PROSPECT
Precision Oscillation and Spectrum Experiment

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Yale University
on behalf of the PROSPECT collaboration

Wright Laboratory

NDM 2018

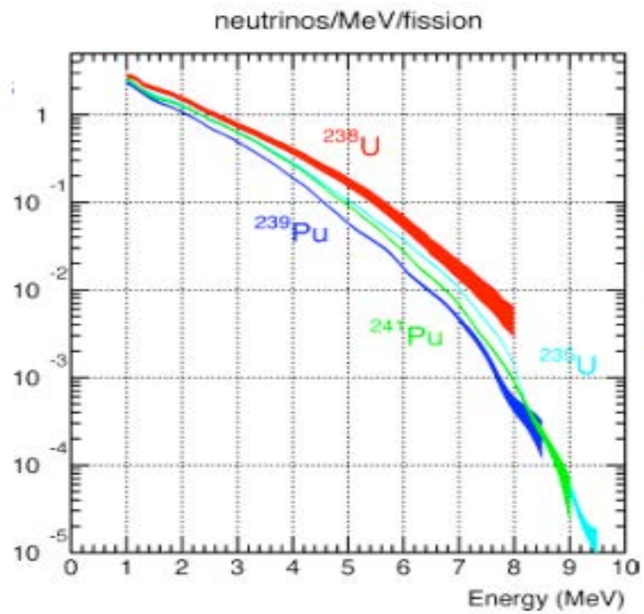
Yale

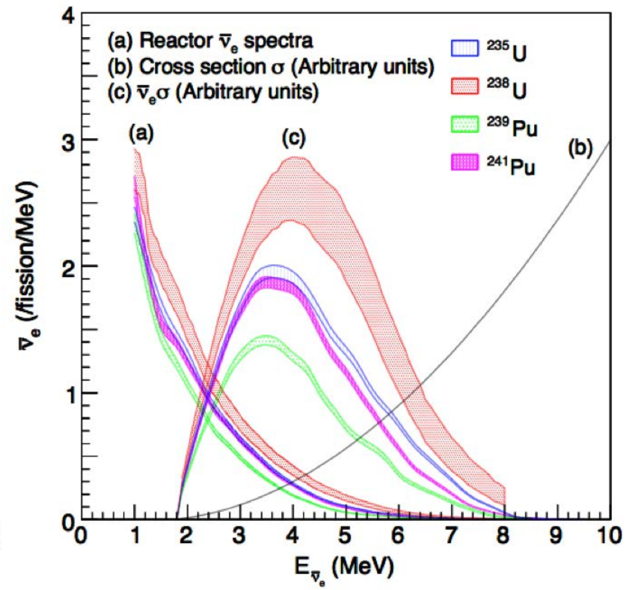
Reactor Antineutrinos

$\overline{\nu}_e$ from β-decays, pure $\overline{\nu}_e$ source

of n-rich fission products

on average ~6 beta decays until stable





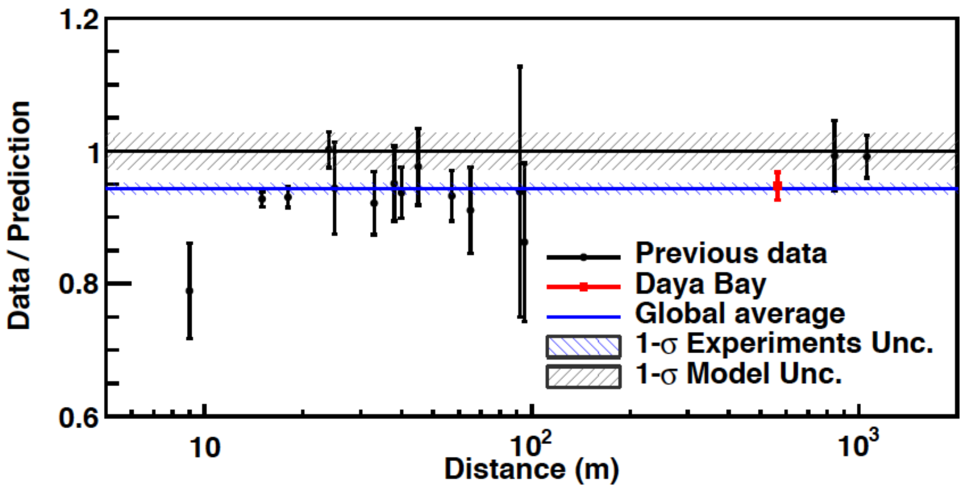
> 99.9% of $\overline{\nu}_e$ are produced by fissions in ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu

mean energy of $\overline{\nu}_e$: 3.6 MeV

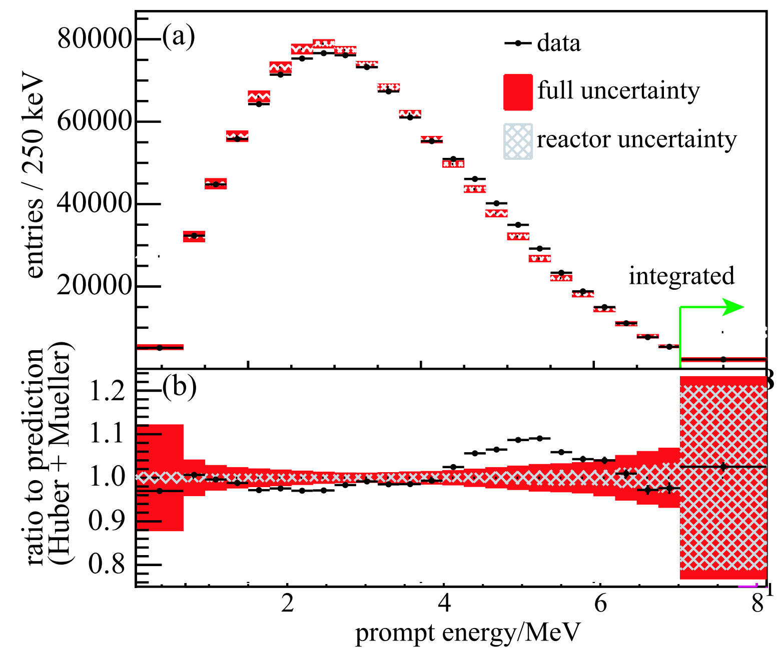
only disappearance experiments possible

Reactor Antineutrino "Anomalies" (RAA)

Flux Deficit



Spectral Deviation



Extra (sterile) neutrino oscillations or artifact of flux predictions?

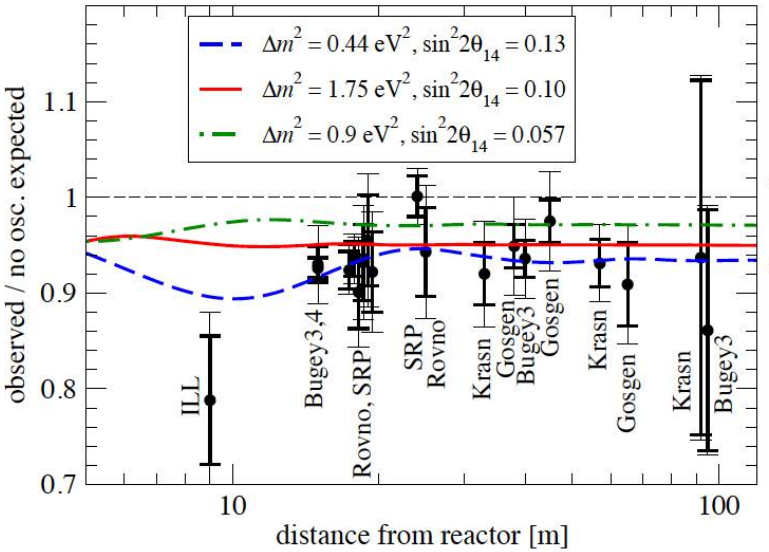
Measured spectrum does not agree with predictions.

Daya Bay,
CPC 41, No. 1 (2017)

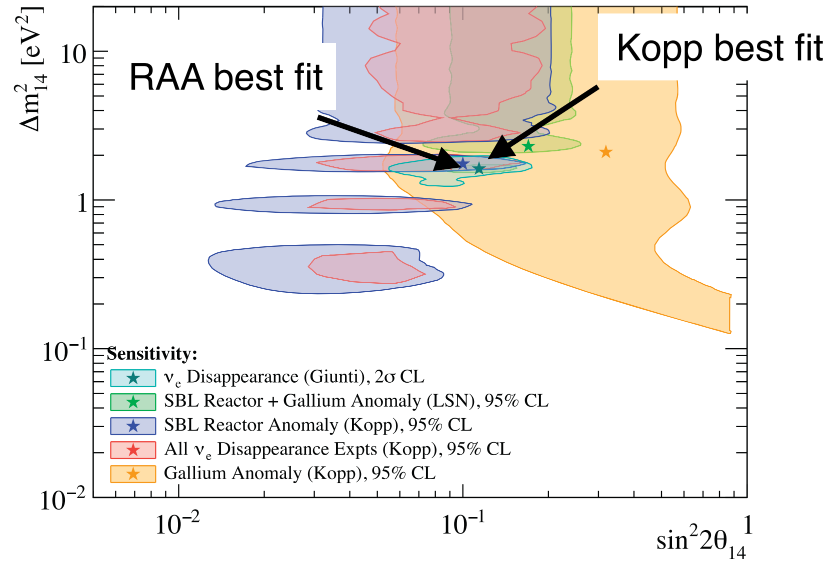
Understanding reactor flux and spectrum anomalies requires additional data

Reactor Antineutrino Flux Deficit

Reactor $\overline{\nu}_e$ flux measurements



$\overline{\nu}_e$ disappearance data



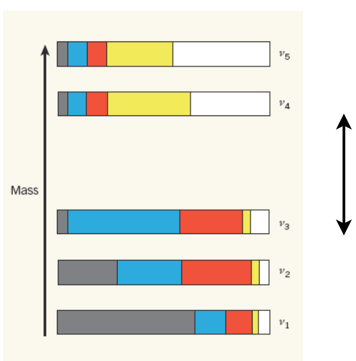
PROSPECT J. Phys. G: 43 (2016)

2011 reanalysis of the predicted reactor flux in tension with global data

Measurements of neutrino source with SAGE/Gallex also show a deficit

new oscillation signal requires:

$\Delta m^2 \sim O(1 eV^2)$ and $\sin^2 2\theta > 10^{-3}$
"sterile" neutrino states



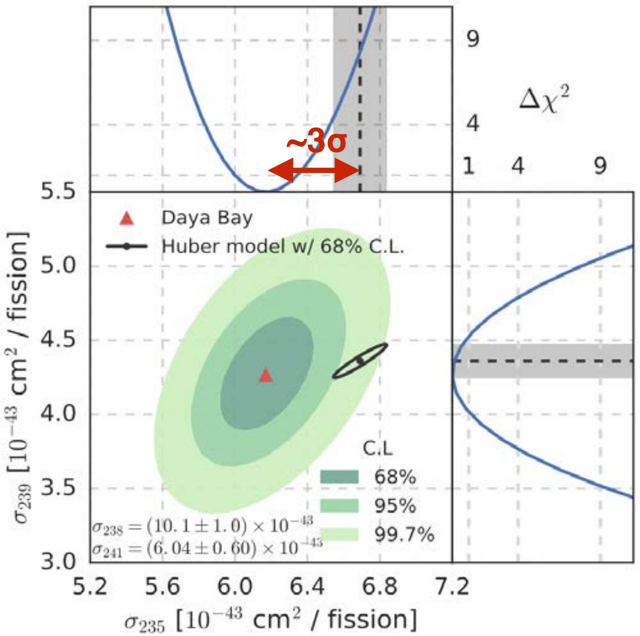
$\Delta m^2_{new} \sim 1$ eV^2

Fuel Evolution and $\overline{\nu}_e$ Fluxes

Isotopes in PWR Reactor
^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu

Daya Bay Fuel Evolution Analysis

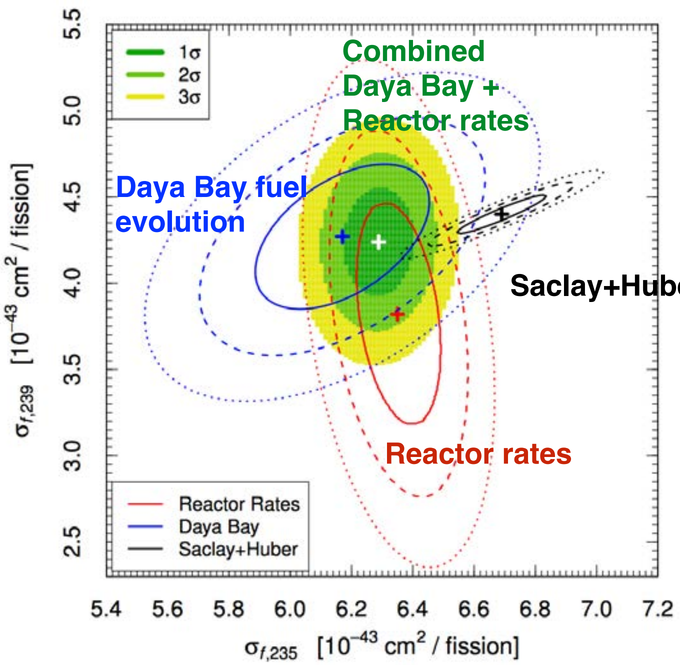
Daya Bay, PRL 118 251801 (2017)



Daya Bay reported IBD yields of ^{235}U and ^{239}Pu using evolution of LEU reactors. Reactor flux model found to be incorrect for ^{235}U.

