First Results from the PROSPECT Short Baseline Reactor Experiment

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For the PROSPECT collaboration

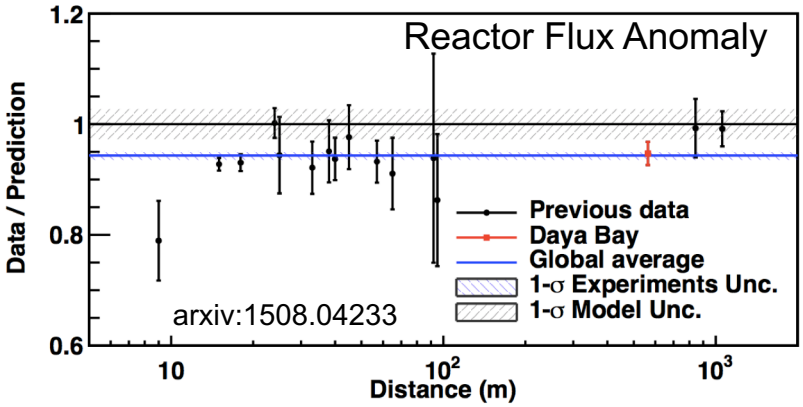
NuFACT 2018

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

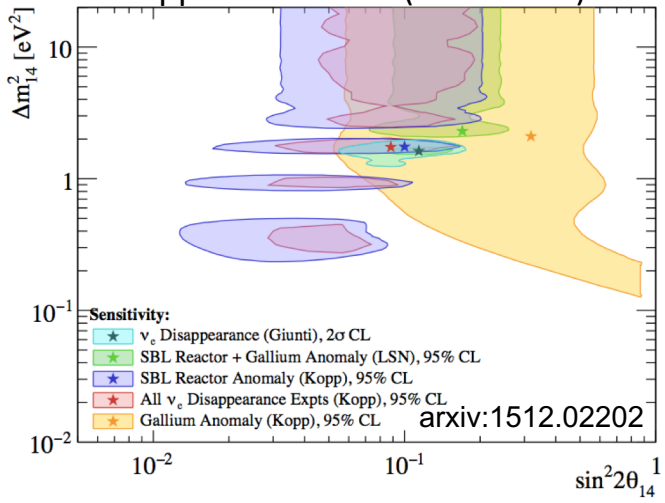
Lawrence Livermore National Laboratory

Motivation

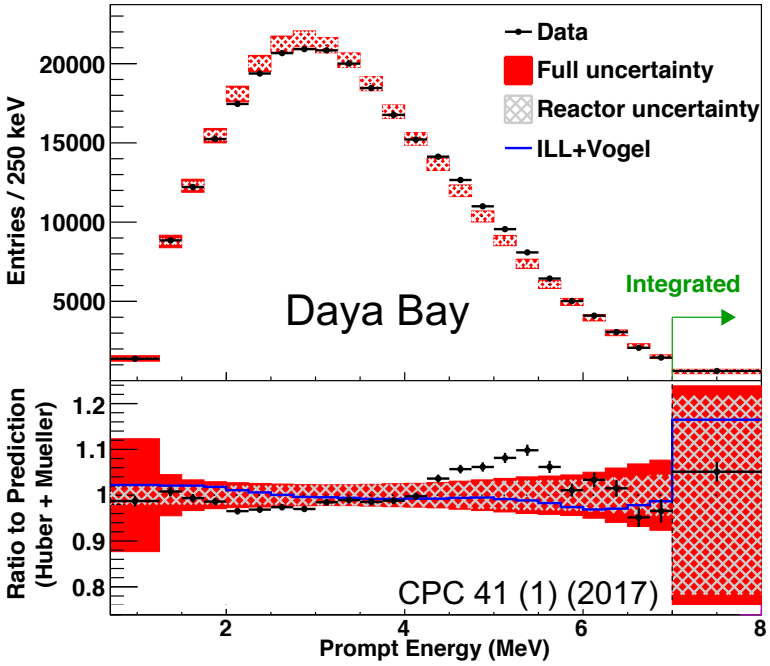
Directly test the hypothesis of a new oscillation with $\Delta m^2 \sim 1\ eV^2$, i.e. oscillation length of few meters



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

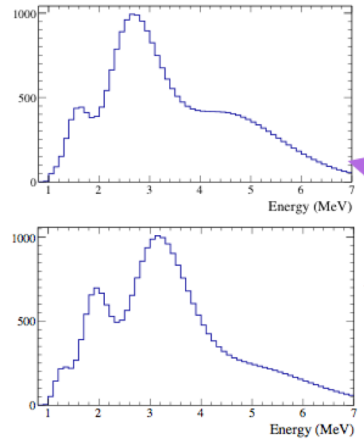


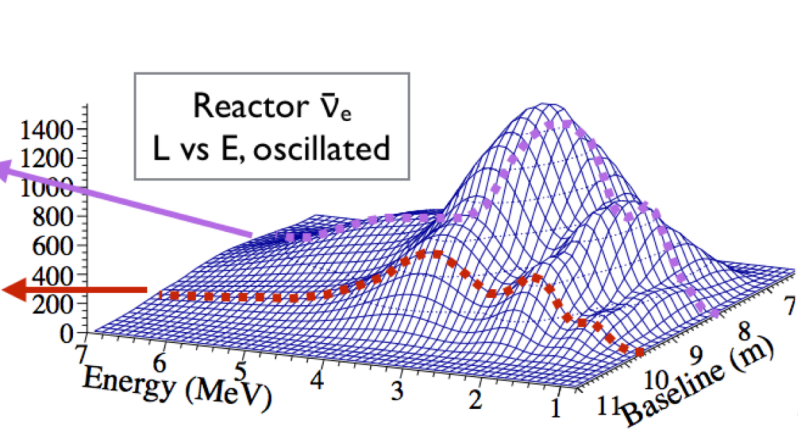
Provide new tests of reactor models by making precision measurements of novel reactor spectra, esp. ^{235}U fuel

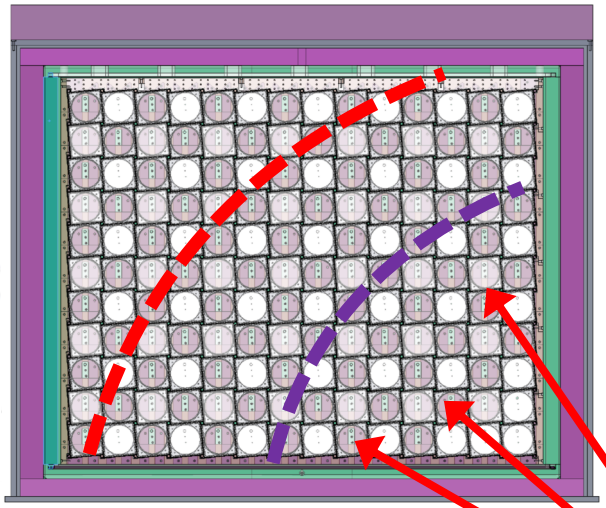


Approach to Short Baseline Reactor Measurements

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





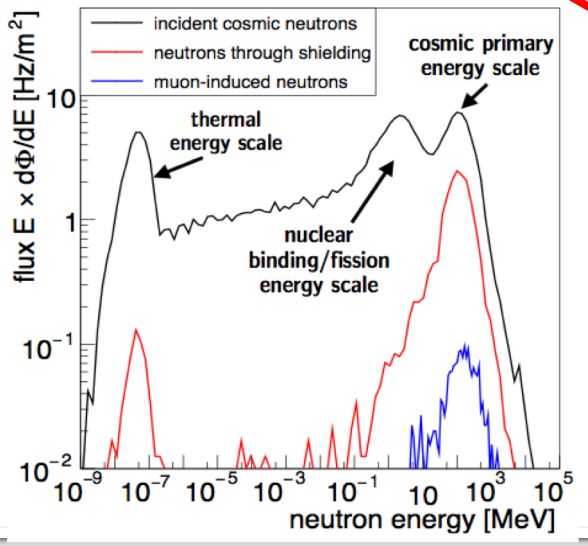


Research reactors generally preferable:

- Access to shortest baselines
- Often use ^{235}U fuel → static fissile inventory
- Compact core dimensions provide greatest sensitivity at $\Delta m2 \sim 1\ eV^2$

But:

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

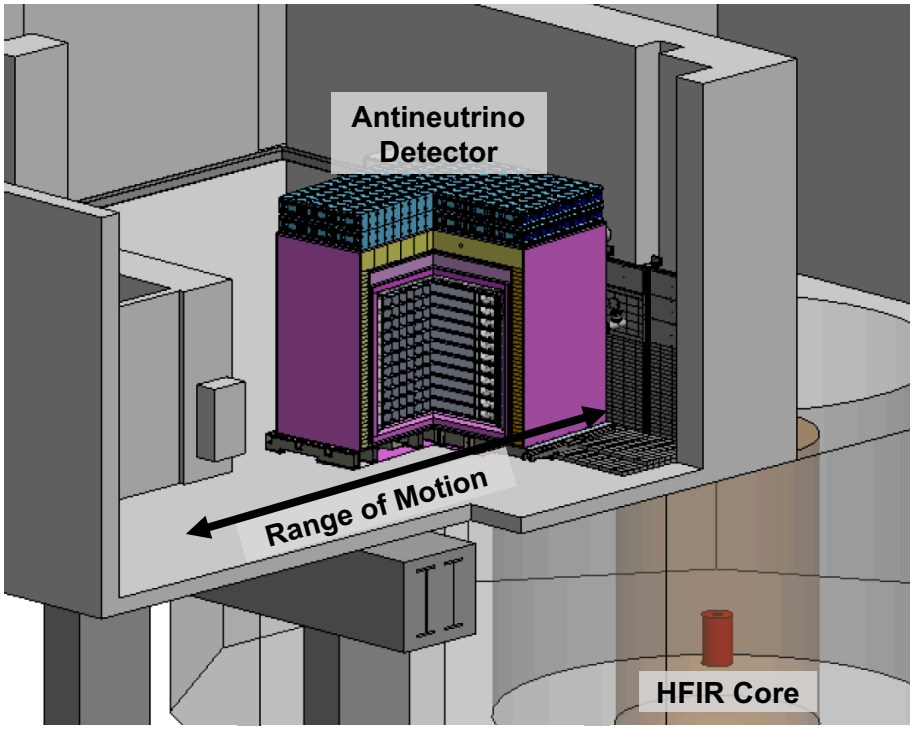


PROSPECT Experiment Overview

Physics Objectives

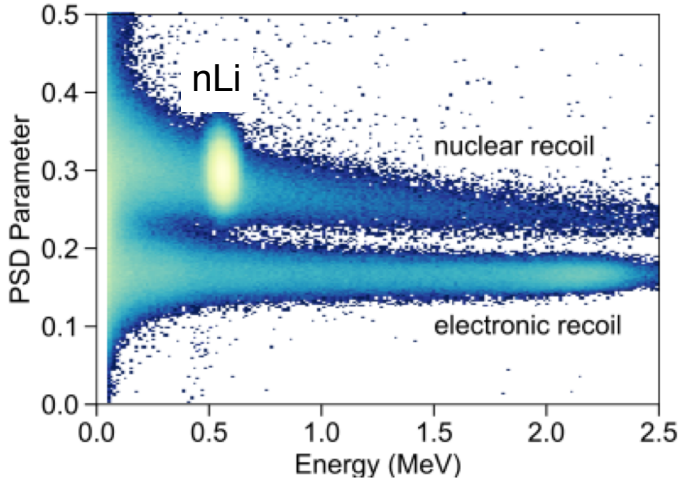
1. Model Independent search for short-baseline oscillation at distances <12m
2. Precision measurement of ^{235}U reactor $\overline{\nu}_e$ spectrum

