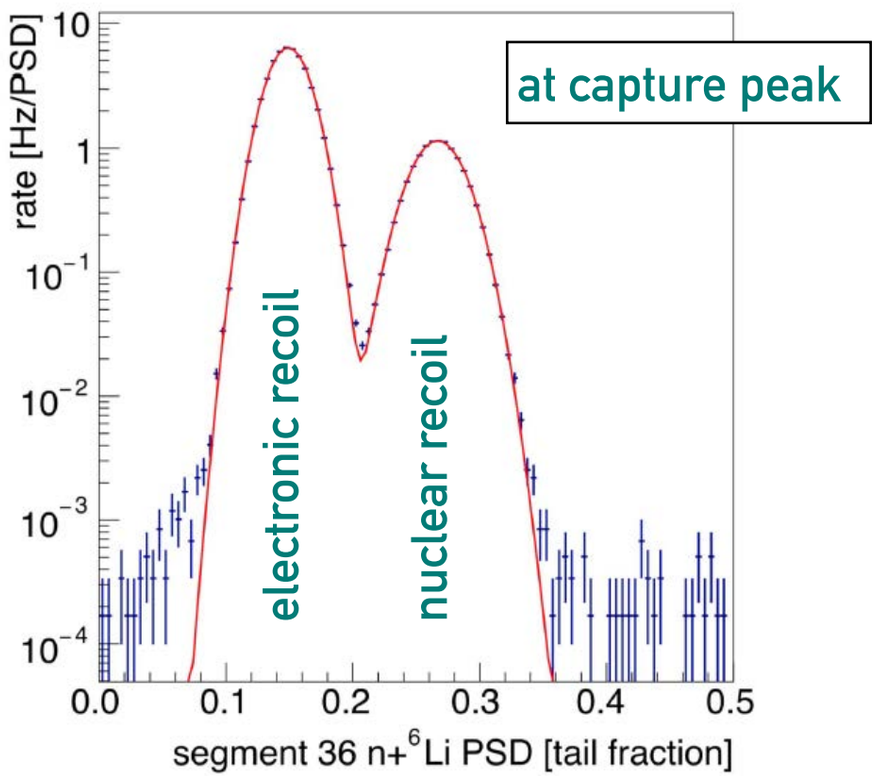


Batches mixed and sparged

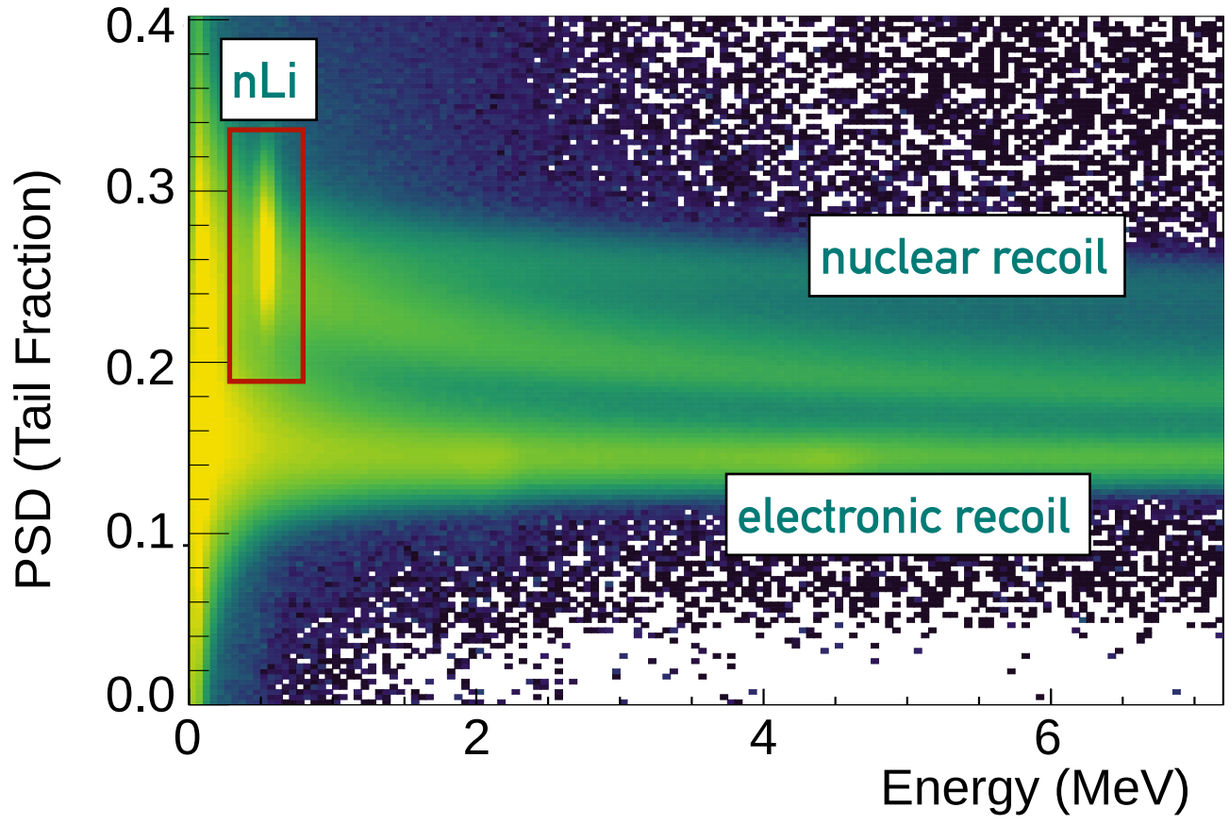


Performance: Pulse Shape Discrimination

Single segment PSD

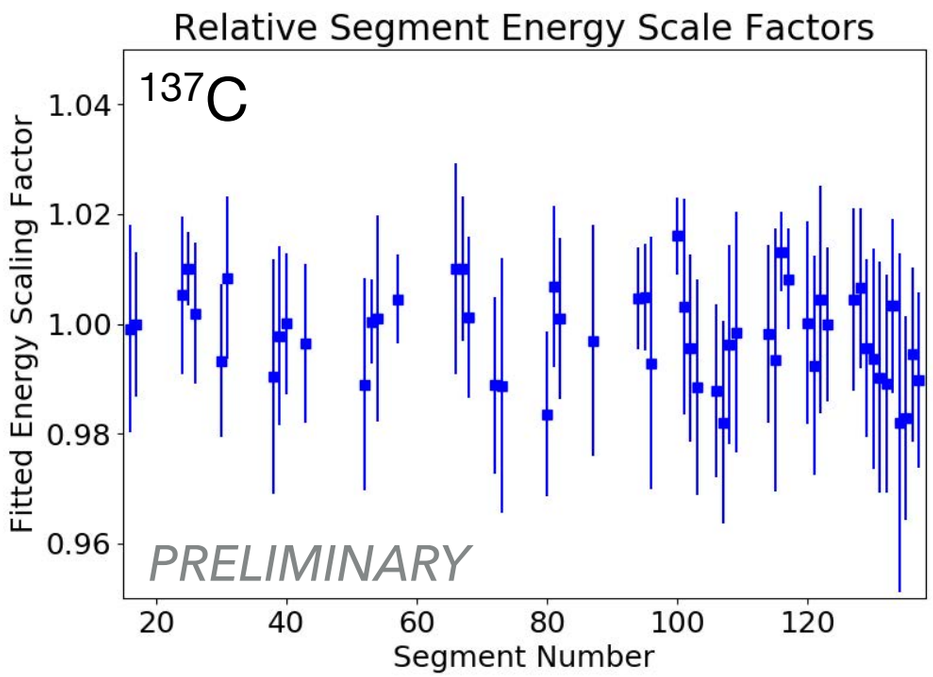


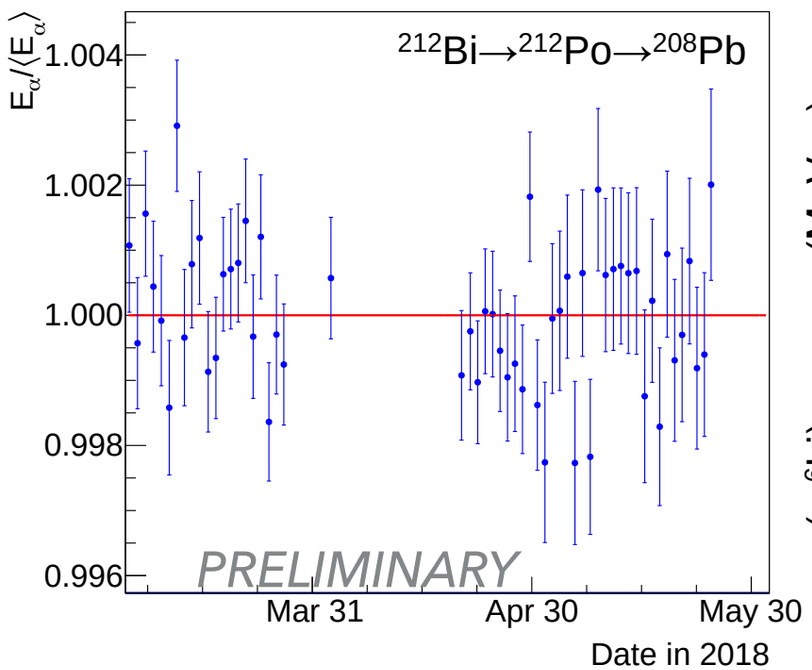
Full detector PSD

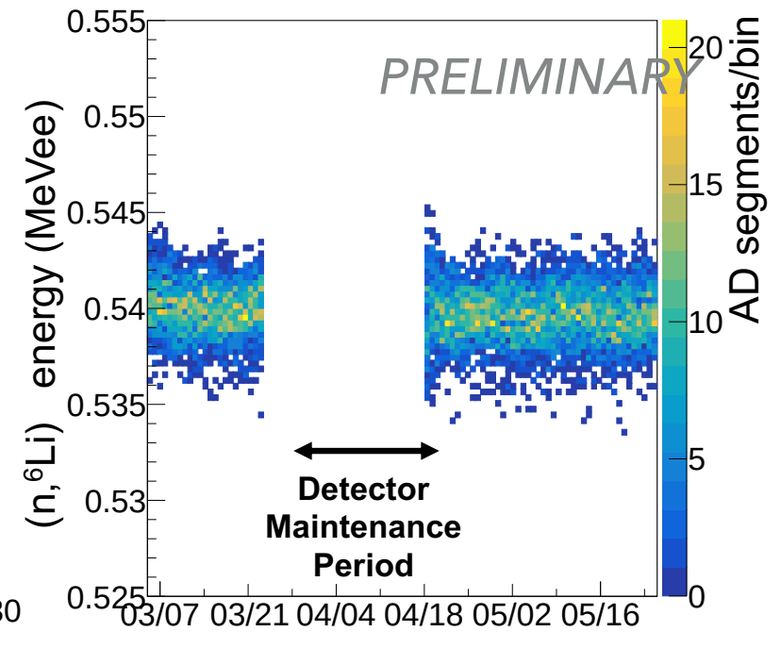


- Excellent discrimination of gamma interactions, and nuclear recoils
- Well separated ^{6}Li-n capture peak
- As dominant backgrounds are cosmogenic fast neutrons, reactor-related gamma rays, and reactor thermal neutrons:
  - Vast majority identified and rejected by PSD for Prompt and Delayed signals

Detector Uniformity and Stability



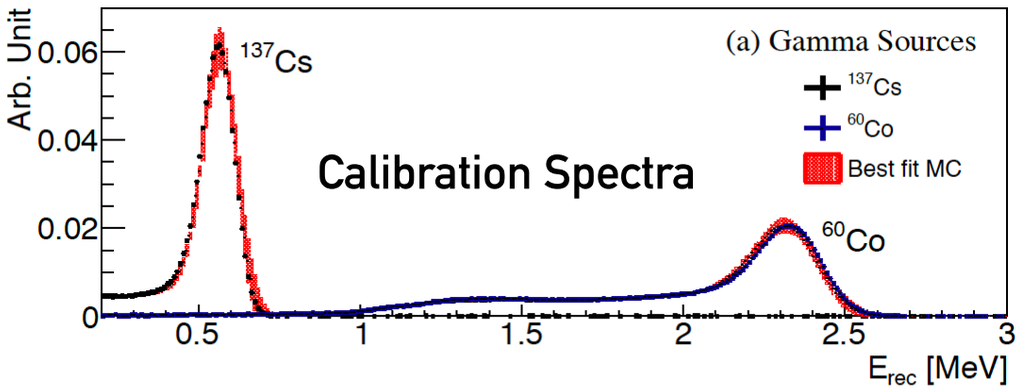


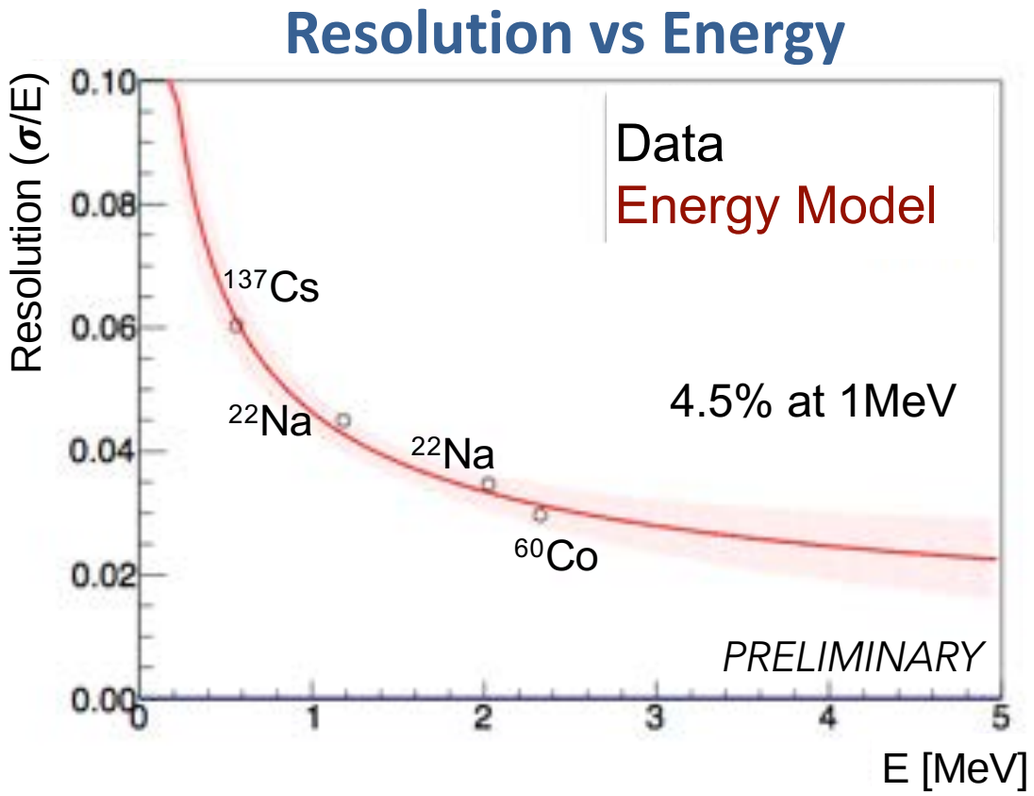


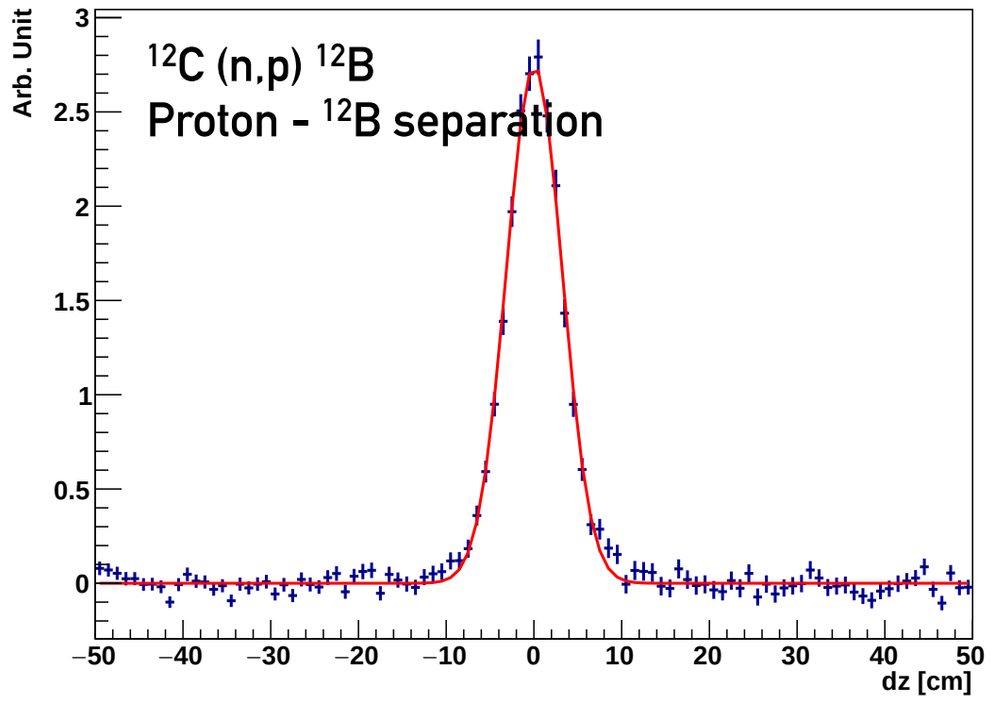
- **Calibration Source Deployment:**
  - 35 calibration source tubes throughout detector to map energy response
  - Segment to segment uniformity ~1%
  - ^{252}Cf source to study neutron capture efficiency
- **Intrinsic radioactive sources**
  - Track uniformity over time with distributed internal single-segment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