Improved Determination of Fluxes

Giunti et al, Phys.Rev. D96 (2017) no.3, 033005



IBD yields calculated from reactor rates (of 26 reactor experiments) do not agree with Daya Bay measurement.

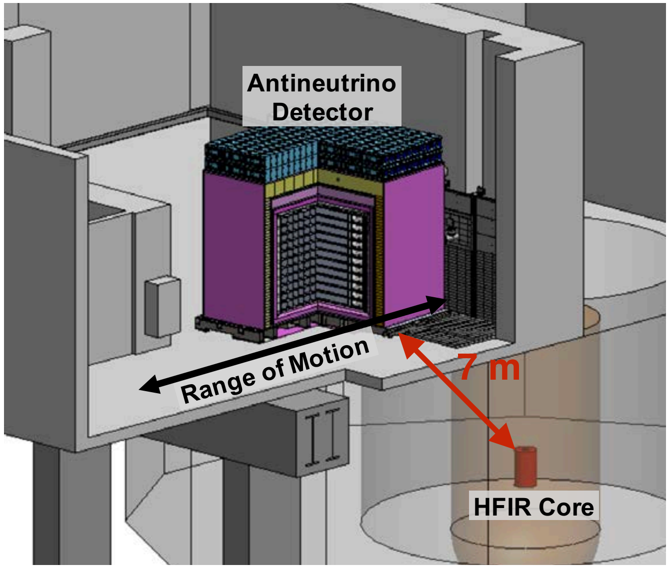
Analysis of Daya Bay with Fuel Burnup

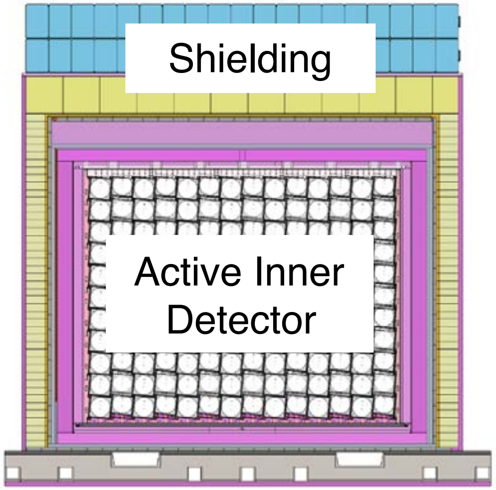
Hayes et al, Phys.Rev.Lett. 120 (2018) no.2, 022503

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

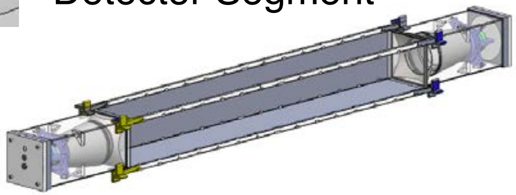
Precision Reactor and Oscillation Experiment

Segmented, ^{6}Li-loaded Movable Detector

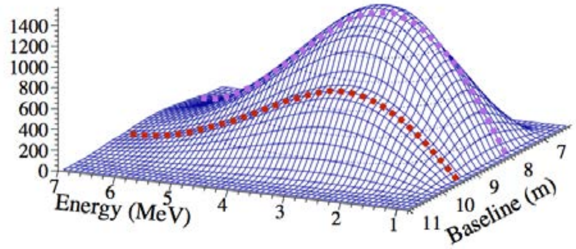




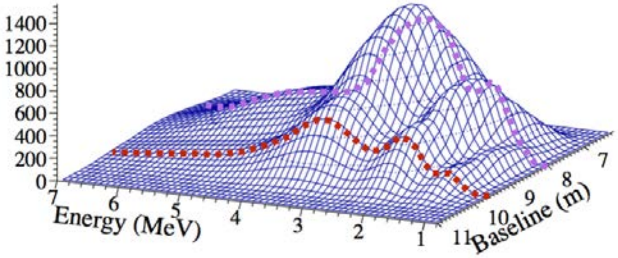
Detector Segment



unoscillated spectrum



oscillated spectrum



Detector Design

^{6}Li liquid scintillator
~4 ton
minimum dead material
movable detector
layered shielding package

Segmented Detector

14x11 segments
double-ended PMT readout
light guides, 5" PMTs
~4.5%/√E resolution

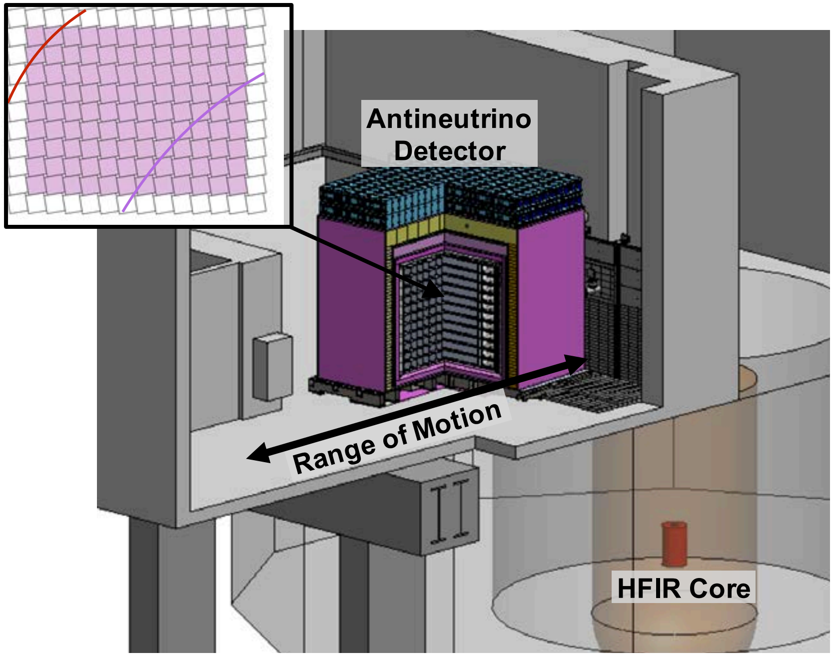
Relative Spectrum Measurement

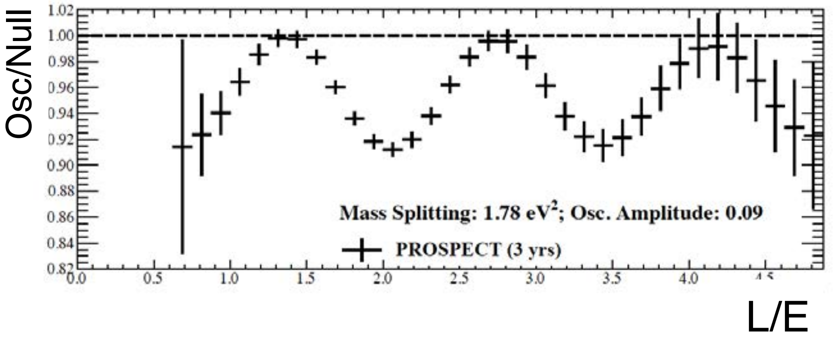
relative measurement of L/E and spectral shape distortions