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



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

Reactor Background
NIMA A806 (2016) 401
arXiv:1506.03547

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

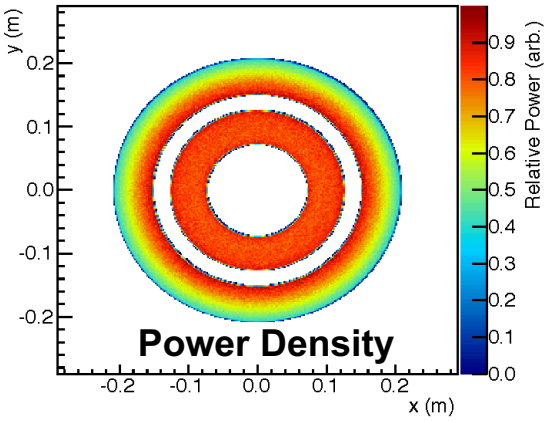
Production Prototype
JINST 13 P06023 (2018)
arXiv:1805.09245

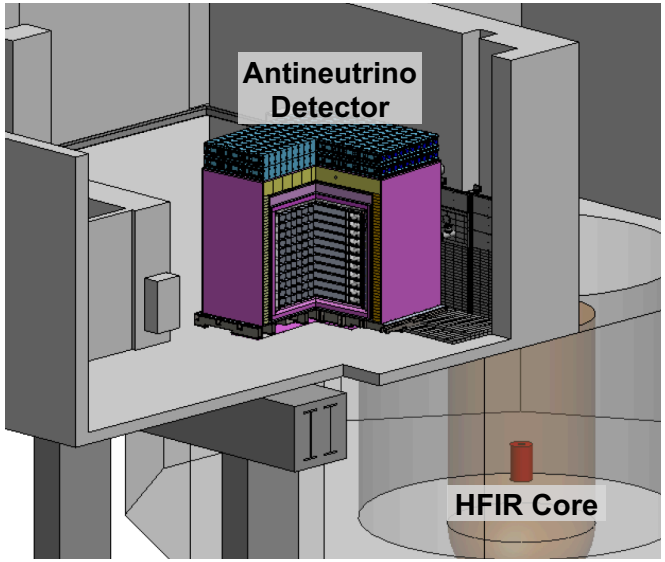
PROSPECT Experiment
Submitted to NIMA
arXiv:1808.00097

Experimental site: High Flux Isotope Reactor @ORNL

Compact Reactor Core

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

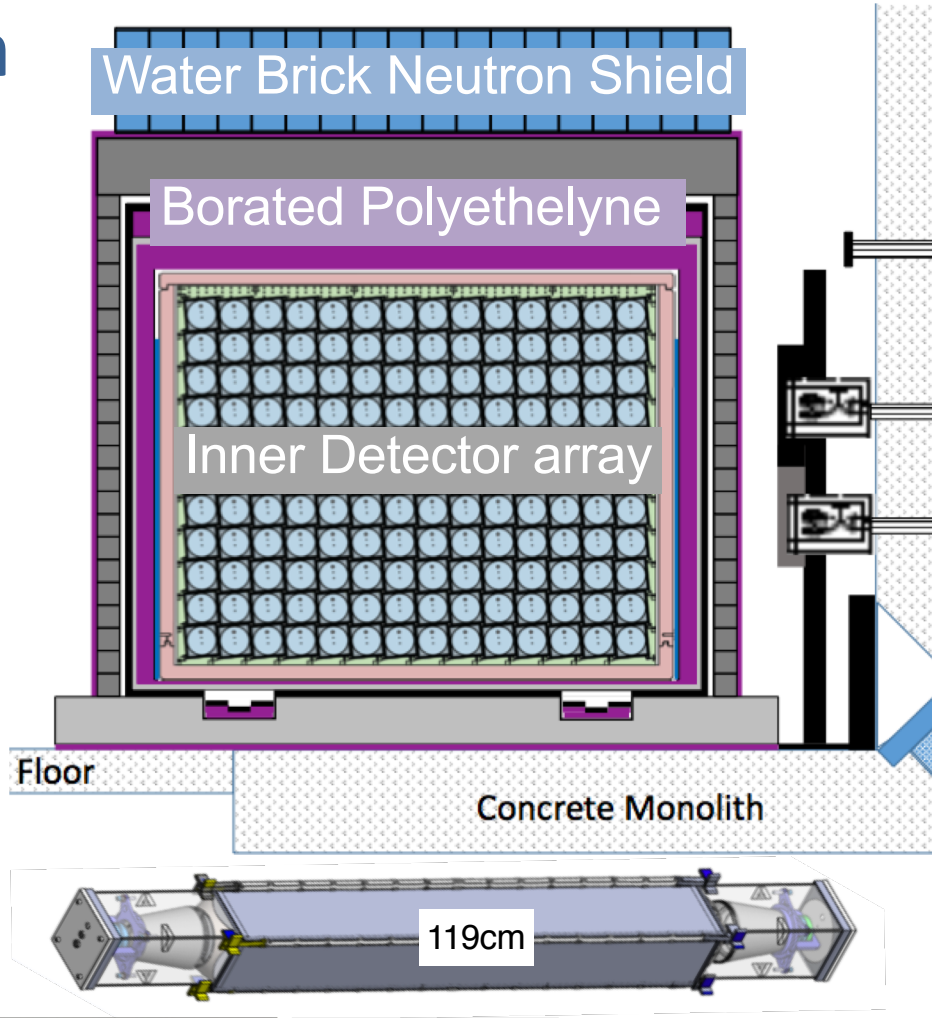


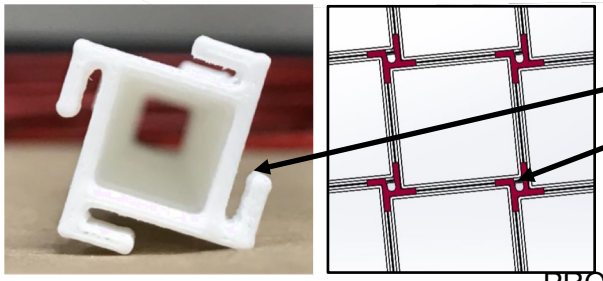


User facility with 24/7 access; Exterior access at grade

PROSPECT Detector Design

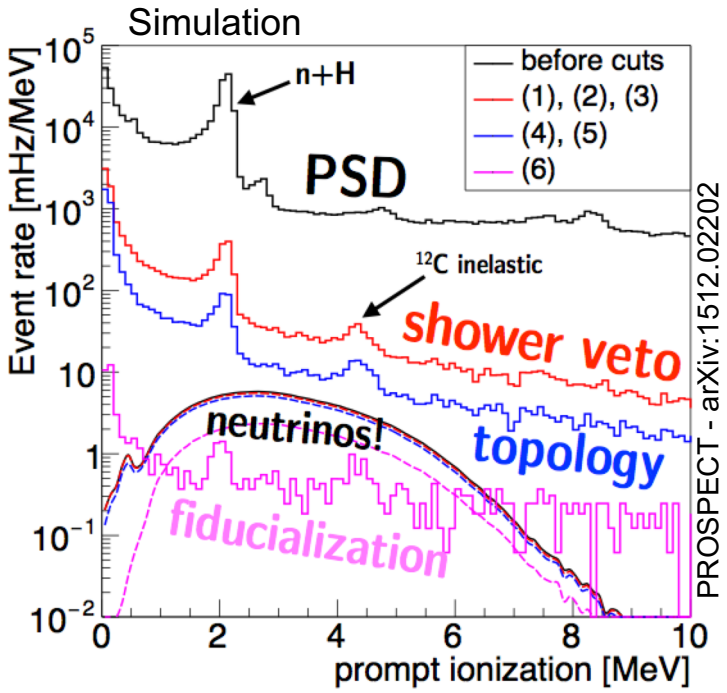
- 154 segments, 119cm x 15cm x 15cm
  - ~25liters of LiLS per segment, total mass: 4ton
- Thin (1.5mm) reflector panels held in place by 3D-printed support rods
- **Segmentation enables:**
  - Calibration access throughout volume
  - Position reconstruction (X,Y)
  - Event topology ID
  - Fiducialization
- Double ended PMT readout for full (X,Y,Z) position reconstruction
- Optimized shielding to reduce reactor and cosmogenic backgrounds

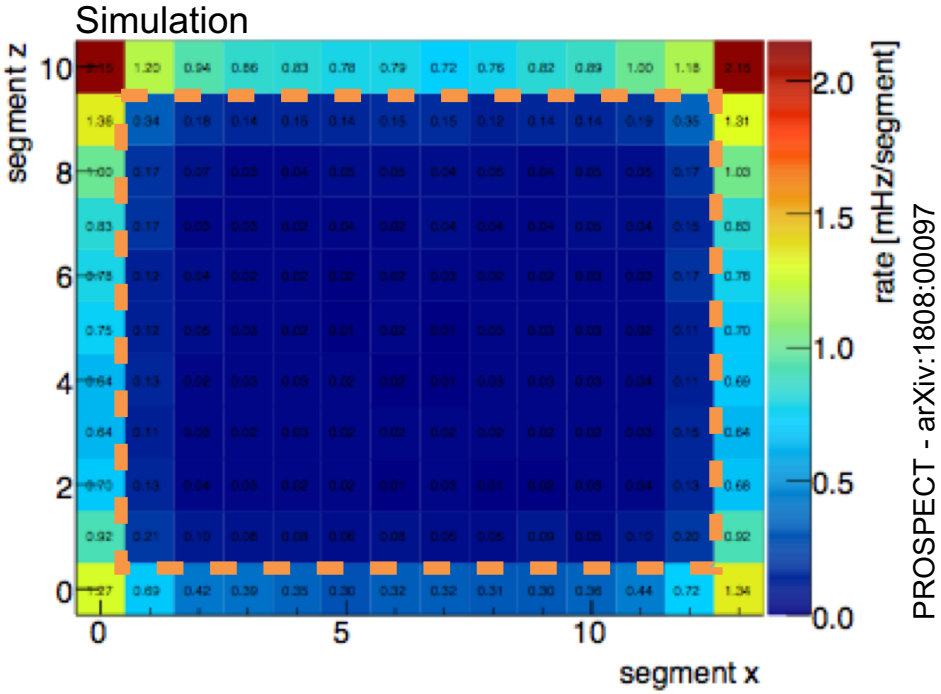




PROSPECT - arXiv:1808.00097

Active Background Suppression





- Detector design features provide background rejection via
  - Efficient recoil & neutron capture identification } PSD & ^{6}Li
  - Multi-interaction & multi-particle identification } Position Reconstruction
  - Fiducialization
- Signal:Background > 1:1 predicted using prototype validated MC; > 10^4 background rejection

ASSEMBLY IN 30S (VIDEO)