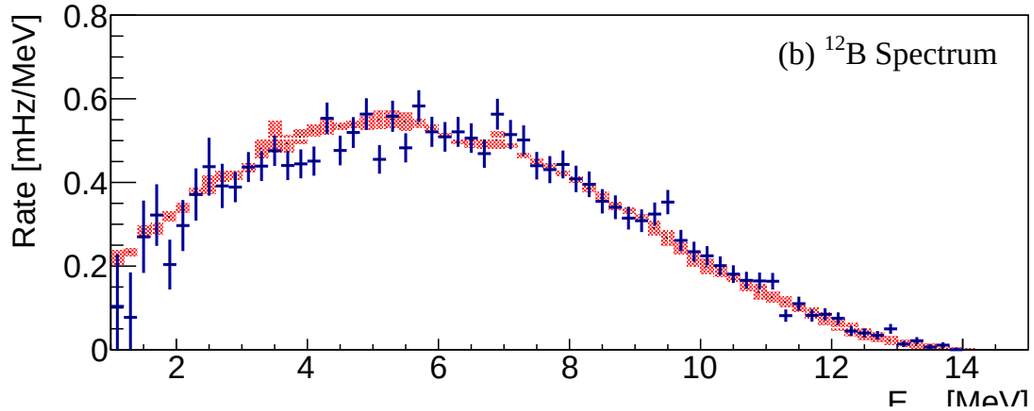
Energy Reconstruction

- Sources deployed throughout detector, measure single segment response
- Full-detector E_{rec} within 1% of E_{true}





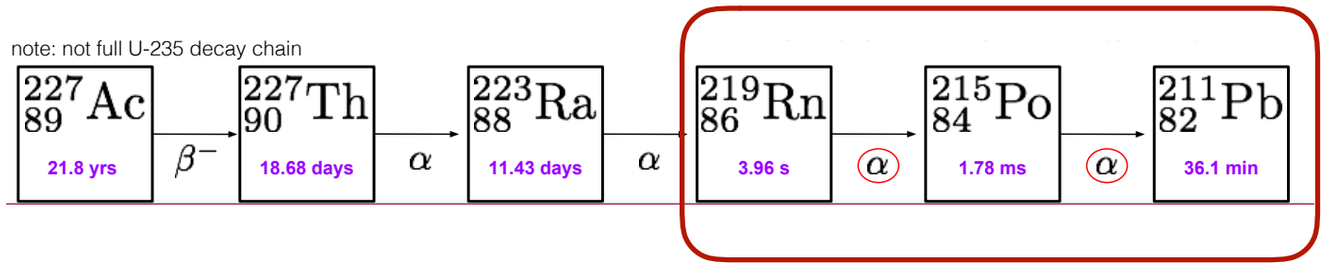




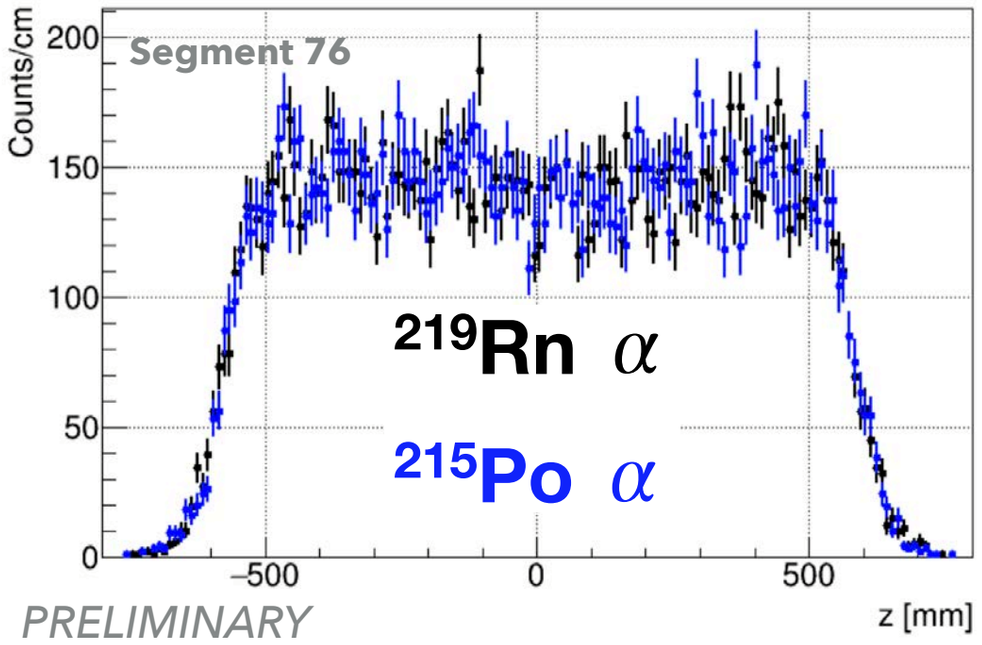
- Fast-neutron tagged ^{12}B
  - High-energy beta spectrum calibration
- High light collection: 795±15 PE/MeV

Relative Segment Volume Determination

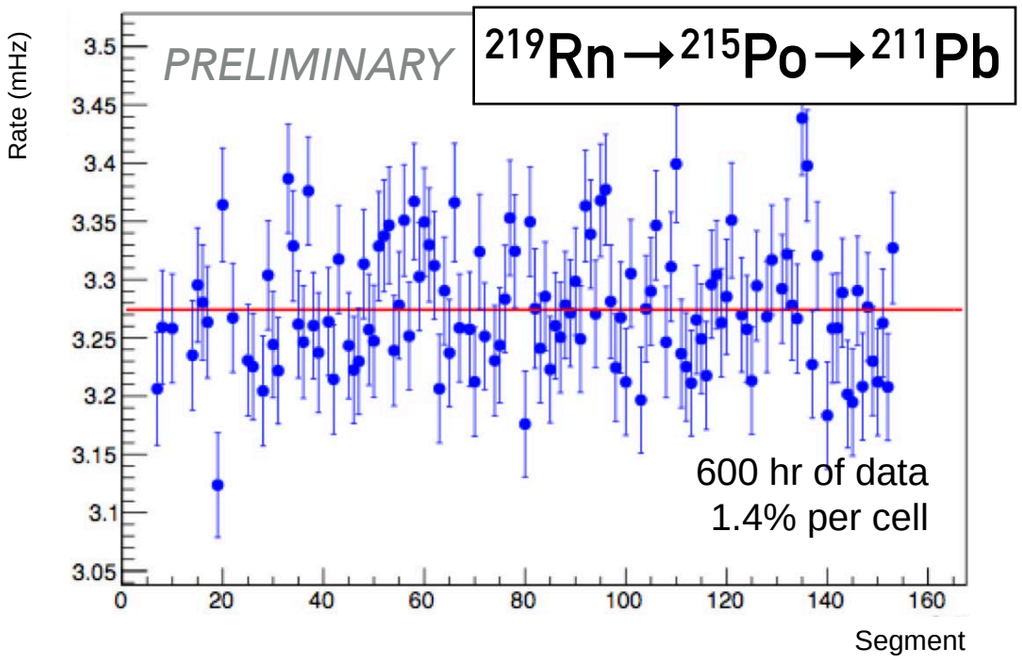
Relative target mass needed for oscillation search