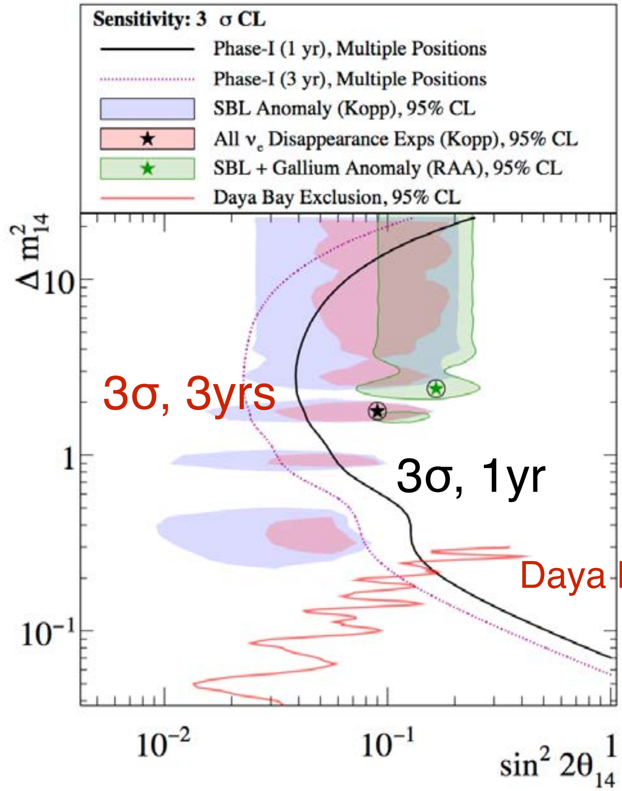
PROSPECT Physics

A Precision Oscillation Experiment

Model-independent test of oscillation of eV-scale neutrinos







Objectives

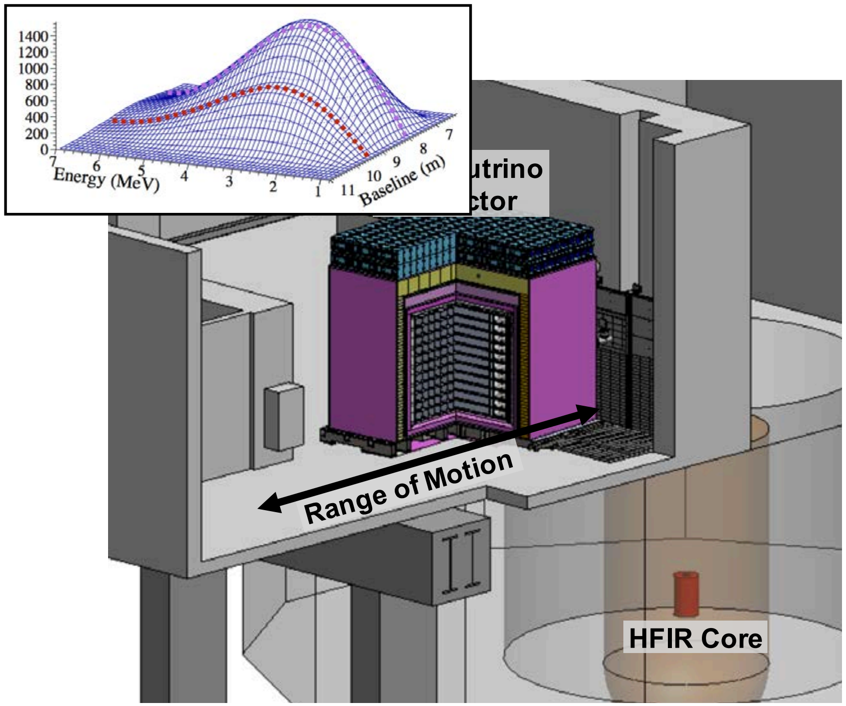
4σ test of best fit after 1 year

>3σ test of favored region after 3 years

PROSPECT Physics

A Precision Spectrum Experiment

A precision measurement of spectrum

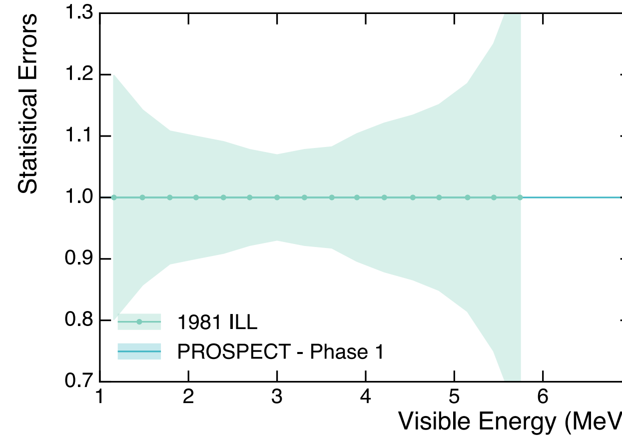


Objectives

Measurement of ^{235}U spectrum

Compare different reactor models

Improvement on ILL

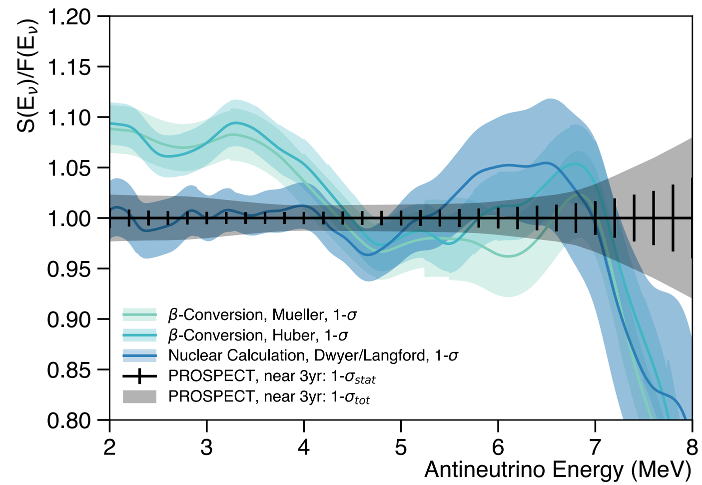


~100k events per year

~4.5%/√E

1981 ILL: ~5000 events

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



Antineutrinos from Reactors

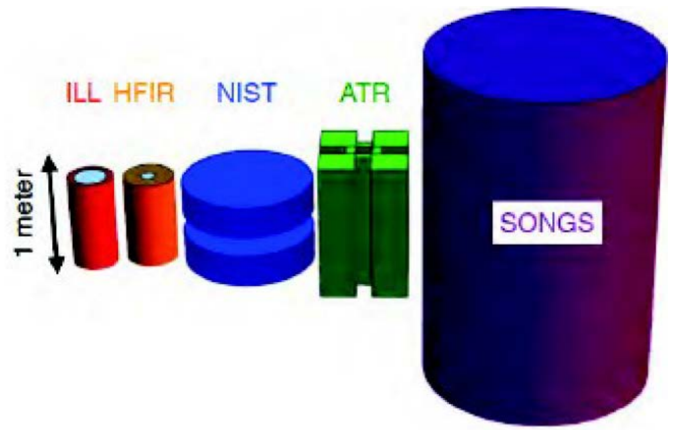
High-powered research reactors

highly-enriched (HEU):
mainly ^{235}U, ~10-100 MW_{th},

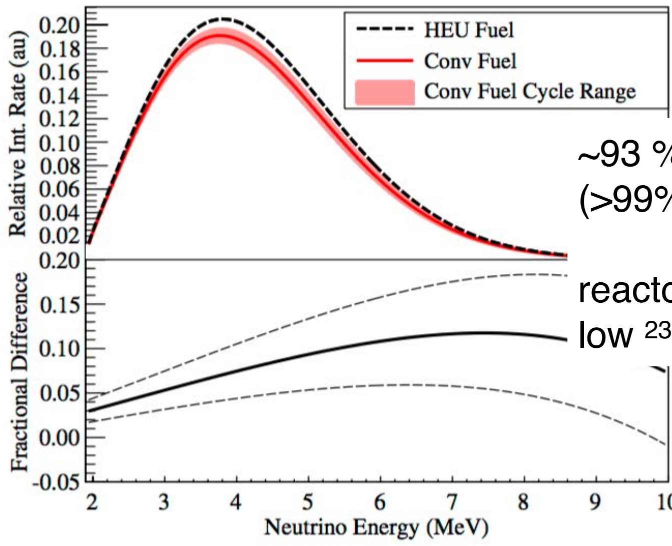
Commercial power reactors

low-enriched (LEU):
many fission isotopes, ~GW_{th}

"Point Source" vs Extended Core



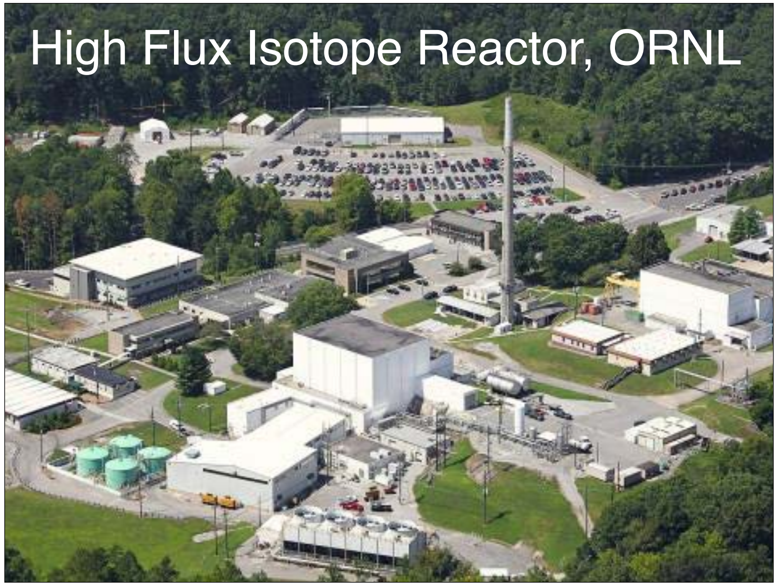
HEU core provides static spectrum of ^{235}U



~93 % ^{235}U enrichment
(>99% $\overline{\nu}_e$ from ^{235}U)

reactor cycles: ~25 days,
low ^{239}P buildup (< 0.5%)

Experimental Site



Access Established on-site operation
User facility, easy 24/7 access

Reactor Core
Power: 85 MW
Core shape: cylindrical
Size: h=0.5m r=0.2m
Duty-cycle: 42%
Fuel: HEU (^{235}U)

>99% of $\overline{\nu}_e$ flux from ^{235}U fission

Surface Neutrino Detection

Very close to research reactor

Reactor-related backgrounds (gammas and thermal n)

Detector will have to operate at the surface (or close to it) so cosmic-ray backgrounds are problematic

Three-pronged approach to backgrounds:

- **New detector design**
- **New liquid scintillator**
- **New shielding design**

PROSPECT Detector Design

154 segments, 119cm x 15cm x 15cm
~25liters per segment, total mass: 4ton

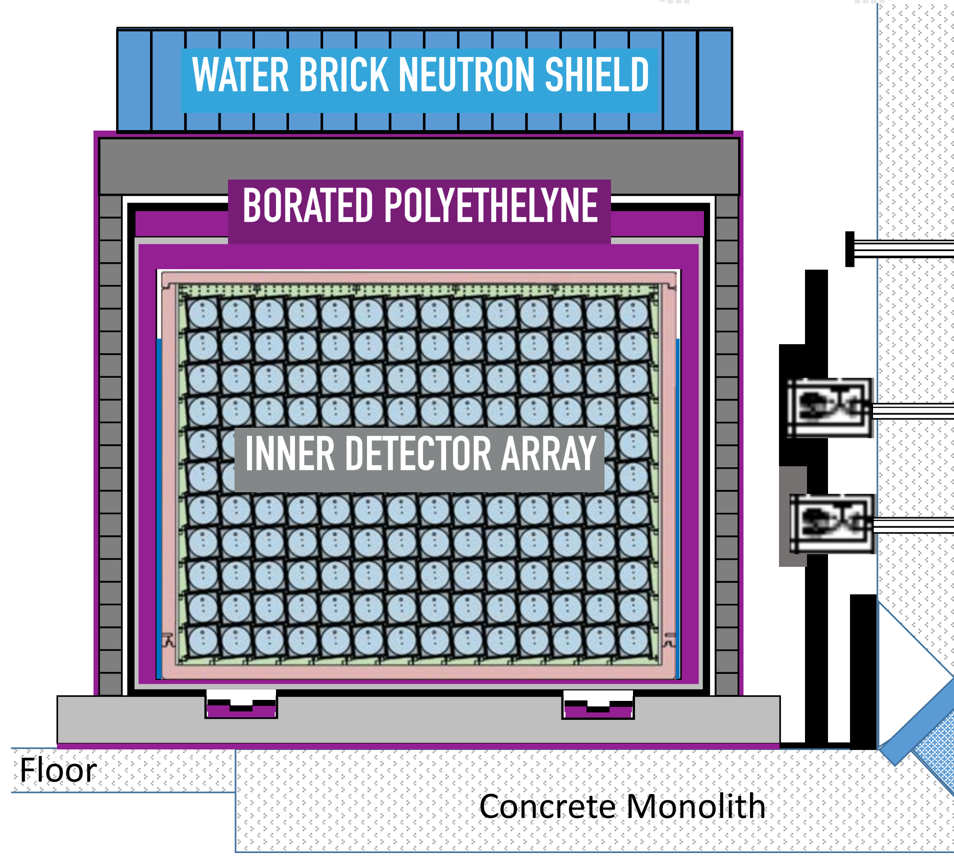
Thin (1.5mm) reflector panels held in place by 3D-printed support rods

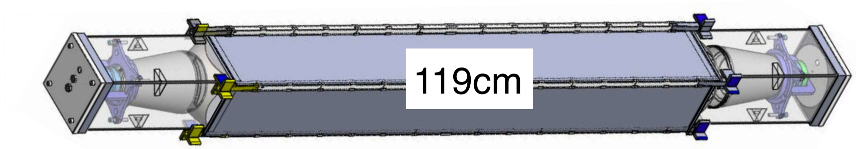
Segmentation enables

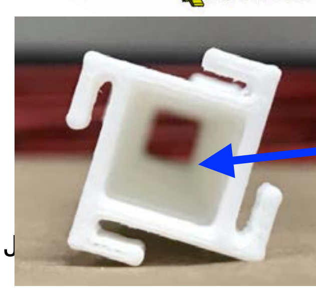
- Calibration access throughout volume
- Position reconstruction (X, Y)
- Event topology ID
- Fiducialization

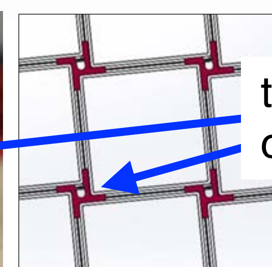
Double ended PMT readout for full (X,Y,Z) position reconstruction

Optimized shielding to reduce cosmogenic backgrounds





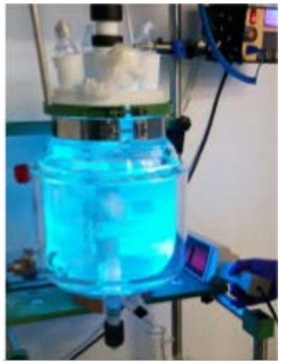




tilted array for calibration access

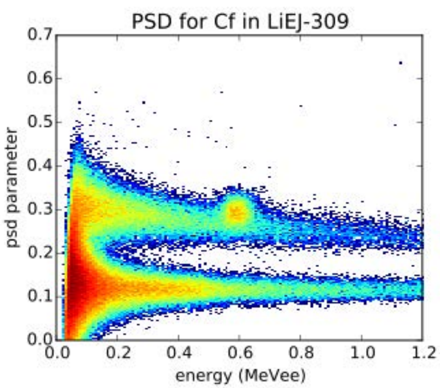
Inner Detector Components

^{6}Li Loaded Liquid Scintillator



Developed non-toxic, non-flammable formulation based on EJ-309

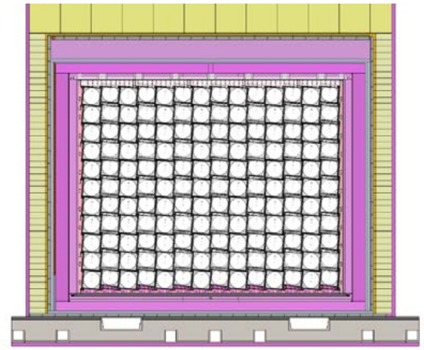
Light Yield
- EJ-309 base: 11500 ph/MeV
- LiLS: 8200 ph/MeV