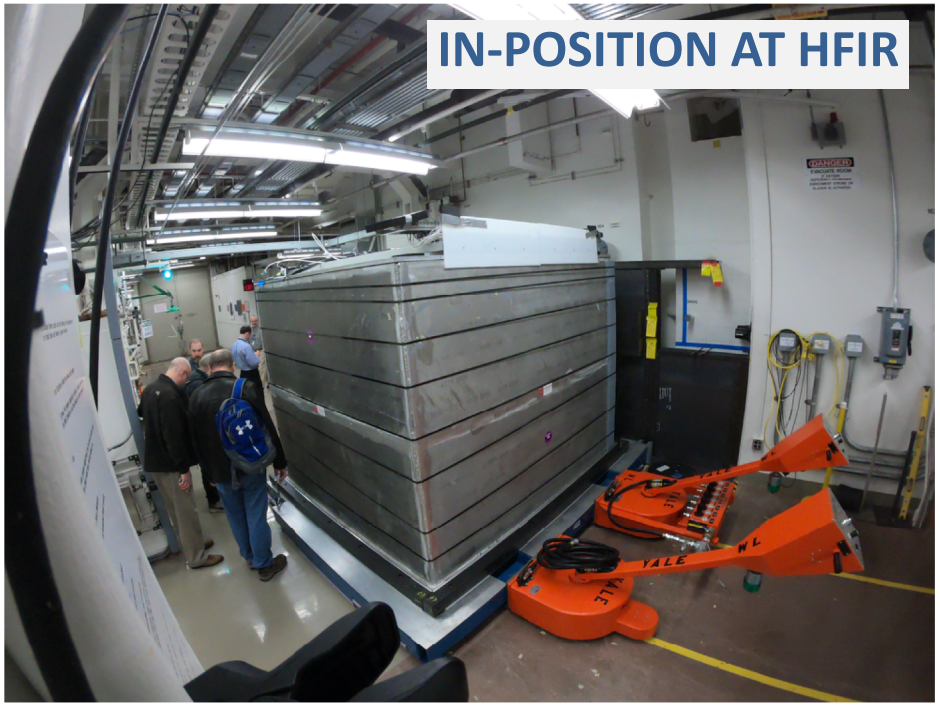
ASSEMBLY OF FIRST ROW

NOVEMBER 1, 2017

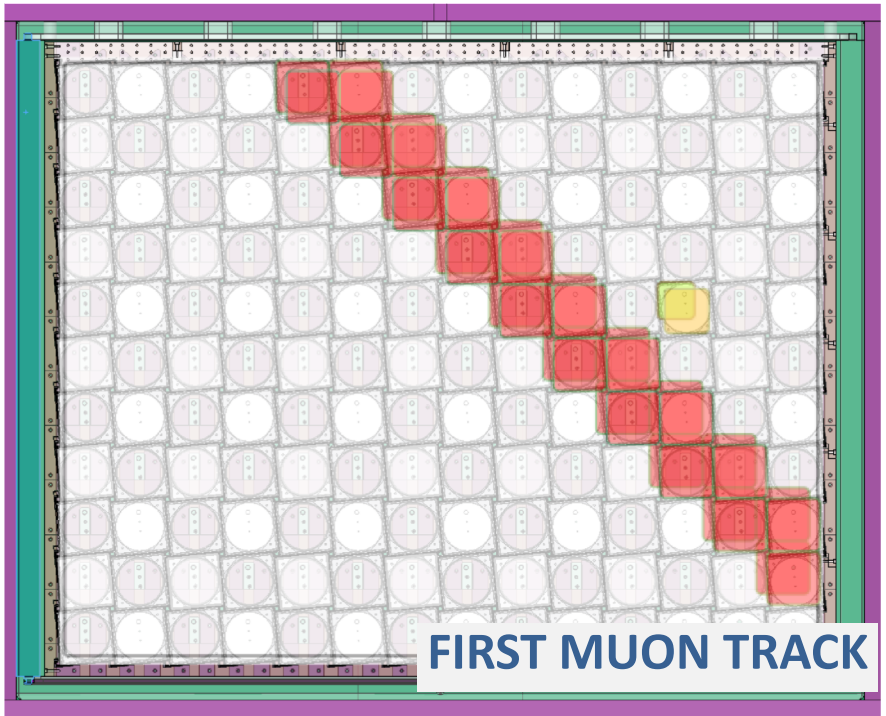
NOVEMBER 17, 2017
FINAL ROW INSTALLATION