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



Uniformity in rates within segment



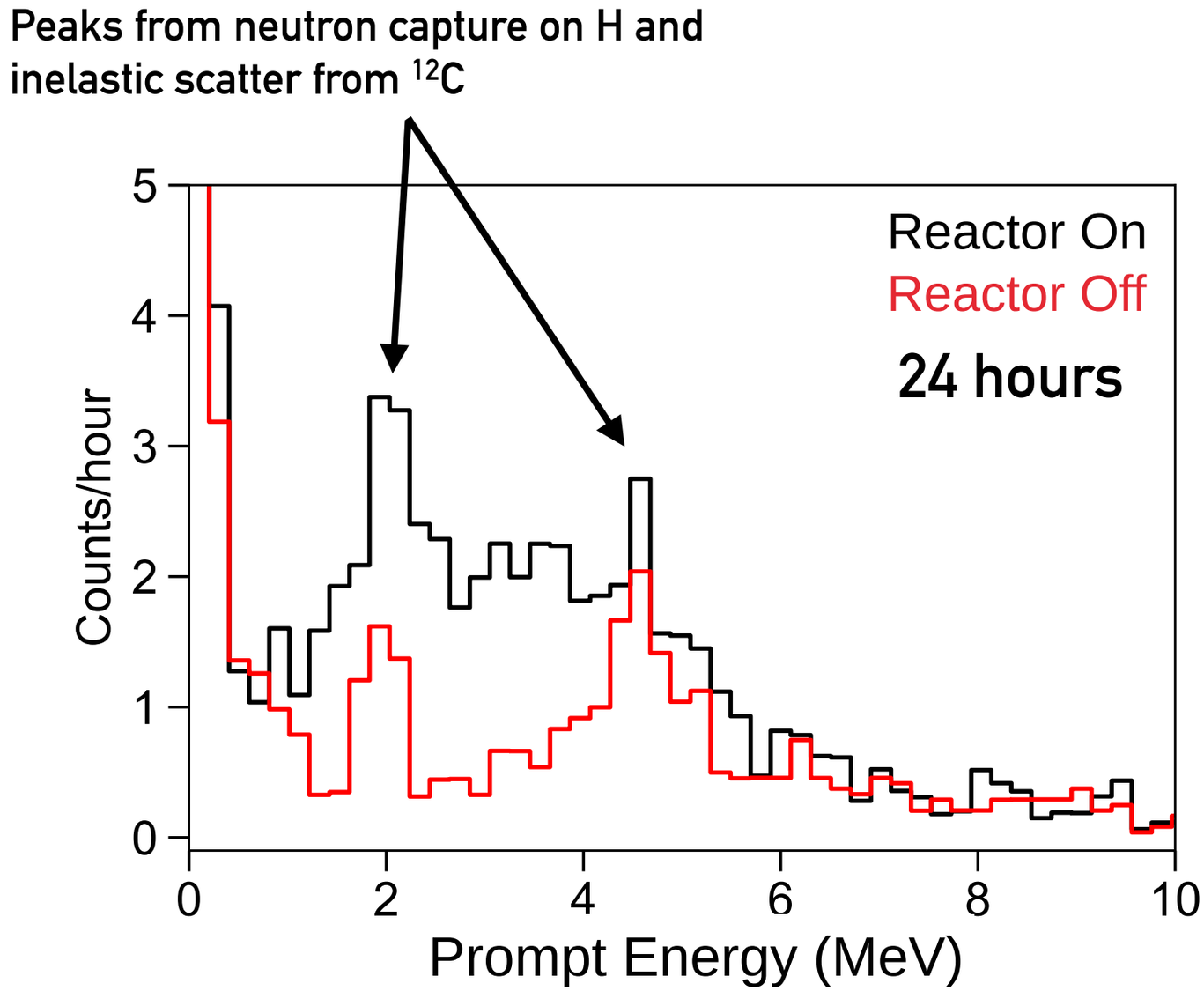
Uniformity in rates between segments

First operations

Began operations March 5, 2018

First 24 hours of operation:

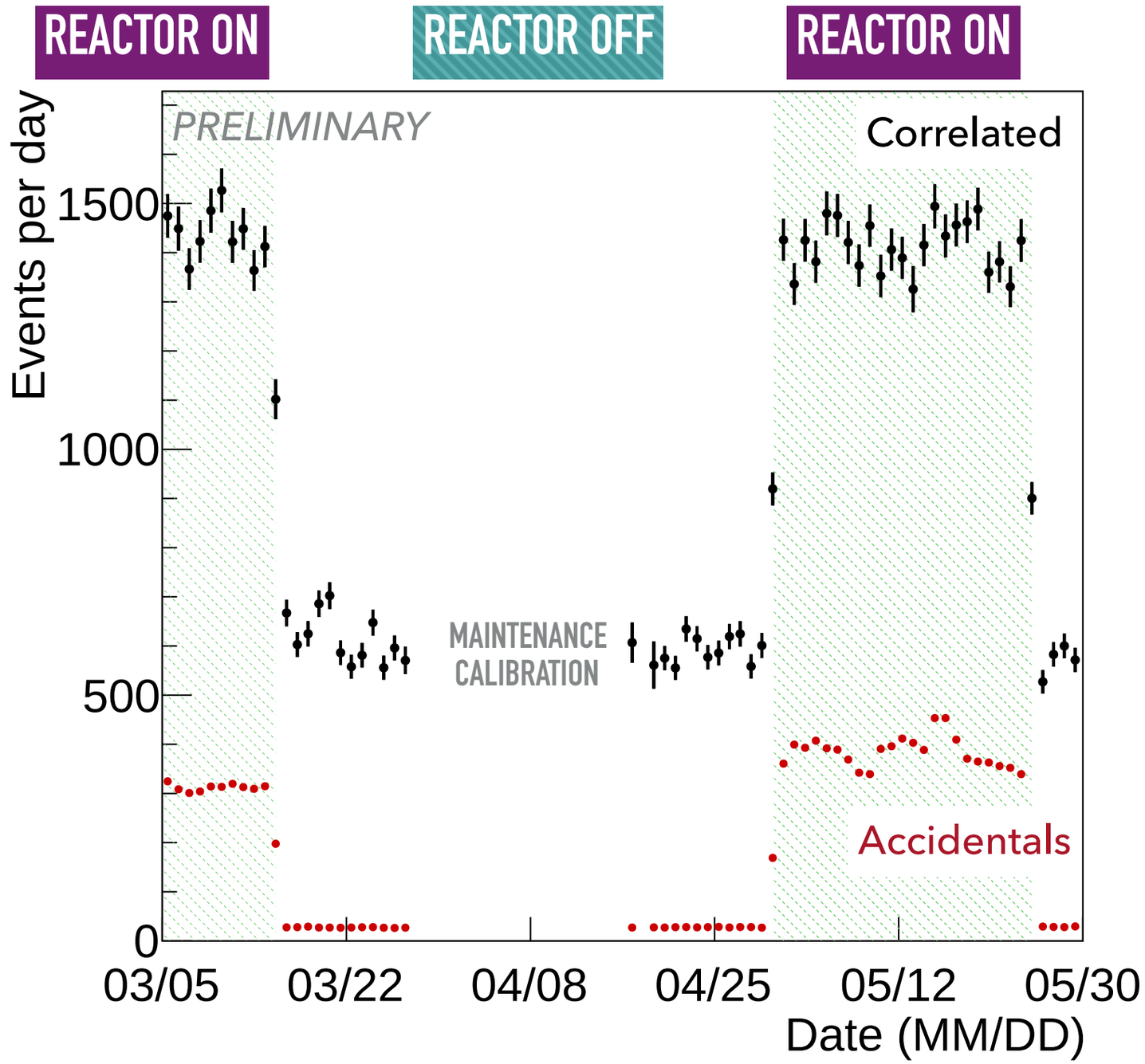
- Reactor On: 1254±30 correlated events between [.8, 7.2MeV]
- Reactor Off: 614±20 correlated events (first off day March 16)
- Time to 5σ detection at earth's surface: < 2hrs



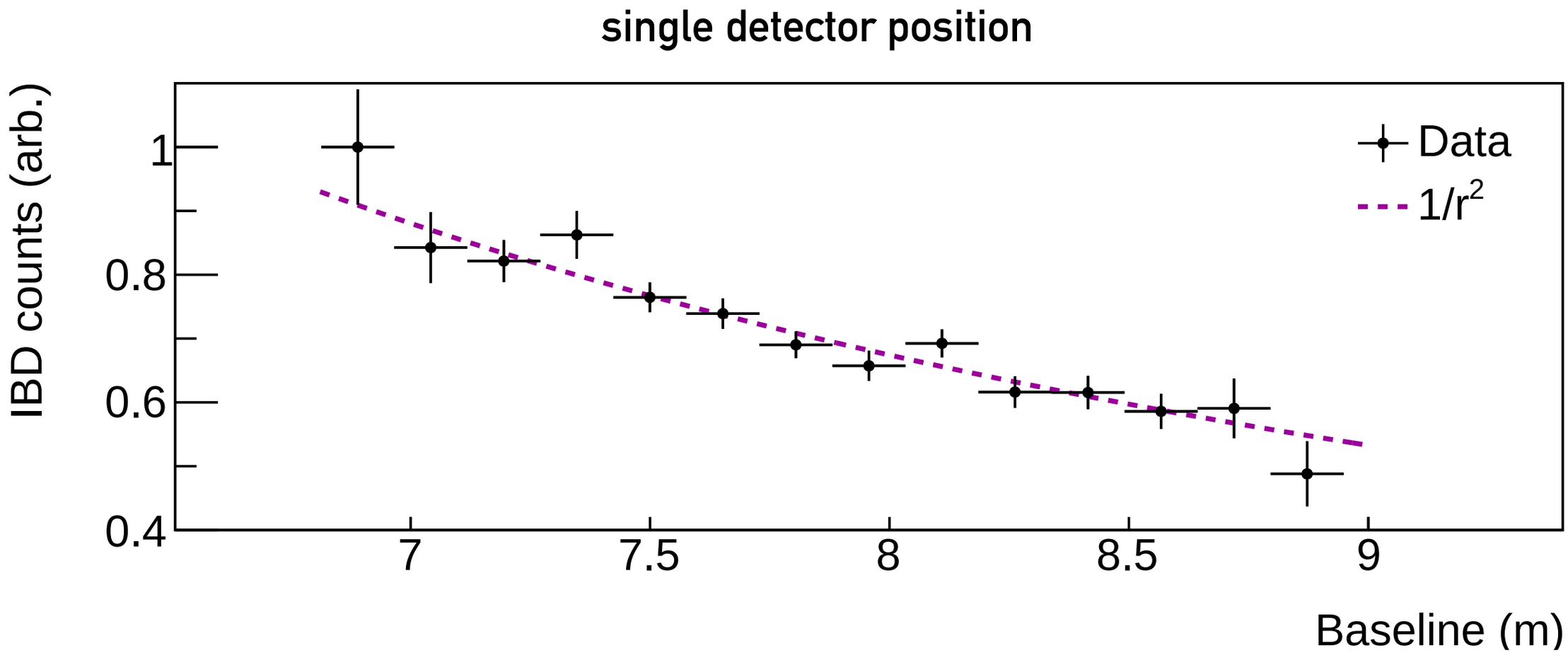
Working on analysis of ^{235}U antineutrino spectrum with current dataset, significant increase in statistics