Excellent PSD performance for neutron capture & heavy recoils

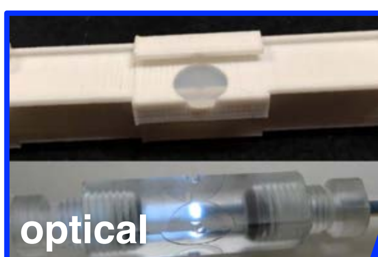
0.1% ^{6}Li loading

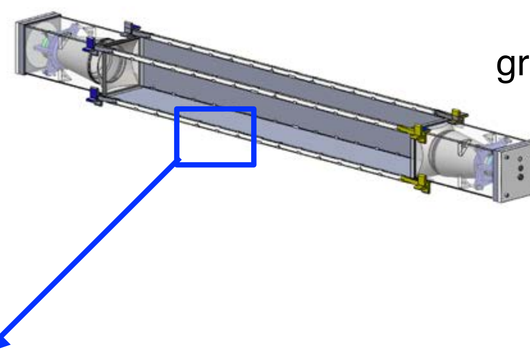
Low mass optical separators



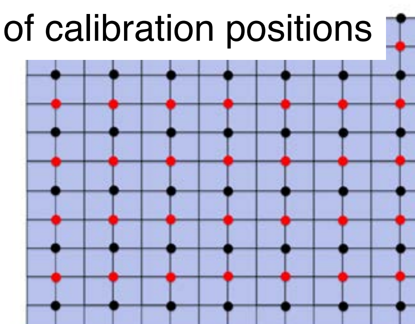
High reflectivity, high-rigidity, low mass reflector system developed

Calibration



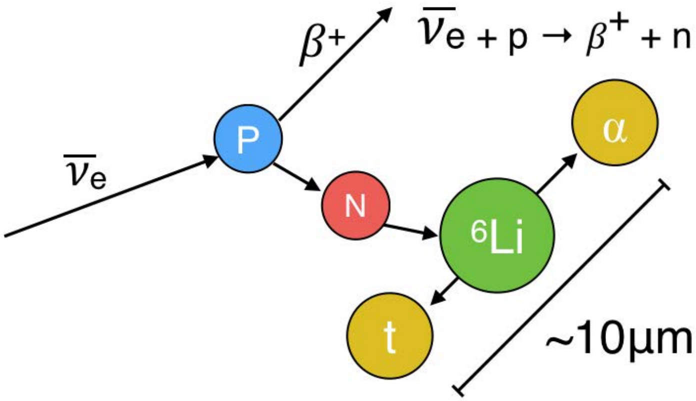


grid of calibration positions



Antineutrino Event Identification with ^{6}Li

Inverse Beta Decay



40μs delayed n capture

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

backgrounds — fast neutron
n-like prompt, n-like delay

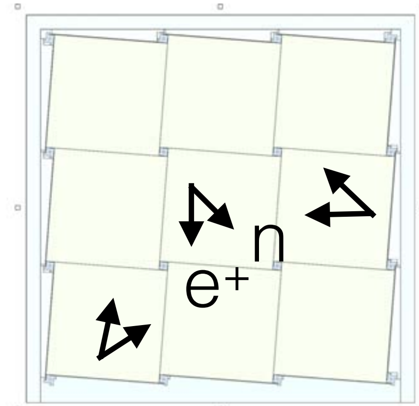
accidental gamma
γ-like prompt, γ-like delay

Background reduction is key challenge

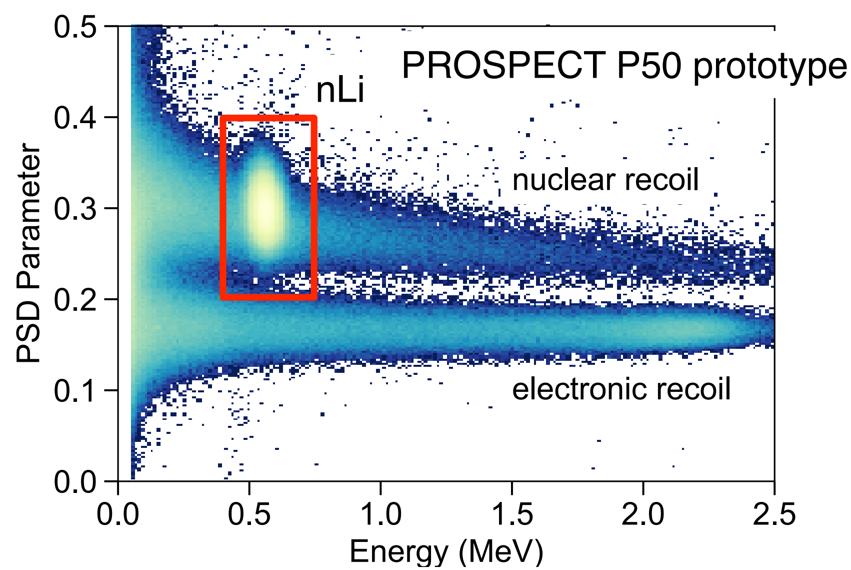
Background Reduction

detector design & fiducialization

IBD event in segmented ^{6}LiLS detector



Pulse Shape Discrimination



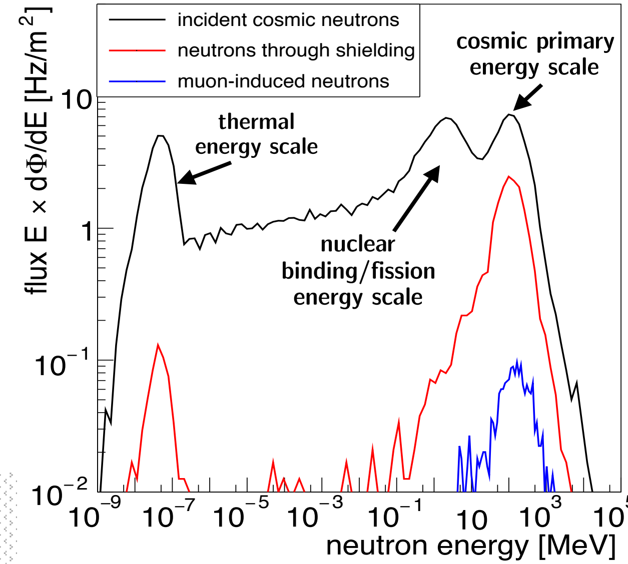
PROSPECT,arXiv:1805.09245

Backgrounds & Shield Design

On-site Measurements

Characterize background field at HFIR, develop localized shielding

PROSPECT, Nucl. Instrum. Meth. A806 (2016) 401–419



PROSPECT Shielding

local shielding next to reactor wall

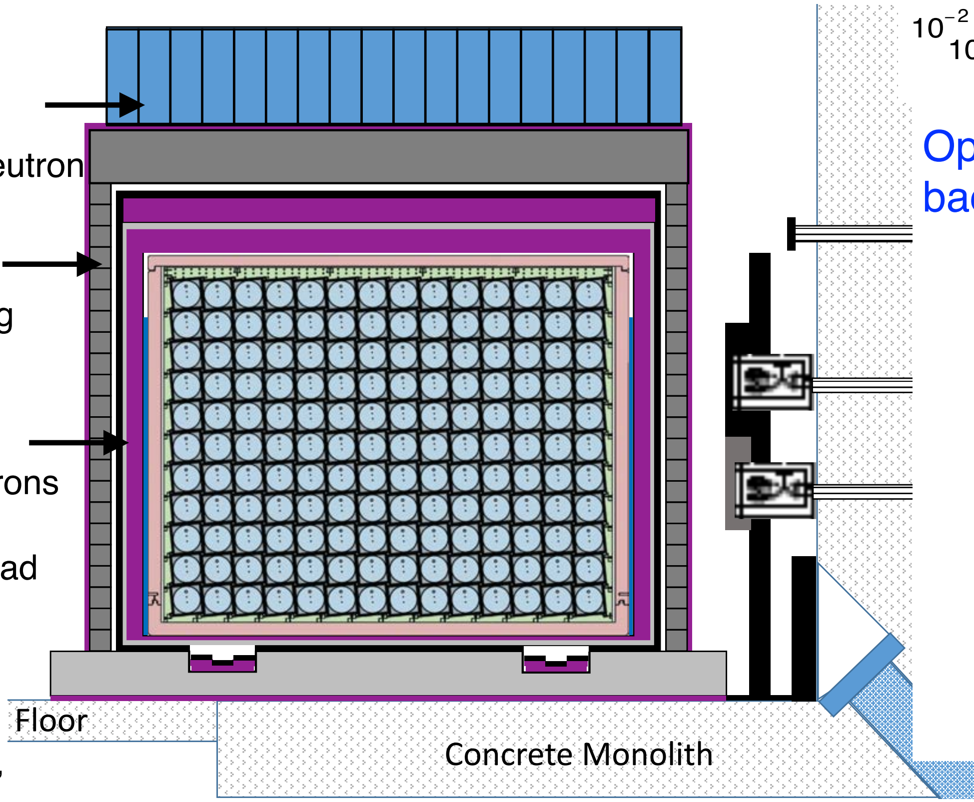
multi-layer passive shield:

water bricks, HDPE, borated HDPE, lead

Water bricks
Polyethylene
Outer neutron shielding for neutron moderation

Lead
High Z shielding

Inner Neutron Shielding
Suppress neutrons produced from spallation on lead



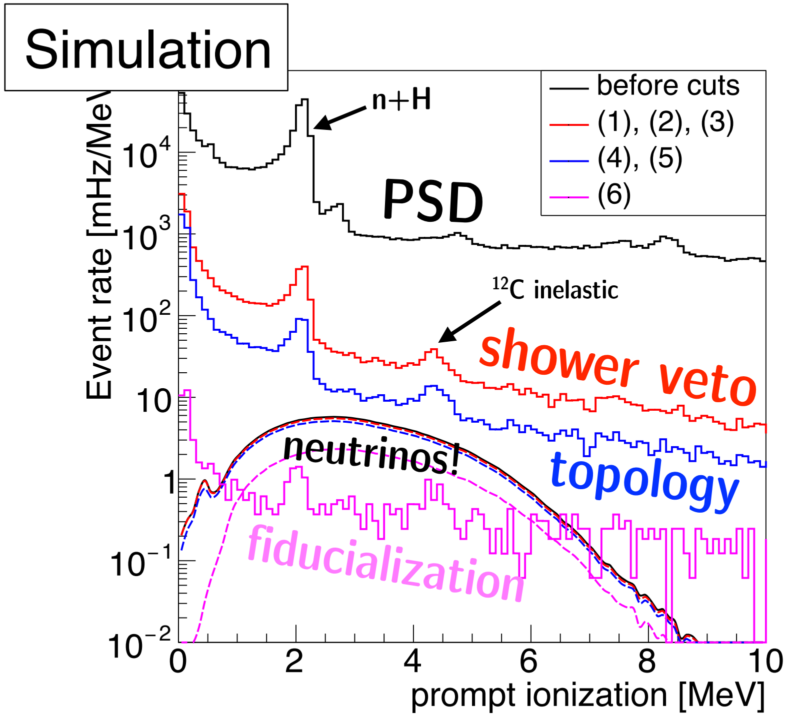
Optimize space, weight, and total background suppression