DEC, 2017 - JAN 2018
DRY COMMISSIONING AT YALE

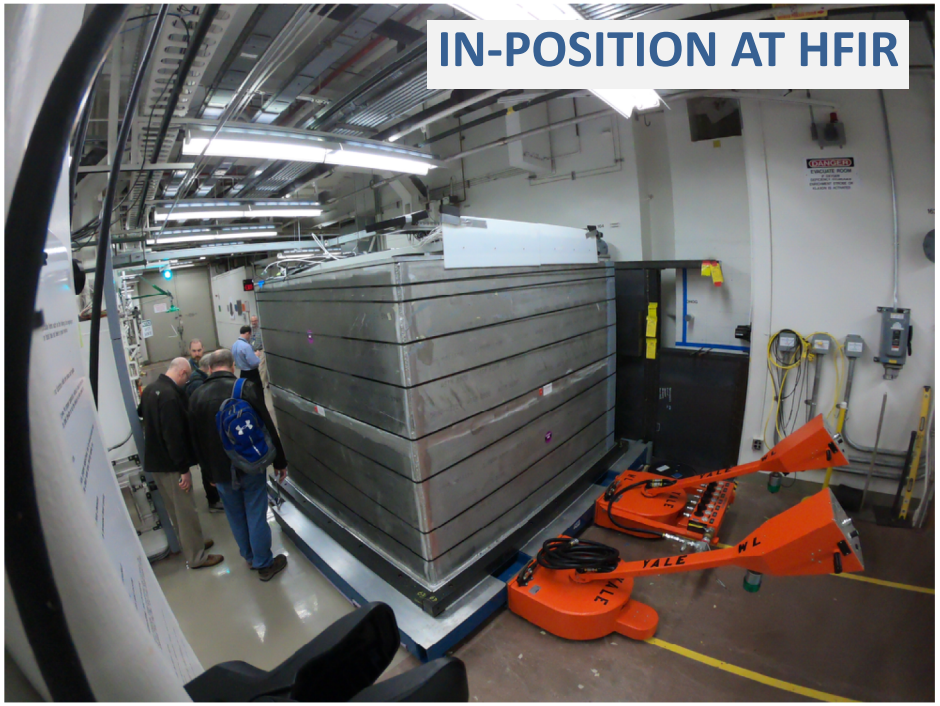

FEBRUARY 2018
ARRIVAL AT ORNL


IN-POSITION AT HFIR


FILLING FROM MIXING TANK


FIRST MUON TRACK

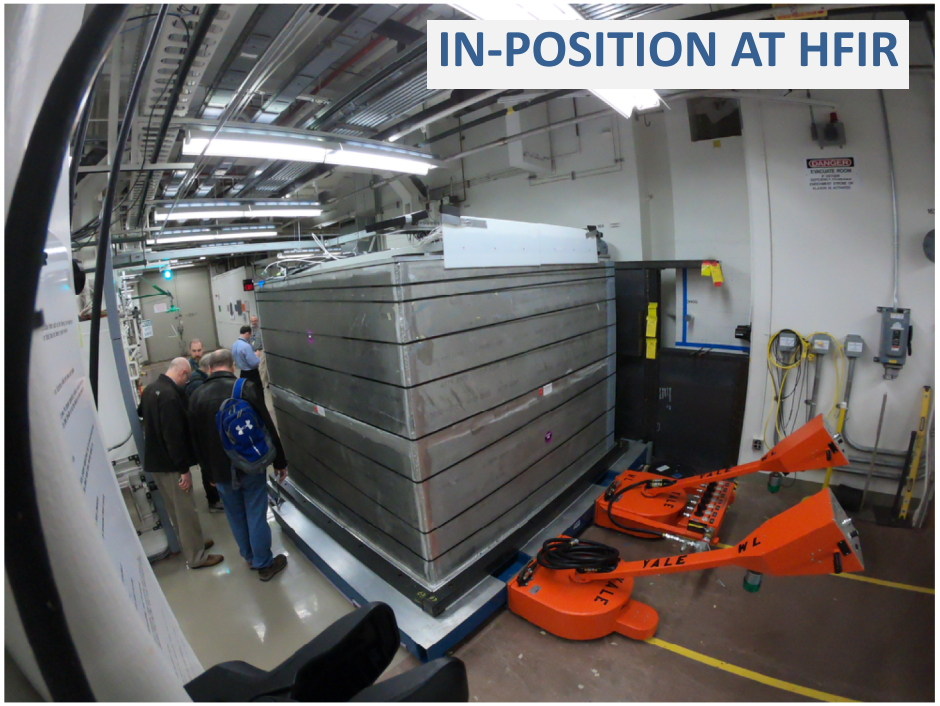

FEBRUARY 2018
ARRIVAL AT ORNL


IN-POSITION AT HFIR

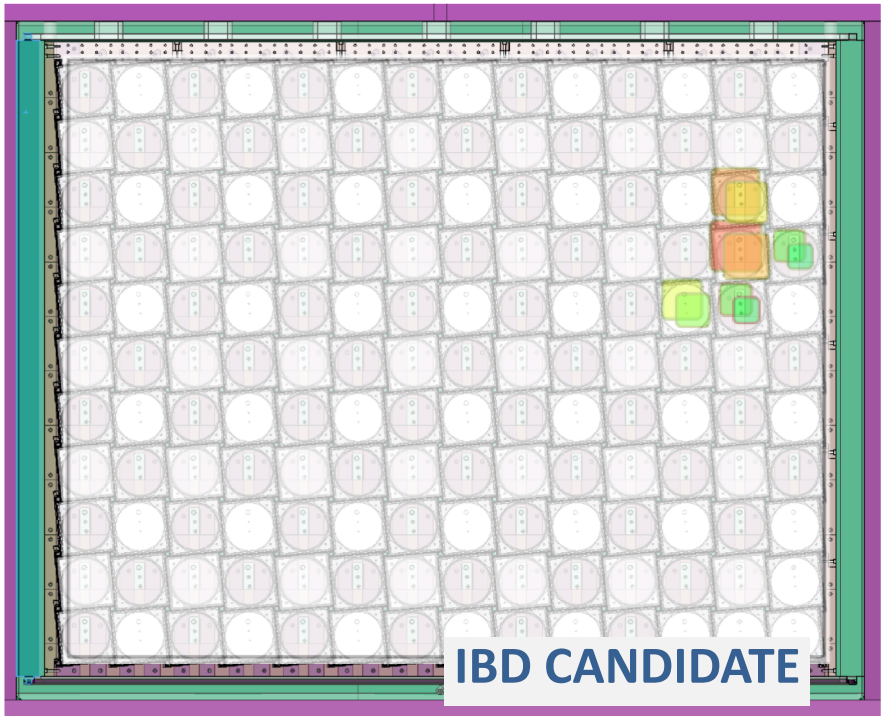

FILLING FROM MIXING TANK


HADRONIC SHOWER


FEBRUARY 2018
ARRIVAL AT ORNL


IN-POSITION AT HFIR

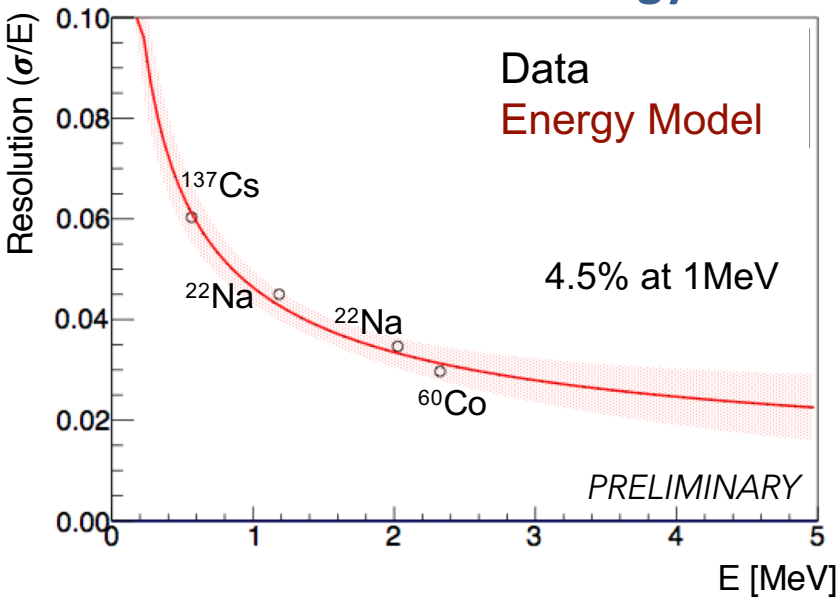

FILLING FROM MIXING TANK


IBD CANDIDATE

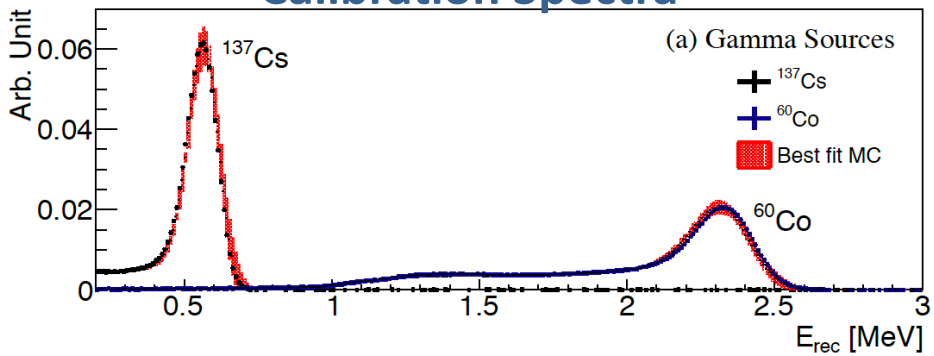
Energy Reconstruction

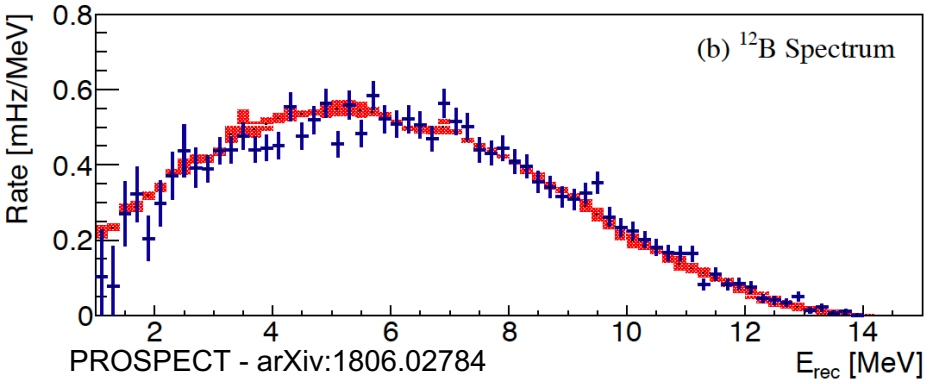
- Sources deployed throughout detector, measure single segment response
- Proton PSD tagged ^{12}B production
  - High-energy beta spectrum calibration
- Full-detector E_{rec} within 1% of E_{true}
- **High light collection: 795±15 PE/MeV**

Resolution vs Energy



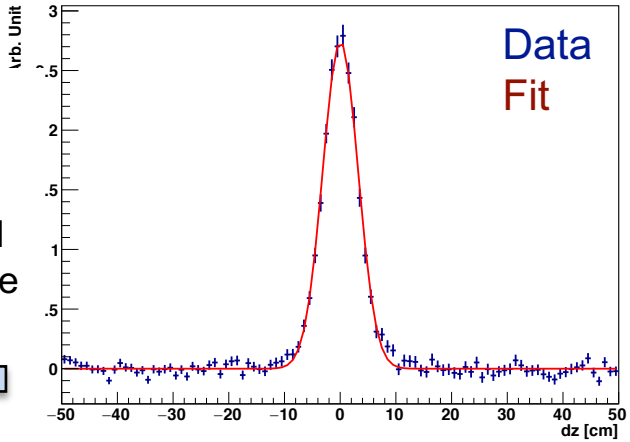
Calibration Spectra



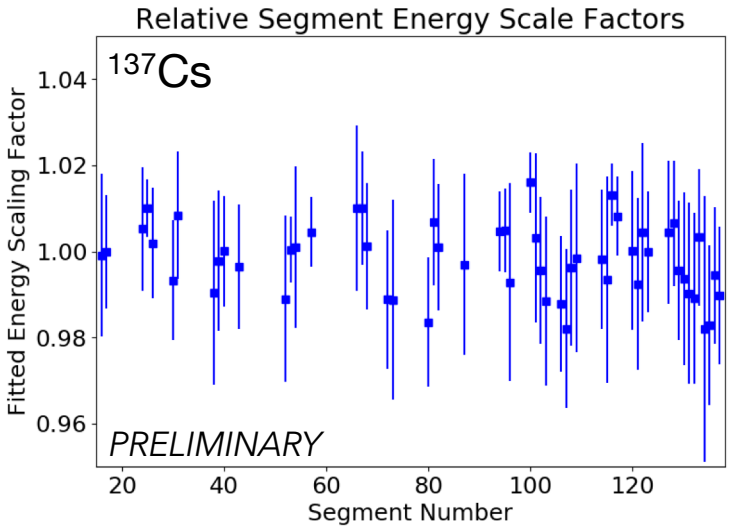


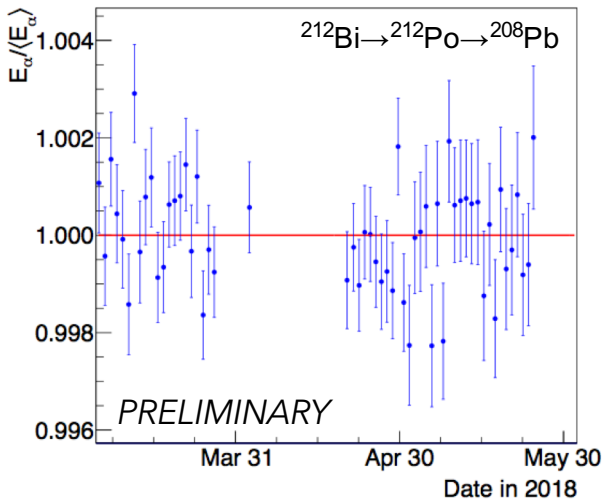
^{12}C(n,p)^{12}B Proton – ^{12}B separation

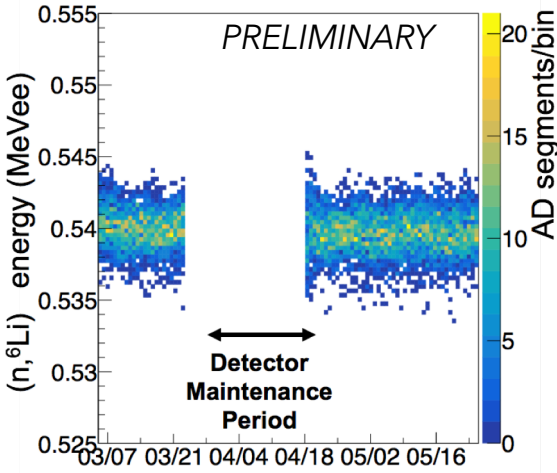
High-purity ^{12}B sample position & time tagged by final state proton



Energy Stability and Uniformity

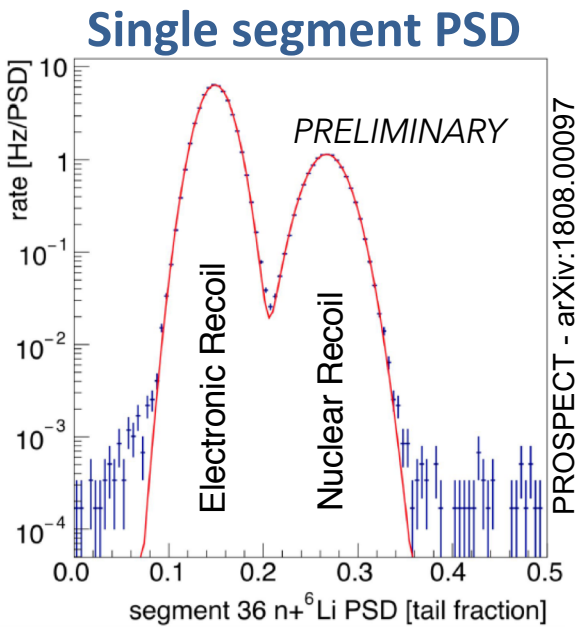


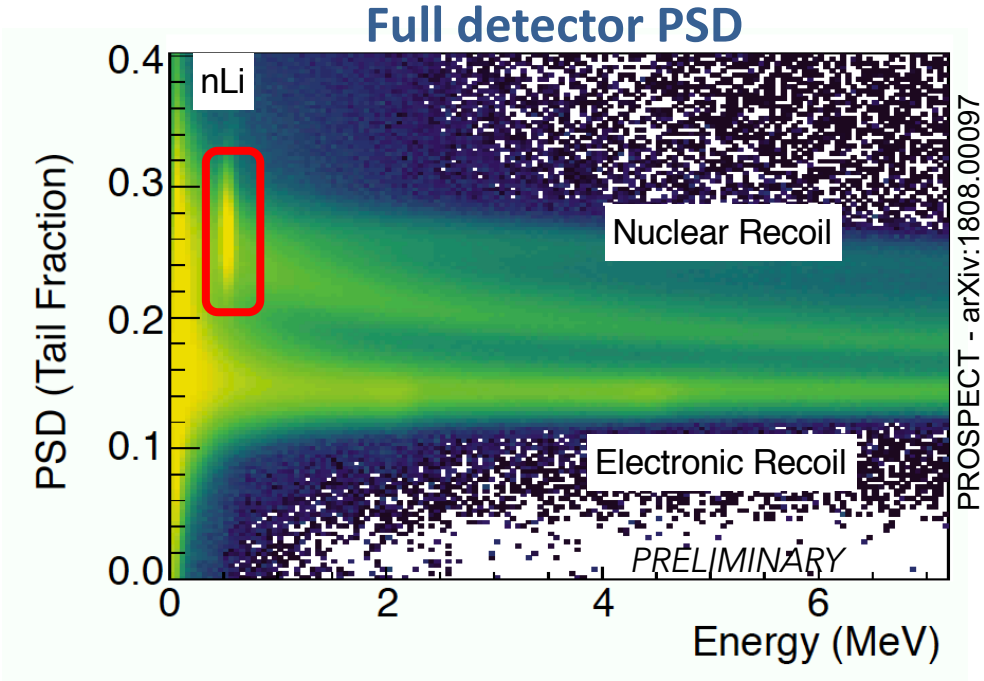




- **Calibration Source Deployment:**
  - 35 calibration source tubes throughout detector to map energy response
  - Segment to segment uniformity ~1%
  - ^{252}Cf source to study neutron capture efficiency
- **Intrinsic radioactive sources**
  - Track uniformity over time with distributed internal single-segment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