Results From First Data Set

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



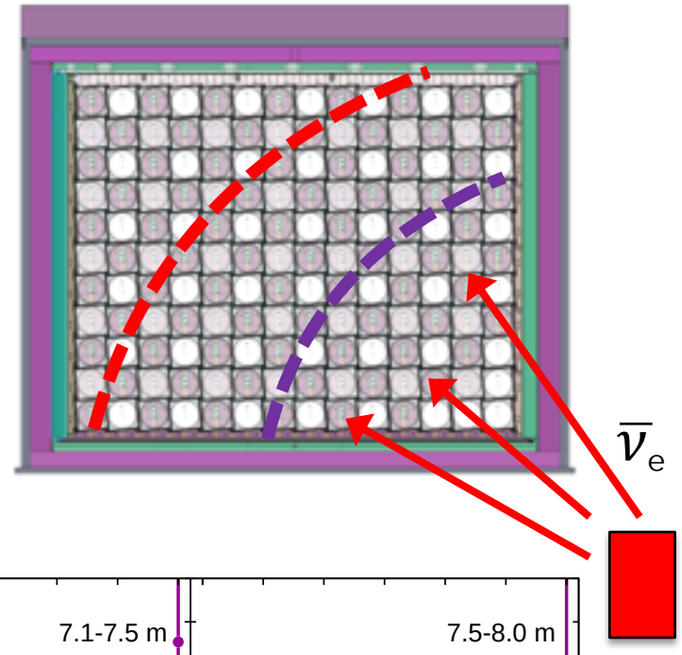
Excellent signal-to-background for a surface detector (< 1mwe overburden)

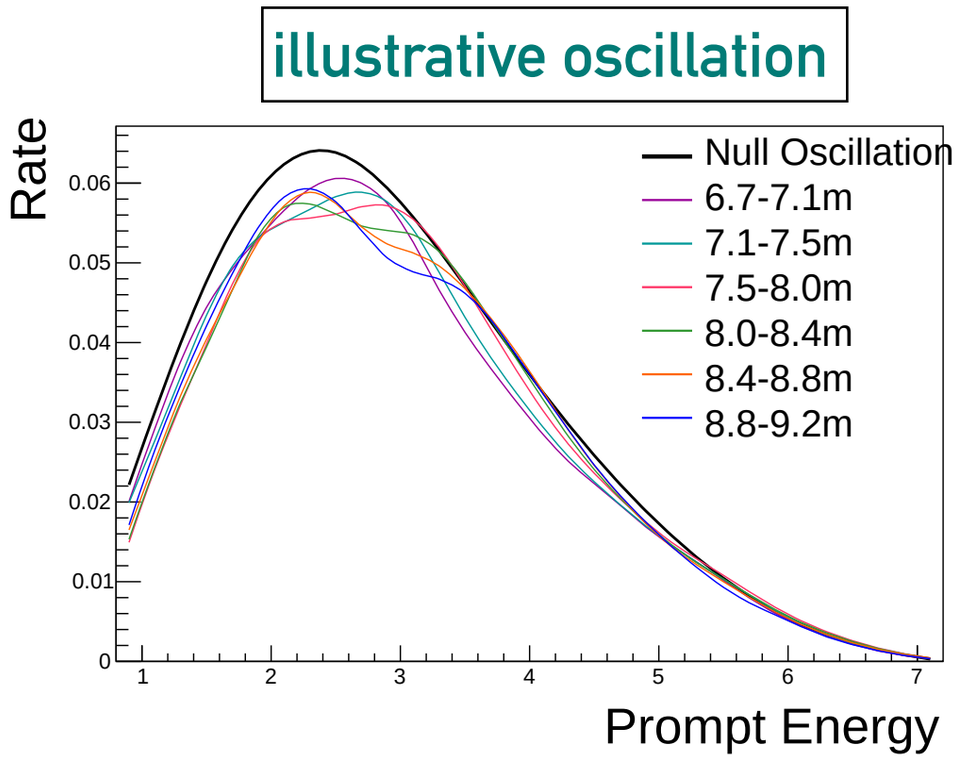


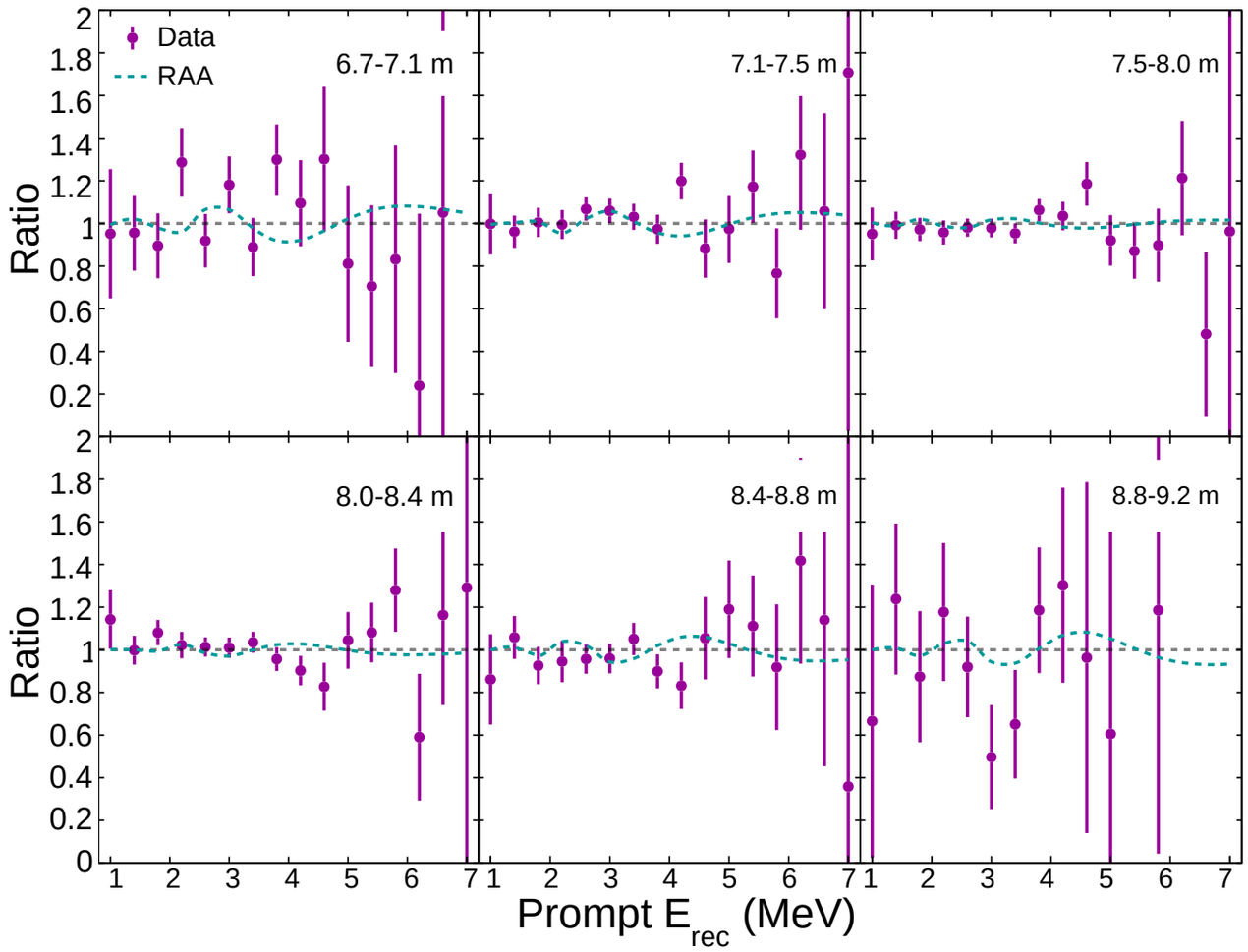
- 108 fiducial segments binned into 14 baselines
  - Wide range of baselines accessible within detector
- Observed change in flux follows $1/r^2$