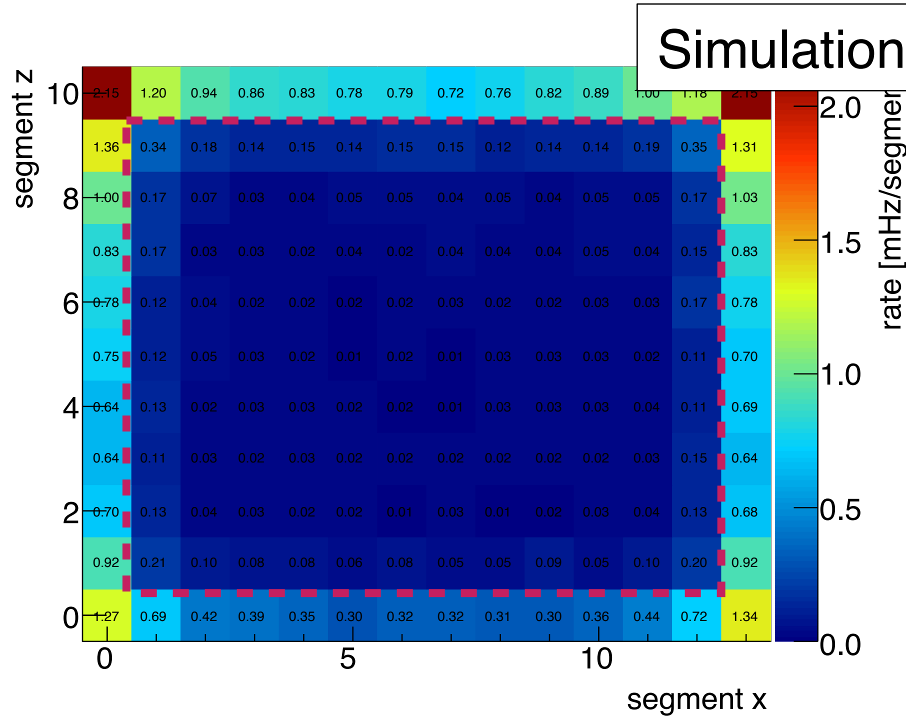
Main problem is ~100MeV neutrons, create majority of IBD-like backgrounds (gamma-like prompt, neutron capture)

Neutron spallation on high-Z shielding increases backgrounds

Need neutron shielding inside lead shielding

Active Background Suppression





PROSPECT Collaboration, J. Phys. G: 43 (2016)

Optimized detector design for background ID and suppression

Combine PSD, shower veto, event topology, and fiducialization

Yields >10^4 active suppression of background

Assembly of First Row
November 1, 2017

Assembly in 30s (video)

Wright Laboratory

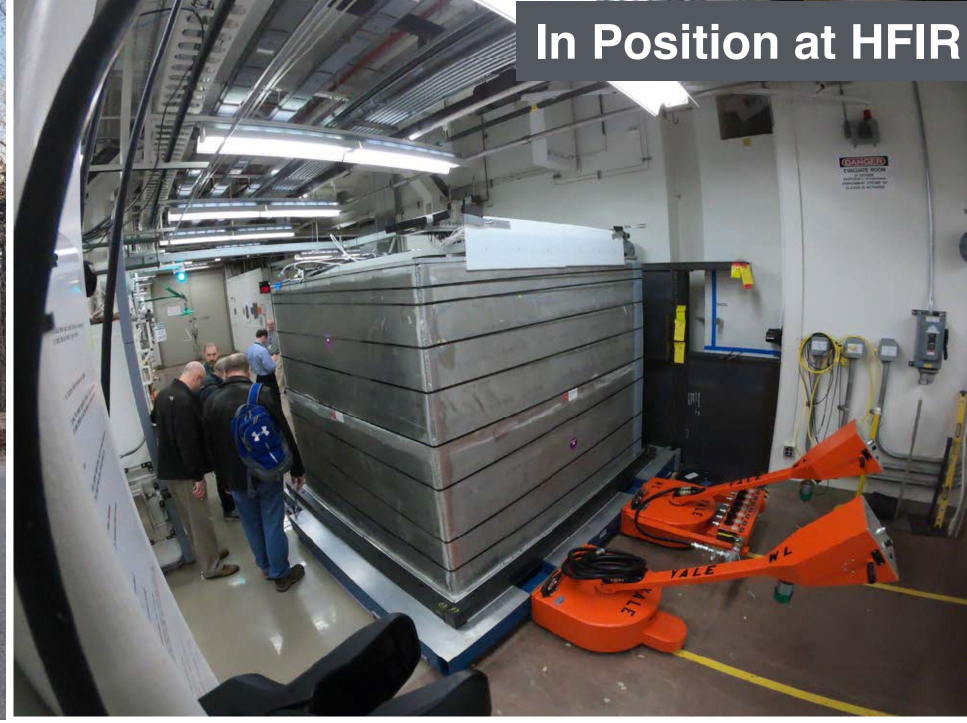
Final Row Installation November 17, 2017