Pulse Shape Discrimination Performance

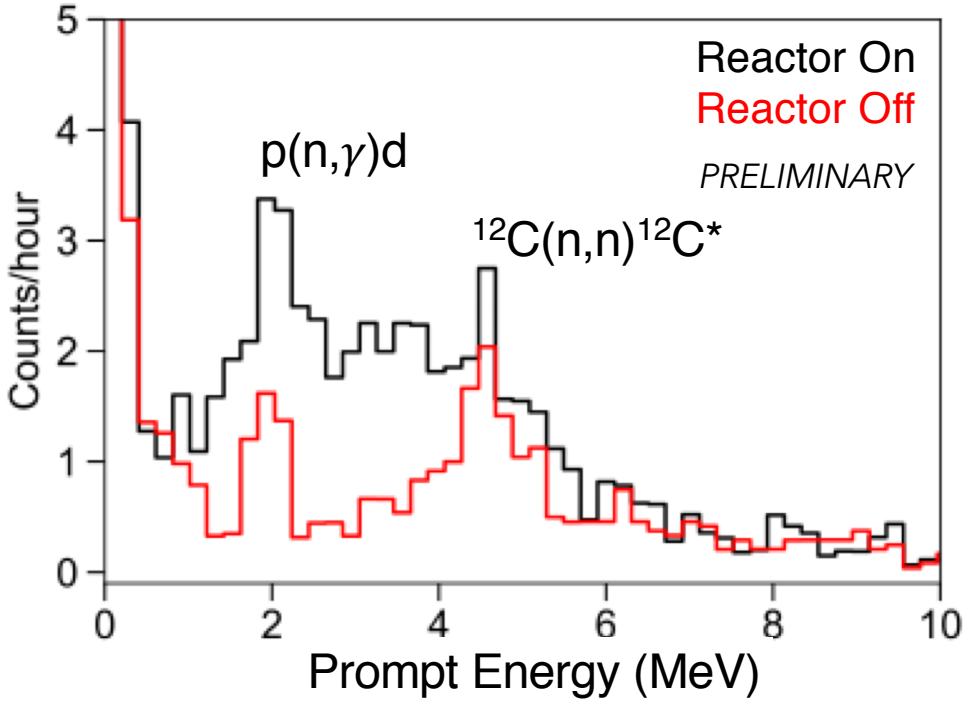




- Excellent particle ID of gamma interactions, neutron captures, and nuclear recoils
- Dominant backgrounds: Cosmogenic fast neutrons, reactor-related gamma rays, reactor thermal neutrons
  - Vast majority identified and rejected by PSD for Prompt and Delayed signals
- **Tag IBDs with high efficiency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

First 24hr of Detector Operation

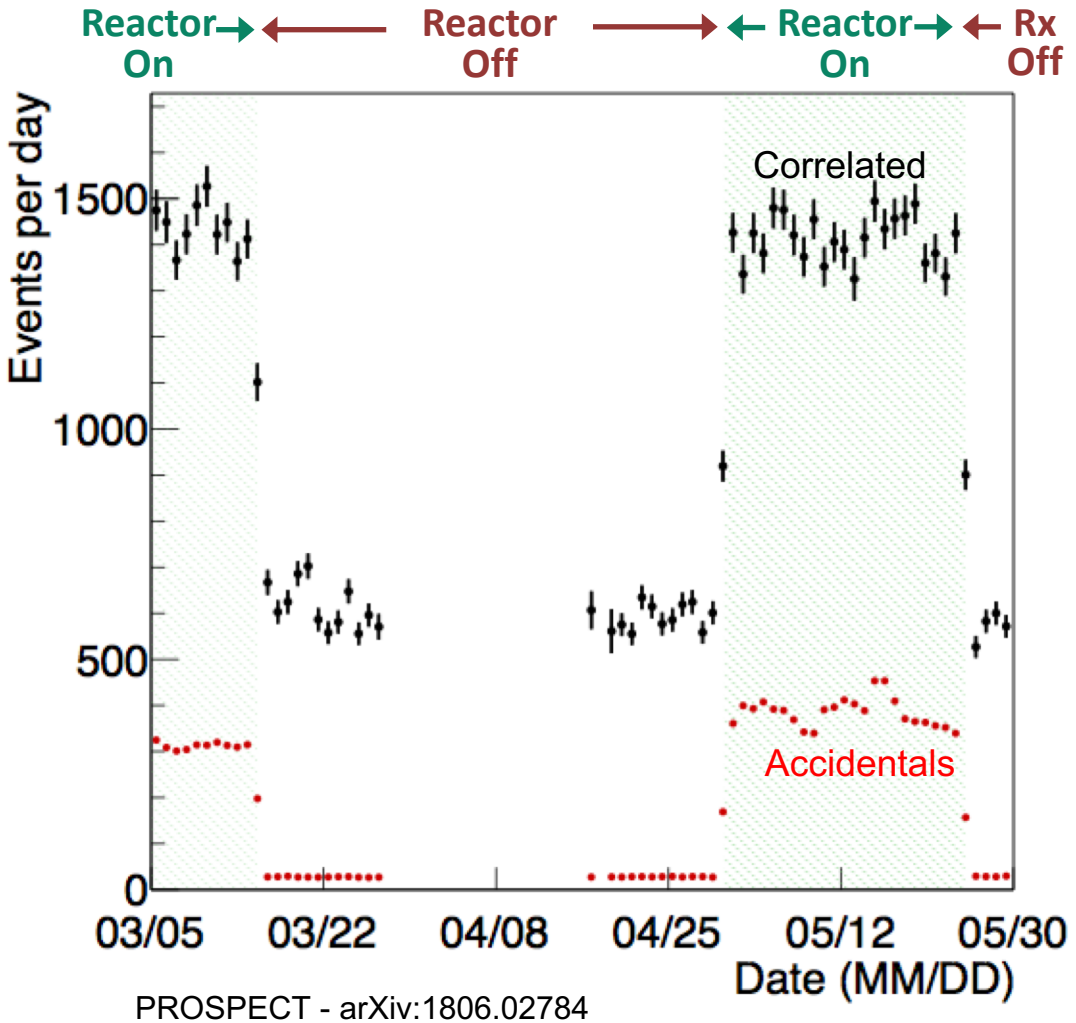
- **March 5, 2018:** Fully assembled detector began operation
- **Reactor On:** 1254±30 correlated events between [.8, 7.2MeV]
- **Reactor Off:** 614±20 correlated events (first off day March 16)
  - Distinct peaks in background from neutron interactions with H and ^{12}C
- Time to 5σ reactor antineutrino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



^{235}U reactor antineutrino spectrum analysis in progress

First Analysis Data Set - *arXiv:1806.02784*

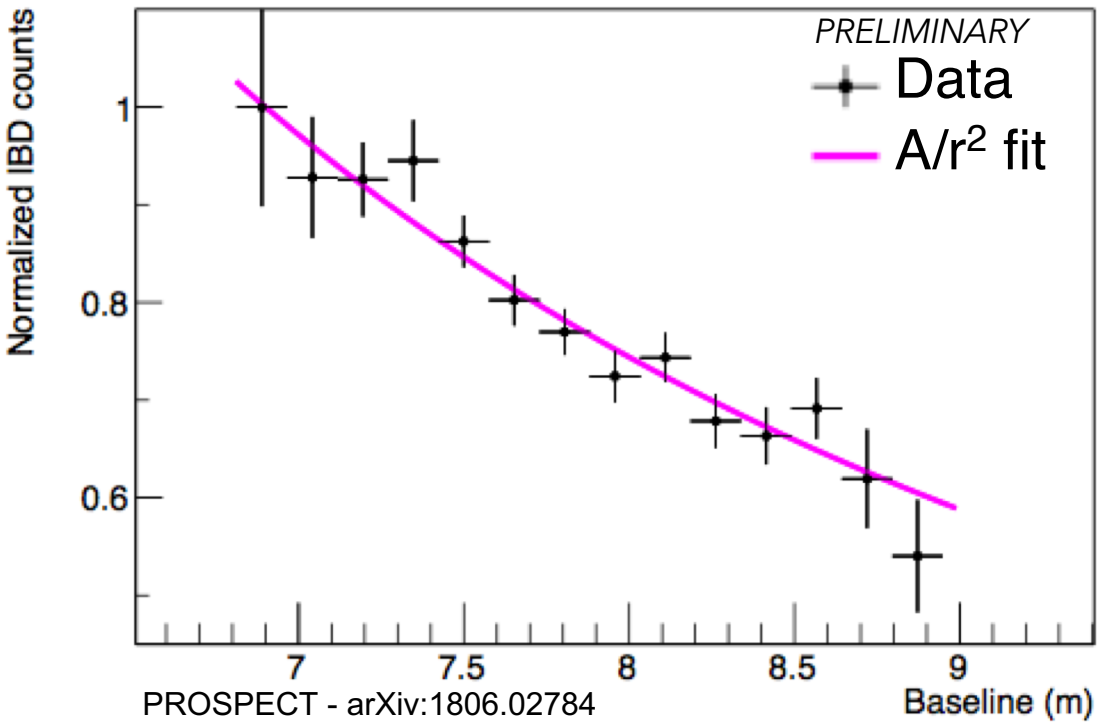
- 33 days of Reactor On
- 28 days of Reactor Off
- Correlated S:B = 1.36
- Accidental S:B = 2.25
- 24,608 IBD interactions
- Average of ~750 IBDs/day
- IBD event selection defined and fro
  on 3 days of data



PROSPECT - arXiv:1806.02784

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

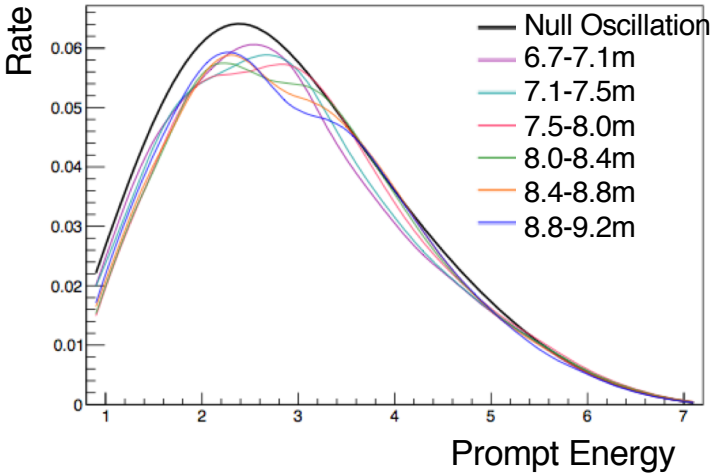
IBD Rate vs Baseline



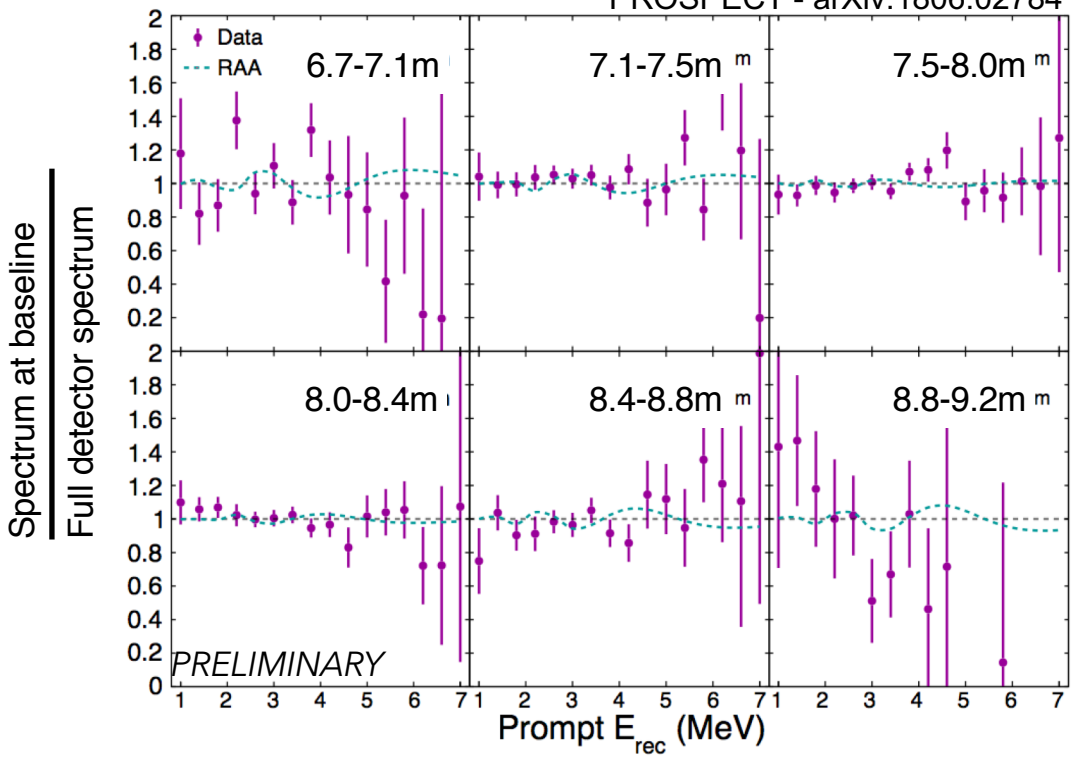
- Observation of $1/r^2$ behaviour within the detector itself
- Cover a wide relative baseline range, even in one detector position