Results From First Data Set

- Compare measured energy spectrum for 6 baselines to the scaled full-detector no-oscillation energy spectrum
- Null oscillation yields a flat spectrum

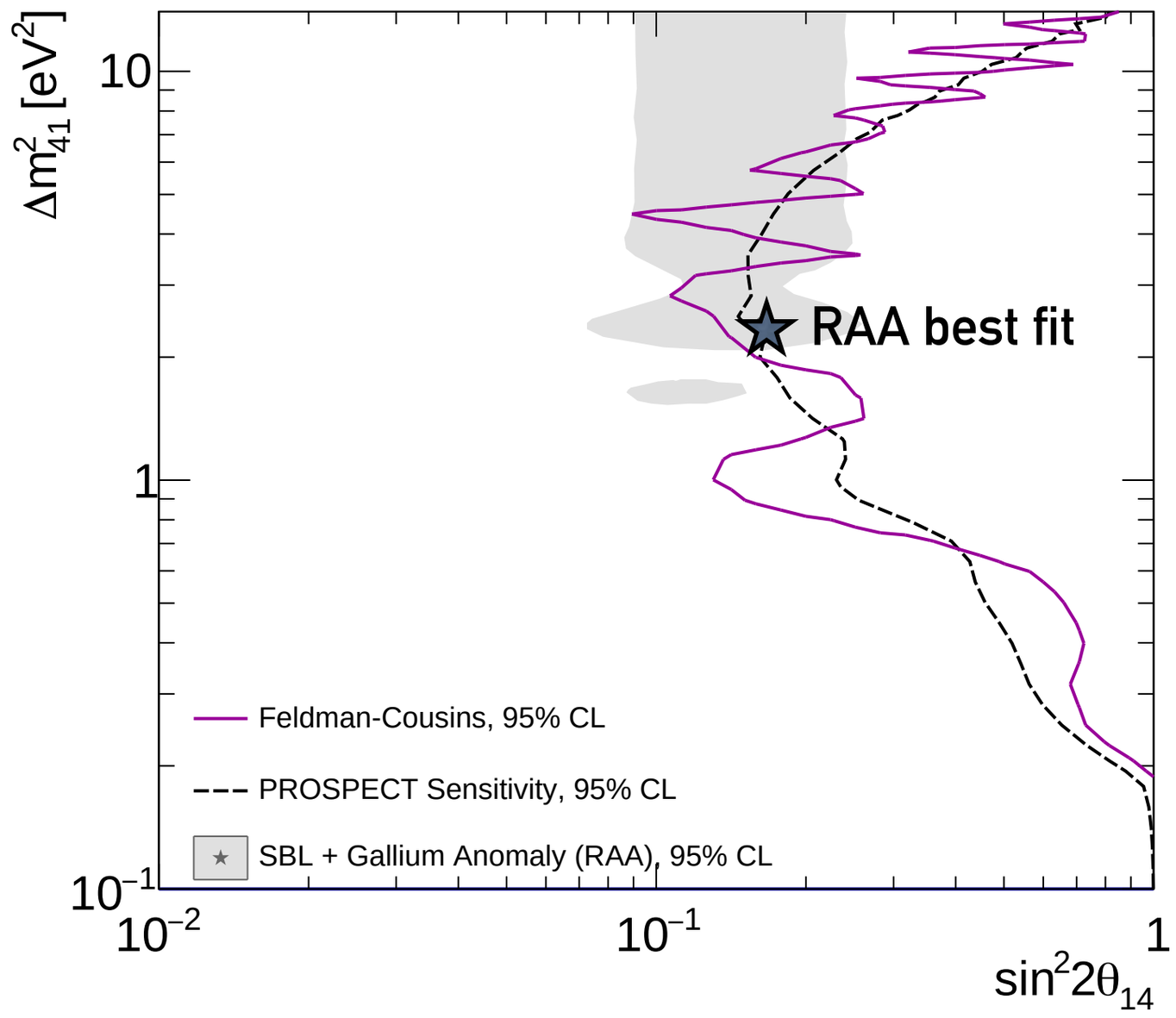






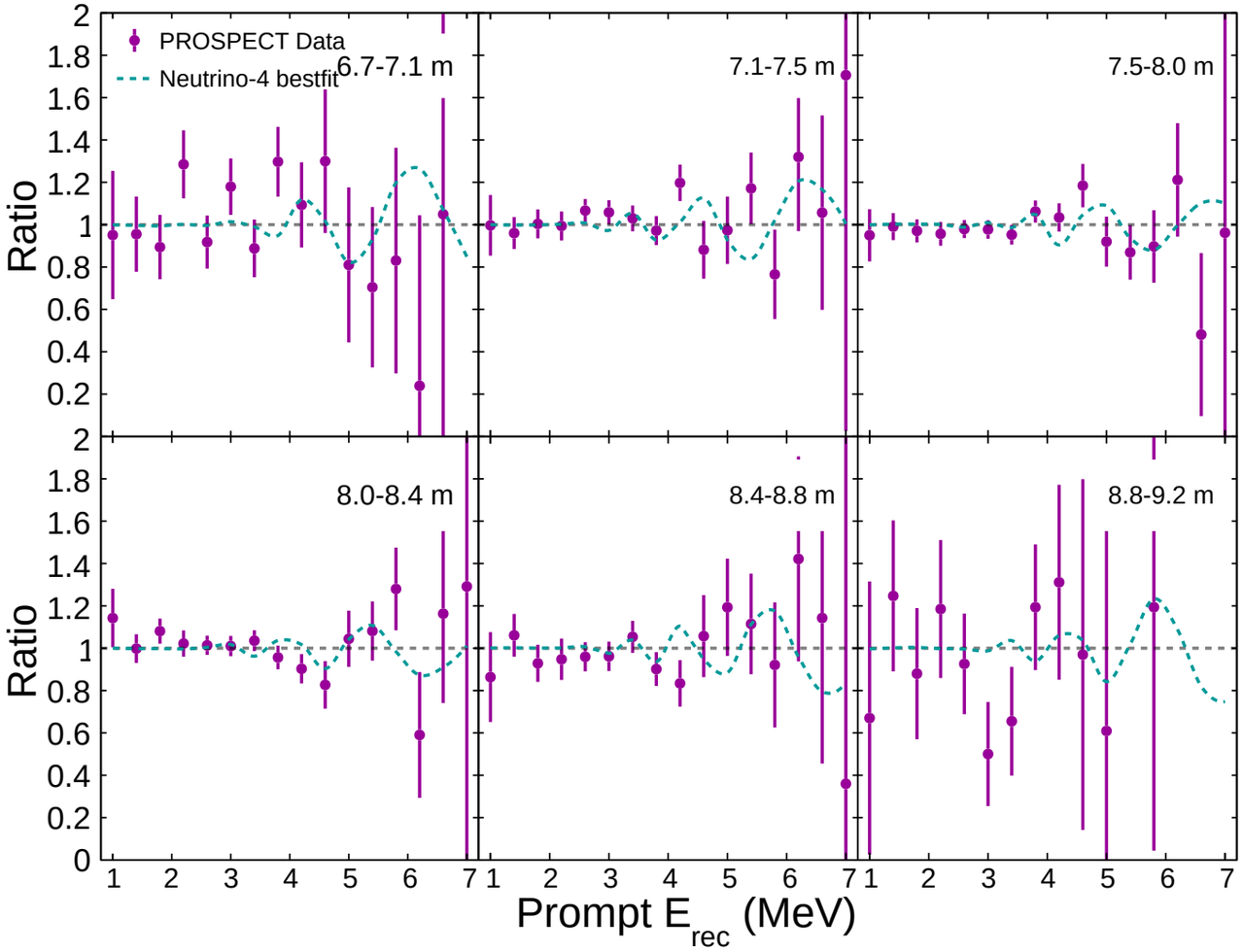
Reactor model independent test of reactor antineutrino anomaly