Wright Laboratory

Dry Commissioning
Dec 2017 - Jan 2018

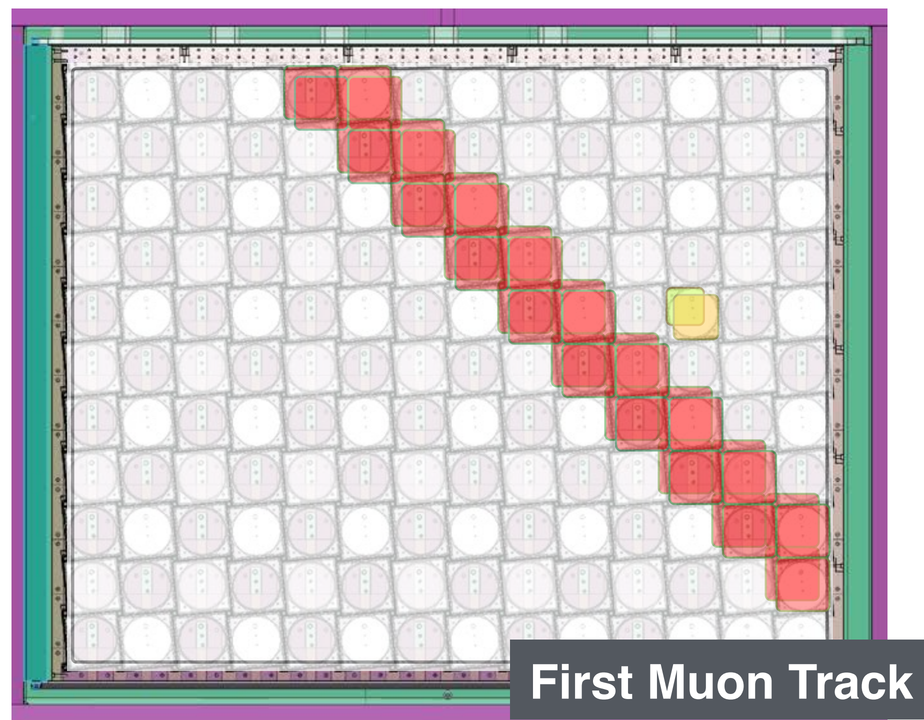
Wright Laboratory

February 2018
Arrival at ORNL



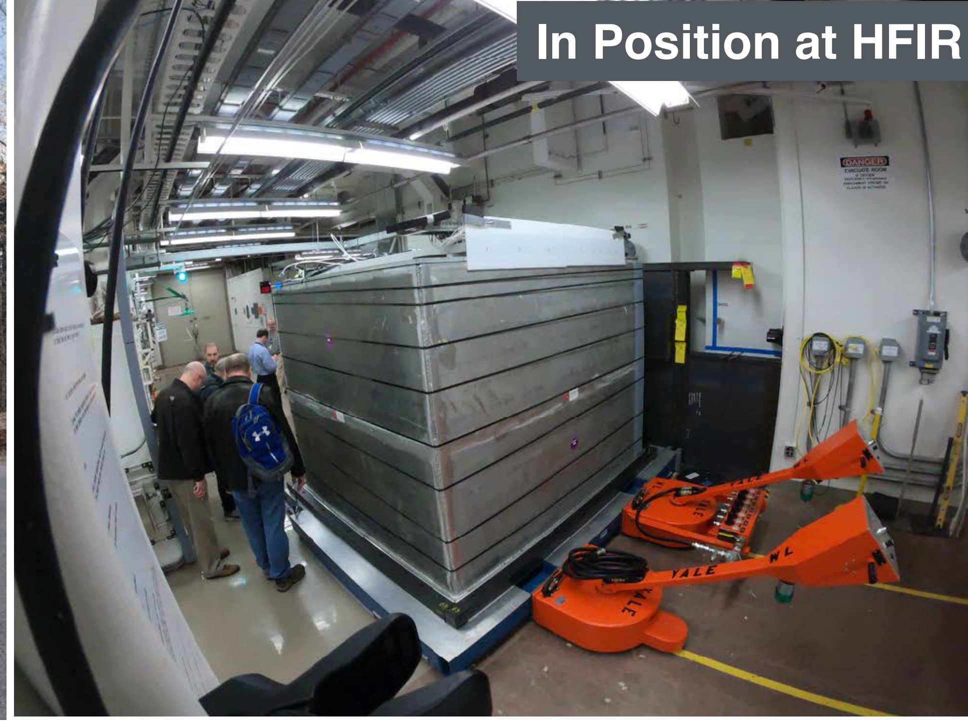
In Position at HFIR

Filling from Mixing Tank



First Muon Track

February 2018
Arrival at ORNL

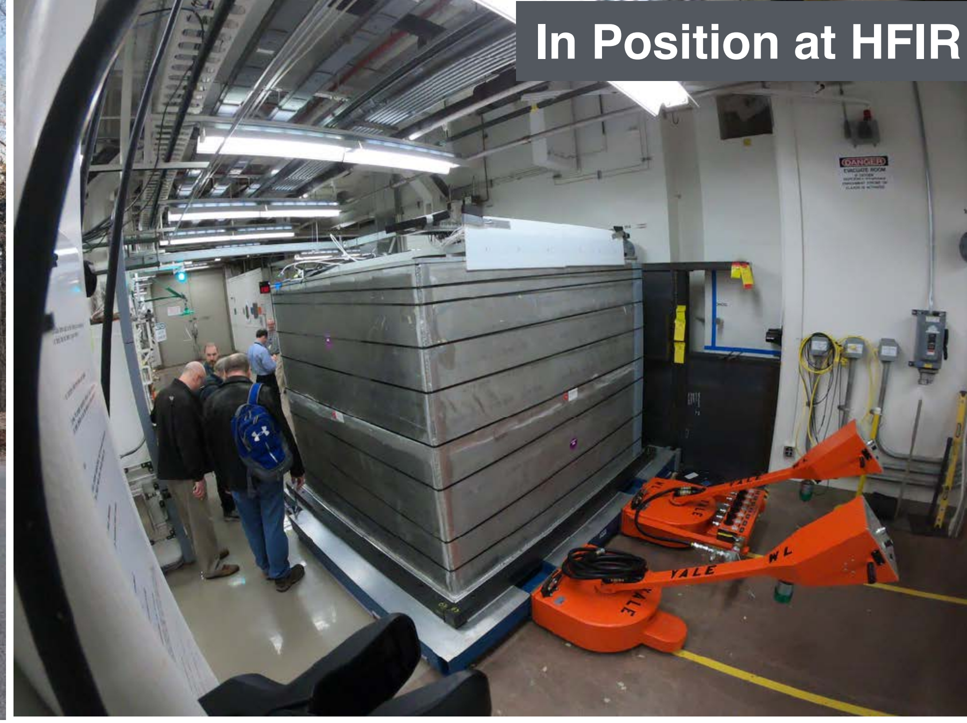


In Position at HFIR

Filling from Mixing Tank

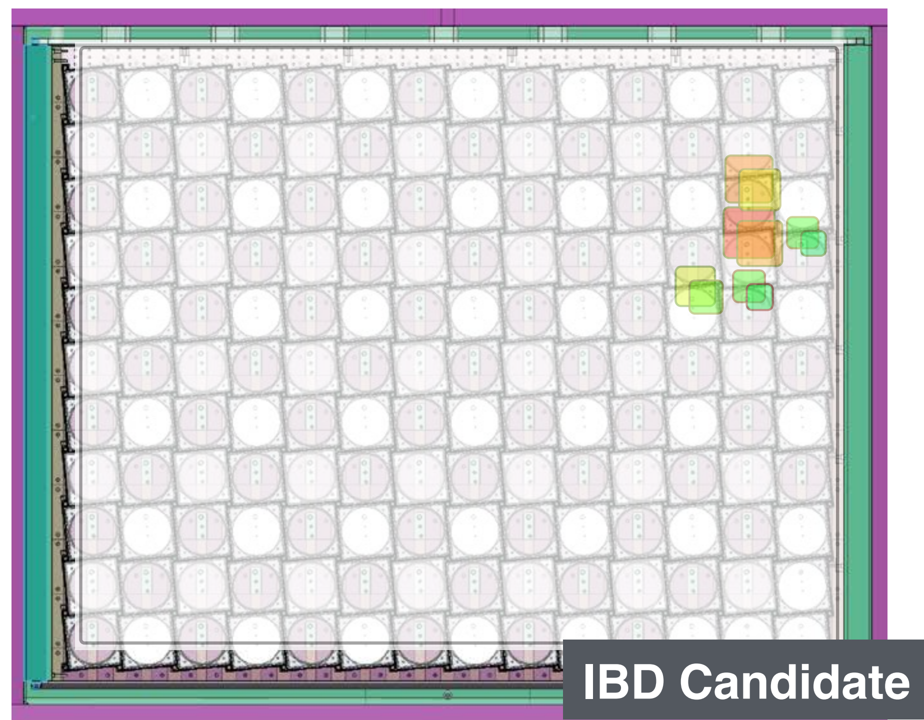
Hadronic Shower


February 2018
Arrival at ORNL



In Position at HFIR

Filling from Mixing Tank


IBD Candidate

Energy Reconstruction

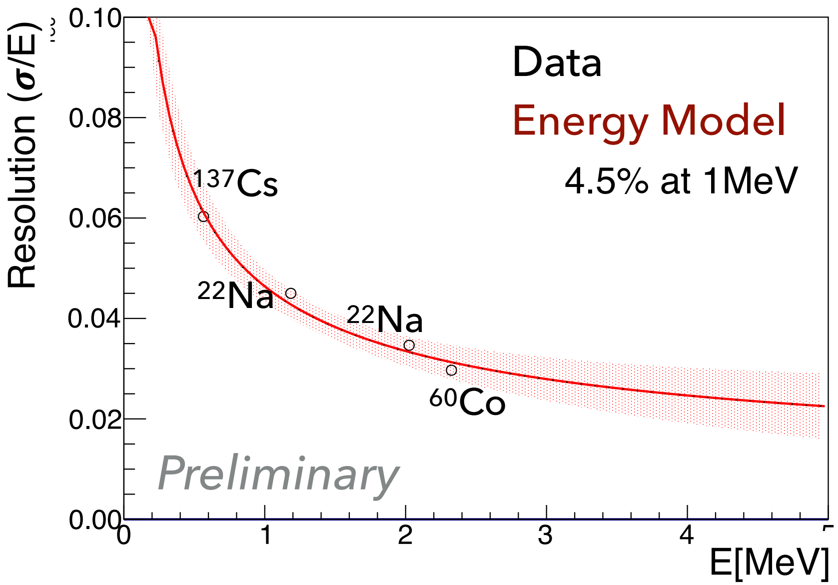
Gamma sources (^{137}Cs, ^{60}Co) deployed throughout detector, measure single segment response

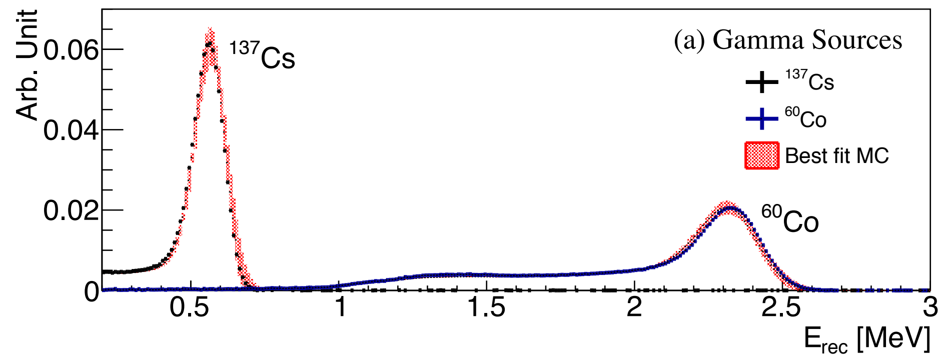
Fast-neutron tagged ^{12}B: High-energy beta spectrum calibration

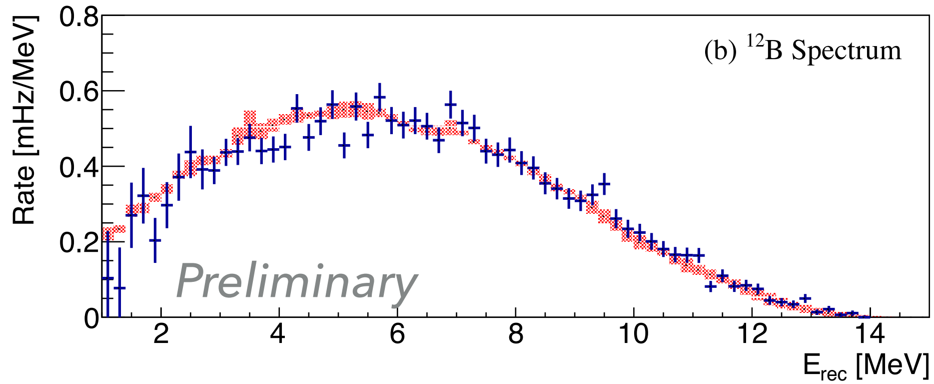
Full-detector E_{rec} within 1% of E_{true}

High light collection: 795±15 PE/MeV

Resolution vs Energy

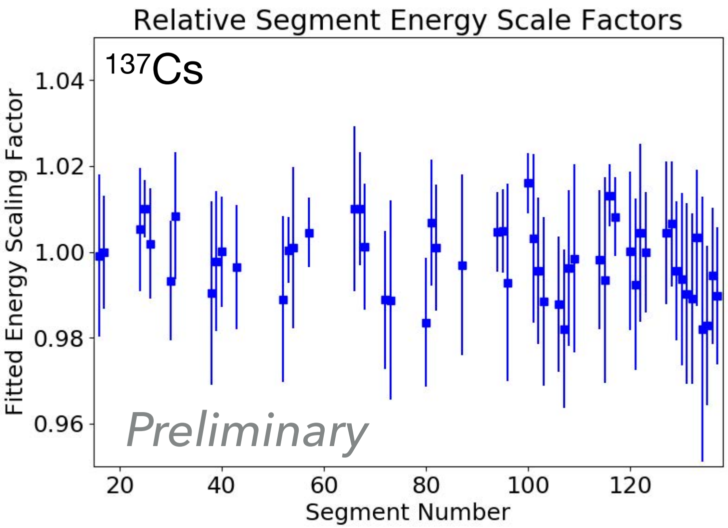


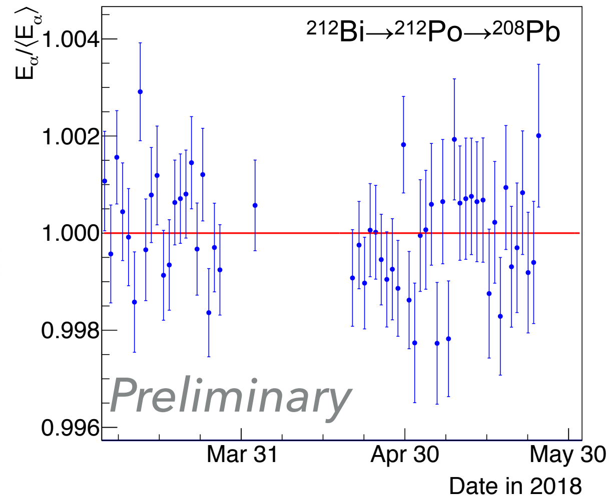


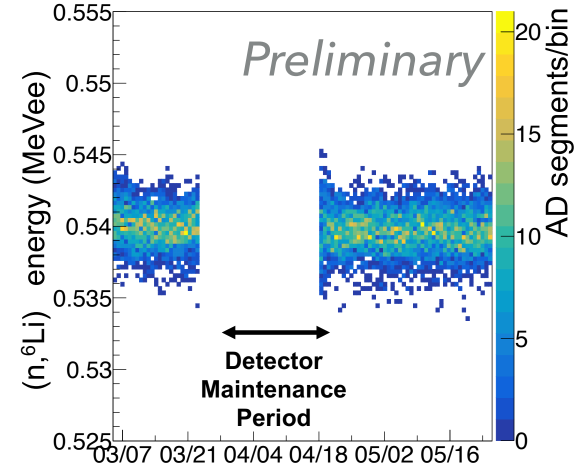


PROSPECT,arXiv:1806.02784

Detector 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%

Effective Segment Volume Measurement

Survey during construction: < 1% variation

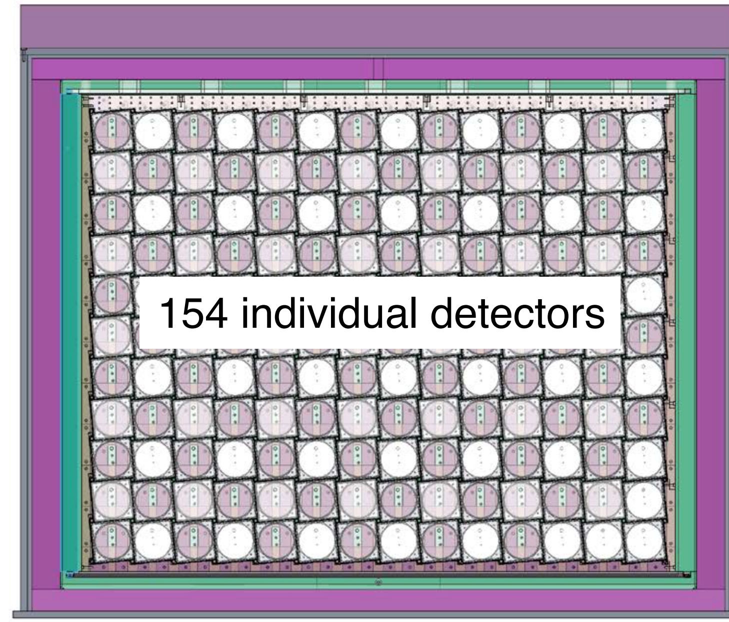
Relative mass vital for oscillation search

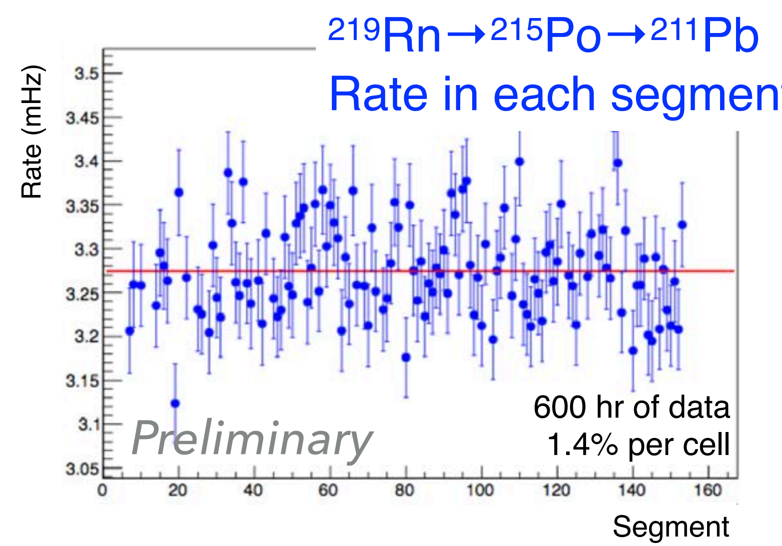
^{227}Ac added to LS prior to filling

Double alpha decay (^{219}Rn→^{215}Po→^{211}Pb), highly localized, easy to ID, 1.78ms lifetime