IBD Spectrum vs Baseline

Illustration of Baseline Dependent Oscillation



PROSPECT - arXiv:1806.02784

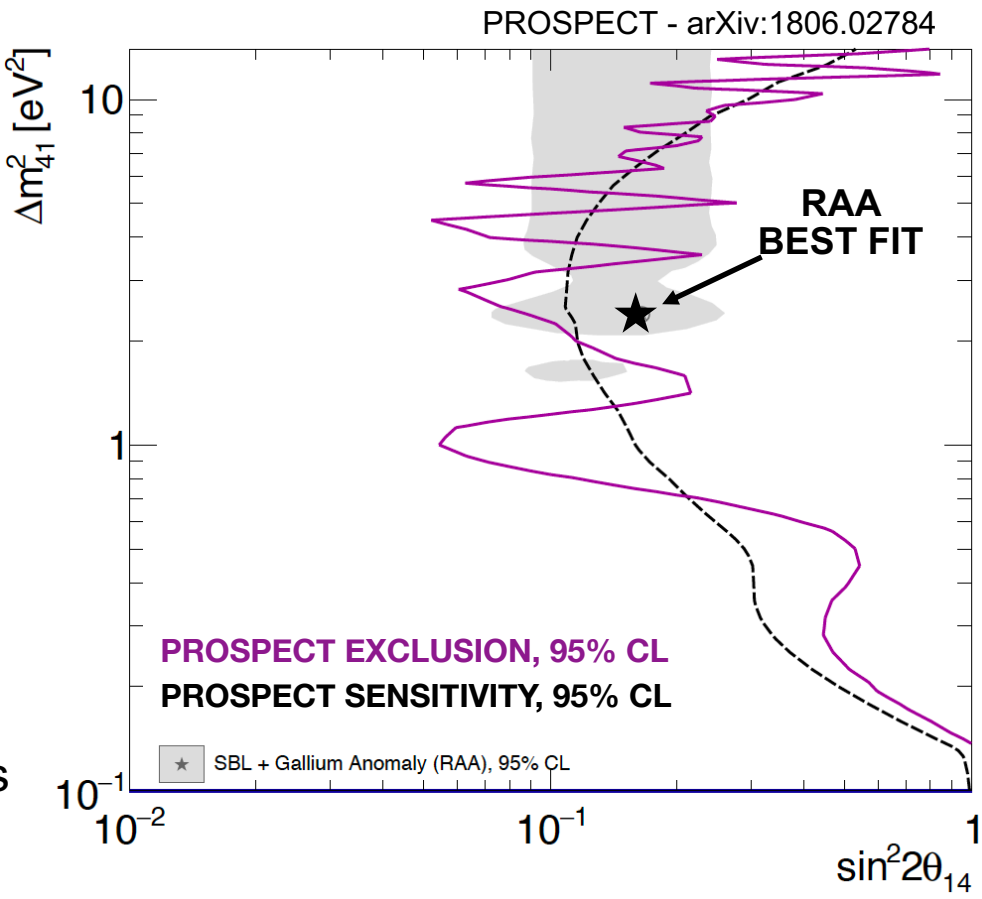


- Compare spectra from 6 baselines to measured full-detector spectrum
- Null-oscillation would yield a flat ratio for all baselines

Direct ratio search for oscillations, independent of reactor models

Oscillation Search Results

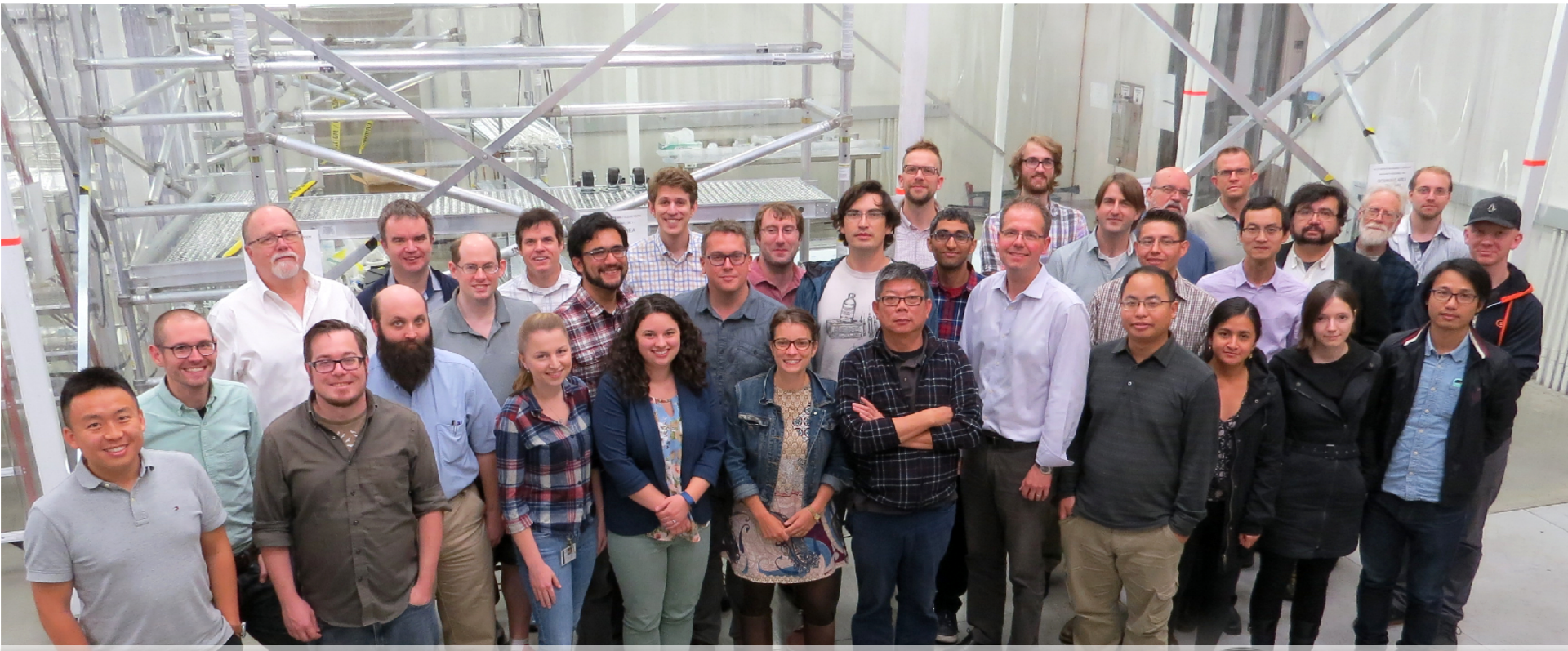
- Build a χ^2 by comparing measured spectra to predicted spectra at each baseline
- Covariance matrices capture all uncertainties and energy/baseline correlations
- Feldman-Cousins based confidence intervals for oscillation search
- Critical χ^2 map generated from toy MC using full signal and background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



Direct test of the Reactor Antineutrino Anomaly

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

PROSPECT Collaboration



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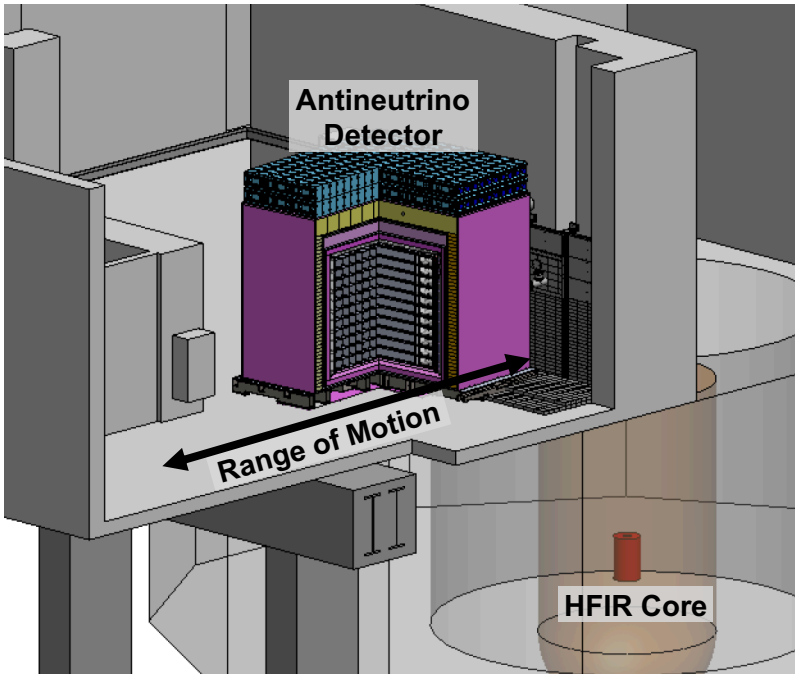
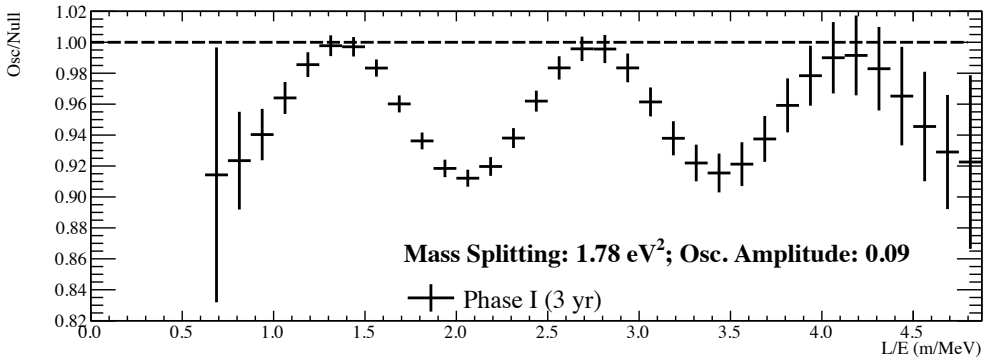
Conclusion

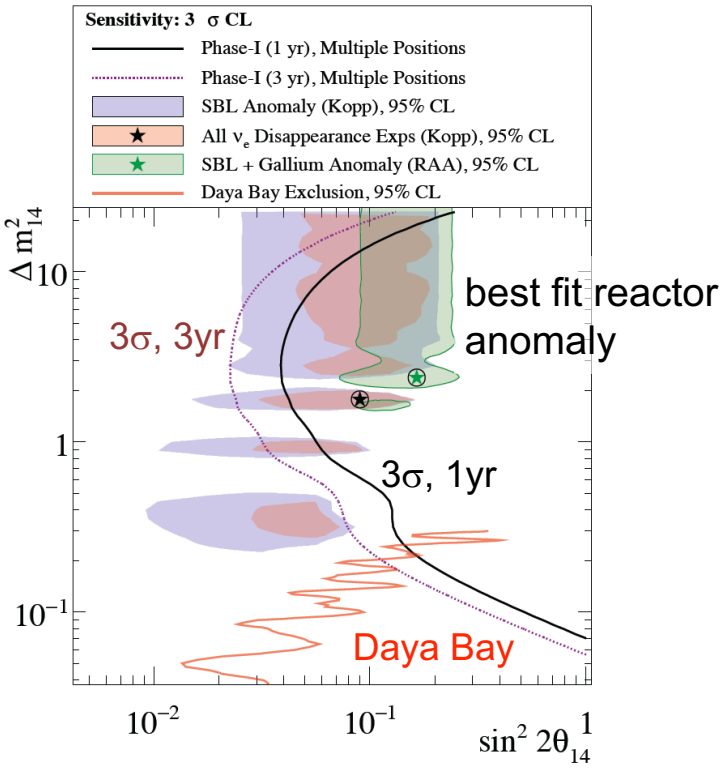
- PROSPECT started data collection in early March 2018
- Observed antineutrinos from HFIR with good signal/background
- Background rejection and energy resolution meet expectations based on comprehensive PROSPECT R&D program
- The PROSPECT Detector provides:
  - opportunity for detailed study of cosmogenic 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
- Working towards a high-statistics ^{235}U spectrum measurement and collecting more data