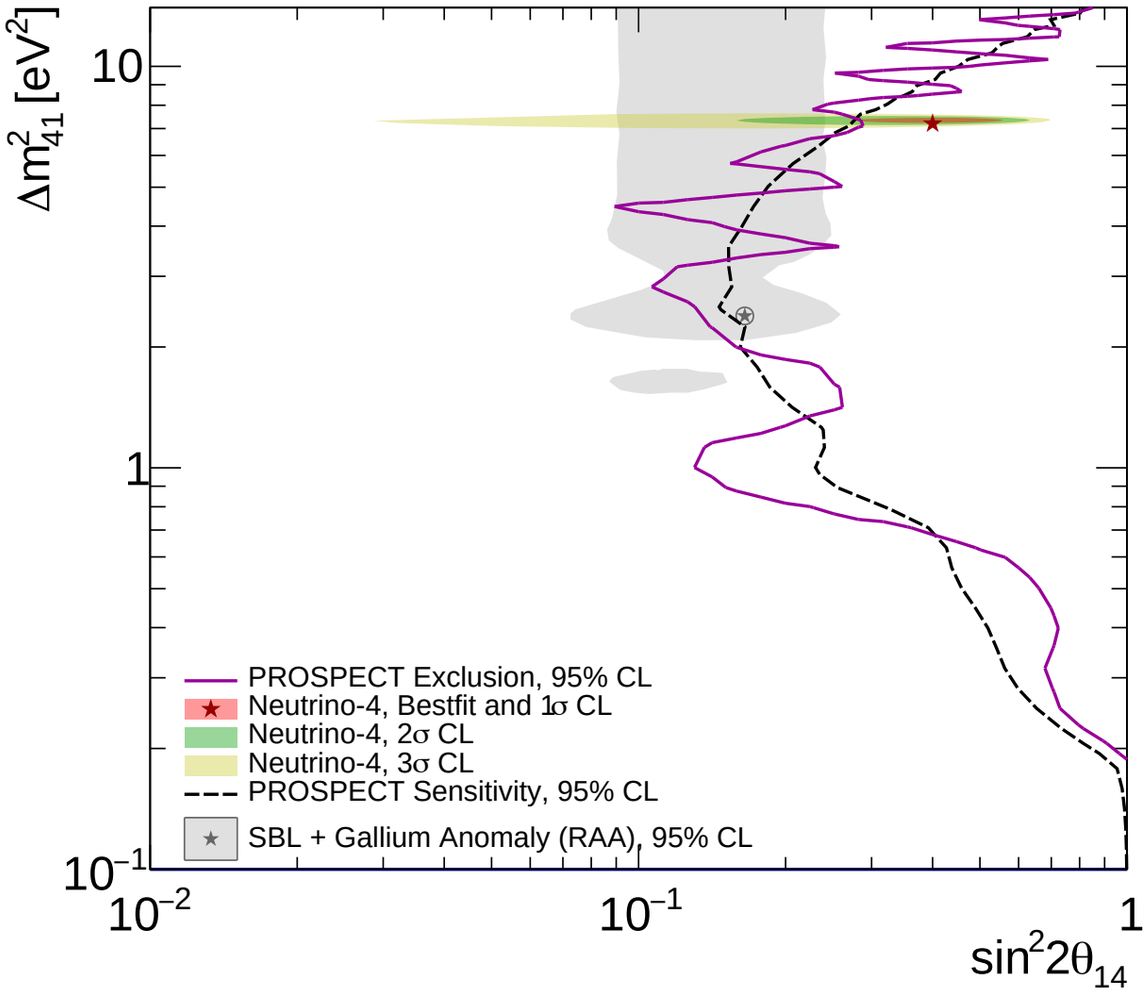
- Feldman-Cousins based confidence intervals for oscillation search
- Covariance matrices captures all uncertainties and energy/ baseline correlations
- Critical χ^2 map generated from toy MC using full covariance matrix
- 95% exclusion curve based on 33 days Reactor On operation



RAA best-fit disfavored at >95% (2.2σ)

Comparison to Neutrino-4





Conclusions and Outlook

- PROSPECT running since March 2018 and is performing well
- Demonstrates technical approach
  - scalable/modular (to a degree)

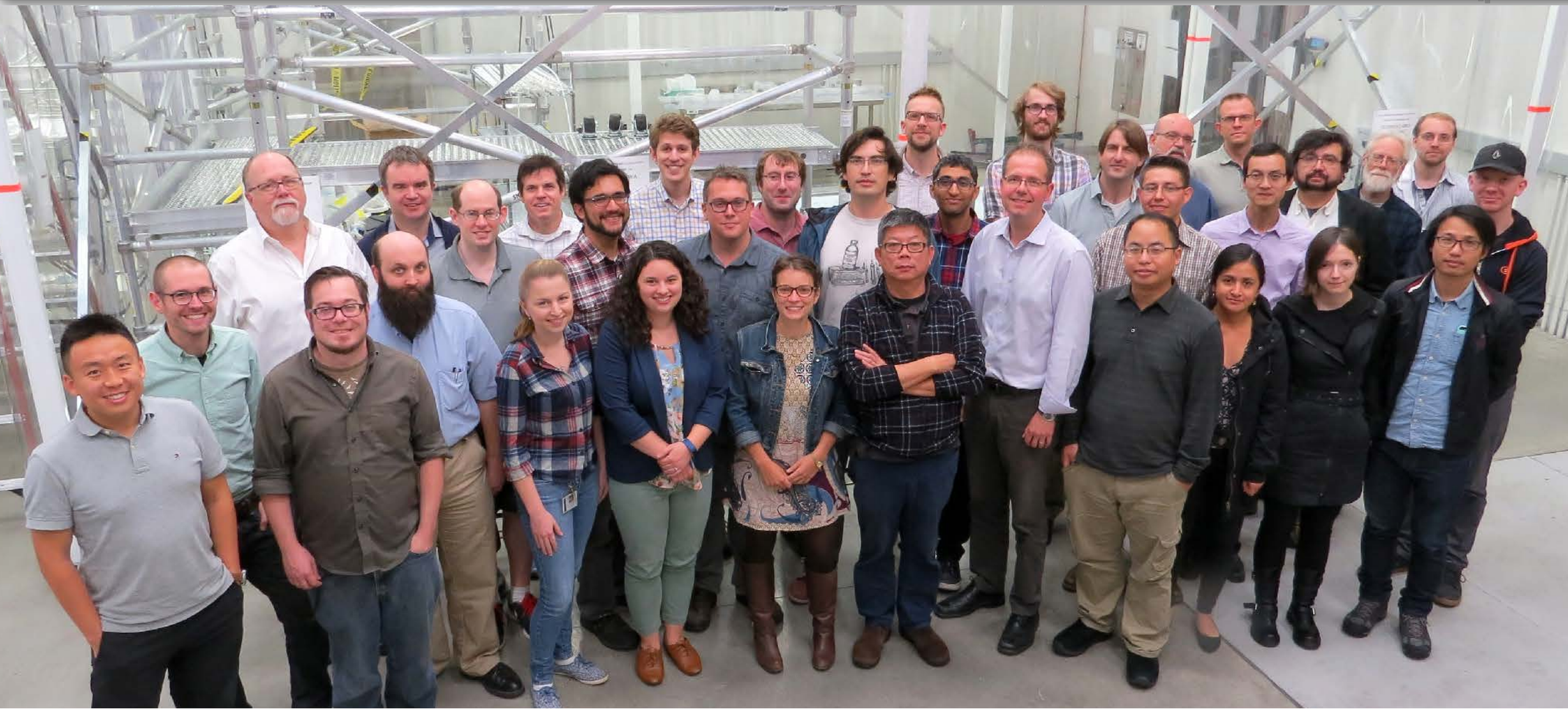
- Very good signal-to-background at the surface (< 1 mwe), consistent with MC/ R&D-based expectations
  - Observed HEU reactor spectrum with ~1 day of data

- First 33 days of data:
  - Address RAA at >2.2 sigma (arXiv: 1806.02784)

- Currently working on:
  - high-statistics spectral analysis (47/40 days On/Off), results soon.
  - Updated oscillation analysis underway
  - By 2019 6 reactor cycles w/ approximately equal off time.