Measured absolute z-position resolution of < 5cm

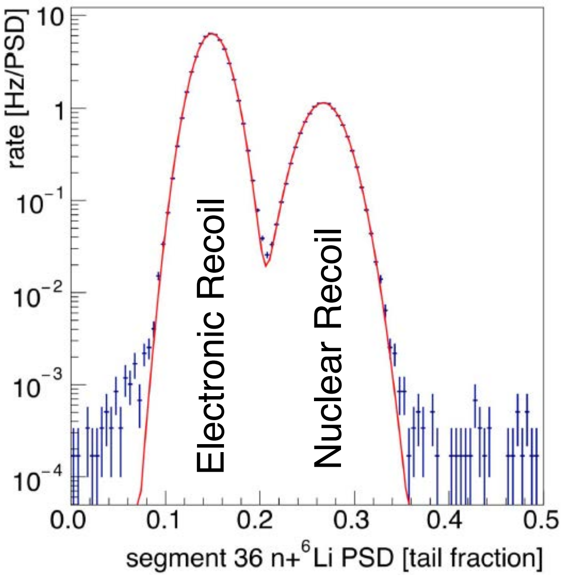
Direct measurement of relative target mass in each segment



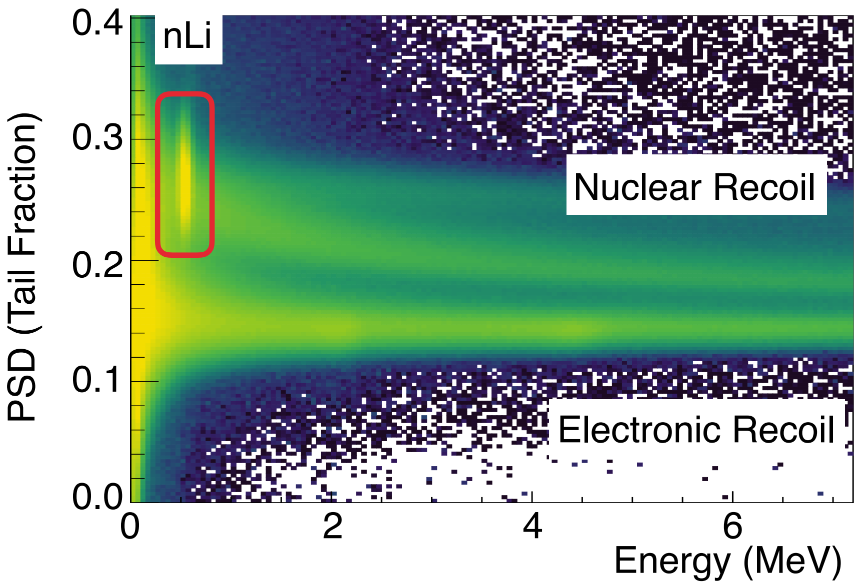


Pulse Shape Discrimination Performance

Single segment



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 24hrs of Detector Operation

PROSPECT

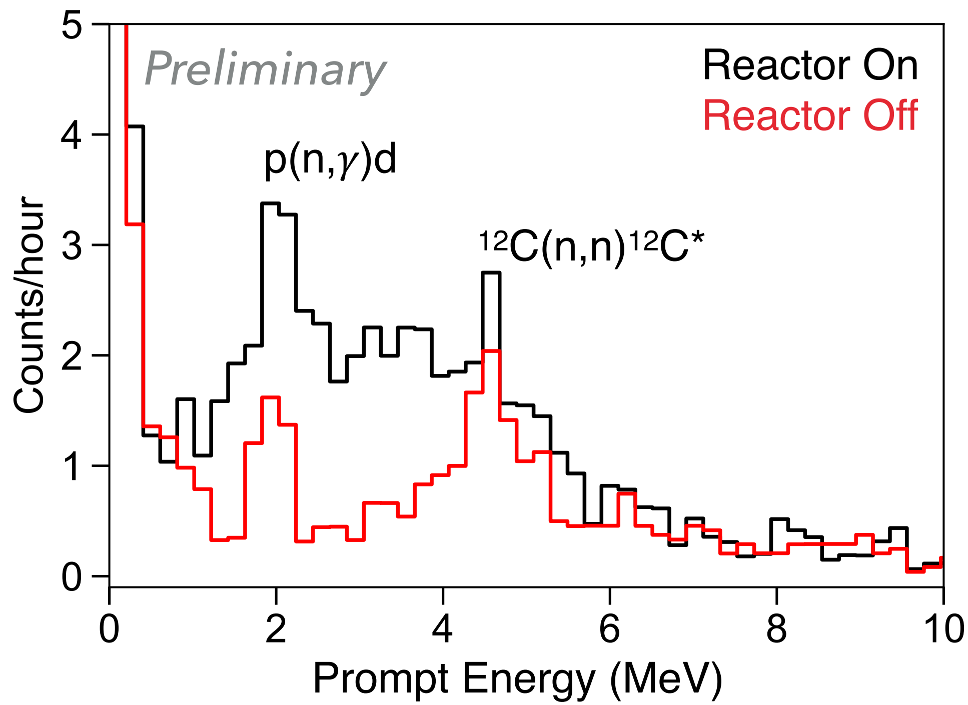
March 5, 2018: Fully assembled detector began operation

Reactor On: 1254±30 correlated events between [.8, 7.2MeV]

Reactor Off: 614±20 correlated events (first off day March 16)

Clear peaks in background from neutron interactions with H and ^{12}C

Time to 5σ detection at earth's surface: ~2hrs



PROSPECT measuring ^{235}U antineutrino spectrum

First Analysis Data Set

33 days of Reactor On

28 days of Reactor Off

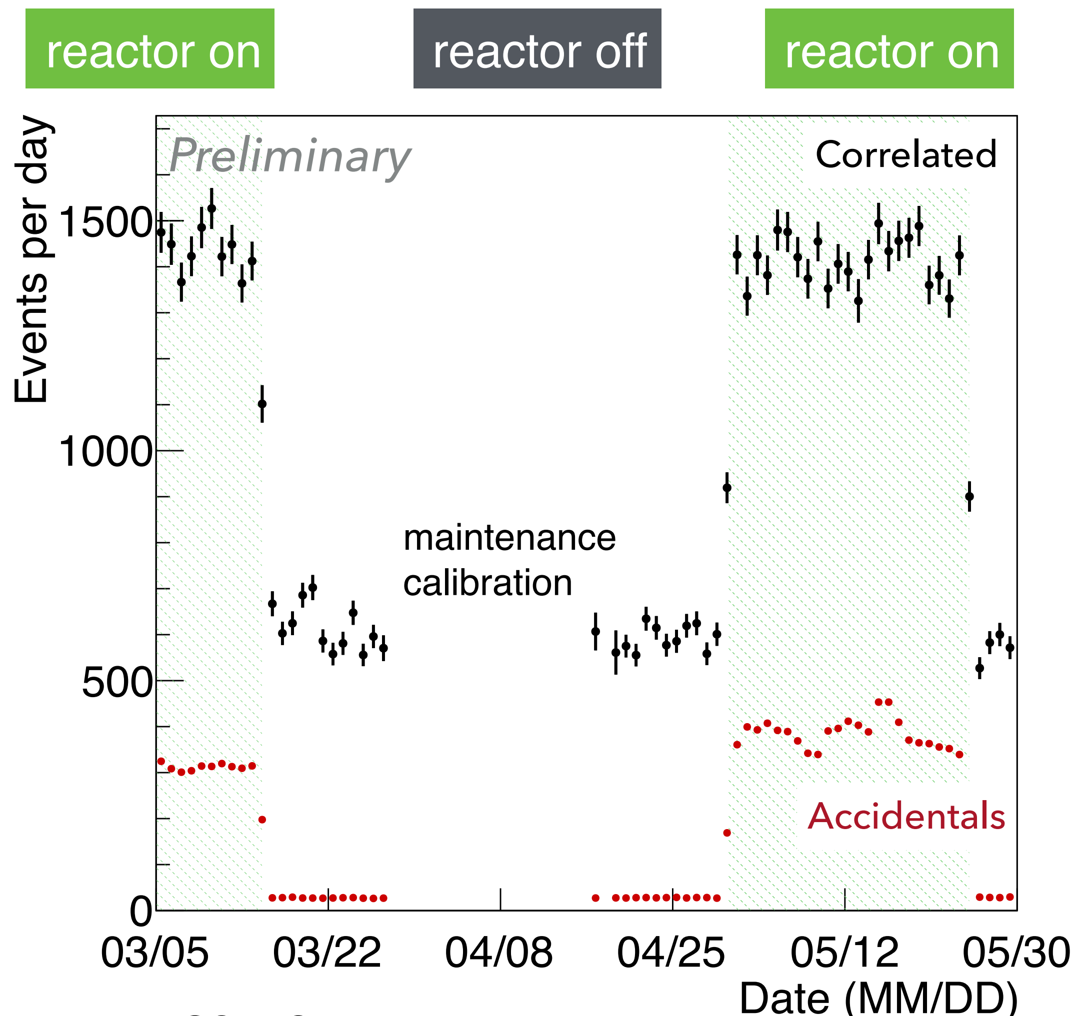
Correlated S/B = 1.36

Accidental S/B = 2.25

24,608 IBDs detected

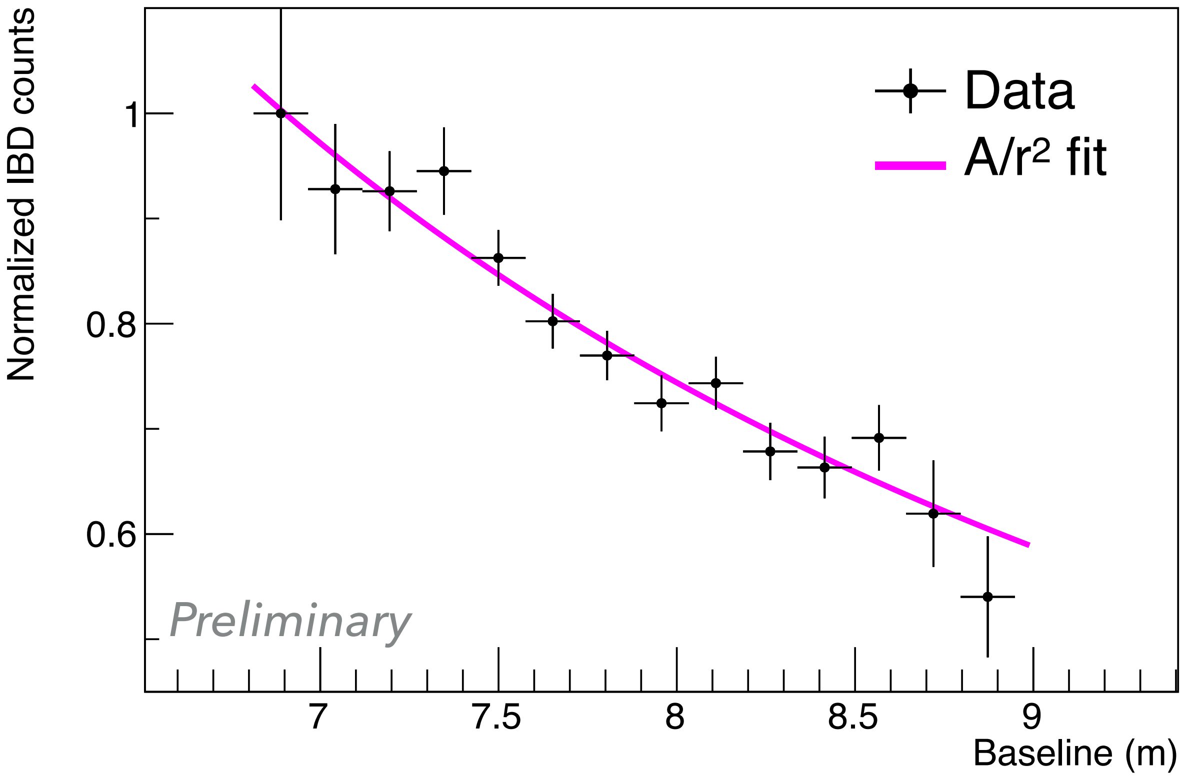
Average of ~750 IBDs/day

IBD event selection defined and frozen on 3 days of data



PROSPECT,arXiv:1806.02784

Neutrino Rate vs Baseline



PROSPECT,arXiv:1806.02784

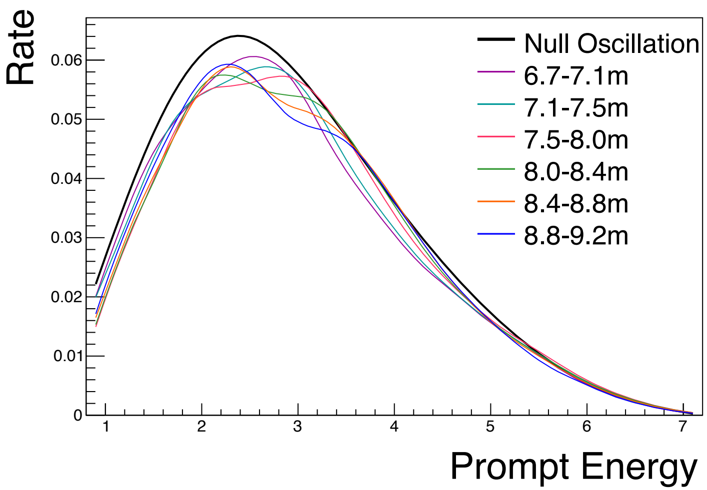
Observation of $1/r^2$ behavior throughout detector volume