PROSPECT Physics - Precision Oscillation Experiment

A model independent experimental approach to test for oscillation of eV-scale neutrinos







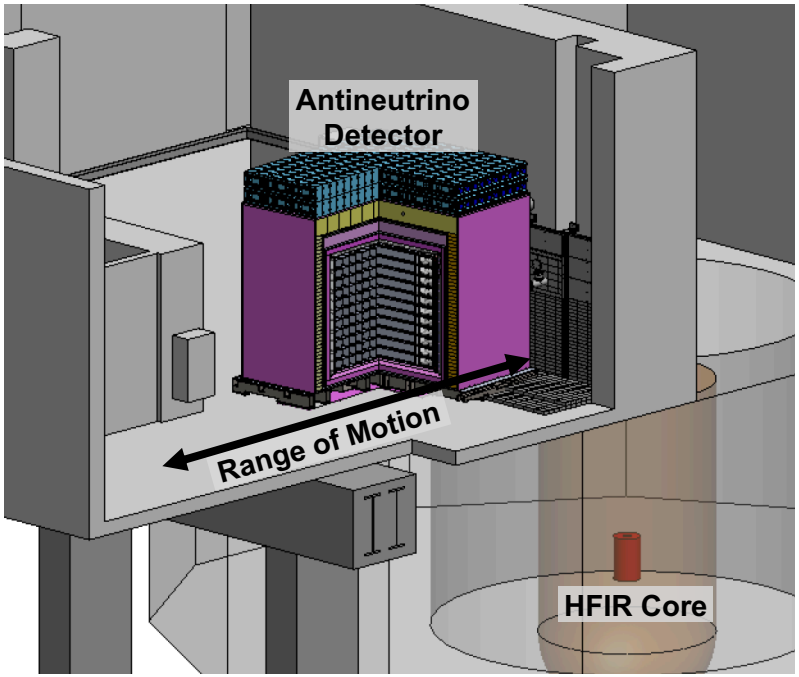
Objectives

4σ test of best fit after 1 year

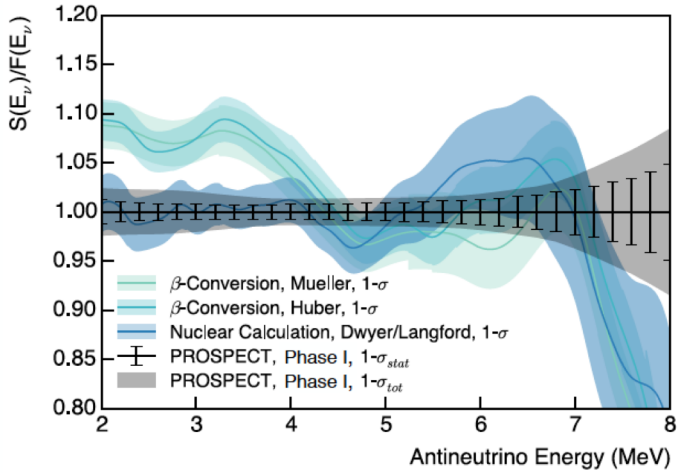
>3σ test of favored region after 3 years

PROSPECT Physics - Precision Spectrum Experiment

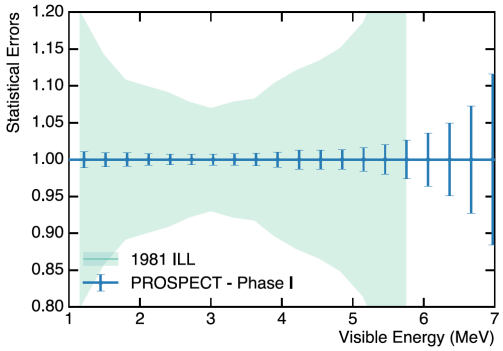
A precision measurement to address spectral unknowns



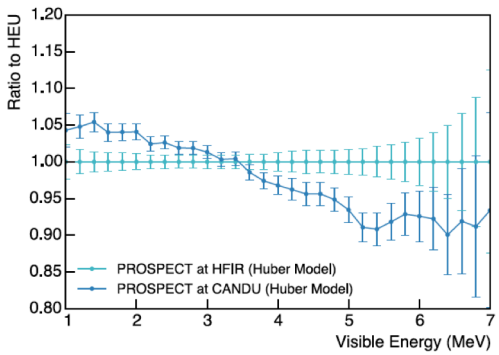
Testing ^{235}U $\bar{\nu}_e$ spectrum models



Large improvement on ILL



Different reactor cores



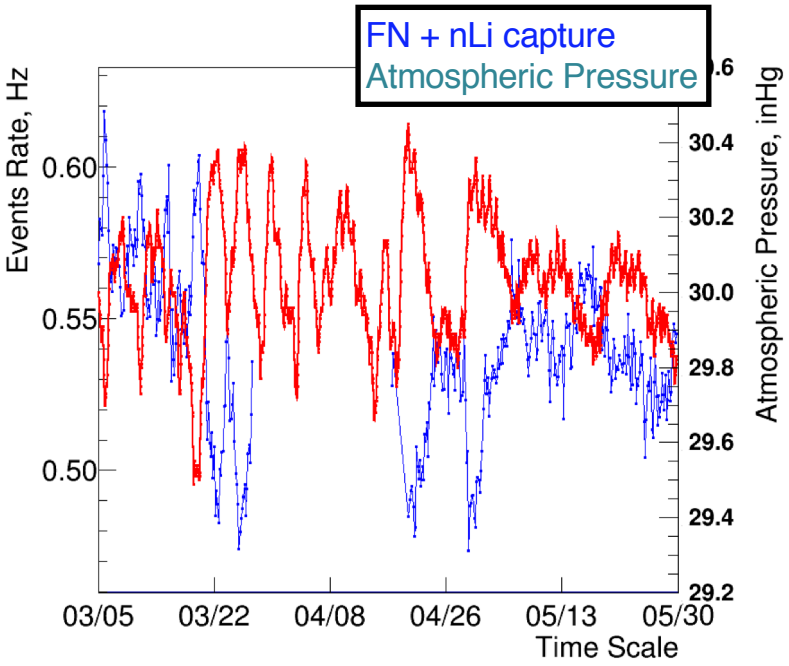
Objectives

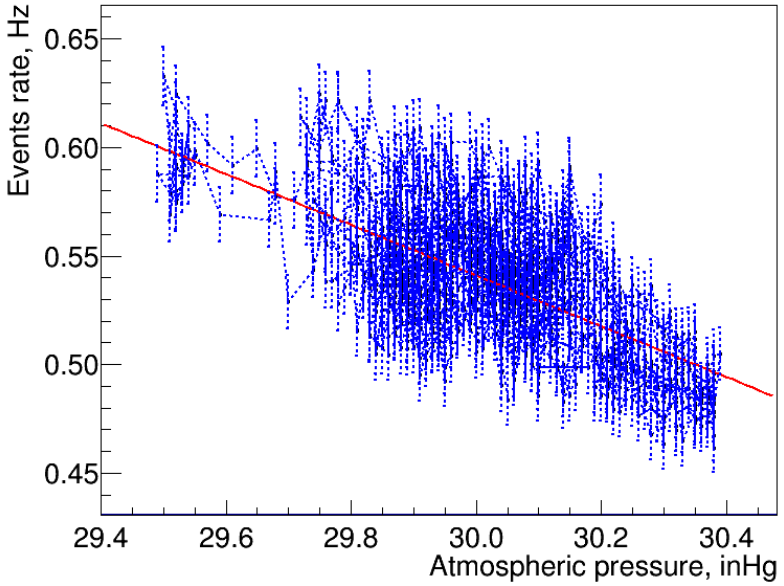
Measurement of ^{235}U spectrum

Compare different reactor models

Compare different reactor cores

Time dependence of Cosmogenic backgrounds





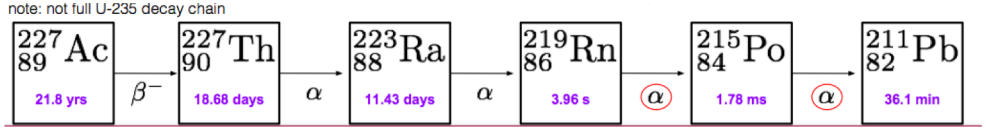
- Correlation between cosmogenic backgrounds and atmospheric pressure