- Expect valuable data on surface near-field operation (safeguards) and related cosmogenic backgrounds going forward
  - Much more to do in exploring full event topology

PROSPECT Collaboration



prospect.yale.edu

HEISING-SIMONS FOUNDATION

U.S. DEPARTMENT OF ENERGY

GRFP NSF GRADUATE RESEARCH FELLOWSHIP PROGRAM

BROOKHAVEN NATIONAL LABORATORY

NIST

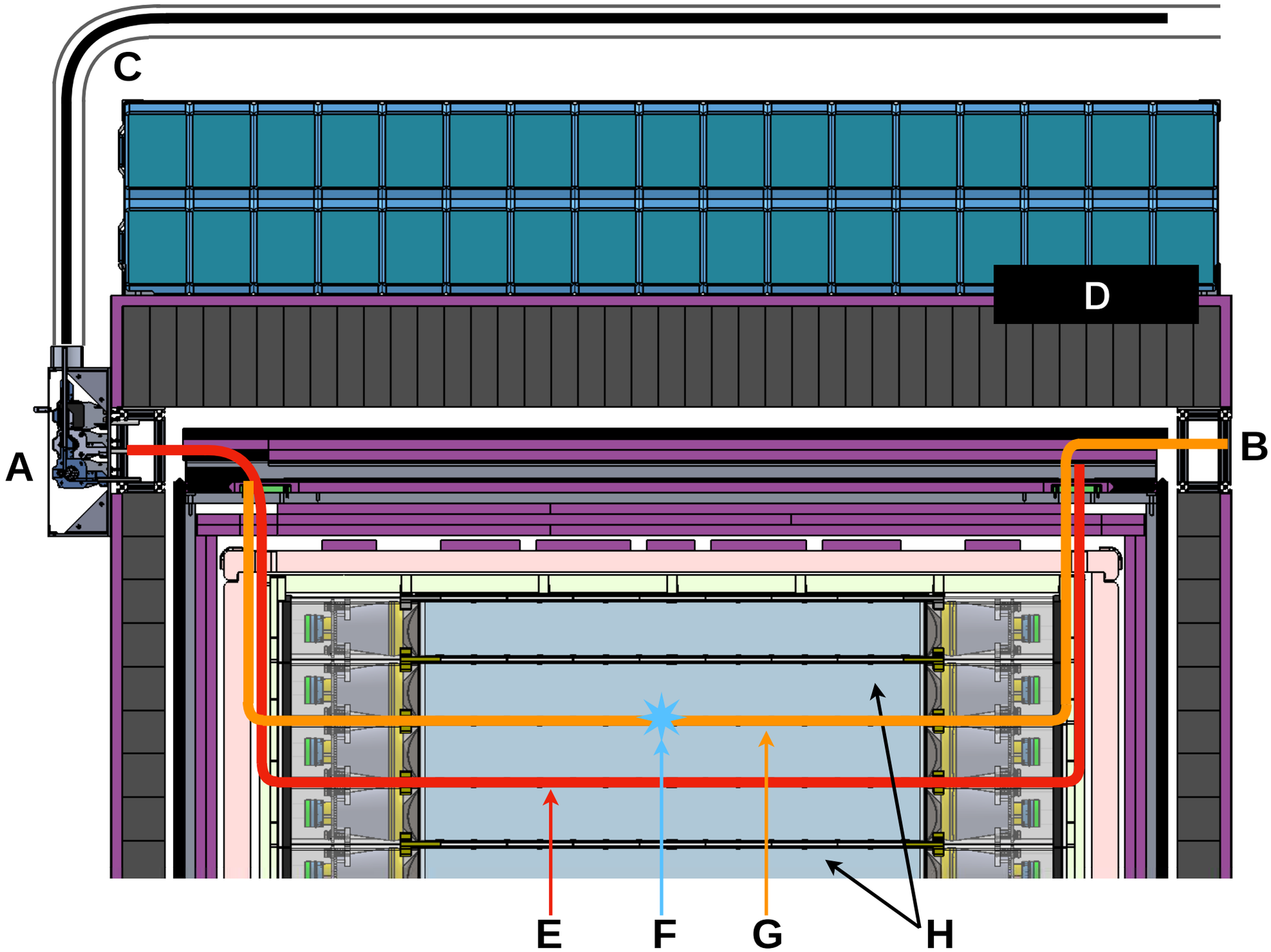
Lawrence Livermore National Laboratory

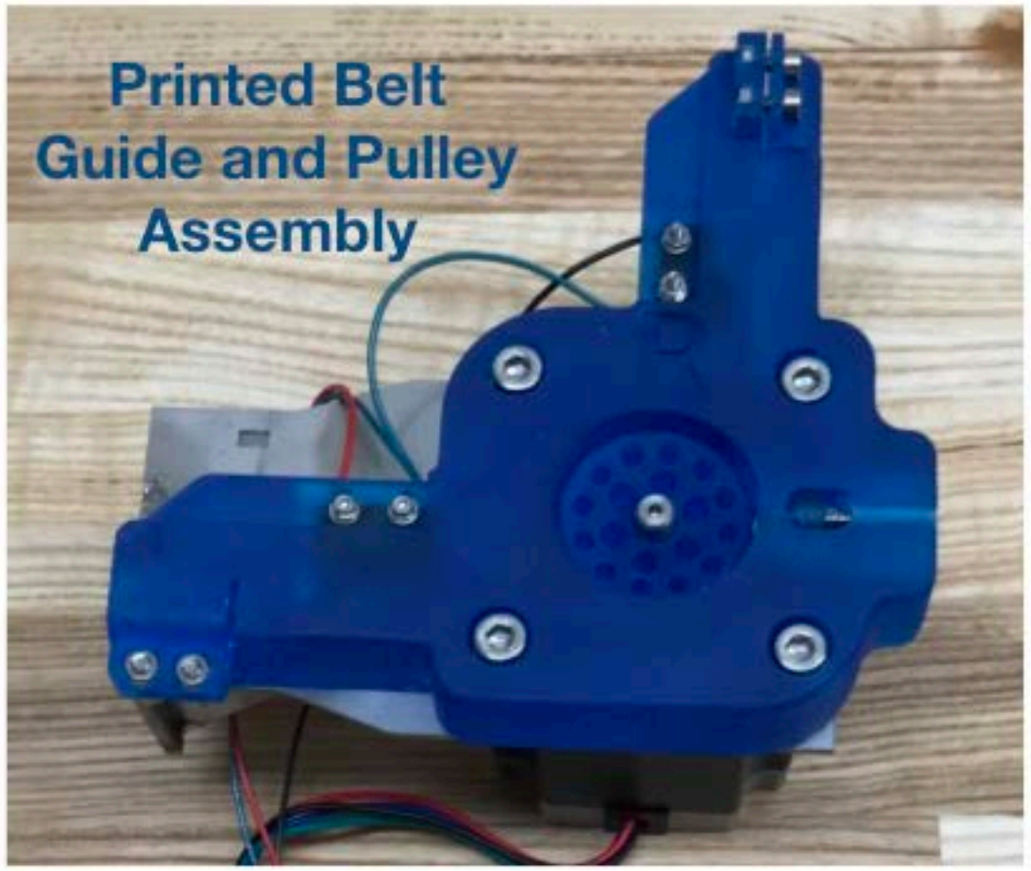
OAK RIDGE National Laboratory

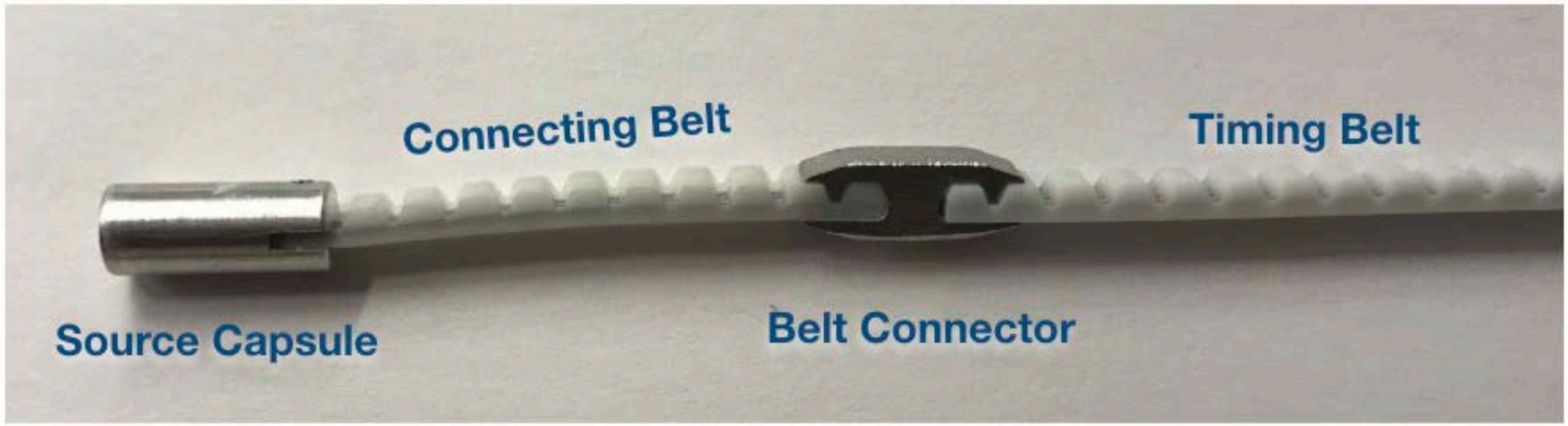
Drexel

Yale

Whitepaper: [arXiv:1309.7647]


C
D
B
A
E
F
G
H


Printed Belt
Guide and Pulley
Assembly


Connecting Belt
Timing Belt
Source Capsule
Belt Connector