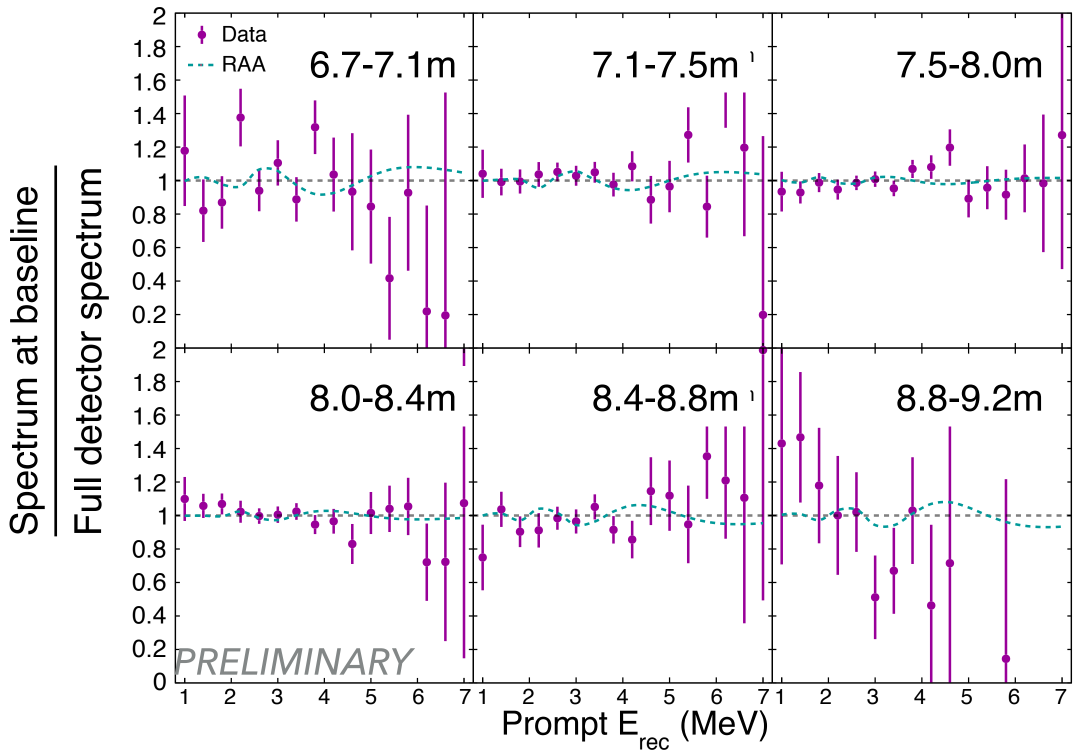
Bin events from 108 fiducial segments into 14 baseline bins

40% flux decrease from front of detector to back

Neutrino Spectrum vs Baseline

Spectral Distortion vs Baseline





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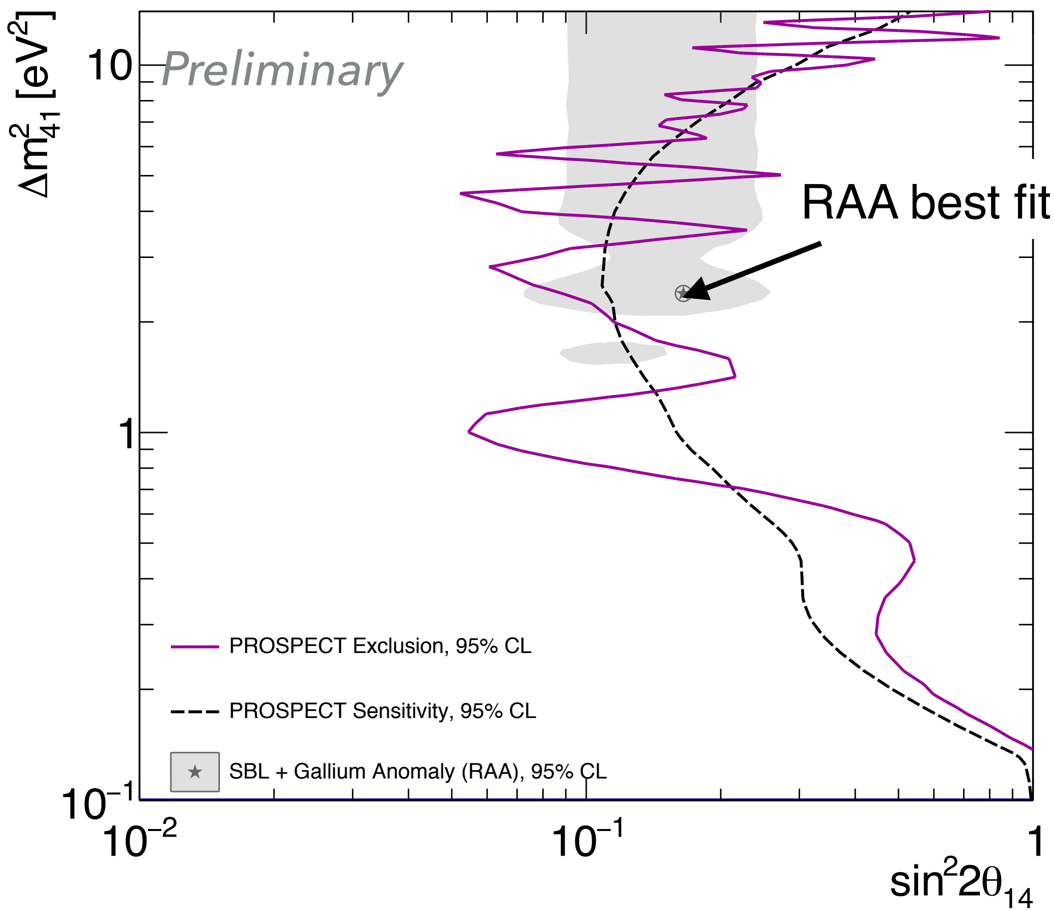
Compare spectra from 6 baselines to measured full-detector spectrum

Null-oscillation would yield a flat ratio for all baselines

Direct ratio search for oscillations, reactor model independent

Oscillation Search Results

- 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
- **Direct test of the Reactor Antineutrino Anomaly**



PROSPECT,arXiv:1806.02784

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

Conclusion and Outlook

PROSPECT started taking data on March 6, 2018

Detector performing well. Background rejection and energy resolution meet expectation and MC.

Observed antineutrinos from HFIR with good signal/background

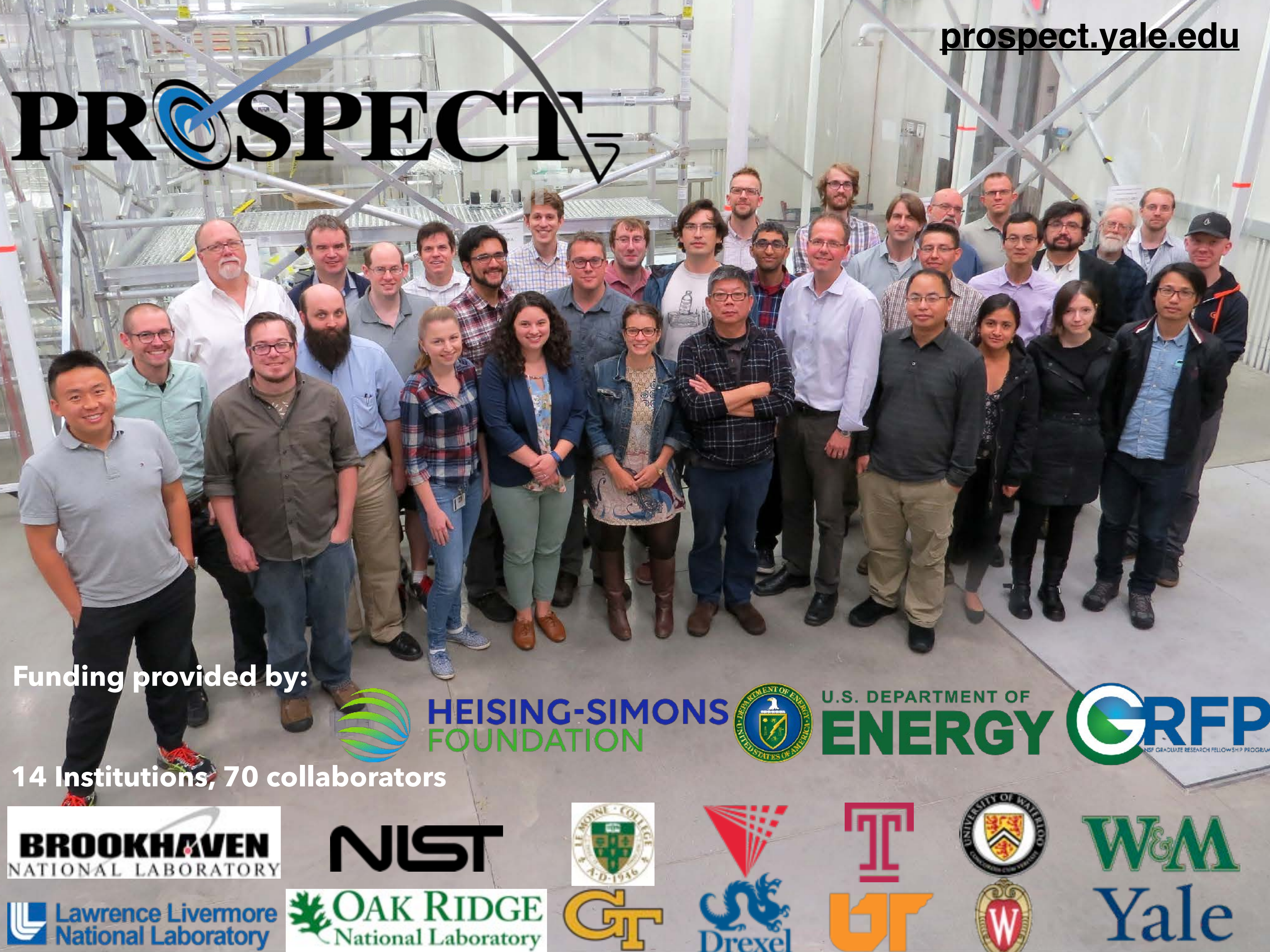
Observed an energy spectrum of antineutrinos at the Earth's surface (1mwe overburden) with 24 hours of data

Working towards a high-statistics ^{235}U spectrum measurement

Opportunity for detailed understanding of cosmogenic backgrounds

First oscillation analysis on 33 days of reactor-on data disfavors the RAA best-fit at 2.3σ (arXiv: 1806.02784)

Based on results of PROSPECT and other experiments sterile neutrinos are increasingly disfavored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