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

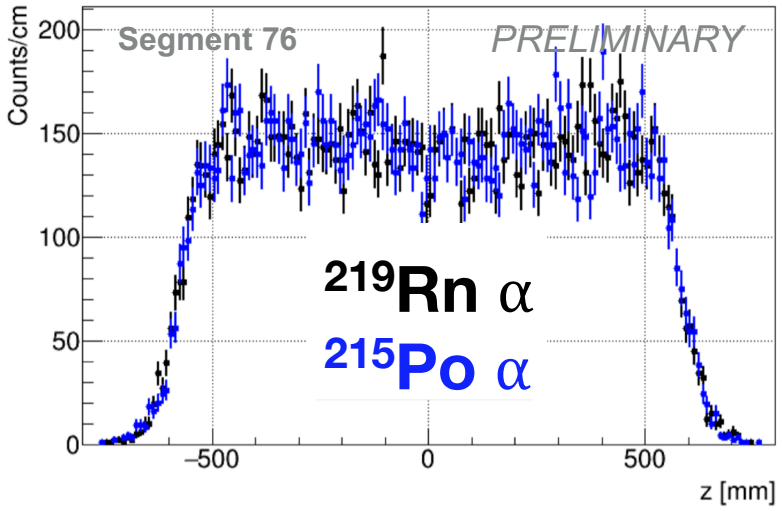
Relative Segment Volume Measurement

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

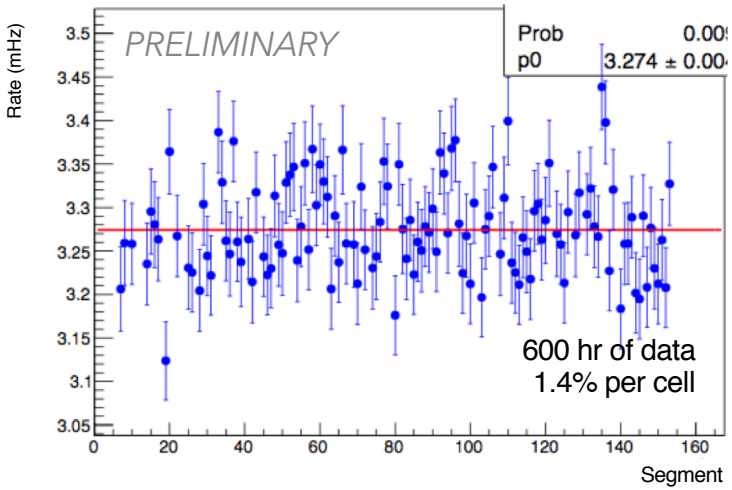
note: not full U-235 decay chain



- ^{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



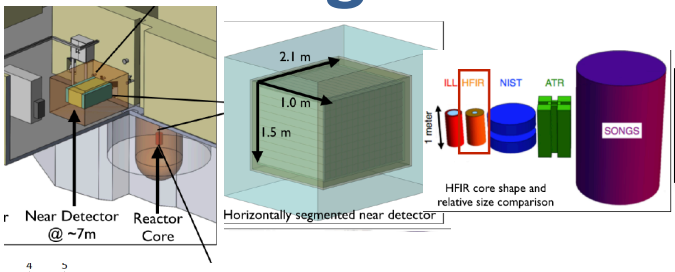
Uniformity in rates within segment

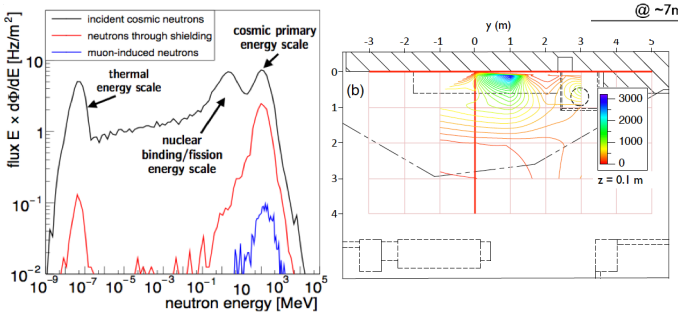


Uniformity in rates between segments

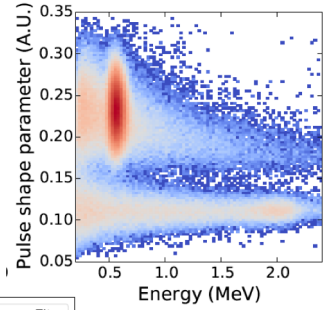
Comprehensive R&D Program

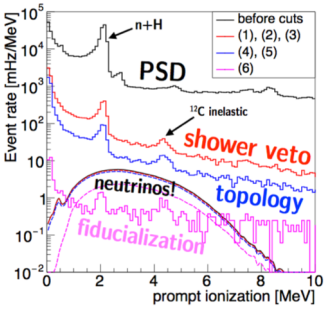
- **Conceptual design for physics and background requirements**
- **Reactor site assessment**



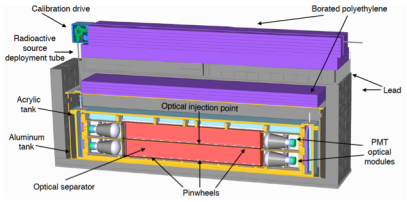


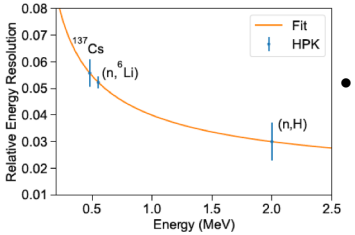
- **Characterize reactor & cosmogenic background**
- **Validate shielding & detector MC with onsite prototypes**





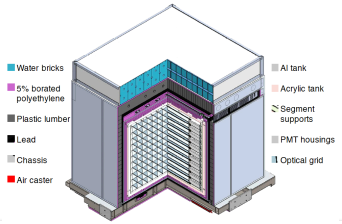
- **Develop detector design and analysis that achieves required S:B**
- **Demonstrate required segment and LiLS performance**

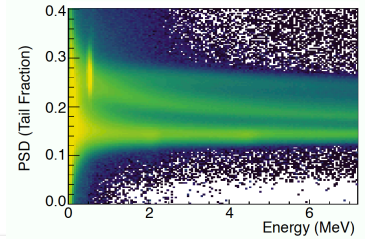




- **Demonstrate required performance with production components**

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





PROSPECT Whitepaper
arXiv:1309.7647

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

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

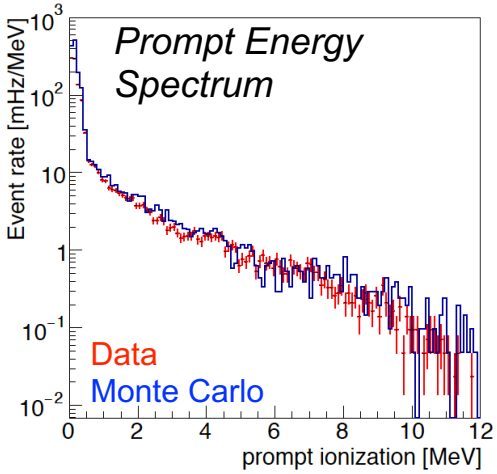
Physics Program
J. Phys. G, 43 113001
arXiv:1512.02202

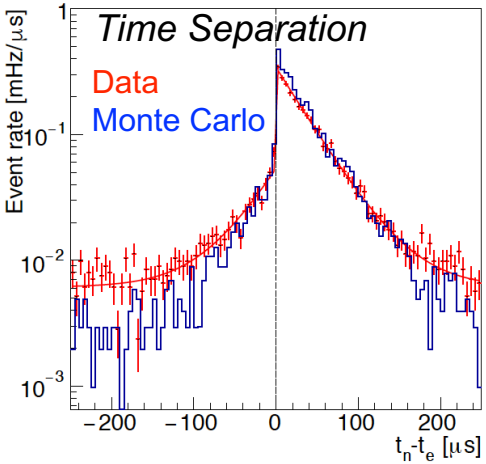
Production Prototype Segment and LiLS
JINST 13 P06023 (2018)
arXiv:1805.09245

PROSPECT Experiment
Submitted to NIMA
arXiv:1808.00097

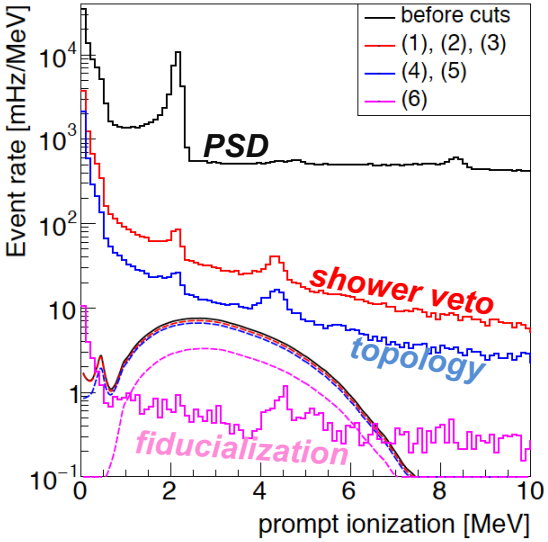
Signal to Background Prediction

Prototype systems provide benchmarking of AD Monte Carlo



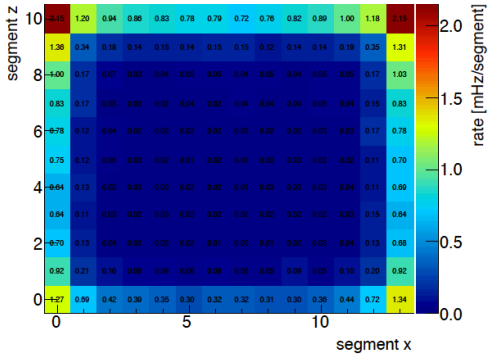


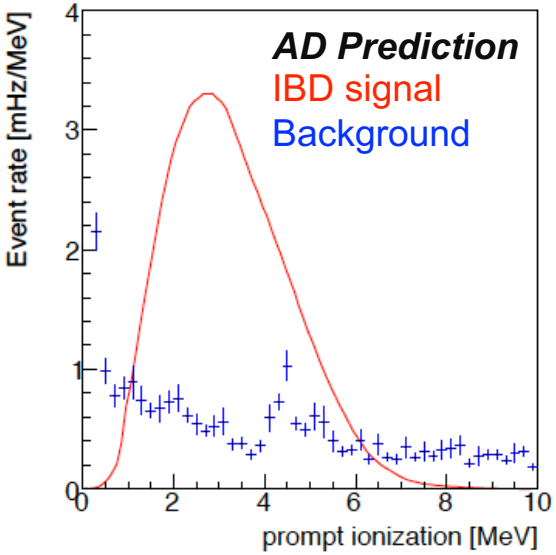
PROSPECT20 Correlated Background Measurements



Background rejection via:

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



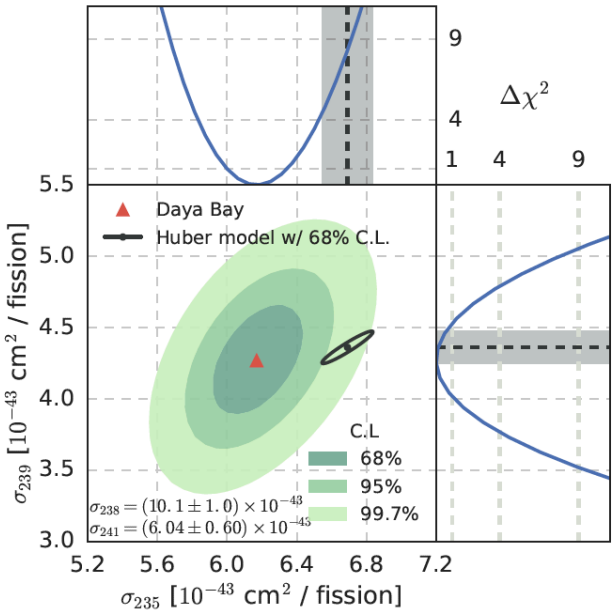


S/B better than 1:1 is predicted for PROSPECT AD. Rate and shape of residual IBD-like background can be measured during numerous reactor off periods.

Flux evolution & IBD Yields

Reactor Flux Evolution

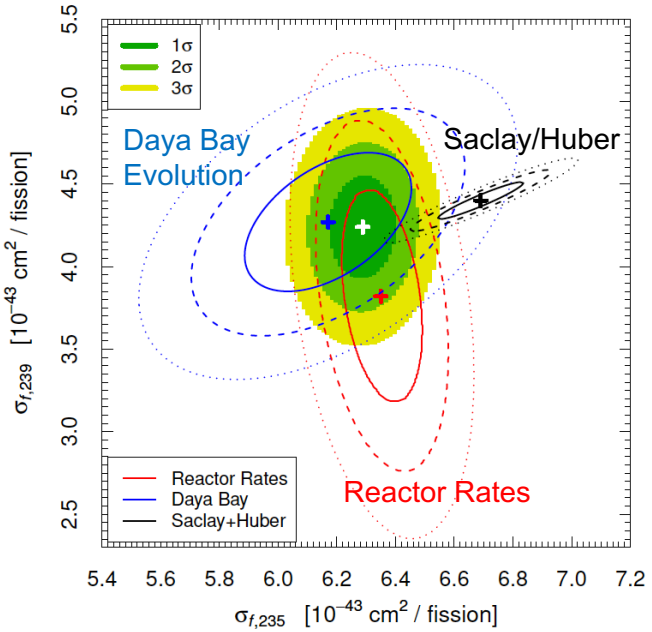
Daya Bay, PRL 118 251801 (2017)



Report IBD yields for U-235 and Pu-239 using change due to fuel evolution – demonstrates prediction for U-235 (at least) is incorrect

Improved Cross Section per Fission Determination

Giunti, arXiv:1704.02276



Tension between IBD yield from 26 previous reactor measurements and Daya Bay

Direct, model independent, search for short baseline oscillation remains well motivated

"not enough information to use the antineutrino flux changes to rule out the possible existence of sterile neutrinos"

Hayes et al, arXiv:1707.07728

"the search for the explanation of the reactor antineutrino anomaly still remains open"

Gunti et al, arXiv:1708.01133